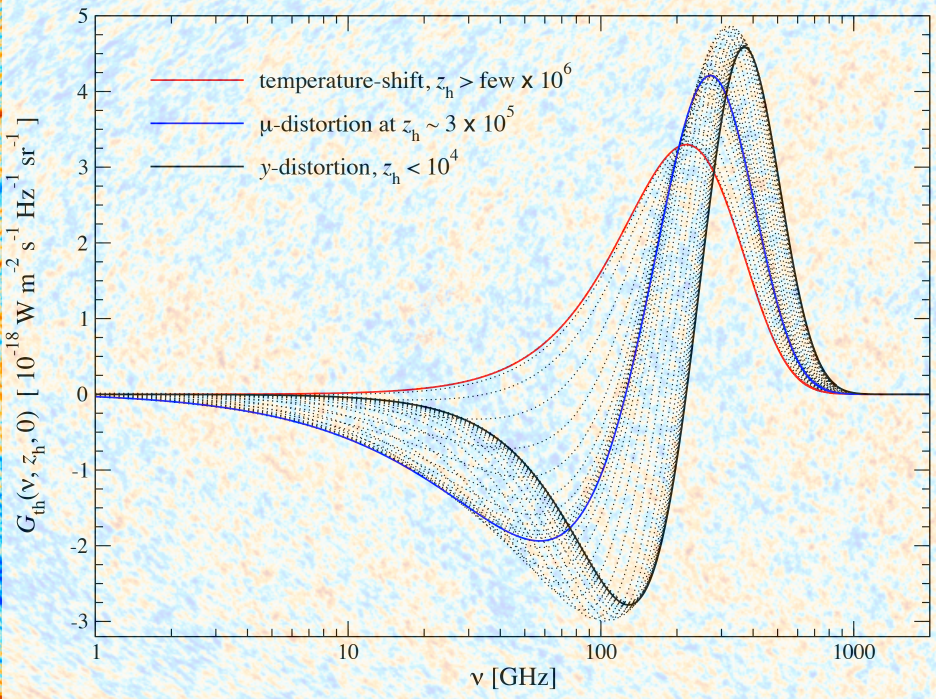
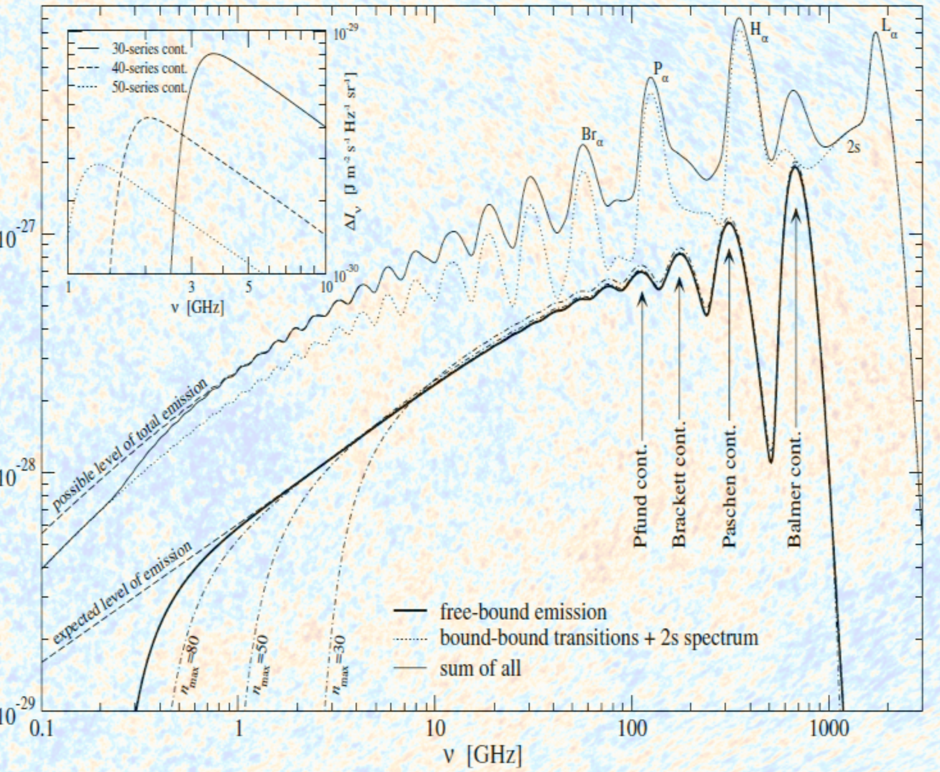
What CMB spectral distortions can teach us about early-universe and particle physics

Primordial Distortions



Cosmological Recombination lines



Jens Chluba

Theory Seminar, Department of Physics

UiO, Oslo, Feb 1st, 2017

MANCHESTER 1824

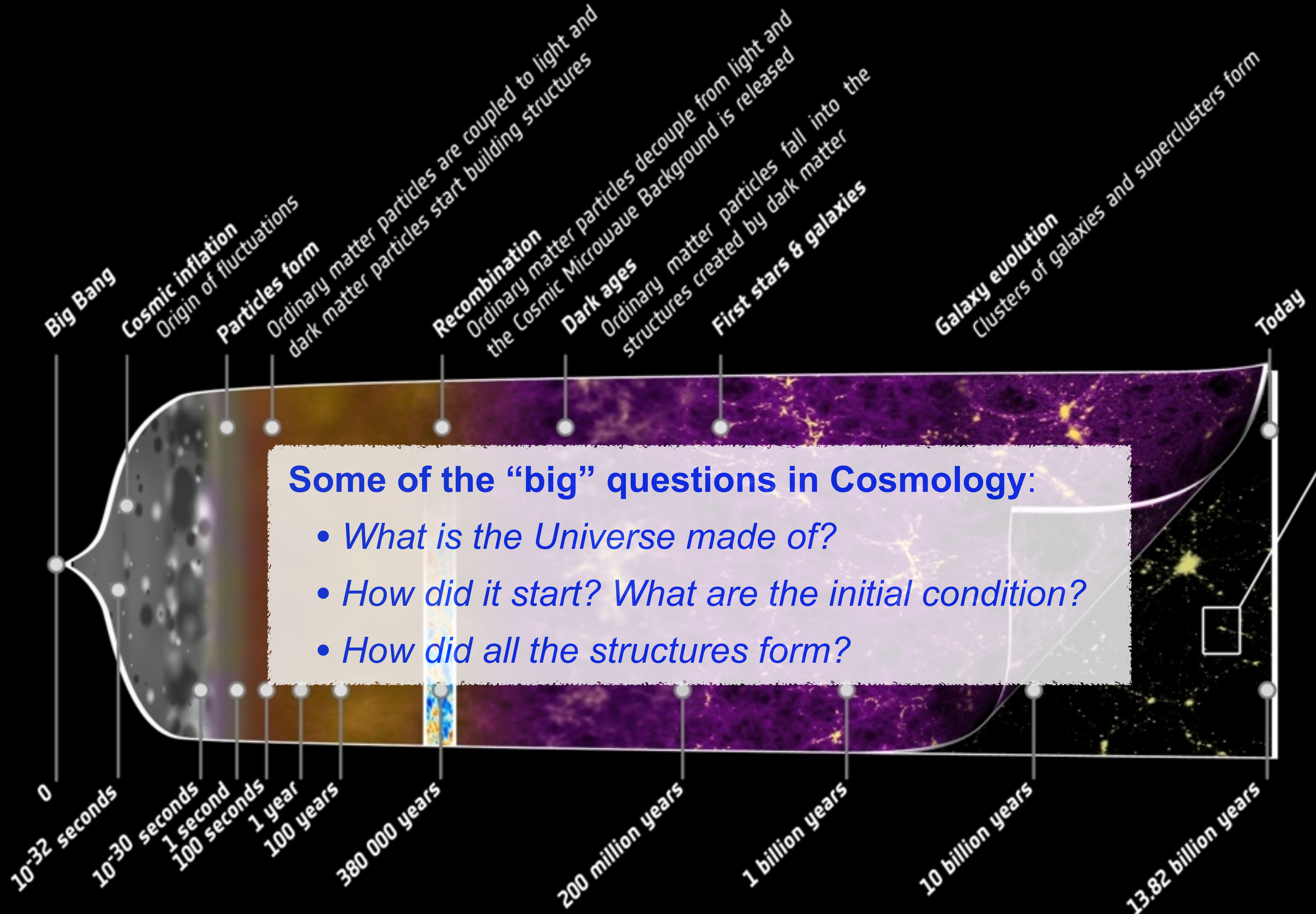
The University of Manchester

THE ROYAL SOCIETY

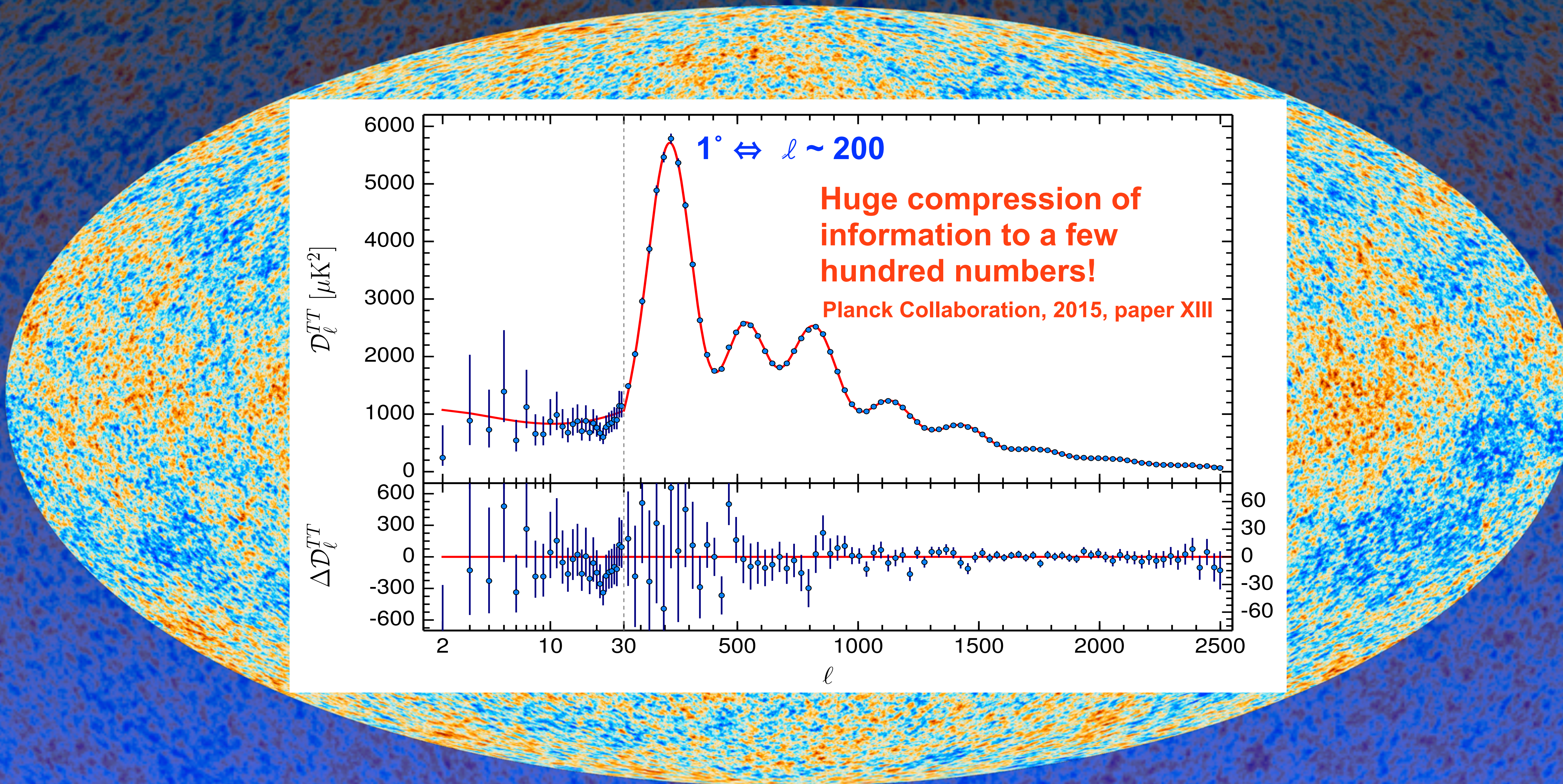
** CMB ≙ Cosmic Microwave Background*

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



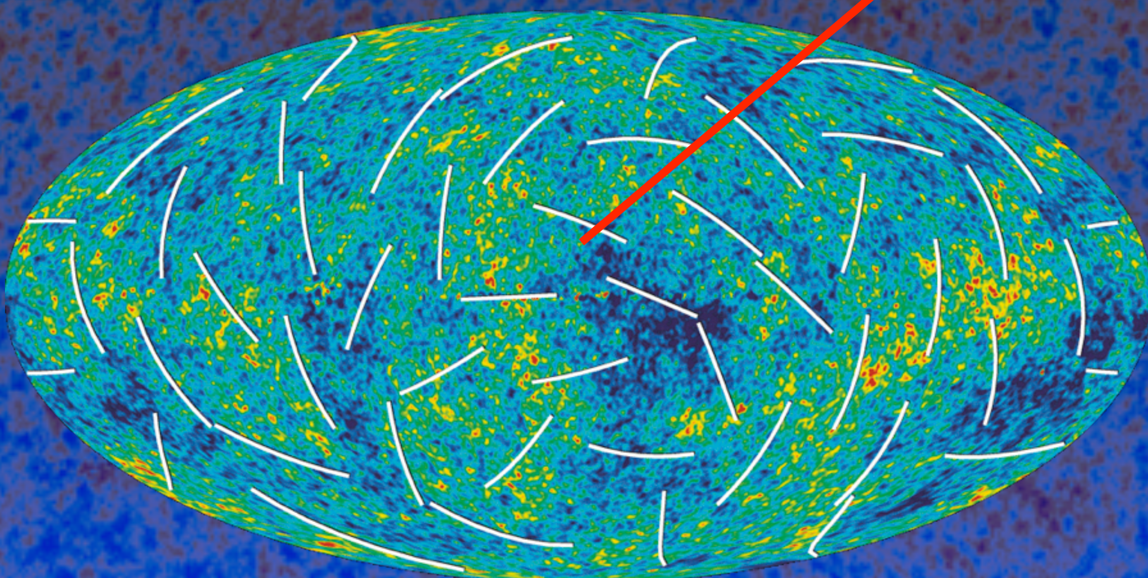
Planck all-sky temperature map

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

CMB Sky → Cosmology

$N_e(z)$ is an important input

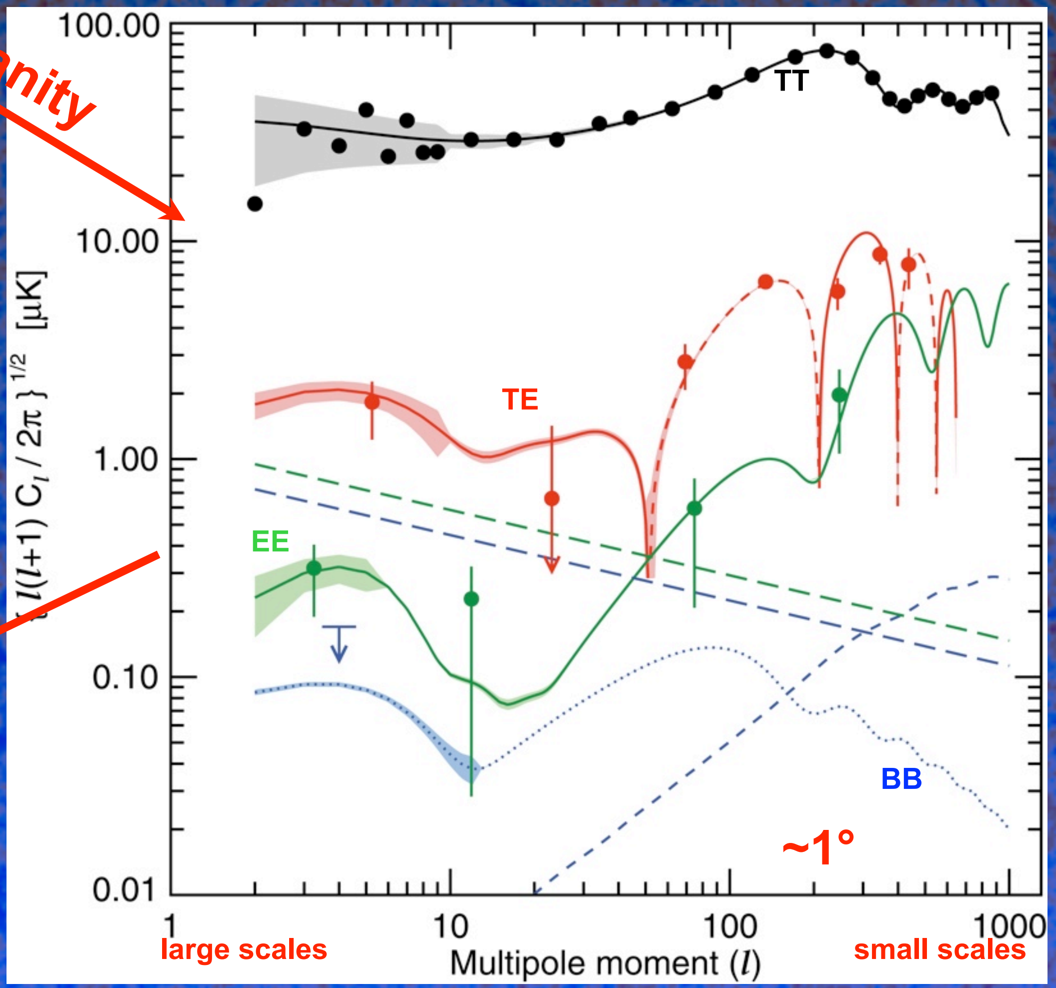
CMB Sky
(temperature & polarization)



a_{lm}

Gaussianity

Power spectra



(Joint) analysis

Cosmological Parameters

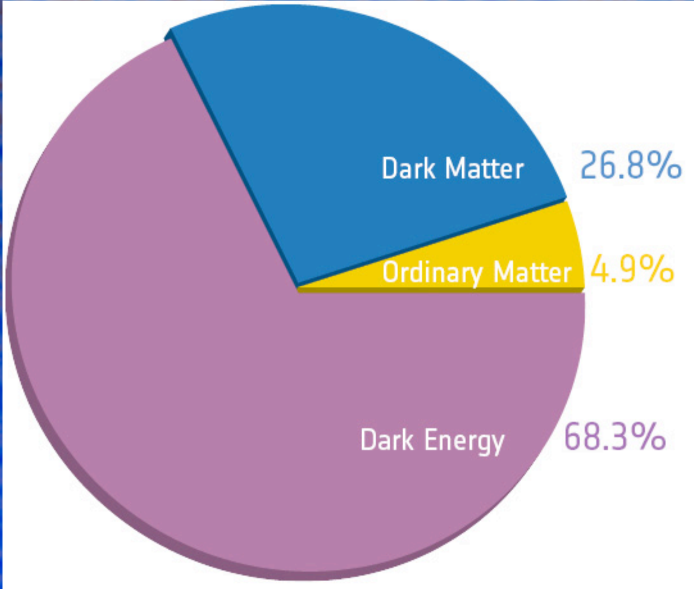
Ω_{tot}, Ω_m, Ω_b, Ω_Λ,
h, τ, n_s,...

Other cosmological Datasets:

Supernovae, large-scale structure/BAO, Lyman-α forest, weak lensing, ...

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

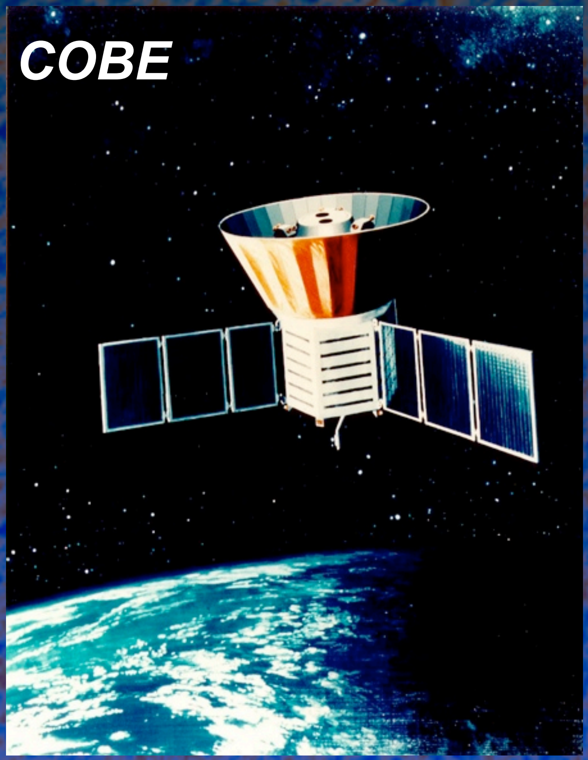
- Standard 6 parameter concordance cosmology with parameters known to percent level precision
- Gaussian-distributed adiabatic fluctuations with nearly scale-invariant power spectrum over a wide range of scales
- cold dark matter ("CDM")
- accelerated expansion today ("Λ")
- Standard BBN scenario → $N_{\rm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

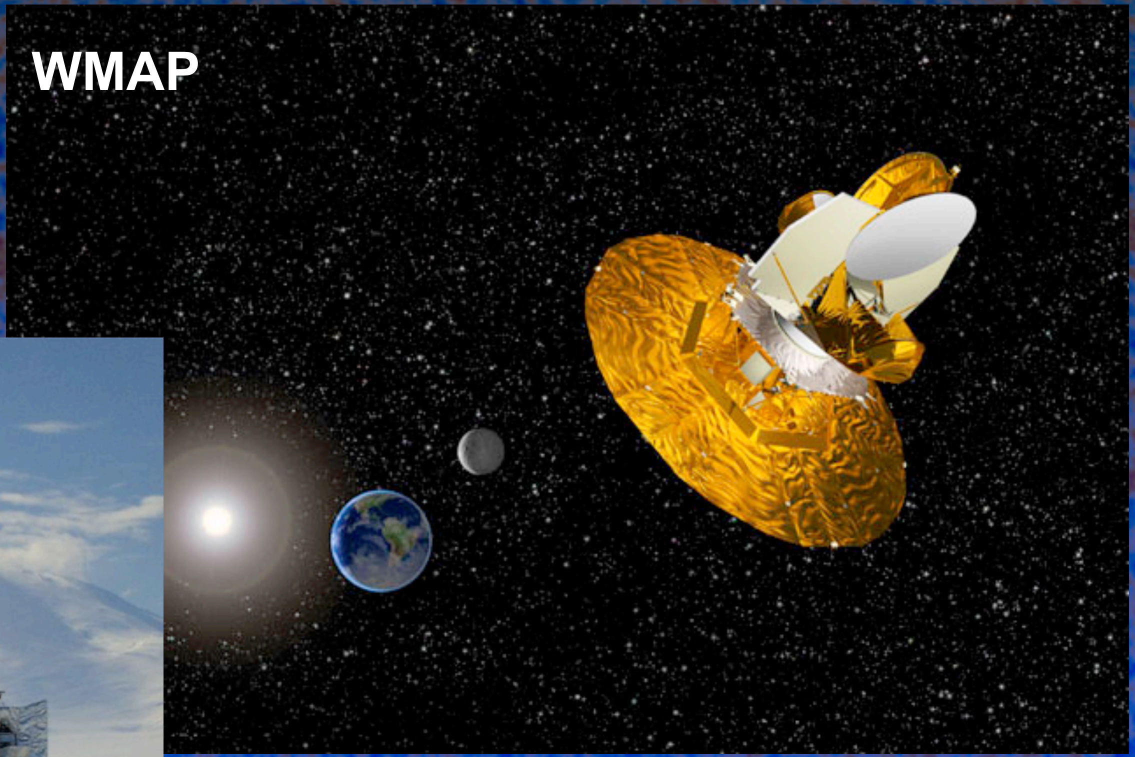


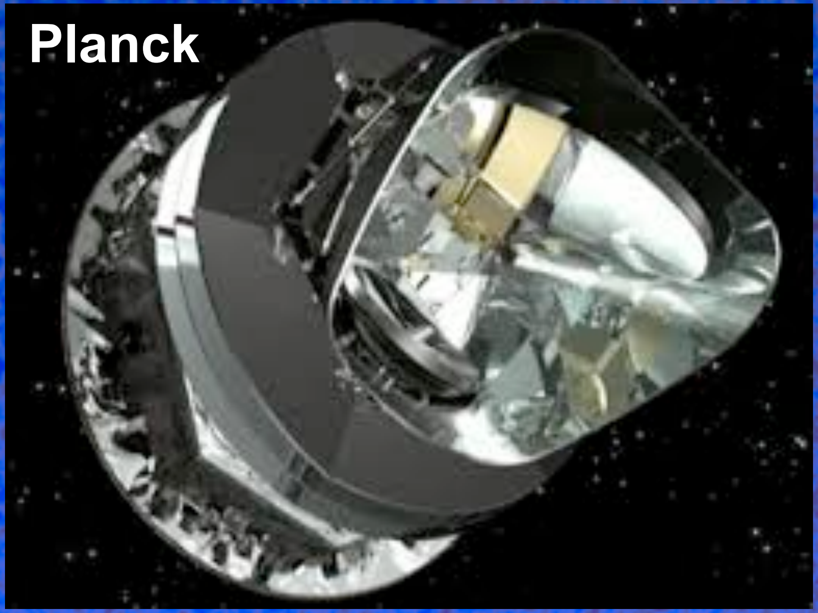
Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_{\rm b}h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_{\rm c}h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010
$100\theta_{\rm MC}$	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
$\ln(10^{10}A_{\rm s})$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
$n_{\rm s}$	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!







VSA, DESI, MAXIMA,

Keck Array, BICEP,

Polarbear, EBEX,

and many more...

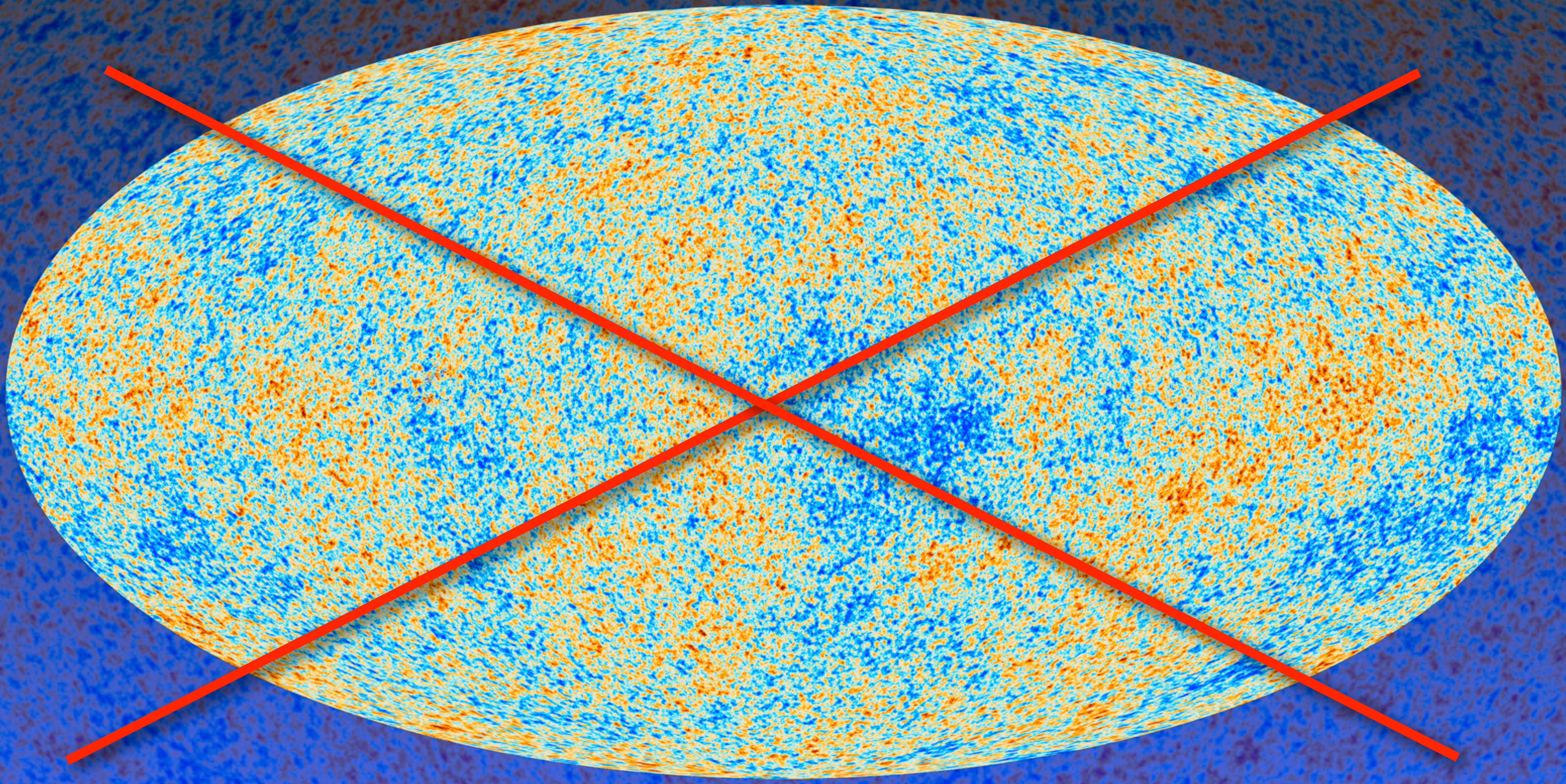
What are the *main* next targets for CMB anisotropies?

