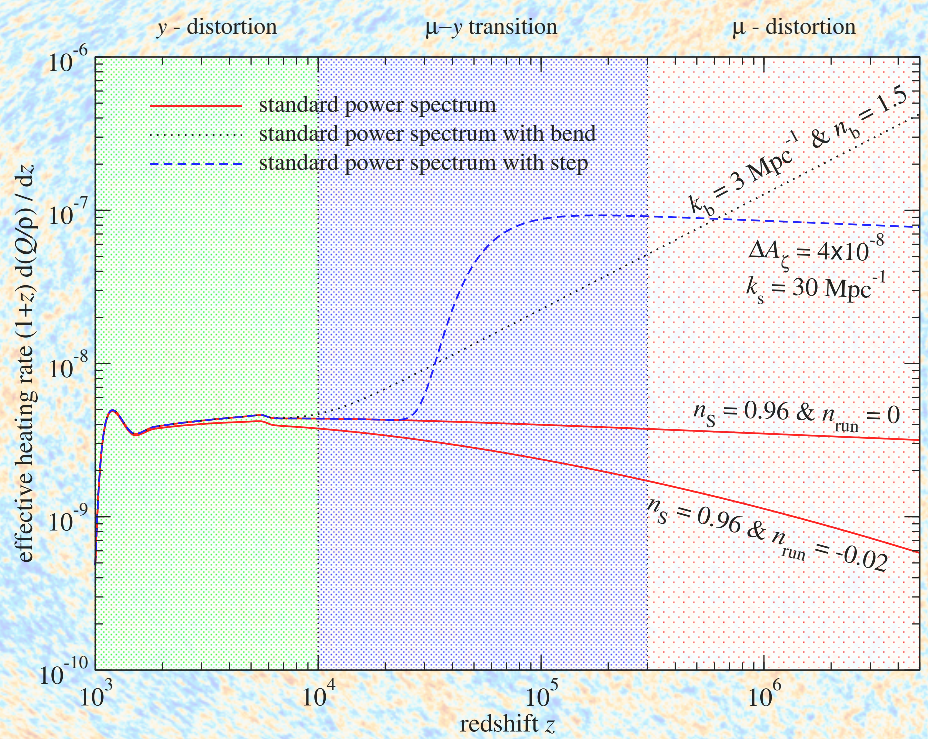
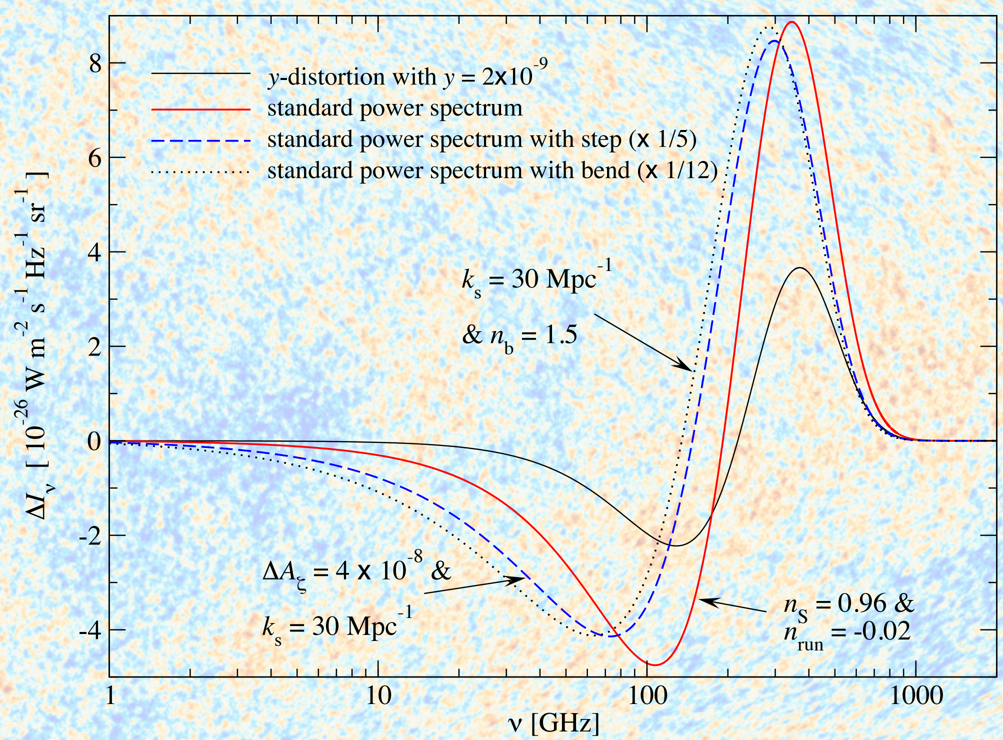
# CMB Spectral Distortions as New Probe of Early-Universe Physics




JOHNS HOPKINS UNIVERSITY

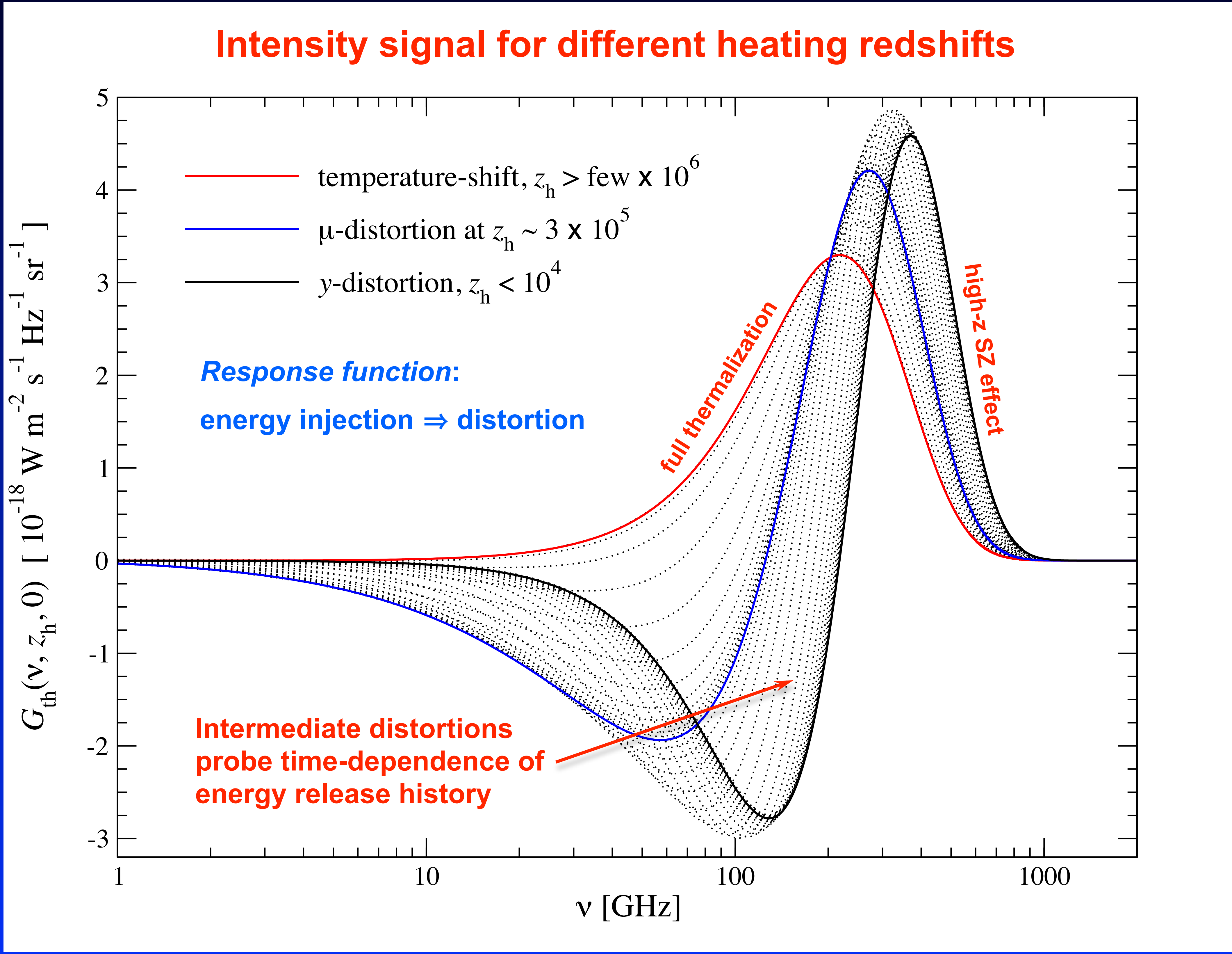

## Jens Chluba


### Lecture II: *Science with CMB Spectral Distortions*

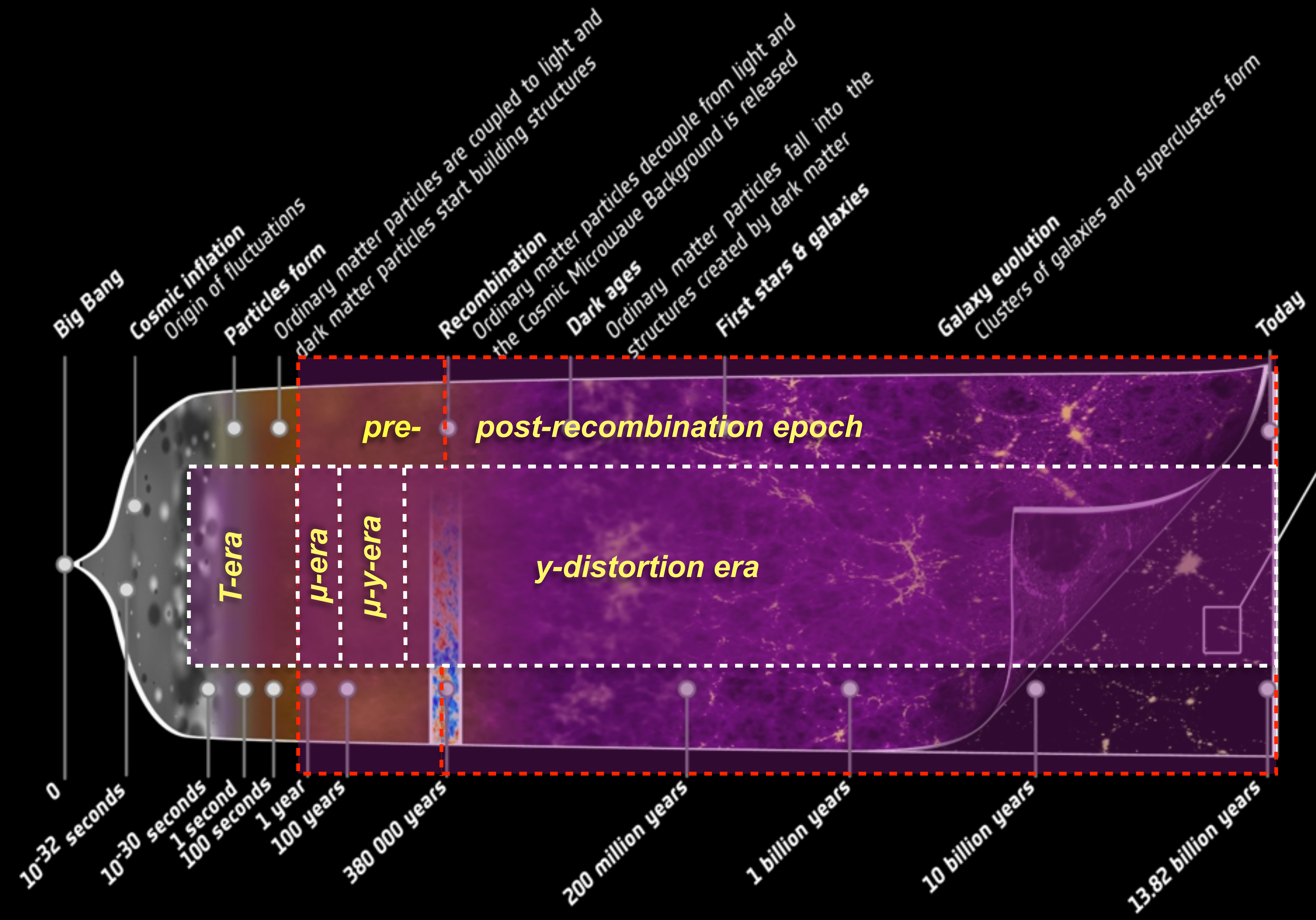
Les Houches, August 2nd, 2013


CITA ICAT
Canadian Institute for Theoretical Astrophysics
L'institut canadien d'astrophysique theorique

# What does the spectrum look like after energy injection?




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



Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
pre-
post-recombination epoch
T-era
μ-era
μ-y-era
y-distortion 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

# Main Goals for this Lecture

- Convince you that future CMB distortions science will be *extremely* exciting!
- Provide an overview for different sources of early-energy release
- Show why the CMB spectrum is a *complementary* probe of inflation physics and particle physics

# Physical mechanisms that lead to spectral distortions

- *Cooling by adiabatically expanding ordinary matter*: $T_\gamma \sim (1+z) \leftrightarrow T_m \sim (1+z)^2$
  **(JC, 2005; JC & Sunyaev 2011; Khatri, Sunyaev & JC, 2011)**
  - continuous *cooling* of photons until redshift $z \sim 150$ via Compton scattering
  - due to huge heat capacity of photon field distortion very small ( $\Delta\rho/\rho \sim 10^{-10}$-$10^{-9}$ )
- Heating by *decaying* or *annihilating* relic particles
  - How is energy transferred to the medium?
  - lifetimes, decay channels, neutrino fraction, (at low redshifts: environments), ...
- *Evaporation of primordial black holes & superconducting strings*
  **(Carr et al. 2010; Ostriker & Thompson, 1987; Tashiro et al. 2012)**
  - rather fast, quasi-instantaneous but also extended energy release
- *Dissipation of primordial acoustic modes & magnetic fields*
  **(Sunyaev & Zeldovich, 1970; Daly 1991; Hu et al. 1994; Jedamzik et al. 2000)**
- *Cosmological recombination*

„high“ redshifts ↑ *pre-recombination epoch*

---

„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 (Heating of medium by X-Rays, Cosmic Rays, etc)

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*Standard sources of distortions*

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*too little time...*

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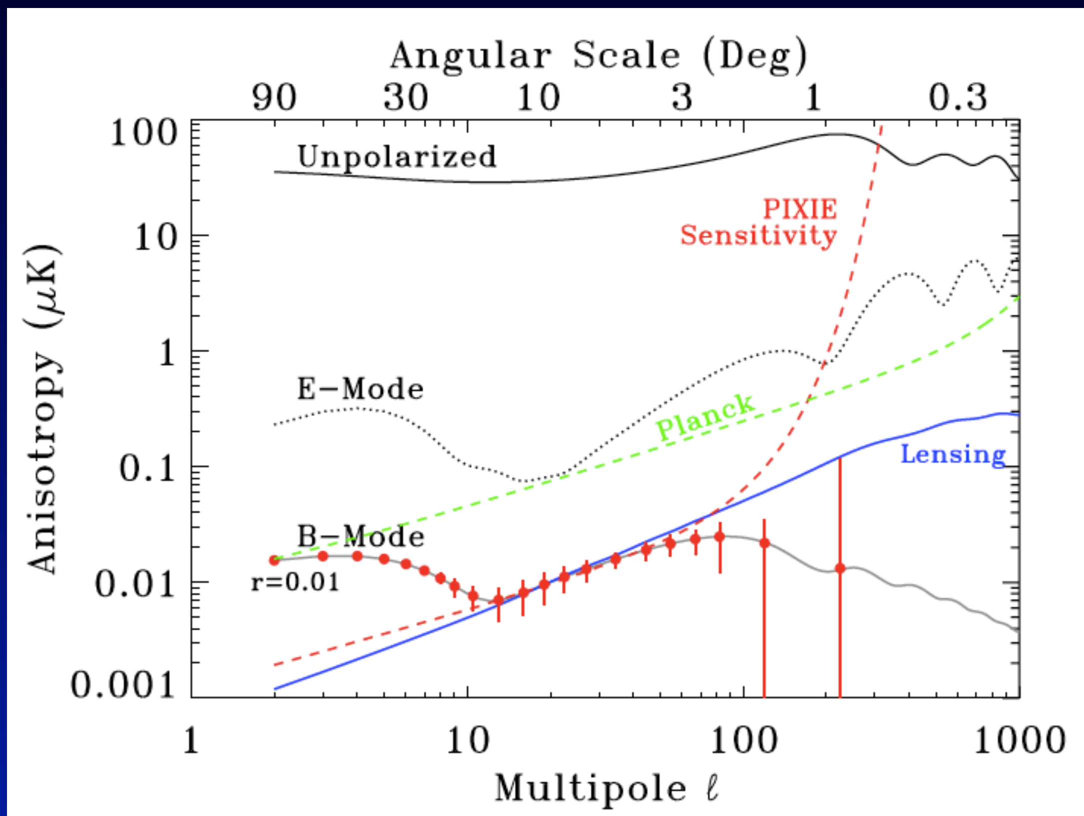
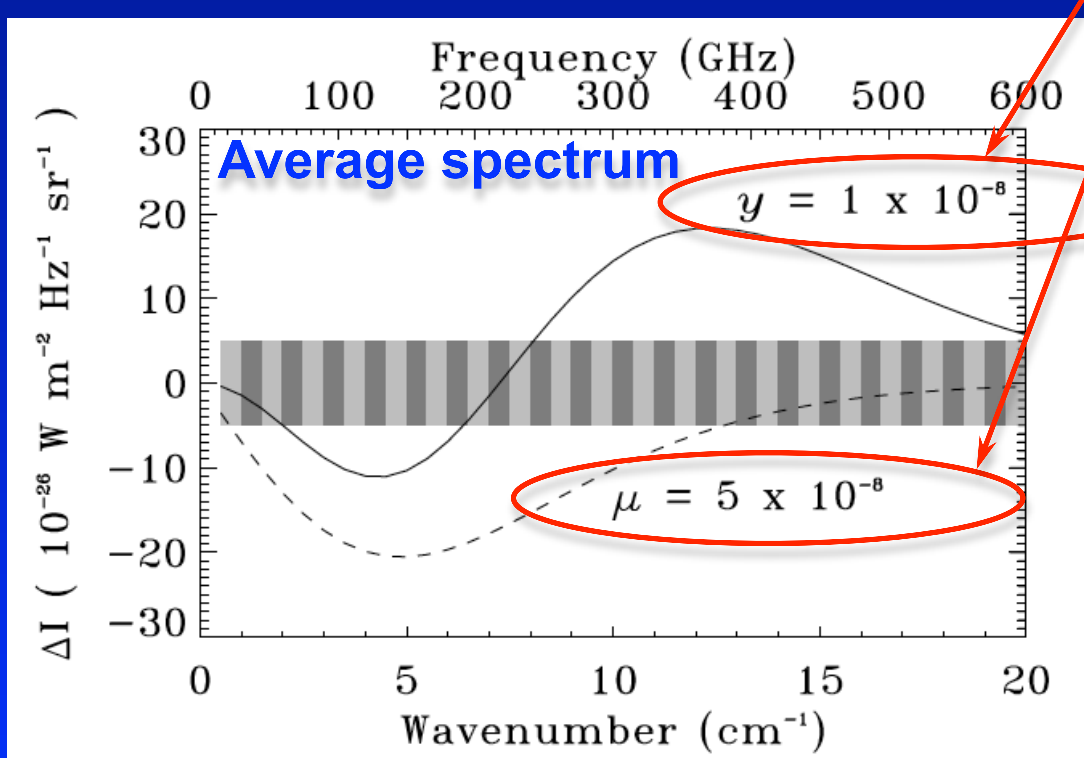
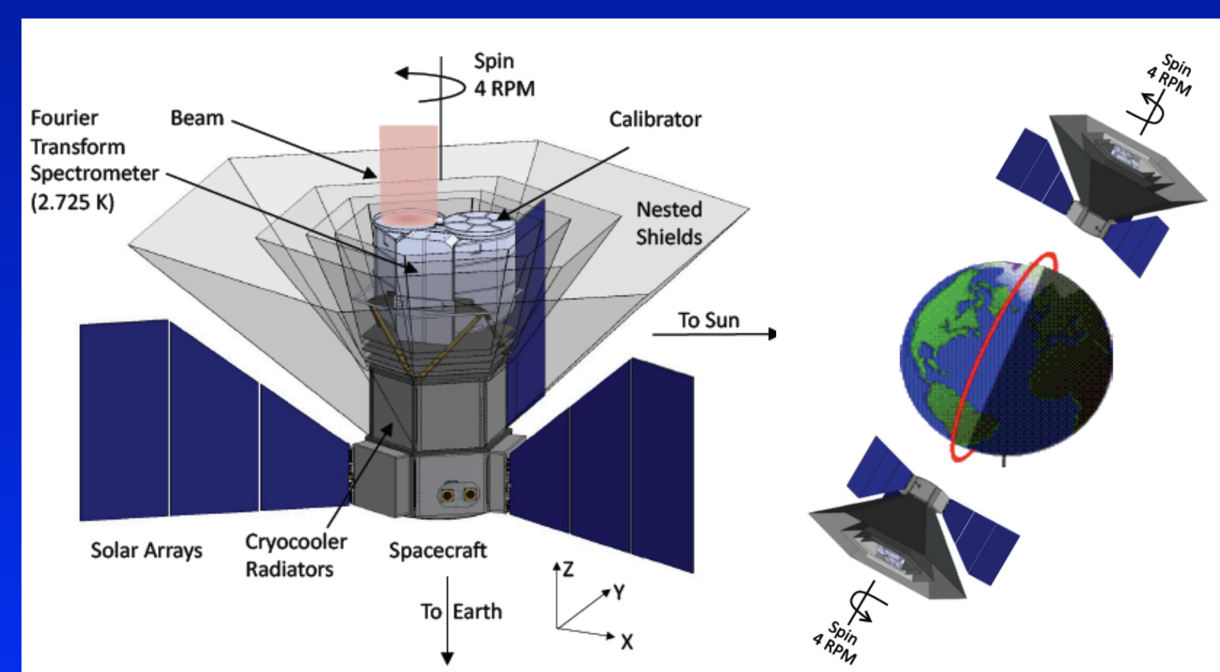
# PIXIE: Primordial Inflation Explorer

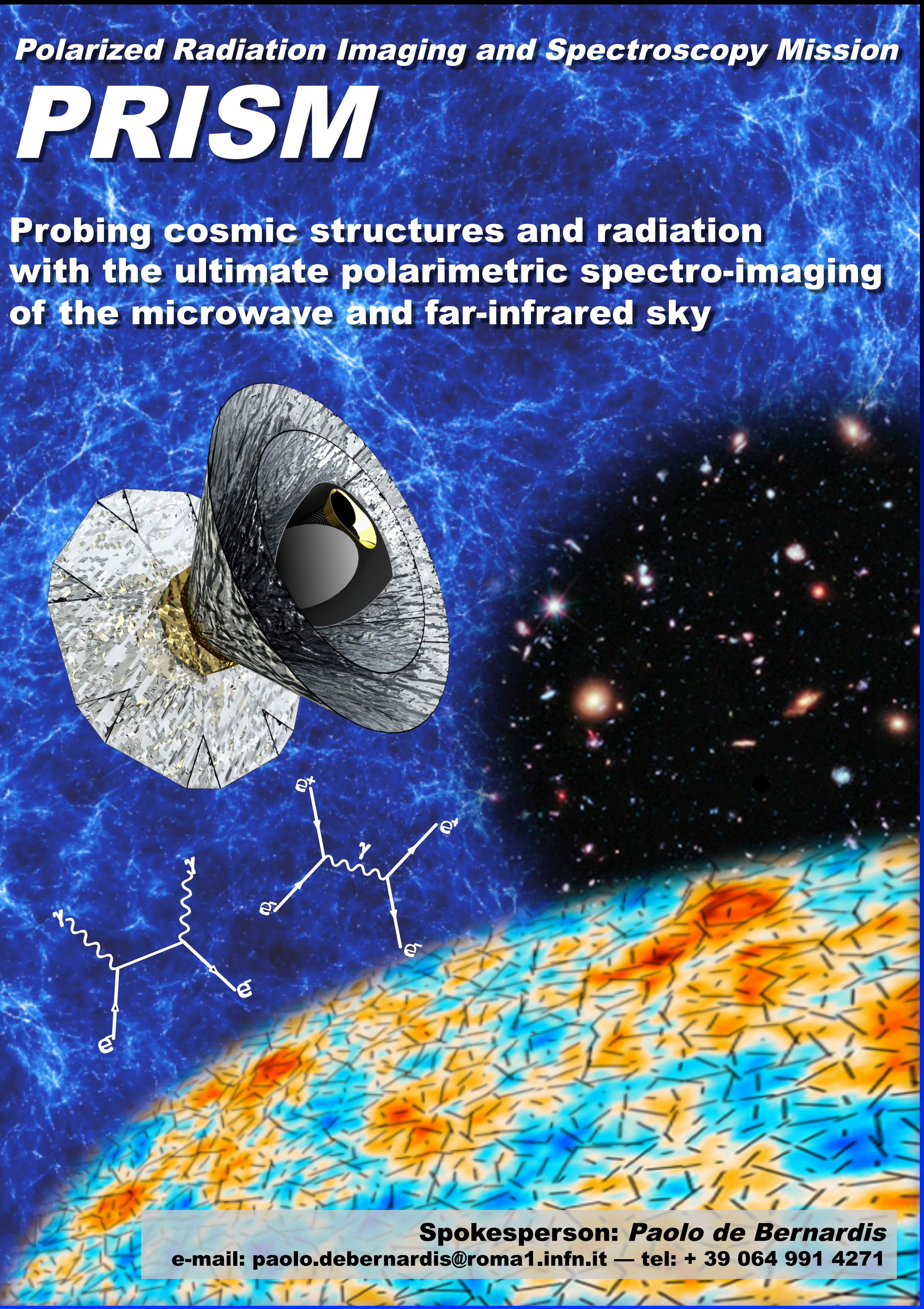



- 400 spectral channel in the frequency range 30 GHz and 6THz (Δv ~ 15GHz)
- about 1000 (!!!) times more sensitive than COBE/FIRAS
- B-mode polarization from inflation ($r \approx 10^{-3}$)
- improved limits on $\mu$ and $y$
- was proposed 2011 as NASA EX mission (i.e. cost ~ 200 M$)




**Kogut et al, JCAP, 2011, arXiv:1105.2044**




Instruments:

- L-class ESA mission
- White paper, May 24th, 2013
- Imager:
  - polarization sensitive
  - 3.5m telescope [arcmin resolution at highest frequencies]
  - 30GHz-6THz [30 broad ($\Delta\nu/\nu$~25%) and 300 narrow ($\Delta\nu/\nu$~2.5%) bands]
- Spectrometer:
  - FTS similar to PIXIE
  - 30GHz-6THz ($\Delta\nu$~15 & 0.5 GHz)

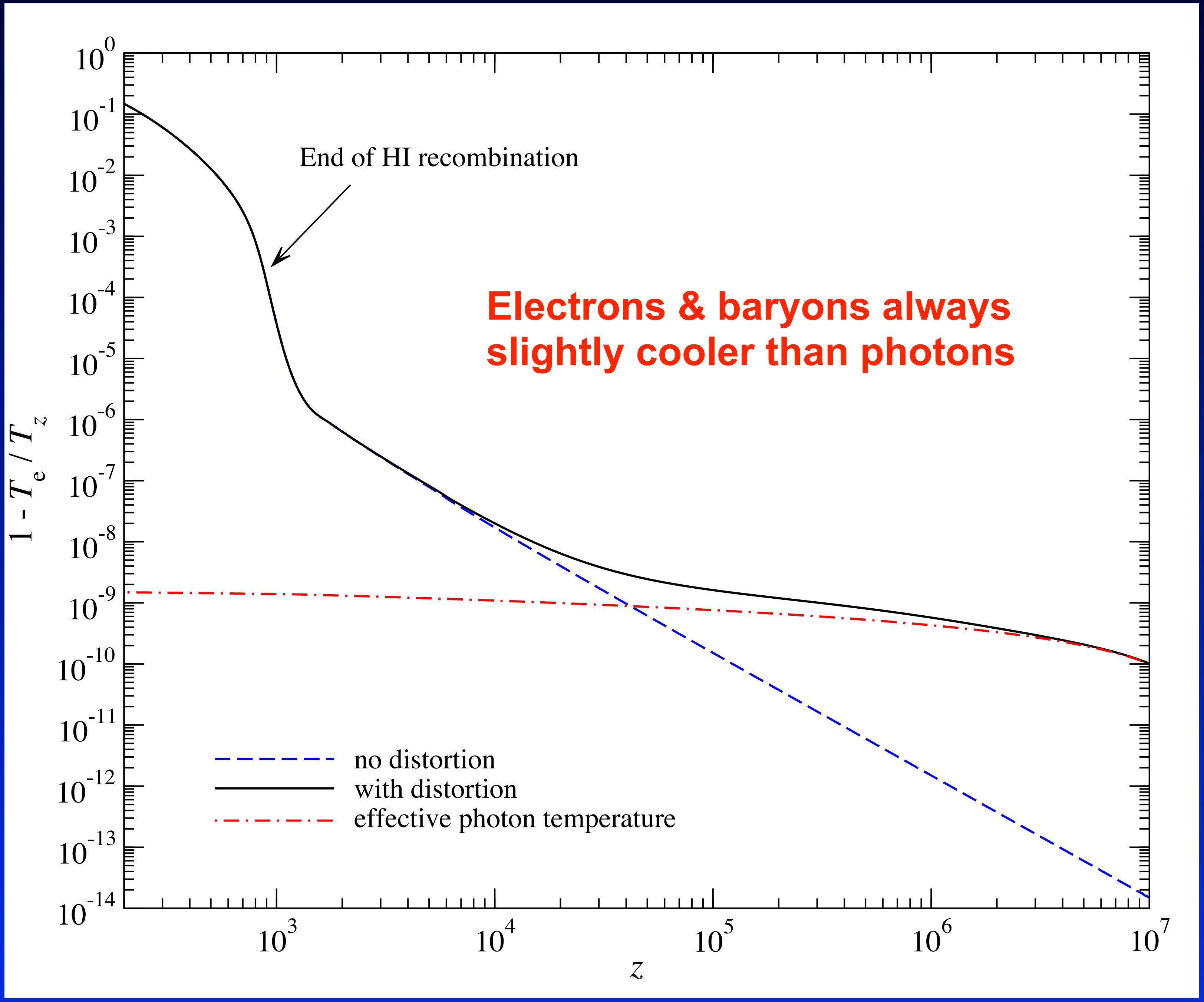
Some of the science goals:

- B-mode polarization from inflation ($r \approx 5\times10^{-4}$)
- count all SZ clusters $>10^{14}\ M_{sun}$
- CIB/large scale structure
- Galactic science
- *CMB spectral distortions*

***Sign up at:***
***http://www.prism-mission.org/***

*Adiabatically cooling ordinary matter*

# Spectral distortion caused by the cooling of ordinary matter




- adiabatic expansion

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

- 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 ($\propto N_X^2$ )

$\Rightarrow$ *cancellation* possible

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**today $x$=2x10$^{-2}$ means ν~1GHz**

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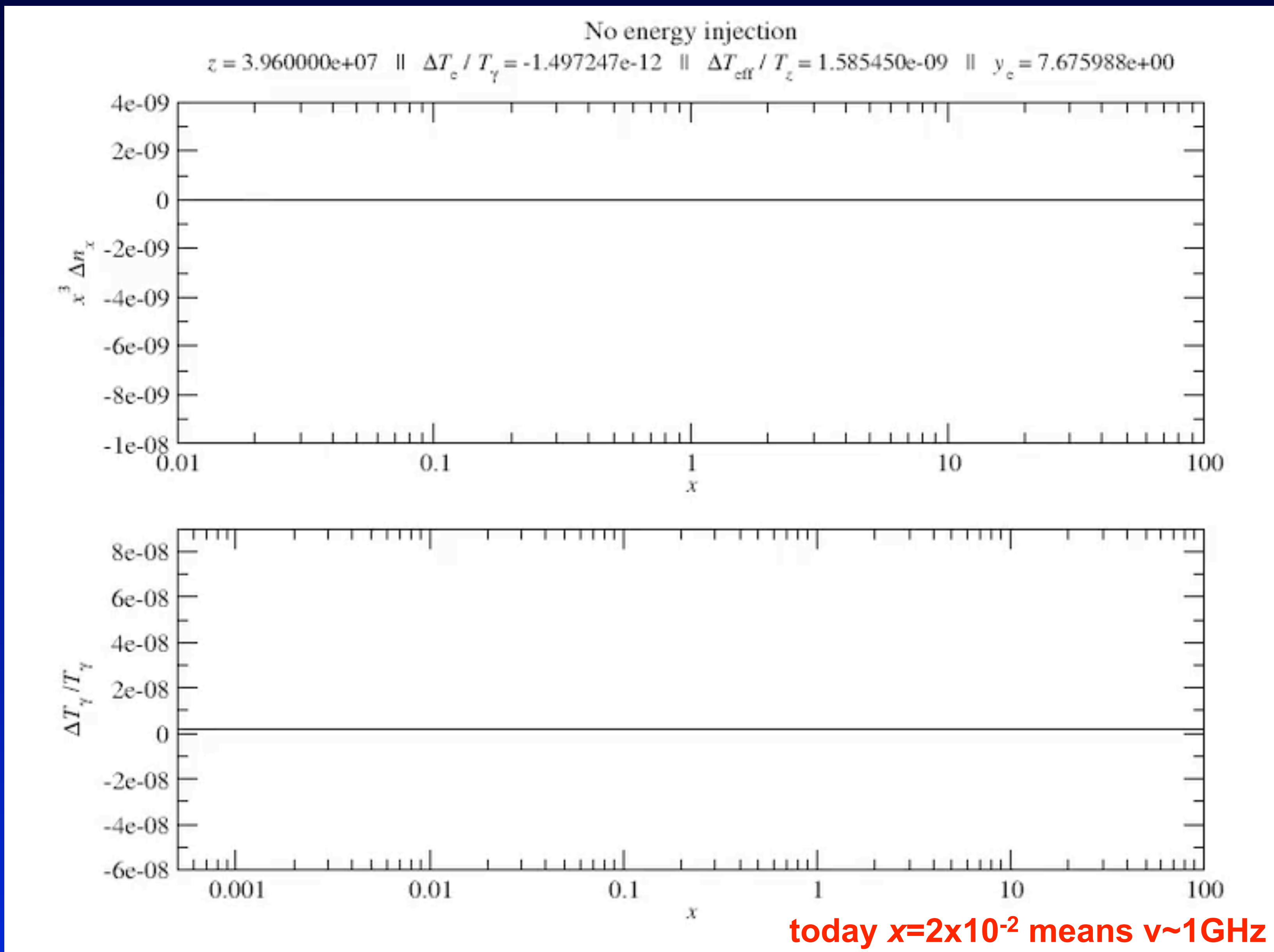


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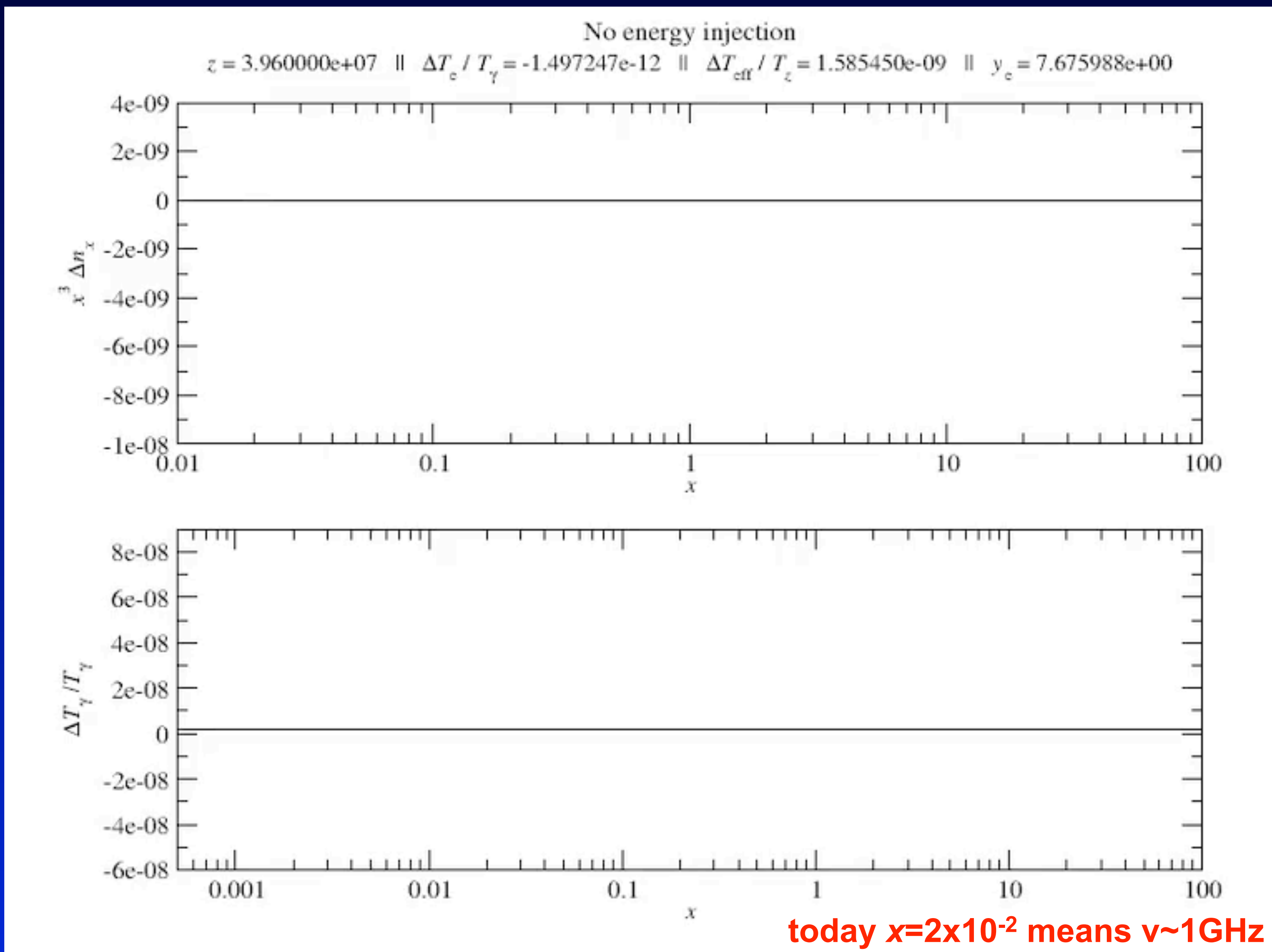


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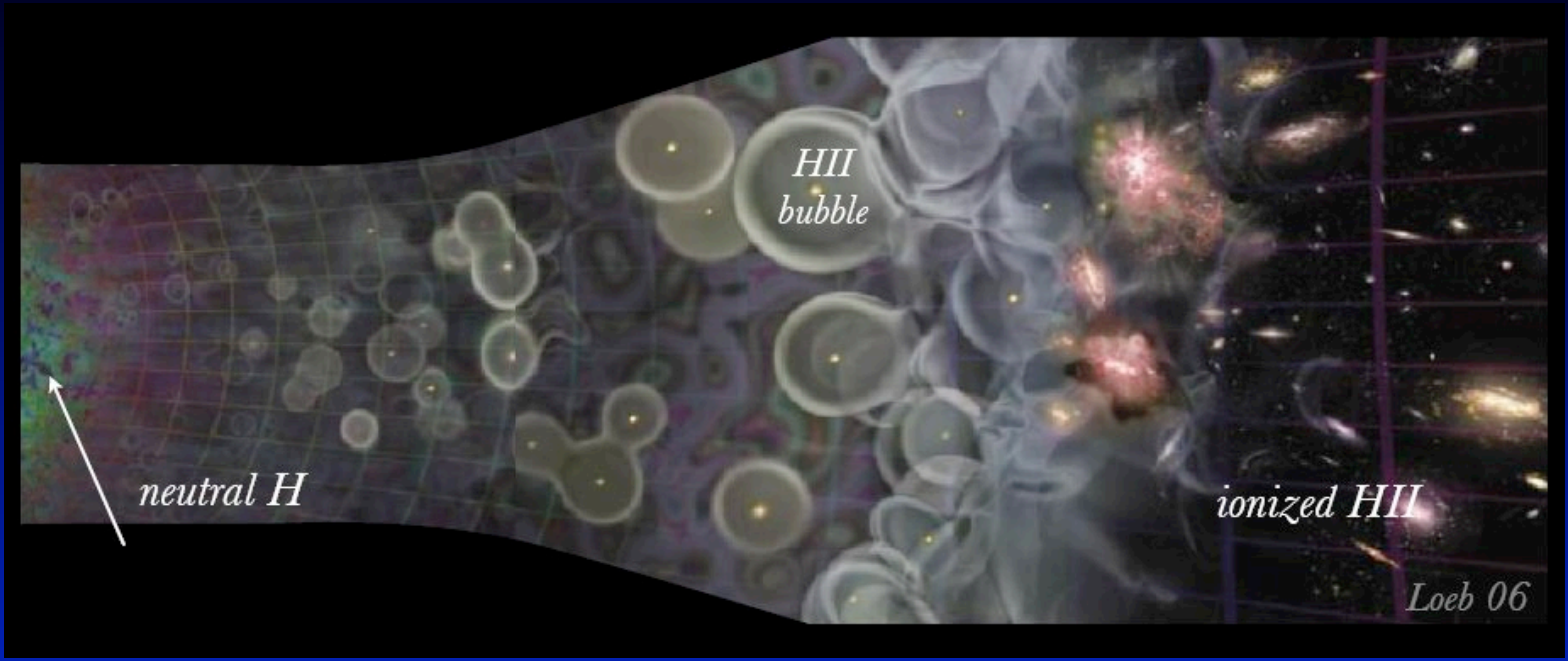
- *negative* $\mu$ and $y$ distortion
- late free-free absorption at very low frequencies
- Distortion a few times below PIXIE's sensitivity

