Testing early Universe physics with upcoming observations

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Biblio :

ED, M. Fasiello, M. Kamionkowski - *2015*

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

J. Chluba, **ED**, M.A. Amin, M. Kamionkowski - *2016*

ED, R. Emami - *2016*

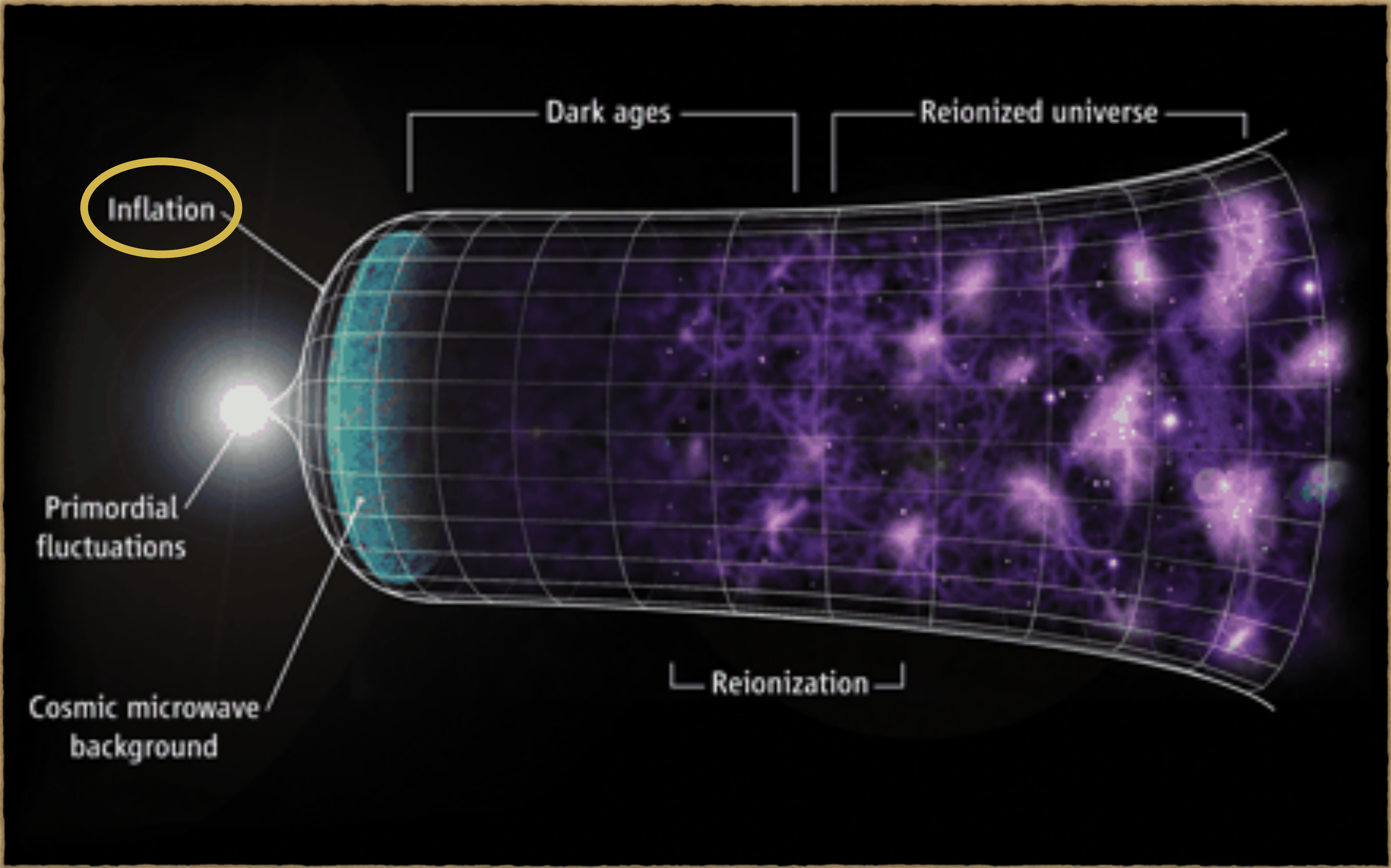
ED, L.M. Krauss, J. Chluba - *2015*

R. Emami, **ED**, J. Chluba, M. Kamionkowski - *2015*

ED, M. Fasiello, T. Fujita - *2016*

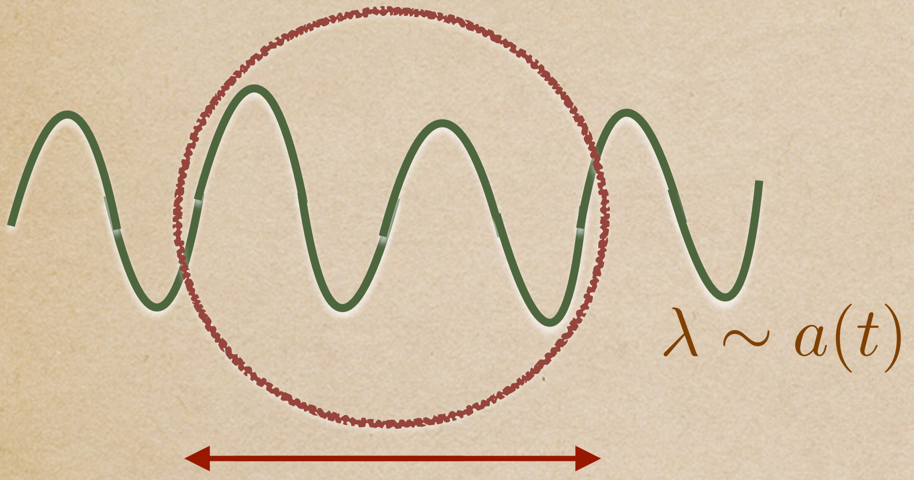
M. Biagetti, **ED**, M. Fasiello, M. Peloso - *2014*

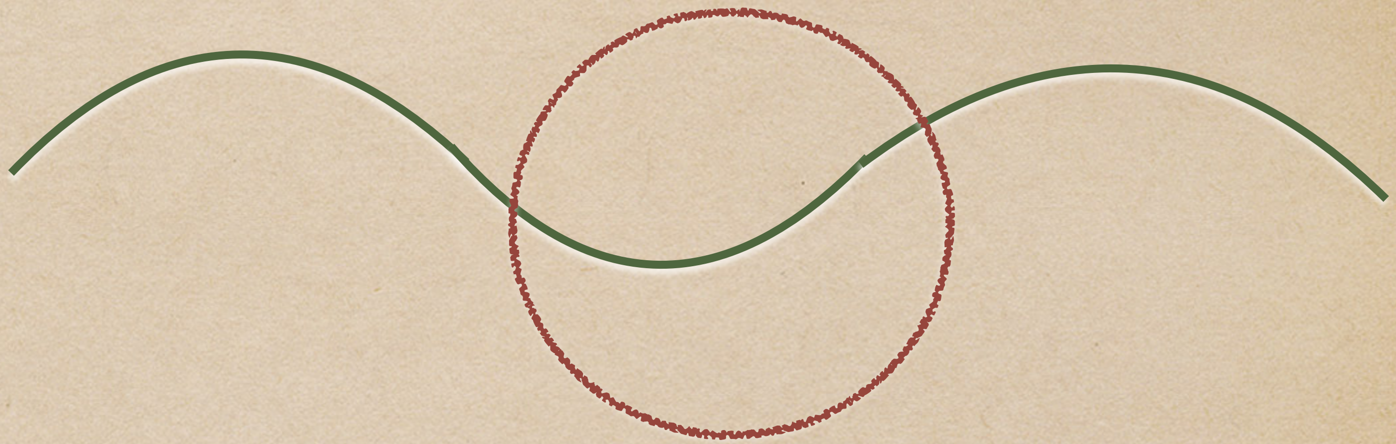
A glance at cosmic history …



Inflation

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

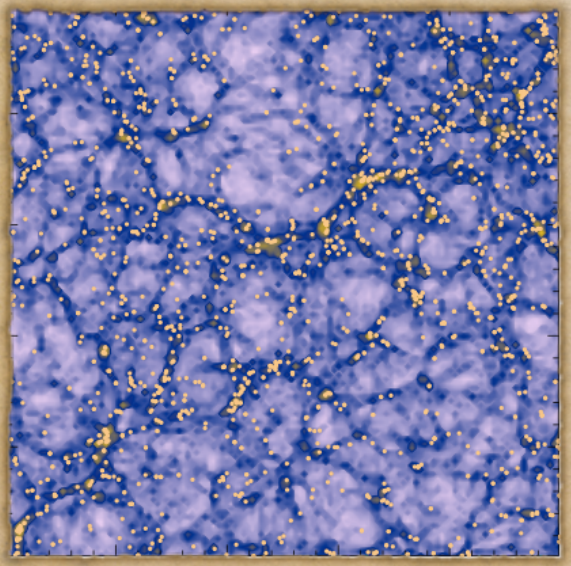




Hubble radius: $\sim 1/H \sim \text{const.}$

Physical scales are stretched by the expansion!

