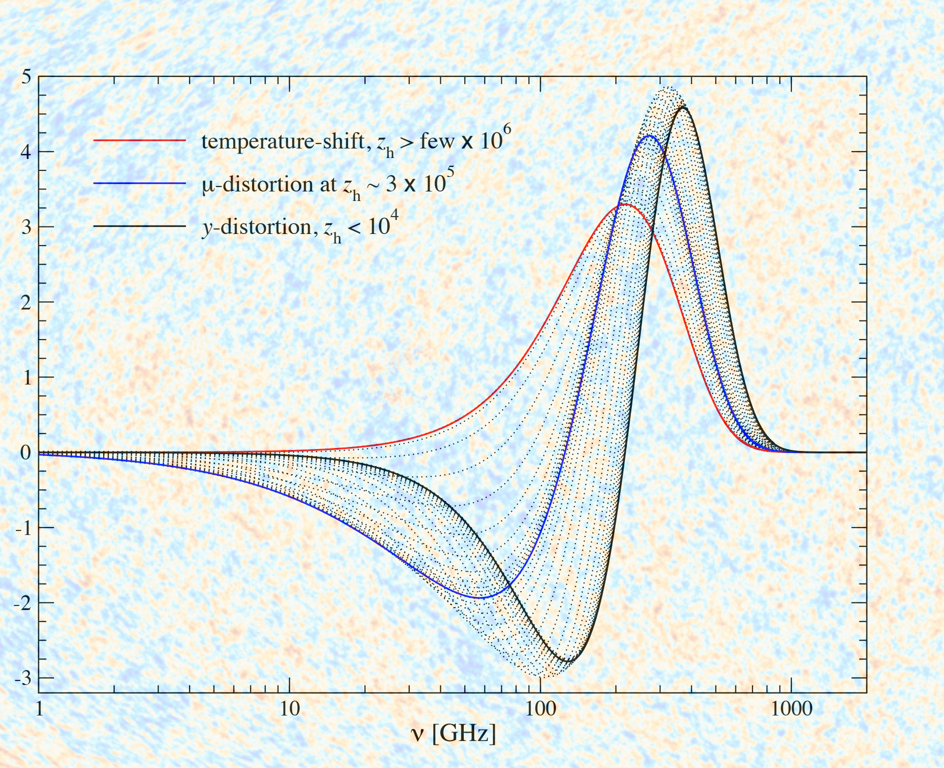
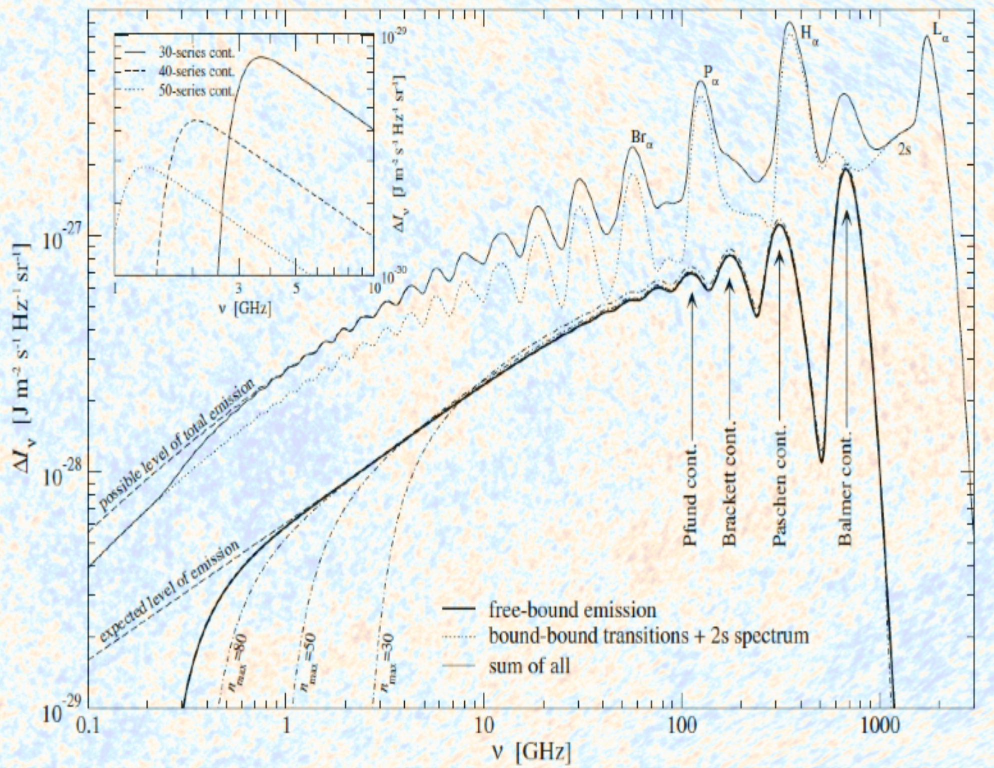
Future Steps in Cosmology using CMB* Spectral Distortions

Primordial Distortions



Cosmological Recombination lines



MANCHESTER
1824
The University of Manchester

Jens Chluba

International School of Physics "Enrico Fermi" 2017

Varenna, Italy, July 7th, 2017

erc
THE ROYAL SOCIETY

** CMB ≙ Cosmic Microwave Background*

Main Goals of the Lecture

- Convince you that future CMB distortions science will be *extremely* exciting and lots of fun!
- Explain in detail how distortions evolve and thermalize
- Definition of different types of distortions (μ, y and r-type)
- Computations of spectral distortions
- Provide an overview for different sources of primordial distortions
- Show you why CMB spectral distortions provide a *complementary* probe of inflation and particle physics

References for the Theory of Spectral Distortions

- Early works
  - Zeldovich & Sunyaev, 1969, Ap&SS, 4, 301
  - Sunyaev & Zeldovich, 1970, Ap&SS, 7, 20
  - Illarionov & Sunyaev, 1975, Sov. Astr., 18, 413

Yakov Zeldovich

Rashid Sunyaev

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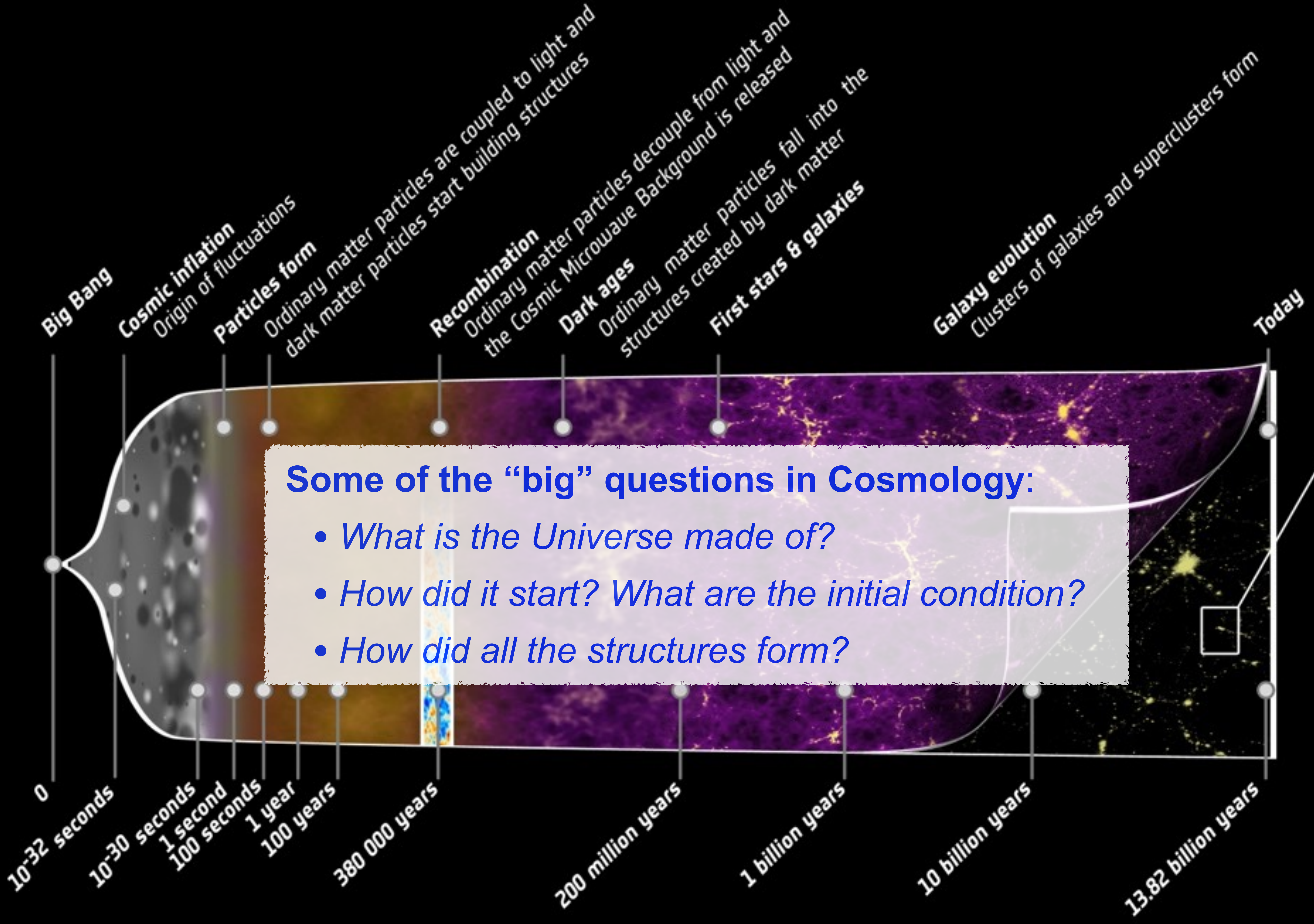
  - Illarionov & Sunyaev, 1975, Sov. Astr., 18, 413
- Additional important milestones
  - Danese & de Zotti, 1982, A&A, 107, 39
  - Burigana, Danese & de Zotti, 1991, ApJ, 379, 1
  - Hu & Silk, 1993, Phys. Rev. D, 48, 485
  - Hu, 1995, PhD thesis
- More recent overviews
  - Sunyaev & JC, 2009, AN, 330, 657
  - JC & Sunyaev, 2012, MNRAS, 419, 1294
  - JC, 2013, MNRAS, 436, 2232 & ArXiv:1405.6938

see also, CUSO *Lecture* notes at:
`www.Chluba.de/Science`

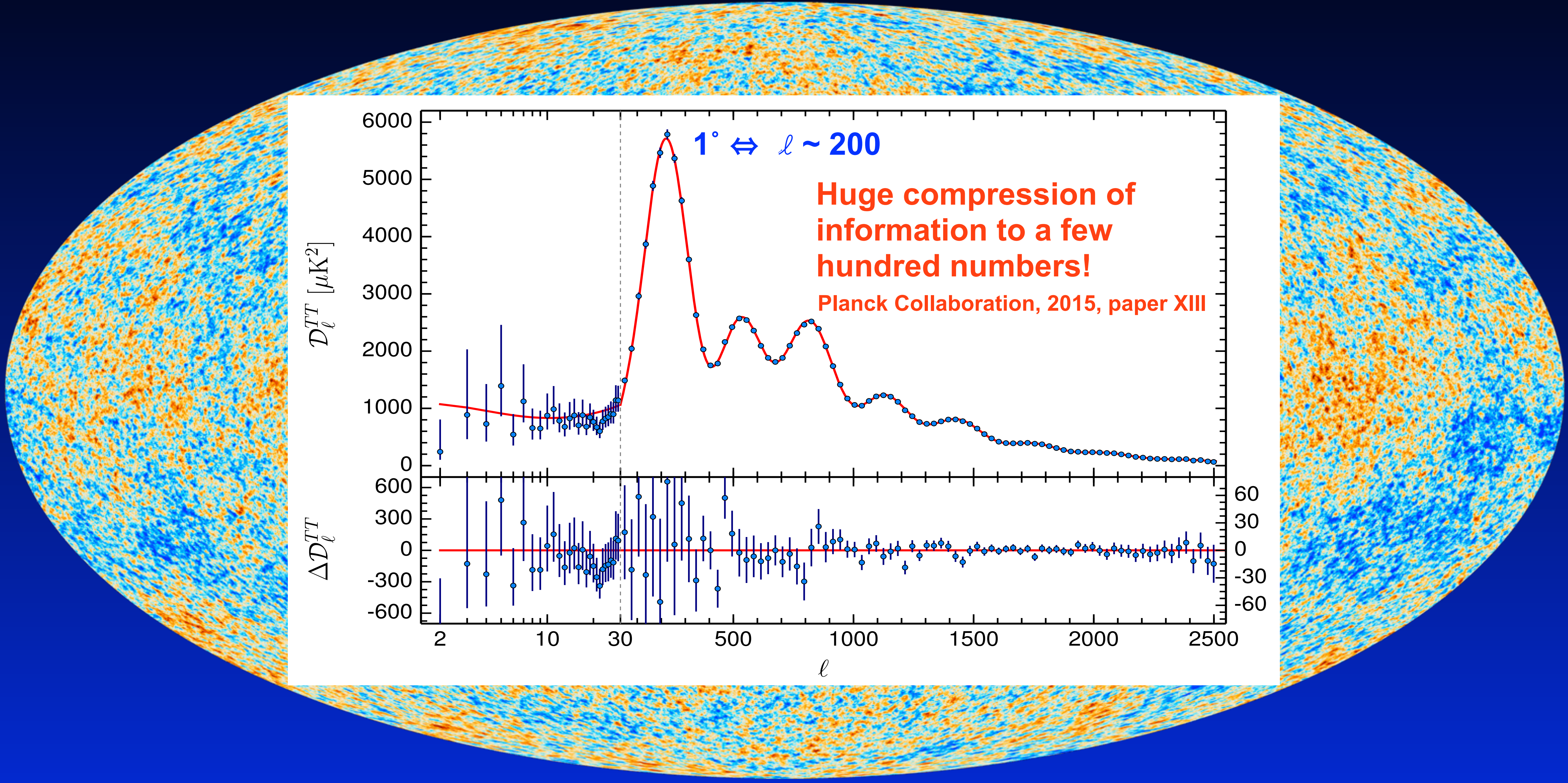
Part I: Why should one be interested in CMB spectral distortions right now?

Some of the “big” questions in Cosmology:

- *What is the Universe made of?*
- *How did it start? What are the initial condition?*
- *How did all the structures form?*



Cosmic Microwave Background Anisotropies



Huge compression of information to a few hundred numbers!

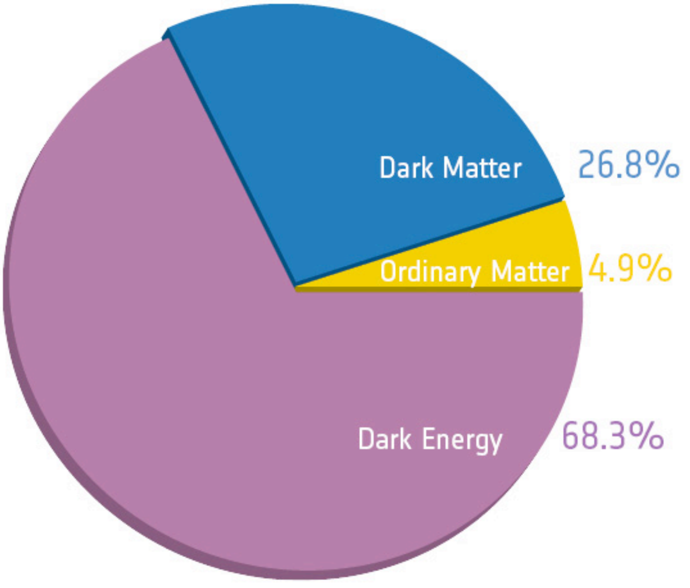
Planck Collaboration, 2015, paper XIII

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!

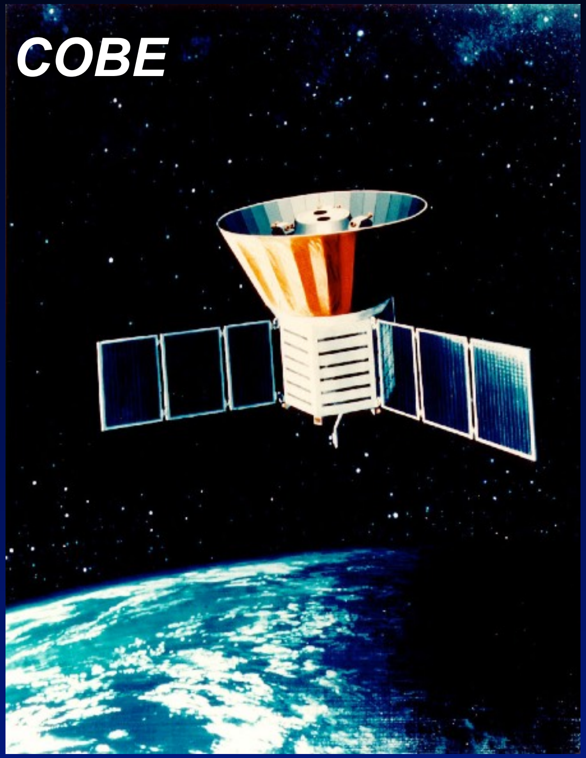
- Standard 6 parameter concordance cosmology with parameters known to percent level precision
- Gaussian-distributed adiabatic fluctuations with nearly scale-invariant power spectrum over a wide range of scales
- cold dark matter (“CDM”)
- accelerated expansion today (“Λ”)
- Standard BBN scenario → N_{eff}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

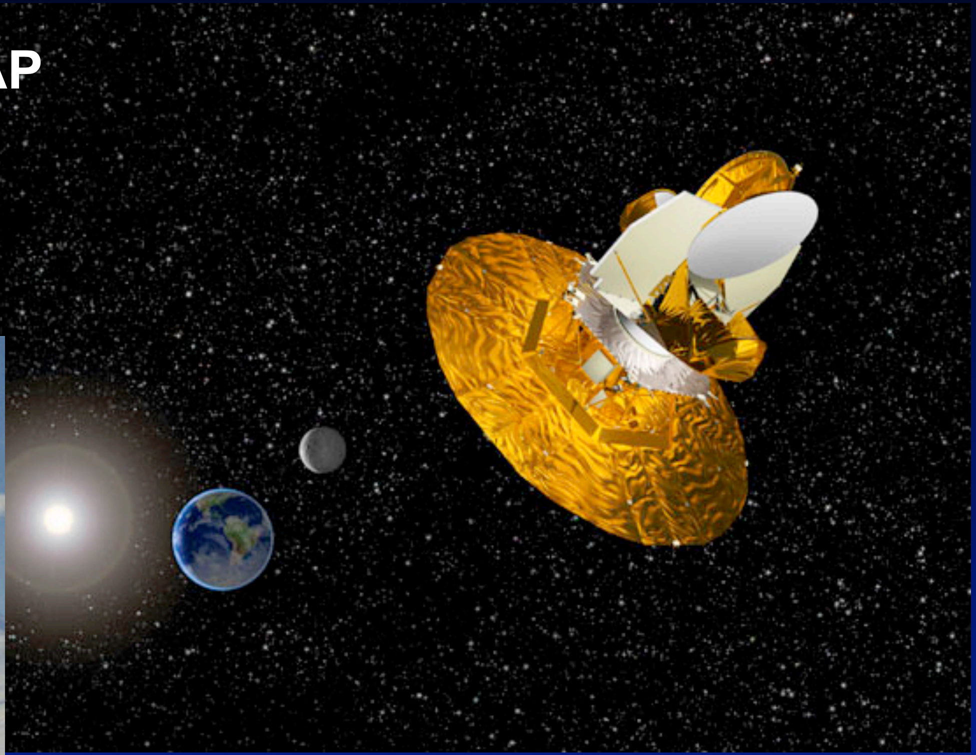


Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 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
$100\theta_{\mathrm{MC}}$	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

Lots of amazing progress over the past decades!

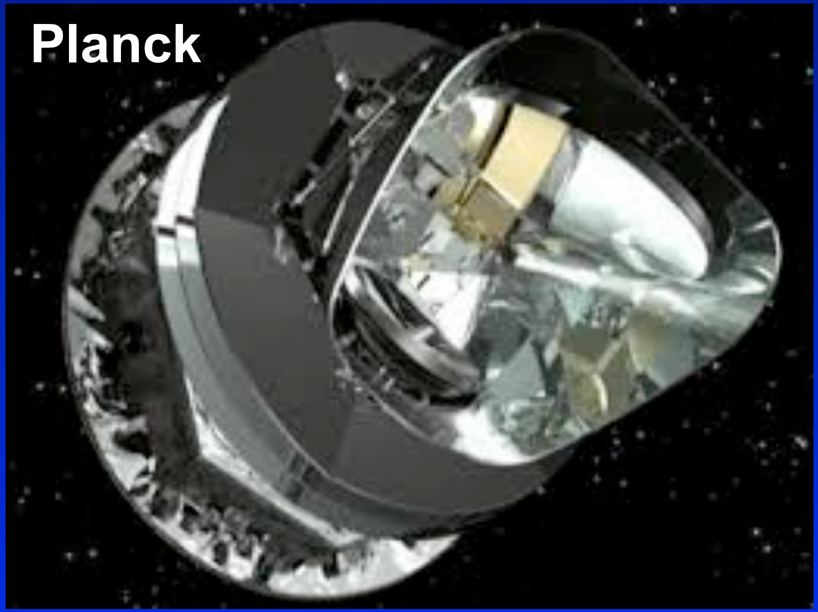

COBE


WMAP


Boomerang

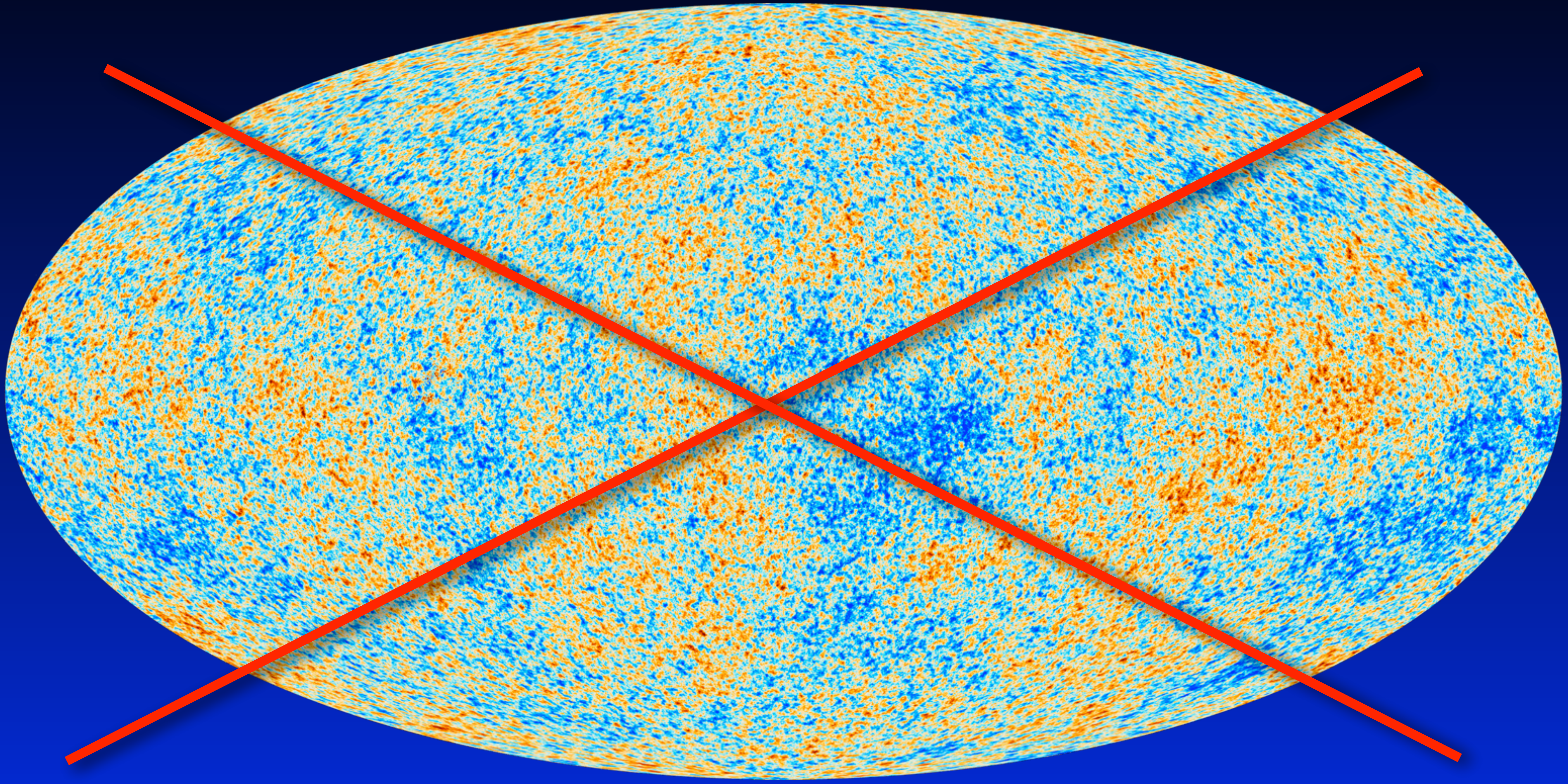

ACT


SPT


Planck

VSA, DESI, MAXIMA,
Keck Array, BICEP,
Polarbear, EBEX,
and many more...

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 provides another independent piece of information!

COBE/FIRAS

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

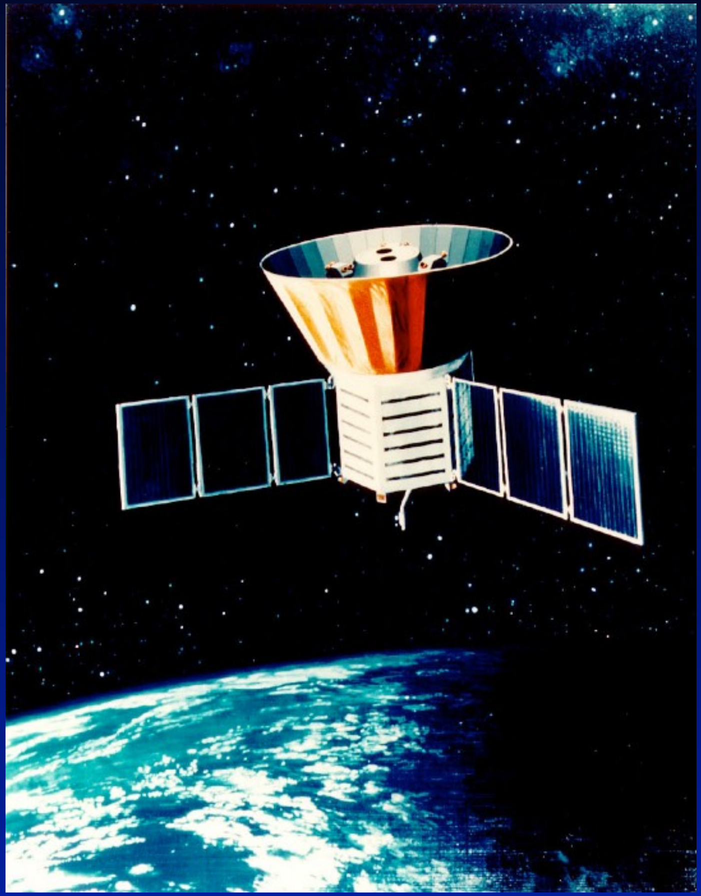
Absolute measurement required!

One has to go to space...

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 the fluctuations

COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)



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

$$|y| \leq 1.5\times10^{-5}$$

$$|\mu| \leq 9\times10^{-5}$$

Mather et al., 1994, ApJ, 420, 439
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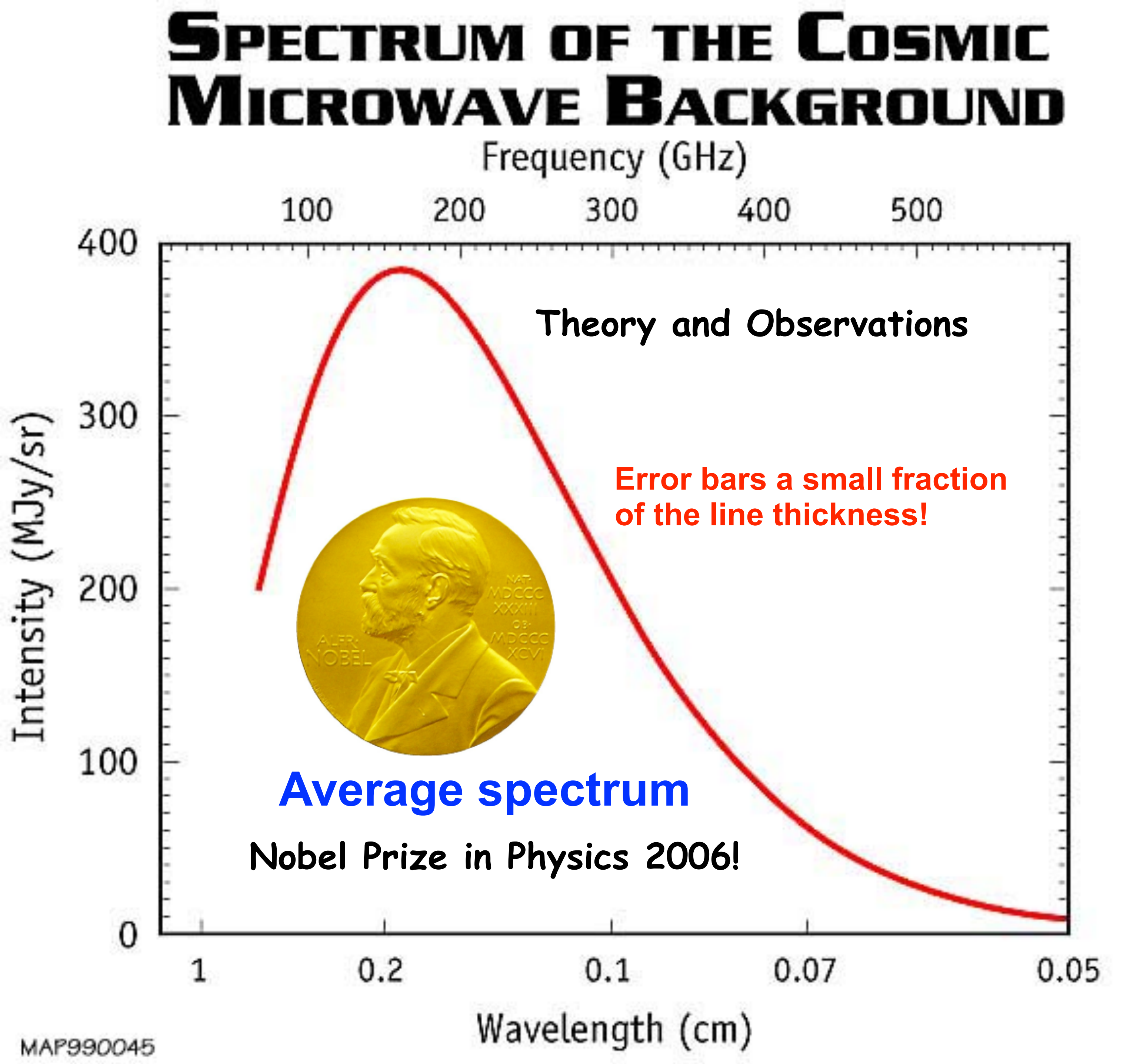


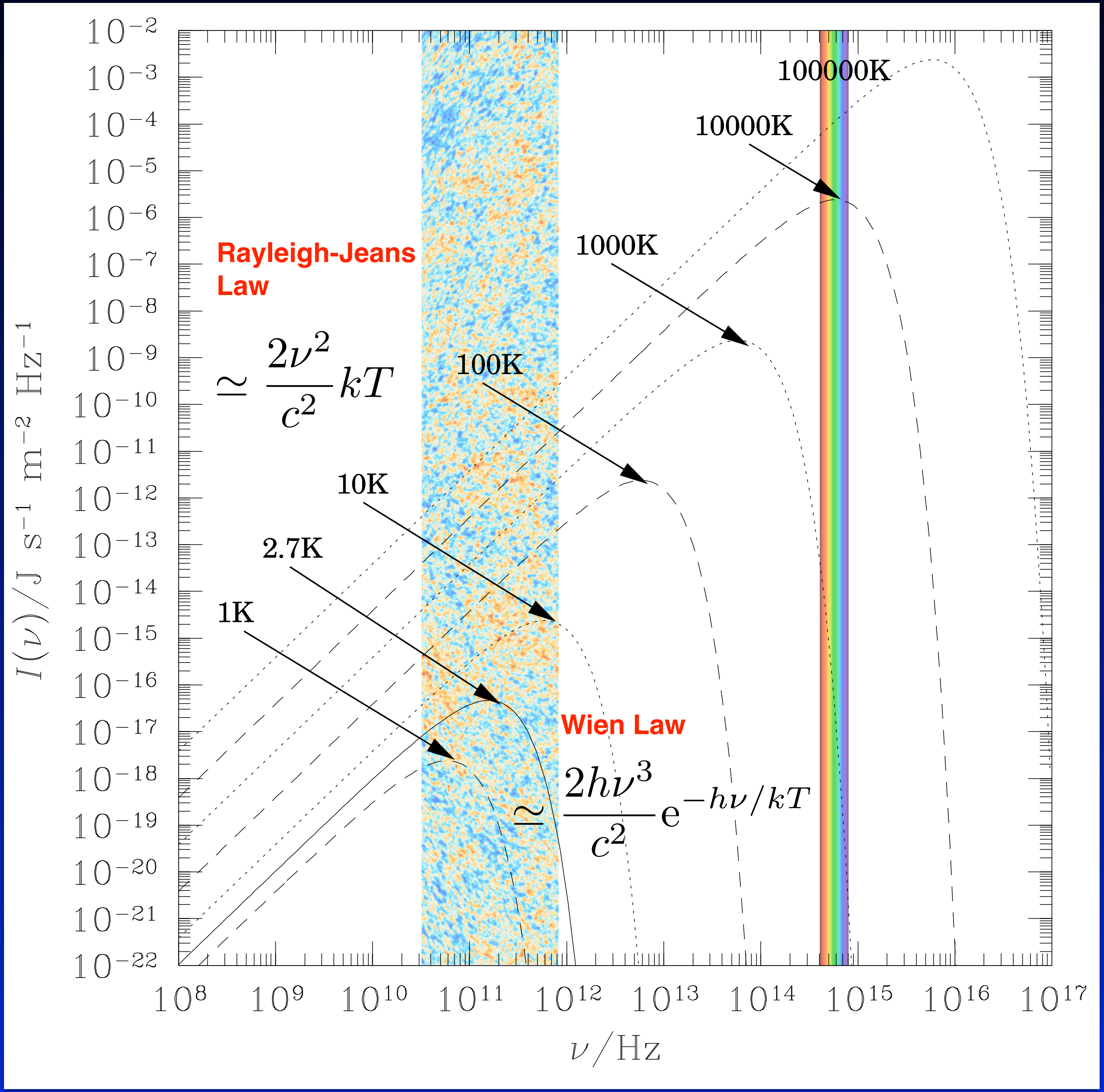
Theory and Observations

Error bars a small fraction of the line thickness!

Average spectrum

Nobel Prize in Physics 2006!

Simple Blackbody Properties



Photon occupation number

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\,n_\nu(T) = \frac{2h}{c^2}\,\frac{\nu^3}{e^{h\nu/kT}-1} = I_o\,\frac{x^3}{e^x-1}$$

$$I_o = \frac{2h}{c^2}\left(\frac{kT}{h}\right)^3 \approx 270\,\mathrm{MJy\,sr^{-1}}\left[\frac{T}{2.725\mathrm{K}}\right]^3$$

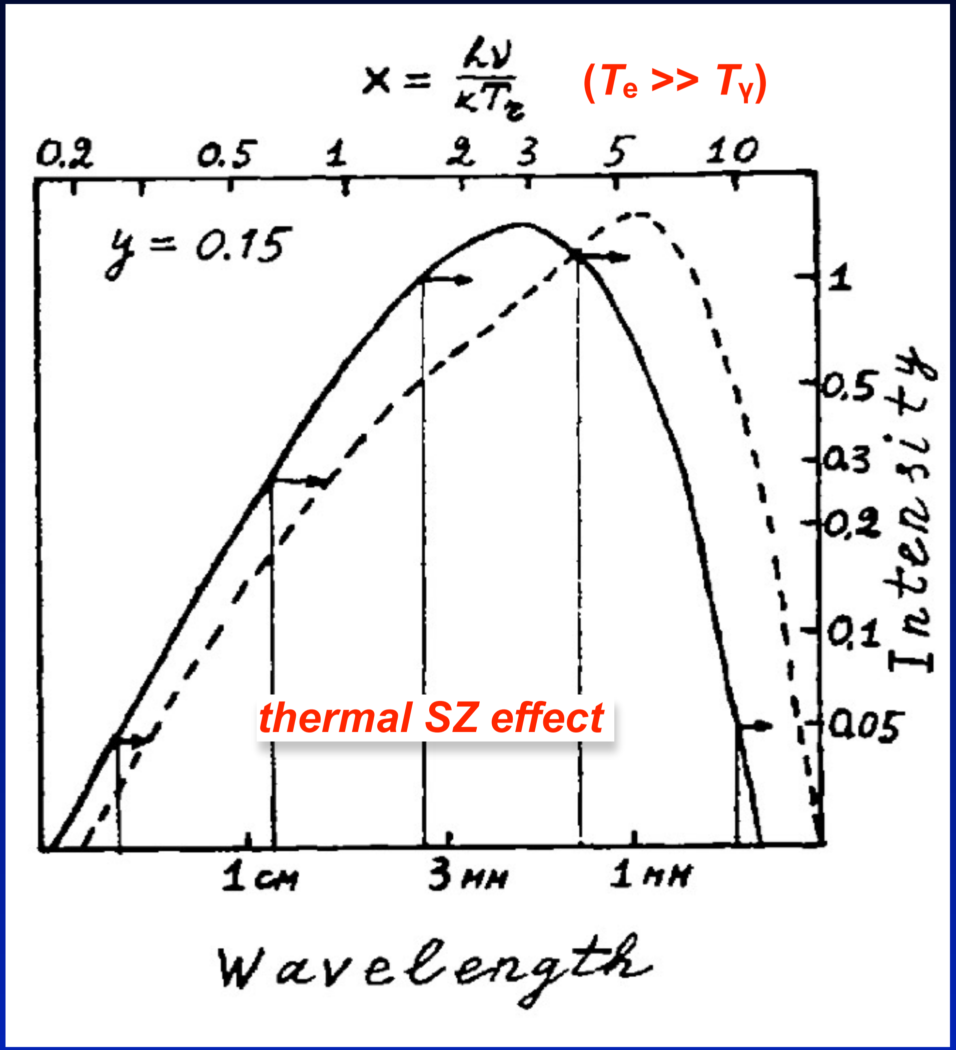
(1 Jy = 10^{-26} J s^{-1} m^{-2} Hz^{-1})

$$x = \frac{h\nu}{kT}$$ (Independent of redshift)

$$\nu_{\max} \approx 58.8\,\mathrm{GHz\,K^{-1}}\,T \approx 160\,\mathrm{GHz}\left[\frac{T}{2.725\,\mathrm{K}}\right] \leftrightarrow x_{\max} \approx 2.821$$

Standard types of primordial CMB distortions

Compton y-distortion



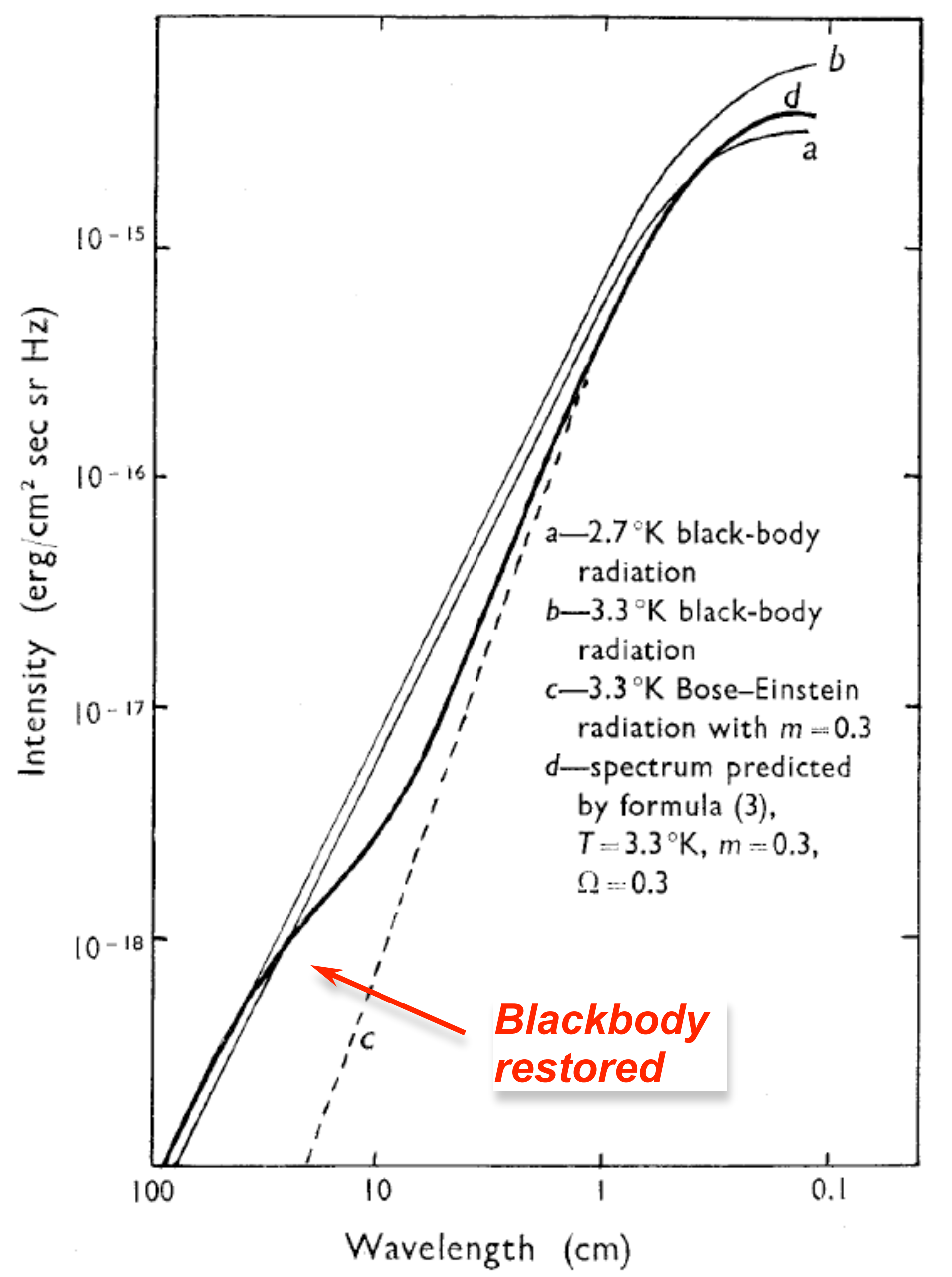
(T_e >> T_γ)

thermal SZ effect

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



Blackbody restored

Sunyaev & Zeldovich, 1970, ApSS, 2, 66

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

Why should one expect some spectral distortion?

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

$N_\gamma \sim 411\ \mathrm{cm}^{-3}\,(1+z)^3 \sim 2\times10^9\,N_b$ (*entropy density dominated by photons*)

$\rho_\gamma \sim 5.1\times10^{-7}\,m_e c^2\ \mathrm{cm}^{-3}\,(1+z)^4 \sim \rho_b \times (1+z)/925 \sim 0.26\ \mathrm{eV\,cm}^{-3}\,(1+z)^4$

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

→ thermalization process (partially) erases distortions

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

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

Some simple statements about distortions

- Start with blackbody: T_γ, $N_\gamma^{\rm bb}(T_\gamma) \propto T_\gamma^3$, and $\rho_\gamma^{\rm bb}(T_\gamma) \propto T_\gamma^4$
- Inject photons (isotropic): ΔN_ν, $\Delta N_\gamma = (4\pi/c)\int \Delta N_\nu \,{\rm d}\nu > 0$

$$\Delta\rho_\gamma = (4\pi/c)\int h\nu\, \Delta N_\nu \,{\rm d}\nu > 0$$

- Effective temperatures: $T_N^* = \left(\frac{h^3 c^3 N_\gamma}{16\pi k^3 \zeta(3)}\right)^{1/3} \approx T_\gamma\left(1+\frac{1}{3}\frac{\Delta N_\gamma}{N_\gamma^{\rm bb}}\right) > T_\gamma$

$$\begin{aligned} N_\gamma &\equiv N_\gamma^{\rm bb}(T_N^*) \\ \rho_\gamma &\equiv \rho_\gamma^{\rm bb}(T_\rho^*) \end{aligned} \quad\Longrightarrow\quad T_\rho^* = \left(\frac{15 h^3 c^3 \rho_\gamma}{8\pi^5 k^4}\right)^{1/4} \approx T_\gamma\left(1+\frac{1}{4}\frac{\Delta\rho_\gamma}{\rho_\gamma^{\rm bb}}\right) > T_\gamma.$$

- For blackbody: $T_N^* = T_\rho^* \quad\Longrightarrow\quad \frac{\Delta\rho_\gamma}{\rho_\gamma^{\rm bb}} \approx \frac{4}{3}\frac{\Delta N_\gamma}{N_\gamma^{\rm bb}}$
- This is a *necessary* condition if you do not want to distort the CMB!
- *Energy release inevitably* creates distortions (need additional photons)

Another simple example: *δ-function photon injection*

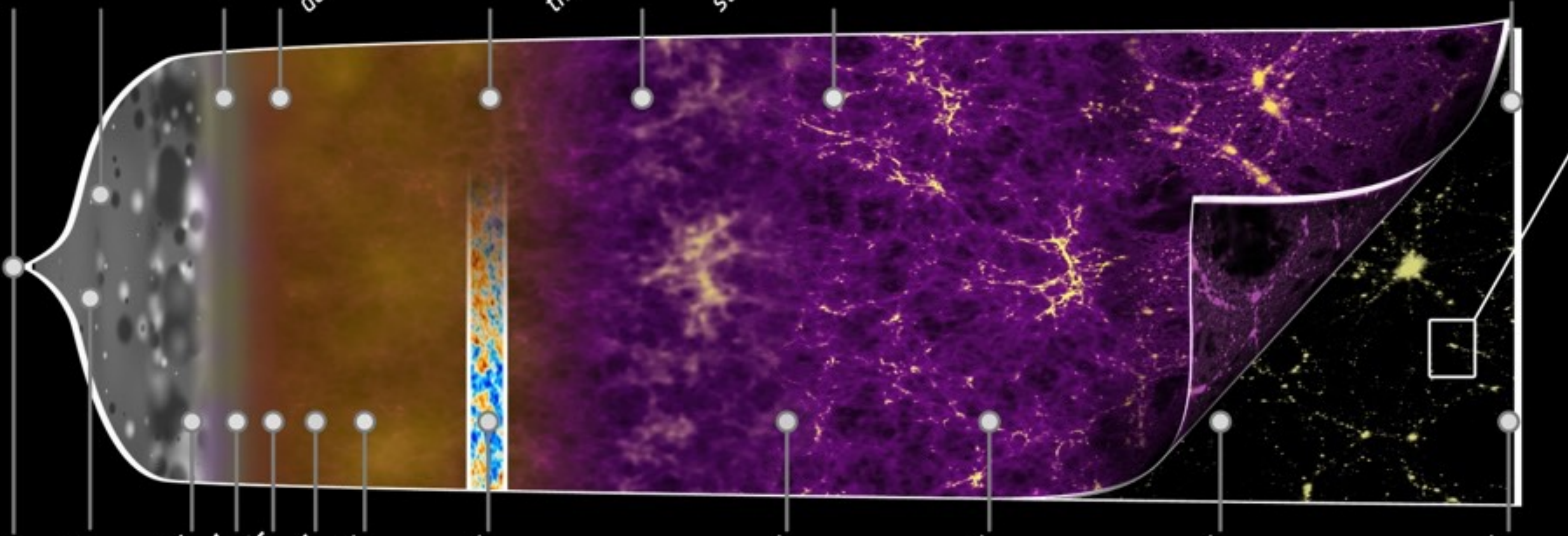
- Assume: $\Delta N_\nu = \frac{c\Delta N_\gamma}{4\pi}\,\delta(\nu-\nu_0) \quad \Longrightarrow \quad \Delta\rho_\gamma = h\nu_0\,\Delta N_\gamma$
- Then $\frac{\Delta\rho_\gamma}{\rho_\gamma^{\rm bb}} = h\nu_0 \frac{\Delta N_\gamma}{\rho_\gamma^{\rm bb}} = \frac{h\nu_0}{2.7kT_\gamma}\,\frac{\Delta N_\gamma}{N_\gamma^{\rm bb}} \equiv \frac{4}{3}\,\frac{\Delta N_\gamma}{N_\gamma^{\rm bb}} \quad \Longrightarrow \quad \frac{h\nu_{\rm c}}{kT_\gamma} \approx 3.6$

$$\nu_{\rm c} \simeq 3.6\,kT_\gamma/h \simeq 204.5\,(1+z)\,{\rm GHz}$$

- Injection at $\nu = \nu_{\rm c}$ $\Longrightarrow$ *only need to redistribute photons over energy*
- Injection at $\nu < \nu_{\rm c}$ $\Longrightarrow$ *need more energy / absorb photons*
- Injection at $\nu > \nu_{\rm c}$ $\Longrightarrow$ *need to add photon / cool photon field*

The thermalization problem really is about redistributing photons over energy and adjusting their number!

Question: Is there enough time to restore full equilibrium?



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

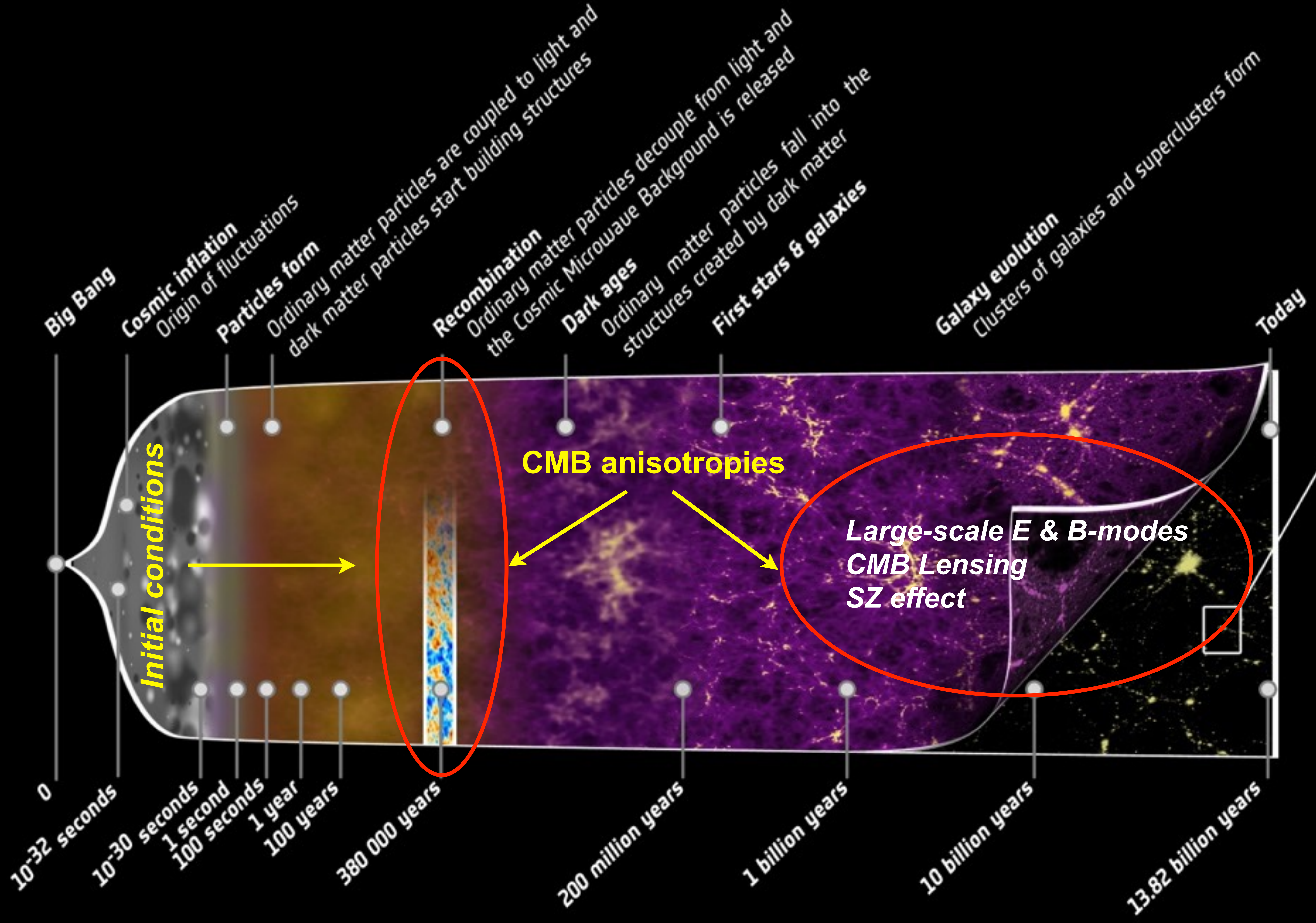
Dark ages
Ordinary matter particles fall into the structures created by dark matter

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

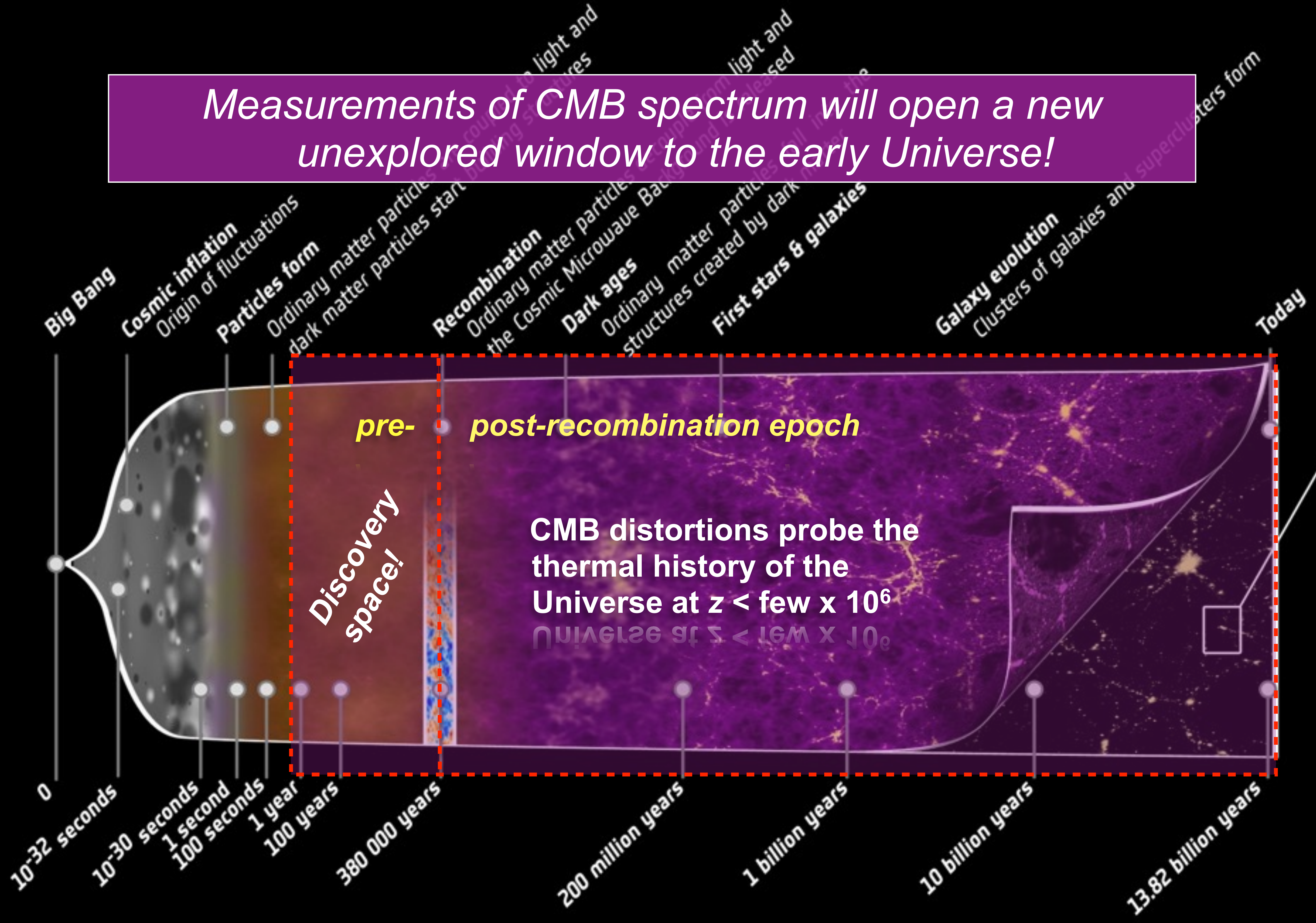


Initial conditions

CMB anisotropies

Large-scale E & B-modes
CMB Lensing
SZ effect

Measurements of CMB spectrum will open a new unexplored window to the early Universe!



