Constraining Gravitational Waves from Inflation

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The University of New South Wales

COSMO19 - Aachen

Outline

- Particle sources during inflation

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

- Tensor fossils

1906.07204 - ED, Fasiello, Tasinato
1504.05993 - ED, Fasiello, Kamionkowski
1407.8204 - ED, Fasiello, Jeong, Kamionkowski

- Polarized Sunyaev–Zeldovich tomography

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

Outline

- Particle sources during inflation

- Tensor fossils

- Polarized Sunyaev–Zeldovich tomography

GW background from inflation

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

$\gamma^i_i = \partial_i \gamma_{ij} = 0$ two polarization states of the graviton

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

anisotropic stress-energy tensor

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

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

scalars vectors tensors

GW background from inflation

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

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

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

anisotropic stress-energy tensor

see also talk by Matteo Fasiello

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

$$\Pi_{ij}^{TT} \propto \underbrace{\{\partial_i\phi\,\partial_j\phi\}^{TT}}_{\text{scalars}} \qquad \underbrace{\{E_iE_j + B_iB_j\}^{TT}}_{\text{vectors}} \qquad \underbrace{\{\sigma_{ij}\}^{TT}}_{\text{tensors}}$$

What kind of sources?

- Spectator fields with small sound speed

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

[Biagetti, Fasiello, Riotto 2012, Biagetti, ED, Fasiello, Peloso 2014, …]

- Auxiliary scalars with time-varying mass

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

[Chung et al. 2000, Senatore et al 2011, …]

- Axion-gauge field models

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

- naturally light inflaton
- sub-Planckian axion decay constant
- support reheating
- interesting for baryogenesis

[Anber - Sorbo 2009, Cook - Sorbo 2011, Barnaby - Peloso 2011, Adshead - Wyman 2011,
Maleknejad - Sheikh-Jabbari, 2011, ED - Fasiello - Tolley 2012, ED - Peloso 2012,
Namba - ED - Peloso 2013, Adshead - Martinec -Wyman 2013, ED - Fasiello - Fujita 2016
Agrawal - Fujita - Komatsu 2017, Caldwell - Devulder 2017, Domcke et al. 2018, …]

Axion-Gauge fields models: SU(2)

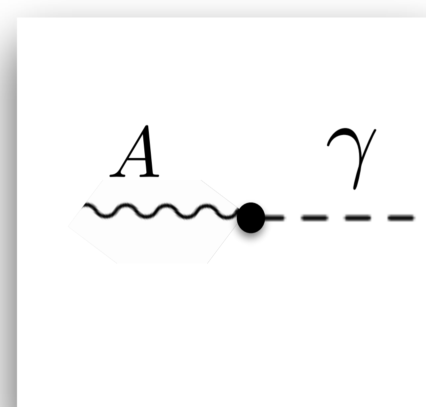
$$\mathcal{L} = \mathcal{L}_{\rm inflaton} \underbrace{- \frac{1}{2}(\partial\chi)^2 - U(\chi) - \frac{1}{4}FF + \frac{\lambda\chi}{4f}F\tilde{F}}_{\mathcal{L}_{\rm spectator}}$$

