Large Field Inflation in String Theory

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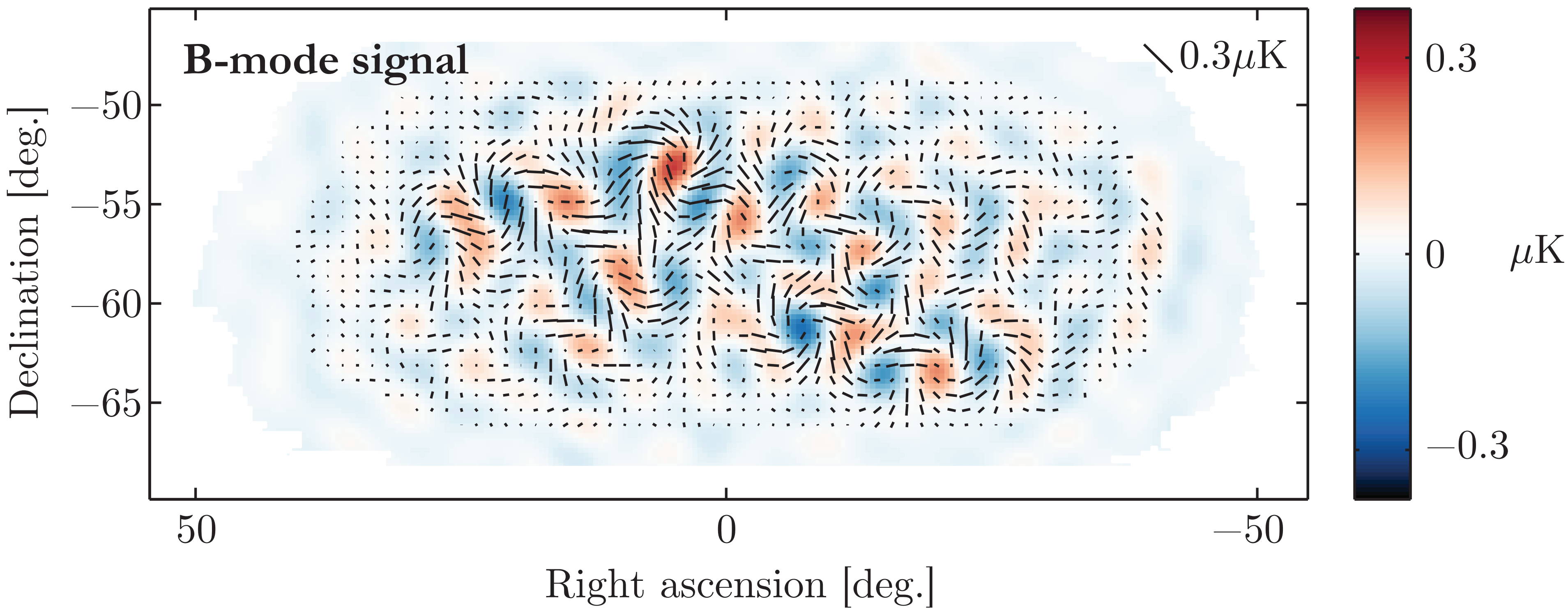
Ongoing discussions w/ J. Brown, F. Marchesano, and I. Garcia-Etxebarria

Primordial B-mode?



BICEP2 Collaboration

Dust is not entirely settled …

[Mortonson & Seljak]; [Flauger, Hill & Spergel];
See on the other hand, [Colley & Gott]

Gravity Waves and Inflation

If the BICEP2 results are confirmed to be primordial, natural interpretations:

- ✦ Inflation took place
- ✦ The energy scale of inflation is the GUT scale

$$E_{\rm inf} \simeq 0.75 \times \left(\frac{r}{0.1}\right)^{1/4} \times 10^{-2} M_{\rm Pl}$$

- ✦ The inflaton field excursion was super-Planckian

$$\Delta\phi \gtrsim \left(\frac{r}{0.01}\right)^{1/2} M_{\rm Pl}$$

Lyth '96

- ✦ Great news for string theory due to strong UV sensitivity!

Assumptions in the Lyth Bound

- single field
- slow-roll
- Bunch-Davies initial conditions
- vacuum fluctuations

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Particle production during inflation can be a source of GWs

$$\left[\partial_\tau^2 + k^2 - \frac{a''}{a}\right](a\,\delta g_{ij}) = S_{ij}$$

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Only known model of particle production shown to give detectable tensors w/o too large non-Gaussianity

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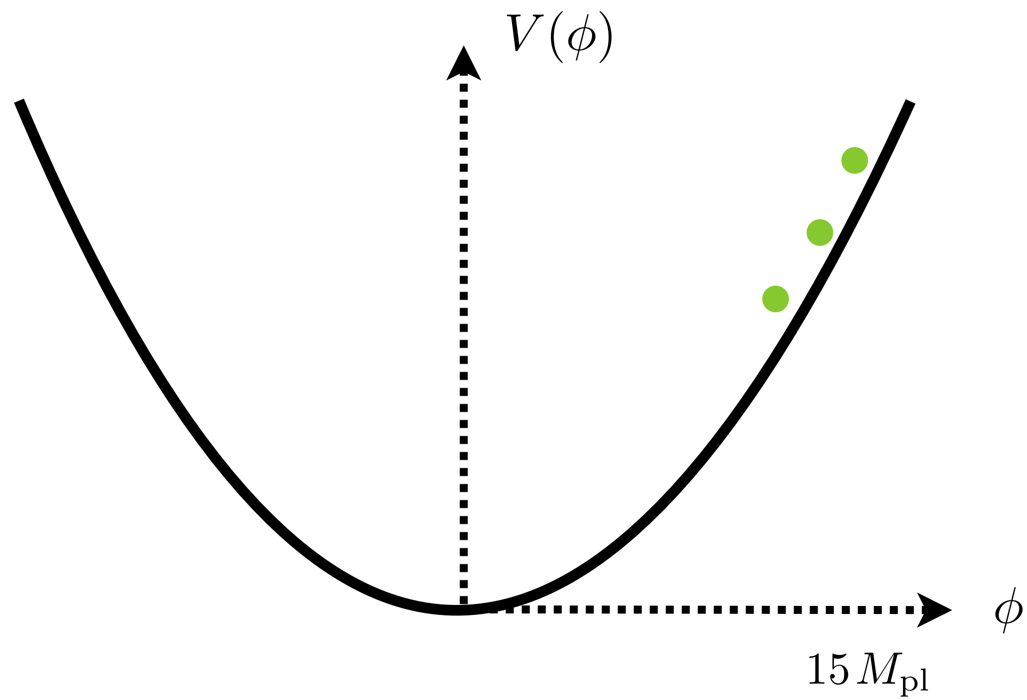
Only known model of particle production shown to give detectable tensors w/o too large non-Gaussianity

- Due to an ***axionic*** a F∧ F coupling, tensor spectrum is ***chiral*** *and* ***non-Gaussian.***
- ***Model building constraints:*** $f/M_P \geq 10^{-4}$ quite natural in string theory

Chaotic Inflation

Linde '86

- A poster child inflation model (also seems favored) is $V = m^2\phi^2$:



  - Loop corrections involving inflaton and gravitons are small due to approximate shift symmetry

$$\phi \mapsto \phi + \text{const.}$$

  - Coupling to UV degrees of freedom in quantum gravity a priori breaks this shift symmetry and lead to corrections that spoil inflation, because of the large field excursions

$$\mathcal{L}_{\rm eff}[\phi] = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 + \sum_{i=1}^{\infty} c_i\,\phi^{2i}\Lambda^{4-2i}$$

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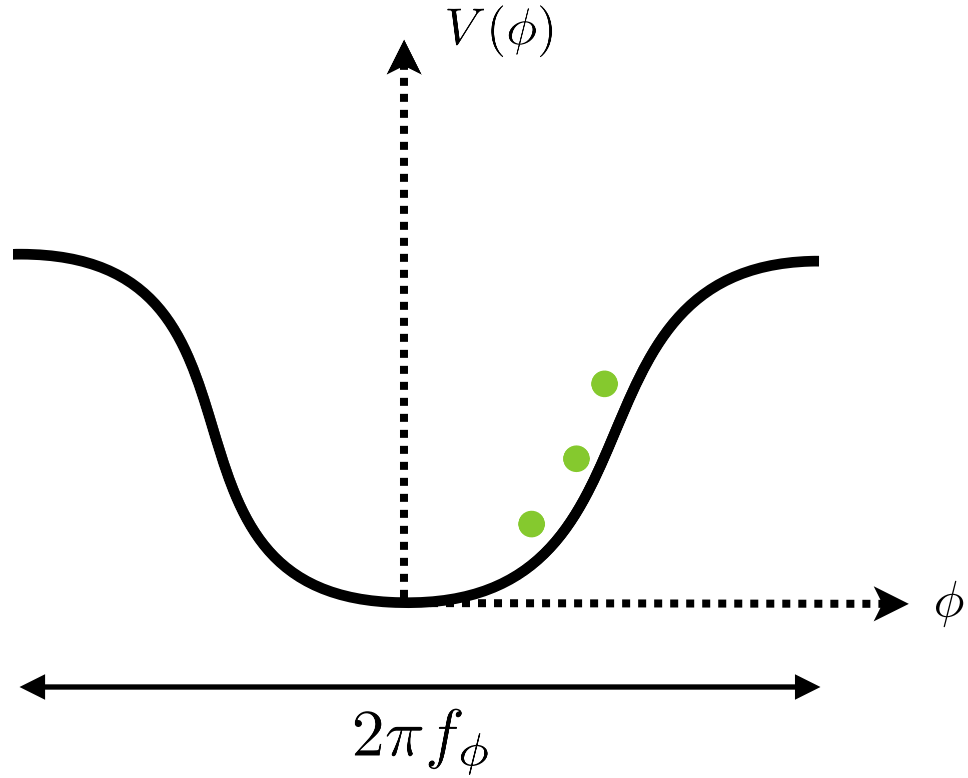
figure taken from Baumann & McAllister '14

