Constraining Gravitational Waves from Inflation

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The University of New South Wales

Nordita— September 2019

Outline

- Brief intro + current bounds
- 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

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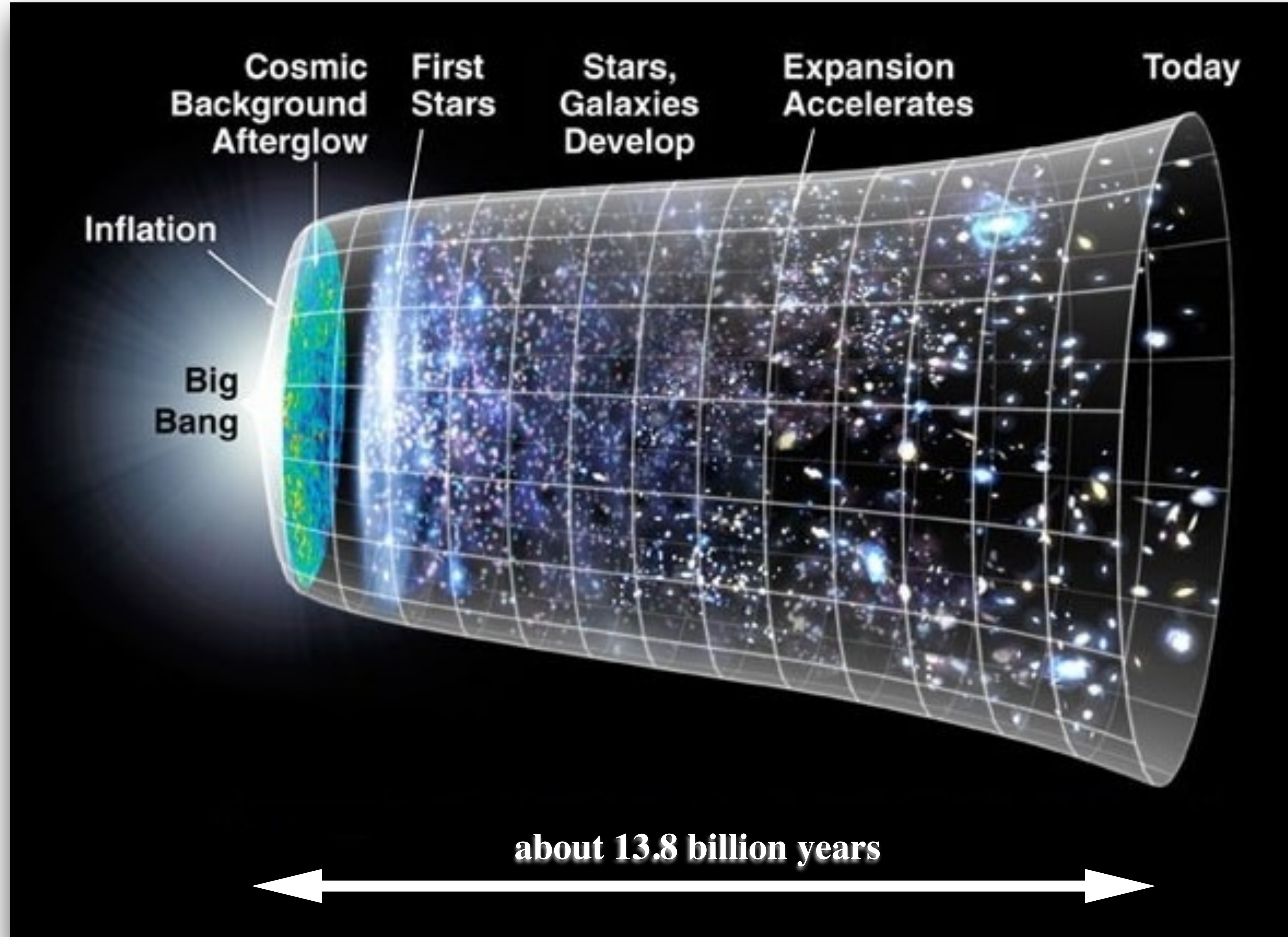
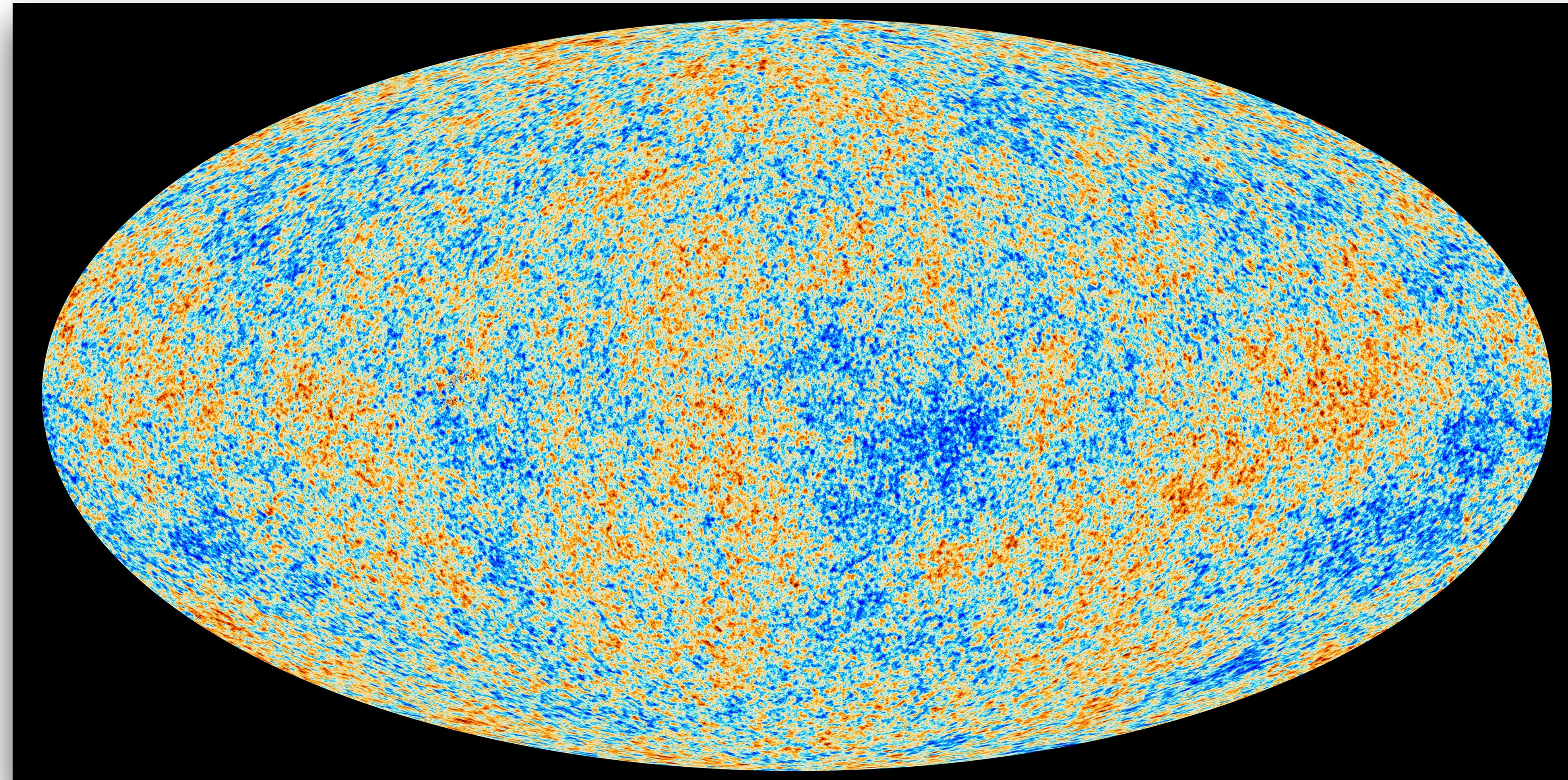
The universe over time



