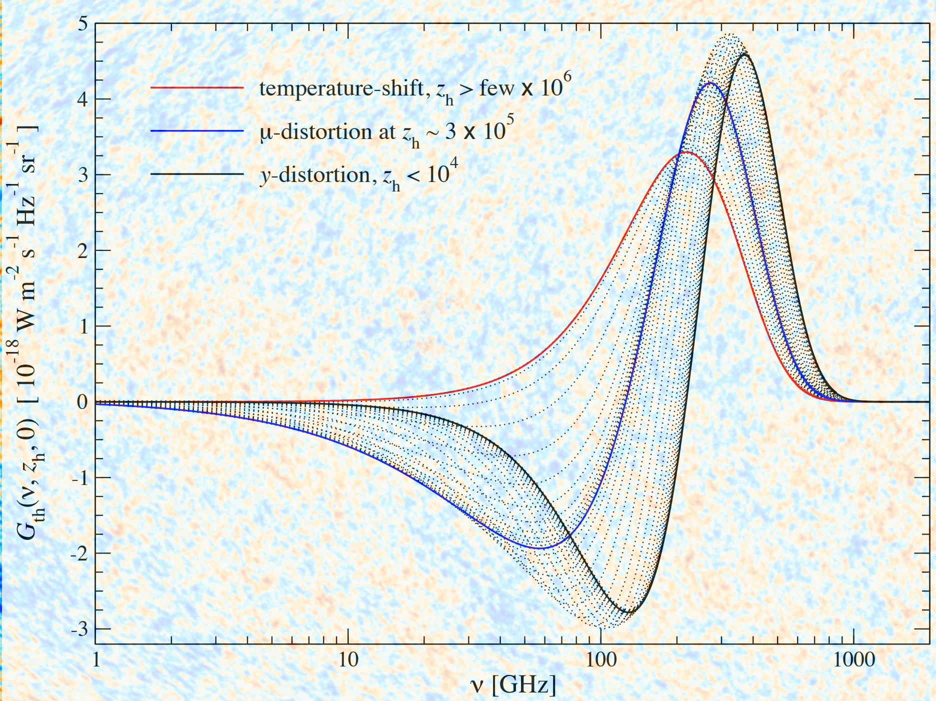
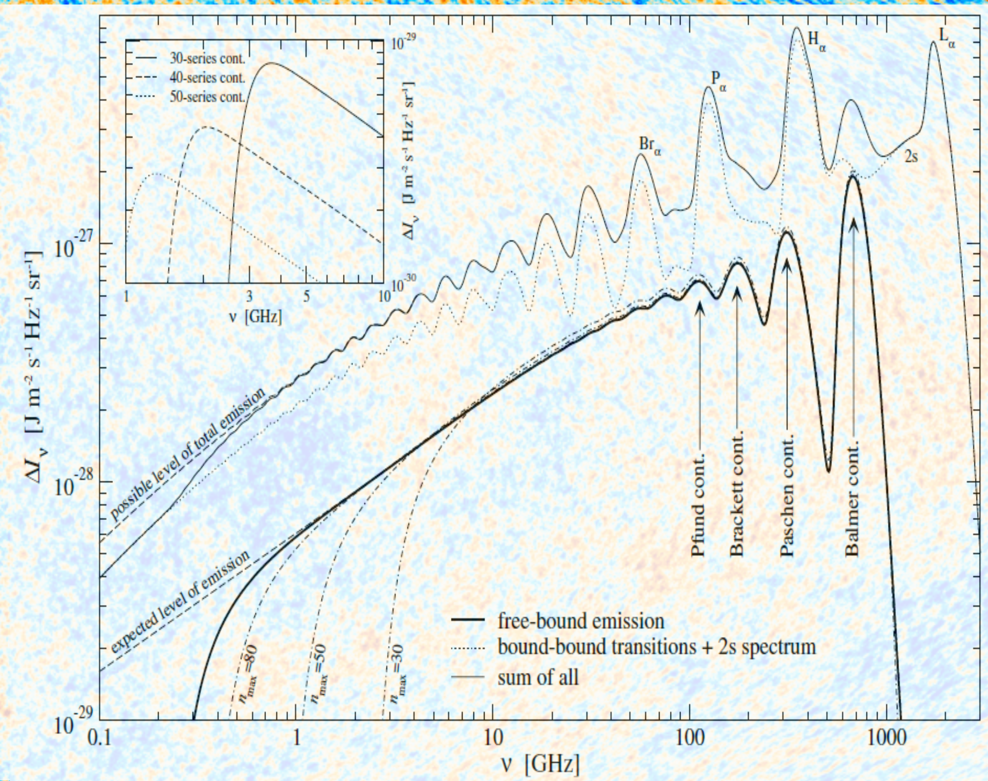
Future Steps in Cosmology with CMB Spectral Distortions