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

- 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: signatures

- Scale dependence
- Chirality
- Non-Gaussianity

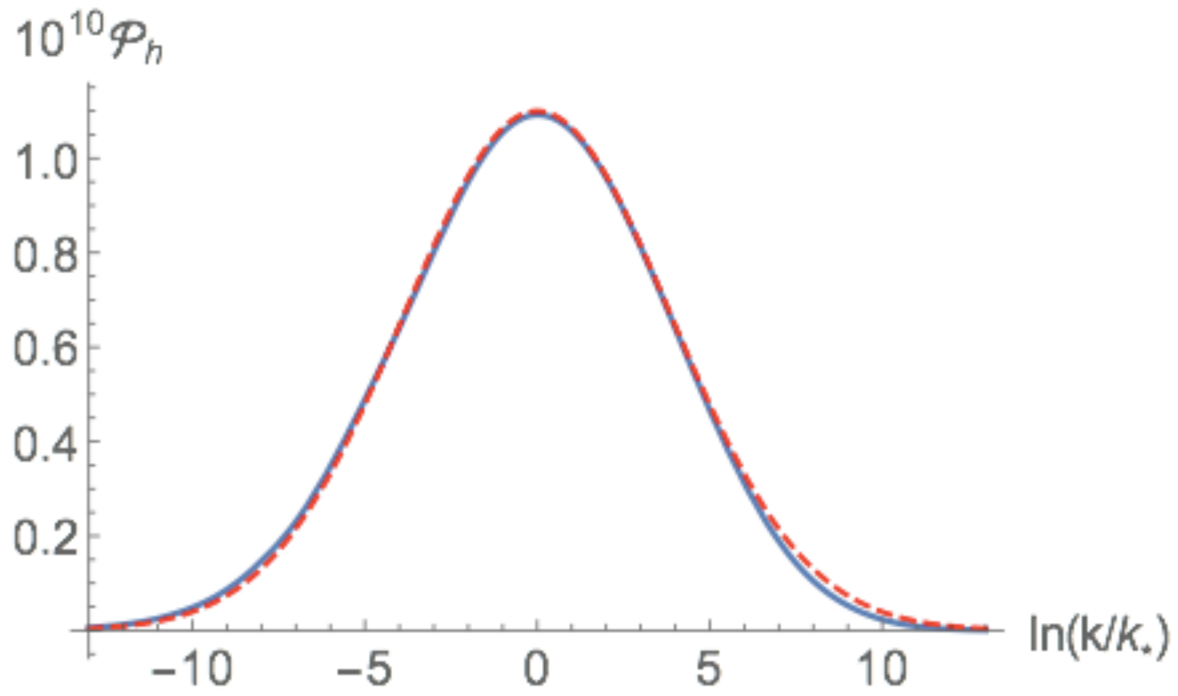
Scale-dependence

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

$$\gamma_L \neq \gamma_R$$

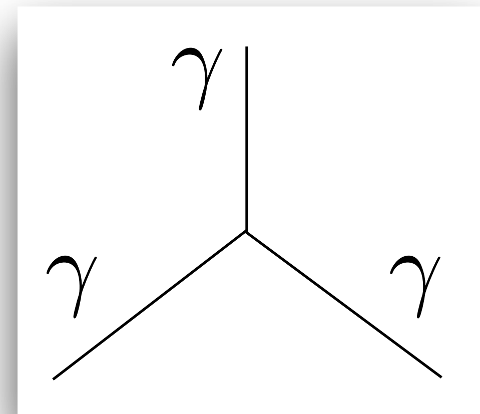
chiral

$\downarrow$

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

Tensor non-Gaussianity

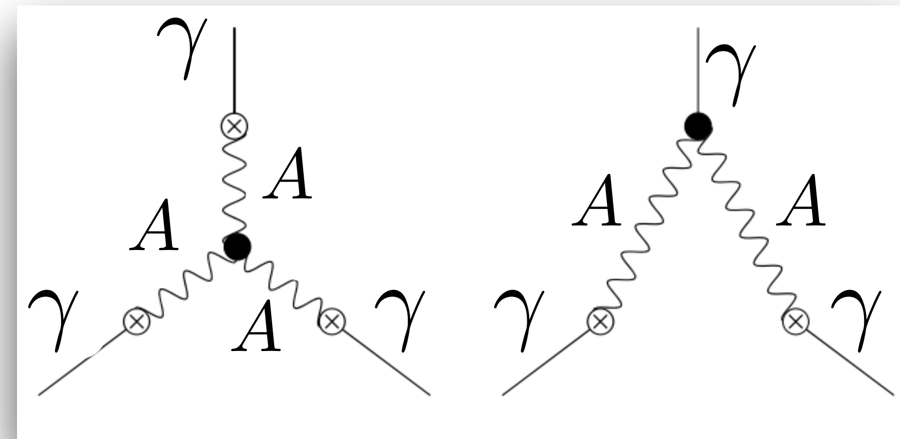
basic single-field inflation



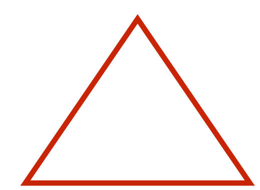
$$f_{NL} = \mathcal{O}(r^2)$$

too small for detection

axion-gauge fields models



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

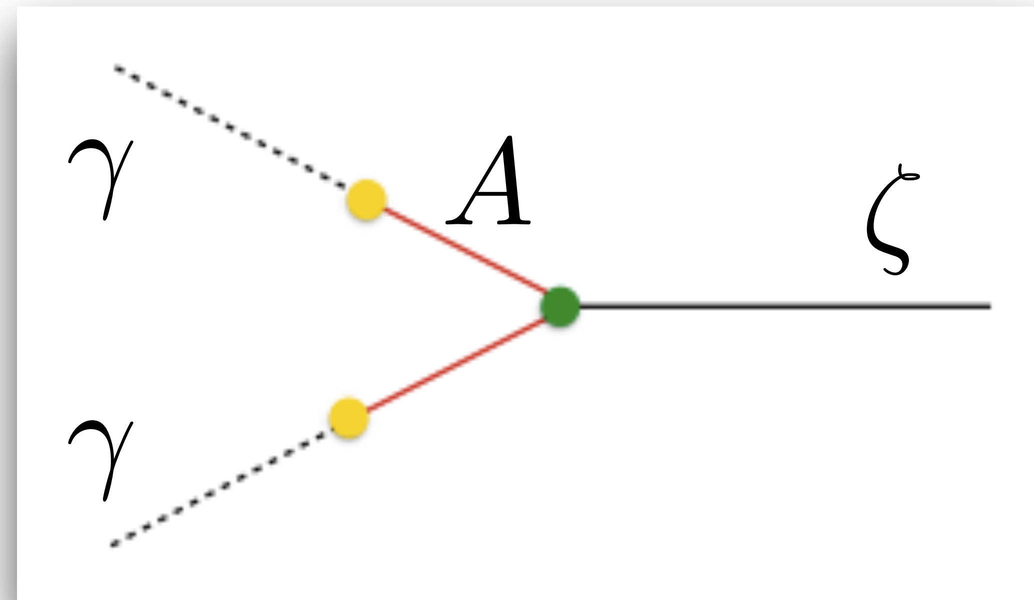


- detectable by upcoming CMB space missions

[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]

