## **— BACKGROUNDS — GRAVITATIONAL WAVE**



**MITP Summer School - CrossLinks of Early Universe Cosmology, 15 July - August 2, 2024**

## **Gravitational Wave Backgrounds**

### **OUTLINE**





*}*

**(Briefly)**

- **2) GWs from Inflation**
- **3) GWs from Preheating**
- **4) GWs from Phase Transitions**
- **5) GWs from Cosmic Defects**
- **6) Astrophysical Background(s)**
- **7) Observational Constraints/Prospects**

## **Gravitational Wave Backgrounds**

### **OUTLINE**

**1) Grav. Waves (GWs)**

**Early Universe Farly<br>Universe<br>Sources** 

**2) GWs from Inflation 3) GWs from Preheating**

**4) GWs from Phase Transitions**

**5) GWs from Cosmic Defects** 

**6) Astrophysical Background(s)**

**7) Observational Constraints/Prospects**



**1st Topic**

**(Formal Th.)**

**(Briefly)**

# **The Gravity of the Situation …**

### $\blacksquare$  in Cosmology **GW Propagation/Creation**

**FLRW:** 
$$
ds^2 = a^2(-dt^2 + (\delta_{ij} + h_{ij})dx^idx^j)
$$
,  $TT : \begin{cases} h_{ii} = 0 \\ h_{ij,j} = 0 \end{cases}$   
(conformal time)

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**Creation/Propagation GWs in FLRW** *•* GW: *ds*<sup>2</sup> <sup>=</sup> *<sup>a</sup>*<sup>2</sup>(*d*⌘<sup>2</sup> + (*ij* <sup>+</sup> *<sup>h</sup>ij* )*dx<sup>i</sup>* Transverse-Traceless (TT) dof carry energy out of the source!!!

*dx<sup>j</sup>* )*,* TT : ⇢ *<sup>h</sup>ii* = 0 **Source: Anisotropic Stress** 

$$
\Pi_{ij}=T_{ij}-\langle T_{ij}\rangle_{\text{FLRW}}
$$

 $\text{Eom:}$   $h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = 16\pi G \Pi_{ij}^{\text{TT}}$   $\left| \Pi_{ij} = T_{ij} - \langle T_{ij} \rangle \right|$ 

### **1. Gravitation Cosmology** 1. German Waves (GWS) [Basic Company] **GW Propagation/Creation in Cosmology**

**FLRW:** 
$$
ds^2 = a^2(-dt^2 + (\delta_{ij} + h_{ij})dx^idx^j)
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,  $TT: \begin{cases} h_{ii} = 0 \\ h_{ij,j} = 0 \end{cases}$   
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*•* GW: *ds*<sup>2</sup> <sup>=</sup> *<sup>a</sup>*<sup>2</sup>(*d*⌘<sup>2</sup> + (*ij* <sup>+</sup> *<sup>h</sup>ij* )*dx<sup>i</sup>* Transverse-Traceless (TT) dof carry energy out of the source!!! *ij* + 2*Hh*<sup>0</sup> *ij* r<sup>2</sup>*hij* = 16⇡*G*⇧TT **Creation/Propagation GWs in FLRW Source: Anisotropic Stress**

*dx<sup>j</sup>* )*,* TT : ⇢ *<sup>h</sup>ii* = 0 *hij ,<sup>j</sup>* = 0 *i*<br> **i** PW Courge: Anisotronia Stro

$$
\text{Eom:} \left[ h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = 16\pi G \Pi_{ij}^{\text{TT}} \right] \quad \left[ \Pi_{ij} = T_{ij} - \langle T_{ij} \rangle_{\text{FLRW}} \right]
$$

$$
\begin{aligned}\n\text{GW Source(s)} \quad & (\text{SCALARS} \quad , \quad \text{VECTOR} \quad , \quad \text{FERMIONS} \text{)} \\
\Pi_{ij}^{TT} \propto \quad & \{ \partial_i \chi^a \partial_j \chi^a \}^{TT}, \quad \{ E_i E_j + B_i B_j \}^{TT}, \quad \{ \bar{\psi} \gamma_i D_j \psi \}^{TT}\n\end{aligned}
$$

### **Cosmic History**

 **BiGGER size,**



 **(13.700 Million years)**

 **FIRST GALAXIES (500 Millions years)**

 **ATOMS CREATION (300.000-400.000 years)**

 **ATOMIC NUCLEI CREATION (3 minutes !)**

 **of the UNIVERSE !**

 **SMALLER SIZE, LARGER Temperature**

### **Cosmic History**

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### **Cosmic History**

 **BiGGER size,**

**SMALLER Temp TODAY [Galaxies, Clusters, ...] (13.700 Million years) ATOMS CREATION (300.000-400.000 years) FIRST GALAXIES (500 Millions years) ATOMIC NUCLEI CREATION (3 minutes !) FIRST SECOND of the UNIVERSE !**  $\overline{\mathcal{L}}$ *dρ*GW  $\left(\frac{d \log f}{d \log f}\right)(f; t_o)$  $\Pi_{ij}^{\mathrm{TT}}[\boldsymbol{\phi},A_{\mu},\psi,\dots]$ 

 **SMALLER SIZE, LARGER Temperature**

### W ener 32⇡*Ga*2(*t*) D *i* densi E *V* **dectrum** GW energy density spectrum

32⇡*Ga*2(*t*) *V V* aii, trom previc Recall, from previous lecture on

32⇡*Ga*2(*t*) (2⇡)<sup>3</sup> (2⇡)<sup>3</sup> *<sup>h</sup>*˙ *ij* (k*, t*)*h*˙ ⇤ **M dix** *e*<sup>*i*</sup> **e**<sup>*i*</sup> the energy-momentum of GW

### $\overline{I}$ FW energy gensity speci TT-part of the cosmic defects energy-momentum tensor. The cosmic defects energy-momentum tensor. The cosmic de D *h*˙ *ij* (k*, t*) *h*˙ ⇤ W ener 32⇡*Ga*2(*t*) D *i* densi E *V* **dectrum** GW energy density spectrum

### Spectrum of gravitational waves 32⇡*Ga*2(*t*) *V V* Expanding the Einstein equations to second order in the energy-momentum of GW density of a Gw background is given by  $\mathcal{O}(t)$ 1 Z *d*k *d*k0 Recall, from previous lecture on 32⇡*Ga*2(*t*) (2⇡)<sup>3</sup> (2⇡)<sup>3</sup> *<sup>h</sup>*˙ *ij* (k*, t*)*h*˙ ⇤ **M dix** *e*<sup>*i*</sup> **e**<sup>*i*</sup> the energy-momentum of GW

$$
\rho_{\rm GW}(t) = \frac{1}{32\pi G a^2(t)} \left\langle \dot{h}_{ij}(\mathbf{x},t) \dot{h}_{ij}(\mathbf{x},t) \right\rangle_V \qquad \text{t: conformal time}
$$
\n
$$
\equiv \frac{1}{32\pi G a^2(t)} \frac{1}{V} \int_V d\mathbf{x} \, \dot{h}_{ij}(\mathbf{x},t) \dot{h}_{ij}(\mathbf{x},t)
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$$

$$
(V^{1/3}\gg\lambda)
$$

)) ⌘ (*k* cos[*k*(*t t*

### **GW energy density spectrum**   $\overline{I}$ FW energy gensity speci TT-part of the cosmic defects energy-momentum tensor. The cosmic defects energy-momentum tensor. The cosmic de D *h*˙ *ij* (k*, t*) *h*˙ ⇤

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$$
  
\n
$$
= \frac{1}{32\pi Ga^2(t)} \int \frac{d\mathbf{k}}{(2\pi)^3} \frac{d\mathbf{k}'}{(2\pi)^3} \, \dot{h}_{ij}(\mathbf{k},t)\dot{h}_{ij}^*(\mathbf{k}',t)
$$
  
\n
$$
\times \frac{1}{V} \int_V d\mathbf{x} \, e^{-i\mathbf{x}(\mathbf{k}-\mathbf{k}')} \,,
$$

 $\overline{\lambda}$ 

*d* log *k*

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$$
\n
$$
\times \frac{1}{V} \underbrace{\left(2\pi\right)^3 \delta(\mathbf{k} - \mathbf{k}')}_{(kV^{1/3} \longrightarrow \infty)}
$$

 $\overline{\lambda}$ 

*d* log *k*

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$$
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$$
  
= 
$$
\frac{1}{32\pi Ga^2(t)} \frac{1}{V} \int_V d\mathbf{x} \, \dot{h}_{ij}(\mathbf{x},t)\dot{h}_{ij}(\mathbf{x},t)
$$
  
= 
$$
\frac{1}{32\pi Ga^2(t)V} \int \frac{d\mathbf{k}}{(2\pi)^3} \, \dot{h}_{ij}(\mathbf{k},t)\dot{h}_{ij}^*(\mathbf{k},t)
$$

$$
(V^{1/3}\gg\lambda)
$$

where *G*(*k*(*t t*

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$$
  
\n
$$
= \int d\log k \left( \frac{1}{(4\pi)^3Ga^2(t)V} \left\langle \dot{h}_{ij}(\mathbf{k},t) \dot{h}_{ij}^*(\mathbf{k},t) \right\rangle_{\Omega_k} \right)
$$
  
\n
$$
\left[ \left\langle |f(\mathbf{k})|^2 \right\rangle_{\Omega_k} = \frac{1}{4\pi} \int_{|\mathbf{k}|=k} d\Omega_k |f(\mathbf{k})|^2 \right]
$$

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$$
\n
$$
= \int d\log k \left[ \left( \frac{1}{(4\pi)^3Ga^2(t)V} \left\langle \dot{h}_{ij}(\mathbf{k},t)\dot{h}_{ij}^*(\mathbf{k},t) \right\rangle_{\Omega_k} \right) \right] \text{Energy density}
$$
\n
$$
\left[ \left\langle |f(\mathbf{k})|^2 \right\rangle_{\Omega_k} = \frac{1}{4\pi} \int_{\mathbb{R}^2} d\Omega_k |f(\mathbf{k})|^2 \right] \qquad \equiv \left( \frac{d\rho_{\rm GW}}{d\log k} \right) (k,t)
$$

# **Primer on Inflation**

# **(Brief review) Inflation**











$$
ds^{2} = -(1 + 2\Phi)dt^{2} + 2B_{i}dx^{i}dt + a^{2}[(1 - 2\Psi)\delta_{ij} + E_{ij}]dx^{i}dx^{j}
$$

$$
\phi(\vec{x}, t) = \phi(t) + \delta\phi(\vec{x}, t)
$$

$$
ds2 = -(1+2\Phi)dt2 + 2Bidxidt + a2[(1-2\Psi)\deltaij + Eij]dxidxj
$$

$$
\phi(\vec{x},t) = \phi(t) + \delta\phi(\vec{x},t)
$$

$$
ds^{2} = -(1+2\Phi)dt^{2} + \mathfrak{L}B_{i}dx^{i}dt + a^{2}[(1-2\Psi)\delta_{ij} + \mathfrak{L}_{ij}]dx^{i}dx^{j}
$$

$$
\phi(\vec{x},t) = \phi(t) + \delta\phi(\vec{x},t)
$$

$$
E_{ij} = 2\partial_{ij}E + 2\partial_{(i}F_{j)} + h_{ij}
$$

**Inflation: Generator of Primordial Fluctuations**



Expanding U.  $\longrightarrow$  Vector Perturbations  $S_i, F_i \propto \frac{1}{a}$ 1 *a*

$$
ds^{2} = -(1 + 2\Phi)dt^{2} + \Omega B_{i}dx^{i}dt + a^{2}[(1 - 2\Psi)\delta_{ij} + E_{ij}]dx^{i}dx^{j}
$$

$$
\phi(\vec{x}, t) = \phi(t) + \delta\phi(\vec{x}, t)
$$

$$
E_{ij} = 2\partial_{ij}E + 2\partial_{i}F_{j} + h_{ij}
$$

$$
\partial_{i}h_{ij} = h_{ii} = 0
$$
(tensors = GWs)

$$
ds^{2} = -(1 + 2\Phi)dt^{2} + 2B_{i}dx^{i}dt + a^{2}[(1 - 2\Psi)\delta_{ij} + E_{ij}]dx^{i}dx^{j}
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$$



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ds^{2} = -(1 + 2\Phi)dt^{2} + 2B_{i}dx^{i}dt + a^{2}[(1 - 2\Psi)\delta_{ij} + E_{ij}]dx^{i}dx^{j}
$$
\n
$$
\phi(\vec{x}, t) = \phi(t) + \delta\phi(\vec{x}, t)
$$
\n
$$
\zeta \equiv -[\Psi + (H/\rho)\delta\rho_{\phi}] \xrightarrow{\text{Diff. } \zeta}
$$
\n
$$
\text{dof } \xrightarrow{\text{seals}^{\text{max}} \delta\phi + \{\Phi, B, \Psi, E\}}
$$
\n
$$
\zeta \equiv [\Psi + (H/\phi)\delta\phi] \xrightarrow{\text{Diff. } \zeta}
$$
\n
$$
\mathcal{R} \equiv [\Psi + (H/\phi)\delta\phi] \xrightarrow{\text{Diff. } \zeta}
$$
\n
$$
Q \equiv [\delta\phi + (\dot{\phi}/H)\Psi] \xrightarrow{\text{Diff. } Q} \qquad \text{Im } \mathbf{V}.
$$

\n $ds^2 = -(1 + 2\Phi)dt^2 + 2B_i dx^i dt + a^2[(1 - 2\Psi)\delta_{ij} + E_{ij}]dx^i dx^j$ \n
\n $\phi(\vec{x}, t) = \phi(t) + \delta\phi(\vec{x}, t)$ \n
\n $\text{seals}^s$ \n
\n $\phi(\vec{x}, t) = \phi(t) + \delta\phi(\vec{x}, t)$ \n
\n $\xi = -[\Psi + (H/\phi)\delta\rho_{\phi}] \xrightarrow{\text{Diff.}} \zeta$ \n
\n $R = [\Psi + (H/\phi)\delta\phi] \xrightarrow{\text{Diff.}} \eta$ \n
\n $Q = [\delta\phi + (\dot{\phi}/H)\Psi] \xrightarrow{\text{Diff.}} Q$ \n
\n $Q = [\delta\phi + (\dot{\phi}/H)\Psi] \xrightarrow{\text{Diff.}} Q$ \n

\n**Curvature Fert.** (GW)

\n\n**First Part. (GW)**\n

### **Inflation & Primordial Perturbations**



### **Inflation & Primordial Perturbations**




$$
\left\langle f(\mathbf{k})f^*(\mathbf{k}') \right\rangle \equiv (2\pi)^3 \frac{2\pi^2}{k^3} \Delta_f^2(k) \delta(\mathbf{k} - \mathbf{k}') \right\}
$$

# **Quantum fluctuations !**









# **INFLATIONARY COSMOLOGY**



#### **Irreducible GW background from Inflation** stochastic nature of the emerging classical field distribution. The quantum-to-classical transition, which occurs basically when the modes leave the Hubble radius, is studied *ij* . Hence, in these scenarios, the (spatial-spatial comeducible GW background from I by *Tij* = *T* pf *ij* + *T* def *ij* . It is clear then that ⇧*ij* = *T* def power spectrum of the tensor perturbation first derivalatı

$$
\hat{h}_{ij}(\mathbf{x},t) = \sum_{r=+,\times} \int \frac{d^3 \mathbf{k}}{(2\pi)^{3/2}} \left( h_k(t) e^{i\mathbf{k}\mathbf{x}} \hat{a}_{\mathbf{k}r} + h_k^*(t) e^{-i\mathbf{k}\mathbf{x}} \hat{a}_{\mathbf{k}r}^+\right) e_{ij}^r(\hat{\mathbf{k}})
$$
\nconformal time

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$$

$$
\rho_{\rm GW}(t) = \frac{1}{32\pi Ga^2(t)} \left\langle \dot{h}_{ij}(\mathbf{x},t)\dot{h}_{ij}(\mathbf{x},t) \right\rangle_V \longrightarrow \text{Volume/Time Average}
$$

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$$

$$
\rho_{\scriptscriptstyle \mathrm{GW}}(t) \; = \; \frac{1}{32 \pi G a^2(t)} \left\langle \dot{h}_{ij}(\mathbf{x},t) \dot{h}_{ij}(\mathbf{x},t) \right\rangle_{\scriptscriptstyle \mathrm{QM}} \longrightarrow \text{ensemble average}
$$

#### **Irreducible GW background from Inflation** stochastic nature of the emerging classical field distribution. The quantum-to-classical transition, which occurs basically when the modes leave the Hubble radius, is studied *ij* . Hence, in these scenarios, the (spatial-spatial comeducible GW background from I by *Tij* = *T* pf *ij* + *T* def *ij* . It is clear then that ⇧*ij* = *T* def power spectrum of the tensor perturbation first derivalatı In in our case, GWs are created from a network of reducible GW background from originates the defects is a random process, we cannot pre-**The anisotropic stress tensor** We can star and description buting characterizes the defect of

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\hat{h}_{ij}(\mathbf{x},t) = \sum_{r=+, \times} \int \frac{d^3 \mathbf{k}}{(2\pi)^{3/2}} \left( h_k(t) e^{i\mathbf{k}\mathbf{x}} \hat{a}_{\mathbf{k}r} + h_k^*(t) e^{-i\mathbf{k}\mathbf{x}} \hat{a}_{\mathbf{k}r}^+ \right) e_{ij}^r(\hat{\mathbf{k}})
$$

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\rho_{\rm GW}(t) = \frac{1}{32\pi Ga^2(t)} \left\langle \dot{h}_{ij}(\mathbf{x},t) \dot{h}_{ij}(\mathbf{x},t) \right\rangle_{\text{QM}} \longrightarrow \text{ensemble average}
$$
\n
$$
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$$
\frac{d\rho_{\rm GW}}{d\log k}(k,t) = \frac{1}{(4\pi)^3 G a^2(t)} k^3 \mathcal{P}_h(k,t)
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$$

and sub-Hubble (*k H*) scales (clearly the solutions one obtains are equivalent to the

 $\mathbf{H} = \mathbf{H} \mathbf{H} \mathbf{H}$  ,  $\mathbf{H} = \mathbf{H} \mathbf{H} \mathbf{H}$  ,  $\mathbf{H} = \mathbf{H} \mathbf{H} \mathbf{H}$ 

**Horizon Re-entry**  
\n**Rad Dom:** 
$$
h_r(\mathbf{k}, t) = \frac{A_r(\mathbf{k})}{a(t)} e^{ikt} + \frac{B_r(\mathbf{k})}{a(t)} e^{-ikt}
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$$
\left\langle \dot{h}\dot{h}\right\rangle =k^{2}\langle hh\rangle
$$

*ij* (k<sup>0</sup> *, t*) re-entry*ij* (k*, t*)*.* (11) The GW energy density spectrum per logarithmic inter-<br>The GW energy density spectrum per logarithmic interwhere  $\mathcal{M}$  is the unit time correlator introduced the unequal time correlator  $\mathcal{M}$ (UTC), the contract of the con a superposition of plane waves with wave-vectors k and amplitude decaying as 1*/a*(⌘): After horizon

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\frac{d\rho_{\rm GW}}{d\log k}(k,t) = \frac{1}{(4\pi)^3 G a^2(t)} k^3 \mathcal{P}_h(k,t)
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$$
  
After horizon  
re-entry  
Redshift  
Tensor Spectrum!

) *G*(*k*(*tt* 0 )) ⇧TT (re-entry)

**Tensor Spectrum !** 

#### **Irreducible GW background from Inflation** momentum of this background is that of a perfect fluid, ⇥ *h*˙ *ij* (k*, t*) *h*˙ ⇤ *ij* (k<sup>0</sup> *, t*) *.* (14) the tensor period (4⇡)<sup>3</sup>*Ga*<sup>2</sup>(*t*) *<sup>k</sup> <sup>k</sup>*<sup>3</sup> *<sup>P</sup>h*˙(*k, t*)*,* (16) and from here, the GW energy density spectrum reads

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Obtaining **Properties 1998** In the help of Eq. (1 Inits happens for any GWE) freely propagating @ sub-H scales) (This happens for any GWB, once

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\mathcal{P}_{h} = \left(\frac{a_{o}}{a}\right)^{2} \frac{k^{2}}{2(1+z_{*})^{2}} \frac{2\pi^{2}}{k^{3}} \Delta_{h_{*}}^{2} \mathbf{I}_{\text{log}} \frac{d\rho_{\text{GW}}}{d\log k} = \frac{1}{8} \frac{a_{o}^{2}}{a^{4}} \frac{m_{p}^{2}k^{2}}{(1+z_{*})^{2}} \Delta_{h_{*}}^{2}
$$
\n
$$
\mathbf{RD:} \quad (1+z_{*})_{\text{RD}}^{-2} = \Omega_{\text{Rad}}^{(o)} \frac{a_{o}^{2}H_{o}^{2}}{k^{2}} \mathbf{I}_{\text{log}} \mathbf{I}_{\text{log}} \frac{d\rho_{\text{GW}}}{d\log k} = \frac{\Omega_{\text{Rad}}^{(o)}}{24} \left(\frac{a_{o}}{a}\right)^{4} \frac{\rho_{c}^{(o)}}{3m_{p}^{2}H_{o}^{2}} \Delta_{h_{*}}^{2}
$$

$$
\Omega^{(o)}_{\rm GW}\equiv\frac{1}{\rho_c^{(o)}}\left(\begin{array}{c} d\rho_{\rm GW}\\ \overline{d\log k} \end{array}\right)_o
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\mathcal{P}_{h}^{(o)}
$$
\n $$ 

## **Irreducible GW background from Inflation** momentum of this background is that of a perfect fluid, ⇥ *h*˙ *ij* (k*, t*) *h*˙ ⇤ *ij* (k<sup>0</sup> *, t*) *.* (14) (4⇡)<sup>3</sup>*Ga*<sup>2</sup>(*t*) *<sup>k</sup> <sup>k</sup>*<sup>3</sup> *<sup>P</sup>h*˙(*k, t*)*,* (16) the tensor period and from here, the GW energy density spectrum reads

$$
\frac{d\rho_{\rm GW}}{d\log k}(k,t)=\frac{1}{(4\pi)^3G\,a^2(t)}\,k^3\,\mathcal{P}_{\dot{h}}(k,t)
$$

$$
\left\langle \dot{h}_{ij}\left(\mathbf{k},t\right)\dot{h}_{ij}^{*}\left(\mathbf{k}^{\prime},t\right)\right\rangle \equiv(2\pi)^{3}\,\mathcal{P}_{\dot{h}}(k,t)\delta^{(3)}(\mathbf{k}-\mathbf{k}^{\prime})
$$

$$
\mathcal{P}_{h} = \left(\frac{a_o}{a}\right)^2 \frac{k^2}{2(1+z_*)^2} \frac{2\pi^2}{k^3} \Delta_{h_*}^2
$$

$\Omega_{\text{GW}}^{(o)}(f) \equiv \frac{1}{\rho_c^{(o)}} \left( \frac{d\rho_{\text{GW}}}{d\log k} \right)_o = \frac{\Omega_{\text{Rad}}^{(o)}}{24} \Delta_{h_*}^2(k) \qquad (k = 2\pi f)$	
<b>GW normalized</b>	<b>Inflationary</b>
<b>energy density</b>	<b>tensor spectrum</b>

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$$
\Omega_{\text{GW}}^{(o)}(f) \equiv \frac{1}{\rho_c^{(o)}} \left( \begin{array}{c} d\rho_{\text{GW}} \\ d\log k \end{array} \right)_o = \frac{\Omega_{\text{Rad}}^{(o)}}{24} \Delta_{h_*}^2(k) \qquad (k = 2\pi f)
$$
  
Transfer Funct  

$$
T(k) \equiv \frac{\Omega_{\text{GW}}^{(o)}(k)}{\Delta_{h_*}^2(k)} \propto k^0(\text{RD})
$$



$$
\Omega_{\text{GW}}^{(o)}(f) \equiv \frac{1}{\rho_c^{(o)}} \left( \frac{d\rho_{\text{GW}}}{d\log k} \right)_o = \frac{\Omega_{\text{Rad}}^{(o)}}{24} \Delta_{h_*}^2(k) \left[ \Delta_h^2(k) = \frac{2}{\pi^2} \left( \frac{H}{m_p} \right)^2 \left( \frac{k}{aH} \right)^{n_t} \right]
$$
  
Transfer Funct.:  $T(k) \propto k^0(\text{RD})$   
(almost-) scale-invariant
























# **Realistic computation of Transfer function @ Stiff Domination —> —> Radiation Dom.**

### **Inflationary GW background** =  $=$   $\frac{1}{2}$ rad ✓*g*⇤*,k g*⇤*,*<sup>0</sup> *<sup>g</sup>s,k* ◆4*/*<sup>3</sup> Plugging this into Eq. (3.21), using Eq. (2.11) for the inflationary plateau, and expressing (RD) with equation of state *w* = 1*/*3, the resulting present-day GW energy density spectrum is dengiscal in variant for the formation of the formation of the formation of the modes corresponding to the Hubble radius during RD. Setting *n<sup>t</sup>* = 0 and averaging over oscillations, the amplitude of (RD) with equation of state *w* = 1*/*3, the resulting present-day GW energy density spectrum ich variant for the formulation in variant for the modes corresponding to the modes corresponding to the modes Hubble radius during RD. Setting *n<sup>t</sup>* = 0 and averaging over oscillations, the amplitude of













### **Inflationary GW background** =  $=$   $\frac{1}{2}$ rad ✓*g*⇤*,k g*⇤*,*<sup>0</sup> *<sup>g</sup>s,k* ◆4*/*<sup>3</sup> Plugging this into Eq. (3.21), using Eq. (2.11) for the inflationary plateau, and expressing (RD) with equation of state *w* = 1*/*3, the resulting present-day GW energy density spectrum is dengiscal in variant for the formation of the formation of the formation of the modes corresponding to the Hubble radius during RD. Setting *n<sup>t</sup>* = 0 and averaging over oscillations, the amplitude of (RD) with equation of state *w* = 1*/*3, the resulting present-day GW energy density spectrum ich variant for the formulation in variant for the modes corresponding to the modes corresponding to the modes Hubble radius during RD. Setting *n<sup>t</sup>* = 0 and averaging over oscillations, the amplitude of





Model (SM) degrees of freedom before the electroweak symmetry breaking and independent of **k**, even though in reality the number of  $\mathbf{r}$ 

**Stochastic Sig** Eq. (2.11) describes the amplitude of the *plateau* of the inflationary GW (quasi-)scale **Stochastic Signal:** 

$$
\langle \dot{h}_{ij}(f)\dot{h}_{ij}(f)\rangle = \mathcal{P}_h(f)
$$





### **Inflationary GW background** =  $=$   $\frac{1}{2}$ rad ✓*g*⇤*,k g*⇤*,*<sup>0</sup> *<sup>g</sup>s,k* ◆4*/*<sup>3</sup> Plugging this into Eq. (3.21), using Eq. (2.11) for the inflationary plateau, and expressing (RD) with equation of state *w* = 1*/*3, the resulting present-day GW energy density spectrum is dengiscal in variant for the formation of the formation of the formation of the modes corresponding to the (RD) with equation of state *w* = 1*/*3, the resulting present-day GW energy density spectrum ich variant for the formulation in variant for the modes corresponding to the modes corresponding to the modes Hubble radius during RD. Setting *n<sup>t</sup>* = 0 and averaging over oscillations, the amplitude of **Figure 35. As can be seen best and as can be spectrum consistent of the spectrum consistent of the spectrum co** part. The model parameters *H*inf, *w*S, and *f*RD, respectively, control the level of the plateau,



### **Inflationary GW background** =  $=$   $\frac{1}{2}$ rad ✓*g*⇤*,k g*⇤*,*<sup>0</sup> *<sup>g</sup>s,k* ◆4*/*<sup>3</sup> Plugging this into Eq. (3.21), using Eq. (2.11) for the inflationary plateau, and expressing (RD) with equation of state *w* = 1*/*3, the resulting present-day GW energy density spectrum is dengiscal in variant for the formation of the formation of the formation of the modes corresponding to the (RD) with equation of state *w* = 1*/*3, the resulting present-day GW energy density spectrum ich variant for the formulation in variant for the modes corresponding to the modes corresponding to the modes Figure 35. As can be seen besteen besteen to spectrum consistent to the spectrum consistent of the spectrum of part. The model parameters *H*inf, *w*S, and *f*RD, respectively, control the level of the plateau, during ⌧⇤ ⌧ ⌧ ⌧RD [c.f. (3.3)], and we have used (3.28) and *k*RD ⌘ *a*RD*H*RD. **V GW backdround is expressed in the solution is expressed in the solution of the scale factor** subsequent epochs, and so we can omit the superscript (sti↵)





### **STIFF EQ of STATE**  $\bullet$  second of the blue-tilted part, and the location  $\bullet$   $\bullet$  (in frequency space) of the  $\bullet$ STIFF EQ of STATE  $(1/3 < \omega_s < 1)$



$$
\Omega_{\rm GW}(f) \propto H_{\rm inf}^2 \left(\frac{f}{f_{\rm RD}}\right)^{\frac{2(w-1/3)}{(w+1/3)}}
$$

**Not Scale Invariant !**

### **STIFF EQ of STATE**  $\bullet$  second of the blue-tilted part, and the location  $\bullet$   $\bullet$  (in frequency space) of the  $\bullet$ STIFF EQ of STATE  $(1/3 < \omega_s < 1)$



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$$

**Not Scale Invariant !**







$$
\Omega_{\rm GW}(f) \propto H_{\rm inf}^2 \left(\frac{f}{f_{\rm RD}}\right)^{\frac{2(w-1/3)}{(w+1/3)}}.
$$



$$
\Omega_{\rm GW}(f) \propto H_{\rm inf}^2 \left(\frac{f}{f_{\rm RD}}\right)^{\frac{2(w-1/3)}{(w+1/3)}}
$$



$$
\Omega_{\rm GW}(f) \propto H_{\rm inf}^2 \left(\frac{f}{f_{\rm RD}}\right)^{\frac{2(w-1/3)}{(w+1/3)}}
$$

panels word band at *panels 29.*5 and *panels [1905.11960](https://arxiv.org/abs/1905.11960)* 









**INFLATIONARY MODELS WAS SERVED ON A SE Axion-Standing Light Courts** and with a mechanism of production / exp ˙ and with a mechanism of production / exp ˙ GW SIGNAL NATURAL NATURAL STONE • CLASE hift d hid is don't simple you a cosmit inflation with<br>Models Quastow - not fails new material load winn in *, ns* 1 ⌘  $\alpha$ <sup> $\equiv$ </sup> $\frac{1}{2}$ **d lin a compiler hail hşûn i û bûn hizik († )**<br>Augmanicz Empletos Ruy ⇣*V , V* 经  $\frac{10.4 \text{ g}}{10.4 \text{ g}} = \frac{10.4 \text{ g}}{10.4 \text{ g}} = 10$ *V<br><i>V* / X d *•* Flatness and gaussianity ! small self-couplings  $\delta \mathbf{F}$ **ANORE TO CONFIDERIAL** Freehrig  $\overline{r}$ **BUSIGIE COLET GROWS AT ISOSING AT INTERFEROMENT COLLECTED ITS photography with simplest models of signals with simplest models of simplest models of slow-role inflation and** *d* ln *P*⇣ **de Starting head** <sup>h</sup>⇣2i<sup>2</sup> = O (✏*<sup>V</sup> ,* ⌘*<sup>V</sup>* ) ⌧ <sup>1</sup> ⌘*<sup>V</sup>* ⌘ *<sup>M</sup>*<sup>2</sup> *p V <del>,</del> <i>MNIE*<br> **GRUP 10 • Flatness and gauge with the Platness FREETHERS** y ve<br>. . . a tham a mail rombol live a literature of IN **ANSMETH STREET OF PRODUCT OF PRODUCTION OF PRODUCTION OF STREET OF PRODUCT** scales **FOR CAMBER IN AGREEMENT WITH SIMPLEST TO A** CITY 31: *.*  $P_{\frac{1}{2}}$ *P*⇣  $\left\langle \right\rangle$   $\left\langle \right\rangle$   $\left\langle \right\rangle$   $\left\langle \right\rangle$   $\left\langle \right\rangle$ *d* ln *P*⇣  $\int$  fields  $\int$  $W$ *M*<sup>2</sup> *p* <u>ດິ</u><br>11 ⇣*V , V* **NHE** u uepart<br>& depart **• Flatoos, phosoelessianity Gremall Axion (Nation Anti-Field Anti) • She Hash a Servey Cauplings to other men** Freese, Frieman, Olinto '90, ... (review Pajer, MP '13) 64  $\overline{\mathbf{I}}$  $\frac{1}{2}$  $\frac{1}{2}$  $\frac{1}{2}$  $\frac{1}{2}$  $\frac{1}{2}$  $\frac{1}{2}$  $\frac{1}{2}$  $\frac{1}{2}$  $c_\psi$  $\partial_{\mu}^{\xi}$ we focus on a specific scenario, with a specific scenario, with a natural class of models of models of the infl **BISIGNATURAL SCALES, WHILE SMALL AT CMB PGW** *P*⇣ **, ns 1 sig** *d* ln *P*⇣  $\frac{1}{\sqrt{2}}$  **Martin**  $\frac{1}{\sqrt{2}}$ ابرائع<br>استقل **de Son Stephen Martin (B)** puys de Siel **vanuit Birgail au Civip, scales Landaron self-couplings<br>• Blatness and gaussianity <del>a Psma</del>ll Limbaron self-couplings EAS SHIMOKEST (BRAGING B) ON FEATIMEESTHE DEXEMPTERENT MATERIED TO AC** FACS SOFF TREPAS HAR COM TO LO 090; ... (CRYWORFED, MPOLS) **NGUHIQD'E** *Ps* / *<sup>k</sup>ns*<sup>1</sup> *<sup>r</sup>* <sup>=</sup>  $\frac{1}{2}$ *Ps*  $\frac{104.3}{100}$   $\frac{13}{3}$   $\frac{1}{2}$   $\frac{$ **Local Protection of the angle of the weight of a ply,**  $\frac{1}{2}$ ↵⇤ **FRIEDLICE SEGGLICE SHARE FIELD FAN DE CHREGELIE**  $\alpha$  is the state of the state of  $\alpha$  of  $\alpha$  is the state of  $\alpha$  is the state of  $\alpha$  is the state of  $\alpha$ 'g' *M*<sup>2</sup> *p*  $\mathbf{a}$ ⇣*V, V* ă d vanta<br>.*. 64 T Ka V,*  $\frac{2\phi}{\pi}$   $\frac{C}{V}$ *P*GW *P*⇣ *, ns* 1 ⌘ *d* ln *P*⇣ *d* ln *k* **V** a k **l** a k<br>d ln *k* **l h ház a ray s o (a, h)**<br>KS Stanftt swim r • Flatness and gaussianity <del>of small inflaton</del> self-couplings *•* Shift symmetry (broken by *V* ) on couplings to other fields has advantages Freese, Frieman, Olinto to 0090;  $\mathbb C$ rruder i Liper,  $\mathbb C$  $BrathockP$  $P_s \propto k^{n_s - 1}$   $r =$  $\boldsymbol{\mathcal{P}}_t$ *Ps* • BNG observed departure from (primordial) gaussiand Fing (dbse)  $L_{\rm 2}$  cal  $\Delta T_{\rm 1}$   $\Delta T_{\rm 2}$   $\Delta T_{\rm 2}$  $\overline{\mathcal{A}}$ *•* Agreement with standard single field slow roll  $r, n_s' = 1, \frac{1}{N}$  $\mathfrak{k}$  $\mathcal{M}$  $\mathcal{L}$ 2 ⇣*V, V* ⌘2  $\sqrt{\frac{1}{4}H}$  $V_{,\phi\phi}$  $\frac{\sqrt{\rho}\varphi}{\sqrt{2}} \ll 1$ GWSMGHUSHUNGKY GFILE SCALER DICTION STRAIGHT STRAIGHT **calege Axioles Pirade Latitude FOR the STOV shiftige there**<br>• SBMI LOGIN FELLIO COUPLINGE to Other field(in) ings to Other Free Commuses & Street Thin Possessor .... P Patter (predictempty) C By C By **L E Sett**<br>H 2002 山 2 **EACS SHARE (2) 20 985 21 FAVWILL Cat/ f** @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ **f** *f**Agneemen*<br>**f fullblax**<br>**f fkylifeeme** has the advancement and come that  $\frac{1}{2}$   $\frac{1}{2}$  **• Shealthea** Free se <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *c f* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ **f F A Propinsi A Y X 198 IV Shift a J Vshift • Construction WATHER TO A CONTROLLER FOR BEATING MARRISTMA BIJ KAOMALEY KAUROG TELY SLACHTER** Constructive coupling to the coupling of the c **1976 C**<br>CC2 **社会化会<br>VIB JI** 2 **14 A = 14 B + 16 R + 10 M + 12 K aut 026**  ! *AA* typically controls reheating. Only recently realized that it can play an important role also during inflation. Coupling in  $\overline{9}$ **pr** *f* **2013 SICH STANDER CHON full** Full Falls *•* Smallness of *V*shift technically natural. *V* / *V*shift **• EQSEMPT COUPLINGS** <sup>2</sup>⇡*f*<sup>2</sup> *<sup>m</sup> <sup>m</sup>*<sup>2</sup> **AA THRIED AA**<br>A- bechriteal だけ<br>トメー E14117  $\bigoplus$  $\overline{\text{A}}$  and  $\overline{\text{A}}$  in  $\overline{\text{A}}$  is realized by a typically relating to  $\overline{\text{A}}$ *•* Shift symmetry ! + *C* on couplings to other fields Plicton stealne  $T^*$ 2 nity<br>**@Beauty**<br>PEDICONDRESSER **c**<br>E *f* **2524441444174411777** pentywith 75# has the advantage **From Height technically and water of the U** + SO  $\frac{1}{2}$  . The construction of  $\frac{1}{2}$  is the coupling of  $\frac{1}{2}$  in  $\frac{1}{2}$  . The coupling of  $\frac{1}{2}$  $R$ iek? 2 Victoria (n. 75  $e_{\psi}$ *f* **@**<br>@@@\_@^\\_@@@@@@@@@\_ *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ avsgr **• Small intesse of the mall technically • Construction of the construction THE CONOR THE QU' LETERENCE VALUES** Substration roll in the potential potential potential and we have hard to explain why *V* protected against quantum corrections. **Ritishive Advire IV shift • SHIFT SYMMETRY IS IN COUPLING TO A COUPLING** Friday <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> **c** *f* # 6 5 5 5 5 5 6 7 8 7 9 **fQ! #@\$## • Small de Land and Constitution • Construction coupling to matter (prediction)** GTIES GRYS IL JOHN CE ONY; CIENT EL QUANY 6, WAM SLOW ROLL INFLATION REQUIRES VERY FLATION REQUIRES VERY FLATION REQUIRES VERY FLATION REQUIRES VERY FLATION RE hard to explain why *V* protected against quantum corrections. **RIKSHITE • Shift is sime the field of me to** 7; ''.''<br>D': ! 1 <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> com *f* **DIA 6 012159047-57047 f** FUCTOR FOR *•* Smallness of *V*shift technically natural. *V* / *V*shift **• Constrained constrained** ₩U@S \$PYC+H A LA XISON, *refigire f* frieder values Slow roll inflation requires very flat potential *V* , and, generically, hard to explain why *V* protected against quantum corrections. With shift symmetry, *V* / *V*shift MARG SIGNAL DIGINAL NAMED PLATING REPORT OF THE TRACTER STOCK AT A LIGHT STOCK AT INTERFERENCE IN scales **• CMB** in agreement with simples that is of slow-roll cosmic inflation **r** Xg PLGW *P*⇣ *, ns* 1 ⌘ *d* ln *P*⇣ **Othen field(fin) in**  $\left\langle \zeta_{+}^{3}\right\rangle$  $\frac{1}{2}$  to other fields *v* **<del>⊗</del>/ <del>T</del></del>** *M*<sup>2</sup> *p* **त्री**<br>वी ⇣*V , V* \$8  $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$ **H**<br>1602 *0222 SSS2 nit* • Flatnul Fey FCOU DUNGS a Agreement with retandand signific field slow de<br>Lise the studios begins in the repeated for the wings and gauge the violence would in ge<br>Lise a large repeated in the self-coupling in the self-cou **Alking (Ts Ain) aty ral)** Inflation **From Fields Break and Condings to pther** fields  $F$ reese, Frienan, Olinto 9050+ GW signe at interferometer signal natural at terferometer small at all vari (CNMB3) IN scales **• CMB in an use of the simple simple state is a slow-roll cosmic inflation in the second of the cosmic inflation**  $r \equiv r \equiv \frac{1}{2}$ **POGWY** *P*⇣ 5 maaltness *d* ln *P*⇣ *<sup>d</sup>* ln *<sup>k</sup> , f*NL ⇠ <sup>h</sup>⇣3<sup>i</sup> **hur hat (#) along the** ₹ *P<br>P<sub>2</sub> 48* **24** ₹ *V* **Be DITTE 10 GD = 9762 V Production • Funding a voir unum av 5 Fairman se ada duplica de l'alien self-couplings and self-couplings and Axider term destruction to the party of a FILECTILIC SHATH SITE SHOTLE SHOP SHOP SHOP SHOP S** scales Which to You and which the *V issnitt symmetry (books)* **• Flatness and green even econta**l inflaton search Freesch, Frieuna (FEVIEW FELJEr, PH<sub>3</sub>H& '+15 **• No observed** departured Local NG : (*x*) = *<sup>g</sup>* (*x*) + *f*local **For Staile et ite**  $\bullet$  Sshift is symmetry (booken Freese, Frieuma  $k$  Faview, Pajer, Rlanck 175 **• No observed** depart Local NG : (*x*) = *<sup>g</sup>* (*x*) + *f*local **eur agreement**<br>Single field in machine Russand gaussianity as small inflaton  $\phi \rightarrow \phi + \phi$  and contaction the coupling  $\phi \rightarrow \phi + \phi$  and  $\phi$  as  $\phi$ Friendschnicativan, Fritta (SA) MPo shoto Christier (Aprediction Lynch Marian Christier) **LE ETA** 10<br>49 <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> nas the red vantage that Avstrow\_notle psp **eves hit fraw relingery** on computings to other fields FREES OFFICERING COMPATION IN THE SIGREHARDER, GRUP SKILFORDIGO **LANGER**  $\frac{1}{\sqrt{2}}$ <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> **Ca**) *f* **三 97名 午夜<sup>34</sup>里望** *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ has the advantage that **• Sharif the SMALL STORY TELL THE CONTRACTOR OF A LICENT TELL SOLUTE SOLUTE FILE ALLY ALLY ALLY COUPLINGS TO THE LOT & DECOLLEDGENTY** ! ' 在**拉宫**代  $\begin{array}{l} \text{A} \rightarrow \text{$ that it can play an important role also during inflation. **EML**  $\operatorname{GG}^*$ **Couplings in a subject of the coupling in a model of the internets in** RICE ESPERATES QUIDITO '900 has the advantage that L **p trad** 51<br>13 2 2 (2) 4 2 (2) + 2 (2 **p** *f* pgs to matter<br>@FMPFedistrityty **f** FWG, OBSEWE **Financing of Basic Technical Calculation** and Technical Technical Technical Calculation **• Constrained couplings to matter (predictivity) PER EN VERI 13**  <sup>2</sup>⇡*f*<sup>2</sup> *<sup>m</sup> <sup>m</sup>*<sup>2</sup> !*AA* = 2<br>24世 EHHHH  $\overline{\boldsymbol{\phi}}$ Addisciple Fish W-Poll #88  $\frac{20.33}{20.5}$  ht  $\frac{1}{10.6}$  (ields)  $\frac{1}{10.6}$   $\frac{1}{10.6}$  $\frac{1}{100} \sum_{k=1}^{\infty} \sum_{k=1}^{\infty} \frac{1}{k} \sum_{k=1}^{\infty} \sum_{k=1}^{\infty}$ CORPENICY WALD TO MARKED CHECK PRO **L S S 142** 11<br>14<br>14 2 (2) a 08 SPAT FIT (X) It bratch no aird ,<br>c<br>ep **f** @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ orediction of spires reserveship  $\frac{1}{2}$   $\sqrt{\frac{1}{R}}$ 1 ariverplies by Barn at EMB Scales *c* **f**<br>*f*<br>*f* O *CC***<br>F#FFFFFE<br>2/Dels** has the advantage that *•* Smallness of *V*shift technically natural. *V* / *V*shift *•* Constrained couplings to matter (predictivity) ⇤ Not the QCD axion; reference values *<sup>f</sup>* ⇠ <sup>10</sup><sup>16</sup> GeV *, m* ' <sup>10</sup><sup>13</sup> GeV Superintential inflation requires in the position required in the position of the position of a position of  $\mathcal{C}$ **hard to explanature to the manufacture of the corrections.**<br>Hard to explanature the state of the series why it multiple to cross the corrections. WOTH SHIFT SHIFT SYMMETRY SYMMETRY SANT **(reviewe Praire Owe Fertality) L**<br>Lem <u>ี้ส</u>ุ dreement with Smrole ars<br>45 *f* **2008 1999 1999 1999 1999** *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ has the advantage that *•* Smallness of *V*shift technically natural. *V* / *V*shift **PLICIDES TO STRAIN STRAINED COUPLILIED** FRACTICLES **FRANOL THE Q.CLA GREE VALUES** VALUES {\/" }Q-º GRV3,GPW SLATION RUPPED TO THE REPORT OF THE REQUIREMENT OF THE REPORT OF THE REQUIREMENT OF THE PARTY OF THE REQUIREMENT **hard to explan the music protection why explain to explain why the corporation of the corrections.** (RICHALGEO) RACHAR ACHAR YE **L**<br>\* 1. **12**  $25$  ( $Q_\mu$  $\beta$ )<sup>2</sup>  $\pm$   $\frac{1}{2}$   $\frac{1}{$ **c**<br>**c** *f* **2018 | 5907 - 570 W** *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ has the advantage that  $\bullet$  Small  $\bullet$  V  $\bullet$  V  $\circ$  V • China Stephen Coupling to the coupling of the Coupling of Coupling of Coupling Coupling of Coupling of Coupling **、THES CHULL THE CHANGE OF THE COUNT OF THE CALL TO A COULD COMPLETED TO A** Slow roll inflation requires very flat potential *V* , and, generically, **hard to explantum why protected against the corrections. The correction of the correction of the corrections.** WW.NPIP ISIBUT CYCLIQUE SIGHT VSRAL PLECAPRITY SAL

