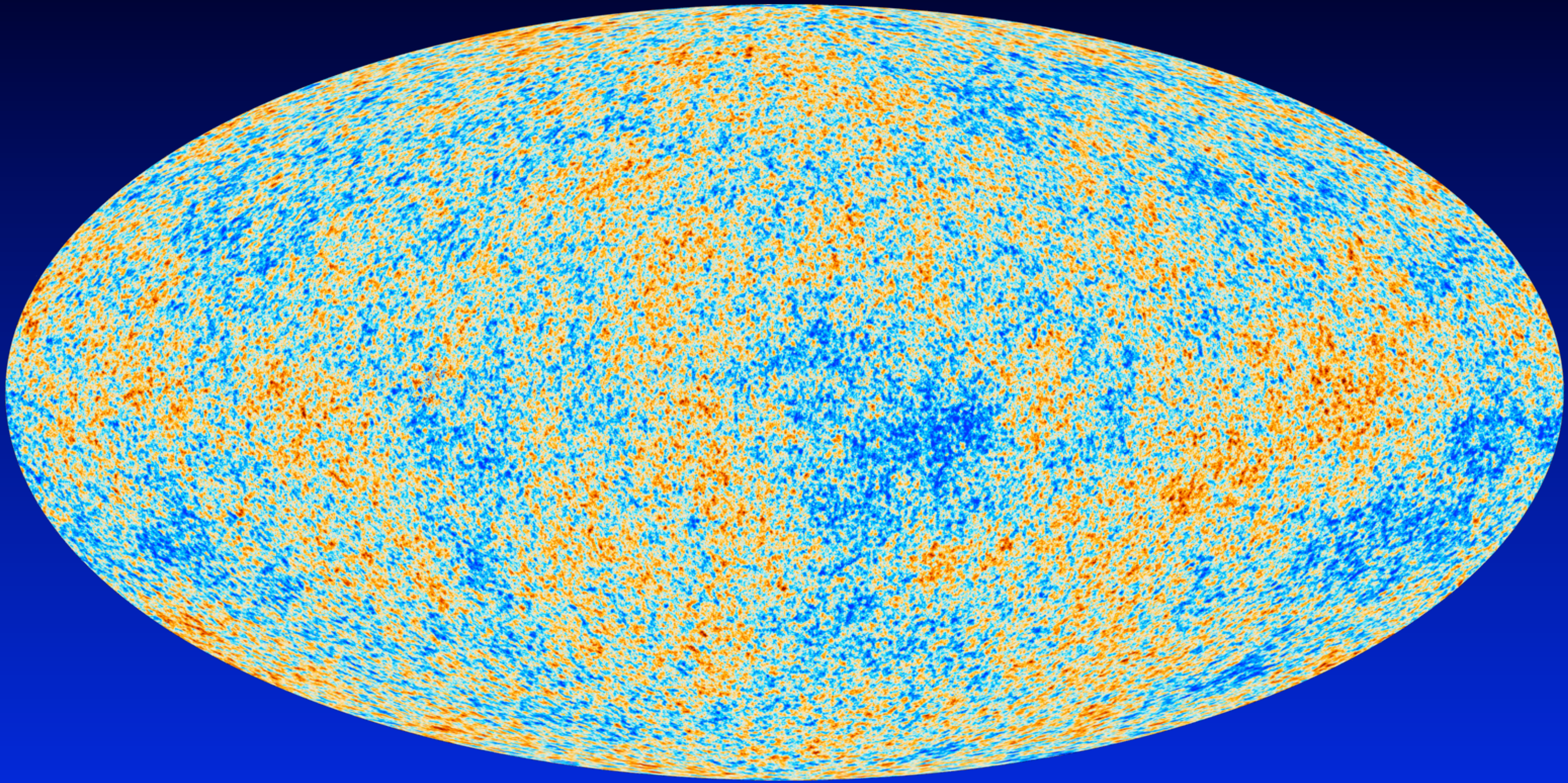
Part II: Distortions for different scenarios and what we may learn by studying them

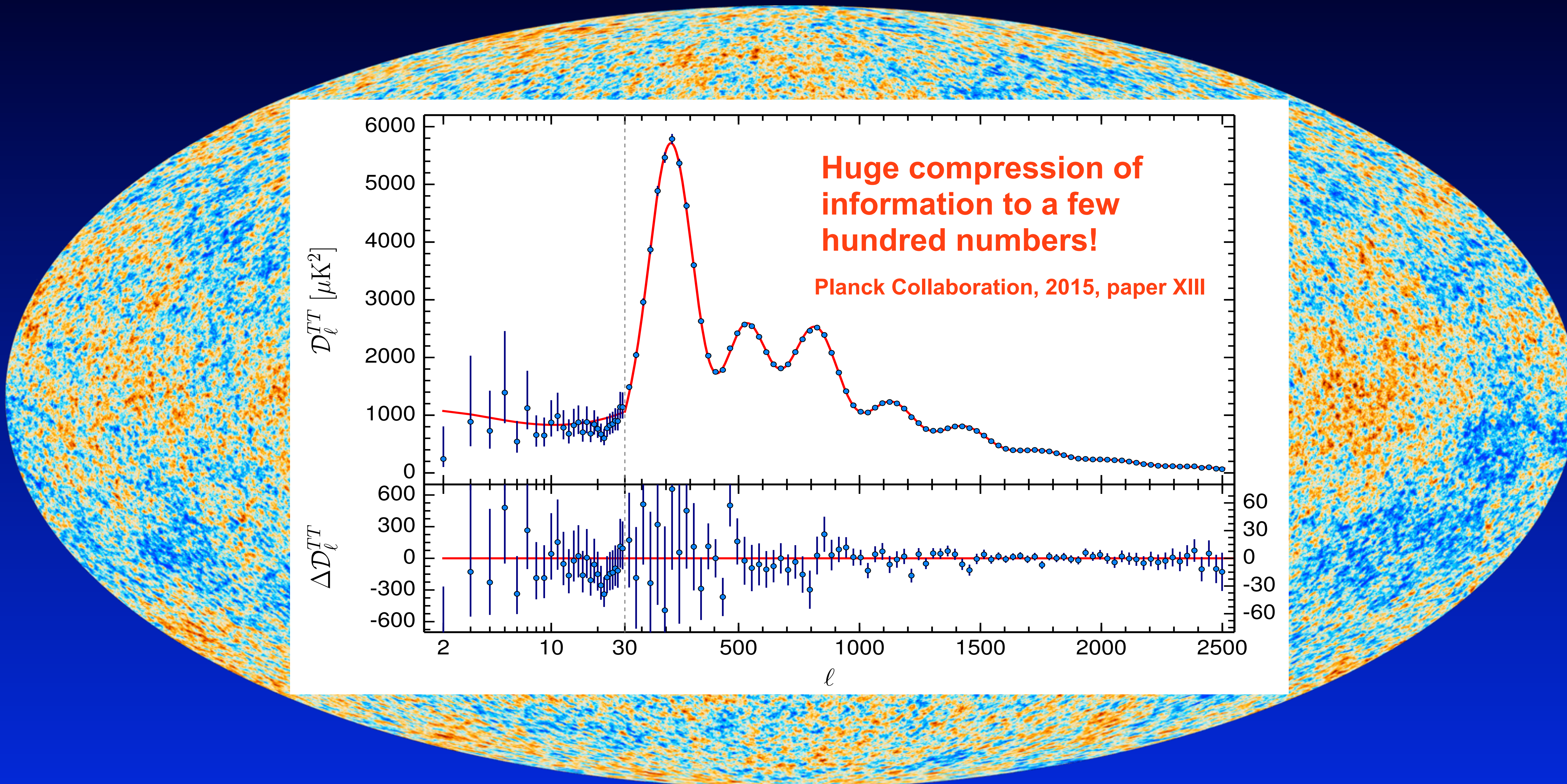
Cosmic Microwave Background Anisotropies



Planck all-sky temperature map

- CMB has a blackbody spectrum in every direction
- tiny variations of the CMB temperature $\Delta T/T \sim 10^{-5}$

Cosmic Microwave Background Anisotropies



Planck all-sky temperature map

- CMB has a blackbody spectrum in every direction
- tiny variations of the CMB temperature $\Delta T/T \sim 10^{-5}$

CMB anisotropies (with SN, LSS, etc...) clearly taught us a lot about the Universe we live in!

- Standard 6 parameter concordance cosmology with parameters known to percent level precision
- Gaussian-distributed adiabatic fluctuations with nearly scale-invariant power spectrum over a wide range of scales
- cold dark matter ("CDM")
- accelerated expansion today ("Λ")
- Standard BBN scenario $\rightarrow N_{\mathrm{eff}}$ and Y_p
- Standard ionization history $\rightarrow N_e$ as a function of z

Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041	1.04077 ± 0.00032	1.04087 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.066 ± 0.016	0.067 ± 0.013	0.079 ± 0.017	0.063 ± 0.014	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9681 ± 0.0044	0.9645 ± 0.0049	0.9653 ± 0.0048	0.9667 ± 0.0040

Planck Collaboration, 2015, paper XIII

What are the *main* next targets for CMB anisotropies?

- CMB temperature power spectrum kind of finished...
- E modes cosmic variance limited to high-l
  - better constraint on τ from large scale E modes
  - refined CMB damping tail science from small-scale E modes
  - CMB lensing and de-lensing of primordial B-modes
- primordial B modes
  - detection of $r \sim 10^{-3}$ *(energy scale of inflation)*
  - upper limit on $n_T < O(0.1)$ as additional 'proof of inflation'
- CMB anomalies
  - stationarity of E and B-modes, lensing potential, etc across the sky
- SZ cluster science
  - large cluster samples and (individual) high-res cluster measurements

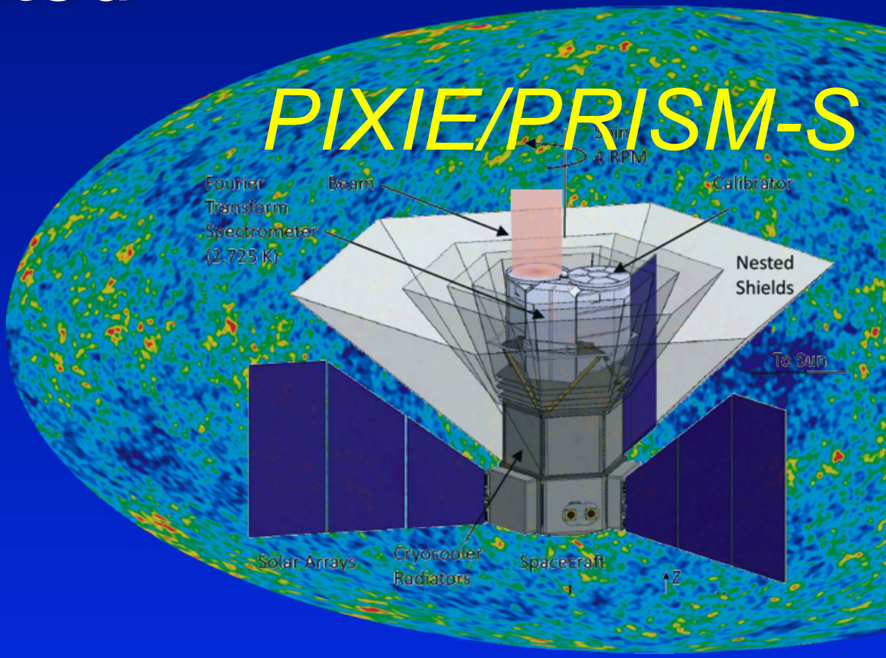
What are the *main* next targets for CMB anisotropies?

- CMB temperature power spectrum kind of finished...
- E modes cosmic variance limited to high-*l*
  - better constraint on τ from large scale E modes
  - refined CMB damping tail science from small-scale E modes
  - CMB lensing and de-lensing of primordial B-modes
- primordial B modes
  - detection of $r \sim 10^{-3}$ *(energy scale of inflation)*
  - upper limit on $n_T < O(0.1)$ as additional 'proof of inflation'
- CMB anomalies
  - stationarity of E and B-modes, lensing potential, etc across the sky
- SZ cluster science
  - large cluster samples and (individual) high-res cluster measurements

Lots of competition to reach these goals!

What can CMB spectral distortions add?

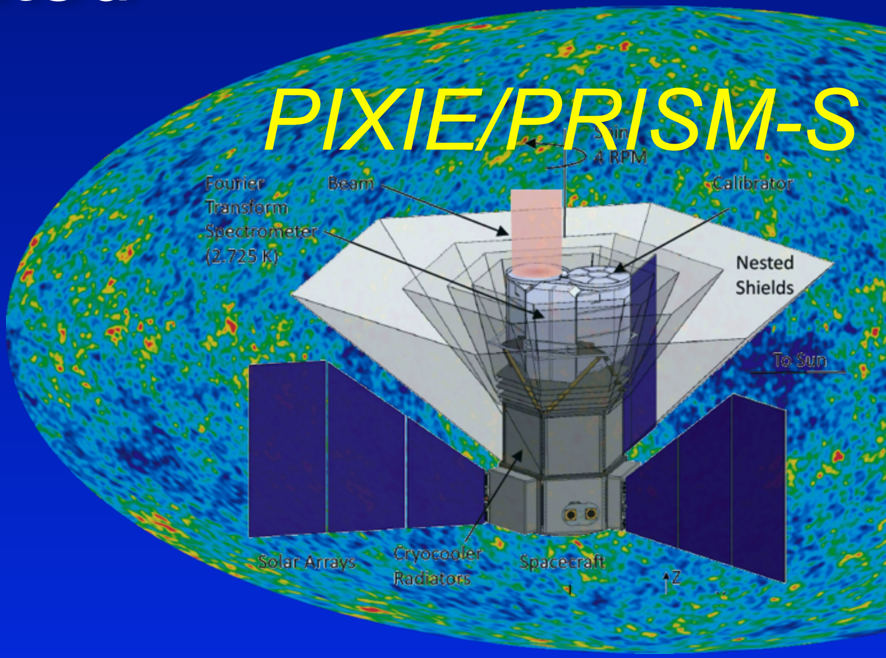
- Add a *new dimension* to CMB science
  - probe the thermal history at different stages of the Universe
- *Complementary* and *independent* information!
  - cosmological parameters from the recombination radiation
  - new/additional test of large-scale anomalies
- Several *guaranteed signals* are expected
  - 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

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!!!

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

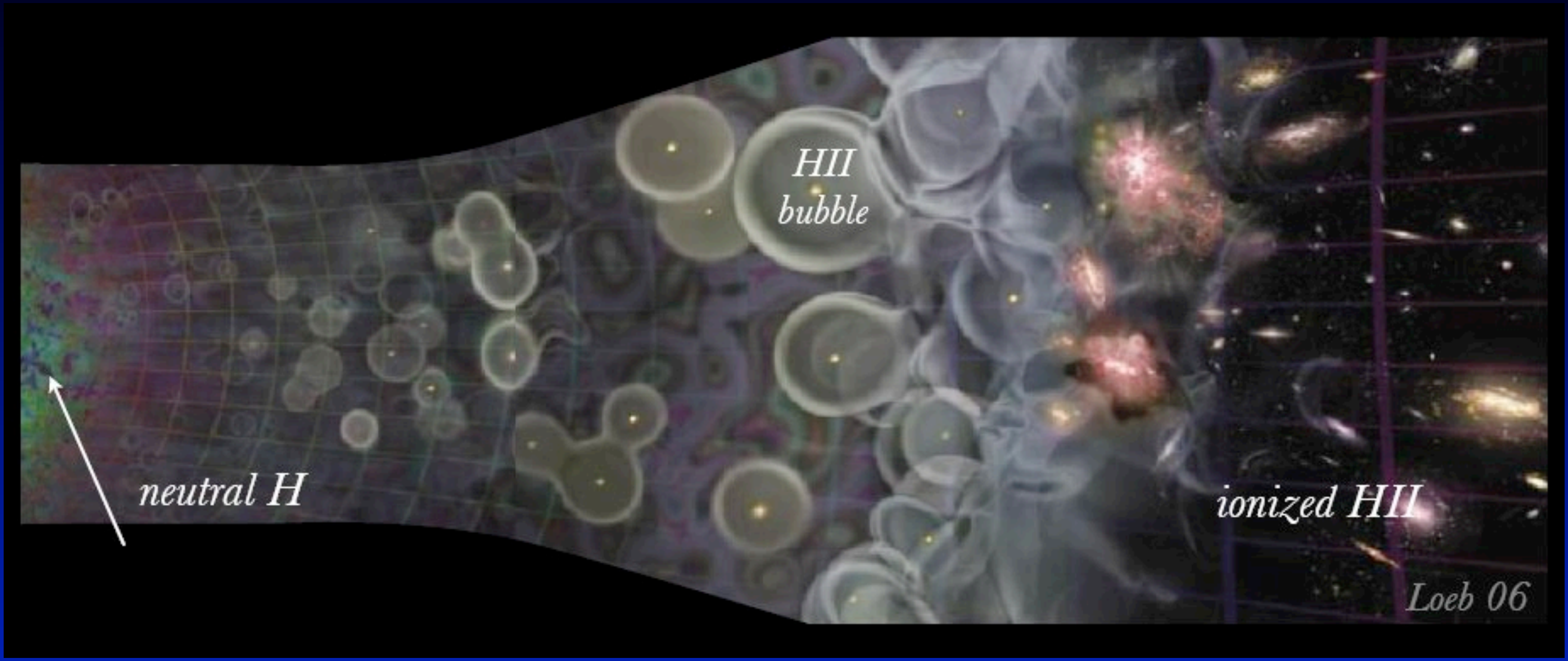
„low“ redshifts

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)
- more exotic processes
  (Lochan et al. 2012; Bull & Kamionkowski, 2013; Brax et al., 2013; Tashiro et al. 2013)

Reionization and structure formation

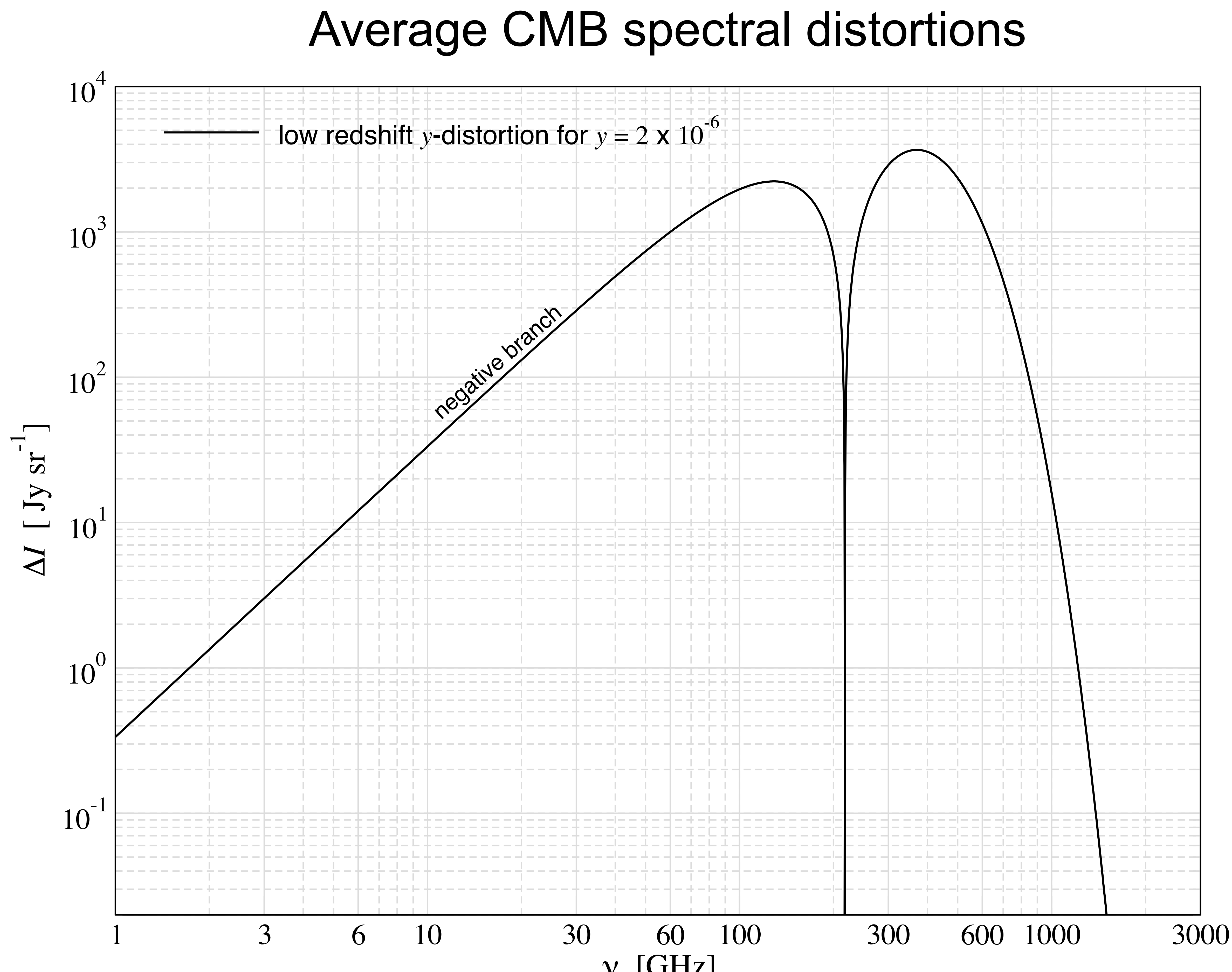
Simple estimates for the distortion



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

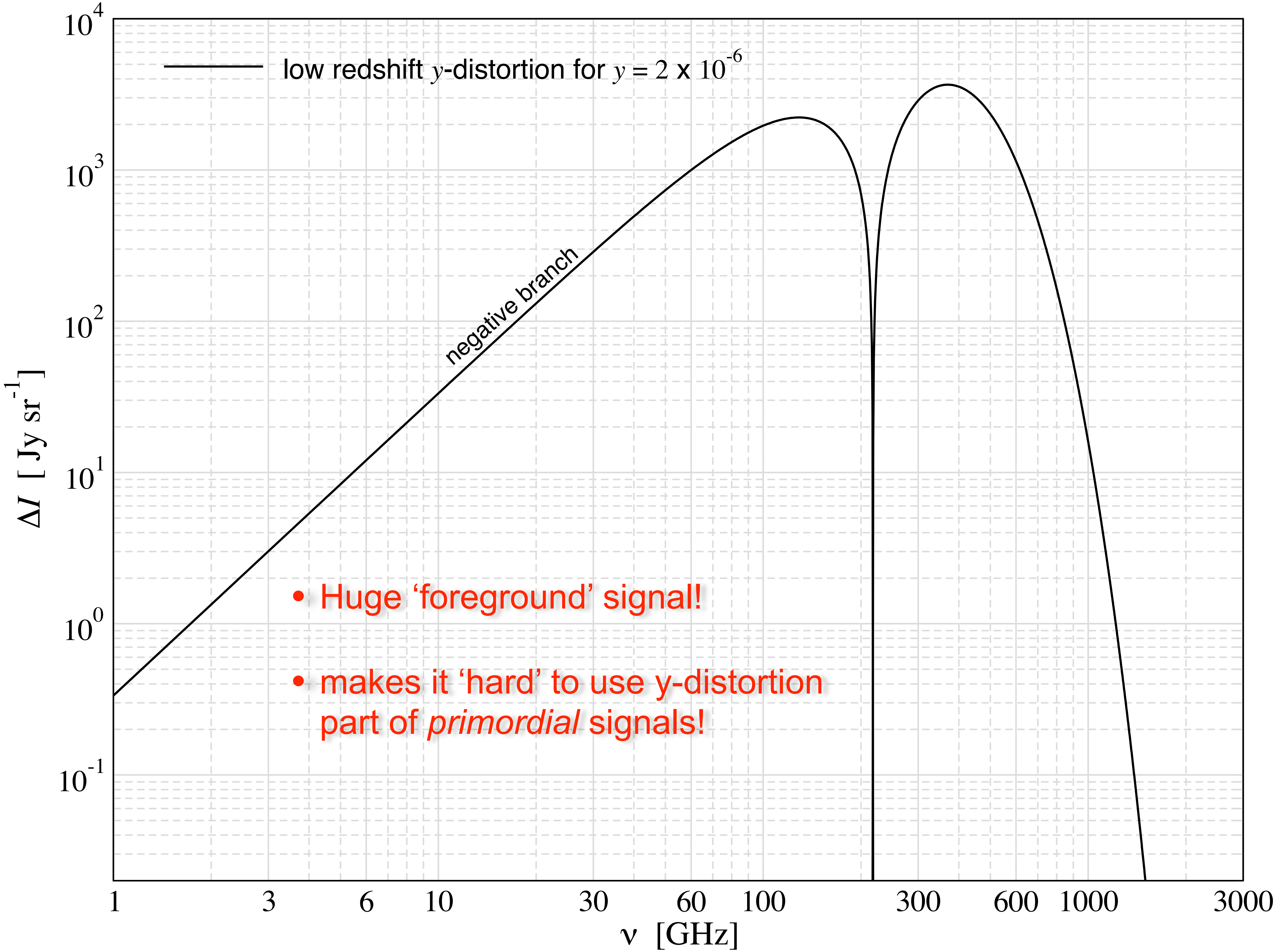
$$\Longrightarrow \quad y \simeq \frac{kT_{\rm e}}{m_{\rm e}c^2}\,\tau \approx 2\times 10^{-7}$$

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

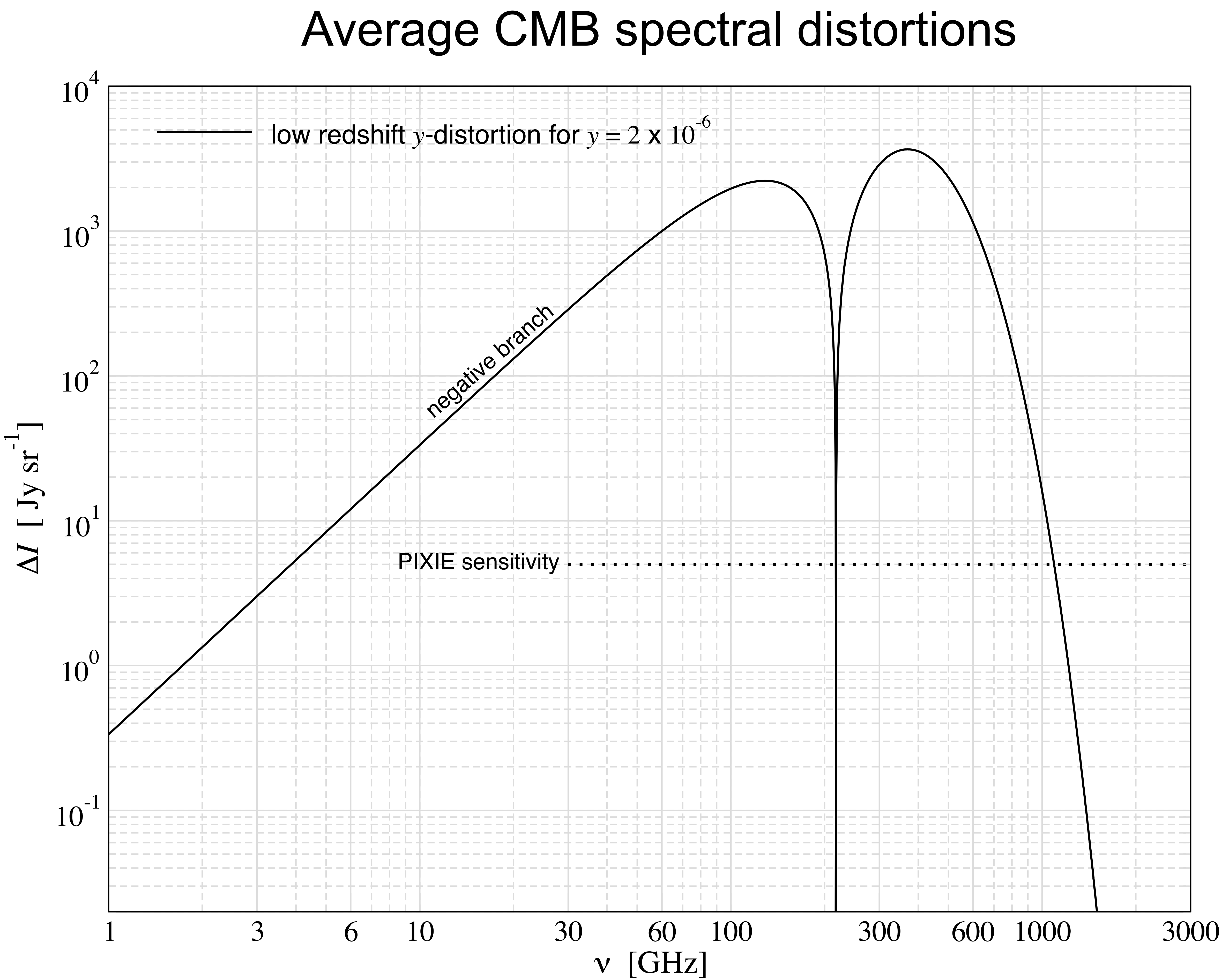


Average CMB spectral distortions
low redshift y-distortion for y = 2 x 10^-6
negative branch
ΔI [Jy sr^-1]
10^4
10^3
10^2
10^1
10^0
10^-1
1
3
6
10
30
60
100
300
600
1000
3000
ν [GHz]

Average CMB spectral distortions

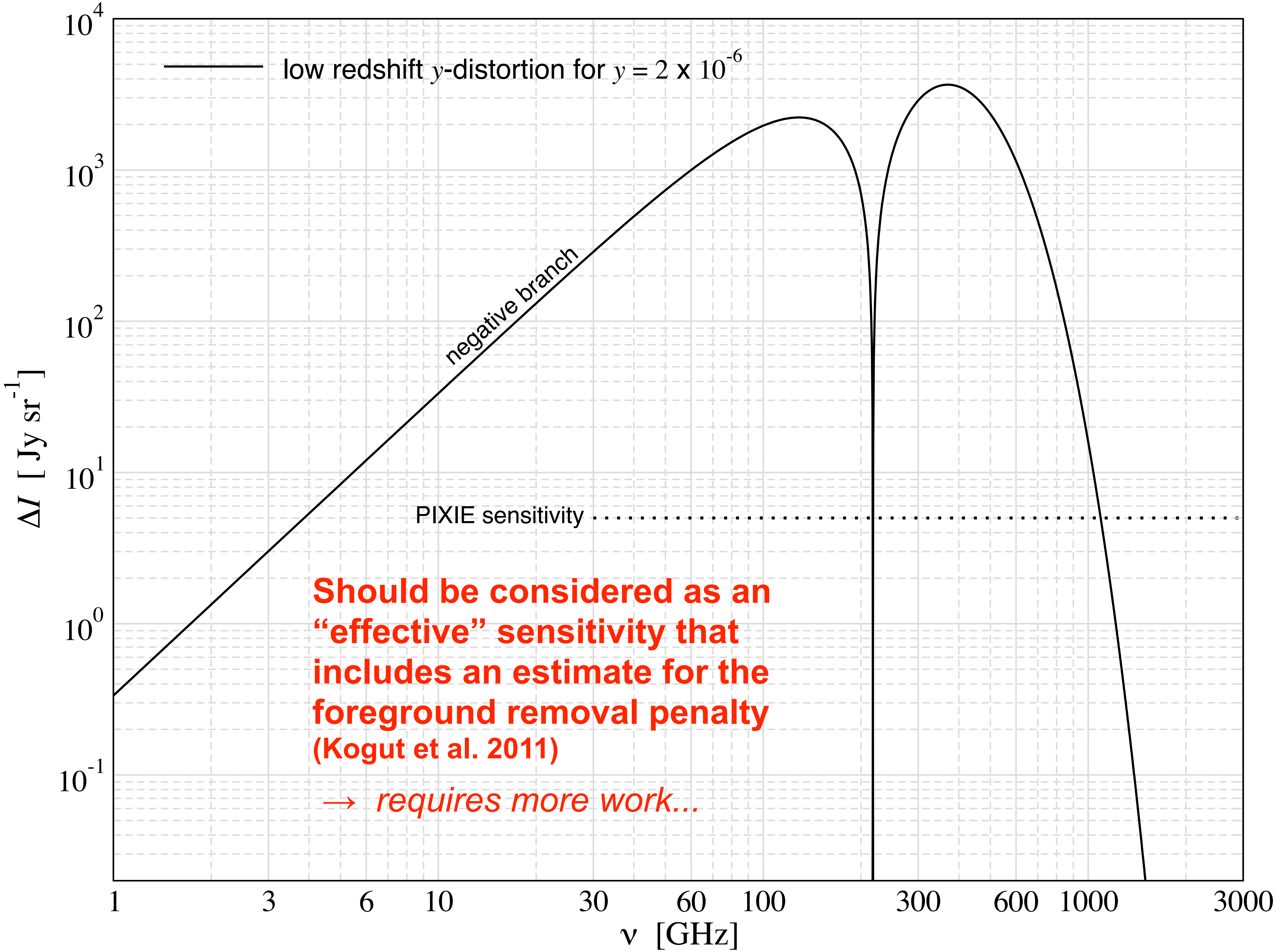


- Huge ‘foreground’ signal!
- makes it ‘hard’ to use y-distortion part of *primordial* signals!



Average CMB spectral distortions
low redshift y-distortion for y = 2 x 10^-6
negative branch
PIXIE sensitivity
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

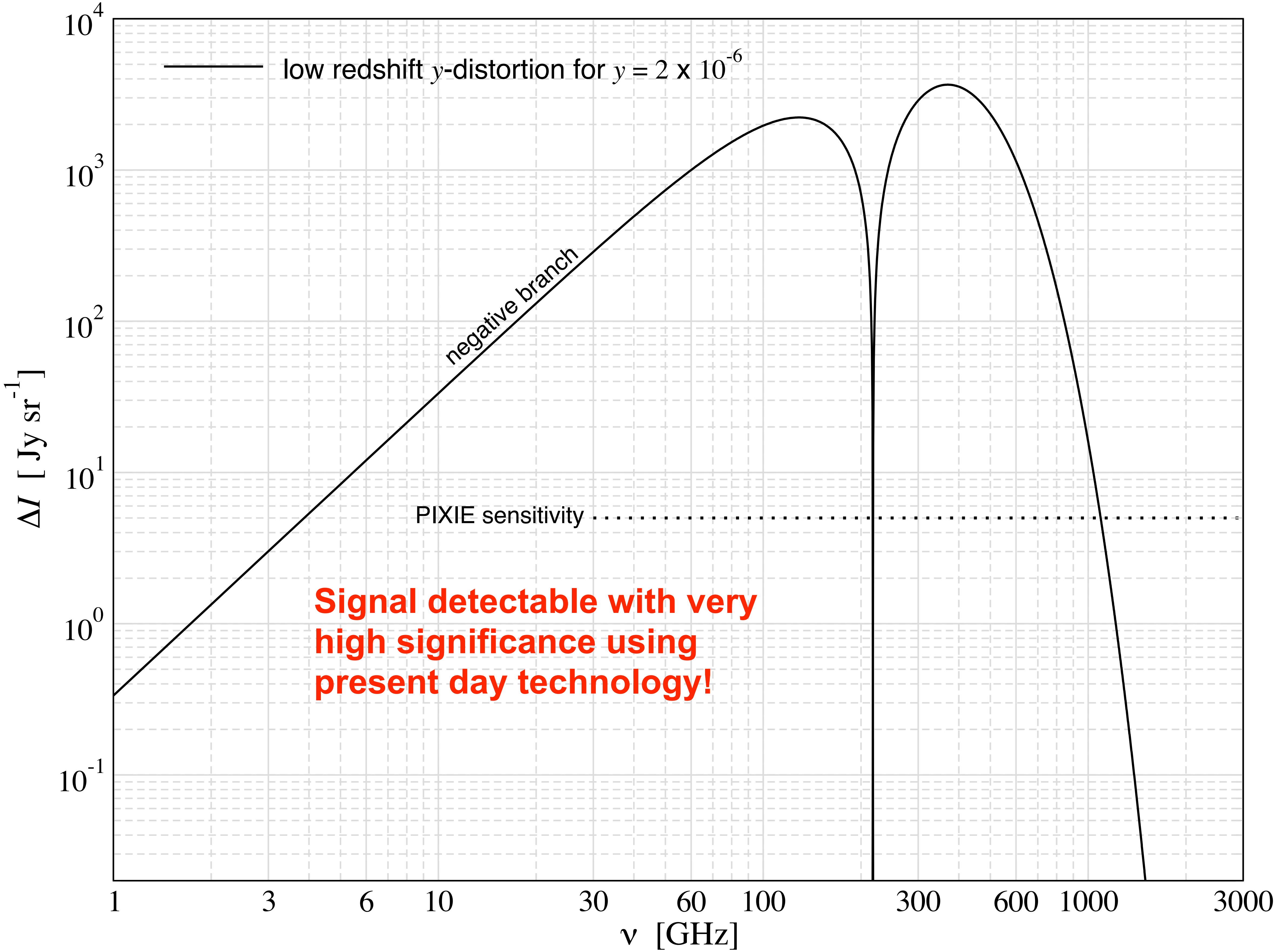
Average CMB spectral distortions



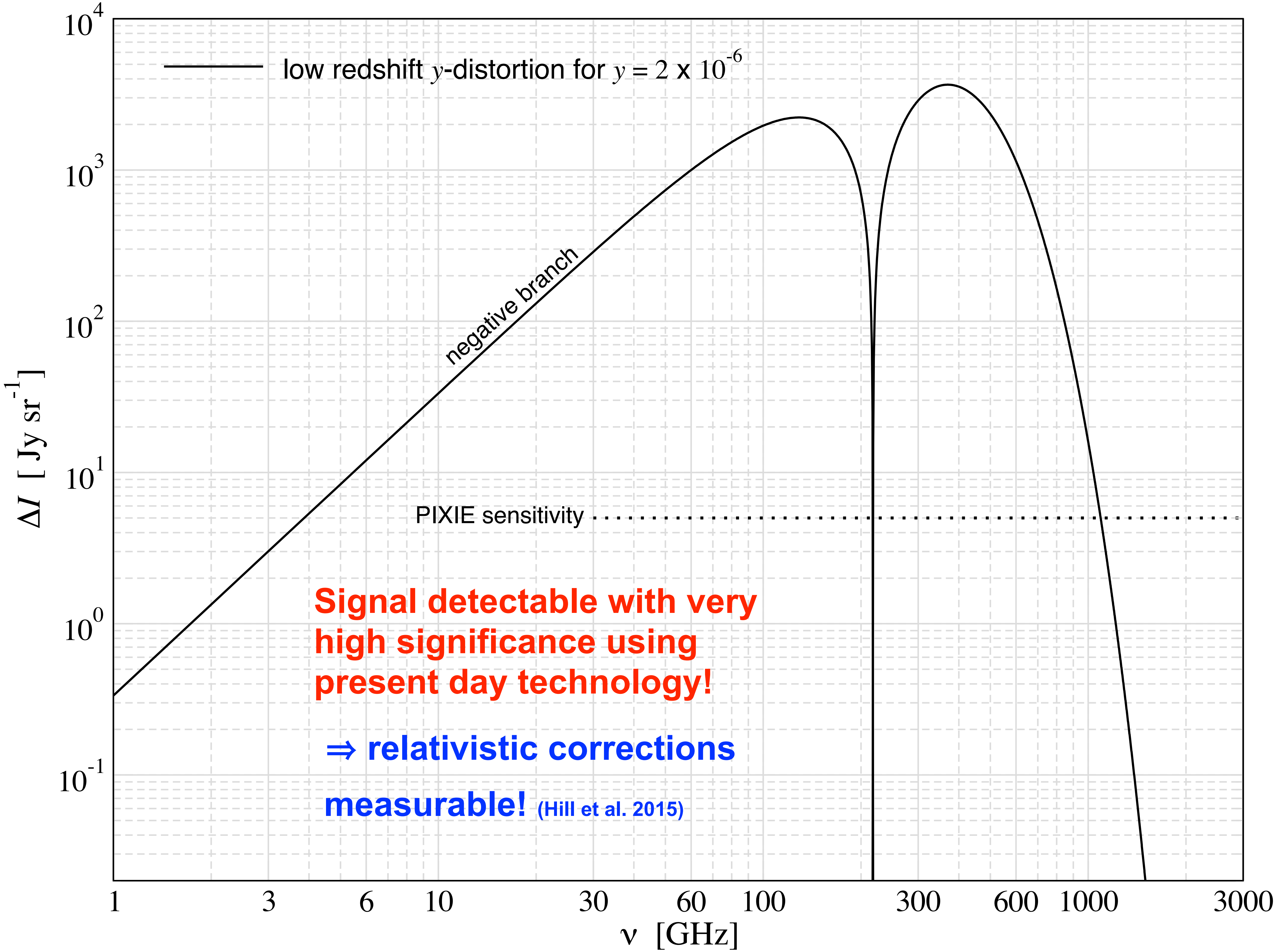
Should be considered as an "effective" sensitivity that includes an estimate for the foreground removal penalty
(Kogut et al. 2011)

→ *requires more work...*

Average CMB spectral distortions



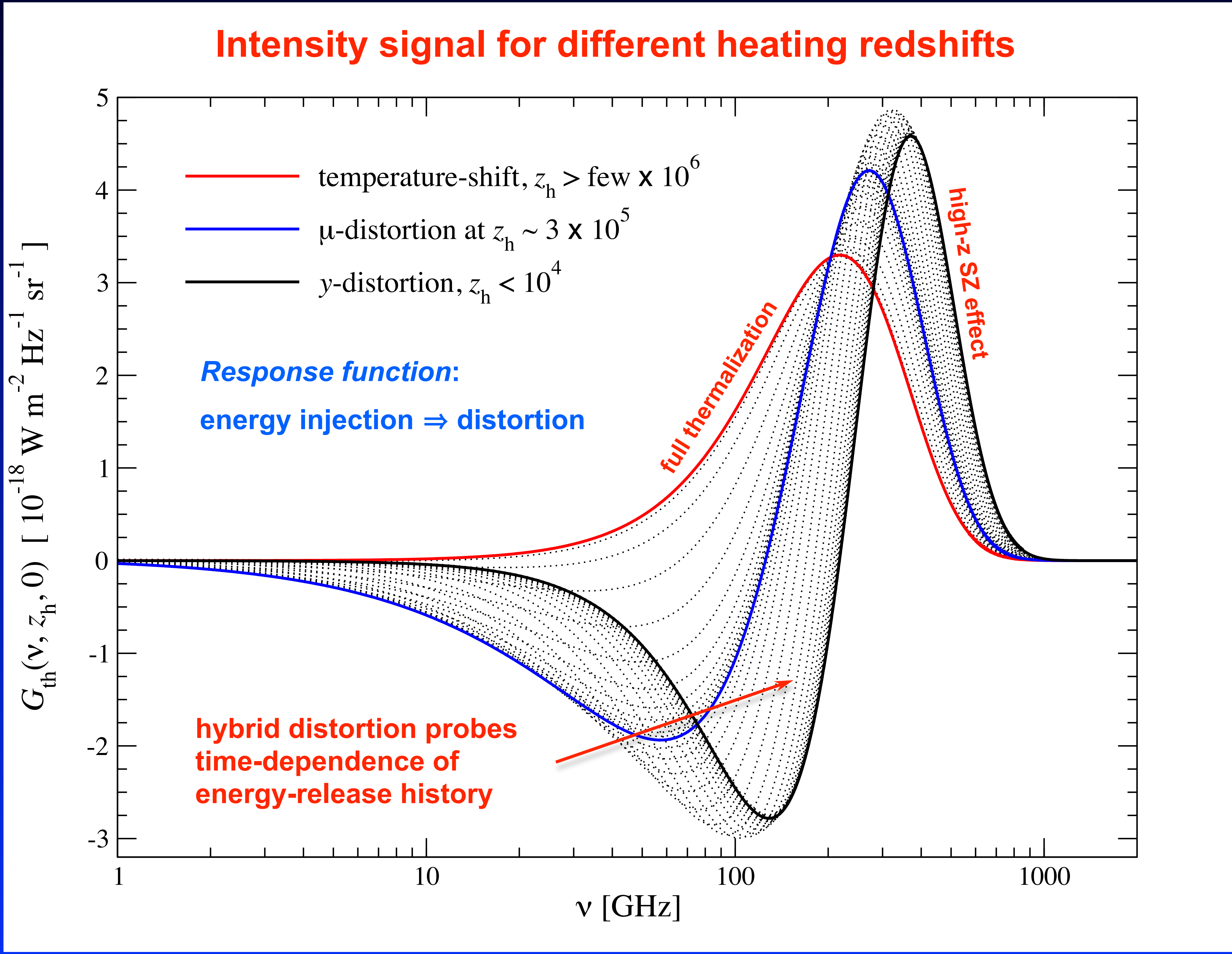
Average CMB spectral distortions



Signal detectable with very high significance using present day technology!

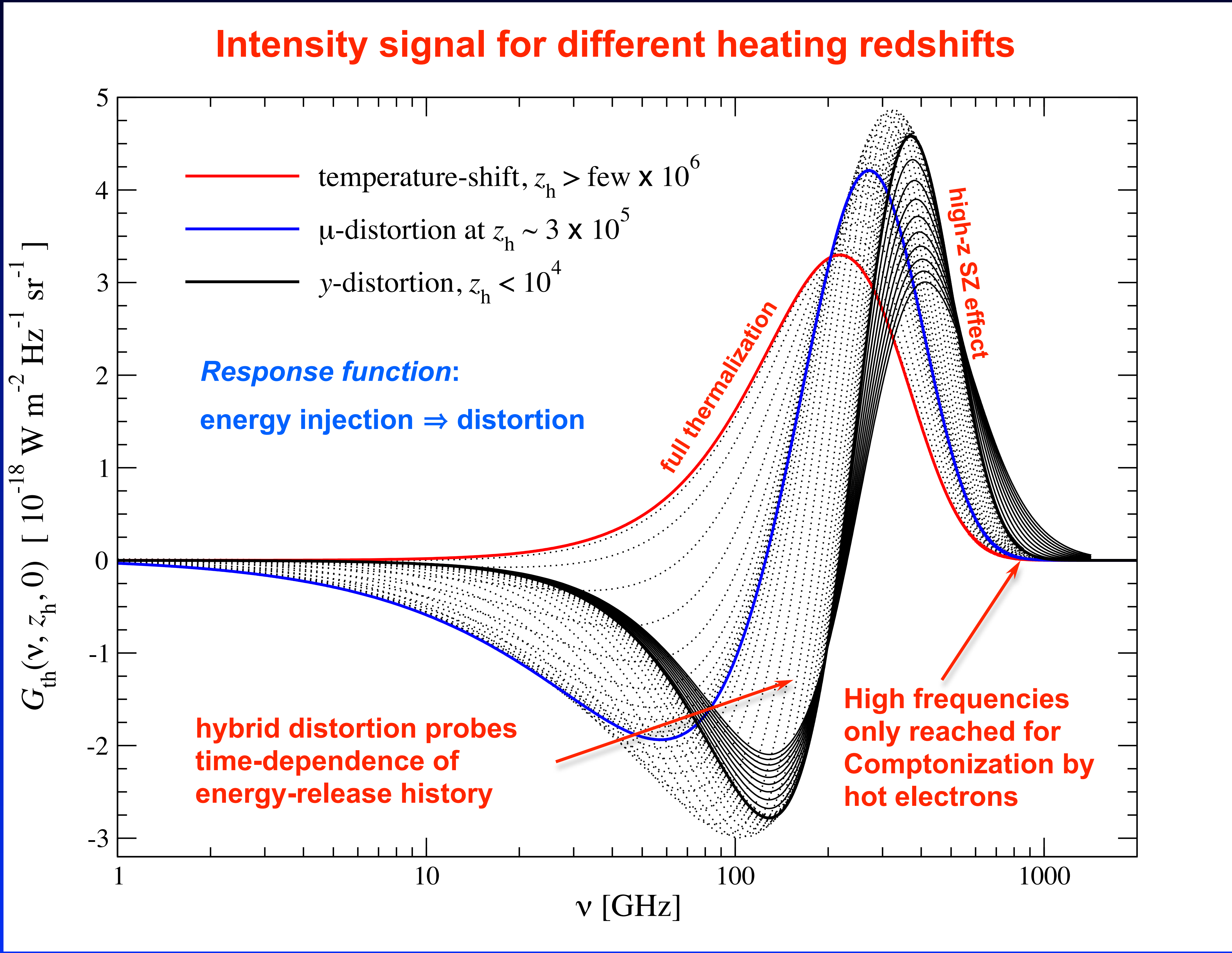
⇒ relativistic corrections measurable! **(Hill et al. 2015)**

Distortion Green's function for energy release



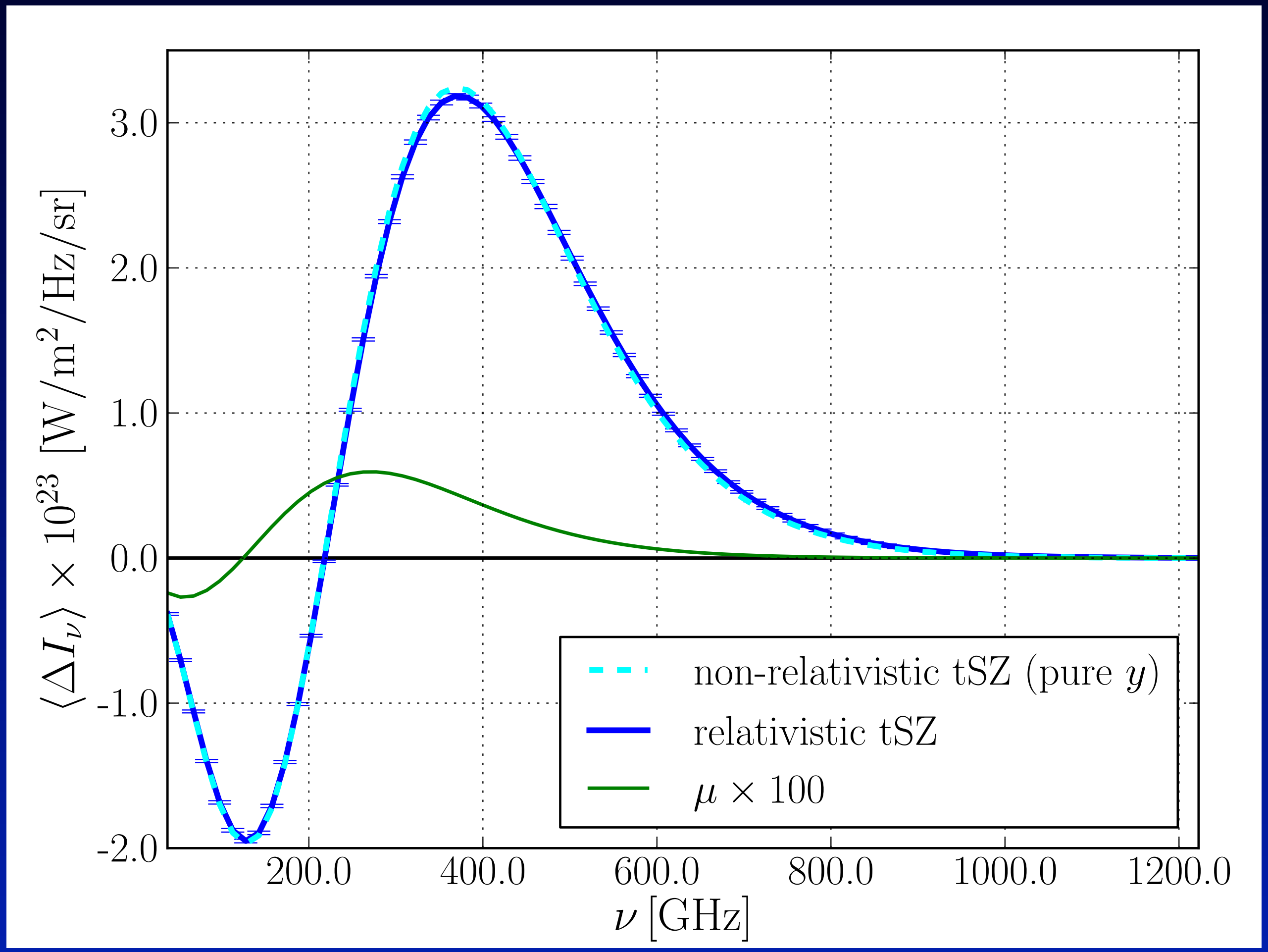
JC & Sunyaev, 2012, ArXiv:1109.6552
JC, 2013, ArXiv:1304.6120

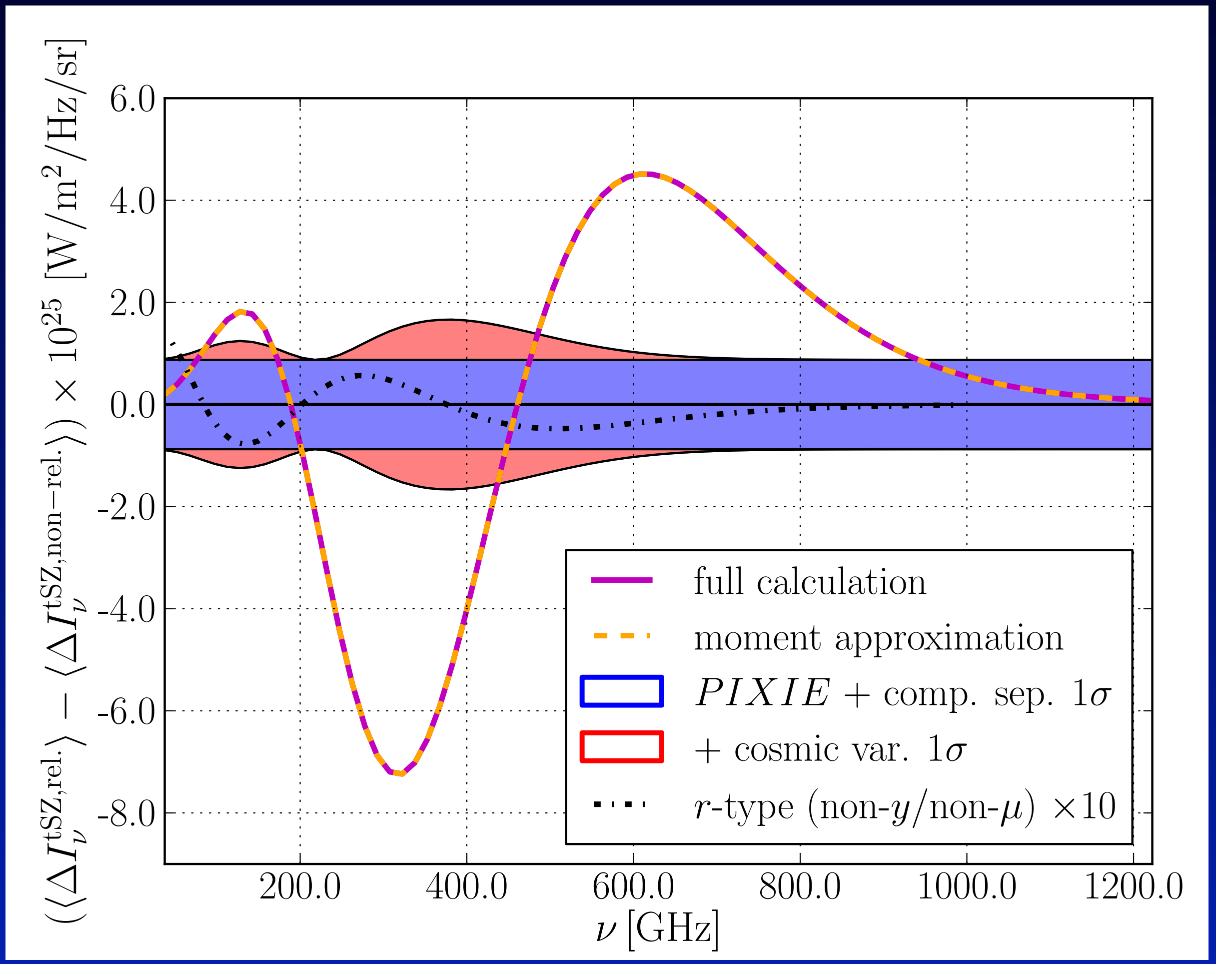
Distortion Green's function for energy release