Primordial Distortions



Cosmological Recombination lines



MANCHESTER 1824

The University of Manchester

Jens Chluba

Cosmology School in the Canary Islands

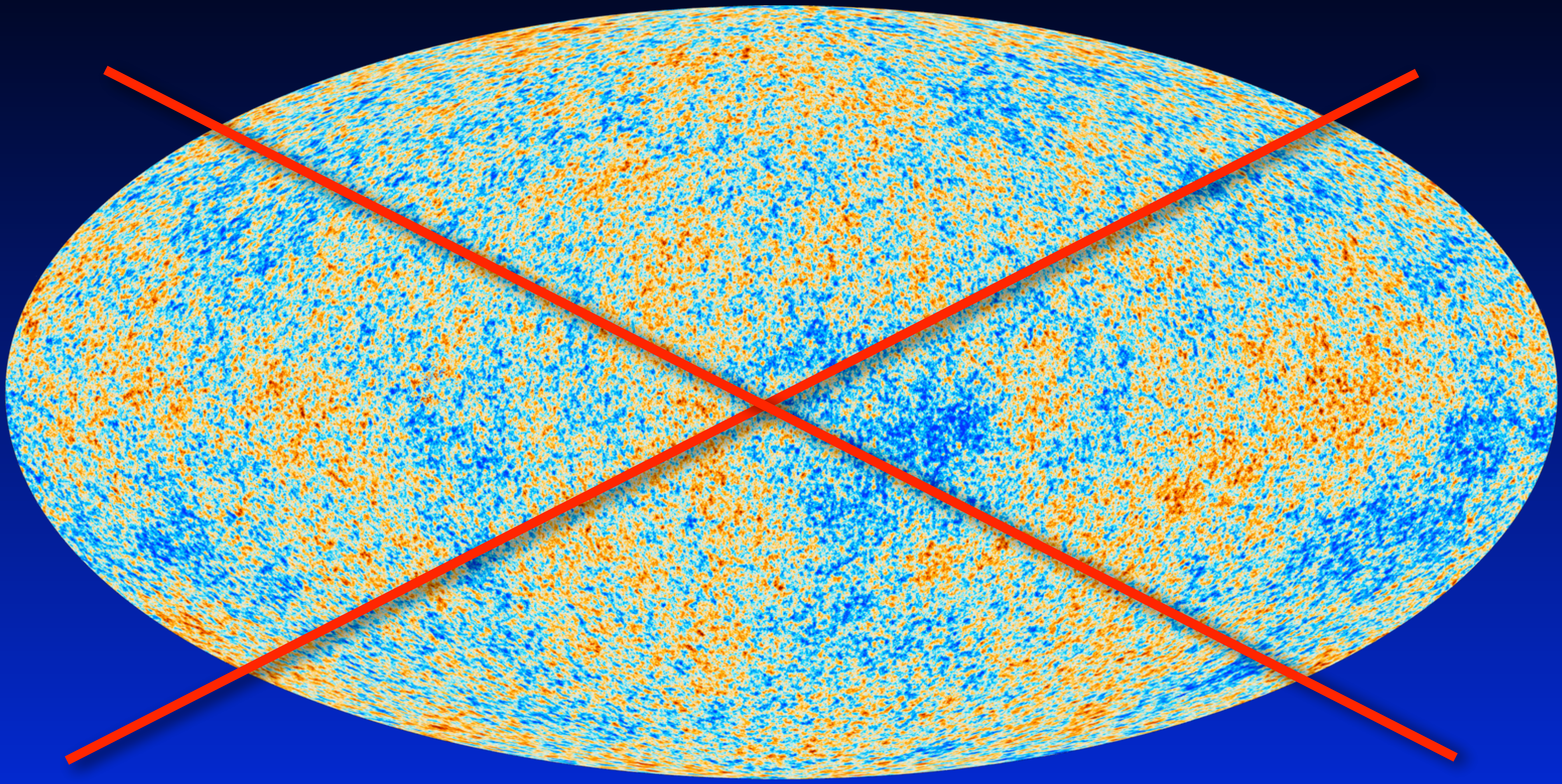
Fuerteventura, Sept 21st, 2017

erc

THE ROYAL SOCIETY

** CMB ≙ Cosmic Microwave Background*

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

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

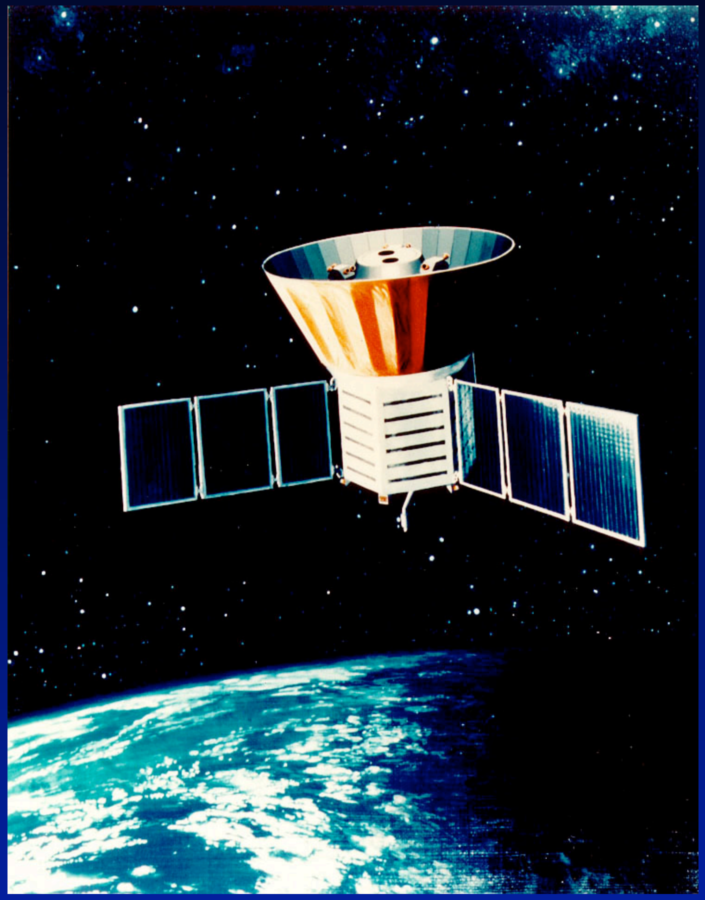
Absolute measurement required!