Natural Inflation

Freese, Frieman, Olinto '90

- String models where the inflaton is an axion in principle can avoid this problem
  - Shift symmetry broken by non-perturbative effects+UV completion, but periodicity is exact
  - In string theory axions generically come from p-forms, so above the KK scale the shift symmetry becomes a gauge symmetry



$$\phi = \int_{\pi_p} C_p$$

$$F_{p+1} = dC_p$$
$$C_p \to C_p + d\Lambda_{p-1}$$

Dimopoulos et al.' 05

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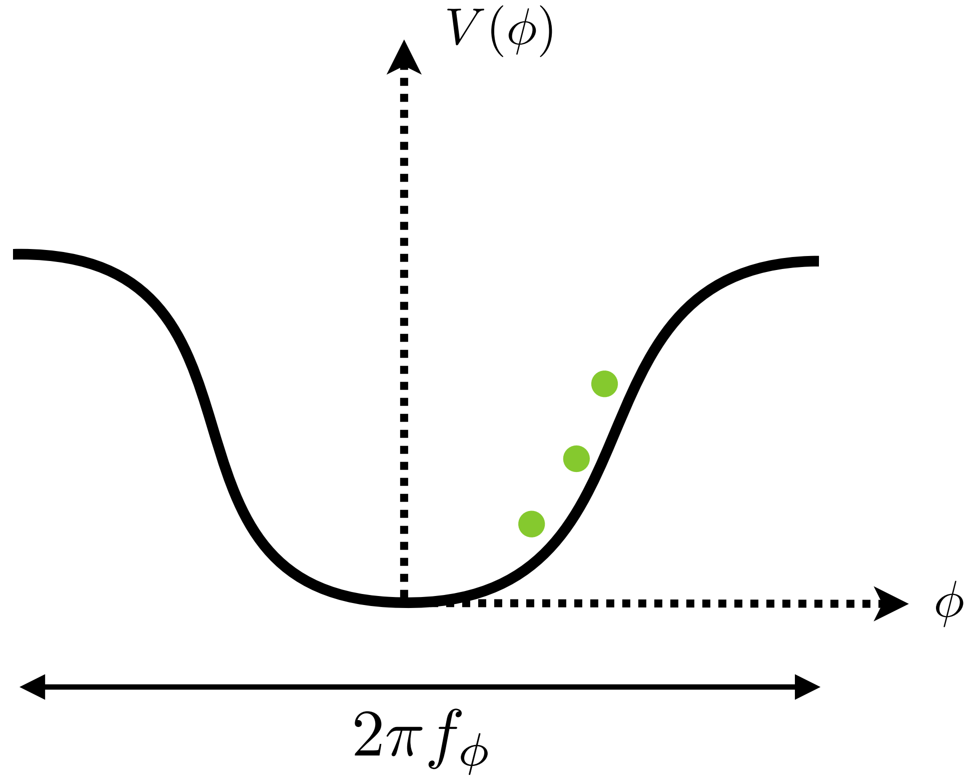
  - Shift symmetry broken by non-perturbative effects+UV completion, but periodicity is exact
  - In string theory axions generically come from p-forms, so above the KK scale the shift symmetry becomes a gauge symmetry
  - However, these axions have sub-Planckian decay constants



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Banks et al. '03 *Svrcek & Witten '06*

Multiple Axions

N-flation *Dimopoulos, Kachru, McGreevy, Wacker '05*

Aligned natural inflation *Kim, Nilles, Peloso '04 [See Nilles's talk]*

Axion Monodromy

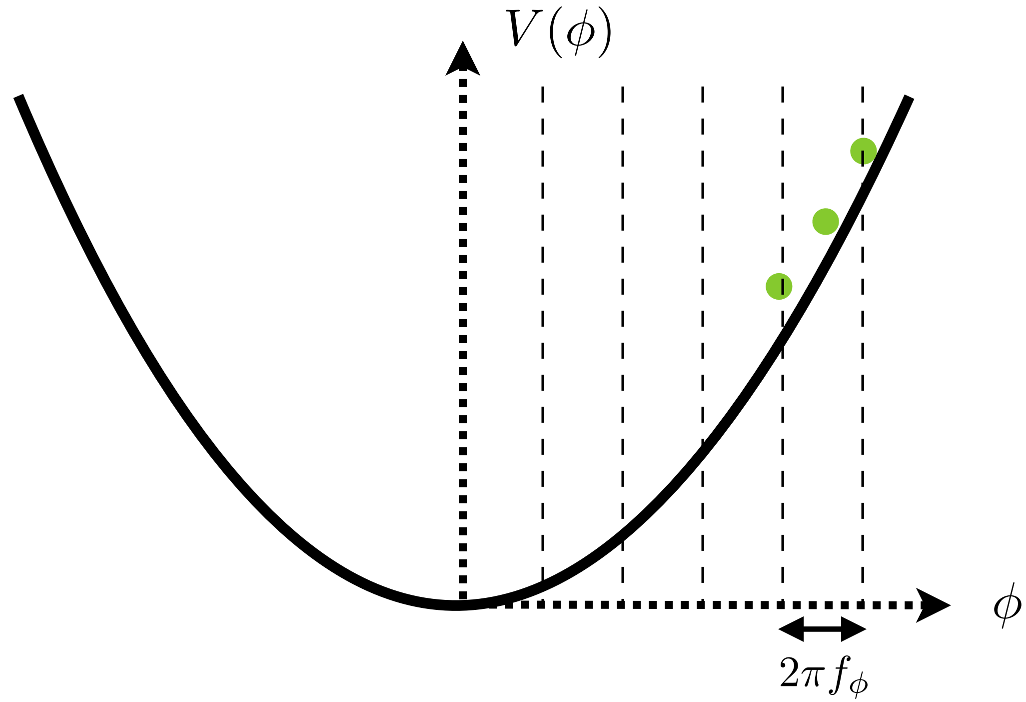
A ***single*** axion goes super-Planckian.

Axion Monodromy Inflation

Siverstein & Westphal '08

Idea:

Combine chaotic inflation and natural inflation



The axion periodicity is lifted, allowing for super-Planckian displacements. The UV corrections to the potential should still be constrained by the underlying symmetry.

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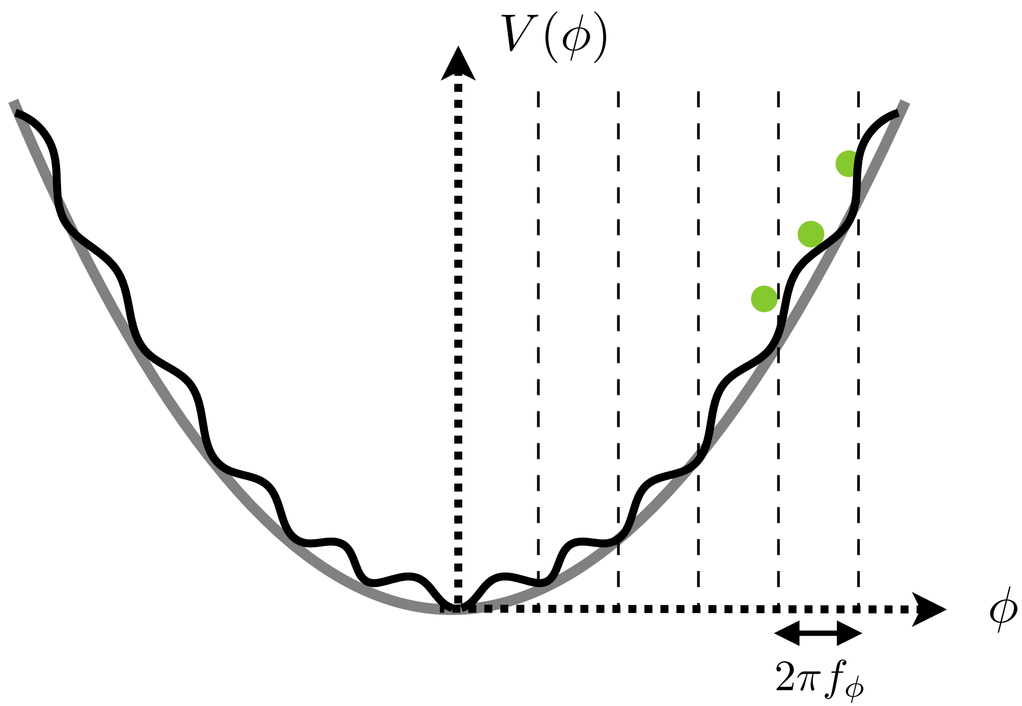

