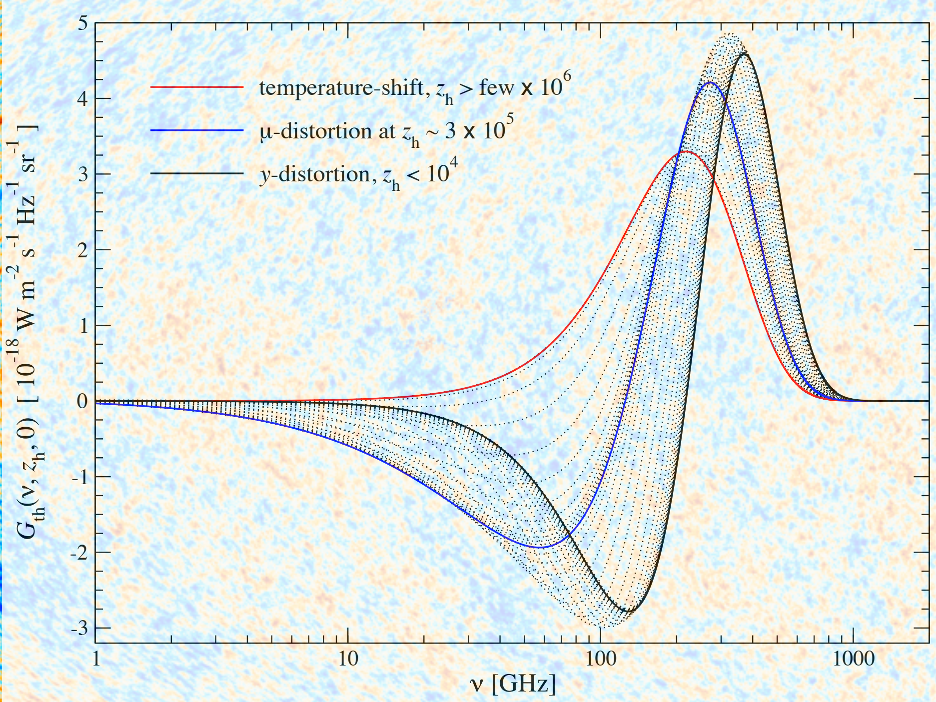
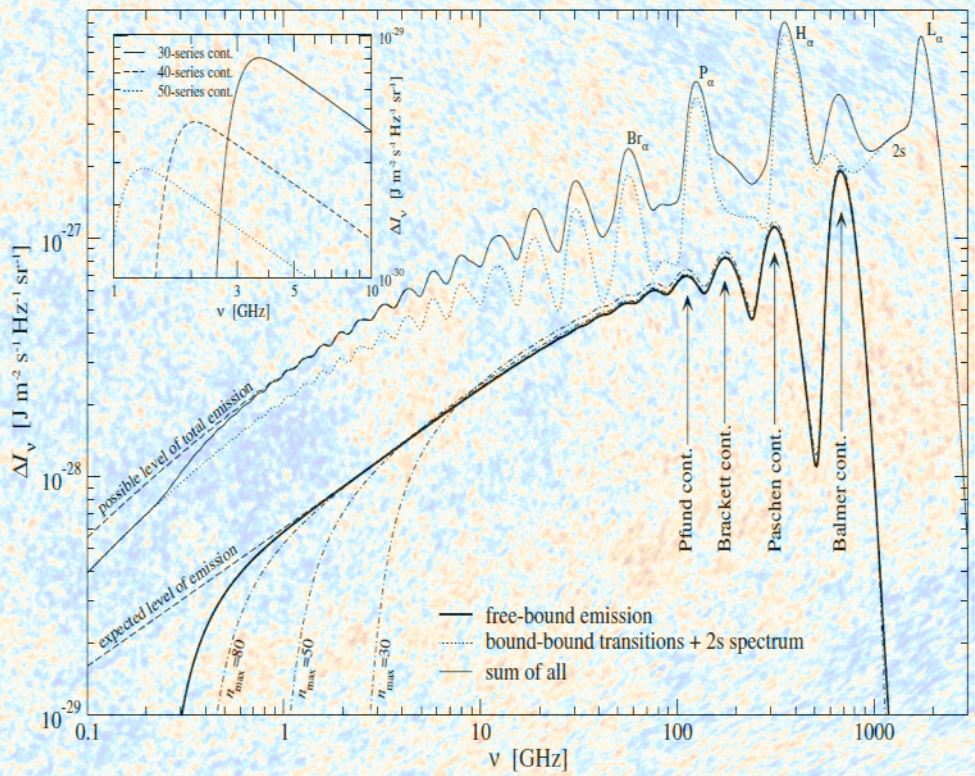
CMB Spectral Distortions in ΛCDM and beyond

Primordial Distortions



Cosmological Recombination lines



Jens Chluba

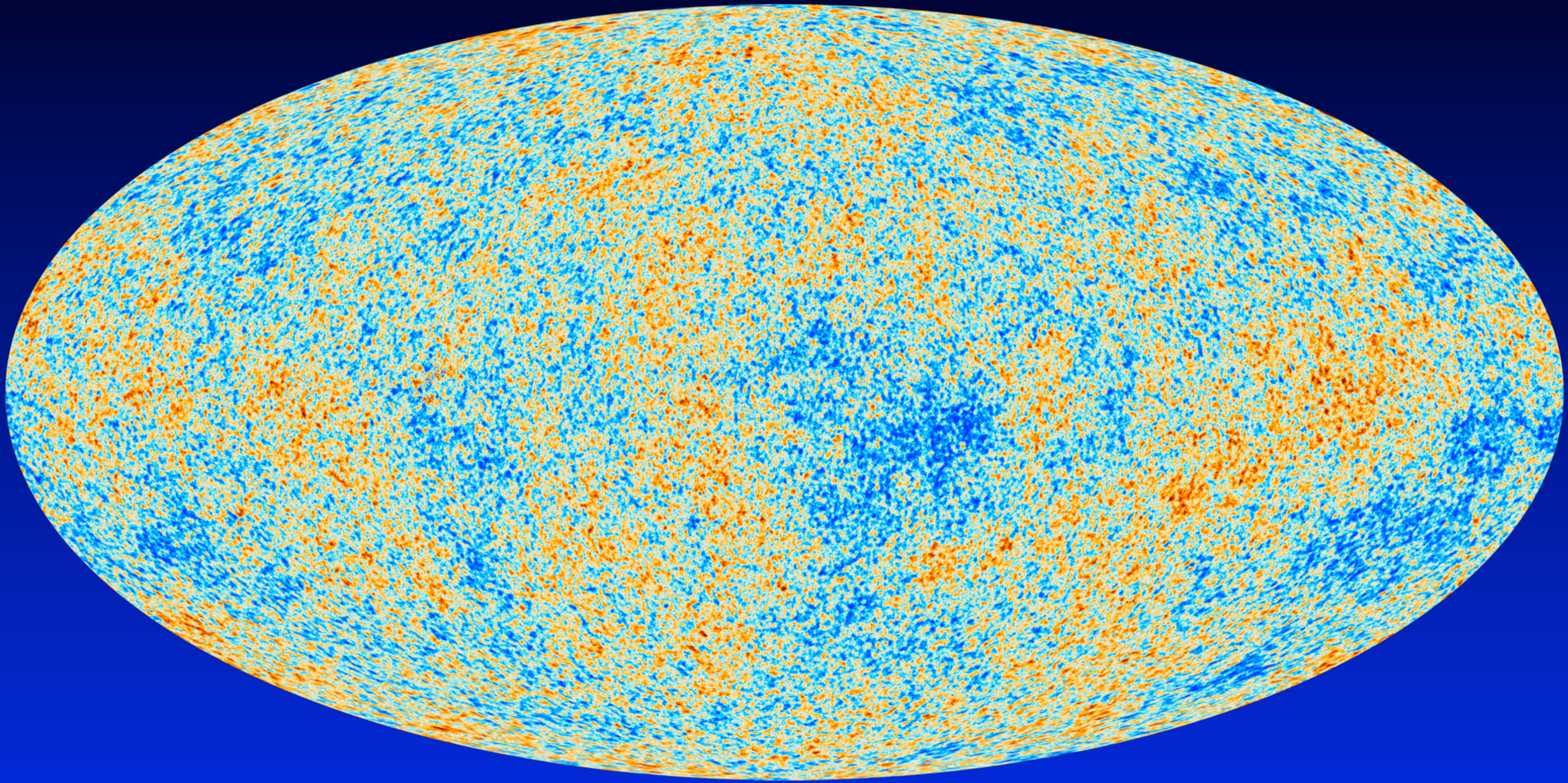
CMB/LSS/21cm Workshop

IFT Madrid, June 20th, 2016

MANCHESTER 1824
The University of Manchester

THE ROYAL SOCIETY

Cosmic Microwave Background Anisotropies



Planck all-sky temperature map

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

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

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

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

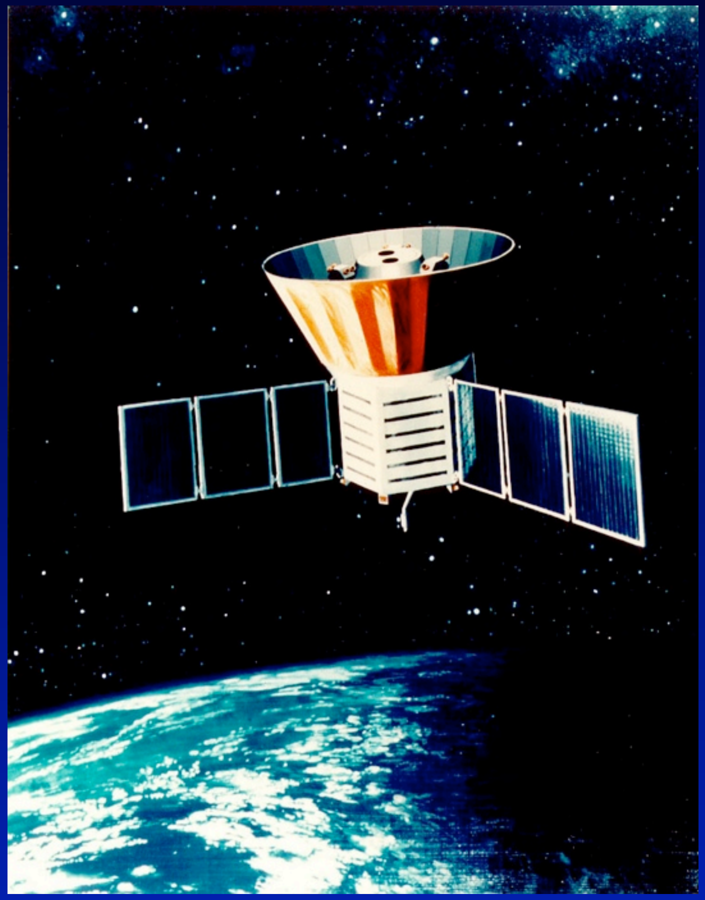
Planck Collaboration, 2015, paper XIII

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

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

Lots of competition to reach these goals!

COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)

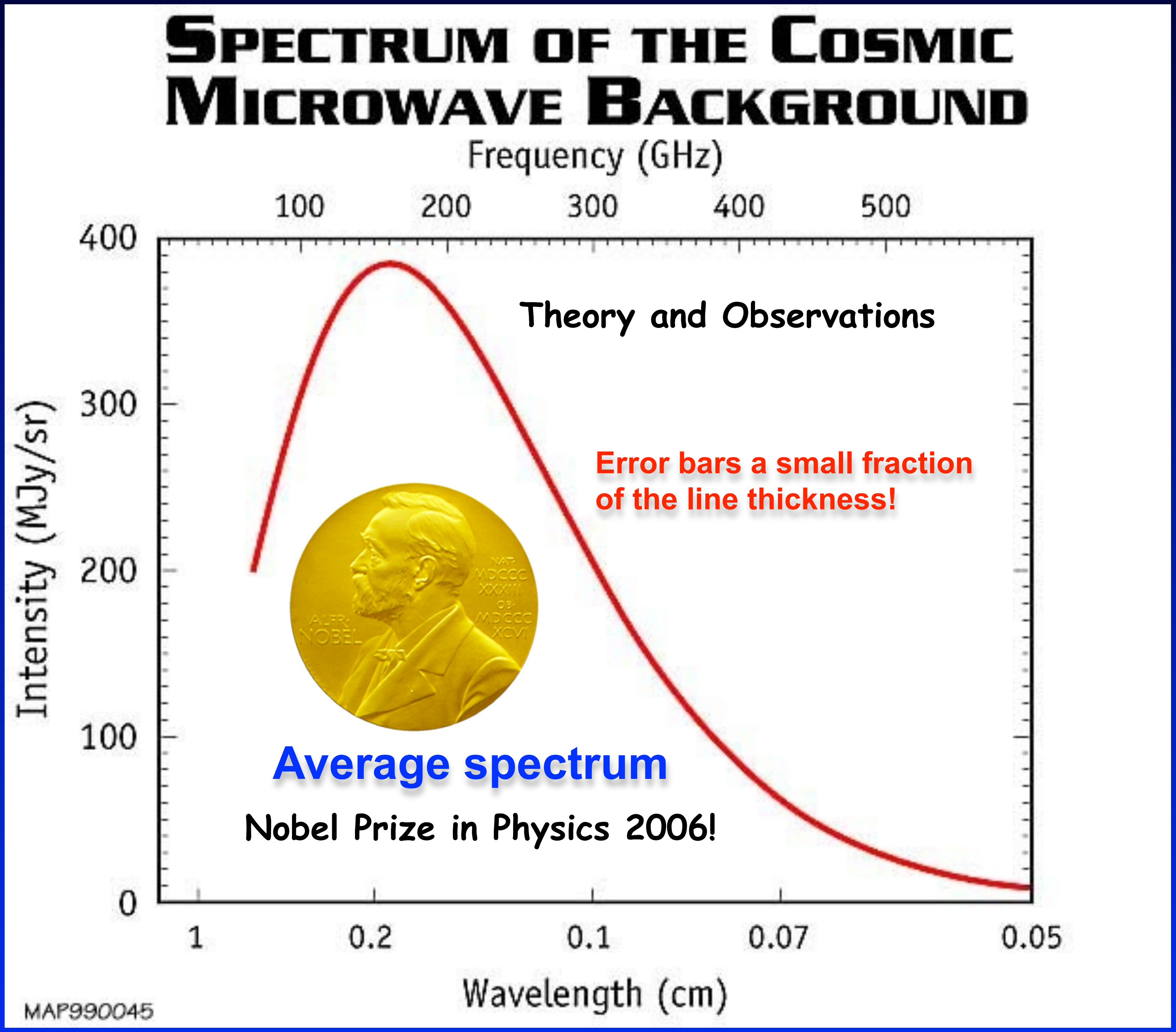


$$T_0 = 2.725 \pm 0.001\,\mathrm{K}$$

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

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

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



Only very small distortions of CMB spectrum are still allowed!

Physical mechanisms that lead to spectral distortions

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  (JC, 2005; JC & Sunyaev 2011; Khatri, Sunyaev & JC, 2011)
- Heating by *decaying* or *annihilating* relic particles
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„high“ redshifts

pre-recombination epoch

„low“ redshifts

post-recombination

- Signatures due to first supernovae and their remnants
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- more exotic processes
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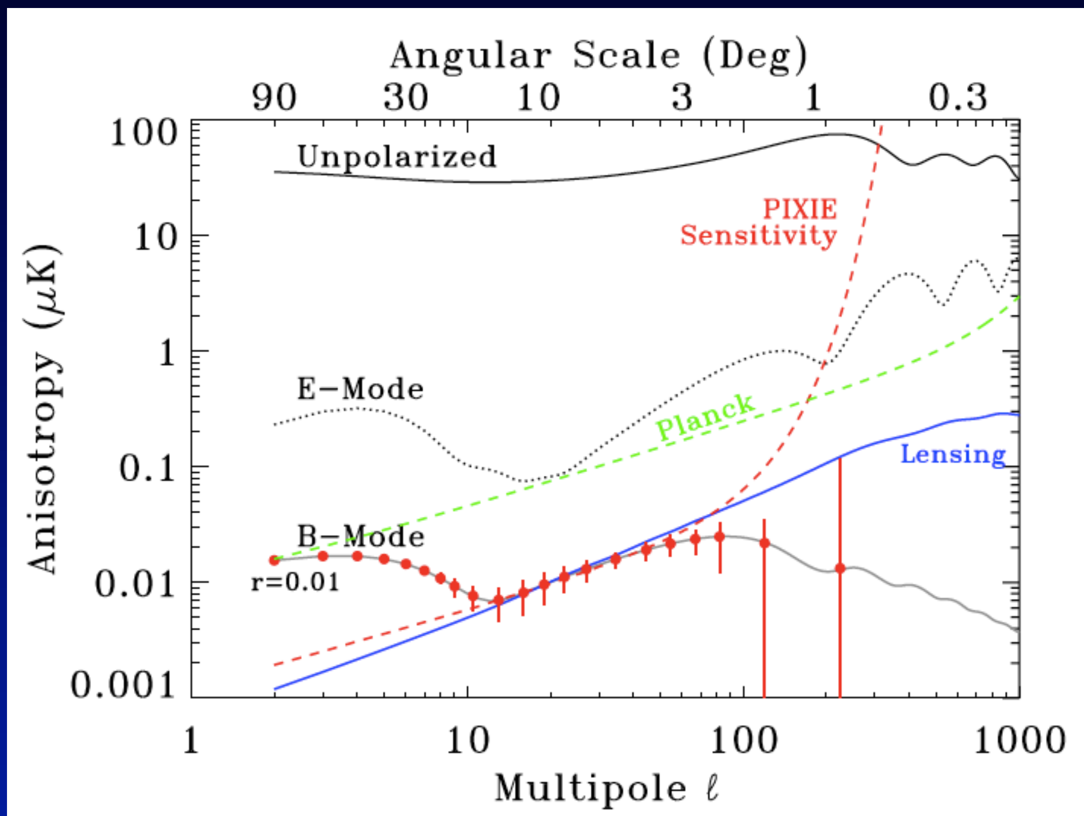
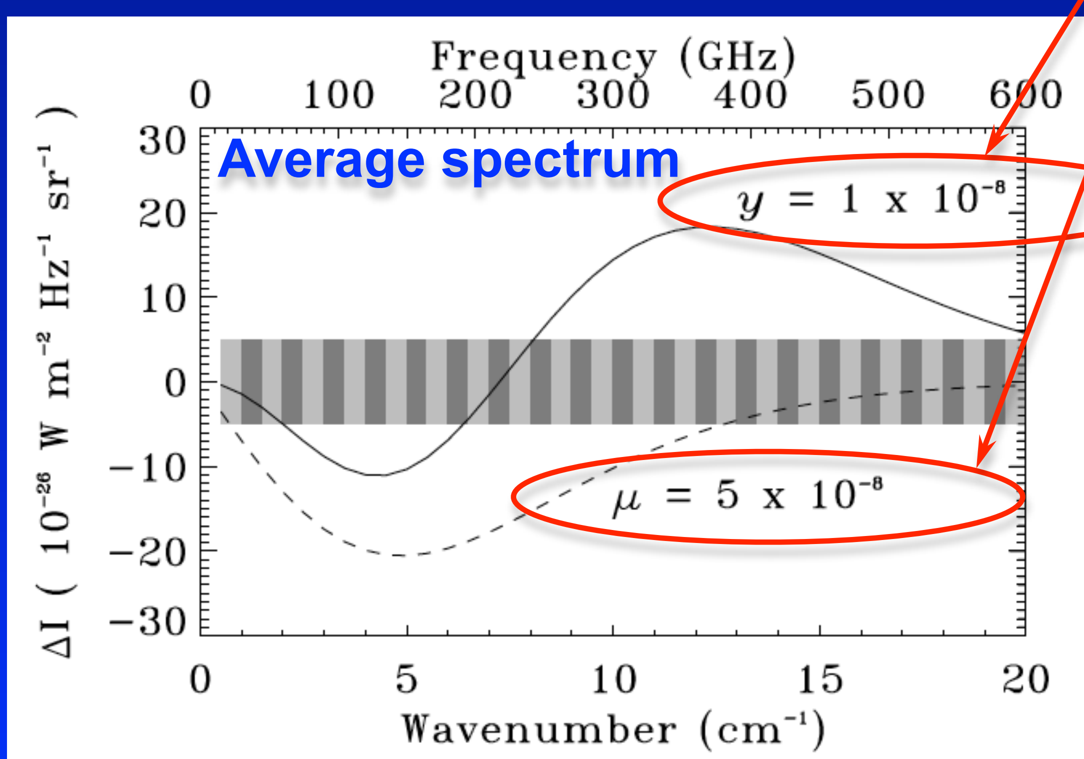
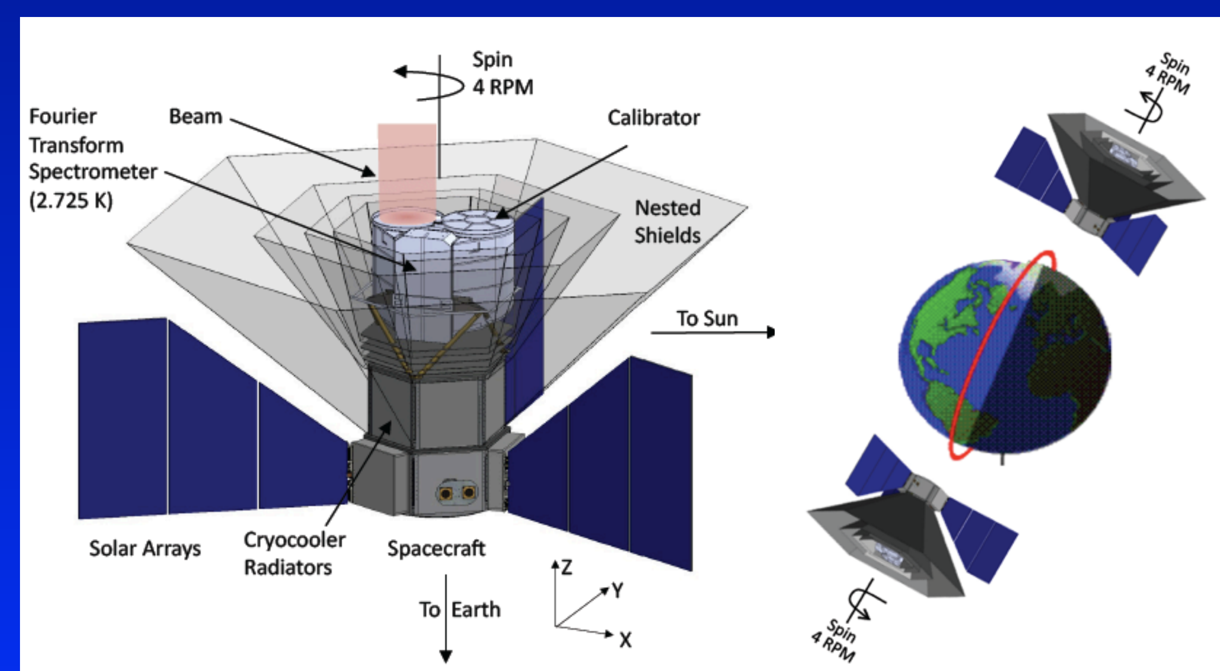
PIXIE: Primordial Inflation Explorer

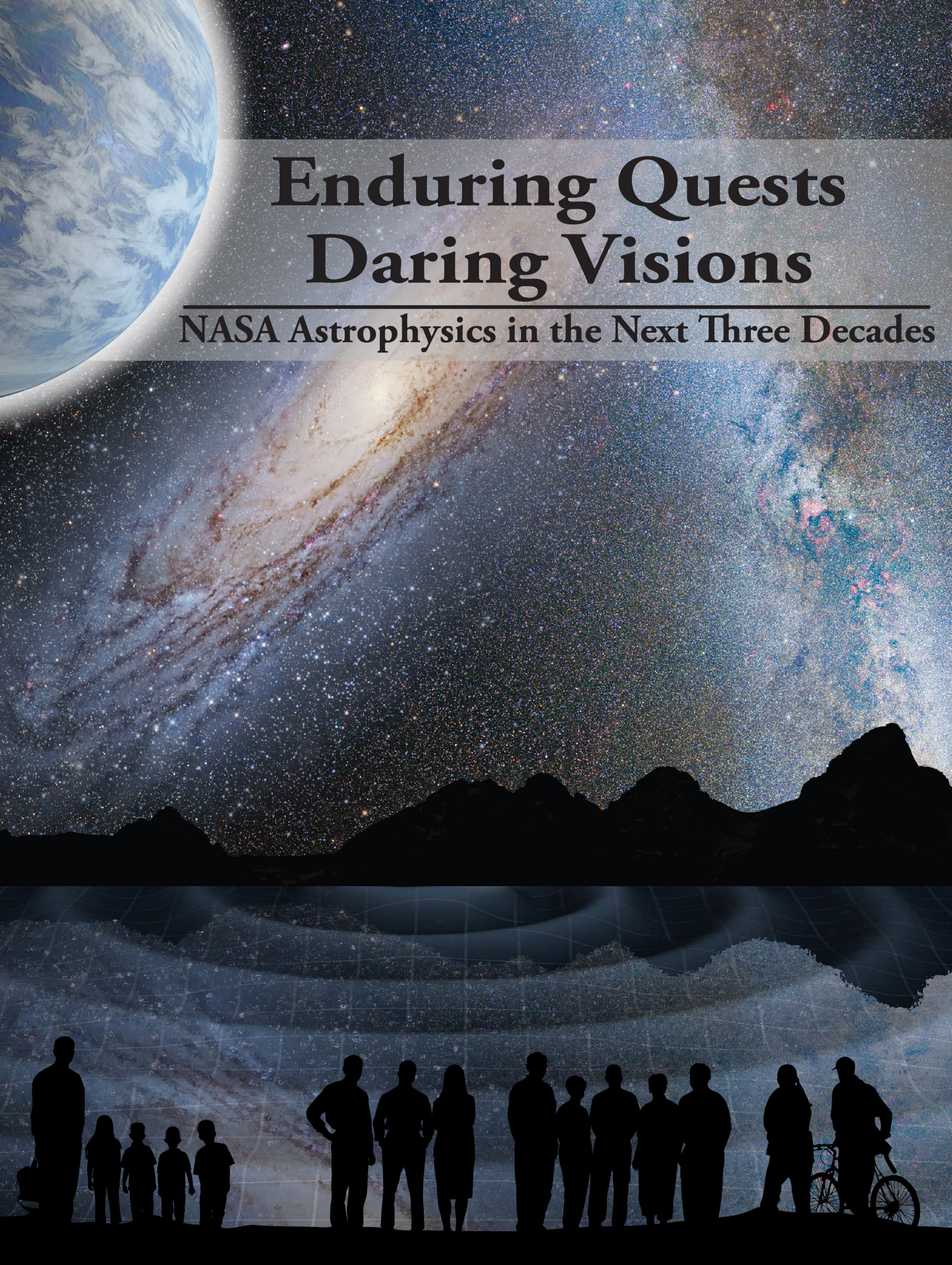


- 400 spectral channel in the frequency range 30 GHz and 6THz (Δv ~ 15GHz)
- about 1000 (!!!) times more sensitive than COBE/FIRAS
- B-mode polarization from inflation ($r \approx 10^{-3}$)
- improved limits on μ and y
- was proposed 2011 as NASA EX mission (i.e. cost ~ 200 M$)





Kogut et al, JCAP, 2011, arXiv:1105.2044



NASA 30-yr Roadmap Study

(published Dec 2013)

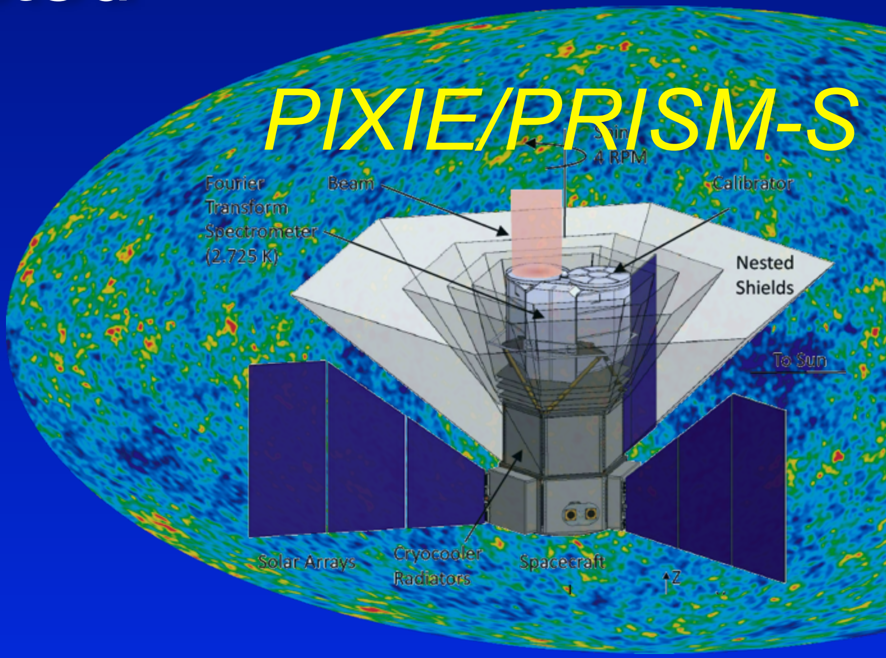
How does the Universe work?

"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."

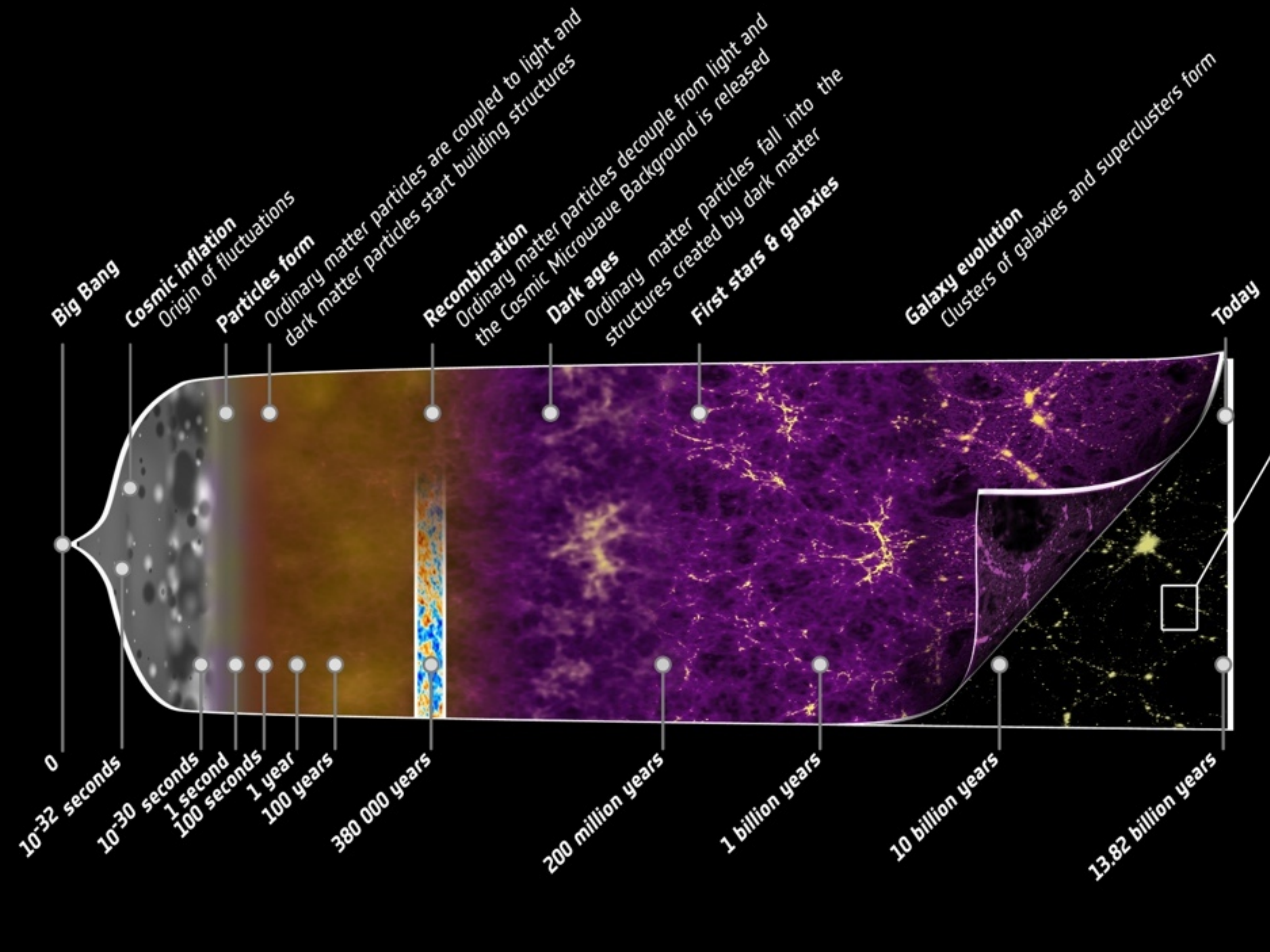
New call from NASA expected end 2016

What can CMB spectral distortions add?