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

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

*Reionization and structure formation*

# Simple estimates for the distortion

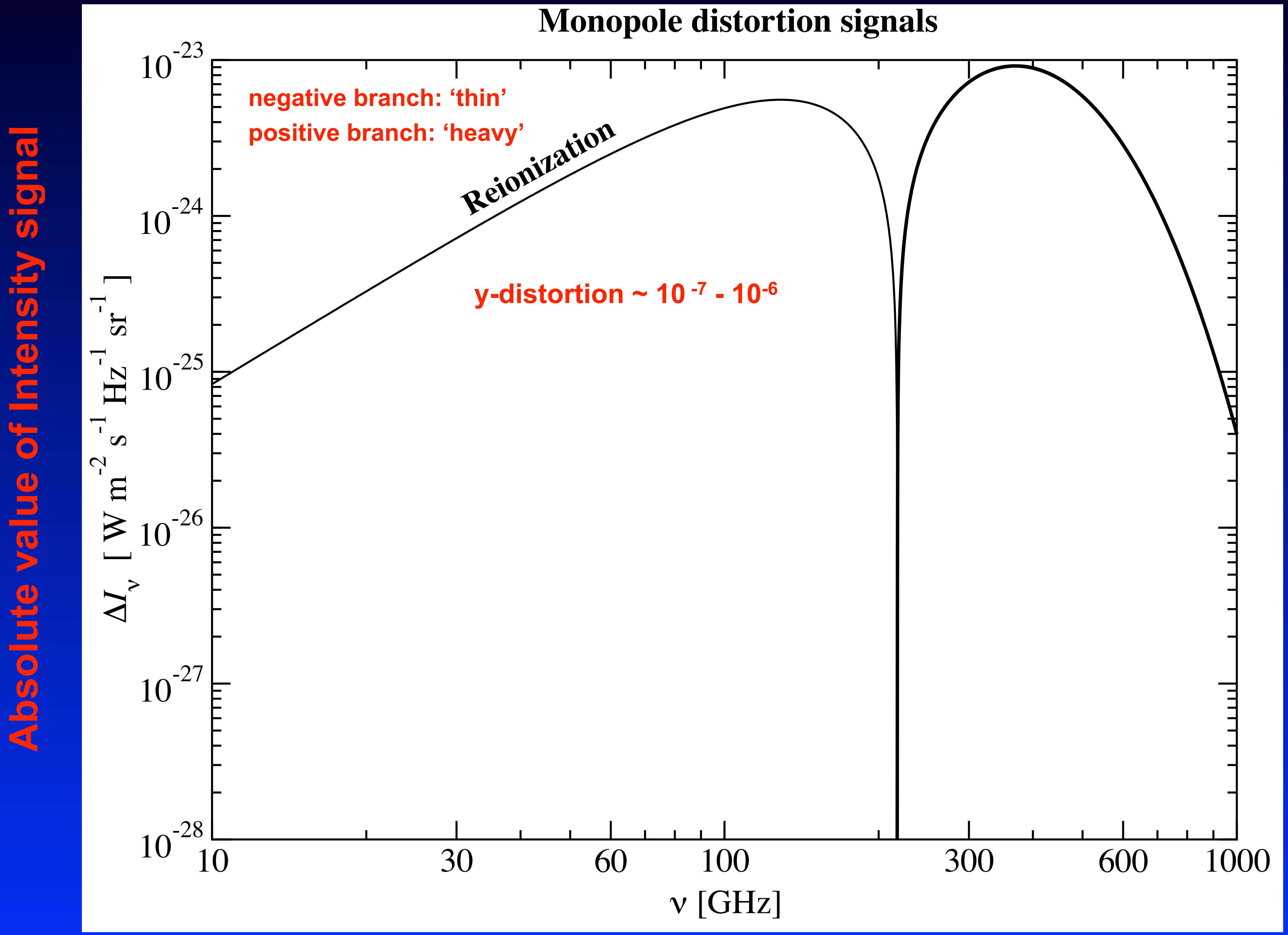



- Gas temperature T ≃ $10^4$ K
- Thomson optical depth $\tau$ ≃ 0.1

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

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

# Average CMB spectral distortions



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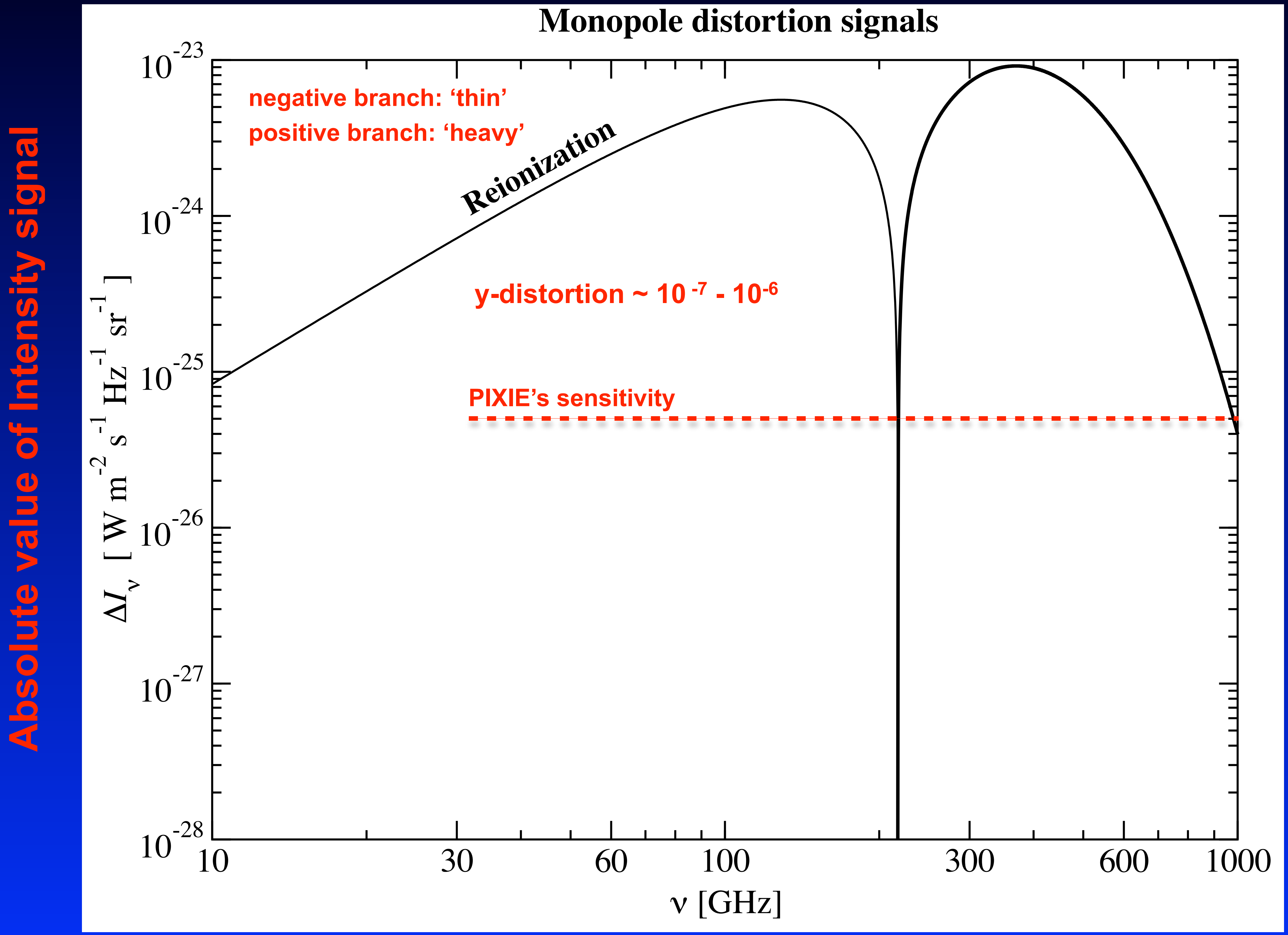
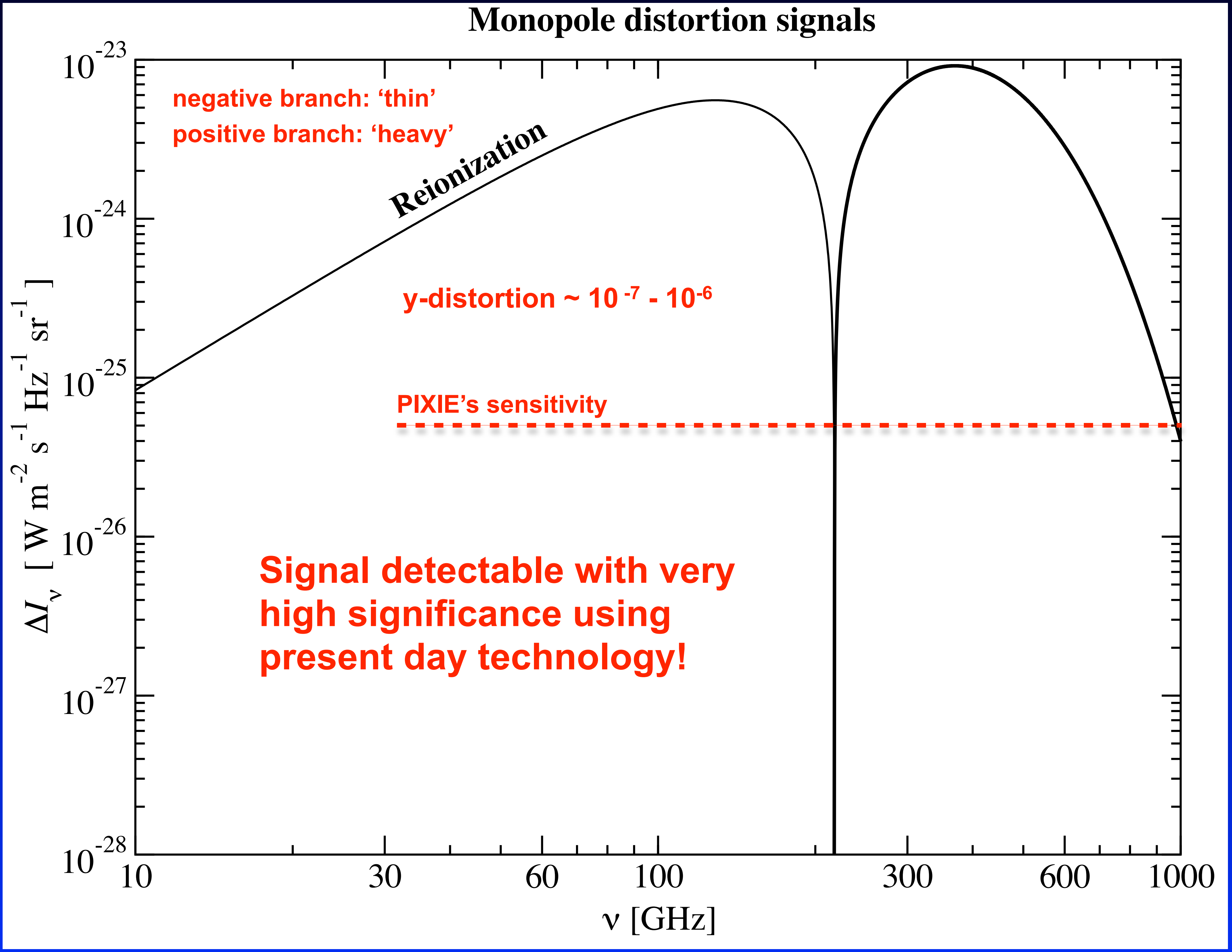
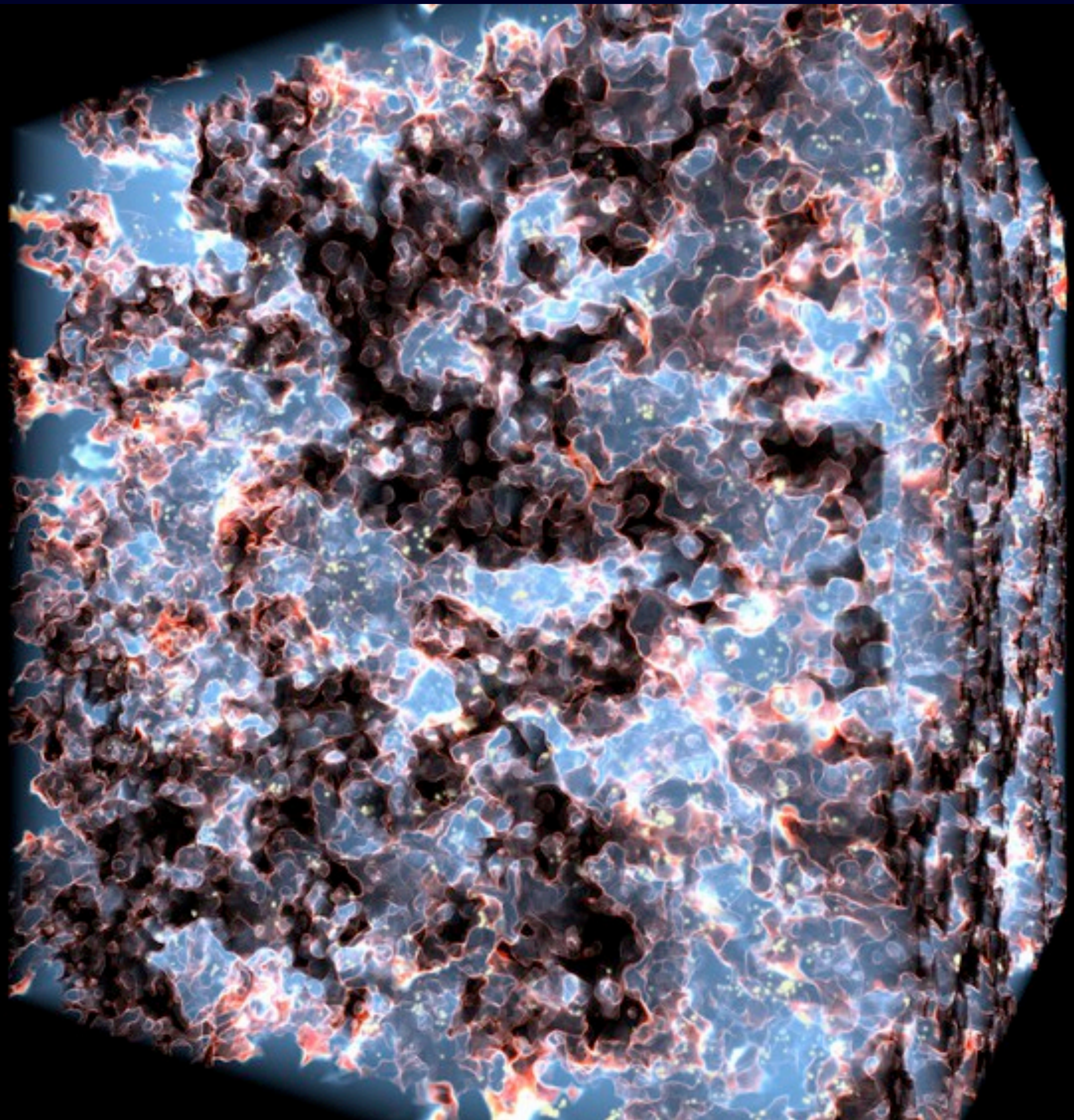


# Average CMB spectral distortions

Absolute value of Intensity signal



# Fluctuations of the y-parameter at large scales

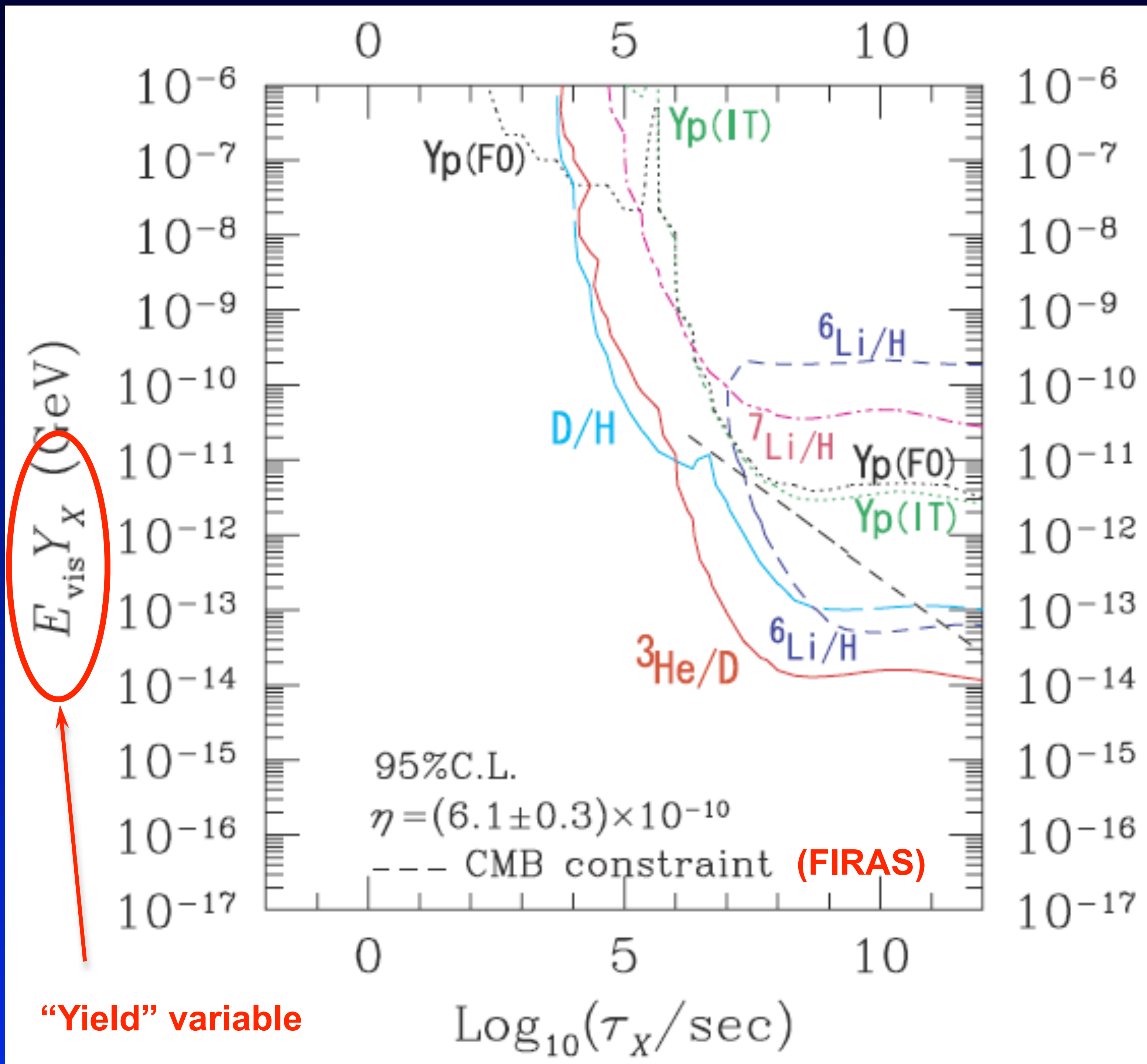


- spatial variations of the optical depth and temperature cause small-spatial variations of the y-parameter at different angular scales
- could tell us about the reionization sources and structure formation process
- additional independent piece of information!

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

*Decaying particles*

# Constraints from measurements of light elements




from Kawasaki et al, 2005

- Yield variable ⇒

  parametrizes the total energy release relative to total entropy density of the Universe

  $$Y_X \simeq N_X/S$$

- $E_{vis}$ hides physics of energy deposition

  (decay channels, neutrino fraction, etc.)

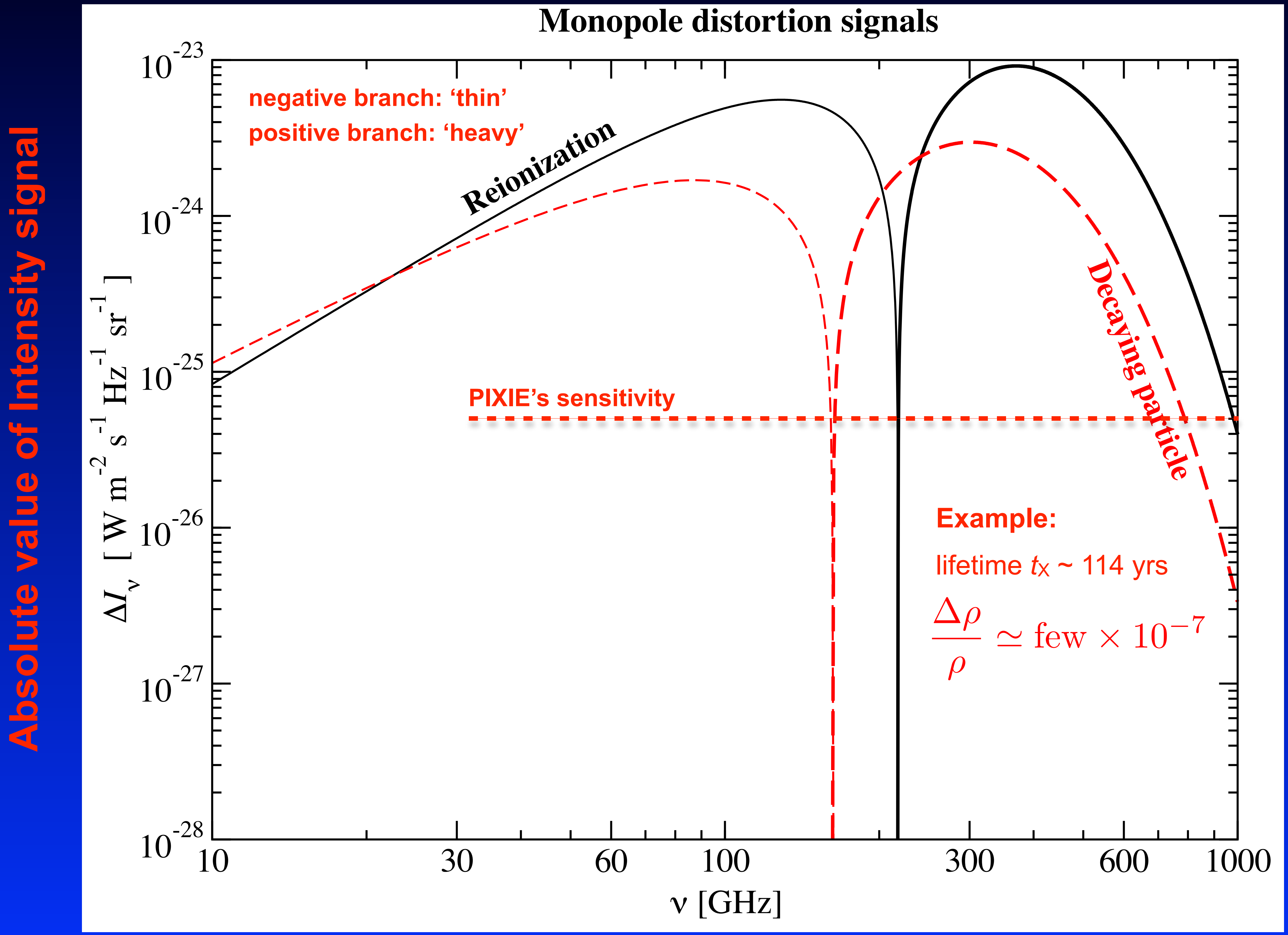
- current CMB limit rather weak....

# Energy release by decaying particles

- Energy release rate $$\frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z} \approx \frac{f^* M_\mathrm{X} c^2}{H(z)(1+z)} \frac{N_\mathrm{X}(z)}{\rho_\gamma(z)} \Gamma_\mathrm{X} \mathrm{e}^{-\Gamma_\mathrm{X} t}$$
- *For computations*: $f_\mathrm{X} = f^* M_\mathrm{X} c^2 N_\mathrm{X}/N_\mathrm{H}$ and $\varepsilon_\mathrm{X} = \dfrac{f_\mathrm{X}}{z_\mathrm{X}}$
- Efficiency factor $f^*$ contains all the physics describing the cascade of decay products
- At high redshift deposited energy goes into heat
- Around recombination and after things become more complicated **(Slatyer et al. 2009; Cirelli et al. 2009; Huts et al. 2009; Slatyer et al. 2013)**

$\Longrightarrow$ *branching ratios into heat, ionizations, and atomic excitation*

# Average CMB spectral distortions



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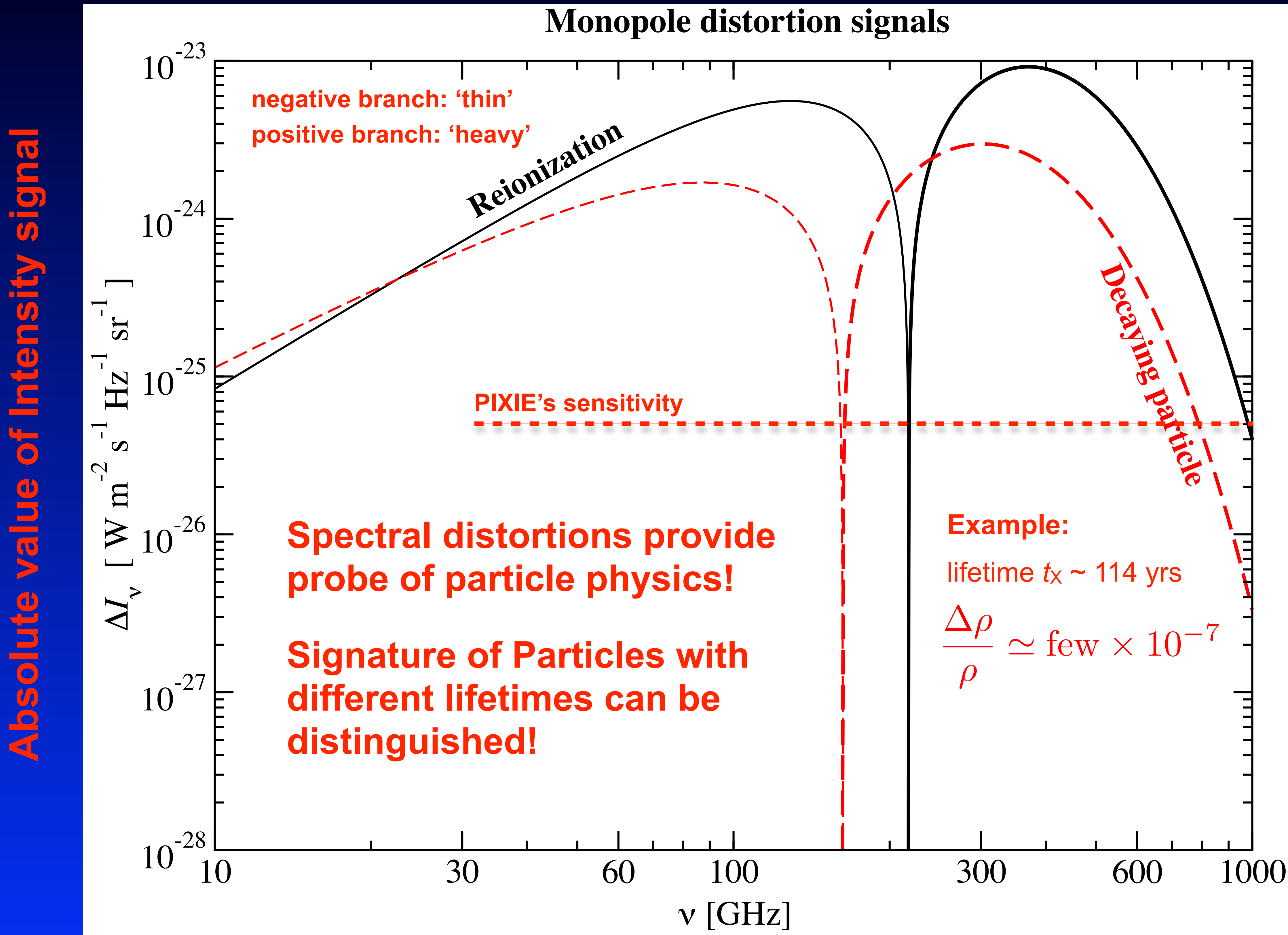
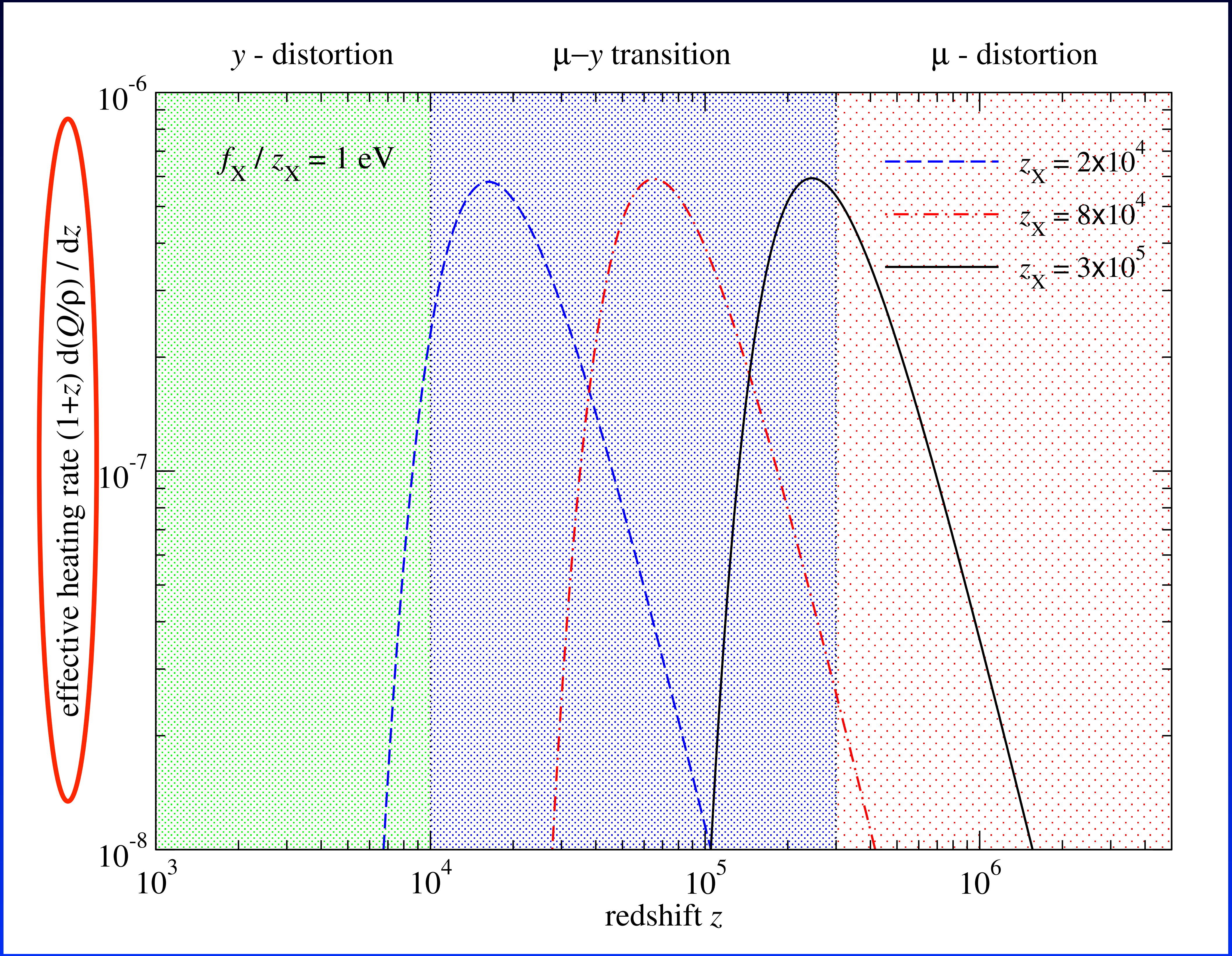


# Decaying particle scenarios

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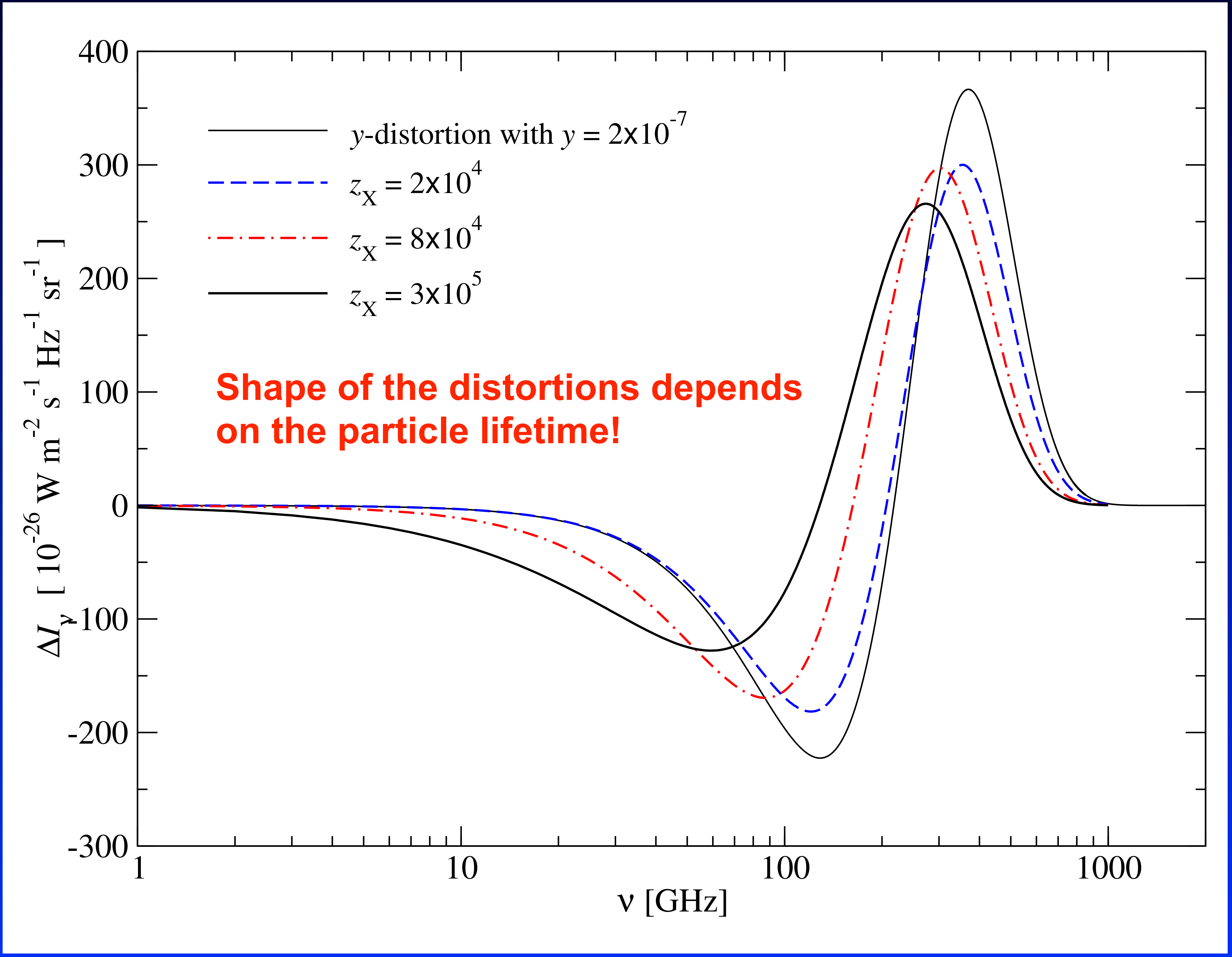


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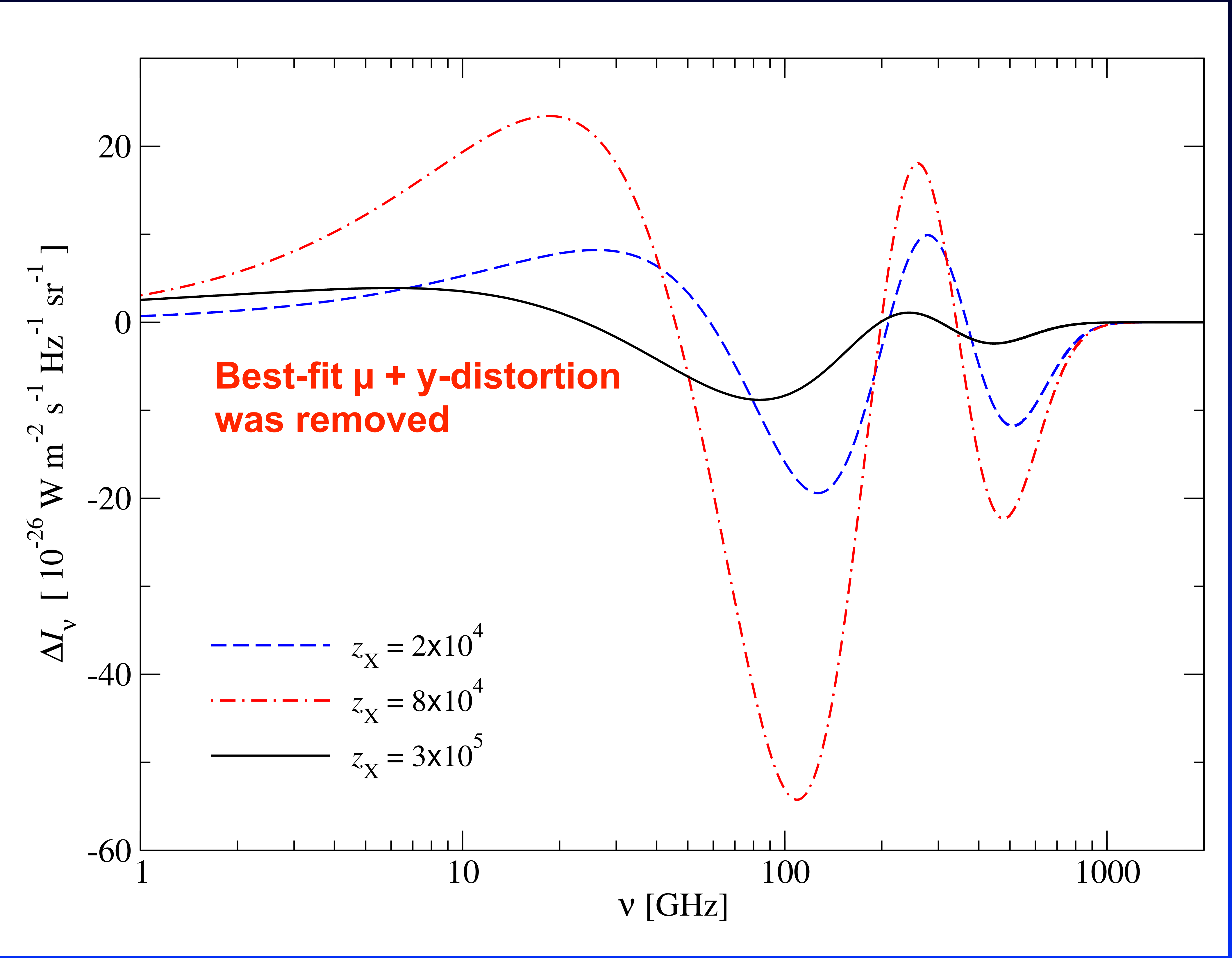


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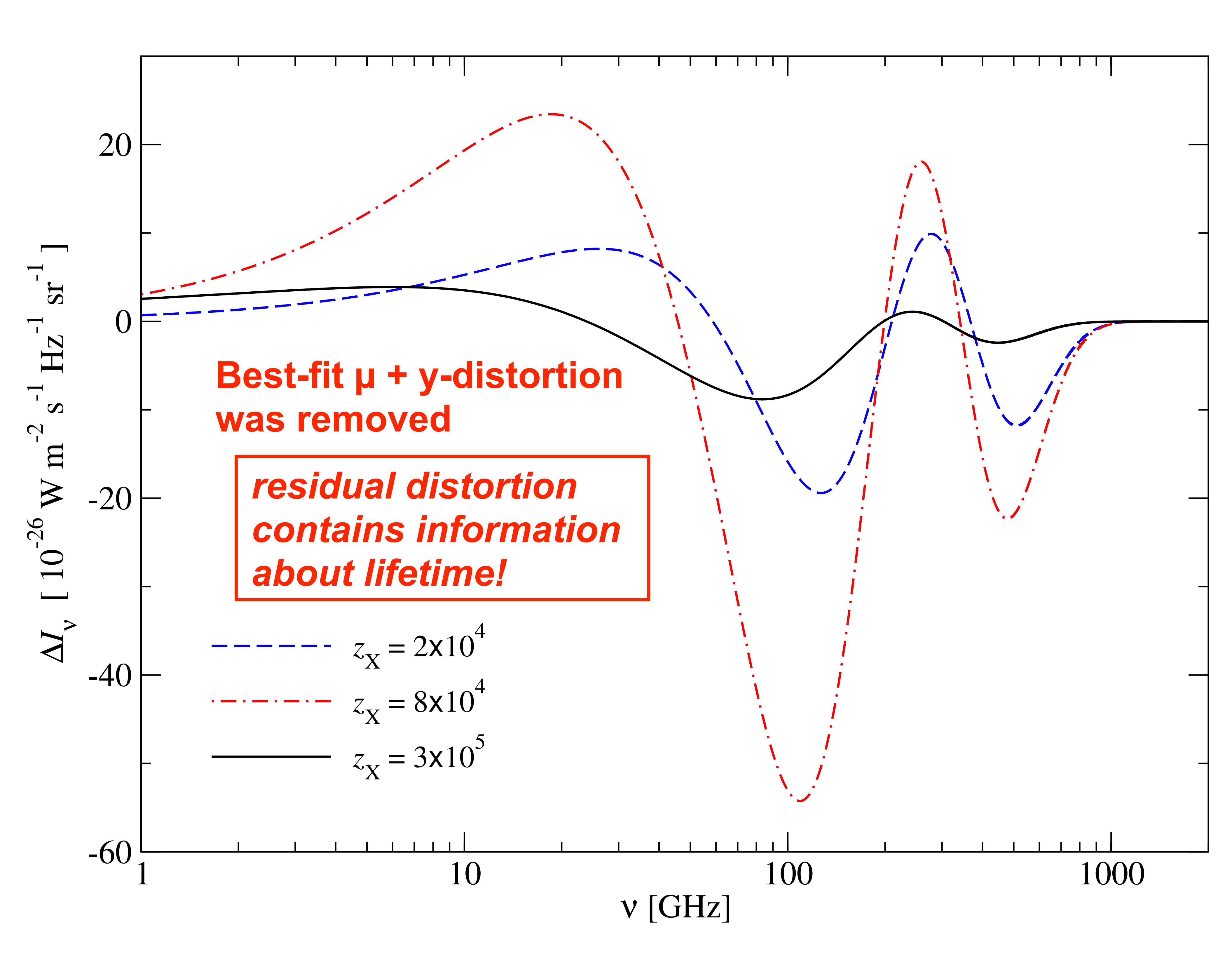


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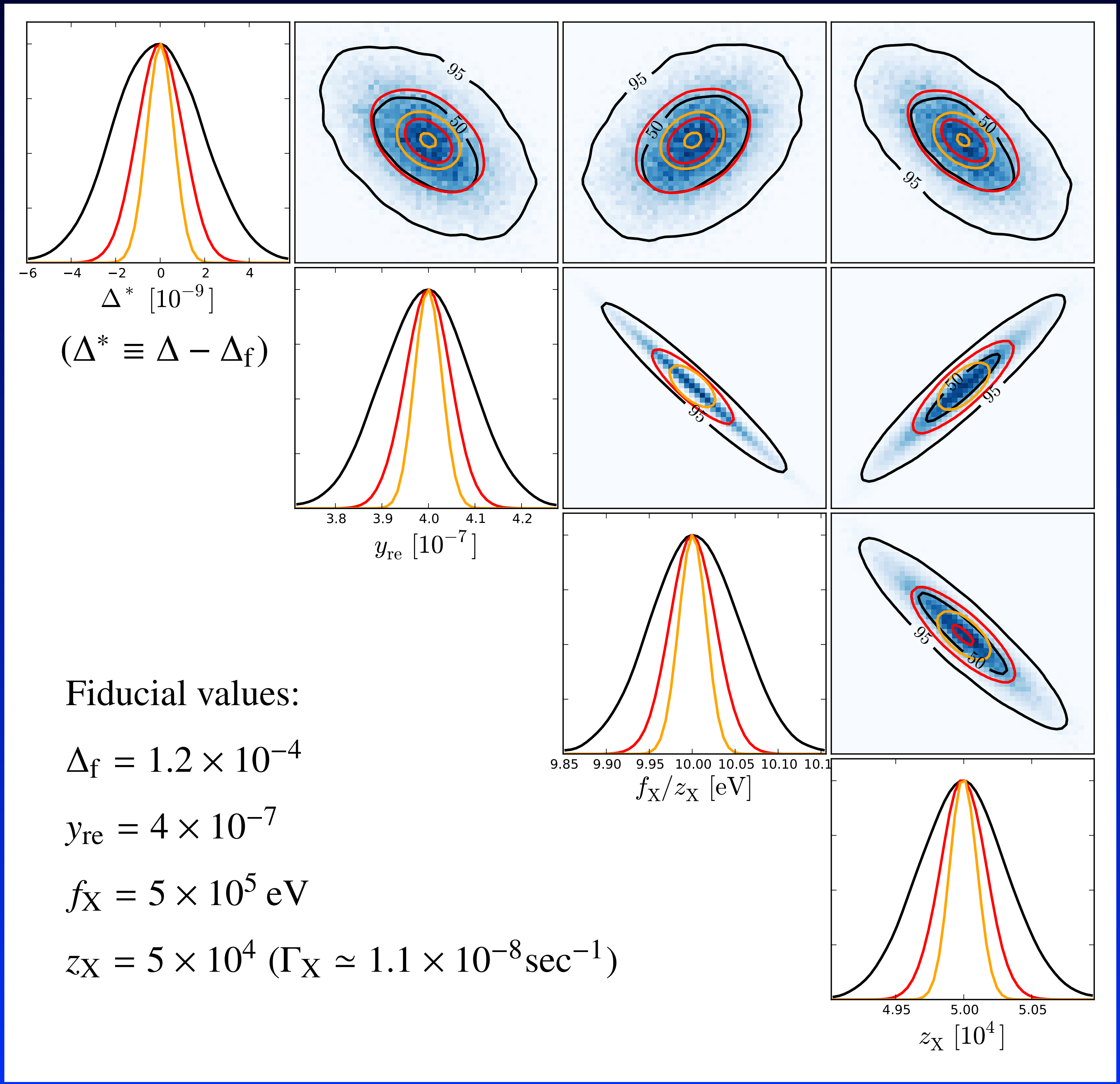


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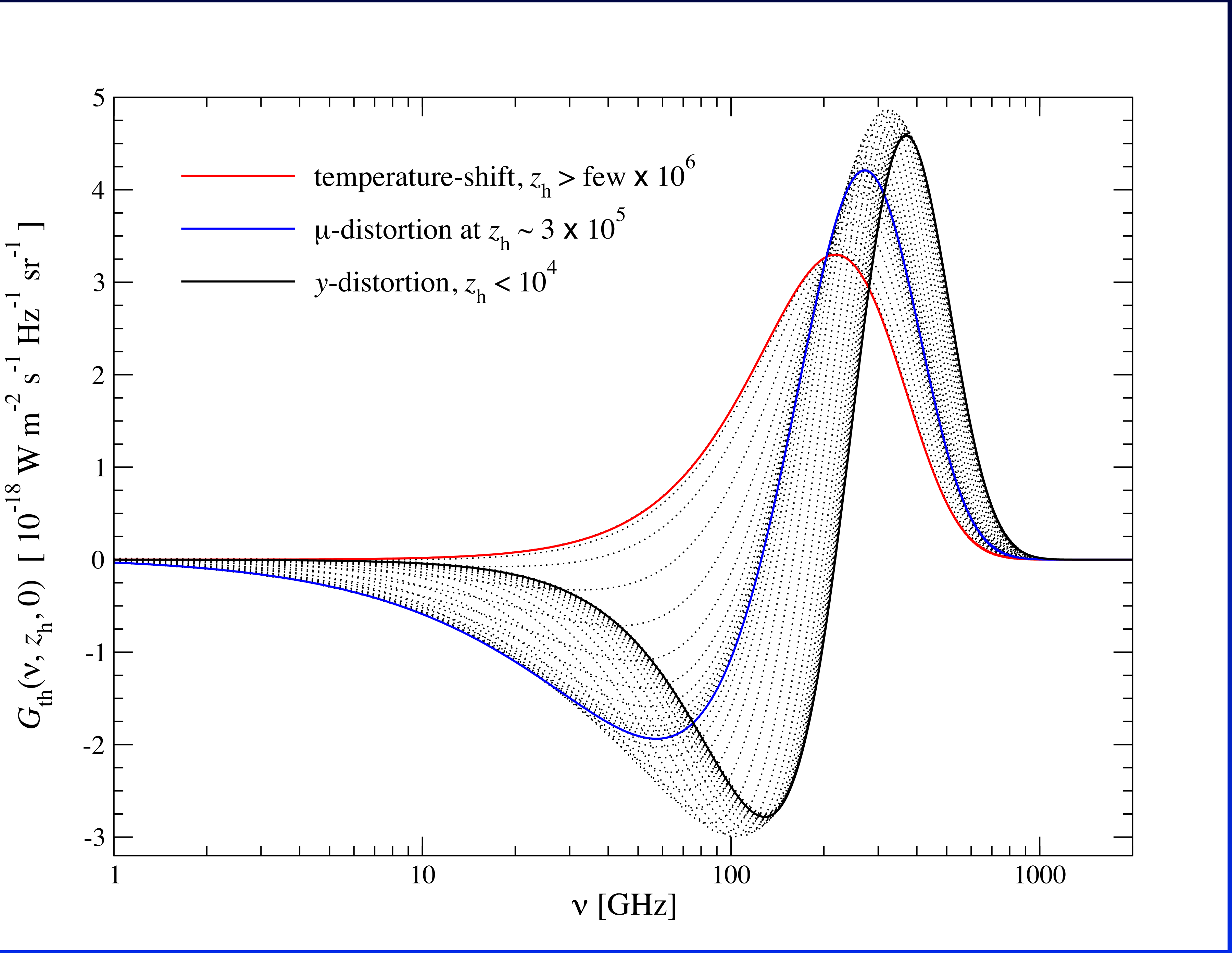
# Using signal eigenmodes to compress the distortion data




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

JC & Jeong, 2013

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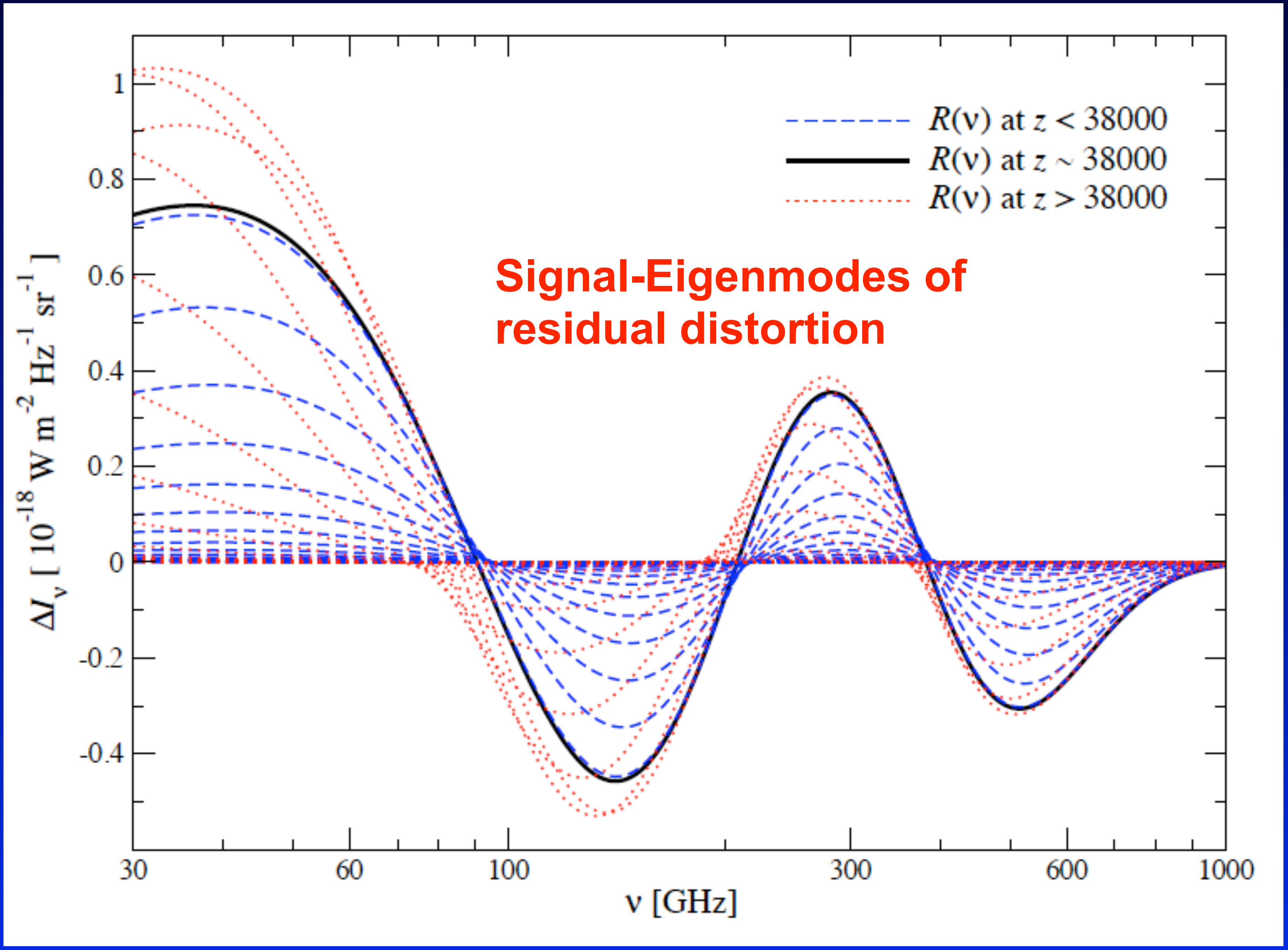


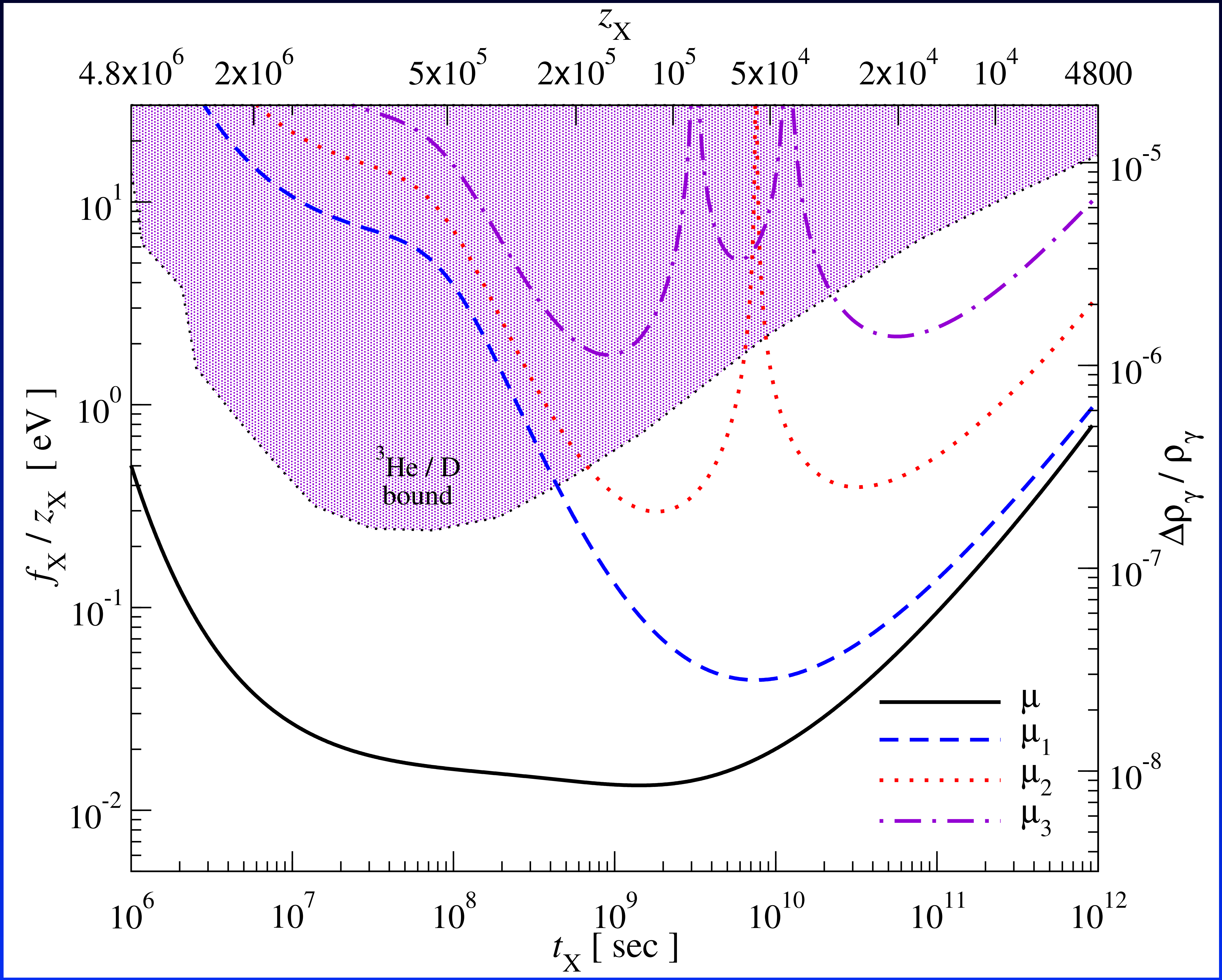

- *Principle component decomposition* of the distortion signal
- compression of the useful information given instrumental settings
- new set of observables

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

- model-comparison + forecasts of errors very simple!

