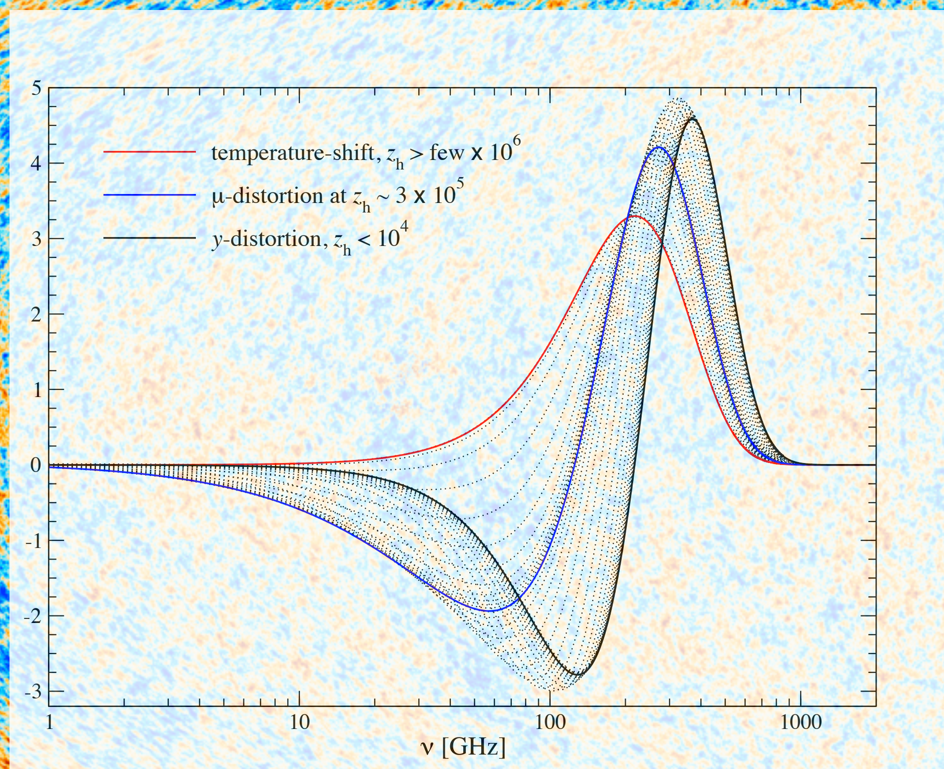
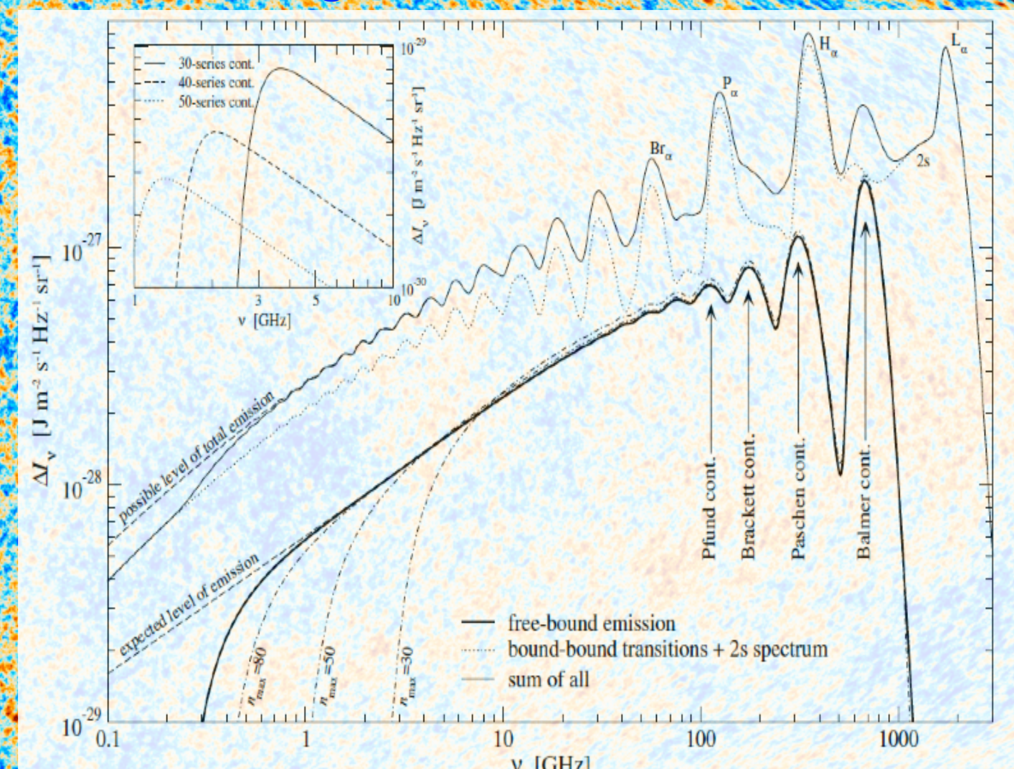
Cosmic Microwave Background and Spectral Distortions III:

Distortions for different scenarios and what we may learn from them

Primordial Distortions



Cosmological Recombination lines



Jens Chluba

MANCHESTER 1824

The University of Manchester

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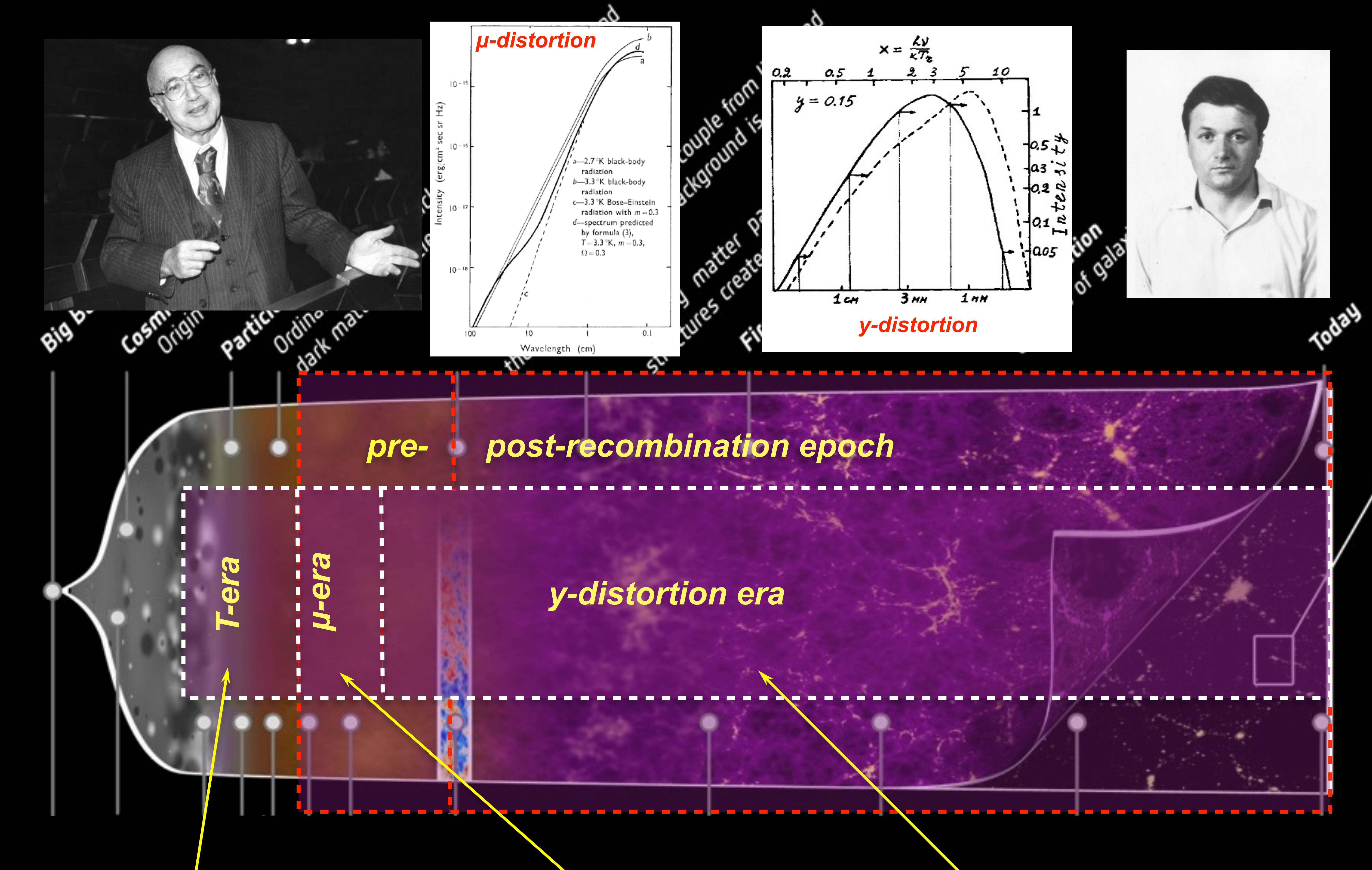
THE ROYAL SOCIETY

ICCUB School: "Hot Topics in Cosmology"

Barcelona, Spain, Oct. 23rd-26th, 2017

** CMB ≙ Cosmic Microwave Background*

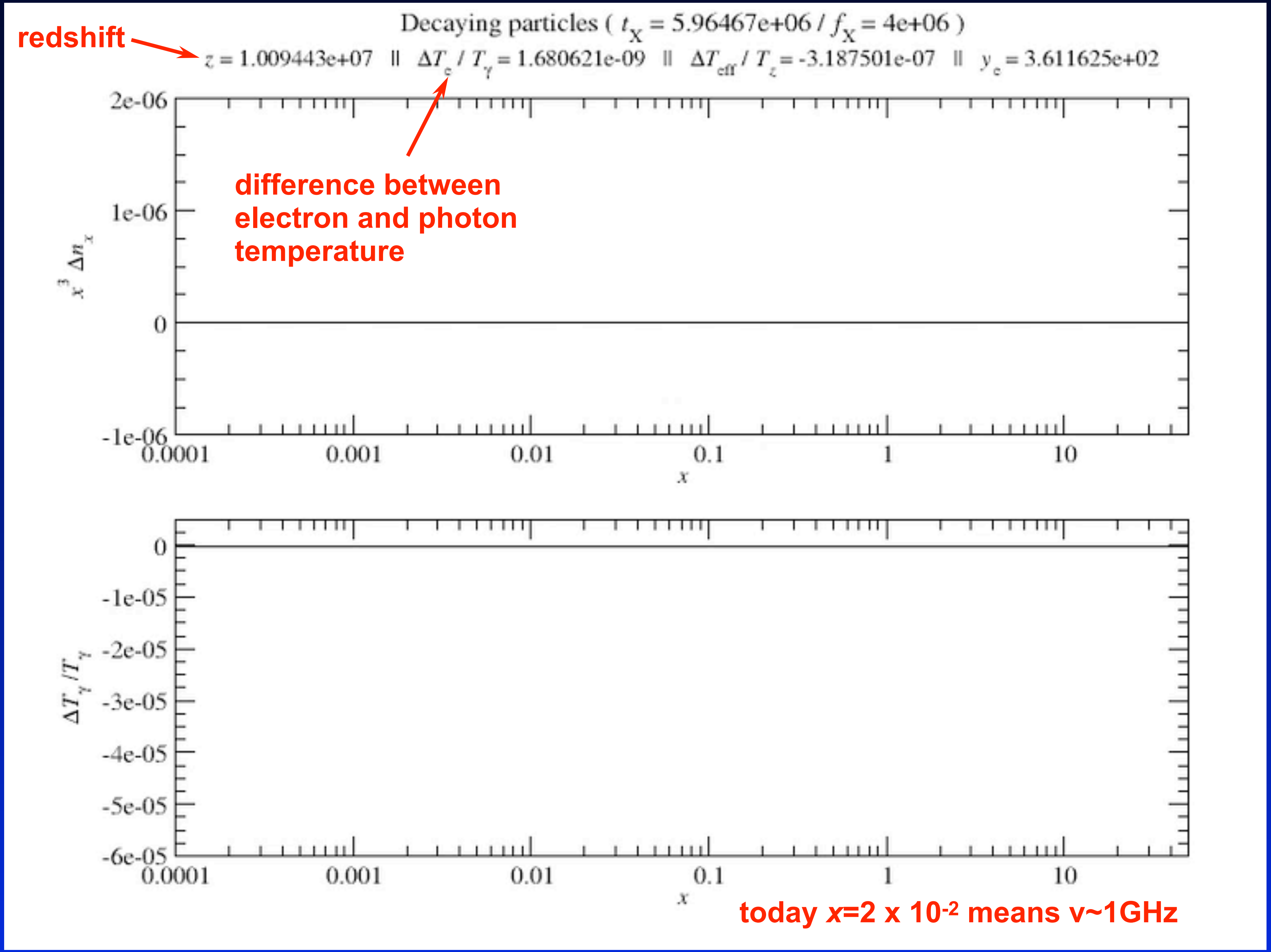


$$\frac{\Delta T}{T} \simeq \frac{1}{4} \left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_T$$

$$\mu \simeq 1.4 \left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_\mu$$

$$y \simeq \frac{1}{4} \left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_y$$

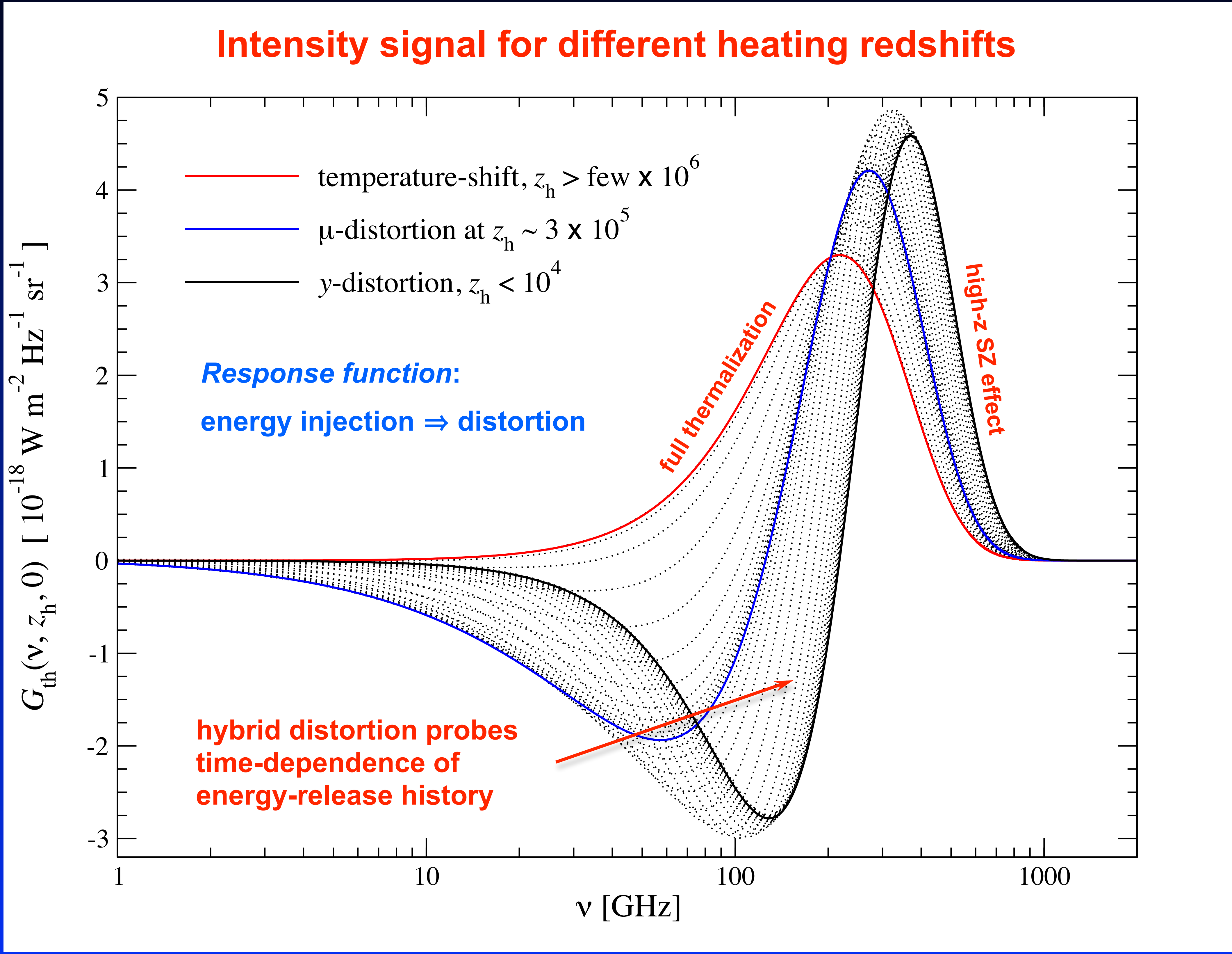
Example: *Energy release by decaying relict particle*



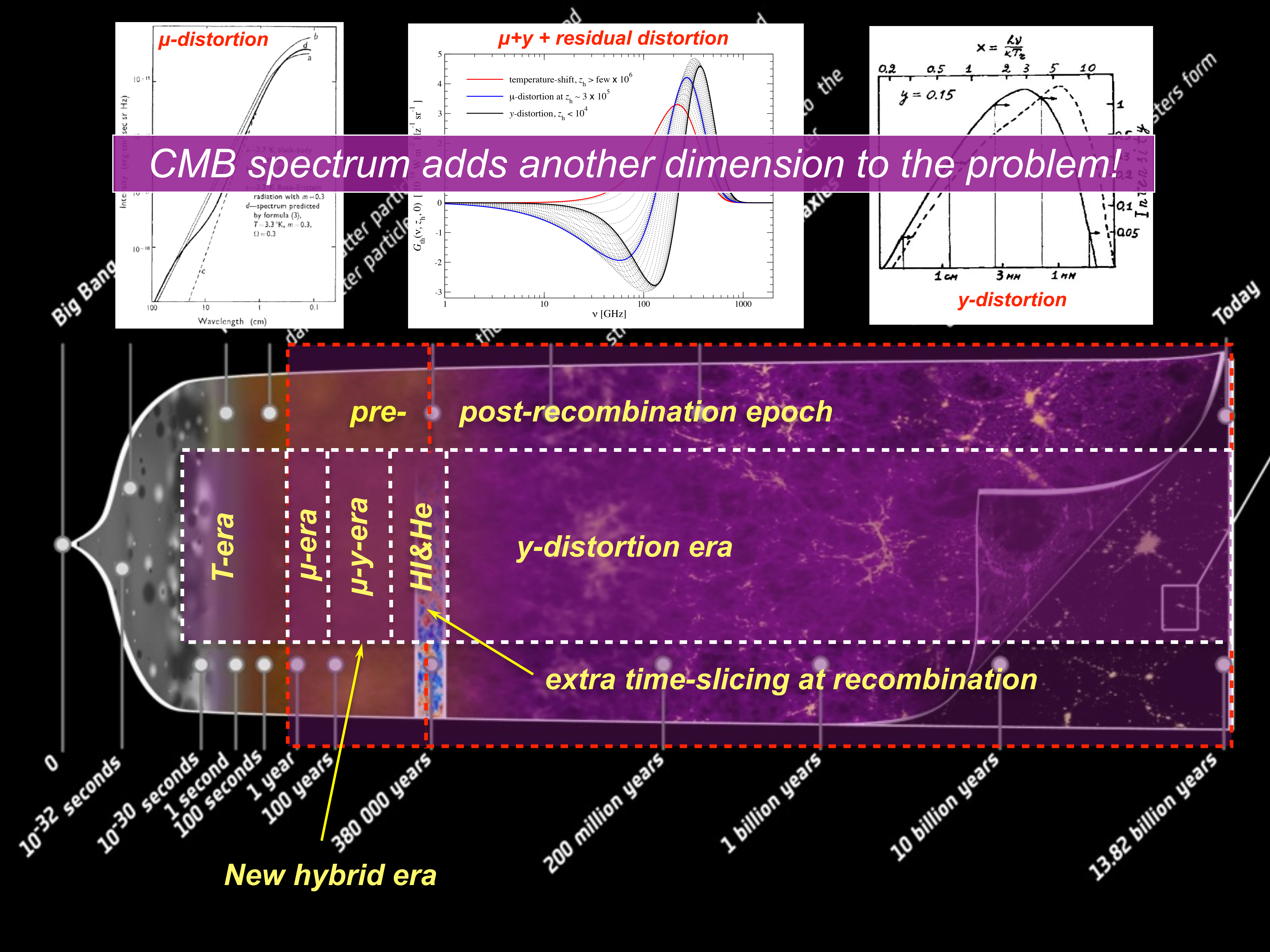
- initial condition: *full equilibrium*
- total energy release: $\Delta\rho/\rho \sim 1.3 \times 10^{-6}$
- most of energy released around: $z_X \sim 2 \times 10^6$
- positive μ-distortion
- high frequency distortion frozen around $z \simeq 5 \times 10^5$
- late ($z<10^3$) free-free absorption at very low frequencies ($T_e < T_\gamma$)

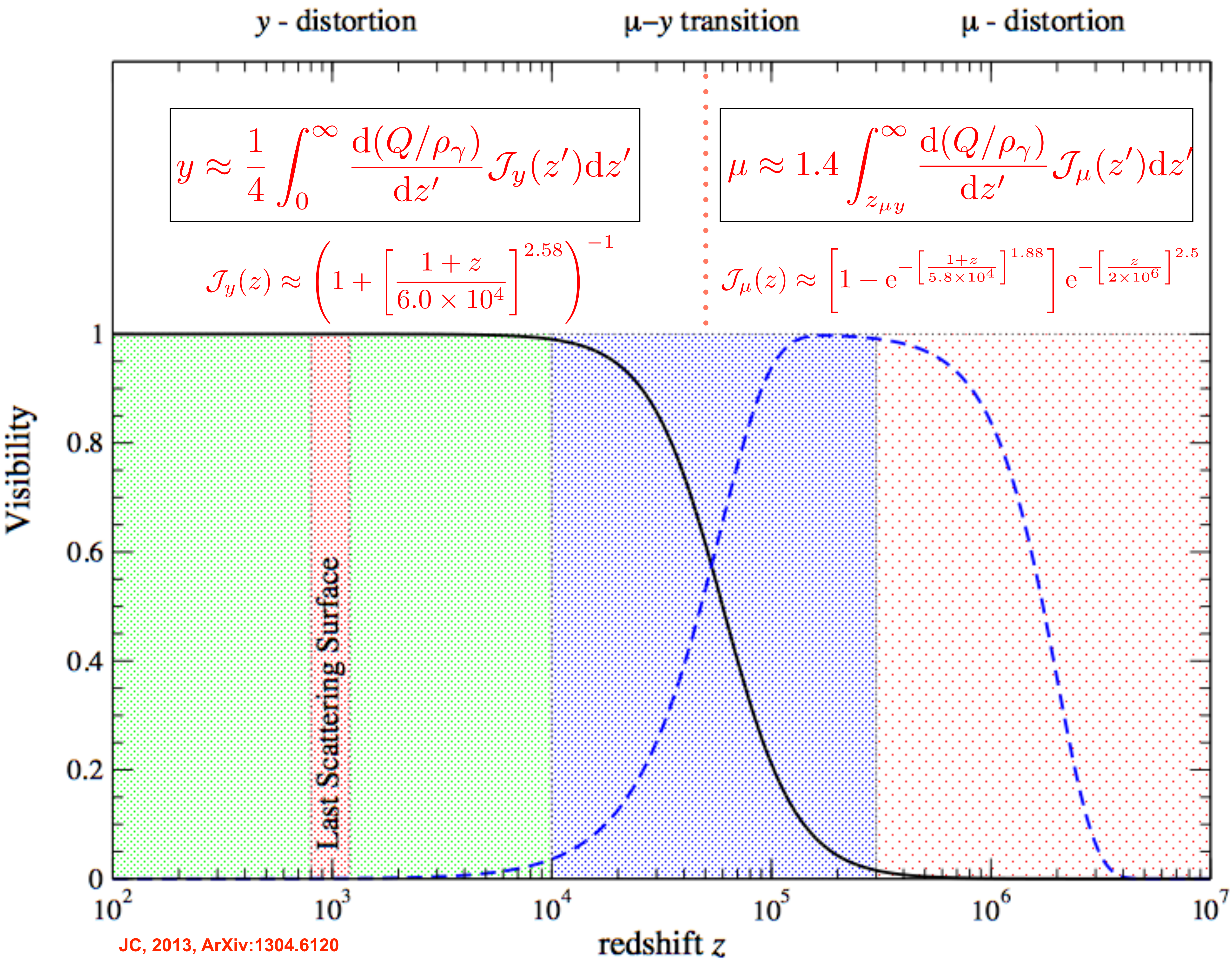
Computation carried out with *CosmoTherm* (JC & Sunyaev 2012)

What does the spectrum look like after energy injection?



JC & Sunyaev, 2012, ArXiv:1109.6552
JC, 2013, ArXiv:1304.6120


CMB spectrum adds another dimension to the problem!
μ-distortion
μ+y + residual distortion
temperature-shift, z_h > few x 10^6
μ-distortion at z_h ~ 3 x 10^5
y-distortion, z_h < 10^4
ν [GHz]
Wavelength (cm)
y-distortion
y = 0.15
Big Bang
Today
pre-
post-recombination epoch
T-era
μ-era
μ-y-era
HI&He
y-distortion era
extra time-slicing at recombination
New hybrid era
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years



y - distortion
μ–y transition
μ - distortion
$y \approx \frac{1}{4}\int_0^\infty \frac{d(Q/\rho_\gamma)}{dz'}\mathcal{J}_y(z')dz'$
$\mathcal{J}_y(z) \approx \left(1+\left[\frac{1+z}{6.0\times10^4}\right]^{2.58}\right)^{-1}$
$\mu \approx 1.4\int_{z_{\mu y}}^\infty \frac{d(Q/\rho_\gamma)}{dz'}\mathcal{J}_\mu(z')dz'$
$\mathcal{J}_\mu(z) \approx \left[1-e^{-\left[\frac{1+z}{5.8\times10^4}\right]^{1.88}}\right]e^{-\left[\frac{z}{2\times10^6}\right]^{2.5}}$
Visibility
Last Scattering Surface
redshift z
JC, 2013, ArXiv:1304.6120

Part III: Distortions for different scenarios and what we may learn by studying them

Physical mechanisms that lead to spectral distortions

Standard sources of distortions

- *Cooling by adiabatically expanding ordinary matter*
  (JC, 2005; JC & Sunyaev 2011; Khatri, Sunyaev & JC, 2011)
- Heating by *decaying* or *annihilating* relic particles
  (Kawasaki et al., 1987; Hu & Silk, 1993; McDonald et al., 2001; JC, 2005; JC & Sunyaev, 2011; JC, 2013; JC & Jeong, 2013)
- *Evaporation of primordial black holes & superconducting strings*
  (Carr et al. 2010; Ostriker & Thompson, 1987; Tashiro et al. 2012; Pani & Loeb, 2013)
- *Dissipation of primordial acoustic modes & magnetic fields*
  (Sunyaev & Zeldovich, 1970; Daly 1991; Hu et al. 1994; JC & Sunyaev, 2011; JC et al. 2012 - Jedamzik et al. 2000; Kunze & Komatsu, 2013)
- *Cosmological recombination radiation*
  (Zeldovich et al., 1968; Peebles, 1968; Dubrovich, 1977; Rubino-Martin et al., 2006; JC & Sunyaev, 2006; Sunyaev & JC, 2009)

pre-recombination epoch

„high“ redshifts

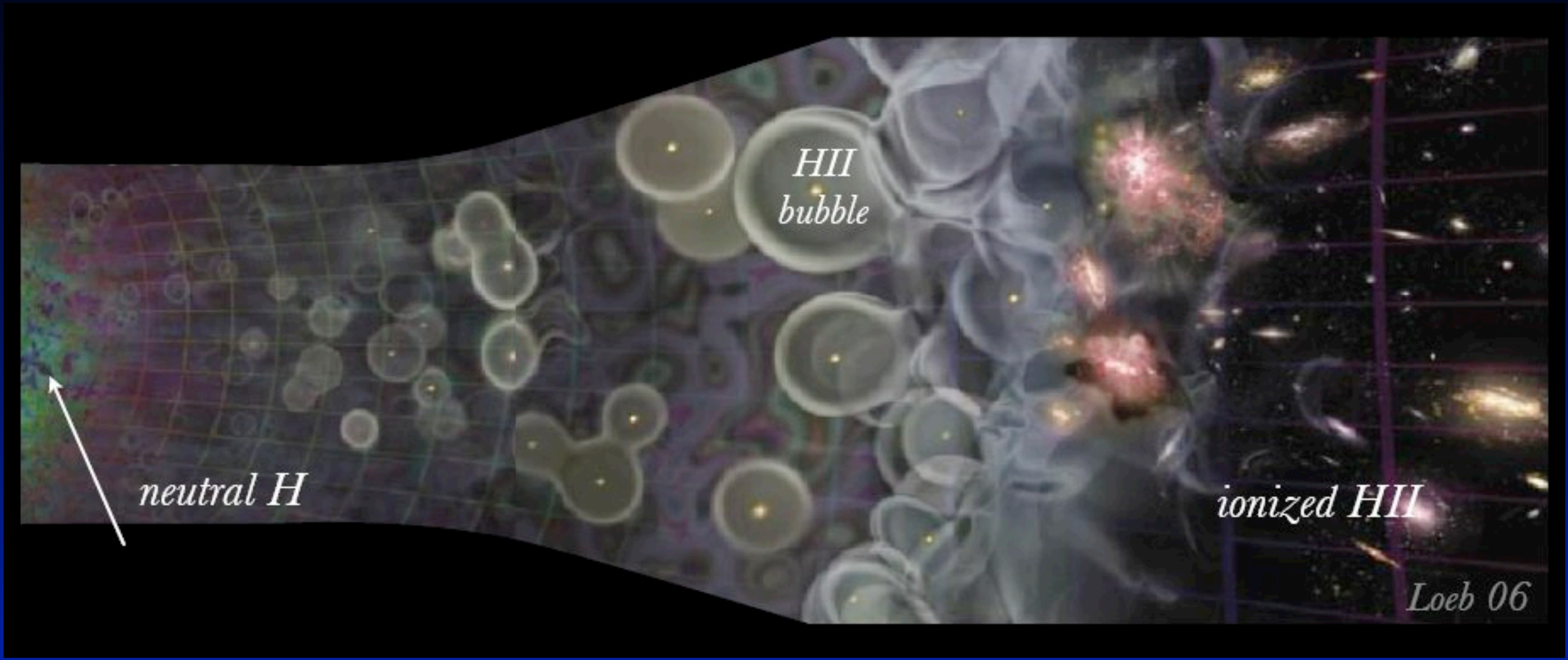
„low“ redshifts

post-recombination

- Signatures due to first supernovae and their remnants
  (Oh, Cooray & Kamionkowski, 2003)
- Shock waves arising due to large-scale structure formation
  (Sunyaev & Zeldovich, 1972; Cen & Ostriker, 1999)
- SZ-effect from clusters; effects of reionization
  (Refregier et al., 2003; Zhang et al. 2004; Trac et al. 2008)
- Additional exotic processes
  (Lochan et al. 2012; Bull & Kamionkowski, 2013; Brax et al., 2013; Tashiro et al. 2013)

Reionization and structure formation

Simple estimates for the distortion

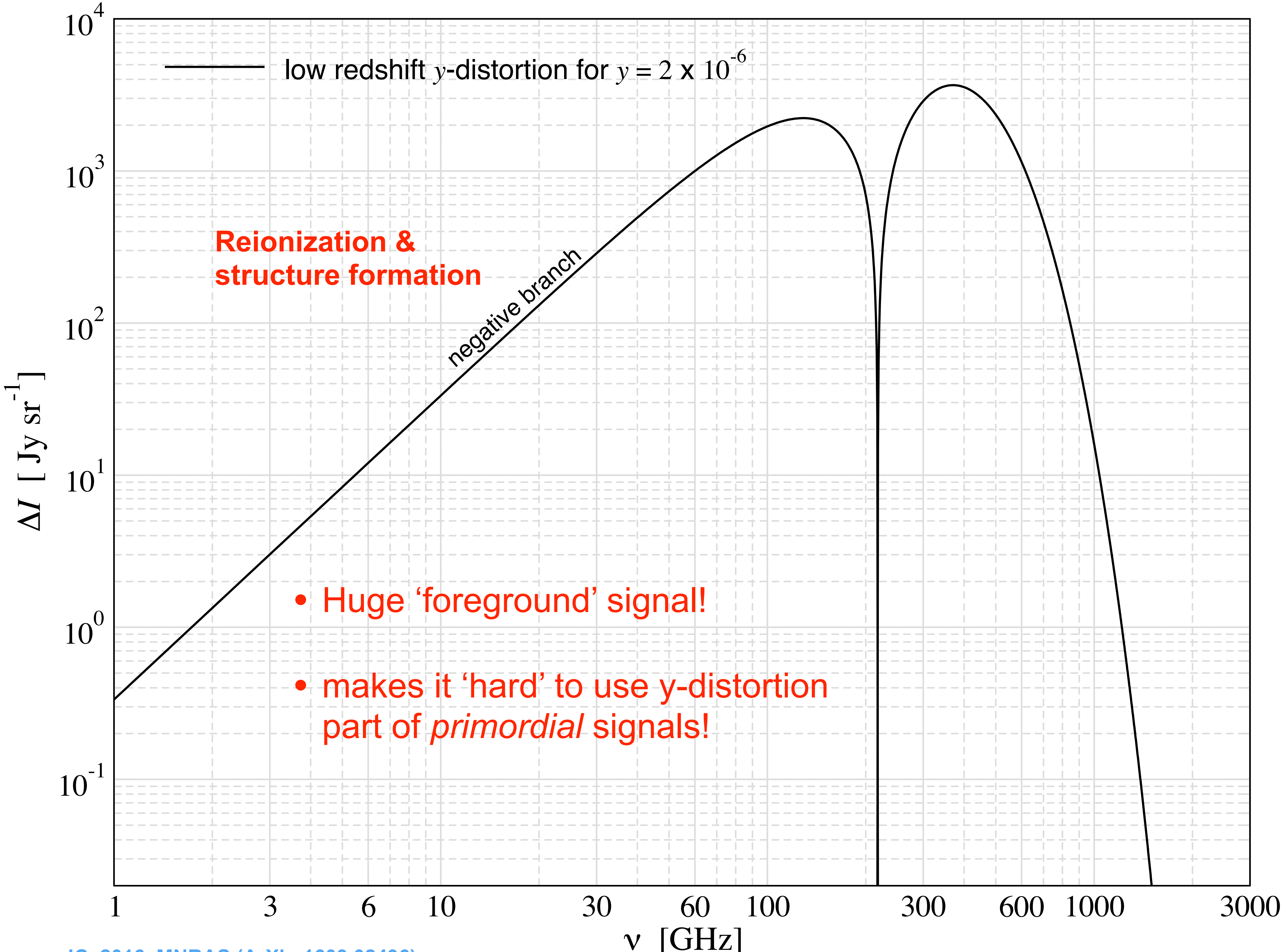


- Gas temperature $T \simeq 10^4$ K
- Thomson optical depth $\tau \simeq 0.1$

$$\Longrightarrow \quad y \simeq \frac{kT_e}{m_e c^2}\tau \approx 2 \times 10^{-7}$$

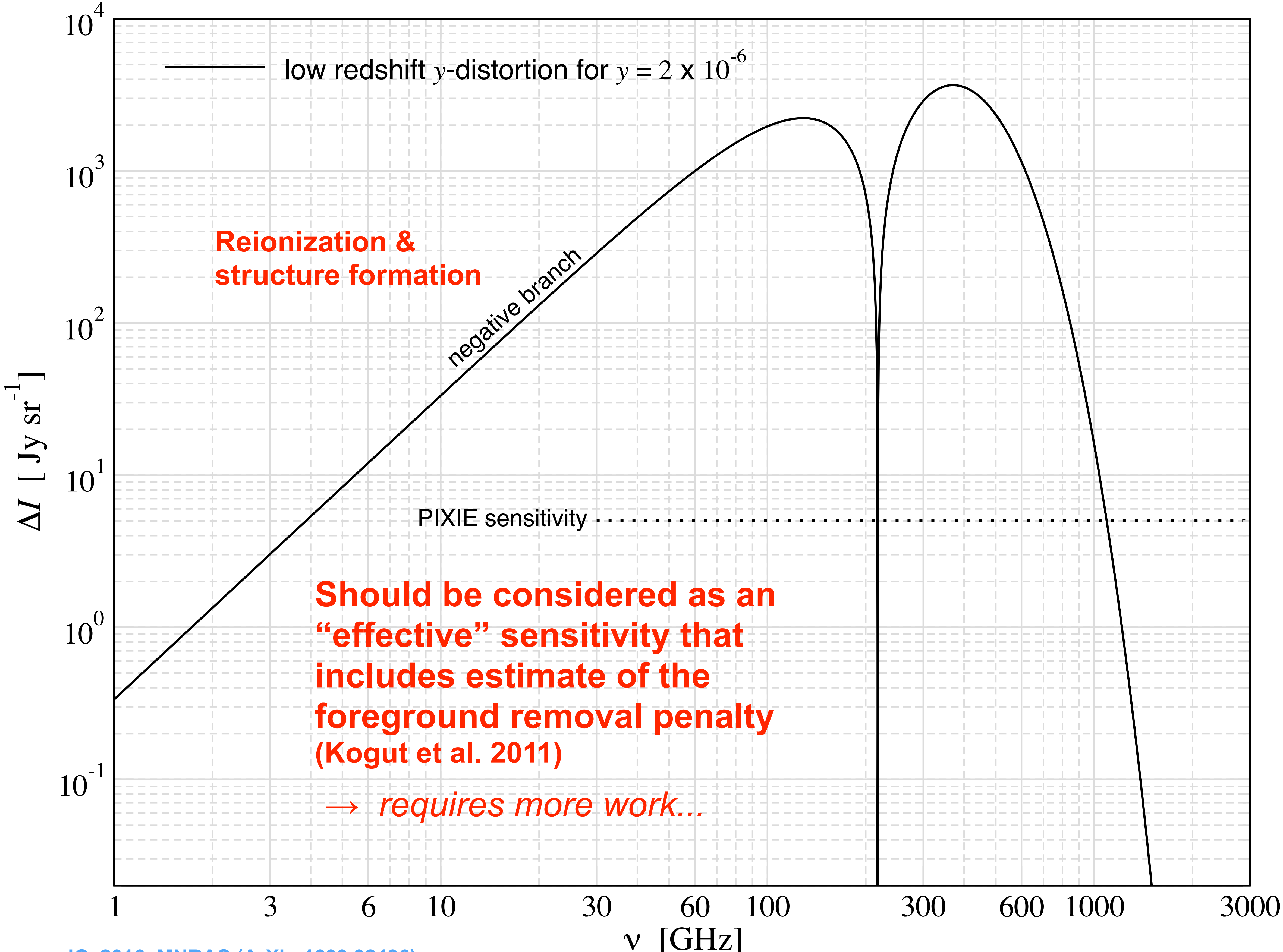
- second order Doppler effect $y \simeq$ few x 10^{-8} (e.g., Hu, Scott & Silk, 1994)
- structure formation / SZ effect (e.g., Refregier et al., 2003) $y \simeq$ few x 10^{-7}-10^{-6}

