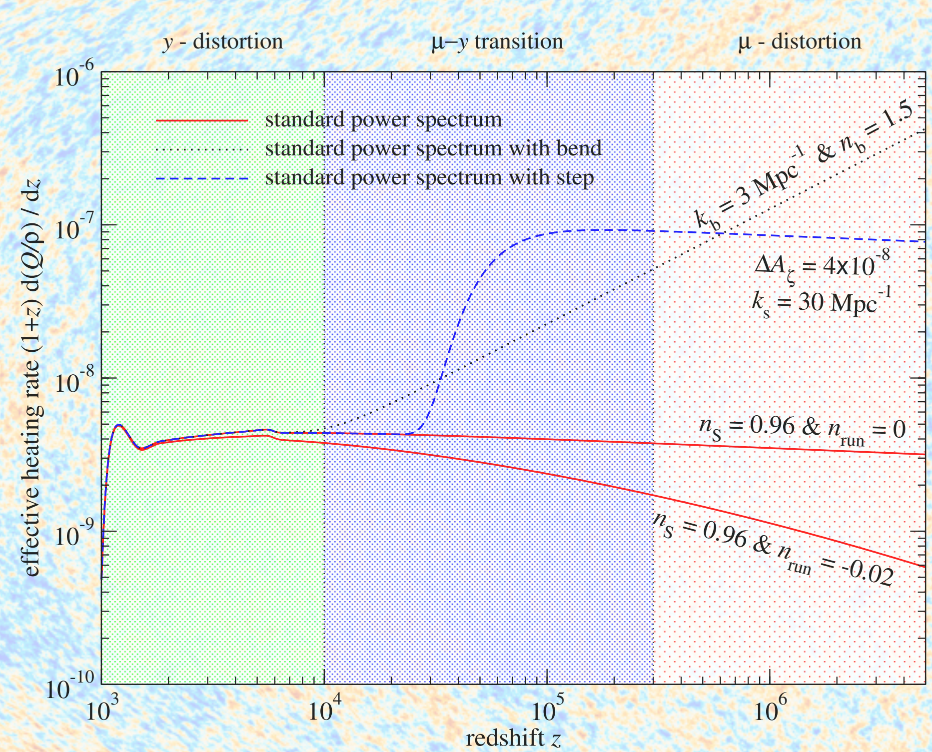
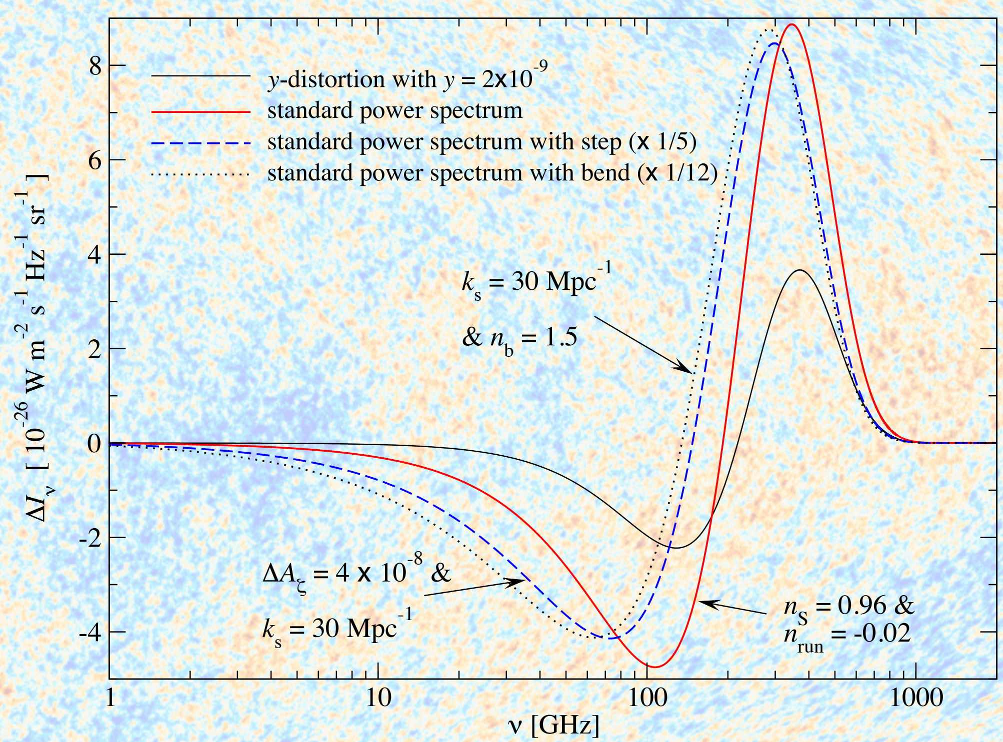
Science with CMB Spectral Distortions: a New Window to Early-Universe and Particle Physics





JOHNS HOPKINS UNIVERSITY

Jens Chluba

KEK Theory Meeting on Particle Physics Phenomenology

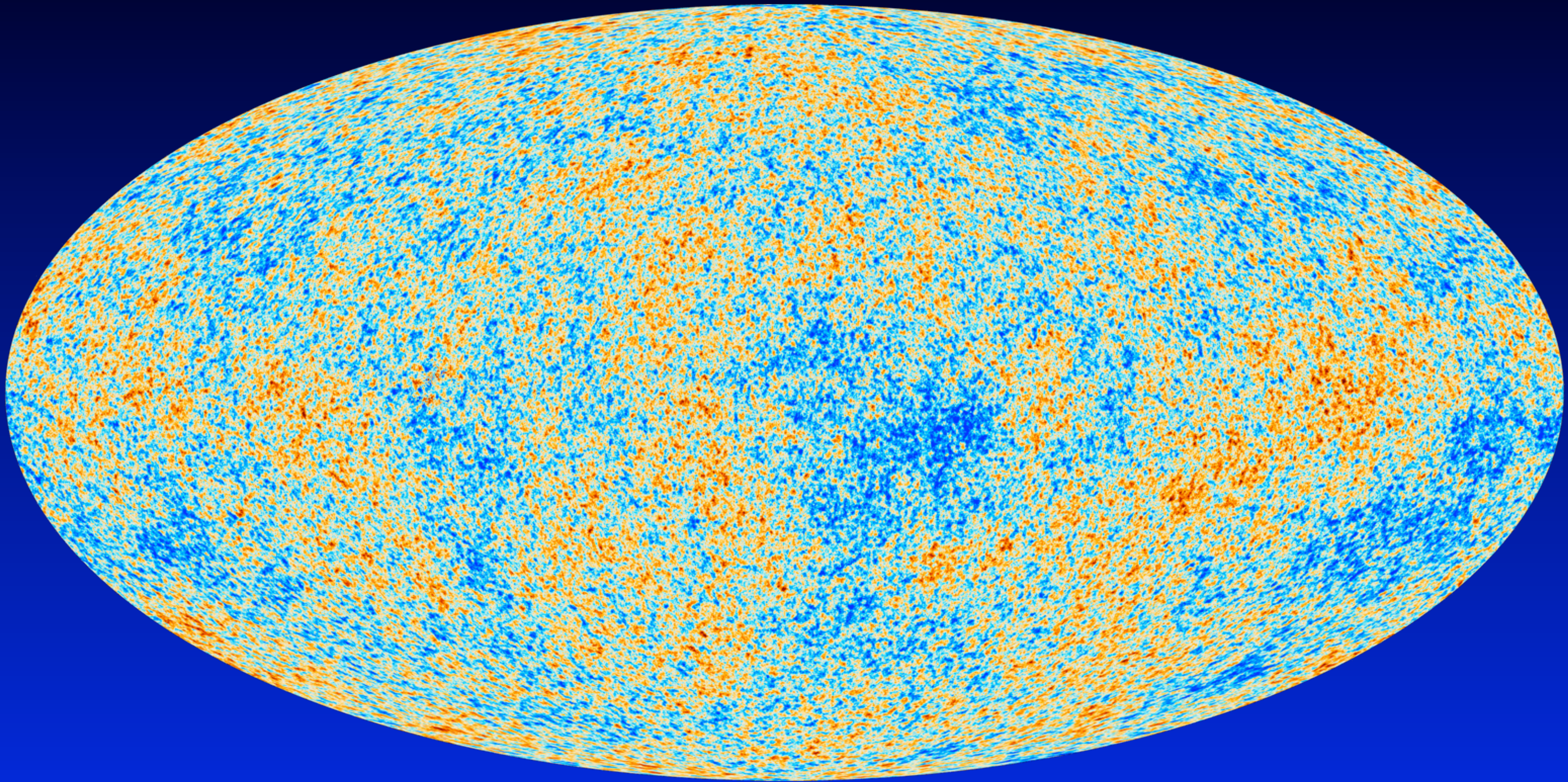
KEK, Japan, Sept 30th - Oct 3rd, 2013

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

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

Cosmic Microwave Background Anisotropies



Planck all sky map

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

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Today we are Interested in the CMB Monopole Signal!!!

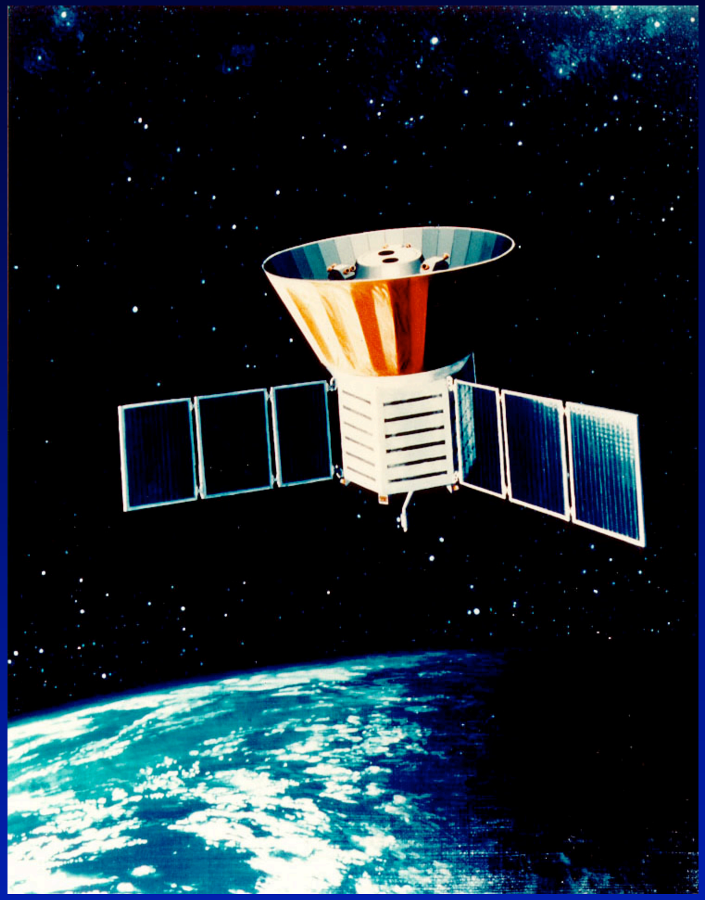
COBE/FIRAS

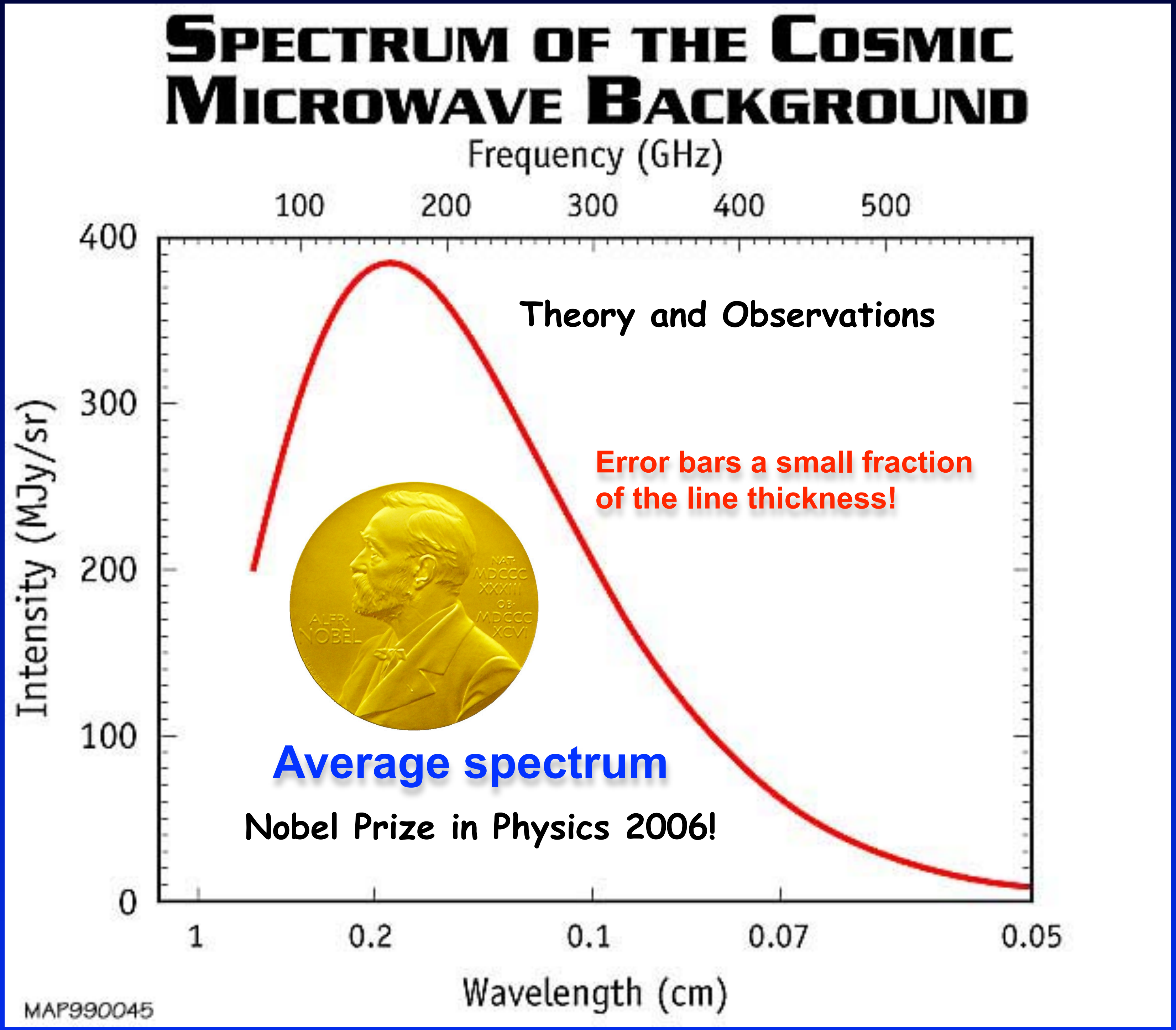
$$T_0 = (2.726 \pm 0.001)\,\mathrm{K}$$

Mather et al., 1994, ApJ, 420, 439
Fixsen et al., 1996, ApJ, 473, 576
Fixsen, 2003, ApJ, 594, 67
Fixsen, 2009, ApJ, 707, 916

- CMB monopole is 10000 - 100000 times larger than fluctuations!

COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)





$$T_0 = 2.725 \pm 0.001\,\mathrm{K}$$

$$|y| \leq 1.5 \times 10^{-5}$$

$$|\mu| \leq 9 \times 10^{-5}$$

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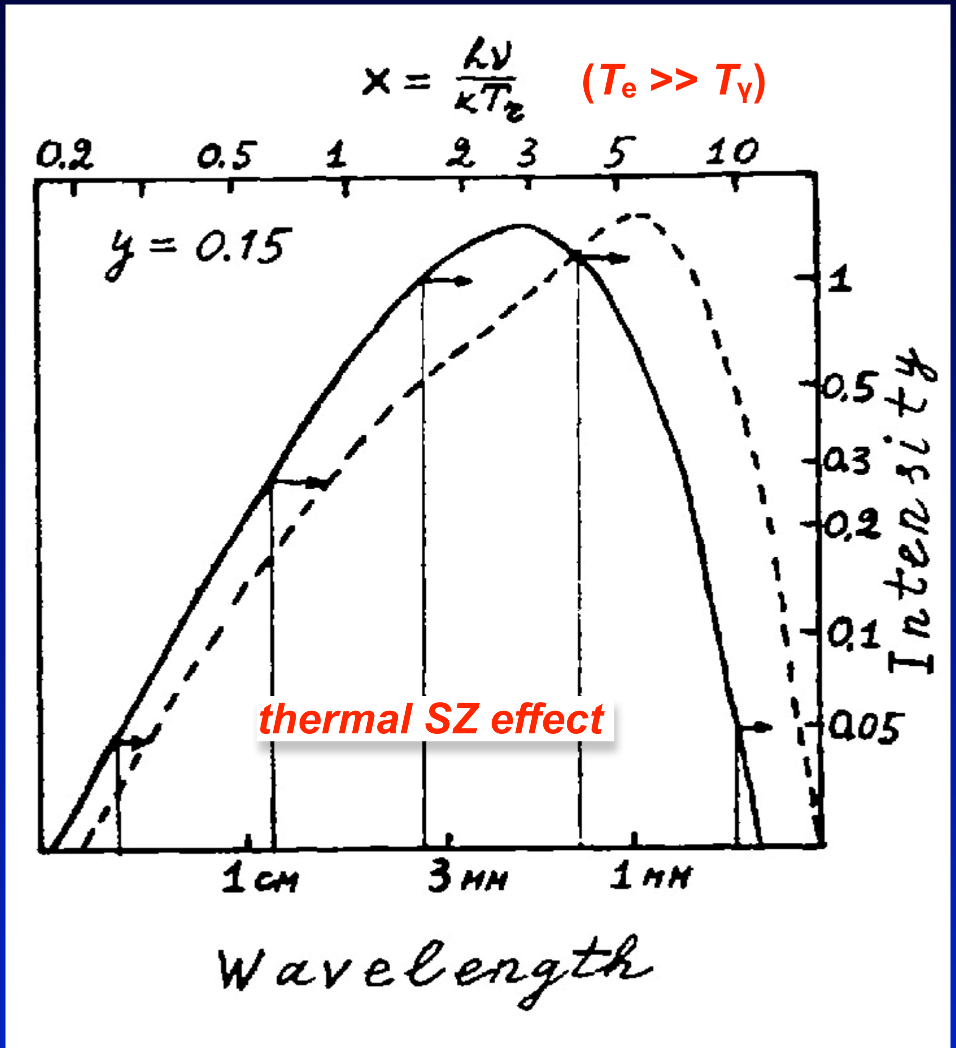
Small Sneak Preview....

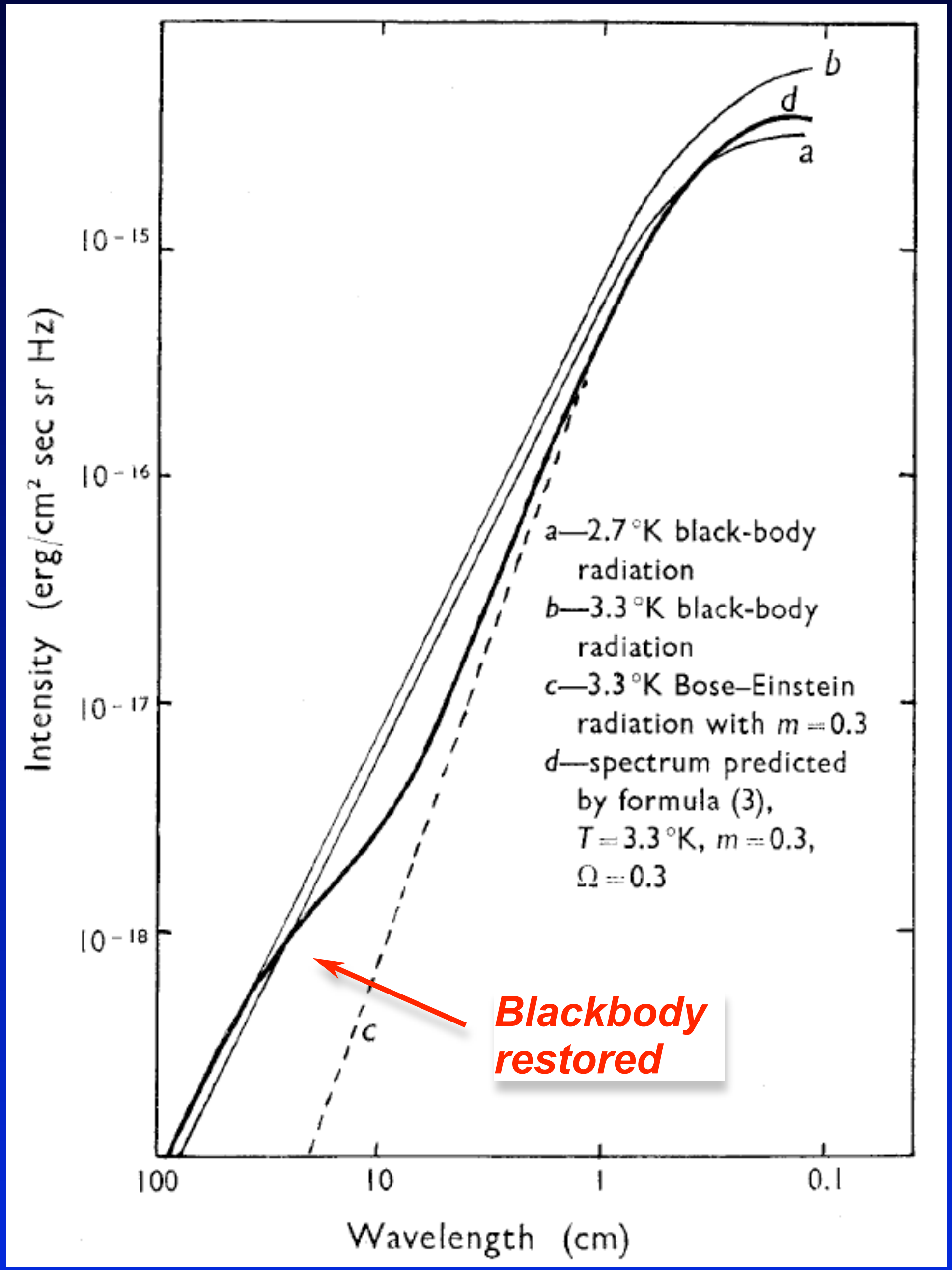
Compton y-distortion



Sunyaev & Zeldovich, 1980, ARAA, 18, 537

- also known from thSZ effect
- up-scattering of CMB photon
- important at late times (z<50000)
- scattering inefficient

Chemical potential μ-distortion



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- important at very times (z>50000)
- scattering very efficient

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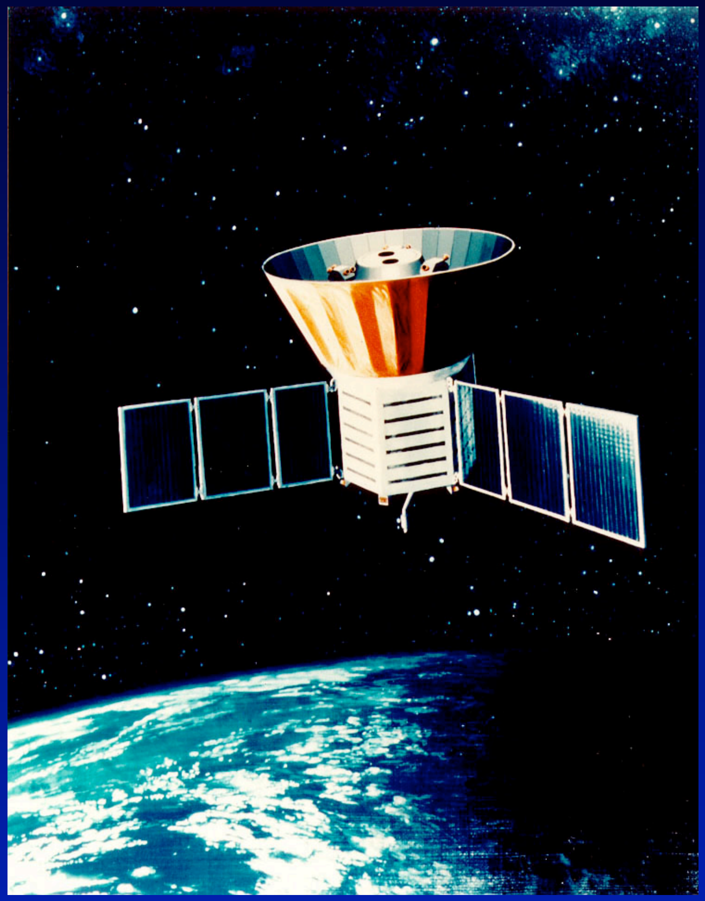

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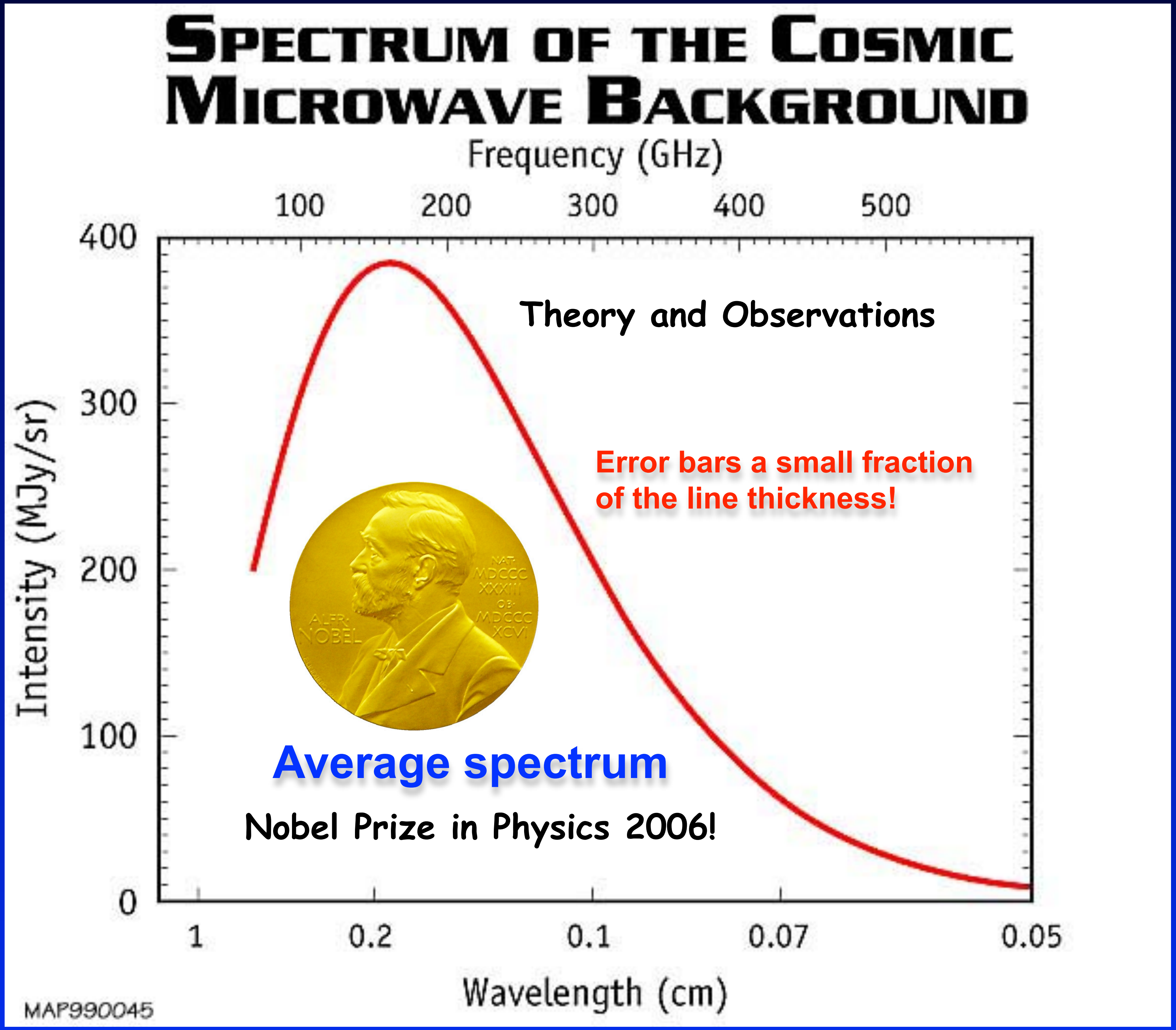

Only very small distortions of CMB spectrum are still allowed!

Why should one expect some spectral distortion?

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Full thermodynamic equilibrium (certainly valid at very high redshift)

- CMB has a blackbody spectrum at every time (not affected by expansion)
- Photon number density and energy density determined by temperature T_γ

$T_\gamma \sim 2.726\,(1+z)$ K

$N_\gamma \sim 411$ cm^{-3} $(1+z)^3 \sim 2{\times}10^9\, N_b$ (*entropy density dominated by photons*)

$\rho_\gamma \sim 5.1{\times}10^{-7}\, m_e c^2$ cm^{-3} $(1+z)^4 \sim \rho_b$ x $(1+z)$ / 925 ~ 0.26 eV cm^{-3} $(1+z)^4$

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Perturbing full equilibrium by

- Energy injection (interaction *matter* ←→ *photons*)
- Production of (energetic) photons and/or particles (i.e. change of entropy)

→ CMB spectrum deviates from a pure blackbody

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(Compton scattering, double Compton and Bremsstrahlung in the expanding Universe)

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Measurements of CMB spectrum place very tight limits on the thermal history of our Universe!

Why bother? No distortion detected so far!??

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 ($\Delta\rho/\rho \sim 10^{-10}$-$10^{-9}$)

Standard sources of distortions

- 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*

pre-recombination epoch

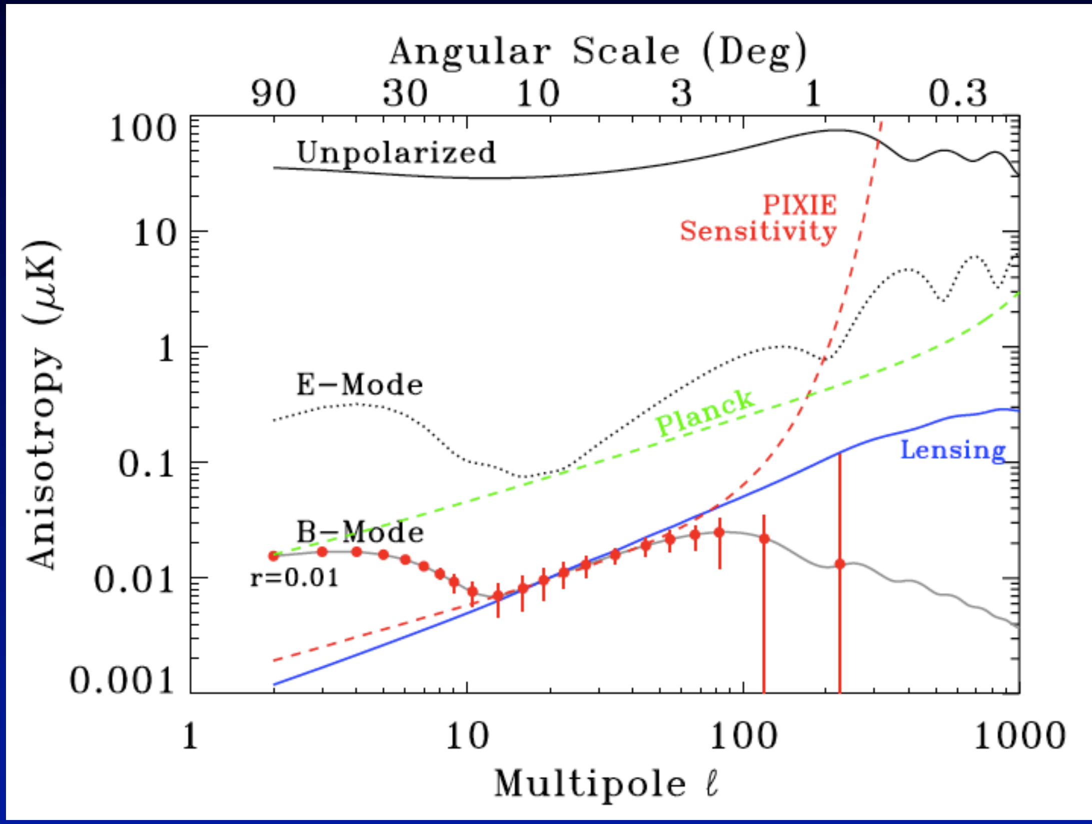
„high“ redshifts

„low“ redshifts

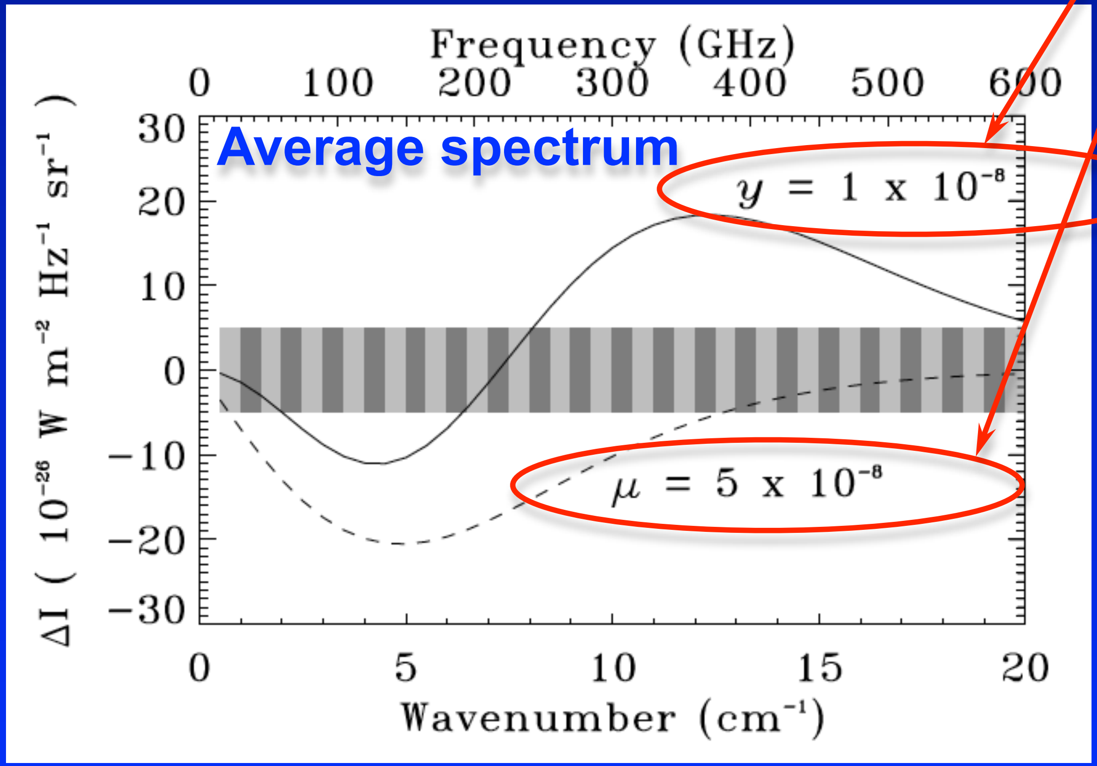
- Signatures due to first supernovae and their remnants
  (Oh, Cooray & Kamionkowski, 2003)
- Shock waves arising due to large-scale structure formation
  (Sunyaev & Zeldovich, 1972; Cen & Ostriker, 1999)
- SZ-effect from clusters; effects of reionization (Heating of medium by X-Rays, Cosmic Rays, etc)

