Probing the early Universe with CMB spectral distortions

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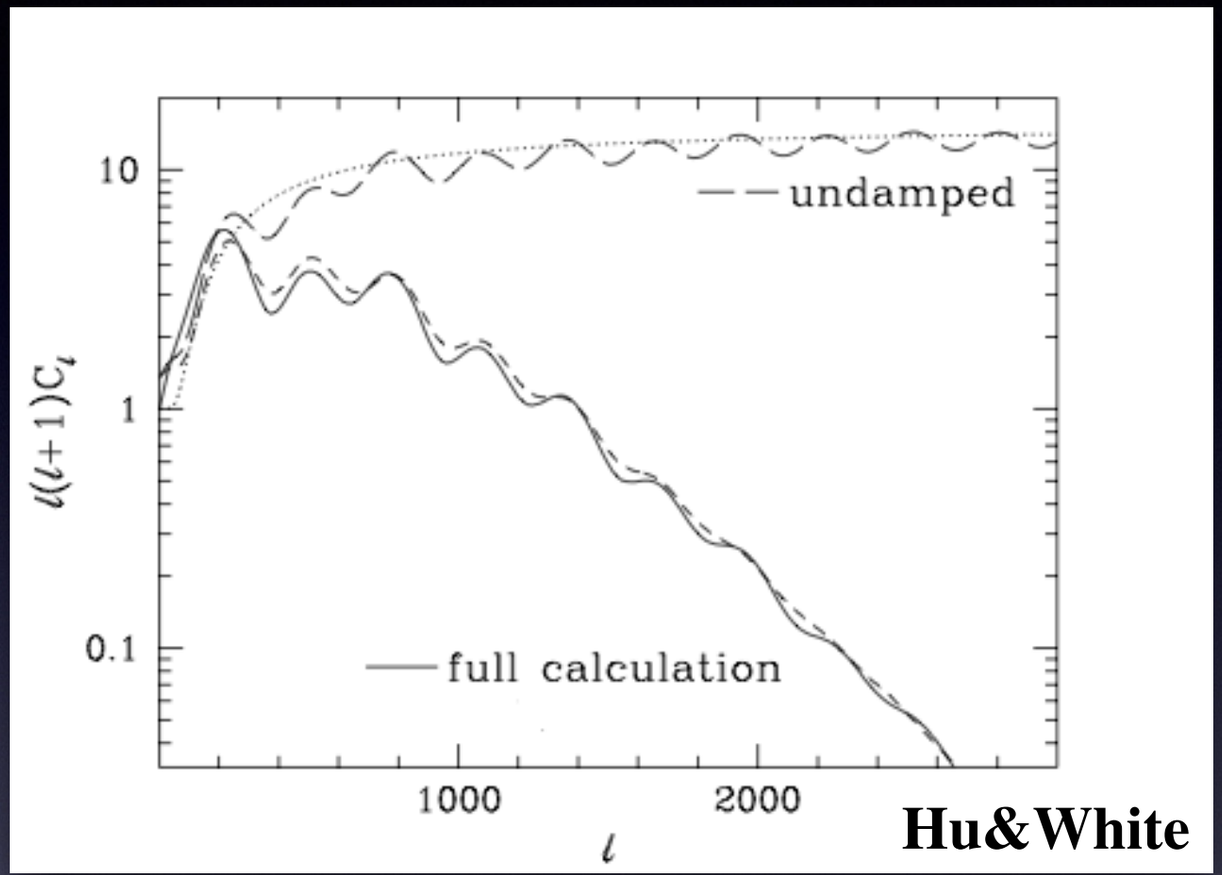
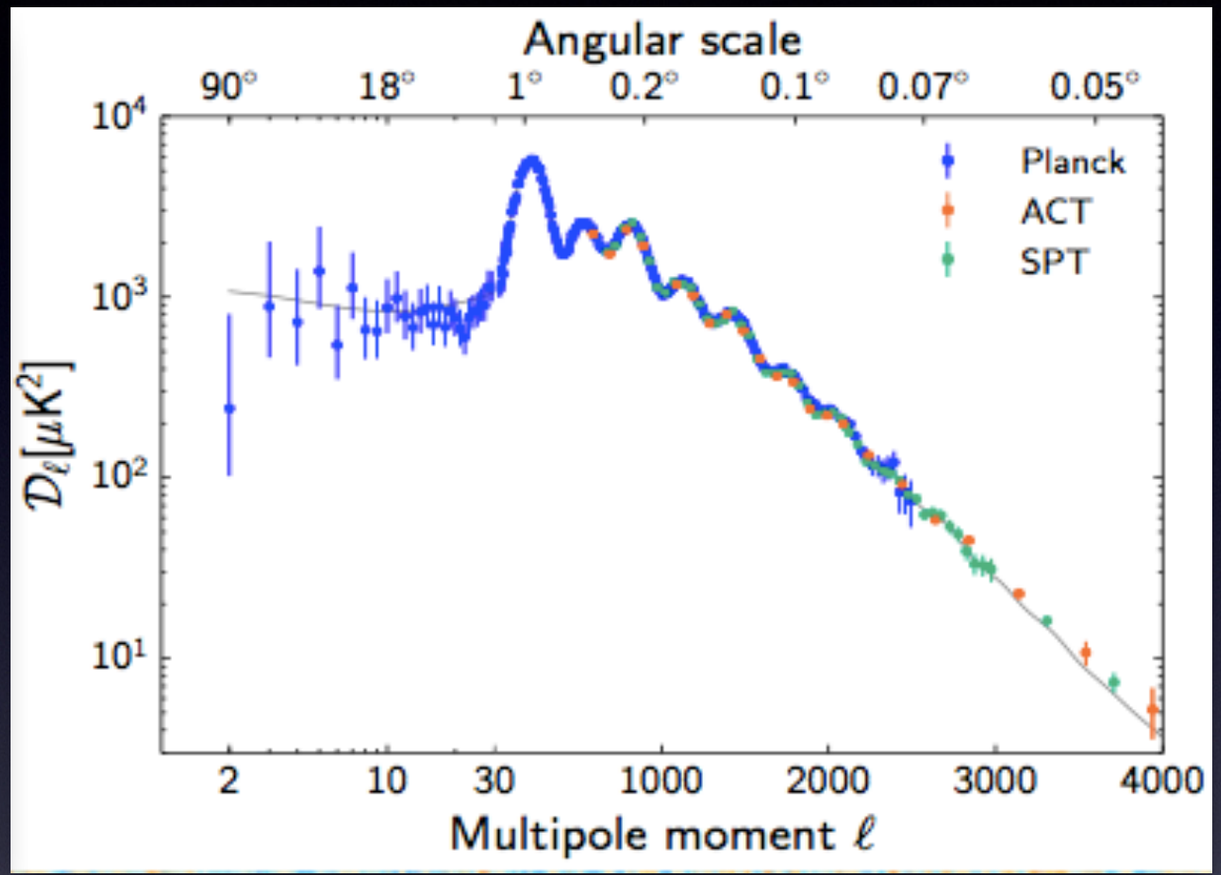
Probing fundamental physics with CMB spectral distortions
CERN — March 13th 2018

Outline

- Spectral distortions and inflation
- Anisotropic distortions and squeezed non-Gaussianity
- Degeneracies