- 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

➡ *CORE*
➡ *PIXIE*
➡ *Litebird*
➡ *CMB S4*

A bright and exciting future with lots of competition!

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

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

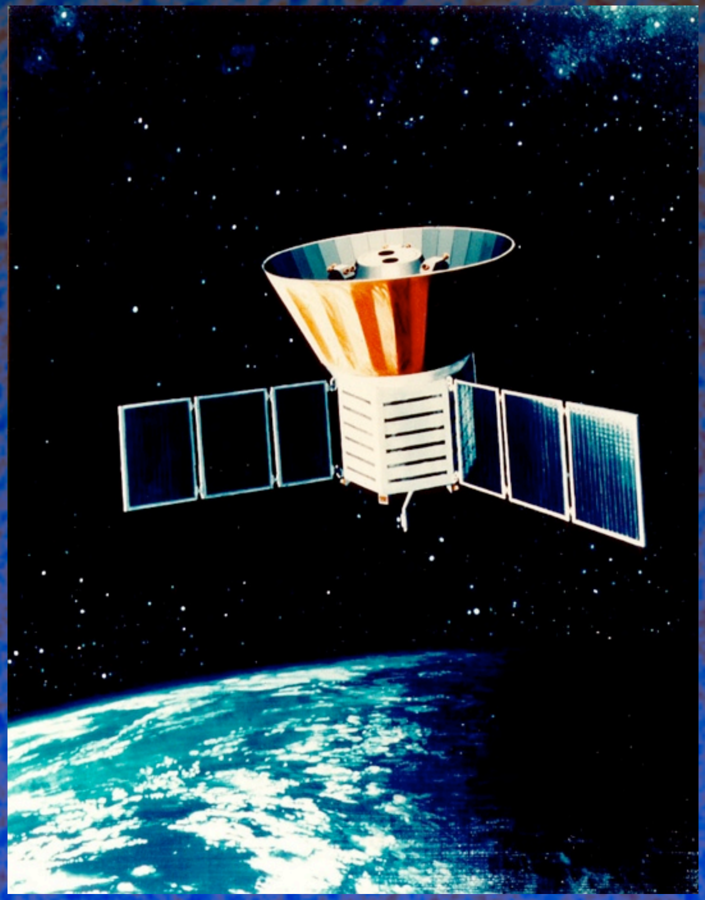
Absolute measurement required!

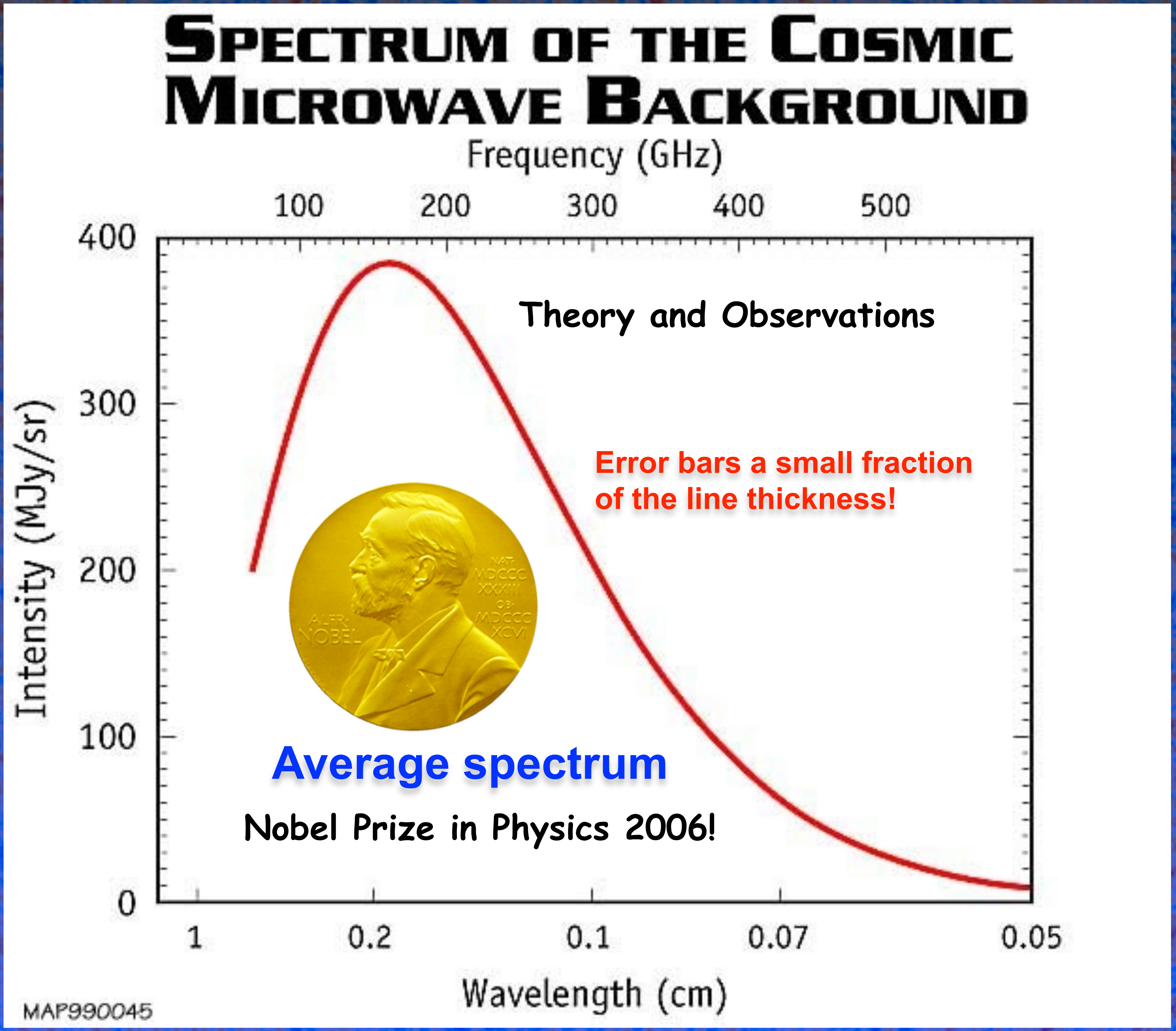
One has to go to space...

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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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

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

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

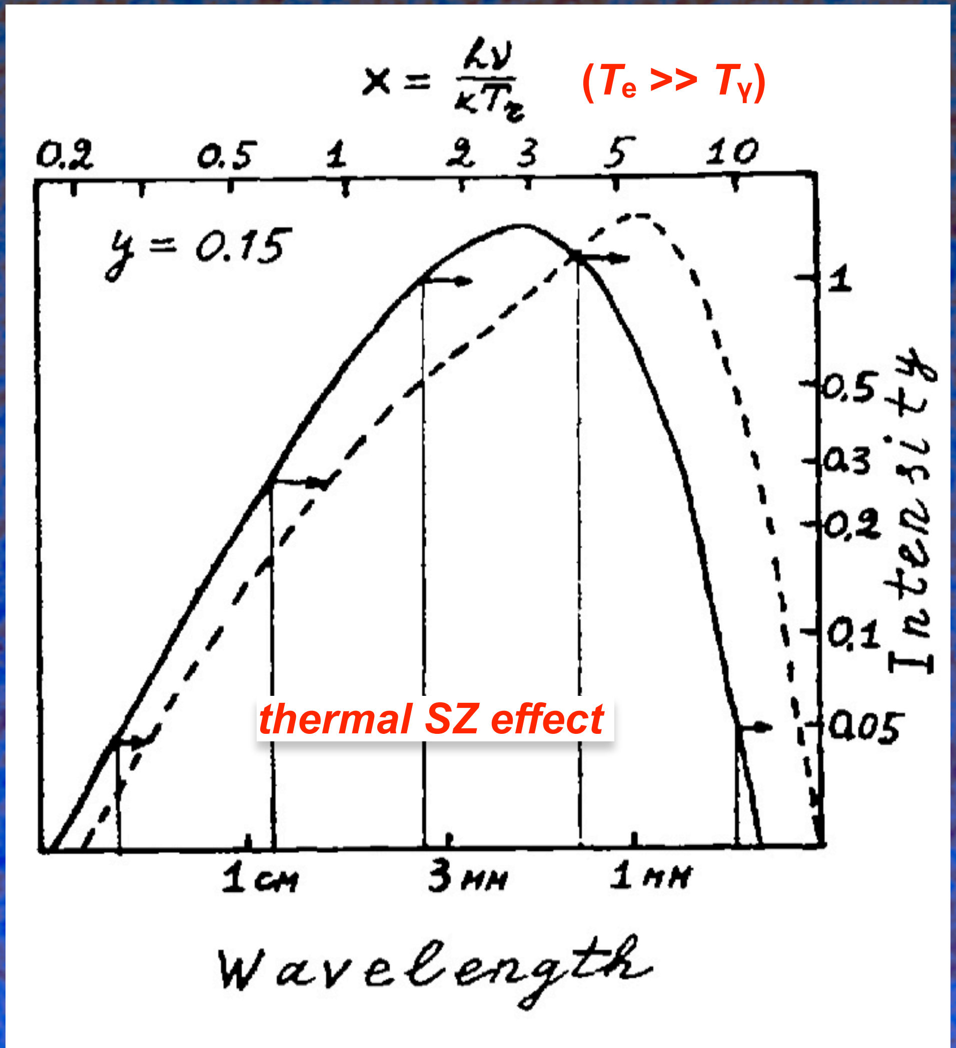
→ thermalization process (partially) erases distortions

(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!

Standard types of primordial CMB distortions

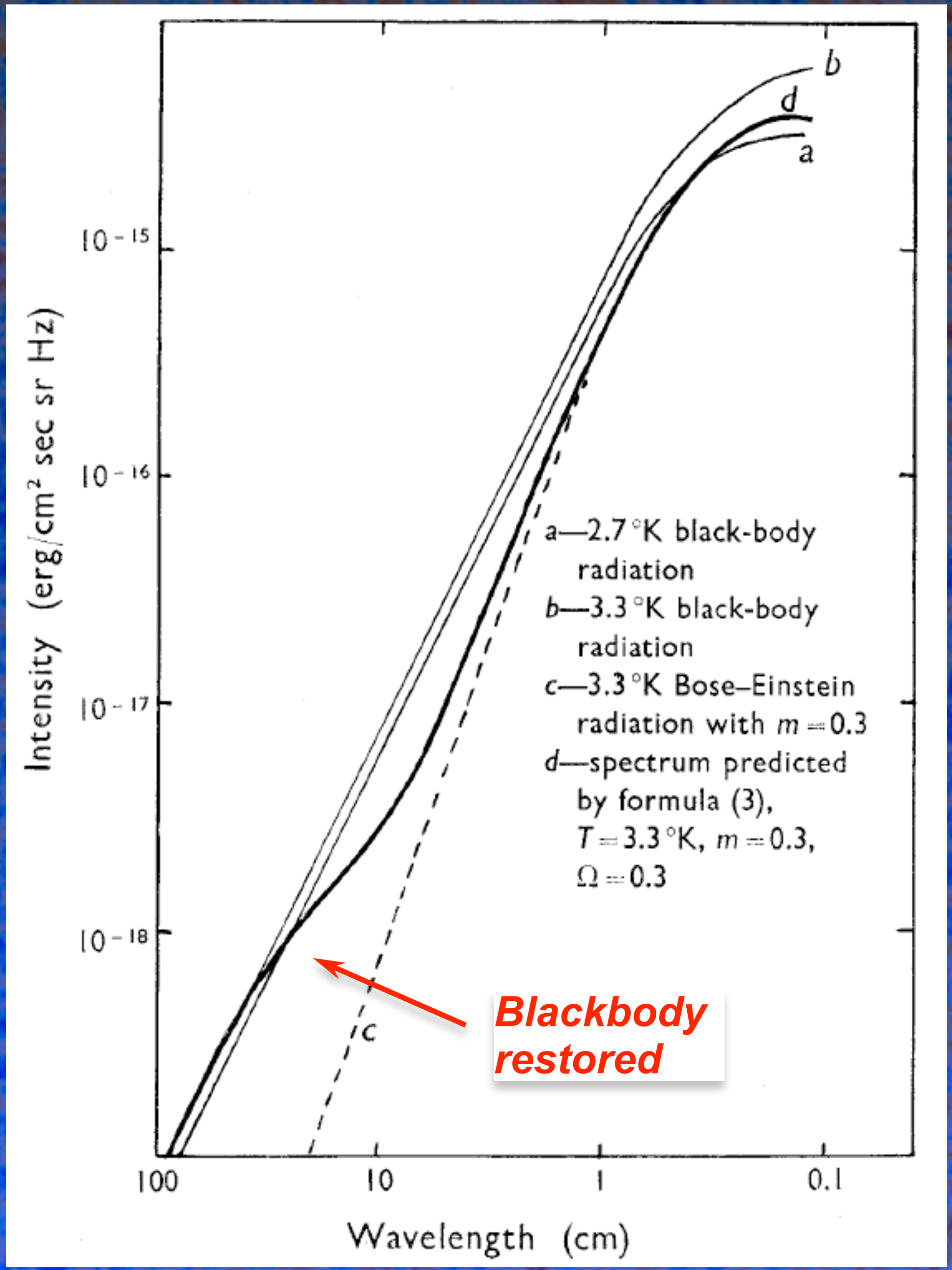
Compton y-distortion



Sunyaev & Zeldovich, 1980, ARAA, 18, 537

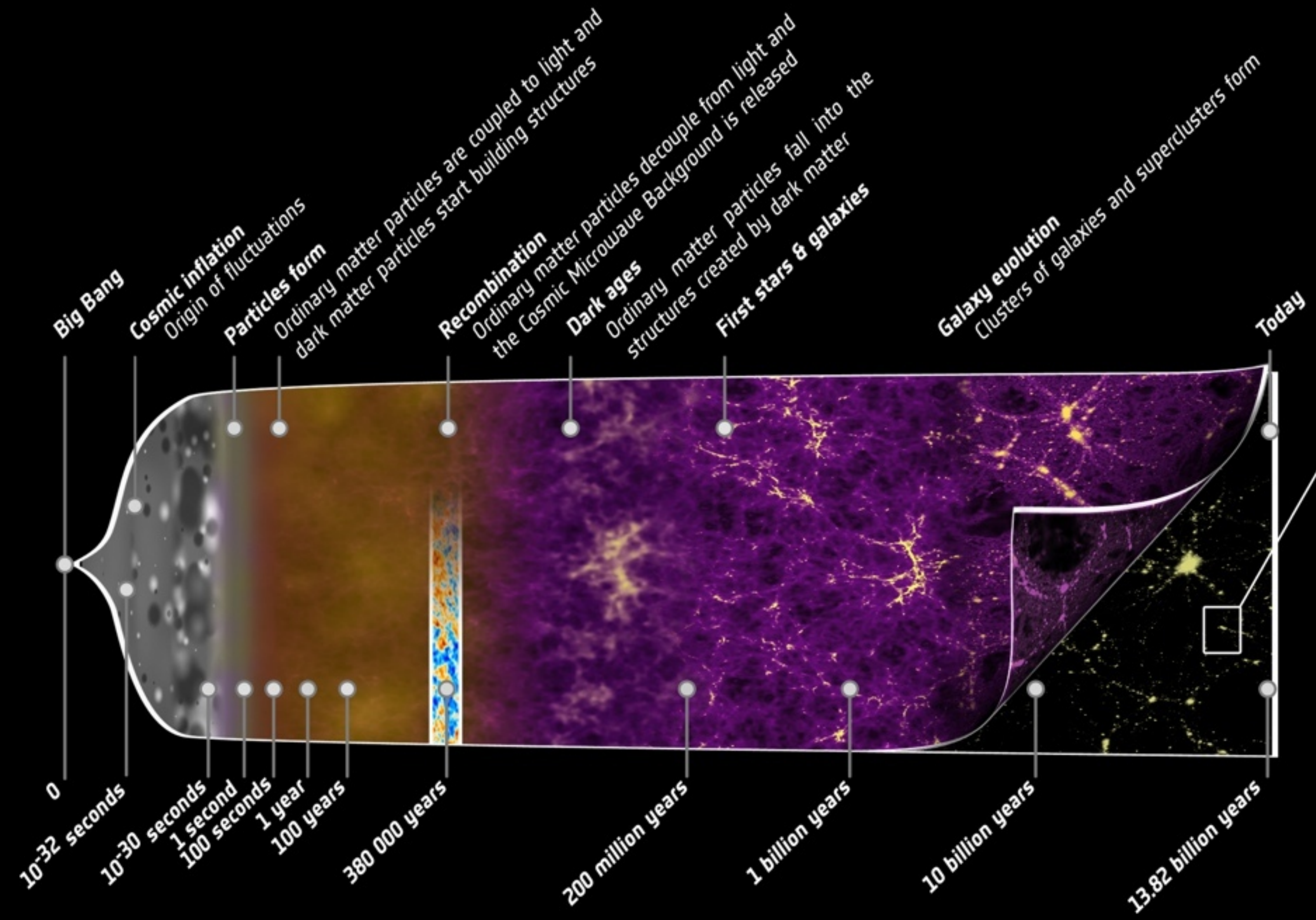
- also known from thSZ effect
- up-scattering of CMB photon
- important at late times (z<50000)
- scattering inefficient

Chemical potential μ-distortion

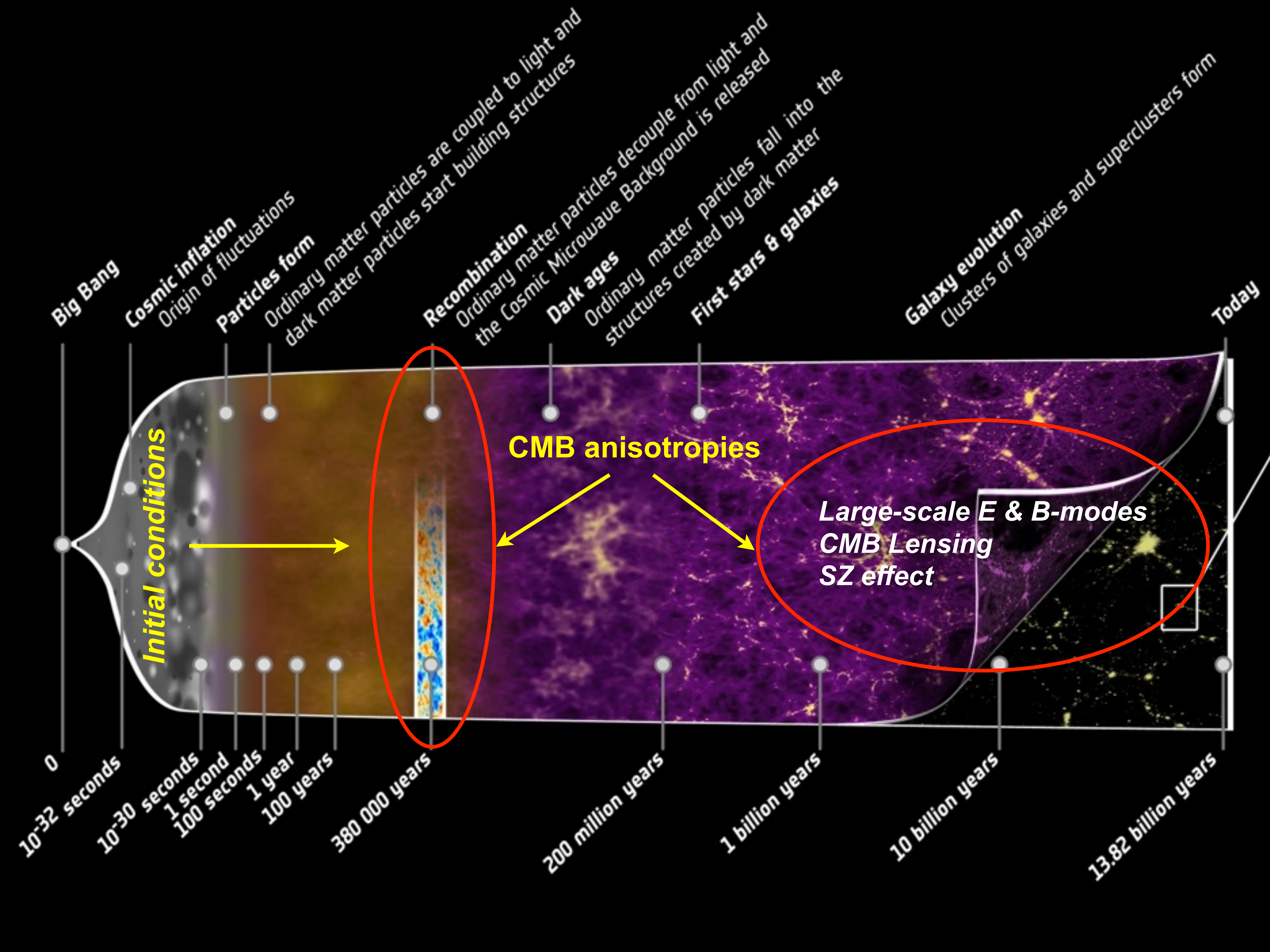


Sunyaev & Zeldovich, 1970, ApSS, 2, 66

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



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



Big Bang
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Clusters of galaxies and superclusters form
Today
Initial conditions
CMB anisotropies
Large-scale E & B-modes
CMB Lensing
SZ effect
0
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380 000 years
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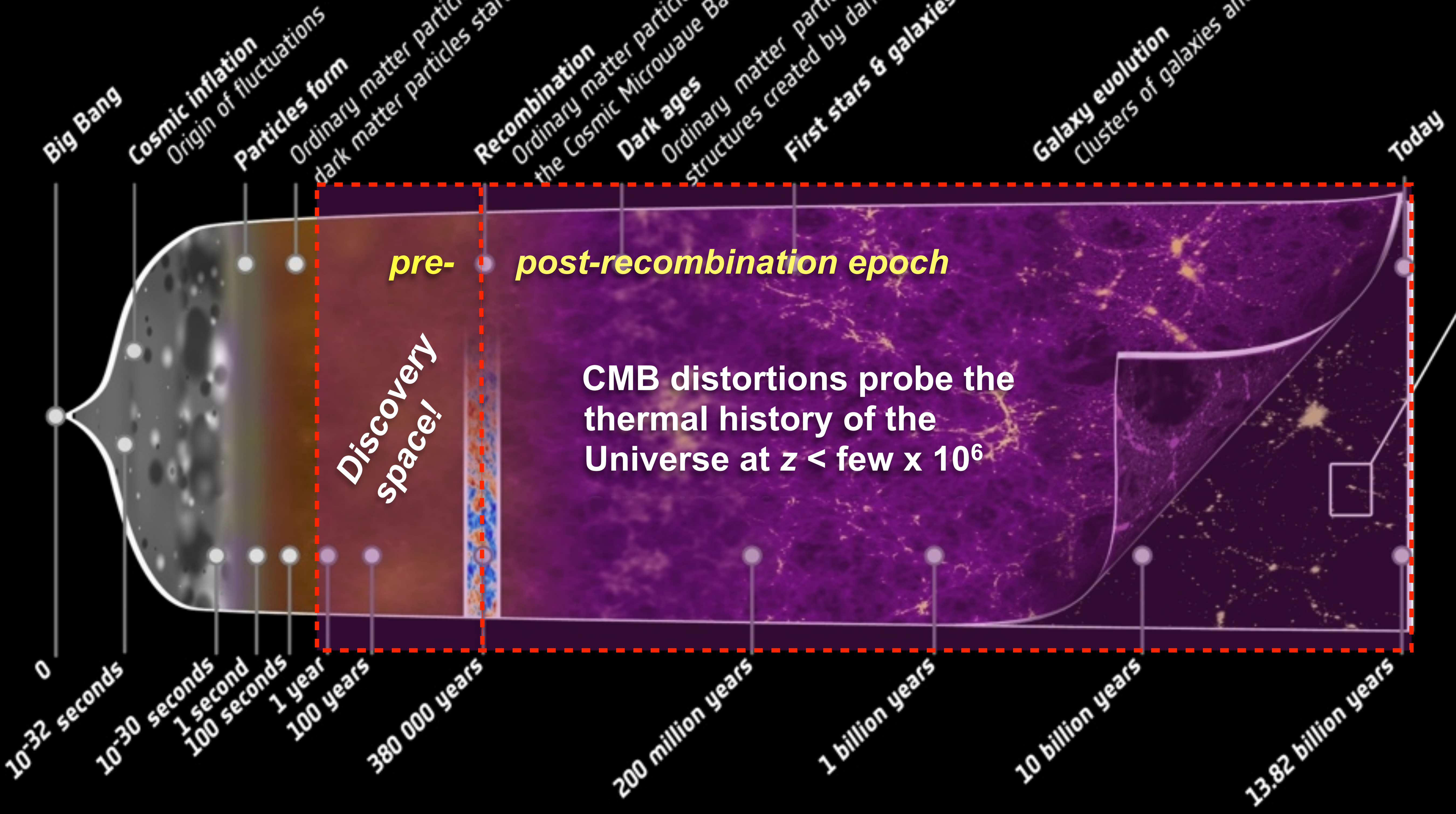
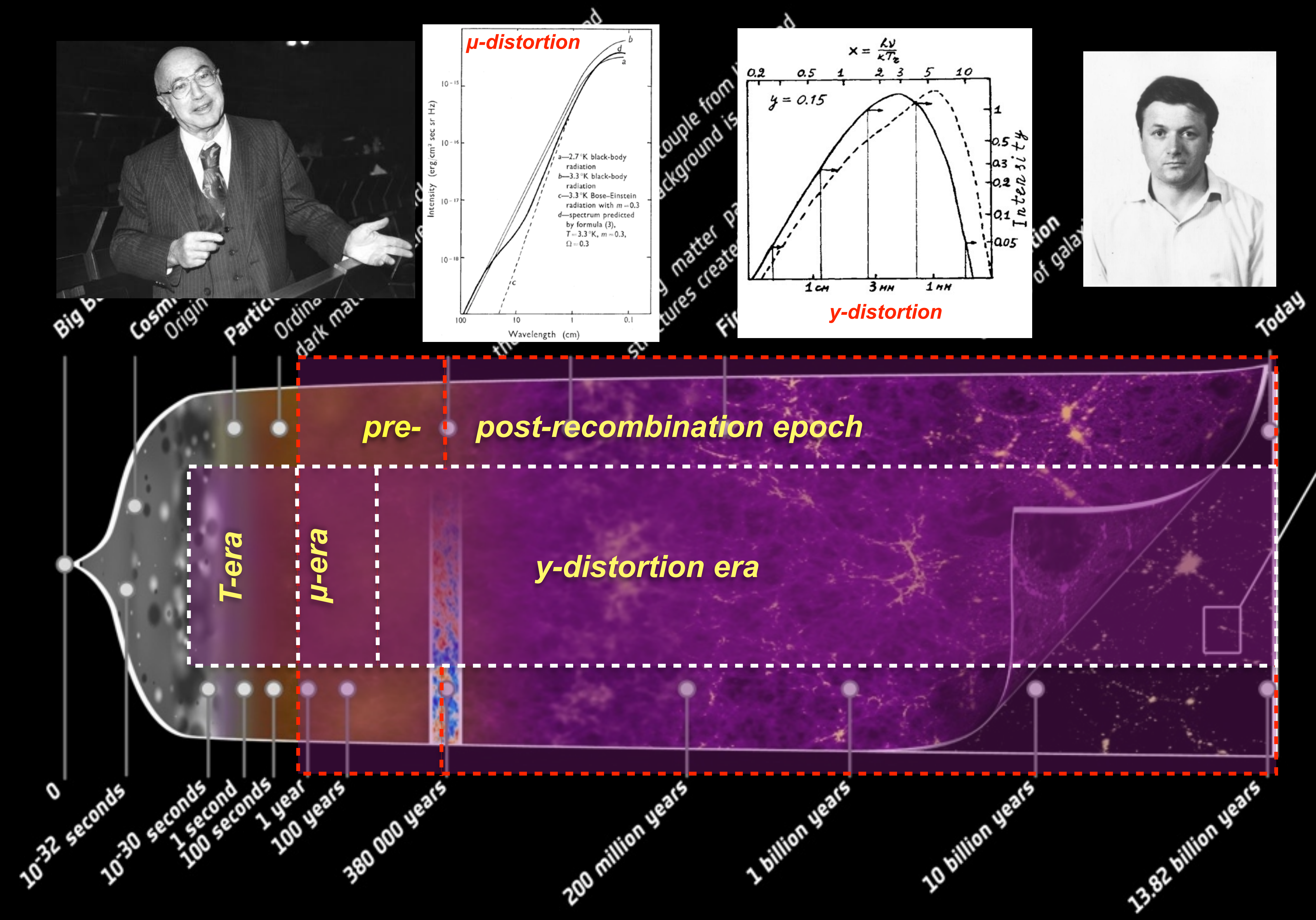
Measurements of CMB spectrum will open a new unexplored window to the early Universe!