- Mechanism for the generation of cosmological fluctuations

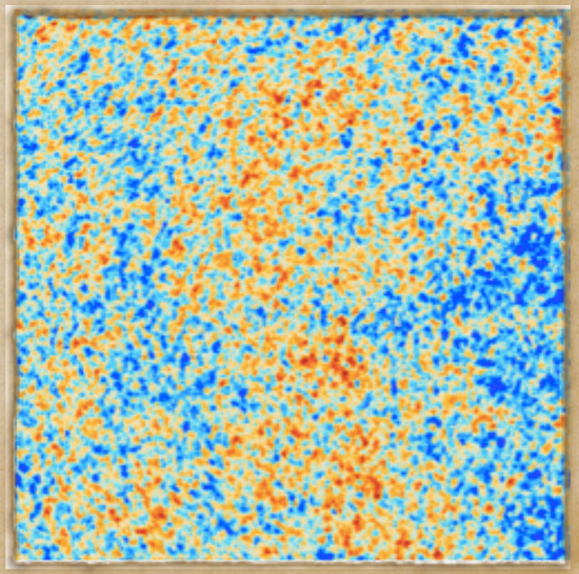


$$\phi(\vec{x},t) = \varphi(t) + \delta\phi(\vec{x},t)$$

Inflaton quantum fluctuations

↓

CMB perturbations
and LSS of the Universe



Inflation

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

Accelerated expansion : $\ddot{a} > 0$

Einstein eqs. : $\frac{\ddot{a}}{a} = -\frac{1}{2\,M_P^2}\,(\rho + 3\,p)$

$$\left.\begin{array}{l} \ddot{a} > 0 \\ \frac{\ddot{a}}{a} = -\frac{1}{2\,M_P^2}\,(\rho + 3\,p) \end{array}\right\} \; p < -\frac{1}{3}\rho$$

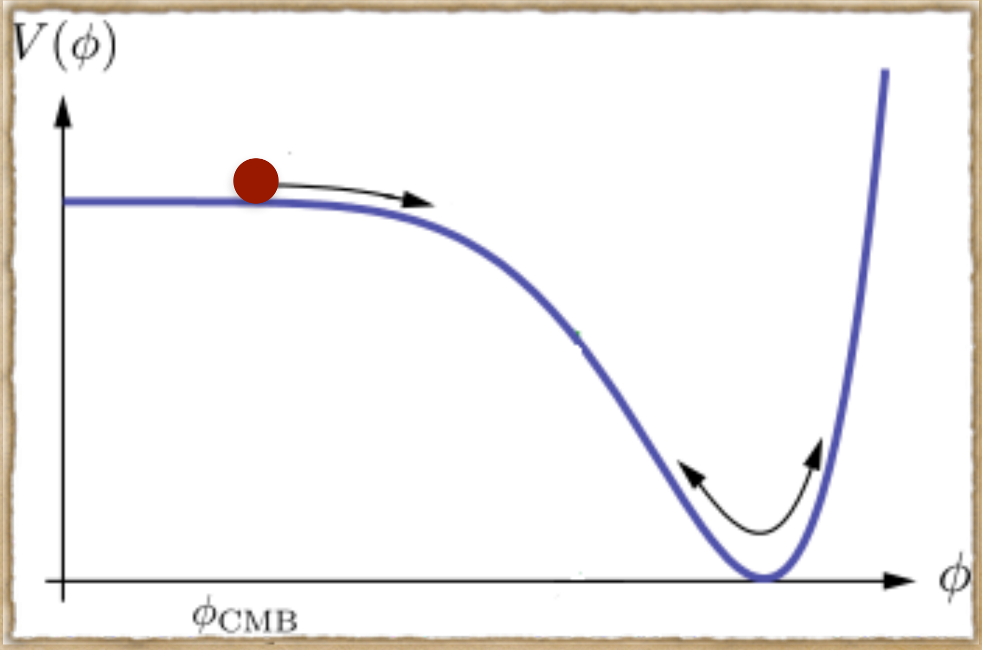
Scalar field :

$$\left.\begin{array}{l} p_\varphi = \frac{\dot{\varphi}^2}{2} - V(\varphi) \approx -V(\varphi) \\ \rho_\varphi = \frac{\dot{\varphi}^2}{2} + V(\varphi) \approx V(\varphi) \end{array}\right\} \; p_\varphi \approx -\rho_\varphi$$

Slow-roll

Einstein eqs. : $\longrightarrow H^2 = \frac{\rho_\varphi}{3\,M_P^2} \approx \frac{V(\varphi)}{3\,M_P^2} \approx$ const.

$$\ddot{\varphi} + 3H\dot{\varphi} + V'(\varphi) = 0$$



Slow-roll parameters

$$\begin{cases} \epsilon \equiv -\frac{\dot{H}}{H^2} = \frac{1}{2}\left(\frac{M_P V_\varphi}{V}\right)^2 \ll 1 \\ \eta \equiv \frac{M_P^2\, V_{\varphi\varphi}}{V} \ll 1 \end{cases}$$

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 !

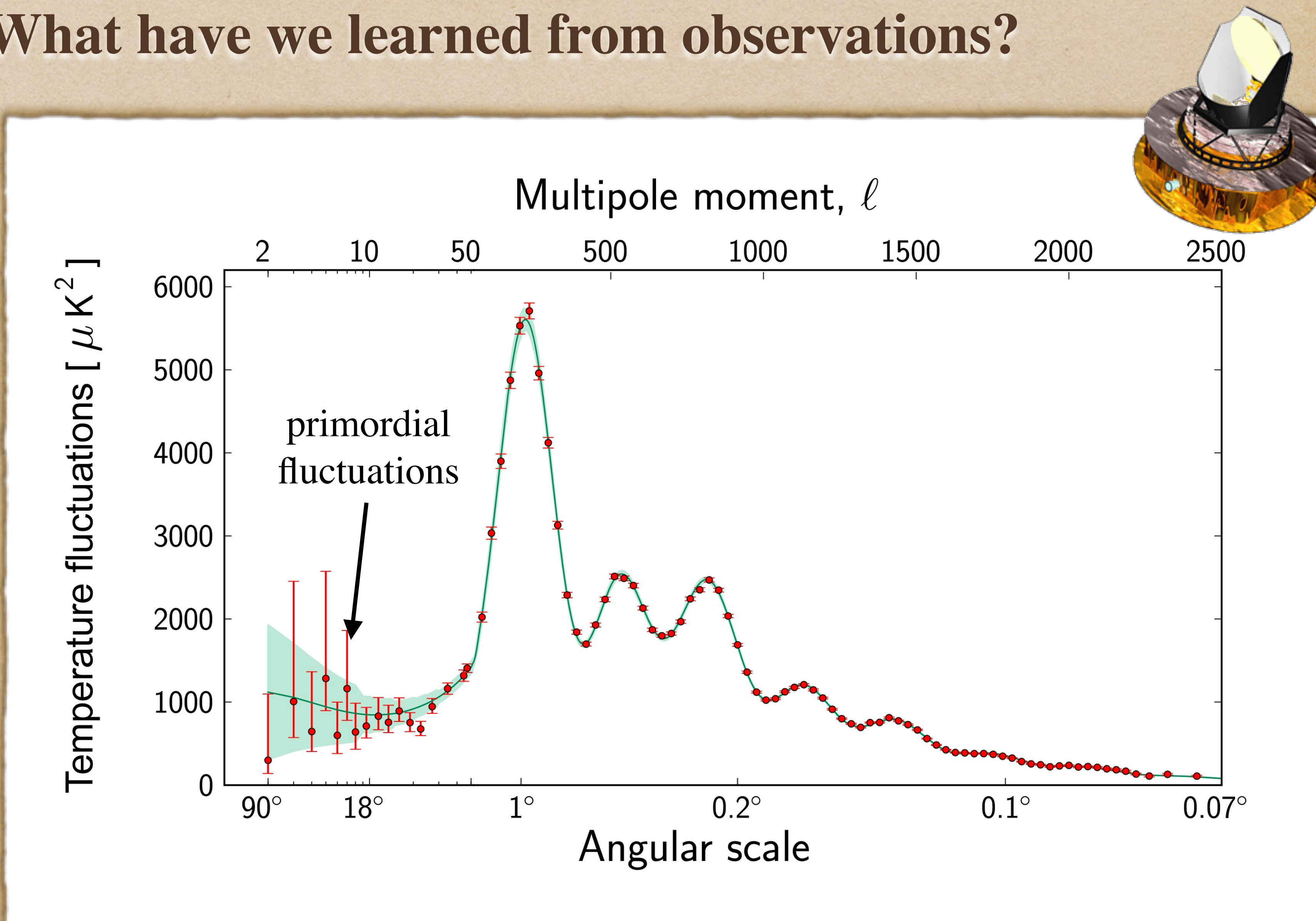
What have we learned from observations?

Scalar fluct. :

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

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

BICEP2/KECK
+Planck



One or more active fields

How do fields interact

Any spectator field

?