JC & Jeong, 2013

# Decaying particle 1σ-detection limits for PIXIE

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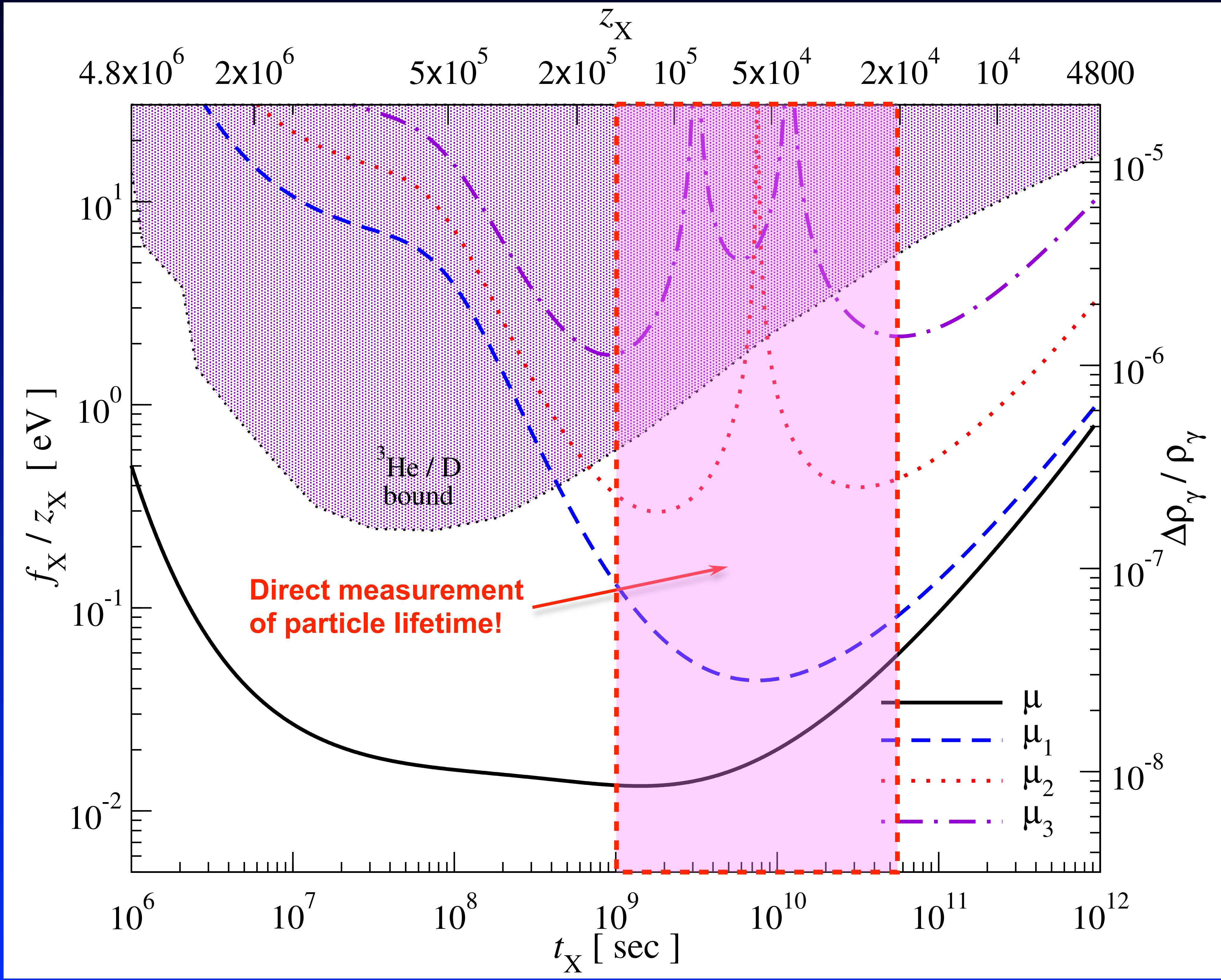
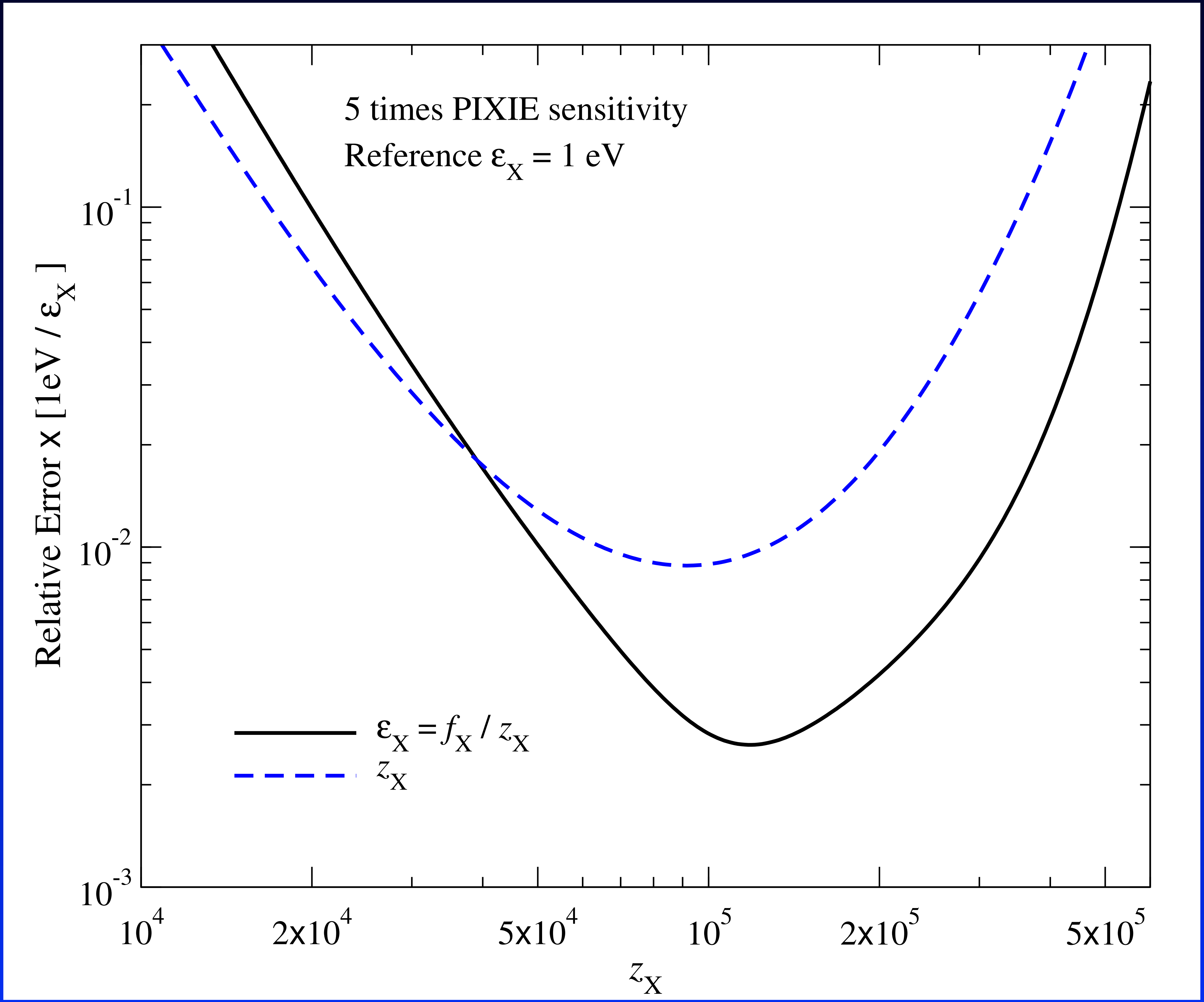



JC & Jeong, 2013

# Decaying particle error forecasts

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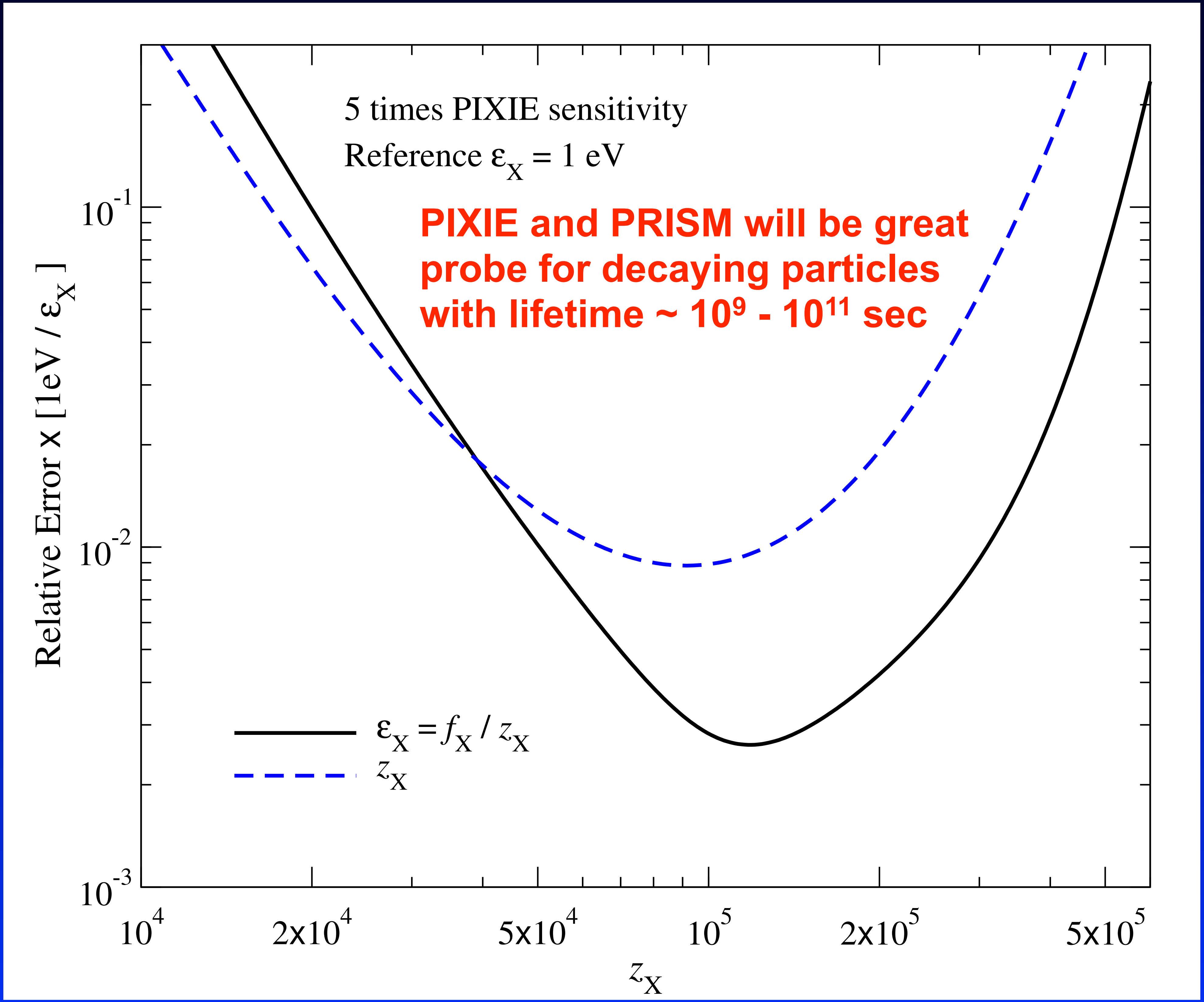
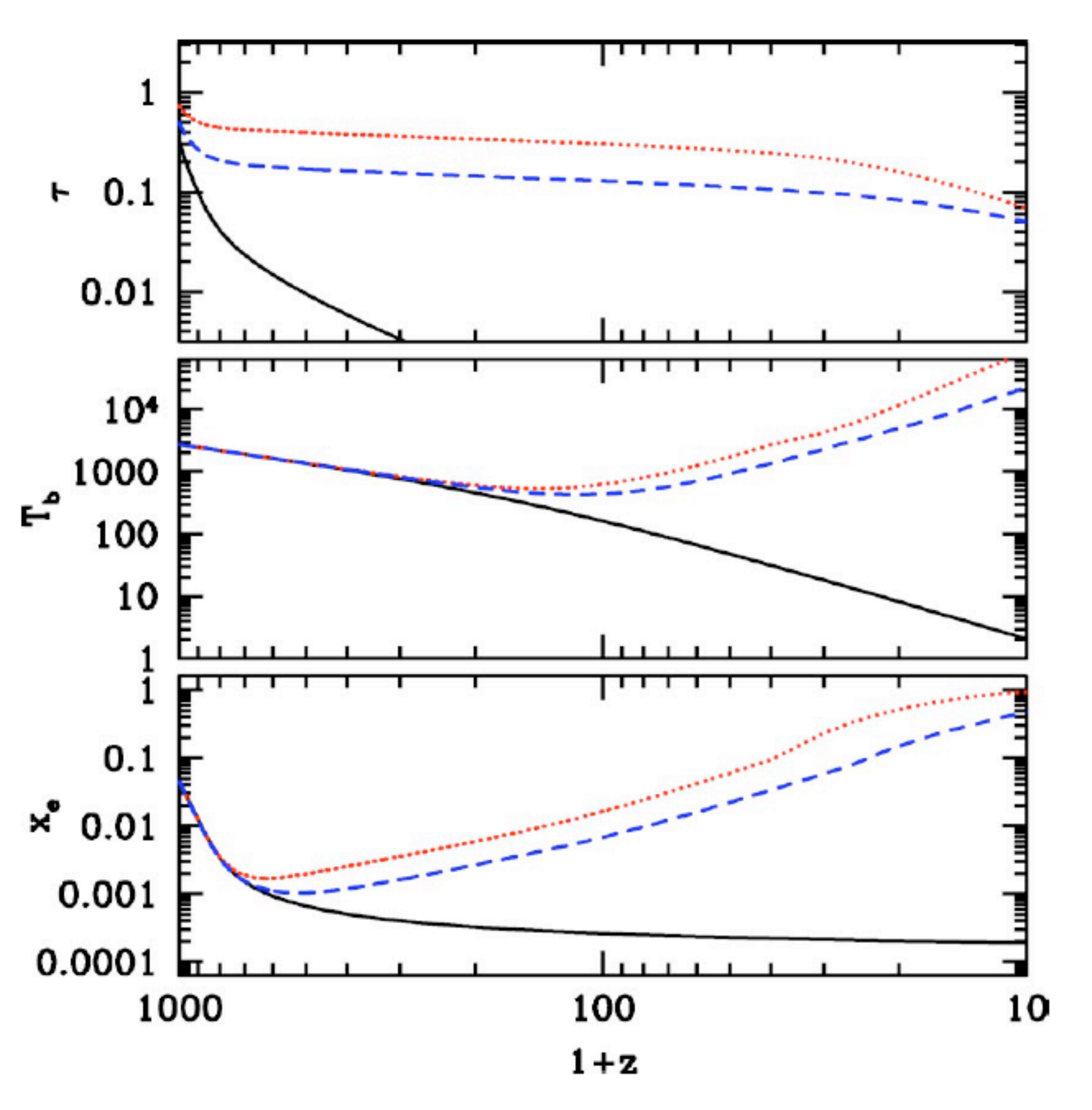



JC & Jeong, 2013

# Decaying particle during & after recombination

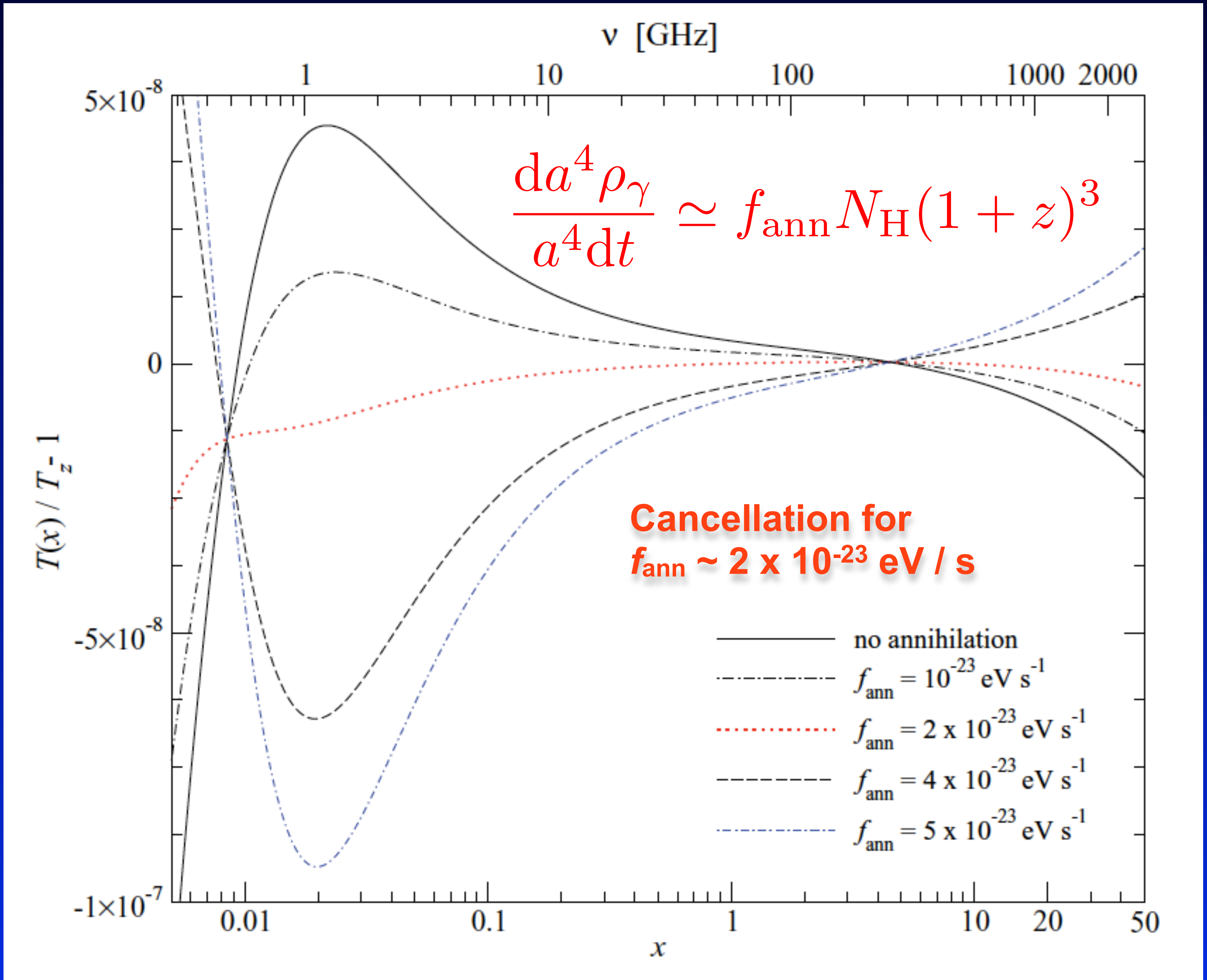



Chen & Kamionkowski, 2004

- Modify recombination history
- this changes Thomson visibility function and thus the CMB temperature and polarization power spectra
- ⇒ CMB anisotropies allow

  probing particles with lifetimes $\gtrsim 10^{12}$ sec
- CMB spectral distortions provide complementary probe!

# Cancellation of cooling by heating from annihilation




- $f_\mathrm{ann}$ ≡ annihilation efficiency
  **(Padmanabhan & Finkbeiner, 2005; JC 2010)**
- CMB anisotropy constraint

  $$f_\mathrm{ann} \lesssim 2 \times 10^{-23} \mathrm{eV s}^{-1}$$

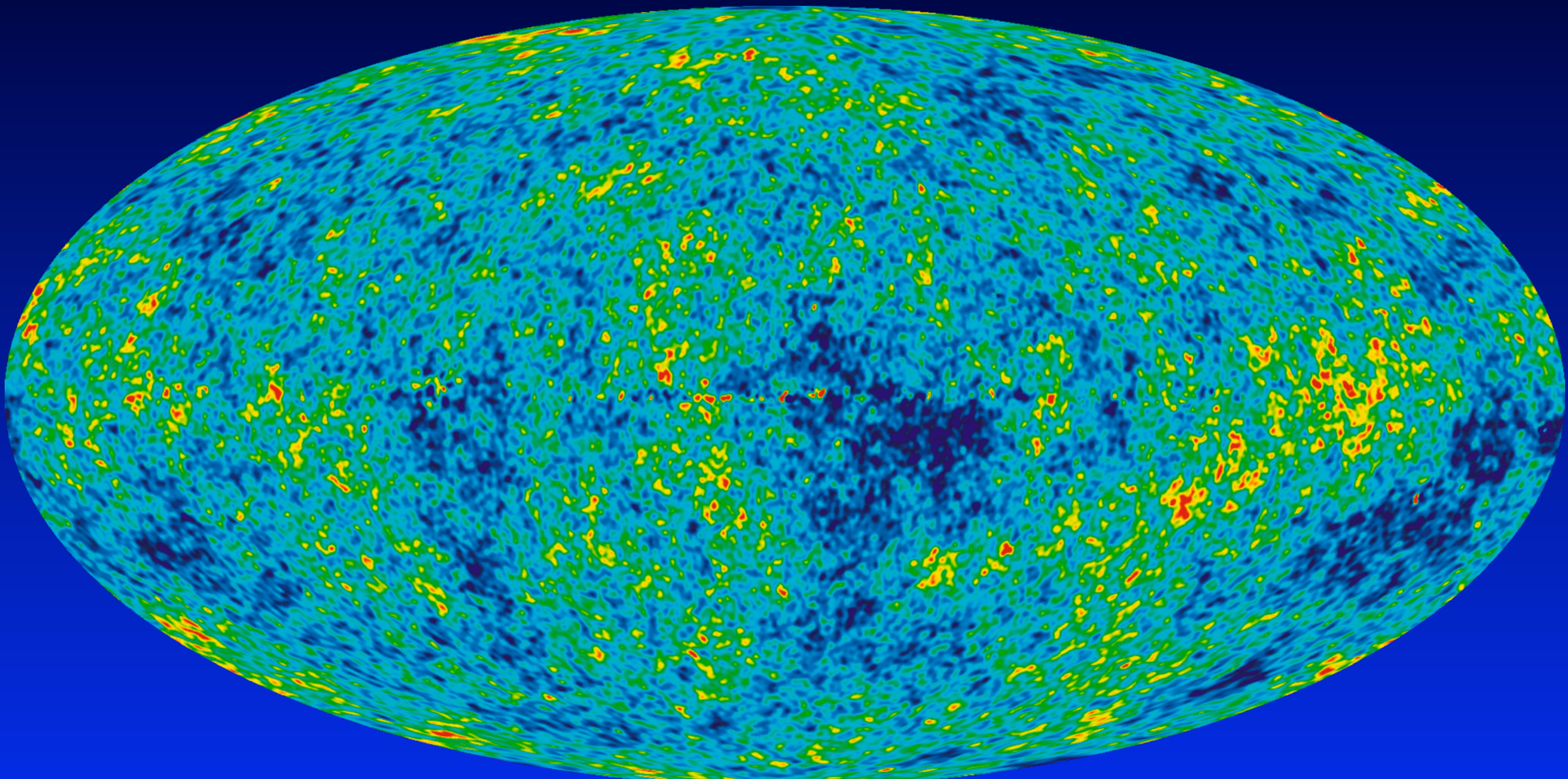
  **(Galli et al., 2009; Slatyer et al., 2009; Huetsi et al., 2009, 2011)**
- Limit from Planck satellite will be roughly *6 times stronger* → more precise prediction for the distortion will be possible
- uncertainty dominated by particle physics
- limits from PIXIE/PRISM several times weaker, *but* independent

**JC & Sunyaev, 2012**

$$f_\mathrm{ann} = 1.1 \times 10^{-24} \frac{100\mathrm{GeV}}{M_X c^2} \left[\frac{\Omega_X h^2}{0.11}\right]^2 \frac{\langle \sigma v \rangle}{3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}}$$

*The dissipation of small-scale acoustic modes*

# Dissipation of small-scale acoustic modes



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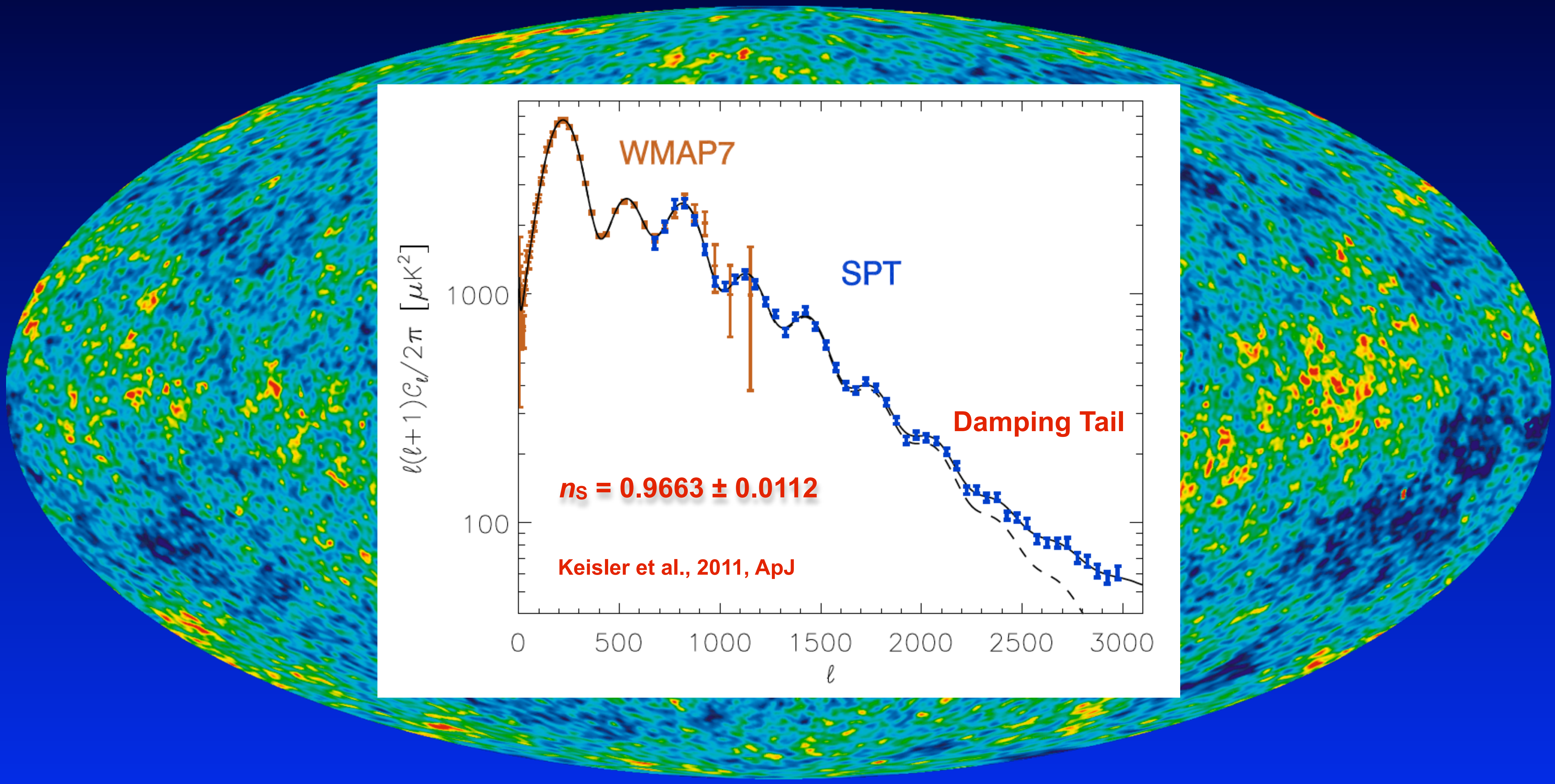

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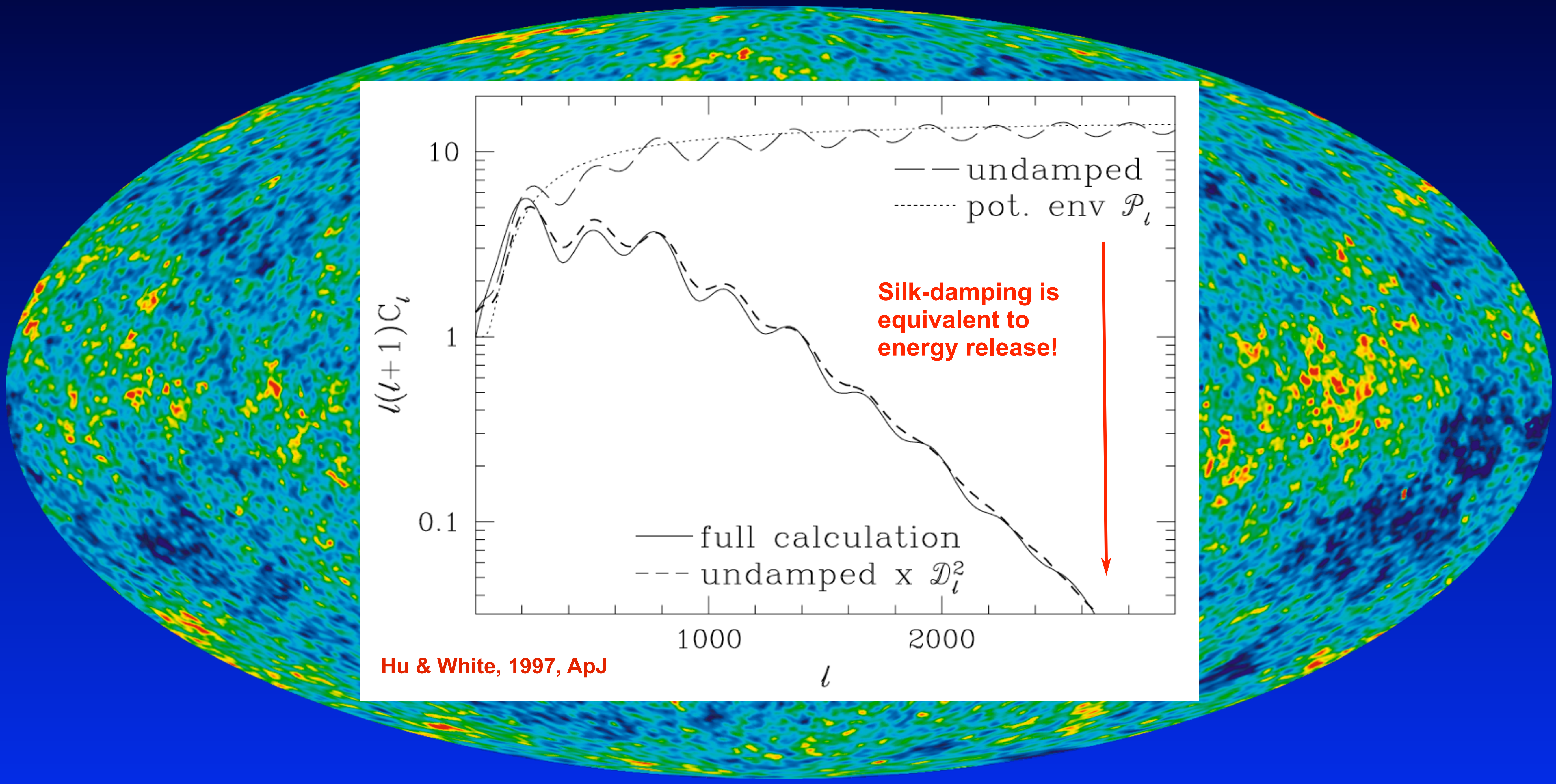

# Energy release caused by dissipation process

'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 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 squeezed limit
  (Pajer & Zaldarriaga, 2012; Ganc & Komatsu, 2012)
- *Type* of the perturbations (adiabatic ↔ isocurvature)
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- *Neutrinos* (or any extra relativistic degree of freedom)

*CMB Spectral distortions provide probe of Inflation physics!!!*

# 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 $\rho$ is ‘*mass density*’ and $c_s$ denotes ‘*sounds speed*’

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

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- 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 in the monopole accounted for**

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

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

**'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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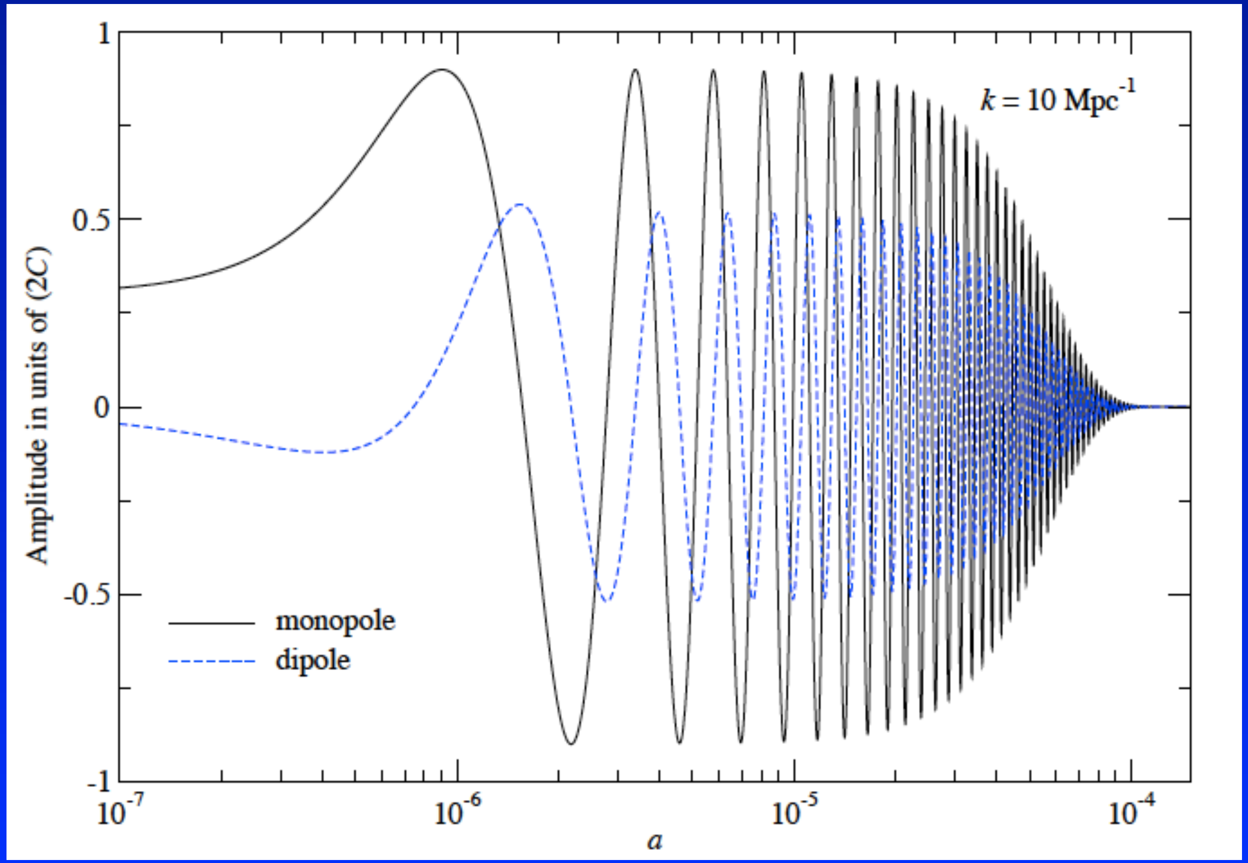


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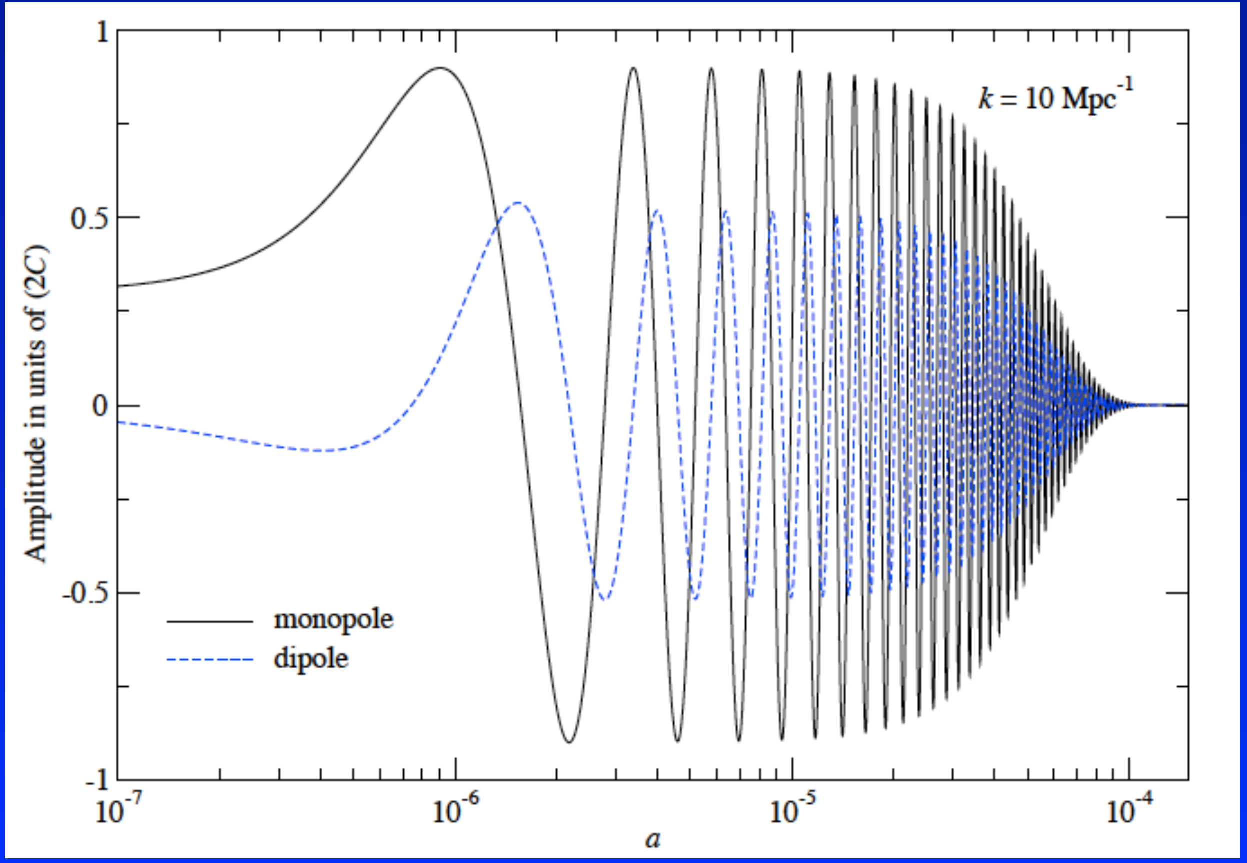
  $\delta\rho/\rho \rightarrow 4(\delta T_0/T) \equiv 4\Theta_0$

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

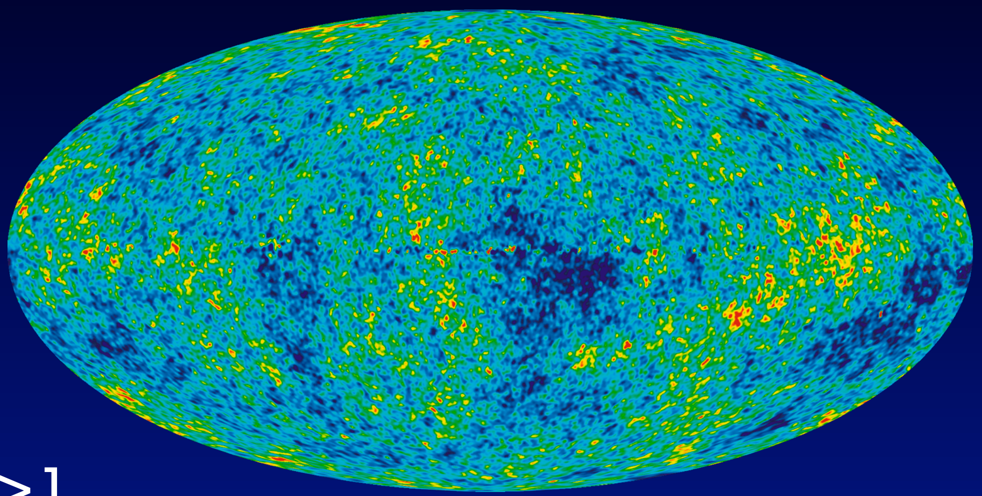



Sunyaev & Zeldovich, 1970
Hu, Scott & Silk, 1994, ApJ

# 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

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



E.g., our snapshot at $z$=0

JC, Khatri & Sunyaev, 2012

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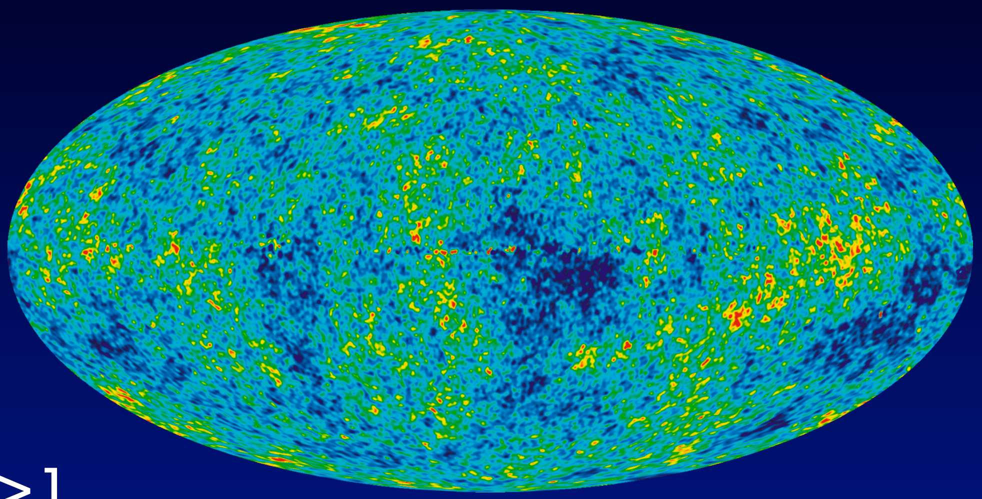

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$$\Rightarrow \quad (a^4 \rho_\gamma)^{-1} \, \mathrm{d}a^4 Q_{ac}/\mathrm{d}t = -6 \, \mathrm{d}<\Theta^2>/\mathrm{d}t$$