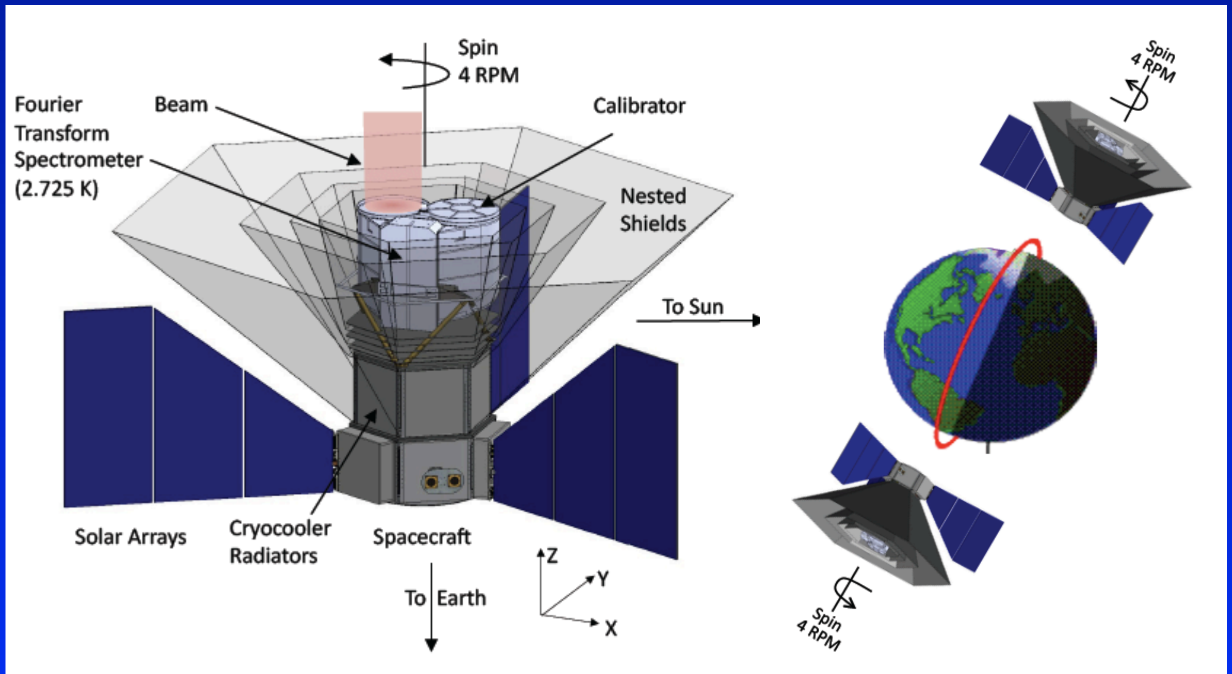
post-recombination

PIXIE: Primordial Inflation Explorer

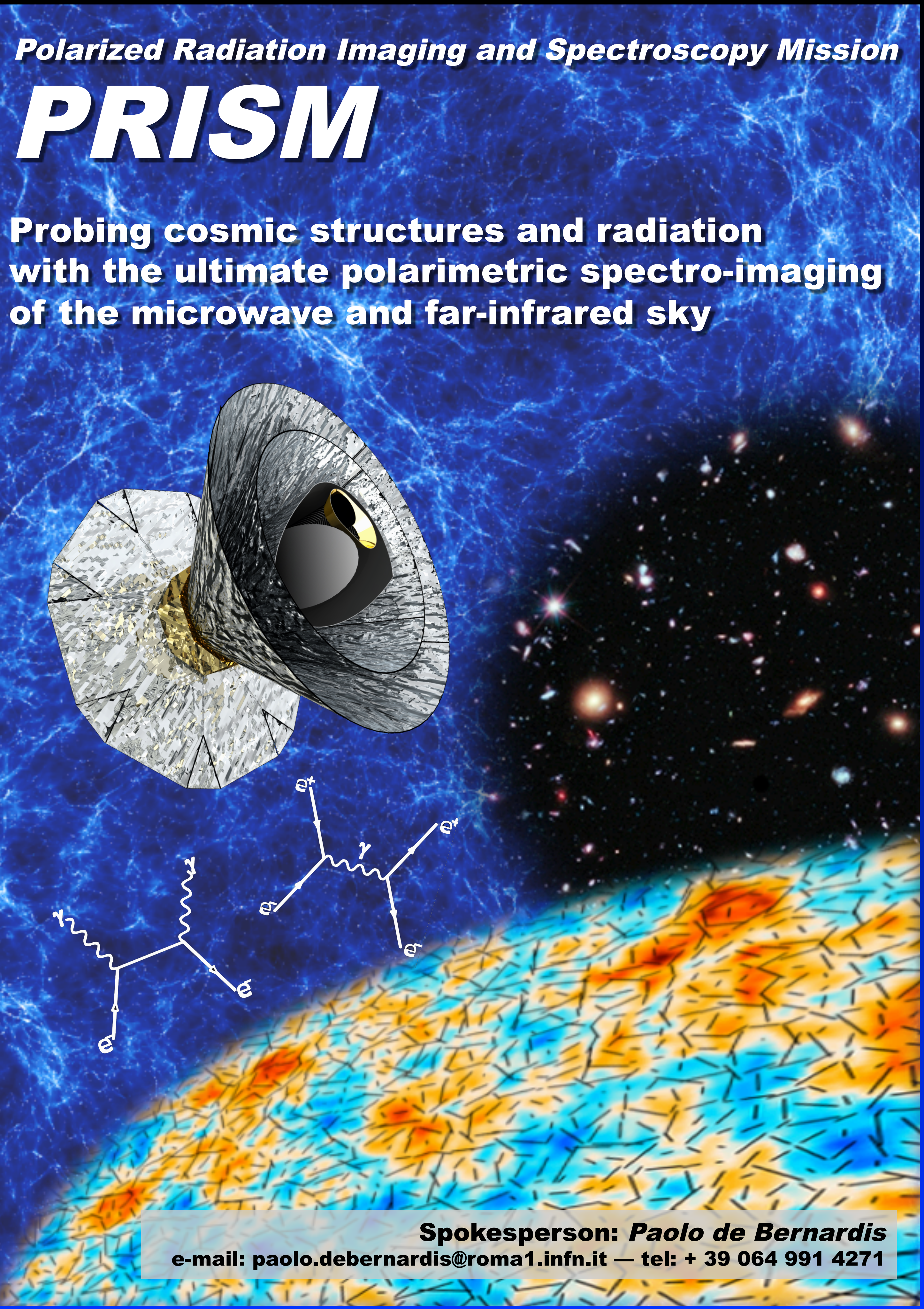


- 400 spectral channel in the frequency range 30 GHz and 6THz (Δv ~ 15GHz)
- about 1000 (!!!) times more sensitive than COBE/FIRAS
- B-mode polarization from inflation ($r \approx 10^{-3}$)
- improved limits on μ and y
- was proposed 2011 as NASA EX mission (i.e. cost ~ 200 M$)





Kogut et al, JCAP, 2011, arXiv:1105.2044



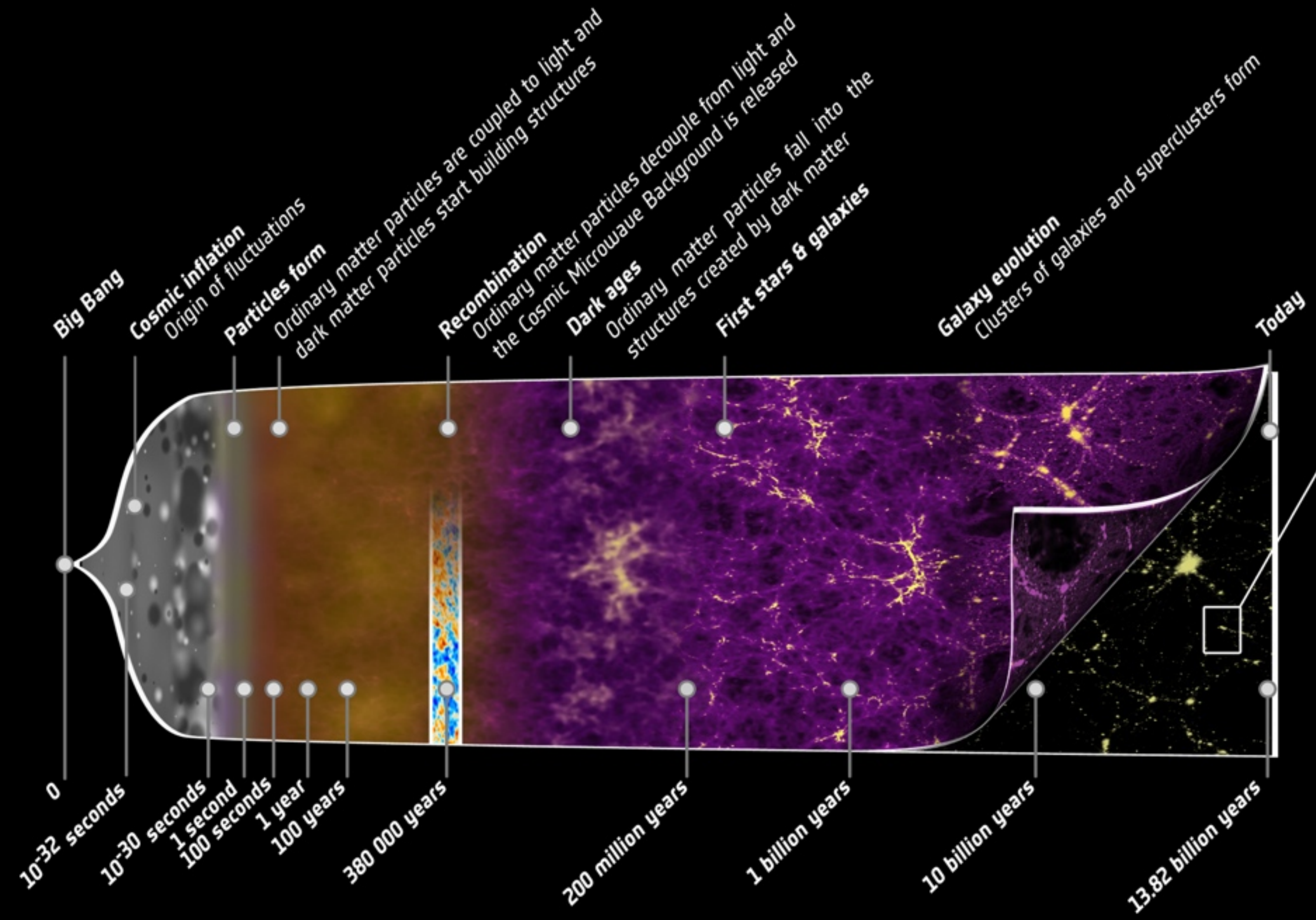
Instruments:

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

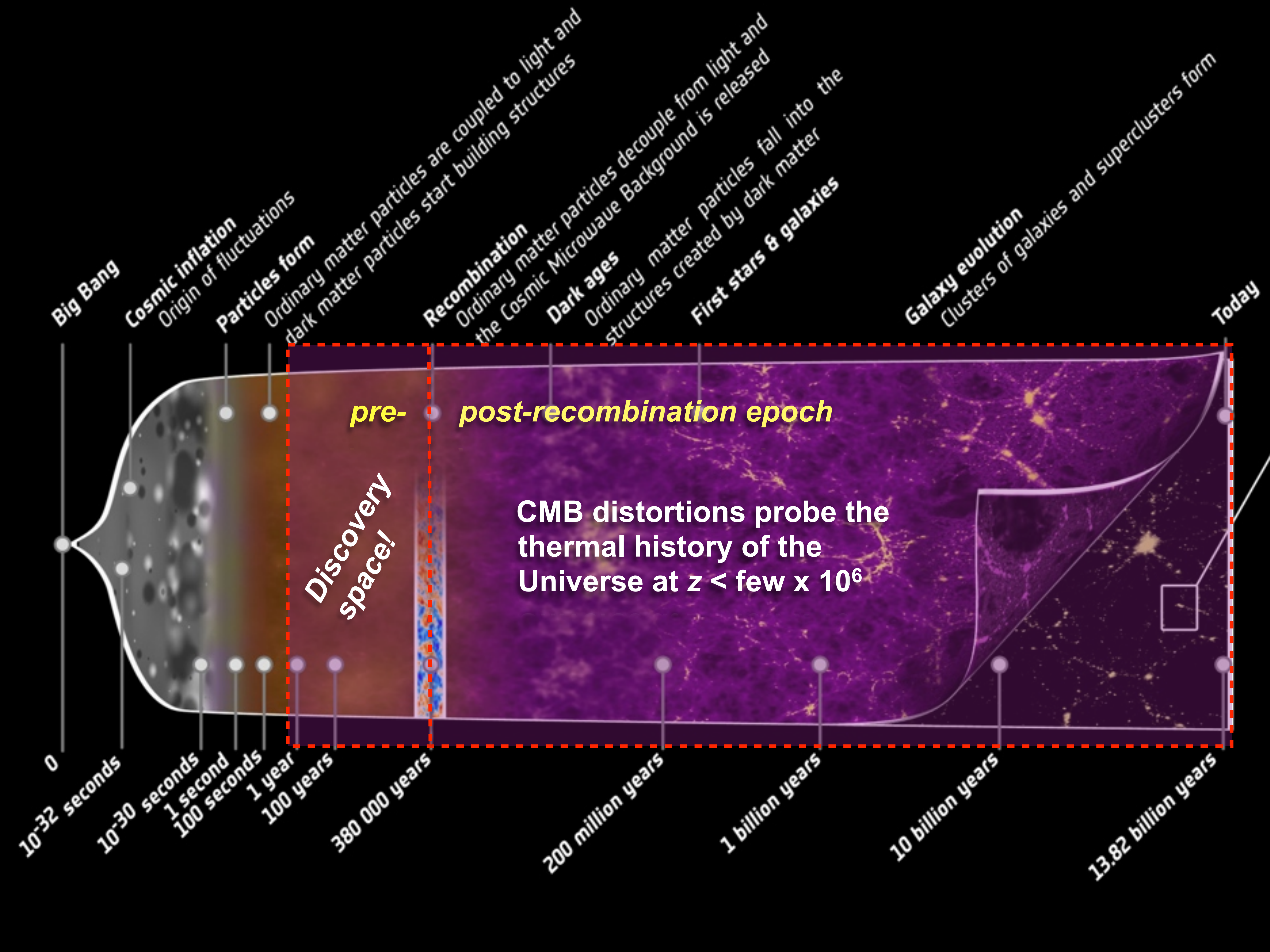
Some of the science goals:

- B-mode polarization from inflation ($r \approx 5\text{x}10^{-4}$)
- 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/



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
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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Discovery space!
CMB distortions probe the thermal history of the Universe at z < few x 10^6
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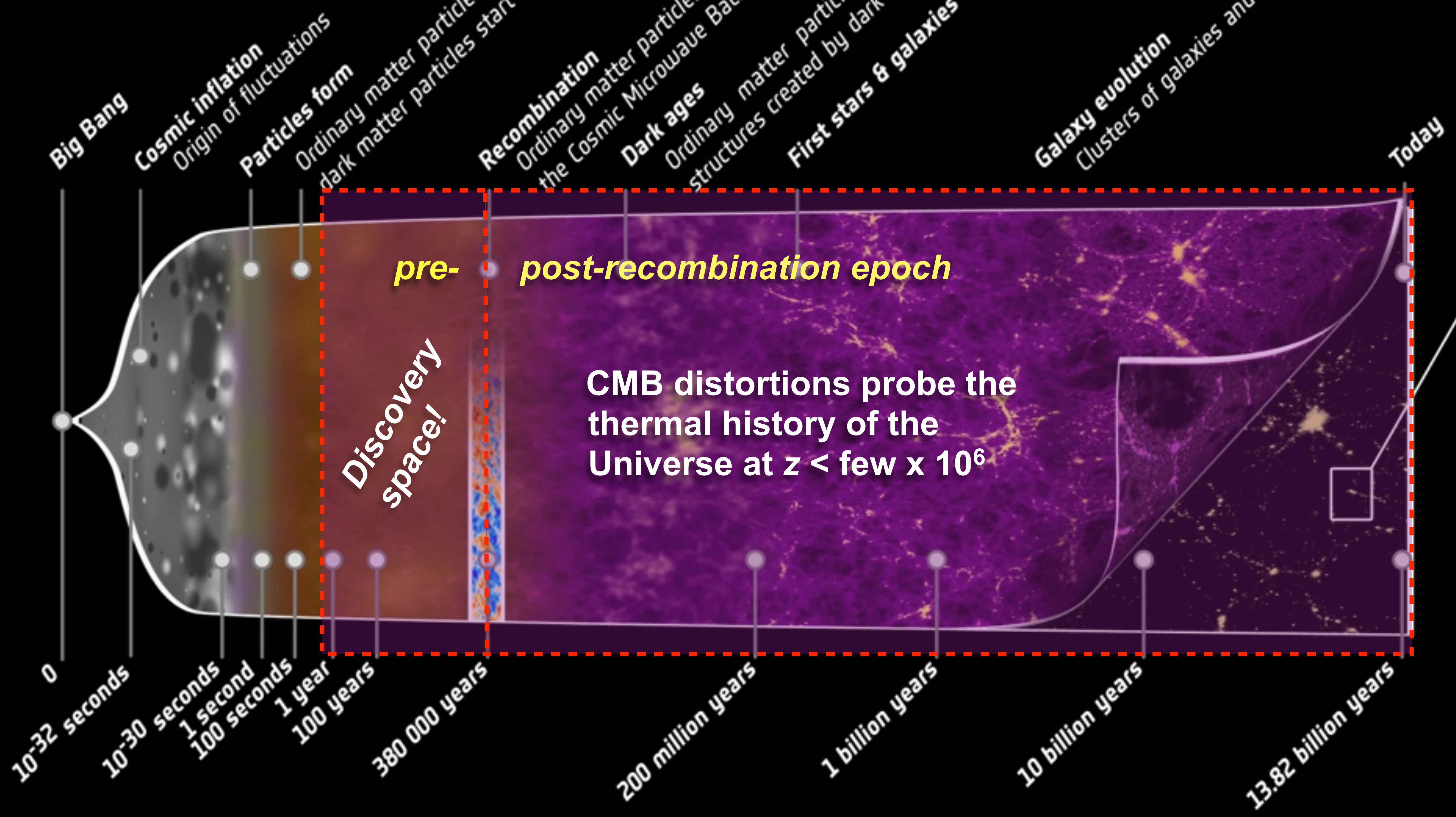
Measurements of CMB spectrum will open a new unexplored window to the early Universe!



How does the thermalization process work?

Some important conditions

- Plasma fully ionized before recombination (z~1000)
  - → free electrons, protons and helium nuclei
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- Hubble expansion
  - → adiabatic cooling of photons [$T_\gamma \sim (1+z)$] and ordinary matter [$T_m \sim (1+z)^2$]
  - → redshifting of photons

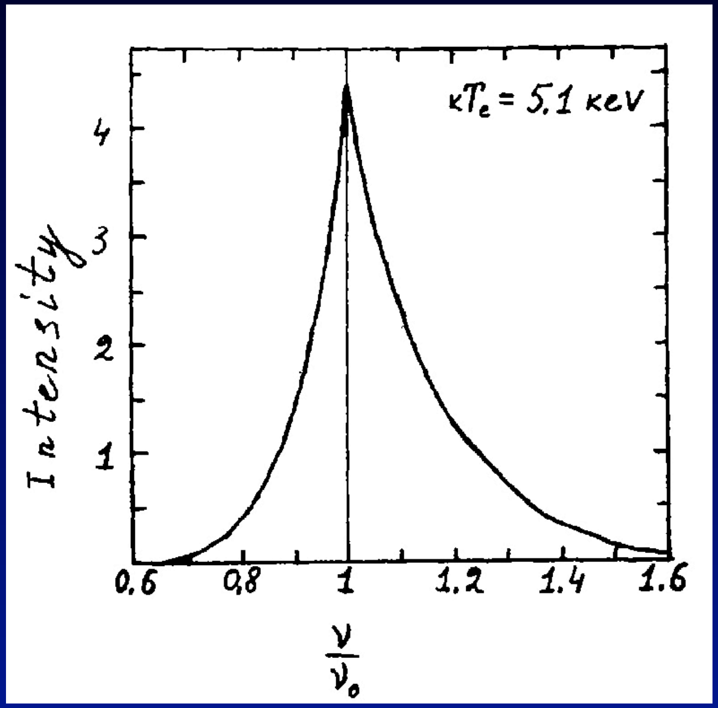
Redistribution of photons by Compton scattering

- Compton scattering $e + \gamma \leftrightarrow e' + \gamma'$

→ *redistribution* of photons in frequency

  - up-scattering due to the ***Doppler*** effect for $h\nu < 4kT_\mathrm{e}$
  - down-scattering because of ***recoil*** (and stimulated recoil) for $h\nu > 4kT_\mathrm{e}$
  - ***Doppler*** broadening $\frac{\Delta\nu}{\nu} \simeq \sqrt{\frac{2kT_\mathrm{e}}{m_\mathrm{e}c^2}}$

→ strongly couples (free) electrons to the CMB photon down to redshifts *z*~150



Sunyaev& Zeldovich, 1980, Ann. Rev. Astr. Astrophy., 18, pp.537

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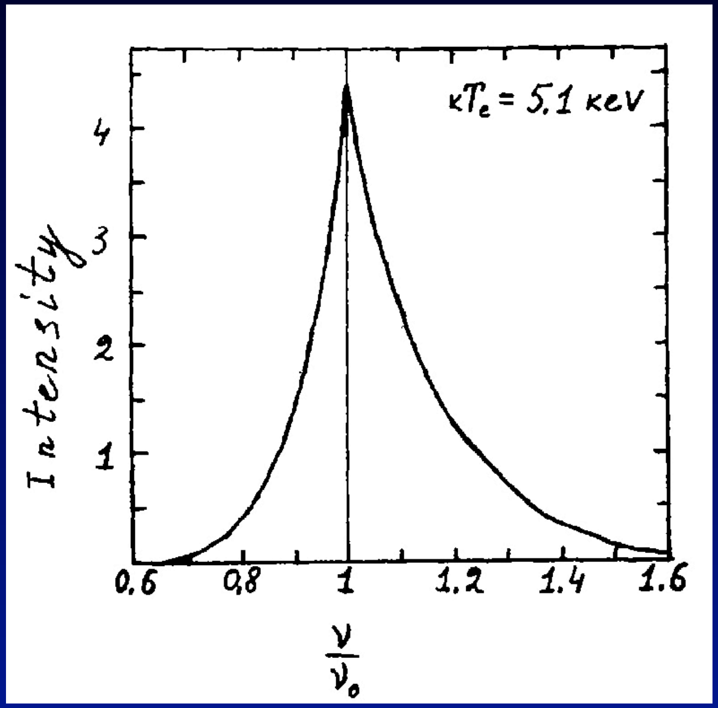
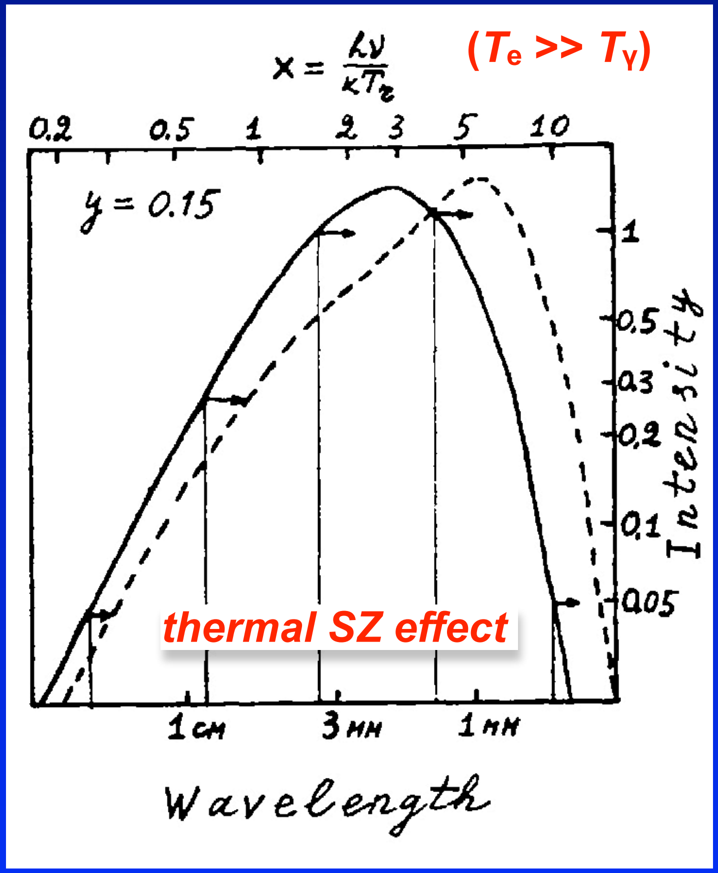
- *Kompaneets Equation* → 'pure' ***y*-distortion**

$$\frac{\Delta I_\nu}{I_\nu} \simeq y \frac{xe^x}{e^x - 1}\left[x\frac{e^x+1}{e^x-1} - 4\right],$$

where $x = \frac{h\nu}{kT_\gamma}$ and $y = \int \frac{k(T_{\rm e} - T_\gamma)}{m_{\rm e}c^2}\sigma_{\rm T} n_{\rm e} {\rm d}l$ << 1

Temperature difference





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Adjusting the photon number

- Bremsstrahlung $e + p \leftrightarrow e' + p + \gamma$

  → 1. order α correction to *Coulomb* scattering

  → production of low frequency photons

  → important for the evolution of the distortion at low frequencies and late times (z< 2 x 10^5)

- Double Compton scattering
  (Lightman 1981; Thorne, 1981)

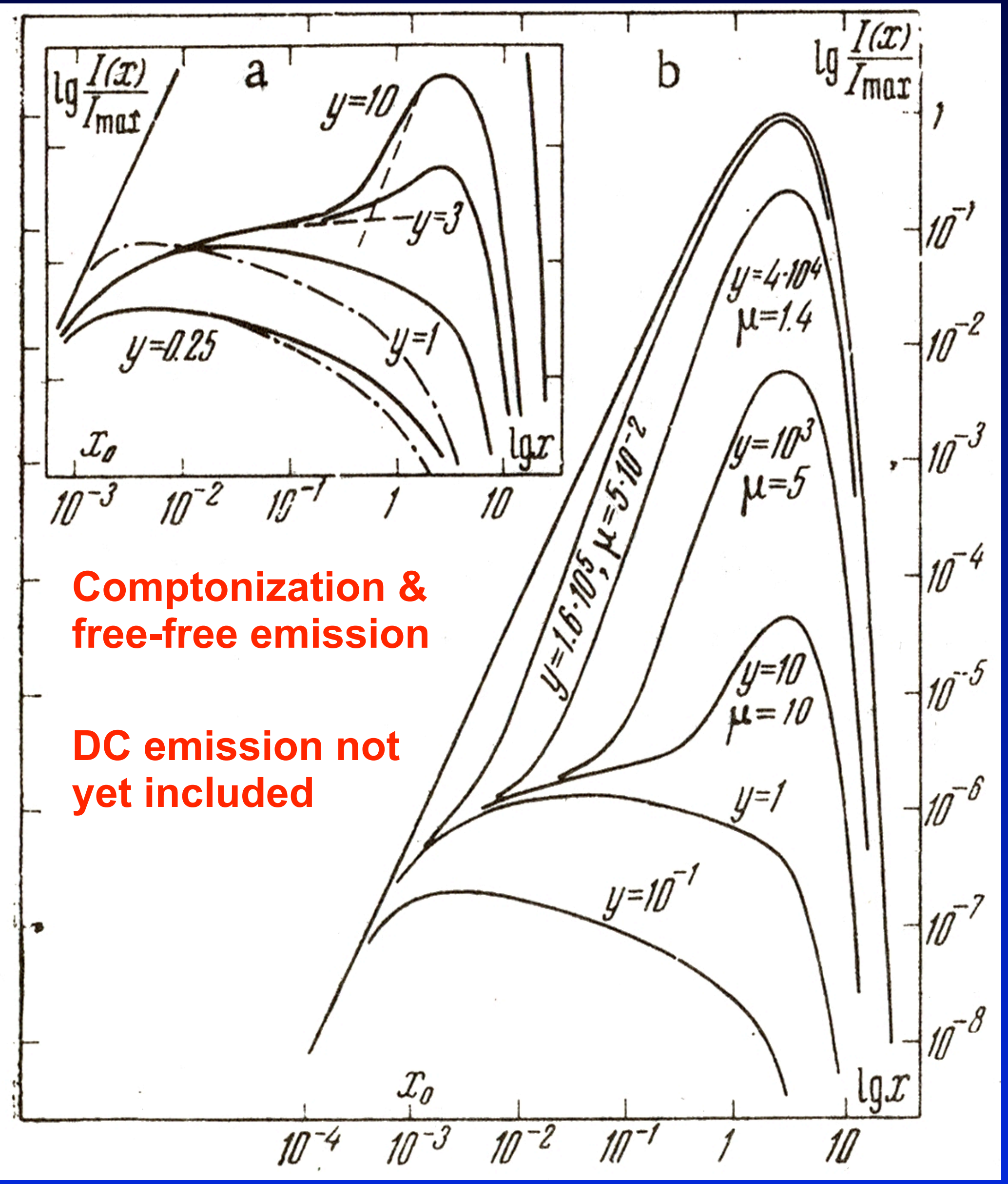
$$e + \gamma \leftrightarrow e' + \gamma ' + \gamma_2$$

  → 1. order α correction to *Compton* scattering

  → was only included later **(Danese & De Zotti, 1982)**

  → production of low frequency photons

  → very important at high redshifts (z > 2 x 10^5)



Illarionov & Sunyaev, 1975, Sov. Astr, 18, pp.413

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- *Fast and quasi-exact! No additional approximations!*

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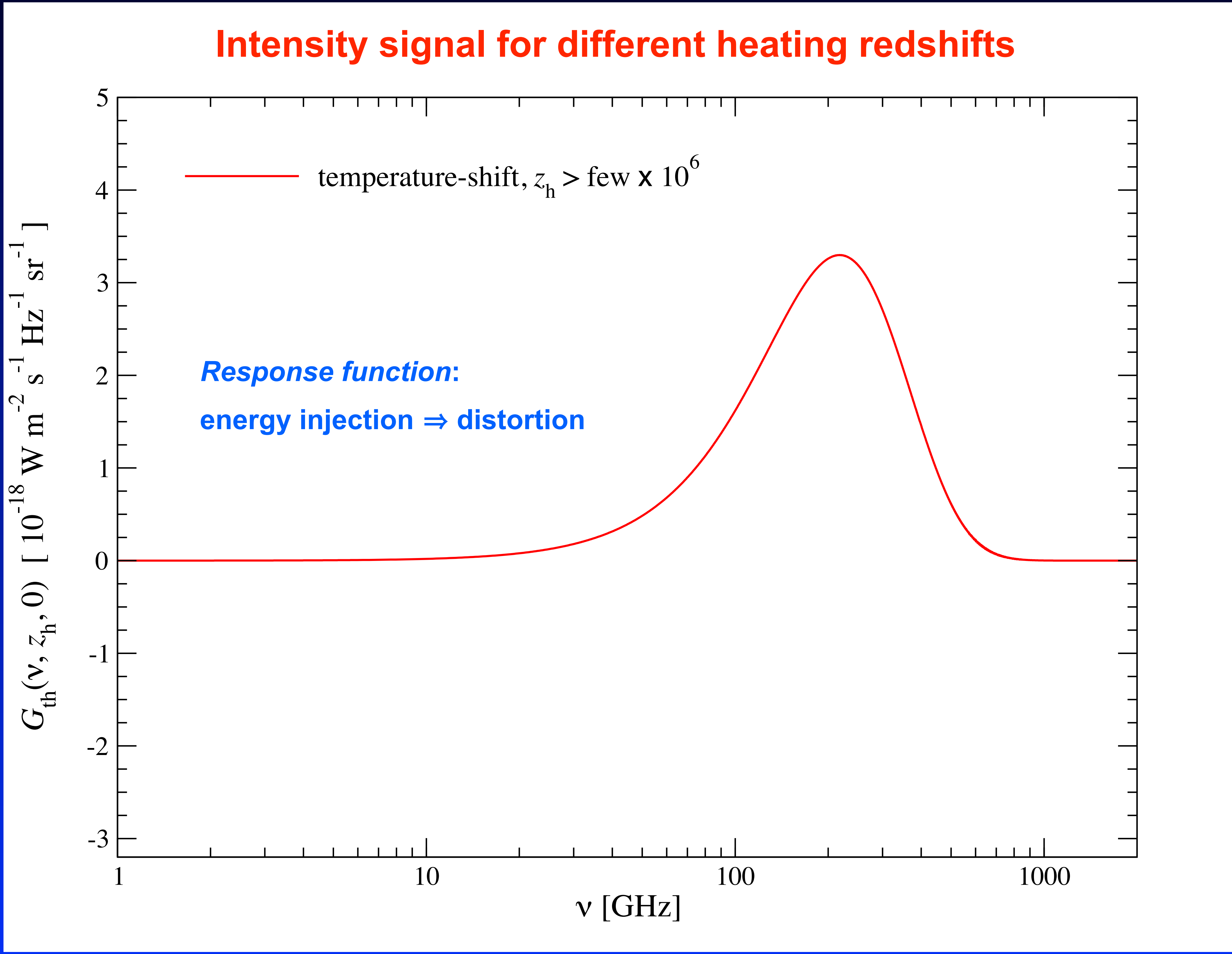

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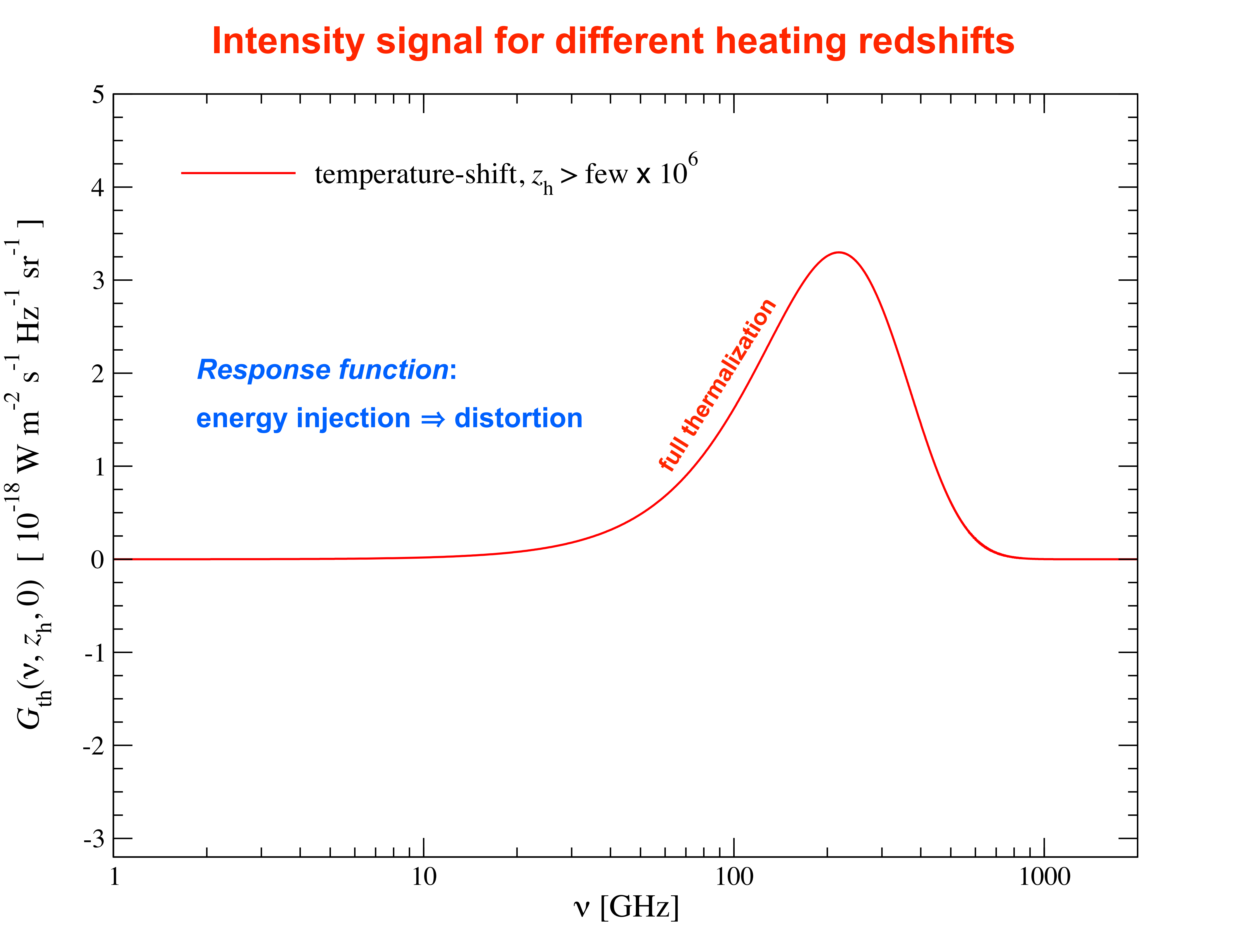

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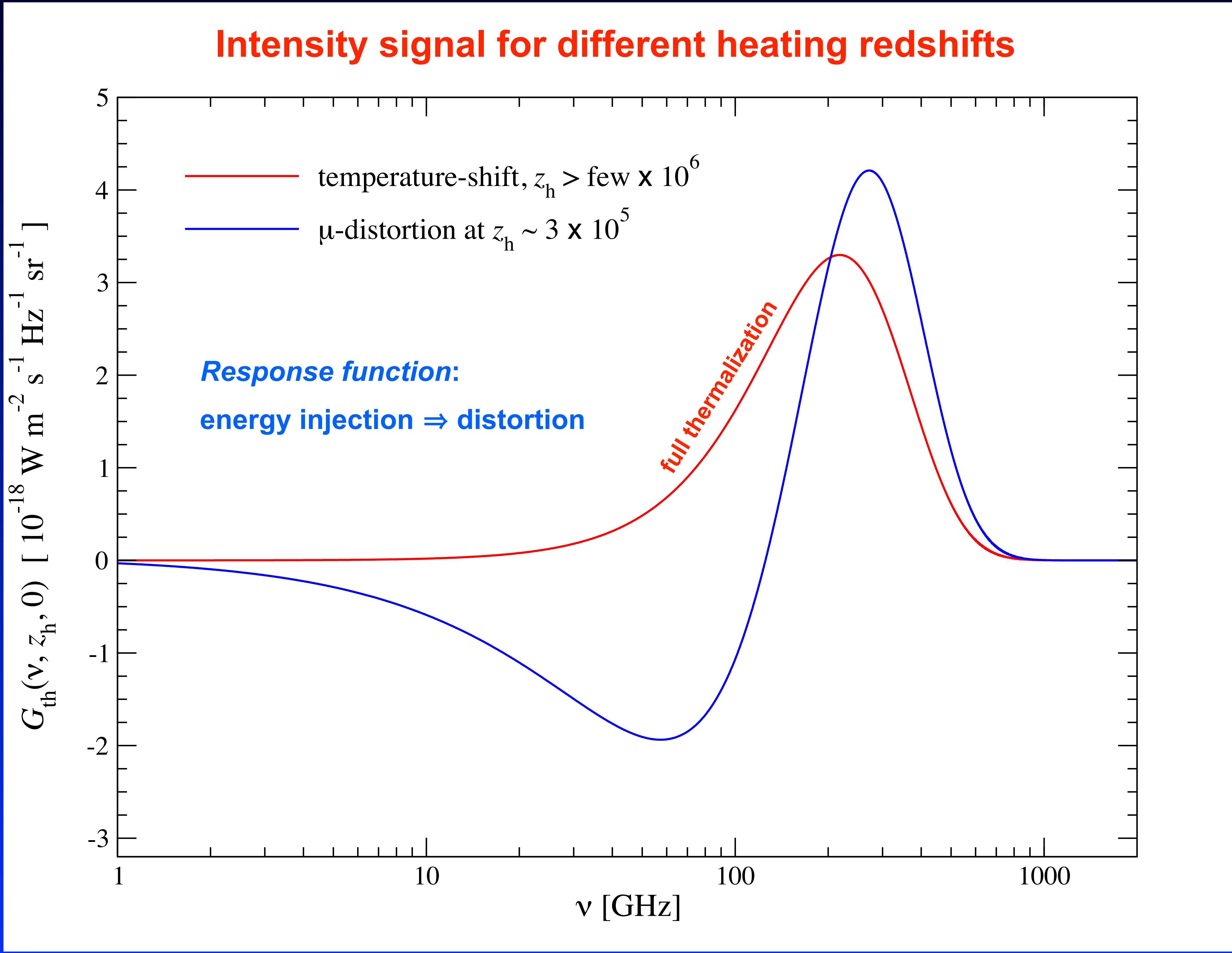