Energy scale of inflation

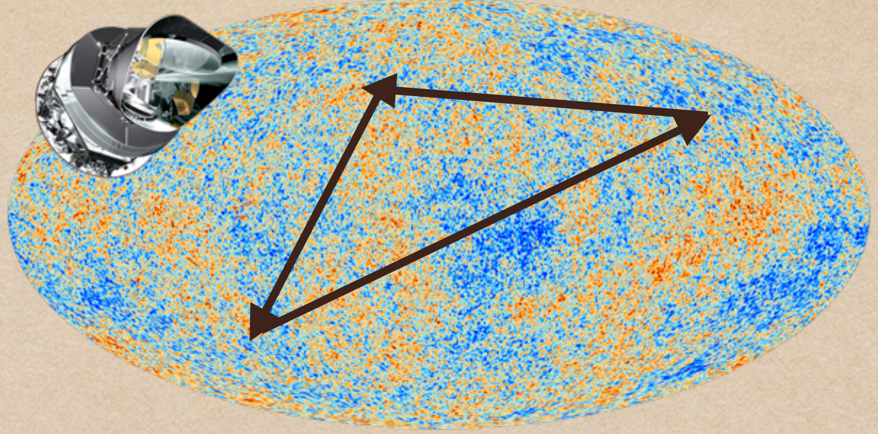
What are the masses of the extra fields

How does inflation end

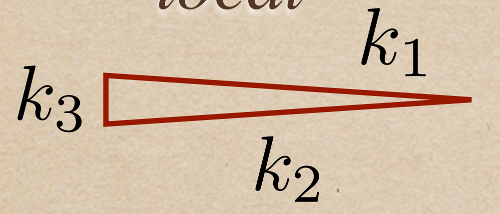
What happens at Reheating

…

Microphysics of inflation: primordial non-Gaussianity

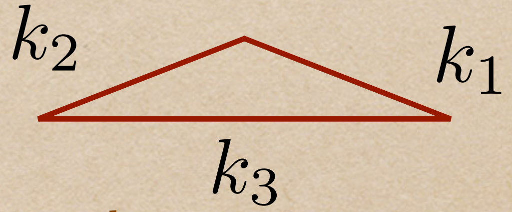


local



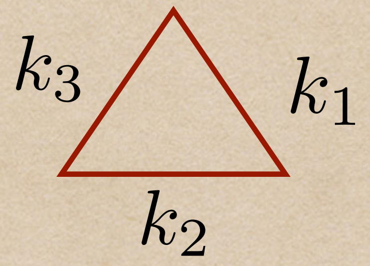
$f_{\rm nl}^{\rm loc} = 0.8 \pm 5$

orthogonal



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

equilateral



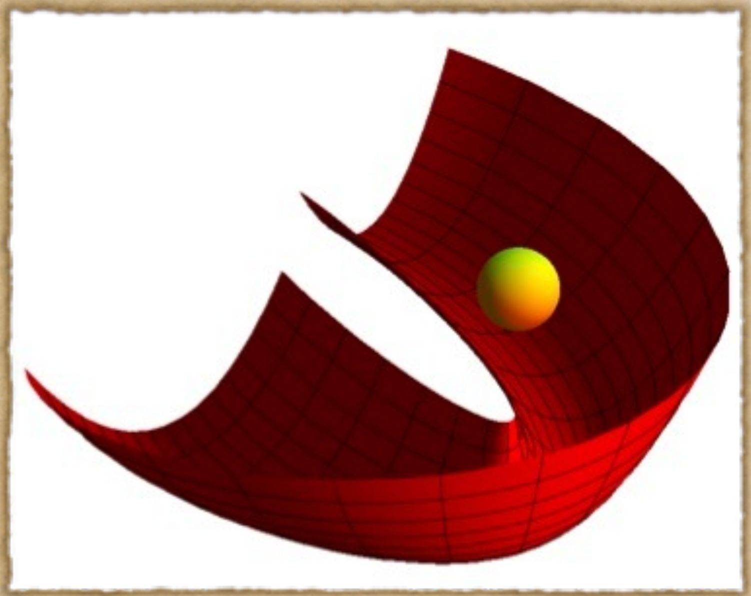
$f_{\rm nl}^{\rm eq} = -4 \pm 43$

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

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

thresholds potentially at reach for upcoming galaxy surveys!

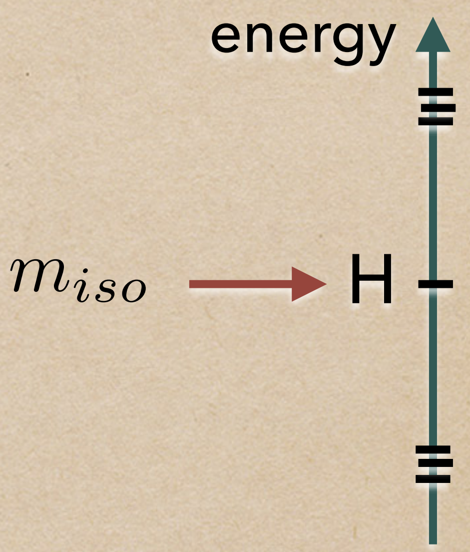
There is more:
e.g. ***intermediate shapes***

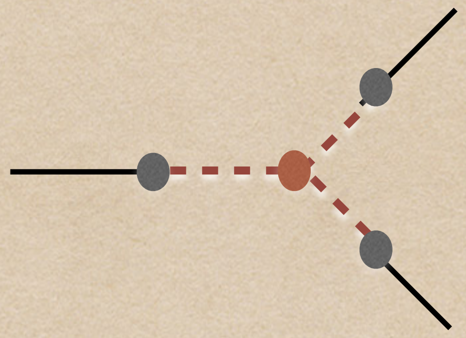


Case study: Quasi-Single-Field

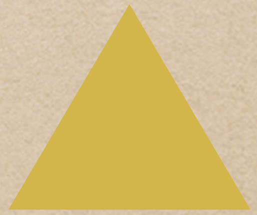
(also SUSY -motivated)

$\left\{ \begin{array}{l} \text{tangent: inflaton} \\ \text{radial: massive isocurvaton} \end{array} \right.$





Bispectrum shape between local and equil.



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

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

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

bispectrum shape delivers info on mass spectrum!

[Chen, Wang, 2010]

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, …)

  I — Fossils from inflation

- CMB experiments :

  Spectral distortions (PRISM, PIXIE, …)

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

  II — A window into primordial perturbations on small scales

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

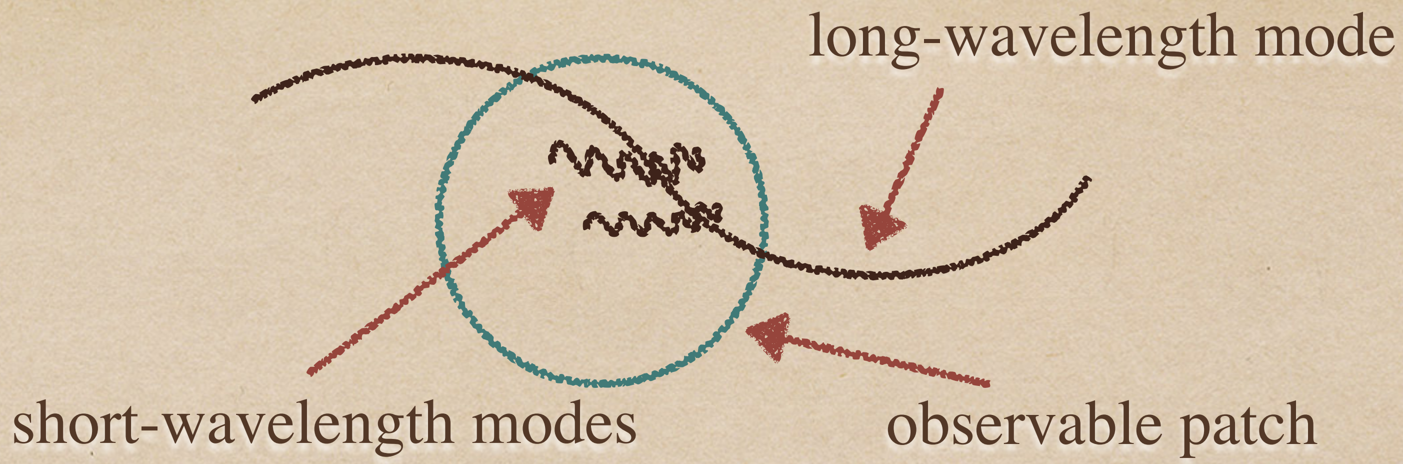
  Origin of B-modes? What can we learn about the **early Universe**?

  III — Inflation and primordial gravitational waves

Fossils from inflation

‘Fossils’ : signatures from **multi-clock** inflationary dynamics

Effect of a long mode on local observables :

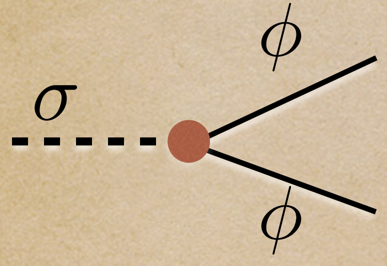


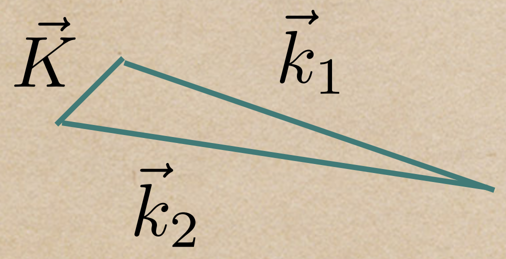
- Gaussian initial conditions
  + statistical homog./isotropy

$$\langle \delta_{\vec{k}_1} \delta_{\vec{k}_2} \rangle = \delta^{(3)}(\vec{k}_1 + \vec{k}_2) P(k_1)$$

diagonal
2p corr.

- Local/squeezed
  non-Gaussianity

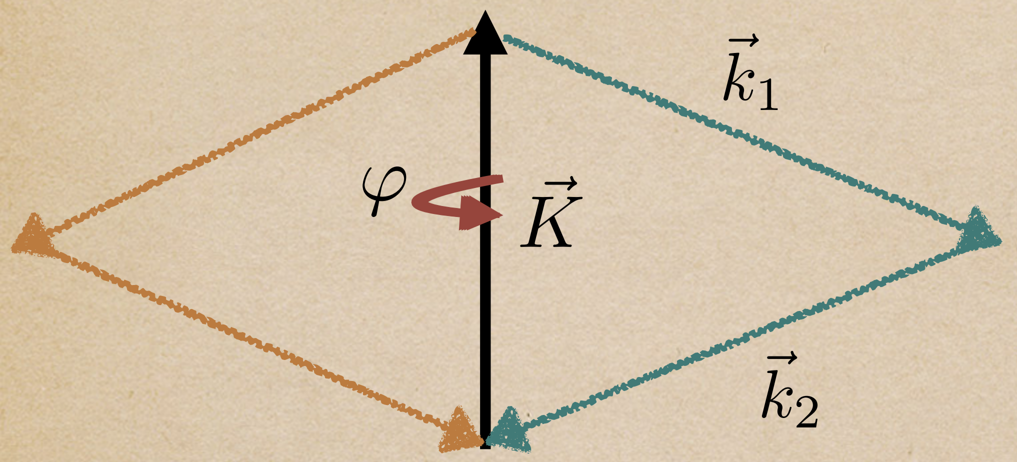




$$\langle \delta_{\vec{k}_1} \delta_{\vec{k}_2} \rangle_{\vec{K}} = \delta^{(3)}(\vec{k}_1 + \vec{k}_2 + \vec{K})$$
$$\times f(\vec{k}_1, \vec{k}_2) A(K)$$

off-diagonal
2p corr.!