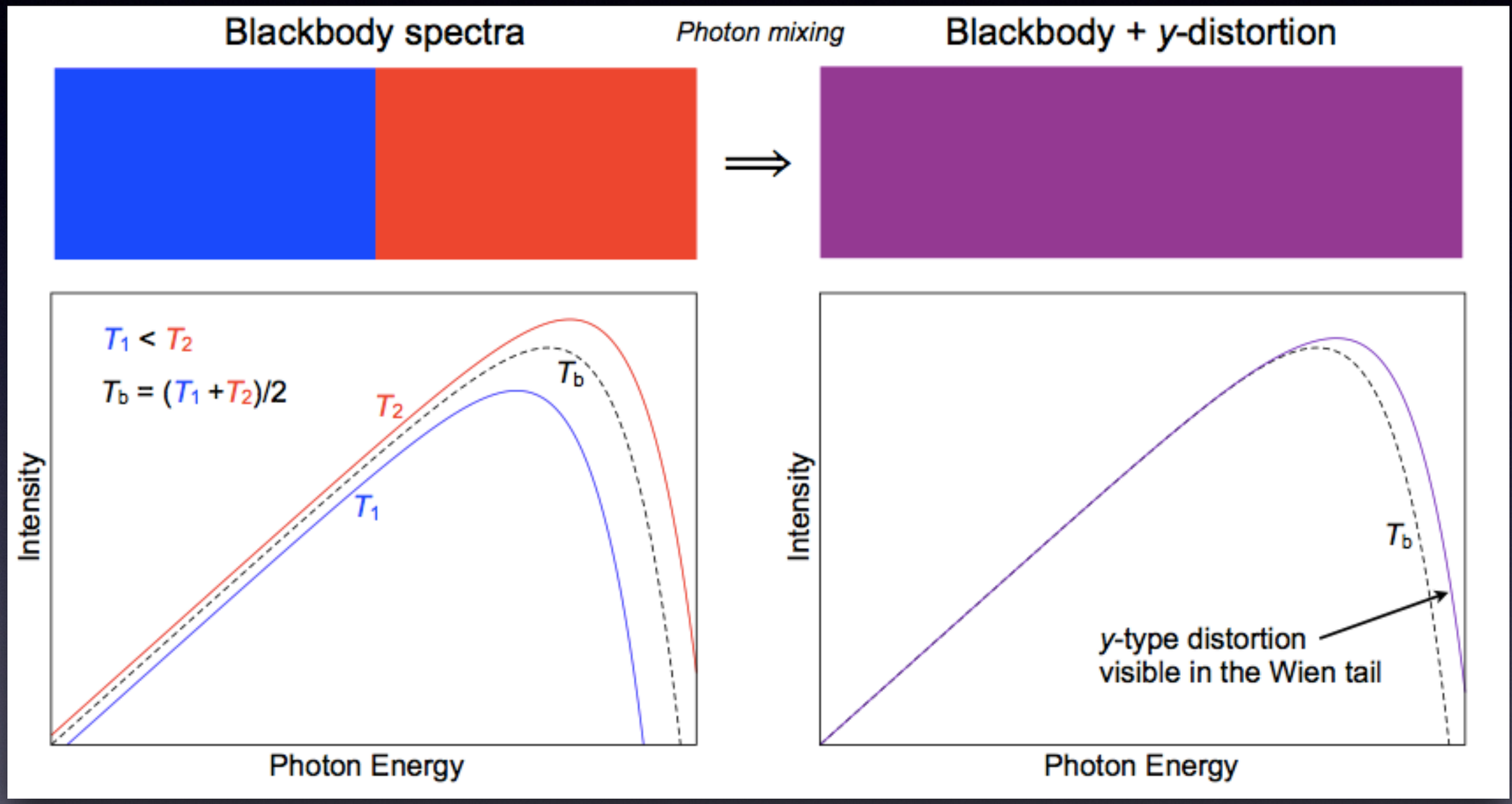
Dissipation of primordial fluctuations





Silk damping: isotropization by photon diffusion

Spectral distortions from diffusion damping



Chluba - Hamann - Patil 2015

energy (density)
released into CMB

μ era onset

2×10^6

$$\mu \approx 1.4 \int_{z_{\mu y}}^{\infty} dz \frac{1}{\rho_\gamma} \frac{dQ}{dz} e^{-(z/z_\mu)^{5/2}}$$

5×10^4

$\mu - y$ transition

energy (density) released into CMB

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$$\mu \approx 1.4 \int_{z_{\mu y}}^{\infty} dz \frac{1}{\rho_\gamma} \frac{dQ}{dz} e^{-(z/z_\mu)^{5/2}}$$

5×10^4 $\mu - y$ transition

Spectral (μ) distortions from diffusion damping:

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

subhorizon evolution

primordial perturbations

$$\sim e^{-\left(k_1^2 + k_2^2\right)/k_D^2(z)}$$

diffusion-damping scale

Spectral distortions from diffusion damping

$$k_D(z) \approx 4 \times 10^{-6} \, (1+z)^{3/2} \ \mathrm{Mpc}^{-1} \qquad \text{(RD era)}$$

Probing modes:

$1 - 50 \, \mathrm{Mpc}^{-1}$ with y distortions $(z \sim 10^3 - 5 \times 10^4)$

$50 - 10^4 \, \mathrm{Mpc}^{-1}$ with μ 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 $\langle \mu(x) \rangle \sim \int [\ldots] P_{\mathcal{R}}(k)$