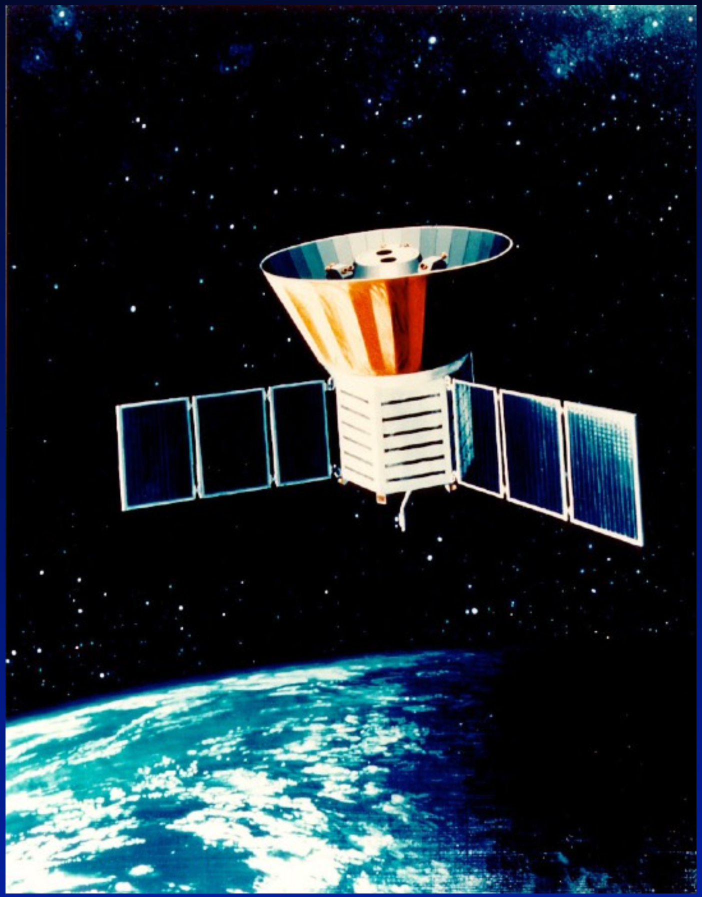
pre-

post-recombination epoch

Discovery space!

CMB distortions probe the thermal history of the Universe at z < few x 10^6

COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)



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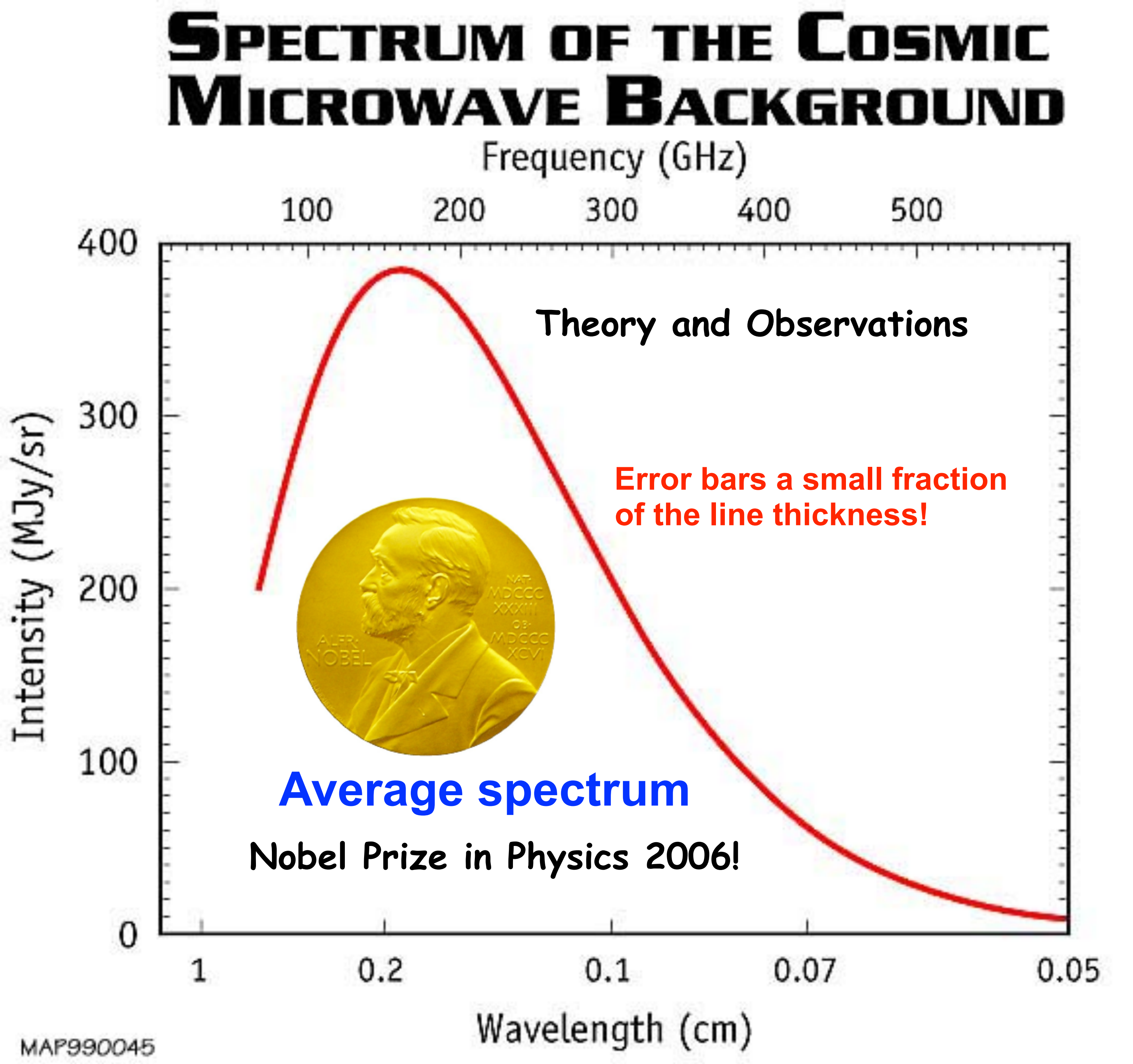

Theory and Observations

Error bars a small fraction of the line thickness!

Average spectrum

Nobel Prize in Physics 2006!

Only very small distortions of CMB spectrum are still allowed!

No primordial distortion found so far!? Why are we at all talking about this then?

Physical mechanisms that lead to spectral distortions

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

pre-recombination epoch

„high“ redshifts

„low“ redshifts

post-recombination

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

Physical mechanisms that lead to spectral distortions

Standard sources of distortions

- *Cooling by adiabatically expanding ordinary matter*
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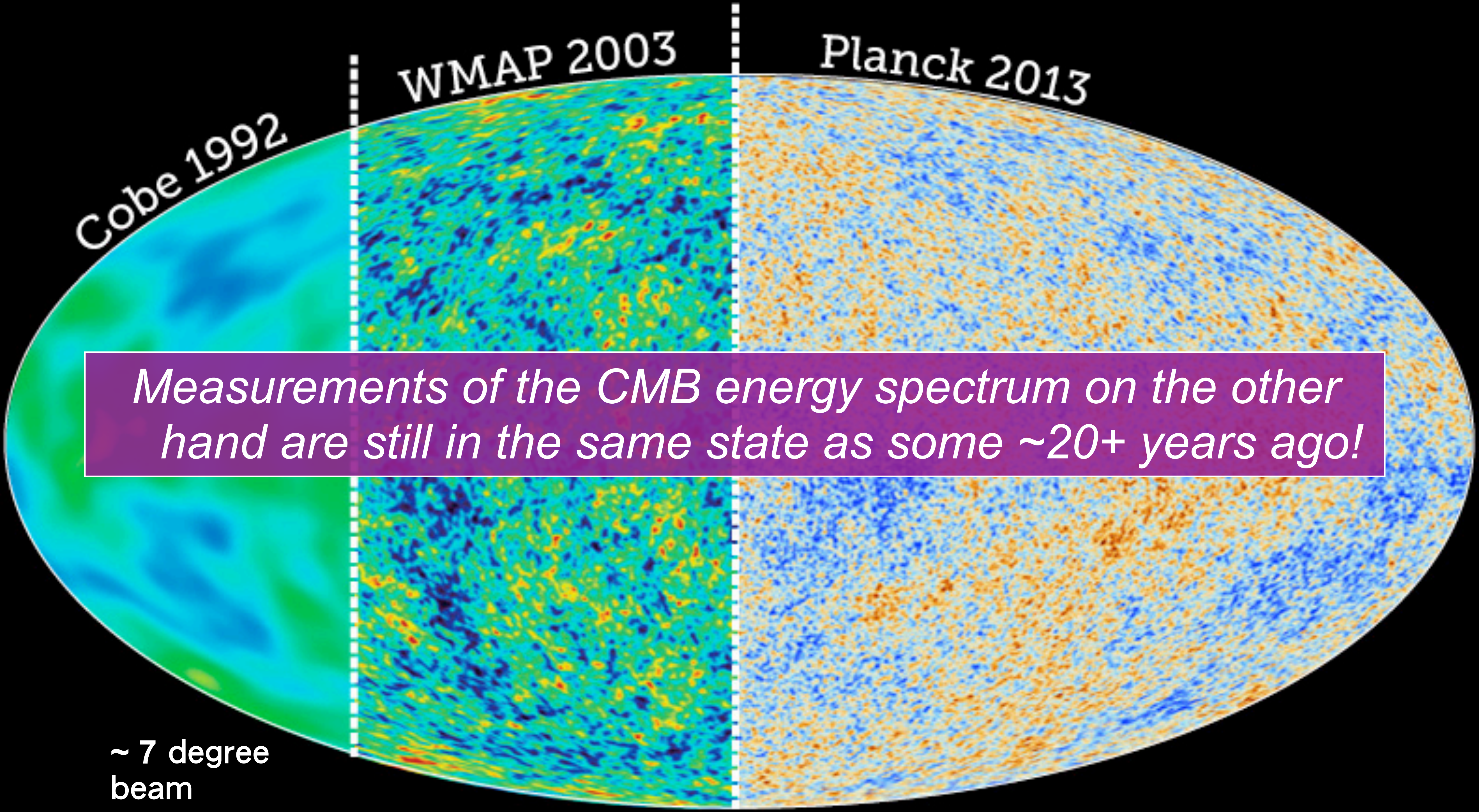
Dramatic improvements in angular resolution and sensitivity over the past decades!



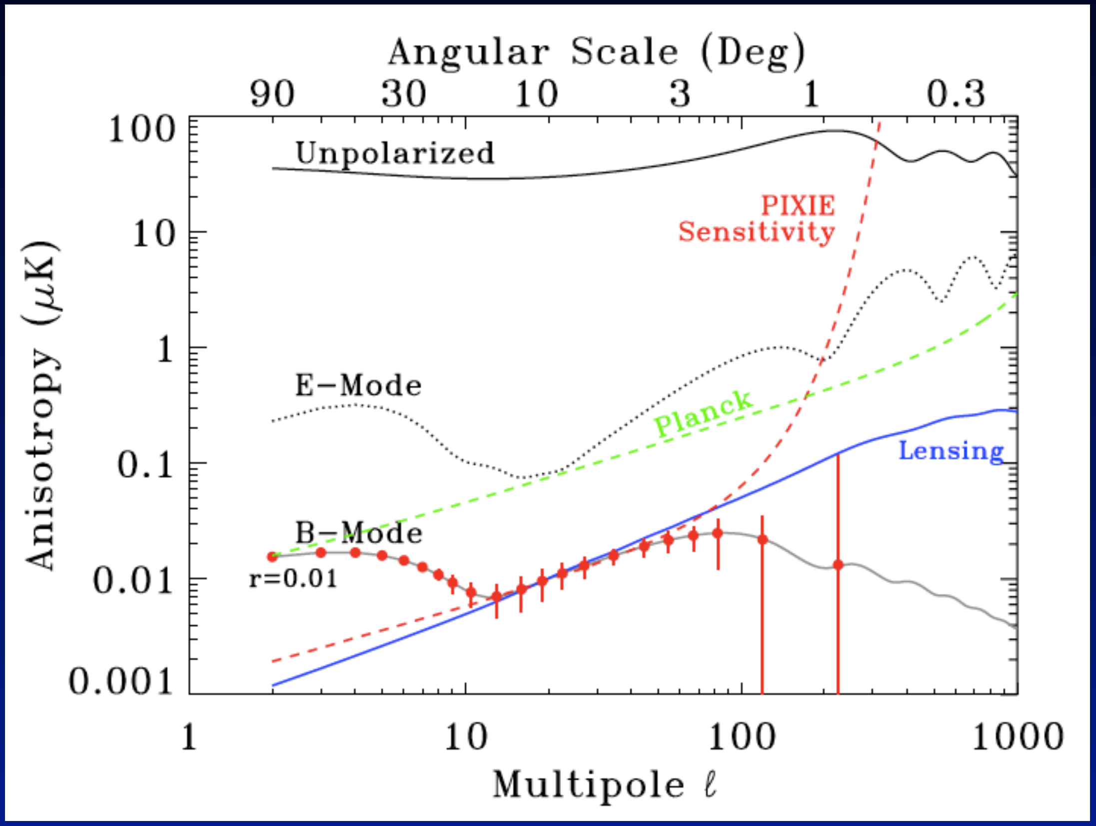
Measurements of the CMB energy spectrum on the other hand are still in the same state as some ~20+ years ago!

~ 7 degree beam

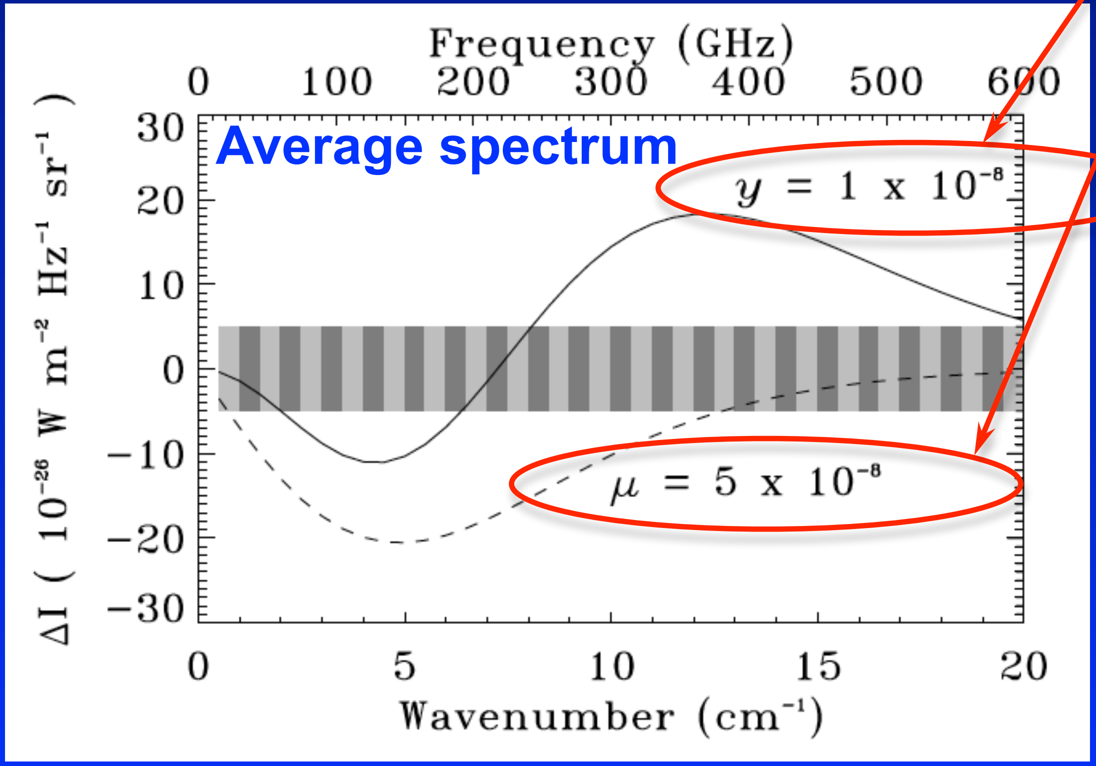
~ 0.3 degree beam

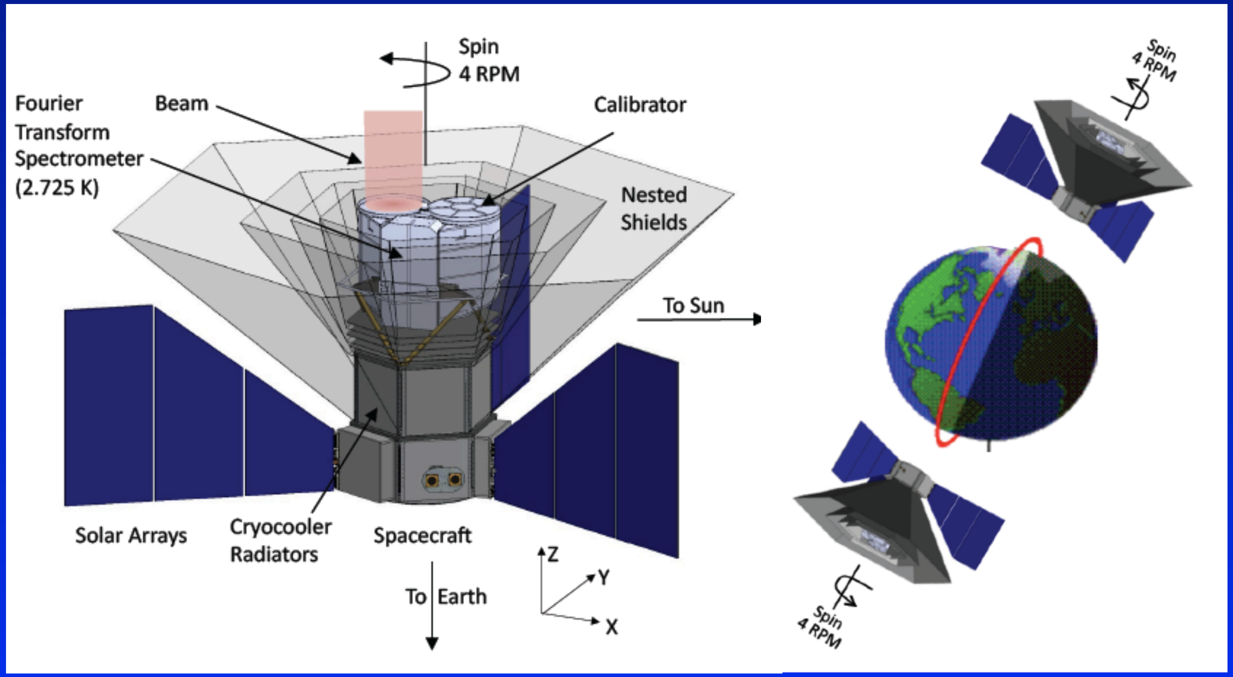
~ 0.08 degree beam

PIXIE: Primordial Inflation Explorer

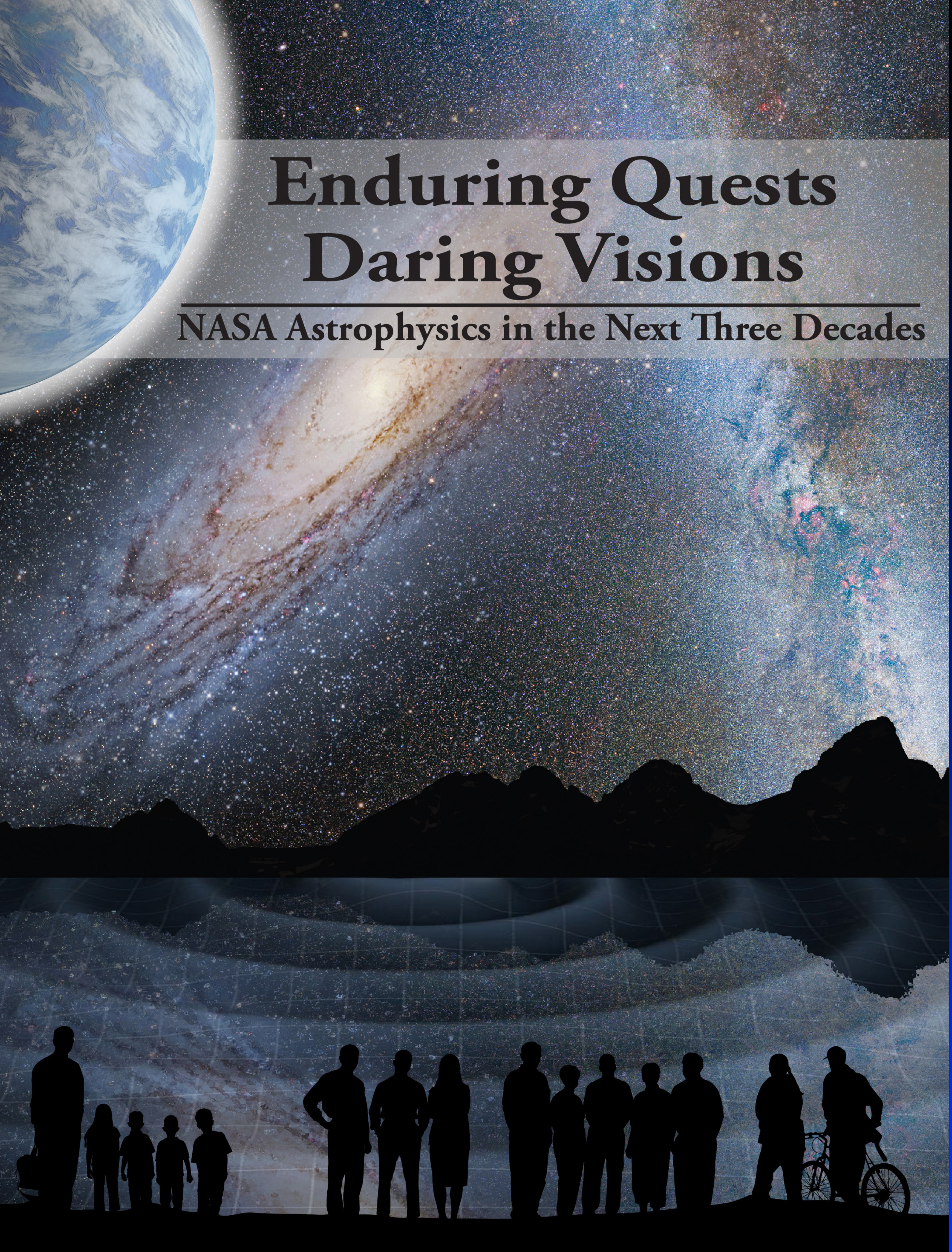


- 400 spectral channel in the frequency range 30 GHz and 6THz (Δν ~ 15GHz)
- about 1000 (!!!) times more sensitive than COBE/FIRAS
- B-mode polarization from inflation ($r \approx 10^{-3}$)
- improved limits on μ and y
- was proposed 2011 as NASA EX mission (i.e. cost ~ 200 M$)





Kogut et al, JCAP, 2011, arXiv:1105.2044



Enduring Quests
Daring Visions
NASA Astrophysics in the Next Three Decades

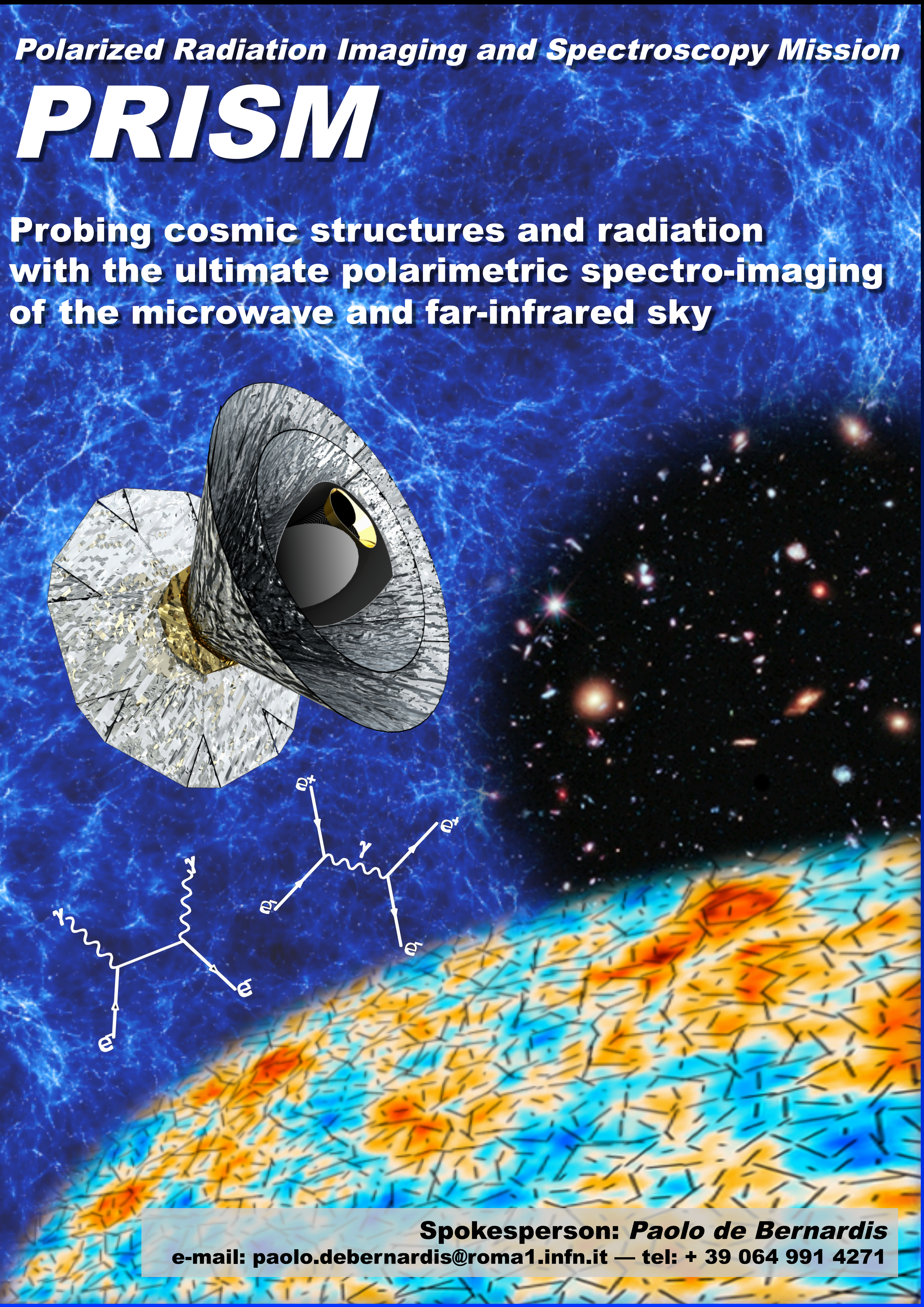
NASA 30-yr Roadmap Study

(published Dec 2013)

How does the Universe work?

"Measure the spectrum of the CMB with precision several orders of magnitude higher than COBE FIRAS, from a moderate-scale mission or an instrument on CMB Polarization Surveyor."

PIXIE was proposed to NASA in Dec 2016. Decision this year!



Polarized Radiation Imaging and Spectroscopy Mission

PRISM

Probing cosmic structures and radiation with the ultimate polarimetric spectro-imaging of the microwave and far-infrared sky

Spokesperson: *Paolo de Bernardis*

e-mail: paolo.debernardis@roma1.infn.it — tel: + 39 064 991 4271

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 ($\Delta\nu/\nu\sim25\%$) and 300 narrow ($\Delta\nu/\nu\sim2.5\%$) bands]
- Spectrometer:
  - FTS similar to PIXIE
  - 30GHz-6THz ($\Delta\nu\sim15$ & 0.5 GHz)

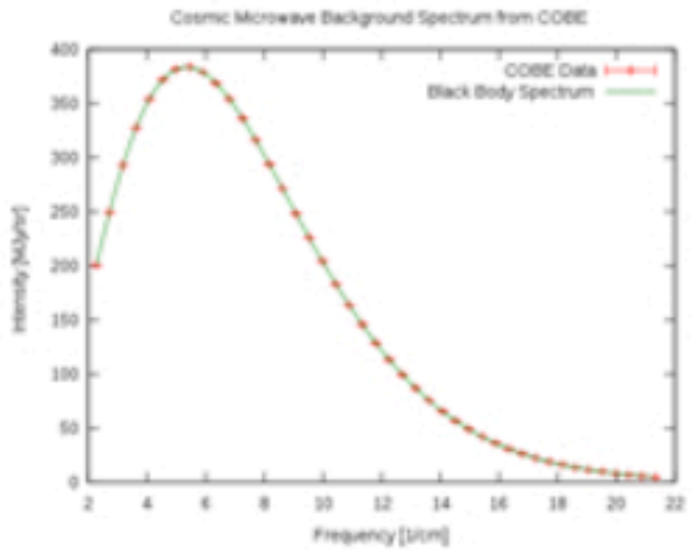
Some of the science goals:

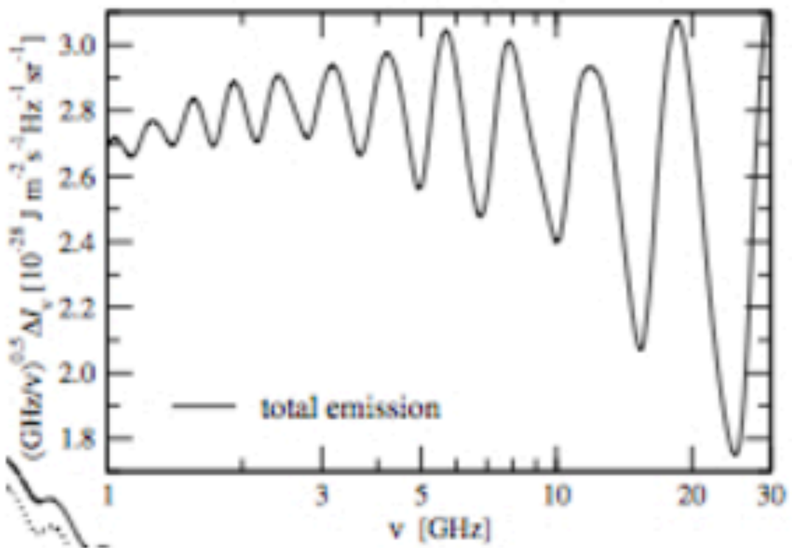
- B-mode polarization from inflation ($r \approx 5\text{x}10^{-4}$)
- count all SZ clusters $>10^{14}$ M_{sun}
- CIB/large scale structure
- Galactic science
- *CMB spectral distortions*

More info at: http://www.prism-mission.org/

Array of Precision Spectrometers for detecting spectral ripples from the Epoch of RecombinAtion

HOME PEOPLE





About APSERa

The Array of Precision Spectrometers for the Epoch of RecombinAtion - APSERa - is a venture to detect recombination lines from the Epoch of Cosmological Recombination. These are predicted to manifest as 'ripples' in wideband spectra of the cosmic radio background (CRB) since recombination of the primeval plasma in the early Universe adds broad spectral lines to the relic Cosmic Radiation. The lines are extremely wide because recombination is stalled and extended over redshift space. The spectral features are expected to be isotropic over the whole sky.

The project will comprise of an array of 128 small telescopes that are purpose built to detect a set of adjacent lines from cosmological recombination in the spectrum of the radio sky in the 2-6 GHz range. The radio receivers are being designed and built at the Raman Research Institute, tested in nearby radio-quiet locations and relocated to a remote site for long duration exposures to detect the subtle features in the cosmic radio background arising from recombination. The observing site would be appropriately chosen to minimize RFI from geostationary satellites and to be able to observe towards sky regions relatively low in foreground brightness.

Part II: Theory of CMB spectral distortions

Some important conditions and assumptions

- Plasma fully ionized before recombination (z~1000)
  - → free electrons, protons and helium nuclei
  - → photon dominated (~2 Billion photons per baryon)
- Coulomb scattering $e + p \leftrightarrow e' + p$
  - → electrons in full thermal equilibrium with baryons
  - → electrons follow thermal Maxwell-Boltzmann distribution
  - → efficient down to very low redshifts (z ~ 10-100)
- Medium homogeneous and isotropic on large scales
  - → thermalization problem rather simple!
  - → in principle *allows very precise computations*
- Hubble expansion
  - → adiabatic cooling of photons [$T_\gamma \sim (1+z)$] and ordinary matter [$T_\mathrm{m} \sim (1+z)^2$]
  - → redshifting of photons (no distortion…)

Photon Boltzmann Equation for Average Spectrum

$$\frac{\mathrm{d}n_\nu}{\mathrm{d}t} = \frac{\partial n_\nu}{\partial t} + \frac{\partial n_\nu}{\partial x_i} \cdot \frac{\mathrm{d}x_i}{\mathrm{d}t} + \frac{\partial n_\nu}{\partial p} \frac{\mathrm{d}p}{\mathrm{d}t} + \frac{\partial n_\nu}{\partial \hat{p}_i} \cdot \frac{\mathrm{d}\hat{p}_i}{\mathrm{d}t} = \mathcal{C}[n]$$

Photon occupation number

Liouville operator

Collision term

- Isotropy & Homogeneity: $\Longrightarrow$ $\frac{\partial n_\nu}{\partial t} - H\nu \frac{\partial n_\nu}{\partial \nu} = \mathcal{C}[n]$
  (⇔ *average* spectrum...)

redshifting term

- Collision term: $\mathcal{C}[n] = \left.\frac{\mathrm{d}n_\nu}{\mathrm{d}t}\right|_{\mathrm{C}} + \left.\frac{\mathrm{d}n_\nu}{\mathrm{d}t}\right|_{\mathrm{BR}} + \left.\frac{\mathrm{d}n_\nu}{\mathrm{d}t}\right|_{\mathrm{DC}}$

Compton Scattering

Bremsstrahlung

Double Compton

redistribution of photon over frequency

adjusting photon number

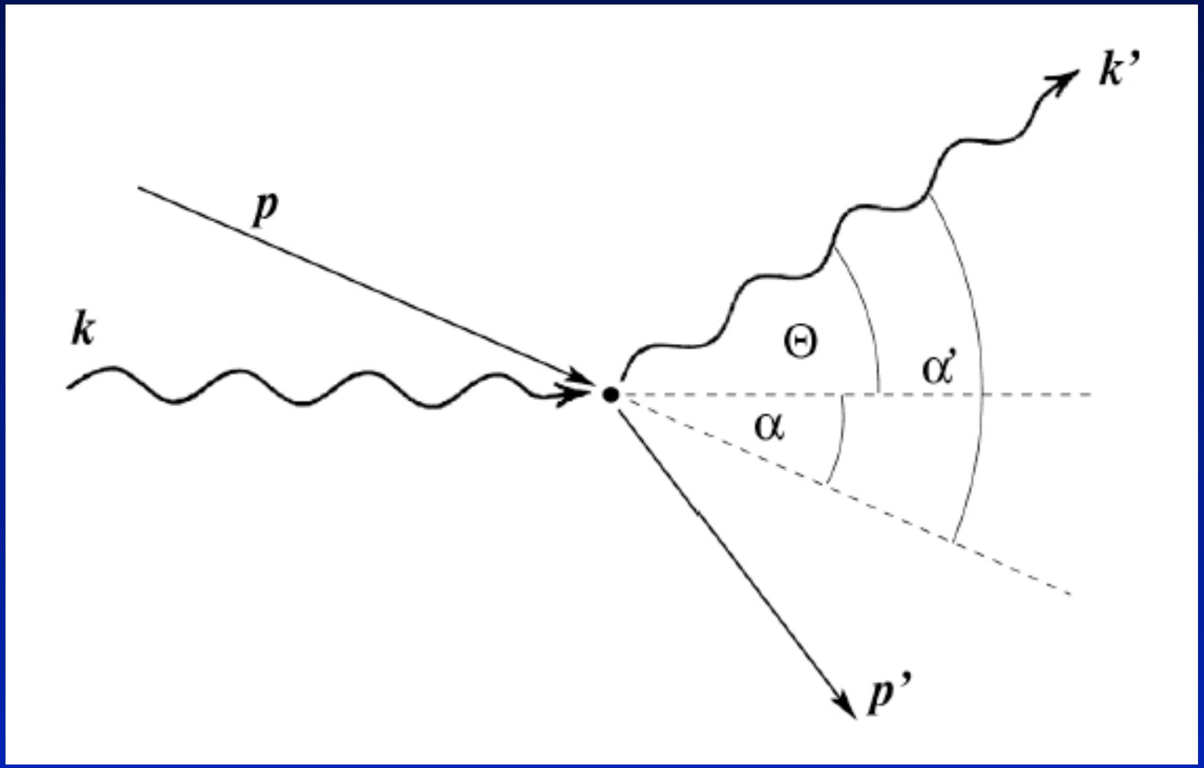
Photon Boltzmann Equation for Average Spectrum

$$\frac{\mathrm{d}n_\nu}{\mathrm{d}t} = \frac{\partial n_\nu}{\partial t} + \frac{\partial n_\nu}{\partial x_i} \cdot \frac{\mathrm{d}x_i}{\mathrm{d}t} + \frac{\partial n_\nu}{\partial p}\frac{\mathrm{d}p}{\mathrm{d}t} + \frac{\partial n_\nu}{\partial \hat{p}_i} \cdot \frac{\mathrm{d}\hat{p}_i}{\mathrm{d}t} = \mathcal{C}[n]$$

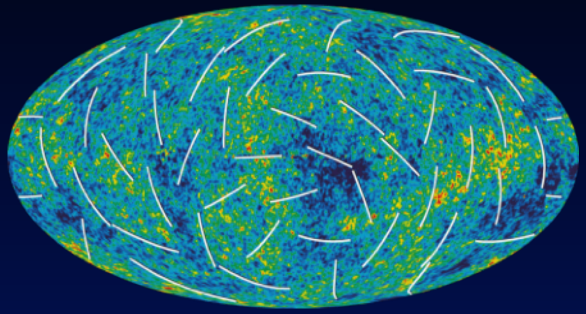
- Isotropy & Homogeneity: $\Longrightarrow \quad \frac{\partial n_\nu}{\partial t} - H\nu \frac{\partial n_\nu}{\partial \nu} = \mathcal{C}[n]$
- Collision term: $\mathcal{C}[n] = \left.\frac{\mathrm{d}n_\nu}{\mathrm{d}t}\right|_{\mathrm{C}} + \left.\frac{\mathrm{d}n_\nu}{\mathrm{d}t}\right|_{\mathrm{BR}} + \left.\frac{\mathrm{d}n_\nu}{\mathrm{d}t}\right|_{\mathrm{DC}}$
- Full equilibrium: $\mathcal{C}[n] \equiv 0$ ⇒ blackbody spectrum conserved
- Energy release: $\mathcal{C}[n] \neq 0$ ⇒ *thermalization process starts*

Redistribution of photons by Compton scattering

- Reaction: $\gamma + e \longleftrightarrow \gamma' + e'$



Redistribution of photons by Compton scattering

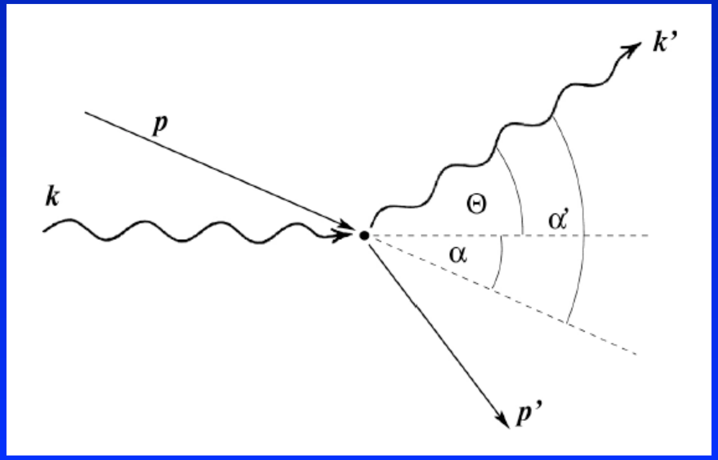


- Reaction: $\gamma + e \longleftrightarrow \gamma' + e'$

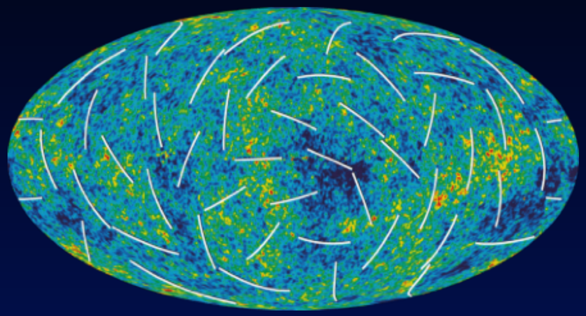
→ *no energy exchange* ⇒ *Thomson limit*

⇒ *important for anisotropies*

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{3\sigma_{\mathrm{T}}}{16\pi}\left[1 + (\hat{\gamma}\cdot\hat{\gamma}')^2\right]$$



Redistribution of photons by Compton scattering



- Reaction: $\gamma + e \longleftrightarrow \gamma' + e'$

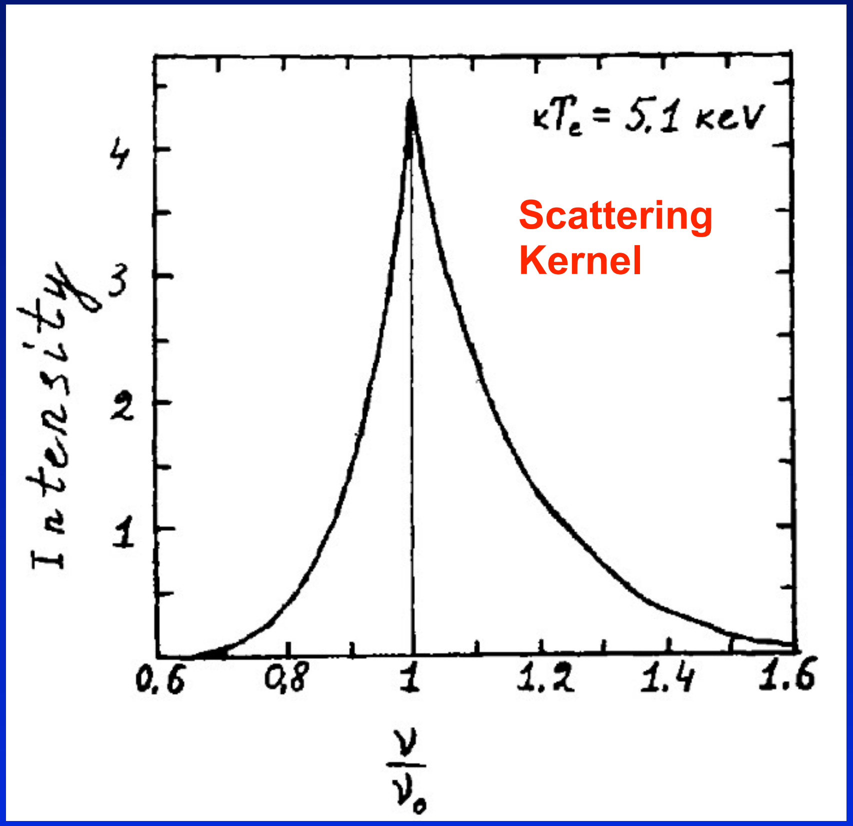
→ *no energy exchange* ⇒ *Thomson limit*

⇒ *important for anisotropies*

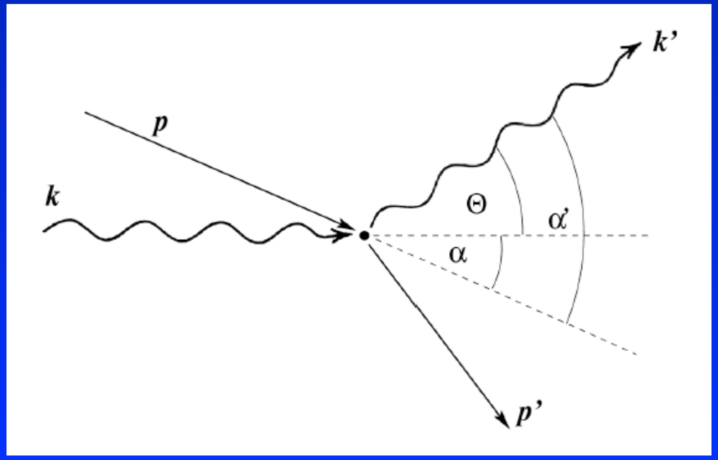
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{3\sigma_\mathrm{T}}{16\pi}\left[1 + (\hat{\gamma}\cdot\hat{\gamma}')^2\right]$$

→ *energy exchange included*

- 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 $\frac{\Delta\nu}{\nu} \simeq \sqrt{\frac{2kT_\mathrm{e}}{m_\mathrm{e}c^2}}$

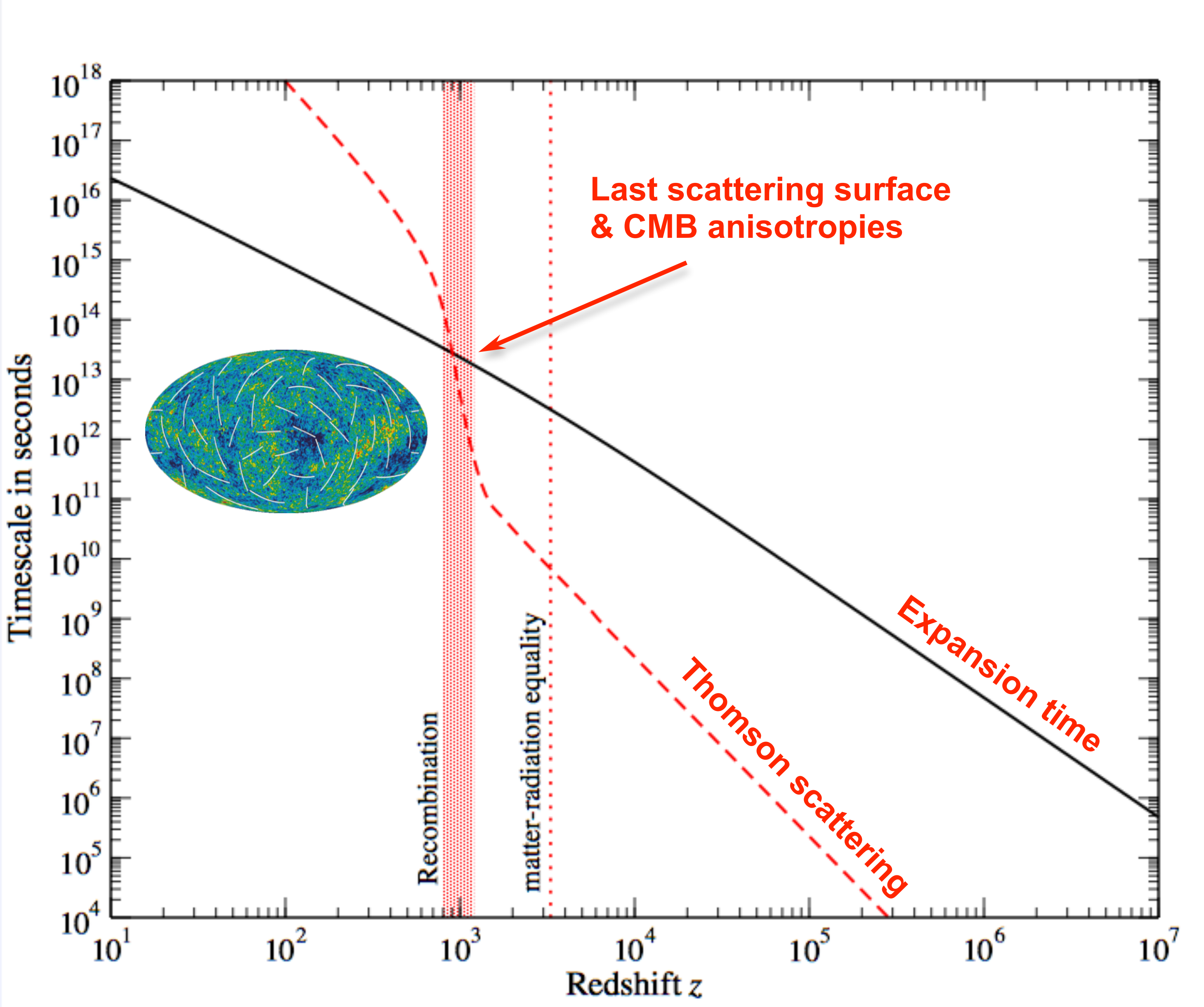


Sunyaev & Zeldovich, 1980, ARAA, 18, 537



Important Timescales for Compton Process

- *Thomson scattering* $t_{\rm C} = (\sigma_{\rm T} N_{\rm e} c)^{-1} \approx 2.3 \times 10^{20} \, \chi_{\rm e}^{-1} (1+z)^{-3} \, {\rm sec}$



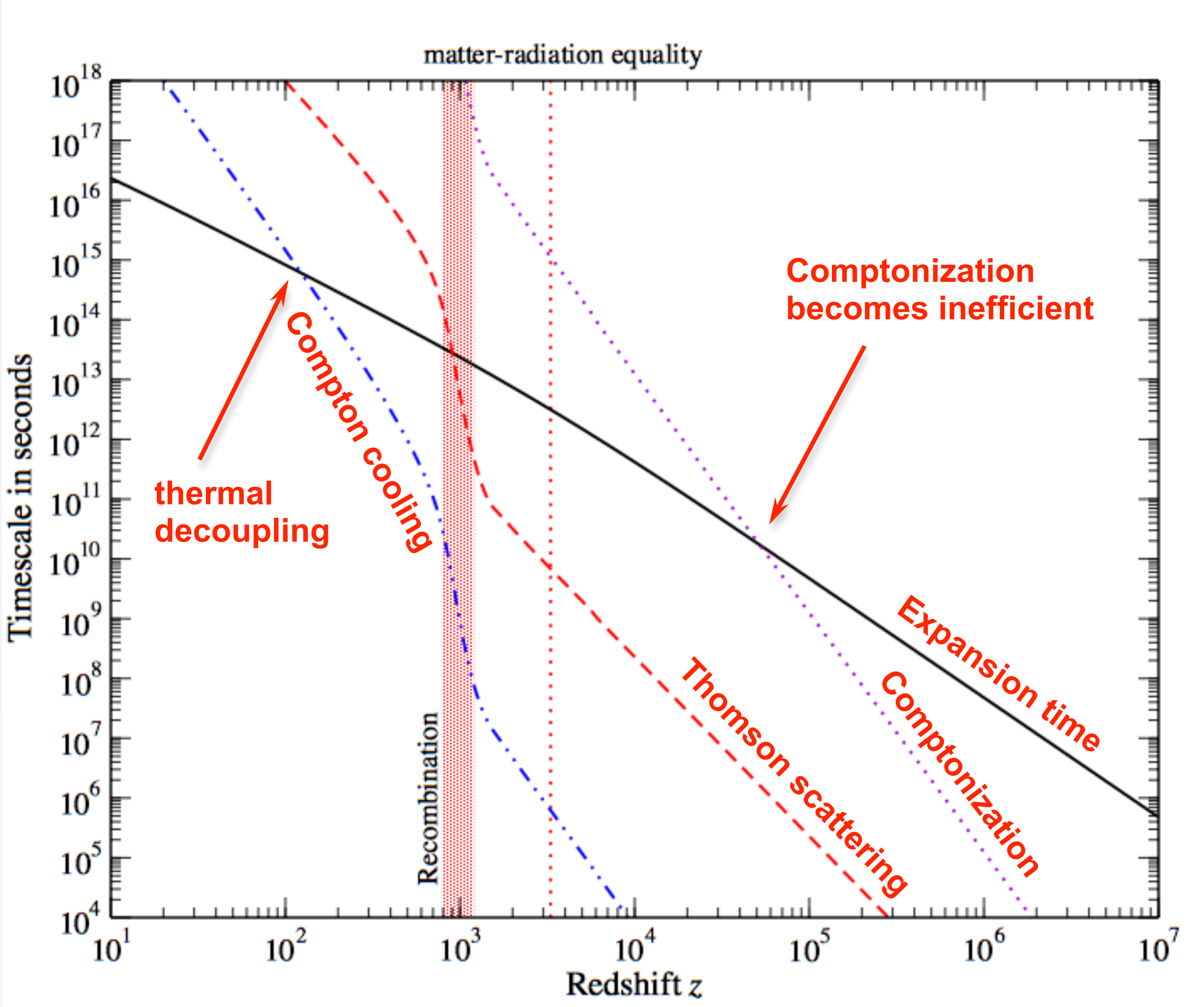
Radiation dominated

$$t_{\rm exp} = H^{-1} \simeq 4.8 \times 10^{19} (1+z)^{-2} \, {\rm sec}$$
$$\simeq 8.4 \times 10^{17} (1+z)^{-3/2} \, {\rm sec}$$

Matter dominated

Important Timescales for Compton Process

- *Thomson scattering* $t_{\rm C} = (\sigma_{\rm T} N_{\rm e} c)^{-1} \approx 2.3 \times 10^{20}\, \chi_{\rm e}^{-1} (1+z)^{-3}\,\rm sec$
- *Comptonization* $t_{\rm K} = \left(4 \frac{kT_{\rm e}}{m_{\rm e} c^2} \sigma_{\rm T} N_{\rm e} c\right)^{-1} \approx 1.2 \times 10^{29}\, \chi_{\rm e}^{-1} (T_{\rm e}/T_\gamma)^{-1} (1+z)^{-4}\,\rm sec$
- *Compton cooling* $t_{\rm cool} = \left(\frac{4\rho_\gamma}{m_{\rm e} c^2} \frac{\sigma_{\rm T} N_{\rm e} c}{(3/2)N}\right)^{-1} \approx 7.1 \times 10^{19}\, \chi_{\rm e}^{-1} (T_{\rm e}/T_\gamma)^{-1} (1+z)^{-4}\,\rm sec$



- *matter temperature starts deviating from Compton equilibrium temperature at z ≲ 100-200*
- *Comptonization becomes inefficient at* $z_{\rm K} \simeq 50000$

⇒ character of distortion changes at $z_{\rm K}$ *!* $\mu \Leftrightarrow y$

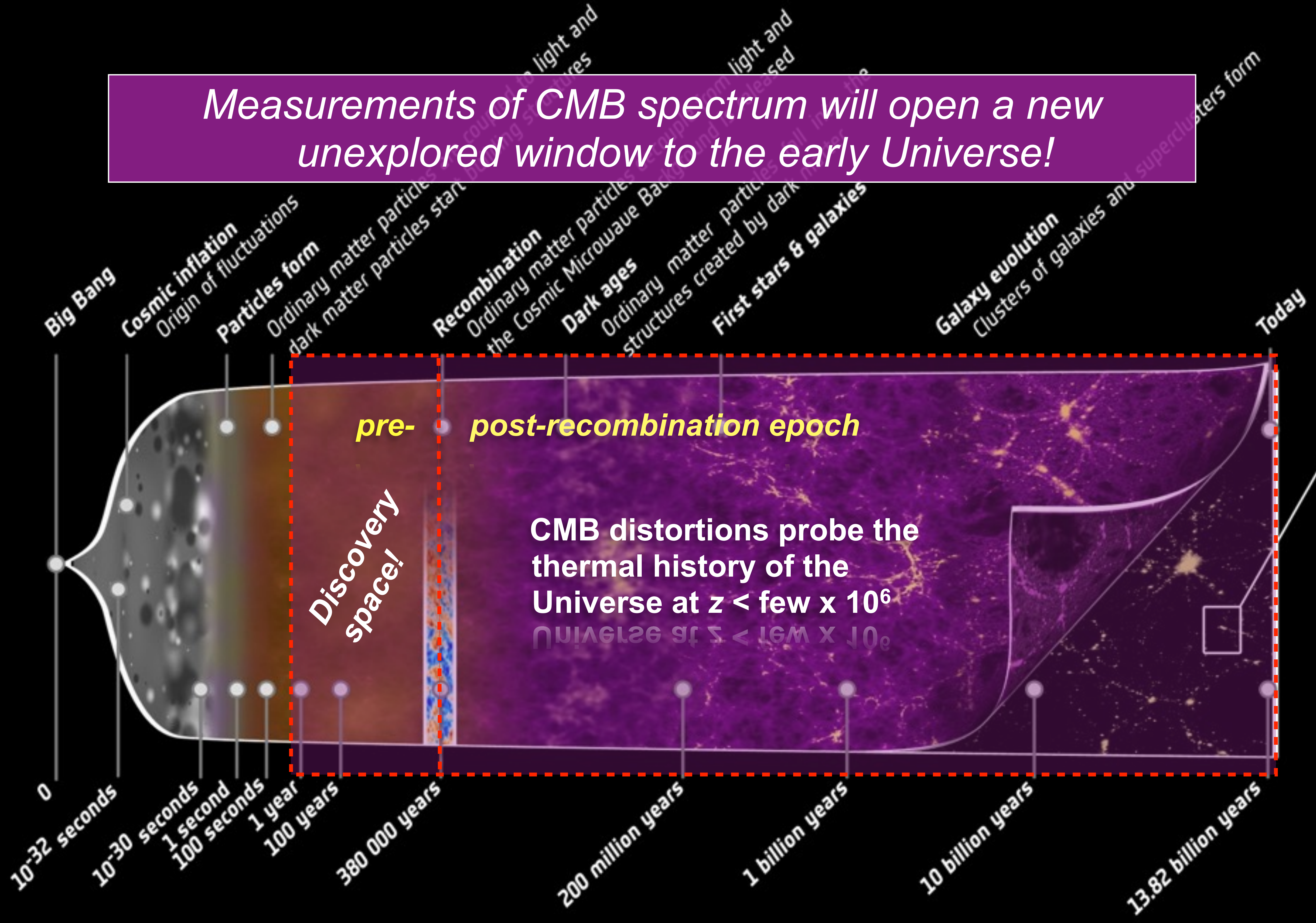
Radiation dominated

$$t_{\rm exp} = H^{-1} \simeq 4.8 \times 10^{19} (1+z)^{-2}\,\rm sec$$

$$\simeq 8.4 \times 10^{17} (1+z)^{-3/2}\,\rm sec$$

Matter dominated

Measurements of CMB spectrum will open a new unexplored window to the early Universe!