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

JC, Khatri & Sunyaev, 2012

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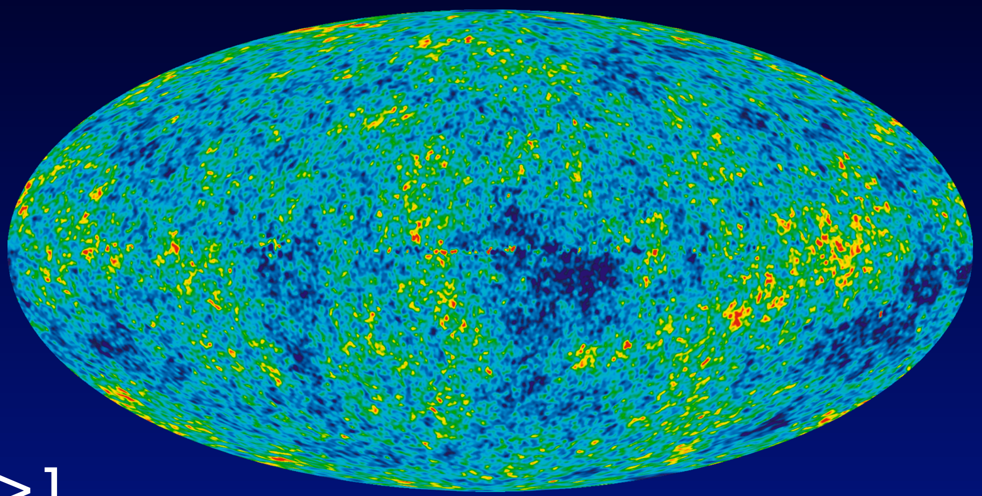


E.g., our **snapshot at *z*=0**

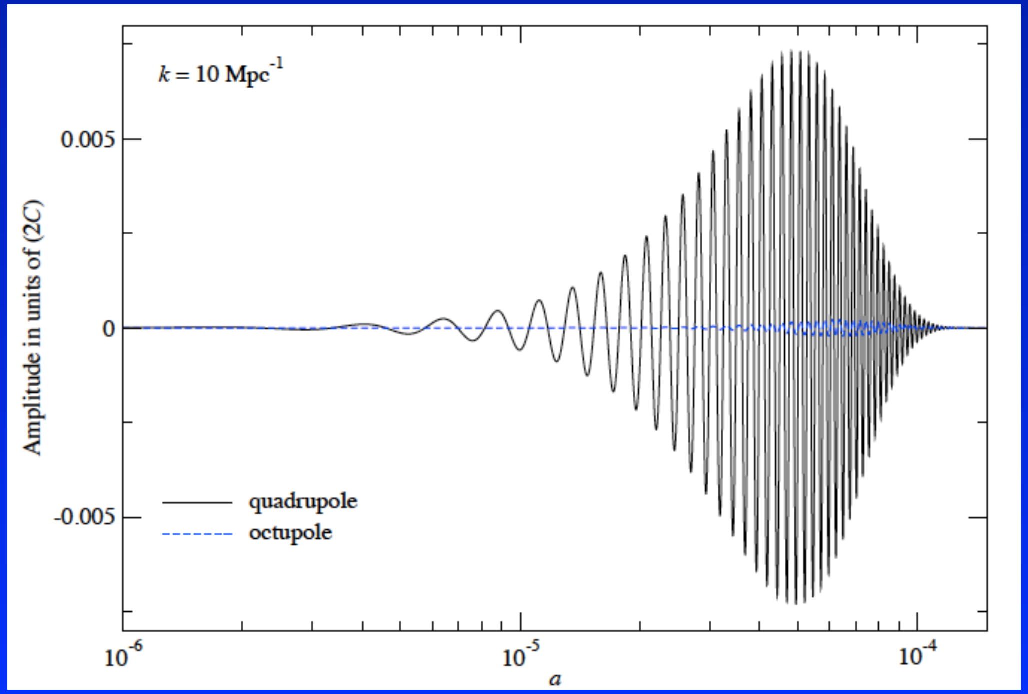
$$<\rho_\gamma> = a_R <T^4> \approx a_R <T>^4 \, [1 + 4\underbrace{<\Theta>}_{==0} + 6<\Theta^2>]$$

$$\Rightarrow \quad (a^4\rho_\gamma)^{-1} \, da^4 Q_{ac}/dt = -6 \, d<\Theta^2>/dt$$

- 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*

$$\Rightarrow \quad (a^4\rho_\gamma)^{-1} \, da^4 Q_{ac}/dt \approx -12 \, d<\Theta_0{}^2>/dt$$

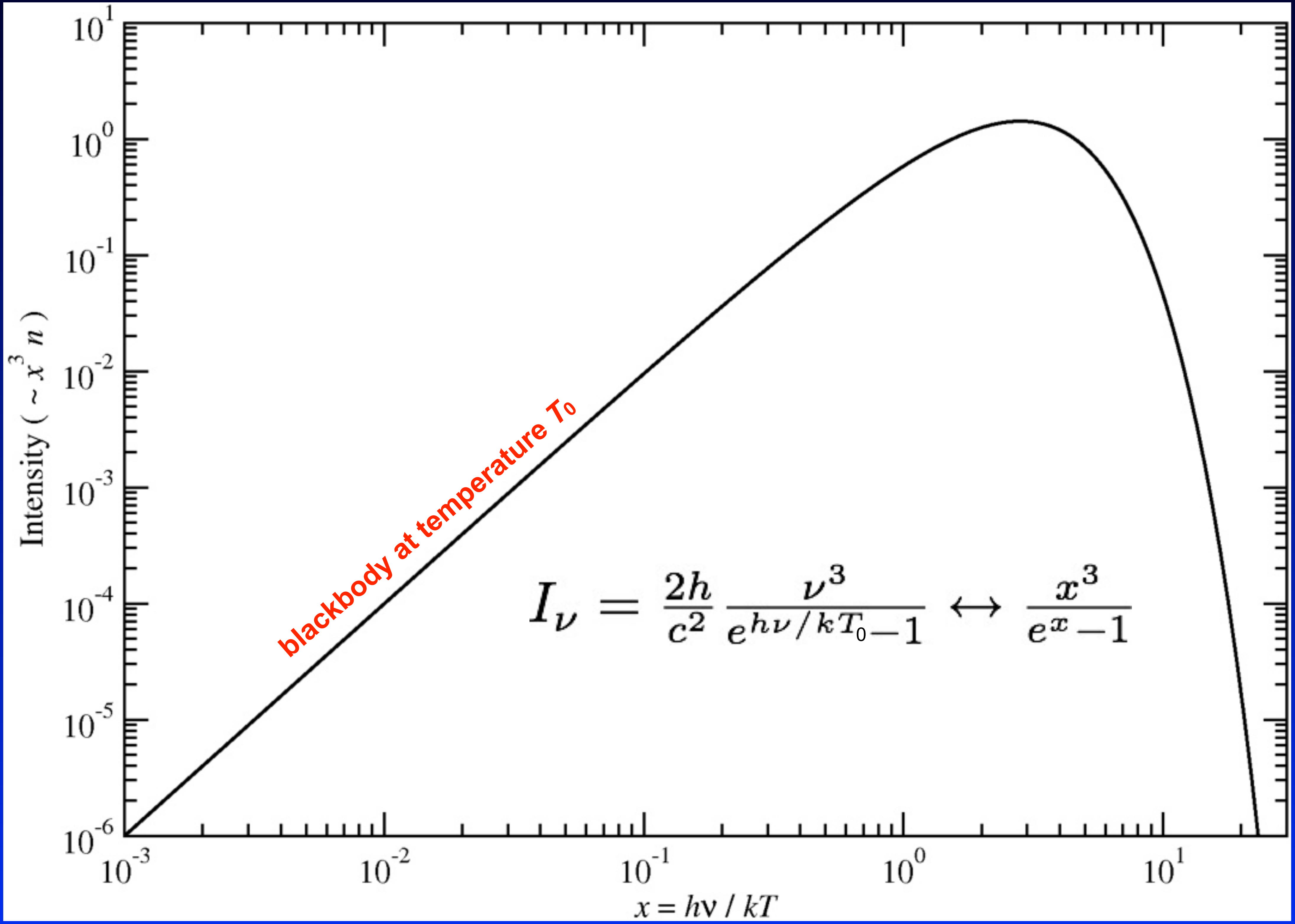
9/4 larger than classical estimate




JC, Khatri & Sunyaev, 2012

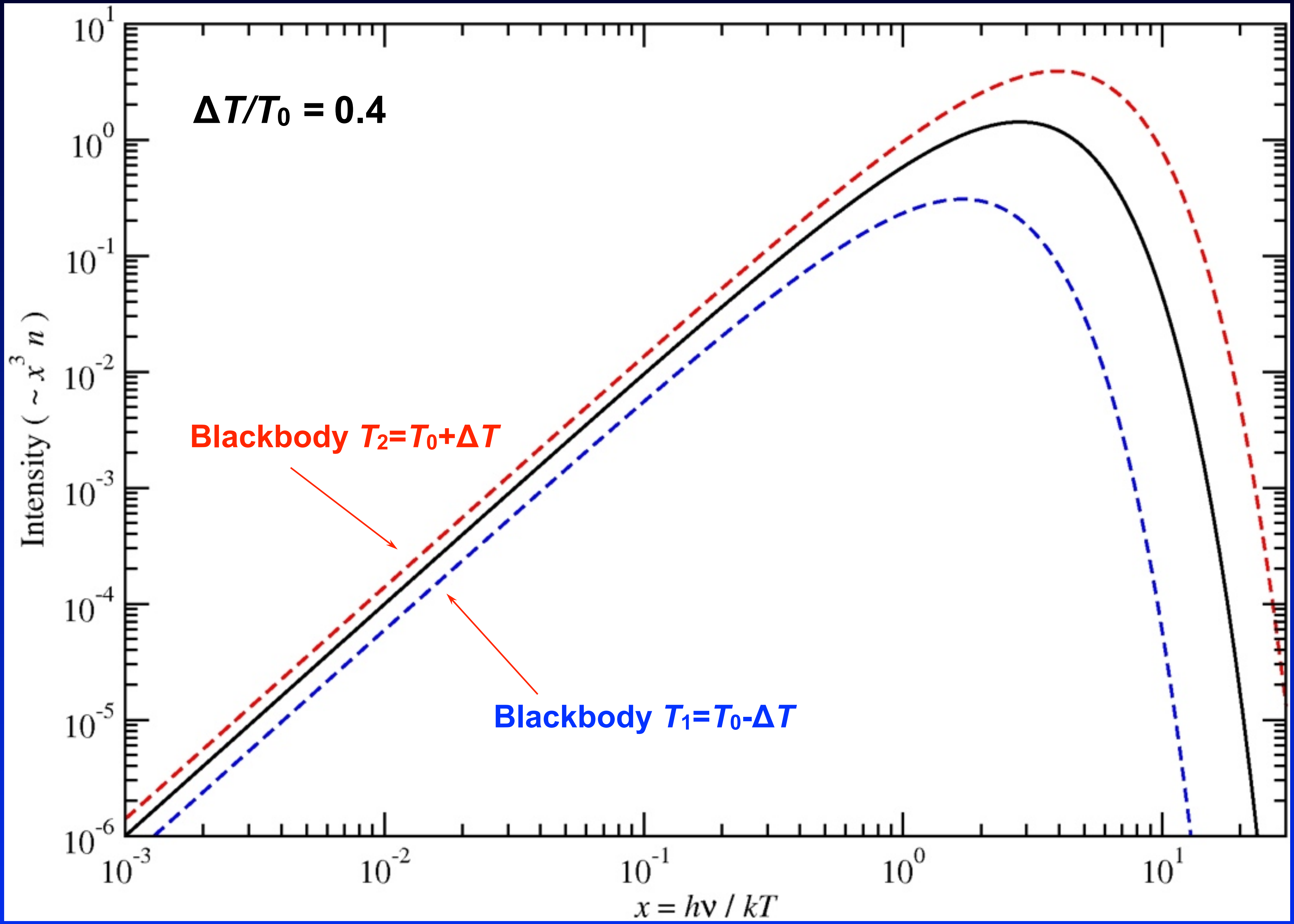
*Where does the 2:1 ratio come from?*

# Superpositions of blackbody spectra




Zeldovich, Illarionov & Sunyaev, 1972
JC & Sunyaev 2004

# Superpositions of blackbody spectra

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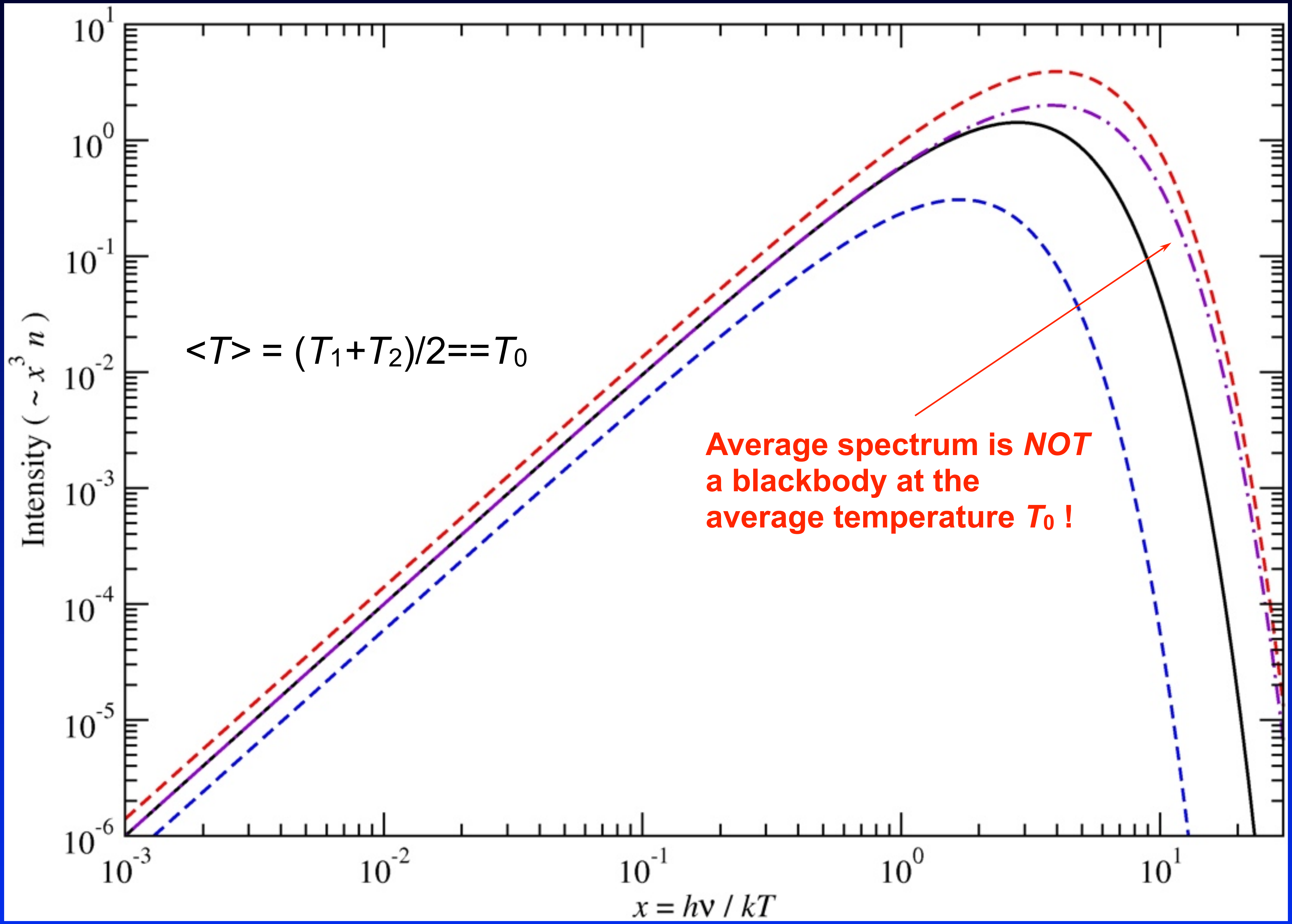
# Superpositions of blackbody spectra

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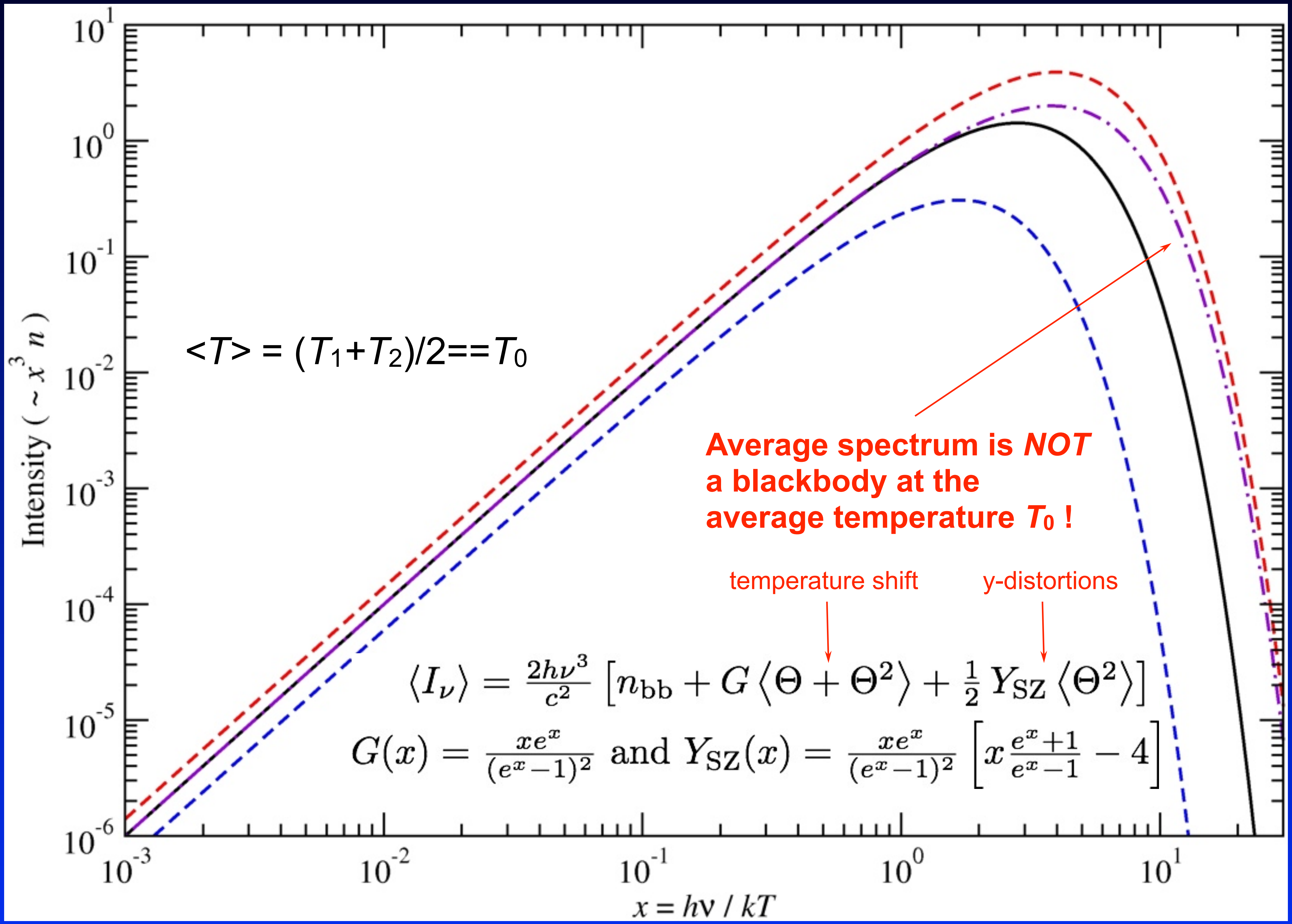


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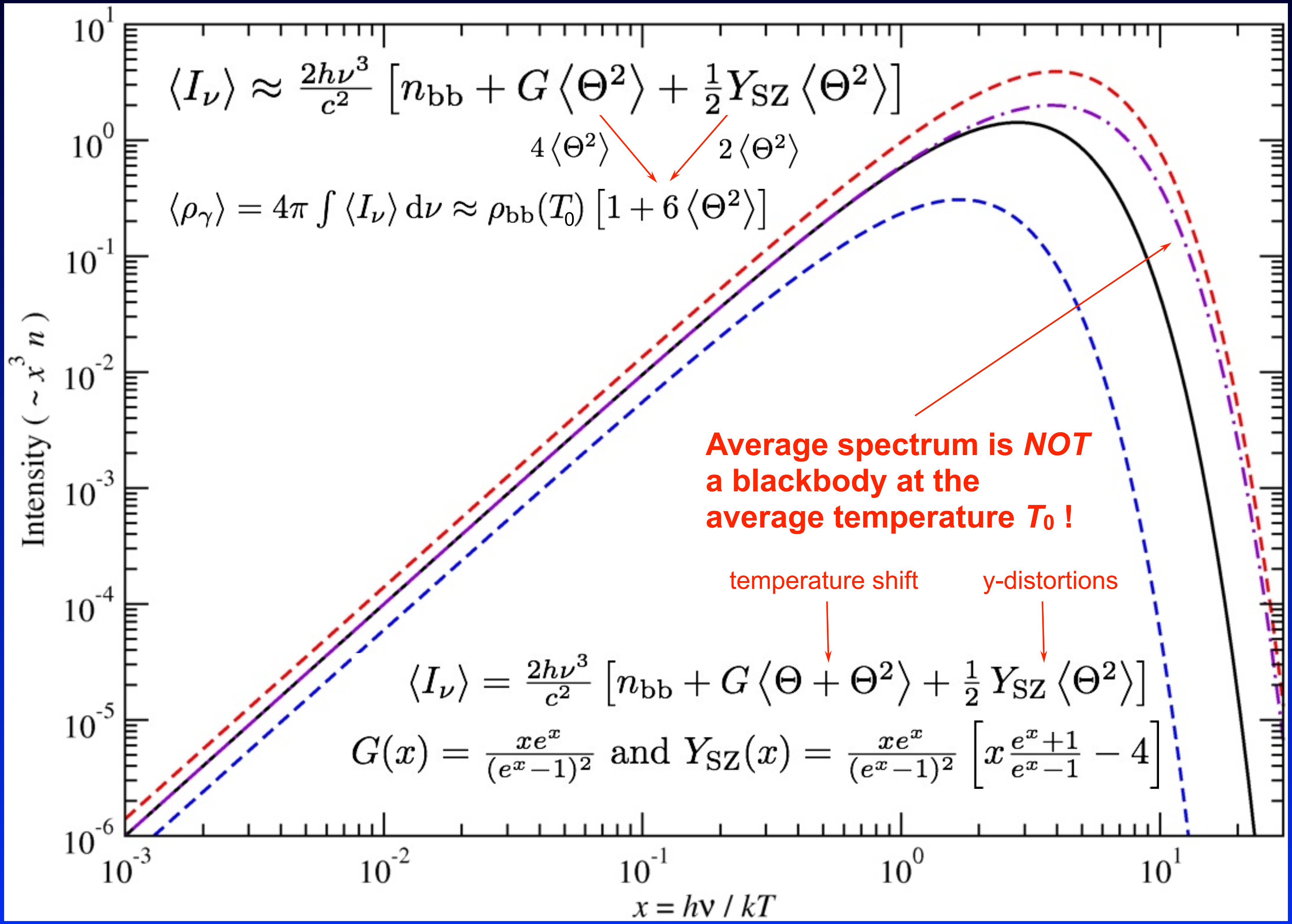


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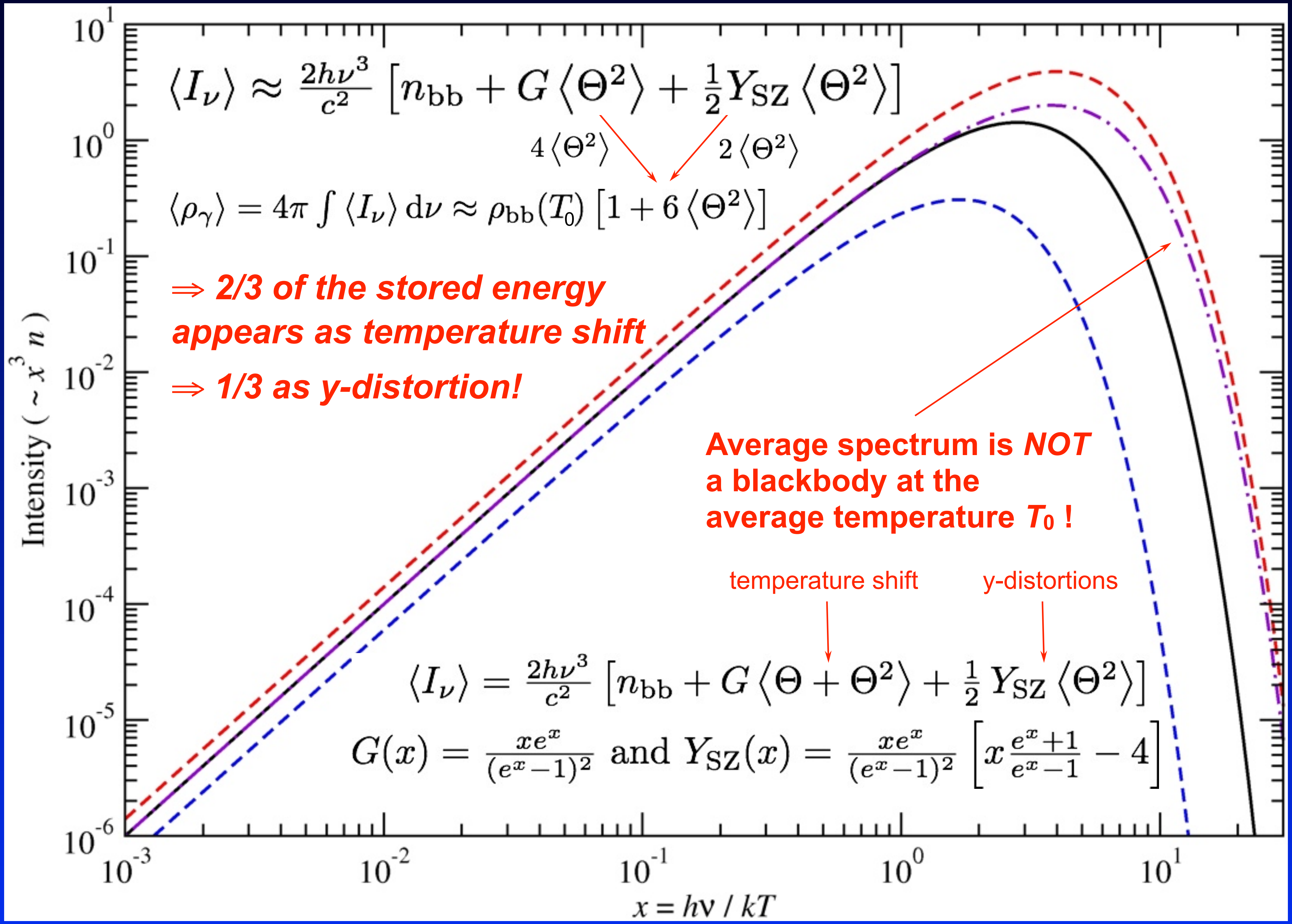


Zeldovich, Illarionov & Sunyaev, 1972
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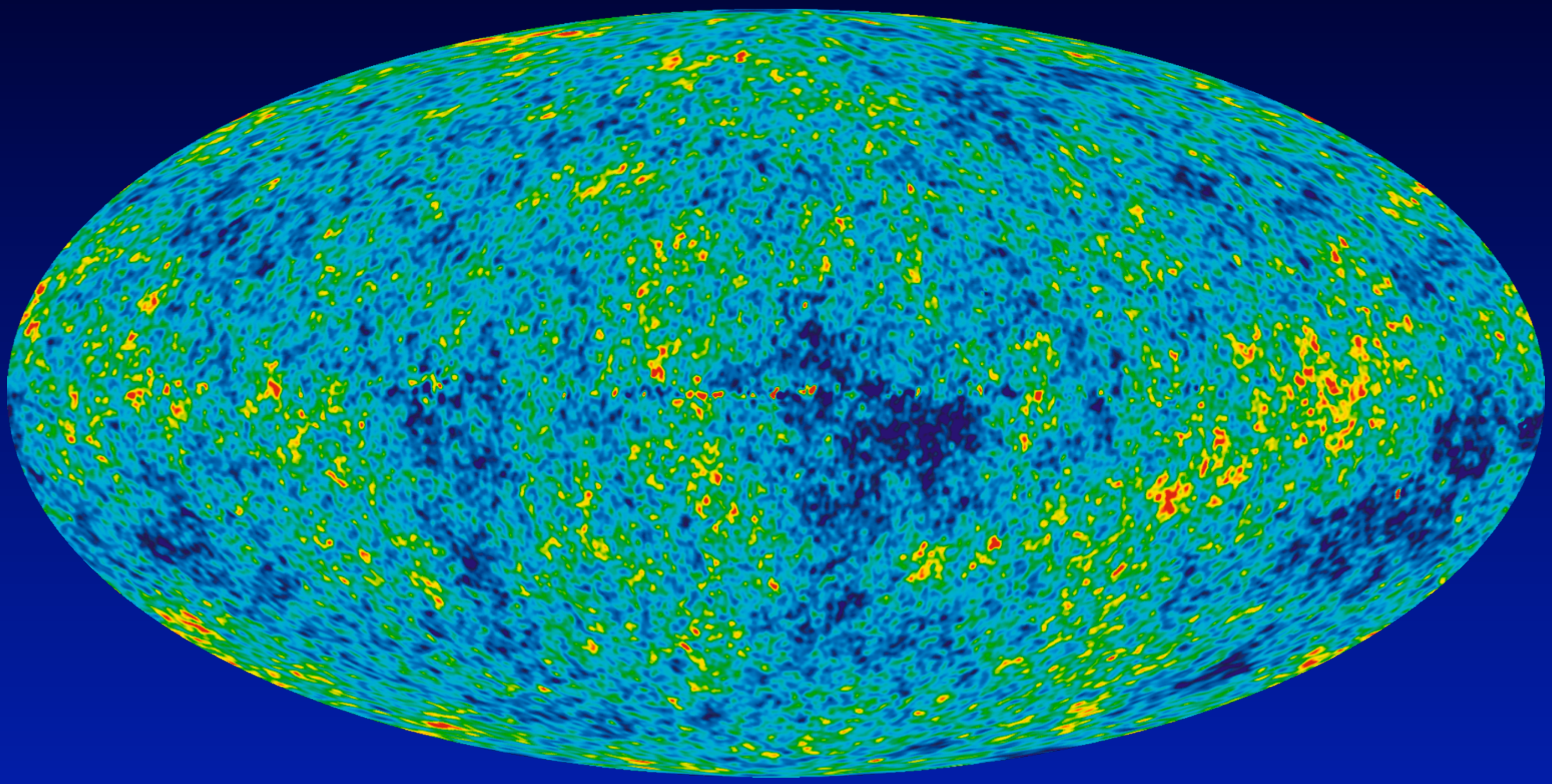
# Distortion caused by superposition of blackbodies



- average spectrum

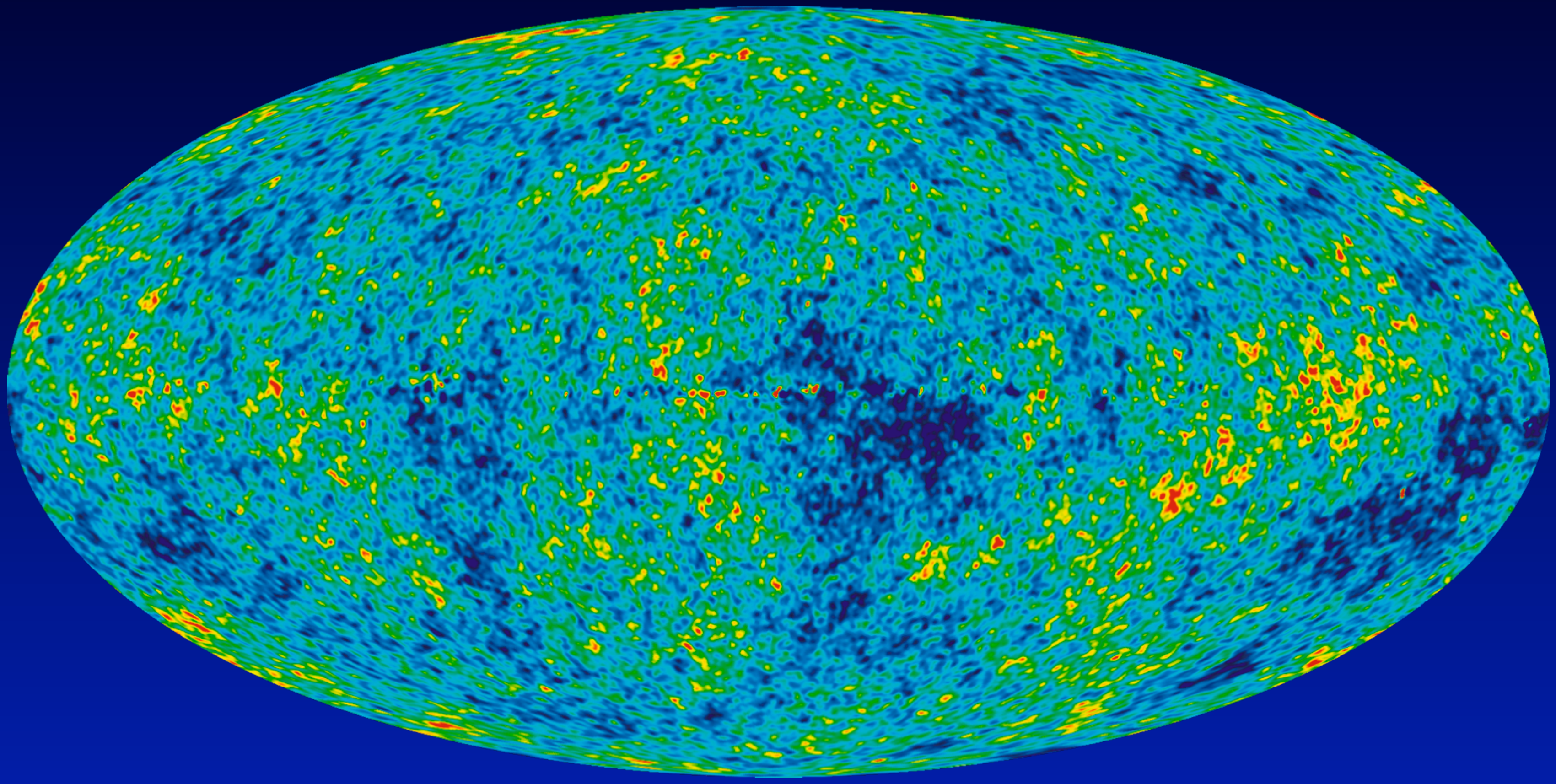
$$\Rightarrow \; y \simeq \frac{1}{2}\left\langle\left(\frac{\Delta T}{T}\right)^2\right\rangle \approx 8\times 10^{-10}$$

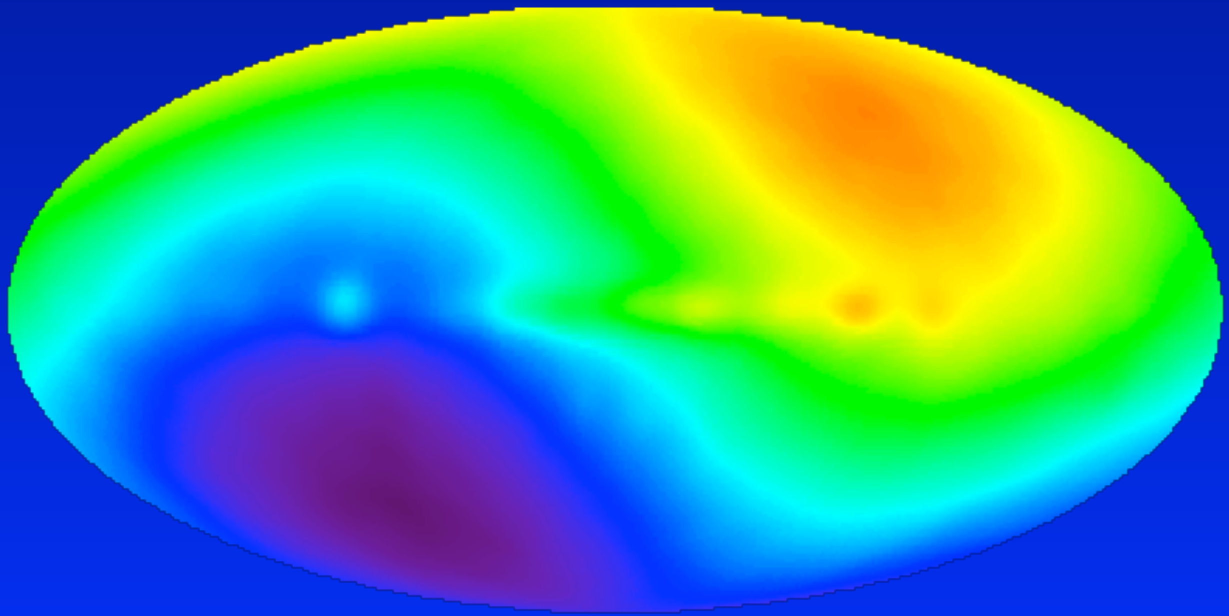
$$\Delta T_{\rm sup} \simeq T\left\langle\left(\frac{\Delta T}{T}\right)^2\right\rangle \approx 4.4{\rm nK}$$

- known with very high precision

JC & Sunyaev, 2004
JC, Khatri & Sunyaev, 2012

# Distortion caused by superposition of blackbodies





COBE/DMR: $\Delta T$ = 3.353 mK

- average spectrum

$$\Rightarrow \; y \simeq \frac{1}{2}\left\langle\left(\frac{\Delta T}{T}\right)^2\right\rangle \approx 8\times10^{-10}$$

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

- known with very high precision

- *CMB dipole* ( $\beta_c \sim 1.23\times10^{-3}$)

$$\Rightarrow \quad y \simeq \frac{\beta_c^2}{6} \approx 2.6\times10^{-7}$$

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

- electrons are up-scattered
- can be taken out at the level of ~ $10^{-9}$

**JC & Sunyaev, 2004**
**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**

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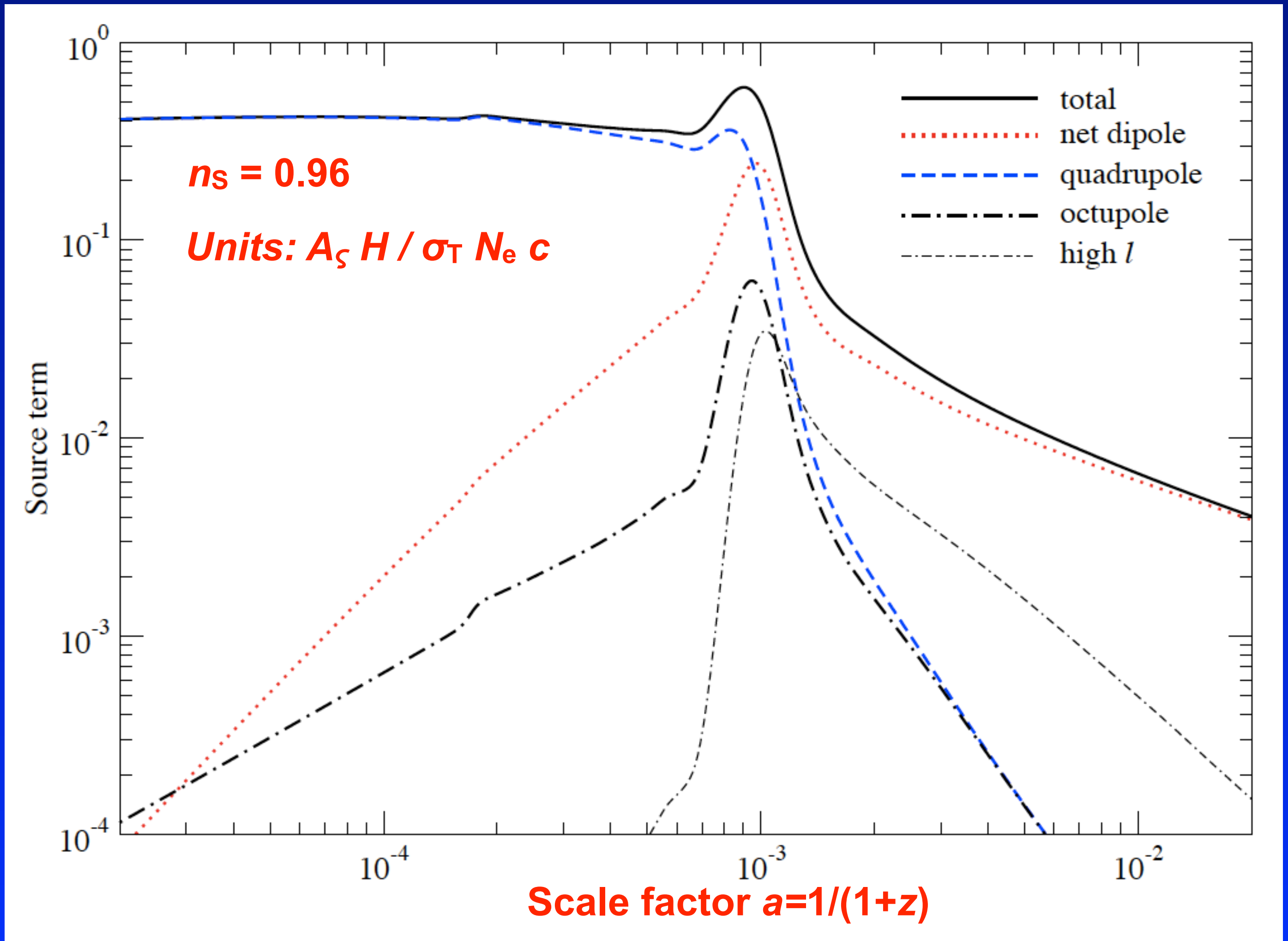
$$\langle XY \rangle = \int \frac{k^2\mathrm{d}k}{2\pi^2} P(k) X(k) Y(k)$$

Primordial power spectrum

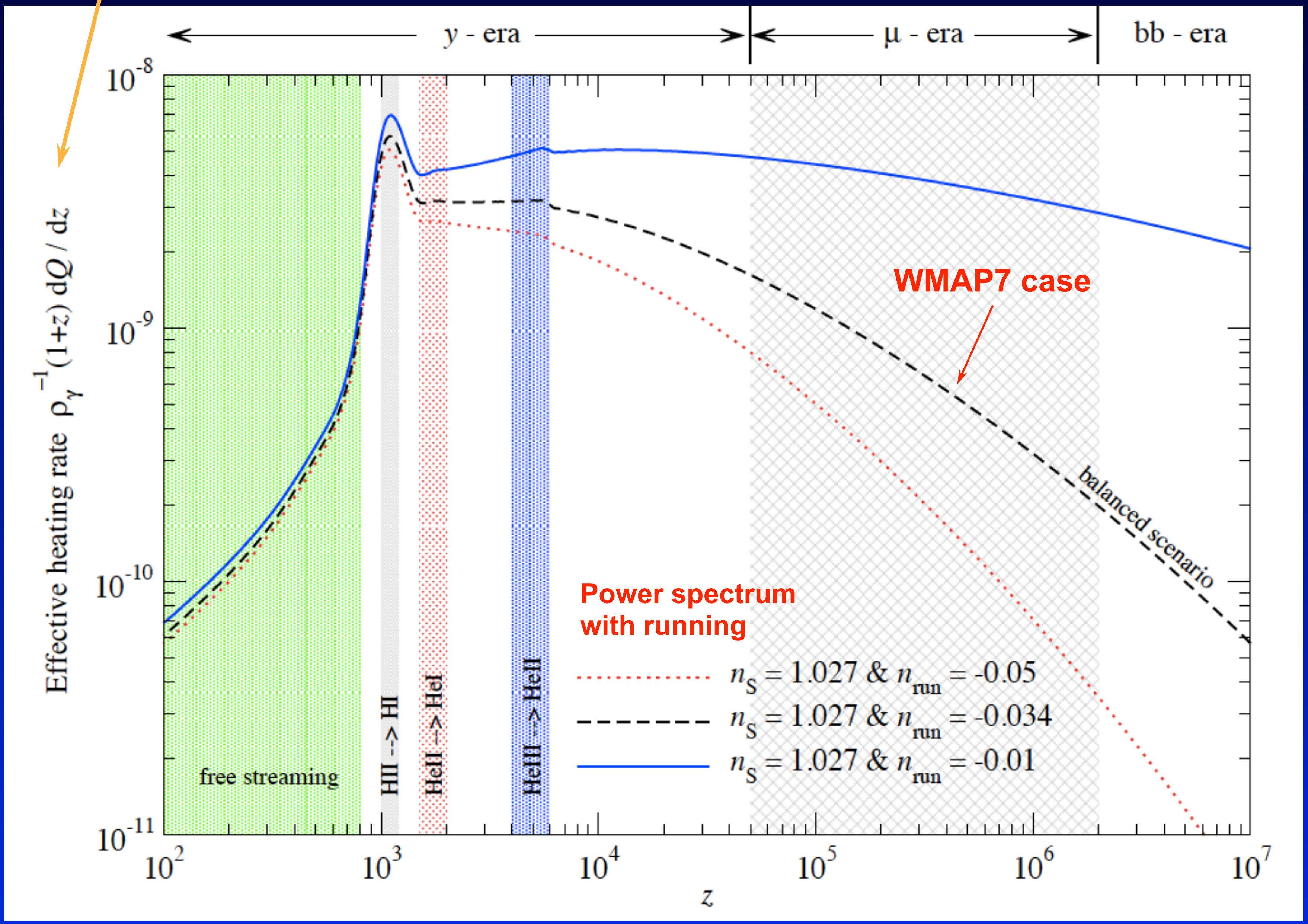
- *quadrupole* dominant at high *z*
- *net dipole* important only at low redshifts
- polarization ~5% effect
- contribution from higher multipoles rather small