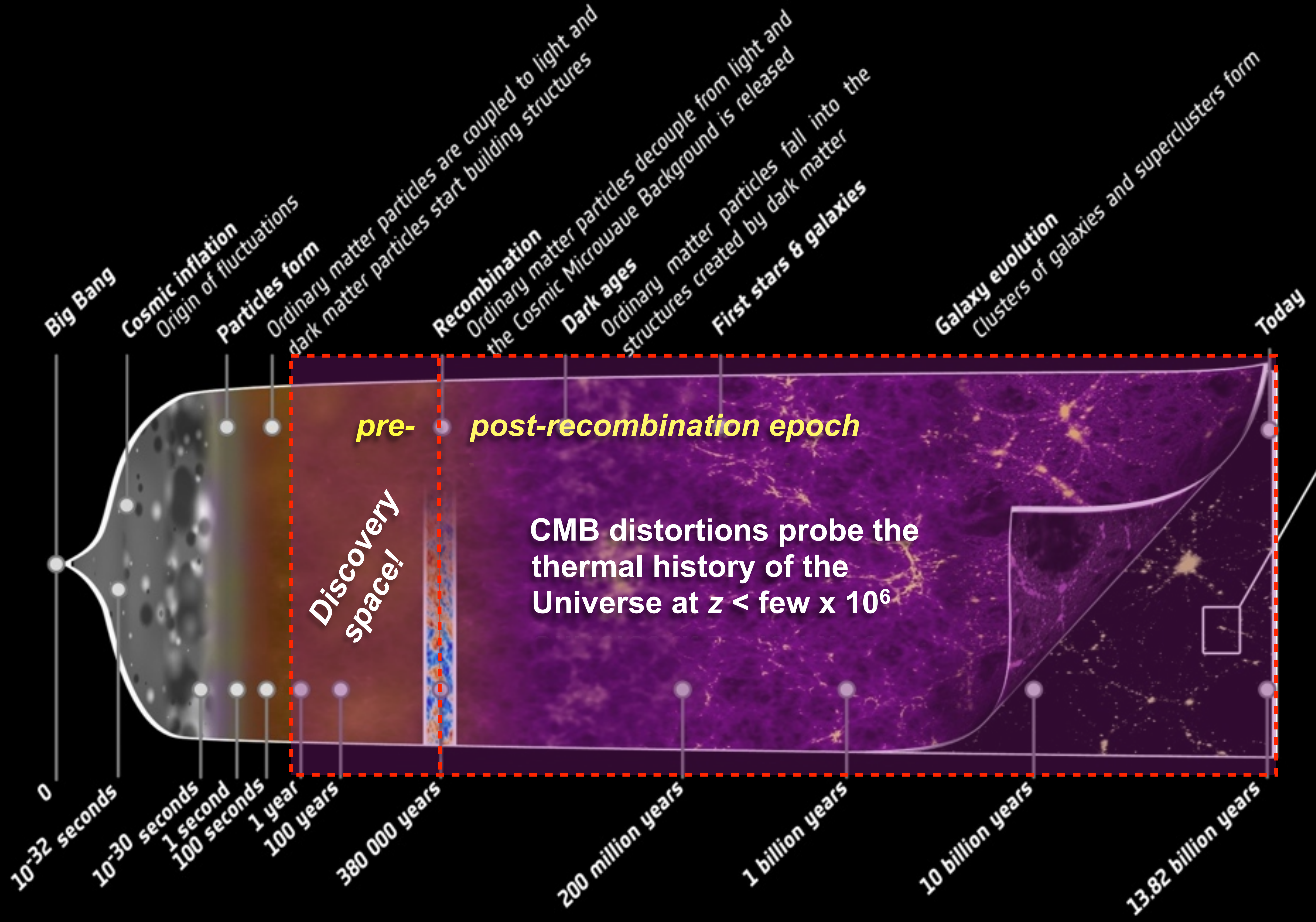
- Add a *new dimension* to CMB science
  - probe the thermal history at different stages of the Universe
- *Complementary* and *independent* information!
  - cosmological parameters from the recombination radiation
  - new/additional test of large-scale anomalies
- Several *guaranteed signals* are expected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



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



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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Clusters of galaxies and superclusters form
Today
pre-
post-recombination epoch
Discovery space!
CMB distortions probe the thermal history of the Universe at z < few x 10^6
0
10^-32 seconds
10^-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
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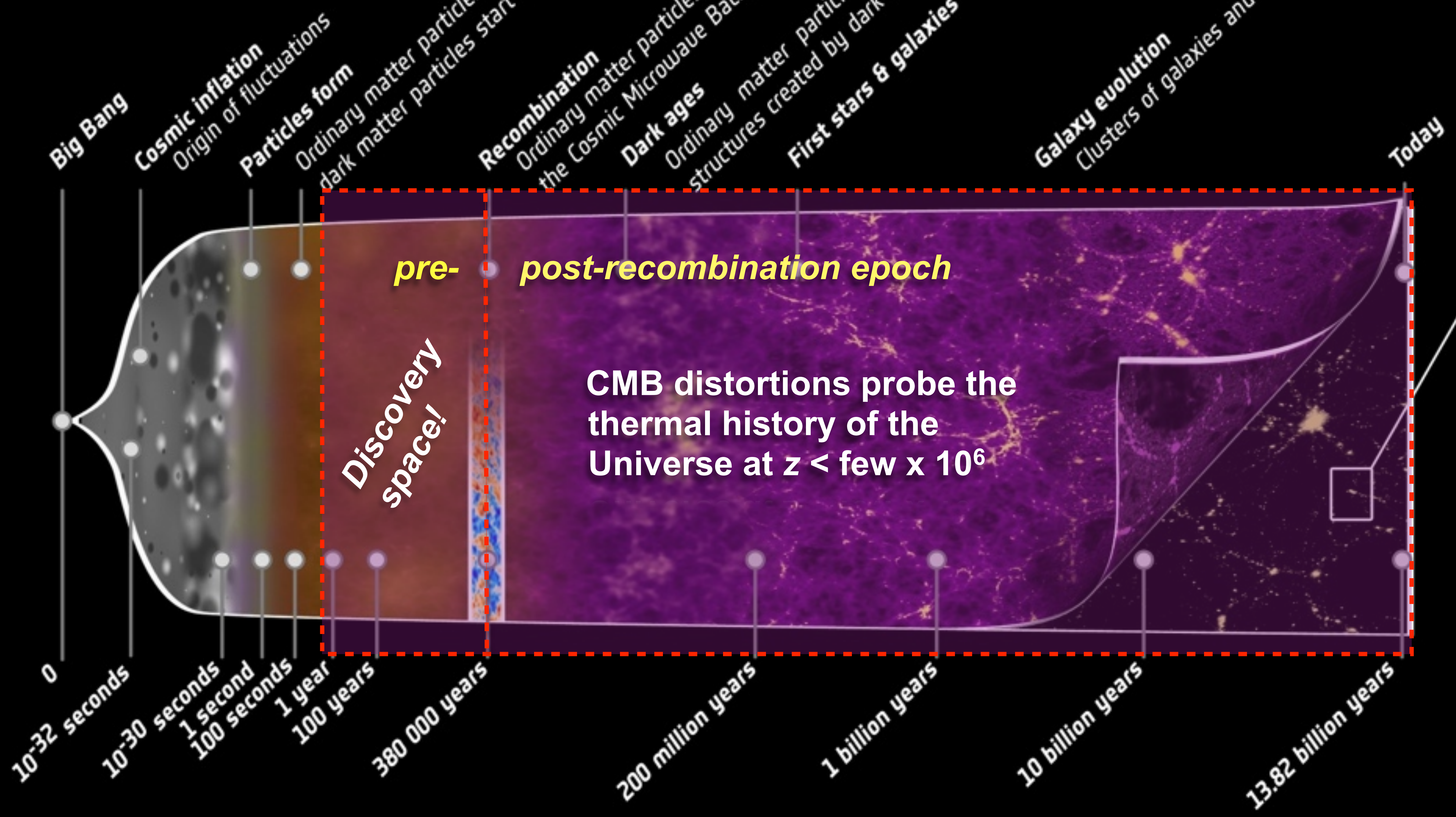
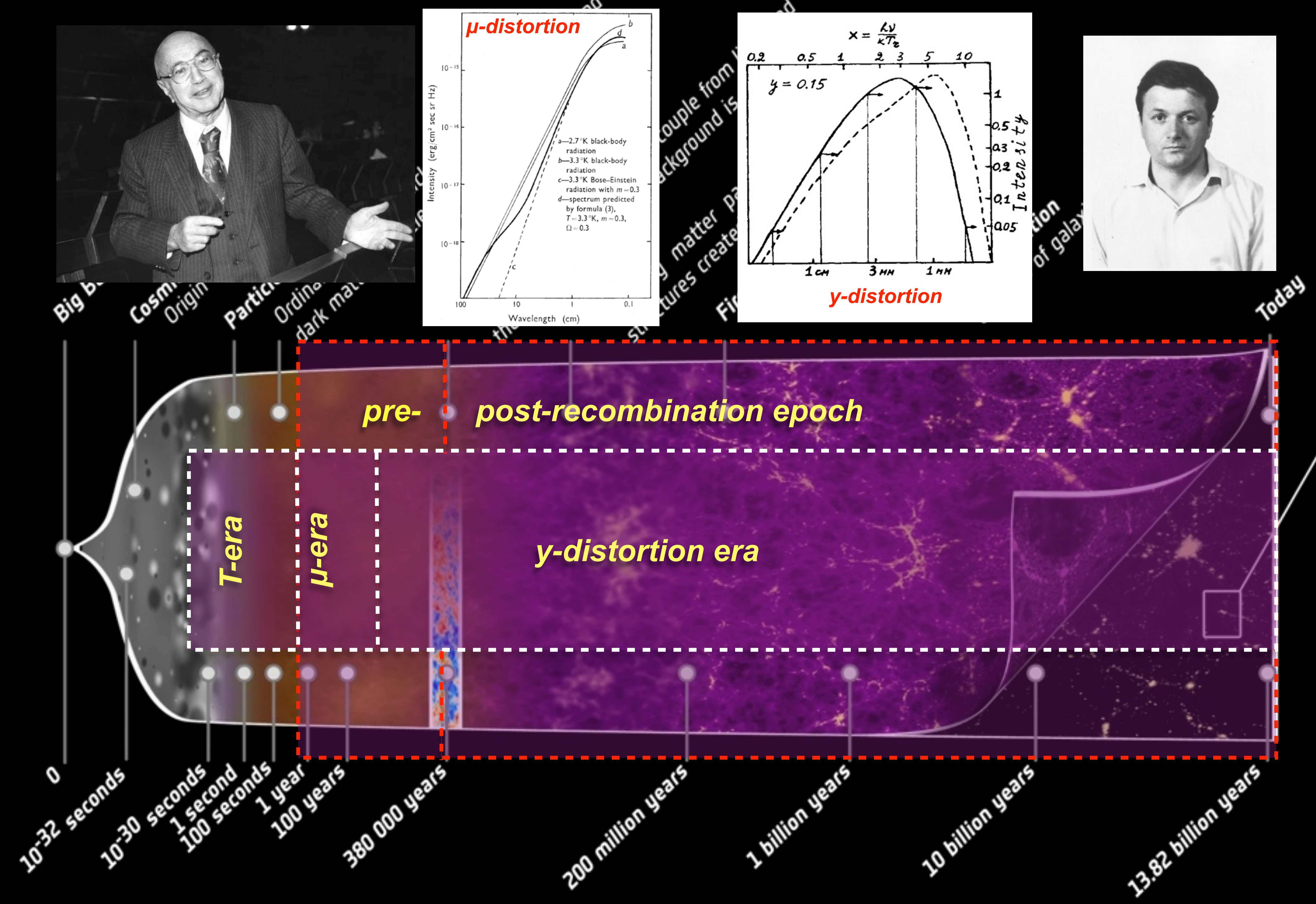
Measurements of CMB spectrum will open a new unexplored window to the early Universe!





μ-distortion
Intensity (erg/cm² sec sr Hz)
Wavelength (cm)
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
x = hν/kT_e
y = 0.15
Intensity
1 см
3 мм
1 мм
y-distortion
pre-
post-recombination epoch
T-era
μ-era
y-distortion era
Today
0
10-32 seconds
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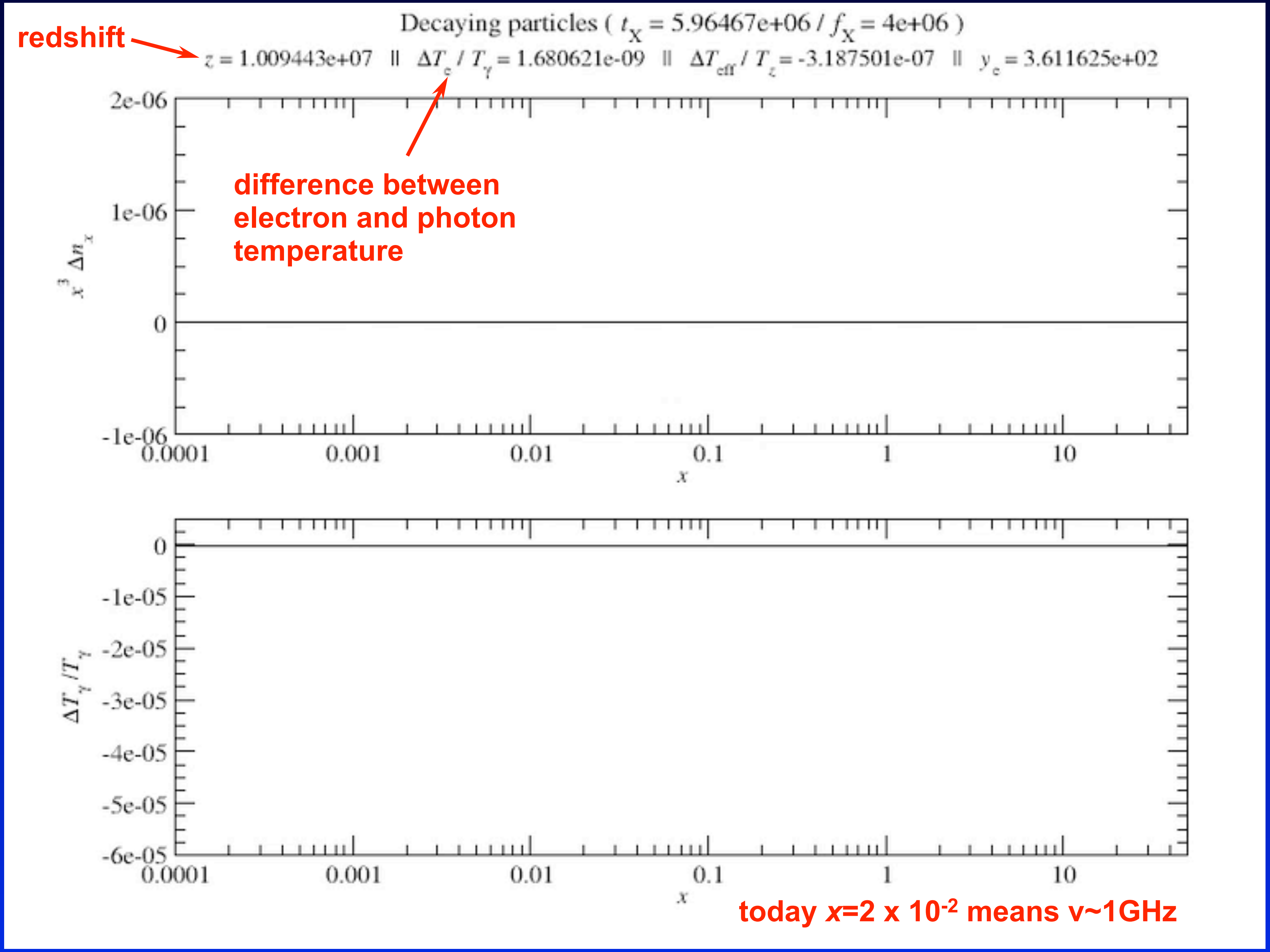
Example: *Energy release by decaying relict particle*



- initial condition: *full equilibrium*
- total energy release: $\Delta\rho/\rho \sim 1.3 \times 10^{-6}$
- most of energy release 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)

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*

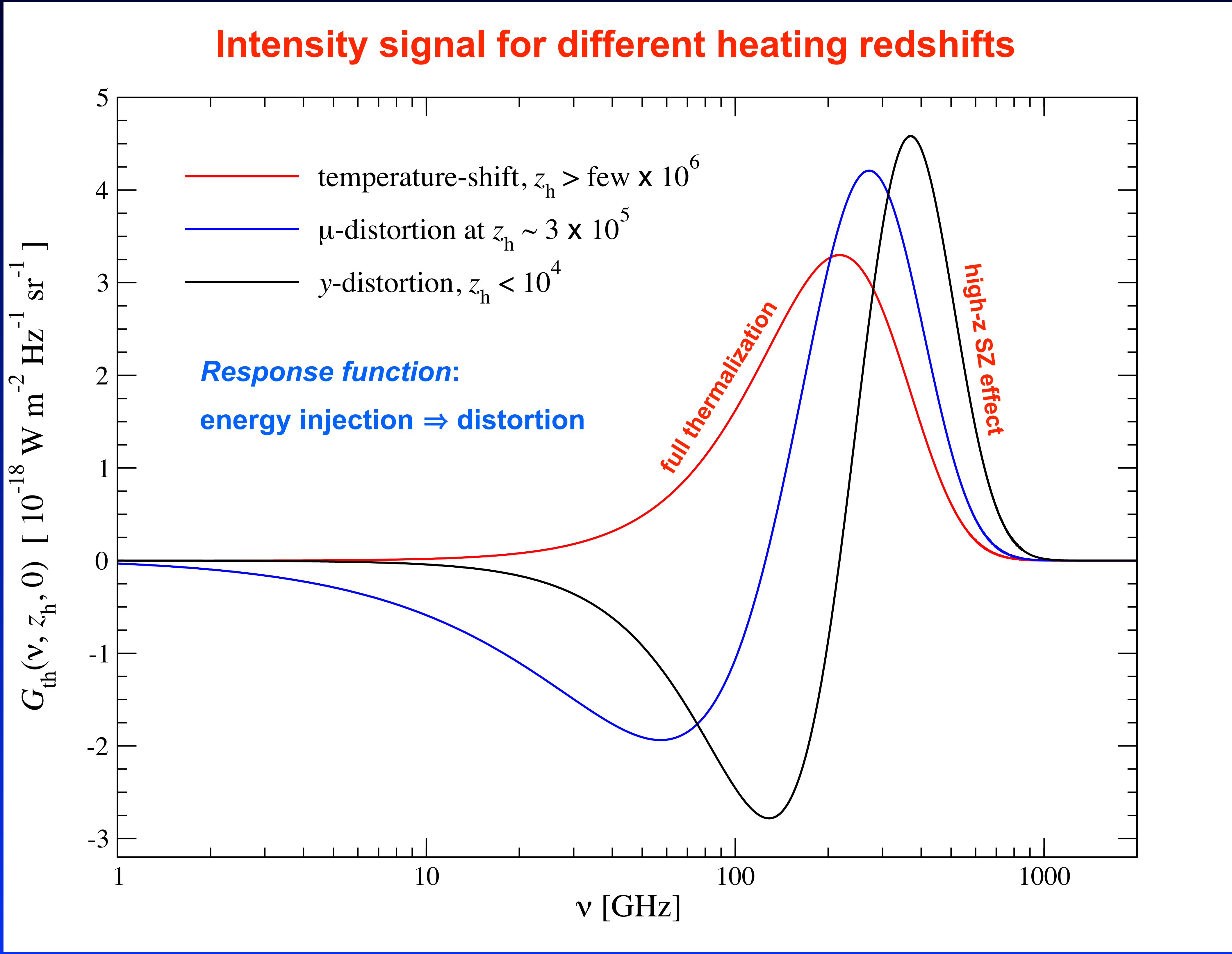
$$\Delta I_\nu \approx \int_0^\infty G_{\rm th}(\nu, z') \frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'} {\rm d}z'$$

Thermalization Green's function

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

CosmoTherm available at: www.Chluba.de/CosmoTherm

Distortion Green's function for energy release



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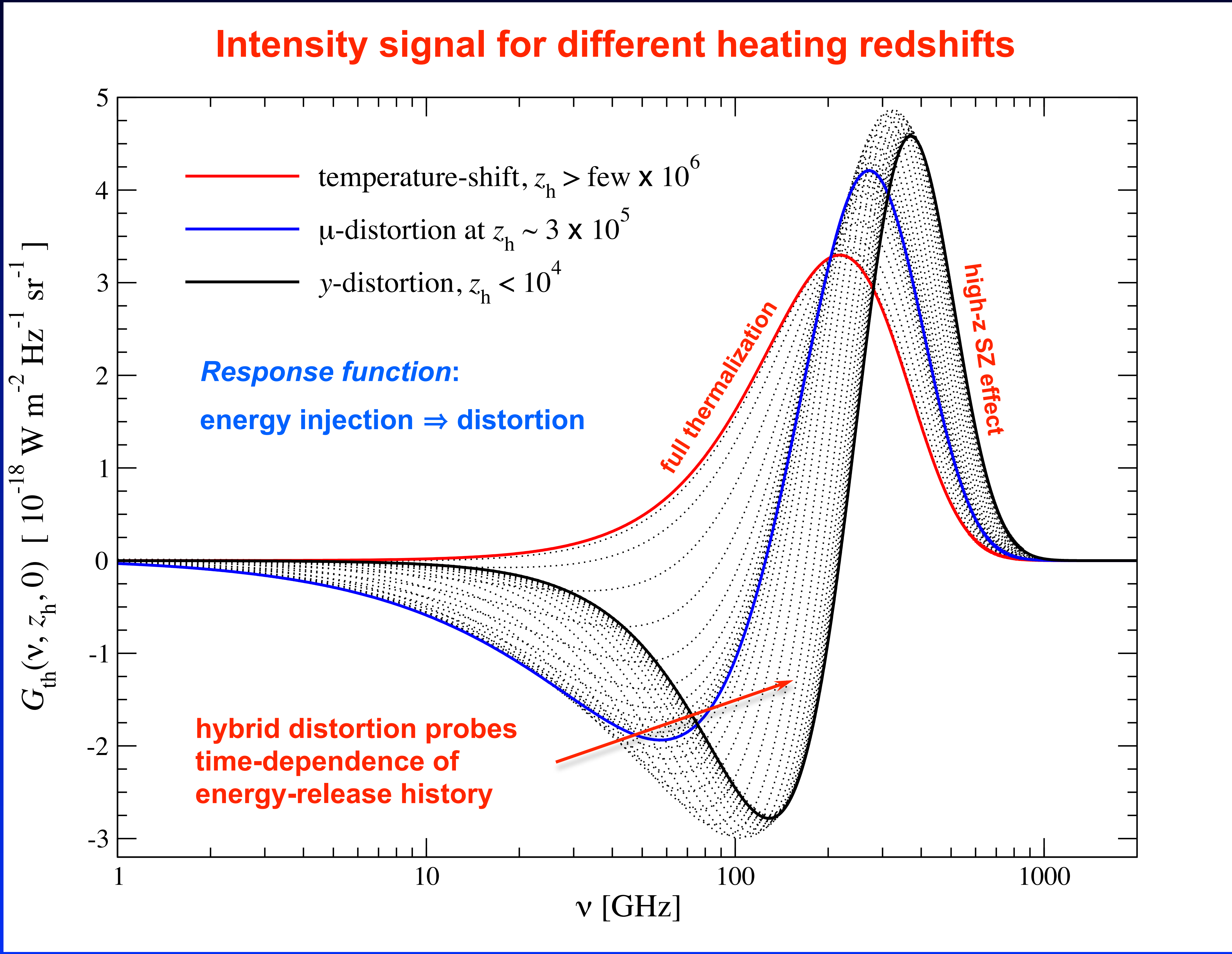

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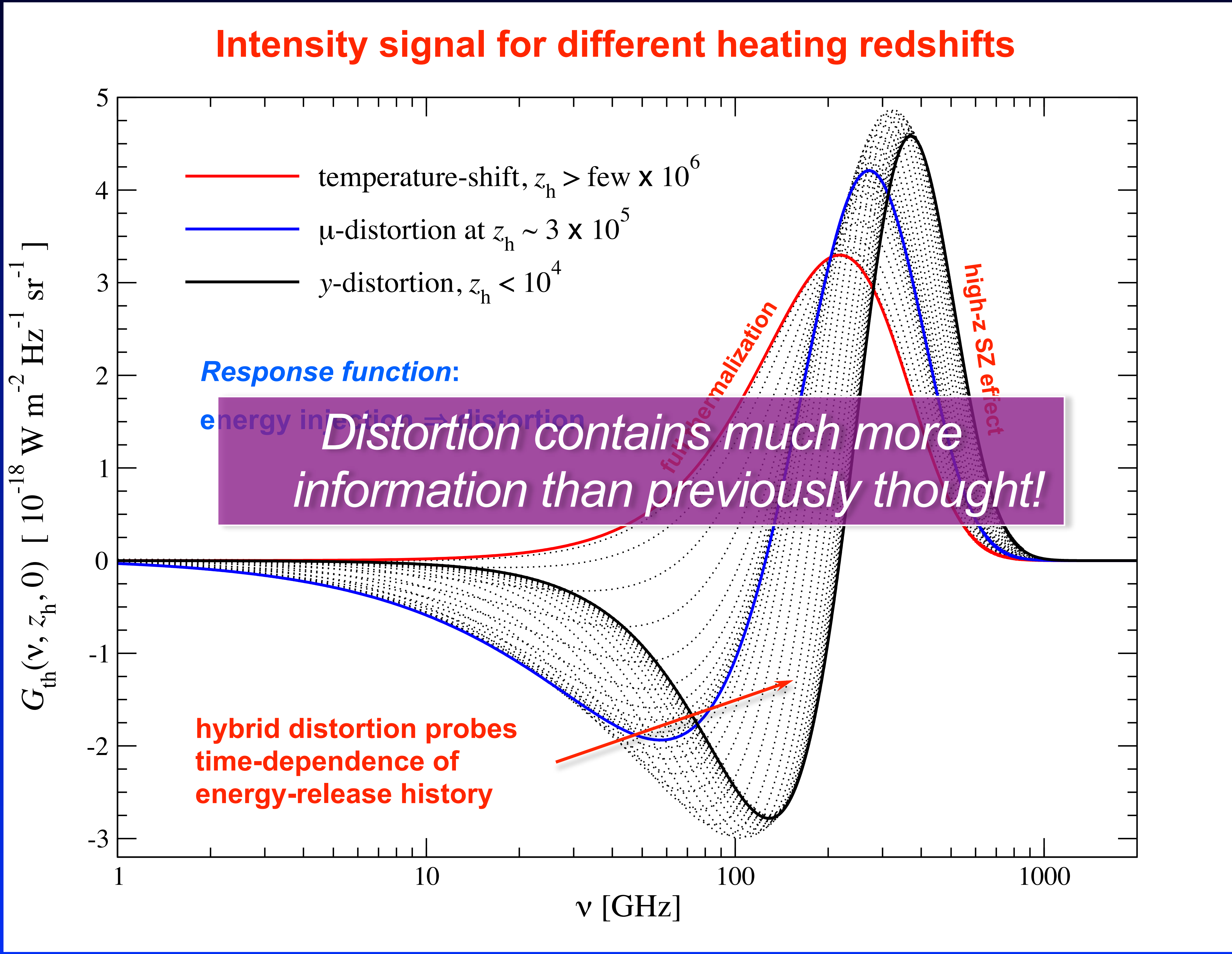

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Transition from y-distortion → μ-distortion

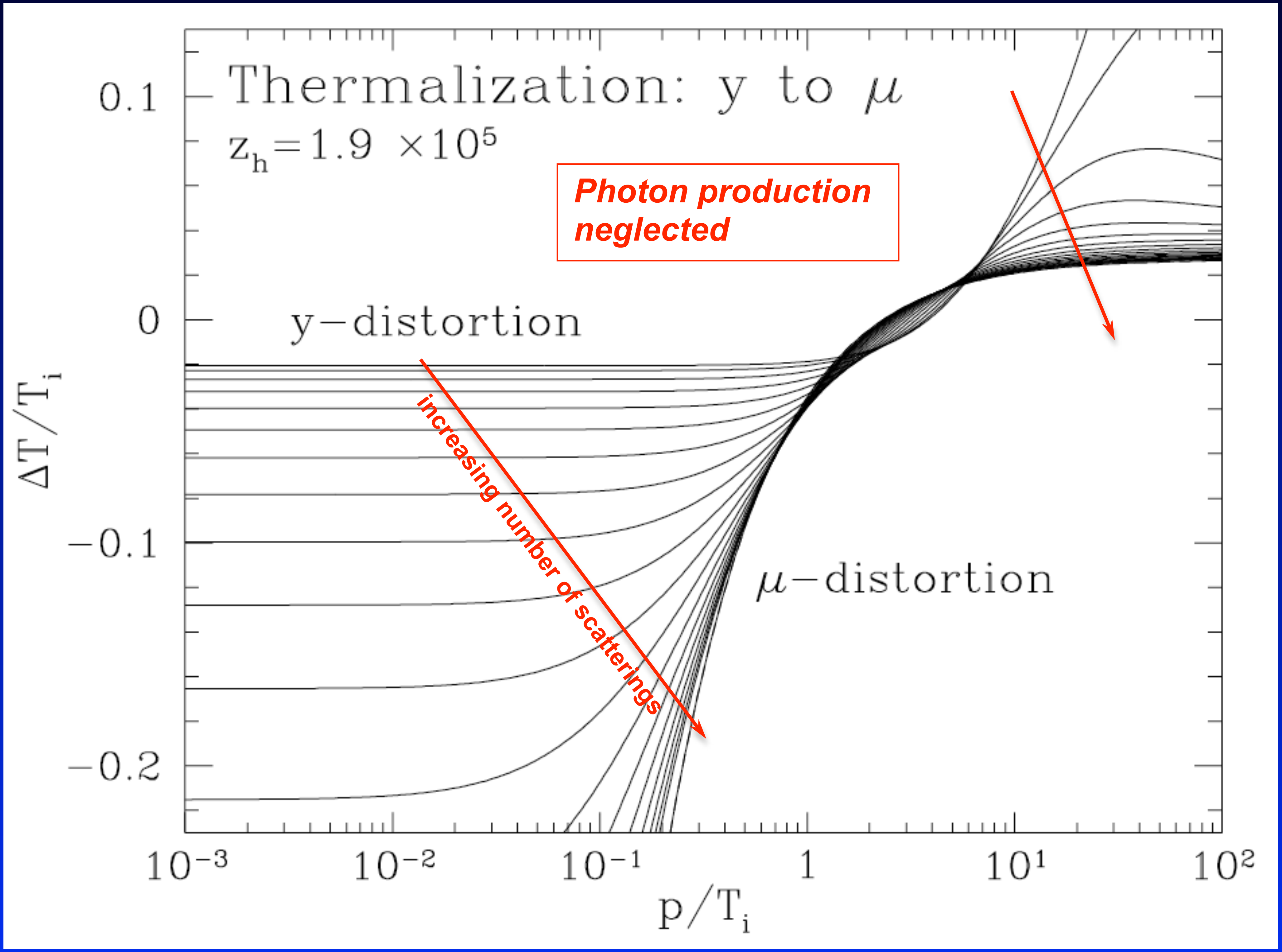

Figure from Wayne Hu's PhD thesis, 1995, but see also discussion in Burigana, 1991