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

Taking the Universe's temperature

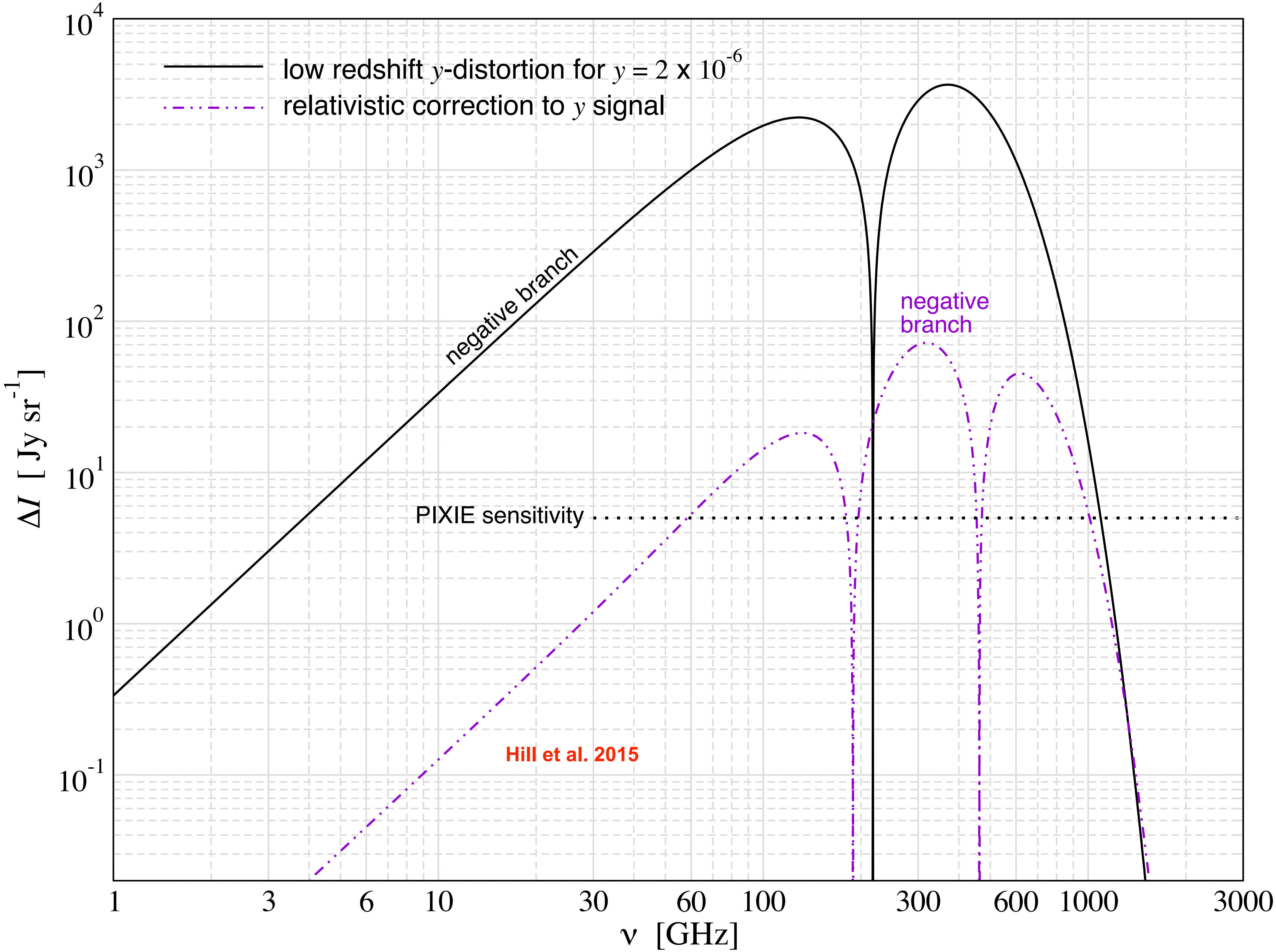




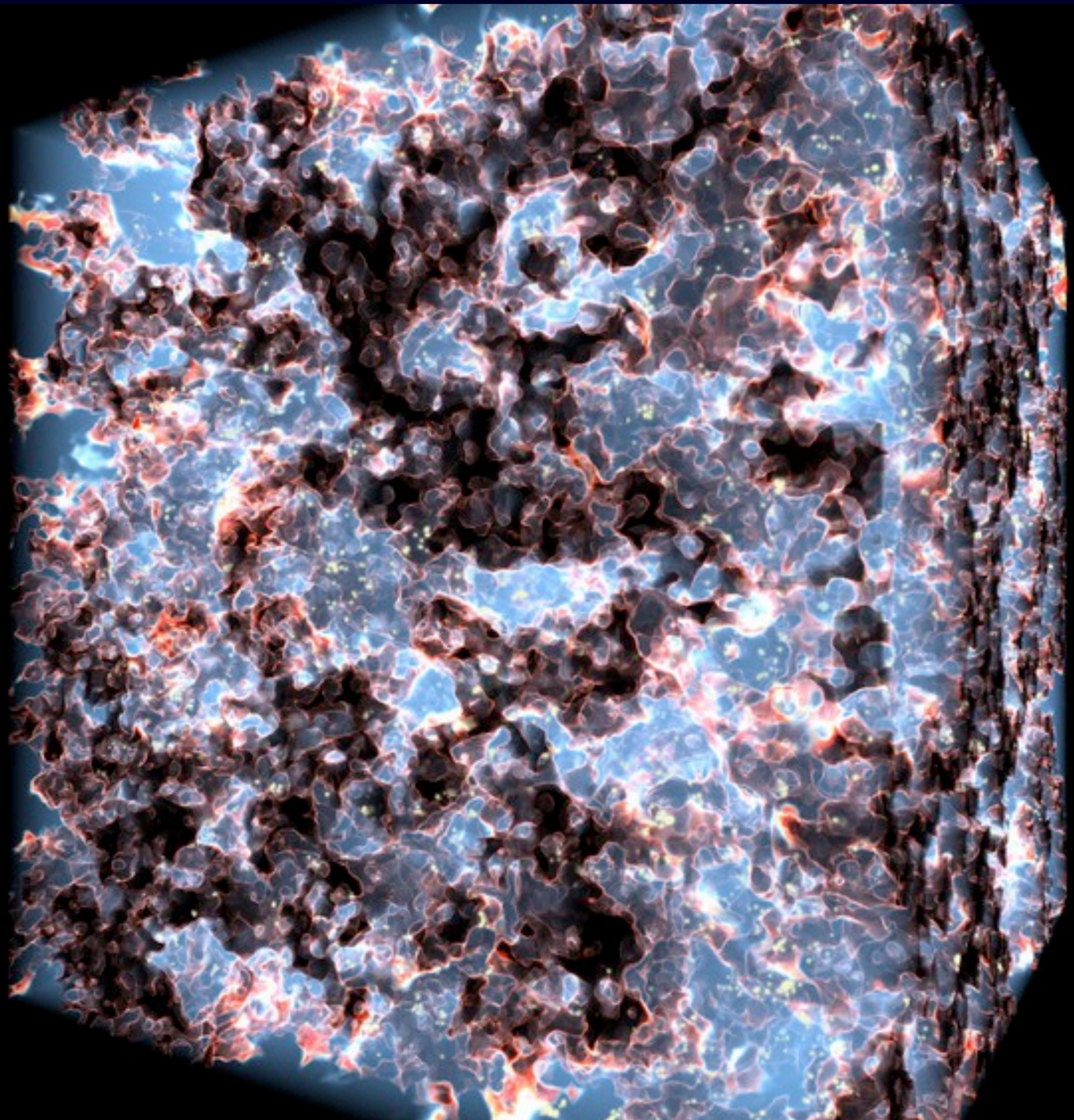
- $\langle y \rangle \simeq 1.8 \times 10^{-6}$ (~ 10% from IGM and reionization rest from ICM)
- > 1000 σ detection with PIXIE-type experiment
- optical depth-weighted temperature: $\langle kT_{\rm e} \rangle_\tau \simeq 0.208\,{\rm keV} (\equiv 2.4 \times 10^6\,{\rm K})$
- ~ 30 σ detection with PIXIE-type experiment

Hill et al., 2015, ArXiv:1507.01583

Average CMB spectral distortions



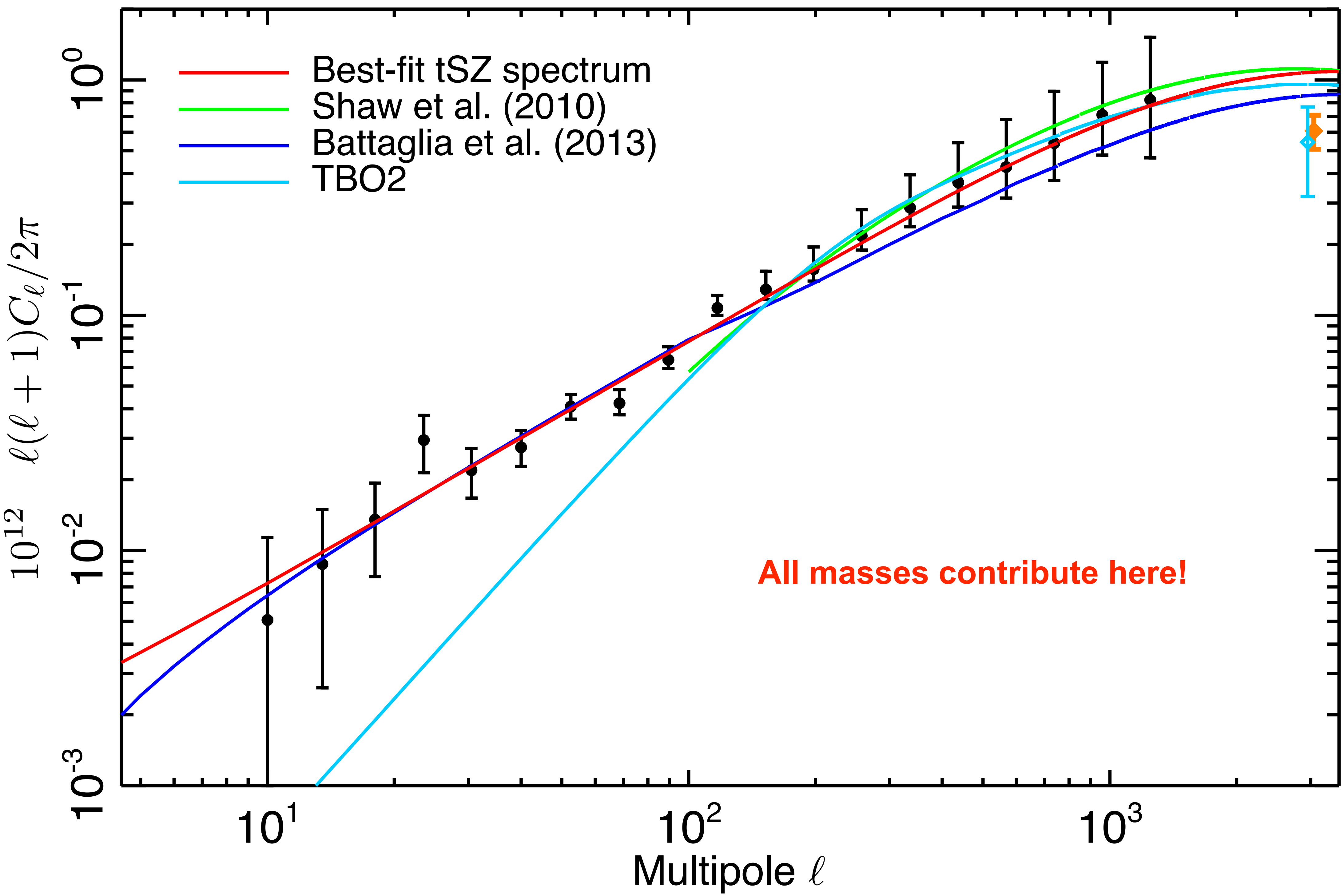
Fluctuations of the y-parameter at large scales



- 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 with other signals

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

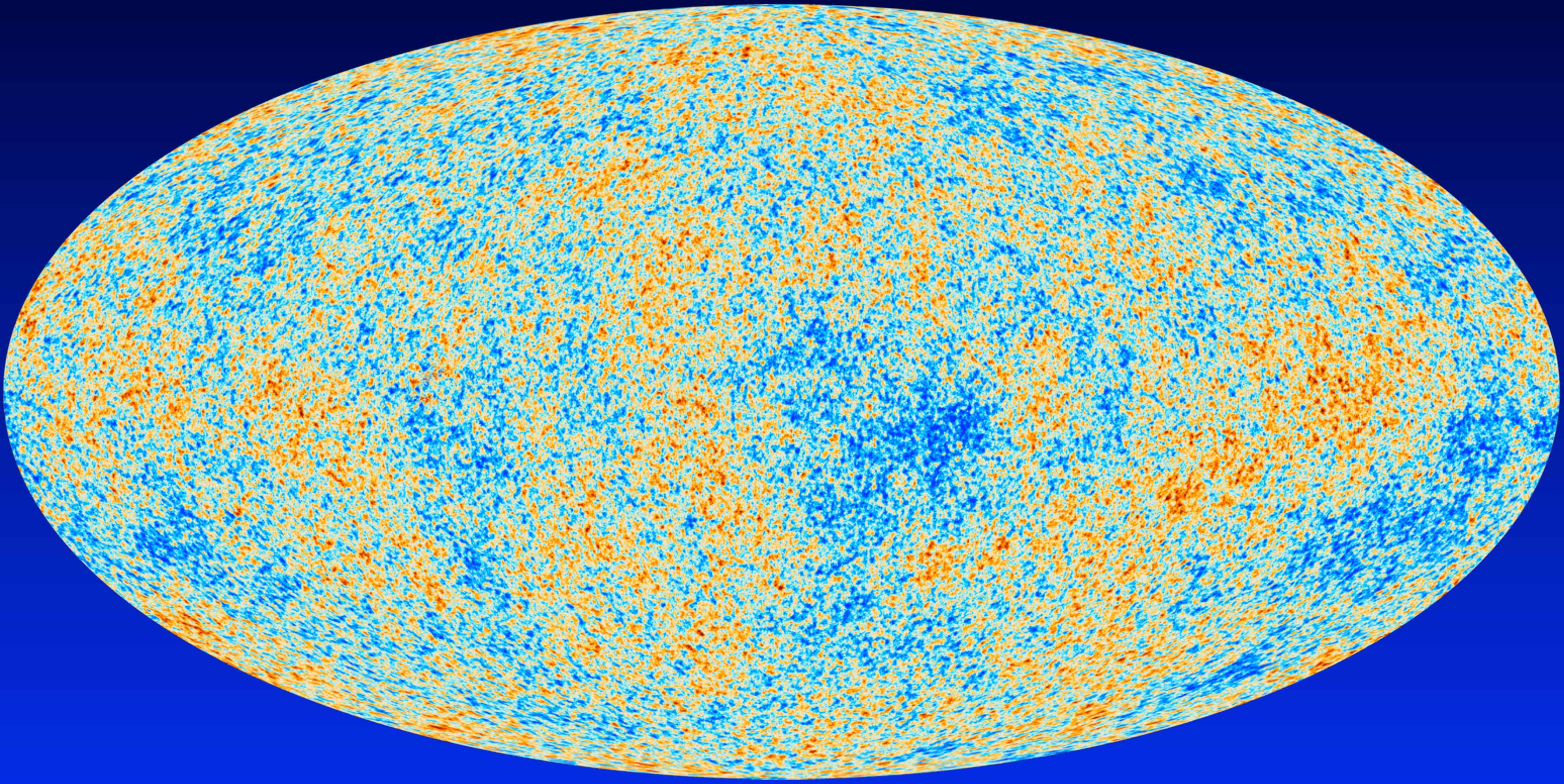
Measured power spectrum for y-parameter



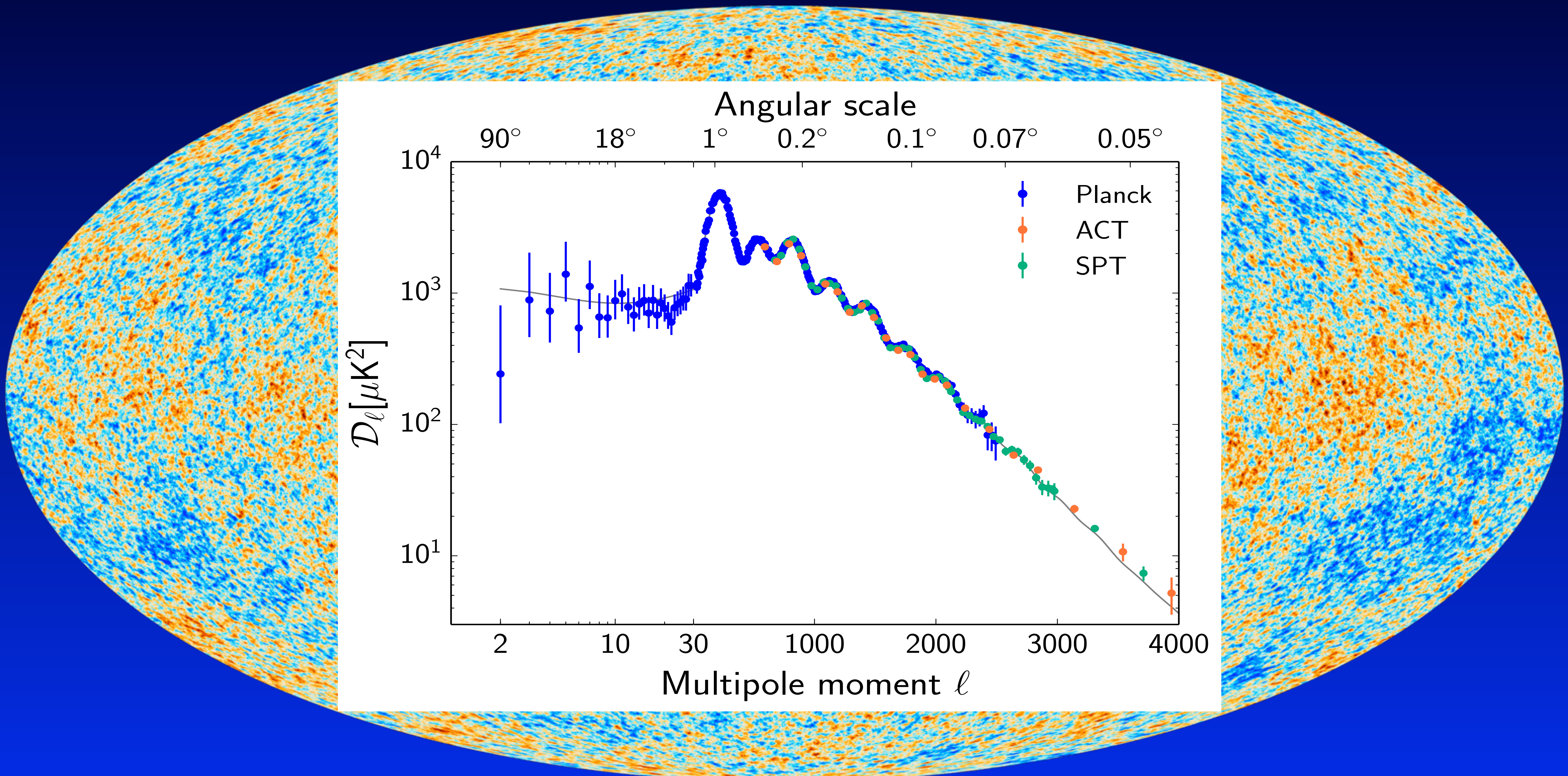
Planck Collaboration, 2015, XXII

The dissipation of small-scale acoustic modes

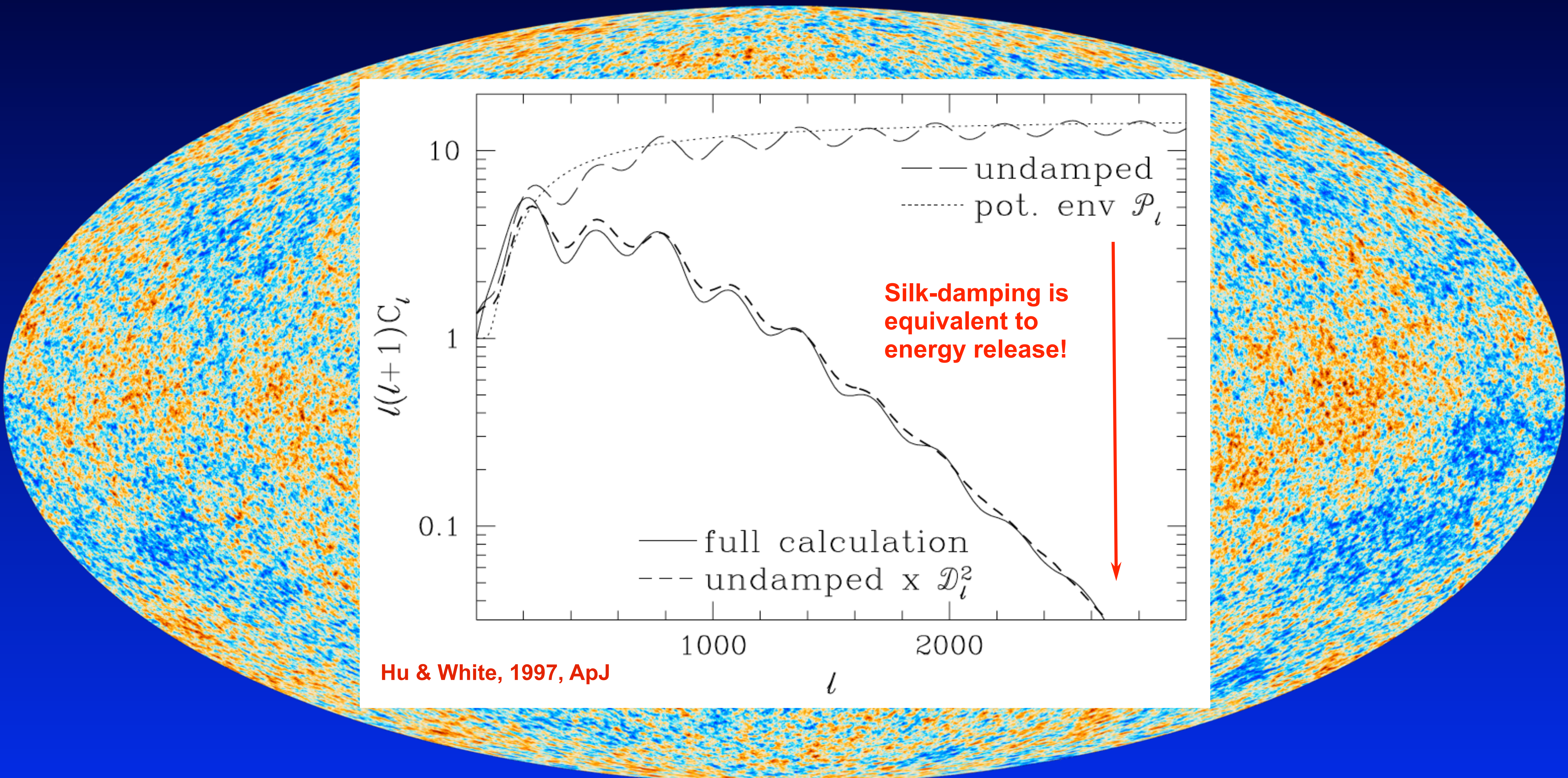
Dissipation of small-scale acoustic modes



Dissipation of small-scale acoustic modes



Dissipation of small-scale acoustic modes



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)

Energy release caused by dissipation process

'Obvious' dependencies:

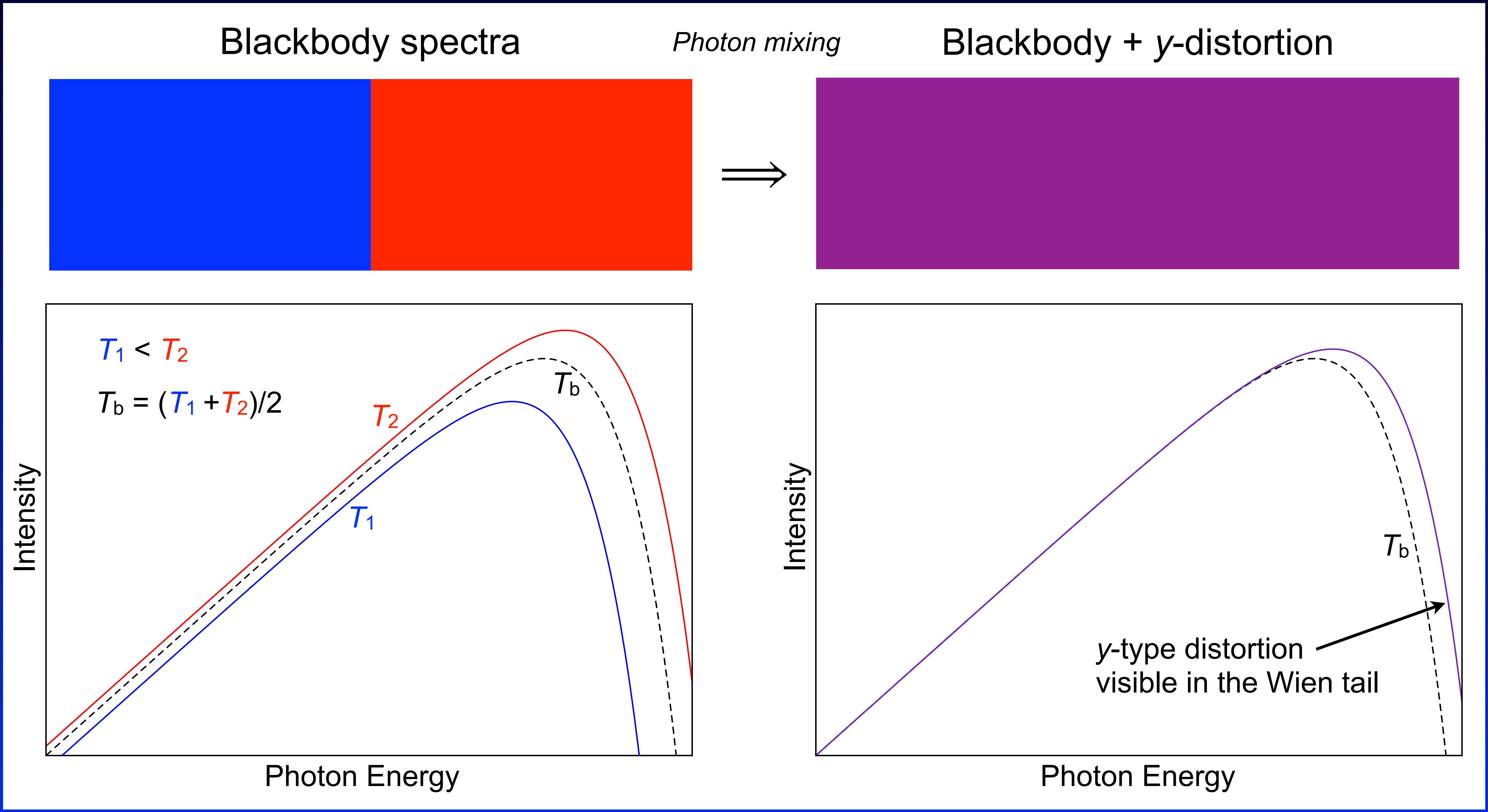
- *Amplitude* of the small-scale power spectrum
- *Shape* of the small-scale power spectrum
- *Dissipation scale* → $k_D \sim (H_0\, \Omega_{rel}^{1/2}\, N_{e,0})^{1/2}\, (1+z)^{3/2}$ at early times

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)

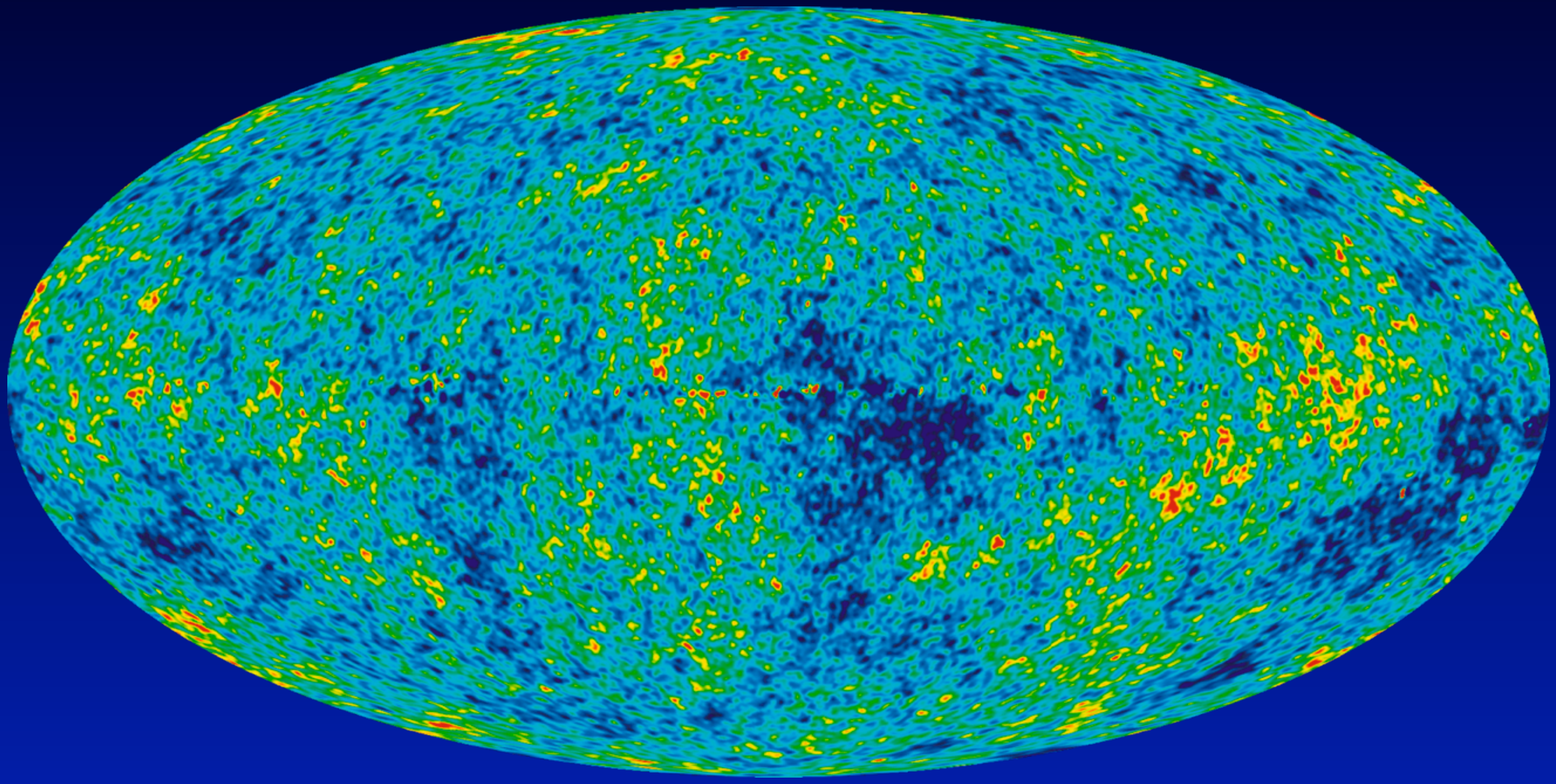
CMB Spectral distortions could add additional numbers beyond 'just' the tensor-to-scalar ratio from B-modes!

Distortion due to mixing of blackbodies



JC, Hamann & Patil, 2015

Distortions caused by superposition of blackbodies



- average spectrum

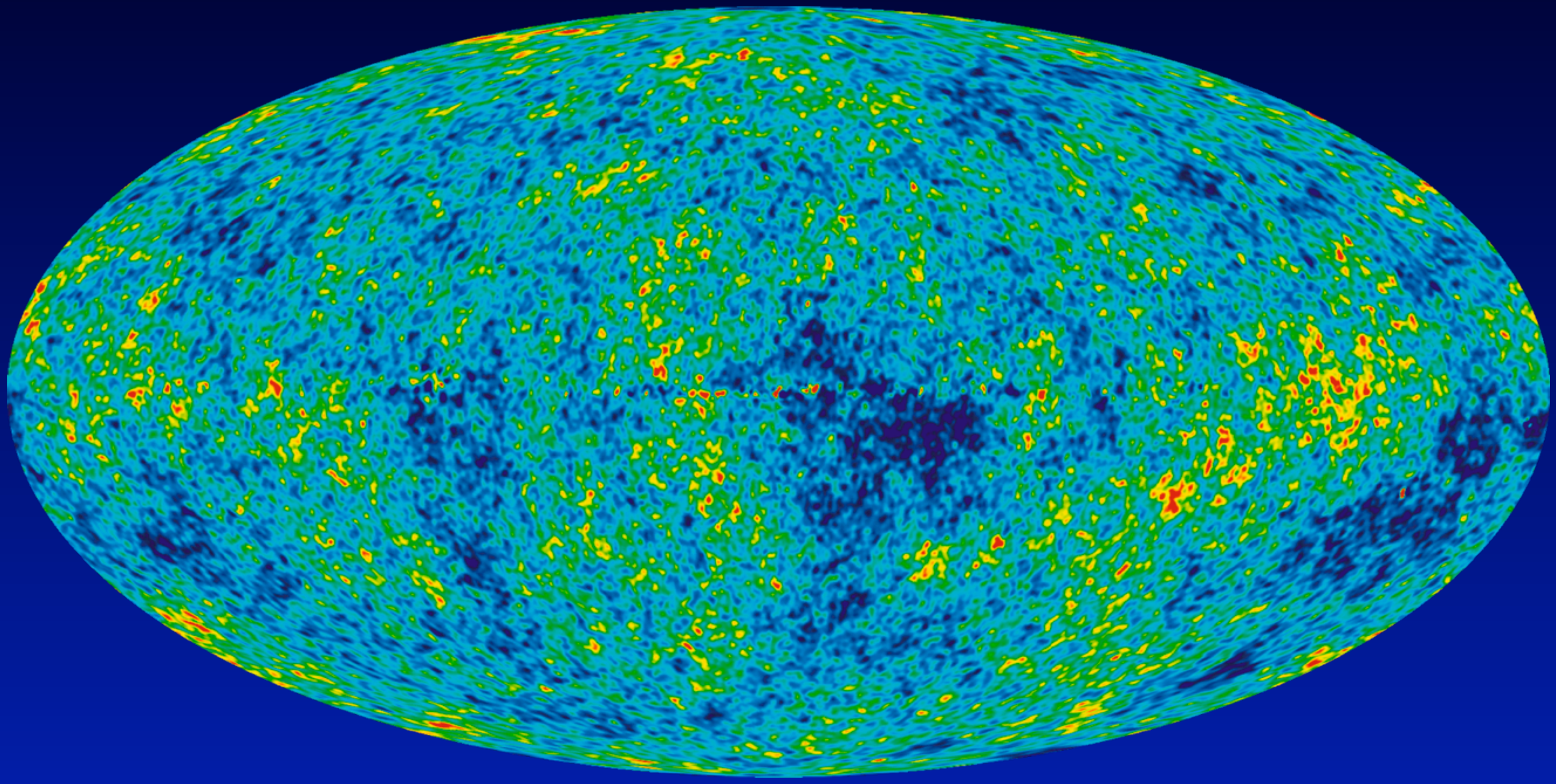
$$\Rightarrow \; y \simeq \frac{1}{2}\left\langle \left(\frac{\Delta T}{T}\right)^2 \right\rangle \approx 8 \times 10^{-10}$$

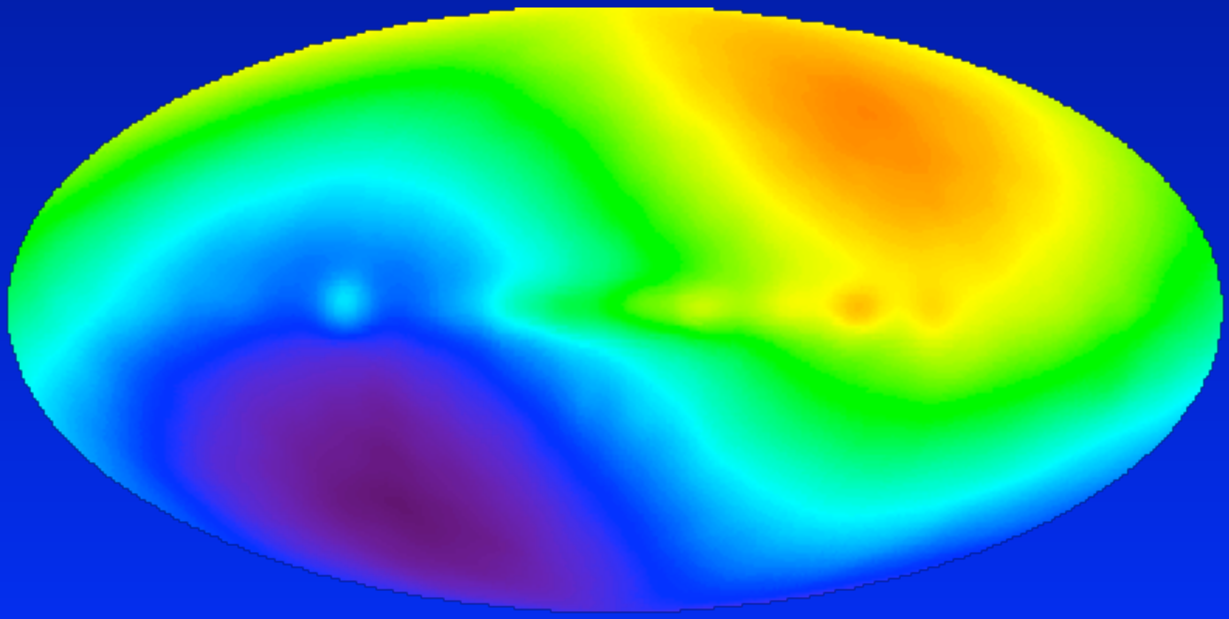
$$\Delta T_{\rm sup} \simeq T \left\langle \left(\frac{\Delta T}{T}\right)^2 \right\rangle \approx 4.4 \rm nK$$

- known with very high precision

JC & Sunyaev, 2004
JC, Khatri & Sunyaev, 2012
JC, 2016, ArXiv:1603.02496

Distortions caused by superposition of blackbodies





- average spectrum

$$\Rightarrow \; y \simeq \frac{1}{2}\left\langle \left(\frac{\Delta T}{T}\right)^2 \right\rangle \approx 8 \times 10^{-10}$$

$$\Delta T_{\rm sup} \simeq T \left\langle \left(\frac{\Delta T}{T}\right)^2 \right\rangle \approx 4.4 \mathrm{nK}$$

- known with very high precision

- *CMB dipole* (β ~ 1.23x10^{-3})

$$\Rightarrow \quad y = \frac{\beta^2}{6} \approx (2.525 \pm 0.012) \times 10^{-7}$$

$$\Delta T_{\rm sup} \simeq T\,\frac{\beta_{\rm c}^2}{3} \approx 1.4 \mu\mathrm{K}$$

- electrons are up-scattered
- can (and should) be taken out down to the level of y ~ 10^{-9}

COBE/DMR: ΔT = 3.353 mK

JC & Sunyaev, 2004
JC, Khatri & Sunyaev, 2012
JC, 2016, ArXiv:1603.02496

How do we compute the effective heating rate?

Dissipation of acoustic modes: ‘classical treatment’

- energy stored in plane sound waves

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

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

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

Dissipation of acoustic modes: ‘classical treatment’

- energy stored in plane sound waves

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

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

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

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

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

  $\delta\rho/\rho \to 4(\delta T_0/T) \equiv 4\Theta_0$ only perturbation in the monopole accounted for

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

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 $R \ll 1$

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

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

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

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

'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

Dissipation of acoustic modes: ‘classical treatment’

- energy stored in plane sound waves

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

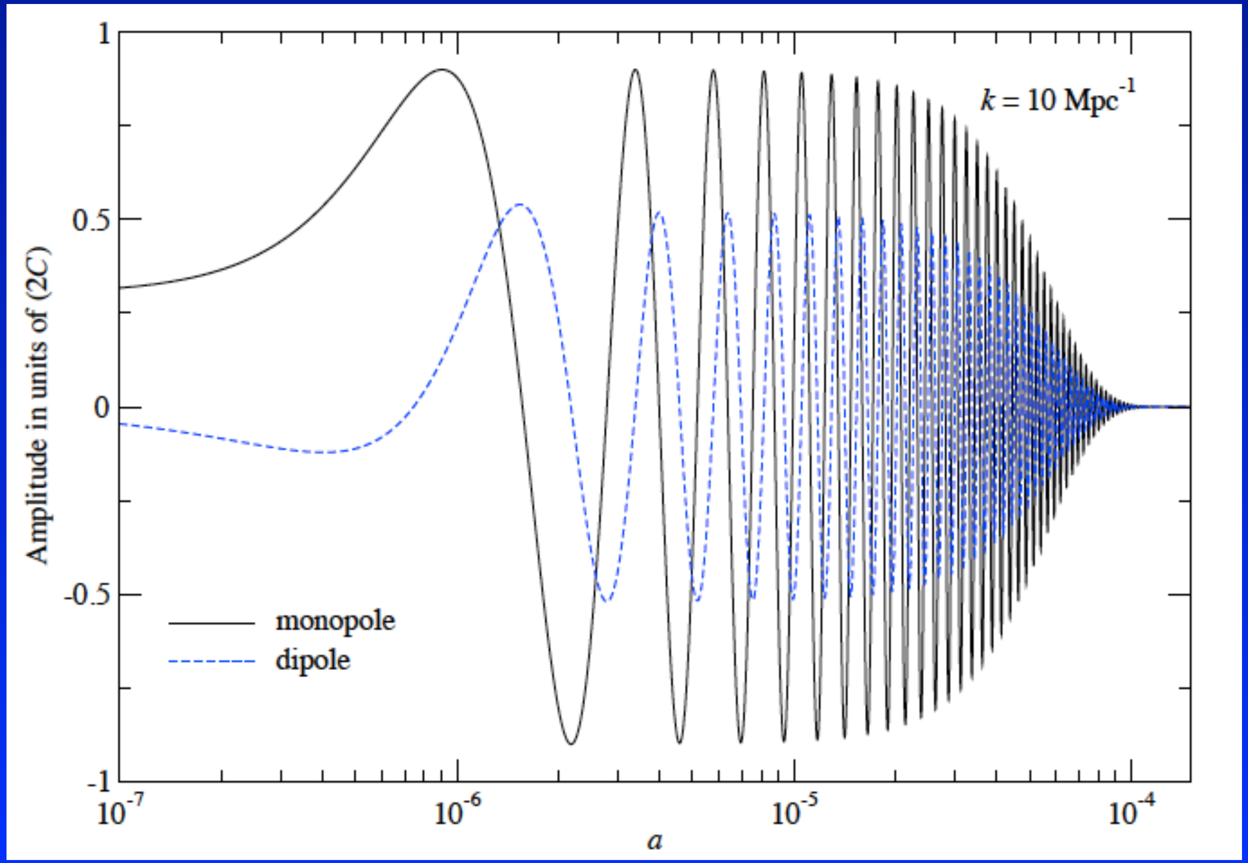
- expression for normal ideal gas where ρ is ‘*mass density*’ and c_s denotes ‘*sounds speed*’

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

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

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

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



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

Dissipation of acoustic modes: 'classical treatment'

- energy stored in plane sound waves

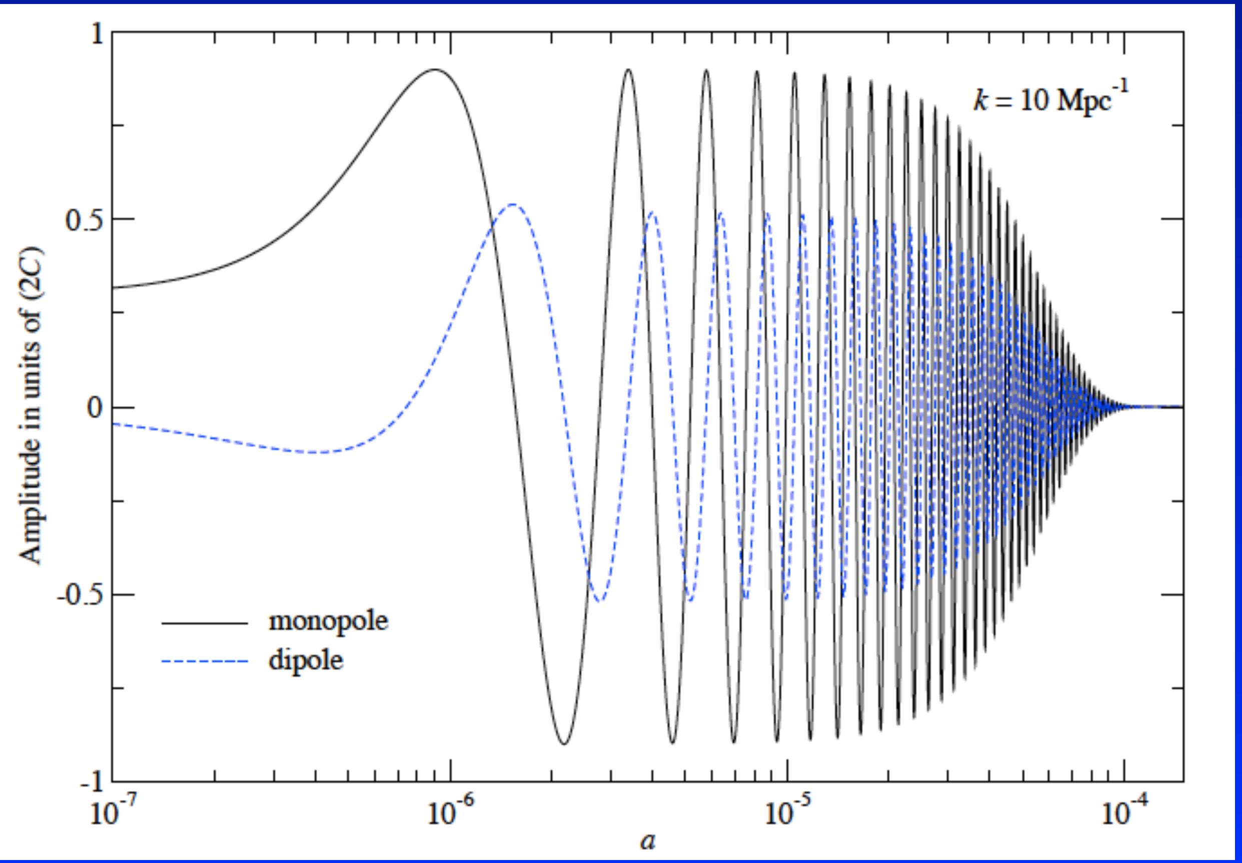
  Landau & Lifshitz, 'Fluid Mechanics', § 65 $\Rightarrow$ $Q \sim c_s^2\, \rho\, (\delta\rho/\rho)^2$

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

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

  $(c_s/c)^2 = [\, 3\,(1+R)\,]^{-1} \sim 1/3$
  $\rho \rightarrow \rho_\gamma = a_R\, T^4$ $\quad\Rightarrow\quad (a^4\rho_\gamma)^{-1}\, \mathrm{d}a^4 Q_{ac}/\mathrm{d}t = -16/3\ \mathrm{d}\langle\Theta_0{}^2\rangle/\mathrm{d}t$
  $\delta\rho/\rho \rightarrow 4(\delta T_0/T) \equiv 4\Theta_0$

- Simple estimate does *not* capture all the physics of the problem:
  - *total energy release is 9/4 ~ 2.25 times larger!*
  - *only 1/3 of the released energy goes into distortions (follows from superposition of blackbodies...)*



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

Early power spectrum constraints from FIRAS

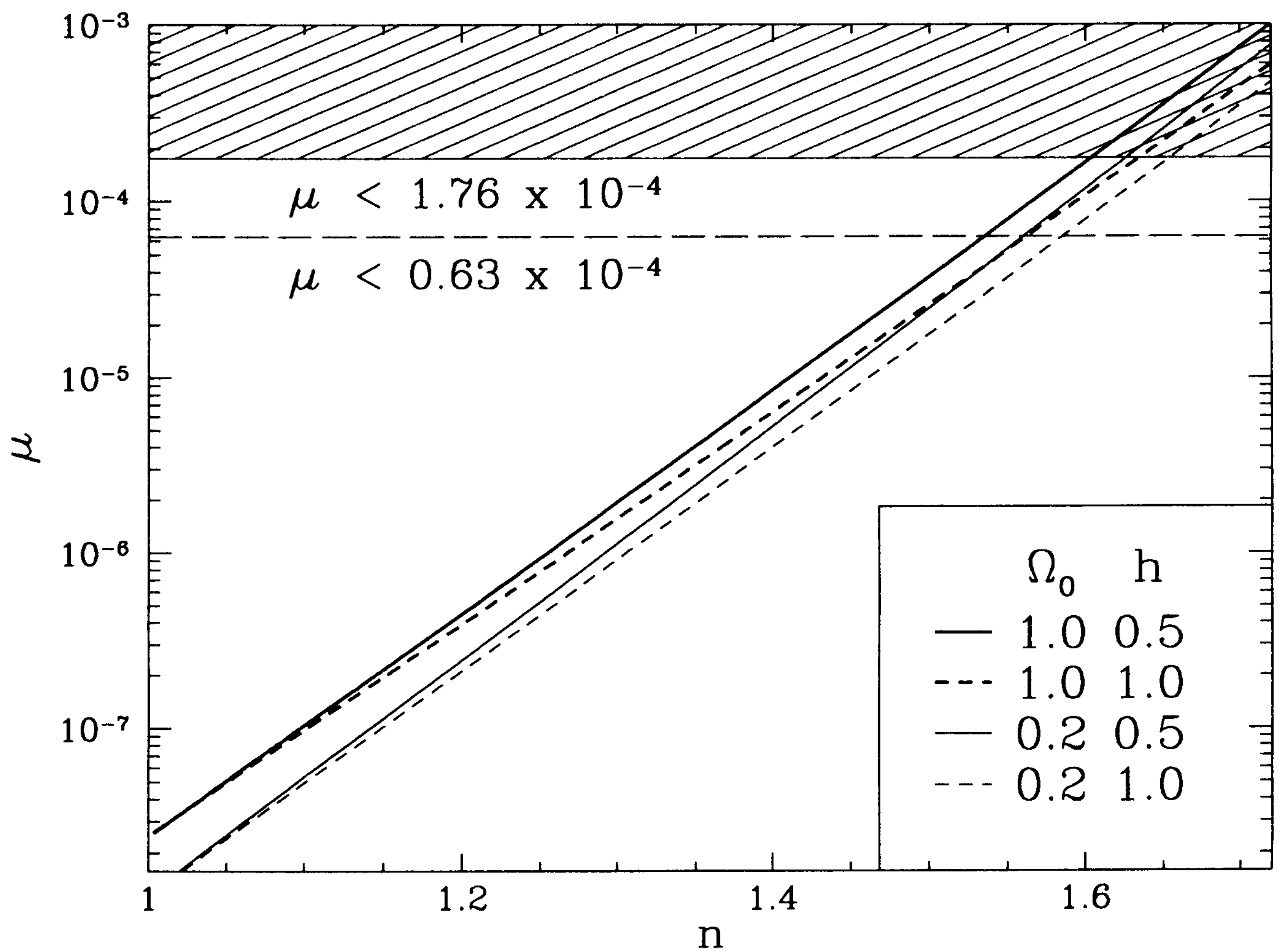


FIG. 1.—Spectral distortion μ, predicted from the full eq. (11), as a function of the power index n for a normalization at the mean of the *COBE* DMR detection $(\Delta T/T)_{10^\circ} = 1.12 \times 10^{-5}$. With the uncertainties on *both* the DMR and FIRAS measurements, the conservative 95% upper 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.