JC, Khatri & Sunyaev, 2012

# Our computation for the effective energy release

scaled such that constant for $n_S$ =1



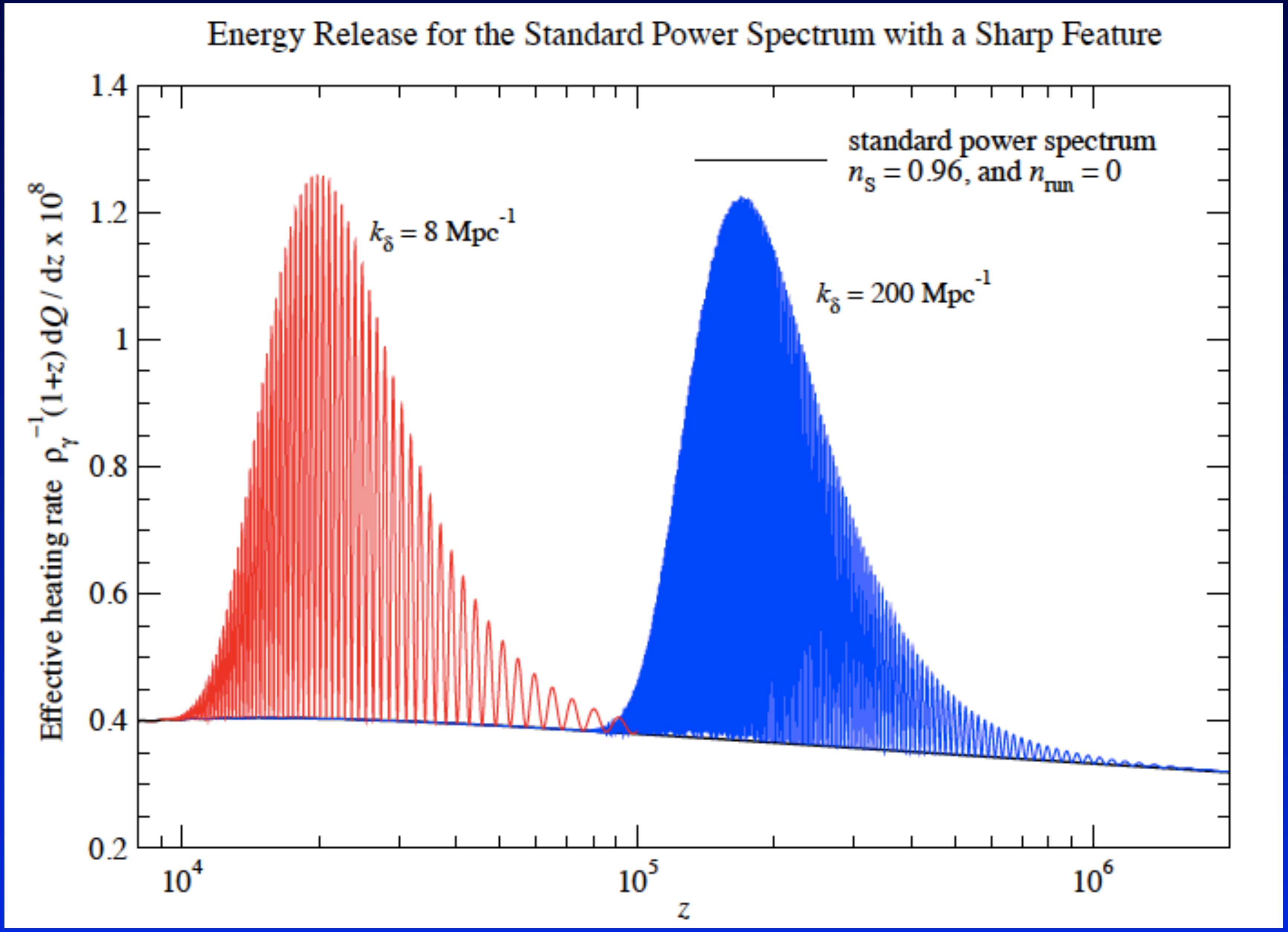

JC, Khatri & Sunyaev, 2012

- Our 2. order perturbation calculation showed that the *classical* picture was slightly inconsistent
- Amplitude of the distortion depends on the small-scale power spectrum
- **Computation carried out with *CosmoTherm***
  **(JC & Sunyaev 2011)**

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

**Primordial power spectrum of curvature perturbations is input for the calculation**

# Which modes dissipate in the μ and y-eras?




JC, Erickcek & Ben-Dayan, 2012

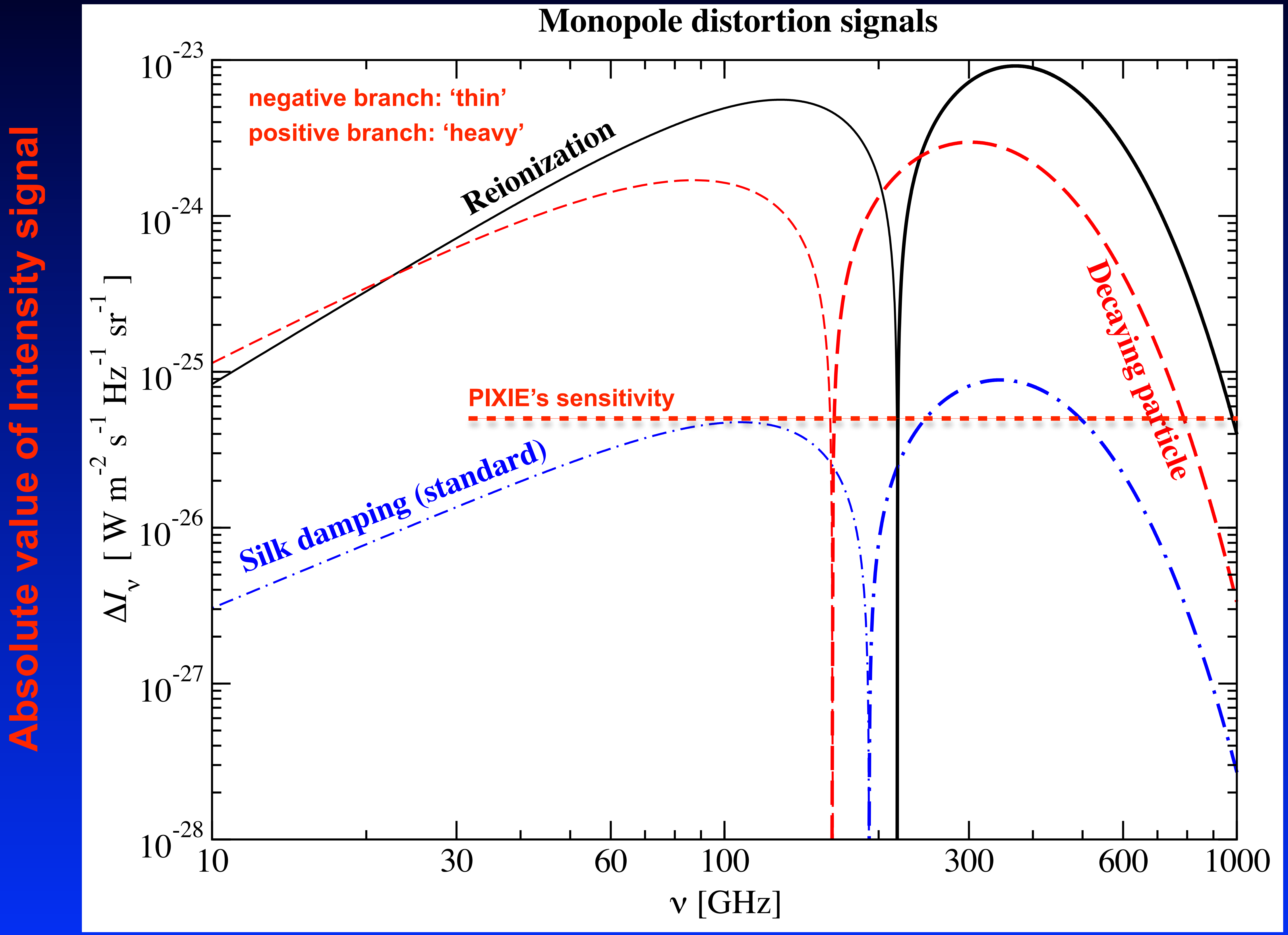
- Single mode with wavenumber $k$ dissipates its energy at

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

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

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

# Average CMB spectral distortions



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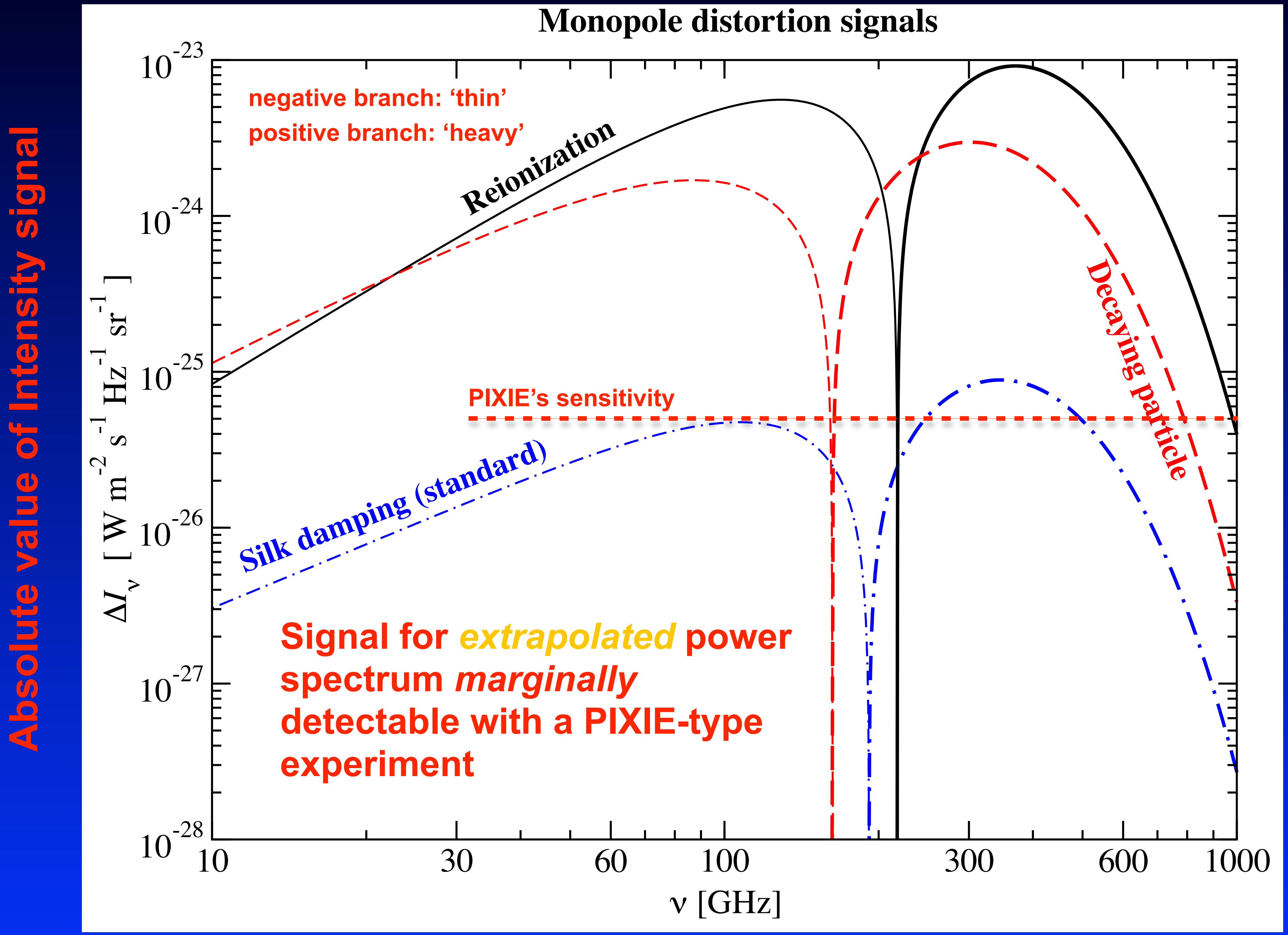
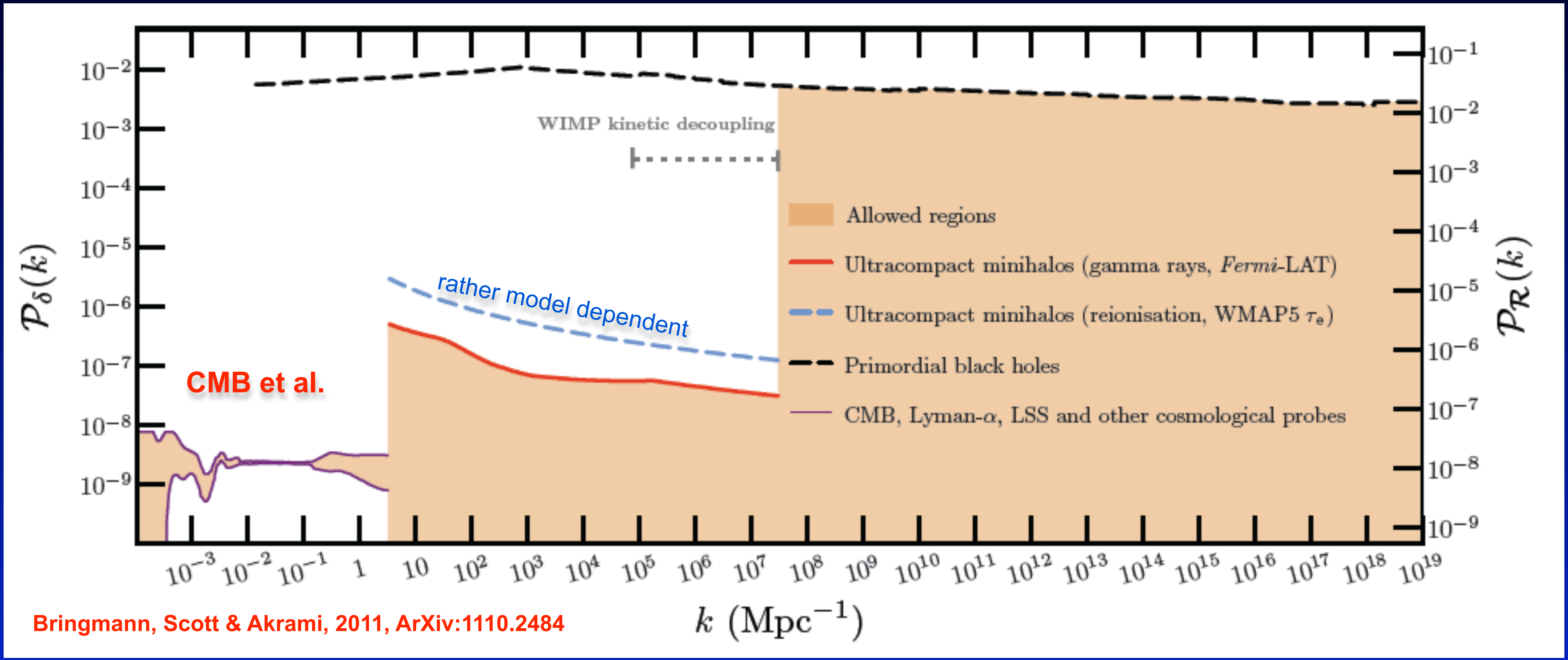


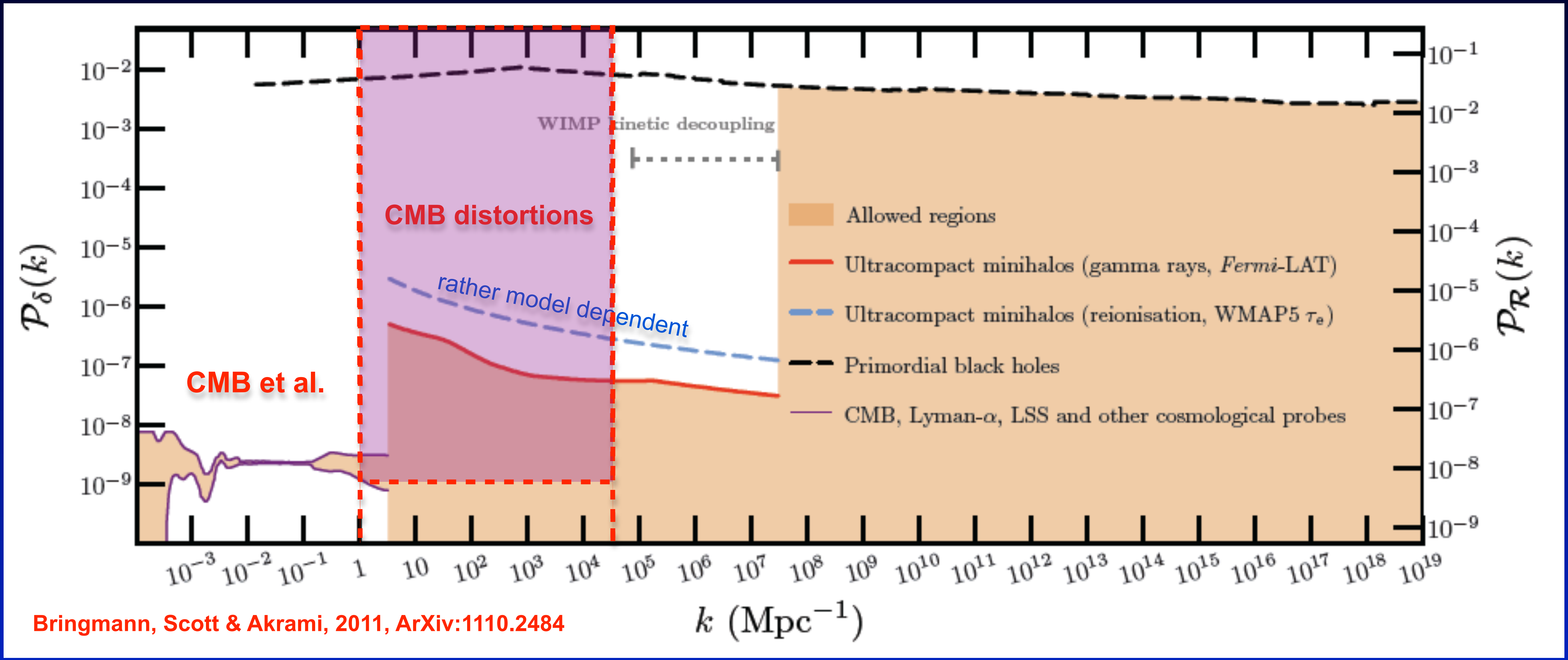
*But this is not all that one could look at !!!*

# Power spectrum constraints



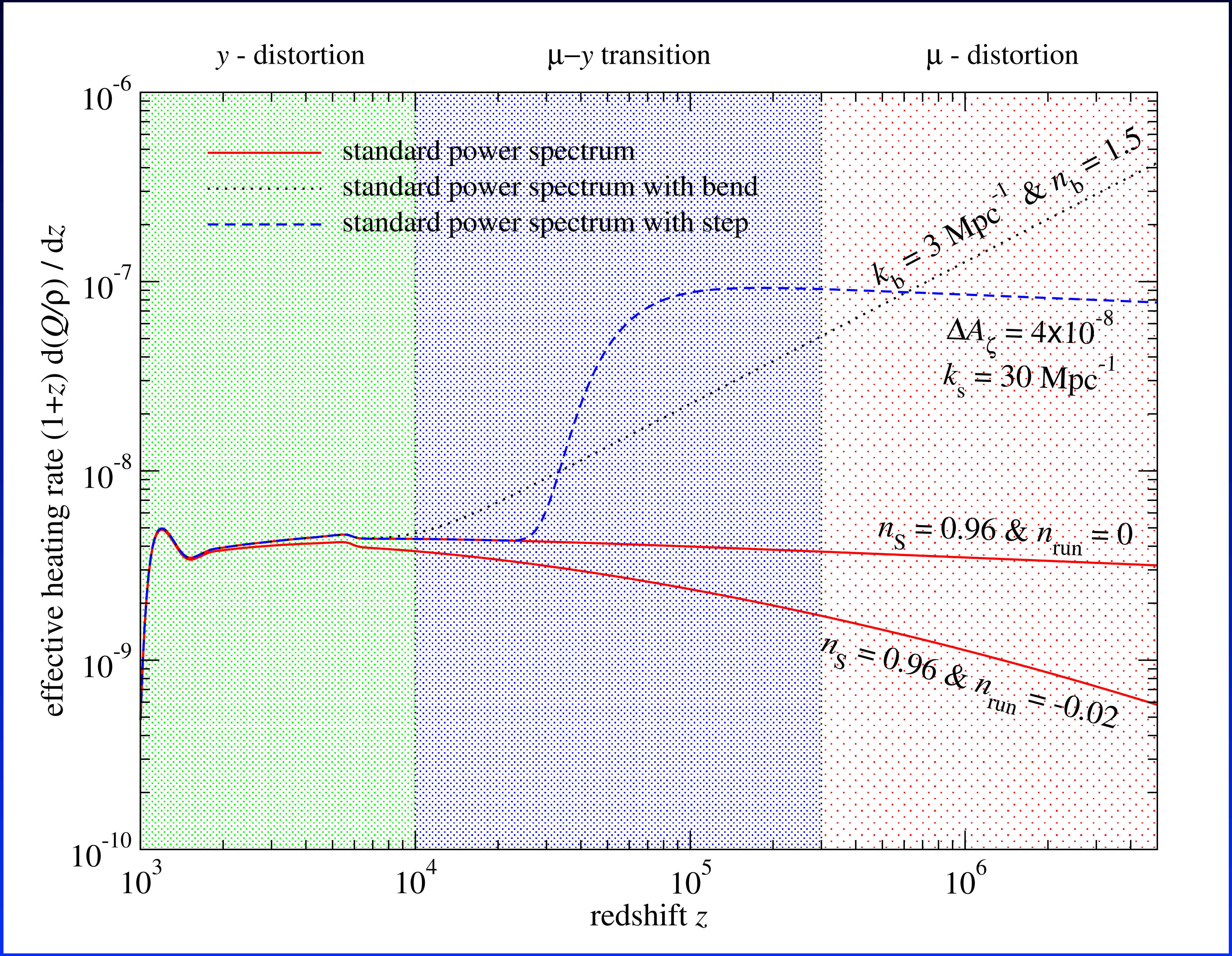

- Amplitude of power spectrum rather uncertain at $k$ > 3 Mpc$^{-1}$
- improving limits at smaller scales would constrain inflationary models

# Power spectrum constraints



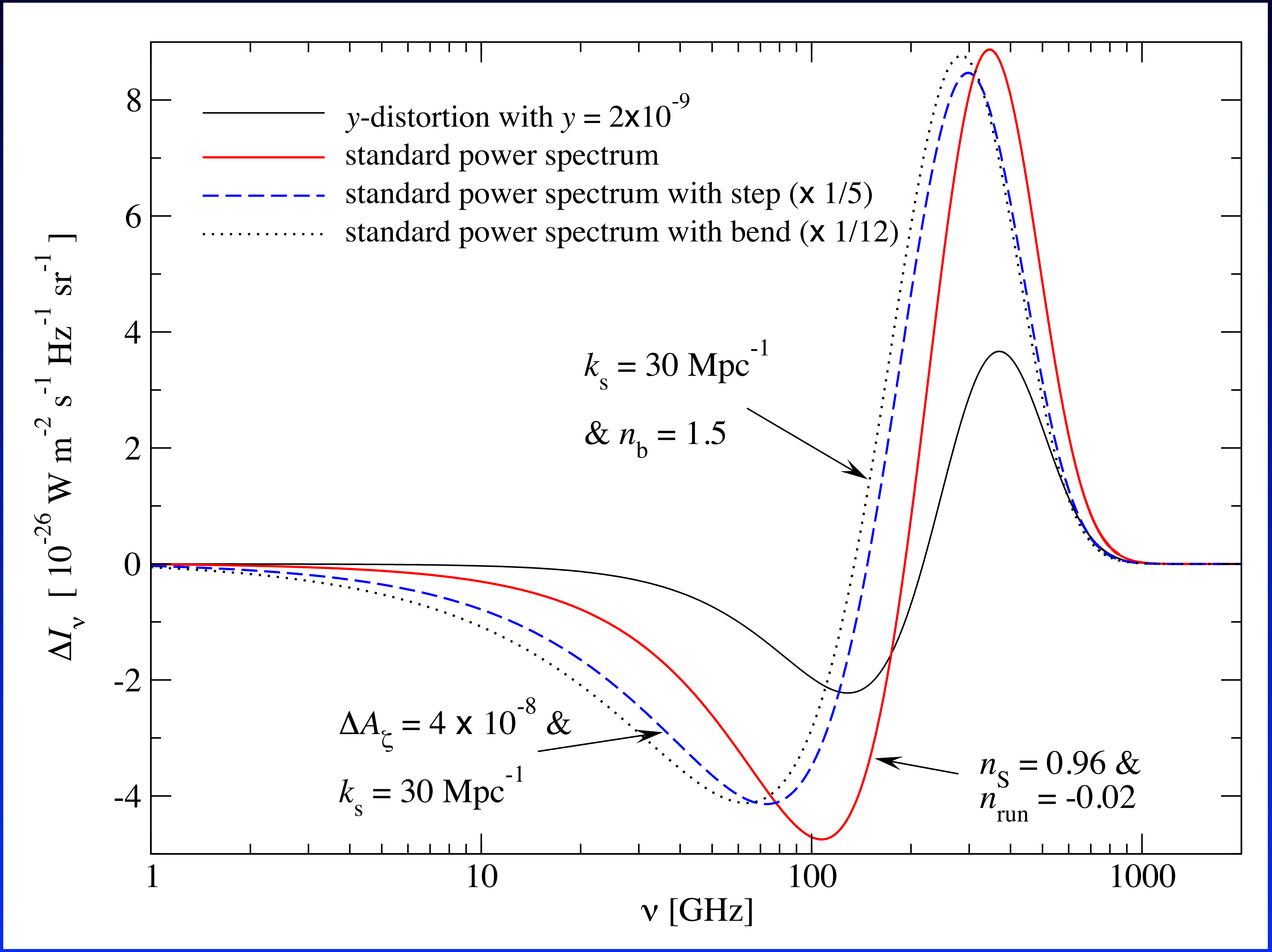

- Amplitude of power spectrum rather uncertain at $k > 3$ Mpc$^{-1}$
- improving limits at smaller scales would constrain inflationary models
- CMB spectral distortions could allow extending our lever arm to $k \sim 10^4$ Mpc$^{-1}$
- See JC, Erickcek & Ben-Dayan, 2012 for constraints on more general P(k)

# Probing the small-scale power spectrum




JC, 2013, Arxiv:1304.6120

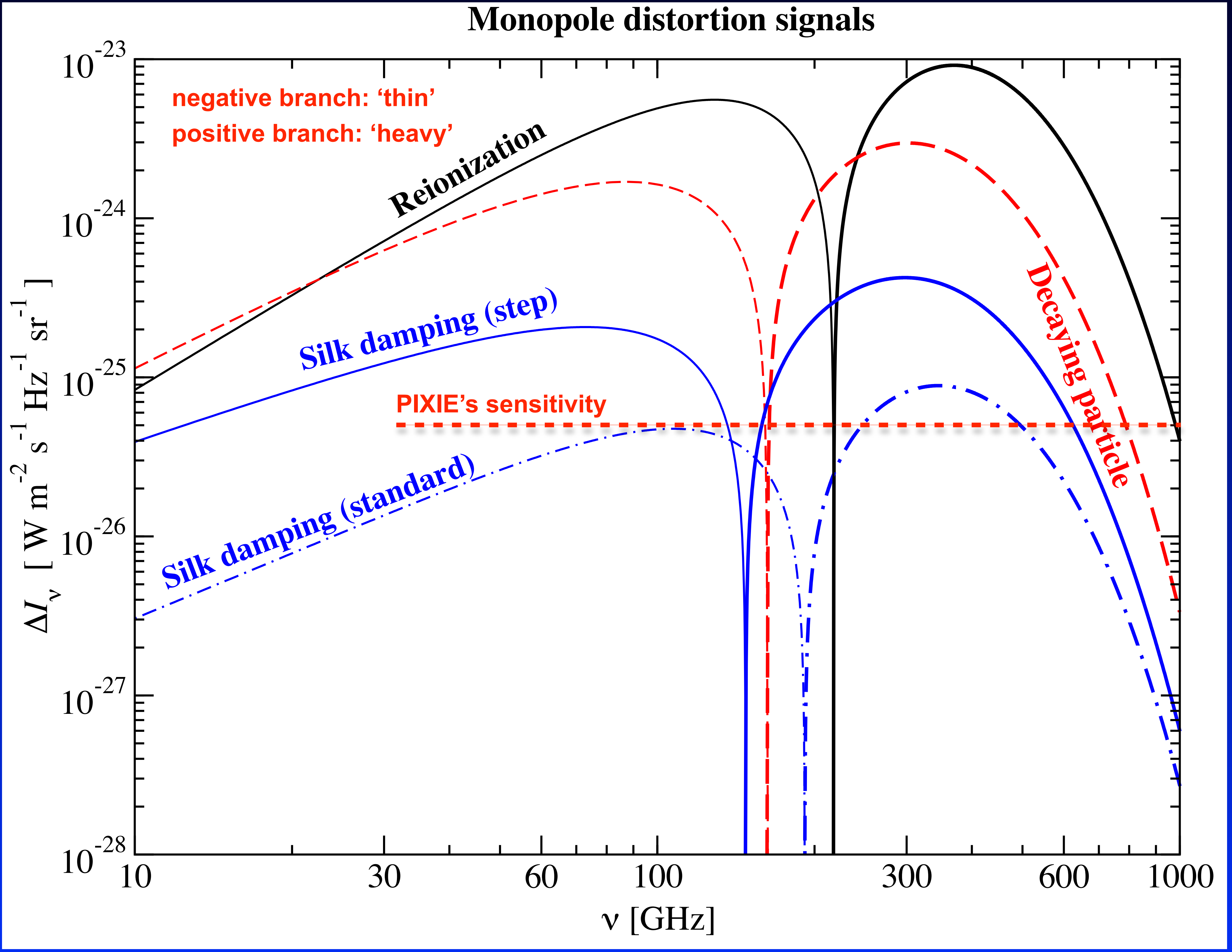
# Probing the small-scale power spectrum




JC, 2013, Arxiv:1304.6120

# Average CMB spectral distortions

Absolute value of Intensity signal



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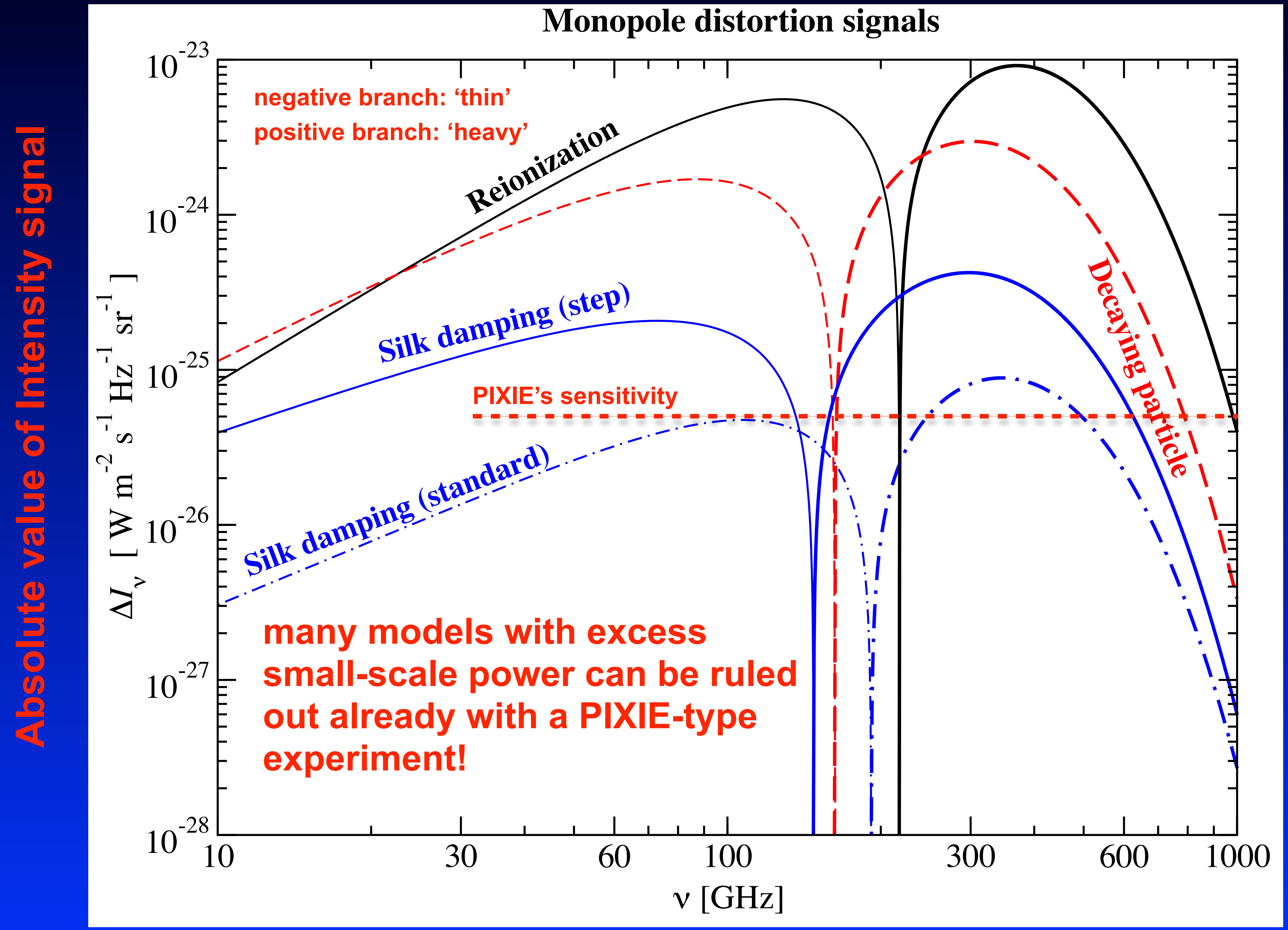

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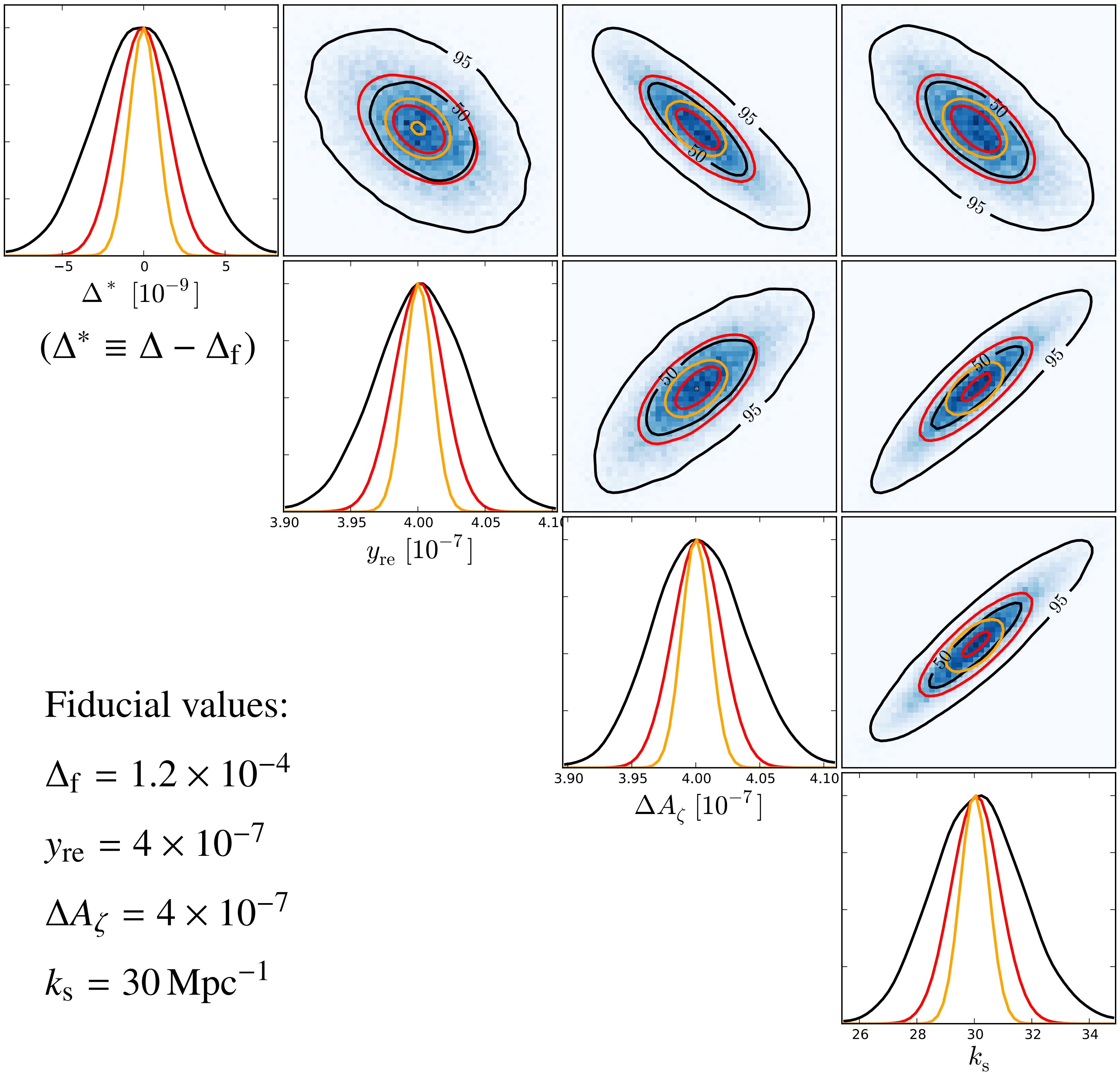



Fiducial values:

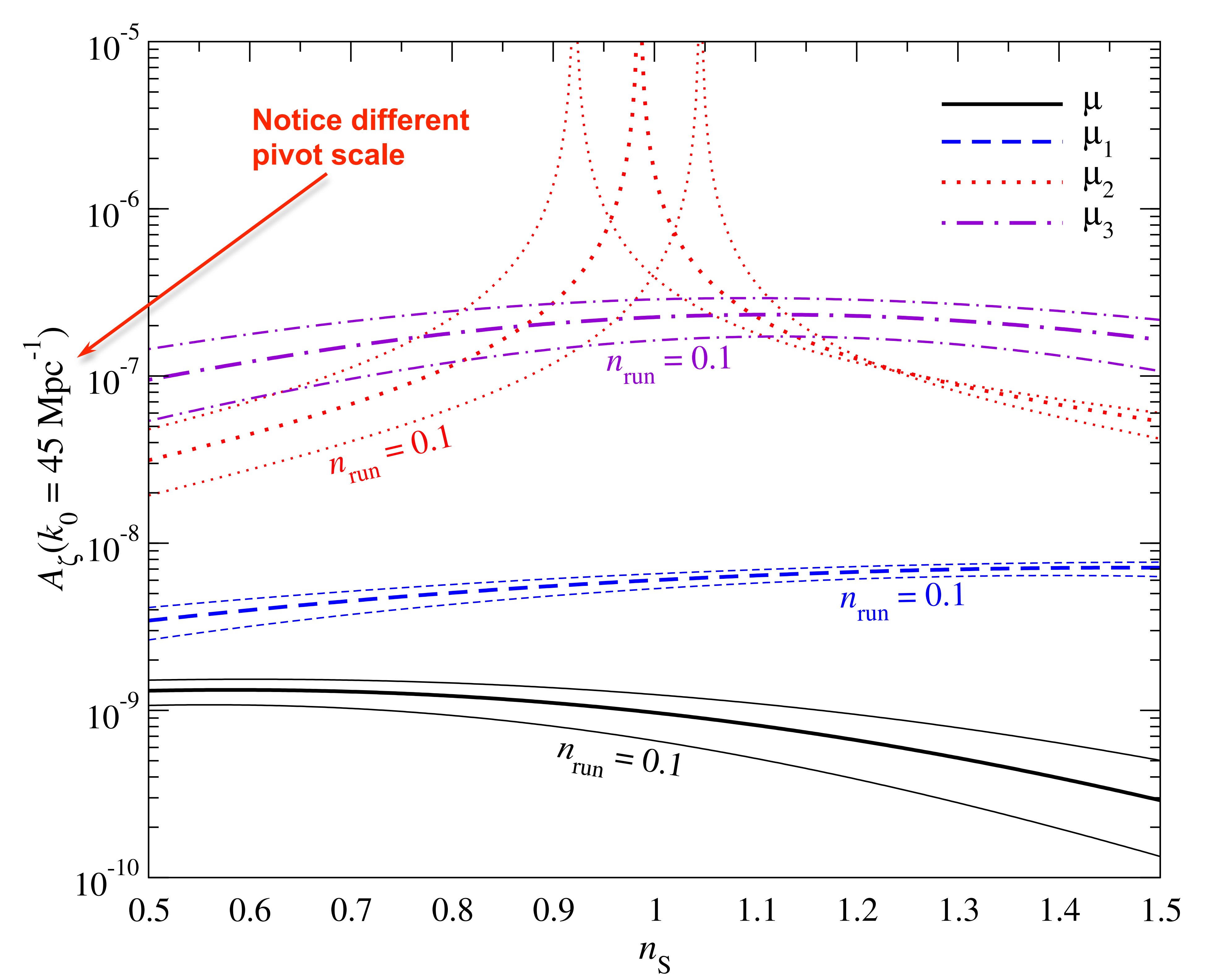
$\Delta_\mathrm{f} = 1.2 \times 10^{-4}$

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

$\Delta A_\zeta = 4 \times 10^{-7}$

$k_\mathrm{s} = 30\,\mathrm{Mpc}^{-1}$

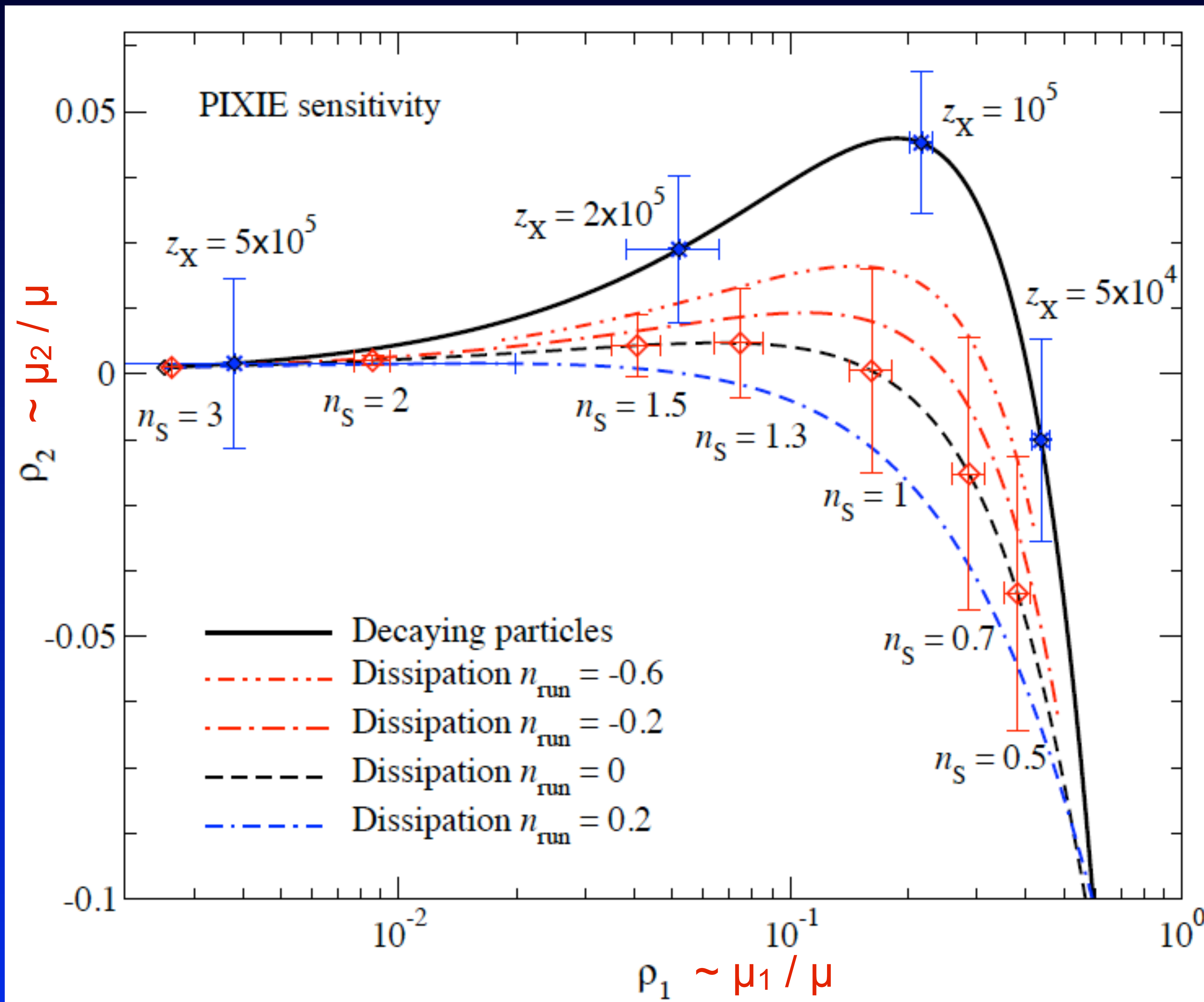
# Dissipation scenario: 1σ-detection limits for PIXIE




JC & Jeong, 2013

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

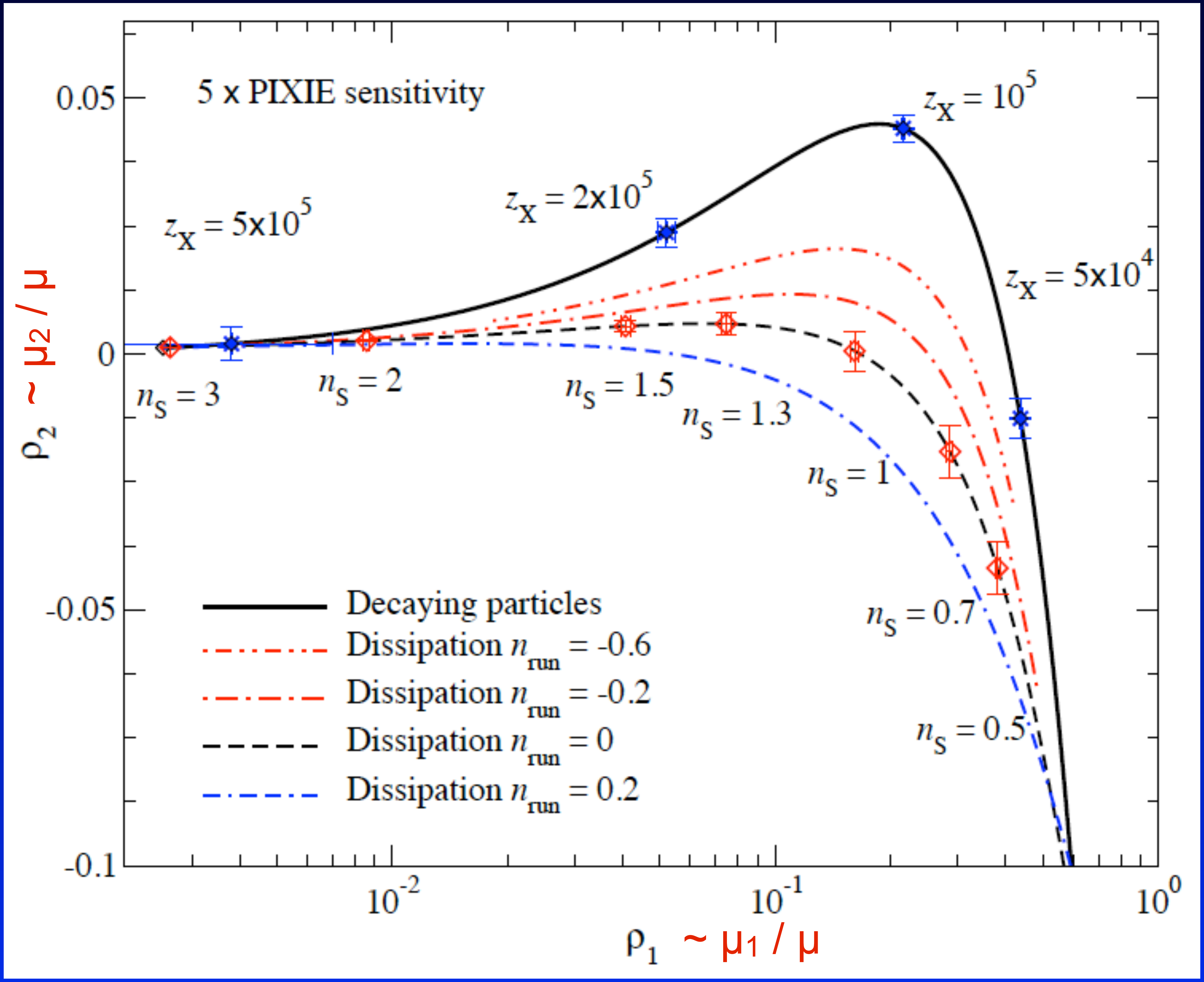
# Distinguishing dissipation and decaying particle scenarios