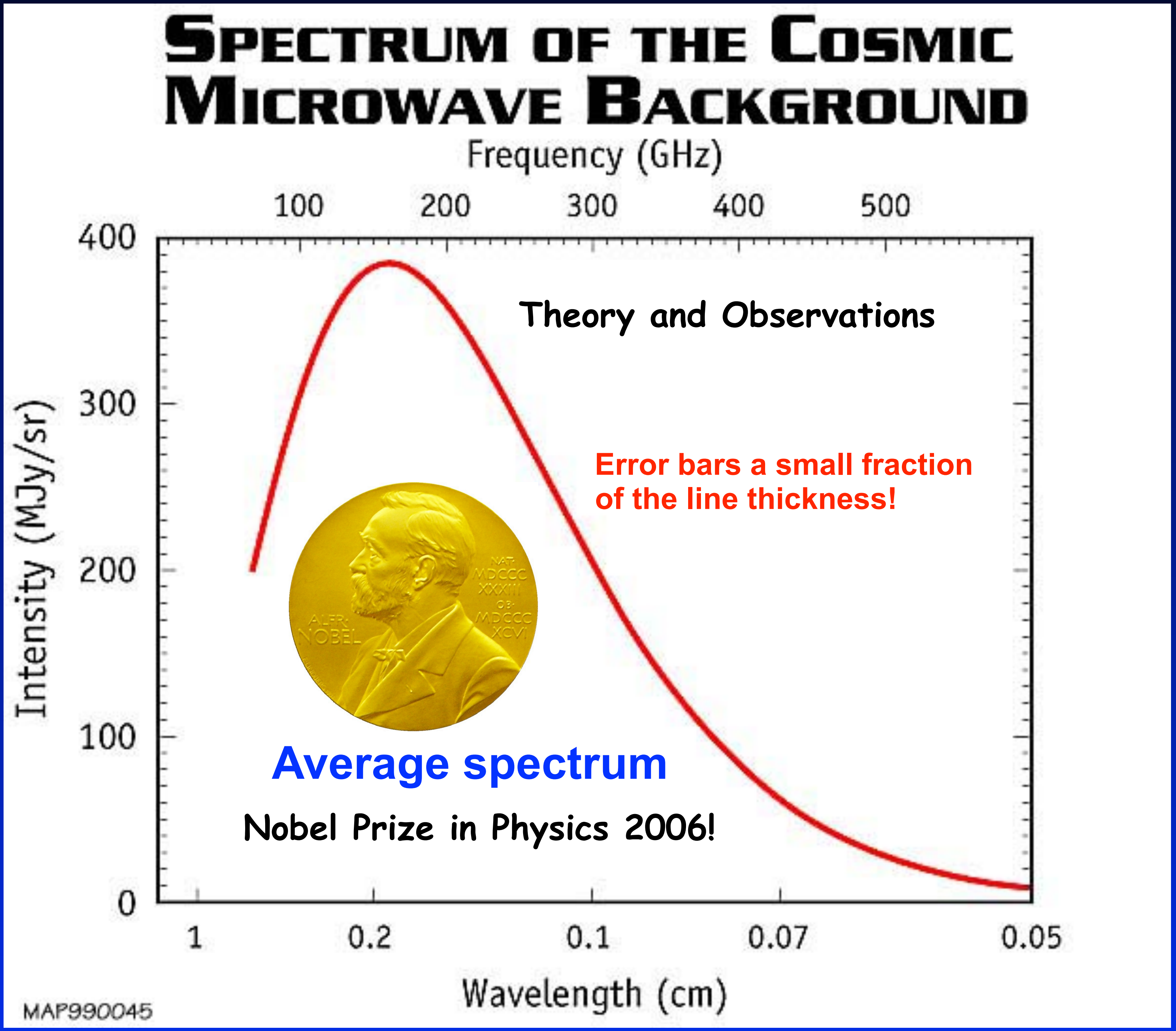
One has to go to space...

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

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

COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)





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

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

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

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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

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

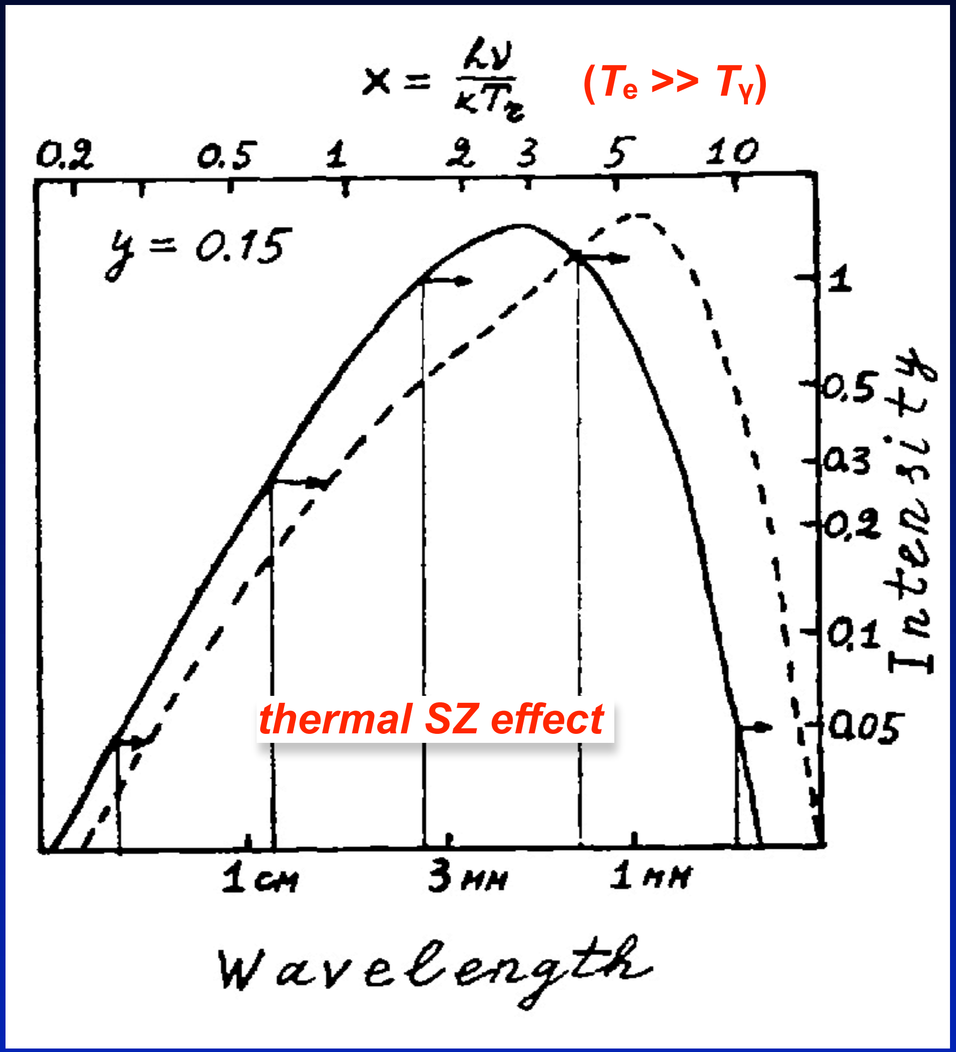
→ thermalization process (partially) erases distortions