Average CMB spectral distortions



JC, 2016, MNRAS (ArXiv:1603.02496)

Average CMB spectral distortions



JC, 2016, MNRAS (ArXiv:1603.02496)

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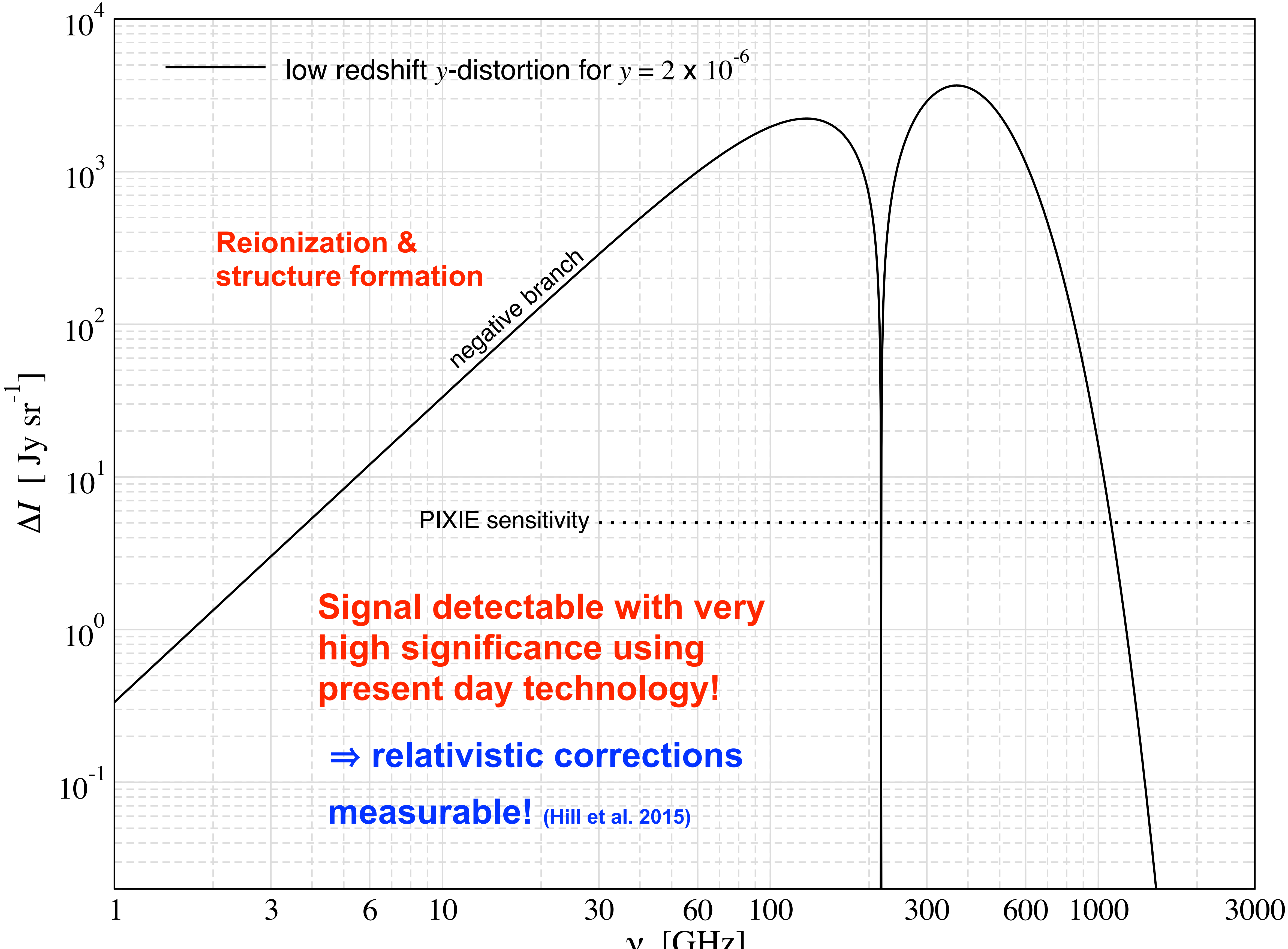

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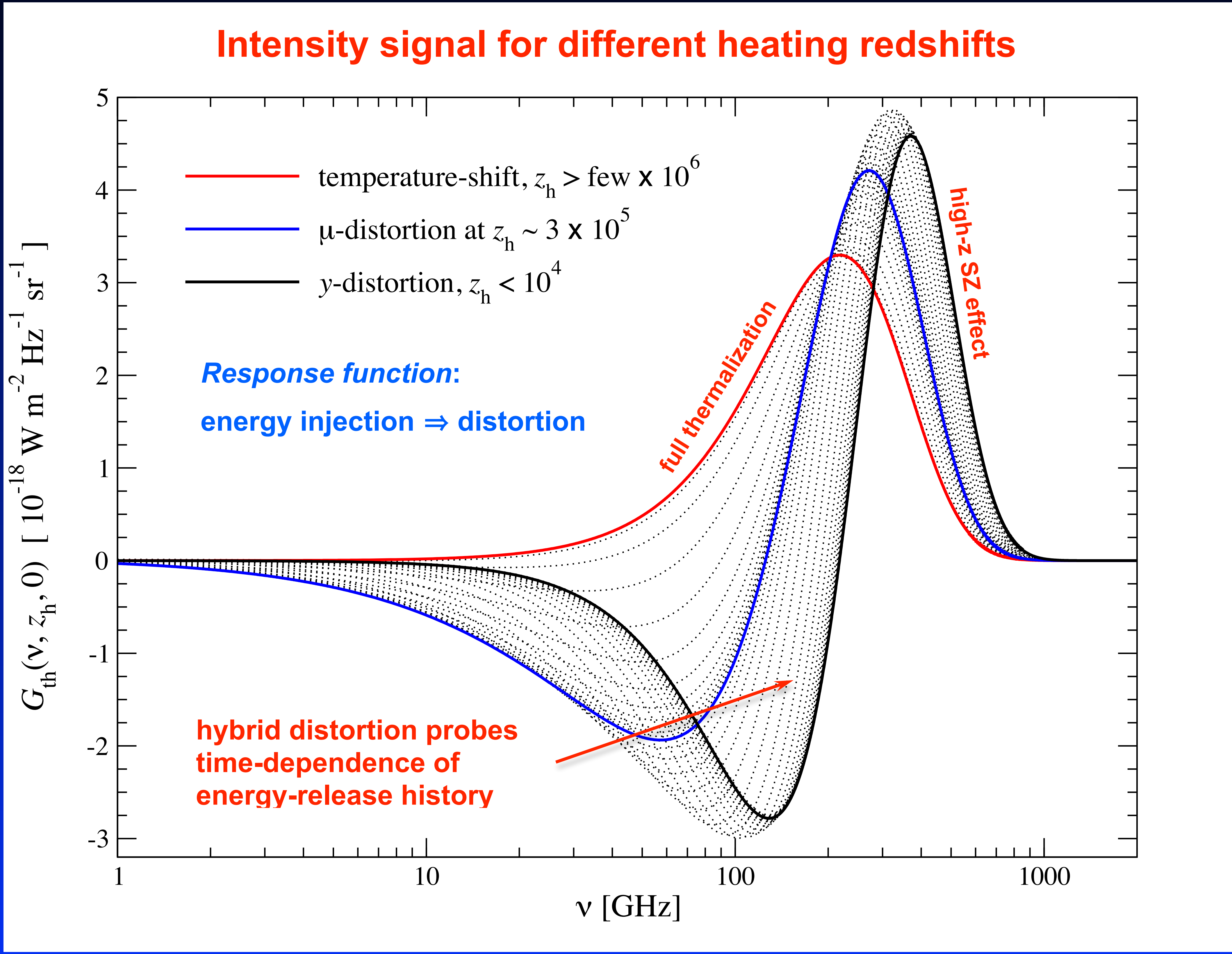

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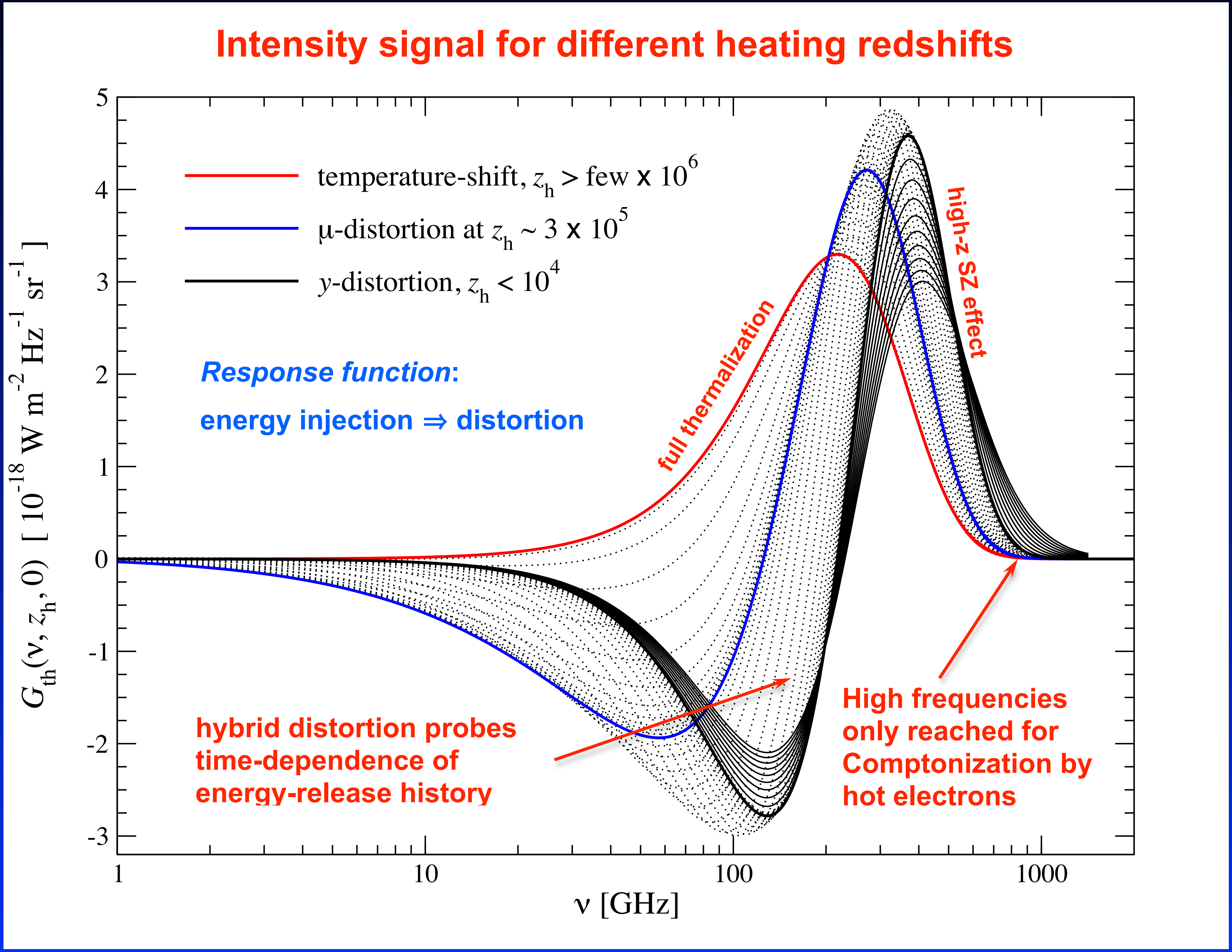

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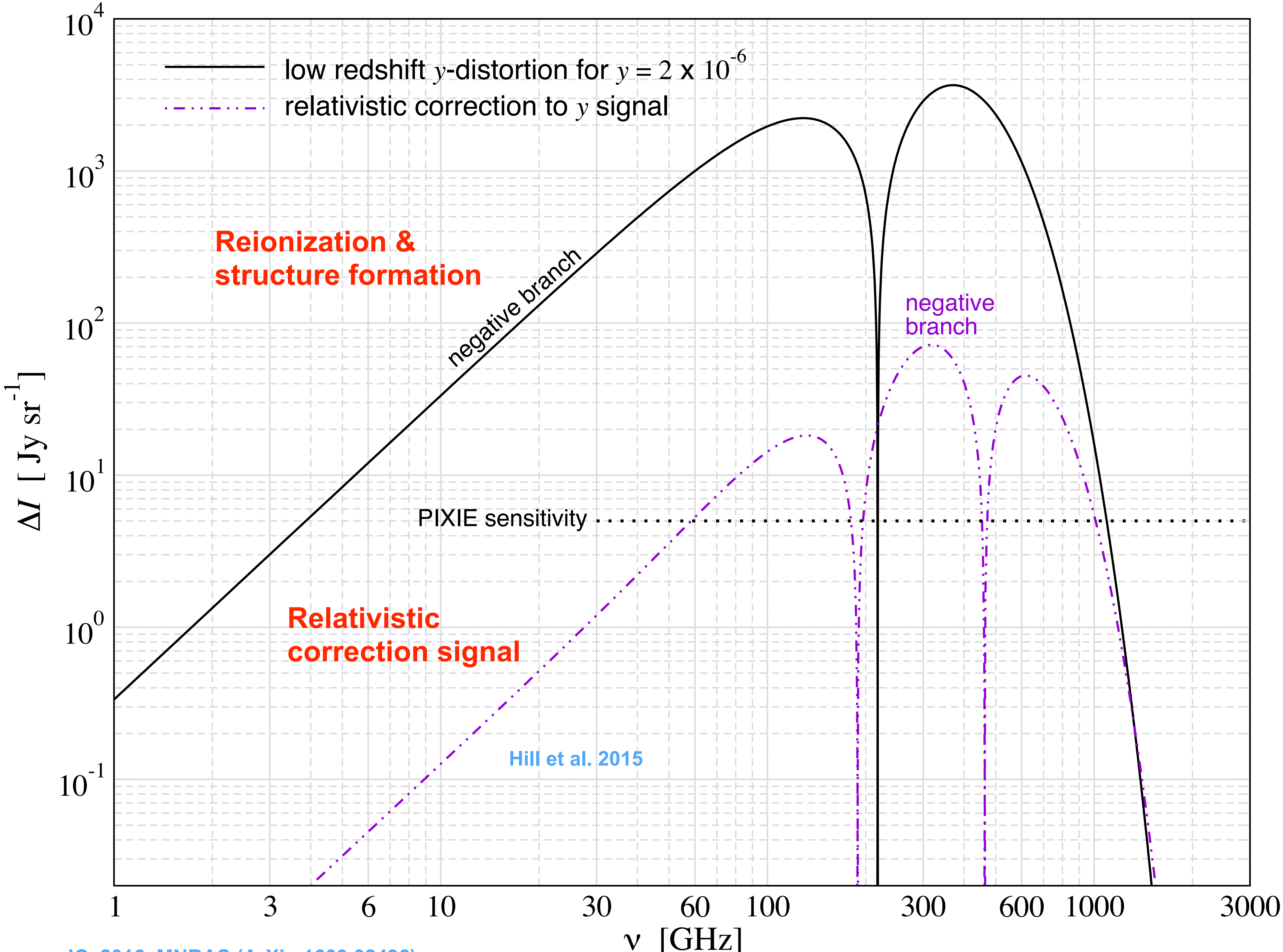
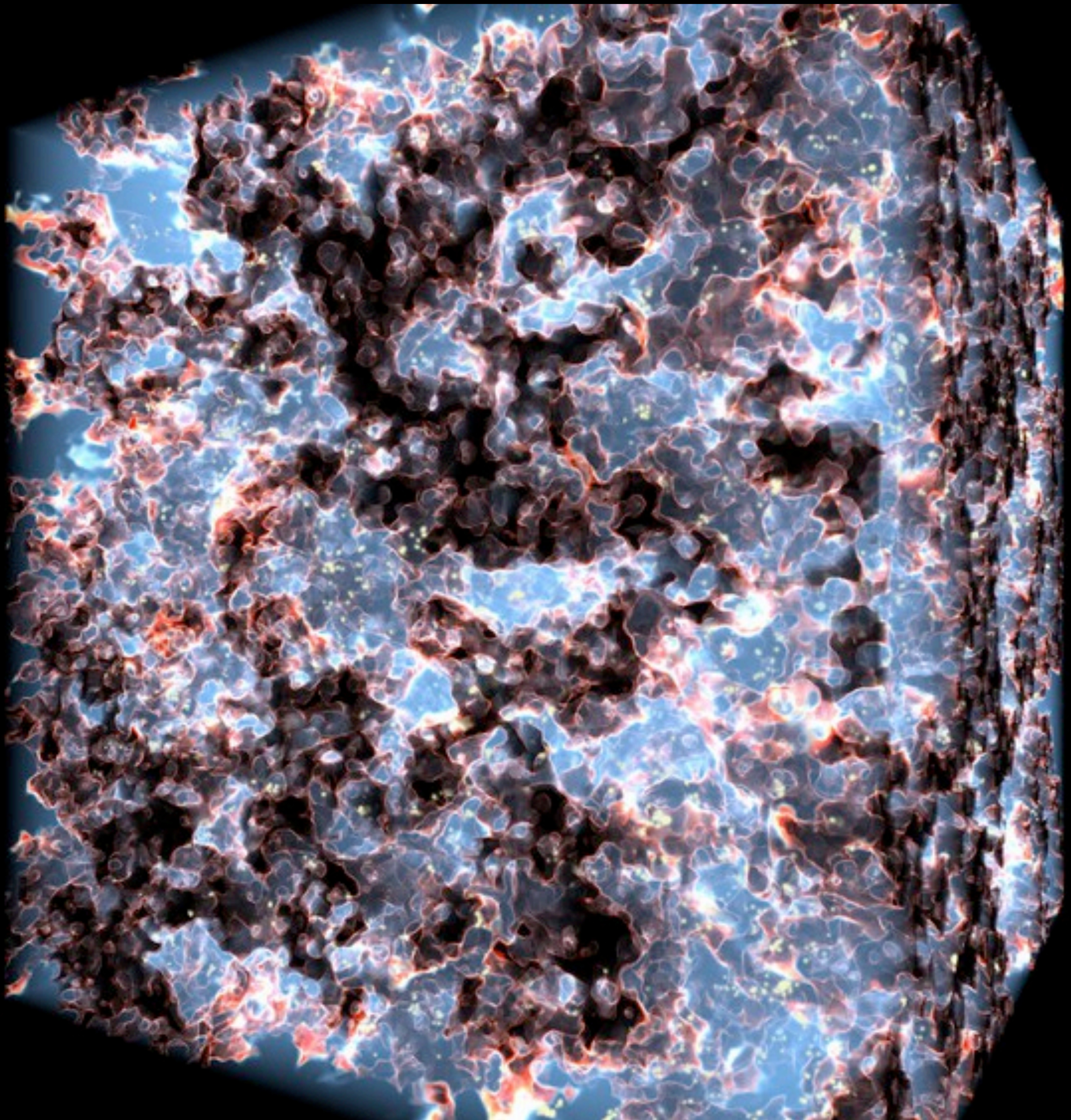


JC, 2016, MNRAS (ArXiv:1603.02496)

Fluctuations of the y-parameter at large scales

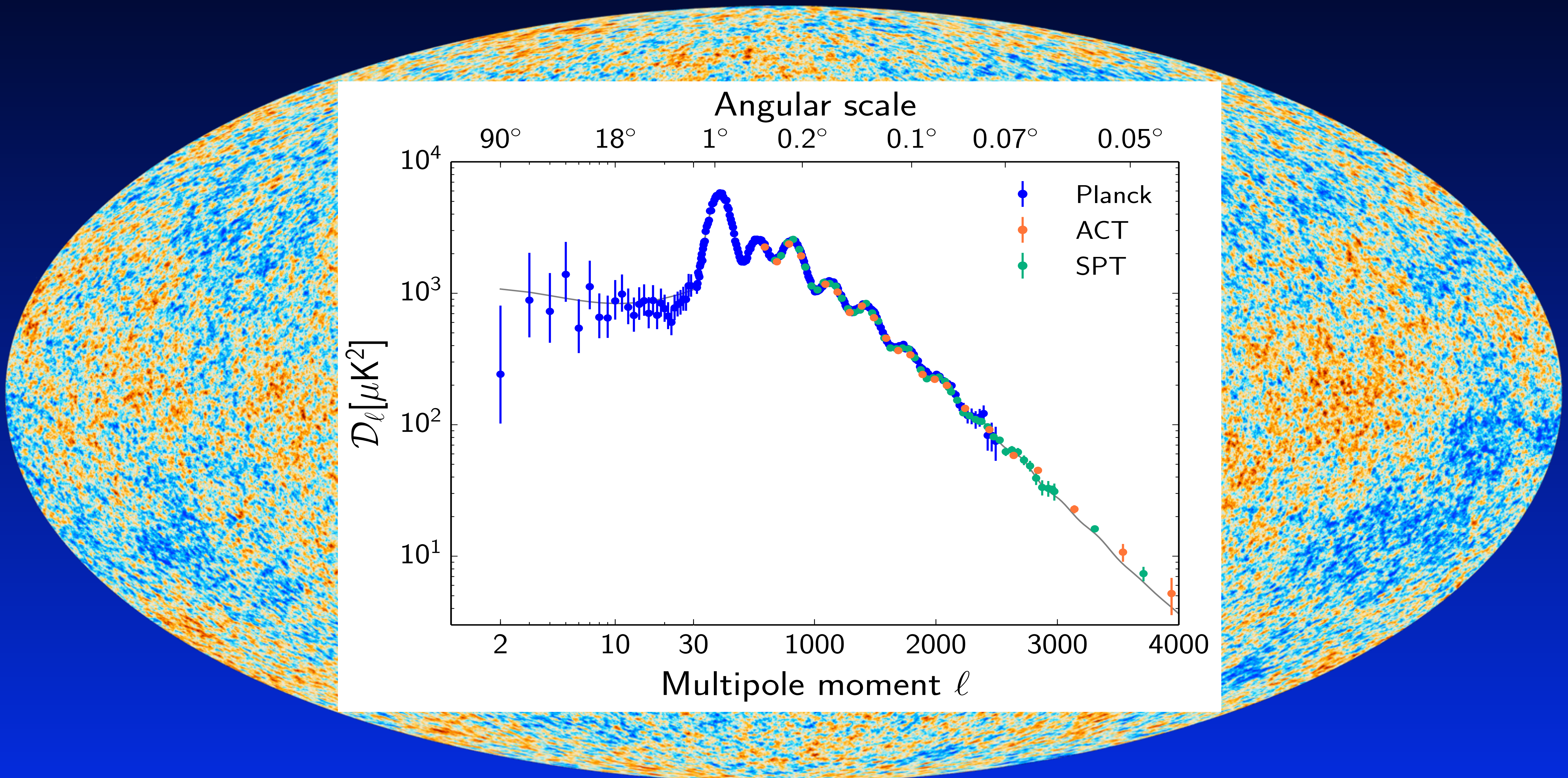


- spatial variations of the optical depth and temperature cause small-spatial variations of the y-parameter at different angular scales
- could tell us about the reionization sources and structure formation process
- additional independent piece of information!
- Cross-correlations

Example:
Simulation of reionization process (1Gpc/h) by *Alvarez* & *Abel*

The dissipation of small-scale acoustic modes

Dissipation of small-scale acoustic modes



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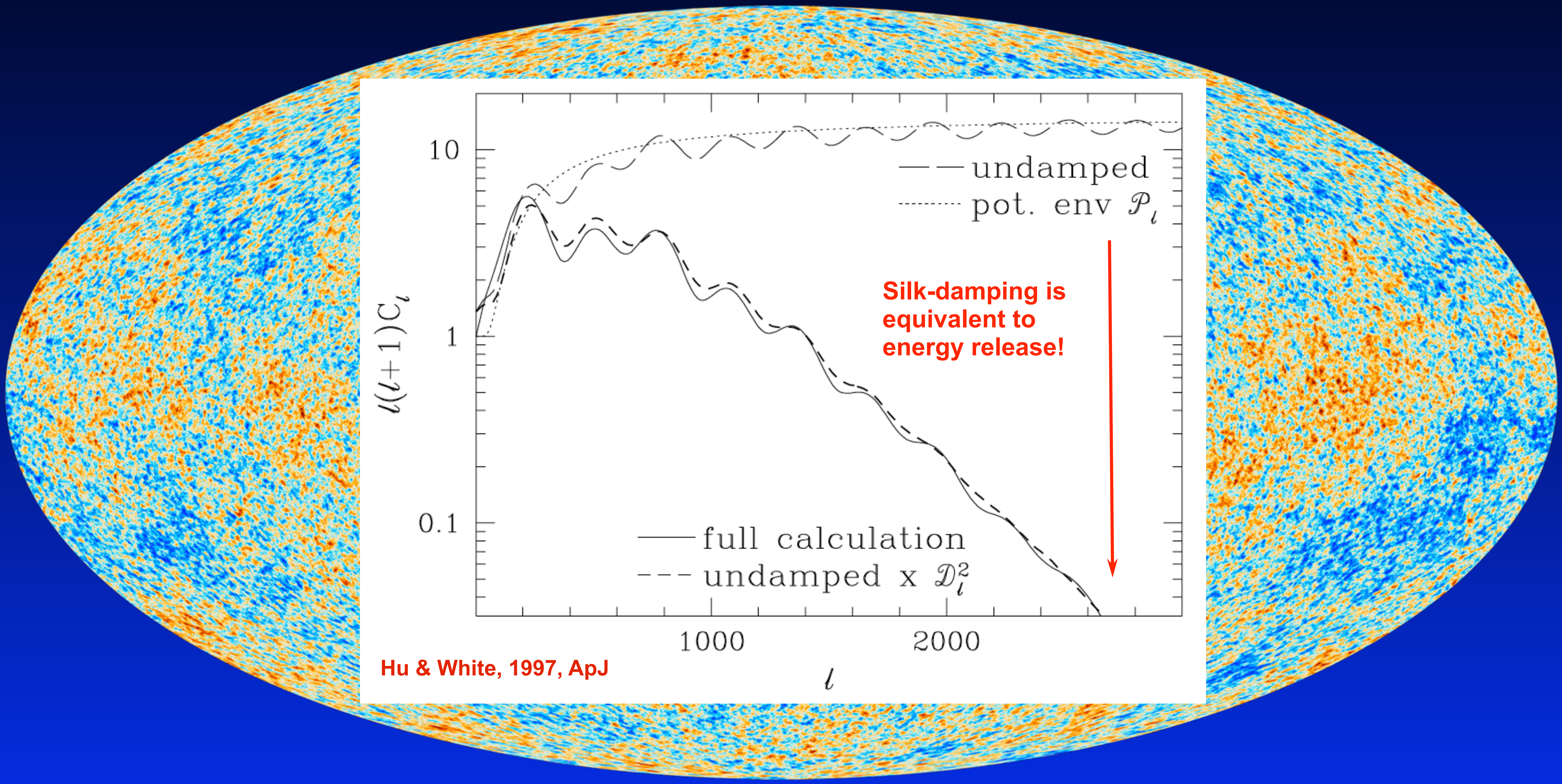


Energy release caused by dissipation process

'Obvious' dependencies:

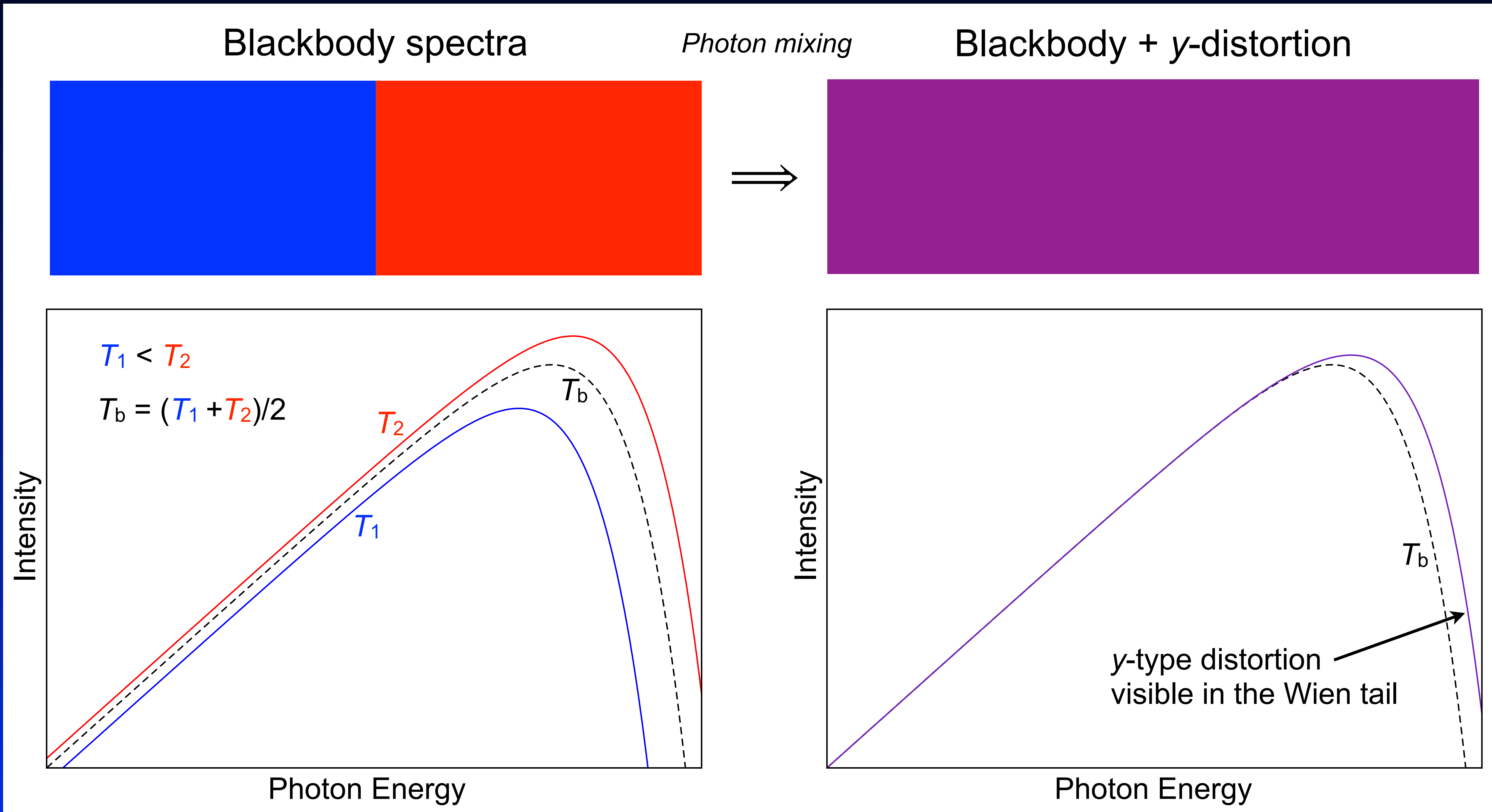
- *Amplitude* of the small-scale power spectrum
- *Shape* of the small-scale power spectrum
- *Dissipation scale* → $k_D \sim (H_0\, \Omega_{rel}^{1/2}\, N_{e,0})^{1/2}\, (1+z)^{3/2}$ at early times

not so 'obvious' dependencies:

- *primordial non-Gaussianity* in the ultra squeezed limit
  (Pajer & Zaldarriaga, 2012; Ganc & Komatsu, 2012)
- *Type* of the perturbations (adiabatic ↔ isocurvature)
  (Barrow & Coles, 1991; Hu et al., 1994; Dent et al, 2012, JC & Grin, 2012)
- *Neutrinos* (or any extra relativistic degree of freedom)

CMB Spectral distortions could add additional numbers beyond 'just' the tensor-to-scalar ratio from B-modes!

Distortion due to mixing of blackbodies



JC, Hamann & Patil, 2015

Classical derivation for the heating rate

Dissipation of acoustic modes: ‘classical treatment’

- energy stored in plane sound waves

  Landau & Lifshitz, ‘Fluid Mechanics‘, § 65 ⇒ $Q \sim c_s^2 \, \rho \, (\delta\rho/\rho)^2$

- expression for normal ideal gas where ρ is ‘*mass density*’ and c_s denotes ‘*sounds speed*’

- photon-baryon fluid with baryon loading $R << 1$

  $(c_s/c)^2 = [\, 3\,(1+R)\,]^{-1} \sim 1/3$

  $\rho \rightarrow \rho_\gamma = a_R \, T^4$

  $\delta\rho/\rho \rightarrow 4(\delta T_0/T) \equiv 4\Theta_0$ ← **only perturbation of the monopole accounted for**

Sunyaev & Zeldovich, 1970
Hu, Scott & Silk, 1994, ApJ

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- expression for normal ideal gas where ρ is '*mass density*' and c_s denotes '*sounds speed*'

- photon-baryon fluid with baryon loading $R \ll 1$

$(c_s/c)^2 = [\,3\,(1+R)\,]^{-1} \sim 1/3$

$\rho \rightarrow \rho_\gamma = a_R\, T^4$

$\delta\rho/\rho \rightarrow 4(\delta T_0/T) \equiv 4\Theta_0$

$$\Rightarrow \quad (a^4\rho_\gamma)^{-1}\, \mathrm{d}a^4 Q_{ac}/\mathrm{d}t = -16/3\, \mathrm{d}\langle\Theta_0^2\rangle/\mathrm{d}t$$

'minus' because *decrease* of Θ at small scales means *increase* for average spectrum

can be calculated using first order perturbation theory

Sunyaev & Zeldovich, 1970
Hu, Scott & Silk, 1994, ApJ

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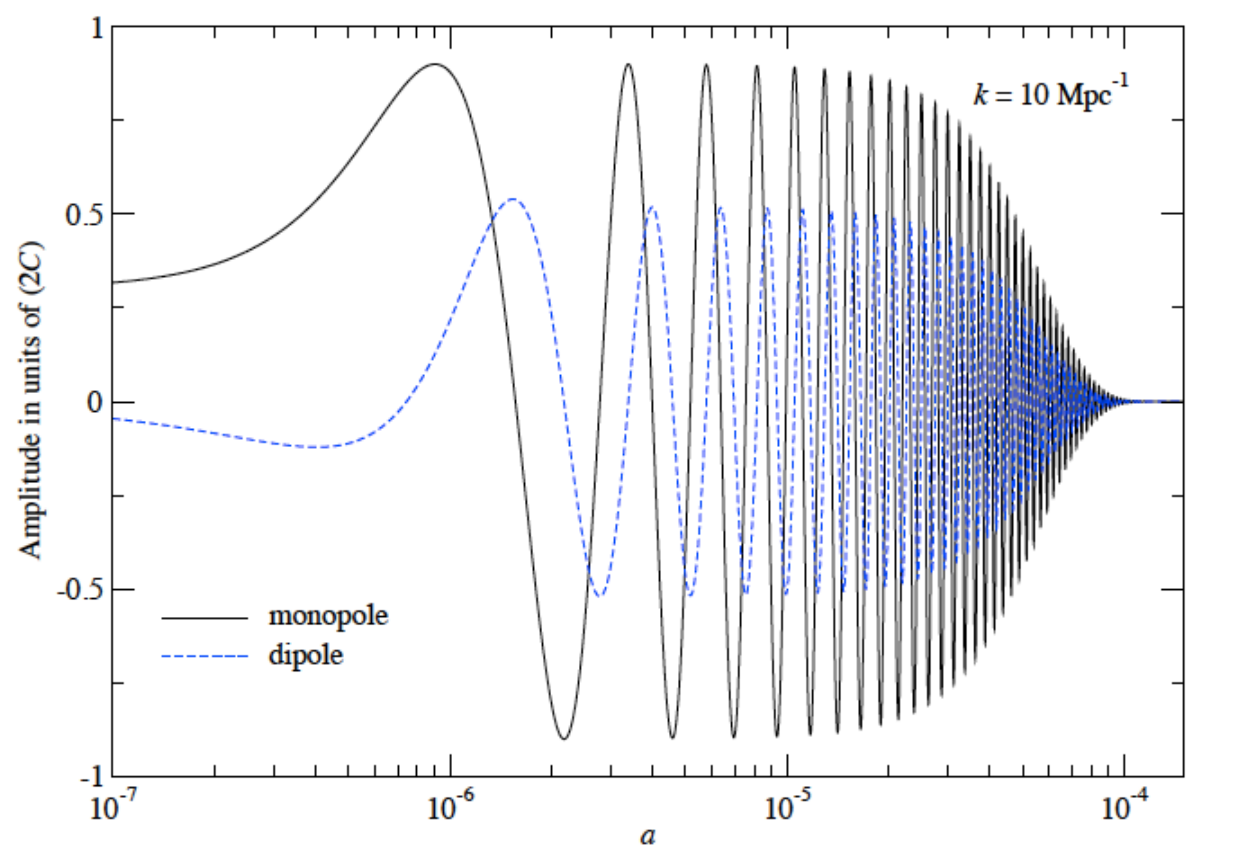

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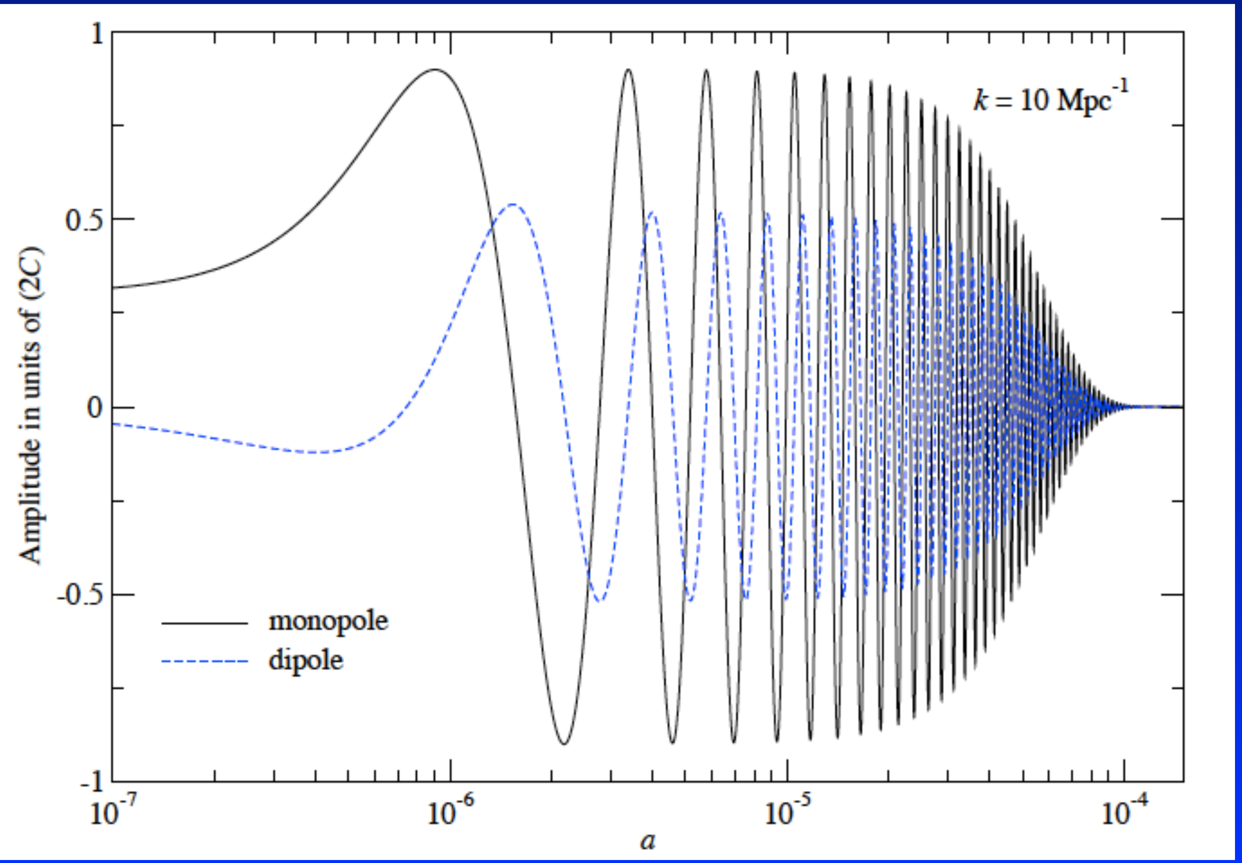
$\delta\rho/\rho \rightarrow 4(\delta T_0/T) \equiv 4\Theta_0$