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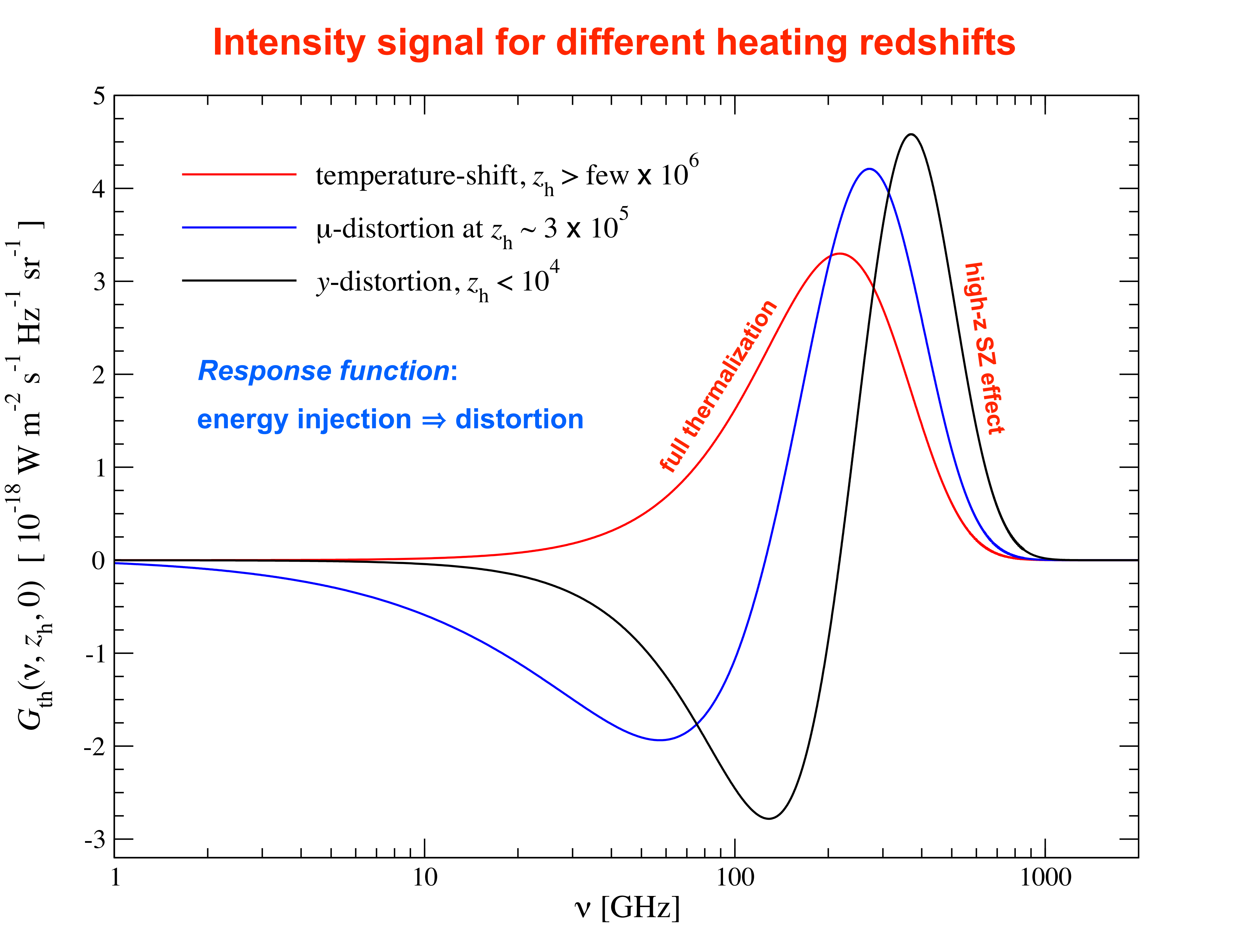

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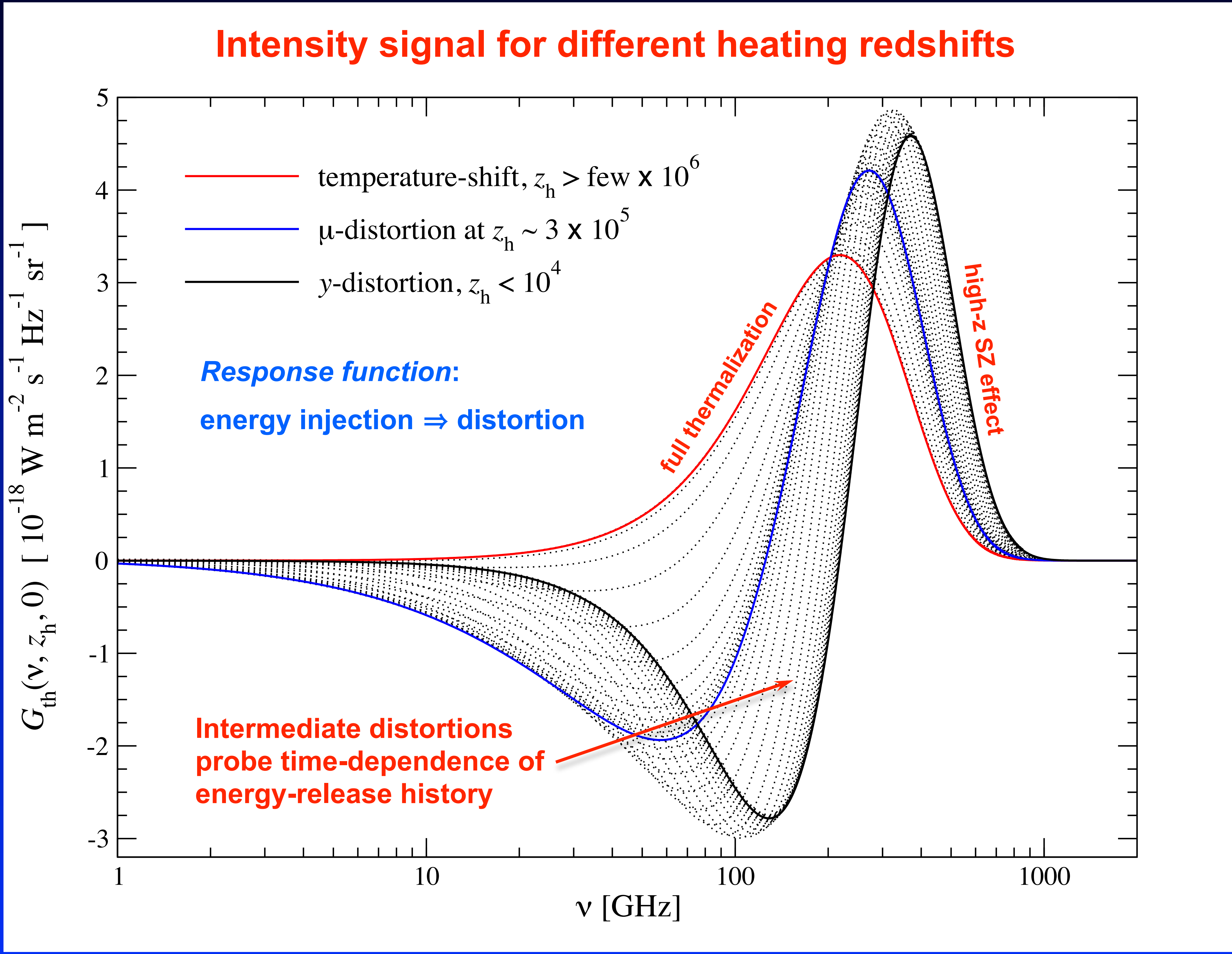

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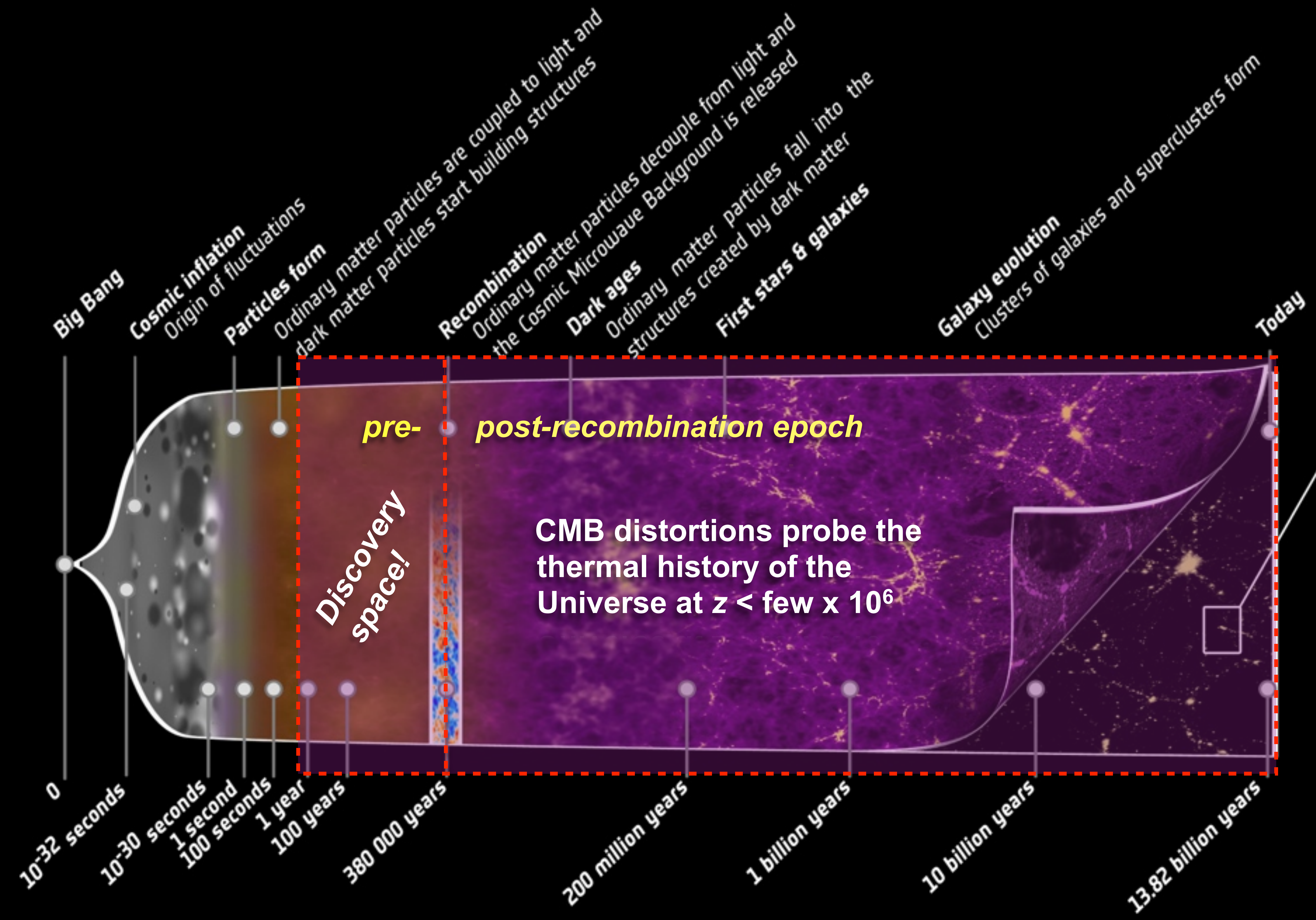

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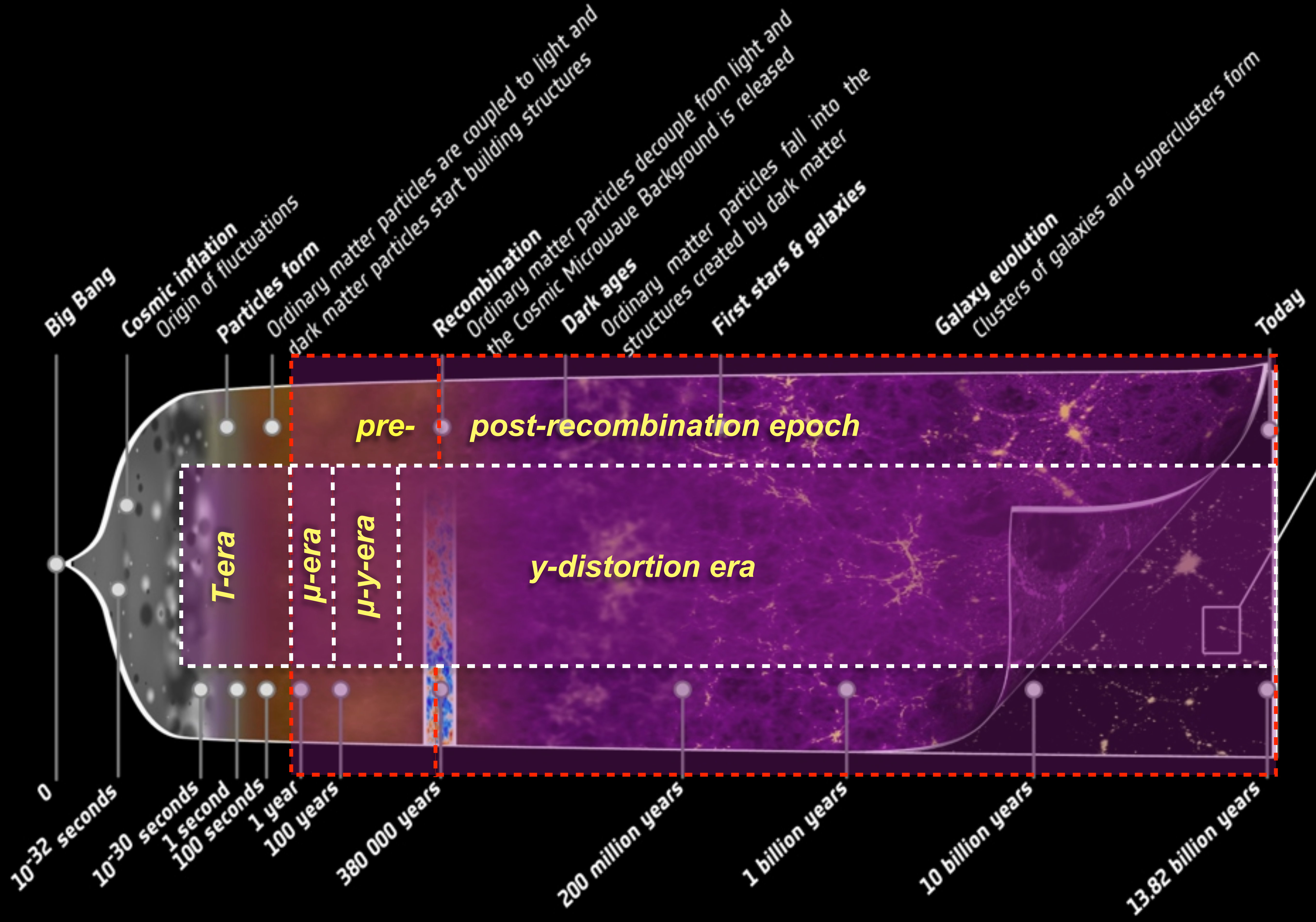


Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles 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

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 ($\Delta\rho/\rho \sim 10^{-10}$-$10^{-9}$)

Standard sources of distortions

- 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

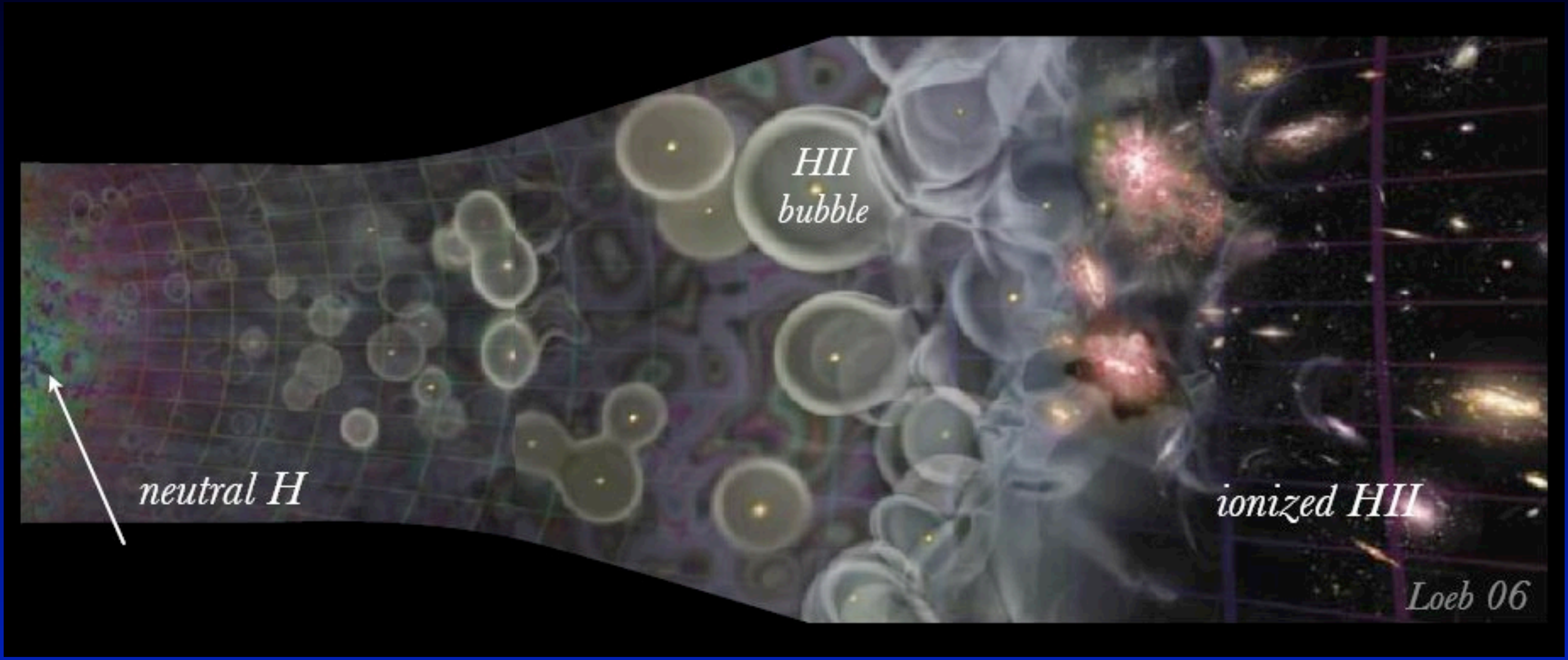
„low" redshifts

- 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)

post-recombination

Reionization and structure formation

Simple estimates for the distortion

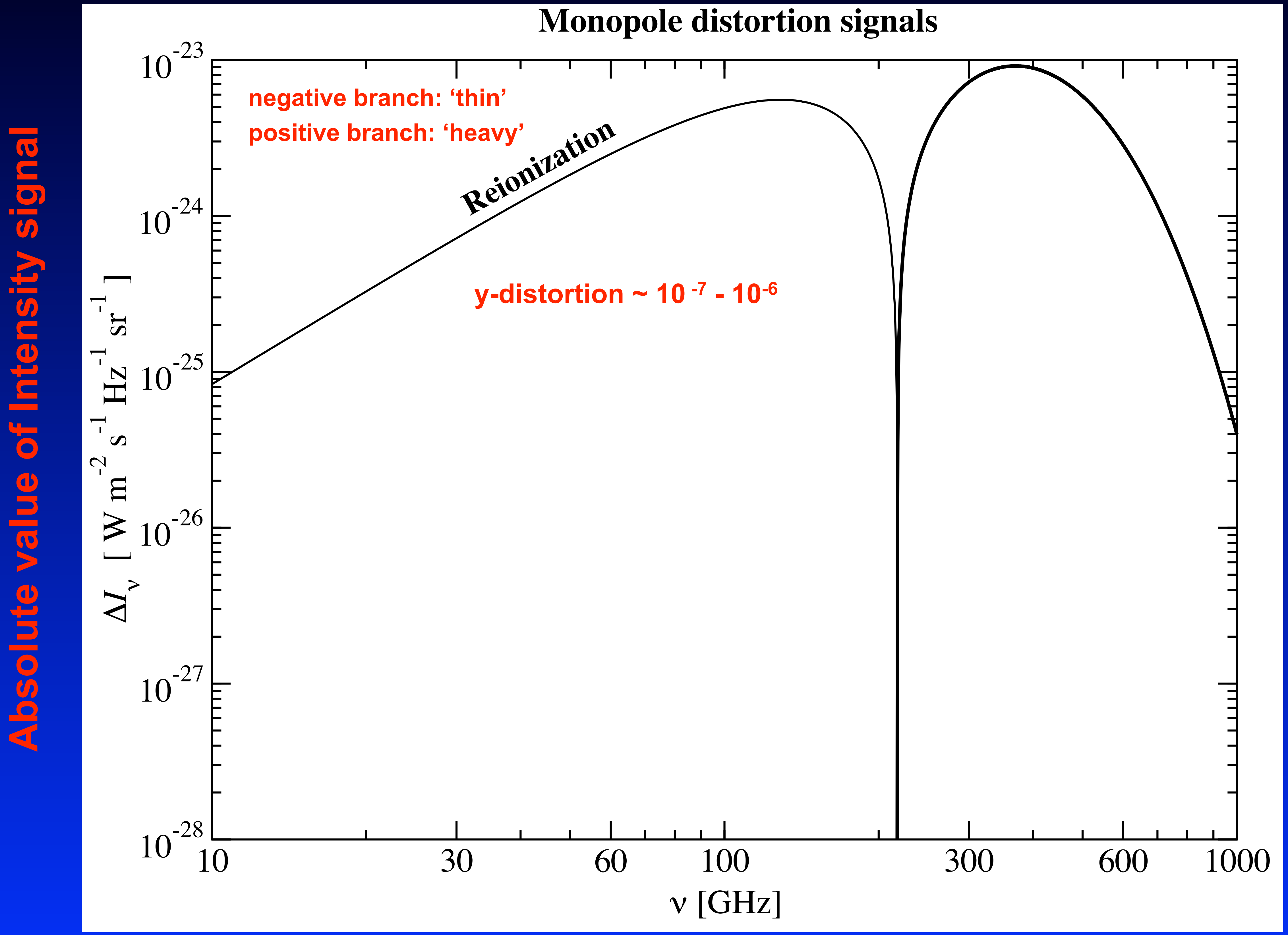


- Gas temperature $T \simeq 10^4$ K
- Thomson optical depth $\tau \simeq 0.1$

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

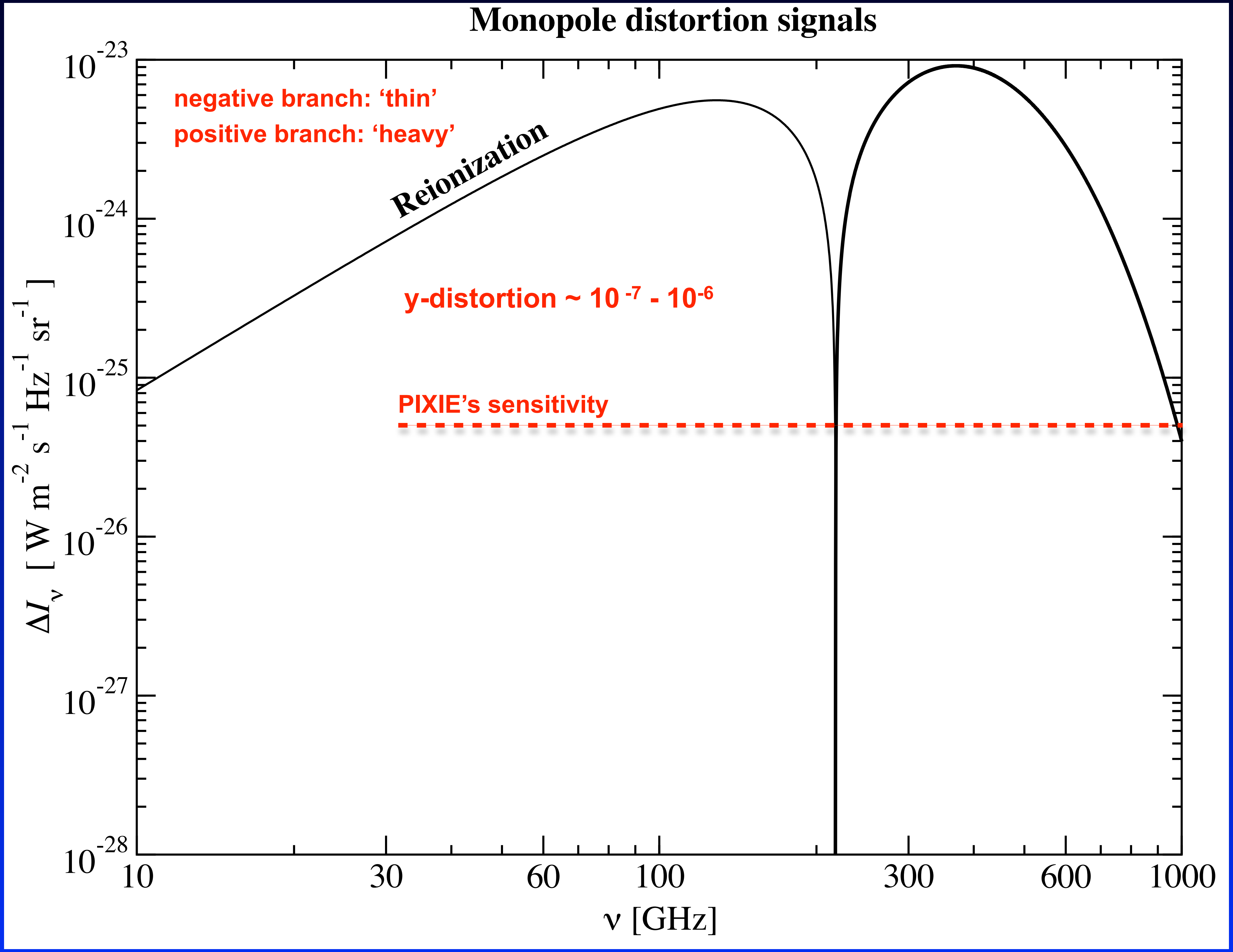
- second order Doppler effect $y \simeq$ few x 10^{-8}
- structure formation / SZ effect (e.g., Refregier et al., 2003) $y \simeq$ few x 10^{-7}-10^{-6}

Average CMB spectral distortions

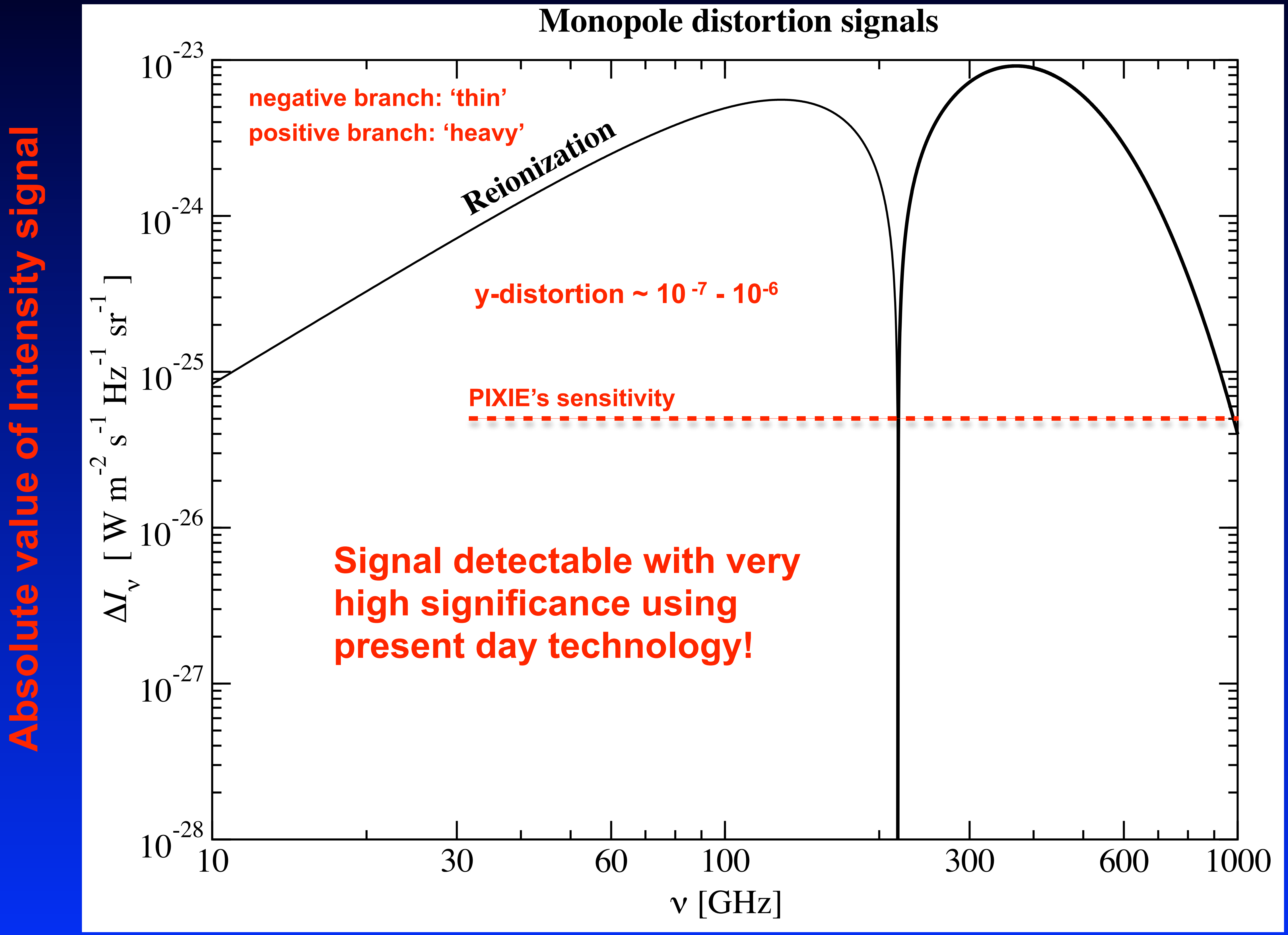


Average CMB spectral distortions

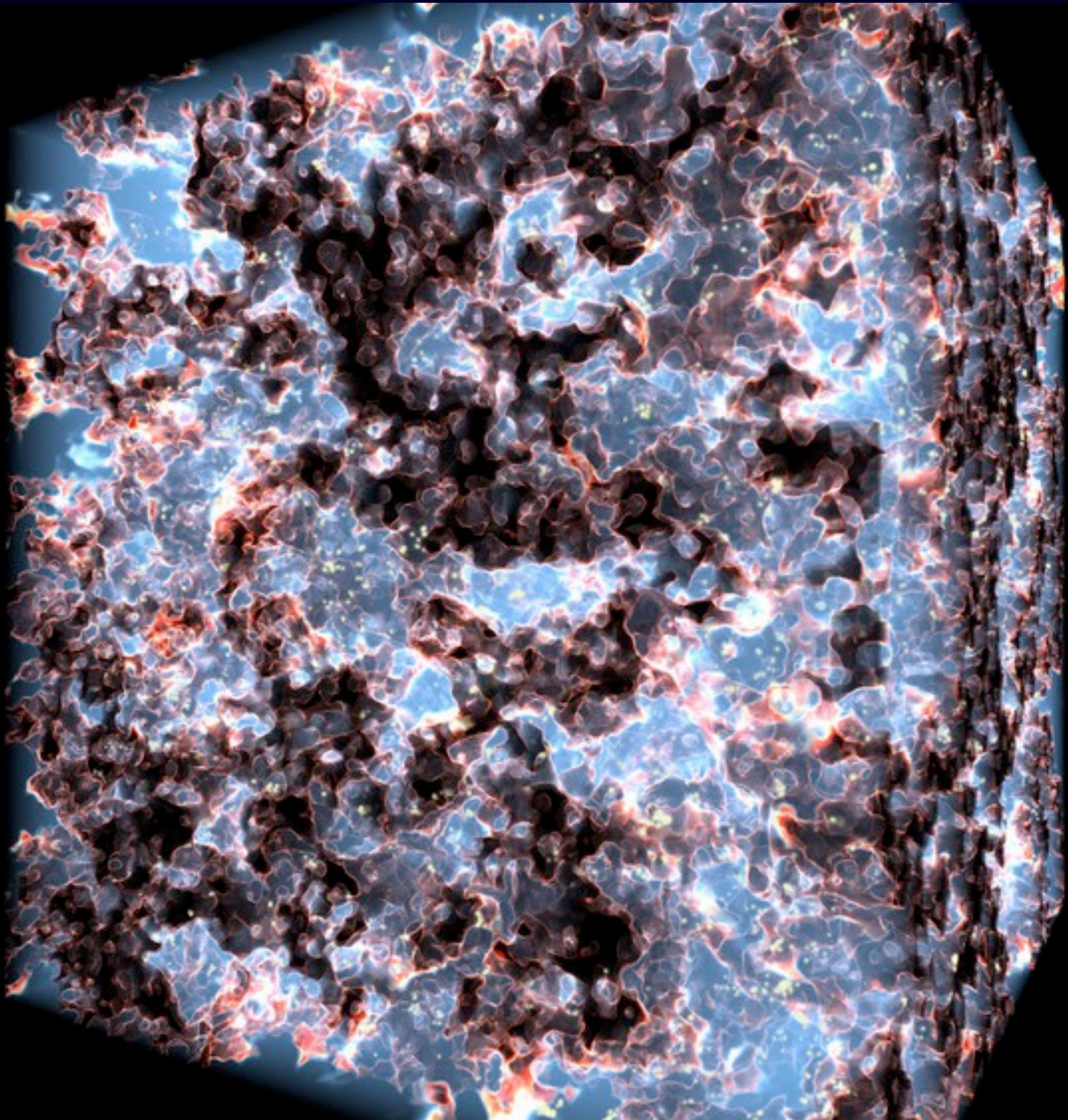
Absolute value of Intensity signal



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*

Decaying particles

Constraints from measurements of light elements

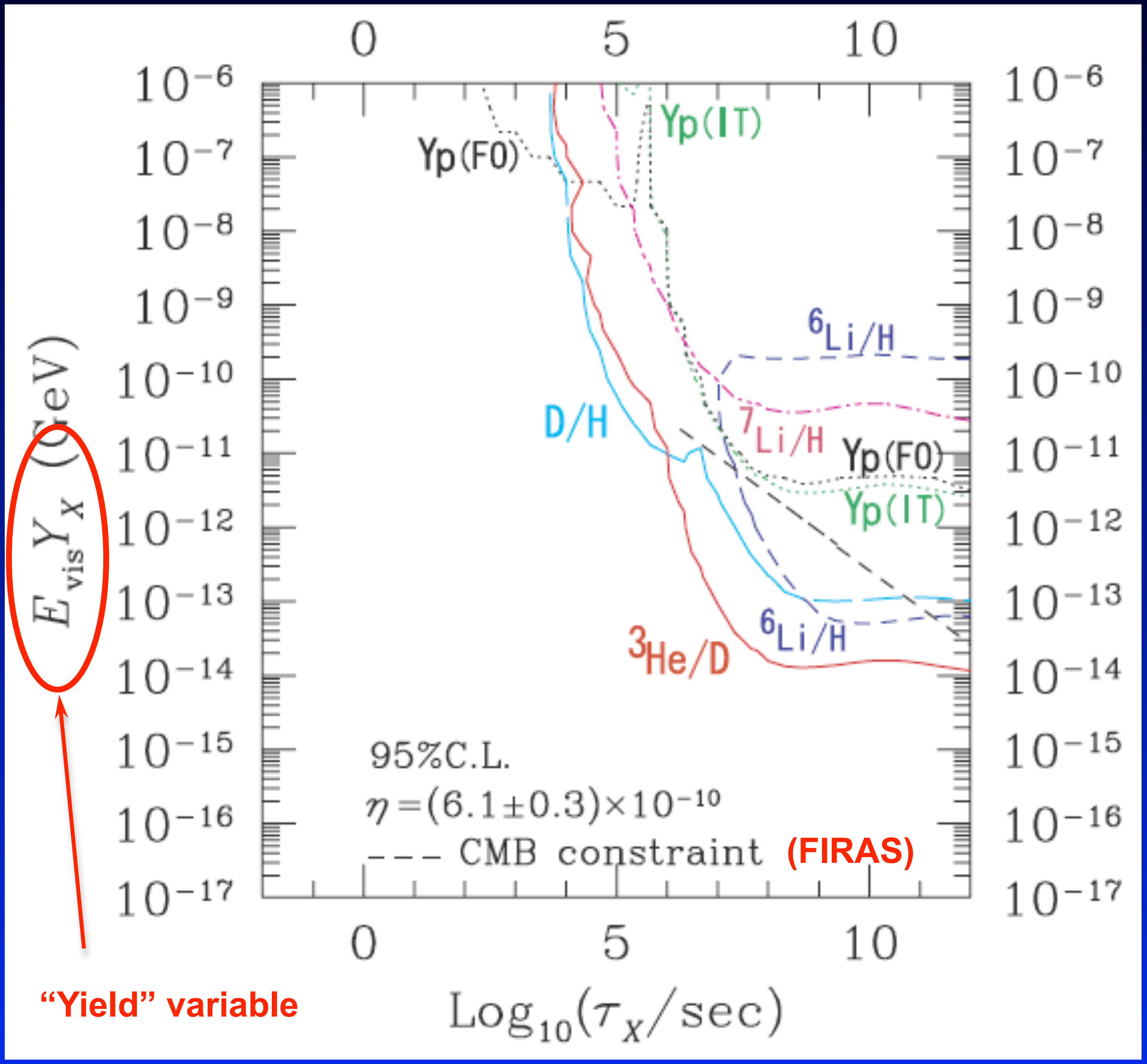


Figure from Kawasaki, Kohri and Moroi, 2005

- Yield variable ⇒

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

  $$Y_X \simeq N_X/S$$

- E_{vis} parametrizes physics of energy deposition

  (decay channels, neutrino fraction, etc.)

