Gravitational Waves from Inflation

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Outline

- General properties and importance for cosmology
- Current bounds and detectability
- Particle sources during inflation
- Tensor fossils
- Polarized Sunyaev–Zeldovich tomography

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- General properties and importance for cosmology
- Current bounds and detectability
- Particle sources during inflation

  1806.05474 - ED, **Fasiello**, Hardwick, Koyama, Wands
  1608.04216 - ED, **Fasiello**, **Fujita**
  1411.3029 - **Biagetti**, ED, **Fasiello**, Peloso

- Tensor fossils

  1708.01587 - **Biagetti**, ED, **Fasiello**
  1407.8204 - ED, **Fasiello**, Jeong, Kamionkowski
  1504.05993 - ED, **Fasiello**, Kamionkowski

- Polarized Sunyaev–Zeldovich tomography

  1810.09463 - Deutsch, ED, **Fasiello**, Johnson, **Muenchmeyer**
  1707.08129 - Deutsch, ED, Johnson, **Muenchmeyer**, Terrana

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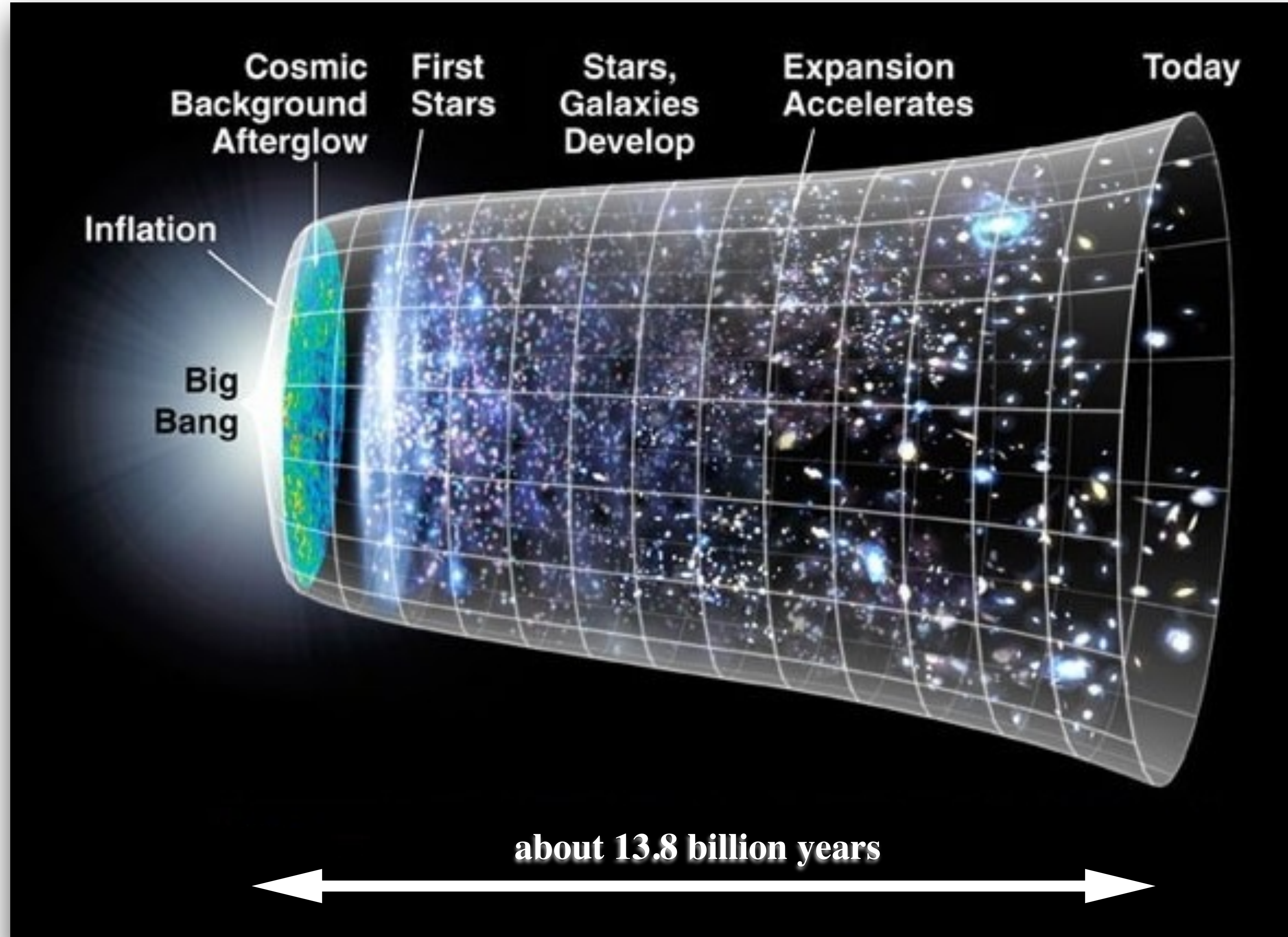
The universe over time



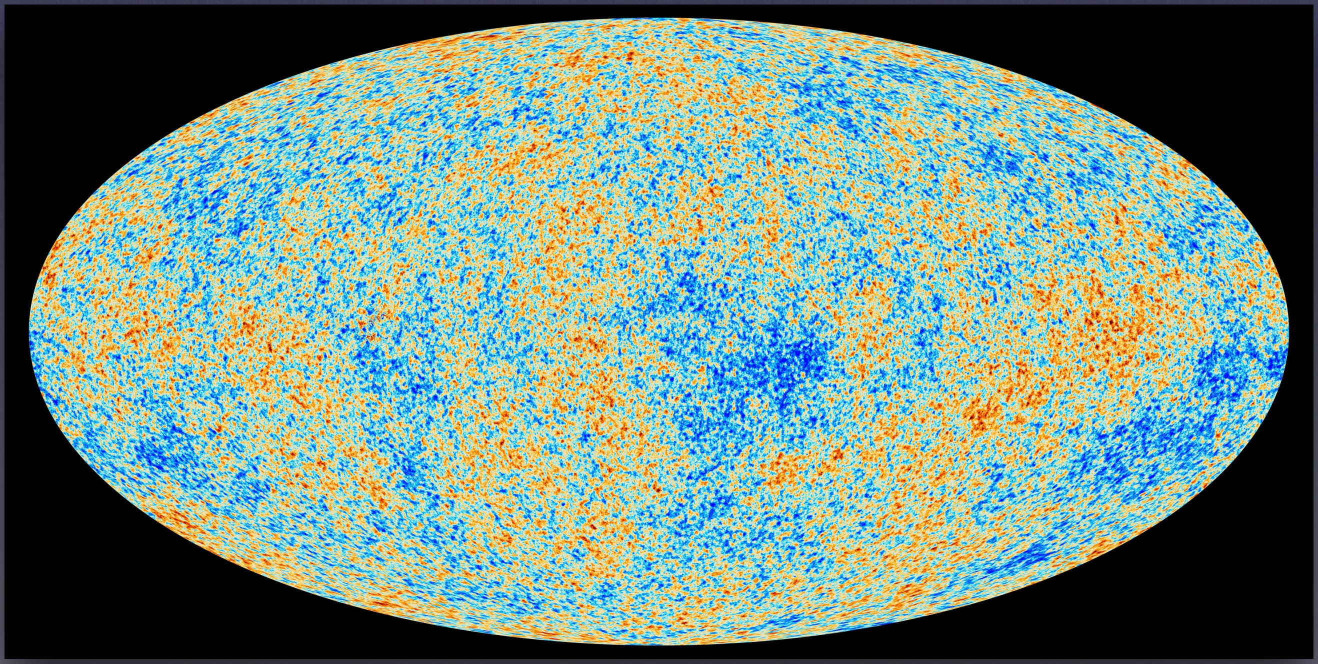
Cosmic Microwave Background

decoupling of radiation from matter occurs at T ~ 3000 K
(today: T ~ 2.7 K)

photons propagate freely after decoupling

↓

fossil radiation, providing a snapshot of the early universe



Primordial Gravitational waves

also a fossil radiation

↓

GW carry direct information about their sources and retain memory of the universe history!

Possible GW production mechanisms in the early universe

- Inflation: amplification of vacuum fluctuations
- Inflation: particle production
- Preheating
- Alternatives to inflation
- Phase transitions
- Cosmic strings
- …

GW:
great potential for discovery of new physics!

Possible GW production mechanisms in the early universe

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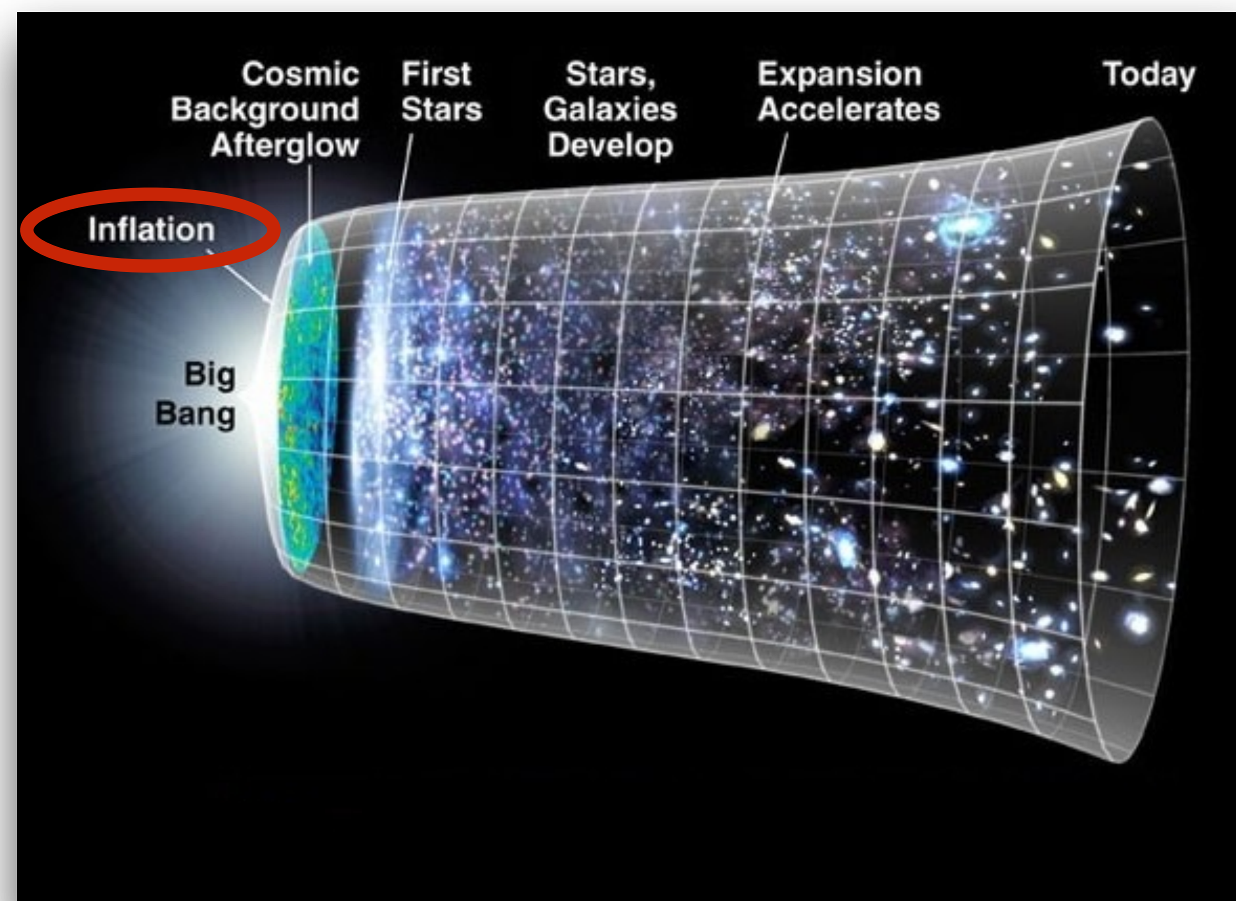
- …

GW:
great potential for discovery of new physics!