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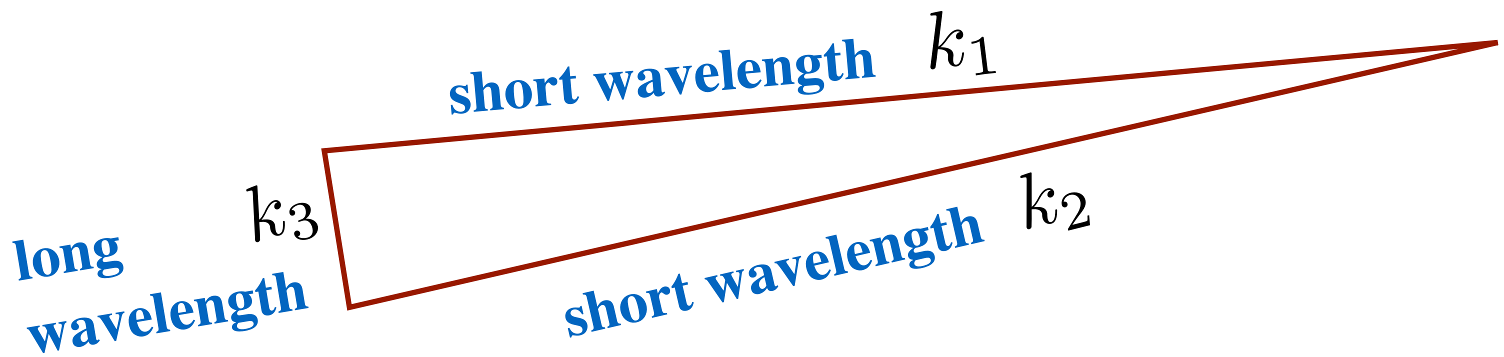
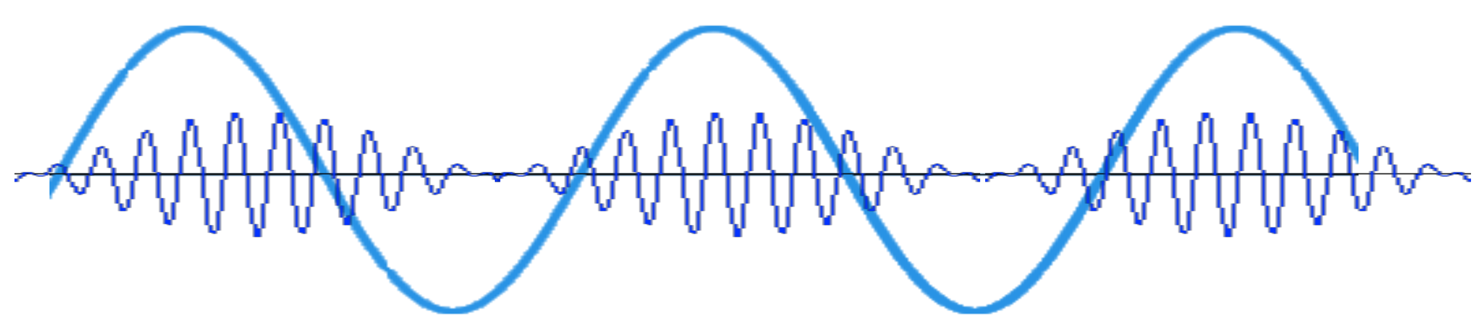
Squeezed non-Gaussianity

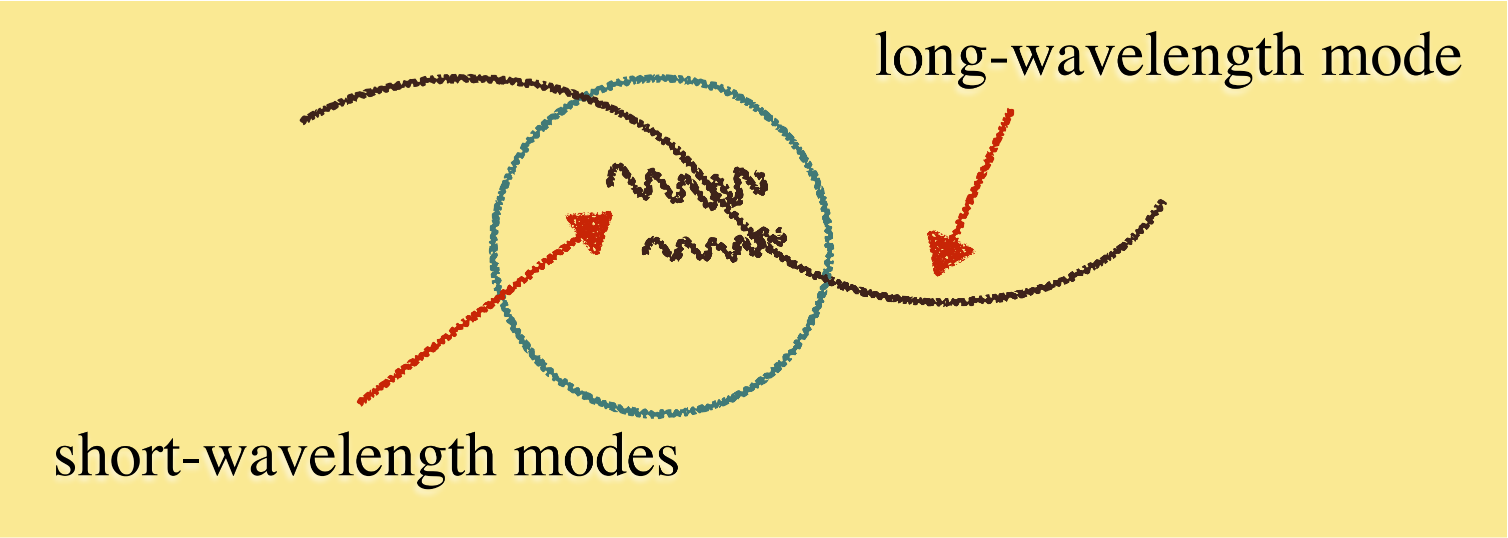


amplitude of long-wavelength modes
coupled with amplitude of short-wavelength modes



Soft limits and fossils

squeezed 3pf affects the 2pf

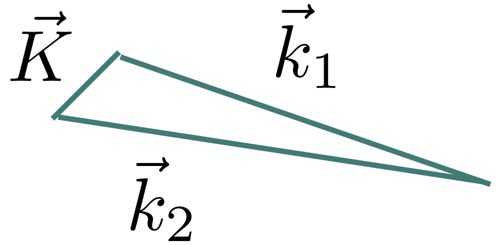


- No squeezed non-Gaussianity $\longrightarrow$ $\langle \delta_{\vec{k}_1} \delta_{\vec{k}_2} \rangle = \delta^{(3)}(\vec{k}_1 + \vec{k}_2) P(k_1)$

diagonal 2p correlation

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

there is also a off-diagonal contribution!