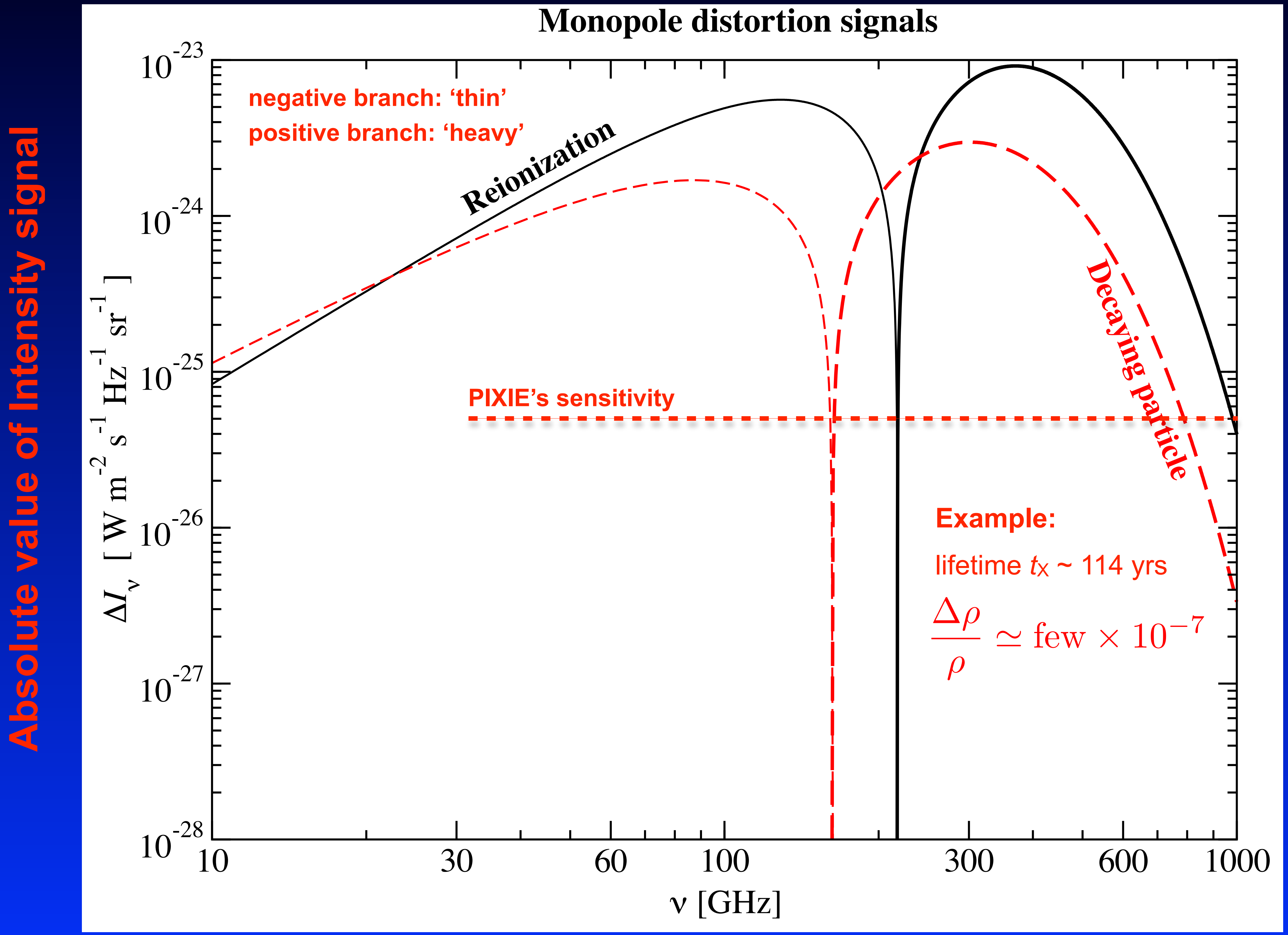
- current CMB limit rather weak....

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 $\varepsilon_\mathrm{X} = \frac{f_\mathrm{X}}{z_\mathrm{X}}$
- 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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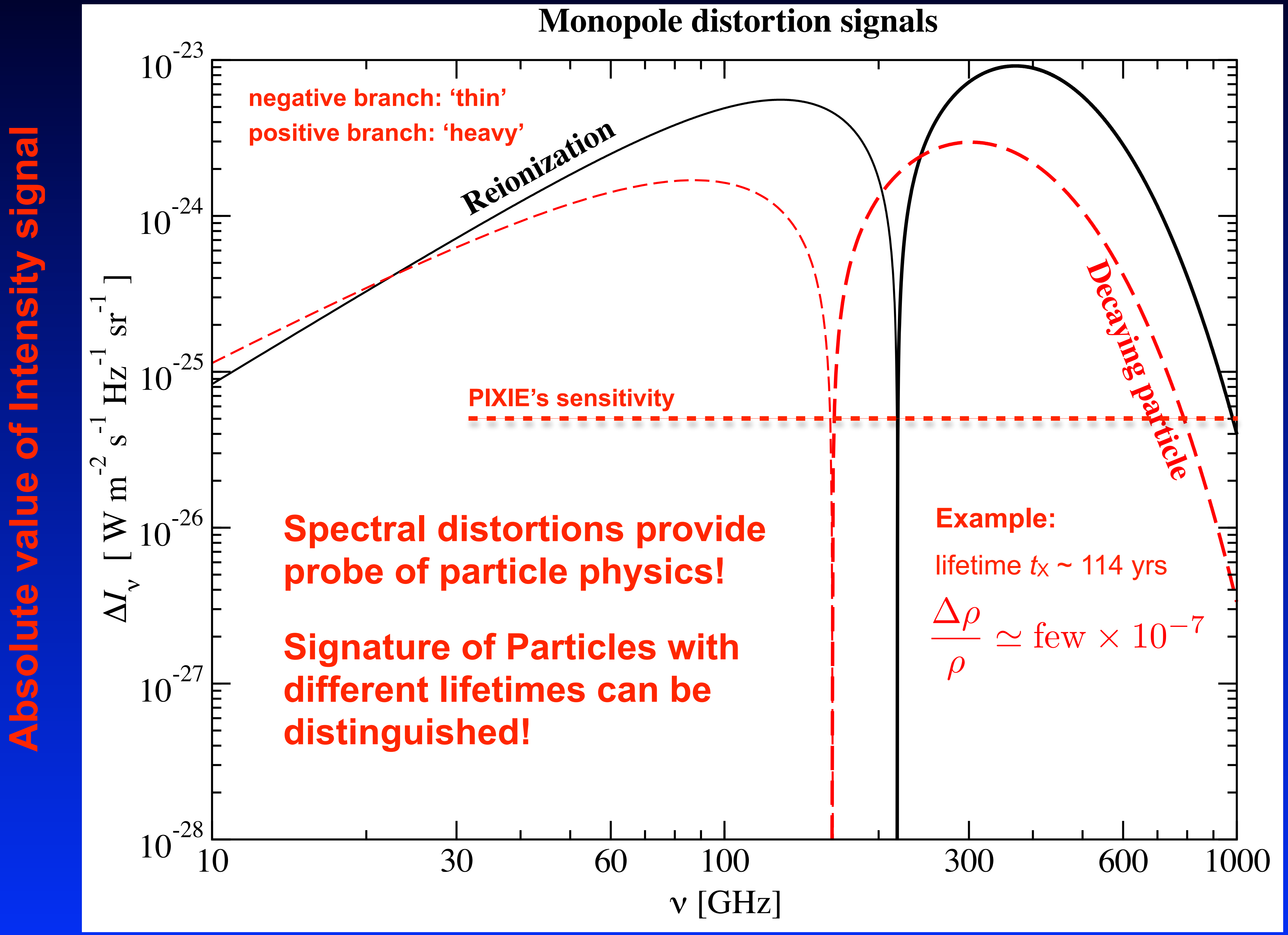
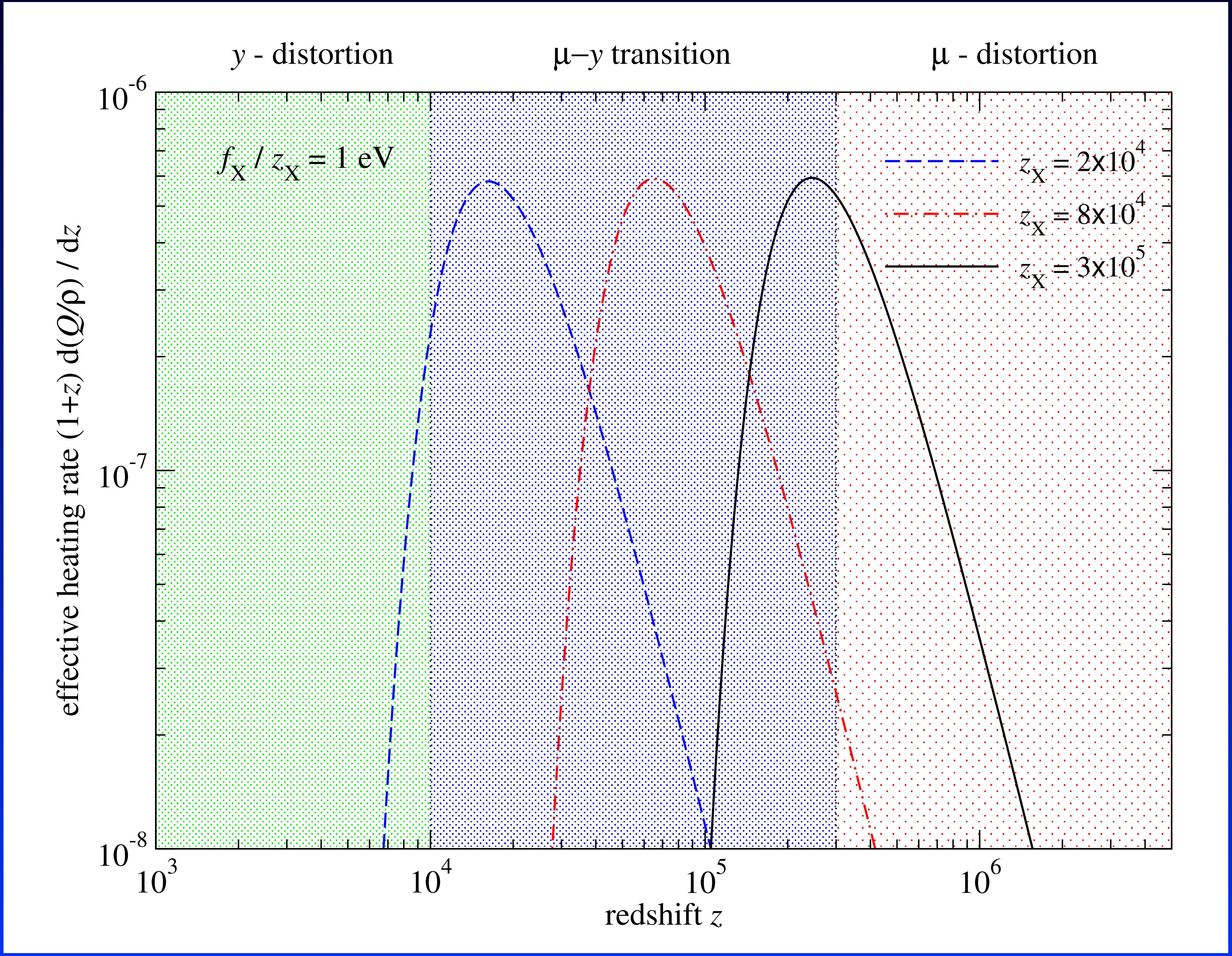


Decaying particle scenarios



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

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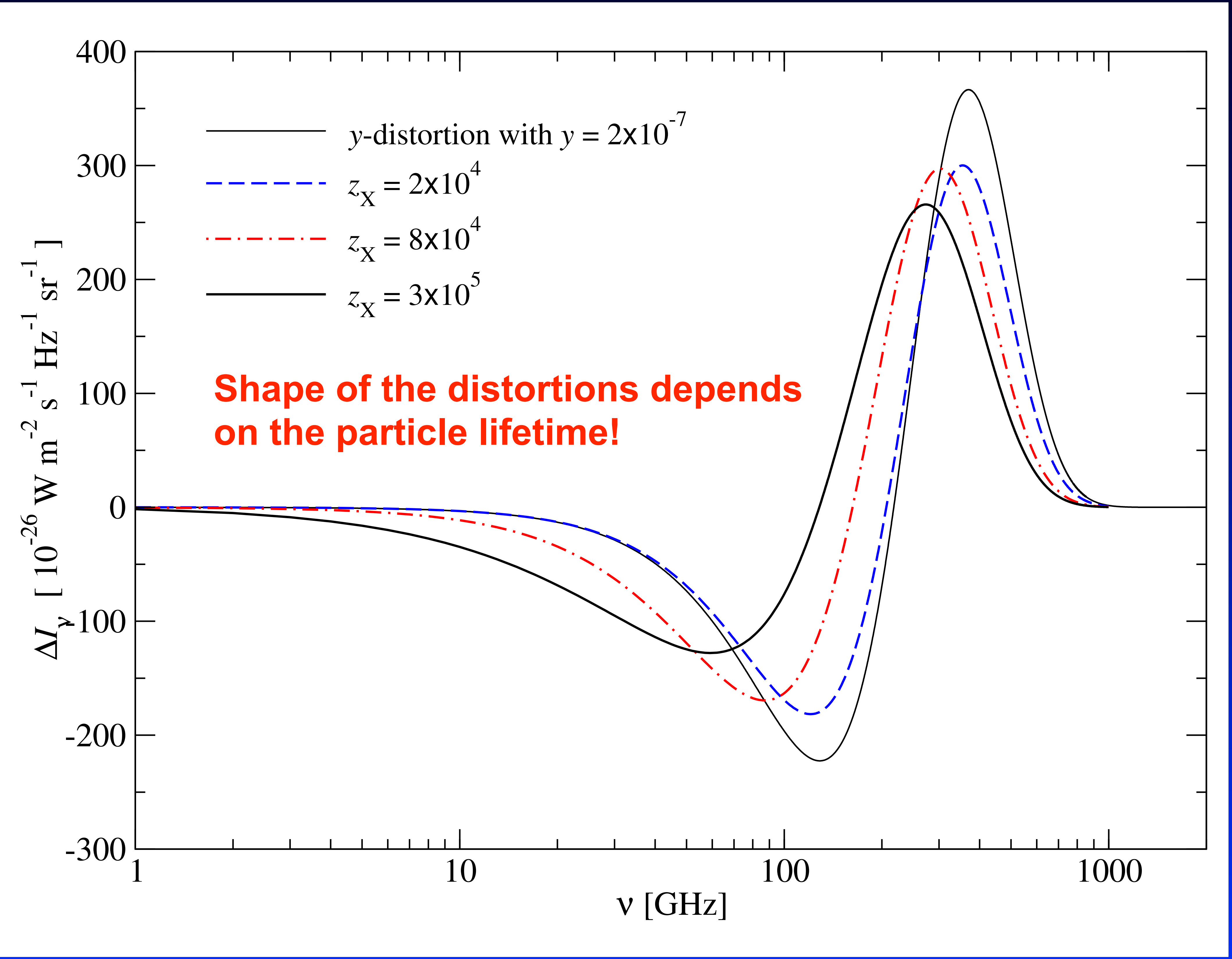

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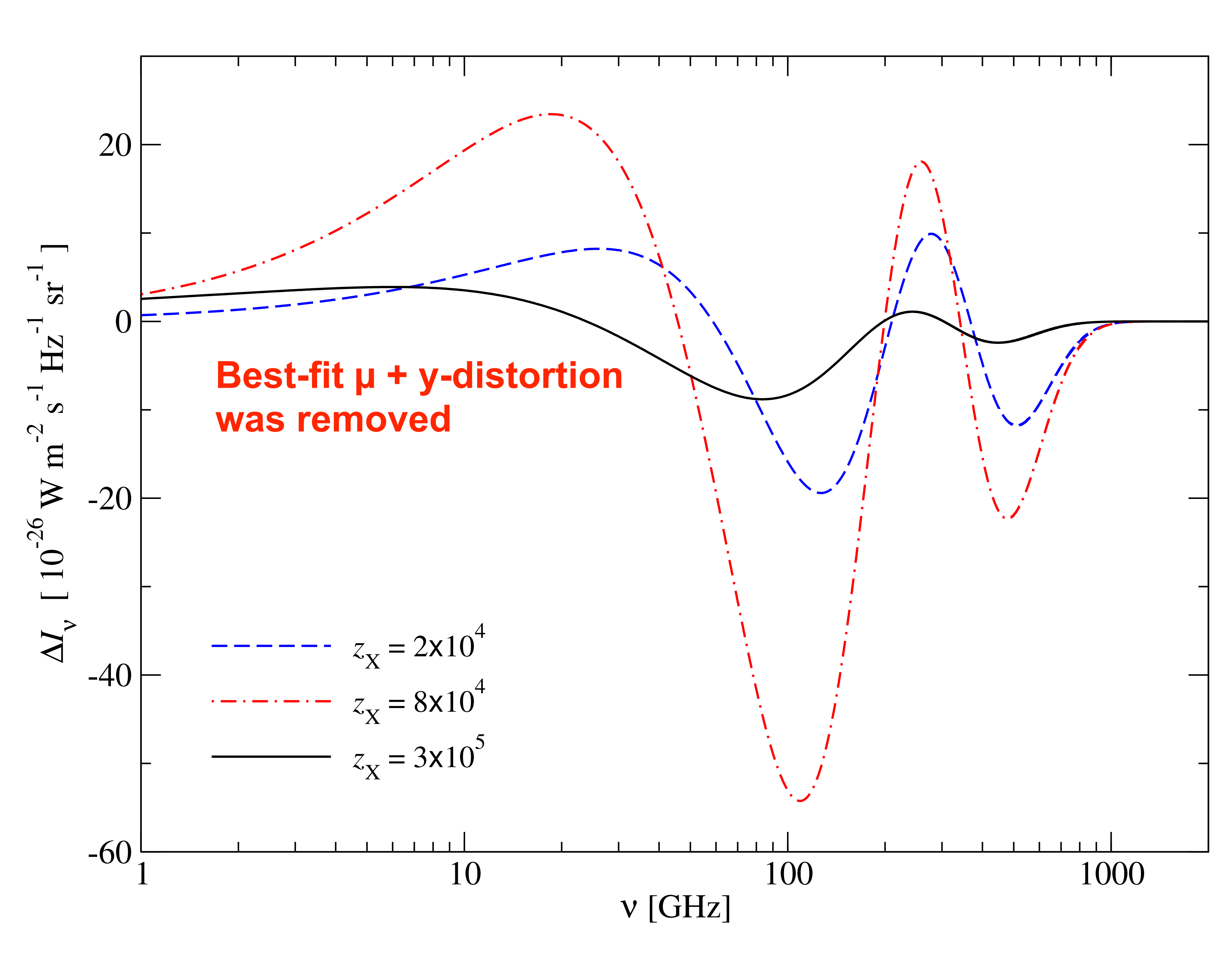
Decaying particle scenarios (information in residual)



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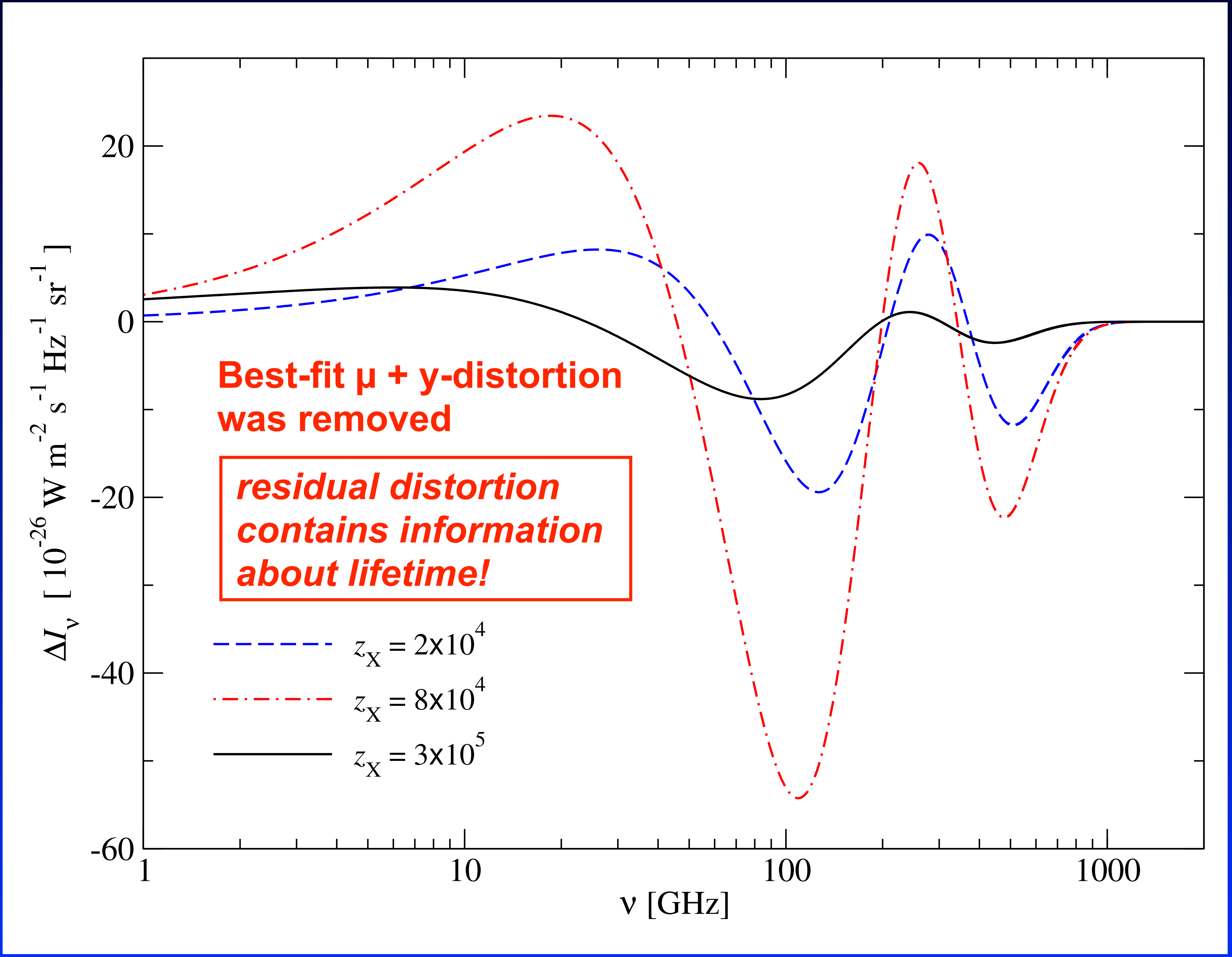

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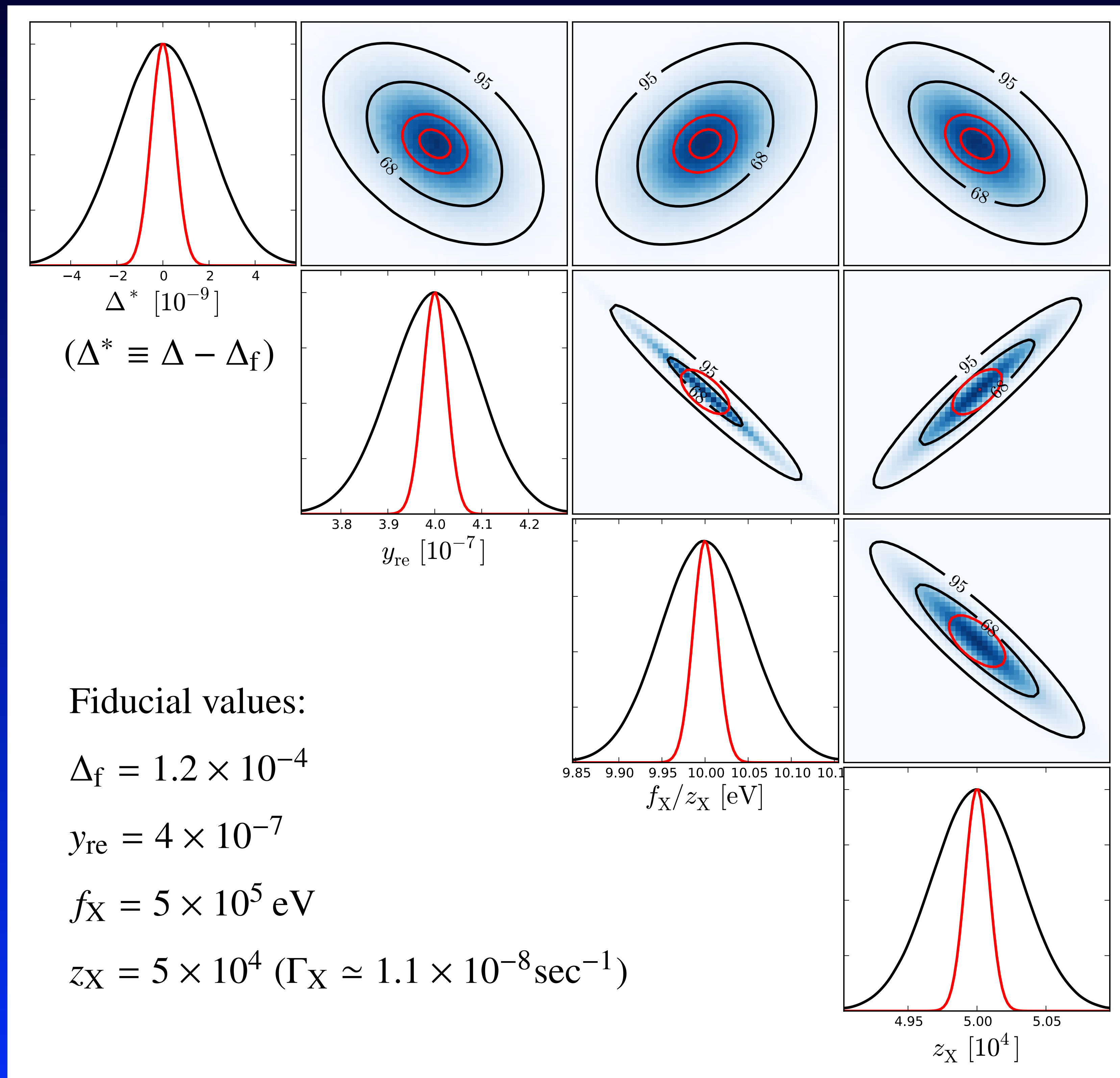

Fiducial values:

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

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

$f_X = 5 \times 10^5$ eV

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

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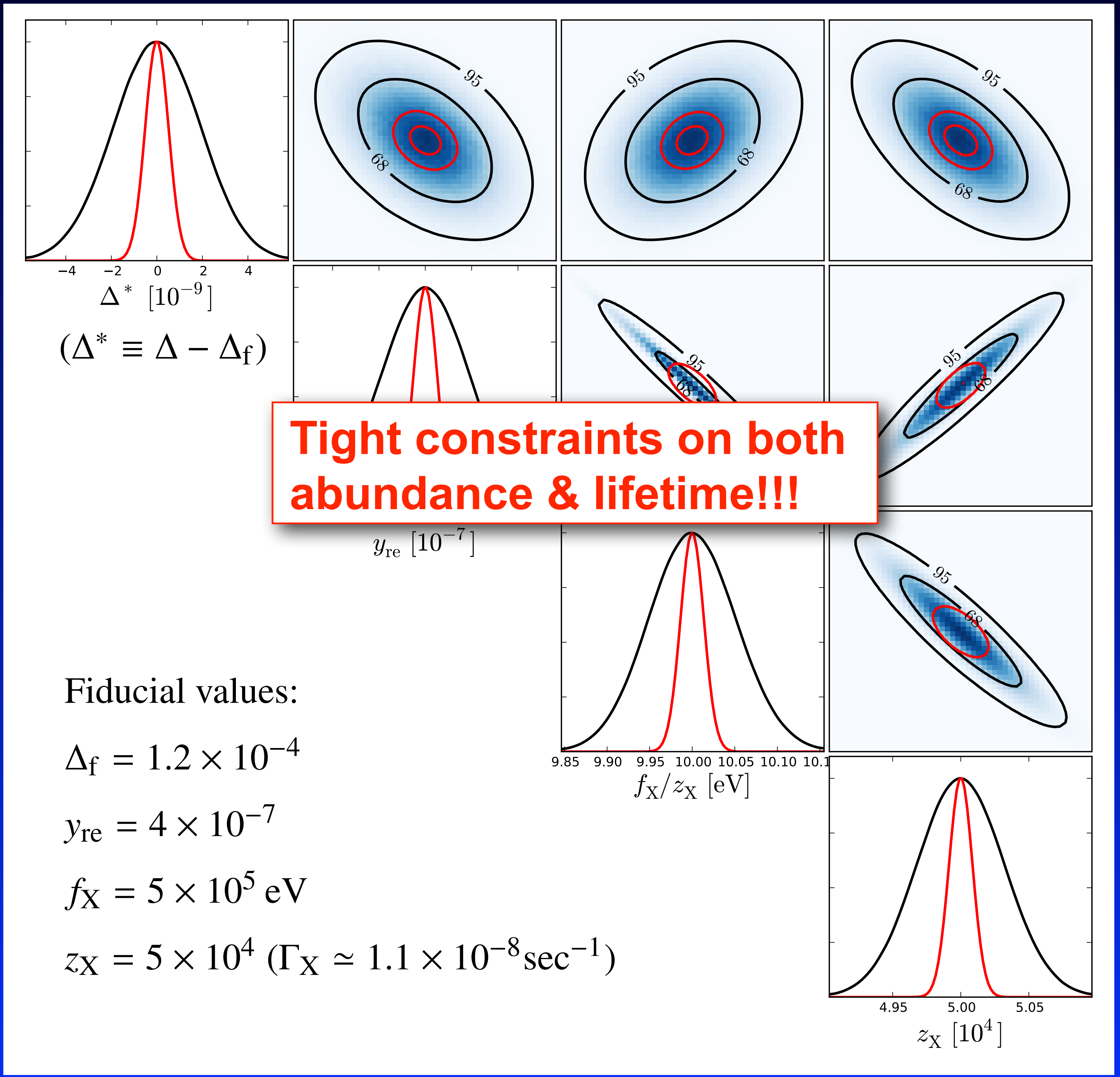

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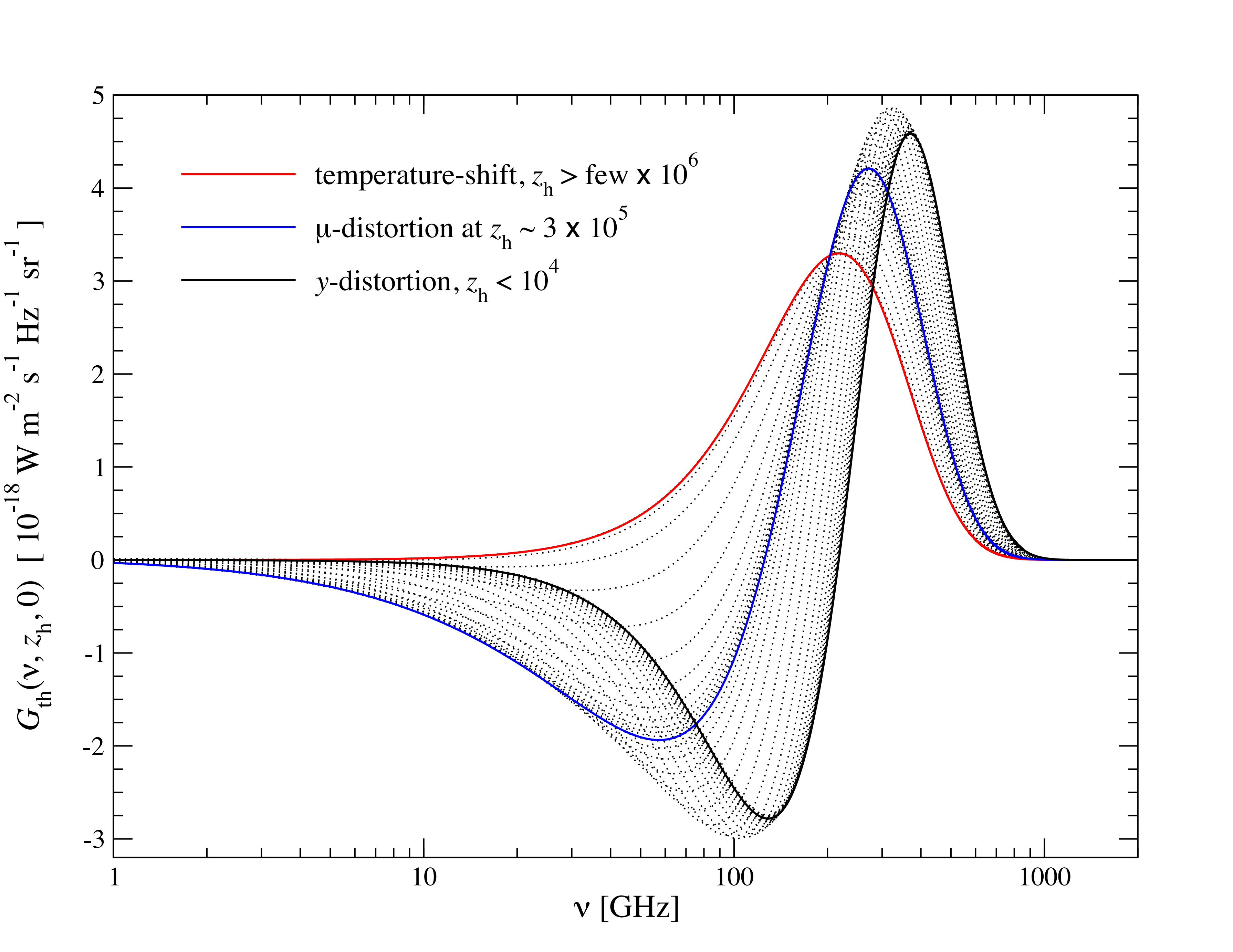
Using signal eigenmodes to compress the distortion data



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

JC & Jeong, 2013

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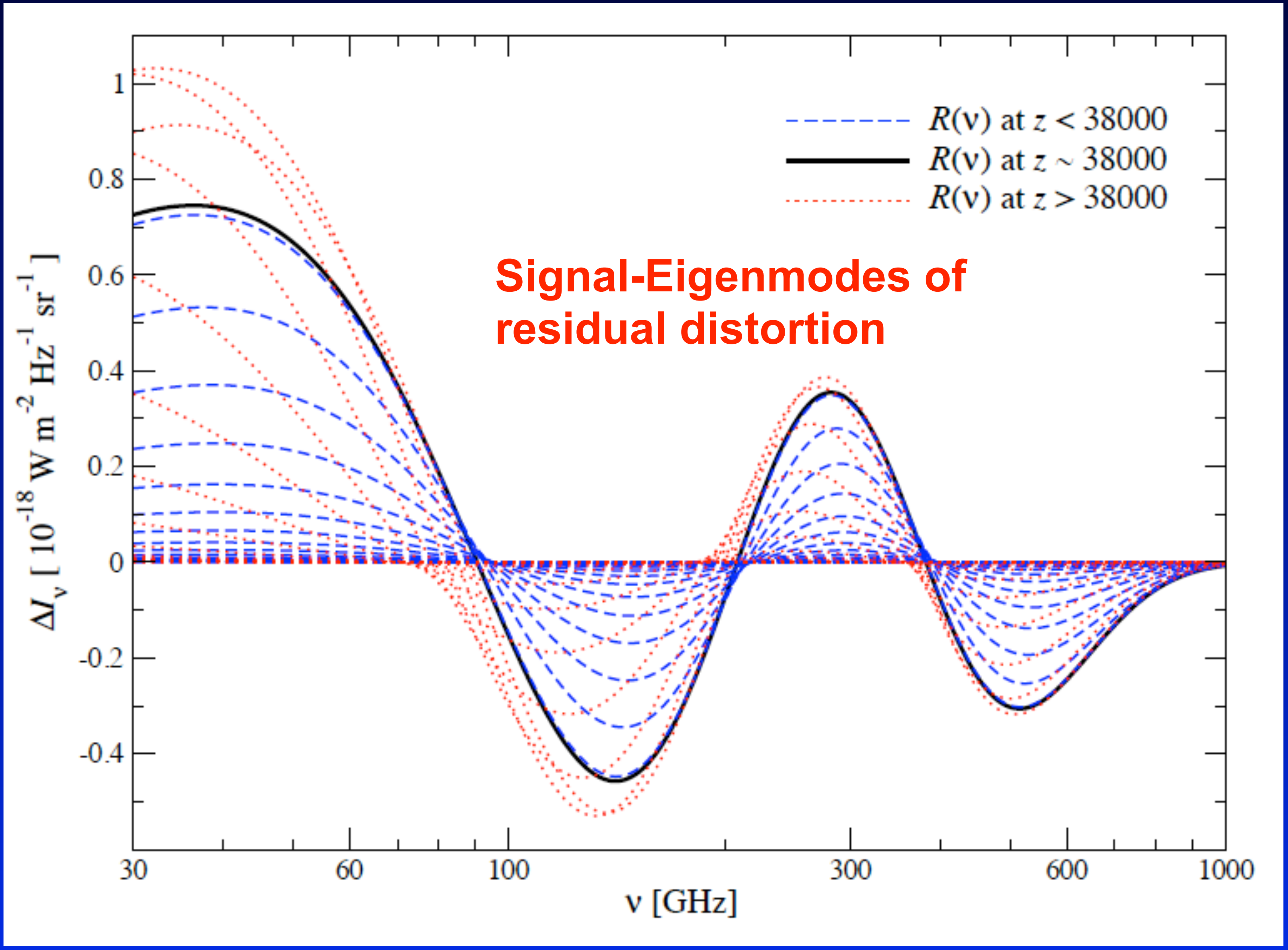
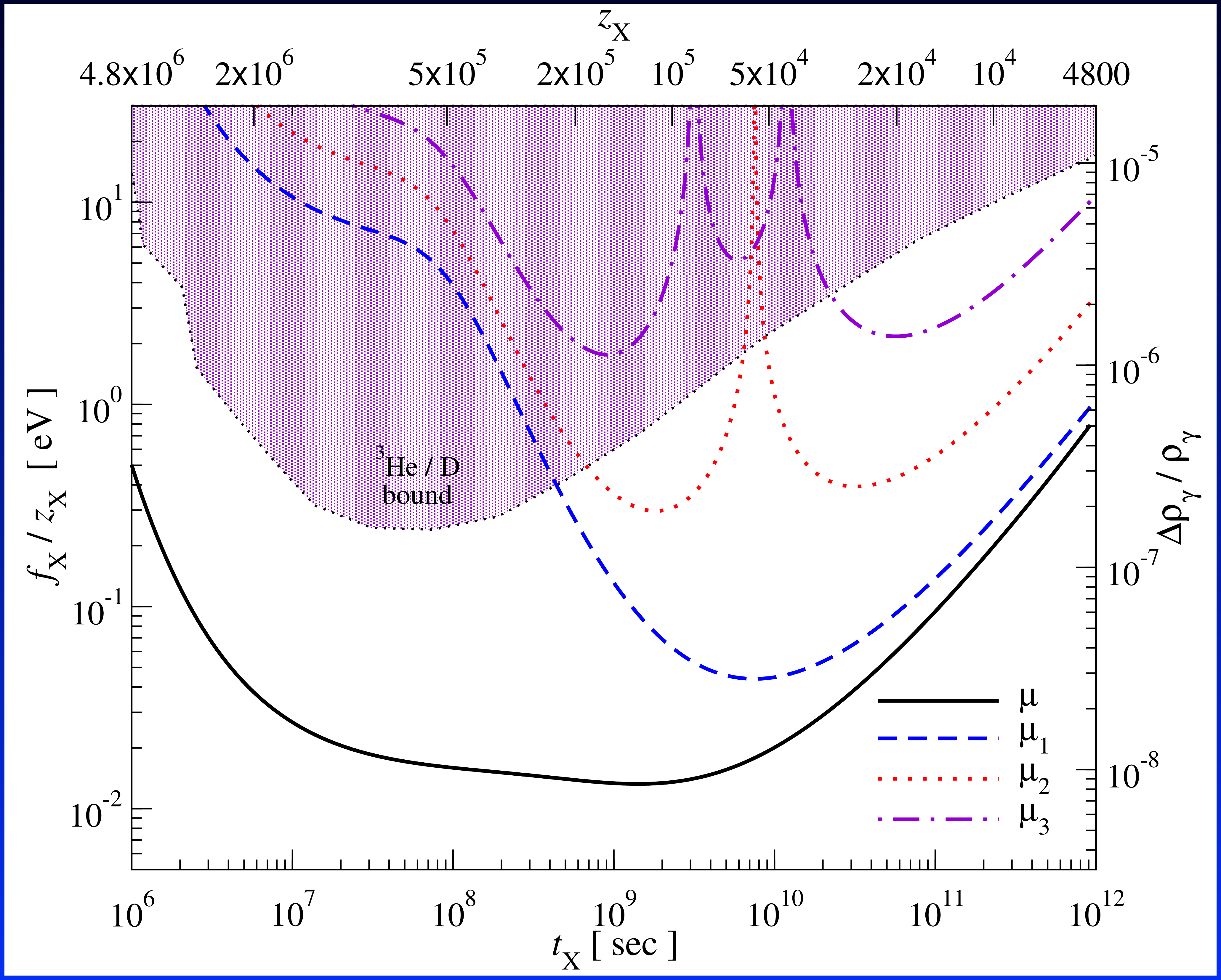


- *Principle component decomposition* of the distortion signal
- compression of the useful information given instrumental settings
- new set of observables

  $p=\{y, \mu, \mu_1, \mu_2, ...\}$
- model-comparison + forecasts of errors very simple!