Inflation

- postulated era of accelerated expansion in the very early universe
- explains why CMB is <u>nearly perfectly uniform</u> across scales that were super horizon at decoupling
- explains how those tiny fluctuations were generated

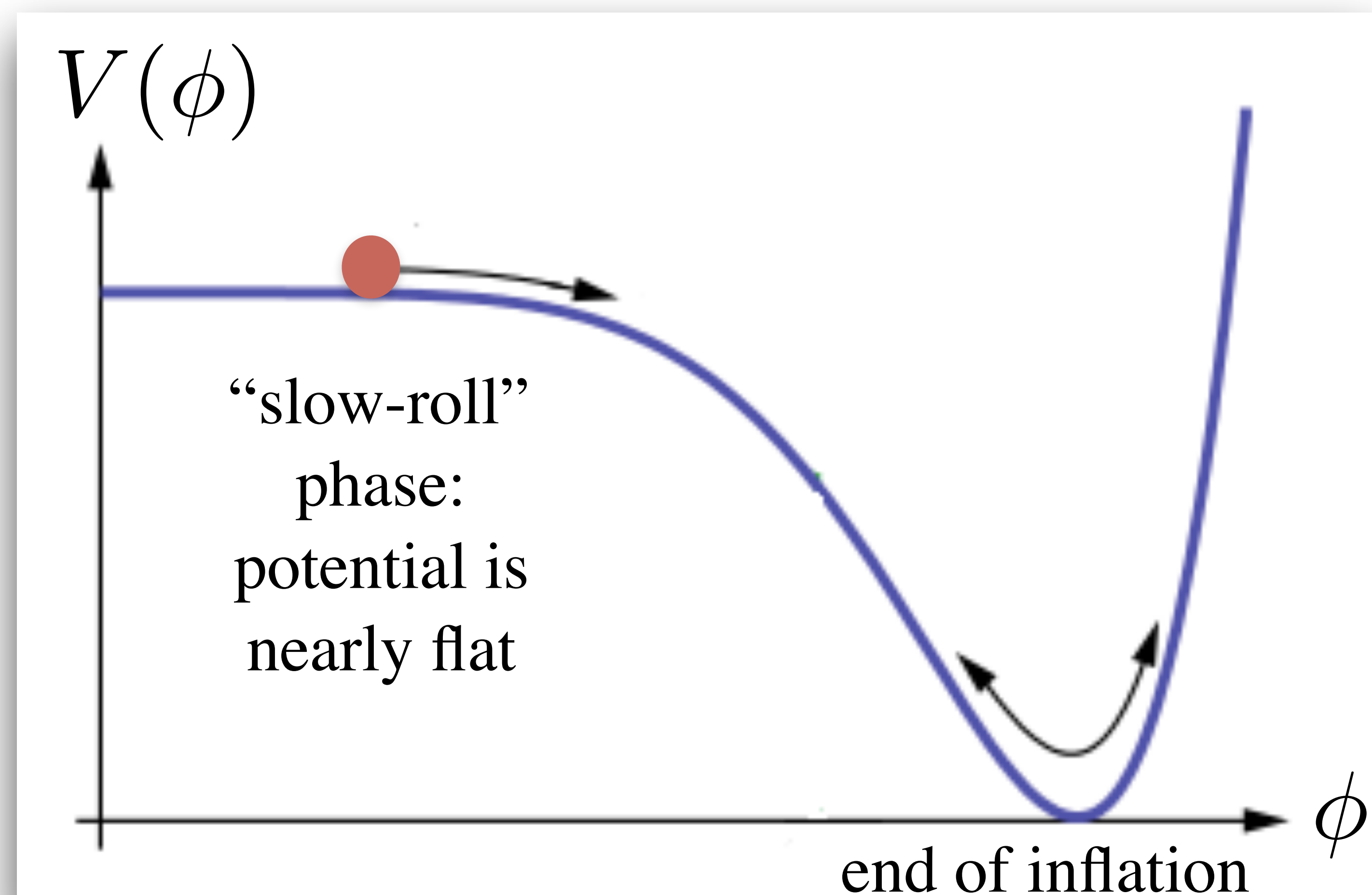


Inflation

Simplest realization: single-scalar field in slow-roll (SFSR)

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

classical
homogeneous
background



Inflation

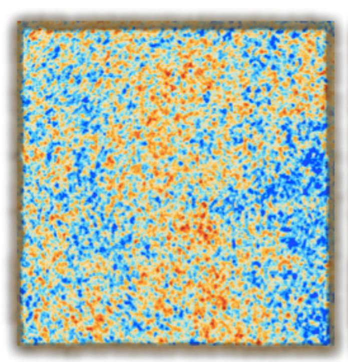
Simplest realization: single-scalar field in slow-roll (SFSR)

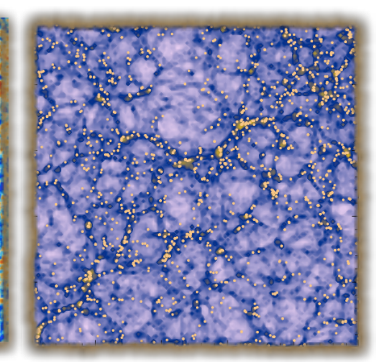
$$\varphi(\vec{x},t) = \phi(t) + \delta\phi(\vec{x},t)$$

quantum
fluctuations

cosmological
perturbations

ΔT $\delta\rho$





Two-point statistics of primordial perturbations: scalars

$$\delta\phi \to \zeta \to \delta T$$

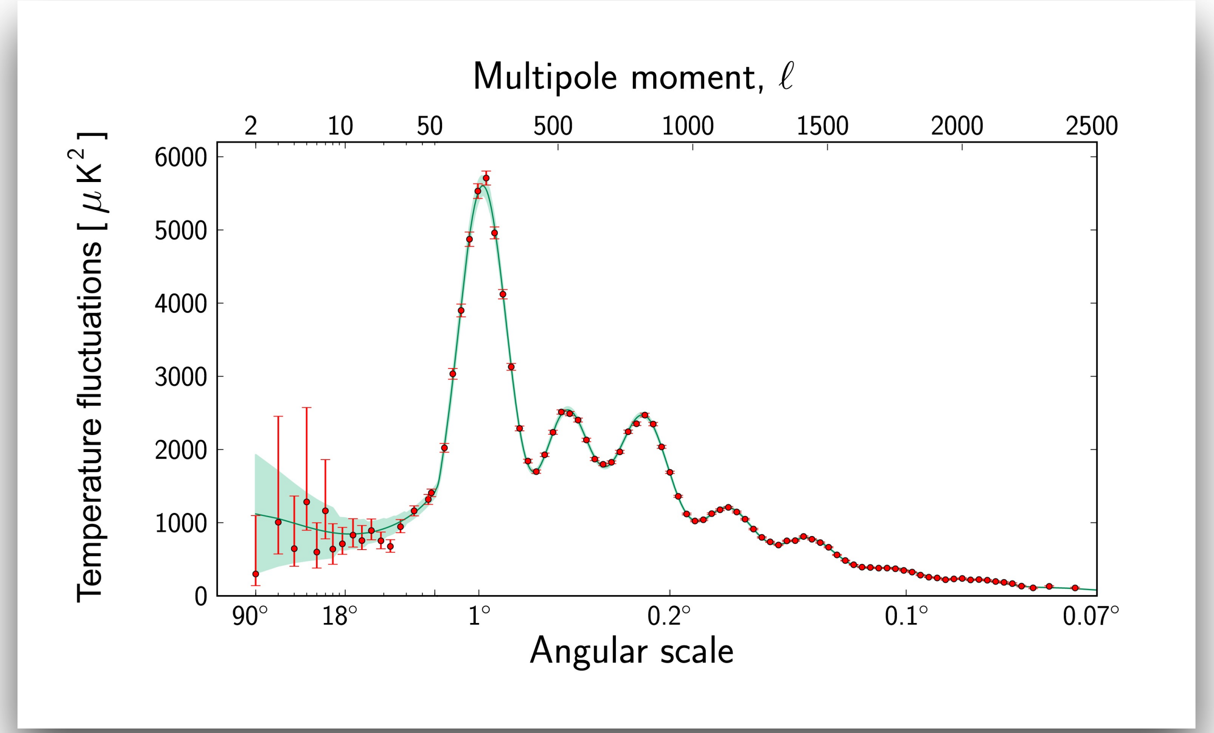
$$\mathcal{P}_\zeta(k) = \frac{1}{8\pi^2}\frac{1}{\epsilon}\frac{H^2}{M_{\rm pl}^2}\left(\frac{k}{k_*}\right)^{n_s - 1}$$

0.968 ± 0.006

2.2×10^{-9}

$[k_* = 0.05\,\mathrm{Mpc}^{-1}, 68\%\mathrm{C.L.}]$

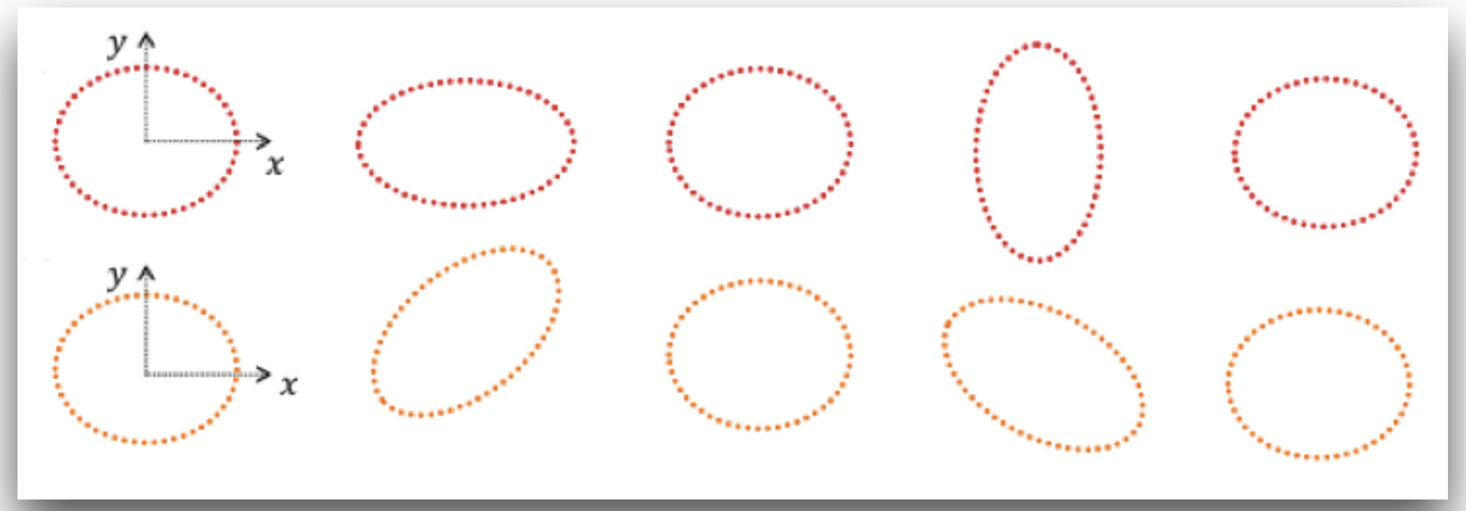
from Planck measurements of CMB anisotropies



Gravitational waves

$$ds^2 = -dt^2 + a^2(t)\left(\delta_{ij} + \gamma_{ij}\right) dx^i dx^j$$

$\gamma_i^i = \partial_i \gamma_{ij} = 0$ **two polarization states of the graviton**



