Testing early Universe physics with upcoming observations

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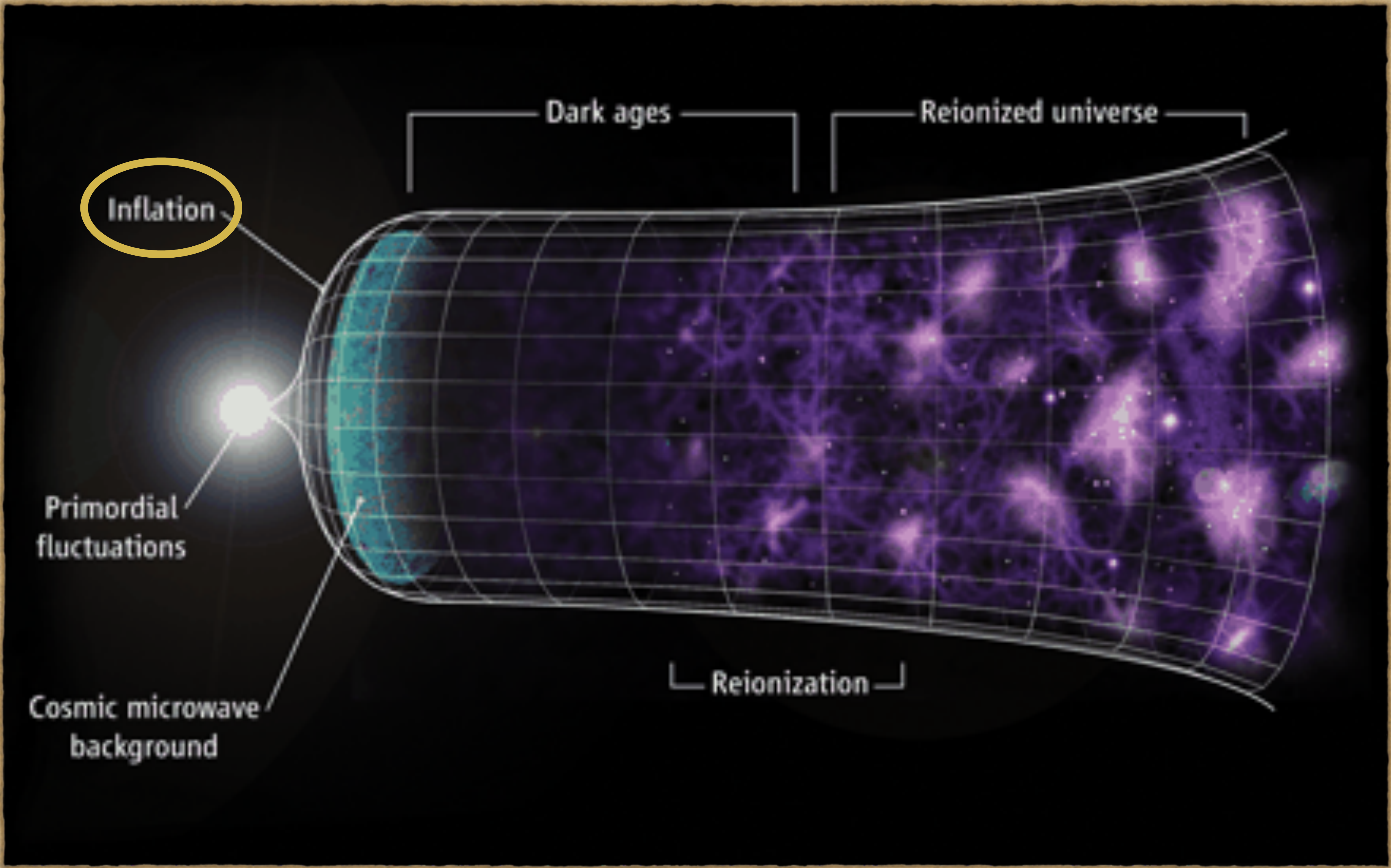
Outline:

- **ED**, M. Fasiello, M. Kamionkowski - *2015*
- **ED**, M. Fasiello, D. Jeong, M. Kamionkowski - *2014*

(1) Fossils from inflation
signatures of long-short mode couplings in galaxy surveys

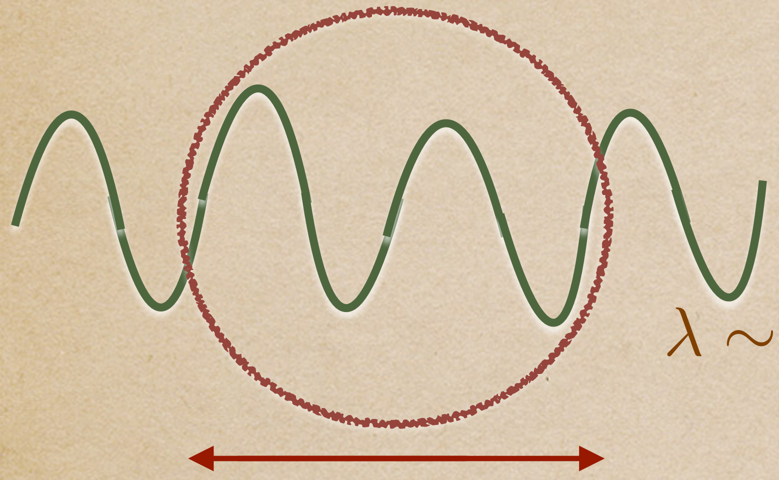
- J. Chluba, **ED**, M.A. Amin, M. Kamionkowski - *2017*
- **ED**, R. Emami - *2016*
- **ED**, L.M. Krauss, J. Chluba - *2015*
- R. Emami, **ED**, J. Chluba, M. Kamionkowski - *2015*

(2) Spectral distortions of the CMB
testing small scales primordial perturbations

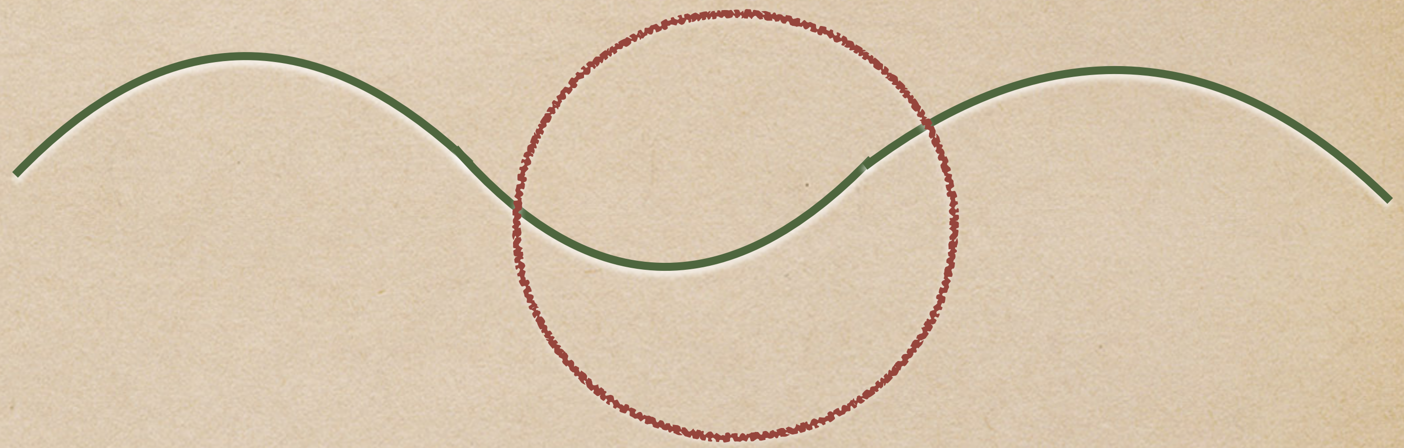

Dark ages
Reionized universe
Inflation
Primordial
fluctuations
Cosmic microwave
background
Reionization

Inflation

- Era of *accelerated (nearly exponential) expansion* in the primordial Universe : $a(t) \sim e^{Ht}$



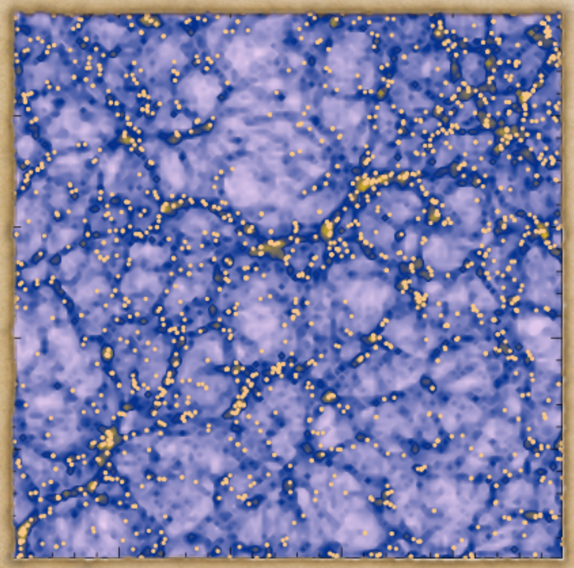
$\lambda \sim a(t)$



Hubble radius: $\sim 1/H \sim \text{const.}$

Physical scales are stretched by the expansion!