Cosmic microwave background

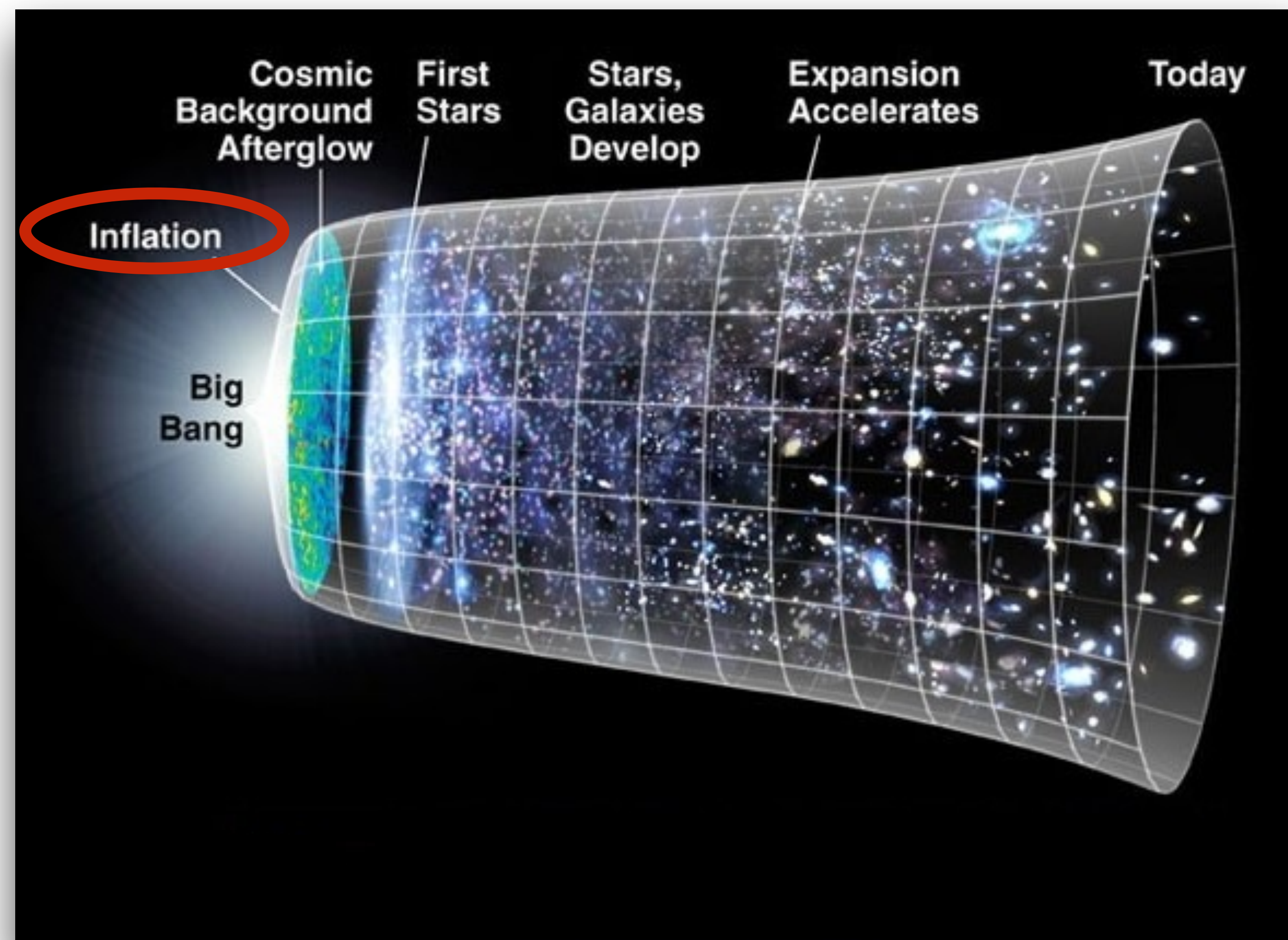


blackbody spectrum: $\bar{T}_{CMB} \sim 2.7\,K$

nearly isotropic: $\Delta T \sim 10^{-5}$

Inflation

- era of accelerated exponential expansion
- explains why CMB is nearly uniform
- explains how those fluctuations are generated
- stochastic gravitational wave background is generated (a key prediction!)

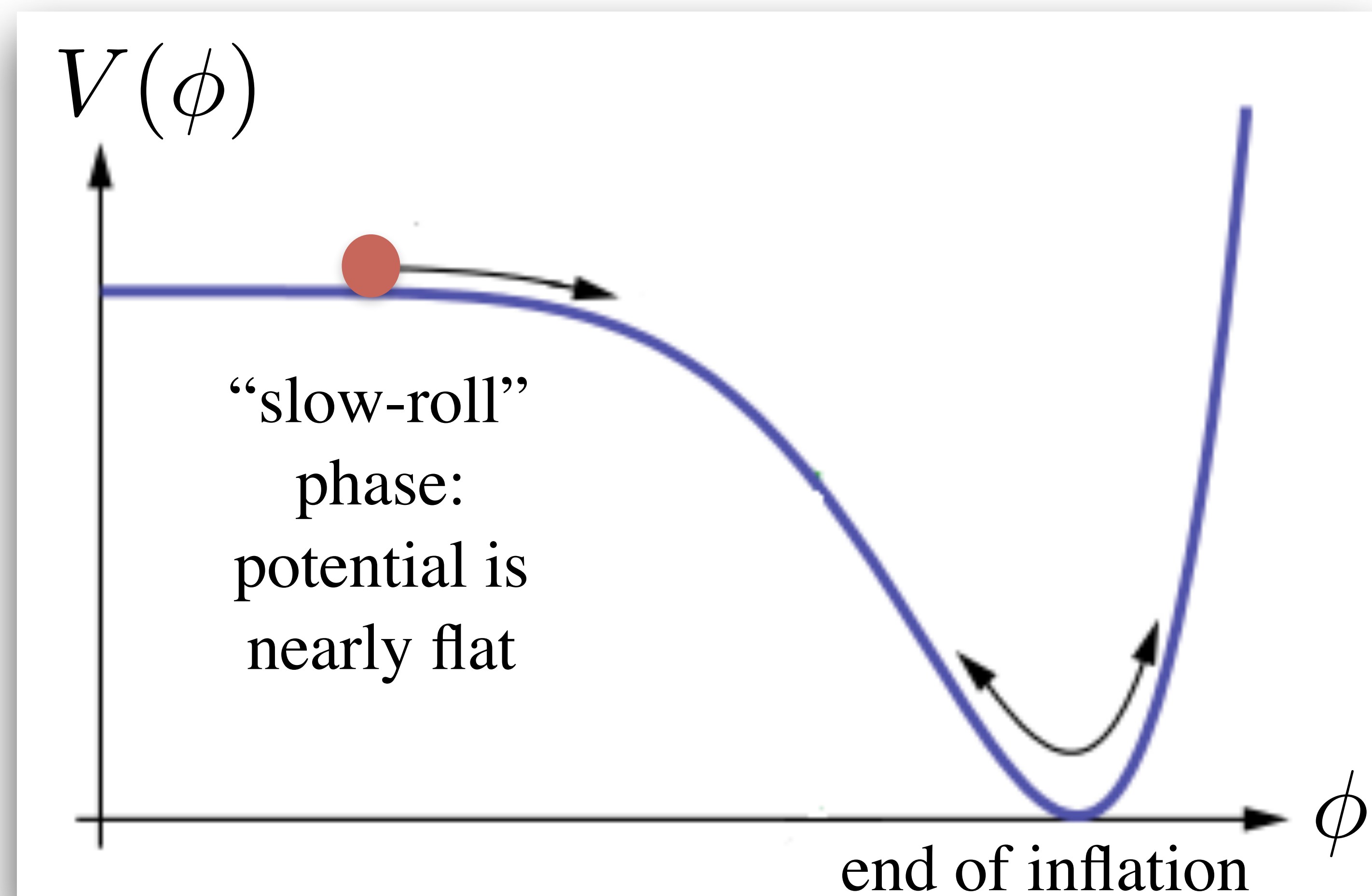


Inflation

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)

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

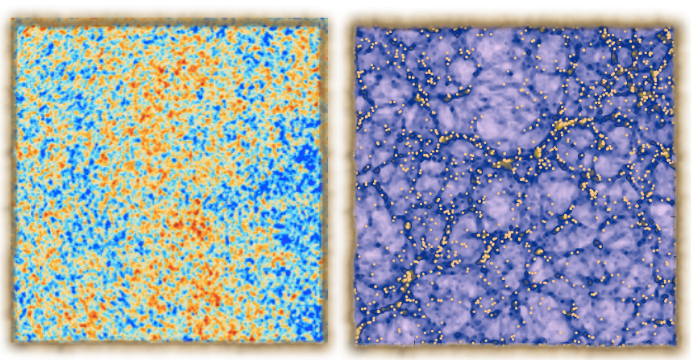
classical homogeneous background

quantum fluctuations

perturbation modes are stretched by the expansion,
become super horizon and freeze out to their value at horizon exit