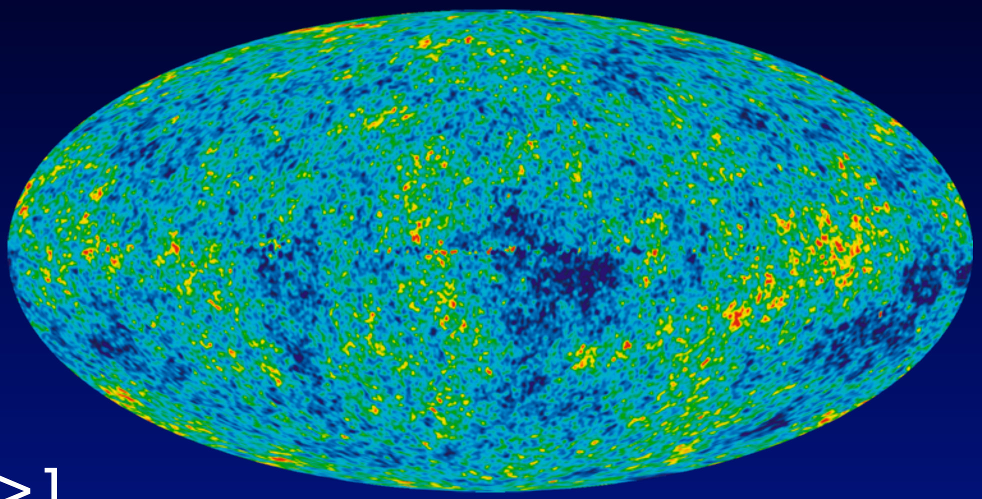
- based on classical estimate for heating rate
- Tightest / cleanest constraint at that point!
- simple power-law spectrum assumed
- *μ~10^{-8} for scale-invariant power spectrum*
- *n_S* $\lesssim$ 1.6

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

$$\langle \rho_\gamma \rangle = a_R \langle T^4 \rangle \approx a_R \langle T \rangle^4 \, [1 + 4\underbrace{\langle \Theta \rangle}_{== 0} + 6\langle \Theta^2 \rangle]$$

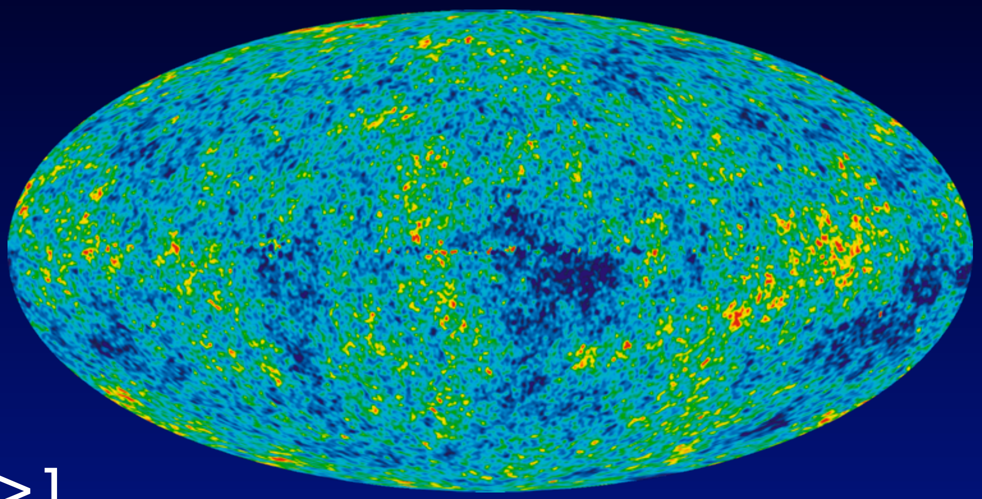


E.g., our snapshot at z=0

JC, Khatri & Sunyaev, 2012

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

$$\langle \rho_\gamma \rangle = a_R \langle T^4 \rangle \approx a_R \langle T \rangle^4 \, [1 + \underbrace{4\langle \Theta \rangle}_{== 0} + 6\langle \Theta^2 \rangle]$$

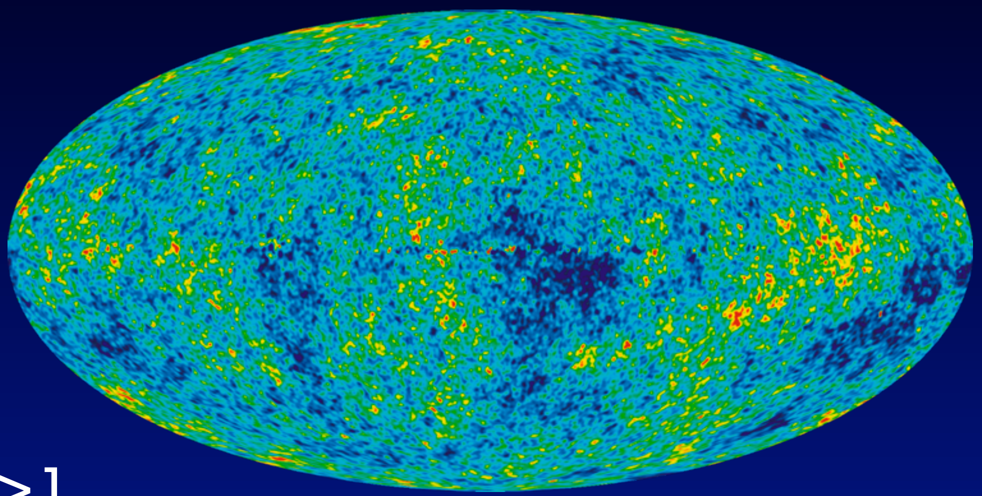
$$\Rightarrow \quad (a^4 \rho_\gamma)^{-1} \, \mathrm{d}a^4 Q_{ac}/\mathrm{d}t = -6 \, \mathrm{d}\langle \Theta^2 \rangle/\mathrm{d}t$$

- Monopole actually drops out of the equation!
- In principle *all* higher multipoles contribute to the energy release

JC, Khatri & Sunyaev, 2012

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

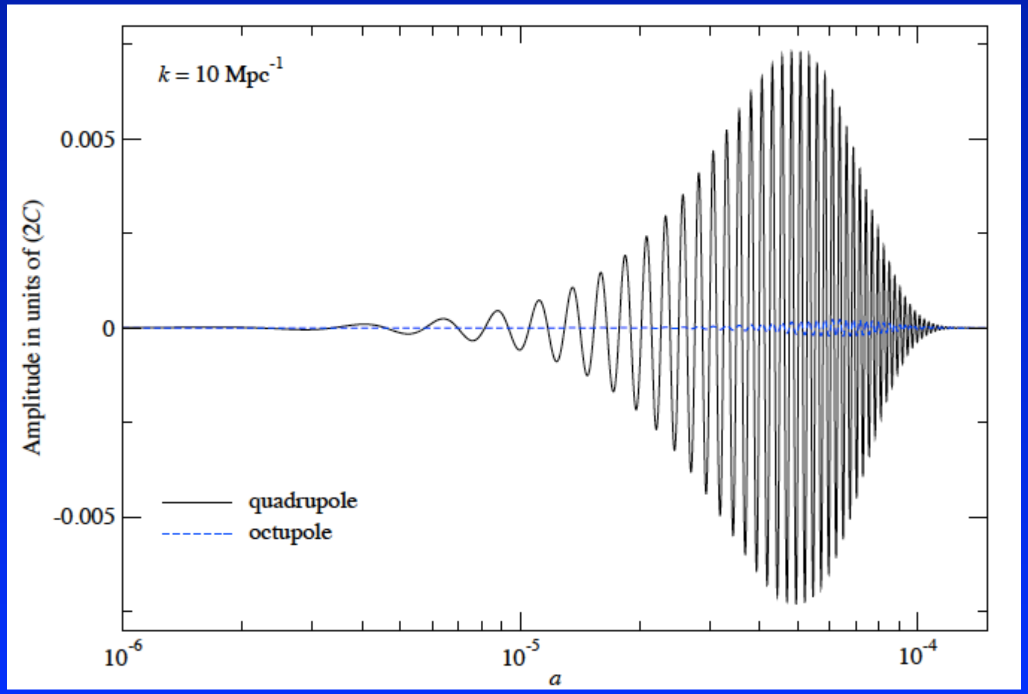
$$\langle \rho_\gamma \rangle = a_R \langle T^4 \rangle \approx a_R \langle T \rangle^4 \, [1 + 4\underbrace{\langle \Theta \rangle}_{==0} + 6\langle \Theta^2 \rangle]$$

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

- 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

Effective energy release caused by damping effect

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

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

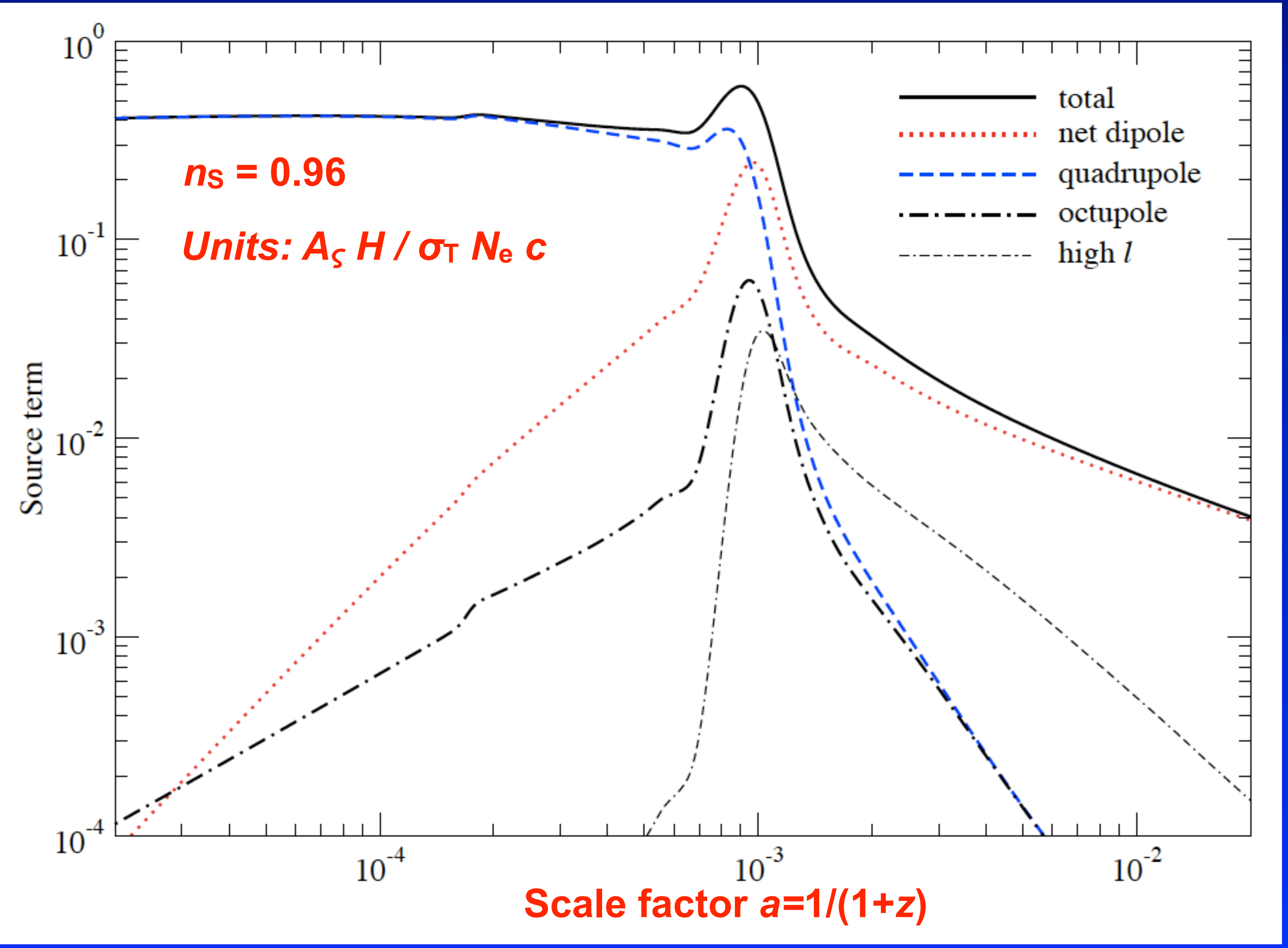
gauge-independent dipole **effect of polarization** **higher multipoles**

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

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

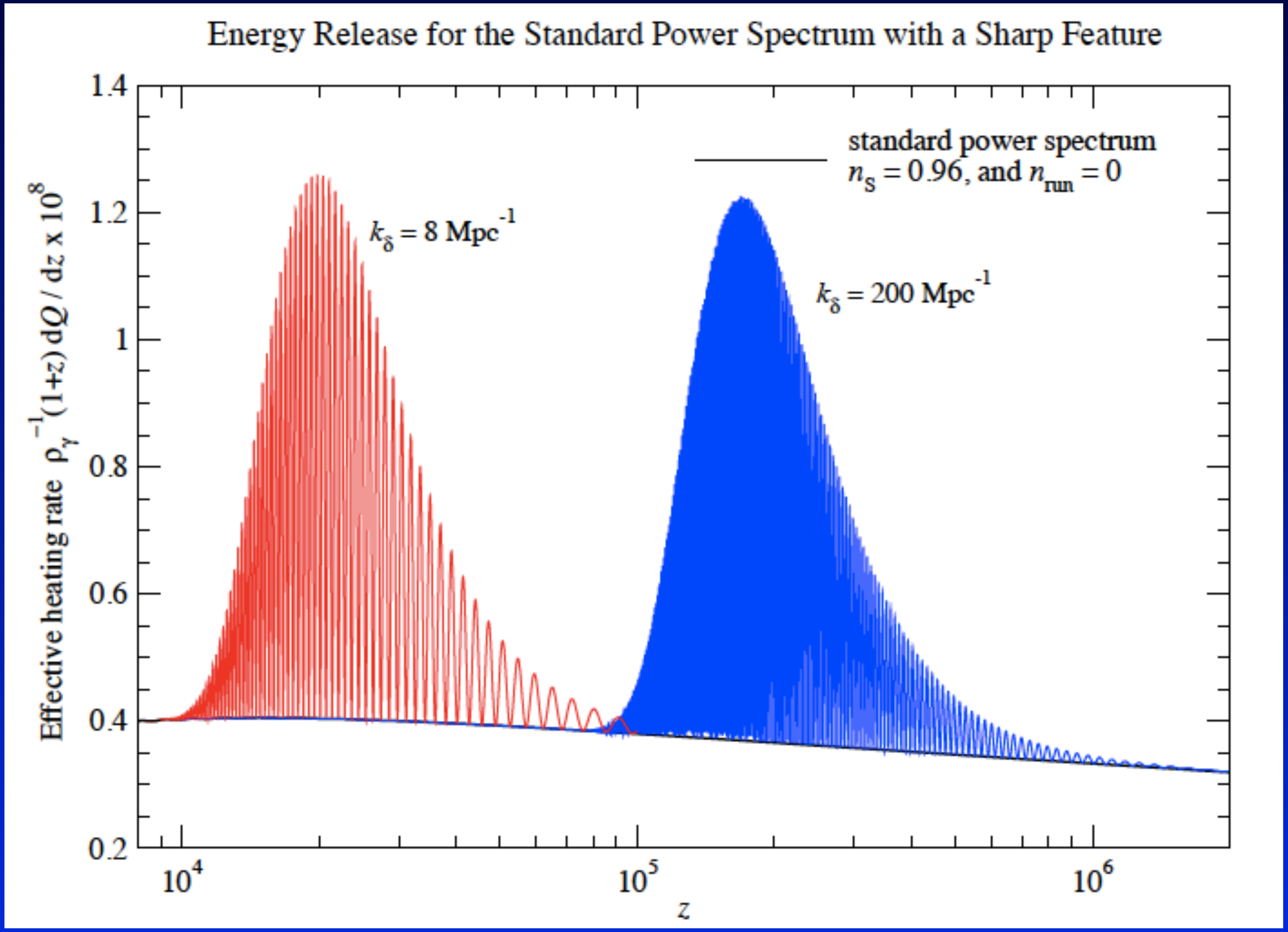
Primordial power spectrum

- *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

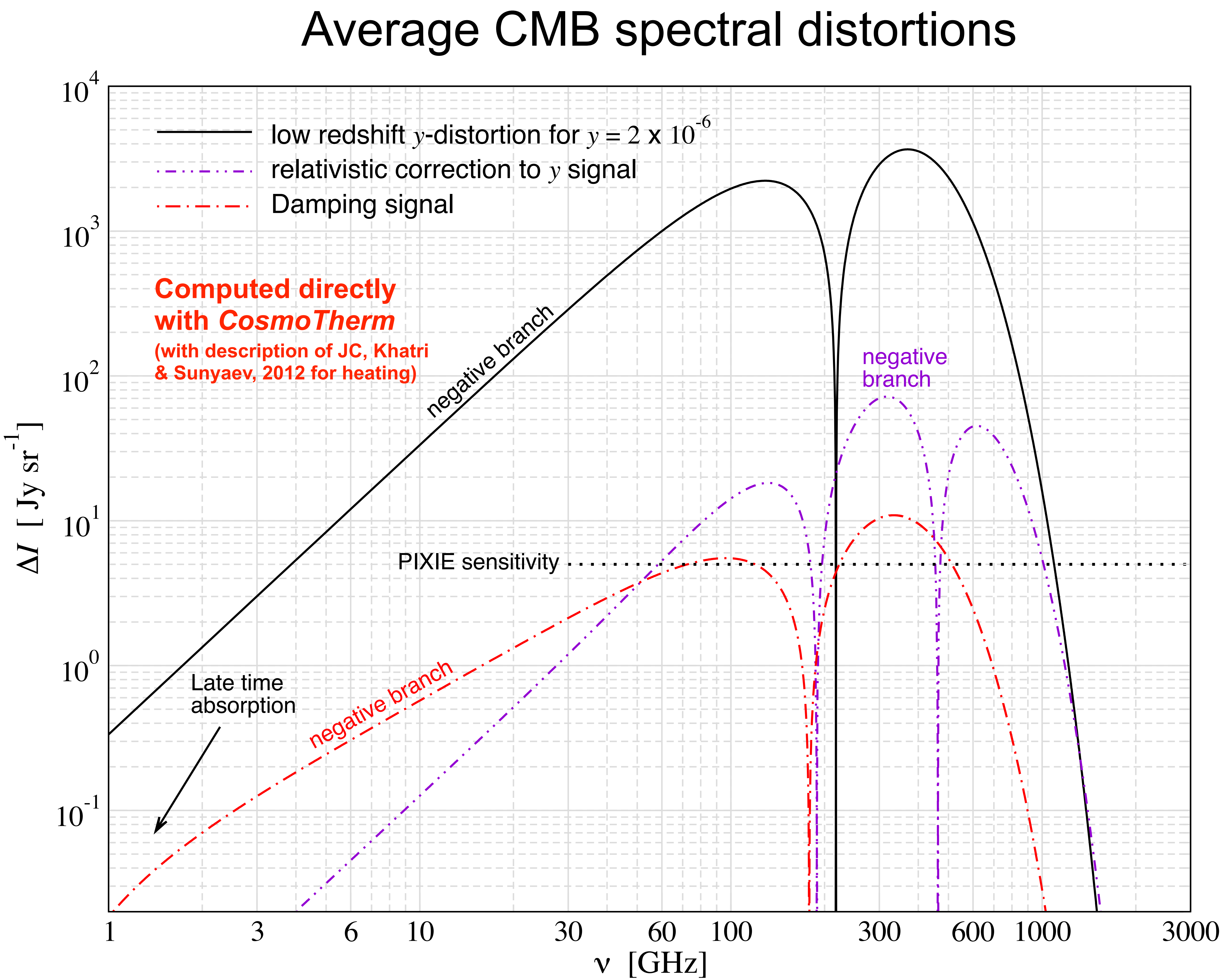
- Single mode with wavenumber k dissipates its energy at

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

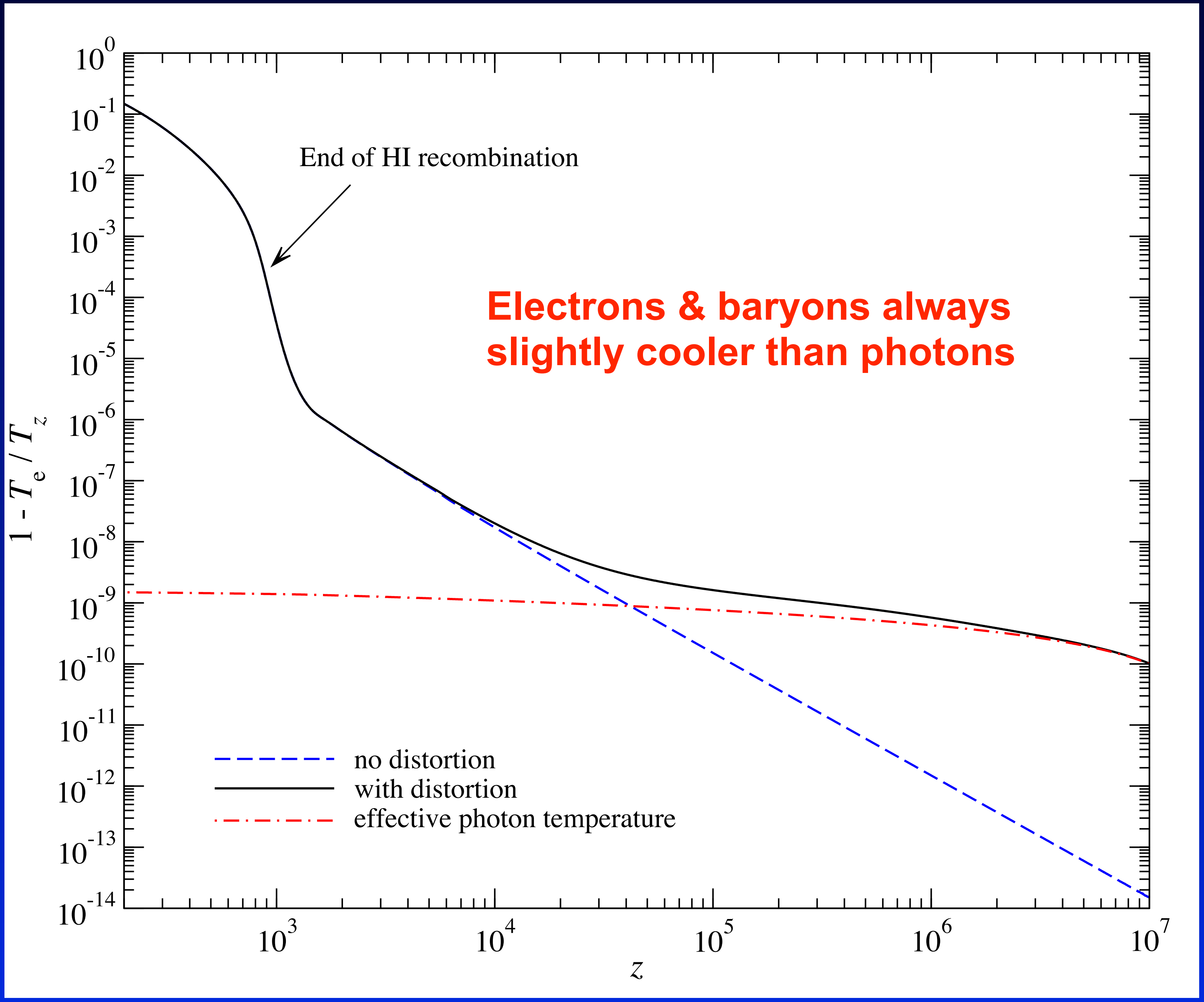
- Modes with wavenumber $50\ \mathrm{Mpc}^{-1} < k < 10^4\ \mathrm{Mpc}^{-1}$ dissipate their energy during the μ-era

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

So what does one expect within ΛCDM?


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
negative branch
PIXIE sensitivity
Late time
absorption
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

Spectral distortion caused by the cooling of ordinary matter



- adiabatic expansion

⇒ $T_\gamma \sim (1+z) \leftrightarrow T_m \sim (1+z)^2$

- photons continuously *cooled* / *down-scattered* since day one of the Universe!
- Compton heating balances adiabatic cooling

$$\Rightarrow \frac{\mathrm{d}a^4\rho_\gamma}{a^4\mathrm{d}t} \simeq -Hk\alpha_\mathrm{h}T_\gamma \propto (1+z)^6$$

- at high redshift same scaling as *annihilation* ($\propto N_X^2$) and *acoustic mode damping*

⇒ partial *cancellation*

JC, 2005; JC & Sunyaev, 2012
Khatri, Sunyaev & JC, 2012

Spectral distortion caused by the cooling of ordinary matter

- adiabatic expansion

⇒ $T_\gamma \sim (1+z) \leftrightarrow T_m \sim (1+z)^2$

- photons continuously *cooled* / *down-scattered* since day one of the Universe!
- Compton heating balances adiabatic cooling

$$\Rightarrow \frac{\mathrm{d}a^4\rho_\gamma}{a^4\mathrm{d}t} \simeq -Hk\alpha_\mathrm{h}T_\gamma \propto (1+z)^6$$

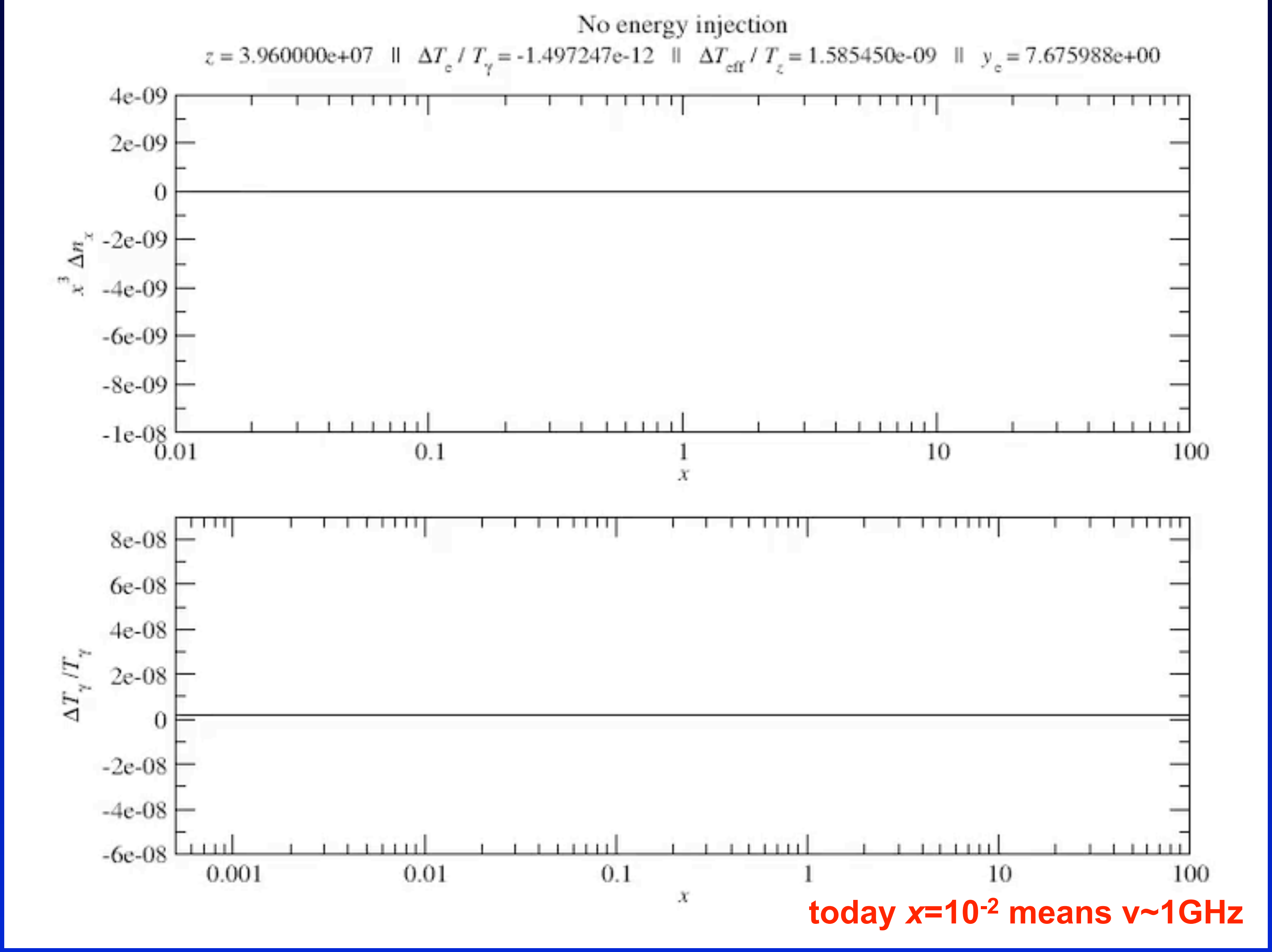
- at high redshift same scaling as *annihilation* ($\propto N_X^2$) and *acoustic mode damping*

⇒ partial *cancellation*

today x=10^{-2} means ν~1GHz

JC, 2005; JC & Sunyaev, 2012
Khatri, Sunyaev & JC, 2012

Spectral distortion caused by the cooling of ordinary matter



- adiabatic expansion

⇒ $T_\gamma \sim (1+z) \leftrightarrow T_m \sim (1+z)^2$

- photons continuously *cooled* / *down-scattered* since day one of the Universe!
- Compton heating balances adiabatic cooling

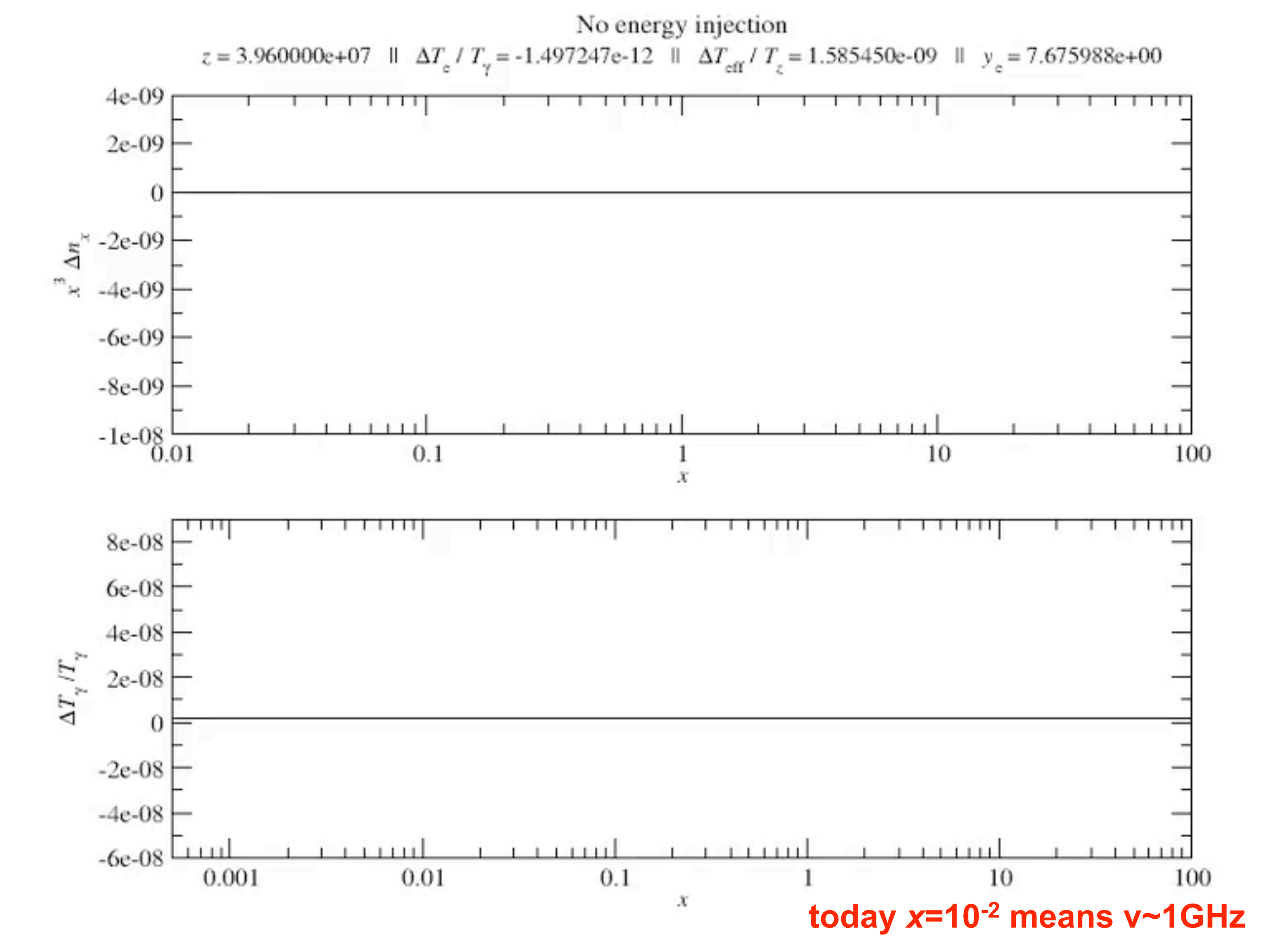
$$\Rightarrow \frac{\mathrm{d}a^4\rho_\gamma}{a^4\mathrm{d}t} \simeq -Hk\alpha_\mathrm{h}T_\gamma \propto (1+z)^6$$

- at high redshift same scaling as *annihilation* ($\propto N_X^2$) and *acoustic mode damping*

⇒ partial *cancellation*

JC, 2005; JC & Sunyaev, 2012
Khatri, Sunyaev & JC, 2012

Spectral distortion caused by the cooling of ordinary matter



$$\mu \simeq 1.4 \left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_\mu \approx -3\times10^{-9} \qquad y \simeq \frac{1}{4} \left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_y \approx -6\times10^{-10}$$

JC, 2005; JC & Sunyaev, 2012
Khatri, Sunyaev & JC, 2012

- adiabatic expansion

⇒ $T_\gamma \sim (1+z) \leftrightarrow T_m \sim (1+z)^2$

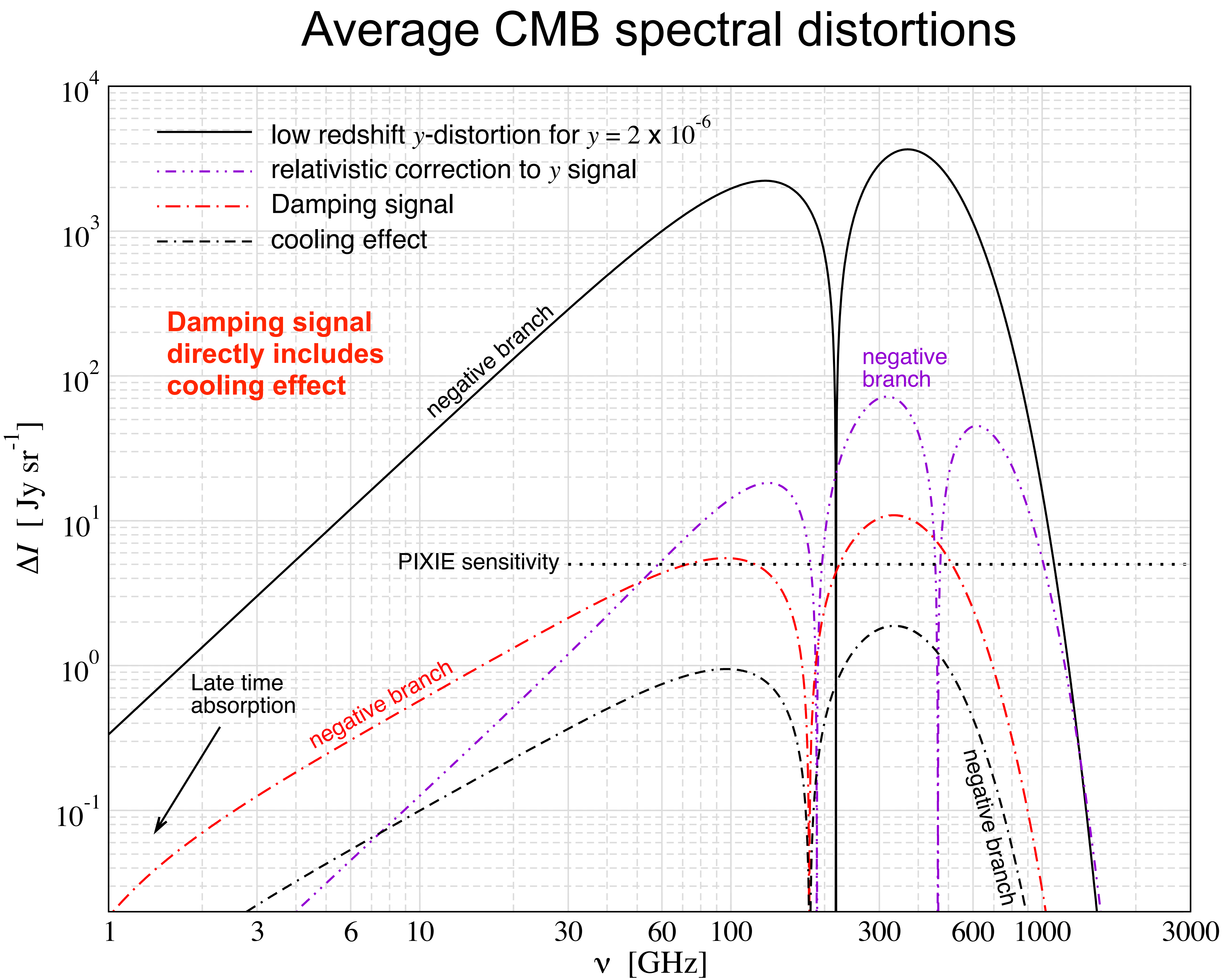
- photons continuously *cooled* / *down-scattered* since day one of the Universe!
- Compton heating balances adiabatic cooling

$$\Rightarrow \frac{\mathrm{d}a^4\rho_\gamma}{a^4\mathrm{d}t} \simeq -Hk\alpha_\mathrm{h}T_\gamma \propto (1+z)^6$$

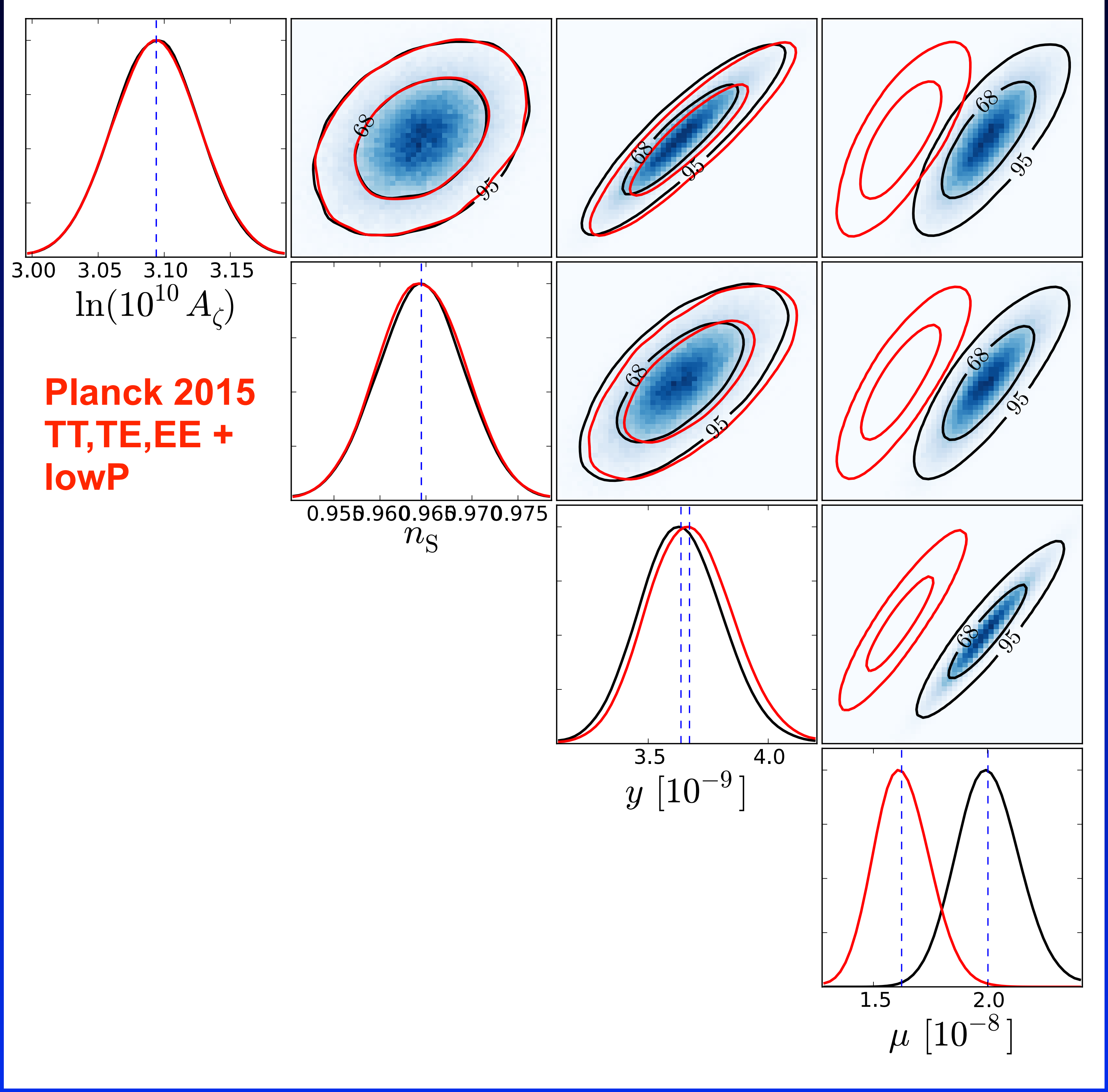
- at high redshift same scaling as *annihilation* ($\propto N_X^2$) and *acoustic mode damping*

⇒ partial *cancellation*

- *negative* μ and y distortion
- late free-free absorption at very low frequencies
- Distortion a few times below PIXIE's current sensitivity

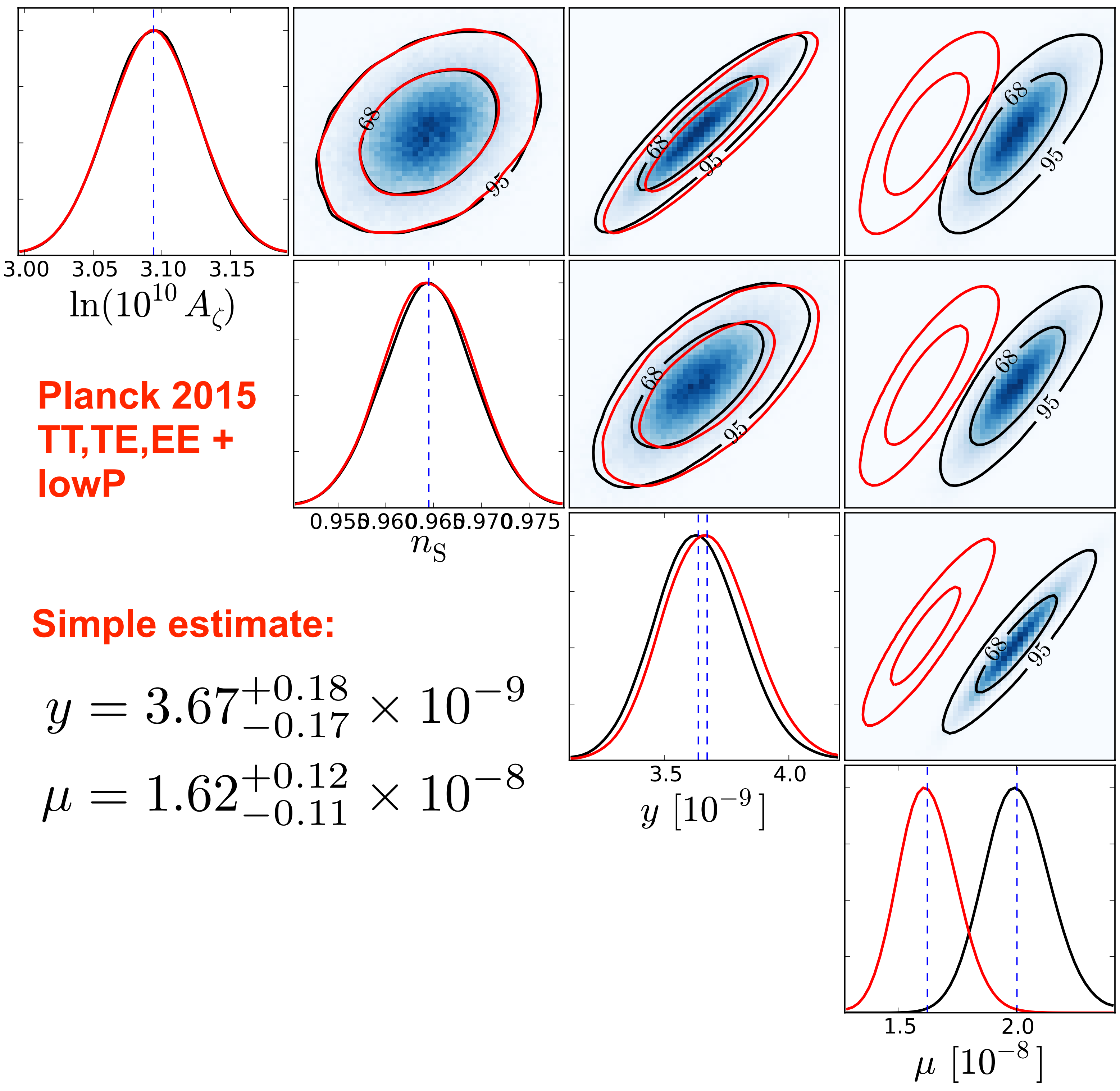

Average CMB spectral distortions
low redshift y-distortion for y = 2 x 10^-6
relativistic correction to y signal
Damping signal
cooling effect
Damping signal
directly includes
cooling effect
negative branch
negative
branch
PIXIE sensitivity
Late time
absorption
negative branch
negative branch
ΔI [Jy 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

Predicted damping distortion in terms of μ and y



JC 2016, ArXiv:1603.02496

Predicted damping distortion in terms of μ and y



Planck 2015 TT,TE,EE + lowP

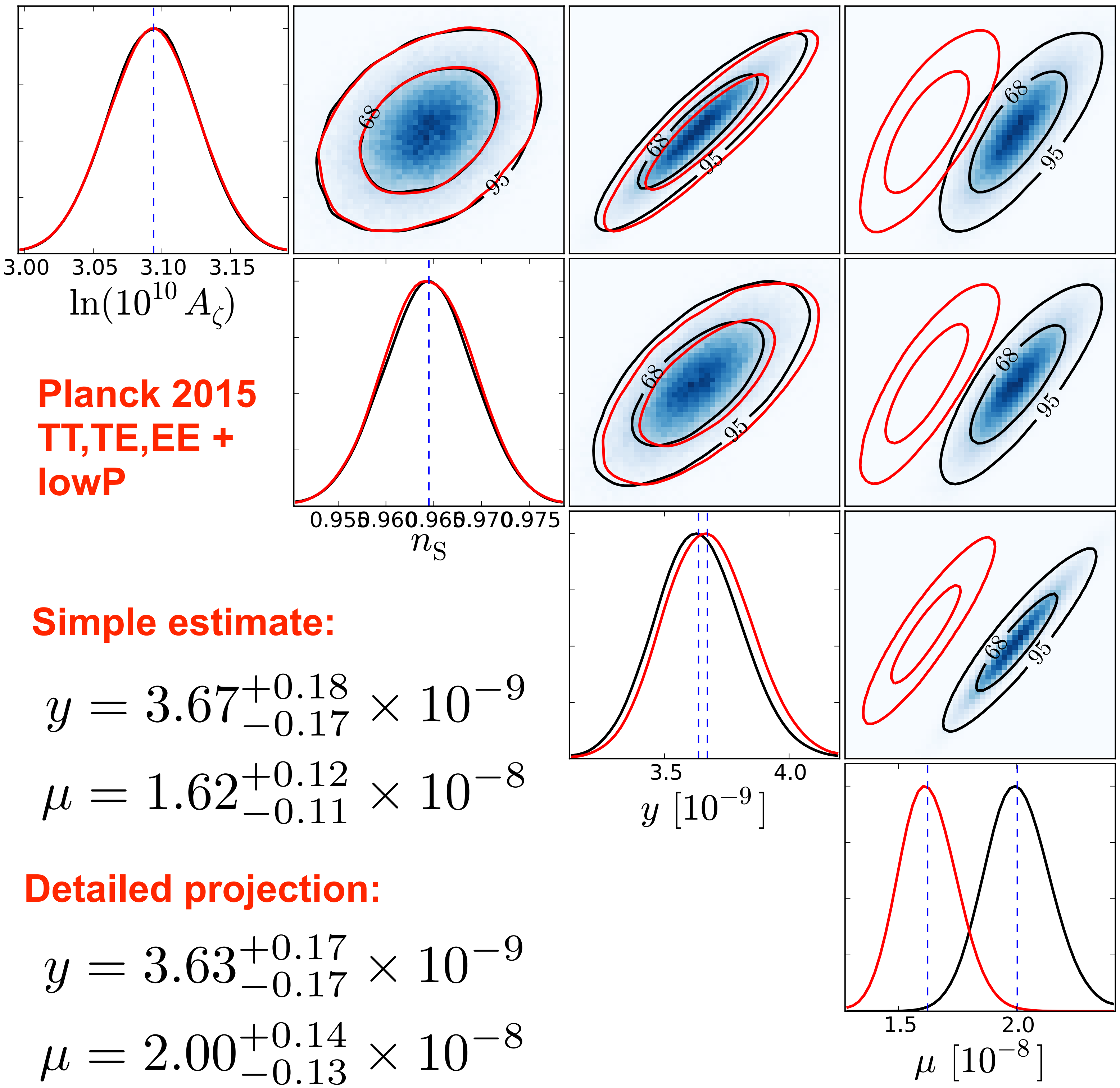
Simple estimate:

$$y = 3.67^{+0.18}_{-0.17} \times 10^{-9}$$

$$\mu = 1.62^{+0.12}_{-0.11} \times 10^{-8}$$

JC 2016, ArXiv:1603.02496

Predicted damping distortion in terms of μ and y



Planck 2015 TT,TE,EE + lowP

Simple estimate:

$$y = 3.67^{+0.18}_{-0.17} \times 10^{-9}$$

$$\mu = 1.62^{+0.12}_{-0.11} \times 10^{-8}$$

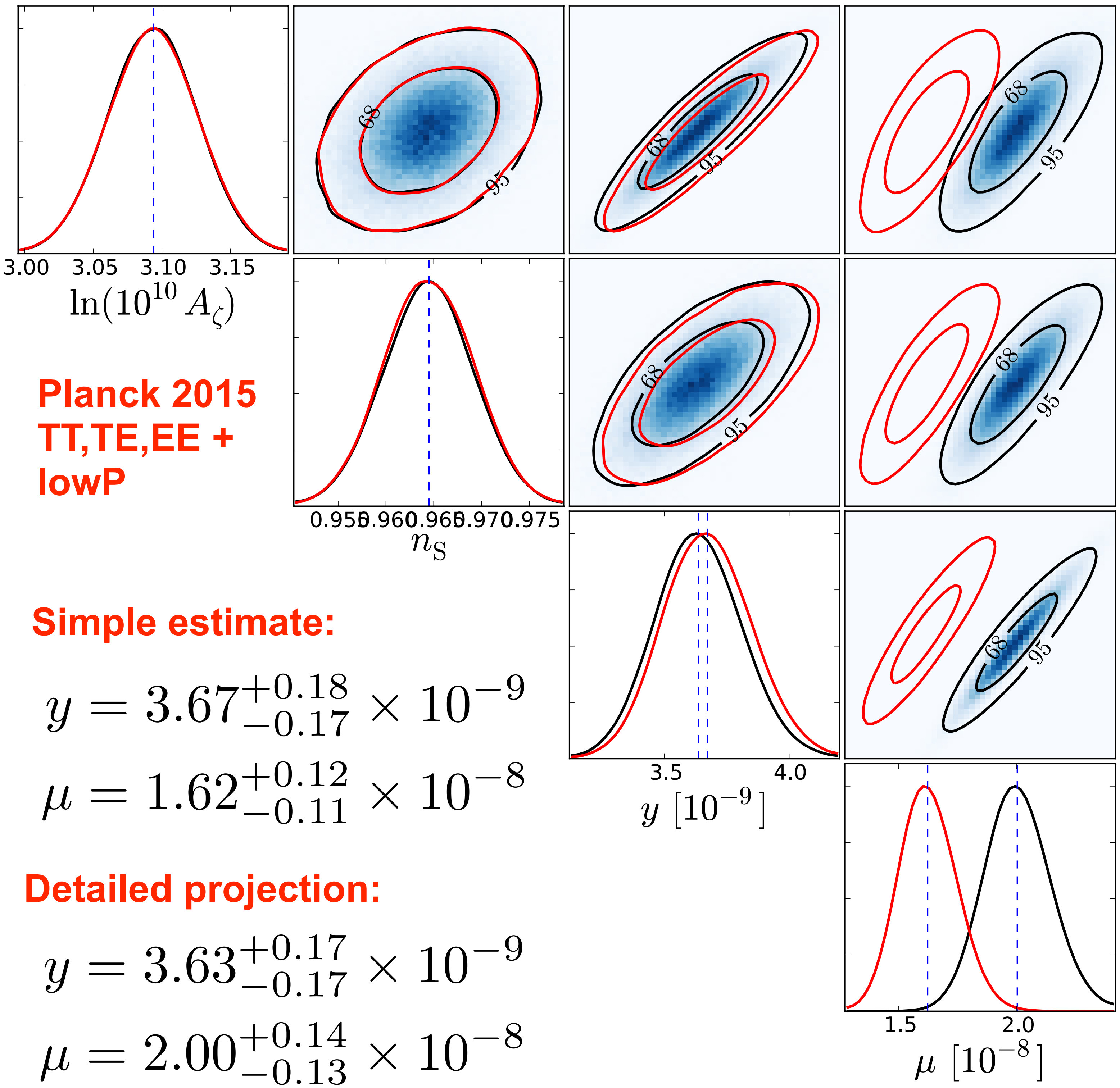
Detailed projection:

$$y = 3.63^{+0.17}_{-0.17} \times 10^{-9}$$

$$\mu = 2.00^{+0.14}_{-0.13} \times 10^{-8}$$

JC 2016, ArXiv:1603.02496

Predicted damping distortion in terms of μ and y



Planck 2015 TT,TE,EE + lowP

Simple estimate:

$$y = 3.67^{+0.18}_{-0.17} \times 10^{-9}$$

$$\mu = 1.62^{+0.12}_{-0.11} \times 10^{-8}$$

Detailed projection:

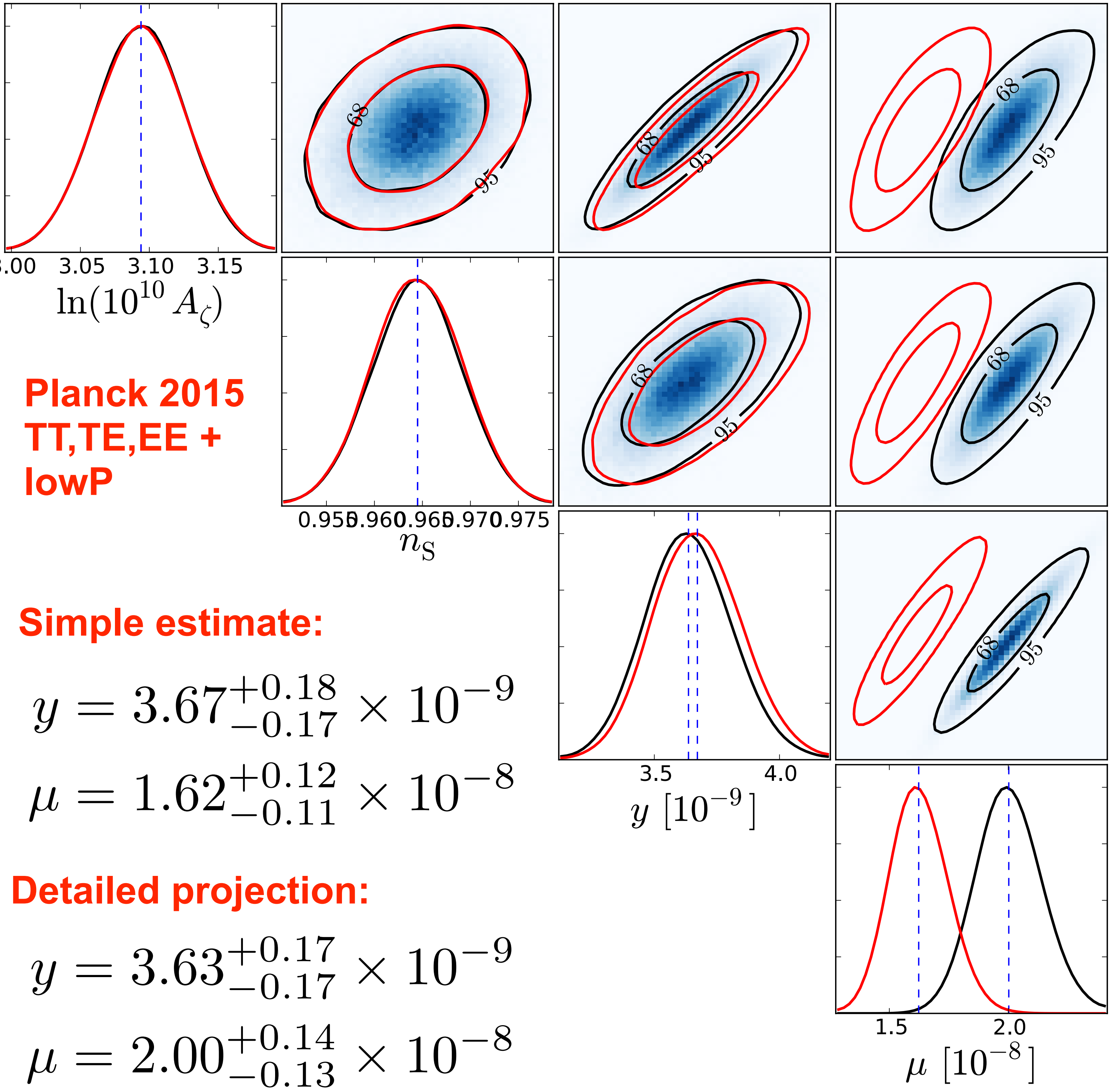
$$y = 3.63^{+0.17}_{-0.17} \times 10^{-9}$$

$$\mu = 2.00^{+0.14}_{-0.13} \times 10^{-8}$$

- *Errors dominated by power spectrum parameters*
- Detailed projections give slightly higher value for μ (~ 2.6σ)
- y-part swamped by low redshift distortion
- μ could be detectable at 1.5σ with PIXIE in current setting (see also JC, Khatri & Sunyaev, 2015)
- a factor of ~3.4 short of clear 5σ detection

JC 2016, ArXiv:1603.02496

Predicted damping distortion in terms of μ and y



Planck 2015 TT,TE,EE + lowP

Simple estimate:

$$y = 3.67^{+0.18}_{-0.17} \times 10^{-9}$$

$$\mu = 1.62^{+0.12}_{-0.11} \times 10^{-8}$$

Detailed projection:

$$y = 3.63^{+0.17}_{-0.17} \times 10^{-9}$$

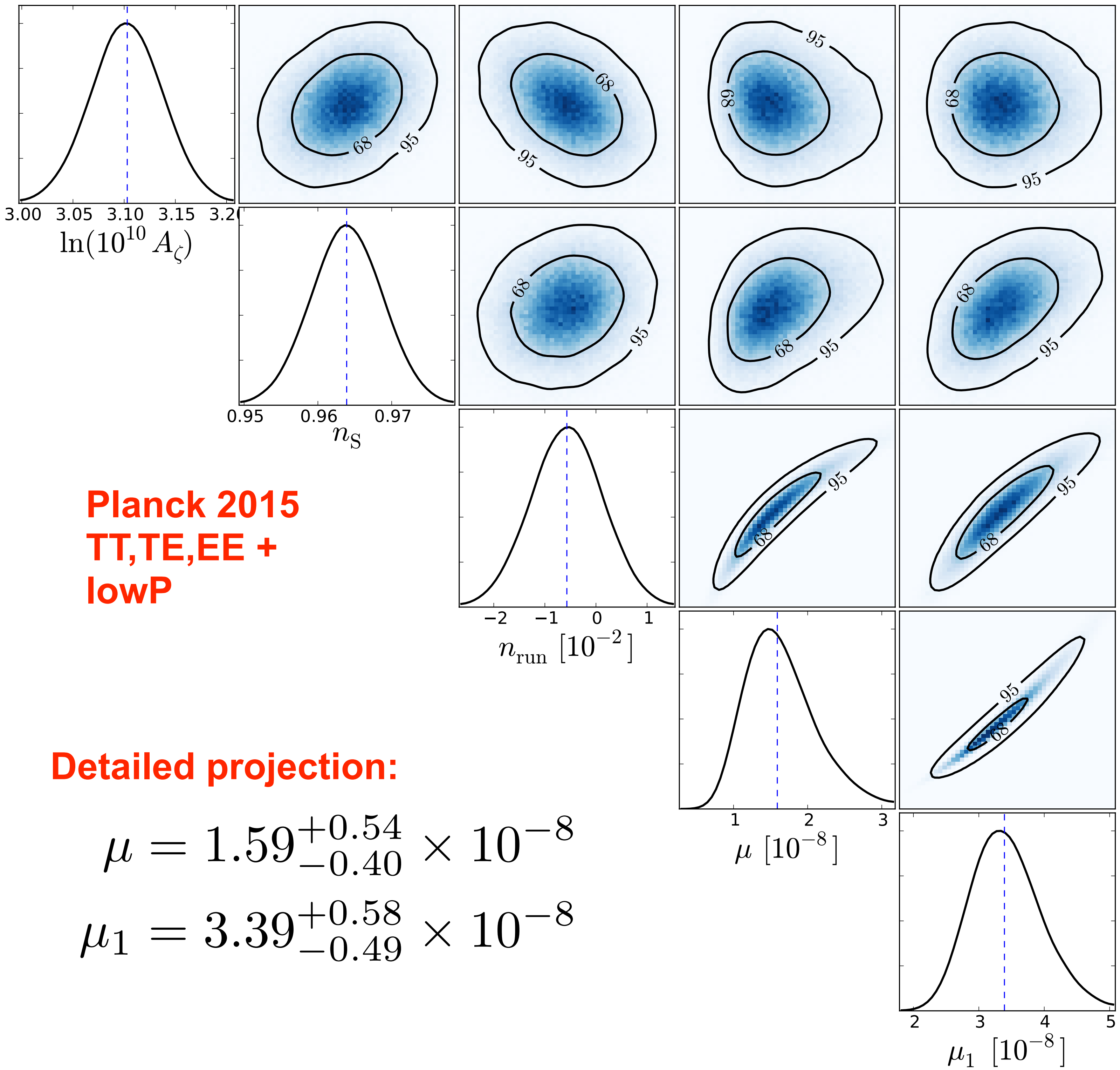
$$\mu = 2.00^{+0.14}_{-0.13} \times 10^{-8}$$

- *Errors dominated by power spectrum parameters*
- Detailed projections give slightly higher value for μ (~ 2.6σ)
- y-part swamped by low redshift distortion
- μ could be detectable at 1.5σ with PIXIE in current setting (see also JC, Khatri & Sunyaev, 2015)
- a factor of ~3.4 short of clear 5σ detection

Improvements of PIXIE are being discussed!