JC & Jeong, 2013

Decaying particle 1σ-detection limits for PIXIE



JC & Jeong, 2013

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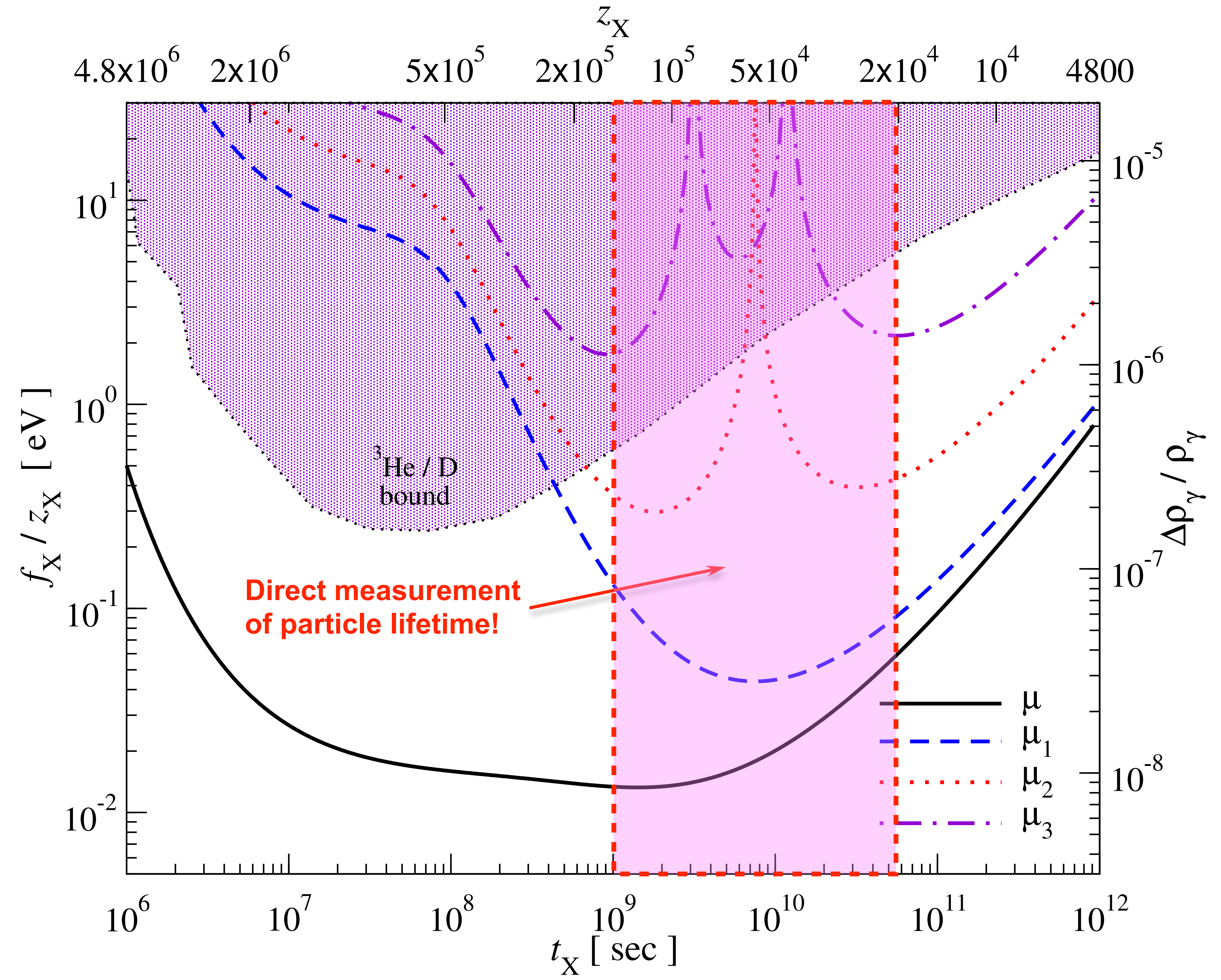
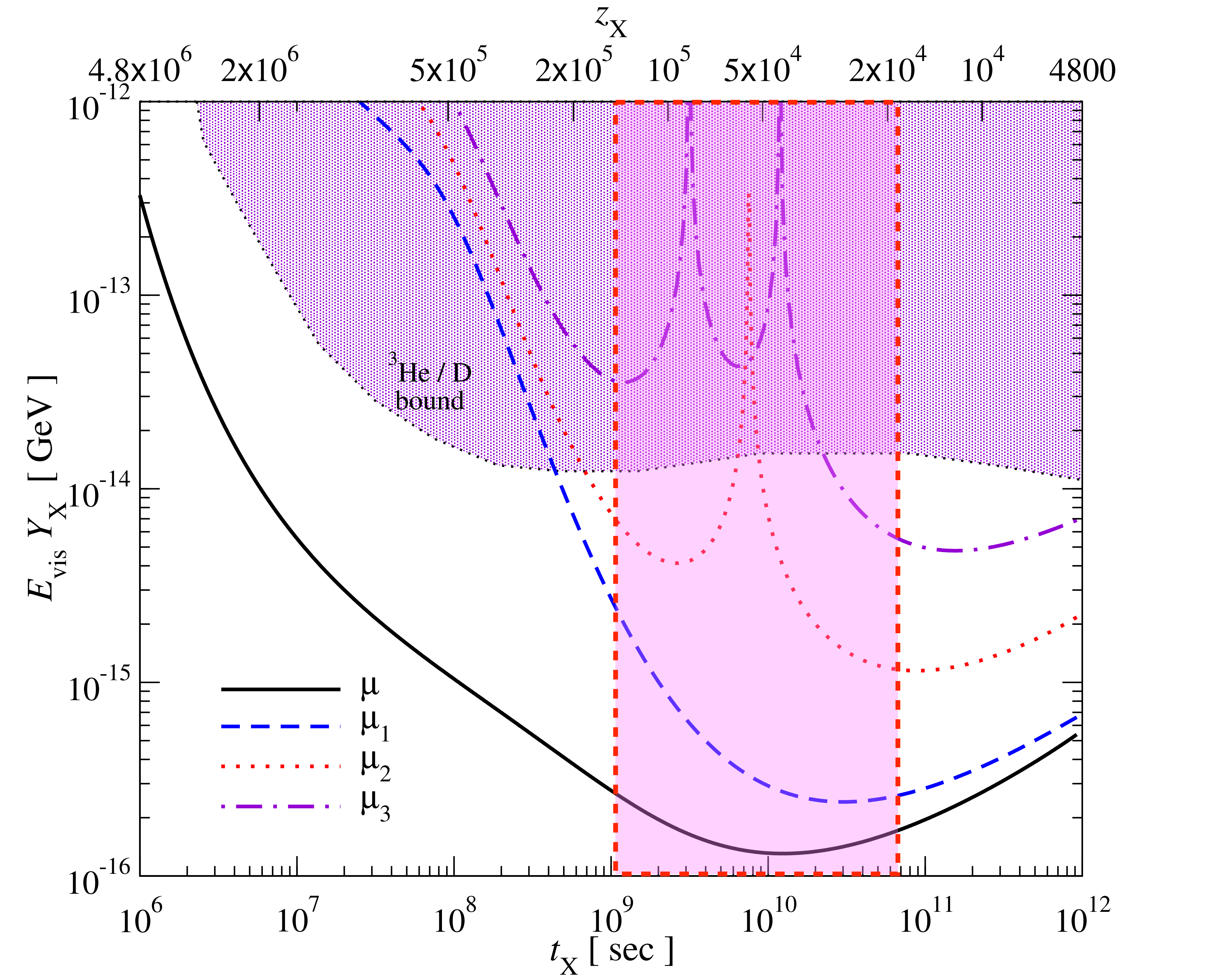
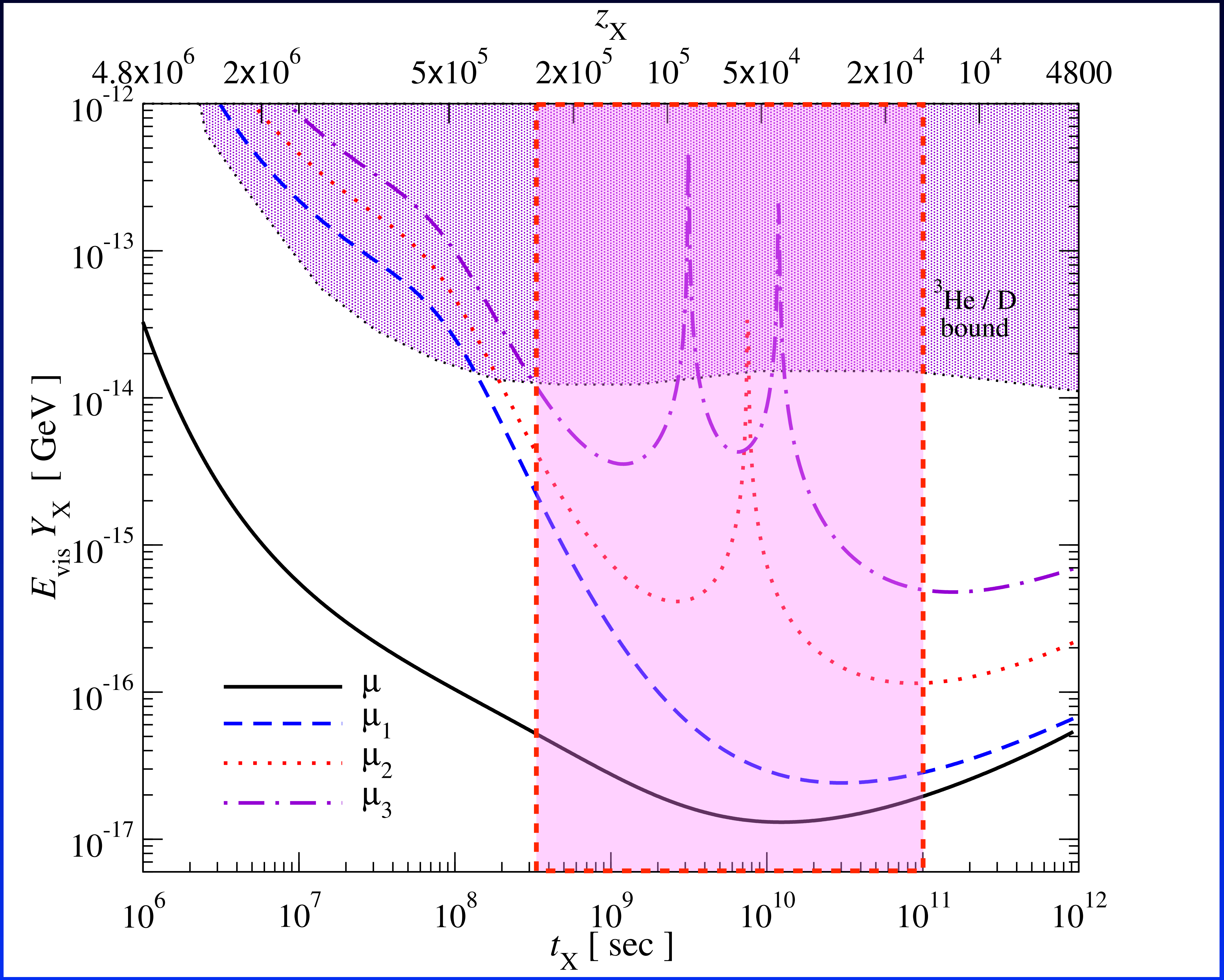


Decaying particle 2σ-detection limits for PIXIE



JC & Jeong, 2013

Decaying particle 2σ-detection limits for PRISM



JC & Jeong, 2013

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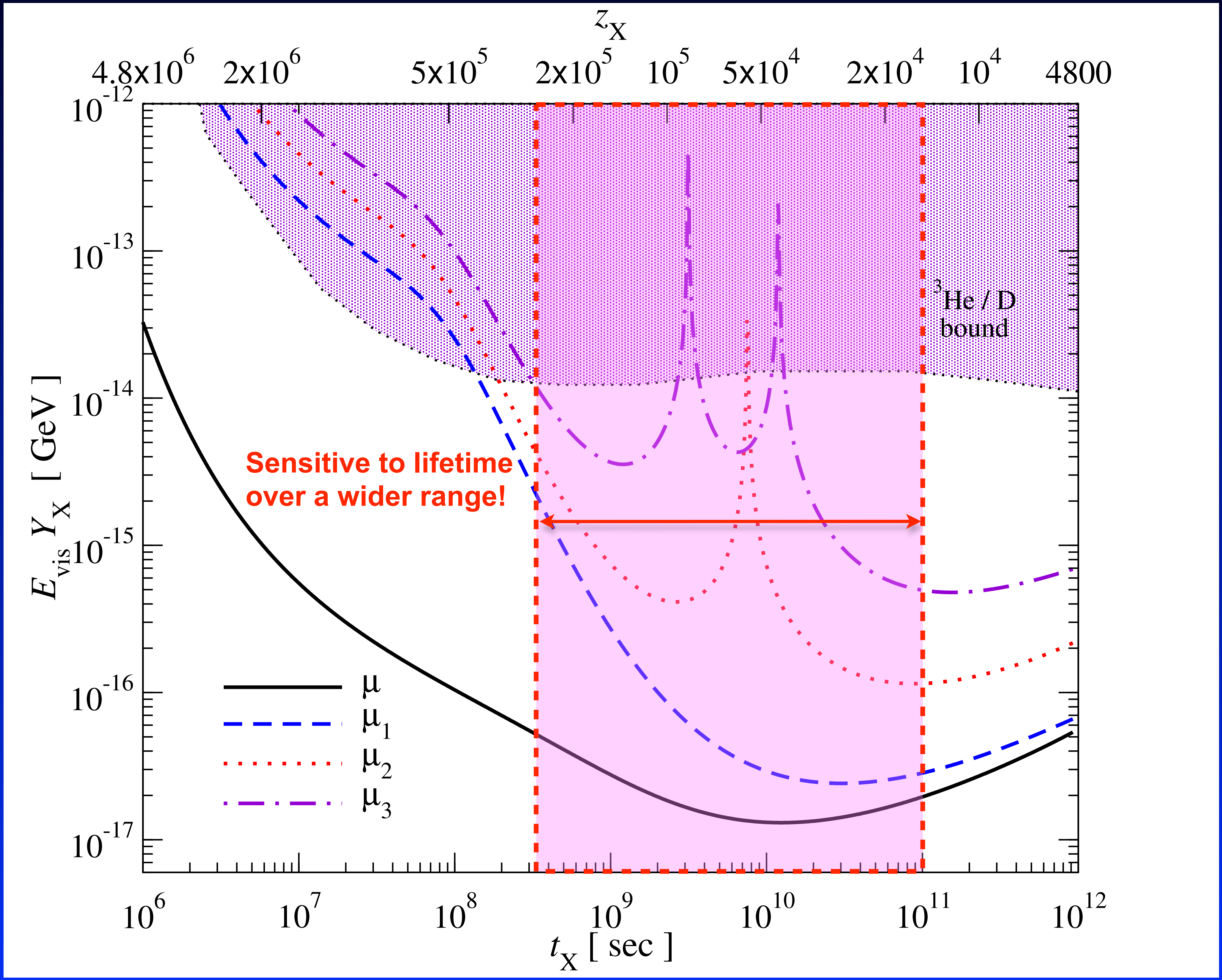

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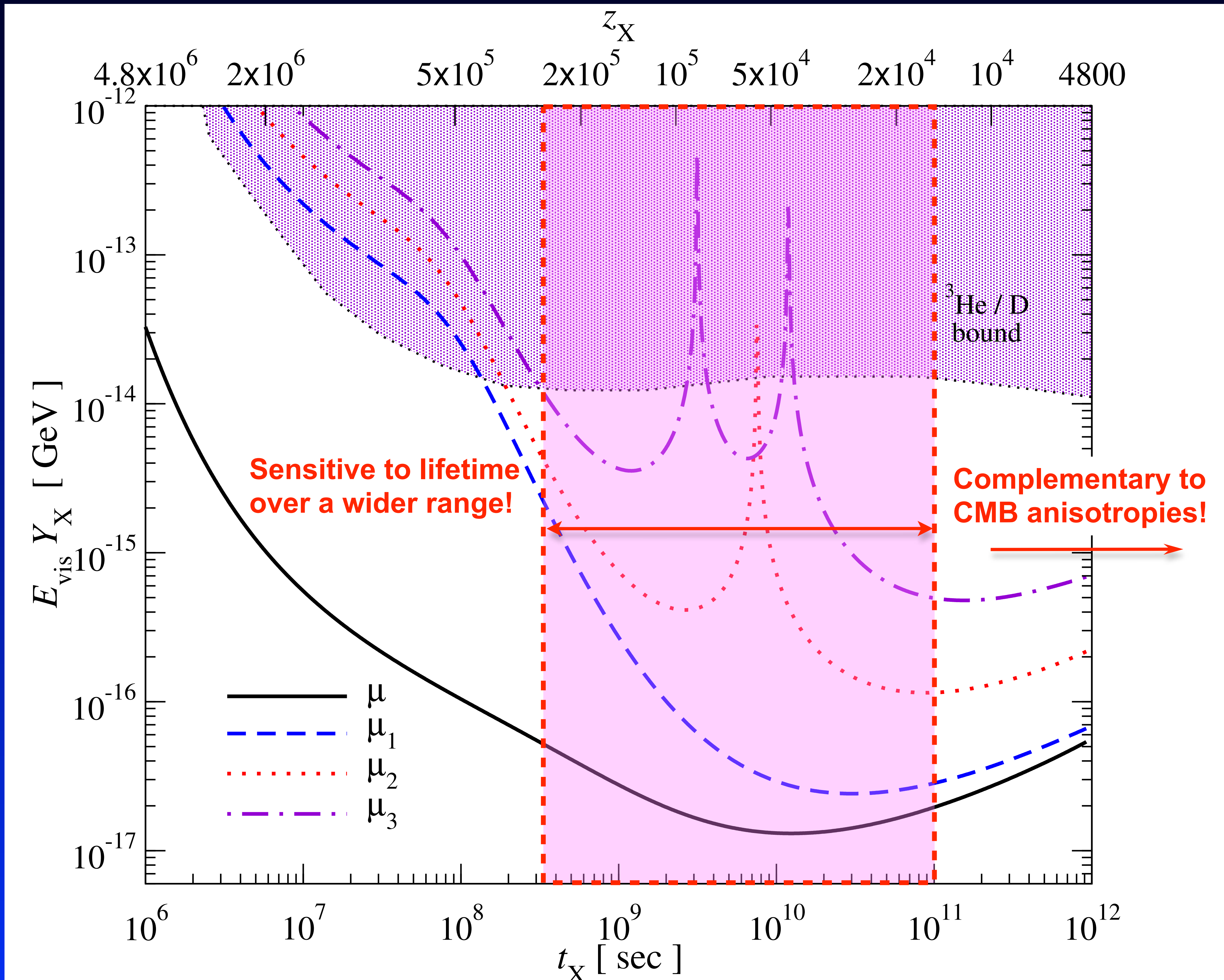
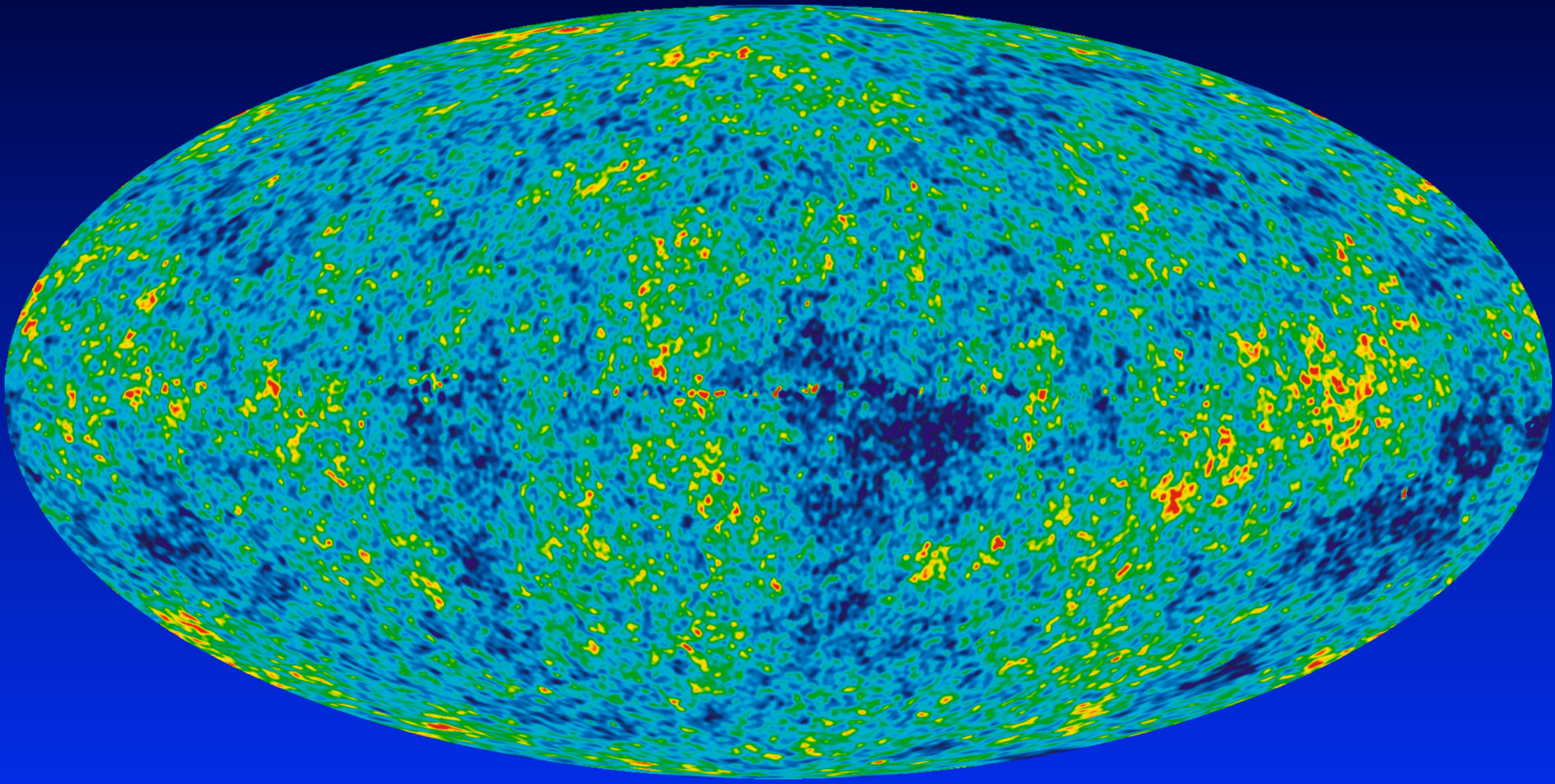


JC & Jeong, 2013

The dissipation of small-scale acoustic modes

Dissipation of small-scale acoustic modes



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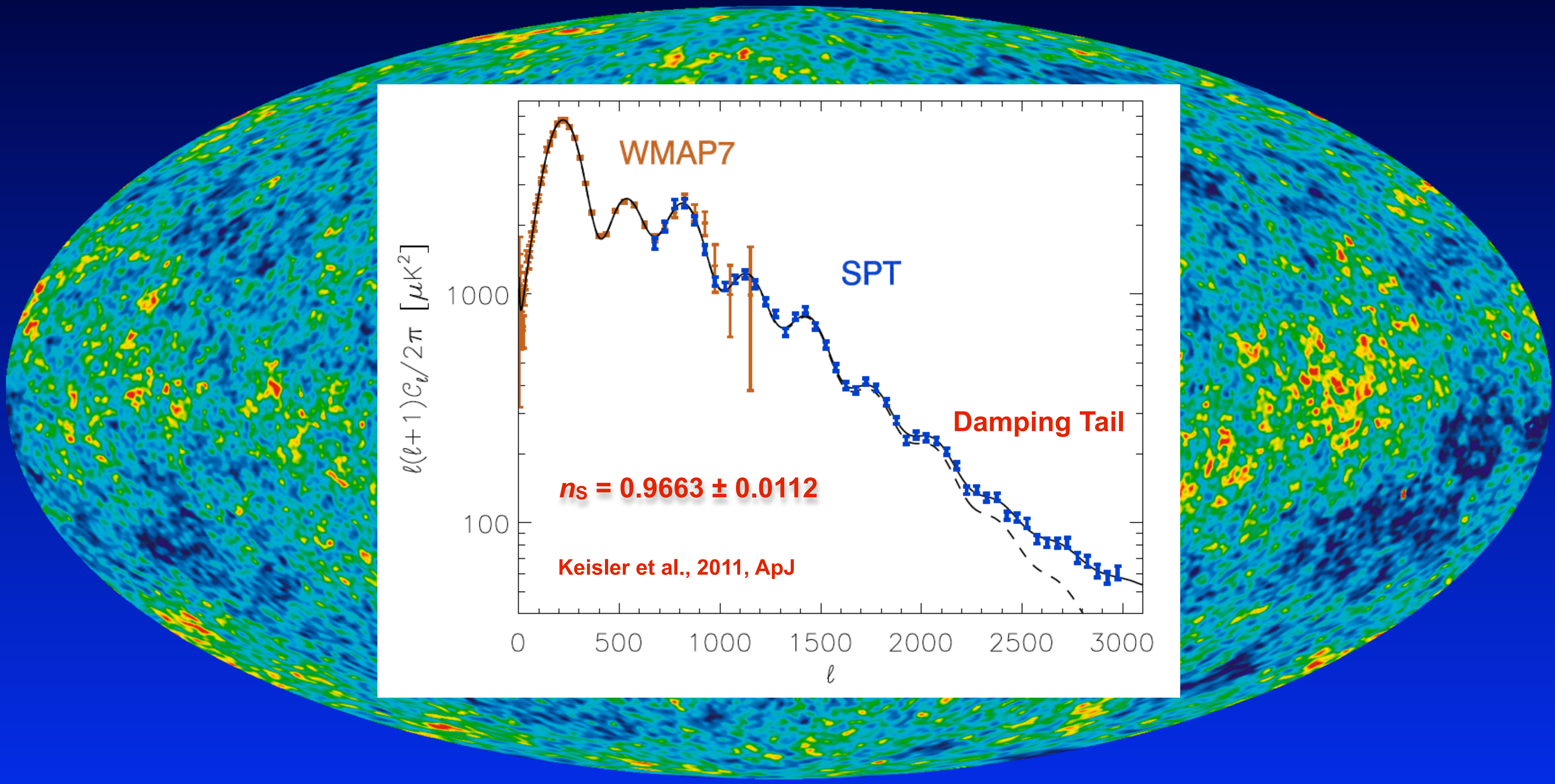

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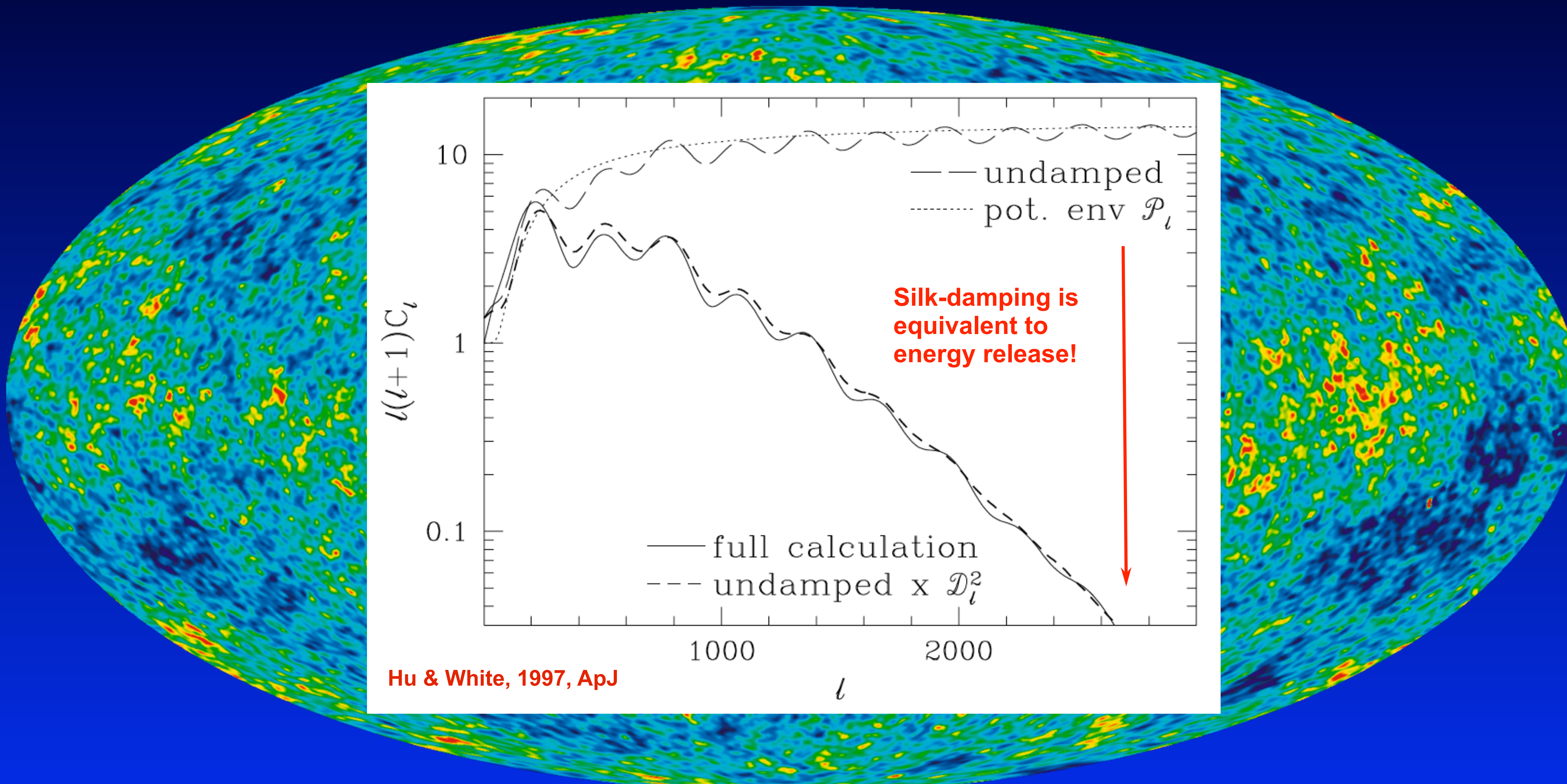

Energy release caused by dissipation process

'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)
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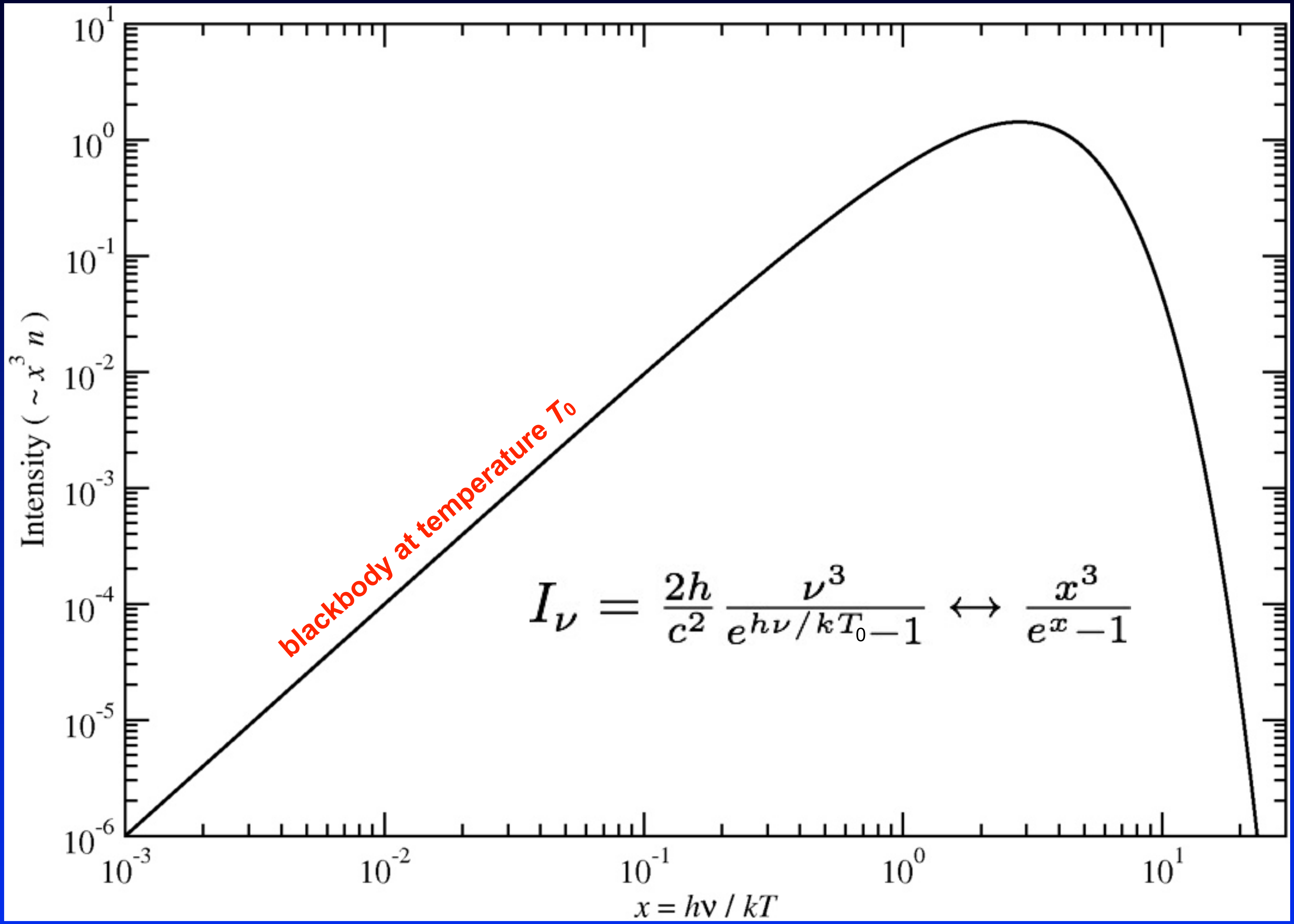
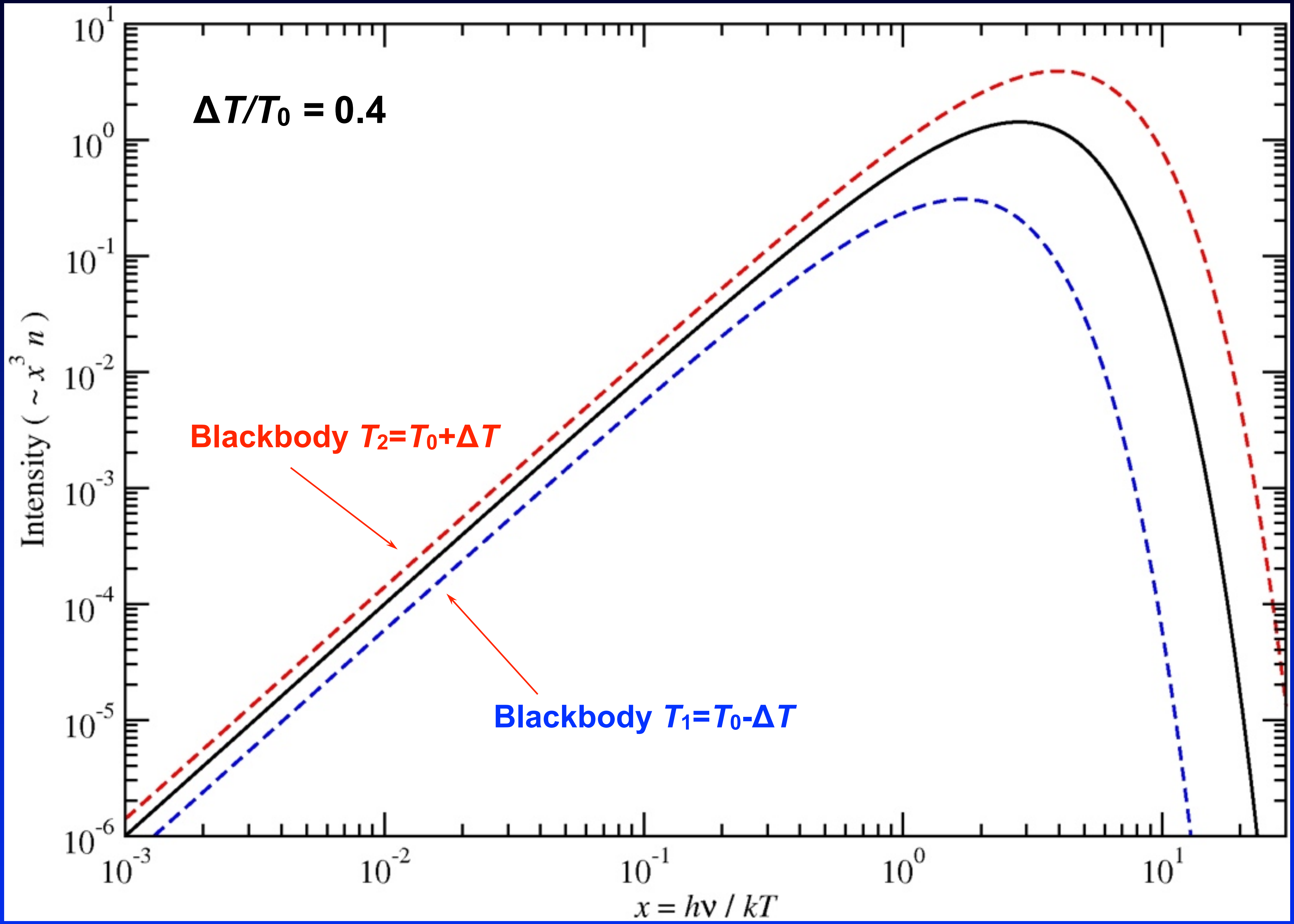
CMB Spectral distortions provide probe of Inflation physics!!!