Probing σ through off-diagonal correlation :

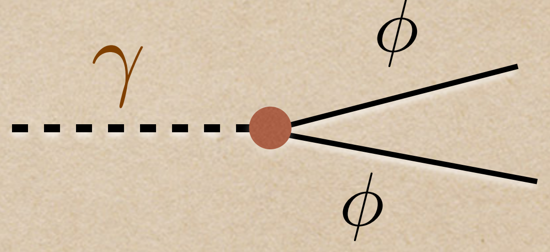


Azimuthal dependence:

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

[Jeong, Kamiomkowski, 2012]

What if σ = tensor mode of the metric:

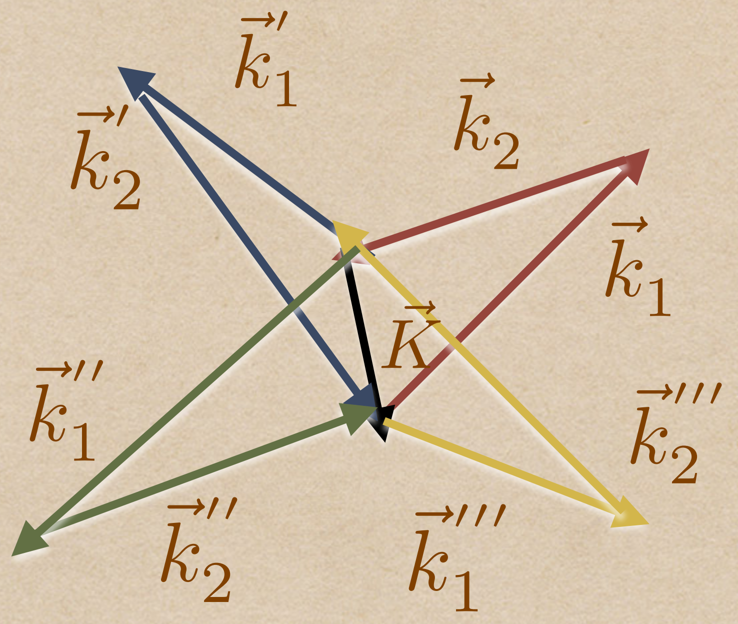


Learning about primordial tensors
through non-Gaussian effects!

[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

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

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

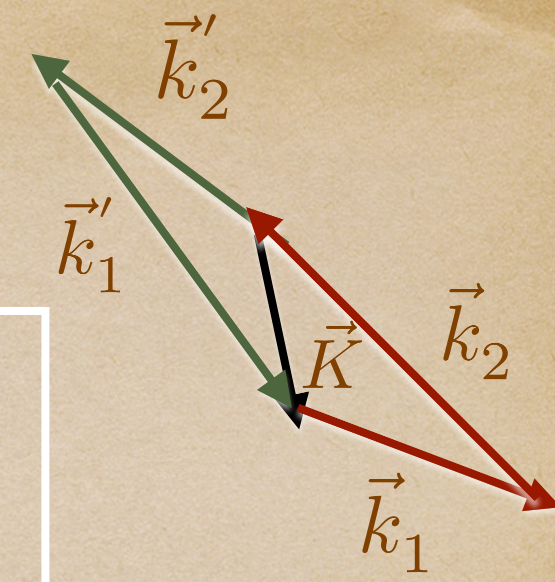
random variable

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 $P_p(K) = A_\gamma \, P^f_\gamma(K)$



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

optimal sum over different K-modes

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

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

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

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 and prospects

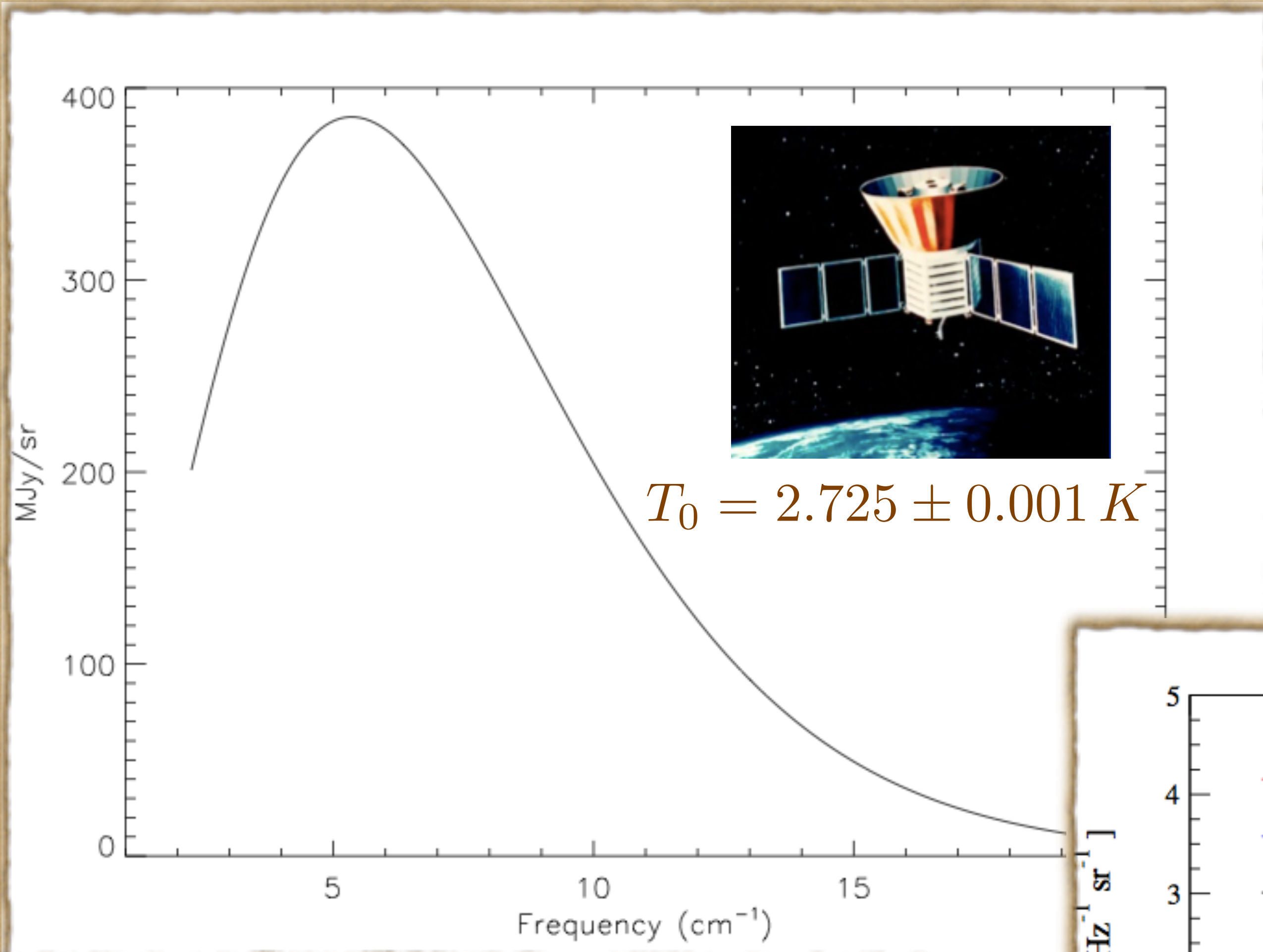
- *Squeezed limit*: powerful discriminant for inflationary models (*single vs multi-clock*)
- Correlations in squeezed limit from inflation: *local observables* affected by *long modes (Anisotropic* effects / *Off-diagonal* correlations*)*
- Necessary to understand effects of <u>long wl. modes</u>:
  — test existence of a long-short correlation
  — correctly map observations to theory

<u>Next</u> :

- Building catalogue of fossil signatures for multi-field models
  $\longrightarrow$ estimating masses/spin/interactions of primordial fields
- Lots more to do on tensor non-Gaussianities (especially timely given B-modes searches!)