JC 2016, ArXiv:1603.02496

Allowing for running of the spectral index



Planck 2015
TT,TE,EE +
lowP

Detailed projection:

$$\mu = 1.59^{+0.54}_{-0.40} \times 10^{-8}$$

$$\mu_1 = 3.39^{+0.58}_{-0.49} \times 10^{-8}$$

- Posteriors more non-Gaussian
- *extended scenario*
- *small* negative running → *lower* value of μ
- μ signal ~1σ above current PIXIE sensitivity
- first residual distortion parameter μ_1 ~ 0.3σ for current PIXIE sensitivity

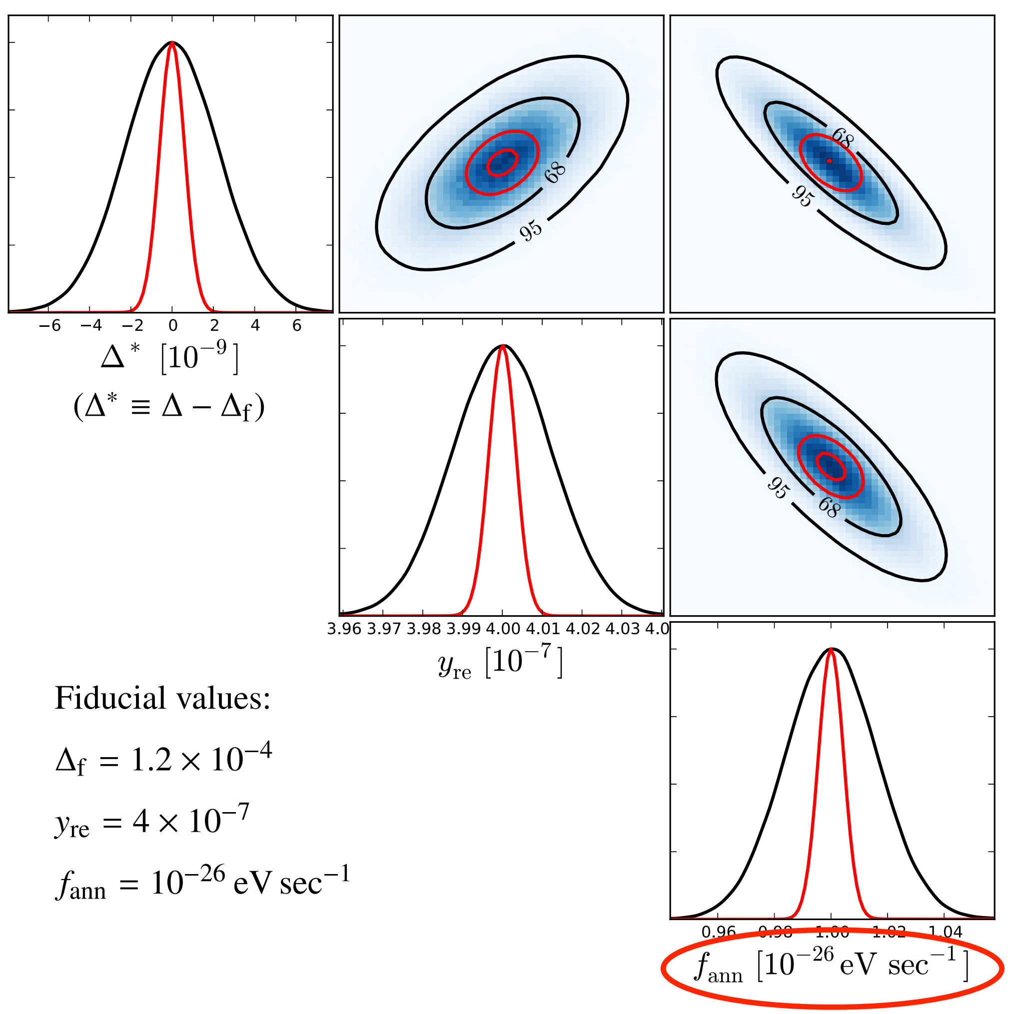
JC 2016, ArXiv:1603.02496

What are the residual distortion parameters?

Why model-independent approach to distortion signal

- Model-dependent analysis makes model-selection non-trivial
- Real information in the distortion signal limited by sensitivity and foregrounds
- *Principle Component Analysis* (PCA) can help optimizing this!
- useful for optimizing experimental designs (*frequencies; sensitivities,* ...)!

Annihilation scenario



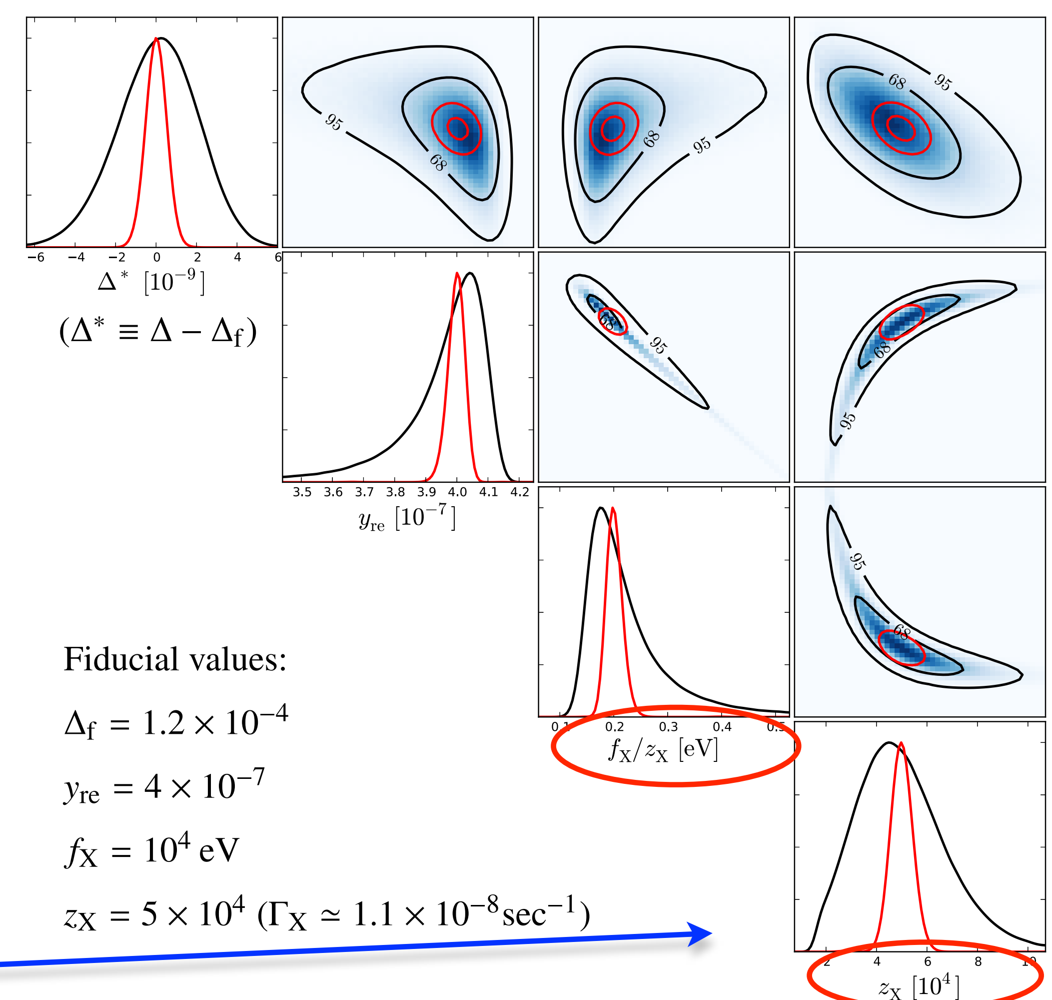
Fiducial values:

$\Delta_f = 1.2 \times 10^{-4}$

$y_{re} = 4 \times 10^{-7}$

$f_{ann} = 10^{-26}$ eV sec^{-1}

Decaying particle scenario



Fiducial values:

$\Delta_f = 1.2 \times 10^{-4}$

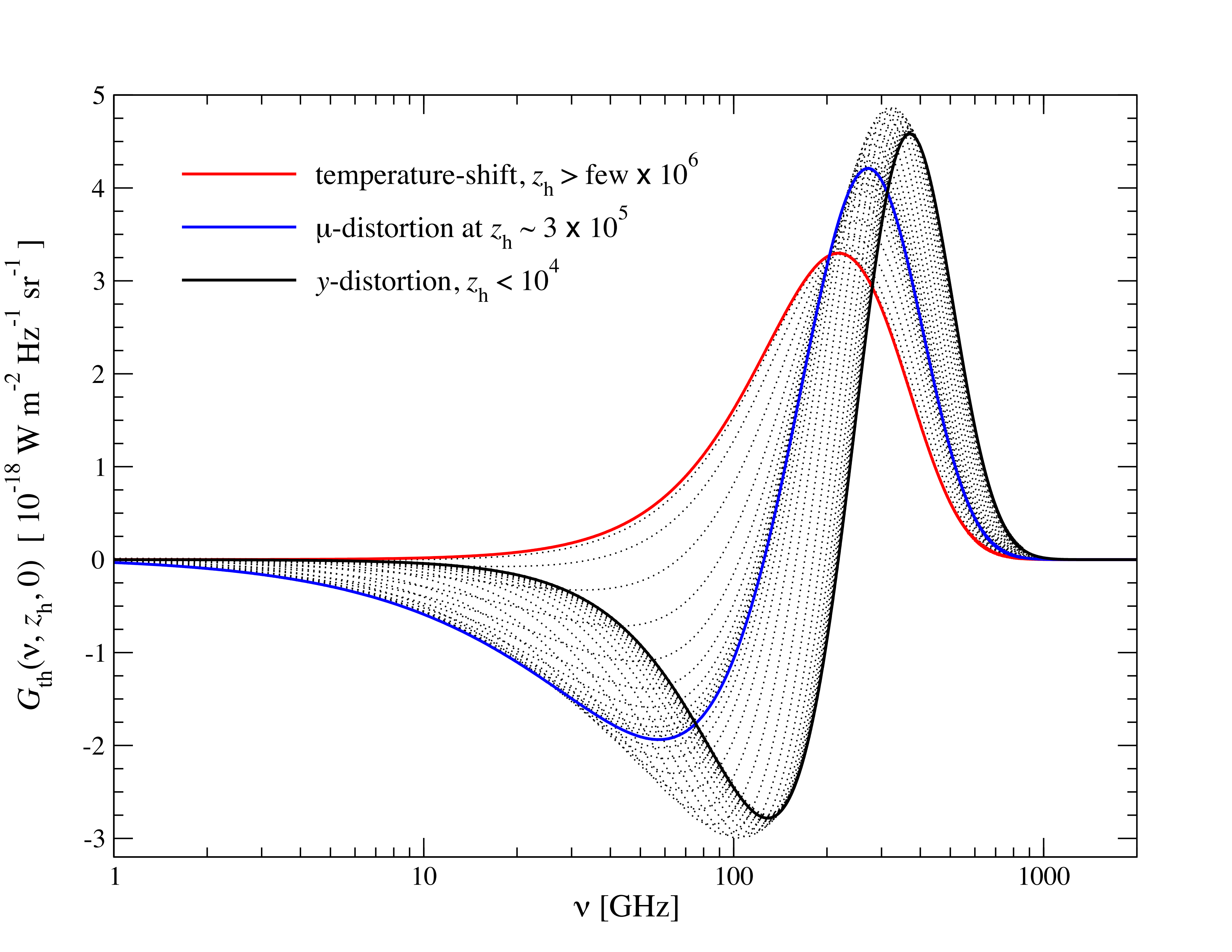
$y_{re} = 4 \times 10^{-7}$

$f_X = 10^4$ eV

$z_X = 5 \times 10^4$ ($\Gamma_X \simeq 1.1 \times 10^{-8}\mathrm{sec}^{-1}$)

How do we compare these?

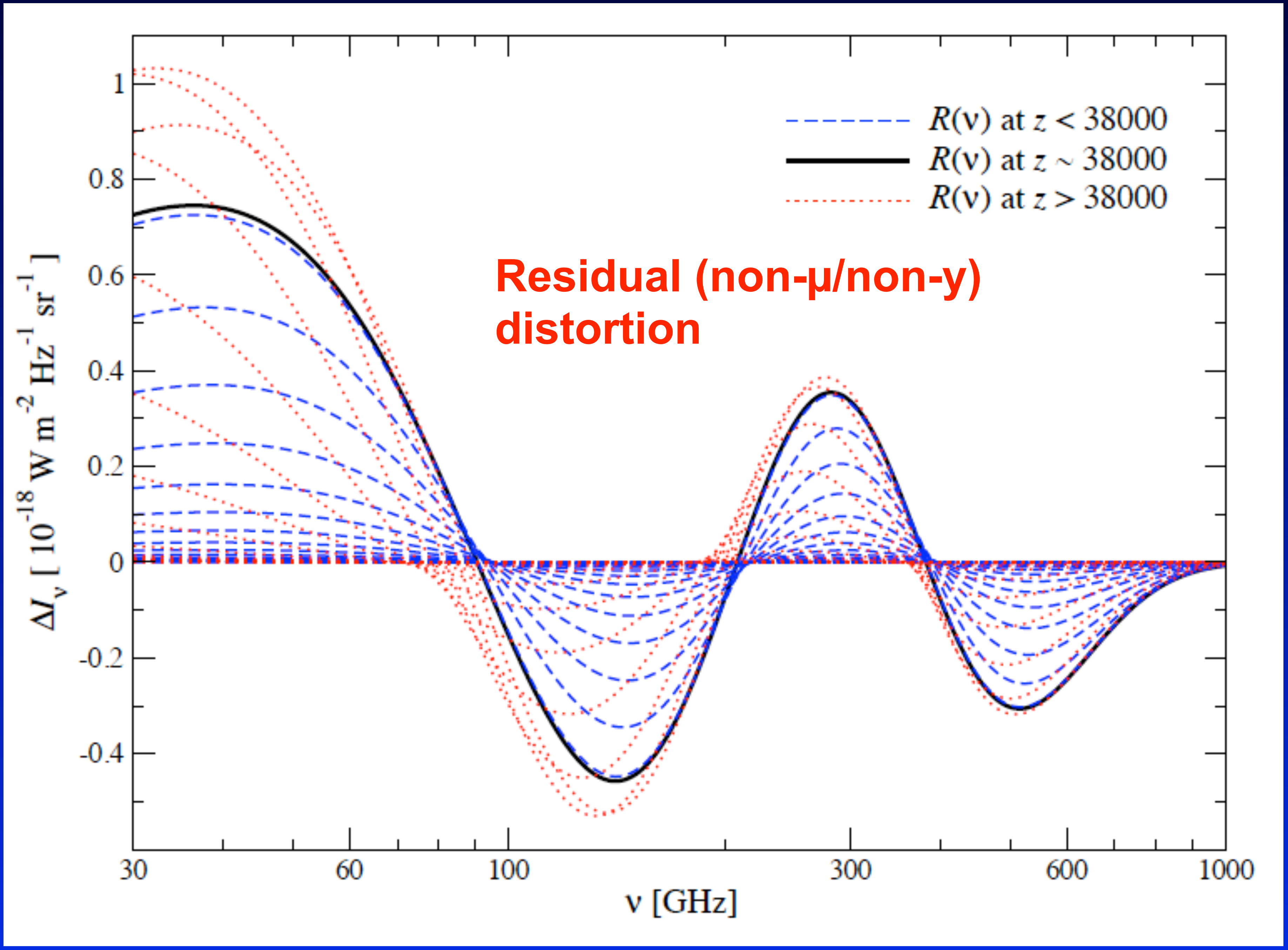
Using signal eigenmodes to compress the distortion data



- *Principle component decomposition* of the distortion signal
- compression of the useful information given instrumental settings

JC & Jeong, 2013

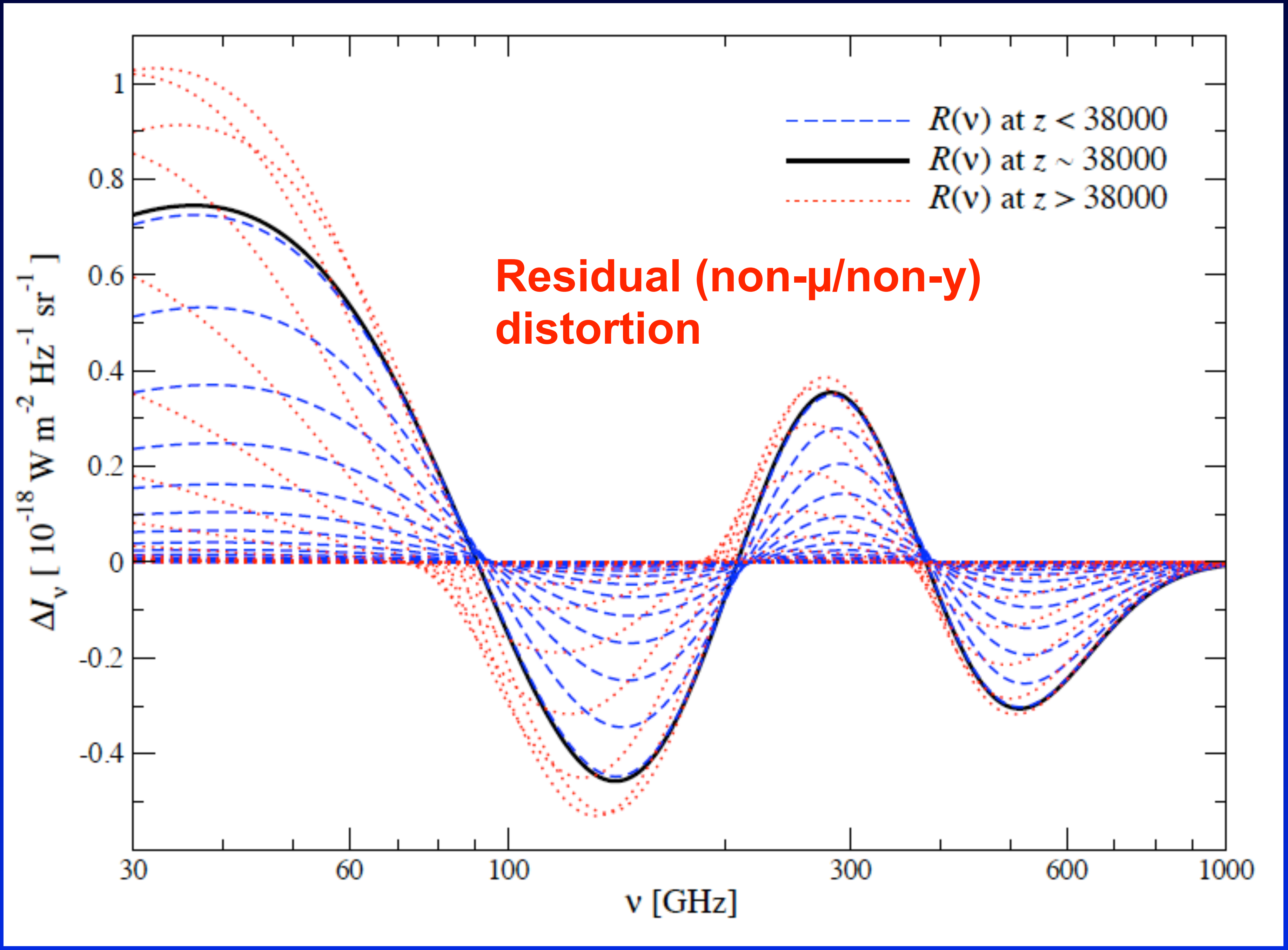
Using signal eigenmodes to compress the distortion data



- *Principle component decomposition* of the distortion signal
- compression of the useful information given instrumental settings

JC & Jeong, 2013

Using signal eigenmodes to compress the distortion data



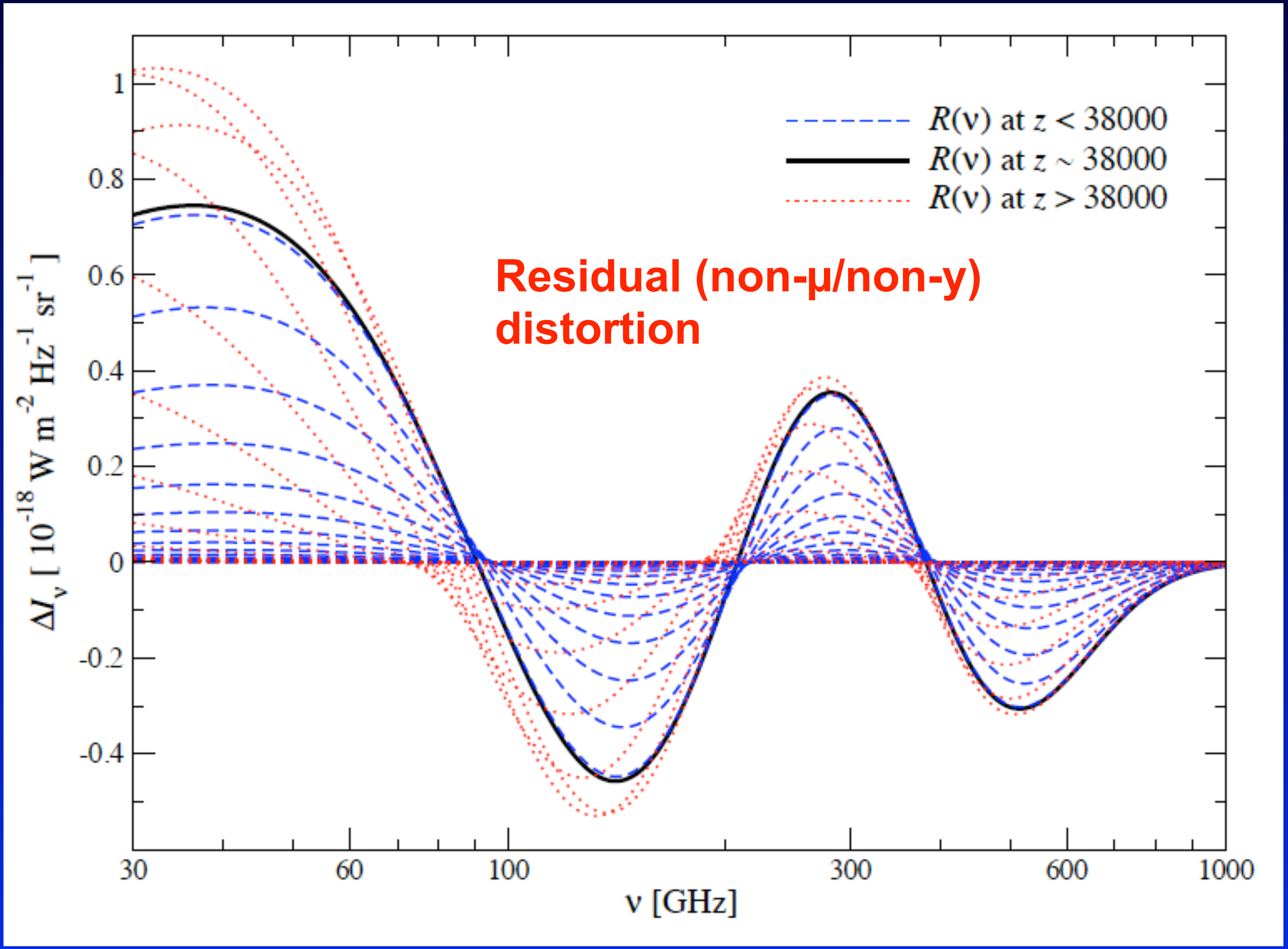
JC & Jeong, 2013

- *Principle component decomposition* of the distortion signal
- compression of the useful information given instrumental settings
- new set of observables

  $p=\{y, \mu, \mu_1, \mu_2, ...\}$

- model-comparison + forecasts of errors very simple!

Using signal eigenmodes to compress the distortion data



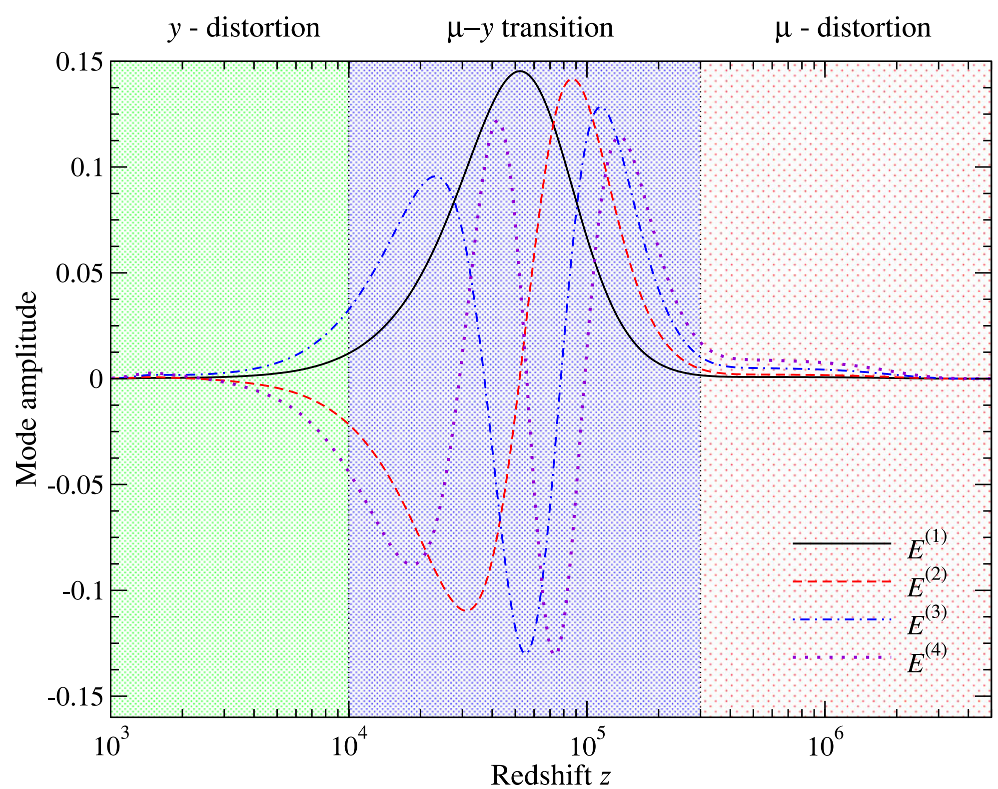
- *Principle component decomposition* of the distortion signal
- compression of the useful information given instrumental settings
- new set of observables

  p={y, μ, μ_1, μ_2, ...}
- model-comparison + forecasts of errors very simple!

JC & Jeong, 2013

Ultimately this may be the only way to learn more!

Eigenmodes for a PIXIE-type experiment



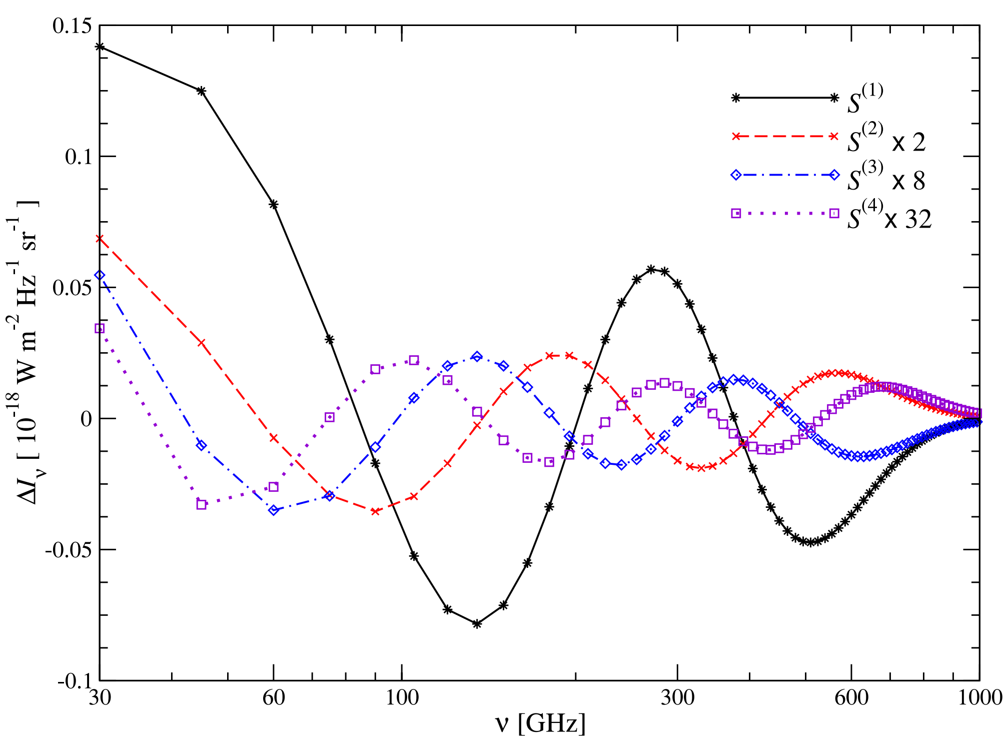


Figure 4. First few eigenmodes $\boldsymbol{E}^{(k)}$ and $\boldsymbol{S}^{(k)}$ for *PIXIE*-type settings ($\nu_{\rm min} = 30\,$GHz, $\nu_{\rm max} = 1000\,$GHz and $\Delta\nu_{\rm s} = 15\,$GHz). In the mode construction, we assumed that energy release only occurred at $10^3 \leq z \leq 5\times10^6$.

Estimated error bars

(under idealistic assumptions...)

$$\frac{\Delta T}{T} \simeq 2\,{\rm nK}\left(\frac{\Delta I_{\rm c}}{5\,{\rm Jy\,sr^{-1}}}\right)$$

$$\Delta y \simeq 1.2\times10^{-9}\left(\frac{\Delta I_{\rm c}}{5\,{\rm Jy\,sr^{-1}}}\right)$$

$$\Delta \mu \simeq 1.4\times10^{-8}\left(\frac{\Delta I_{\rm c}}{5\,{\rm Jy\,sr^{-1}}}\right)$$

Table 1. Forecasted 1σ errors of the first six eigenmode amplitudes, $\boldsymbol{E}^{(k)}$. We also give $\varepsilon_k = 4\sum_i S_i^{(k)}/\sum_i G_{i,T}$, and the scalar products $\boldsymbol{S}^{(k)}\cdot\boldsymbol{S}^{(k)}$ (in units of $[10^{-18}\,{\rm W\,m^{-2}\,Hz^{-1}\,sr^{-1}}]^2$). The fraction of energy release to the residual distortion and its uncertainty are given by $\varepsilon \approx \sum_k \varepsilon_k\,\mu_k$ and $\Delta\varepsilon \approx (\sum_k \varepsilon_k^2 \Delta\mu_k^2)^{1/2}$, respectively. For the mode construction we used *PIXIE*-settings ($\{\nu_{\rm min},\ \nu_{\rm max},\ \Delta\nu_{\rm s}\} = \{30,\ 1000,\ 15\}\,$GHz and channel sensitivity $\Delta I_{\rm c} = 5\times10^{-26}\,{\rm W\,m^{-2}\,Hz^{-1}\,sr^{-1}}$). The errors roughly scale as $\Delta\mu_k \propto \Delta I_{\rm c}/\sqrt{\Delta\nu_{\rm s}}$.

k	$\Delta\mu_k$	$\Delta\mu_k/\Delta\mu_1$	ε_k	$\boldsymbol{S}^{(k)}\cdot\boldsymbol{S}^{(k)}$
1	1.48×10^{-7}	1	-6.98×10^{-3}	1.15×10^{-1}
2	7.61×10^{-7}	5.14	2.12×10^{-3}	4.32×10^{-3}
3	3.61×10^{-6}	24.4	-3.71×10^{-4}	1.92×10^{-4}
4	1.74×10^{-5}	1.18×10^{2}	8.29×10^{-5}	8.29×10^{-6}
5	8.52×10^{-5}	5.76×10^{2}	-1.55×10^{-5}	3.45×10^{-7}
6	4.24×10^{-4}	2.86×10^{3}	2.75×10^{-6}	1.39×10^{-8}

JC & Jeong, 2013

Partial recovery of energy release history

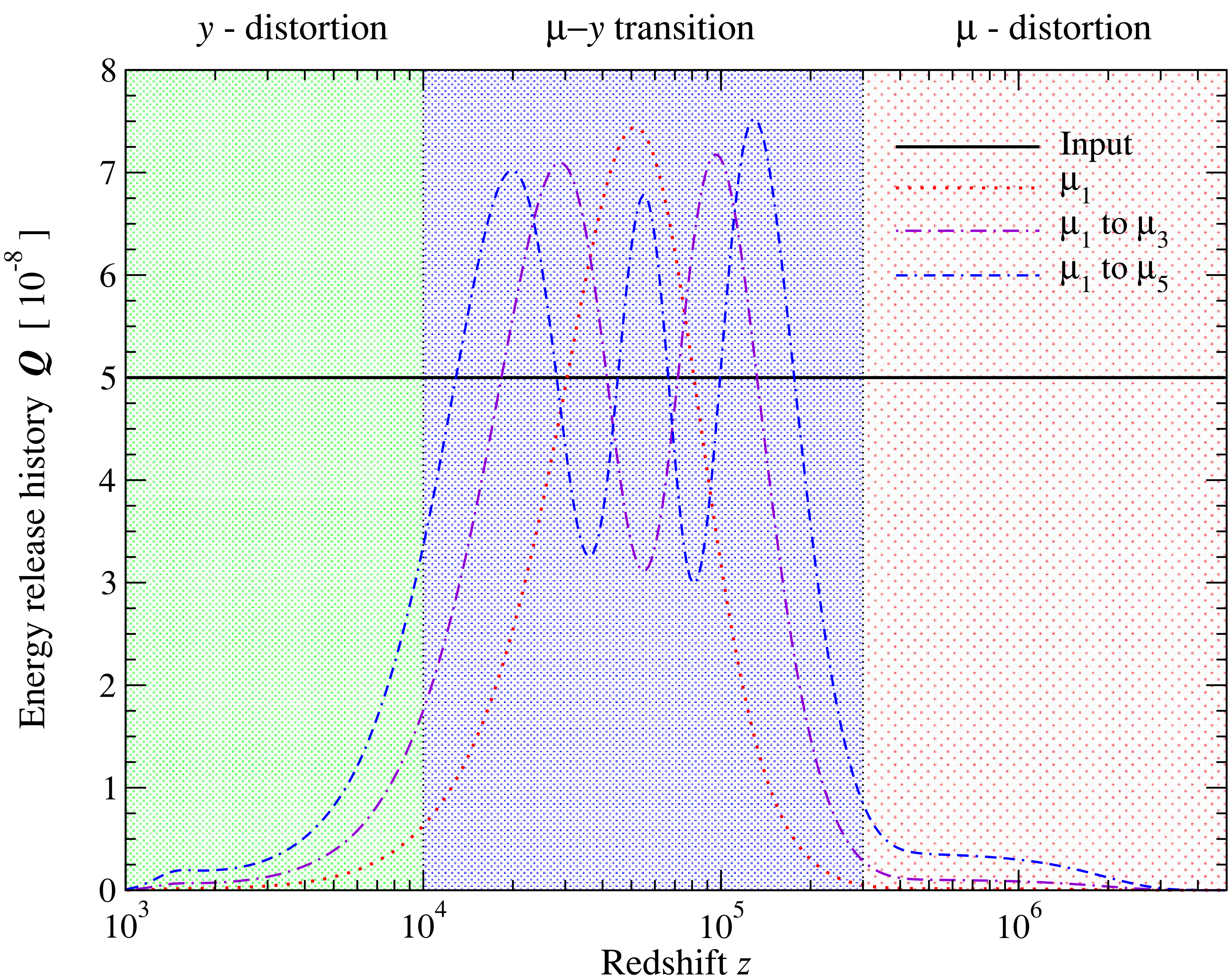
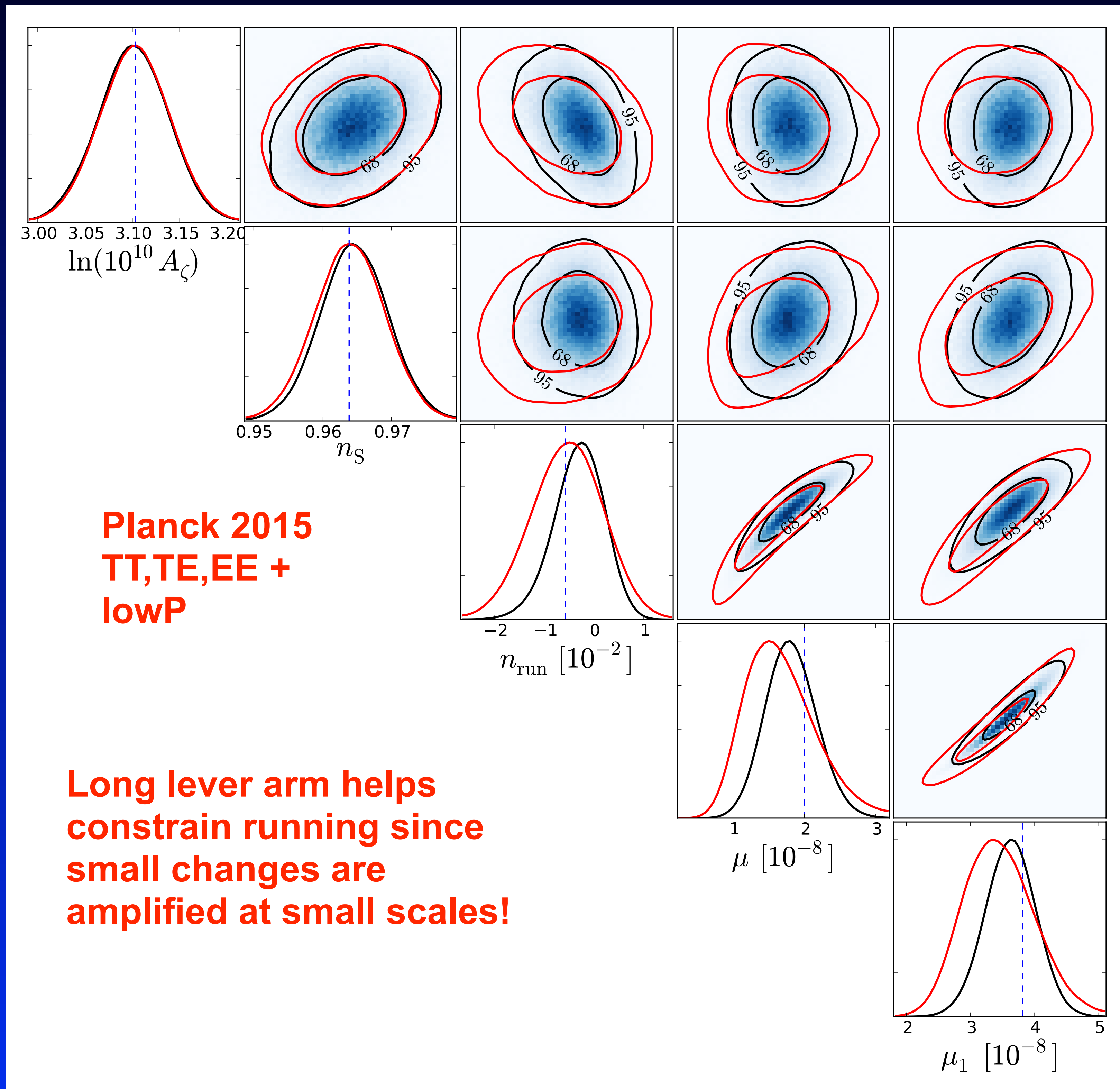


Figure 6. Partial recovery of the input energy-release history, $\mathcal{Q} = 5 \times 10^{-8}$.

- 'wiggly' recovery of input thermal history possible
- redshift resolution depends on sensitivity and distortion amplitude

JC & Jeong, 2013

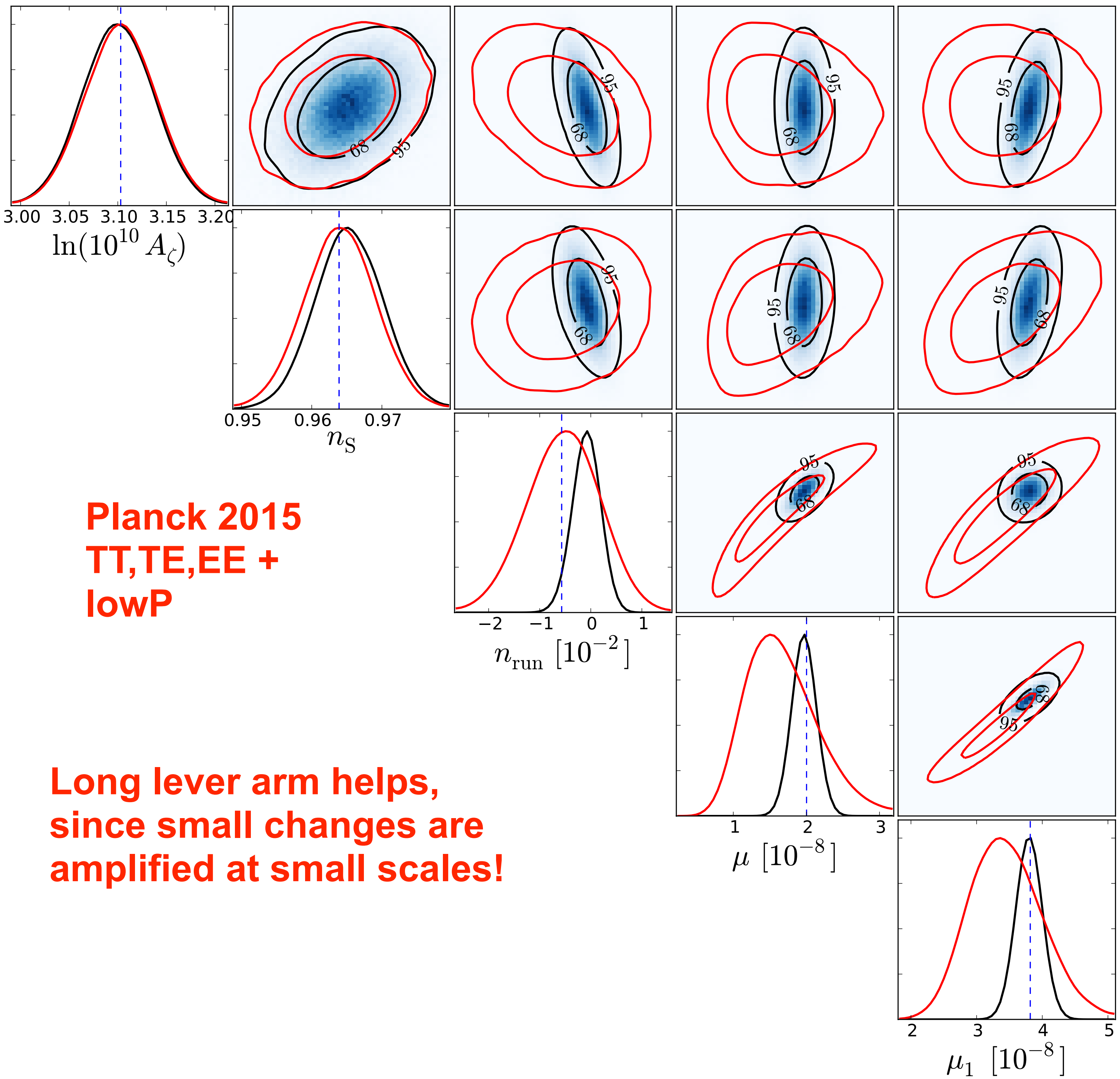
Testing running with distortions



- combined constraint Planck & PIXIE not affected much by distortion information
- at ~3.4 x PIXIE, constraint on running improved ~1.5 times
- centroid moves towards fiducial model

JC 2016, ArXiv:1603.02496

Testing running with distortions



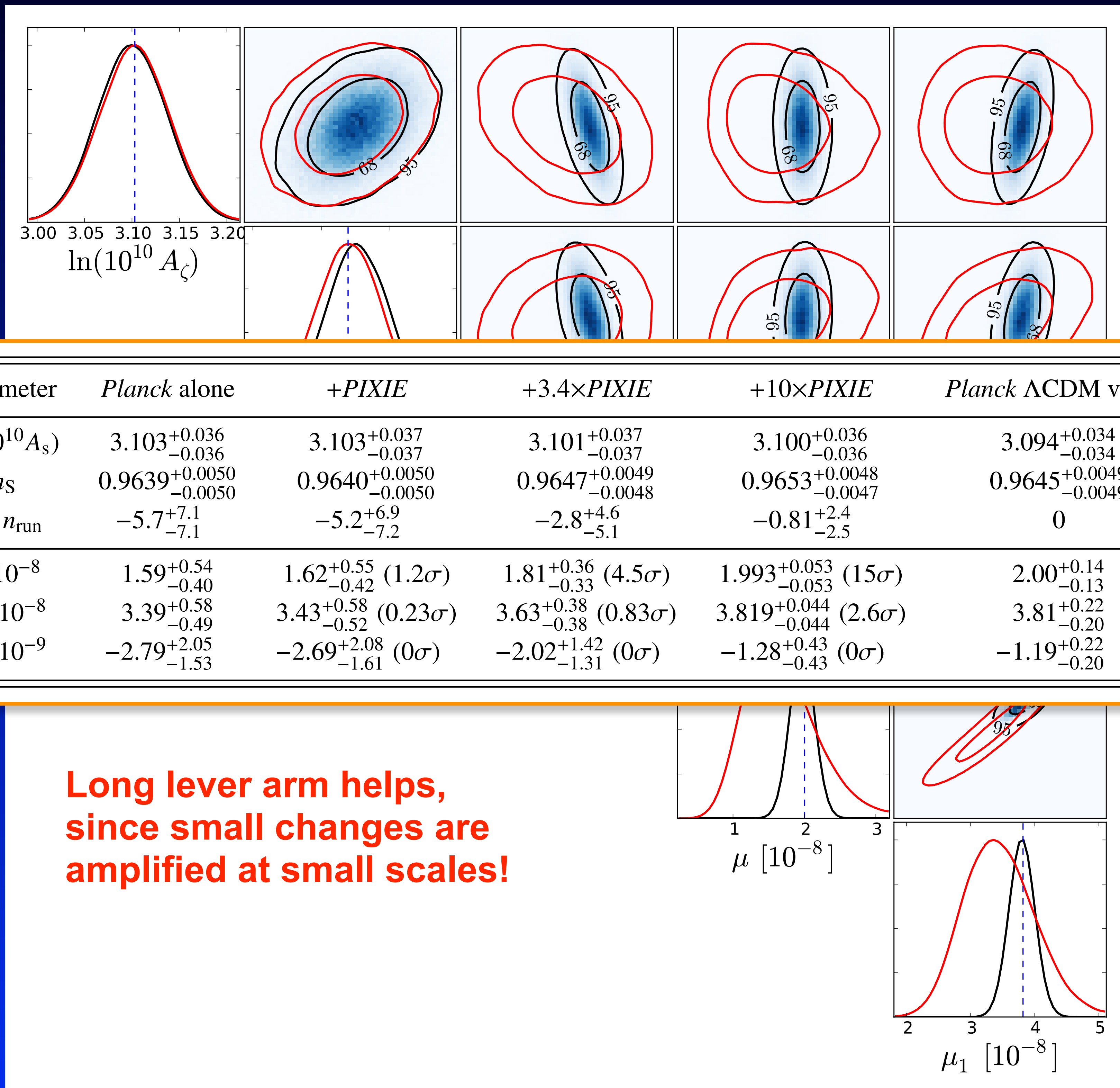
Planck 2015 TT,TE,EE + lowP

Long lever arm helps, since small changes are amplified at small scales!

