Probing the early Universe with CMB spectral distortions

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Outline

- Brief introduction
- Distortions from dissipation of primordial fluctuations
  - Average distortions and power spectrum constraints
  - Anisotropic distortions and squeezed non-Gaussianity
- Degeneracies
CMB blackbody spectrum: observations

departures from a perfect black-body are smaller than one part in 100000
CMB spectral distortions

\[ z \approx 2 \times 10^6 \]
Thermalization physics

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

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

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

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

- for small distortions, fixed background cosmology, neglecting r dist.
\[ \mathcal{I}_y(z) \approx \left(1 + \left[\frac{1+z}{6 \times 10^4}\right]^{2.58}\right)^{-1} \]

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

approximately models the transition era neglecting r distortions

Chluba 2013
Thermalization physics

\[ \mu(\vec{x}, z) \approx 1.4 \int \frac{d}{d z'} \left[ \frac{Q(\vec{x}, z')}{\rho_\gamma} \right] J_\mu(z') dz' \]

\[ y(\vec{x}, z) \approx \frac{1}{4} \int \frac{d}{d z'} \left[ \frac{Q(\vec{x}, z')}{\rho_\gamma} \right] J_y(z') dz' \]

Energy branching ratios
We predict spectral distortions from:

- Cooling from ordinary matter in the expanding universe
- Heating by decay/annihilation of relic particles / dark matter
- Dissipation of primordial fluctuations
- Dissipation of primordial magnetic fields
- Cosmological recombination radiation
- Sunyaev-Zel’dovich / reionization effects
- Primordial black holes evaporation / accretion
- Topological defects
We predict spectral distortions from:

- Cooling from ordinary matter in the expanding universe
- Heating by decay/annihilation of relic particles / dark matter
- **Dissipation of primordial fluctuations**
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Dissipation of primordial fluctuations

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

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

\( y \)-type distortion visible in the Wien tail
primordial fluctuations

dissipation

thermalization physics
\[ \mu \approx 1.4 \int_{z}^{\infty} \frac{d}{dz'} \left[ \frac{Q(\vec{x}, z')}{\rho_{\gamma}} \right] J_{\mu}(z') dz' \]

energy (density)
released into CMB

energy partition function
Spectral ($\mu$) distortions from diffusion damping:

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

\[ \sim e^{-\left(\frac{k_1^2 + k_2^2}{2k_D^2(z)}\right)} \]
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. 1 – 50 Mpc\(^{-1}\) with \(y\) distortions (\(z \sim 10^3 - 5 \times 10^4\))

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

\sim 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
We will detect distortions from inflationary perturbations for power spectrum predicted by the basic inflationary model.

- No running: [Khatri, Sunyaev, Chluba, 2012]
- Guaranteed discovery: \(3 \times \text{PIXIE} = \text{guaranteed discovery}\)
  - Detection (95% CL)
  - Exclusion of SFSR (95% CL): [Cabass, Melchiorri, Pajer, 2016]
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

Chluba et al 2015
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Anisotropic spectral distortions

What if spectral distortions are found to depend on direction:

it may be due to squeezed non-Gaussianity!
Anisotropic spectral distortions

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
Why is squeezed non-Gaussianity so important?
Soft limits in inflation

*Extra* fields

\[ \zeta, \gamma \quad \sigma \]

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

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

- **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

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

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

Local ansatz

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

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
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

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

*Emami - ED - Chluba - Kamionkowski 2015*
Anisotropic spectral distortions

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

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

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

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

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

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

\[ C^{\mu T}_{\ell} \approx 12 f_{\text{nl}}^{\mu} C^{TT}_{\ell} \]

\[ C^{y T}_{\ell} \approx 12 f_{\text{nl}}^{y} C^{TT}_{\ell} \]

- repeat for \( y \) distortions . . .

- calculation in real space for local ansatz

- \( y \)-distortion especially important if fnl scale-dependent

- constraining nG w/o specific parameterizations for scale-dependence

- tSZ contamination for \( y \)-distortion signals

Creque - Sarbinowski - Bird - Kamionkowski 2016, Ota 2016, Ravenni - Liguori - Bartolo - Shiraishi 2017, ...
Window functions

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

\[ k = k' \]
Window functions

\[ \mu \text{ distortion } \quad k \neq k' \]

\[ y \text{ distortion } \quad k \neq k' \]
Some applications/results

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

$$C^{\ell XT}_{\ell} \approx 12 C^{TT,SW}_{\ell} f_{\text{nl}}(k_X) \langle X \rangle \int d\ln k \, \mathcal{P}_{\mathcal{R}}(k) W_X(k, z_{\text{rec}})$$

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

$$C^{\ell XT}_{\ell} = 12 \int \frac{dC^{XT}(k_T)}{d\ln k_T} \frac{4\pi}{25} \mathcal{P}_{\mathcal{R}}(k_T) j^2_{\ell}(k_T r_L) d\ln k_T \int d\ln k \, f_{\text{NL}}(k) \mathcal{P}_{\mathcal{R}}(k) \bar{W}_X(k, k_T, z_{\text{rec}})$$
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
Degeneracies

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

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

- Heating by decay/annihilation of relic particles — effects from dark matter
- Dissipation of primordial magnetic fields
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Gravitinos in the early Universe

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

\[ V(\phi) \]

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

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

\( V(\phi) \)

inflation

Reheating

inflaton decays

\[ T_{rh} \]

ordinary radiation/matter eras

relic gravitinos quickly \textit{diluted}

gravitinos production by:

- \textit{rapid inflaton oscillations}
- \textit{scatterings in the hot plasma}
• 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:
\[
\frac{\Delta \rho_\gamma}{\rho_\gamma} \approx \left[ \frac{\Delta \rho_\gamma}{\rho_\gamma} \right]_\mu + \left[ \frac{\Delta \rho_\gamma}{\rho_\gamma} \right]_y
\]

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

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

Model-dependence:

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

\[
\epsilon_{3/2} \quad (\text{fraction of initial energy going into CMB})
\]

Constraining:

\[
T_{\text{rh}} \quad (\text{reheating temperature})
\]

\[
m_{3/2} \quad (\text{mass of gravitinos})
\]

\[
\Gamma_{3/2} = \frac{N_{\text{dec}} m_{3/2}^3}{(2\pi) M_P^2}
\]
Gravitino case study for spectral distortions

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

ED - Chluba - Krauss 2015
Conclusions and outlook

- With spectral distortions we can probe primordial fluctuations on a separate window!

- We provided:
  - simple analytical estimates for local shapes and smoothly varying \( \text{fnl} \) from real space calculations
  - a systematic framework to compute cross-correlations of anisotropic distortions and temperature anisotropies

- 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