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
y-distortion
y = 0.15
1 см
3 мм
1 мм
Intensity
pre-
post-recombination epoch
T-era
μ-era
y-distortion era
Today
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
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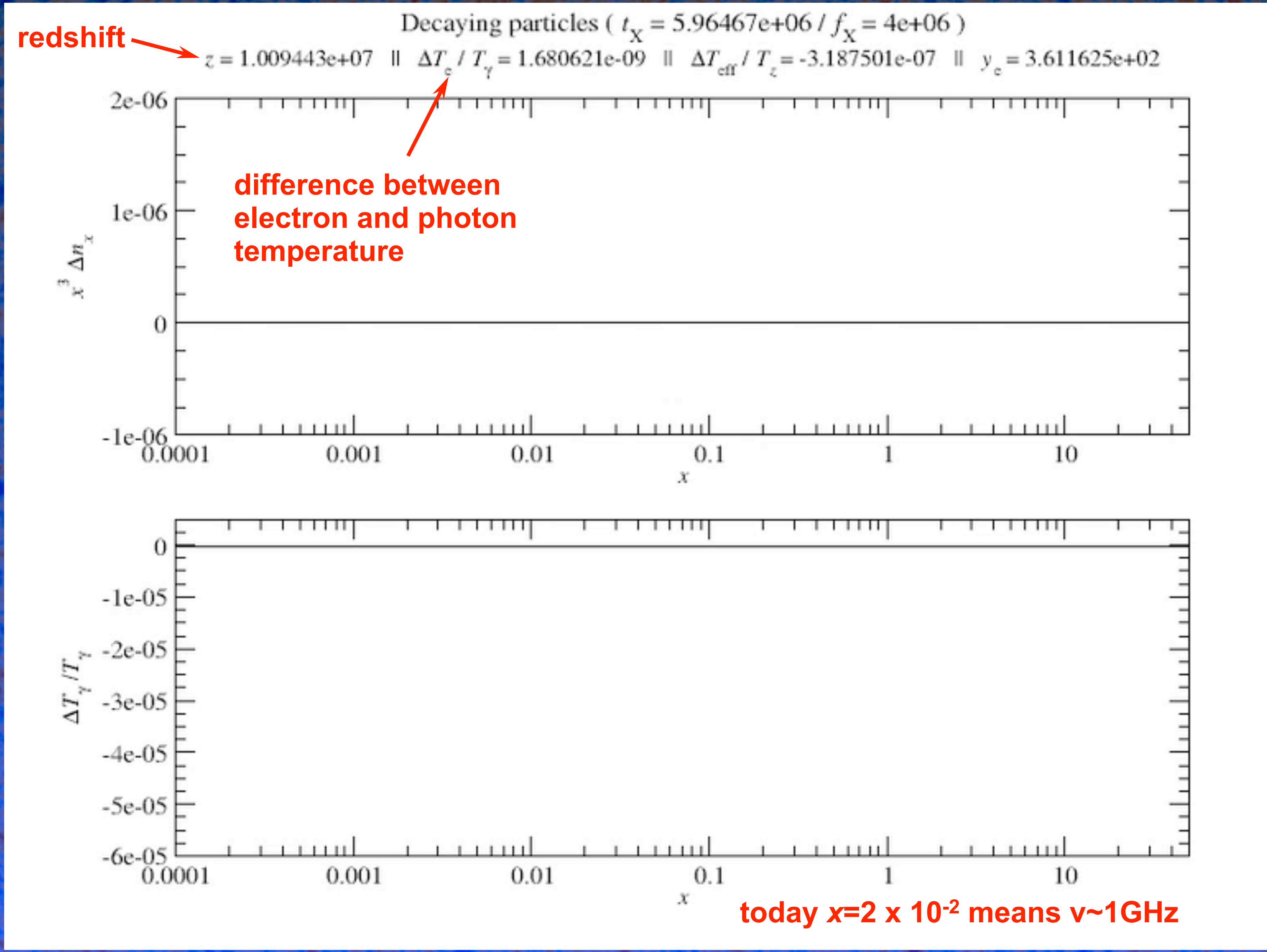
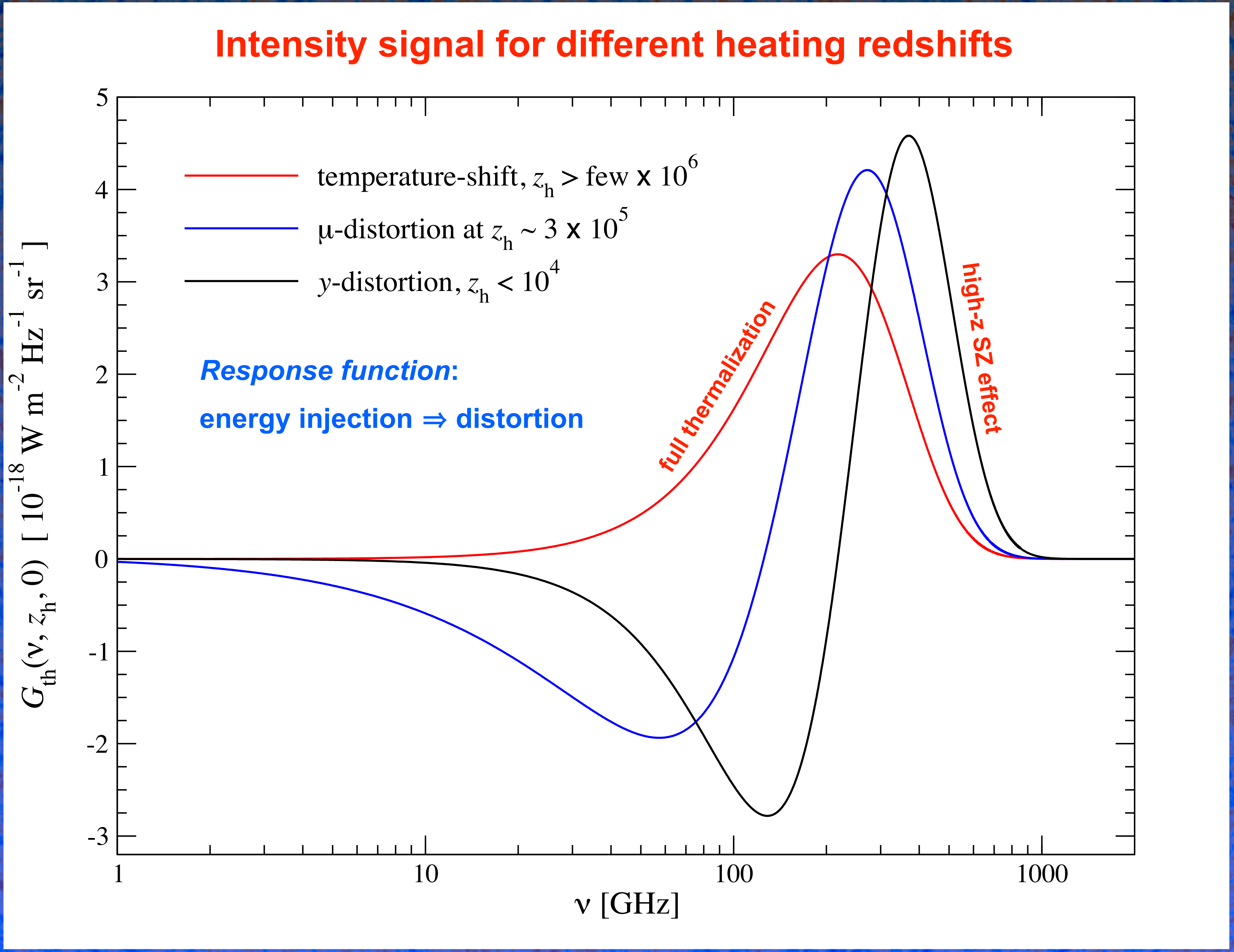
Example: *Energy release by decaying relict particle*



- 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)

What does the spectrum look like after energy injection?



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

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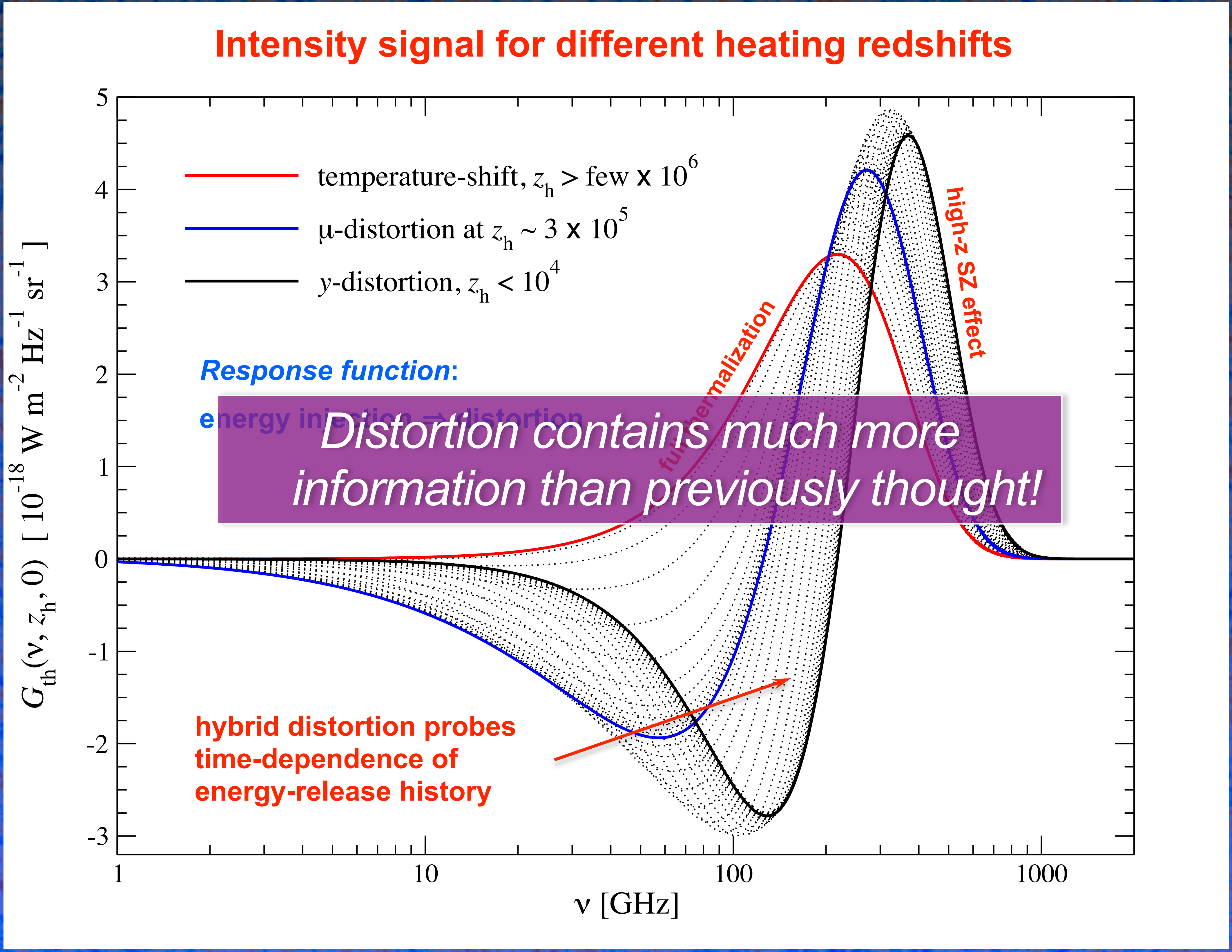

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Transition from y-distortion → μ-distortion

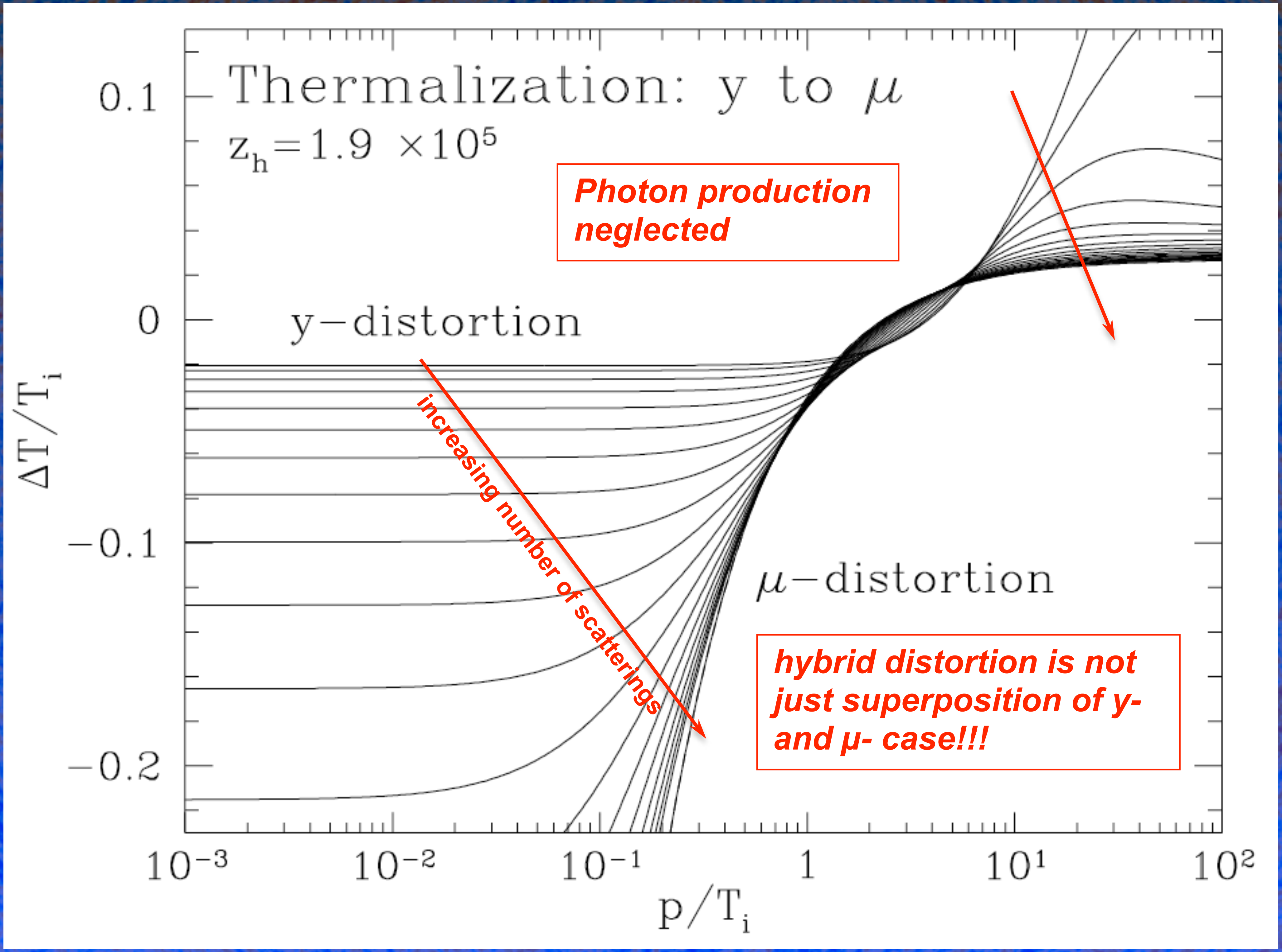
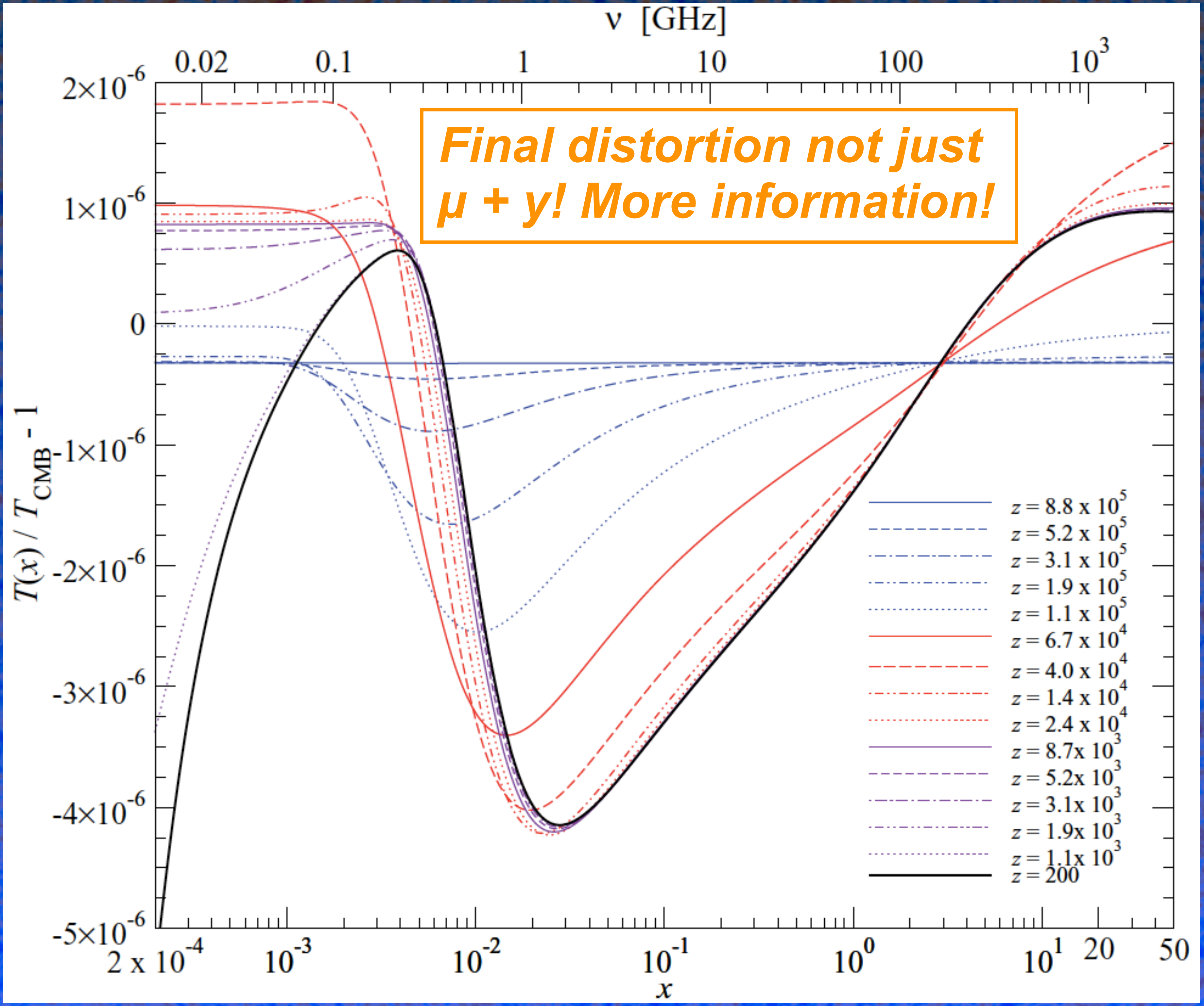


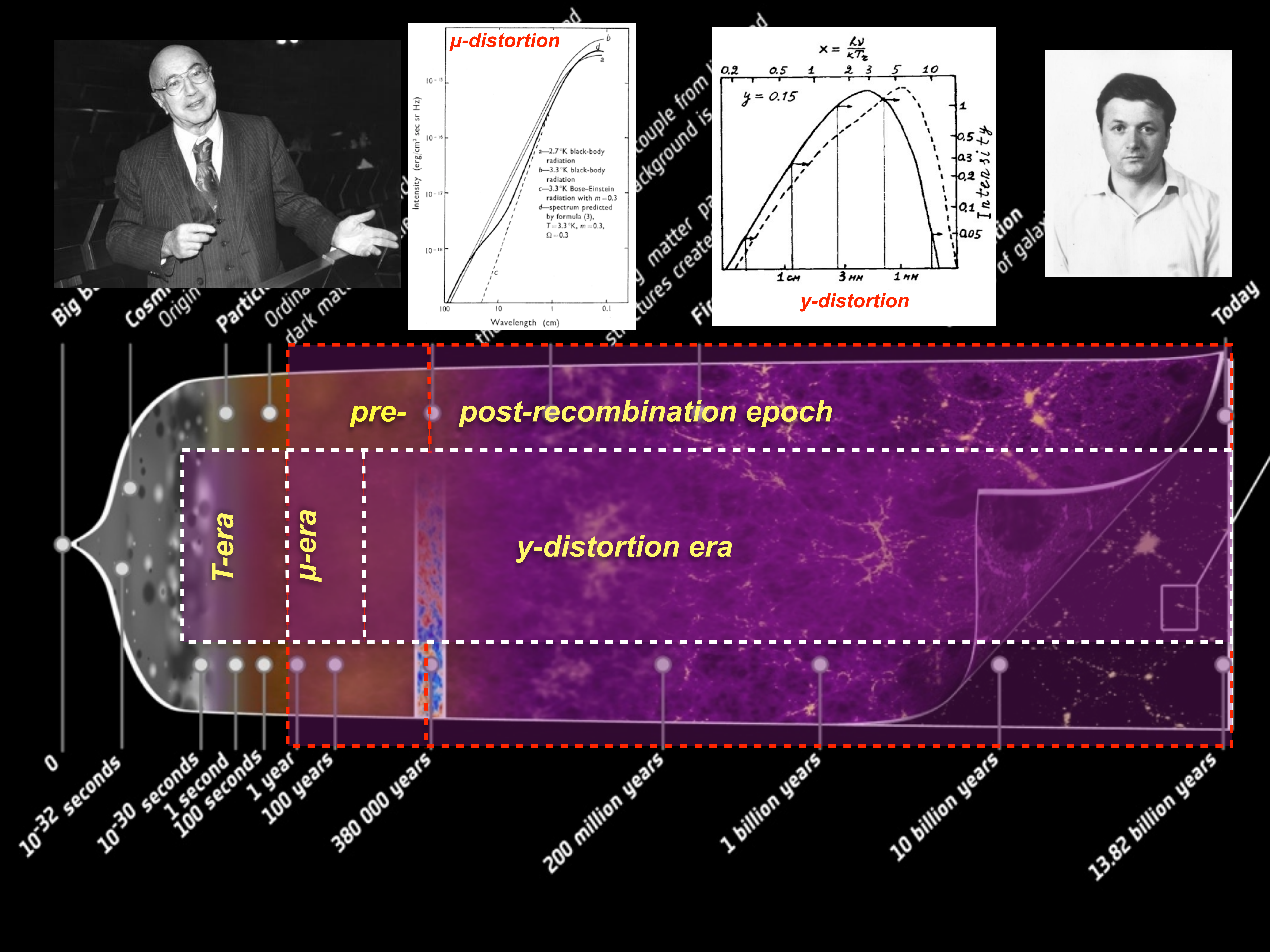
Figure from Wayne Hu's PhD thesis, 1995, but see also discussion in Burigana, 1991

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!