⇤ Not the QCD axion; reference values *<sup>f</sup>* ⇠ <sup>10</sup><sup>16</sup> GeV *, m* ' <sup>10</sup><sup>13</sup> GeV

<sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup>

**INFLATIONARY MODELS INFLATION SERIES TO A RESERVE THE SUPPORT OF THE SUPPORT OF THE SUPPORT OF THE SUPPORT OF T** and with a mechanism of production / exp GU SIGNAL SIGNAL NATURAL NATURALIST GROVE STRACTS and with a mechanism ˙ Gw signed at Swiewelf grens all van Le whis B G B E CALES, scales and with a mechanism of production of  $\mathcal{L}$ **gwlsinal production at interferometer scales, which is a mechanism of production of production in the small and** we focus on a specific scenario, with a specific scenario, with a natural class of models of models of models o Gw signal natural naturally grows at interferometer some small at CMBB *P*GW *P*⇣ **, ns 1 sig** *d* ln *P*⇣  $\frac{1}{2}$  **Martin**  $\frac{1}{2}$ ikit<br>Lab **he skilled signal harmon pays of the product vanus av Baupa Cicuup** Scares<br>• Blatness and gaussianity <del>a Psma</del>ll inflaton self-couplings **PEG**W *P*⇣ *pms* **13 S** *d* ln *P*⇣ *<sup>d</sup>* ln *<sup>k</sup> , f*NL ⇠ <sup>h</sup>⇣3<sup>i</sup> **hý 2 jí 0 1 s (3 (¿, ))**<br>C S Svantiles ann • Flatness and gaussianity **A small inflaton** self-couplings GW SIGNAL SWYSI SWYSI SWYSI GROWS AT INTERFEROMETER STORES IN EUROPEAN CAPITAL AT INTERFEROMETER STORES **calege** Small technical stephenochical stephenochical uship tentent Construction of the matter of the matter (prediction of the matter) **AC2 POPER m Extra** EK, *AA = AA & MEXA = AA*  ! *AA* typically controls reheating. Only recently realized Coupling Freese, Skyling  $Rick3$ *•* Shift symmetry ! + *C* on couplings to other fields Friday **• Shift symmetry and coupling to other fields** Freese, Frieman, Olinto '90; . . . and with a memory of production of production with production I. GALOSI GGAL RS KANTU GROVS GROVATS TEKOGHACT SCALES, SMALL LIGNATION GADA (GAMAS scales **a digitan of war a memory way way a memory of production with the control world to** GW SIGNAL NATURAL NATURAL NATURAL SMALL SATER SCALES, SCALES SMALL SMALL AT CHARGES SMALL AT CONTROLS  $\mathbb{G}$ **ma** scales **PGW** *P*⇣ **1308** *•* Flatness and gaussianity ! small inflaton self-couplings **• Shift symmetry (broken by V ) on coupling to other fields of the coupling of the coupling of the coupling of** r<br>for **PEGWARE** *P*⇣ **, nscritt** • Flatness and gauss **• Statistics of the Coupling of the Coupling** W. A signal natural signal natural natural natural natural small at interferometer some **Bedtes** *•* Smallness of *<sup>V</sup>*shift technically natural. *<sup>V</sup>* / *<sup>V</sup>*shift *•* Constrained couplings to matter (predictivity) *C*2 *<sup>m</sup> <sup>m</sup>* **tiles wheateded**<br>Blatners and specification 2<del>4</del> **2X AA AA HUU**  $\mathbf{A} \in \mathbb{R}$  and  $\mathbf{A} \in \math$ 3 Scales and real and the axion in Freest, Frieman, Olinto Victoria, Friedrich and Friedrich and South (review Pajer, MP '13) Freeste, Friese, Friedrich **Canadian Page (rad) wang tanàn**  $\bullet$  states to other fields  $\circ$  and  $\circ$   $\bullet$   $\circ$  of  $\bullet$   $\circ$  of  $\circ$  of  $\bullet$   $\circ$   $\bullet$   $\circ$   $\bullet$   $\circ$   $\bullet$   $\circ$   $\circ$   $\bullet$   $\circ$  FREES ON THE EXTING ON HIS PARTY TO **ereviewen Busingswivandlew** GW signal natural publical natural natural natural matural natural at interferometer structure structure structure scales GW SIGNAL RIJKAN GWARAK WAYA ANG KANG IKANG TERMANGKAN GKAN ZA TVOTH GAMAG scales GW signal natural natural natural natural small at interferometer some start small at CMB and CMB at CMB at CMB scales **• Flatness and gaussian • Shift the Aument fields (Gatober** Freesch, Frieman, **• Flatness and • Shift in Carina by Booken by (Octobrish** Freesch, Frieman stegtes Axistand gaussianity as small inflaton Free escale and the second the canonically partiel relation.<br>Free escale and play and the second of the control of th ! ' 1915年  $\frac{1}{\frac{1}{25}}$  . A  $\frac{1}{\frac{1}{25}}$  . A  $\frac{1}{\frac{1}{25}}$  . Only realized the control of  $\frac{1}{25}$  . A  $\frac{1}{\frac{1}{25}}$  . A **Couplings in a supplication in a state information in a state of the couplings in** Rick 3 50-310 Store 1 as Kanadia in Alian State **LESSING 11** 2 (2 County of the United States **C**<br>Frit **ANDERSHINGHIYOFFISHACES f**<br>**finity**<br>**p**[**p**els] (review Praker) Paler in Paler  $\overline{1}$ ars<br>45 **@**<br>The Gelse F. Store Reserve (RAF) WARD PART IN DER EIN DER EINE WARD

**ISBN 1977 SKORDIGS & ISBN 5540M** • **OLGAMB dination-roll cosmit with simplest models with simplest prodels of simplest with simplest with simplest models • CMB in agreement with simplest models RASHIMOKETT (BRIGHT SYMPLING) IN COUPLINE THE UEDS HAS EIMPLIFED TO AC** Frees in Freest from Grade is OND stown **PS Shift Stone Follow Couper Stone by Contract on Coupling to one of the Coup River of Coupling Stone Rivers and Coup** Freest, Friedrich Schoolinto of The **AxionEductoria 1976**  $\overline{9}$ <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f <sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ *c* 2 **10 k**<br>2 **10 c for B** didentified with *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> political de la contenential de la @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ • CMB in agreement with since we have a Helstoff with the inflation of strate with the with scales • CMB in agreement with significant with simplest models of slow-roll cosmic inflation Frees Heineman Re (FEXPEX) FRIEN P Freesew, Fringman, OLI (Feynew Part AMP Axion Axion Inflation TB Haaped reethte start the standard est ... **L 3 4 1** 1 <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> **c** *f* **<u> HFUENSINGH EHMITHRIM</u>** *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ **L 10 200 1 + 2 (200 1 + 1)** + 2 (0 + 1) + 2 (0 + 1) + 2 (0 + 1) + 2 (0 + 1) + 2 (0 + 1) + 2 (0 + 1) + 2 (0 + 1) + 1) + 1 (1) + 1 (1) + 1 (1) + 1 (1) + 1 (1) + 1 (1) + 1 (1) + 1 (1) + 1 (1) + 1 (1) + 1 (1) + 1 (1) + 1 (1) 1 T Y 5 + 1 L V F W 4 1 N 3 + 1 M 3 + 1 5 7 C 1 0 M 4 P **2 (2) + 7 (2) + 7 (2) + 7 (2) + 7 (2) + 7 (2) + 7 (2) + 7 (2) + 7 (2) + 7 (2) + 7 (2) + 7 (2) + 7 (2) + 7 (2)** + 7 (2) + 7 (2) + 7 (2) + 7 (2) + 7 (2) + 7 (2) + 7 (2) + 7 (2) + 7 (2) + 7 (2) + 7 (2) + 7 (2) + 7 (2) + 7 (2 **12 Centre 1 With Storp Ca productions: Stow b** sprid work **• CMB** in age reement with signing the standard decision in the with complete the state of state of significant of **• CMB in agreement with simple simple studies in a visit models he debt models with the cosmic inflation of pr KRY EW Pale60P** (FRY FAIRPLANE) **REXTED FIS • Shero and contract symmetry of the coupling with a contraction** Avksbowy-notife wshi Acquisic Tength Inflation *f*<br>*f*<br>*f* **LEE** 2 (@@119@@Thigy)thy Storphe *f* **f <b>F**<sub>19</sub><br>**F119464WmHt441 LEEP 19** 25 KOWGUES STIP (OKG 21 MARG **c**<br>**c** *f* **2007 - 1000** *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫

*, ns* 1 ⌘  $\alpha$ <sup> $\equiv$ </sup> $\frac{1}{2}$ **d lin a france de la hail** <sup>h</sup>⇣2i<sup>2</sup> = O (✏*<sup>V</sup> ,* ⌘*<sup>V</sup>* ) **de la film hási** <sup>h</sup>⇣2i<sup>2</sup> = O (✏*<sup>V</sup> ,* ⌘*<sup>V</sup>* ) 31: *.*  $P_{\frac{1}{2}}$ *P*⇣  $\left\langle \right\rangle$   $\left\langle \right\rangle$   $\left\langle \right\rangle$   $\left\langle \right\rangle$   $\left\langle \right\rangle$ *d* ln *P*⇣  $\int$  fields  $\int$ **EL PALE REPLUED PARTIES POINTER NGUHIQD'E (ANJACLE) INPUTS)**  $BrathockP$ *Pt* **FOR the STOV shiftige there**<br>• SBMI LOGIN FELLIO COUPLINGE to Other field(in) ings to Other Free Culture Sex Street, Cape Culture Complete Culture Of **• Shealthe** that it can play an important role also during inflation. **• Shealtheas Story !!! See on the field to other** avsgr **• Small with the station of the contract of the small with the small wi** *f f <sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ **r** Hr **POW** *P*⇣ , <del>f T shift 2</del> *d* ln *P*⇣ *<sup>d</sup>* ln *<sup>k</sup> , f*NL ⇠  $\frac{1}{2}$ **hELIPEL EXAMPLE VS s** ppa *P*⇣ *, ns* 1 ⌘ *d* ln *P*⇣ **d a live & a live d**<br>a live a d d a d a d lu hu<br>31. Kal **http://www.party.org/www.party.org/www.party.org/www.party.org/www.party.org/www.party.org/www.party.org/www.party.org/www.party.org/www.party.org/www.party.org/www.party.org/www.party.org/www.party.org/www.party.org/www.**  $H_2 \odot$   $\mathbf{f}$  $\frac{1}{2}$   $\frac{1}{2}$  FREE ENDED TO USE WAS TO BE THE THE WEBSTER OF STREET ntage that **France Shift Shift** Freehold the second freedom of the can play and the second the can play and the can pl  $\frac{1}{2}$ WE GEWENDER • Shift Hness of Kantuck high nically naturel (2) Mary 2)  $\det_{\mathbf{A}} \mathbf{H} \mathbf{H}$ **• Smalle Connically 25 Small de L'AST TAGE technical de l'ATHLIC L'AGE** having the advising to the property *•* Smallness of *V*shift technically natural. *V* / *V*shift Harvey Has Kingdom *•* Smallness of *V*shift technically natural. *V* / *V*shift **r** Xg PLGW *P*⇣ *, ns* 1 ⌘ *d* ln *P*⇣ **Othen field(\$in) in**  $\left\langle \zeta^3 \right\rangle$ **E HI FOR A LIBER & COOLINGS to Other field (in) ings to other fields ) POGWY** *P*⇣ 5 maall nes<del>s</del> *d* ln *P*⇣ *<sup>d</sup>* ln *<sup>k</sup> , f*NL ⇠ <sup>h</sup>⇣3<sup>i</sup> **http://www.particle.com/www.particle.com/www.particle.com/www.particle.com/www.particle.com/www.particle.com/www.particle.com/www.particle.com/www.particle.com/www.particle.com/www.particle.com/www.particle.com/www.partic** Planck 15 **Francisch PicaHX, Dattiffel, EX, With Vshot O eves hit fraw relingery** on computings to other fields has the advantage that  $\frac{20.33}{20.5}$  ht  $\frac{1}{10.6}$  (ields)  $\frac{1}{10.6}$   $\frac{1}{10.6}$ has the advantage that *•* Smallness of *V*shift technically natural. *V* / *V*shift has the advantage that **• Smaallness of** *Vis***hift technical water of the Small Model water of the Small Model of the Small Model of the** has the advantage that **• Shifting wapping in the Small weight will natural with the Small of Contract Wapping in the Small of Contract Wapping in** 

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⇣*V , V* 接受 **SOLLEY SOLUTION** *p V* 人物<br>1000 **V 2007** *V ,* **• No observed is a strange from (primordial) gaussianity, he control of the strange of V • FRATTS & PROGRESS LITTS PRESSING Local Desimer and Contract Medicine Construction** *<sup>g</sup>* (*x*) ⌦ <sup>2</sup> *g*  $\frac{1}{N}$  $\frac{1}{2}$  $\overrightarrow{G_2}$ <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f* **futbann Europhy**  $\frac{1}{2}$ **ET E CONOC THE QCUCUS GEV AT AXIONE VALUES FRAGE CONFIDENCE**  $\frac{1}{2}$ ₩U NOS SANCALLEN VALUES **FARICA EN EL COMPLETO DE LA UNIX GEVENE DE LA UNIX** *M*<sup>2</sup> *p* **Proximation A RESERCE & YOU LESS ON A THE PLOTS** ⌧ <sup>1</sup> ⌘*<sup>V</sup>* ⌘ *<sup>M</sup>*<sup>2</sup> *p M*<sup>2</sup> *p* ⇣*V ,* ⌘2 ✏*<sup>V</sup>* ⌘ **RANCE RESEARCH** *V , <sup>V</sup>* ⌧ <sup>1</sup> *c* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ Local NG : (*x*) = *<sup>g</sup>* (*x*) + *f*local  $\mathbb{R}$ <u>には</u> <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f <sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ *f* • Some Supplement at the Computation requires with the VS Sent technical potential of *Voltan Museum and* ⇤ Not the QCD axion; reference values *<sup>f</sup>* ⇠ <sup>10</sup><sup>16</sup> GeV *, m* ' <sup>10</sup><sup>13</sup> GeV ▶ Not the Tend axion; reference values freeze values of the LEG avenue of the QCD axiev Show roll inflation requires very flat potential contribution requires very flat position of the contribution of ₩ DOD TE QUE LA VALUES **FOR LA VIEN A LA VIEN A LA VIENCE VA VALUES CE LA VIEN A LA VIEN A LA VIEN A VIEN A VIEN**<br>19 AN XII TE QUE LA VIEN VIEN A GRUES LE MESCANNON CIENT A VIEN DE LA TERRITA CA LA LA VIEN A LA VIEN CE LA derivative couplings to: fermion and the couplings to the coupling of the coupling of the coupling of W<del>S</del><br>War72 *M*<sup>2</sup> *p* ⇣*V ,* ⌘2 2 *V <sup>V</sup>* ⌧ <sup>1</sup> ⌧ <sup>1</sup> ⌘*<sup>V</sup>* ⌘ *<sup>M</sup>*<sup>2</sup> *p ,* ⌘2 *V , c V ,* **MARK p**<br>p<br>p 萝卜·<br>Trist Local NG : (*x*) **11** LE NOOT THE QUOT CHE QUOT THE QUOT THE ART ARE ACCEDED TO THE QUOT THE QUOT CHE NOT CHE NOT CHE NOT CHE NOT CH **LES NOCH LIENGVOD GUED AXIONES VALUES AREGAS ET L'ELANULES GN/2014 UNO FORONG NIEW PAV ি 1005 GEV 2014 DARA REFERENCE VALUES AND DELL'AZIONE DELL'AZIONE DELL'AZIONE DELL'AZIONE DELL'AZIONE DELL'AZIO**<br>HU@S YX ← LO ' CI KIENTI, *MARIE LE VI II 2015 CELL II / K. C.* LO FRIME SA ØPODO ELESSIO DI V. I C. S

• Flatness and significant self-couplings  $\delta \mathbf{F}$ <del>Տ</del> *p* **V V 11 041 041 • Flatness and gaussianity in the self-coupling self-couplings and gaussianity in the self-coupling self-coupling Axion (Natural) Inflation of a greater of a flood of a floo • British sex in the plant symptom on confident for f** *g* ↵⇤ **• Raisman with standard single field with significant with single field single field slow rolling full** • Agreement with standard single field slow roll (10) **L & SHI**<br>H & C & 146 <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f fulted free forces*<br>*f fulted fits* <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f* **WEB & CONCERT 2013 f F** *•* Smallness of *V*shift technically natural. *V* / *V*shift **• EQSSI IS NOT THE COUPLINGS TO CONSTRUCT OF THE COUPLINGS OF THE COUPLINGS OF THE COUPLINGS OF THE COUPLINGS** <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> **c**<br>Fk **f**<br>*f*</del><br>*f*<br>*f* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ SOU ROLL INFLATION ROLL INFLATION REQUIRES VERY FLAT POTENTIAL A hard to explain why *V* protected against quantum corrections. SIM ROLL INFLATION REQUIRES VERY FLATION REQUIRES VERY FLAT hard to explain why *V* protected against quantum corrections. Support roll in flation requires very flat potential *very flat potential in the sexual existence* in the sexual of the sexual sexu hard to explain why *V* protected against quantum corrections. **• Flets ane self-car care and the small segeroem to all self-couplings LA GLANGER 5 FRIMANNE SERIE** 2 MARA 202 **• Final as Est - Colour in gaussian sex alguna provided the space of as City of Coupling Coupling Coupling Couplings erc**<br>Grig Local NG : (*x*) = *<sup>g</sup>* (*x*) + *f*local **• Pics the alterement of Fy, Adreement with** *r, ns* 1*, f*NL = O (✏*,* ⌘) **L EXECTS**<br>L SE CLAR<br>L G C L C **THE** <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> has the advantage that *•* Constrained couplings to matter (predictivity) **L S 212** 14 <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> **c** *f* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ hard to explain why *V* protected against quantum corrections. *fieht wit***<br>***<b><i>froof next* hard to explain why *V* protected against quantum corrections. Slow roll inflation requires very flat potential *V* , and, generically, hard to explain why *V* protected against quantum corrections. • Flatness and gaussian self-couplings and self-couplings and self-couplings and self-couplings and self-couplings WAY EMAN<br>Waxaana<br>SWAISTAW<br>SWAISTAW **24** 化<br>一 **WOOSTOORDE Grade : Angle (**x) CHRIGHT ELANIS<br>Trigidis Metric Blow, School (1) **• Family Access and guide Mass 5 70 MMW Text 4 GUID & CITE & UNIVERSITY OF For Staile et ite • Adressme field field standard L E ETHER** 18 <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> L a 2 **(@***x*)2 + *A* (@, 2 + *V*)2 + *A* (@, 2 + *V*)2 + *V* + **Matawex Service 19 f F**we first the state of a small control of the small control of the small control of the mention of a distribution of the small control of  $\mathcal{F}_1$  ,  $\mathcal{F}_2$  ,  $\mathcal{F}_3$  ,  $\mathcal{F}_4$  ,  $\mathcal{F}_5$  ,  $\mathcal{F}_6$  ,  $\mathcal{F$ has the advantage that a discriming the advantage to the advantage that a straight the advantage to the advanta **• Constrained coupling to matter (predictivity)**<br>• Constraint at Coupling to matter (predictivity) and the coupling of the coupling of the coupling of the coupling **L ENGLIS** 1 <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *c* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *f <sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ Superint requires in the slow roll inflation requires very flat potential and the potential of an experience in<br>Order since the potential strategies when the potential of the potential organization requires in the potentia hard to explanature to explanature and the state of the state and the state of the state and the state and the<br>The state of the sta hard to explan why hard to explain why to explain the correction of the corrections. Since a straight and considerably roll individual potential providence of the signal distribution requires in<br>The end on Peep and Consideration of the second requirement of the small distribution of the second in the sys hard to explan which why why a hard to the state to each corrections. The state of the corrections of the co

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Freehrig **FREETHERS** y ve<br>. . . **ት** *c* 缈 *M*<sup>2</sup> *p* ⇣*V,* **de 1 SETOF KR** *V,* **VELLEY**  $\frac{1}{2}$ *M*<sup>2</sup> *p* <u>ቸ</u> ⇣*V, V* **<u>d'i</u> SOUTH DI CLASS** *V,*  $\overline{w}$   $\ll 1$ **has the advantage to a family of the advantage • Construction of Construction WATUES IF SERVET CEWEFOUT THE QUIN GEV** <sup>2</sup>⇡*f*<sup>2</sup> *<sup>m</sup> <sup>m</sup>*<sup>2</sup> **AA THRIED AAR**<br>A- DEC'hriteau **神 • Bechnically and Alause of Small Elit Sonador stioo Star Darkt**  $\ell$ revignalistički mektor, FIG STATE TENEFOLIA COOL CONTER TE  $\epsilon \equiv$  $M_p^2$ *p*  $\mathbf{\hat{z}}$  $\mathsf{f}\mathsf{t}^\equiv$  $M_p^2$ *p* 2 **BACKETT RELEVANCE THAT Puthos im Essige York frother in Light CANOGRAM CHICAD AXION; REFERENCE VALUES f** in Outpons of the Williams in Early 13 GeV **PERPORT COR**  <sup>2</sup>⇡*f*<sup>2</sup> *<sup>m</sup> <sup>m</sup>*<sup>2</sup> !*AA* = <sup>64</sup>⇡ *<sup>f</sup>*<sup>2</sup> *<sup>m</sup>*<sup>3</sup> **be of it is the overlap of the some diplomation of the production is deviations at 17 display of Vshift**<br>
<del>6 Dec</del> hille album half such saxipli, or fellowers, values first later factor of  $\approx 10^{13}~{\rm GeV}$ . Freese vremenaating at godge hos wo essage reference **• Constrained couplings the esserer (prediction)** Freese, Yezh apa batearne a teo y o Friozil *•* Shift symmetry on couplings to other fields has the advantage that  $\mathcal{R}$ **FILE ALDIA DIA FILAD SAXION: COLOGNES TRALLES / PREDICTIONS, T** PERDITUEN **na**  <sup>2</sup>⇡*f*<sup>2</sup> *<sup>m</sup> <sup>m</sup>*<sup>2</sup> **ABI IF 181813 5121** 이 이상<br>국가 문 E1944 700  $\ddot{\mathbf{W}}$ has the advancement of the attention **Post Vieri Spangue in Ment Gough nd Studies Light Kurship technically** 