A window into primordial perturbations on *small scales*

Cosmic Microwave spectrum from COBE/FIRAS



$T_0 = 2.725 \pm 0.001\,K$

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

↓

<u>Distortion</u> of the blackbody spectrum

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

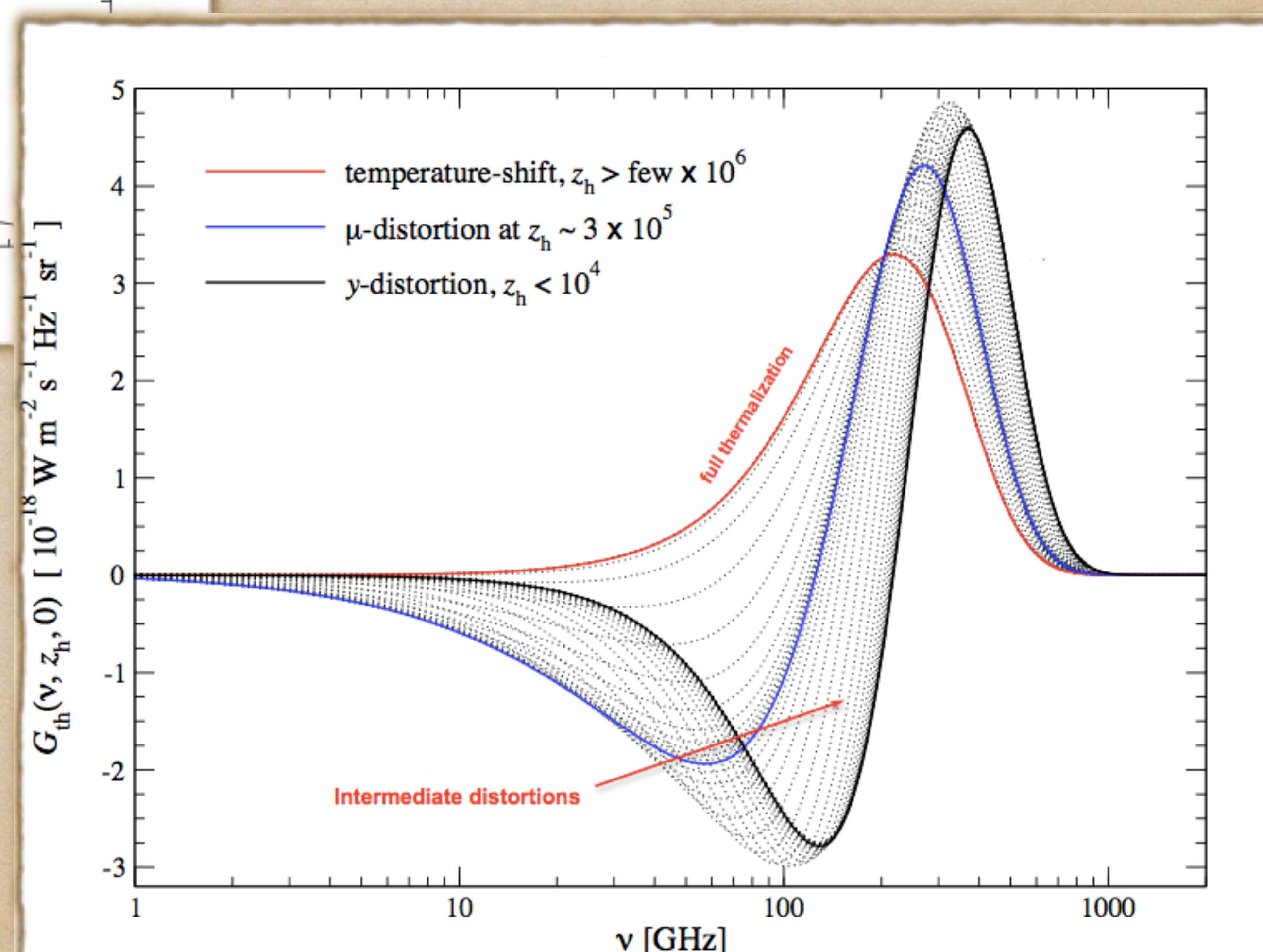
energy-injection rate

Deviations allowed from FIRAS:

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

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

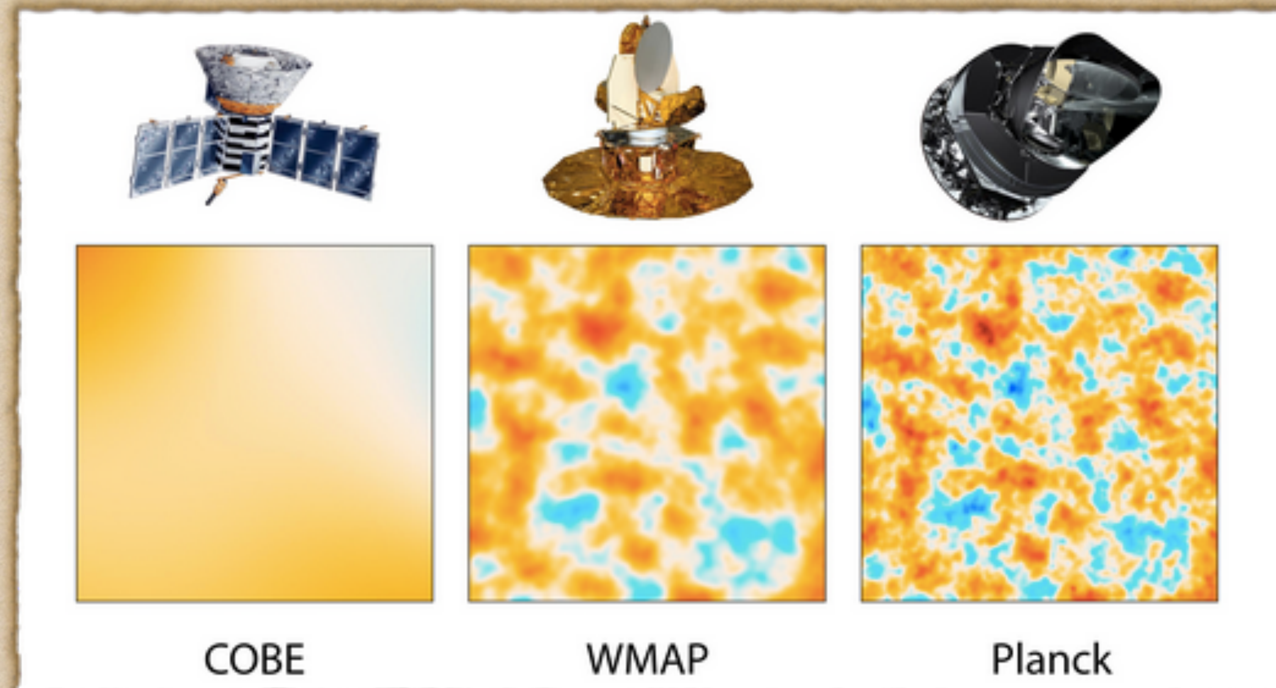
[Fixsen et al., 1996]



[Chluba, 2013]

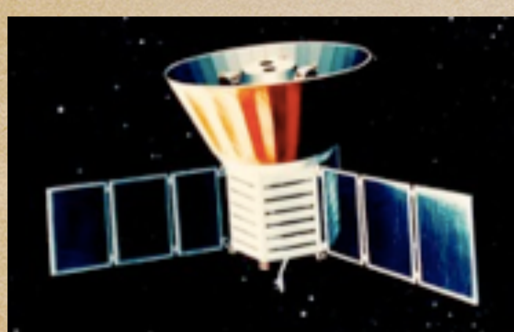
Why spectral distortions matter?

CMB anisotropies:
(~20 yrs)



Spectral distortions:

COBE/FIRAS

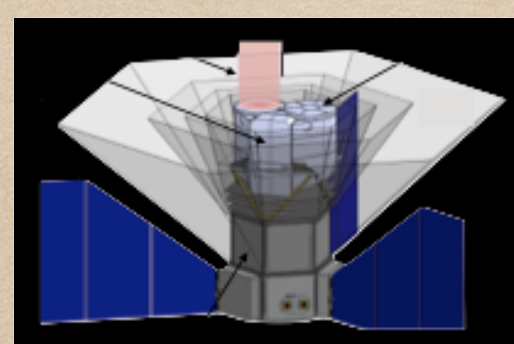


$|\mu| \lesssim 9 \times 10^{-5}$

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

[Fixsen et al., 1996]

PIXIE



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

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

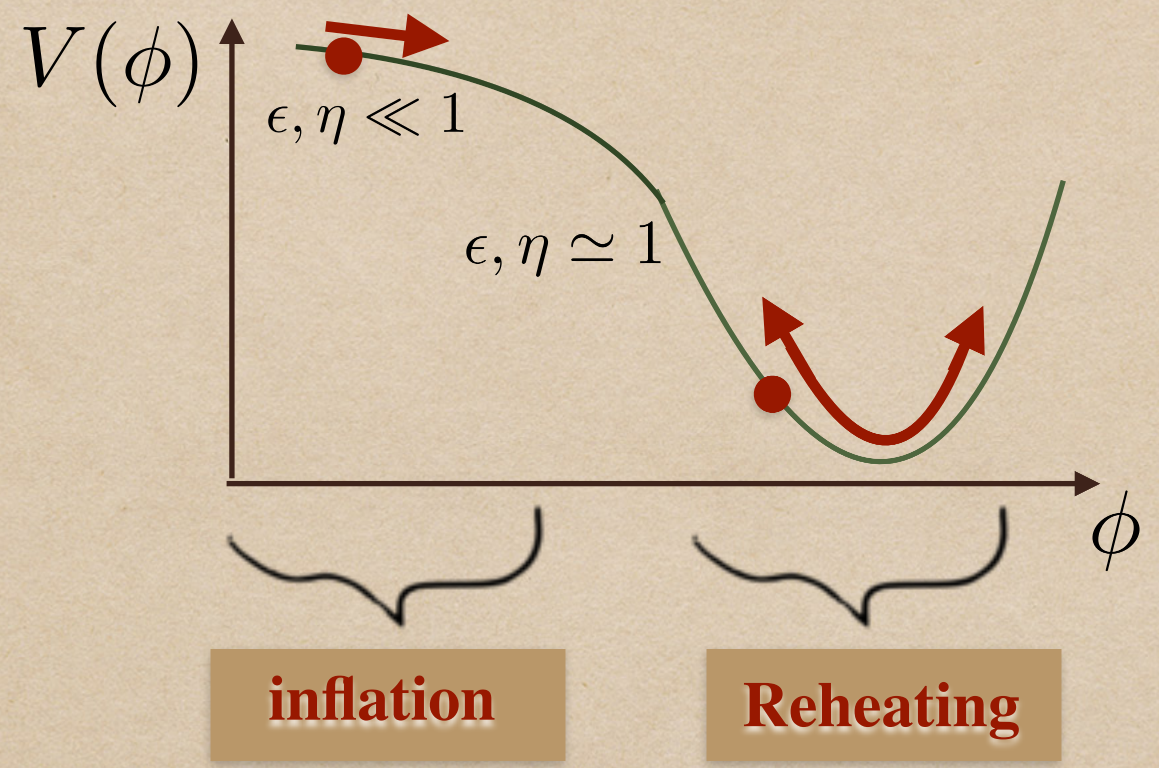
[Kogut et al., 2011]

Mechanisms producing SDs include:

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

Gravitinos in the early Universe

- predicted in SUGRA
- spin 3/2 super-partners of gravitons
- SUSY-breaking scale: $F \sim \sqrt{m_{3/2} M_P}$



$V(\phi)$ dominates

inflation decays $\longrightarrow$ $\boxed{T_{\rm rh}}$ $\longrightarrow$ ordinary radiation/ matter eras

relic gravitinos quickly *diluted*

gravitinos production by:

- *rapid inflaton oscillations*
- *scatterings in the hot plasma*

- Thermal production:

$$\frac{dn_{3/2}}{dt} + 3\,H\,\cancelto{0}{n_{3/2}} \simeq \langle \sigma_{\rm tot}|v|\rangle n_{\rm light}^2 \longrightarrow \boxed{\frac{n_{3/2}}{s} \simeq 10^{-2}\,\frac{T_{\rm rh}}{M_P}}$$

[instantaneous reheating approx.]