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

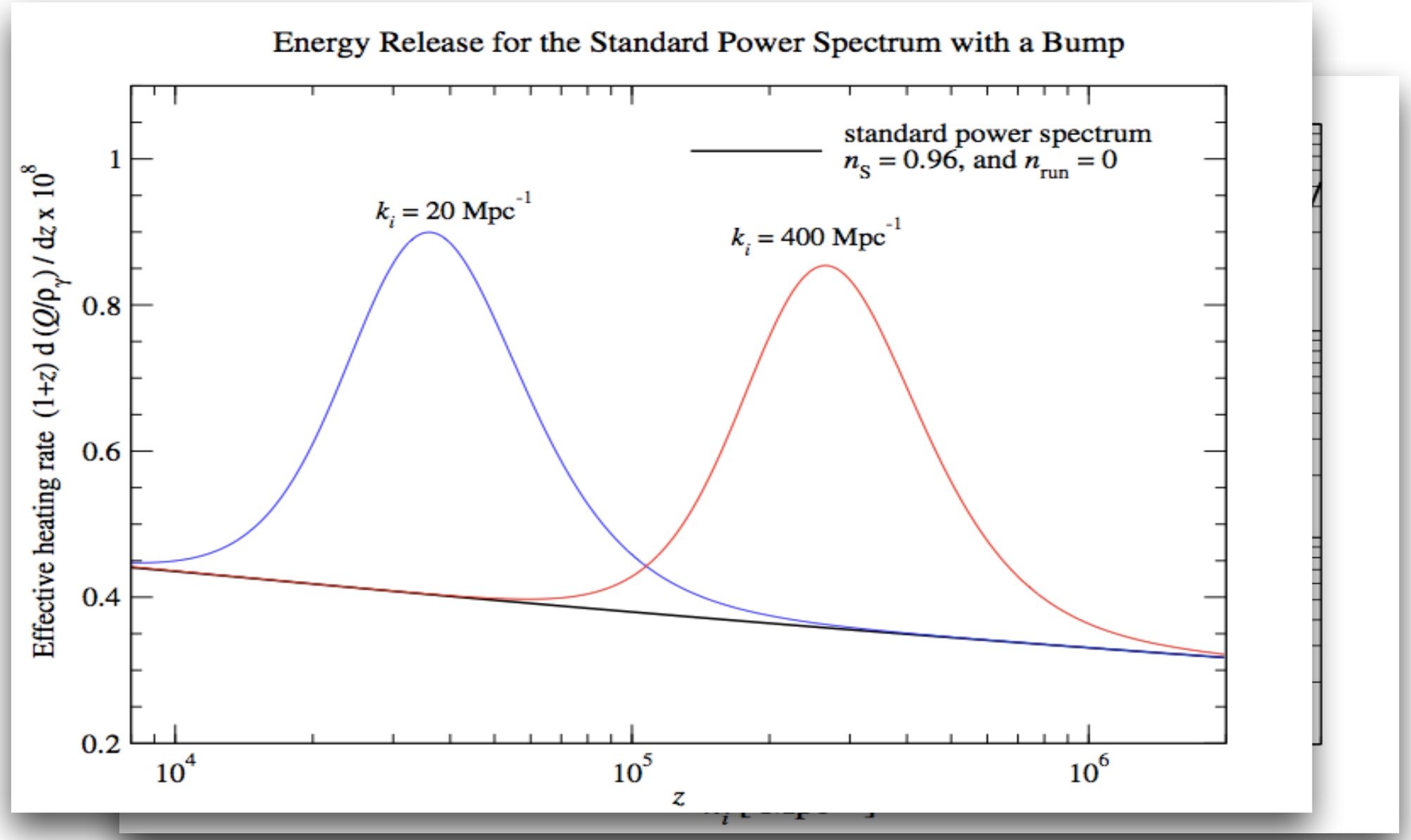
- primordial tensor power spectrum

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

- isocurvature perturbations

  Chluba - Grin 2013, Ota - Sekiguchi - Tada - Yokoyama 2014, …

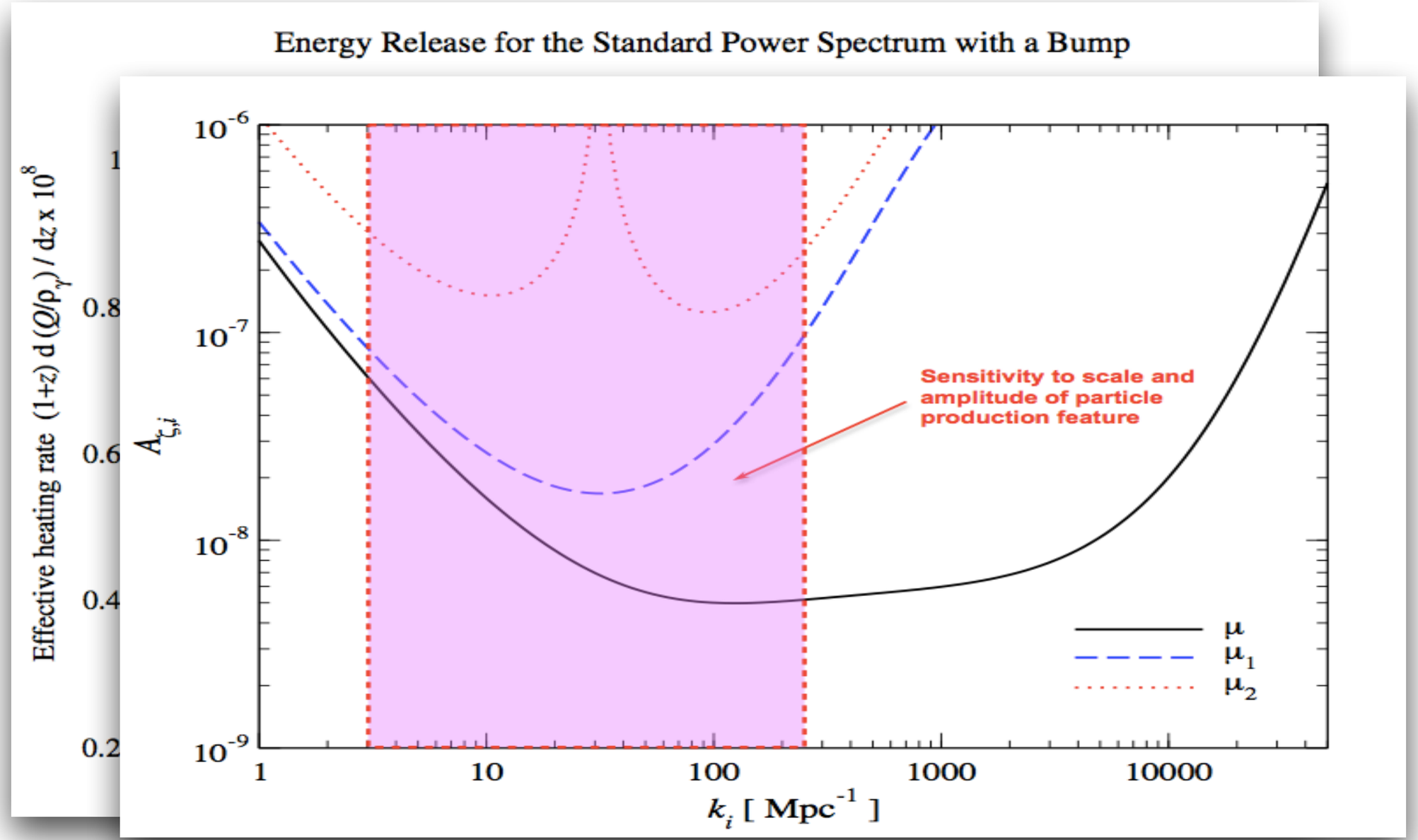
Example of power spectrum constraints



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

Chluba - Hamann - Patil 2015

Example of power spectrum constraints



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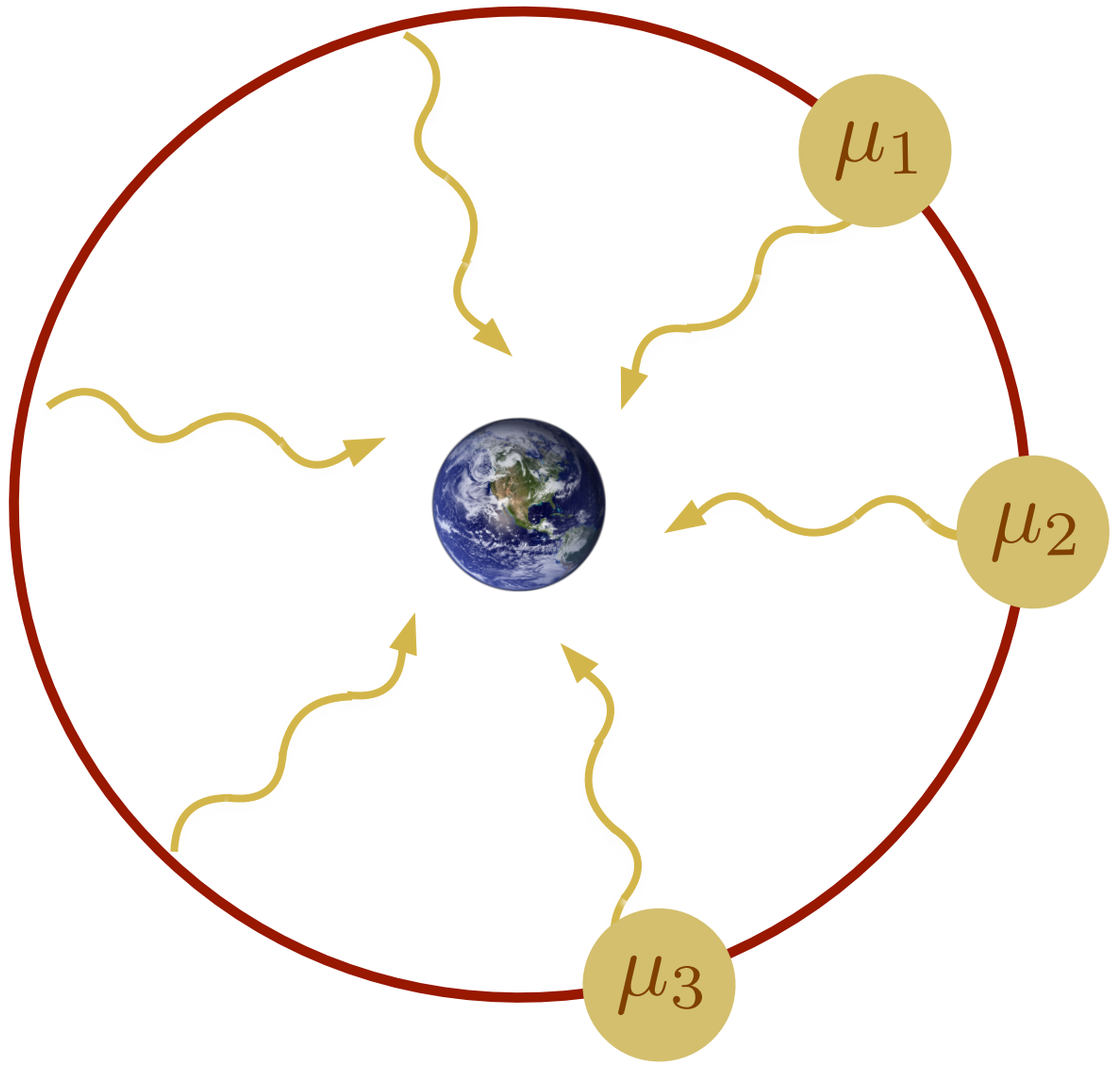
Chluba - Hamann - Patil 2015