- Simple estimate does *not* capture all the physics of the problem:
  (JC, Khatri & Sunyaev, 2012)
  - *total energy release is 9/4 ~ 2.25 times larger!*
  - *only 1/3 of the released energy goes into distortions*



Sunyaev & Zeldovich, 1970
Hu, Scott & Silk, 1994, ApJ

Early power spectrum constraints from FIRAS

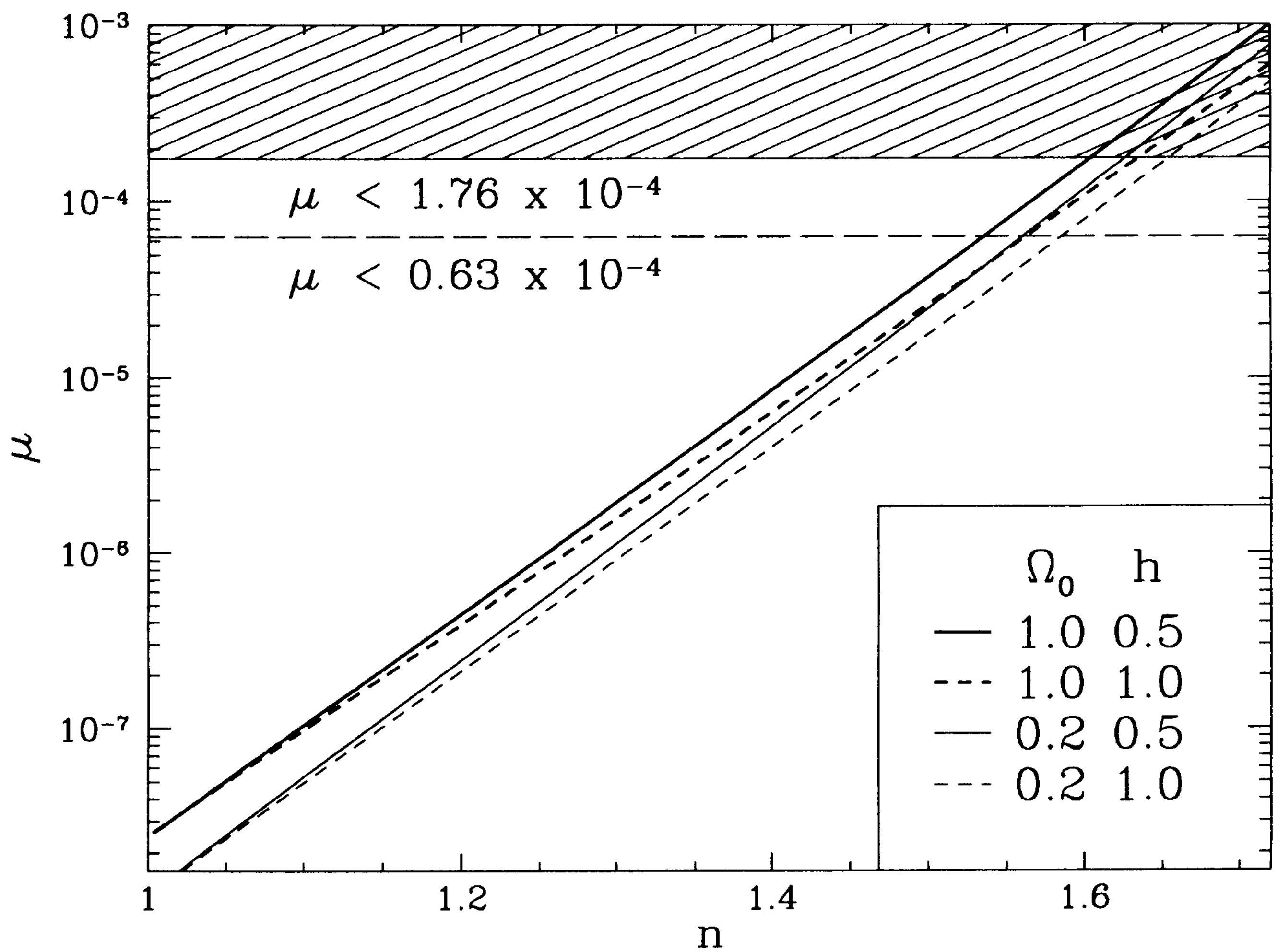


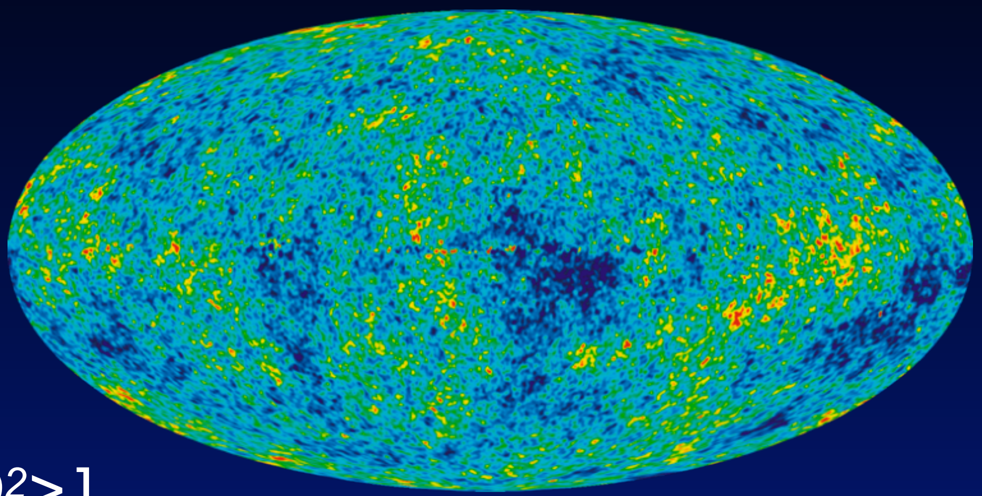
FIG. 1.—Spectral distortion μ, predicted from the full eq. (11), as a function of the power index n for a normalization at the mean of the *COBE* DMR detection $(\Delta T/T)_{10°} = 1.12 \times 10^{-5}$. With the uncertainties on *both* the DMR and FIRAS measurements, the conservative 95% upper limit is effectively $\mu < 1.76 \times 10^{-4}$ (see text). The corresponding constraint on n is relatively weakly dependent on cosmological parameters: $n < 1.60$ ($h = 0.5$) and $n < 1.63$ ($h = 1.0$) for $\Omega_0 = 1$ and quite similar for $0.2 < \Omega_0 = 1 - \Omega_\Lambda < 1$ universes. These limits are nearly independent of Ω_B. We have also plotted the optimistic 95% upper limit on $\mu < 0.63 \times 10^{-4}$ for comparison as discussed in the text.

- based on classical estimate for heating rate
- Tightest / cleanest constraint at that point!
- simple power-law spectrum assumed
- *μ~10^{-8} for scale-invariant power spectrum*
- $n_S \lesssim 1.6$

Hu, Scott & Silk, 1994

Dissipation of acoustic modes: 'microscopic picture'

- after inflation: photon field has spatially varying temperature T
- average energy stored in photon field at any given moment



E.g., our snapshot at z=0

$$\langle \rho_\gamma \rangle = a_R \langle T^4 \rangle \approx a_R \langle T \rangle^4 \, [1 + 4\langle\Theta\rangle + 6\langle\Theta^2\rangle]$$

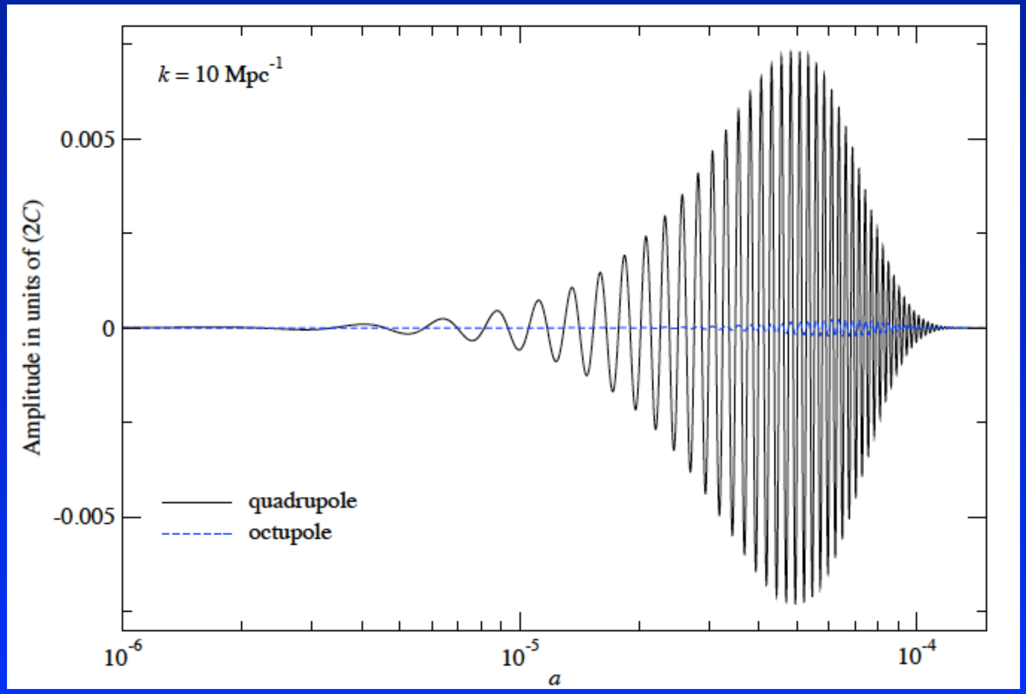
== 0

$$\Rightarrow \quad (a^4\rho_\gamma)^{-1}\, \mathrm{d}a^4 Q_{ac}/\mathrm{d}t = -6\, \mathrm{d}\langle\Theta^2\rangle/\mathrm{d}t$$

- Monopole actually drops out of the equation!
- In principle *all* higher multipoles contribute to the energy release
- At high redshifts ($z \geq 10^4$):
  - *net (gauge-invariant) dipole and contributions from higher multipoles are negligible*
  - *dominant term caused by quadrupole anisotropy*

$$\Rightarrow \quad (a^4\rho_\gamma)^{-1}\, \mathrm{d}a^4 Q_{ac}/\mathrm{d}t \approx -12\, \mathrm{d}\langle\Theta_0^2\rangle/\mathrm{d}t$$

9/4 larger than classical estimate



JC, Khatri & Sunyaev, 2012

Effective energy release caused by damping effect

- Effective heating rate from full 2x2 Boltzmann treatment **(JC, Khatri & Sunyaev, 2012)**

$$\frac{1}{a^4\rho_\gamma}\frac{\mathrm{d}a^4 Q_{\rm ac}}{\mathrm{d}t} = 4\sigma_{\rm T} N_{\rm e} c \left\langle \frac{(3\Theta_1-\beta)^2}{3} + \frac{9}{2}\Theta_2^2 - \frac{1}{2}\Theta_2(\Theta_0^{\rm P}+\Theta_2^{\rm P}) + \sum_{l\geq 3}(2l+1)\Theta_\ell^2 \right\rangle$$

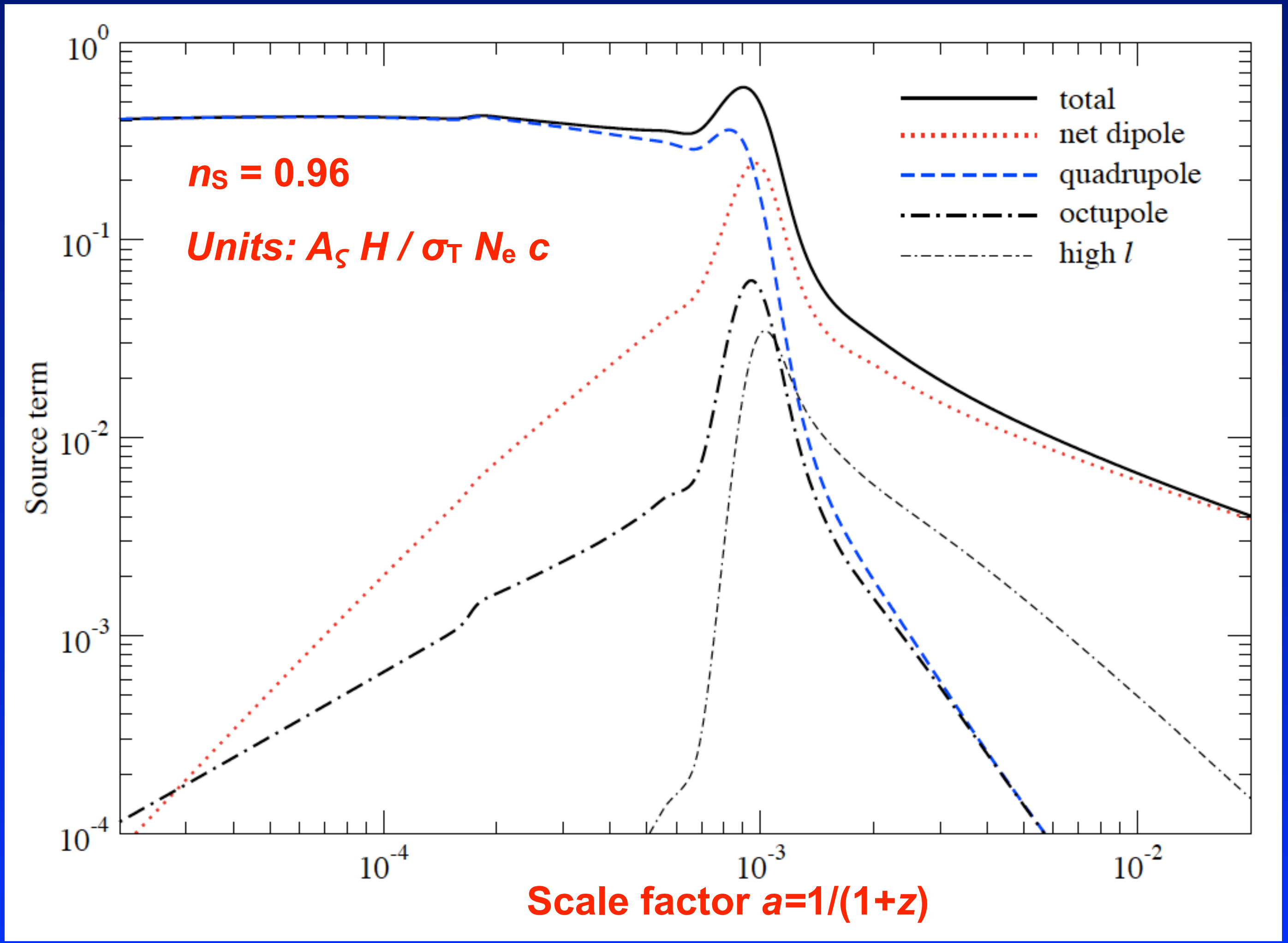
$$\Theta_\ell = \frac{1}{2}\int \Theta(\mu)P_\ell(\mu)\mathrm{d}\mu$$

gauge-independent dipole **effect of polarization** **higher multipoles**

$$\langle XY\rangle = \int \frac{k^2\mathrm{d}k}{2\pi^2}P(k)X(k)Y(k)$$

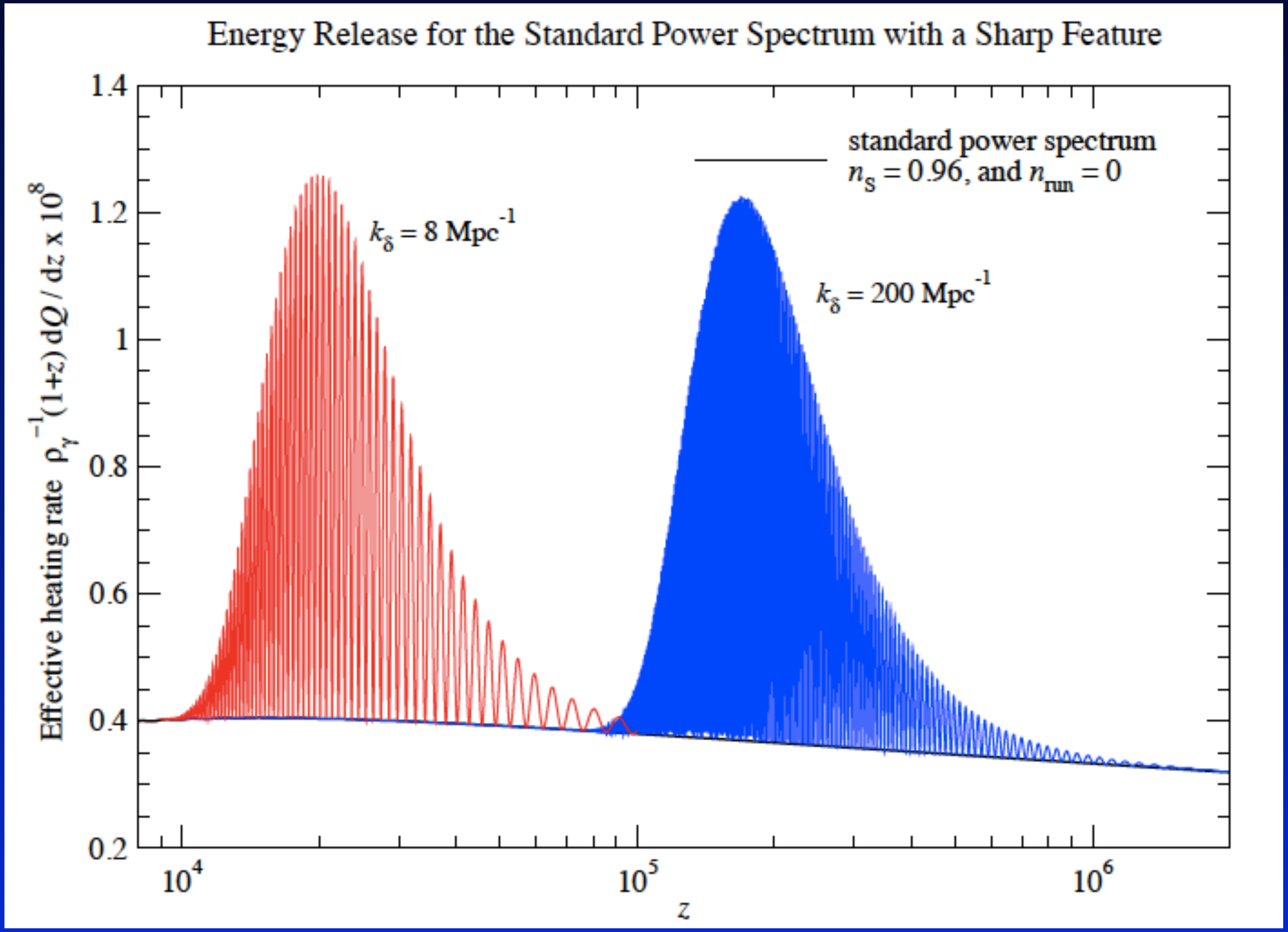
Primordial power spectrum

- *quadrupole* dominant at high *z*
- *net dipole* important only at low redshifts
- polarization ~5% effect
- contribution from higher multipoles rather small



JC, Khatri & Sunyaev, 2012

Which modes dissipate in the μ and y-eras?



JC, Erickcek & Ben-Dayan, 2012

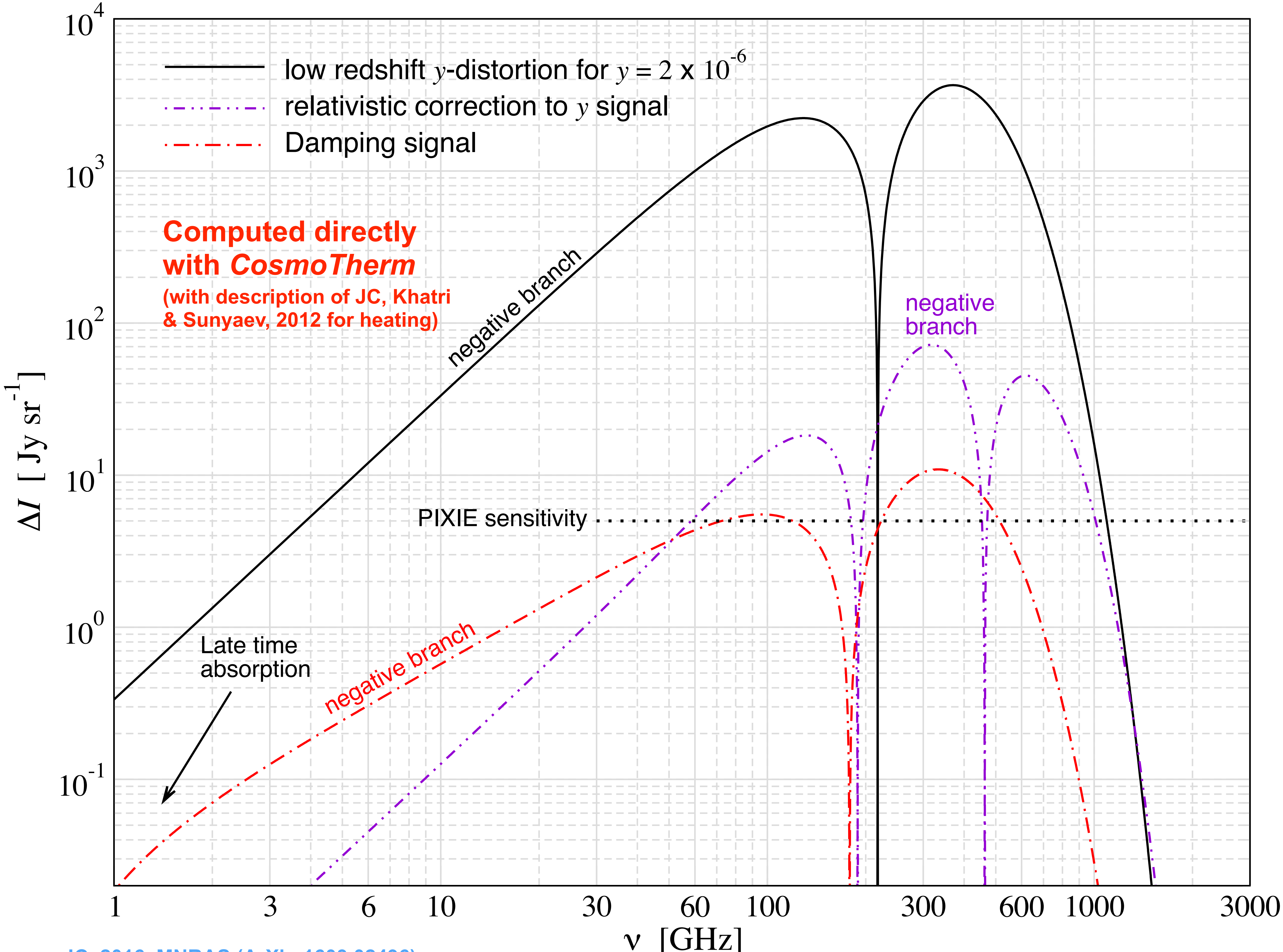
- Single mode with wavenumber k dissipates its energy at

  $z_d \sim 4.5\mathrm{x}10^5(k\ \mathrm{Mpc}/10^3)^{2/3}$

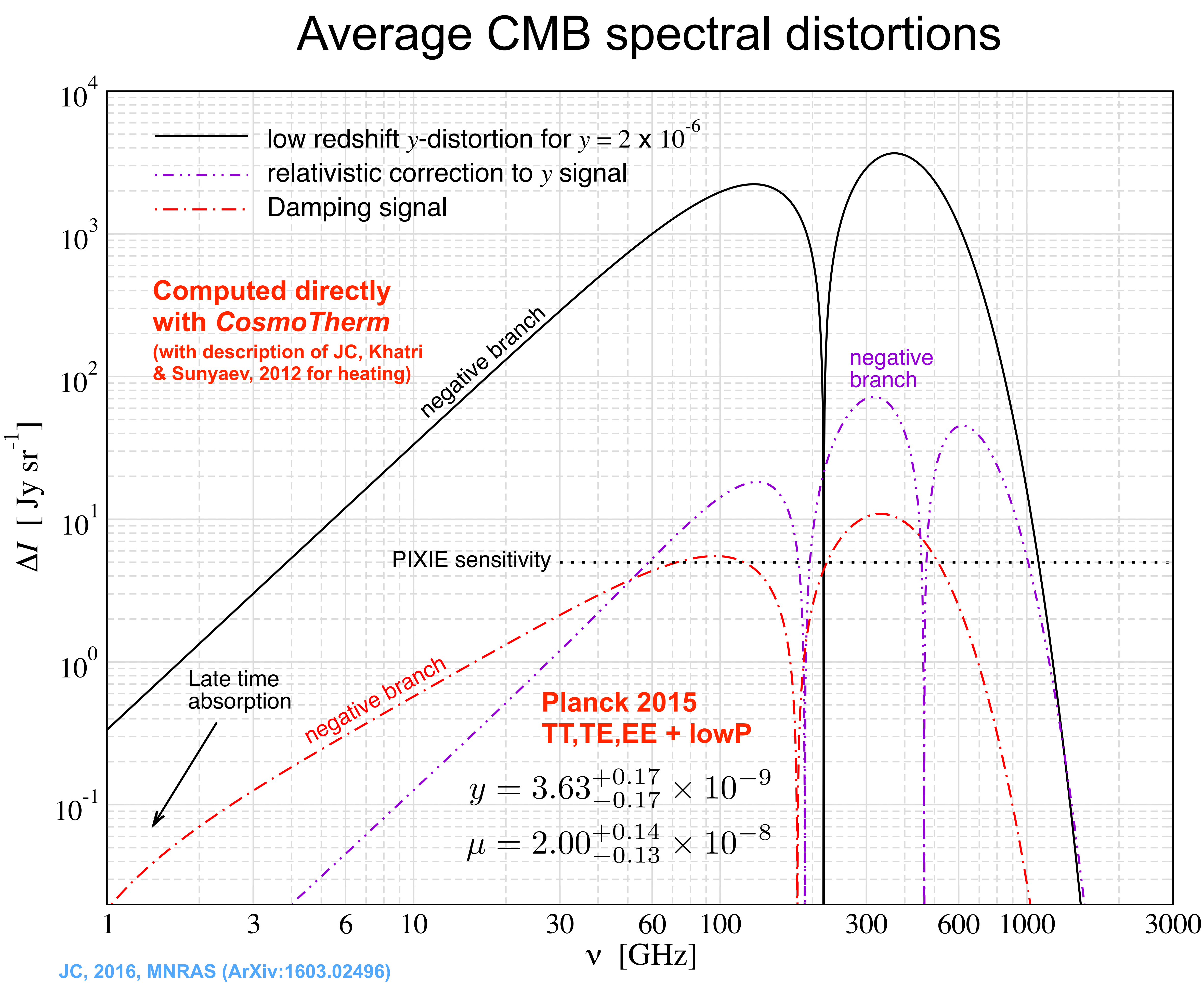
- Modes with wavenumber $50\ \mathrm{Mpc}^{-1} < k < 10^4\ \mathrm{Mpc}^{-1}$ dissipate their energy during the μ-era

- Modes with $k < 50\ \mathrm{Mpc}^{-1}$ cause y-distortion

Average CMB spectral distortions

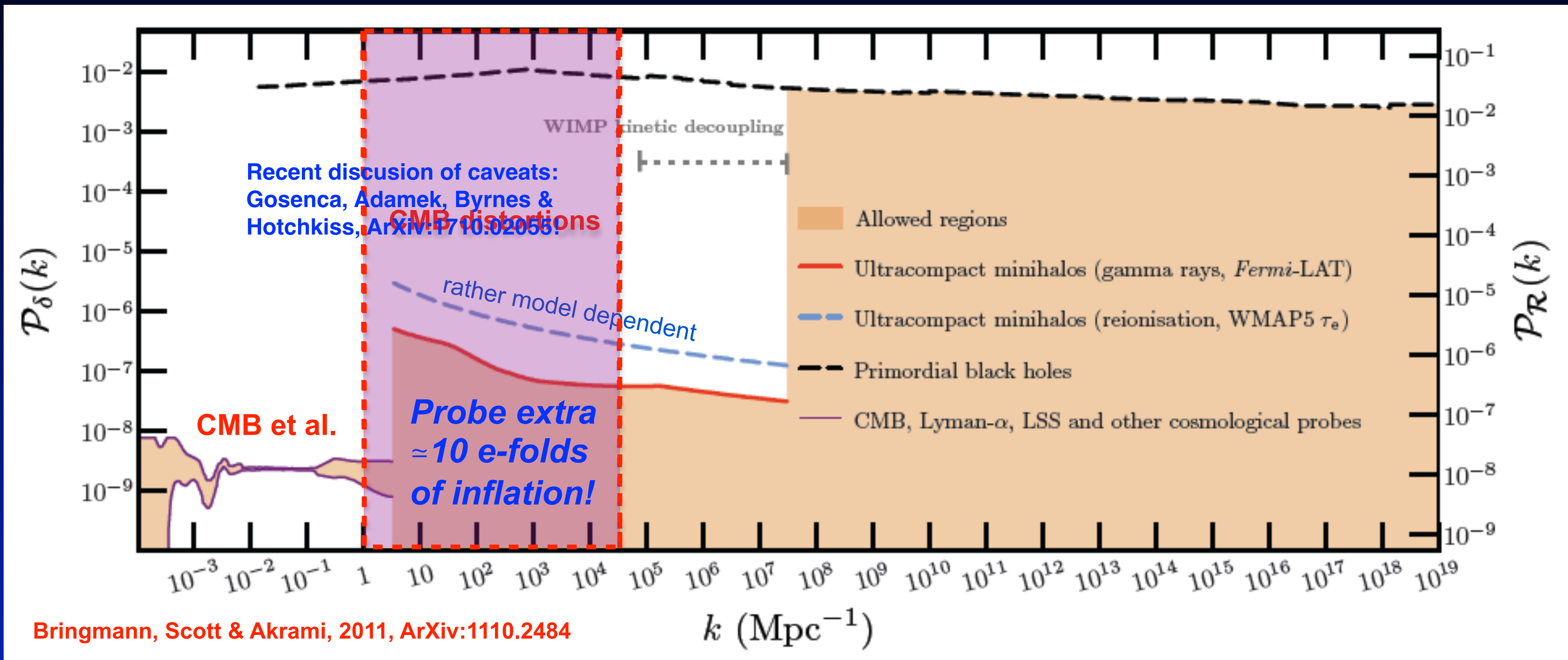


JC, 2016, MNRAS (ArXiv:1603.02496)



Average CMB spectral distortions
low redshift y-distortion for y = 2 x 10^-6
relativistic correction to y signal
Damping signal
Computed directly
with CosmoTherm
(with description of JC, Khatri
& Sunyaev, 2012 for heating)
negative branch
negative
branch
PIXIE sensitivity
Late time
absorption
negative branch
Planck 2015
TT,TE,EE + lowP
$y = 3.63^{+0.17}_{-0.17} \times 10^{-9}$
$\mu = 2.00^{+0.14}_{-0.13} \times 10^{-8}$
ΔI [Jy sr^-1]
ν [GHz]
10^4
10^3
10^2
10^1
10^0
10^-1
1
3
6
10
30
60
100
300
600
1000
3000
JC, 2016, MNRAS (ArXiv:1603.02496)

Distortions provide general power spectrum constraints!



- Amplitude of power spectrum rather uncertain at $k > 3$ Mpc^{-1}
- improved limits at smaller scales can *rule out* many *inflationary models*
- CMB spectral distortions would *extend* our *lever arm* to $k \sim 10^4$ Mpc^{-1}
- very *complementary* piece of information about early-universe physics

e.g., JC, Khatri & Sunyaev, 2012; JC, Erickcek & Ben-Dayan, 2012; JC & Jeong, 2013

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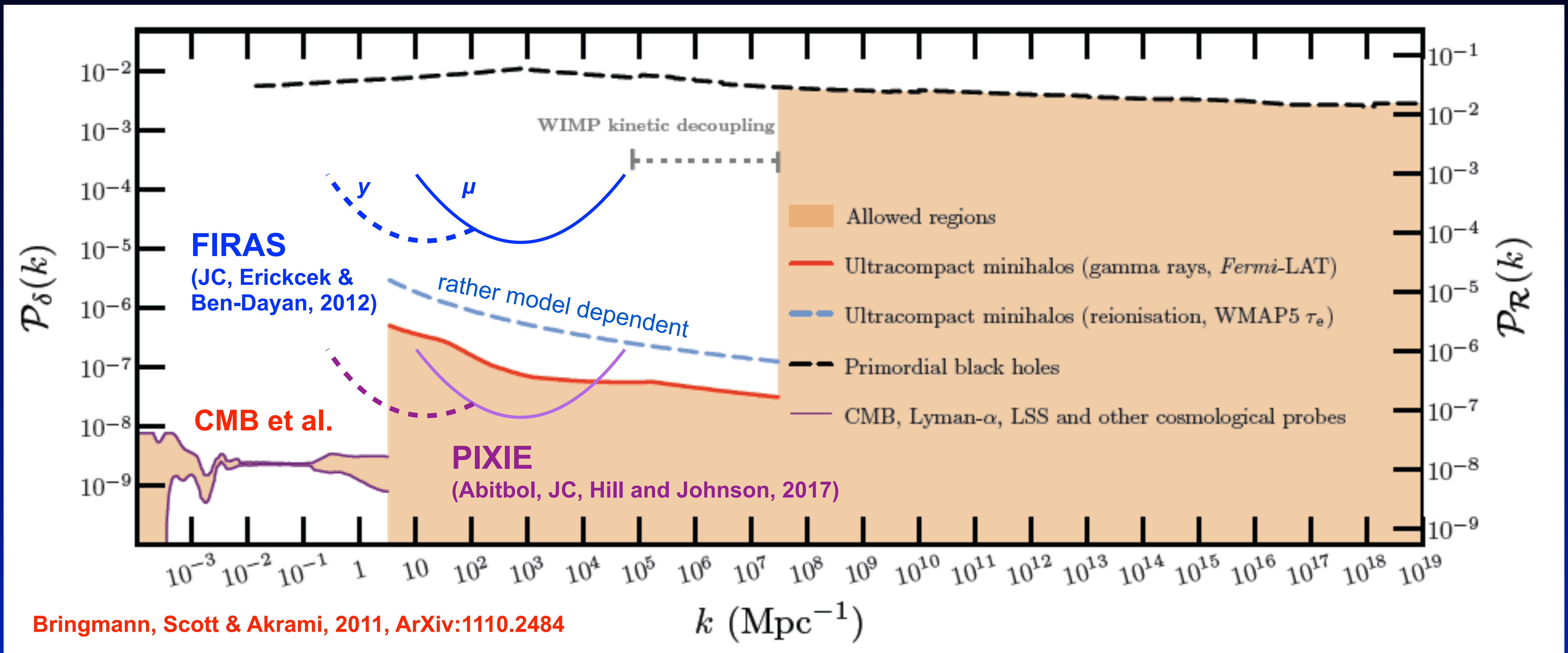