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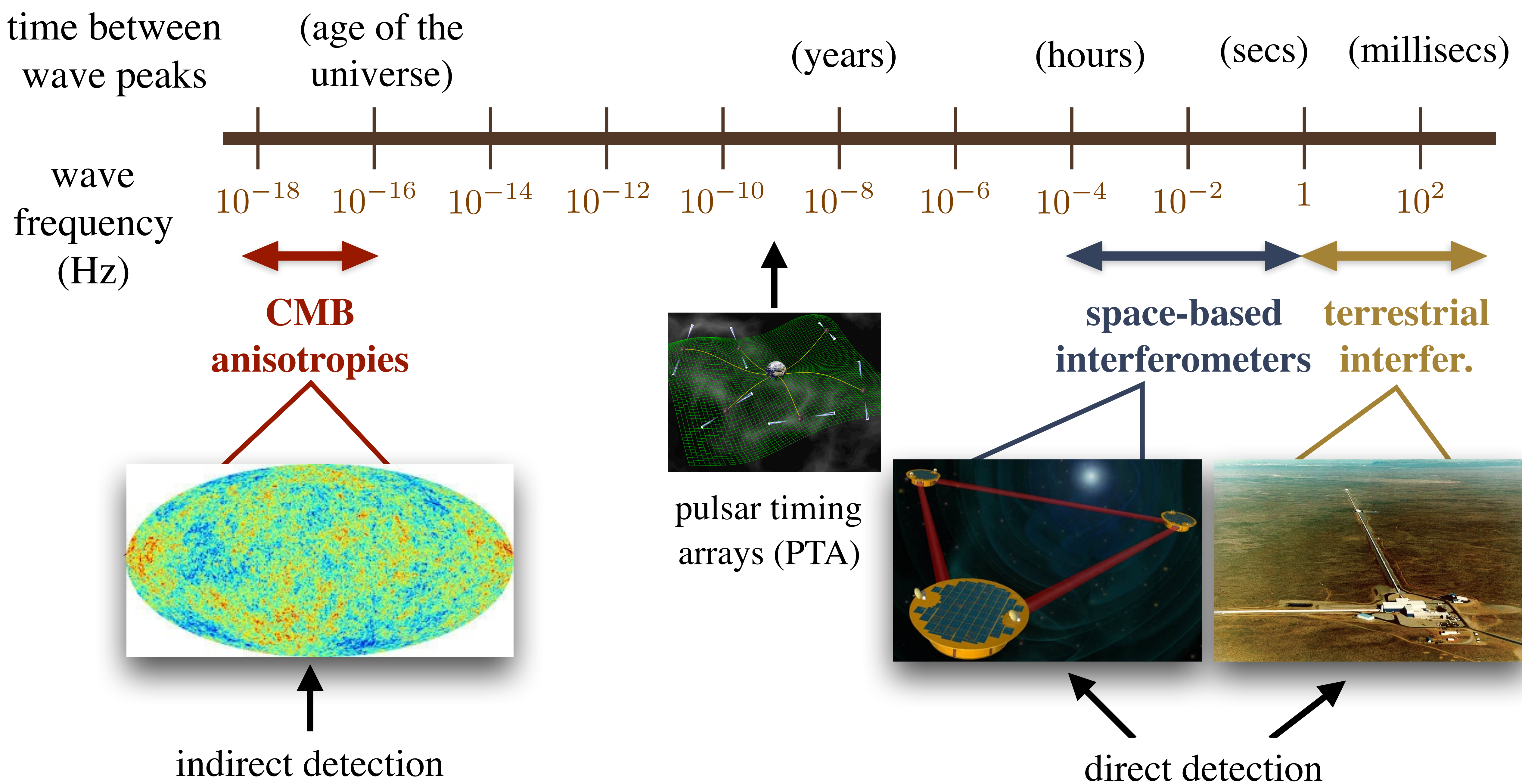
Scales — Experiments



Observational bounds/sensitivities

$r_{[0.05\,\mathrm{Mpc}^{-1}]} < 0.06$

BICEP2/KECK+Planck

$\longrightarrow$

$H \lesssim 5 \times 10^{13}\,\mathrm{GeV}$

upper bound on the energy scale of inflation

$\longrightarrow$ $\sigma(r) = 0.0005$

(CMBS4)

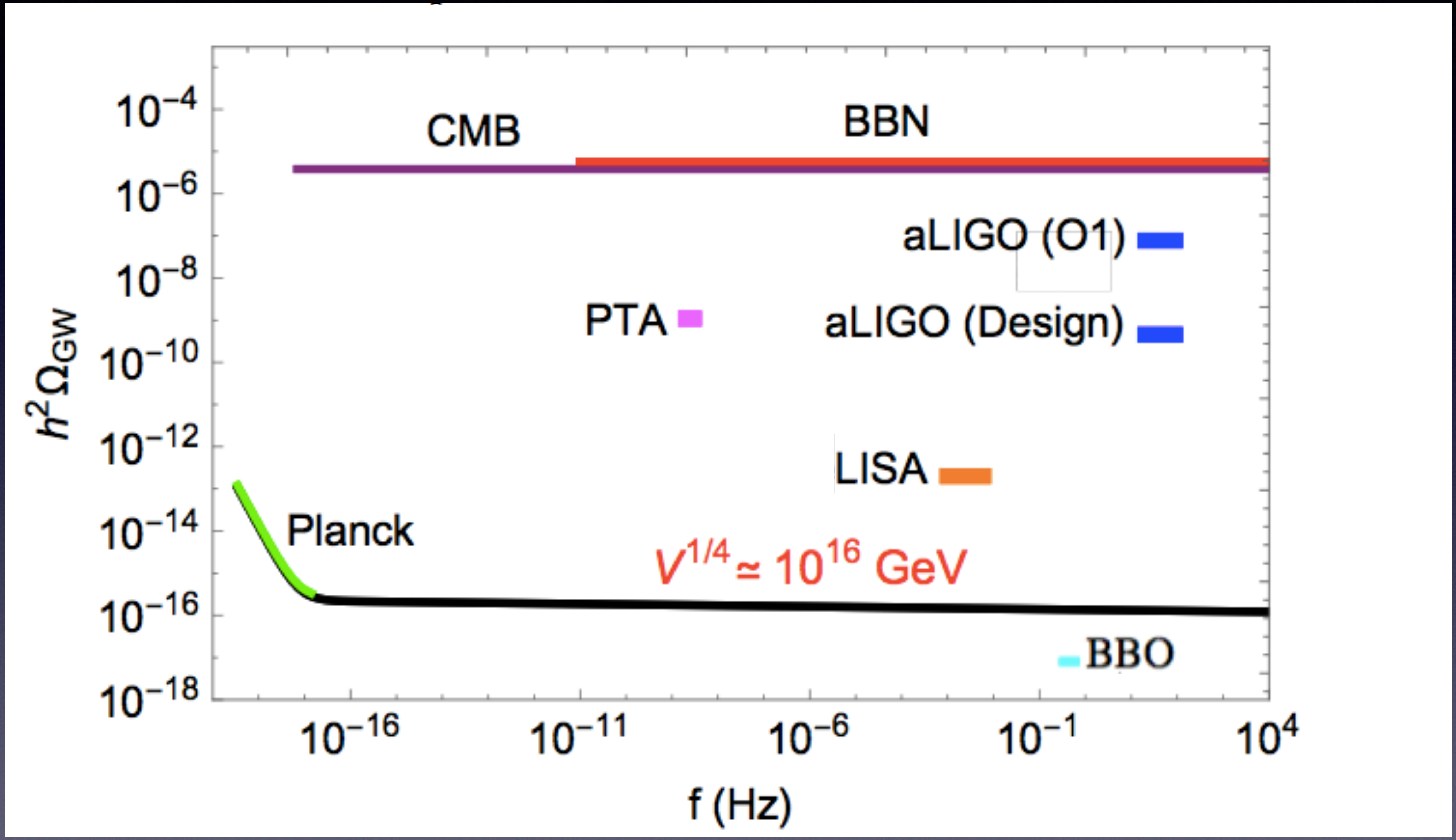
Implications for model building:

$$\frac{\Delta\phi}{M_{\rm pl}} \gtrsim \left(\frac{r_*}{8}\right)^{1/2} \mathcal{N}_* \gtrsim \left(\frac{r_*}{0.01}\right)^{1/2}$$

threshold for large field inflation

$$\boxed{r \equiv \frac{\mathcal{P}_\gamma}{\mathcal{P}_\zeta}}$$

Observational bounds/sensitivities



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GW background from inflation

$$\ddot{\gamma}_{ij} + 3H\dot{\gamma}_{ij} + k^2\gamma_{ij} = 16\pi G\,\Pi_{ij}^{TT}$$

anisotropic stress-energy tensor (from δT_{ij})

- **homogeneous** solution: GWs from **vacuum fluctuations**

- **inhomogeneous** solution: GWs from **sources**

$$\Pi_{ij}^{TT} \propto \quad \{\partial_i\phi\,\partial_j\phi\}^{TT} \quad \{E_iE_j + B_iB_j\}^{TT} \quad \{\sigma_{ij}\}^{TT}$$

scalars — vectors — tensors

GW background from inflation

- **homogeneous** solution: GWs from **vacuum fluctuations**

energy scale of inflation

$$\mathcal{P}_\gamma^{\mathrm{vacuum}}(k) = \frac{2}{\pi^2}\frac{H^2}{M_{\mathrm{pl}}^2}\left(\frac{k}{k_*}\right)^{n_T}$$

$n_T = -r/8$

red tilt:
amplitude decreases
as we go towards
smaller scales

and non-chiral!!!

GW background from inflation

$$\ddot{\gamma}_{ij} + 3H\dot{\gamma}_{ij} + k^2\gamma_{ij} = 16\pi G\,\Pi_{ij}^{TT}$$

- **inhomogeneous** solution: GWs from **sources**

INFLATON + **SPECTATOR** SECTOR

negligible energy density
compared to the inflaton

$$P_\gamma^{\rm tot} = P_\gamma^{\rm vacuum} + P_\gamma^{\rm spectator}$$

Why additional fields?

- **Natural** from a top-down perspective:
  plenty of candidates from string theory (e.g. moduli fields, axions, Kaluza-Klein modes, gauge fields…)

- **Interesting** for phenomenology:
  qualitatively different signatures w.r.t. basic single-field inflation
  $\longrightarrow$ **testable!**

Scalar field (I)

- Spectator fields with small sound speed

$$P(X,\sigma)$$

- subdominant at the background level
- relevant for perturbations

$$X \equiv -(\partial\sigma)^2$$

$$c_s^2 = \frac{P_X}{P_X + \dot{\sigma}_0^2 P_{XX}} < 1$$

small sound speed:
from integrating out heavy fields

$$\ddot{\gamma}_{ij} + 3H\dot{\gamma}_{ij} + k^2\gamma_{ij} = 16\pi G\,\Pi_{ij}^{TT} \propto \partial_i\sigma\partial_j\sigma$$

$$P_\gamma^{\rm spectator} \propto \frac{1}{c_s^n}\frac{H^4}{M_P^4}$$

Sourced may be comparable to or (just slightly) larger than vacuum

Breaking standard r—H relation: $r = f(\epsilon, c_s)$

[Biagetti, Fasiello, Riotto 2012, Biagetti, ED, Fasiello, Peloso 2014, Fujita, Yokoyama, Yokoyama, 2014]

Scalar field (II)