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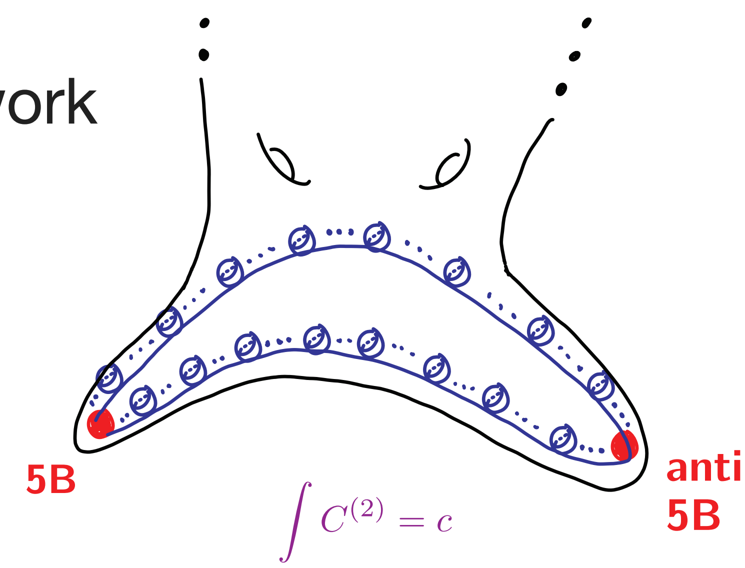
Early developments:

- ✦ McAllister, Silverstein, Westphal → String scenarios
- ✦ Kaloper, Lawrence, Sorbo → 4d framework



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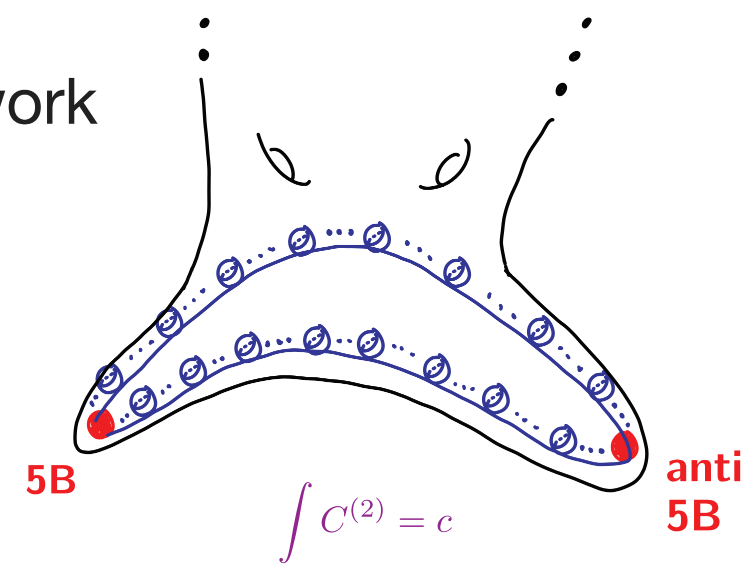

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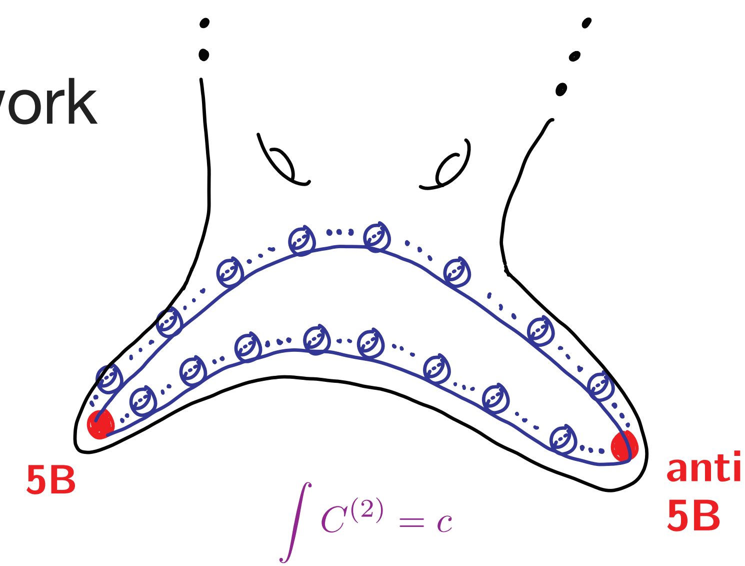

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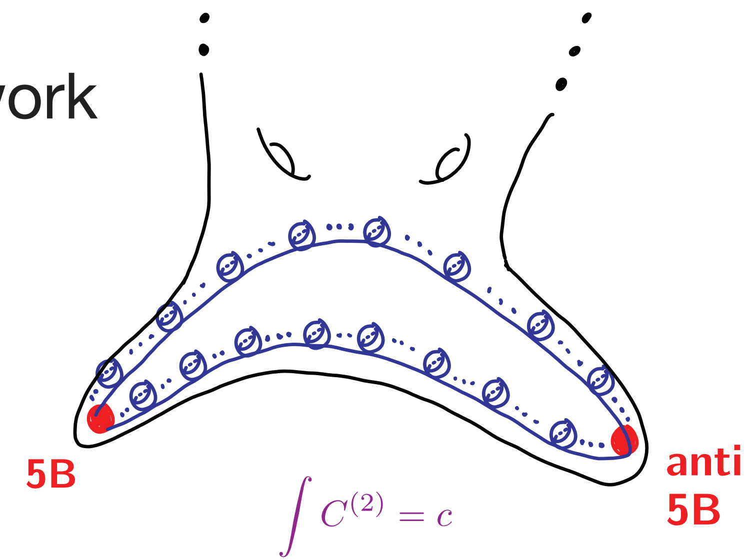
See also Palti, Weigand; Blumenhagen, Plauschinn; Hebecker, Kraus, Witowski; Ibañez, Valenzuela; Hassler, Lüst, Massai; McAllister, Silverstein, Westphal, Wrase; ....



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F-term Axion Monodromy Inflation

Obs: Axion Monodromy ~ Giving a mass to an axion

- Done in string theory within the moduli stabilization program: adding ingredients like background fluxes generate superpotentials in the effective 4d theory

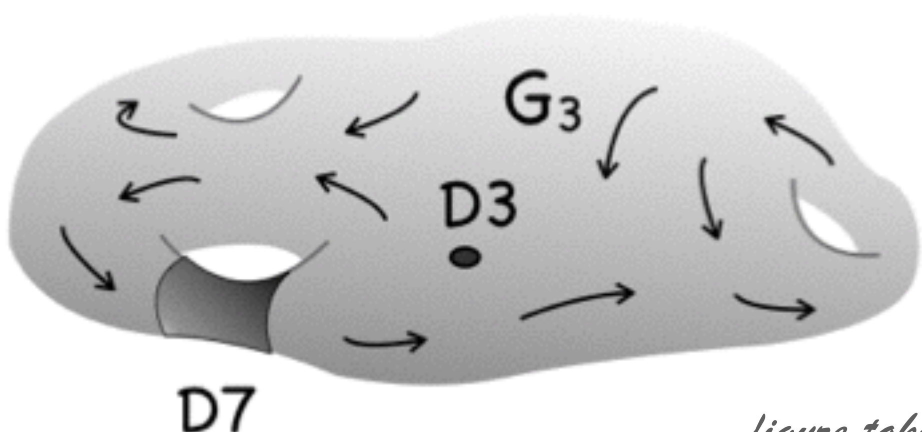

figure taken from Ibañez & Uranga '12

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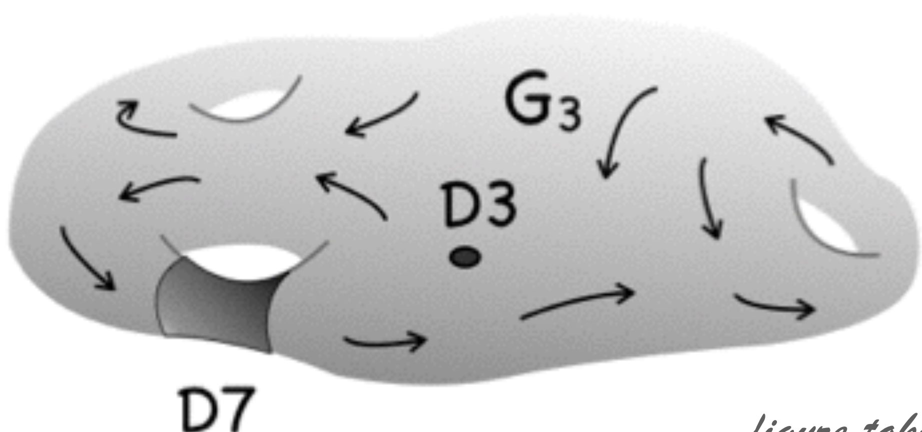