cosmological perturbations

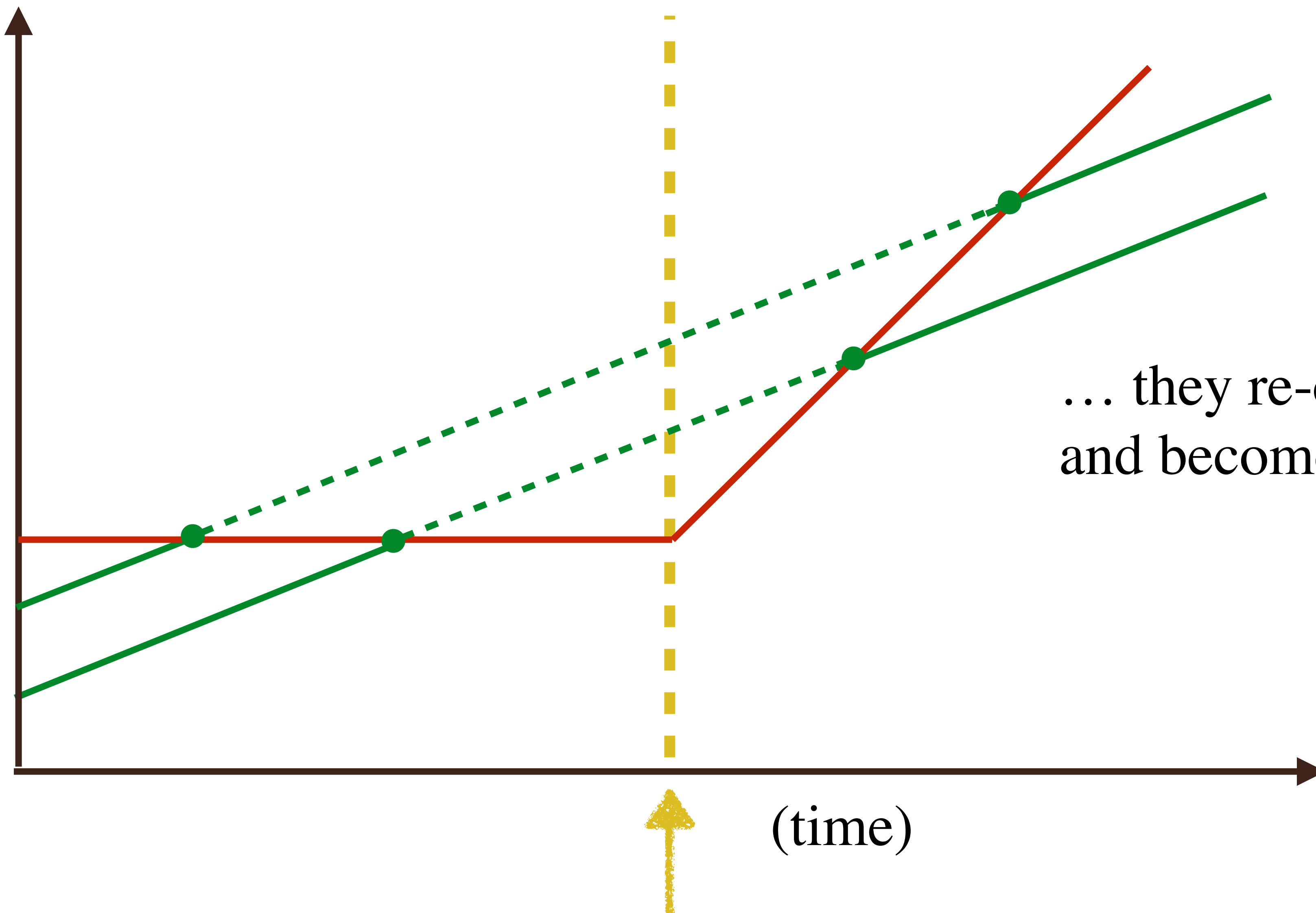
ΔT $\quad$ $\delta\rho$



Scales

wavenumber → e-folding → time of re-entry

k $\quad$ N_k



Perturbation modes leave horizon during inflation and freeze out to

… they re-enter after inflation and become dynamical again

Two-point statistics of primordial perturbations: scalars

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

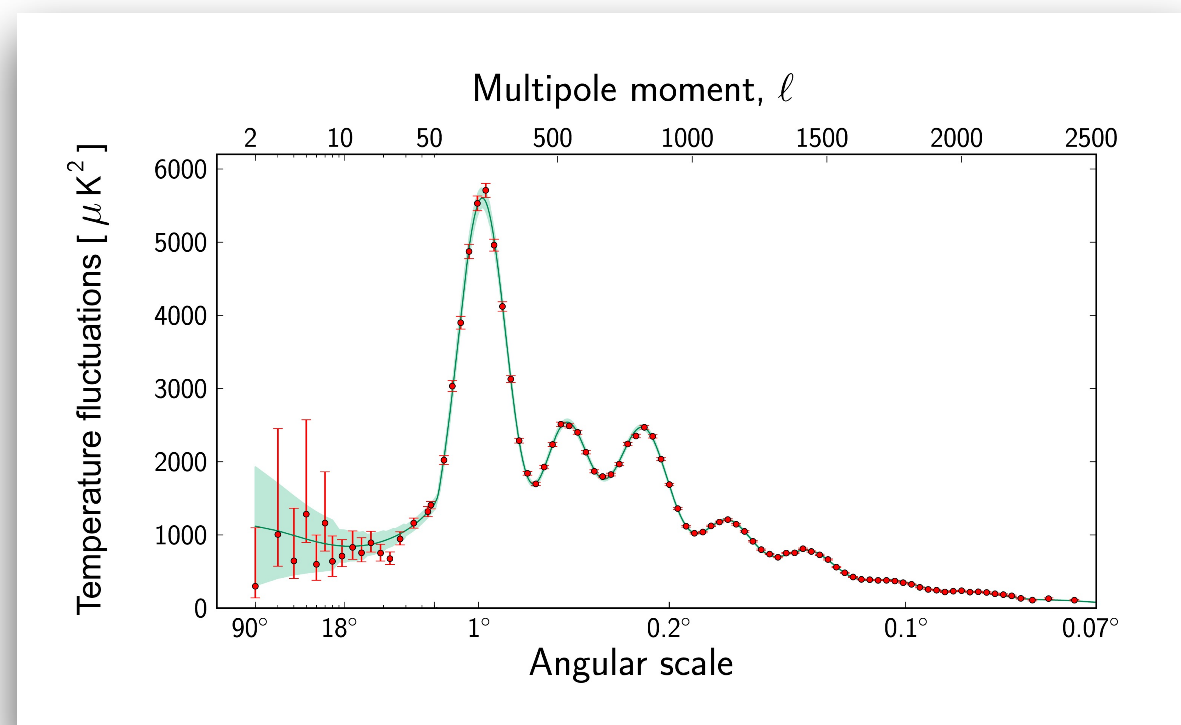
$$\mathcal{P}_\zeta(k) = \frac{1}{8\pi^2}\frac{1}{\epsilon}\frac{H^2}{M_{\rm pl}^2}\left(\frac{k}{k_*}\right)^{n_s-1}$$

0.9649 ± 0.0042

2×10^{-9}

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

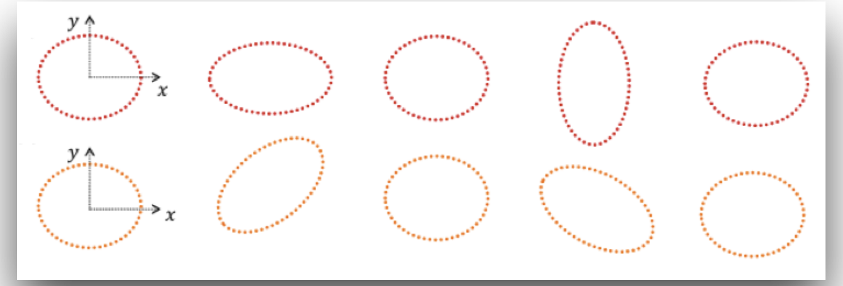
from Planck (2018)



GW background from inflation

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

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



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

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

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

GW background from inflation

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

energy scale of inflation

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

$n_T = -r/8$

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

red tilt: amplitude decreases as we go towards smaller scales

and non-chiral!!!

Observational bounds/sensitivities

$$r_{0.002\,\mathrm{Mpc}^{-1}} < 0.056$$

(Planck+BICEP2/KECK)

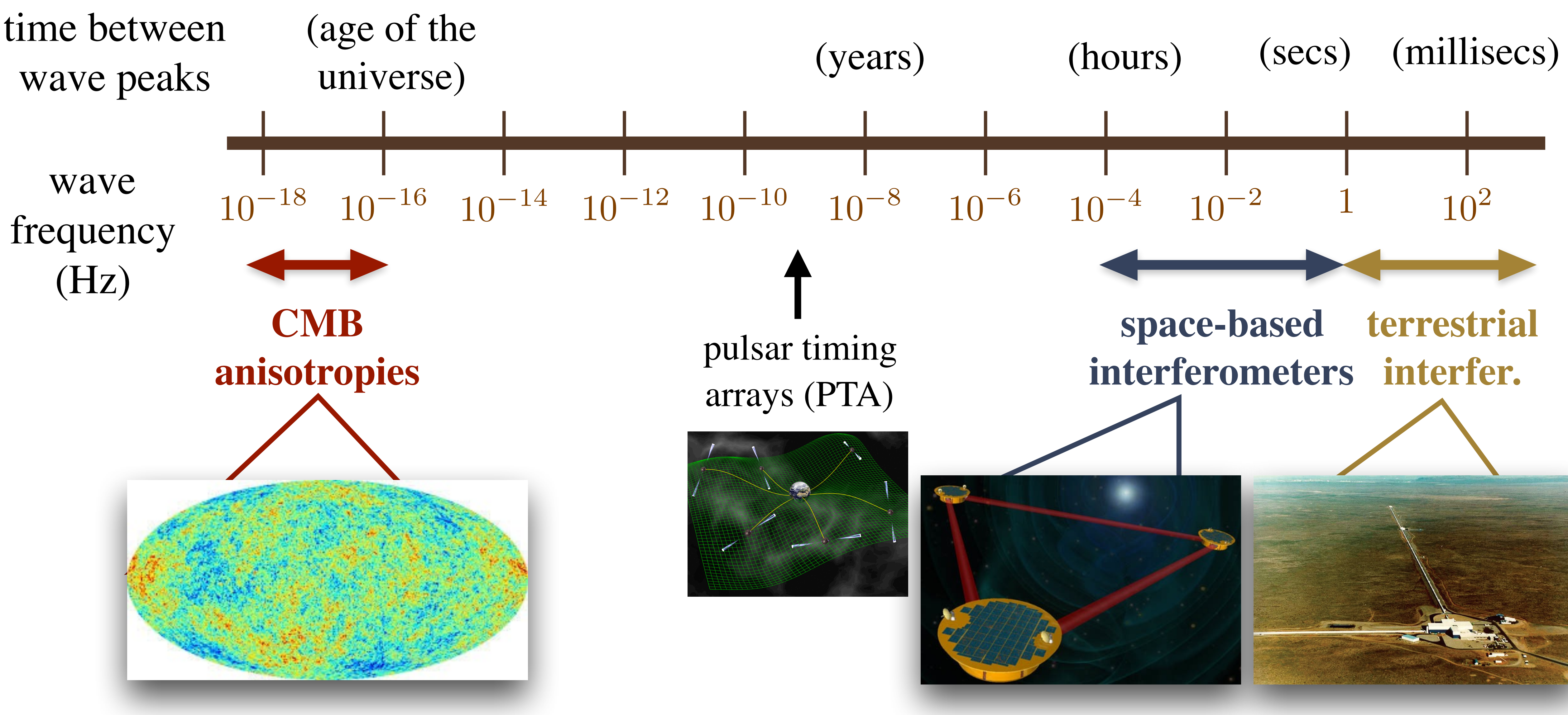
$$V^{1/4} \lesssim 1.6 \times 10^{16}\mathrm{GeV}$$