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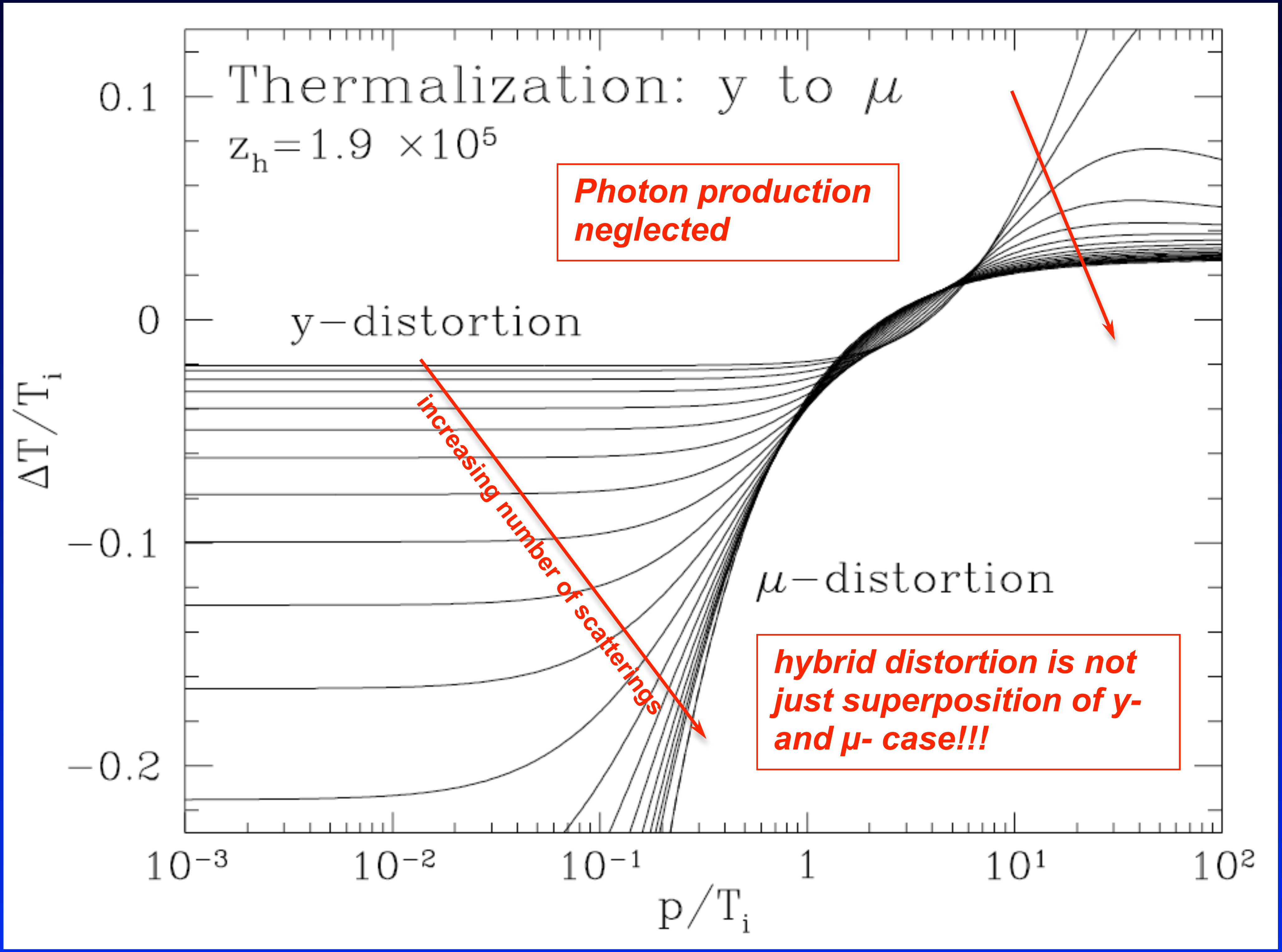

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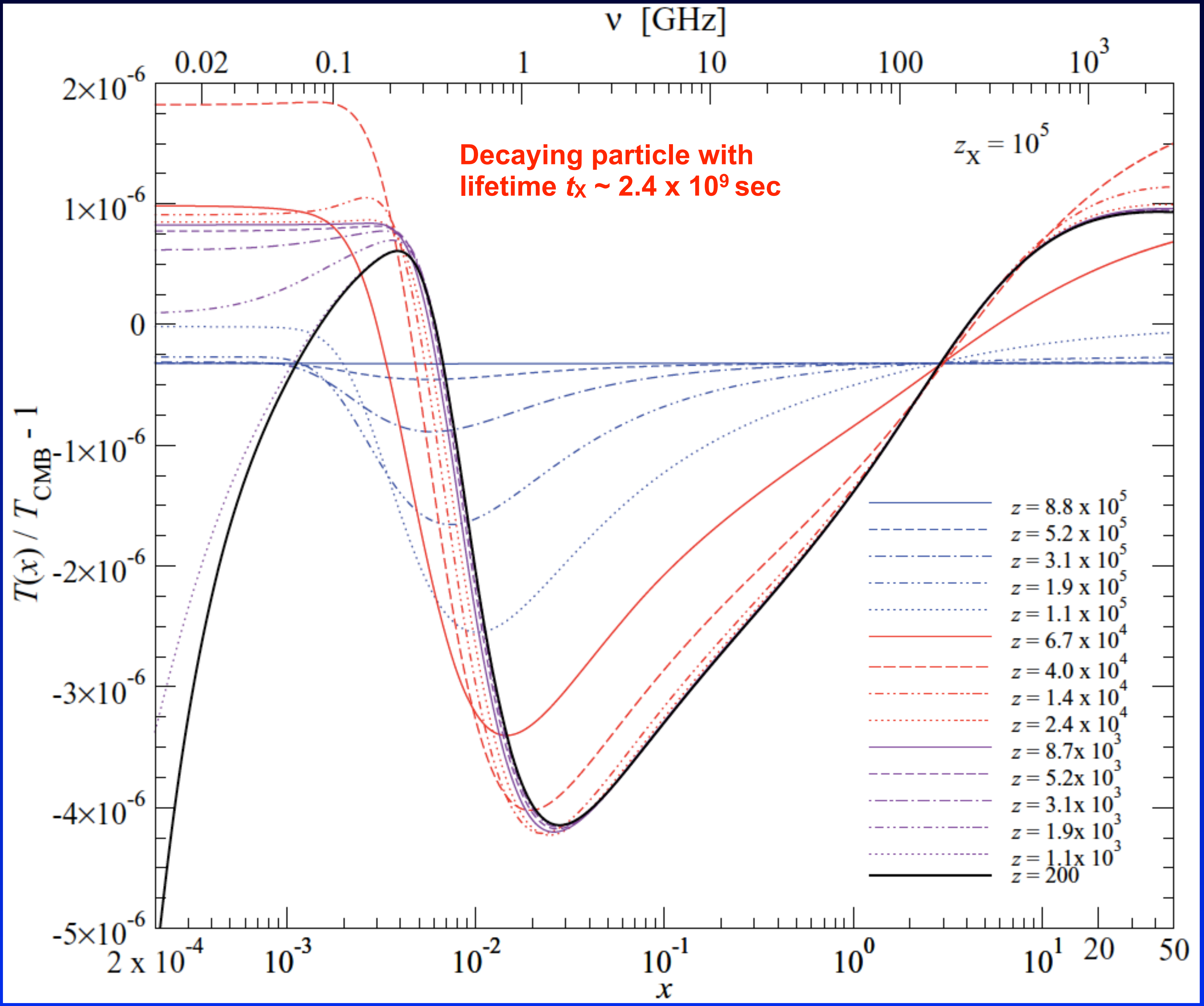
Distortion *not* just superposition of μ and y-distortion!



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

First explicit calculation that showed that there is more!

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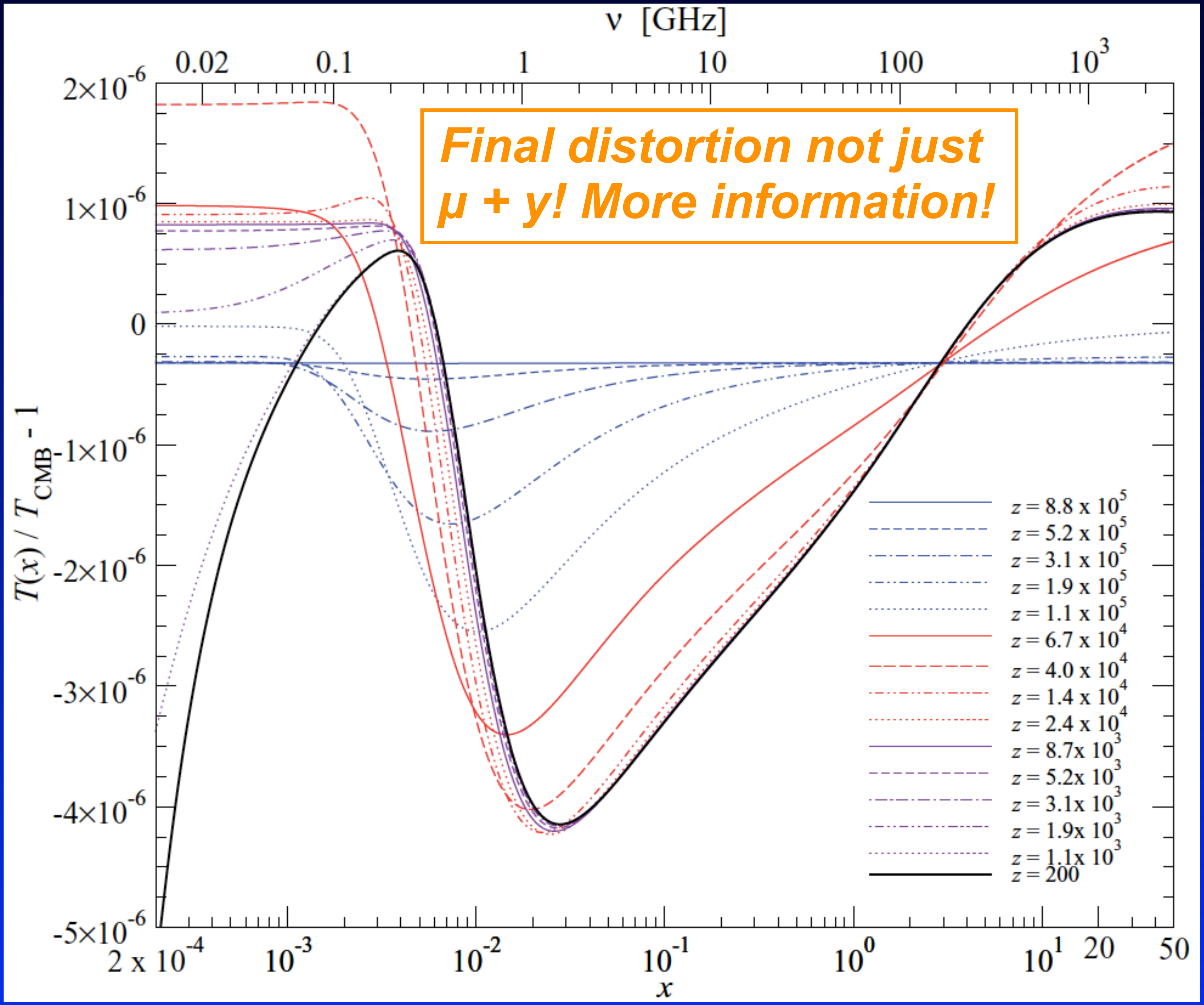

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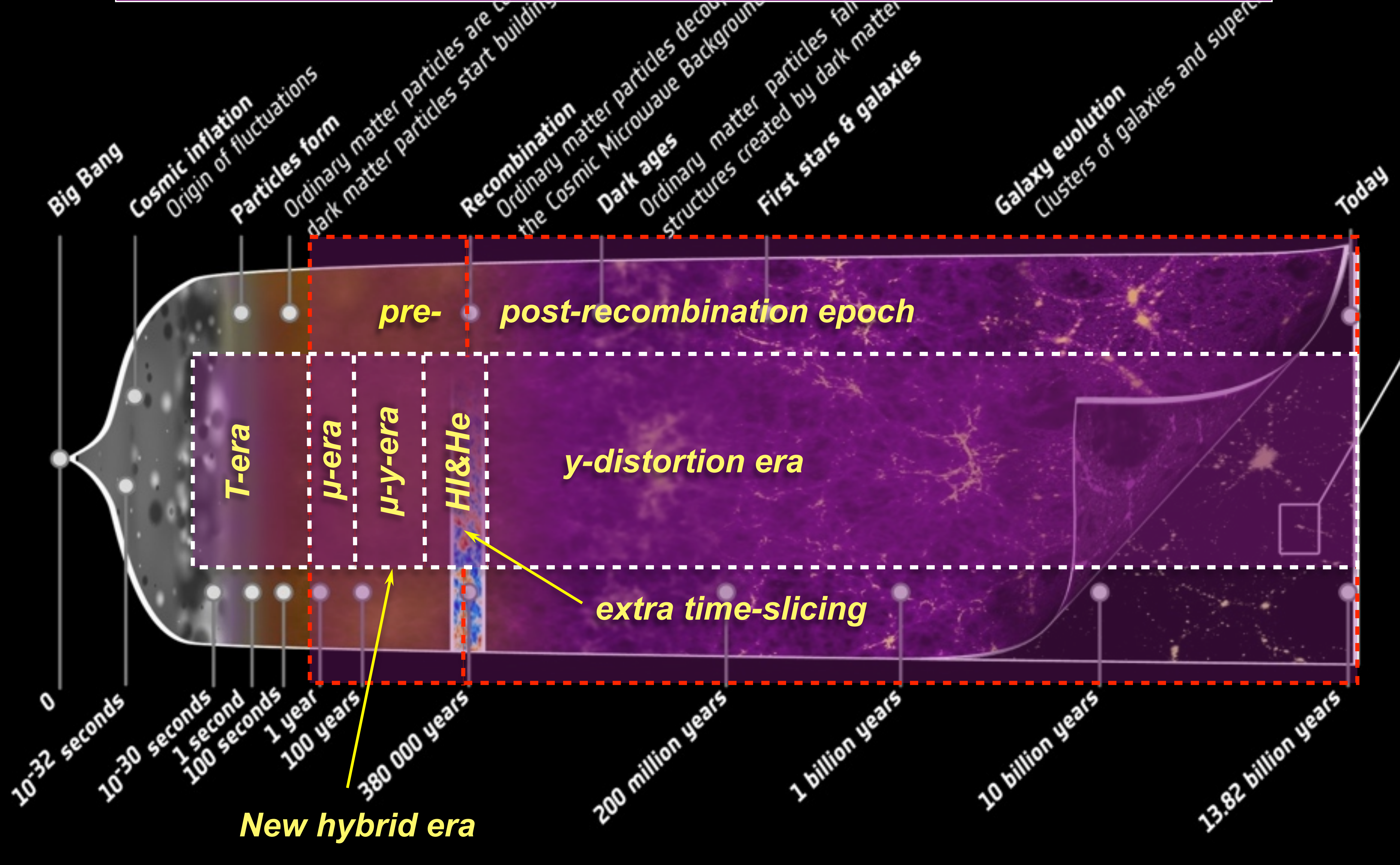
CMB spectrum adds another dimension to the problem!



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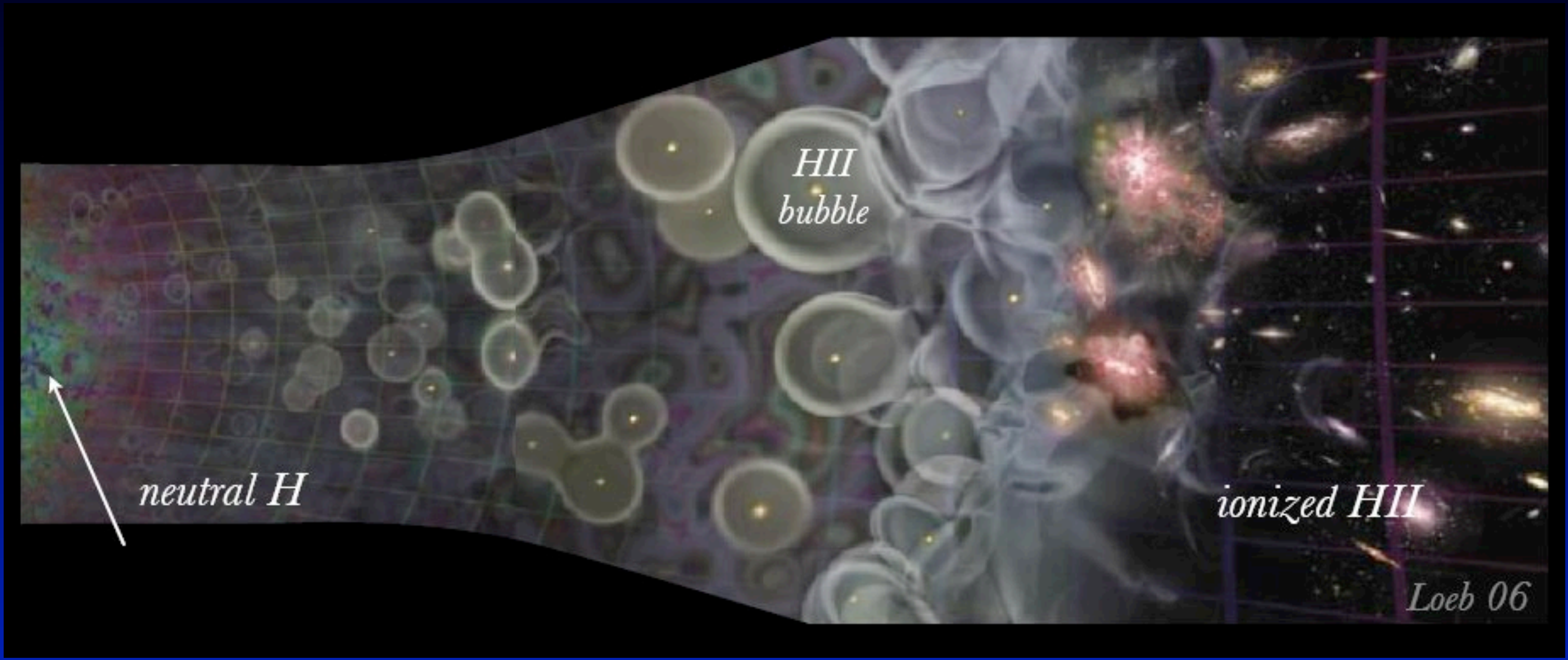
Reionization and structure formation

Simple estimates for the distortion

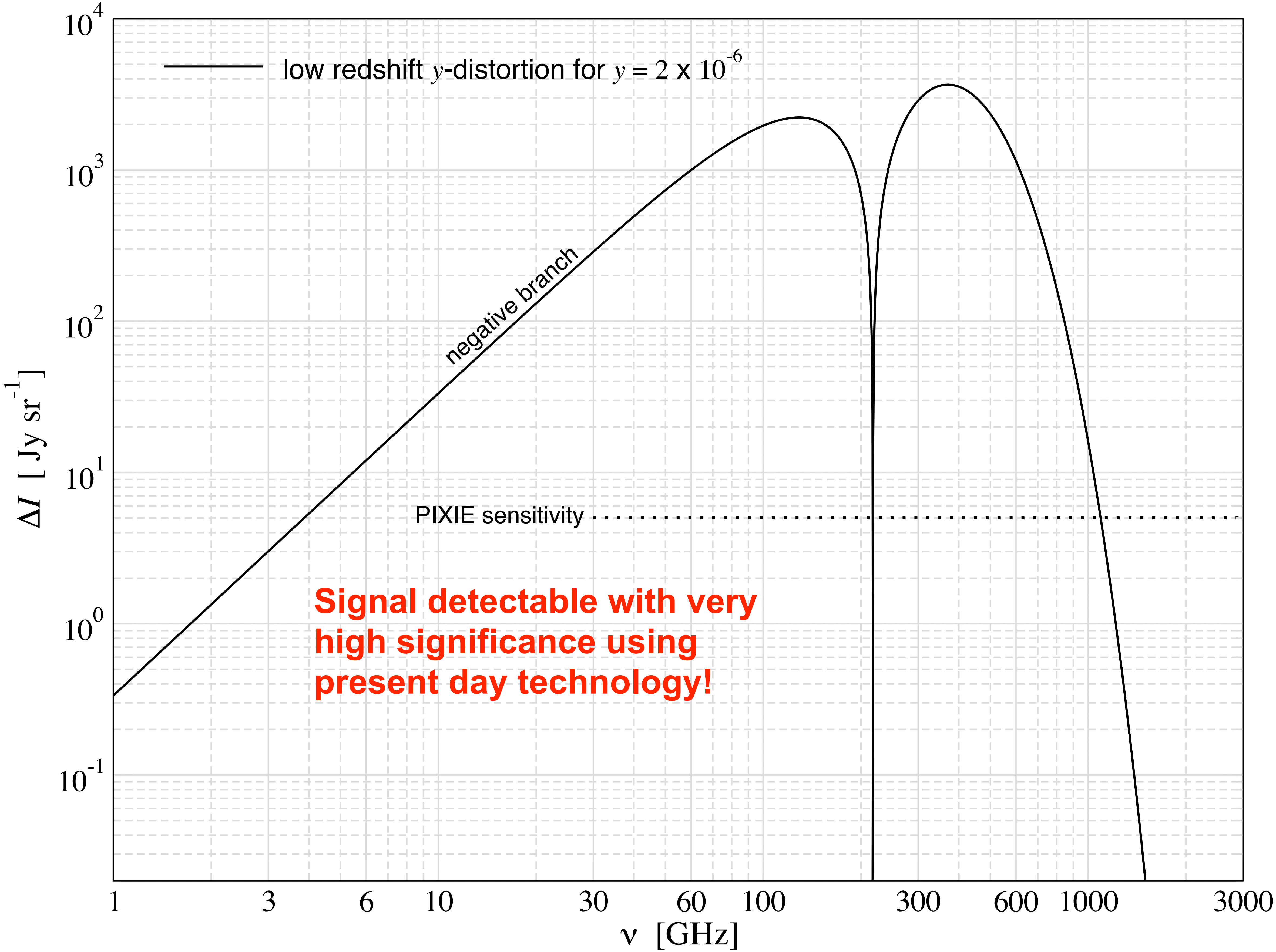


- Gas temperature $T \simeq 10^4$ K
- Thomson optical depth $\tau \simeq 0.1$

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

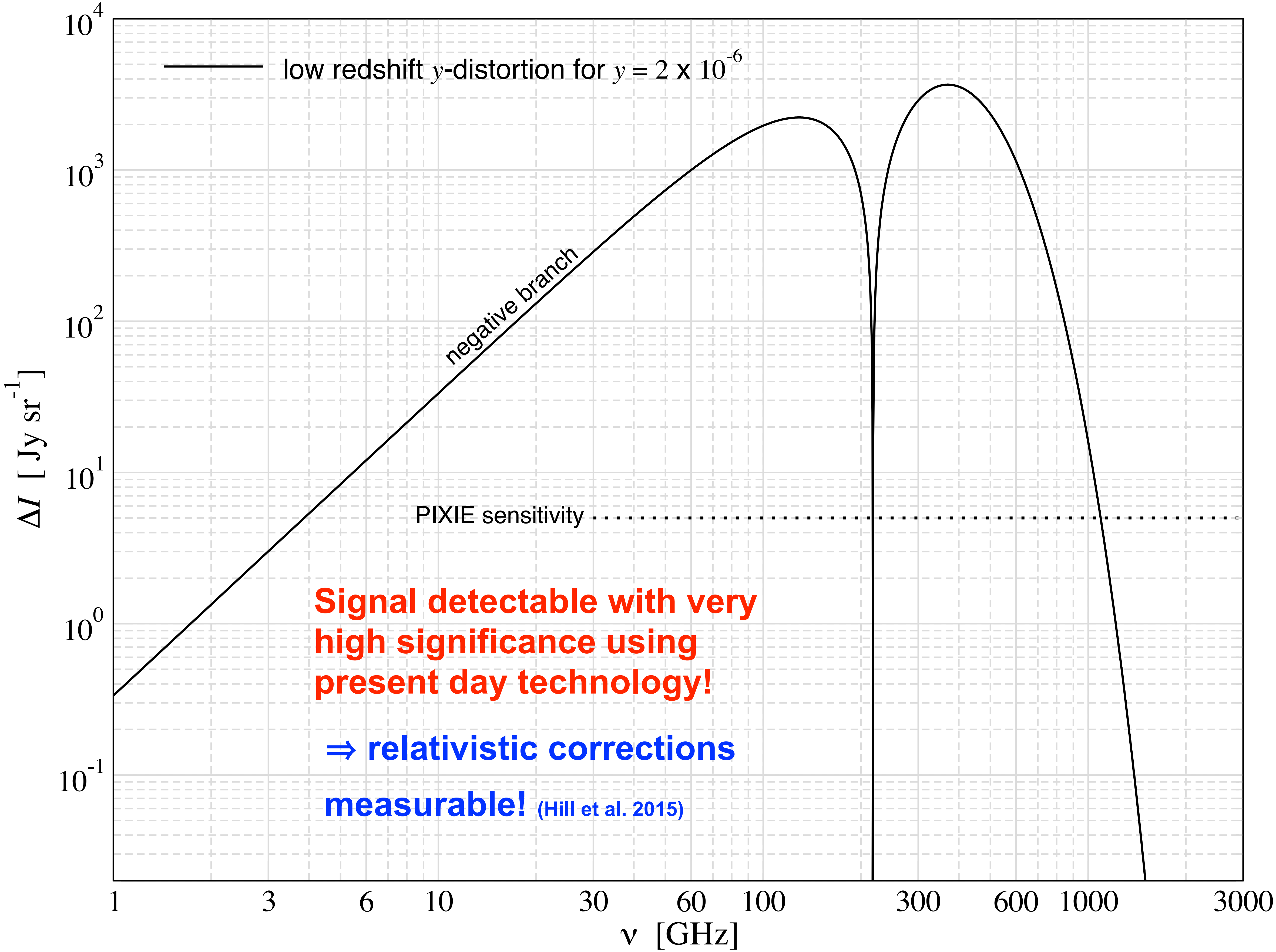
- second order Doppler effect $y \simeq$ few x 10^{-8}
- structure formation / SZ effect (e.g., Refregier et al., 2003) $y \simeq$ few x 10^{-7}-10^{-6}

Average CMB spectral distortions

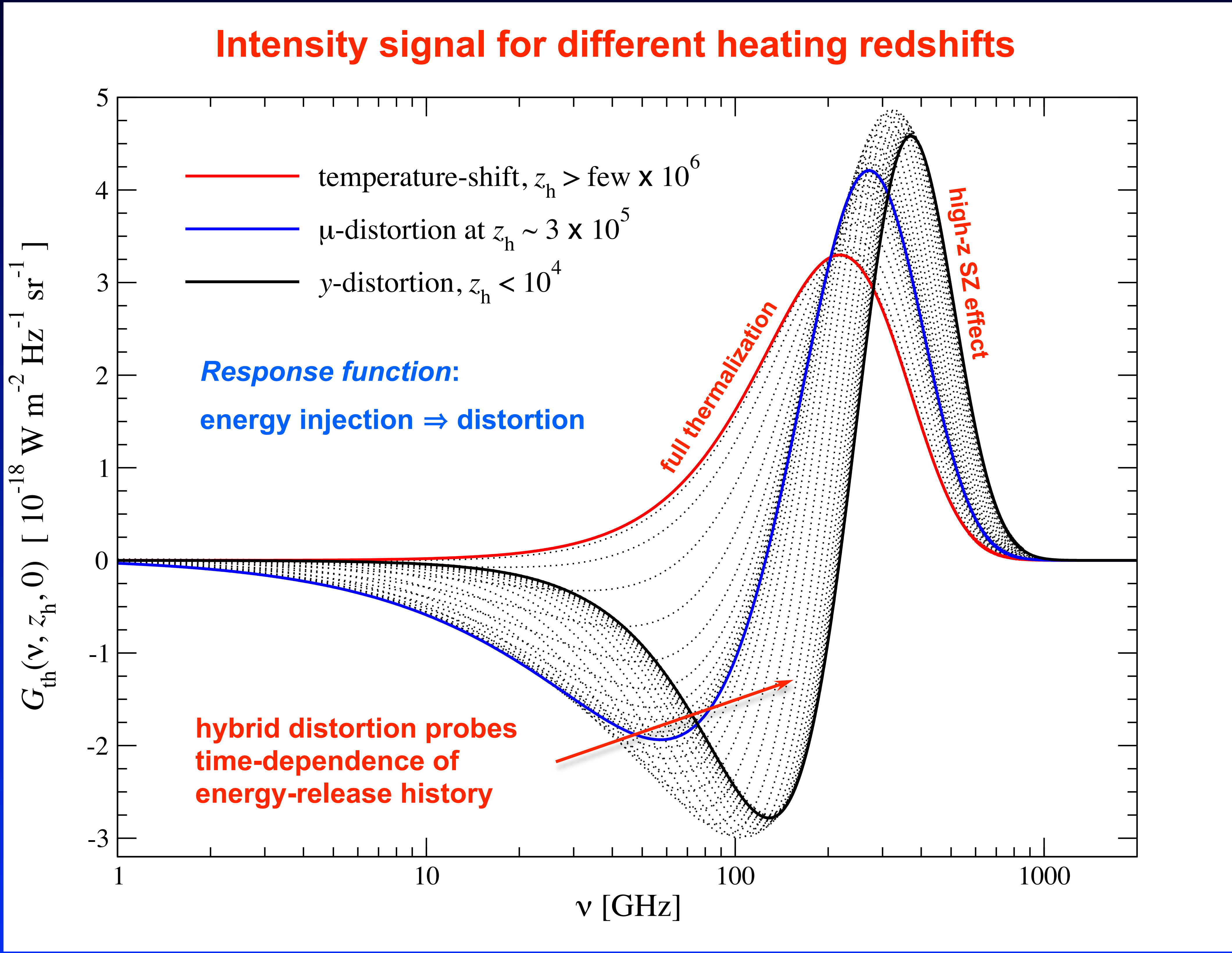


Signal detectable with very high significance using present day technology!