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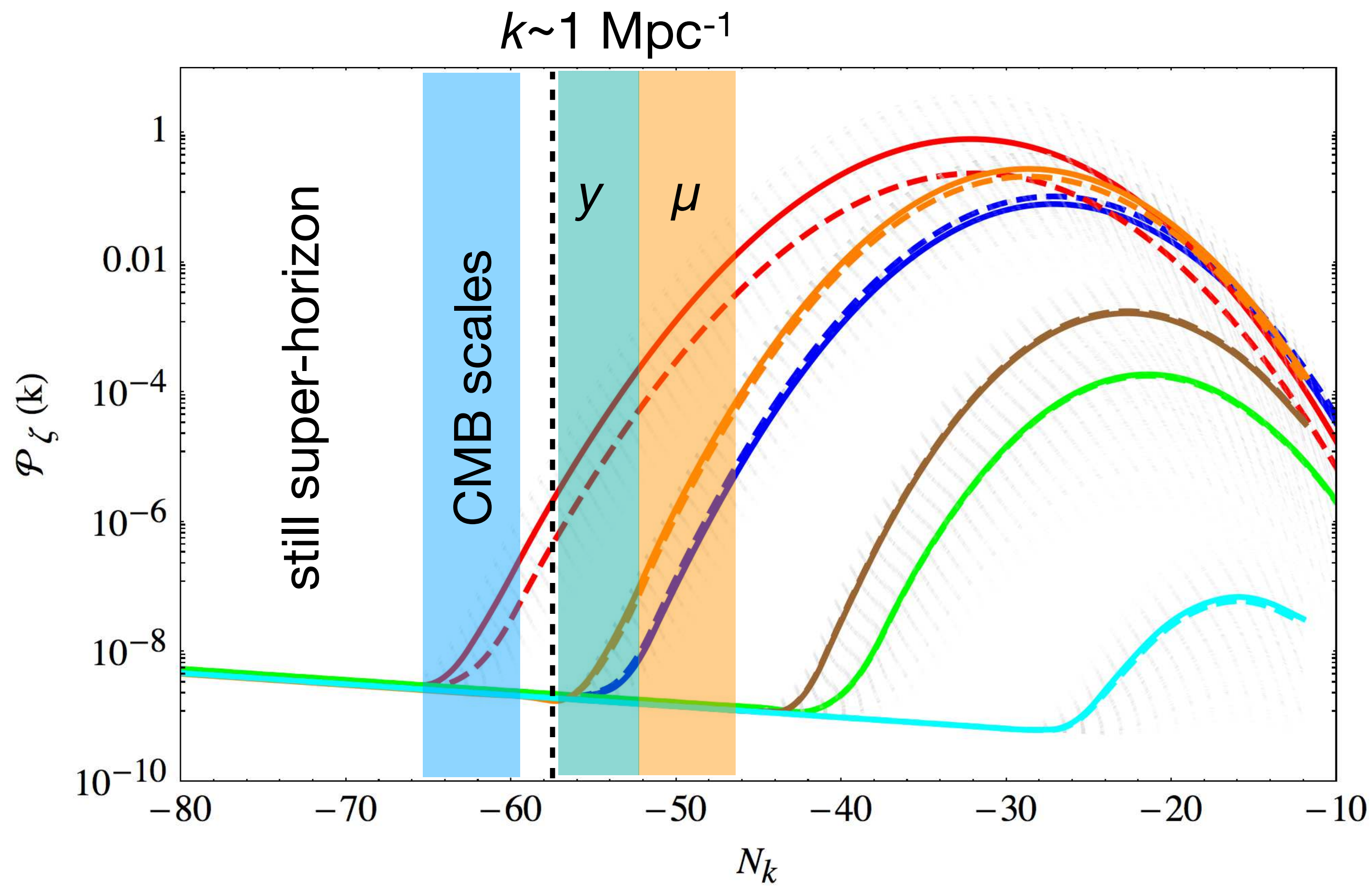
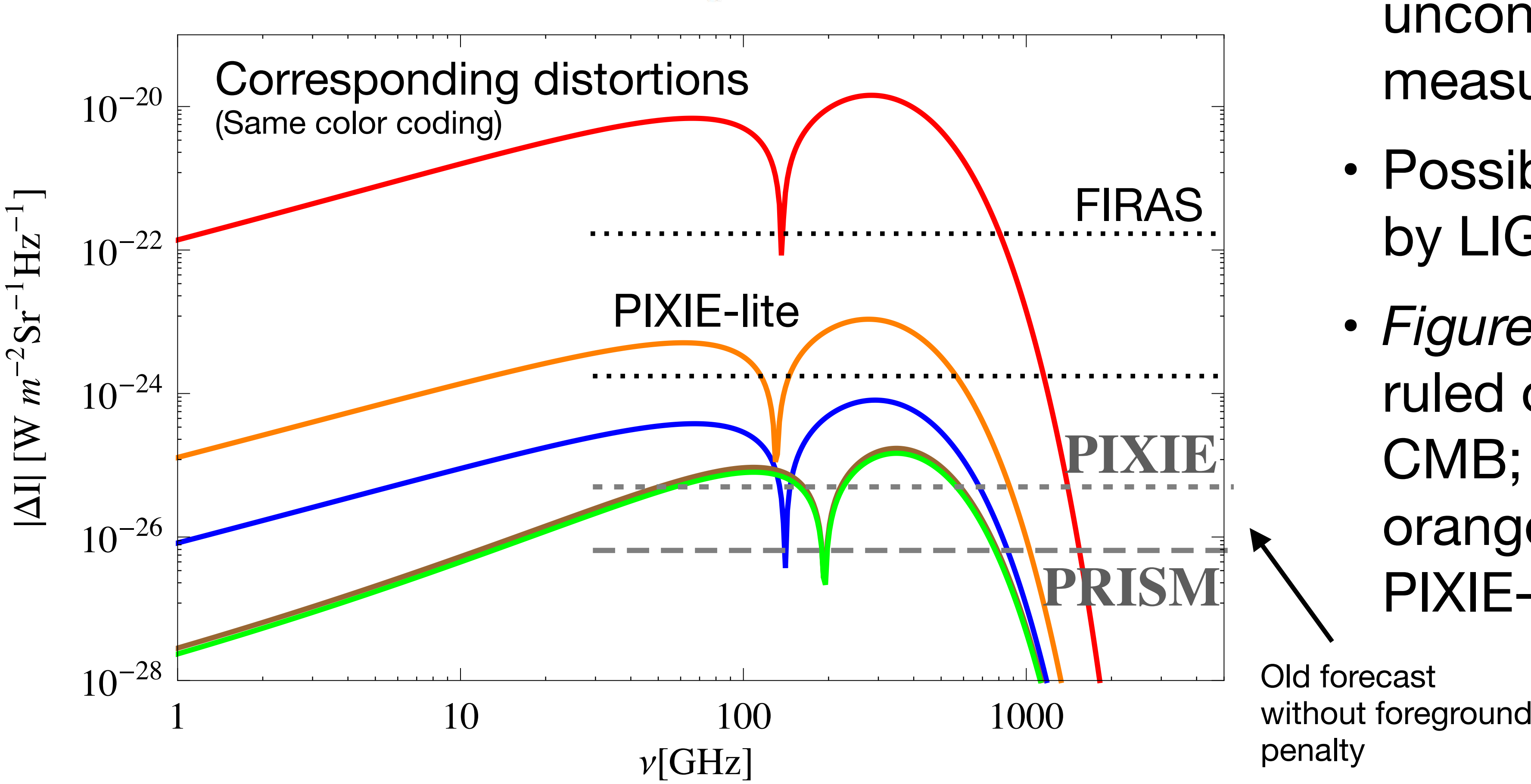
Enhanced small-scale power in hybrid inflation

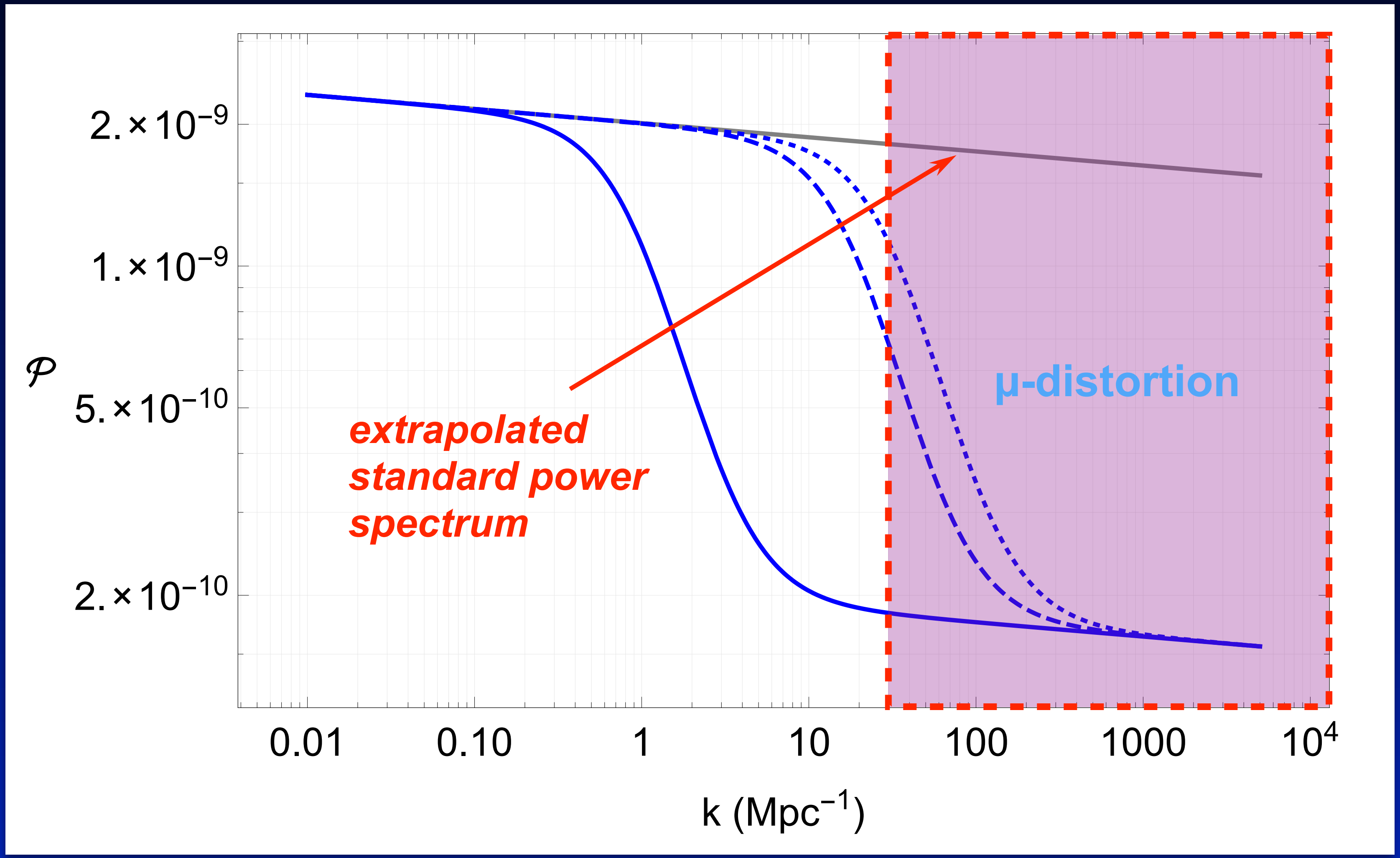




- Hybrid Inflation models cause enhanced small-scale power
- Motivated to explain seeds of supermassive blackholes seen in basically all galaxies
- μ and y distortions sensitive to enhancement at scales $1\ \mathrm{Mpc}^{-1} \lesssim k \lesssim 2\times10^{4}\ \mathrm{Mpc}^{-1}$
- Can constrain cases that are unconstrained by CMB measurements at large scales
- Possible link to BH mergers seen by LIGO??
- *Figure*: case with red line already ruled out by FIRAS (!) and today's CMB; distortions sensitive to orange and blue case; other cases PIXIE-lite is not sensitive to

Figures adapted from Clesse & Garcia-Bellido, 2015

Shedding Light on the ‘Small-Scale Crisis’



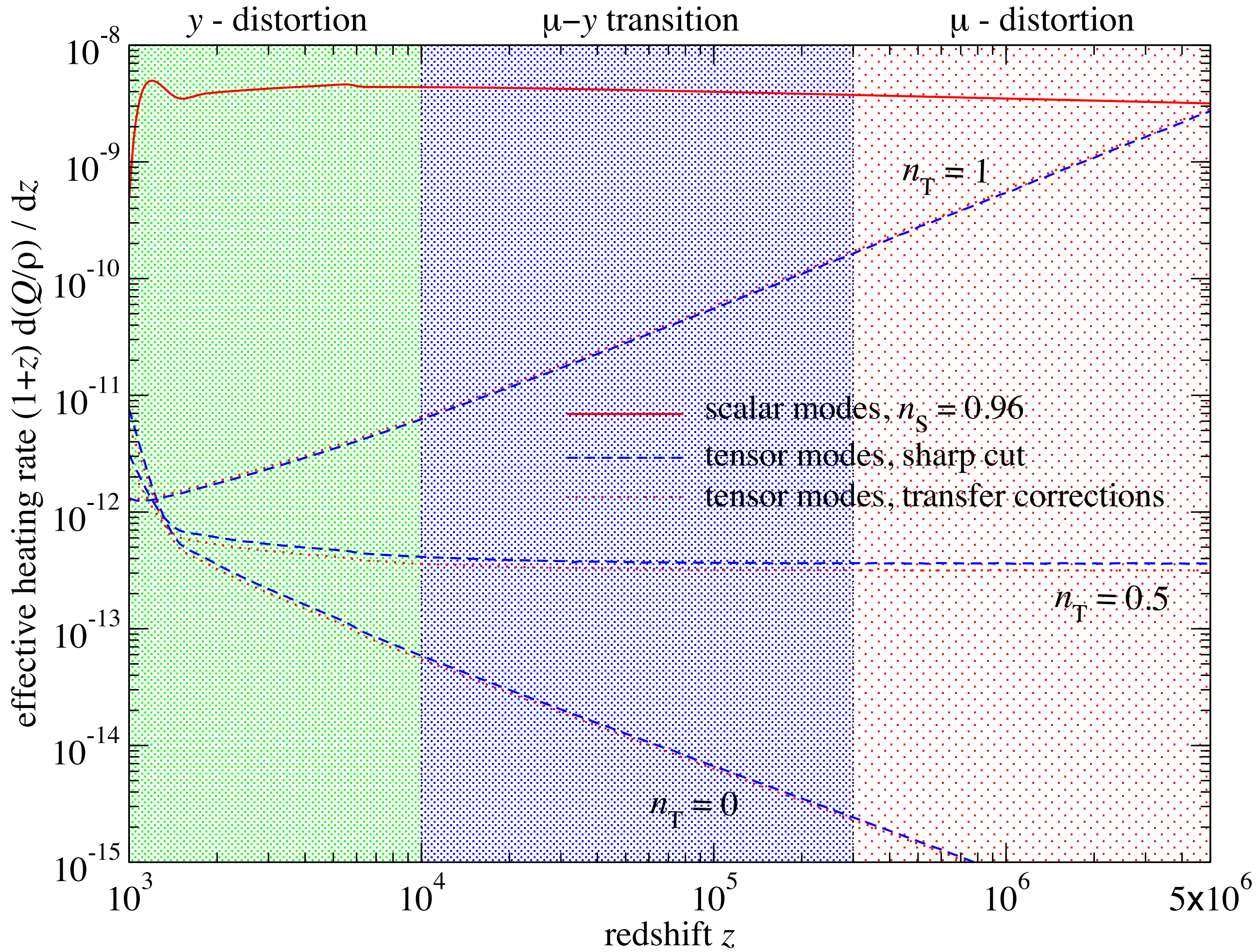
- ‘missing satellite’ problem
- ‘too-big-to-fail’
- Cusp-vs-core problem

⇒ Are these caused by a *primordial* or *late-time* suppression?

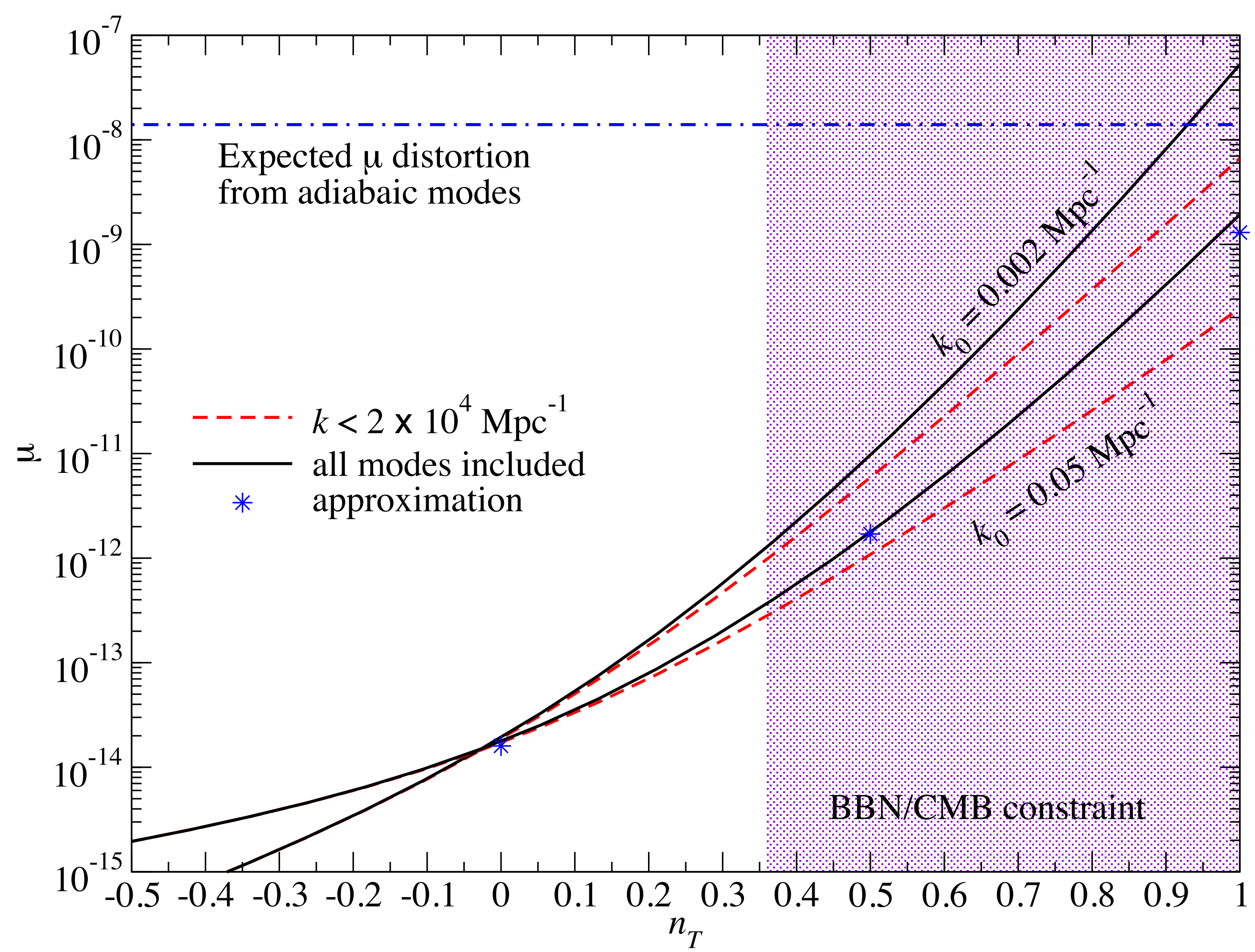
- A primordial suppression would result in a very small μ-distortions
- Spectral distortion measurements might be able to test this question

Nakama, JC & Kamionkowski, ArXiv:1703.10559

Dissipation of tensor perturbations



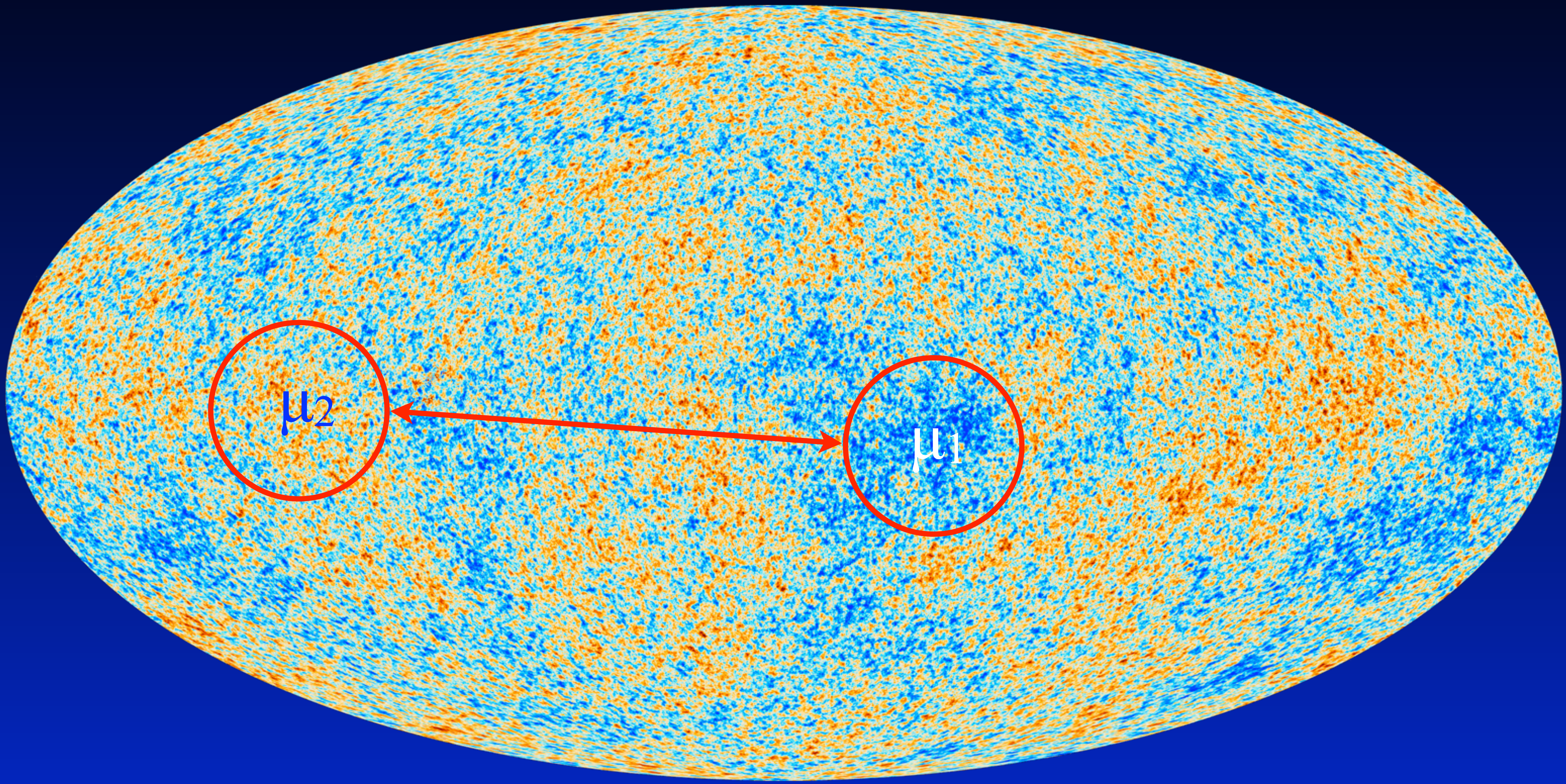
- distortion signal very small compared to adiabatic modes
- no severe *contamination* in simplest cases
- models with 'large' distortion already constrained by BBN/CMB



- heating rate can be computed similar to adiabatic modes
- heating rate much smaller than for scalar perturbations
- roughly constant per dlnz for n_T~0.5

JC, Dai, Grin et al., 2014, ArXiv:1407.3653

Spatially varying heating and dissipation of acoustic modes for non-Gaussian perturbations



- Uniform heating (e.g., dissipation in Gaussian case or quasi-uniform energy release)
  → distortion practically the same in different directions
- Spatially varying heating rate (e.g., due to *ultra-squeezed limit non-Gaussianity* or *cosmic bubble collisions*)
  → distortion varies in different directions

Pajer & Zaldarriaga, 2012; Ganc & Komatsu, 2012; Biagetti et al., 2013; JC et al., 2016

Signals for ultra-squeezed non-Gaussianity

- Different correlation signals (see Emami et al, 2015)

$$C_\ell^{\mu T} \simeq 12 f_{\rm nl}^{\mu}\, C_\ell^{TT} \qquad\qquad f_{\rm nl}^{\mu} \simeq f_{\rm nl}(740\,{\rm Mpc}^{-1}) \simeq 220\left(\frac{\mu_{\rm min}}{10^{-9}}\right)\left(\frac{\langle\mu\rangle}{2\times10^{-8}}\right)^{-1}$$

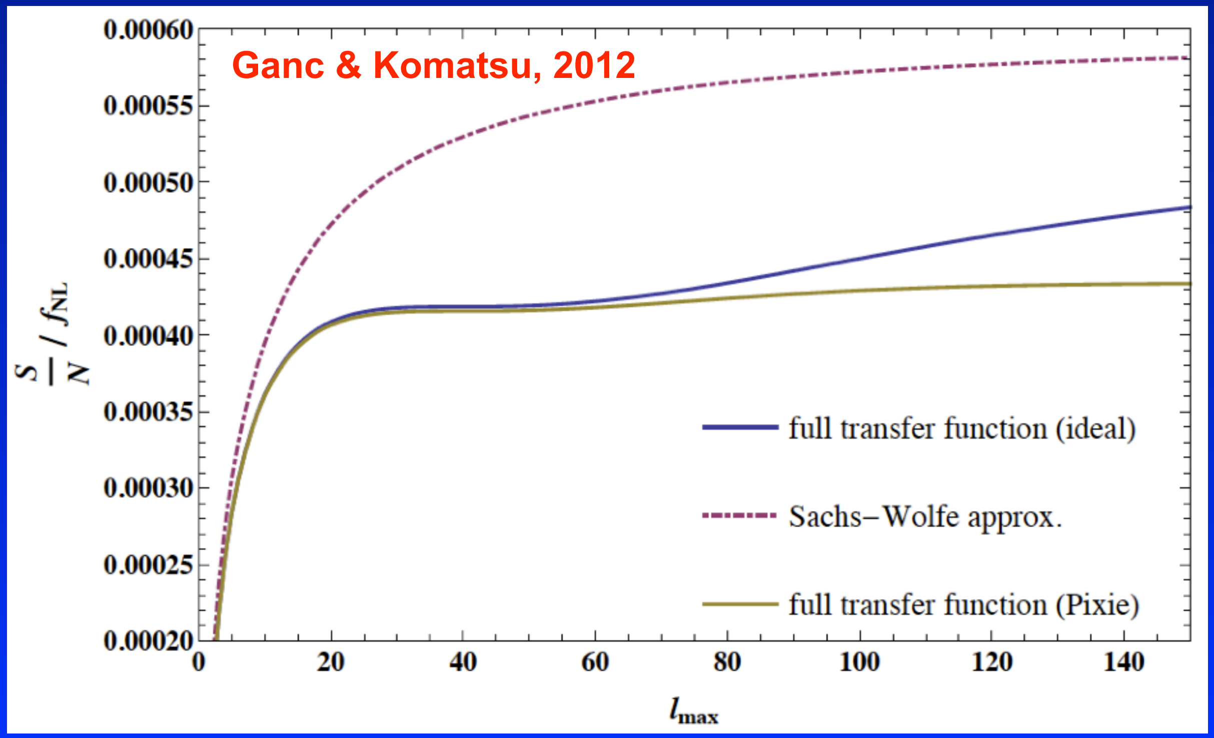
$$\Leftrightarrow$$

$$C_\ell^{yT} \simeq 12 f_{\rm nl}^{y}\, C_\ell^{TT} \qquad\qquad f_{\rm nl}^{y} \simeq f_{\rm nl}(7\,{\rm Mpc}^{-1}) \simeq 220\left(\frac{y_{\rm min}}{2\times10^{-10}}\right)\left(\frac{\langle y\rangle}{4\times10^{-9}}\right)^{-1}$$

- achievable sensitivity depends on *monopole* distortion!
- μT "*cleanest*" signal since it can only be created at early times
- yT also created by ISW but *scale-dependence* could help distinguishing it from the high-z signal
  (→ see new calculations by Ravenni et al., 1707.04759)
- possible link to *CMB anomalies?*

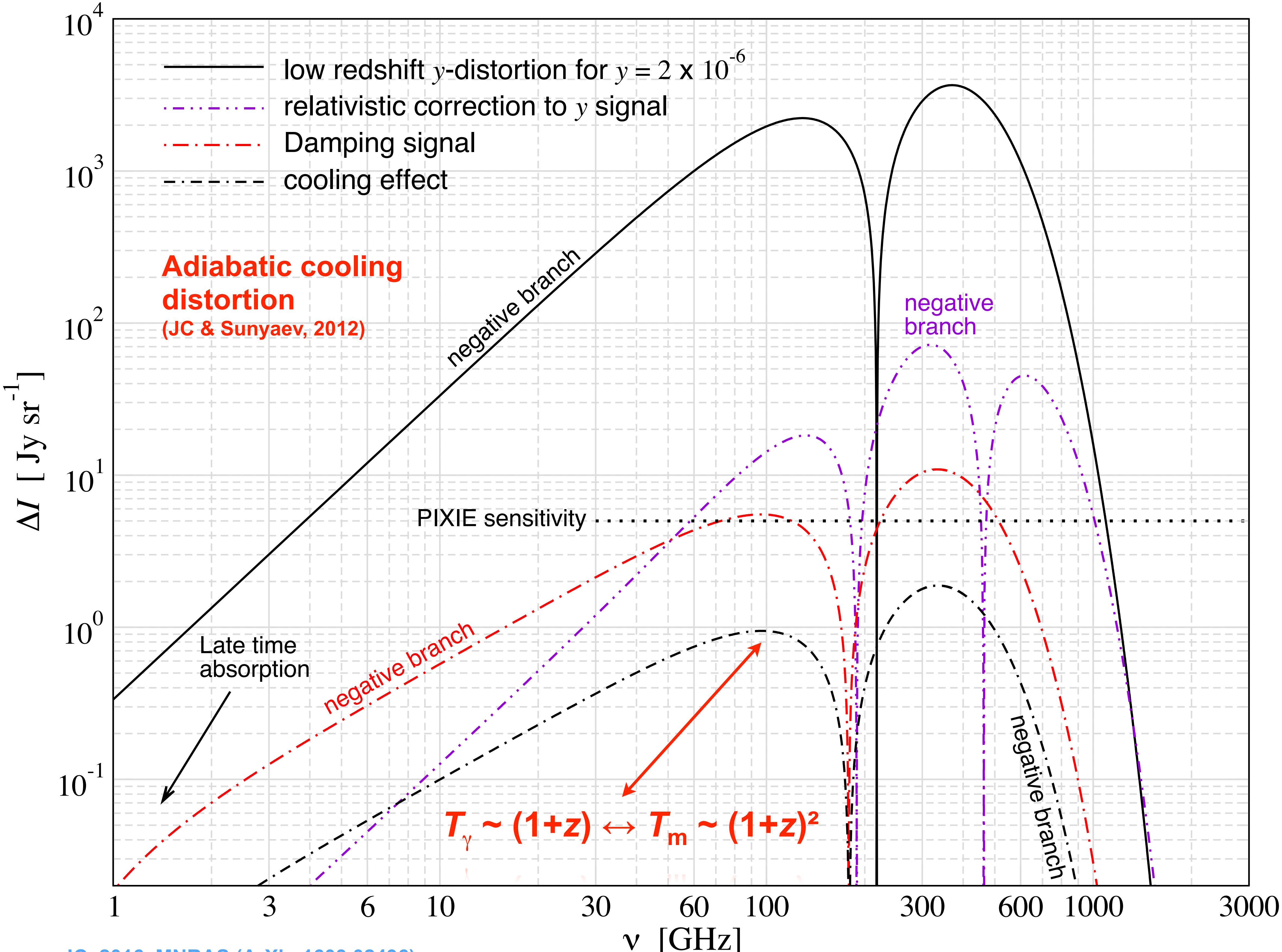
Requirements

- *precise cross-calibration of frequency channels*
- higher angular resolution does not improve cumulative S/N much
  (→ *PIXIE-like experiment may be enough*)



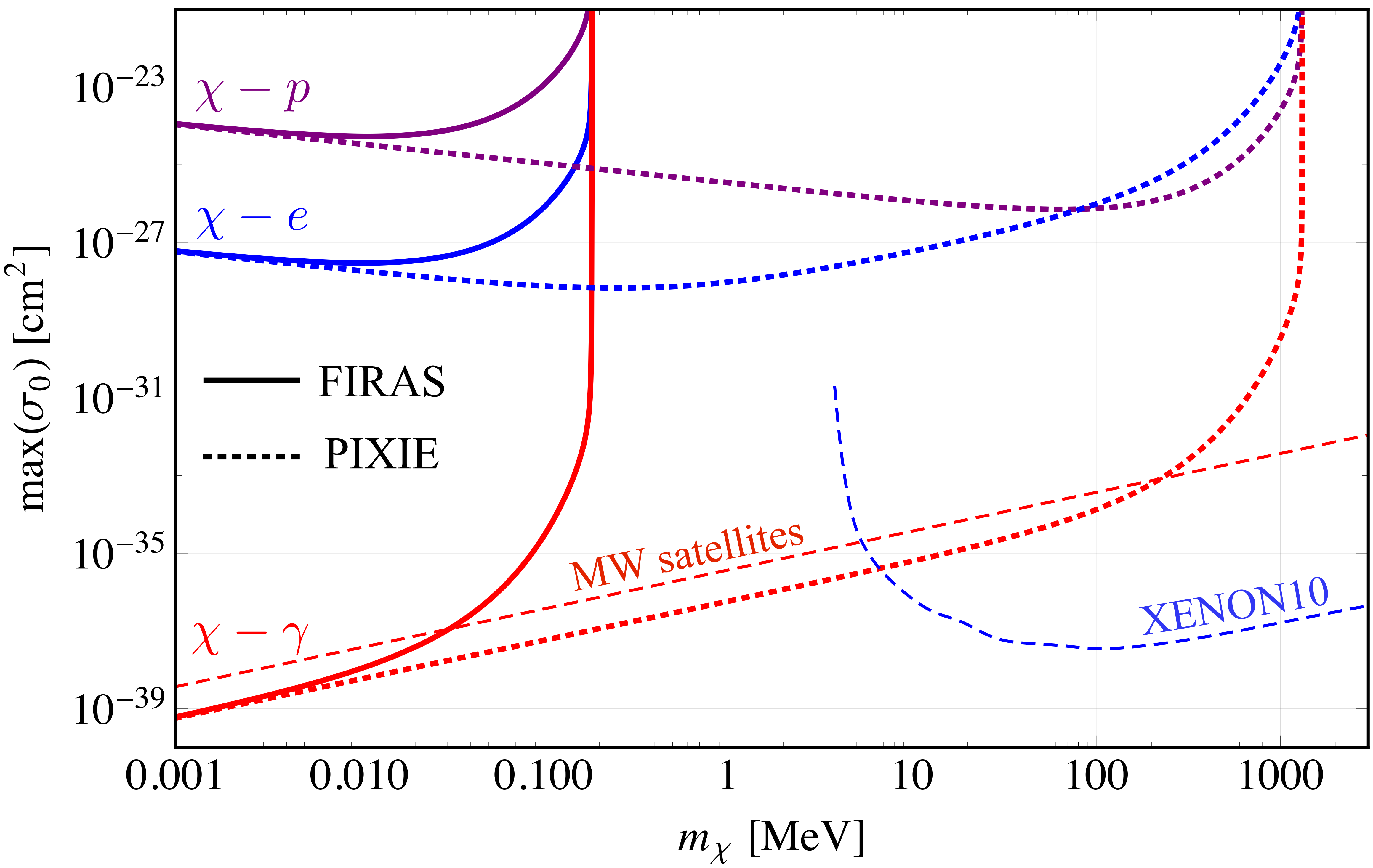
Energy extraction due to adiabatic cooling of matter

Average CMB spectral distortions



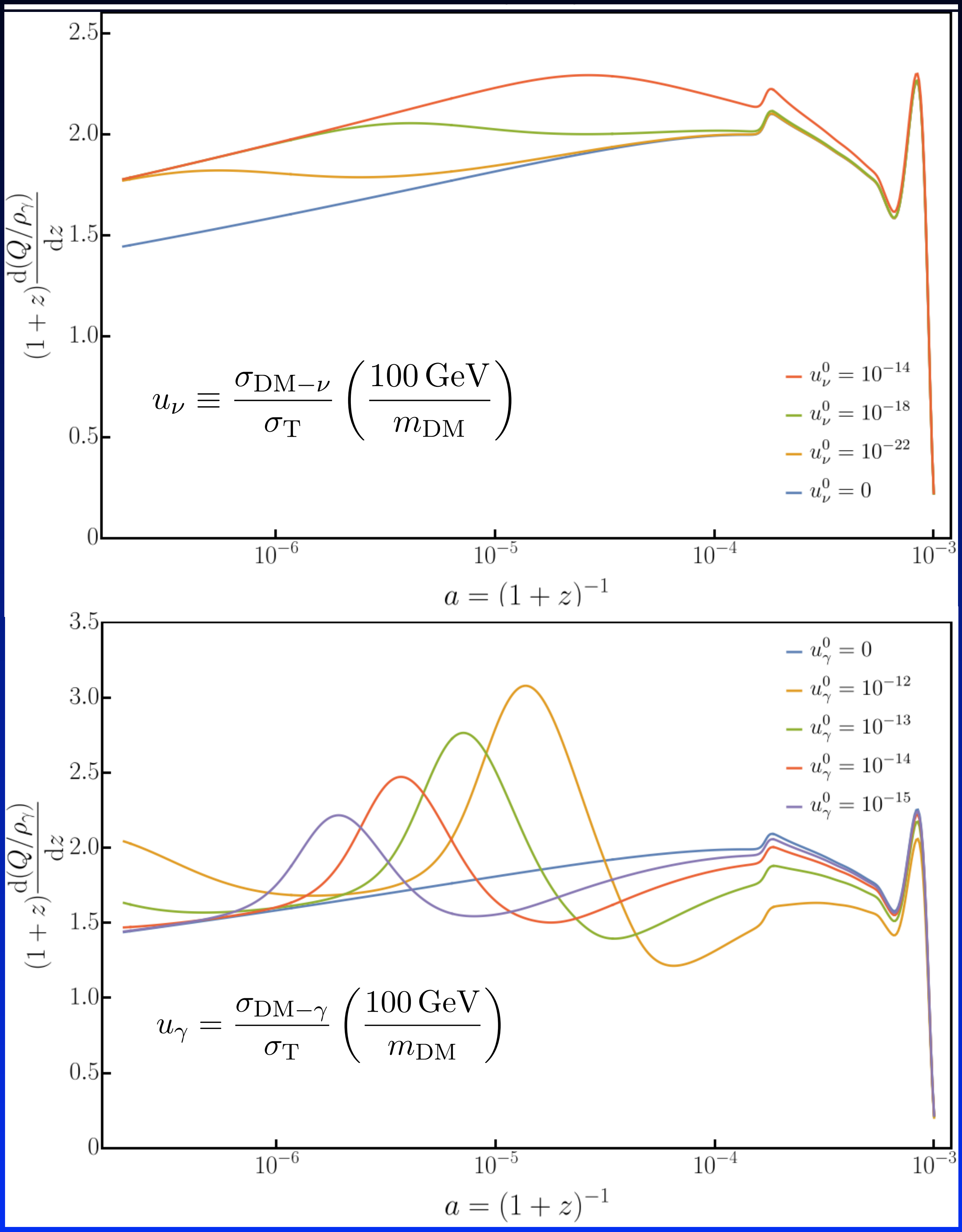
JC, 2016, MNRAS (ArXiv:1603.02496)

Distortion constraints on DM interactions through adiabatic cooling effect



Ali-Haimoud, JC & Kamionkowski, 2015

Constrain interactions of DM with neutrinos/photons



- Dissipation is increased
- Enhances μ distortion
- Interesting complementary probe

- Early-time dissipation enhanced → larger μ
- Later, modes already gone, so less heating
- Dissipation scale larger early on

Diacoumis & Wong, 2017, 1707.07050

The cosmological recombination radiation

Simple estimates for hydrogen recombination

Hydrogen recombination:

- per recombined hydrogen atom an energy of ~ 13.6 eV in form of photons is released
- at z ~ 1100 → $\Delta\varepsilon/\varepsilon$ ~ 13.6 eV N_b / (N_γ 2.7kT_r) ~ 10^{-9} - 10^{-8}

→ recombination occurs at redshifts $z < 10^4$

→ At that time the *thermalization* process doesn't work anymore!

→ There should be some *small* spectral distortion due to additional Ly-α and 2s-1s photons!
(Zeldovich, Kurt & Sunyaev, 1968, ZhETF, 55, 278; Peebles, 1968, ApJ, 153, 1)

→ In 1975 ***Viktor Dubrovich*** emphasized the possibility to observe the recombinational lines from n > 3 and Δn << n!