μ-distortion
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y = 0.15
Intensity
y-distortion
Today
pre-
post-recombination epoch
T-era
μ-era
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0
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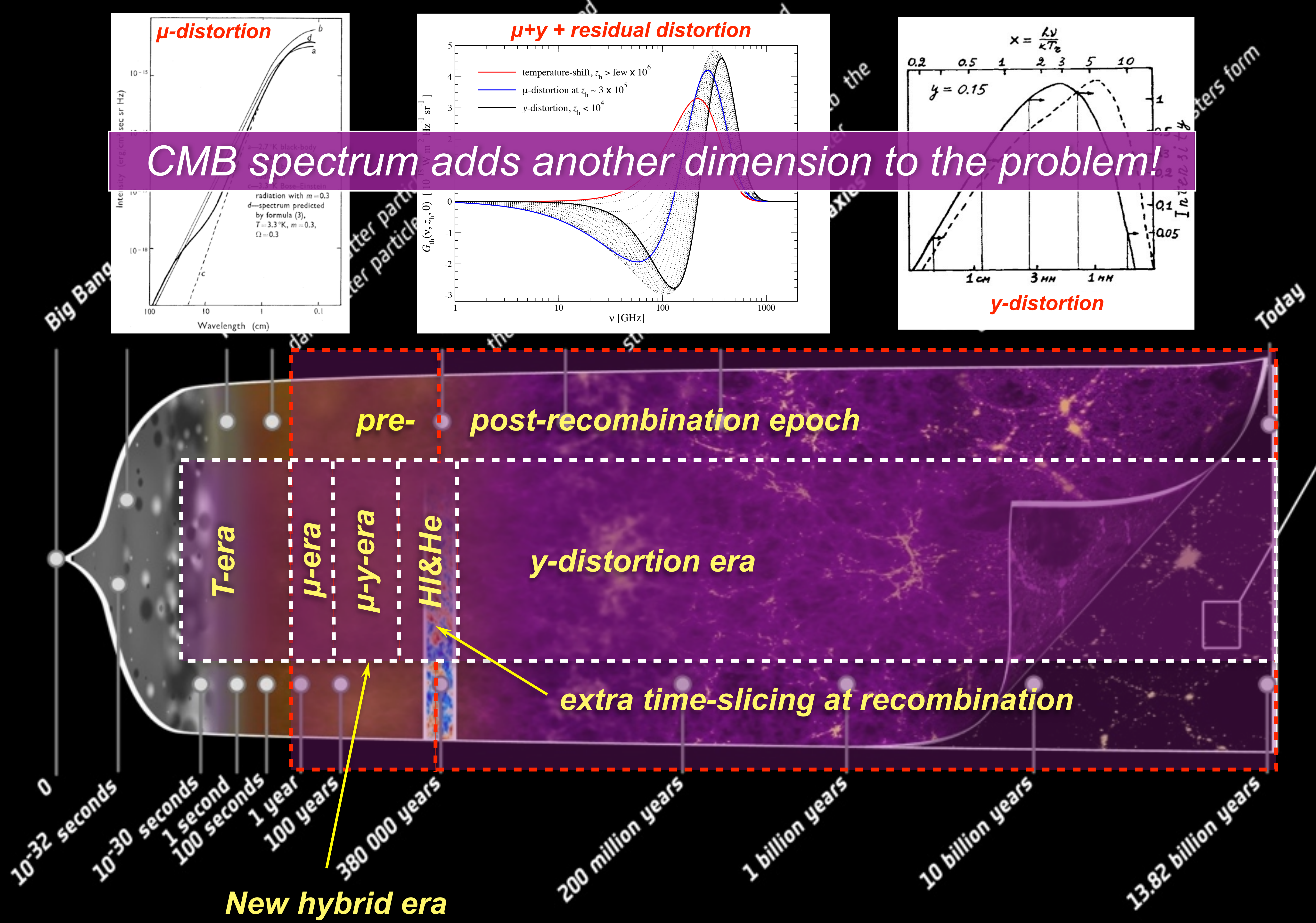
CMB spectrum adds another dimension to the problem!
μ-distortion
Intensity (erg cm⁻² sec sr Hz)
Wavelength (cm)
μ+y + residual distortion
temperature-shift, z_h > few x 10^6
μ-distortion at z_h ~ 3 x 10^5
y-distortion, z_h < 10^4
ν [GHz]
y-distortion
y = 0.15
Big Bang
Today
pre-
post-recombination epoch
T-era
μ-era
μ-y-era
HI&He
y-distortion era
extra time-slicing at recombination
0
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380 000 years
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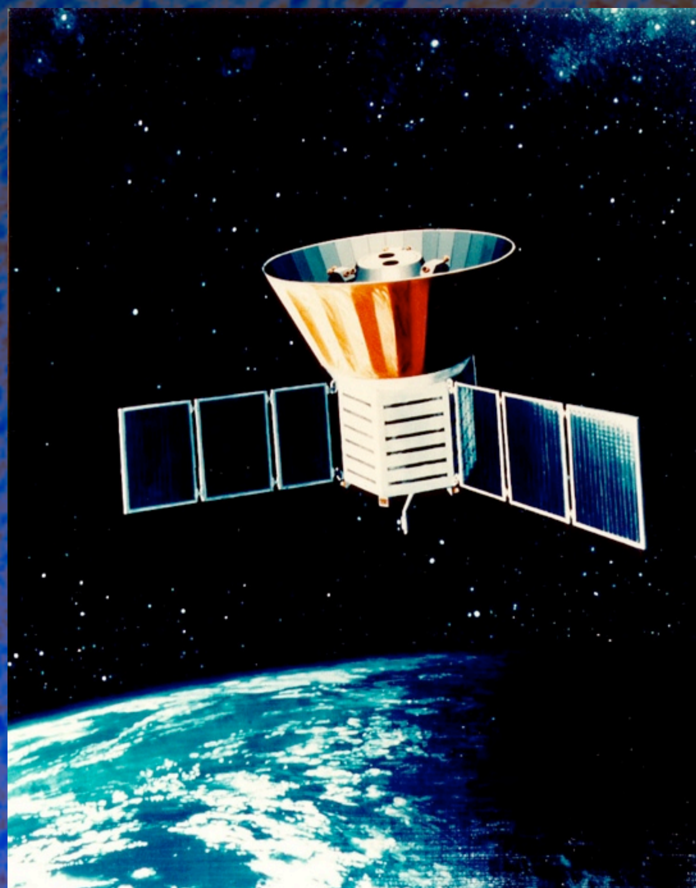
10 billion years
13.82 billion years
New hybrid era

COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)



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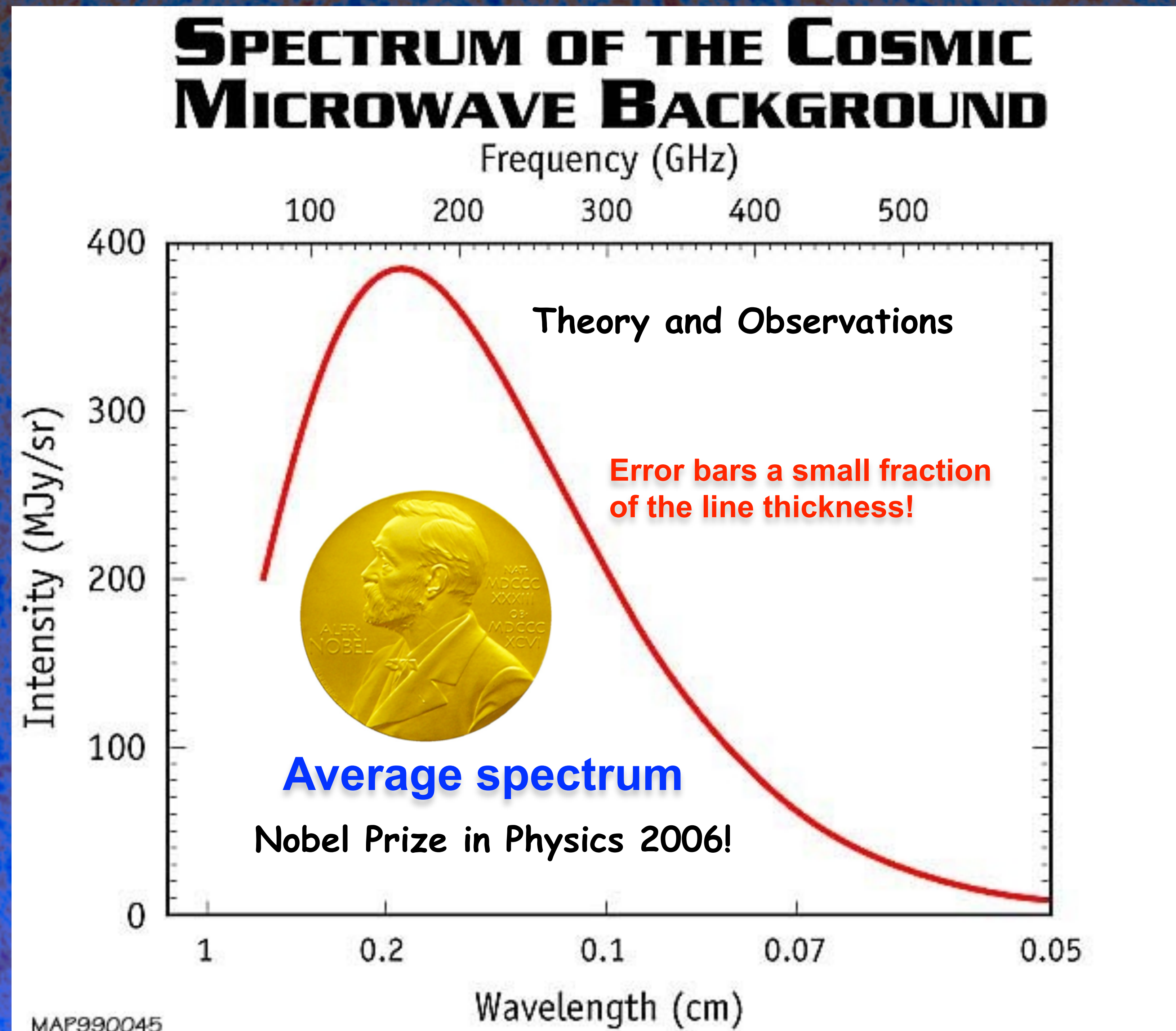

Only very small distortions of CMB spectrum are still allowed!

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)
- more 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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„high“ redshifts ↑ ***pre-recombination epoch***

„low“ redshifts ↓ ***post-recombination***

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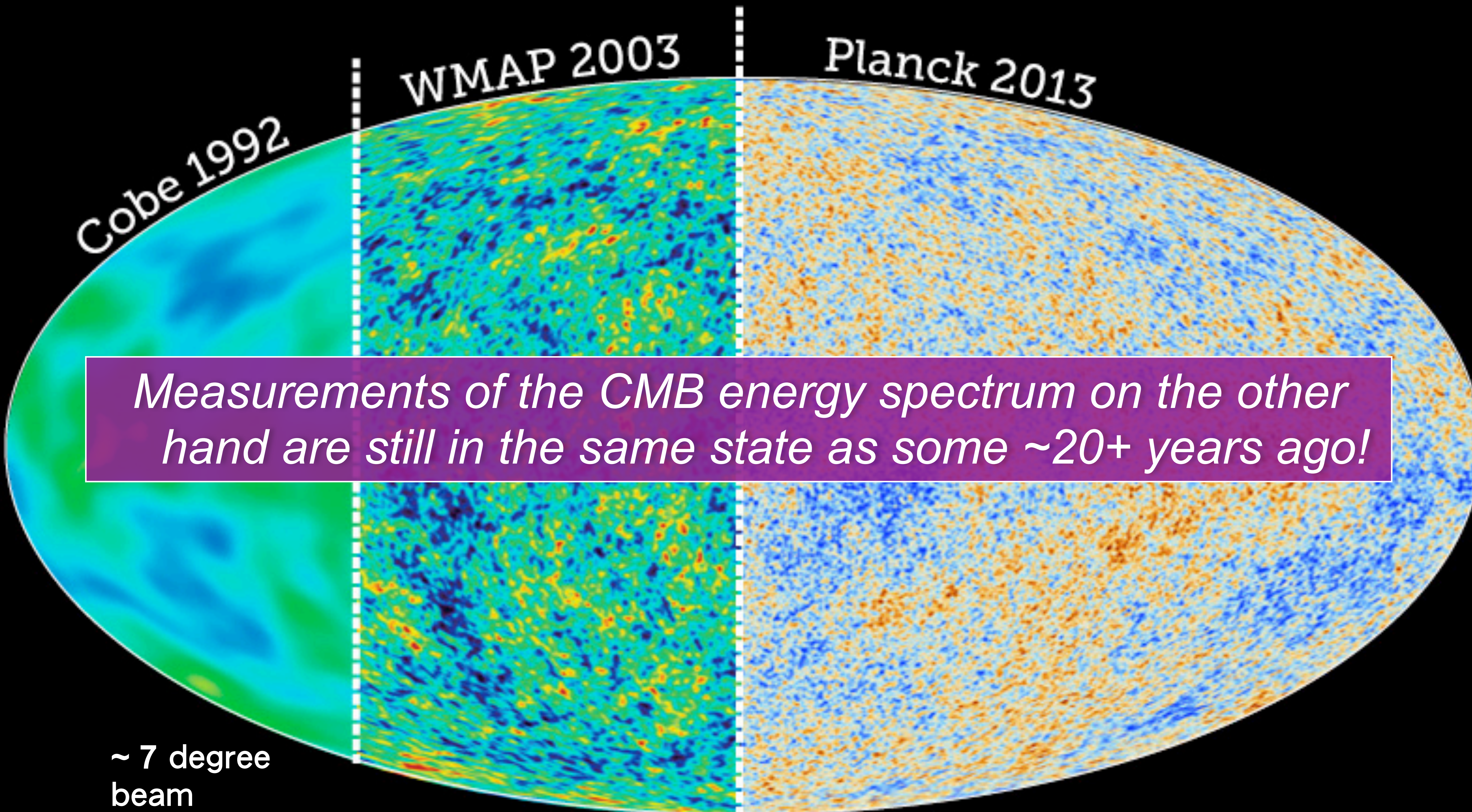
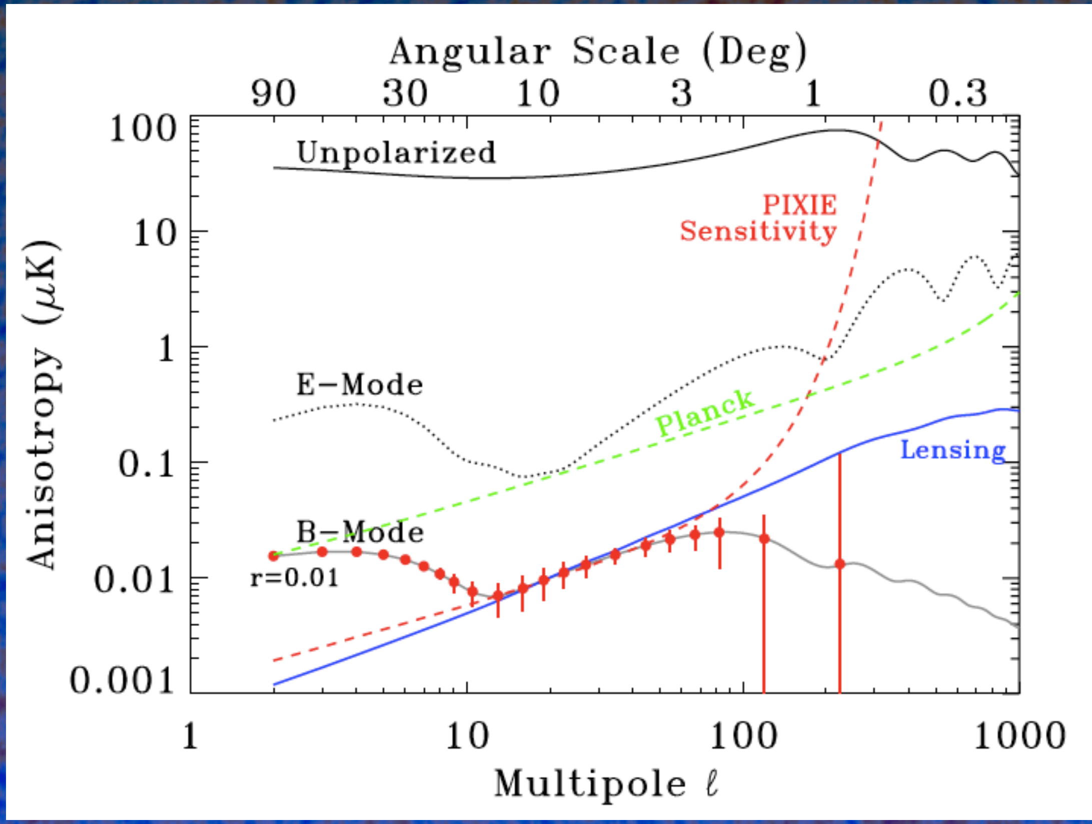
Dramatic improvements in angular resolution and sensitivity over the past decades!

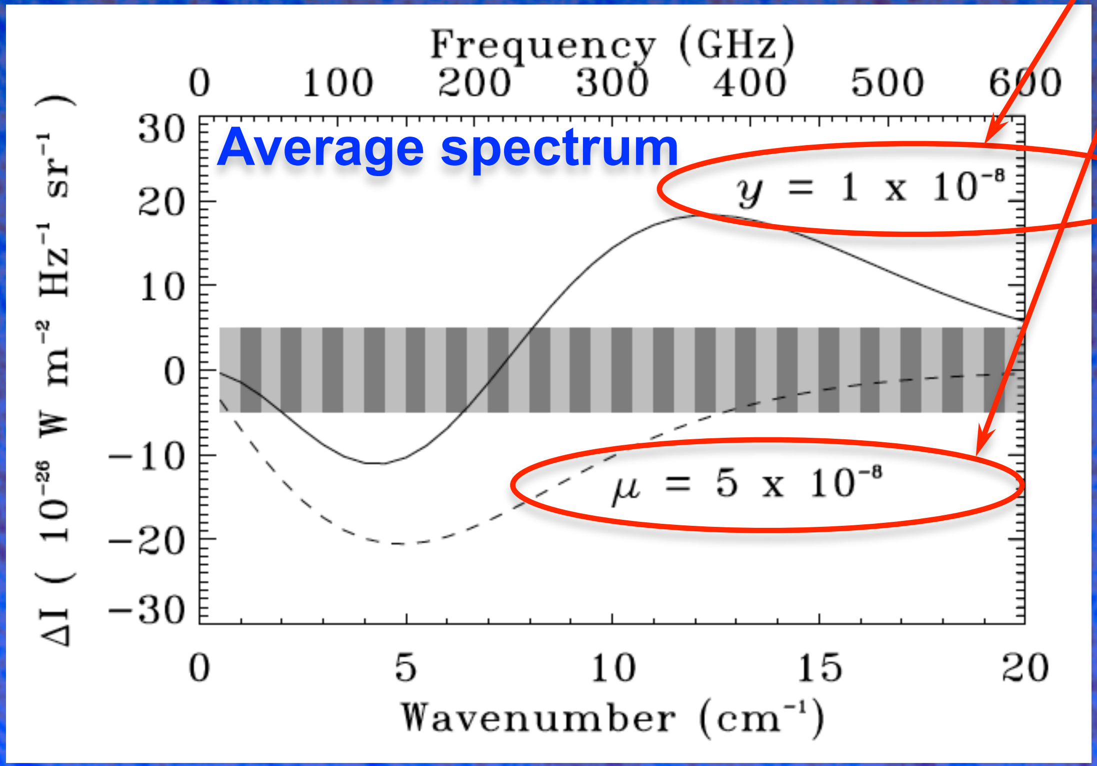


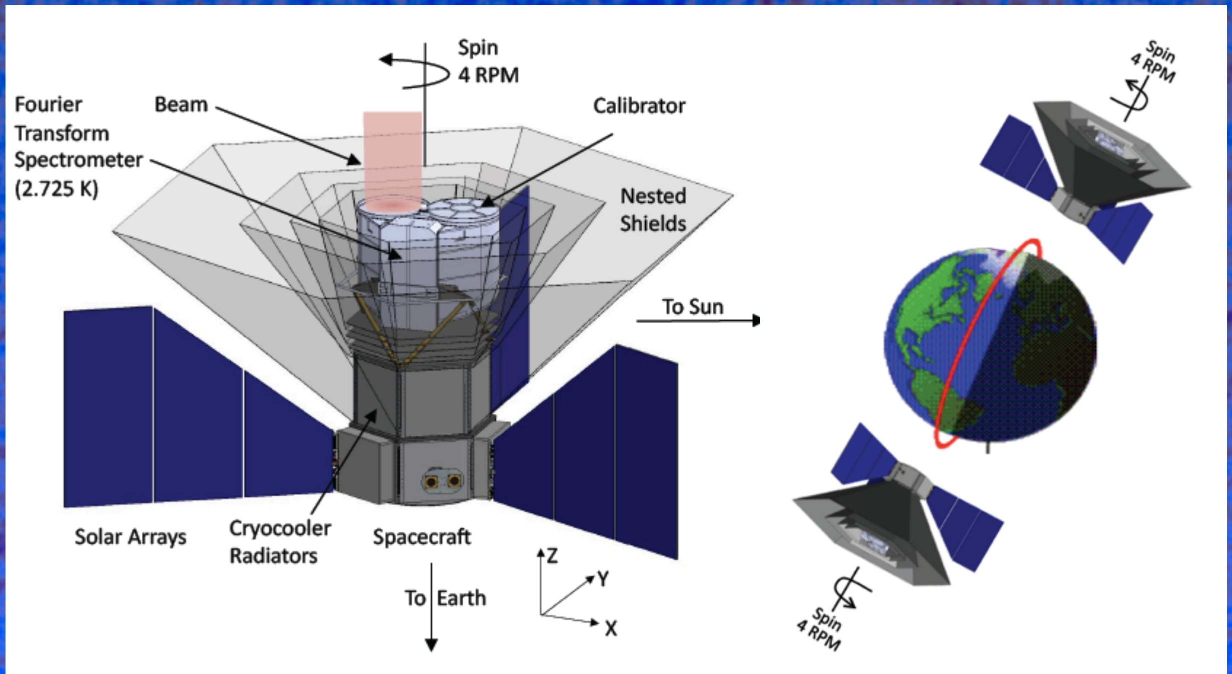
Measurements of the CMB energy spectrum on the other hand are still in the same state as some ~20+ years ago!

PIXIE: Primordial Inflation Explorer

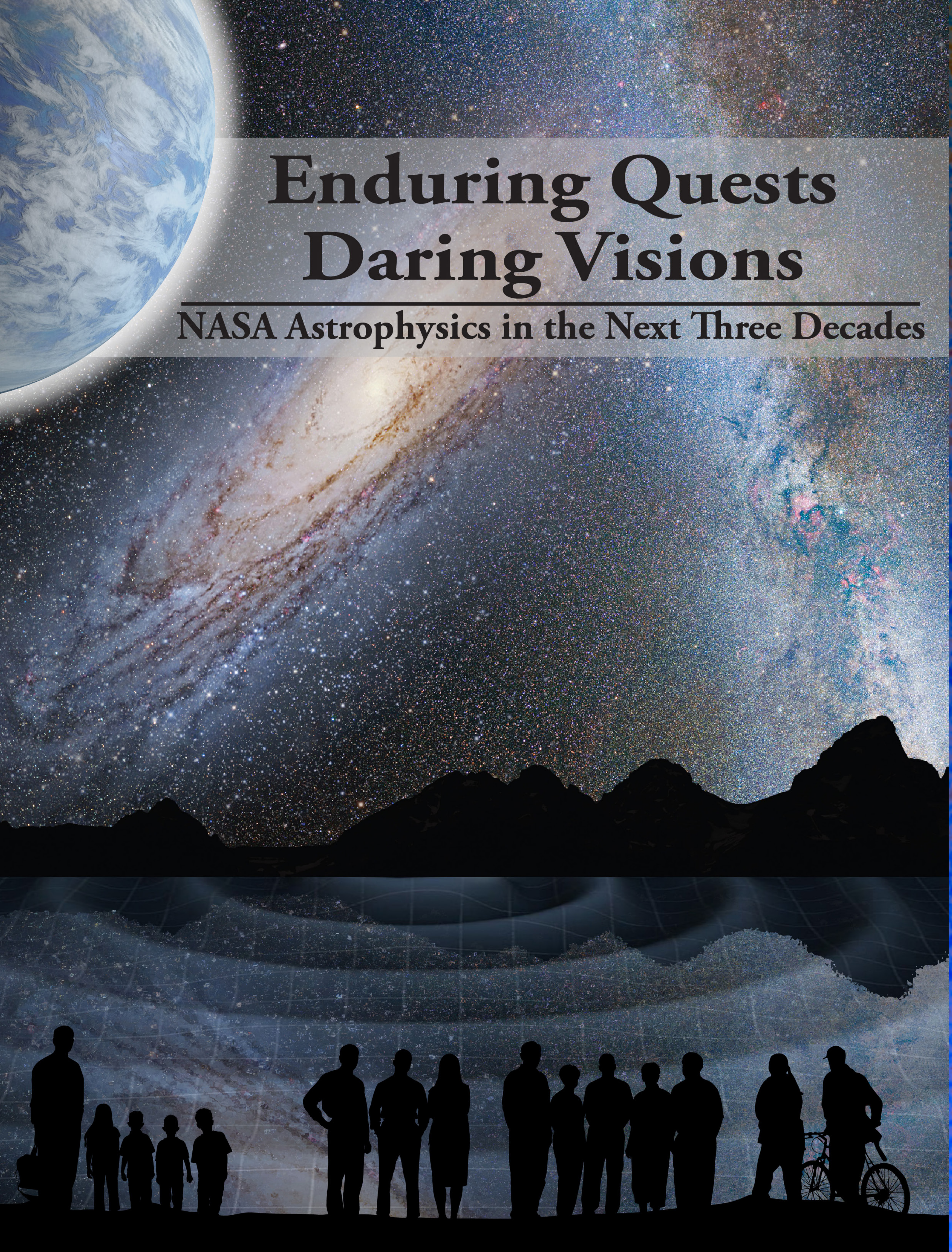


- 400 spectral channel in the frequency range 30 GHz and 6THz (Δv ~ 15GHz)
- about 1000 (!!!) times more sensitive than COBE/FIRAS
- B-mode polarization from inflation ($r \approx 10^{-3}$)
- improved limits on μ and y
- was proposed 2011 as NASA EX mission (i.e. cost ~ 200 M$)





Kogut et al, JCAP, 2011, arXiv:1105.2044



NASA 30-yr Roadmap Study

(published Dec 2013)

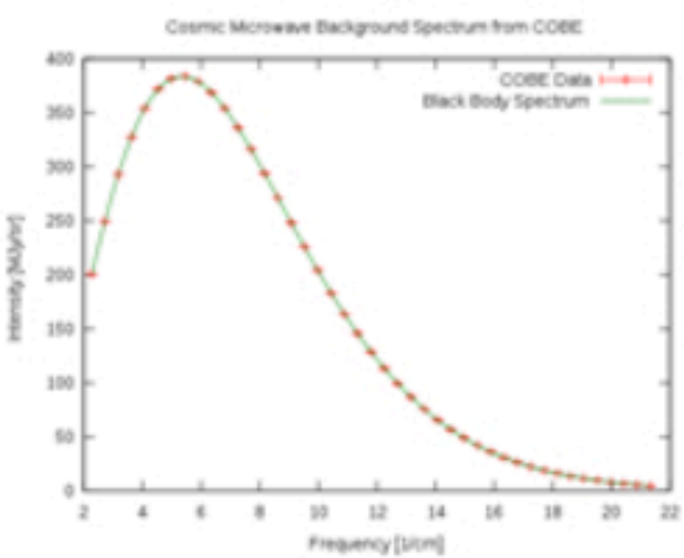
How does the Universe work?

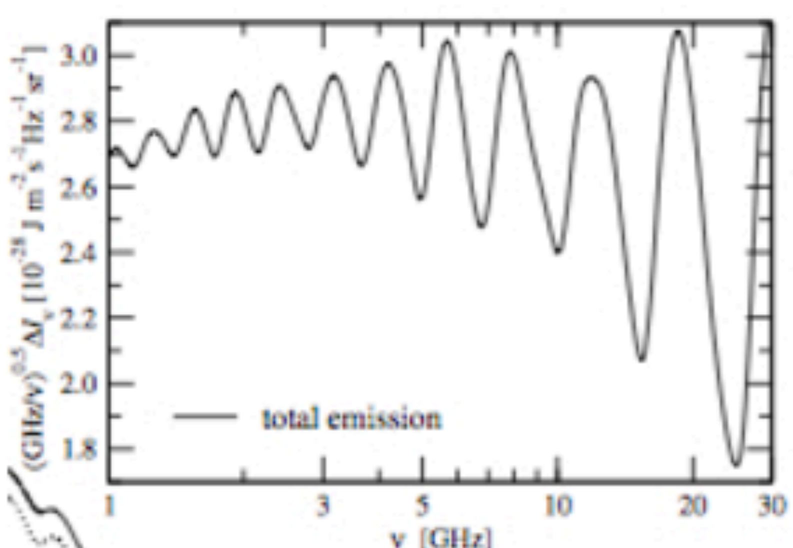
"Measure the spectrum of the CMB with precision several orders of magnitude higher than COBE FIRAS, from a moderate-scale mission or an instrument on CMB Polarization Surveyor."

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

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.