(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!

Standard types of primordial CMB distortions

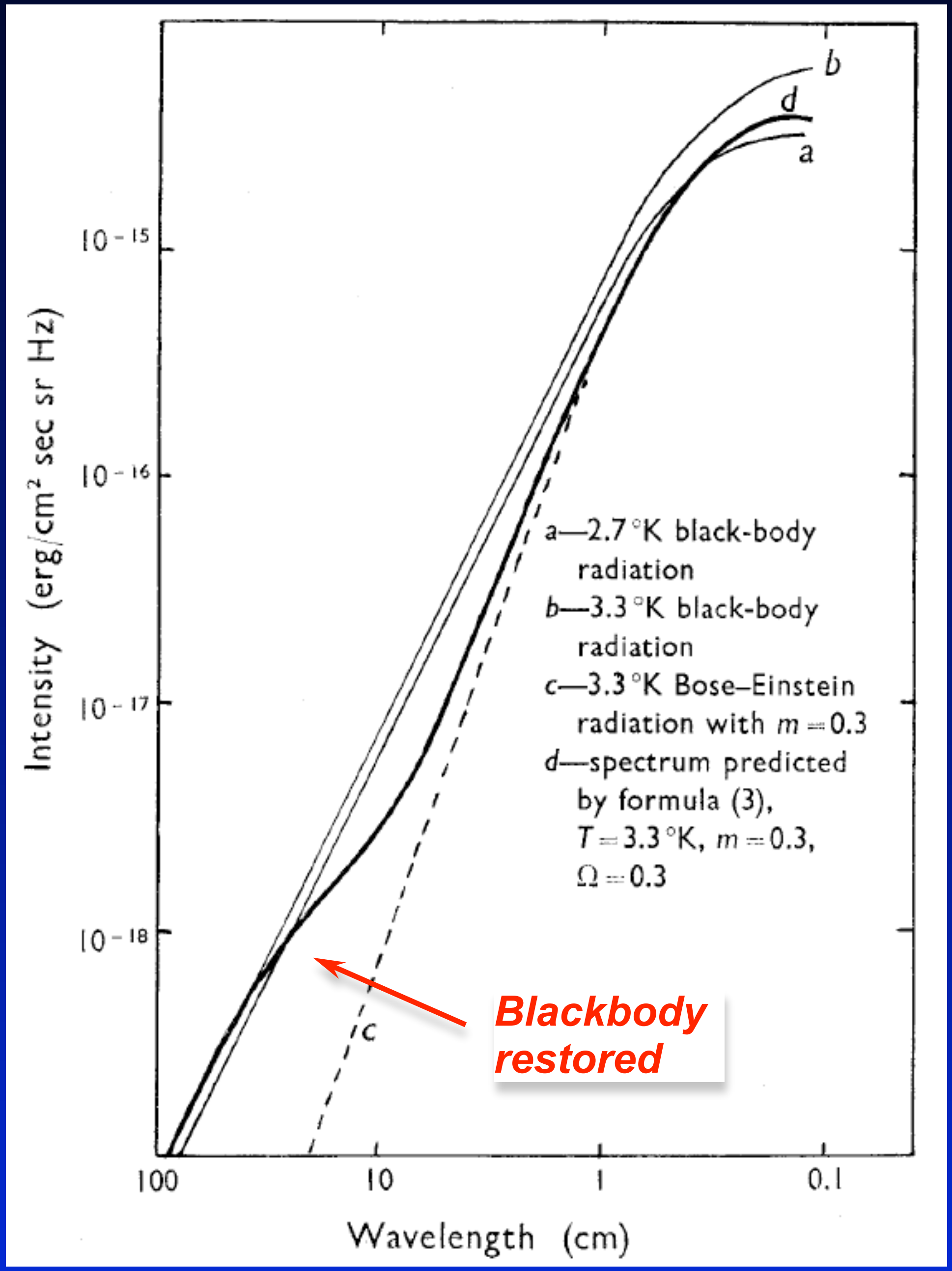
Compton y-distortion



Sunyaev & Zeldovich, 1980, ARAA, 18, 537

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