First recombination computations completed in 1968!

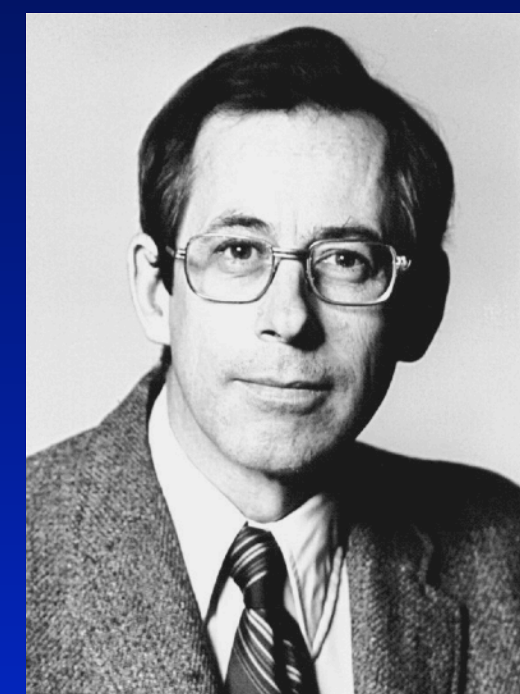
Yakov Zeldovich

Vladimir Kurt
(UV astronomer)

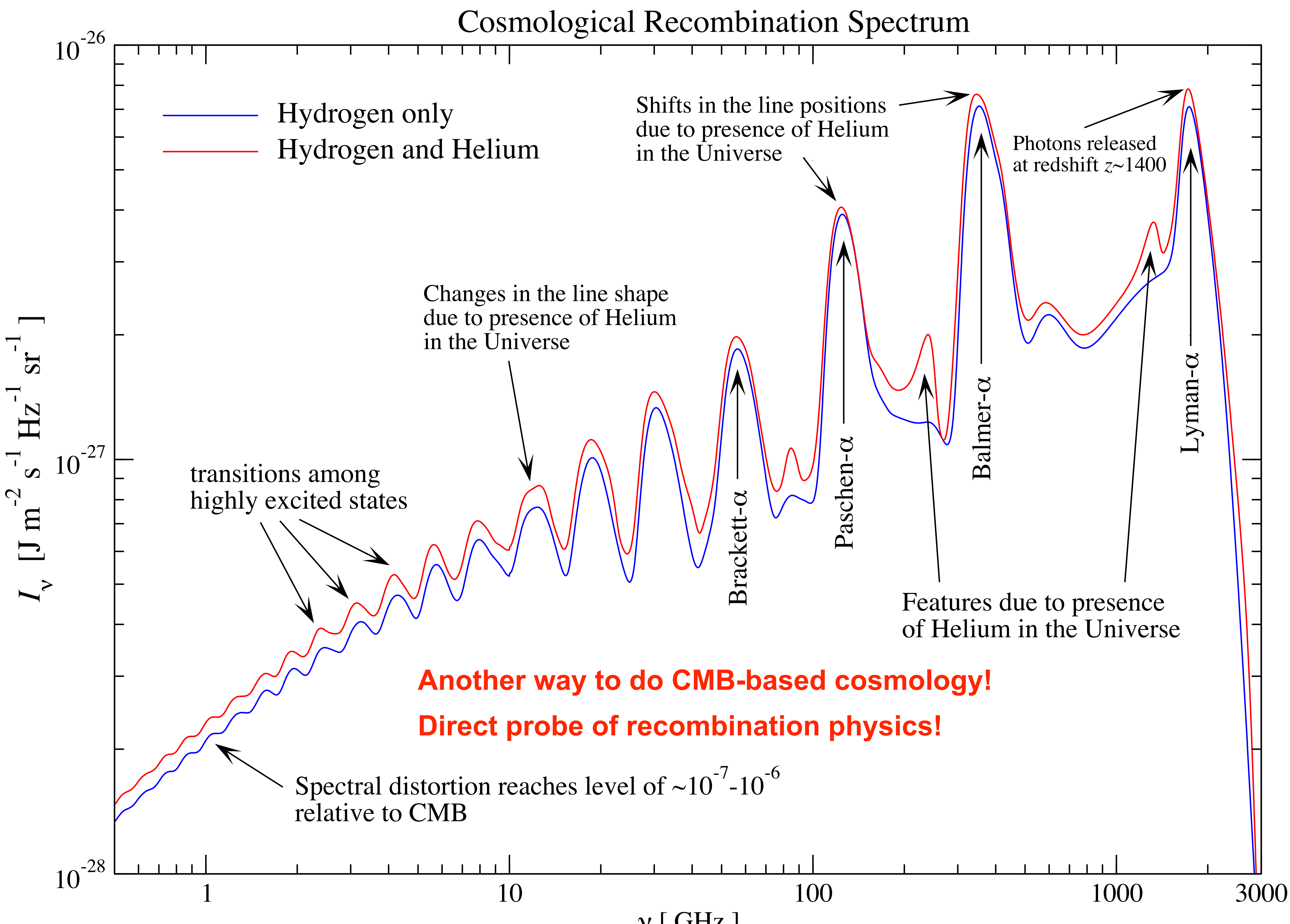
Moscow

Rashid Sunyaev

Princeton

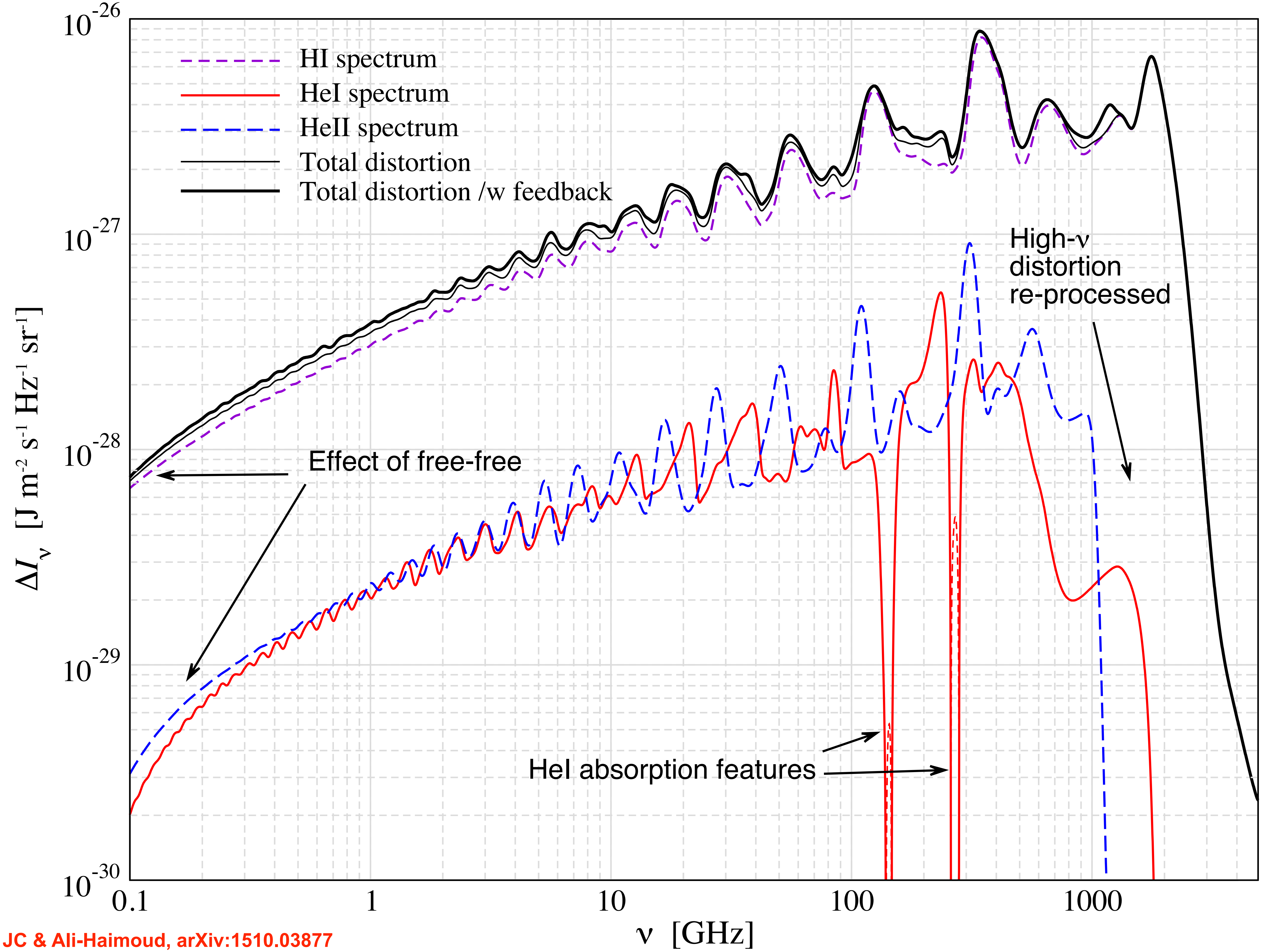


Jim Peebles



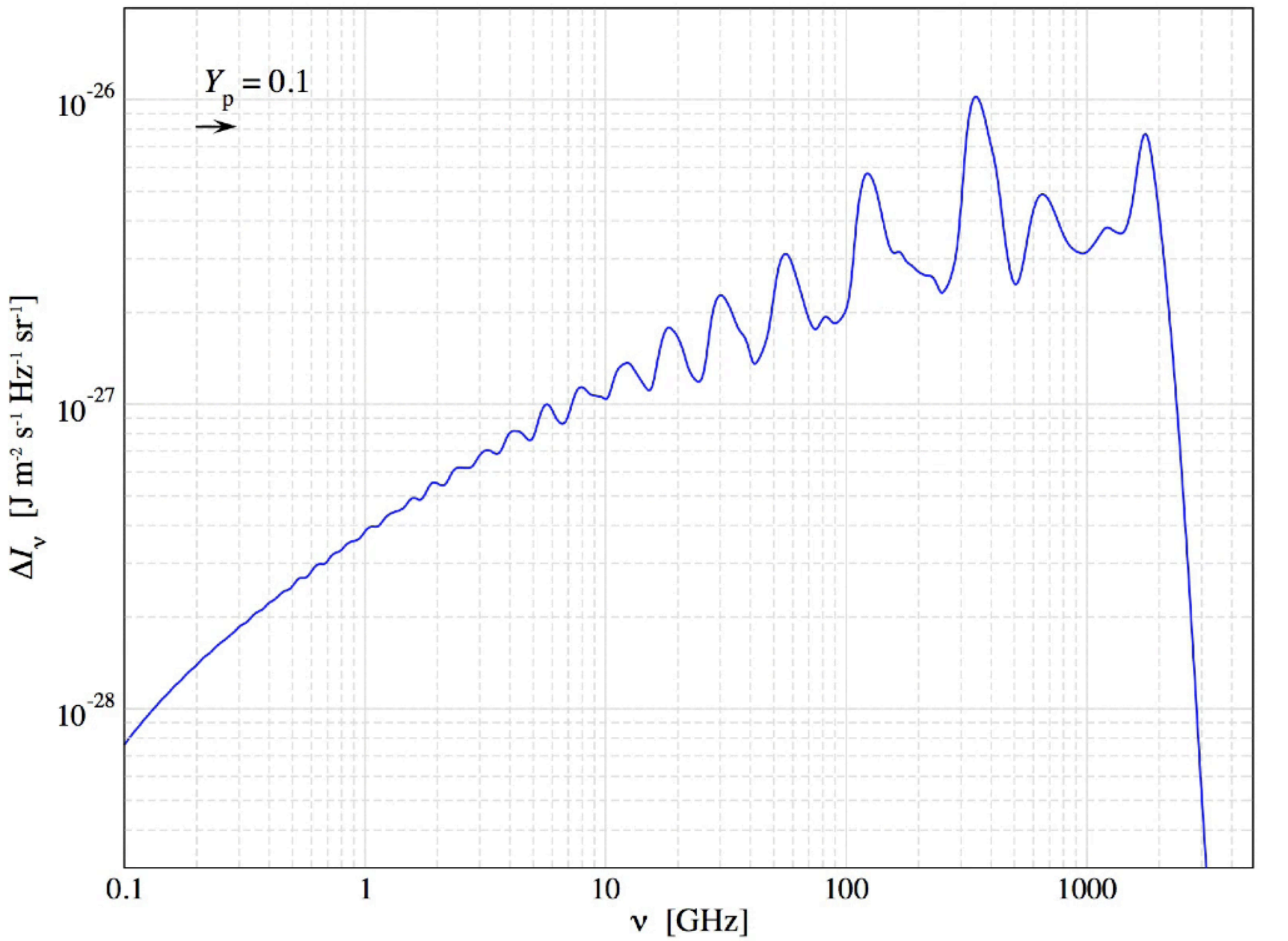
Rubino-Martin et al. 2006, 2008; Sunyaev & JC, 2009

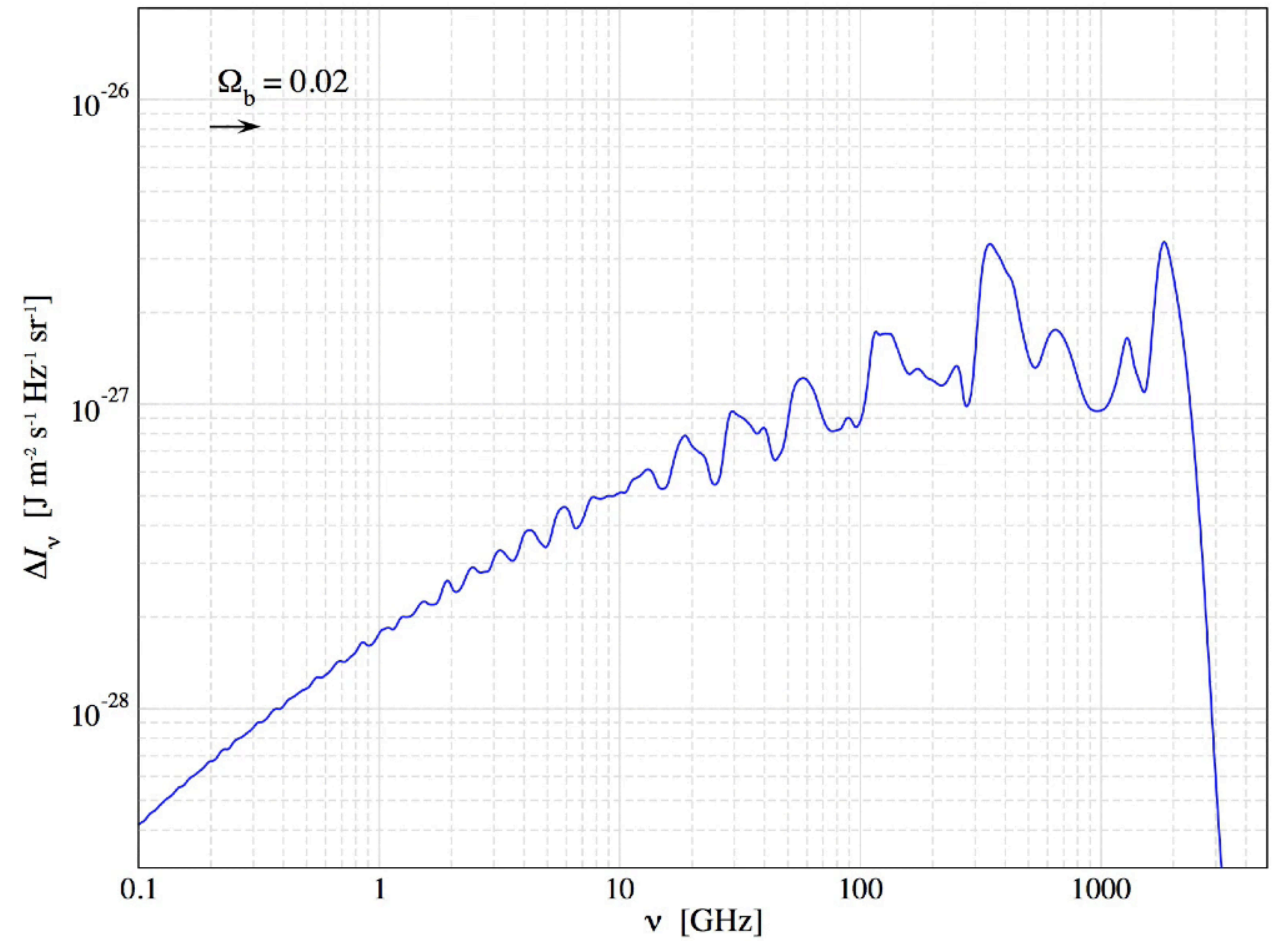
New detailed and fast computation!



JC & Ali-Haimoud, arXiv:1510.03877

CosmoSpec: fast and accurate computation of the CRR



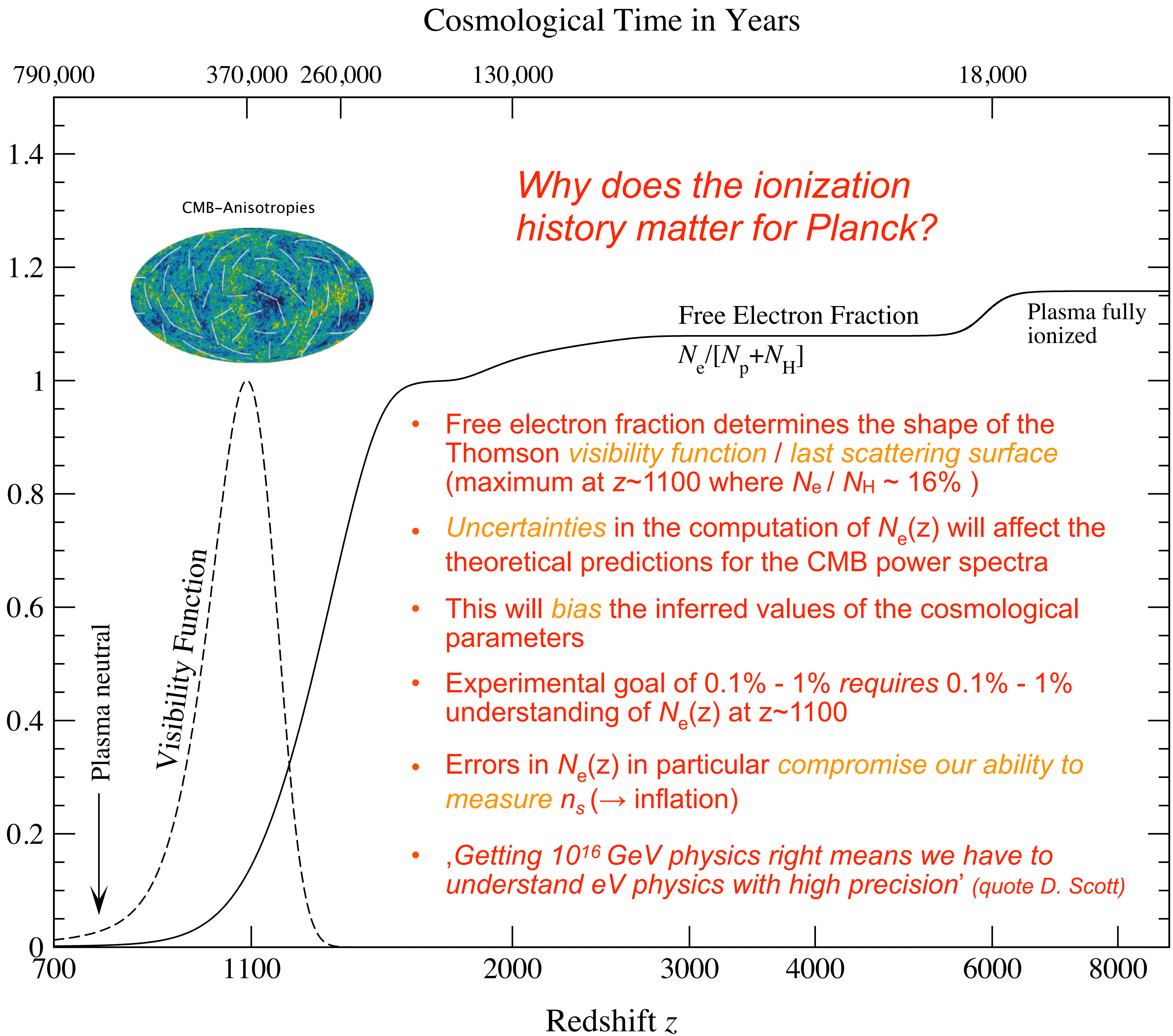


- Like in old days of CMB anisotropies!
- detailed forecasts and feasibility studies
- non-standard physics (variation of α, energy injection etc.)

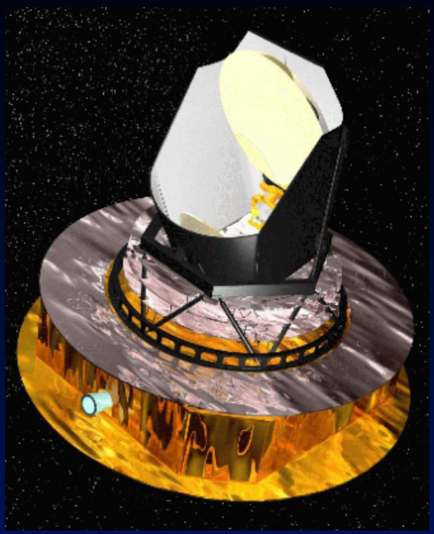
CosmoSpec will be available here:

www.Chluba.de/CosmoSpec

JC & Ali-Haimoud, arXiv:1510.03877

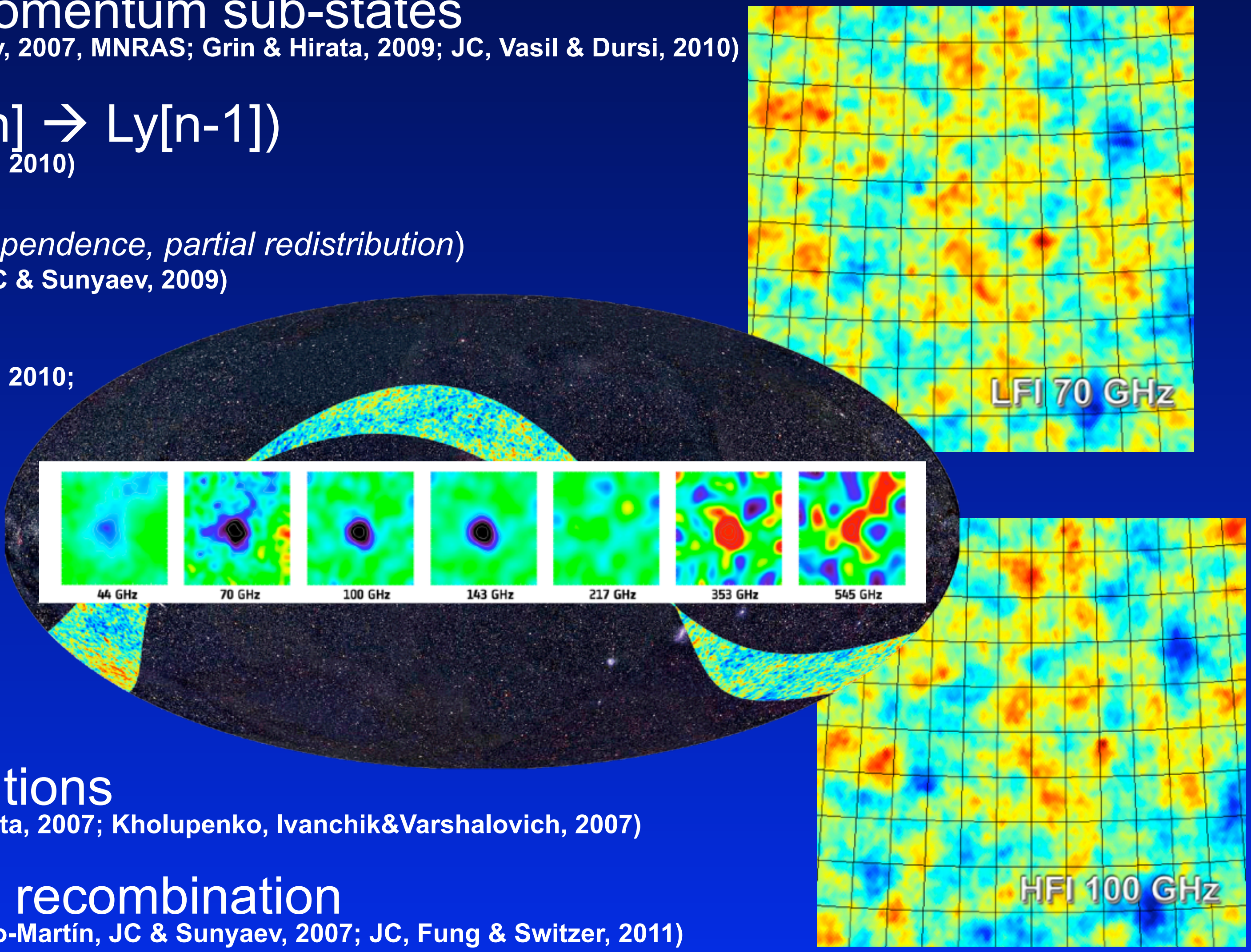

Cosmological Time in Years
790,000
370,000
260,000
130,000
18,000
Why does the ionization history matter for Planck?
CMB-Anisotropies
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully ionized
Plasma neutral
Visibility Function
• Free electron fraction determines the shape of the Thomson visibility function / last scattering surface (maximum at z~1100 where N_e / N_H ~ 16%)
• Uncertainties in the computation of N_e(z) will affect the theoretical predictions for the CMB power spectra
• This will bias the inferred values of the cosmological parameters
• Experimental goal of 0.1% - 1% requires 0.1% - 1% understanding of N_e(z) at z~1100
• Errors in N_e(z) in particular compromise our ability to measure n_s (→ inflation)
• ‚Getting 10^{16} GeV physics right means we have to understand eV physics with high precision' (quote D. Scott)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
700
1100
2000
3000
4000
6000
8000
Redshift z

Getting the job done for *Planck*



Hydrogen recombination

- Two-photon decays from higher levels
  (Dubrovich & Grachev, 2005, Astr. Lett., 31, 359; Wong & Scott, 2007; JC & Sunyaev, 2007; Hirata, 2008; JC & Sunyaev 2009)
- Induced 2s two-photon decay for hydrogen
  (JC & Sunyaev, 2006, A&A, 446, 39; Hirata 2008)
- Feedback of the Lyman-α distortion on the 1s-2s two-photon absorption rate
  (Kholupenko & Ivanchik, 2006, Astr. Lett.; Fendt et al. 2008; Hirata 2008)
- Non-equilibrium effects in the angular momentum sub-states
  (Rubiño-Martín, JC & Sunyaev, 2006, MNRAS; JC, Rubiño-Martín & Sunyaev, 2007, MNRAS; Grin & Hirata, 2009; JC, Vasil & Dursi, 2010)
- Feedback of Lyman-series photons (Ly[n] $\rightarrow$ Ly[n-1])
  (JC & Sunyaev, 2007, A&A; Kholupenko et al. 2010; Haimoud, Grin & Hirata, 2010)
- Lyman-α escape problem (*atomic recoil, time-dependence, partial redistribution*)
  (Dubrovich & Grachev, 2008; JC & Sunyaev, 2008; Forbes & Hirata, 2009; JC & Sunyaev, 2009)
- Collisions and Quadrupole lines
  (JC, Rubiño-Martín & Sunyaev, 2007; Grin & Hirata, 2009; JC, Vasil & Dursi, 2010; JC, Fung & Switzer, 2011)
- Raman scattering
  (Hirata 2008; JC & Thomas , 2010; Haimoud & Hirata, 2010)



Helium recombination

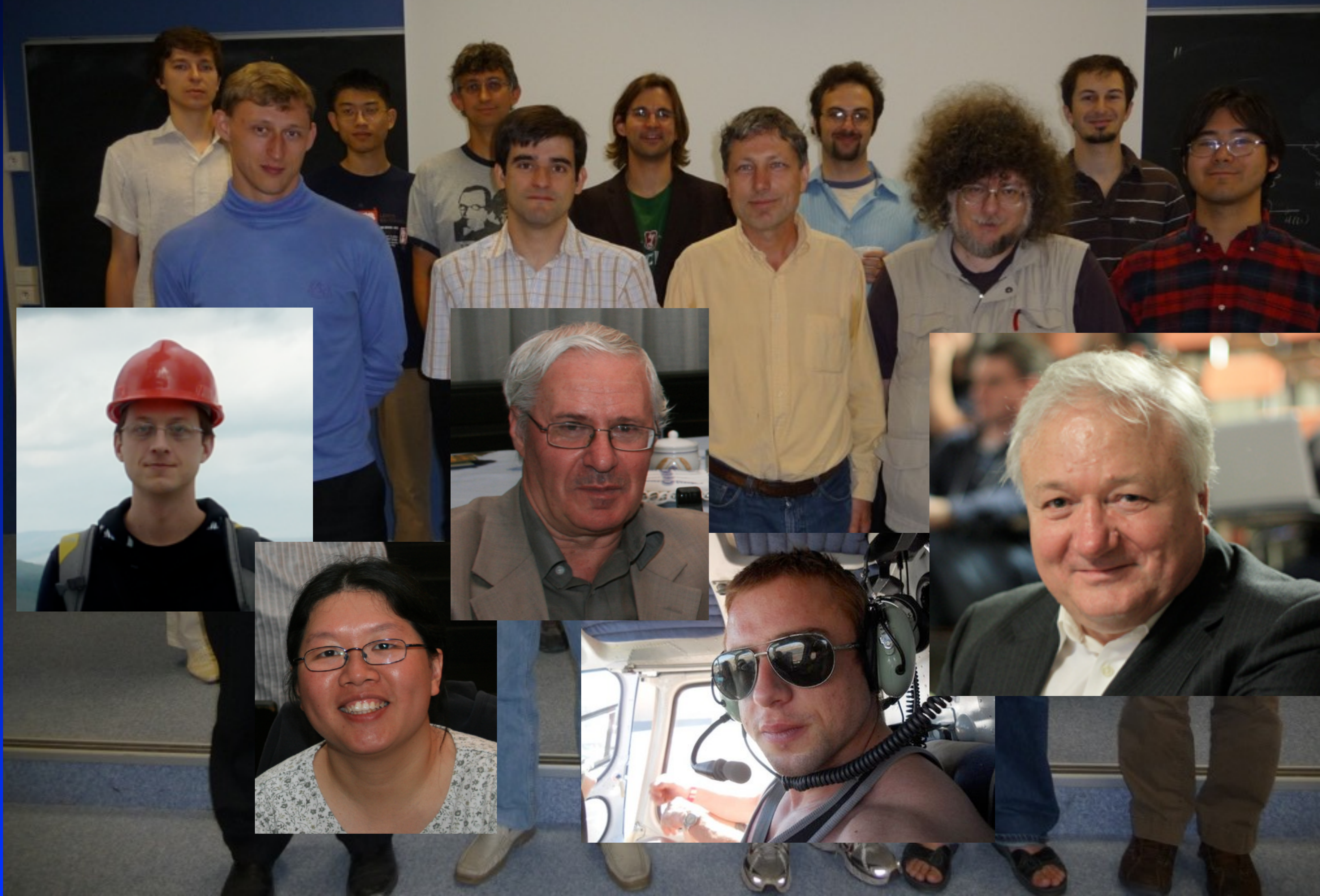
- Similar list of processes as for hydrogen
  (Switzer & Hirata, 2007a&b; Hirata & Switzer, 2007)
- Spin forbidden 2p-1s triplet-singlet transitions
  (Dubrovich & Grachev, 2005, Astr. Lett.; Wong & Scott, 2007; Switzer & Hirata, 2007; Kholupenko, Ivanchik&Varshalovich, 2007)
- Hydrogen continuum opacity during He I recombination
  (Switzer & Hirata, 2007; Kholupenko, Ivanchik & Varshalovich, 2007; Rubiño-Martín, JC & Sunyaev, 2007; JC, Fung & Switzer, 2011)
- Detailed feedback of helium photons
  (Switzer & Hirata, 2007a; JC & Sunyaev, 2009, MNRAS; JC, Fung & Switzer, 2011)

$\Delta N_e \; / \; N_e \sim 0.1\ \%$

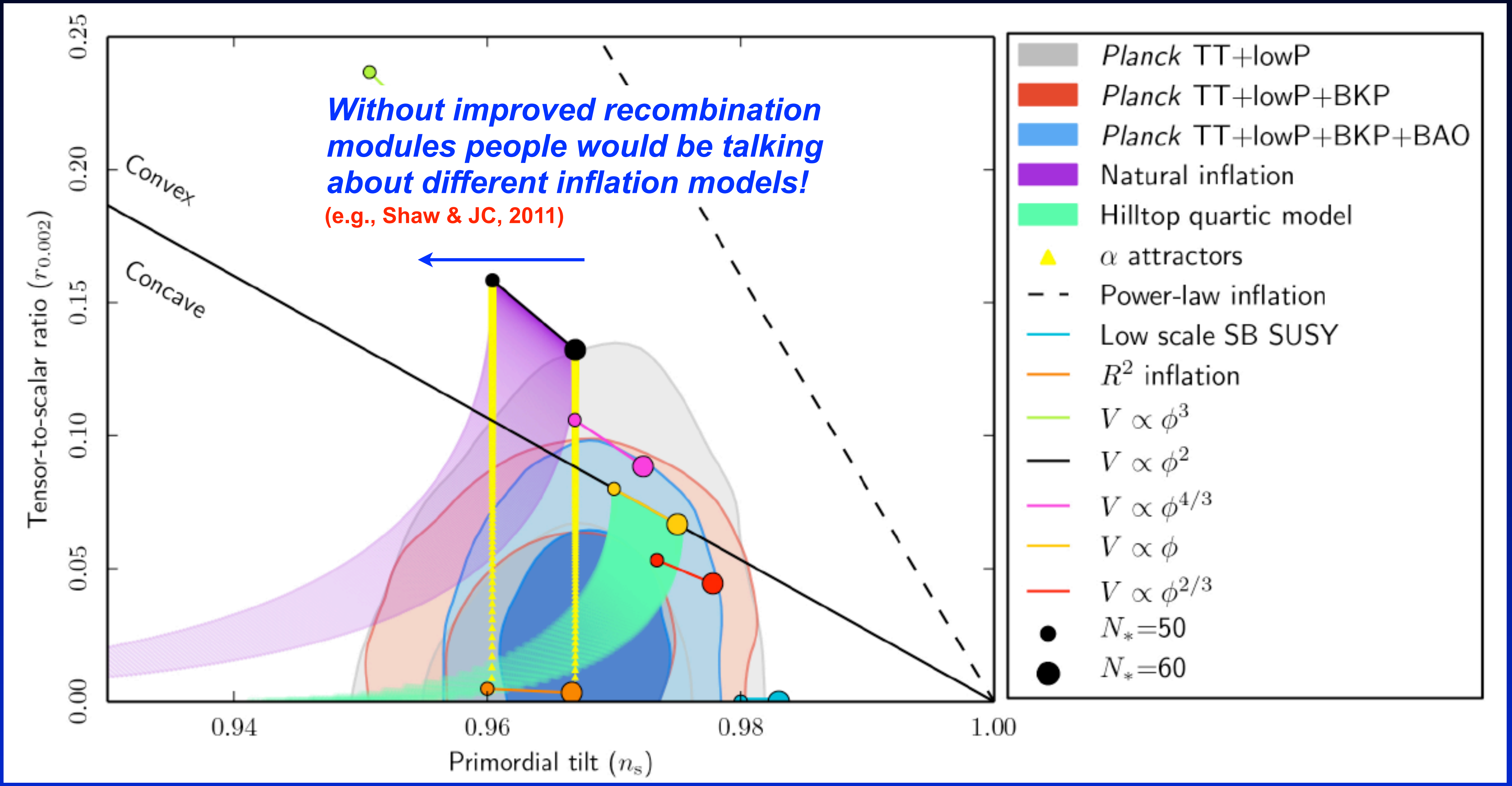
Solving the problem for the *Planck* Collaboration was a common effort!