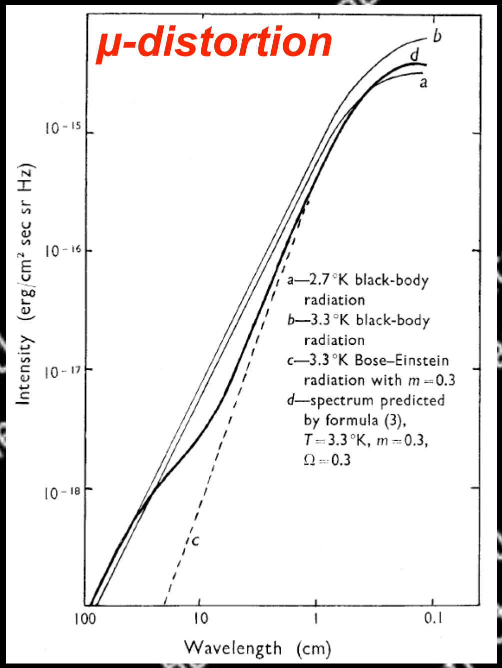


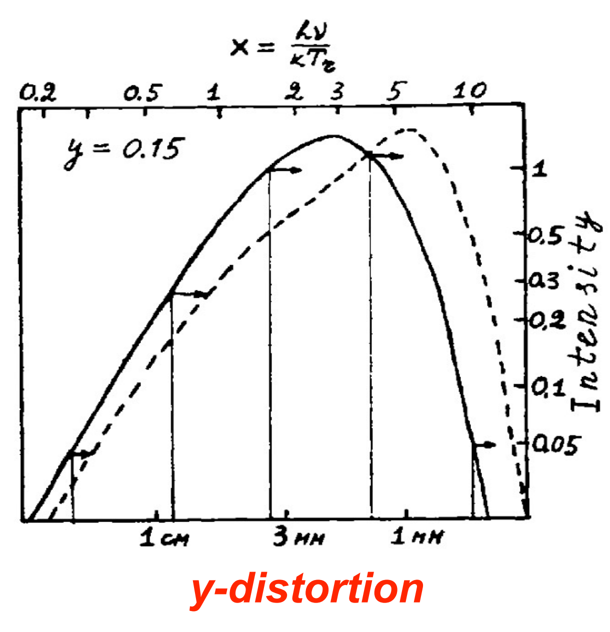
pre-

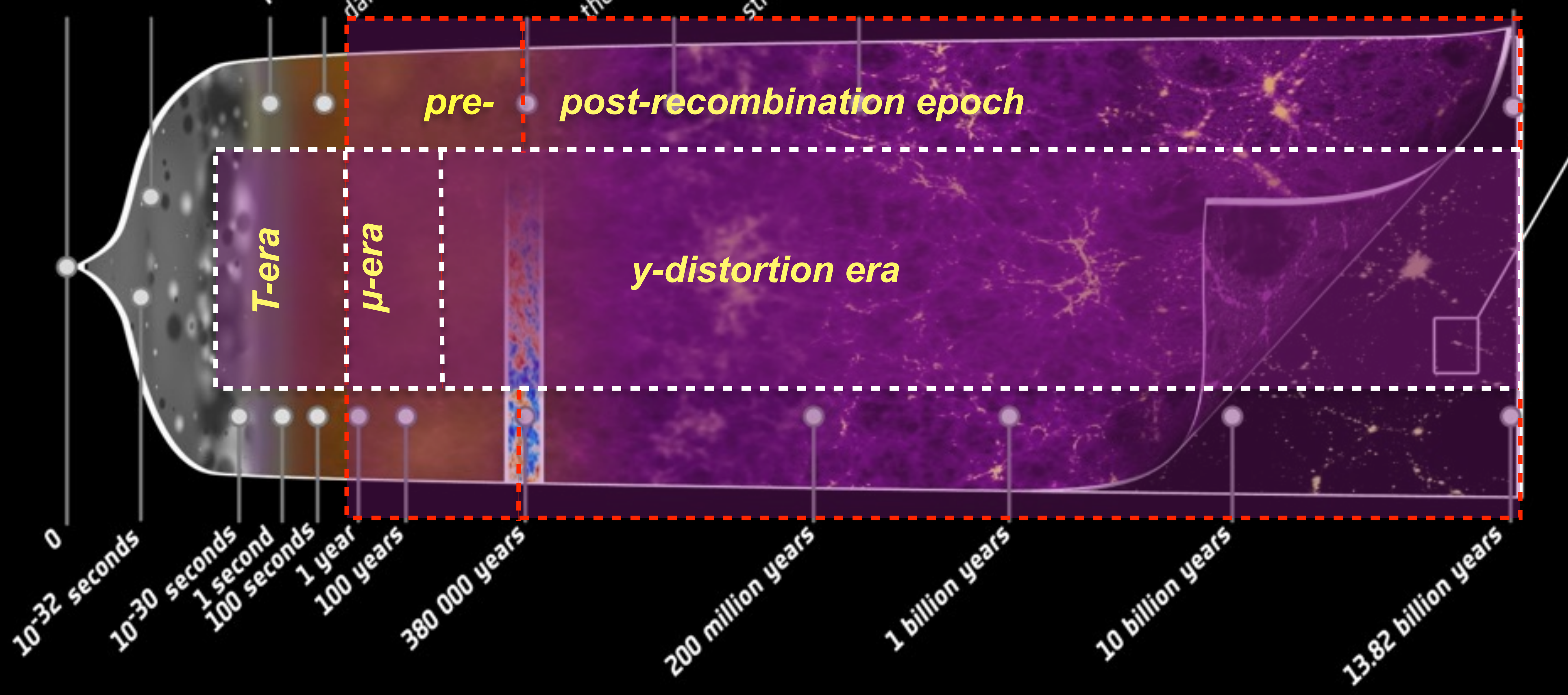
post-recombination epoch

Discovery space!

CMB distortions probe the thermal history of the Universe at $z <$ few x 10^6







pre-

post-recombination epoch

T-era

μ-era

y-distortion era

What are y- and μ-distortions?

Compton y-distortion / thermal SZ effect

- *Kompaneets equation:* $$\left.\frac{\mathrm{d}n}{\mathrm{d}\tau}\right|_{\mathrm{C}} \approx \frac{\theta_{\mathrm{e}}}{x^2}\frac{\partial}{\partial x}x^4\left[\frac{\partial n}{\partial x} + \frac{T_\gamma}{T_{\mathrm{e}}}n(1+n)\right]$$
- *insert:* $n \approx n^{\mathrm{bb}} = 1/(\mathrm{e}^x - 1) \quad \Longrightarrow \quad \Delta n \approx y\,Y(x)$ *with* $y \ll 1$

$$y = \int \frac{k[T_{\mathrm{e}} - T_\gamma]}{m_{\mathrm{e}}c^2}\,\sigma_{\mathrm{T}}N_{\mathrm{e}}c\,\mathrm{d}t$$

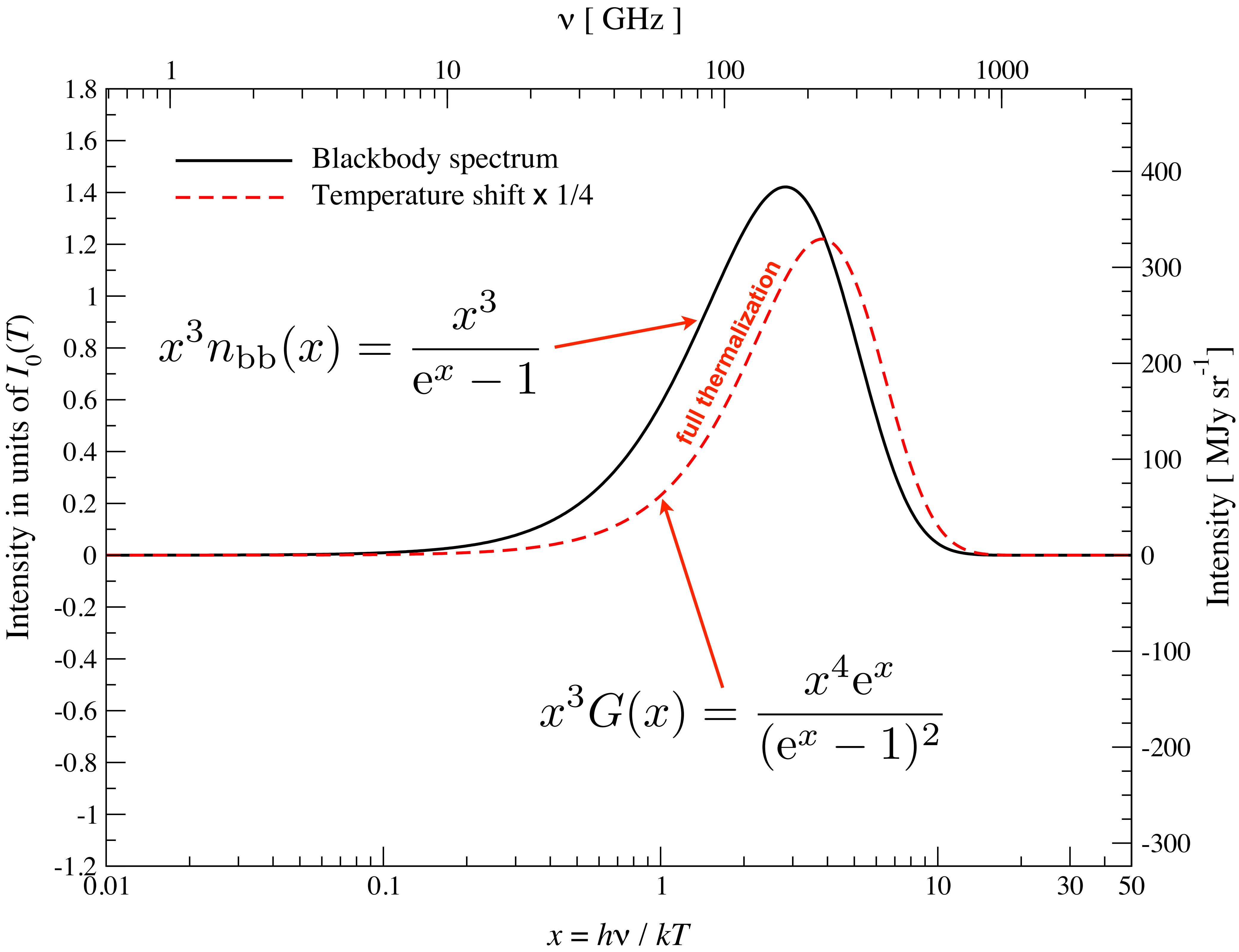
Compton y-parameter

$$\boxed{Y(x) = \frac{x\mathrm{e}^x}{(\mathrm{e}^x-1)^2}\left[x\frac{\mathrm{e}^x+1}{\mathrm{e}^x-1} - 4\right]}$$

spectrum of y-distortion (↔ SZ effect)

- *if* $T_{\mathrm{e}} = T_\gamma \quad \Longrightarrow \quad \left.\frac{\mathrm{d}n}{\mathrm{d}\tau}\right|_{\mathrm{C}} = 0$ *(kinetic equilibrium with electrons)*
- *if* $T_{\mathrm{e}} < T_\gamma \quad \Longrightarrow$ *down-scattering of photons / heating of electrons*
- *if* $T_{\mathrm{e}} > T_\gamma \quad \Longrightarrow$ *up-scattering of photons / cooling of electrons*
- *for* $T_{\mathrm{e}} \gg T_\gamma \quad \Longrightarrow$ *thermal Sunyaev-Zeldovich effect (up-scattering)*

Simplest spectral shapes

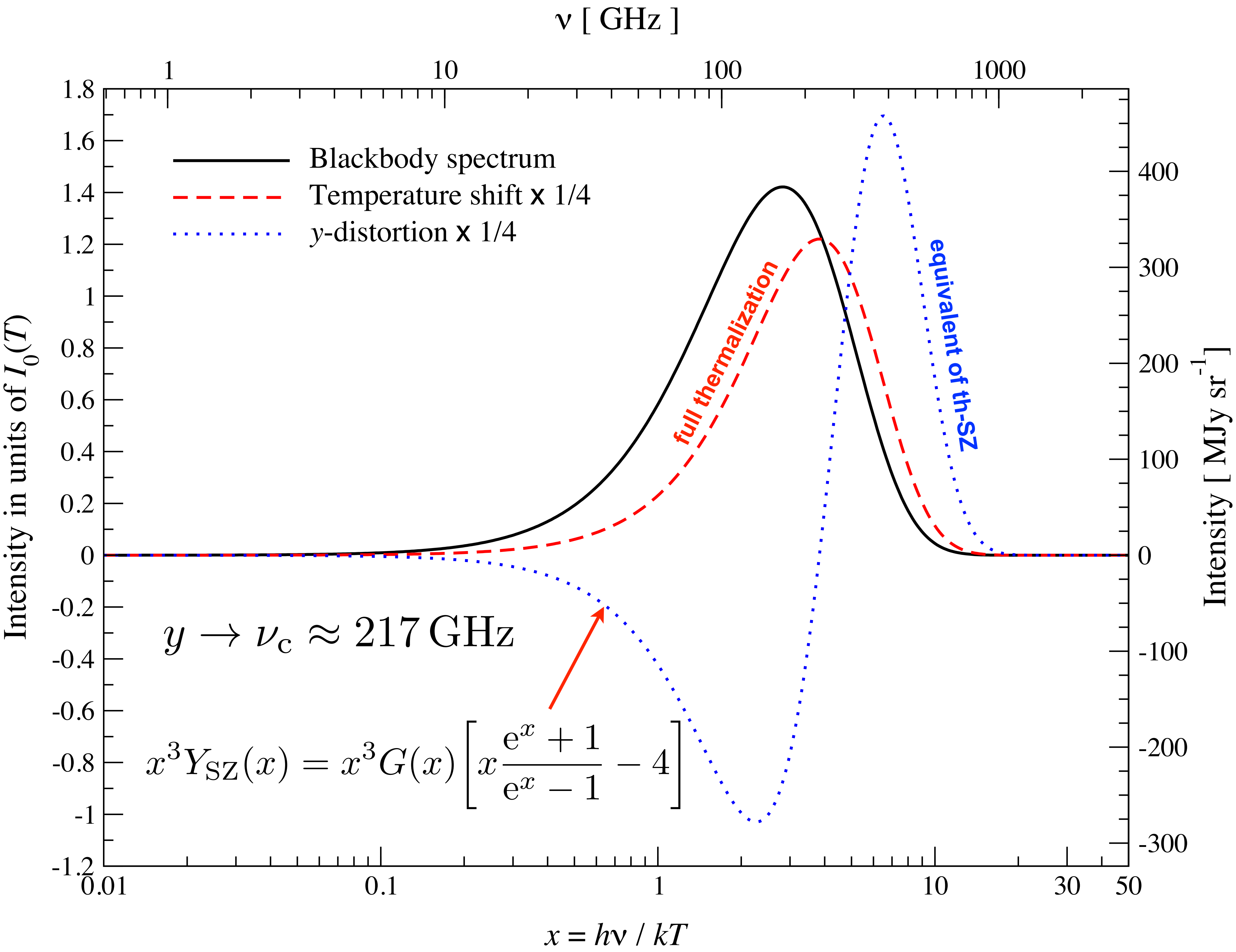


$$x^3 n_{\rm bb}(x) = \frac{x^3}{{\rm e}^x - 1}$$

$$x^3 G(x) = \frac{x^4 {\rm e}^x}{({\rm e}^x - 1)^2}$$

$$I_0 = (2h/c^2)(kT_0/h)^3 \approx 270\,{\rm MJy\,sr}^{-1}$$

Simplest spectral shapes



$$y \rightarrow \nu_{\rm c} \approx 217\,{\rm GHz}$$

$$x^3 Y_{\rm SZ}(x) = x^3 G(x)\left[x\frac{{\rm e}^x+1}{{\rm e}^x-1} - 4\right]$$

$$I_0 = (2h/c^2)(kT_0/h)^3 \approx 270\,{\rm MJy\,sr}^{-1}$$

Chemical Potential / μ-parameter

- *Limit of “many” scatterings* $\Longrightarrow$ $\left.\frac{\mathrm{d}n}{\mathrm{d}\tau}\right|_{\mathrm{C}} \approx 0$

**“Kinetic equilibrium”
to scattering**

- *Kompaneets equation:* $\Longrightarrow$ $\partial_x n \approx -\frac{T_\gamma}{T_{\mathrm{e}}} n(1+n)$

$$\left.\frac{\mathrm{d}n}{\mathrm{d}\tau}\right|_{\mathrm{C}} \approx \frac{\theta_{\mathrm{e}}}{x^2}\frac{\partial}{\partial x}x^4\left[\frac{\partial n}{\partial x} + \frac{T_\gamma}{T_{\mathrm{e}}}n(1+n)\right]$$

Chemical Potential / μ-parameter

- *Limit of "many" scatterings* $\Longrightarrow \quad \left.\frac{\mathrm{d}n}{\mathrm{d}\tau}\right|_{\mathrm{C}} \approx 0$

"Kinetic equilibrium" to scattering

- *Kompaneets equation:* $\Longrightarrow \quad \partial_x n \approx -\frac{T_\gamma}{T_{\mathrm{e}}} n(1+n)$

- *for* $T_\gamma = T_{\mathrm{e}} \quad \Longrightarrow \quad n = n^{\mathrm{bb}}(x) = 1/(\mathrm{e}^x - 1)$

chemical potential parameter (*"wrong" sign*)

- *any spectrum can be written as:* $n(x) = 1/(\mathrm{e}^{x+\mu(x)} - 1)$

$$\Longrightarrow \quad (1 + \partial_x \mu) = -\frac{T_\gamma}{T_{\mathrm{e}}} \quad \Longrightarrow \quad x + \mu = x\frac{T_\gamma}{T_{\mathrm{e}}} + \mu_0$$

constant

- *General equilibrium solution: Bose-Einstein spectrum with*

$T_\gamma = T_{\mathrm{e}} \equiv T_{\mathrm{eq}} \quad \text{and} \quad \mu_0 = \text{const}$ ($\equiv 0$ for blackbody)

Something is missing? How do you fix T_{e} and μ_0?

Final definition of μ-type distortion

- *initial condition:* $N_\gamma = N^{\rm bb}_\gamma(T_\gamma)$ and $\rho_\gamma = \rho^{\rm bb}_\gamma(T_\gamma)$
- *after energy release* ⇒

$$N^{\rm bb}_\gamma(T_\gamma) = N^{\rm BE}_\gamma(T_{\rm e}, \mu_0) \approx N^{\rm bb}_\gamma(T_\gamma)\left(1 + 3\frac{\Delta T}{T_\gamma} - \overset{\approx 1.368}{\frac{\pi^2}{6\zeta(3)}}\mu_0\right)$$

$$\rho^{\rm bb}_\gamma(T_\gamma) + \Delta\rho_\gamma = \rho^{\rm BE}_\gamma(T_{\rm e}, \mu_0) \approx \rho^{\rm bb}_\gamma(T_\gamma)\left(1 + 4\frac{\Delta T}{T_\gamma} - \overset{\approx 1.111}{\frac{90\zeta(3)}{\pi^4}}\mu_0\right)$$

- *Solution:* $\frac{\Delta T}{T_\gamma} \approx \frac{\pi^2}{18\zeta(3)}\mu_0 \approx 0.456\,\mu_0$ *and* $\boxed{\mu_0 \approx 1.401\,\frac{\Delta\rho_\gamma}{\rho_\gamma}}$

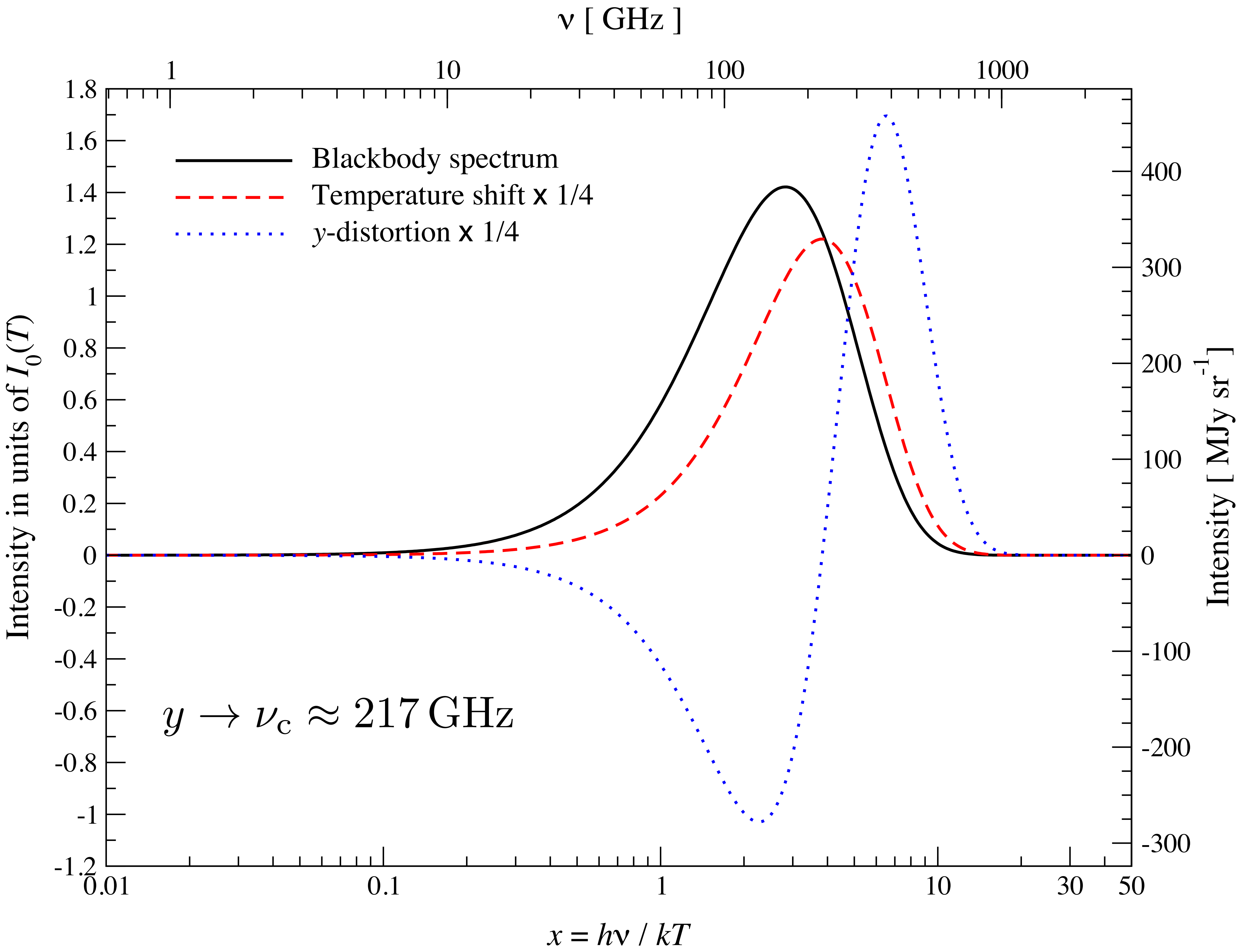
$$\Longrightarrow \quad \boxed{M(x) = G(x)\left[\frac{\pi^2}{18\zeta(3)} - \frac{1}{x}\right]}$$

μ-distortion spectrum
(photon number conserved)

- $\mu_0 > 0$ ⇒ *too few photons / too much energy*
- $\mu_0 < 0$ ⇒ *too many photons / too little energy*

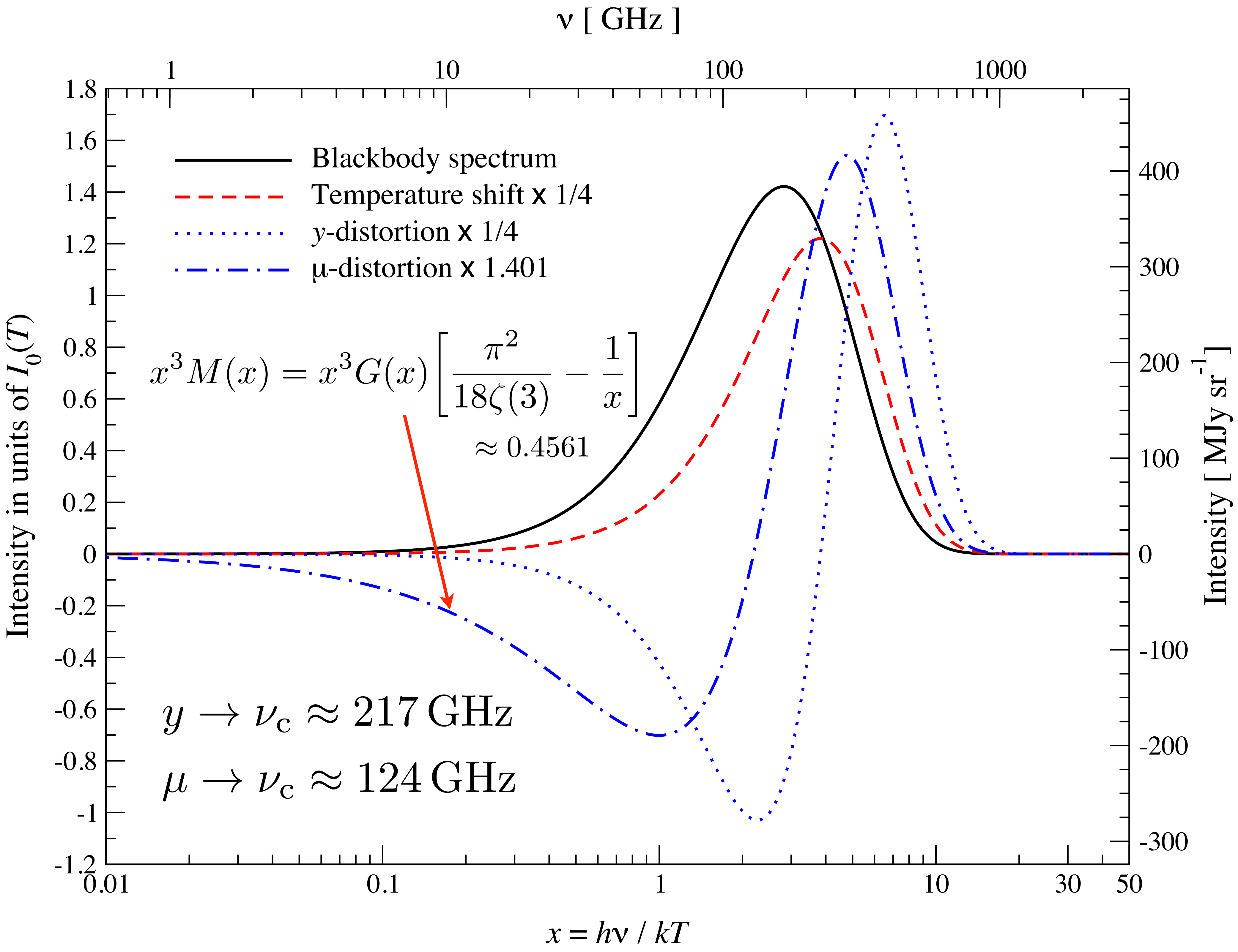
$$\frac{\Delta\rho_\gamma}{\rho^{\rm bb}_\gamma} \approx \frac{4}{3}\,\frac{\Delta N_\gamma}{N^{\rm bb}_\gamma}$$

Simplest spectral shapes



$$I_0 = (2h/c^2)(kT_0/h)^3 \approx 270\,\mathrm{MJy\,sr}^{-1}$$

Simplest spectral shapes



$$x^3 M(x) = x^3 G(x) \left[\frac{\pi^2}{18\zeta(3)} - \frac{1}{x} \right]$$

$$\approx 0.4561$$

$$y \rightarrow \nu_{\rm c} \approx 217\,{\rm GHz}$$

$$\mu \rightarrow \nu_{\rm c} \approx 124\,{\rm GHz}$$

$$I_0 = (2h/c^2)(kT_0/h)^3 \approx 270\,{\rm MJy\,sr^{-1}}$$

What about photon production processes?

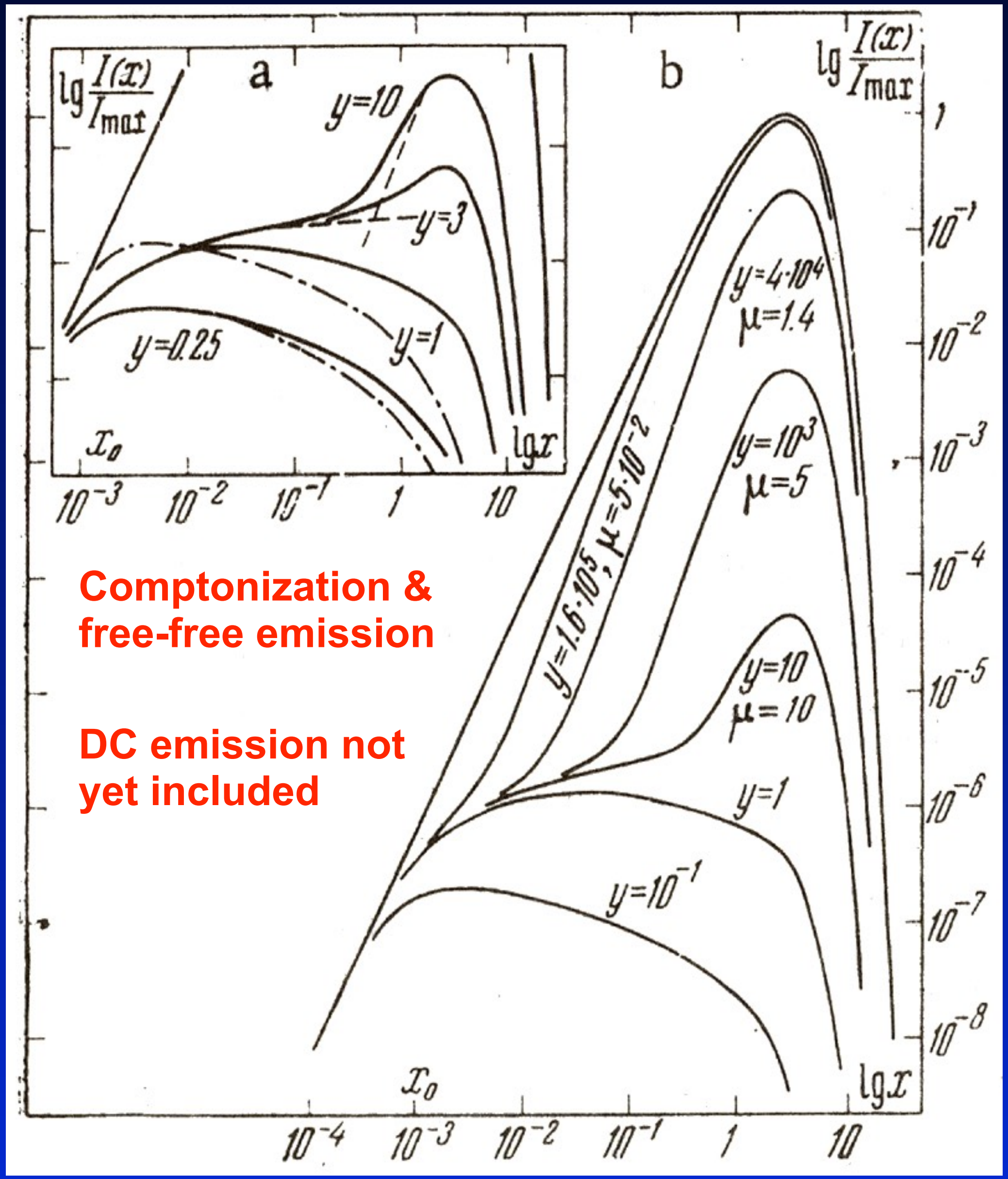
Adjusting the photon number

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

  → 1. order α correction to *Coulomb* scattering

  → production of low frequency photons

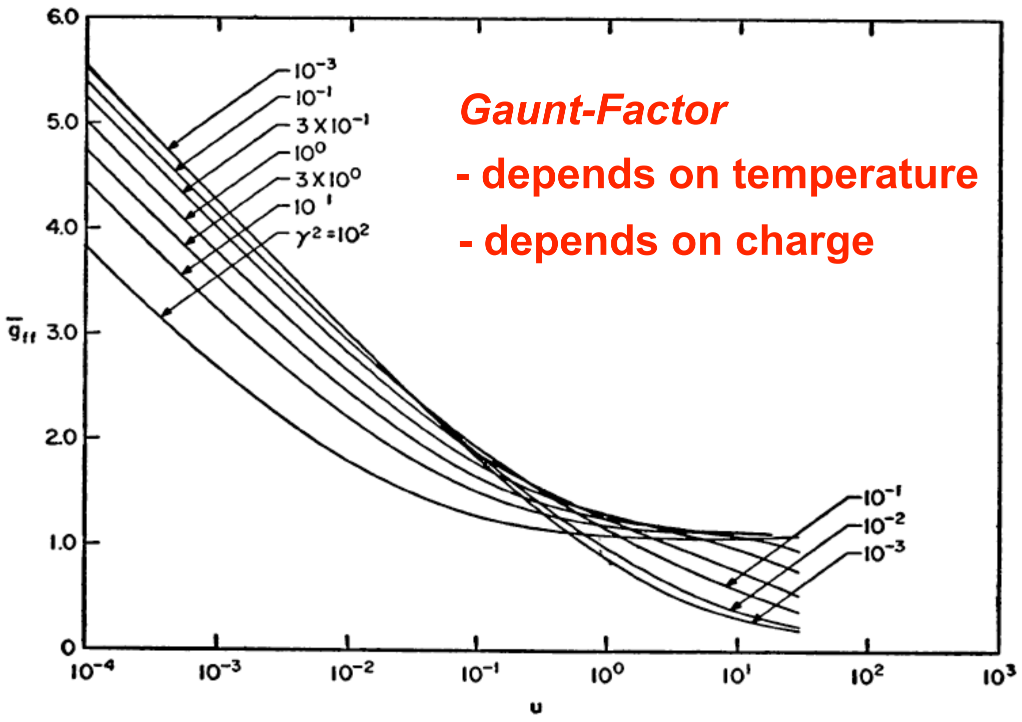
  → important for the evolution of the distortion at low frequencies and late times (z< 2 x 10^5)



Comptonization & free-free emission

DC emission not yet included

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



Gaunt-Factor

- depends on temperature

- depends on charge

FIG. 5.—Temperature-averaged free-free Gaunt factor versus $u = h\nu/kT$ for various values of $\gamma^2 = Z^2Ry/kT$.

Karzas & Latter, 1961, ApJS, 6, 167

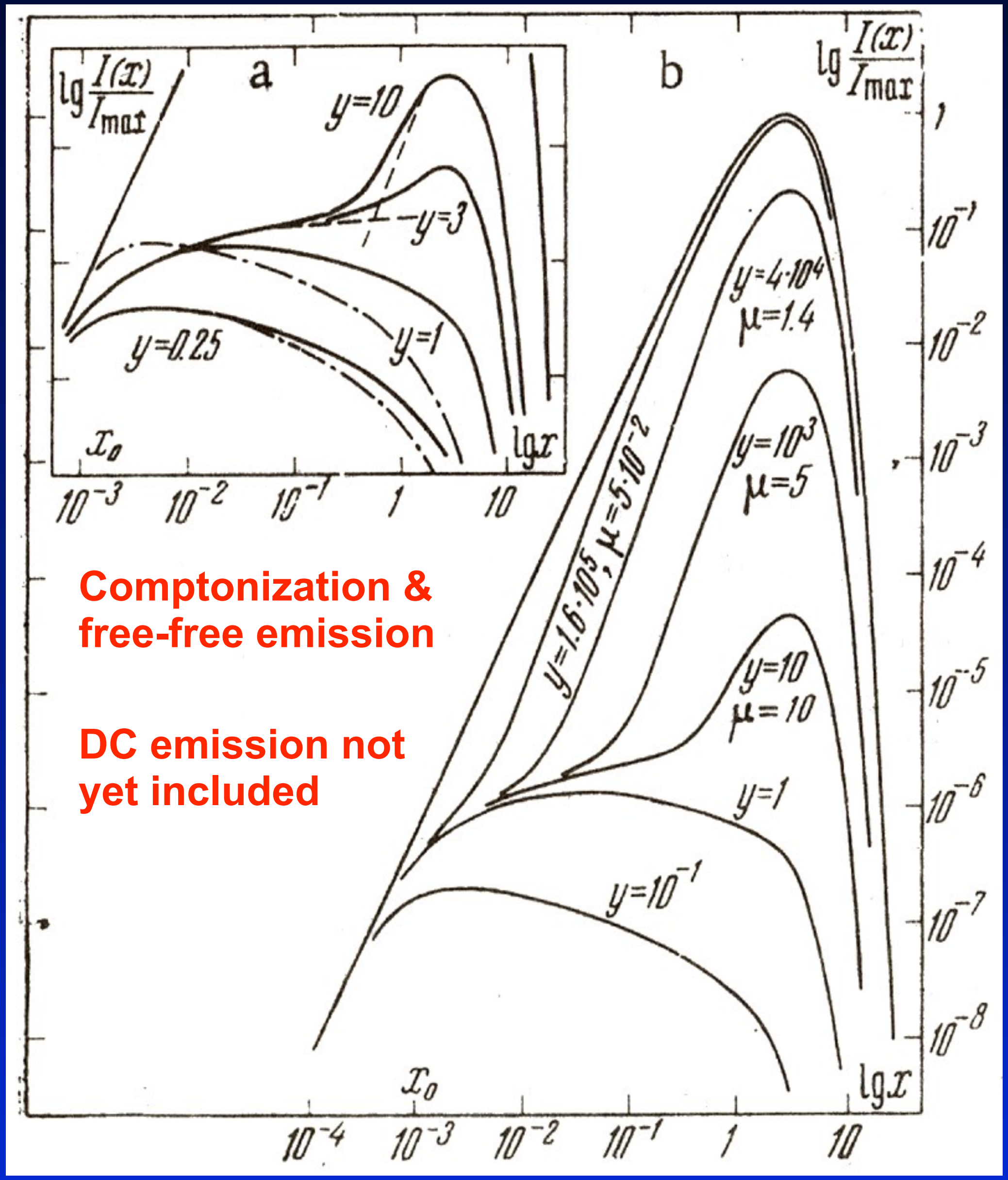
Adjusting the photon number

- 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 ($z < 2 \times 10^5$)

- 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 ($z > 2 \times 10^5$)



Comptonization & free-free emission

DC emission not yet included

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

Final Set of evolution equations

Photon field

$$\frac{\partial f}{\partial \tau} \approx \frac{\theta_{\rm e}}{x^2}\frac{\partial}{\partial x}x^4\left[\frac{\partial}{\partial x}f + \frac{T_\gamma}{T_{\rm e}}\,f(1+f)\right] + \frac{K_{\rm BR}\,{\rm e}^{-x_{\rm e}}}{x_{\rm e}^3}[1-f\,({\rm e}^{x_{\rm e}}-1)] + \frac{K_{\rm DC}\,{\rm e}^{-2x}}{x^3}[1-f\,({\rm e}^{x}\;\;-1)]+S(\tau,x)$$

$$K_{\rm BR} = \frac{\alpha}{2\pi}\frac{\lambda_{\rm e}^3}{\sqrt{6\pi}\,\theta_{\rm e}^{7/2}}\sum_i Z_i^2 N_i\,\bar{g}_{\rm ff}(Z_i, T_{\rm e}, T_\gamma, x_{\rm e}), \qquad K_{\rm DC} = \frac{4\alpha}{3\pi}\,\theta_\gamma^2\,I_{\rm dc}\,g_{\rm dc}(T_{\rm e}, T_\gamma, x)$$

$$\bar{g}_{\rm ff}(x_{\rm e}) \approx \begin{cases} \frac{\sqrt{3}}{\pi}\ln\left(\frac{2.25}{x_{\rm e}}\right) & \text{for} \quad x_{\rm e} \le 0.37 \\ 1 & \text{otherwise} \end{cases}, \qquad g_{\rm dc} \approx \frac{1+\frac{3}{2}x+\frac{29}{24}x^2+\frac{11}{16}x^3+\frac{5}{12}x^4}{1+19.739\theta_\gamma-5.5797\theta_{\rm e}}.$$

$$I_{\rm dc} = \int x^4 f(1+f)\,{\rm d}x \approx 4\pi^4/15$$

Ordinary matter temperature

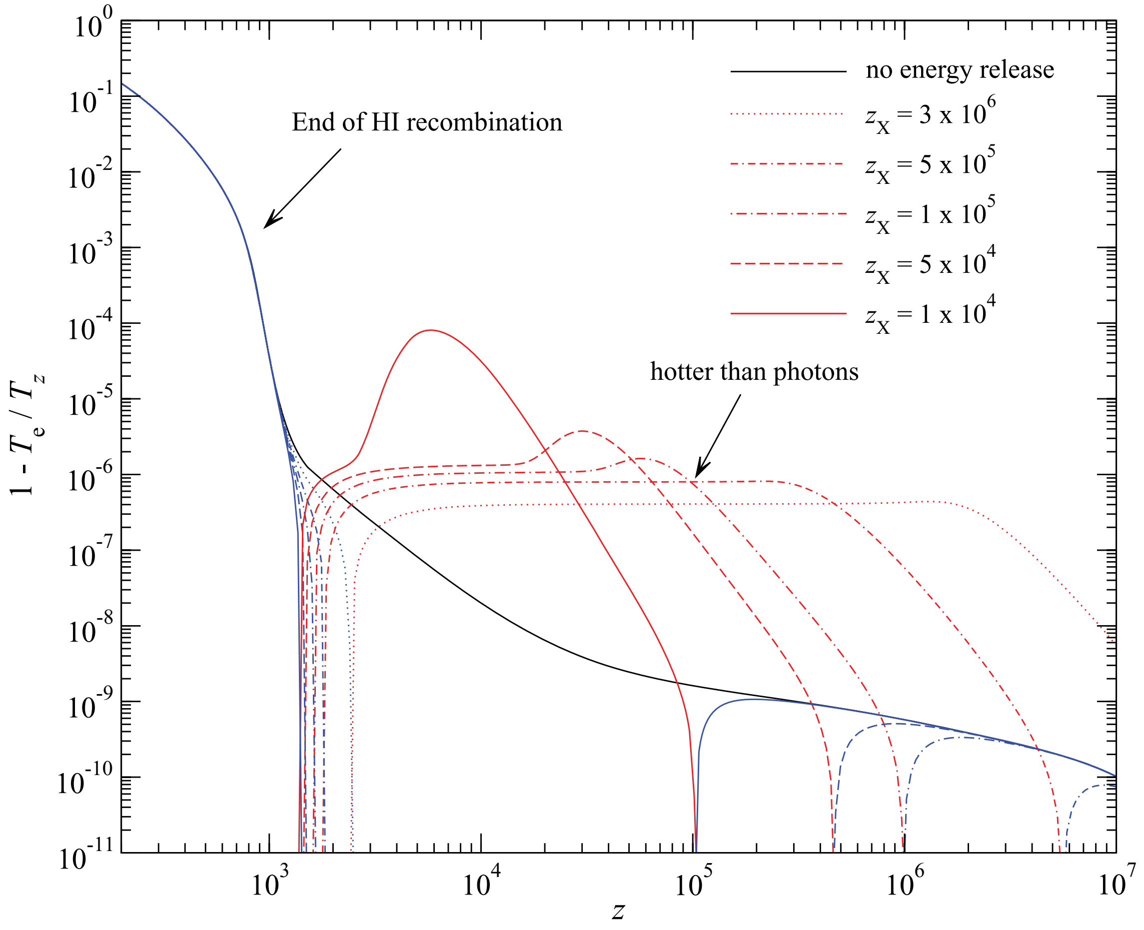
$$\frac{{\rm d}\rho_{\rm e}}{{\rm d}\tau} = \frac{{\rm d}(T_{\rm e}/T_\gamma)}{{\rm d}\tau} = \frac{t_{\rm T}\dot{Q}}{\alpha_{\rm h}\theta_\gamma} + \frac{4\tilde{\rho}_\gamma}{\alpha_{\rm h}}[\rho_{\rm e}^{\rm eq}-\rho_{\rm e}] - \frac{4\tilde{\rho}_\gamma}{\alpha_{\rm h}}\mathcal{H}_{\rm DC,BR}(\rho_{\rm e}) - H\,t_{\rm T}\,\rho_{\rm e}.$$

$$k\alpha_{\rm h} = \frac{3}{2}k[N_{\rm e}+N_{\rm H}+N_{\rm He}] = \frac{3}{2}kN_{\rm H}[1+f_{\rm He}+X_{\rm e}] \qquad \rho_{\rm e}^{\rm eq} = T_{\rm e}^{\rm eq}/T_\gamma$$

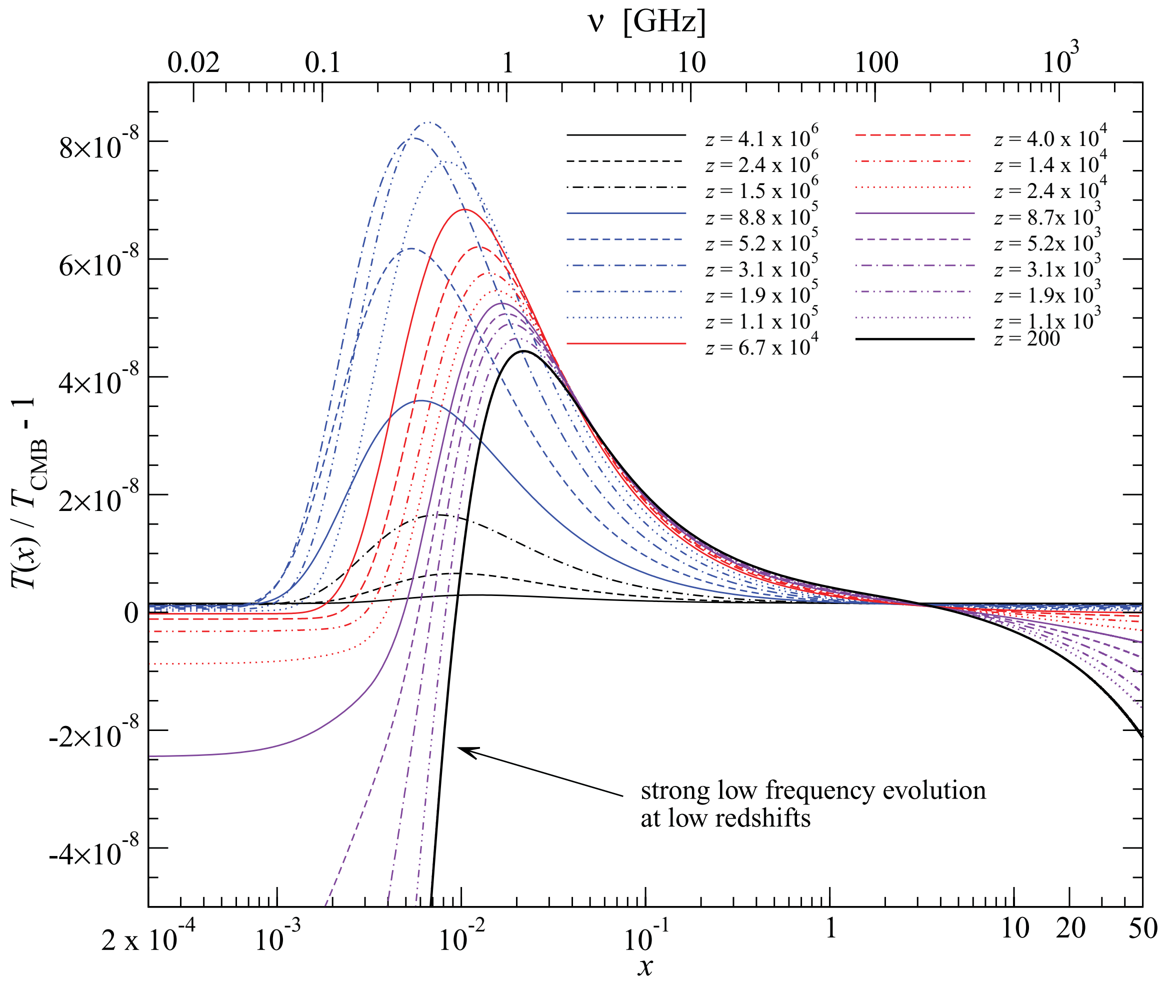
$$\tilde{\rho}_\gamma = \rho_\gamma/m_{\rm e}c^2 \qquad T_{\rm e}^{\rm eq} = T_\gamma\frac{\int x^4 f(1+f)\,{\rm d}x}{4\int x^3 f\,{\rm d}x} \equiv \frac{h}{k}\frac{\int \nu^4 f(1+f)\,{\rm d}\nu}{4\int \nu^3 f\,{\rm d}\nu}$$

CosmoTherm: a new flexible thermalization code

- Solve the thermalization problem for a *wide range* of energy release histories
- several scenarios already implemented *(decaying particles, damping of acoustic modes)*
- first *explicit* solution of time-dependent energy release scenarios
- open source code
- will be available at `www.Chluba.de/CosmoTherm/`
- Main reference: JC & Sunyaev, MNRAS, 2012 (arXiv:1109.6552)

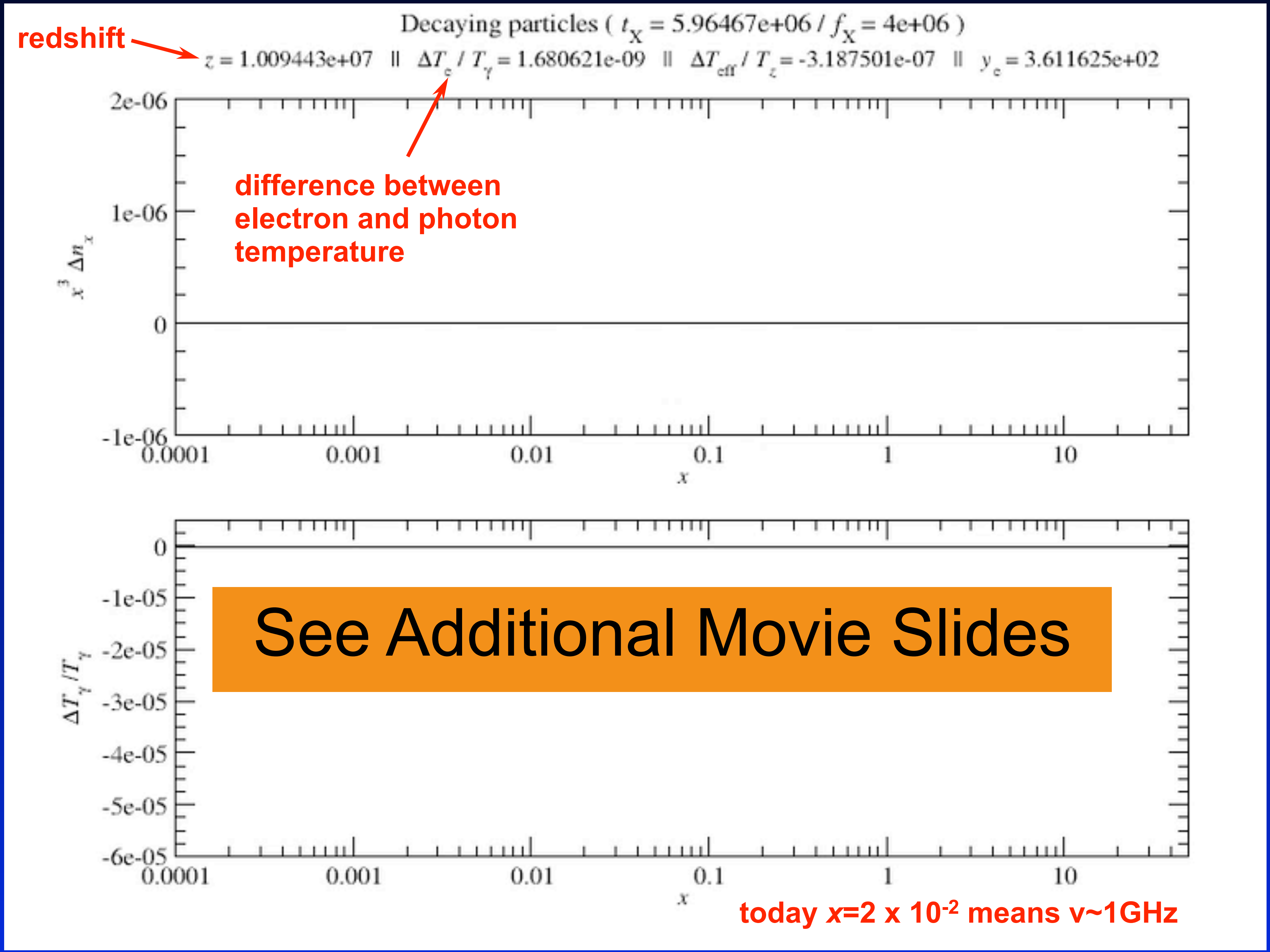


Electron temperature evolution



Evolution of distortion

Example: *Energy release by decaying relict particle*



redshift

difference between electron and photon temperature

See Additional Movie Slides

today x=2 x 10^{-2} means ν~1GHz

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

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

Is there a simple way to include the effect of photon production at low frequencies?

