Probing the early Universe with CMB spectral distortions

Ema Dimastrogiovanni
Case Western Reserve University

Probing fundamental physics with CMB spectral distortions
CERN — March 13th 2018
Outline

- Spectral distortions and inflation
- Anisotropic distortions and squeezed non-Gaussianity
- Degeneracies
Dissipation of primordial fluctuations

Silk damping: isotropization by photon diffusion
Spectral distortions from diffusion damping

\[ T_b = \frac{T_1 + T_2}{2} \]

\[ T_1 < T_2 \]

\( y \)-type distortion visible in the Wien tail
\[ \mu \approx 1.4 \int_{z_{\mu y}}^{\infty} dz \frac{1}{\rho_{\gamma}} \frac{dQ}{dz} e^{-\left(\frac{z}{z_{\mu y}}\right)^{5/2}} \]

energy (density)
released into CMB

\[ \mu \quad \text{era onset} \]
\[ 2 \times 10^6 \]

\[ 5 \times 10^4 \]

\[ \mu - y \quad \text{transition} \]
Spectral ($\mu$) distortions from diffusion damping:

$$Q \sim \rho_\gamma \langle \delta_\gamma^2 \rangle_p \sim \int d^3k_1 d^3k_2 \langle T_{k_1}(t) T_{k_2}(t) \rangle_p R_{\vec{k}_1} R_{\vec{k}_2} e^{i(\vec{k}_1 + \vec{k}_2) \cdot \vec{x}}$$

**Subhorizon evolution**

**Primordial perturbations**
Spectral distortions from diffusion damping

\[ k_D(z) \approx 4 \times 10^{-6} (1 + z)^{3/2} \text{ Mpc}^{-1} \quad \text{(RD era)} \]

Probing modes:

- \(1 - 50 \text{ Mpc}^{-1}\) with \(y\) distortions \((z \sim 10^3 - 5 \times 10^4)\)
- \(50 - 10^4 \text{ Mpc}^{-1}\) with \(\mu\) distortions \((z \sim 5 \times 10^4 - 2 \times 10^6)\)

~ 10 additional e-folding w.r.t. CMB anisotropies
Spectral distortions from diffusion damping

- Complementarity to CMB anisotropies / galaxy surveys: probing smaller scales — later times during inflation
  - enlarging the observable inflationary window
  - testing scale-dependence of inflationary observables
Spectral distortions from diffusion damping:
2pf from the averaged distortions

- primordial (scalar) power spectrum \( \langle \mu(x) \rangle \sim \int [\ldots] P_R(k) \)

  Chluba - Erickcek - Ben-Dayan 2012, Enqvist - Sekiguchi - Takahashi 2015,
  Cabass - Melchiorri - Pajer 2016, …, see also Giovanni Cabass’ talk this afternoon

- primordial tensor power spectrum

  Ota - Takahashi - Tashiro - Yamaguchi 2014, Chluba - Dai - Grin - Amin -
  Kamionkowski 2014, …

- isocurvature perturbations

  Chluba - Grin 2013, Ota - Sekiguchi - Tada - Yokoyama 2014, …
Example of power spectrum constraints

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

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

What if spectral distortions are found to depend on direction:

it may be due to squeezed non-Gaussianity!
Squeezed non-Gaussianity: amplitude of long-wavelength modes coupled with amplitude of short-wavelength modes
Anisotropic spectral distortions

Squeezed non-Gaussianity: amplitude of long-wavelength modes coupled with amplitude of short-wavelength modes

short wavelength fluctuations \rightarrow \text{spectral distortions} \quad \text{distortions-temperature correlations}

long wavelength fluctuations \rightarrow \text{temperature anisotropies}
Why do we care (a lot!) about squeezed non-Gaussianity?
Soft limits in inflation

SINGLE-CLOCK inflation: soft-limits not observable

\[ \lim_{k_{N+1} \to 0} \left[ \begin{array}{c} k_2 \\ k_1 \\ k_3 \\ k_N \\ k_{N+1} \end{array} \right] \sim 0 \]

Intuitive understanding:

Super-horizon modes freeze-out + standard initial conditions

soft mode rescales background for hard modes

Mathematical derivation:

Form of N-point functions controlled by symmetries (invariance under space diffs.)