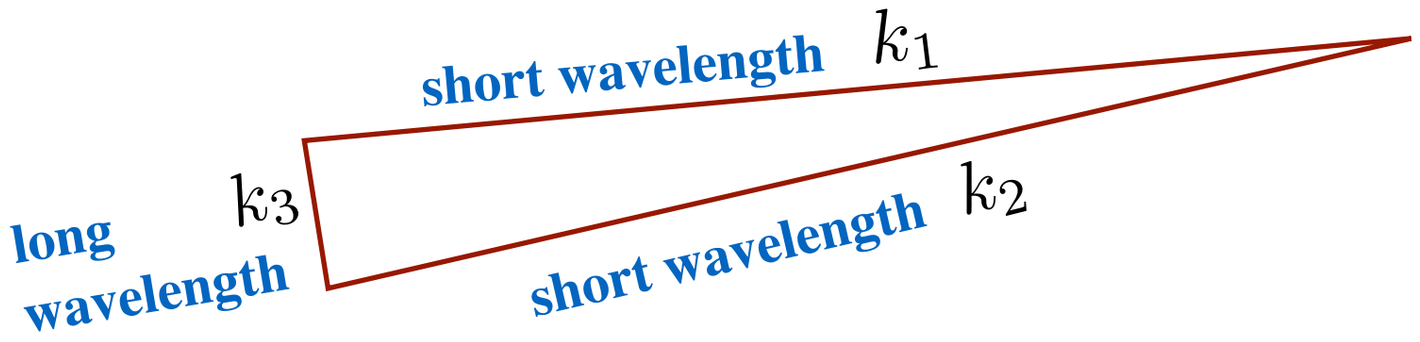
Anisotropic spectral distortions

What if spectral distortions are found to depend on direction:

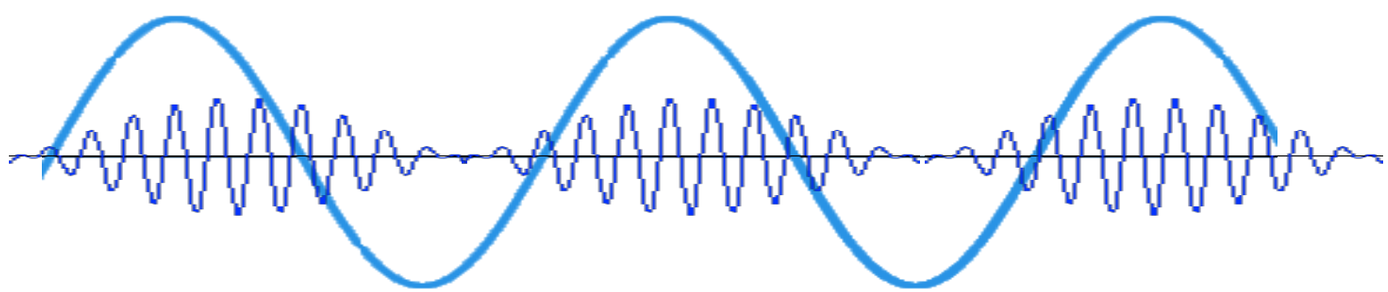


it may be due to squeezed non-Gaussianity!

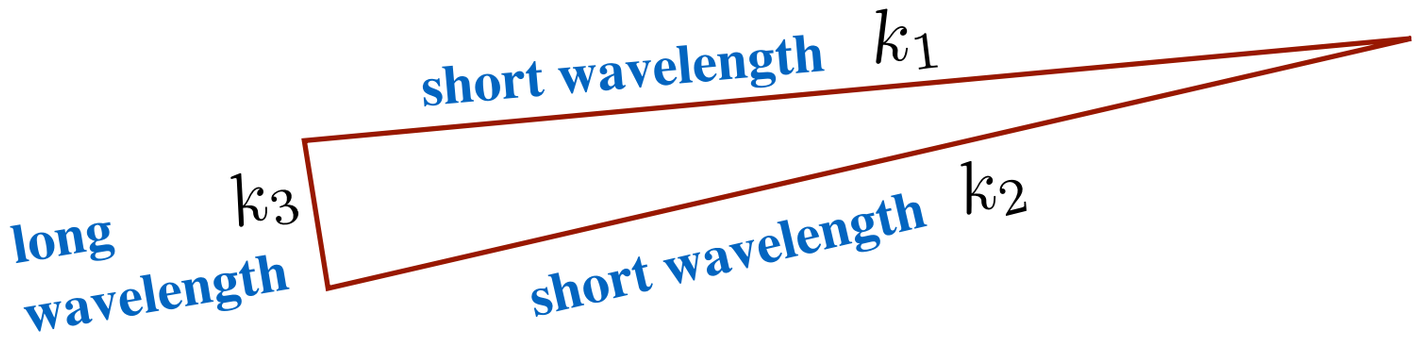
Anisotropic spectral distortions



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

short wavelength fluctuations → spectral distortions

long wavelength fluctuations → temperature anisotropies

} distortions--temperature correlations

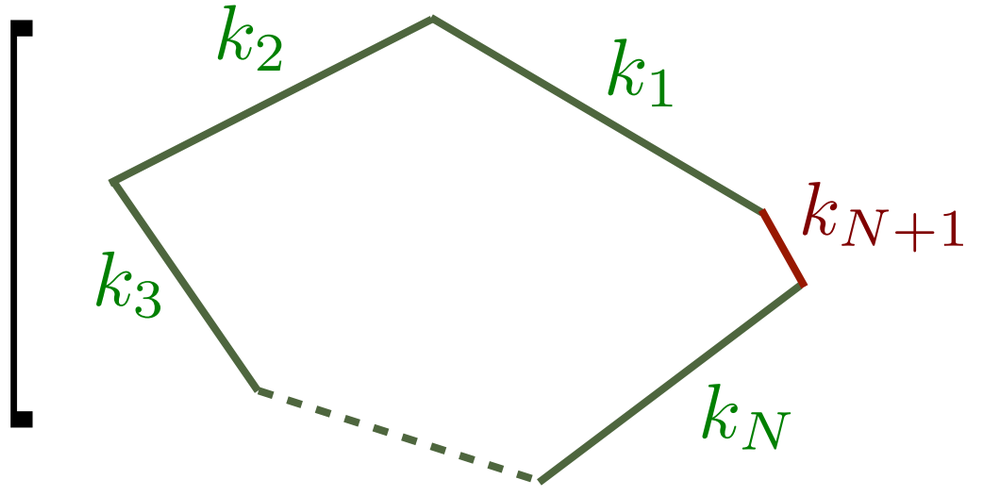
Pajer - Zaldarriaga 2012, Ganc - Komatsu 2012, Biagetti - Perrier - Riotto - Desjacques 2013

Why do we care (a lot!) about squeezed non-Gaussianity?