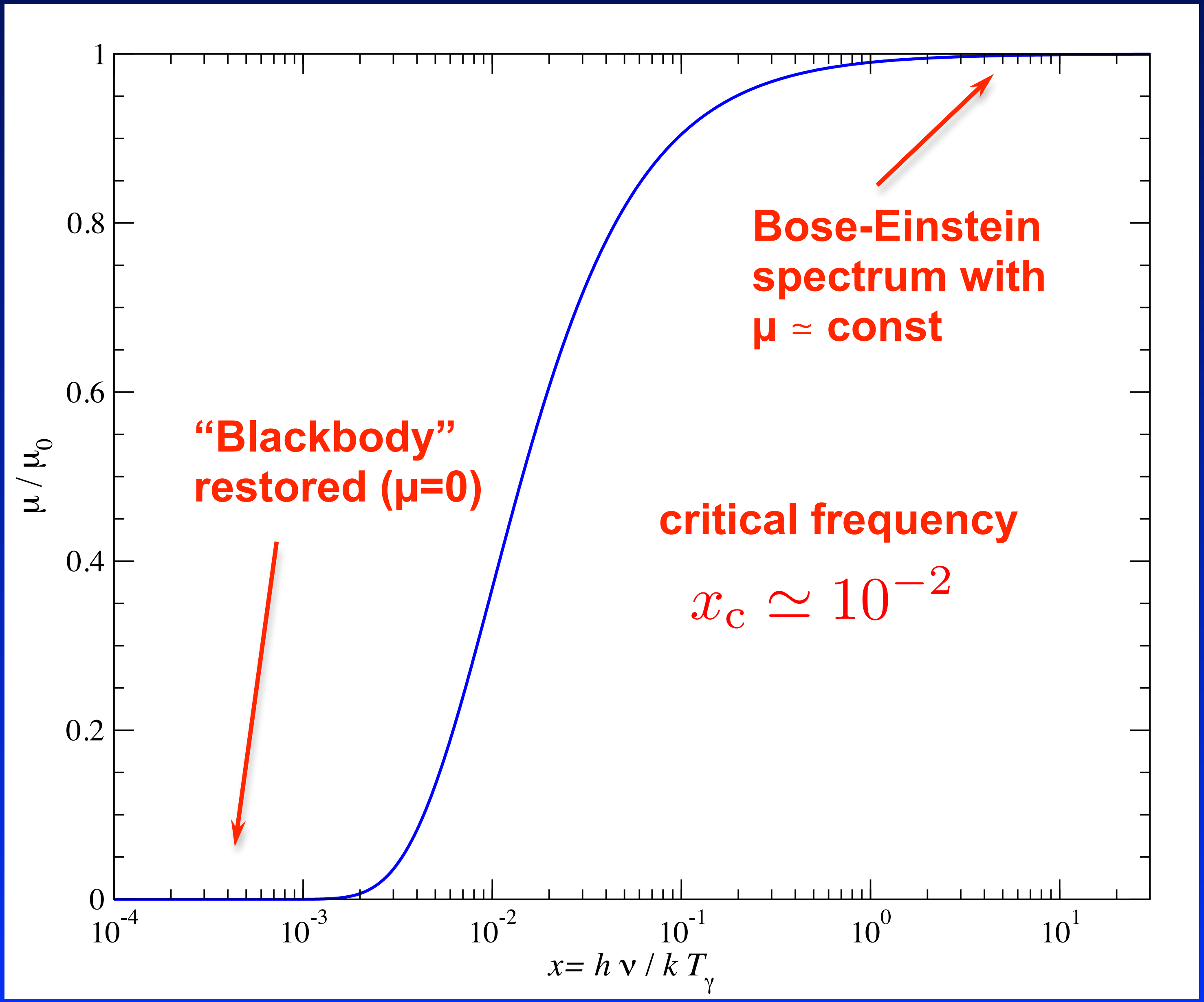
Analytic Approximation for μ-distortion

- *Comptonization efficient!* $\Longrightarrow \quad \left.\frac{\mathrm{d}n}{\mathrm{d}\tau}\right|_{\mathrm{C}} + \left.\frac{\mathrm{d}n}{\mathrm{d}\tau}\right|_{\mathrm{em/abs}} \approx 0$
- *low frequency limit & small distortion* $\Longrightarrow \quad \mu(x,z) \approx \mu_0(z)\,\mathrm{e}^{-x_{\mathrm{c}}(z)/x}$

(**e.g., see Sunyaev & Zeldovich, 1970, ApSS, 7, 20; Hu 1995,** PhD Thesis)

critical frequency

chemical potential at high frequencies



"Blackbody" restored (μ=0)

Bose-Einstein spectrum with μ ≃ const

critical frequency

$x_{\mathrm{c}} \simeq 10^{-2}$

$$n = \frac{1}{\mathrm{e}^{x+\mu(x,z)} - 1}$$

Analytic Approximation for μ-distortion

- *Comptonization efficient!* $\Longrightarrow$ $\left.\frac{\mathrm{d}n}{\mathrm{d}\tau}\right|_{\rm C} + \left.\frac{\mathrm{d}n}{\mathrm{d}\tau}\right|_{\rm em/abs} \approx 0$

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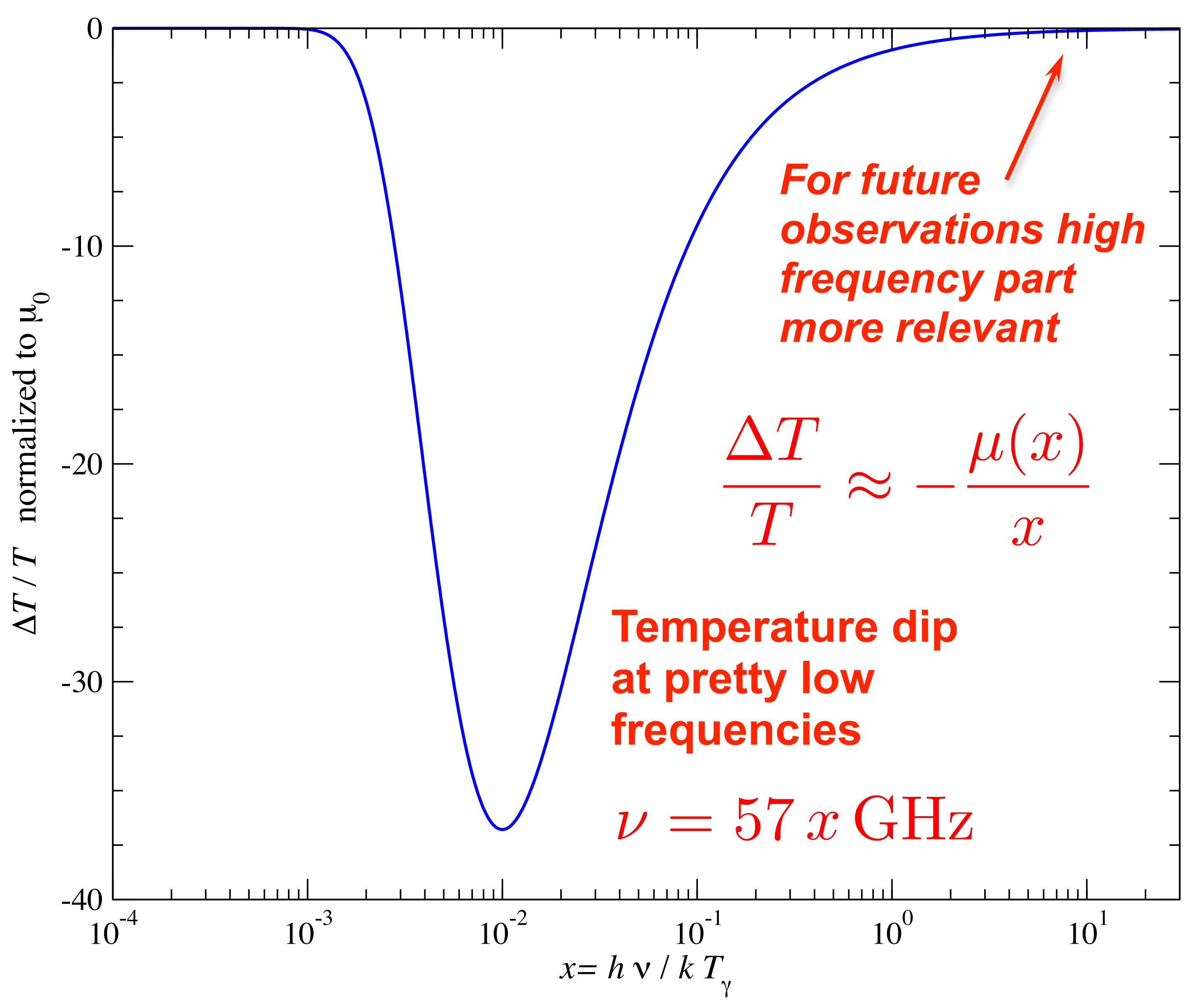
(e.g., see Sunyaev & Zeldovich, 1970, ApSS, 7, 20; Hu 1995, PhD Thesis)

chemical potential at high frequencies



For future observations high frequency part more relevant

$$\frac{\Delta T}{T} \approx -\frac{\mu(x)}{x}$$

Temperature dip at pretty low frequencies

$$\nu = 57\,x\,\mathrm{GHz}$$

$$n = \frac{1}{\mathrm{e}^{x+\mu(x,z)} - 1}$$

Analytic Approximation for μ-distortion

- *Comptonization efficient!* $\Longrightarrow$ $$\left.\frac{\mathrm{d}n}{\mathrm{d}\tau}\right|_{\mathrm{C}} + \left.\frac{\mathrm{d}n}{\mathrm{d}\tau}\right|_{\mathrm{em/abs}} \approx 0$$

- *low frequency limit & small distortion* $\Longrightarrow$ $$\mu(x,z) \approx \mu_0(z)\,\mathrm{e}^{-x_{\mathrm{c}}(z)/x}$$

(**e.g., see Sunyaev & Zeldovich, 1970, ApSS, 7, 20; Hu 1995,** PhD Thesis)

Last step: How does μ₀(z) depend on z?

Analytic Approximation for μ-distortion

- *Comptonization efficient!* $\Longrightarrow$ $\left.\frac{\mathrm{d}n}{\mathrm{d}\tau}\right|_{\mathrm{C}} + \left.\frac{\mathrm{d}n}{\mathrm{d}\tau}\right|_{\mathrm{em/abs}} \approx 0$

- *low frequency limit & small distortion* $\Longrightarrow$ $\mu(x, z) \approx \mu_0(z)\,\mathrm{e}^{-x_{\mathrm{c}}(z)/x}$

(e.g., see Sunyaev & Zeldovich, 1970, ApSS, 7, 20; Hu 1995, PhD Thesis)

- *Use μ(x, z) to estimate the total photon production rate at low frequencies ⇒ determines at which rate μ_0 reduces*

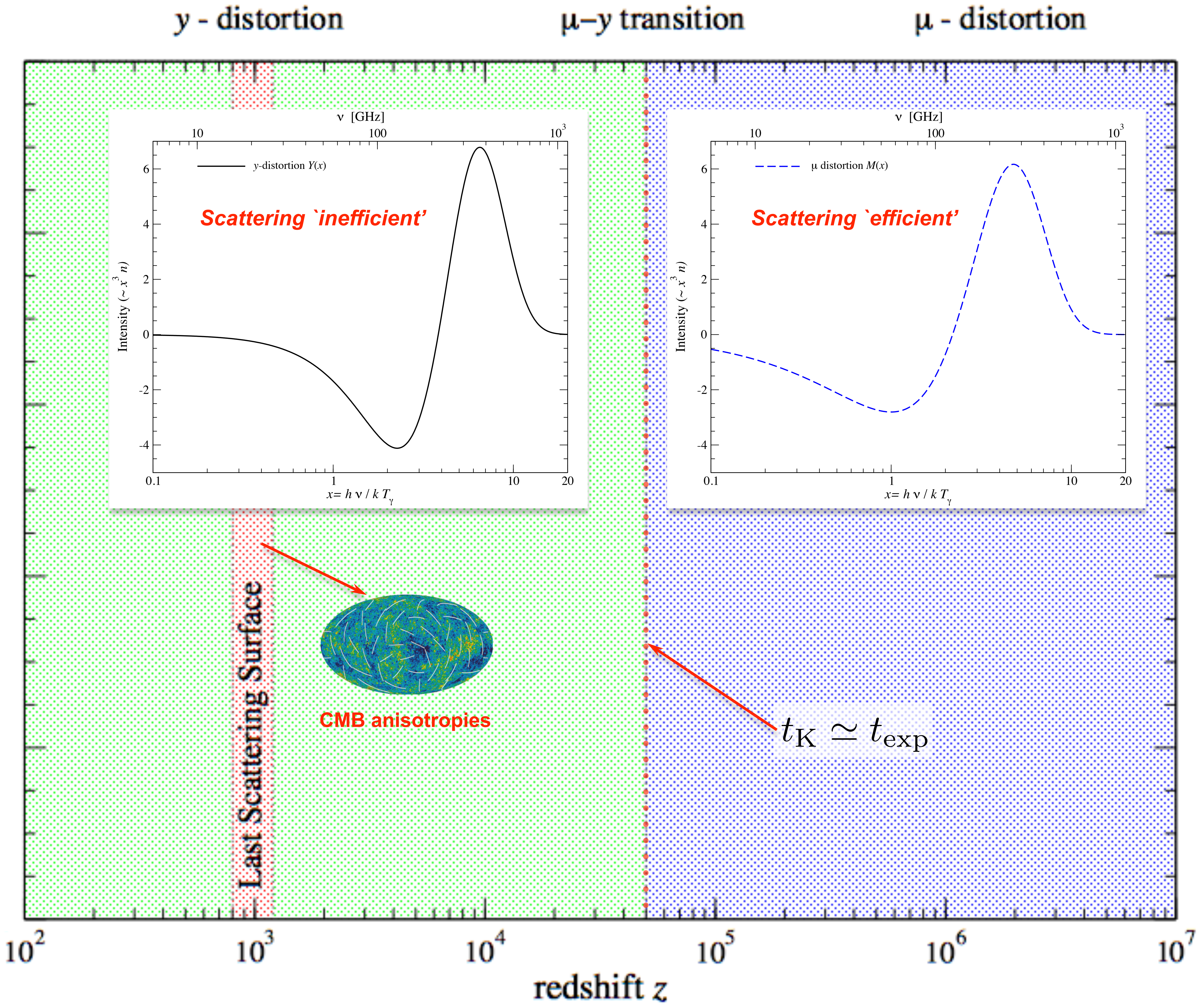
$$\mu_0 \approx 1.401\,\frac{\Delta\rho_\gamma}{\rho_\gamma} \quad \Longrightarrow \quad \mu_0 \approx 1.4 \int_{z_{\mathrm{K}}}^{\infty} \frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z'}\,\mathcal{J}_\mu(z')\mathrm{d}z'$$

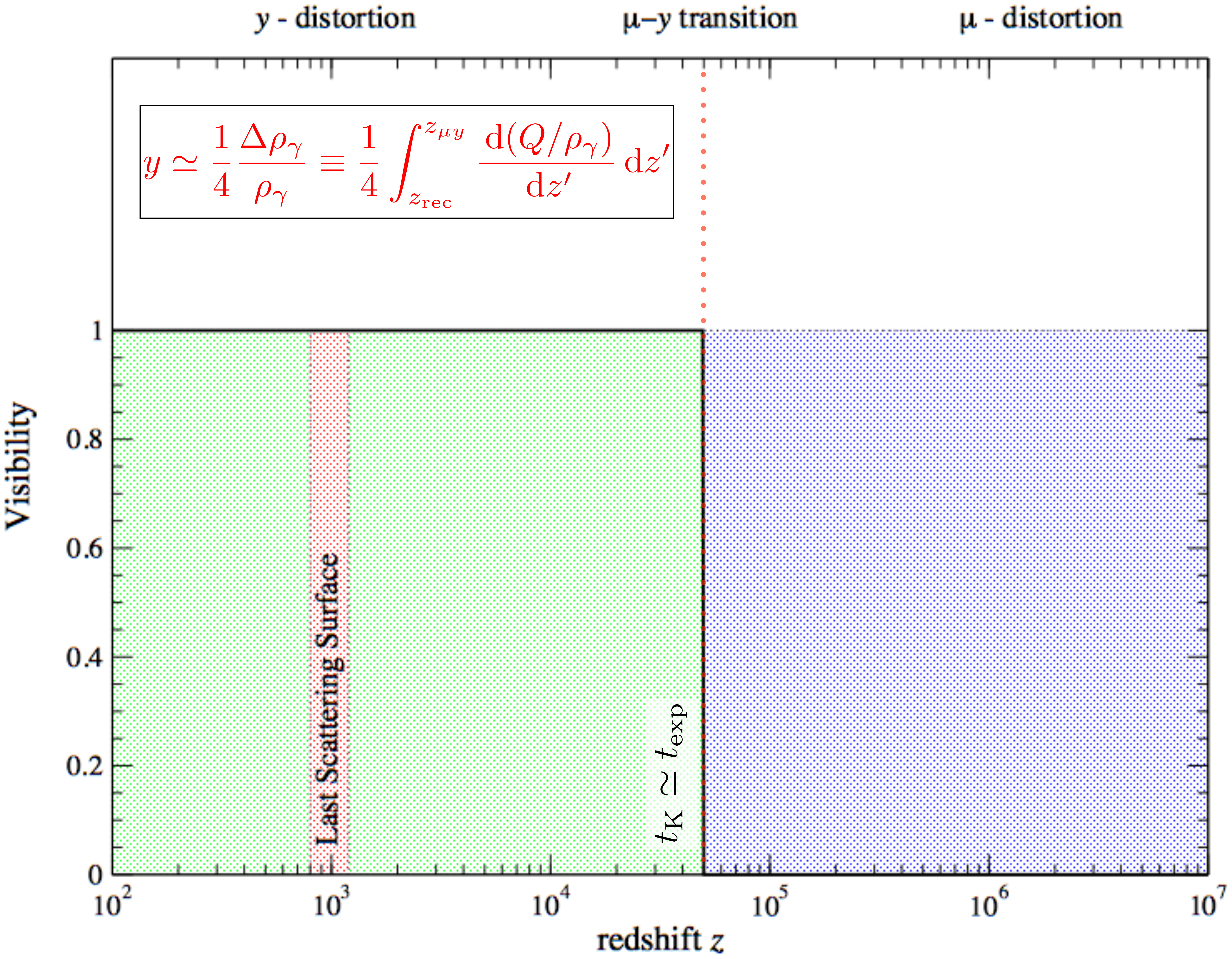
Set by DC process

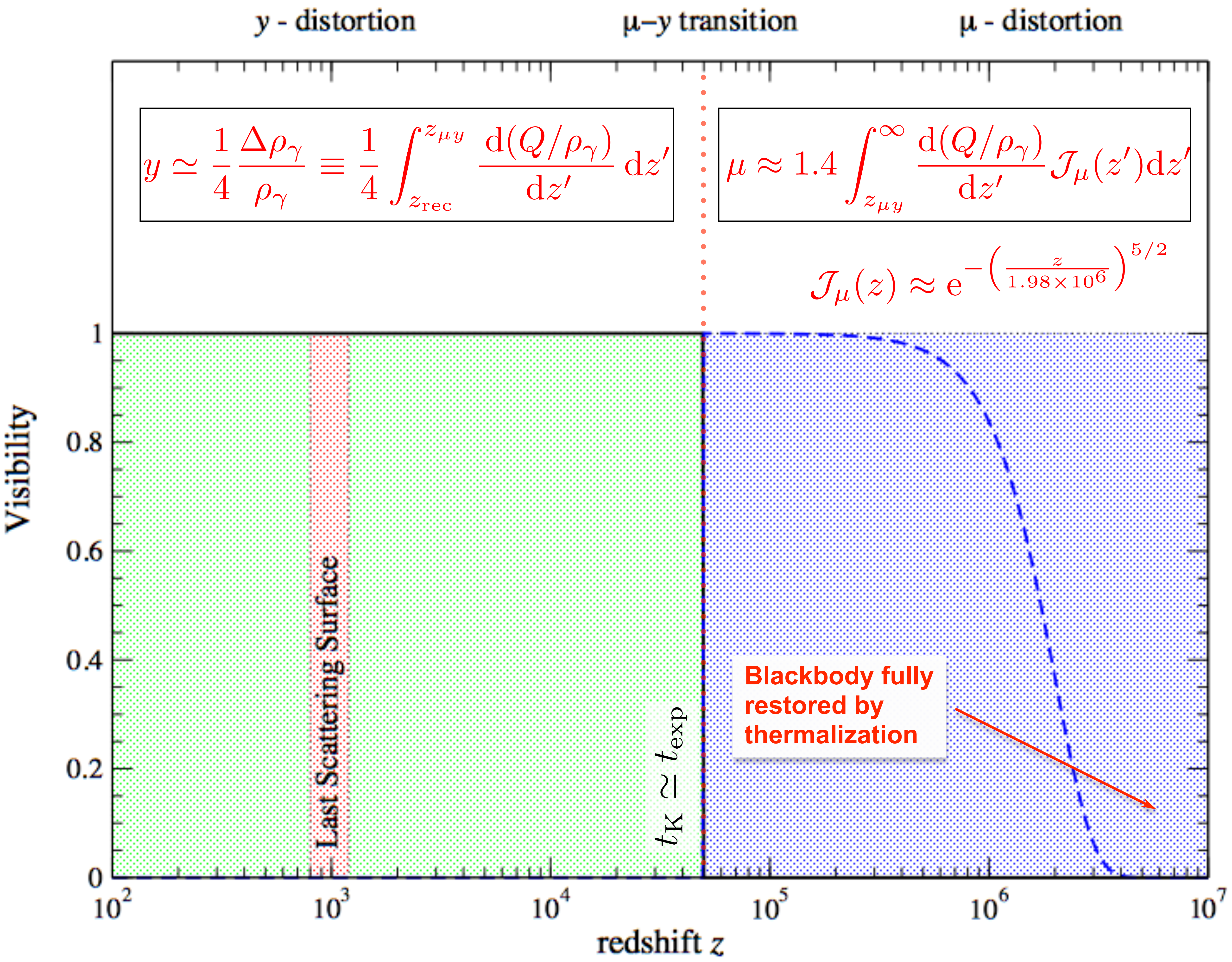
- *μ-distortion visibility function:* $\mathcal{J}_\mu(z) \approx \mathrm{e}^{-(z/z_\mu)^{5/2}}$ *with* $z_\mu \approx 2 \times 10^6$

- *Transition between μ and y modeled as simple step function*

Classical approximations for μ and y


y - distortion
μ–y transition
μ - distortion
ν [GHz]
10
100
10^3
y-distortion $Y(x)$
Scattering `inefficient'
Intensity ($\sim x^3 n$)
6
4
2
0
-2
-4
0.1
1
10
20
$x = h\nu / kT_\gamma$
μ distortion $M(x)$
Scattering `efficient'
Last Scattering Surface
CMB anisotropies
$t_K \simeq t_{\exp}$
10^2
10^3
10^4
10^5
10^6
10^7
redshift z


y - distortion
μ–y transition
μ - distortion
$y \simeq \frac{1}{4}\frac{\Delta\rho_\gamma}{\rho_\gamma} \equiv \frac{1}{4}\int_{z_{\rm rec}}^{z_{\mu y}} \frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'}\,{\rm d}z'$
Visibility
1
0.8
0.6
0.4
0.2
0
Last Scattering Surface
$t_{\rm K} \simeq t_{\rm exp}$
10^2
10^3
10^4
10^5
10^6
10^7
redshift z

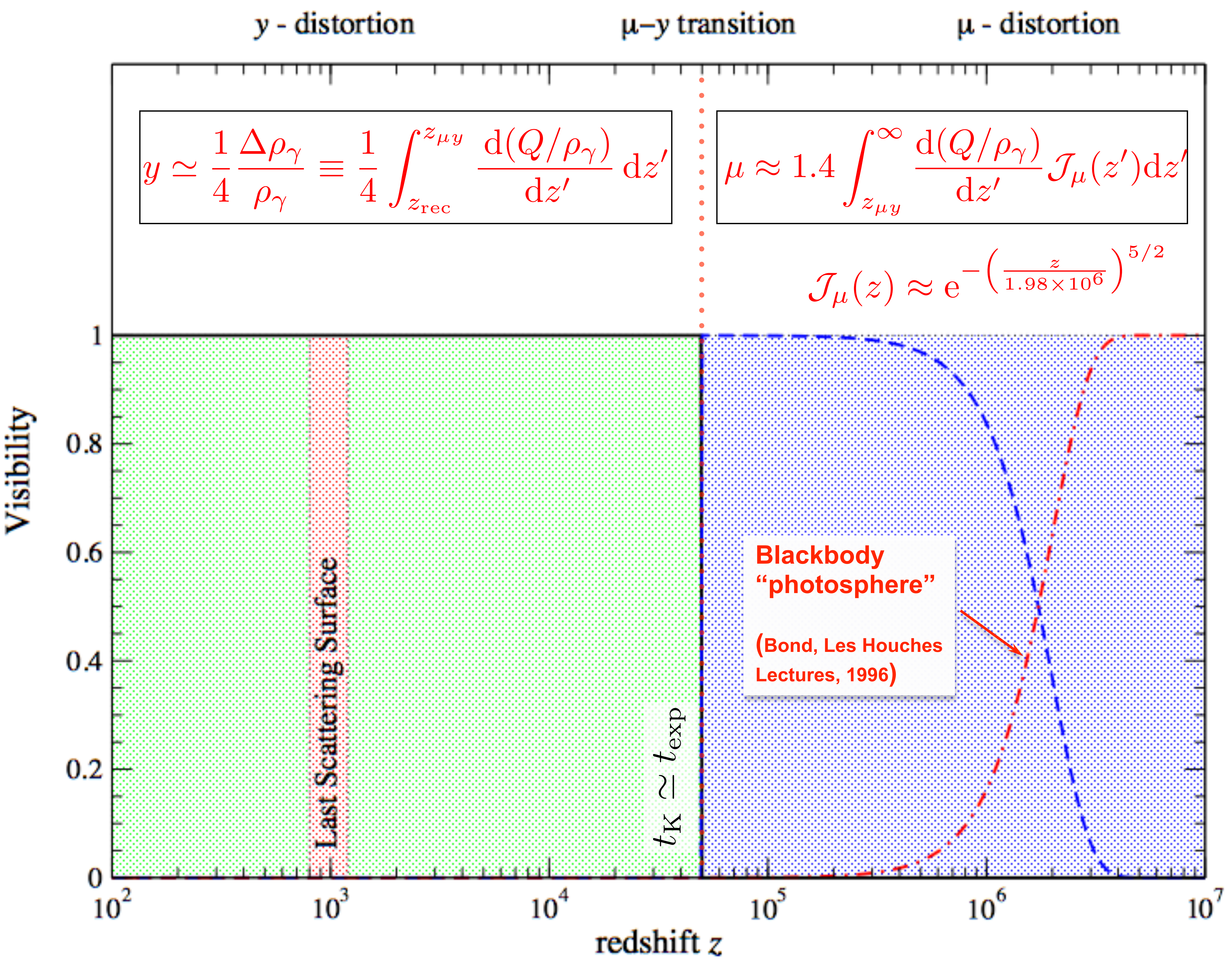


$$y \simeq \frac{1}{4}\frac{\Delta\rho_\gamma}{\rho_\gamma} \equiv \frac{1}{4}\int_{z_{\rm rec}}^{z_{\mu y}} \frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'}\,{\rm d}z'$$

$$\mu \approx 1.4\int_{z_{\mu y}}^{\infty}\frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'}\,\mathcal{J}_\mu(z')\,{\rm d}z'$$

$$\mathcal{J}_\mu(z) \approx {\rm e}^{-\left(\frac{z}{1.98\times10^6}\right)^{5/2}}$$

Blackbody fully restored by thermalization



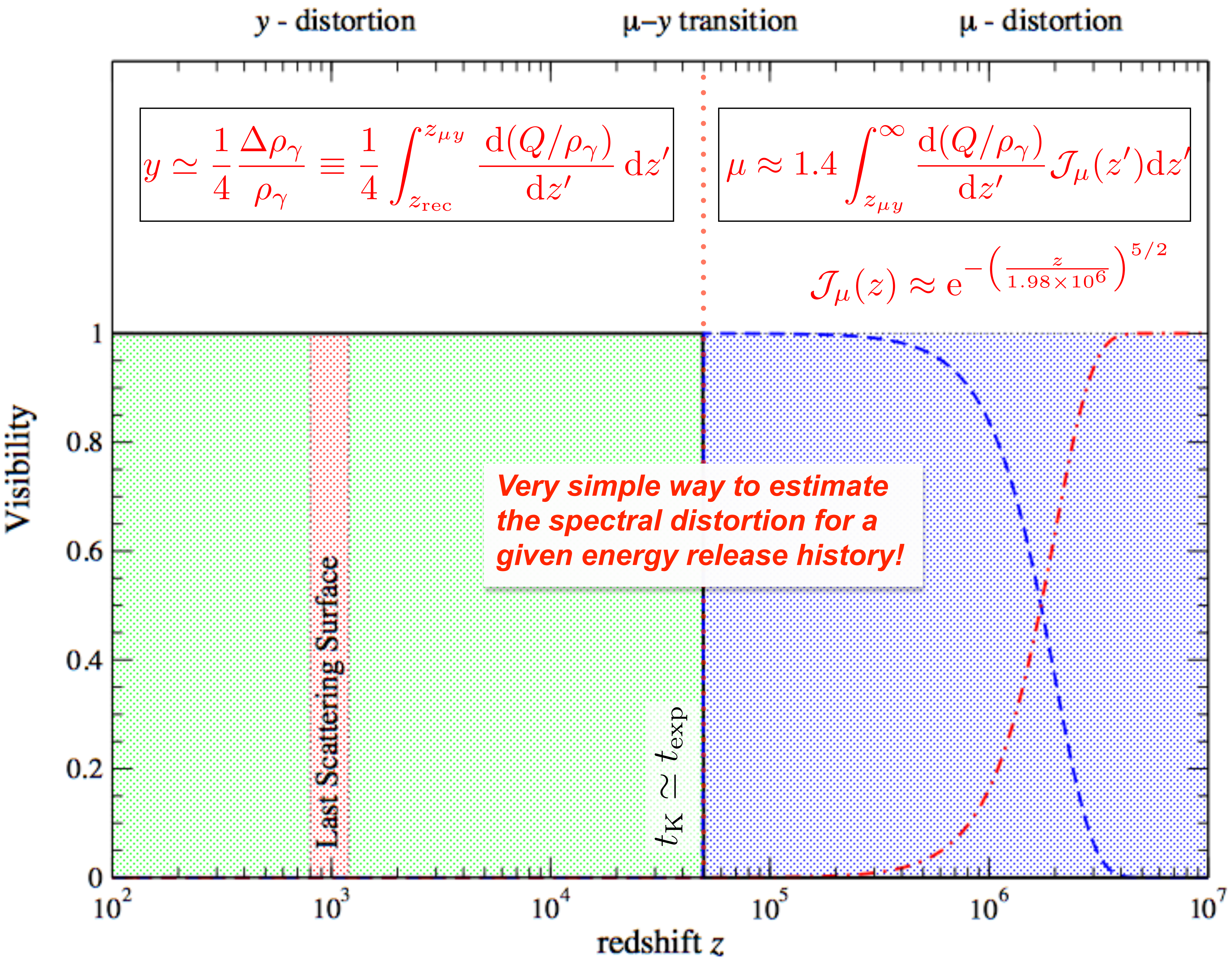
$$y \simeq \frac{1}{4}\frac{\Delta\rho_\gamma}{\rho_\gamma} \equiv \frac{1}{4}\int_{z_\mathrm{rec}}^{z_{\mu y}} \frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z'}\,\mathrm{d}z'$$

$$\mu \approx 1.4 \int_{z_{\mu y}}^{\infty} \frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z'}\mathcal{J}_\mu(z')\mathrm{d}z'$$

$$\mathcal{J}_\mu(z) \approx \mathrm{e}^{-\left(\frac{z}{1.98\times10^6}\right)^{5/2}}$$

Blackbody “photosphere”

(Bond, Les Houches Lectures, 1996)



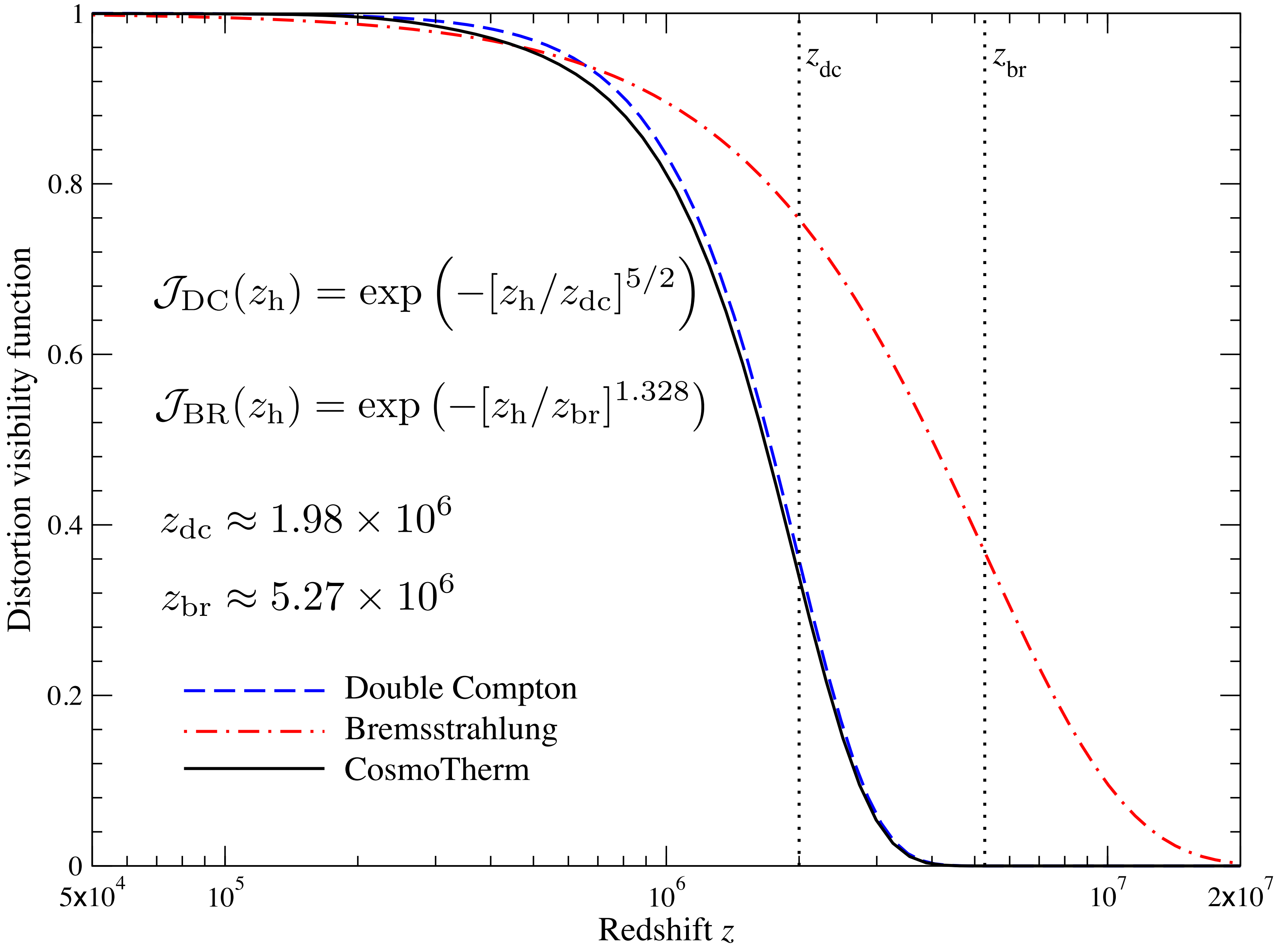
$$y \simeq \frac{1}{4}\frac{\Delta\rho_\gamma}{\rho_\gamma} \equiv \frac{1}{4}\int_{z_{\rm rec}}^{z_{\mu y}} \frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'}\,{\rm d}z'$$

$$\mu \approx 1.4\int_{z_{\mu y}}^{\infty} \frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'}\,\mathcal{J}_\mu(z'){\rm d}z'$$

$$\mathcal{J}_\mu(z) \approx {\rm e}^{-\left(\frac{z}{1.98\times10^6}\right)^{5/2}}$$

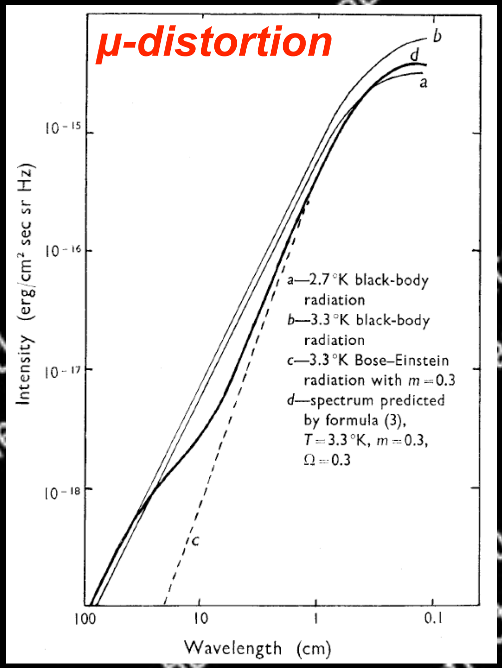
Very simple way to estimate the spectral distortion for a given energy release history!

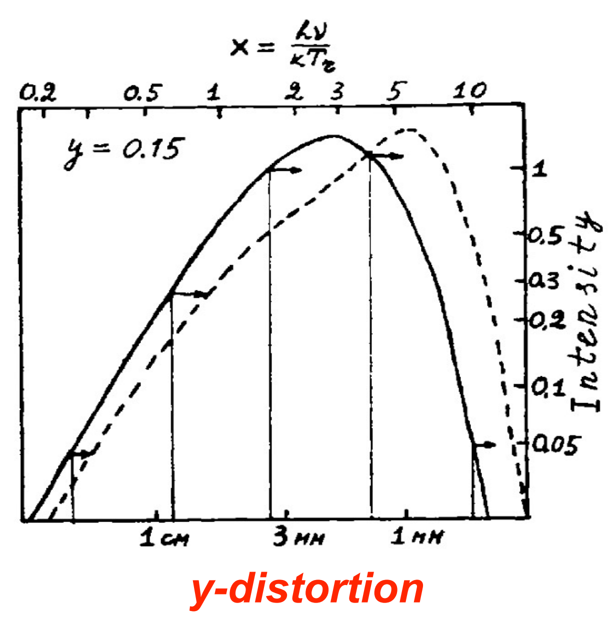
Distortion visibility for BR and DC

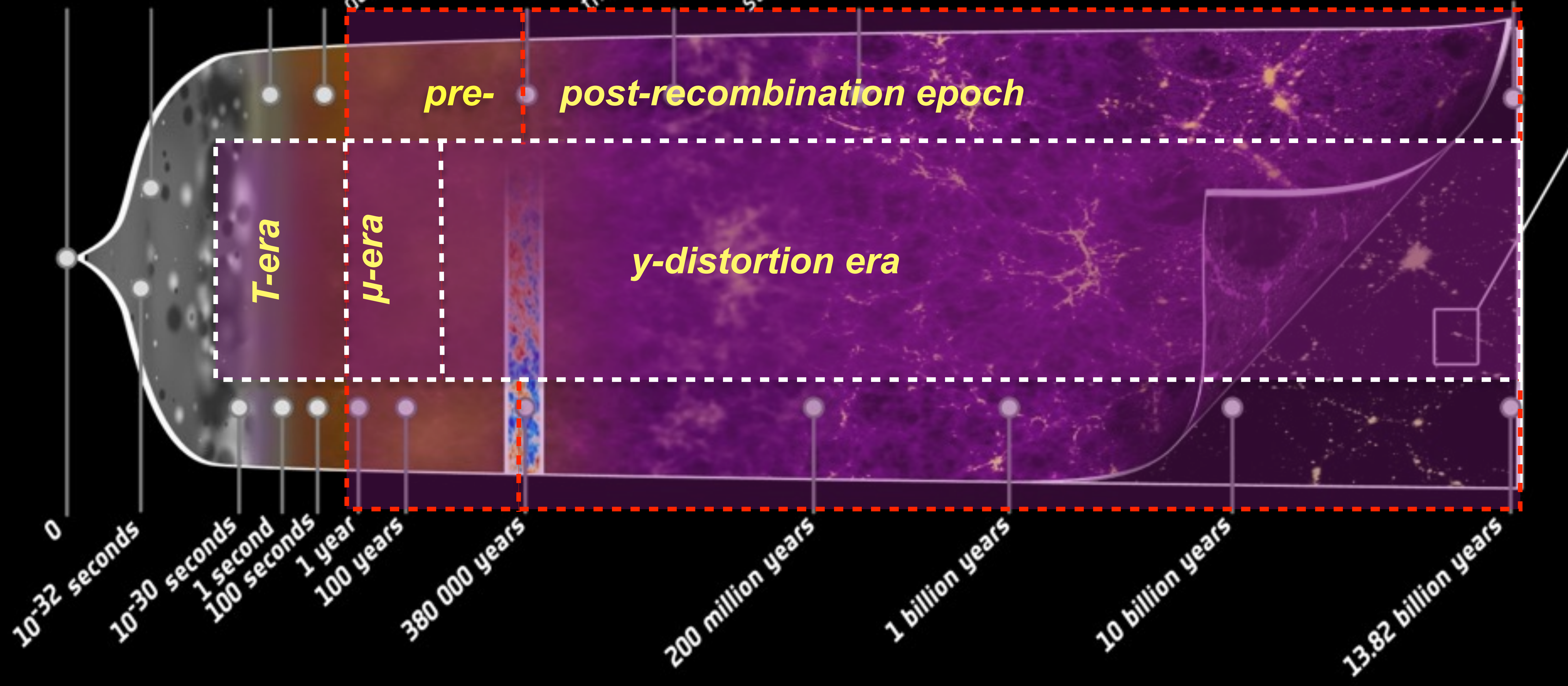


- Original estimates only included the effect of BR
- Double Compton emission was first included by Danese & de Zotti, 1982
- DC changes the distortion visibility quite strongly

Double Compton emission is really crucial !!!


μ-distortion
Intensity (erg/cm² sec sr Hz)
10⁻¹⁵
10⁻¹⁶
10⁻¹⁷
10⁻¹⁸
a—2.7 °K black-body radiation
b—3.3 °K black-body radiation
c—3.3 °K Bose–Einstein radiation with m = 0.3
d—spectrum predicted by formula (3), T = 3.3 °K, m = 0.3, Ω = 0.3
a
b
c
d
100
10
1
0.1
Wavelength (cm)


x = hν/kT_r
0.2
0.5
1
2
3
5
10
y = 0.15
1
0.5
0.3
0.2
0.1
0.05
Intensity
1 cm
3 mm
1 mm
y-distortion


Big B
Cosm
Origin
Partic
Ordina
dark mat
couple from
ckground is
matter pa
tures create
Fi
tion
of gala
Today
pre-
post-recombination epoch
T-era
μ-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

What about the μ-y transition regime?

Is the transition really as abrupt?

Quasi-Exact Treatment of the Thermalization Problem

- *For real forecasts of future prospects a precise & fast method for computing the spectral distortion is needed!*
- *Case-by-case computation of the distortion (e.g., with CosmoTherm, JC & Sunyaev, 2012, ArXiv:1109.6552) still rather time-consuming*
- *But: distortions are small ⇒ thermalization problem becomes linear!*
- *Simple solution: compute "response function" of the thermalization problem ⇒ Green's function approach (JC, 2013, ArXiv:1304.6120)*
- *Final distortion for fixed energy-release history given by*

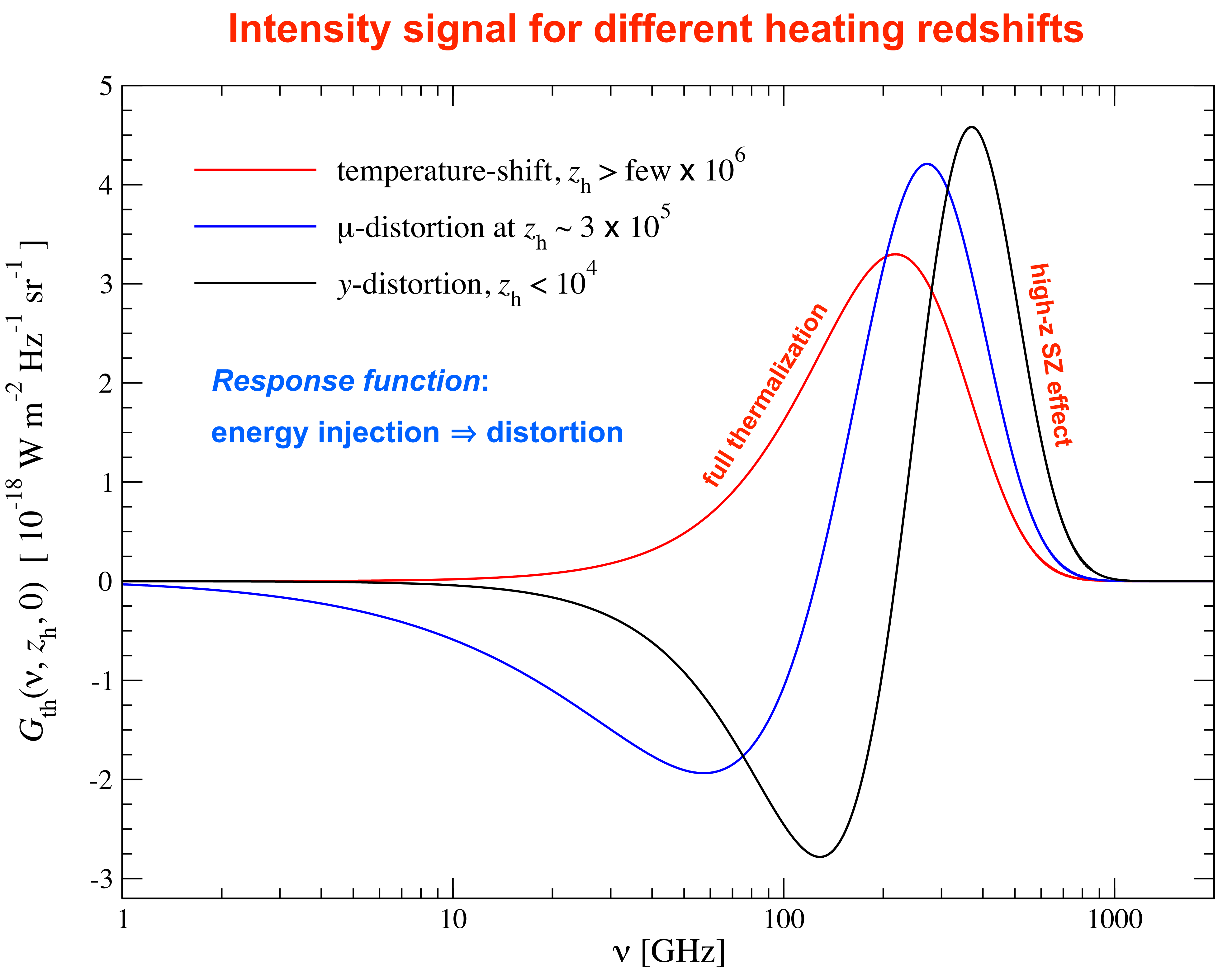
$$\Delta I_\nu \approx \int_0^\infty G_{\rm th}(\nu, z') \frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'} {\rm d}z'$$

Thermalization Green's function

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

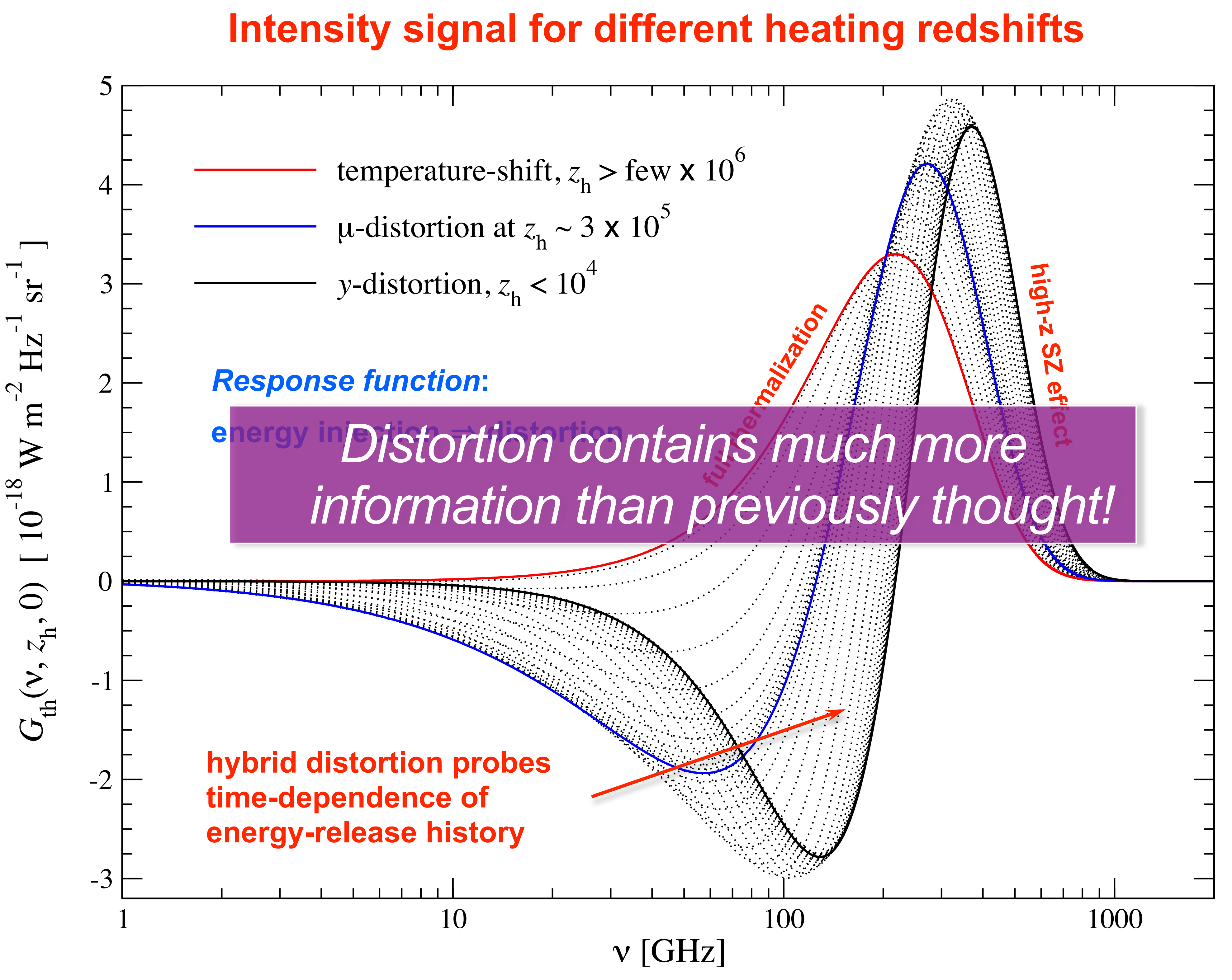
CosmoTherm available at: www.Chluba.de/CosmoTherm

What does the spectrum look like after energy injection?



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

What does the spectrum look like after energy injection?



Intensity signal for different heating redshifts

Response function:

energy injection ⇒ distortion

Distortion contains much more information than previously thought!