Superpositions of blackbody spectra



Zeldovich, Illarionov & Sunyaev, 1972
JC & Sunyaev 2004

Superpositions of blackbody spectra



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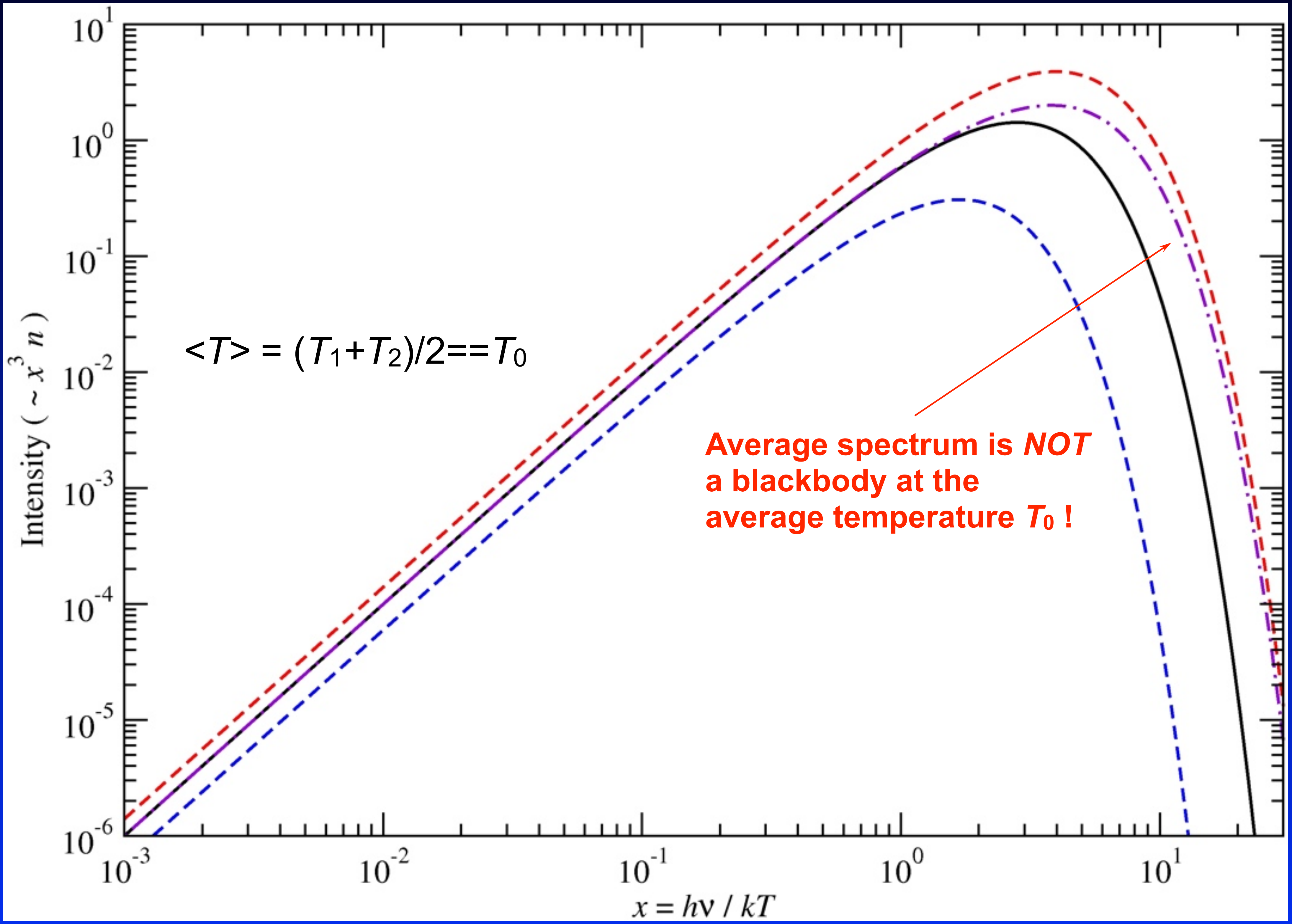

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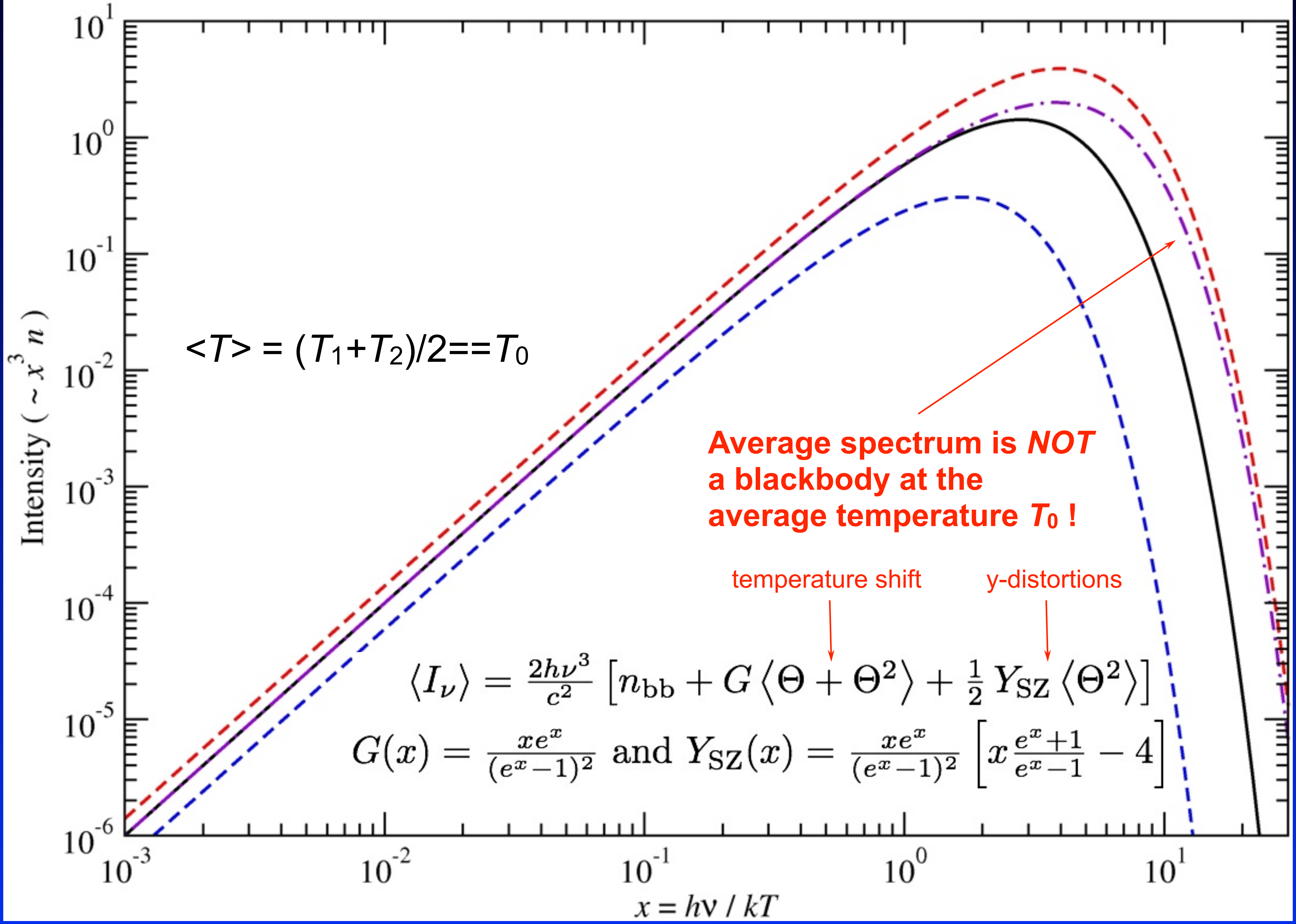

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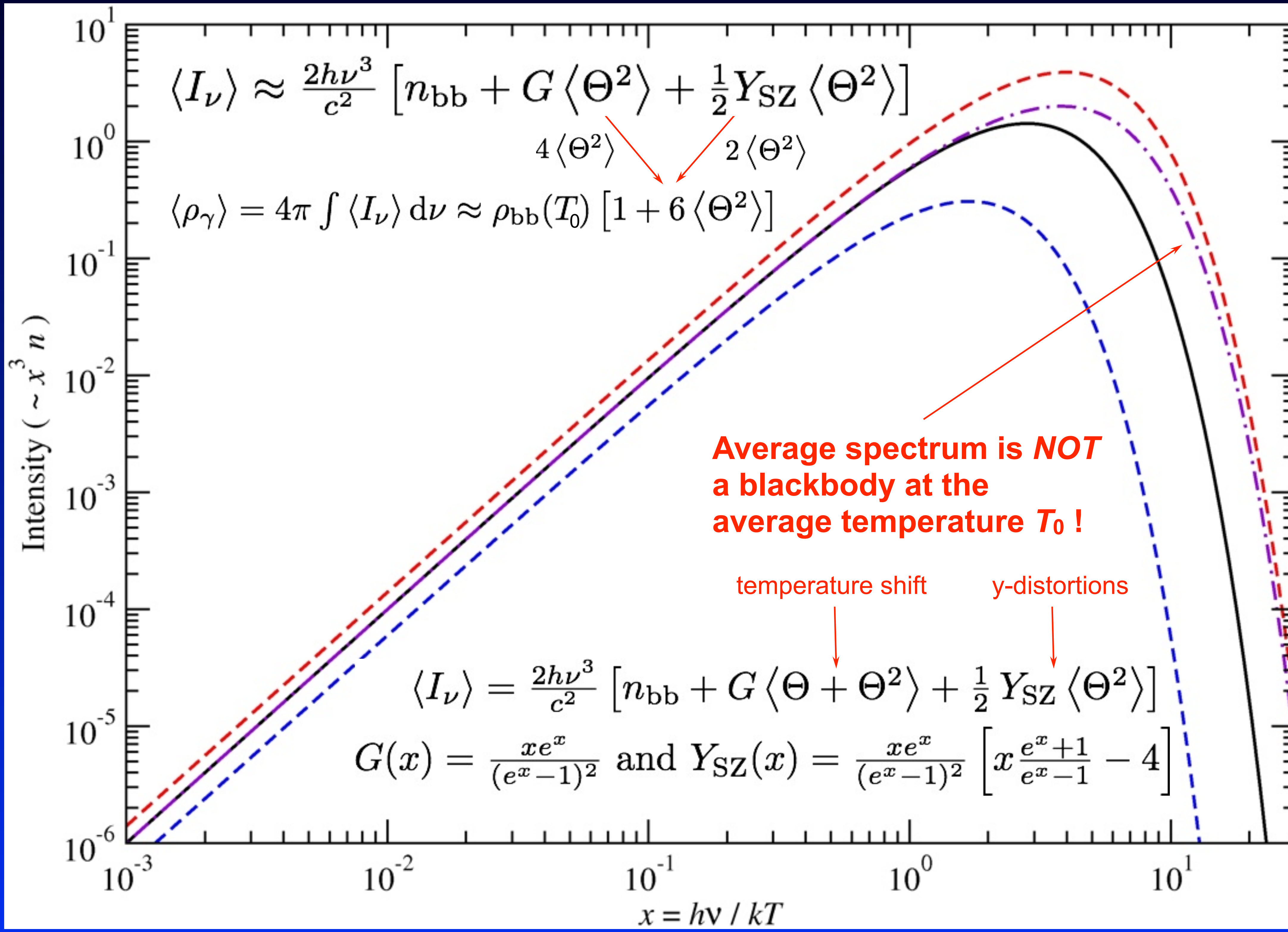

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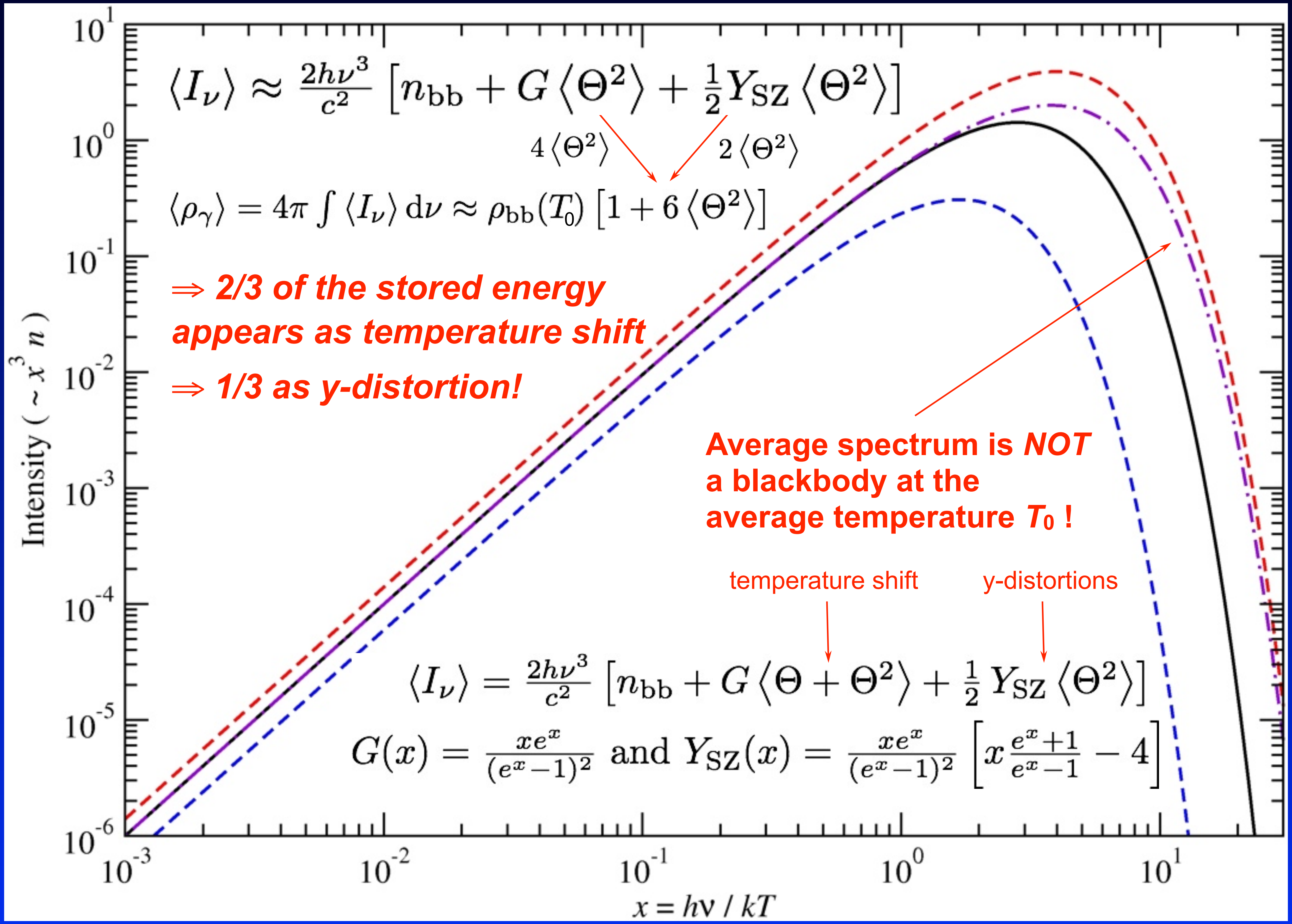

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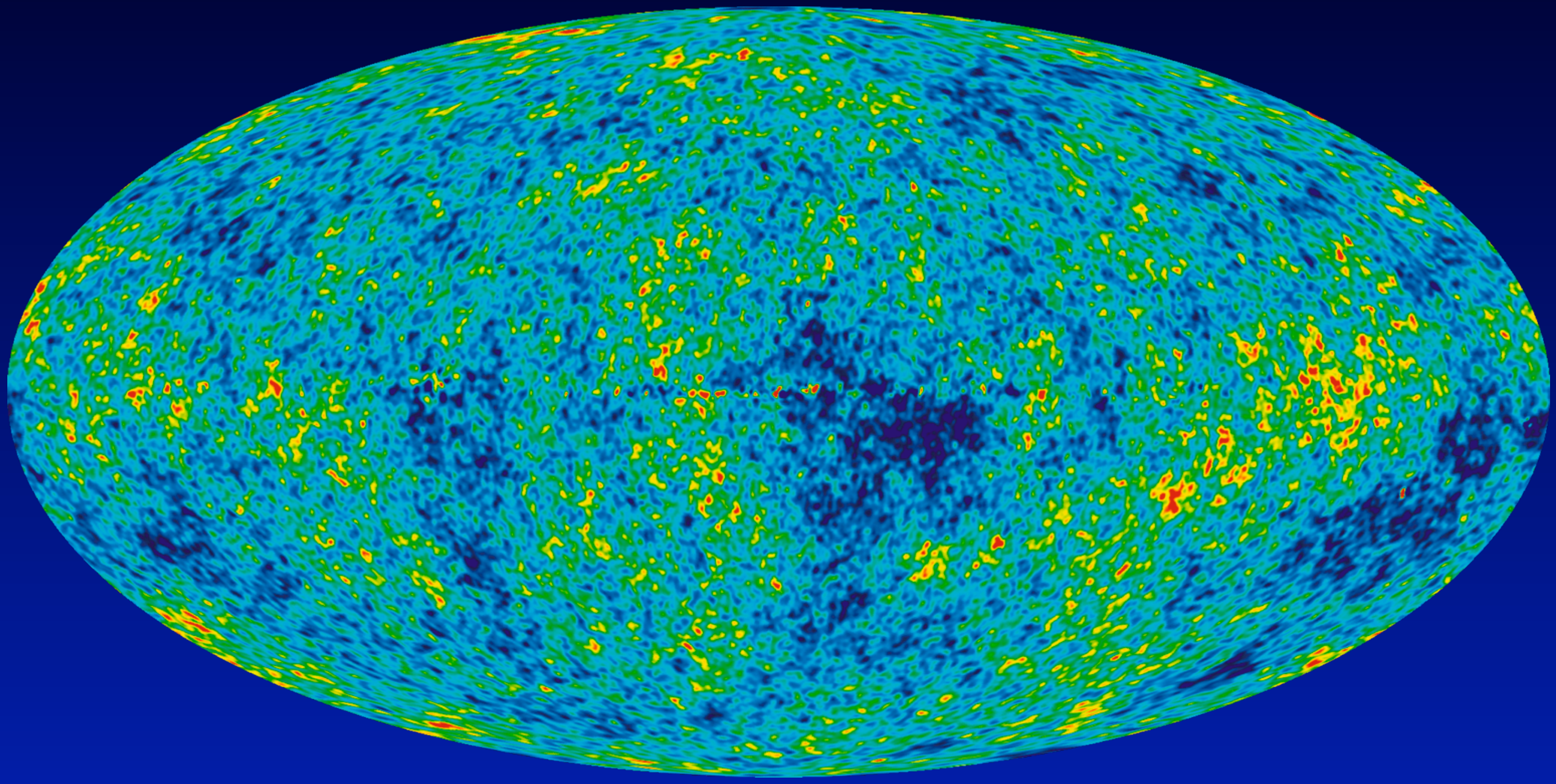
Distortion caused by superposition of blackbodies



- 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

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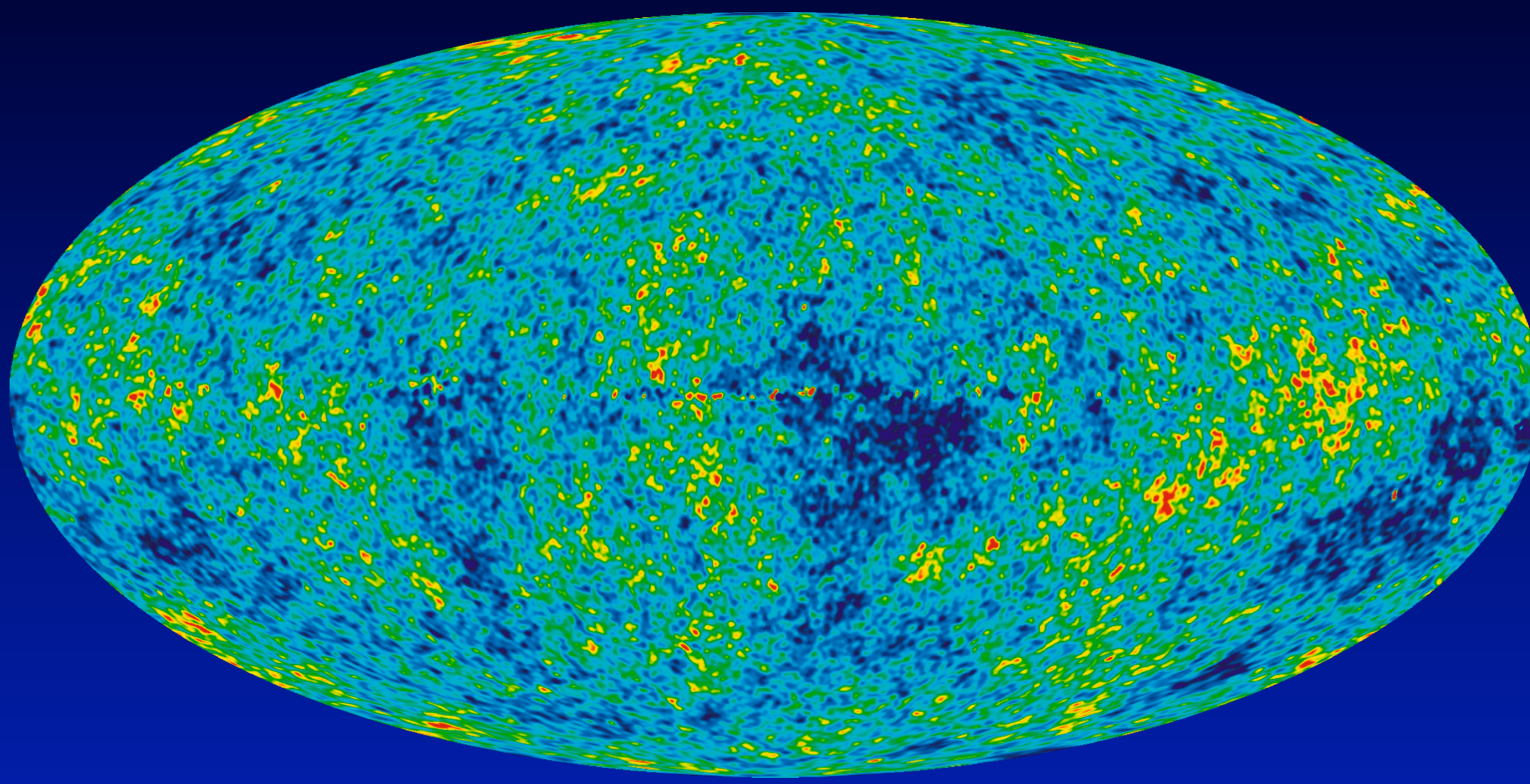

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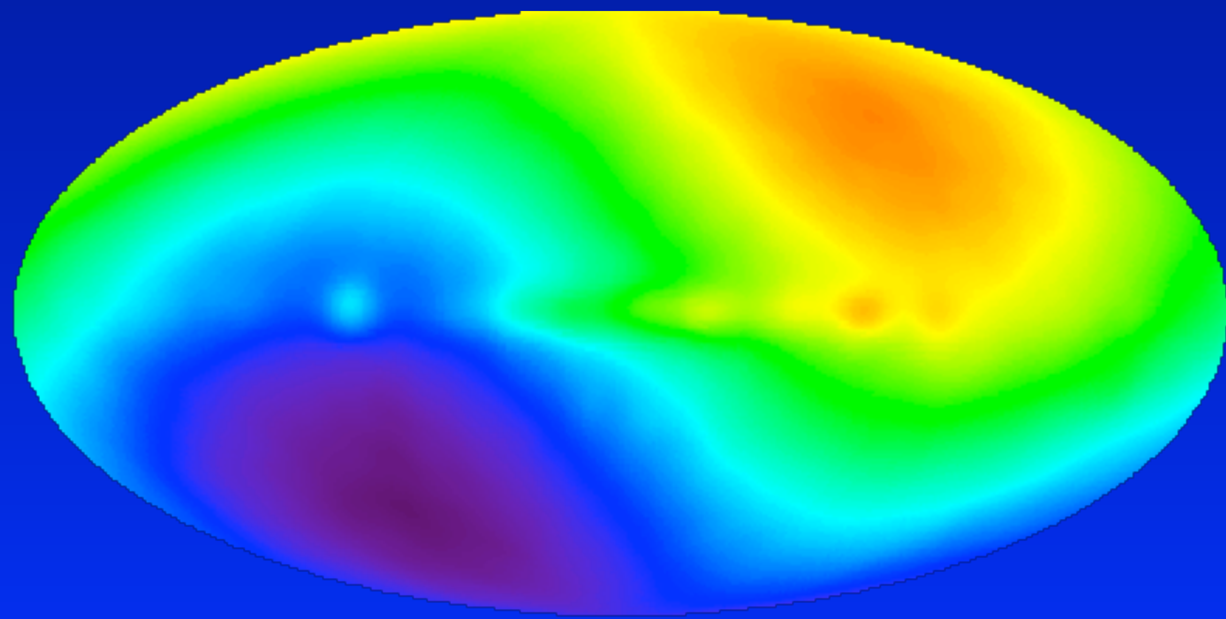


- *CMB dipole* (β_c ~ 1.23x10^{-3})

$$\Rightarrow \quad y \simeq \frac{\beta_c^2}{6} \approx 2.6 \times 10^{-7}$$

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

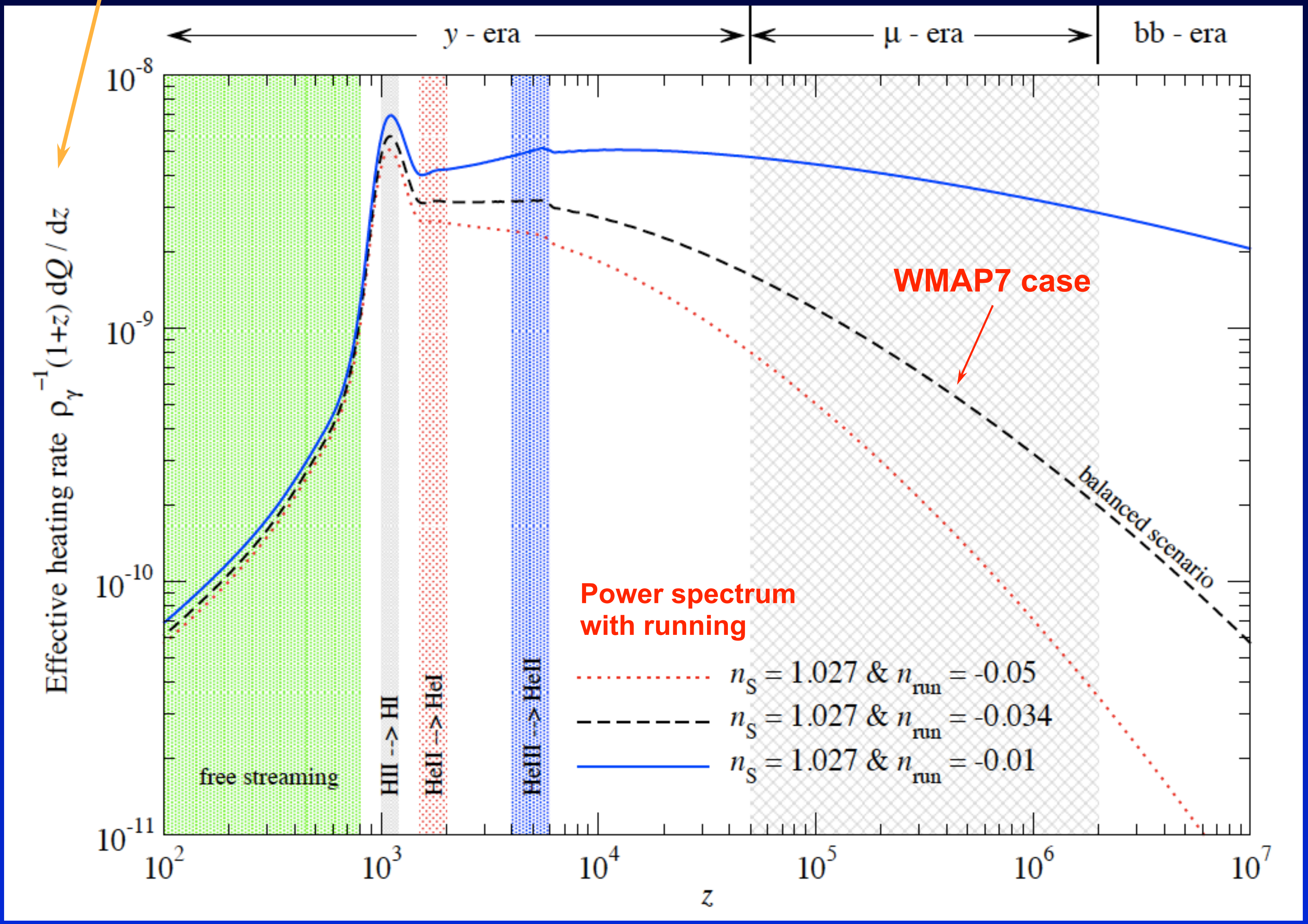
- electrons are up-scattered
- can be taken out at the level of ~ 10^{-9}

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

COBE/DMR: ΔT = 3.353 mK

Our computation for the effective energy release

scaled such that constant for n_S =1



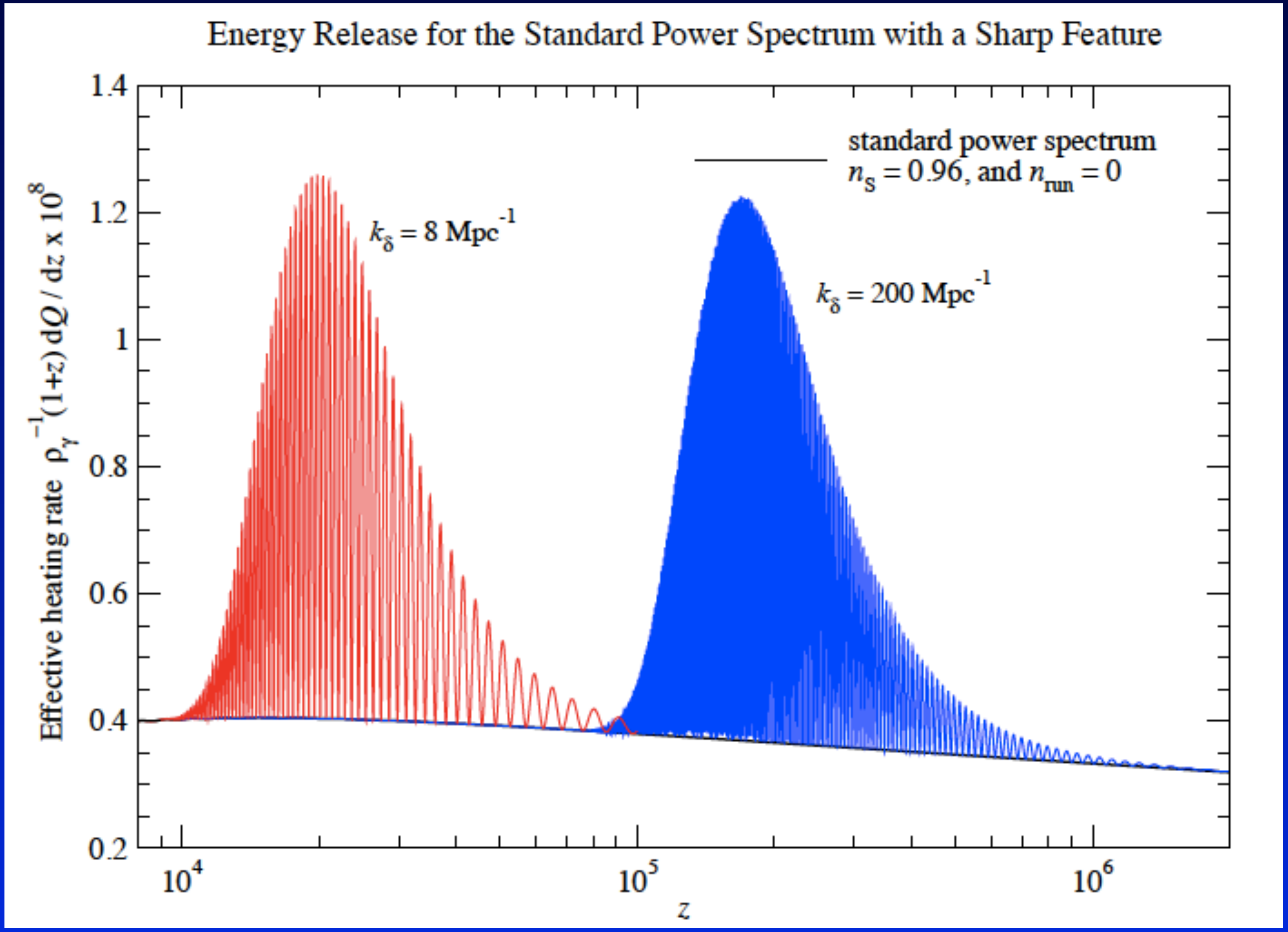
JC, Khatri & Sunyaev, 2012

- 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

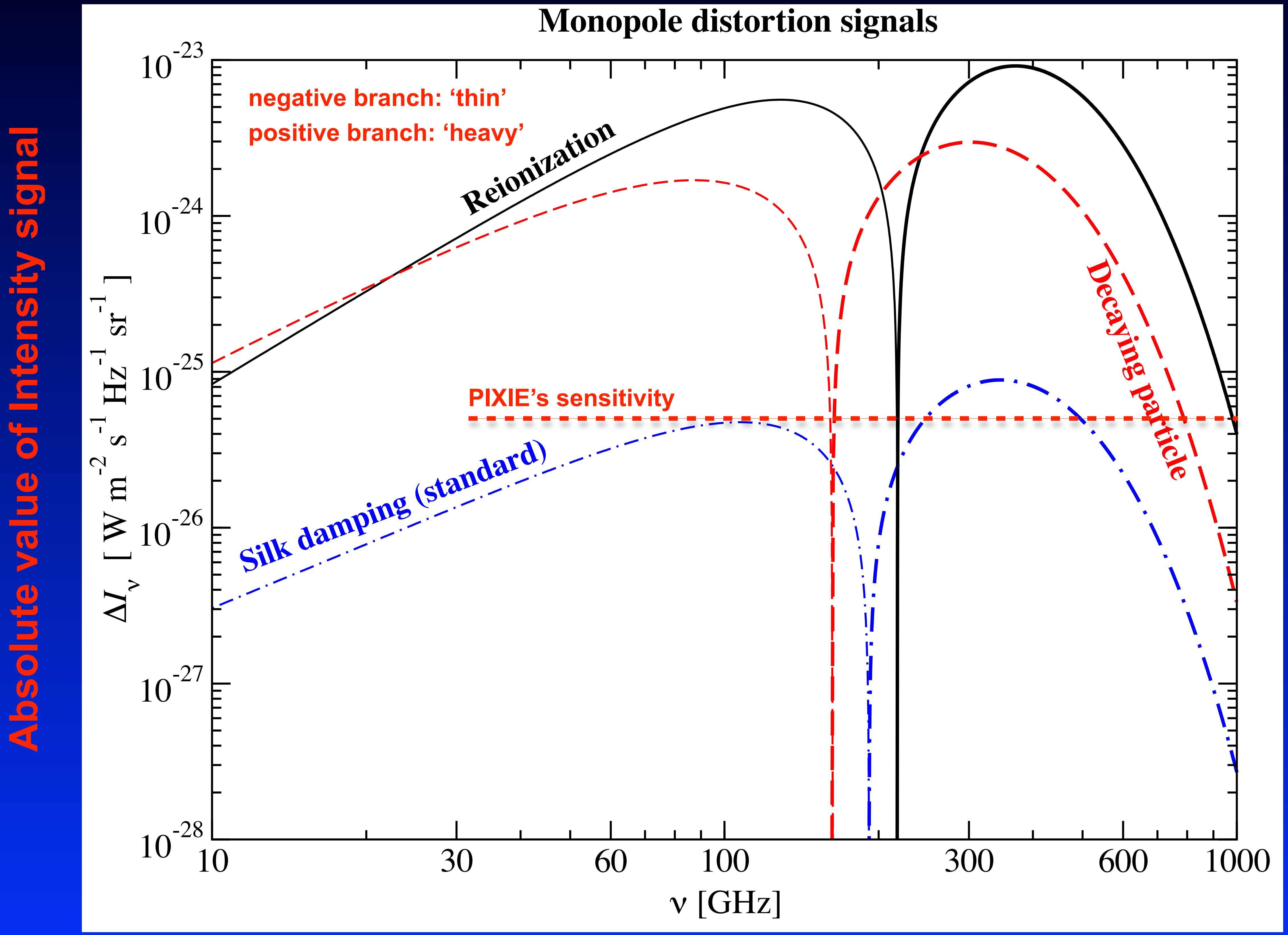
- Single mode with wavenumber k dissipates its energy at