- combined constraint Planck & PIXIE not affected much by distortion information
- at ~3.4 x PIXIE, constraint on running improved ~1.5 times
- centroid moves towards fiducial model
- at 10 x PIXIE, constraint on running improved 3 times over Planck alone
- μ could be detected at ~15σ and μ_1 at ~2.6σ
- combining with future imager (e.g., COrE+) *distortions* could still improve constraint on running (e.g., JC & Jeong, 2014)

JC 2016, ArXiv:1603.02496

Testing running with distortions



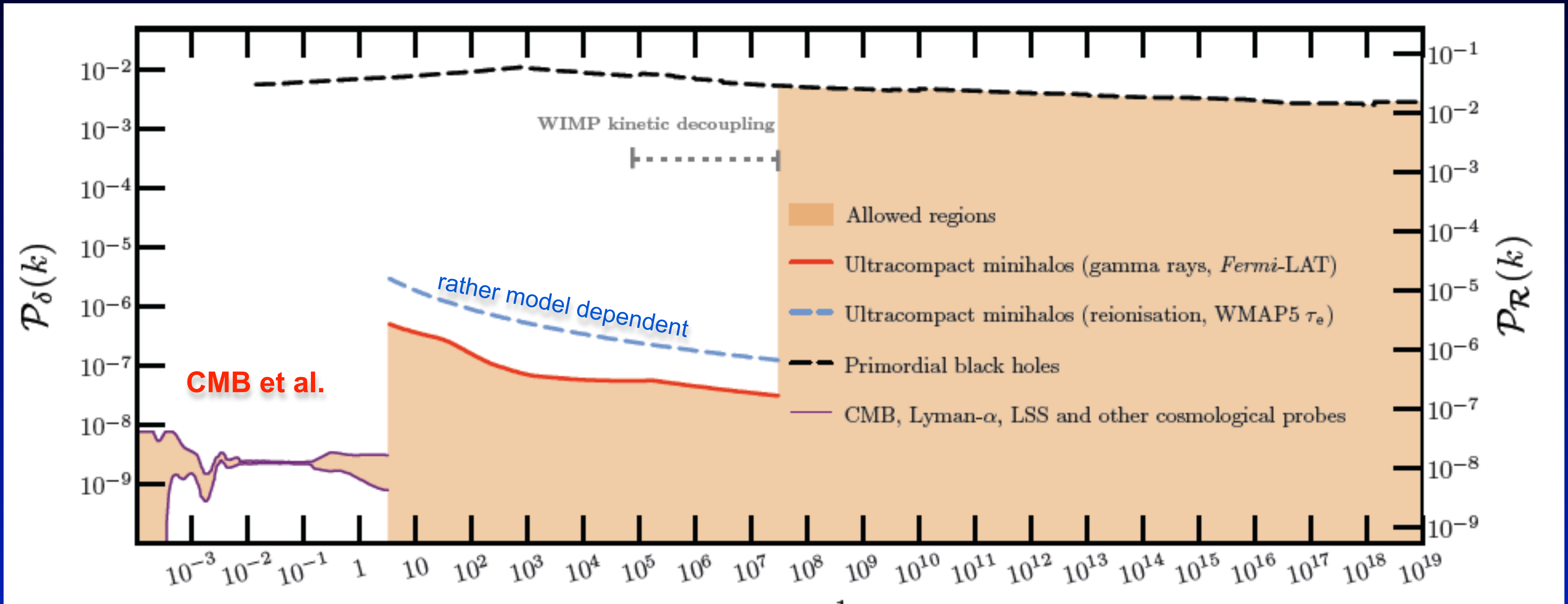
Parameter	*Planck* alone	+*PIXIE*	+3.4×*PIXIE*	+10×*PIXIE*	*Planck* ΛCDM values
$\ln(10^{10}A_s)$	$3.103^{+0.036}_{-0.036}$	$3.103^{+0.037}_{-0.037}$	$3.101^{+0.037}_{-0.037}$	$3.100^{+0.036}_{-0.036}$	$3.094^{+0.034}_{-0.034}$
n_S	$0.9639^{+0.0050}_{-0.0050}$	$0.9640^{+0.0050}_{-0.0050}$	$0.9647^{+0.0049}_{-0.0048}$	$0.9653^{+0.0048}_{-0.0047}$	$0.9645^{+0.0049}_{-0.0049}$
$10^3 n_{\rm run}$	$-5.7^{+7.1}_{-7.1}$	$-5.2^{+6.9}_{-7.2}$	$-2.8^{+4.6}_{-5.1}$	$-0.81^{+2.4}_{-2.5}$	0
$\mu/10^{-8}$	$1.59^{+0.54}_{-0.40}$	$1.62^{+0.55}_{-0.42}$ (1.2σ)	$1.81^{+0.36}_{-0.33}$ (4.5σ)	$1.993^{+0.053}_{-0.053}$ (15σ)	$2.00^{+0.14}_{-0.13}$
$\mu_1/10^{-8}$	$3.39^{+0.58}_{-0.49}$	$3.43^{+0.58}_{-0.52}$ (0.23σ)	$3.63^{+0.38}_{-0.38}$ (0.83σ)	$3.819^{+0.044}_{-0.044}$ (2.6σ)	$3.81^{+0.22}_{-0.20}$
$\mu_2/10^{-9}$	$-2.79^{+2.05}_{-1.53}$	$-2.69^{+2.08}_{-1.61}$ (0σ)	$-2.02^{+1.42}_{-1.31}$ (0σ)	$-1.28^{+0.43}_{-0.43}$ (0σ)	$-1.19^{+0.22}_{-0.20}$

Long lever arm helps, since small changes are amplified at small scales!

- combined constraint Planck & PIXIE not affected much by distortion information
- at ~3.4 x PIXIE, constraint on running improved ~1.5 times
- centroid moves towards fiducial model
- at 10 x PIXIE, constraint on running improved 3 times over Planck alone
- μ could be detected at ~15σ and μ_1 at ~2.6σ
- combining with future imager (e.g., COrE+) *distortions* could still improve constraint on running (e.g., JC & Jeong, 2014)

JC 2016, ArXiv:1603.02496

Distortions provide general power spectrum constraints!

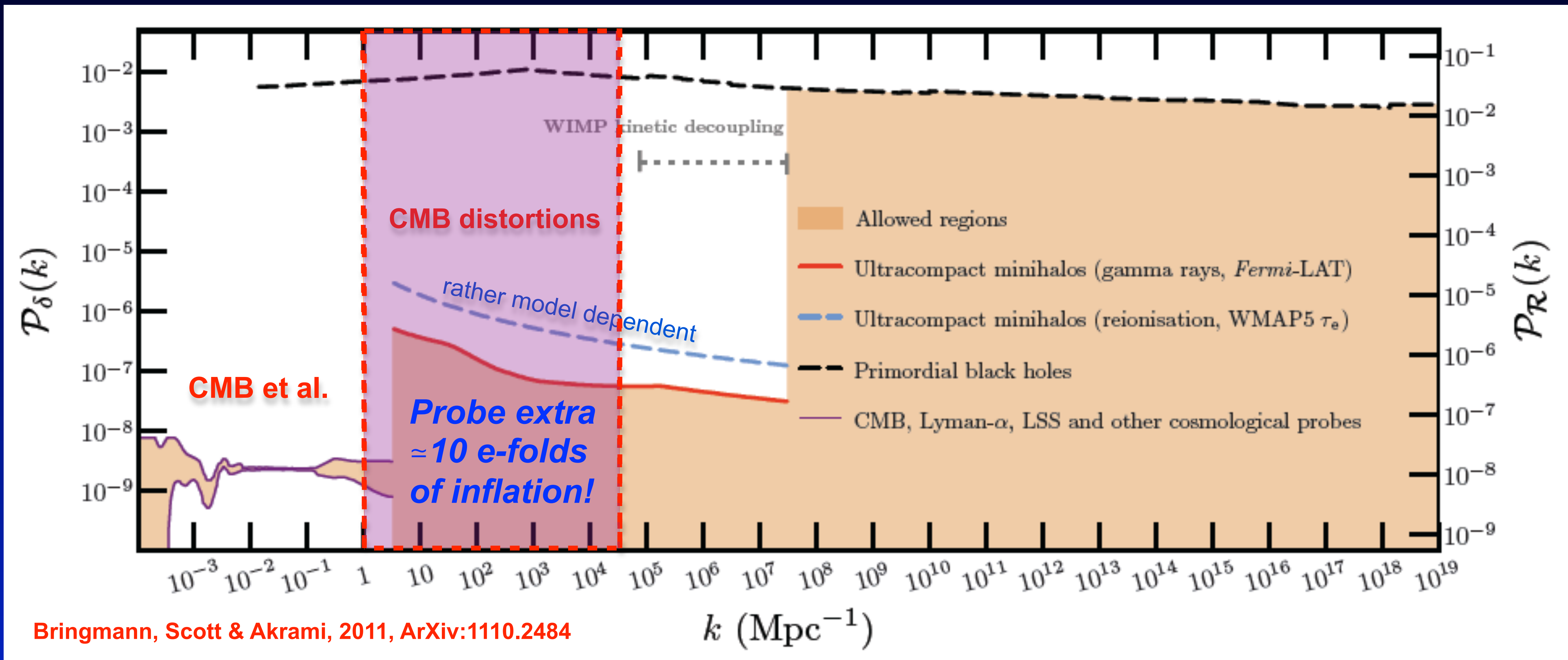


Bringmann, Scott & Akrami, 2011, ArXiv:1110.2484

- Amplitude of power spectrum rather uncertain at $k > 3$ Mpc^{-1}
- improved limits at smaller scales can *rule out* many *inflationary models*

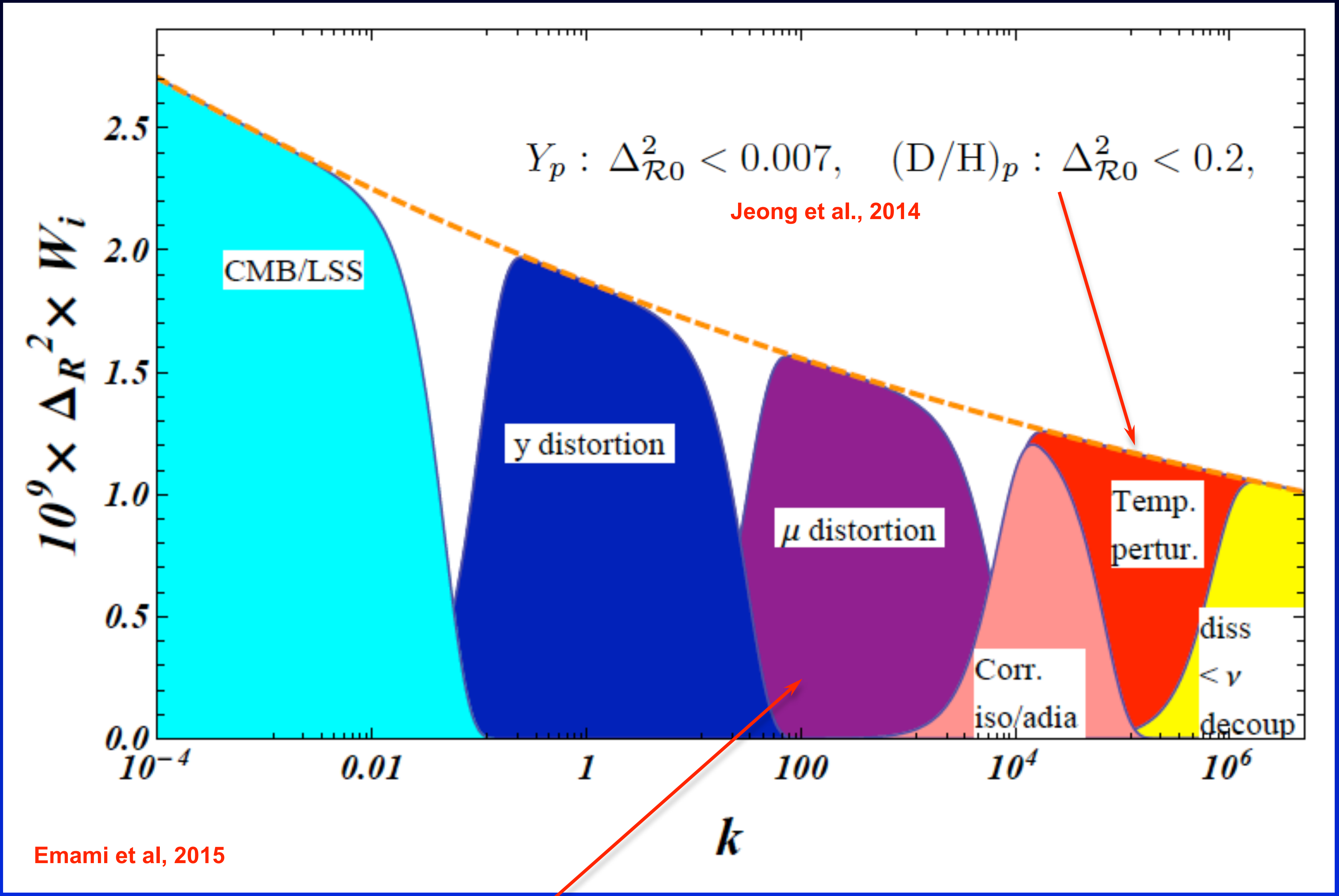
e.g., JC, Khatri & Sunyaev, 2012; JC, Erickcek & Ben-Dayan, 2012; JC & Jeong, 2013

Distortions provide general power spectrum constraints!



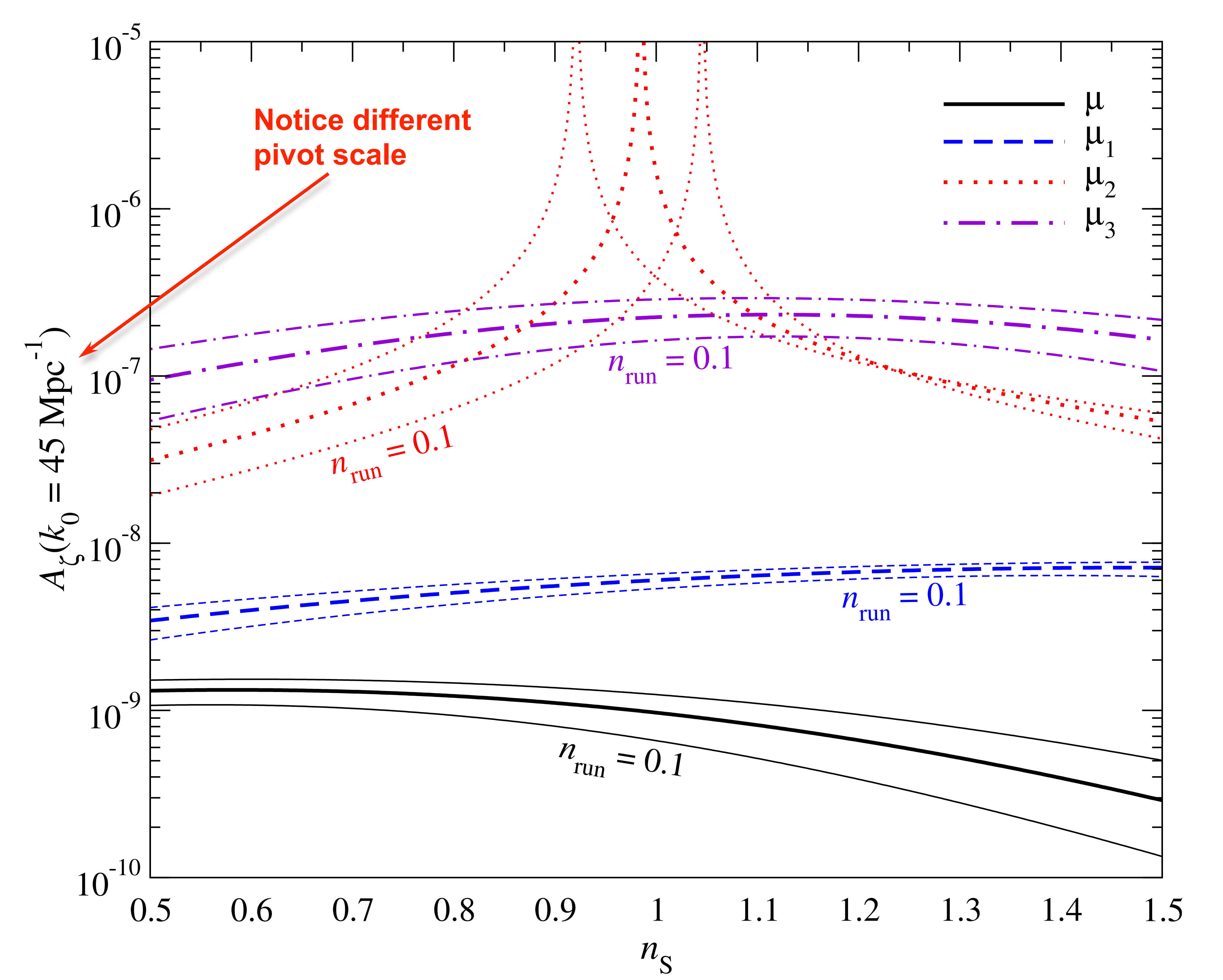
- Amplitude of power spectrum rather uncertain at $k > 3$ Mpc^{-1}
- improved limits at smaller scales can *rule out* many *inflationary models*
- CMB spectral distortions would *extend* our *lever arm* to $k \sim 10^4$ Mpc^{-1}
- very *complementary* piece of information about early-universe physics

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



- *Ultra-squeezed limit non-Gaussianity* (Pajer & Zaldarriaga, 2012; Ganc & Komatsu, 2012)

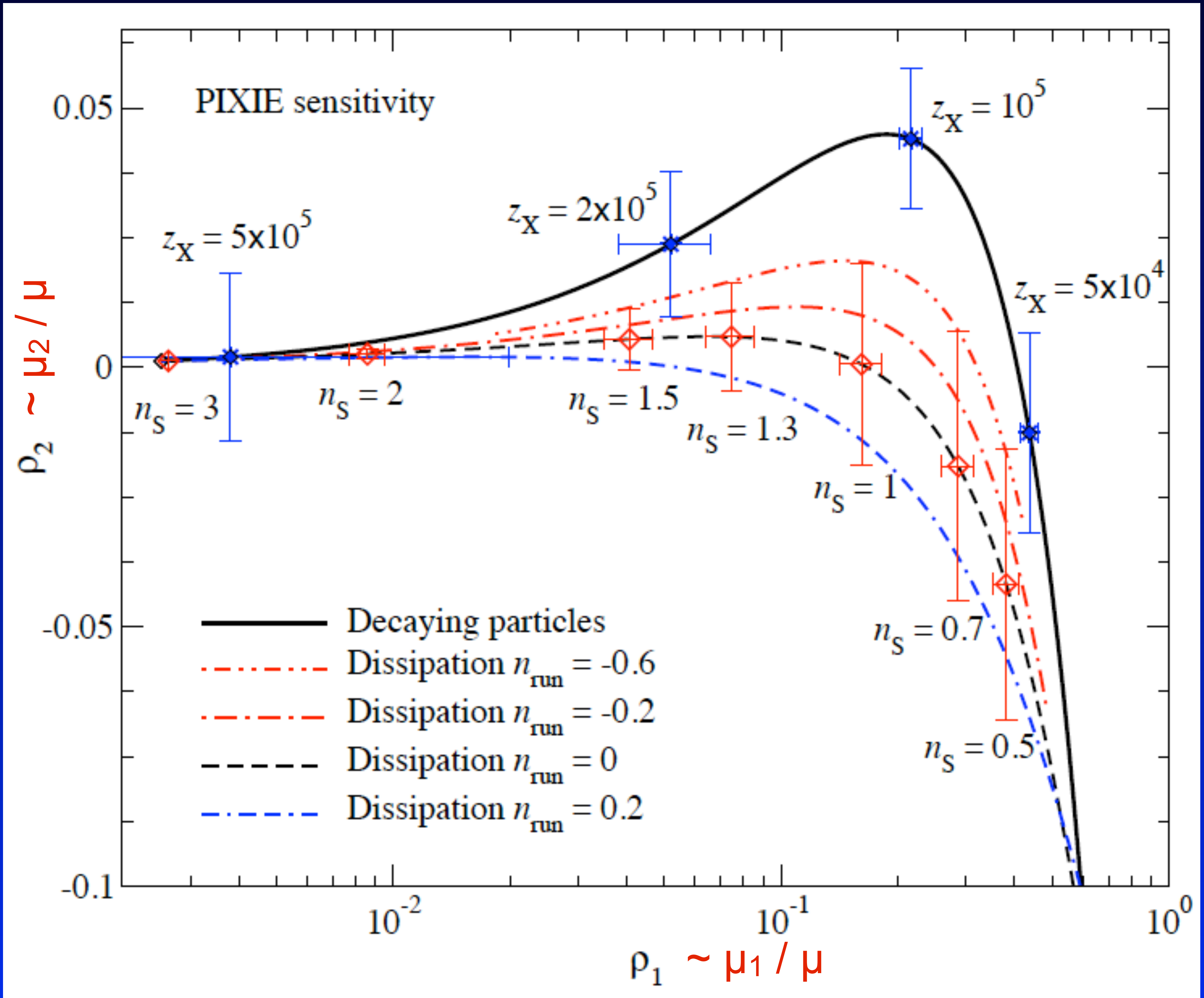
Dissipation scenario: 1σ-detection limits for PIXIE



JC & Jeong, 2013

$$P_\zeta(k) = 2\pi^2 A_\zeta k^{-3} (k/k_0)^{n_S - 1 + \frac{1}{2} n_{run} \ln(k/k_0)}$$

Distinguishing dissipation and decaying particle scenarios

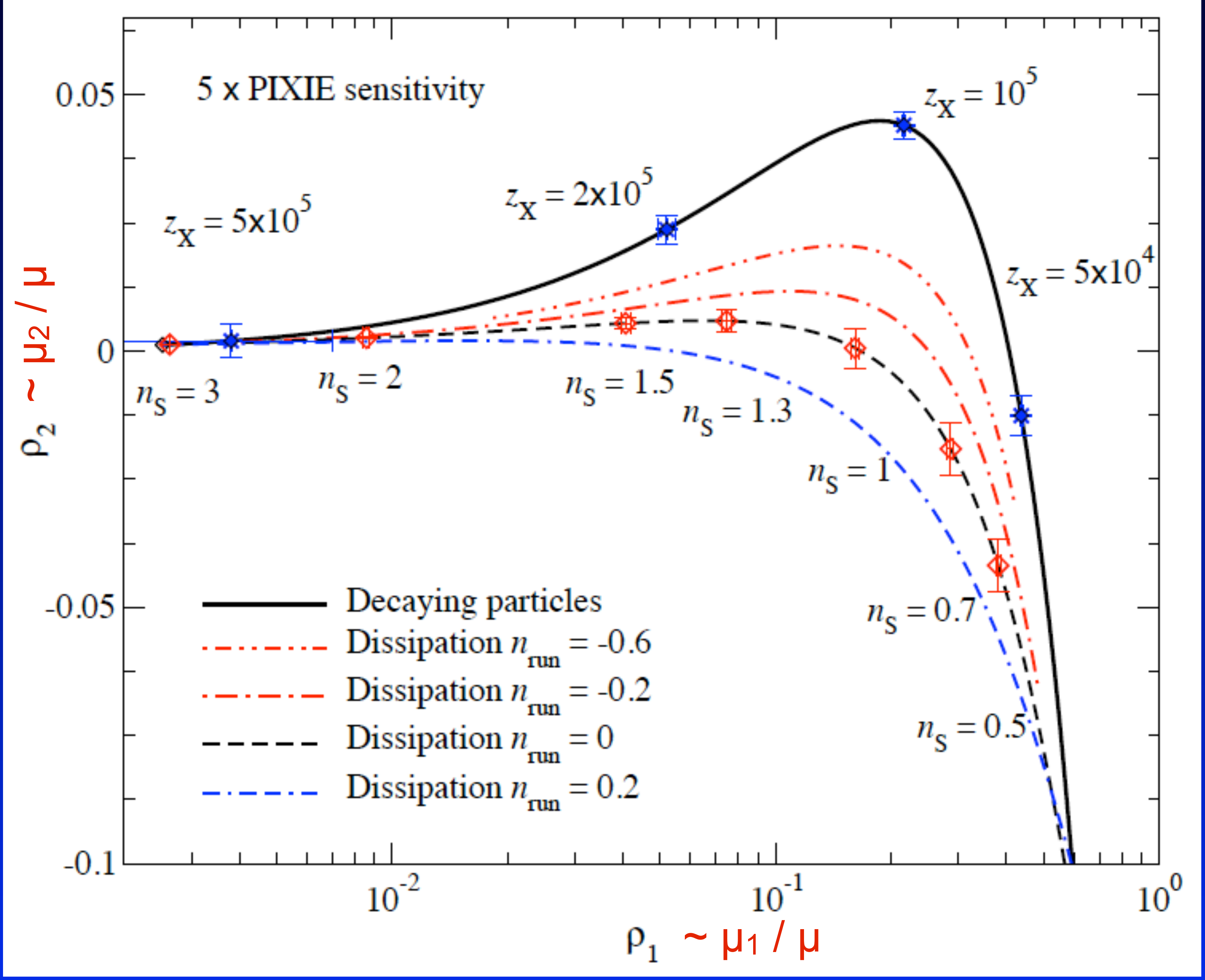


- measurement of μ, μ_1 & μ_2
- trajectories of decaying particle and dissipation scenarios differ!
- scenarios can in principle be distinguished

$$A_\zeta = 5 \times 10^{-8}$$

JC & Jeong, 2013

Distinguishing dissipation and decaying particle scenarios

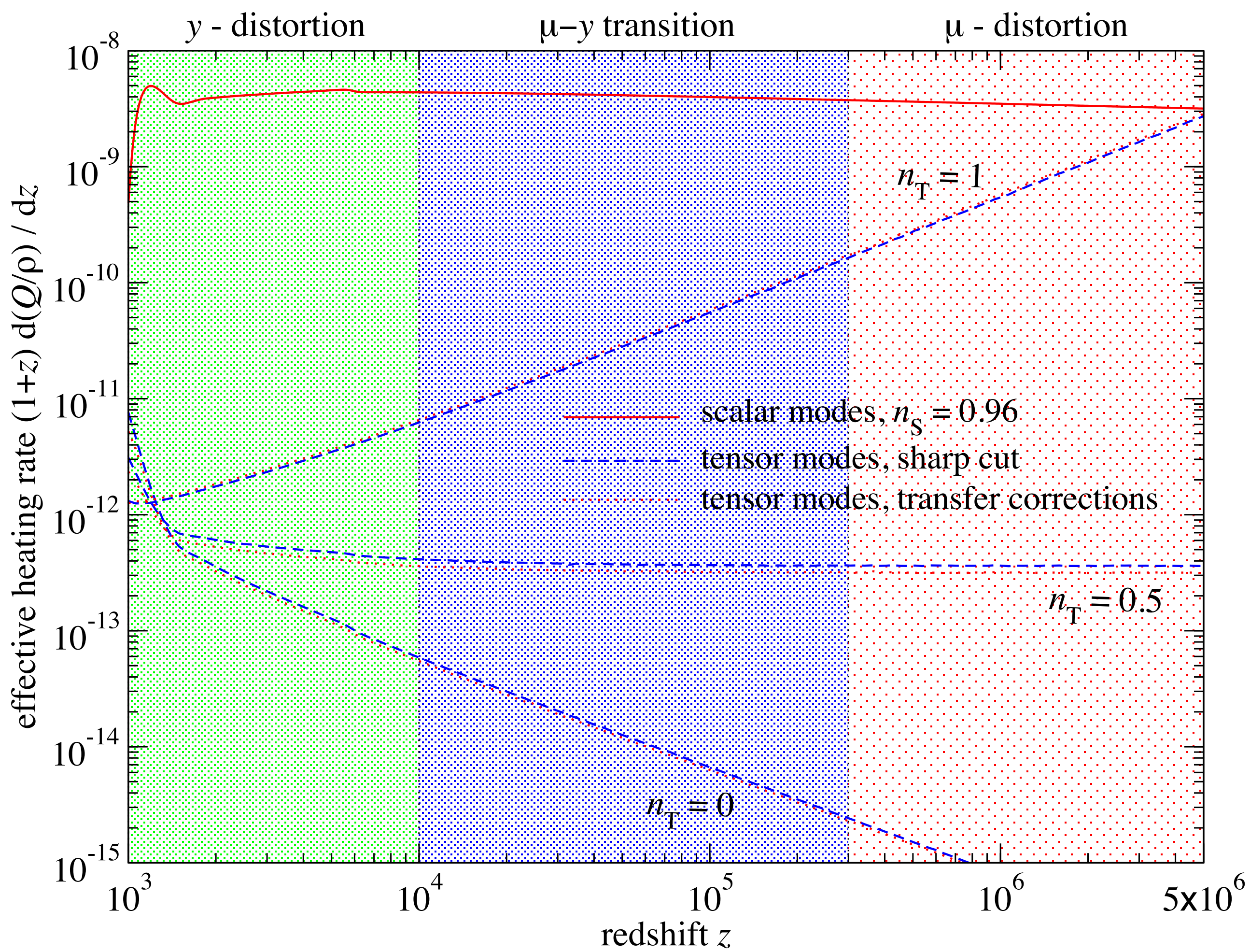


- measurement of μ, μ_1 & μ_2
- trajectories of decaying particle and dissipation scenarios differ!
- scenarios can in principle be distinguished

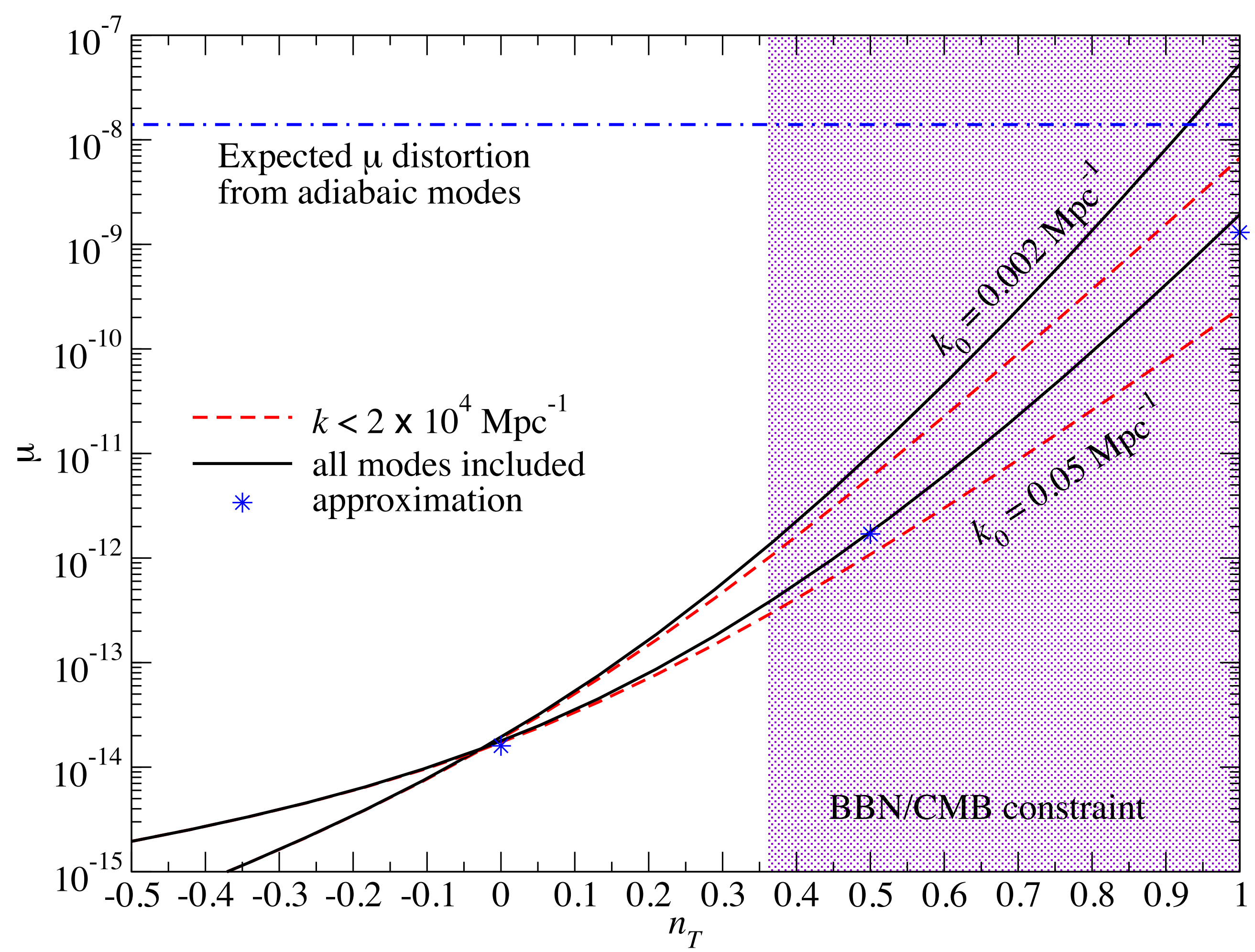
$$A_\zeta = 5 \times 10^{-8}$$

JC & Jeong, 2013

Dissipation of tensor perturbations



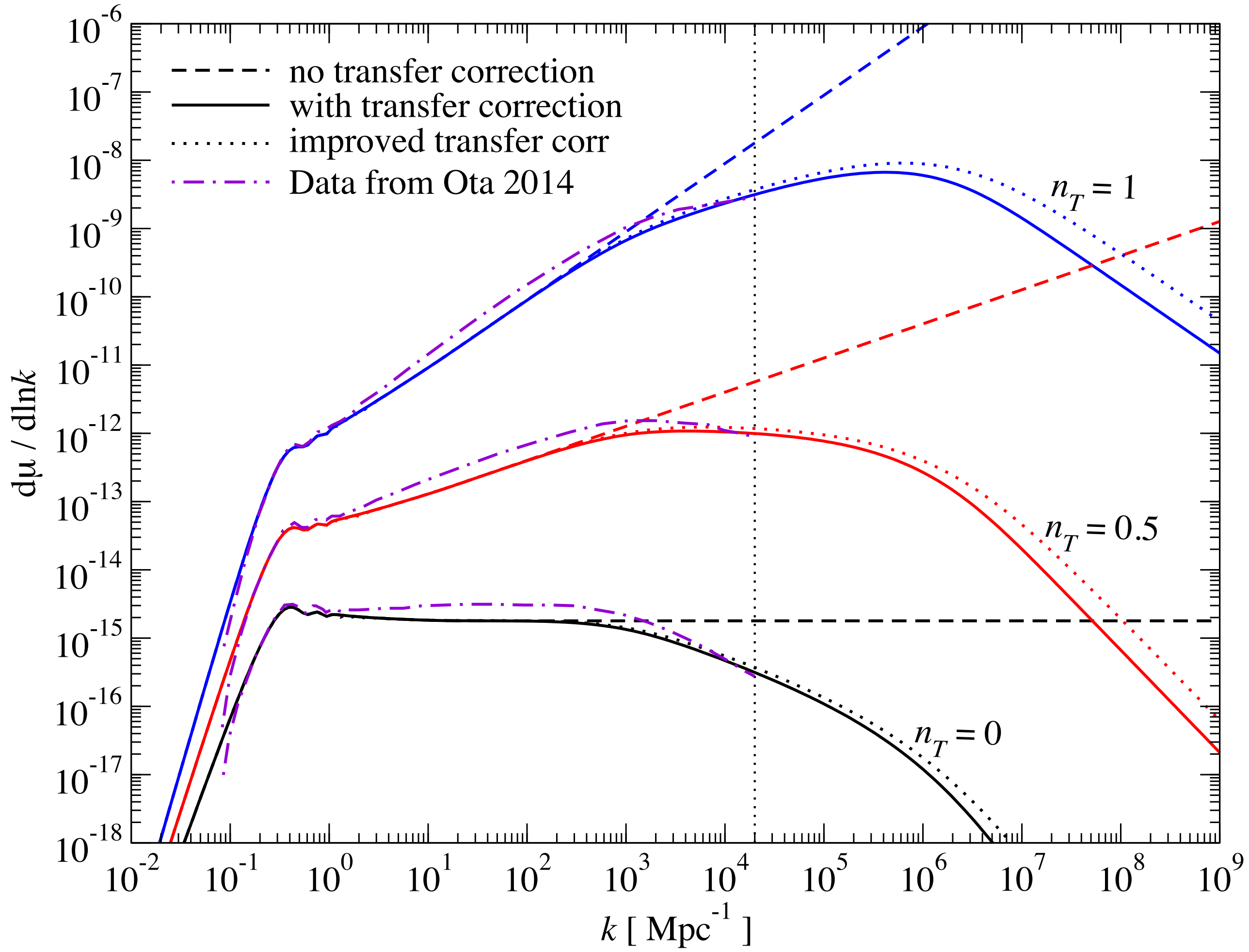
- distortion signal very small compared to adiabatic modes
- no severe *contamination* in simplest cases
- models with 'large' distortion already constrained by BBN/CMB



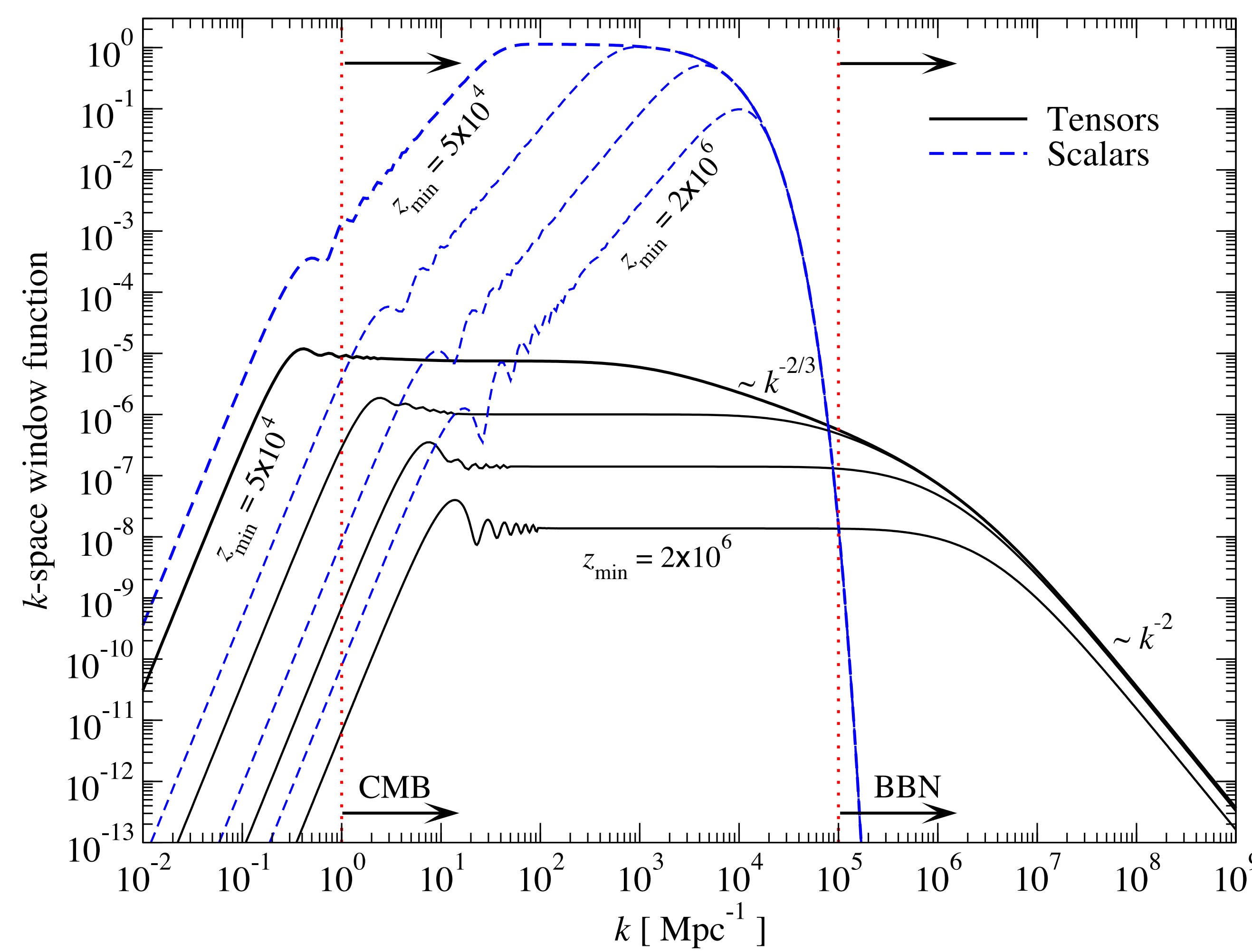
- heating rate can be computed similar to adiabatic modes
- heating rate much smaller than for scalar perturbations
- roughly constant per dlnz for n_T~0.5

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

Comparison of the distortion window functions



- adiabatic modes sensitive to a smaller range of scales
- tensors even have contributions from close to the horizon scale
- power-law decay at small scales



- small-scale modes important for blue tensor power spectra
- Ota et al. underestimated distortion in this case ~7 times

$$\mu_i \approx \int_0^\infty \frac{k^2 \mathrm{d}k}{2\pi^2} P_i(k) W_i(k)$$

JC et al., 2014, ArXiv:1407.3653

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 → $\Delta\varepsilon/\varepsilon \sim 13.6\ \mathrm{eV}\ N_b\ /\ (N_\gamma\, 2.7kT_r) \sim 10^{-9}$ - 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!

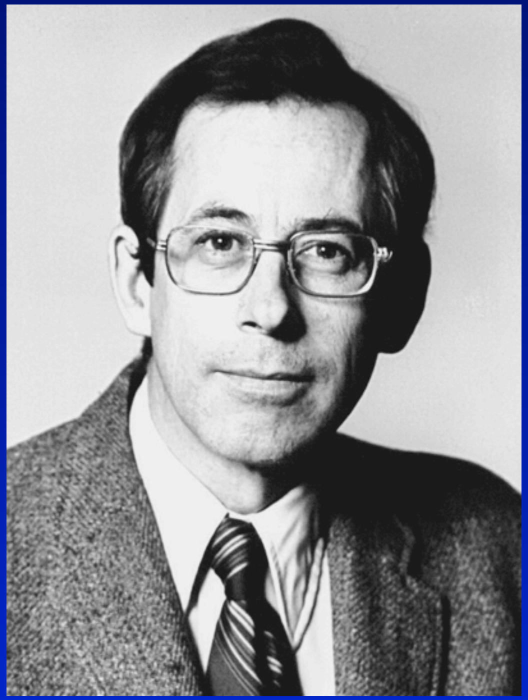
Yakov Zeldovich

Vladimir Kurt
(UV astronomer)

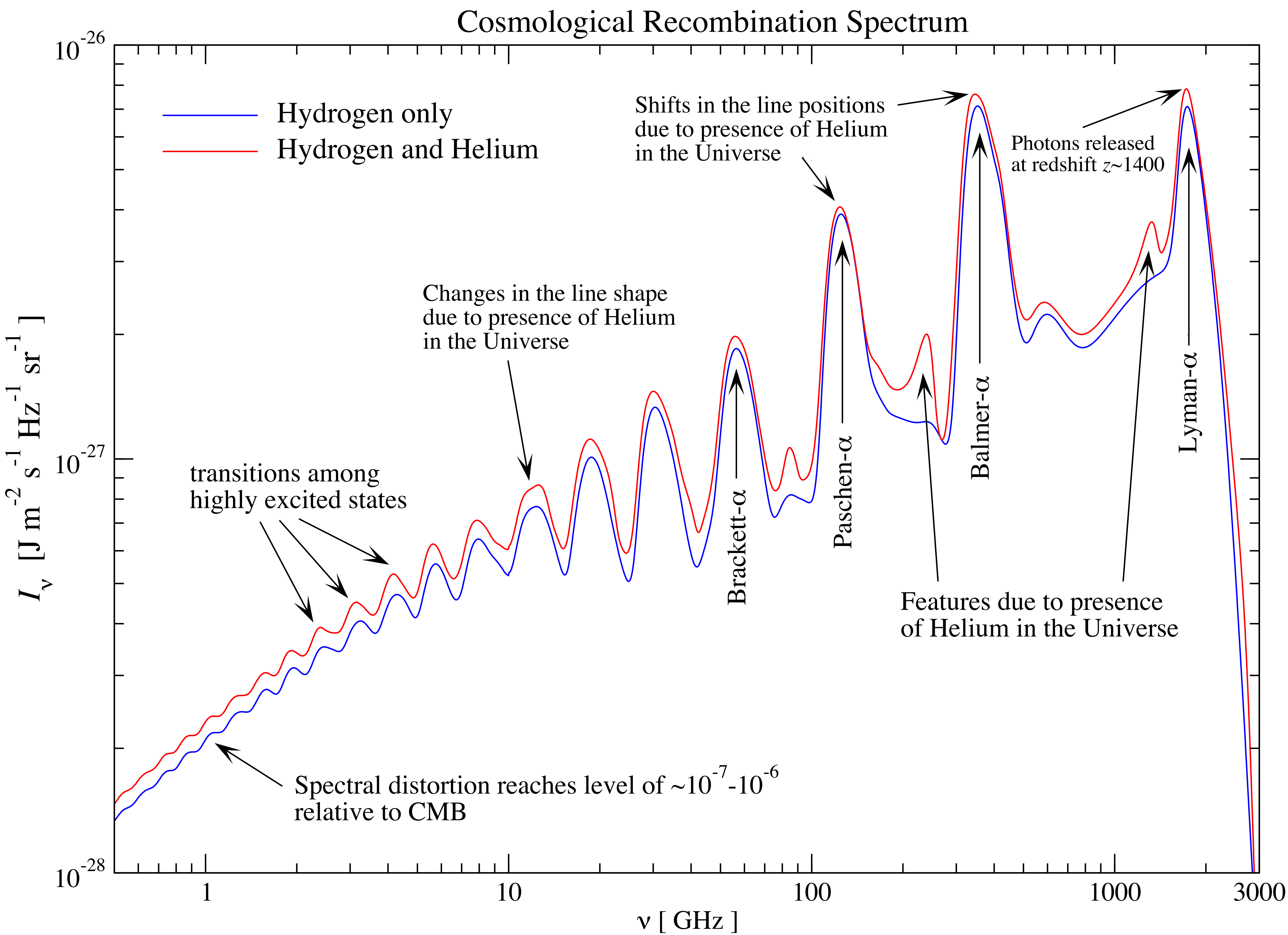
Moscow

Rashid Sunyaev

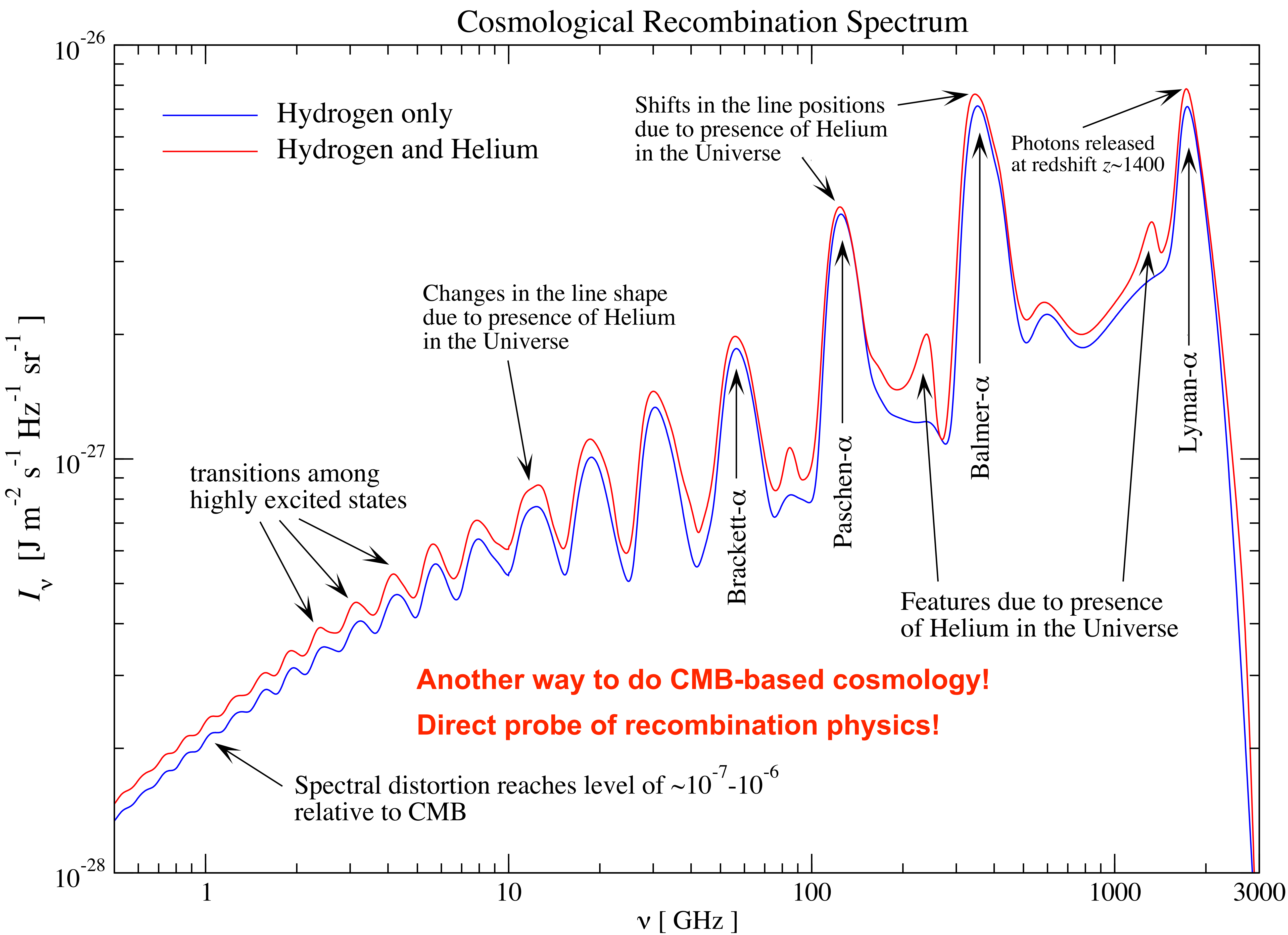
Princeton



Jim Peebles



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

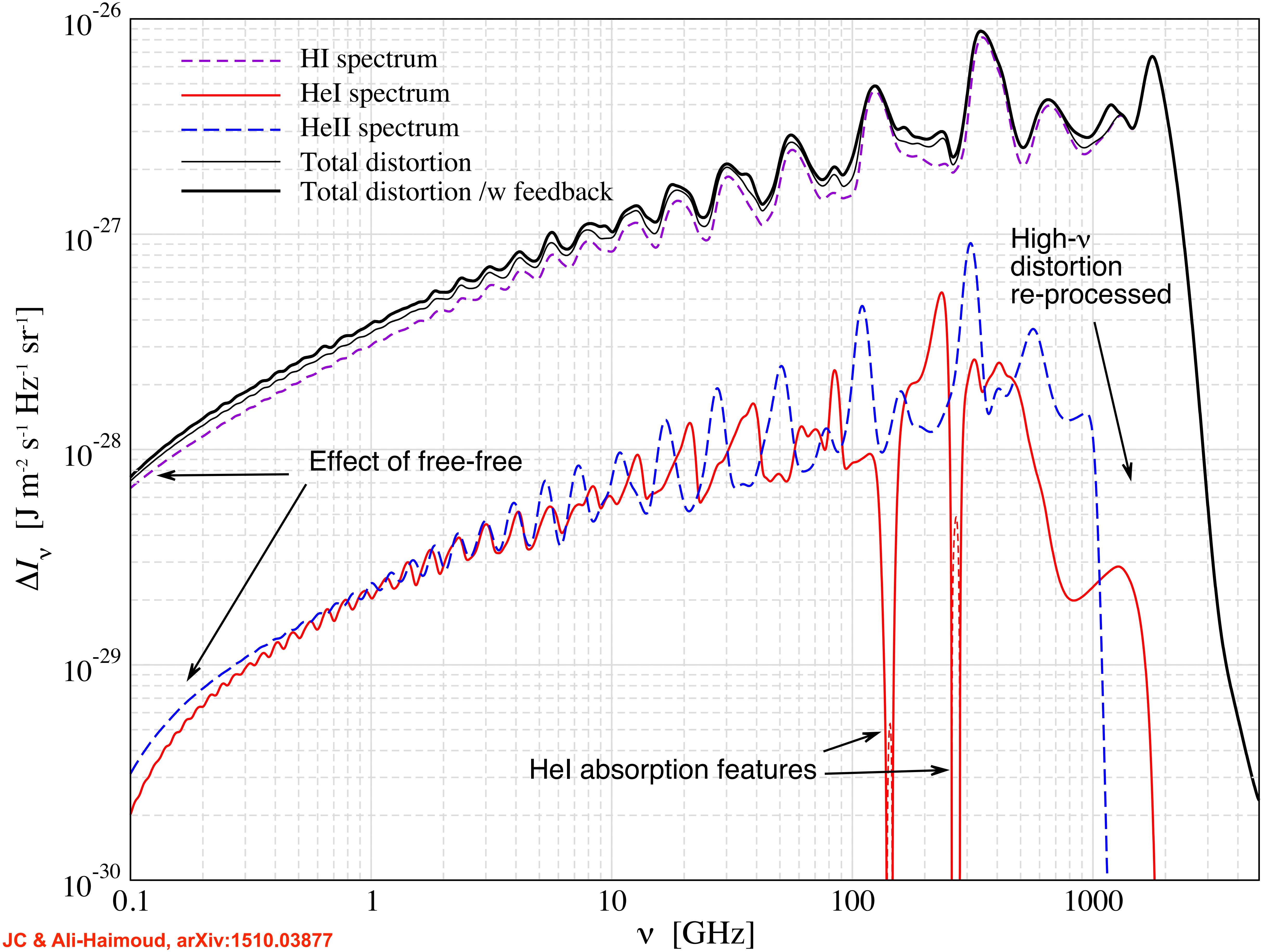


Another way to do CMB-based cosmology!

Direct probe of recombination physics!

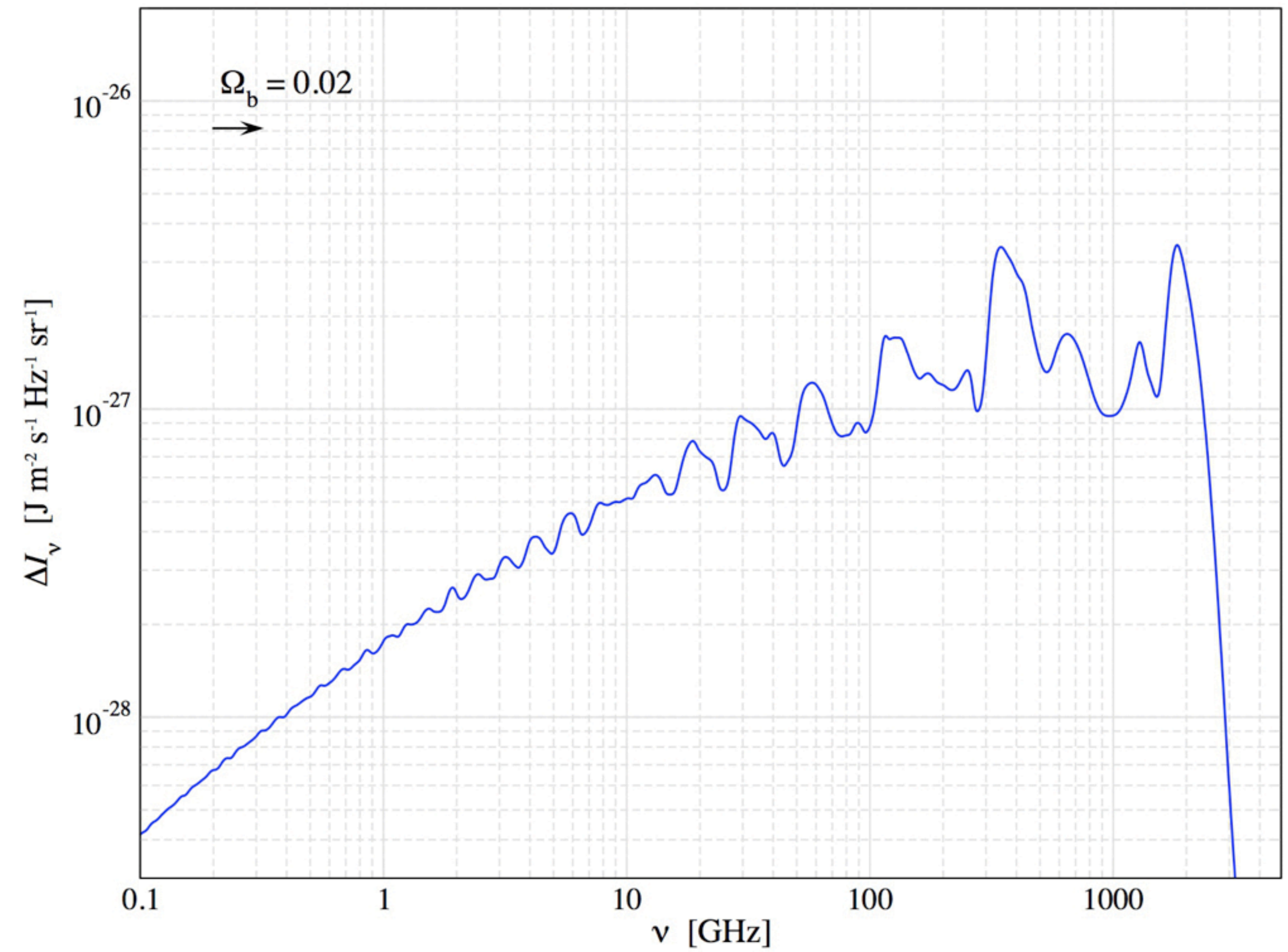
Rubino-Martin et al. 2006, 2008; Sunyaev & JC, 2009

New detailed and fast computation!