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✦ Done in string theory within the moduli stabilization program: adding ingredients like background fluxes generate superpotentials in the effective 4d theory

Idea: Use same techniques to generate an inflation potential

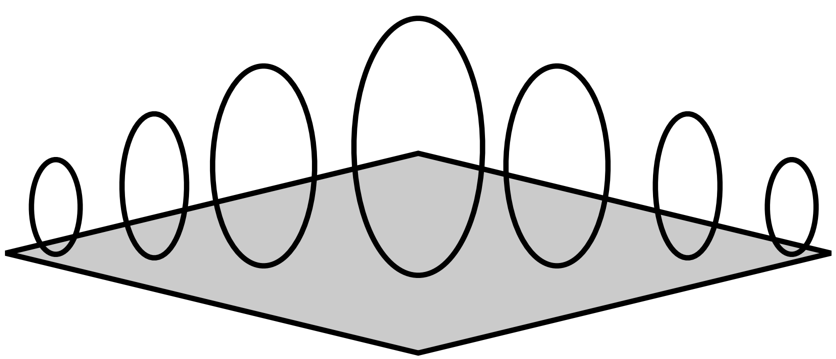
- Simpler models, all sectors understood at weak coupling
- Spontaneous SUSY breaking, no need for brane-anti-brane
- Clear endpoint of inflation, allows to address reheating

Toy Example: Massive Wilson line

- Simple example of axion: (4+d)-dimensional gauge field integrated over a circle in a compact space Π_d

$$\phi = \int_{S^1} A_1 \qquad \text{or} \qquad A_1 = \phi(x)\,\eta_1(y)$$

- ϕ massless if $\Delta\eta_1 = 0 \Rightarrow S^1$ is a non-trivial circle in Π_d
  exact periodicity and (pert.) shift symmetry
- ϕ massive if $\Delta\eta_1 = -\mu^2\,\eta_1 \Rightarrow kS^1$ homologically trivial in Π_d
  (non-trivial fibration)



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$$F_2 = dA_1 = \phi\, d\eta_1 \sim \mu\phi\, \omega_2$$

$\Rightarrow$ shifts in ϕ increase energy via the induced flux F_2

$\Rightarrow$ periodicity is broken and shift symmetry approximate

MWL and twisted tori

- Simple way to construct massive Wilson lines: consider compact extra dimensions Π_d with circles fibered over a base, like the twisted tori that appear in flux compactifications

- There are circles that are not contractible but do not correspond to any harmonic 1-form. Instead, they correspond to torsional elements in homology and cohomology groups

$$\mathrm{Tor}\, H_1(\Pi_d, \mathbb{Z}) = \mathrm{Tor}\, H^2(\Pi_d, \mathbb{Z}) = \mathbb{Z}_k$$

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- Simplest example: twisted 3-torus $\tilde{\mathbb{T}}^3$

$$H_1(\tilde{\mathbb{T}}^3, \mathbb{Z}) = \mathbb{Z} \times \mathbb{Z} \times \mathbb{Z}_k$$

two normal 1-cycles ($\mathbb{Z} \times \mathbb{Z}$) — one torsional 1-cycle ($\mathbb{Z}_k$)

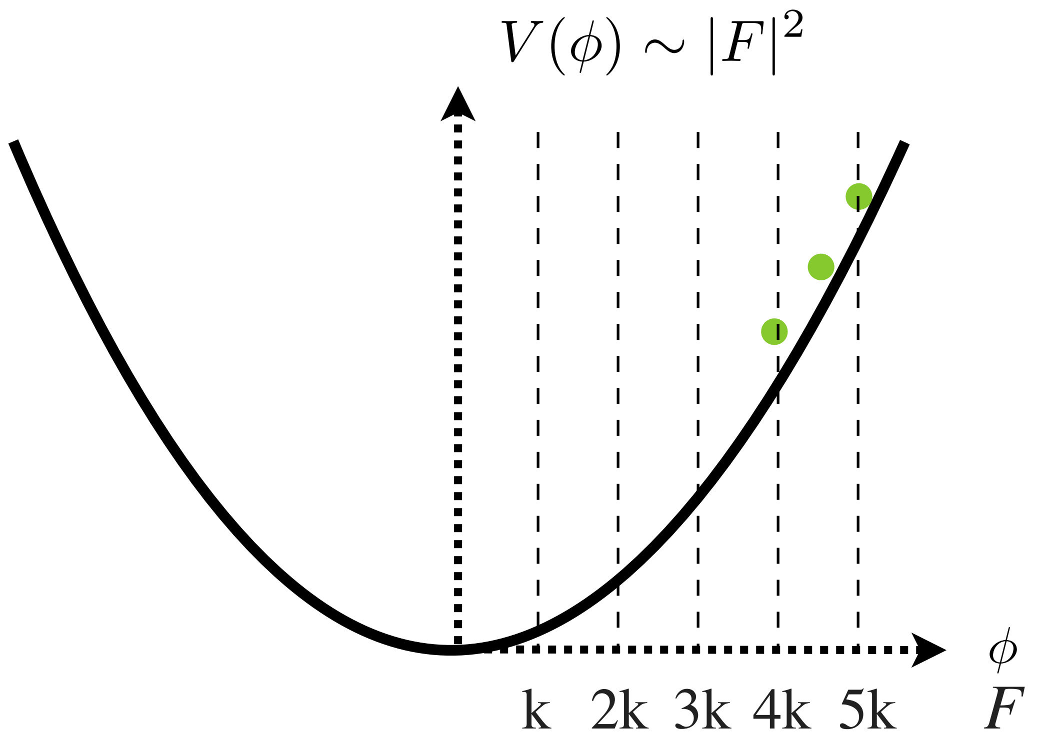
$$d\eta_1 = k dx^2 \wedge dx^3 \longrightarrow F = \phi\, k\, dx^2 \wedge dx^3$$

$\downarrow$

under a shift $\phi \to \phi + 1$
F_2 increases by k units

$$\mu = \frac{kR_1}{R_2 R_3}$$

MWL and monodromy



Question:

How does monodromy and approximate shift symmetry help prevent wild UV corrections?

Torsion and gauge invariance

- Twisted tori torsional invariants are not just a fancy way of detecting non-harmonic forms, but are related to a hidden gauge invariance of these axion-monodromy models
- Let us again consider a 7d gauge theory on $M^{1,3} \times \tilde{\mathbb{T}}^3$
  - Instead of A_1 we consider its magnetic dual V_4

$$V_4 = C_3 \wedge \eta_1 + b_2 \wedge \sigma_2 \xrightarrow{d\eta_1 = k\,\sigma_2} dV_4 = dC_3 \wedge \eta_1 + (db_2 - kC_3) \wedge \sigma_2$$

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  - From dimensional reduction of the kinetic term:

$$\int d^7x\, |dV_4|^2 \longrightarrow \int d^4x\, |dC_3|^2 + \frac{\mu^2}{k^2} |db_2 - kC_3|^2$$

    - Gauge invariance $C_3 \to C_3 + d\Lambda_2 \qquad b_2 \to b_2 + k\Lambda_2$
    - Generalization of the Stückelberg Lagrangian

Quevedo & Trugenberger '96

Effective 4d theory

- The effective 4d Lagrangian

$$\int d^4x \, |dC_3|^2 + \frac{\mu^2}{k^2} |db_2 - kC_3|^2$$

describes a massive axion, has been applied to QCD axion ⇒ generalized to arbitrary V(ϕ)

Kallosh et al. '95
Dvali, Jackiw, Pi '05
Dvali, Folkerts, Franca '13

- Reproduces the axion-four-form Lagrangian proposed by Kaloper and Sorbo as 4d model of axion-monodromy inflation with mild UV corrections

$$\int d^4x \, |F_4|^2 + |d\phi|^2 + \phi F_4$$

$$F_4 = dC_3$$
$$d\phi = *_4 db_2$$

Kaloper & Sorbo '08

- It is related to an F-term generated mass term

Groh, Louis, Sommerfeld '12

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- Gauge symmetry ⇒ UV corrections only depend on F_4

$$\mathcal{L}_{\text{eff}}[\phi] = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}\mu^2\phi^2 + \Lambda^4 \sum_{i=1}^{\infty} c_i \frac{\phi^{2i}}{\Lambda^{2i}}$$