Soft limits in inflation

SINGLE-CLOCK inflation: soft-limits not observable

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



$$\sim 0$$

Intuitive understanding :

Super-horizon modes freeze-out
+
standard initial conditions

→ soft mode rescales background for hard modes

Mathematical derivation :

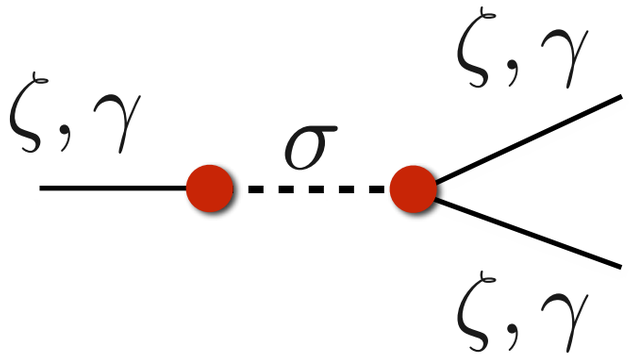
Form of N-point functions controlled by symmetries (invariance under space diffs.)

Maldacena 2003, Creminelli - Zaldarriaga 2004

Soft limits in inflation

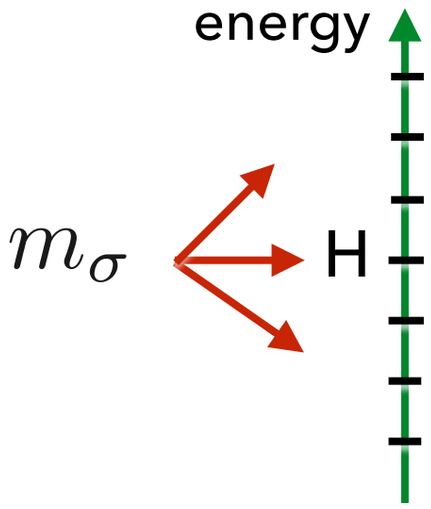
MULTI-CLOCK inflation: soft limits can be observable

- ***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

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

- from small-wavelength modes
- centered around x

- Local ansatz

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

- 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

Emami - ED - Chluba - Kamionkowski 2015

Anisotropic spectral distortions

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

Emami - ED - Chluba - Kamionkowski 2015

Anisotropic spectral distortions

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

$$\left.\begin{aligned} \frac{\Delta\mu}{\mu} &\approx \frac{\delta\left\langle\mathcal{R}^2\right\rangle}{\left\langle\mathcal{R}^2\right\rangle} \approx \frac{12}{5}\mathrm{f_{nl}}\mathcal{R}_L(\vec{x}) \\ \frac{\Delta T}{T} &\approx \frac{\mathcal{R}_L}{5} \quad \text{(SW limit)} \end{aligned}\right\} \; C_\ell^{\mu T} \approx 12\,\mathrm{f_{nl}} C_\ell^{TT}$$

Emami - ED - Chluba - Kamionkowski 2015

Anisotropic spectral distortions

repeat for y distortions . . .

$$C_\ell^{\mu T} \approx 12\, \mathrm{f}_{\mathrm{nl}}^{\mu} C_\ell^{TT}$$

$$C_\ell^{yT} \approx 12\, \mathrm{f}_{\mathrm{nl}}^{y} C_\ell^{TT}$$

- calculation in real space for local ansatz
- y- distortion especially important if 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?

Creque - Sarbinowski - Bird - Kamionkowski 2016, Ota 2016, Ravenni - - Liguori - Bartolo - Shiraishi 2017, …

Systematic formulation

primordial fluctuations

dissipation

thermalization physics

spatial evolution

Chluba - ED - Amin - Kamionkowski 2016

Thermalization physics

$$\frac{\partial n_\nu}{\partial t} - H\,\nu\,\frac{\partial n_\nu}{\partial \nu} = \left.\frac{dn_\nu}{dt}\right|_{\rm C} + \left.\frac{dn_\nu}{dt}\right|_{\rm DC} + \left.\frac{dn_\nu}{dt}\right|_{\rm BR}$$

$$\frac{dT_{\rm m}}{dt} = -2HT_{\rm m} + \left.\frac{dT_{\rm m}}{dt}\right|_{\rm C} + \left.\frac{dT_{\rm m}}{dt}\right|_{\rm DC/BR} + \frac{\dot{Q}(t)}{k\alpha_{\rm h}}$$

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

$$G_{\rm th}(\nu, z_{\rm h}, 0) \approx \frac{\mathcal{J}_y(z_{\rm h})}{4}\,Y_{\rm SZ}(\nu) + 1.4\,\mathcal{J}_\mu(z_{\rm h})\,M(\nu) + \frac{1-\mathcal{J}(z_{\rm h})}{4}\,G(\nu)$$

- for small distortions, fixed background cosmology, neglecting r dist.

Chluba 2013

Thermalization physics

$$y(\vec{x},z) \approx \frac{1}{4}\int_z^\infty \frac{d}{dz'}\left[\frac{Q(\vec{x},z')}{\rho_\gamma}\right]\mathcal{J}_y(z')dz'$$

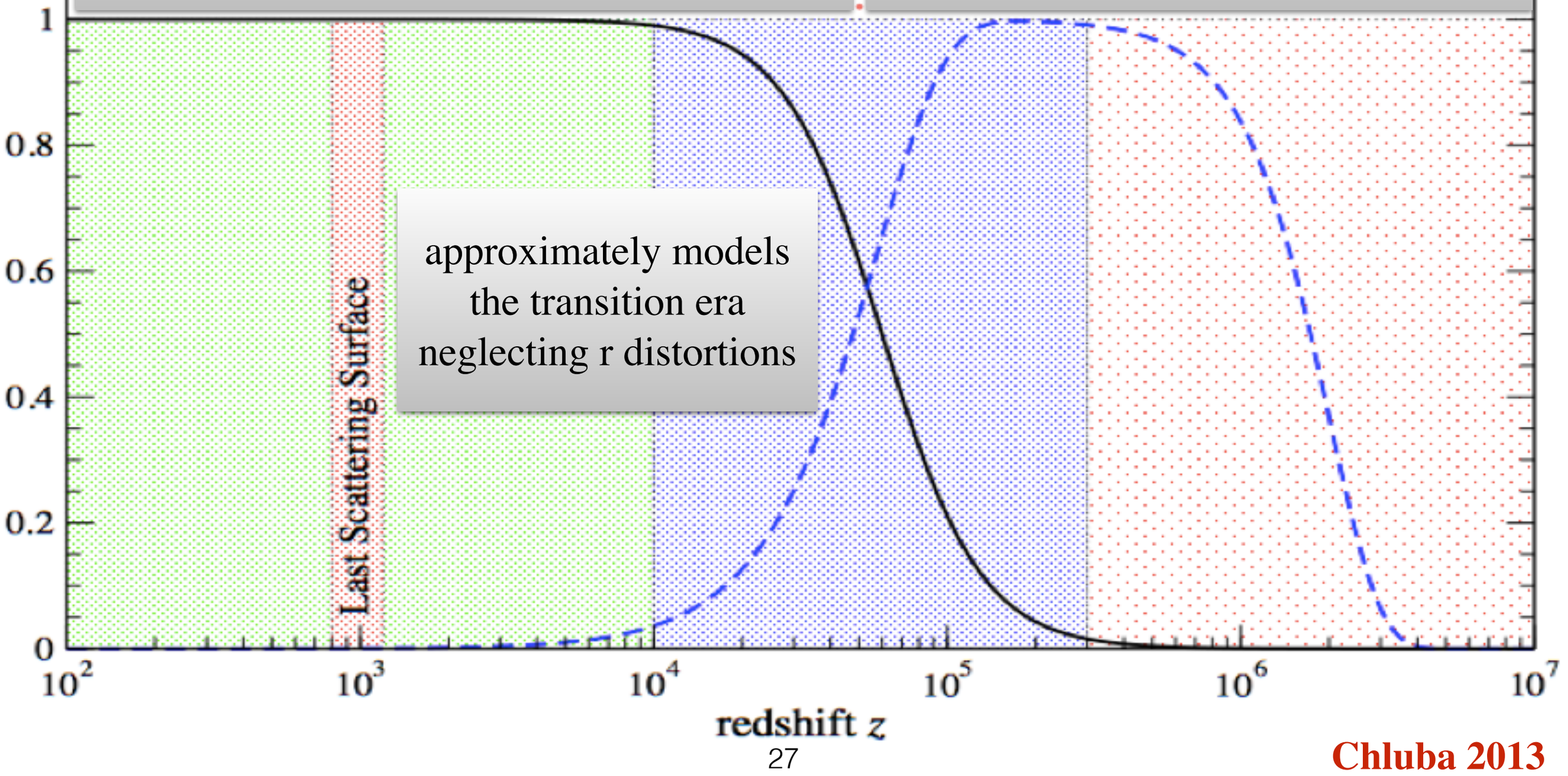
$$\mu(\vec{x},z) \approx 1.4\int_z^\infty \frac{d}{dz'}\left[\frac{Q(\vec{x},z')}{\rho_\gamma}\right]\mathcal{J}_\mu(z')dz'$$