JC & Ali-Haimoud, arXiv:1510.03877

CosmoSpec: fast and accurate computation of the CRR



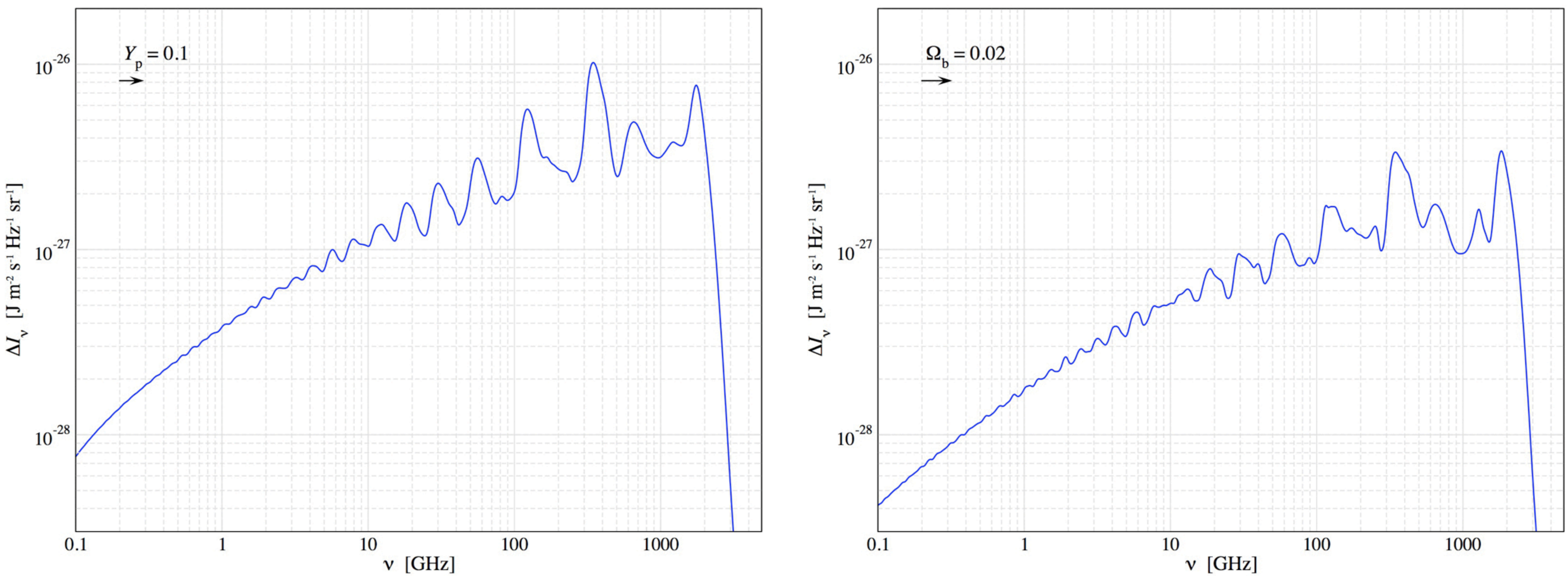
- Like in old days of CMB anisotropies!
- detailed forecasts and feasibility studies
- non-standard physics (variation of α, energy injection etc.)

CosmoSpec will be available here:

www.Chluba.de/CosmoSpec

JC & Ali-Haimoud, arXiv:1510.03877

CosmoSpec: fast and accurate computation of the CRR

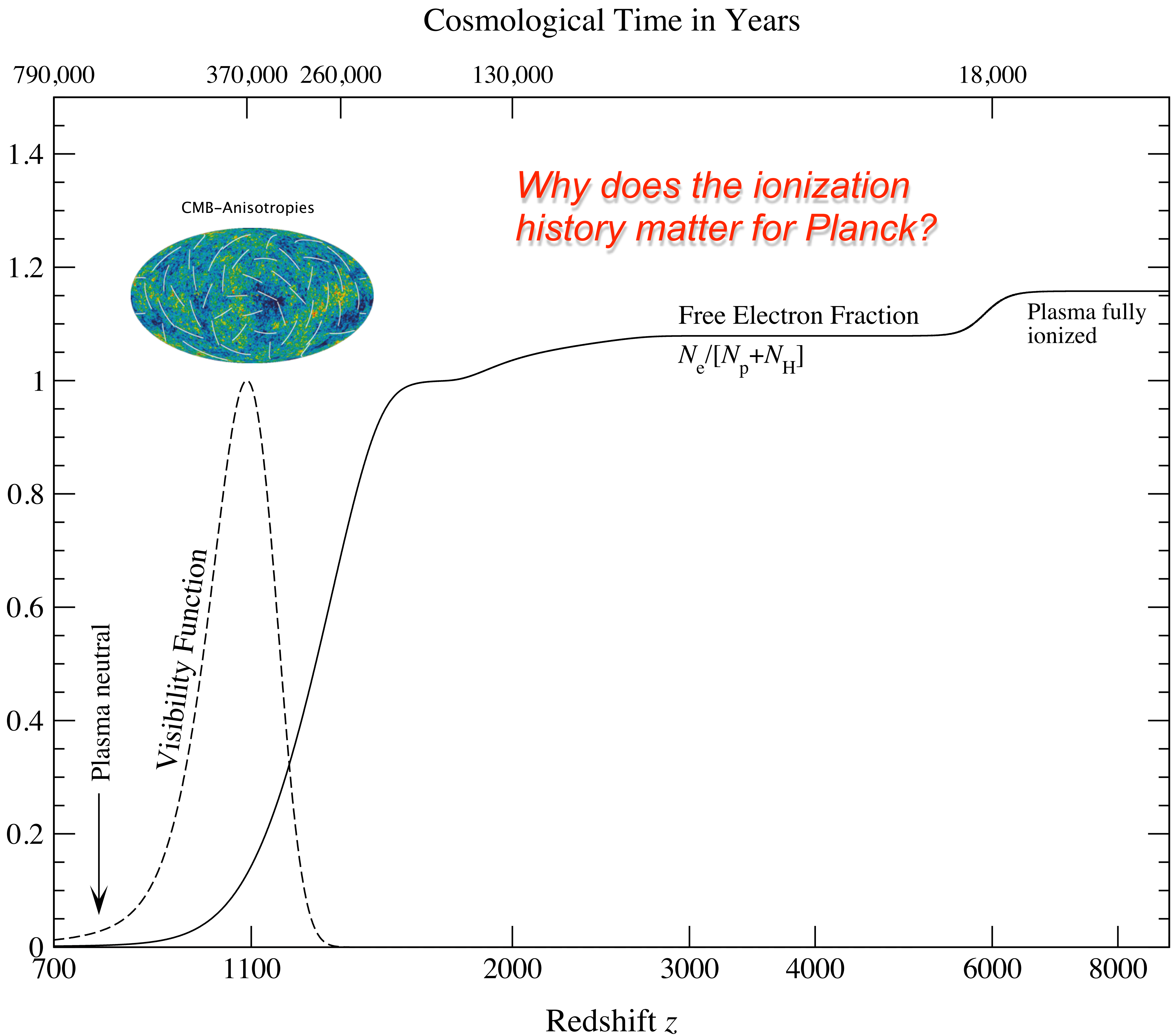


- Like in old days of CMB anisotropies!
- detailed forecasts and feasibility studies
- non-standard physics (variation of α, energy injection etc.)

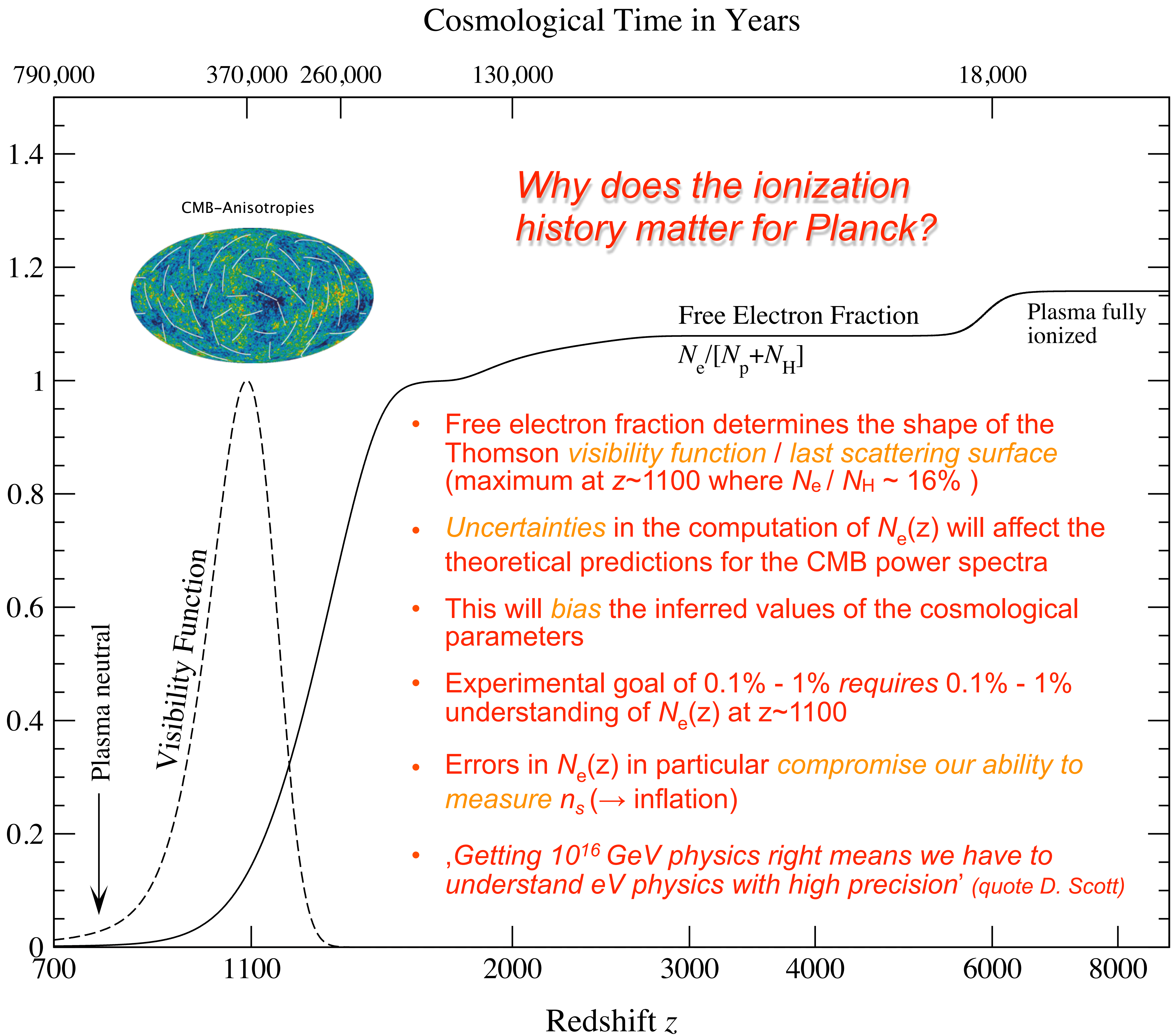
CosmoSpec will be available here:

www.Chluba.de/CosmoSpec

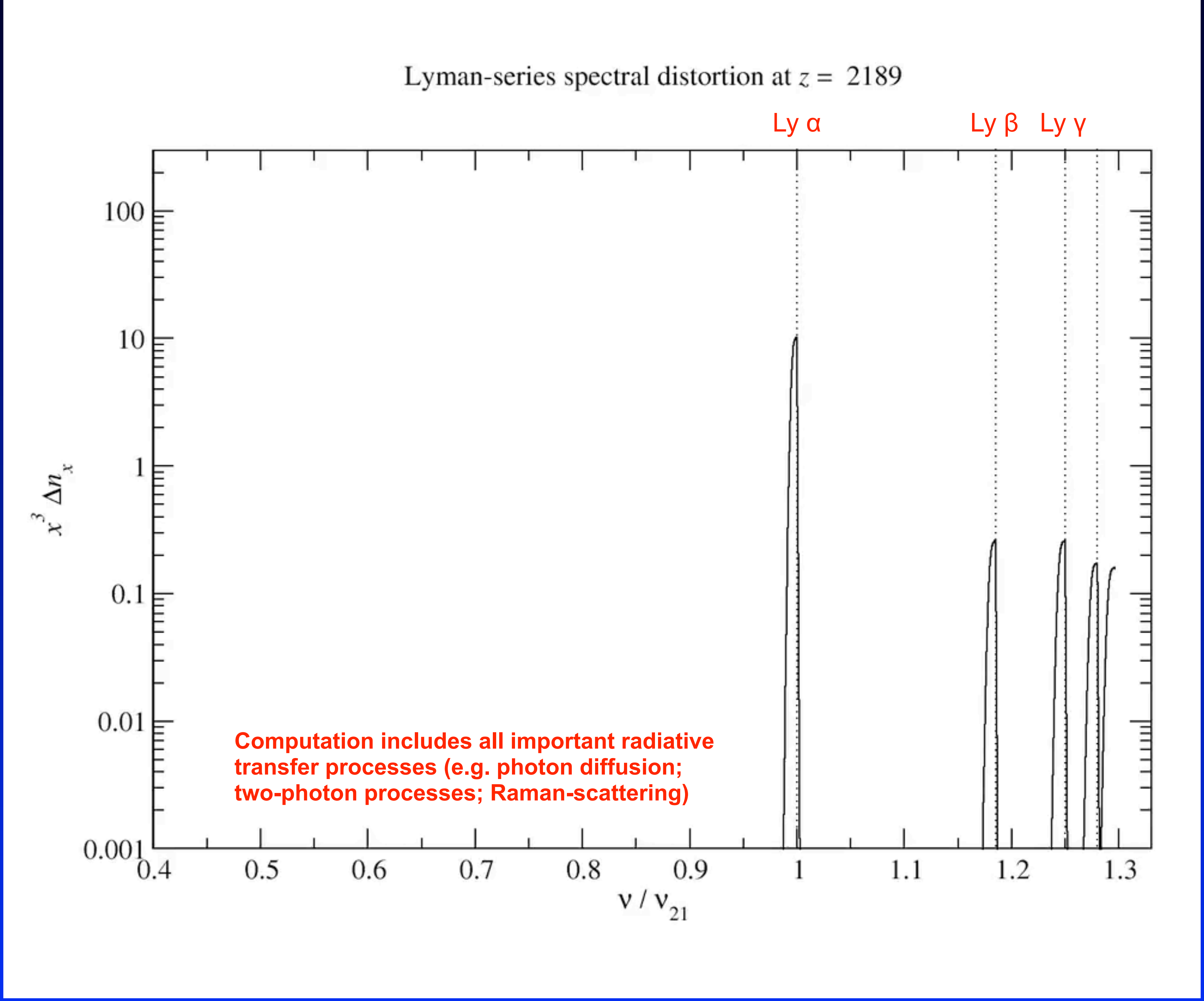
JC & Ali-Haimoud, arXiv:1510.03877



Cosmological Time in Years
790,000
370,000
260,000
130,000
18,000
1.4
1.2
1
0.8
0.6
0.4
0.2
0
CMB-Anisotropies
Why does the ionization history matter for Planck?
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully ionized
Visibility Function
Plasma neutral
700
1100
2000
3000
4000
6000
8000
Redshift z

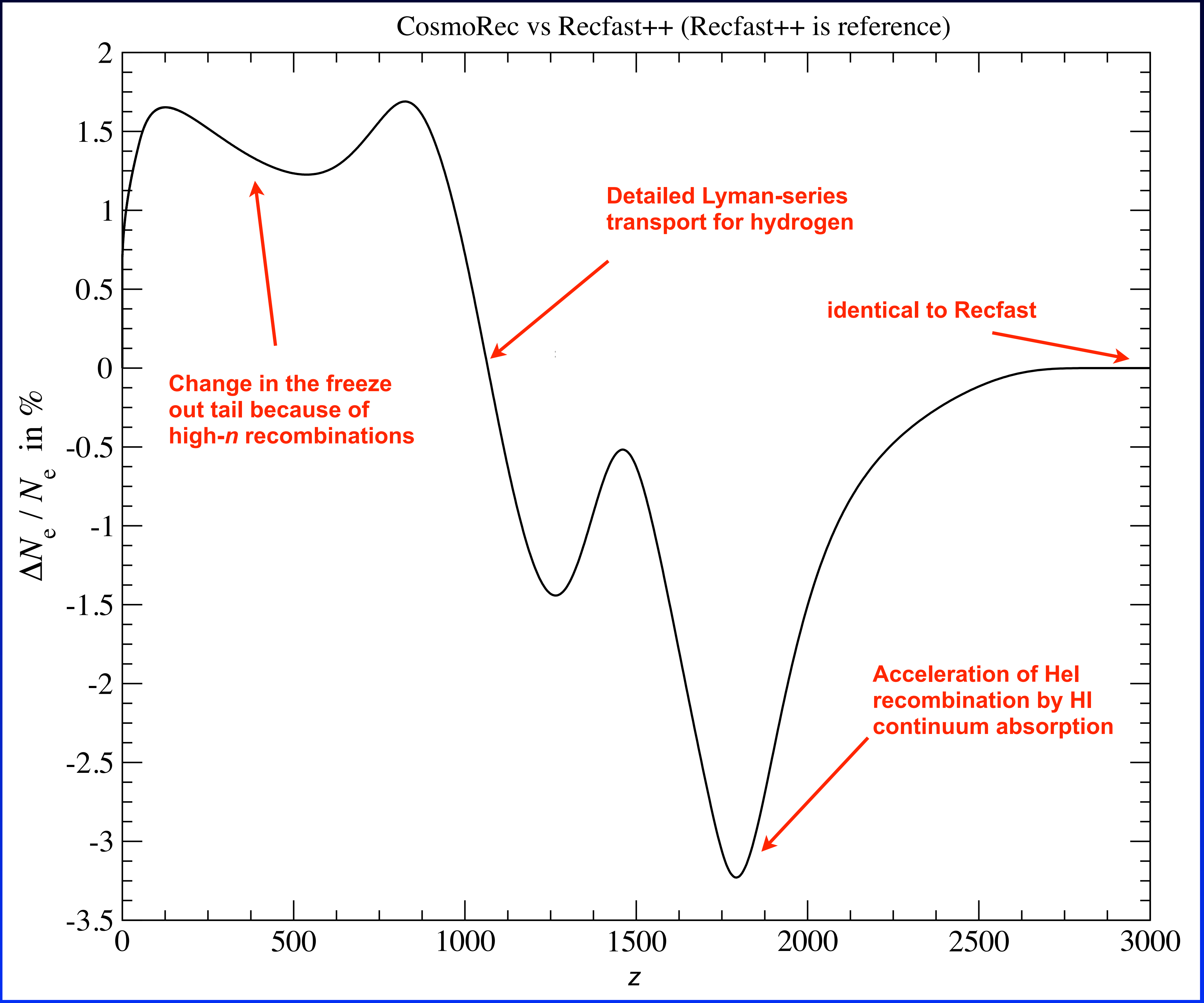

Cosmological Time in Years
790,000
370,000
260,000
130,000
18,000
Why does the ionization history matter for Planck?
CMB-Anisotropies
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully ionized
Plasma neutral
Visibility Function
• Free electron fraction determines the shape of the Thomson *visibility 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

Evolution of the HI Lyman-series distortion



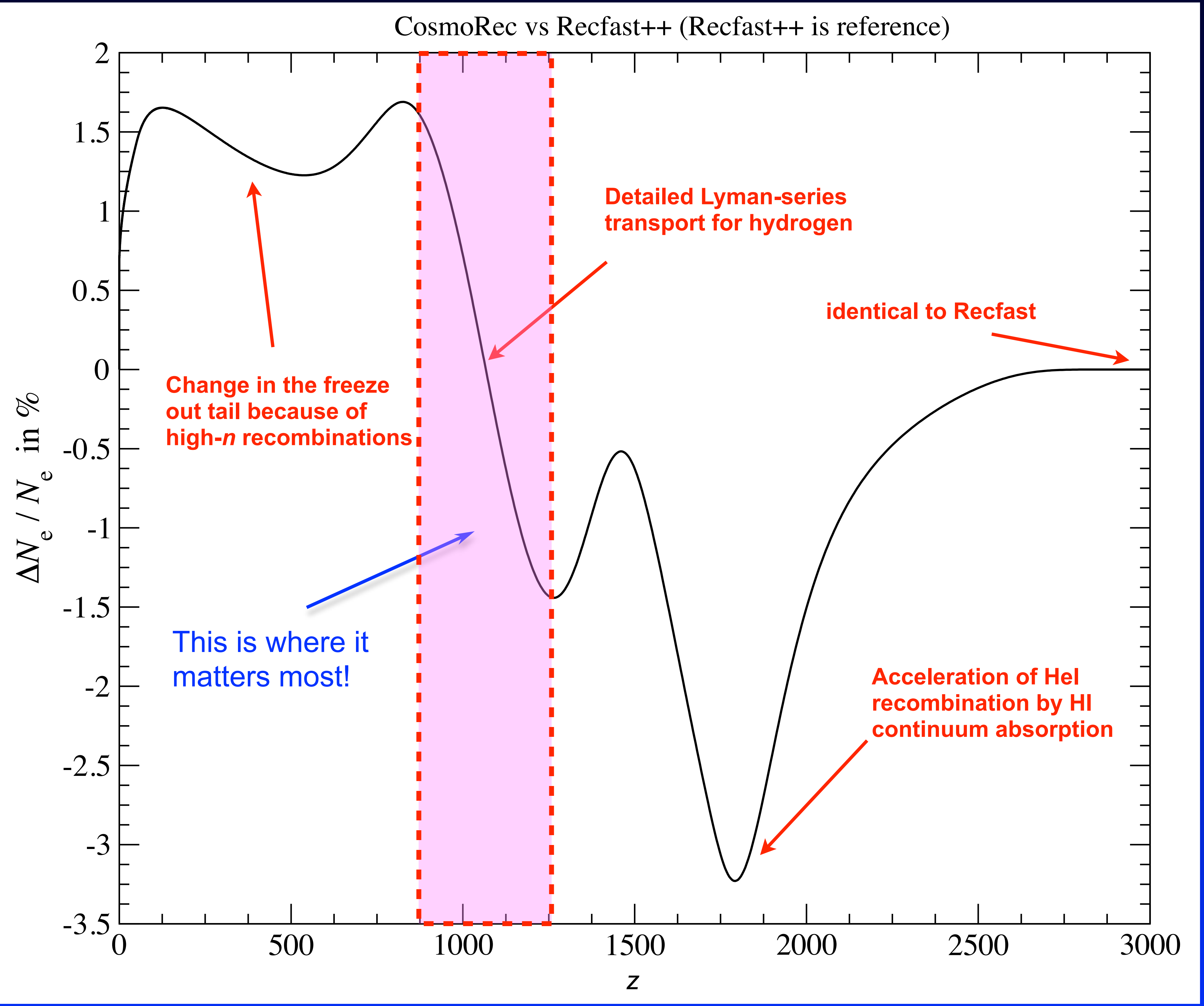
JC & Thomas, MNRAS, 2010

Cumulative Changes to the Ionization History



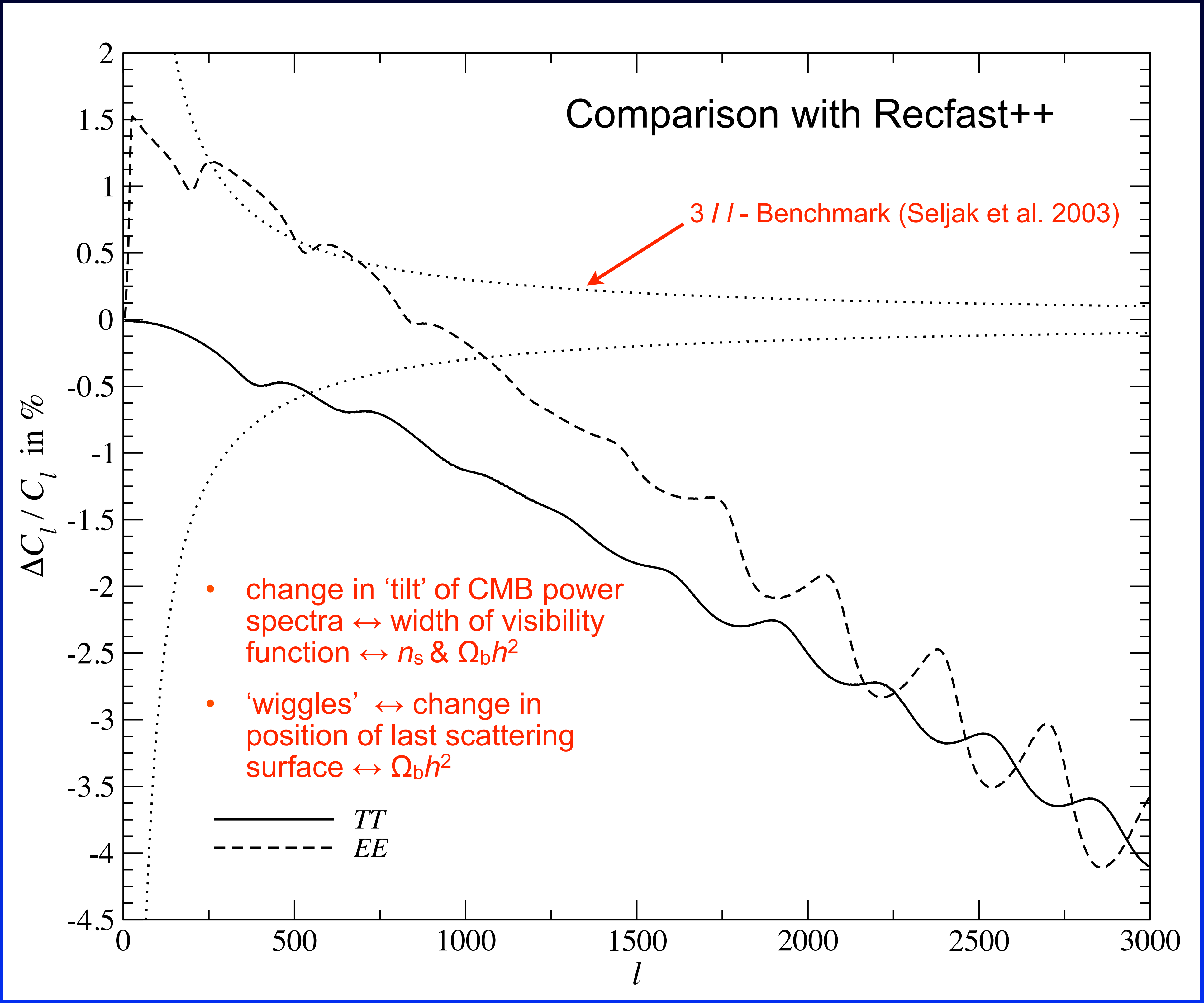
JC & Thomas, MNRAS, 2010; Shaw & JC, MNRAS, 2011

Cumulative Changes to the Ionization History



JC & Thomas, MNRAS, 2010; Shaw & JC, MNRAS, 2011

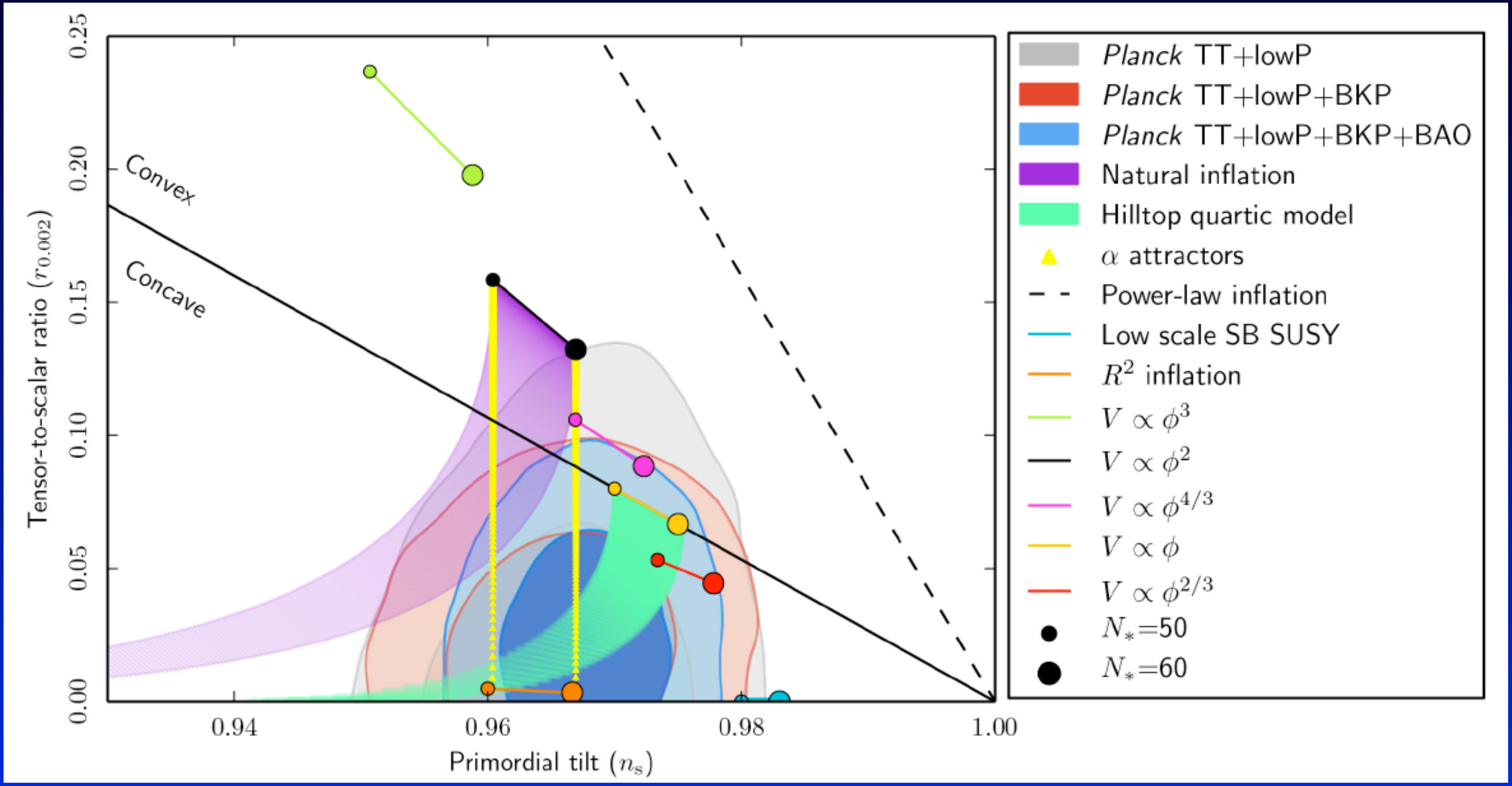
Cumulative Change in the CMB Power Spectra



CITA ICAT

Shaw & JC, MNRAS, 2011

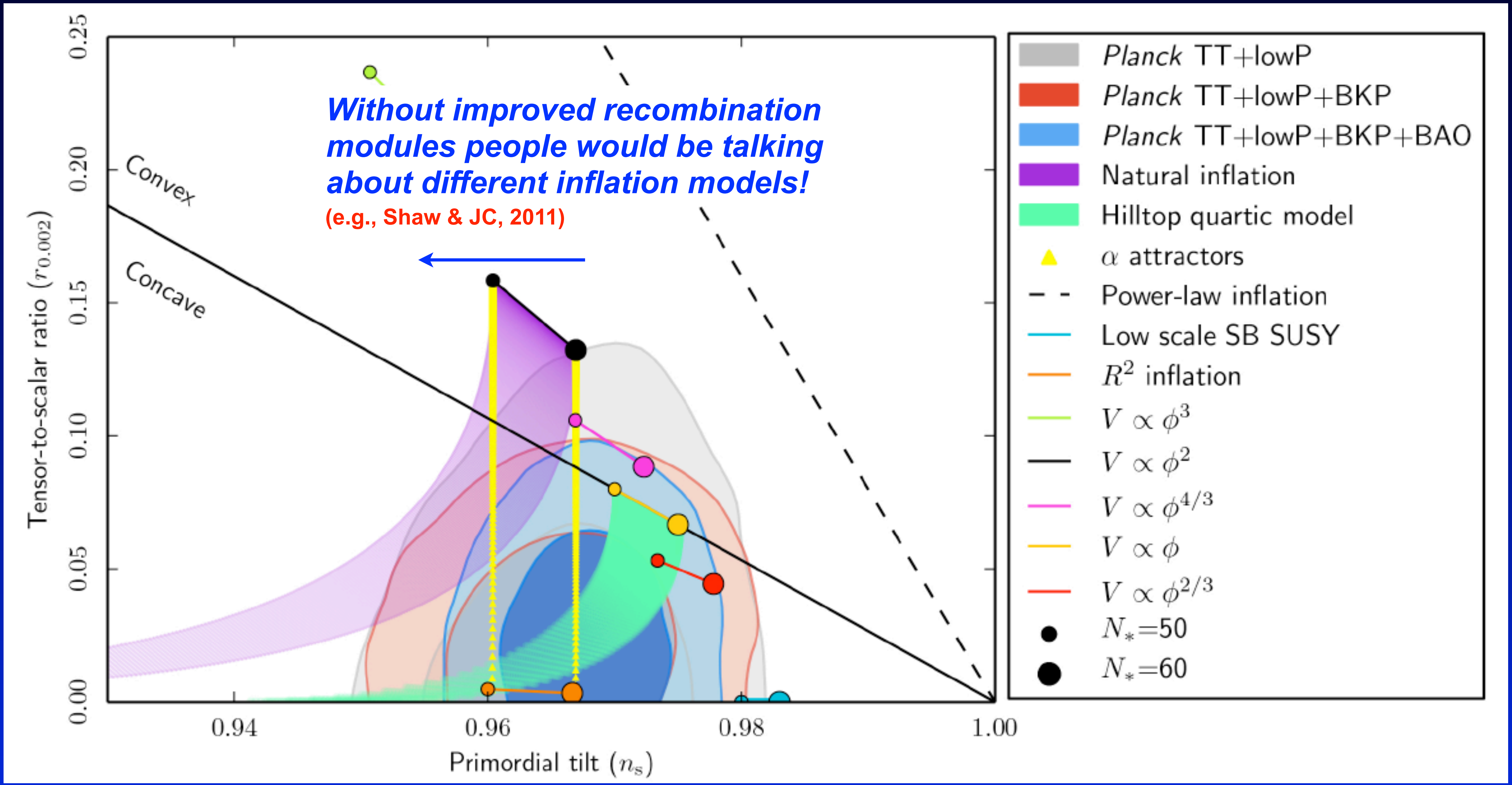
Importance of recombination for inflation constraints



Planck Collaboration, 2015, paper XX

- Analysis uses refined recombination model (CosmoRec/HyRec)

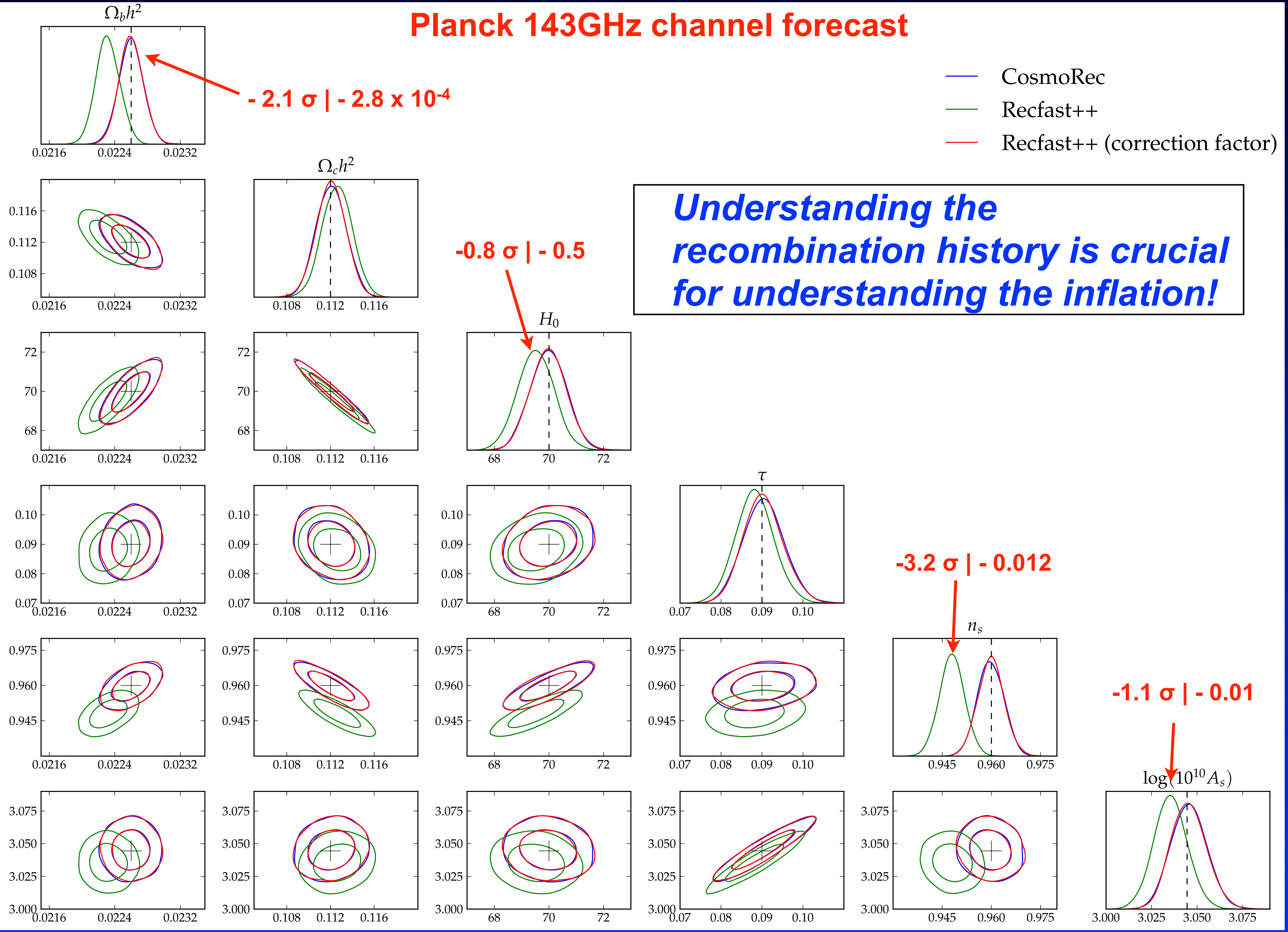
Importance of recombination for inflation constraints



Planck Collaboration, 2015, paper XX

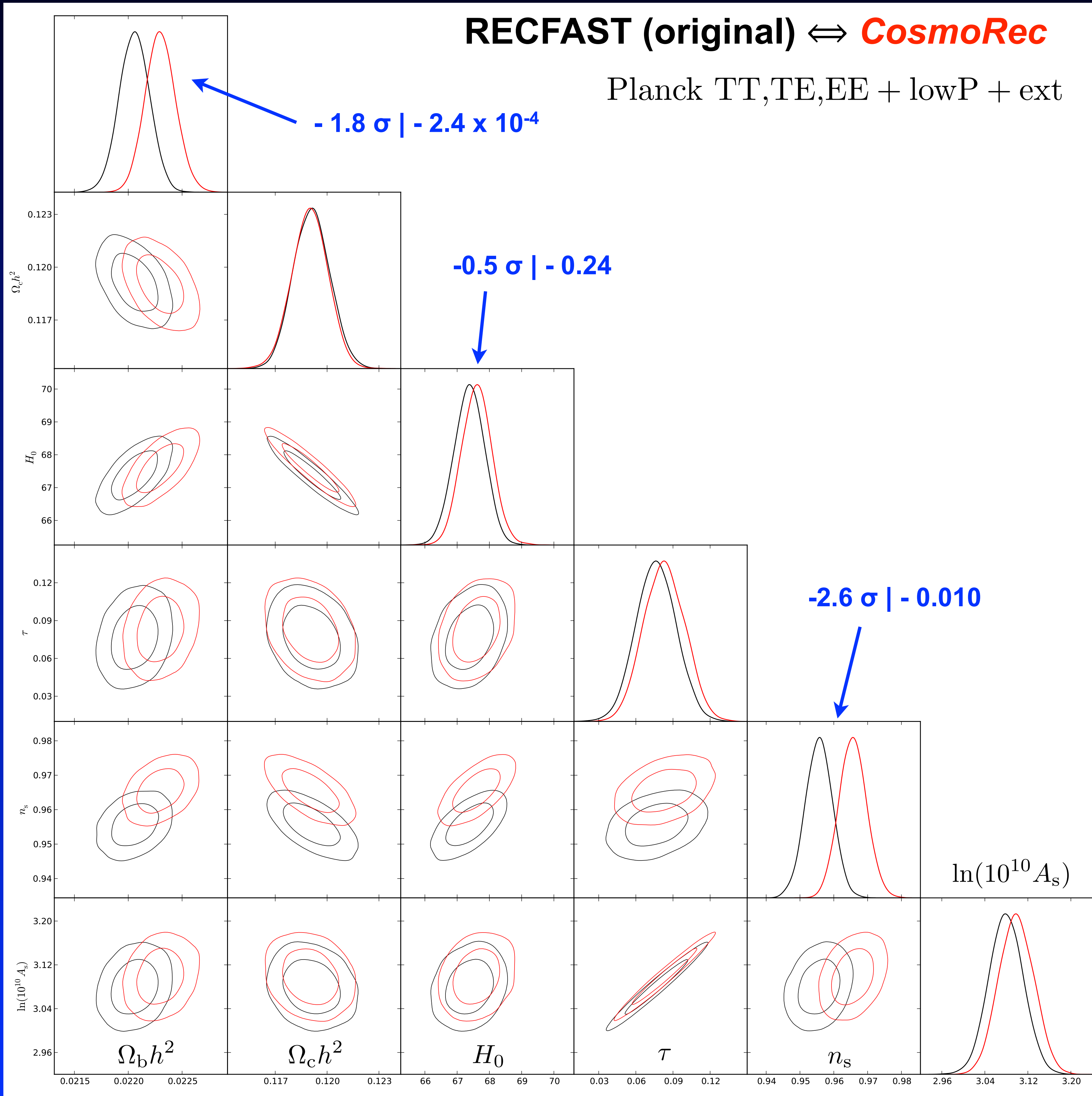
- Analysis uses refined recombination model (CosmoRec/HyRec)

Importance of recombination



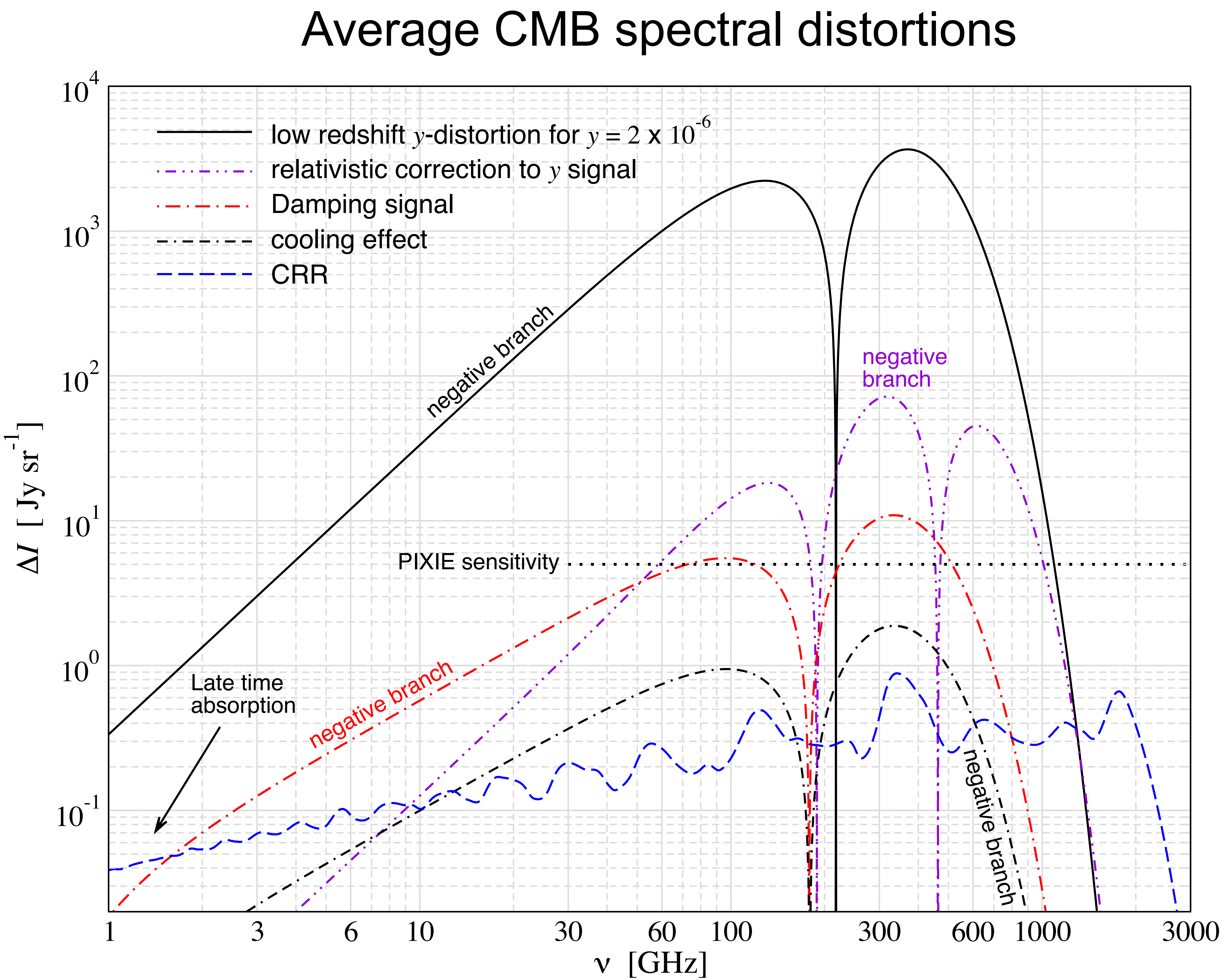
Shaw & JC, 2011, and references therein

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



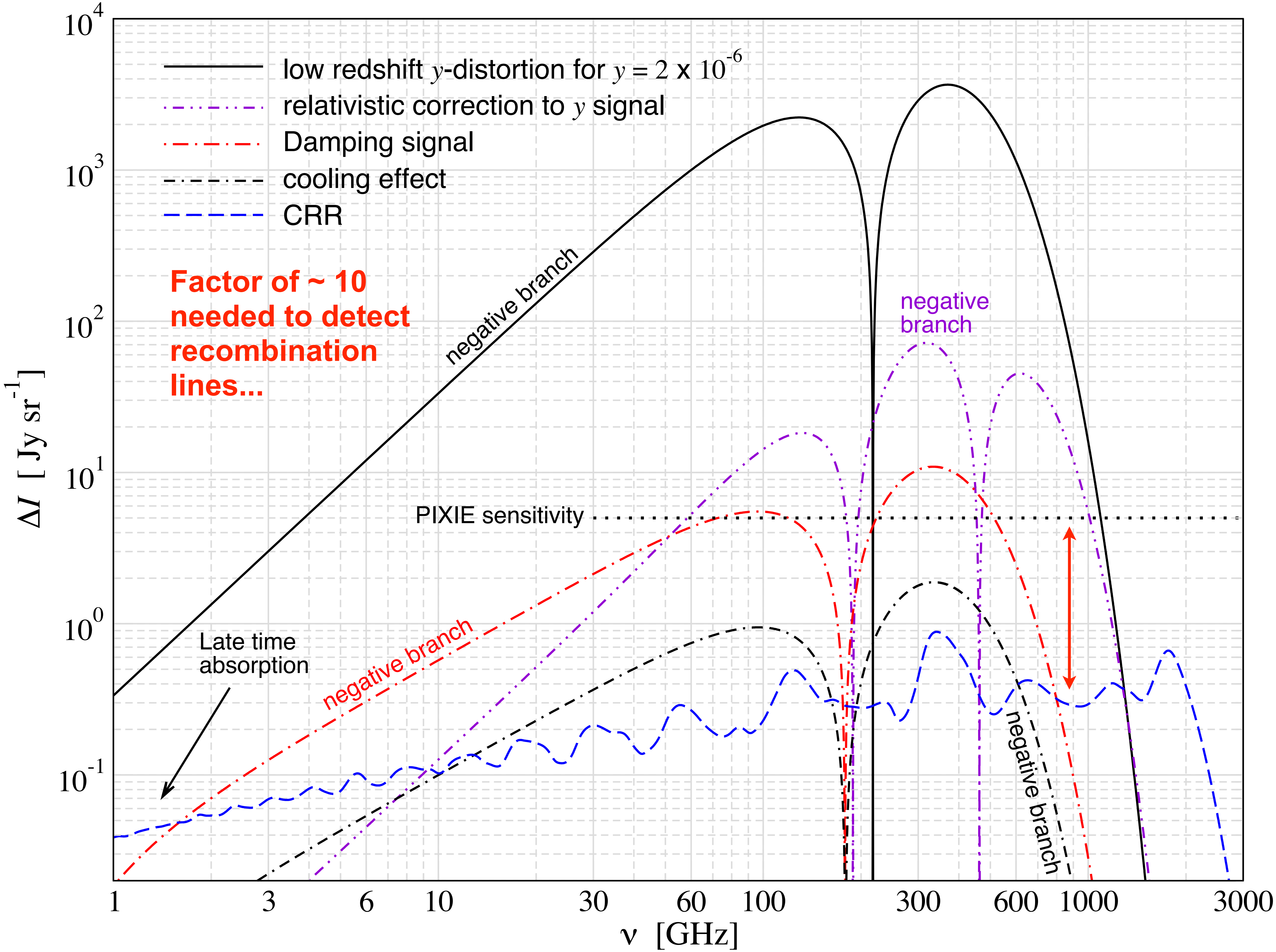
- Biases a little less significant with real *Planck* data
- absolute biases very similar
- In particular n_s would be biased significantly

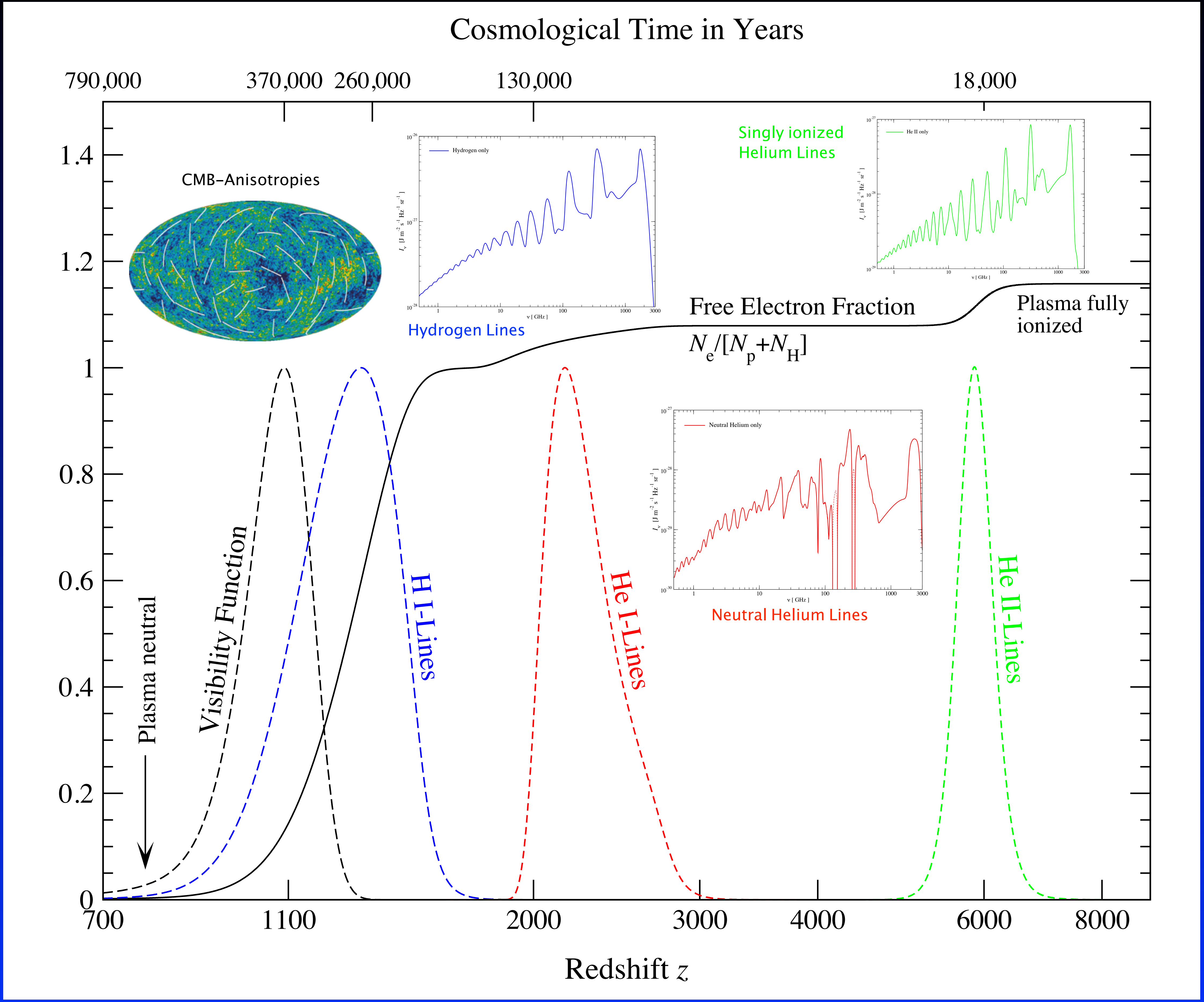
Planck Collaboration, XIII 2015



Average CMB spectral distortions
low redshift y-distortion for y = 2 x 10^-6
relativistic correction to y signal
Damping signal
cooling effect
CRR
negative branch
negative branch
negative branch
negative branch
PIXIE sensitivity
Late time absorption
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