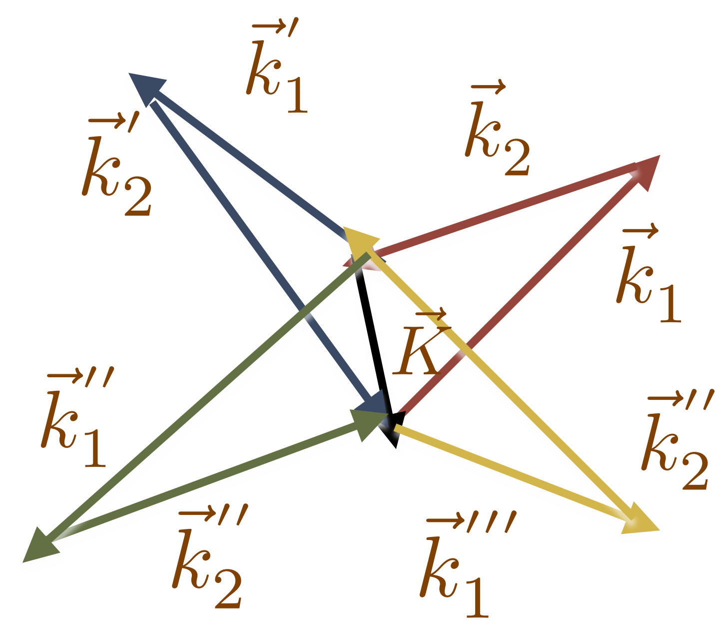


Soft limits and fossils

<u>super-Hubble K</u>:
constrain tensor modes amplitude/interactions with induced quadrupole anisotropy

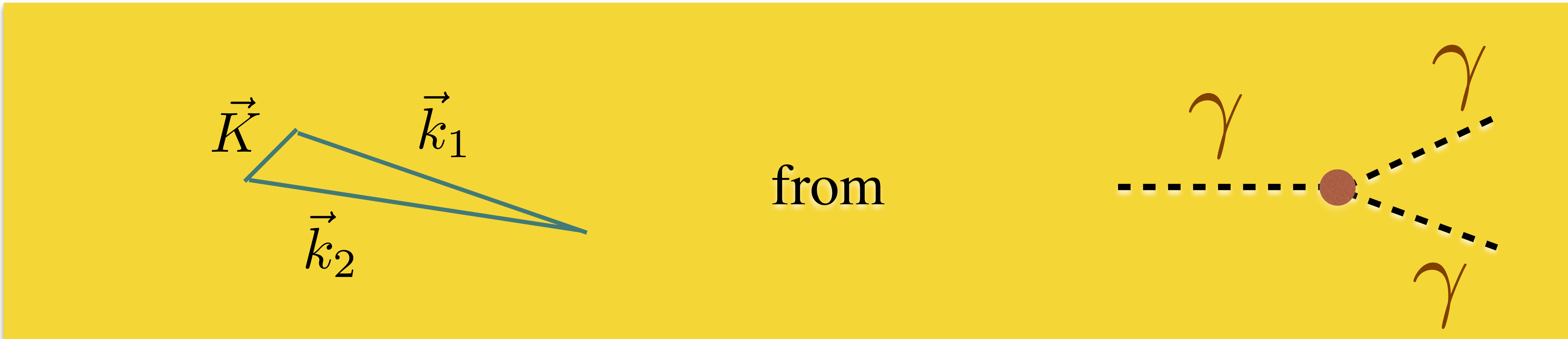
$$P_\zeta(\mathbf{k},\mathbf{x}_c)|_{\gamma_L} = P_\zeta(k)\Big(1+\mathcal{Q}_{\ell m}(\mathbf{x}_c,\mathbf{k})\hat{k}_\ell\hat{k}_m\Big)$$

<u>sub-Hubble K</u>:
estimate tensor modes amplitude from off-diagonal correlations



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

Soft limits and fossils

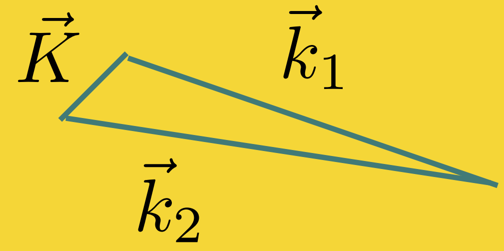


<u>super-Hubble K</u>:
constrain tensor modes amplitude/interactions
with induced quadrupole anisotropy

$$P_\gamma(\mathbf{k}, \mathbf{x}_c)|_{\gamma_L} = P_\gamma(k)\Big(1 + \mathcal{Q}_{\ell m}(\mathbf{x}_c, \mathbf{k})\hat{k}_\ell \hat{k}_m\Big)$$

[ED, Fasiello, Tasinato 2019]

Soft limits and fossils



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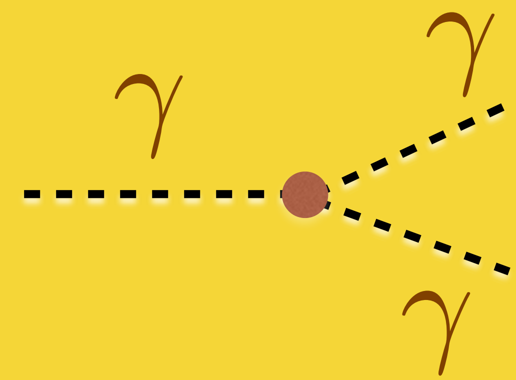


<u>super-Hubble K</u>:
constrain tensor modes amplitude/interactions
with induced quadrupole anisotropy

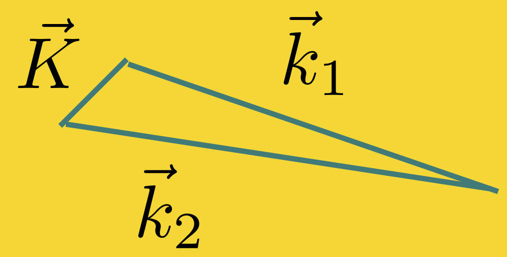
$$P_\gamma(\mathbf{k}, \mathbf{x}_c)|_{\gamma_L} = P_\gamma(k)\left(1 + \mathcal{Q}_{\ell m}(\mathbf{x}_c, \mathbf{k})\hat{k}_\ell \hat{k}_m\right)$$