Energy branching ratios

y distortion μ - y transition μ distortion

$$\mathcal{J}_y(z) \approx \left(1 + \left[\frac{1+z}{6\times 10^4}\right]^{2.58}\right)^{-1}$$

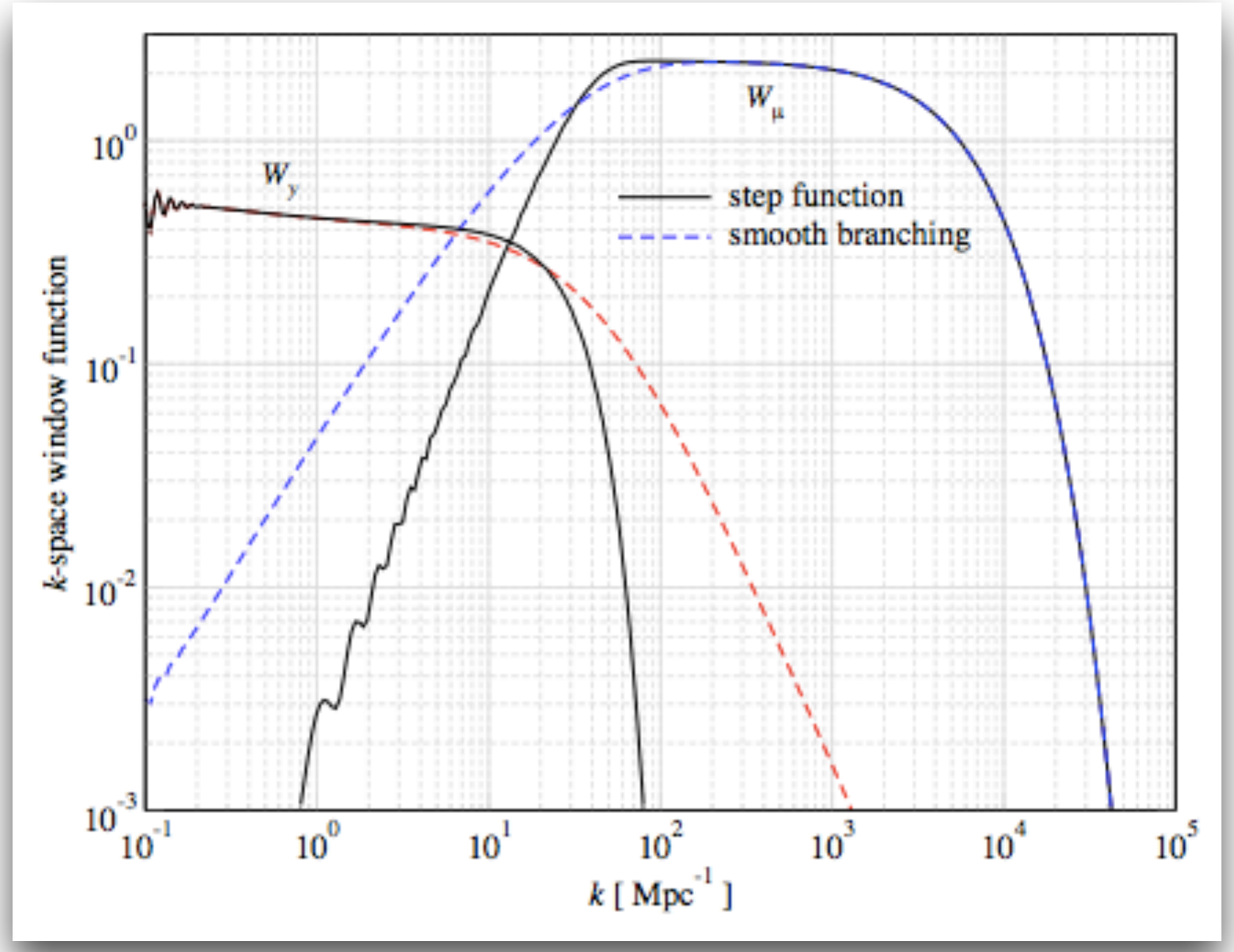
$$\mathcal{J}_\mu(z) \approx \left[1 - \exp\left(-\left[\frac{1+z}{5.8\times 10^4}\right]^{1.88}\right)\right] e^{-\left[\frac{z}{2\times 10^6}\right]^{2.5}}$$