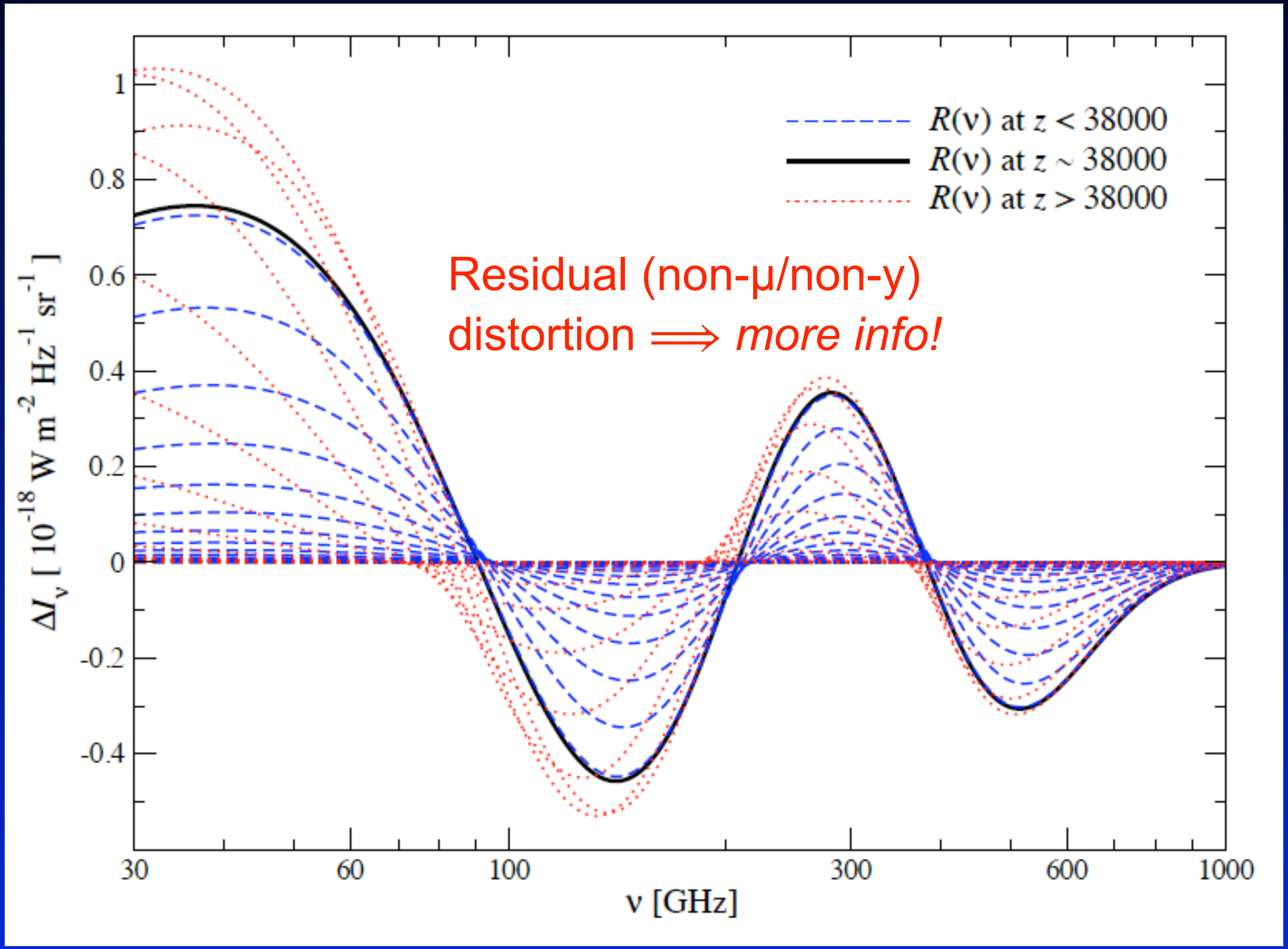
further thermalization

high-z SZ effect

hybrid distortion probes time-dependence of energy-release history

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

Explicitly taking out the superposition of *T*, μ & y distortion

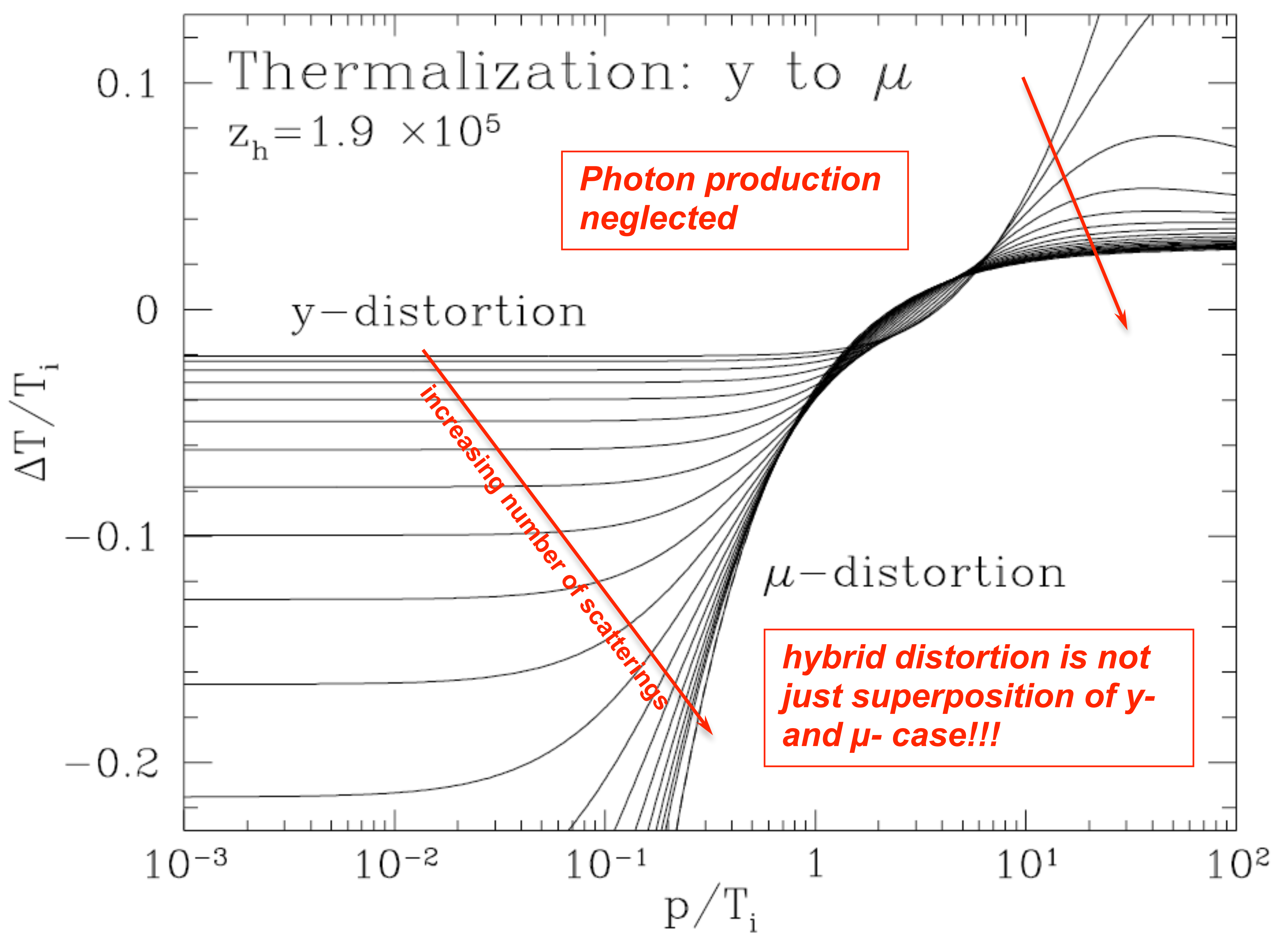


Residual (non-μ/non-y) distortion ⟹ *more info!*

- *Allows us to distinguish different energy release scenarios!*

JC & Sunyaev, 2012, ArXiv:1109.6552
JC, 2013, ArXiv:1304.6120; JC, 2013, ArXiv:1304.6121; JC & Jeong, 2013

Transition from y-distortion → μ-distortion

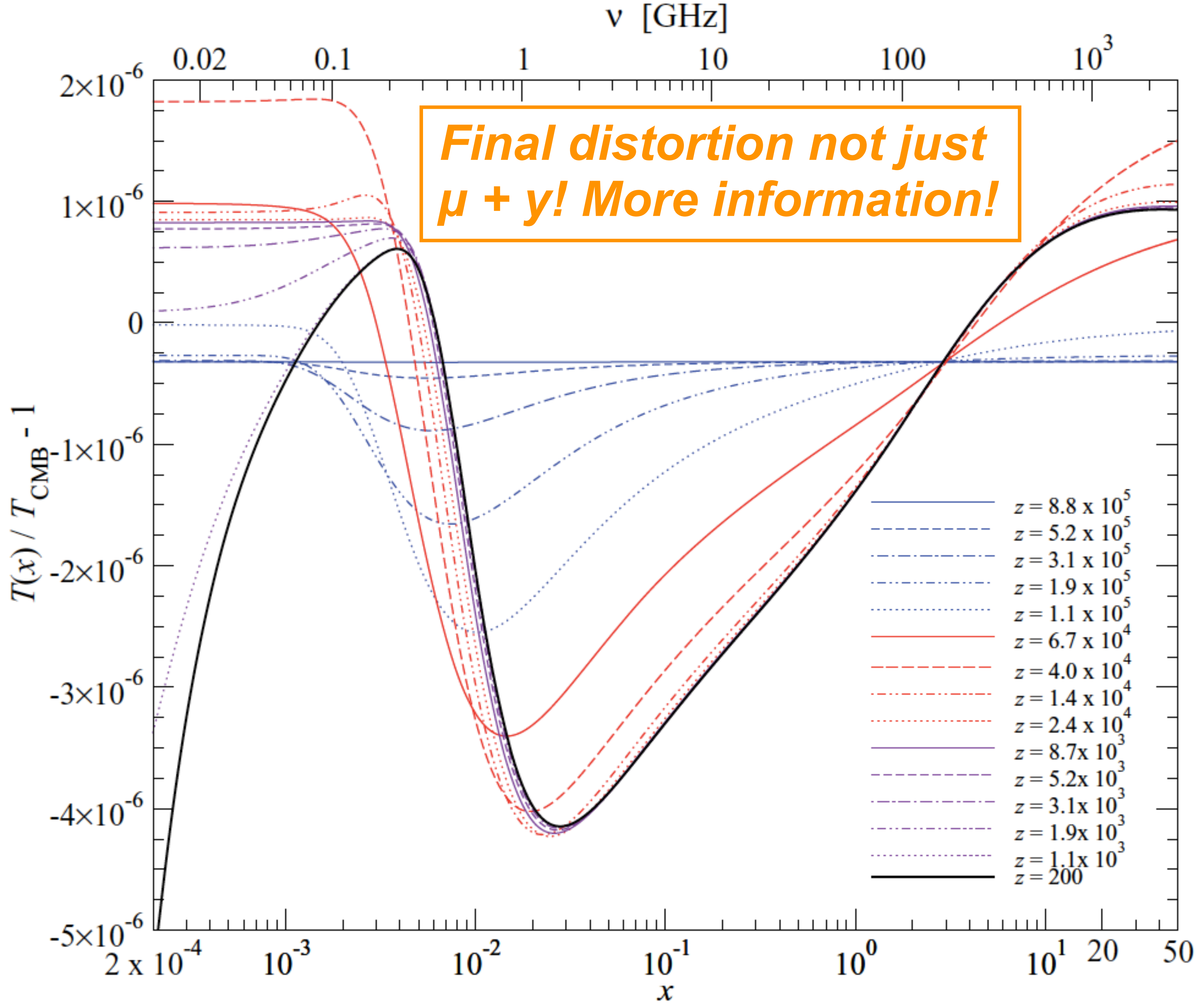


Photon production neglected

hybrid distortion is not just superposition of y- and μ- case!!!

Figure from Wayne Hu's PhD thesis, 1995, but see also discussion in Burigana, 1991

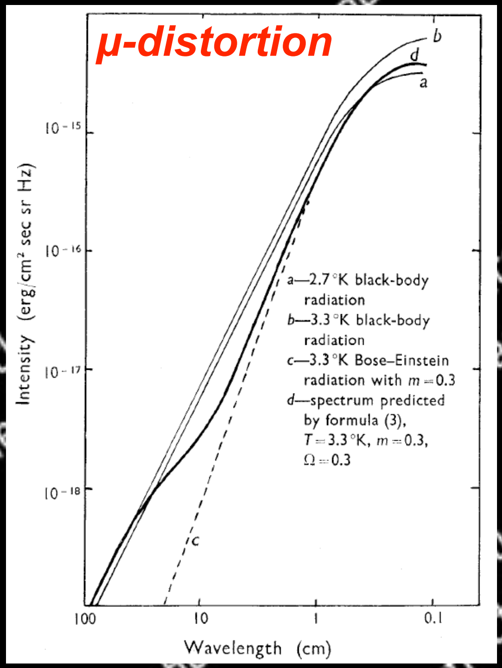
Distortion *not* just superposition of μ and y-distortion!



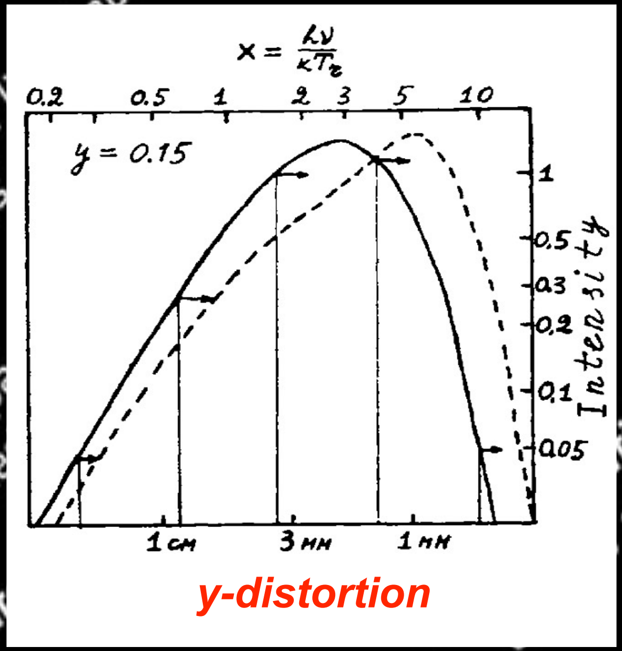
Final distortion not just μ + y! More information!

Computation carried out with *CosmoTherm* (JC & Sunyaev 2011)

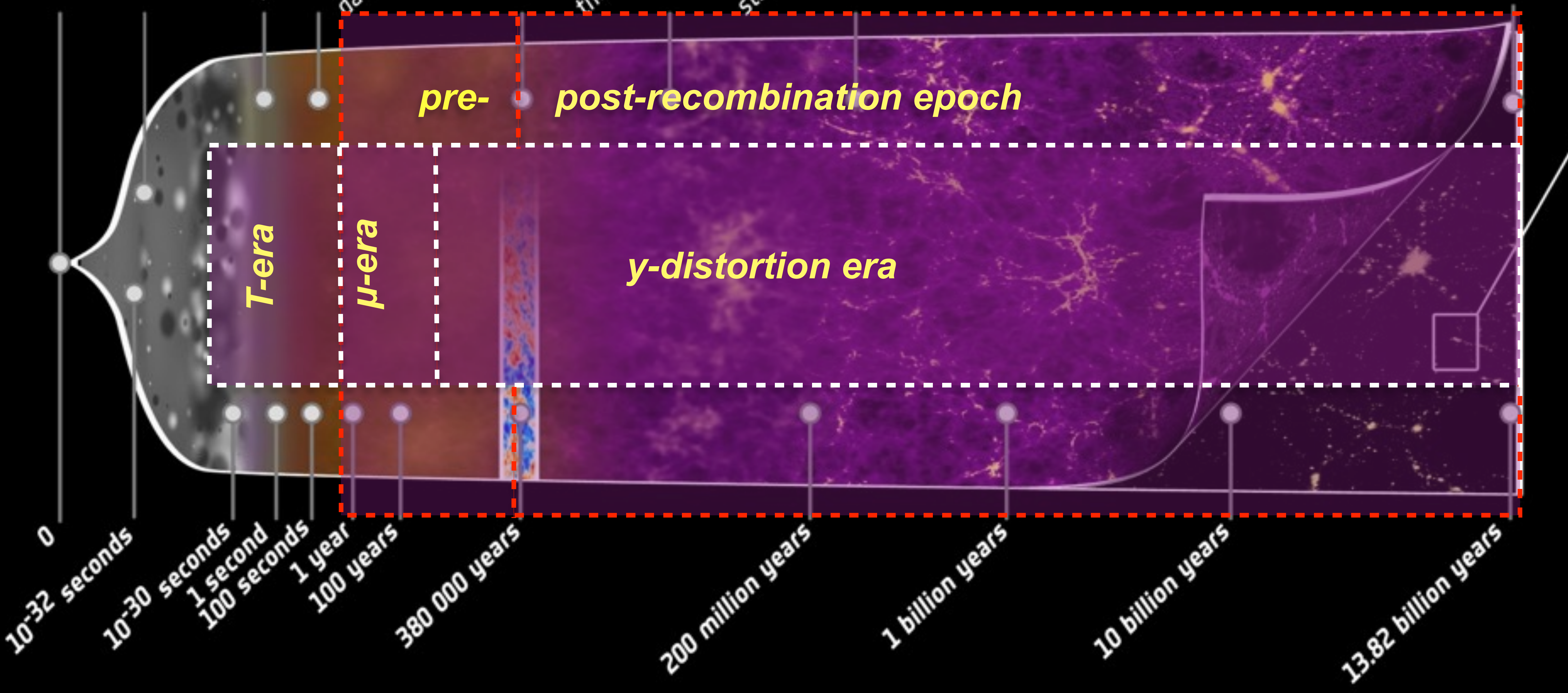
First explicit calculation that showed that there is more!



μ-distortion



y-distortion



pre-

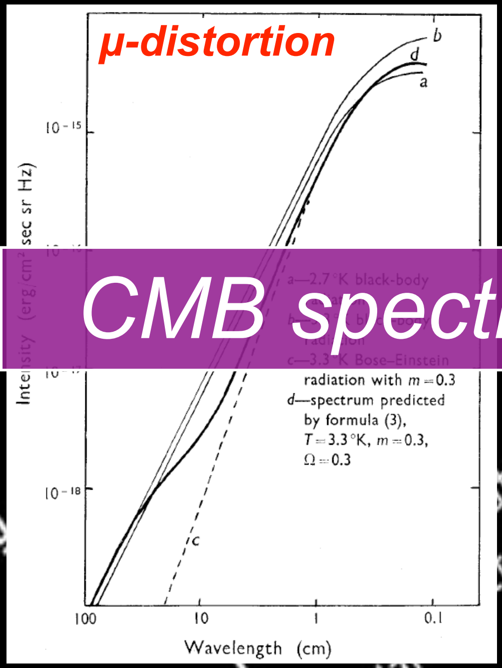
post-recombination epoch

T-era

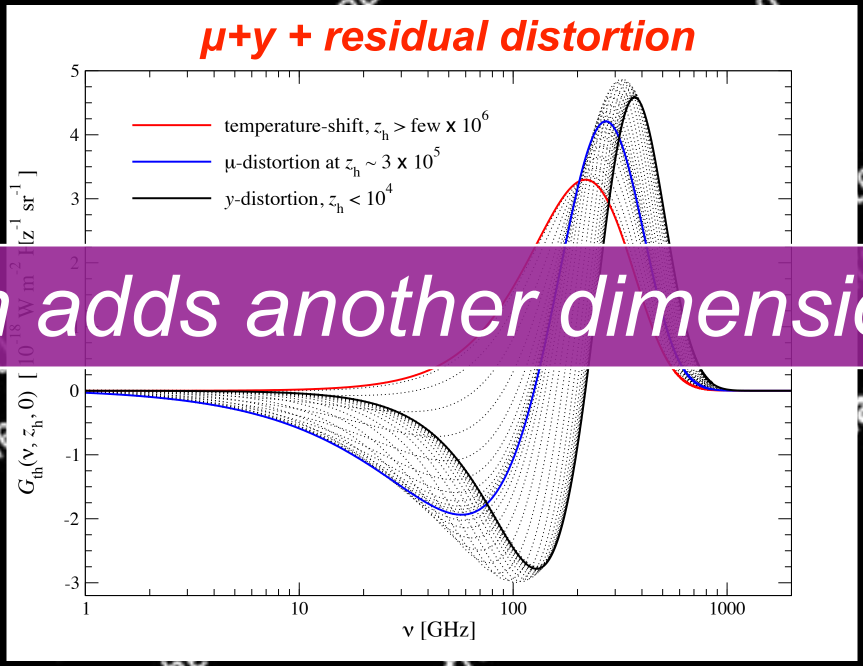
μ-era

y-distortion era

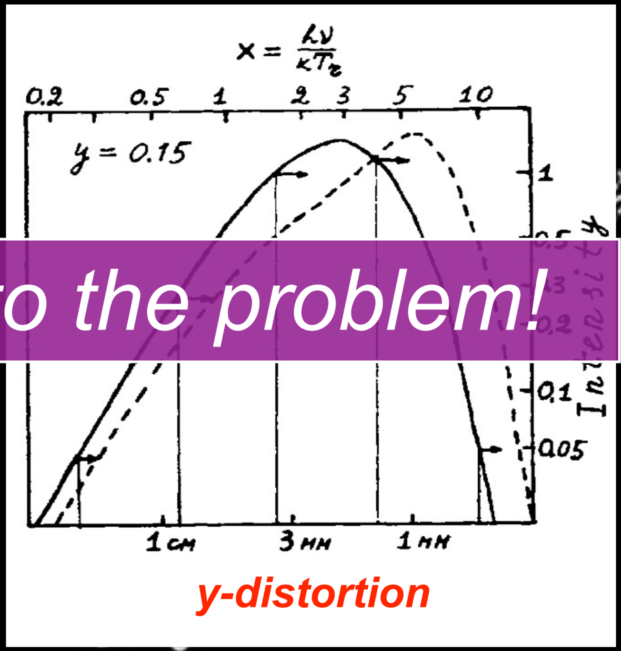
CMB spectrum adds another dimension to the problem!



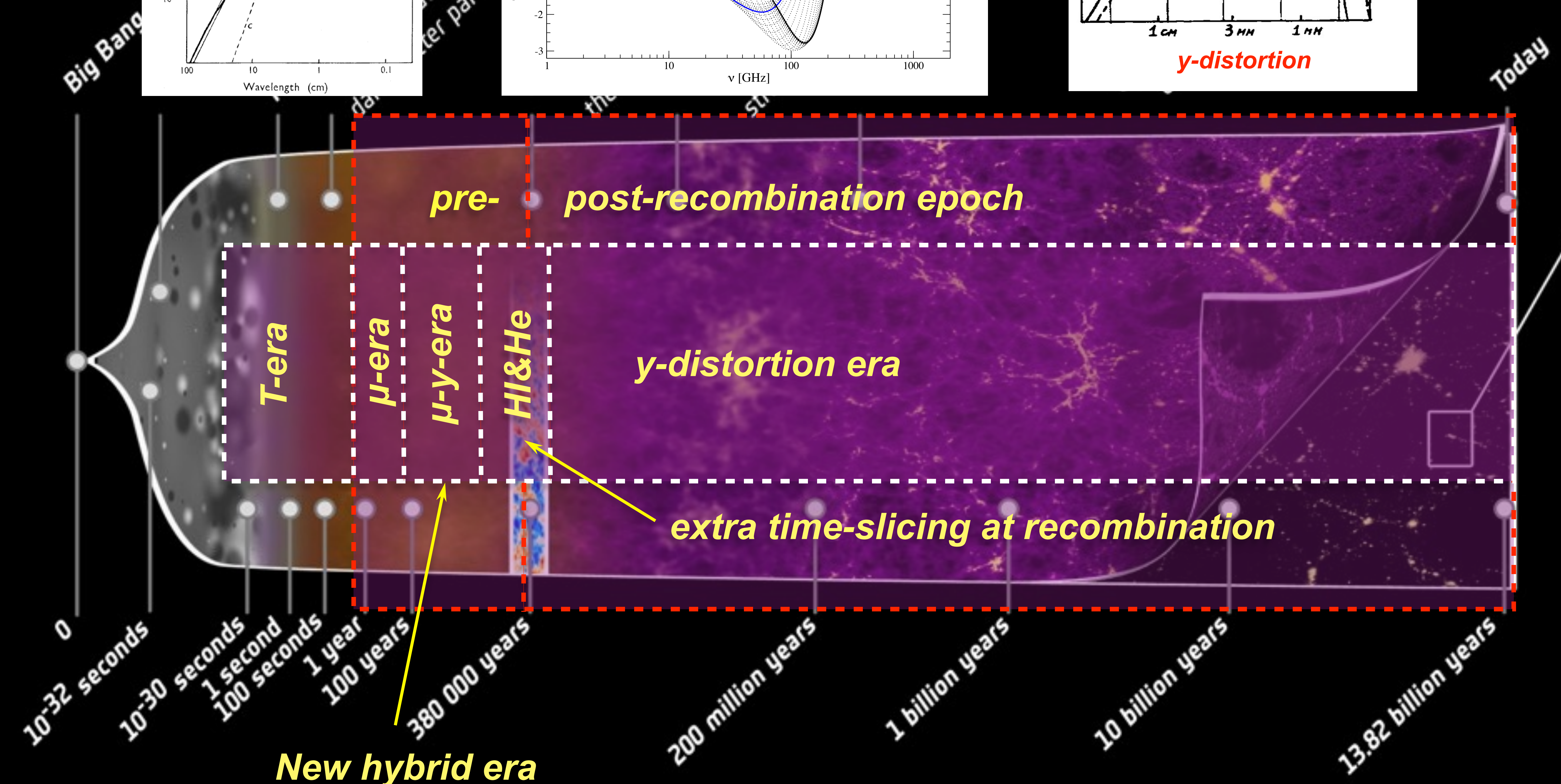
μ-distortion



μ+y + residual distortion



y-distortion



pre-

post-recombination epoch

T-era

μ-era

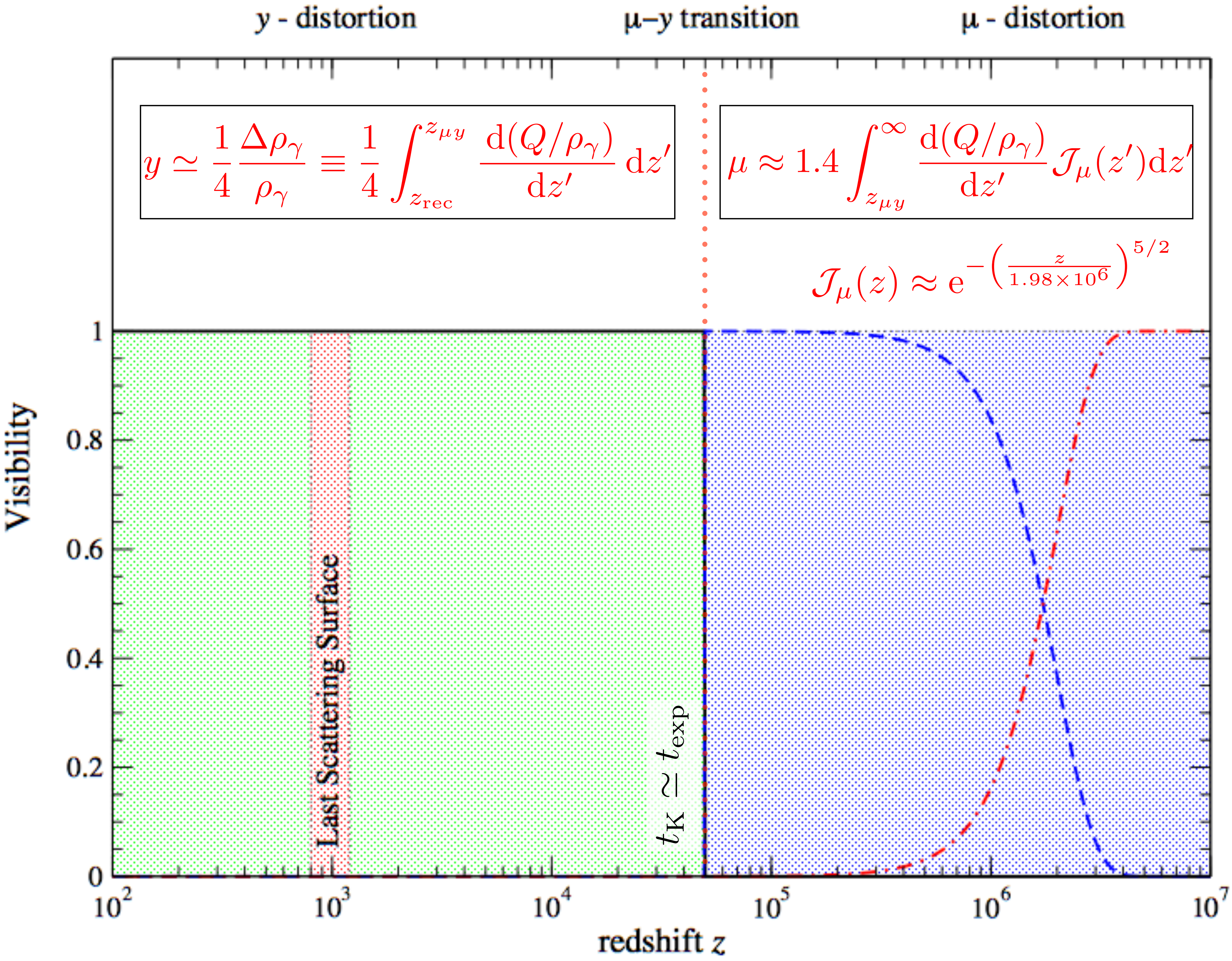
μ-y-era

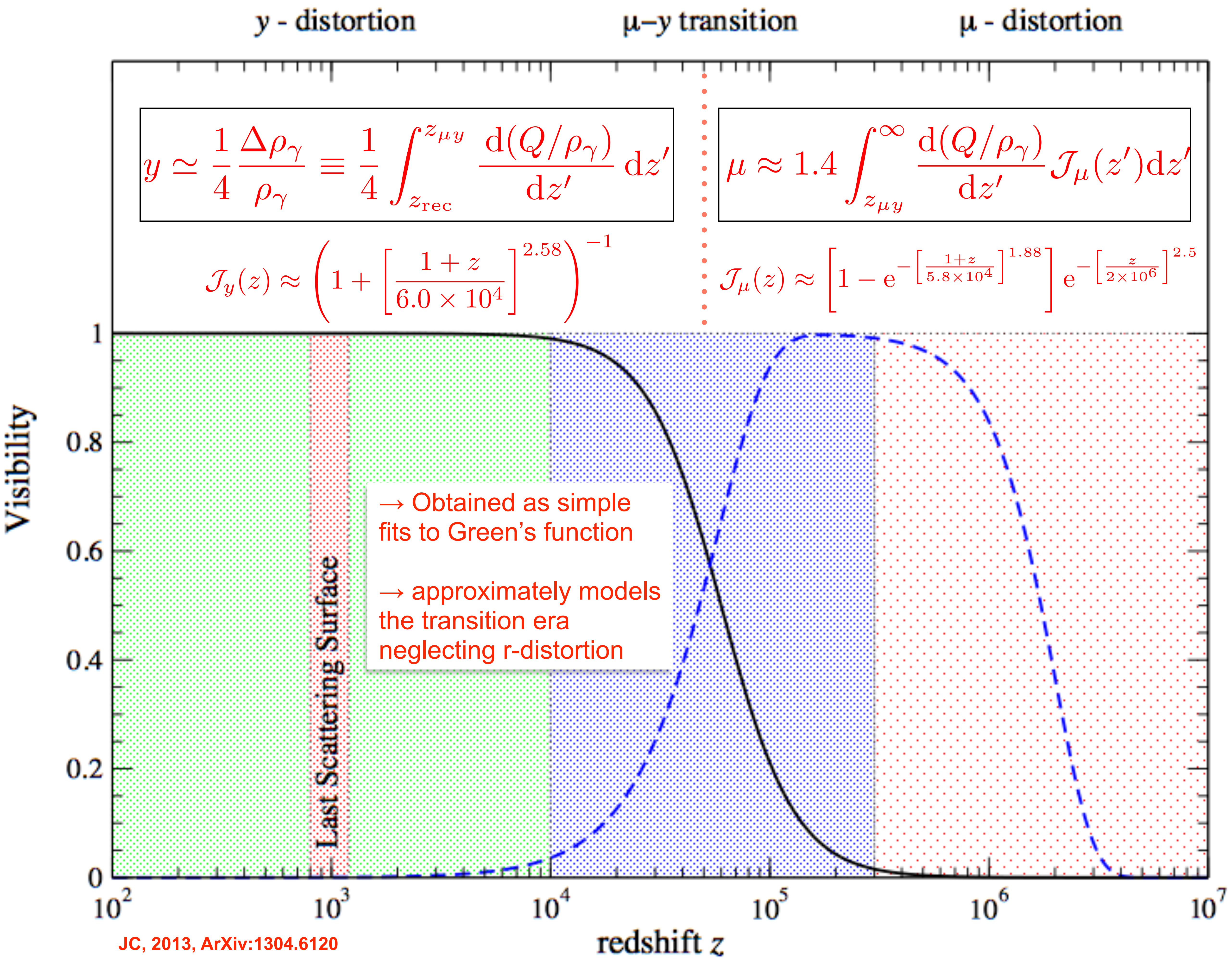
HI&He

y-distortion era

extra time-slicing at recombination

New hybrid era


y - distortion
μ–y transition
μ - distortion
$y \simeq \frac{1}{4}\frac{\Delta\rho_\gamma}{\rho_\gamma} \equiv \frac{1}{4}\int_{z_{\rm rec}}^{z_{\mu y}} \frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'}\,{\rm d}z'$
$\mu \approx 1.4 \int_{z_{\mu y}}^{\infty} \frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'}\mathcal{J}_\mu(z'){\rm d}z'$
$\mathcal{J}_\mu(z) \approx {\rm e}^{-\left(\frac{z}{1.98\times10^6}\right)^{5/2}}$
Visibility
1
0.8
0.6
0.4
0.2
0
Last Scattering Surface
$t_{\rm K} \simeq t_{\rm exp}$
10^2
10^3
10^4
10^5
10^6
10^7
redshift z



$$y \simeq \frac{1}{4}\frac{\Delta\rho_\gamma}{\rho_\gamma} \equiv \frac{1}{4}\int_{z_{\rm rec}}^{z_{\mu y}} \frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z'}\,\mathrm{d}z'$$

$$\mu \approx 1.4\int_{z_{\mu y}}^{\infty} \frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z'}\,\mathcal{J}_\mu(z')\,\mathrm{d}z'$$

$$\mathcal{J}_y(z) \approx \left(1+\left[\frac{1+z}{6.0\times10^4}\right]^{2.58}\right)^{-1}$$

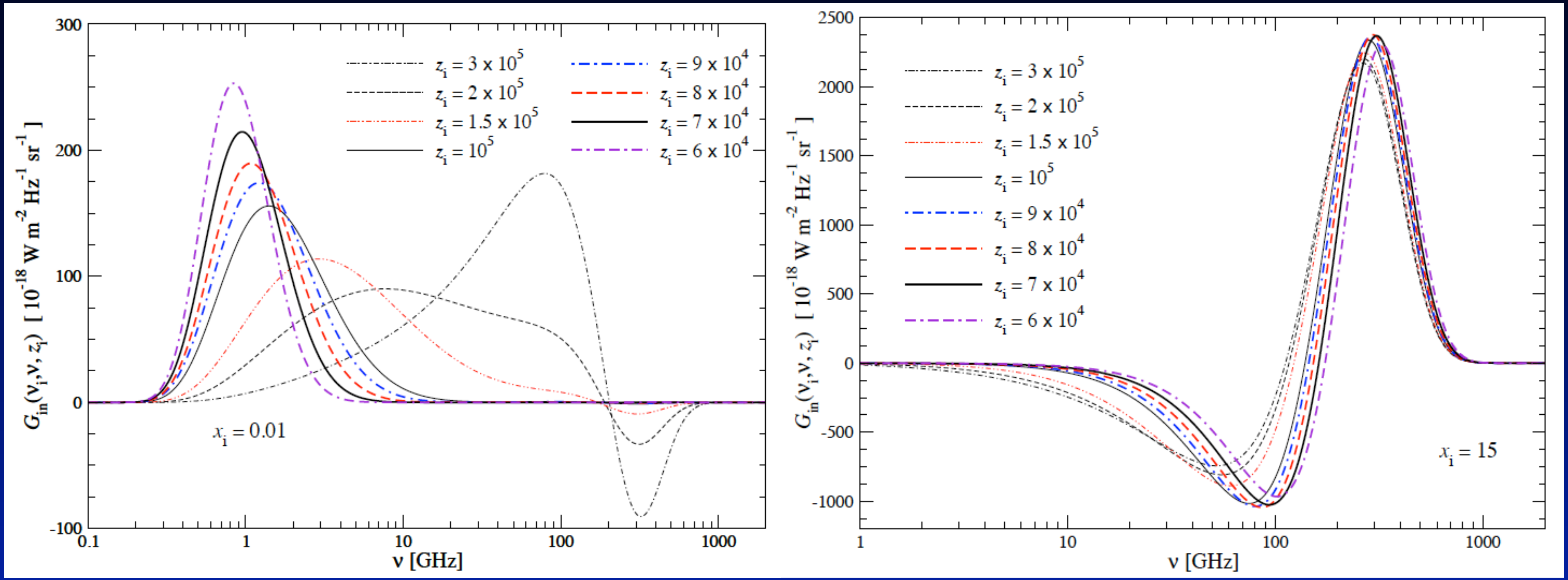
$$\mathcal{J}_\mu(z) \approx \left[1-\mathrm{e}^{-\left[\frac{1+z}{5.8\times10^4}\right]^{1.88}}\right]\mathrm{e}^{-\left[\frac{z}{2\times10^6}\right]^{2.5}}$$

→ Obtained as simple fits to Green's function

→ approximately models the transition era neglecting r-distortion

JC, 2013, ArXiv:1304.6120

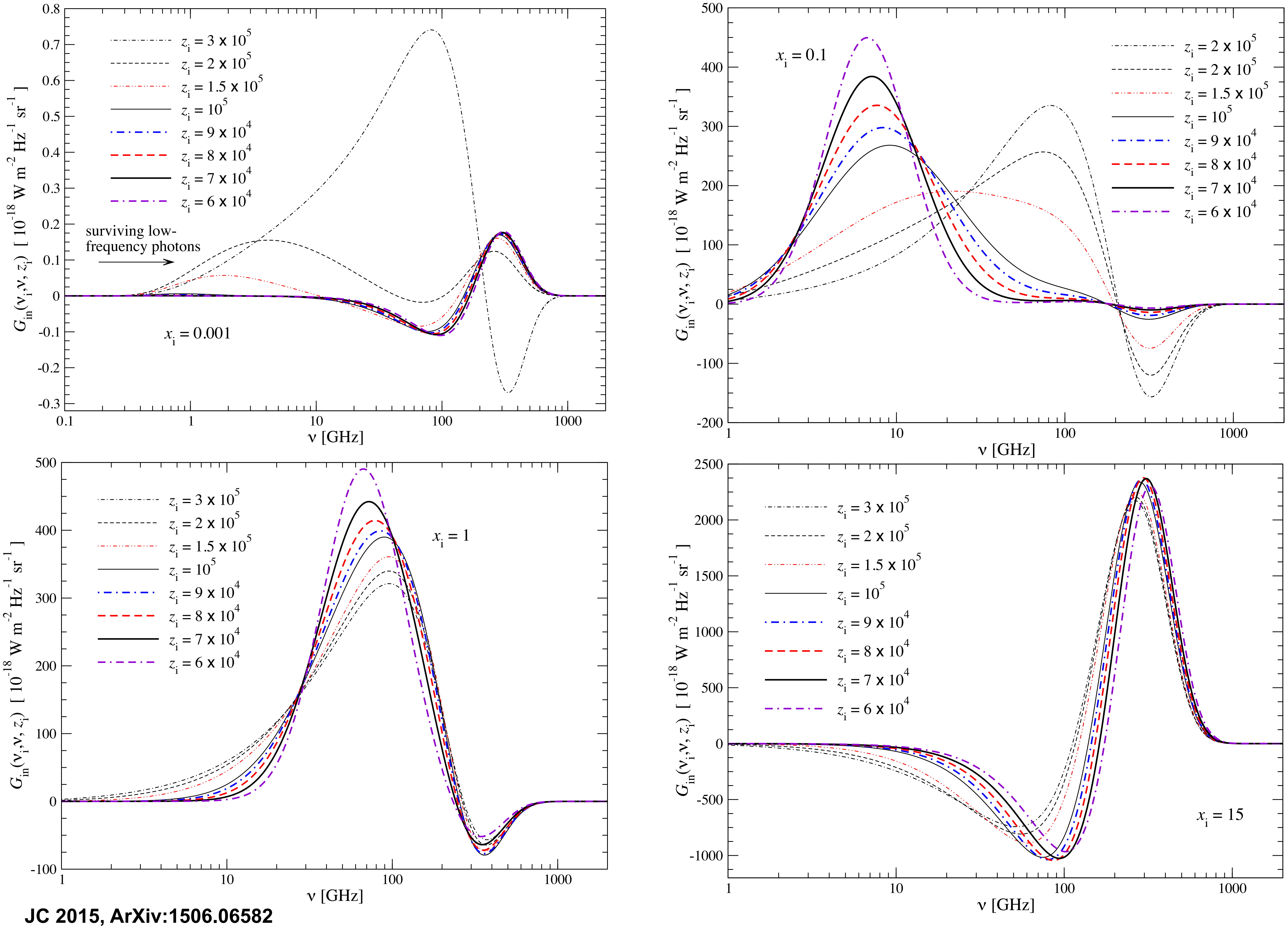
Green’s function for photon injection



- 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

Photon injection at later times



JC 2015, ArXiv:1506.06582

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

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

post-recombination

Physical mechanisms that lead to spectral distortions

Photon injection

- *Cooling by adiabatically expanding ordinary matter*
  (JC, 2005; JC & Sunyaev 2011; Khatri, Sunyaev & JC, 2011)
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  (Kawasaki et al., 1987; Hu & Silk, 1993; McDonald et al., 2001; JC, 2005; JC & Sunyaev, 2011; JC, 2013; JC & Jeong, 2013)
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- other exotic processes
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Part III: Distortions for different scenarios and what we may learn by studying them

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„low“ redshifts

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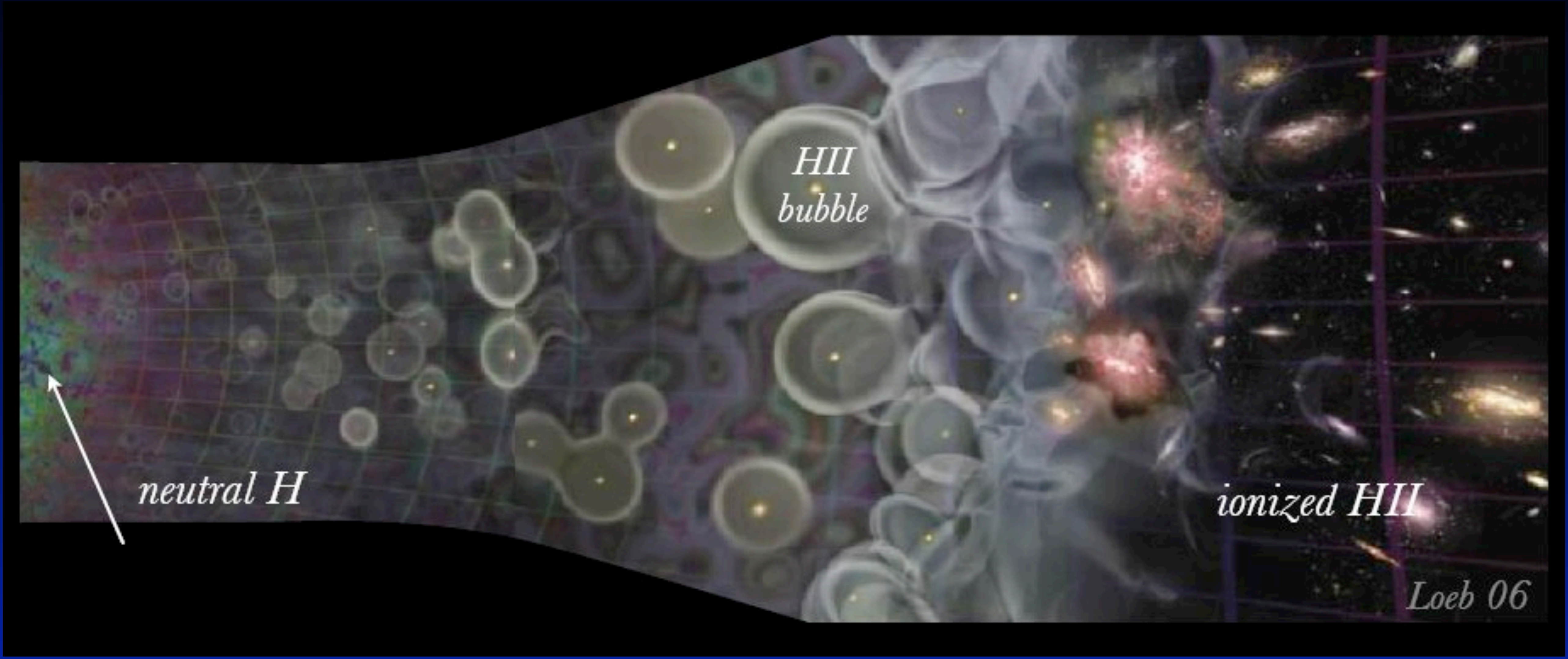
  (Sunyaev & Zeldovich, 1972; Cen & Ostriker, 1999)
- SZ-effect from clusters; effects of reionization
  (Refregier et al., 2003; Zhang et al. 2004; Trac et al. 2008)
- Additional exotic processes
  (Lochan et al. 2012; Bull & Kamionkowski, 2013; Brax et al., 2013; Tashiro et al. 2013)

Reionization and structure formation

Simple estimates for the distortion

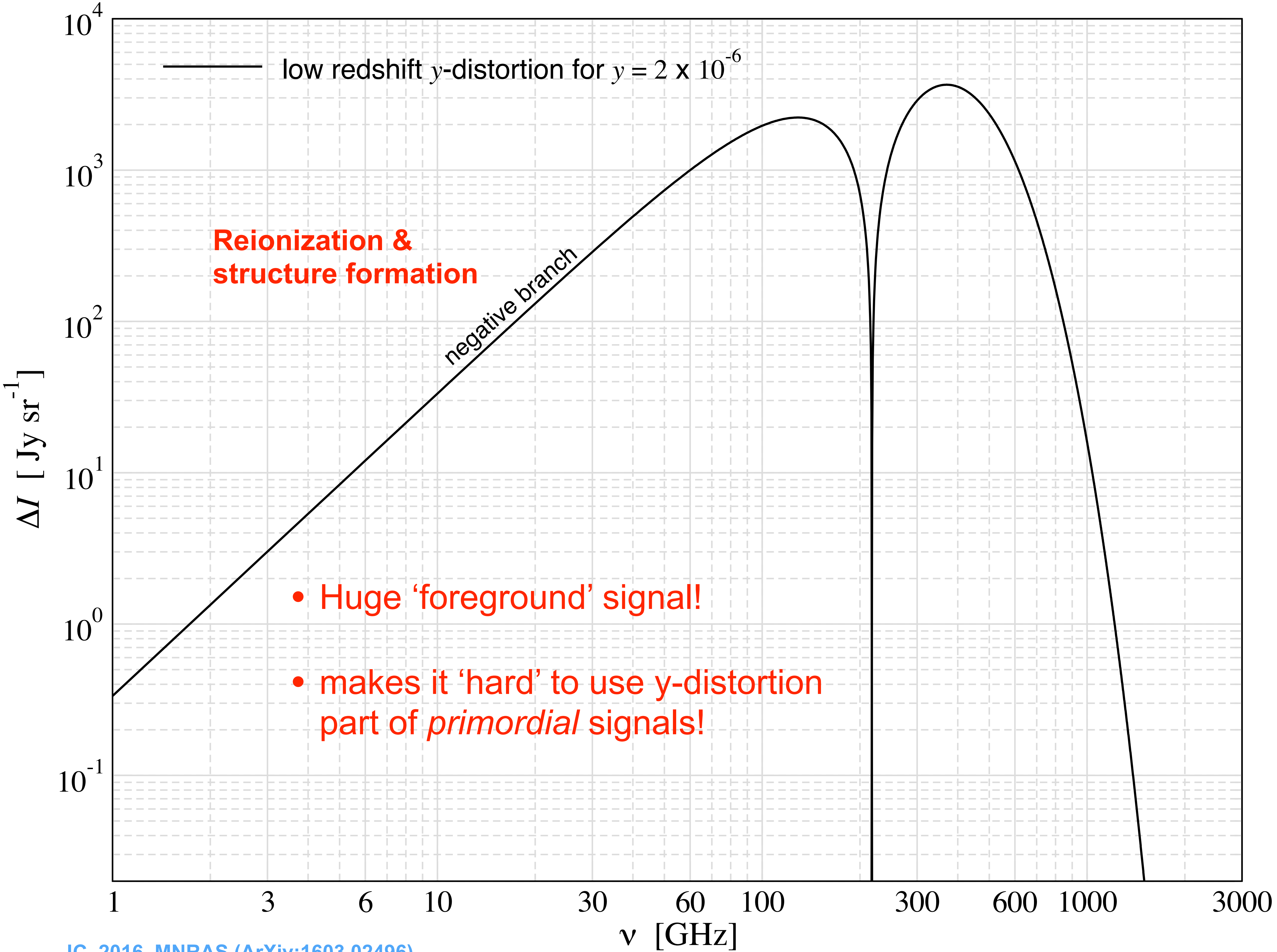


- Gas temperature $T \simeq 10^4$ K
- Thomson optical depth $\tau \simeq 0.1$

$$\Longrightarrow \quad y \simeq \frac{kT_{\rm e}}{m_{\rm e}c^2}\,\tau \approx 2\times10^{-7}$$

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

Average CMB spectral distortions

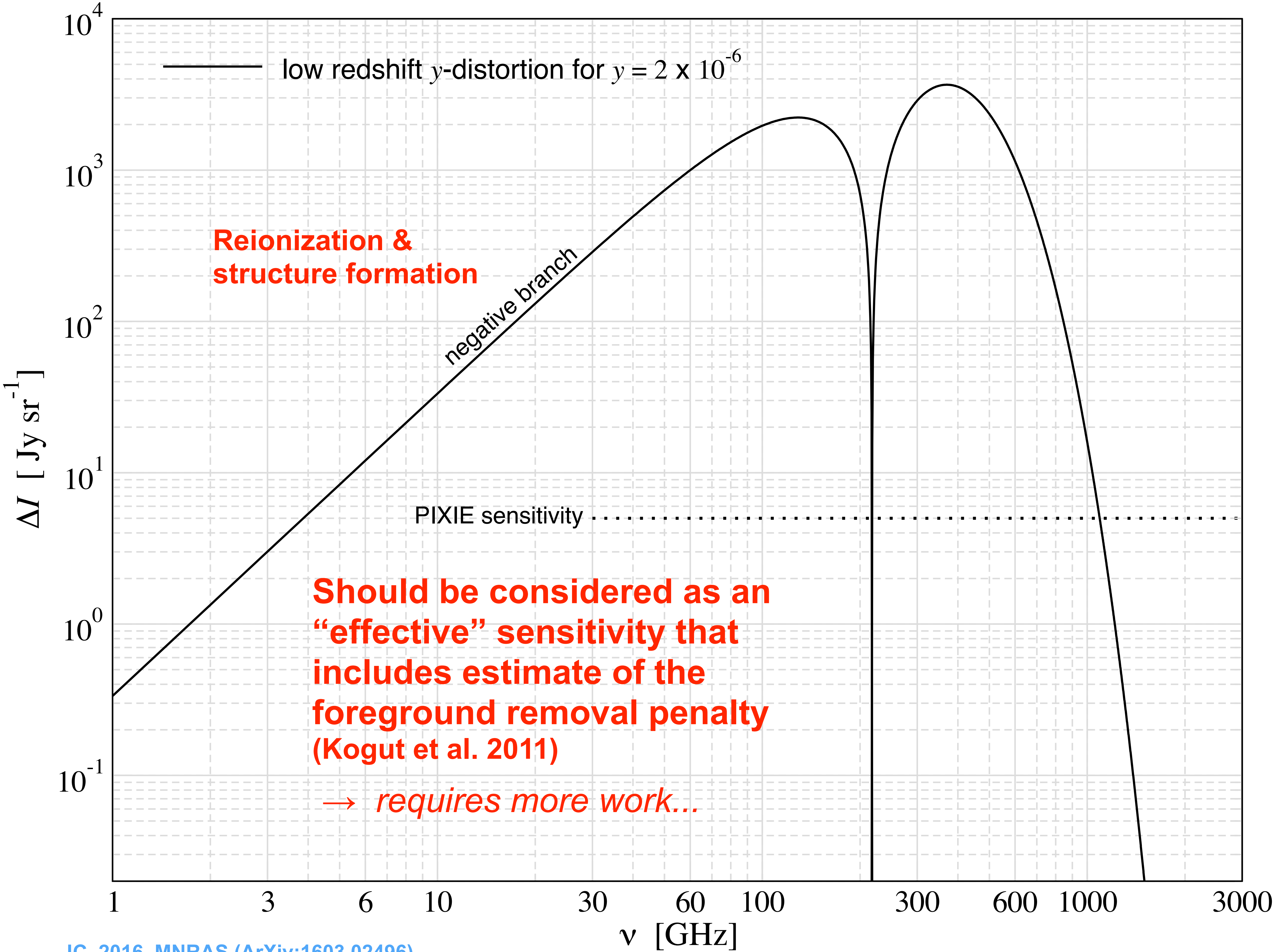


Reionization & structure formation

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

JC, 2016, MNRAS (ArXiv:1603.02496)

Average CMB spectral distortions



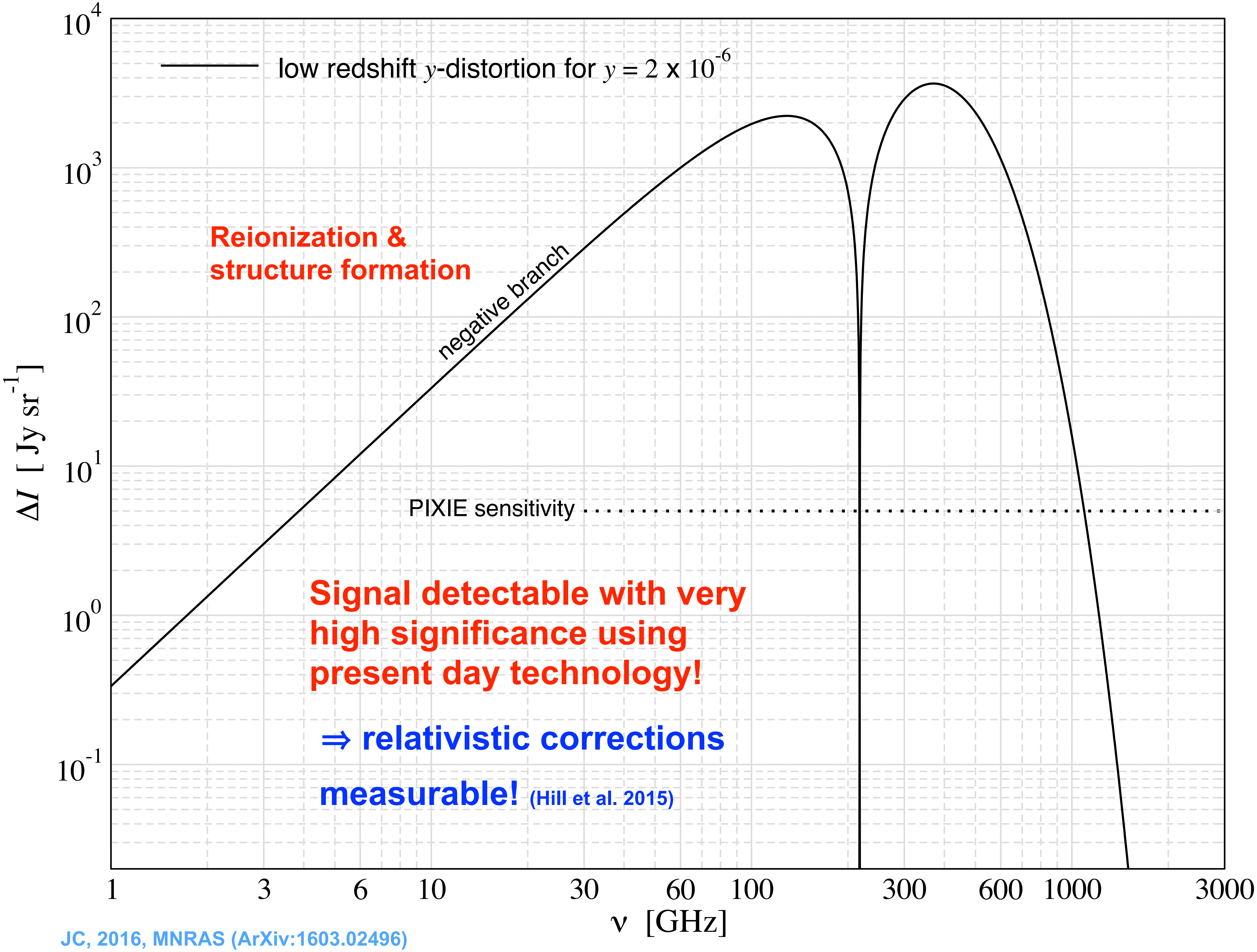
Reionization & structure formation

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

→ *requires more work...*

JC, 2016, MNRAS (ArXiv:1603.02496)

Average CMB spectral distortions



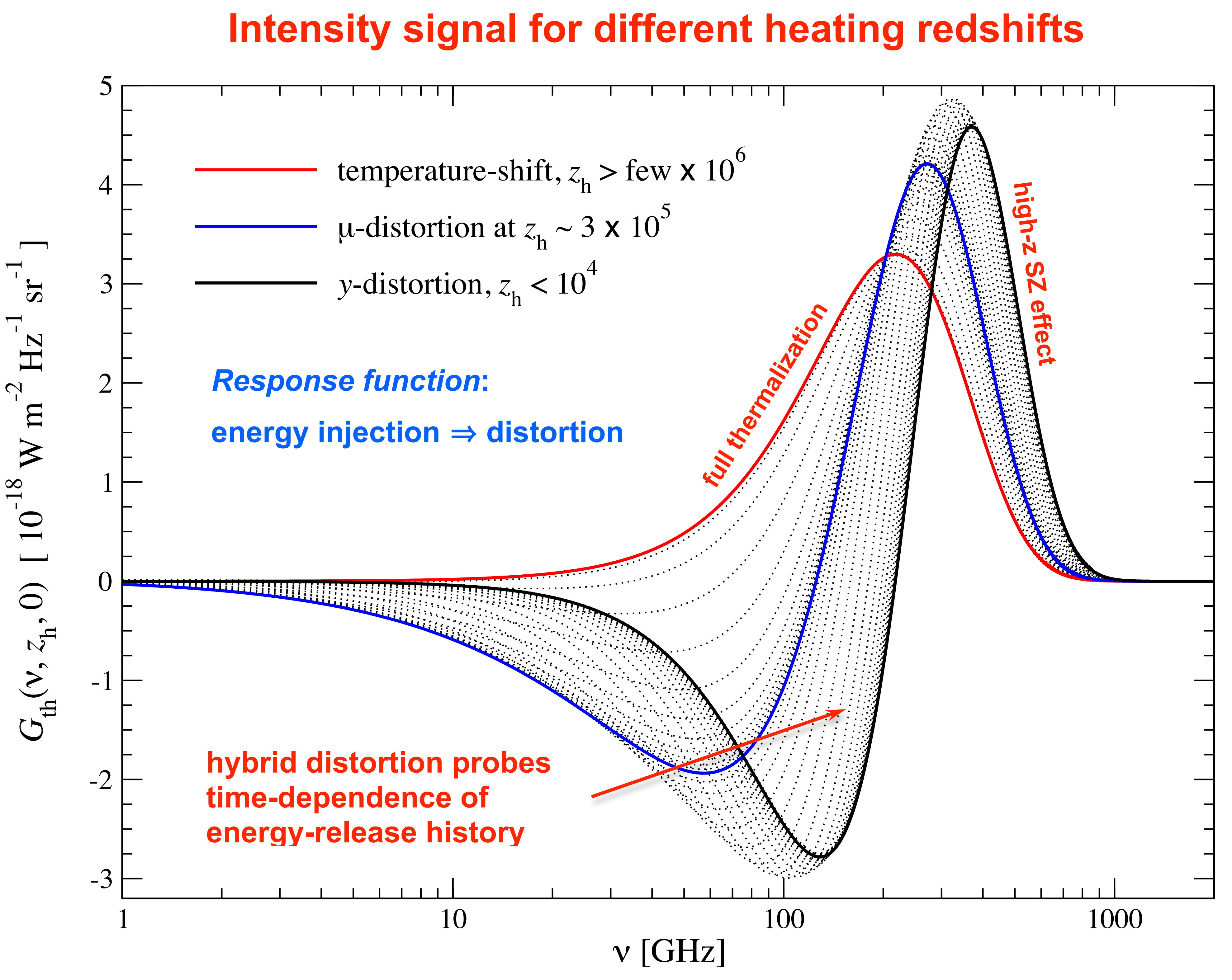
Reionization & structure formation

Signal detectable with very high significance using present day technology!