Physical mechanisms that lead to spectral distortions

Standard sources of distortions

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

pre-recombination epoch

„high" redshifts

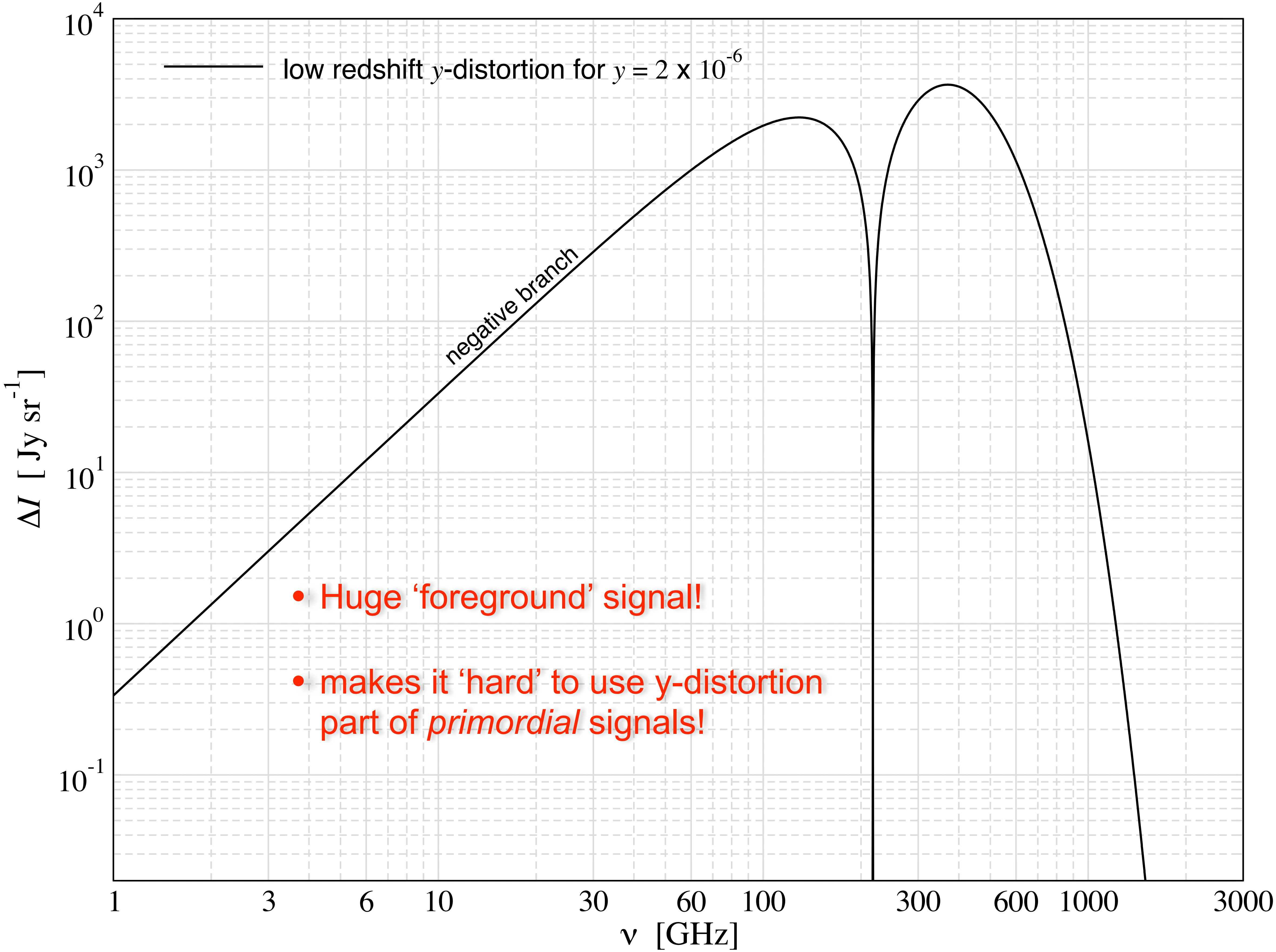
„low" redshifts

post-recombination

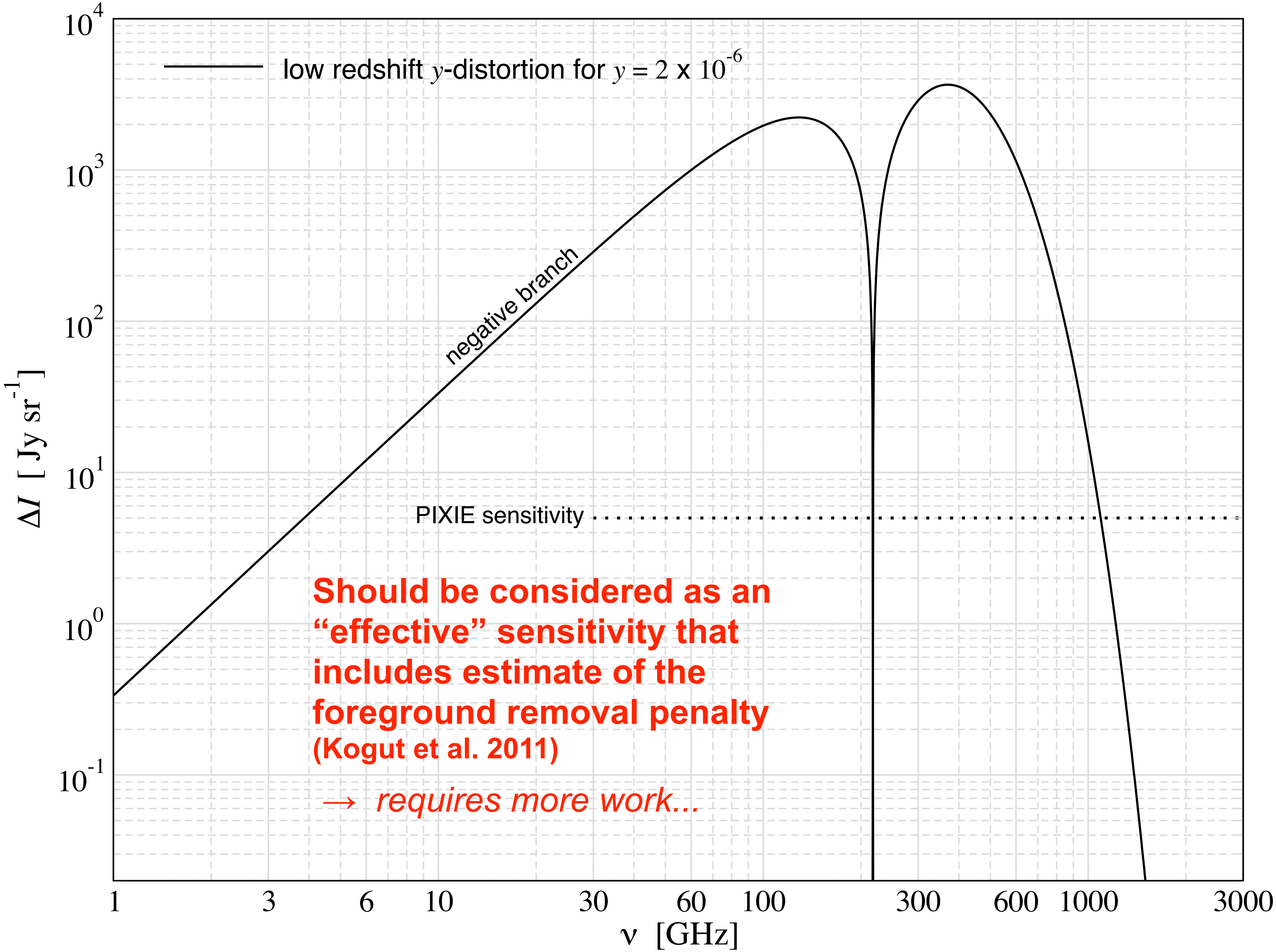
- Signatures due to first supernovae and their remnants
  (Oh, Cooray & Kamionkowski, 2003)
- Shock waves arising due to large-scale structure formation
  (Sunyaev & Zeldovich, 1972; Cen & Ostriker, 1999)
- SZ-effect from clusters; effects of reionization
  (Refregier et al., 2003; Zhang et al. 2004;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

Reionization and structure formation

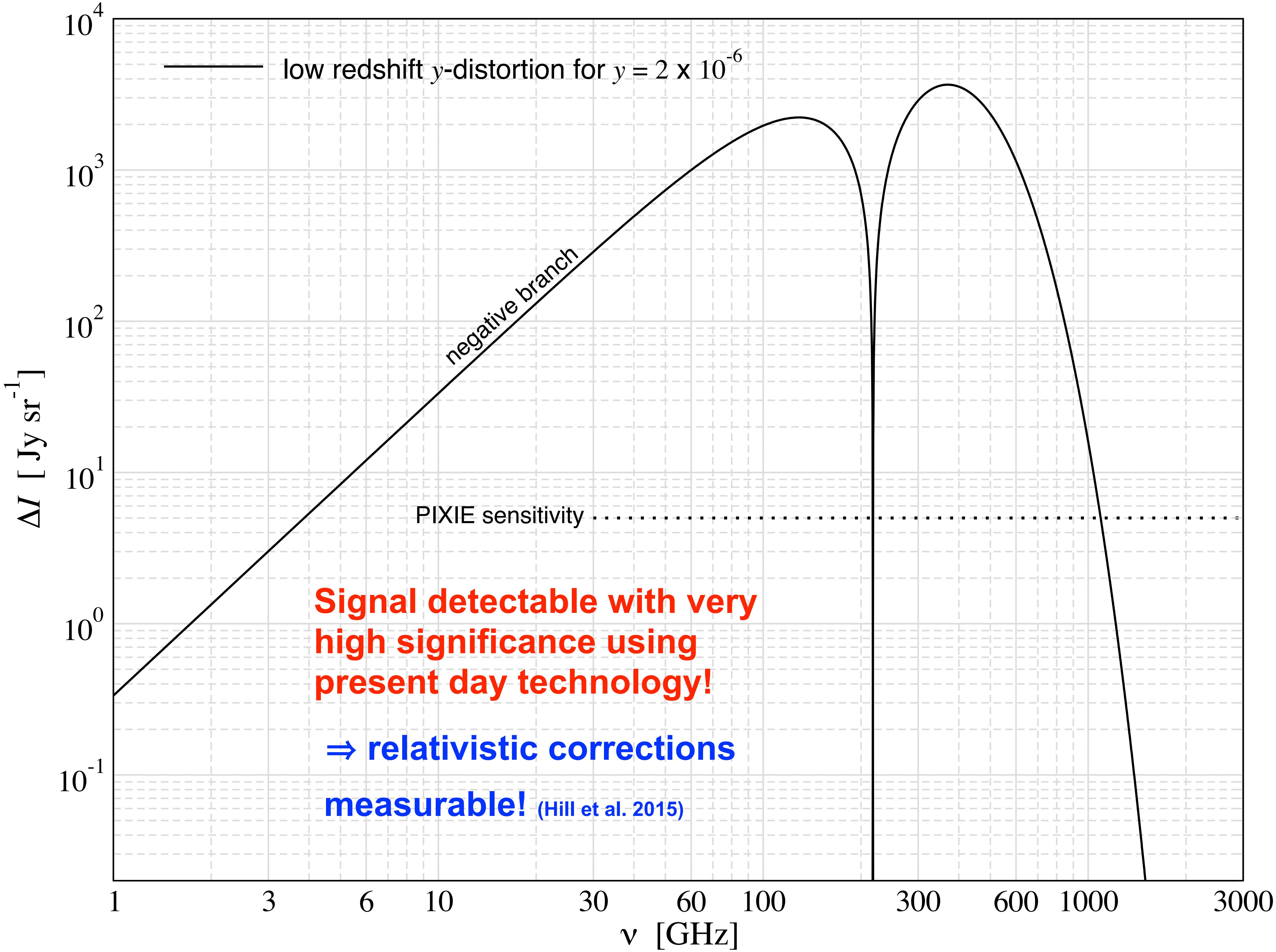
Average CMB spectral distortions



Average CMB spectral distortions



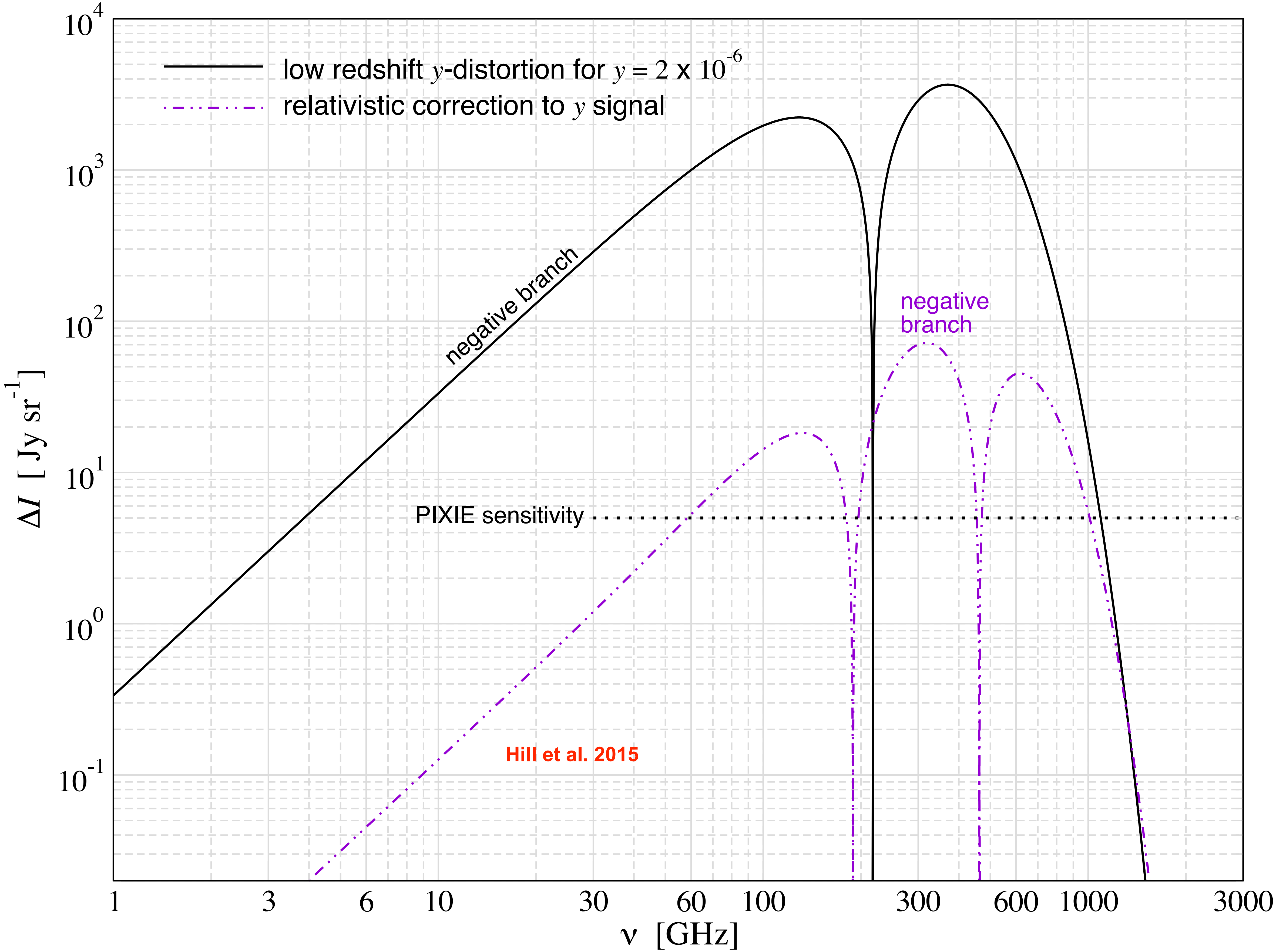
Average CMB spectral distortions



Signal detectable with very high significance using present day technology!

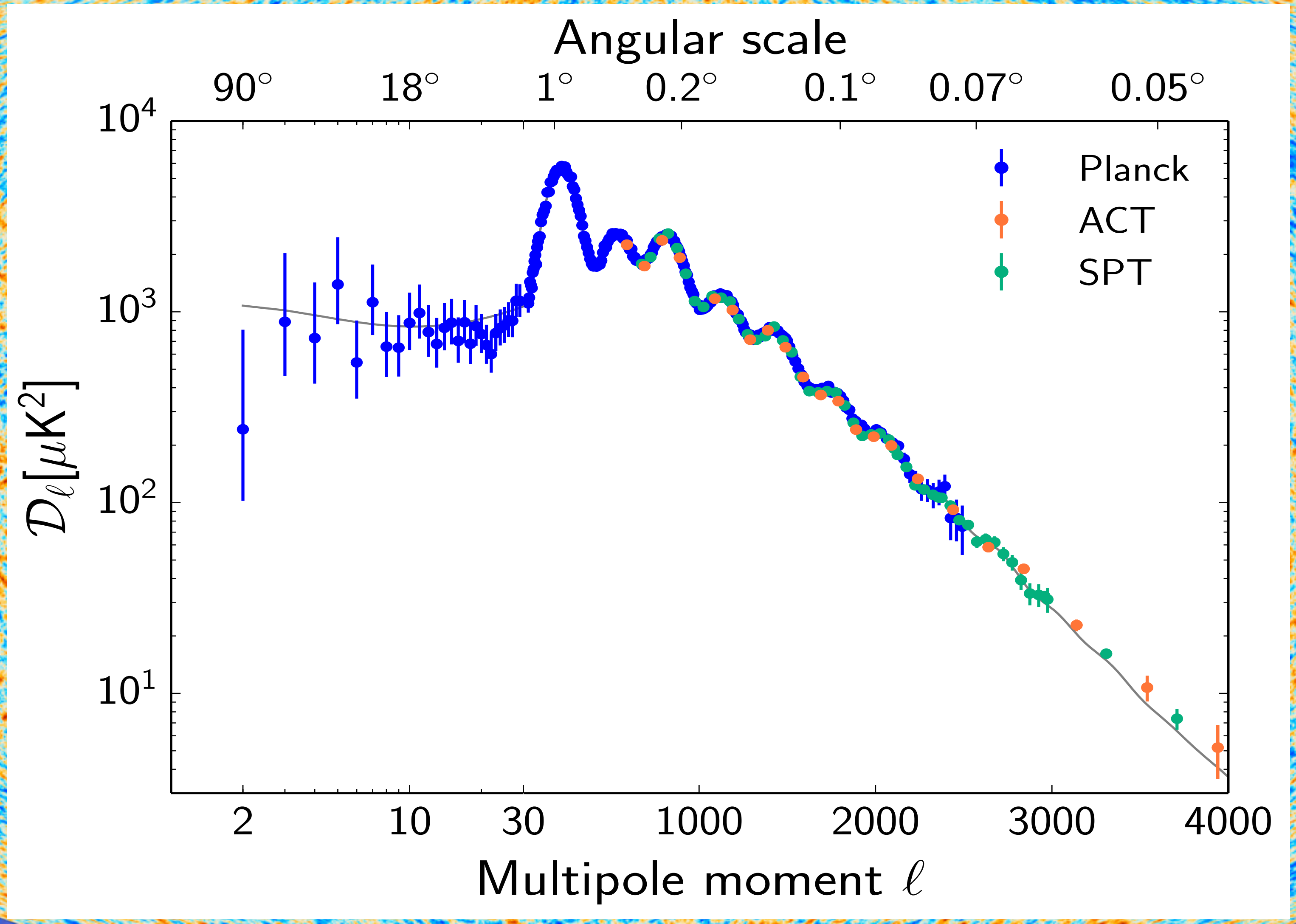
⇒ relativistic corrections measurable! **(Hill et al. 2015)**

Average CMB spectral distortions

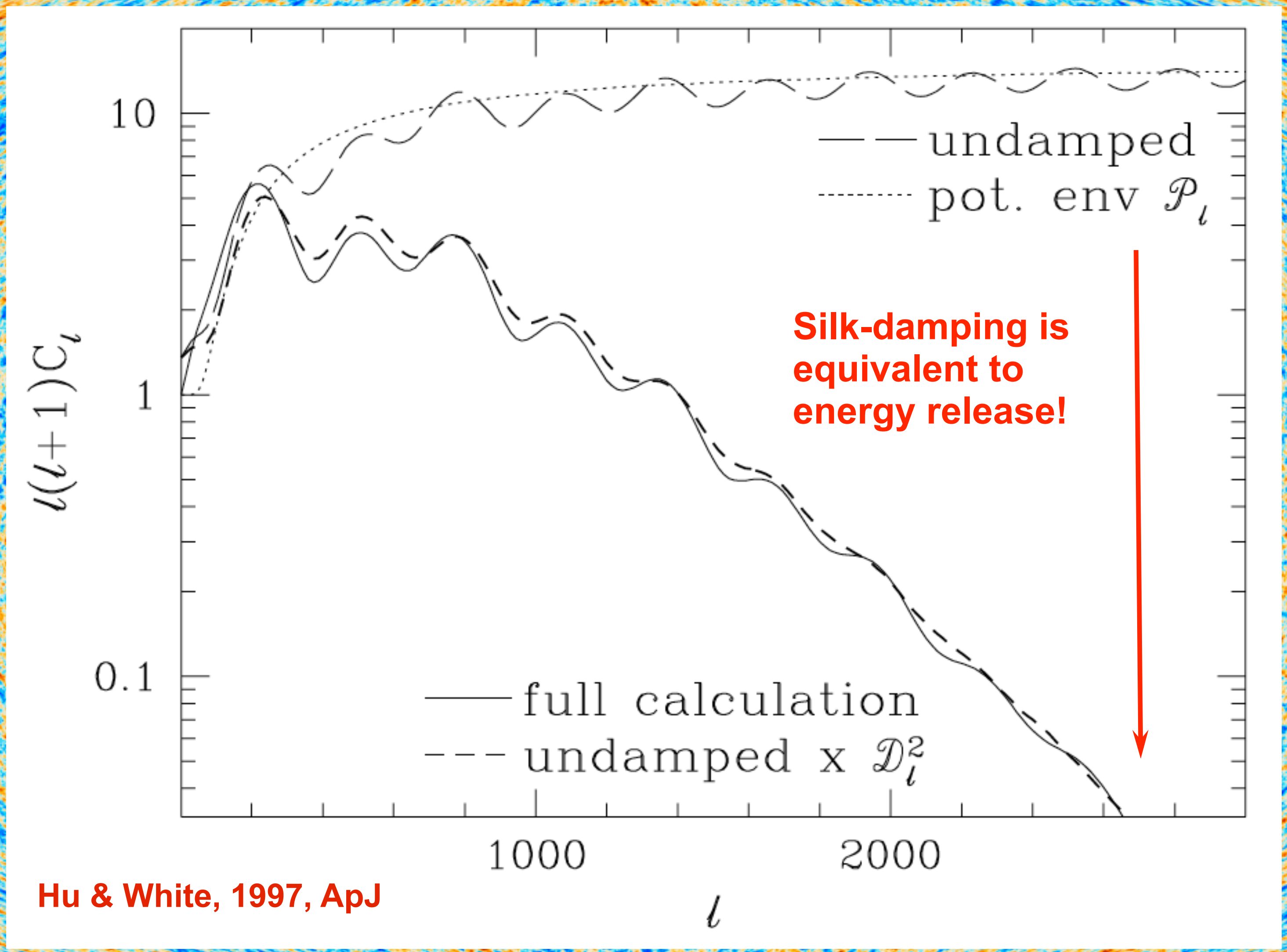


The dissipation of small-scale acoustic modes

Dissipation of small-scale acoustic modes



Dissipation of small-scale acoustic modes



Energy release caused by dissipation process

'Obvious' dependencies:

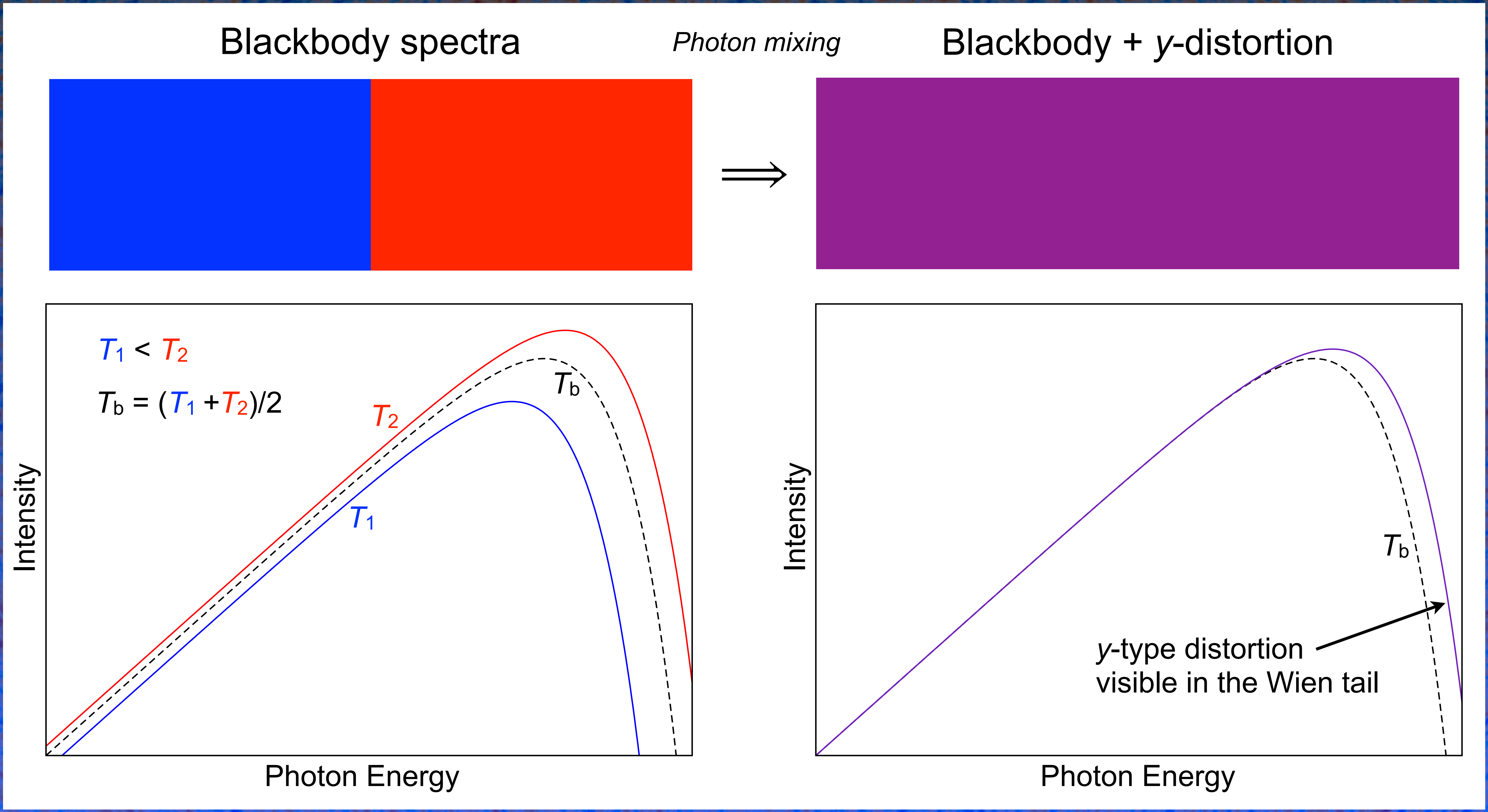
- *Amplitude* of the small-scale power spectrum
- *Shape* of the small-scale power spectrum
- *Dissipation scale* → $k_D \sim (H_0\, \Omega_{rel}^{1/2}\, N_{e,0})^{1/2}\, (1+z)^{3/2}$ at early times

not so 'obvious' dependencies:

- *primordial non-Gaussianity* in the ultra squeezed limit
  (Pajer & Zaldarriaga, 2012; Ganc & Komatsu, 2012)
- *Type* of the perturbations (adiabatic ↔ isocurvature)
  (Barrow & Coles, 1991; Hu et al., 1994; Dent et al, 2012, JC & Grin, 2012)
- *Neutrinos* (or any extra relativistic degree of freedom)

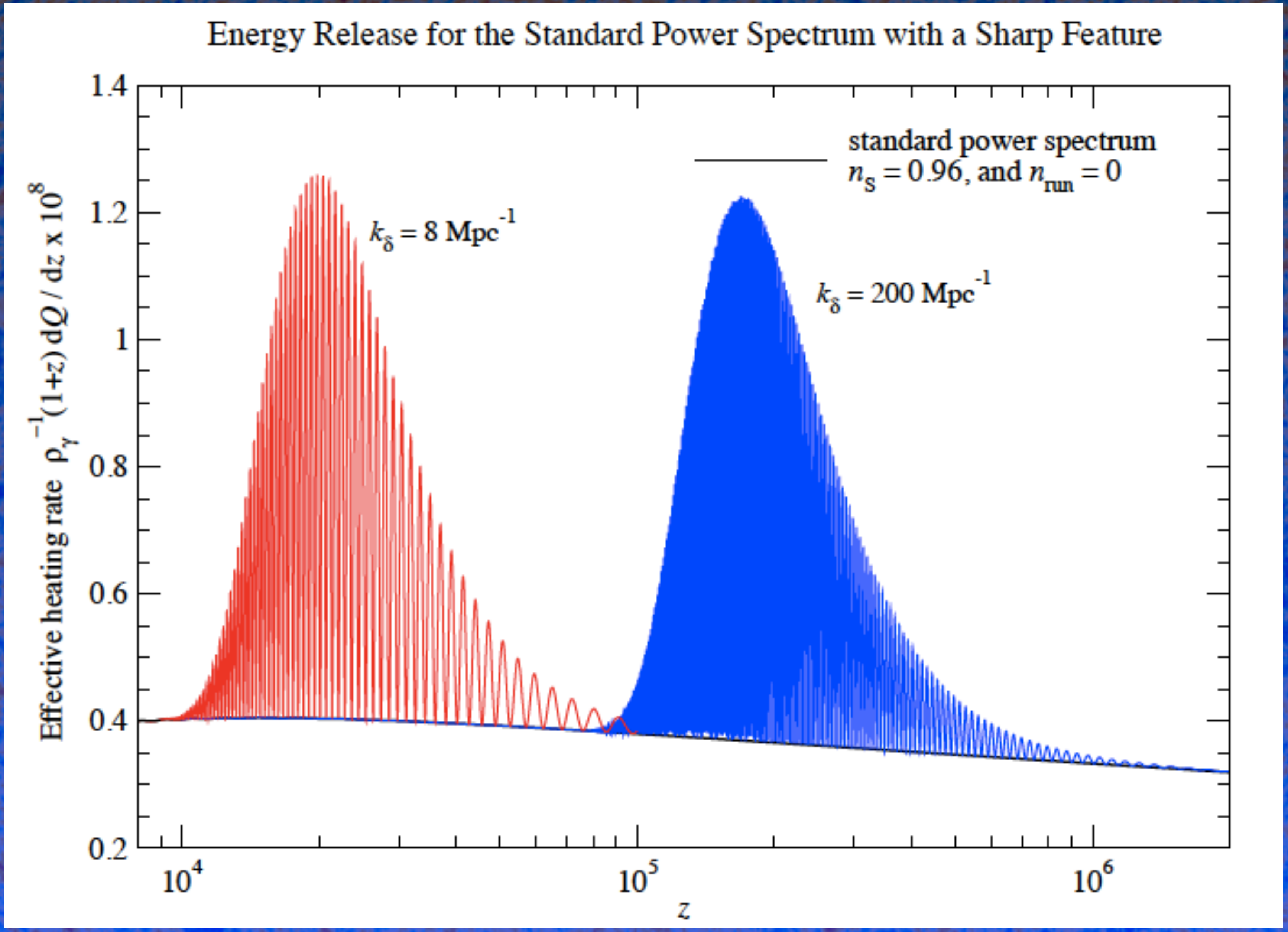
CMB Spectral distortions could add additional numbers beyond 'just' the tensor-to-scalar ratio from B-modes!