Maldacena 2003, Creminelli - Zaldarriaga 2004
Soft limits in inflation

MULTI-CLOCK inflation: soft limits can be observable

Extra fields

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

squeezed bispectrum delivers info on mass spectrum!!!
Soft limits in inflation

MULTI-CLOCK inflation: soft limits can be observable

- **Extra** fields
  - see e.g. Chen - Wang 2009, ED - Fasiello - Kamionkowski 2015, ED - Emami 2016, Biagetti - ED - Fasiello 2017, …

- **Non-Bunch Davies** initial states
  - see e.g. Holman - Tolley 2007, Ganc - Komatsu 2012, Brahma - Nelson - Shandera 2013, …

- **Broken space diffs**
  (e.g. space-dependent background)
  - see e.g. Endlich et al. 2013, ED - Fasiello - Jeong - Kamionkowski 2014, …

probe for (extra) fields, pre-inflationary dynamics, (non-standard) symmetries
squeezed non-Gaussianity:

powerful observable for inflation
Anisotropic spectral distortions

\[ \mu(\vec{x}) \sim R^2(\vec{x}) \]

- from small-wavelength modes
- centered around \( x \)

- Local ansatz
  \[ R(\vec{x}) = r(\vec{x}) + \frac{3}{5} f_{nl} r^2(\vec{x}) \]

- Long-short mode decomposition
  \[ R(\vec{x}) = R_L(\vec{x}) + R_s(\vec{x}) \]

from long-wavelength Fourier modes
from short-wavelength Fourier modes
Anisotropic spectral distortions

- Local ansatz
  \[ \mathcal{R}(\vec{x}) = r(\vec{x}) + \frac{3}{5} f_{n1} r^2(\vec{x}) \]

- Long-short mode decomposition
  \[ \mathcal{R}(\vec{x}) = \mathcal{R}_L(\vec{x}) + \mathcal{R}_s(\vec{x}) \]
  - from long-wavelength Fourier modes
  - from short-wavelength Fourier modes

\[ \mathcal{R}_s(\vec{x}) \approx r_s(\vec{x}) \left[ 1 + \frac{6}{5} f_{n1} \mathcal{R}_L(\vec{x}) \right] \]

Emami - ED - Chluba - Kamionkowski 2015
Anisotropic spectral distortions

\[ \mu(x) \sim \mathcal{R}^2(x) \]
from small-wavelength modes
centered around \( x \)

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

\[ \frac{\Delta \mu}{\mu} \approx \frac{\delta \langle \mathcal{R}^2 \rangle}{\langle \mathcal{R}^2 \rangle} \approx \frac{12}{5} f_{nl} \mathcal{R}_L(x) \]

\[ \frac{\Delta T}{T} \approx \frac{\mathcal{R}_L}{5} \] (SW limit)

\[ C_{\ell}^{\mu T} \approx 12 f_{nl} C_{\ell}^{TT} \]

Emami - ED - Chluba - Kamionkowski 2015
Anisotropic spectral distortions

\[ C_{\ell}^{\mu T} \approx 12 \, f_{\text{nl}}^{\mu} \, C_{\ell}^{TT} \]

\[ C_{\ell}^{y T} \approx 12 \, f_{\text{nl}}^{y} \, C_{\ell}^{TT} \]

- calculation in real space for local ansatz
- \( y \)-distortion especially important if \( \text{fnl} \) scale-dependent
- constraining \( nG \) w/o specific parameterizations for scale-dependence
- how well can we do for \( y \) distortion given \( tSZ \) contamination? and including polarization?