Upper bound on the energy scale of inflation

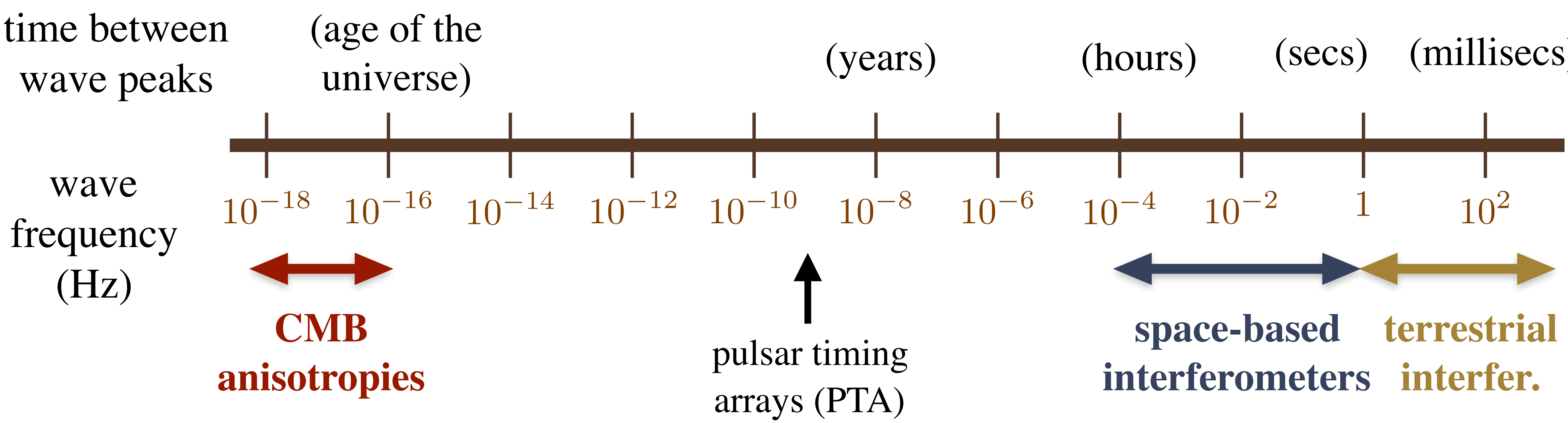
$$\sigma(r) \to 0.0005$$

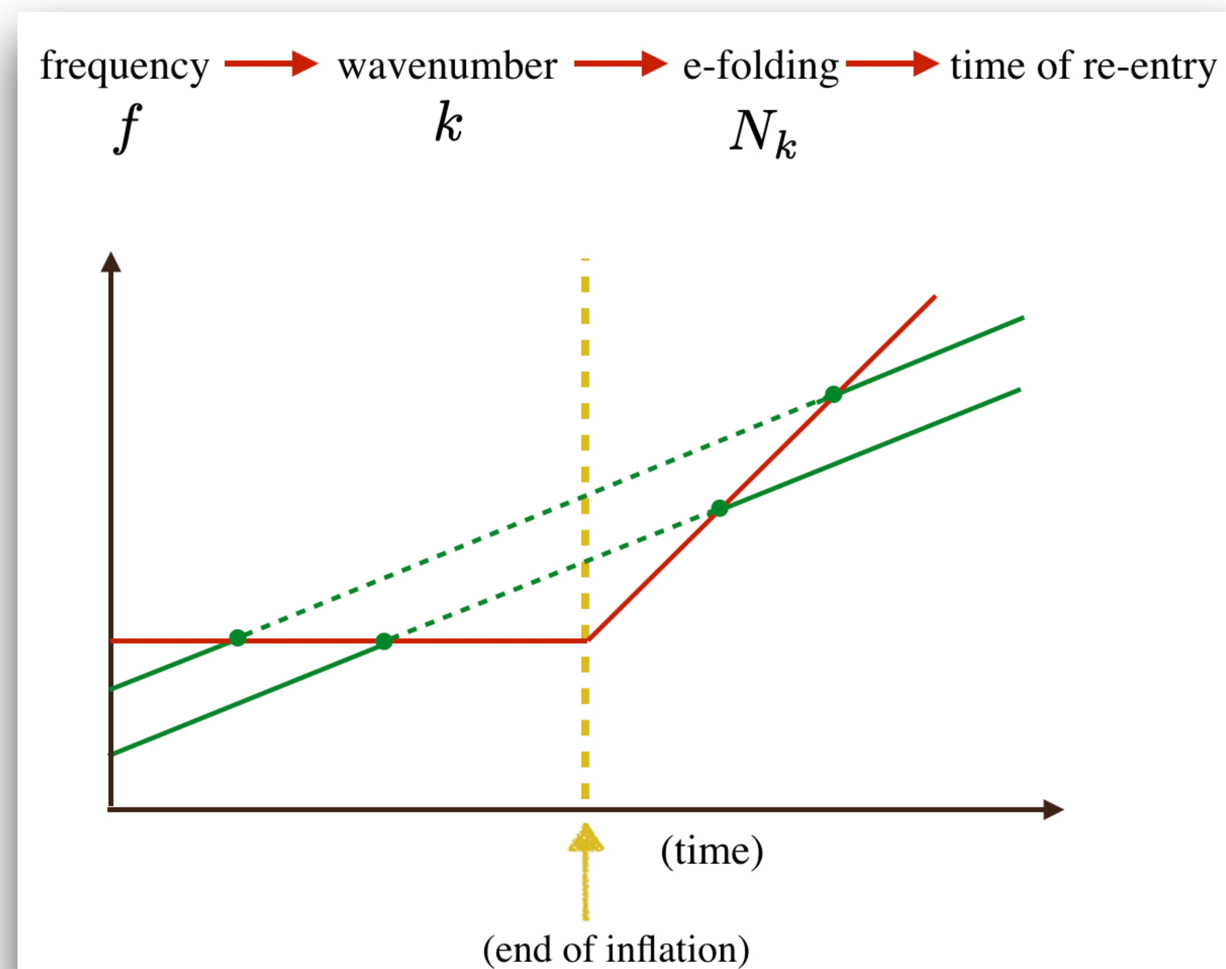
<u>Next generation</u>:
BICEP Array, SPT-3G,
Simons Observatory, CMB-S4,
LiteBIRD, PICO, …