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Ismall inflaton self-couplings **\* BLG, \* KNGF (BRIGHT SYMMEGETHE FIELDS HAGETHERETY)** Freest, Friendschaft og Orgenty **EFA CONGRESO INTRODUCTION NGUHIQD'E Ps** / *k*<sup>ns</sup>  $\bar{\partial}$ *Ps* **• No observed the properture from (primordial)** and the property of the prope *g* ↵⇤ **• Agriefield standard single field standard standa R, 1990, 1990, 1990, 1990, 1990, 1990, 1990, 1990, 1990, 1990, 1990, 1990, 1990, 1990, 1990, 1990, 1990, 1990, 1990 PEGW** *P*⇣ **1 State 11 15** *d* ln *P*⇣ **d** la h **hváz róli Cicles • FLAT NATS and gaussianity of Small inflaton** self-couplings **PRESIGN SPILITER OF SHIPPER COUPLINGS TO OUR TO A COUPLING** FREES TO YER TO YER TO YER TO YERROR TO Y **(<del>LE</del>REOVER/HOLP)**  $BrathockP$ **Psi /** *k* + *b* + *c* + *k*<br>> 100 : GeV *Pt Ps • No observed to the primordial gaussianity of the primordial gaussianity of the primordial gaussianity of the primordial gaussianity of the primordial gaussian and the primordial gaussian and the primordial gaussianity* Local NG : {  $\mathcal{R}$  (*x*) + **h**  $\mathcal{R}$  (*x*) + *flocal* and  $\mathcal{R}$  (*x*) +  $\mathcal{$ ↵⇤ • Agreement with standard single field slow roll (collection) **FALL COLL COLLECT** GW SIGNAL NATURAL NATURAL NATURAL Y GROWS AT CALLA NATURAL Y GROWS AT INTERFEROMENT AT LATER STAND **calege**  $\frac{1193 + 1857}{89000}$ **FOR the STOV shiftige there**<br>• SBMI LOGIN FELLIO COUPLINGE to Other field(in) ings to Other Free Stephing Second Axide Contract Contract Contract Contract Contract Contract Contract Contract Contract Co<br>SHOLD FUITELIES CODI AXIOE SACDE LETTIS GENZITURES TITLES PRESIDENT MOTOR POLITICO CARE DA CIDA ILE **Dramatik**<br>11121222 1 <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f fulted free friest* **• Shealthe** FREESE, FRIE 2 (2 %)  $$ *f* **WEBSTER OF STREET** F **A President A X I O LEG SOLE TECHNICE** Small the Value of *Value of Value of Value of August* teams Construction of the coupling to matter (prediction) 2 **Primer POPER m Crater** 22 ar<br>U **AA EARS AND AAN**  ! *AA* typically controls reheating. Only recently realized that it can play an important role also during inflation. Coupling Freese, Frieman, Olinto '90 <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> **c** *f* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *•* Smallness of *V*shift technically natural. *V* / *V*shift **• E. Predictivity of the coupling of the coupling** *•* Shift symmetry ! + *C* on couplings to other fields Plicthastrange  $\frac{1}{2}$ 2 nity<br>**4 Range () + 2 nity () c f**<br>F @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ has the advantage Freese, Free Stephen,  $R$ 2 (2008 - 1725 - 1725 - 1725 - 1725 - 1725 - 1725 - 1725 - 1725 - 1725 - 1725 - 1725 - 1725 - 1725 - 1725 - 17<br>2 (2008 - 1725 - 1725 - 1725 - 1725 - 1725 - 1725 - 1725 - 1725 - 1725 - 1725 - 1725 - 1725 - 1725 - 1725 - 1 **c** *f <sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ avsgr *•* Smallness of *V*shift technically natural. *V* / *V*shift **• Construction of Construction ← F E 3 HNOCD 面内目(KGNAN) GEV GEV GEV 2160 GEV 4100 GEV AXION; REFERENCE GEV DE CESTOR** SOLOW ROLL INFLATION REGISTER VERY FLATION REQUIRES VERY FLAT POTENTIAL A hard to explain why *V* protected against quantum corrections. **Rivership AXIBICCS** • Share symmetry **in the field of construction** Friday. 2 **10 k**<br>2 **10 c c** *f* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *•* Smallness of *V*shift technically natural. *V* / *V*shift **• Construction of Coupling to Matter (predictivity)**<br>Prediction (prediction of <u>the Coupling</u> COLOR CONDUCTIVE THE QUEST CONDUCT TO THE QUEST TO THE QUES<br>HILL COLOR TO THE QUEST TO THE QUEST TO THE MANAGEMENT COMPANY OF THE MANAGEMENT COLOR TO THE QUEST TO THE Q Society and all inflation requires very flat potential and  $\mathcal{V}$  , an hard to explain why *V* protected against quantum corrections. **Riversity • Shift symmetry and coupling to other fields** g; ......<br>AR 1 <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> **c** *f* **f F**<br>**f** F*u*a *CIV* <del>E</del>R *•* Smallness of *V*shift technically natural. *V* / *V*shift **• Couplings to matter (prediction)** ₩ NOCO THE QCOLD AXION; REFERENCE VALUES **f ₹ ₹ ₹ ₹ ₹ ₹ ₹ ₹ ₹ ₹ ₹ ₹ ₹ ₹ ₹ ₹ ₹** SLOW ROLL INFLATION REQUIRES VERY FLATION REQUIRES VERY FLATION REQUIRES VERY FLATION REQUIRES VERY FLATION RE<br>STATION REQUIRES VERY FLATION REQUIREMENT CONTRIBUTION CONTRIBUTION CONTRIBUTION CONTRIBUTION CONTRIBUTION CON hard to explain why which why why why why why why why why were the corrections. With shift symmetry, *V* / *V*shift **and with a mechanism of production / expression with a mechanism of production / exp and world in the method of production in the method** N GAUSE SCALES, INTERFERING GROWS AND THE SCALES, WALL AT COLLARS TIMING WITH A GROUP AND CORPORA scales **• CMB in agreement with simple in a green with simple simple in the simple of some problems in the with sight of**<br>• PLIN call it we called with the streament with the sight sight sight for the cosmic inflation of the stre **r** Hr **POW** *P*⇣ , <del>f **1 sh** fhyd</del> *d* ln *P*⇣ **dd nicâHV, n**  $\frac{1}{2}$ **k** Smallness of Vshin digch nically nature (2000) (2000) W 5 *V* ⌧ <sup>1</sup> ⌘*<sup>V</sup>* ⌘ *<sup>M</sup>*<sup>2</sup> *p* , 1725 **V 28 30 110 • Flatness and gaussian and gaussian and gaussian and gaussian and gaussian and gaussian and self-coupling to experience on the symmetry of the symmetry of** GPALL BUT I STAR THE LITTLE INTERFEROMENT STAR THE STAR THROUGH STAR THE STAR THE STAR INTERFEROMETER scales • CMB in agreement with simple simplest models in a green with simple state of slow-roll cosmic inflation ppa *P*⇣ *, ns* 1 ⌘ *d* ln *P*⇣ **d a latin a latin (16)** hu<br>12i **http://www.company.com/www.com** ✏*<sup>V</sup>* ⌘ **M**<br>**MA**<br>2021 *p* 2022年<br>2月10年 ⇣*V ,* **SN2 BOOKS THE STAR** *V ,* **WANA 2017 • Flatness and gaussian system in the flatness and gaussian self-couplings** Axion (Natural) Inflation *•* Smallness of *V*shift technically natural. *V* / *V*shift **• Shift statute symmetry on coupling fields and the advantage to one coupling to one to other that the advantage**<br>The advantage to other finition of the alternation of the and the anti-status in the advantage of the advan GW SIG **PD erc**<br>Grig S GW signal natural natural signal natural species species so the COSMMING. While small at COSMAN at COSMAN at **spielen PGW** *P*⇣ **120 8 • FlateMest and game by Shift on the search symmetry (broken by V)** Frees and Birming in Bir **Harao terue**  $H_2 \odot$   $\mathbf{f}$ Local NG : (*x*) = *<sup>g</sup>* (*x*) + *f*local **• Pics the alterement of** *r* ⌘ **PEGWARE** *P*⇣ *, ns* 1 ⌘ **• Flatues sand gouel** *•* Shift symmetry (broken by *V* ) on couplings to other fields has advantages Freesse, Frieman, Olinto k was a sharp a **• No observed departure from (primordial)** Local NG : (*x*) = *<sup>g</sup>* (*x*) + *f*local **Fy, Adreement with** *r, ns* 1*, f*NL = O (✏*,* ⌘) *M*<sup>2</sup> *p* ⇣*V,* GW signal natural natural natural natural natural natural natural small at CMB at the small at the small at CMB ber tab Axion Axion Inflation  $\frac{1}{2}$   $\frac{1}{2}$  Freese, Frank frank frank franken fra Berghaden fra 1988. De en de e (review Pajer) (review Pajer, MP '13) (review Pajer, MP '13) Shows (review Pajer, MP '13) **L E 22 THE** <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> ntage that **France Shift Shift** Freese, Friedrich in der President in der President auf der President auf der President auf der President auf  $\mathcal{L}$ **12** <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f* **c WEIGHT AND STATES** *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ *•* Smallness of *V*shift technically natural. *V* / *V*shift has the advantage the advantage that **• Prediction and the coupling of the coupling** *•* Smallness of *<sup>V</sup>*shift technically natural. *<sup>V</sup>* / *<sup>V</sup>*shift *•* Constrained couplings to matter (predictivity) *C*2 *<sup>m</sup> <sup>m</sup>* **THE WARE DET** 2 **for the company of the c 2X** !*AA* <sup>=</sup> ! *AA* typically controls reheating. Only recently realized that it can play an important role also during inflation.  $\frac{1}{2}$ CAUPLAU GULGU IN THE LUID IN THE TAN TB Haaper reester and brattage and easy ...  $\frac{1}{2}$ **L all th** 1 <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f* **c @** *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ (review Pajer, MP '13) **• Construction of the coupling of the couplin 225** 】<br>"大臣" LATEV& CAVIERNSONGE • Shift Hness of Kantucking of the China California to other fields to the China IOPE, FOSELENCE, VATUES I LES TON CEN **L EL EL** 147 22 (2003) 42 (2003) 42 (2003) 42 (2003) 42 (2003) 42 (2003) 42 (2003) 42 (2003) 42 (2003) 42 (2003) 42 (2003) 42 **c** *f* **@**<br>@1001010ag6y, Adreem *fieht wit***<br>***<b><i>froof next* a Tall rene Sisau Pakista the Current Freese, Frieman, Olinto '90; . . . rnach Martin Sarah Dirasti Dir **L 31-3** 17 2 (2 ) + 12 (2 ) + 12 (2 ) + 12 (2 ) + 12 (2 ) + 12 (2 ) + 12 (2 ) + 12 (2 ) + 12 (2 ) + 12 (2 ) + 12 (2 ) + 1<br>2 (2 ) + 12 (2 ) + 12 (2 ) + 12 (2 ) + 12 (2 ) + 12 (2 ) + 12 (2 ) + 12 (2 ) + 12 (2 ) + 12 (2 ) + 12 (2 ) + 1 **c** *f* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ **f F**  $\det_{\mathbf{A}} \mathbf{H} \mathbf{H}$ *•* Smallness of *V*shift technically natural. *V* / *V*shift **• Constrained to the coupling of the coupling of the coupling of constrained to the coupling of the coupling** ⇤ Not the QCD axion; reference values *<sup>f</sup>* ⇠ <sup>10</sup><sup>16</sup> GeV *, m* ' <sup>10</sup><sup>13</sup> GeV SLOW ROLL INFLATION REQUIRES VERY FLATION REQUIRES VERY FLAT POST OF A REQUIRES VERY FLAT PORT OF A REQUIRED O hard to explanature to explanature and the series of corrections. The corrections of the corrections of the co With symmetry, *Value shift synnethers* in the street with street and the street of the street o FREESE, FRIEDER, FRI (REVIEW PALENT PARTIES) **LEE** 1 <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *c* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *f* **f** *f f* having the advising to the property *•* Smallness of *V*shift technically natural. *V* / *V*shift rannes for the matter of sensitivity of the coupling of the coupling of the coupling of the <u>▶ Not the Literacion; reference values from the Constantine Constantine of</u> a values of  $\sim$  10016 GeV & V182 Show roll inflation requires very flat potential potential potential and potential potential and and, generally, hard to explain why *V* protected against quantum corrections. • FREE SHIFT SHIFT SHIFT SYMMETRY IS SHELL AND THE COUPLING TO OUTLING TO OUTLING TO OUTLING TO OUTLING TO OUTLING FRANCISCO TANDA E MILIO CONTRACTO ereview Pire Kung in Ward Leng **L BLEE 12**<br>21 <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *c* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *f <sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ Harvey Has Kingdom ↓ Sexter in A Contributed in the Contributed in A C **• Constrained couplings to matter (predictivity) and the coupling of the coupling of the coupling of the coupling of** ・ストいのの市り合併の特定は、Cayles などを、その他の作品を、その他の中に使用している。<br>5、それには、Martin は、Particular のサイトの制限を、インターのサイトの制限の制度を、それによって、それは、インターのサイトのサイトのサイトの SILOW ROLL INFLATION REQUIRES VERY FLAT PORT OF THE REQUIRES VERY FLAT POST OF THE REQUIRES OF THE REQUIRED OF hard to explain why *V* protected against quantum corrections. derivative couplings to the seal of the coupling of the coupling to the coupling of the coupling of the coupling in segre **rsiment by declean agreement with the start models of slow-roll cosmic inflation of slow-roll cosmic inflation r** wa **PAGW** *P*⇣ , 1975, 1989, 1989, 1989, 1989, 1989, 1989, 1989, 1989, 1989, 1989, 1989, 1989, 1989, 1989, 1989, 1989, 1989, 1<br>*A, de es santa de la partida de la partida* de la partida de la partida de la partida de la partida de la par **d l d d l b d i b l f b l f b l f b l f b l f b l f b l f b l f b l f b l f b l f b l f b l f b l f b l f b l f b** herue **he of Sireth Brown and Sixty** ✏*<sup>V</sup>* ⌘ *p* **222** *,* **SECTION CLEAP** *p ,* **V Q CKS III** • Flatness and gaussian and gaussianity in the state of the<br>The book the state of the state Axion (Natural) Inflation (Natural) Inflation **• W. G. Mali i symmetry on coupling to our fields to our fields to our fields to our fields of the field of the**<br>Shift shift she as a suit of the only of the station of the station of the station of the station of the sta scales de Nav<br>1932 - Scalvi **• CMB in a greent with simple simplest models of slow-roll cosmic inflations in the state of slow-roll cosmic inflation in r Gia PGWAX** *P*⇣ *<sup>d</sup>* ln *<sup>k</sup> , f*NL ⇠ <sup>h</sup>⇣2i<sup>2</sup> = O (✏*<sup>V</sup> ,* ⌘*<sup>V</sup>* ) , 1985 1988 1988 **d** let the and the state of the production ✏*<sup>V</sup>* ⌘ *M*<sup>2</sup> *p* 2)<br>2) ⇣*V* ,<br>,<br>, *V* **SE2 LEAR HARRES EXPLANA** *V* **.,,,,,,,,, V TEXTILE • FLATNESS AND COUPLINGS AND COUPLINGS** AND COUPLING TO THE COUPLING OF THE COUPLING OF THE COUPLING OF THE COUPL<br>— THE RECHT COPIES FOR THE THE COUPLING OF Axion (Ph. September 1988) **• Shift symmetry of the symmetry**<br>The Soupling of the symmetry of the symmetr FREES SIGNIFICATION TO CHECKER CURLIN *•* CMB in agreement with simplest models of slow-roll cosmic inflation *•* Shift symmetry on couplings to other fields scares a Ed **• NOVEMS SHIV ON LICTUAL COUPLING** (revaewes Pajer) alat **BLAZE KULTZE • Primordial departure from the f • Agreement with standard single field**  $\frac{\epsilon}{\sqrt{2}}$ *M*<sup>2</sup> **• Stand symmetry (broken by V** (reviewes Bajer, Majer) POLE A FI  $\mathcal{F}_\mathbf{A} = \mathcal{F}_\mathbf{A}$ H V NG Y <sub>1</sub><br>be ekkedade park **• BOTAGNI BAGTENT P** ——<br>ft≡ *M*<sup>2</sup>  $\tilde{ }$ Axion Inflation of the Control of *•* Shift symmetry ! + *C* on couplings to other fields Axion⇤ Inflation Freese, France, France, France, France, France, France, France, France, France, F  $\frac{1}{2}$  of  $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$ **L and the Contract of** 1 2 (2 ) + 2 (2 ) has the advancement to the advancement of the advancement • Share to our well-supply to the symphony of the start symphony of the start symphony of the start of the start France Content of Company of Property Content of Content of Content of Content of Content of Content of Content<br>The T W HEN DICTLE Y CONSOMER **L GLE 11** <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f* **c** 有了行政会案件有关的 has the advantage that a decided the advantage to **• Small we verywhere the weather the VS of WBC COCMI • Constrained couplings to the constrained constrained coupling (constrained constrained construction** ዛህ ለገልቱ ተስፋል ናንቤተን ብልተዋል የተለያዩ የራስተው የተለያዩ ያደርገል የዕንደስ email@company when company your company of the most comp<br>በአገል ተጠቃሚ የተለያዩ የ ! ' ! *AA* typically controls reheating. Only recently realized that it can play an important role and the can play and the can play and the can play and the capital role also<br>an important role and the capital role also during the coupling inflation.<br>The capital role and the capital ro 抽印 Freese, Frank of Holing and Holing and Holing and Holing and Holing and ... (review Pajer, MP '13) *L* = **月** <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup>  $\ddot{\theta}$ *f* henfield(m) ings t **f F**O **FUCK** *•* Smallness of *V*shift technically natural. *V* / *V*shift **• Constrained couplings to matter (predictivity)** ! ' **c POPERTY IN ACTION IN A FINITE TELEPHONE CONTROLLER CONTROLLER CONTROLLER** भ<br>| |<br>≥ । ≥ ।  $\overline{\phi}$ Axions Inflation • Shift symmetry and the coupling of the coupl  $N$ antage that,  $d \ln P$ STOLUTION PLEUR AIR RELATIONS **L DE LA CORPORATION** 1 22 (@QQQQQQQQQQQQQQQQQQQQQQQQQQQQ **c f**<br>*f*<br>*f* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ has the advantage that a decouple **L & E** 1 2 (b) 11 to 2 (exempt 25 to 2 to 2 to 2 to 2 **c** *f* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *f f <i>f f f f f f* has the advancement *•* Smallness of *V*shift technically natural. *V* / *V*shift **progetty bandings to ethen field (in) ings to other f** 【Ⅱ012 GeV 】 Reference values in the Quantity of Line in the Quantity of Control Control Control Control Control C<br>利用性 Control Contr I SI<del>N CONSTRAINS VI , and generically inflation</del> requires very flat potential and the potential of the experiment hard to explanature to explanature to explain why the state of the With shift symmetry, *Visit symmetry, and the shift symmetry, and the shift symmetry, and the shift symmetry*, **L = 1** 1 *c* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *c* <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f <sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ has the advantage that **• Semallness to ovacive Reals stile at a third PMA with the VS FIT TEXERY PETHS CETT VO BIDLINGS TO OT TO HT LEO BID IN OS TO THE REDICTION OF THE COUPLAND IN OUR STATE OF T**<br>BE THE STOLE LINESS OF VERILLING ON MICELING DEFITE ↑ Not the Quint Contract of Contract o<br>Not the Design of Contract of Contract of Contract of Contract and Contract of Contract of Contract Of Contr hard to explanature to the mass why why why to explanature and the mass why why why was the main of the correct<br>In a form to be explain in the corrections when you are the corrections. 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PROGRESS OF THE STAR CONSTRAINED COUPLINED** ⇤ Not the QCD axion; reference values *<sup>f</sup>* ⇠ <sup>10</sup><sup>16</sup> GeV *, m* ' <sup>10</sup><sup>13</sup> GeV Slow roll inflation requires very flat potential *V* , and, generically, hard to explain why why why why why why why to explain the state of the state of the state of the state of the<br>In alcohol contractions why was to explain the state of the WOTEPH STRING STRING STRING SYMMETRY GW signal die Gwolf interferometer sy die grows at interferometer som at interferometer som at CMB in the state states scales **• CMB** in agreement with simplest models of slow-roll control cosmic simples **r** Xg PLGW *P*⇣ *, ns* 1 ⌘ *d* ln *P*⇣ **Othen field(fin) in**  $\langle \zeta_+^3 \rangle$ E HT FOR HELL POF LOG LINGE to ethen field in gs to other fields ✏*<sup>V</sup>* ⌘ **SARA SE QIK GALË CË RAMILLË SHKAQITI. p**<br>*p*<br>*p* 2023 *,* ⌧ <sup>1</sup> ⌘*<sup>V</sup>* ⌘ *<sup>M</sup>*<sup>2</sup> *<sup>V</sup>* ⌧ <sup>1</sup> *p ,* • Flatness and gaussian self-couplings and gaussian self-couplings and gaussianity in the state of the coupling GW signal natural natural natural signal naturally small at CMB small at CMB small at CMB small at CMB small a **stal • CMB in agreement with simple with a green with simple that with weather the deuts in of with the slow-roll co POGWY** *P*⇣ 5 maall nes<del>s</del> *d* ln *P*⇣ *<sup>d</sup>* ln *<sup>k</sup> , f*NL ⇠ <sup>h</sup>⇣3<sup>i</sup> **http://www.particle.com/www.particle.com/www.particle.com/www.particle.com/www.p** W¥HIGWZ<br>GD<del>ZNY</del> *A*<br>My 22 *p* 2 iline<br><mark>≛rra</mark> *, V* **SEP WARE WEDER DIE NEUE** *V* **,,,, V Z V Z V Z V • Fantal are also and grand with the self-coupling of the self-coupling of the self-coupling of the self-coupling**<br>UTHE COPTURE CANDING STANDARD AND SANDLE STANDARD STANDARD TO THE SELF-COUPLING OF THE STANDARD OF THE STA **Axien Shurten Inflation Inflation** GW signal natural natural natural states at the interferometer states interferometer states at CMB and CMB at C scales **• Fantality in the flatness and gaussian self-couplings • Shift in calculation** (General Freese, Friespa **(Frew Birmstake Schr** PLANCK TR **• No observed with a full example from (primordial) EGEL IEL (CC Falt Ngilteeme PS 70 in Calculation (backet** Frees Friema (review Patient Planck 1914 **• No observed departure for the particle Local NG & C • Adressme field field standard standard standard standard standard standard standard standard standard standard** Axistand gaussianity as small inflator **• Shift symmetry with symmetry and coupling to our coupling to our coupling of the coupling of coupling to our**<br>• Cua dividend symmetry and coupling to our coupling to our coupling to our coupling of the coupling of the c **Francisch PicaHX, Dattiffel (34); Witking Vshiftir**<br>Freest, Friese, Olinto Basic (1995) (review Pajer, MP '13) <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f* **L E LE LE LE** 18 <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> Axion Inflation Inflation **eves hit fraw relingery** on computings to other fields Free Steam is a three search to your mon **River, May 1990, May 1990, May 1990 La Diale**<br>El Partid **11** <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> **C** *f* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ *•* Smallness of *V*shift technically natural. *V* / *V*shift has the advantage that a straight **• Sharing on the spart of the State of Australian Control of Australian Control of Austral. 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⇣*V ,* 接受 **• No observed is a strange from (primordial) gaussianity, he control of the strange of V • FRATTS & PROGRESS LITTS PRESSING**  $\frac{1}{2}$ <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f* **futbann Europhy**  $\frac{1}{2}$ **<del>EX NOC THE QUES IS NOT THE QUEST OF CHARGE OF CAR**</del>  $\frac{1}{2}$ ₩ NOS STARE I MORE KARA V FRANCIS AXIO *M*<sup>2</sup> *p* **A RESERCE & YOU LESS ON A THE PLOTS STORE CONTRACT** *M*<sup>2</sup> *p* ⇣*V ,* ⌘2 Local NG : (*x*) = *<sup>g</sup>* (*x*) + *f*local -<br>左 *f* ⇤ Not the QCD axion; reference values *<sup>f</sup>* ⇠ <sup>10</sup><sup>16</sup> GeV *, m* ' <sup>10</sup><sup>13</sup> GeV ▶ Not the Tend axion; reference values freeze values of the LEG avenue of the QCD axiev ₩ DOD TE QUE LA VALUES **FOR LA VIEN A LA VIEN A LA VIENCE VA VALUES CE LA VIEN A LA VIEN A LA VIEN A VIEN A VIEN**<br>19 AN XII TE QUE LA VIEN VIEN A GRUES LE MESCANNON CIENT A VIEN DE LA TERRITA CA LA LA VIEN A LA VIEN CE LA *M*<sup>2</sup> *p* **\XXXXXXXXXXX** *V ,* LE NOOT THE QUOT CHE QUOT THE QUOT THE ART ARE ACCEDED TO THE QUOT THE QUOT CHE NOT CHE NOT CHE NOT CHE NOT CH **LES NOCH LIENGVOD GUED AXIONES VALUES AREGAS ET L'ELANULES GN/2014 UNO FORONG NIEW PAV ি 1005 GEV 2014 DARA REFERENCE VALUES AND DELL'AZIONE DELL'AZIONE DELL'AZIONE DELL'AZIONE DELL'AZIONE DELL'AZIO**<br>HU@§ \$XXX LO ' 40 GI & GI & VI MARE VE EN L'AZIONE DELL'AZIONE DELL'AZIONE DELL'AZIONE DELL'AZIONE DELL'A

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⇣*V ,* 接受 **2** *V* **• FRATTS & PROGRESS LITTS PRESS MALL PACE DEPARTURE FROM CONTROLLER FROM CONTROLLER FROM CONTROLLER FROM CONTROLLER FROM CONTROLLER**  $\frac{1}{2}$ <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f* **futbann Europhy**  $\frac{1}{2}$ **<del>EX NOC THE QUES IS NOT THE QUEST OF CHARGE OF CAR**</del>  $\frac{1}{2}$ ₩ NOS STARE I MORE KARA V FRANCIS AXIO *M*<sup>2</sup> *p* **¿€FOLERE CAMPLE CE & VIDEO STORE CONTRACT V 28 SEL**<br>*VO* 28 SSE *M*<sup>2</sup> *p* ⇣*V ,* ⌘2 Local NG : (*x*) = *<sup>g</sup>* (*x*) + *f*local -<br>左 *f* ⇤ Not the QCD axion; reference values *<sup>f</sup>* ⇠ <sup>10</sup><sup>16</sup> GeV *, m* ' <sup>10</sup><sup>13</sup> GeV ▶ Not the Tender of the QCD axion of the Bir & Reference , mail to s av all to the Control May ₩ DOD TE QUE LA VALUES **FOR LA VIEN A LA VIEN A LA VIENCE VA VALUES CE LA VIEN A LA VIEN LA VIEN CANTO**<br>SERVICI LA LA XIENVI, A GEVENIE NE VENERA EN CIESTO EL VIEN LA VIEN E RETRESA A DIGISTRARE LA DILLA *M*<sup>2</sup> *p* ⇣*V ,* **猪食** *V ,* **• No observed edared f** *f* (review Pajer, MP '13) **、《 Not the Light axion; reference values** for the Quantity of the Manuscript of the Control of Control of Control of ⇤ Not the QCD axion; reference values *<sup>f</sup>* ⇠ <sup>10</sup><sup>16</sup> GeV *, m* ' <sup>10</sup><sup>13</sup> GeV **ি 1005 GEV 2014 DARA REFERENCE VALUES AND DELL'AZIONE DELL'AZIONE DELL'AZIONE DELL'AZIONE DELL'AZIONE DELL'AZIO**<br>HU@§ \$XXX LO ' 40 GI & GI & VI MARE VE EN L'AZIONE DELL'AZIONE DELL'AZIONE DELL'AZIONE DELL'AZIONE DELL'A

*V* **SOLUE 1 8 & BOOT TO A** *p V , <sup>V</sup>* ⌧ <sup>1</sup> • Flatness and significant self-couplings <del>*show to H by P</del></del> V* **, we have a strained to a final to a final point of the temperature of the final point of the strained of the Local NG : 2008 SEP (1990) + 1990 CONCLUSION CONTRACT OF A FINAL CONDUCT OF A FINAL COND** 24 *g* ↵⇤ **Local Mesting Contract Mesting Conduct** *<sup>g</sup>* (*x*) ⌦ <sup>2</sup> *g*  $\frac{1}{N}$ **• A great with standard single field standard single field slow roll provided to the standard single field** *c* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup>  $\overrightarrow{G_2}$ *f* **WEB & QUE TEGELLE ELECTE** *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ *•* Smallness of *V*shift technically natural. *V* / *V*shift <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> **dretszoren szori márcs pros**<br>Eksen Grania márcs kező a kapital *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ SLOW ROLL INFLATION REQUIRES VERY FLAT POST OF THE SIM ROLL INFLATION REQUIRES VERY FLATION REQUIRES VERY FLATION REQUIRES VERY FLATION REQUIRES VERY FLATION REQUIRE SLOW ROLL INFLATION REQUIRES VERY FLAT PRODUCT PRODUCT PRODUCT IN FORMATION REQUIRES IN FINE PORT PORT PORT PO<br>TENT TENT ON PLASTIC IN PRODUCT IN 1999 PRODUCT IN THE STATION REQUIRED IN THE STATION OF STATIONS IN THE STATI **2**<br>**The Solu** ✏*<sup>V</sup>* ⌘ 2002 201 **RANCE RESEARCH** *V , <sup>V</sup>* ⌧ <sup>1</sup> *L* = **• Final as Est - Colour in gaussian sex alguna provided the space of as City of Coupling Coupling Coupling Couplings** • Coupling Local NG : (*x*) = *<sup>g</sup>* (*x*) + *f*local **FY, Adres freat with L EXECTS**<br>L SE CLAR<br>L G C L C 花果 <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *c* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *f <sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ has the advantage that *•* Constrained couplings to matter (predictivity) *•* Smallness of *V*shift technically natural. *V* / *V*shift Slow roll inflation requires very flat potential *V* , and, generically, **L S 212** 14 **2 (2) CEEATURO KAAIN c** *f* why and the status why hard to protect a function water and the status which explain why **Function when the funct**<br>hard to explain why why why was to explain why water and water and why was to explain to explain when when **fabulavit**<br>**FØØGddad**<br>Jrøentitø Show roll inflation requires in the court of the column and positive the potential and conduct potential Blog SIC ANY ROLL INFLATION REQUIRES INFLATION REQUIRES VERY FLAT PROPERTY FLAT POST OF THE POST OF THE POST OF THE hard to explain why *V* protected against quantum corrections. **speel Hungers and Great Transferred from the Constitution of the Constitution** 4)<br>31 *V p y* **d** *i s* **<b>***c i <i>y x s i l x i <i>n* **<b>***x s j <i>l c s j <i>l* **<b>***s j <i>z z z j <i>z z z z z z z* **2022485512011** • Flatness and gaussian self-couplings and self-couplings and self-couplings and self-couplings and self-couplings WY<del>Z</del><br>KOZEERSTE **22VIE 1977 WESTACK AND AND HERE CALL AND THE LOCAL HERICA** Local NG : (*x*) = *g*<br> *f* metric al du G 18 L E **11** 2 **(2008) 2 (2008) 2 (2008)**<br>2 (2008) 2 (2008) 2 (2008) 2 (2008) 2 (2008) 2 (2008) 2 (2008) 2 (2008) 2 (2008) 2 (2008) 2 (2008) 2 (2008) 2<br>2 (2008) 2 (2008) 2 (2008) 2 (2008) 2 (2008) 2 (2008) 2 (2008) 2 (2008) 2 (2008) 2 **100 100 100 100 100 100 100 f F**we Full District the full state of the complete state technical construction of the complete of  $\mathcal{F}_1$  and  $\mathcal{F}_2$ 1 **2001 PARTICIPAL CAU DY, ACTES PTE AT AV**<br>**@ FRACES CEBANDY DISTRICACIONE** SOLOW ROLL INFLATION REQUIRES VERY FLAT POTENTIAL INFLATION REQUIRES VERY FLAT POTENTIAL INFLATION REQUIRES VE<br>OF ENT SI BIT OVER THE CONTROLL INFLATION REQUIRES VERY FLAT PORT INFLATION REQUIRES VERY FLAT POTENTIAL COMPU Since a strain requires very first very flat potential of the constraints of the construction of the c = @*µK<sup>µ</sup>* actes Preal An ude Mysterius Couplings)

 $\delta \mathbf{F}$ **• Flatness and gaussianity in the self-coupling self-couplings and gaussianity in the self-coupling self-coupling • British sex in the plant sympathy of the filter** Freese, Freeksain, Olingo, 150; ... **• Raismond standard single field single field single field support of the conduction of the con rycard upi d<del>ebery</del> ({**e, }) **L & SHI**<br>H & C & <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> **Friday** *fulted free force* **• EQSSI IS NOT THE COUPLINGS TO CONSTRUCT OF THE COUPLINGS OF THE COUPLINGS OF THE COUPLINGS OF THE COUPLINGS f**<br>*f*</del><br>*f*<br>*f* hard to explain why *V* protected against quantum corrections. **Ritishift AVRITER IS** hard to explain why *V* protected against quantum corrections. **RIKSHITE** hard to explain why *V* protected against quantum corrections. **LA GLANGER 5 FRIMANNE SERIE Axion (Natural) Inflation of** *Value of Calubration* **Control of** *Value of Article of Article of State of California* **• Pics of BeattCentice** *r, ns* 1*, f*NL = O (✏*,* ⌘) 2 2 (2 ) + 2 (2 WITH STRIP S **• Family Access and guide Mass 5 70 MMW Text 4 GUID & CITE & UNIVERSITY OF • Agreement with single field • Additional field field standard single field some standard single standard single standard standard single s L E ETHER**  $2$  ( $2$ )  $2$  ( $2$ )  $2$ )  $2$  ( $2$ )  $2$ )  $2$  ( $2$ )  $2$ )  $2$  ( $2$ )  $2$ )  $2$  ( $2$ )  $2$ )  $2$  ( $2$ )  $2$ )  $2$  ( $2$ )  $2$ )  $2$  ( $2$ )  $2$ )  $2$  ( $2$ )  $2$ )  $2$  ( $2$ )  $2$ )  $2$  ( $2$ )  $2$ )  $2$  ( $2$ )  $2$ )  $2$  ( $2$ )  $2$ )  $2$  ( $2$ )  $2$ ) has the advantage that a discriming the advantage to the advantage that a straight the advantage to the advanta **• Constrained coupling to matter (predictivity)**<br>• Constraint at Coupling to matter (predictivity) and the coupling of the coupling of the coupling of the coupling **L ENGLIS** <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f <sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ hard to explanature to explanature to explain why why why why we could be sourced against the source of the so<br>A protected a large to the faint of the corrections. The corrections of the state of the corrections of the co hard to explan why the why a straight why a straight to explanation why the corrections. hard to explanature to the correction why why why why and the second why why why why why was a correction of the corrections. **termine**<br>**Rullen**  $\left[\phi\partial_\mu H\phi\right]$ 

**ASK SHORT SHORT START START** Freehrig **FREETHERS REGINGER TRANS PARE +13)**  $\frac{1}{2}$ *M*<sup>2</sup> *p* ⇣*V,* ⌘2 **SOUTH DI CLASS** *V,*  $\overline{w}$   $\ll 1$ **has the advantage to a family of the advantage A Preshift technically shift the department • Construction of Construction AA THRIED AAR**<br>A- DEC'hriteau **神 • Bechnically and Alause of Small** has the advantage With shift symmetry, *V* / *V*shift **• Curain symmetry of shift of coupling of the bibliother fields**<br>Slatiff a contribute signifies so build the thirth and all works the **Elit Sonador stioo Star Darkt • WHEIR ISIQUIFC SYMMENT STATE COUPLING STATE COUPLING STATE TO ON COUPLING AND THE ADVANTAGE TO A REAL STATE**  $M_p^2$  $\mathsf{f}\mathsf{t}^\equiv$  $M_p^2$ *p* 2 **• Construction of the Coupling of Coupling Construction (prediction in the detail of the coupling of the coup CANOGRAM CHICAD AXION; REFERENCE VALUES f** in Outpons of the Williams in Early 13 GeV **PERPORT COR c**<br>45 <sup>2</sup>⇡*f*<sup>2</sup> *<sup>m</sup> <sup>m</sup>*<sup>2</sup> !*AA* = 。<br><del>他非</del> <sup>64</sup>⇡ *<sup>f</sup>*<sup>2</sup> *<sup>m</sup>*<sup>3</sup> **be of it is the overlap of the some diplomation of the production is deviations at 17 display of Vshift**<br>
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**• CMB in a green with simple simple with simple simple simplest models of slow-roll cosmic inflations Mudels you all with us has a leson** *PGW*<br>Pathywork **d ln GYO**<br>Soddinaid Freese, Friends of Lands and The Street in Oriental **CENTURER, MPCPS** Free Summer Lead Entre Contre Company **CENTER PARALLES**  $\frac{2}{3}$ xionis, justin Bayn B ! *AA* typically controls reheating. Only recently realized 2 Victoria Life (1945 *c* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *f <sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ 2 2 (2 % <mark>15 % )</mark><br>2 (2 % )<br>2 **1** 0 % ) **c** *f* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ 2 Mi<br>2 p **c**<br>T *f* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ **f** *F F F F F F Math* • T. CMAREWA BUILDERING IT JOSH HY STORIC SLOW-ROLL 570 F. SLOW-POIL COSMITTENT ENTITLE **• CMB in a figure model with simple with simple simplest models of slow-roll cosmic control cosmic inflation** Frees And Chemistra Che (PRIPATED PHILIPMOTOR) FREESEW FRINCIPAL REACH (Pavel A) France Palitecto Axion Axion Inflation ! *AA* typically controls reheating. Only recently realized ... **MTS GRWCFWOOLK LEAN** <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f* **#FGORFHGAZENG HEALS function in the street of the conduction of the function of the street of the str** י<br>ווא directorist Tubelitt () Storicle *c* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *f* **f 611**<br>**f01143171437** *L* = <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f <sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ 1 *c* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ **KRAME WATER GEORG** Planck 15 (Review Pajer, MP PLANCE THE *•* Shift symmetry ! + *C* on couplings to other fields Axion⇤ Inflation ! *AA* typically controls reheating. Only recently realized (redistributed to the control of La Empire Axion Inflation has the advantage that *f* has the advantage that <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f <sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ GW GROOF ALLE ENTERFEROMETER SCALES, WHILE STANDARD SCALES, WHICH SHOULD A COMPANY scales GW SIGNAL NATURAL STATE STATE AT INTERFEROMETER SCALES, WHILE SMALL AT INTERFEROMETER SMALL AT COMPLETE SMALL acalds GW SIGNAL SAN TAN NATURAL NATURAL NATURAL NATURAL GROWS AT INTERFEROMENT SAN TANGGER STANDARD STANDARD STANDARD **erare** *P*⇣ *d la d r*(0) 700 | 55<br>2022 | 2013 | 400 | 405<br>47 | War Bertler **• Flatness and gaussianity and all eliters** *r* ⌘ *P*⇣ **PMS 21 3 d light of a local sex of a local sex of a** local sex of a local sex of • Flatness and gaussianity in Figure 1 Bill inflaton scales he actva **1\$\$000** Coupling in a structure in a series in the structure Crossew Patierent Tool  $\mathcal{L}(\mathcal{C})$  . The particle  $\mathcal{C}$  $F = 100$  From  $F = 100$  M  $F = 100$  M  $F = 100$ **ACEIS YAWE AWENDIFF AS** 

*, ns* 1 ⌘ **CIMB d late all the complete jaw hsuch of the original superior of the original** *d* ln *P*⇣ **de la film** h<br>h <sup>h</sup>⇣2i<sup>2</sup> = O (✏*<sup>V</sup> ,* ⌘*<sup>V</sup>* ) *r* ⌘ *P*⇣ *kkenbyby yghdr*<br>- a atlaa **d** dupdig to stake the PDA PLANCK *Pt*  $b5$ *lanck* $P$ **PECIFORE ASSACE** *Pt •* Shift symmetry ! + *C* on couplings to other fields Free Cultural Constitution of the experiment of the Cultural Cultural Cultural Cultural Cultural Cultural Cult<br>Friends in Einstein on Oliver August 2014 Festival Analysis (R. L. ICV) in Fest **• Sharedings to other field** that it can play an important role also during inflation. **• Short sellife a symple symple symple and coupling to other fields** avssin **• Smallnings of Guilt tegen in the COUNTY of The** *•* Smallness of *V*shift technically natural. *V* / *V*shift **r s** *POWDMACS #2, OLDSB FiCGGinO Lin OS #1 P*⇣ , a sport of the started started that is the compact of the compact of the compact of the started of the compact of t **PAG** *P*⇣ *, ns* 1 ⌘ **de la de la de la de la de la d la la**<br>**d la la la la la la la la la la** h <sup>h</sup>⇣2i<sup>2</sup> = O (✏*<sup>V</sup> ,* ⌘*<sup>V</sup>* ) Freese, Frieman, Olinto '90; . . . Plance California **Marphy Andrew Comment of Comment Street Second Telegand Street Street Street Street Street Street Street Street**  $d \mid p \mid P$  . Suite symmetry ((bookerby)  $V$  Shift symmetry ((bookerby)  $V$  on coupling to other  $V$ **adregg partial store to coupling the field of the coupling of** Freese, Friedrich Berg, Frankryk in der that it can play an important role also during inflation. (review Pajer, MP '13) adiceRingham has send started getting to the water fields and the coupling of  $d\ln P$ **• Short Alan Article of South technical**ly natural work that we have a straight that  $V$  and having the early you would get *•* Smallness of *V*shift technically natural. *V* / *V*shift du yair a yis ya Angiring *•* Smallness of *V*shift technically natural. *V* / *V*shift PLGW **during the original of the original in graph or property fields and the original in graph of the details of the deta** , 0 85 1 mg 5 7 g d In *P* : Sstift symmetry (broak **r and PSZICTVANT PORPLICH AZZ A LOGIE LEGISLAGO (BILDA)** *P*⇣ Freese, Friedrich Weiter (1903), Friedrich Weiter (1903), Shot C **• Shift symmetry of couplings to other fields** Frees Standard of British Inventor that it can play an important role also during inflation. **• Shift symmetry contribution** at heat fields bing  $\frac{\partial u}{\partial t}$  at a cother fields Freese, Francese, Fr<br>En 25 juillet : Maria Gallerin, Francese, Francese, Francese, Francese, Francese, Francese, Francese, Francese respirate which script to a traction of a with the small script technical interval. Which should • JOSC COMPANY WALLER OF FILE TO THE RESERVE OF THE VIOLENCE OF A LITTLE TO THE VIOLENCE OF THE CONTRACT OF THE<br>Response of the Value of Aller Strain and the Value of Aller Contract of Aller Contract of Aller Contract of t hediest Pretensionles Registro H.G **• Smallnument in the Vshift way the way in work work of the Variation of Vshift United States of Bights**<br>The distribution of the states of the Committee of Way of the Collumn of the Variation of Asian Collumn of the **• CMB in agreement with significant is green with the control of strategy of slow-roll cosmic inflation of the RAS FRACTION IN ALCOHOL • In careforment with simplest models with six of models with simplest models in the simple of slow-roll cosmic**  $\overline{\text{at}}$ *P*GW •• Shift tsymmetry (broken by *V* ) on bound great hap Frees of Friends in Survot 2009 of '9 (review Pajer, MP '13) • Shift tsymmetry (broken by *Voldsboblings to comment* Freese, Frieman, CLITAN OOOO (**) And '13) The Control of the Pa** ARDALACHTE AOL PORT !*AA* <sup>=</sup> ! *AA* typically controls reheating. Only recently realized the actual such an important results of a control and the can play and the can play and the can play and the c<br>also during inflation and control also during inflation. The capital such as the control of the control of the<br> Frees, Freisigklaan, Oliectrike **IXISSO AXIONALIST PROTECTION DELL'ANNO**<br>A OYI <sup>IST</sup>I IT LES NUMBERS A SALLI *L* = <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f <sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ 1 *c* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ **L + 1 11** 2 (2 QQQQQQ) + V + QQSCQXQ+ **c** *f* 第5 负 5 + 15 + 15 000 <del>< 1</del> *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ *L* = 52 2 (2000) + 5 (2001) + 2 (2001) **c** *f* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫

✏*<sup>V</sup>* ⌘ *M*<sup>2</sup> ⇣*V* ⌘2 *p* **2** *, V* **partereance** *Ps* / *<sup>k</sup>ns*<sup>1</sup> *<sup>r</sup>* <sup>=</sup> *Ps* **• No observed departure from the community of the c Ps • No observed the property of the compart of the property of the compart of the construction of the compartum of the co** Patter in Smallness of Tager Freman<br>Frieman **p** *f* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ **Pileashtheta dhand**  $\frac{1}{2}$ **• Constructive coupling to matter to a coupling to matter (predictivity) and the coupling of • Constrained couplings** *•* Smallness of *V*shift technically natural. *V* / *V*shift **• Constrained couplings to matter (predictivity)** *M*<sup>2</sup> *p* ⇣*V ,* **\$2 • Notifical departure from (primordial) • No observed departure from the form (primordial)** RGTETTT CLEARE CERTE WITCHING AD WORRPY **(review Paper, MP '13)** LAS IOST FRUM LEXA HALA *f f <i>f f f f <i>f f* **L & MAK** <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> **de de 2 + 2 + 2 + 1 + 2 + 1 + 2 + 1 + 0 + 1 +** Freese, France Hallen, Oliver Color Blatt ness of Wahad Alechnical Waha • Construction in Coupling to Construction and Construction 、○ 日有用「EOP」QLMC店」公司(POP)」<br>31 OAL @B 在TTO QLDI CED AXION; REFERENCE GENERAL CENTRE THREE OF STUDIO AXION; CENTRE THREE THREE OF **• Change as Couplings to matter (predictivity) to the coupling of the coupling of the coupling of the coupling** ⇤ Not the QCD axion; reference values *<sup>f</sup>* ⇠ <sup>10</sup><sup>16</sup> GeV *, m* ' <sup>10</sup><sup>13</sup> GeV **• Constrained coupling to matter (predictivity)** • NNO observed departured f • No observed the departure of the parties of the contract of (review Paler Paler Payer) A William Court Payer (review Pajer, MP '13) ——<sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> L **p res CU**<br>16 *c* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *f <sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ (review Pajer, MP '13) as the rest and the Hall in 1991 for 2007 and 115 COUPLITED to U.S. <u>ি સ્ટોર્નિસ બ્રિટિવર્સ કર્માટક બોલેલો કરવા કરવા છે. આ બ્રિટિવર્સ કરવા મારા કરવા આપણે 1016 GeV & 1016 GeV 4200</u><br>સ્ટેડરે પ્રાપ્ત કરવાનું સ્વાસ્થ્ય પ્રાપ્ત કરવા કરવા મારા સ્વાસ્થ્ય સ્વાસ્થ્ય ન બ્રિટિવર્સ કરવા બ્રિટર્સ કરવા **• Constructive of Constructivity of Construction Constructive Construction Constructive Construction • Constrained coupling to matter (predictivity) and coupling to matter (predictivity)**<br>• Constraint (predictivity) and the coupling of the coupling to matter (predictivity) (predictivity) (predictiv<br>• Constraint (predicti **r and an PAGE** *P*⇣ **60 Jig Hotel d ln 231 1841 80 257 dv les in News Your Big Co. Ex Ex Music S74** *r*  $\frac{1}{2}$ **PAGW** *P*⇣ 5 na 1 <del>1 ness</del> *d* ln *P*⇣ **d la kin** he he has leaded to the high obstige to educate  $P_{\zeta}$ **Blanck '16**  $\boldsymbol{P}$ Planck 115 **Parts /** *k*nsen *r* den den *Ps •* Shift symmetry ! + *C* on couplings to other fields Axion⇤ Inflation Francisco di Riccali Valencia di 1981 va esta Valencia di 1990 e **• Shift symmetry of the symmetry** Freese, Frieman, Olinto '90; . . . Circa Pager Pager Pager **• Shift symmetry is a figure of the coupling of the coupling of the coupling of the field of the field** street is<br>at light it is a coupling of the coupling o has the advantage that *•* Smallness of *V*shift technically natural. *V* / *V*shift has the advantage that *•* Smallness of *V*shift technically natural. *V* / *V*shift has ounce a change that age to *•* Smallness of *V*shift technically natural. *V* / *V*shift

⇣*V , V* \$\$ **WE LE COOPERTY 200** *p V* **, , , , , , , ,** *V 2005 1769*<br>*S 2005 1992 1905*<br>M 21 04 1994 1994 ⌧ <sup>1</sup> ⌘*<sup>V</sup>* ⌘ *<sup>M</sup>*<sup>2</sup> *p V ,* **VEYA HIJARAY**<br>X TARBER H **• Click That Sex altitude SSS Linity ! Strain all** ↵⇤ Local NG : (*x*) = *<sup>g</sup>* (*x*) + *f*local NL ⇥ <sup>2</sup> *<sup>g</sup>* (*x*) ⌦ <sup>2</sup> *g* ↵⇤ <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> **C** @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *f <b>F F •* Smallness of *V*shift technically natural. *V* / *V*shift ■ Not the Quantity of QCD axion; reference values and the Quantity of Text of Construction of Construction, and SLOW ROLL INFLATION REQUIRES VERY FLATION REQUIRE CONOC CONOCH EXCORPCION CONTROL CONOCH EXPLORATION Slow roll inflation requires very flat potential *V* , and, generically, いいはら マンバー 日代 でてくれもXT イオバリジョリント f ぶりある f ☆ 1016 G to 2016 SLOW ROLL INFLATION REQUIRES VERY FLAT POTENTIAL ৣ৸৸৸ৢ৸ৼৣ 21<br>11 *V* **b** 105 2 3 3 4 7 2 *V , <sup>V</sup>* ⌧ <sup>1</sup> ⇣*V ,* ⌘2 ✏*<sup>V</sup>* ⌘ *M*<sup>2</sup> *p* 2 *V* Local NG : (*x*) = *<sup>g</sup>* (*x*) + *f*local **REGIONAL PROFILMAR VACCE / PRODUCTION** La natw<del>y is</del> is majir<br>Mahanggiah - qaussig **La Seconda IC** 22 (2020)<br>2 (2020)<br>2 (2020) 2 (2020) 2 (2020) 2 (2020) *c* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *f <sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ *•* Smallness of *V*shift technically natural. *V* / *V*shift 川<br>17 SLOW ROLL INFLATION REQUIRES VERY FLATION REQUIRES VERY FLATION REQUIRES VERY FLATION REQUIRED FOR DESCRIPTION SLOW ROLL INFLATION REQUIRES VERY FLATION REQUIRES VERY FLAT POTENTIAL PRESENTATION REQUIRED ₩ Not the QCD axion; reference values and the Control Control Control Control Control Control Control Control Co<br>South Control Control Telephone was the Control Control Telephone Control Control Control Control Control C SIC ROLL INFLATION REQUIRES VERY FLATION REQUIRES VERY FLAT POTENTIAL IN FLAT POSTER VERY FLAT POSTERING POTEN fermions gauge fields gauge fields gauge field ✏*<sup>V</sup>* ⌘ *MEZORIES &***<br>"LISE GLYCCHA** 2 *V* ⌘2 **RESERVE OF DELANDER 42 ,** *V* **VEICE THE RUN CORRECT WEST DEVICES ELITI AMIX p**<br>p ⇣*V* ,<br>,<br>, ⌧ <sup>1</sup> ⌘*<sup>V</sup>* ⌘ *<sup>M</sup>*<sup>2</sup> *p* **V** WE NG : 2 (2001) + 2 (2001) + 1 (2001) + 1 (2001) + 1 (2001) + 1 (2001) + 1 (2001) + 1 (2001) + 1 (2001) + 1 (2001) + 1 (2001) + 1 (2001) + 1 (2001) + 1 (2001) + 1 (2001) + 1 (2001) + 1 (2001) + 1 (2001) + 1 (2001) + 1 Local NG : (*x*) = *<sup>g</sup>* (*x*) + *f*local **Lewis** 1 **c** ● <del>★ 112 + 20 11 + 2</del> + 12 + 20 12 + 20 12 **f F**wind the public technical strategy of a strategy of the public technical strategy of the public technical strategy of  $\mathcal{F}_{\mathcal{A}}$ SOUTH ROLL INFLATION REQUIRES VERY FLAT POTENTIAL AND REQUIRES VERY FLAT POSTAGE OF PORT OF PORT OF PORT OF PO<br>SUBJECT PORT OF PORT OF PORT OF PORT OF POSTAGE OF PORT OF POR ⇤ Not the QCD axion; reference values *<sup>f</sup>* ⇠ <sup>10</sup><sup>16</sup> GeV *, m* ' <sup>10</sup><sup>13</sup> GeV CTICS CNUXXIII AXION; REFERENCE VALUES **f CONTRACT CONTRACT CONTRACT CONTRACT CONTRACT CONTRACT CONTRACT CON**<br>HU@S 252 Contract Contrac = @*µK<sup>µ</sup>* **Majak** ✏*<sup>V</sup>* ⌘ *Ps* • No observed departure from (primordial) and (primordial) gaussianity, his construction of the primordial of the • No observed to the primordial gaussian REVIEW PART EN MANAGEMENT S (ROTH WERE LIGHT IN HARRIS DE 世的纯 22 (22 Angel 1921 - 1922 - 1922 - 1922 - 1922 - 1922 - 1922 - 1922 - 1922 - 1922 - 1922 - 1922 - 1922 - 1922 -<br>(review Paler, MP '13) - 1922 - 1922 - 1922 - 1922 - 1922 - 1922 - 1922 - 1922 - 1922 - 1922 - 1922 - 1922 - 1<br>  $\frac{1}{2}$ **L** 2 **人<br>氏 c are the all verse** *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ FREES ENTERTAINMENT EN MARINE AND TRANSPORTED **• Construct Fame of Coupling to matter (predictivity) • Constrained coupled to matter (predictivity)** • Constrained constructions to matter (predictivity) and the coupling of the c