- Decay rate: $\boxed{\Gamma_{3/2} = \frac{N_{\rm eff}}{2\pi}\frac{m_{3/2}^3}{M_P^2}}$

[effective number of decay channels]

- Cosmology with gravitinos:

stable / unstable with stable relics: $T_{\rm rh} \lesssim 3\times 10^{11}\left(\frac{m_{\rm LSP}}{100\,{\rm GeV}}\right)^{-1} h^2\,{\rm GeV}$ (overclosure bound)

decaying after Big-bang nucleosynthesis (BBN): light elements destruction

decaying during μ or y eras: SDs

[$1\,{\rm MeV} - 10\,{\rm keV}$]

[Pagels, Primack, 1982 - Weinberg, 1982 - Ellis et al., 1992 - Feng, 2002 - …]

SDs bounds

Total energy release: $$\frac{\Delta\rho_\gamma}{\rho_\gamma} \approx \left[\frac{\Delta\rho_\gamma}{\rho_\gamma}\right]_\mu + \left[\frac{\Delta\rho_\gamma}{\rho_\gamma}\right]_y \equiv 4\,y \approx \int \mathcal{J}\,\mathcal{J}_y \frac{1}{\rho_\gamma}\frac{dE}{dt}\,dt$$

$$\equiv \frac{\mu}{1.4} \approx \int \mathcal{J}\,\mathcal{J}_\mu \frac{1}{\rho_\gamma}\frac{dE}{dt}\,dt$$

$$\begin{cases} \mathcal{J}(z) \approx e^{-[z/(2\times 10^6)]^{5/2}} \\ \mathcal{J}_y(z) \approx \left[1 + \left(\frac{1+z}{6\times 10^4}\right)^{2.58}\right]^{-1} \\ \mathcal{J}_\mu(z) \approx 1 - \mathcal{J}_y(y) \end{cases}$$

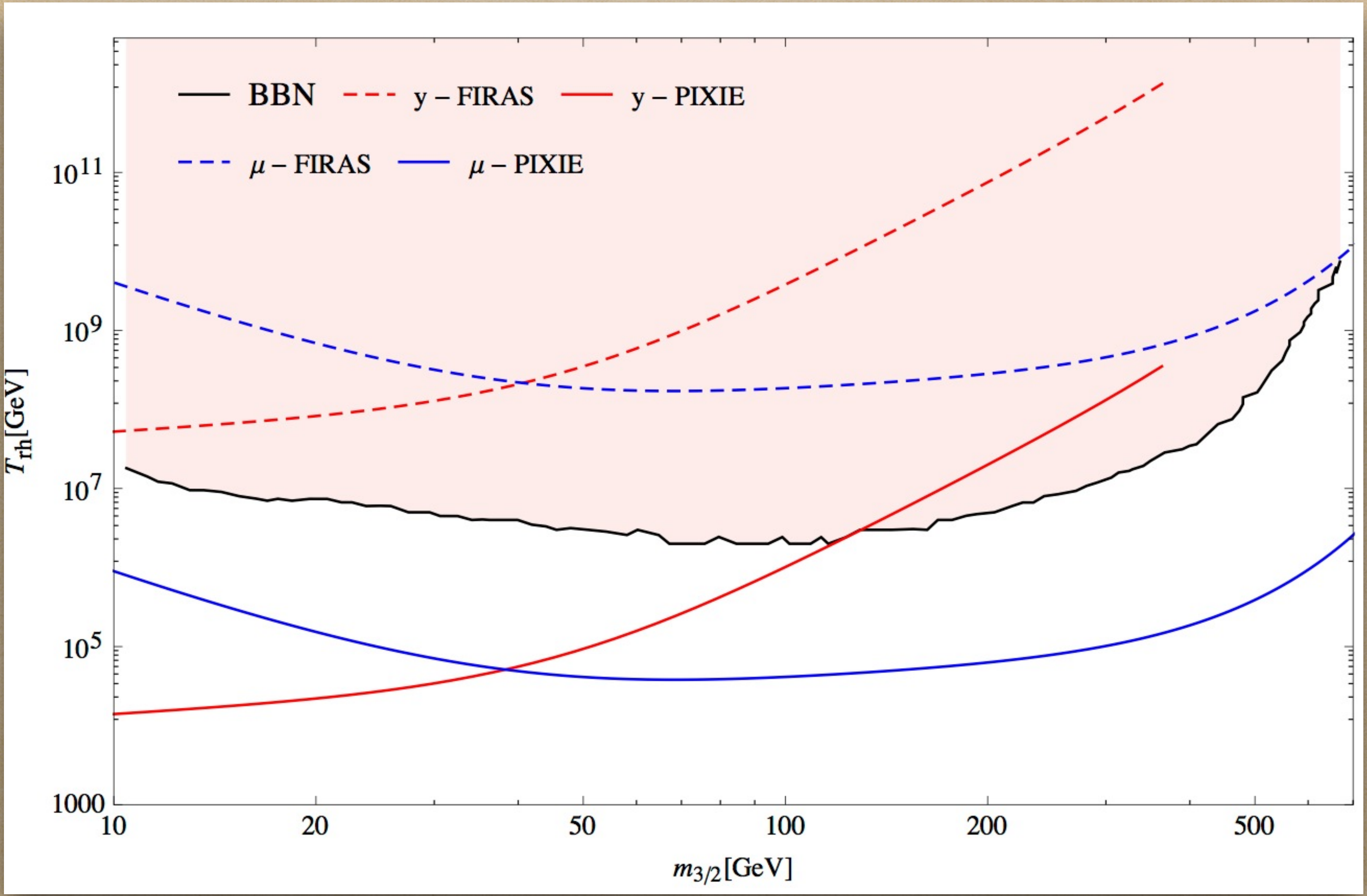
$$\frac{dE}{dt} = \epsilon_{3/2}\, m_{3/2}\, \frac{1}{a^3(t)}\frac{d}{dt}\left[a^3(t)\, n_{3/2}(t)\right]$$

Model-dependence: $\begin{cases} N_{\rm eff} & \text{(effective number of decay channels)} \\ \epsilon_{3/2} & \text{(fraction of initial energy going into CMB)} \end{cases}$

Constraining: $\begin{cases} T_{\rm rh} & \text{(reheating temperature)} \\ m_{3/2} & \text{(mass of gravitinos)} \end{cases}$

[**ED**, L. M. Krauss, J. Chluba -2015]

Example : $G \to \gamma + \tilde{\gamma}$



$B_{[G\to\gamma+\tilde{\gamma}]} = 1$

[**ED**, L. M. Krauss, J. Chluba -2015]

Summary and prospects

- Competitive bounds from SDs on particle decays/annihilations
- Gravitinos from Reheating: constraints on SUSY/ scale of inflation

Next :

- *Residual (r-type) distortions:* more observables!

$(10^4 \lesssim z \lesssim \text{few} \times 10^5)$

$$p = \{\mu, y, \mu_k\} \quad \begin{cases} \mu_1^{(\mathrm{DL})} \simeq 3 \times 10^{-7} \\ \mu_2^{(\mathrm{DL})} \simeq 2 \times 10^{-6} \\ \mu_3^{(\mathrm{DL})} \simeq 7 \times 10^{-6} \end{cases}$$

- *Photon (vs energy) injection :*
  different treatment of thermalization problem

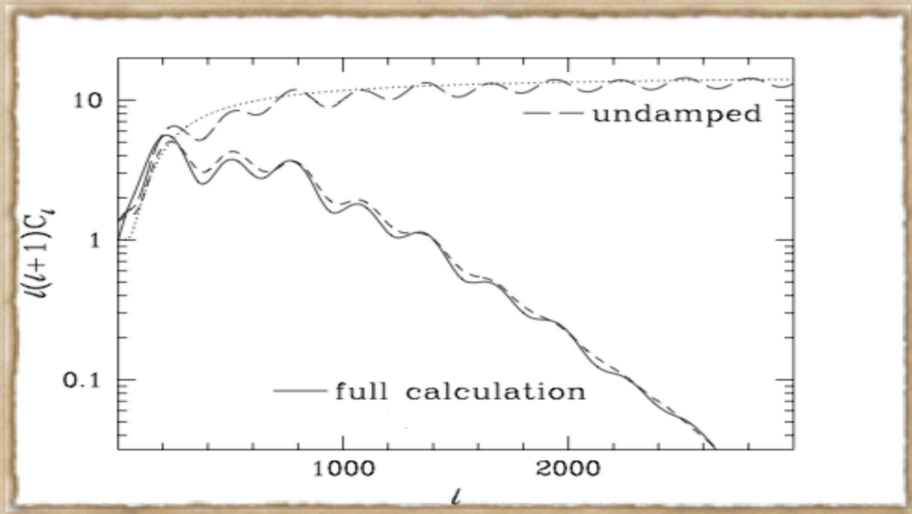
- *Post-recombination decays :*
  different treatment of energy exchange as plasma recombines