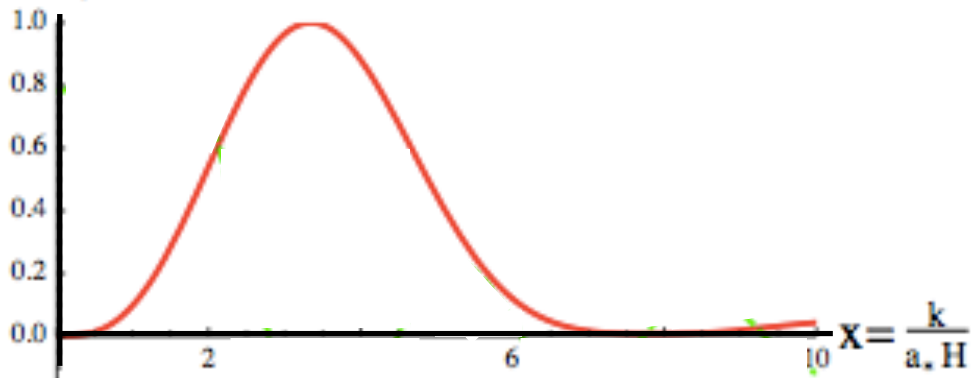
- Auxiliary scalars with time-varying mass

$$\frac{g^2}{2}\left(\phi-\phi_*\right)^2\chi^2$$

particle **burst** when inflaton crosses over ϕ_* value

graviton (**and scalar fluctuations!**) production

features in the power spectra

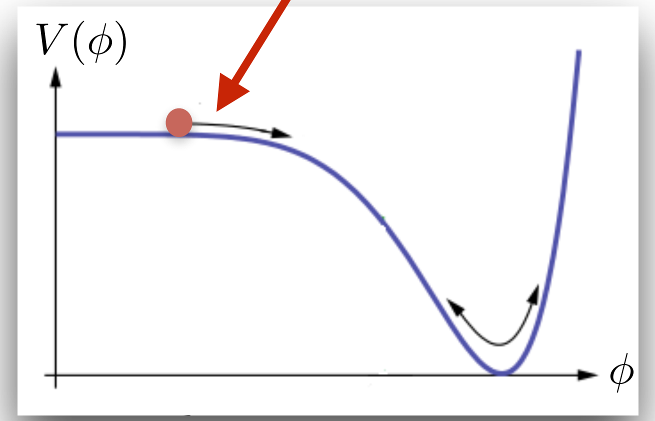


[Chung et al., 2000, Senatore et al, 2011, Pearce et al, 2017]

Axion-Gauge fields models: genesis

- Generic requirement for inflation: nearly flat potential: $\epsilon, \ |\eta| \ll 1$

$$\epsilon \equiv \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2 \ , \ \eta \equiv M_p^2 \frac{V''}{V}$$



… but flatness may be spoiled by radiative corrections!

- Flatness protected by axionic shift symmetry $\phi \rightarrow \phi + c$

$\longrightarrow$ Natural Inflation $\quad V(\varphi) = \Lambda^4 \left[1 - \cos\left(\varphi/f\right)\right]$

[Freese, Frieman, Olinto 1990]

- Agreement with observations requires: $f \gtrsim M_P$

undesirable constraint on the theory

[Kallosh, Linde, Susskind, 1995, Banks et al, 2003]

Axion-Gauge fields models: motivation

$$\frac{\lambda\chi}{4f}F\tilde{F}$$

- naturally light inflaton
- sub-Planckian axion decay constant
- support reheating

Axion-Gauge fields models: SU(2)

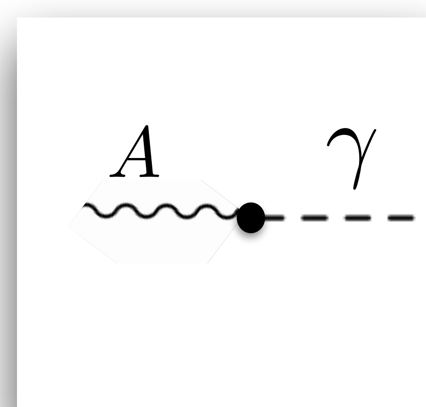
$$\mathcal{L} = \mathcal{L}_{\rm inflaton} \underbrace{- \frac{1}{2}(\partial\chi)^2 - U(\chi) - \frac{1}{4}FF + \frac{\lambda\chi}{4f}F\tilde{F}}_{\mathcal{L}_{\rm spectator}}$$

$$\mathcal{L}_{\rm inflaton} \rightarrow P_{\gamma,\rm vacuum} \qquad \mathcal{L}_{\rm spectator} \rightarrow P_{\gamma,\rm sourced}$$

- Inflaton field dominates energy density of the universe
- Spectator sector contribution to curvature fluctuations negligible

$$\boxed{\begin{aligned} A_0^a &= 0 \\ A_i^a &= aQ\delta_i^a \end{aligned}}$$ slow-roll background attractor solution

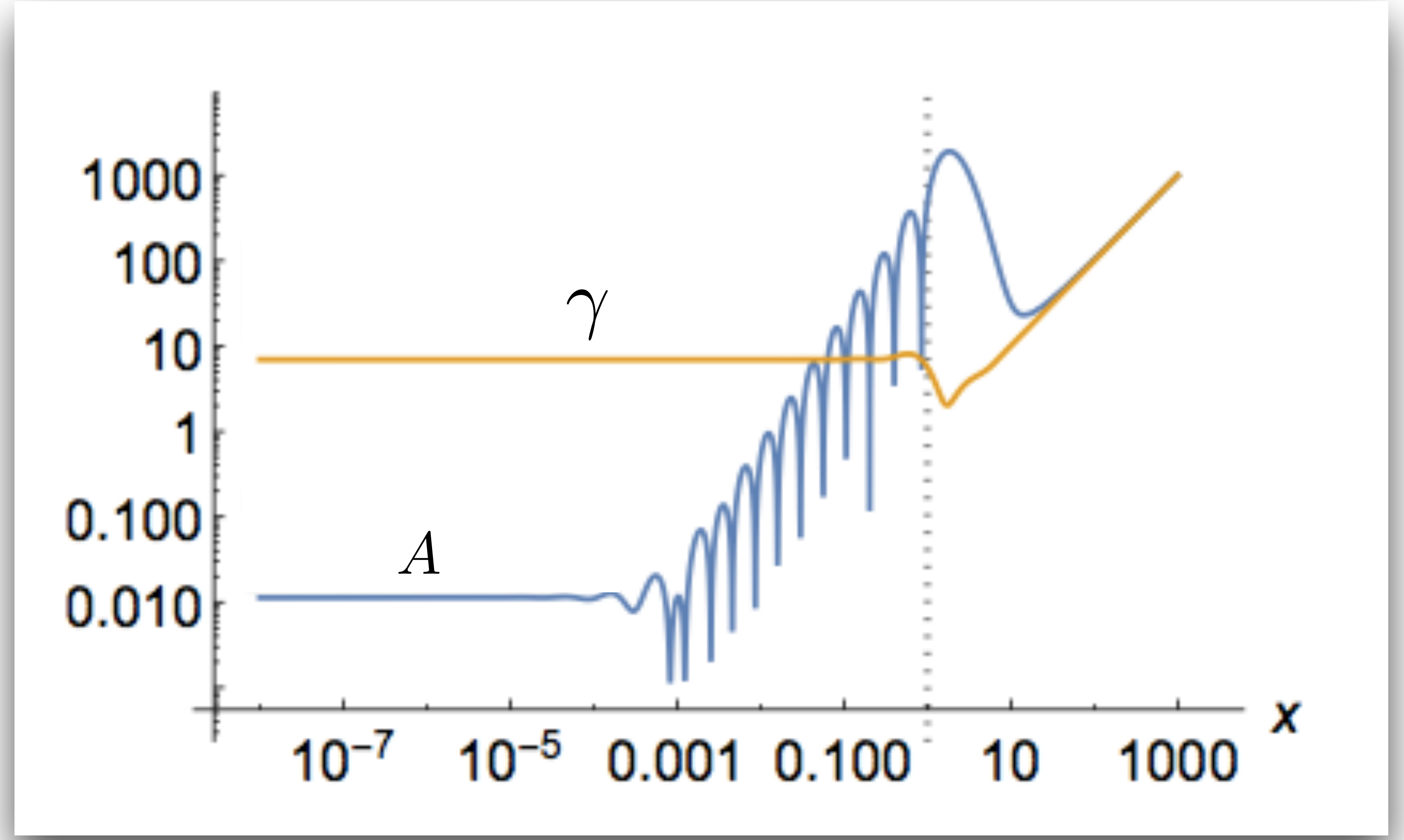
$$\boxed{\delta A_i^a = t_{ai} + \ldots}$$ TT-component



[ED-Fasiello-Fujita 2016]

Axion-Gauge fields models: SU(2)

One helicity of the gauge field fluctuations is amplified from coupling with axion $\longrightarrow$ the same helicity of the tensor mode is amplified



[ED-Fasiello-Fujita 2016]

Axion-Gauge fields models: signatures

- Scale dependence
- Chirality
- Non-Gaussianity

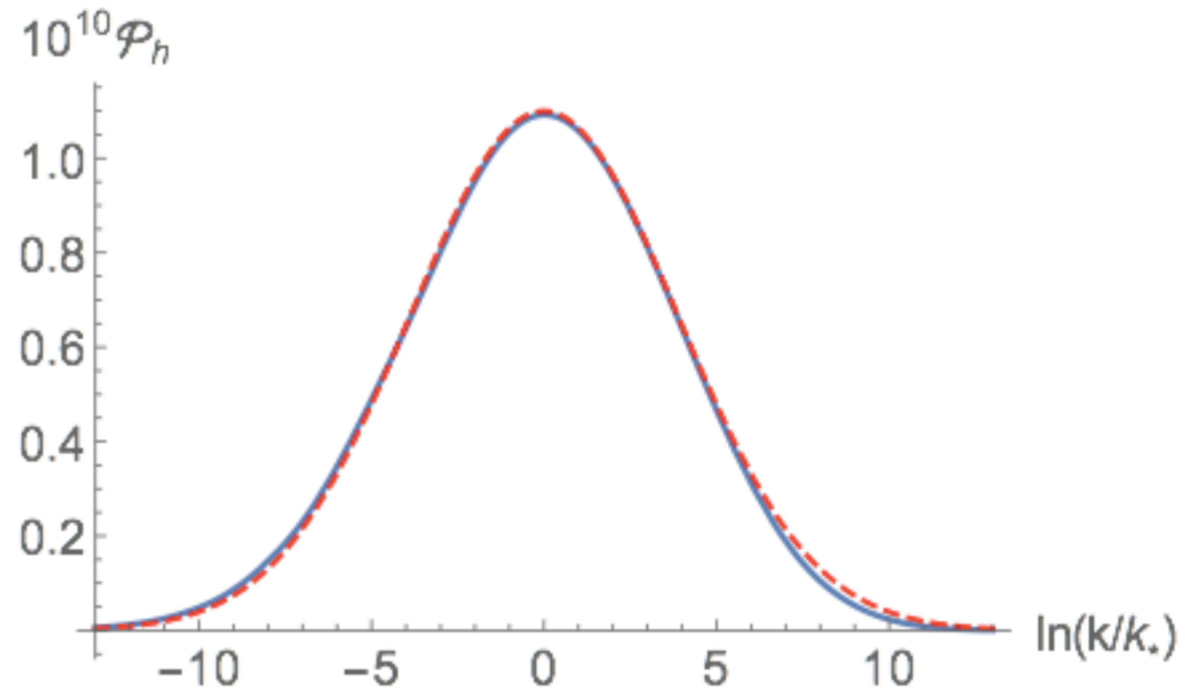
Scale-dependence

basic single-field inflation

$$n_T \simeq -r/8$$

(nearly flat spectrum)

axion-gauge fields models



- detectably large and running n_T
- bump may occur at small scales

[ED-Fasiello-Fujita 2016, Thorne et al, 2017]

Chirality

basic single-field inflation

$$\gamma_L = \gamma_R$$

non-chiral

$$\langle TB \rangle, \langle EB \rangle = 0$$

(parity conservation)

axion-gauge fields models

$$\gamma_L \neq \gamma_R$$

chiral

$$\langle TB \rangle, \langle EB \rangle \neq 0$$

Detectable at 2σ by LiteBIRD for r > 0.03

[Thorne et al, 2017]