- Mechanism for the generation of cosmological fluctuations

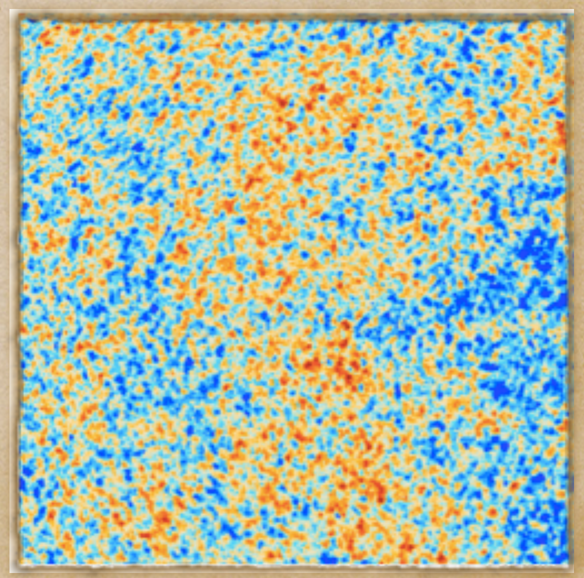


$$\phi(\vec{x},t) = \varphi(t) + \delta\phi(\vec{x},t)$$

Inflaton quantum fluctuations

↓

CMB perturbations
and LSS of the Universe



Predictions: power spectra (SFSR)

Scalar fluctuations : $\delta\phi \longrightarrow (\delta T/\bar{T} - \delta\rho/\bar{\rho})$ $\qquad P_S \sim \frac{1}{\epsilon}\left(\frac{H}{M_P}\right)^2 k^{n_s-1}$

Tensor fluctuations / primordial gravity waves : $\qquad P_T \sim \left(\frac{H}{M_P}\right)^2 k^{n_T}$

Energy-scale of inflation !

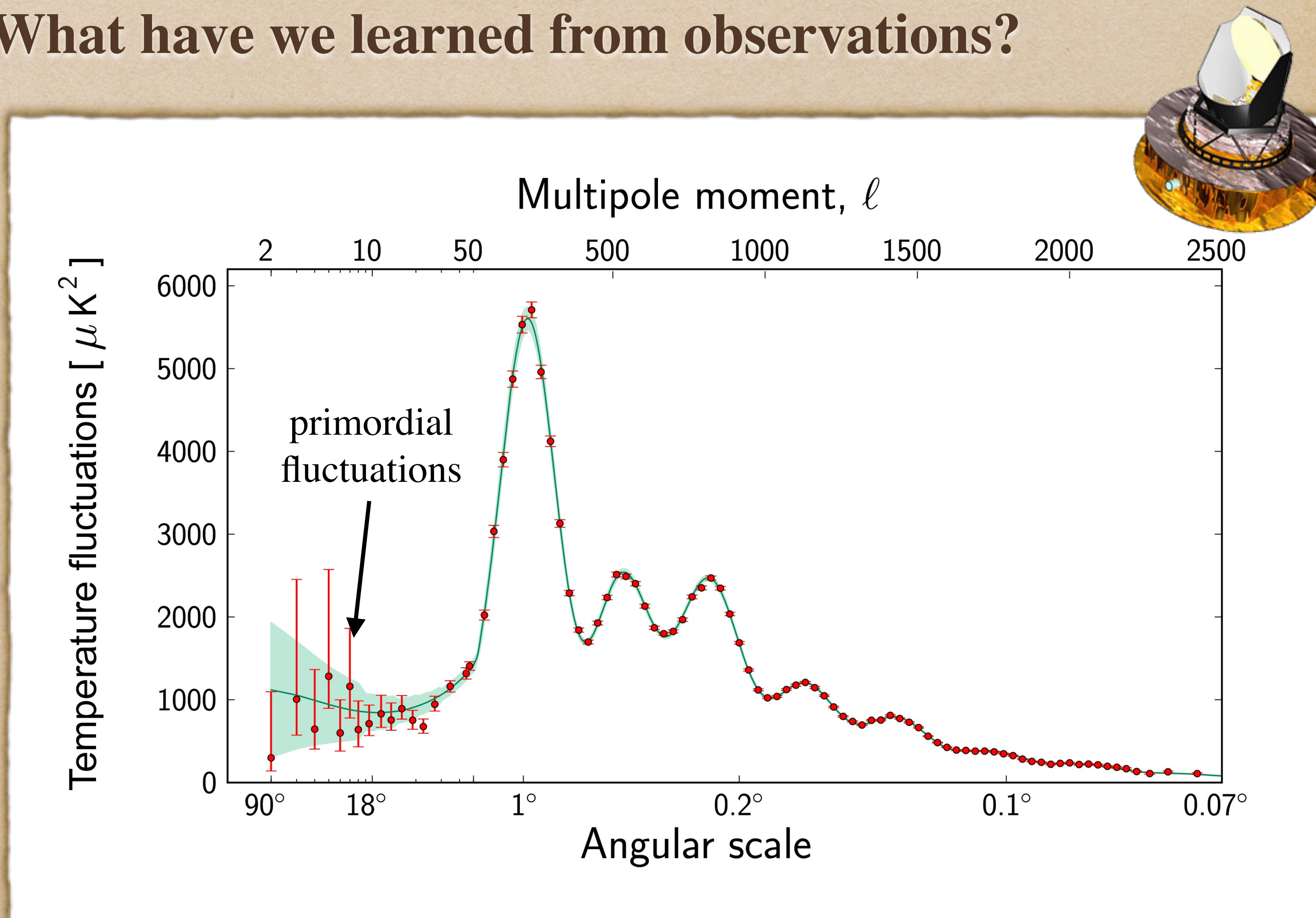
What have we learned from observations?

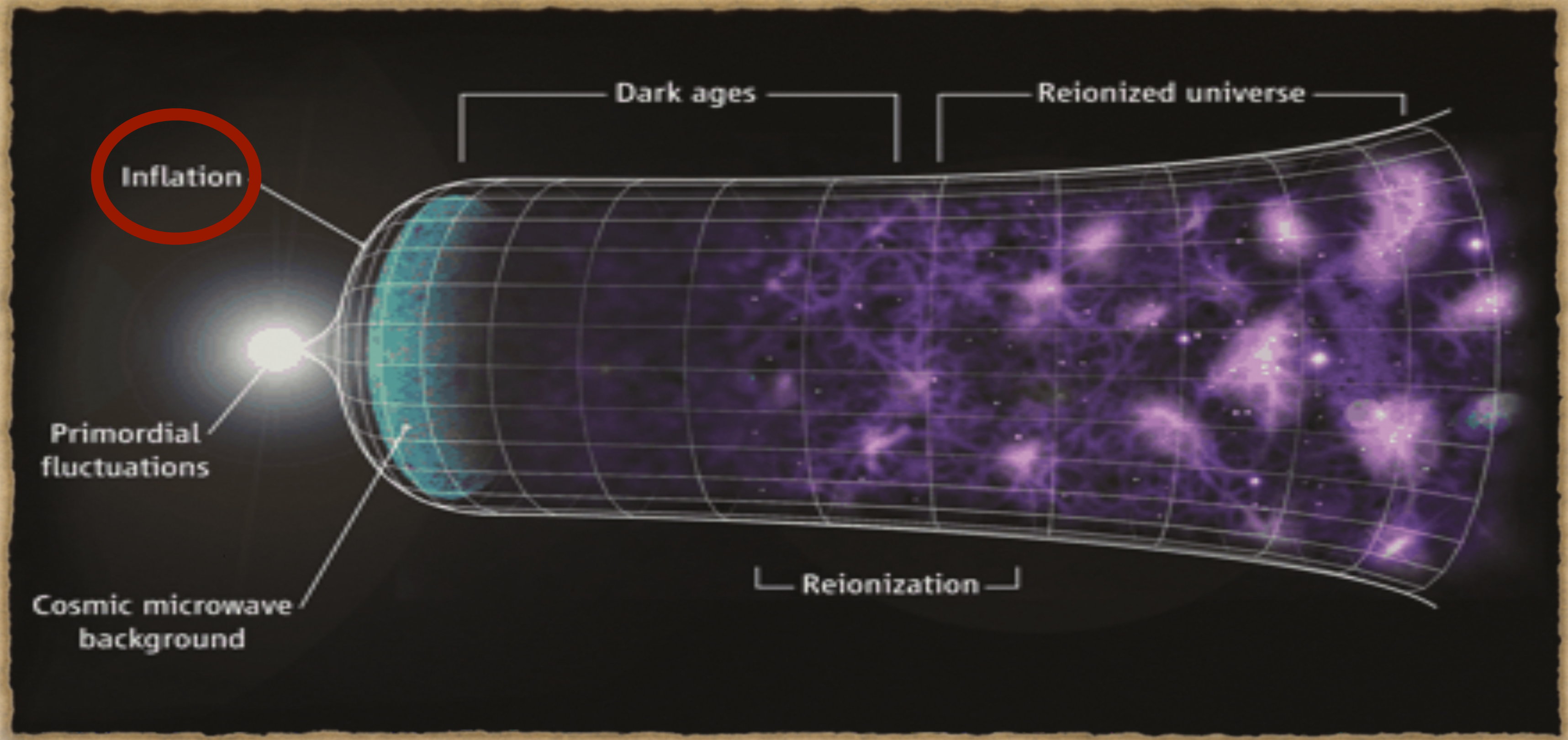
Scalar fluct. :