- *Complete particles cascade :*
  likely to strengthen current bounds

SDs from diffusion damping

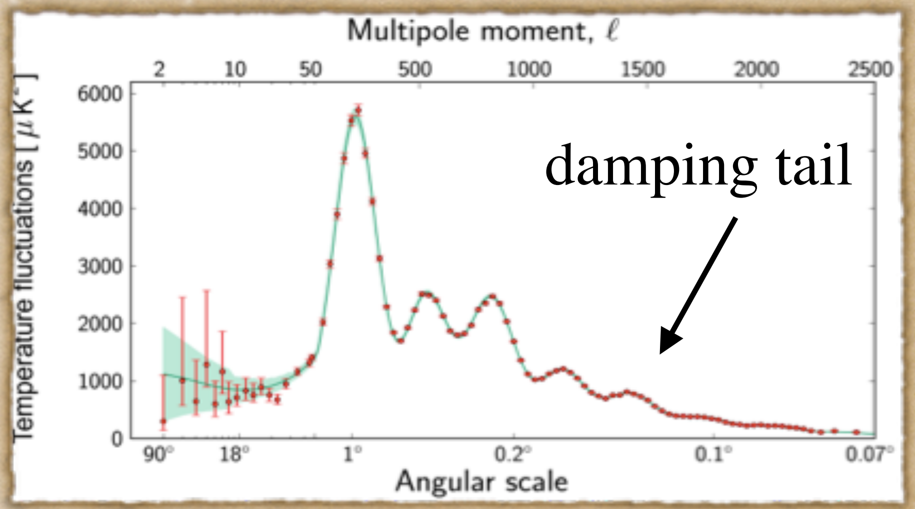
Primordial fluctuations
re-enter Hubble radius
after inflation

Isotropization
by photon
diffusion



[Hu&White, 1996]

[Planck]



Effective **energy release** into CMB

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

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

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

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

$(10^5 \leq l \leq 10^8)$

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

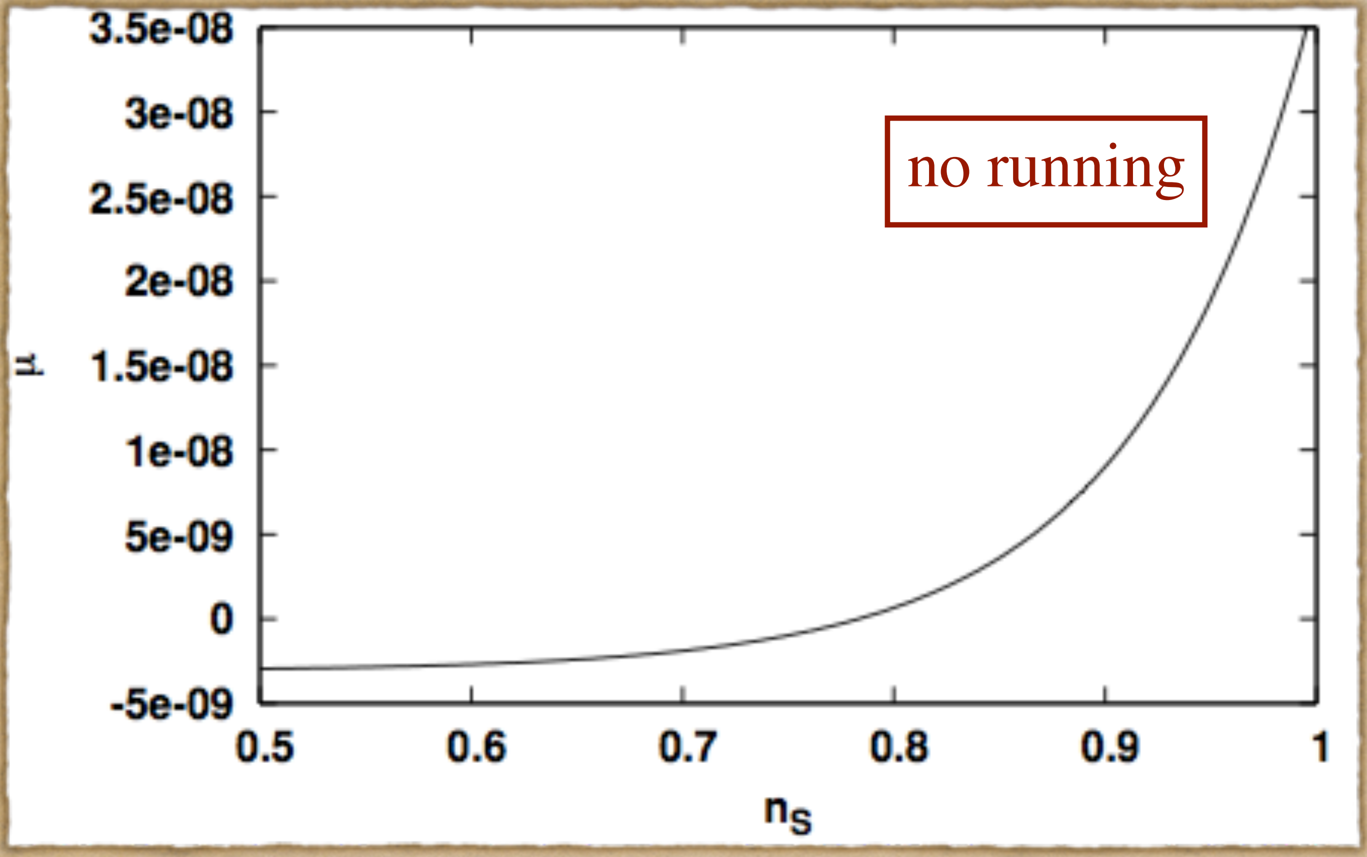
Power spectrum constraints: SFSR

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

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

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

[Khatri, Sunyaev, Chluba, 2012]



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

Sensitivity for μ distortion

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

E.g. : $\begin{cases} \text{n=1} \leftarrow \text{PIXIE} \\ \text{n=10} \leftarrow \text{PRISM} \end{cases}$

3 x PIXIE = *guaranteed discovery*

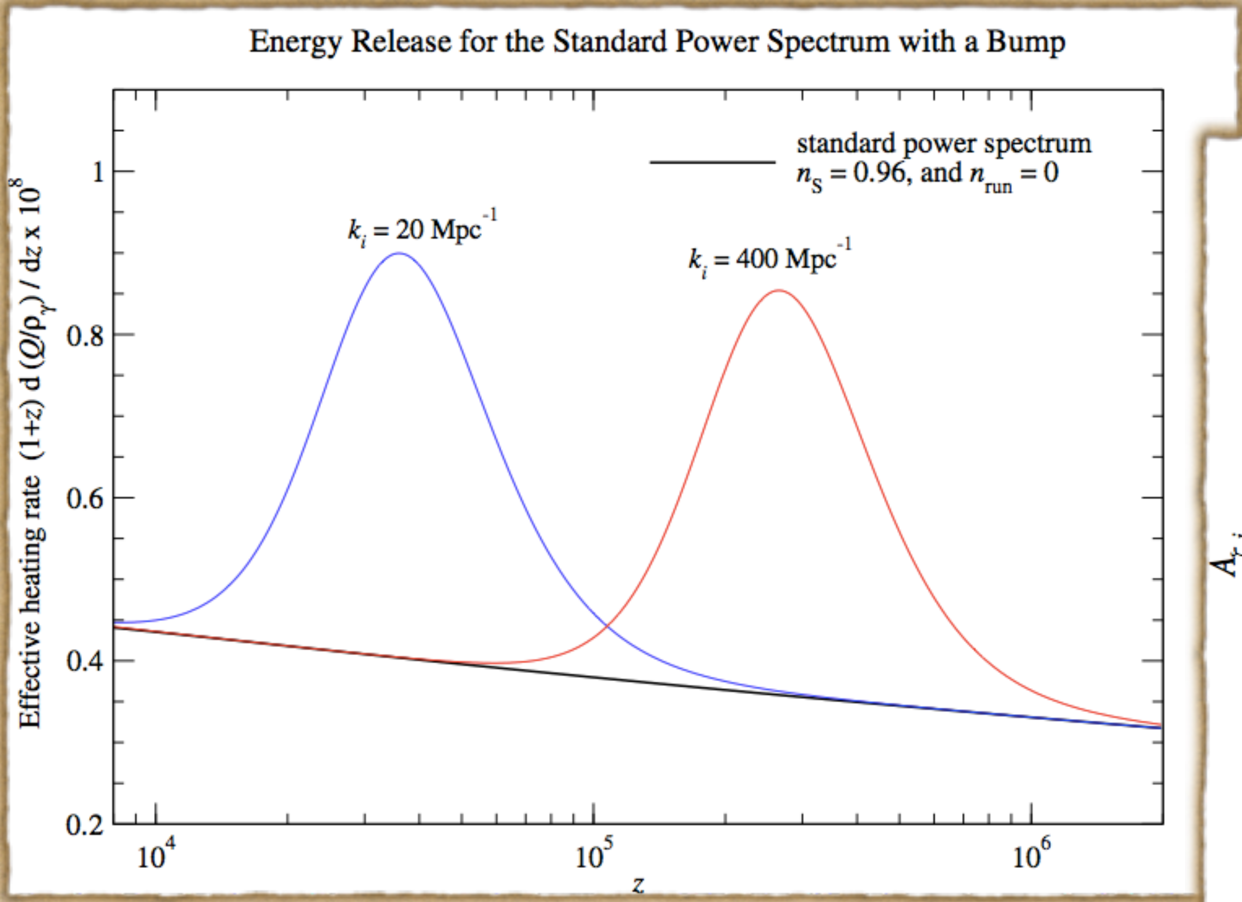
detection (95% CL)