Chirality

basic single-field inflation

$$\gamma_L = \gamma_R$$

non-chiral

axion-gauge fields models

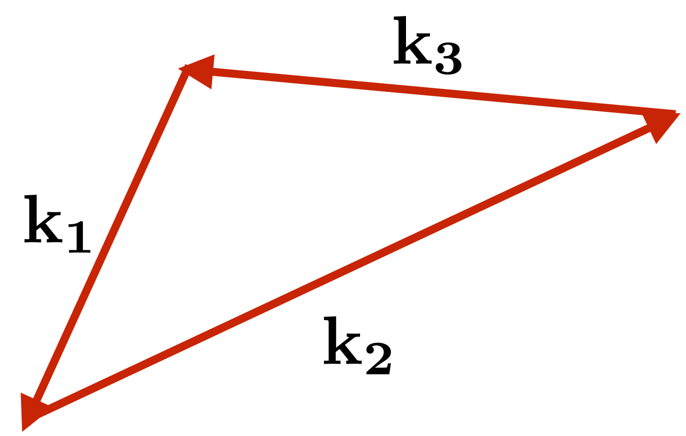
$$\gamma_L \neq \gamma_R$$

chiral

$\downarrow$

Interferometers:
need advanced design with multiple
(non co-planar) detectors
[Thorne et al. 2017, Smith-Caldwell 2016]

Non-Gaussianity: beyond the power spectrum

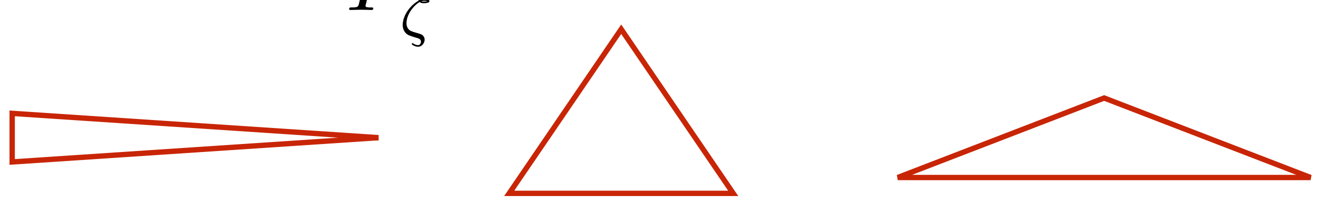


$$\langle \gamma^{\lambda_1}_{\mathbf{k_1}} \gamma^{\lambda_2}_{\mathbf{k_2}} \gamma^{\lambda_3}_{\mathbf{k_3}} \rangle = (2\pi)^3 \delta^{(3)}(\mathbf{k_1} + \mathbf{k_2} + \mathbf{k_3}) B_\gamma^{\lambda_1 \lambda_2 \lambda_3}(k_1, k_2, k_3)$$

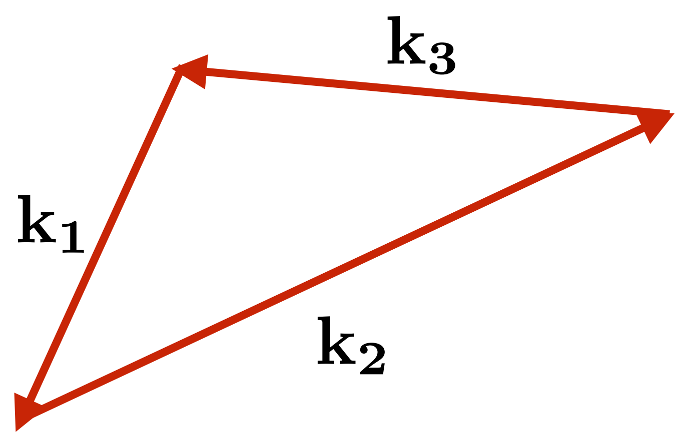
tensor bispectrum

amplitude: $f_{NL} = \dfrac{B}{P_\zeta^2}$

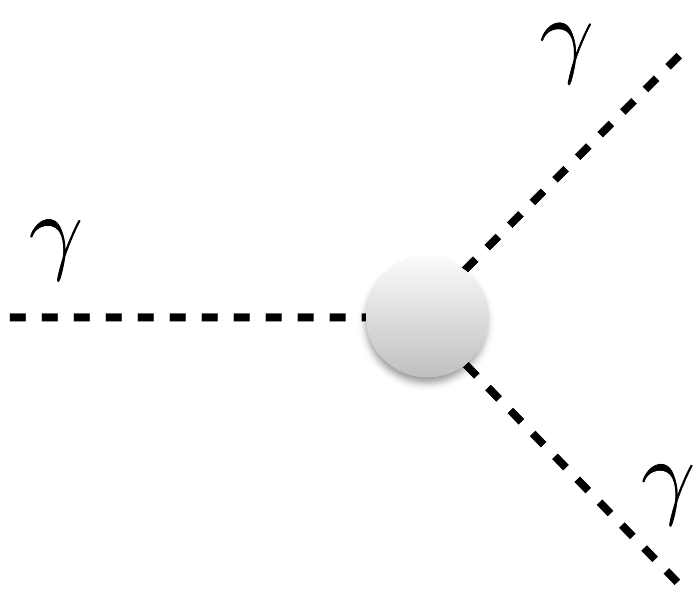
shape:



Tensor non-Gaussianity

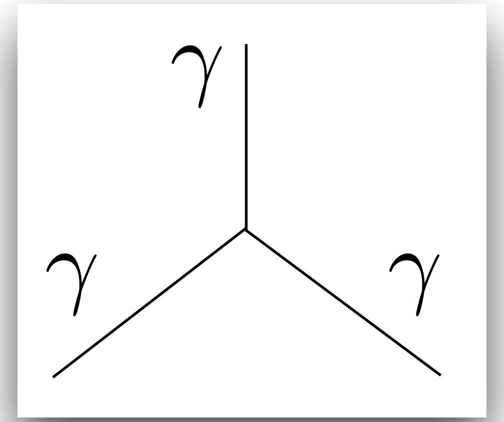


from interactions of the tensors with other fields or from self-interactions



Tensor non-Gaussianity

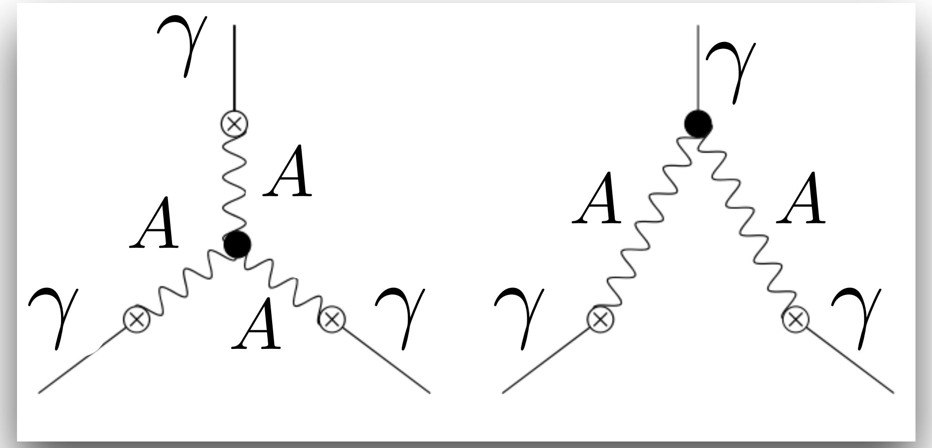
basic single-field inflation



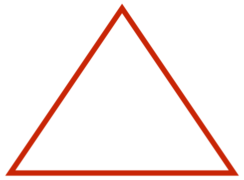
$$f_{NL} = \mathcal{O}(r^2)$$

too small for detection

axion-gauge fields models



$$f_{NL} = r^2 \cdot \frac{50}{\epsilon_B}$$

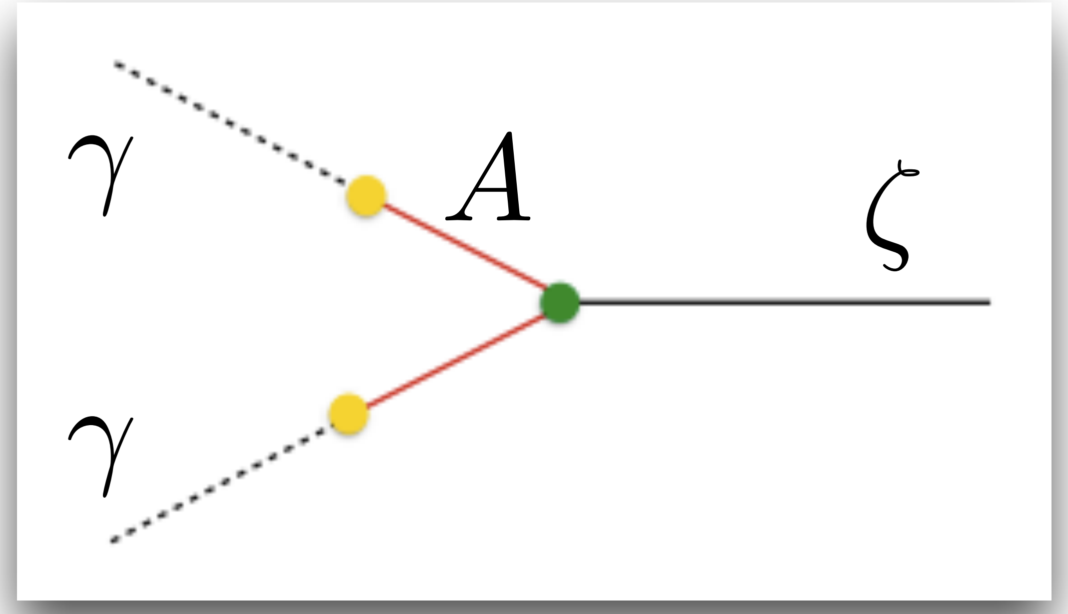


- detectable by upcoming CMB space missions

[Agrawal - Fujita - Komatsu 2017]

Mixed (scalar-tensor) non-Gaussianity

testing interactions of tensors and matter fields



potentially observable!

[ED - Fasiello - Hardwick - Koyama - Wands 2018, Fujita - Namba - Obata 2018]

Inflationary GWs from vacuum fluctuations

- Energy scale of inflation: $V_{\rm infl}^{1/4} \approx 10^{16}\mathrm{GeV}\,(r/0.01)^{1/4}$

  $H \approx 2 \times 10^{13}\sqrt{r/0.01}\,\mathrm{GeV}$

- Scalar field excursion (Lyth bound): $\Delta\phi/M_P \gtrsim (r/0.01)^{1/2}$

- Red tilt: $n_T \simeq -2\epsilon = -r/8$

- Non-chiral: $P_L = P_R$

- Nearly Gaussian: $f_{NL} \ll 1$

One or more of these predictions may be easily violated beyond the minimal set-up!