- Shift sym in ϕ
- Gauge sym in F_4

→ $$\mu^2\phi^2 \sum_n c_n \left(\frac{\mu^2\phi^2}{\Lambda^4}\right)^n$$

⇒ suppressed corrections up to the scale where $V(\phi) \sim \Lambda^4$

⇒ effective scale for corrections $\Lambda \rightarrow \Lambda_{\text{eff}} = \Lambda^2/\mu$

Effective 4d theory

- Effective 4d Lagrangian

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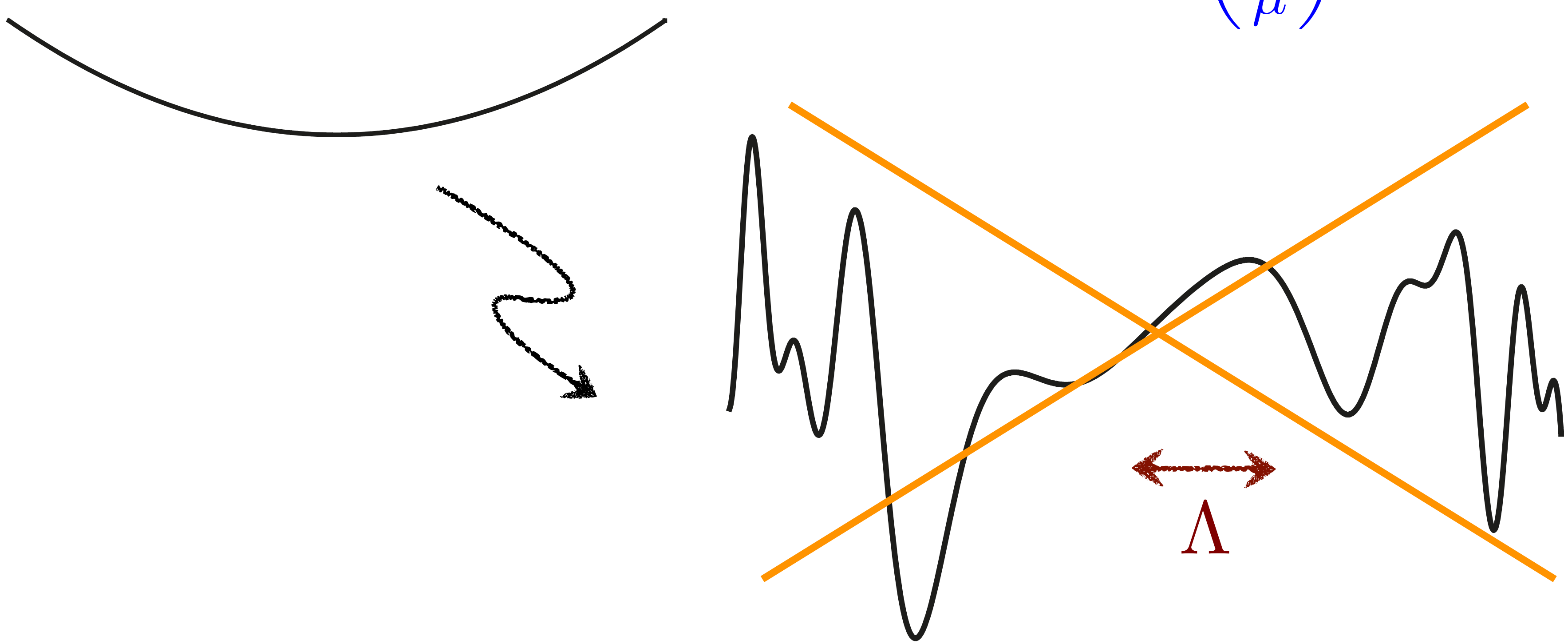
$$\Lambda \to \Lambda_{\rm eff} = \Lambda \left(\frac{\Lambda}{\mu} \right)$$



Discrete symmetries and domain walls

- The integer k in the Lagrangian

$$\int d^4x\, |F_4|^2 + \frac{\mu^2}{k^2}|db_2 - kC_3|^2$$

corresponds to a discrete symmetry of the theory broken spontaneously once a choice of four-form flux is made. This amounts to choose a branch of the scalar potential

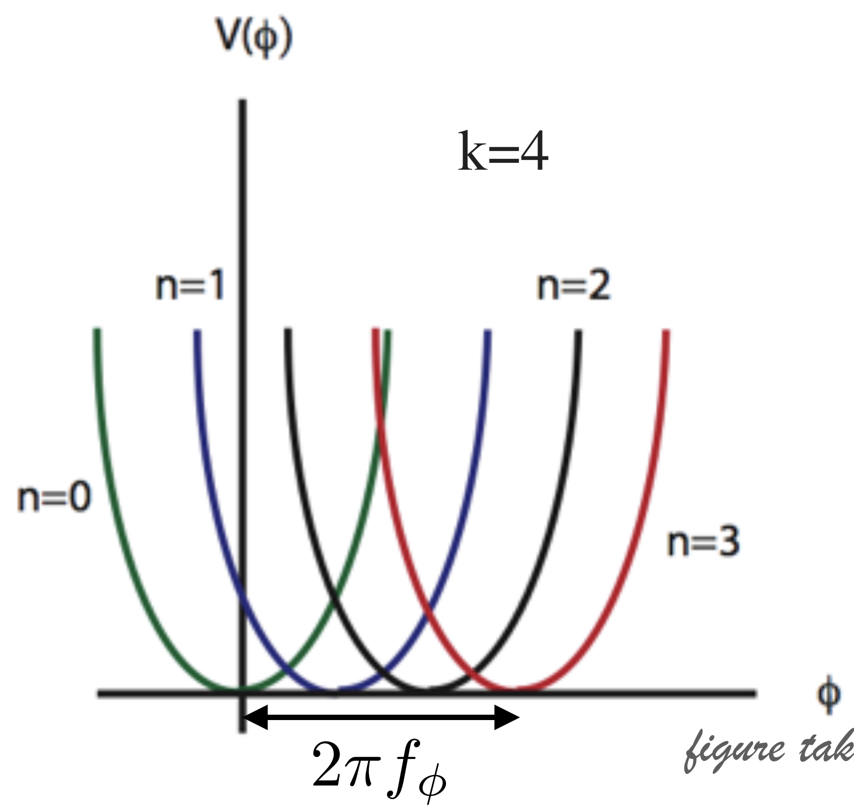


figure taken from Kaloper & Lawrence '14

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- Branch jumps are made via nucleation of domain walls that couple to C_3, and this puts a maximum to the inflaton range

- Tunneling rate between branches

$$P = e^{-S} = e^{-\sigma \times R_0^3}$$

where σ = domain wall tension, R_0 = bubble radius

$$R_0^3(\Delta V) = R_0^2\sigma \Rightarrow R_0 = \sigma/\Delta V$$

Discrete symmetries and domain walls

- This gives the usual Coleman formula for 4D field theory:

$$P = e^{-\frac{27\pi^2\sigma^4}{2(\Delta V)^3}}$$

- In string theory models, σ = tension of branes wrapping an internal cycle, ΔV ~ V/N, we found in a single modulus case:

$$S = \frac{g_s^8}{(M_s L)^{24}} \left(\frac{N M_P^4}{V} \right)^3$$

w/ Brown

- Even with the high inflation scale suggested by BICEP,

$$\frac{V}{M_P^4} \lesssim 10^{-8}$$

- Tunneling is (marginally) suppressed for $M_s L \gtrsim 10$ and $g_s \lesssim 1$.