Average CMB spectral distortions



Distortion Green's function for energy release



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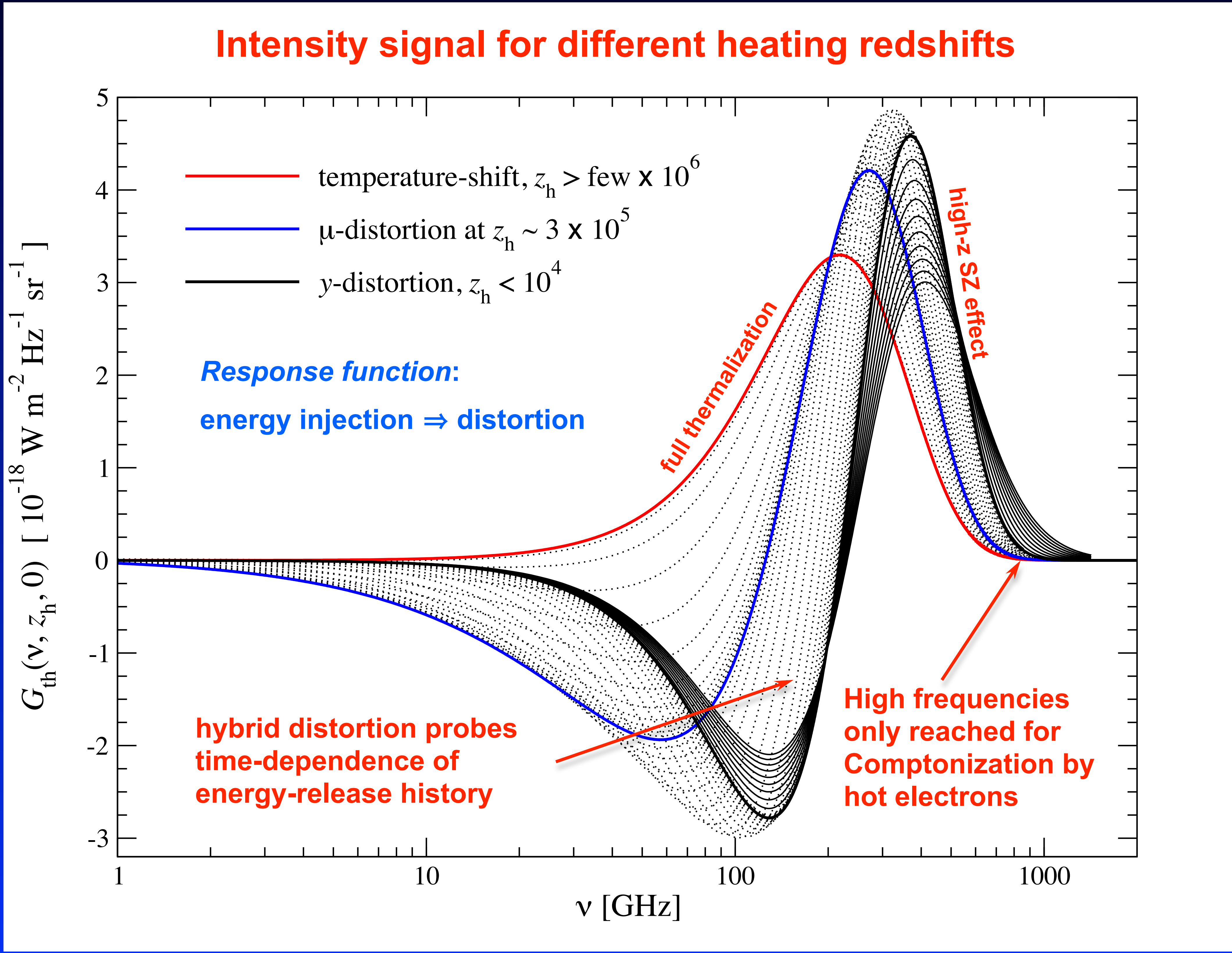

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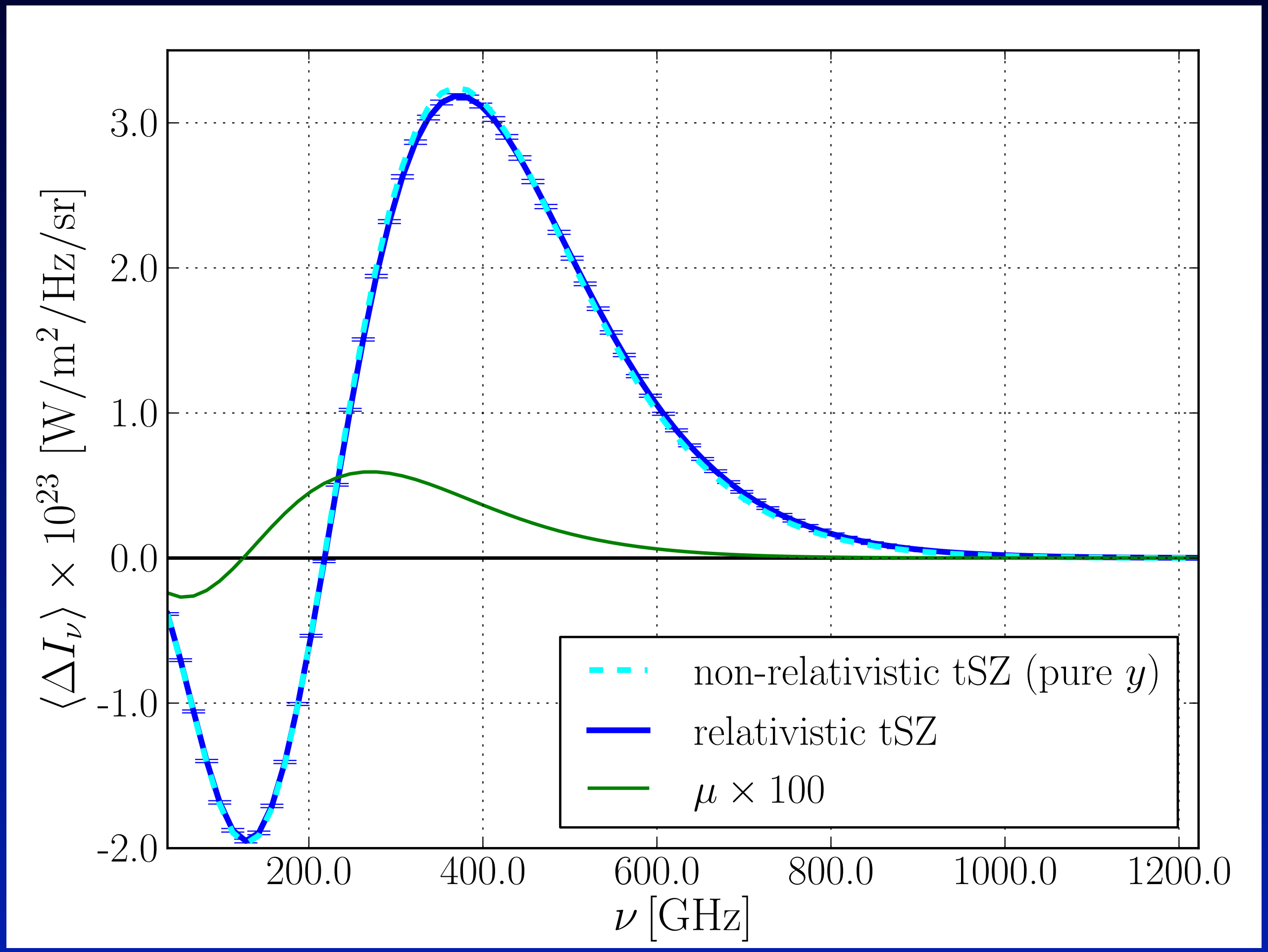
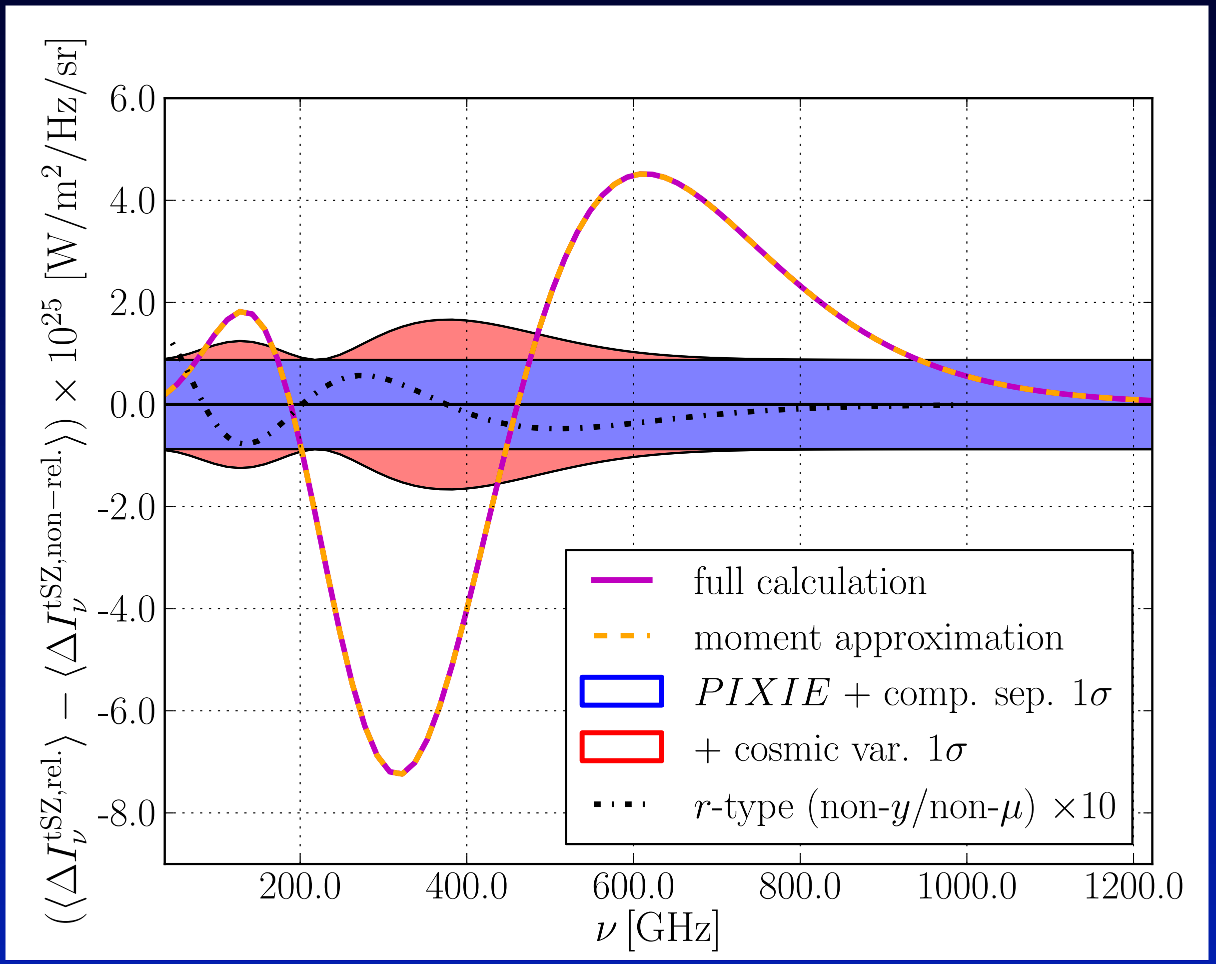
Taking the Universe's temperature

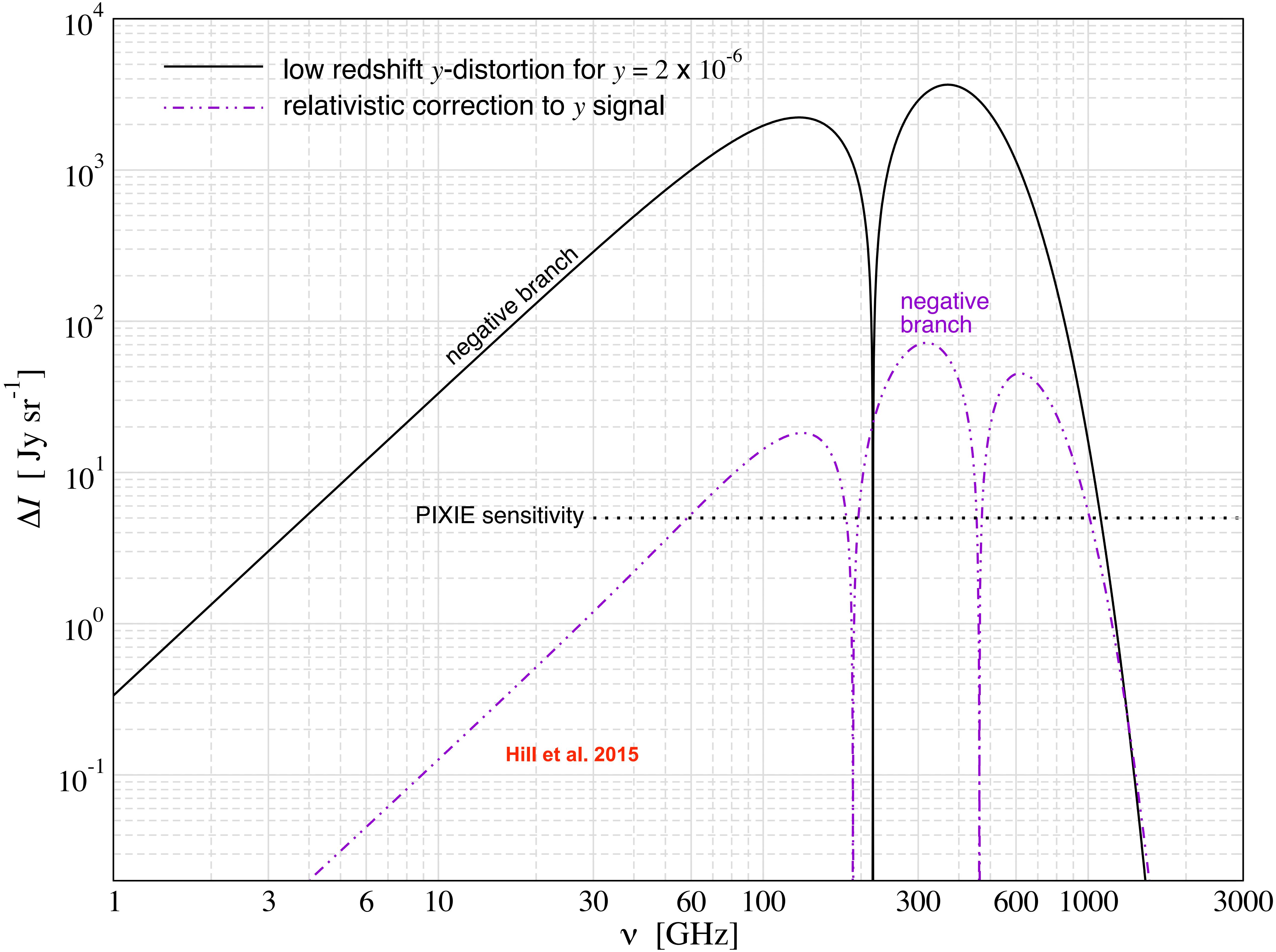




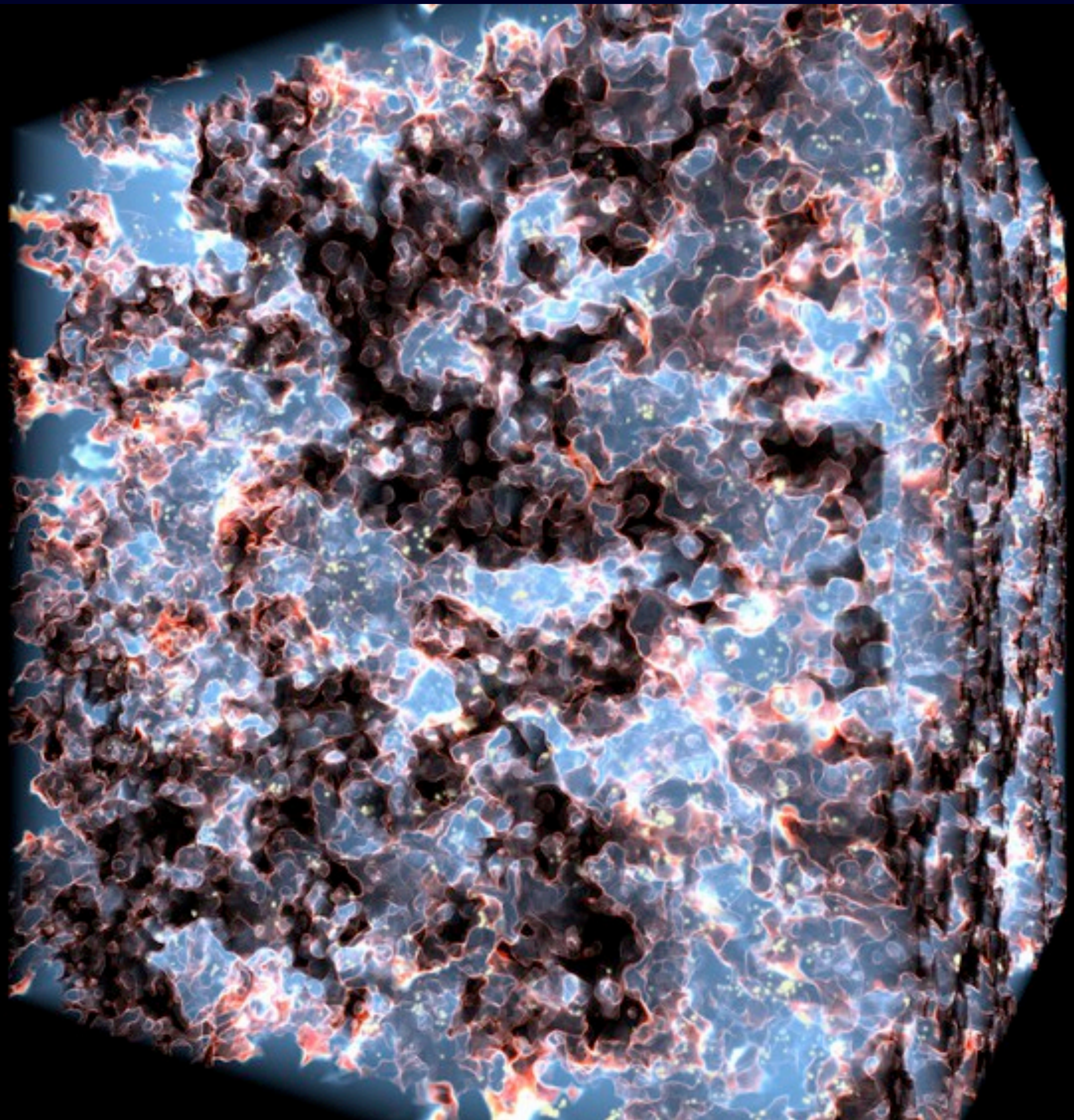
- $\langle y \rangle \simeq 1.8 \times 10^{-6}$ (~ 10% from IGM and reionization rest from ICM)
- > 1000 σ detection with PIXIE-type experiment
- optical depth-weighted temperature: $\langle kT_{\rm e} \rangle_\tau \simeq 0.208\,{\rm keV} (\equiv 2.4 \times 10^6\,{\rm K})$
- ~ 30 σ detection with PIXIE-type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

Hill et al., 2015, ArXiv:1507.01583

Average CMB spectral distortions



Fluctuations of the y-parameter at large scales

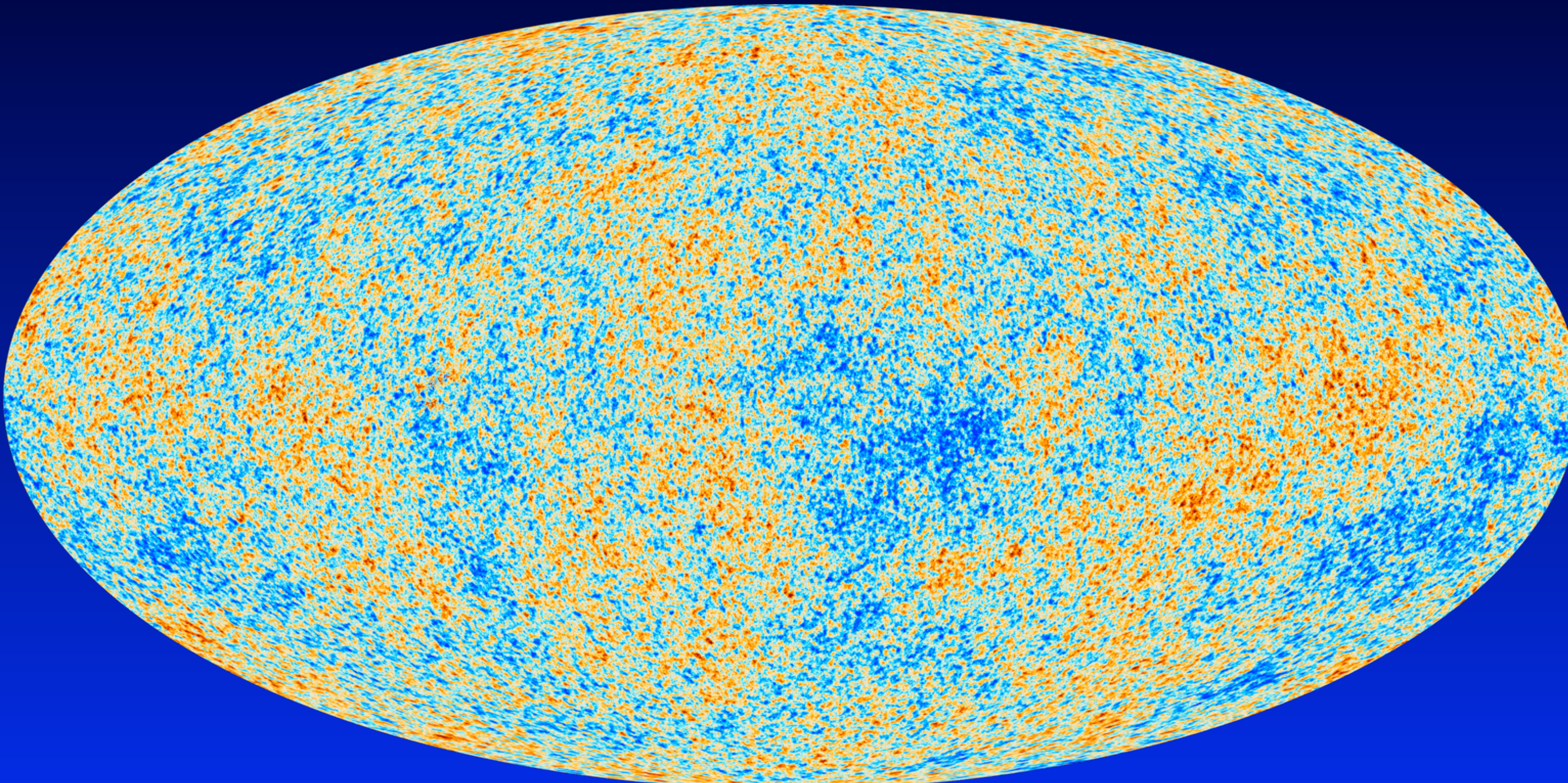


- spatial variations of the optical depth and temperature cause small-spatial variations of the y-parameter at different angular scales
- could tell us about the reionization sources and structure formation process
- additional independent piece of information!
- Cross-correlations with other signals

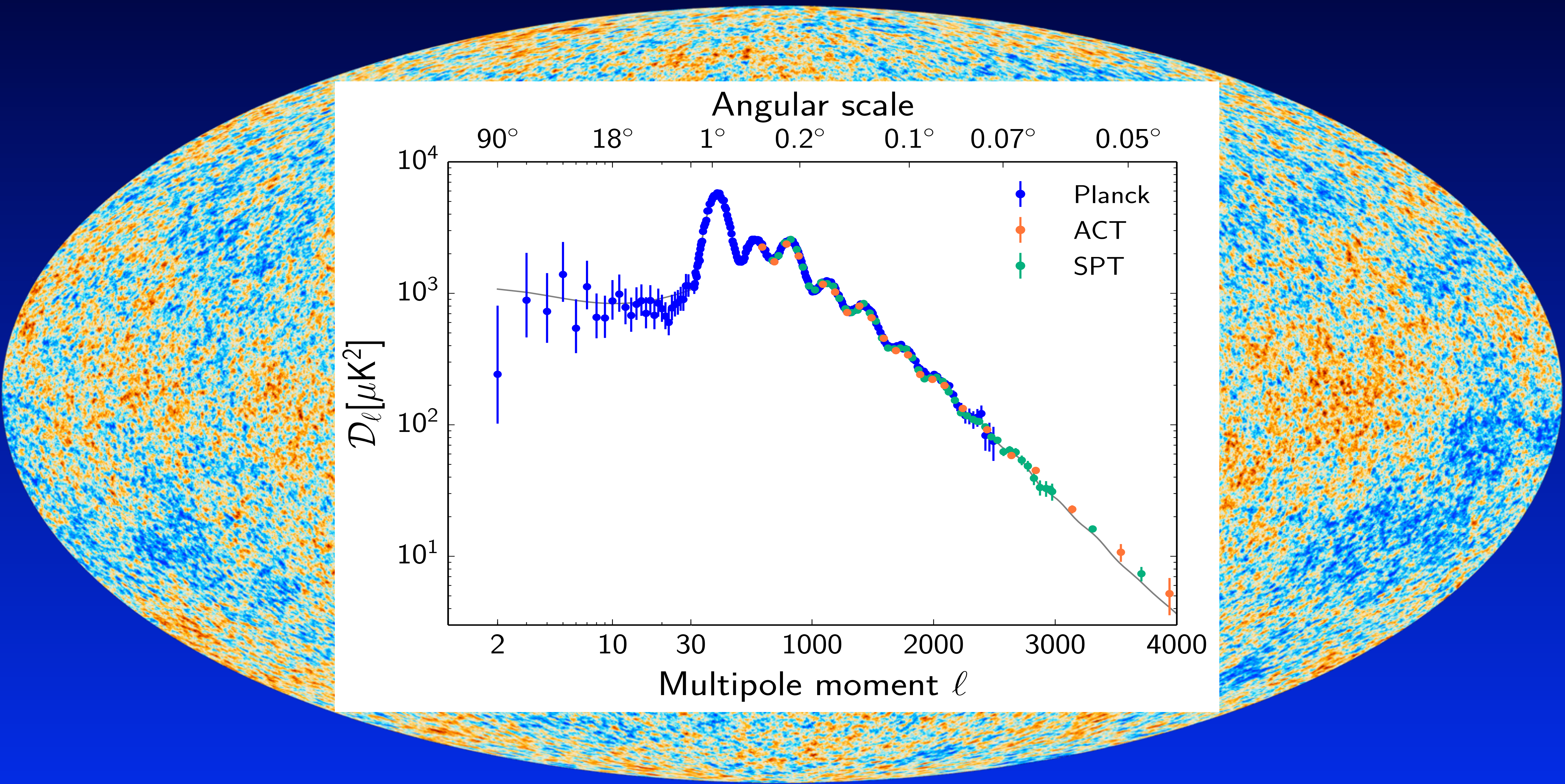
Example:
Simulation of reionization process (1Gpc/h) by *Alvarez* & *Abel*

The dissipation of small-scale acoustic modes

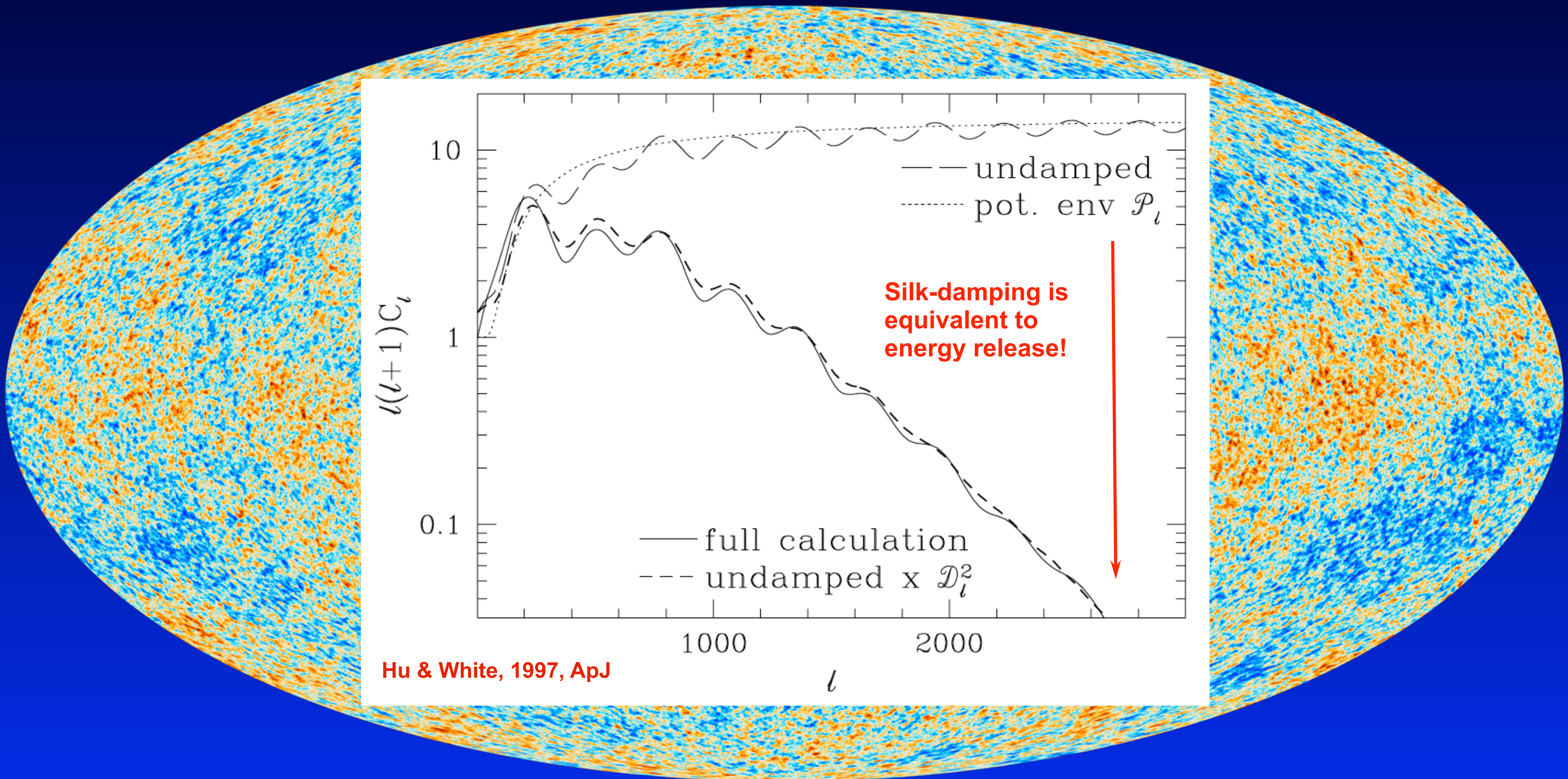
Dissipation of small-scale acoustic modes



Dissipation of small-scale acoustic modes



Dissipation of small-scale acoustic modes



Hu & White, 1997, ApJ

Energy release caused by dissipation process

'Obvious' dependencies:

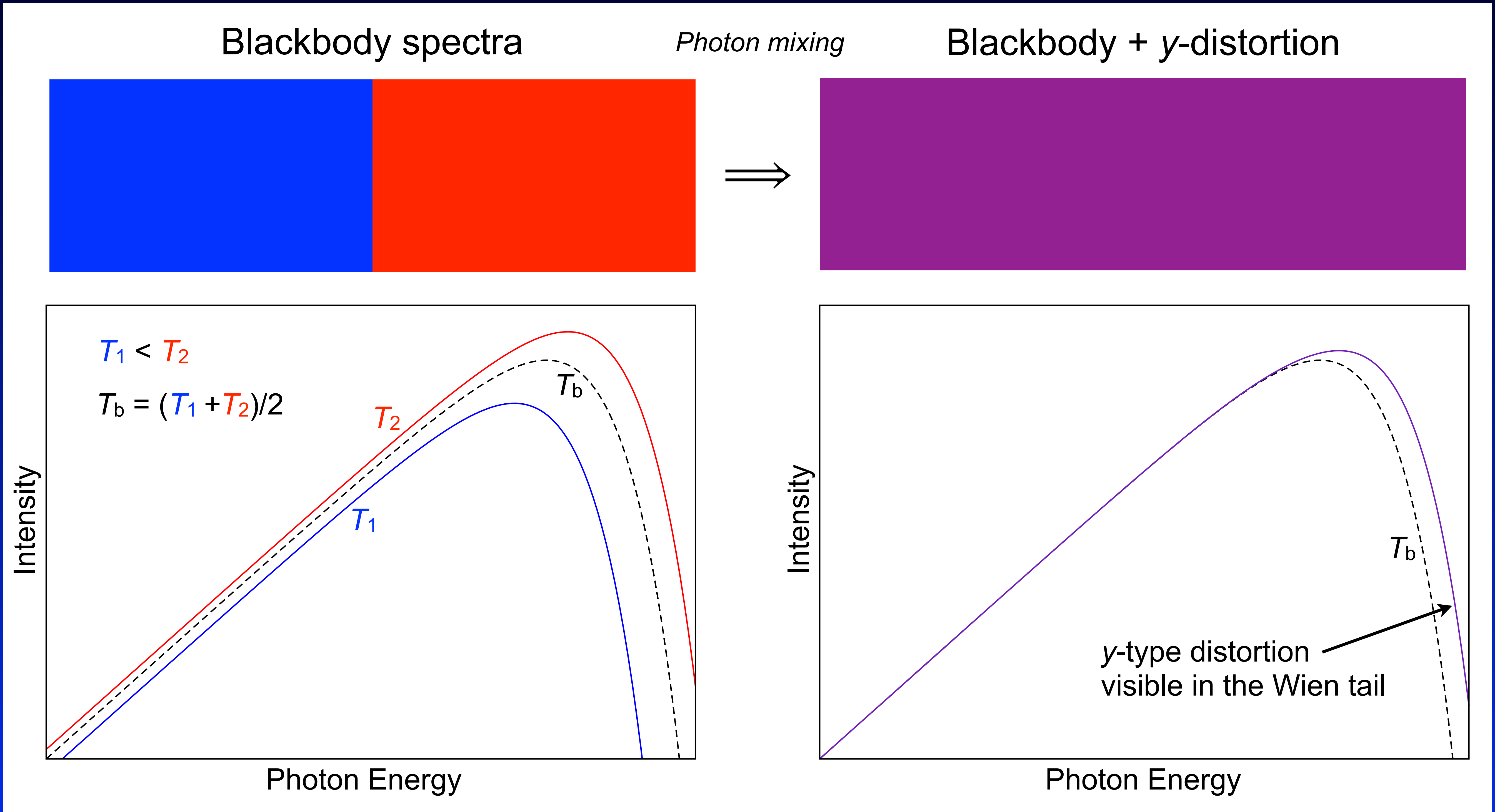
- *Amplitude* of the small-scale power spectrum
- *Shape* of the small-scale power spectrum
- *Dissipation scale* → $k_D \sim (H_0\, \Omega_{rel}^{1/2}\, N_{e,0})^{1/2}\, (1+z)^{3/2}$ at early times

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)

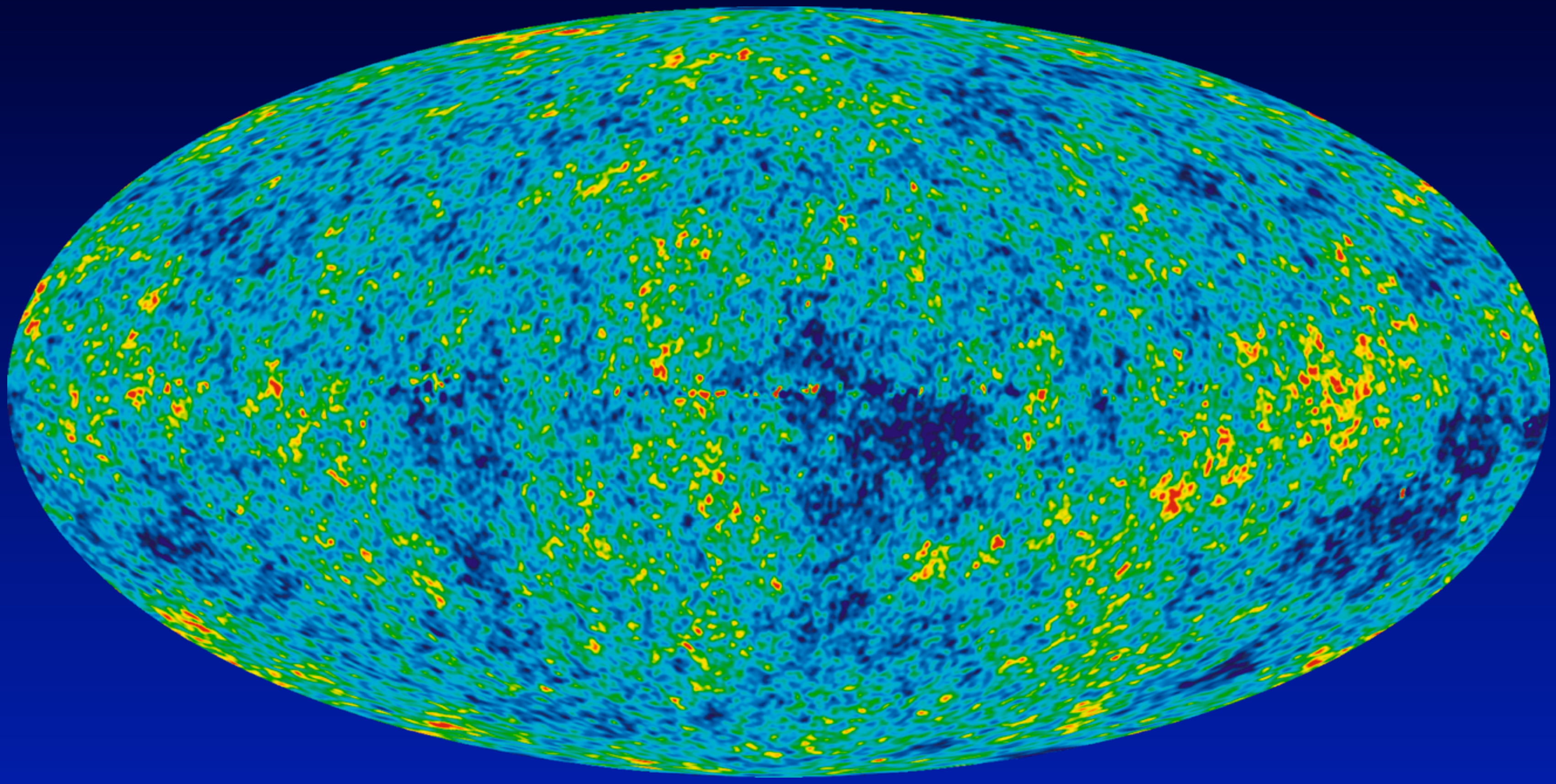
CMB Spectral distortions could add additional numbers beyond 'just' the tensor-to-scalar ratio from B-modes!