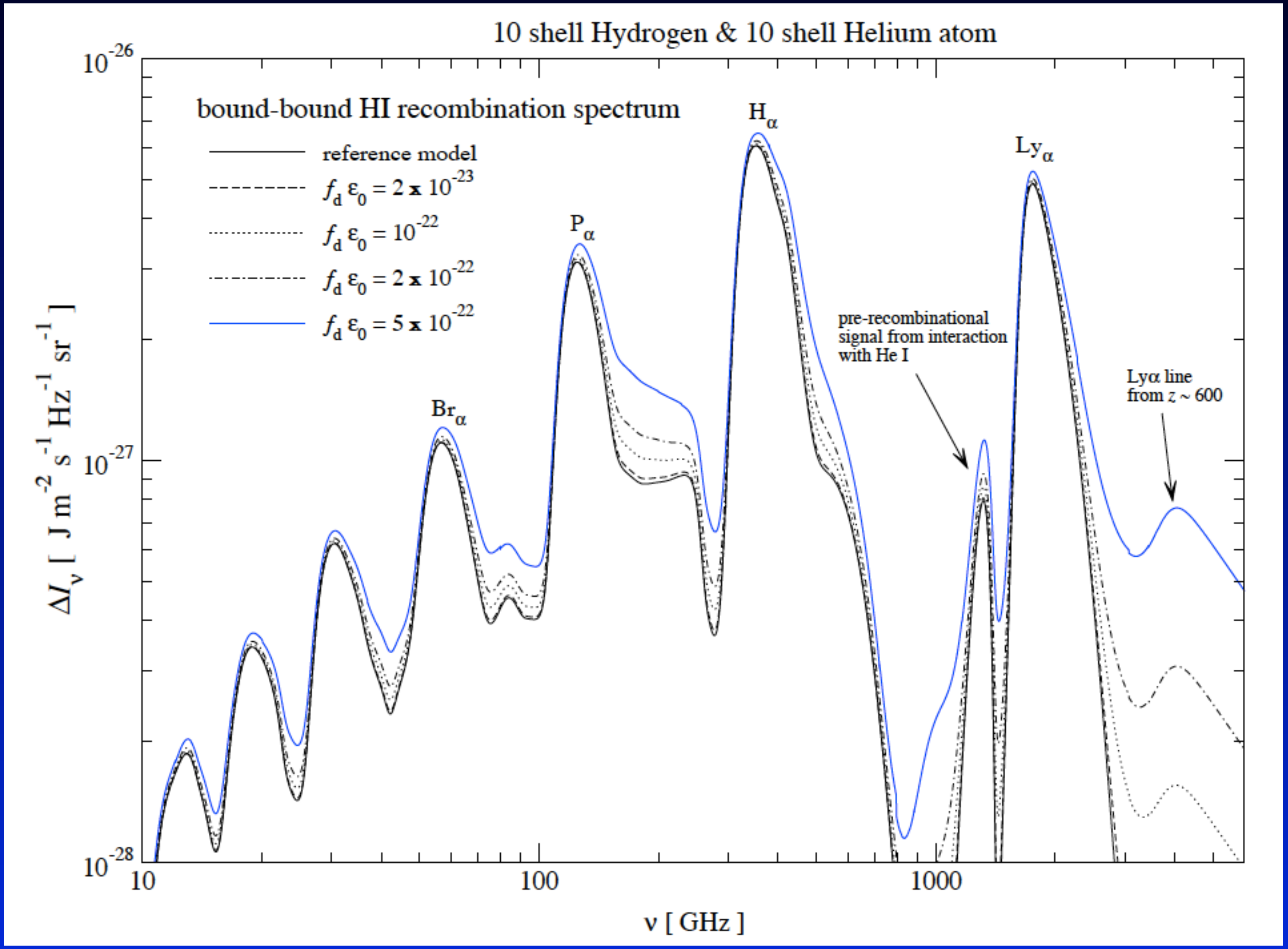
Average CMB spectral distortions





Cosmological Time in Years
790,000
370,000
260,000
130,000
18,000
CMB–Anisotropies
Hydrogen only
Hydrogen Lines
Singly ionized
Helium Lines
He II only
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully
ionized
Neutral Helium only
Neutral Helium Lines
Visibility Function
Plasma neutral
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



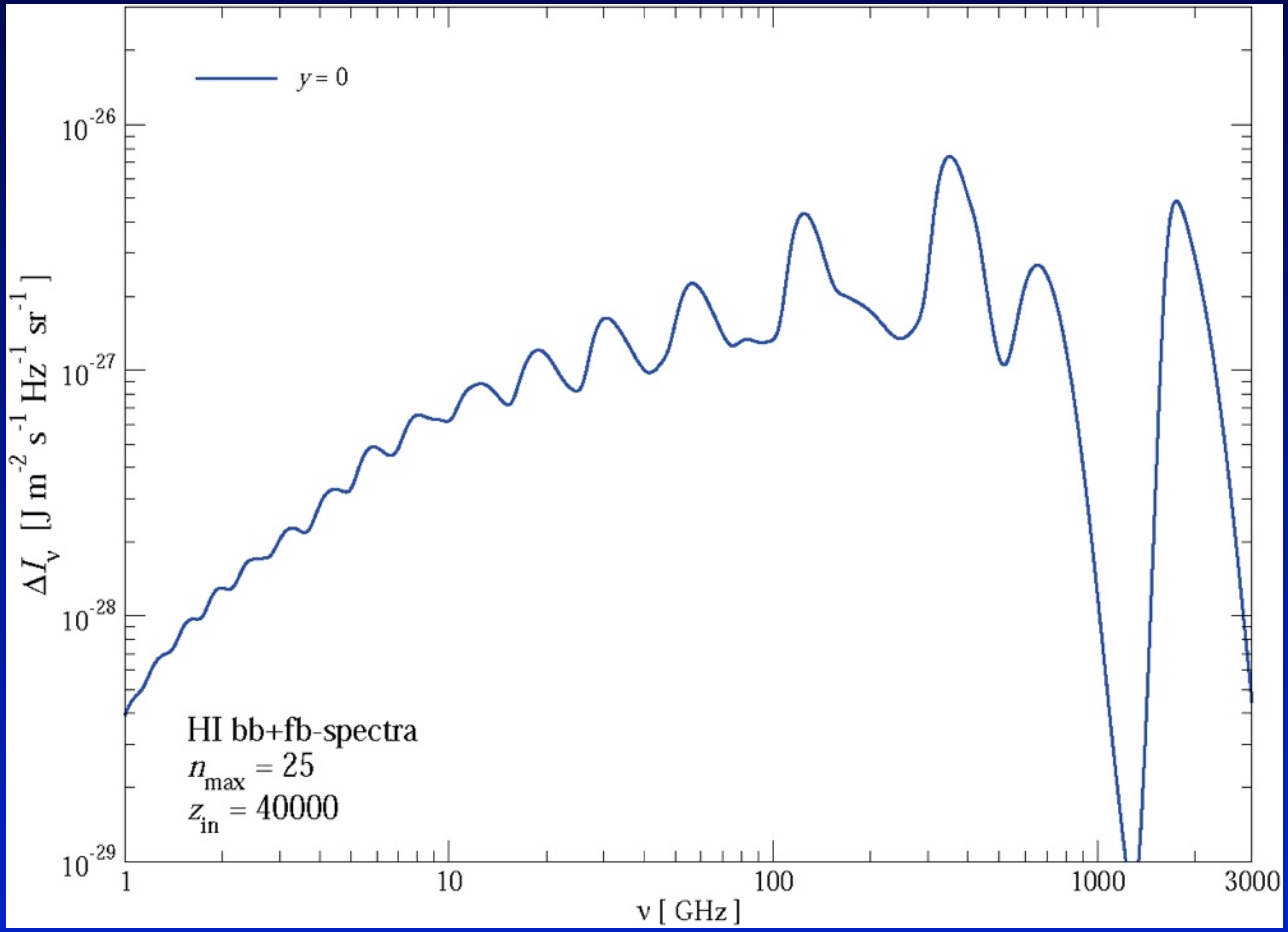
JC, 2009, arXiv:0910.3663

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

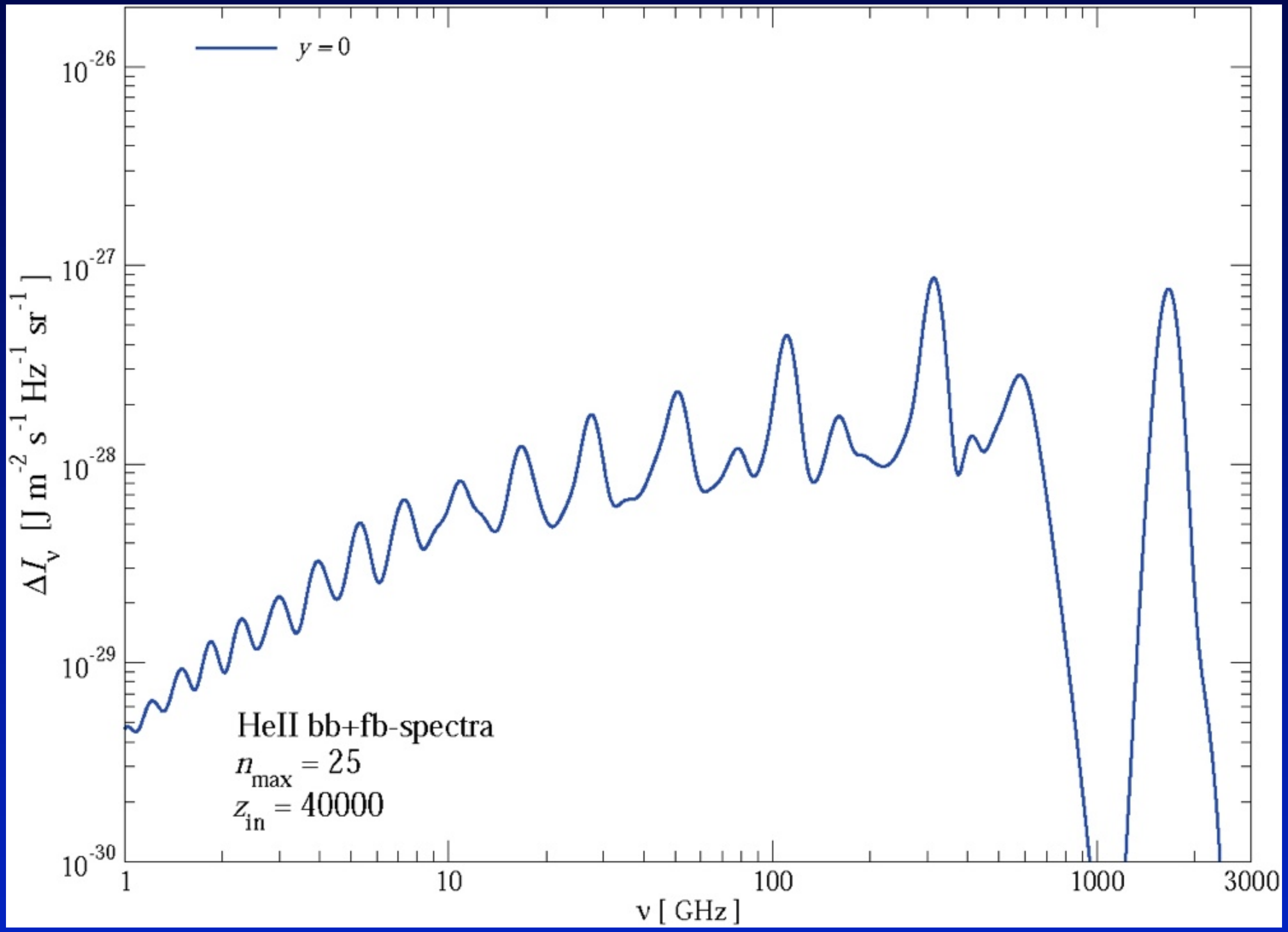
CMB spectral distortions after single energy release

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

Hydrogen



Helium +

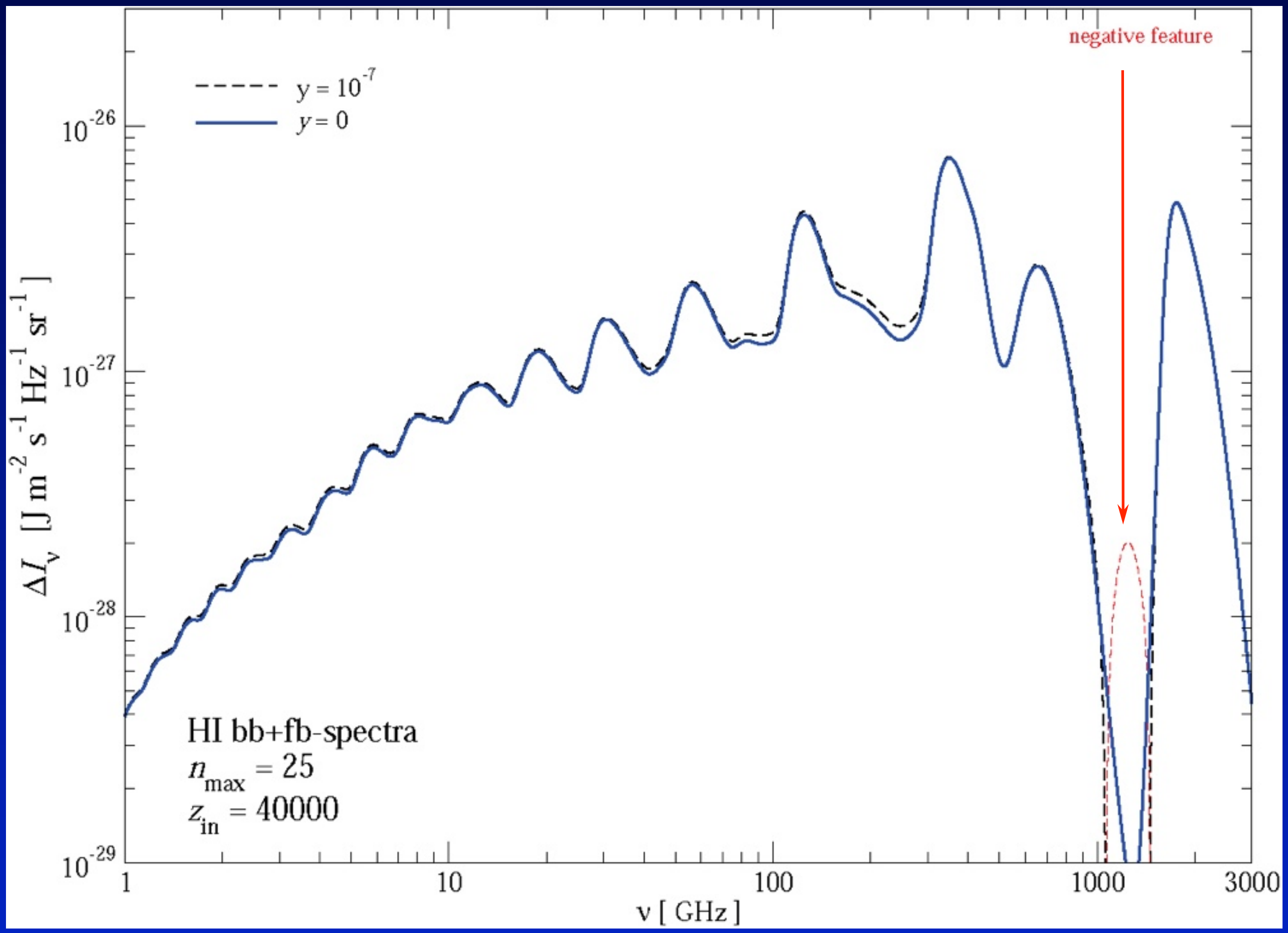


JC & Sunyaev, 2008, astro-ph/0803.3584

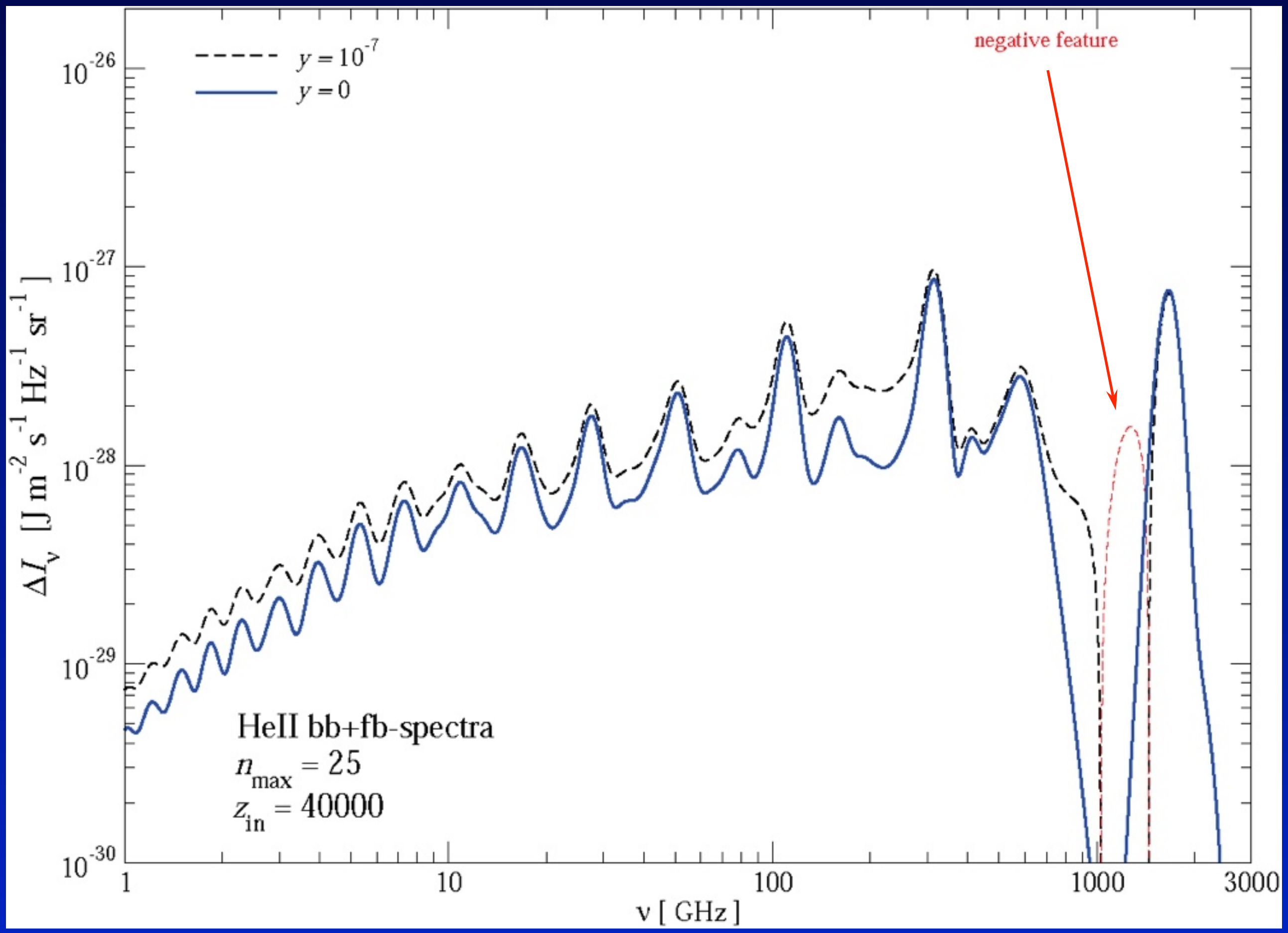
CMB spectral distortions after single energy release

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

Hydrogen



Helium +

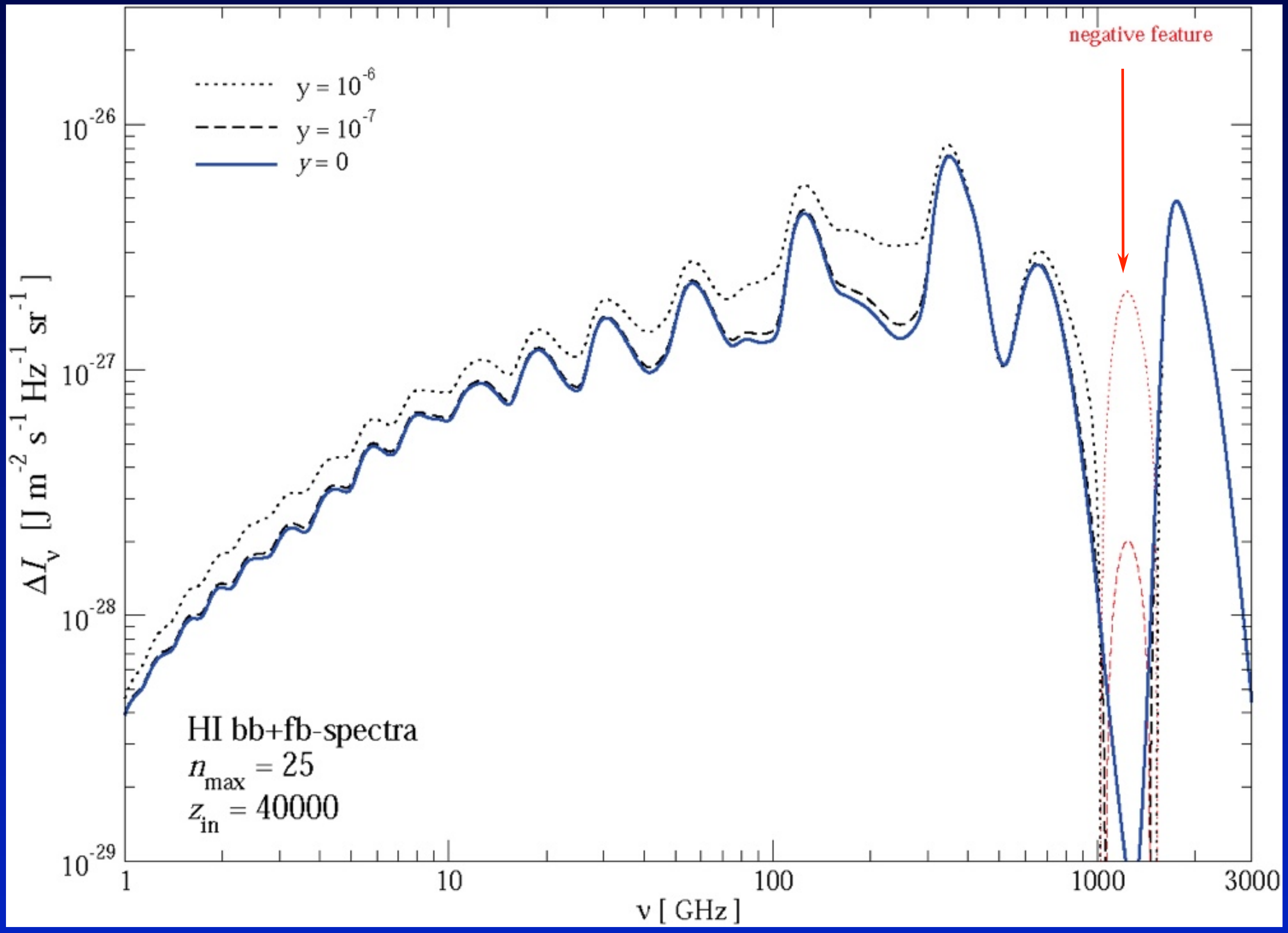


JC & Sunyaev, 2008, astro-ph/0803.3584

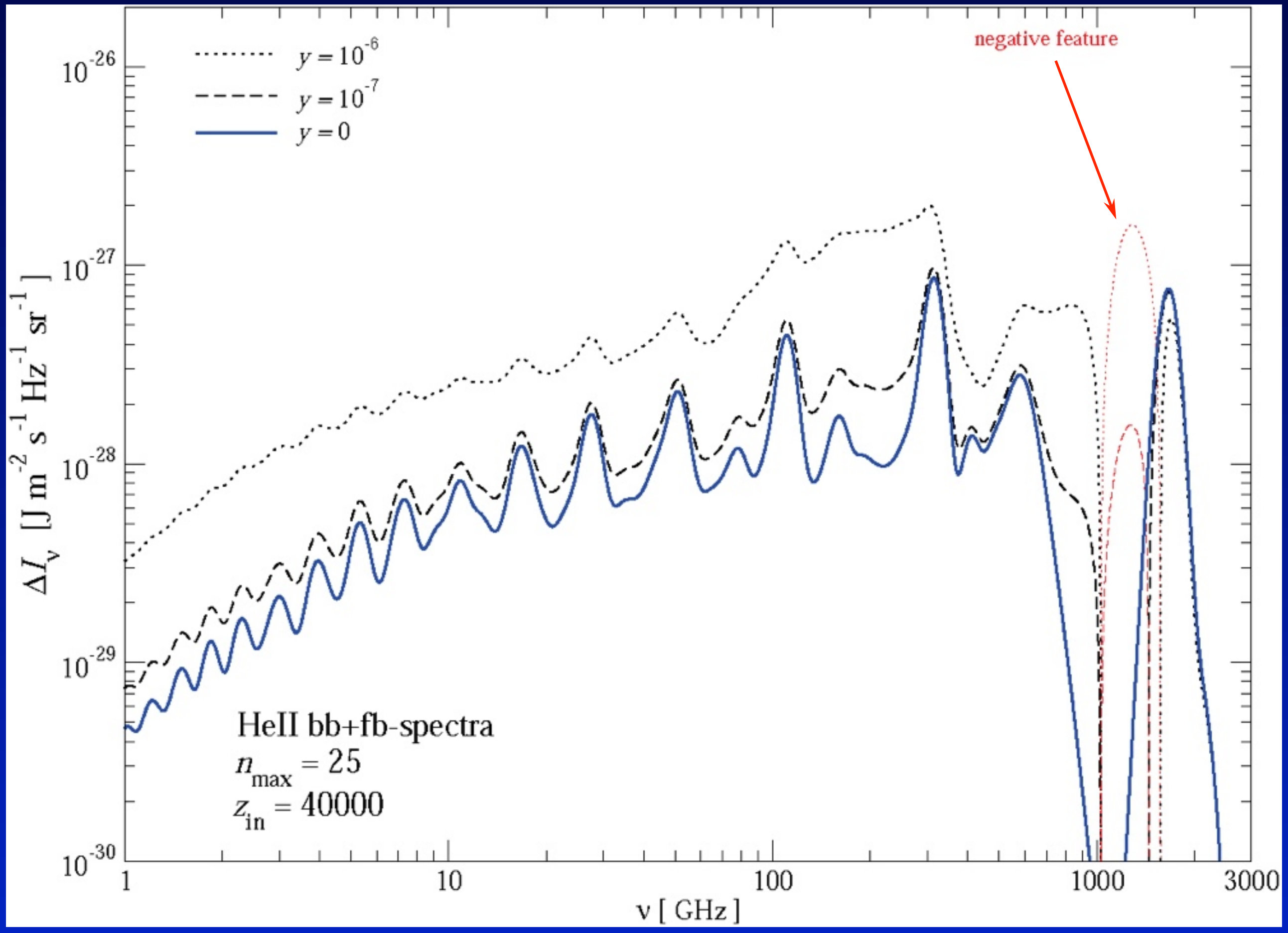
CMB spectral distortions after single energy release

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

Hydrogen



Helium +

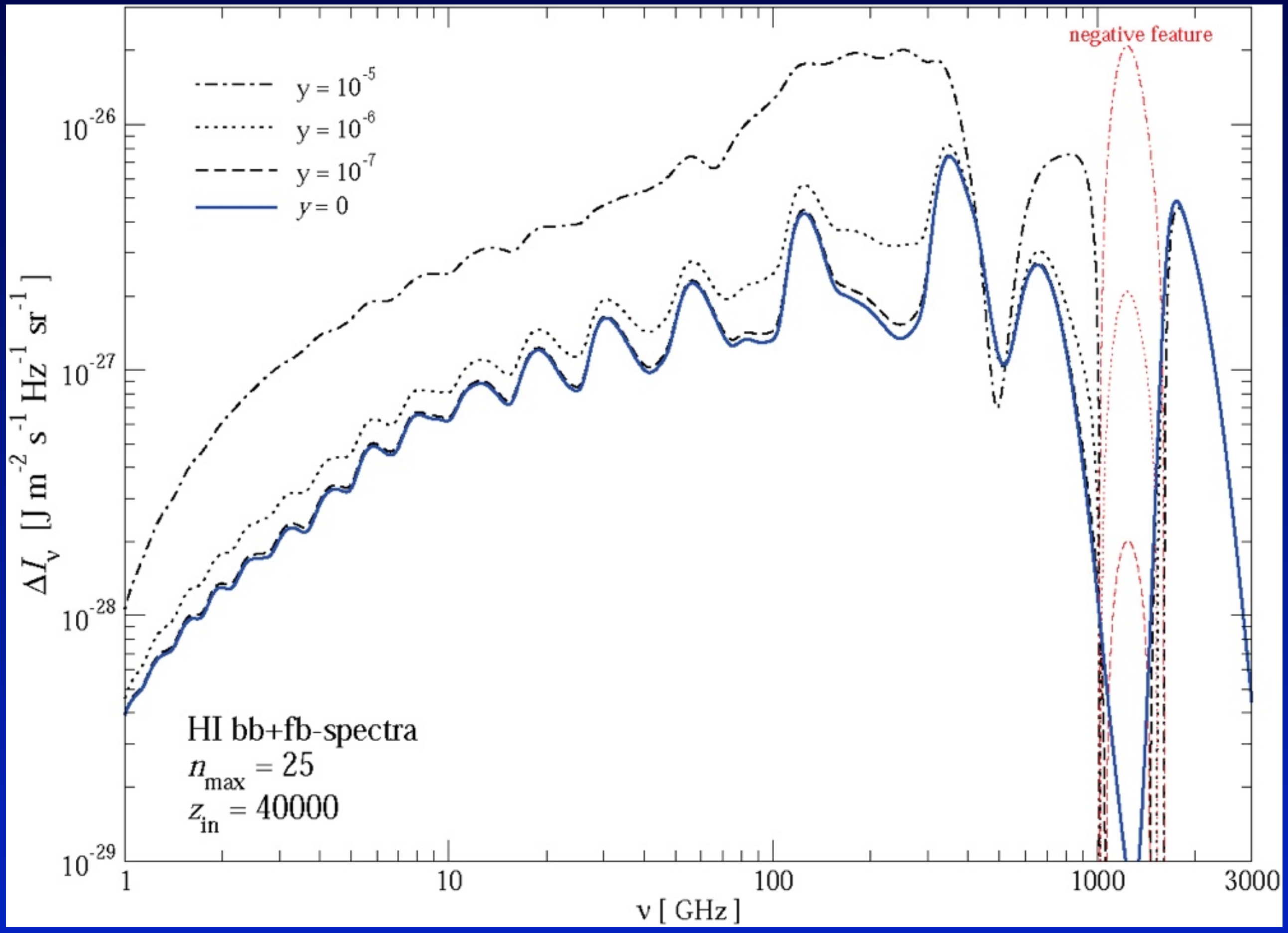


JC & Sunyaev, 2008, astro-ph/0803.3584

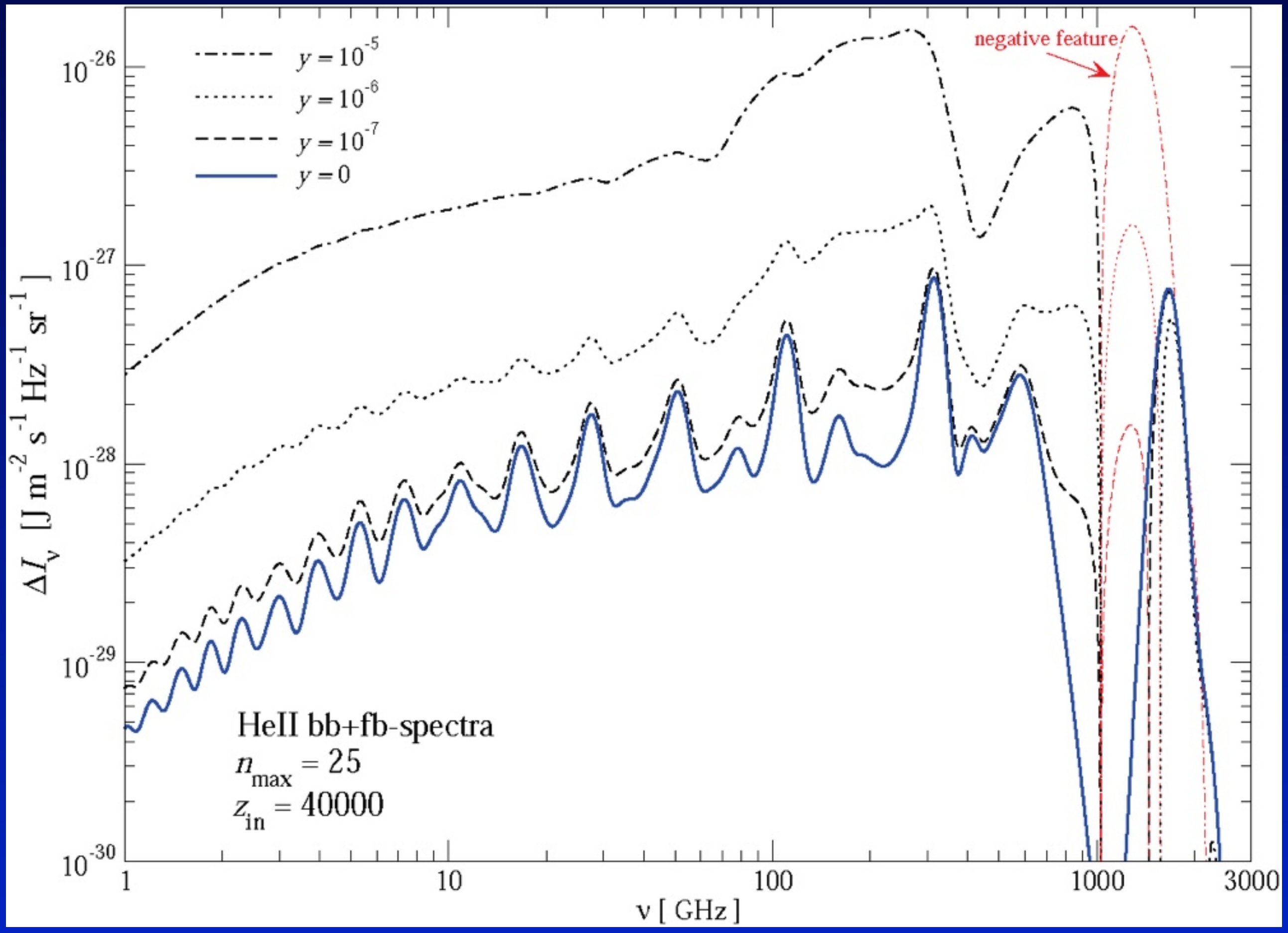
CMB spectral distortions after single energy release

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

Hydrogen



Helium +

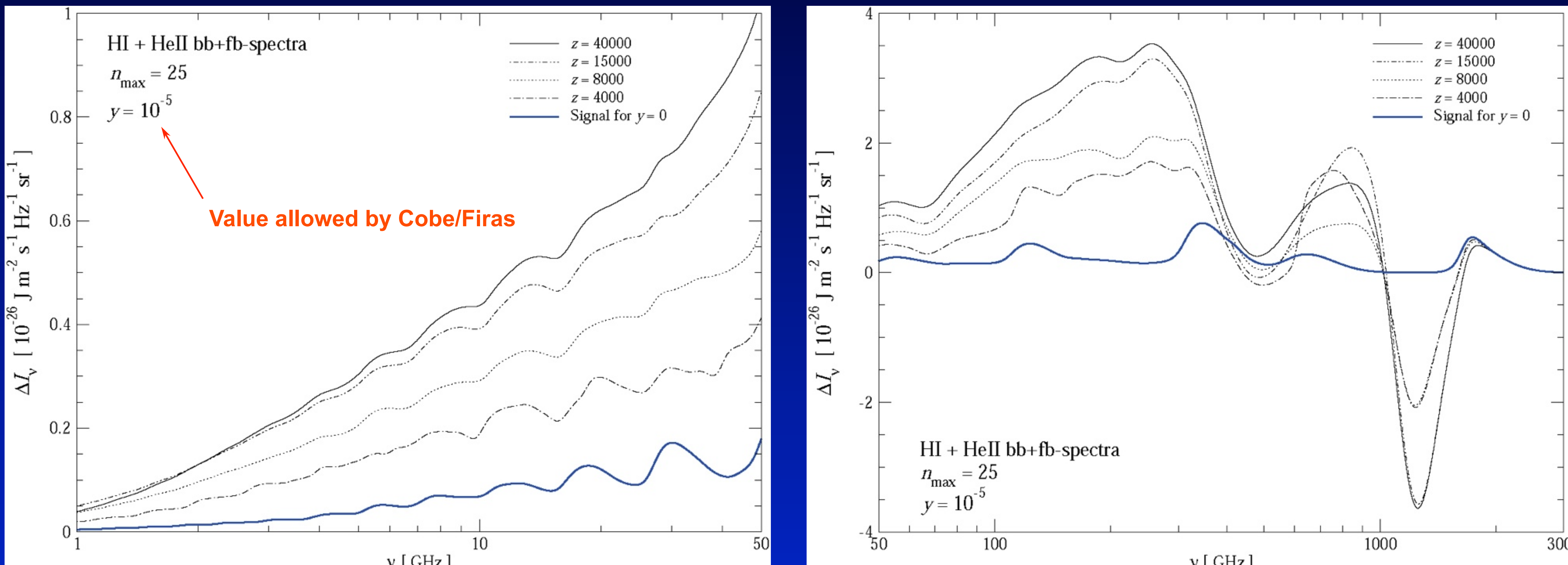


JC & Sunyaev, 2008, astro-ph/0803.3584

- 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

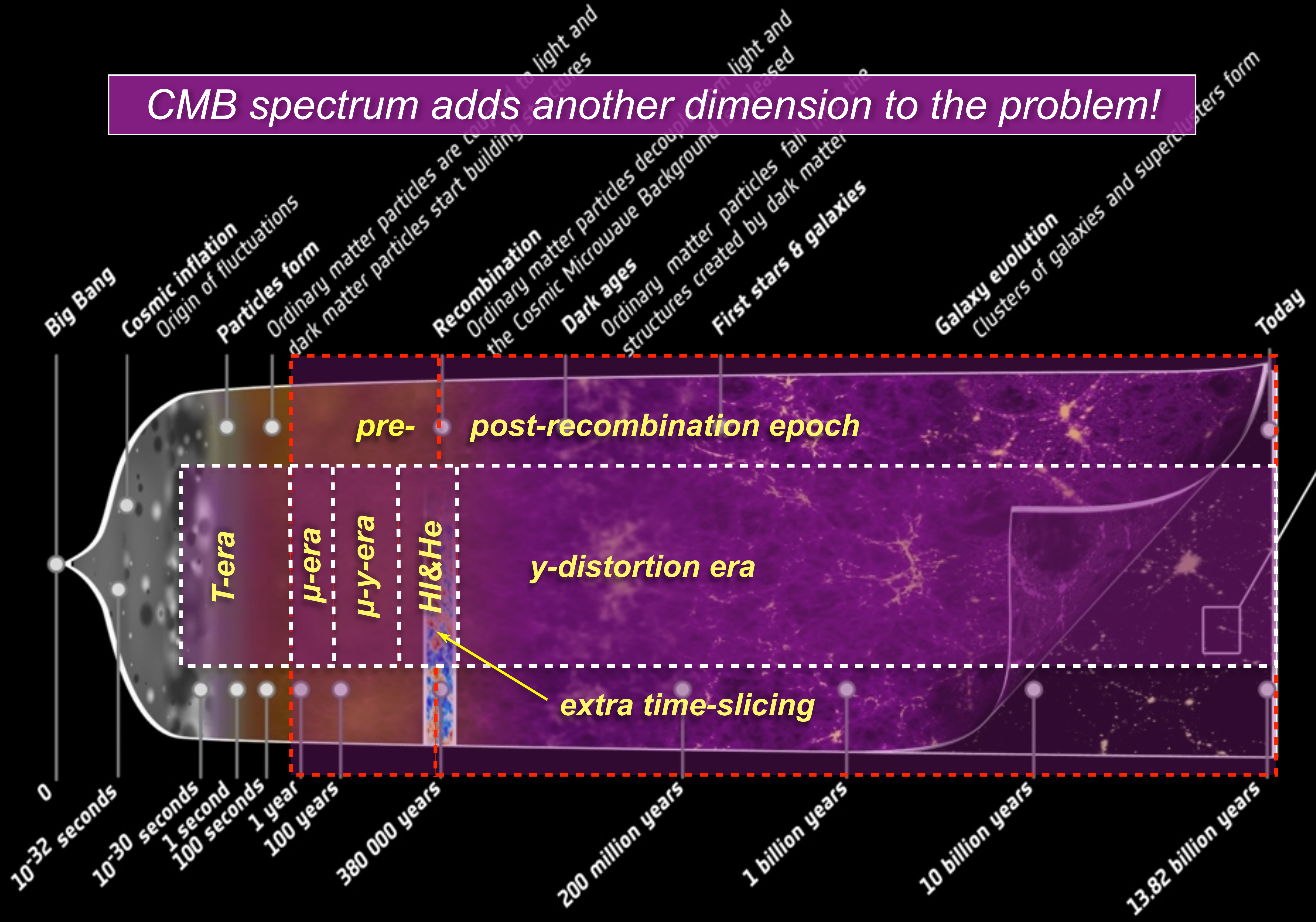
Hydrogen and Helium +



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...

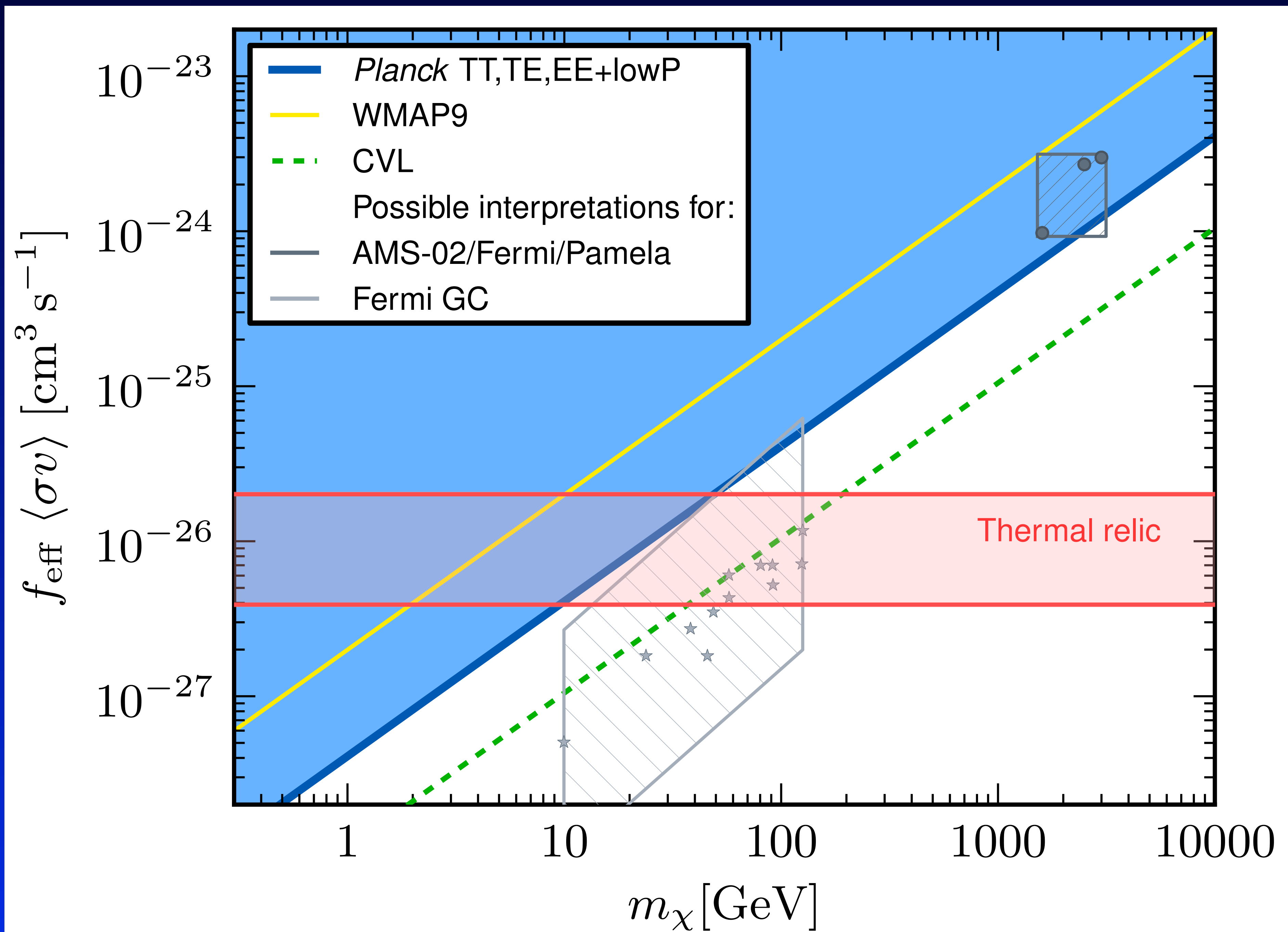
Why is this interesting?

- 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

95% c.l.

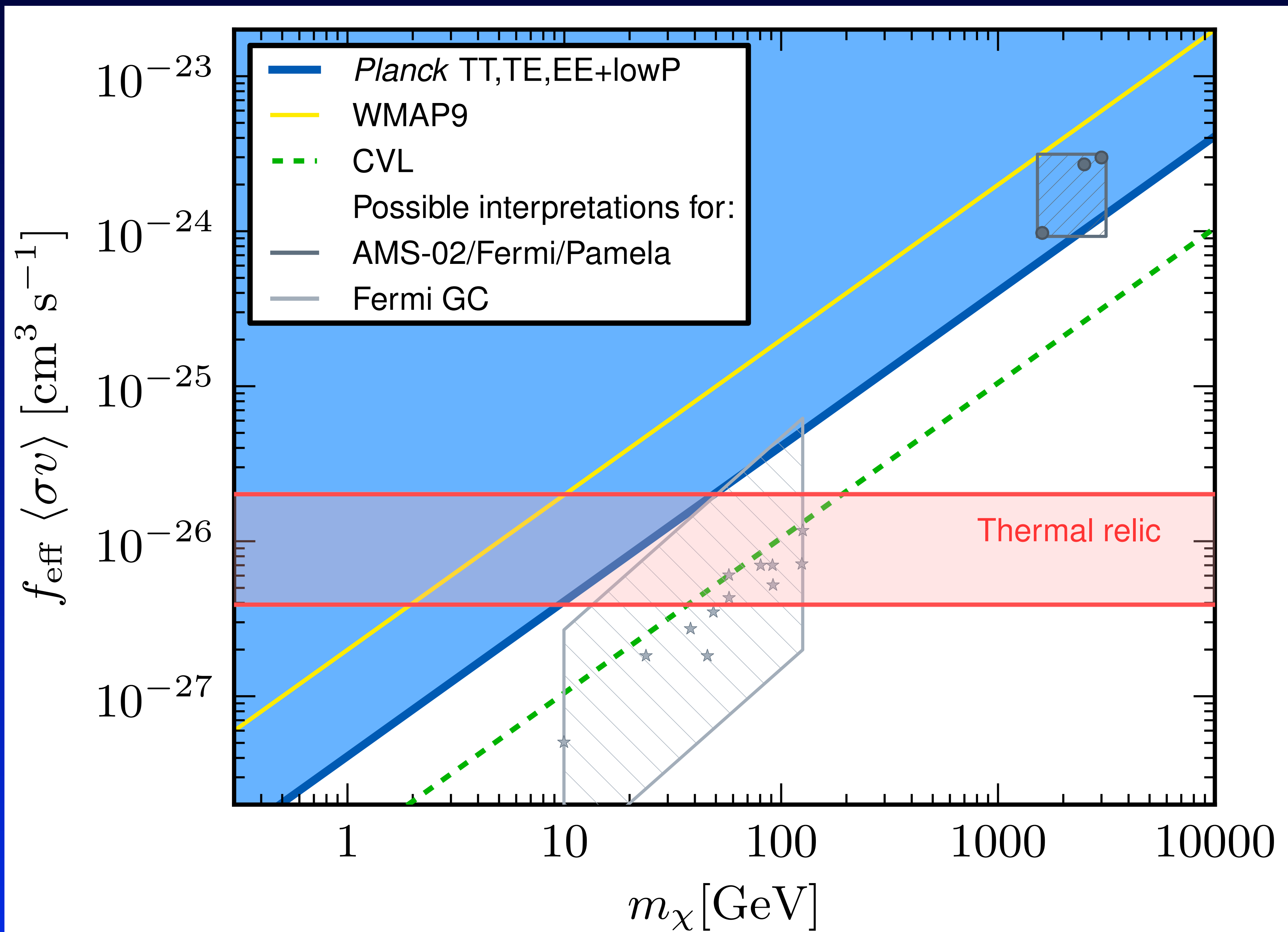


Planck Collaboration, paper XIII, 2015

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

Latest Planck limits on annihilation cross section

95% c.l.

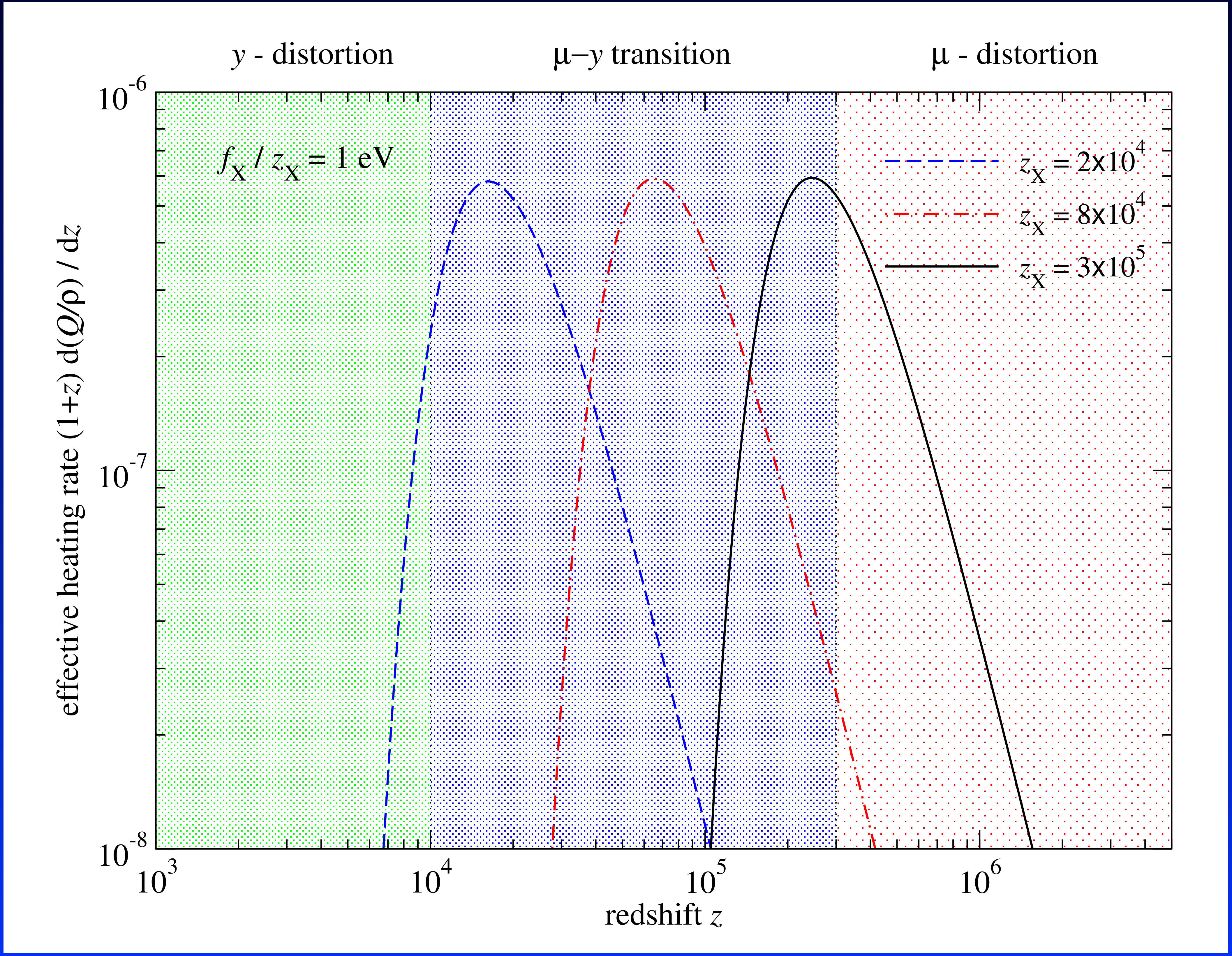


- AMS/Pamela models in tension
- but interpretation model-dependent
- Sommerfeld enhancement?
- clumping factors?
- annihilation channels?

Planck Collaboration, paper XIII, 2015

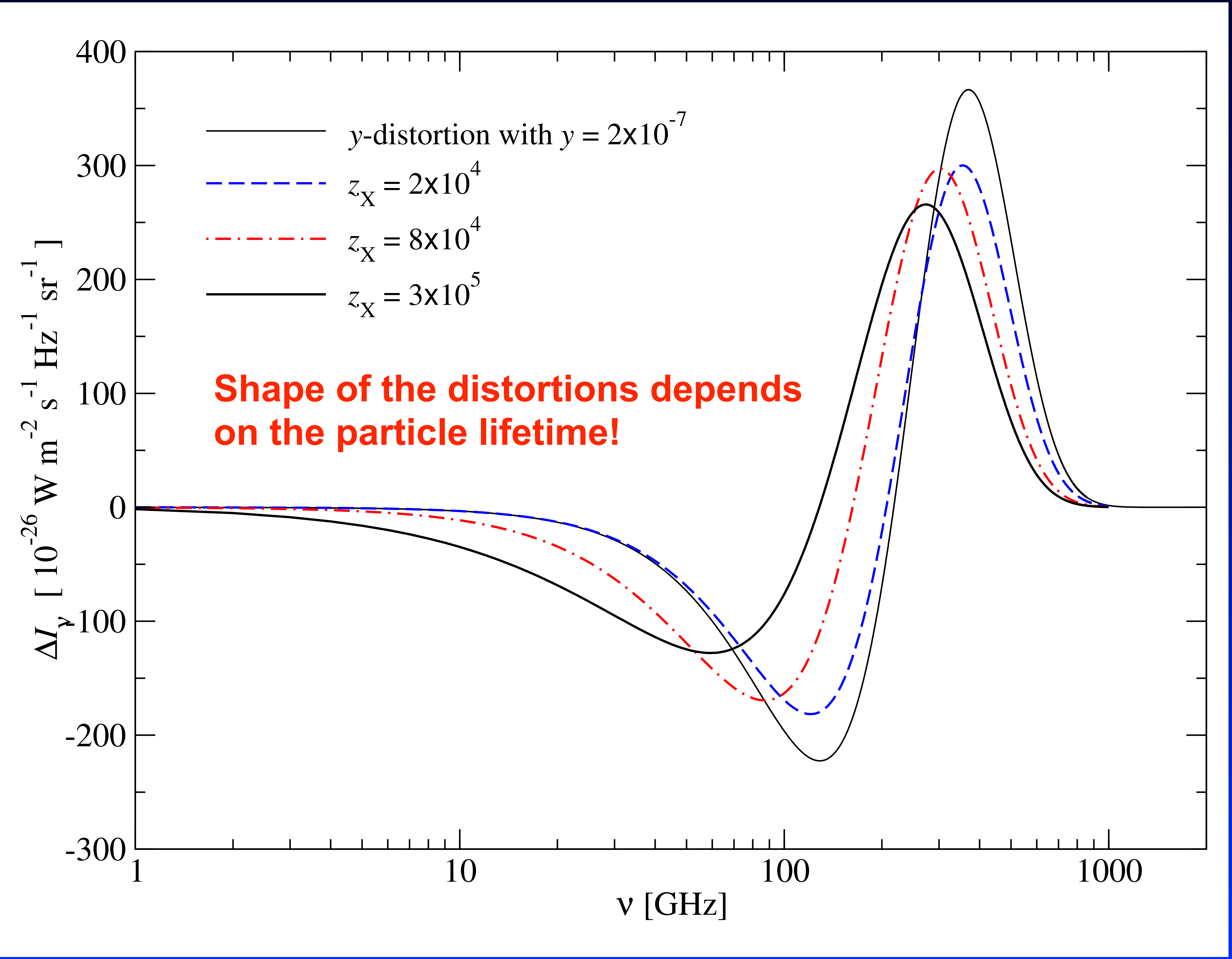
For current constraint only (weak) upper limits from distortion...