- Other interesting tunneling channels in string theory.

w/ Marchesano and Garcia-Etxebarria

Massive Wilson lines in string theory

- Simple example of MWL in string theory: D6-brane on $M^{1,3} \times \tilde{\mathbb{T}}^3$
- An inflaton vev induces a non-trivial flux F_2 proportional to ϕ but now this flux enters the DBI action

$$\sqrt{\det\left(G + 2\pi\alpha' F_2\right)} \;=\; d\text{vol}_{M^{1,3}}\;\left(|F_2|^2 + \text{corrections}\right)$$

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- For small values of ϕ we recover chaotic inflation, but for large values the corrections are important and we have a potential of the form

$$V = \sqrt{L^4 + \langle\phi\rangle^2} - L^2$$

Similar to the D4-brane model of Silverstein and Westphal except for the inflation endpoint

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Massive Wilson lines and flattening

- The DBI modification

$$\langle\phi\rangle^2 \to \sqrt{L^4 + \langle\phi\rangle^2} - L^2$$

can be interpreted as corrections due to UV completion

- E.g., integrating out moduli such that H < m_{mod} < M_{GUT} will correct the potential, although not destabilise it

Kaloper, Lawrence, Sorbo '11

- In the DBI case the potential is flattened: argued general effect due to couplings to heavy fields

Dong, Horn, Silverstein, Westphal '10

- Large vev flattening also observed in examples of confining gauge theories whose gravity dual is known [Witten'98]

Dubovsky, Lawrence, Roberts '11

- α' corrections are important for inflation even w/ a symmetry

Other string examples

- We can integrate a bulk p-form potential C_p over a p-cycle to get an axion

$$F_{p+1} = dC_p, \quad C_p \to C_p + d\Lambda_{p-1} \qquad\qquad c = \int_{\pi_p} C_p$$

- If the p-cycle is torsional we will get the same effective action

$$\int d^{10}x |F_{9-p}|^2 \longrightarrow \int d^4x \, |dC_3|^2 + \frac{\mu^2}{k^2} |db_2 - kC_3|^2$$

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- The topological groups that detect this possibility are

$$\mathrm{Tor}\, H_p(\mathbf{X}_6, \mathbb{Z}) = \mathrm{Tor}\, H^{p+1}(\mathbf{X}_6, \mathbb{Z}) = \mathrm{Tor}\, H^{6-p}(\mathbf{X}_6, \mathbb{Z}) = \mathrm{Tor}\, H_{5-p}(\mathbf{X}_6, \mathbb{Z})$$

one should make sure that the corresponding axion mass is well below the compactification scale (e.g., using warping)

Franco, Galloni, Retolaza, Uranga '14

Other string examples

- Axions also obtain a mass with background fluxes
- Simplest example: $\phi = C_0$ in the presence of NSNS flux H_3

$$W = \int_{\mathbf{X}_6} (F_3 - \tau H_3) \wedge \Omega \qquad \tau = C_0 + i/g_s$$

- We also recover the axion-four-form potential

$$\int_{M^{1,3}\times \mathbf{X}_6} C_0 H_3 \wedge F_7 = \int_{M^{1,3}} C_0 F_4 \qquad F_4 = \int_{\mathrm{PD}[H_3]} F_7$$

Other string examples

- Axions also obtain a mass with background fluxes
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- M-theory version: *Beasley, Witten '02*
- A rich set of superpotentials obtained with type IIA fluxes

$$\int_{\mathbf{X}_6} e^{J_c} \wedge (F_0 + F_2 + F_4) \qquad J_c = J + iB$$

→ **potentials higher than quadratic**

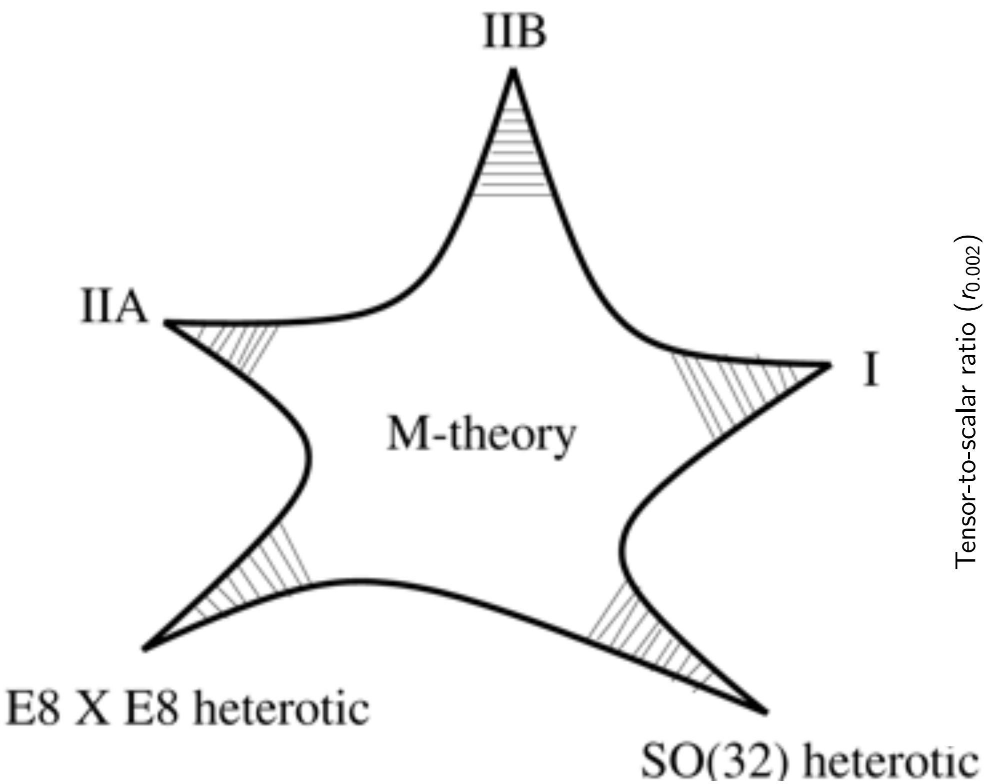
- Massive axions detected by torsion groups in K-theory

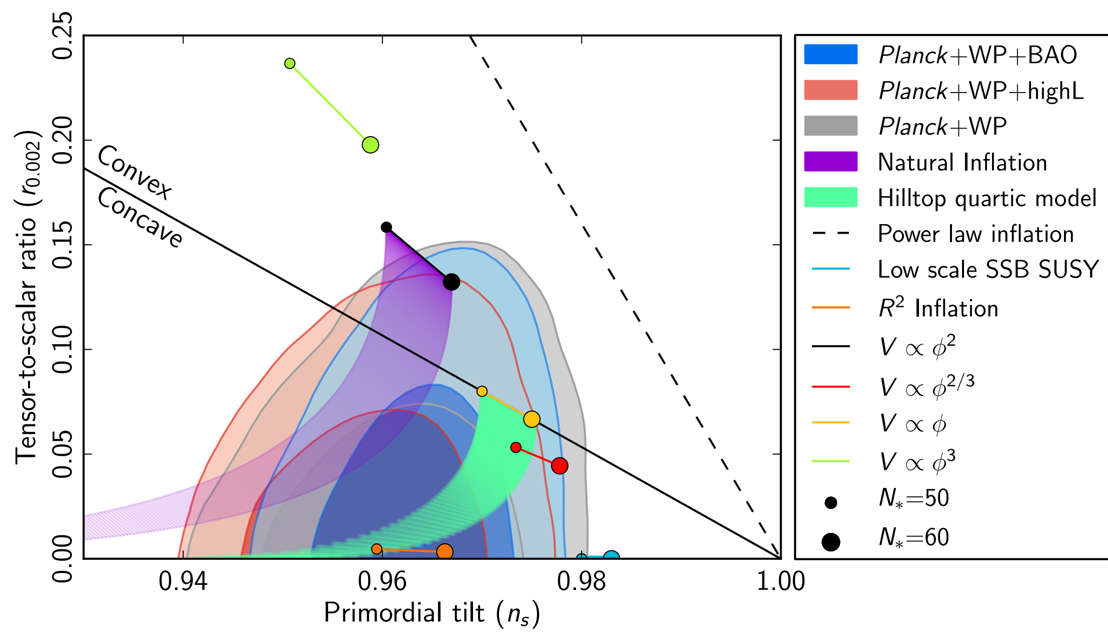
Conclusions

- Axion monodromy is an elegant idea that combines chaotic and natural inflation, aiming to prevent disastrous UV corrections to the inflaton potential.
- We have discussed its ***concrete*** implementation in a ***new*** framework, dubbed F-term axion monodromy inflation compatible with spontaneous supersymmetry breaking.
- In a simple set of models the inflaton is a massive Wilson line. They show the mild UV corrections for large inflaton vev.
- Effective action reproduces the axion-four-form action proposed by Kaloper and Sorbo. Discrete symmetries classified by K-theory torsion groups.
- α' corrections to EFT *[Garcia-Etxebarria, Hayashi, Savelli, GS, '12; Junghans, GS, '14]* important for inflation & moduli stabilization.