Systematic formulation

- Primordial fluctuations
- Dissipation
- Thermalization physics
- Spatial evolution
Thermalization physics

\[
\frac{\partial n_\nu}{\partial t} - H \nu \frac{\partial n_\nu}{\partial \nu} = \left| \frac{dn_\nu}{dt} \right|_C + \left| \frac{dn_\nu}{dt} \right|_D + \left| \frac{dn_\nu}{dt} \right|_{BR}
\]

\[
\frac{dT_m}{dt} = -2HT_m + \left| \frac{dT_m}{dt} \right|_C + \left| \frac{dT_m}{dt} \right|_{DC/BR} + \frac{\dot{Q}(t)}{k\alpha_h}
\]

\[
\Delta I_\nu(z = 0) = \int G_{\text{th}}(\nu, z', 0) \frac{d(Q/\rho_\gamma)}{dz'} dz'
\]

\[
G_{\text{th}}(\nu, z_h, 0) \approx \frac{J_y(z_h)}{4} Y_{SZ}(\nu) + 1.4 J_\mu(z_h) M(\nu) + \frac{1 - J(z_h)}{4} G(\nu)
\]

* for small distortions, fixed background cosmology, neglecting r dist.
Thermalization physics

\begin{align*}
y(\bar{x}, z) &\approx \frac{1}{4} \int_{z}^{\infty} \frac{d}{dz'} \left[ \frac{Q(\bar{x}, z')}{\rho_\gamma} \right] J_y(z')dz' \\
\mu(\bar{x}, z) &\approx 1.4 \int_{z}^{\infty} \frac{d}{dz'} \left[ \frac{Q(\bar{x}, z')}{\rho_\gamma} \right] J_\mu(z')dz'
\end{align*}

Energy branching ratios
\[ J_y(z) \approx \left( 1 + \left[ \frac{1 + z}{6 \times 10^4} \right]^{2.58} \right)^{-1} \]

\[ J_\mu(z) \approx \left[ 1 - \exp\left( -\left[ \frac{1 + z}{5.8 \times 10^4} \right]^{1.88} \right) \right] e^{-\left( \frac{z}{2 \times 10^6} \right)^{2.5}} \]

approximately models the transition era neglecting r distortions
Window functions

\[ X(\vec{x}, z) \approx \int \frac{d^3 k}{(2\pi)^3} \frac{d^3 k'}{(2\pi)^3} e^{i \vec{x} \cdot (\vec{k} + \vec{k}')} \mathcal{R}(\vec{k}) \mathcal{R}(\vec{k}') W_X(k, k', z) \]

\[ k = k' \]
Window functions

$$\mu \text{ distortion } k \neq k'$$

$$y \text{ distortion } k \neq k'$$
Some applications/results

- Example: local bispectrum — smoothly varying $f_{\text{nl}}(k)$

$$C_{\ell}^{XT} \approx 12 C_{\ell}^{TT,SW} f_{\text{nl}}(k_X) \langle X \rangle$$

$$\int d \ln k \ P_R(k) W_X(k, z_{rec})$$

- Example: local bispectrum — generic $f_{\text{nl}}(k)$ dependence

$$C_{\ell}^{XT} = 12 \int \frac{dC^{XT}(k_T)}{d \ln k_T} \frac{4 \pi}{25} P_R(k_T) j_{\ell}^2(k_T r_L) d \ln k_T$$

$$\int d \ln k \ f_{\text{NL}}(k) P_R(k) \bar{W}_X(k, k_T, z_{rec})$$
Some applications/results

\[ f_{\text{nl}} = 1 \]
Observability

- Example: local, smooth bisp., $\mu$ -T case, PIXIE-like experiment

$$f_{nl}(k_\mu) \lesssim 4500 \left[ \frac{\langle \mu \rangle}{2.3 \times 10^{-8}} \right]^{-1} \quad (68\% c.l.)$$

- Bounds weaker than those obtained with CMB anisotropies, however: complementary probes!

- Larger signal if:
  - power spectrum is large on small scales
  - bispectrum is scale-dependent
  - bispectrum shape is enhanced in the squeezed limit w.r.t. local

Chluba - ED - Amin - Kamionkowski 2016

Ganc - Komatsu 2012
Degeneracies

Probing inflation with spectral distortions:
need to characterize & quantify other possible sources of distortions

... including those from “exotic” physics! E.g.:

- dark matter effects

- decays/annihilations of relics (see Subir Sarkar’s talk on Wed.)

- primordial magnetic fields (see Kerstin Kunze’s talk)

- primordial black holes (see Juan Garcia-Bellido’s talk on Wed.)