- measurement of $\mu$, $\mu_1$ & $\mu_2$
- trajectories of decaying particle and dissipation scenarios differ!
- scenarios can in principle be distinguished

JC & Jeong, 2013

# Distinguishing dissipation and decaying particle scenarios

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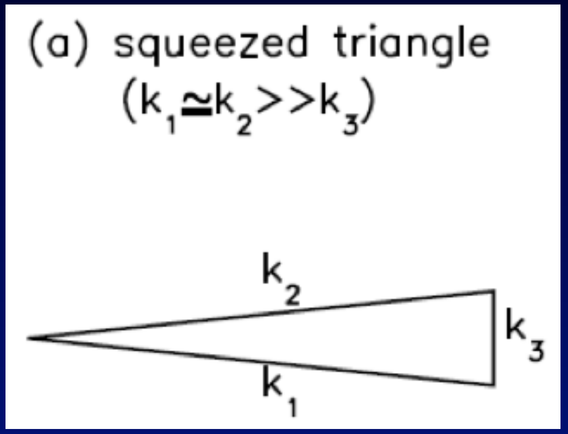
JC & Jeong, 2013

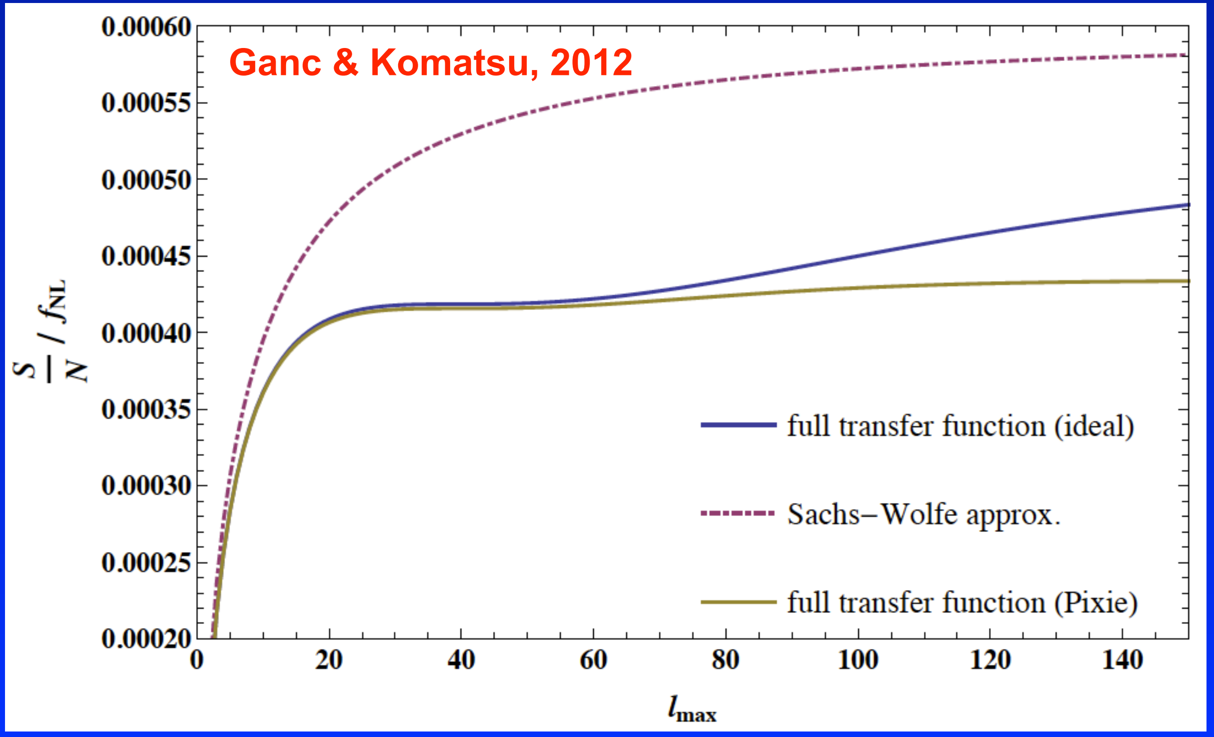
# Modified μ-distortion in the squeezed limit



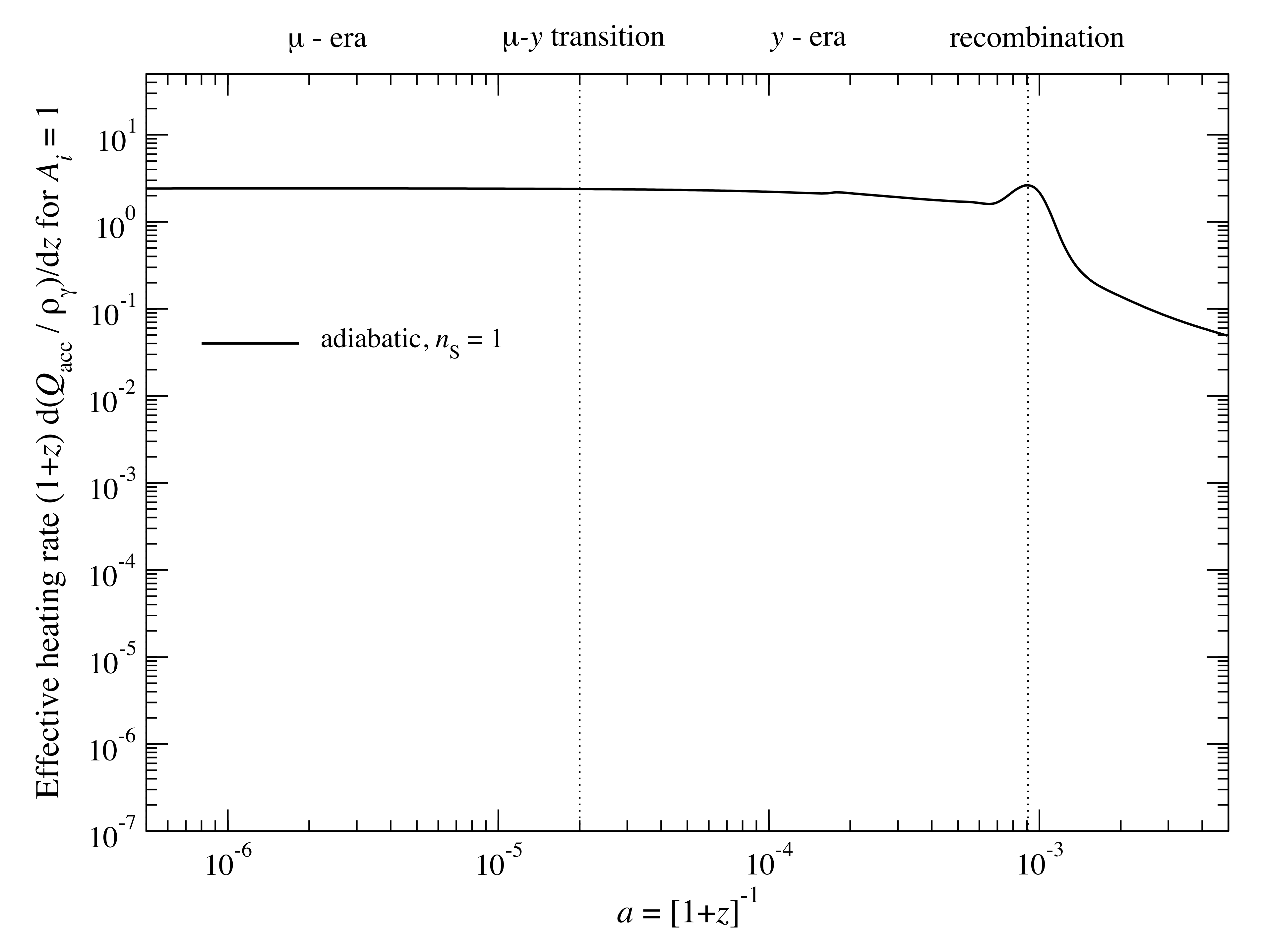

- Modes that dissipate energy have $k_1 \approx k_2 >> k_3$
- Non-Gaussian power spectrum → presence of positive long-wavelength mode enhances small-scale power
- More small-scale power → larger μ-distortion
- → Spatially varying μ-distortion caused by non-Gaussianity! (Pajer & Zaldarriaga, 2012; Ganc & Komatsu, 2012)
- Non-vanishing μ-T correlation at large scales
- Might be detectable with PIXIE-type experiment for $f_{NL} > 10^3$

Requirements

- precise cross-calibration of frequency channels
- higher angular resolution does not improve cumulative S/N



# Dependence of heating rate on the perturbation type




- Adiabatic modes: heating rate ~ $1/z$ at high $z$

JC & Grin, 2013

$$P_i(k) = 2\pi^2 A_i k^{-3} (k/k_0)^{n_i - 1}$$

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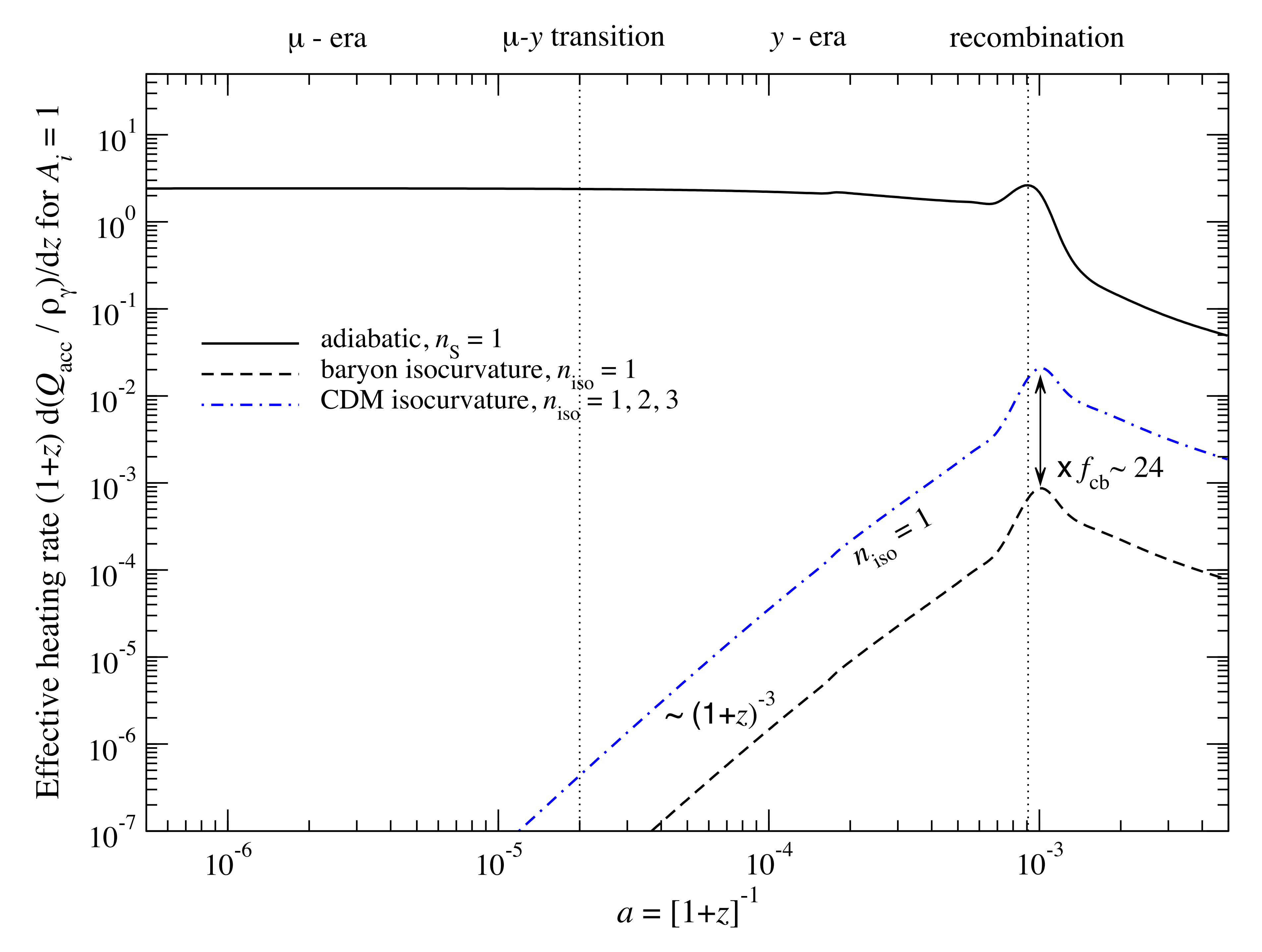



- Adiabatic modes: heating rate ~ $1/z$ at high $z$
- baryon/CDM iso-curvature modes:

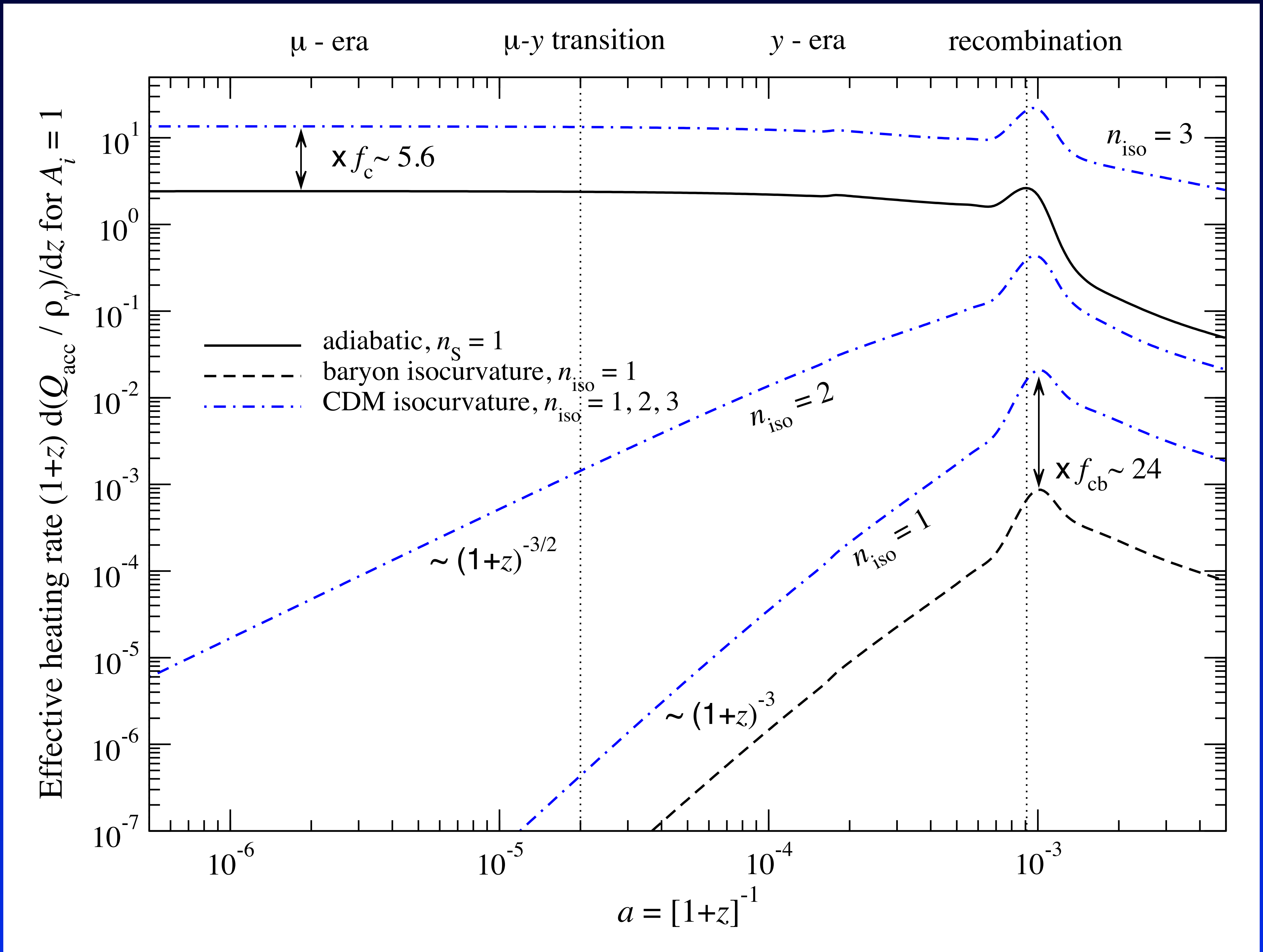
  $A \sim k/k_{eq}$

  during radiation dominated epoch

JC & Grin, 2013

$$P_i(k) = 2\pi^2 A_i k^{-3} (k/k_0)^{n_i - 1}$$

# Dependence of heating rate on the perturbation type




- Adiabatic modes: heating rate ~ $1/z$ at high $z$
- baryon/CDM iso-curvature modes:

  $A \sim k/k_{eq}$

  during radiation dominated epoch
- $n_{iso} \sim 3 \Rightarrow$ heating rate ~ $1/z$

JC & Grin, 2013

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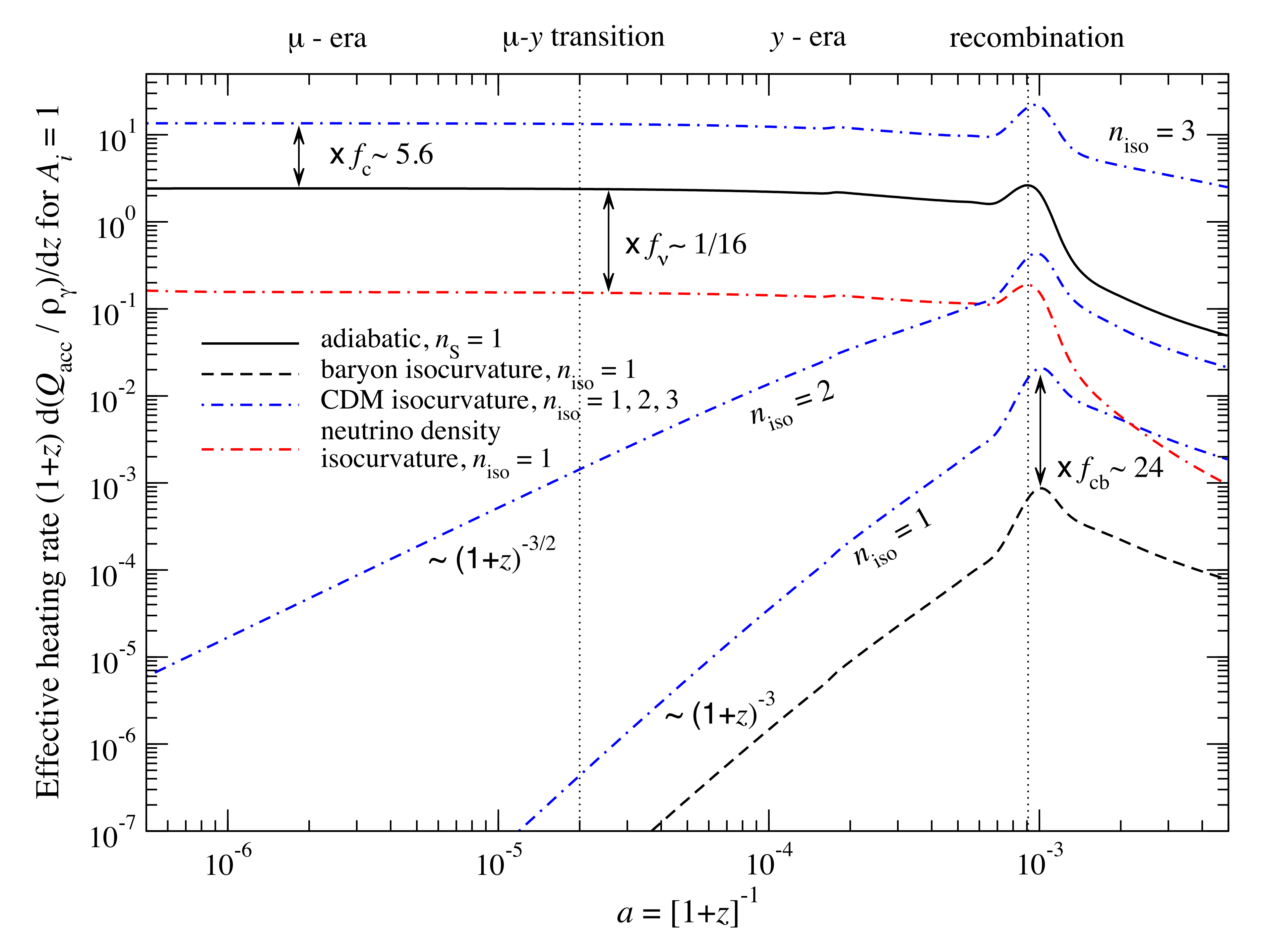


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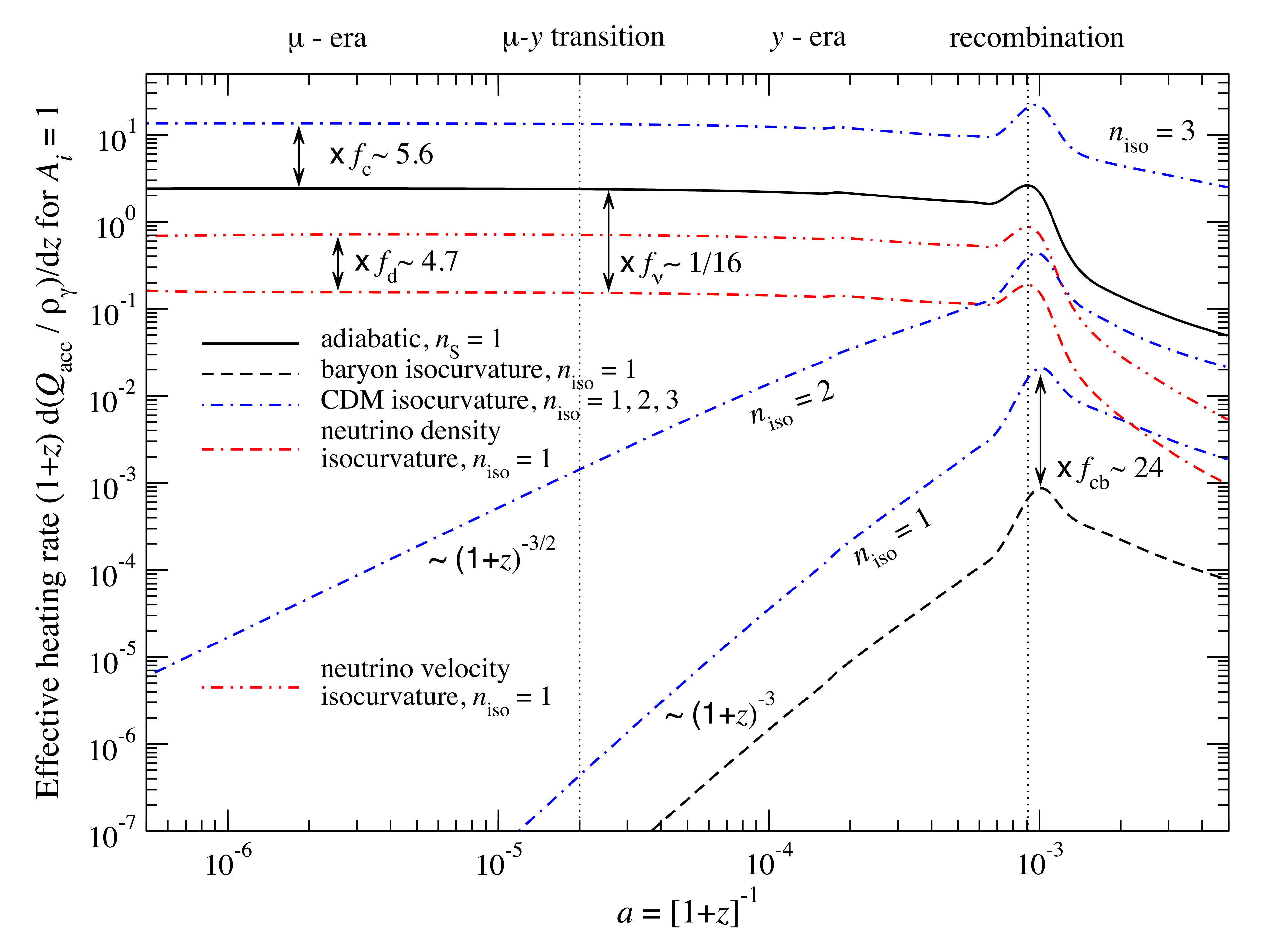


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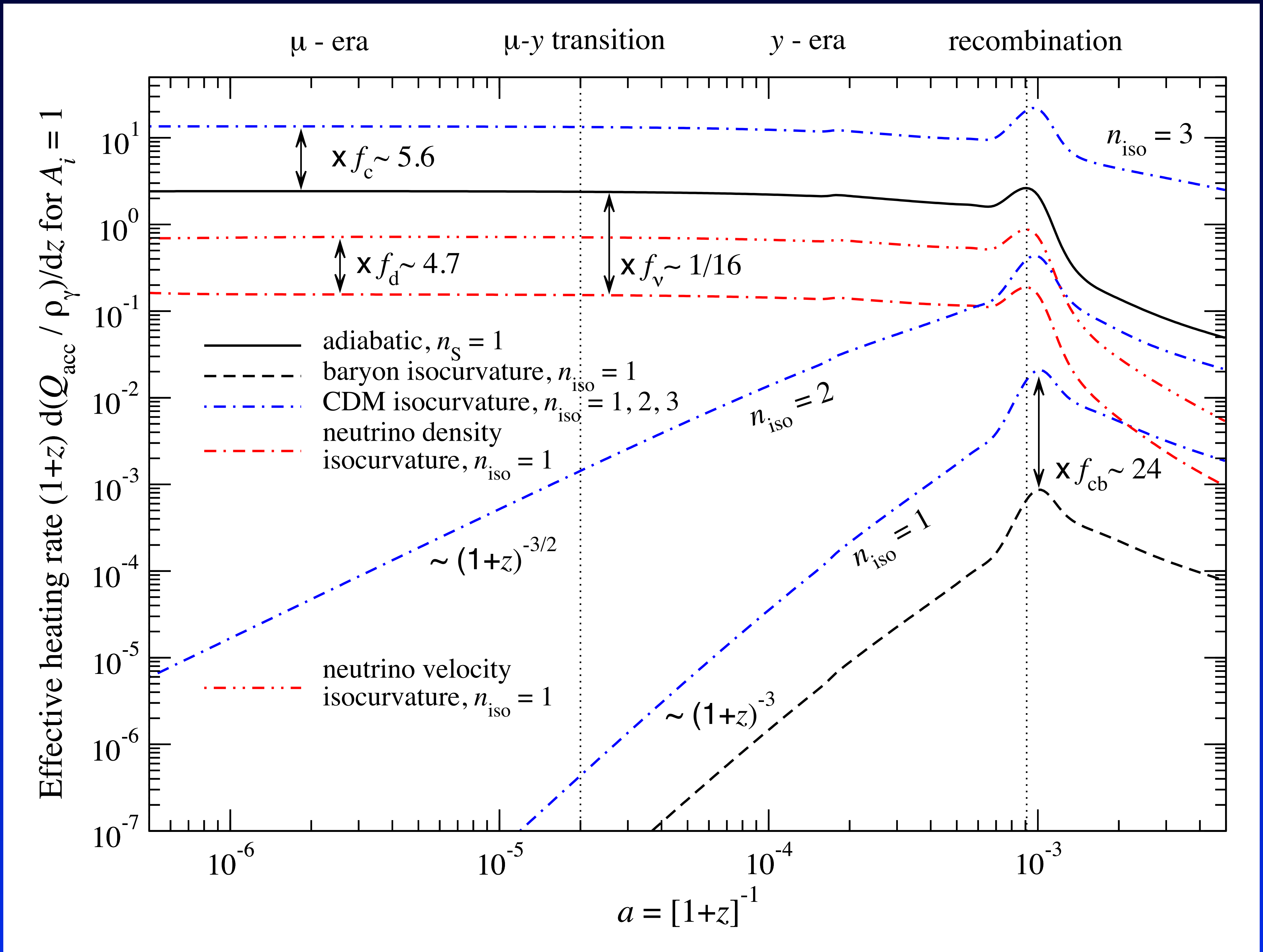


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  $A \sim k/k_{eq}$

  during radiation dominated epoch
- $n_{iso} \sim 3 \Rightarrow$ heating rate ~ $1/z$
- neutrino iso-curvature modes very similar to adiabatic modes
- compensated isocurvature modes: practically no heating

JC & Grin, 2013

$$P_i(k) = 2\pi^2 A_i k^{-3} (k/k_0)^{n_i - 1}$$

*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!

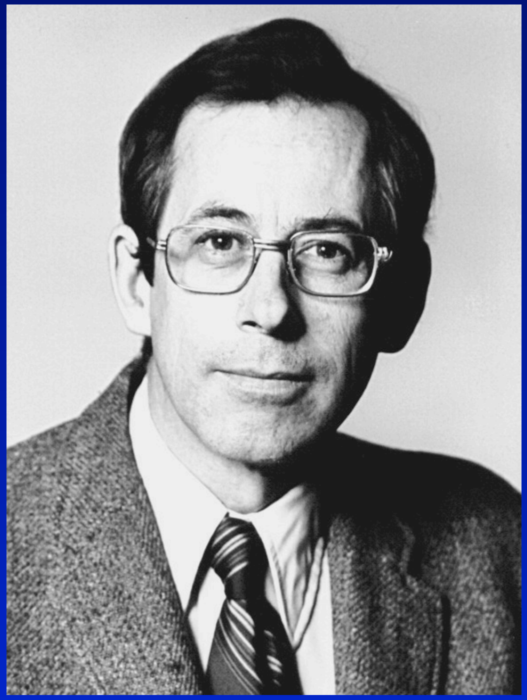
# First recombination computations completed in 1968!

Yakov Zeldovich

**Moscow**

**Princeton**

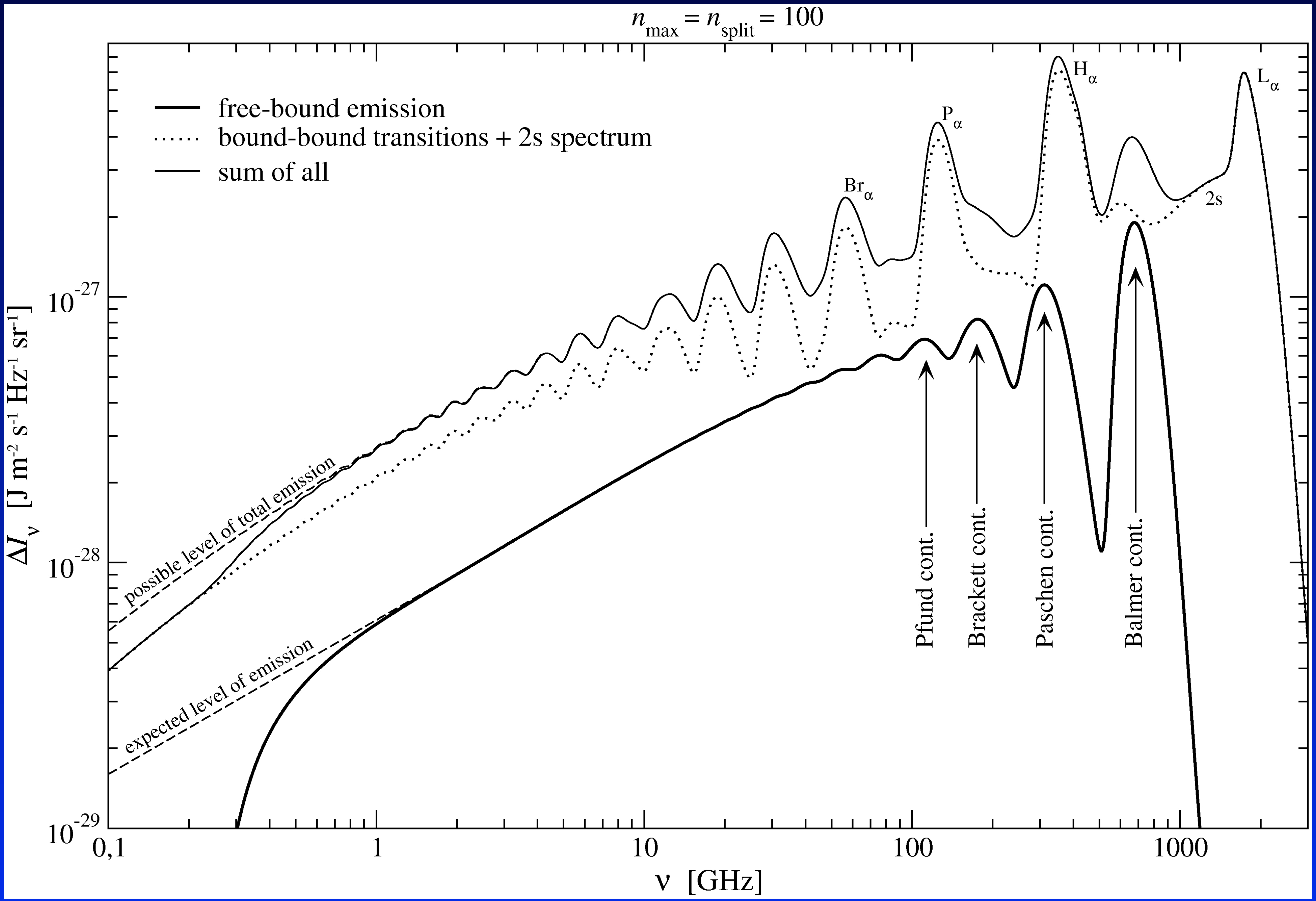
Rashid Sunyaev



Jim Peebles

Vladimir Kurt
(UV astronomer)

# 100-shell hydrogen atom and continuum
## *CMB spectral distortions*




**bound-bound & 2s:**

- at $\nu$ > 1GHz: distinct features
- slope ~ 0.46

**free-bound:**

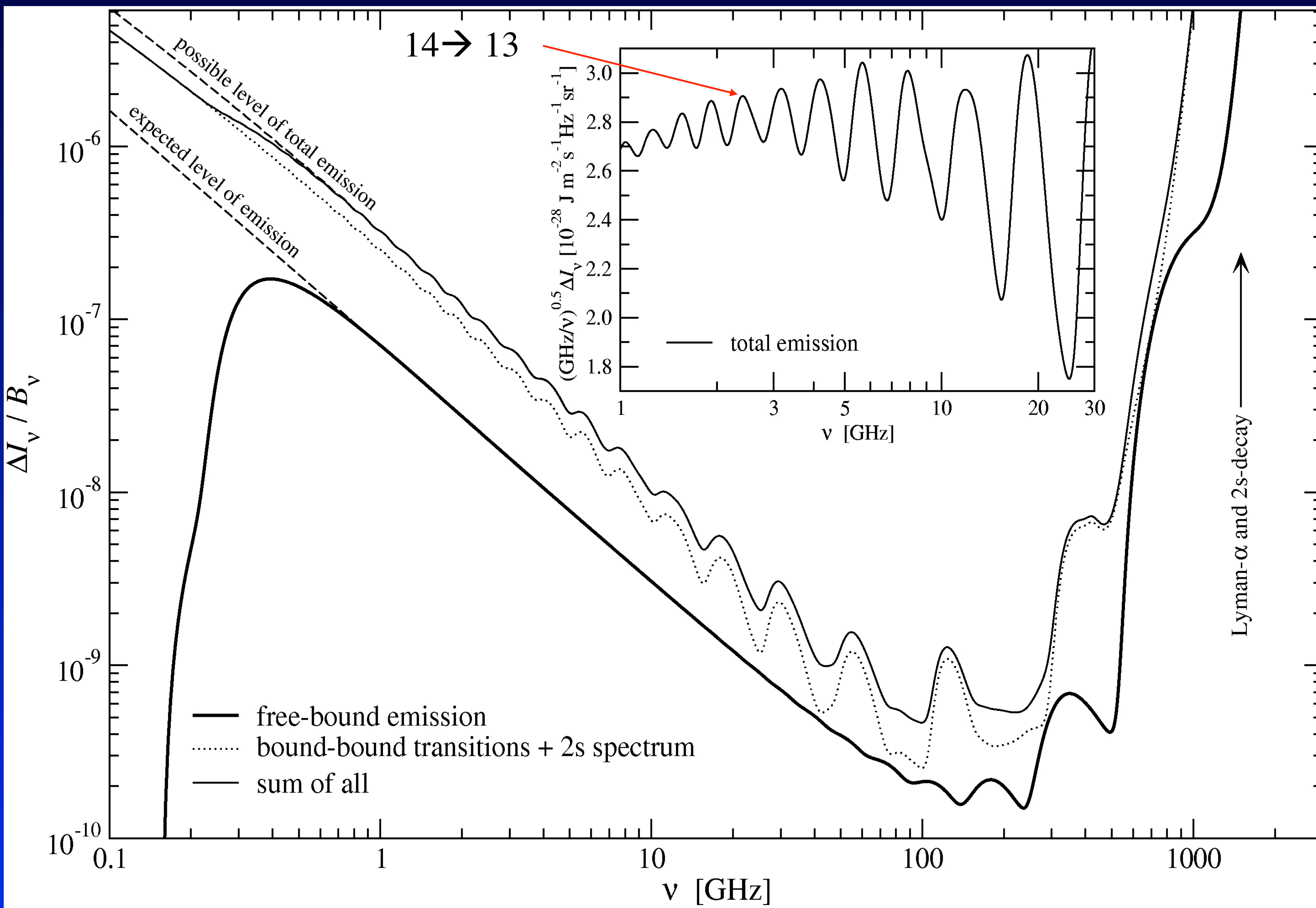
- only a few features distinguishable
- slope ~ 0.6

**Total:**

- f-b contributes ~ 30% and more
- Balmer cont. ~ 90%
- Balmer: 1$\gamma$ per HI
- in total 5$\gamma$ per HI

**JC & Sunyaev, 2006, A&A, 458, L29 (astro-ph/0608120)**

# 100-shell hydrogen atom and continuum
## *Relative distortions*




**Wien-region:**

- $L_\alpha$ and 2s distortions are very strong
- but CIB more dominant

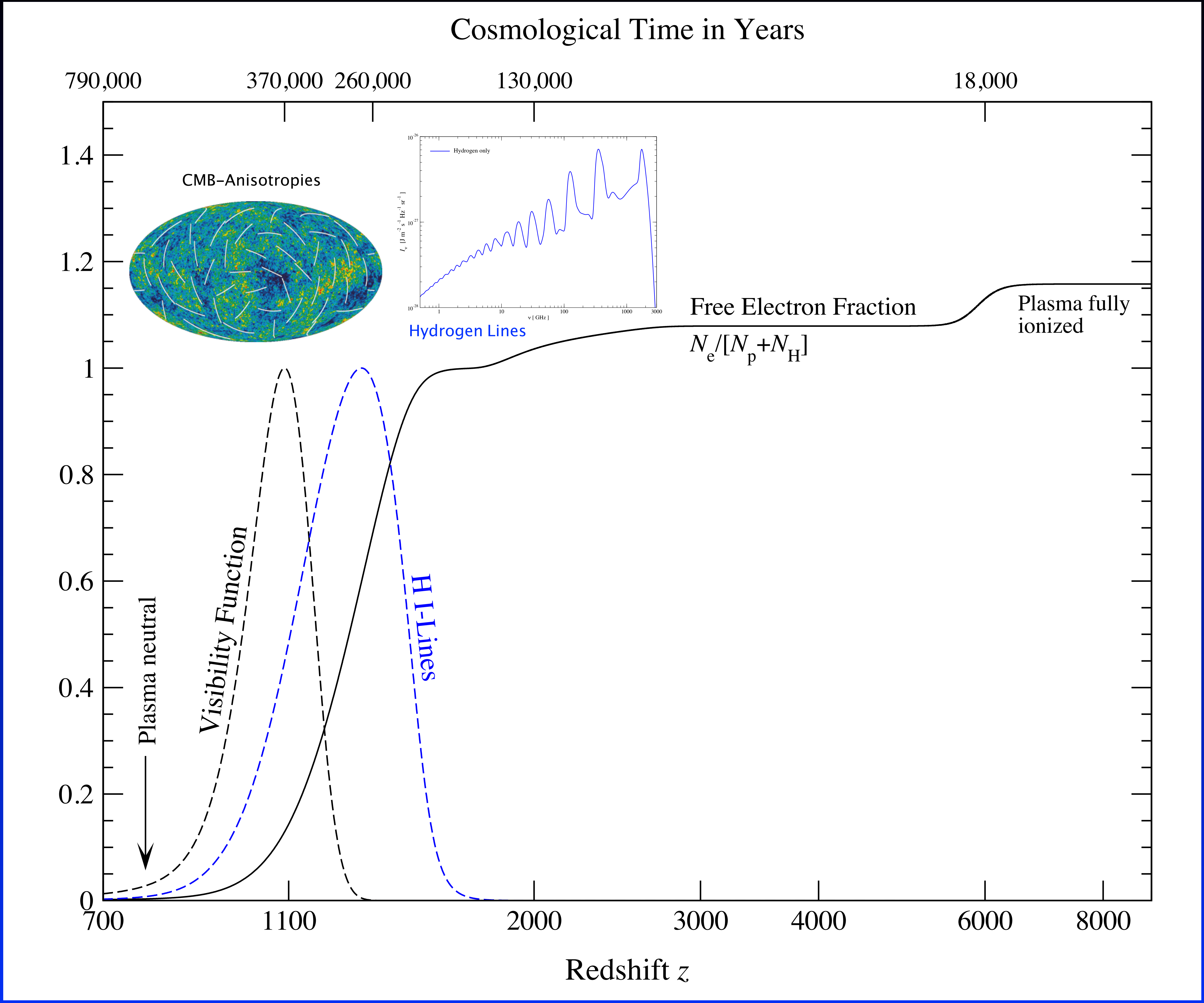
**@ CMB maximum:**

- relative distortions extremely small
- strong ν-dependence

**RJ-region:**

- relative distortion exceeds level of ~ $10^{-7}$ below ν ~ 1-2 GHz
- oscillatory frequency dependence with ~ 1-10 percent-level amplitude:
- *hard to mimic by known foregrounds or systematics*

JC & Sunyaev, 2006, A&A, 458, L29 (astro-ph/0608120)



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
Hydrogen only
Hydrogen Lines
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully ionized
Visibility Function
Plasma neutral
H I-Lines
700
1100
2000
3000
4000
6000
8000
Redshift $z$

# What about the contributions from helium recombination?

- Nuclear reactions: $Y_p$~0.24 ←→ $N_{HeI}$ / $N_H$ ~8 %

  → expected photon number rather small

- ***BUT:***

  (*i*) *two* epochs of He recombination
  HeIII→HeII at *z*~6000 and HeII→HeI at *z*~2500

  (*ii*) Helium recombinations faster

  → more *narrow* features with *larger* amplitude

  (*iii*) non-trivial superposition

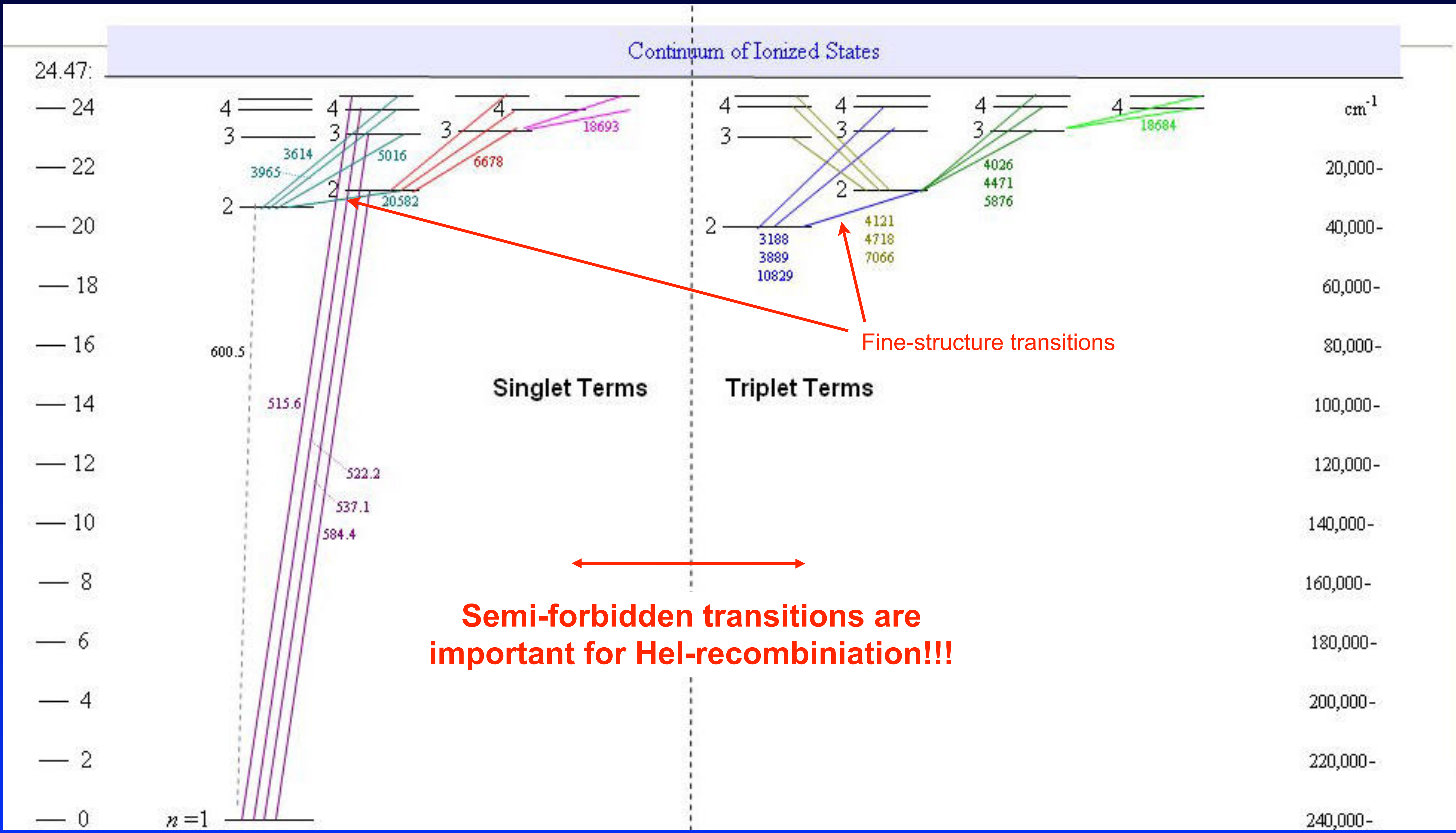
  → local amplification possible

  (*iv*) reprocessing of HeII & HeI photons by HeI and HI

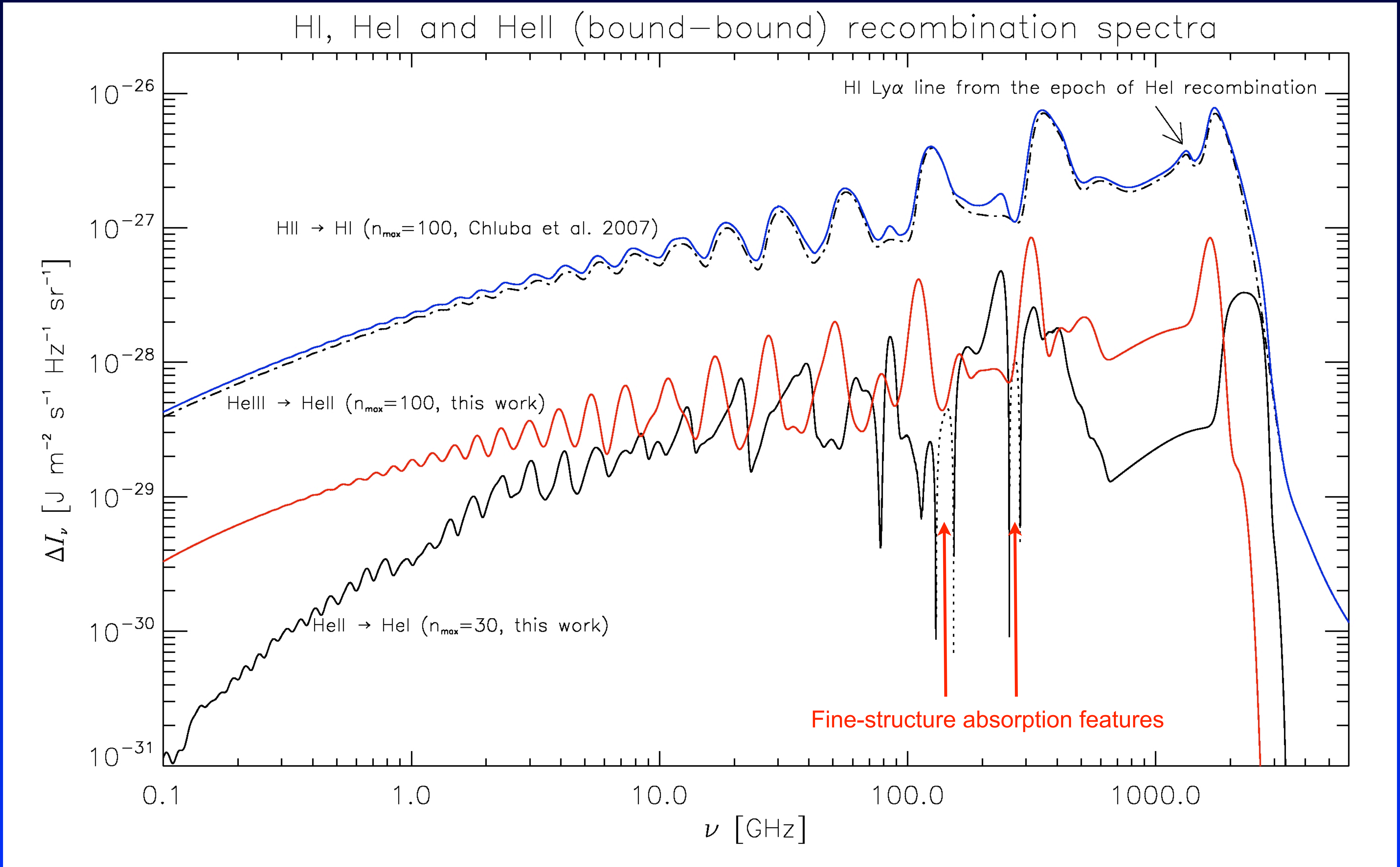
  → increases the number of helium-related photons