Scales — Experiments

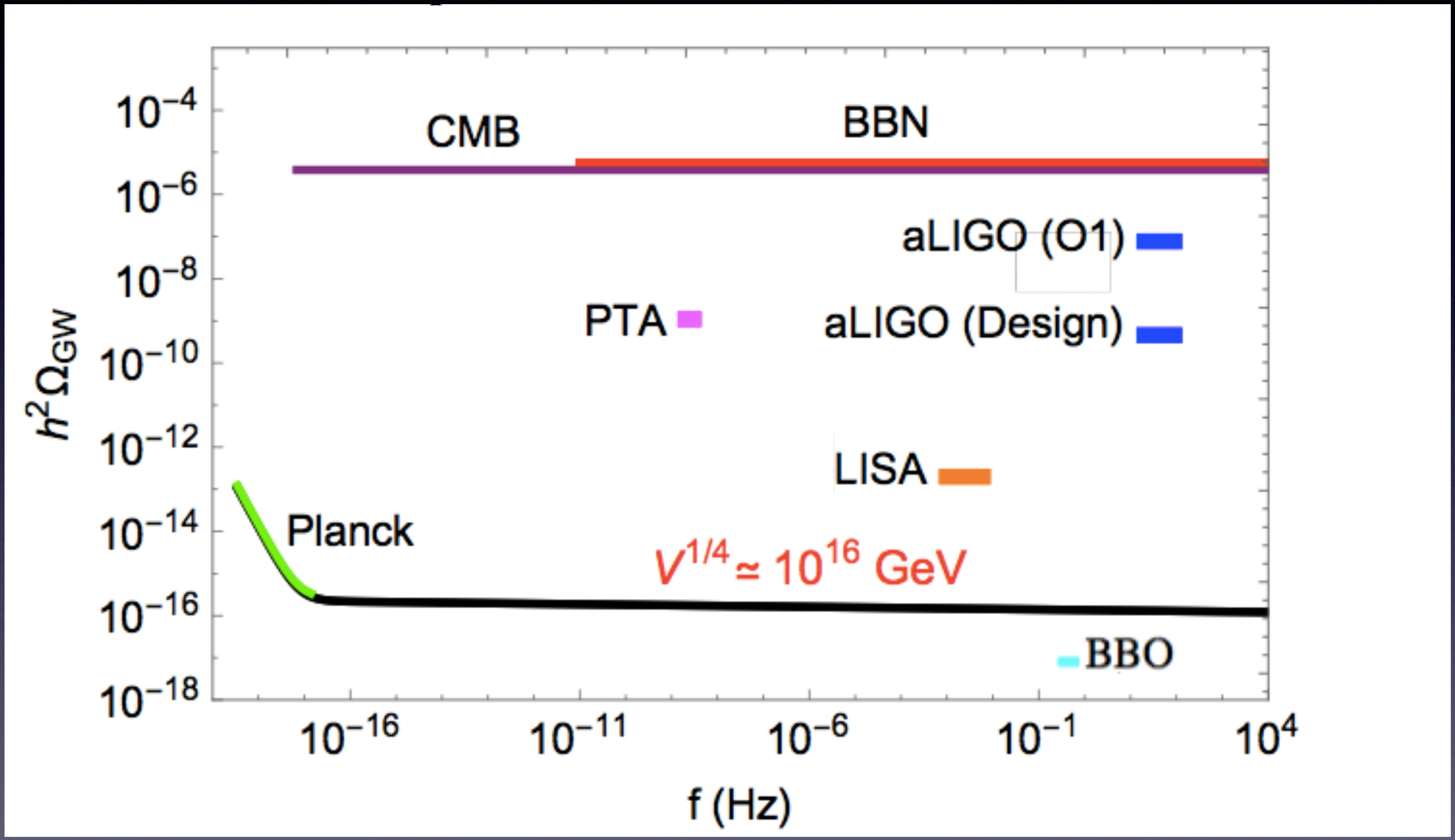


Scales — Experiments





Observational bounds/sensitivities



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GW background from inflation

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

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

INFLATON + **SPECTATOR** SECTOR

negligible energy density
compared to the inflaton

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

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, Garcia-Bellido - Peloso - Unal 2016, Agrawal - Fujita - Komatsu 2017, …]

Axion-Gauge fields models: SU(2)

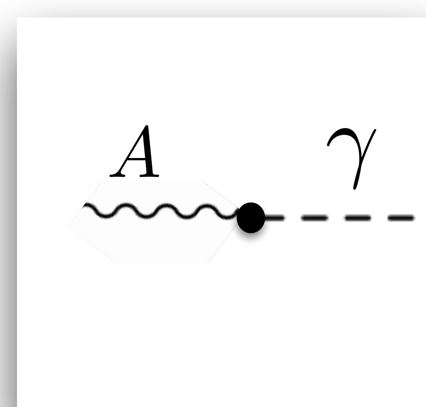
$$\mathcal{L} = \mathcal{L}_{\rm inflaton} \boxed{- \frac{1}{2}(\partial\chi)^2 - U(\chi) - \frac{1}{4}FF + \frac{\lambda\chi}{4f}F\tilde{F}}$$

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

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

$$\boxed{\begin{aligned} A^a_0 &= 0 \\ A^a_i &= aQ\delta^a_i \end{aligned}}$$ slow-roll background attractor solution

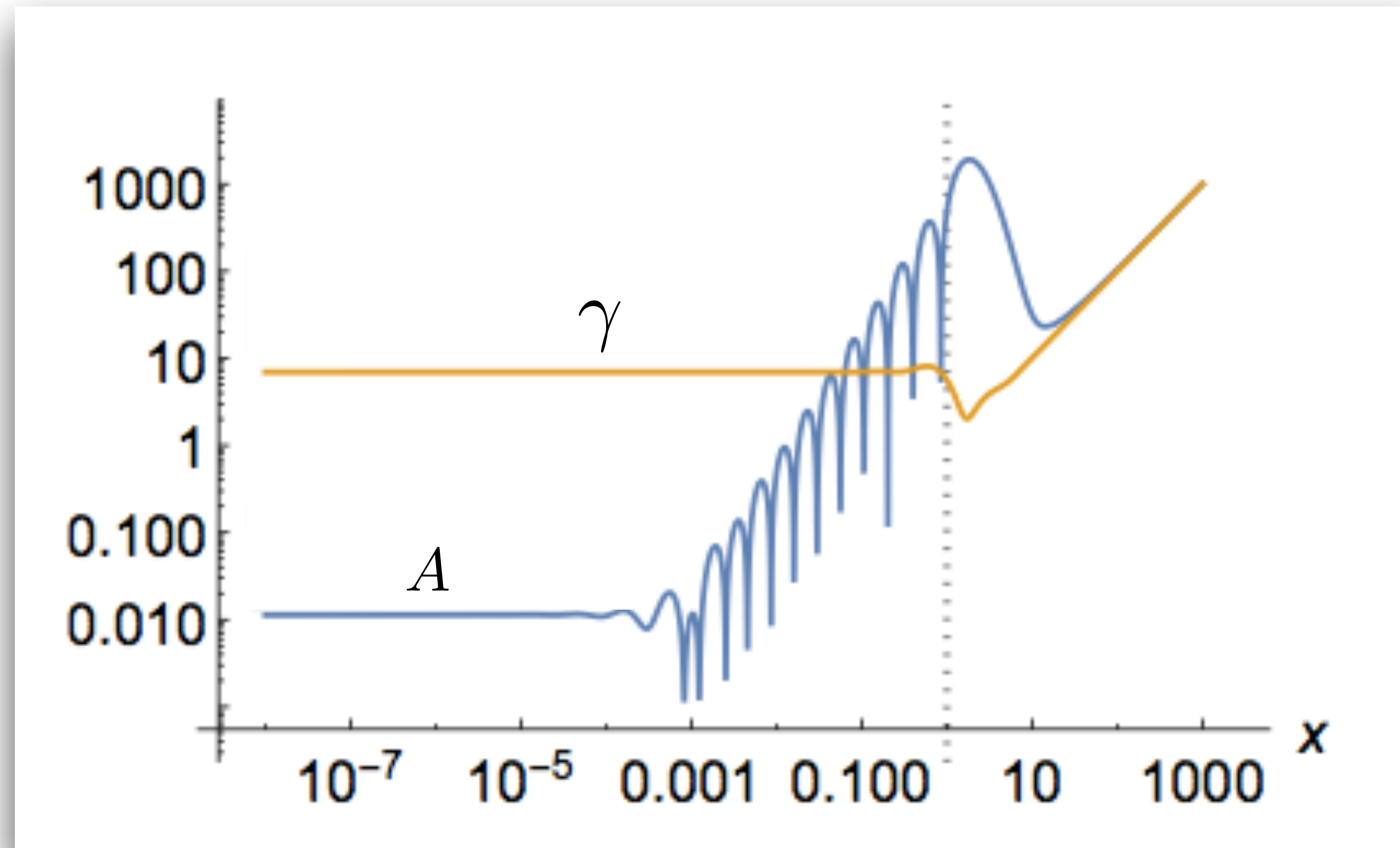
$$\boxed{\delta A^a_i = t_{ai} + \ldots}$$ TT-component



[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

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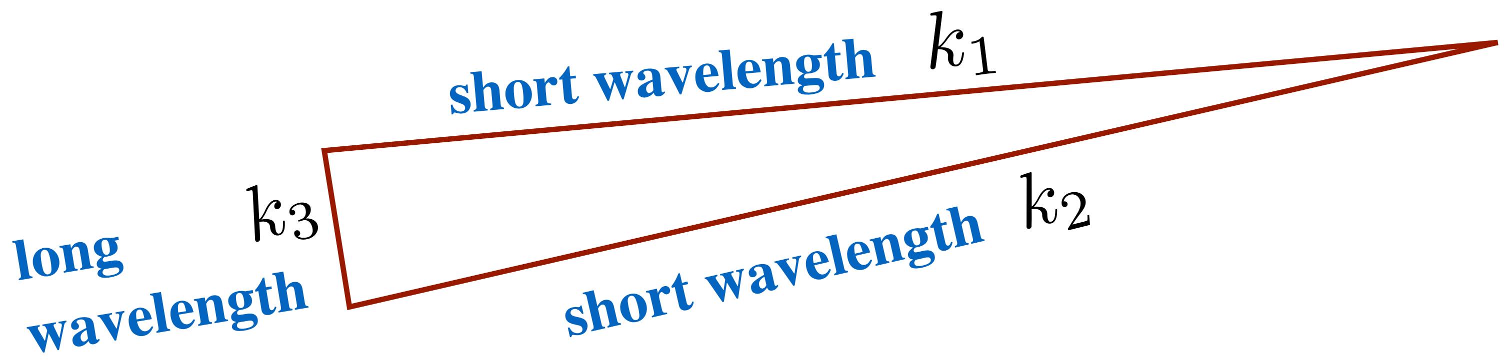
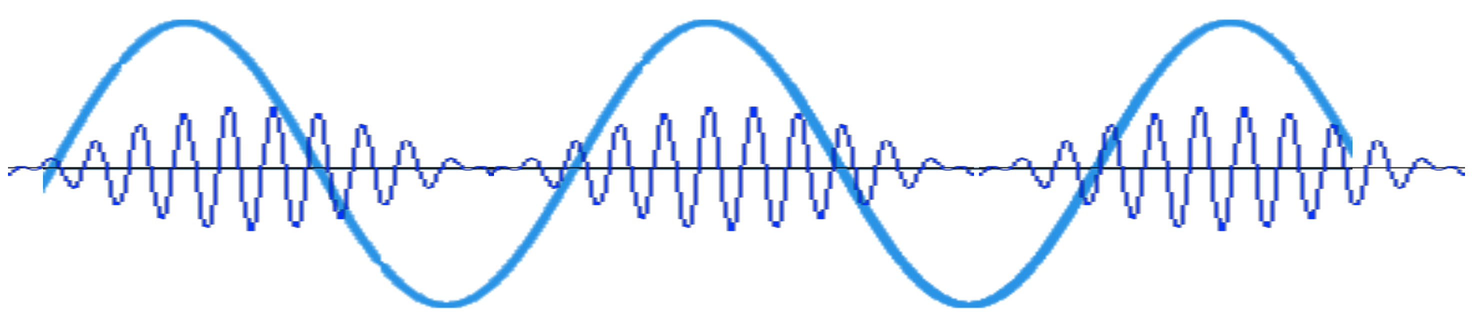
Squeezed non-Gaussianity