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

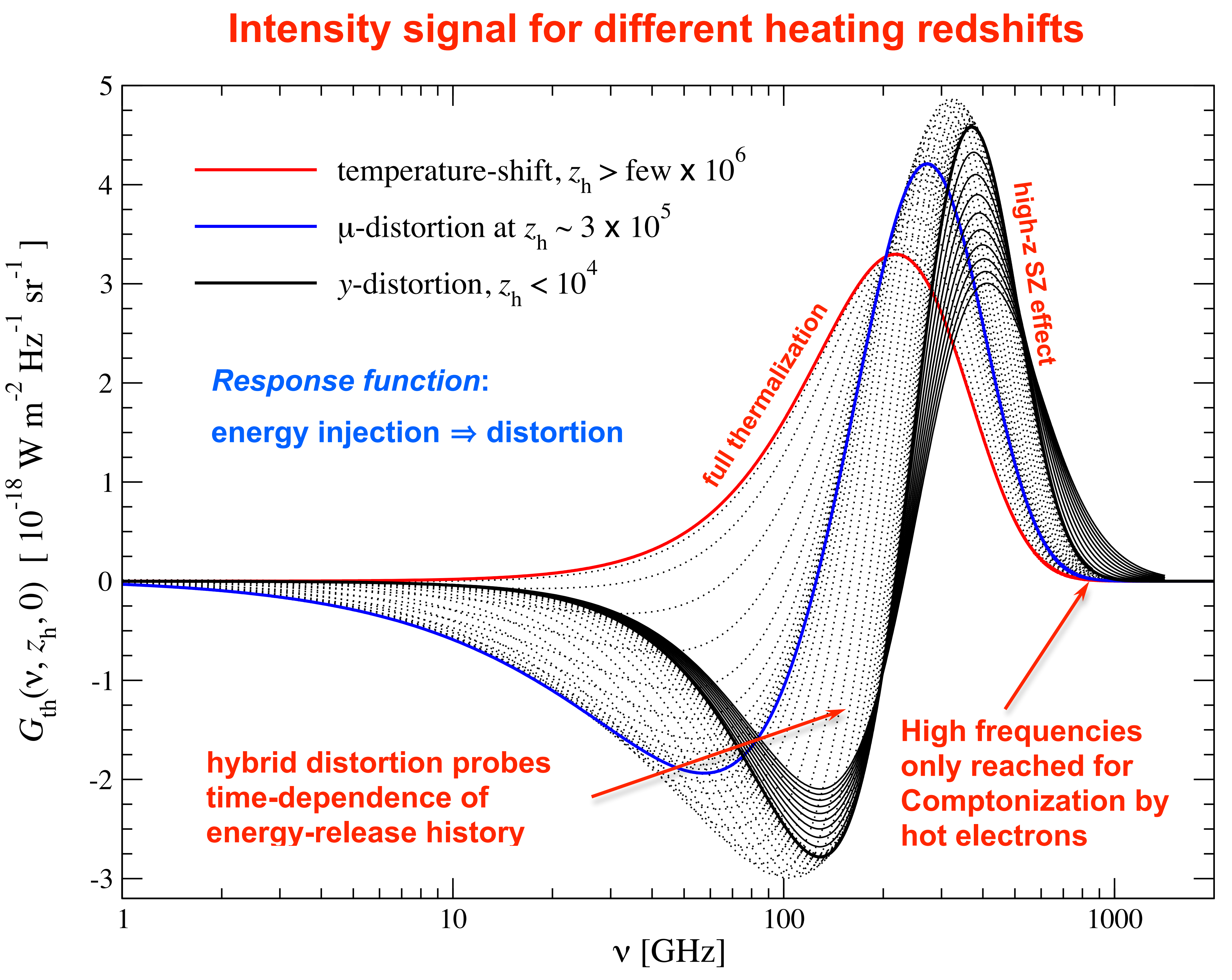
JC, 2016, MNRAS (ArXiv:1603.02496)

What does the spectrum look like after energy injection?



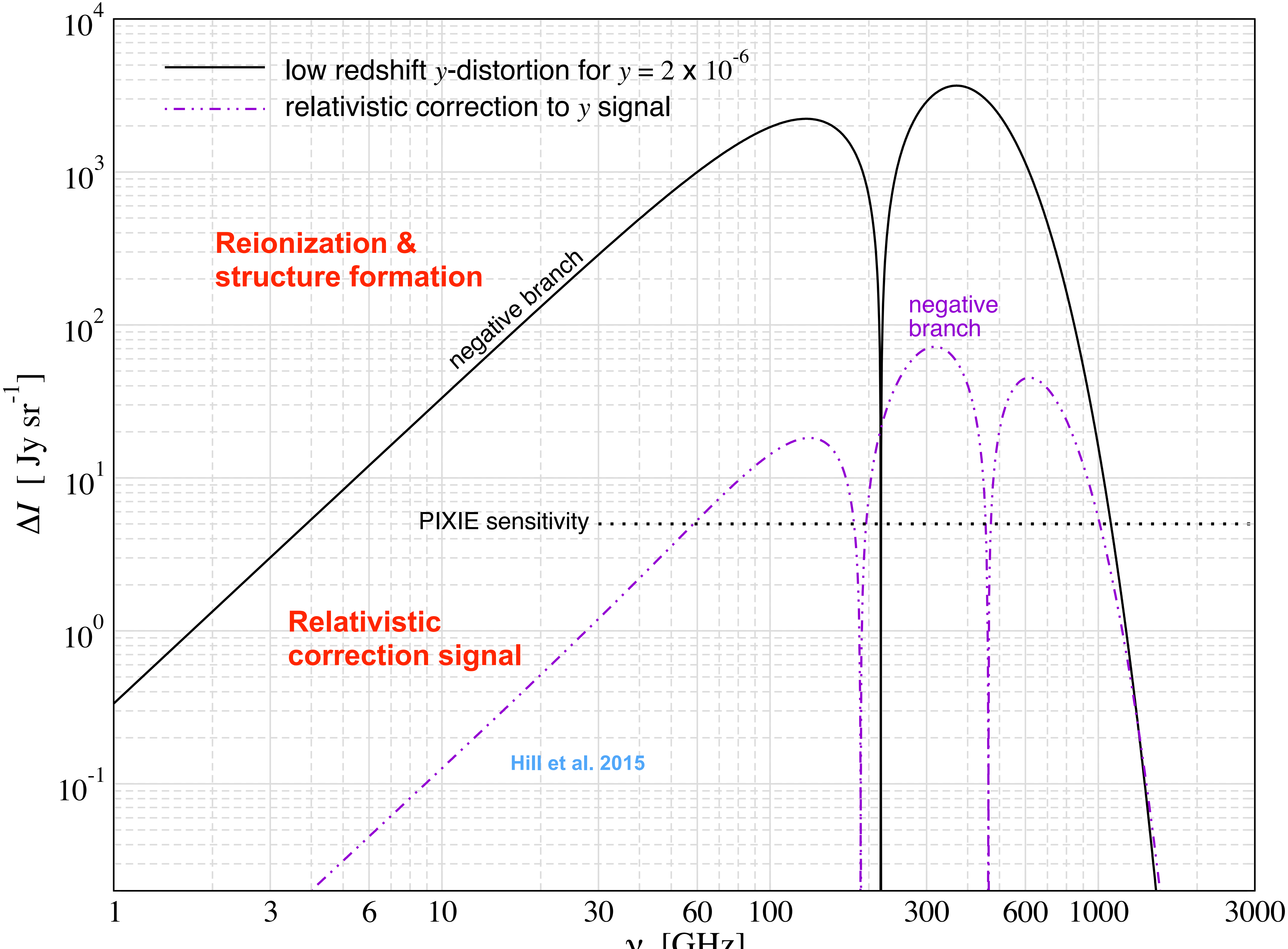
JC & Sunyaev, 2012, ArXiv:1109.6552
JC, 2013, ArXiv:1304.6120

What does the spectrum look like after energy injection?



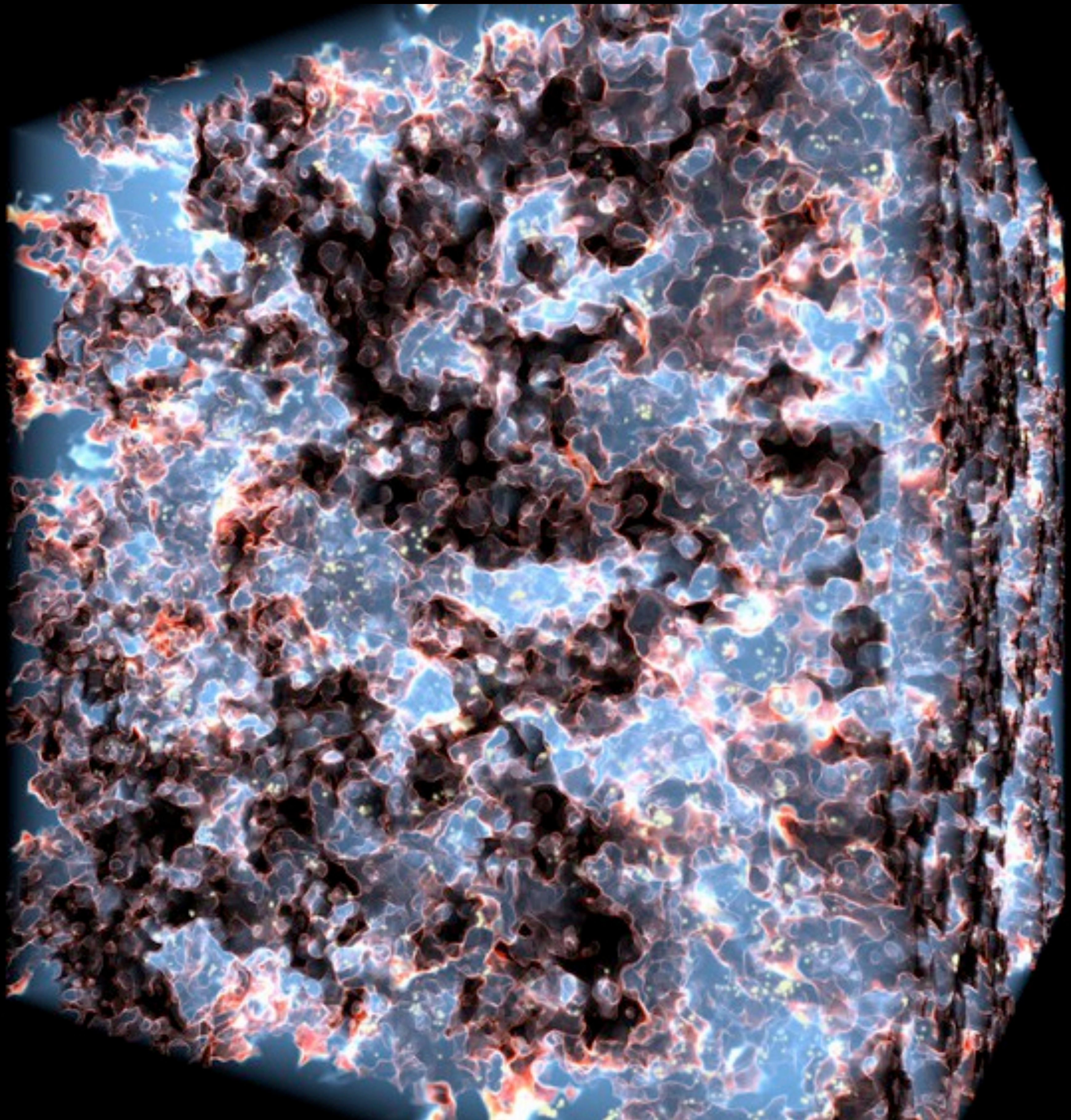
JC & Sunyaev, 2012, ArXiv:1109.6552
JC, 2013, ArXiv:1304.6120

Average CMB spectral distortions



JC, 2016, MNRAS (ArXiv:1603.02496)

Fluctuations of the y-parameter at large scales

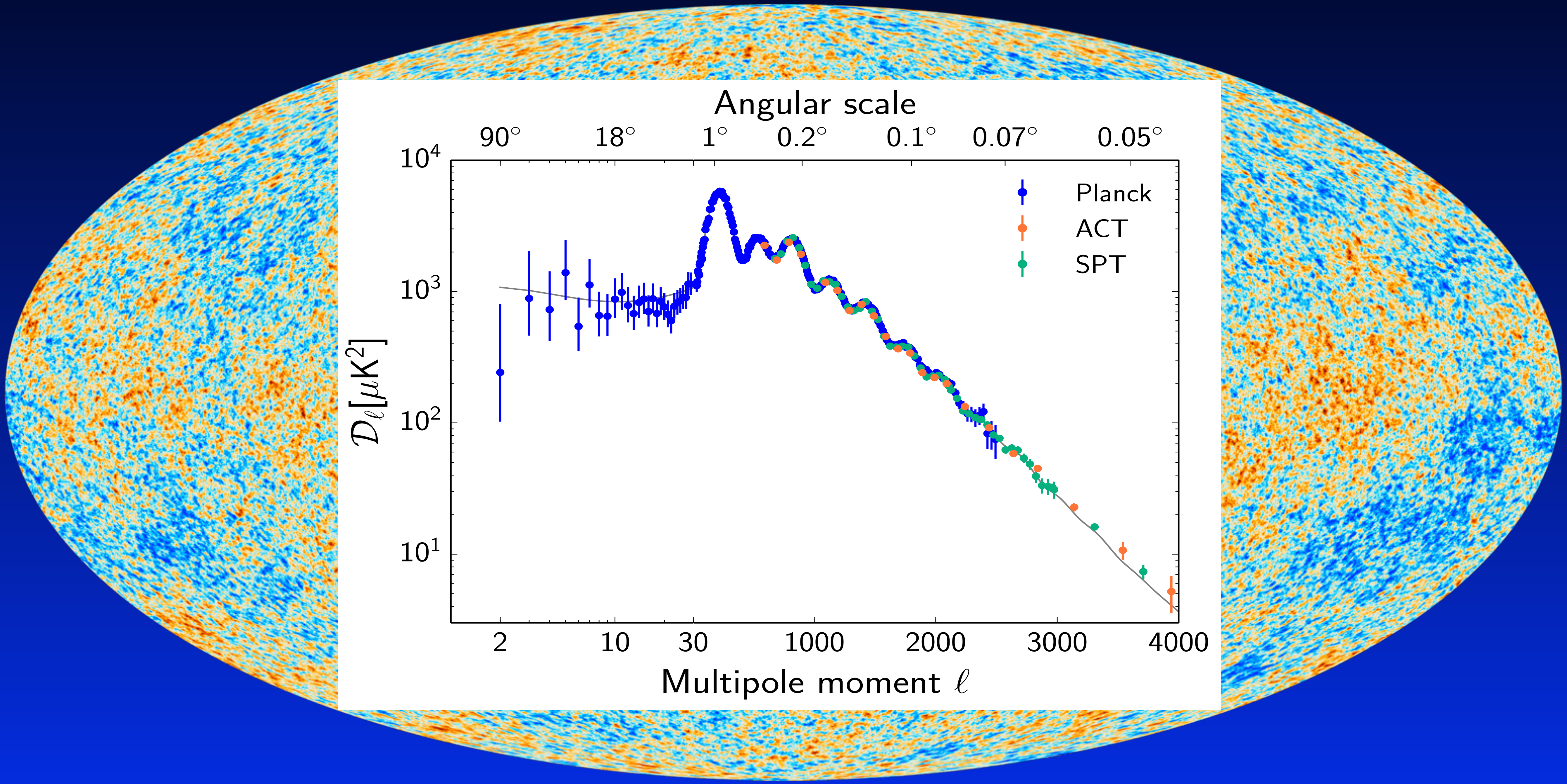


- spatial variations of the optical depth and temperature cause small-spatial variations of the y-parameter at different angular scales
- could tell us about the reionization sources and structure formation process
- additional independent piece of information!
- Cross-correlations

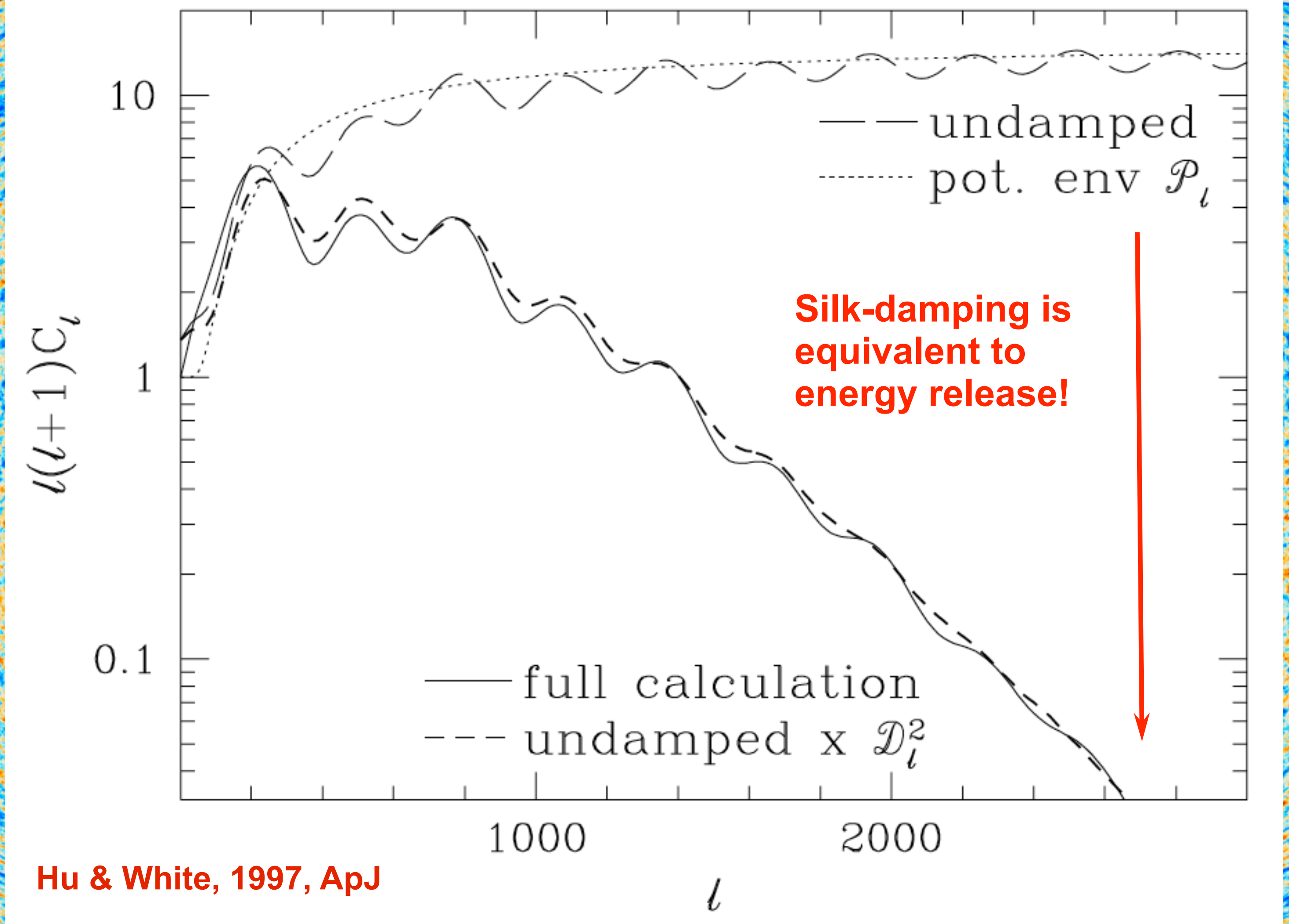
Example:
Simulation of reionization process (1Gpc/h) by *Alvarez* & *Abel*

The dissipation of small-scale acoustic modes

Dissipation of small-scale acoustic modes



Dissipation of small-scale acoustic modes



Silk-damping is equivalent to energy release!

Hu & White, 1997, ApJ

Energy release caused by dissipation process

'Obvious' dependencies:

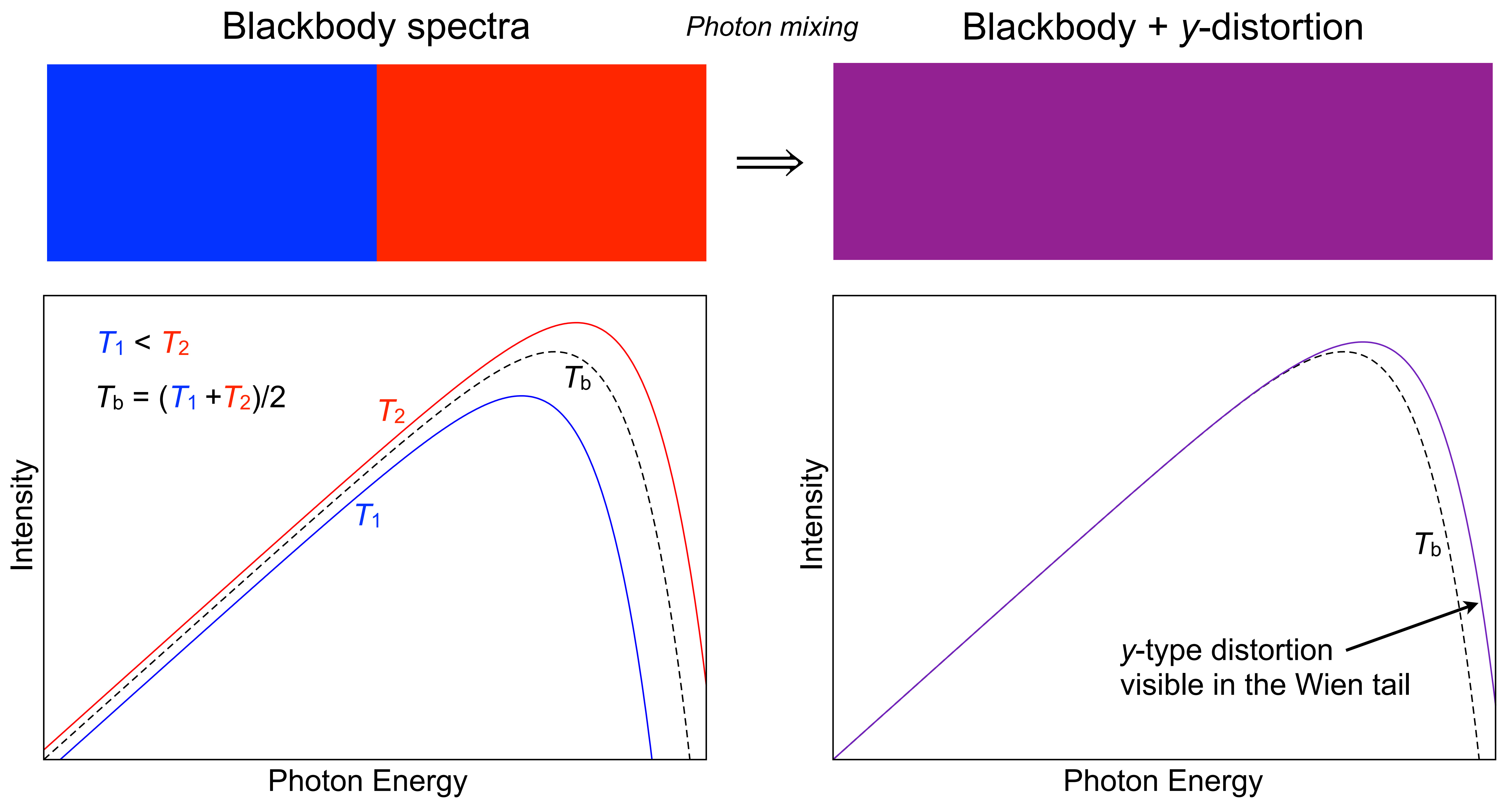
- *Amplitude* of the small-scale power spectrum
- *Shape* of the small-scale power spectrum
- *Dissipation scale* → $k_D \sim (H_0\, \Omega_{rel}^{1/2}\, N_{e,0})^{1/2}\, (1+z)^{3/2}$ at early times

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

Early power spectrum constraints from FIRAS

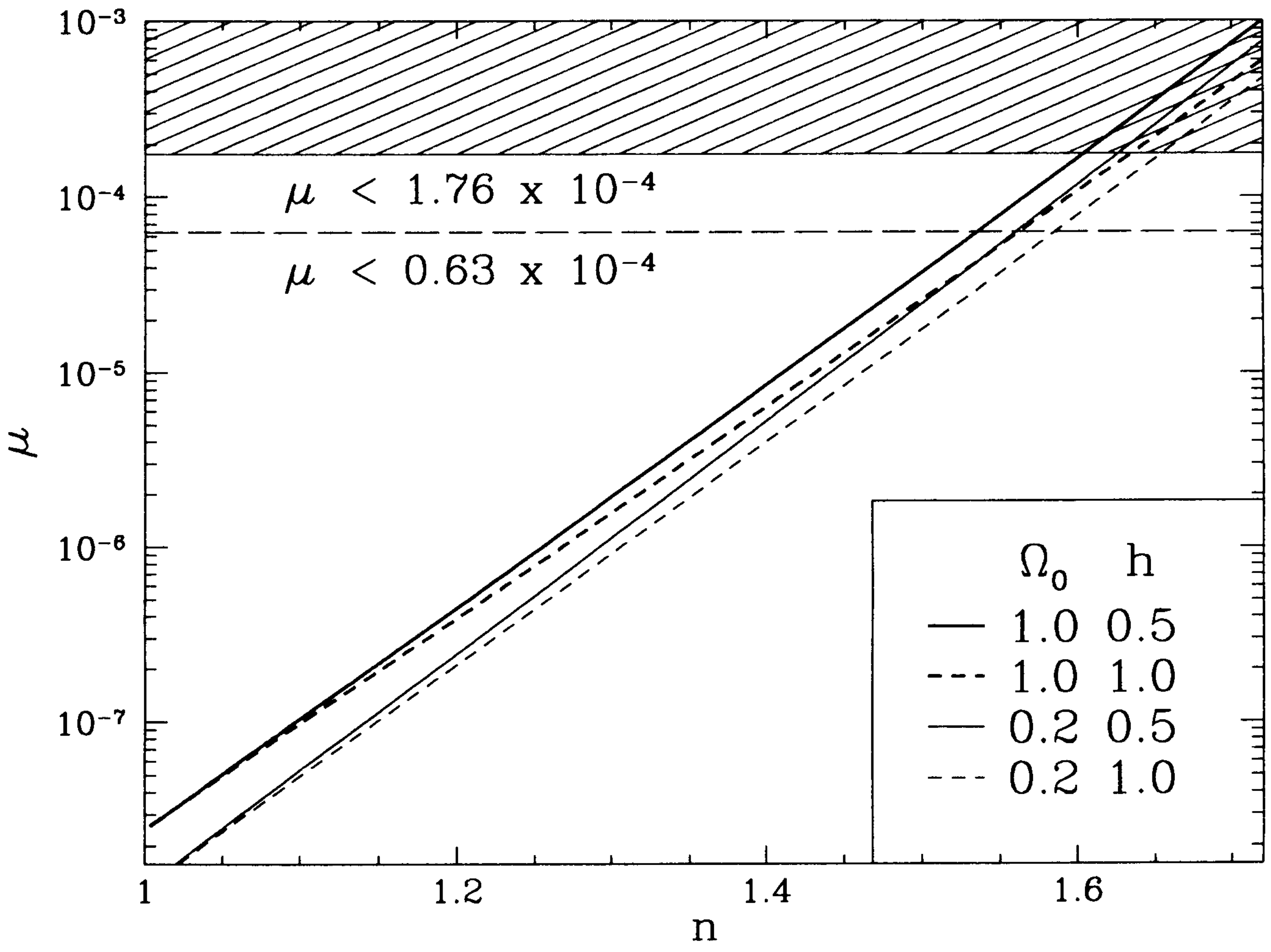


FIG. 1.—Spectral distortion μ, predicted from the full eq. (11), as a function of the power index n for a normalization at the mean of the *COBE* DMR detection $(\Delta T/T)_{10^\circ} = 1.12 \times 10^{-5}$. With the uncertainties on *both* the DMR and FIRAS measurements, the conservative 95% upper 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
- *$\mu \sim 10^{-8}$ for scale-invariant power spectrum*
- $n_S \lesssim 1.6$

Hu, Scott & Silk, 1994

Effective energy release caused by damping effect

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

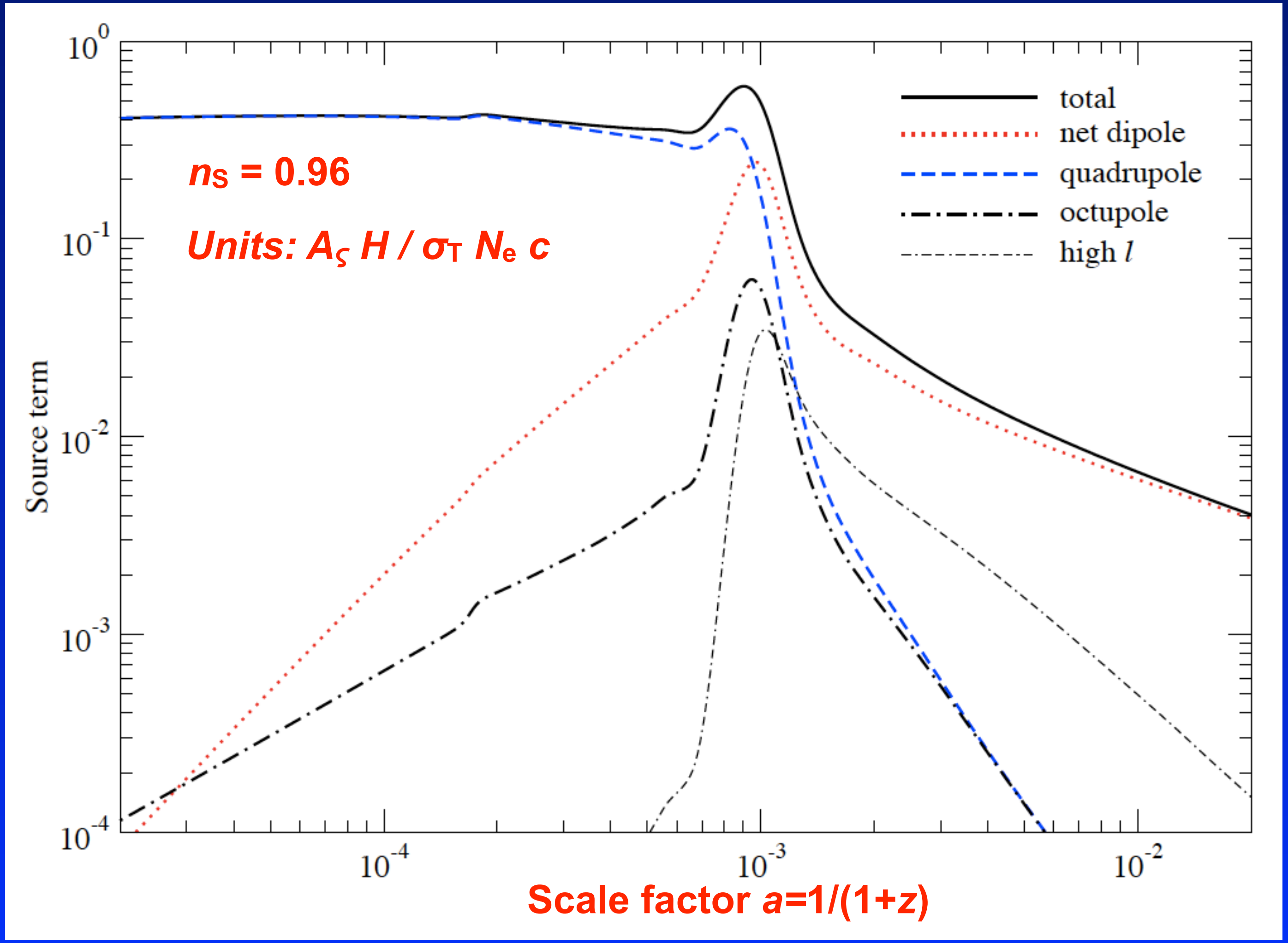
$$\frac{1}{a^4\rho_\gamma}\frac{\mathrm{d}a^4 Q_{\rm ac}}{\mathrm{d}t} = 4\sigma_{\rm T} N_{\rm e} c \left\langle \frac{(3\Theta_1-\beta)^2}{3} + \frac{9}{2}\Theta_2^2 - \frac{1}{2}\Theta_2(\Theta_0^{\rm P}+\Theta_2^{\rm P}) + \sum_{l\geq 3}(2l+1)\Theta_\ell^2\right\rangle$$

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



$n_S = 0.96$

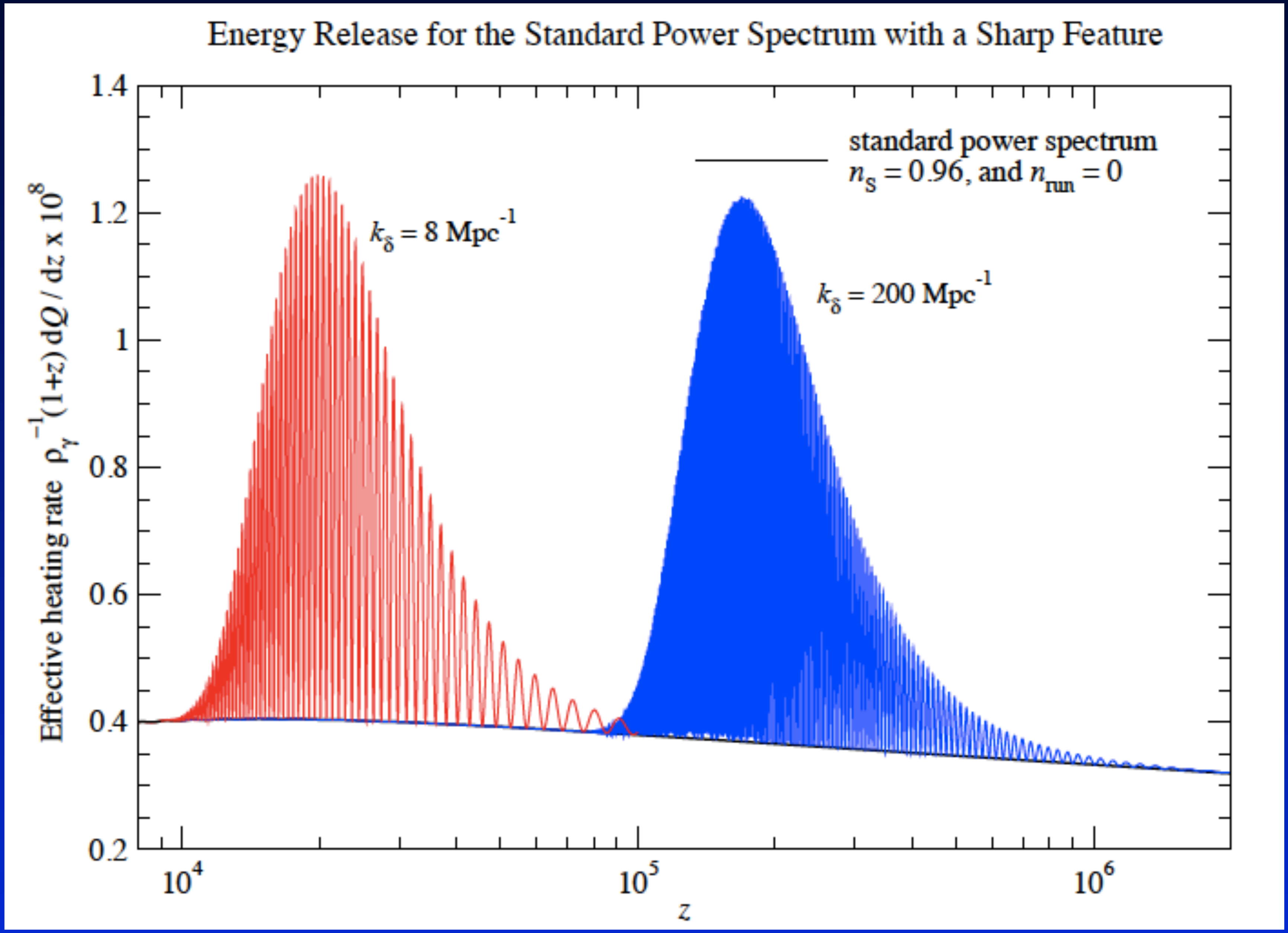
Units: $A_S\, H / \sigma_T N_e c$

Scale factor $a=1/(1+z)$

- *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

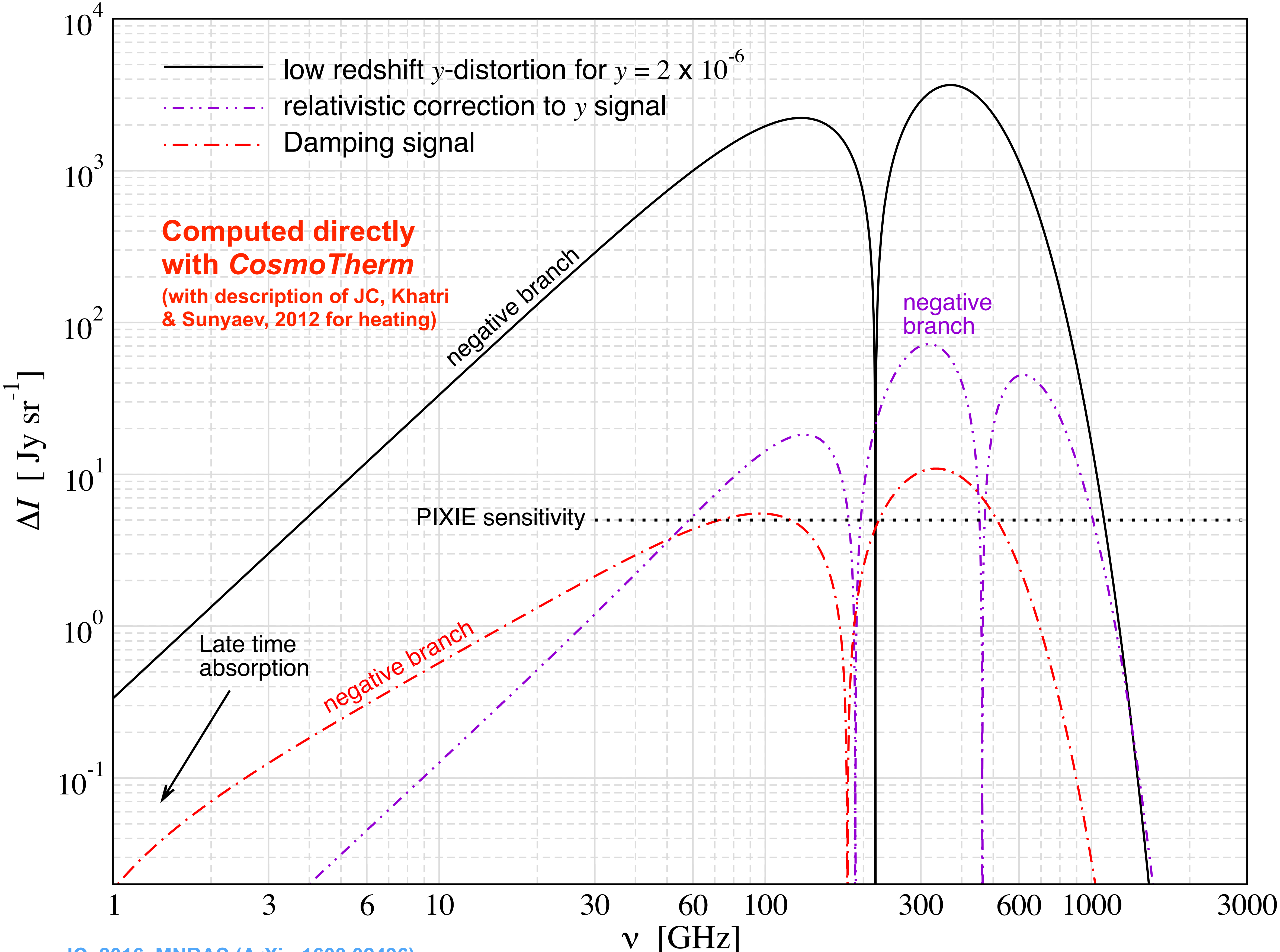
- Single mode with wavenumber *k* dissipates its energy at

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

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

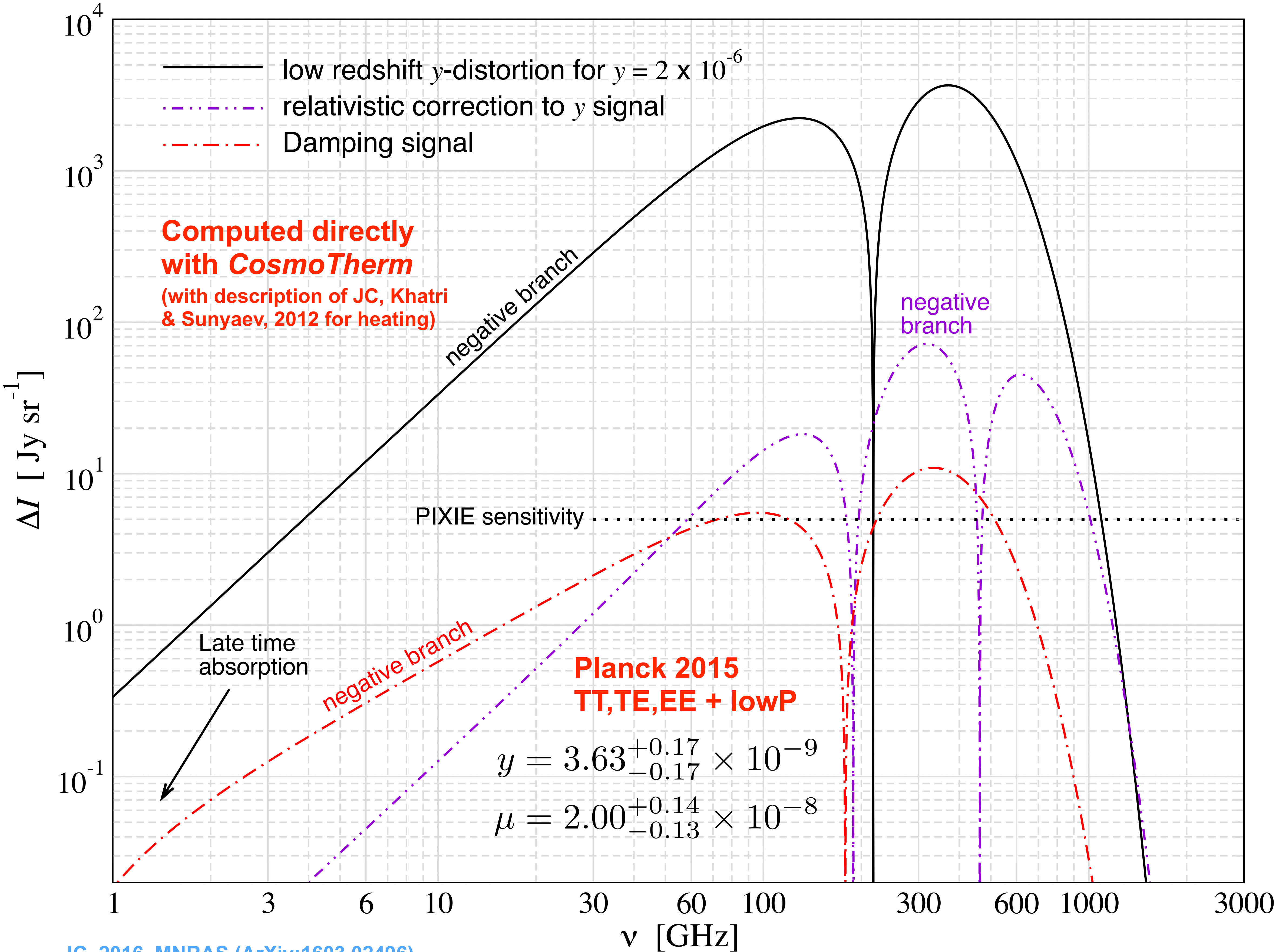
- Modes with *k* < 50 Mpc^{-1} cause *y*-distortion

Average CMB spectral distortions



JC, 2016, MNRAS (ArXiv:1603.02496)

Average CMB spectral distortions



Computed directly with *CosmoTherm*

(with description of JC, Khatri & Sunyaev, 2012 for heating)

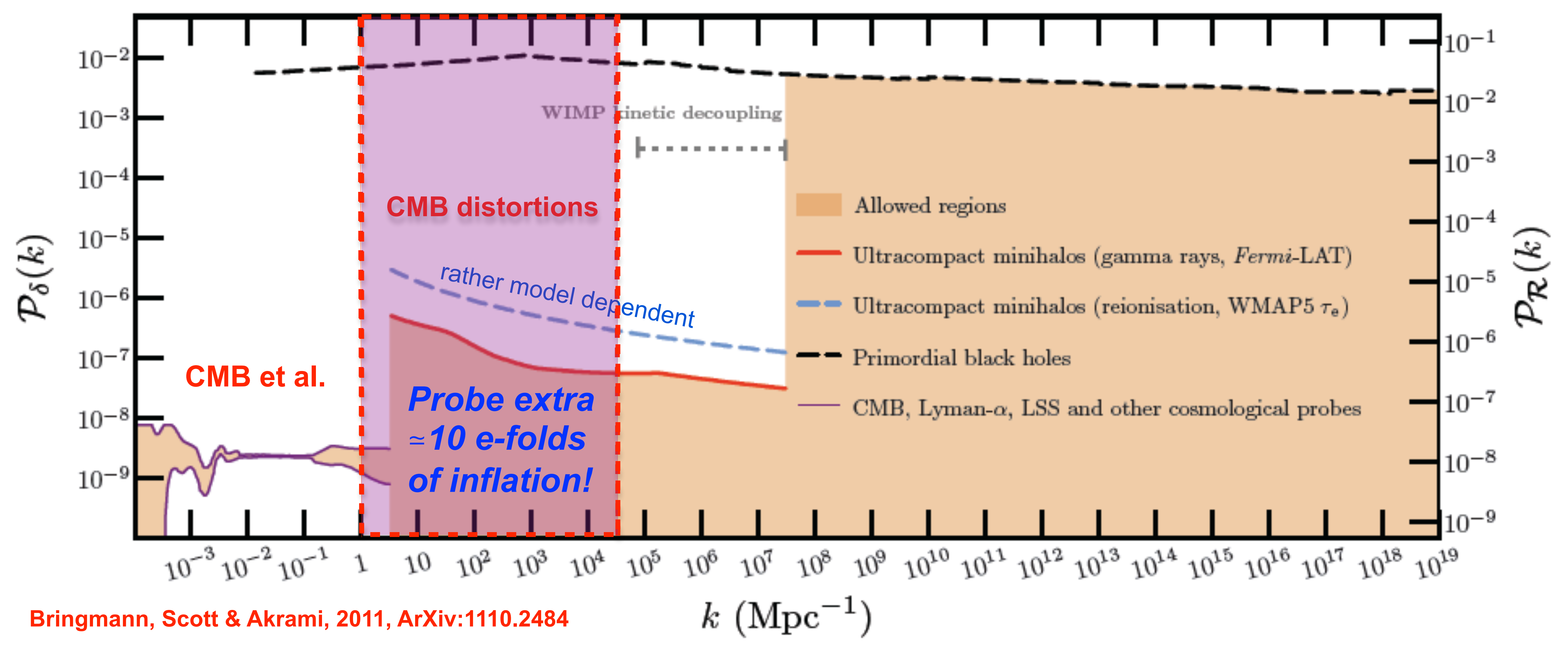
Planck 2015 TT,TE,EE + lowP

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

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

JC, 2016, MNRAS (ArXiv:1603.02496)

Distortions provide general power spectrum constraints!

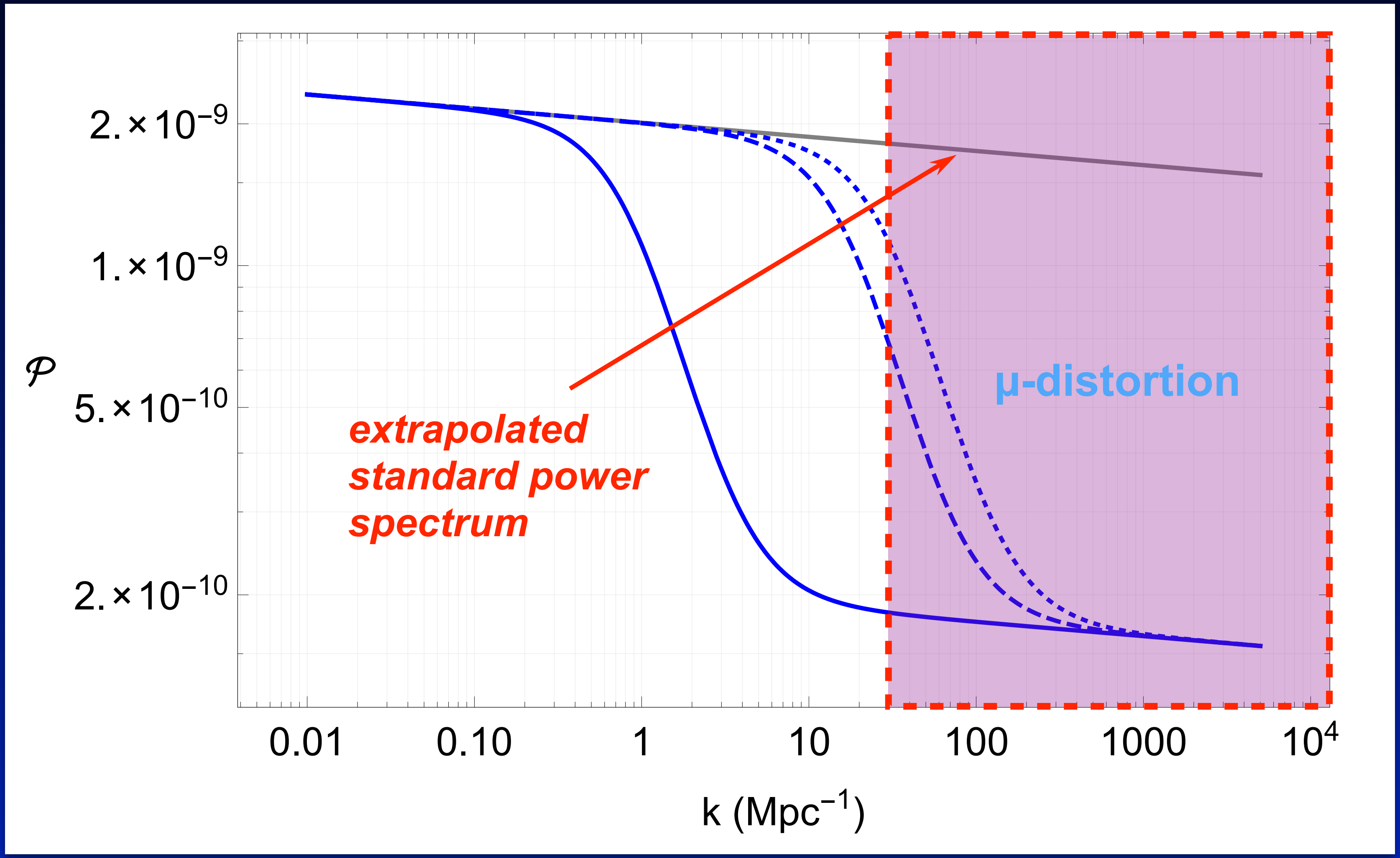


Bringmann, Scott & Akrami, 2011, ArXiv:1110.2484

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

Shedding Light on the 'Small-Scale Crisis'



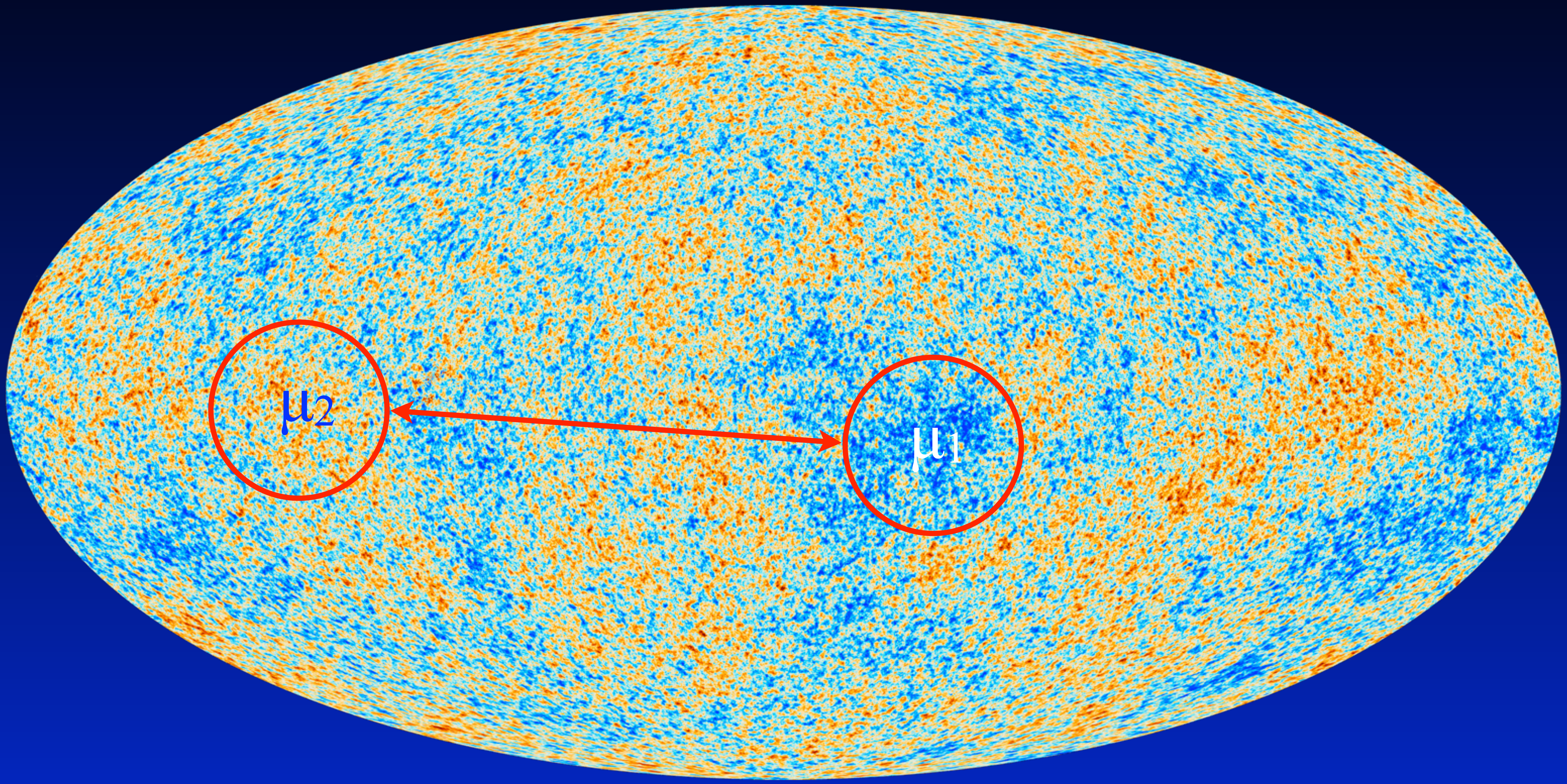
- 'missing satellite' problem
- 'too-big-to-fail'
- Cusp-vs-core problem

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

- A primordial suppression would result in a very small μ-distortions
- Spectral distortion measurements can test this question!