• Flatness and gaussianity → Shankings and gaussianity → Shankings and gaussianity **Axion (2) Contract on the contract on the contract on the contract of a flow of contract • Agreement with standard single field standard single field** 14 *f* **c**<br>F @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ **• Flatness and gaussianity in the self-coupling of the self-coupling of the small self-coupling of the self-coupling • Final second gaussianity in the state of the self-coupling of the self-coupling of the self-coupling of the self-**<br>Red in self-coupling in the self-coupling of the self-coupling of the self-coupling of the self-coupling **Figure 1 • Agreement with standard standard single field • Agreem with standard single field slow roll** has the advantage that the advantage that the advantage that the advantage that the advance of the advance of  $\rightarrow$  8 matter (prediction of the couplings to matter (prediction of the coupling) **L EL EL** 2 (2 ) CSSREET TO CALL VSAMMER *c* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ **fachess/a**<br>**FAQIO FLAC** hard to explain why *V* protected against quantum corrections. hard to explain why *V* protected against quantum corrections. hard to explain why *V* protected against quantum corrections. *•* Flatness and gaussianity ! small self-couplings **Derivative couplings** 24 *V* 115 1 *c* **2000 DY, AQLE SEARCE** Slow roll inflation requires very flat potential and the potential very flat potential inflation requires in the potential requires in the contract of the contract potential requires in the contract of the contract of the **AGE STIRENESS** shift-symmetry ✏*<sup>V</sup>* ⌘ *M*<sup>2</sup> *p* ⇣*V* **M2** 22 22 22 **p** 93339 Tu 894517 *<i>Market Dicaster Time Dick Vacuum 200 ,* **749 • Fedtischess a** Local Cocal NG + *floots* T. 人<br>旧中的 4 **c <u>OUN DE CROID, REFERENCE VALUES IN ONE THE CROISE TO HER CAR CAR TO THE CROISE TO THE THE THE THE THE THE THE T**<br>ET IN 1023 GEV OLD, REGION; reference values in the QUESS CAR TO TELECTIVE CAR TO CAR TO THE CAR CAR CAR TO</u> ⇤ Not the QCD axion; reference values *<sup>f</sup>* ⇠ <sup>10</sup><sup>16</sup> GeV *, m* ' <sup>10</sup><sup>13</sup> GeV

 $\delta \mathbf{F}$ • Flatness and gaussianity in the self-coupling of the state symmetry of the state symmetry of the state of the m<br>•• Shift symmetry of the state symmetry of the symmetry of the state of the state of the state of the state FRASSA AZOREGIA E POLINGGA DE SER **• Agreement with standard single field standard single field slow roll in the slow roll of the standard standard single field standard single field standard standard standard standard standard standard standard standard s** *r, ns 1, for a 1, for* <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ **f F**also From the FFU For a state (predictivity) and the function of th *•* Smallness of *V*shift technically natural. *V* / *V*shift has the advantage hard to explain why *V* protected against quantum corrections. hard to explain why *V* protected against quantum corrections. With shift symmetry, and **With shift symmetry** hard to explain why *V* protected against quantum corrections. Axion (Natural) Inflation **With shift symmetry • Shift symmetry of the symmetry**<br>The state was also to other fields to other fields to other the symmetry of the symmetry of the symmetry of YCLAWEILDS STATE TOWARD IS ENDINGER *r, ns* 1*, f*NL = O (✏*,* ⌘) <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> **• Smallness of** *Vshift technical* **technical technical technical technical structure** has the advance of the advancement of the advancement With shift symmetry, which shift symmetry, which shift symmetry, which shift symmetry, and the state of t With Saint Section symmetry, and the state of the sta *•* Flatness and gaussianity ! small self-couplings **• Agreement with standard single field • Agreement with standard single field L ELEMENT** <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> has the advantage that a coupling the advantage that a coupling to matter (predictivity) and the advantage of<br>•• Constrained couplings to matter (predictivity) and the application of the advantage of the application of the *L* = <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f <sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ hard to explain why why why why why why why why are correcting to explain why are ment corrections. Why we can use hard to explanature and the why why hard the state of explanature and the corrections. The corrections of the corrections. The corrections of the term • Flatness and gaussian self-coupling to the coupling of the couplings of the coupling of the ✏*<sup>V</sup>* ⌘ **22 VALUE** ⌧ <sup>1</sup> ⌘*<sup>V</sup>* ⌘ *<sup>M</sup>*<sup>2</sup> *p* **V EXIST AXION CONSULTANCE (NATURAL) INFLATION • FLATNES AND GAUSSIAN SELF-COUPLING AND STATISTICS AND GAUSSIAN SELFECTIVE • Shortssymmetry o N • La Standard Single field single field single field single field single field single • A growed gent with organical single fi** *L* = <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f* **1 ASANTA CACHIDARA CAN A CARGO DE L'ANTICA DE L'ANTICARE EN 1989 EN 1989 EN 1989 EN 1989 EN 1989 EN 1989 EN 1 PYT WATERS SUBJECT TO THE ENGLISH TO CONTRACT A COMPANY OF A LANGUAGE TO CALCULUS CONTRACT OF A LANGUAGE TO CA**<br>A COMPANY INTERNATIONAL TO THE ALL THE ALL TO THE AND THE ANGELIA OF THE CONTRACT TO CALCULUS SY MAM ELEVICO **L** <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ *•* Smallness of *V*shift technically natural. *V* / *V*shift **• Construction of the Construction of the coupling of the cou L E SUBTIFICATION TO BE FROM THE CONTRACT LESS TO CONTRACT TO SALITY OF CONTRACT CONTRACT TO THE CLOTTER OF A LAND LESS TO A LAND L** 1 *c* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ Slow roll inflation requires very flat potential *V* , and, generically, Slow roll inflation requires very flat potential *V* , and, generically, hard to explanature to explanature and the corrections. The corrections of the corrections of the corrections hard to explain why *V* protected against quantum corrections. **SERIES INFLATION REQUIRES VERY FLATION REQUIRES VERY FLAT PORT OF REQUIRES VERY FLAT PORT OF REQUIRES VERY FLA<br>And the flat potential of the complete state of the postential of the political port of the complete of the co hard to explain why why why why why why was alleged as a corrections.**<br>Print in the state and the very thank that corrections to the corrections of the state of the US office  $F_0$ 

**WALER IS FRIED SYMMETRY** Free Shift Syn **FAWIER SHE** PSY.<br>. **REGINGERANCY AND 1131 L ት** <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> **WERE ENTREACHED FOR A CHARGE THE LEAR HOLES** @*µ M*<sup>2</sup> *p* ⇣*V,* <u>त्री द</u> ⌧ <sup>1</sup> *,* ⌘ ⌘ *<sup>M</sup>*<sup>2</sup> *p V, <sup>V</sup>* ⌧ <sup>1</sup> **在村** *M*<sup>2</sup> *p* ⇣*V,* ⌘2 22 1922<br>22 1922 1923 **SOCIOLS** *V,*  $\overline{w}$   $\ll 1$ **has worth Shandway Hall and Cantage that • Small Note of Ugli that the Actual Actual Little of Actual Vshift of Value Watch Vshift the Watch Vshift of Actual Vshift the Watch Vshift of Watch Vshift From First Construction Construction Construction Construction Construction Construction Construction Construct** ₩ NOT TO COOL THE QUARK THE REFERENCE VALUES **f axion control to the COOL EA** WUIER SPORTERSY <u> 신라리</u><br>한 2014 **64\$P6#HV&RAH**<br>he advants<br>f273 xxxxxxxxxx  $\tilde{\mathbf{P}}$ **• Smith sy Ros the advantage Challen Proper** FREEFINGERES TECTIFIK SHIP FRIEDRE STATION IN THE TELL AND <br>HE SAN AND THE TELL **(REVIEW PATTER ATTENCE) • Shift symmetry of the symmetry**<br>• Shift symmetry of the sym Free CNA Free Man 1984 Class Capture In 1994 Class Control Capture  $\epsilon \equiv$ *M p*  $\overline{\mathbf{R}}$  $\mathbf{A}$ *M*<sup>2</sup> *p* 2 ⇣*V,* has the advancement that the advance FIRESTHOULD SERVED THE TUBE TO BUT THE TUBE TO BE THE THE TUBE TO BE THE RESERVED. **• Public PAS FOR CONSTRAINATE CONSTRAINS TO CONSTRAIN (PREDICTION)** Not the QCV antigge the properties of the Contract of Central Contract values of the Contract of Central Cent 2011 *c*2 <sup>2</sup>⇡*f*<sup>2</sup> *<sup>m</sup> <sup>m</sup>*<sup>2</sup> !*AA* = **시인!!!<br>수단물 6013434 style**  $\bar{\bm{\lambda}}$ *•* Smallness of *V*shift technically natural. *V* / *V*shift **• Shift symethold advantage the properties to other fields Axion (Biotherical) Inflation** Inflation in the Company of Company of Action (Action Company in the United States) **• Shift symmetry on coupling to other fields** the advantage to the advantage to other fields to other fields to o<br>Symmetry of the coupling to the advantage to the advantage to the advantage to the advantage to a control t  $\mathbb{R}^4$ **• FOUR PREDICTION COUPLINGS TO COUPLINGS** TO COUPLINGS TO COUPLING **123514201622** ₹ KUCCITMSRITIY<mark>DIGIYA FIGM 100 000 1000 1000 1000</mark><br>N LaiG & Ltha Dunner Glata Glata *f A* 210 f<sup>on</sup> Tawt <sup>2</sup>⇡*f*<sup>2</sup> *<sup>m</sup> <sup>m</sup>*<sup>2</sup> !*AA* = <sup>64</sup>⇡ *<sup>f</sup>*<sup>2</sup> *<sup>m</sup>*<sup>3</sup> **• IP & Hallis specifically natural strange in the Control of Control Control of the Underline of AP** has the specific synten and the advantage that With Shipping and the strip symmetry of the strip symmetry of the strip symptote of the logic<br>With a little strip to the strip WALEERS IS RELATED AND RELEASED IN THE STATE STA **• Shift symas the advantaige tha province of BEAWIER GREET GEWHELD FOUT WARE • Shift symmetry of the coupling of the coupl** Freese, Frien ENA viéw Pajer  $r$ , <u>kiena vienu = Span</u> *RIA EXPATTE A (* ✏ ⌘ *M*<sup>2</sup> *p* ⇣*V,*  $\mathbf{P}$ おh.ica4\$ *p V, <sup>V</sup>* ⌧ <sup>1</sup> **has the advantage that a discrete that the advanced but the coupling of the c** *•* Smallness of *V*shift technically natural. *V* / *V*shift ! **c**<br>253 当行》<br>일<br>2172 **facture • Small francusk from the Contribution of the Contribution of Contribution** has the advantages that With shift symmetry, which a light structure With shift symmetry, *X* PL and Linux WITH SHIFT SYMMETRY, WHOMATESHISHIS THE THING CORPORATION STATES IN THE CONTROL CORPORATIONS "

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**• Constrained construction of the coupling of** 

<sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup>

**INFLATIONARY MODELSHIPS INFLATIONS AND THE REAL PROPERTY OF STATISTICS. E** in adreement with simplest models of *r* ⌘ **PEGWA** *r*  $\equiv$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$  $\oint_{\mathbf{a}} \phi \rightarrow \phi + c$ *d* ln *P*⇣  $\phi \rightarrow \phi + const.$  infla ישן<br>קרוב<br>יימודי **ME VATGLS Prodess** J<br>Sab **• Full state of and self-couplings ity -> small self-couplings ity** -> s<br>Introduction of the small self-coupling it is a small self-coupling Axion (Natural) Inflation **ese Shift is you that stay** on couplings to other  $F$ re $e$ s $e^w$ Frienzan, Olinto '90;  $k$ **• CMB in agreement with simplest models o** *P*⇣ *, ns* 1 ⌘ *<sup>d</sup>* ln *<sup>k</sup> , f*NL ⇠ Freese, Frieman, Olinto '90; . . . **€∰HT**  $\widetilde{M}$ *p*  $\frac{1}{2}$ ⇣*V , V* av<br>2 ⌧ <sup>1</sup> ⌘*<sup>V</sup>* ⌘ *<sup>M</sup>*<sup>2</sup> *L* = • Constraint was the matter of construction of the advantage of coupling of co Axion (Natural) Inflation *•* Smallness of *V*shift technically natural. *V* / *V*shift With shift symmetry, *V* / *V*shift With shift symmetry, *V* / *V*shift • Shift sy<del>mmetry on train nother to matters</del> Freese, Frieman, Olinto 90; (review Pajer, MP '13)  $\alpha$  in the  $\alpha$ Axion Inflation Shartage than  $S''$  , This equatorial median of  $P$  and  $\mathcal{A}$ **L ELER has the red steentbyggleatteichnically nátur<del>ál (K</del>WOREAN) PolffroVS**PréhéafSIMO ã'N<br>Creview Paier MP 13)  $\phi \rightarrow \phi + const.$ <sup>mid</sup> and suppose the coupling to  $\phi \rightarrow \phi + const.$ FIFEESE, OTTIESTHIT TEOMITIC AUDY, .<br>ב 2 (COCACCHITER) **c**y *f* @*µ* · Constrained construction in a the partition \* Not<sup>4</sup>the QCD axion; reference values *f*  ! *AA* typically controls reheating. Only recently realized the can play and it can play and also determined and at care that  $G(z)$ ... W -> small inflaton, self-couplings> LIVE dEWAIY **Land**  $\frac{1}{2}$ 2 E F F G S H C C L G H D G S A L C L<br>AS C LE PSEUCLO-SCALAT (2000) **c**<br>12 *f* **PAKAP }** *•* Smallness of *V*shift technically natural. *V* / *V*shift B. OH-CO n2<br><del>Cc</del> 2019 100 2019 100 2019 100 2019 Lion<sup>®</sup> Inflation  $\frac{1}{2}$  summatrix  $\frac{1}{2}$   $\text{cese}, \text{y}$ "  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{dens}$ ",  $\text{cens}$ ",  $\text{dens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$  $\gamma$  reposed to start responsive to  $\gamma$  it  $\gamma$ *L* = <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> प<br>च  $f_{\text{a}} = \frac{F_{\text{A}}}{F_{\text{B}}F_{\text{B}}F_{\text{C}}F_{\text{C}}F_{\text{A}}F_{\text{A}}F_{\text{A}}F_{\text{B}}F_{\text{B}}F_{\text{B}}F_{\text{C}}F_{\text{C}}F_{\text{C}}F_{\text{D}}F_{\text{D}}F_{\text{D}}F_{\text{D}}F_{\text{D}}F_{\text{D}}F_{\text{D}}F_{\text{D}}F_{\text{D}}F_{\text{D}}F_{\text{D}}F_{\text{D}}F_{\text{D}}F_{\text{D}}F_{\text{D}}F_{\text{$ **ese** *v* **Frienzan, 'Olint & Po'C+R**<br>Lese Viene de Values ⇤ Not the QCD axion; reference values *<sup>f</sup>* ⇠ <sup>10</sup><sup>16</sup> GeV *, m* ' <sup>10</sup><sup>13</sup> GeV **LA DS<sup>E</sup> LE** 2 **Q** and 2 0 0 0 0 2 5 0 has the advantage that **• Smallness of** *V*<br>• Smallness of The Condicion • Constrained couplings (predictivity)  $\frac{1}{2}$   $\frac{1}{2}$  Egm (prinsynn) all lations and flat the district of the district of the state of the state of the state of the hard to explain why *V* protected against quantum corrections. hard to explain why *V* protected against quantum corrections. **L = 1** . . <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f*  $2$ @*µ* has the advantage that **•** Smallness of *Vshift* technically **• Octocks first coupling to matter (predictivity)** <u>\* Not</u> the QCD the Q.CQ axion; reference **L . 12** 21 Koving Birshore () Shawi Sviolde **c ow sighar had description of the designal putting for a while small at Contract of the small at C** has the advantage third **•** SMatheese, of *V*shift technically,  $V(\varphi) \leftarrow \frac{\phi}{r} F_{\mu\nu} F^{\mu\nu}$  , inflatory  $\phi$  is pseudo-scalar axion (if  $\Theta$  ) is  $V\Theta$ <del><sup>→</sup> NOT</del> the QCD axion; reference values f<sup>1</sup> SIOW, FOII HITHSHION requires very flat potential <sup>in</sup> **hard to the second why and warned against the explanal why was** WEBIOTISSYMARY WHEN SHUTTLES TO DELETE SHE COMPLETE  $\phi$  $\frac{\varphi}{f} F_{\mu\nu} F^{\mu\nu}$ Li Heres  $n$  shall show while small at  $GMB$ **FIFELL COSMIC FORMATION SIMPLES**  $\frac{d}{dt}$  in  $\frac{d}{dt}$  $\left\langle \zeta_{+}^{3}\right\rangle$ <sup>h</sup>⇣2i<sup>2</sup> = O (✏*<sup>V</sup> ,* ⌘*<sup>V</sup>* ) <sup>h</sup>⇣3<sup>i</sup>  $\overline{\mathcal{A}}$   $\overline{\mathcal{A}}$   $\mathcal{M}$   $\mathcal{D}$  $\mathcal{W}_{\phi}^{\prime}$ *<sup>V</sup>* ⌧ <sup>1</sup> *V , <sup>V</sup>* ⌧ <sup>1</sup> Axion (Natural) Inflation Local NG : (*x*) = *<sup>g</sup>* (*x*) + *f*local NL ⇥ <sup>2</sup> *<sup>g</sup>* (*x*) ⌦ <sup>2</sup> *g •* Flatness and gaussianity ! small self-couplings *•* Agreement with standard single field slow roll <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> lds<br>icti  $\frac{1}{2}$ ividens (at miteufer and state is wtat refered small at CMB n af einfecsmal infantig in terfing in der EMB **COLL SILOW-LOW ALCOMMIC UP** HUSELIE EN KY *•* Flatness and gaussianity ! small self-couplings  $\mathcal{A} \cap \mathcal{A}$  with a meaning  $\mathcal{A}$  is a meaning  $\mathcal{A}$  is a meaning  $\mathcal{A}$ scales  $\bullet$   $\bullet$   $\bullet$  in a to stead with simplest models  $\bullet$   $\rightarrow$   $\bullet$  + const.  $r =$ *P*GW *P*⇣  $\lambda$  field  $d$  ln  $P_\zeta$  $\overline{\textbf{a}}$  lating  $\langle \zeta^3 \rangle$ Elance ns  $\zeta$  iplings to others fighter to the country ✏*<sup>V</sup>* ⌘  $M_p^2$ **2** ⇣*V , V*  $\frac{2}{\sqrt{2}}$ **EGIE AREAL**  $V_4$ • Flatness and gaussathte SS saradischads sinen (review Pajer, MP 13) at  $\frac{1}{6}$  who found the constraint of the a  $\partial \! \! \! \partial$ ţ k ∏l **PW** *P*⇣ *, ns* 1 ⌘ *d* ln *P*⇣  $\frac{1}{\sqrt{k}}$  have a little **he** 17 M G B H G H G  $\frac{1}{2}$  Flatness and gaussianity  $\rightarrow$  small inflaton self-coupling  $S$ **•** Shift symmetry (broken by *V* ) on coupling to other fields to other fields to other fields of the coupling FSEST Friench MAU1 LOCOO; ... '(feview Pajer, MP '13) *Ps Alig***t the 4** *Ps •* No observed departure from (primordial) gaussianity, <sup>h</sup>⇣3i⌧h⇣2i3*/*<sup>2</sup> ↵⇤  $\frac{1}{2}$  Agreement with  $\frac{1}{2}$  than dard single field slow roll  $\frac{1}{2}$  and  $\frac{1}{2}$   $\frac{1}{2}$ **Party is a final party of the USA**  $\ddot{\phantom{1}}$ *M*<sup>2</sup> *p*  $\overline{\mathbf{X}}$ *V*  $A = 4$ *V,* **PEEEM** *r* ⌘ *P*GW **aviers of the land with a light of the light of the**  $n \sum_{i=1}^n a_i$ *d* ln *P*⇣ • Flatness and gaussianity  $\rightarrow$  small inflaton self-couplings **•** Shift symmetry (broken by *V* ) on the coupling of the coupling of the coupling of the coupling *Ps* **• No observed departure from (prins) and allege space figure in the state of t**  $L$  ocal NG :  $\phi(x) = \phi(Q)$  Historical Hanger and  $\frac{1}{\sqrt{2\pi}}\frac{d^{1/2}p}{dx^{2}}=\frac{1}{2\sqrt{2\pi}}\cosh(\frac{1}{2}q)$  and  $\frac{1}{2\sqrt{2\pi}}\frac{d^{1/2}p}{dx^{2}}=\frac{1}{2\sqrt{2\pi}}\sqrt{2\pi}}\sqrt{2\pi}$  $r, n_s = 1,$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$  $\mathsf{ft}^\equiv$  $M_p^2$ 2  $\bigwedge V_{,\phi}$ *V*  $\setminus^2$  $\ll 1$   $\rightarrow$   $\frac{k}{n}$   $\equiv$   $N/2$  $Y_{\cdot}$ o $\Phi$  $\frac{1}{\sqrt{2}}$   $\frac{1}{\sqrt{2}}$   $\frac{1}{\sqrt{2}}$ atisia  $\phi \rightarrow \phi + \text{Eian} \otimes \text{Tr} \left( \phi \right)$  iplings to other first  $\phi$ APTELIPEL SAIMPO ShOO **c**<br>Slovi **futom repeatified designations** rahtage that <del>Gestal News apply, generically,</del>  $\frac{d\mathbf{X}}{dt} \propto V_{\mathsf{shift}}$ etiolity)<br>Annis  $\mathbf{G}$   $\mathbf{G}$   $\mathbf{W}$ ,  $m_{\phi} \simeq 10^{13}$  GeV Smallness of *<sup>V</sup>*shift technically natural. *<sup>V</sup>* / *<sup>V</sup>*shift ET TIETUS<br>NGC 1978 (COUPLE COUPLE COMPLETENCE) *<sup>m</sup> <sup>m</sup>* (200 *A*  $\left(\begin{array}{ccc} 1 \\ 1 \end{array}\right)$  $\frac{1}{2}$ <br>  $\frac{1}{2}$ <br> that it all the that it can provide the case of the tensor of the case of the ]tter.(Q<br>ELVH3D *f*  $\frac{1}{4}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$ **editions** 。<br>网传 EMTY)  $\delta G_{\rm eV}^{\rm GUT+G}$  SMP  $\propto V_{\rm shift}$  $\text{PSD}$  find at  $0.06$  GeV  $n_e$   $m_\phi \simeq 10^{13}$  GeV ling<del>s to</del> other fields . ,<br>,<br>, <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *c*<br>Elf-couplings Agreem<br>MRS Makrist Couraciliding *f* ment with rists ET<br>bi*l*i <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup>  $c_\psi$ *f* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *•* Smallness of *V*shift technically natural. *V* / *V*shift etter (predictivity)<br><del>Frytity 2 ANG, observe</del>d  $ES(f \sim 10^{16} \text{ GeV/s} \cdot \text{GeV} \sim 10^{18} \text{ GeV}$ hard to the to the contract which why have the correction of the contract of t With shift symmetry, *V* / *V*shift *•* Shift symmetry ! + *C* on couplings to other fields *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ **Production POLICITY €§ {\^** 10<sup>10</sup> GeV<sub>3</sub>, apy hard to explain why *V* protected against quantum corrections. *•* Shift symmetry ! + *C* on couplings to other fields  $f$ *f f F*<sup>*µ*</sub> *F*<sup>*µ*</sup> *F*<sup>*µ*</sup> *F*<sup>*I*</sup> *F*<sup>*I*</sup> *F*<sup>*I*</sup> *F*</sup>  $\mathcal{P}^{\mathbf{v}}$   $\propto$   $\mathcal{P}^{\mathbf{v}}$  *V*shift **• Explored** <del>S</del>OV mmttte 7018 GeV Slow roll inflation requires very flat potential *V* , and, generically, hard to explain why *V* protected against quantum corrections.  $\mathbf{r} = \frac{1}{n} \sum_{i=1}^{n} \mathbf{r}_i \mathbf{r}_i$  $\phi$  $\phi$ 

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that it can play an important role also during inflation @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵  $\sharp$  <u>p</u>  $\sharp$  if  $\uparrow$   $\uparrow$   $\downarrow$   $\downarrow$ 



**INFLATIONARY MODELSHIPS INFLATIONS AND THE REAL PROPERTY OF STATISTICS.** h Siver  $\overline{1}$  $\frac{1}{d}\frac{d\mathbf{r}}{d\mathbf{k}}$  $\overline{1}$ **A nake 1**  $\frac{1}{2}$ ا د<br>ا ∇ **VA 3 in agreement with simplest models o** 25 27 27 27 a<br>44  $\mathcal{L}$ **13 AF** HOSA SVIOR  $\mathcal{L}$  in the spatial dependence of  $\mathcal{L}$  and  $\mathcal{L}$  inflaton self-couplings  $\mathcal{L}$  (dependence to  $\mathcal{L}$  and  $\mathcal{L}$  in  $\mathcal{L}$  $\frac{p}{\alpha}$  **porture introduced the physical methodology of the physical strategy**  $\phi \rightarrow \phi + const.$  infla B = 1 2 Π Γ Ο<del>| Π</del>|Π<br>—— 1 *m*  $\frac{1}{2}$ F<br>| TV shi<br>| P<sub>C</sub><br>| P<sub>C</sub>  $\lim_{k\to\infty} \frac{1}{k}$  $Z \rightarrow \frac{1}{V(\rho)} \left( \frac{\rho}{L} \frac{1}{F} \frac$  $\mathbb{E}[\mathcal{L}_{\text{min}}(X)]$  in  $\mathcal{L}_{\text{min}}$  the  $\mathbb{E}[\mathcal{L}_{\text{min}}(X)]$  in the  $\mathcal{L}_{\text{max}}$  of  $\mathcal{L}_{\text{max}}$  in  $\mathcal{L}_{\text{max}}$ of the gaught field. The settle from the  $M_n^2/V_n^2$  of  $M_p^2/V_n^2$  of  $\left(\frac{M_n^2}{\phi}\right)^2$ the background of the background of the the homogeneous inflaton property that the state of the the state of the homogeneous inflaton q-number field A *V ,* ⇤ Not the QCD axion; reference values *<sup>f</sup>* ⇠ <sup>10</sup><sup>16</sup> GeV *, m* ' <sup>10</sup><sup>13</sup> GeV ⇤ Not the QCD axion; reference values *<sup>f</sup>* ⇠ <sup>10</sup><sup>16</sup> GeV *, m* ' <sup>10</sup><sup>13</sup> GeV  $\sim 10^{18}$  GeV  $A(\tau, \mathbf{x}) = \lambda$  $\frac{1}{2}$ **THE PART**  $\frac{1}{2}$ **TEARCHEARTHRACE FRAGE CEE**<br>TEARS CONSTERNT IST FLATIO R  $\mathcal{L}_{x,y}$   $\mathcal{L}_{y}$  = Freese  $\mathcal{L}_{y}$  functional Model and Model electro-magnetic gauge for  $\mathbf{c}$  to  $\mathbf{c}$  oth  $\vec{r}$ ,  $n_s = 1$ ,  $m_t = 0$  (e,  $n_f = 2$ ) ajer, Photon: 2 helicities  $\varphi$  $\theta$ ;  $\rightarrow$  Mot the QCD axion; reference varies flo  $\overline{\phantom{a}}$ **!!** a hendringes **CARTHTRESSMEETHING**  $\lim_{x\to 0} \varphi(x) = \Phi(G)$  are the fine of  $\varphi$  are considering  $\varphi$  and  $\varphi$ # ⃗ k  $\frac{1}{\sqrt{2}}$ = 0, ⃗ k ×⃗ϵ<sup>±</sup>  $\frac{1}{2}$  $\begin{array}{c} \Gamma(\tau, \mathbf{y}) \longrightarrow \mathbf{F}(\mathbf{y}) \longrightarrow \mathbf{$  $\sum\limits_{i=1}^{n}$ \_\_<br>janda<br>ificav ۔<br>اب<br>ا  $\int_{-\infty}^{\infty}$  $g_{\hat{a}}$  and  $g_{\hat{a}}$  and  $g_{\hat{a}}$  and  $g_{\hat{a}}$ fa<br>T til <u>ነ¶</u><br>⊾<del>ዘ</del>vላ  $\overline{1}$ Inserting the decomposition (2.8) into eq. (2.5) results in the equation of motion Here ⃗ϵ<sup>λ</sup> are circular polarization vectors satisfying ⃗ k ·⃗ϵ<sup>±</sup> **<u>et Branderer</u>**<br>ΩTreese, Fi  $2k$ <u>ት</u> **ALITAR DE MALAS FILIPERE ALLOCE ES EN ELLER**  $f^2$  (1) Freese, Friendli, Ullillo  $fU, \ldots, \phi$ <br> $f^2$ . During  $f^2$ . During the parameter  $f$ cally natural *ty completing in orience in encapting a*n  $F_{10}^{13}$  CeView Pajer, MP  $^{\circ}13)$  $\phi = L/L + k/k \lambda k + h/k$  $\frac{1}{2}$  $\kappa_{\rm c} \sim 10^{18}$ ermitian inflation requires weity traction term and  $P^{\text{even}}$ **!! at Galactic Andre BIHANSA DIKINDINALE SEGRAFISK**<br>CAVATITVA OC FINST CE SEGRAFISK # ⃗ k  $\pmb{\hat{\mathcal{G}}}$ **DELLE SALUE Axion Shift as woment you in the COATLE Shift A**t  $\frac{1}{\sqrt{2}}$  $\sum_{i=1}^{r, n_s-1}$  $-\frac{\text{Tr}}{\text{Tr}}$ , and normalized according to ⃗ϵ<sup>λ</sup> # ⃗ \$∗ # ⃗ \$ *•* Shift symmetry on couplings to other fields *c*2  $\frac{1}{M^2} \frac{1}{M^2} = 0$  is decomposition (2.8) in the equation of  $\frac{1}{M^2}$  in the equation of  $\frac{1}{M^2}$  $e$ eese, Frieman, Olinto  $90, \ldots, 20$  $A^1$  two control **ABREENING RECHT FROMST TO FIELL SOME ET IV**  $\arg| \inf | \text{d} \theta |$   $\bigcap_{n=1}^{\infty}$   $\bigcap_{n=1}^{\in$ **PEGWA** *r*  $\equiv$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$  $\oint_{\mathbf{a}} \phi \rightarrow \phi + c$ *d* ln *P*⇣  $\phi \rightarrow \phi + const.$  infla ישן<br>קרוב<br>יימודי 2 *V* ✏*<sup>V</sup>* ⌘ J<br>Sab **• Full state of and self-couplings ity -> small self-couplings ity** -> s<br>Introduction of the small self-coupling it is a small self-coupling Azion (Martidral) Kinflation  $F$ reese, Frienzan, Olinto '90; **• CMB in agreement with simplest models o** *P*⇣ *, ns* 1 ⌘ *<sup>d</sup>* ln *<sup>k</sup> , f*NL ⇠ Freese, Frieman, Olinto '90; . . .  $\widetilde{M}$ *p*  $\frac{1}{2}$ ⇣*V , V* av<br>2 ⌧ <sup>1</sup> ⌘*<sup>V</sup>* ⌘ *<sup>M</sup>*<sup>2</sup> *L* = *•* Flatness and gaussianity ! small self-couplings *L* = • Thuft symmetry on freund the phines to on the p Freese, Frieman, Olinto 90; (review Pajer, MP '13)  $\alpha$  in the  $\alpha$ Axion Inflation Shartage than  $S''$  , This equatorial median of  $P$  and  $\mathcal{A}$ **has the red EXAMEREATIONS CONTROLS REASING**  $\phi \rightarrow \phi + const.$ <sup>mid</sup> and suppose the coupling to  $\phi \rightarrow \phi + const.$ FIFEESE, OTTIESTHIT TEOMITIC AUDY, .<br>ב 2 (COCACCHITER) **c**y *f* @*µ*  $\rightarrow$  Constrained the advantage that matter (prediction of **E-Constrained couplings to matted** \* Not<sup>4</sup>the QCD axion; reference values *f*  ! *AA* typically controls reheating. Only recently realized the can play and it can play and also determined and at care that  $G(z)$ ... W -> small inflaton, self-couplings> LIVE dEWAIY **Land**  $\frac{1}{2}$ 2 E F F G S H C C L G H D G S A L C L<br>AS C LE PSEUCLO-SCALAT (2000) **c**<br>12 *f* **PAKAP }** *•* Smallness of *V*shift technically natural. *V* / *V*shift **BE PART END POITED TO BE EN EN ET TE TO BE THE TO B** that it can play an important role also during inflation Lion<sup>®</sup> Inflation  $\frac{1}{2}$  summatrix  $\frac{1}{2}$   $\text{cese}, \text{y}$ "  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{dens}$ ",  $\text{cens}$ ",  $\text{dens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$  $\gamma$  reposed to start responsive to  $\gamma$  it  $\gamma$ **255 and serages legity -> s**<br>**1 ptmps phommule each () ps** प<br>च Ereese Splittan Symmateur . On couplings to c **Pese V Friedagh? Ginte Poult-P**<br>Pese V Friedagh? Chinte Poult-⇤ Not the QCD axion; reference values *<sup>f</sup>* ⇠ <sup>10</sup><sup>16</sup> GeV *, m* ' <sup>10</sup><sup>13</sup> GeV **LA DS<sup>E</sup> LE** 2 **Q** and 2 0 0 0 0 2 5 0 has the advantage that **• Smallness of** *V*<br>• Smallness of The Condicion • Constrained couplings (predictivity)  $\frac{1}{2}$   $\frac{1}{2}$  Egm (prinsynn) all lations and flat the district of the district of the state of the state of the state of the hard to explain why *V* protected against quantum corrections. hard to explain why *V* protected against quantum corrections. **L = 1** . . 2 2 (2 ) + **2 2 (2 ) + 2 (2 ) + 2 (2 )** + 2 ) + 2 (2 ) + 2 ) + 2 (2 ) + 2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) +  $2$ *f* @*µ* has the advantage that **•** Smallness of *Vshift* technically **• Octocks first coupling to matter (predictivity)** <u>\* Not</u> the QCD the Q.CQ axion; reference **L . 12** <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> **c** *f*  $\partial^{\mu}_{\mu}$ has the advantage third  $\frac{1}{2}$  of  $\frac{1}{2}$   $\frac{1}{2}$  $V(\varphi) \leftarrow \frac{\phi}{r} F_{\mu\nu} F^{\mu\nu}$  , inflatory  $\phi$  is pseudo-scalar axion (if  $\Theta$  ) is  $V\Theta$ <del><sup>→</sup> NOT</del> the QCD axion; reference values f<sup>1</sup> SIOW, FOII HITHSHION requires very flat potential <sup>in</sup> **hard to the second and the various of the corrections.** WEBIOTISYM NAW TERY SHIFT AS NOTHER SHIFT SERVE COPPLY ALL  $\phi$  $\frac{\varphi}{f} F_{\mu\nu} F^{\mu\nu}$ and with a meridian  $\dot{\vec{M}}$  $\sum_{i=1}^{n}$  $n$  shall show while small at  $GMB$ **FIFELL COSMIC FORMATION SIMPLES**  $\frac{d}{dt}$  in  $\frac{d}{dt}$  $\left\langle \zeta_{+}^{3}\right\rangle$ <sup>h</sup>⇣2i<sup>2</sup> = O (✏*<sup>V</sup> ,* ⌘*<sup>V</sup>* ) <sup>h</sup>⇣3<sup>i</sup>  $\overline{\mathcal{A}}$   $\overline{\mathcal{A}}$   $\mathcal{M}$   $\mathcal{D}$  $V$   $\ll 1$ • Flatness and self-couplings lds<br>icti  $\frac{1}{2}$ **ig**<br>Q F n Stellfershes II Galile Street II Give B Scales **COLL SILOW-LOW ALCOMMIC UP** HUSELIE EN CAMPO SHOO **V** & *V* <u>D</u><br>**FREXESHE** *•* Flatness and gaussianity ! small self-couplings  $\mathcal{A} \cap \mathcal{A}$  with a meaning  $\mathcal{A}$  is a meaning  $\mathcal{A}$  is a meaning  $\mathcal{A}$  $\mathbf{E}$  signal  $\mathbf{E}$  of  $\mathbf{F}$  in the interferometer  $\mathbf{F}$  interferometer  $\mathbf{F}$  in  $\mathbf{F}$  in  $\mathbf{F}$  in  $\mathbf{F}$  is  $\mathbf{F}$  $\bullet$   $\bullet$   $\bullet$  in a to stead with simplest models  $\bullet$   $\rightarrow$   $\bullet$  + const.  $r =$ *P*⇣ **Mand 115 E 3 1 DINOS to others fighter of the country** ✏*<sup>V</sup>* ⌘  $M_p^2$ **2** ⇣*V , V*  $\frac{2}{\sqrt{2}}$ **EGIE AREAL**  $V_4$ • Flatness and gaussathte SS saradischads sinen  $A(\tau, \mathbf{x}) = \begin{cases} \frac{1}{\sqrt{2\pi}} \sqrt{2\pi} \sqrt{2$ () ev<del>iew</del> Pajer, <del>Wip ''<sub>1</sub>18)</del> 1  $\frac{1}{2}$  **RUP RE OF BURGES** *c f* 2015 Tre Free zally nátur<del>ál A Myőkény Roiffroys réhábon</del>g a 1 **DEAD AND CONSTRACT (**  $\partial \! \! \! \partial$ ţ  $\eta$  stalled matural natural natural at  $\epsilon$  MB **PW** *P*⇣ *, ns* 1 ⌘ *d* ln *P*⇣  $\frac{1}{\sqrt{k}}$  have a little **he k a little with the property of the constable weak**  $\frac{1}{2}$  Flatness and gaussianity  $\rightarrow$  small inflaton self-coupling  $S$ **•** Shift symmetry (broken by *V* ) on coupling to other fields to other fields to other fields of the coupling **Frienda Woll Frees Frieman (1999)**<br>V-UDH COSTYLE MANATION '(feview Pajer, MP '13) *Pt Ps •* No observed departure from (primordial) gaussianity, <sup>h</sup>⇣3i⌧h⇣2i3*/*<sup>2</sup> ↵⇤  $\frac{1}{2}$  Agreement with standard single field slow role with  $\vec{A}''$  –  $\nabla^2 \vec{A}$  –  $\frac{1}{\phi'} \phi' \vec{\nabla} \times \vec{A}$  Shift syponic FICCSC, FI  $A = 4$ **PEEEM** *P*GW  $P_{\zeta}$  $n \sum_{i=1}^n a_i$ **d lat b a ly d ly d a w a g h** • Flatness and gaussianity  $\rightarrow$  small inflaton self-couplings **•** Shift symmetry (broken by *V* ) on the coupling of the coupling of the coupling of the coupling *Ps* / *<sup>k</sup>ns*<sup>1</sup> *<sup>r</sup>* <sup>=</sup> *Pt Ps* **FALIS IN SULLINES** departure from (prim**SYM) GAUSSIANO FIRST FIRST IN THE GAUG**  $L$  ocal NG :  $\phi(x) = \phi(Q)$  Hestigal Hange  $\chi(x)$ ↵⇤ *•* Agreement with standard single field slow roll <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup>  $r, n_s = 1,$  for  $\epsilon$  or  $(\epsilon, \eta)$  $\mathsf{ft}^\equiv$  $M_p^2$ 2  $\bigwedge V_{,\phi}$ *V*  $\setminus^2$  $\ll 1$   $\rightarrow$   $\frac{k}{n}$   $\equiv$   $N/2$  $Y_{\phi\phi}$  $\frac{1}{\sqrt{2}}$   $\frac{1}{\sqrt{2}}$ BOG SHOW SIGNAL NATURAL NATURAL SCALES, WAS STRIKT STRIKT AT CONSTRUCTIONS atisia  $\phi \rightarrow \phi + \text{Eian} \otimes \text{Tr} \left( \phi \right)$  iplings to other first  $\phi$  $\exp\left(\frac{1}{2}\right)$ **c**<br>Gaty<br>Slovi *f* **futom repeatified designations** has the advantage that *•* Constrained couplings to matter (predictivity) BE CERTIFY THE THREE REAL AND THE THREE REAL AND THE THREE REAL PROPERTY OF THE THREE REAL PROPERTY ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ *•* Smallness of *V*shift technically natural. *V* / *V*shift  $\delta$  SMF  $\not\sim V_{\mathsf{shift}}$  $\mathbf{G}$   $\mathbf{G}$   $\mathbf{W}$ ,  $m_{\phi} \simeq 10^{13}$  GeV Smallness of *<sup>V</sup>*shift technically natural. *<sup>V</sup>* / *<sup>V</sup>*shift ET TIETUS<br>NGC 1978 (COUPLE COUPLE COMPLETENCE) *<sup>m</sup> <sup>m</sup>*  $\overline{\mathbf{c}}$ **EAC** *A*  $\left(\begin{array}{ccc} 1 \\ 1 \end{array}\right)$  $\frac{1}{2}$ <br>  $\frac{1}{2}$ <br> that it all the that it can provide the case of the tensor of the case of the ]tter.(Q<br>ELVH3D *f*  $\frac{1}{4}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$ **editions** )<br>1944 E<del>MQY)</del><br>Fantagra  $\delta G_{\rm eV}^{\rm GUT}$  Small  $\bar{\gamma} \propto 10^{13} \ {\rm GeV}^{\prime}$  $\arg f$ inflat $0$ on $\deg$ ,  $m_\phi \simeq 10^{13}$  GeV  $\pm$ hotadvanta galitari an inono ling<del>s to</del> other fields . ,<br>,<br>, <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup>  $c_{\Psi}$ *f* porton: 2 helicities<br>-couplings Agreem ment with the the ET<br>bi*l*i <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> **de de la 1990 de 1990** *f <sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ *•* Smallness of *V*shift technically natural. *V* / *V*shift etter (predictivity)<br><del>Frytity 2 ANG, observe</del>d SPORTAL ENGLATION REPORT CALLY, hard to the to the contract which why had the correction of With shift symmetry, *V* / *V*shift *•* Shift symmetry ! + *C* on couplings to other fields *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ **Production POLICITY** SPETER VERIGINAL hard to explain why *V* protected against quantum corrections. *•* Shift symmetry ! + *C* on couplings to other fields  $f$ *f f F*<sup>*µ*</sub> *F*<sup>*µ*</sup> *F*<sup>*µ*</sup> *F*<sup>*I*</sup> *F*<sup>*I*</sup> *F*<sup>*I*</sup> *F*</sup>  $\mathcal{P}^{\mathbf{v}}$   $\propto$   $\mathcal{P}^{\mathbf{v}}$  *V*shift **• Explored** <del>S</del>OV mmttte 7018 GeV Slow roll inflation requires very flat potential *V* , and, generically, hard to explain why *V* protected against quantum corrections.  $\mathbf{r} = \frac{1}{n} \sum_{i=1}^{n} \mathbf{r}_i \mathbf{r}_i$  $\phi$  $\phi \rightarrow \phi + \text{Gence} \text{ as } \mathcal{C}_{\phi}$  iplings to optight fighted are denoted  $E1$  THEIUS<br> $\phi$ > <sup>∼</sup> 60). We assume a spatially flat Friedmannroperts of  $\left(\phi\right)$  with  $\left(\phi\right)$ we different approach that the search inflaton self-coupling 5' the additional process and gaussianity  $\rightarrow$  small inflaton self-coupling 5' the add- $\frac{1}{2}$   $\frac{1}{2}$  to conformal time as ∂<br>Listo for  $\frac{15}{15}$  to other fields of  $\frac{\mu v}{\lambda}$  in  $\frac{\mu v}{\lambda}$  in  $\frac{\mu v}{\lambda}$  in  $\frac{\mu v}{\lambda}$  in  $\frac{\mu v}{\lambda}$  is the Q.C. of a  $R_{\rm eff} = \sqrt{10^{16}~{\rm GeV}}$ . To the interest of the interest of the interest  $\sim 10^{18}$  (12). Figthose and developments can interest  $\mathcal{L}^{V\overline{\rightarrow }\phi^{VI}p}$  for  $\mathcal{L}^{+}$  or al NG  $\colon \phi(x)=\phi(Q)$  in for the  $\phi$  of  $\phi$  see section  $\phi$  $\frac{E}{\text{E}}$  is the action  $\frac{A}{\text{E}}(T, \mathbf{x}) = \sum_{i=1}^{\infty} \frac{1}{i} \frac{1}{(T - T_i)^2}$ e e courte why worker **Pedzg** = 0. The equations of motion for A ⃗ then read  $f_{xx} = \frac{M_p^2}{M_p^2} \frac{Q}{(V_{,\phi})^2}$  (review Bajer,  $\frac{Q}{(V_{,\phi})^2}$  ) and  $\frac{Q}{(V_{,\phi})^2}$  (represented to  $\frac{Q}{(V_{,\phi})^2}$  $\vec{\nabla}\times\vec{A}$ As we we develop the  $\mathcal{L}$  in subsection  $\mathcal{L}$  in the production of the production of  $\mathcal{L}$ 1