Distortion due to mixing of blackbodies



JC, Hamann & Patil, 2015

Which modes dissipate in the μ and y-eras?



JC, Erickcek & Ben-Dayan, 2012

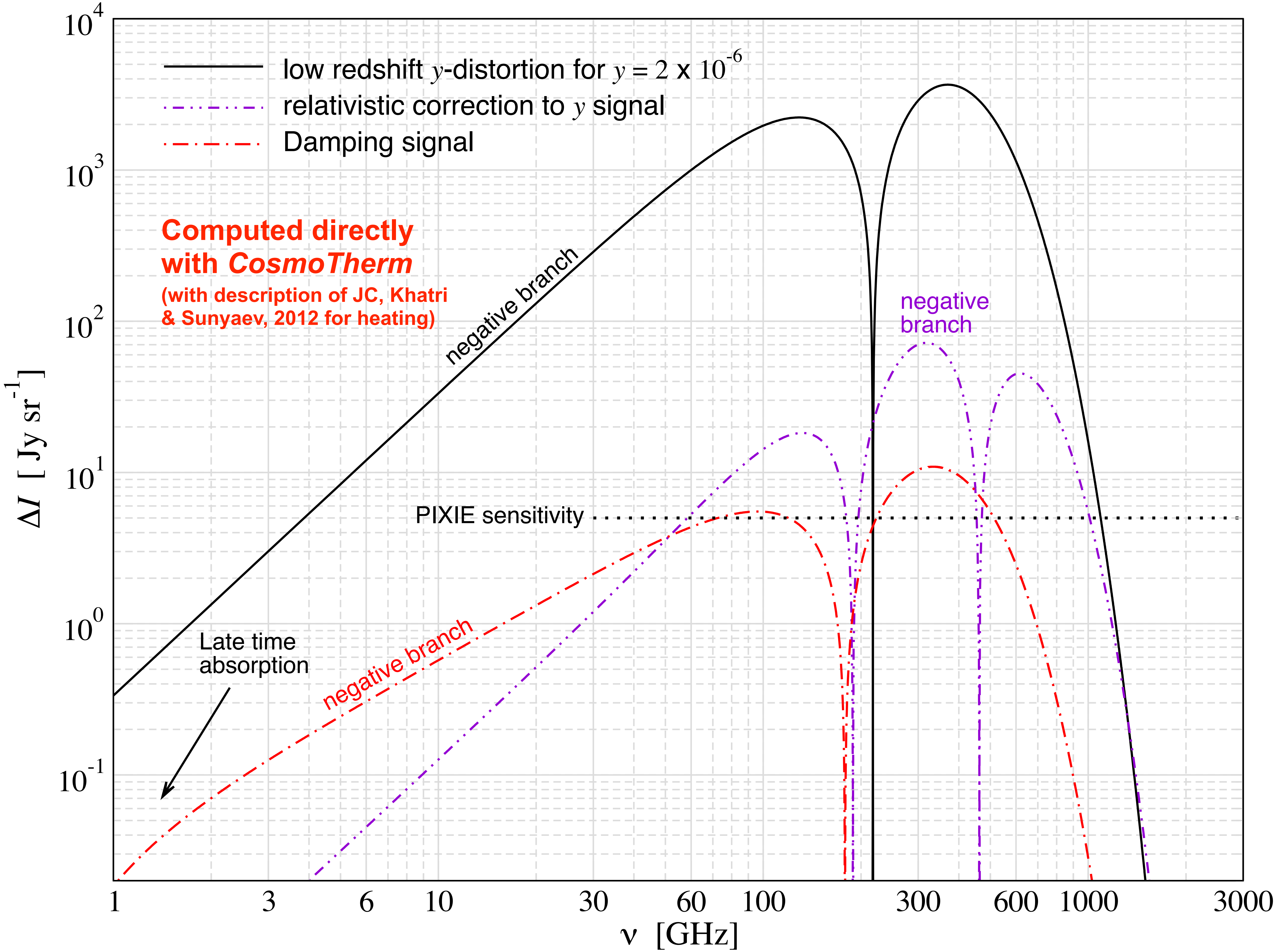
- Single mode with wavenumber *k* dissipates its energy at

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

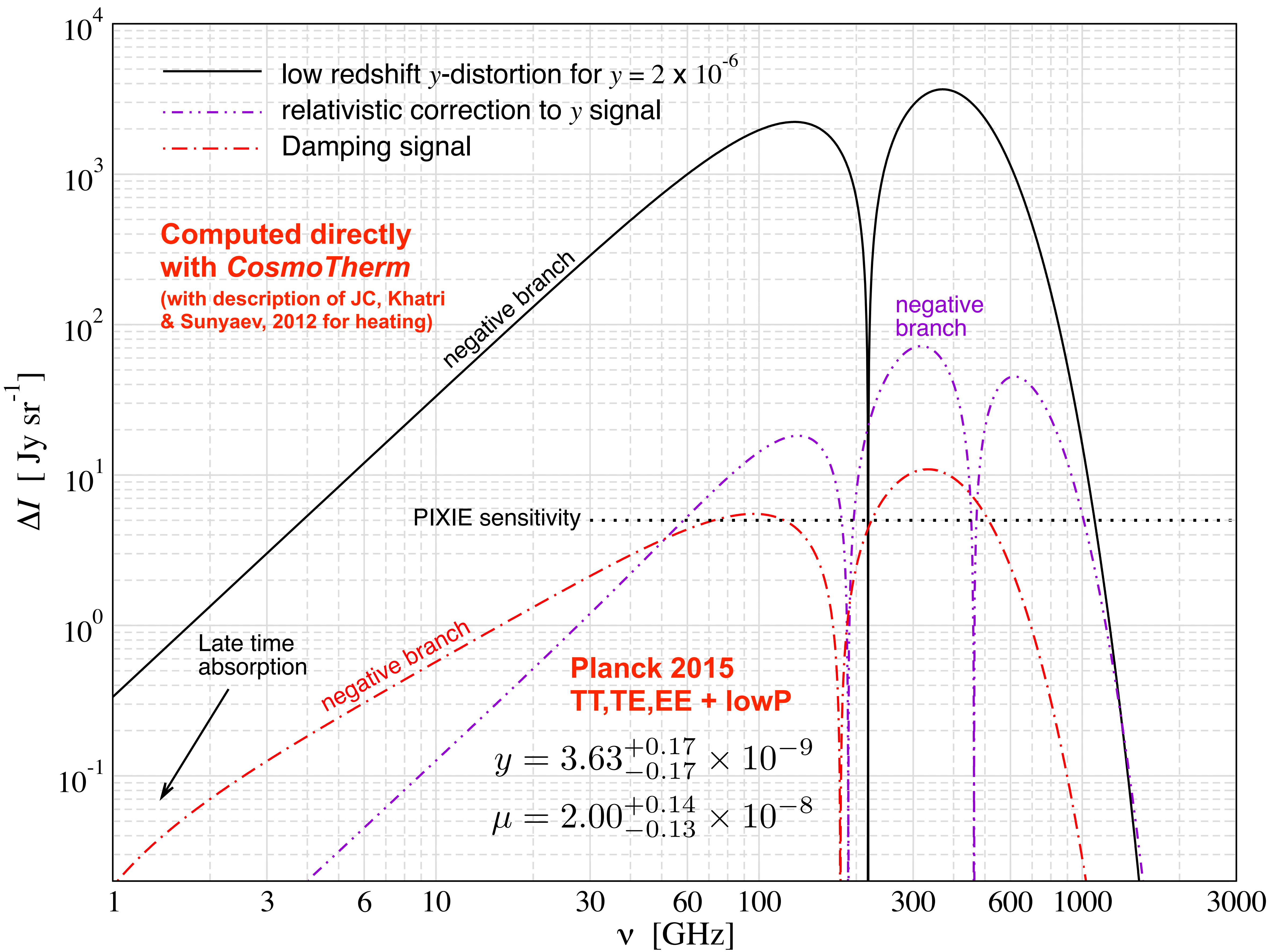
- Modes with wavenumber $50\ \text{Mpc}^{-1} < k < 10^4\ \text{Mpc}^{-1}$ dissipate their energy during the *μ*-era

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

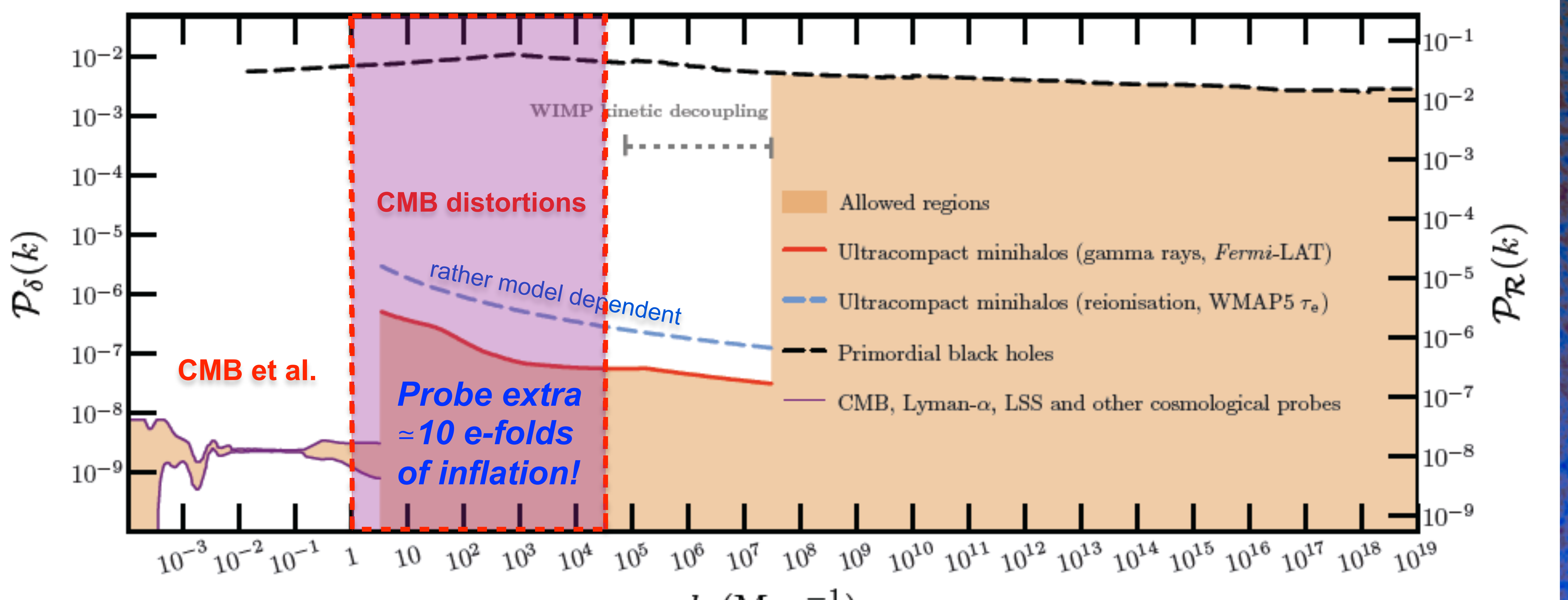
Average CMB spectral distortions



Average CMB spectral distortions



Distortions provide general power spectrum constraints!

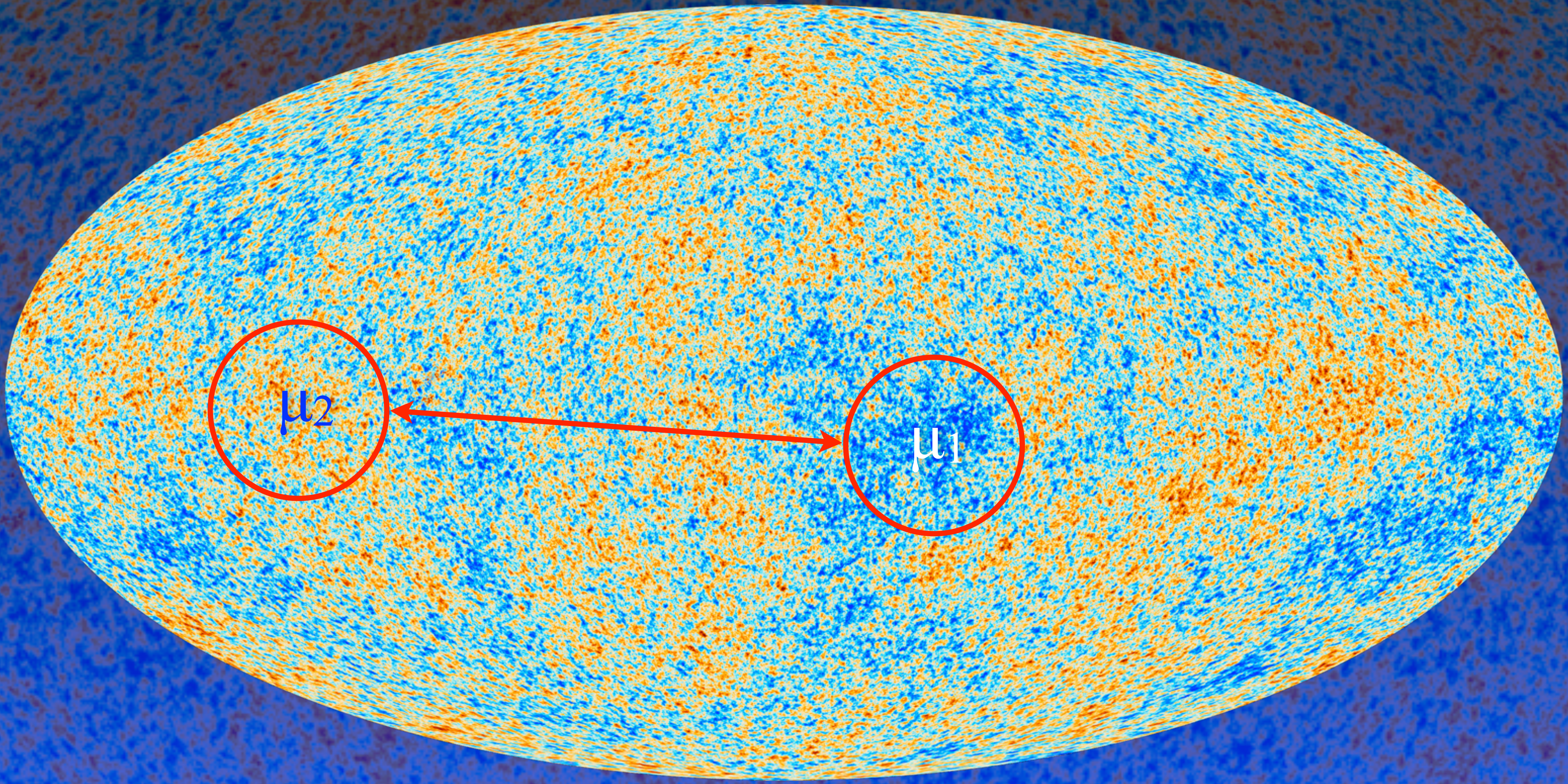


Bringmann, Scott & Akrami, 2011, ArXiv:1110.2484

- 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

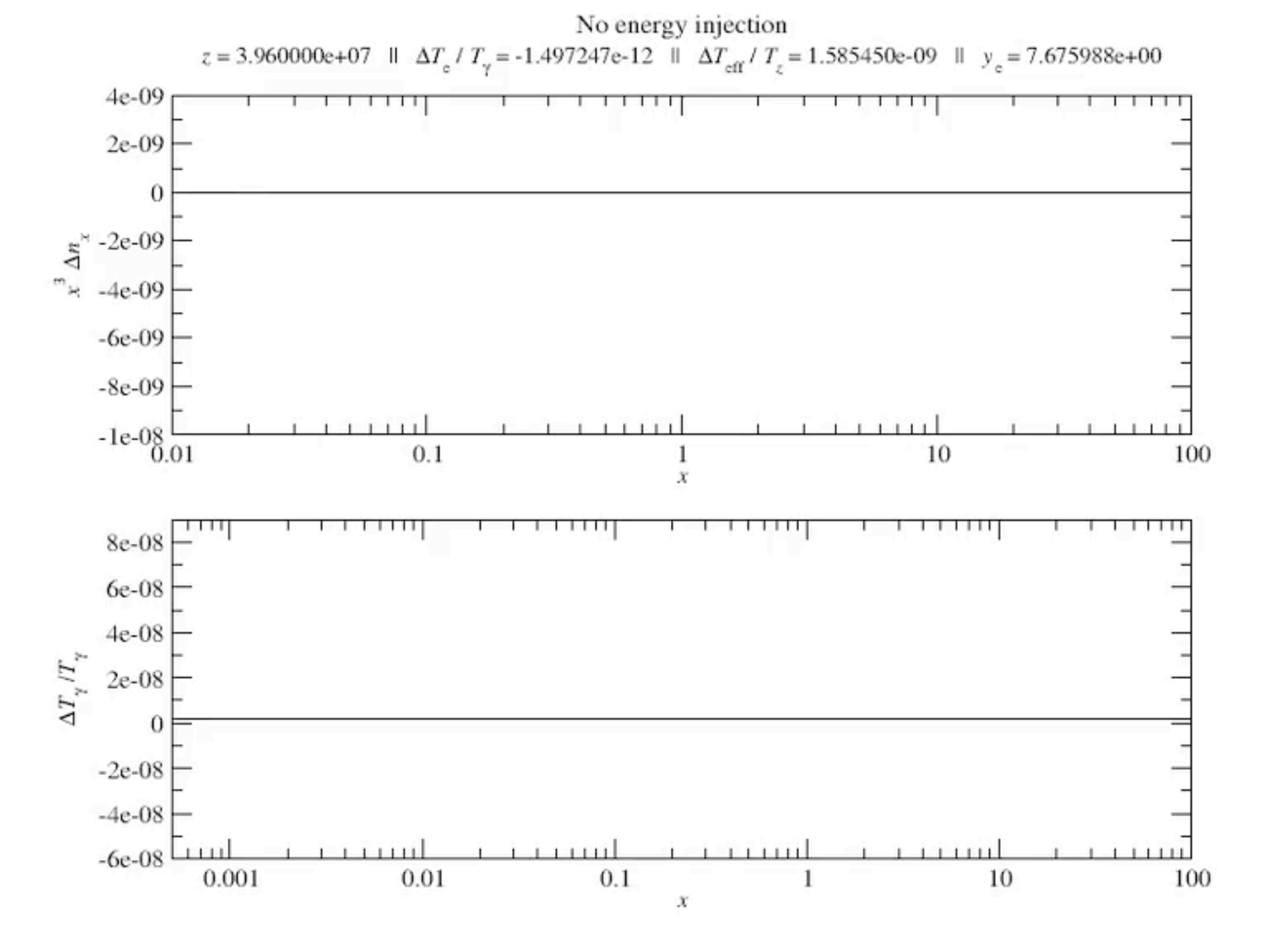
Spatially varying heating and dissipation of acoustic modes for non-Gaussian perturbations



- 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



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

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

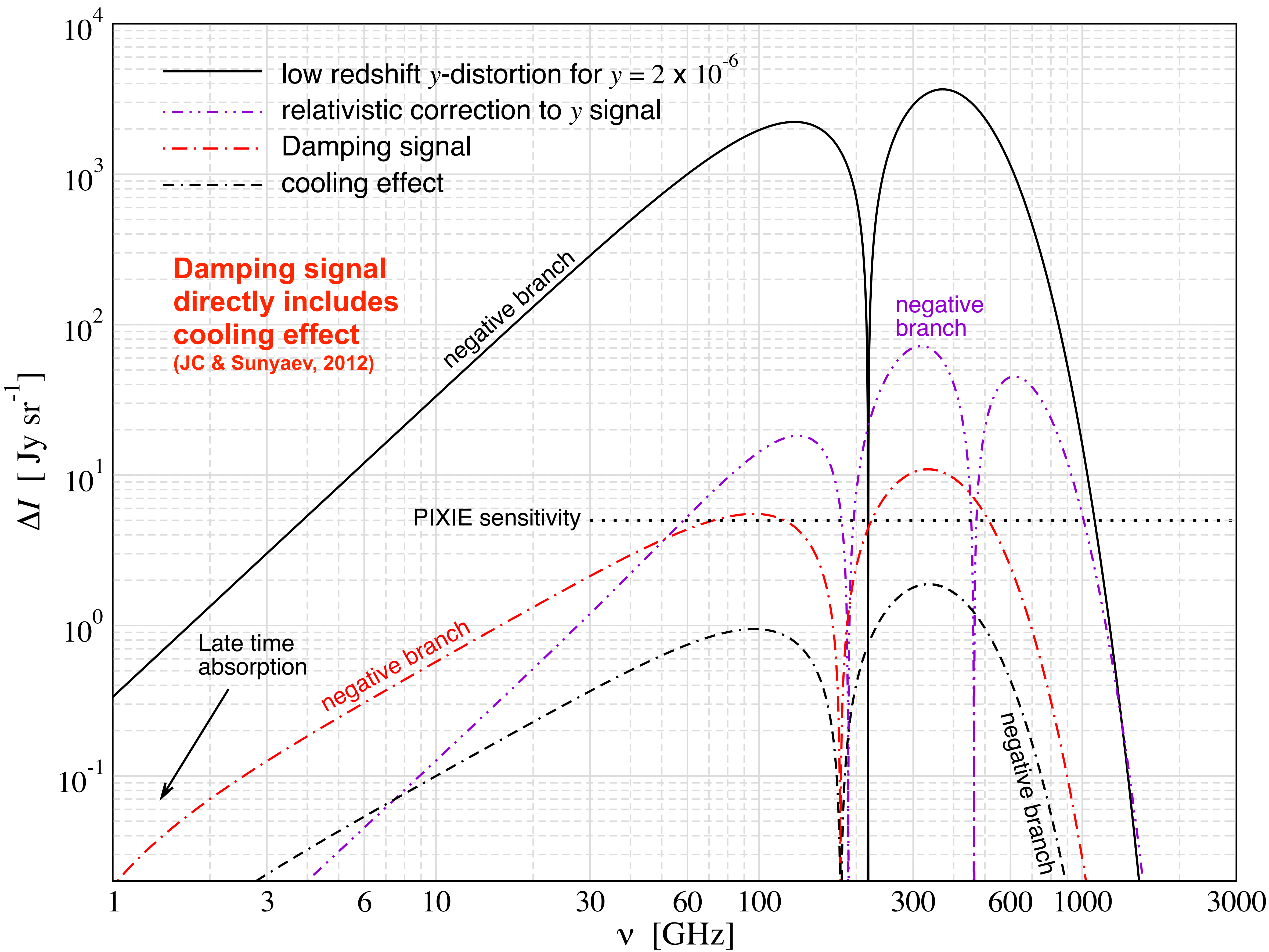
$$\Rightarrow \frac{\mathrm{d}a^4\rho_\gamma}{a^4\mathrm{d}t} \simeq -Hk\alpha_\mathrm{h}T_\gamma \propto (1+z)^6$$