so far …

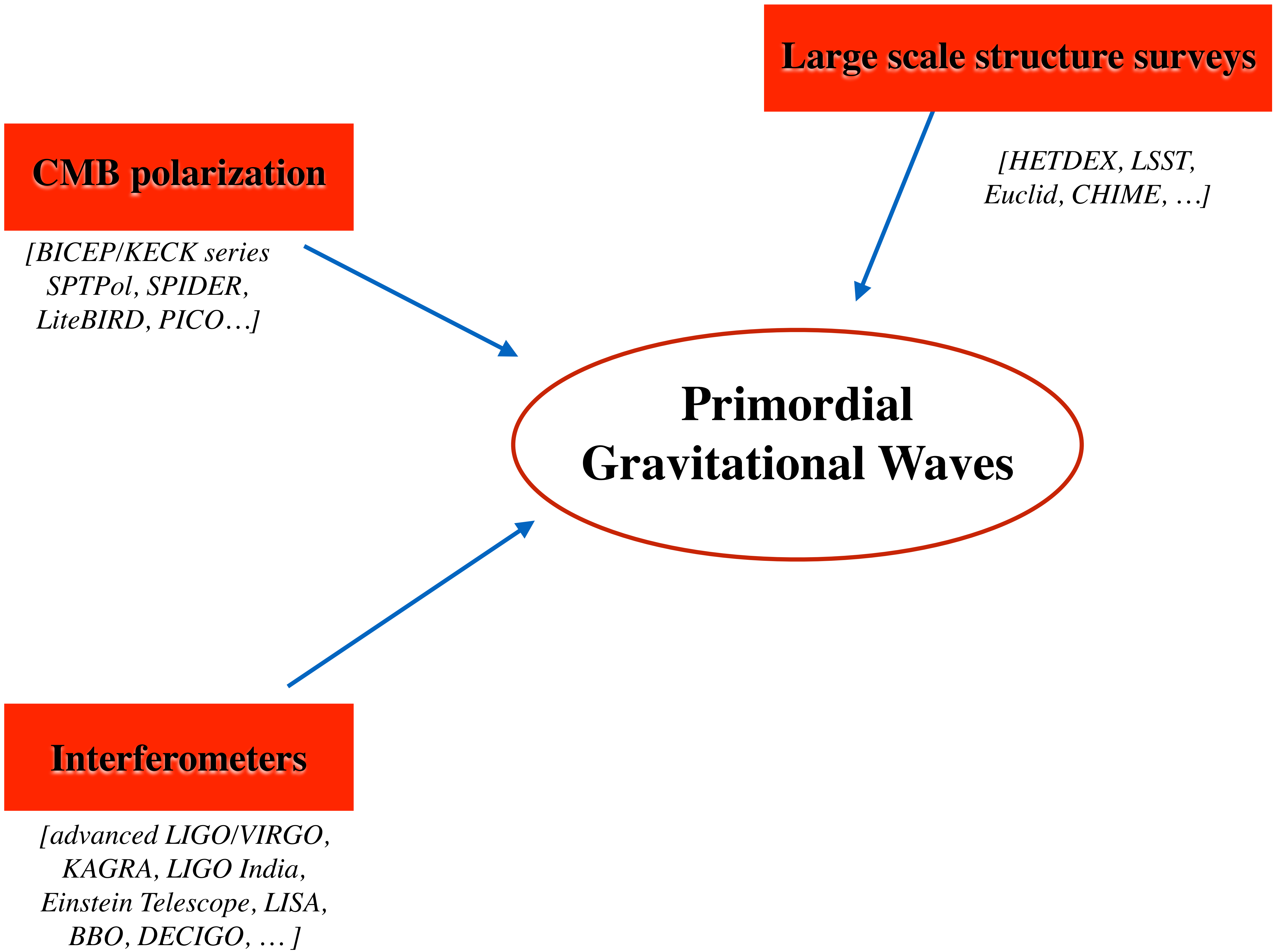
CMB polarization

*[BICEP/KECK series
SPTPol, SPIDER,
LiteBIRD, PICO…]*

Primordial Gravitational Waves

Interferometers

*[advanced LIGO/VIRGO,
KAGRA, LIGO India,
Einstein Telescope, LISA,
BBO, DECIGO, …]*


Large scale structure surveys
[HETDEX, LSST,
Euclid, CHIME, …]
CMB polarization
[BICEP/KECK series
SPTPol, SPIDER,
LiteBIRD, PICO…]
Primordial
Gravitational Waves
Interferometers
[advanced LIGO/VIRGO,
KAGRA, LIGO India,
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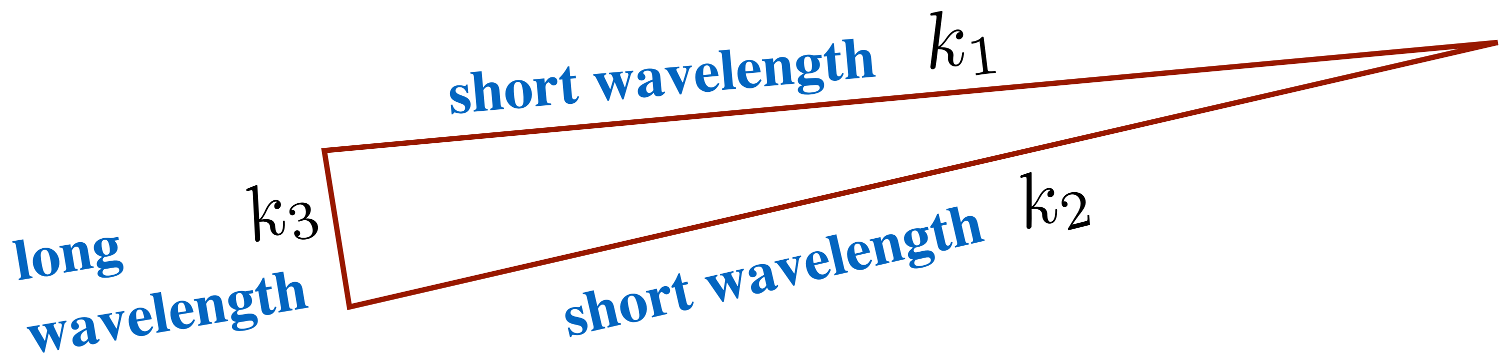
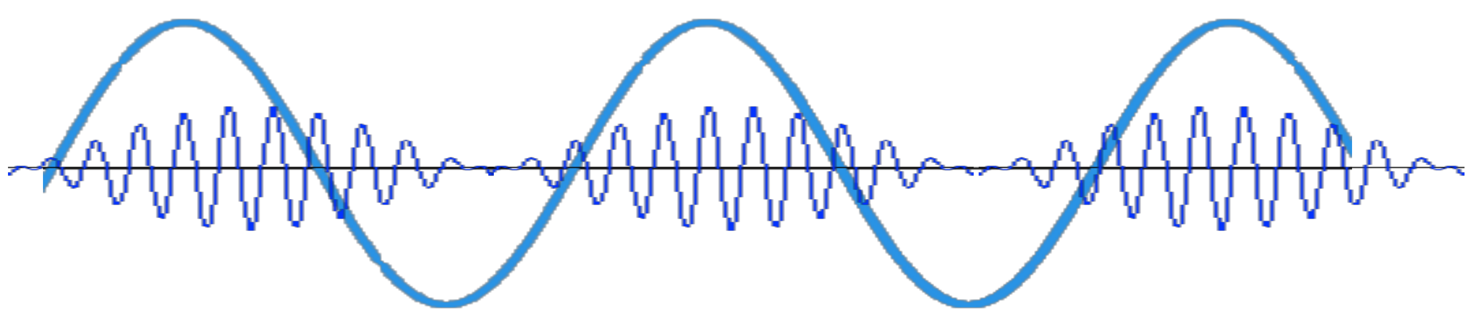
Squeezed non-Gaussianity

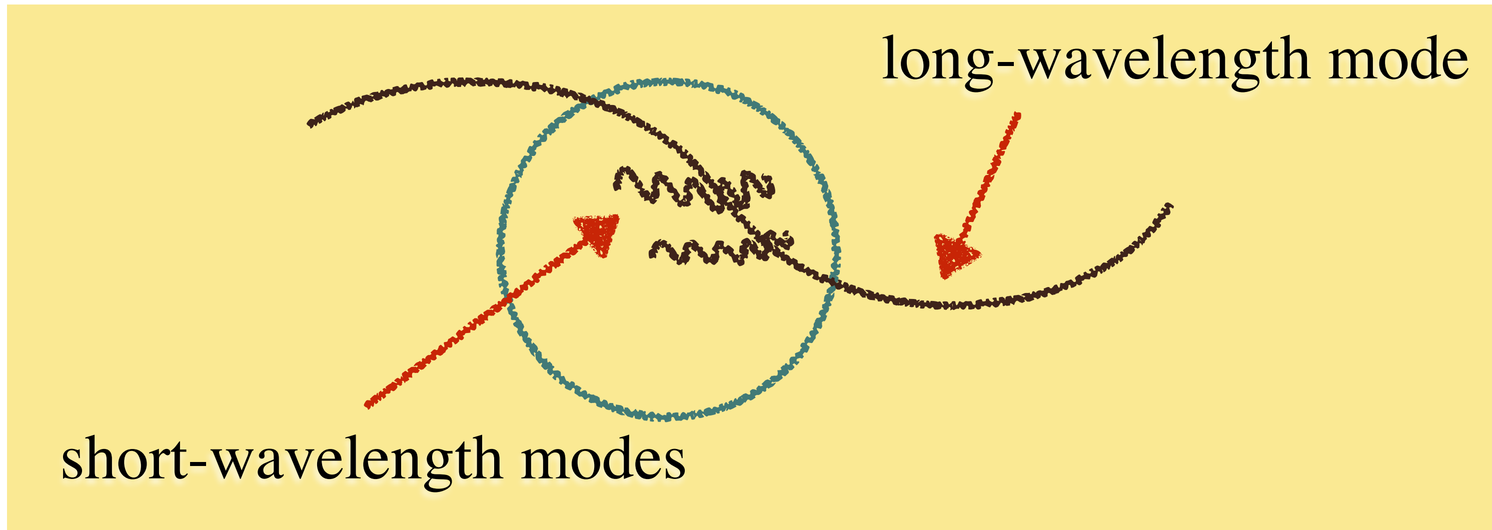


amplitude of long-wavelength modes
coupled with amplitude of short-wavelength modes



Soft limits and fossils

squeezed <u>3pf</u> affects the <u>2pf</u>

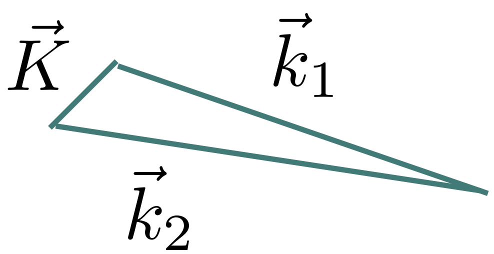


- No squeezed non-Gaussianity $\longrightarrow$ $\langle \delta_{\vec{k}_1} \delta_{\vec{k}_2} \rangle = \underline{\delta^{(3)}(\vec{k}_1 + \vec{k}_2)} P(k_1)$

diagonal
2p correlation

- Squeezed non-Gaussianity $\longrightarrow$ $\langle \delta_{\vec{k}_1} \delta_{\vec{k}_2} \rangle_{\vec{K}} = \underline{\delta^{(3)}(\vec{k}_1 + \vec{k}_2 + \vec{K})}$

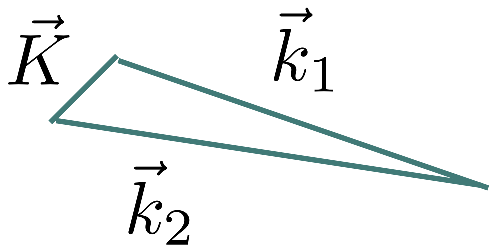
$$\times f(\vec{k}_1, \vec{k}_2) A(K)$$



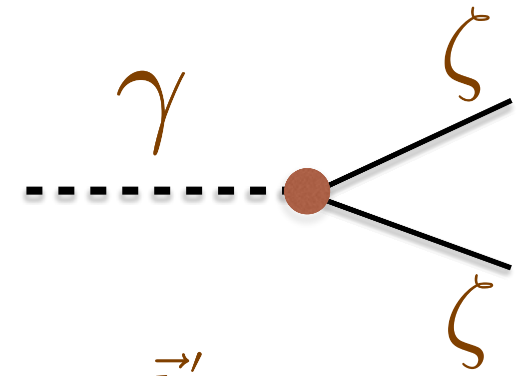
there is also a
off-diagonal
contribution!