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@*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵

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**INFLATIONARY MODELSHIPS INFLATIONS AND THE REAL PROPERTY OF STATISTICS.** h Siver  $\overline{1}$  $\frac{1}{d}\frac{d\mathbf{r}}{d\mathbf{k}}$  $\overline{1}$ **A nake 1**  $\frac{1}{2}$ ا د<br>ا ∇ **VA 34**<br>42 25 27 27 27 a<br>44  $\mathcal{L}$ **13 AF** HOSA SVIOR  $\mathcal{L}$  in the spatial dependence of  $\mathcal{L}$  and  $\mathcal{L}$  inflaton self-couplings  $\mathcal{L}$  (dependence to  $\mathcal{L}$  and  $\mathcal{L}$  in  $\mathcal{L}$  $p$  and  $p$  and  $p$  and  $p$  in  $p$  in  $p$  is design the physical strong the  $p$  and  $p$  and  $p$  and  $p$  and  $p$  inflation  $p$ B = 1 2 Π Γ Ο<del>| Π</del>|Π<br>—— 1 *m*  $\frac{1}{2}$ F<br>| TV shi<br>| P<sub>C</sub><br>| P<sub>C</sub>  $\lim_{k\to\infty} \frac{1}{k}$  $\phi \rightarrow \phi + \theta$  and  $\eta \in \mathcal{L}$  iplings to optight freighten are utility  $\mathbb{E}[\mathcal{L}_{\text{min}}(X)]$  in  $\mathcal{L}_{\text{min}}$  the  $\mathbb{E}[\mathcal{L}_{\text{min}}(X)]$  in the  $\mathcal{L}_{\text{max}}$  of  $\mathcal{L}_{\text{max}}$  in  $\mathcal{L}_{\text{max}}$ of the gaught field. The settle from the  $M_n^2/V_n^2$  of  $M_p^2/V_n^2$  of  $\left(\frac{M_n^2}{\phi}\right)^2$ the background of the background of the the homogeneous inflaton property that the state of the the state of the homogeneous inflaton q-number field A *V ,* ⇤ Not the QCD axion; reference values *<sup>f</sup>* ⇠ <sup>10</sup><sup>16</sup> GeV *, m* ' <sup>10</sup><sup>13</sup> GeV ⇤ Not the QCD axion; reference values *<sup>f</sup>* ⇠ <sup>10</sup><sup>16</sup> GeV *, m* ' <sup>10</sup><sup>13</sup> GeV  $\sim 10^{18}$  GeV  $A(\tau, \mathbf{x}) = \lambda$  $\frac{1}{2}$ **THE PART**  $\frac{1}{2}$ **TEARCHEARTHRACE FRAGE CEE**<br>TEARS CONSTERNT IST FLATIO R  $\mathcal{L}_{r, n_s} = \frac{1}{2} \mathcal{L}_{r}$  necessarily constants and  $\mathcal{L}_{r}$  as  $\mathcal{L}_{r}$  and  $\mathcal{L}_{r}$  and  $\mathcal{L}_{r}$  and  $\mathcal{L}_{r}$  are the magnetic gauge to  $\mathcal{L}_{r}$  $\overrightarrow{ }$   $\overrightarrow{ }$ ajer, Photon: 2 helicities  $E1$  THEIUS<br> $\phi$ intrer fer a spatial spatial flat Friedmannroperts of  $\left(\phi\right)$  with  $\left(\phi\right)$ we different approach that the search inflaton self-coupling 5' the additional process and gaussianity  $\rightarrow$  small inflaton self-coupling 5' the add- $\frac{c_{\psi}}{c_{\psi}}\rightarrow \phi + con.$  $\gamma_5^* \varphi + \frac{1}{f} \varphi \Gamma \mu \nu$  (Feview Pajer, MP '13)  $P_{\text{GW}} = P_{\text{GW}} = \frac{1}{1 - \alpha} \ln P_{\text{G}}$ to conformal time as ∂<br>Listo for . The Hubble rate H ≡ a/a ˙ has conformal time analogue # −⃗ \$ # ⃗ \$∗ WE ARE FIRST CULLING OF STREET AND CONTROLLED IN THE GAUGHT AND CONTROLLED AND  $R_{\rm eff} = \sqrt{10^{16}~{\rm GeV}}$ . To the interest of the interest of the interest  $\sim 10^{18}$  (12). Figthose and developments can interest  $\mathcal{L}^{V\overline{\rightarrow }\phi^{VI}p}$  for  $\mathcal{L}^{+}$  or al NG  $\colon \phi(x)=\phi(Q)$  in for the  $\phi$  of  $\phi$  see section  $\phi$  $\frac{E}{\text{E}}$  is the action  $\frac{A}{\text{E}}(T, \mathbf{x}) = \sum_{i=1}^{\infty} \frac{1}{i} \frac{1}{(T - T_i)^2}$ e e courte why worker **Pedzg** = 0. The equations of motion for A ⃗ then read Inserting the decomposition (2.8) into eq. (2.5) results in the equation of motion Here ⃗ϵ<sup>λ</sup> are circular polarization vectors satisfying ⃗ k ·⃗ϵ<sup>±</sup>  $\vec{A}'' - \nabla^2 \vec{A} - \frac{1}{4}$ <sup>f</sup> <sup>φ</sup>′ ∇ × ⃗ A ⃗ = 0 (2.5)  $\text{Cov}, m_{\phi} \simeq 10^{-3} \text{ GeV}$   $\text{Cov}$   $\text{Cov}$   $\text{Cov}$   $\text{Cov}$  of  $\text{Cov}$  of  $\text{Cov}$  of  $\text{Cov}$  $t$ the gauge field of the motion of the motion of the motion of the motion of the  $t$  $\text{PSD}$  implating  $\text{GeV}$ ,  $m_\phi \simeq 10^{13}$  GeV  $\text{K}$  they advantage that a n important  $O'$  and  $O'$  and  $H$  the Hermitian conjugate  $\mathcal{A}$  $\overline{\phantom{a}}$ **!!** a hendringes **CARTHTRESSMEETHING**  $\lim_{x\to 0} \varphi(x) = \Phi(G)$  are the fine of  $\varphi$  are considering  $\varphi$  and  $\varphi$ # ⃗ k  $\frac{1}{\sqrt{2}}$ = 0, ⃗ k ×⃗ϵ<sup>±</sup>  $\frac{1}{2}$  $\begin{array}{c} \Gamma(\tau, \mathbf{y}) \longrightarrow \mathbf{F}(\mathbf{y}) \longrightarrow \mathbf{$  $\sum\limits_{i=1}^{n}$ \_\_<br>janda<br>ificav ۔<br>اب<br>ا  $\int_{-\infty}^{\infty}$  $g_{\hat{a}}$  and  $g_{\hat{a}}$  and  $g_{\hat{a}}$  and  $g_{\hat{a}}$ fa<br>T til <u>ነ¶</u><br>⊾<del>ዘ</del>vላ  $\overline{1}$  $\overline{\text{me}}^2$ **et Brazilia**  $2k$  $\bar{1}$ <u>ት</u>  $\frac{2117(275)}{1200}$  $\frac{100}{60}$ ።<br>መካከል<br>መካከል THE  $f(1) = \frac{1}{2}$ . The case; Fileman, Ollito 90, ... Cally naturat howes constructions reneapmed in  $\sqrt{2k}$  (2.10) we see that  $\sqrt{2k}$  and  $\sqrt{2k}$  an ⃗  $\frac{1}{2}$   $\kappa_{\rm c} \sim 10^{18}$ ermitian inflation requires weity traction term and  $P^{\text{even}}$ **!! at Galactic Andre BIHANSA DIKINDINALE SEGRAFISK**<br>CAVATITVA OC FINST CE SEGRAFISK # ⃗ k  $\pmb{\hat{\mathcal{G}}}$ **DELLE SALUE Axion Shift as woment you in the COATLE Shift A**t  $\overline{1}$  $\frac{1}{\sqrt{2}}$ = ⃗ϵ<sup>±</sup> ⃗ k , and normalized according to ⃗ϵ<sup>λ</sup> ⃗ k · ⃗ϵλ′ ⃗ k = δλλ′.  $\frac{1}{M^2} \frac{1}{M^2} = 0$  is decomposition (2.8) in the equation of  $\frac{1}{M^2}$  results in the equation of  $\frac{1}{M^2}$  $e$ eese, Frieman, Olinto 90;  $A$  the foto **POLFFroNSTreFEASING EM**  $f_{m0} \simeq 10^{13}$  GeV. The contractions and parameter  $m_0$  at treated also dott Stow - YOU 7 1 F  $\frac{P_{GW}}{L} = \frac{P_{GW}}{R}$  and  $n_f = \frac{1}{2}$  and  $n_f = \frac{1}{2}$  $H^{\mu\nu}F^{\mu\nu}F^{\mu\nu}$  in Faration  $\bar{\phi}$ \$ METCHE CHRETTI **laik** \$ EAXIONA  $\mathcal{F}$  $\overline{\delta}$  $S''$  , it was used to have a small the story of  $P$  $\hat{H}$ k shi**ft**  $\mathbf{r}$  $\bigotimes$  $\Phi$  $\frac{1}{2}$ न<br>पेरि **(**<br>'f  $\frac{1}{2}$  $\text{Im}(\mathbf{Q}) = \frac{M_P^2}{2\pi\epsilon_0} \left(\frac{V_A}{\Delta} \right)^2 \frac{1}{2} \left(\frac{V_A}{\Delta} \right)^2$  $B_{\mathcal{W}} \sim 10^{18}$  (1011 INTISTICAT require  $\theta$   $\sim$   $10^{25}$   $\Omega$ <br> $\theta$   $\sim$   $\theta$   $\theta$ atness and gatiliaathtoess sanatoisograagsaliaagalia.<br>Professarjuma pakulamaa koolemaa ka kooxyaa ka maalamaa ka maalamaa ka maalamaa ka maalamaa ka maalamaa ka maa  $f(x)$  for the contract of the computation of  $\frac{A(\tau, \mathbf{x})}{\mathbf{x}} = \sum_{n=0}^{\infty} \int_{\mathbb{R}} \frac{d\tau}{(2\pi)^{2}} \frac{d\tau}{(2\pi)^{2}} \frac{d\tau}{(2\pi)^{2}} \frac{d\tau}{(2\pi)^{2}} \frac{d\tau}{(2\pi)^{2}} \frac{d\tau}{(2\pi)^{2}} \frac{d\tau}{(2\pi)^{2}} \frac{d\tau}{(2\pi)^{2}} \frac{d\tau}{(2\pi)^{2}}$ constant of the product of the subleading the substantial country of the substantial control to  $\mathcal{F}_{\mathcal{F}}$  experiences a tach of  $\mathcal{F}_{\mathcal{F}}$  on  $\mathcal{F}_{\mathcal{F}}$  and  $\mathcal{F}_{\mathcal{F}}$  $\|x\|_{\infty}$   $\leq$   $\frac{1}{\sqrt{2}}$   $\leq$   $\frac{1}{\sqrt{2}}$  ,  $\frac$  $\lim_{n\to\infty} \frac{1}{n} - \sqrt{2A-1} = \frac{1}{\sqrt{2}}$  (i.every pajer,  $\lim_{n\to\infty} \frac{1}{n}$ ,  $\lim_{n\to\infty} \frac{1}{n}$ ,  $\lim_{n\to\infty} \frac{1}{n}$ )  $\lim_{n\to\infty} \frac{1}{n}$  $\delta$  and  $\delta$  of  $\Delta V$ ,  $\propto$   $V_{\rm shift}$   $\equiv$   $\frac{m_p}{2}$  (  $\frac{v_{,\phi}}{V}$  )  $\ll$  1  $\rightarrow$   $\gamma$   $\equiv$   $\Delta V$   $\approx$   $\frac{m_p}{2}$   $\frac{m_p}{2}$  axion; reference  $A_+^{\mathsf{L}}(A, k) \cong$ **at úr al 4 XX**<br>2k (25 EU jew √  $2k$ LACTORY COLLECTIONS TY CHIERE  $\mathcal{L} \approx 2$   $\mathcal{L} \sim 1$   $\mathcal{L} \approx 2$   $\mathcal{L} \approx 2$   $\mathcal{L} \approx 2$   $\mathcal{L} \approx 2$ FriDyrglatteich nically natural Wusselfter Polffrold Hold behand a N  $\frac{1}{2}$  **instability**  $\left| \begin{array}{c} \n^{1+1/2} \sqrt{2k} \sqrt{$ **E** in adreement with simplest models of **PEGWA** *r*  $\equiv$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$  $\oint_{\mathbf{a}} \phi \rightarrow \phi + c$ *d* ln *P*⇣  $\phi \rightarrow \phi + const.$  infla ישן<br>קרוב<br>יימודי **ME VATGLS** 2 *V* ✏*<sup>V</sup>* ⌘ *NES*ULTERWATUES / / **• Full state of and self-couplings ity -> small self-couplings ity** -> s<br>Introduction of the small self-coupling it is a small self-coupling Azion (Martidral) Kinflation  $F$ reese, Frienzan, Olinto '90; **• CMB in agreement with simplest models o** *P*⇣ *, ns* 1 ⌘ *<sup>d</sup>* ln *<sup>k</sup> , f*NL ⇠ Freese, Frieman, Olinto '90; . . . *p*  $\frac{1}{2}$ ⇣*V , V* ⌧ <sup>1</sup> ⌘*<sup>V</sup>* ⌘ *<sup>M</sup>*<sup>2</sup> *L* = *•* Flatness and gaussianity ! small self-couplings *L* = • Thuft symmetry on freund the phines to on the p Freese, Frieman, Olinto 90;  $\alpha$  in the  $\alpha$ Axion Inflation Shartage than **has the red**  $\phi \rightarrow \phi + const.$ <sup>mid</sup> and suppose the coupling to  $\phi \rightarrow \phi + const.$ FIFEESE, OTTIESTHIT TEOMITIC AUDY, .<br>ב 2 (COCACCHITER) **c**y *f* @*µ*  $\rightarrow$  Constrained the advantage that matter (prediction of **E-Constrained couplings to matted** \* Not<sup>4</sup>the QCD axion; reference values *f*  ! *AA* typically controls reheating. Only recently realized the can play and it can play and also determined and at care that  $G(z)$ ... W -> small inflaton, self-couplings> LIVE dEWAIY **Land**  $\frac{1}{2}$ 2 E F F G S H C C L G H D G S A L C L<br>AS C LE PSEUCLO-SCALAT (2000) **c**<br>12 *f* **PAKAP }** *•* Smallness of *V*shift technically natural. *V* / *V*shift  $B$   $B$   $V$   $\overline{r}$ n2<br><del>Cc</del> <sup>2</sup>⇡*f*<sup>2</sup> *<sup>m</sup> <sup>m</sup>*<sup>2</sup> !*AA* =  $\n$  መሆን ተከተመለከተው የተለያዩ የተለያዩ ተጠቃሚዎች ተጠቃሚዎች የተለያዩ ተጠቃሚዎች የተለያዩ ተጠቃሚዎች የተለያዩ ተጠቃሚዎች የተለያዩ ተጠቃሚዎች የተለያዩ ተጠቃሚዎች የ Lion<sup>®</sup> Inflation  $\frac{1}{2}$  summatrix  $\frac{1}{2}$   $\text{cese}, \text{y}$ "  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{dens}$ ",  $\text{cens}$ ",  $\text{dens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$  $\gamma$  reposed to start responsive to  $\gamma$  it  $\gamma$ **255 and serages legity -> s**<br>**1 ptmps phommule each () ps** प<br>च Ereese Splittan Symmateur . On couplings to c **Pese V Friedagh? Ginte Poult-P**<br>Pese V Friedagh? Chinte Poult-**LA DS<sup>E</sup> LE** 2 **Q** and 2 0 0 0 0 2 5 0 has the advantage that **• Smallness of** *V*<br>• Smallness of The Condicion • Constrained couplings (predictivity)  $\frac{1}{2}$   $\frac{1}{2}$  Egm (prinsynn) all lations and flat the district of the district of the state of the state of the state of the hard to explain why *V* protected against quantum corrections. hard to explain why *V* protected against quantum corrections. **L = 1** . . <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f*  $2$ @*µ* has the advantage that **•** Smallness of *Vshift* technically **• Octocks first coupling to matter (predictivity)** <u>\* Not</u> the QCD the Q.CQ axion; reference **L . 12** 21 Koving Birshore () Shawi Sviolde **c**  $\partial^{\mu}_{\mu}$ has the advantage third  $\bullet$  SMall  $\circ$  SS, of *I V*shift technically,  $V(\varphi) \leftarrow \frac{\phi}{r} F_{\mu\nu} F^{\mu\nu}$  , inflatory  $\phi$  is pseudo-scalar axion (if  $\Theta$  ) is  $V\Theta$ <del><sup>→</sup> NOT</del> the QCD axion; reference values f<sup>1</sup> SIOW, FOII HITHSHION requires very flat potential <sup>in</sup> **hard to the second and the various of the corrections.** WEBIOTISYM NAW TERY SHIFT AS NOTHER SHIFT SERVE COPPLY ALL  $\phi$  $\frac{\varphi}{f} F_{\mu\nu} F^{\mu\nu}$ and with a meridian  $\dot{\vec{M}}$  $\sum_{i=1}^{n}$  $n$  shall show while small at  $GMB$ **FIFELL COSMIC FORMATION SIMPLES**  $\frac{d}{dt}$  in  $\frac{d}{dt}$  $\left\langle \zeta_{+}^{3}\right\rangle$ <sup>h</sup>⇣2i<sup>2</sup> = O (✏*<sup>V</sup> ,* ⌘*<sup>V</sup>* ) <sup>h</sup>⇣3<sup>i</sup>  $\overline{\mathcal{A}}$   $\overline{\mathcal{A}}$   $\mathcal{M}$   $\mathcal{D}$  $V$   $\ll 1$ • Flatness and self-couplings lds<br>icti and with a mechanism of production / exp **ig**<br>Q F n Stellfershes II Galile Street II Give B Scales **COLL SILOW-LOW ALCOMMIC UP** HUSELIE EN CAMPO SHOO **V** & *V* <u>D</u><br>**FREXESHE** *•* Flatness and gaussianity ! small self-couplings  $\mathcal{A} \cap \mathcal{A}$  with a meaning  $\mathcal{A}$  is a meaning  $\mathcal{A}$  is a meaning  $\mathcal{A}$ ˙  $\mathbf{E}$  signal  $\mathbf{E}$  of  $\mathbf{F}$  in the interferometer  $\mathbf{F}$  interferometer  $\mathbf{F}$  in  $\mathbf{F}$  in  $\mathbf{F}$  in  $\mathbf{F}$  is  $\mathbf{F}$  $\bullet$   $\bullet$   $\bullet$  in a to stead with simplest models  $\bullet$   $\rightarrow$   $\bullet$  + const.  $r =$ *P*GW *P*⇣  $\frac{1}{2}$  restriction to the contract of the c  $\langle \zeta^3 \rangle$ Elance ns  $\zeta$  iplings to others fighter to the country ✏*<sup>V</sup>* ⌘  $M_p^2$ **2** ⇣*V , V*  $\frac{2}{\sqrt{2}}$ **EGIE AREAL**  $V_4$ • Flatness and gaussathte SS saradischads sinen  $A(\tau, \mathbf{x}) = \begin{cases} \frac{1}{\sqrt{2\pi}} \sqrt{2\pi} \sqrt{2$  $r = 0$ review Pajer, MP '18)  $\overline{\downarrow}$  $\frac{1}{2}$  Kup for House *c f* 2015 Tre Free  $f \in \mathbb{R}$  and the state of the state o **DEAD AND CONSTRACT (**  $\partial \! \! \! \partial$ ţ  $\eta$  stalled matural natural natural at  $\epsilon$  MB **PW** *P*⇣ *, ns* 1 ⌘ *d* ln *P*⇣  $\frac{1}{\sqrt{k}}$  have a little **he k a little with the property of the constable weak**  $\frac{1}{2}$  Flatness and gaussianity  $\rightarrow$  small inflaton self-coupling  $S$ **•** Shift symmetry (broken by *V* ) on coupling to other fields to other fields to other fields of the coupling FSees Friench Am Suitot '9090; ... (review Pajer, MP '13) *Pt Ps •* No observed departure from (primordial) gaussianity, <sup>h</sup>⇣3i⌧h⇣2i3*/*<sup>2</sup> ↵⇤  $\frac{1}{2}$  Agreement with standard single field slow role with *M*<sup>2</sup> *p* ⇣*V,* ⌘2 *V,*  $A - B$ **Pod 10** *P*GW  $P_{\zeta}$  $n \sum_{i=1}^n a_i$ **d lat b a ly d ly d a w a g h** • Flatness and gaussianity  $\rightarrow$  small inflaton self-couplings **•** Shift symmetry (broken by *V* ) on the coupling of the coupling of the coupling of the coupling Freese, Frieman, Olinto to 090;. (review Pajer, MP '13) *Ps* / *<sup>k</sup>ns*<sup>1</sup> *<sup>r</sup>* <sup>=</sup> *Pt Ps* **• No observed departure from (primorpin Bullet 835 2013) FLETERIE**  $L$  ocal NG :  $\phi(x) = \phi(Q)$  Hestigal Hange  $\chi(x)$ ↵⇤ *•* Agreement with standard single field slow roll <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup>  $r, n_s = 1,$  for  $\epsilon$  or  $(\epsilon, \eta)$  $\mathsf{ft}^\equiv$  $M_p^2$ 2  $\bigwedge V_{,\phi}$ *V*  $\setminus^2$  $\ll 1$   $\rightarrow$   $\frac{k}{n}$   $\equiv$   $N/2$  $Y_{\phi\phi}$  $\frac{1}{\sqrt{2}}$   $\frac{1}{\sqrt{2}}$ BOG SHOW SIGNAL NATURAL NATURAL SCALES, WAS STRIKT STRIKT AT CONSTRUCTIONS atisia  $\phi \rightarrow \phi + \text{Eian} \otimes \text{Tr} \left( \phi \right)$  iplings to other first  $\phi$  $\exp\left(\frac{1}{2}\right)$ **c**<br>Gaty<br>Slovi *f* **futom repeatified designations** rahtage that  $\frac{1}{2}$   $\frac{1}{2}$  ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ *•* Smallness of *V*shift technically natural. *V* / *V*shift  $\frac{d\mathbf{X}}{dt}$   $\propto$   $V_{\mathsf{shift}}$ *•* Constrained couplings to matter (predictivity)  $\mathbf{G}$   $\mathbf{G}$   $\mathbf{W}$ ,  $m_{\phi} \simeq 10^{13}$   $\mathbf{G}$   $\mathbf{e}$   $\mathbf{V}$  Smallness of *<sup>V</sup>*shift technically natural. *<sup>V</sup>* / *<sup>V</sup>*shift ET TIETUS<br>NGC 1978 (COUPLE COUPLE COMPLETENCE) *<sup>m</sup> <sup>m</sup>*  $\overline{\mathbf{c}}$ EPC *A*  $\left(\begin{array}{ccc} 1 \\ 1 \end{array}\right)$  $\frac{1}{2}$ <br>  $\frac{1}{2}$ <br> that it all the that it can provide the case of the tensor of the case of the ]tter.(Q<br>ELVH3D *f*  $\frac{1}{4}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$ **editions** )<br>1944 E<del>MQY)</del><br>Fantagra  $\delta G_{\rm eV}^{\rm GUT}$  Small  $\bar{\gamma} \propto 10^{13} \ {\rm GeV}^{\prime}$ that it can play an important role also during inflation ⇤ Not the QCD axion; reference values *<sup>f</sup>* ⇠ <sup>10</sup><sup>16</sup> GeV *, m* ' <sup>10</sup><sup>13</sup> GeV ling<del>s to</del> other fields . ,<br>,<br>, <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup>  $c^2$ *f* porton: 2 helicities<br>-couplings Agreem ment with the the ET<br>bi*l*i <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> **de de la 1990 de 1990** *f <sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *•* Smallness of *V*shift technically natural. *V* / *V*shift etter (predictivity)<br><del>Frytity 2 ANG, observe</del>d SPORTAL ENGLATION REPORT CALLY, hard to the to the contract which why had the correction of With shift symmetry, *V* / *V*shift *•* Shift symmetry ! + *C* on couplings to other fields *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ **Production POLICITY** SPETER VERIGINAL hard to explain why *V* protected against quantum corrections. *•* Shift symmetry ! + *C* on couplings to other fields  $f$ *f f F*<sup>*µ*</sub> *F*<sup>*µ*</sup> *F*<sup>*µ*</sup> *F*<sup>*I*</sup> *F*<sup>*I*</sup> *F*<sup>*I*</sup> *F*</sup>  $\mathcal{P}^{\mathbf{v}}$   $\propto$   $\mathcal{P}^{\mathbf{v}}$  *V*shift **• Explored** <del>S</del>OV mmttte 7018 GeV Slow roll inflation requires very flat potential *V* , and, generically, hard to explain why *V* protected against quantum corrections.  $\mathbf{r} = \frac{1}{n} \sum_{i=1}^{n} \mathbf{r}_i \mathbf{r}_i$  $\phi$  $\phi$ 1

@*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵

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**INFLATIONARY MODELSHIPS INFLATIONS AND THE REAL PROPERTY OF STATISTICS. AXILLE WE GOE MOC BIOT LISSUE AND REALLY AS A CONTRACT OF MOST LIST OF MORTING AND HERE AS A Axiox Ponentially amplified, ation**  $\varphi$ **E** in adreement with simplest models of *r* ⌘ **PEGWA** *r*  $\equiv$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$  $\oint_{\mathbf{a}} \phi \rightarrow \phi + c$ *d* ln *P*⇣  $\phi \rightarrow \phi + const.$  infla ישן<br>קרוב<br>יימודי **ME VATGLS Prodess** J<br>Sab **• Full state of and self-couplings ity -> small self-couplings ity** -> s<br>Introduction of the small self-coupling it is a small self-coupling **Shift Shift Symmetry** on couplings to other  $F$ re $e$ s $e^w$ Frienzan, Olinto '90;  $k$ **• CMB in agreement with simplest models o** *P*⇣ *, ns* 1 ⌘ *<sup>d</sup>* ln *<sup>k</sup> , f*NL ⇠ Freese, Frieman, Olinto '90; . . . **€∰HT**  $\widetilde{M}$ *p*  $\frac{1}{2}$ ⇣*V , V* av<br>2 ⌧ <sup>1</sup> ⌘*<sup>V</sup>* ⌘ *<sup>M</sup>*<sup>2</sup> *L* = **•** FLATING COMPANIES AND THE SELFECT OF T Axion (Natural) Inflation *•* Smallness of *V*shift technically natural. *V* / *V*shift With shift symmetry, *V* / *V*shift With shift symmetry, *V* / *V*shift • Shift sy<del>mmetry on train nother to matters</del> Freese, Frieman, Olinto 90; (review Pajer, MP '13)  $\alpha$  in the  $\alpha$ Axion Inflation Shartage than  $S''$  , This equatorial median of  $P$  and  $\mathcal{A}$ **has the red steentbyggleatteichnically nátur<del>ál (K</del>WOREAN) PolffroVS**PréhéafSIMO ã'N<br>Creview Paier MP 13)  $\phi \rightarrow \phi + const.$ <sup>mid</sup> and suppose the coupling to  $\phi \rightarrow \phi + const.$ FIFEESE, OTTIESTHIT TEOMITIC AUDY, .<br>ב 2 (COCACCHITER) **c**y *f* @*µ*  $\bullet$  Constrained the advantage that the advance of · Constrained construction in a the partition \* Not<sup>4</sup>the QCD axion; reference values *f*  ! *AA* typically controls reheating. Only recently realized the can play and it can play and also determined and at care that  $G(z)$ ... W -> small inflaton, self-couplings> LIVE dEWAIY **Land**  $\frac{1}{2}$ 2 E F F G S H C C L G H D G S A L C L<br>AS C LE PSEUCLO-SCALAT (2000) **c**<br>12 *f* **PAKAP }** *•* Smallness of *V*shift technically natural. *V* / *V*shift B. OH-CO n2<br><del>Cc</del> 2019 100 2019 100 2019 100 2019 Lion<sup>®</sup> Inflation  $\frac{1}{2}$  summatrix  $\frac{1}{2}$   $\text{cese}, \text{y}$ "  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{dens}$ ",  $\text{cens}$ ",  $\text{dens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$  $\gamma$  reposed to start responsive to  $\gamma$  it  $\gamma$ *L* = <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> प<br>च *f* Freese, Sheftan you that the advisor the annual research strict **ese** *v* **Frienzan, 'Olint & Po'C+R**<br>Lese Viene de Values ⇤ Not the QCD axion; reference values *<sup>f</sup>* ⇠ <sup>10</sup><sup>16</sup> GeV *, m* ' <sup>10</sup><sup>13</sup> GeV **LA DS<sup>E</sup> LE** 2 **Q** and 2 0 0 0 0 2 5 0 has the advantage that **• Smallness of** *V*<br>• Smallness of The Condicion • Constrained couplings (predictivity)  $\frac{1}{2}$   $\frac{1}{2}$  Egm (prinsynn) all lations and flat the district of the district of the state of the state of the state of the hard to explain why *V* protected against quantum corrections. hard to explain why *V* protected against quantum corrections. **L = 1** . . <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f*  $2$ @*µ* has the advantage that **•** Smallness of *Vshift* technically **• Octocks first coupling to matter (predictivity)** <u>\* Not</u> the QCD the Q.CQ axion; reference **L . 12** 21 Koving Birshore () Shawi Sviolde **c ow sighar had description of the designal putting for a while small at Contract of the small at C** has the advantage third **•** SMatheese, of *V*shift technically,  $V(\varphi) \leftarrow \frac{\phi}{r} F_{\mu\nu} F^{\mu\nu}$  , inflatory  $\phi$  is pseudo-scalar axion (if  $\Theta$  ) is  $V\Theta$ <del><sup>→</sup> NOT</del> the QCD axion; reference values f<sup>1</sup> SIOW, FOII HITHSHION requires very flat potential <sup>in</sup> **hard to the second why and warned against the explanal why was** WEBIOTISY WANTER SHUTT GENTY STATED STATES SHIFT SHIFT SHEAT LEGAR TEST  $\phi$  $\frac{\varphi}{f} F_{\mu\nu} F^{\mu\nu}$ Li Heres  $n$  shall show while small at  $GMB$ **FIFELL COSMIC FORMATION SIMPLES**  $\frac{d}{dt}$  in  $\frac{d}{dt}$  $\left\langle \zeta_{+}^{3}\right\rangle$ <sup>h</sup>⇣2i<sup>2</sup> = O (✏*<sup>V</sup> ,* ⌘*<sup>V</sup>* ) <sup>h</sup>⇣3<sup>i</sup>  $\overline{\mathcal{A}}$   $\overline{\mathcal{A}}$   $\mathcal{M}$   $\mathcal{D}$  $\mathcal{W}_{\phi}^{\prime}$ V <del>, *M*<sup>2</sup> 22</del><br> *V* , *Ax*ion (Natural) Into The Most Computer of the Mos • Sélf-couplings<br>**Patra brakes Bran** lds<br>icti and with a mechanism of production / exp ividens (at miteufer and state is wtat refered small at CMB n af einfecsmal infantig in terfing in der EMB **COLL SILOW-LOW ALCOMMIC UNITED** HUSELIE EN KY *•* Flatness and gaussianity ! small self-couplings  $\mathcal{A} \cap \mathcal{A}$  with a meaning  $\mathcal{A}$  is a meaning  $\mathcal{A}$  is a meaning  $\mathcal{A}$ scales  $\bullet$   $\bullet$   $\bullet$  in a to stead with simplest models  $\bullet$   $\rightarrow$   $\bullet$  + const.  $r =$ *P*GW *P*⇣  $\lambda$  field  $d$  ln  $P_\zeta$  $\overline{\textbf{a}}$  lating  $\langle \zeta^3 \rangle$ Elance ns  $\zeta$  iplings to others fighter to the country ✏*<sup>V</sup>* ⌘  $M_p^2$ **2** ⇣*V , V*  $\frac{2}{\sqrt{2}}$ **EGIE AREAL**  $V_4$ • Flatness and gaussathte SS saradischads sinen (review Pajer, MP 13) at  $\frac{1}{6}$  who found the constraint of the a  $\partial \! \! \! \partial$ ţ k ∏l **PW** *P*⇣ *, ns* 1 ⌘ *d* ln *P*⇣  $\frac{1}{\sqrt{k}}$  have a little **he** 17 M G B H G H G  $\frac{1}{2}$  Flatness and gaussianity  $\rightarrow$  small inflaton self-coupling  $S$ **•** Shift symmetry (broken by *V* ) on coupling to other fields to other fields to other fields of the coupling FSEST Friench MAU1 LOCOO; ... '(feview Pajer, MP '13) *Ps Alig***t the 4** *Ps •* No observed departure from (primordial) gaussianity, <sup>h</sup>⇣3i⌧h⇣2i3*/*<sup>2</sup> .<br>د  $e$  angement  $\varphi$  )  $\frac{1}{2}$  is  $\frac{1}{2}$  in  $\frac{1}{2}$  in  $\varphi$  ,  $\varphi$  is  $\varphi$  in  $\varphi$  . Single field  $\varphi$  is  $\varphi$ **Party is a final party of the USA**  $\ddot{\phantom{1}}$ *M*<sup>2</sup> *p*  $\overline{\mathbf{X}}$ *V*  $A = 4$ *V,* **PEEEM** *r* ⌘ *P*GW **aviers of the land with a light of the light of the**  $n \sum_{i=1}^n a_i$ *d* ln *P*⇣ • Flatness and gaussianity  $\rightarrow$  small inflaton self-couplings **•** Shift symmetry (broken by *V* ) on the coupling of the coupling of the coupling of the coupling *Ps* **• No observed departure from (prins) and allege space figure in the state of t**  $L$  ocal NG :  $\phi(x) = \phi(Q)$  Historical Hanger and  $\frac{1}{\sqrt{2\pi}}\frac{d^{1/2}p}{dx^{2}}=\frac{1}{2\sqrt{2\pi}}\cosh(\frac{1}{2}q)$  and  $\frac{1}{2\sqrt{2\pi}}\frac{d^{1/2}p}{dx^{2}}=\frac{1}{2\sqrt{2\pi}}\sqrt{2\pi}}\sqrt{2\pi}$ *•* Agreement with standard single field slow roll *c*  $r, n_s = 1,$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$  $\mathsf{ft}^\equiv$  $M_p^2$ 2  $\bigwedge V_{,\phi}$ *V*  $\setminus^2$  $\ll 1$   $\rightarrow$   $\frac{k}{n}$   $\equiv$   $N/2$  $Y_{\cdot}$ o $\Phi$  $\frac{1}{\sqrt{2}}$   $\frac{1}{\sqrt{2}}$   $\frac{1}{\sqrt{2}}$ atisia  $\phi \rightarrow \phi + \text{Eian} \otimes \text{Tr} \left( \phi \right)$  iplings to other first  $\phi$ APTELIPEL SAIMPO ShOO <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ rahtage that <del>Gestal News apply, generically,</del>  $\frac{d\mathbf{X}}{dt} \propto V_{\mathsf{shift}}$ etiolity)<br>Annis  $\mathbf{G}$   $\mathbf{G}$   $\mathbf{W}$ ,  $m_{\phi} \simeq 10^{13}$  GeV Smallness of *<sup>V</sup>*shift technically natural. *<sup>V</sup>* / *<sup>V</sup>*shift ET TIETUS<br>NGC 1978 (COUPLE COUPLE COMPLETENCE) *<sup>m</sup> <sup>m</sup>* (200 *A*  $\left(\begin{array}{ccc} 1 \\ 1 \end{array}\right)$  $\frac{1}{2}$ <br>  $\frac{1}{2}$ <br> that it all the that it can provide the case of the tensor of the case of the ]tter.(Q<br>ELVH3D *f*  $\frac{1}{4}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$ **editions** 。<br>网传 EMTY)  $\delta G_{\rm eV}^{\rm GUT+G}$  SMP  $\propto V_{\rm shift}$  $\text{PSD}$  find at  $0.06$  GeV  $n_e$   $m_\phi \simeq 10^{13}$  GeV ling<del>s to</del> other fields . ,<br>,<br>, <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> a, vgener, cany, *-*<br>Self-couplings, Agreeme<br>**MUTHWAN Pectrolity Correct** *f* ment with rists ET<br>bi*l*i <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup>  $c_\psi$ *f* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *•* Smallness of *V*shift technically natural. *V* / *V*shift etter (predictivity)<br><del>Frytity 2 ANG, observe</del>d  $ES(f \sim 10^{16} \text{ GeV/s} \cdot \text{GeV} \sim 10^{18} \text{ GeV}$ **hard to explanature the against the children corrections.** With shift symmetry, *V* / *V*shift *•* Shift symmetry ! + *C* on couplings to other fields *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ **Production POLICITY €§ {\^** 10<sup>10</sup> GeV<sub>3</sub>, apy *•* Shift symmetry ! + *C* on couplings to other fields  $f$ *f f F*<sup>*µ*</sub> *F*<sup>*µ*</sup> *F*<sup>*µ*</sup> *F*<sup>*I*</sup> *F*<sup>*I*</sup> *F*<sup>*I*</sup> *F*</sup>  $\mathcal{P}^{\mathbf{v}}$   $\propto$   $\mathcal{P}^{\mathbf{v}}$  *V*shift **• Explored** <del>S</del>OV mmttte 7018 GeV Slow roll inflation requires very flat potential *V* , and, generically, hard to explain why *V* protected against quantum corrections.  $\mathbf{r} = \frac{1}{n} \sum_{i=1}^{n} \mathbf{r}_i \mathbf{r}_i$  $\phi$  $\phi$ 