Recombination Physics Meeting in Orsay 2008

see: http://www.b-pol.org/RecombinationConference/



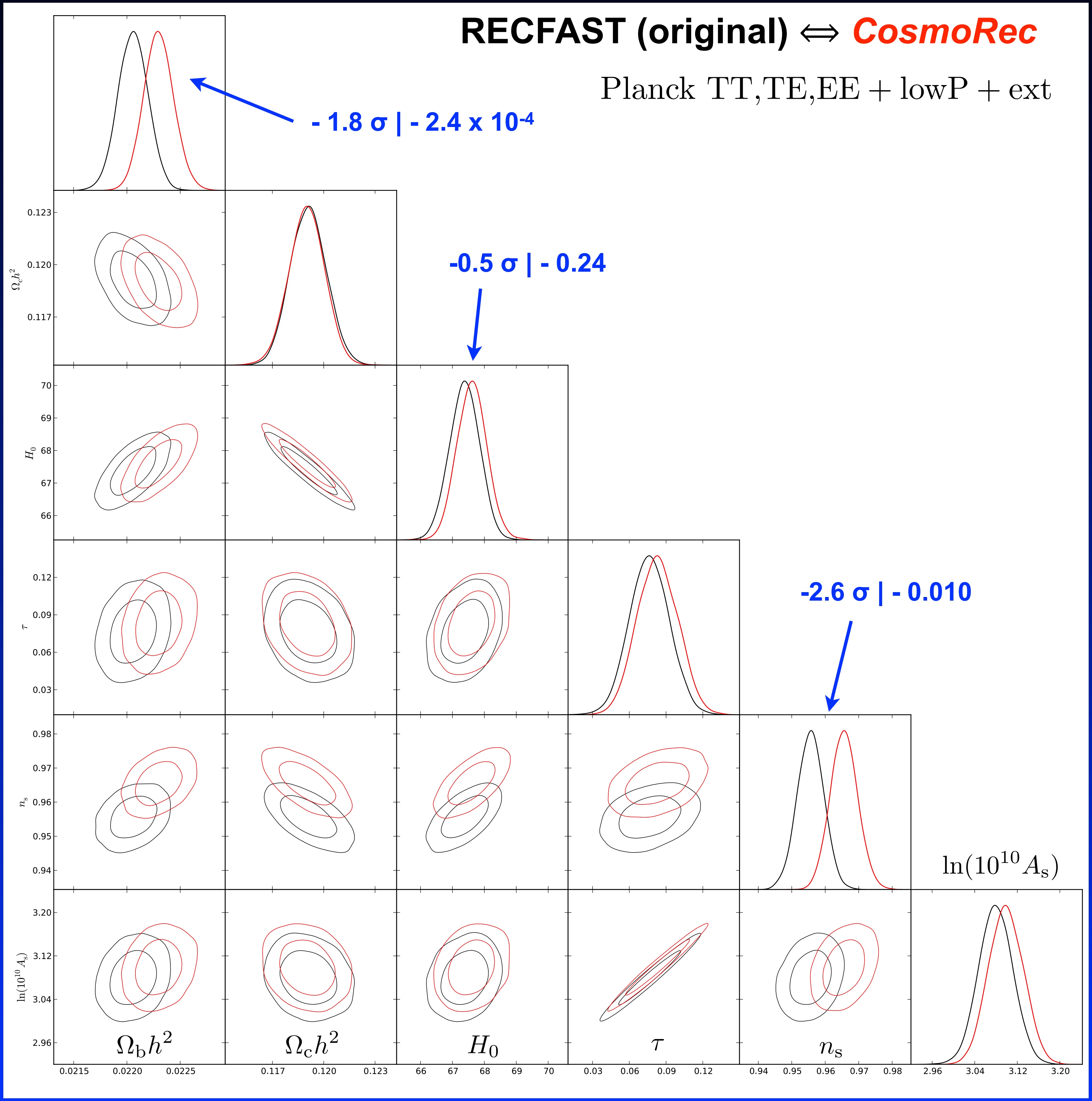
Importance of recombination for inflation constraints



Planck Collaboration, 2015, paper XX

- Analysis uses refined recombination model (`CosmoRec`/`HyRec`)

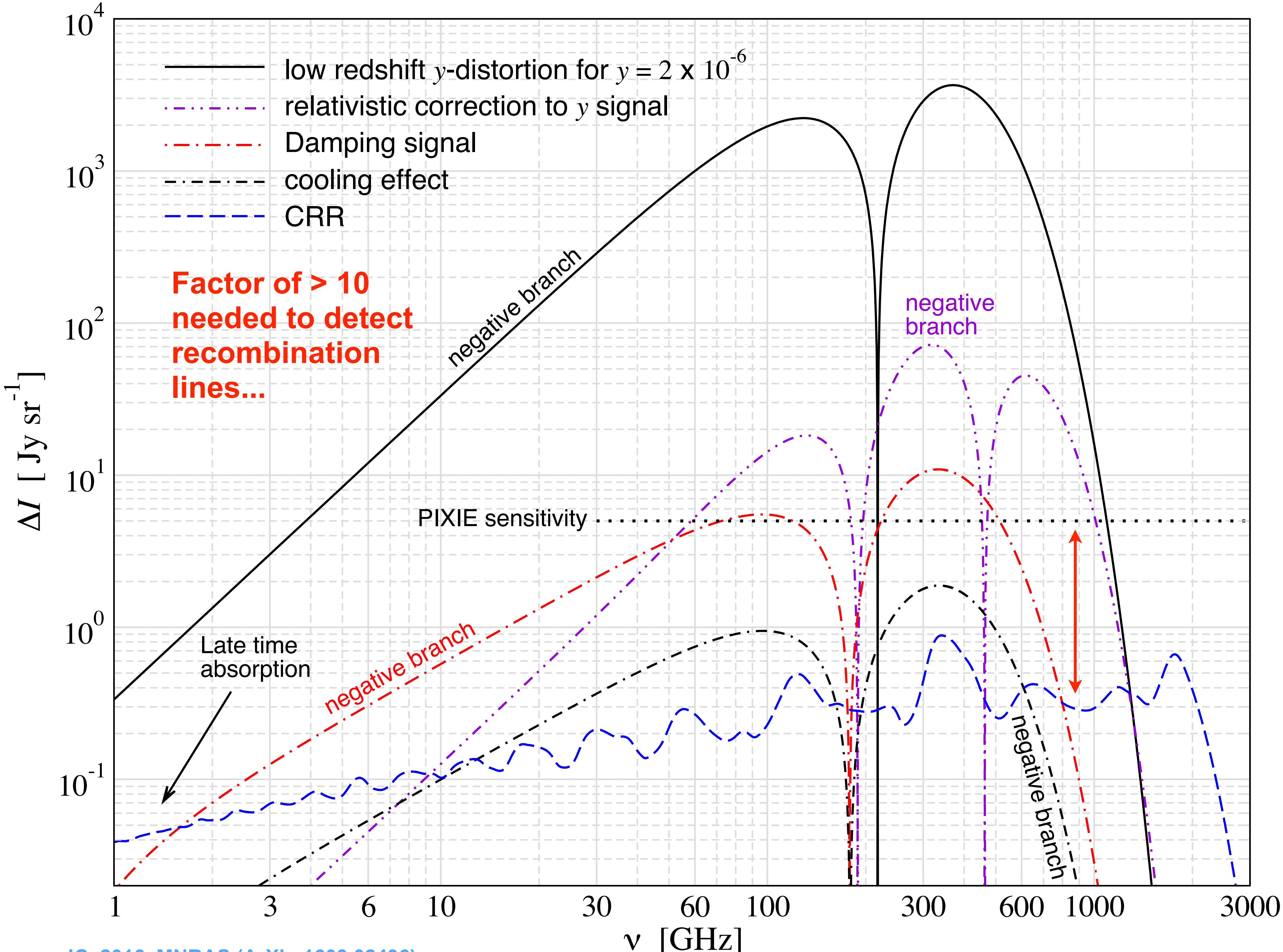
Biases as they *would* have been for *Planck*



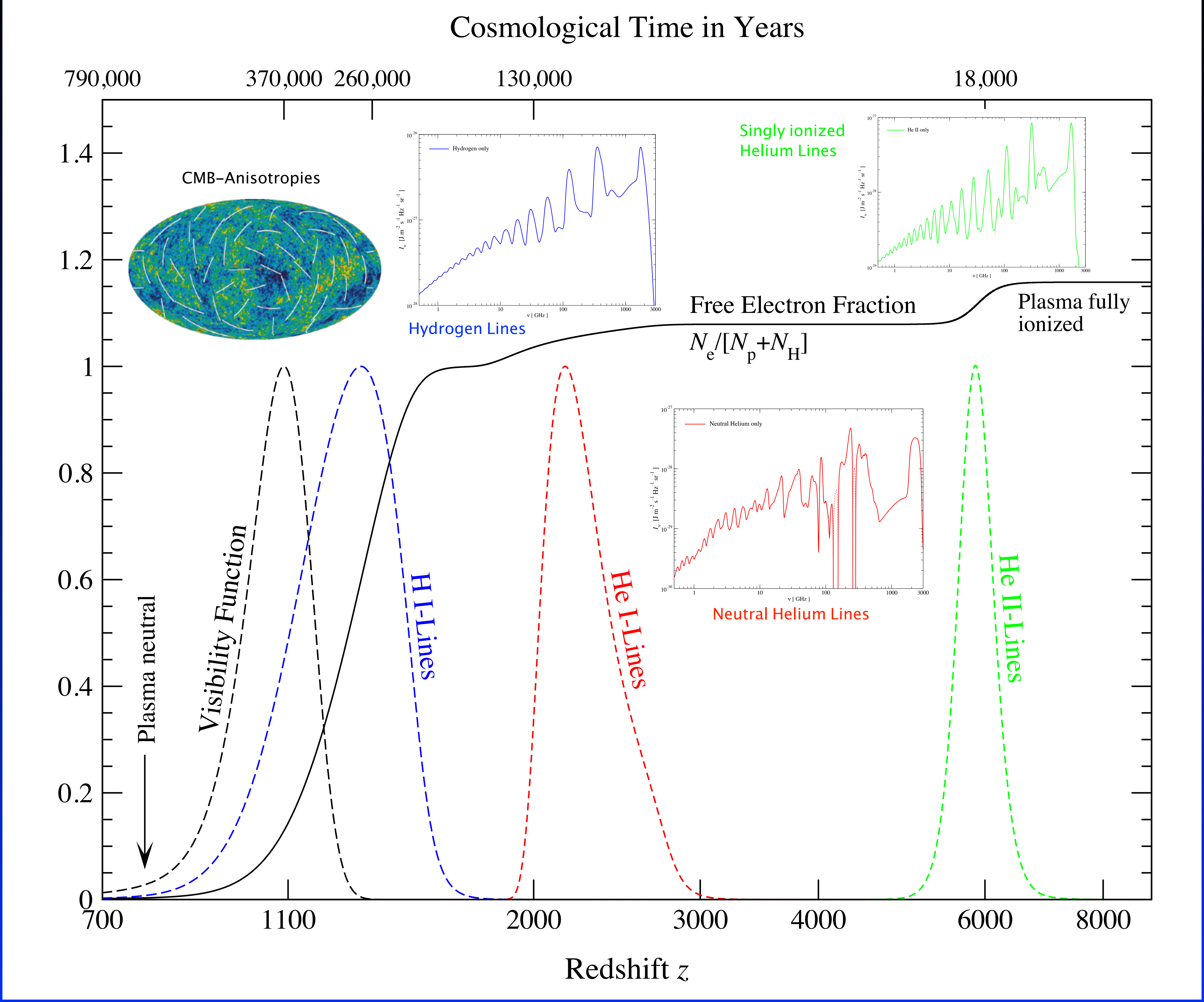
- Biases a little less significant with real *Planck* data
- absolute biases very similar
- In particular n_s would be biased significantly

Planck Collaboration, XIII 2015

Average CMB spectral distortions



JC, 2016, MNRAS (ArXiv:1603.02496)



Cosmological Time in Years
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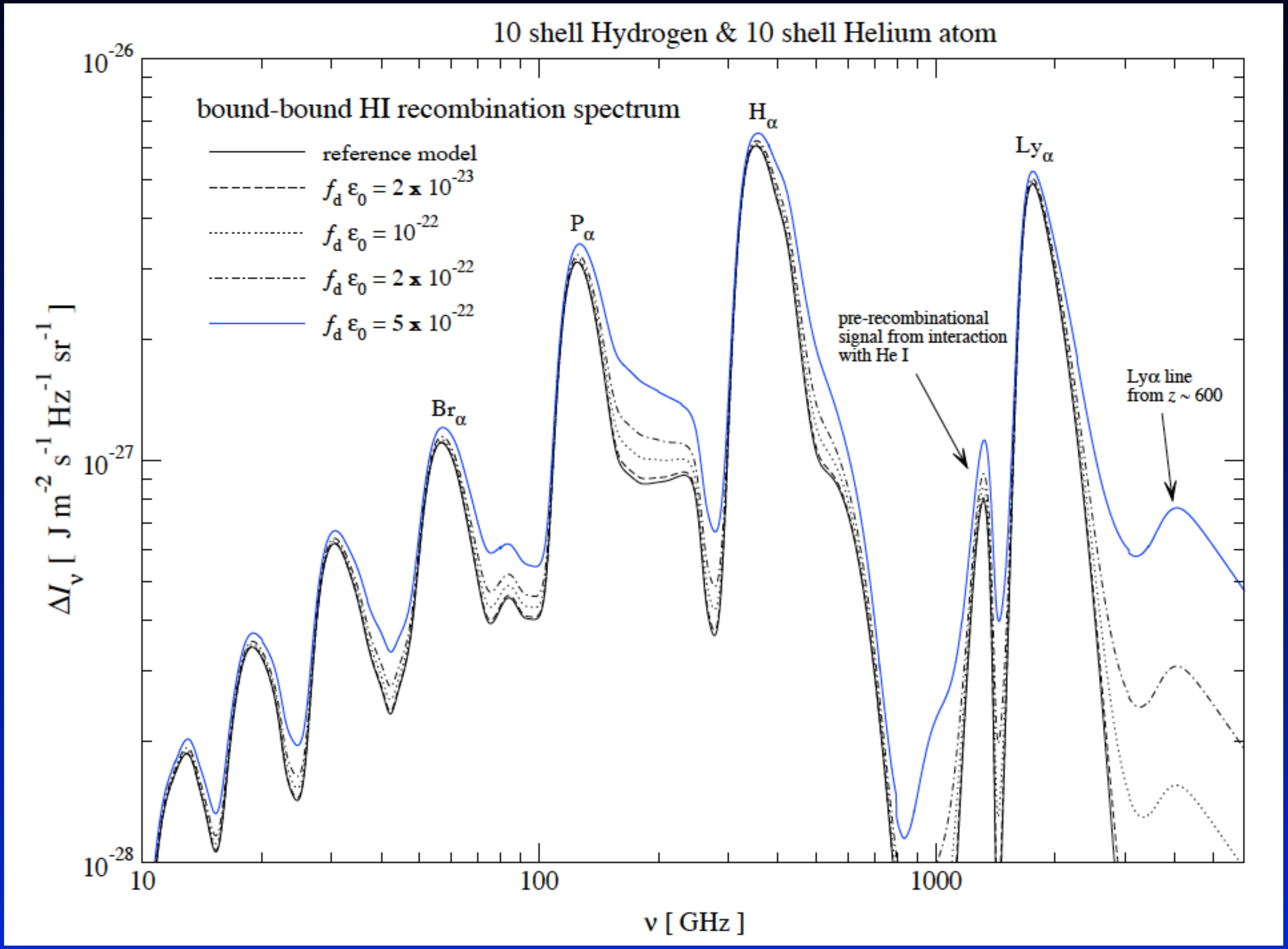
CMB–Anisotropies
Hydrogen Lines
Singly ionized
Helium Lines
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully
ionized
Neutral Helium Lines
Plasma neutral
Visibility Function
H I-Lines
He I-Lines
He II-Lines
1.4
1.2
1
0.8
0.6
0.4
0.2
0
700
1100
2000
3000
4000
6000
8000
Redshift z

Dark matter annihilations / decays



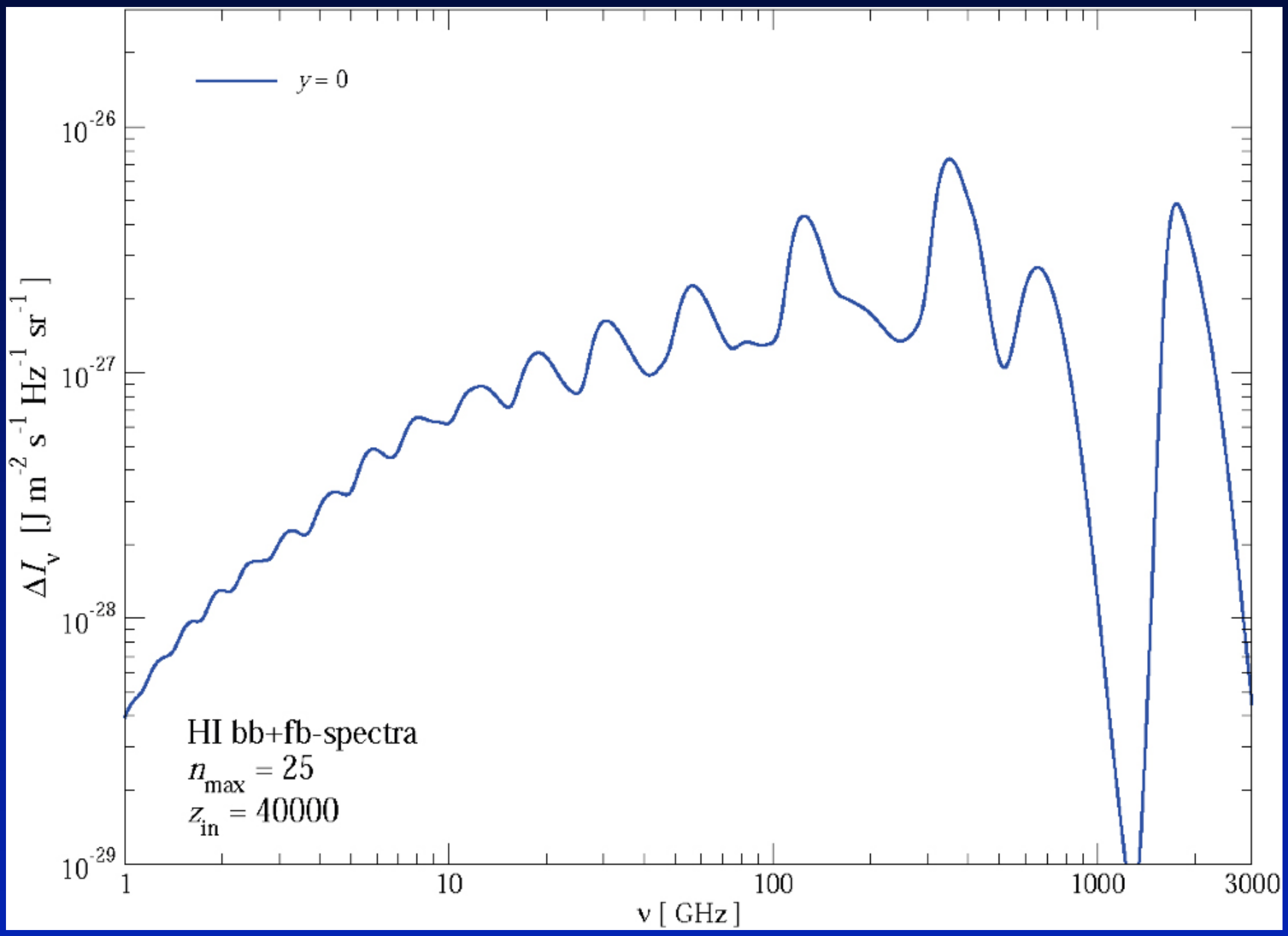
JC, 2009, arXiv:0910.3663

- Additional photons at all frequencies
- Broadening of spectral features
- Shifts in the positions

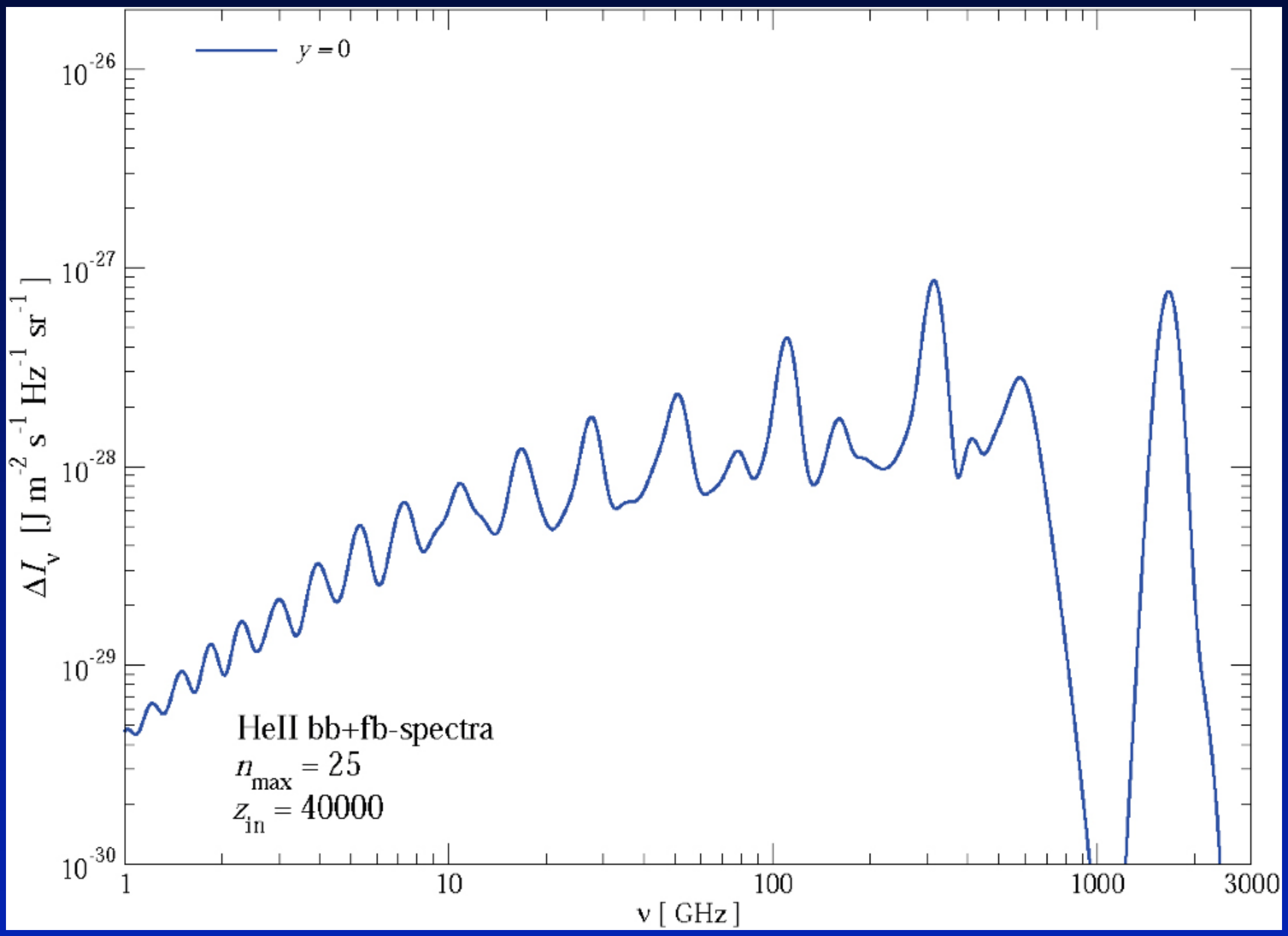
CMB spectral distortions after single energy release

25 shell HI and HeII bb&fb spectra: dependence on y

Hydrogen



Helium +



JC & Sunyaev, 2008, astro-ph/0803.3584

CMB spectral distortions after single energy release

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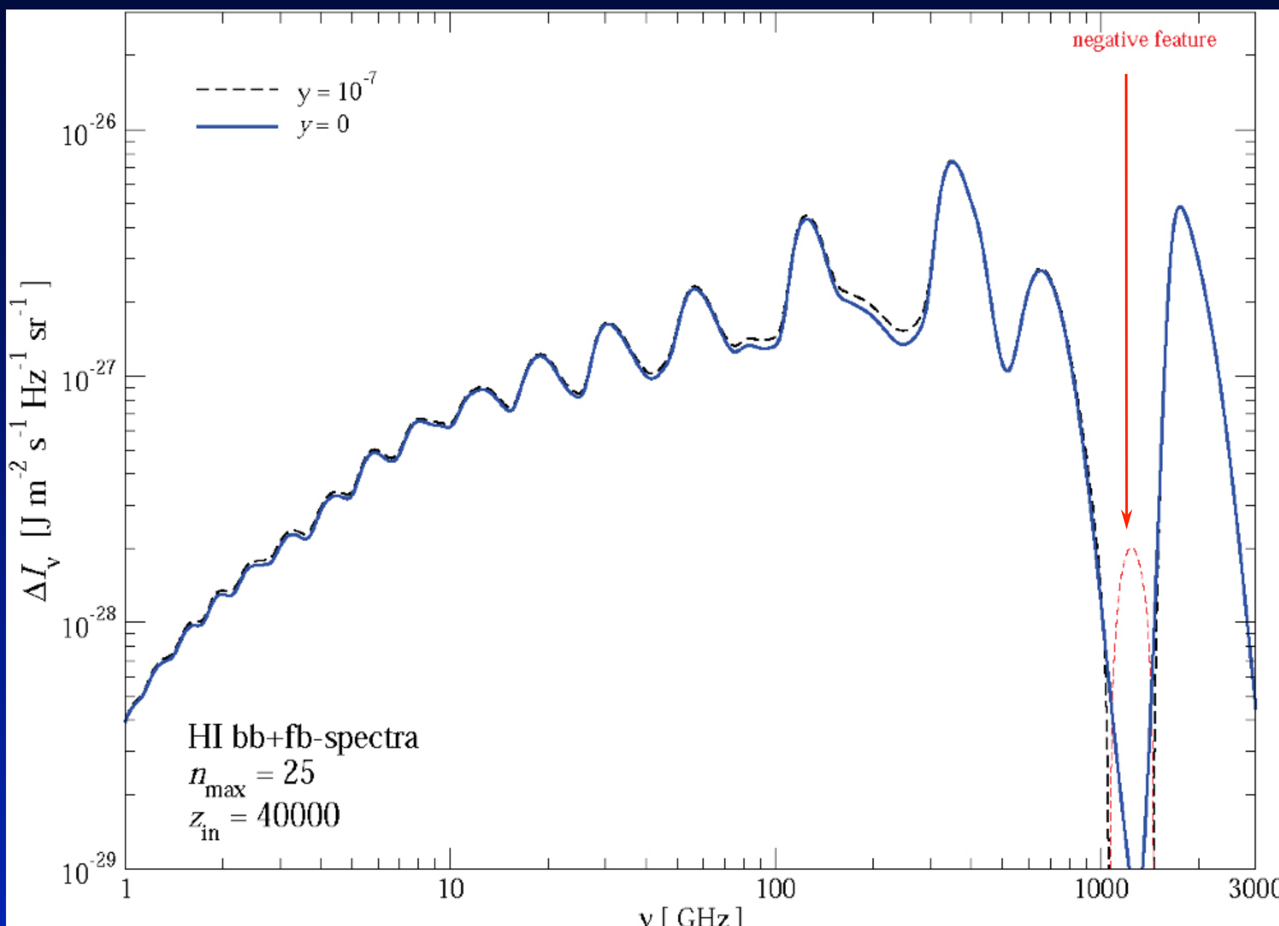
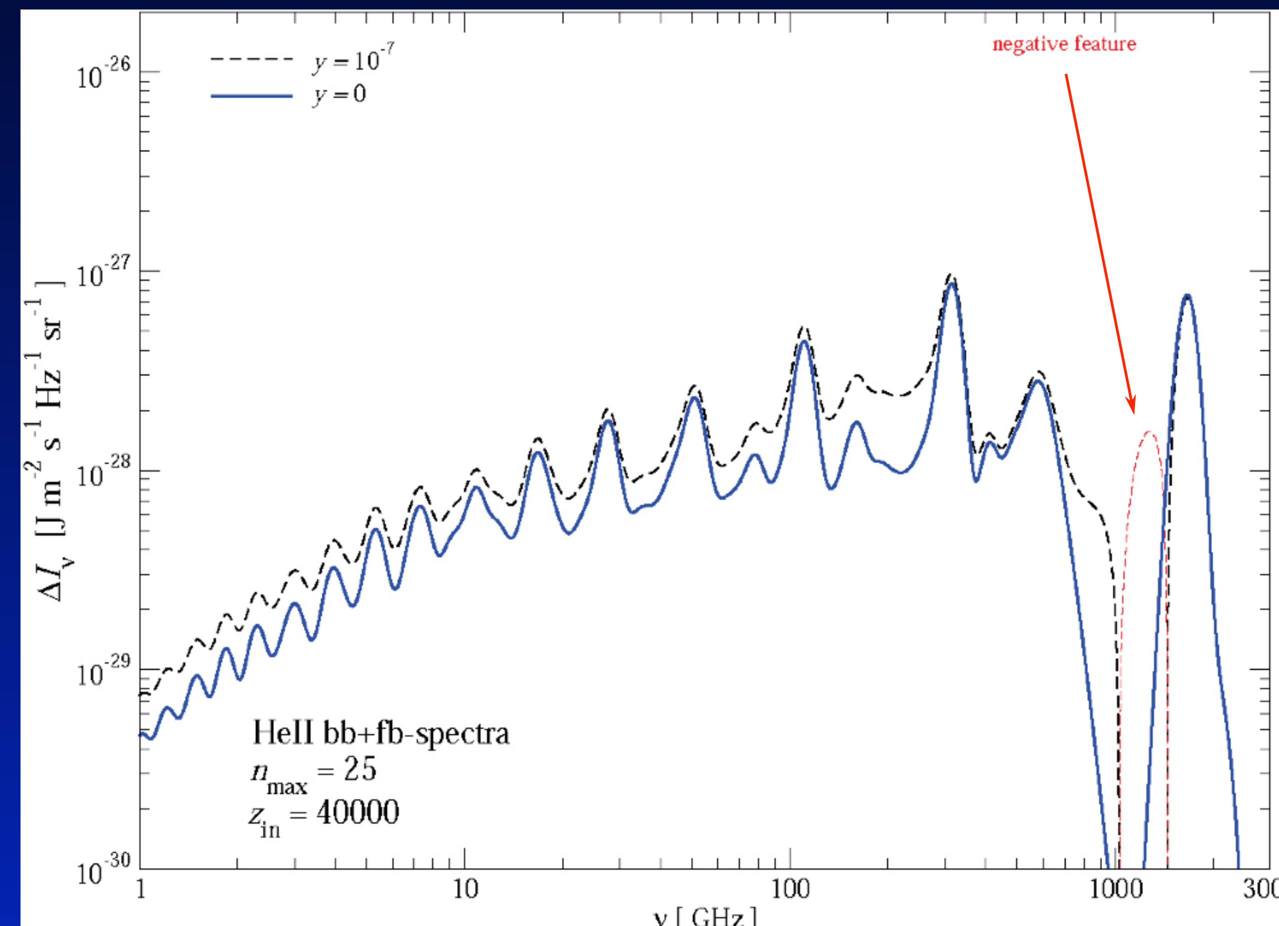


Helium +



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CMB spectral distortions after single energy release

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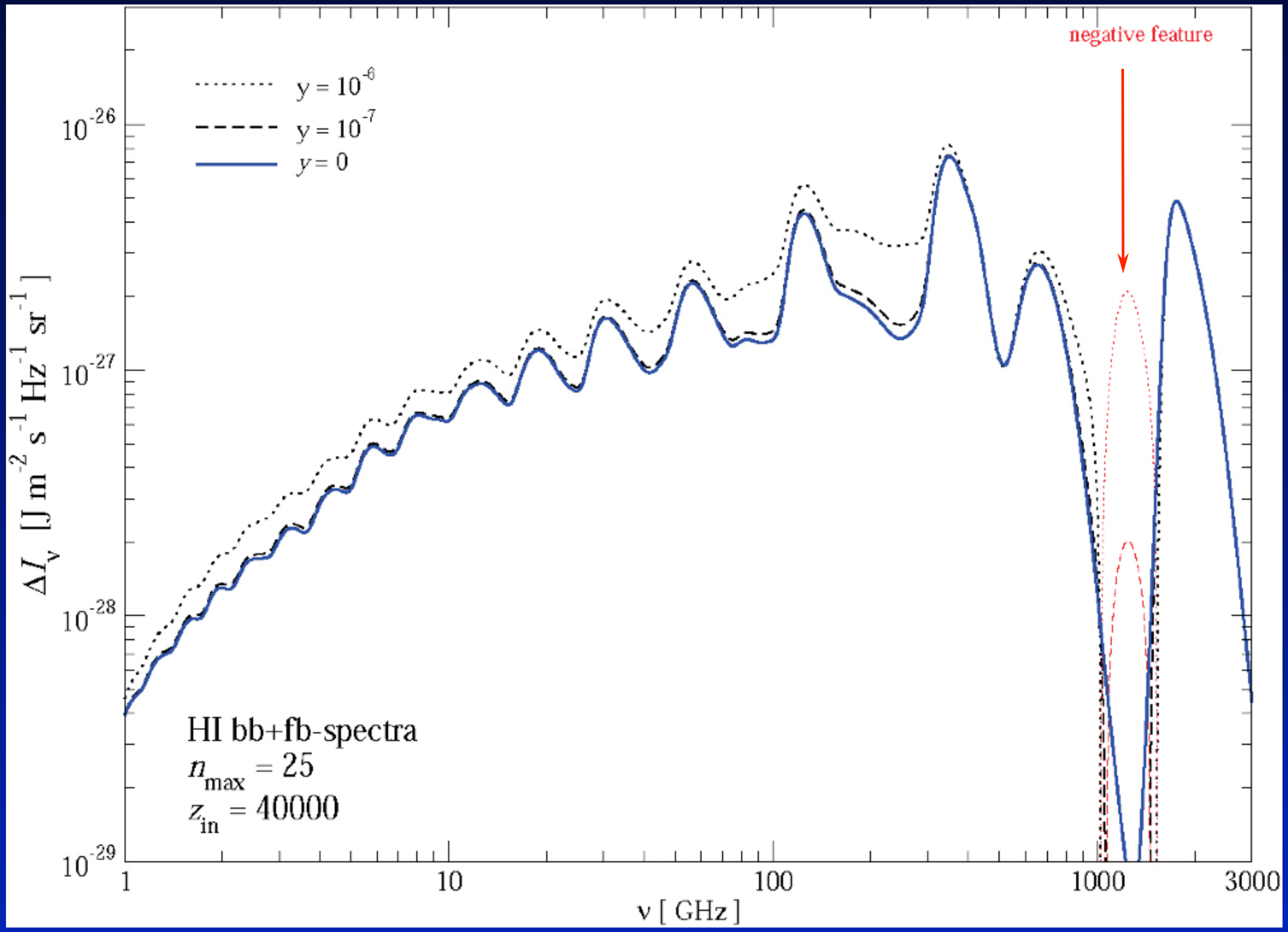
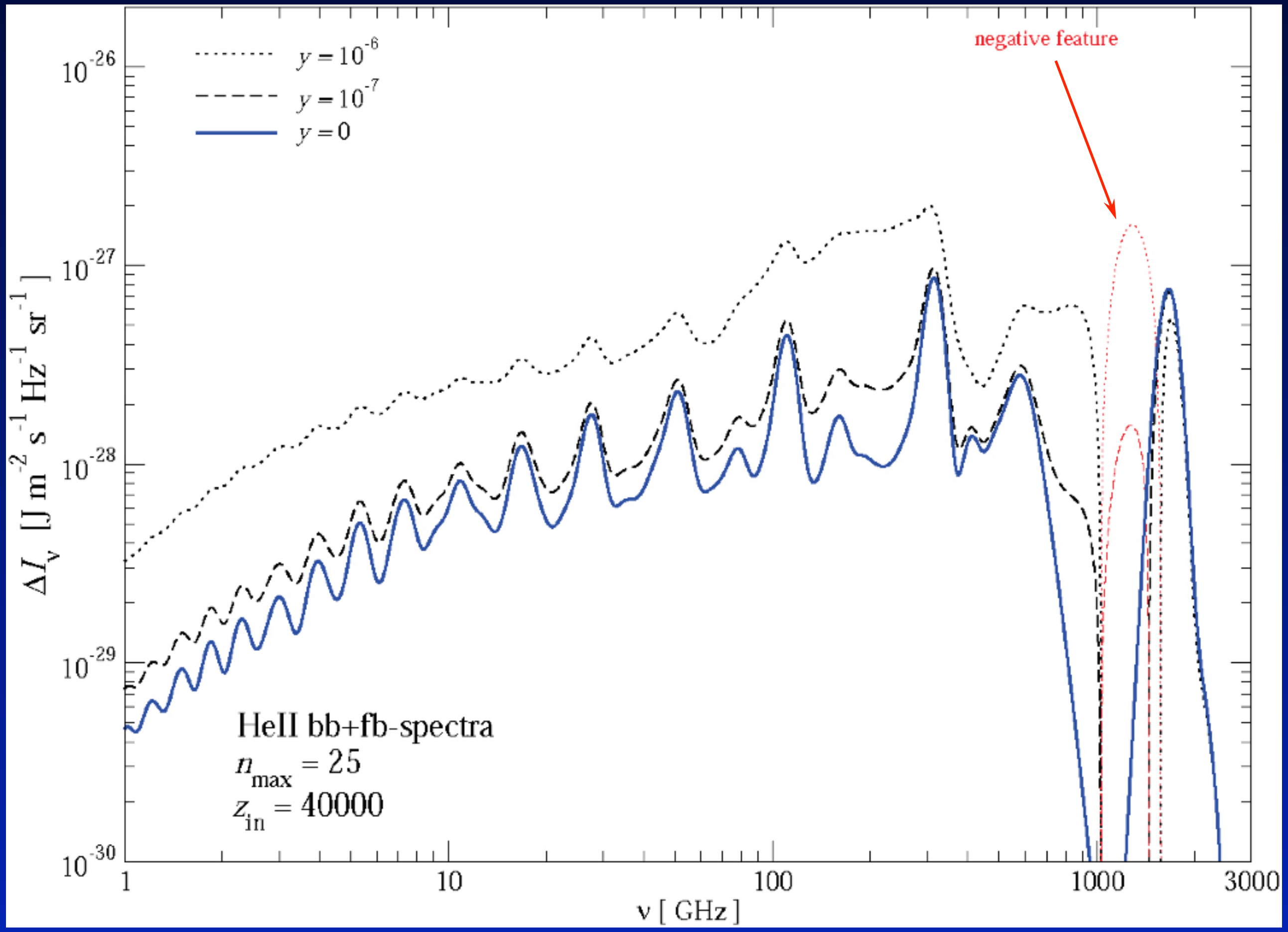