Soft limits and fossils

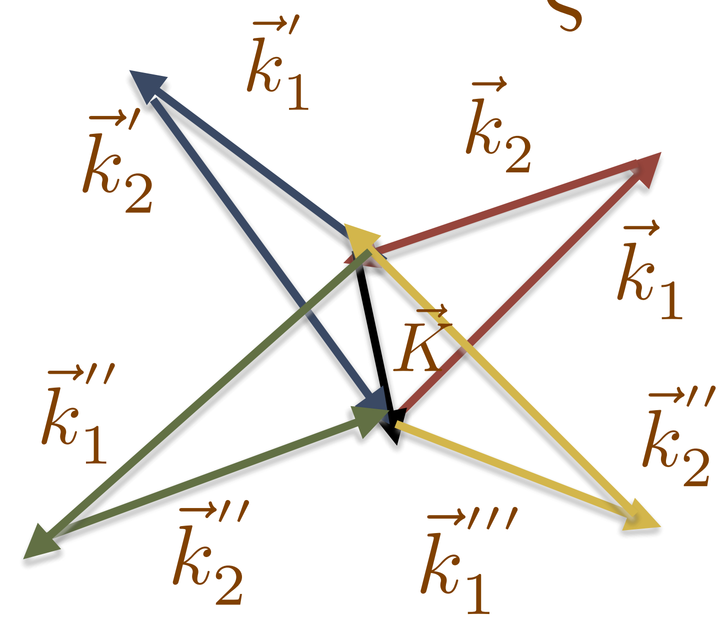
If



comes from



estimate tensor modes amplitude
from off-diagonal correlations



Learning about primordial tensors
through non-Gaussian effects!

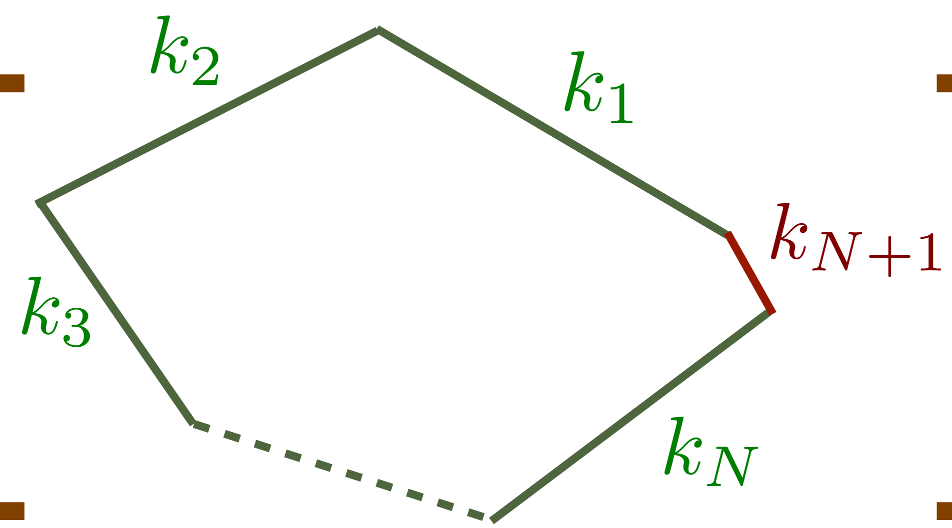
[ED, Fasiello, Jeong, Kamionkowski - 2014, ED, Fasiello, Kamionkowski - 2015, Biagetti, ED, Fasiello - 2017]

Why is squeezed non-Gaussianity so important?

Soft limits in inflation

SINGLE-FIELD (single-clock) inflation: soft-limits **not** observable

$$\lim_{k_{N+1}\to 0}\Big[$$



$$\Big] \sim 0$$

<u>Intuitive understanding</u> :

- Super-horizon modes freeze-out
- Standard initial conditions

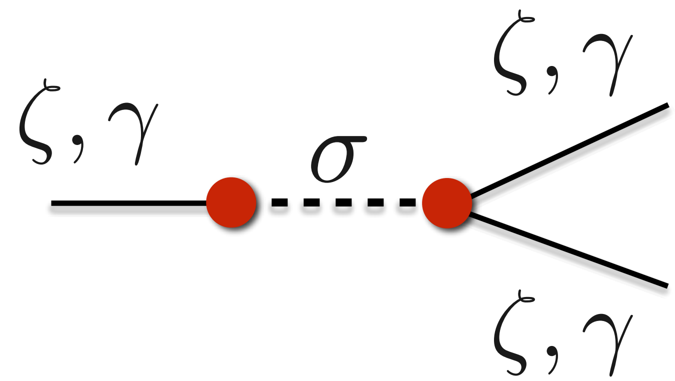
→

Soft mode rescales background for hard modes
Effect can be gauged away!

[Maldacena 2003, Creminelli, Zaldarriaga 2004]

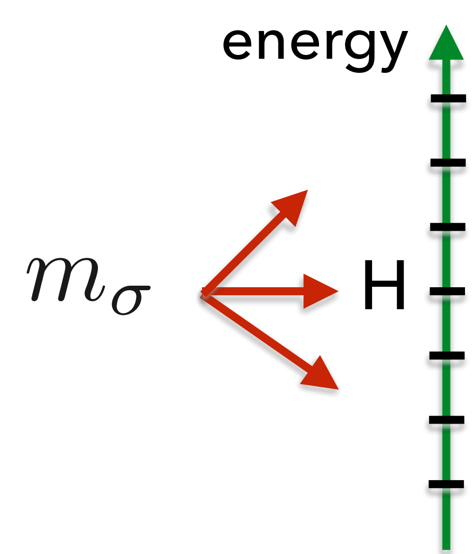
Soft limits in inflation

- ***Extra*** fields



Soft limits reveal (extra) fields mediating inflaton or graviton interactions

squeezed bispectrum delivers info on mass spectrum!!!



Soft limits in inflation

- ***Extra*** fields
  [Chen - Wang 2009, ED - Fasiello - Kamionkowski 2015, ED - Emami 2016, Biagetti - ED - Fasiello 2017, …]
- ***Non-Bunch Davies*** initial states
  [Holman - Tolley 2007, Ganc - Komatsu 2012, Brahma - Nelson - Shandera 2013, …]
- ***Broken space diffs***
  (e.g. space-dependent background)
  [Endlich et al. 2013, ED - Fasiello - Jeong - Kamionkowski 2014, …]

probe for (extra) fields, pre-inflationary dynamics, (non-standard) symmetry patterns

Tensor fossils

- Learning about primordial gravitational waves through non-Gaussian effects

- Local observables affected by long modes (anisotropic effects / off-diagonal correlations)

- Effects from “squeezed” tensor-scalar-scalar bispectrum particularly effective at constraining inflation!

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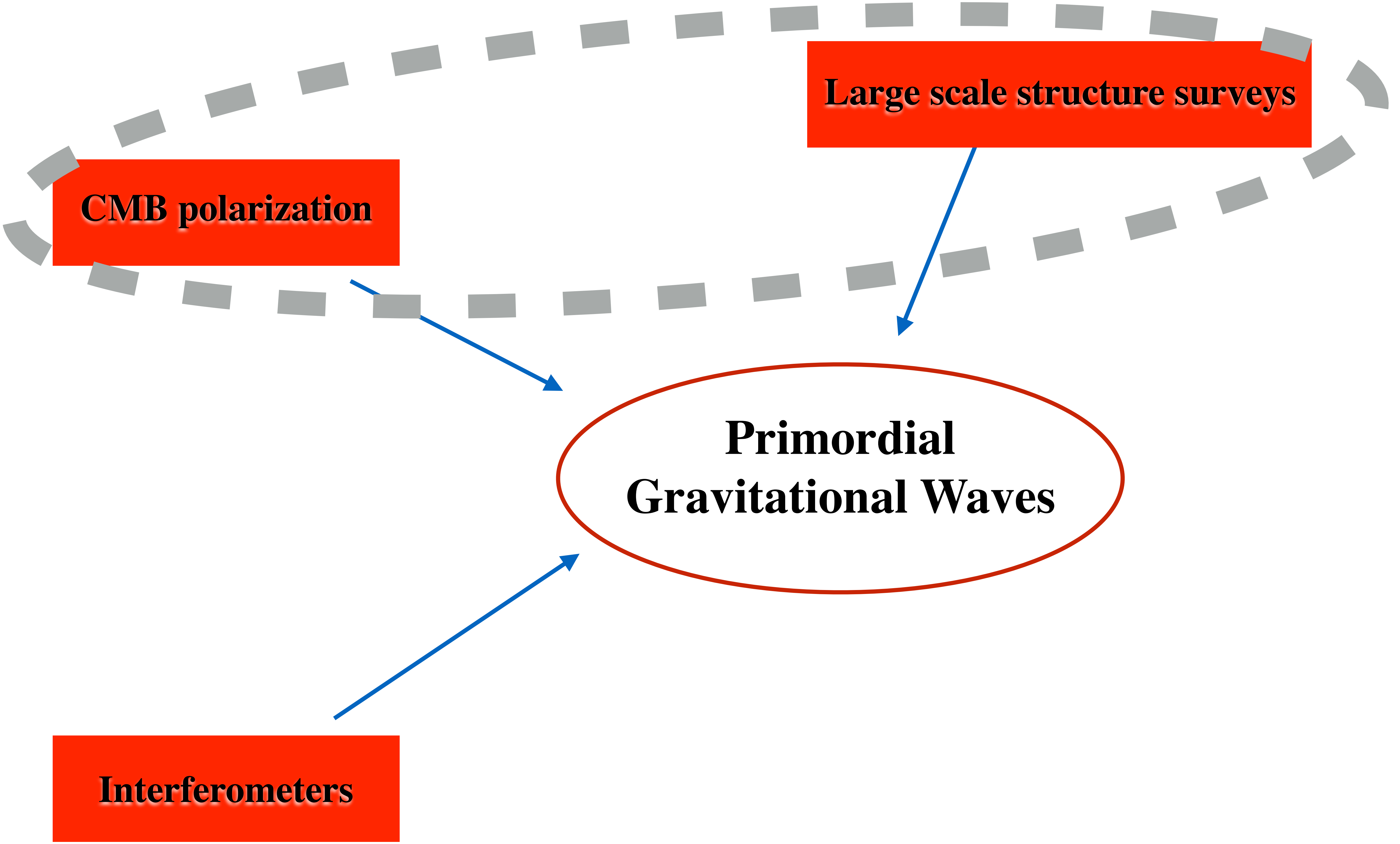
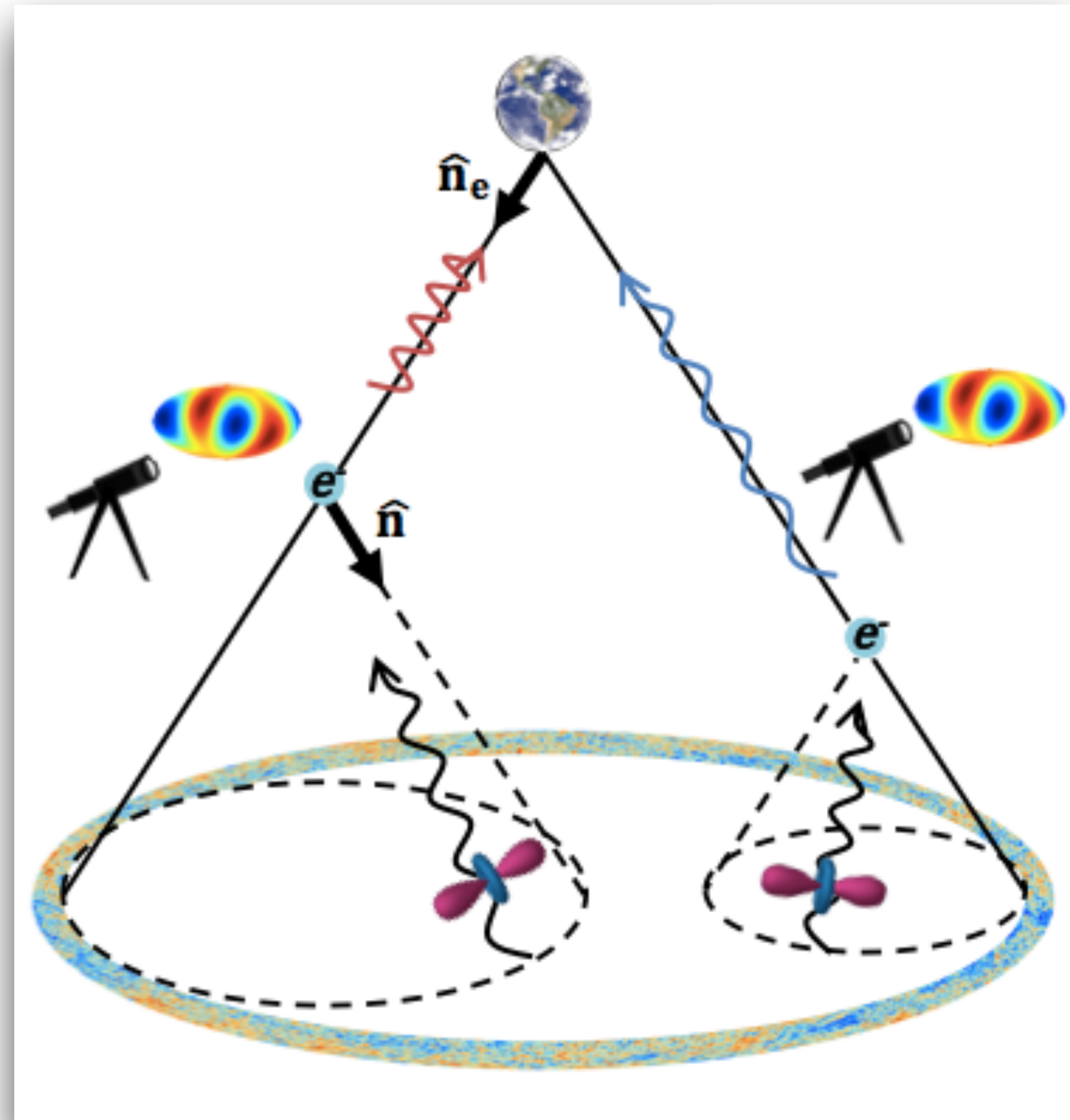
- Tensor fossils
- Polarized Sunyaev–Zeldovich tomography