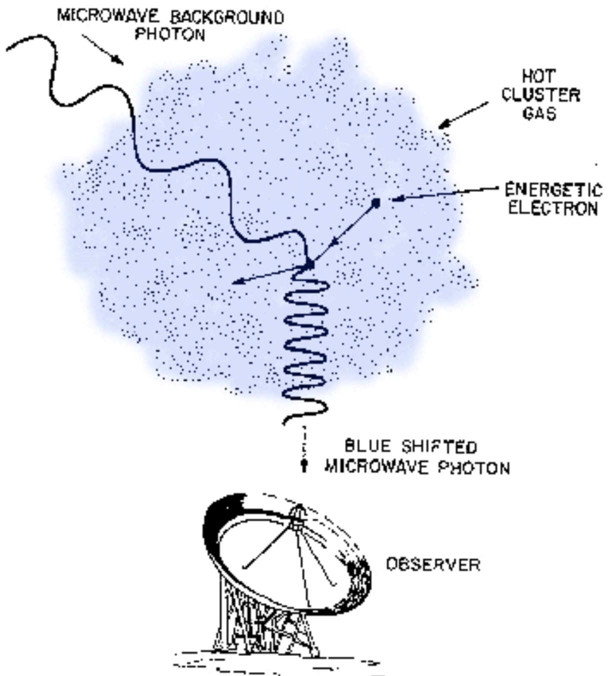
Chemical potential μ-distortion

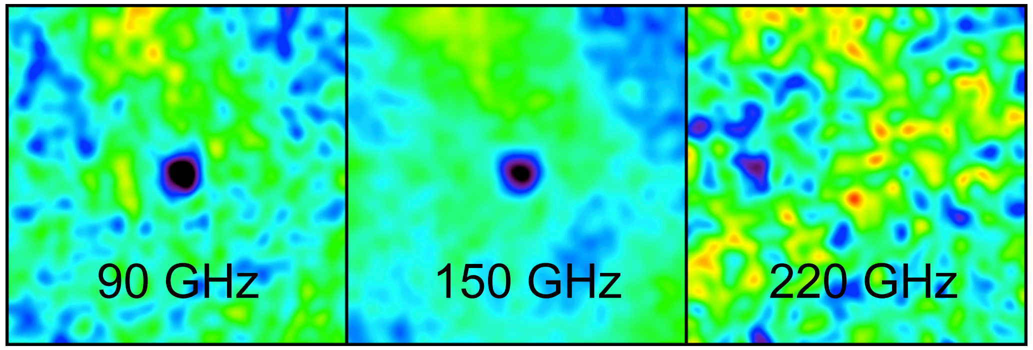


Sunyaev & Zeldovich, 1970, ApSS, 2, 66

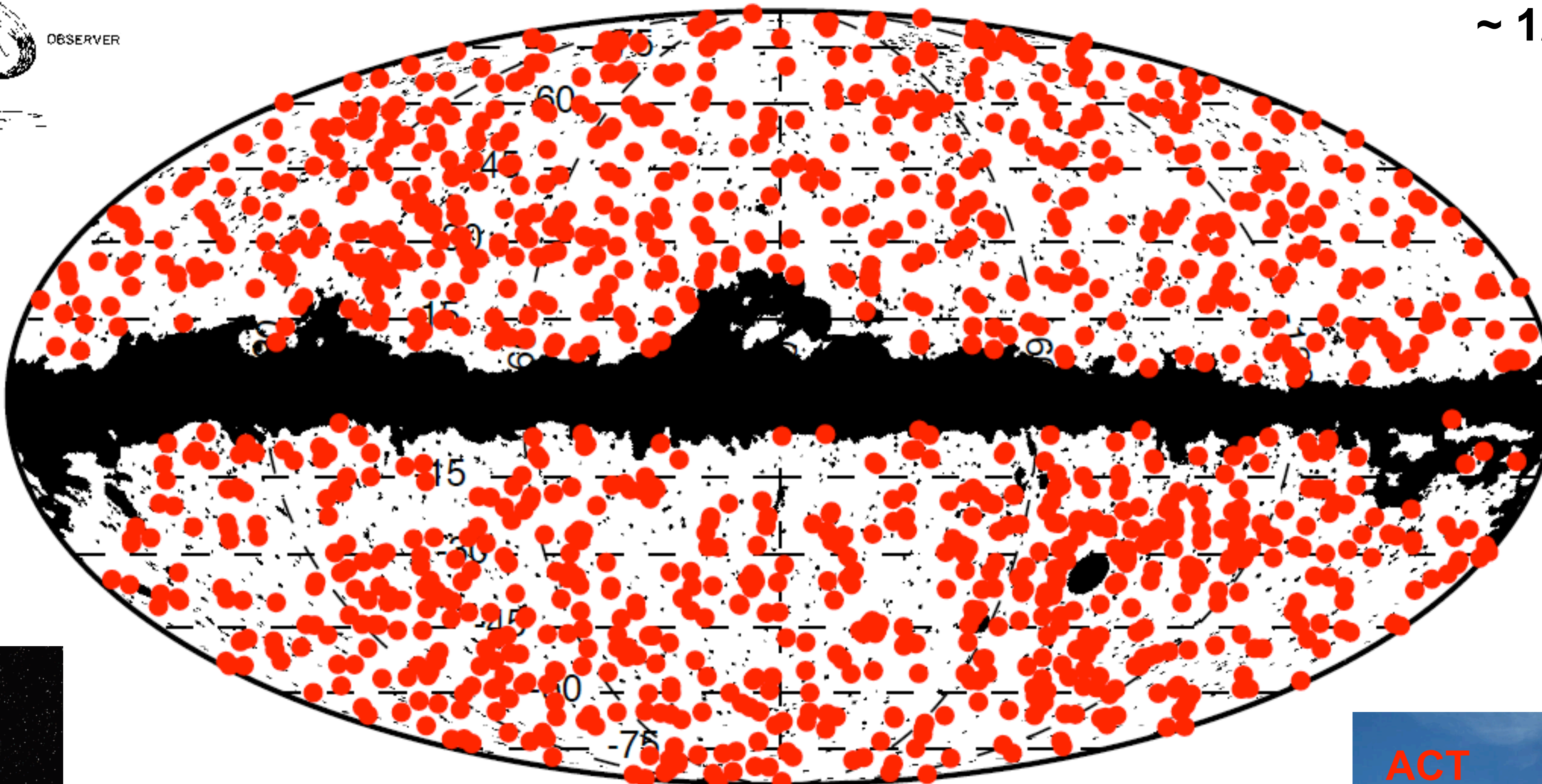
- important at very times (z>50000)
- scattering `very efficient'