Conclusions

- A broad class of large field inflationary scenarios that can be implemented in any limit of string theory w/ rich pheno:

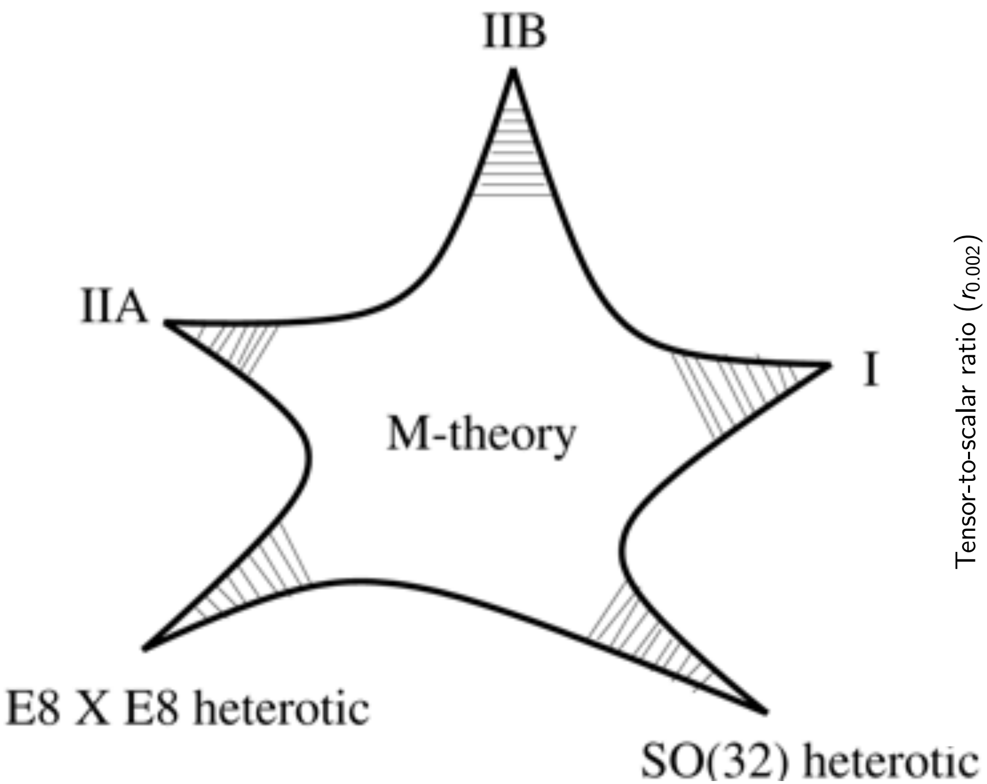


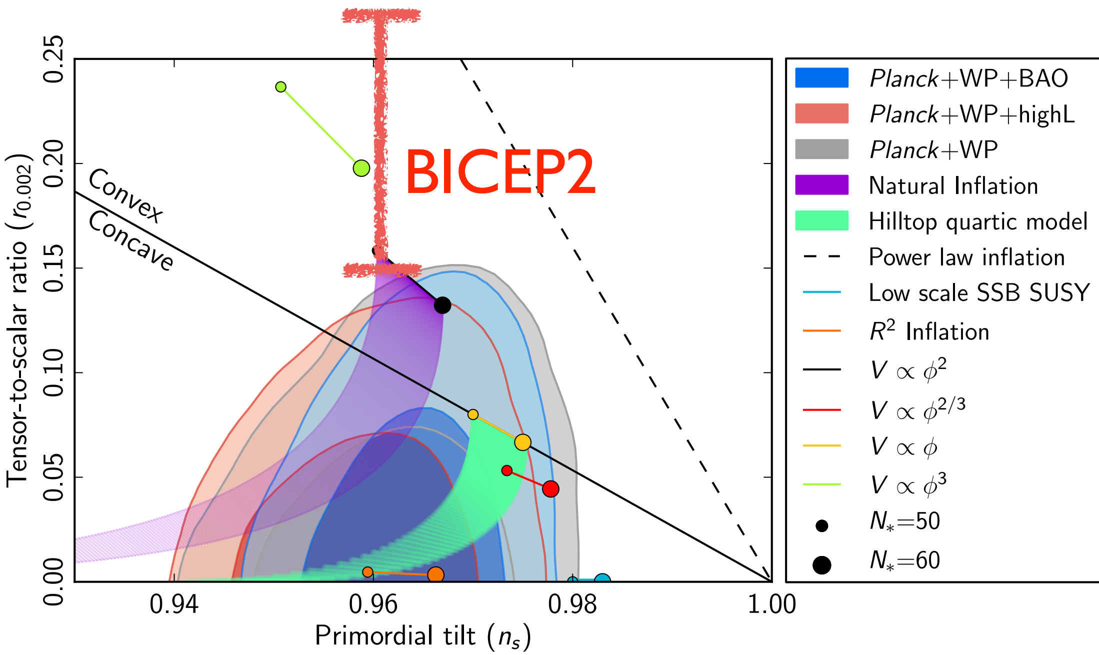


- Moduli stabilization needs to be addressed in detailed models [See Blumenhagen's talk]

Conclusions

- A broad class of large field inflationary scenarios that can be implemented in any limit of string theory w/ rich pheno:





- Moduli stabilization needs to be addressed in detailed models [See Blumenhagen's talk]

Gordon Research Conferences

String Theory & Cosmology

New Ideas Meet New Experimental Data

May 31 - June 5, 2015
The Hong Kong University of Science and Technology
Hong Kong, China

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Gary Shiu

Vice Chair:
Ulf Danielsson

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Applications for this meeting must be submitted by **May 3, 2015**. Please apply early, as some meetings become oversubscribed (full) before this deadline. If the meeting is oversubscribed, it will be stated here. *Note*: Applications for oversubscribed meetings will only be considered by the Conference Chair if more seats become available due to cancellations.

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Danke!

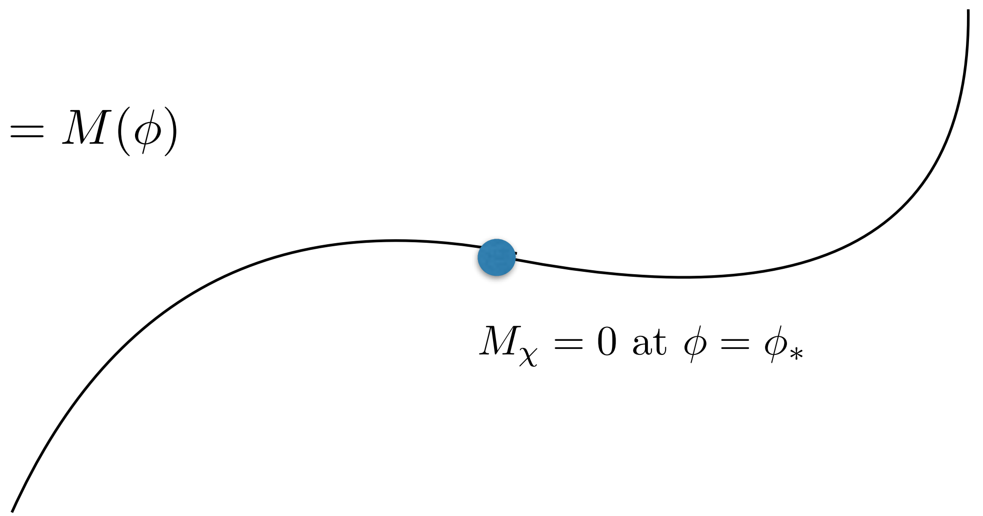
Particle Production

Usual assumption: $$\left[\partial_\tau^2 + k^2 - \frac{a''}{a}\right](a\,\delta g_{ij}) = S_{ij} \quad , \quad S_{ij} = 0$$

Particle production can provide a source of S_{ij}

Simplest model: an additional scalar field χ

$$M_\chi = M(\phi)$$



$$M_\chi = 0 \text{ at } \phi = \phi_*$$

[Chung, Kolb, Riotto and Tkachev];[Cook, Sorbo]; [Senatore, Silverstein and Zaldarriaga]; [N. Barnaby, J. Moxon, R. Namba, M. Peloso, G. Shiu and P. Zhou]

- χ particles quickly become non-relativistic, quadrupole moment (source of GWs) is suppressed.
- Source highly non-Gaussian scalar perturbations not suppressed by the small quadrupole moment.

Particle Production - Axion Model

A workable model: [N. Barnaby, J. Moxon, R. Namba, M. Peloso, G. Shiu and P. Zhou]

$$S = \int d^4x \sqrt{-g} \left[\frac{M_p^2}{2} R - \underbrace{\frac{1}{2}(\partial\varphi)^2 - V(\varphi)}_{\text{inflaton sector}} - \underbrace{\frac{1}{2}(\partial\psi)^2 - U(\psi) - \frac{1}{4}F^2 - \frac{\psi}{4f}F\tilde{F}}_{\text{hidden sector}} \right]$$

- *Continuous* production of relativistic vector quanta.

- Only known model of particle production during inflation that
  1. produces significant amount of GWs,
  2. avoids strong non-Gaussianity of scalar perturbations.