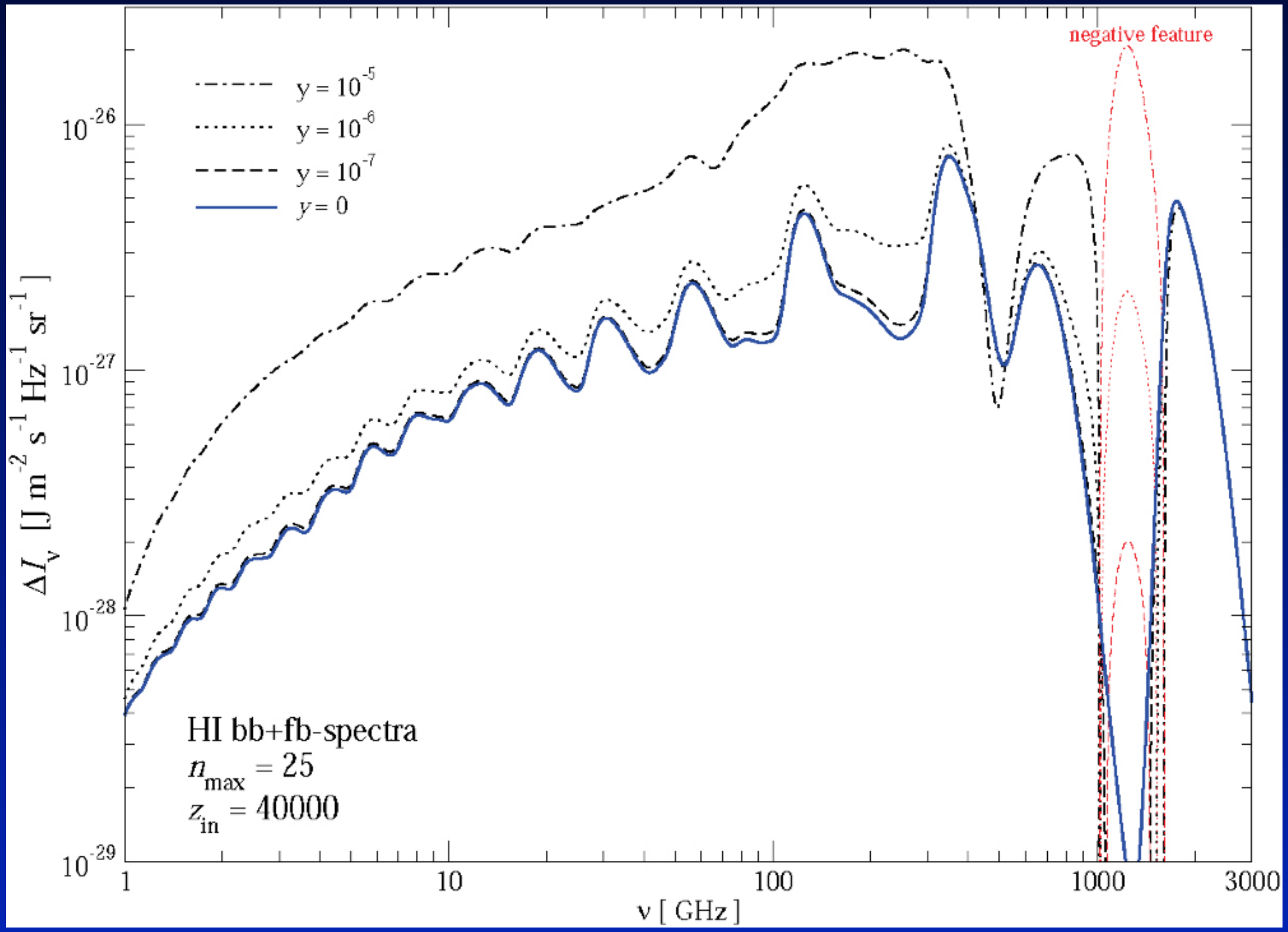
Helium +



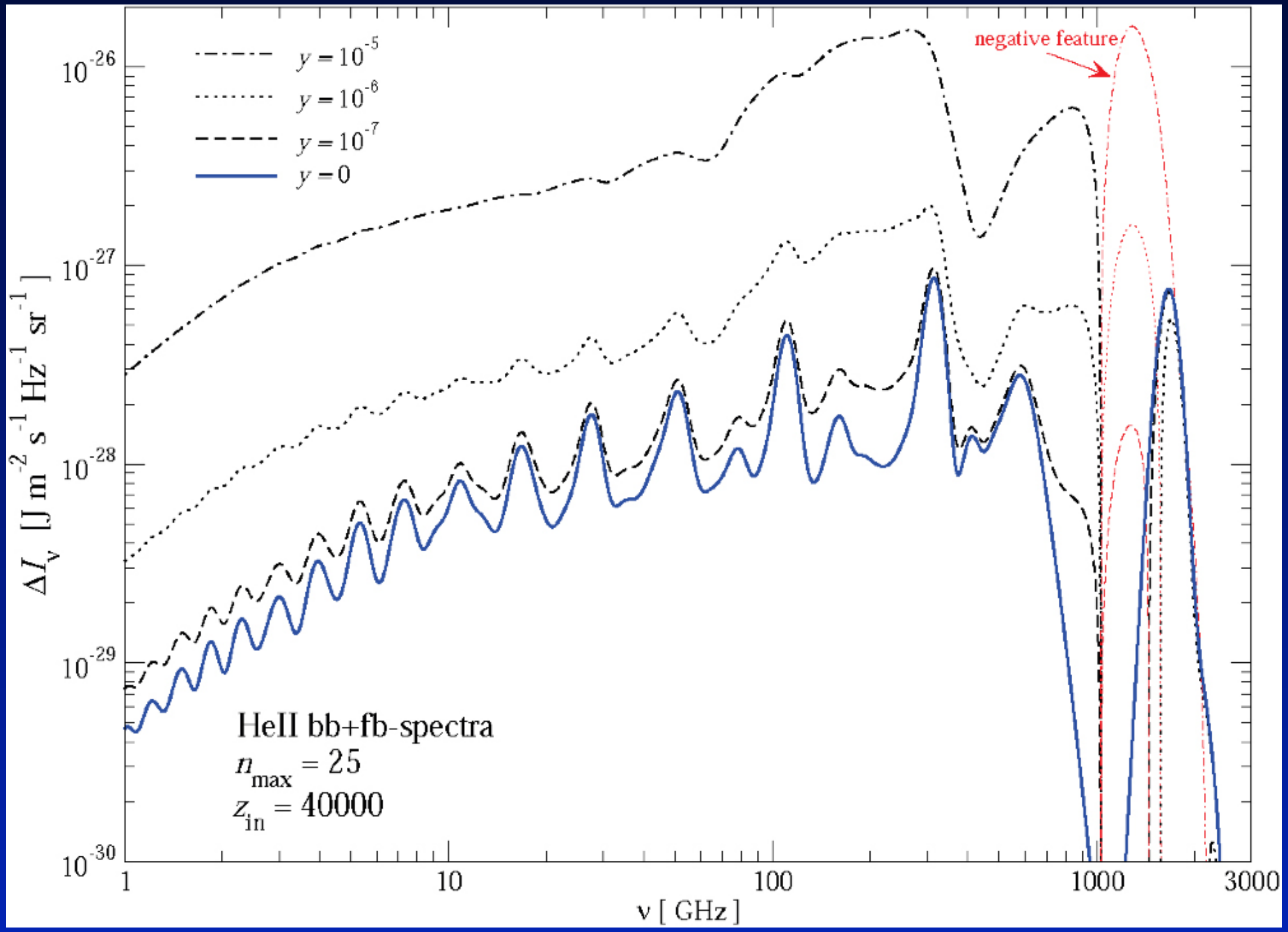
JC & Sunyaev, 2008, astro-ph/0803.3584

CMB spectral distortions after single energy release
25 shell HI and HeII bb&fb spectra: dependence on y

Hydrogen



Helium +



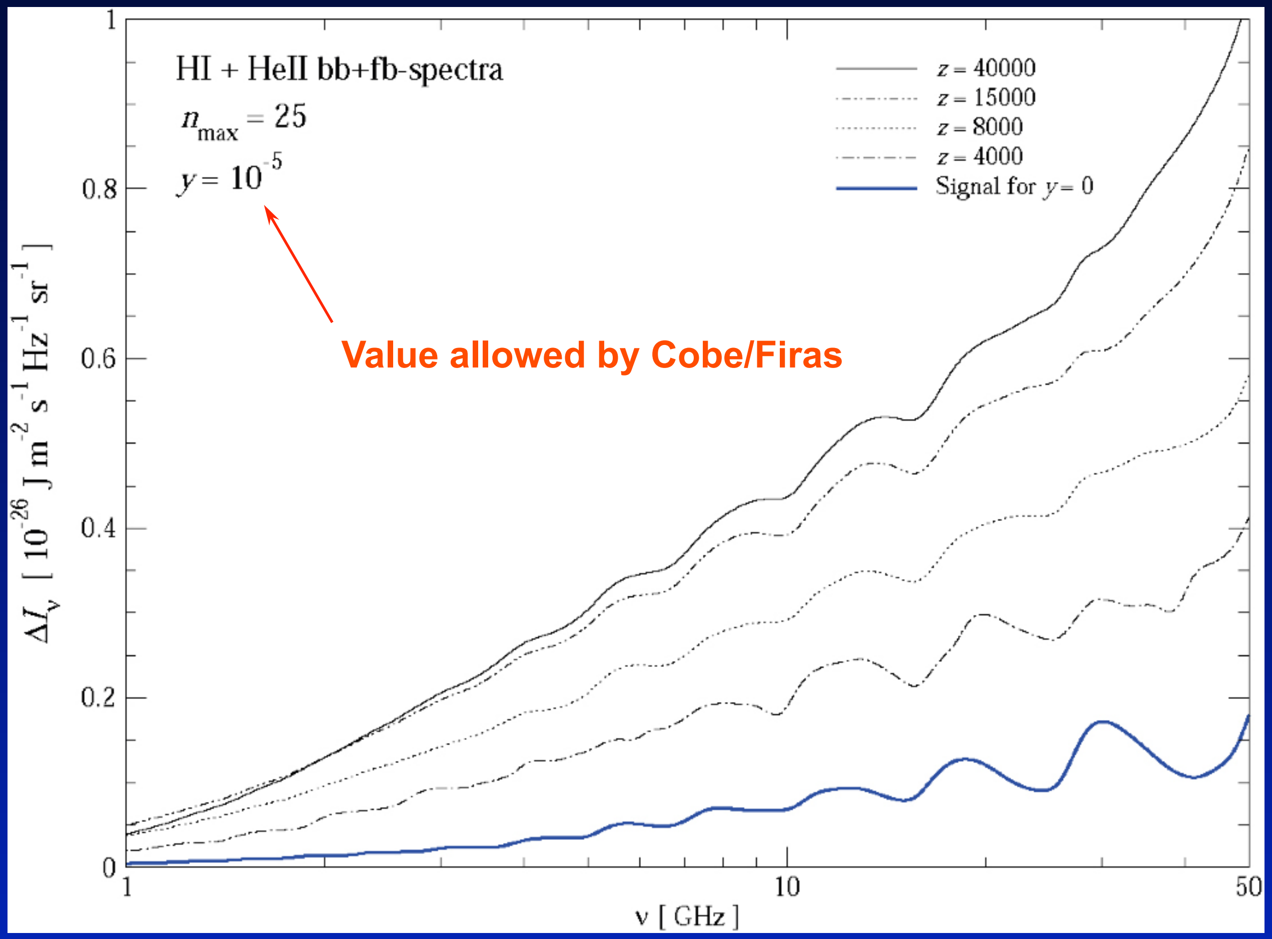
JC & Sunyaev, 2008, astro-ph/0803.3584

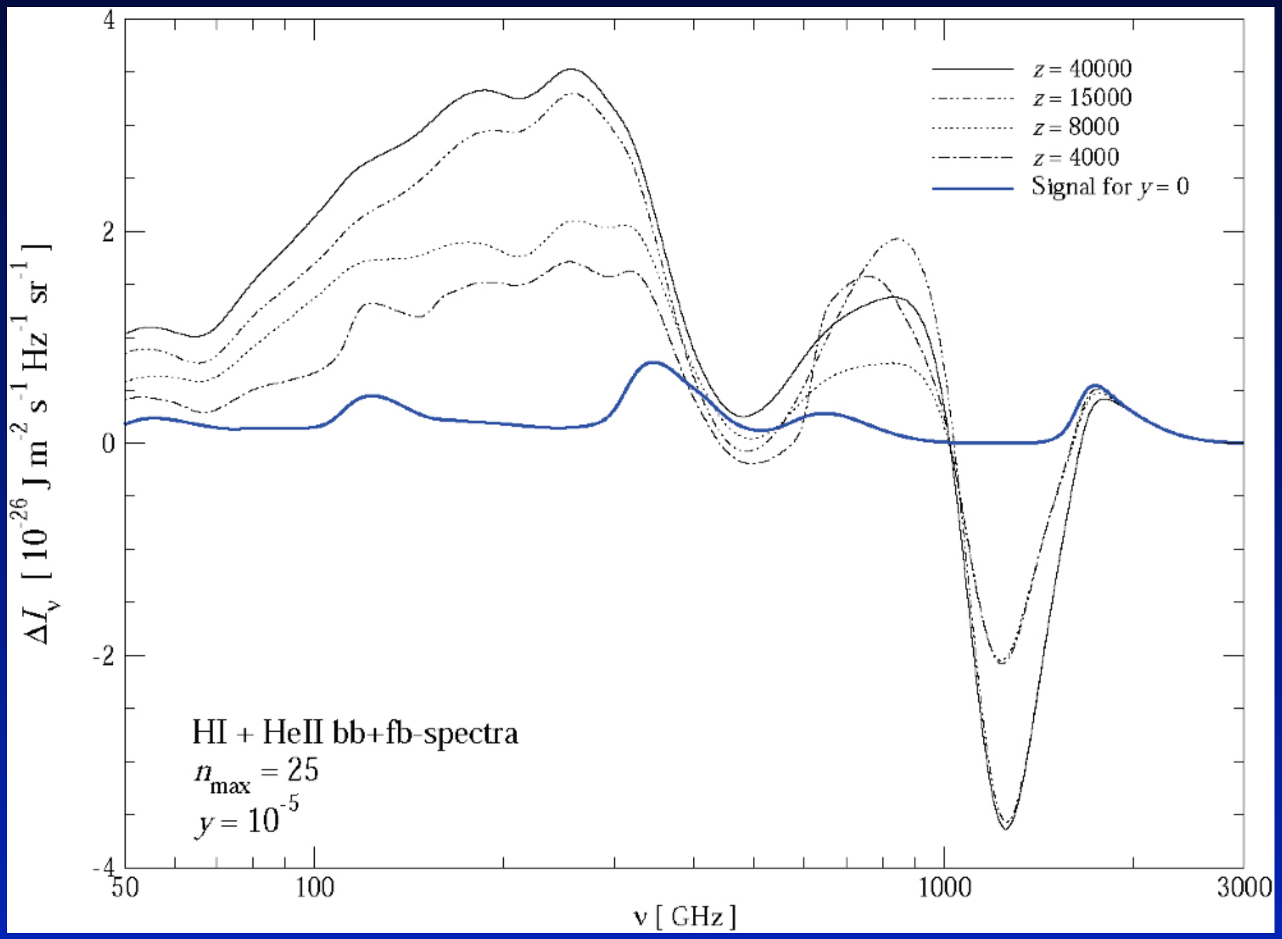
- Large increase in the total amplitude of the distortions with value of *y*!
- Strong emission-absorption feature in the Wien-part of CMB (absent for *y*=0!!!)
- HeII contribution to the pre-recombinational emission as strong as the one from Hydrogen alone !

CMB spectral distortions after single energy release

25 shell HI and HeII bb&fb spectra: dependence on z

Hydrogen and Helium +

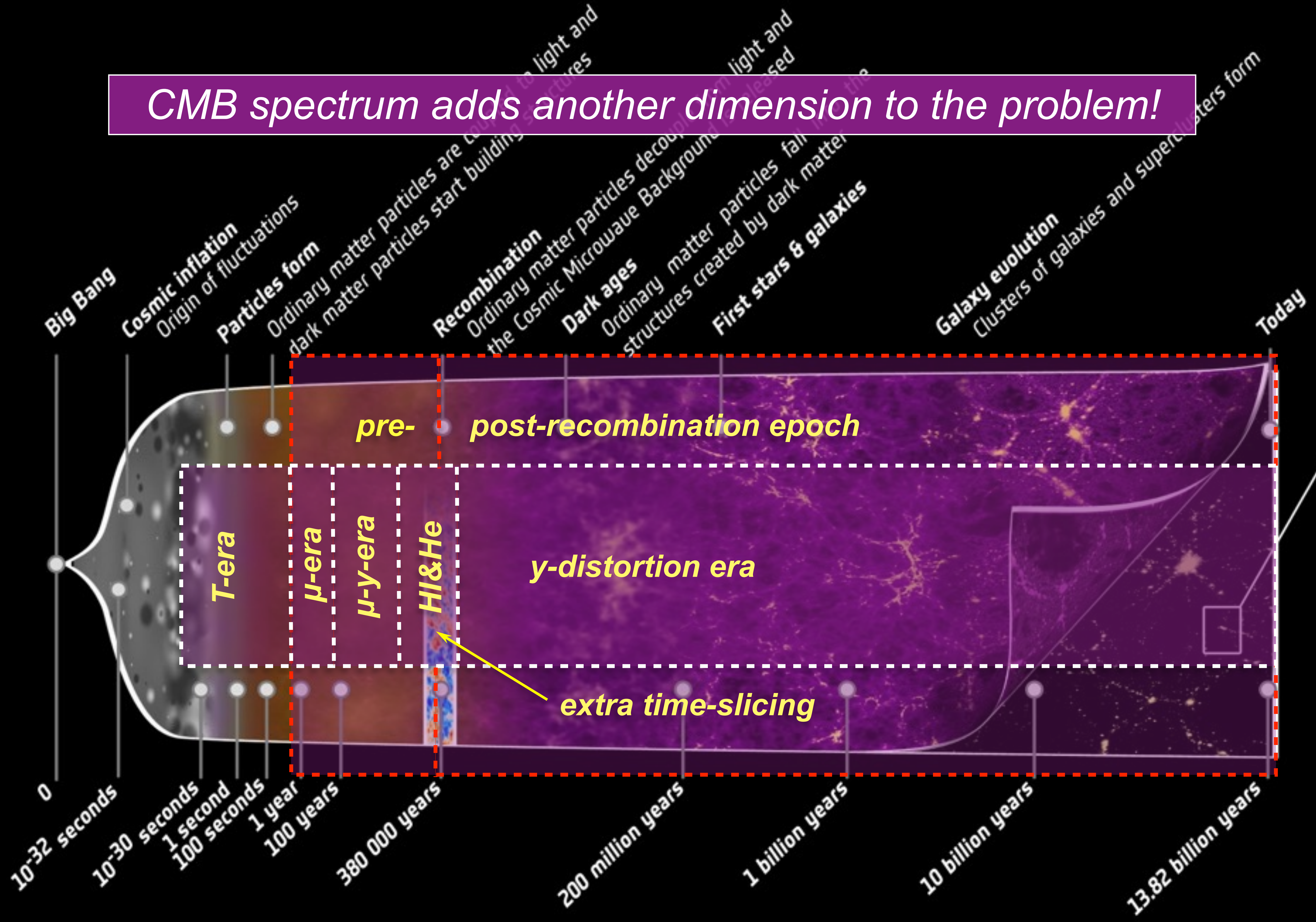




JC & Sunyaev, 2008, astro-ph/0803.3584

- Large increase in the total amplitude of the distortions with injection redshift!
- Number of spectral features depends on injection redshift!
- Emission-Absorption feature increases ~2 for energy injection z ⇒11000

CMB spectrum adds another dimension to the problem!



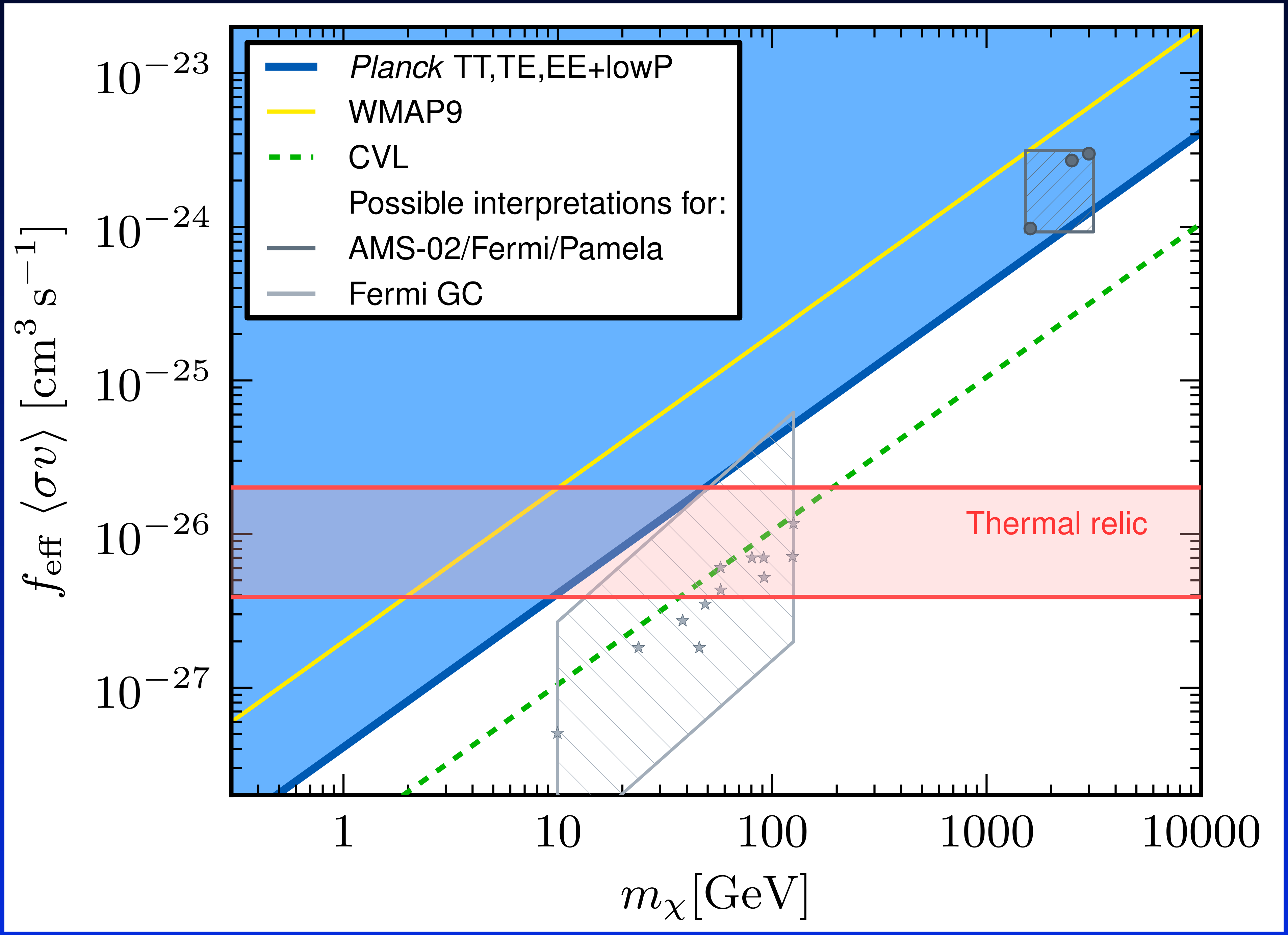
Annihilating/decaying (dark matter) particles

Why is this interesting?

- A priori no specific particle in mind
- *But:* we do not know what dark matter is and where it really came from!
- Was dark matter thermally produced or as a decay product of some heavy particle?
- is dark matter structureless or does it have internal (excited) states?
- sterile neutrinos? moduli? Some other relic particle?
- From the theoretical point of view really no shortage of particles to play with...

CMB spectral distortions offer a new independent way to constrain these kind of models

Latest Planck limits on annihilation cross section

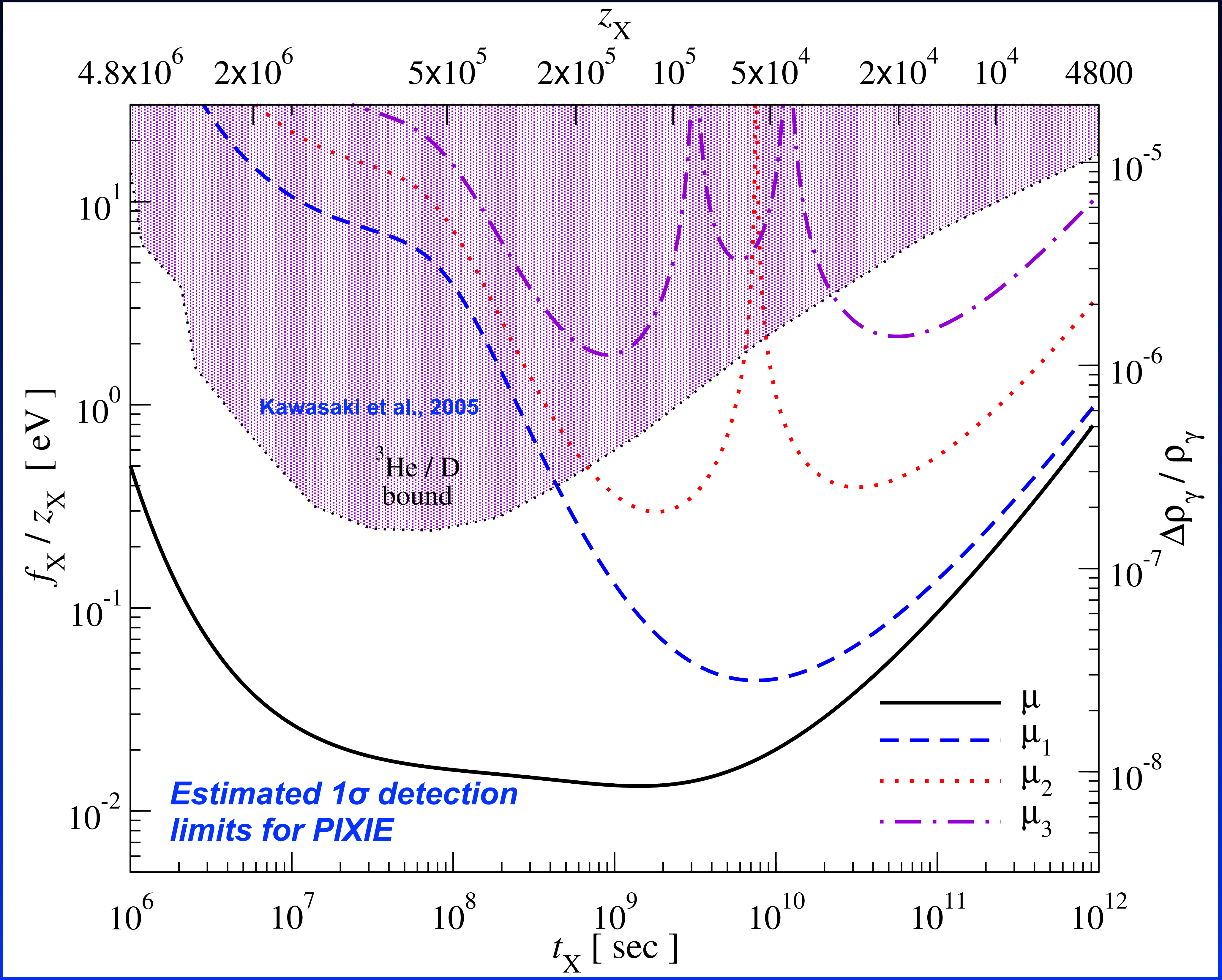


Planck Collaboration, paper XIII, 2015

- AMS/Pamela models in tension
- but interpretation model-dependent
- Sommerfeld enhancement?
- clumping factors?
- annihilation channels?

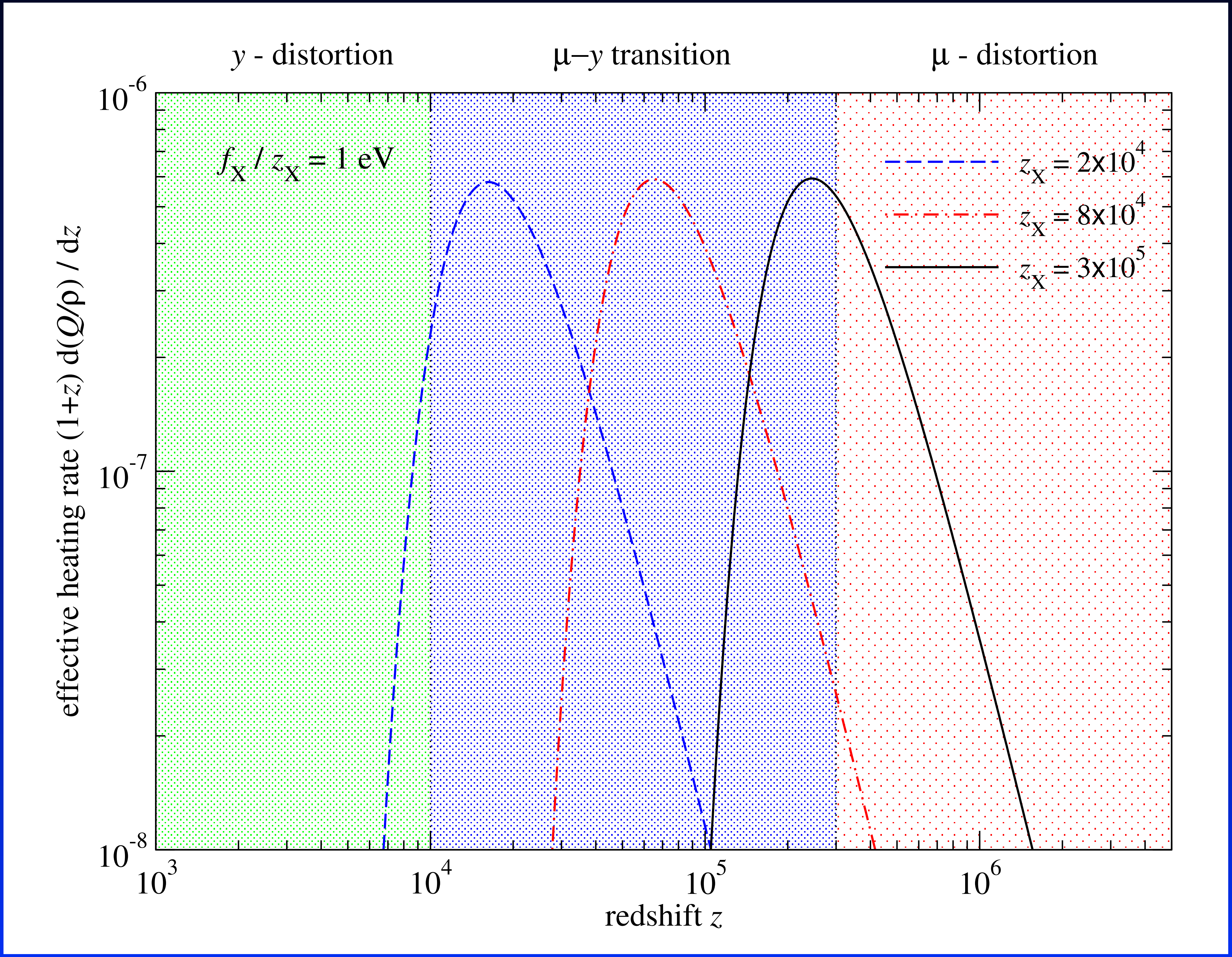
For current constraint only (weak) upper limits from distortion...

Distortions could shed light on decaying (DM) particles!



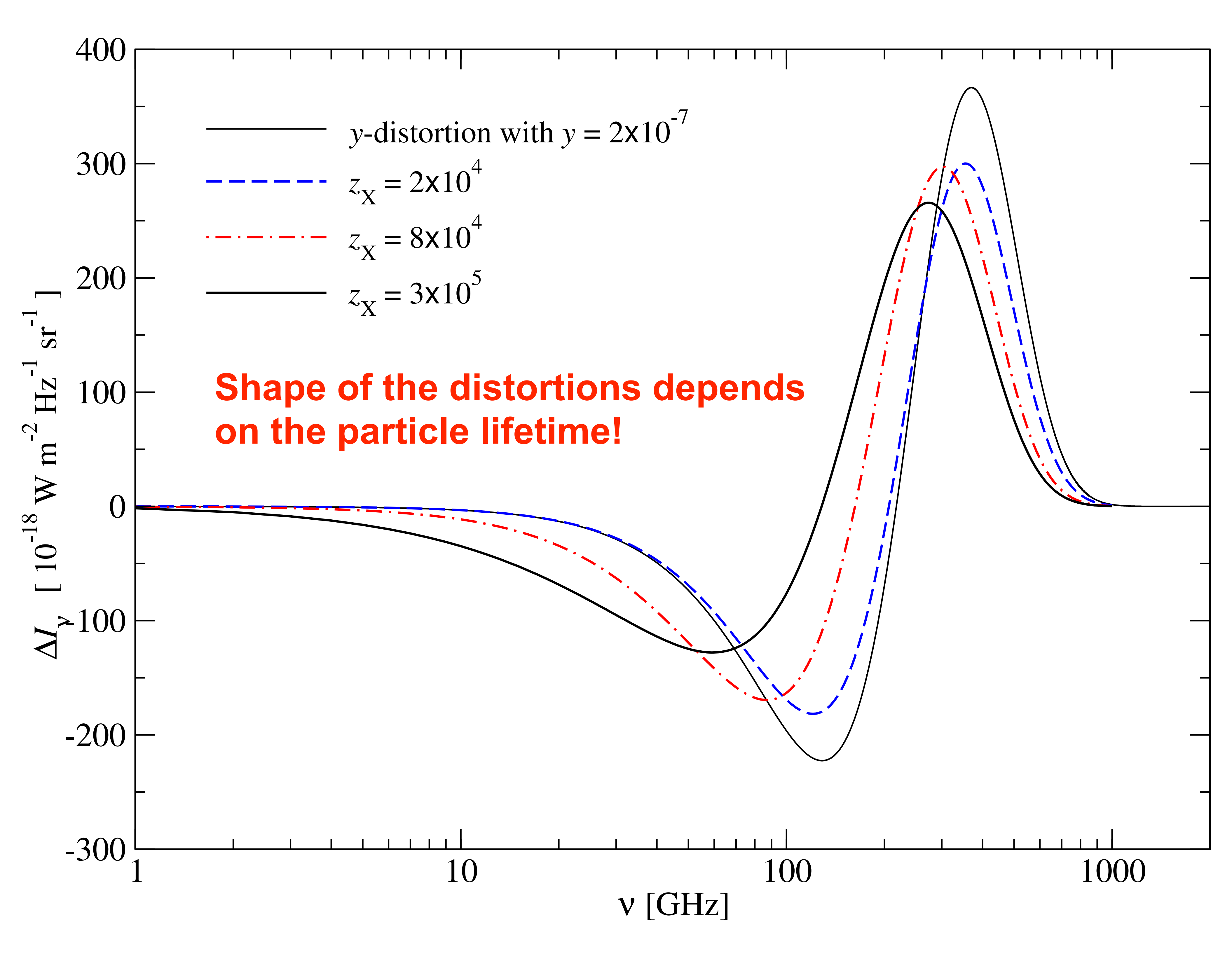
JC & Jeong, 2013

Decaying particle scenarios



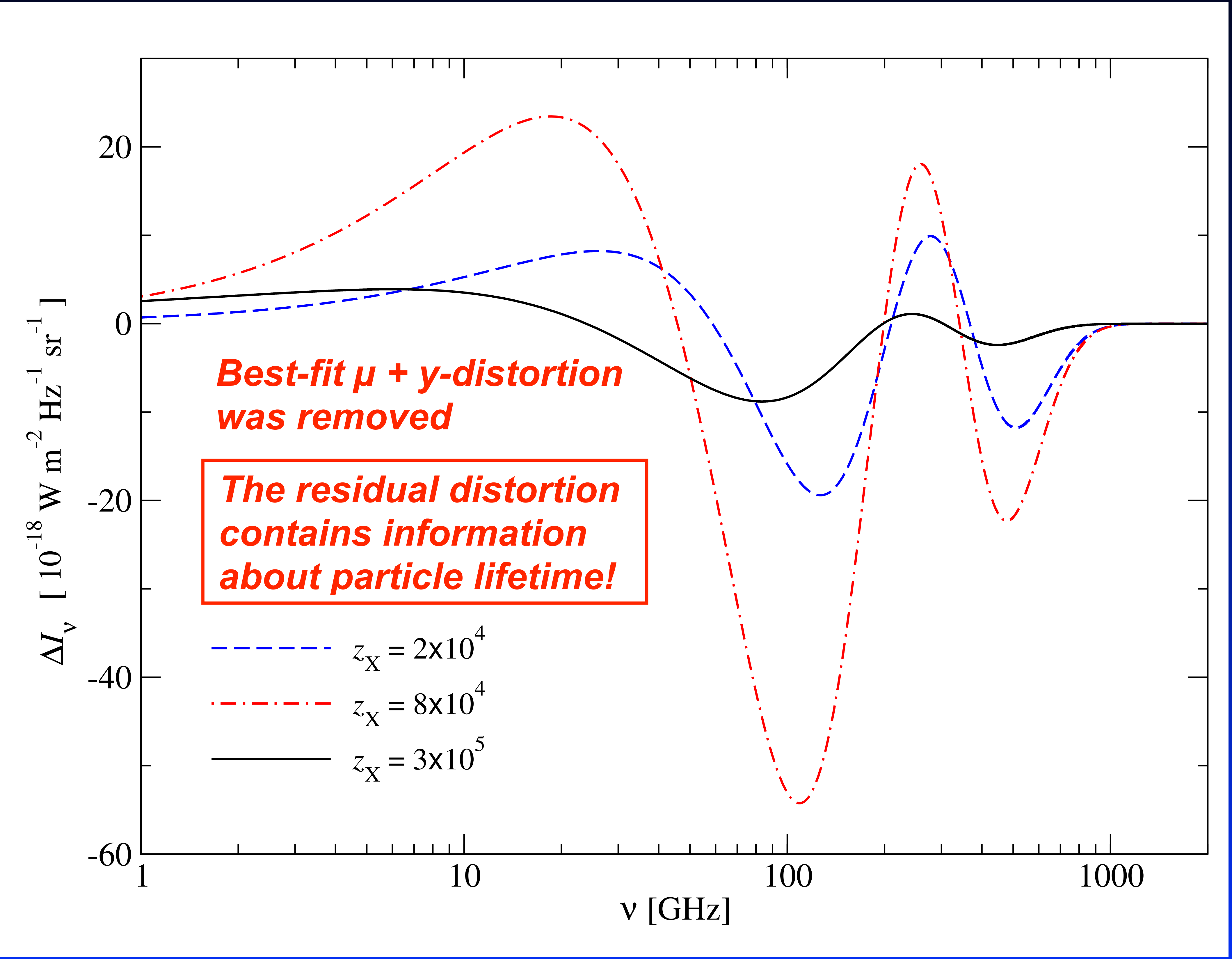
JC & Sunyaev, 2011, Arxiv:1109.6552
JC, 2013, Arxiv:1304.6120

Decaying particle scenarios



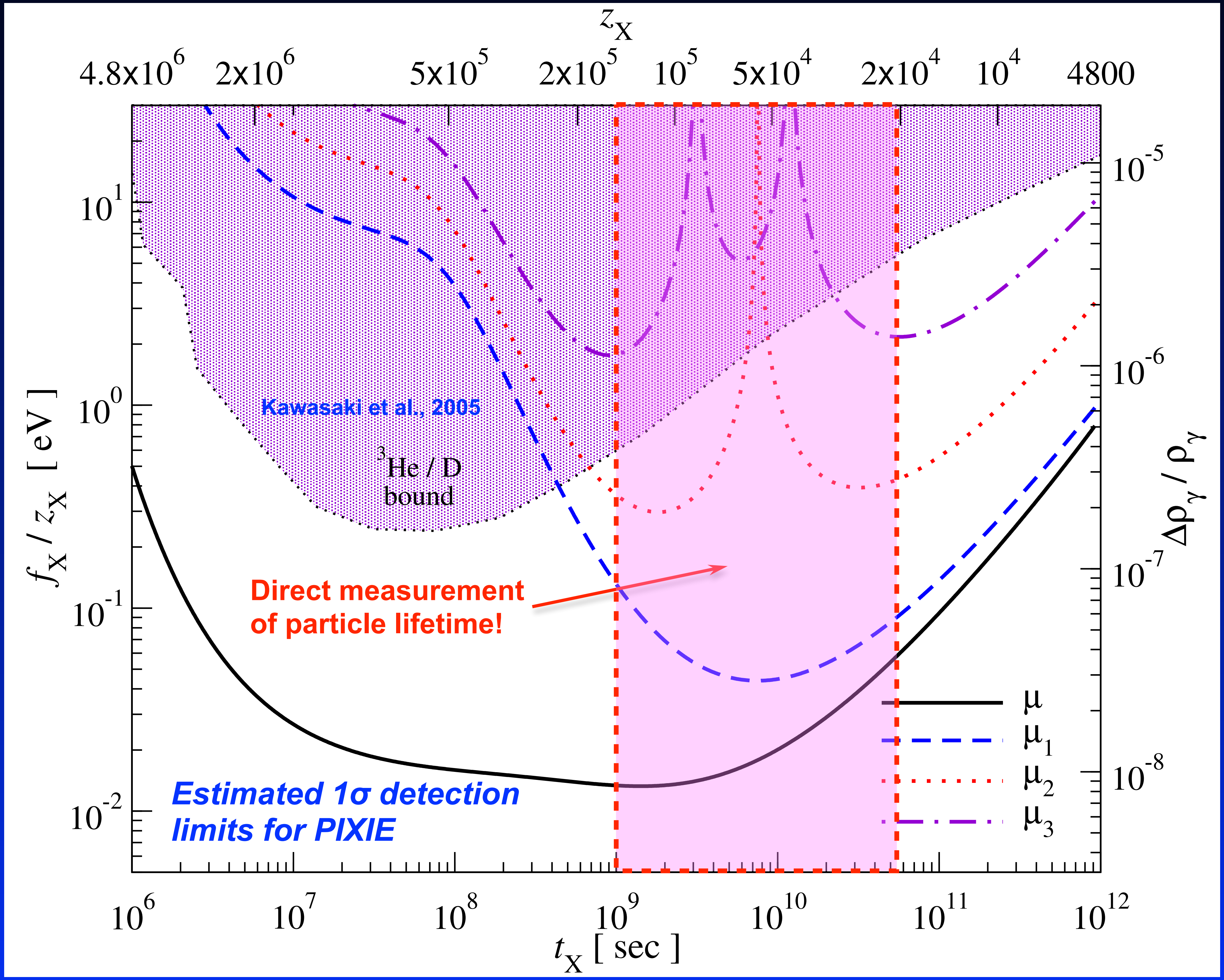
JC & Sunyaev, 2011, Arxiv:1109.6552
JC, 2013, Arxiv:1304.6120

Decaying particle scenarios (information in residual)



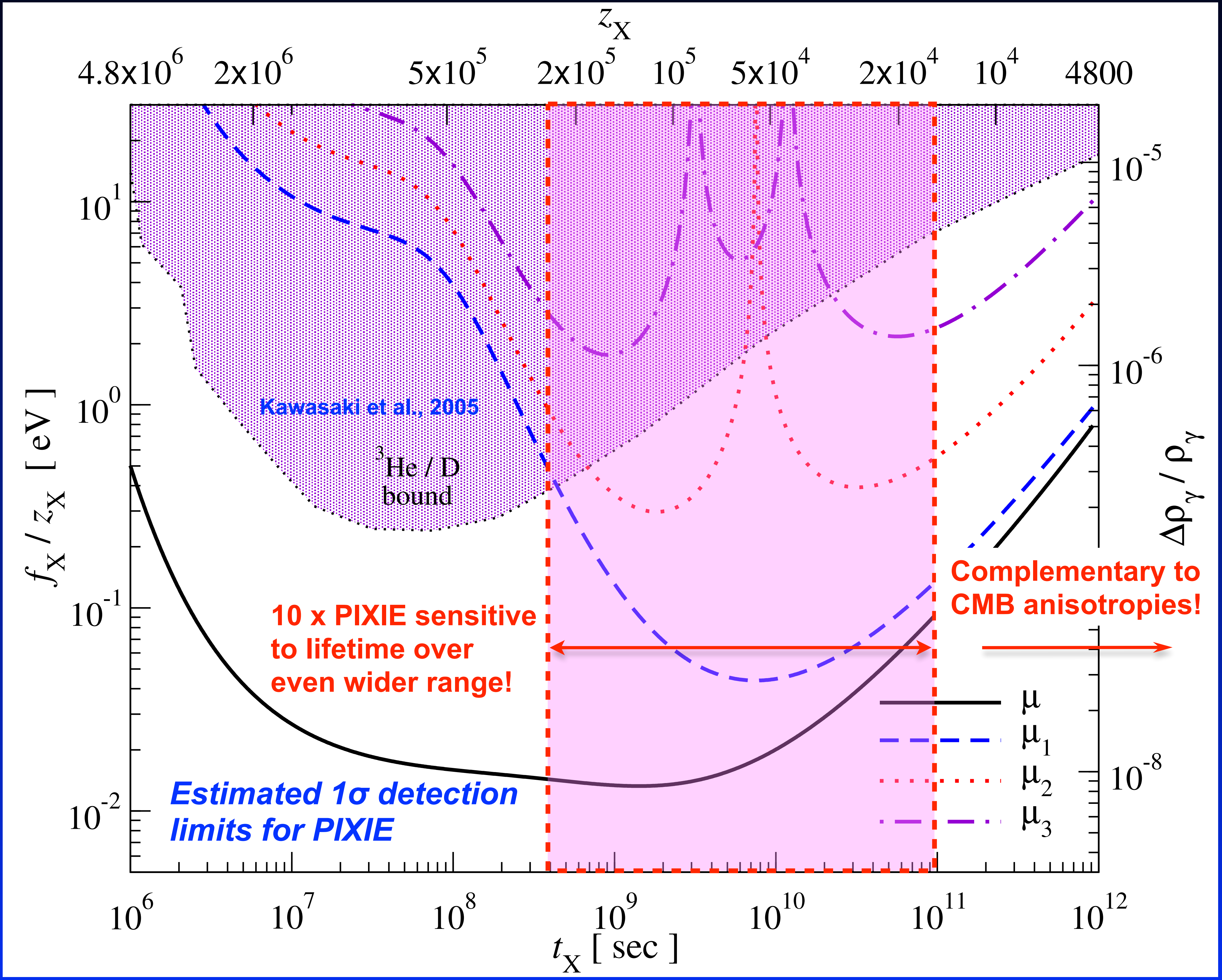
JC & Sunyaev, 2011, Arxiv:1109.6552
JC, 2013, Arxiv:1304.6120

Distortions could shed light on decaying (DM) particles!