- topological defects

...
Degeneracies

Probing inflation with spectral distortions: need to characterize & quantify other possible sources of distortions... including those from “exotic” physics!

- dark matter effects

- decays/annihilations of relics

- primordial magnetic fields
  - Kerstin Kunze’s talk

- primordial black holes (see Juan Garcia-Bellido’s talk on Wed.)

- topological defects

- ...

Spectral distortions from macroscopic dark matter

dark matter formed in the early Universe (QCD phase transition) in the form of composite baryonic objects of approximate nuclear density and macroscopic size (“macros”)

macros cool slowly (by emission of neutrinos and photons) distorting the CMB (as well as affecting the cosmic neutrino background)

... distortion from these objects would be detectable by a PIXIE-like experiment

(with Saurabh Kumar, Glenn Starkman, Craig Copi, Bryan Lynn)
Degeneracies

Probing inflation with spectral distortions:
need to characterize & quantify other possible sources of distortions

... including those from “exotic” physics! E.g.:

- dark matter effects
  

- decays/annihilations of relics (see Subir Sarkar’s talk on Wed.)

- primordial magnetic fields (see Kerstin Kunze’s talk)

- primordial black holes (see Juan Garcia-Bellido’s talk on Wed.)

- topological defects

...
Gravitinos in the early Universe

- predicted in SUGRA
- spin 3/2 super-partners of gravitons
- their mass is related to SUSY-breaking scale

\[ V(\phi) \]

\[ \epsilon, \eta \ll 1 \]

\[ \epsilon, \eta \approx 1 \]

---

**inflation**

\[ V(\phi) \] dominates

relic gravitinos quickly *diluted*

**Reheating**

inflaton decays

gravitinos production by:

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

ordinary radiation/ matter eras

\[ T_{rh} \]
• Gravitinos thermal production during reheating:

\[ \frac{n_{3/2}}{s} \approx 10^{-2} \frac{T_{\text{rh}}}{M_P} \]

• Cosmology with gravitinos: bounds on Trh from
  • overclosure of the universe (stable/unstable)
  • light elements destruction from decay products
  • spectral distortions of the CMB from decay products

Gravitino case study for spectral distortions

Total energy release:

\[
\frac{\Delta \rho_\gamma}{\rho_\gamma} \approx \left[ \frac{\Delta \rho_\gamma}{\rho_\gamma} \right]_\mu + \left[ \frac{\Delta \rho_\gamma}{\rho_\gamma} \right]_y
\]

Model-dependence:

\[
\frac{\mu}{1.4} \approx \int \mathcal{I}_{bb} \mathcal{I}_{\mu} \frac{1}{\rho_\gamma} \left( \frac{dQ}{dt} \right) dt
\]

\[
4y \approx \int \mathcal{I}_{bb} \mathcal{I}_{y} \frac{1}{\rho_\gamma} \left( \frac{dQ}{dt} \right) dt
\]

\[
\Gamma_{3/2} = \frac{N_{\text{dec}} m_{3/2}^3}{(2\pi) M_P^2}
\]

Constrainting:

- \( T_{rh} \) (reheating temperature)
- \( m_{3/2} \) (mass of gravitinos)

\( N_{\text{dec}} \) (effective number of decay channels)

\( \epsilon_{3/2} \) (fraction of initial energy going into CMB)
Gravitino case study for spectral distortions

\[ G \rightarrow \gamma + \tilde{\gamma} \]
branching ratio = 1

ED - Chluba - Krauss 2015
Conclusions and outlook

We provided:

- simple analytical estimates for local shapes and smoothly varying $f_{nl}$ from real space calculations
- systematic framework to compute cross-correlations of anisotropic distortions and temperature anisotropies

Important points:

- squeezed limit is a powerful observable for inflation: totally worth it to extend range of scale by probing $y_T$!
- distortions-T correlations depend on the isotropic distortions, so average needed also to break model-degeneracy
- need to characterize additional “exotic” (i.e. from unknown physics) spectral distortions
- competitiveness of spectral distortions w.r.t. other probes (e.g. BBN) when probing decays of relics in the early universe