Distortion due to mixing of blackbodies



JC, Hamann & Patil, 2015

Distortions caused by superposition of blackbodies

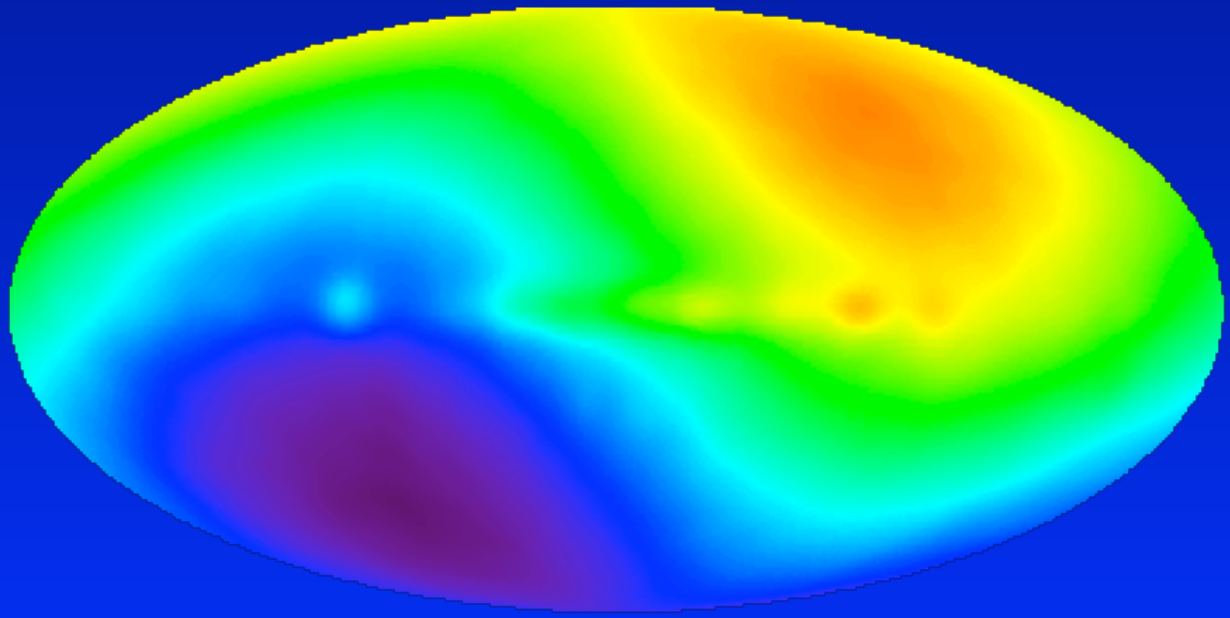


- average spectrum

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

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

- known with very high precision



COBE/DMR: *ΔT* = 3.353 mK

- *CMB dipole* (*β* ~ 1.23×10^{-3})

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

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

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

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

Effective energy release caused by damping effect

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

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

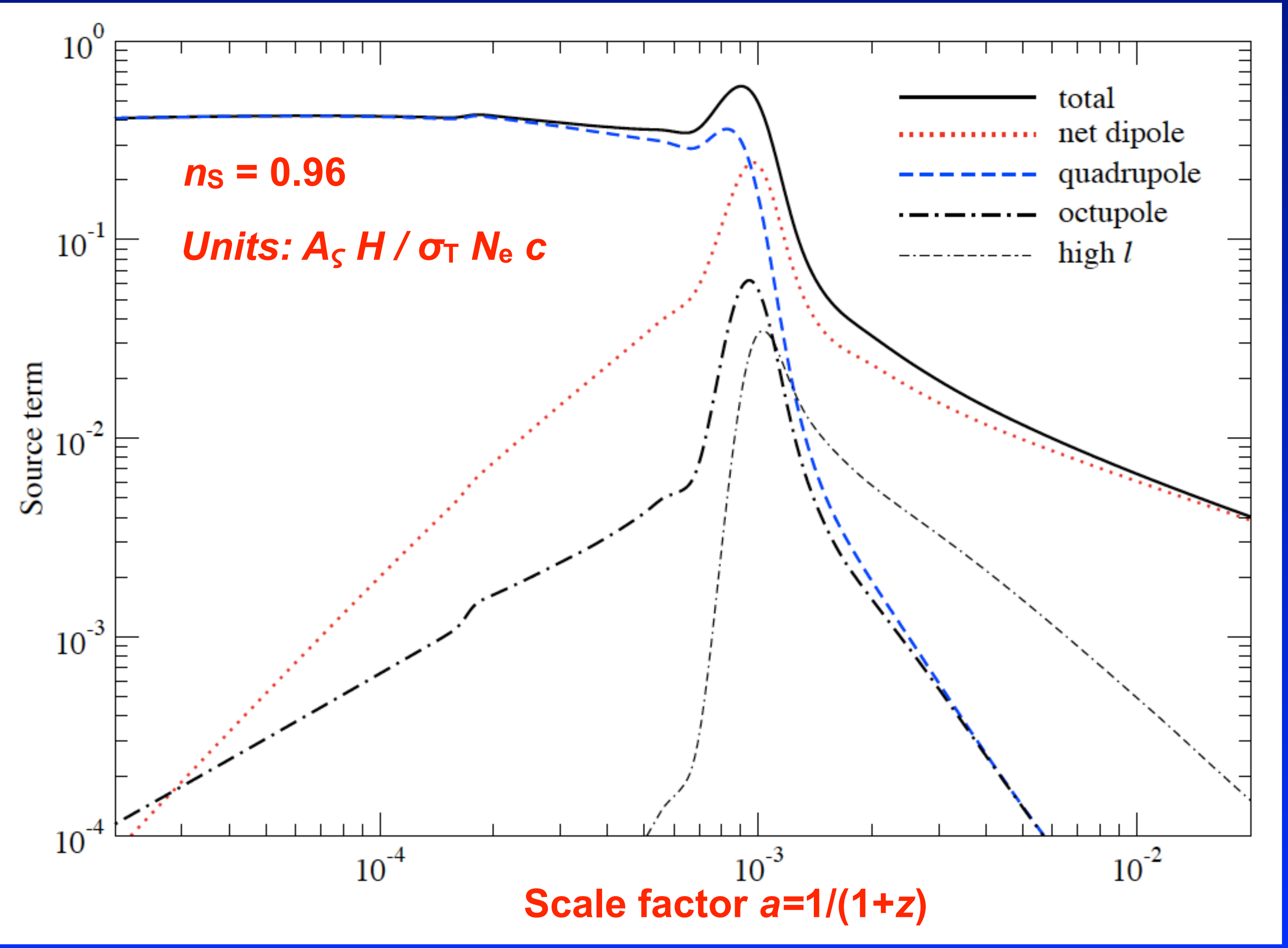
$$\Theta_\ell = \frac{1}{2}\int \Theta(\mu) P_\ell(\mu)\mathrm{d}\mu$$

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

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

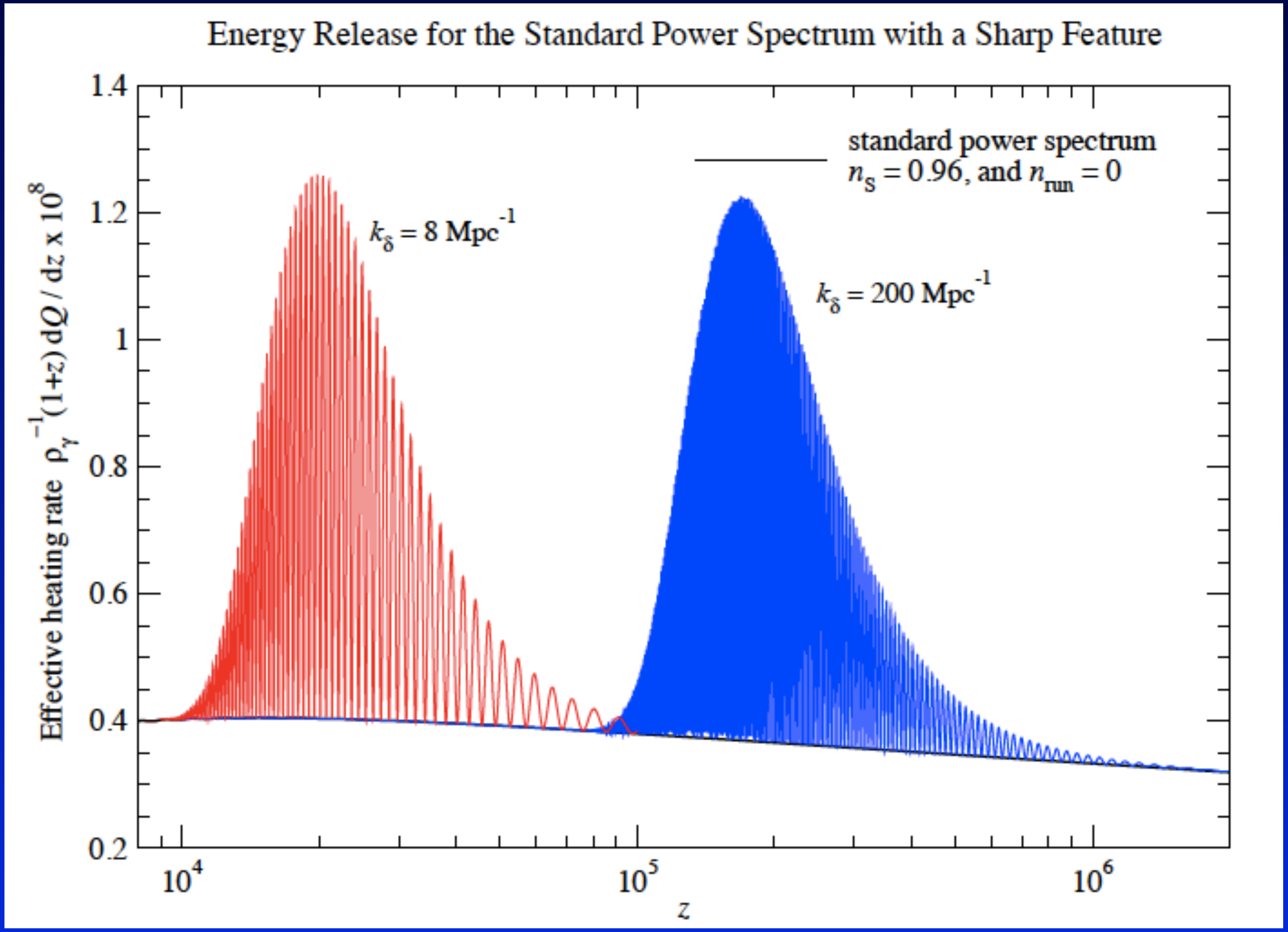
Primordial power spectrum

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



JC, Khatri & Sunyaev, 2012

Which modes dissipate in the μ and y-eras?



JC, Erickcek & Ben-Dayan, 2012

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

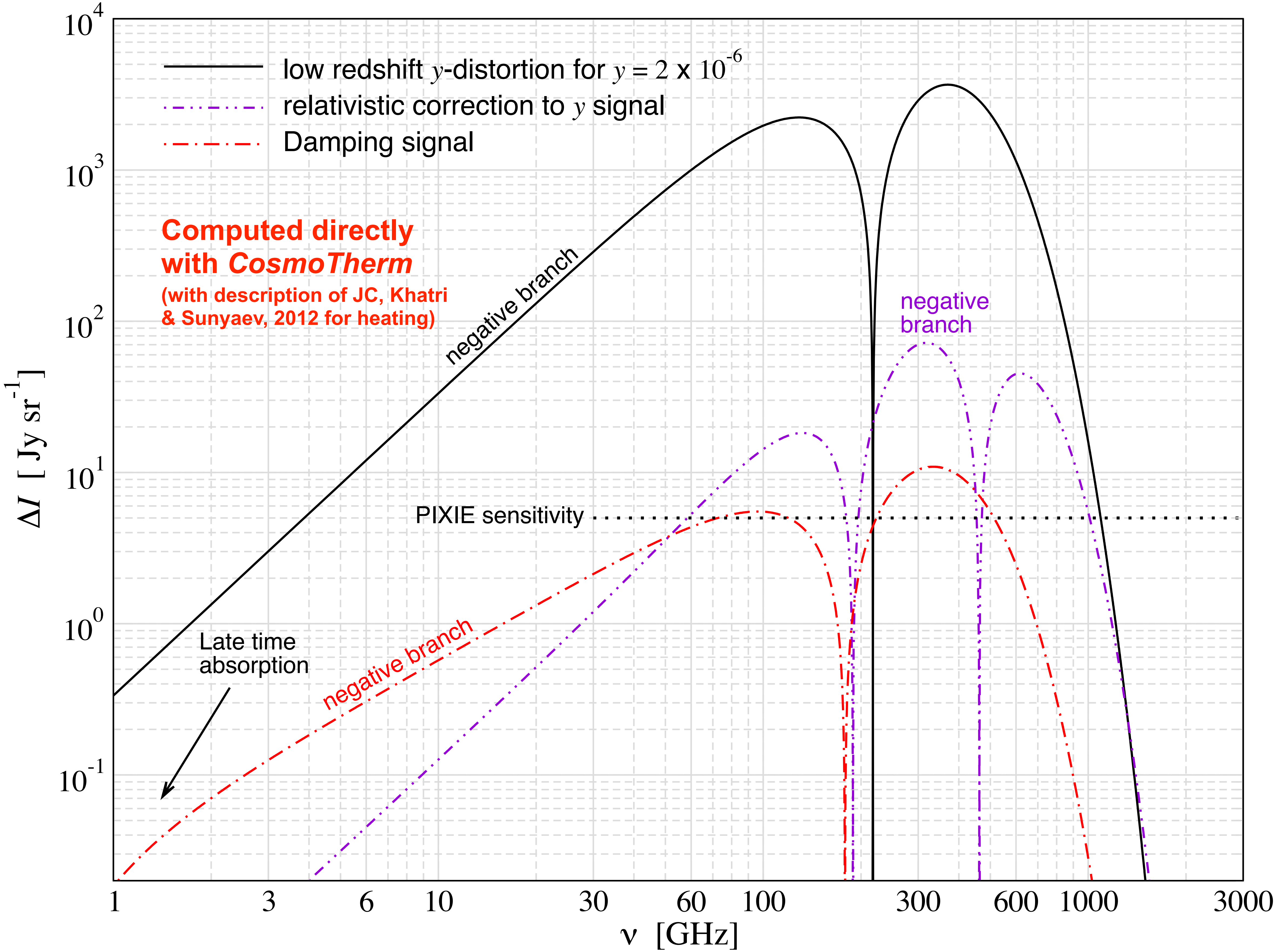
$z_d \sim 4.5\times10^5 (k\,\text{Mpc}/10^3)^{2/3}$

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

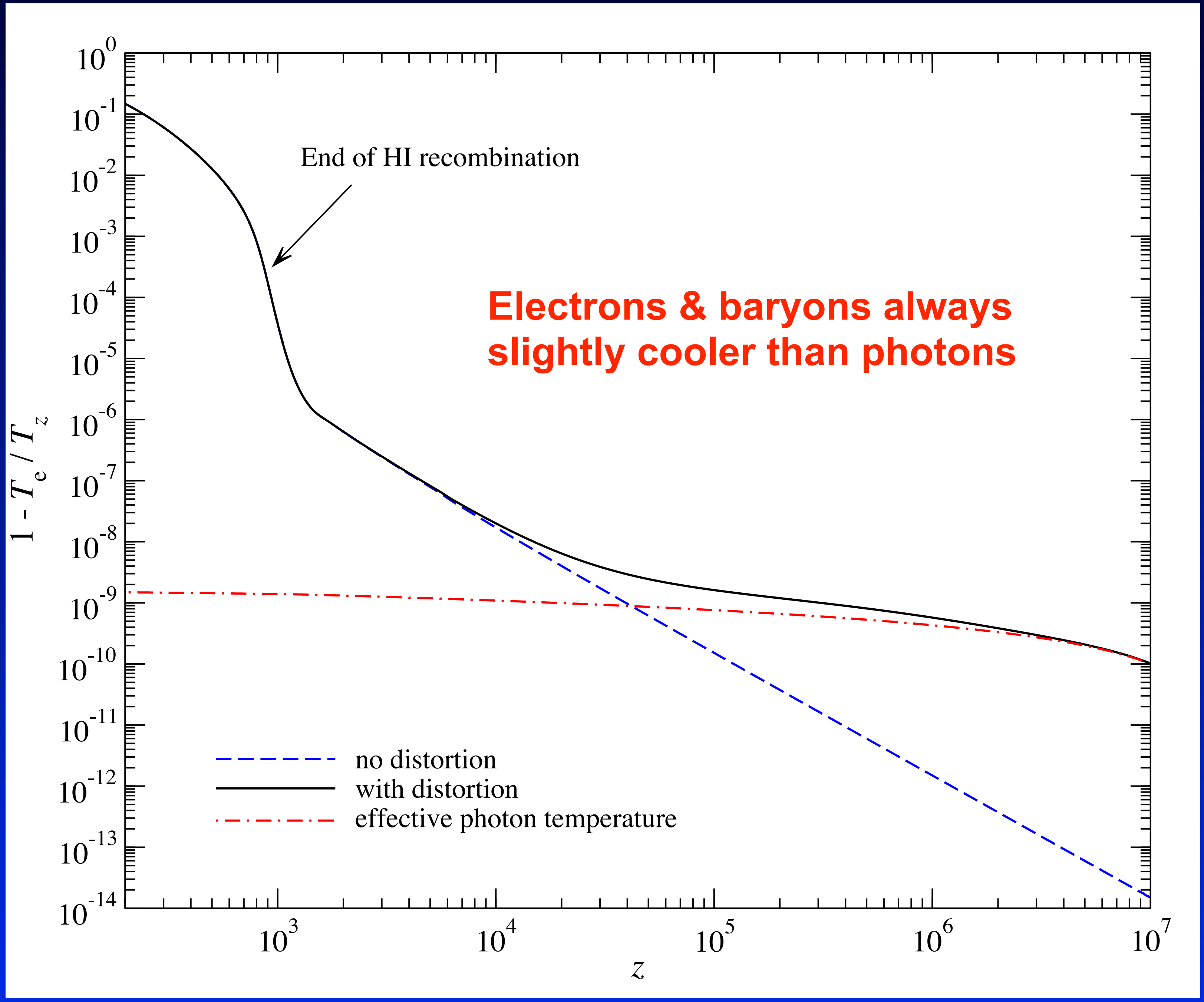
- Modes with *k* < 50 Mpc^{-1} cause *y*-distortion

So what does one expect within ΛCDM?

Average CMB spectral distortions



Spectral distortion caused by the cooling of ordinary matter



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

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

- adiabatic expansion

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

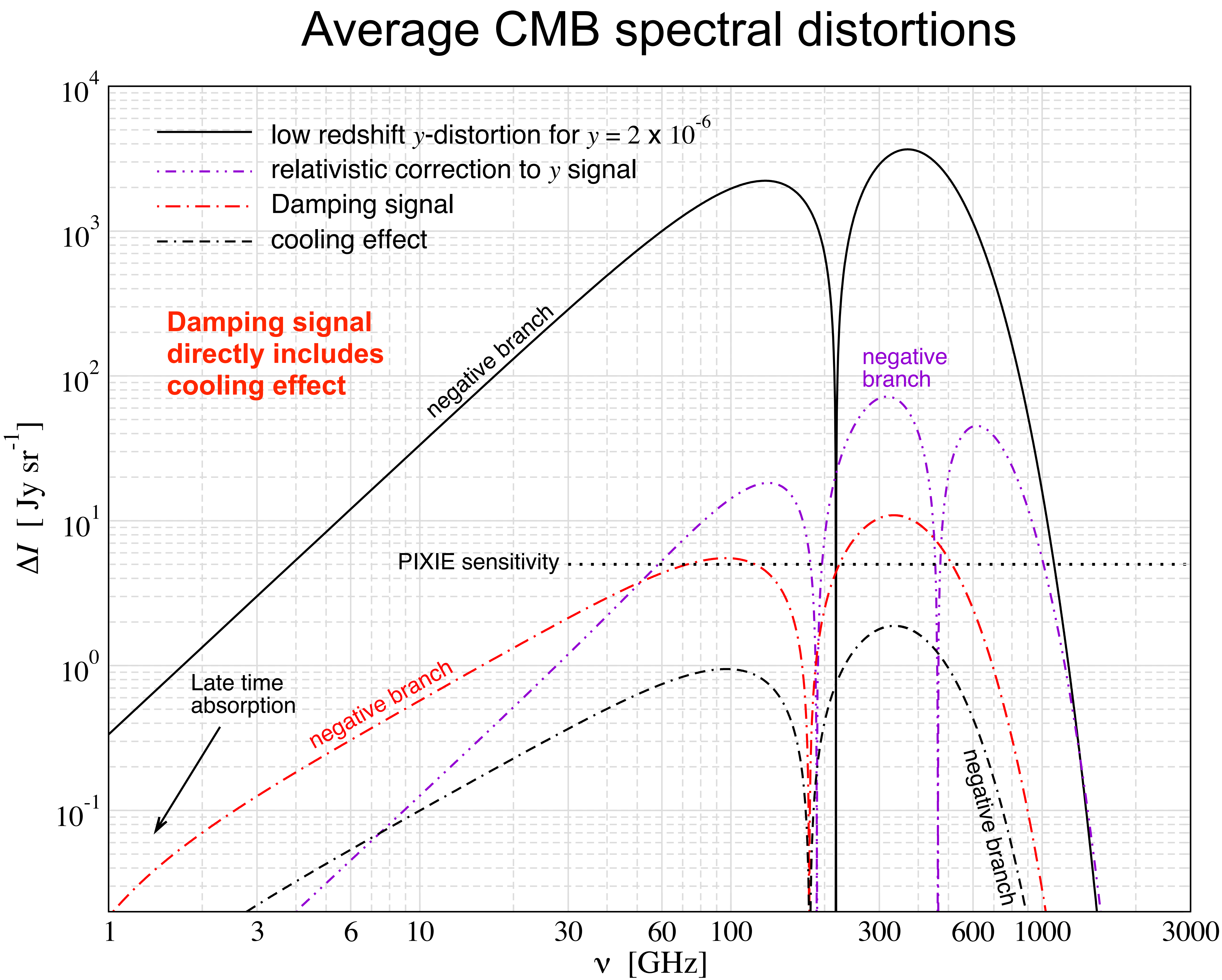
- photons continuously *cooled* / *down-scattered* since day one of the Universe!
- Compton heating balances adiabatic cooling

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

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

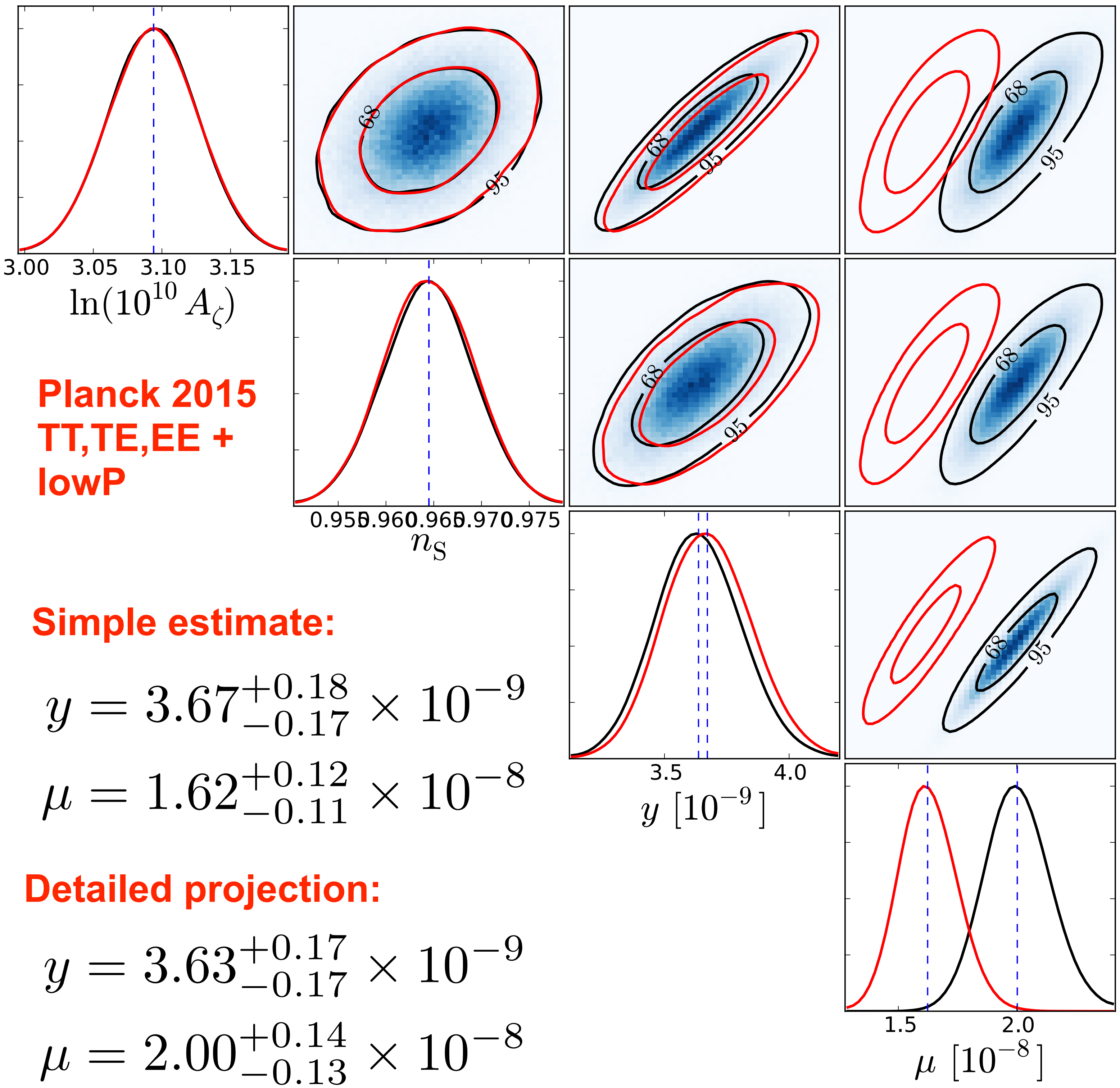
$\Rightarrow$ partial *cancellation*

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



Average CMB spectral distortions
low redshift y-distortion for y = 2 x 10^-6
relativistic correction to y signal
Damping signal
cooling effect
Damping signal
directly includes
cooling effect
negative branch
negative
branch
PIXIE sensitivity
Late time
absorption
negative branch
negative branch
ΔI [Jy sr^-1]
ν [GHz]
10^4
10^3
10^2
10^1
10^0
10^-1
1
3
6
10
30
60
100
300
600
1000
3000

Predicted damping distortion in terms of μ and y



Planck 2015 TT,TE,EE + lowP

Simple estimate:

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

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

Detailed projection:

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

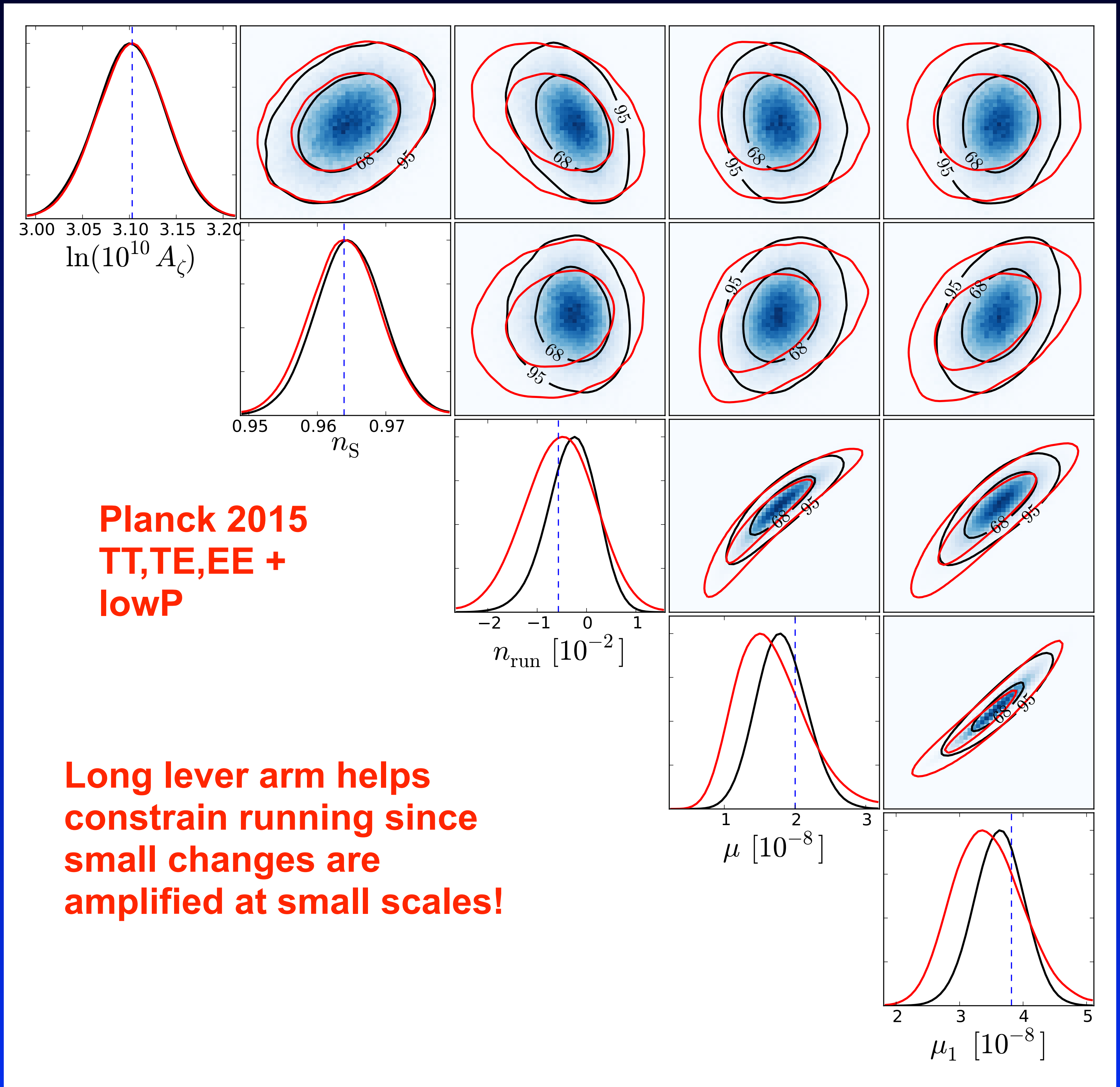
$$\mu = 2.00^{+0.14}_{-0.13} \times 10^{-8}$$

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

Improvements of PIXIE are being discussed!