Nakama, JC & Kamionkowski, ArXiv:1703.10559

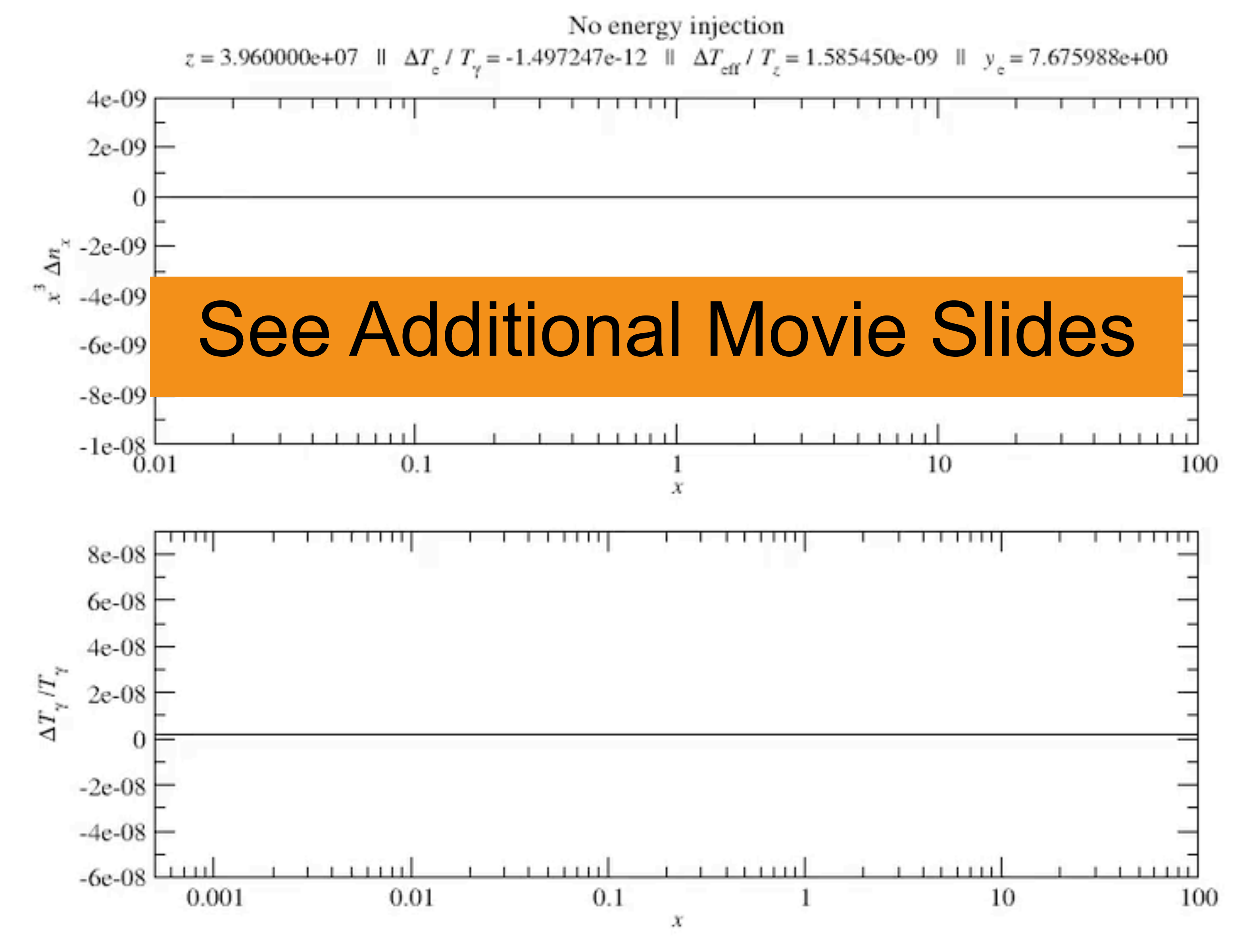
Spatially varying heating and dissipation of acoustic modes for non-Gaussian perturbations



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

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

Spectral distortion caused by the cooling of ordinary matter



See Additional Movie Slides

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

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

- 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

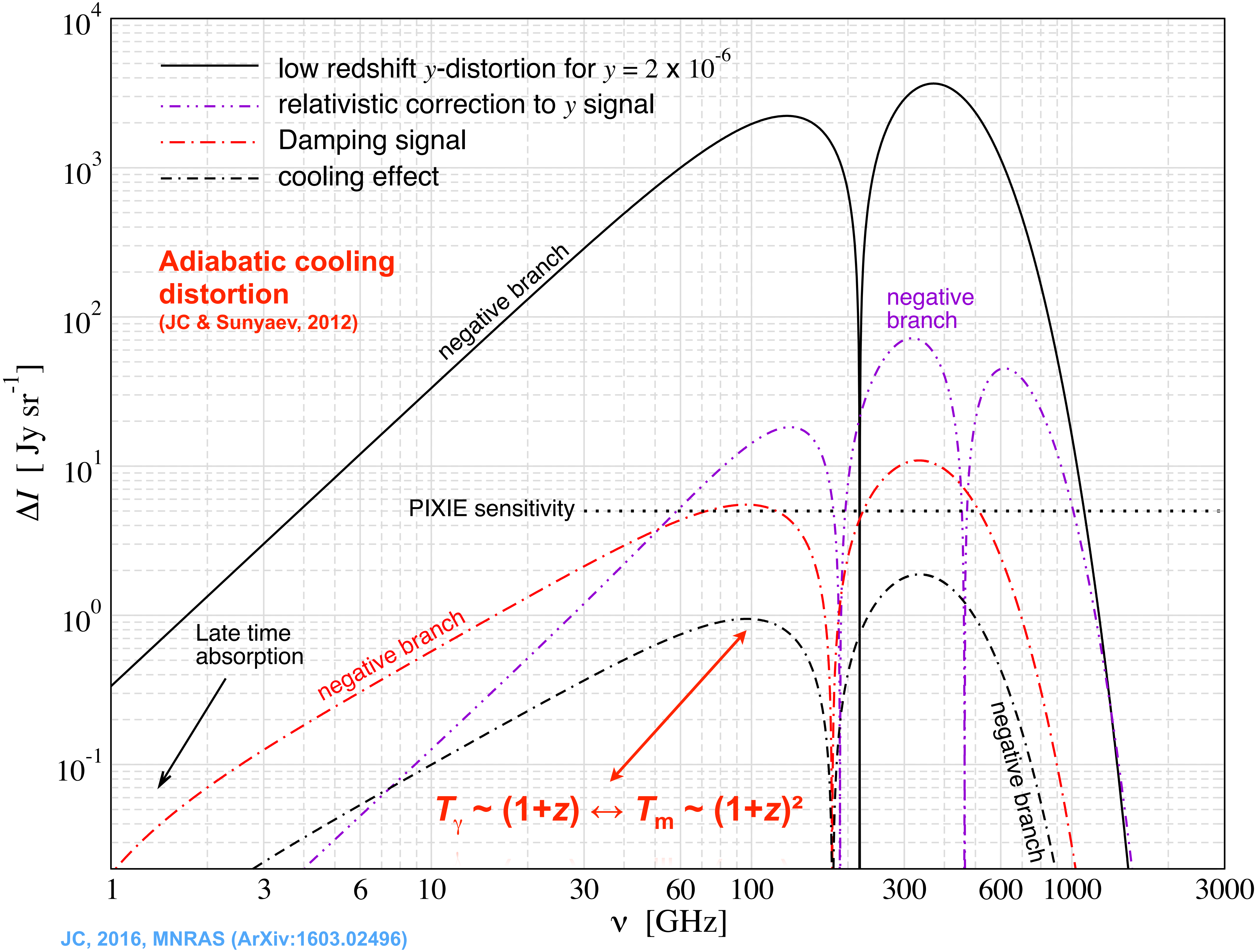
$$\Rightarrow \frac{\mathrm{d}a^4\rho_\gamma}{a^4\mathrm{d}t} \simeq -Hk\alpha_\mathrm{h}T_\gamma \propto (1+z)^6$$

- 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



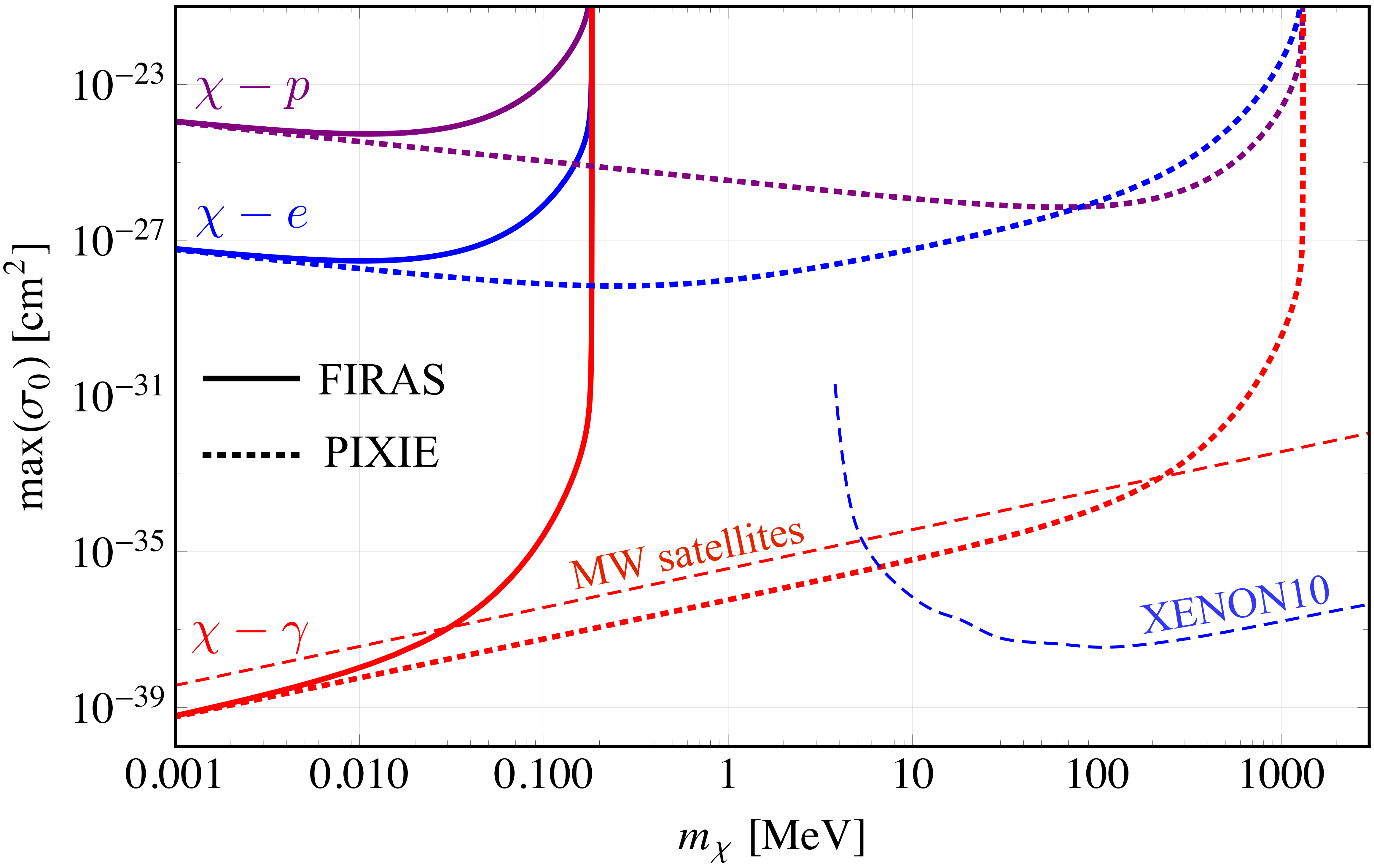
Adiabatic cooling distortion

(JC & Sunyaev, 2012)

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

JC, 2016, MNRAS (ArXiv:1603.02496)

Distortion constraints on DM interactions through adiabatic cooling effect



Ali-Haimoud, JC & Kamionkowski, 2015

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!

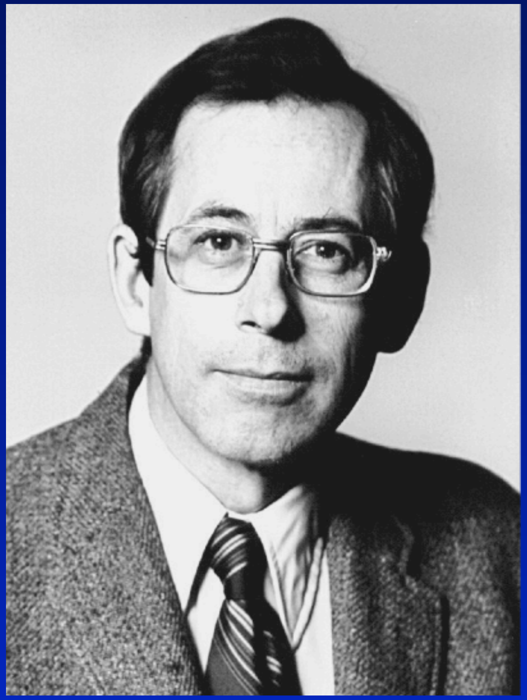
Moscow

Princeton

Yakov Zeldovich

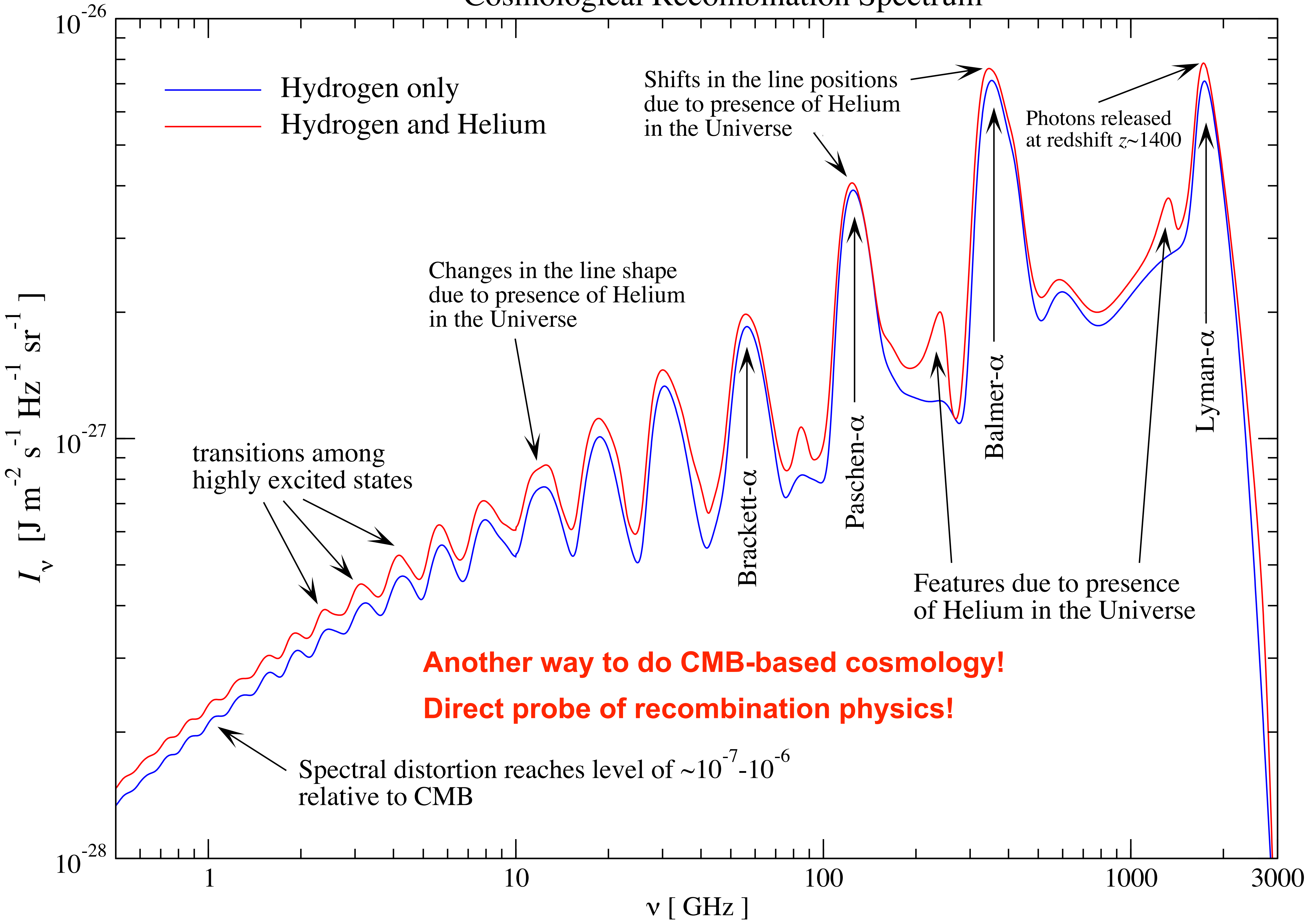
Vladimir Kurt
(UV astronomer)

Rashid Sunyaev



Jim Peebles

Cosmological Recombination Spectrum

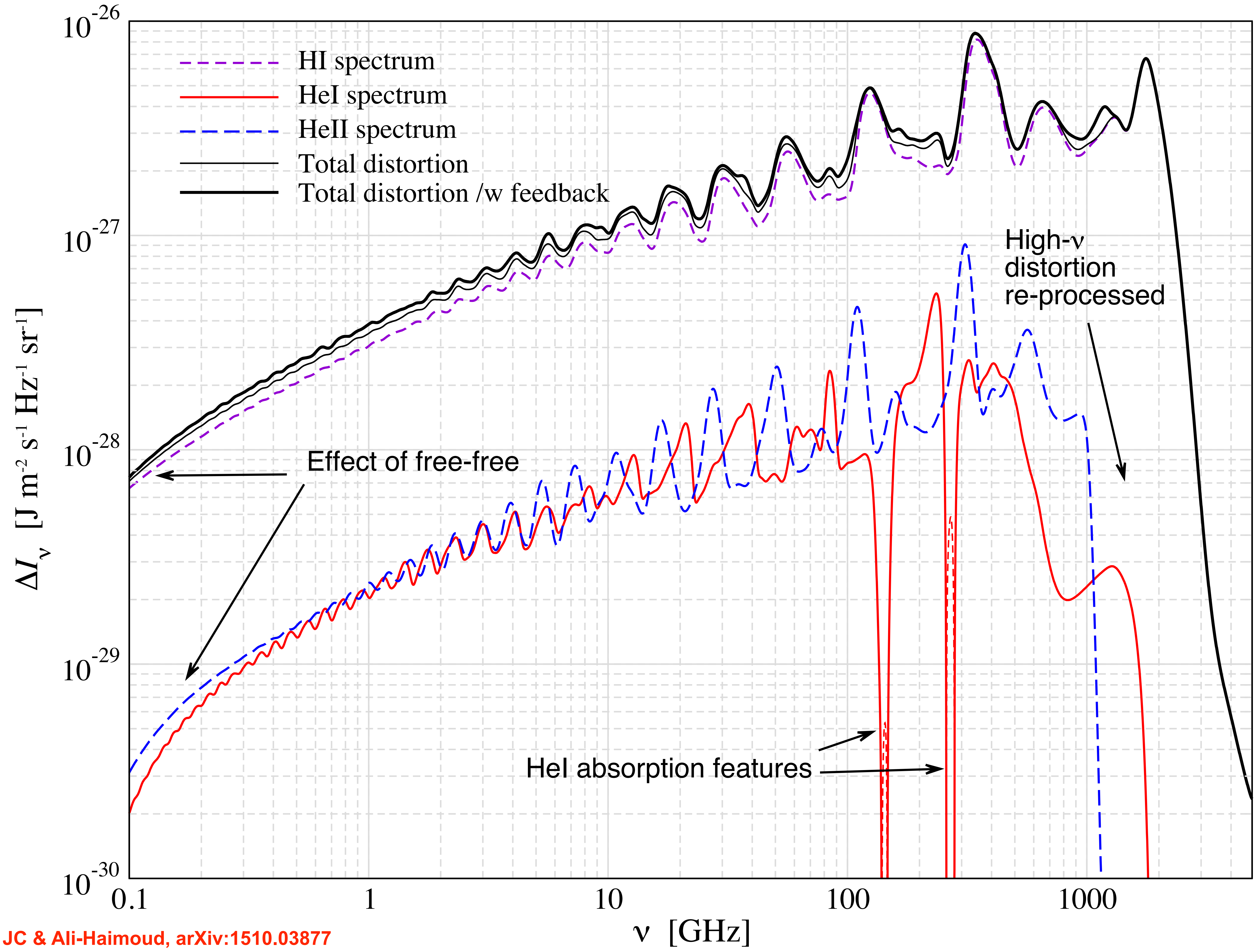


Another way to do CMB-based cosmology!

Direct probe of recombination physics!

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

New detailed and fast computation!



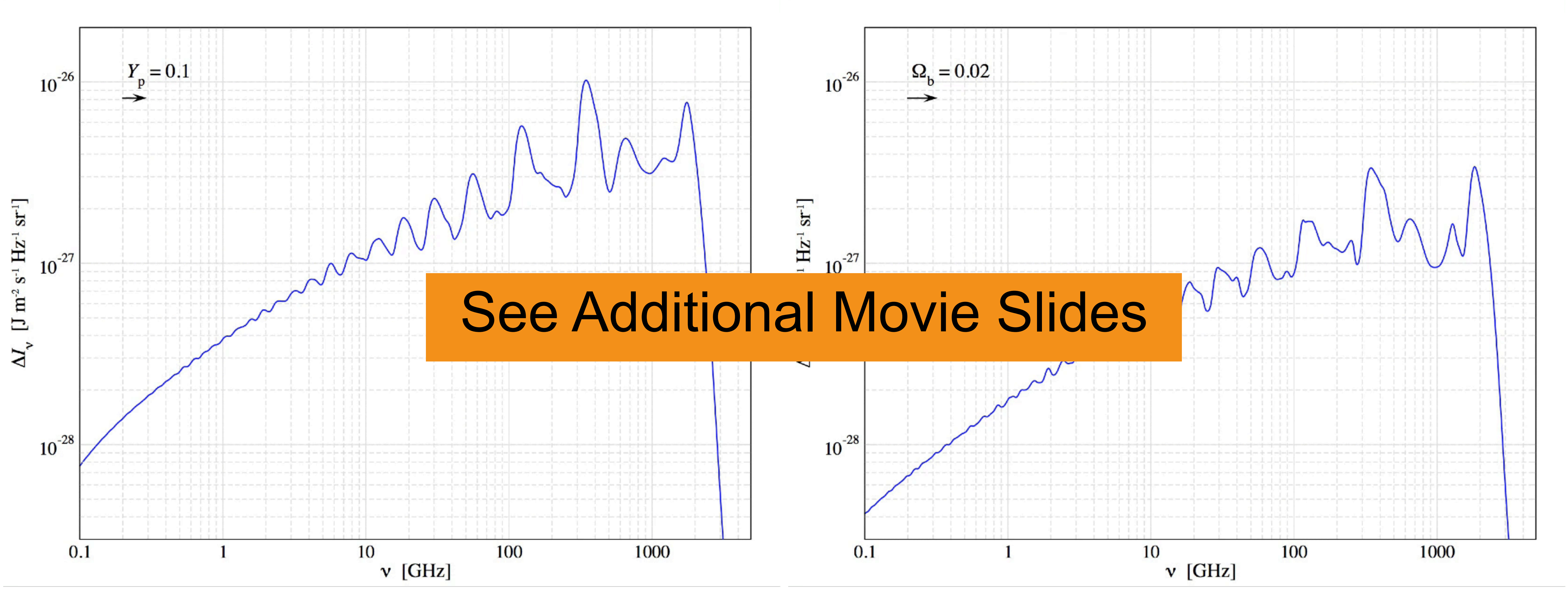
Effect of free-free

High-ν distortion re-processed

HeI absorption features

JC & Ali-Haimoud, arXiv:1510.03877

CosmoSpec: fast and accurate computation of the CRR



See Additional Movie Slides

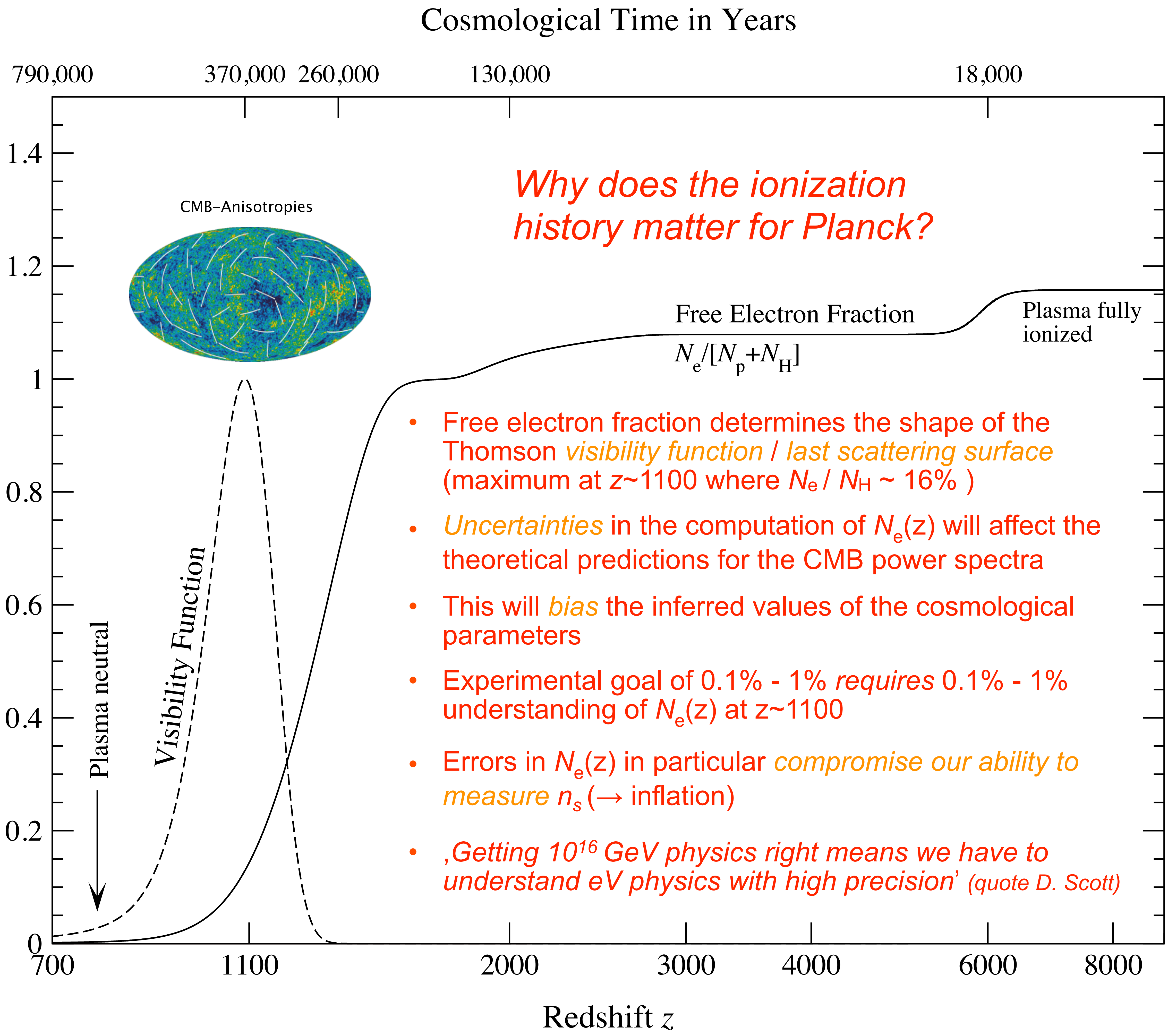
- Like in old days of CMB anisotropies!
- detailed forecasts and feasibility studies
- non-standard physics (variation of α, energy injection etc.)

CosmoSpec will be available here:

www.Chluba.de/CosmoSpec

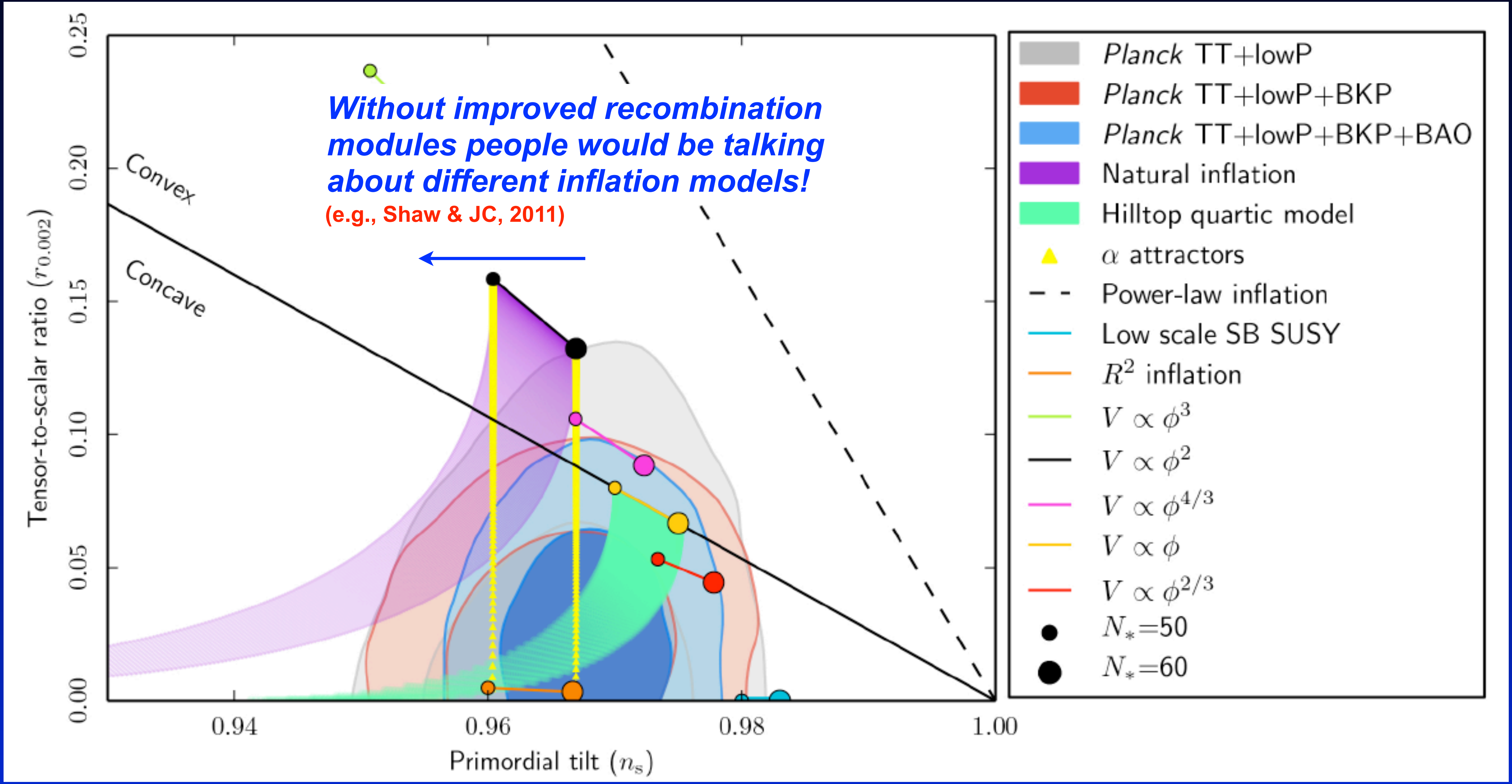
JC & Ali-Haimoud, arXiv:1510.03877

Why does the ionization history matter for Planck?



- 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)*

Importance of recombination for inflation constraints



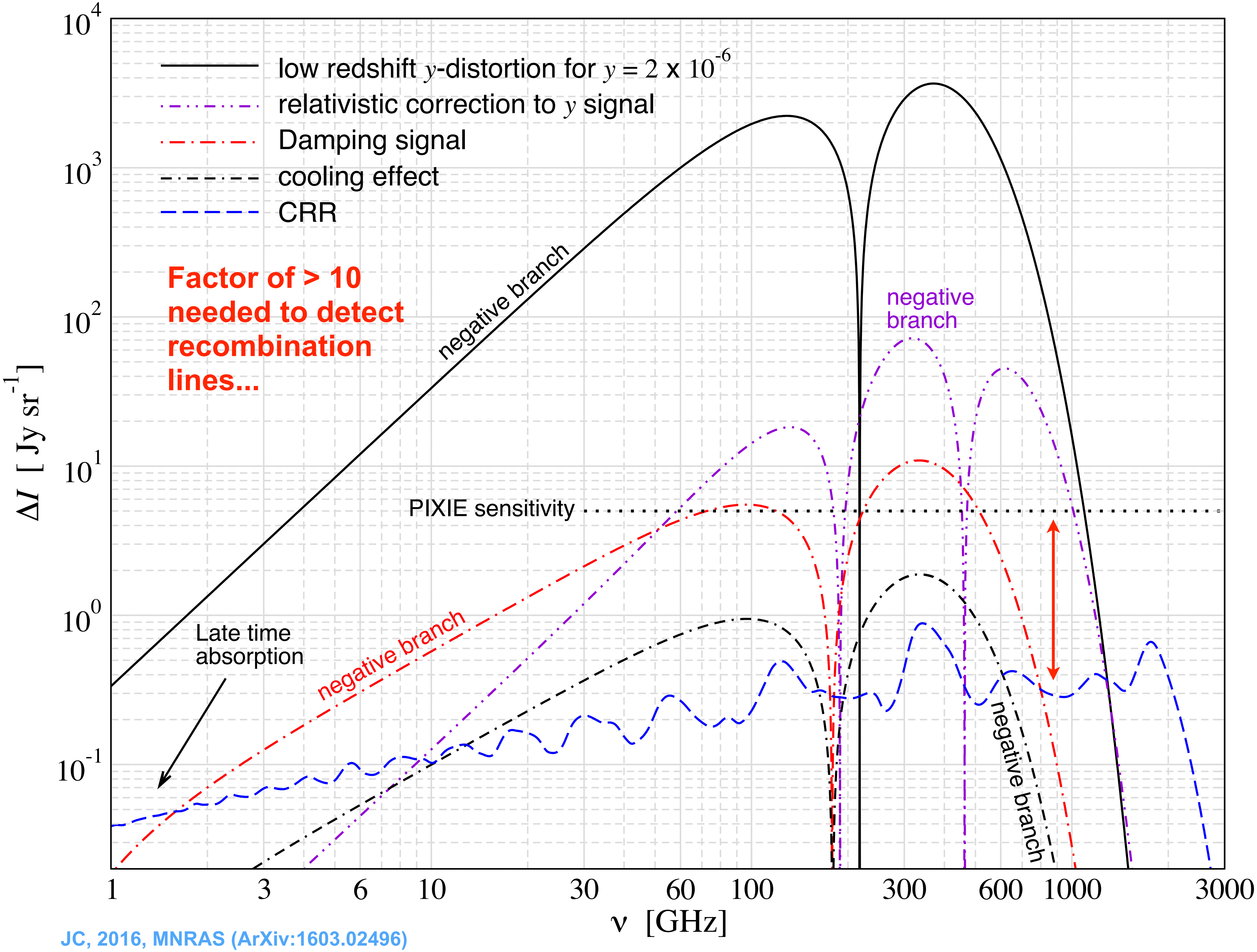
Without improved recombination modules people would be talking about different inflation models!

(e.g., Shaw & JC, 2011)

Planck Collaboration, 2015, paper XX

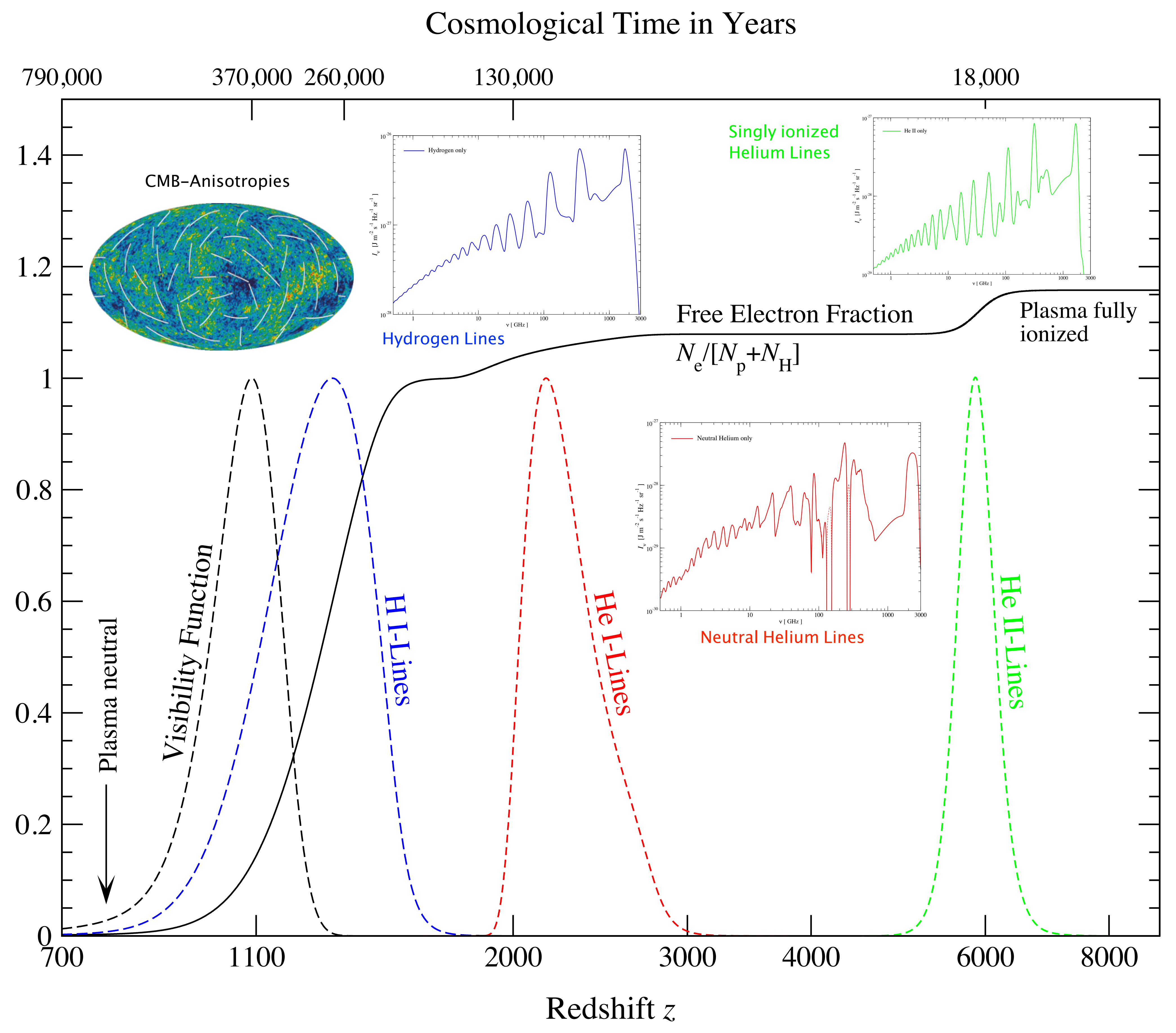
- Analysis uses refined recombination model (`CosmoRec`/`HyRec`)

Average CMB spectral distortions

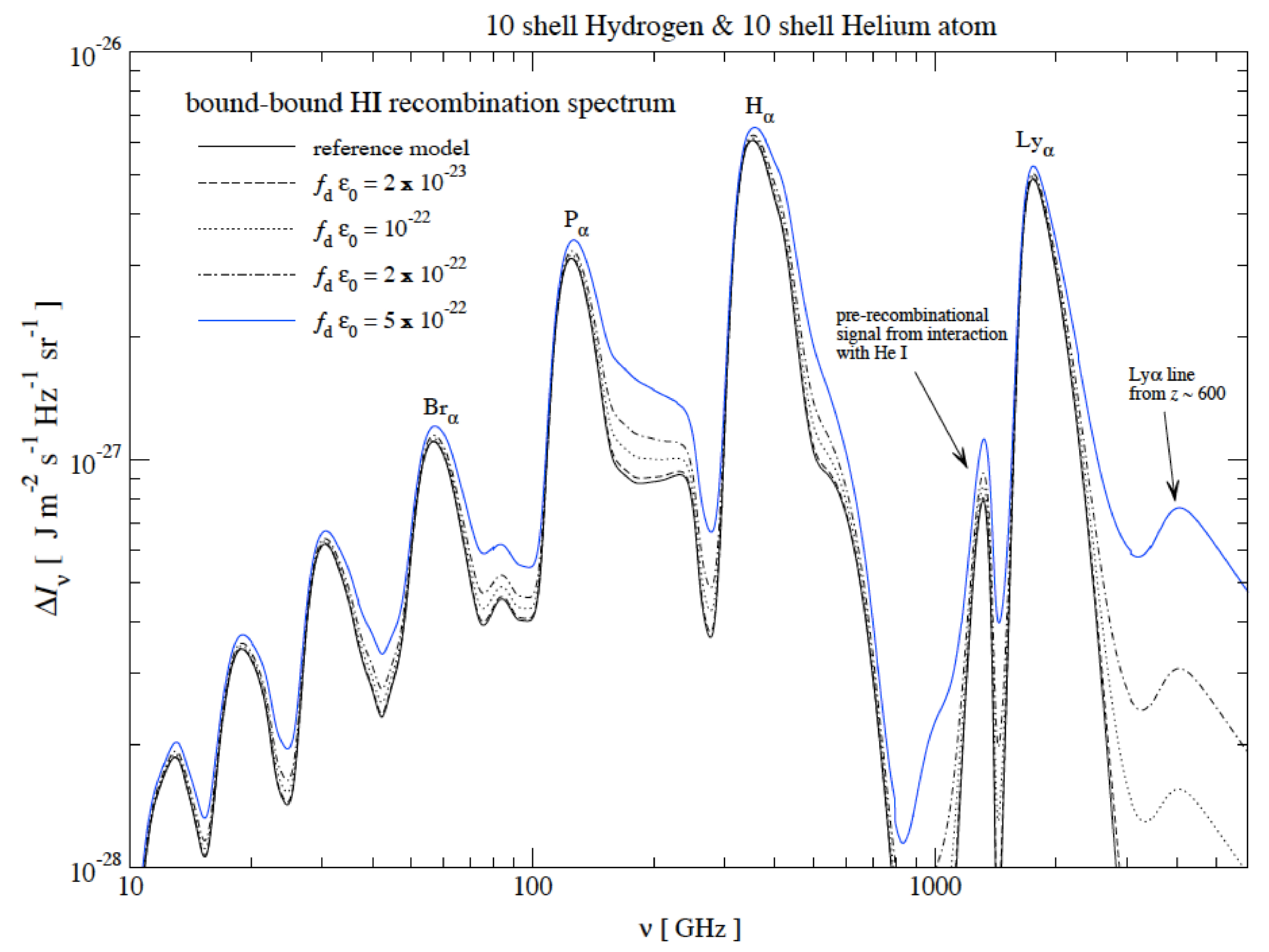


Factor of > 10 needed to detect recombination lines...

JC, 2016, MNRAS (ArXiv:1603.02496)


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
700
1100
2000
3000
4000
6000
8000
Redshift z
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
ν [GHz]
I_ν [J m^{-2} s^{-1} Hz^{-1} sr^{-1}]

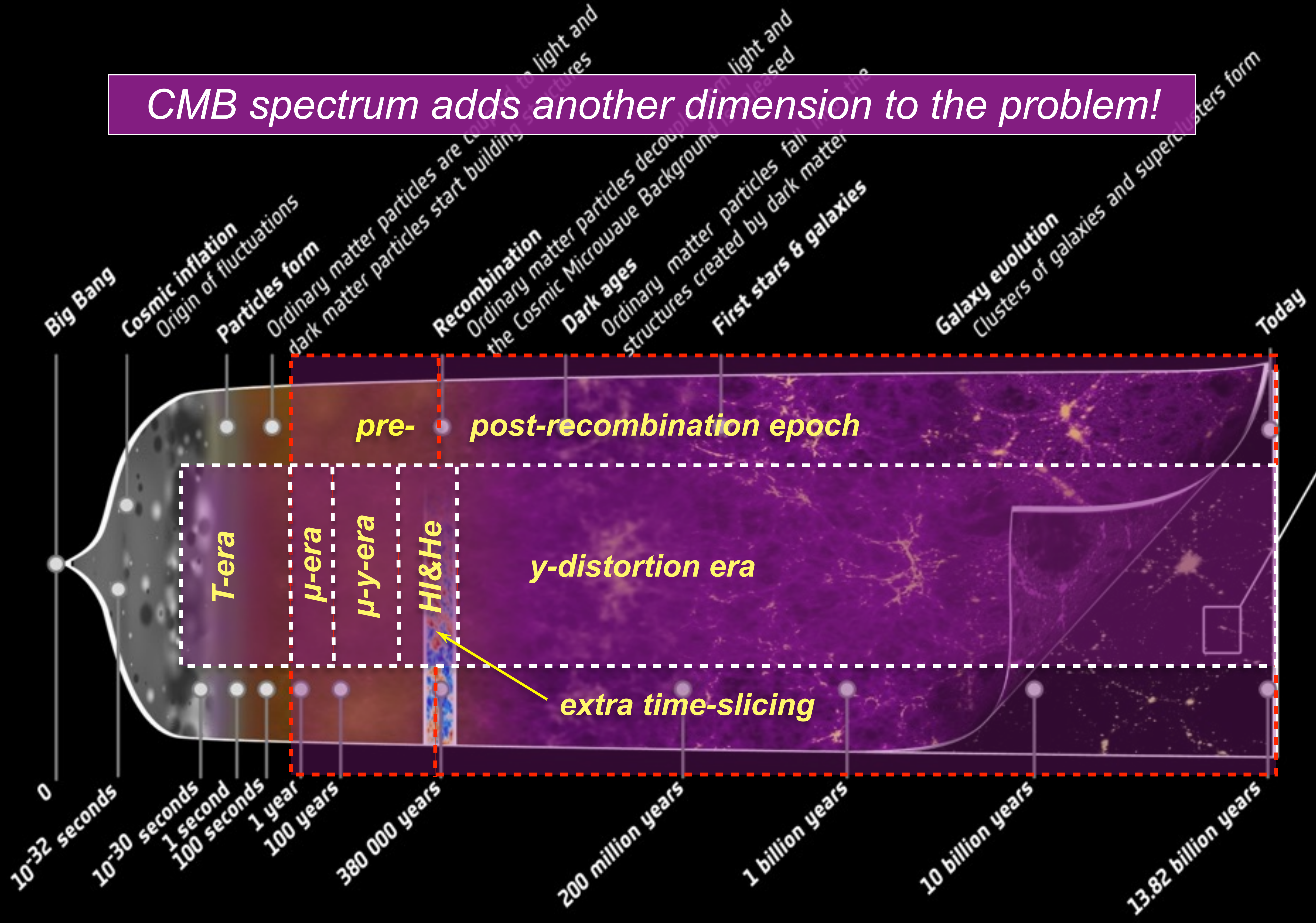
Dark matter annihilations / decays



JC, 2009, arXiv:0910.3663

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

CMB spectrum adds another dimension to the problem!



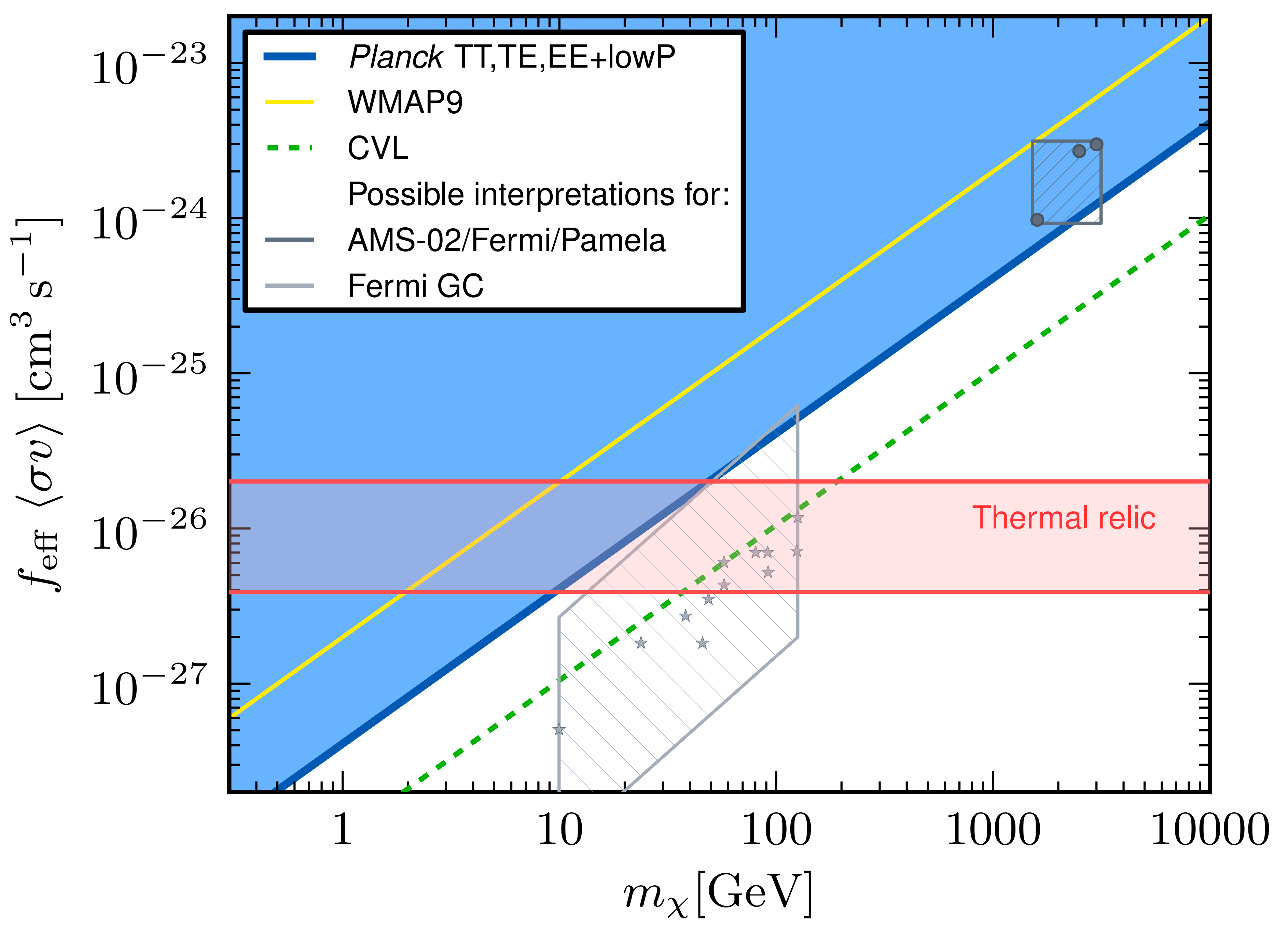
Annihilating/decaying (dark matter) particles

Why is this interesting?