[ED, Fasiello, Tasinato 2019]

<u>Important remark</u>: primordial bispectrum highly suppressed on small scales
(superposition of signals from a large number of Hubble patches
+ Shapiro time-delay)

[Bartolo, De Luca, Franciolini, Lewis, Peloso, Riotto 2018]

Soft limits and fossils



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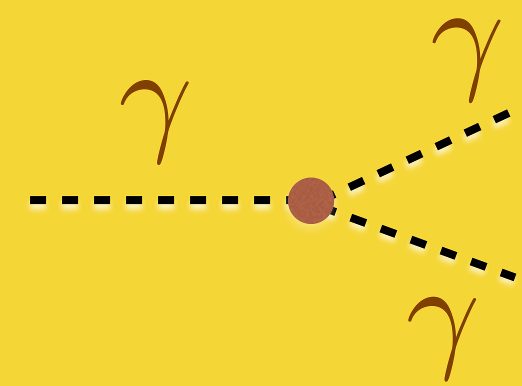


<u>super-Hubble K</u>:
constrain tensor modes amplitude/interactions
with induced quadrupole anisotropy

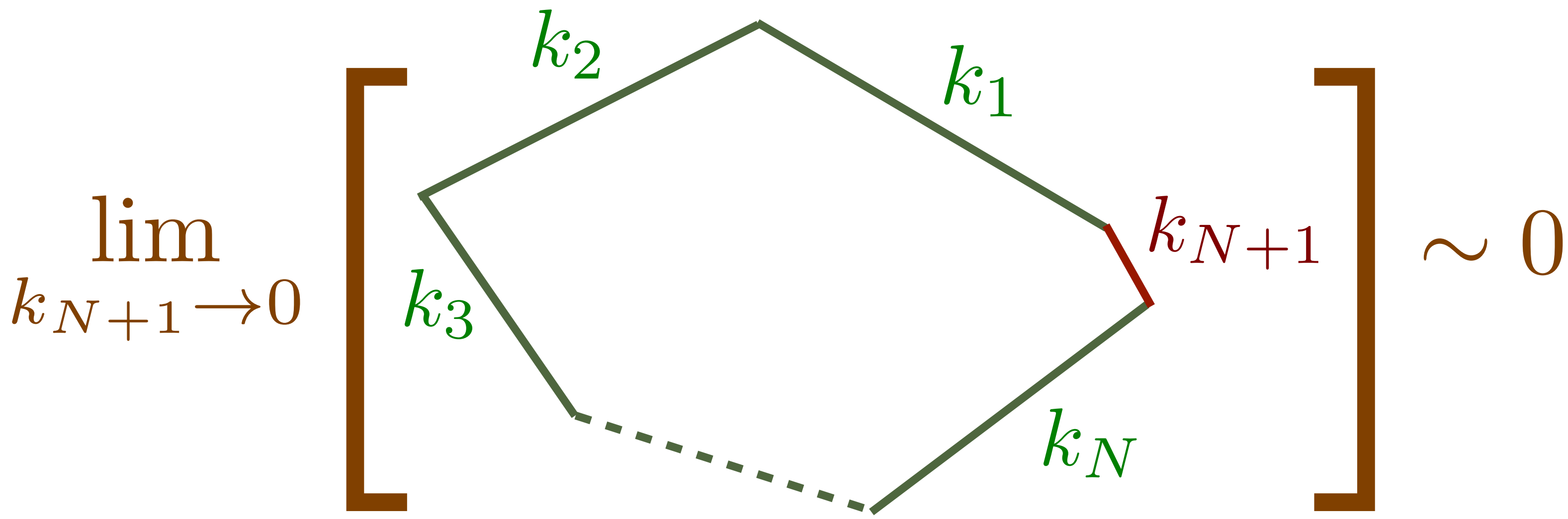
$$P_\gamma(\mathbf{k}, \mathbf{x}_c)|_{\gamma_L} = P_\gamma(k)\Big(1 + \mathcal{Q}_{\ell m}(\mathbf{x}_c, \mathbf{k})\hat{k}_\ell \hat{k}_m\Big)$$

Crucial observable for tensor non-Gaussianity
at interferometer scales!

[ED, Fasiello, Tasinato 2019]

Soft limits in inflation

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



<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

  [Chen - Wang 2009, ED - Fasiello - Kamionkowski 2015, 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