JC 2016, ArXiv:1603.02496

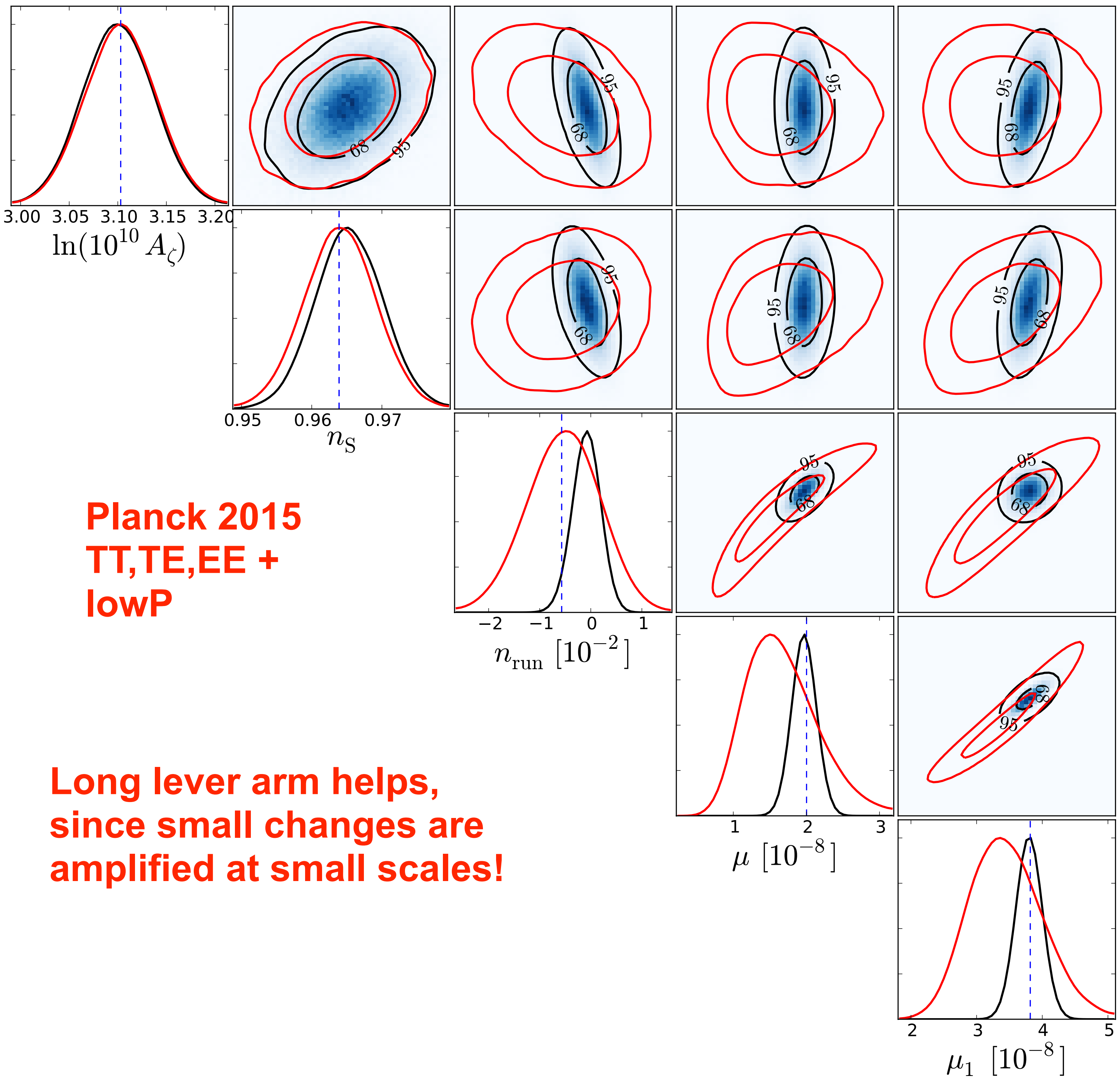
Testing running with distortions



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

JC 2016, ArXiv:1603.02496

Testing running with distortions



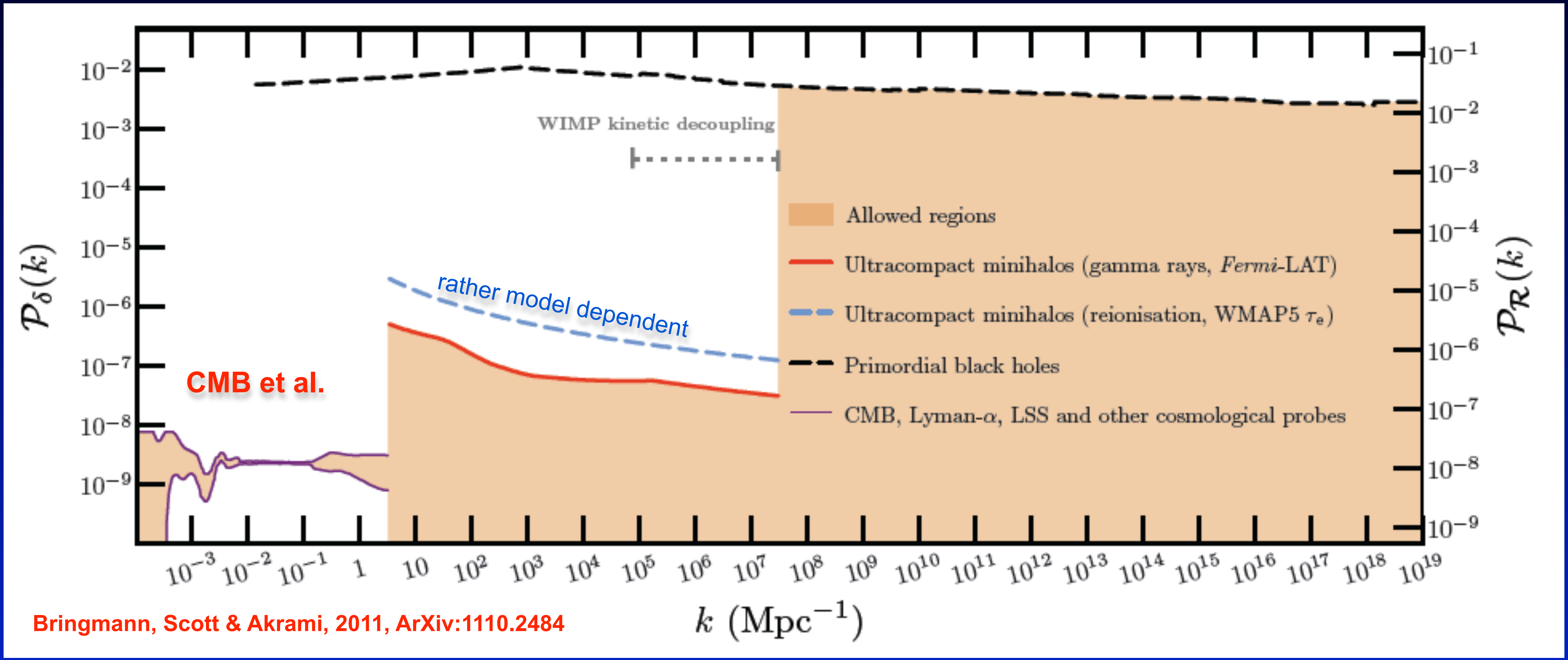
Planck 2015 TT,TE,EE + lowP

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

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

JC 2016, ArXiv:1603.02496

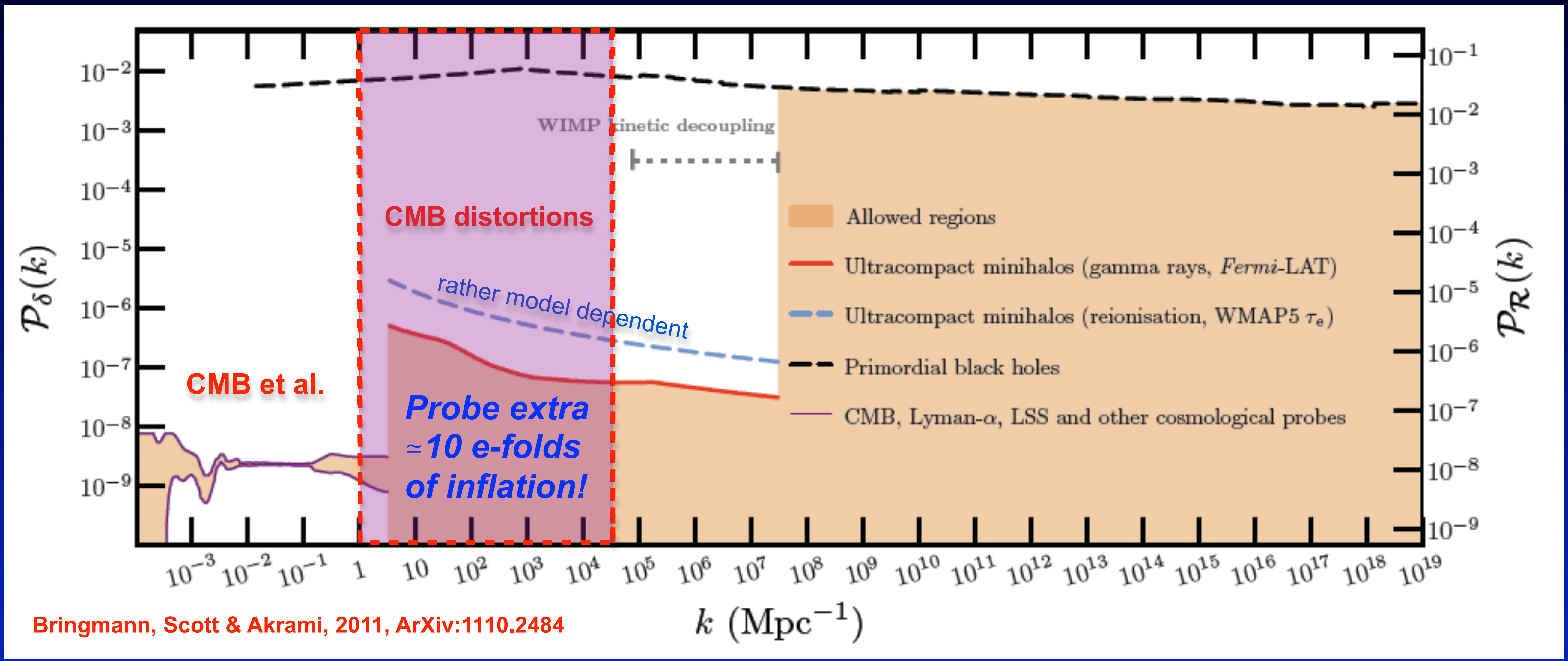
Distortions provide general power spectrum constraints!



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

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

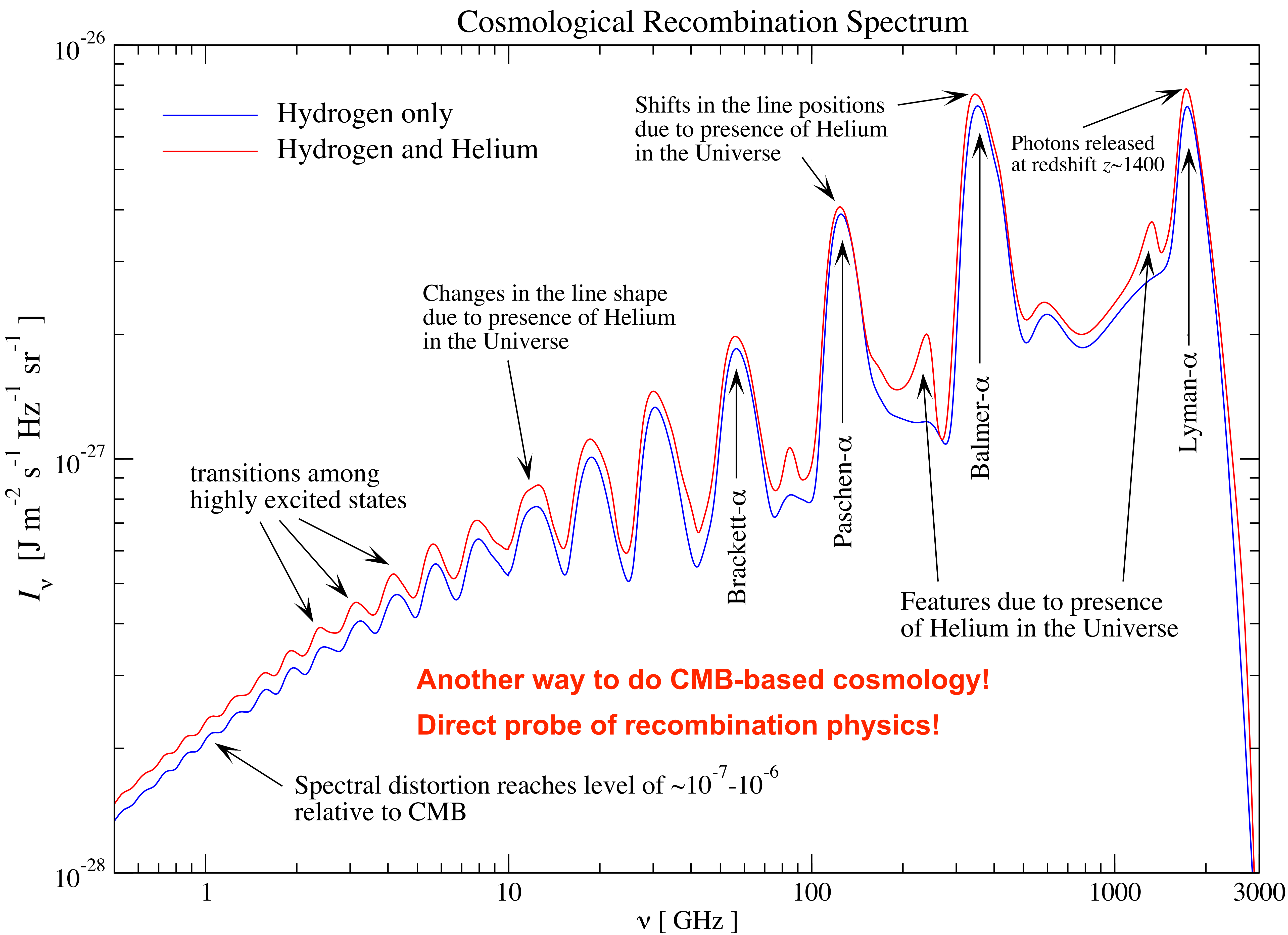
Distortions provide general power spectrum constraints!



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

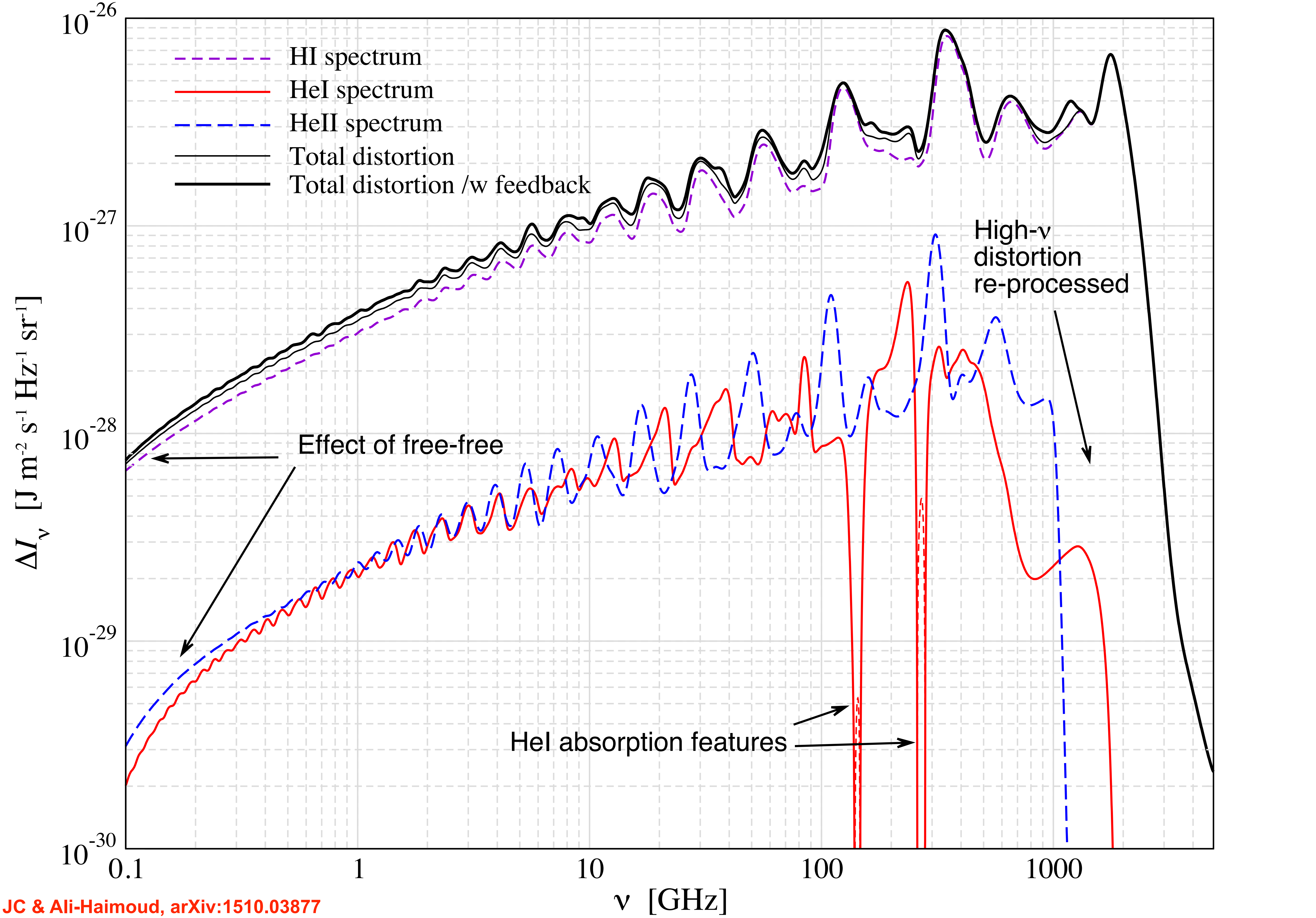
e.g., JC, Khatri & Sunyaev, 2012; JC, Erickcek & Ben-Dayan, 2012; JC & Jeong, 2013

The cosmological recombination radiation



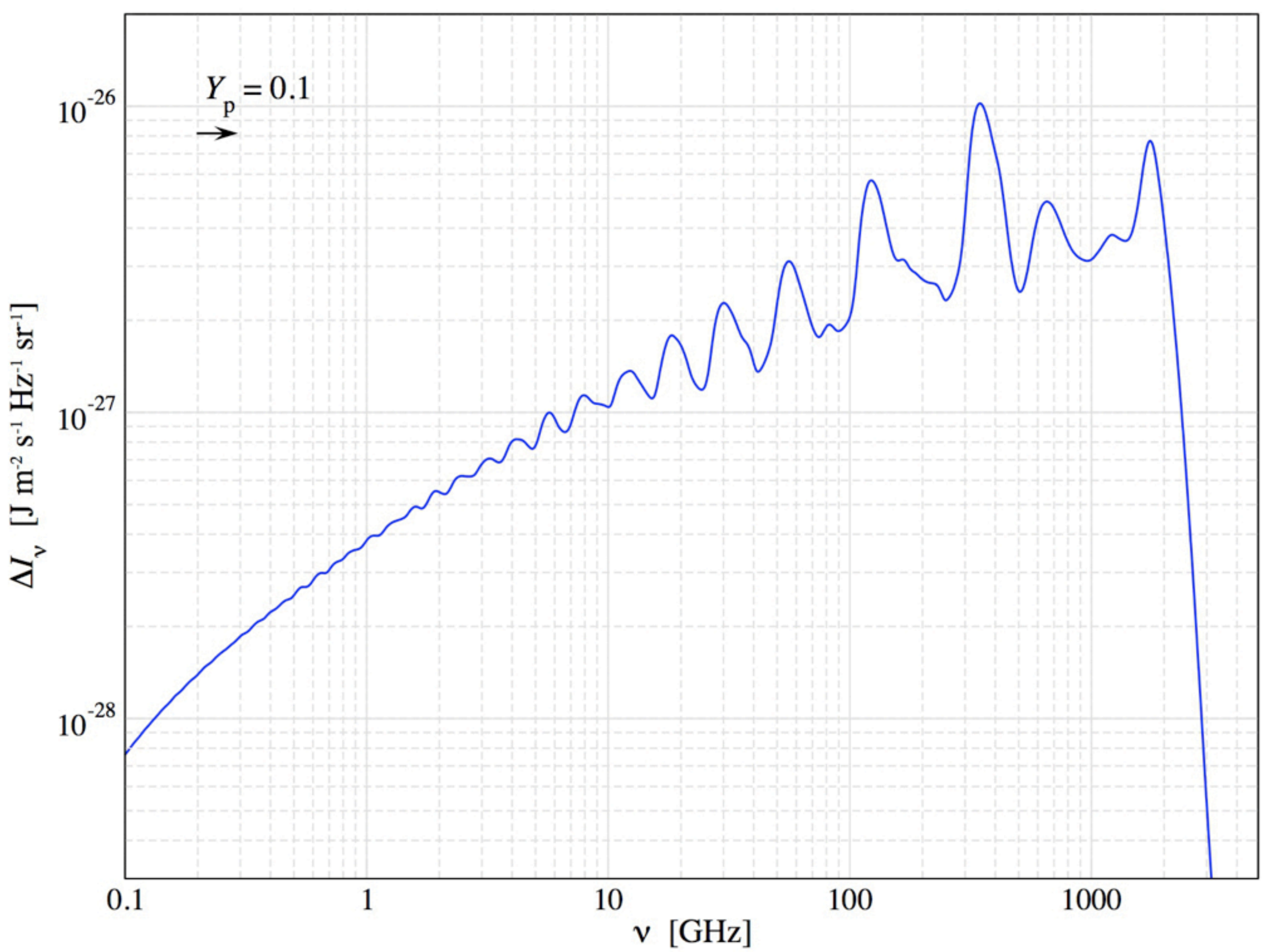
Rubino-Martin et al. 2006, 2008; Sunyaev & JC, 2009

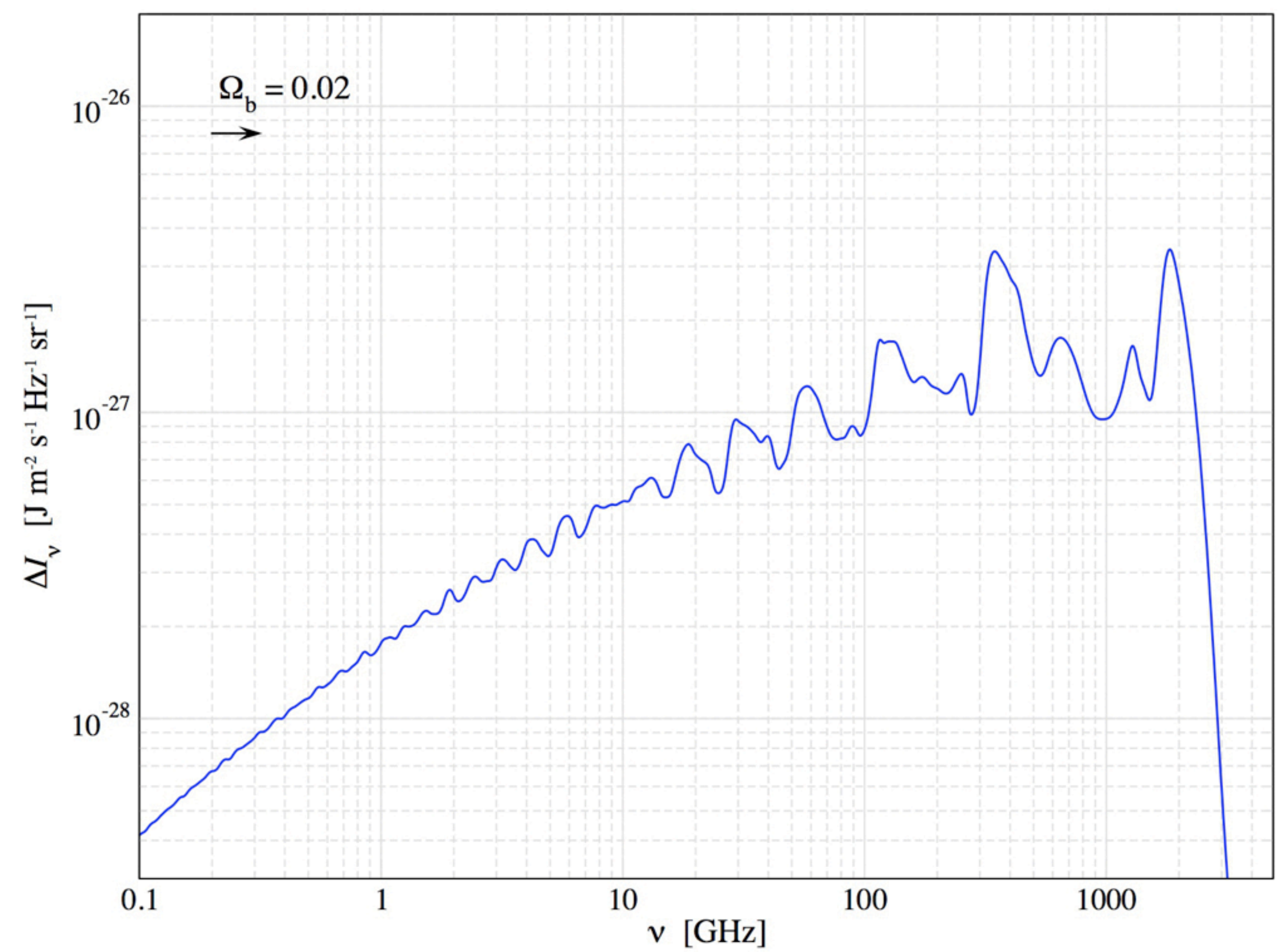
New detailed and fast computation!



JC & Ali-Haimoud, arXiv:1510.03877

CosmoSpec: fast and accurate computation of the CRR



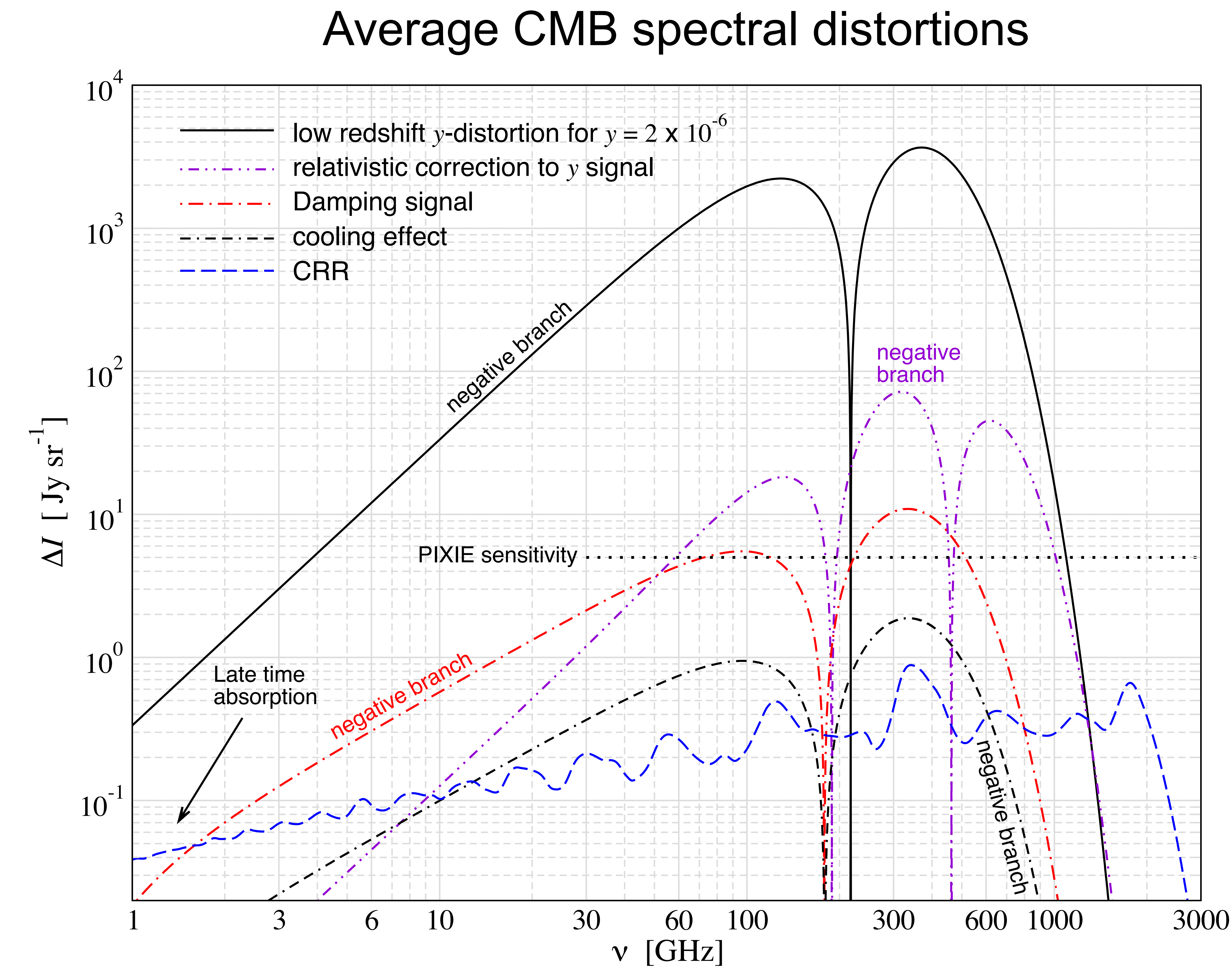


- Like in old days of CMB anisotropies!
- detailed forecasts and feasibility studies
- non-standard physics (variation of α, energy injection etc.)