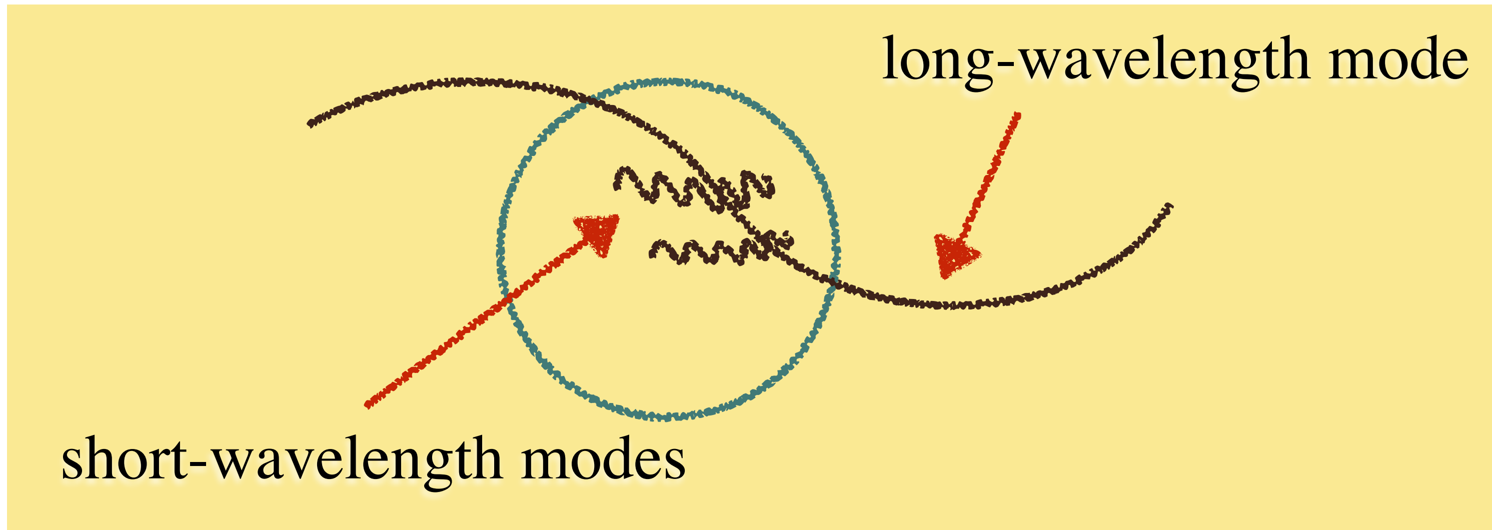


amplitude of long-wavelength modes
coupled with amplitude of short-wavelength modes



Soft limits and fossils

squeezed 3pf affects the 2pf

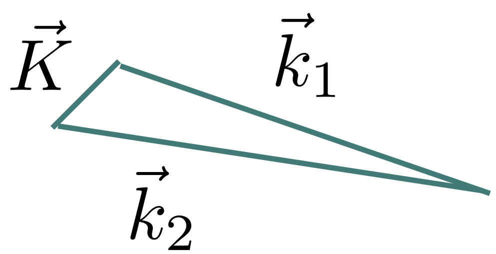


- No squeezed non-Gaussianity $\Rightarrow$ $\langle \delta_{\vec{k}_1} \delta_{\vec{k}_2} \rangle = \delta^{(3)}(\vec{k}_1 + \vec{k}_2) P(k_1)$

diagonal 2p correlation

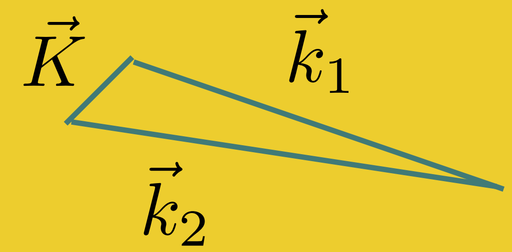
- Squeezed non-Gaussianity $\Rightarrow$ $\langle \delta_{\vec{k}_1} \delta_{\vec{k}_2} \rangle_{\vec{K}} = \delta^{(3)}(\vec{k}_1 + \vec{k}_2 + \vec{K})$
$\times f(\vec{k}_1, \vec{k}_2) A(K)$

there is also a off-diagonal contribution!

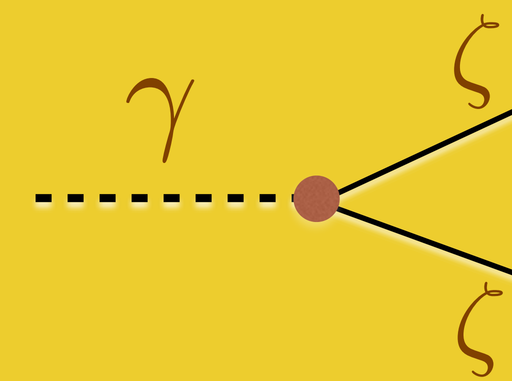


Soft limits and fossils

If



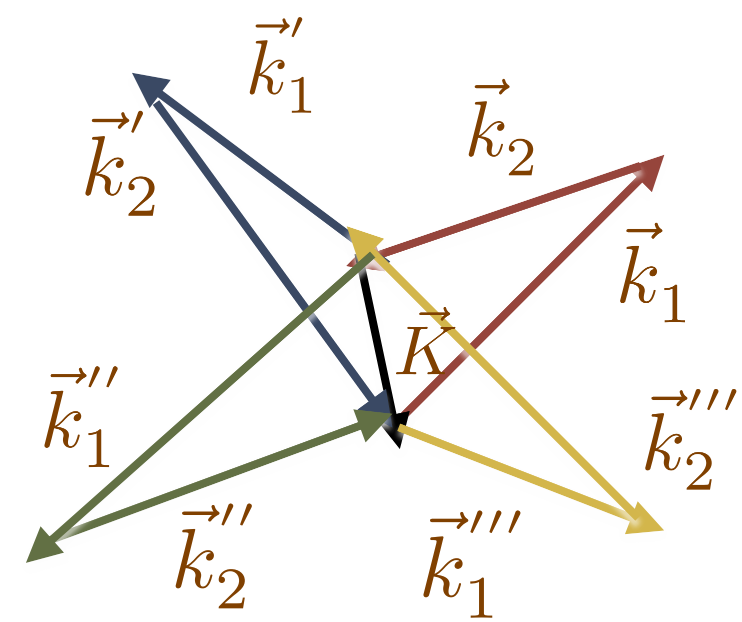
comes from



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

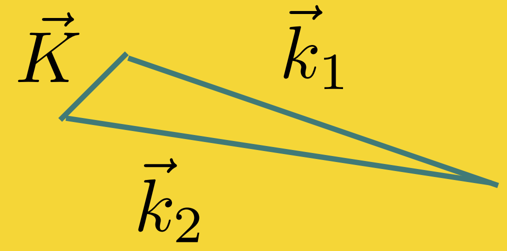
$$P_\zeta(\mathbf{k}, \mathbf{x}_c)|_{\gamma_L} = P_\zeta(k)\Big(1 + \mathcal{Q}_{\ell m}(\mathbf{x}_c, \mathbf{k})\hat{k}_\ell \hat{k}_m\Big)$$

<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



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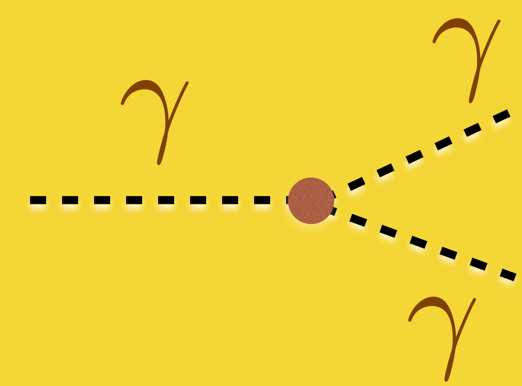