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

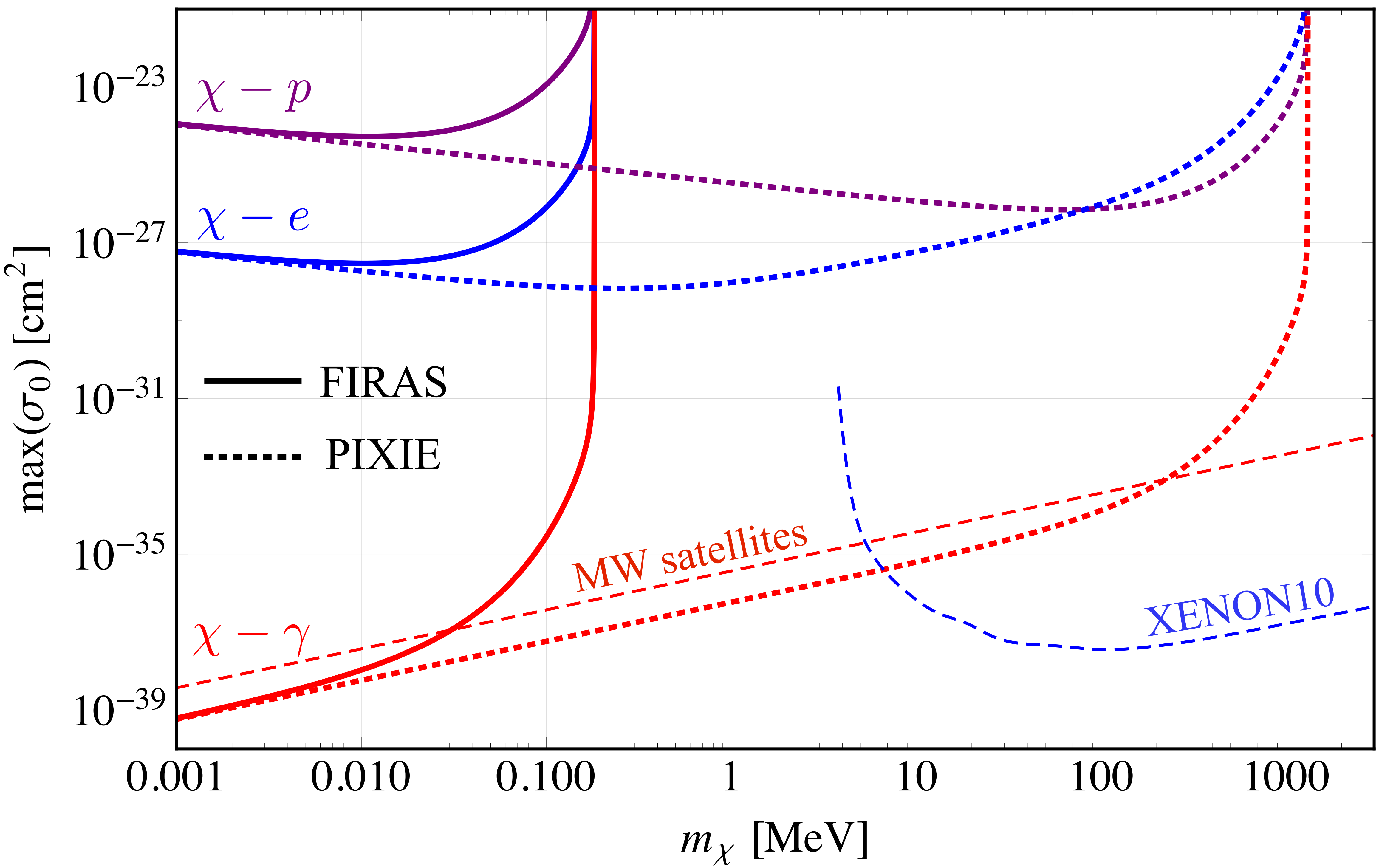
⇒ partial *cancellation*

- *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

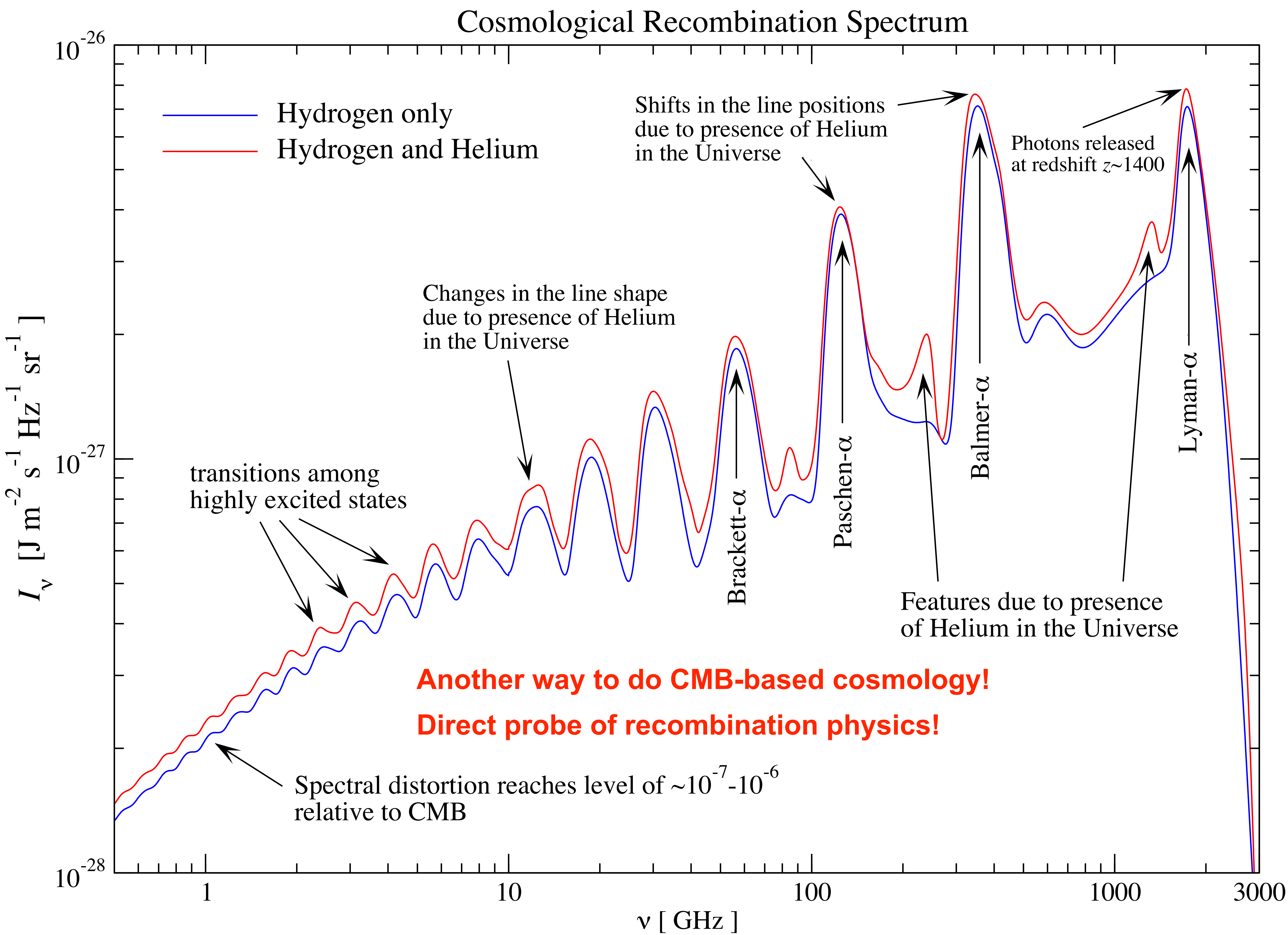


Distortion constraints on DM interactions through cooling effect



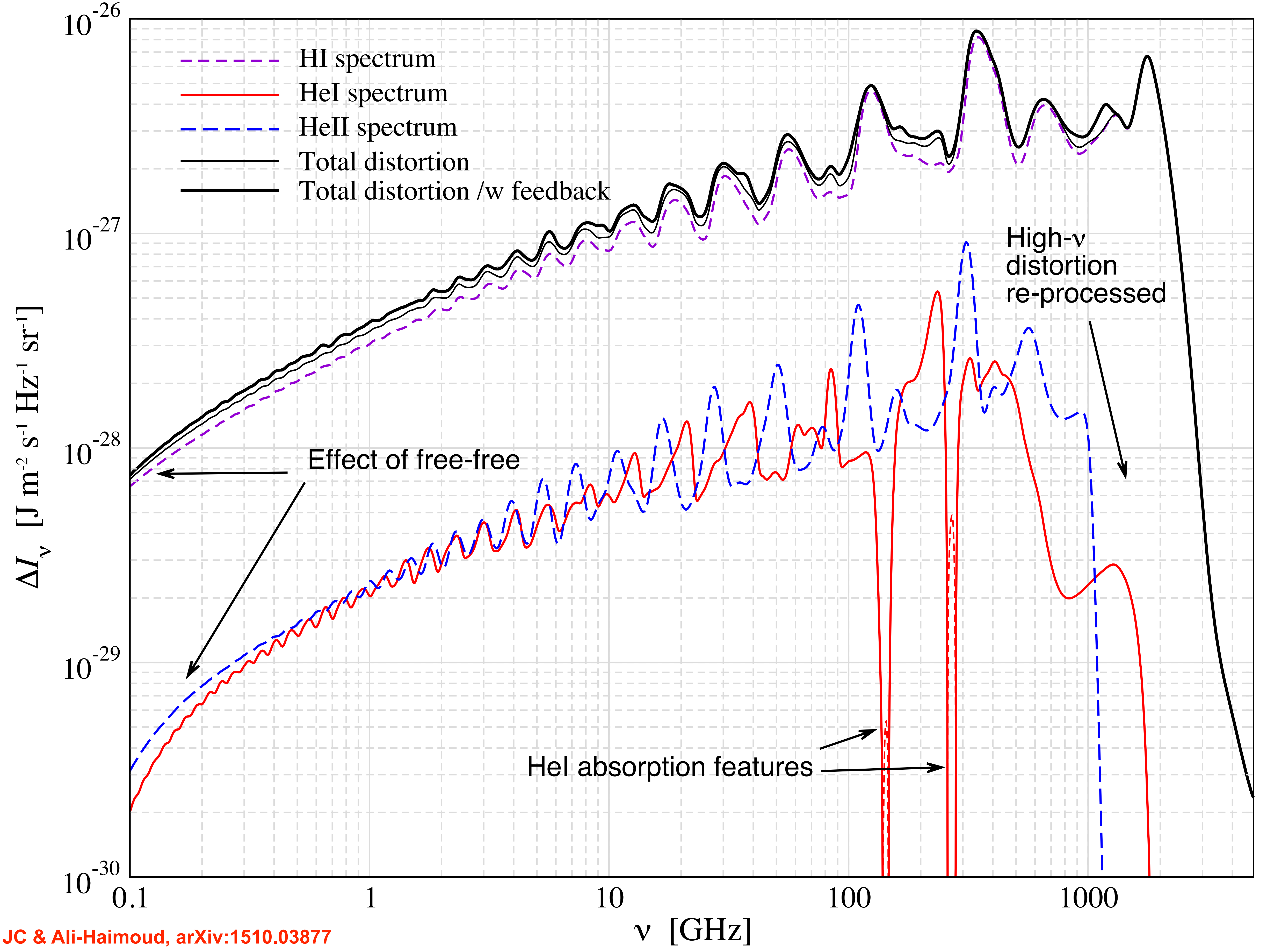
Ali-Haimoud, JC & Kamionkowski, 2015

The cosmological recombination radiation



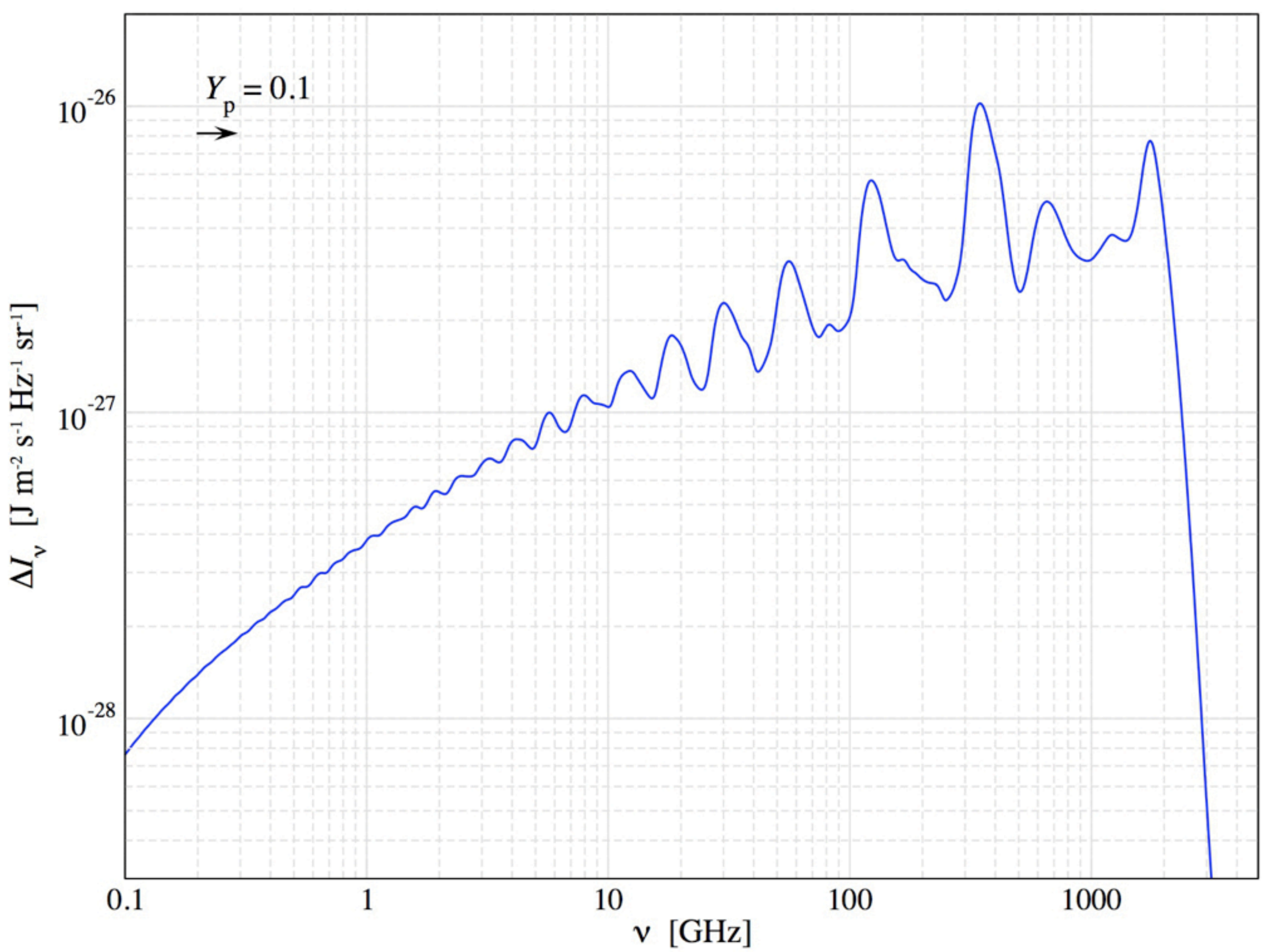
Rubino-Martin et al. 2006, 2008; Sunyaev & JC, 2009

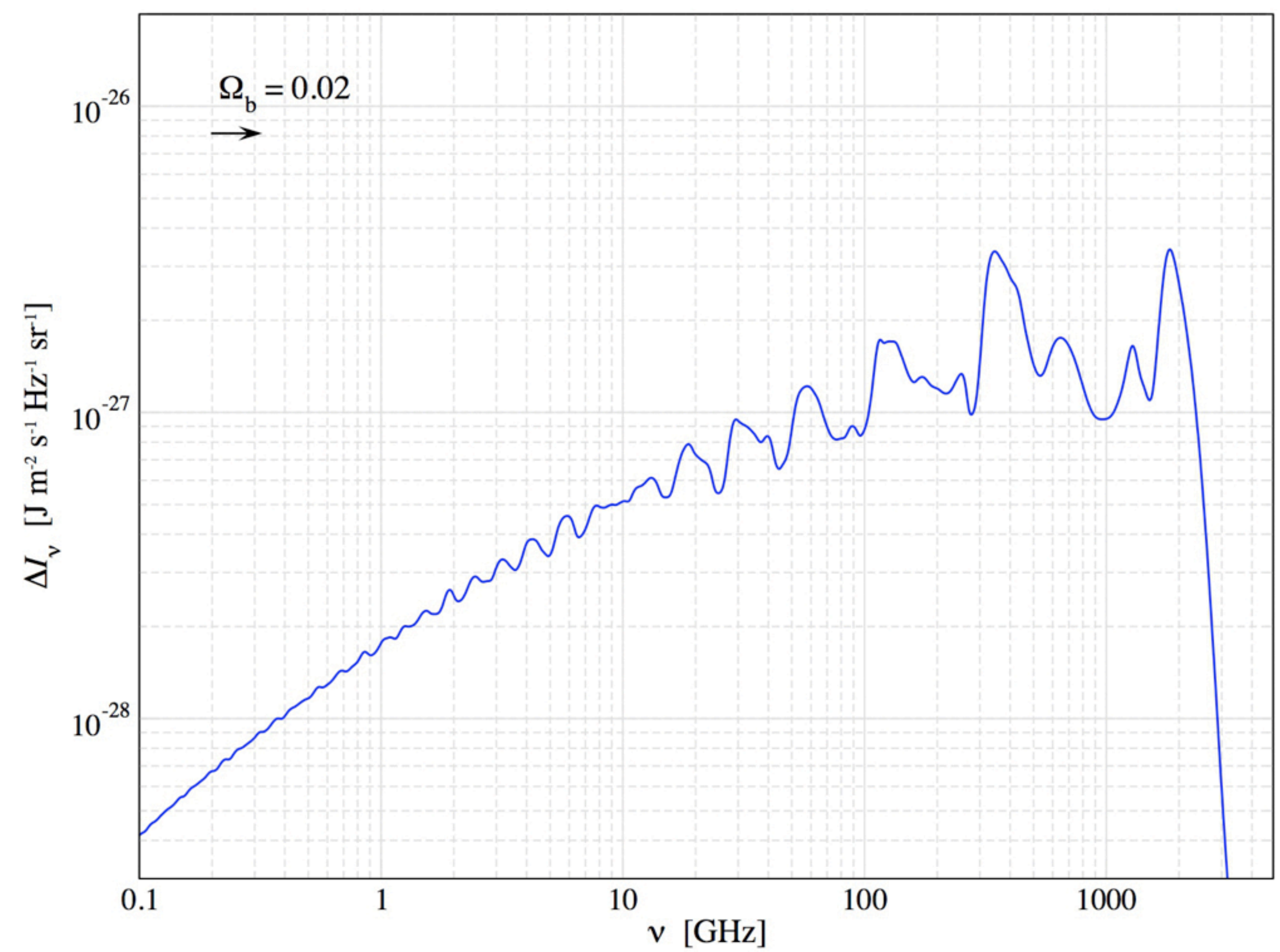
New detailed and fast computation!



JC & Ali-Haimoud, arXiv:1510.03877

CosmoSpec: fast and accurate computation of the CRR





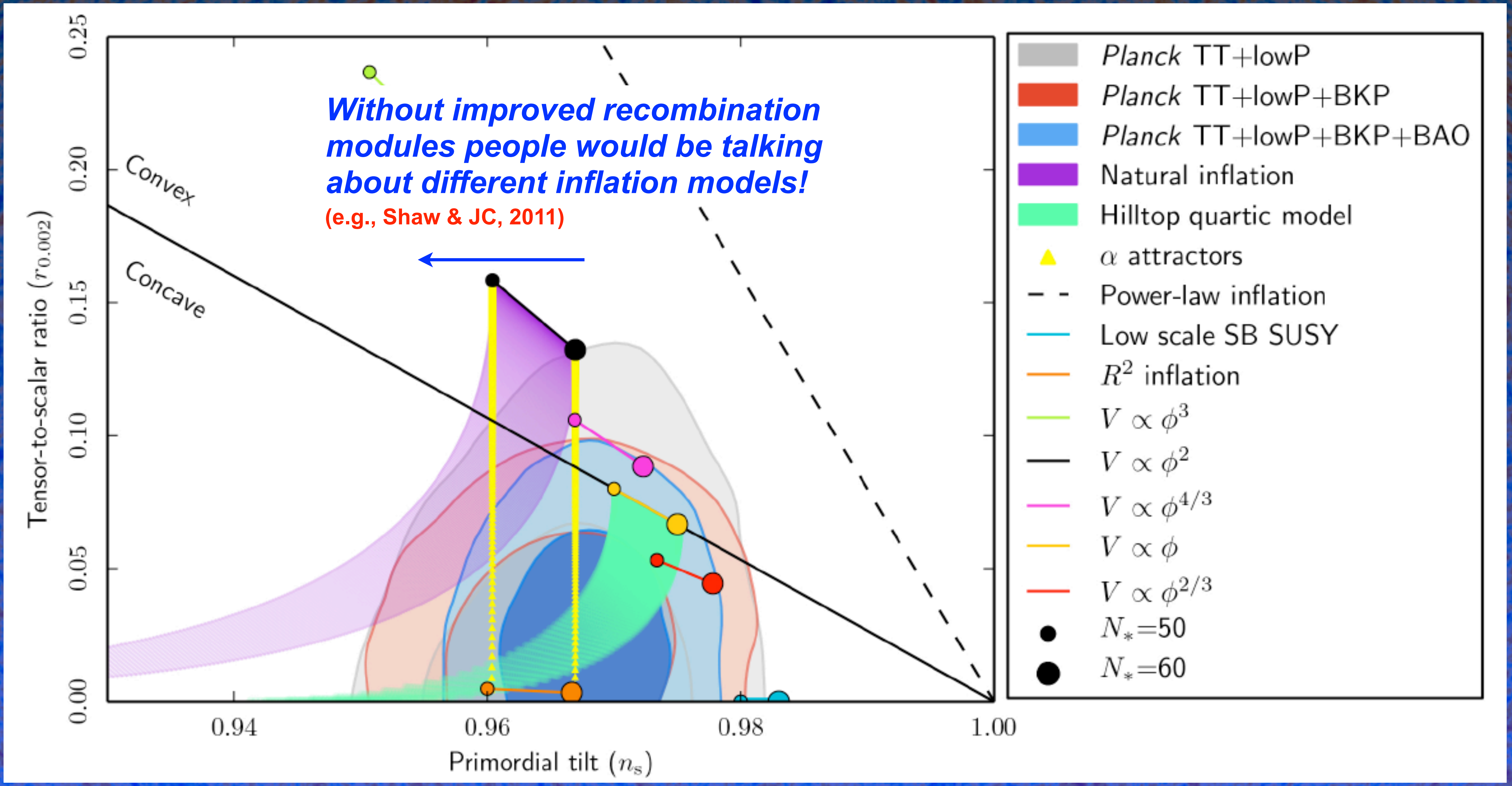
- Like in old days of CMB anisotropies!
- detailed forecasts and feasibility studies
- non-standard physics (variation of α, energy injection etc.)

CosmoSpec will be available here:

www.Chluba.de/CosmoSpec

JC & Ali-Haimoud, arXiv:1510.03877

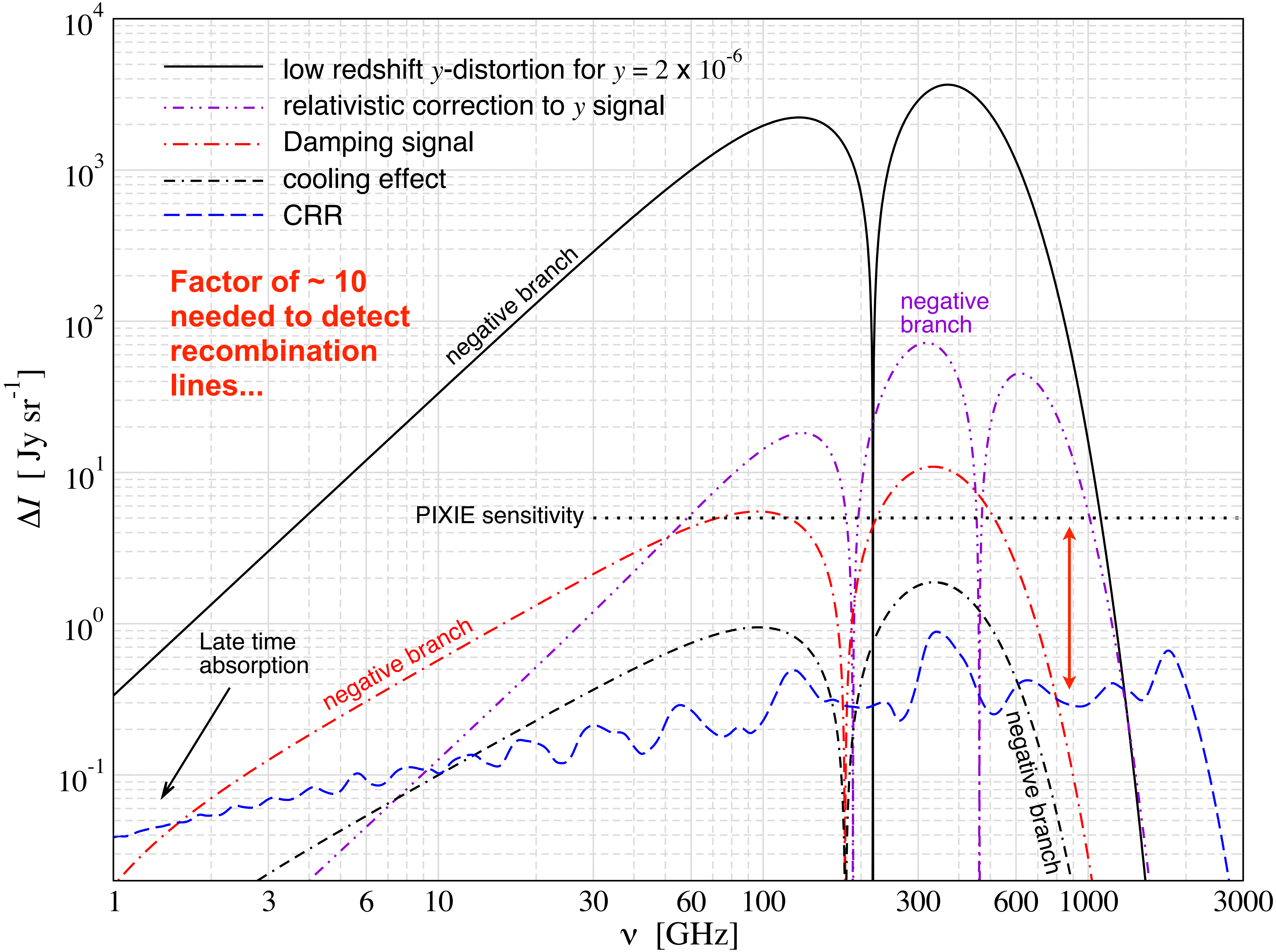
Importance of recombination for inflation constraints

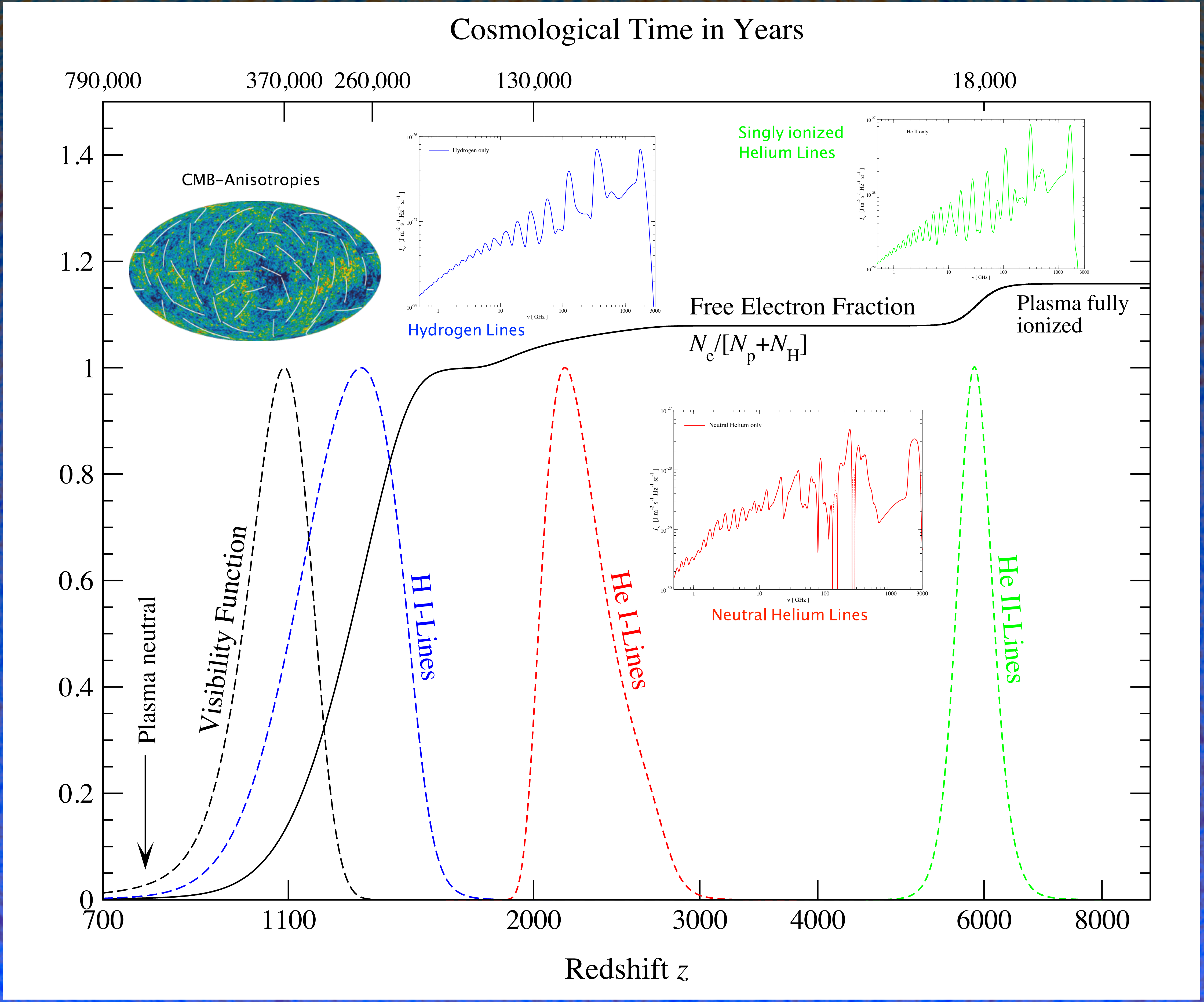


Planck Collaboration, 2015, paper XX

- Analysis uses refined recombination model (CosmoRec/HyRec)