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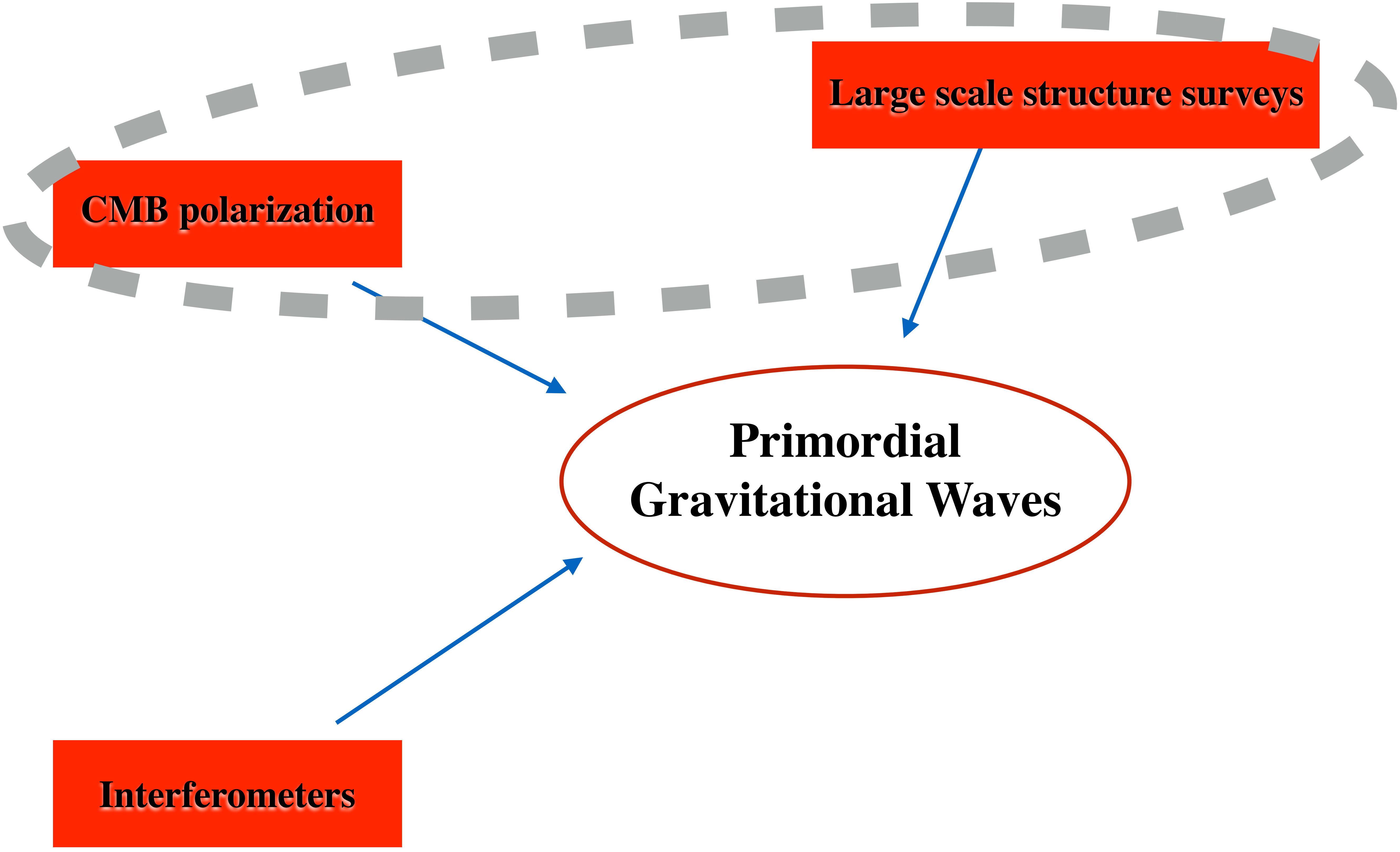
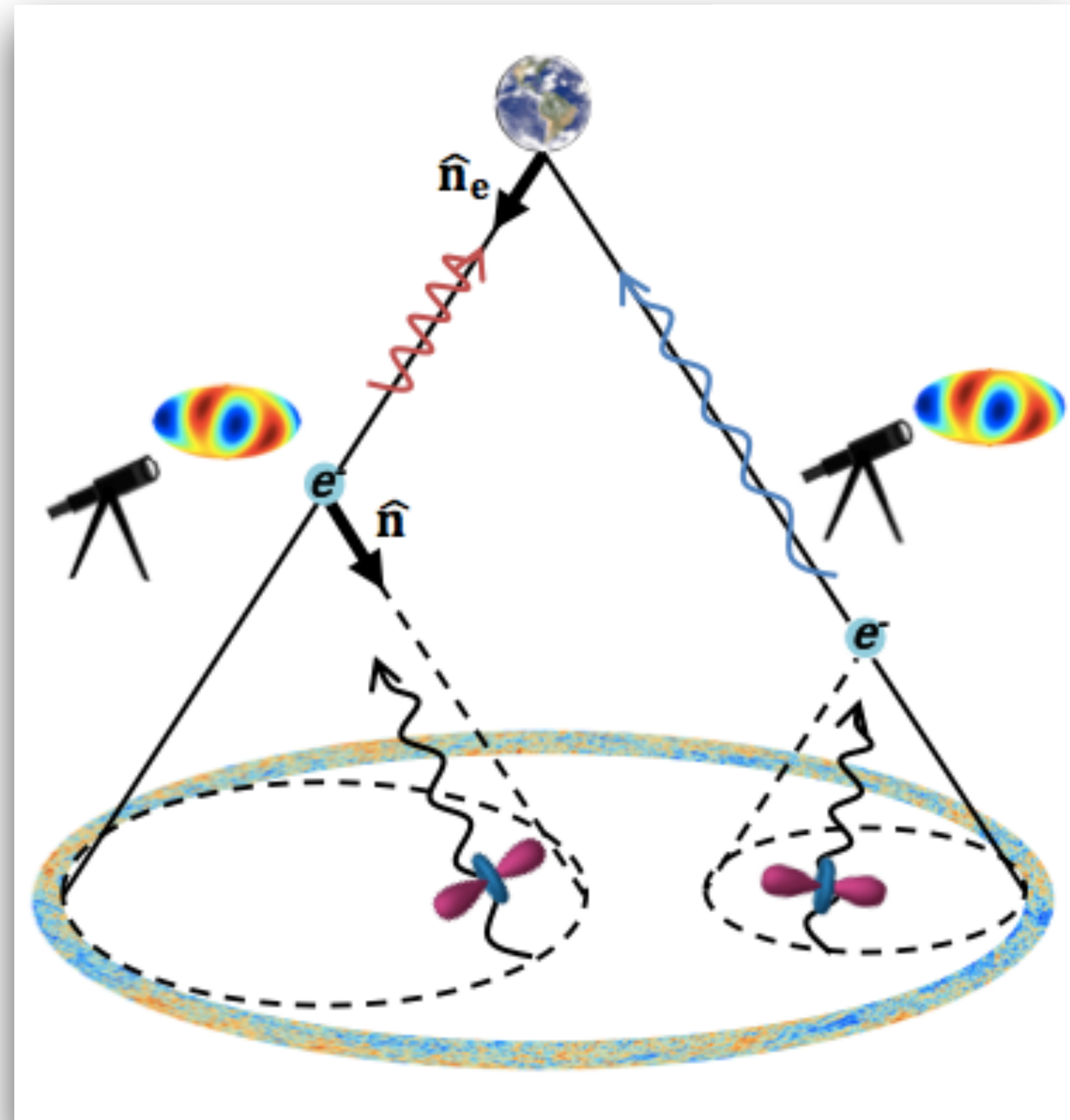