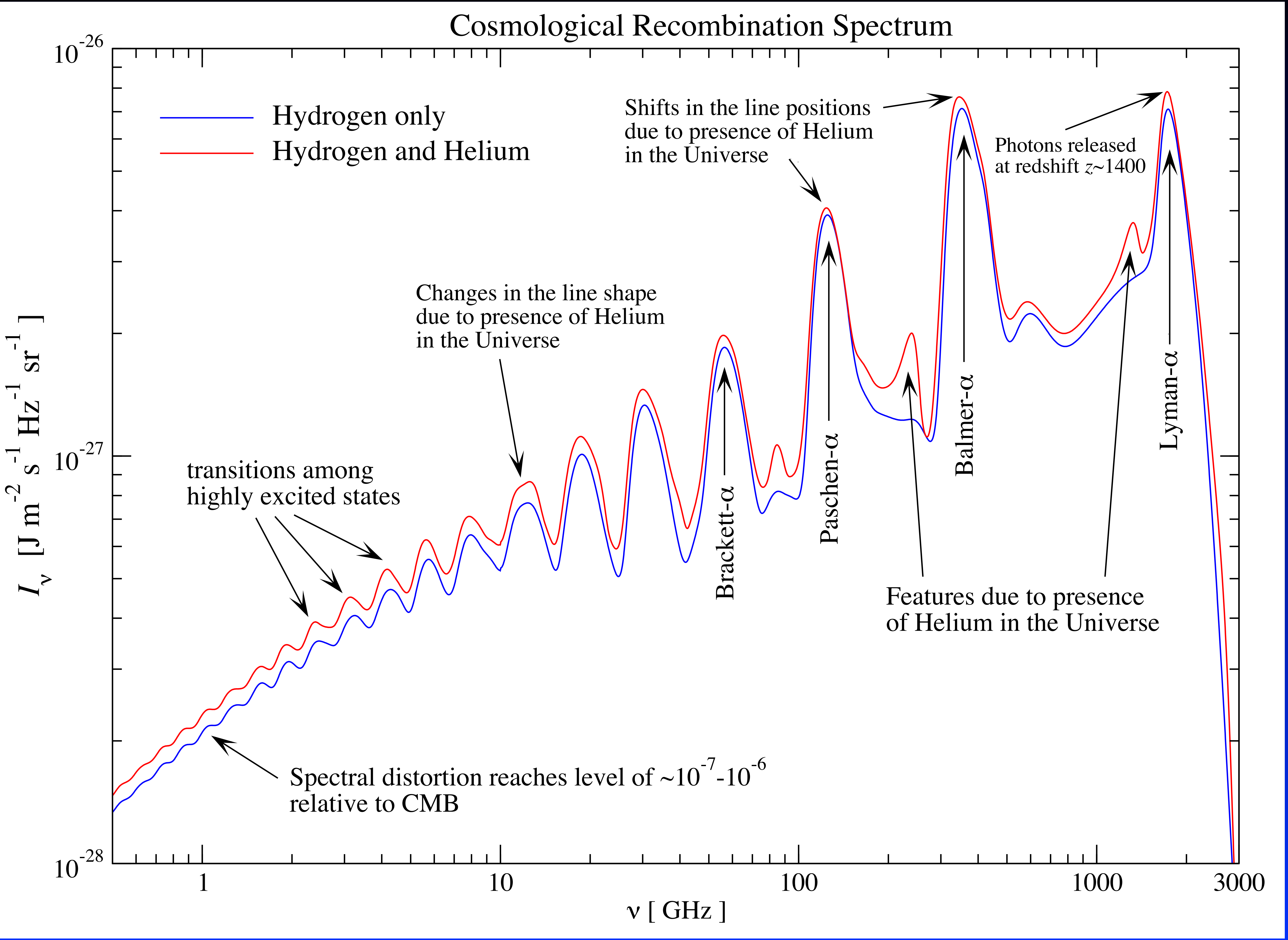
→ May opens a way to ***directly*** measure the primordial (pre-stellar!!!) helium abundance!

# Grotrian diagram for neutral helium

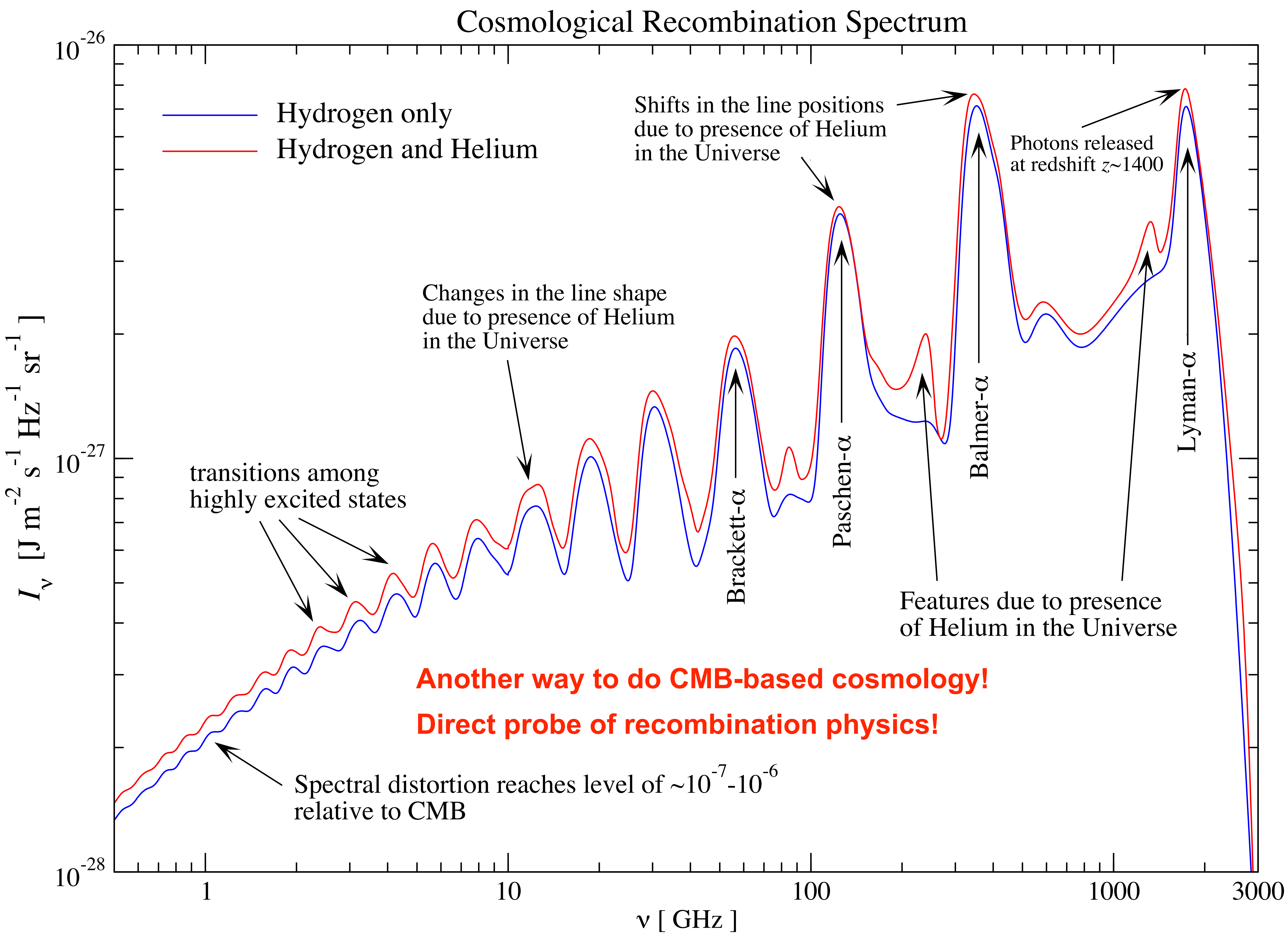


# Helium contributions to the cosmological recombination spectrum



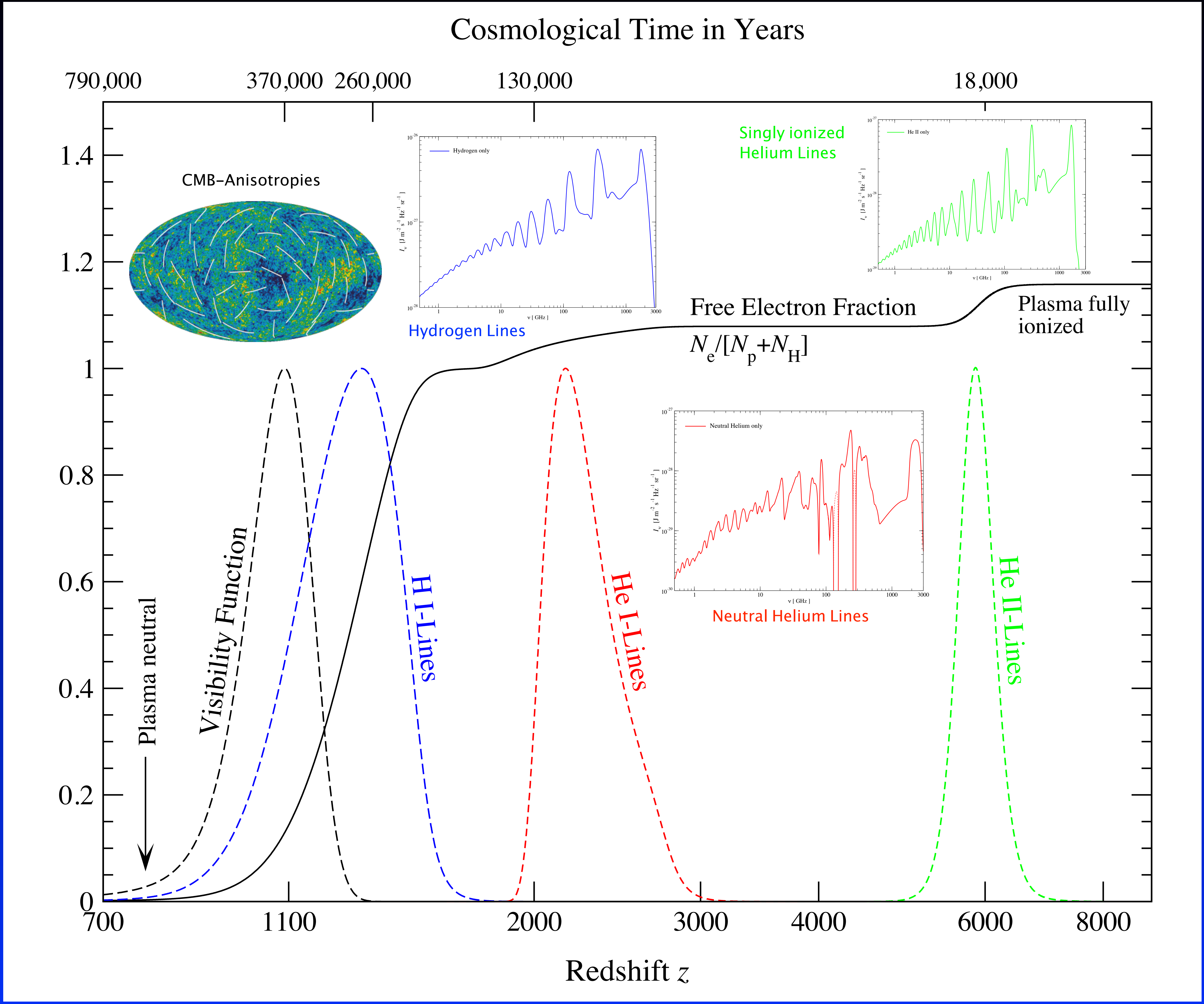


Cosmological Recombination Spectrum
Hydrogen only
Hydrogen and Helium
Shifts in the line positions due to presence of Helium in the Universe
Photons released at redshift z~1400
Changes in the line shape due to presence of Helium in the Universe
transitions among highly excited states
Brackett-α
Paschen-α
Balmer-α
Lyman-α
Features due to presence of Helium in the Universe
Spectral distortion reaches level of ~10^-7-10^-6 relative to CMB
I_ν [J m^-2 s^-1 Hz^-1 sr^-1]
ν [ GHz ]
10^-26
10^-27
10^-28
1
10
100
1000
3000




**Another way to do CMB-based cosmology!**

**Direct probe of recombination physics!**



Cosmological Time in Years
790,000
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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
Plasma neutral
Visibility Function
H I-Lines
He I-Lines
He II-Lines
Redshift $z$

# What would we actually learn by doing such hard job?

***Cosmological Recombination Spectrum opens a way to measure:***

→ **the specific *entropy* of our universe (related to $\Omega_b h^2$)**

→ **the CMB *monopole* temperature $T_0$**

→ ***the pre-stellar abundance of helium $Y_p$***

→ ***If recombination occurs as we think it does, then the lines can be predicted with very high accuracy!***

→ ***In principle allows us to directly check our understanding of the standard recombination physics***

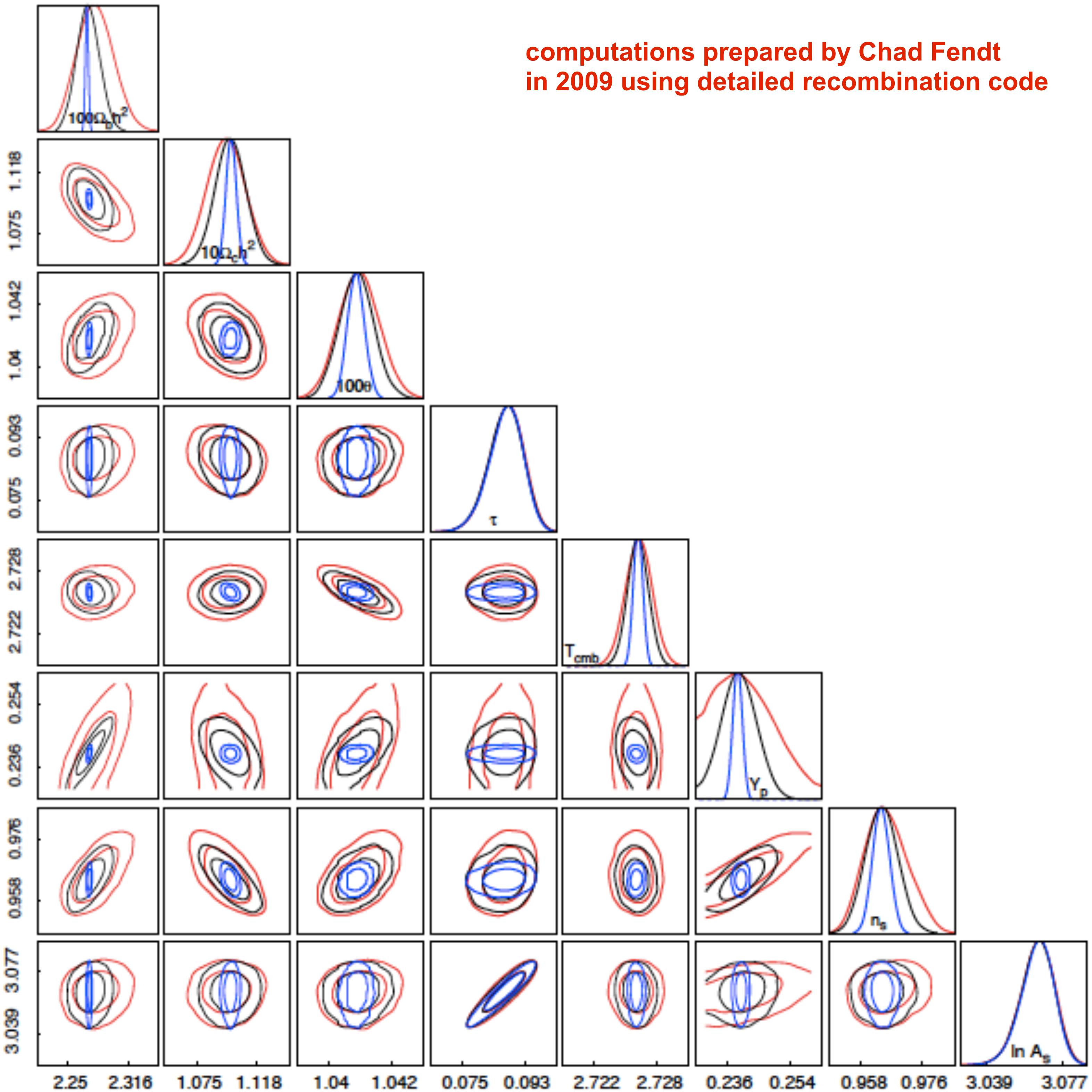
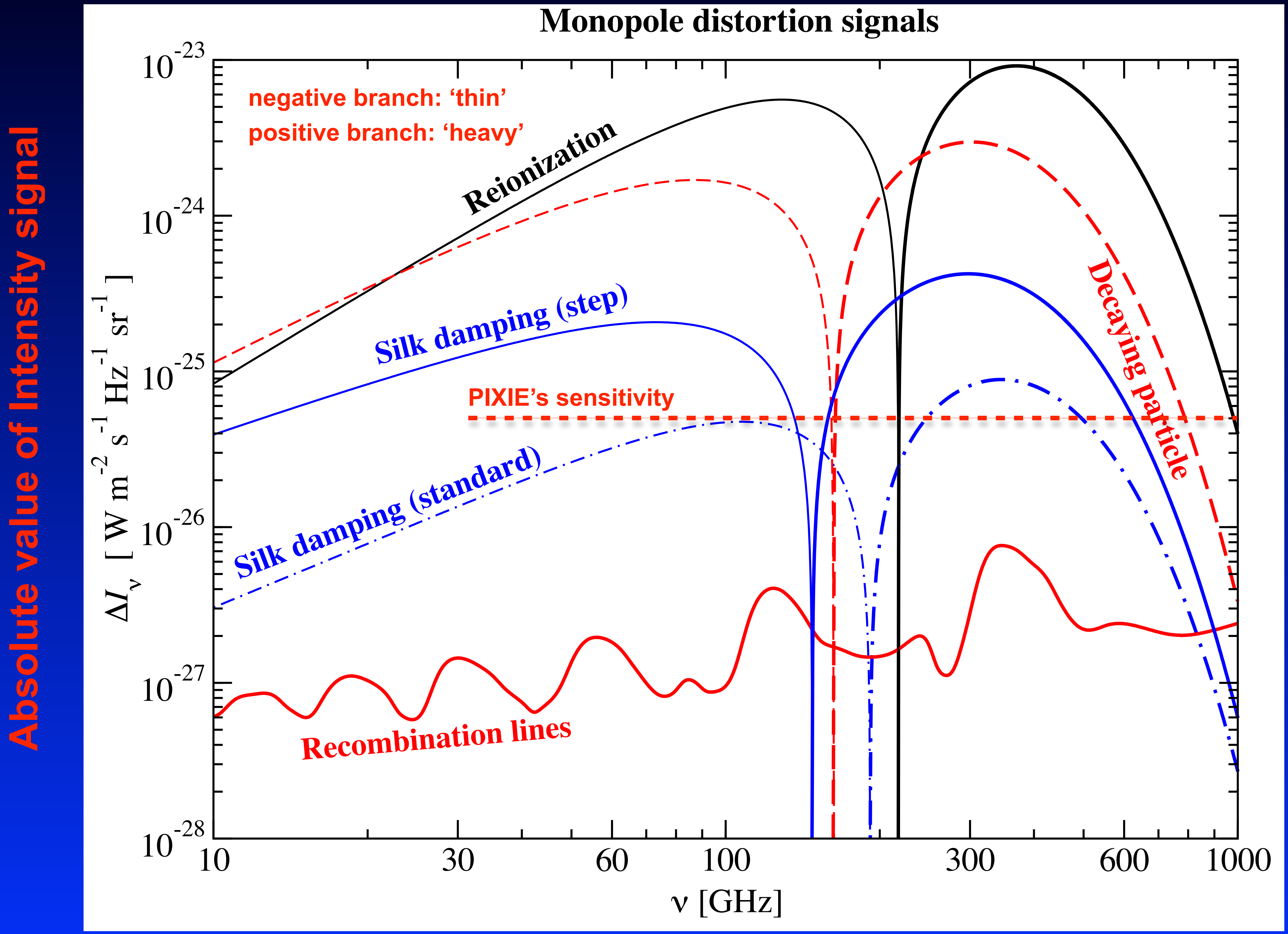


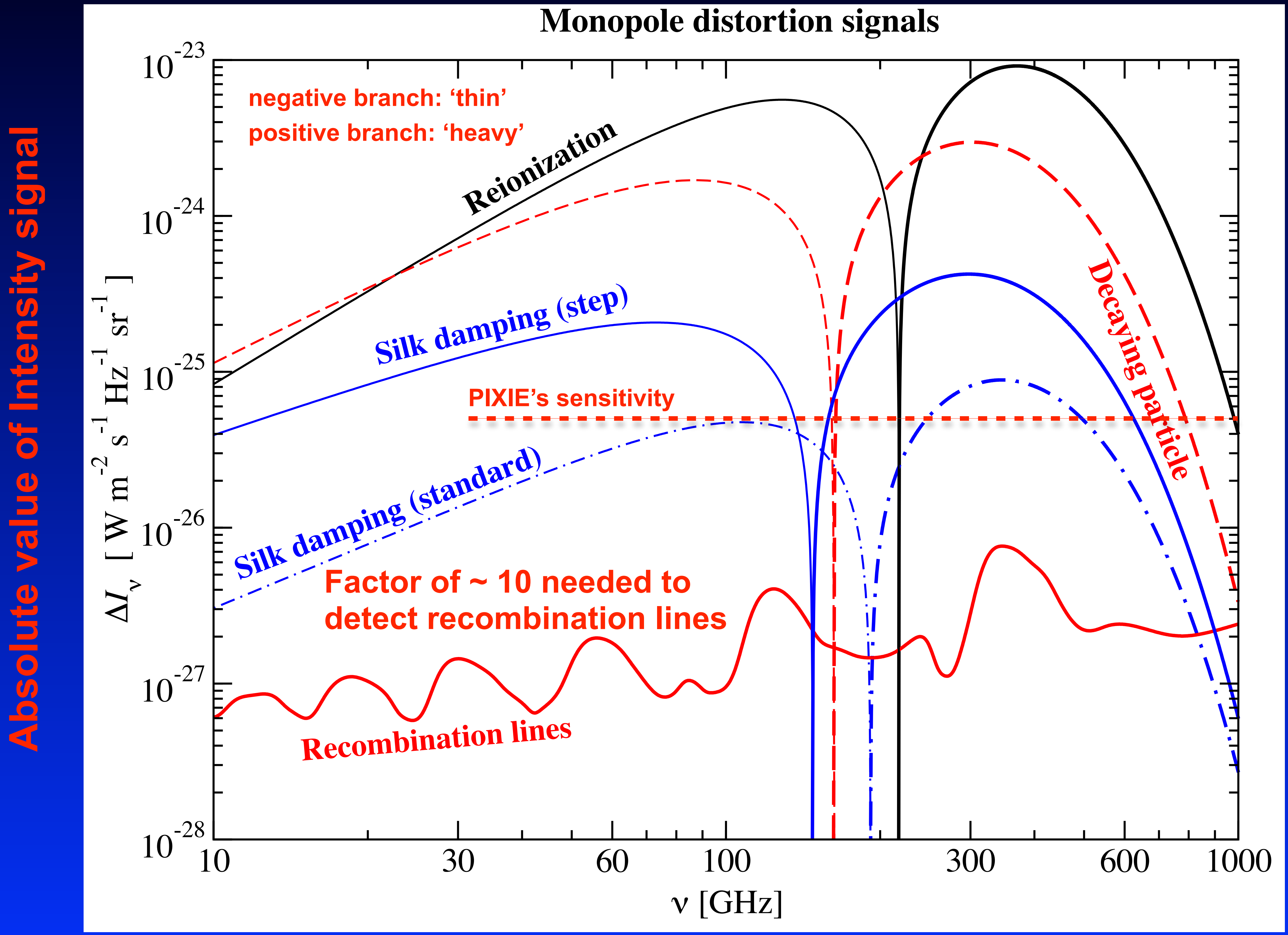

Figure 7.3: The 1 and 2 dimensional marginalized parameter posterior using the CMB spectral distortions. All three cases constrain the CMB power spectrum using a Gaussian likelihood based on Planck noise levels. The black line adds constraints due to a 10% measurement of the spectral distortions, while the blue line assumes a 1% measurement. The red line does not include the data from the spectral distortions.

- CMB based cosmology alone
- Spectrum helps to break some of the parameter degeneracies
- Planning to provide a module that computes the recombination spectrum in a fast way
- detailed forecasts: which lines to measure; how important is the absolute amplitude; how accurately one should measure; best frequency resolution;

# Average CMB spectral distortions



# Average CMB spectral distortions



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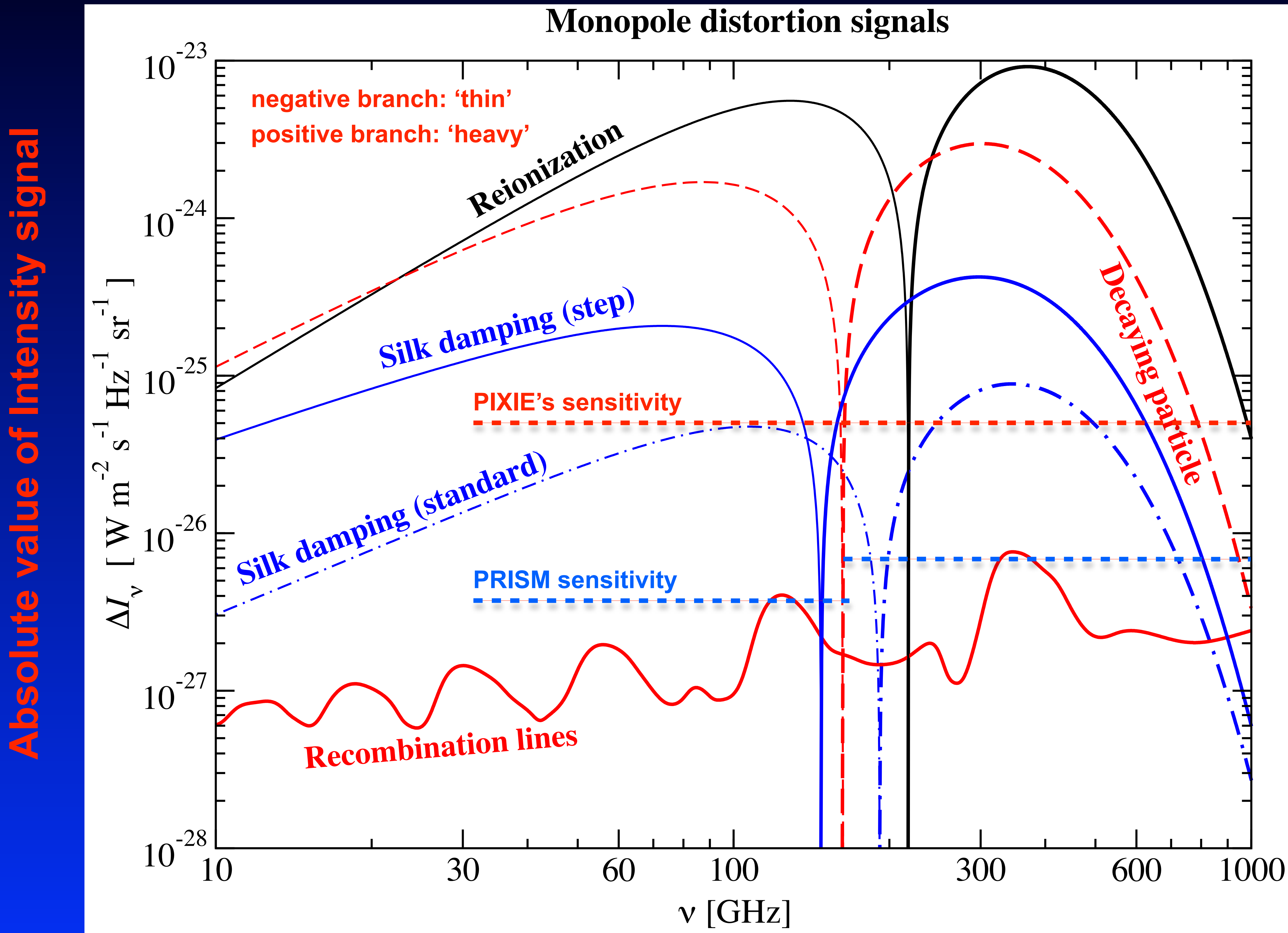
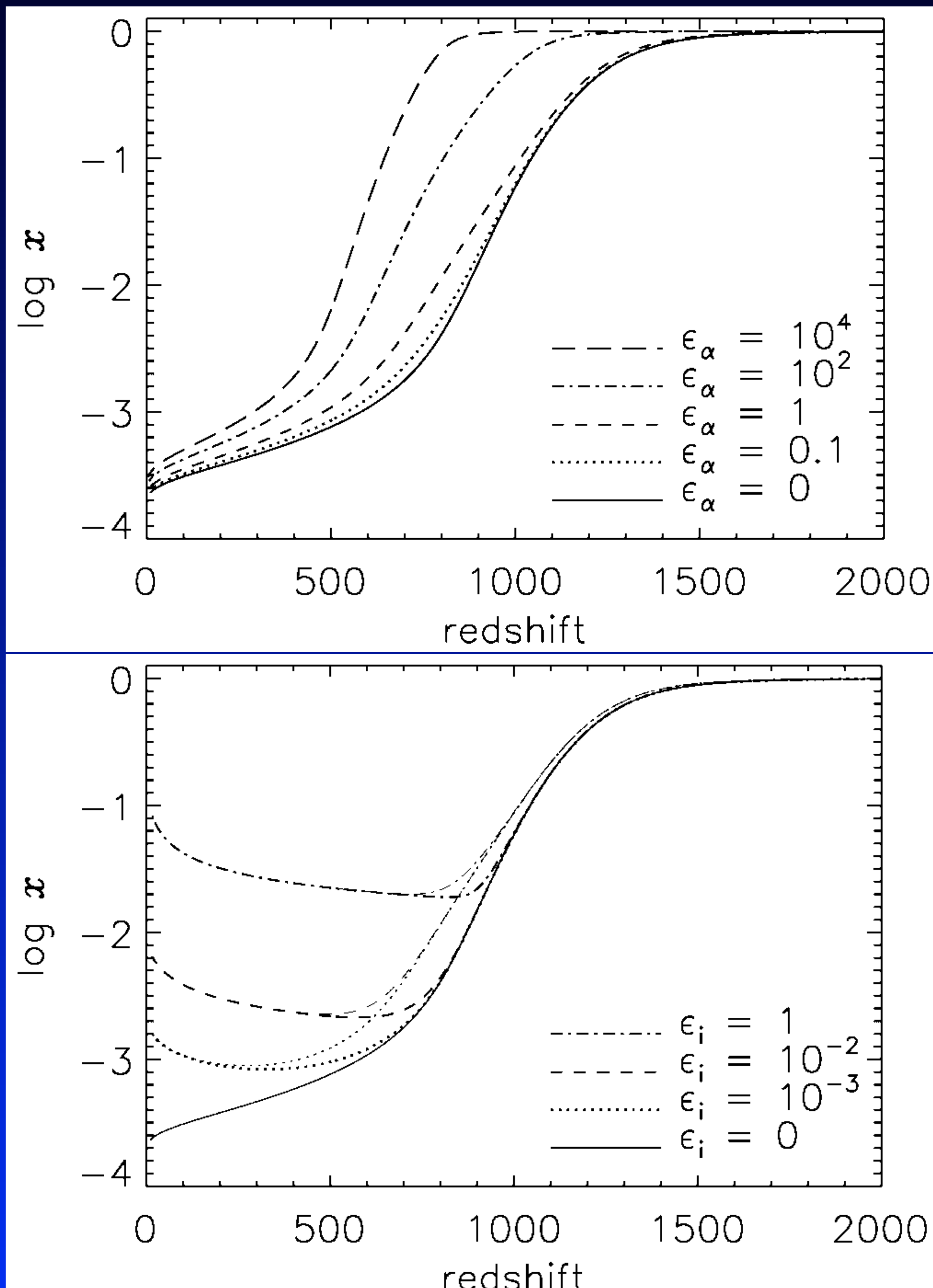


*But this is again not all!*

# Extra Sources of Ionizations or Excitations

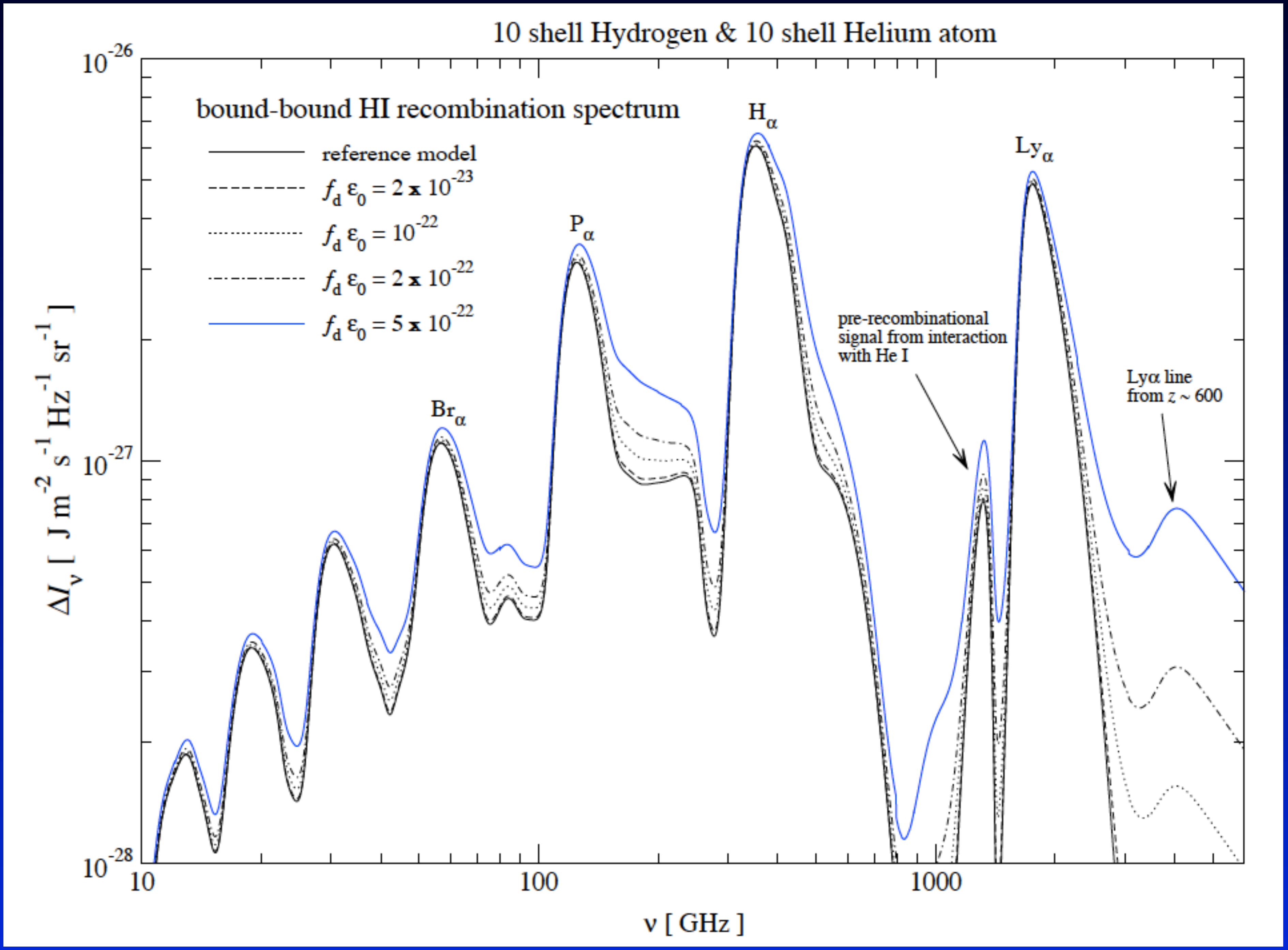



Peebles, Seager & Hu, ApJ, 2000

- ‚Hypothetical' source of extra photons parametrized by $\varepsilon_\alpha$ & $\varepsilon_i$
- Extra excitations ⇒ delay of Recombination
- Extra ionizations ⇒ affect 'freeze out' tail
- This affects the Thomson visibility function
- From WMAP ⇒ $\varepsilon_\alpha < 0.39$ & $\varepsilon_i < 0.058$ at 95% confidence level (Galli et al. 2008)

- Extra ionizations & excitations should also lead to additional photons in the recombination radiation!!!
- This in principle should allow us to check for such sources at z~1000

# Dark matter annihilations / decays




JC, 2009, arXiv:0910.3663

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

# Pre-recombination atomic transitions after possible early energy release

- pure blackbody CMB

  → *no net emission or absorption of photons before recombination epoch!*

- non-blackbody CMB
  (Lyubarsky & Sunyaev, 1983)

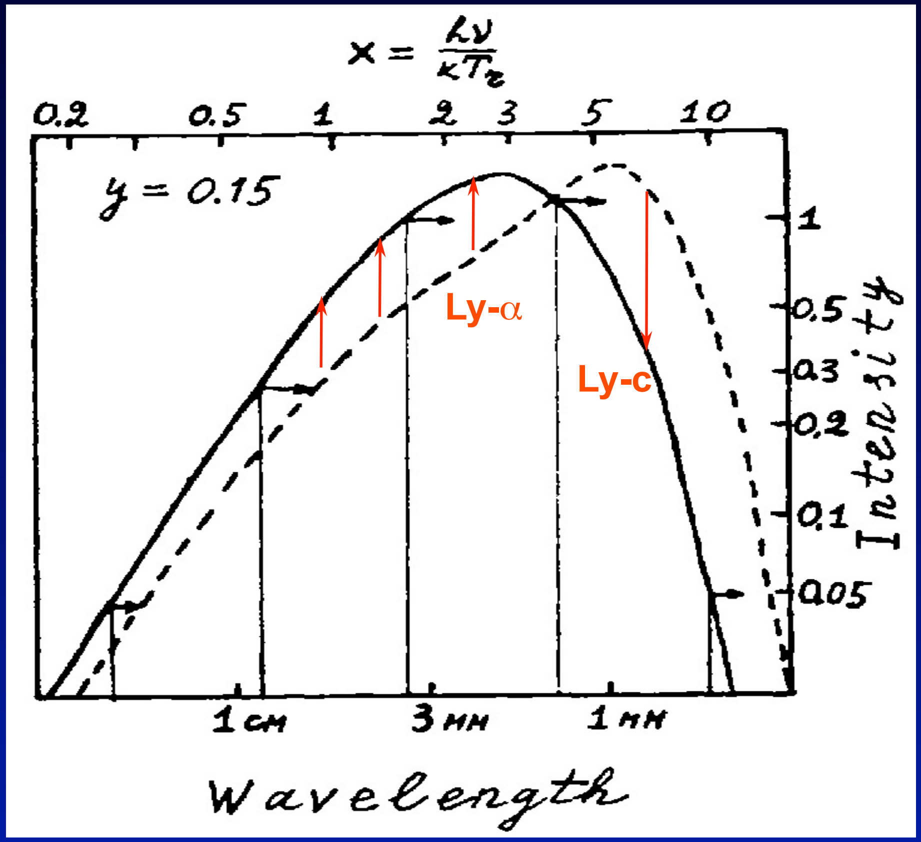
  → atoms "try" to restore full equilibrium

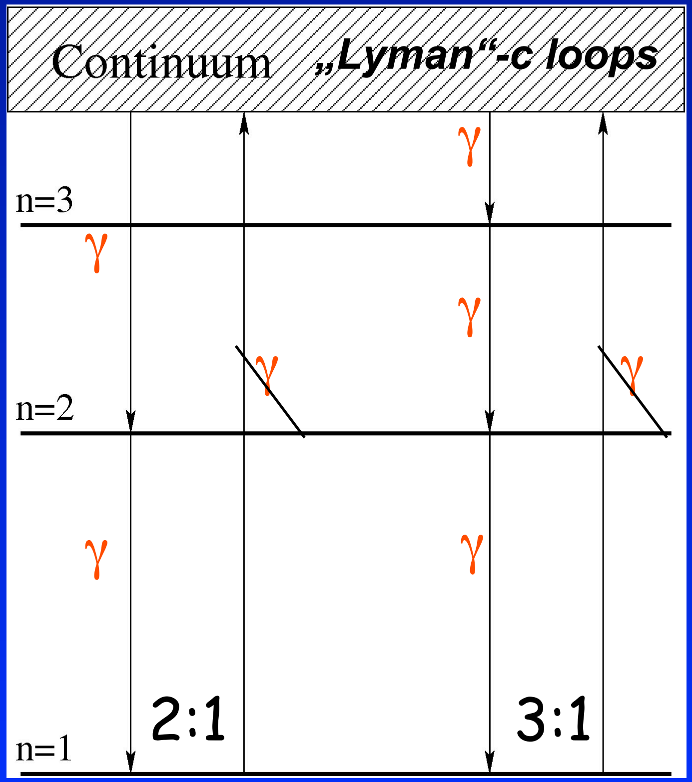
  → *atomic cycles* develop (cont.→ bound → cont.)