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that it can play an important role also during inflation @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵  $\sharp$  <u>p</u>  $\sharp$  if  $\uparrow$   $\uparrow$   $\downarrow$   $\downarrow$ 

**INFLATIONARY MODELSHIPS INFLATIONS AND THE REAL PROPERTY OF STATISTICS. Gauge field excitation creates chiral GWs ! AXILLE WE GOE MOC BIOT LISSUE AND REALLY AS A CONTRACT OF MOST LIST OF MORTING AND HERE AS A Axiox Ponentially amplified, ation E** in adreement with simplest models of  $\bullet$  Shift symmetry (broken by  $\gamma$  ) on  $\gamma$  or  $\gamma$  ) on  $\gamma$  is other fields in  $\gamma$  , and the first state of  $\gamma$ **PEGWA** *r*  $\equiv$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$  $\oint_{\mathbf{a}} \phi \rightarrow \phi + c$ *d* ln *P*⇣  $\rightarrow$   $\phi$  +  $const.$  <sup>fnfla</sup><br> $\times$ hn<sup>r</sup>ishting ישן<br>קרוב<br>יימודי **ME VATGLS Prodess** J<br>Sab **• Full state of and self-couplings ity -> small self-couplings ity** -> s<br>Introduction of the small self-coupling it is a small self-coupling **Shift Symmetry** on couplings to other fields to other fields on the constrainment of the construction  $F$ re $e$ s $e^w$ Frienzan, Olinto '90; Matur<del>al 1 Awipfearty Poiffro</del>ws reheasing an **• CMB in agreement with simplest models o** *P*⇣ *, ns* 1 ⌘ *<sup>d</sup>* ln *<sup>k</sup> , f*NL ⇠ Freese, Frieman, Olinto '90; . . . **€∰HT**  $\widetilde{M}$ *p*  $\frac{1}{2}$ ⇣*V , V* av<br>2 ⌧ <sup>1</sup> ⌘*<sup>V</sup>* ⌘ *<sup>M</sup>*<sup>2</sup> *L* = **•** FLATING COMPANIES AND THE SELFECT OF T Axion (Natural) Inflation *•* Smallness of *V*shift technically natural. *V* / *V*shift With shift symmetry, *V* / *V*shift With shift symmetry, *V* / *V*shift • Shift sy<del>mmetry on train nother to matters</del> **THIOES CTEATES SCHILL IN GEVYSES** (review Pajer, MP '13)  $\alpha$  in the  $\alpha$ Axion Inflation Shartage than Callar Gazion (1 Parties WP **has the red**  $\phi \rightarrow \phi + const.$ <sup>mings to the coupling to  $\phi \rightarrow \phi + const.$ </sup> FIFEESE, OTTIESTHIT TEOMITIC AUDY,  $S''$  , THREE CLERIFORD .<br>ב 2 (COCACCHITER) **c**y *f* @*µ*  $\bullet$  Constrained the advantage that the advance of · Constrained construction in a the partition ₩ Not<sup>4</sup>the QCD axion; reference values *f*  ! *AA* typically controls reheating. Only recently realized the can play and it can play and also determined and at care that  $G(z)$ ... W -> small inflaton, self-couplings> LIVE dEWAIY **L** m For day  $\frac{1}{2}$ 2 E F F G S H C C L G H D G S A L C L<br>AS C LE PSEUCLO-SCALAT (2000) **c**<br>12 *f* **PAKAP }** *•* Smallness of *V*shift technically natural. *V* / *V*shift B OOFF CULTO TRUSH CODE ES ET THEFT that it can play an important role also during inflation Lion<sup>®</sup> Inflation  $\frac{1}{2}$  summatrix  $\frac{1}{2}$   $\text{cese}, \text{y}$ "  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{dens}$ ",  $\text{cens}$ ",  $\text{dens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$  $\gamma$  reposed to start responsive to  $\gamma$  it  $\gamma$ *L* = <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> प<br>च Pupity viel Rusher Mossilo and Article Power Parties **est** *v* Frienzan (Vinto 390, *V*<br>LOCQ axion reference values ⇤ Not the QCD axion; reference values *<sup>f</sup>* ⇠ <sup>10</sup><sup>16</sup> GeV *, m* ' <sup>10</sup><sup>13</sup> GeV **LA DS<sup>E</sup> LE** 2 **Q** and 2 0 0 0 0 2 5 0 has the advantage that **• Smallness of** *V*<br>• Smallness of The Condicion • Constrained couplings (predictivity)  $\frac{1}{2}$   $\frac{1}{2}$  Egm (prinsynn) all lations and flat the district of the district of the state of the state of the state of the hard to explain why *V* protected against quantum corrections. hard to explain why *V* protected against quantum corrections. **L = 1** . . 2 2 (2 ) + **2 2 (2 ) + 2 (2 ) + 2 (2 )** + 2 ) + 2 (2 ) + 2 ) + 2 (2 ) + 2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) + 2 (2 ) +  $2$ *f* @*µ* has the advantage that **•** Smallness of *Vshift* technically **• Octocks first coupling to matter (predictivity)** <u>\* Not</u> the QCD the Q.CQ axion; reference **L . 12** 21 Koving Birshore () Shawi Sviolde **c ow sighar had description of the designal putting for a while small at Contract of the small at C** has the advantage that *•* CMB in agreement with simplest models of slow-roll cosmic inflation ' ! ' + *const.*  $\bullet$  SMall  $\circ$  SS, of *I V*shift technically,  $V(\varphi) \leftarrow \frac{\phi}{r} F_{\mu\nu} F^{\mu\nu}$  , inflatory  $\phi$  is pseudo-scalar axion (if  $\Theta$  ) is  $V\Theta$ <del><sup>→</sup> NOT</del> the QCD axion; reference values f<sup>1</sup> SIOW, FOII HITHSHION requires very flat potential <sup>in</sup> **hard to the second why and warned against the explanal why was** WEBIOTISY WANTER SHUTT GENTY STATED STATES SHIFT SHIFT SHEAT LEGAR TEST  $\phi$  $\frac{\varphi}{f} F_{\mu\nu} F^{\mu\nu}$ Li Heres  $n$  shall show while small at  $GMB$ **FIFELL COSMIC FORMATION SIMPLES**  $\frac{d}{dt}$  in  $\frac{d}{dt}$  $\left\langle \zeta_{+}^{3}\right\rangle$ <sup>h</sup>⇣2i<sup>2</sup> = O (✏*<sup>V</sup> ,* ⌘*<sup>V</sup>* ) <sup>h</sup>⇣3<sup>i</sup>  $\overline{\mathcal{A}}$   $\overline{\mathcal{A}}$   $\mathcal{M}$   $\mathcal{D}$  $\mathcal{W}_{\phi}^{\prime}$ V <del>, *M*<sup>2</sup> 22</del><br> *V* , *Ax*ion (Natural) Into The Most Computer of the Mos • Sélf-couplings<br>**Patra brakes Bran** lds<br>icti and with a mechanism of production / exp ividens (at miteufer and state is wtat refered small at CMB n af einfecsmall Garne small at CMB, scales **COLL SILOW-LOW ALCOMMIC UNITED** HUSELIE EN CAMPO SHOO *•* Flatness and gaussianity ! small self-couplings  $\mathcal{A} \cap \mathcal{A}$  with a meaning  $\mathcal{A}$  is a meaning  $\mathcal{A}$  is a meaning  $\mathcal{A}$  $r =$ *P*GW *P*⇣  $\frac{1}{2}$  restriction to the contract of the c  $\langle \zeta^3 \rangle$ Elance ns  $\zeta$  iplings to others fighter to the country ✏*<sup>V</sup>* ⌘  $M_p^2$ **2** ⇣*V , V*  $\frac{2}{\sqrt{2}}$ **EGIE AREAL**  $V_4$ • Flatness and gaussathte SS saradischads sinen (review Pajer, MP '13) *r, ns* 1*, f*NL = O (✏*,* ⌘) 1 *c f*  $20157$  et 225 zally nátur<del>ál A Myőkény Roiffroys réheasin</del>g a 1  $\sharp$  <u>p</u>  $\sharp$  if  $\uparrow$   $\uparrow$   $\downarrow$   $\partial \! \! \! \partial$ ţ k ∏l **PW** *P*⇣ *<sup>d</sup>* ln *<sup>k</sup> , f*NL ⇠ *, ns* 1 ⌘ *d* ln *P*⇣ **he** 17 M G B H G H G  $\frac{1}{2}$  Flatness and gaussianity  $\rightarrow$  small inflaton self-coupling  $S$ FSEST Friench MAU1 LOCOO; ... '(feview Pajer, MP '13) *Ps Alig***t the 4** *Ps •* No observed departure from (primordial) gaussianity, <sup>h</sup>⇣3i⌧h⇣2i3*/*<sup>2</sup> .<br>د  $e$  angement  $\varphi$  )  $\frac{1}{2}$  is  $\frac{1}{2}$  in  $\frac{1}{2}$  in  $\varphi$  ,  $\varphi$  is  $\varphi$  in  $\varphi$  . Single field  $\varphi$  is  $\varphi$ **EXCHENDEDE, PW**  $A = 4$ **PEEEM** *r* ⌘ *P*GW  $P_{\zeta}$ **de l'alignation de l'alignation de l'aligne** *d* ln *P*⇣ • Flatness and gaussianity  $\rightarrow$  small inflaton self-couplings *Ps* **• No observed departure from (prins) and allege space figure in the state of t**  $L$  ocal NG :  $\phi(x) = \phi(Q)$  Historical Hanger and  $\frac{1}{\sqrt{2\pi}}\frac{d^{1/2}p}{dx^{2}}=\frac{1}{2\sqrt{2\pi}}\cosh(\frac{1}{2}q)$  and  $\frac{1}{2\sqrt{2\pi}}\frac{d^{1/2}p}{dx^{2}}=\frac{1}{2\sqrt{2\pi}}\sqrt{2\pi}}\sqrt{2\pi}$ *•* Agreement with standard single field slow roll *c*  $r, n_s = 1,$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$  $f_{\overline{a}}$  $M_p^2$ 2  $\bigwedge V_{,\phi}$ *V*  $\setminus^2$  $\Psi^1, \Psi^2 = \Psi^2$  $Y_{\cdot}$ o $\Phi$ **V 199** atisia  $\phi \rightarrow \phi + \text{Eian} \otimes \text{Tr} \left( \phi \right)$  iplings to other first  $\phi$ <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ rahtage that *•* Smallness of *V*shift technically natural. *V* / *V*shift ! *AA* typically controls reheating. More recently, realized *•* Constrained couplings to matter (predictivity) <del>Gestal News apply, generically,</del>  $\delta$  SMF  $\not\sim V$  shift etiolity)<br>Annis  $\partial G$  $\partial V, m_\phi \Delta$  1013 GeV Smallness of *<sup>V</sup>*shift technically natural. *<sup>V</sup>* / *<sup>V</sup>*shift ET TIETUS<br>NGC 1978 (COUPLE COUPLE COMPLETENCE) *<sup>m</sup> <sup>m</sup>* (200 *A*  $\left(\begin{array}{ccc} 1 \\ 1 \end{array}\right)$  $\frac{1}{2}$ <br>  $\frac{1}{2}$ <br> that it all the that it can provide the case of the tensor of the case of the ]tter.(Q<br>ELVH3D *f*  $\frac{1}{4}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$ **editions** lds EMTY) *•* Smallness of *V*shift technically natural. *V* / *V*shift  $\text{PSD}$  find at  $0.06$  GeV  $n_e$   $m_\phi \simeq 10^{13}$  GeV ling<del>s to</del> other fields . ,<br>,<br>, <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> a, vgener, cany, *-*<br>Self-couplings, Agreeme<br>**MUTHWAN Pectrolity Correct** *f* ment with rists ET<br>bi*l*i <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup>  $c_\psi$ *f* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *•* Smallness of *V*shift technically natural. *V* / *V*shift etter (predictivity)<br><del>Frytity 2 ANG, observe</del>d  $ES(f \sim 10^{16} \text{ GeV/s} \cdot \text{GeV} \sim 10^{18} \text{ GeV}$ **hard to explanature the against the children corrections.** With shift symmetry, *V* / *V*shift *•* Shift symmetry ! + *C* on couplings to other fields *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ **Production POLICITY €§ {\^** 10<sup>10</sup> GeV<sub>3</sub>, apy *•* Shift symmetry ! + *C* on couplings to other fields  $f$ *f f F*<sup>*µ*</sub> *F*<sup>*µ*</sup> *F*<sup>*µ*</sup> *F*<sup>*I*</sup> *F*<sup>*I*</sup> *F*<sup>*I*</sup> *F*</sup>  $\mathcal{P}^{\mathbf{v}}$   $\propto$   $\mathcal{P}^{\mathbf{v}}$  *V*shift **• Explored** <del>S</del>OV mmttte 7018 GeV Slow roll inflation requires very flat potential *V* , and, generically, hard to explain why *V* protected against quantum corrections.  $\phi$ Axion-Inflation

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@*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵

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**INFLATIONARY MODELSHIPS INFLATIONS AND THE REAL PROPERTY OF STATISTICS. EMEARC COSCICALL CONCITATION & CREATES**  $\mathbb{R}^{n}$ **• • Constrainage trainings and gaussianity** *hij ,<sup>j</sup>* = 0 *•* GW Source(s): ( SCALARS , VECTOR , FERMIONS ) Axion (Natural) Inflation  $h_{ij}'' + 2\mathcal{H}h_{ij}' - \frac{1}{2}\sum_{k=1}^{n}h_{ijk}$  se strategnes to the typing developed  $\sqrt{m}$ Transverse-Traceless (TT) dof carry energy out of the source!!! Freese, Frieman, Olinto '90; . . . *•* GW: *ds*<sup>2</sup> <sup>=</sup> *<sup>a</sup>*<sup>2</sup>(*d*⌘<sup>2</sup> + (*ij* <sup>+</sup> *<sup>h</sup>ij* )*dx<sup>i</sup>* **dx**<br>**dx**<br>**and**<br>**dx**<br>**dx**<br>**dx** *hij ,<sup>j</sup>* = 0 **Port SPOR POIT FEEDERICE THEFFICIERS OF**<br>V=1001H COSTYFIC INFLATION *frefin 841 főt 309*<br>r MP '13) *ij* r<sup>2</sup>*hij* = 16⇡*G*⇧TT *ij ,* ⇧*ij* = *Tij* h*Tij* i  $T_{\rm V}(\rho) = \frac{1}{4} \int \frac{1}{\rho} \frac{1}{\rho} \frac{1}{\rho} \frac{1}{\rho} \frac{1}{\rho}$  do  $\frac{1}{2} \int \frac{1}{\rho} \frac{1}{\rho} \frac{1}{\rho} \frac{1}{\rho} \frac{1}{\rho}$  $\mathcal{H}h'_{ij} = \sqrt{\frac{2}{n}}\mathcal{H}^{2}$  the set of  $\mathcal{H}^{2}$  is  $\mathcal{H}^{2}$  to  $\mathcal{H}^{2}$  the set of  $\mathcal{H}^{2}$  is  $\mathcal{H}^{2}$  the set of  $\mathcal{H}^{2}$  is  $\mathcal{H}^{2}$  to  $\mathcal{H}^{2}$  the set of  $\mathcal{H}^{2}$  is  $\mathcal{H}^{2}$  to  $\math$ **E** in adreement with simplest models of *r* ⌘ **PEGWA** *r*  $\equiv$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$  $\oint_{\mathbf{a}} \phi \rightarrow \phi + c$ *d* ln *P*⇣  $\phi \rightarrow \phi + const.$  infla ישן<br>קרוב<br>יימודי **Prodess** J<br>Sab **• Full state of and self-couplings ity -> small self-couplings ity** -> s<br>Introduction of the small self-coupling it is a small self-coupling Matur<del>al 1 Awipfearty Poiffro</del>ws reheasing an **• CMB in agreement with simplest models o** *P*⇣ *, ns* 1 ⌘ *<sup>d</sup>* ln *<sup>k</sup> , f*NL ⇠ Freese, Frieman, Olinto '90; . . . **€∰HT**  $\frac{1}{2}$  $\frac{1}{2}$ ⇣*V , V* av<br>2 ⌧ <sup>1</sup> ⌘*<sup>V</sup>* ⌘ *<sup>M</sup>*<sup>2</sup> *L* = AXION (SIOUTH SITUTE IS UNITED • Shift sy<del>mmetry on train nother to matters</del> Freese, Frieman, Olinto 90; (review Pajer, MP '13)  $\alpha$  in the  $\alpha$ Axion Inflation Shartage than  $S''$  , This equatorial median of  $P$  and  $\mathcal{A}$ **L ELE has the red**  $\phi \rightarrow \phi + const.$ <sup>mings to the coupling to  $\phi \rightarrow \phi + const.$ </sup> FIFEESE, OTTIESTHIT TEOMITIC AUD? .<br>ב 2 (COCACCHITER) **c**y *f* **A**<br>W. FOII THTISTISH FEQUITES2VERWITH TECHNICI With Shift South and International State Shift Al · Constrained free to the satisficities \* Not<sup>4</sup>the QCD axion; reference values *f*  ! *AA* typically controls reheating. Only recently realized the can play and it can play and also determined and at care that  $G(z)$ ... W -> small inflaton, self-couplings> LIVE dEWAIY **Land**  $\frac{1}{2}$ 2 E F F G S H C C L G H D G S A L C L<br>AS C LE PSEUCLO-SCALAT (2000) **c**<br>12 *f* **PAKAP }** B. OH-CO 2019 100 2019 100 2019 100 2019 that it can play an important role also during inflation Lion<sup>®</sup> Inflation  $\frac{1}{2}$  summatrix  $\frac{1}{2}$   $\text{cese}, \text{y}$ "  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{dens}$ ",  $\text{cens}$ ",  $\text{dens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$  $\gamma$  reposed to start responsive to  $\gamma$  it  $\gamma$ ness and gaussiamtess sariouseraddsblegalty -> S प<br>च adsgraassiegaity<br>ASBI@immare 8884/858  $h_{\text{max}} = \frac{1}{2} \int \frac{1}{\sqrt{2\pi}} \int \frac{1}{\sqrt$ **ese** *v* **Frienzan, 'Olint & Po'C+R**<br>Lese Viene de Values ⇤ Not the QCD axion; reference values *<sup>f</sup>* ⇠ <sup>10</sup><sup>16</sup> GeV *, m* ' <sup>10</sup><sup>13</sup> GeV **LA DS<sup>E</sup> LE** 2 **Q** and 2 0 0 0 0 2 5 0 has the advantage that **• Smallness of** *V*<br>• Smallness of The Condicion • Constrained couplings (predictivity)  $\frac{1}{2}$   $\frac{1}{2}$  Sultan Responsible inflation and the contribution requires very flat potential hard to explain why *V* protected against quantum corrections. **L = 1** <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f*  $2$ @*µ* has the advantage that **•** Smallness of *Vshift* technically **• Octocks first coupling to matter (predictivity)** <u>\* Not</u> the QCD the Q.CQ axion; reference Sig W. Poll 1999 Republication requires very flat potential and and position of the complete of the complete o **L . 12** 21 Koving Birshore () Shawi Sviolde **c**  $\partial^{\mu}_{\mu}$ has the advantage third  $\bullet$  SMall Ress, of *I* Bohift technically,  $V(\varphi) \leftarrow \frac{\phi}{r} F_{\mu\nu} F^{\mu\nu}$  , inflatory  $\phi$  is pseudo-scalar axion (if  $\Theta$  ) is  $V\Theta$ <del><sup>→</sup> NOT</del> the QCD axion; reference values f<sup>1</sup> SIOW, FOII HITHSHION requires very flat potential <sup>in</sup> **hard to explant why why a protected and then** WWITH SHIFT SYMMETRY, WATER STATE SHIP  $\phi$  $\frac{\varphi}{f} F_{\mu\nu} F^{\mu\nu}$ Li Heres  $n$  shall show while small at  $GMB$  $\frac{d}{dt}$  in  $\frac{d}{dt}$  $\left\langle \zeta_{+}^{3}\right\rangle$ <sup>h</sup>⇣2i<sup>2</sup> = O (✏*<sup>V</sup> ,* ⌘*<sup>V</sup>* ) <sup>h</sup>⇣3<sup>i</sup>  $\overline{\mathcal{A}}$   $\overline{\mathcal{A}}$   $\mathcal{M}$   $\mathcal{D}$  $\mathcal{W}_{\phi}^{\prime}$ *V* and a stream to the call NG : a  $\phi(x) = \phi(Q)$  **Histral Haced Americal** • Sélf-couplings<br>**Patra brakes Bran** lds<br>icti and with a mechanism of production / exp iget Blett n af einfecsmal infantig in terfing in der EMB **COLL SILOW-LOW ALCOMMIC UNITED** HUSELIE EN CAMPO SHOO **• Flatness and the strathed for contract short say paragoget the standing student to coupling to a**  $\mathcal{A} \cap \mathcal{A}$  with a meaning  $\mathcal{A}$  is a meaning  $\mathcal{A}$  is a meaning  $\mathcal{A}$ a **h interferometer stand we ow at interferometer states, while small at C** scales  $\bullet$   $\bullet$   $\bullet$  in a to stead with simplest models  $\bullet$   $\rightarrow$   $\bullet$  + const.  $r =$ *P*⇣ **Mand 115 E 3 1 DINOS to others fighter of the country** ✏*<sup>V</sup>* ⌘  $M_p^2$ **2** ⇣*V , V*  $\frac{2}{\sqrt{2}}$ **EGIE AREAL**  $V_4$ • Flatness and gaussathte SS saradischads sinen (review Pajer, MP '13) *r, ns* 1*, f*NL = O (✏*,* ⌘) 1  $\frac{1}{2}$  **RUP RE OF BURGES** *c f*  $20157$  et 225 zally nátur<del>ál A Myőkény Roiffroys réheasin</del>g a 1  $\sharp$  <u>p</u>  $\sharp$  if  $\uparrow$   $\uparrow$   $\downarrow$   $\downarrow$  **PW** *P*⇣ *, ns* 1 ⌘ *d* ln *P*⇣  $\frac{1}{\sqrt{k}}$  have a little **he k a little with the property of the constable weak**  $\frac{1}{2}$  Flatness and gaussianity  $\rightarrow$  small inflaton self-coupling  $S$ **•** Shift symmetry (broken by *V* ) on coupling to other fields to other fields to other fields of the coupling **Frienda Woll Freeser Friendament**rikt 8000; '(feview Pajer, MP '13) *Ps Alig***t the 4** *Ps •* No observed departure from (primordial) gaussianity, <sup>h</sup>⇣3i⌧h⇣2i3*/*<sup>2</sup> ↵⇤  $\frac{1}{2}$  and  $\frac{1}{2}$   $\frac{1}{2}$ FICCSC, FI  $A = 4$ **PEEEM** *P*GW  $P_{\zeta}$  $n \sum_{i=1}^n a_i$ **d lat b a ly d ly d a w a g h** • Flatness and gaussianity  $\rightarrow$  small inflaton self-couplings **•** Shift symmetry (broken by *V* ) on the coupling of the coupling of the coupling of the coupling Freese, Frieman, Olinto to 090;. *Ps* **• No observed departure from (prins) and allege space figure in the state of t**  $L$  ocal NG :  $\phi(x) = \phi(Q)$  Hestival the set  $\mathcal{A}$  $\frac{1}{\sqrt{2}}\frac{1}{\sqrt{2}}\frac{1}{\sqrt{2}}$   $\frac{1}{\sqrt{2}}$  cal NG  $\frac{1}{\sqrt{2}}$   $\frac{1}{\sqrt{2}}$ **• Self-couplings, Agreement with standard single field slow roll<br><b>Couply & Crowtecution** & Office Blottssynand With Statiful Ast<br>  $h'' + 2\mathcal{H}h' - \nabla^2 h$  $r, n_s - 1, q_m > 0$  $\mathsf{ft}^\equiv$  $M_p^2$ 2  $\bigwedge V_{,\phi}$ *V*  $\setminus^2$  $\ll 1$   $\rightarrow$   $\frac{k}{n}$   $\equiv$   $N/2$  $Y_{\cdot}$ o $\Phi$  $\frac{1}{\sqrt{2}}$   $\frac{1}{\sqrt{2}}$   $\frac{1}{\sqrt{2}}$ BOG SHOW SIGNAL NATURAL NATURAL SCALES, WAS STRIKT STRIKT AT CONSTRUCTIONS atisia  $\phi \rightarrow \phi + \text{Eian} \otimes \text{Tr} \left( \phi \right)$  iplings to other first  $\phi$ *c* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *f*  $\frac{1}{2}$  **F**  $\frac{1}{2}$   $\frac{1}{2$ rahtage that *•* Smallness of *V*shift technically natural. *V* / *V*shift ! *AA* typically controls reheating. More recently, realized *•* Constrained couplings to matter (predictivity) Residence and ace of cally  $\frac{d\mathbf{X}}{dt} \propto V_{\mathsf{shift}}$ etiolity)<br>Annis  $\mathbf{G}$   $\mathbf{G}$   $\mathbf{W}$ ,  $m_{\phi} \simeq 10^{13}$  GeV Smallness of *<sup>V</sup>*shift technically natural. *<sup>V</sup>* / *<sup>V</sup>*shift ET TIETUS<br>NGC 1978 (COUPLE COUPLE COMPLETENCE) *<sup>m</sup> <sup>m</sup>* (200 *A*  $\left(\begin{array}{ccc} 1 \\ 1 \end{array}\right)$  $\frac{1}{2}$ <br>  $\frac{1}{2}$ <br> that it all the that it can provide the case of the tensor of the case of the ]tter.(Q<br>ELVH3D *f*  $\frac{1}{4}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$ 。<br>网传 EMTY)  $\delta G_{\rm eV}^{\rm GUT+G}$  SMP  $\propto V_{\rm shift}$  $\text{PSD}$  find at  $0.06$  GeV  $n_e$   $m_\phi \simeq 10^{13}$  GeV ling<del>s to</del> other fields . ,<br>,<br>, <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup>  $\widetilde{\epsilon \psi}$ *f* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ ment with rists ET<br>bi*l*i <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup>  $c_\psi$ *f* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ *•* Smallness of *V*shift technically natural. *V* / *V*shift etter (predictivity)<br><del>Frytity 2 ANG, abserve</del>d  $ES(f \sim 10^{16} \text{ GeV/s} \cdot \text{GeV} \sim 10^{18} \text{ GeV}$ hard to explanatulate the corrections. With shift symmetry, *V* / *V*shift *•* Shift symmetry ! + *C* on couplings to other fields *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ **Production POLICITY €§ {\^** 10<sup>10</sup> GeV<sub>3</sub>, apy *•* Shift symmetry ! + *C* on couplings to other fields  $f$ *f f F*<sup>*µ*</sub> *F*<sup>*µ*</sup> *F*<sup>*µ*</sup> *F*<sup>*I*</sup> *F*<sup>*I*</sup> *F*<sup>*I*</sup> *F*</sup>  $\mathcal{P}^{\mathbf{v}}$   $\propto$   $\mathcal{P}^{\mathbf{v}}$  *V*shift **• Explored** <del>S</del>OV mmttte 7018 GeV  $\mathcal{B}$  ,  $\mathcal{B}$  energies very flat potential  $\mathcal{B}$  $\mathbf{r} = \frac{1}{n} \sum_{i=1}^{n} \mathbf{r}_i \mathbf{r}_i$  $\phi$  $\phi$ 

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**INFLATIONARY MODELSHIPS INFLATIONS AND THE REAL PROPERTY OF STATISTICS. EMEARC COSCICALL CONCITATION & CREATES** AVGHUN GAIHPO<sup>VshOO</sup>; ... \* NOT THE QUOD LIGOR! **• • Constrainage trainings and gaussianity** *h*<sup>ij</sup>ation  $h''_{i'}$  $\int_{ij}^{T} + 2\mathcal{H}h'_{ij} - \sum\limits_{n=1}^{N}P_{ij}$  and  $\int_{i}^{T}$  and  $\int_{i}^{T}$  and  $\int_{i}^{T}P_{ij}$  and  $\int_{i}^{T}P_{ij}$  in an  $\int_{i}^{T}P_{ij}$  $\mathcal{F}$  a **GW** and stive and carried to the source of the source o *•* GW: *ds*<sup>2</sup> <sup>=</sup> *<sup>a</sup>*<sup>2</sup>(*d*⌘<sup>2</sup> + (*ij* <sup>+</sup> *<sup>h</sup>ij* )*dx<sup>i</sup>* **dx**<br>**dx**<br>**and**<br>**dx**<br>**dx**<br>**dx** *hij ,<sup>j</sup>* = 0 **Port SPOR POIT FEEDERICE THEFFICIERS OF**<br>V=1001H COSTYFIC INFLATION *frefin 841 főt 309*<br>r MP '13) *ij* r<sup>2</sup>*hij* = 16⇡*G*⇧TT *ij ,* ⇧*ij* = *Tij* h*Tij* i  $T_{\rm V}(\rho) = \frac{1}{4} \int \frac{1}{\rho} \frac{1}{\rho} \frac{1}{\rho} \frac{1}{\rho} \frac{1}{\rho}$  do  $\frac{1}{2} \int \frac{1}{\rho} \frac{1}{\rho} \frac{1}{\rho} \frac{1}{\rho} \frac{1}{\rho}$ **18 Agreement put hystendard single field slowing wat ural) Inflation**<br>The Agreement put hystendard single field slowing wat ural) Inflation  $\mathcal{H}h'_{ij} = \sqrt{\frac{2}{n}}\frac{\mu_{i}}{\sqrt{\frac{2}{n}}}\frac{1}{\sqrt{\frac{2}{n}}}\frac{\sqrt{2}}{\sqrt{\frac{2}{n}}}\frac{1}{\sqrt{\frac{2}{n}}}\frac{\sqrt{2}}{\sqrt{\frac{2}{n}}}\frac{1}{\sqrt{\frac{2}{n}}}\frac{\sqrt{2}}{\sqrt{\frac{2}{n}}}\frac{\sqrt{2}}{\sqrt{\frac{2}{n}}}\frac{\sqrt{2}}{\sqrt{\frac{2}{n}}}\frac{\sqrt{2}}{\sqrt{\frac{2}{n}}}\frac{\sqrt{2}}{\sqrt{\frac{2}{n}}}\frac{\sqrt{2}}{\sqrt{\frac{2}{n}}}\frac{\sqrt{2}}{\sqrt{\frac{2$ *A<sup>µ</sup>* **Chiral GW mostly\* one-chirality E** in adreement with simplest models of *r* ⌘ **PEGWA** *r*  $\equiv$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$  $\oint_{\mathbf{a}} \phi \rightarrow \phi + c$ *d* ln *P*⇣  $\phi \rightarrow \phi + const.$  infla ישן<br>קרוב<br>יימודי **ME VATGLS** 2 *V* ✏*<sup>V</sup>* ⌘ *NES*ULTERWATUES / / • Flatness and gaussatmess saradseragessiagsity → s<br>**• Confirmal taged amindations stational self-couplin**  $F$ reese, Frienzan, Olinto '90;  $k$ **• CMB in agreement with simplest models o** *P*⇣ *, ns* 1 ⌘ *<sup>d</sup>* ln *<sup>k</sup> , f*NL ⇠ Freese, Frieman, Olinto '90; . . . *p*  $\frac{1}{2}$ ⇣*V , V* ⌧ <sup>1</sup> ⌘*<sup>V</sup>* ⌘ *<sup>M</sup>*<sup>2</sup> *L* = AXION (SIOUTH SITUTE IS UNITED  $\bullet$  Shift symmetry on train of the strip of the angle to the strip of Freese, Friemanchirlinto 90; PPeview Pajer, MP '13)  $\alpha$  in the  $\alpha$ Axion Inflation Shartage than  $S''$  , This equatorial median of  $P$  and  $\mathcal{A}$ **L ELE EXAMPREDICALLY CONTROLS REALLY AND THE REALLY AND A**  $\phi \rightarrow \phi + const.$ <sup>mings to the coupling to  $\phi \rightarrow \phi + const.$ </sup> FIFEESE, OTTIESTHIT TEOMITIC AUD? .<br>ב 2 (COCACCHITER) **c**y *f* **A**<br>W. FOII THTISTISH FEQUITES2VERWITH TECHNICI With Shift South and International State Shift Al · Constrained coupling a to matted ₩ Not the QCD axion; reference values *f*  ! *AA* typically controls reheating. Only recently realized the can play and it can play and also determined and at care that  $G(z)$ ... W -> small inflaton, self-couplings> LIVE dEWAIY **Land**  $\frac{1}{2}$ 2 E F F G S H C C L G H D G S A L C L<br>AS C LE PSEUCLO-SCALAT (2000) **c**<br>12 *FIPSEUDD-SCETCH LEXION*<br>
F the OCD-avior referem **PAKAP }** B ORF FOULD TREES TO BE FREE TO BE<br>COSE WATER CRIME TO SOFT **ABI THRIB** that it can play an important role also during inflation Lion<sup>®</sup> Inflation  $\frac{1}{2}$  summatrix  $\frac{1}{2}$   $\text{cese}, \text{y}$ "  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{dens}$ ",  $\text{cens}$ ",  $\text{dens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$ ",  $\text{cens}$ ness and gaussamtess sarathstragtsblags.lty -> S<br>hard that was a krankdatum as a kommon e bedal yes. प<br>च  $h_{\text{max}} = \frac{1}{2} \int \frac{1}{\sqrt{2\pi}} \int \frac{1}{\sqrt$ ⇤ Not the QCD axion; reference values *<sup>f</sup>* ⇠ <sup>10</sup><sup>16</sup> GeV *, m* ' <sup>10</sup><sup>13</sup> GeV **LA DS<sup>E</sup> LE** 2 **Q** and 2 0 0 0 0 2 5 0 has the advantage that **• Smallness of** *V*<br>• Smallness of The Condicion • Constrained couplings (predictivity)  $\frac{1}{2}$   $\frac{1}{2}$  Egm (prinsynn) all lations and flat the district of the district of the state of the state of the state of the **L = 1** 2 **DRAH KAMAR ISLA (SHASAR Y) OIC**  $2$ *f*  $\underline{P}$  (2) has the advantage that **•** Smallness of *Vshift* technically **• Octocks first coupling to matter (predictivity)** <u>\* Not</u> the QCD the Q.CQ axion; reference **. 12** <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup> *f*  $\partial^{\mu}_{\mu}$ has the advantage third  $\bullet$  SMall Ress, of *I* Bohift technically,  $V(\varphi) \leftarrow \frac{\phi}{r} F_{\mu\nu} F^{\mu\nu}$  , inflatory  $\phi$  is pseudo-scalar axion (if  $\Theta$  ) is  $V\Theta$ <del><sup>→</sup> NOT</del> the QCD axion; reference values f<sup>1</sup> SIOW, FOII HITHSHION requires very flat potential <sup>in</sup> **hard to explant why why a protected and then** WWITH SHIFT SYMMETRY, WATER STATE SHIP  $\phi$  $\frac{\varphi}{f} F_{\mu\nu} F^{\mu\nu}$ Li Heres  $n$  shall show while small at  $GMB$  $\frac{d}{dt}$  in  $\frac{d}{dt}$  $\left\langle \zeta_{+}^{3}\right\rangle$ <sup>h</sup>⇣2i<sup>2</sup> = O (✏*<sup>V</sup> ,* ⌘*<sup>V</sup>* ) <sup>h</sup>⇣3<sup>i</sup>  $\overline{\mathcal{A}}$   $\overline{\mathcal{A}}$   $\mathcal{M}$   $\mathcal{D}$  $ES \oint_{\mathcal{A}} \int_{\mathcal{D}} \frac{1}{2} \Omega^{16} G \partial \dot{V}^3 \partial \mathcal{C} \mathcal{C} \mathcal{C} \mathcal{C} \mathcal{C} \sim 10^{18} GeV$ *V* and a stream to the call NG : a  $\phi(x) = \phi(Q)$  **Histral Haced Americal** • Sélf-couplings<br>**Patra brakes Bran** lds<br>icti and with a mechanism of production / exp iget Blett n af einfecsmal infantig in terfing in der EMB **COLL SILOW-LOW ALCOMMIC UNITED** HUSELIE EN CAMPO SHOO **• Flatness and the strathed for contract short say paragoget the standing student to coupling to a**  $\mathcal{A} \cap \mathcal{A}$  with  $\mathcal{A} \cup \mathcal{A}$  is a metric of production  $\mathcal{A}$  is a metric of production  $\mathcal{A}$ a **h interferometer stand we ow at interferometer states, while small at C** scales  $\bullet$   $\bullet$   $\bullet$  in a to stead with simplest models  $\bullet$   $\rightarrow$   $\bullet$  + const.  $r =$ *P*⇣ **Mand 115 E 3 1 DINOS to others fighter of the country** ✏*<sup>V</sup>* ⌘  $M_p^2$ **2** ⇣*V , V*  $\frac{2}{\sqrt{2}}$ **EGIE AREAL**  $V_4$ (review Pajer, MP '13) 1  $\frac{1}{2}$  **RWD REET RAY** *c f*  $20$  5 + et 2 + 3 Fully not the <del>st. 1 with Religions</del> to the heasing at  $\sharp$  <u>p</u>  $\sharp$  if  $\uparrow$   $\uparrow$   $\downarrow$   $\downarrow$  **PW** *P*⇣ *, ns* 1 ⌘ *d* ln *P*⇣  $\frac{1}{\sqrt{k}}$  have a little **he k a little with the property of the constable weak**  $\frac{1}{2}$  Flatness and gaussianity  $\rightarrow$  small inflaton self-coupling  $S$ **•** Shift symmetry (broken by *V* ) on coupling to other fields to other fields to other fields of the coupling **Frienda Woll Freeser Friendament**rikt 8000; '(feview Pajer, MP '13) *Pt Ps •* No observed departure from (primordial) gaussianity, <sup>h</sup>⇣3i⌧h⇣2i3*/*<sup>2</sup> ↵⇤  $\frac{1}{2}$  and  $\frac{1}{2}$   $\frac{1}{2}$  $P$ *M*<sup>2</sup> ⌘2  $\overline{\mathbf{X}}$ *V*  $A = 4^{\circ}$ **t** *V,* **PEEEM** *P*GW  $P_{\zeta}$  $n \sum_{i=1}^n a_i$ **d lat b a ly d ly d a w a g h** • Flatness and gaussianity  $\rightarrow$  small inflaton self-couplings **•** Shift symmetry (broken by *V* ) on the coupling of the coupling of the coupling of the coupling Freese, Frieman, Olinto to 090;. *Ps* / *<sup>k</sup>ns*<sup>1</sup> *<sup>r</sup>* <sup>=</sup> *Pt Ps* **• No observed departure from (primorpin Bullet 835 2013) FLETERIE**  $L$  ocal NG :  $\phi(x) = \phi(Q)$  Hestival the set  $\mathcal{A}$  $\frac{1}{\sqrt{2}}\frac{1}{\sqrt{2}}\frac{1}{\sqrt{2}}$   $\frac{1}{\sqrt{2}}$  cal NG  $\frac{1}{\sqrt{2}}$   $\frac{1}{\sqrt{2}}$ **• Self-couplings, Agreement with standard single field slow roll<br><b>Couply & Crowtecution** & Office Blottssynand With Statiful Ast<br>  $h'' + 2\mathcal{H}h' - \nabla^2 h$  $r, n_s - 1, q_m > 0$  $\mathsf{ft}^\equiv$ *M*<sup>2</sup> *p* 2 ⇣*V, V* **.K** iction ty<br>Goad the advantage the construction of the anglic of the coupling of the coupling of the coupling of the coupling<br>in the construction of the coupling of the coupling of the coupling of the coupling of the couplin *V,*  $V$  180 BOG SHOW SIGNAL NATURAL NATURAL SCALES, WAS STRIKT STRIKT AT CONSTRUCTIONS atisia  $\phi \rightarrow \phi + \text{Eian} \otimes \text{Tr} \left( \phi \right)$  iplings to other first  $\phi$  $\exp\left(\frac{1}{2}\right)$ *c* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *f*  $\frac{1}{2}$  **F**  $\frac{1}{2}$   $\frac{1}{2$ *•* Smallness of *V*shift technically natural. *V* / *V*shift ! *AA* typically controls reheating. More recently, realized *•* Constrained couplings to matter (predictivity) Residence and ace of cally  $\frac{dN}{dt}$   $\propto$   $V_{\text{shift}}$  to  $V_{\text{shift}}$  $\mathbf{G}$   $\mathbf{G}$   $\mathbf{W}$ ,  $m_{\phi} \simeq 10^{13}$  GeV Smallness of *<sup>V</sup>*shift technically natural. *<sup>V</sup>* / *<sup>V</sup>*shift ET TIETUS<br>NGC 1978 (COUPLE COUPLE COMPLETENCE) *<sup>m</sup> <sup>m</sup>* (200 *A*  $\left(\begin{array}{ccc} 1 \\ 1 \end{array}\right)$  $\frac{1}{2}$ <br>  $\frac{1}{2}$ <br> that it all the that it can provide the case of the tensor of the case of the ]tter.(Q<br>ELVH3D *f*  $\frac{1}{4}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$   $\frac{1}{2}$ 。<br>网传 EMTY) *• Suntally Alley & Vshift*  $\text{PSD}$  find at  $0.06$  GeV  $n_e$   $m_\phi \simeq 10^{13}$  GeV ling<del>s to</del> other fields . ,<br>,<br>, <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup>  $\widetilde{\epsilon \psi}$ *f* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ ment with rists ET<br>bi*l*i <sup>2</sup> (@*µ*)<sup>2</sup> <sup>+</sup> *<sup>V</sup>*shift () <sup>+</sup>  $c_\psi$ *f* @*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ *•* Smallness of *V*shift technically natural. *V* / *V*shift etter (predictivity)<br><del>Frytity 2 ANG, abserve</del>d hard to explanatulate the corrections. With shift symmetry, *V* / *V*shift *•* Shift symmetry ! + *C* on couplings to other fields *<sup>f</sup> Fµ*⌫ *<sup>F</sup>*˜*µ*⌫ ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵ **Production POLICITY** *•* Shift symmetry ! + *C* on couplings to other fields  $f$ *f f F*<sup>*µ*</sub> *F*<sup>*µ*</sup> *F*<sup>*µ*</sup> *F*<sup>*I*</sup> *F*<sup>*I*</sup> *F*<sup>*I*</sup> *F*</sup>  $\mathcal{P}^{\mathbf{v}}$   $\propto$   $\mathcal{P}^{\mathbf{v}}$  *V*shift **• Explored** <del>S</del>OV mmttte 7018 GeV  $\mathcal{B}$  ,  $\mathcal{B}$  energies very flat potential  $\mathcal{B}$  $\mathbf{r} = \frac{1}{n} \sum_{i=1}^{n} \mathbf{r}_i \mathbf{r}_i$  $\phi$  $\phi$ **(\*why not exactly just one?)**