- nearly-scale invariant $n_s = 0.968 \pm 0.006$

Tensor fluct. :
tensor-to-scalar ratio
r < 0.07

BICEP2/KECK +Planck





Any spectator field

One or more active fields

How do fields interact

Energy scale of inflation

What are the masses of the extra fields

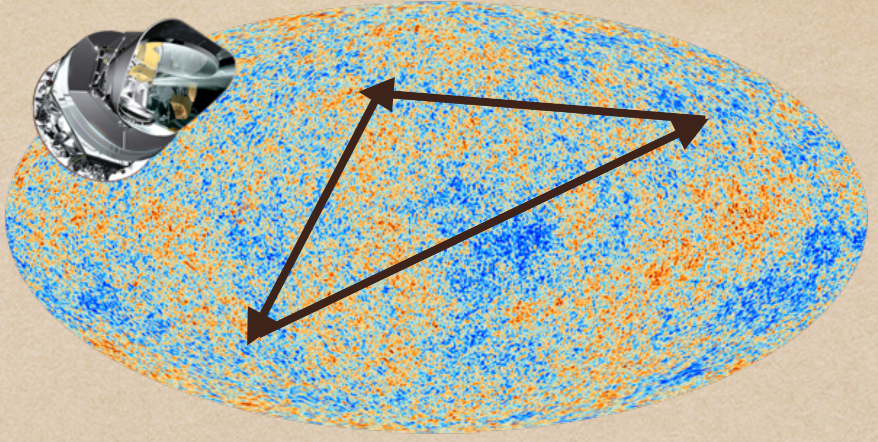
How does inflation end

Is it inflation

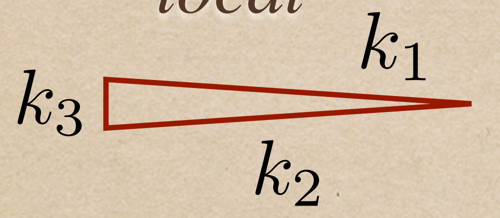
?

. . .

Microphysics of inflation: primordial non-Gaussianity

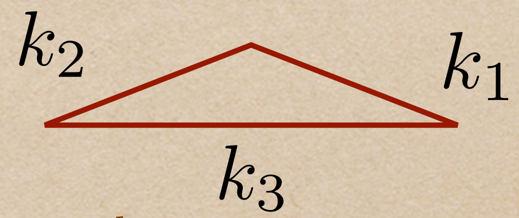


local



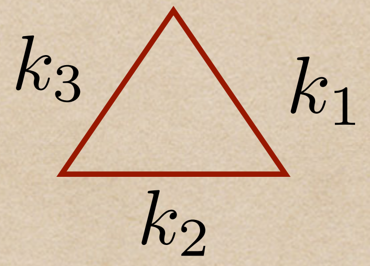
$f_{\rm nl}^{\rm loc} = 0.8 \pm 5$

orthogonal



$f_{\rm nl}^{\rm orth} = -26 \pm 21$

equilateral



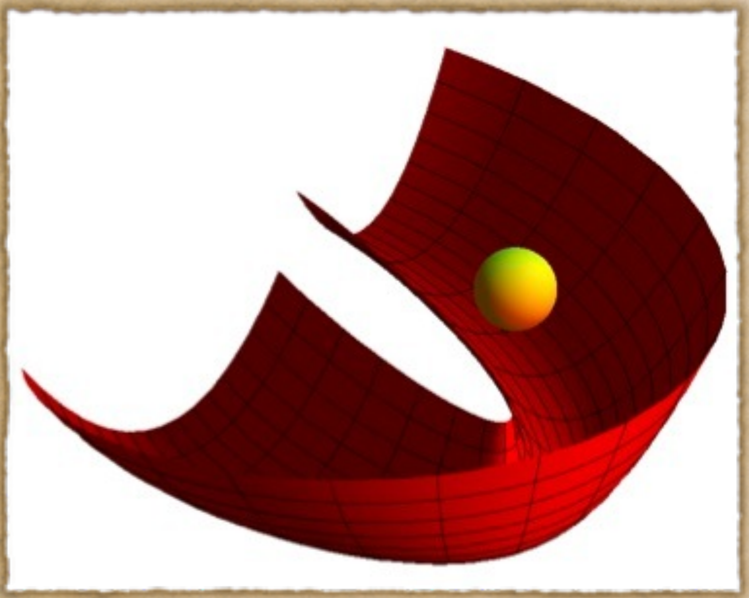
$f_{\rm nl}^{\rm eq} = -4 \pm 43$

$f_{\rm nl}^{\rm loc} \gtrsim \mathcal{O}(1)$ → ~~single-clock~~

$f_{\rm nl}^{\rm eq,\, orth} \gtrsim \mathcal{O}(1)$ → ~~slow-roll~~

thresholds potentially at reach for upcoming galaxy surveys!

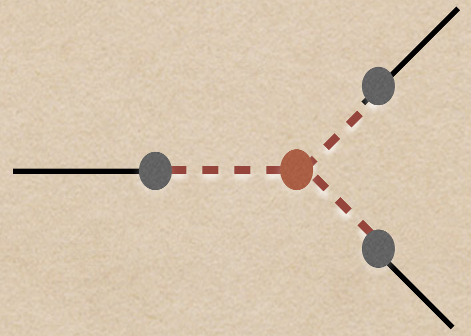
There is more:
e.g. ***intermediate shapes***

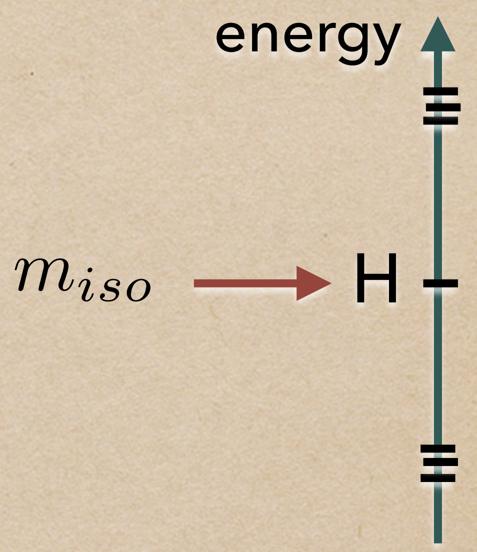


Case study: Quasi-Single-Field

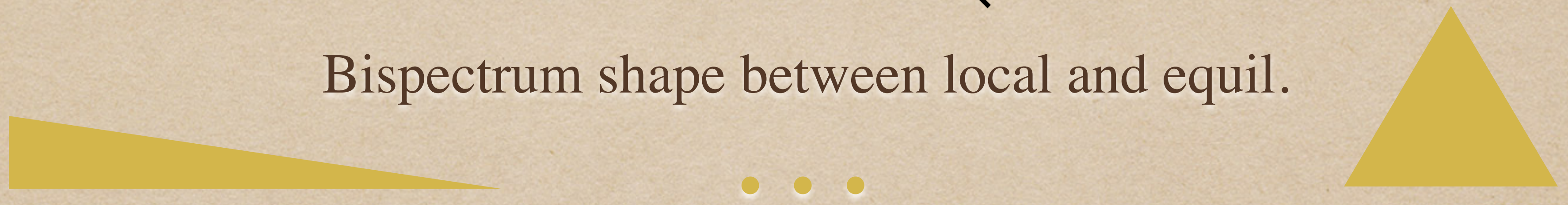
- tangent: inflaton
- radial: massive isocurvaton

(also SUSY -motivated)





Bispectrum shape between local and equil.



$m_{iso} \to 0$ . . . $m_{iso} \to 3\,H/2$

$$\mathcal{B}|_{squ.} \sim \frac{1}{k_1^3 k_3^3}\left(\frac{k_3}{k_1}\right)^{3/2 - f(m_{iso})}$$

$$f(m_{iso}) \equiv \sqrt{\frac{9}{4} - \frac{m_{iso}^2}{H^2}}$$

bispectrum shape delivers info on mass spectrum!

[Chen, Wang, 2010][Baumann, Green, 2011]

What happens next?