approximately models the transition era neglecting r distortions

Chluba 2013

Window functions

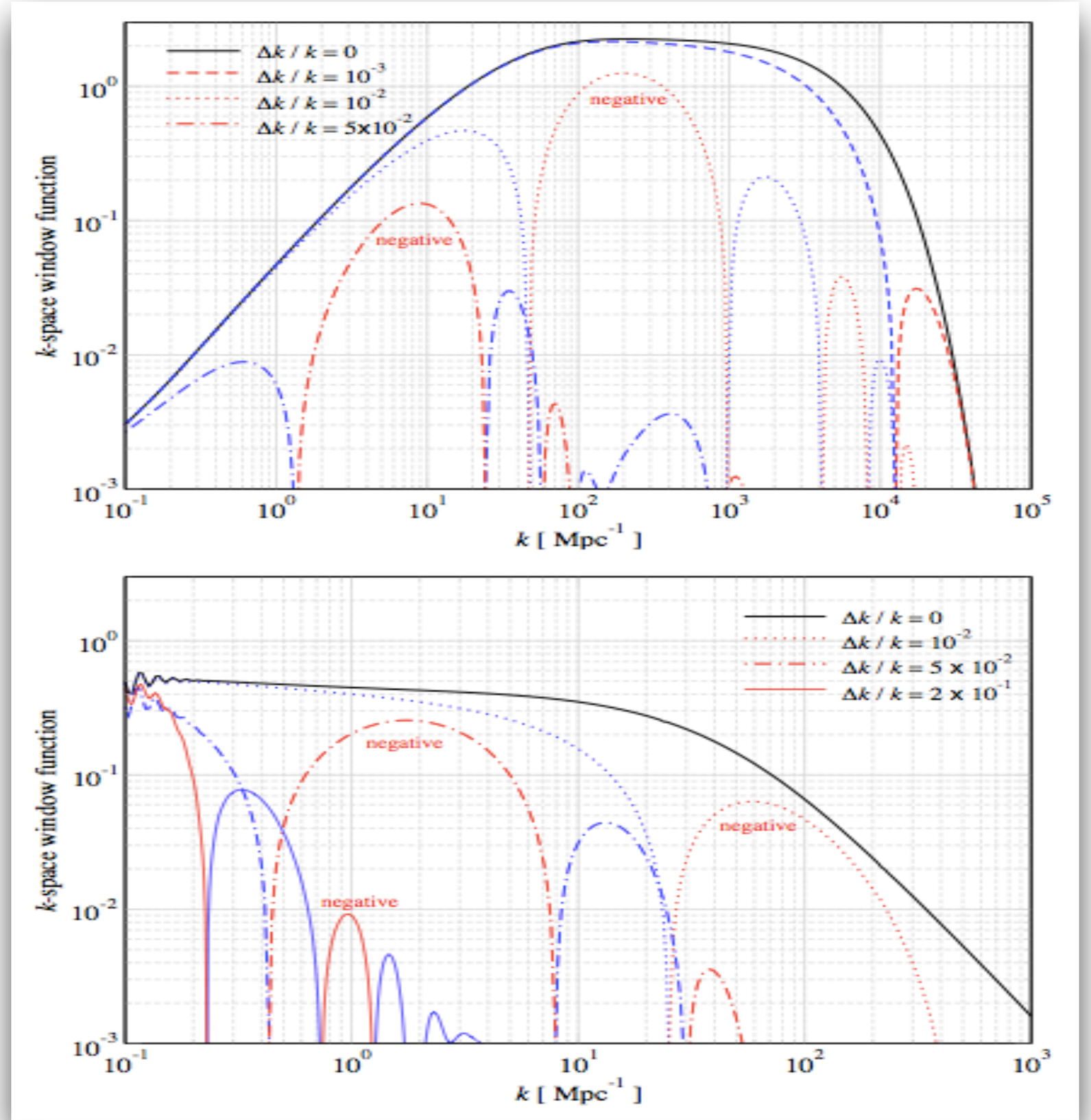


$$k = k'$$

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

Chluba - ED - Amin - Kamionkowski 2016

Window functions



μ distortion
$k \neq k'$

y distortion
$k \neq k'$

Chluba - ED - Amin - Kamionkowski 2016

Some applications/results

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

$$C_\ell^{XT} \approx 12\, C_\ell^{TT,\rm SW}\, \mathrm{f}_{\rm nl}(k_X) \langle X \rangle$$

$$\int d\ln k\; \mathcal{P}_{\mathcal{R}}(k) W_X(k, z_{\rm rec})$$

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

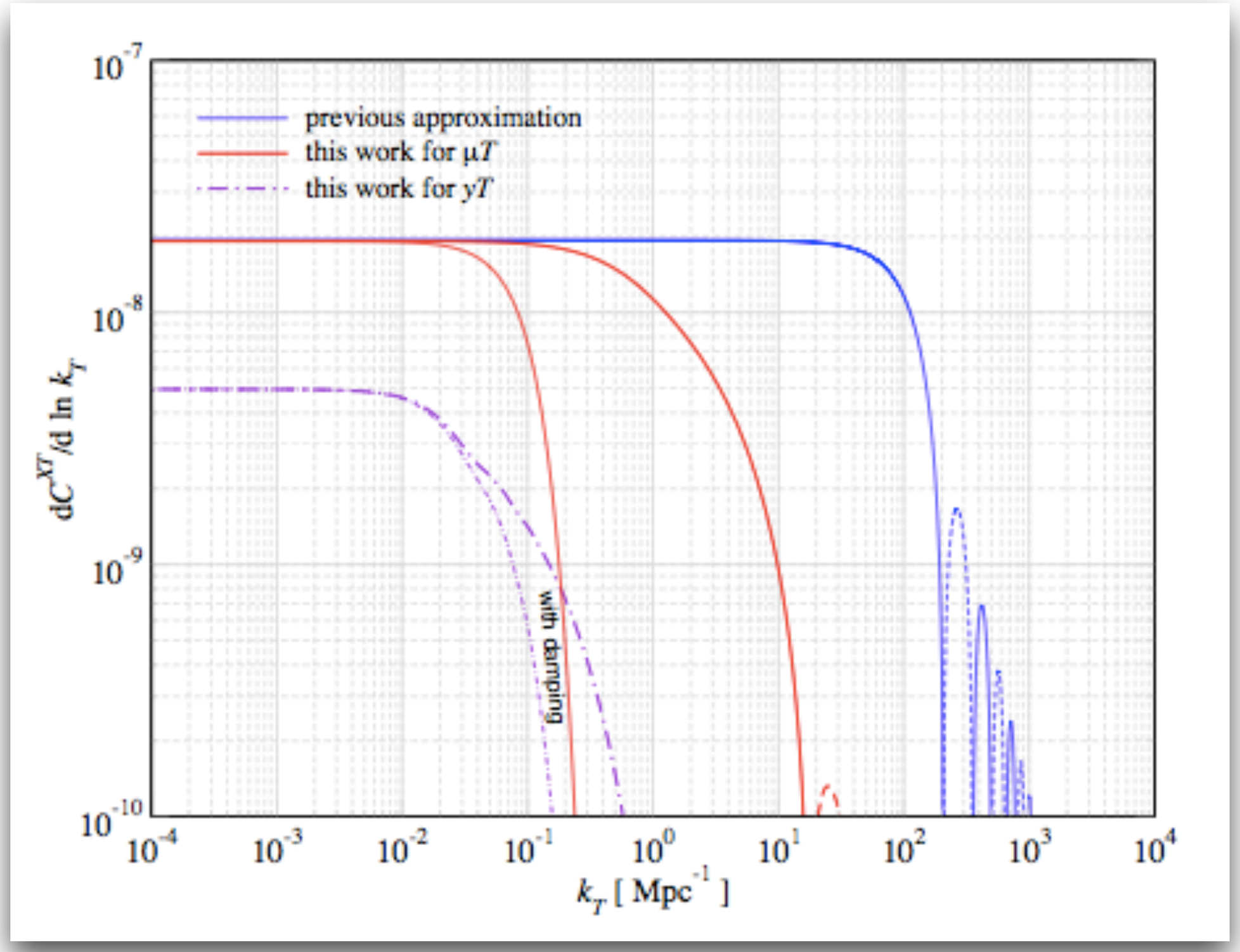
$$C_\ell^{XT} = 12 \int \frac{dC^{XT}(k_T)}{d\ln k_T} \frac{4\pi}{25}\, \mathcal{P}_{\mathcal{R}}(k_T)\, j_\ell^2(k_T r_L)\, d\ln k_T$$

$$\int d\ln k\, f_{\rm NL}(k)\, \mathcal{P}_{\mathcal{R}}(k)\, \bar{W}_X(k, k_T, z_{\rm rec})$$

Chluba - ED - Amin - Kamionkowski 2016

Some applications/results

$f_{\rm nl} = 1$



Chluba - ED - Amin - Kamionkowski 2016

Observability

- Example: local, smooth bisp.,μ -T case, PIXIE-like experiment

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

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

Chluba - ED - Amin - Kamionkowski 2016

- 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

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

  Ali-Haımoud - Chluba - Kamionkowski 2015, Nakama - Chluba - Kamionkowski 2017, Diacoumis - Wong 2017, …, see Pasquale Serpico’s talk on Wed., Yacine Ali-Haımoud’s talk & discussion session on Thur., Suvodip Mukherjee’s & James Diacoumis’ talks on Friday

- 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
- …

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  Kamionkowski 2017, Diacc

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  Suvodip Mukherjee's & Jan

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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)