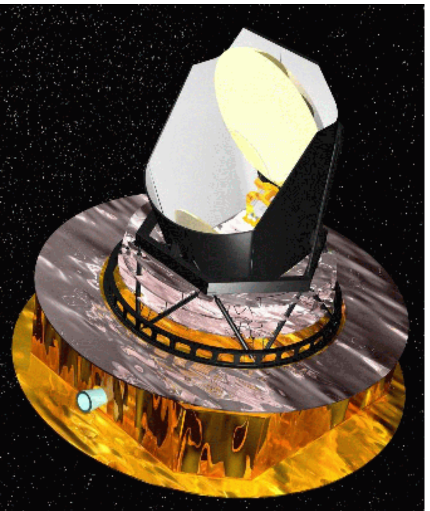
Thermal SZ effect is now routinely observed!





~ 1230 objects





Planck Collaboration, 2013, paper XXIV

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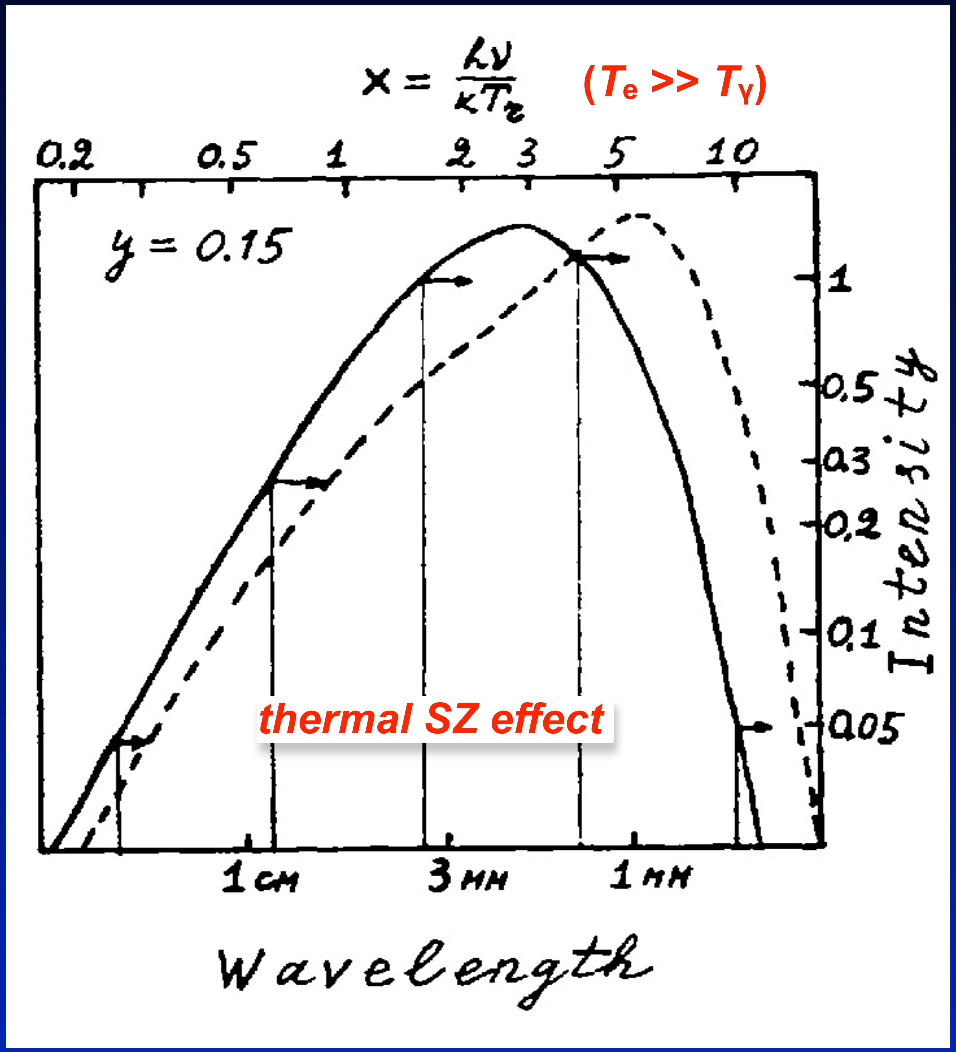