- Galaxy surveys :

photometric/spectroscopic (DESI, LSST, Euclid, SPHEREx, …) and *21cm* (CHIME, …)

Microphysics of inflation (**primordial non-Gaussianity**, running/features of primordial power spectrum, …)

Fossils from inflation

- CMB experiments :

Spectral distortions (PRISM, PIXIE, …)

Testing post- and **pre-recombination** physics

Primordial perturbations on small scales

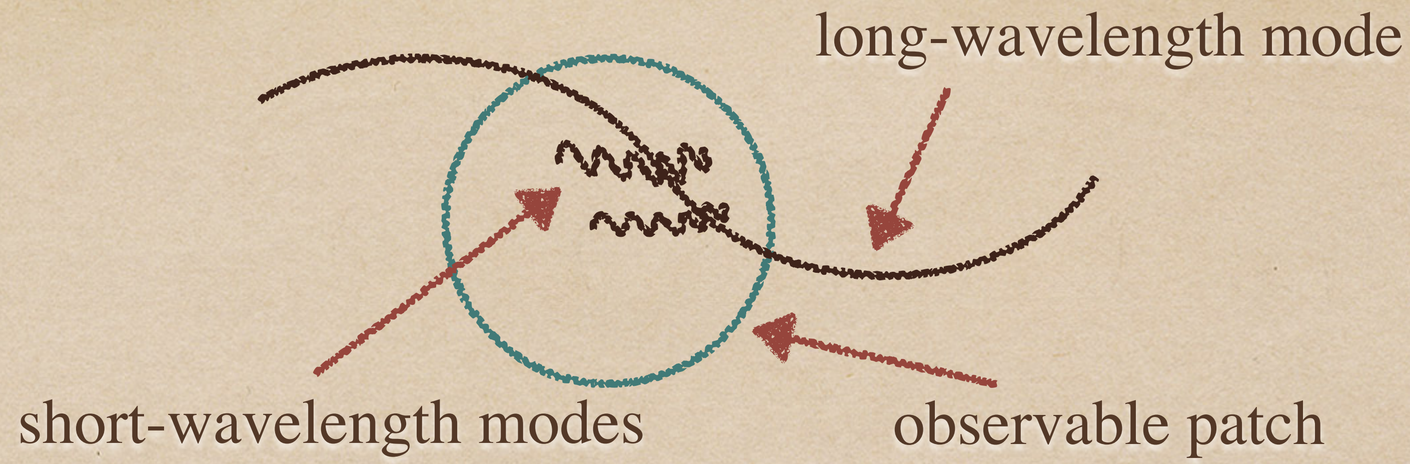
B-modes (BICEP/KECK series, SPTPol, SPIDER, PIXIE, …)

Origin of B-modes? What can we learn about the **early Universe**?

Fossils from inflation

*signatures of **multi-clock** inflationary dynamics*

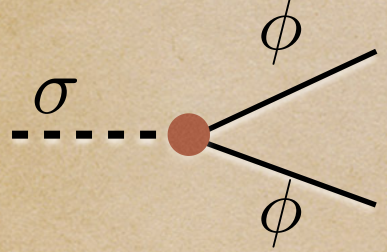
Effect of a long mode on local observables :



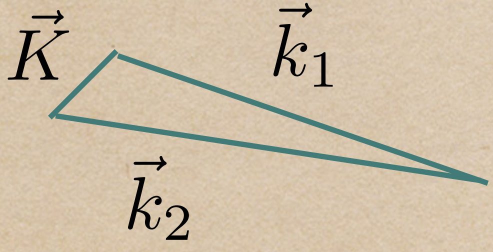
- Gaussian initial conditions + statistical homog./isotropy → $\langle \delta_{\vec{k}_1} \delta_{\vec{k}_2} \rangle = \delta^{(3)}(\vec{k}_1 + \vec{k}_2) P(k_1)$

diagonal 2p corr.

- Local/squeezed non-Gaussianity



→

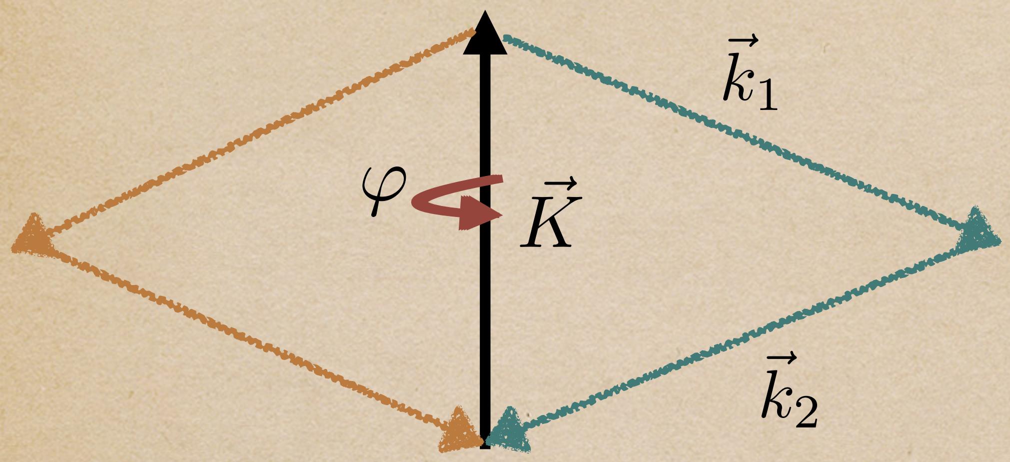


→

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

off-diagonal 2p corr.!

Probing σ through off-diagonal correlation :

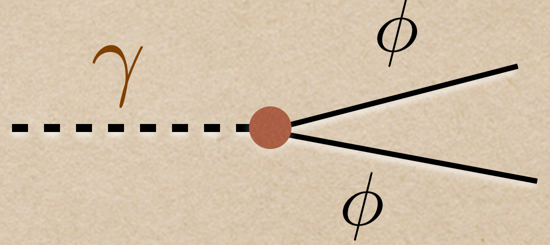


Azimuthal dependence:

- Scalar → no φ dependence
- Vector → $\cos\varphi$, $\sin\varphi$
- Tensor → $\cos 2\varphi$, $\sin 2\varphi$

[Jeong, Kamiomkowski, 2012]

What if σ = tensor mode of the metric:

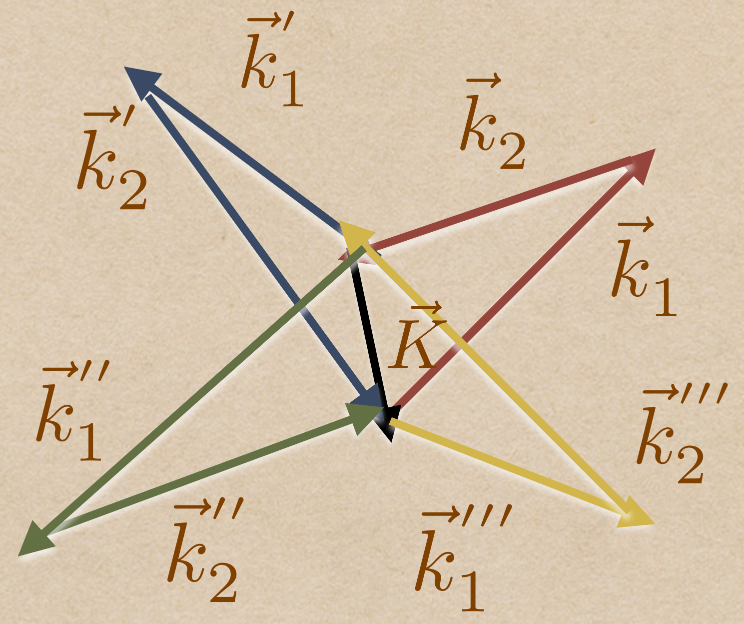


Learning about primordial tensors through non-Gaussian effects!

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

Estimating tensor modes amplitude :

$$\langle \delta_{\vec{k}_1} \delta_{\vec{k}_2} \rangle_{\gamma_p(\vec{K})} \sim (2\pi)^3 \delta^{(3)}(\vec{k}_1 + \vec{k}_2 + \vec{K}) \gamma_p^*(\vec{K}) \frac{B_p(\vec{k}_1, \vec{k}_2, \vec{K})}{P_\gamma^p(K)}$$



- Naive estimator:

$$\widehat{\gamma_p(\vec{K})} = \sum_{\vec{k}_1 + \vec{k}_2 = -\vec{K}} \frac{\delta_{\vec{k}_1} \delta_{\vec{k}_2}}{B_p(\vec{k}_1, \vec{k}_2, \vec{K}) / P_\gamma^p(K)}$$

- Optimal estimator for a single mode : inverse variance weighting

$$\widehat{\gamma_p(\vec{K})} = \sigma^2 \sum_{\vec{k}} \frac{|B_p(\vec{K},\vec{k},\vec{K}-\vec{k})/P_\gamma^p(K)|^2}{2V\, P^{tot}(k) P^{tot}(|\vec{K}-\vec{k}|)} \delta_{\vec{k}} \delta_{\vec{K}-\vec{k}}$$

$$\sigma^2 = \left[\sum_{\vec{k}} \frac{|B_p(\vec{K},\vec{k},\vec{K}-\vec{k})/P_\gamma(K)|^2}{2V\, P^{tot}(k) P^{tot}(|\vec{K}-\vec{k}|)}\right]^{-1}$$