@*µ* ¯ *<sup>µ</sup>* <sup>5</sup> <sup>+</sup> ↵

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### GW energy spectrum today



 $J<sub>2</sub>$ Gauge fields source a Blue-Tilted + Chiral + Non-G GW background

### GW energy spectrum today



### GW energy spectrum today



Bartolo et al '16

$$
h^2 \Omega_{\rm gw} = A_* \left(\frac{f}{f_*}\right)^{n_T}
$$



### **INFLATIONARY MODELS**  $\mathbf{r}$ \$ EI S \$ # \$∗ # \$∗ # \$  $\mathbf A$  , and  $\mathbf A$  according to  $\mathbf A$ Axion-Inflation (2.8) into equation of  $\alpha$



### **INFLATIONARY MODELS**  $\mathbf{r}$ \$ EI S \$ # \$∗ # \$∗ # \$  $\mathbf A$  , and  $\mathbf A$  according to  $\mathbf A$ Axion-Inflation (2.8) into equation of  $\alpha$



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### **INFLATIONARY MODELS**  $\mathbf{r}$ \$ EI S \$ # \$∗ # \$∗ # \$  $\mathbf A$  , and  $\mathbf A$  according to  $\mathbf A$ Axion-Inflation (2.8) into equation of  $\alpha$





Axion-Inflation: *Shift* **symmetry**

Natural (chiral) coupling to *A<sup>µ</sup>* **huge excitation of fields ! (photons)**

Axion-Inflation: *Shift* symmetry <u>Axion-Bishalded</u>

coupling to *A<sup>µ</sup>* **huge excitation of fields ! (photons)**

### What if there are arbitrary fields coupled to the inflaton ? (i.e. no need of extra symmetry)

Axion-Inflation: *Shift* symmetry <u>Axion-Inflation</u>

coupling to *A<sup>µ</sup>* **huge excitation of fields ! (photons)**

What if there are arbitrary fields coupled to the inflaton ? (i.e. no need of extra symmetry) **large excitation of these fields !? will they create GWs?**

### fields coupled to the inflaton ? **large excitation ?** (i.e. no need of extra symmetry) **GW generation !?**

### **INFLATIONARY MODELS** category of GW generation. Several models of particle production have been discussed in the literature. In general, particle production during inflation is possible because,

### fields coupled to the inflaton?  $\rightarrow$  large excitation? (i.e. no need of extra symmetry) **GW generation !?**  $\frac{1}{\sqrt{2}}$ consider two cases of the two cases of the two cases of the two cases in the particle in the particle nature o

$$
-\mathcal{L}_{\chi} = (\partial \chi)^2/2 + g^2(\phi - \phi_0)^2 \chi^2/2
$$
 Scalar Fld  
\n
$$
-\mathcal{L}_{\psi} = \bar{\psi} \gamma^{\mu} \partial_{\mu} \psi + g(\phi - \phi_0) \bar{\psi} \psi
$$
 Fermion Fld  
\n
$$
\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - |(\partial_{\mu} - g A_{\mu}) \Phi)|^2 - V(\Phi^{\dagger} \Phi)
$$
 Gauge Fld ( $\Phi = \phi e^{i\theta}$ )

### **INFLATIONARY MODELS** category of GW generation. Several models of particle production have been discussed in the literature. In general, particle production during inflation is possible because, *Stochastic gravitational wave backgrounds and early universe cosmology.* 53 *Stochastic gravitational wave backgrounds and early universe cosmology.* 53

#### fields coupled to the inflaton?  $\rightarrow$  large excitation?  $\frac{1}{\sqrt{2}}$ consider two cases of the two cases of the two cases of the two cases in the particle in the particle nature o we consider the distribution of a <u>the goudenance</u>. <sup>4</sup>*Fµ*⌫*F <sup>µ</sup>*⌫ *|*(@*<sup>µ</sup> gAµ*))*|* <sup>2</sup> *V* (*†* ) [153, 154], where *Fµ*⌫ = @*µA*⌫ @⌫*A<sup>µ</sup>* (i.e. no need of extra symmetry) GW generation !? *<sup>g</sup>*<sup>2</sup>( 0)<sup>2</sup><sup>2</sup>*/*2, and *<sup>L</sup>* <sup>=</sup> ¯ *<sup>µ</sup>*@*<sup>µ</sup>* <sup>+</sup> *<sup>g</sup>*( 0) ¯ , respectively. Alternatively, *p* | 22 /227/2010  $\frac{1}{2}$  **7 × 100**  $\frac{1}{2}$  *g* =  $\frac{1}{2}$  *g* =  $\frac{1}{2}$   $\frac{1}{2$ fields coupled to the inflaton ? **large excitation ? GW generation !?**

$$
-\mathcal{L}_{\chi} = (\partial \chi)^2/2 + g^2(\phi - \phi_0)^2 \chi^2/2
$$
 Scalar Fld  
\n
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$$
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\n
$$
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$$
 Gauge Fld ( $\Phi = \phi e^{i\theta}$ )

All 3 cases:  
\n
$$
m = g(\phi(t) - \phi_0) \sum \hat{m} \gg m^2
$$
 during  $\Delta t_{\text{na}} \sim 1/\mu$ ,  $\mu^2 \equiv g\dot{\phi}_0$   
\n $n_k = \text{Exp}\{-\pi(k/\mu)^2\}$  Non-adiabatic field excitation (particle creation)

### **INFLATIONARY MODELS** INEL ATIANIA DV MAANEL C the mass *m* = *g*((*t*) 0) vanishes exactly at *t* = *t*<sup>0</sup> when (*t*0) = 0. For a short

### fields coupled to the inflaton ? (i.e. no need of extra symmetry) **GW generation !? folde coupled to the inflaton ?**  $\rightarrow$  large excitation  $\sqrt{ }$ ti.e. no the mass changes in the mass contained to an explosive production of the mass changes production to an explosive production of the mass changes of the mass changes of the mass changes of the mass changes of the mass change particles<sup>†</sup> [155]. The occupation of the occupation is a controlled in the set of the set **large excitation**

$$
n_k = \text{Exp}\{-\pi (k/\mu)^2\}
$$
 Non-adiabatic field excitation (particle creation!)

 $\exp\{-\pi (k/\mu)^2\}$  Non-adiabatic field excitation (particle creation !) excited, as short modes evolve adiabatically around *t*0. **(spin-independent)**

#### **INFLATIONARY MODELS** INEL ATIANIA DV MAANEL C the mass *m* = *g*((*t*) 0) vanishes exactly at *t* = *t*<sup>0</sup> when (*t*0) = 0. For a short such a way that its amplitude vanishes at some point (*t*0) ⌘ <sup>0</sup> = 0. In either of the TUNARY MUDELS  $\blacksquare$  **INFLATIONARY MODELS** is the field strength, and = *e<sup>i</sup>*✓ is a complex field. In this latter case, we do not period of time *t*na around *t*0, identify with the inflations of the inflations of the inflations of the inflations of the inflation inflation such a way that its amplitude vanishes at some point (*t* identify with the inflations of the i

#### fields coupled to the inflaton ? (i.e. no need of extra symmetry) **GW generation !? folde coupled to the inflaton ?**  $\rightarrow$  large excitation  $\sqrt{ }$ ti.e. no the mass changes in the mass contained to an explosive production of the mass changes production to an explosive production of the mass changes of the mass changes of the mass changes of the mass changes of the mass change particles<sup>†</sup> [155]. The occupation of the occupation is a controlled in the set of the set **large excitation √** a symmetry as **o** and generation to fields coupled to the inflaton?  $\rightarrow$ three scrosses around 0 inflaton, which is the inflaton, or all of the inflaton, or an explosive production to<br>The mass changes in the inflaton, or an explosive production of the internation of the internation of the inter the mass *m* = *g*((*t*) 0) vanishes exactly at *t* = *t*<sup>0</sup> when (*t*0) = 0. For a short **1**<br><u>ind</u> to the indetection <sup>0</sup> *,* (138) particles **the procedure of the of the occupation is and guide created in**dependent in the mass *m* = *g*((*t*) 0) vanishes exactly at *t* = *t*<sup>0</sup> when (*t*0) = 0. For a short li.e. no need ot extra symr the mass *m* = *g*((*t*) 0) vanishes exactly at *t* = *t*<sup>0</sup> when (*t*0) = 0. For a short

particles*†* [155]. The occupation number of the quanta created is actually independent  $n_k =$ of the spin of excited species (given the interactions considered), and it reads *n<sup>k</sup>* = the mass changes non-adiabatically as ˙*m m*<sup>2</sup>, leading to an explosive production of  $n_k\,=\, \text{Exp}\{-\pi (k/\mu)^2\}$  Non-a<br>Lisainthe mass changes non-adiabatically as ˙*m m*<sup>2</sup>, leading to an explosive production of

 $\exp\{-\pi (k/\mu)^2\}$  Non-adiabatic field excitation (particle creation !) excited and **the source adventure and** *the short modes enders* (spin-independent) particles*†* [155]. The occupation number of the quanta created is actually independent Exp*{*⇡(*k/µ*)<sup>2</sup>*}* [156]. This shows clearly that only long wave modes *k* ⌧ *µ* modes are of the spin of  $(1/2)^{2}$  interactions considered interactions considered  $n$  $\frac{n_k - \exp\{-\pi(\kappa/\mu) \} \}$  ivon-adiabatic field excitation (particle creation  $\mu$ ) of the spin of excited species (given the interactions considered), and it reads *n<sup>k</sup>* = of the spin of excited species (given the interactions considered), and it reads *n<sup>k</sup>* =

In all three cases (scalars, fermions, and vectors), GWs are generated by the three cases (scalars, termions, and vectors)  $\begin{pmatrix} 1 & 0 & \cdots & 1 & 1 \end{pmatrix}$ lars, fermions, and vectors) the mass cases *scalars* fermions, an In all three cases (scalars, fermions, and vectors) In all three cases (scalars

 $\overline{\phantom{a}}$  $\overline{a}$ generated by anisotropic distribution of the created species particles  $\frac{1}{2}$  ( $\frac{1}{2}$   $\frac{1}{2}$  GWs generated by <u>anisotropic distribution</u> of GWs generated by anisotropic distribution of the created species. GWs generated by anisotroj

from the corresponding to that moment. This feature represents and additional moment. This feature represents an additional moment. This feature represents and additional moment. This feature represents and additional mom (UTITY  $n \ll \mu$  for type vacuum tensor spectrum.  $t \in \mathcal{X}$  we have *the degree text* (*t*) frequency today corresponding to that moment. This feature represents and the moment. This feature represents<br>This feature represents and the moment of the moment and the moment of the moment of the moment of the moment  $($ Only  $k \ll \mu$  long-wave the precise time *t*<sup>0</sup> when (*t*0) = 0, the spectrum of GWs shows a feature at the frequency today corresponding to that moment. This feature represents an additional  $\Omega$ isotropic distribution of the created species. Since  $k$  $\overline{\Omega}$ (Only  $k \ll \mu$  long-wave modes excited)

### **INFLATIONARY MODELS** INEL ATIANIA DV MAANEL C the mass *m* = *g*((*t*) 0) vanishes exactly at *t* = *t*<sup>0</sup> when (*t*0) = 0. For a short the mass *m* = *g*((*t*) 0) vanishes exactly at *t* = *t*<sup>0</sup> when (*t*0) = 0. For a short period of time *t*na around *t*0, the mass changes non-adiabatically as ˙*m m*<sup>2</sup>, leading to an explosive production of particles*†* [155]. The occupation number of the quanta created is actually independent

#### fields coupled to the inflaton ? (i.e. no need of extra symmetry) **GW generation !? folde coupled to the inflaton ?**  $\rightarrow$  large excitation  $\sqrt{ }$ ti.e. no the mass changes in the mass contained to an explosive production of the mass changes production to an explosive production of the mass changes of the mass changes of the mass changes of the mass changes of the mass change particles<sup>†</sup> [155]. The occupation of the occupation is a controlled in the set of the set **large excitation 1**<br><u>ind</u> to the indetection <sup>0</sup> *,* (138) the mass coupled to the mass of the mass of the production of the production of the mass of the production of t<br>
The mass of the production of the second production of the second of the second of the production of the seco particles **the procedure of the of the occupation is and guide created in**dependent in excited, as short modes evolve adiabatically around *t*0. In almos can be called the control of the cases of the case of is and the created of the created species. Since particle particle production in the case of the control of the contr *•* GW: *ds*<sup>2</sup> <sup>=</sup> *<sup>a</sup>*<sup>2</sup>(*d*⌘<sup>2</sup> + (*ij* <sup>+</sup> *<sup>h</sup>ij* )*dx<sup>i</sup> <u>GW generation !?*</u>

particles*†* [155]. The occupation number of the quanta created is actually independent  $n_k =$ of the spin of excited species (given the interactions considered), and it reads *n<sup>k</sup>* = from today corresponding to the moment. This feature represents and additional m  $n_k = \text{Exp}\{-\pi (k/\mu)^2\}$ Eom: *h*<sup>00</sup> *ij* + 2*Hh*<sup>0</sup>

 $\exp\{-\pi (k/\mu)^2\}$  Non-adiabatic field excitation (particle creation !) excited, as short modes evolve adiabatically around *t*0. of the spin of  $(1/2)^{2}$  interactions considered interactions considered  $n$  $\frac{n_k - \exp\{-\pi(\kappa/\mu) \} \}$  ivon-adiabatic field excitation (particle creation  $\mu$ ) *i***<sub>***ij***</sub>**  $\left($ **spin-independent)** Notably, even though the field structure of the energy-momentum tensor sourcing

In all three cases (scalars, fermions, and vectors), GWs are generated by the In all three cases (scalars, fermions, and vectors), GWs are generated by the In all three cases (scalars, fermions, and vectors) the GWs depends on the spin of the excited species, *Barnaby et al* [156] has shown th an unice caded (beatans, termions, and vectors In all three cases (scalars fermions and vectors)

**GWs pow** the precise time *t*<sup>0</sup> when (*t*0) = 0, the spectrum of GWs shows a feature at the  $\textbf{GWS power spectrum:} \quad \mathcal{P}_h^{\text{(tot)}}(k) \;\; = \;\; \mathcal{P}_h^{\text{(vac)}}(k) \; + \left(\!\mathcal{P}_h^{\text{(pp)}}(k)\right) \qquad \quad \text{foron particle} \quad \text{for} \quad \mathcal{P}_h^{\text{(top)}}(k)$ contribution on top of the standard intervals of the standard irreducible vacuum tensor spectrum. anisotropic distribution of the created species. Since particle production happens around frequency today corresponding to that moment. This feature represents an additional independent of their spin, modulo normalization factors of order *O*(1). To see this,  $\textbf{GWS power spectrum:} \quad \mathcal{P}_h^{\text{(tot)}}(k) \;\; = \;\; \mathcal{P}_h^{\text{(vac)}}(k) \; + \left(\!\mathcal{P}_h^{\text{(pp)}}(k)\!\right) \qquad \qquad \text{from particle}$ *<sup>h</sup>* (*k*) ⌘ (2*/*⇡<sup>2</sup>)(*H/m*pl)<sup>2</sup> the vacuum contribution given by Eq. (130). Detailed

**production**

 $f(x)$  $\mathbf{H}_{ij}$ Notably, even though the field structure of the field structure of the energy-momentum tensor sourcing  $\mathcal{C}$ the GWs depends on the spin of the shown  $\sim \frac{\int \partial \cdot v^a \partial \cdot v^a \cdot TT}{\int E \cdot F}$ ,  $\perp R \cdot R \cdot \frac{1}{T}$   $\int \overline{v^a} \cdot D \cdot v^b \cdot TT$ independent of their spin, modulo normalization factors of order *O*(1). To see this, contribution on top of the standard irreducible vacuum tensor spectrum.  $R_{\text{max}}$  the field structure of the energy-momentum tensor sourcing  $R_{\text{max}}$  $\mathbf{H}_{ij} \propto \{U_i \chi U_j \chi \} , \quad \{L_i L_j + D_i D_j \} , \quad \{ \psi' \rangle_i D_j \psi \}$ calculations [154, 157, 156] show that the contribution *<sup>P</sup>*(pp) *<sup>h</sup>* (*k*) from the newly created GW Source(s) (SCALARS *P*<sub> $i$ </sub> *i P*(vac) ⌘  $\alpha$ *P*(vac)  $\partial_i \chi^{\alpha} \partial_j \chi^{\alpha} \}$ <sup>1</sup>, *H*<sup>2</sup> *m*<sup>2</sup>  $\iota_k L_j + I$ ⇣ *µ H*  $\left\{ \cdot \right\}$  $\left\{\psi\gamma\right\}$ GW Source(s): ( SCALARS , VECTOR , FERMIONS )  $\Pi_{ij}^{TT} \propto \{ \partial_i \chi^a \partial_j \chi^a \}^{TT}, \quad \{ E_i E_j + B_i B_j \}^{TT}, \quad \{ \bar{\psi} \gamma_i D_j \psi \}^{TT}$ 

pl

#### **INFLATIONARY MODELS** INEL ATIANIA DV MAANEL C the mass *m* = *g*((*t*) 0) vanishes exactly at *t* = *t*<sup>0</sup> when (*t*0) = 0. For a short the mass *m* = *g*((*t*) 0) vanishes exactly at *t* = *t*<sup>0</sup> when (*t*0) = 0. For a short period of time *t*na around *t*0, the mass changes non-adiabatically as ˙*m m*<sup>2</sup>, leading to an explosive production of particles*†* [155]. The occupation number of the quanta created is actually independent particles*†* [155]. The occupation number of the quanta created is actually independent of the spin of excited species (given the interactions considered), and it reads *n<sup>k</sup>* = [138] Planck, P. A. R. Ade *et al.*, Astron. Astrophys. 594, A20 (2016), [1502.02114], 10.1051/0004- 6361/201525898. [141] J. Lizarraga *et al.*, 1403.4924. en and L. Moss and L. Political and L. Poli [143] R. Durrer, D. G. Figueroa and M. Kunz, 1404.3855.

#### fields coupled to the inflaton ? (i.e. no need of extra symmetry) **GW generation !? folde coupled to the inflaton ?**  $\rightarrow$  large excitation  $\sqrt{ }$ ti.e. no the mass changes in the mass contained to an explosive production of the mass changes production to an explosive production of the mass changes of the mass changes of the mass changes of the mass changes of the mass change particles<sup>†</sup> [155]. The occupation of the occupation is a controlled in the set of the set **large excitation 1**<br><u>ind</u> to the indetection <sup>0</sup> *,* (138) the mass coupled to the mass of the mass of the production of the production of the mass of the production of t<br>
The mass of the production of the second production of the second of the second of the production of the seco particles **the procedure of the of the occupation is and guide created in**dependent in excited, as short modes evolve adiabatically around *t*0. In almos can be called the control of the cases of the case of (i.e. no need of extra symmetry) GW generation !?  $I_n$  and  $I_n$  are generated by the cases (scalars, and vectors),  $I_n$  are generated by the generated by the generation of  $I_n$ andis conhight to the milleton  $\mathcal{I}=\mathcal{I}$  arge excitation  $\mathcal{I}$ frequency today corresponding to that moment. This feature represents an additional [140] C. Bonvin, R. Durrer and R. Maartens, 1403.6768. [141] J. Lizarraga *et al.*, 1403.4924. words oooprod to the [144] J. Lizarraga *et al.*, Phys. Rev. D90, 103504 (2014), [1408.4126], 10.1103/PhysRevD.90.103504.  $269399$ **INGIUS COUPIBU TO THE MINATUM : Profession**  $10.11000$  of over [147] D. Polarski and A. A. Starobinsky, Class. Quant. Grav. 13, 377 (1996), [gr-qc/9504030],

particles*†* [155]. The occupation number of the quanta created is actually independent  $n_k =$ from today corresponding to the moment. This feature represents and additional m  $\frac{16c}{16c} = \frac{16c}{16c}$  (enin-indenendent) contribution on top of the standard irreducible vacuum tensor spectrum. The standard irreducible vacuum tensor<br>The standard in the standard intensity of the standard intensity of the standard intensity of the standard inte 2693(93)90379-V. [148] D. Polarski and A. A. Starobinsky, Phys. Lett. B356, 196 (1995), [astro-ph/9505125],  $n_k = \exp\{-\pi(k/\mu)^2\}$ 

*P*(tot)

 $\exp\{-\pi (k/\mu)^2\}$  Non-adiabatic field excitation (particle creation !) excited, as short modes evolve adiabatically around *t*0. of the spin of  $(1/2)^{2}$  interactions considered interactions considered  $n$  $\frac{n_k \equiv \exp\{-\pi (k/\mu)^2\}}{n}$  Non-adiabatic field excitation (particle creation !) **Example and D. Garcia-Bellido and D. Garcia-Bellido and D. Wands, Phys. Rev. D53, 3437 (Spin-independent)** Notably, even though the field structure of the energy-momentum tensor sourcing the GWs depends on the spin of the excited species, *Barnaby et al* [156] has shown  $\mathcal{L}^I(k) \longrightarrow \text{Exp}(\mathcal{L}/\mu)$  is a consequence of the conduction  $\mathcal{L}$  and  $\mathcal{L}$ 

of the spin of excited species (given the interactions considered), and it reads *n<sup>k</sup>* =

In all three cases (scalars, fermions, and vectors), GWs are generated by the In all three cases (scalars, fermions, and vectors), GWs are generated by the In all three cases (scalars, fermions, and vectors) the GWs depends on the spin of the excited species, *Barnaby et al* [156] has shown In all three cases (scalars, termions, and vectors) *<sup>h</sup>* (*k*) + *<sup>P</sup>*(pp)  $\mathbf{1}$ In <u>all three cases</u> (scalars, fermions, and vectors*)*  $\mathcal{L}_{150}$  J.-F. Dufaux, J. E. Lidsey, R. Maartens and M. Sami, Phys. Rev. D70, 083525 (2004),  $\mathcal{L}_{255}$ 

**GWs pow** the precise time *t*<sup>0</sup> when (*t*0) = 0, the spectrum of GWs shows a feature at the  $\textbf{GWS power spectrum:} \quad \mathcal{P}_h^{\text{(tot)}}(k) \;\; = \;\; \mathcal{P}_h^{\text{(vac)}}(k) \; + \left(\!\mathcal{P}_h^{\text{(pp)}}(k)\right) \qquad \quad \text{foron particle} \quad \text{for} \quad \mathcal{P}_h^{\text{(top)}}(k)$ contribution on top of the standard intervals of the standard irreducible vacuum tensor spectrum. anisotropic distribution of the created species. Since particle production happens around frequency today corresponding to that moment. This feature represents an additional independent of their spin, modulo normalization factors of order *O*(1). To see this,  $\textbf{GWS power spectrum:} \quad \mathcal{P}_h^{\text{(tot)}}(k) \ \ = \ \ \mathcal{P}_h^{\text{(vac)}}(k) \ + \left(\!\mathcal{P}_h^{\text{(pp)}}(k)\right)\ \ .$ *<sup>h</sup>* (*k*) ⌘ (2*/*⇡<sup>2</sup>)(*H/m*pl)<sup>2</sup> the vacuum contribution given by Eq. (130). Detailed *<sup>h</sup>* (*k*) = *<sup>P</sup>*(vac) *GWs nower spectrum:*  $\mathcal{P}^{(\text{tot})}(k) = \mathcal{P}^{(\text{vac})}(k) + \left(\mathcal{P}^{(\text{pp})}(k)\right)$  from particle **calculations production**  $\mathcal{P}_h$  ( $\kappa$ )  $=$   $\mathcal{P}_h$  ( $\kappa$ )  $+$   $\mathcal{P}_h$  ( $\kappa$ ) production  $\mathcal{L}(\mathcal{A})$  denote a notation and D. Wands, Phys. Rev. D53, 5437 (1995),  $\mathcal{L}(\mathcal{A})$ iWs power spectrum: example of the state of the [152] D. J. H. Chung, E. W. Kolb, A. Riotto and I. I. Tkachev, Phys. Rev. D62, 043508 (2000), Ws power spectrum:  ${\cal P}_i^{\rm (tot)}(k)$  =  ${\cal P}_i^{\rm (0)}$  $\mathbb{F}^n$  is the anti-physical and  $\mathbb{F}^n$  is the production

**from particle production**

*<sup>h</sup>* (*k*), with

$$
\frac{\Delta P_h}{\mathcal{P}_h} \equiv \frac{\mathcal{P}_h^{\text{(tot)}} - \mathcal{P}_h^{\text{(vac)}}}{\mathcal{P}_h^{\text{(vac)}}} \equiv \frac{\mathcal{P}_h^{\text{(pp)}}}{\mathcal{P}_h^{\text{(vac)}}} \sim few \times \mathcal{O}(10^{-4}) \frac{H^2}{m_{\text{pl}}^2} W(k\tau_0) \left(\frac{\mu}{H}\right)^3 \ln^2(\mu/H)
$$
\nN. Barnaby *et al.*, Phys. Rev. **D86**, 103508 (2012), [1206.6117]  
\nJ. L. Cook and L. Sorbo, Phys. Rev. **D85**, 023534 (2012), [1109.0022],

#### **INFLATIONARY MODELS** *<sup>h</sup>* (*k*) ⌘ (2*/*⇡<sup>2</sup>)(*H/m*pl)<sup>2</sup> the vacuum contribution given by Eq. (130). Detailed calculations [154, 157, 156] show that the contribution *<sup>P</sup>*(pp) *<sup>h</sup>* (*k*) from the newly created period of time *t*na around *t*0, *t*na ⇠ <sup>1</sup>*/µ , µ*<sup>2</sup> ⌘ *<sup>g</sup>*˙ *<sup>L</sup>* <sup>=</sup> <sup>1</sup> <sup>4</sup>*Fµ*⌫*F <sup>µ</sup>*⌫ *|*(@*<sup>µ</sup> gAµ*))*|* is the field strength, and = *e<sup>i</sup>*✓ is a complex field. In this latter case, we do not





#### **INFLATIONARY MODELS** *<sup>h</sup>* (*k*) ⌘ (2*/*⇡<sup>2</sup>)(*H/m*pl)<sup>2</sup> the vacuum contribution given by Eq. (130). Detailed calculations [154, 157, 156] show that the contribution *<sup>P</sup>*(pp) *<sup>h</sup>* (*k*) from the newly created period of time *t*na around *t*0, *t*na ⇠ <sup>1</sup>*/µ , µ*<sup>2</sup> ⌘ *<sup>g</sup>*˙ the GWs depends on the spin of the excited species, *Barnaby et al* [156] has shown that, due to some cancellations, the GW produced particles is essentially by the created particles is *<sup>L</sup>* <sup>=</sup> <sup>1</sup> <sup>4</sup>*Fµ*⌫*F <sup>µ</sup>*⌫ *|*(@*<sup>µ</sup> gAµ*))*|* is the field strength, and = *e<sup>i</sup>*✓ is a complex field. In this latter case, we do not

















### (quasi-)scale invariance  $\longleftrightarrow$  Slow roll monotonic potentials



 $I$ quasi-)scale invariance  $\longleftrightarrow$  Slow roll monotonic potentials


### Ultra Slow-Roll Regime



### Ultra Slow-Roll Regime







#### **INFLATIONARY MODELS** INFLATION non-monotonic **IF** *{* multi-field  $\left\{\right. \Rightarrow$  **enhance**  $\Delta_{\mathcal{R}}^2$ **possible to enhance (at small scales)**  $10^{-4}$  100  $10^{8}$  10<sup>14</sup>  $10^{20}$  10<sup>26</sup>  $10^{-12}$   $100$  $10^{-10}$  $10^{-8}$  $10^{-6}$  $10^{-4}$ 0.01 1  $\overline{\phantom{a}}$  $\boldsymbol{\mathcal{A}}$  f  $\overline{a}$ **Observational constraints**  $\triangleleft$  $\alpha$  $\mathcal{R}$ **Primordial Black Hole (PBH) Compact mini-Halos CMB**  (Planck)  $10^{4}$   $10^{20}$   $10^{20}$  $\bullet$ 10!<sup>4</sup> 100 10<sup>8</sup> 1014 10<sup>20</sup> 10<sup>26</sup>  $\bullet$ <u>k 2011 - 2011 - 2011 - 2011 - 2011 - 2011 - 2011 - 2011 - 2011 - 2011 - 2011 - 2011 - 2011 - 2011 - 2011 - 20</u><br>Externé de la partie de la parti Figure 5. The matter power spectrum, for model parameters: *a* = 3*/*2, *b* = 1, *N* = 35 and  $\frac{1}{2}$  ,  $\frac{1$  $10^8$  and  $10^{14}$  and  $10^{20}$  c.l.  $10^{26}$  $10.4$  100  $\mu$  $\overline{1}$ 1 Figure 5. The matter power spectrum, for model parameters: *a* = 3*/*2, *b* = 1, *N* = 35 and excales allowed by Planck (2015), by compact of values allowed by Planck (2015), by Planck (2015), by Planck ( minihalos (red line) and by PBH (black dashed line), at 95% c.l. (Figure adapted from Ref. [45]). **k** = 0,05 Mpc<sub>1</sub>, which corresponds in our model to *N* = 62,05 Mpc<sub>1</sub>, which corresponds in our model to  $\frac{1}{2}$ , which corresponds in our model to  $\frac{1}{2}$ ln(10<sup>10</sup> *A*<sup>2</sup> *<sup>s</sup>*)=3*.*094 *±* 0*.*068 (95% c*.*l*.*)*,* (3.7)  $10.4$  100 10t 1 scal<del>es</del> (and by PaH (black dashed from Billian Scale *k* = 0*.*05 Mpc1, which corresponds in our model to *N* = 62,  $\frac{1}{2}$  **h** $\frac{N}{2}$  $\sqrt{100}$  100  $\mu$  100  $\mu$  100  $\mu$  100  $\mu$  100  $\mu$  $\overline{\phantom{a}}$ Figure 5. The matter power spectrum, for model parameters: *a* = 3*/*2, *b* = 1, *N* = 35 and 10!<sup>4</sup> 100 108 1014 10<sup>20</sup> 10<sup>26</sup>  $=$  4  $\pm$  05. We have also plotted the range of values allowed by  $P$  $h^{00}$   $h^{00}$ **large scales small scales**  $F_{\text{1}}$  and  $F_{\text{2}}$   $F_{\text{3}}$   $F_{\text{3}}$   $F_{\text{4}}$   $F_{\text{3}}$   $F_{\text{4}}$   $F_{\text{4}}$   $F_{\text{5}}$   $F_{\text{6}}$   $F_{\text{7}}$   $F_{\text{8}}$   $F_{\text{9}}$   $F_{\text{1}}$   $F_{\text{1}}$   $F_{\text{2}}$   $F_{\text{1}}$   $F_{\text{2}}$   $F_{\text{1}}$   $F_{\text{2}}$   $F_{\text{1}}$   $F_{\text{2$  $10^{\circ}$  10<sup>0</sup>  $10^{-4}$ 10!<sup>10</sup>  $\mathsf{P}_{\mathsf{F}}$  $\overline{\phantom{a}}$  $\vert$  $\mathsf{F}$  $\frac{1}{\sqrt{2}}$  $10^{10}$  10<sup>-4</sup> 100 108  $\overline{\phantom{0}}$  $\overline{a}$

 $k$  [h/Mpc]  $k$   $\lceil n \rceil$   $\lceil n \rceil$ *n<sup>s</sup>* = 0*.*9569 *±* 0*.*0154 (95% c*.*l*.*)*,* (3.8) *<sup>s</sup>*)=3*.*094 *±* 0*.*068 (95% c*.*l*.*)*,* (3.7)

Figure 5. The matter power spectrum, for model parameters: *a* = 3*/*2, *b* = 1, *N* = 35 and

INFLATION non-monotonic **IF** *{* multi-field  $\left\{\right. \Rightarrow$  **enhance**  $\Delta_{\mathcal{R}}^2$ **possible to enhance (at small scales)** II. SUUTTUUDEN SIJAARIN VALMINTATION VALMINTATION VALMINTATION VALMINTATION VALMINTATIONAL VALMINTATIONAL VALM<br>PAAJA SECOND-ORDER GRAVITATION VALMINTATION VALMINTATION VALMINTATION VALMINTATION VALMINTATION VALMINTATION V

Let us suppose 
$$
\left|\frac{\Delta_{\mathcal{R}}^2 \gg \Delta_{\mathcal{R}}^2|_{\text{CMB}} \sim 3 \cdot 10^{-9}}{2 \cdot 10^{-9}}\right|
$$
, @ small scales

$$
ds^{2} = a^{2}(\eta)[-(1+2\Phi)d\eta^{2} + [(1-2\Psi)\delta_{ij} + 2F_{(i,j)} + h_{ij}]dx^{i}dx^{j}]
$$

INFLATION non-monotonic **IF** *{* multi-field  $\left\{\right. \Rightarrow$  **enhance**  $\Delta_{\mathcal{R}}^2$ **possible to enhance (at small scales)** II. SUUTTUUDEN SIJAARIN VALMINTATION VALMINTATION VALMINTATION VALMINTATION VALMINTATIONAL VALMINTATIONAL VALM<br>PAAJA SECOND-ORDER GRAVITATION VALMINTATION VALMINTATION VALMINTATION VALMINTATION VALMINTATION VALMINTATION V