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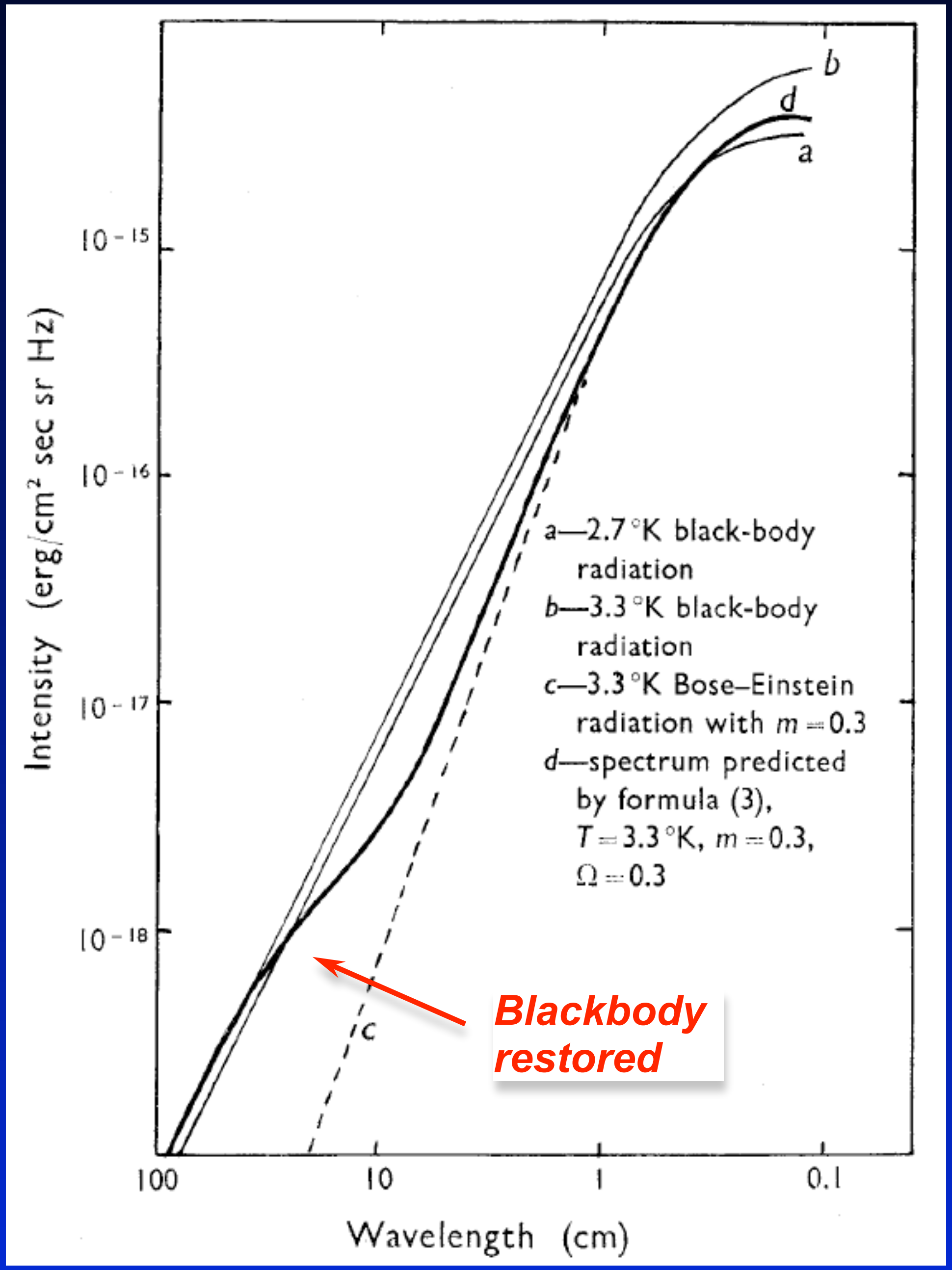