Large scale structure surveys
CMB polarization
Primordial
Gravitational Waves
Interferometers

Polarized Sunyaev-Zel’dovich effect



- Polarization from Thomson scattering of (quadrupolar) radiation by free electrons

- Used to obtain a map of the remote (= locally observed) CMB **quadrupole**

- Additional information w.r.t. primary CMB (scattered photons from off our past light cone)

Polarized Sunyaev-Zel'dovich effect

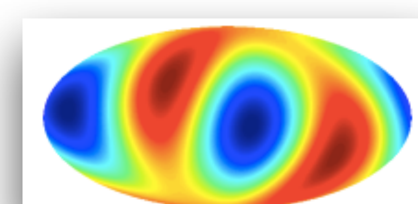
$$(Q \pm iU)(\hat{n}_e)\big|_{\rm pSZ} = -\frac{\sqrt{6}}{10}\sigma_T \int d\chi_e \; a(\chi_e)\, n_e(\hat{n}_e, \chi_e)\, \tilde{q}_{\rm eff}^{\pm}(\hat{n}_e, \chi_e)$$

$$\tilde{q}_{\rm eff}^{\pm}(\hat{n}_e, \chi) = \sum_{m=-2}^{2} q_{\rm eff}^{m}(\hat{n}_e, \chi_e)\, {}_{\pm 2}Y_{2m}(\hat{n}_e)$$

$$q_{\rm eff}^{m}(\hat{n}_e, \chi_e) = \int d^2\hat{n}\, \left[\Theta(\hat{n}_e, \chi_e, \hat{n}) + \Theta^T(\hat{n}_e, \chi_e, \hat{n})\right] Y_{2m}^{*}(\hat{n})$$

"Remote" (observed at the location of the scatterer) CMB quadrupole

<u>Notice</u>: $q_{\rm eff}^{m}(\mathbf{\hat{n}_e}, \chi_e \to 0) = a_{2m}^{T}$



pSZ tomography

Reconstructing the remote quadrupole field from CMB-LSS cross-correlation:

$$\left\langle \left(Q \pm iU\right)\Big|_{pSZ} \delta(\bar{\chi}_e) \right\rangle \sim \langle \delta \; q^{\pm} \; \delta \rangle \sim \boxed{q^{\pm}(\hat{n}_e, \bar{\chi}_e)\langle \delta \, \delta \rangle(\bar{\chi}_e)}$$

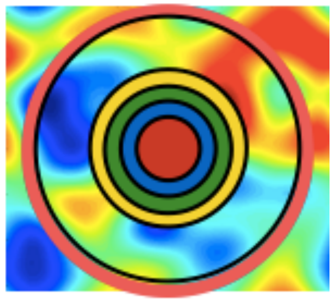
tracer of electron
number density

ensemble average
over small-scales
(q treated as a fixed
deterministic field)

long-wavelength
modulation of
small-scale power

[Kamionkowski, Loeb 1997, Alizadeh, Hirata 2012, Deutsch, ED, Johnson, Muenchmeyer, Terrana - 2017]

pSZ tomography



Bin-averaged quadrupole field moments decomposition:

$$\bar{q}^{\pm\,\alpha}(\hat{n}_e) = \sum_{\ell m} a^{q\,\pm\alpha}_{\ell m}\, {}_{\pm 2}Y_{\ell m}(\hat{n}_e)$$

$$\begin{cases} a^{q,E\,\alpha}_{\ell m} = -\dfrac{1}{2}\left(a^{q\,+\,\alpha}_{\ell m} + a^{q\,-\,\alpha}_{\ell m}\right) \\ a^{q,B\,\alpha}_{\ell m} = -\dfrac{1}{2i}\left(a^{q\,+\,\alpha}_{\ell m} - a^{q\,-\,\alpha}_{\ell m}\right) \end{cases}$$

scalars/ tensors

tensors only

<u>Optimal unbiased estimator</u> : X = E, B

binned density field

$$\boxed{\hat{a}^{q,X\,\alpha}_{\ell m} = \sum_{\ell_1 m_1 \ell_2 m_2} \left(W^{X,E}_{\ell m \ell_1 m_1 \ell_2 m_2}\, a^{E}_{\ell_1 m_1} + W^{X,B}_{\ell m \ell_1 m_1 \ell_2 m_2}\, a^{B}_{\ell_1 m_1}\right) \Delta\tau^{\alpha}_{\ell_2 m_2}}$$

[A.-S. Deutsch, ED, M.C. Johnson, M. Muenchmeyer, A. Terrana - 2017]

Primordial gravitational wave phenomenology with pSZ tomography

full set of correlations between primary CMB and reconstructed remote quadrupole field

$a^{\mathrm{T}}_{\ell m}$	primary CMB temperature
$a^{\mathrm{qE}}_{\ell m}(\chi)$	E-mode remote quadrupole field
$a^{\mathrm{qB}}_{\ell m}(\chi)$	B-mode remote quadrupole field
$\left.\begin{matrix} a^{\mathrm{E}}_{\ell m} \\ a^{\mathrm{B}}_{\ell m} \end{matrix}\right\}$	primary CMB polarization

[A.-S. Deutsch, ED, M. Fasiello, M.C. Johnson, M. Muenchmeyer - 2018]

$$C^{XX}_{\ell,\alpha\alpha'} = \int d\ln k \, \Delta^X_{\ell\alpha}(k)\Delta^X_{\ell\alpha'}(k) \, \mathcal{P}_h, \quad X = \{qE, qB\}$$

$$C^{qEX}_{\ell,\alpha} = \int d\ln k \, \Delta^{qE}_{\ell\alpha}(k)\Delta^X_{\ell}(k) \, \mathcal{P}_h, \quad X = \{T, E\}$$

$$C^{qBB}_{\ell,\alpha} = \int d\ln k \, \Delta^{qB}_{\ell\alpha}(k)\Delta^B_{\ell}(k) \, \mathcal{P}_h,$$

$$C^{XY}_{\ell} = \int d\ln k \, \Delta^X_{\ell}(k)\Delta^Y_{\ell}(k) \, \mathcal{P}_h, \quad X, Y = \{T, E\}$$

$$C^{qEqB}_{\ell,\alpha\alpha'} = \Delta_c \int d\ln k \, \Delta^{qE}_{\ell\alpha}(k)\Delta^{qB}_{\ell\alpha'}(k) \, \mathcal{P}_h,$$

$$C^{qEB}_{\ell,\alpha} = \Delta_c \int d\ln k \, \Delta^{qE}_{\ell\alpha}(k)\Delta^B_{\ell}(k) \, \mathcal{P}_h,$$

$$C^{qBX}_{\ell\alpha} = \Delta_c \int d\ln k \, \Delta^{qB}_{\ell\alpha}(k)\Delta^X_{\ell}(k) \, \mathcal{P}_h, \quad X = \{T, E\}$$

$$C^{XB}_{\ell} = \Delta_c \int d\ln k \, \Delta^X_{\ell}(k)\Delta^B_{\ell}(k) \, \mathcal{P}_h, \quad X = \{T, E\}$$

chirality

primordial tensor power spectrum

[A.-S. Deutsch, ED, M. Fasiello, M.C. Johnson, M. Muenchmeyer - 2018]

Fisher matrix forecast to derive exclusion bounds

- parameters in the primordial tensor power spectrum for the SU(2) model

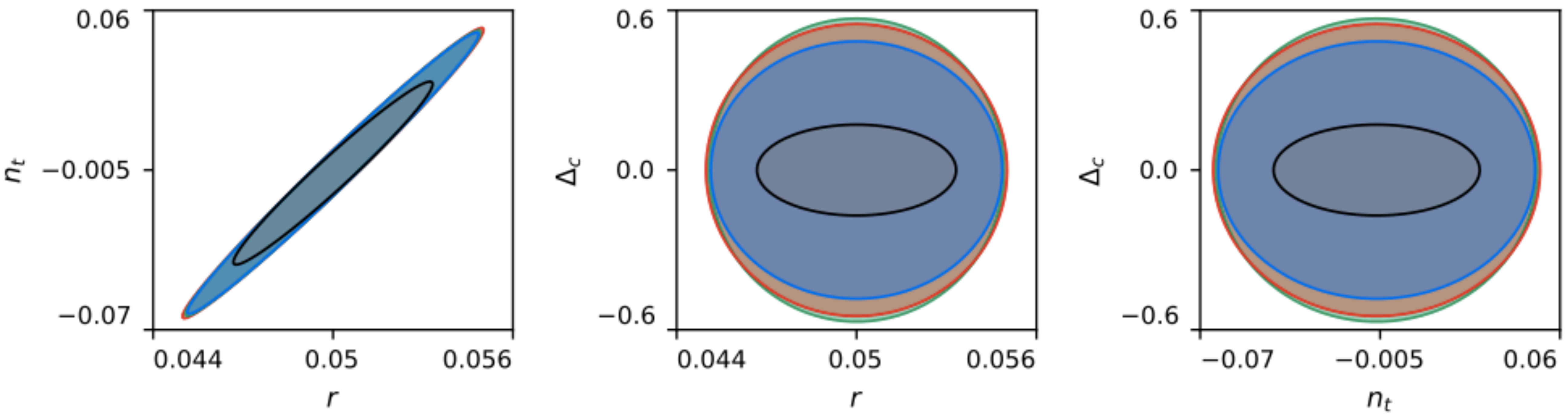
  amplitude r

  scale-dependence n_T

  chirality Δ_c

[A.-S. Deutsch, ED, M. Fasiello, M.C. Johnson, M. Muenchmeyer - 2018]

Forecasted parameter constraints



- **green**: zero-noise cosmic variance limit using primary CMB T, E, B
- **red**: T, E, B, qE, qB with instrumental noise $1\,\mu K - \mathrm{arcmin}$
- **blue**: T, E, B, qE, qB with instrumental noise $0.1\,\mu K - \mathrm{arcmin}$
- **grey**: T, E, B, qE, qB with no instrumental noise

pSZ tomography

improvements on constraints on phenomenological models of the tensor sector w.r.t. using the primary CMB (only)

Observers: optimize future missions to go after these signals

Primordial gravitational waves

- an important probe of the early universe and its evolution

- can lead to discovery of new physics

- testable on a vast range of scales (and from cross-correlations of different probes!)

- different observables (not only r and Ω_{GW}) to characterize them and identify their sources