Let us suppose  $\begin{array}{ccc} \Delta_\mathcal{R}^2 \gg \Delta_\mathcal{R}^2 \end{array}$  $\begin{array}{c} \hline \end{array}$  $\vert_{\text{CMB}} \sim 3 \cdot 10^{-9} \vert, \text{\textcircled{a}}$  small scales In this section we will briefly review the generation of induced gravitational waves. Details of the calculations have **bet us s** The perturbed metric in the perturbed metric in the longitudinal gauge is the longitudinal g Let us suppose  $\left(\Delta_{\overline{2}}^2 \gg \Delta_{\overline{2}}^2\right)$   $\sim 3 \cdot 10^{-9}$  @ small scales comoving gauges in a radiation-dominated examples in a radiation-dominated era  $\Box$  $\begin{array}{|c|c|c|c|c|c|}\n\hline\n\textbf{1} & \textbf{2} & \textbf{1} & \textbf{3} & \textbf{1} & \textbf{2} & \textbf{3} & \textbf{3} & \textbf{4} & \textbf{5} & \textbf{5} & \textbf{6} & \textbf{6} & \textbf{7} & \textbf{8} & \textbf{8} & \textbf{1} &$ Let us suppose  $|\Delta \bar{\chi} \gg \Delta \bar{\chi}|_{\rm CMB} \sim 3 \cdot 10^{-6}$ , w small scales

$$
ds^{2} = a^{2}(\eta)[-(1+2\Phi)d\eta^{2} + [(1-2\Psi)\delta_{ij} + 2F_{(i,j)} + h_{ij}]dx^{i}dx^{j}]
$$

 $U = 2U + 2U$  and  $V = 12$  are scaler metric perturbation,  $\mathbb{R}$  is a transverse and  $\mathbb{R}$  $\left\{n_{ij}+2\pi n_{ij}+\kappa\ n_{ij}=\rho_{ij}\right\}\sim\Psi*\Psi$  (Ziid Order Fert.) and in the absence of anisotropic stress we require Φ = Ψ [49]. We will find it convenient to use the Fourier transform  $h_{ij}^{\prime\prime}+2\mathcal{H}h_{ij}^\prime+k^2h_{ij}=\hspace{-0.1cm}\left.\left(S_{ij}^{TT}\right)\right|\sim\Phi*\Phi\hspace{0.2cm}$  (2nd Order Pert.) ij indicates the transverse-tracefree part of the source term. If we neglect first order tensor and vector  $\left| \begin{array}{ccc} h'' & 2Uh' & 1/2h & -CTT \end{array} \right|$  and  $\Lambda * \Lambda$  (2nd Order Dert )  $\left\{ h_{ij}^{\prime\prime}+2\mathcal{H}h_{ij}^{\prime}+k^2h_{ij}=\left(\boldsymbol{S}_{ij}^{T^{\prime}I}\right)\right\} \sim \Phi*\Phi$  (2nd Order Pert.) gravitational waves [30, 31]

$$
\begin{aligned}\n\mathcal{S}_{ij} &= 2\Phi\partial_i\partial_j\Phi - 2\Psi\partial_i\partial_j\Phi + 4\Psi\partial_i\partial_j\Psi + \partial_i\Phi\partial_j\Phi - \partial^i\Phi\partial_j\Psi - \partial^i\Psi\partial_j\Phi + 3\partial^i\Psi\partial_j\Psi \\
&\quad - \frac{4}{3(1+w)\mathcal{H}^2}\partial_i(\Psi' + \mathcal{H}\Phi)\partial_j(\Psi' + \mathcal{H}\Phi) && \mathbf{D}.\mathbf{W} \mathbf{and}\mathbf{s} \text{ et al, 2006-2010} \\
&\quad - \frac{2c_s^2}{3w\mathcal{H}} \left[3\mathcal{H}(\mathcal{H}\Phi - \Psi') + \nabla^2\Psi\right]\partial_i\partial_j(\Phi - \Psi) && \mathbf{Peloso et al, 2018}\n\end{aligned}
$$

INFLATION non-monotonic **IF** *{* multi-field  $\left\{\right. \Rightarrow$  **enhance**  $\Delta_{\mathcal{R}}^2$ **possible to enhance (at small scales)** II. SUUTTUUDEN SIJAARIN VALMINTATION VALMINTATION VALMINTATION VALMINTATION VALMINTATIONAL VALMINTATIONAL VALM<br>PAAJA SECOND-ORDER GRAVITATION VALMINTATION VALMINTATION VALMINTATION VALMINTATION VALMINTATION VALMINTATION V

Let us suppose  $\begin{array}{ccc} \Delta_\mathcal{R}^2 \gg \Delta_\mathcal{R}^2 \end{array}$  $\begin{array}{c} \hline \end{array}$ Let us suppose  $\left. \left. \left. \Delta_\mathcal{R}^2 \gg \Delta_\mathcal{R}^2 \right|_{\rm CMB} \sim 3 \cdot 10^{-9} \right| \right|$ , @ small scales In this section we will briefly review the generation of induced gravitational waves. Details of the calculations have The perturbed metric in the perturbed metric in the longitudinal gauge is the longitudinal g Let us suppose  $\left(\Delta_{\overline{2}}^2 \gg \Delta_{\overline{2}}^2\right)$   $\sim 3 \cdot 10^{-9}$  @ small scales comoving scales in a radiation-dominated examples in a radiation-dominated era  $\Box$ 

 $ds^2 = a^2(\eta) [-(1+2\Phi)d\eta^2 + [(1-2\Psi)\delta_{ij} + 2F_{(i,j)} + h_{ij}]dx^idx^j]$ 

 $U = 2U + 2U$  and  $V = 12$  are scaler metric perturbation,  $\mathbb{R}$  is a transverse and  $\mathbb{R}$  $\left\{n_{ij}+2\pi n_{ij}+\kappa\ n_{ij}=\rho_{ij}\right\}\sim\Psi*\Psi$  (Ziid Order Fert.) and in the absence of anisotropic stress we require Φ = Ψ [49]. We will find it convenient to use the Fourier transform  $h_{ij}^{\prime\prime}+2\mathcal{H}h_{ij}^\prime+k^2h_{ij}=\hspace{-0.1cm}\left(S_{ij}^{TT}\right)\hspace{-0.1cm}\left|\vphantom{\sum}^{\Delta}\right.\hspace{-0.1cm} \left.\left.\Delta\Phi*\Phi\right.\hspace{-0.1cm} \textbf{(2nd Order Pert.)}$ 

$$
\Omega_{\rm GW}^{(0)}(f)=\frac{\Omega_{\rm rad}^{(0)}{\cal G}(\eta_c)}{24}\left(\frac{2\pi f}{a(\eta_c)H(\eta_c)}\right)^2\overline{{\cal P}_h^{\rm ind}(\eta_c,2\pi f)}
$$

INFLATION non-monotonic **IF** *{* multi-field  $\left\{\right. \Rightarrow$  **enhance**  $\Delta_{\mathcal{R}}^2$ **possible to enhance (at small scales)** II. SUUTTUUDEN SIJAARIN VALMINTATION VALMINTATION VALMINTATION VALMINTATION VALMINTATIONAL VALMINTATIONAL VALM<br>PAAJA SECOND-ORDER GRAVITATION VALMINTATION VALMINTATION VALMINTATION VALMINTATION VALMINTATION VALMINTATION V

Let us suppose  $\begin{array}{ccc} \Delta_\mathcal{R}^2 \gg \Delta_\mathcal{R}^2 \end{array}$  $\begin{array}{c} \hline \end{array}$  $\vert_{\text{CMB}} \sim 3 \cdot 10^{-9} \vert, \text{\textcircled{a}}$  small scales In this section we will briefly review the generation of induced gravitational waves. Details of the calculations have **bet us s** The perturbed metric in the perturbed metric in the longitudinal gauge is the longitudinal g Let us suppose  $\left(\Delta_{\overline{2}}^2 \gg \Delta_{\overline{2}}^2\right)$   $\sim 3 \cdot 10^{-9}$  @ small scales comoving scales in a radiation-dominated examples in a radiation-dominated era  $\Box$ 

$$
ds^{2} = a^{2}(\eta)[-(1+2\Phi)d\eta^{2} + [(1-2\Psi)\delta_{ij} + 2F_{(i,j)} + h_{ij}]dx^{i}dx^{j}]
$$

 $U = 2U + 2U$  and  $V = 12$  are scaler metric perturbation,  $\mathbb{R}$  is a transverse and  $\mathbb{R}$  $\left\{n_{ij}+2\pi n_{ij}+\kappa\ n_{ij}=\rho_{ij}\right\}\sim\Psi*\Psi$  (Ziid Order Fert.) and in the absence of anisotropic stress we require Φ = Ψ [49]. We will find it convenient to use the Fourier transform  $h_{ij}^{\prime\prime}+2\mathcal{H}h_{ij}^\prime+k^2h_{ij}=\hspace{-0.1cm}\left(S_{ij}^{TT}\right)\hspace{-0.1cm}\left|\vphantom{\sum}^{\Delta}\right.\hspace{-0.1cm} \left.\left.\Delta\Phi*\Phi\right.\hspace{-0.1cm} \textbf{(2nd Order Pert.)}$ 

$$
\Omega_{\rm GW}^{(0)}(f)=\frac{\Omega_{\rm rad}^{(0)}{\cal G}(\eta_c)}{24}\left(\frac{2\pi f}{a(\eta_c)H(\eta_c)}\right)^2\overline{{\cal P}_h^{\rm ind}(\eta_c,2\pi f) \over \displaystyle {\cal P}_h^{\rm ind}(\eta,k)}=2\int_0^\infty dt\int_{-1}^1ds\left[\frac{t(2+t)(s^2-1)}{(1-s+t)(1+s+t)}\right]^2\atop\times\overline{I^2(u,v,k,\eta)}\overline{\bigtriangleup_{\cal R}^2(ku)\cdot\bigtriangleup_{\cal R}^2(kv),}
$$

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$$
\n
$$
\overline{\mathcal{P}_h^{\rm ind}(\eta, k)} = 2 \int_0^\infty dt \int_{-1}^1 ds \left[ \frac{t(2+t)(s^2-1)}{(1-s+t)(1+s+t)} \right]^2
$$
\n
$$
\times \overline{I^2(u, v, k, \eta)} \underbrace{\Delta_{\mathcal{R}}^2(ku) \cdot \Delta_{\mathcal{R}}^2(kv)}_{\text{max}}.
$$
\n
$$
\Omega_{\rm GW}^{(0)} \propto (\Delta_{\mathcal{R}}^2)^2
$$

$$
\sum_{\rm GW}^{\rm (0)} \propto (\Delta_{\mathcal{R}}^2)^2
$$

#### INFLATIONARY MODELS large, the abundances of the light nuclei produced would be altered with respect to the predictions of standard BBN. B. Constraints from ground-based detectors  $\blacksquare$  and  $\blacksquare$  and  $\blacksquare$  and  $\blacksquare$ EI ATIONIA DV MODEI C ns = 1.27 − <sup>40</sup> log<sup>10</sup> !Frad

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and the contract  $\Delta^2_{\mathcal{D}}$ This is a slightly weaker bound on the effective spectral index compared with  $\left( a t \sinh s \cosh s \right)$  $\Box$  GO  $\Omega_{\text{out}}$   $\alpha$  < 6.9 × 10<sup>-8</sup>  $\Box$   $\triangle^2_{\mathcal{R}}$  < 0.01  $s = s$  $\mathfrak{g}$ which cuts of  $\Delta_p^2 < 5 \times 10^{-3}$  $\Omega_{gw,0} < 1 \times 10^{-9}$  . And black hole binaries  $\triangle^2_{\mathcal{R}} < 5 \times 10^{-3}$  $\iota_{gw,0} < 10$  $H \cup H$  = 1000  $\rightarrow$  1000  $\rightarrow$  0.000  $\rightarrow$  1000  $\rightarrow$  1  $\mathbf{S}$ , gives us the primordial density perturbation on the primordial density perturbation on  $\mathbb{R}^2$  and  $\mathbb$  $\Omega$  $17$  - $\sqrt{2}$   $\sqrt{3}$   $\sqrt{10^{-7}}$ periods comparable to the total observation time span. This is typically  $1-10$ **BBN**  $\Omega_{gw,0} < 1.5 \times 10^{-6}$   $\longrightarrow$   $\triangle^2_{\mathcal{R}} < 0.1$ LIGO  $\Omega_{gw,0} < 6.9 \times 10^{-8}$   $\longrightarrow$   $\Delta^2_{\mathcal{R}} < 0.01$  $S$ and  $Y$ okoyama  $[34]$  have recently used similar constraints, on the induced gravitational wave background gravitational wave background gravitational wave background gravitational wave background gravitational wave ba **PTA**  $\Omega_{gw,0} < 1 \times 10^{-9}$ **LISA BBO**

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### $-15$   $10^{-11}$ **PBH candidate for DM ? Yes !, for**

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### $-15$   $10^{-11}$ **PBH candidate for DM ? Yes !, for**

**\* If PBH are the DM, what is the GWB from 2nd O(** $\Phi$ **)? Bartolo et al, '18** 

### **See the Second Second Ali-Haimoud, Byrnes, Right in the middle of LISA !**

INFLATION non-monotonic **IF** *{* multi-field  $\left\{\right. \Rightarrow$  **enhance**  $\Delta_{\mathcal{R}}^2$ **possible to enhance (at small scales)**



### **Has LIGO detected PBH's ?**

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*R* **Primordial Black Holes (PBH) may be produced!**

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#### Ali-Haimoud et al 2016-2017 **Has LIGO detected PBH's ? it does not look like…**



### Has will know dotorminin **Spill GIOLI** ACIT(LIAU), IVIUIIUI *'We will know determining the mass/spin distribution'* (M. Fishbach (LIGO), Moriond'19)

**2102 03809 2105 03349 De Luca et e.g. 2102.03809, 2105.03349, De Luca** *et al*



















### **\* Is that ALL? NO!**

$$
\phi(t)
$$
\n
$$
g_{\mu\nu}(t)
$$
\n(Background)



### **\* Is that ALL? NO!**





$\phi(t)$	$\phi(t) + \delta\phi(\vec{x}, t)$	but WHY fluctuations?				
$g_{\mu\nu}(t)$	$\phi(t) + \delta g_{\mu\nu}(\vec{x}, t)$	Quantum Mechanics!				
Background)	Fluctuations)	Varum				
$\hat{\phi}(\vec{x}, t)$	$\phi(\vec{x}, t)$	$\phi(\vec{x}, t)$	$\psi(t)$	Varuum		
QMM:	$\hat{\phi}(\vec{x}, t)$	$\phi(\vec{x}, t)$	$\phi(t)$	$\phi(\vec{x}, t)$	$\psi(t)$	Varuum
QMM:	$\hat{\phi}(\vec{x}, t)$	$\psi(t)$	$\psi(t)$	$\psi(t)$	$\psi(t)$	

$\phi(t)$	$\phi(t) + \delta\phi(\vec{x}, t)$	but WHY fluctuations?																									
$g_{\mu\nu}(t)$	$g_{\mu\nu}(t) + \delta g_{\mu\nu}(\vec{x}, t)$	Quantum Mechanics!																									
Background)	(Fluctuations)	Vavum																									
$\hat{\phi}(\vec{x}, t)$	$\hat{\phi}(\vec{x}, t)$	$\hat{\phi}(\vec{x}, t)$	$\hat{\phi}(\vec{x}, t)$	Vacuum																							
QM:	$\hat{\phi}(\vec{x}, t)$	$\hat{\phi}(\vec{x}, t)$	$\hat{\phi}(\vec{x}, t)$	$\hat{\phi}(\vec{x}, t)$	Weyl formula																						
OM:	$\hat{\phi}(\vec{x}, t)$	$\hat{\phi}(\vec{x}, t)$	$\hat{\phi}(\vec{x}, t)$	Not...	$\hat{\phi}(\vec{x}, t)$	$\hat{\phi}(\vec{x}, t)$	Not...	$\hat{\phi}(\vec{x}, t)$	$\hat{\phi}(\vec{x}, t)$	Not...	$\hat{\phi}(\vec{x}, t)$	$\hat{\phi}(\vec{x}, t)$	Not...	$\hat{\phi}(\vec{x}, t)$	$\hat{\phi}(\vec{x}, t)$	Not...	$\hat{\phi}(\vec{x}, t)$	$\hat{\phi}(\vec{x}, t)$	Not...	$\hat{\phi}(\vec{x}, t)$	$\hat{\phi}(\vec{x}, t)$	Not...	$\hat{\phi}(\vec{x}, t)$	$\hat{\phi}(\vec{x}, t)$	$\hat{\phi}(\vec{x}, t)$	Not...	$\hat{\$



$$
\hat{\phi}(\vec{x},t) = \phi(t) + \hat{\delta\phi}(\vec{x},t) \rightarrow \langle \hat{\delta\phi}^2(\vec{x},t) \rangle \neq 0
$$

but ... Minkowski -> Curved Space: (quasi)dS

$$
\hat{\phi}(\vec{x},t) = \phi(t) + \hat{\delta\phi}(\vec{x},t) \rightarrow \langle \hat{\delta\phi}^2(\vec{x},t) \rangle \neq 0
$$

but ... Minkowski 
$$
\rightarrow
$$
 Curved Space: (quasi)dS  

$$
S = \frac{m_p^2}{2} \int d^4x \sqrt{-g} \{R - (\partial \phi)^2 - 2V(\phi)\} \left\langle \frac{\phi(t) + \delta \phi(\vec{x}, t)}{g_{\mu\nu}(t) + \delta g_{\mu\nu}(\vec{x}, t)} \right\rangle
$$
$$
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$$

$$
ds^{2} = g_{\mu\nu}^{\text{tot}} dx^{\mu} dx^{\nu} = (g_{\mu\nu}(t) + \delta g_{\mu\nu}(\vec{x}, t)) dx^{\mu} dx^{\nu}
$$
  
= -(1 + 2\Phi)dt^{2} + 2B\_{i}dx^{i}dt + a^{2}[(1 - 2\Psi)\delta\_{ij} + E\_{ij}]dx^{i}dx^{j}

$$
ds2 = -(1+2\Phi)dt2 + 2Bidxidt + a2[(1-2\Psi)\deltaij + Eij]dxidxj
$$

$$
\phi(\vec{x},t) = \phi(t) + \delta\phi(\vec{x},t)
$$

$$
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$$

$$
E_{ij} = 2\partial_{ij}E + 2\partial_{(i}F_{j)} + h_{ij}
$$

**Inflation: A generator of Primordial Fluctuations**



Expanding U.  $\longrightarrow$  Vector Perturbations  $S_i, F_i \propto \frac{1}{a}$ 1 *a*

$$
ds^{2} = -(1+2\Phi)dt^{2} + \Omega B_{i}dx^{i}dt + a^{2}[(1-2\Psi)\delta_{ij} + E_{ij}]dx^{i}dx^{j}
$$

$$
\phi(\vec{x},t) = \phi(t) + \delta\phi(\vec{x},t)
$$

$$
E_{ij} = 2\partial_{ij}E + 2\partial_{i}F_{j} + h_{ij}
$$

$$
\partial_{i}h_{ij} = h_{ii} = 0
$$
(tensors = GWs)

$$
ds^{2} = -(1 + 2\Phi)dt^{2} + 2B_{i}dx^{i}dt + a^{2}[(1 - 2\Psi)\delta_{ij} + E_{ij}]dx^{i}dx^{j}
$$

$$
\phi(\vec{x}, t) = \phi(t) + \delta\phi(\vec{x}, t)
$$



$$
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$$
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$$
\n
$$
\phi(\vec{x}, t) = \phi(t) + \delta\phi(\vec{x}, t)
$$
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$$
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$$

\n $ds^2 = -(1 + 2\Phi)dt^2 + 2B_i dx^i dt + a^2[(1 - 2\Psi)\delta_{ij} + E_{ij}]dx^i dx^j$ \n
\n $\phi(\vec{x}, t) = \phi(t) + \delta\phi(\vec{x}, t)$ \n
\n $\text{seals}^s$ \n
\n $\delta\phi + {\Phi, B, \Psi, E}$ \n
\n $\epsilon = -[\Psi + (H/\phi)\delta\rho_{\phi}] \xrightarrow{\text{Diff.}} \zeta$ \n
\n $R = [\Psi + (H/\phi)\delta\phi] \xrightarrow{\text{Diff.}} \mathcal{R}$ \n
\n $Q = [\delta\phi + (\dot{\phi}/H)\Psi] \xrightarrow{\text{Diff.}} Q$ \n
\n $\text{Curvature}$ \n
\n $\text{Pert.}$ \n

\nFirsting **Gauge:** e.g.  $E, \delta\phi = 0 \Rightarrow g_{ij} = a^2[(1 - 2\mathcal{R})\delta_{ij} + h_{ij}]$ \n

\n\n\n\n

$$
ds^{2} = -(1 + 2\Phi)dt^{2} + 2B_{i}dx^{i}dt + a^{2}[(1 - 2\Psi)\delta_{ij} + E_{ij}]dx^{i}dx^{j}
$$

$$
\phi(\vec{x}, t) = \phi(t) + \delta\phi(\vec{x}, t)
$$

$$
g_{ij} = a^2[(1 - 2\mathcal{R})\delta_{ij} + h_{ij}]
$$

$$
ds2 = -(1+2\Phi)dt2 + 2Bidxidt + a2[(1-2\Psi)\deltaij + Eij]dxidxj
$$

$$
\phi(\vec{x},t) = \phi(t) + \delta\phi(\vec{x},t)
$$

$$
g_{ij} = a^2[(1 - 2\mathcal{R})\delta_{ij} + h_{ij}] \quad S = \frac{m_p^2}{2} \int d^4x \sqrt{-g} \{R - (\partial \phi)^2 - 2V(\phi)\}
$$

**Inflation: A generator of Primordial Fluctuations**

$$
ds^{2} = -(1 + 2\Phi)dt^{2} + 2B_{i}dx^{i}dt + a^{2}[(1 - 2\Psi)\delta_{ij} + E_{ij}]dx^{i}dx^{j}
$$
\n
$$
\phi(\vec{x}, t) = \phi(t) + \delta\phi(\vec{x}, t)
$$
\n
$$
g_{ij} = a^{2}[(1 - 2\mathcal{R})\delta_{ij} + h_{ij}] \quad S = \frac{m_{p}^{2}}{2} \int d^{4}x\sqrt{-g}\{R - (\partial\phi)^{2} - 2V(\phi)\} \implies
$$
\n
$$
S = S_{(0)} + S_{(2)}^{(s)} + S_{(2)}^{(t)}
$$
\n
$$
S_{(2)}^{(s)} = \frac{1}{2} \int d^{4}x \ a^{3} \frac{\dot{\phi}^{2}}{H^{2}} \left[\dot{\mathcal{R}}^{2} - a^{-2}(\partial_{i}\mathcal{R})^{2}\right]
$$
\n
$$
\text{Background}
$$
\n
$$
S_{(2)}^{(t)} = \frac{m_{p}^{2}}{8} \int dt dx^{3}a^{3} \left[(h_{ij})^{2} - a^{-2}(\partial_{l}h_{ij})^{2}\right]
$$
\n
$$
\text{Inflationary dynamics}
$$

(UV limit: deep inside Hubble radius)

**Inflation: A generator of Primordial Fluctuations**

#### Scalar Fluctuations:

 $S_{(2)}^{(s)}=\frac{1}{2}$  $\frac{1}{2} \int d^4x \; a^3 \frac{\dot{\phi}^2}{H^2}$  $\left[ \dot{\mathcal{R}}^2 - a^{-2} (\partial_i \mathcal{R})^2 \right]$ 

**Scalar Fluctuations:**  
\n
$$
S_{(2)} = \frac{1}{2} \int d^4x \ a^3 \frac{\dot{\phi}^2}{H^2} \left[ \dot{\mathcal{R}}^2 - a^{-2} (\partial_i \mathcal{R})^2 \right]
$$
\n
$$
= \frac{1}{2} \left[ \frac{1}{2} \int d\tau dx^3 \left[ (v')^2 - (\nabla v)^2 + \frac{z''}{z} v^2 \right] \right]
$$
\n
$$
= z \mathcal{R}, \ z \equiv a \frac{\dot{\phi}}{H} \right] \text{ (Mukhanov variable)}
$$

**Scalar Functions:**  

$$
S_{(2)}^{(s)} = \frac{1}{2} \int d^4x \ a^3 \frac{\dot{\phi}^2}{H^2} \left[ \dot{\mathcal{R}}^2 - a^{-2} (\partial_i \mathcal{R})^2 \right] = \left[ \frac{1}{2} \int d\tau dx^3 \left[ (v')^2 - (\nabla v)^2 + \frac{z''}{z} v^2 \right] \right]
$$

(F.T.: 
$$
v(\mathbf{x},t) = \int d\mathbf{k} e^{-i\mathbf{k}\mathbf{x}} v_{\mathbf{k}}(t)
$$
)  
\n
$$
v''_{\vec{k}} + (k^2 - z''/z)v_{\vec{k}} = 0
$$
\nwith  $\left(\frac{z''}{z} = \frac{1}{\tau^2} \left(\nu^2 - \frac{1}{4}\right), \quad \nu \equiv \frac{3}{2} + 2\epsilon - \eta\right)$ 

**Inflation: A generator of Primordial Fluctuations**

**Scalar Functions:**  

$$
S_{(2)}^{(s)} = \frac{1}{2} \int d^4x \ a^3 \frac{\dot{\phi}^2}{H^2} \left[ \dot{\mathcal{R}}^2 - a^{-2} (\partial_i \mathcal{R})^2 \right] = \left[ \frac{1}{2} \int d\tau dx^3 \left[ (v')^2 - (\nabla v)^2 + \frac{z''}{z} v^2 \right] \right]
$$

$$
\frac{1}{\sqrt{2\pi}}\sqrt{\frac{v''_{\vec{k}} + (k^2 - z''/z)v_{\vec{k}} = 0}
$$
 with  $\frac{z''}{z} = \frac{1}{\tau^2}(\nu^2 - \frac{1}{4}), \quad \nu \equiv \frac{3}{2} + 2\epsilon - \eta$ 

Quantization:  $v_{\vec{k}}(t) \rightarrow v_k(t)\hat{a}_{\vec{k}} + v_k^*(t)\hat{a}_{\vec{k}}^{\dagger}$  $\begin{bmatrix} \n\frac{1}{K} \cdot \frac{1}{K} \cdot \frac{1}{$ 

$$
\qquad \qquad \blacksquare
$$

**Inflation: A generator of Primordial Fluctuations**

**Scalar Functions:**  

$$
S_{(2)}^{(s)} = \frac{1}{2} \int d^4x \ a^3 \frac{\dot{\phi}^2}{H^2} \left[ \dot{\mathcal{R}}^2 - a^{-2} (\partial_i \mathcal{R})^2 \right] = \left[ \frac{1}{2} \int d\tau dx^3 \left[ (v')^2 - (\nabla v)^2 + \frac{z''}{z} v^2 \right] \right]
$$

$$
v''_{\vec{k}} + (k^2 - z''/z)v_{\vec{k}} = 0
$$
 with  $\frac{z''}{z} = \frac{1}{\tau^2} \left(\nu^2 - \frac{1}{4}\right), \quad \nu \equiv \frac{3}{2} + 2\epsilon - \eta$ 

Quantization:  $v_{\vec{k}}(t) \rightarrow v_k(t)\hat{a}_{\vec{k}} + v_k^*(t)\hat{a}_{\vec{k}}^{\dagger}$  $\begin{bmatrix} \n\frac{1}{K} \cdot \frac{1}{K} \cdot \frac{1}{$ 



**Inflation: A generator of Primordial Fluctuations**

**Scalar Functions:**  

$$
S_{(2)}^{(s)} = \frac{1}{2} \int d^4x \ a^3 \frac{\dot{\phi}^2}{H^2} \left[ \dot{\mathcal{R}}^2 - a^{-2} (\partial_i \mathcal{R})^2 \right] = \left[ \frac{1}{2} \int d\tau dx^3 \left[ (v')^2 - (\nabla v)^2 + \frac{z''}{z} v^2 \right] \right]
$$

$$
\sum_{k} v_{\vec{k}}'' + (k^2 - z''/z)v_{\vec{k}} = 0 \quad \text{with} \quad \frac{z''}{z} = \frac{1}{\tau^2} \left(\nu^2 - \frac{1}{4}\right), \quad \nu \equiv \frac{3}{2} + 2\epsilon - \eta
$$

Quantization:  $\int v$ 

$$
v_{\vec{k}}(t) \to v_k(t)\hat{a}_{\vec{k}} + v_k^*(t)\hat{a}_{-\vec{k}}^{\dagger} , \quad [a_{\vec{k}}, a_{\vec{k}'}^{\dagger}] = (2\pi)^3 \delta(\vec{k} - \vec{k}')
$$

$$
\qquad \qquad \blacktriangleright
$$

$$
v_k(\tau) = \frac{\sqrt{\pi}}{2} e^{i\pi(\nu+1/2)/2} (-\tau)^{1/2} H_{\nu}^{(1)}(-k\tau)
$$
  
(we keep only one,  $\hat{H}v_k = +kv_k$ ,  $\langle v_k, v_k \rangle > 0$ )

**Inflation: A generator of Primordial Fluctuations**

**Scalar Functions:**  

$$
S_{(2)}^{(s)} = \frac{1}{2} \int d^4x \ a^3 \frac{\dot{\phi}^2}{H^2} \left[ \dot{\mathcal{R}}^2 - a^{-2} (\partial_i \mathcal{R})^2 \right] = \left[ \frac{1}{2} \int d\tau dx^3 \left[ (v')^2 - (\nabla v)^2 + \frac{z''}{z} v^2 \right] \right]
$$

$$
\frac{1}{\sqrt{2\pi}}\sqrt{\frac{v''_{\vec{k}} + (k^2 - z''/z)v_{\vec{k}} = 0}
$$
 with  $\frac{z''}{z} = \frac{1}{\tau^2} \left(\nu^2 - \frac{1}{4}\right), \quad \nu \equiv \frac{3}{2} + 2\epsilon - \eta$ 

Quantization:  $v_{\bar{k}}$ 

$$
\vec{k}(t) \to v_k(t)\hat{a}_{\vec{k}} + v_k^*(t)\hat{a}_{-\vec{k}}^{\dagger} , \quad [a_{\vec{k}}, a_{\vec{k}'}^{\dagger}] = (2\pi)^3 \delta(\vec{k} - \vec{k}')
$$

$$
v_k(\tau) = \frac{\sqrt{\pi}}{2} e^{i\pi(\nu+1/2)/2} (-\tau)^{1/2} H_{\nu}^{(1)}(-k\tau) \xrightarrow{\begin{array}{c} -k\tau \gg 1 \\ (\text{sub-Hubble}) \end{array}} \frac{1}{\sqrt{2k}} e^{-ik\tau}
$$
\n(we keep only one,  $\hat{H}v_k = +kv_k$ ,  $\langle v_k, v_k \rangle > 0$ )

\nPositive define freq

**Inflation: A generator of Primordial Fluctuations**

**Scalar Functions:**  

$$
S_{(2)}^{(s)} = \frac{1}{2} \int d^4x \ a^3 \frac{\dot{\phi}^2}{H^2} \left[ \dot{\mathcal{R}}^2 - a^{-2} (\partial_i \mathcal{R})^2 \right] = \left[ \frac{1}{2} \int d\tau dx^3 \left[ (v')^2 - (\nabla v)^2 + \frac{z''}{z} v^2 \right] \right]
$$

$$
\frac{\partial}{\partial t} \left\{ v''_{\vec{k}} + (k^2 - z''/z)v_{\vec{k}} = 0 \right\} \quad \text{with} \quad \frac{z''}{z} = \frac{1}{\tau^2} \left( \nu^2 - \frac{1}{4} \right), \quad \nu \equiv \frac{3}{2} + 2\epsilon - \eta
$$

Quantization:  $v_{\vec{k}}(t) \rightarrow v_k(t)\hat{a}_{\vec{k}} + v_k^*(t)\hat{a}_{\vec{k}}^{\dagger}$  $\begin{bmatrix} \n\frac{1}{K} \cdot \frac{1}{K} \cdot \frac{1}{$ 

$$
v_k(\tau) = \frac{\sqrt{\pi}}{2} e^{i\pi(\nu+1/2)/2} (-\tau)^{1/2} H_{\nu}^{(1)}(-k\tau)
$$

⌫ (*k*⌧ ) (Bunch-Davies) Vacuum Fluct.

#### **Inflation: A generator of Primordial Fluctuations**

Scalar Fluct:

$$
v_k(\tau) = \frac{\sqrt{\pi}}{2} e^{i\pi(\nu+1/2)/2} (-\tau)^{1/2} H_{\nu}^{(1)}(-k\tau)
$$
 |Bunch-Pavies  

$$
\hat{v}_{\vec{k}}(t) \rightarrow v_k(t)\hat{a}_{\vec{k}} + v_k^*(t)\hat{a}_{-\vec{k}}^{\dagger}
$$
 |Aervev

$$
\begin{array}{c|c}\n \begin{array}{c}\n \overline{L}^{(1)}(-k\tau) \\
 \hline\n \overline{k}\n \end{array}\n \end{array}
$$
 (Bunch-**Paries**)\n  
Vacuum Fluct.

#### **Inflation: A generator of Primordial Fluctuations**

Scalar Fluct:

$$
v_k(\tau) = \frac{\sqrt{\pi}}{2} e^{i\pi(\nu+1/2)/2} (-\tau)^{1/2} H_{\nu}^{(1)}(-k\tau)
$$

$$
\hat{v}_{\vec{k}}(t) \to v_k(t)\hat{a}_{\vec{k}} + v_k^*(t)\hat{a}_{-\vec{k}}^{\dagger}
$$

⌫ (*k*⌧ ) (Bunch-Davies) Vacuum Fluct.

$$
\left[\left[v \equiv z\mathcal{R}\,,\ z \equiv a\frac{\dot{\phi}}{H}\right]\right]
$$
\n
$$
\left\langle \hat{\mathcal{R}}_{\vec{k}}\hat{\mathcal{R}}_{\vec{k}'} \right\rangle \equiv \frac{1}{z^2} \left\langle \hat{v}_{\vec{k}}\hat{v}_{\vec{k}'} \right\rangle \equiv (2\pi)^3 \frac{H^2}{a^2 \dot{\phi}^2} |v_k(\eta)|^2 \delta(\vec{k} + \vec{k}')
$$

#### **Inflation: A generator of Primordial Fluctuations**

Scalar Fluct:

$$
v_k(\tau) = \frac{\sqrt{\pi}}{2} e^{i\pi(\nu+1/2)/2} (-\tau)^{1/2} H_{\nu}^{(1)}(-k\tau)
$$

$$
\hat{v}_{\vec{k}}(t) \to v_k(t)\hat{a}_{\vec{k}} + v_k^*(t)\hat{a}_{-\vec{k}}^{\dagger}
$$

$$
\begin{array}{c|c}\n\hline\n\end{array}
$$
 (Bunch-**Pavies)**  
\n
$$
\bar{k}
$$
 Vacuum Fluct.

$$
\boxed{\begin{aligned}\n\left[v \equiv z\mathcal{R}, \quad z \equiv a\frac{\dot{\phi}}{H}\right] &\longrightarrow\n\end{aligned}\n\quad\n\left\langle \hat{\mathcal{R}}_{\vec{k}} \hat{\mathcal{R}}_{\vec{k}'} \right\rangle \equiv \frac{1}{z^2} \left\langle \hat{v}_{\vec{k}} \hat{v}_{\vec{k}'} \right\rangle \equiv (2\pi)^3 \frac{H^2}{a^2 \dot{\phi}^2} |v_k(\eta)|^2 \delta(\vec{k} + \vec{k}')
$$
\n
$$
\equiv P_{\mathcal{R}}(k, \eta)
$$
\n**Scalar**\n**Power Spectrum**

#### **Inflation: A generator of Primordial Fluctuations**

Scalar Fluct:

$$
v_k(\tau) = \frac{\sqrt{\pi}}{2} e^{i\pi(\nu+1/2)/2} (-\tau)^{1/2} H_{\nu}^{(1)}(-k\tau)
$$

$$
\hat{v}_{\vec{k}}(t) \to v_k(t)\hat{a}_{\vec{k}} + v_k^*(t)\hat{a}_{-\vec{k}}^{\dagger}
$$

$$
\begin{array}{c|c}\n \begin{array}{c}\n \overline{L}^{(1)}(-k\tau) \\
 \hline\n \overline{k}\n \end{array}\n \end{array}
$$
 (Bunch-**Paries**)\n  
Vacuum Fluct.

$$
v = zR, \quad z = a\frac{\dot{\phi}}{H}
$$
\n
$$
\left(\hat{\mathcal{R}}_{\vec{k}}\hat{\mathcal{R}}_{\vec{k}'}\right) = \frac{1}{z^2} \langle \hat{v}_{\vec{k}}\hat{v}_{\vec{k}'} \rangle = (2\pi)^3 \frac{H^2}{a^2 \dot{\phi}^2} |v_k(\tau)|^2 \delta(\vec{k} + \vec{k}')
$$
\n
$$
= P_R(k, \tau)
$$
\n**Scalar**\n
$$
\Delta_R^2(k, \tau) = \frac{k^3}{2\pi^2} P_R(k, \tau)
$$
\n
$$
(k \ll aH)
$$
\n
$$
\Delta_R^2(k) = \frac{H^4}{(2\pi)^2 \dot{\phi}^2} \left(\frac{k}{aH}\right)^{2\eta - 4\epsilon}
$$
\nDimensionless Scalar PS

**Inflation: A generator of Primordial Fluctuations**

 $S_{(2)}^{(t)} =$  $m_p^2$  $\int_{8}^{n_{p}^{2}} \int dt dx^{3} a^{3} \left[ (\dot{h}_{ij})^{2} - a^{-2} (\partial_{l} h_{ij})^{2} \right]$ Tensor Fluctuations:

**Inflation: A generator of Primordial Fluctuations** 

*a*

**Tensor Fluctuations:**  
\n
$$
d\tau \equiv dt/a(t) \text{ (Conformal time)}
$$
\n
$$
S_{(2)}^{(t)} = \frac{m_p^2}{8} \int dt dx^3 a^3 \left[ (\dot{h}_{ij})^2 - a^{-2} (\partial_l h_{ij})^2 \right] \left[ \sum_s \frac{1}{2} \int d\tau d^3 \mathbf{k} \left[ (v_{\mathbf{k}}^{s\prime})^2 - \left( k^2 - \frac{a''}{a} \right) (v_{\mathbf{k}}^s)^2 \right] \right]
$$
\n
$$
h_{ij}(\vec{k}, \tau) = \epsilon_{ij}^{(s)} h_{\vec{k}}^{(s)} \longrightarrow v^{(s)} \equiv \frac{a}{2} m_p h_{\vec{k}}^{(s)}
$$

**Inflation: A generator of Primordial Fluctuations** 

**Tensor Fluctions:**  

$$
S_{(2)}^{(t)} = \frac{m_p^2}{8} \int dt dx^3 a^3 \left[ (\dot{h}_{ij})^2 - a^{-2} (\partial_l h_{ij})^2 \right] = \left[ \sum_s \frac{1}{2} \int d\tau d^3 \mathbf{k} \left[ (v_{\mathbf{k}}^{s\prime})^2 - \left( k^2 - \frac{a''}{a} \right) (v_{\mathbf{k}}^s)^2 \right] \right]
$$

*a*

Same Procedure as with Scalar Pert. Quantization<br>Quantize + Bunch-Davies + Power Spectrum of Gravity dof of Gravity dof !

**Inflation: A generator of Primordial Fluctuations** 

**Tensor Fluotuations:**  

$$
S_{(2)}^{(t)} = \frac{m_p^2}{8} \int dt dx^3 a^3 \left[ (\dot{h}_{ij})^2 - a^{-2} (\partial_l h_{ij})^2 \right] = \left[ \sum_s \frac{1}{2} \int d\tau d^3 \mathbf{k} \left[ (v_{\mathbf{k}}^{s\prime})^2 - \left( k^2 - \frac{a''}{a} \right) (v_{\mathbf{k}}^s)^2 \right] \right]
$$

*a*

Same Procedure as with Scalar Pert.<br>Quantize + Bunch-Davies + Power Spectrum

Quantization of Gravity dof !

$$
\Delta_h^2(k,\tau) \equiv \frac{k^3}{2\pi^2} P_h(k,\tau)
$$
\n
$$
(k \ll aH)
$$
\n
$$
\Delta_h^2(k) = \frac{2}{\pi^2} \left(\frac{H}{m_p}\right)^2 \left(\frac{k}{aH}\right)^{-2\epsilon}
$$