<u>super-Hubble K</u>:
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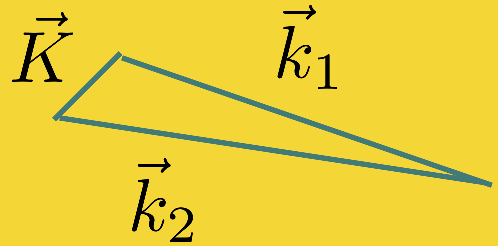
$$P_\gamma(\mathbf{k}, \mathbf{x}_c)|_{\gamma_L} = P_\gamma(k)\Big(1 + \mathcal{Q}_{\ell m}(\mathbf{x}_c, \mathbf{k})\hat{k}_\ell \hat{k}_m\Big)$$

[ED, Fasiello, Tasinato 2019]

Soft limits and fossils



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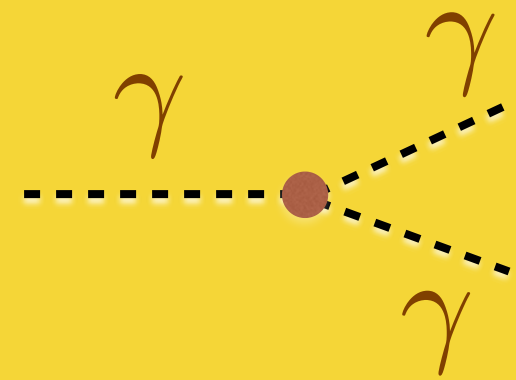

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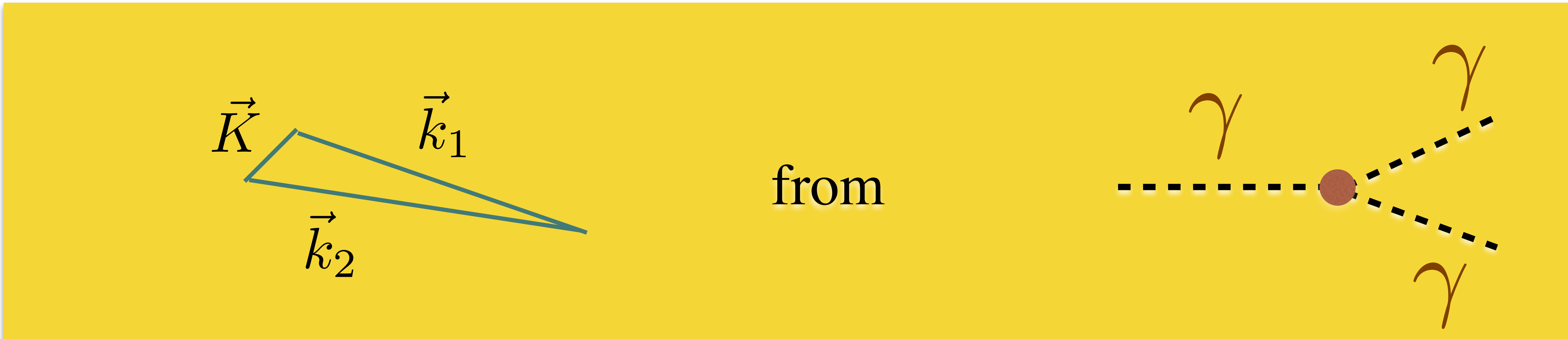
[ED, Fasiello, Tasinato 2019]

<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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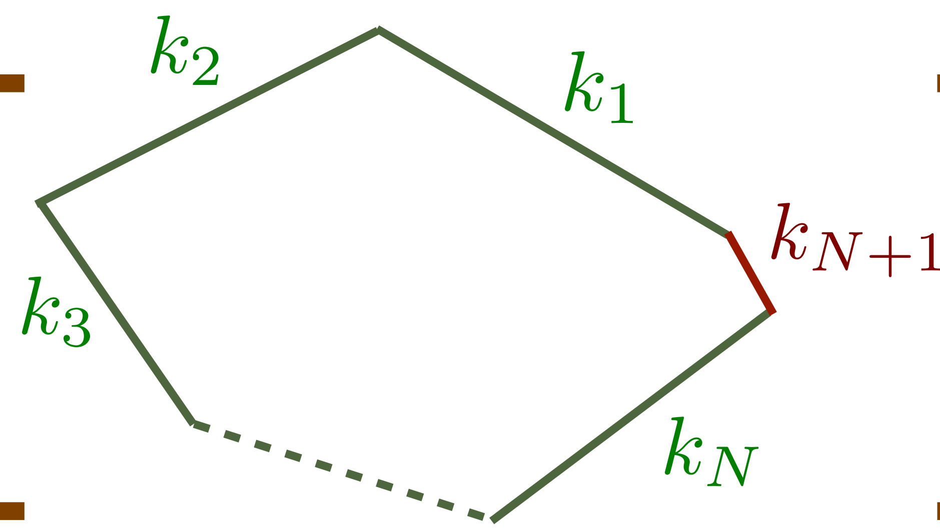
$\boxed{\text{Crucial observable for tensor non-Gaussianity at interferometer scales!}}$

[ED, Fasiello, Tasinato 2019]

Soft limits in inflation

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

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



$$\Bigg] \sim 0$$

<u>Intuitive understanding</u> :

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

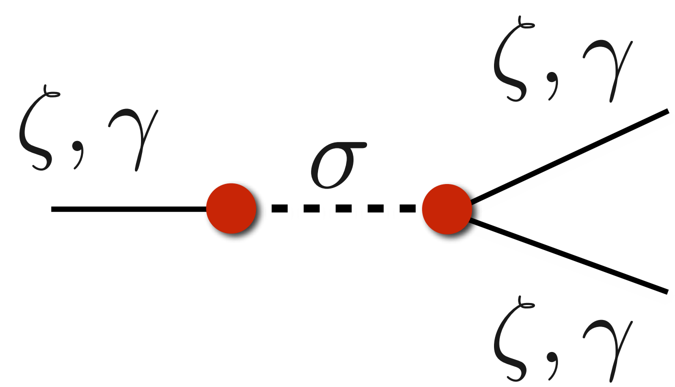
→

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

[Maldacena 2003, Creminelli, Zaldarriaga 2004]

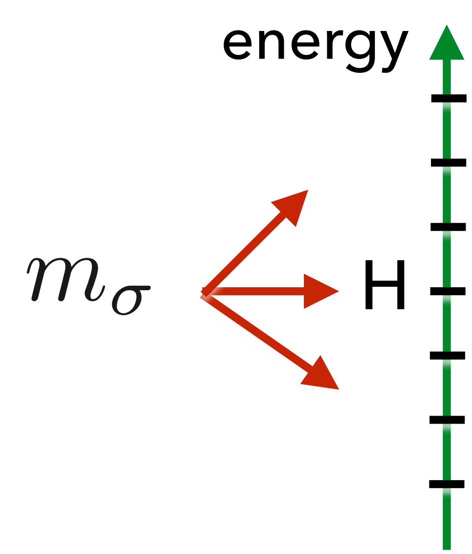
Soft limits in inflation

- ***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, 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, Ricciardone - Tasinato 2016, …]

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)

- Quadrupole anisotropy crucial observable for tensor non-Gaussianity at interferometer scales