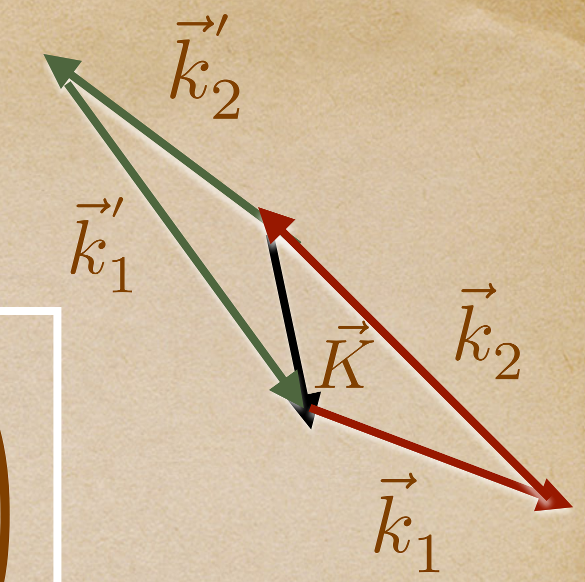
random variable

variance

$$\{y_i, \sigma_i^2\}$$

$$\hat{y} = \frac{\sum_i (y_i/\sigma_i^2)}{\sum_j (1/\sigma_j^2)} \qquad \sigma^2 = \left(\sum_i \frac{1}{\sigma_i^2}\right)^{-1}$$

- Optimal estimator for power amplitude: stochastic GW background with $P_p(K) = A_\gamma \, P^f_\gamma(K)$



$$\widehat{A_\gamma} = \sigma_\gamma^2 \sum_{p,\vec{K}} \frac{(P^f_\gamma(K))^2}{(P^n_p(K))^2} \left(\frac{\widehat{|\gamma_p(\vec{K})|^2}}{V} - P^n_p(K) \right)$$

optimal sum over different K-modes

$$\begin{cases} \sigma_\gamma^{-2} = \sum_{p,\vec{K}} \frac{(P^f_\gamma(K))^2}{2(P^n_p(K))^2} \\ P^n_p \equiv \left[\sum_{\vec{k}} \frac{|B_p(\vec{K},\vec{k},\vec{K}-\vec{k})/P_\gamma(K)|^2}{2V P^{tot}(k) P^{tot}(|\vec{K}-\vec{k}|)} \right]^{-1} \end{cases}$$

$$\mathcal{B}_{\gamma\zeta\zeta} \simeq \beta P_\gamma P_\zeta$$

$$\sigma_\gamma \propto \frac{1}{\beta^2} \left(\frac{k_{max}}{k_{min}} \right)^{-3}$$

Which classes of models predict these signatures at observable levels?

~~single-clock ccs~~

- (n+1)-point function fixed in terms of n-point functions (soft limit for one of the modes)
- Apply if super-horizon modes freeze + standard initial conditions (rescaling of background for short modes)
- Derived from symmetries of the action (invariance under space diffs)
  [Maldacena 2003, Creminelli-Zaldarriaga 2004, Goldberger et al 2013, . . .]

- *Isocurvature* modes (multi-field)
- *Non-Bunch Davies* initial states
  [Holman - Tolley 2007, Brahma-Nelson-Shandera 2013, …]
- *Broken space diffs* (e.g. solid inflation/space-dependent background)
  [Endlich et al., 2013, Bartolo et al, 2015]

Fossil signatures at reach for upcoming observations (e.g. Euclid or 21cm)!

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

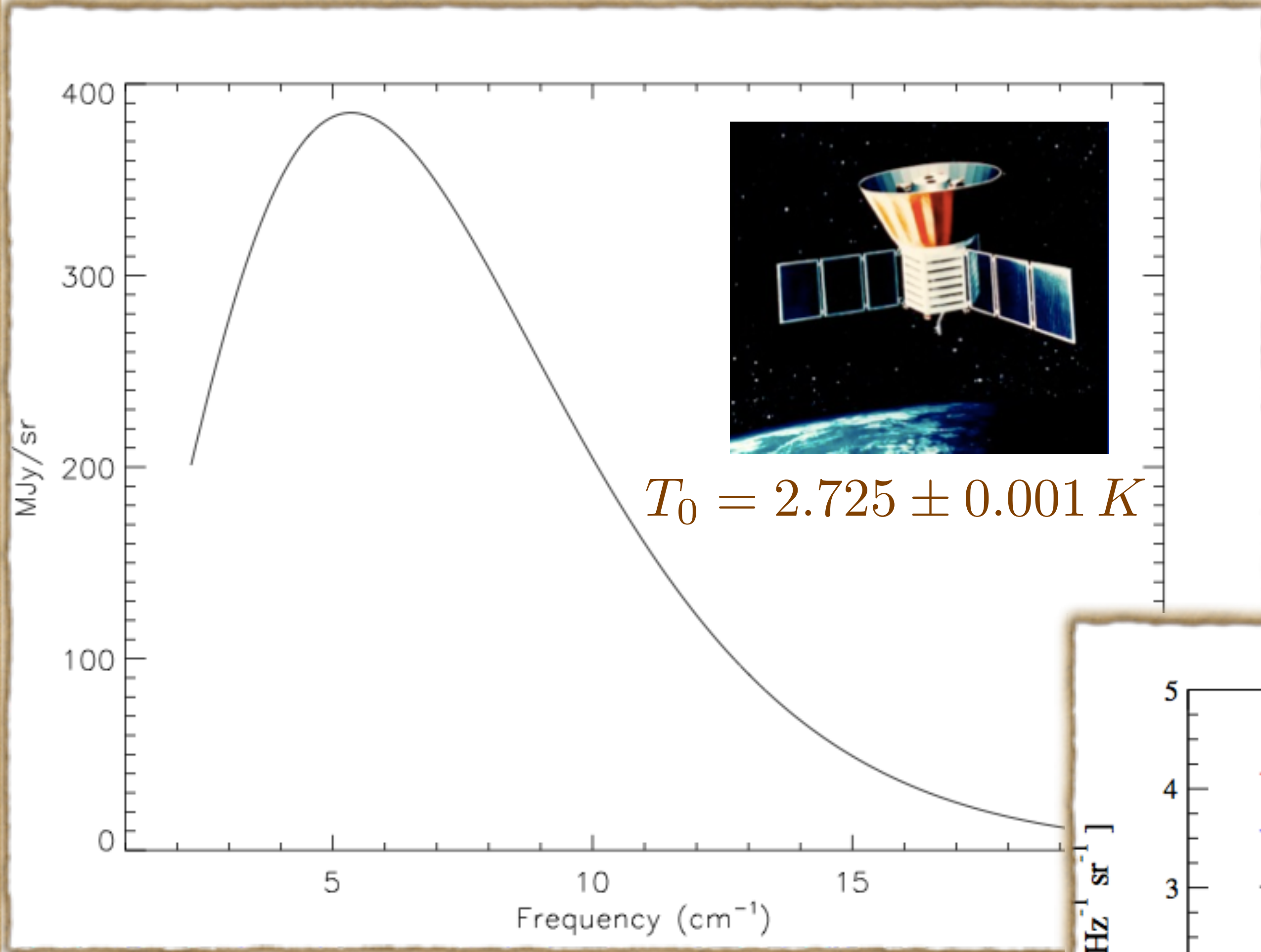
Summary

- *tss* correlation in the squeezed limit affects density power spectrum (*off-diagonal/quadrupolar anisotropy*)
- signatures observable if arising from models that evade ccs: another *test for single-clock inflation* besides the scalar (squeezed) bispectrum
- Primordial *GWs amplitude* may be estimated from off-diagonal correlation!