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

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

Degeneracies

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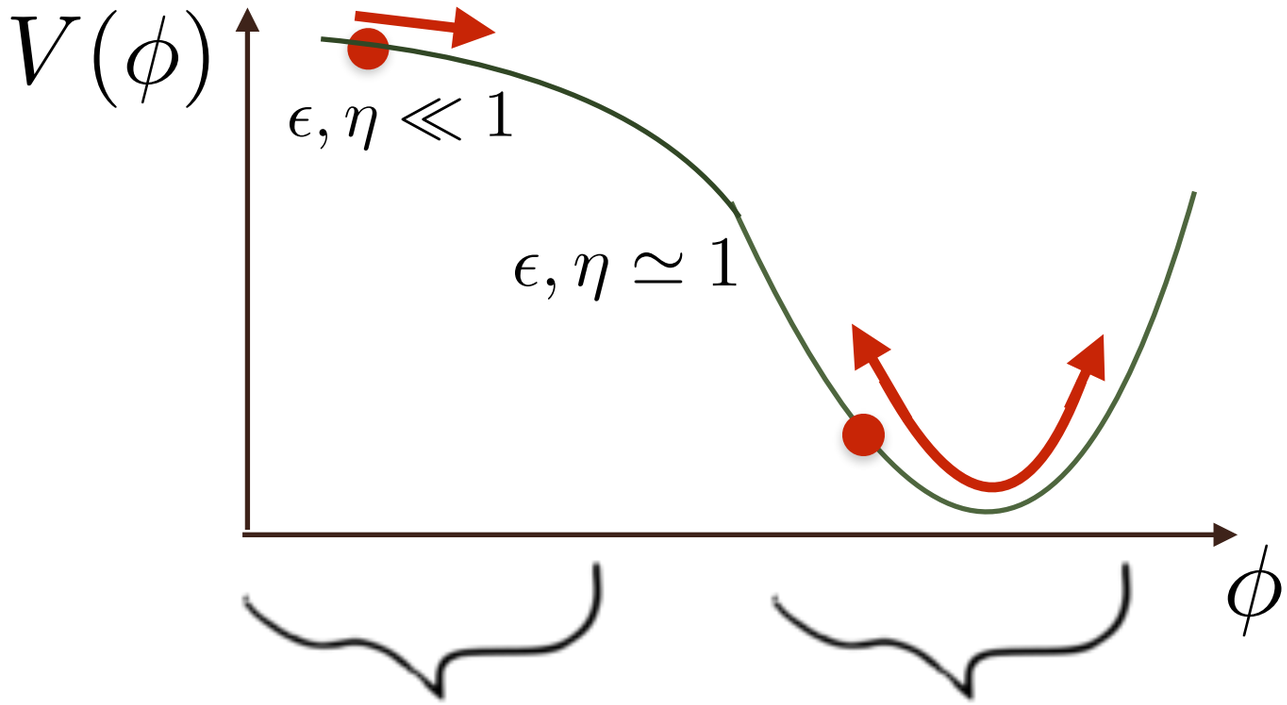
Gravitinos in the early Universe

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



$V(\phi)$ dominates

relic gravitinos quickly *diluted*

inflaton decays → $T_{\rm rh}$ → ordinary radiation/ matter eras

gravitinos production by:

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

- Gravitinos thermal production during reheating:

$$\frac{n_{3/2}}{s} \approx 10^{-2} \frac{T_{\rm rh}}{M_P}$$

- 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

[Pagels - Primack 1982, Weinberg 1982, Ellis - Gelmini - Lopez - Nanopoulos - Sarkar 1992, Feng 2002 - …]

Gravitino case study for spectral distortions

Total energy release:

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

$$\frac{\mu}{1.4} \approx \int \mathcal{J}_{\rm bb}\,\mathcal{J}_\mu \frac{1}{\rho_\gamma}\left(\frac{{\rm d}Q}{{\rm d}t}\right) dt$$

$$4y \approx \int \mathcal{J}_{\rm bb}\,\mathcal{J}_y \frac{1}{\rho_\gamma}\left(\frac{{\rm d}Q}{{\rm d}t}\right) dt$$

Model-dependence:

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

$$\Gamma_{3/2} = \frac{N_{\rm dec}}{(2\pi)}\frac{m_{3/2}^3}{M_{\rm P}^2}$$

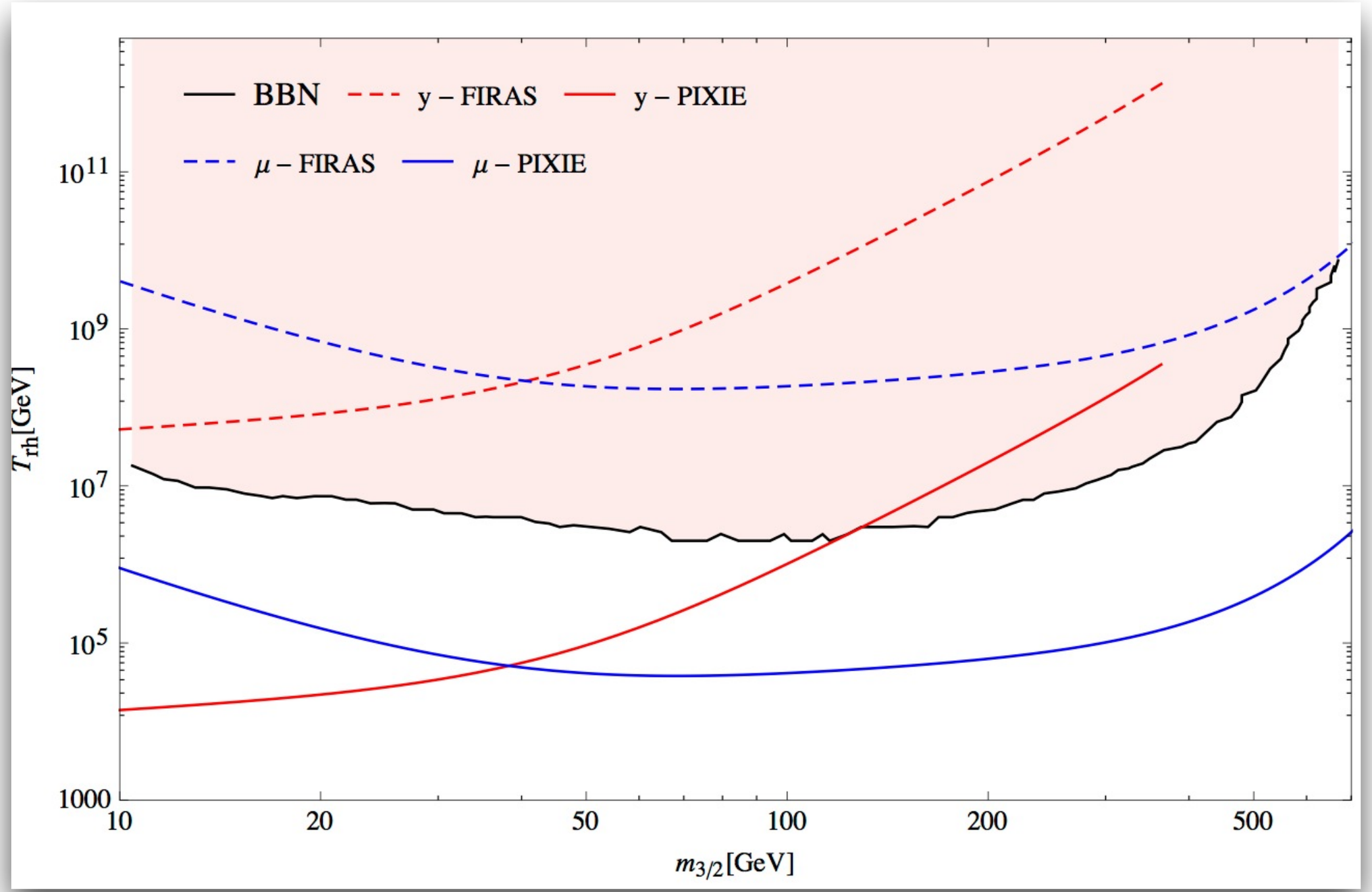
$\epsilon_{3/2}$ (fraction of initial energy going into CMB)

Constraining: $T_{\rm rh}$ (reheating temperature)

$m_{3/2}$ (mass of gravitinos)

ED - Chluba - Krauss 2015

Gravitino case study for spectral distortions



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

$$\text{branching ratio} = 1$$

ED - Chluba - Krauss 2015

Conclusions and outlook

We provided:

- **simple analytical estimates for local shapes and smoothly varying fnl 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 yT!**
- **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**