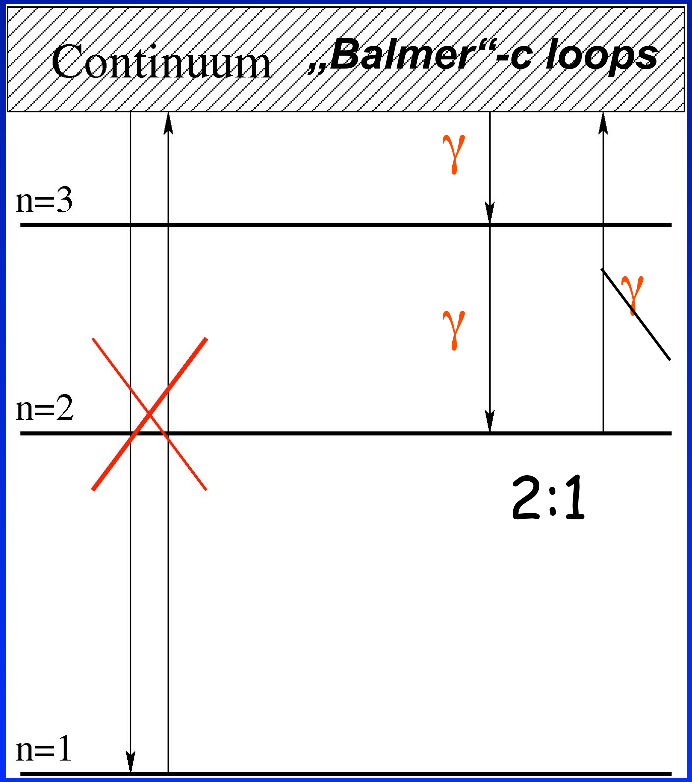
  → "splitting" of photons

  → cycles mainly end in Lyman-continuum

  → Balmer-cont. cycles work just before recombination



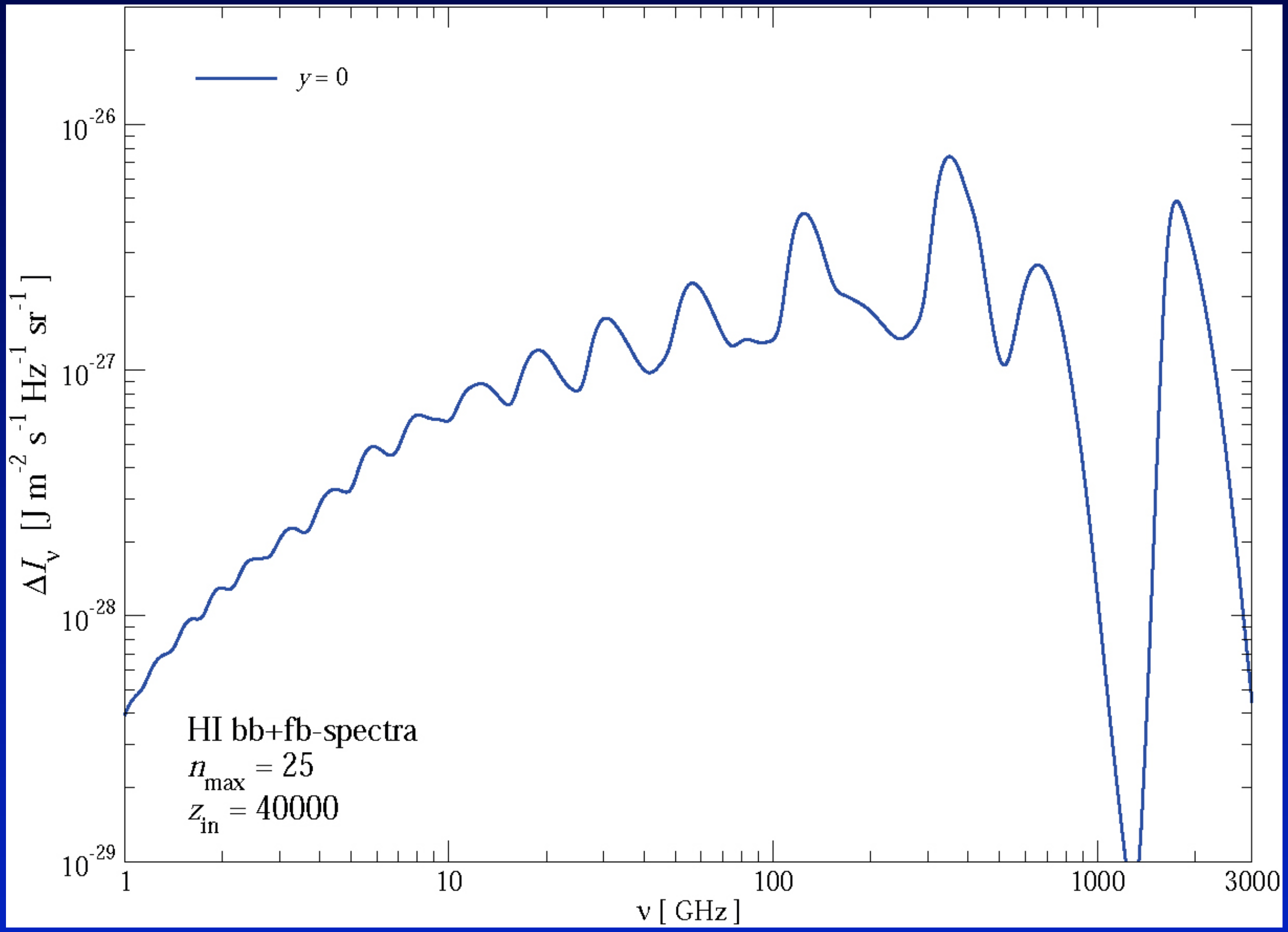



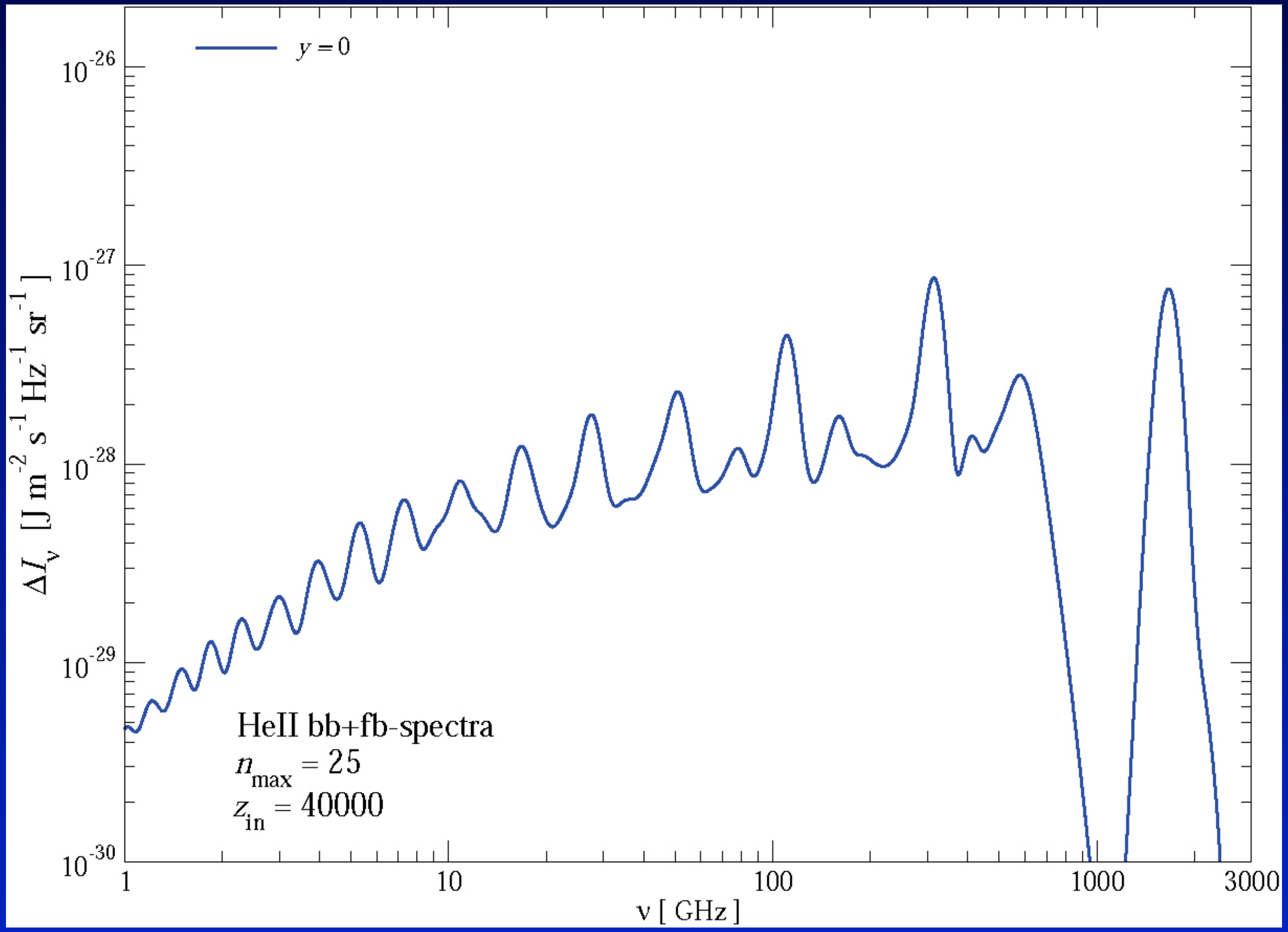
# CMB spectral distortions after single energy release

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

Hydrogen




Helium +




**JC & Sunyaev, 2008, astro-ph/0803.3584**

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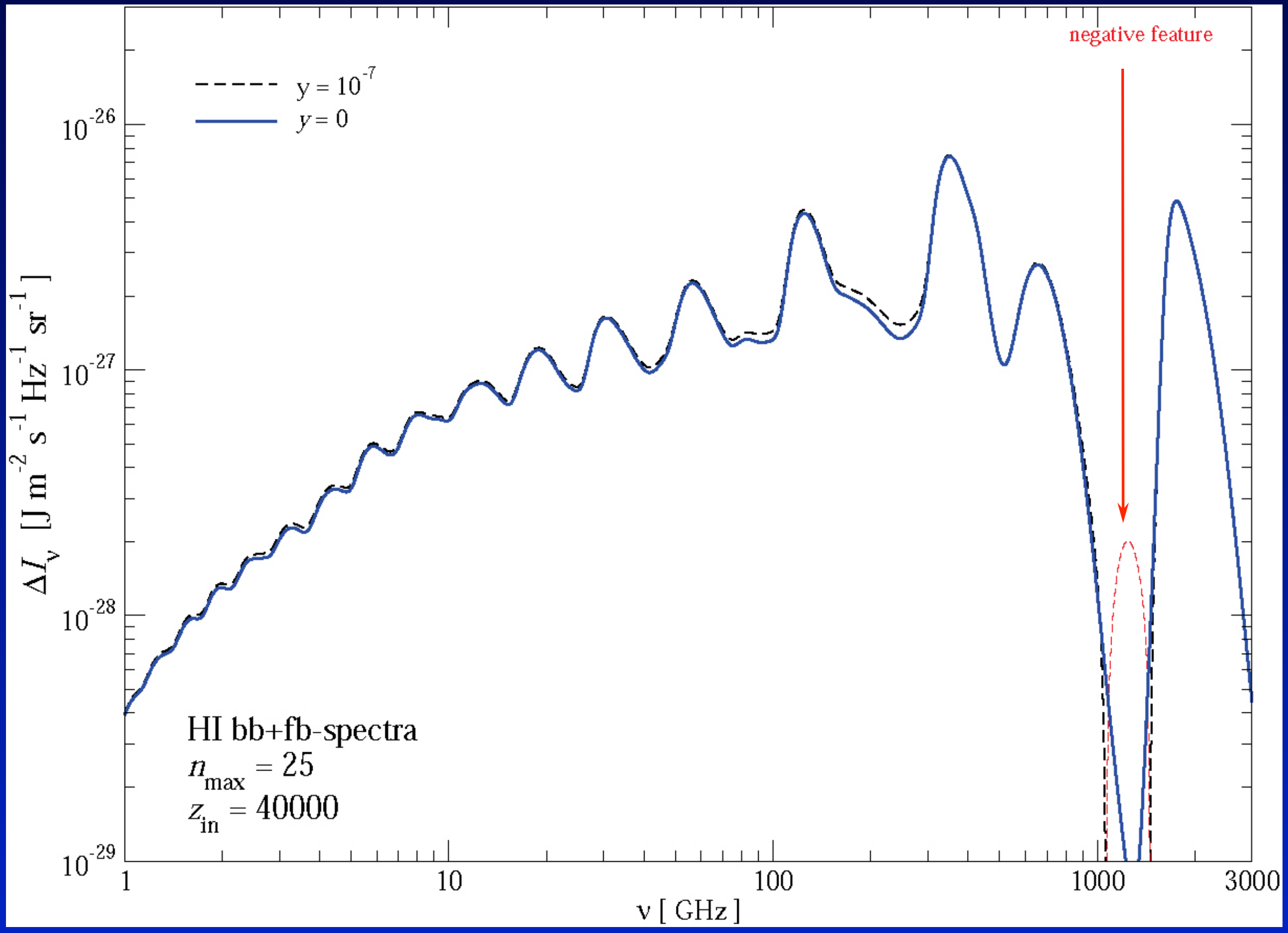


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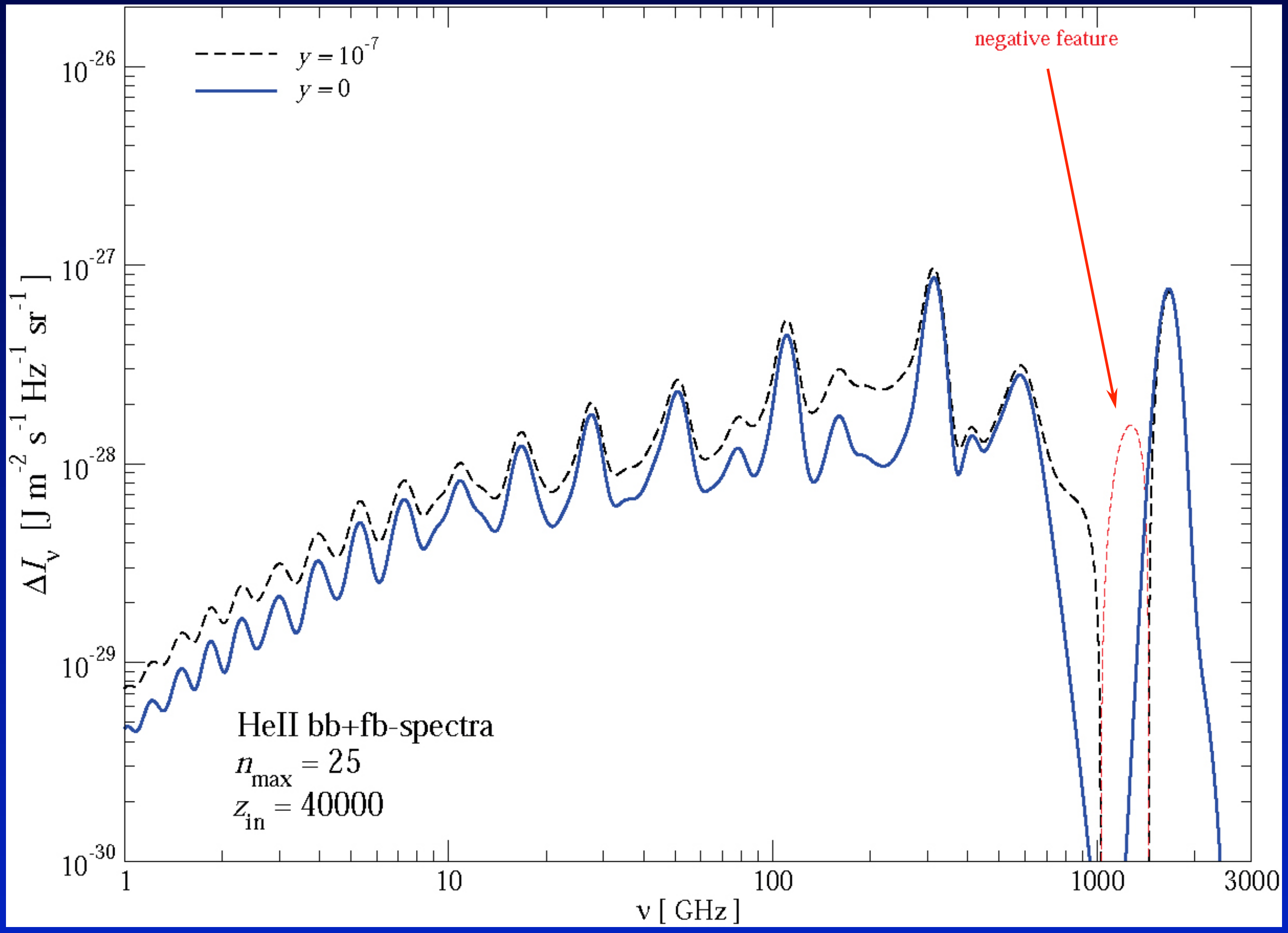


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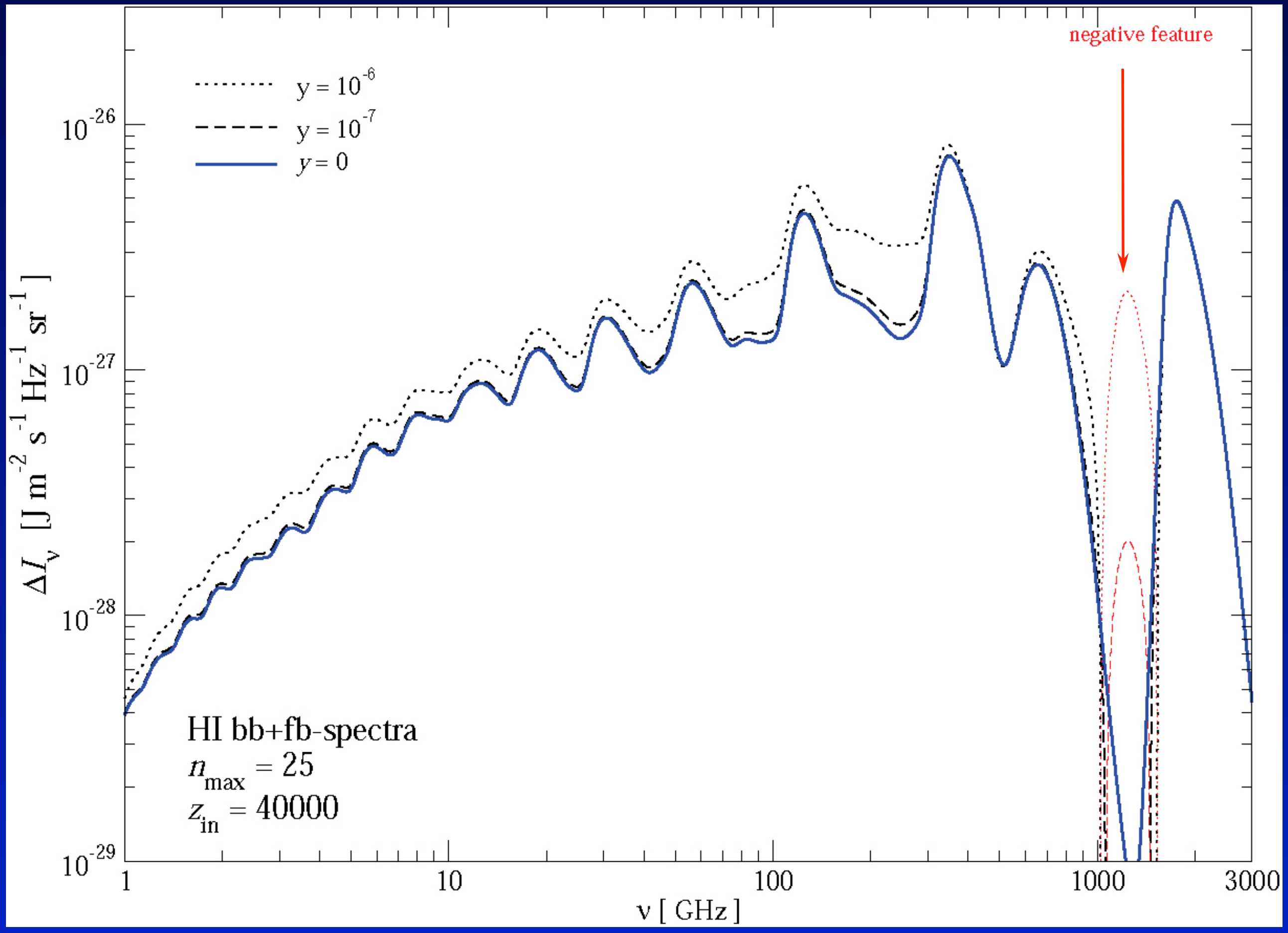
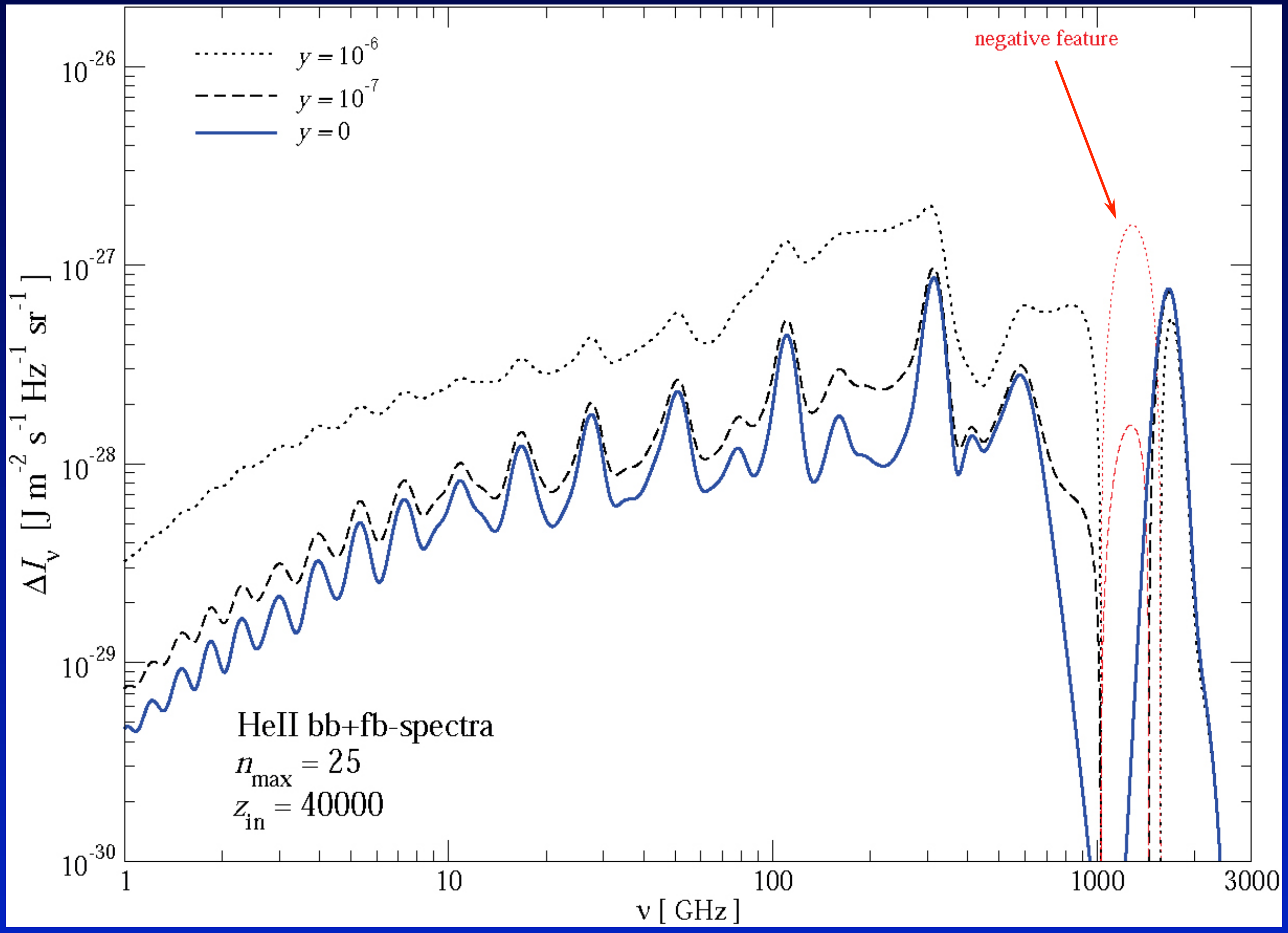



Helium +

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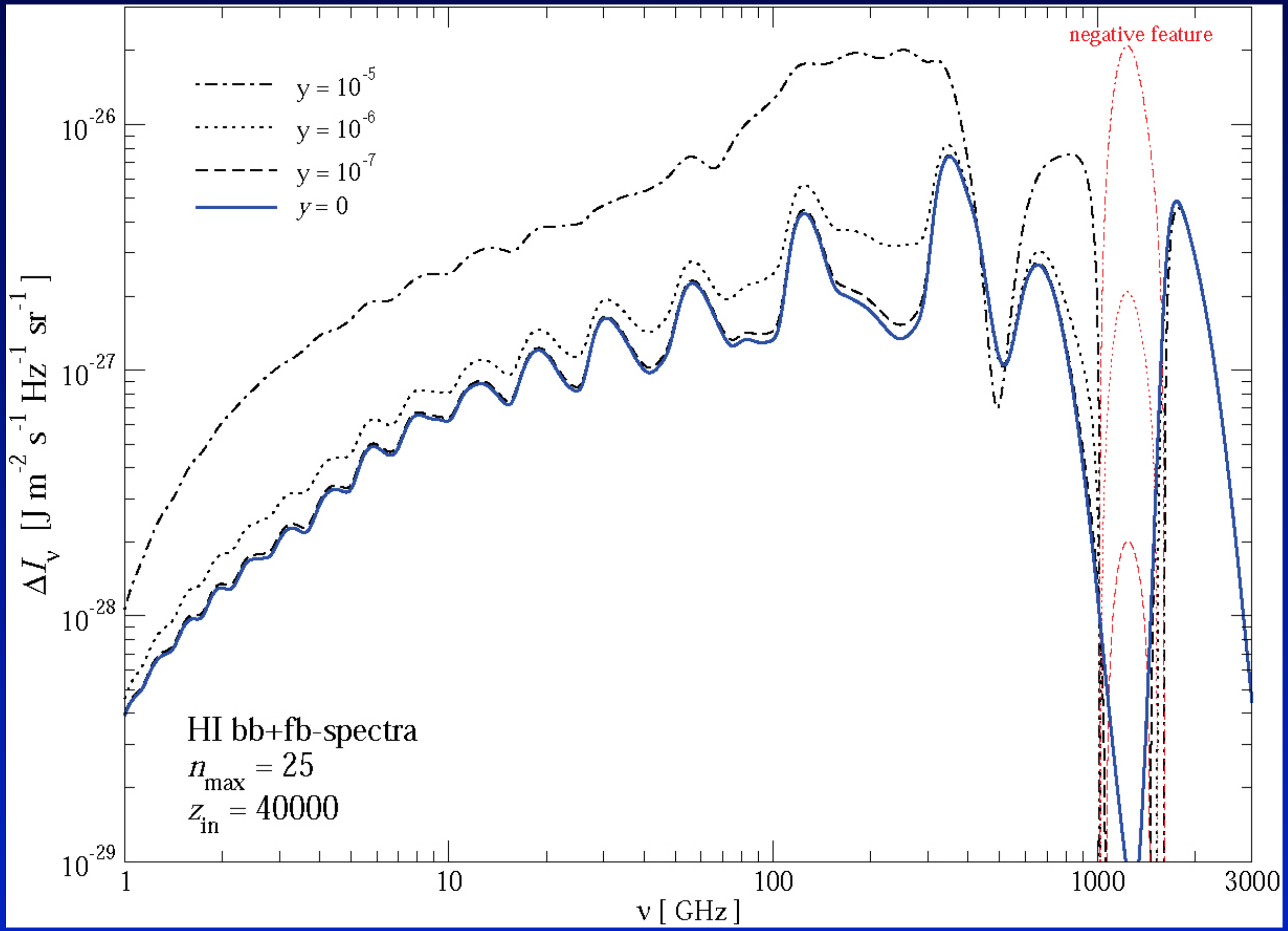
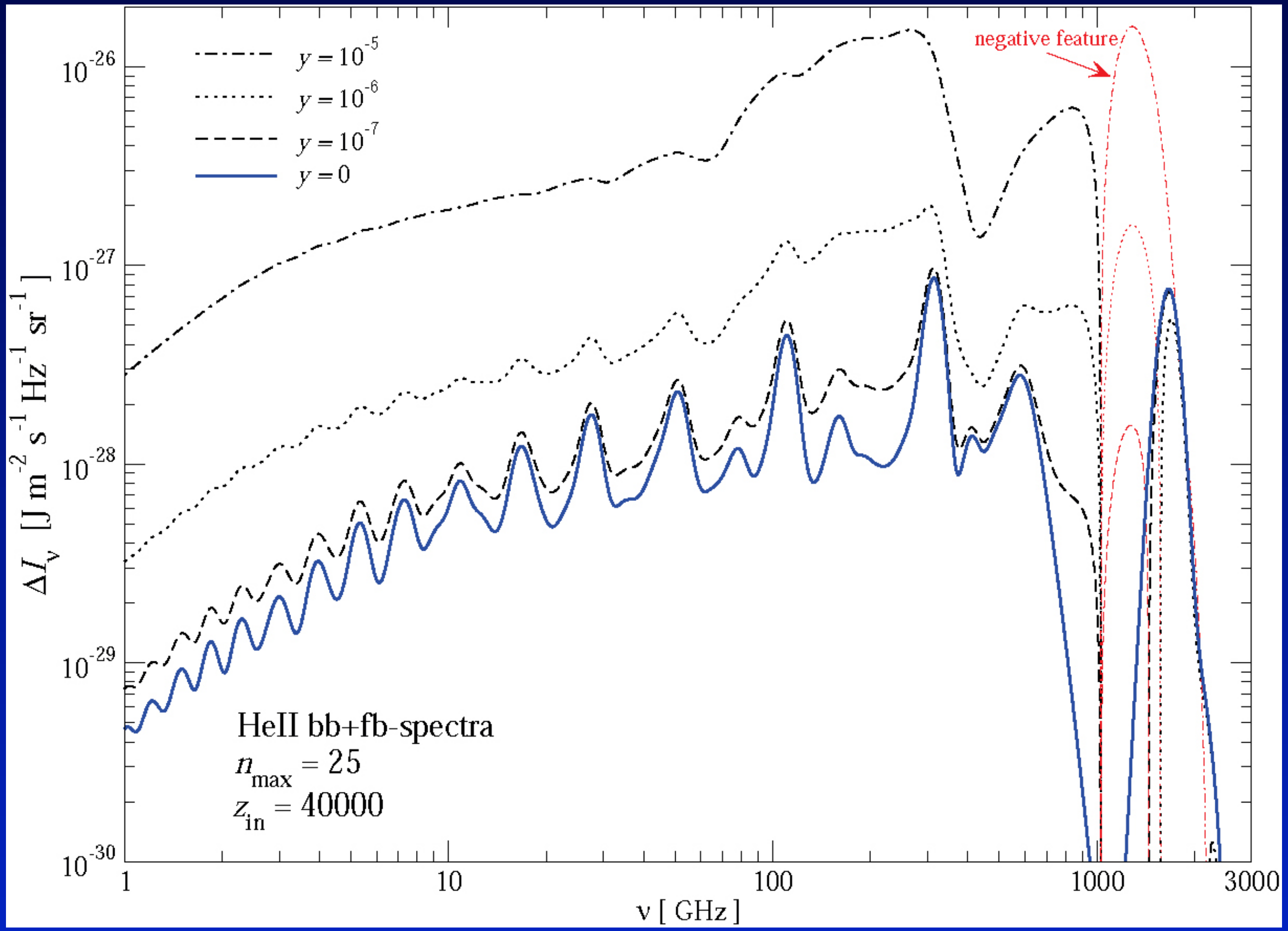
Hydrogen




Helium +



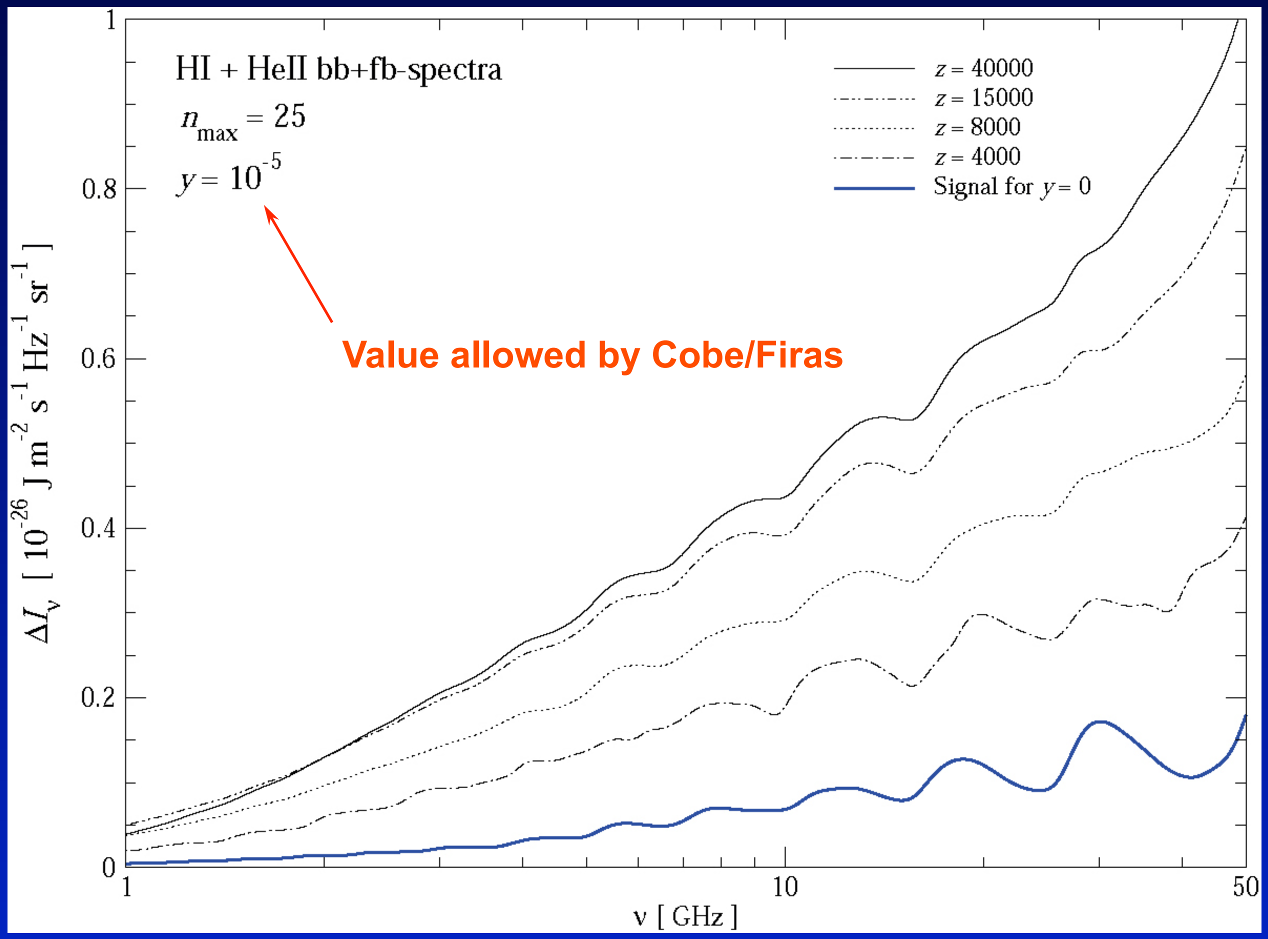

**JC & Sunyaev, 2008, astro-ph/0803.3584**

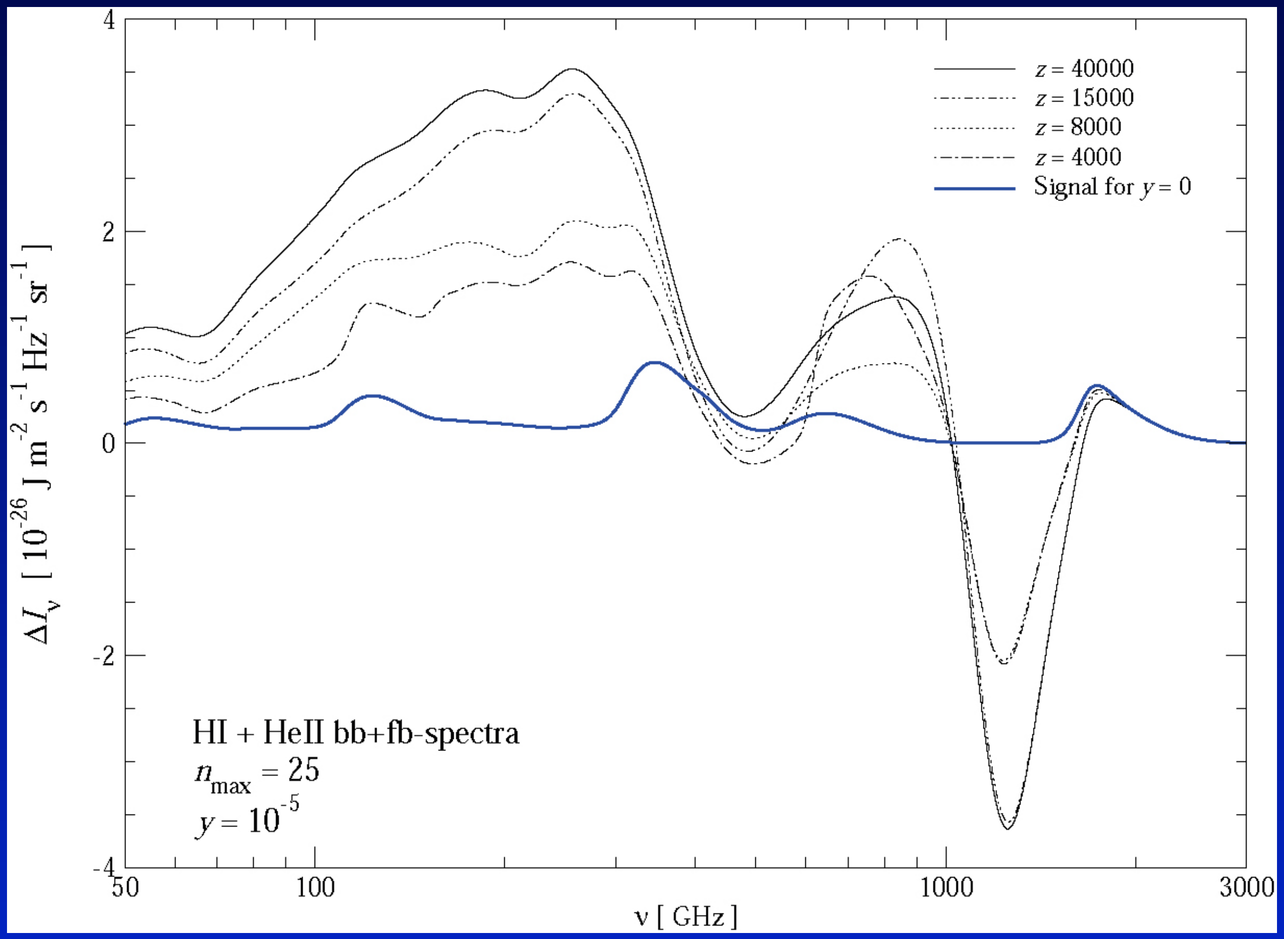
- Large increase in the total amplitude of the distortions with value of *y*!
- Strong emission-absorption feature in the Wien-part of CMB (absent for *y*=0!!!)
- HeII contribution to the pre-recombinational emission as strong as the one from Hydrogen alone !

# 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

# What would we actually learn by doing such hard job?

***Cosmological Recombination Spectrum opens a way to measure:***

→ **the specific *entropy* of our universe (related to $\Omega_b h^2$)**

→ **the CMB *monopole* temperature $T_0$**

→ ***the pre-stellar abundance of helium $Y_p$***

→ ***If recombination occurs as we think it does, then the lines can be predicted with very high accuracy!***

→ ***In principle allows us to directly check our understanding of the standard recombination physics***

***If something unexpected or non-standard happened:***

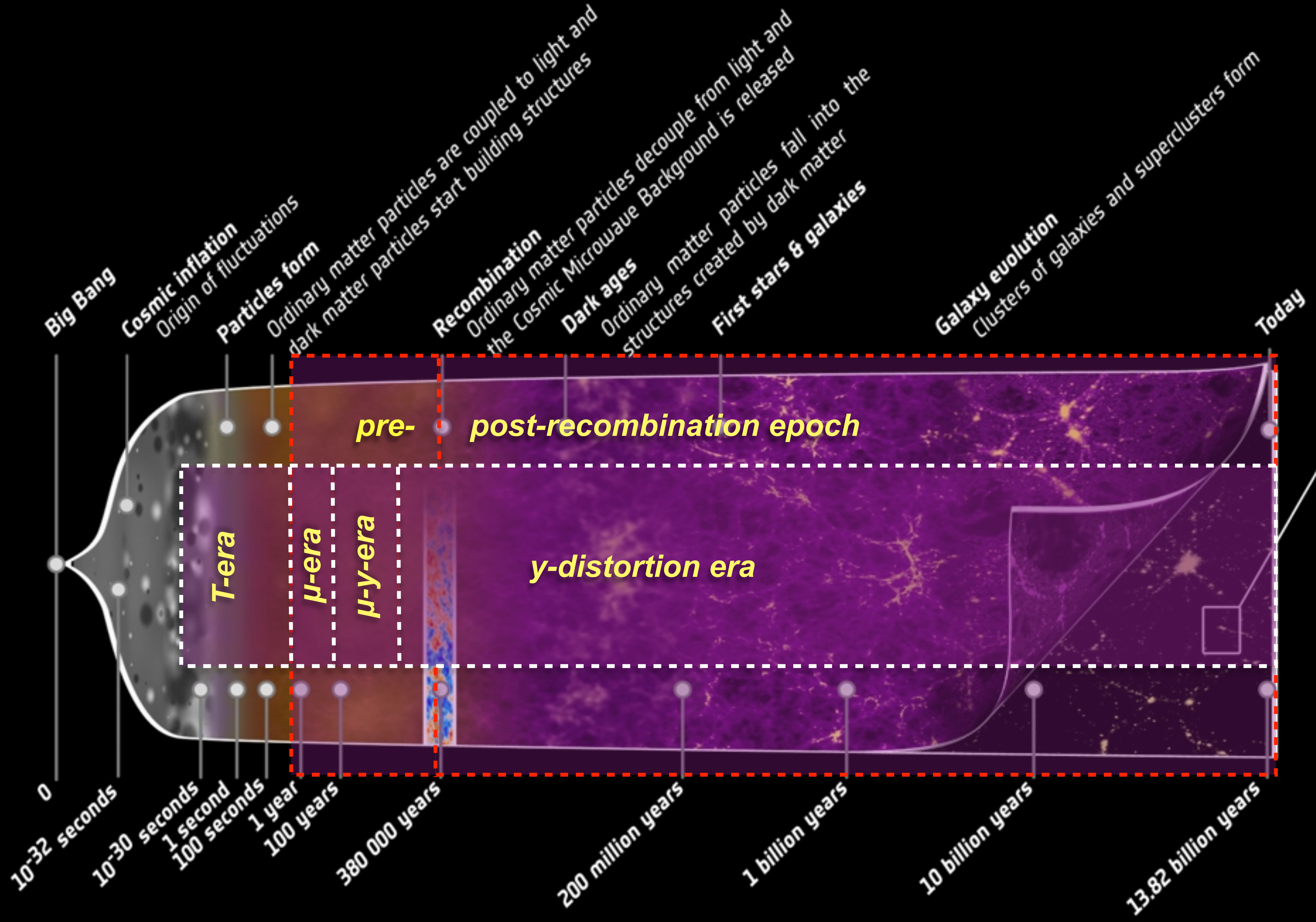
→ ***non-standard thermal histories should leave some measurable traces***

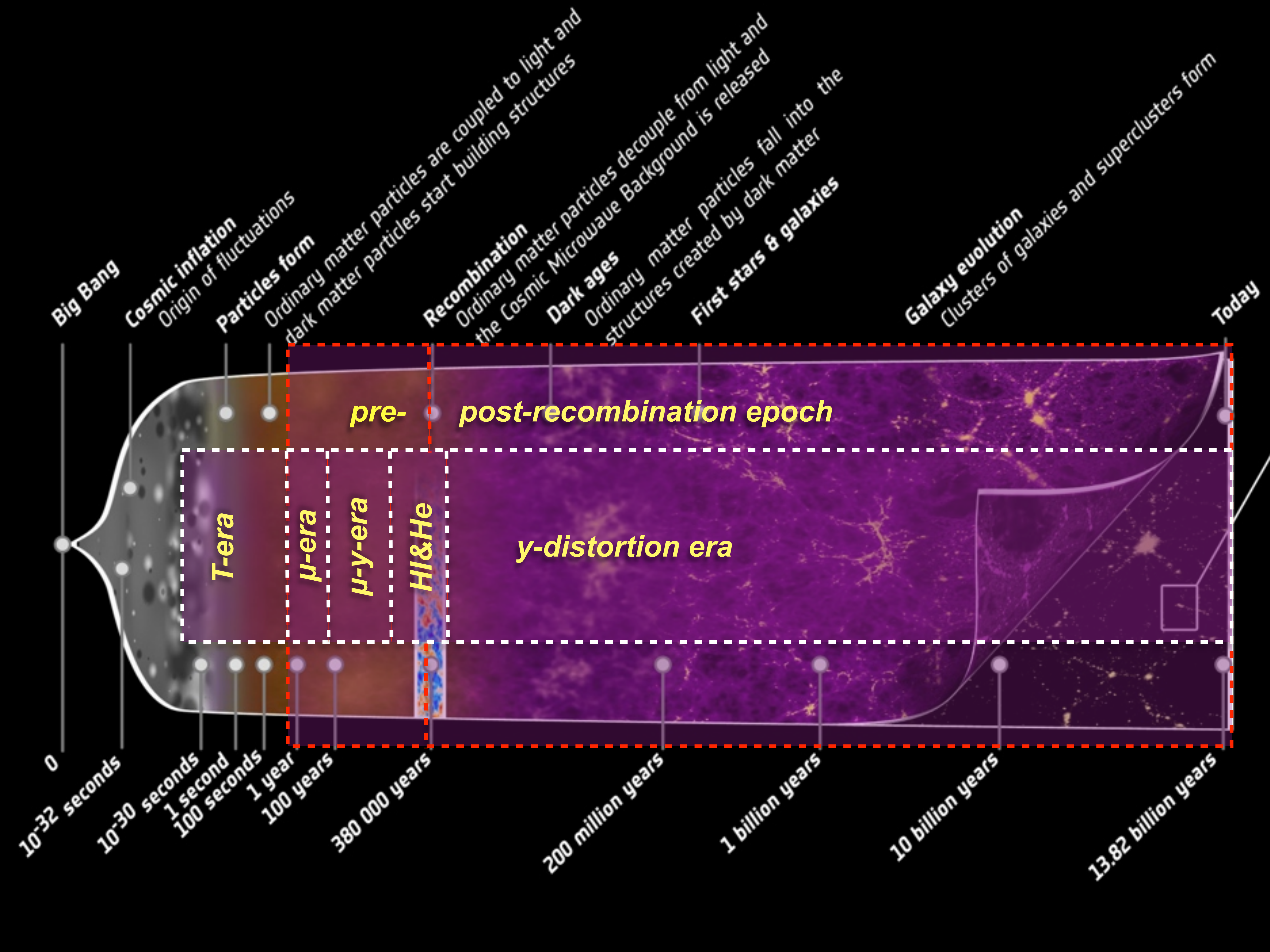
→ ***direct way to measure/reconstruct the recombination history!***

→ **possibility to distinguish *pre-* and *post-recombination y*-type distortions**

→ ***sensitive to energy release during recombination***

→ **variation of fundamental constants**


Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
pre-
post-recombination epoch
T-era
μ-era
μ-y-era
y-distortion 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



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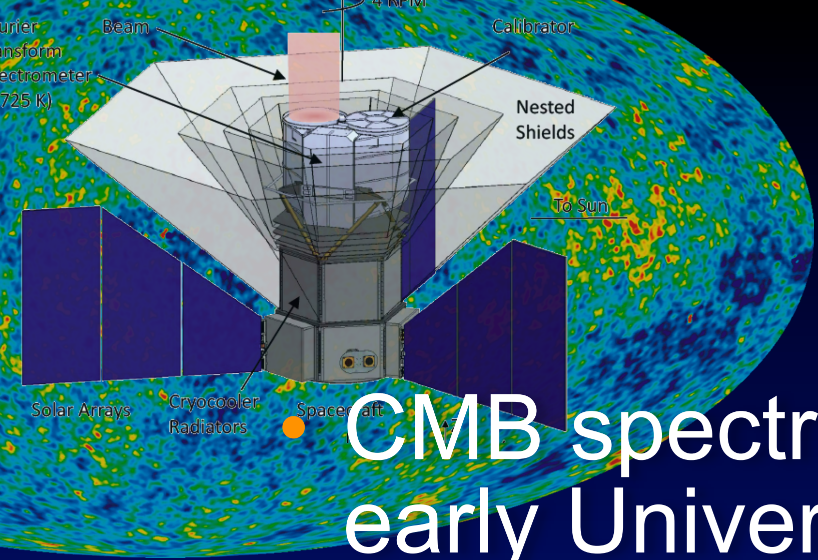


# Summary

- CMB spectral distortions open a *new window* to the early Universe and inflationary epoch
- *complementary* and *independent* source of information about our Universe *not* just confirmation
- simplicity of thermalization physics allows making very *precise predictions* for the distortions caused by different heating mechanisms
- 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!