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

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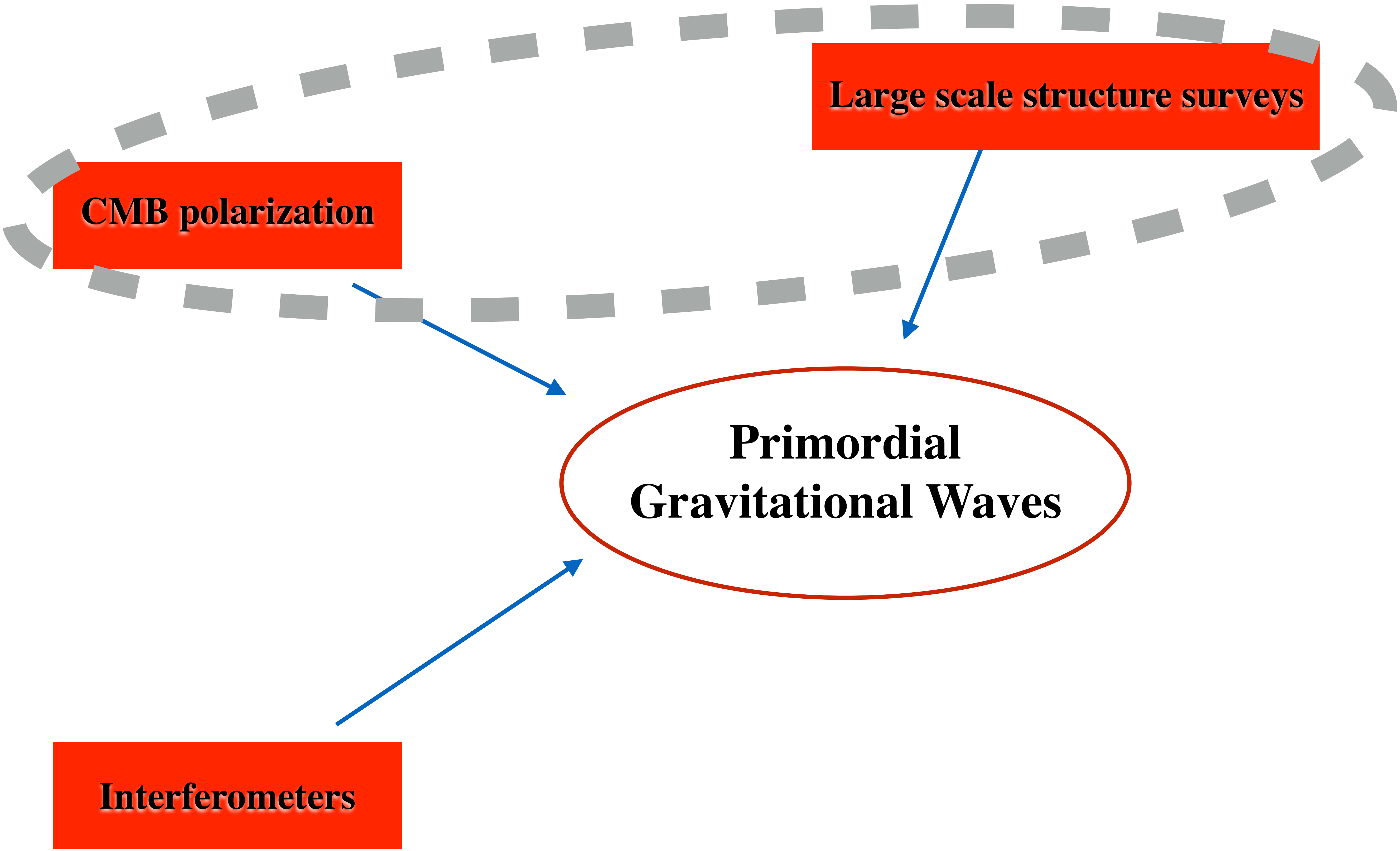
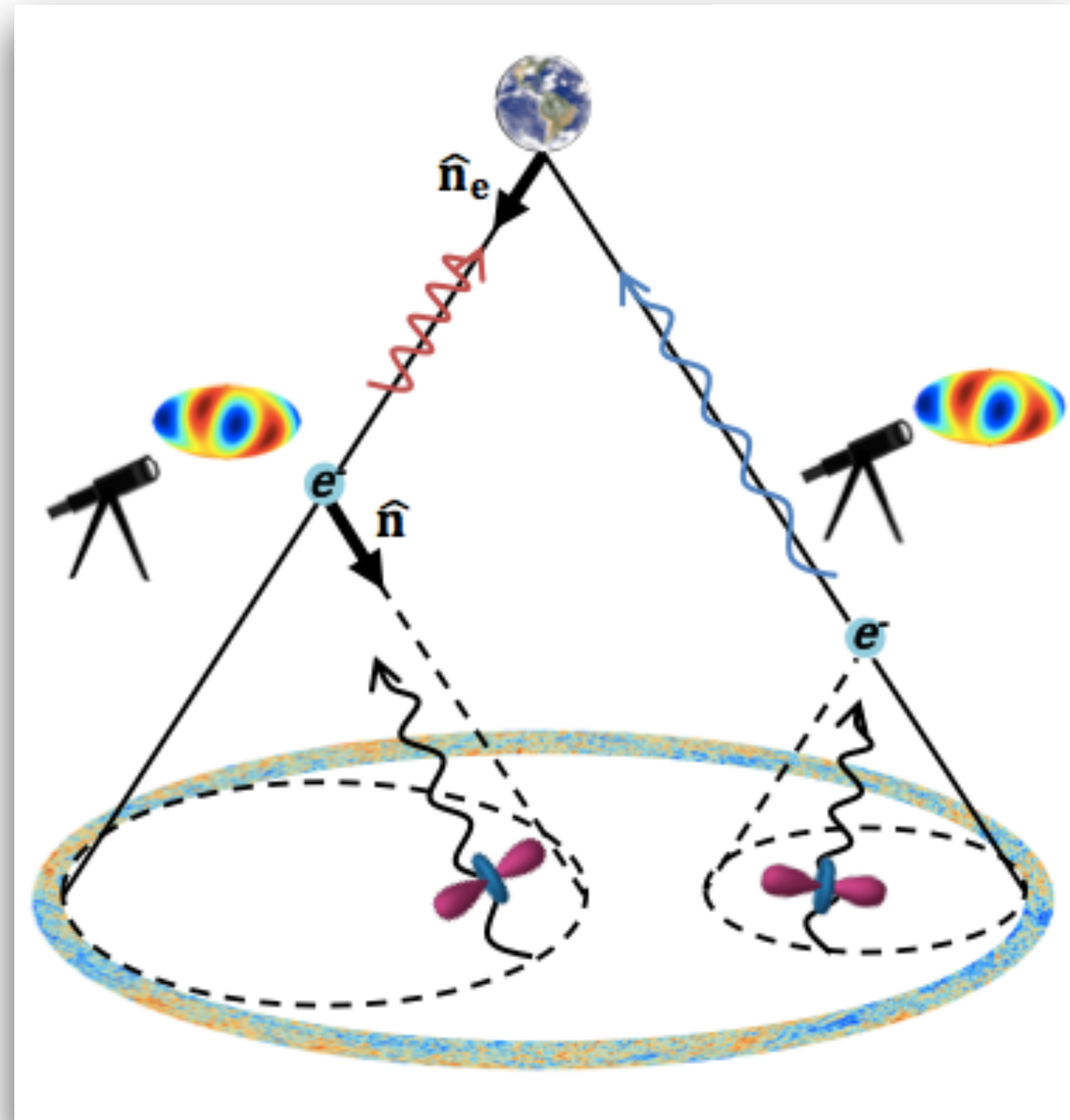

Large scale structure surveys
CMB polarization
Primordial Gravitational Waves
Interferometers

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)

Polarized Sunyaev-Zel'dovich effect

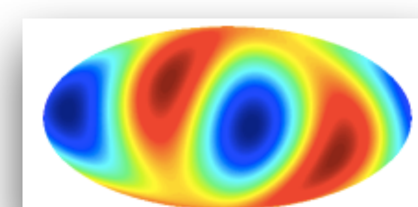
$$(Q \pm iU)(\hat{n}_e)\big|_{\rm pSZ} = -\frac{\sqrt{6}}{10}\sigma_T \int d\chi_e \; a(\chi_e)\, n_e(\hat{n}_e, \chi_e)\, \tilde{q}^{\pm}_{\rm eff}(\hat{n}_e, \chi_e)$$

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

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

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

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



pSZ tomography

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

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

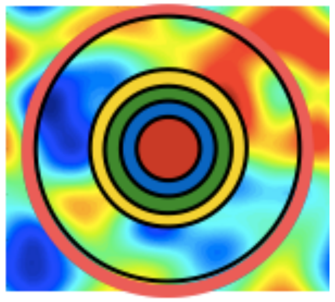
tracer of electron
number density

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:

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

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

scalars/ tensors

tensors only

binned density field

Optimal unbiased estimator : X = E, B

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

[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

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

- Our parameters:

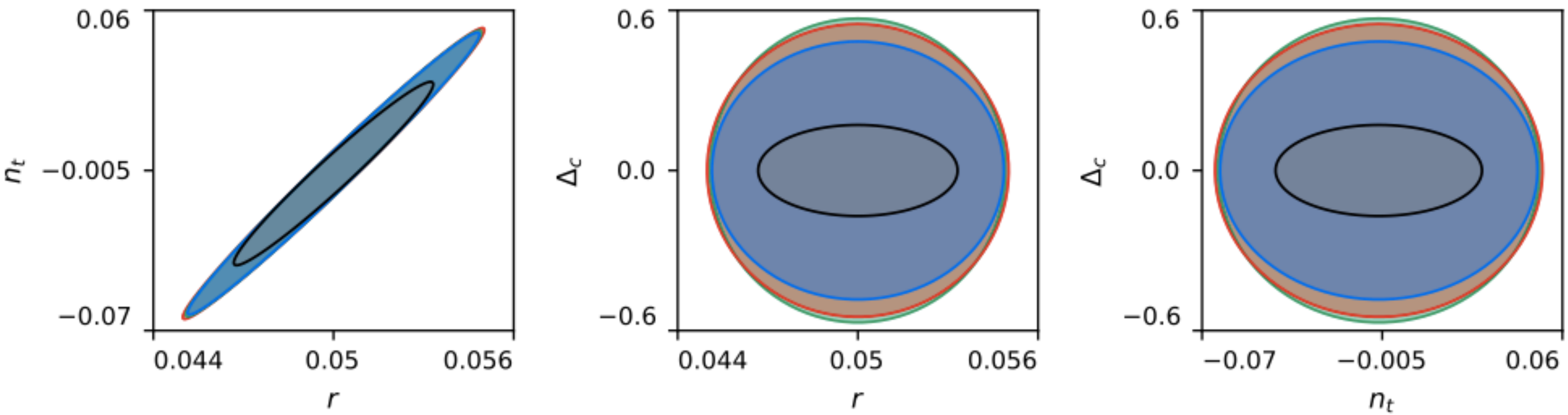
amplitude r

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]

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!