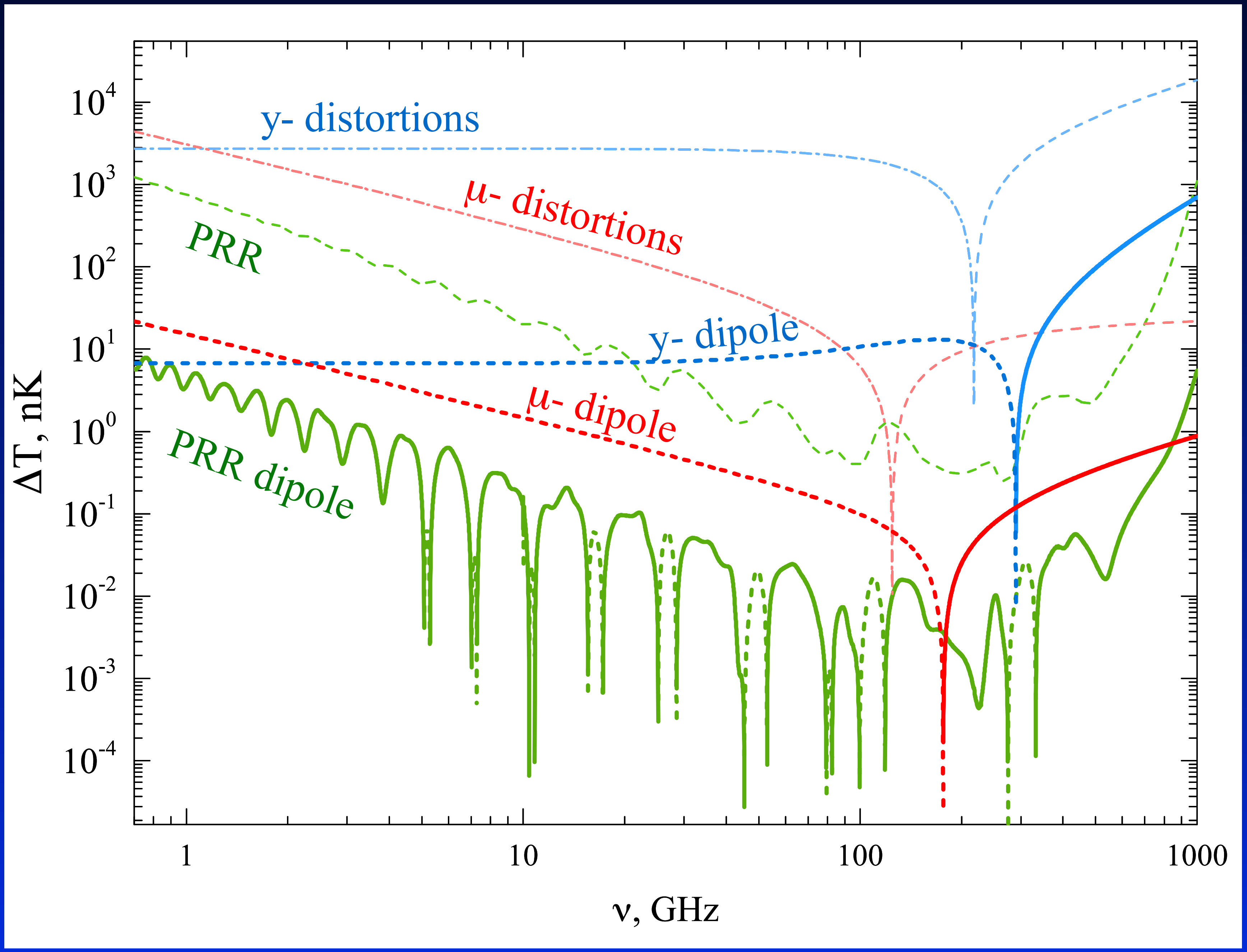
JC & Jeong, 2013

Distortions could shed light on decaying (DM) particles!



JC & Jeong, 2013

Spectral distortions of the CMB dipole



- motion with respect to CMB blackbody monopole

⇒ *CMB temperature dipole*

- including primordial distortions of the CMB

⇒ *CMB dipole is distorted*

$$\eta_{\rm d}(\nu, \mathbf{n}) \approx -\nu \partial_\nu \eta_{\rm m}(\nu)\, \beta \cos\Theta$$

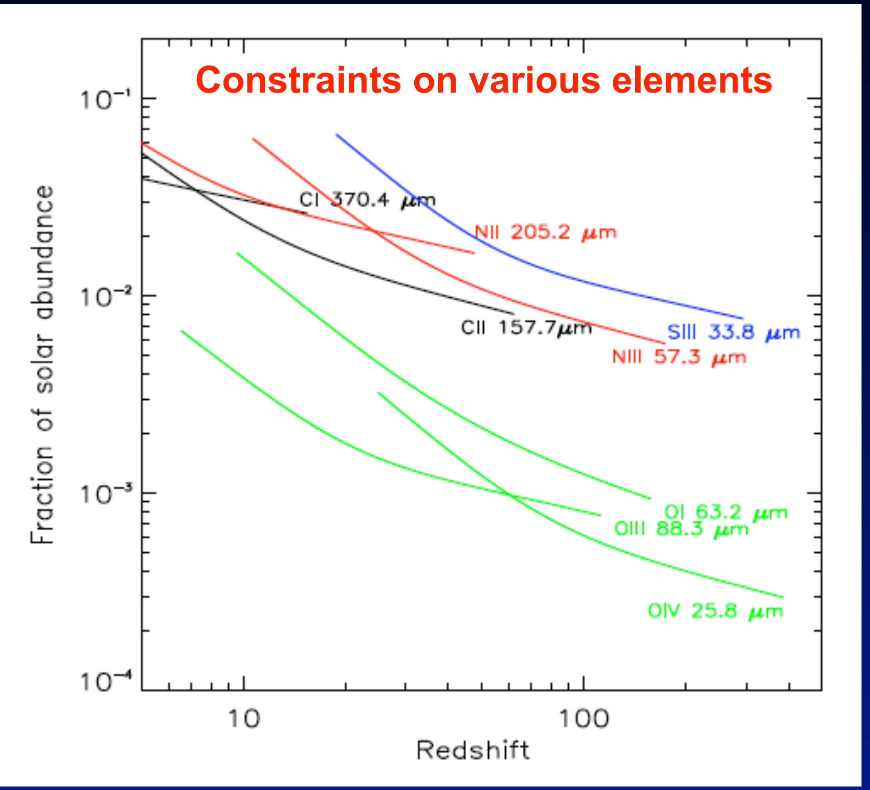
- spectrum of the dipole is sensitive to the *derivative* of the monopole spectrum
- anisotropy does not need *absolute* calibration but just *inter-channel* calibration
- *but* signal is ~1000 times smaller...
- *foregrounds* will also leak into the dipole in this way
- check of *systematics*

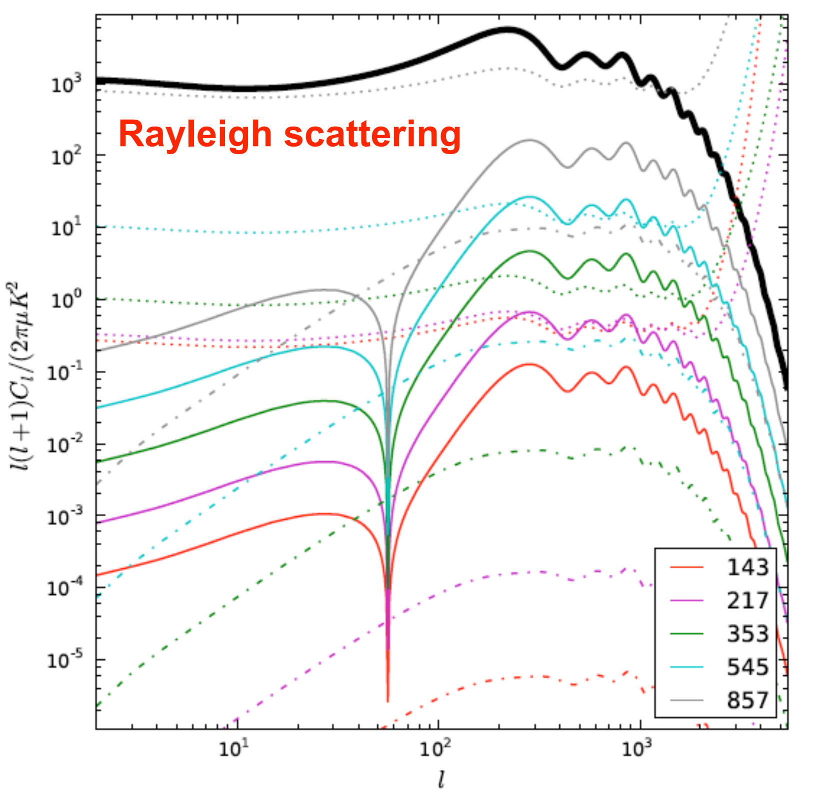
Balashev, Kholupenko, JC, Ivanchik & Varshalovich, ApJ, 2015 (ArXiv:1505.06028)

Other extremely interesting new signals

- Scattering signals from the dark ages
  (e.g., Basu et al., 2004; Hernandez-Monteagudo et al., 2007; Schleicher et al., 2009)
  - constrain abundances of chemical elements at high redshift
  - learn about star formation history
- Rayleigh / HI scattering signals
  (e.g., Yu et al., 2001; Rubino-Martin et al., 2005; Lewis 2013)
  - provides way to constrain recombination history
  - important when asking questions about $N_{\rm eff}$ and $Y_{\rm p}$
- Free-free signals from reionization
  (e.g., Burigana et al. 1995; Trombetti & Burigana, 2013)
  - constrains reionization history
  - depends on clumpiness of the medium

All these effects give spectral-spatial signals, and an absolute spectrometer will help with channel cross calibration!



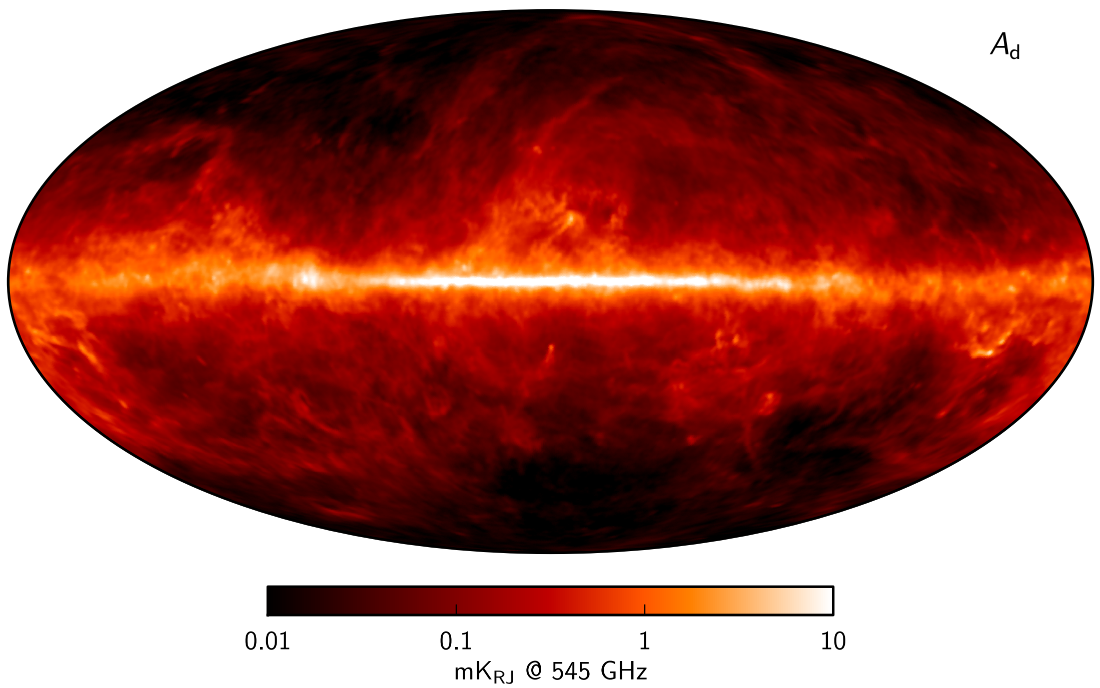


Foreground problem for CMB spectral distortions

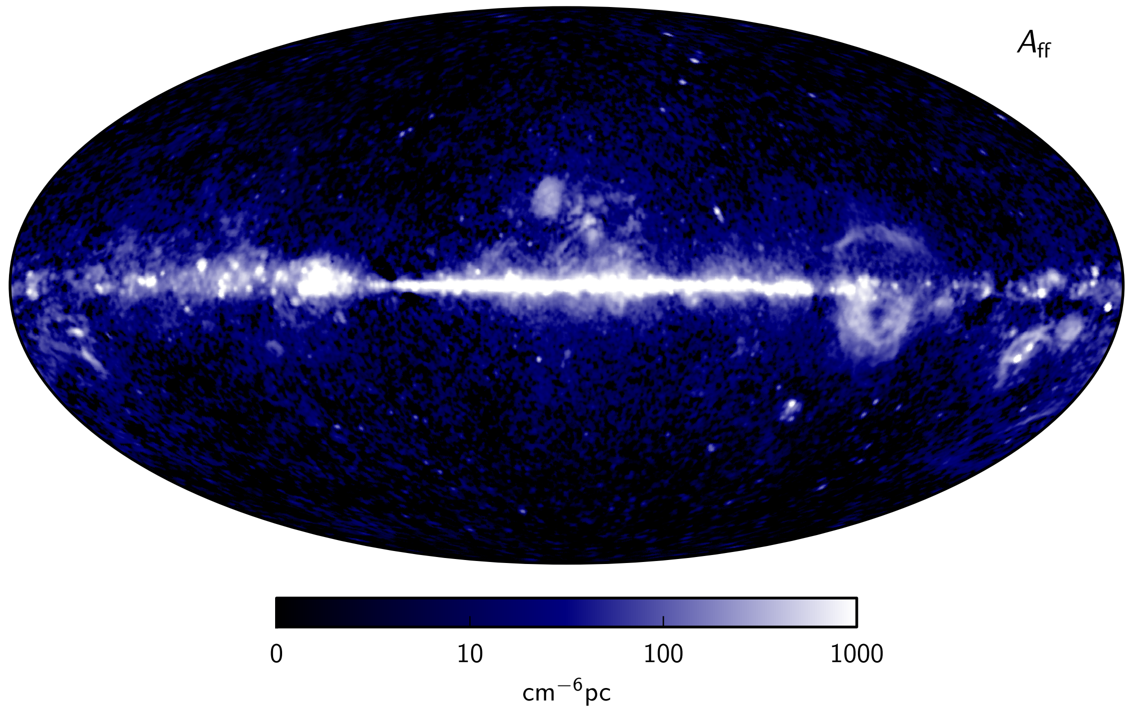
- Distortion signals *quite* small even if spectrally different
- spatially varying foreground signals across the sky
  - Introduces new spectral shapes (*superposition of power-laws, etc.*)
  - Scale-dependent SED
  - Similar problem for B-mode searches
- New foreground parametrization required
  - Moment expansion (JC, Hill & Abitbol, 2017)
- many frequency channels with high sensitivity required
  - PIXIE stands best chance at tackling this problem
- Synergies with CMB imagers have to be exploited
  - Maps of foregrounds can be used to model contributions to average sky-signal
  - absolute calibration (from PIXIE) can be used for calibration of imagers

Some of the foregrounds and their spatial variation

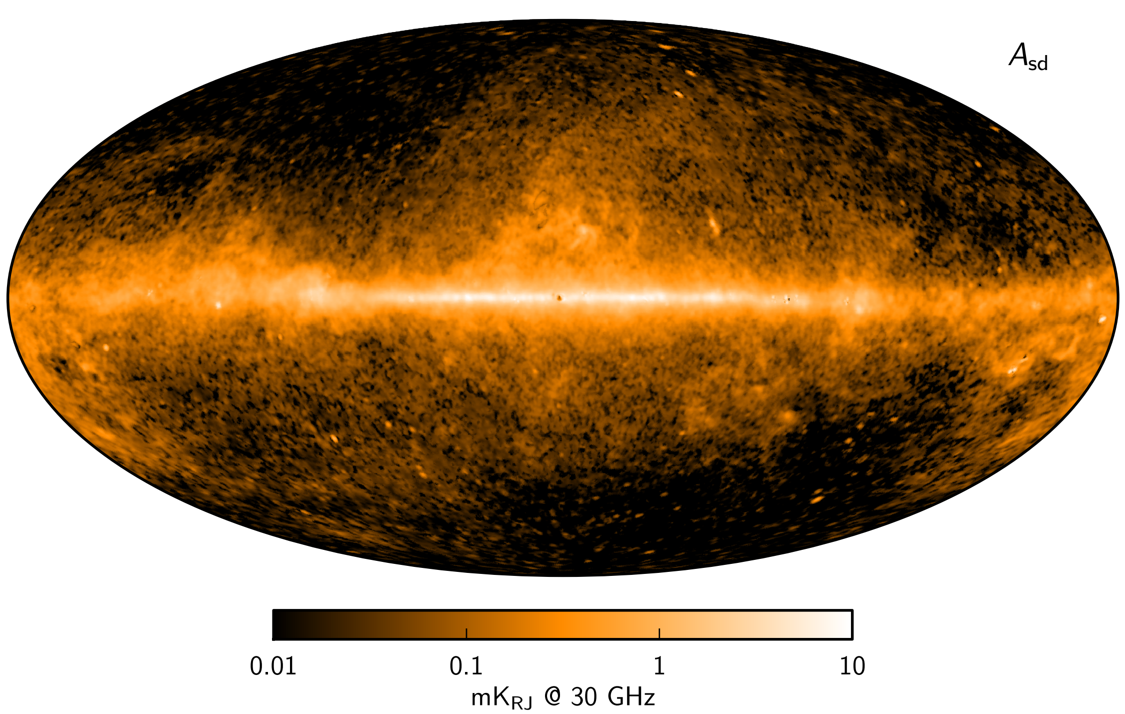
Thermal dust



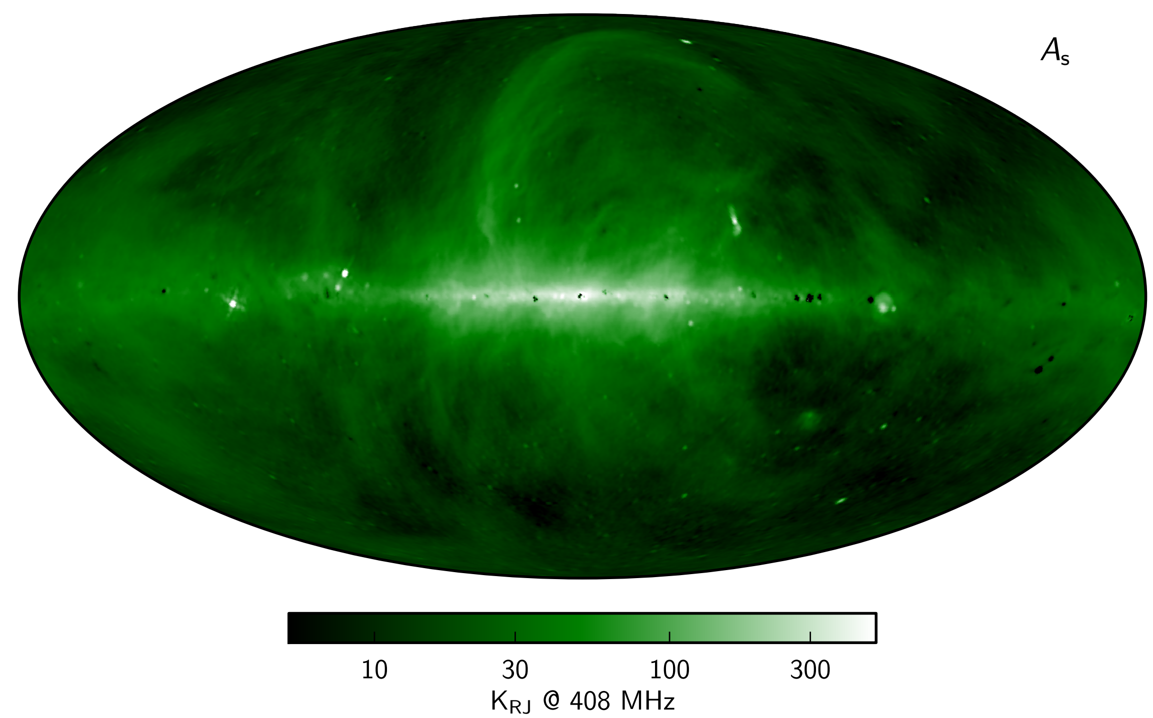
free-free emission



Spinning dust



Synchrotron



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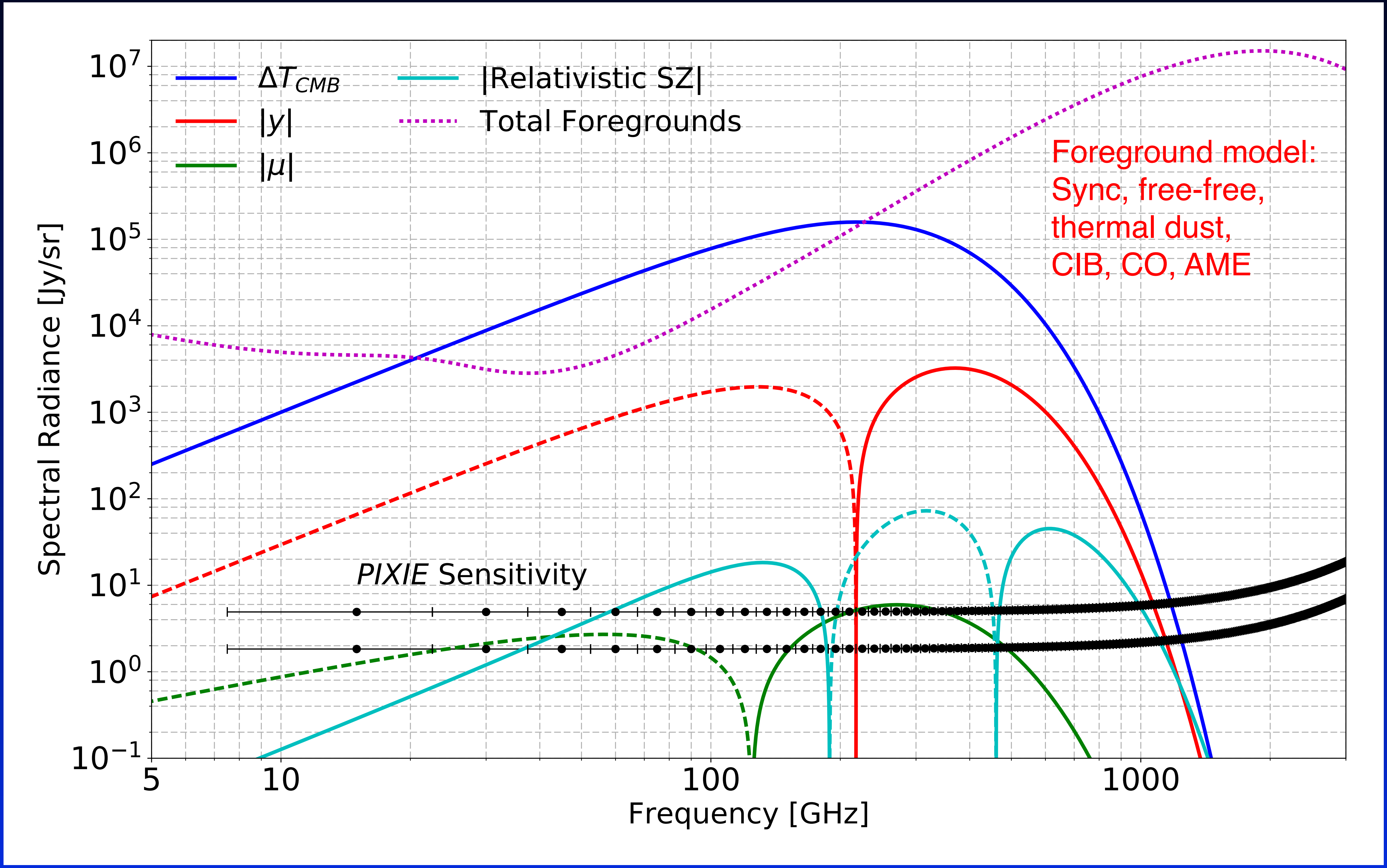
Comparison of distortion signals with foregrounds



Abitbol, JC & Hill, 1705.01534

Forecasted sensitivities for PIXIE

Sky Model	CMB (baseline)	CMB	Dust, CO	Sync, FF, AME	Sync, FF, Dust	Dust, CIB, CO	Sync, FF, Dust, CIB	Sync, FF, AME Dust, CIB, CO
# of parameters	4	4	8	9	11	11	14	16
$\sigma_{\Delta_T}[10^{-9}]$	2.3 (52k σ)	0.86 (140k σ)	2.2 (55k σ)	3.9 (31k σ)	9.7 (12k σ)	5.3 (23k σ)	59 (2000σ)	75 (1600σ)
$\sigma_y[10^{-9}]$	1.2 (1500σ)	0.44 (4000σ)	0.65 (2700σ)	0.88 (2000σ)	2.7 (660σ)	4.8 (370σ)	12 (150σ)	14 (130σ)
$\sigma_{kT_{\rm eSZ}}[10^{-2}$ keV]	2.9 (42σ)	1.1 (113σ)	1.8 (71σ)	1.3 (96σ)	4.1 (30σ)	7.8 (16σ)	11 (11σ)	12 (10σ)
$\sigma_\mu[10^{-8}]$	1.4 (1.4σ)	0.53 (3.8σ)	0.55 (3.6σ)	1.7 (1.2σ)	2.6 (0.76σ)	0.75 (2.7σ)	14 (0.15σ)	18 (0.11σ)

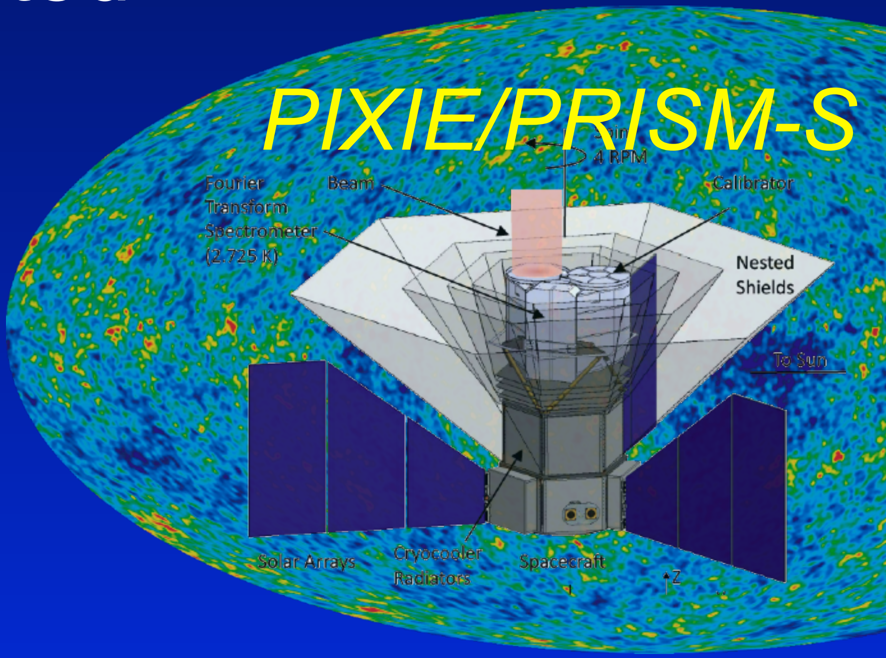
Parameter	1% / −−	10% / 10%	1% / 1%	none (no μ)	10% / 10% (no μ)	1% / 1% (no μ)
$\sigma_{\Delta_T}[10^{-9}]$	194 (619σ)	75 (1600σ)	18 (6500σ)	17 (7200σ)	4.4 (27000σ)	3.7 (33000σ)
$\sigma_y[10^{-9}]$	32 (55σ)	14 (130σ)	5.9 (300σ)	9.1 (194σ)	4.6 (380σ)	4.6 (390σ)
$\sigma_{kT_{\rm eSZ}}[10^{-2}$ keV]	23 (5.5σ)	12 (10σ)	8.6 (14σ)	12 (11σ)	7.9 (16σ)	7.6 (17σ)
$\sigma_\mu[10^{-8}]$	47 (0.04σ)	18 (0.11σ)	4.7 (0.43σ)	–	–	–

- Greatly improved limit on μ expected, but a detection of ΛCDM value will be hard
- Measurement of relativistic correction signal very robust even with foregrounds
- Low-frequency measurements from the ground required!

Abitbol, JC & Hill, 1705.01534

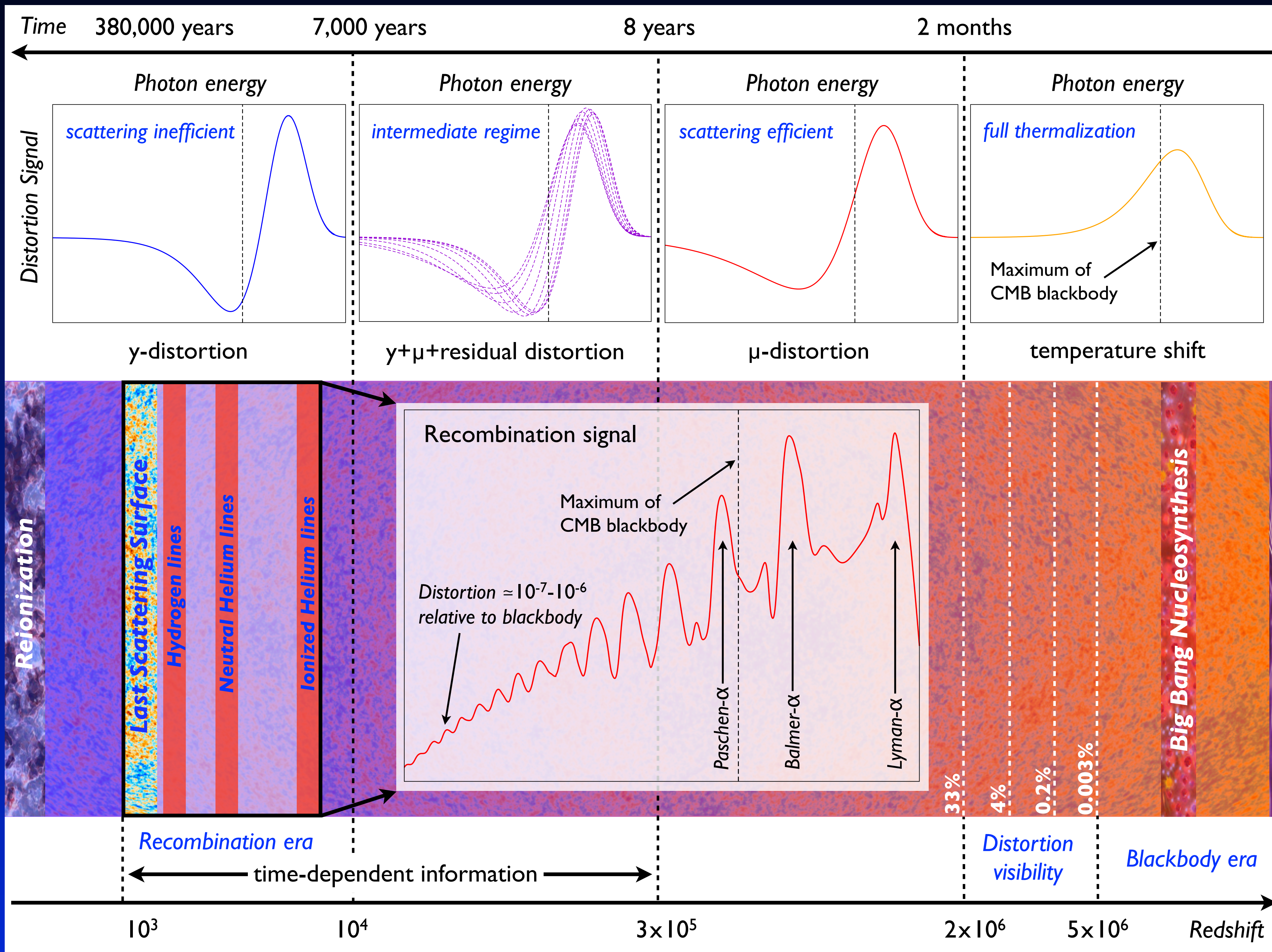
What can CMB spectral distortions add?

- Add a *new dimension* to CMB science
  - probe the thermal history at different stages of the Universe
- *Complementary* and *independent* information!
  - cosmological parameters from the recombination radiation
  - new/additional test of large-scale anomalies
- Several *guaranteed signals* are expected
  - y-distortion from low redshifts
  - damping signal & recombination radiation
- Test various *inflation* models
  - damping of the small-scale power spectrum
- *Discovery* potential
  - decaying particles and other exotic sources of distortions



All this largely without any competition from the ground!!!

Uniqueness of CMB Spectral Distortion Science



Guaranteed distortion signals in ΛCDM

New tests of inflation and particle/dark matter physics

Signals from the reionization and recombination eras

Huge discovery potential

Complementarity and synergy with CMB anisotropy studies

Chluba & Sunyaev, MNRAS, 419, 2012
Chluba et al., MNRAS, 425, 2012
Silk & Chluba, Science, 2014
Chluba, MNRAS, 2016