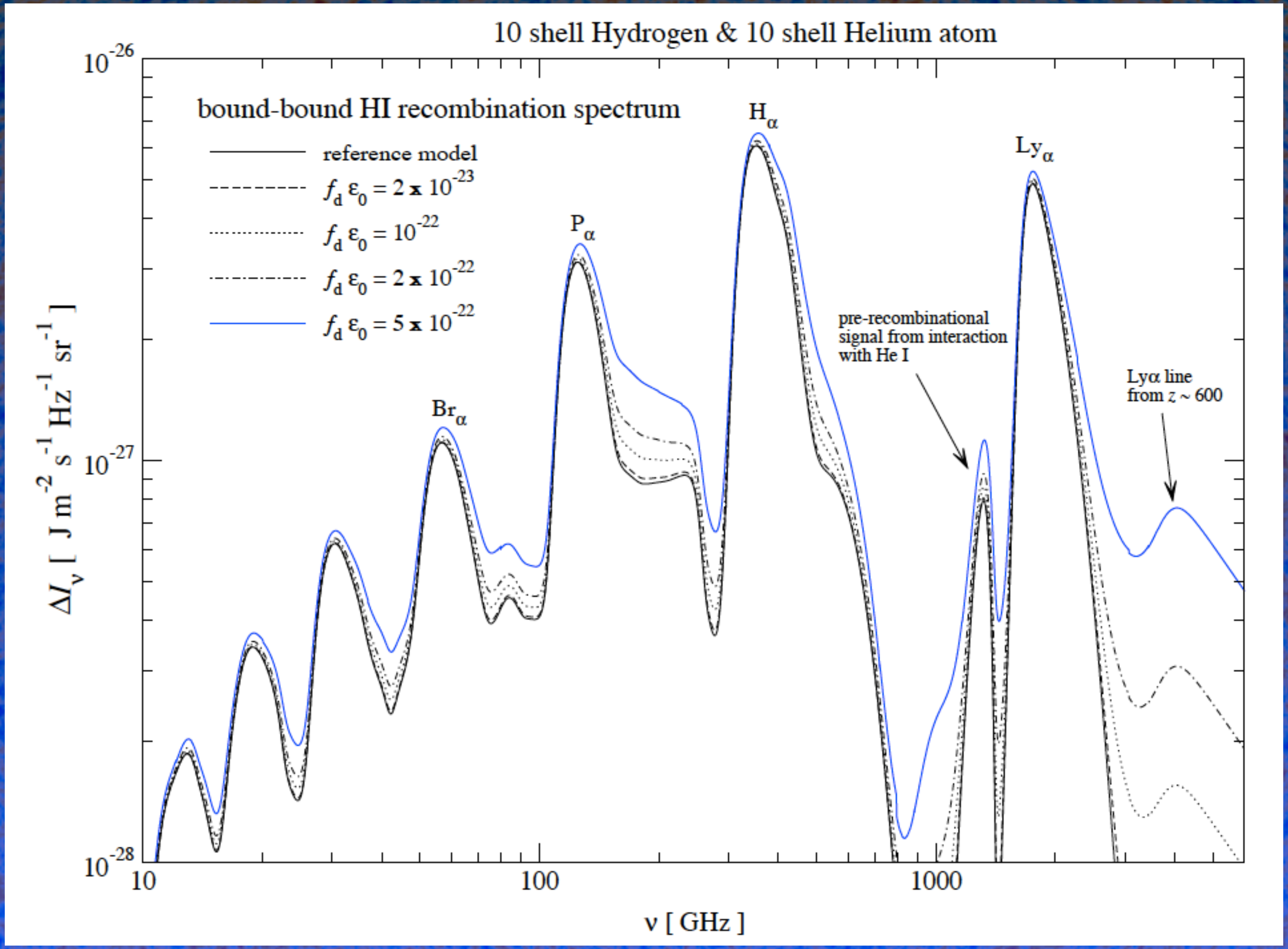
Average CMB spectral distortions





Cosmological Time in Years
790,000
370,000
260,000
130,000
18,000
1.4
1.2
1
0.8
0.6
0.4
0.2
0
CMB-Anisotropies
Hydrogen only
Hydrogen Lines
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
700
1100
2000
3000
4000
6000
8000
Redshift z

Dark matter annihilations / decays



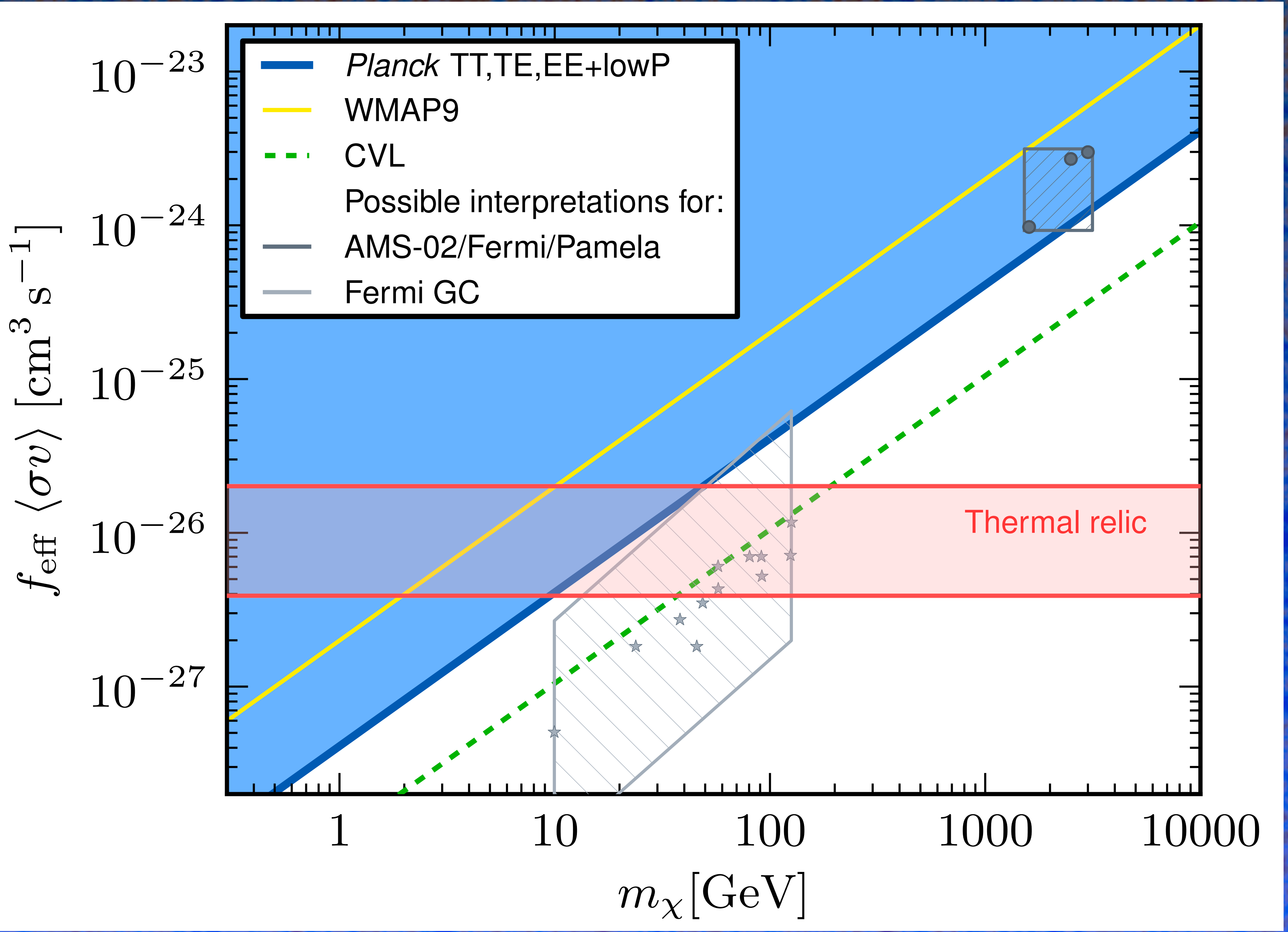
JC, 2009, arXiv:0910.3663

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

Annihilating/decaying (dark matter) particles

Latest Planck limits on annihilation cross section

95% c.l.

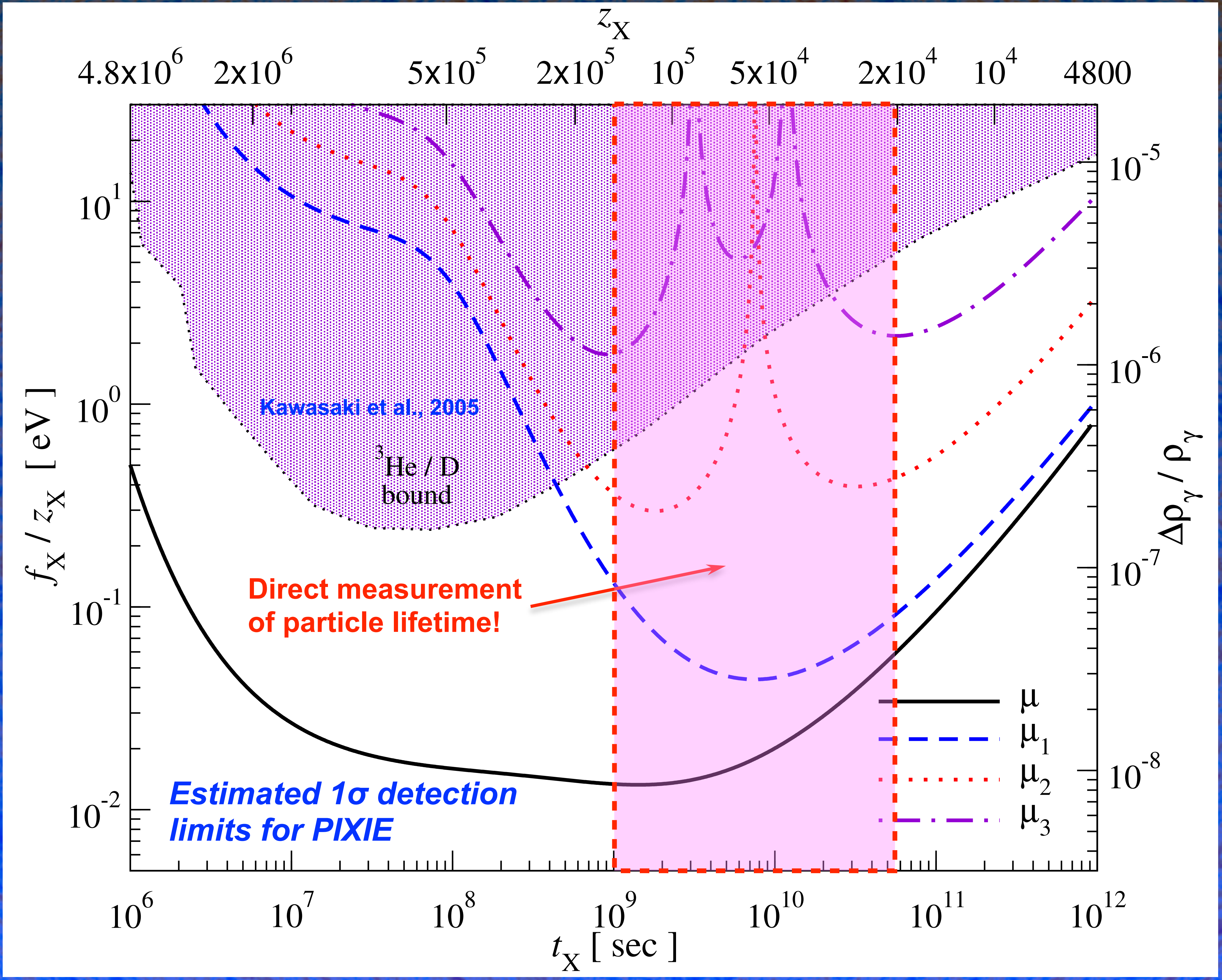


Planck Collaboration, paper XIII, 2015

- 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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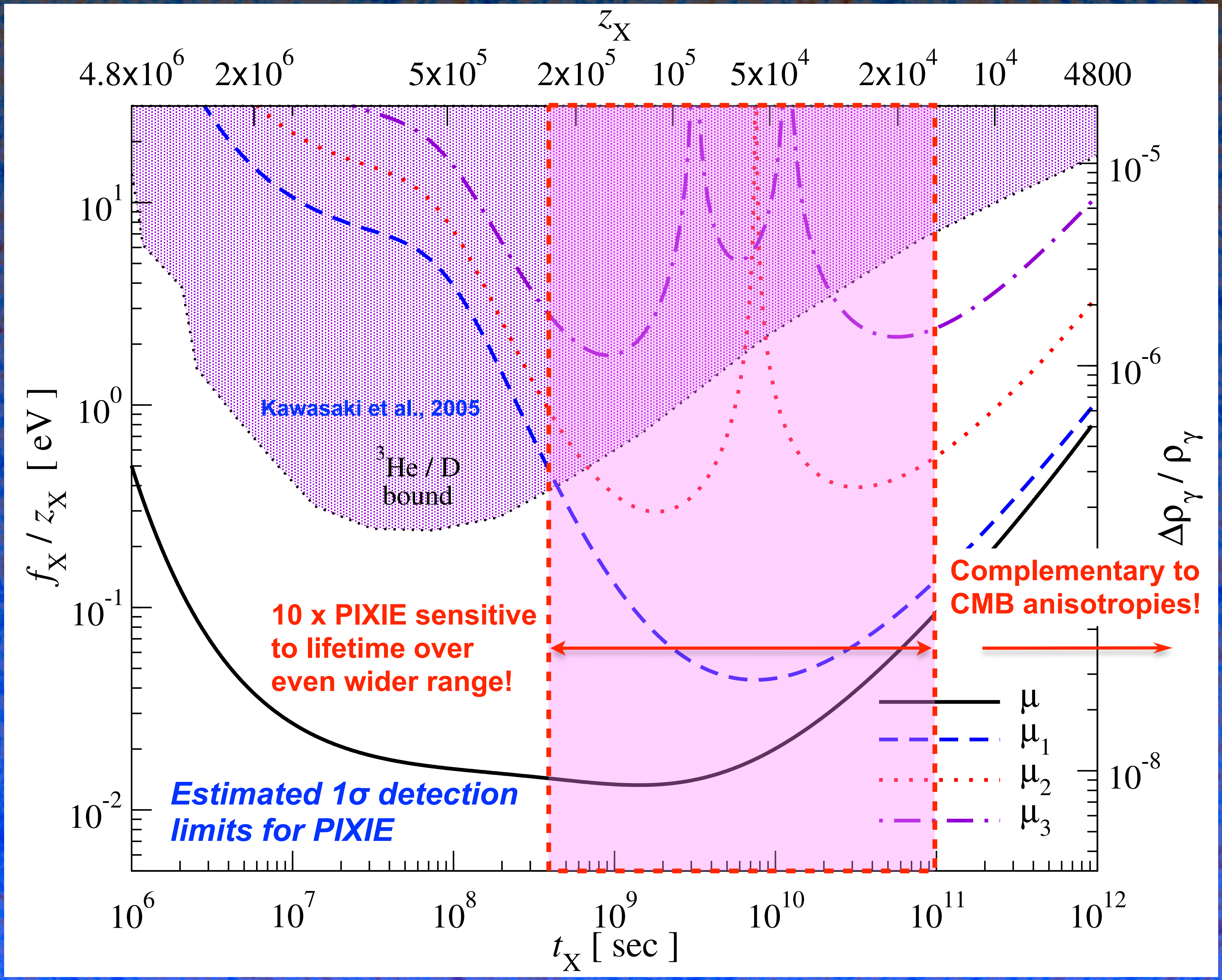
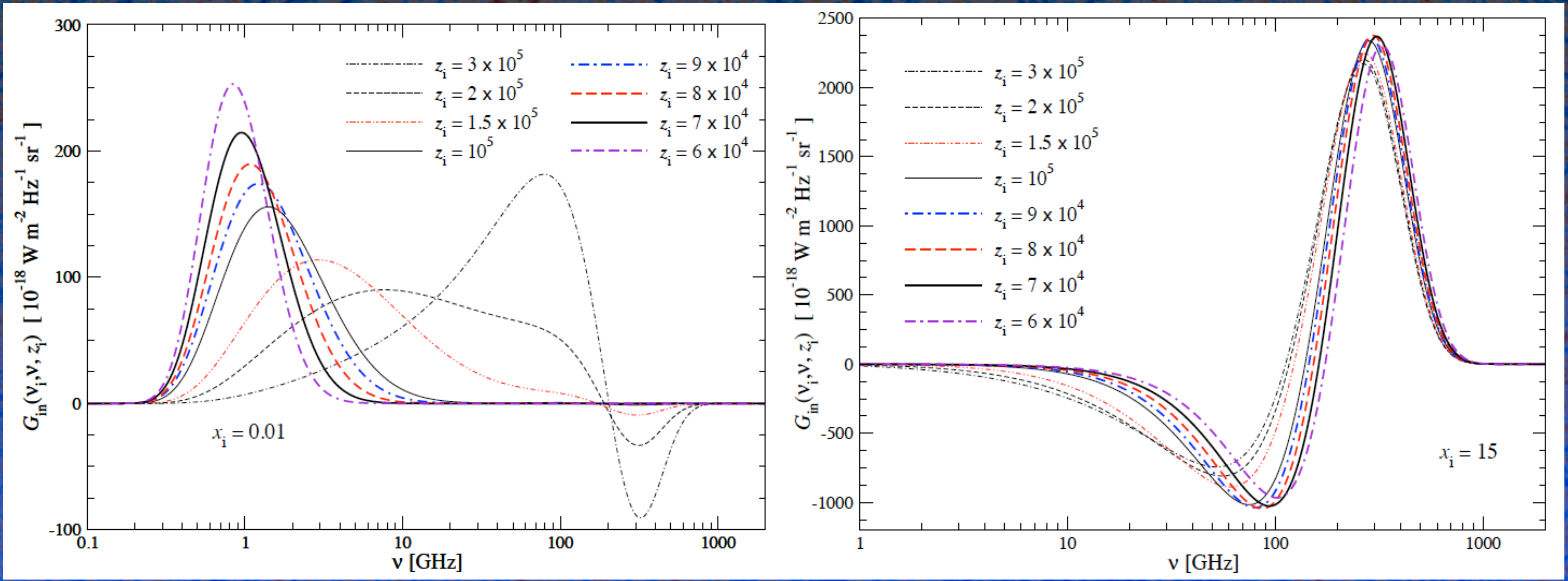


JC & Jeong, 2013

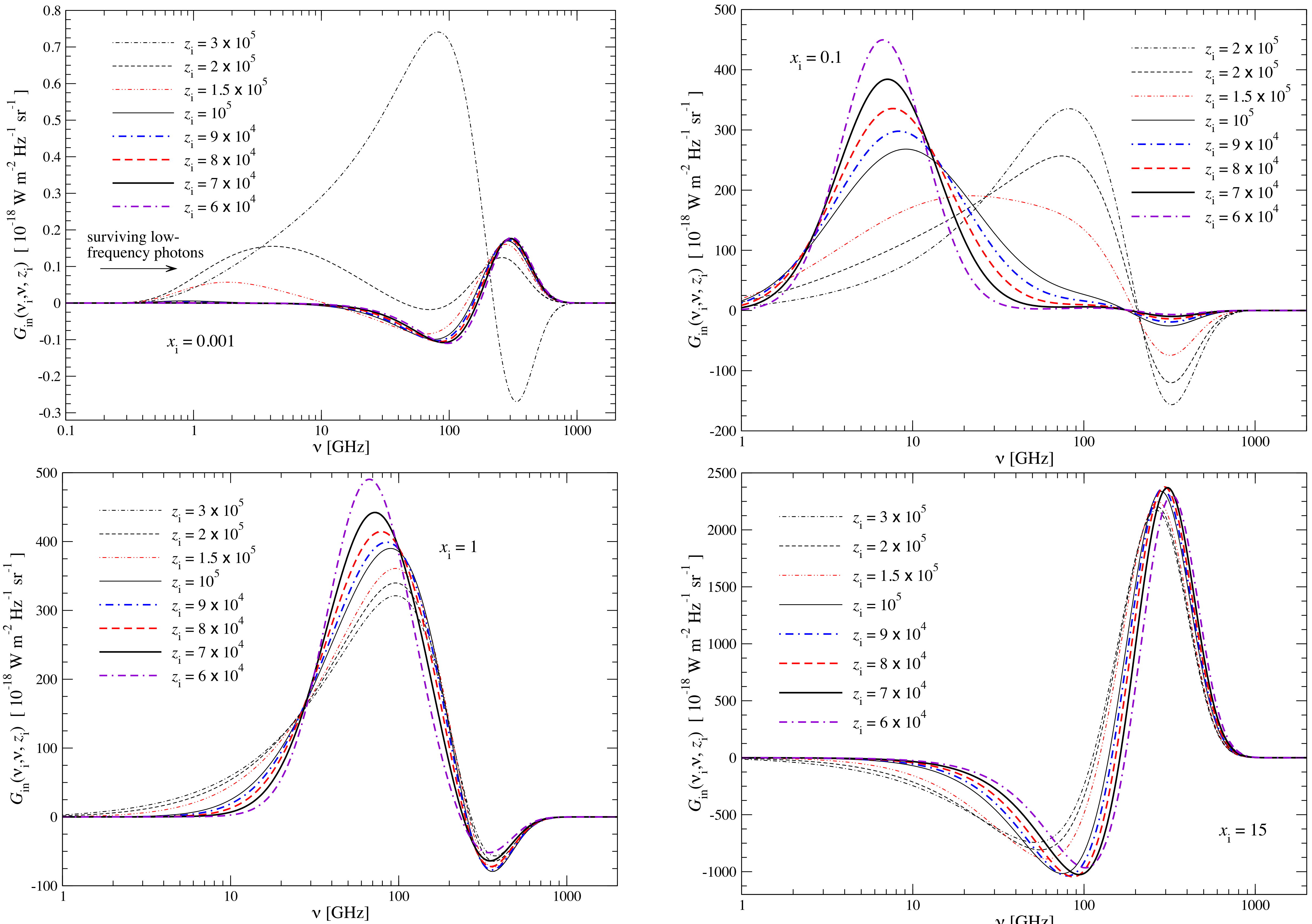
Green's function for photon injection



- 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

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pre-recombination epoch

„high" redshifts

„low" redshifts

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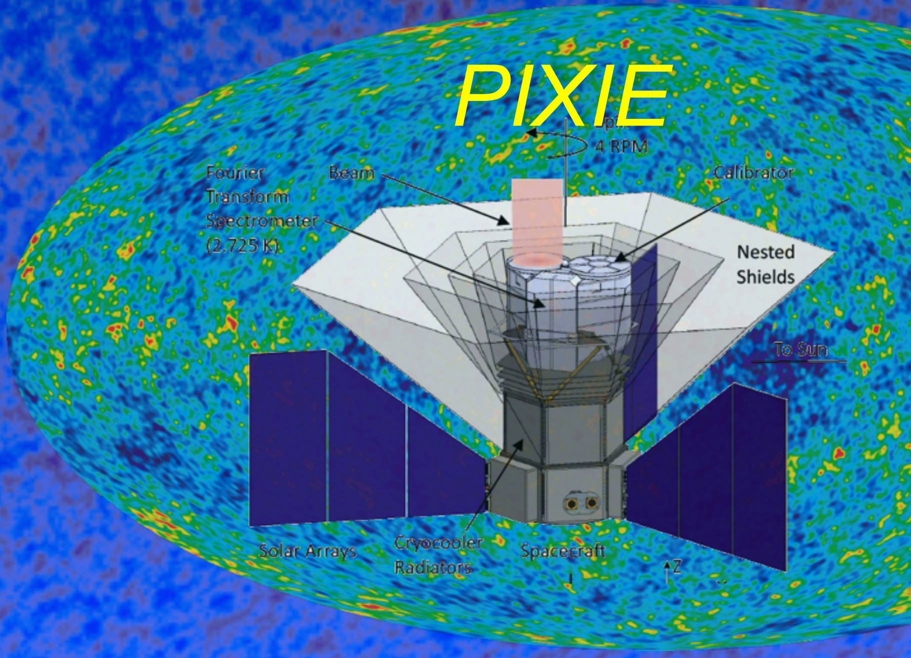
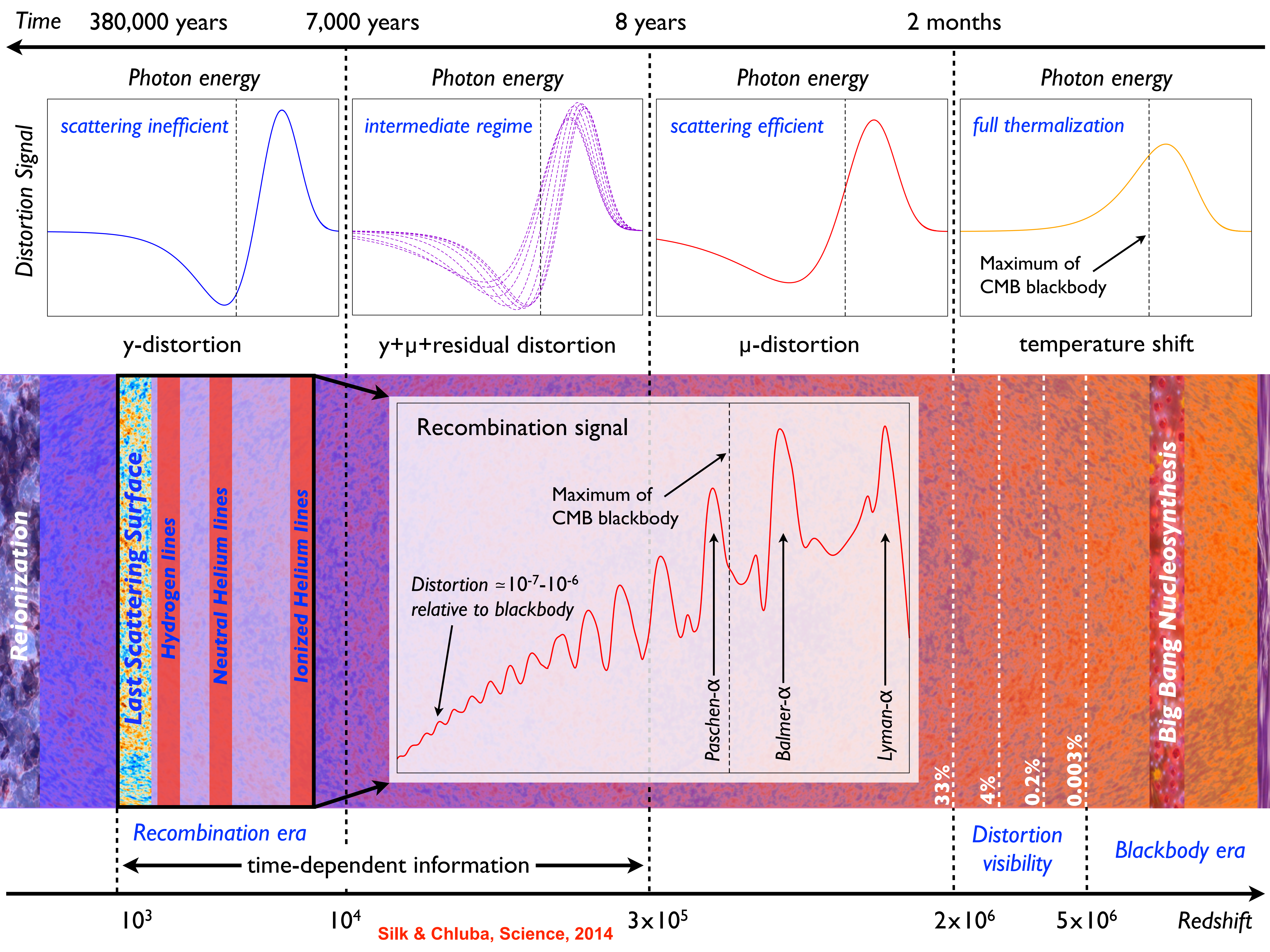
What can CMB spectral distortions add?

- 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!




Time
380,000 years
7,000 years
8 years
2 months
Photon energy
Photon energy
Photon energy
Photon energy
Distortion Signal
scattering inefficient
intermediate regime
scattering efficient
full thermalization
Maximum of
CMB blackbody
y-distortion
y+μ+residual distortion
μ-distortion
temperature shift
Reionization
Last Scattering Surface
Hydrogen lines
Neutral Helium lines
Ionized Helium lines
Recombination signal
Maximum of
CMB blackbody
Distortion ≃10-7-10-6
relative to blackbody
Paschen-α
Balmer-α
Lyman-α
33%
4%
0.2%
0.003%
Big Bang Nucleosynthesis
Recombination era
time-dependent information
Distortion
visibility
Blackbody era
10³
10⁴
3x10⁵
2x10⁶
5x10⁶
Redshift
Silk & Chluba, Science, 2014