Spectral distortions of the CMB

A window into primordial perturbations on ***small scales***

Cosmic Microwave spectrum from COBE/FIRAS



$T_0 = 2.725 \pm 0.001\, K$

Energy/photon injections into CMB at $z \lesssim 2 \times 10^6$

↓

Distortion of the blackbody spectrum

energy-injection rate

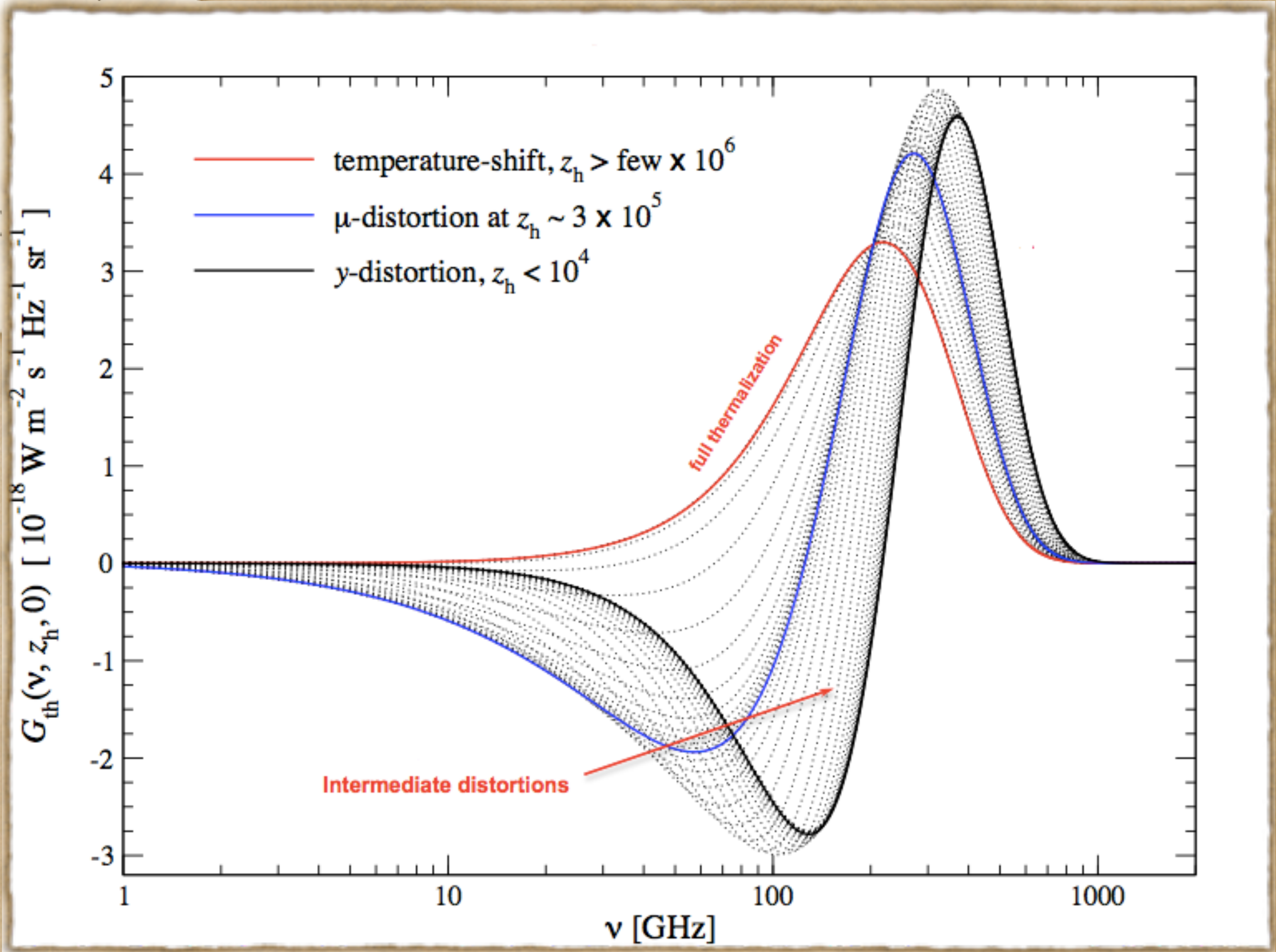
$$\Delta I_\nu \approx \int G_{\rm th}(\nu, z') \frac{d(Q/\rho_\gamma)}{dz'} dz'$$

Deviations allowed from FIRAS:

$|\mu| \lesssim 9 \times 10^{-5}$

$|y| \lesssim 1.5 \times 10^{-5}$

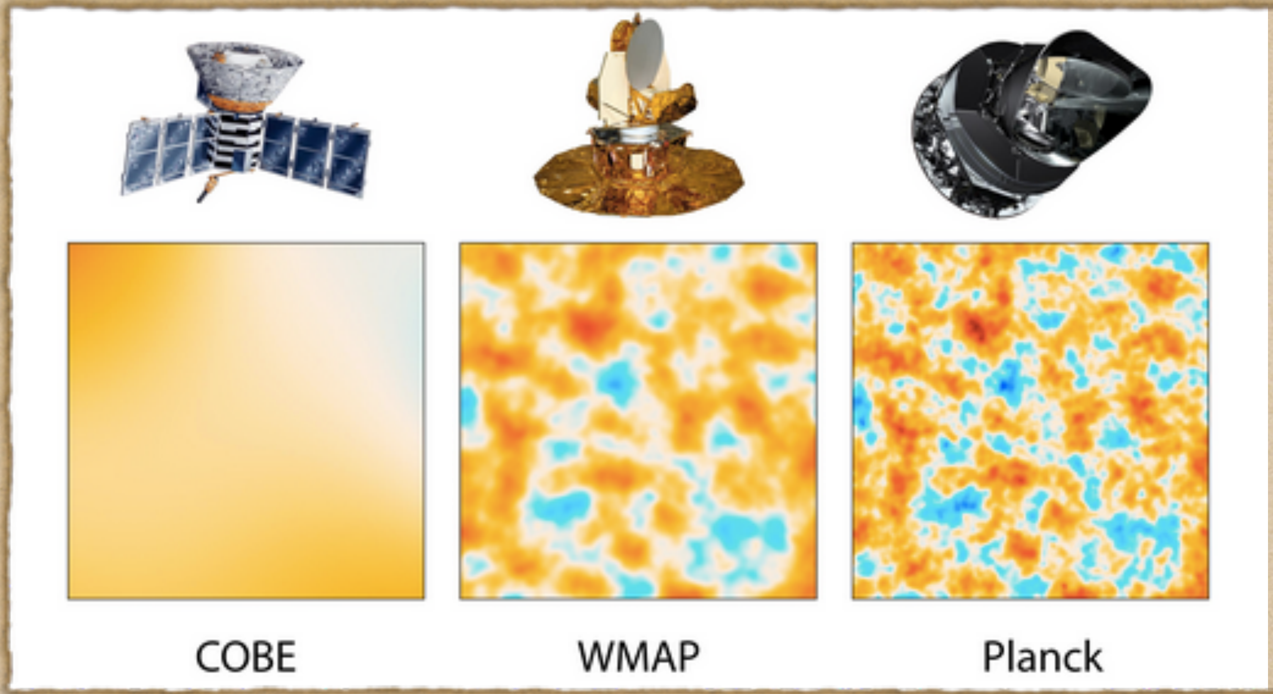
[Fixsen et al., 1996]



[Chluba, 2013]

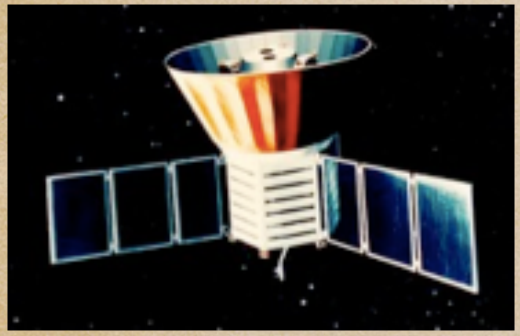
Why spectral distortions matter?

CMB anisotropies:
(~20 yrs)



Spectral distortions:

COBE/FIRAS

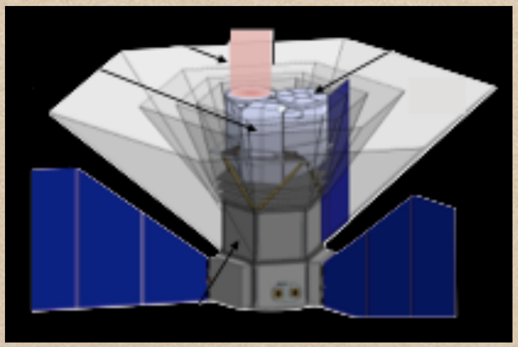


$|\mu| \lesssim 9 \times 10^{-5}$

$|y| \lesssim 1.5 \times 10^{-5}$

[Fixsen et al., 1996]

PIXIE



$|\mu| \lesssim 2 \times 10^{-8}$

$|y| \lesssim 4 \times 10^{-9}$

[Kogut et al., 2011]

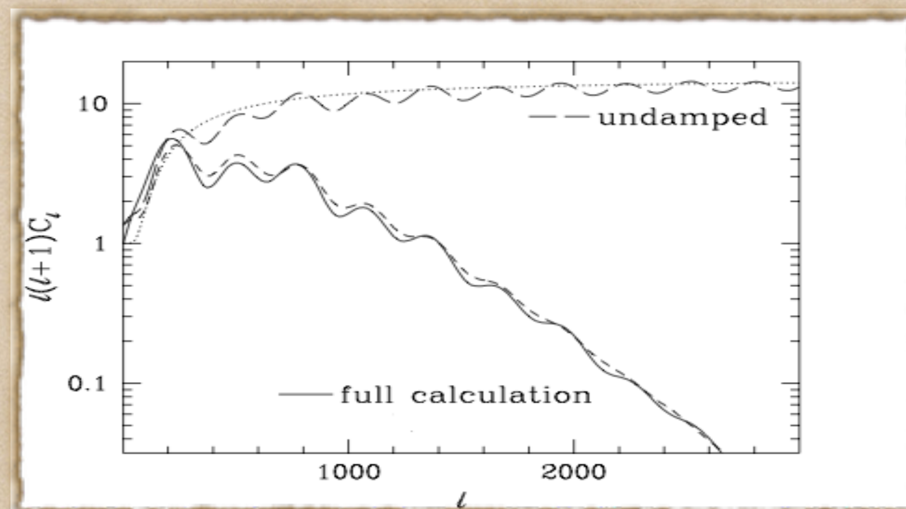
Mechanisms producing SDs include:

- Cosmological recombination
- Reionization, structure formation
- Dissipation of magnetic fields
- Decay/annihilation of particles
- Dissipation of primordial fluctuations
- …