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

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

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

Average CMB spectral distortions



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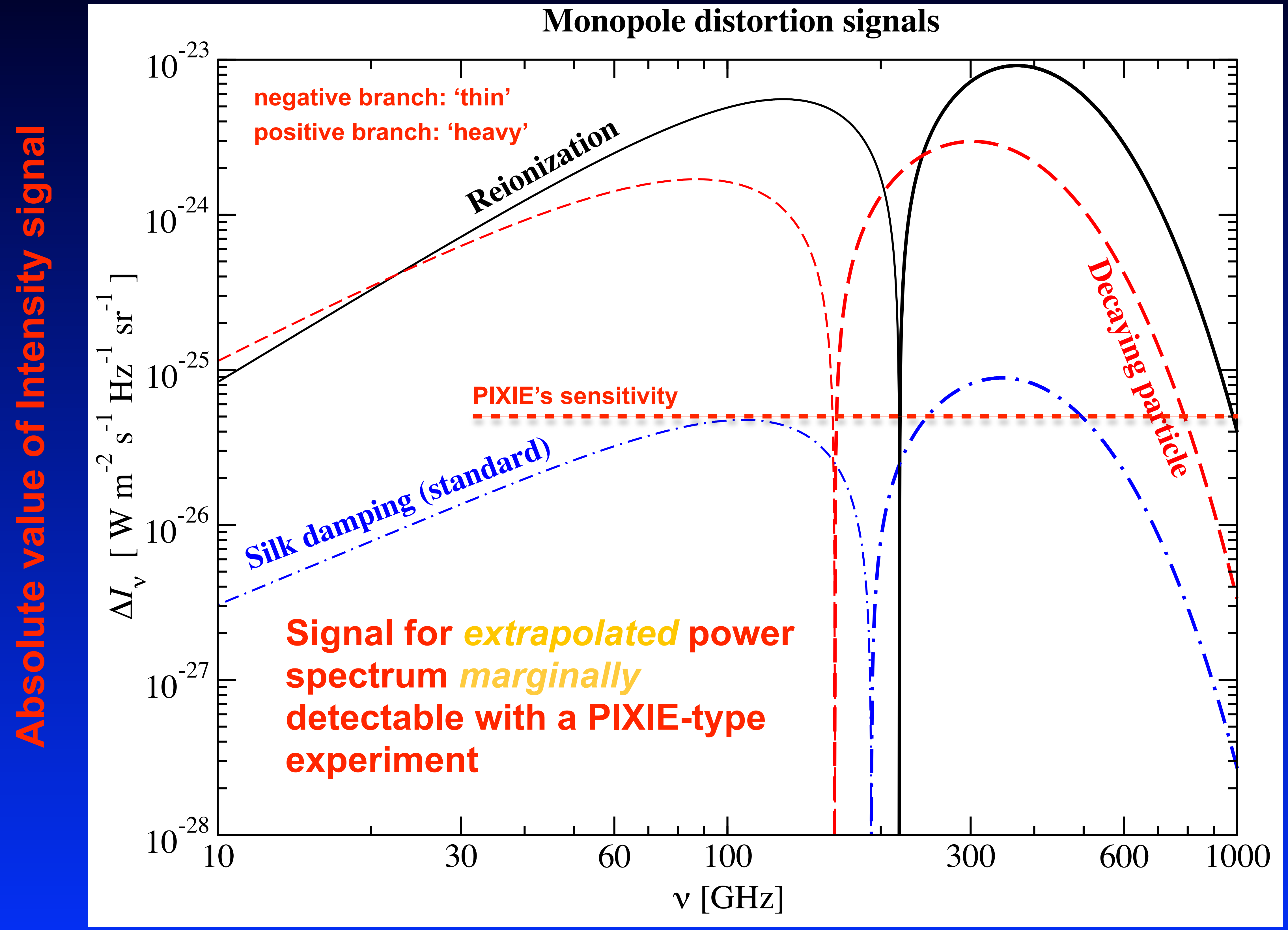
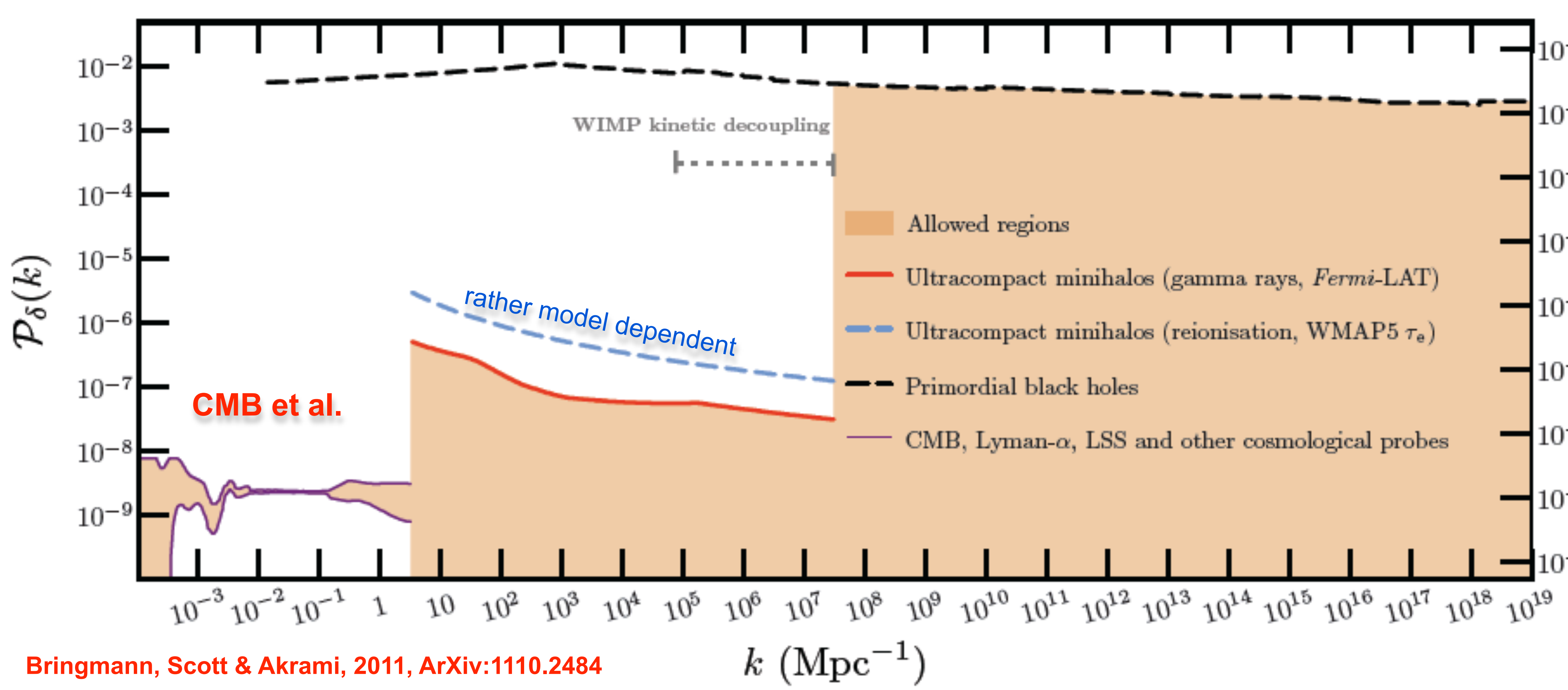


But this is not all that one could look at !!!

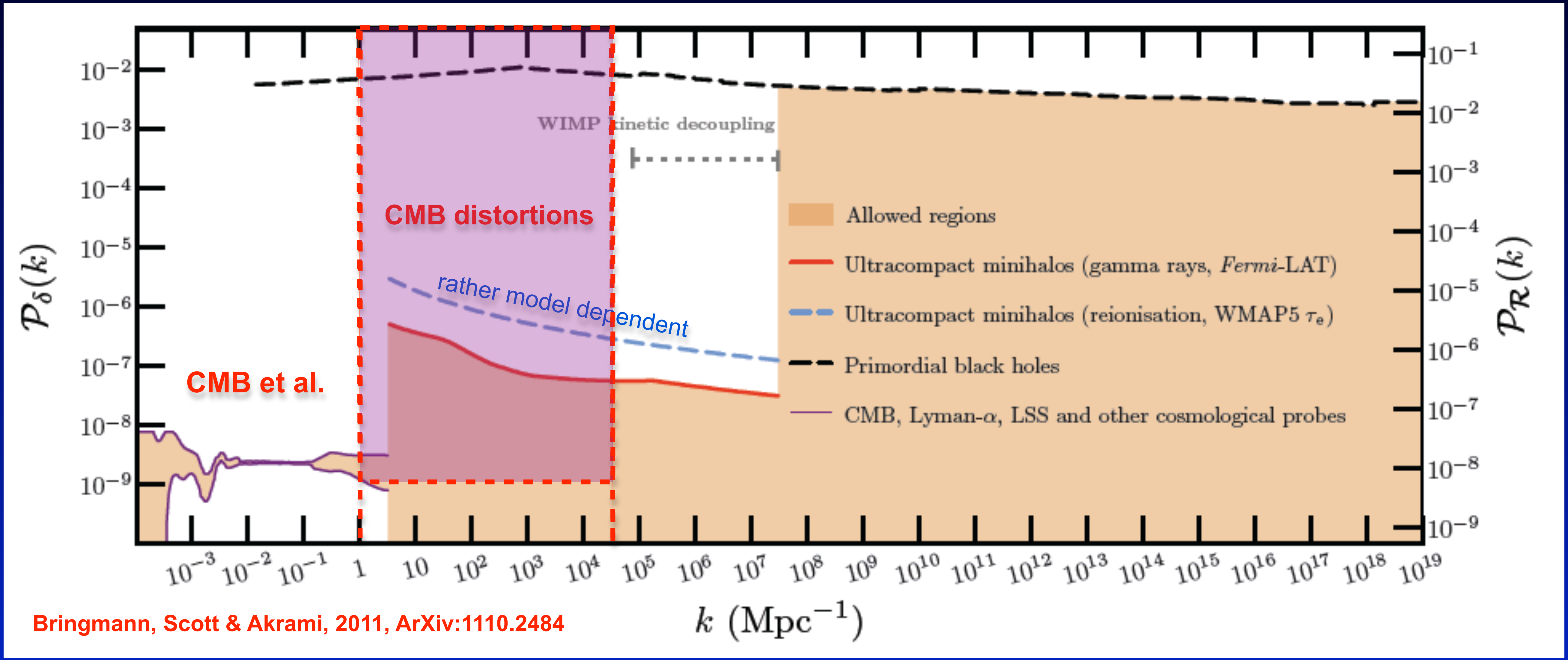
Power spectrum constraints



Bringmann, Scott & Akrami, 2011, ArXiv:1110.2484

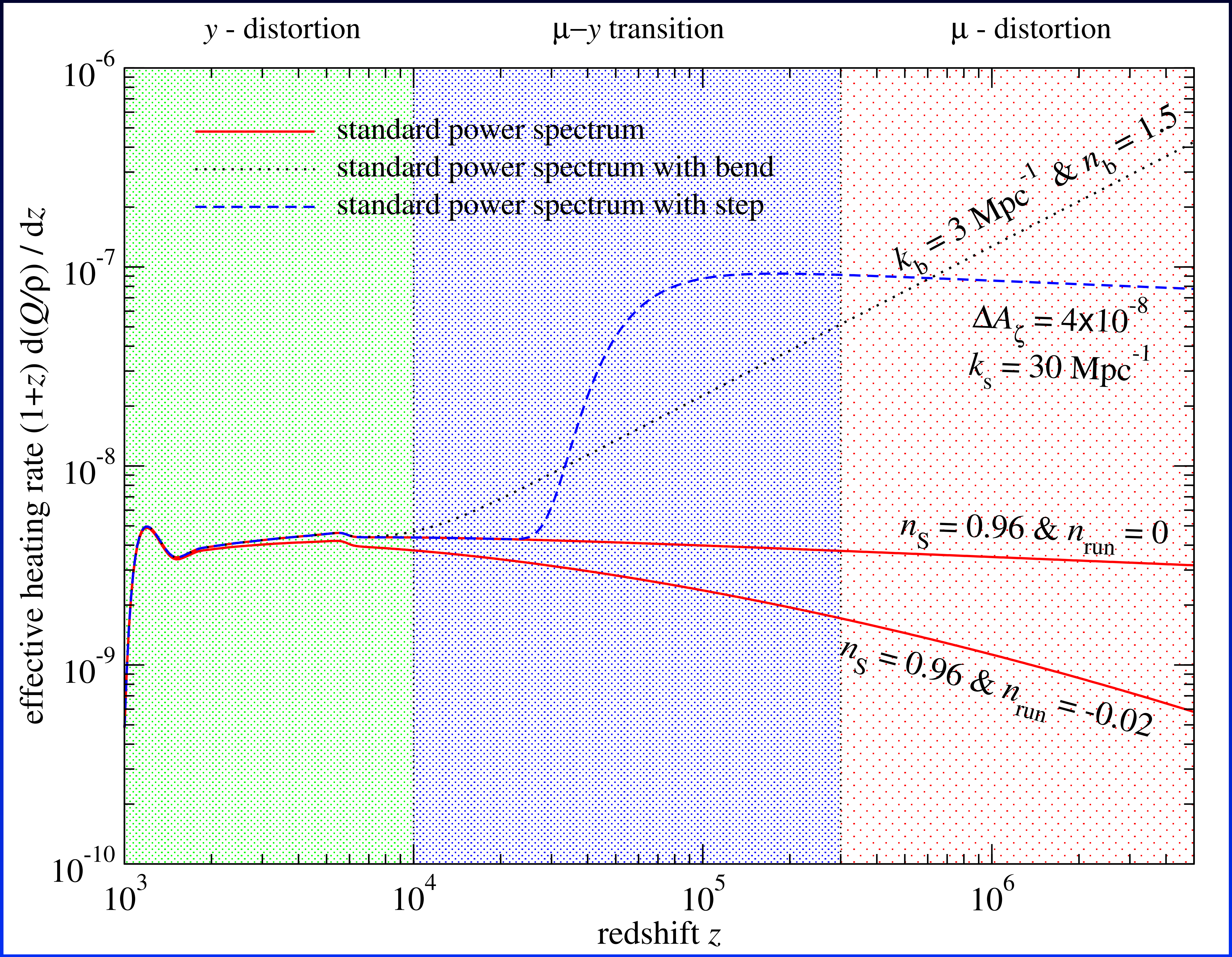
- Amplitude of power spectrum rather uncertain at $k > 3$ Mpc^{-1}
- improving limits at smaller scales would constrain inflationary models

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

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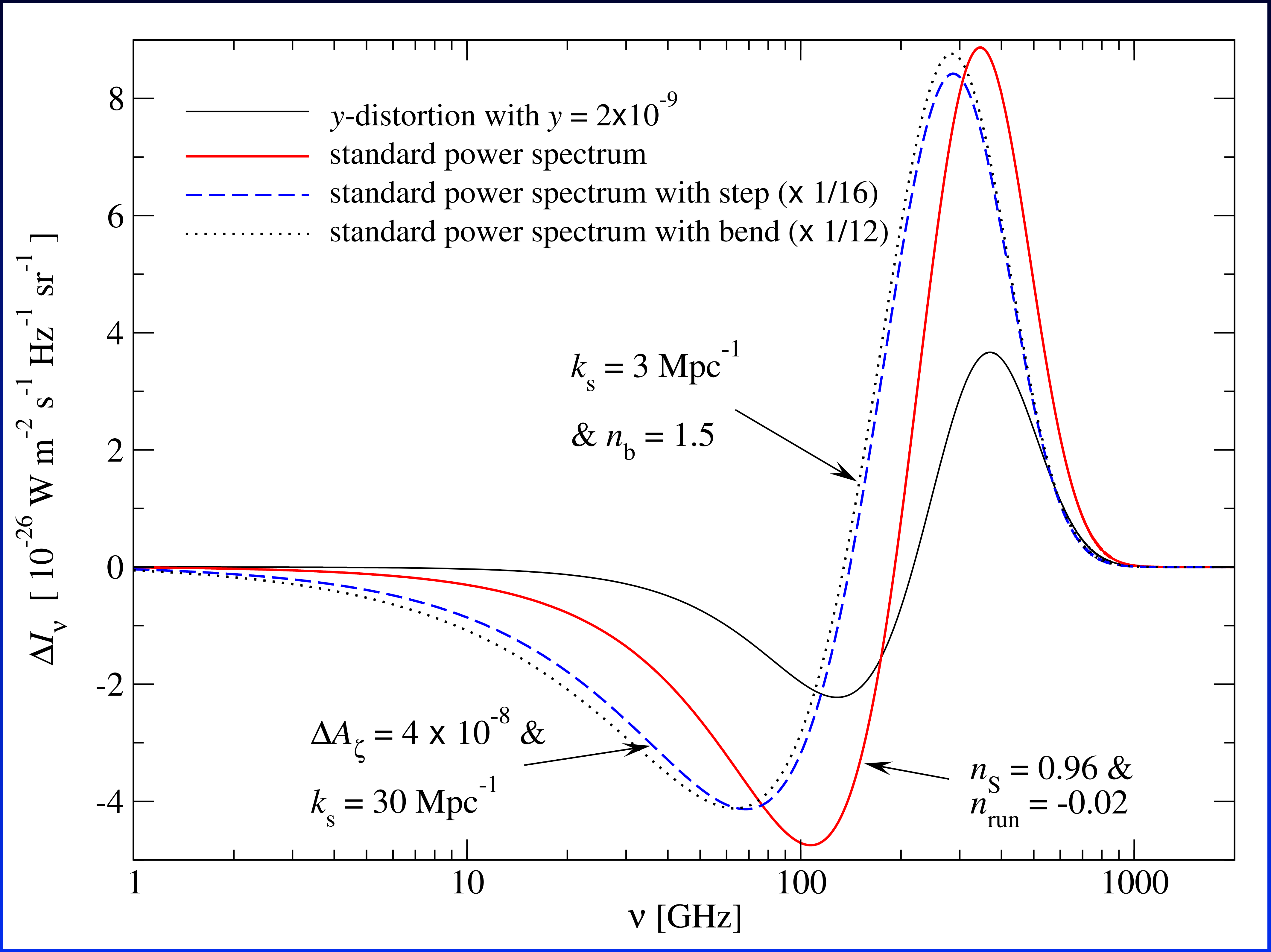

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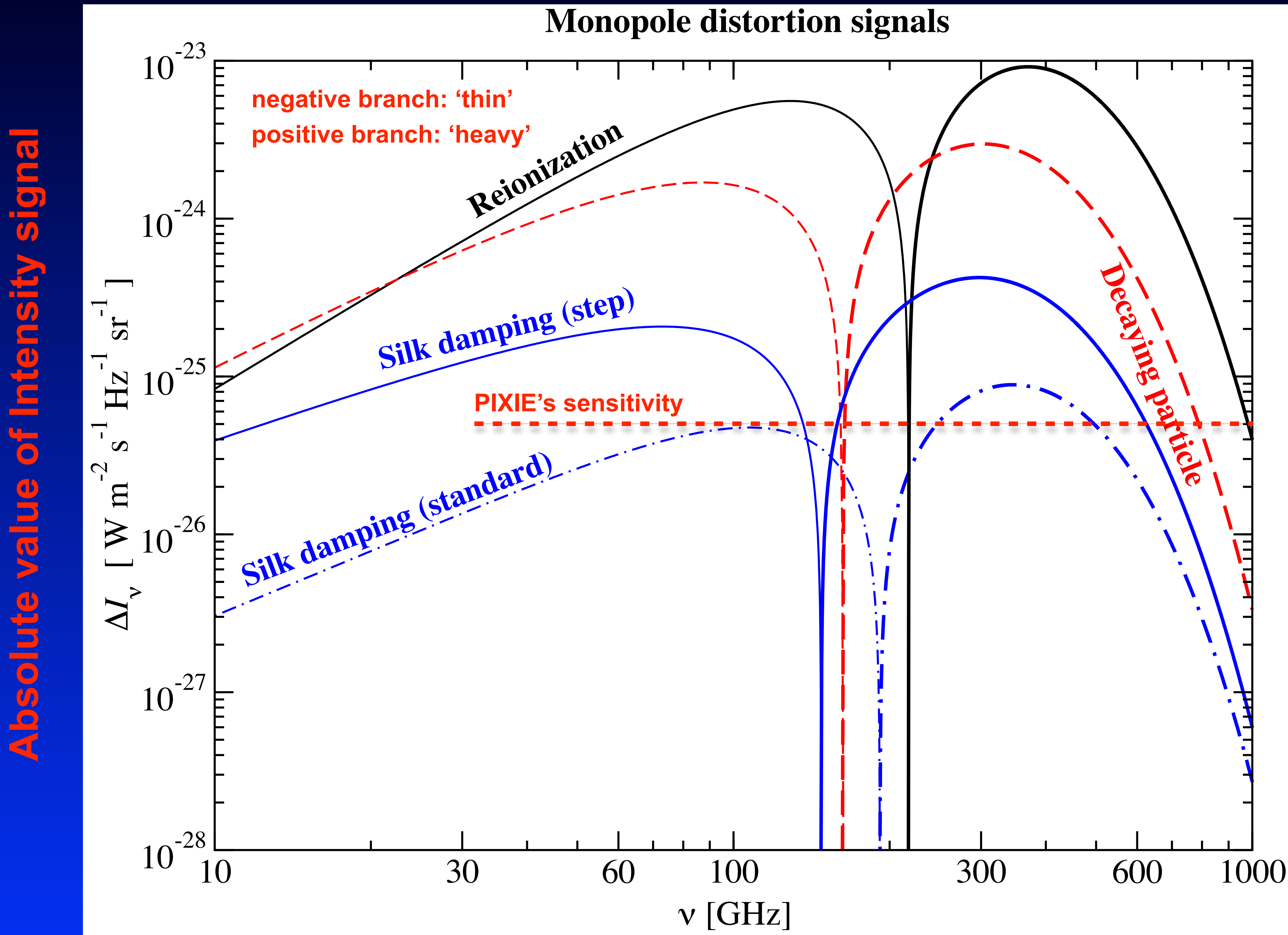
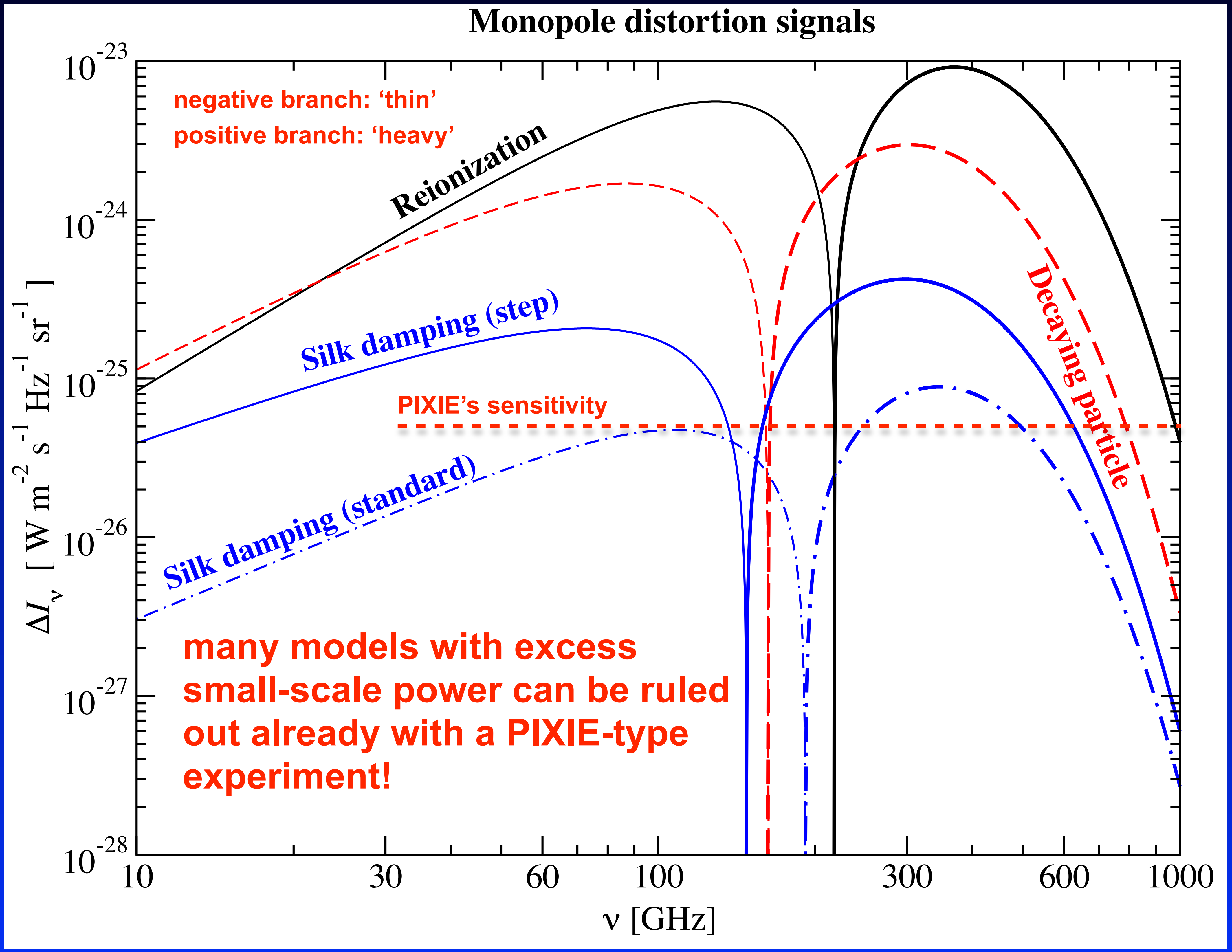
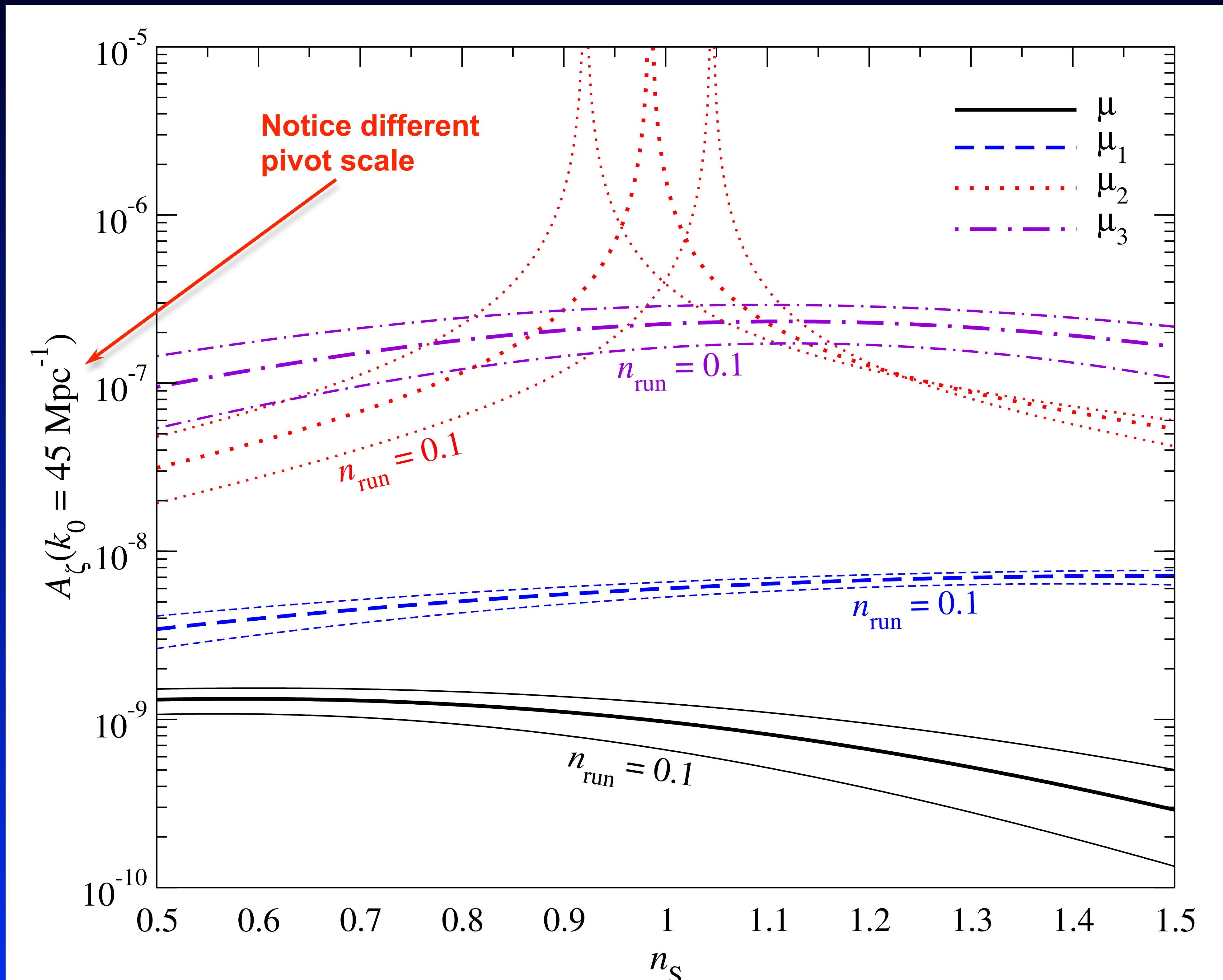


Average CMB spectral distortions

Absolute value of Intensity signal



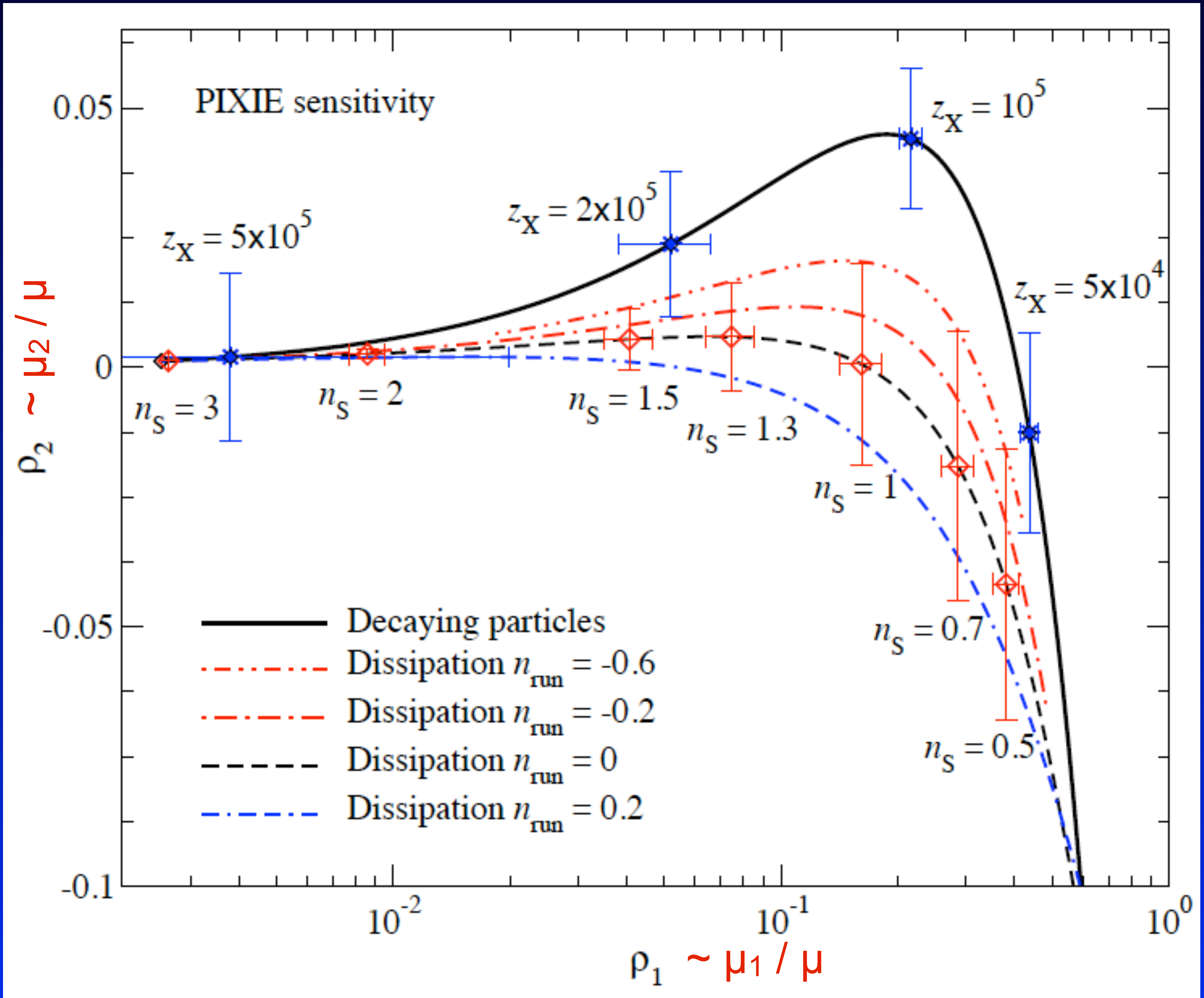
Dissipation scenario: 1σ-detection limits for PIXIE



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

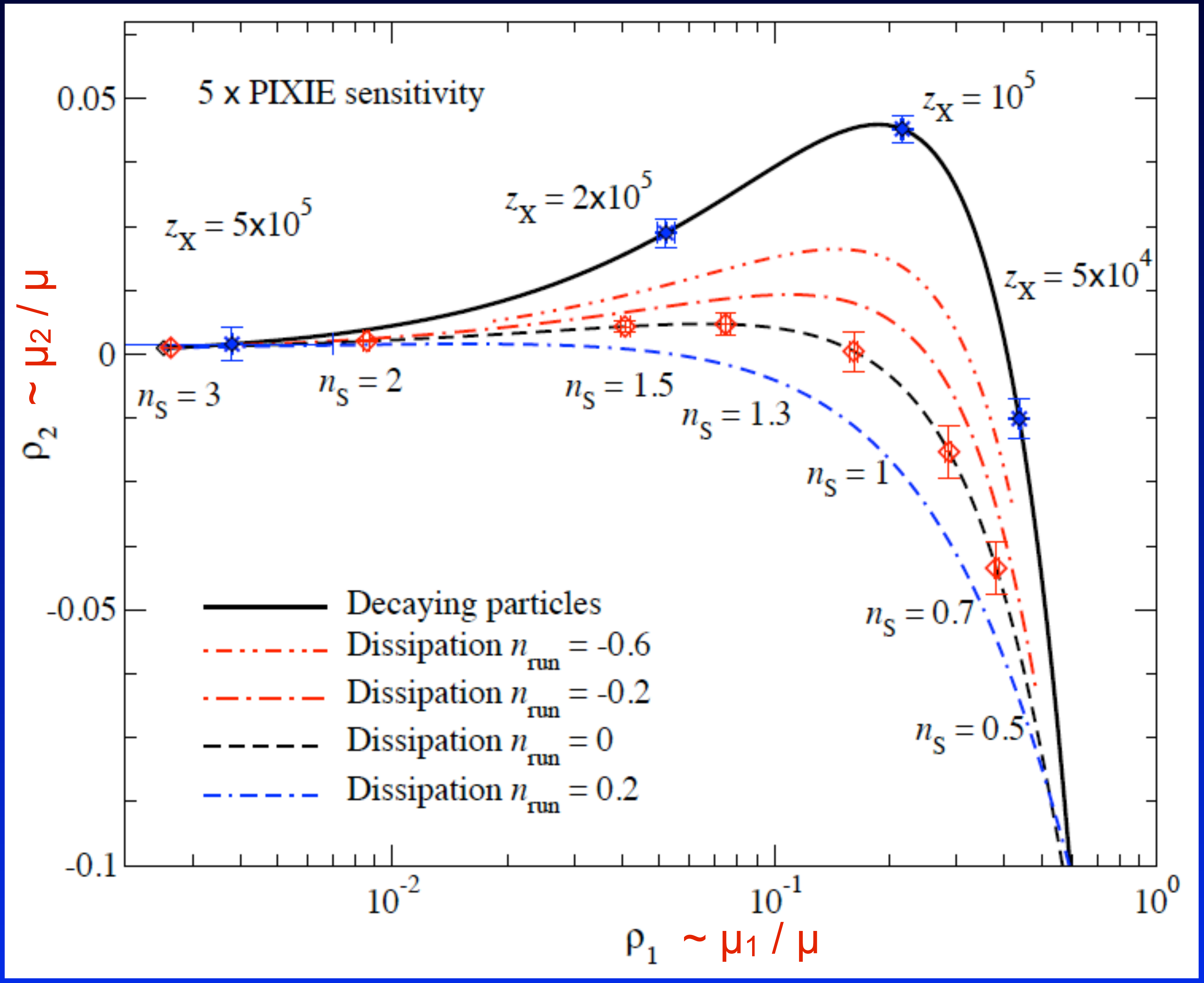


- measurement of μ, μ_1 & μ_2
- trajectories of decaying particle and dissipation scenarios differ!
- scenarios can in principle be distinguished