Large scale structure surveys
CMB polarization
Primordial
Gravitational Waves
Interferometers

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)

PGW 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
$\left.\begin{array}{l} a^{\mathrm{E}}_{\ell m} \\ a^{\mathrm{B}}_{\ell m} \end{array}\right\}$	primary CMB polarization

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

PGW phenomenology with 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

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

Primordial gravitational waves

- a very important probe of inflation
- can lead to discovery of new physics
- testable on a vast range of scales (and from cross-correlations of different probes!)
- different observables (amplitude, chirality, scale dependence, non-Gaussianity) to characterize them and identify their sources

Thank you!

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

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

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

Sourced may be comparable to vacuum fluctuations

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)

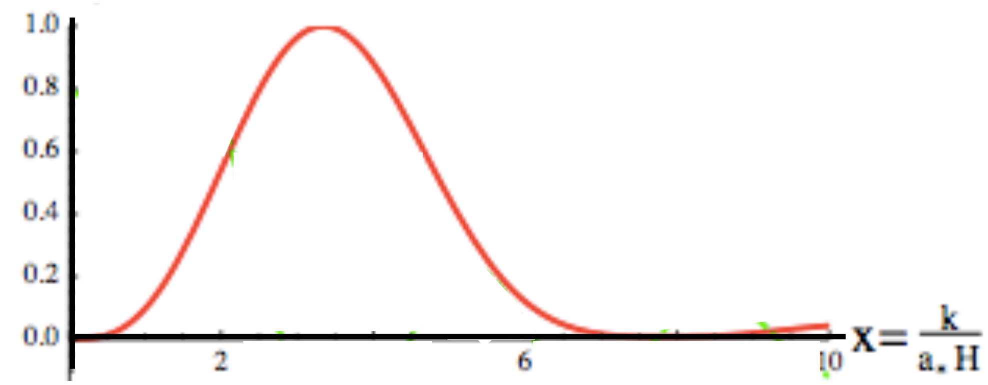
- Auxiliary scalars with time-varying mass

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

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

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

features in the power spectra

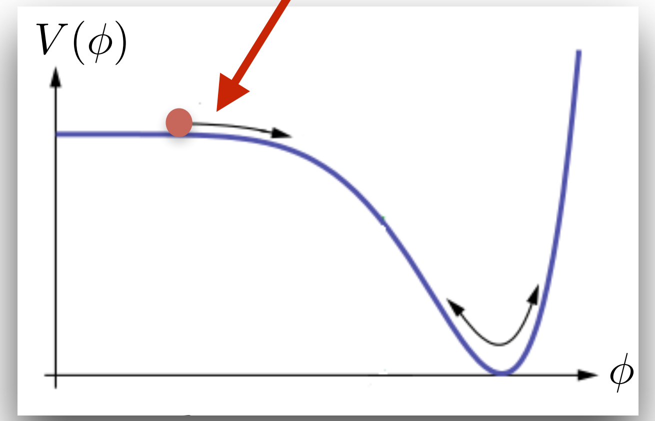


[Chung et al., 2000, Senatore et al, 2011, Pearce et al, 2017]

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 $\phi \to \phi + c$

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

[Freese, Frieman, Olinto 1990]