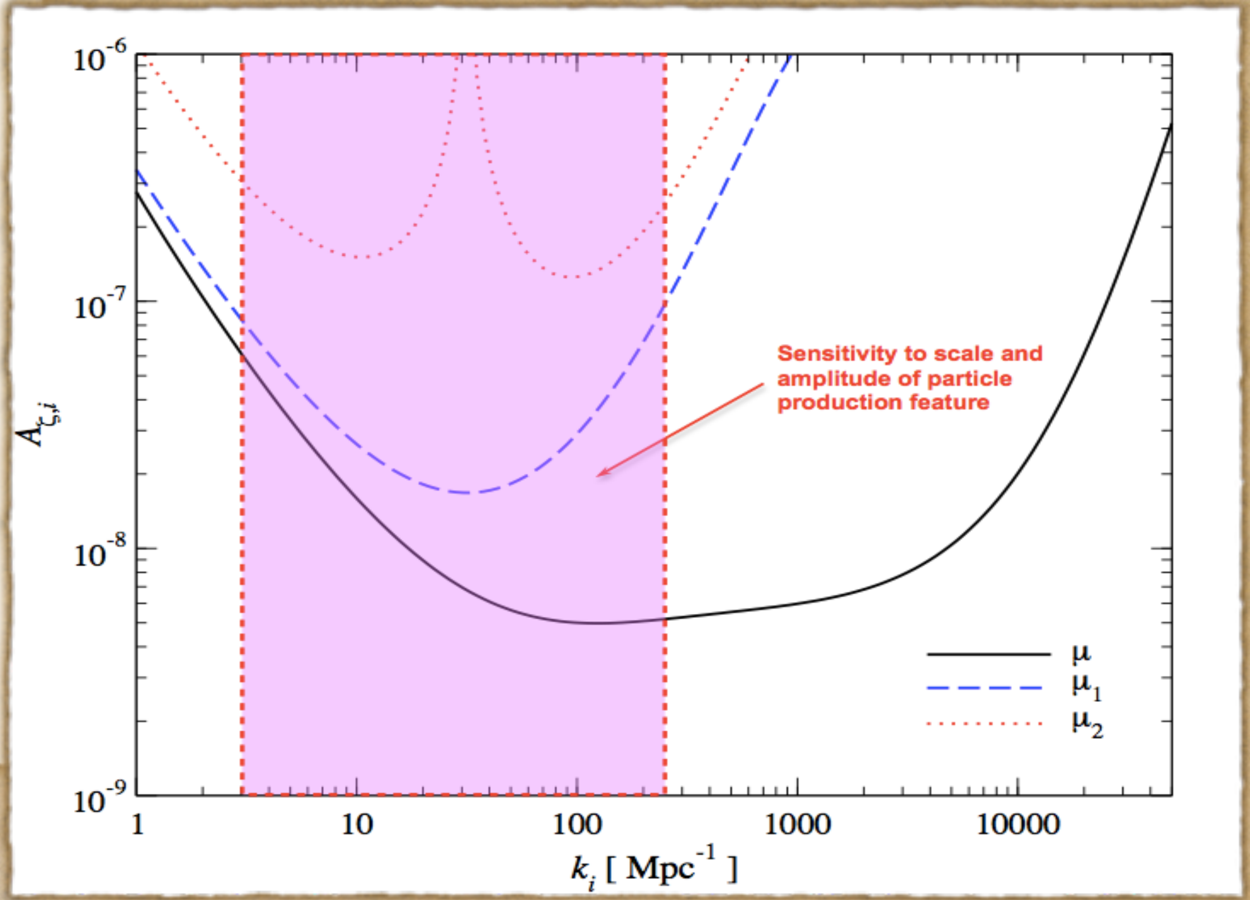
exclusion of SFSR (95% CL)

[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]

<u>General note:</u>

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

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

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

$$\frac{\Delta T}{T} \sim \frac{\mathcal{R}}{5}$$

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

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

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

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

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 and prospects

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

$\longrightarrow$ **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 :

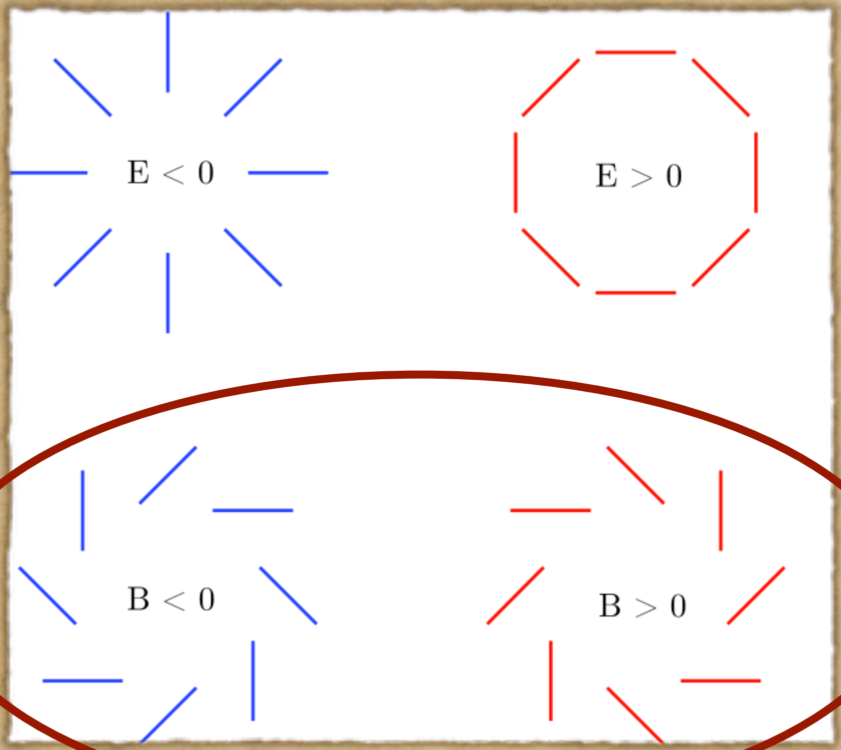
— **More non-Gaussian *observables*, e.g. :**

- Cross-correlating distortions with *polarization*
- 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, …

Inflation and primordial *gravitational waves*

B-modes polarization



BICEP2/KECK+Planck

$$r < 0.07$$

Stage-IV CMB experiments : $\sigma(r) \sim 0.001$

Non-inflationary sources for primordial B-modes? Some examples:

— Primordial magnetic fields [Bonvin, Durrer, Maartens 2014, …]

— Phase transitions [Krauss, J-Smith, Mathur, Dent 2010, Caprini et al., 2015, …]

— Topological defects [Lizarraga et al. 2014 - Moss, Pogosian 2014, …]

— Alternatives to inflation (e.g. string gas cosmology [Brandenberger et al, 2007], ekpyrotic scenarios [Khoury et al, 2001], …)

— Modified gravity (e.g. a non-zero graviton mass) [Dubovsky et al, 2010, Cusin et al. 2014, Fasiello and Ribeiro, 2015, …]

GWs from inflation: SFSR

- Production from tensor modes of the metric

$$ds^2 = a^2(\tau)\left[-d\tau^2 + (\delta_{ij} + \gamma_{ij}(\tau,\vec{x}))dx^i dx^j\right]$$

transverse & traceless

- Primordial tensor power spectrum

$$\mathcal{P}_\gamma \sim \left(\frac{H}{M_P}\right)^2 k^{n_T}$$

energy scale of inflation

$$V_{\rm infl}^{1/4} \approx 10^{16}{\rm GeV}\,(r/0.01)^{1/4}$$

- Consistency relations

$$n_T \simeq -2\epsilon = -r/8$$

(red-spectrum)

- Lyth bound $\Delta\phi/M_P \gtrsim (r/0.01)^{1/2}$ (small vs large field)

Alternative inflationary production mechanisms

- Spectator fields with small sound speed

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

$$\left[\partial_\tau^2 + k^2 - \frac{a''}{a}\right](a\,\gamma_{ij}) = S_{ij} \qquad S_{ij} \sim \mathcal{O}(\delta\sigma^2/c_s^n)$$

source of GW
(= 0 if free-field)

Main challenge: sourcing tensors to observable level without affecting scalar sector (e.g. large nG)!

Important : inflaton not directly coupled to source!

- Particle production / gauge fields:

  — Auxiliary scalars with time-varying masses : $\sum_i \chi_i^2\,(\phi - \phi_i)^2$

  [Chung et al., 2000, Senatore et al, 2011, Pearce et al, 2016]

  — Gauge fields coupled to axions : $\chi\, F\, \tilde{F}$

  [Sorbo 2011, Mukohyama et al. 2012-2014, ED-Fasiello-Fujita 2016, …]

* Breaking standard r ⟷ H correspondence

* Distinct signature can arise: blue spectrum (⟶ interesting also for direct detection!); parity-violation (⟶ TB, EB)

Many possibilities for discovery …

An exciting road ahead
for cosmology!

Final summary

Fossils from inflation : signatures of long-short mode couplings in galaxy surveys

Spectral distortions: testing primordial perturbations on small scales and BSM physics

Inflation and primordial gravitational waves: production mechanisms for GWs and the r-H correspondence