CosmoSpec will be available here:

www.Chluba.de/CosmoSpec

JC & Ali-Haimoud, arXiv:1510.03877



Average CMB spectral distortions
low redshift y-distortion for y = 2 x 10^-6
relativistic correction to y signal
Damping signal
cooling effect
CRR
negative branch
negative branch
negative branch
negative branch
PIXIE sensitivity
Late time absorption
ΔI [Jy sr^-1]
ν [GHz]
10^4
10^3
10^2
10^1
10^0
10^-1
1
3
6
10
30
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600
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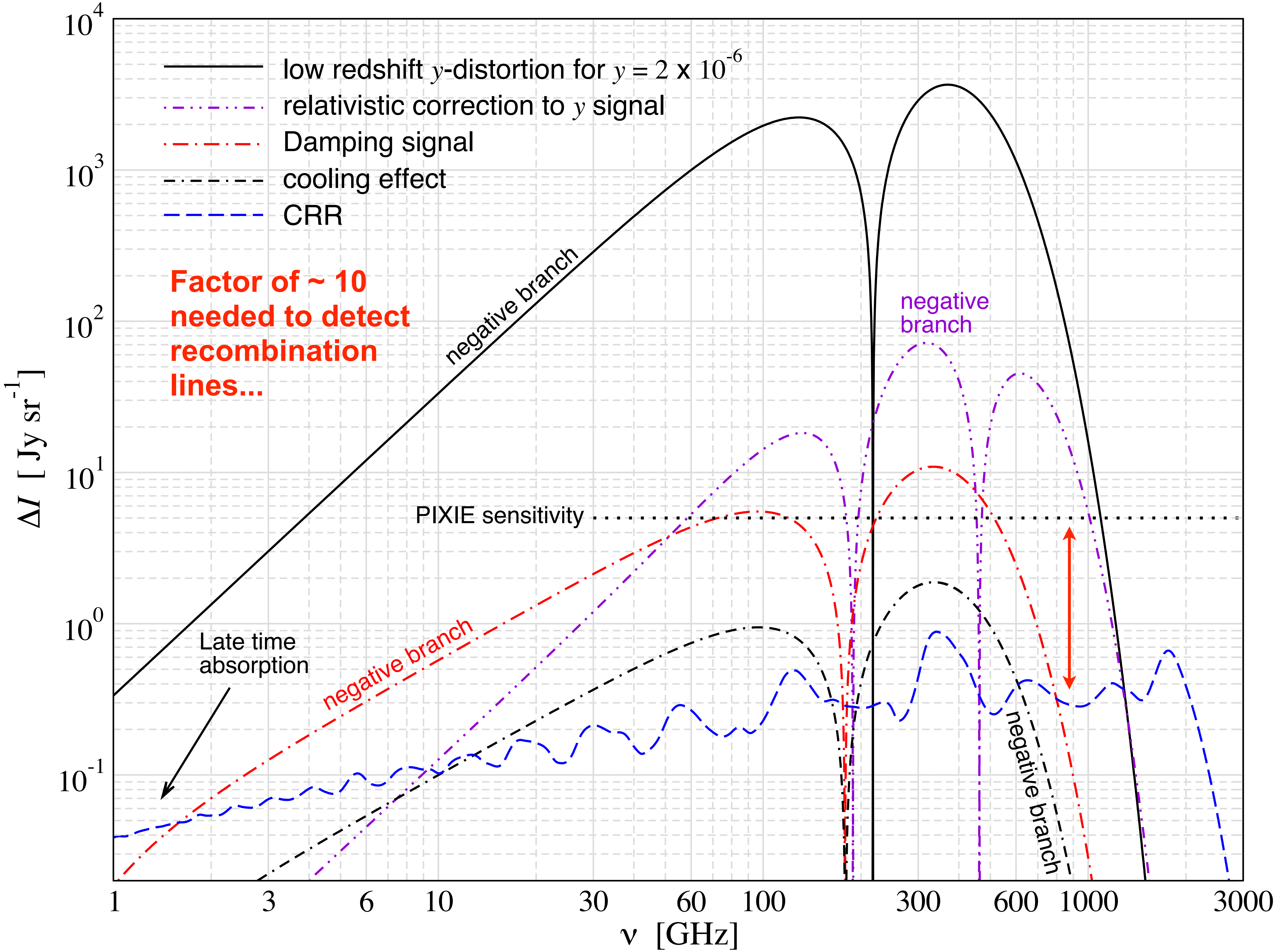
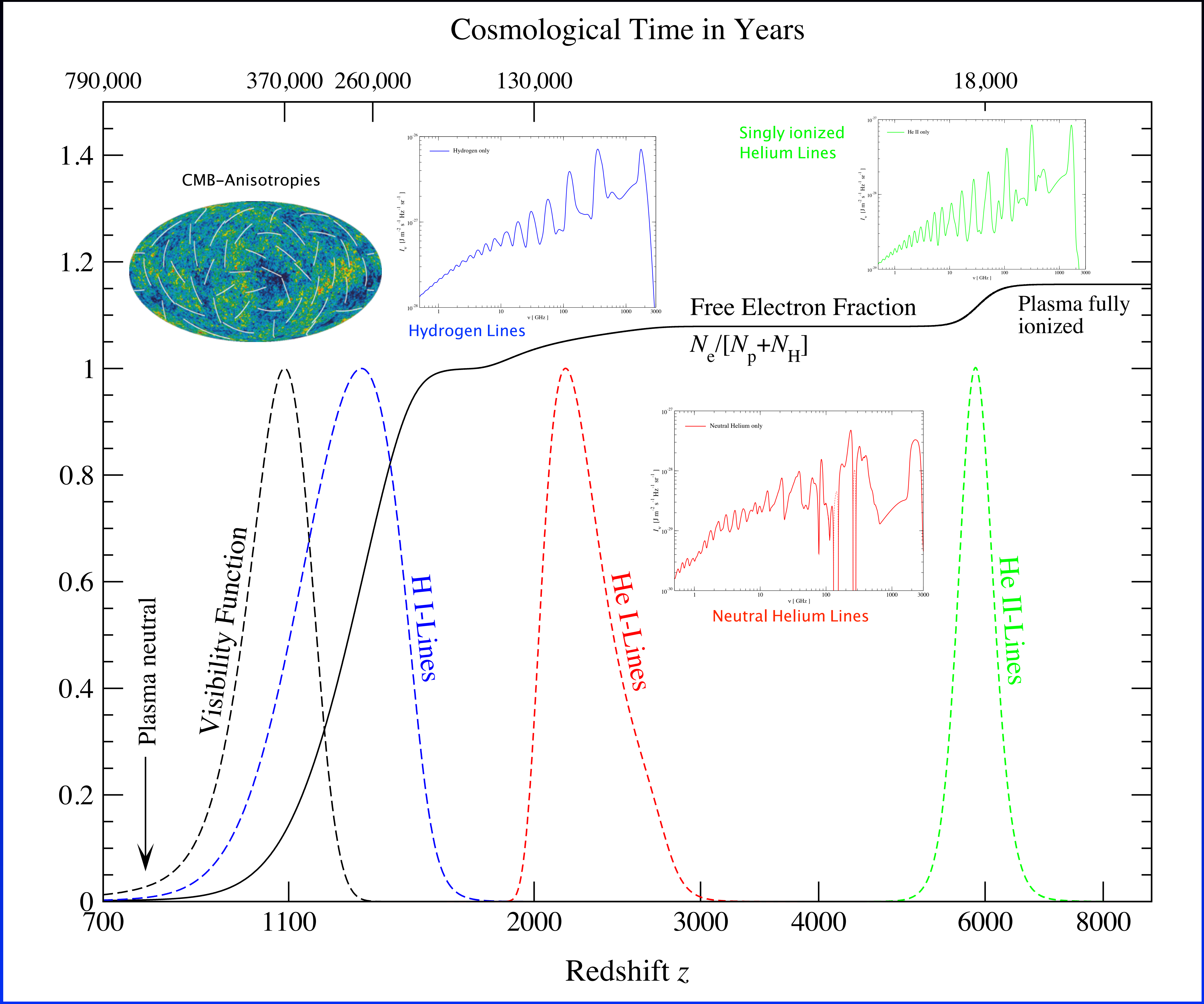
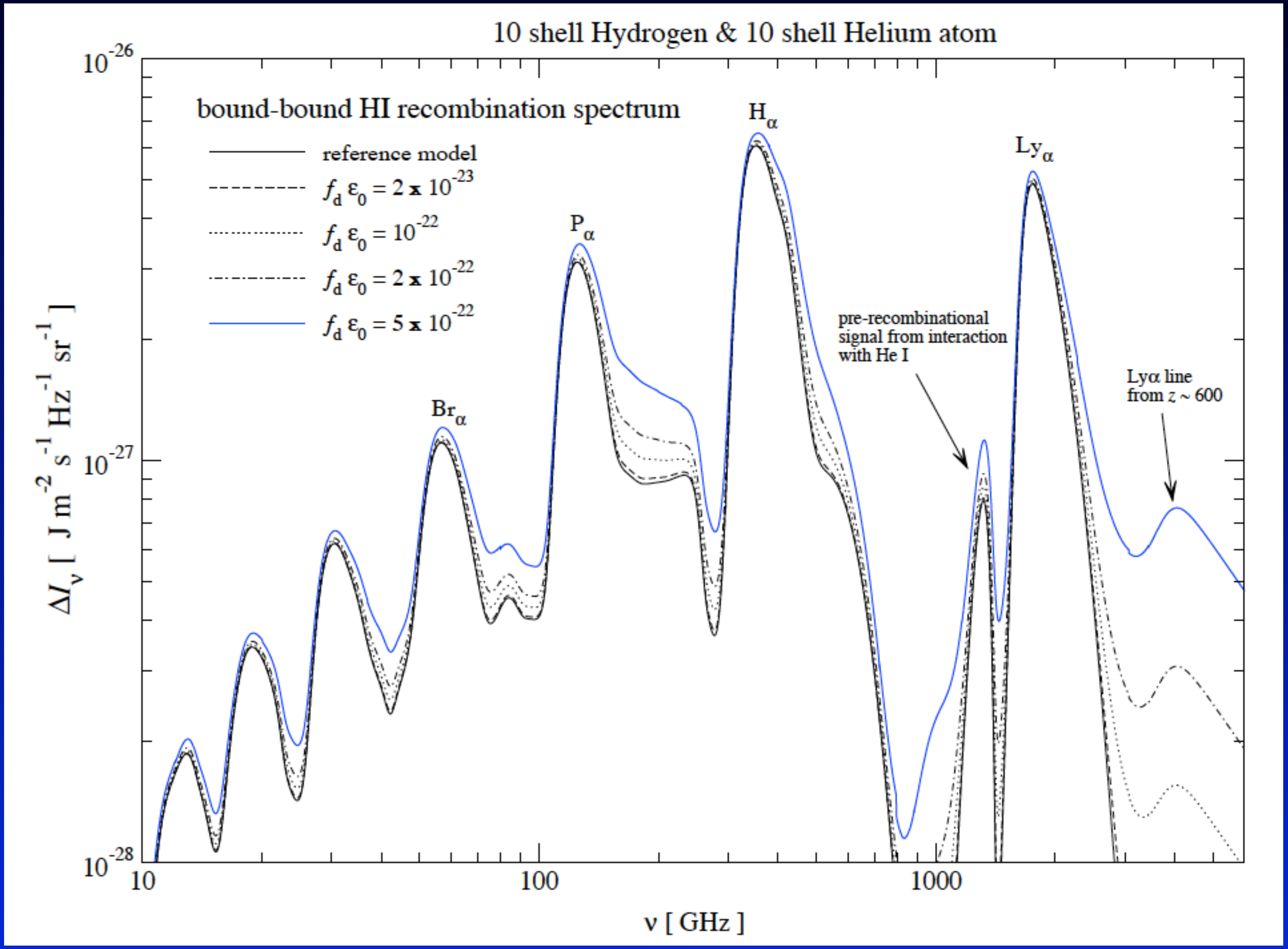
3000

Average CMB spectral distortions




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

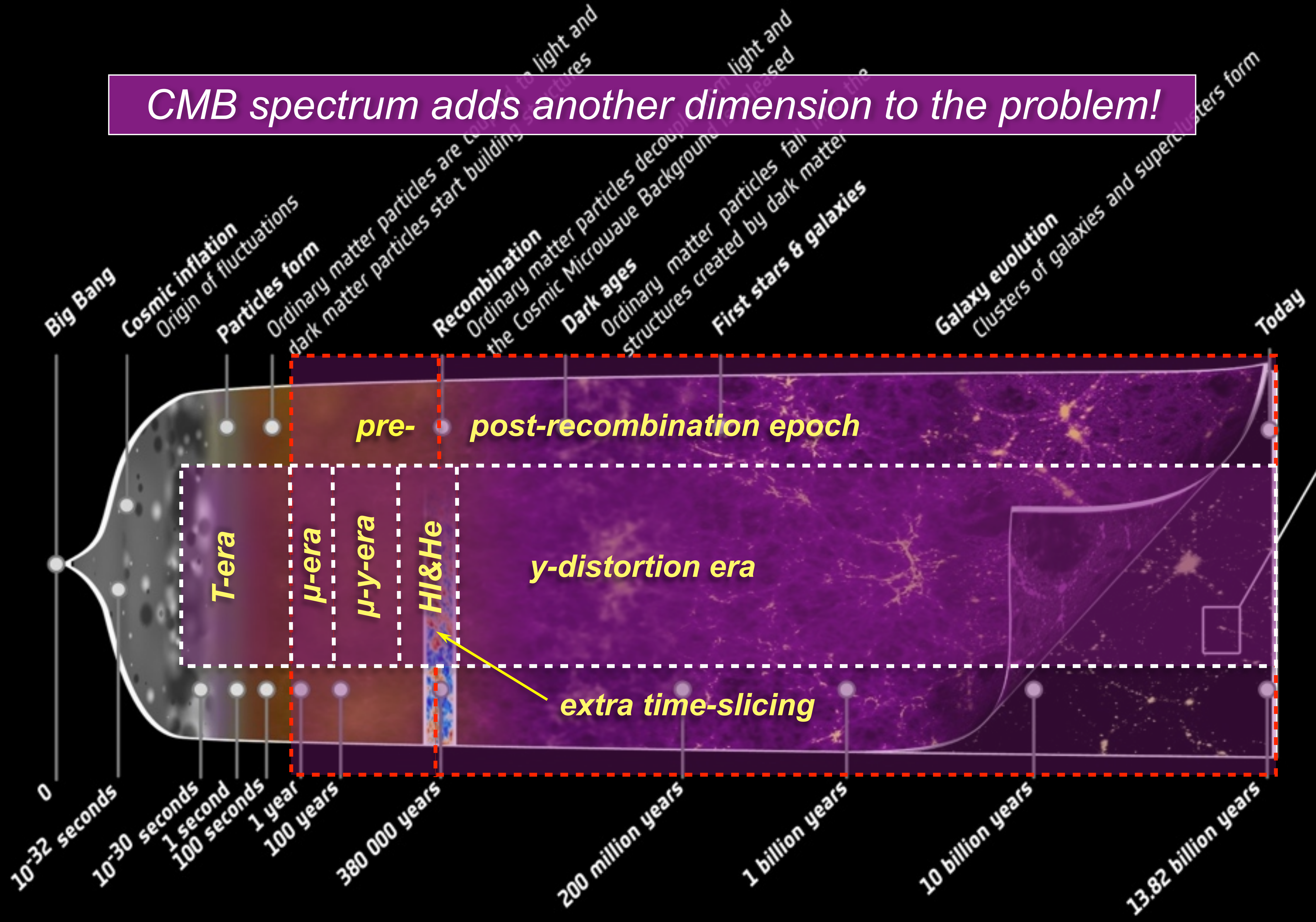
Dark matter annihilations / decays



JC, 2009, arXiv:0910.3663

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

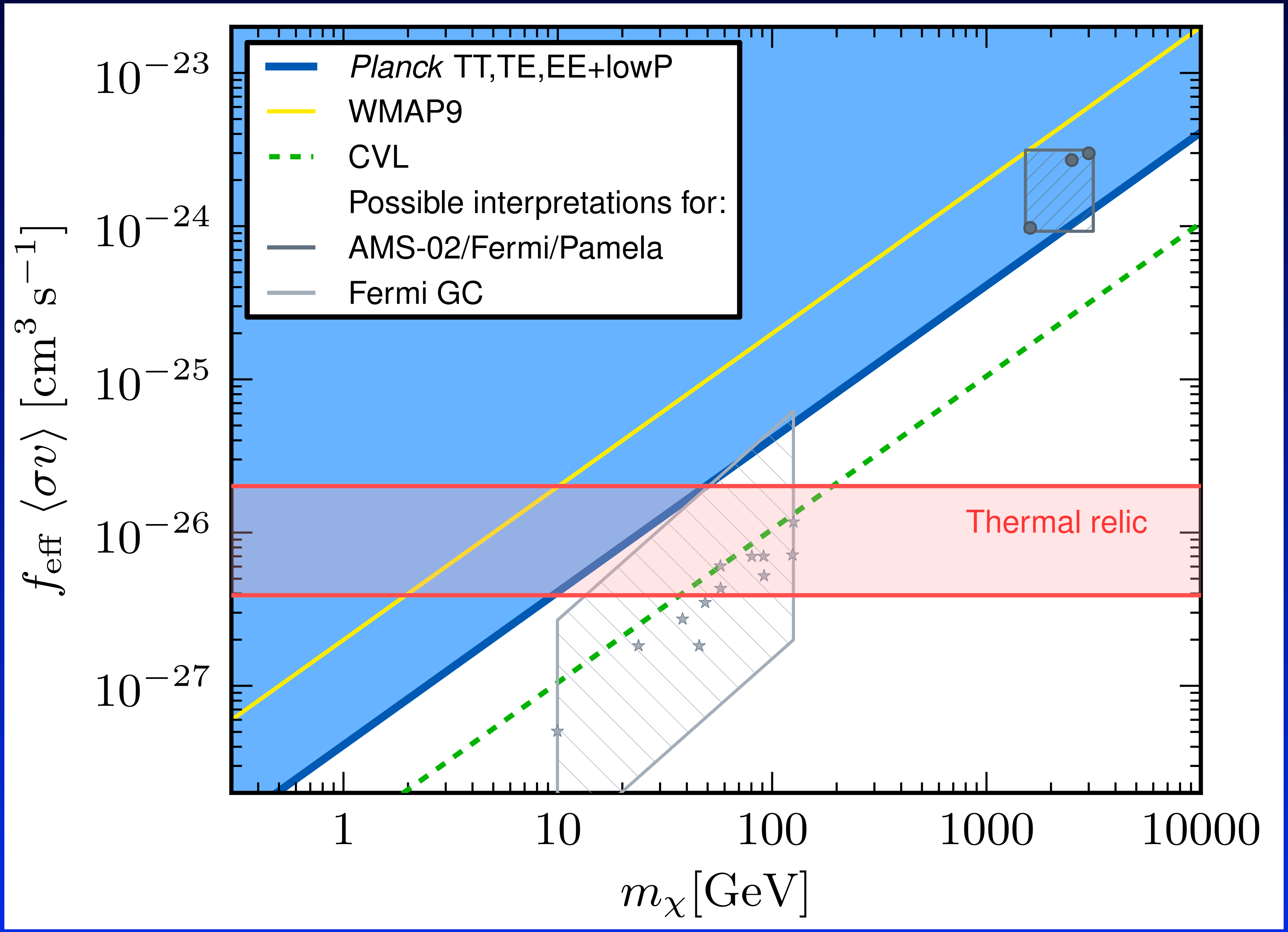
CMB spectrum adds another dimension to the problem!



Annihilating/decaying (dark matter) particles

Latest Planck limits on annihilation cross section

95% c.l.

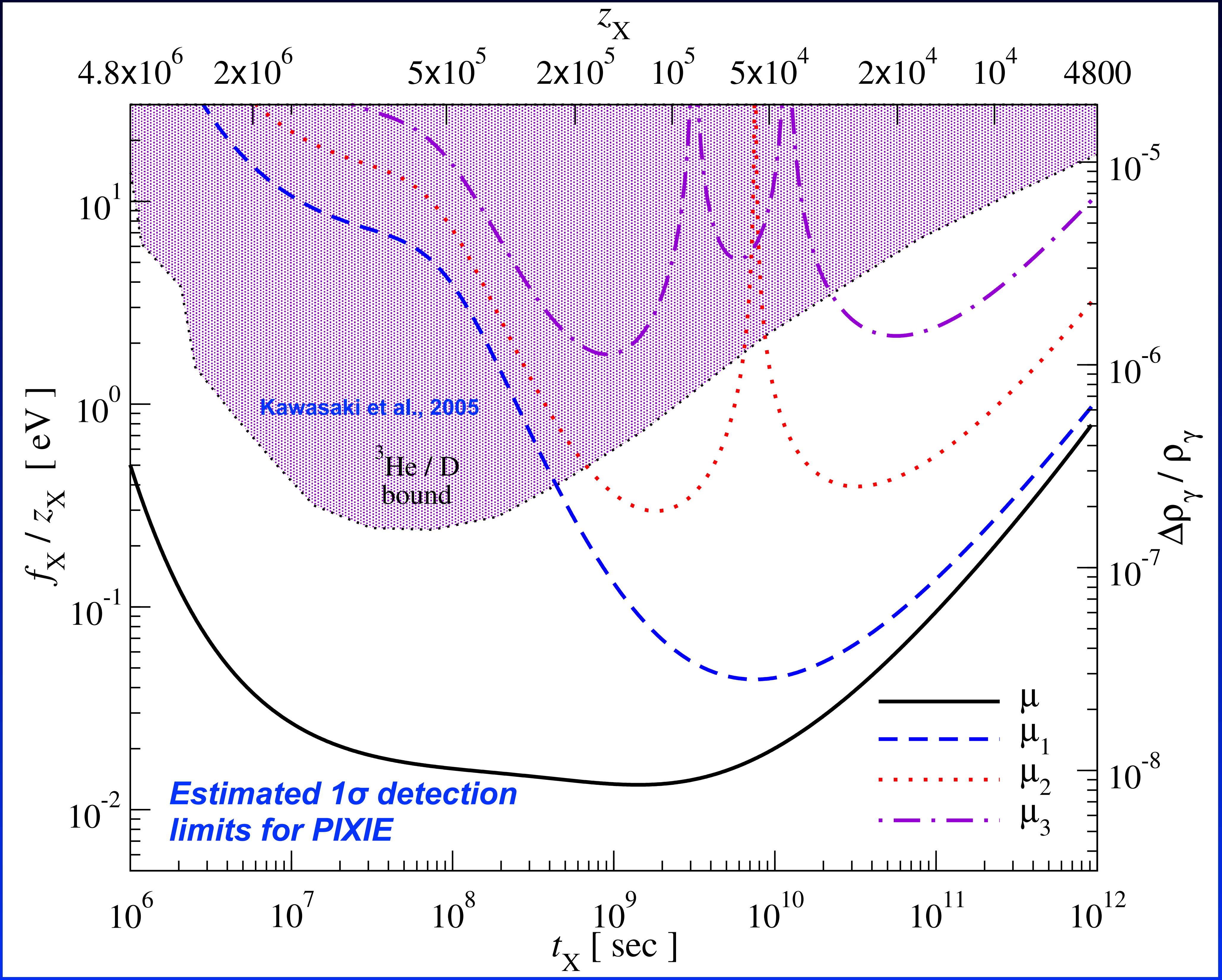


Planck Collaboration, paper XIII, 2015

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

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

Distortions could shed light on decaying (DM) particles!



JC & Jeong, 2013

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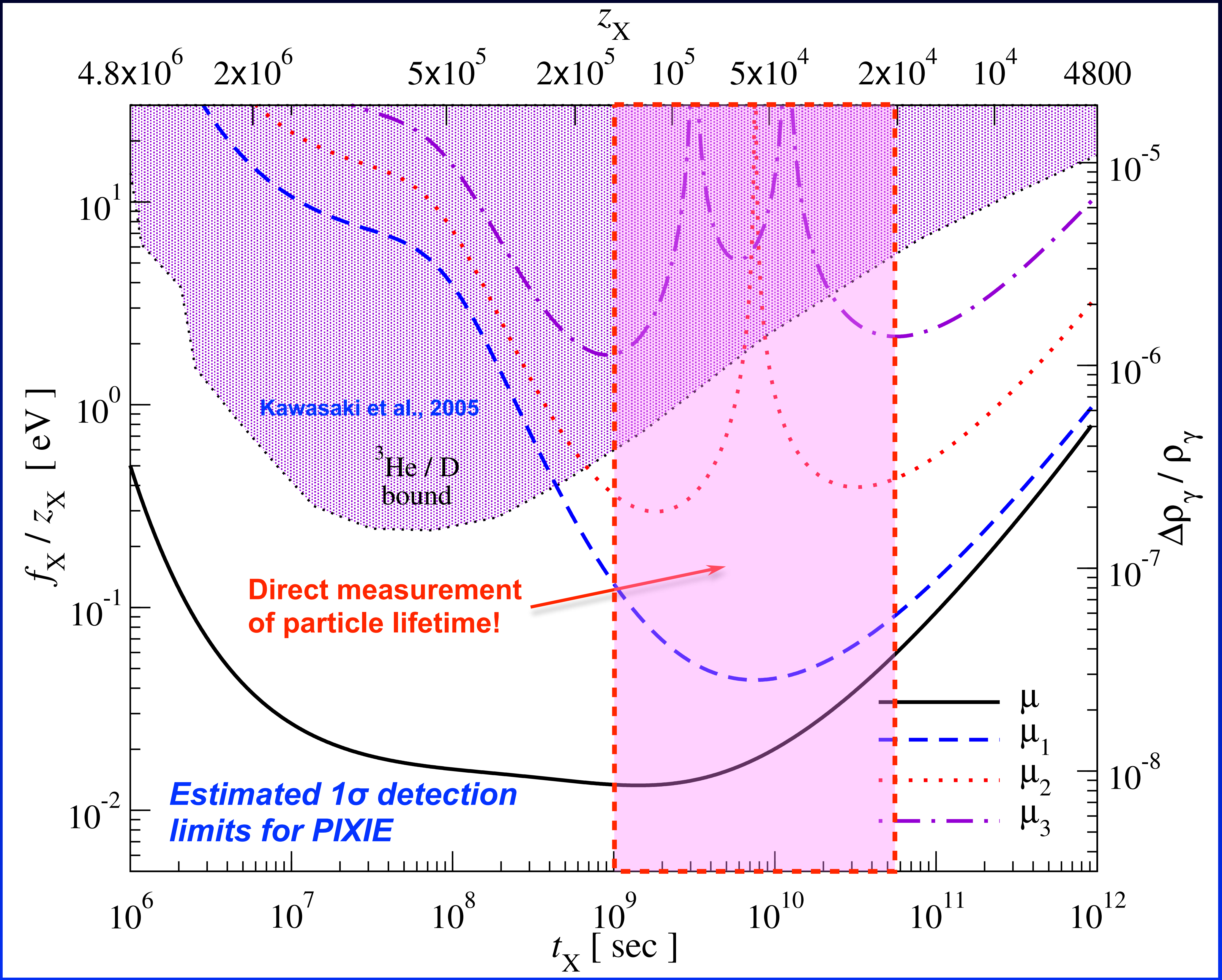

JC & Jeong, 2013

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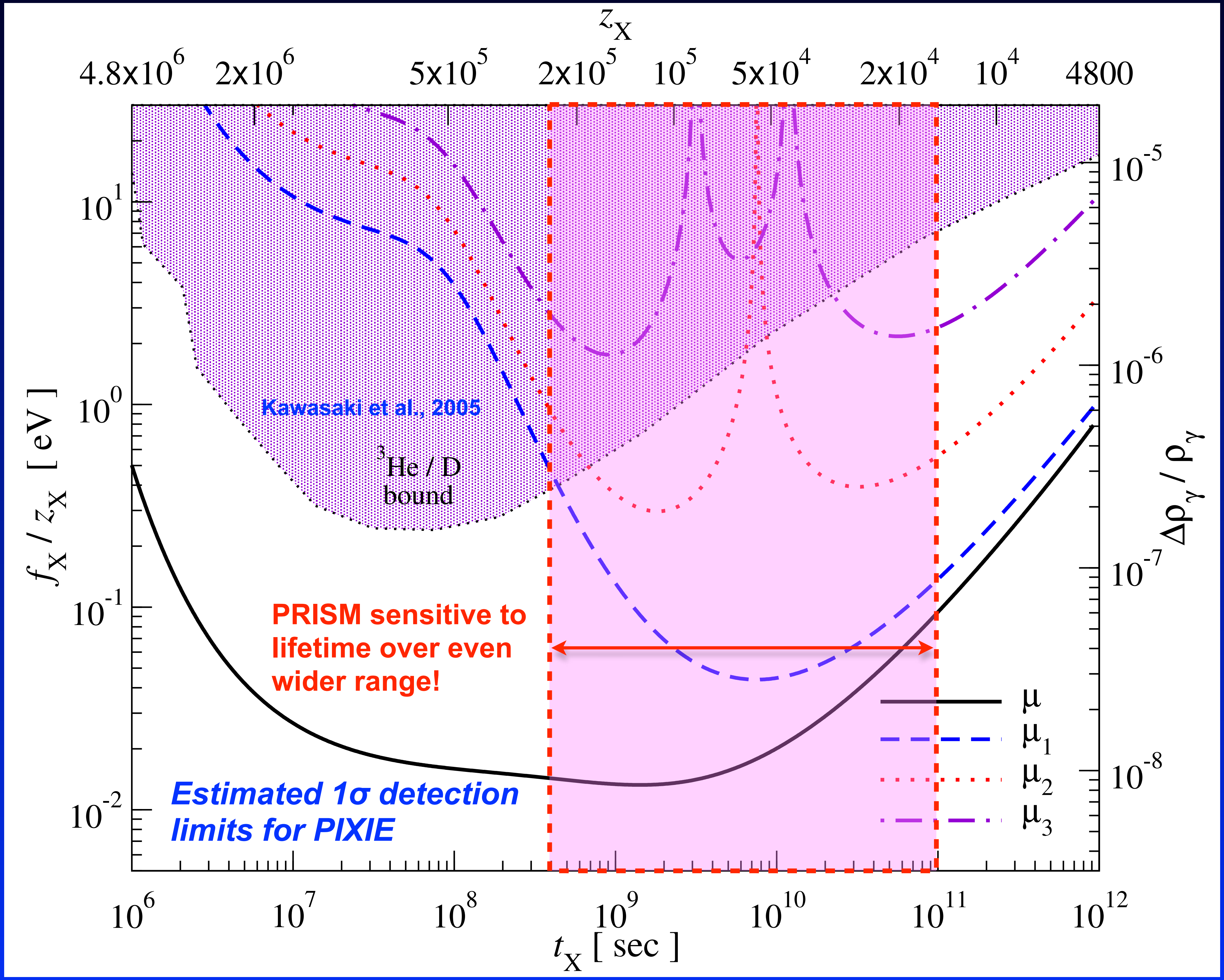