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

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

Latest Planck limits on annihilation cross section



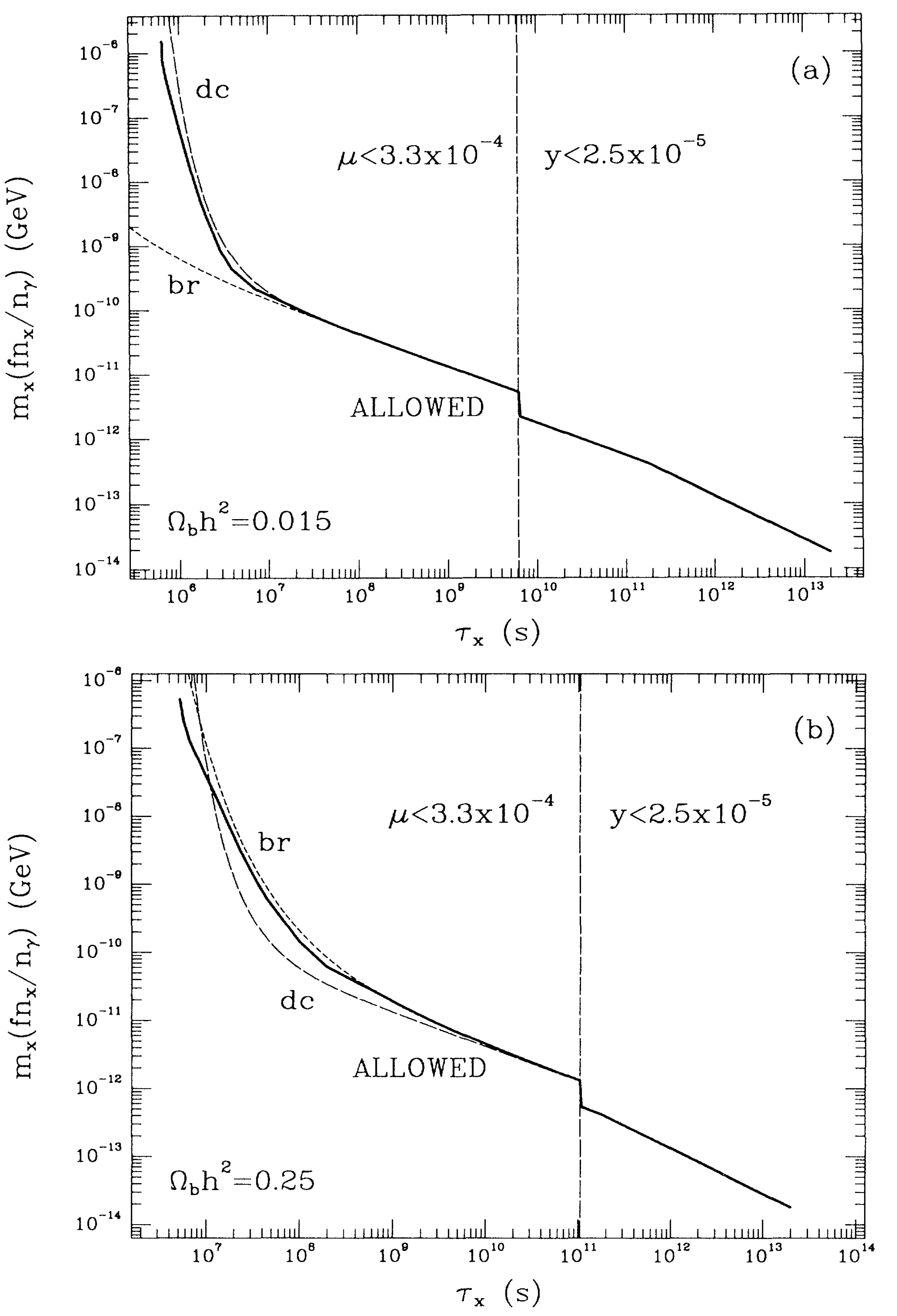
Planck Collaboration, paper XIII, 2015

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

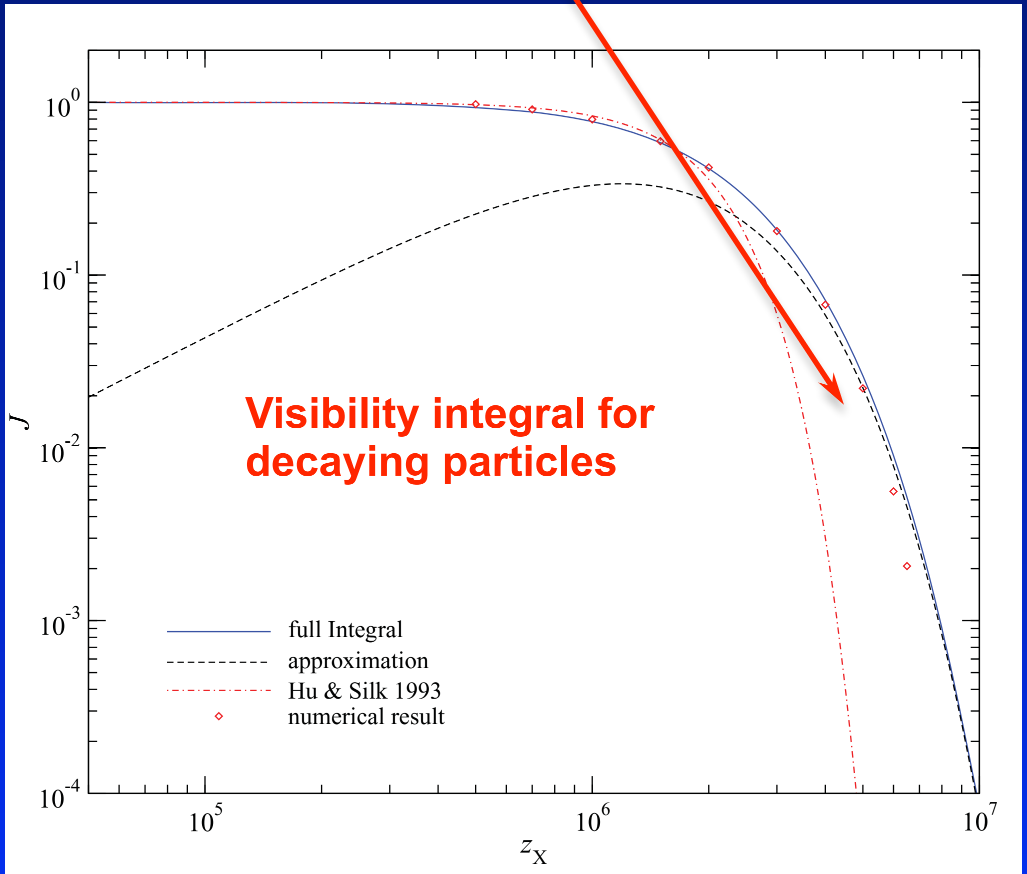
For current constraint only (weak) upper limits from distortion...

Early constraints from CMB measurements

- Simple estimates for μ and y-distortion from energy arguments just like we discussed above
- Early COBE/FIRAS limits
- constraint a little tighter for short lifetimes than estimated...



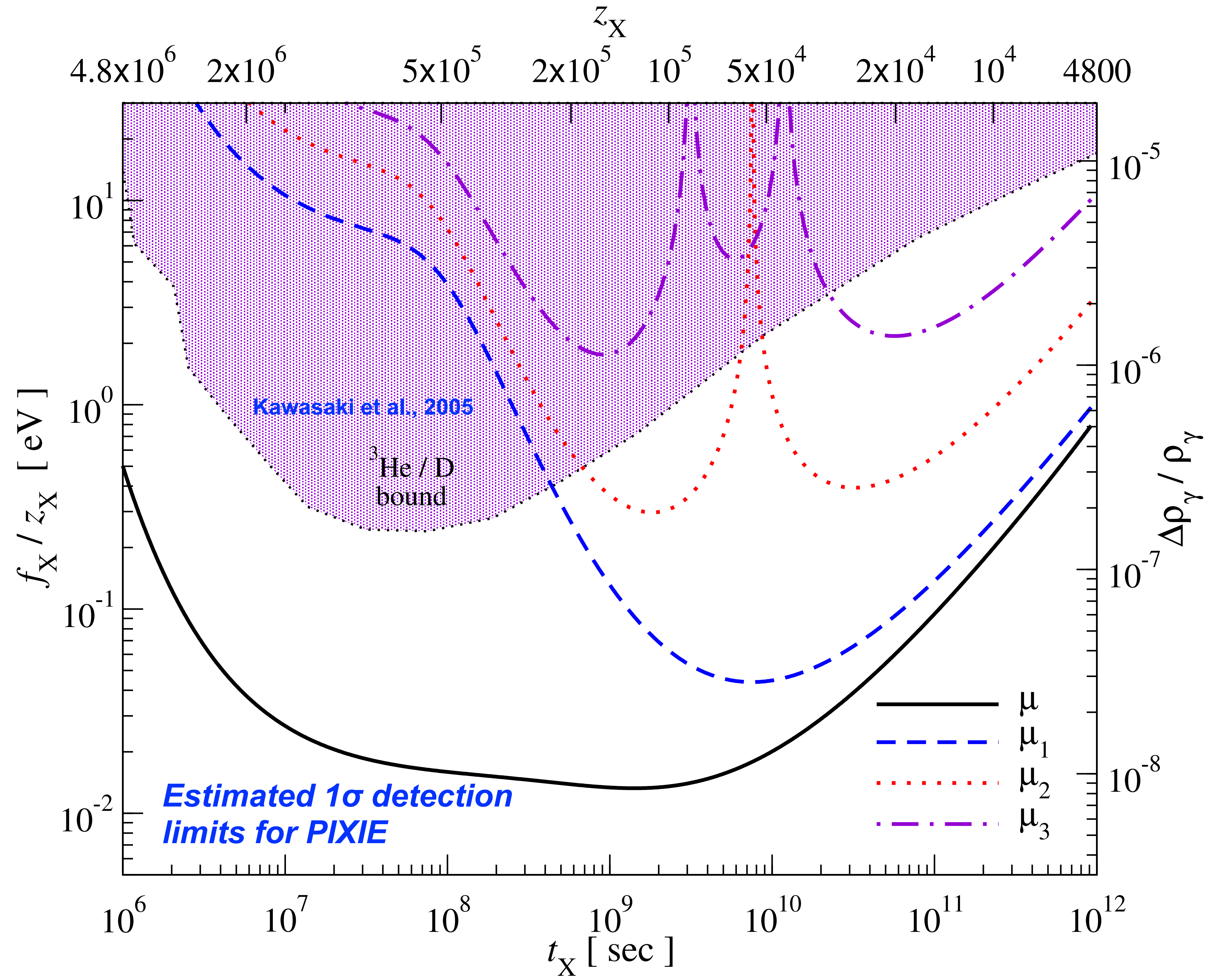
Hu & Silk, 1993



Visibility integral for decaying particles

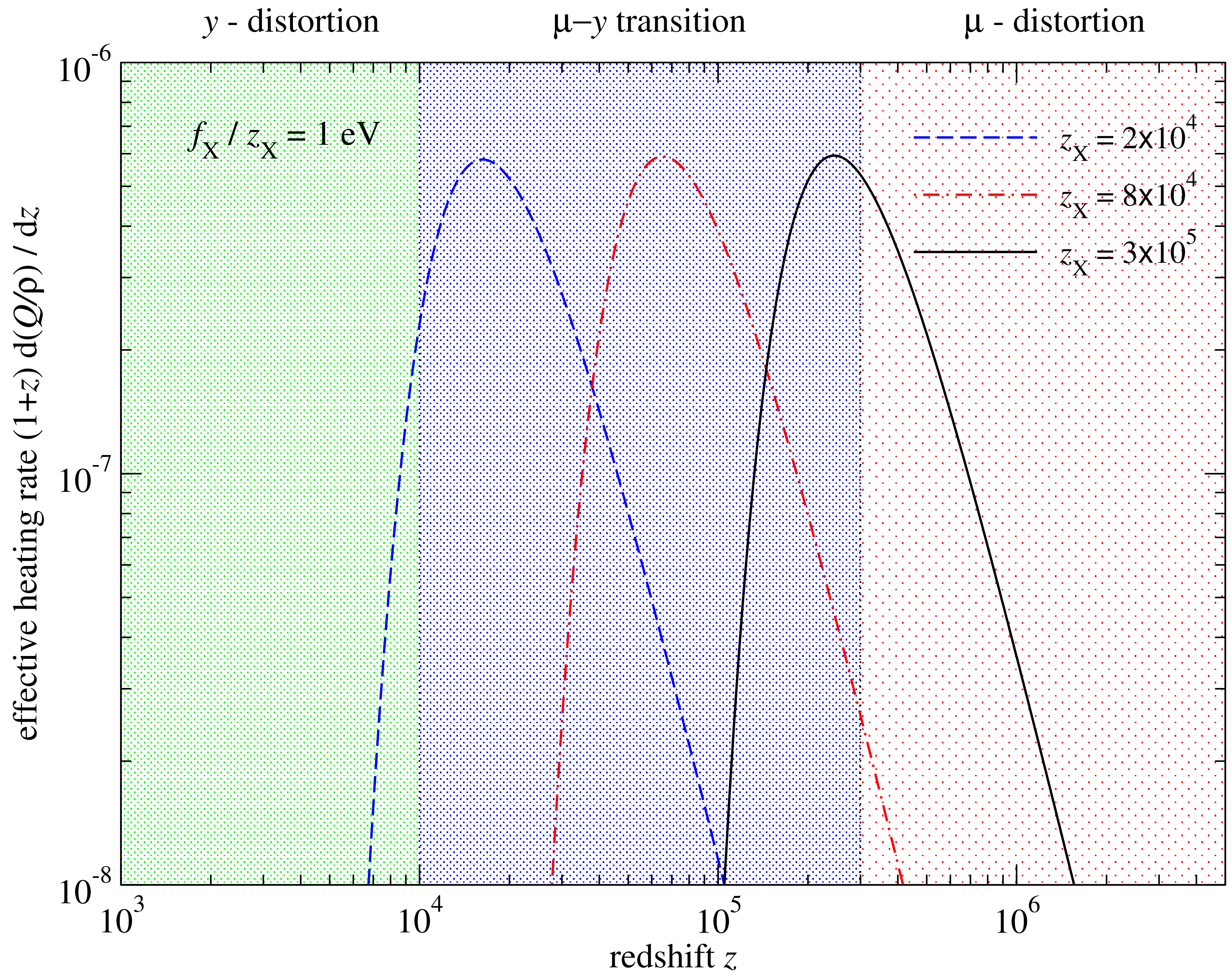
JC, 2005; JC & Sunyaev, 2012

Distortions could shed light on decaying (DM) particles!



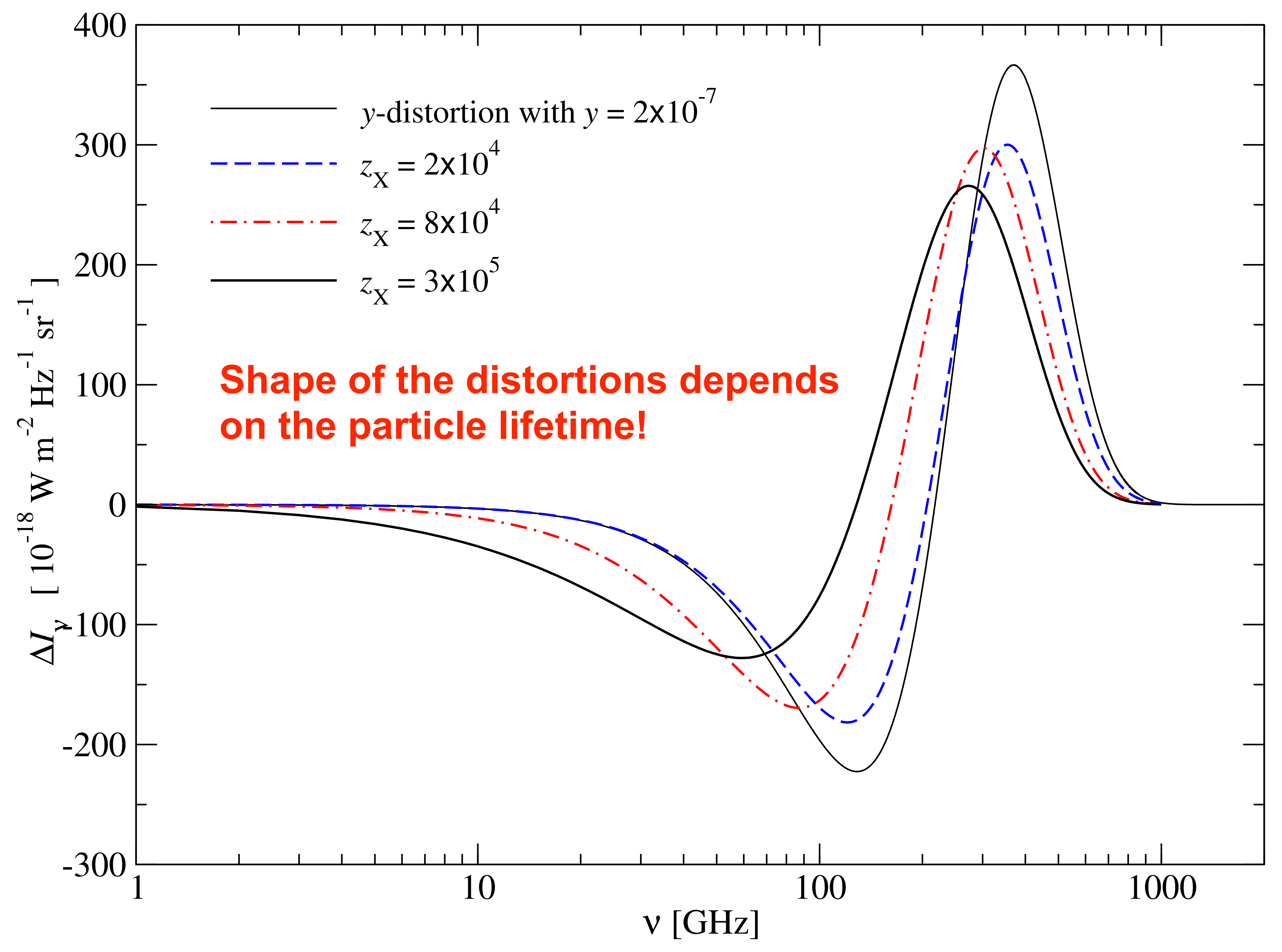
JC & Jeong, 2013

Decaying particle scenarios



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

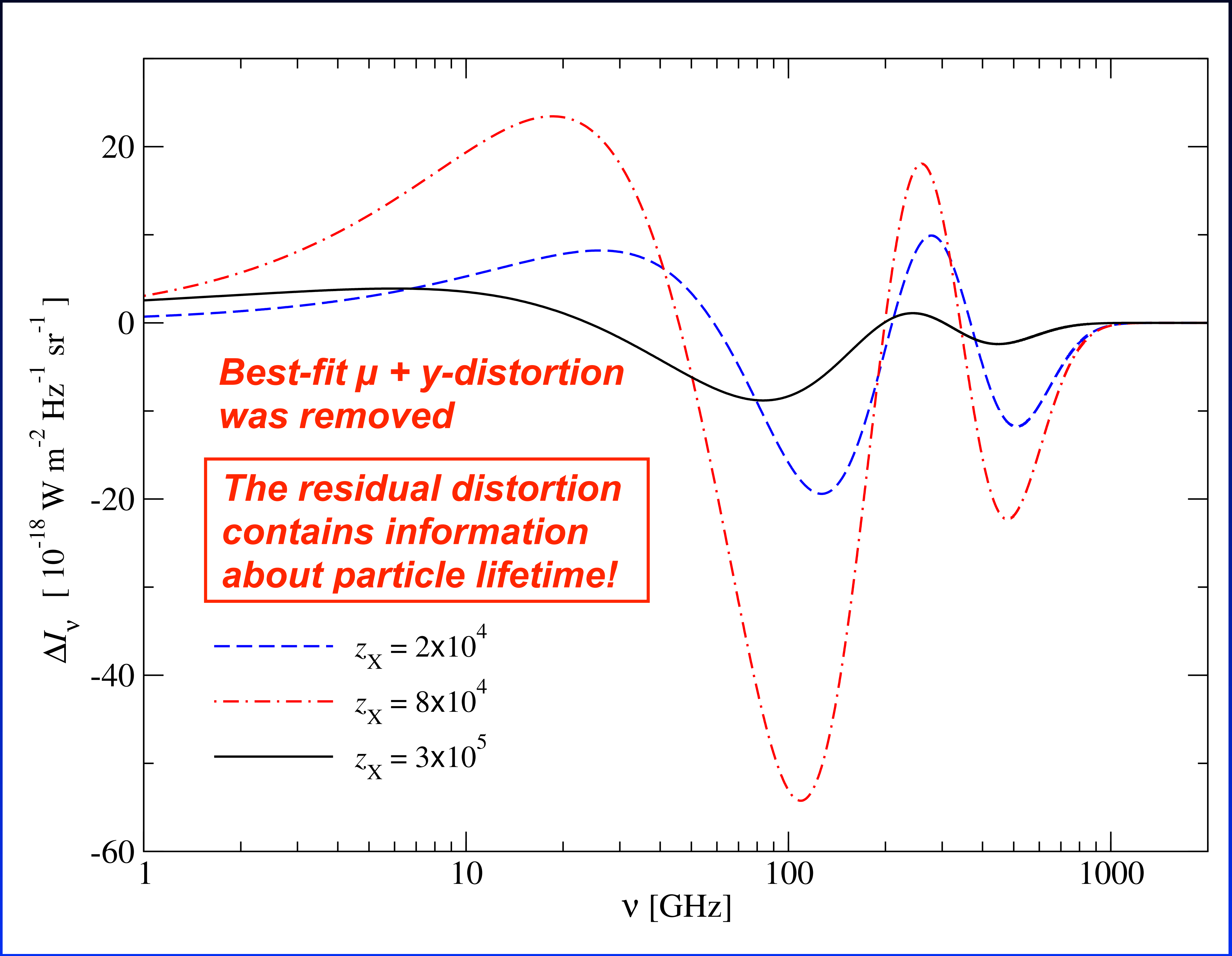
Decaying particle scenarios



Shape of the distortions depends on the particle lifetime!

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

Decaying particle scenarios (information in residual)

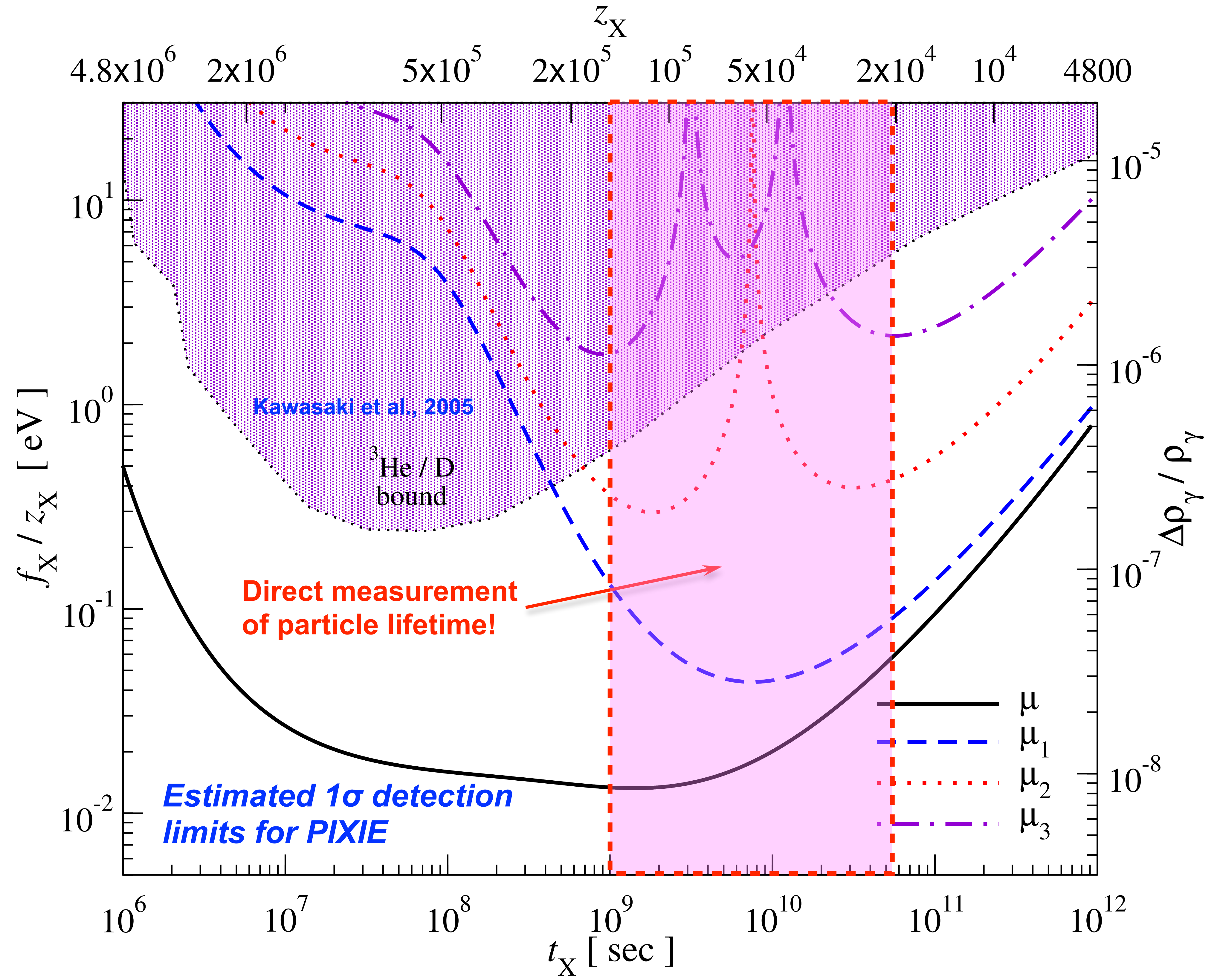


Best-fit μ + y-distortion was removed

The residual distortion contains information about particle lifetime!

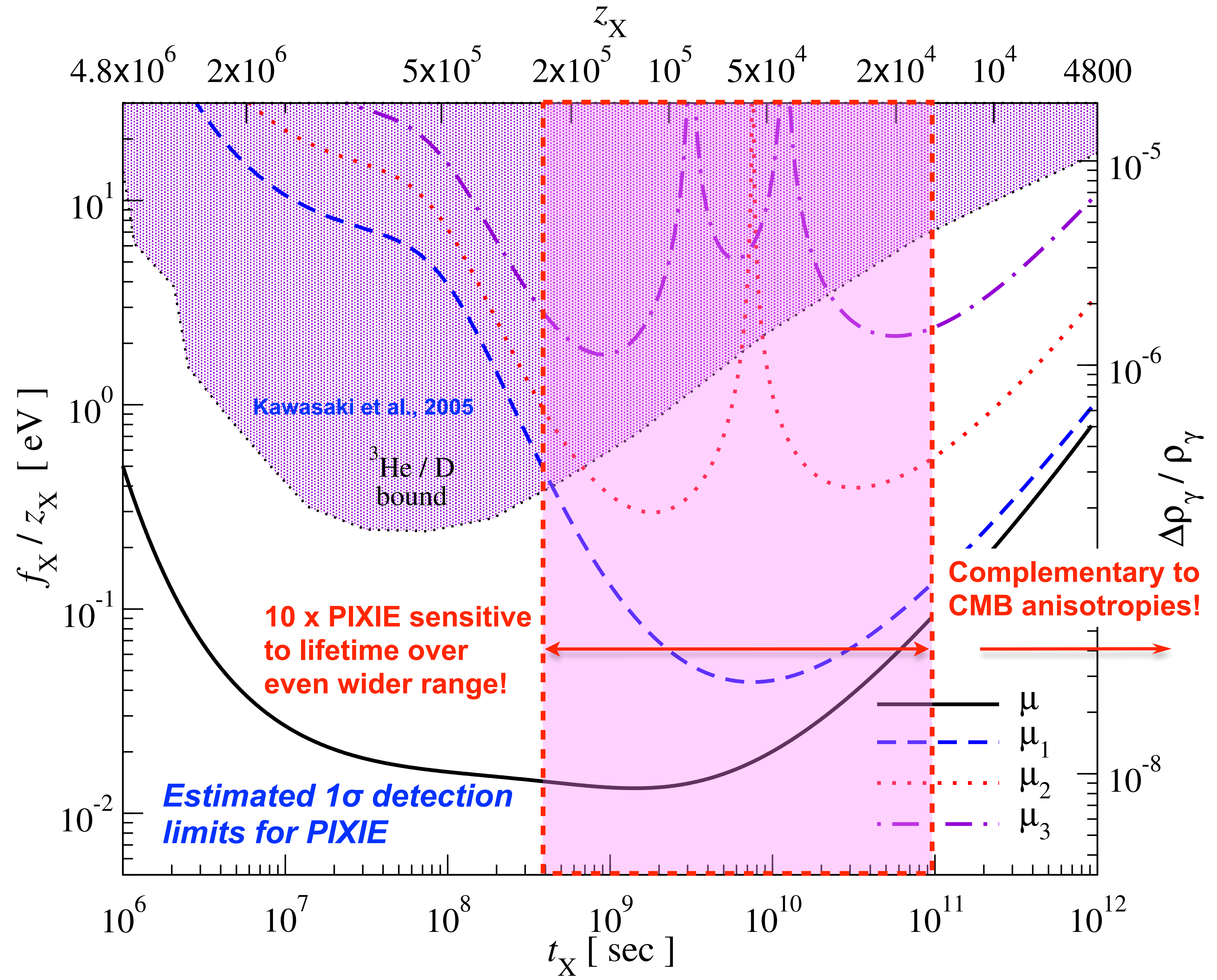
JC & Sunyaev, 2011, Arxiv:1109.6552
JC, 2013, Arxiv:1304.6120

Distortions could shed light on decaying (DM) particles!



JC & Jeong, 2013

Distortions could shed light on decaying (DM) particles!



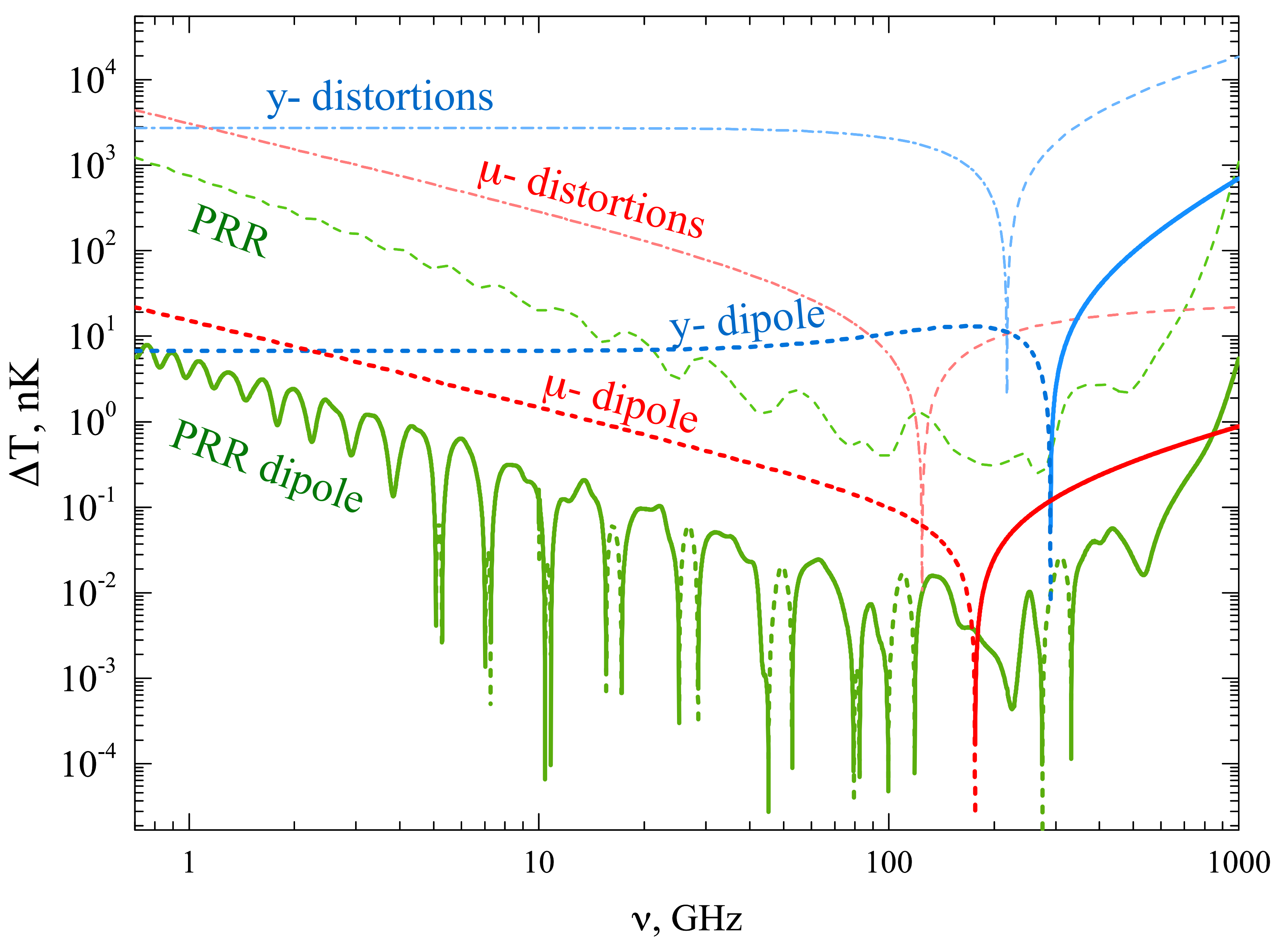
10 x PIXIE sensitive to lifetime over even wider range!

Complementary to CMB anisotropies!

Estimated 1σ detection limits for PIXIE

JC & Jeong, 2013

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*

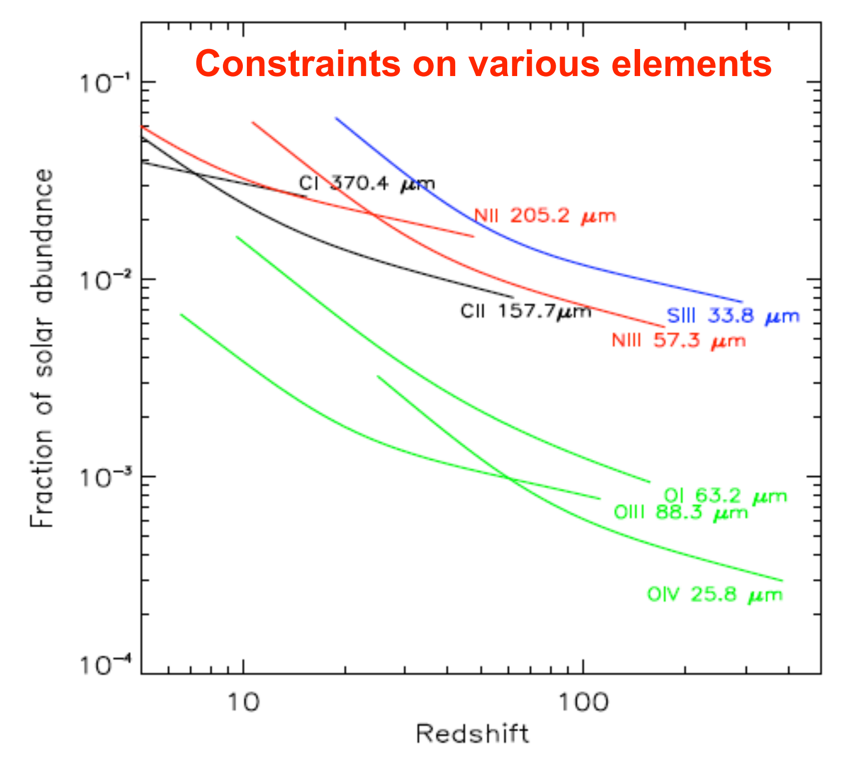
$$\eta_{\rm d}(\nu, \mathbf{n}) \approx -\nu \partial_\nu \eta_{\rm m}(\nu)\, \beta \cos\Theta$$

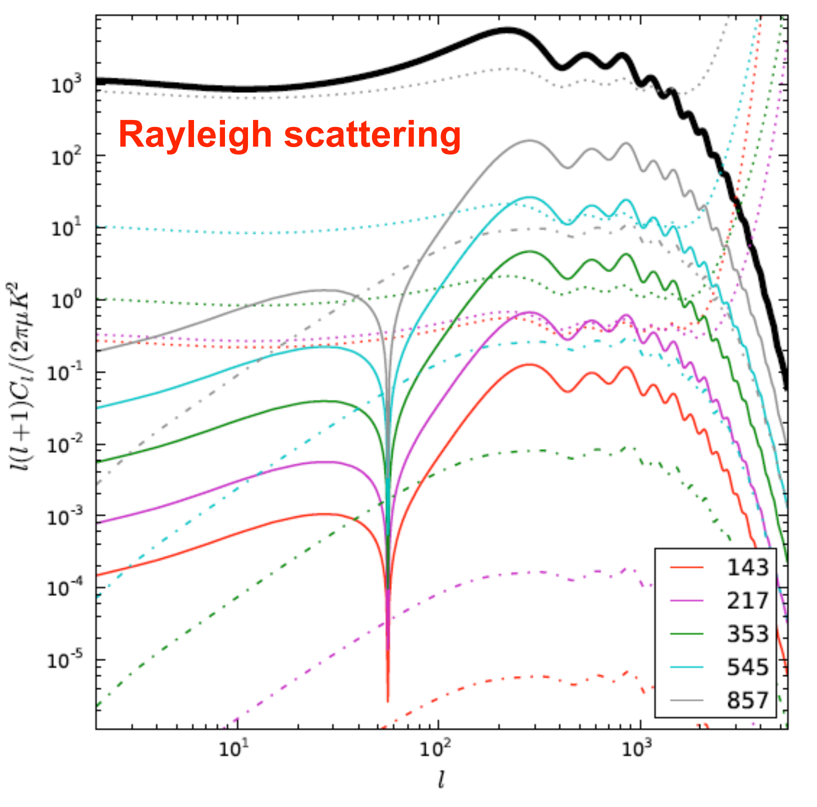
- spectrum of the dipole is sensitive to the *derivative* of the monopole spectrum
- anisotropy does not need *absolute* calibration but just *inter-channel* calibration
- *but* signal is ~1000 times smaller...
- *foregrounds* will also leak into the dipole in this way
- check of *systematics*

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_{eff} and Y_{p}
- Free-free signals from reionization
  (e.g., Burigana et al. 1995; Trombetti & Burigana, 2013)
  - constrains reionization history
  - depends on clumpiness of the medium

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

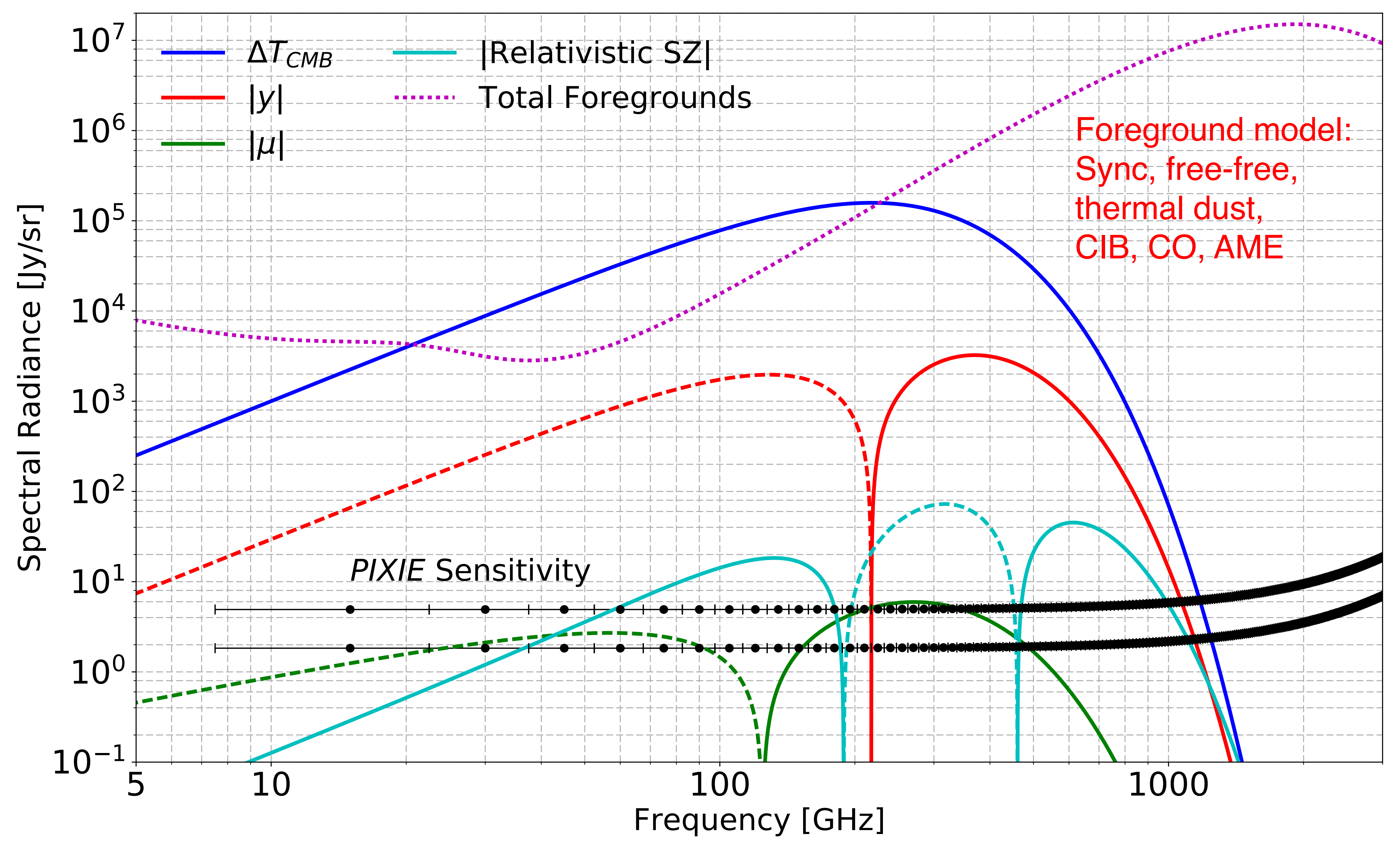




Foreground problem for CMB spectral distortions

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

Comparison of distortion signals with foregrounds



Foreground model:
Sync, free-free,
thermal dust,
CIB, CO, AME

Abitbol, JC & Hill, 2017, in preparation

Effect of foregrounds on distortion parameters

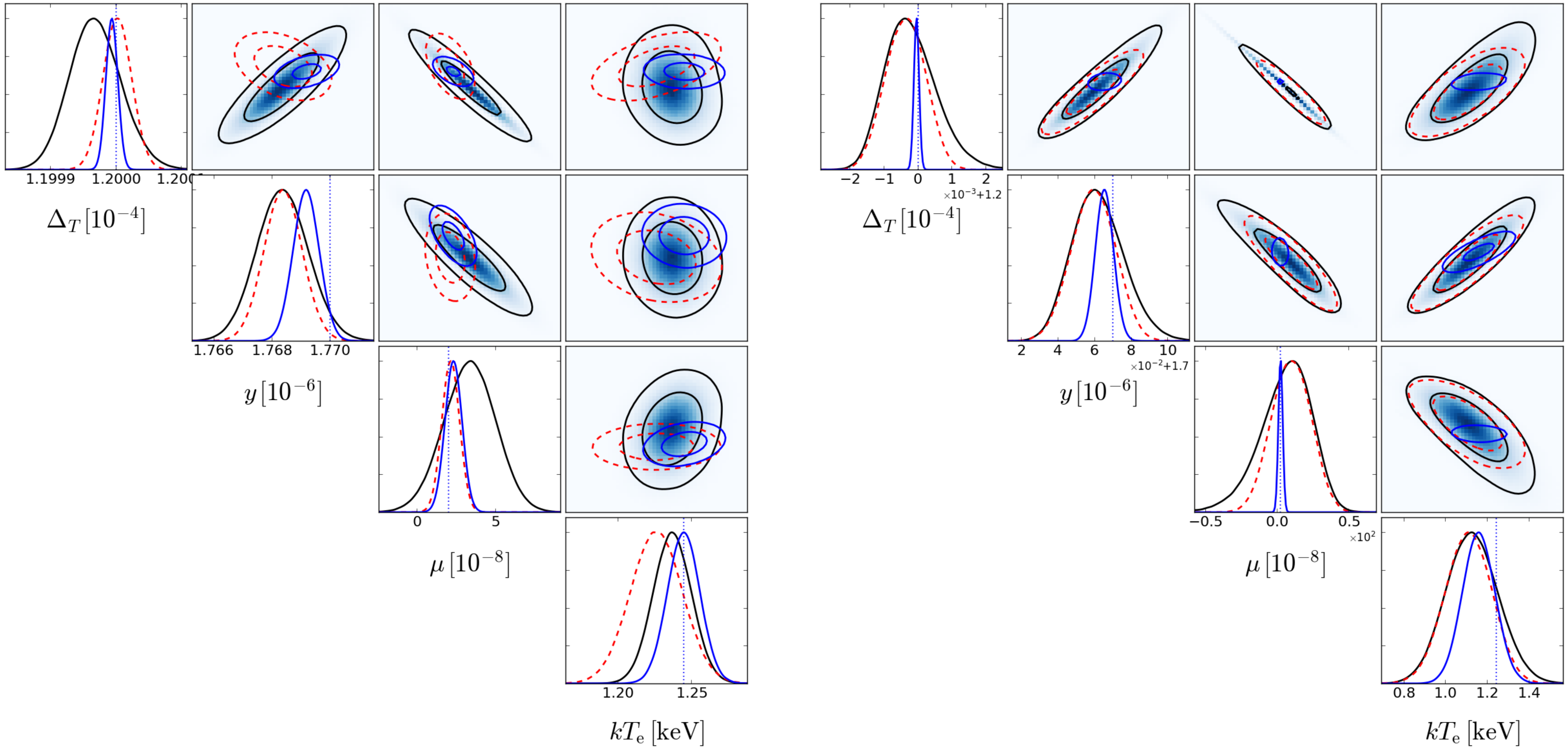
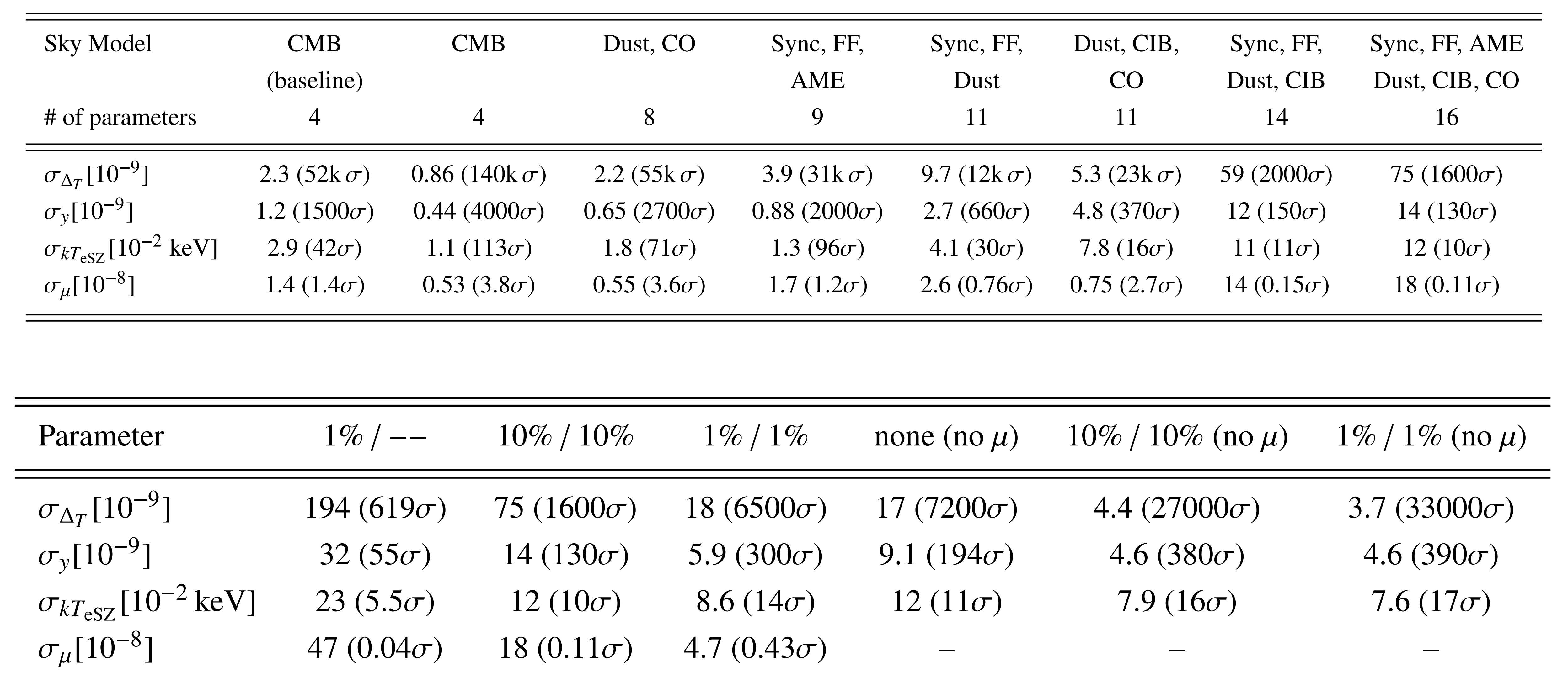


Figure 3. Comparison of the CMB spectral distortion parameter contours for varying foreground complexity. – Left panel: CMB-only (blue), CMB+Dust+CO (red) and CMB+Sync+FF+AME (black) parameter cases. Adding Dust+CO has a small effect on μ, while adding Sync+FF+AME has a moderate effect on kT_eSZ. – Right panel: CMB+Dust+CIB+CO (blue), CMB+Sync+FF+Dust+CIB (red) and all foregrounds (black) parameter cases. The degradation of μ due to the foregrounds is more severe than that for the other parameters.

Abitbol, JC & Hill, 2017, in preparation

Forecasted sensitivities for PIXIE



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

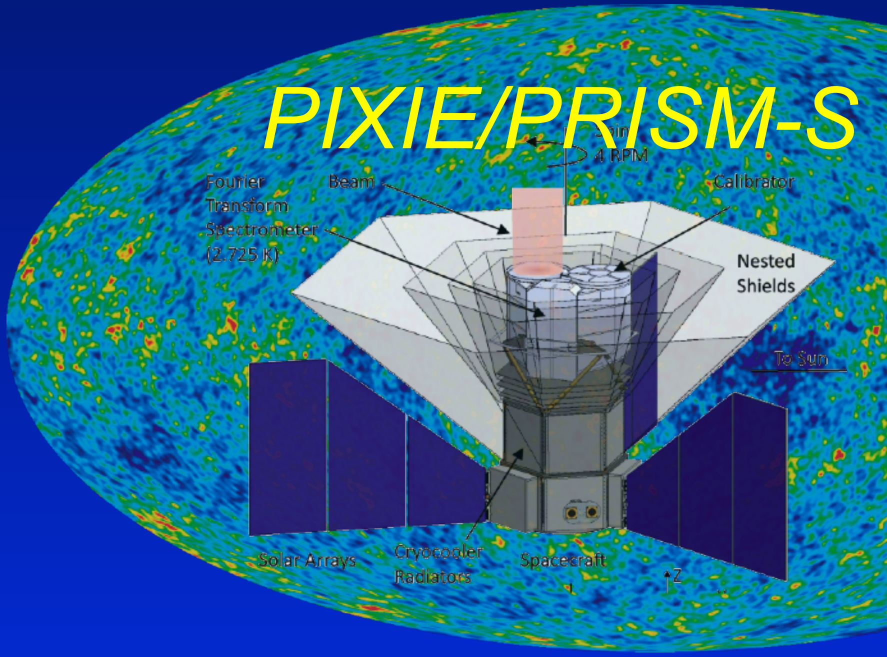
Parameter	1% / −−	10% / 10%	1% / 1%	none (no μ)	10% / 10% (no μ)	1% / 1% (no μ)
$\sigma_{\Delta_T}[10^{-9}]$	194 (619σ)	75 (1600σ)	18 (6500σ)	17 (7200σ)	4.4 (27000σ)	3.7 (33000σ)
$\sigma_y[10^{-9}]$	32 (55σ)	14 (130σ)	5.9 (300σ)	9.1 (194σ)	4.6 (380σ)	4.6 (390σ)
$\sigma_{kT_{\rm eSZ}}[10^{-2}$ keV]	23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

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

Abitbol, JC & Hill, 2017, in preparation

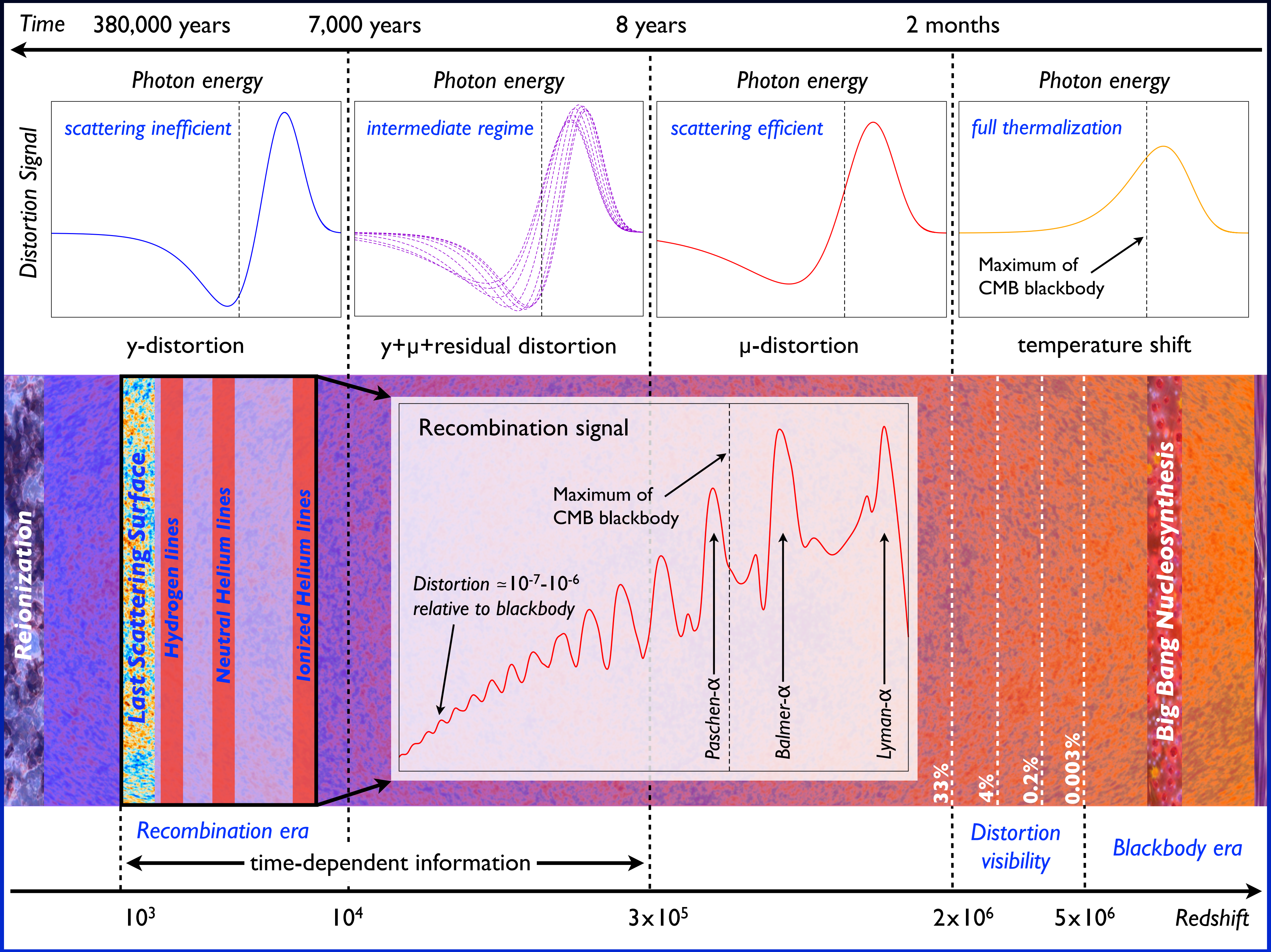
What can CMB spectral distortions add?

- 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


PIXIE/PRISM-S

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

Uniqueness of CMB Spectral Distortion Science



Guaranteed distortion signals in ΛCDM

New tests of inflation and particle/dark matter physics

Signals from the reionization and recombination eras

Huge discovery potential

Complementarity and synergy with CMB anisotropy studies

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