SDs from diffusion damping

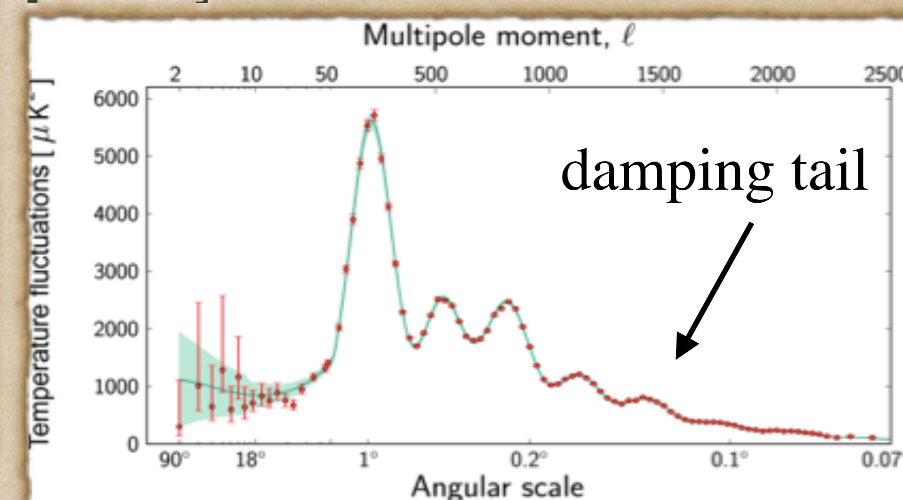
Primordial fluctuations
re-enter Hubble radius
after inflation

Isotropization by photon diffusion



[Hu&White, 1996]

[Planck]



Effective **energy release** into CMB

[Hu et al., 1994]
[Chluba et al., 2012]

$$\frac{d(Q/\rho_\gamma)}{dz} \sim \int dk\, k^4 \mathcal{P}_\zeta(k)\, e^{-[2\,k^2/k_D^2(z)]}$$

$$k_D^2(z) \approx \left(4\times 10^{-6}(1+z)^{3/2}\mathrm{Mpc}^{-1}\right)^2$$

(damping scale)

Probing scales k: $\begin{cases} [50, 10^4]\ \mathrm{Mpc}^{-1} & \text{(with } \mu \text{ distortion)} \\ [1, 50]\ \mathrm{Mpc}^{-1} & \text{(with } y \text{ distortion)} \end{cases}$

probing ~ **10** extra inflationary e-folds!

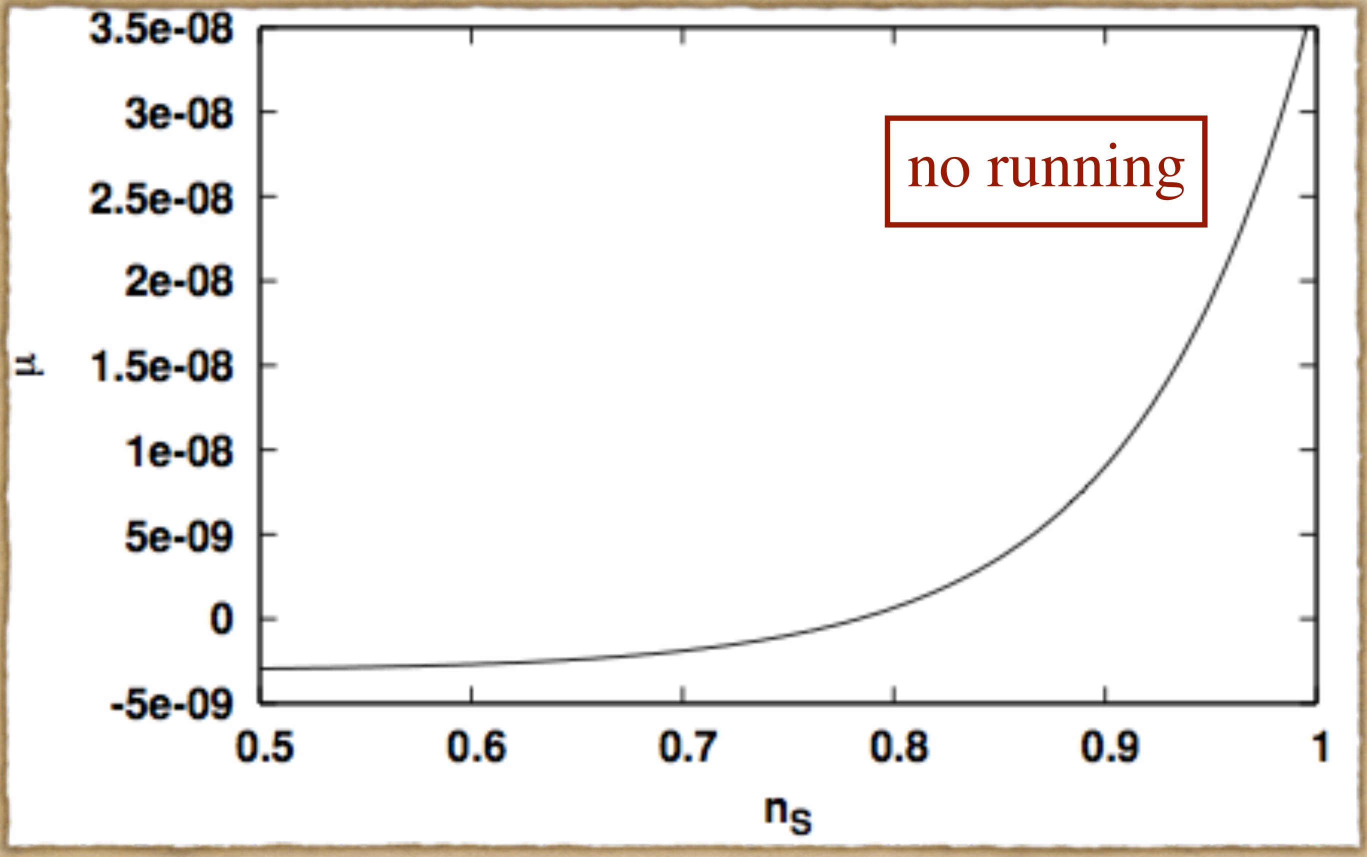
Power spectrum constraints: SFSR

$$\mathcal{P}_\zeta(k) = A_\zeta \left(\frac{k}{k_*}\right)^{n_s - 1 + \frac{1}{2}\{\mathrm{d}n_s/\mathrm{d}\ln k\}\ln(k/k_*)}$$

$$\begin{cases} n_s = 0.968 \pm 0.006 \\ \mathrm{d}n_s/\mathrm{d}\ln k = -0.006 \pm 0.007 \end{cases}$$

Planck temperature + polarization data on large angular scales (68% CL)

[Khatri, Sunyaev, Chluba, 2012]



E.g. for ns = 0.96: $\frac{Q^{z=5\times10^4}_{z=2\times10^6}}{\rho_\gamma} \simeq \mathcal{O}(10^{-8})$

Sensitivity for μ distortion

$\sigma_\mu = (1/n) \times 10^{-8}$

E.g. : n=1 ← PIXIE; n=10 ← PRISM

3 x PIXIE = *guaranteed discovery*

→ detection (95% CL)

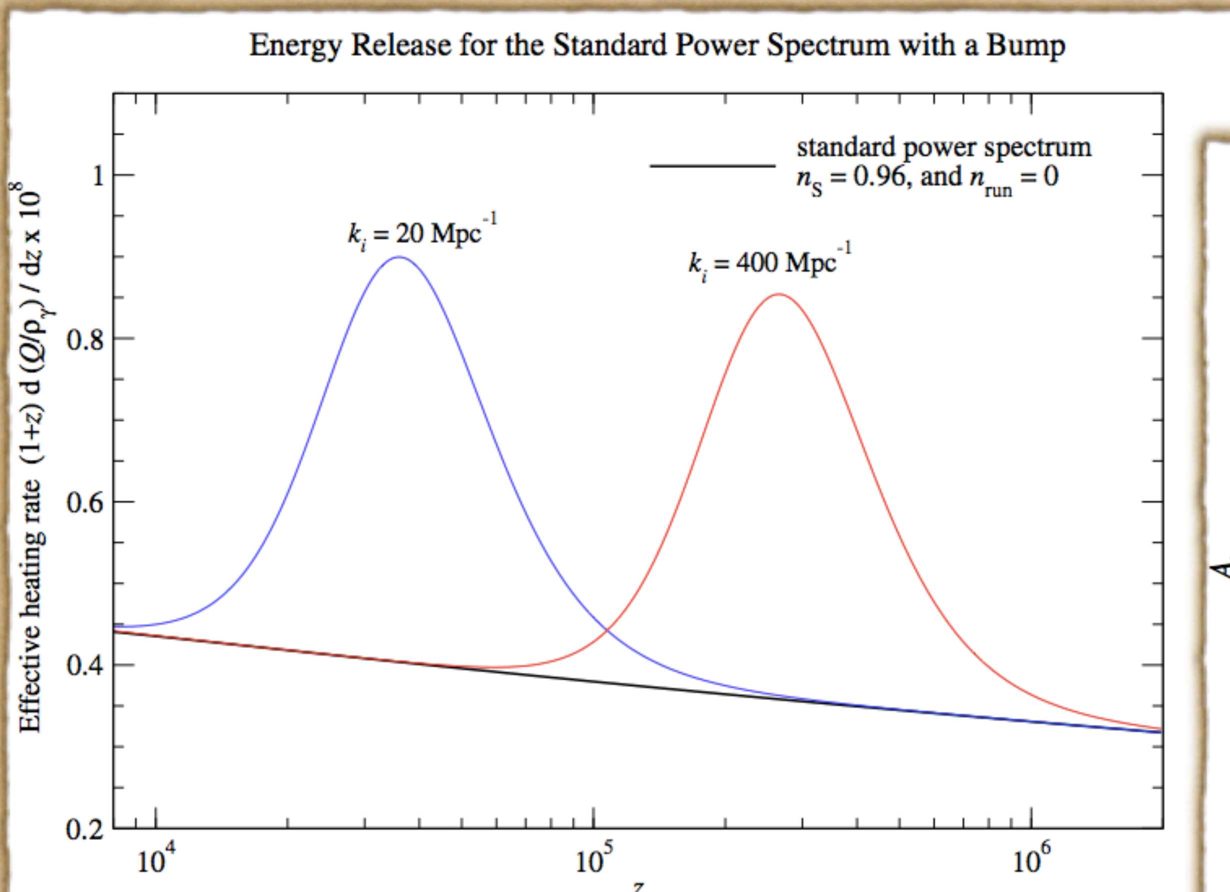
→ exclusion of SFSR (95% CL)