JC & Jeong, 2013

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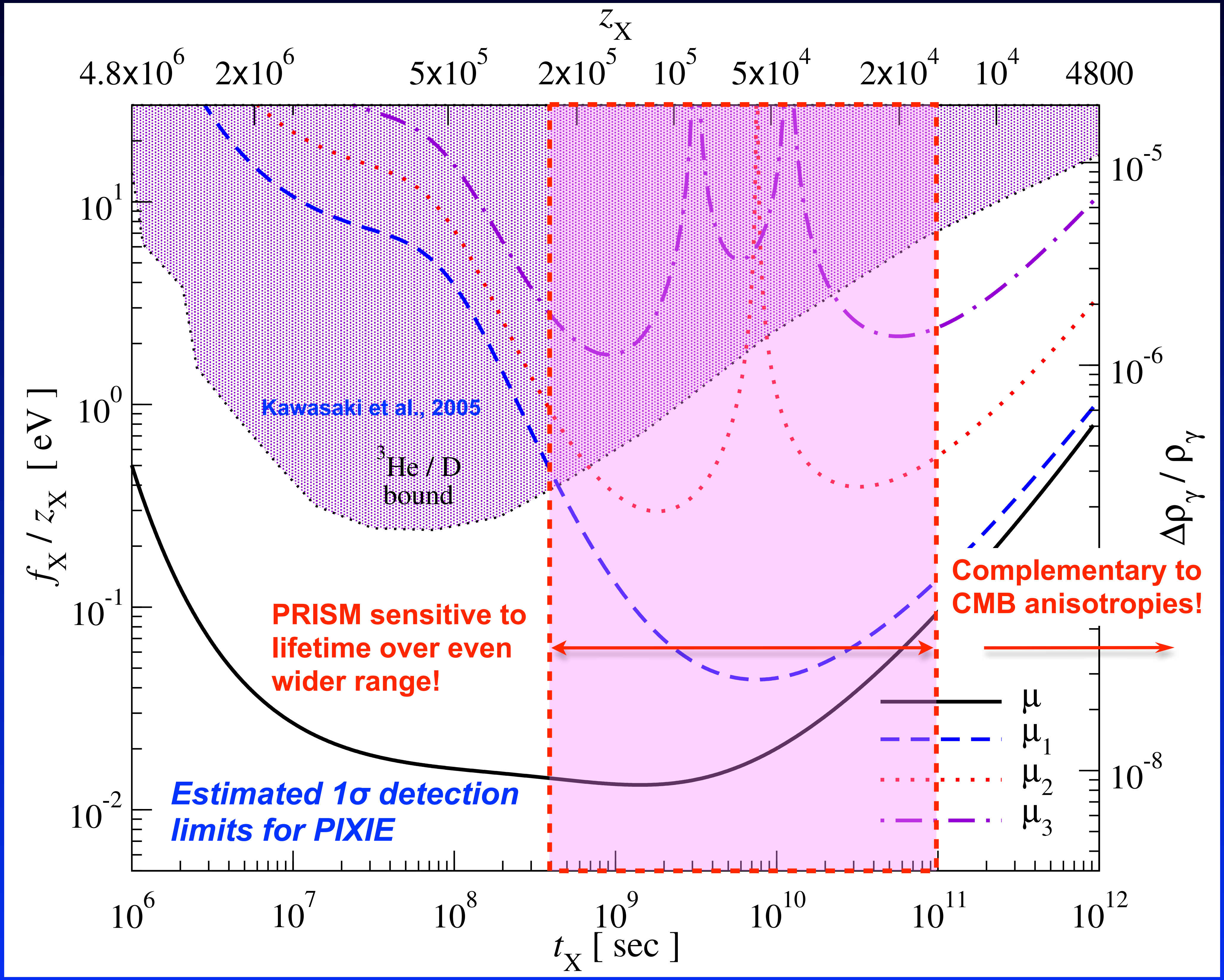
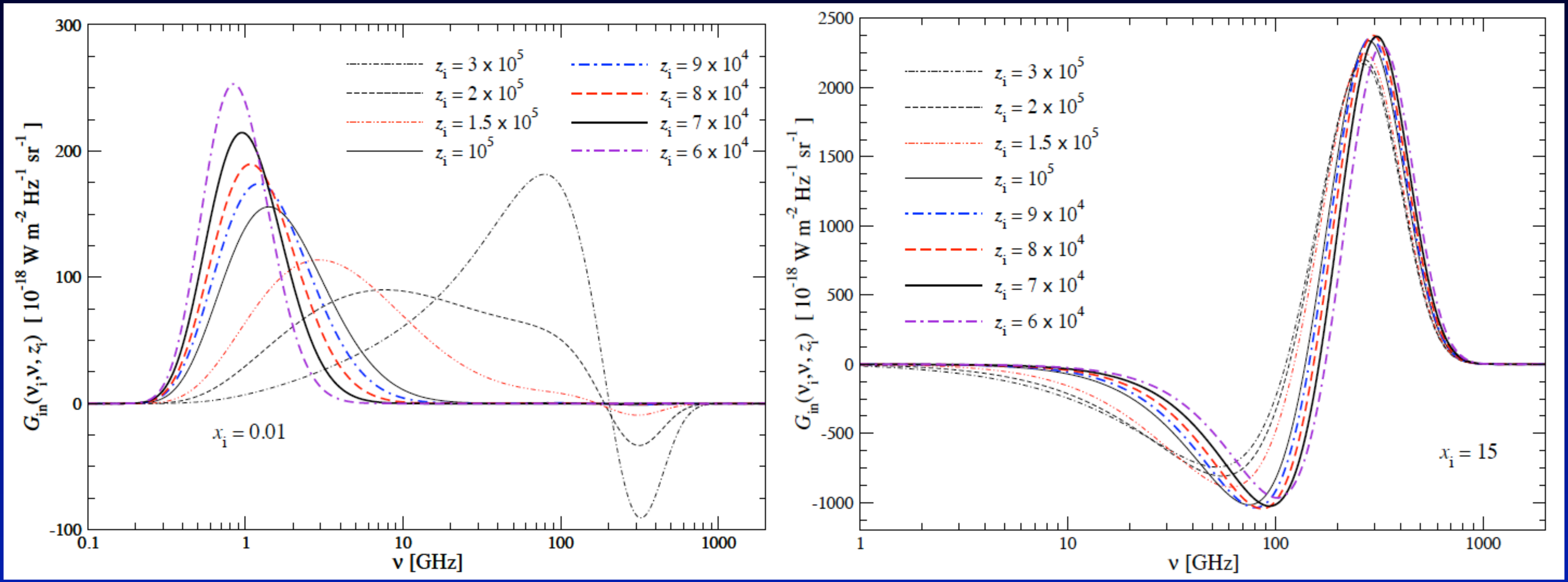


JC & Jeong, 2013

Green's function for photon injection



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

JC 2015, ArXiv:1506.06582

Physical mechanisms that lead to spectral distortions

Standard sources of distortions

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

pre-recombination epoch

„high“ redshifts

„low“ redshifts

post-recombination

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

Physical mechanisms that lead to spectral distortions

Photon injection

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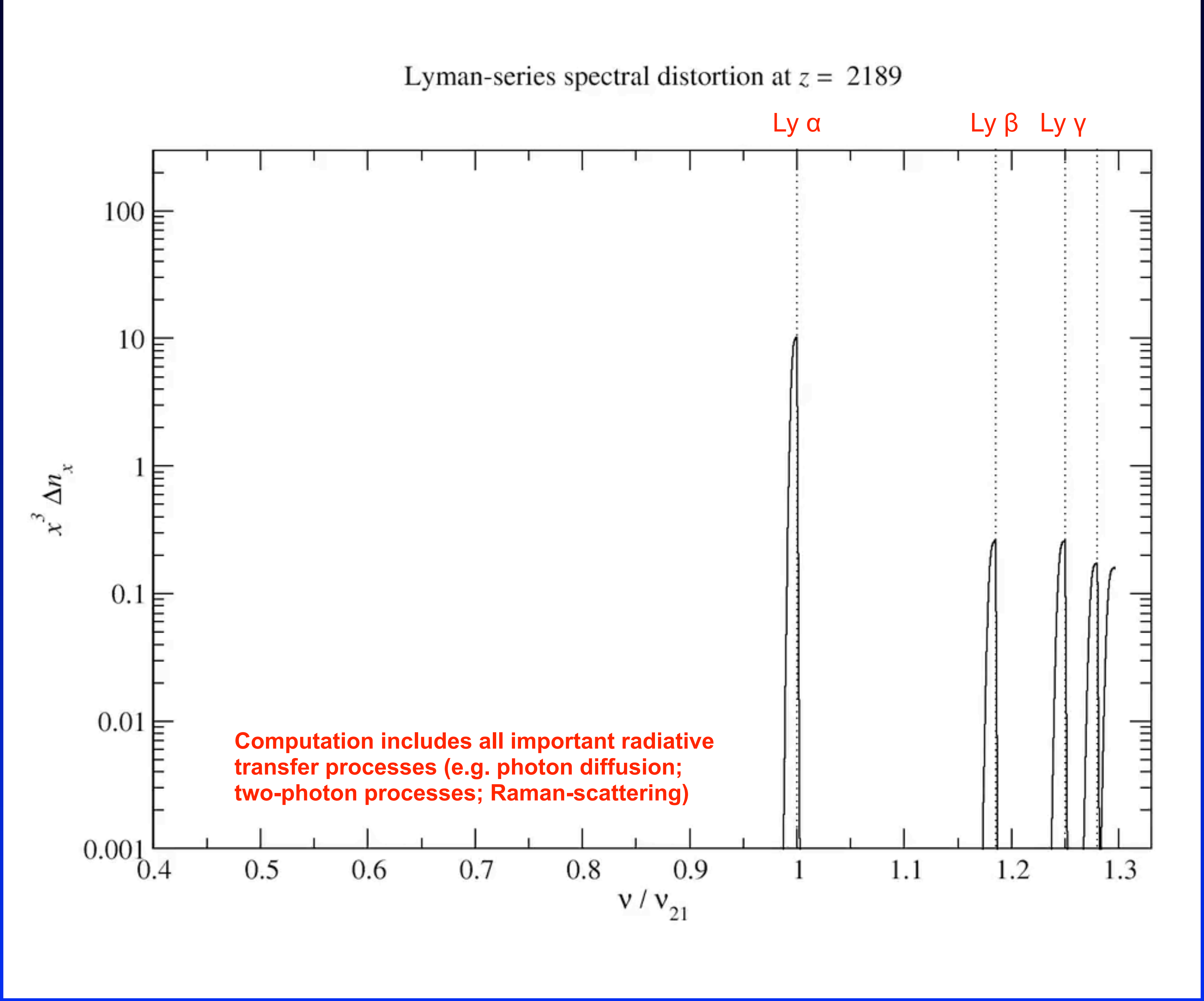
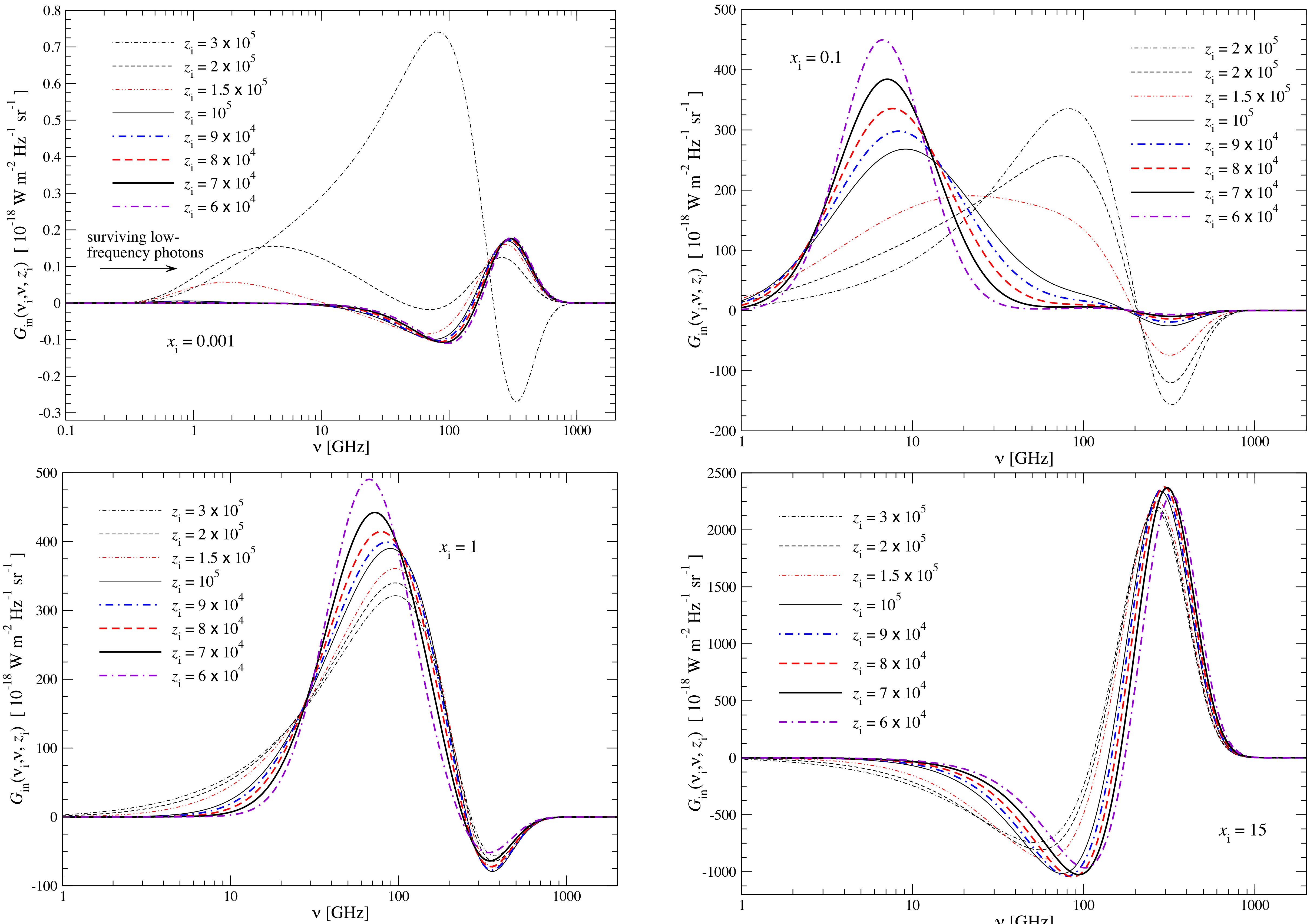
Evolution of the HI Lyman-series distortion



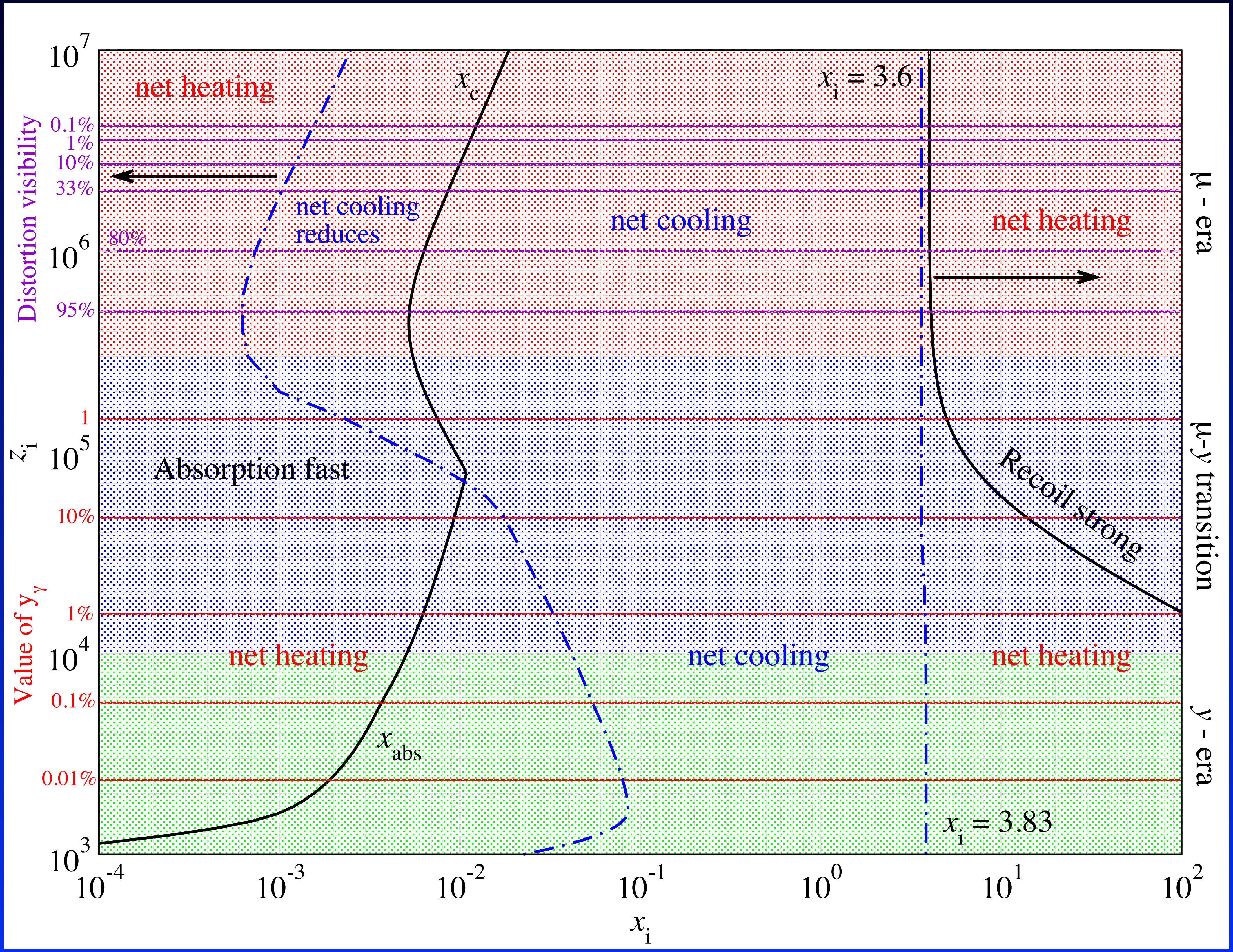
JC & Thomas, MNRAS, 2010

Photon injection at later times



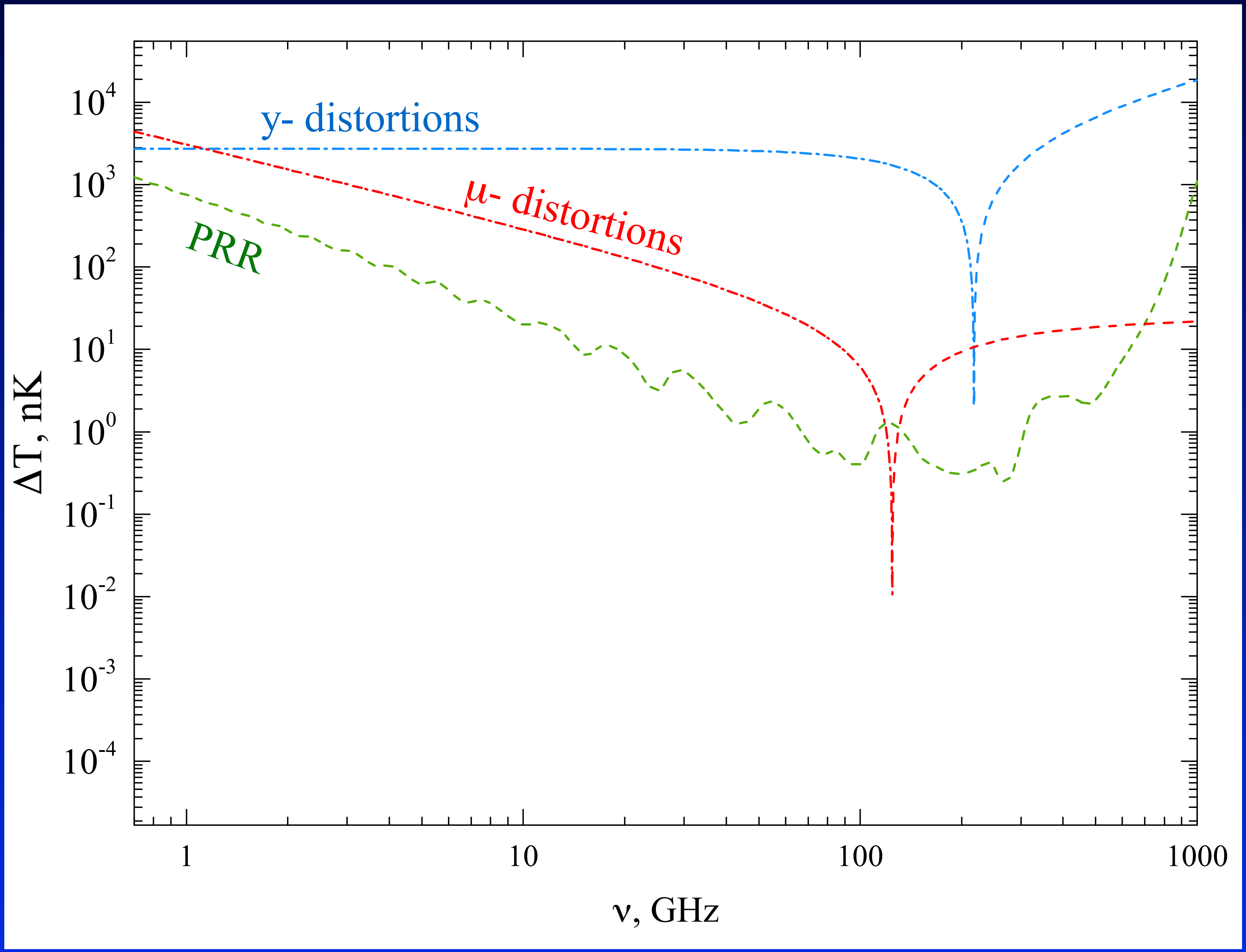
JC 2015, ArXiv:1506.06582

Different regimes for photon injection



JC 2015, ArXiv:1506.06582

Spectral distortions of the CMB dipole



- motion with respect to CMB blackbody monopole

⇒ *CMB temperature dipole*

- including primordial distortions of the CMB

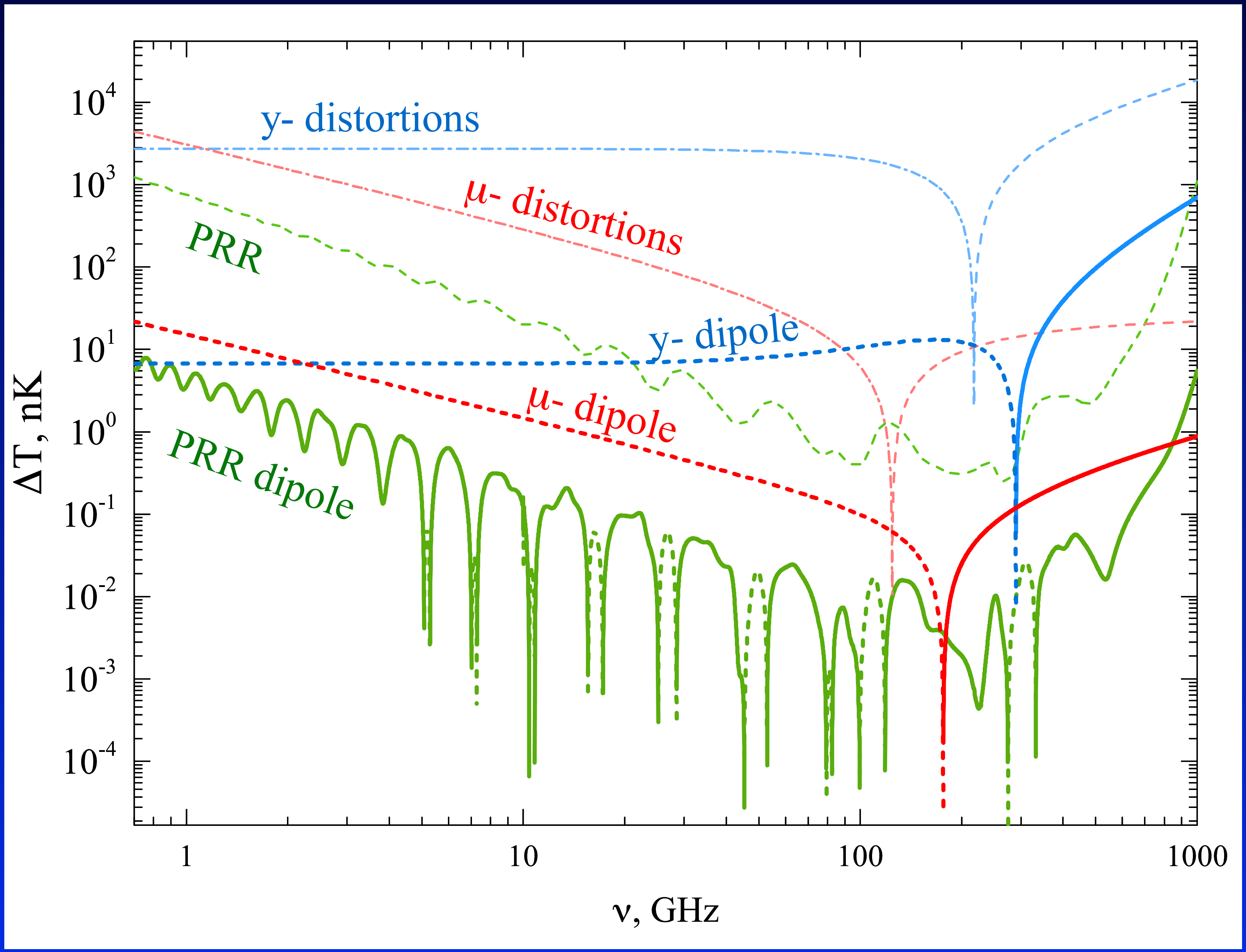
⇒ *CMB dipole is distorted*

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

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

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

Spectral distortions of the CMB dipole



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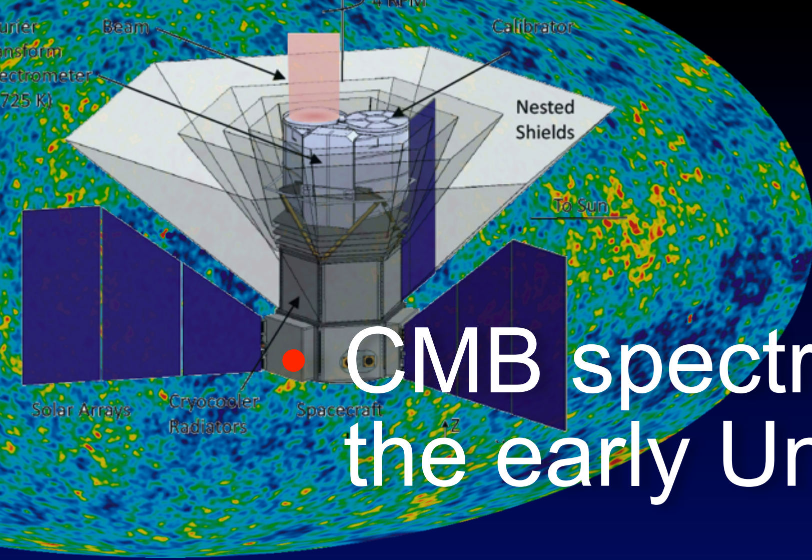
- anisotropy does not need *absolute* calibration but just *inter-channel* calibration
- *but* signal is ~1000 times smaller...
- *foregrounds* will also leak into the dipole in this way
- check of *systematics*

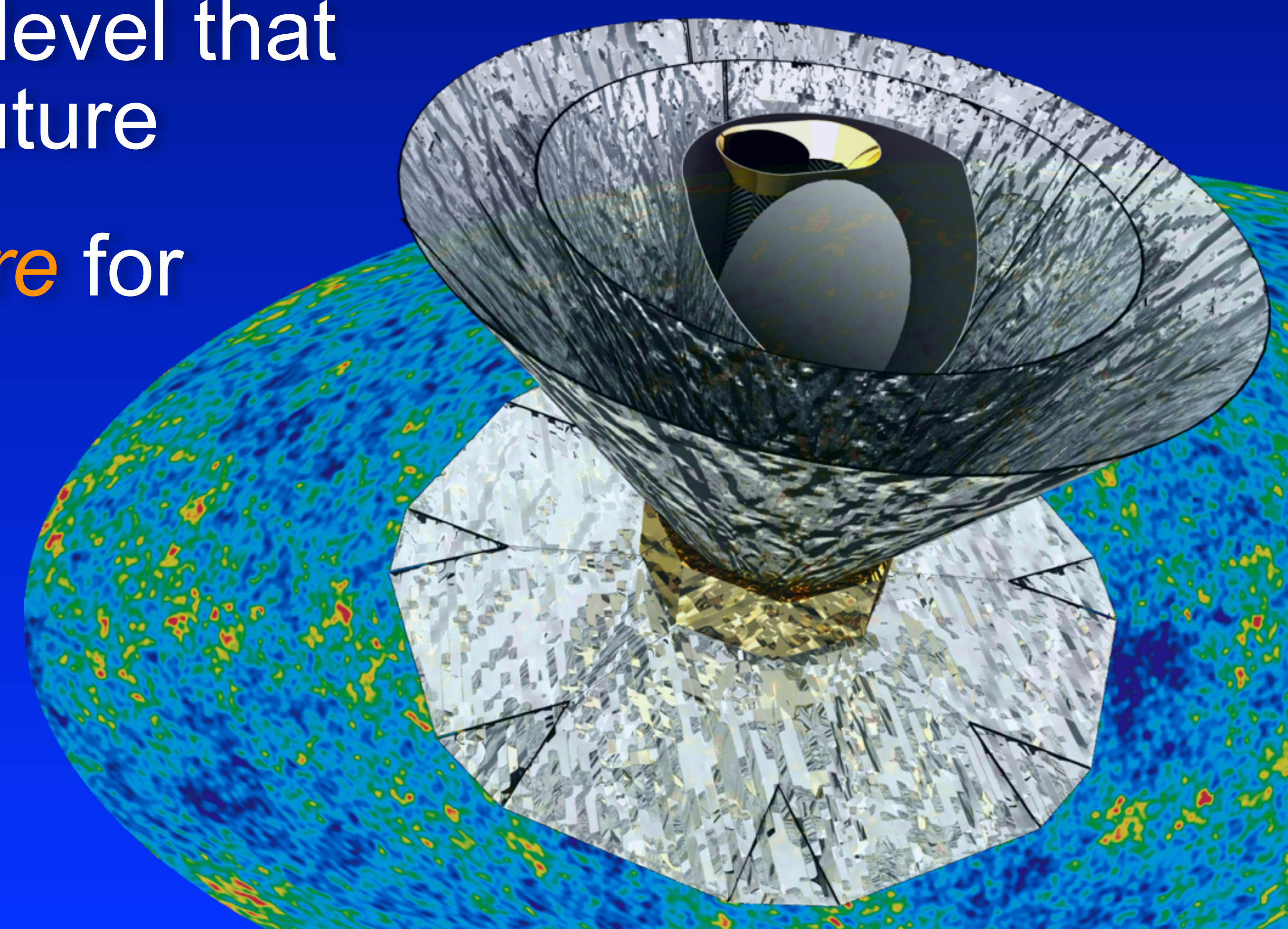
Balashev, Kholupenko, JC, Ivanchik & Varshalovich, ApJ, 2015 (ArXiv:1505.06028)

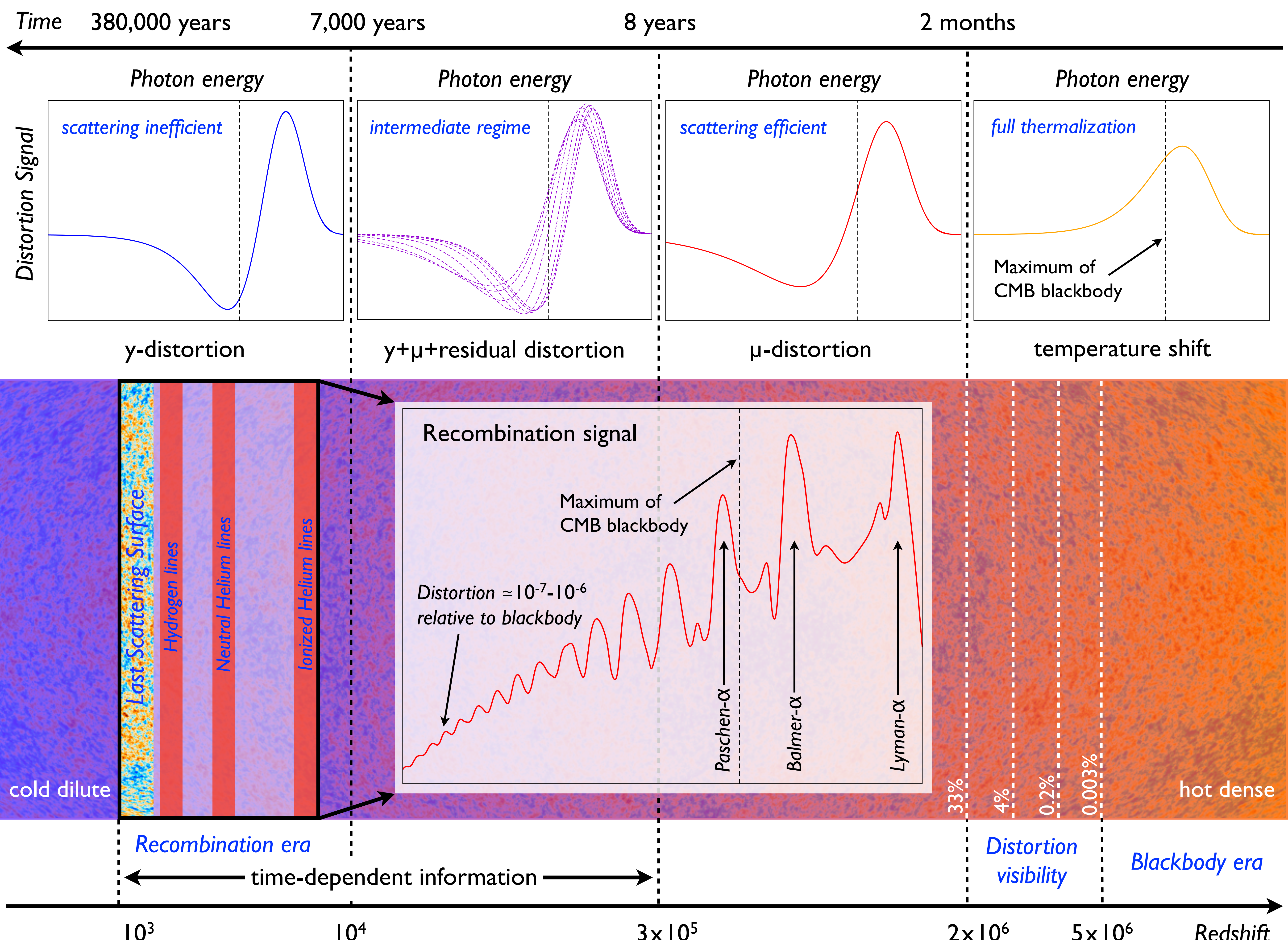


Conclusions

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

We should make use of all this information!





Silk & Chluba, Science, 2014