Decaying particle scenarios



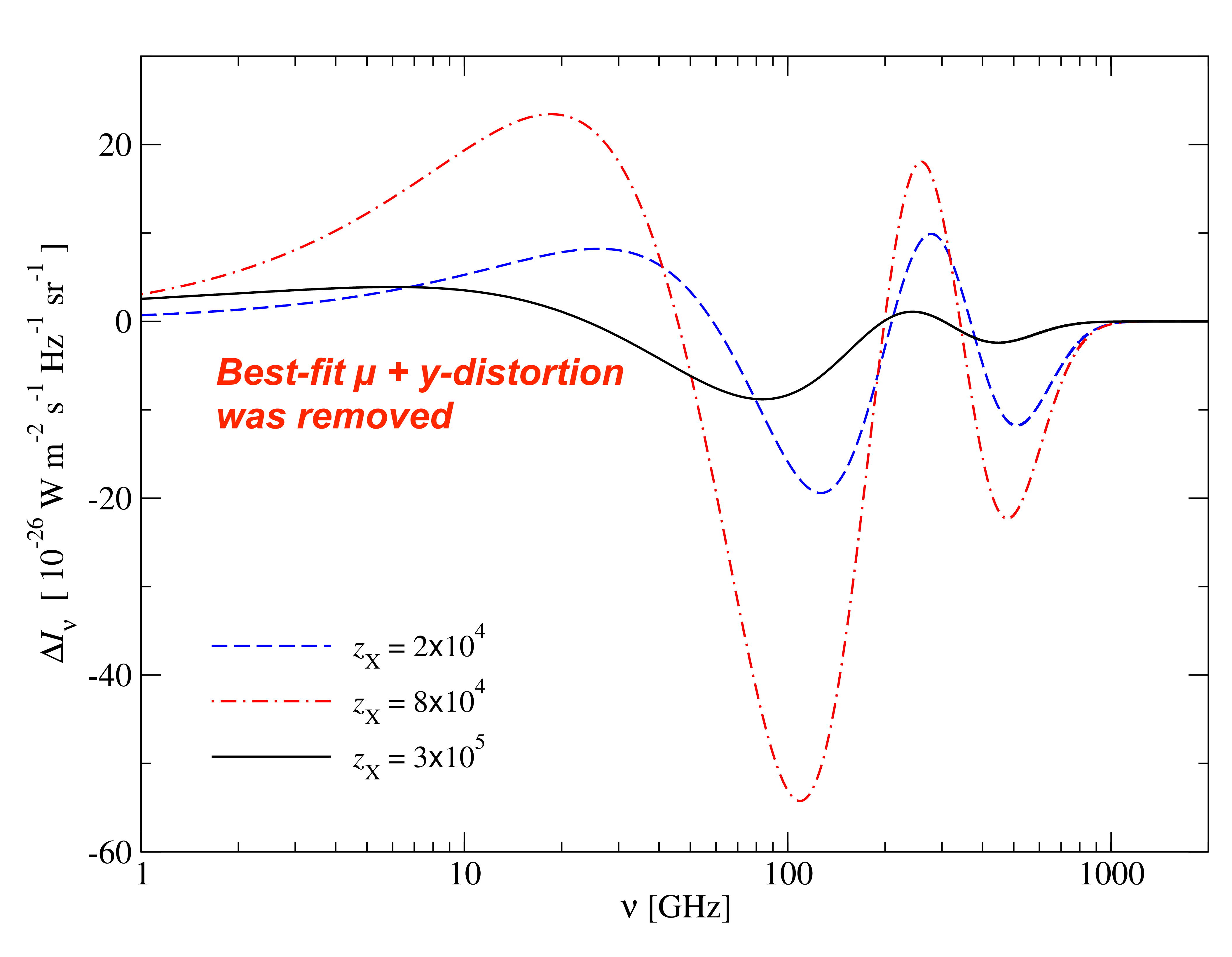
JC & Sunyaev, 2011, Arxiv:1109.6552
JC, 2013, Arxiv:1304.6120

Decaying particle scenarios



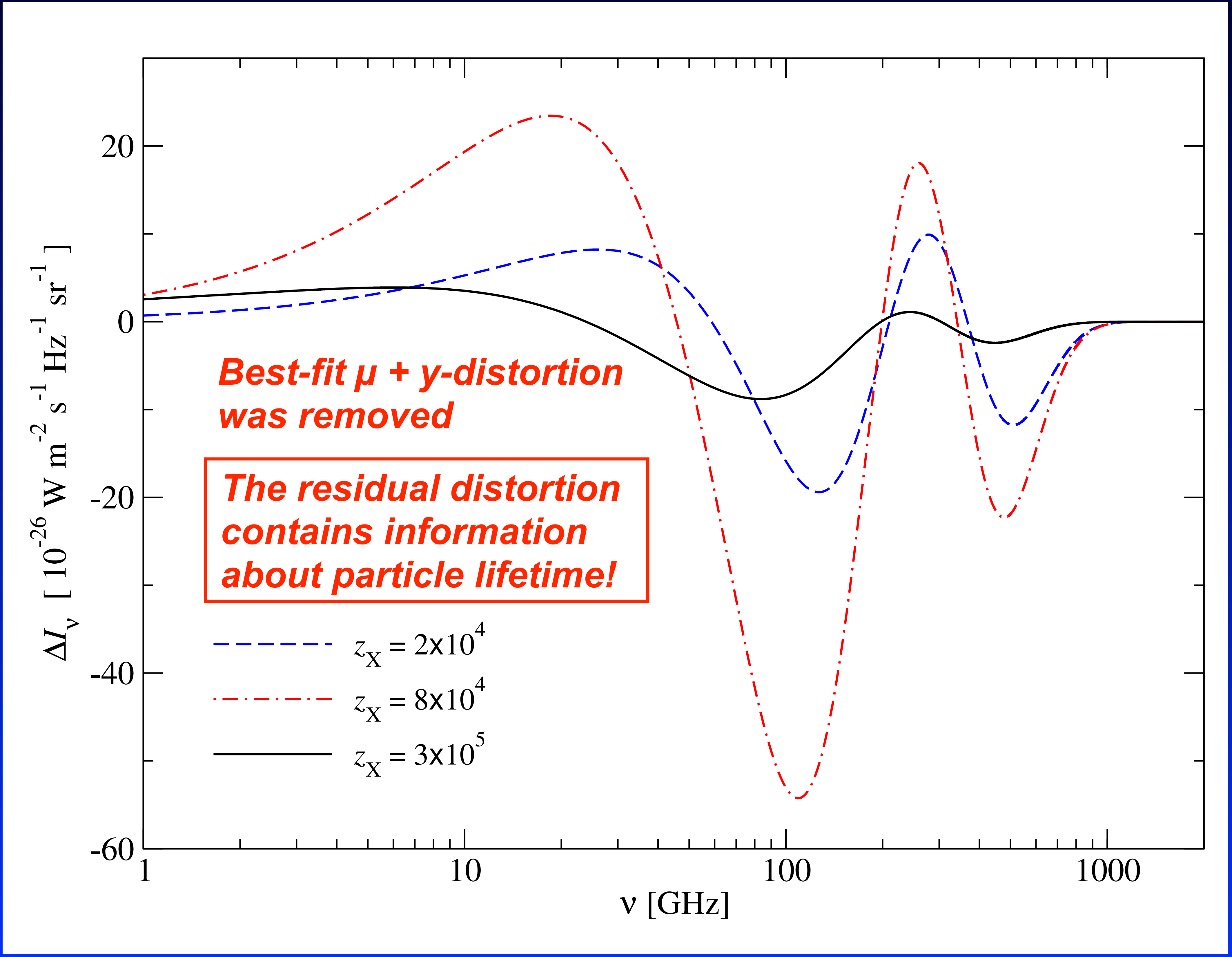
JC & Sunyaev, 2011, Arxiv:1109.6552
JC, 2013, Arxiv:1304.6120

Decaying particle scenarios (information in residual)



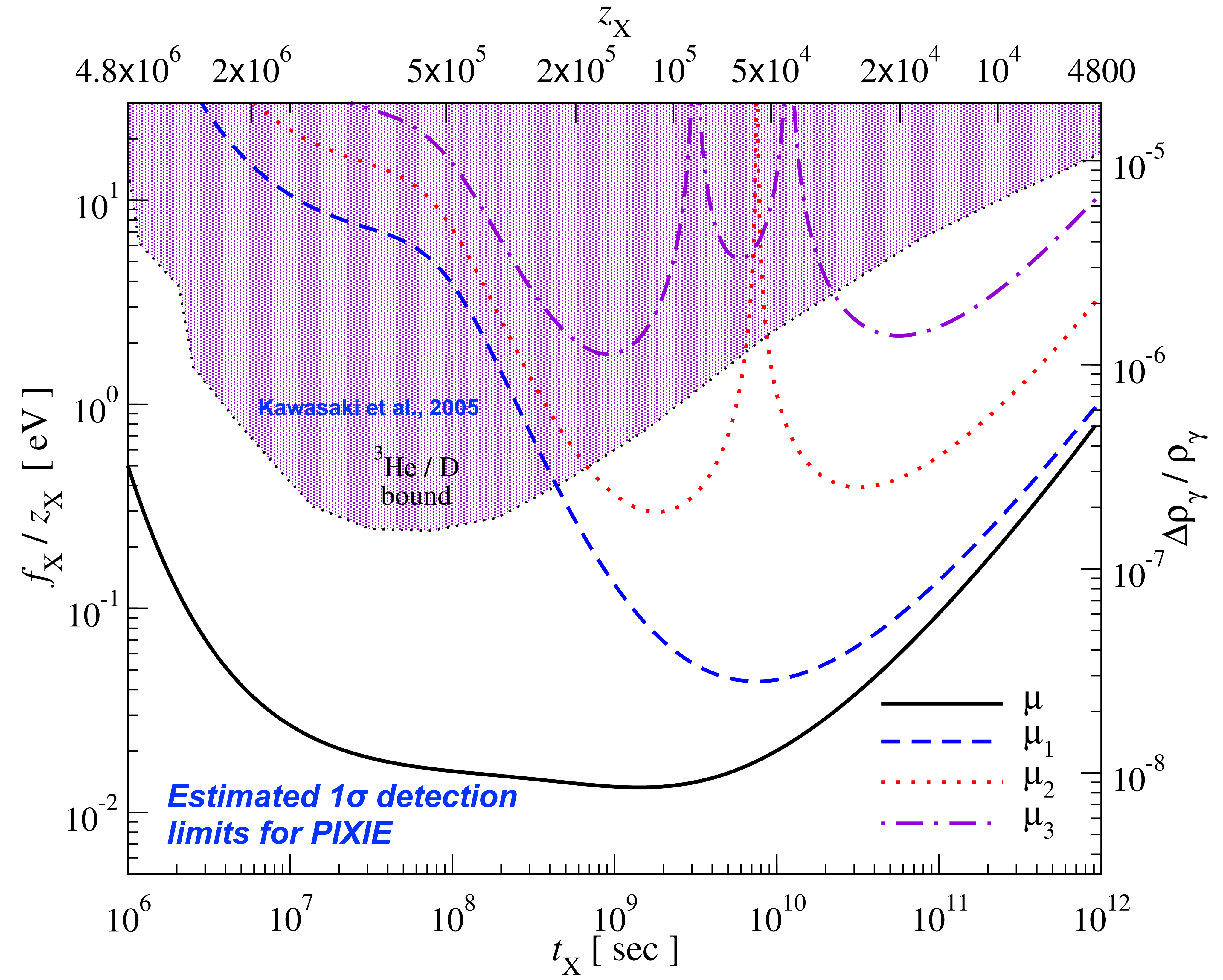
JC & Sunyaev, 2011, Arxiv:1109.6552
JC, 2013, Arxiv:1304.6120

Decaying particle scenarios (information in residual)



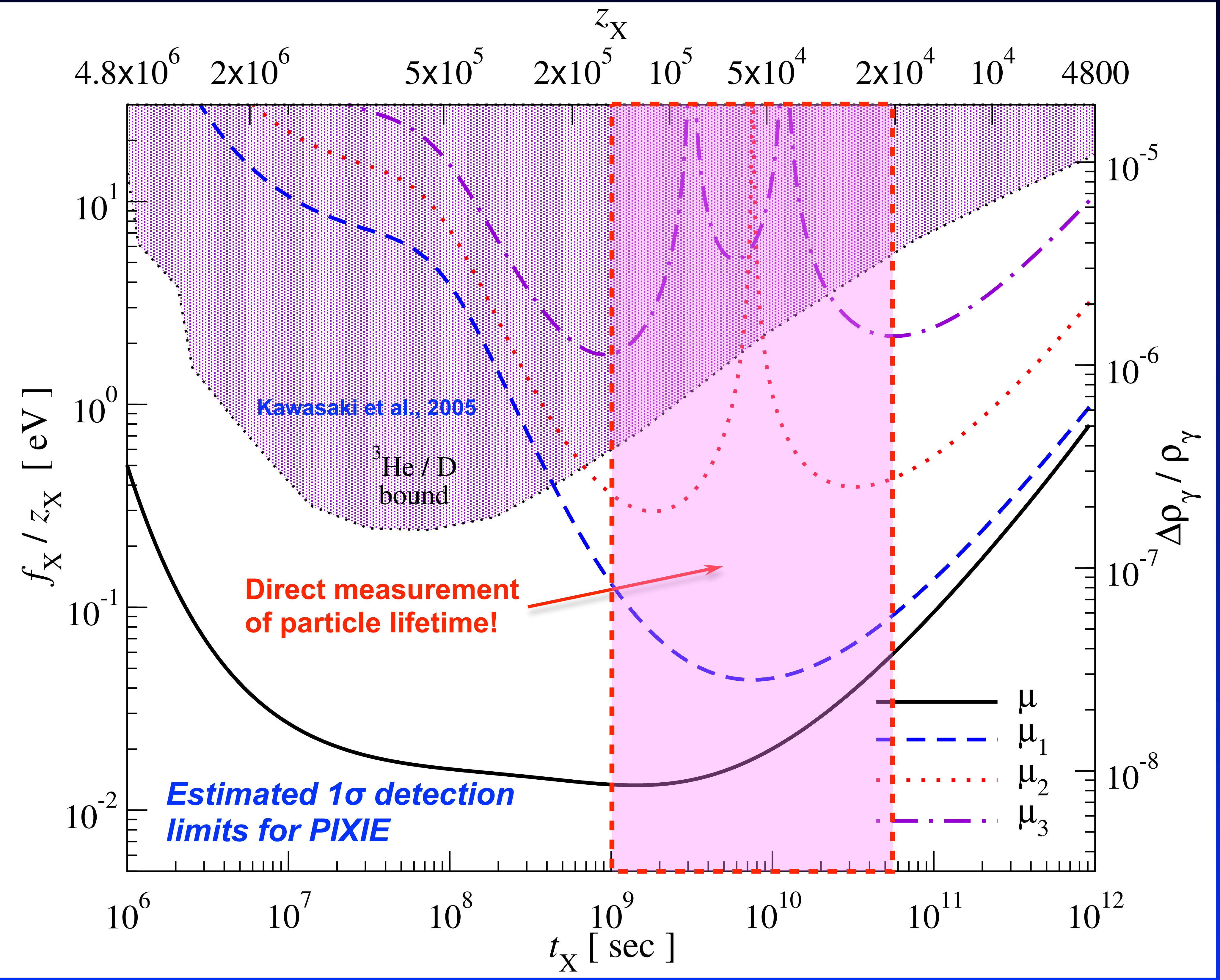
JC & Sunyaev, 2011, Arxiv:1109.6552
JC, 2013, Arxiv:1304.6120

Distortions could shed light on decaying (DM) particles!



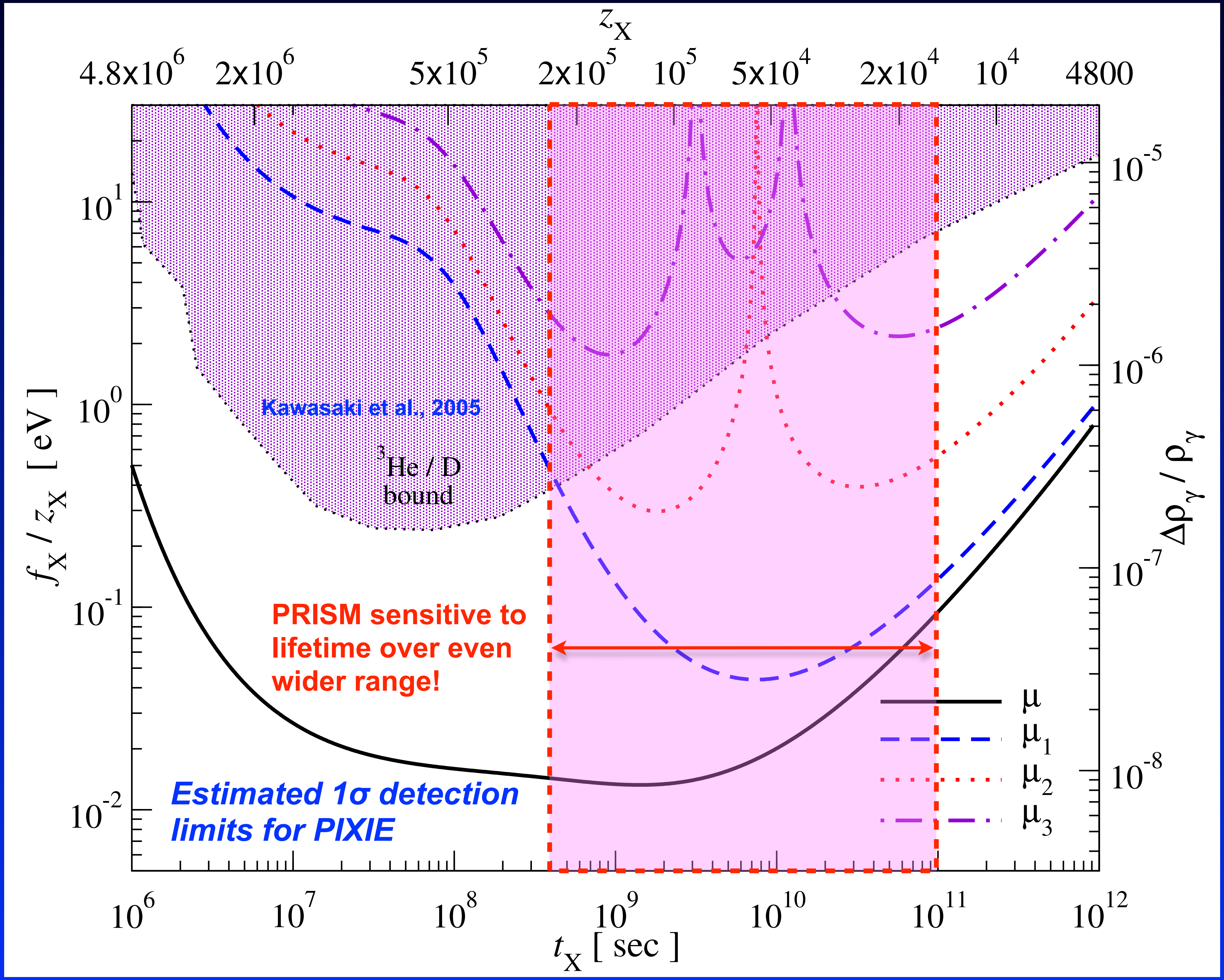
JC & Jeong, 2013

Distortions could shed light on decaying (DM) particles!



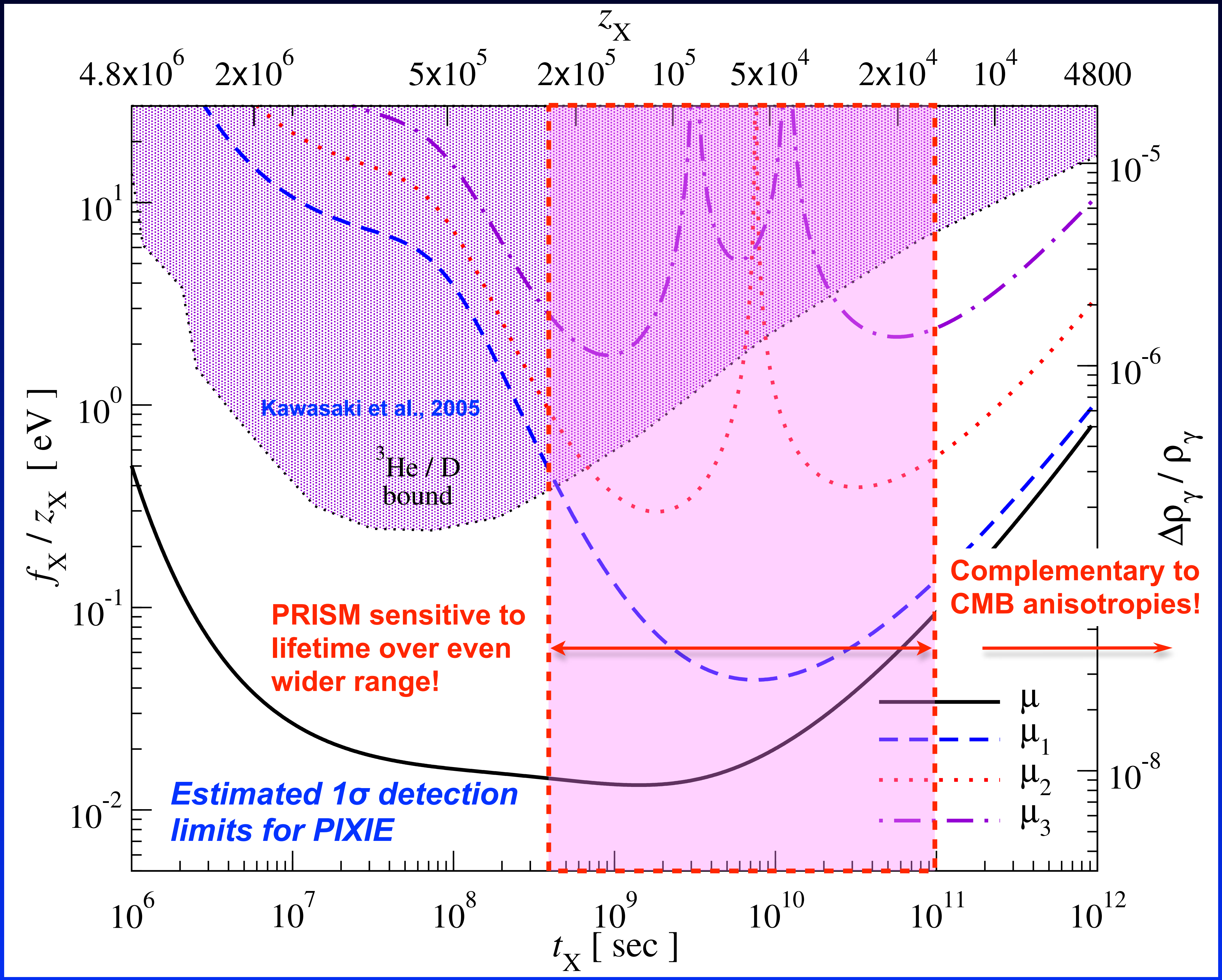
JC & Jeong, 2013

Distortions could shed light on decaying (DM) particles!



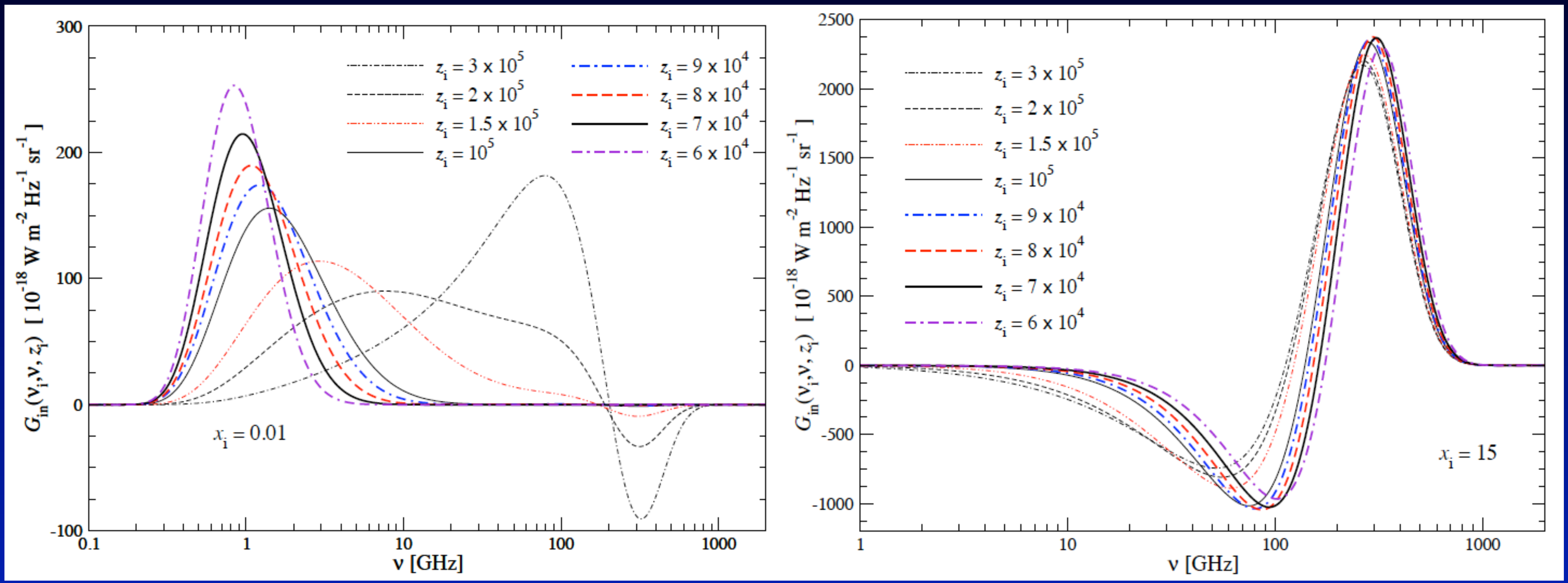
JC & Jeong, 2013

Distortions could shed light on decaying (DM) particles!



JC & Jeong, 2013

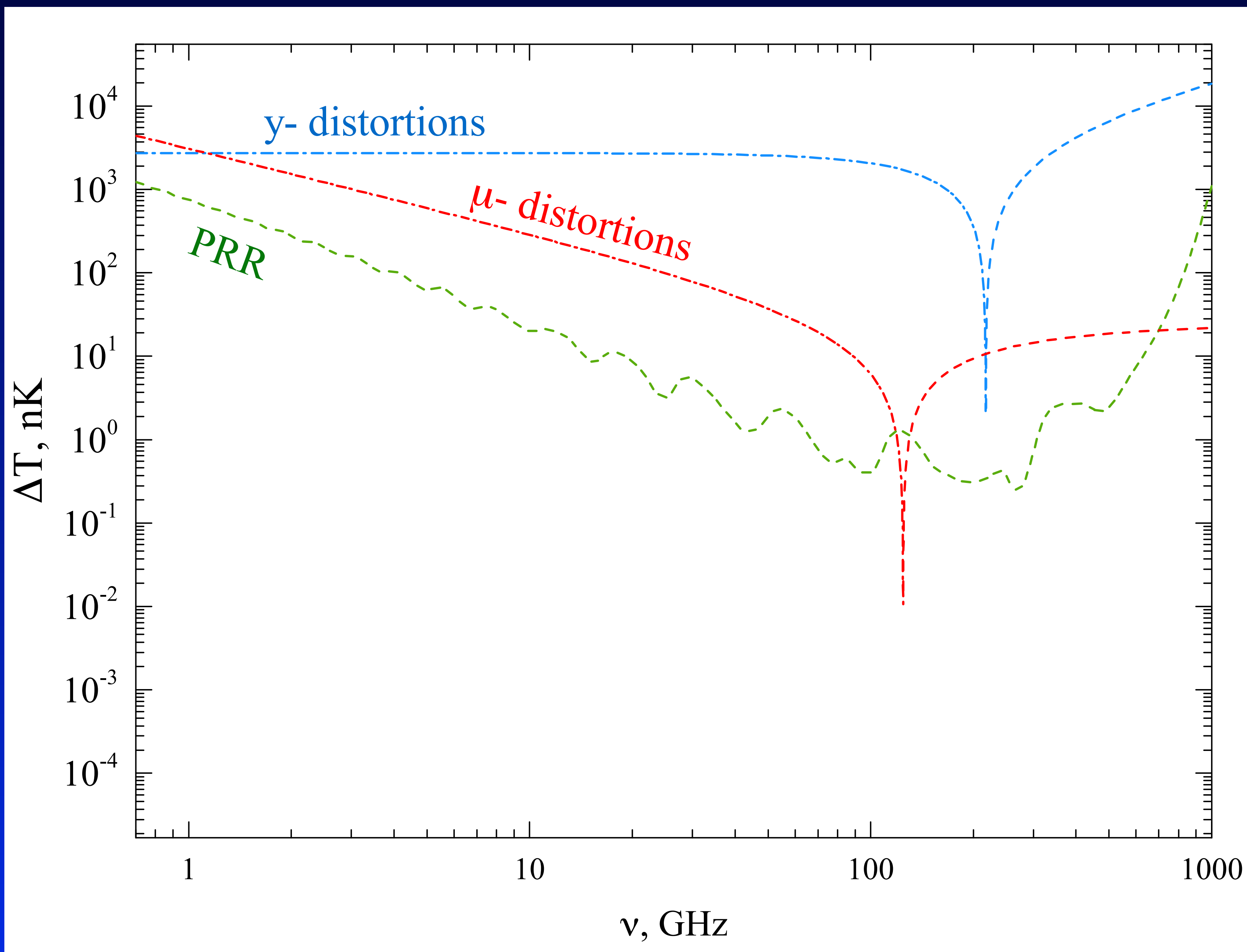
Green's function for photon injection



- Photon injection Green's function gives even richer phenomenology of distortion signals
- Depends on the details of the photon production process for redshifts z < few x 10^5
- difference between high and low frequency photon injection

JC 2015, ArXiv:1506.06582

Spectral distortions of the CMB dipole



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

- motion with respect to CMB blackbody monopole

⇒ *CMB temperature dipole*

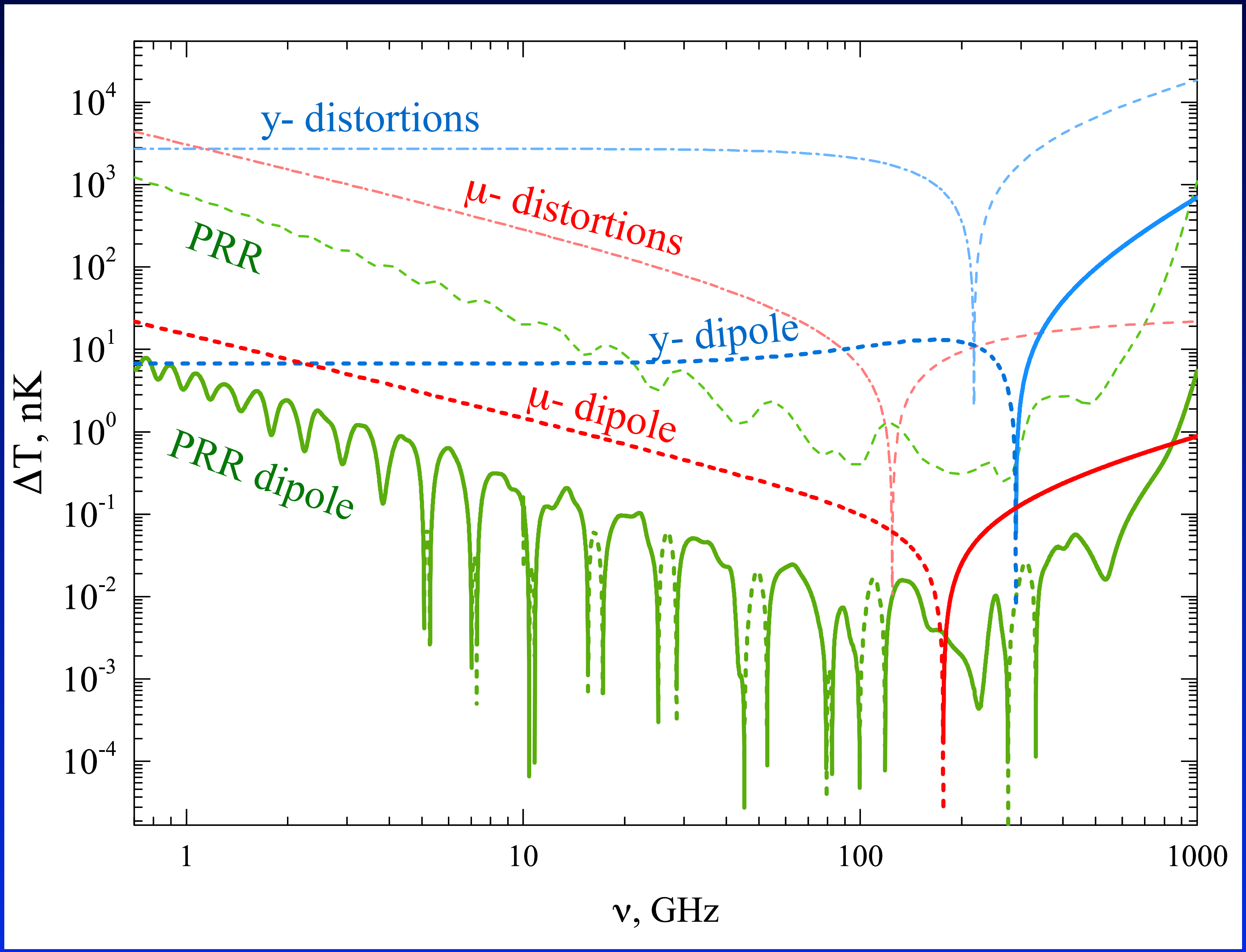
- including primordial distortions of the CMB

⇒ *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*

Spectral distortions of the CMB dipole



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

- motion with respect to CMB blackbody monopole

⇒ *CMB temperature dipole*

- including primordial distortions of the CMB

⇒ *CMB dipole is distorted*

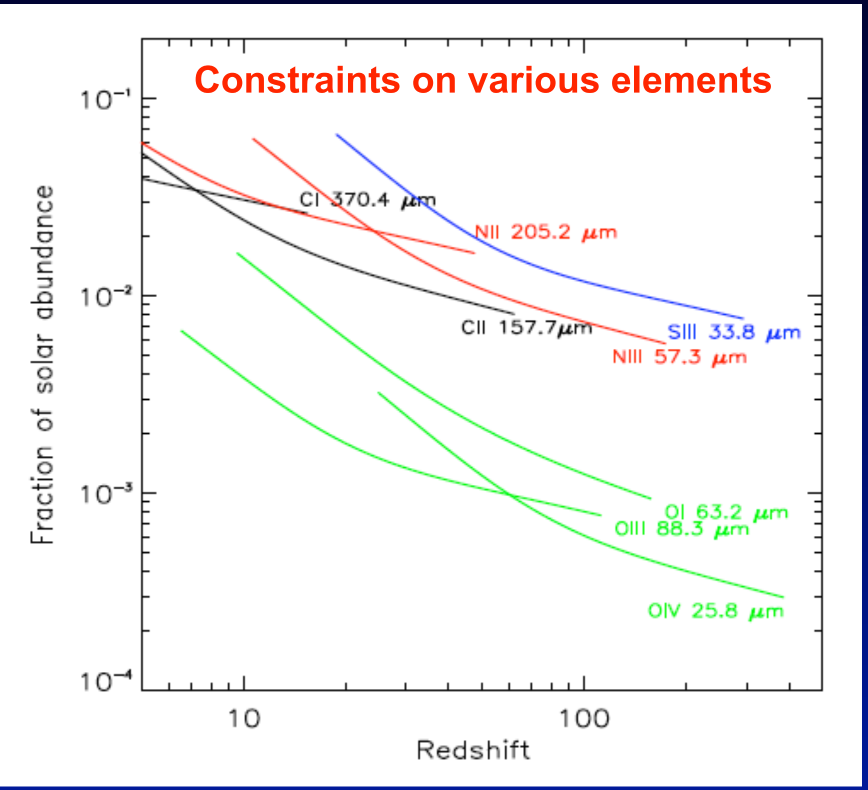
$$\eta_{\rm d}(\nu, \mathbf{n}) \approx -\nu \partial_\nu \eta_{\rm m}(\nu)\, \beta \cos\Theta$$

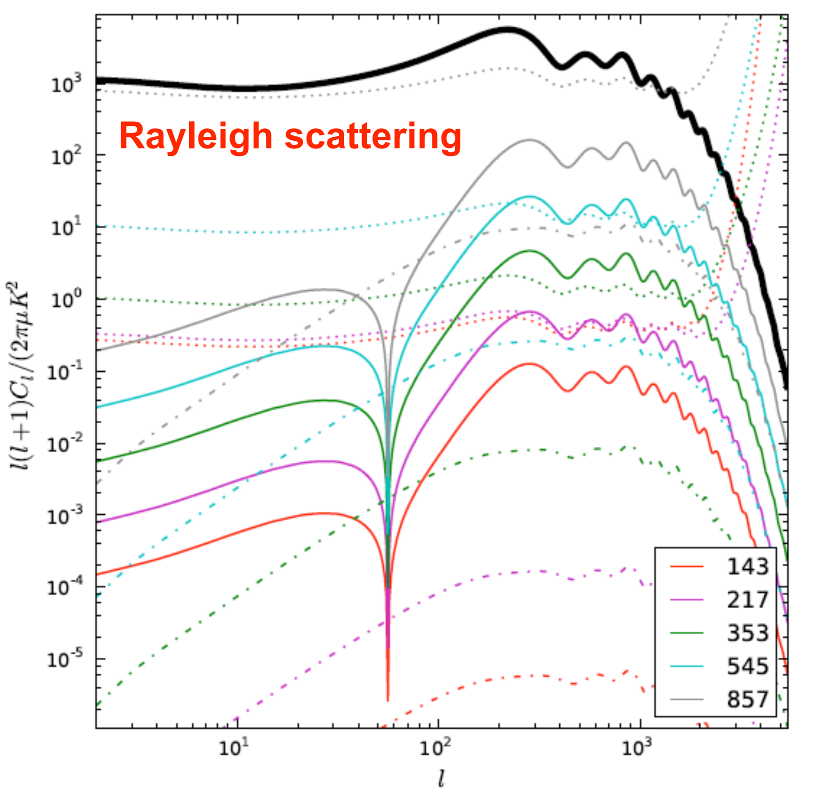
- spectrum of the dipole is sensitive to the *derivative* of the monopole spectrum
- anisotropy does not need *absolute* calibration but just *inter-channel* calibration
- *but* signal is ~1000 times smaller...
- *foregrounds* will also leak into the dipole in this way
- check of *systematics*

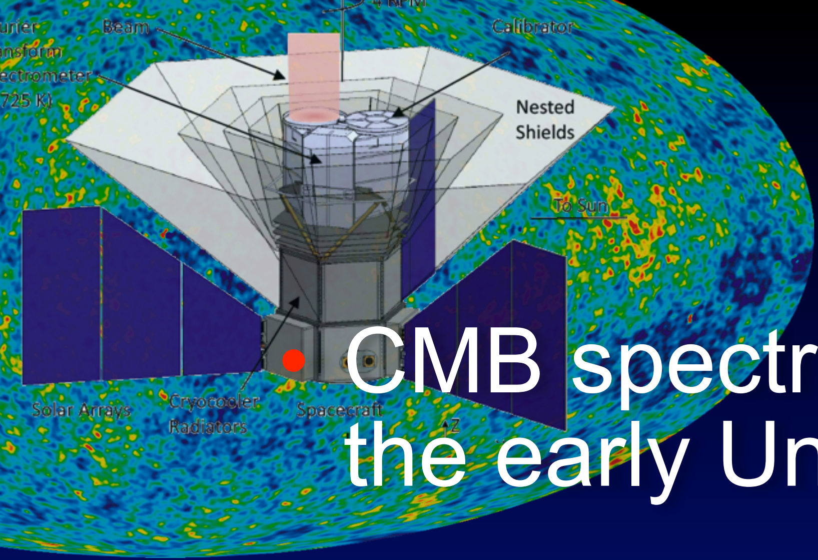
Other extremely interesting new signals

- 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!

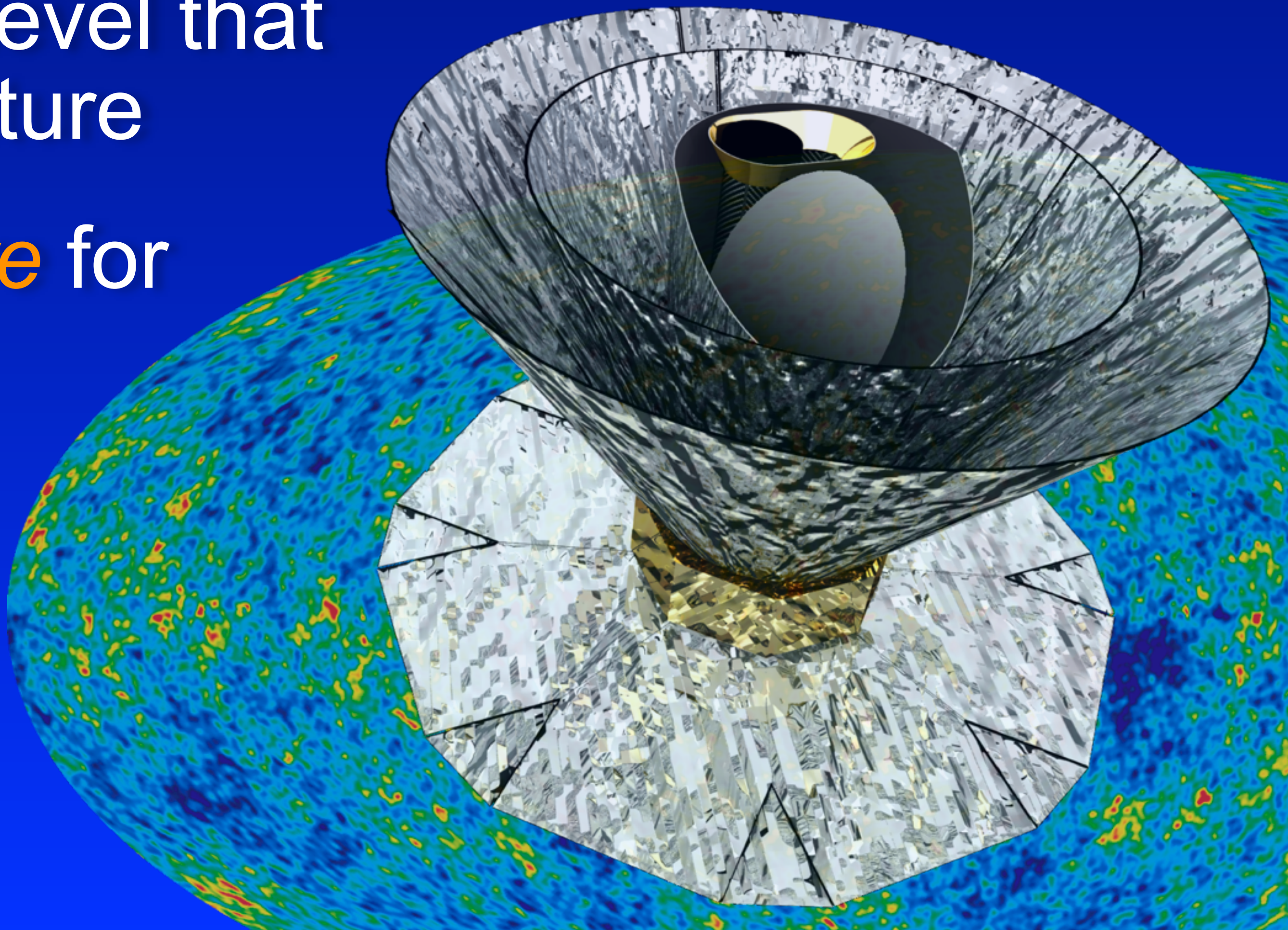


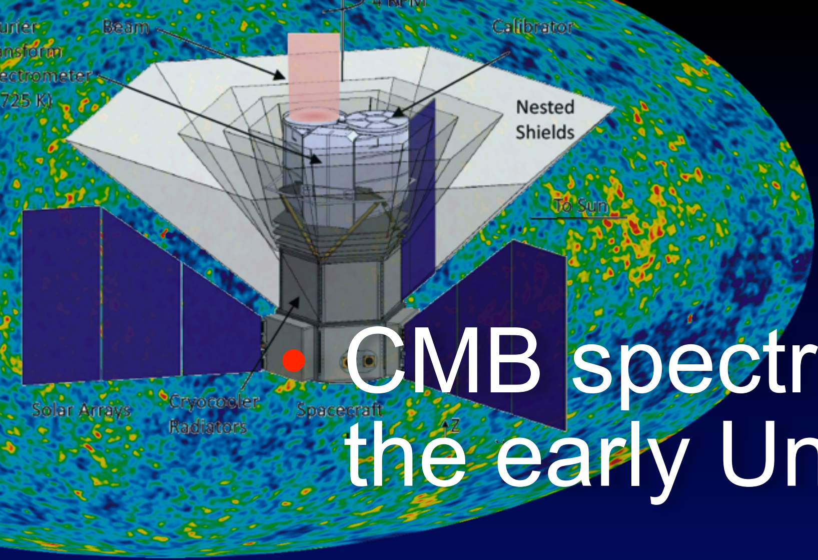




Conclusions

- CMB spectral distortions *will* open a *new window* to the early Universe
- new probe of the *inflation epoch* and *particle physics*
- *complementary* and *independent* source of information *not* just confirmation
- in *standard cosmology* several processes lead to *early energy release* at a level that will be detectable in the future
- extremely interesting *future* for CMB-based science!

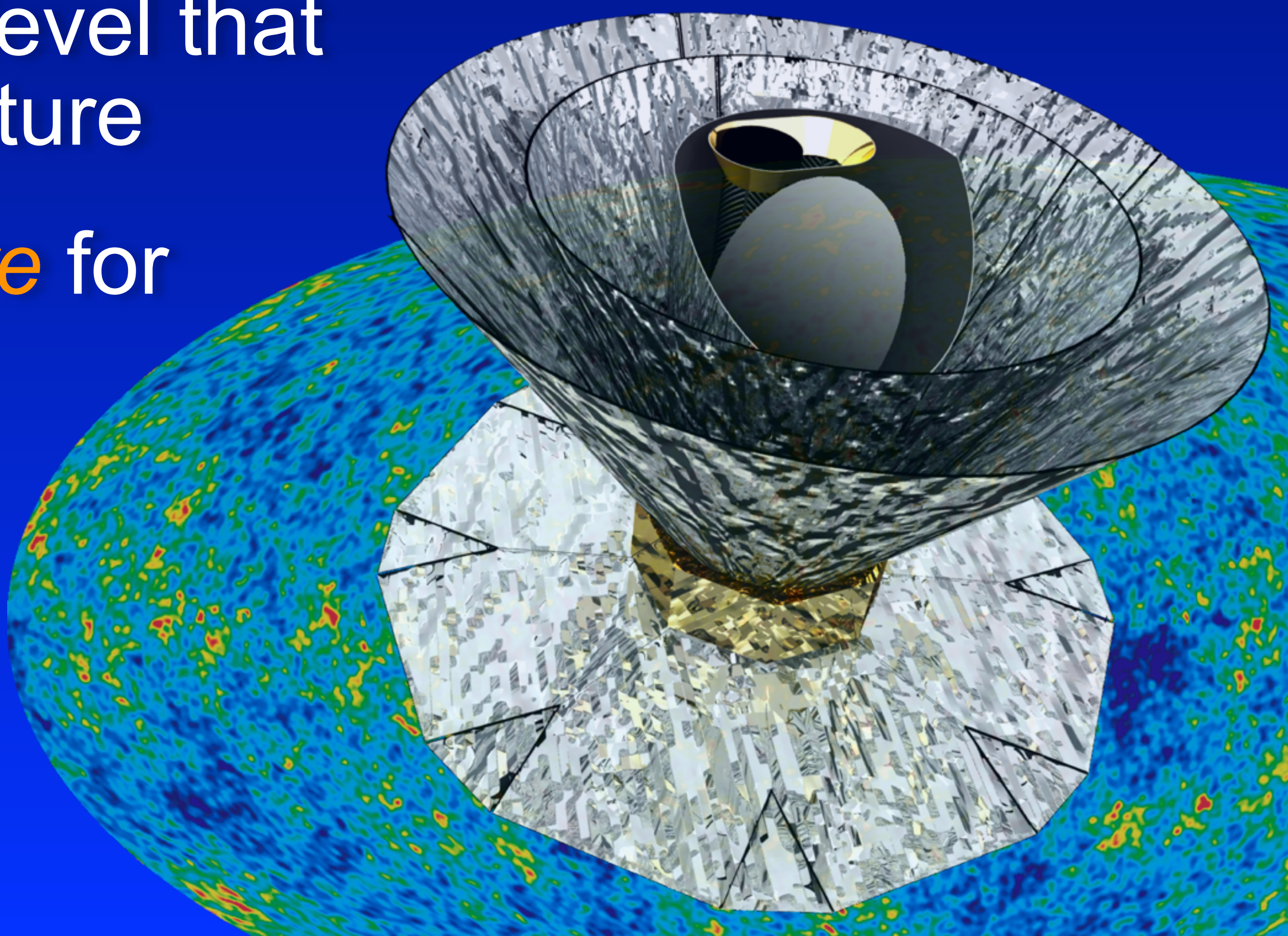


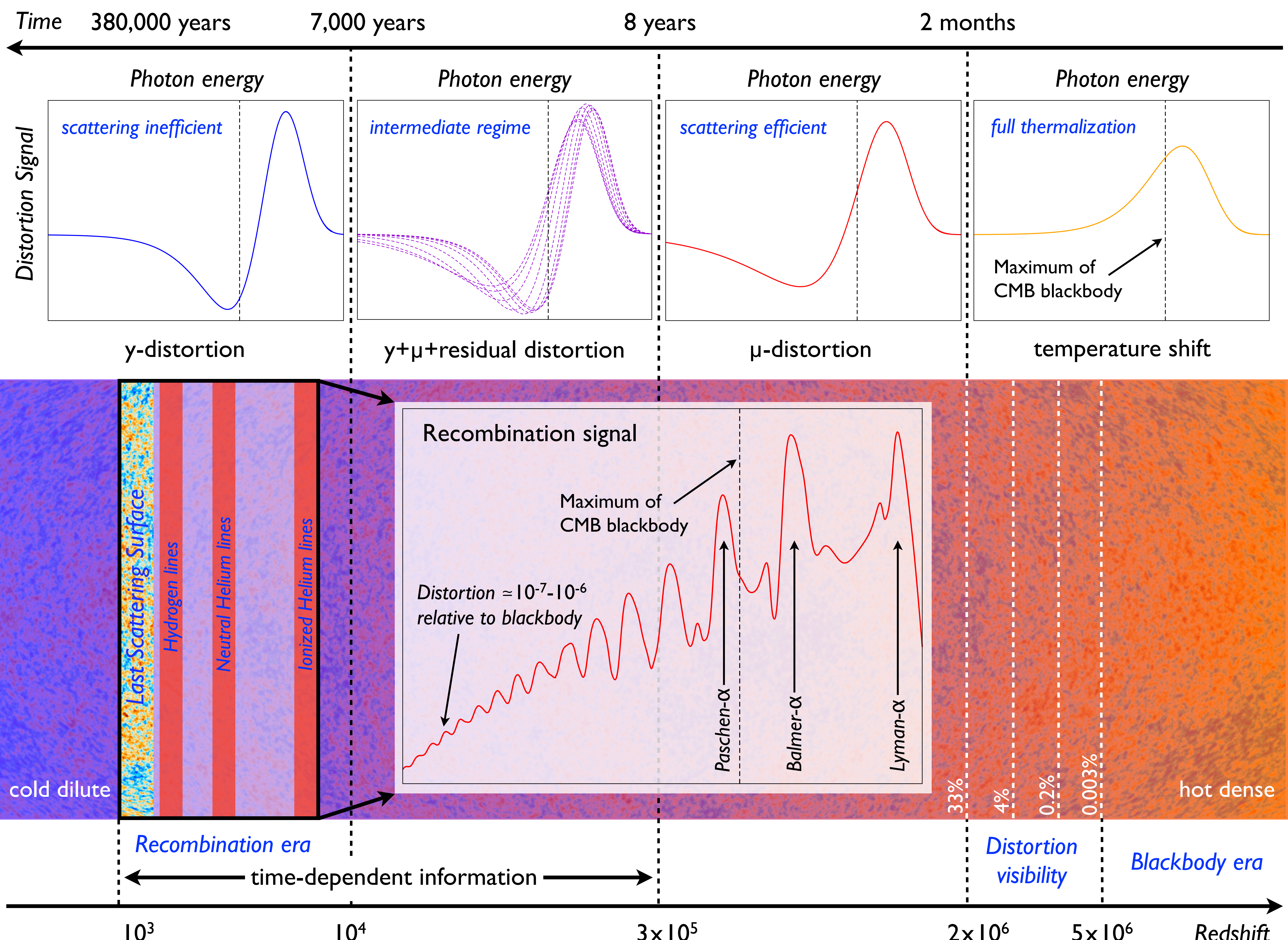


Conclusions

- CMB spectral distortions *will* open a *new window* to the early Universe
- new probe of the *inflation epoch* and *particle physics*
- *complementary* and *independent* source of information *not* just confirmation
- in *standard cosmology* several processes lead to *early energy release* at a level that will be detectable in the future
- extremely interesting *future* for CMB-based science!

We should make use of all this information!





Silk & Chluba, Science, 2014