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

JC & Jeong, 2013

Distinguishing dissipation and decaying particle scenarios



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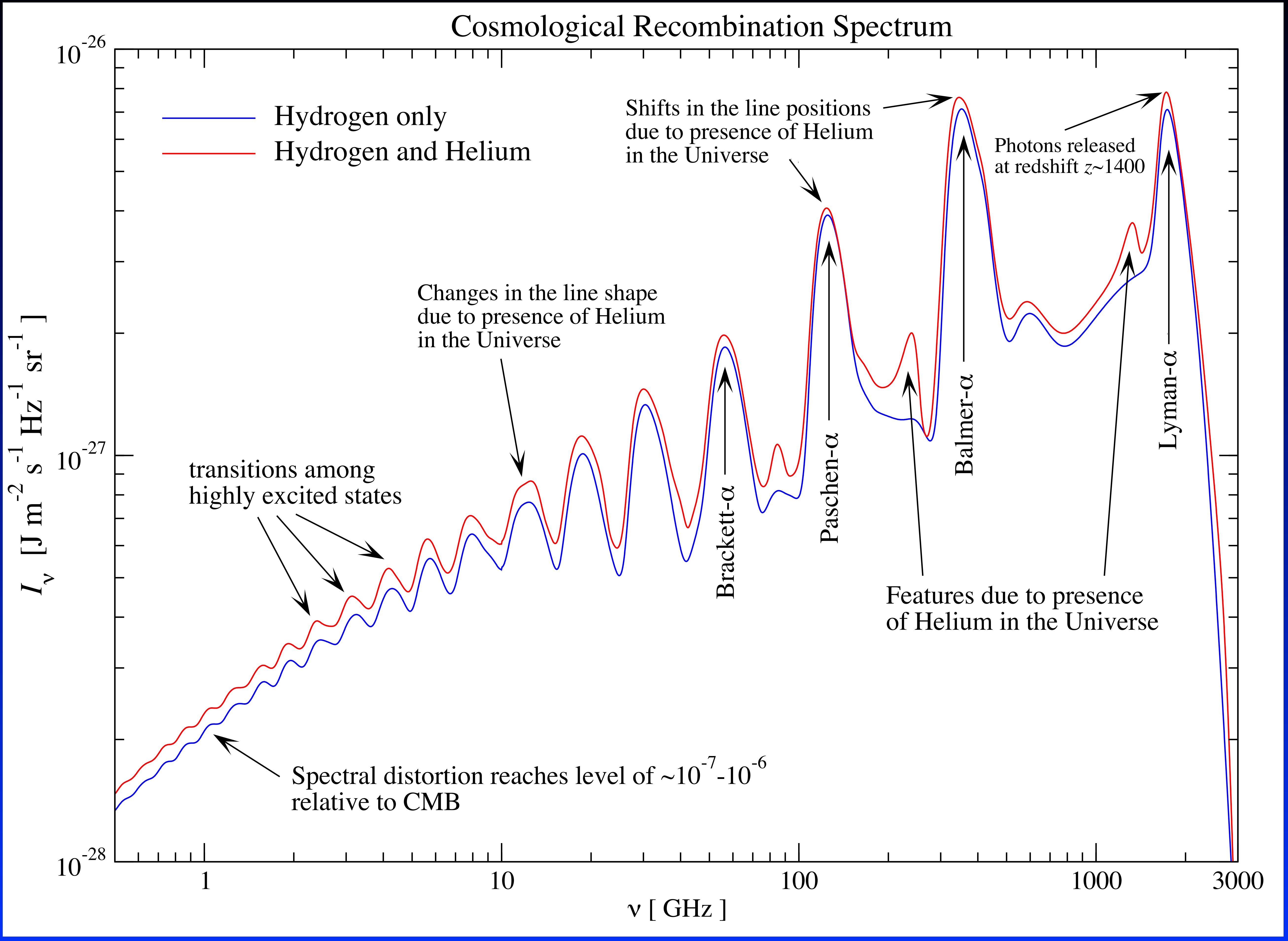
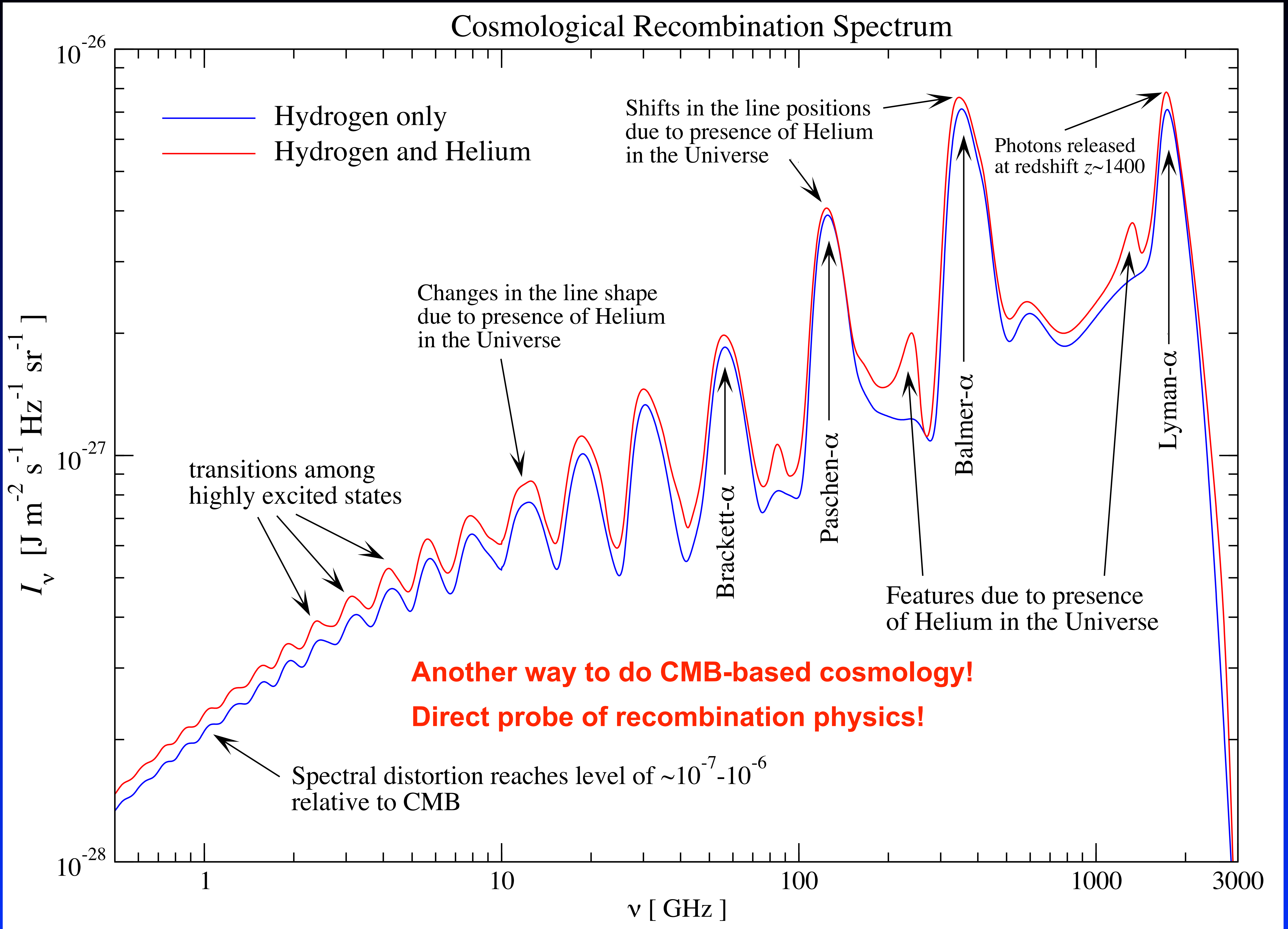
JC & Jeong, 2013

The cosmological recombination radiation


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



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Features due to presence of Helium in the Universe
Another way to do CMB-based cosmology!
Direct probe of recombination physics!
Spectral distortion reaches level of ~10^-7-10^-6 relative to CMB
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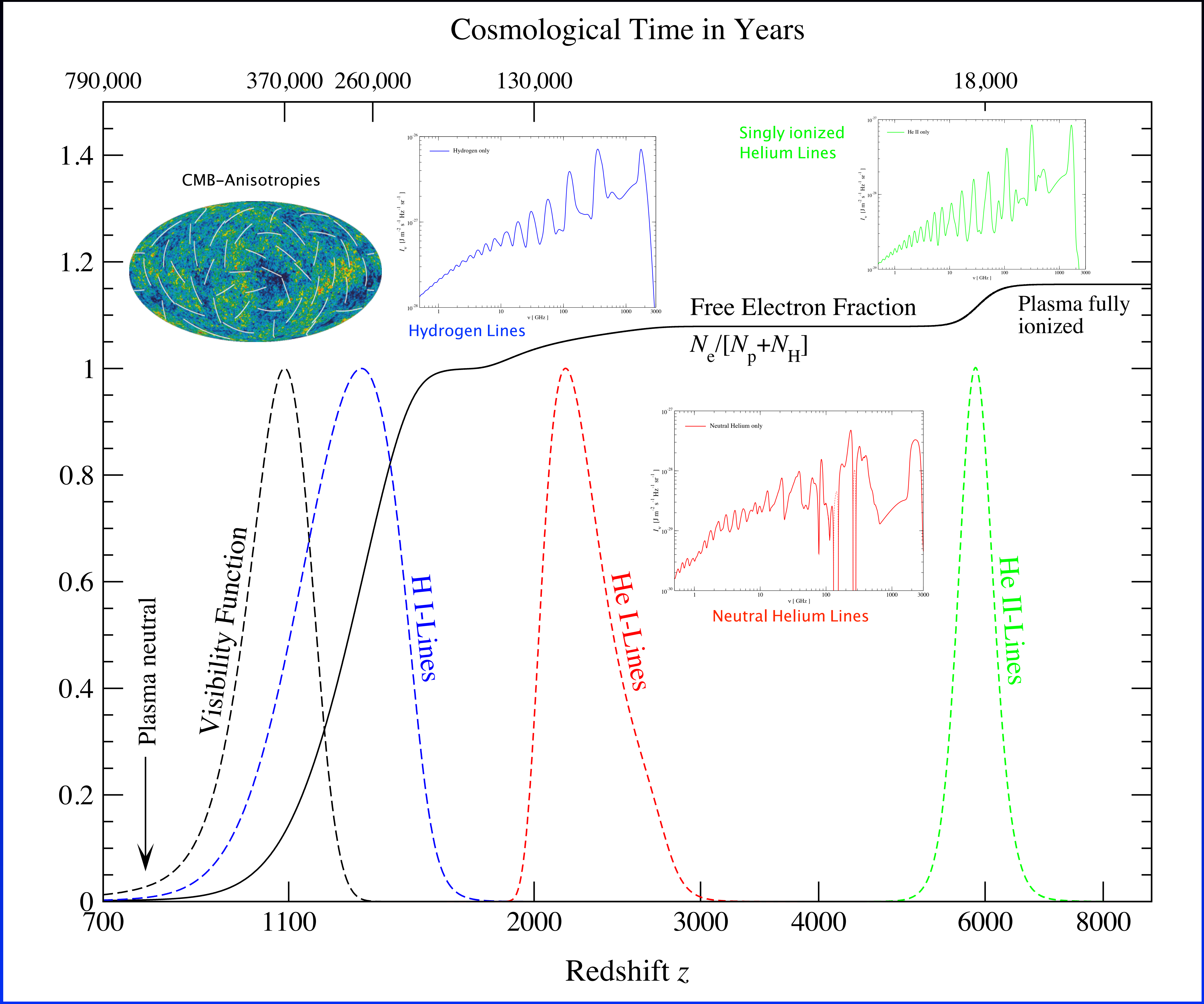
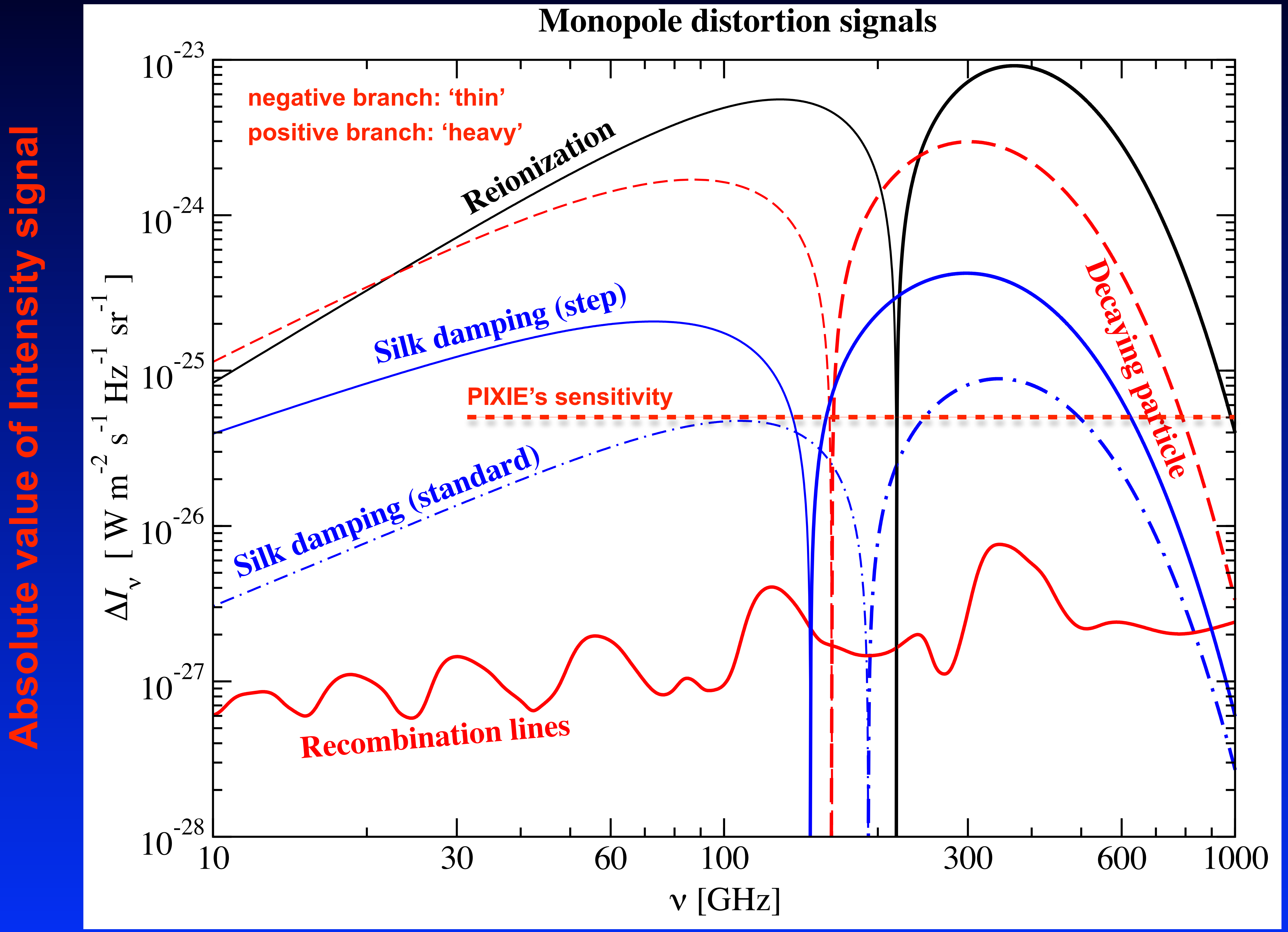
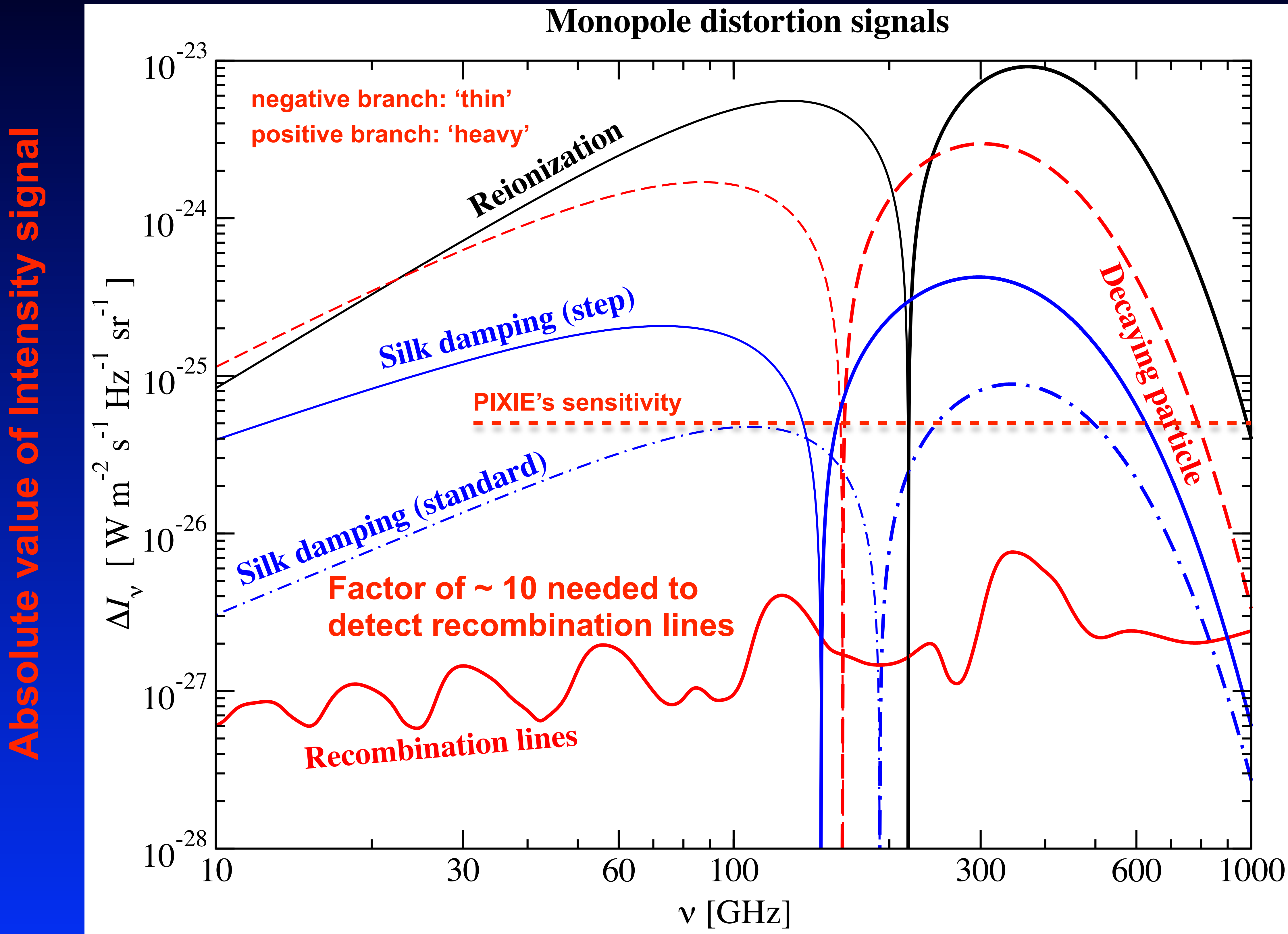


Cosmological Time in Years
790,000
370,000
260,000
130,000
18,000
CMB–Anisotropies
Hydrogen Lines
Singly ionized Helium Lines
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully ionized
Neutral Helium Lines
Plasma neutral
Visibility Function
H I-Lines
He I-Lines
He II-Lines
Hydrogen only
Neutral Helium only
He II only
1.4
1.2
1
0.8
0.6
0.4
0.2
0
700
1100
2000
3000
4000
6000
8000
Redshift z

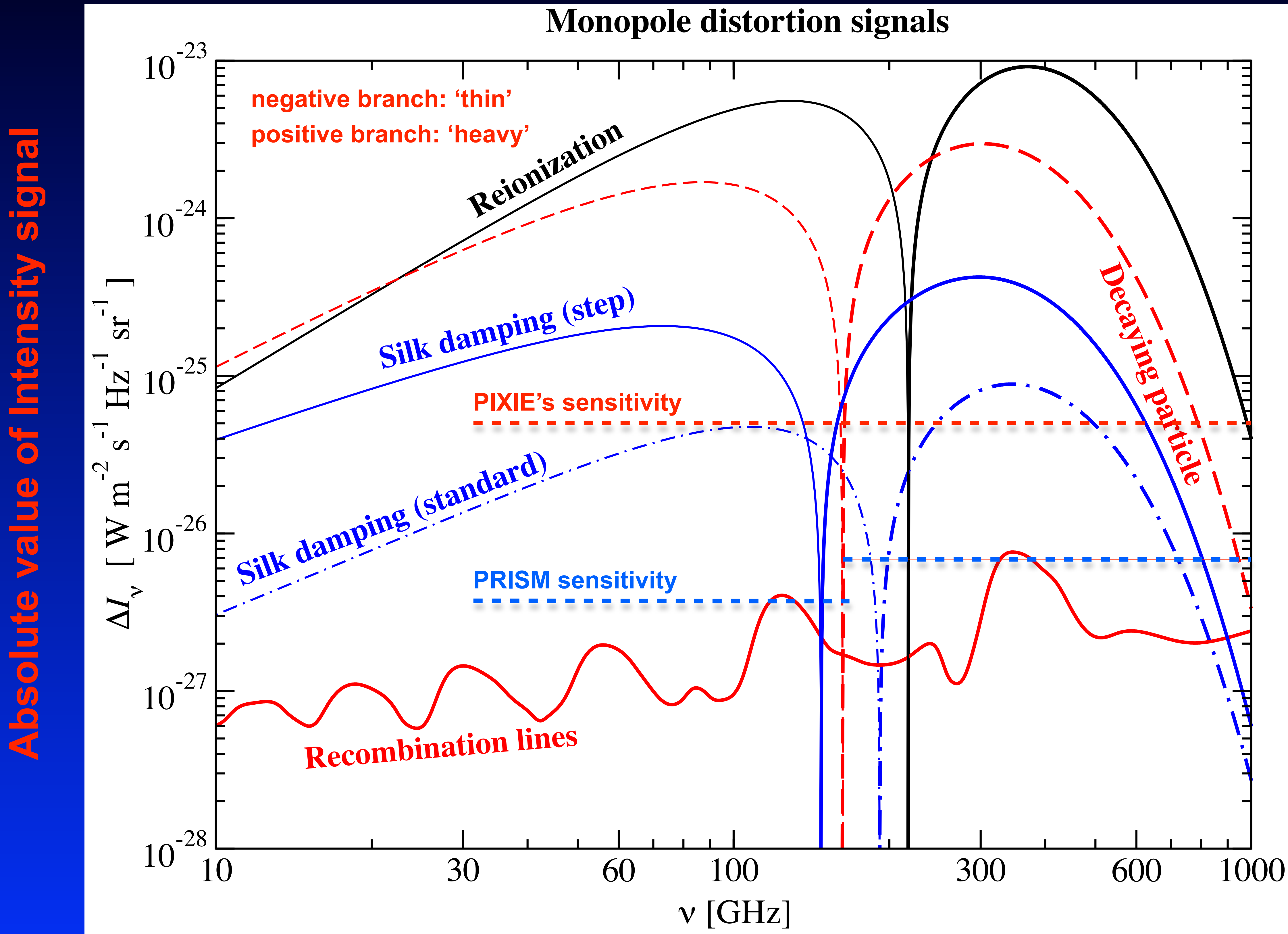
Average CMB spectral distortions



Average CMB spectral distortions



Average CMB spectral distortions



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***

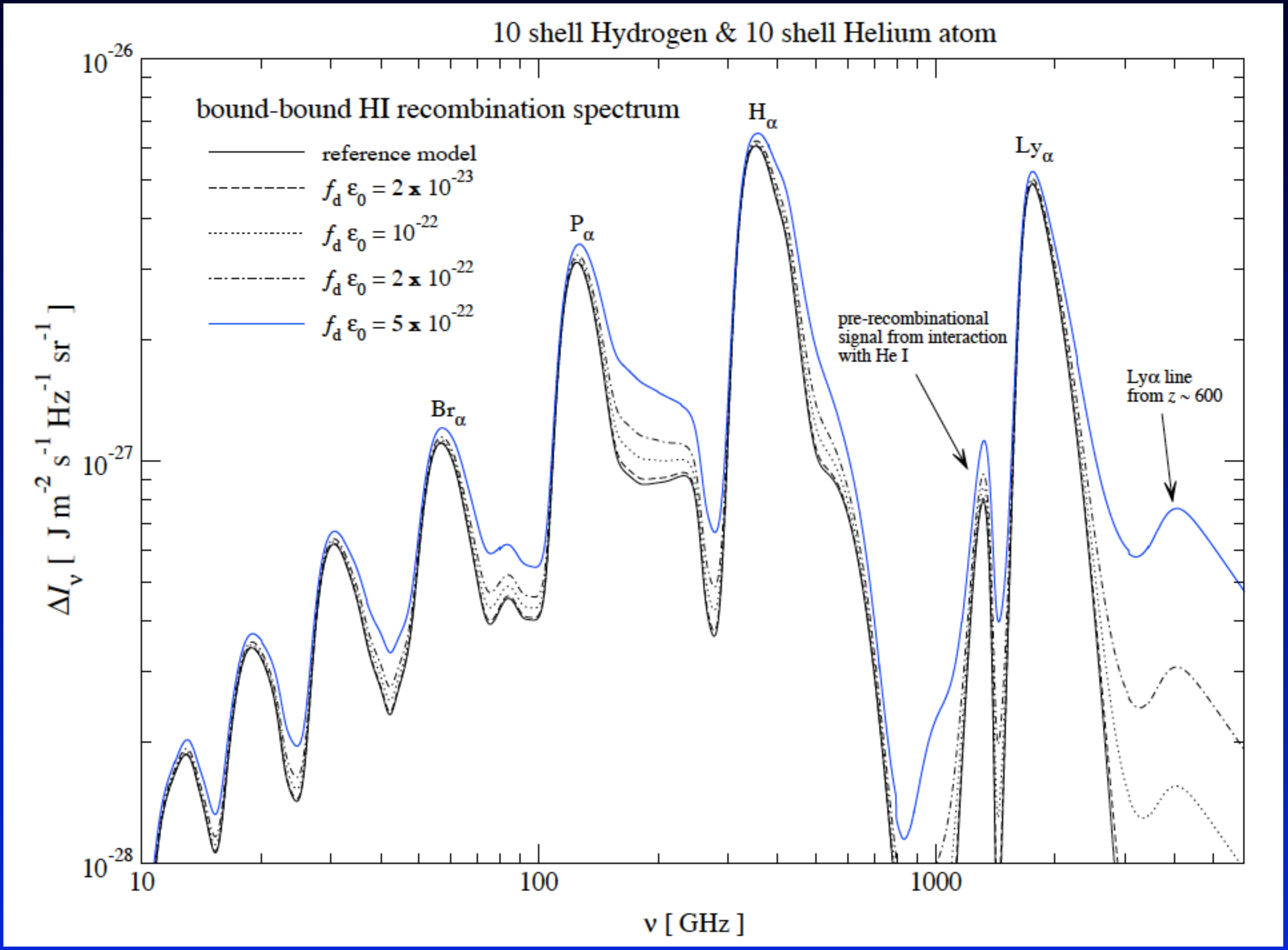
→ ***direct way to measure/reconstruct the recombination history!***

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

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

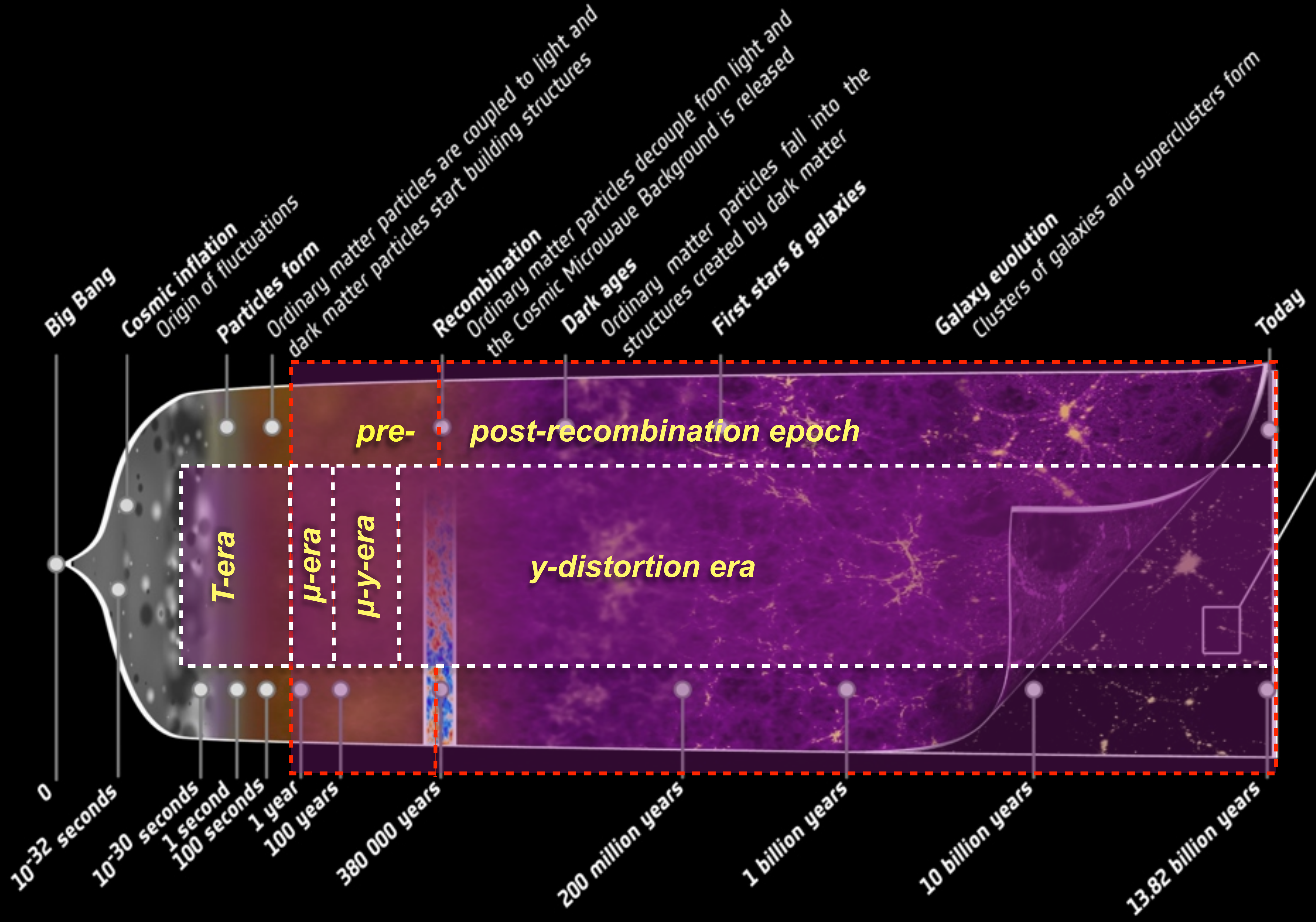
→ **variation of fundamental constants**

Dark matter annihilations / decays

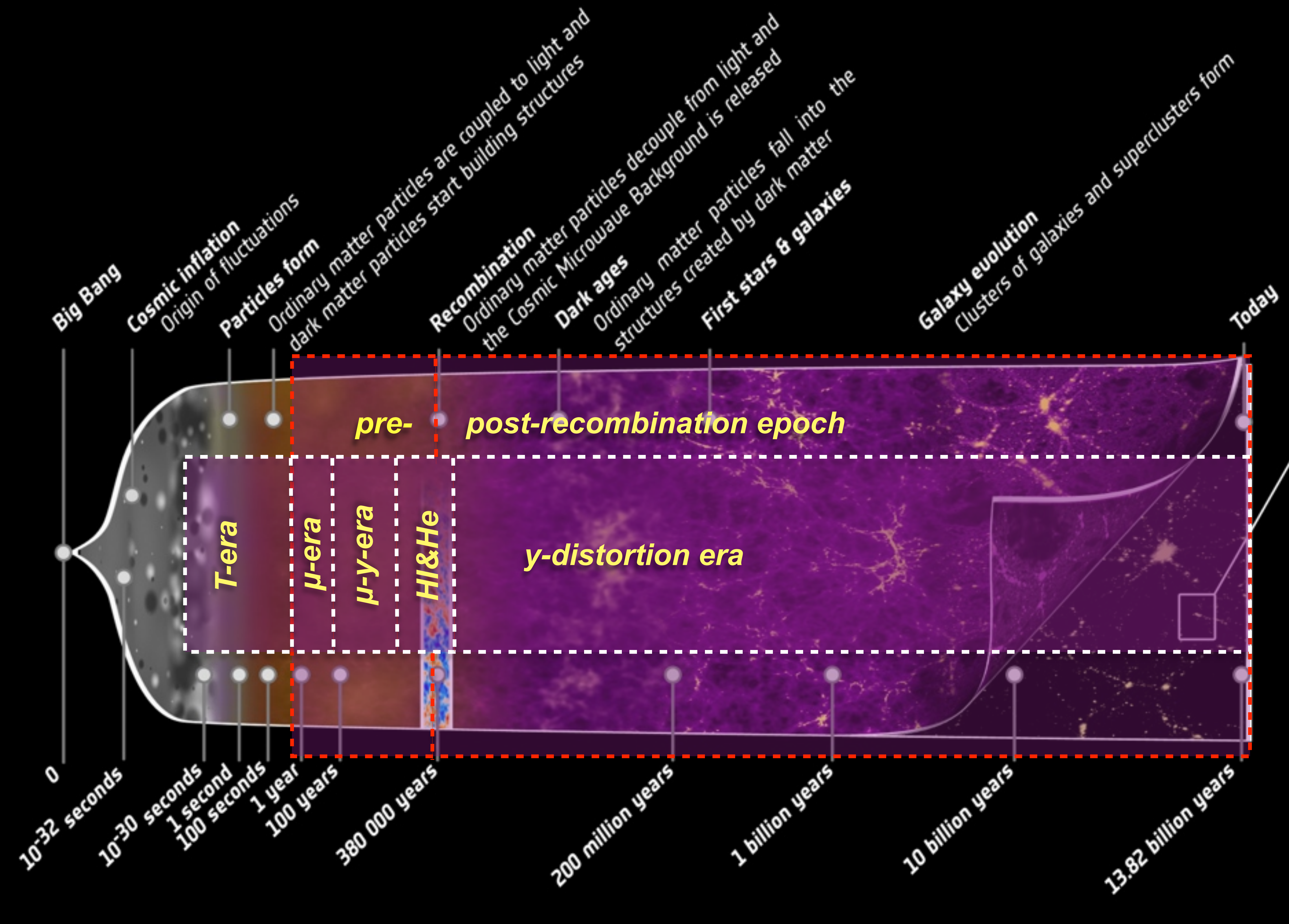


JC, 2009, arXiv:0910.3663

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



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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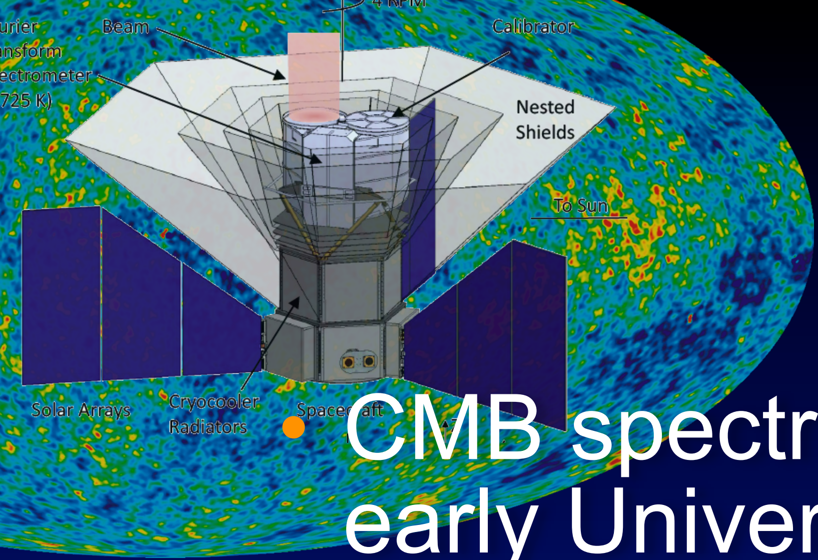

Conclusions

- 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!