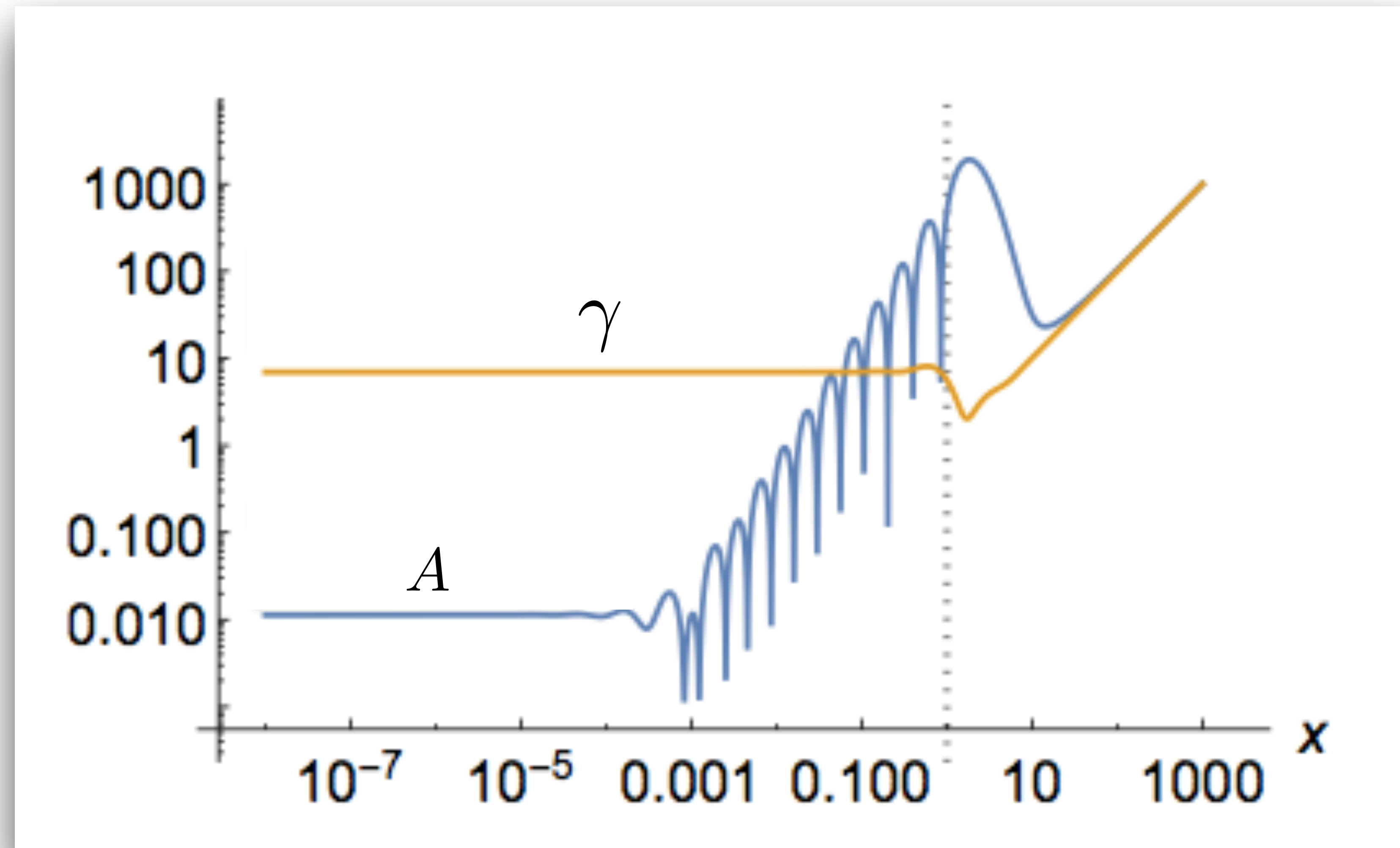
- Agreement with observations requires: $f \gtrsim M_P$

undesirable constraint on the theory

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

Axion-Gauge fields models: SU(2)

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



[ED-Fasiello-Fujita 2016]

Polarized Sunyaev-Zel'dovich effect

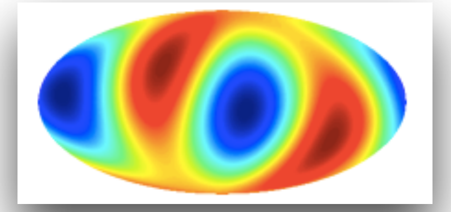
$$(Q \pm iU)(\hat{n}_e)\big|_{\rm pSZ} = -\frac{\sqrt{6}}{10}\sigma_T \int d\chi_e \; a(\chi_e)\, n_e(\hat{n}_e, \chi_e)\, \tilde{q}^{\pm}_{\rm eff}(\hat{n}_e, \chi_e)$$

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

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

“Remote” (observed at the location of the scatterer) CMB quadrupole

<u>Notice</u>: $q^m_{\rm eff}(\mathbf{\hat{n}_e}, \chi_e \to 0) = a^T_{2m}$



pSZ tomography

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

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

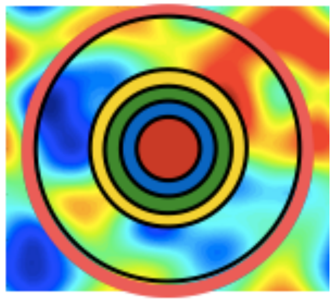
tracer of electron
number density

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:

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

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

scalars/ tensors

tensors only

Optimal unbiased estimator : 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]

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

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

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

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

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

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

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

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

chirality

primordial tensor power spectrum

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

Fisher matrix forecast to derive exclusion bounds

- Our parameters:

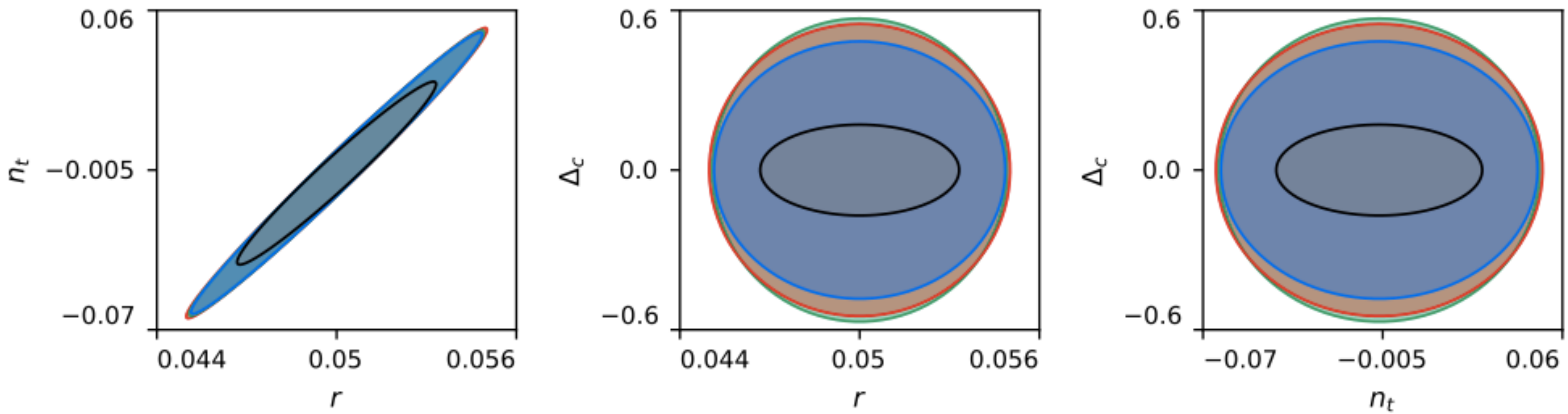
amplitude r

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

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