- Interesting signatures:
  1. Parity violation in GWs
  2. Non-Gaussian tensor fluctuations
  3. Can accommodate blue tilt in tensor spectrum

  …

Gauge Field Production

- Time dependence of axion sources gauge fields

$$\left[\partial_\tau^2 + k^2 \pm \frac{2k\xi}{\tau}\right] A_\pm(\tau,k) \simeq 0\,, \quad \xi \equiv \frac{\dot{\bar\psi}}{2Hf}\,,$$

- One helicity mode is copiously produced:

$$A_+ \simeq \left(\frac{-\tau}{8\xi k}\right)^{1/4} \mathrm{e}^{\pi\xi - 2\sqrt{-2\xi k\tau}}\,, \quad \partial_\tau A_+ \simeq \sqrt{\frac{2\xi k}{-\tau}}\, A_+\,.$$

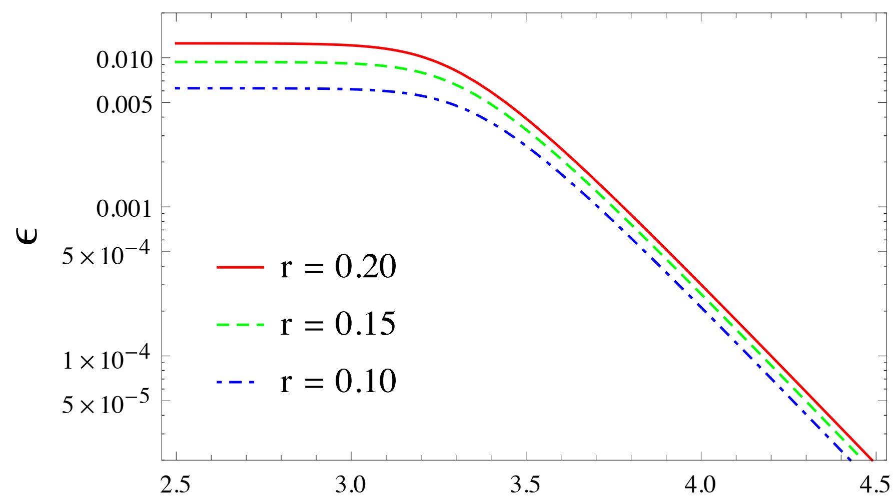
- Effects on scalar and tensor spectrum:

$$P_\zeta \simeq \mathcal{P}\left(1 + 2.5\cdot 10^{-6}\,\epsilon^2\,\mathcal{P}\,\frac{\mathrm{e}^{4\pi\xi}}{\xi^6}\right) \qquad P_{\mathrm{GW}} \simeq 16\,\epsilon\,\mathcal{P}\left(1 + 3.4\cdot 10^{-5}\,\epsilon\,\mathcal{P}\,\frac{\mathrm{e}^{4\pi\xi}}{\xi^6}\right)$$

- **Negligible effects on scalar spectrum**

$$P_\zeta \simeq \mathcal{P}\,\frac{1-0.0735\epsilon}{1-0.0046r}$$

- **Sourced GWs *dominate* over vacuum fluctuations in tensor spectrum for ξ≧ 3.4**

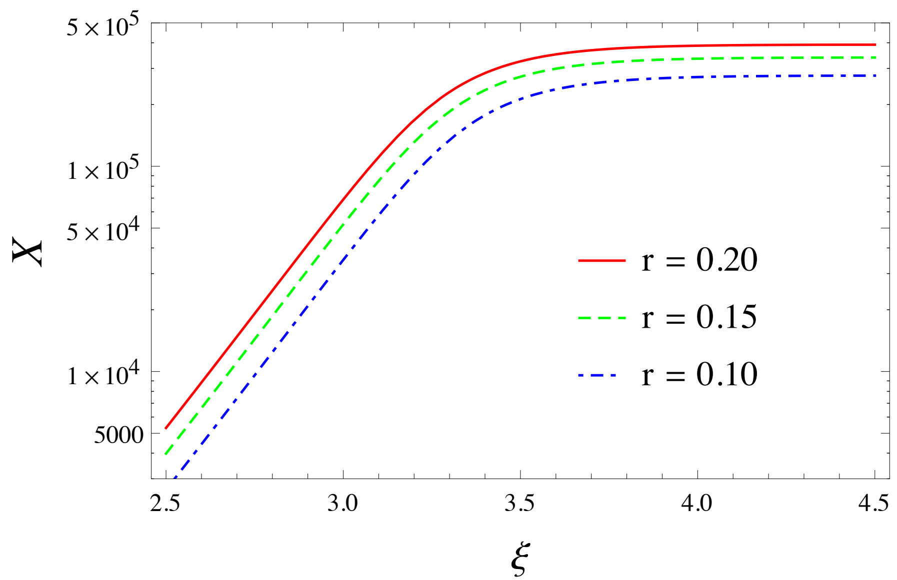


Tensor Non-Gaussianity

- Sourced tensor modes can leave sizable non-Gaussianity of nearly equilateral shape on CMB temperature anisotropies & polarization.

[Cook, Sorbo]

- Decisive parameter: $X \equiv \epsilon \frac{e^{2\pi\xi}}{\xi^3}$



X saturates to:

$$X \simeq 43\sqrt{\frac{r}{P_\zeta}} \simeq 3.5 \cdot 10^5 \sqrt{\frac{r}{0.15}} \, .$$

- PLANCK temperature data can detect $X \approx 5 \times 10^5$ at 1σ.
- Inclusion of E-mode polarization data can improve the 1σ limit to

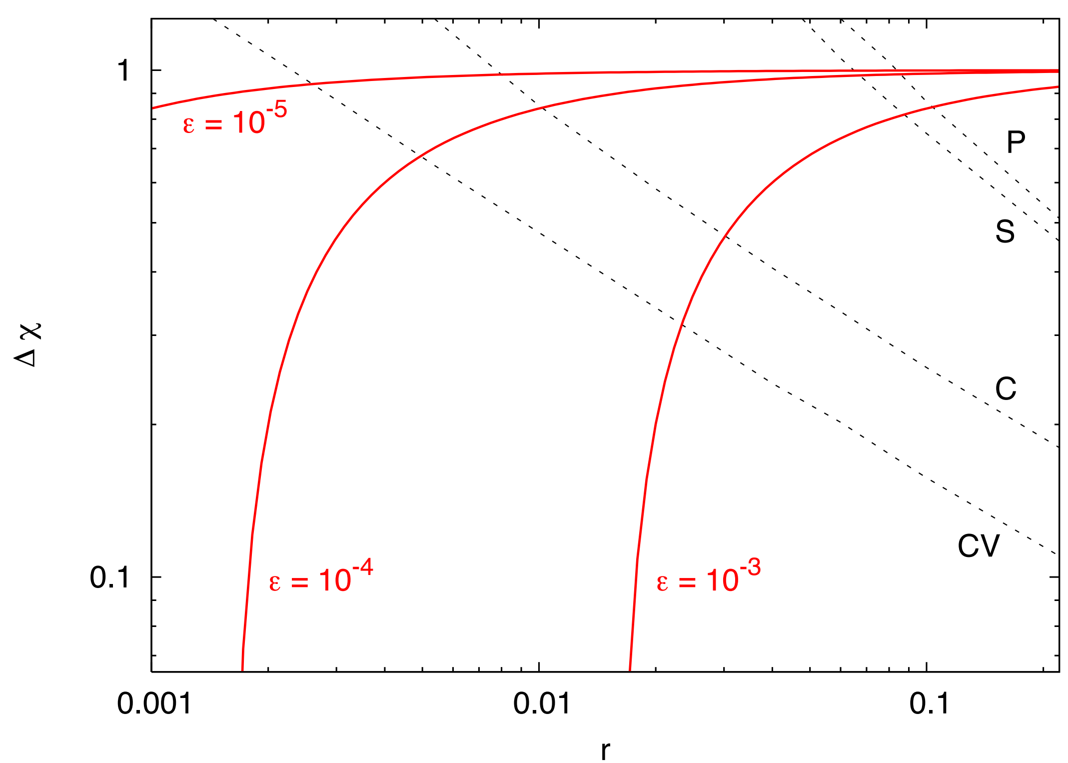
  $X \approx 3.8 \times 10^5$ (PLANCK) and 2.9×10^5 (PRISM)

- Inclusion of B-mode polarization data can probe the full range of this model.

[Shiraishi, Ricciardone and Saga]

Parity Violating Effects

- Only one helicity of GWs is efficiently generated since $A_+ + A_+ \to h_R$
- Level of Chirality: $\Delta\chi \equiv \frac{P^R_{\rm GW} - P^L_{\rm GW}}{P^R_{\rm GW} + P^L_{\rm GW}} \simeq \frac{3.4 \cdot 10^{-5}\, \epsilon\, \mathcal{P}\, \frac{e^{4\pi\xi}}{\xi^6}}{1 + 3.4 \cdot 10^{-5}\, \epsilon\, \mathcal{P}\, \frac{e^{4\pi\xi}}{\xi^6}}$



PLANCK, SPIDER, CMBPol
and a (hypothetical)
cosmic variance limited experiment

[N. Barnaby, J. Moxon, R. Namba, M. Peloso, G. Shiu and P. Zhou]

Forecasted constraints (or signals) come from $l \lesssim 10$ [Gluscevic, Kamionkowski]; do not expect constraints from BICEP2 (their jackknifed <TB> & <EB> signals appears consistent with zero).