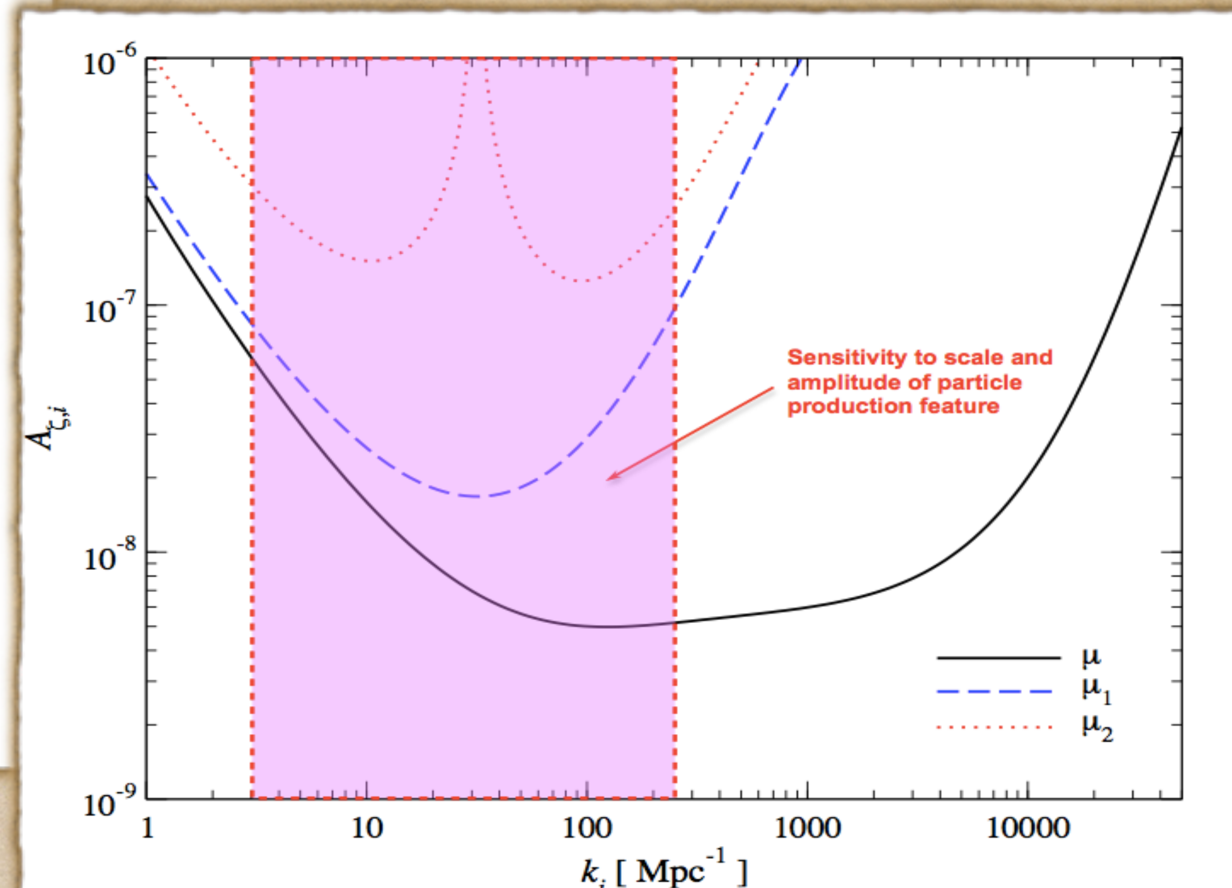
[Cabass, Melchiorri, Pajer, 2016]

Power spectrum constraints: ~~SFSR~~

$$\mu \approx 2.2 \int \mathcal{P}_\zeta \left[e^{-\left(\frac{k \cdot \mathrm{Mpc}}{5400}\right)^2} - e^{-\left(\frac{k \cdot \mathrm{Mpc}}{31.6}\right)^2} \right] d\ln k$$

$$y \approx 0.4 \int \mathcal{P}_\zeta(k) e^{-\left(\frac{k \cdot \mathrm{Mpc}}{31.6}\right)^2} d\ln k$$





- e.g. from particle production
- bump of amplitude $A_{\zeta,i}$, localized around k_i
- intermediate distortions to remove degeneracies

[Chluba et al., 2015]

General note:

bounds from SDs competitive w.r.t.those from PBHs and UCMHs!

Bispectrum constraints

- Bispectrum in the squeezed limit from distortion-temperature correlation

[Pajer - Zaldarriaga, 2012]

Example: local ansatz $\mathcal{R}(\vec{x}) = r(\vec{x}) + \frac{3}{5} f_{nl}\, r^2(\vec{x})$

Long-short mode decomposition: $\mathcal{R} = \mathcal{R}_L + \mathcal{R}_s$

$$\mathcal{R}_s(\vec{x}) \approx r_s(\vec{x}) \left[1 + \frac{6}{5} f_{nl}\, \mathcal{R}_L(\vec{x}) \right]$$

$$\frac{\Delta T}{T} \sim \frac{\mathcal{R}}{5}$$
$$\frac{\Delta d}{d} \sim \frac{\delta \langle \mathcal{R}^2 \rangle}{\langle \mathcal{R}^2 \rangle}$$
$$\longrightarrow \quad C_l^{(T,d)} \sim f_{nl}(k_d)\, C_l^{TT}$$

k_d: $(1-50)\mathrm{Mpc}^{-1}$ for y; $(50-10^4)\mathrm{Mpc}^{-1}$ for μ

k_T: $\lesssim 0.01\, \mathrm{Mpc}^{-1}$ (large angle CMB temp. fluct.)

J. Chluba, ED, M.A. Amin, M. Kamionkowski - 2016, ED, R. Emami - 2016
R. Emami, ED, J. Chluba, M. Kamionkowski - 2015

Scale-dependence of non-Gaussianity

Smallest detectable μ-T and y-T correlations (1-σ):

- template: $B_{\mathcal{R}} \simeq \frac{12}{5} f_{nl}(k_s) P_{\mathcal{R}}(k_s) P_{\mathcal{R}}(k_L)$
- uniform f_{nl} signal on μ and y scales

$$f_{nl}^{(\mu)} \simeq 10^2 \left(\frac{\mu_{\min}}{10^{-9}}\right)\left(\frac{\langle\mu\rangle}{2\times 10^{-8}}\right)^{-1}$$

$$f_{nl}^{(y)} \simeq 10^2 \left(\frac{y_{\min}}{2\times 10^{-10}}\right)\left(\frac{\langle y\rangle}{4\times 10^{-9}}\right)^{-1}$$

smallest detectable monopoles for a given experiment

$$\langle\mu\rangle \approx \int d\log k\, \Delta^2_{\mathcal{R}}(k) W_\mu(k)$$

$$\langle y\rangle \approx \int d\log k\, \Delta^2_{\mathcal{R}}(k) W_y(k)$$

[Emami, ED, Chluba, Kamionkowski - 2015]

Summary

SDs from diffusion damping gives access to ~10 extra inflationary e-folds!

⟶ **Vast range of modes** to uncover statistics of **primordial fluctuations**

	k/Mpc	*fnl*
CMB anisot./galaxy surveys	$(10^{-4} - 1)$	bispectrum / off-diagonal correlations, …
y distortion	$(1 - 50)$	y -T correlation
μ distortion	$(50 - 10^4)$	μ -T correlation

Next :

— **More non-Gaussian *observables*, e.g. :**

- Including *residual (r-type)* distortions $(10^4 \lesssim z \lesssim \text{few} \times 10^5)$

— **Evaluating *non-primordial* distortions:**
e.g. from black-holes, (BSM/DM)particles decays/annihilations, …

Thank you