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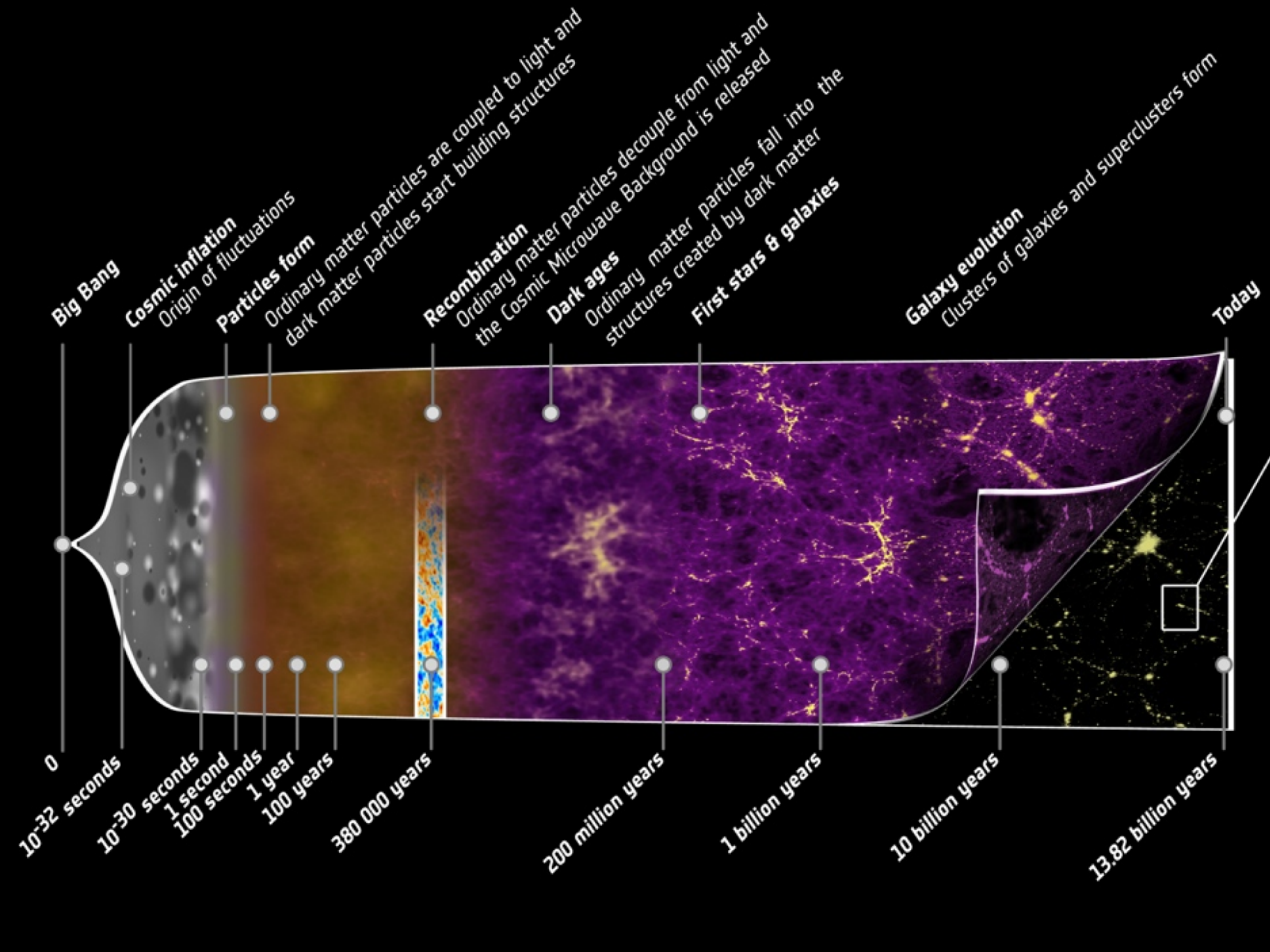
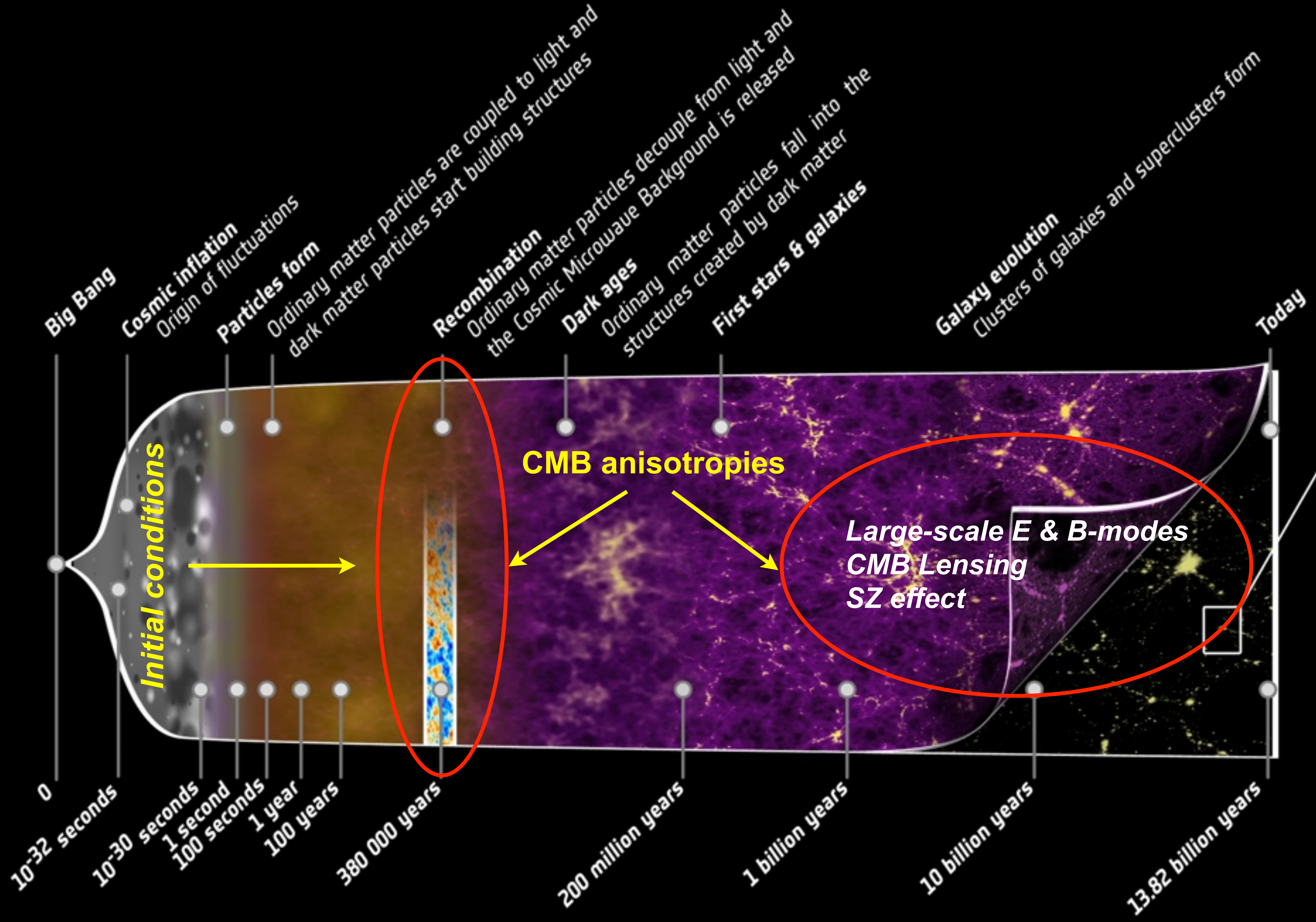


Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
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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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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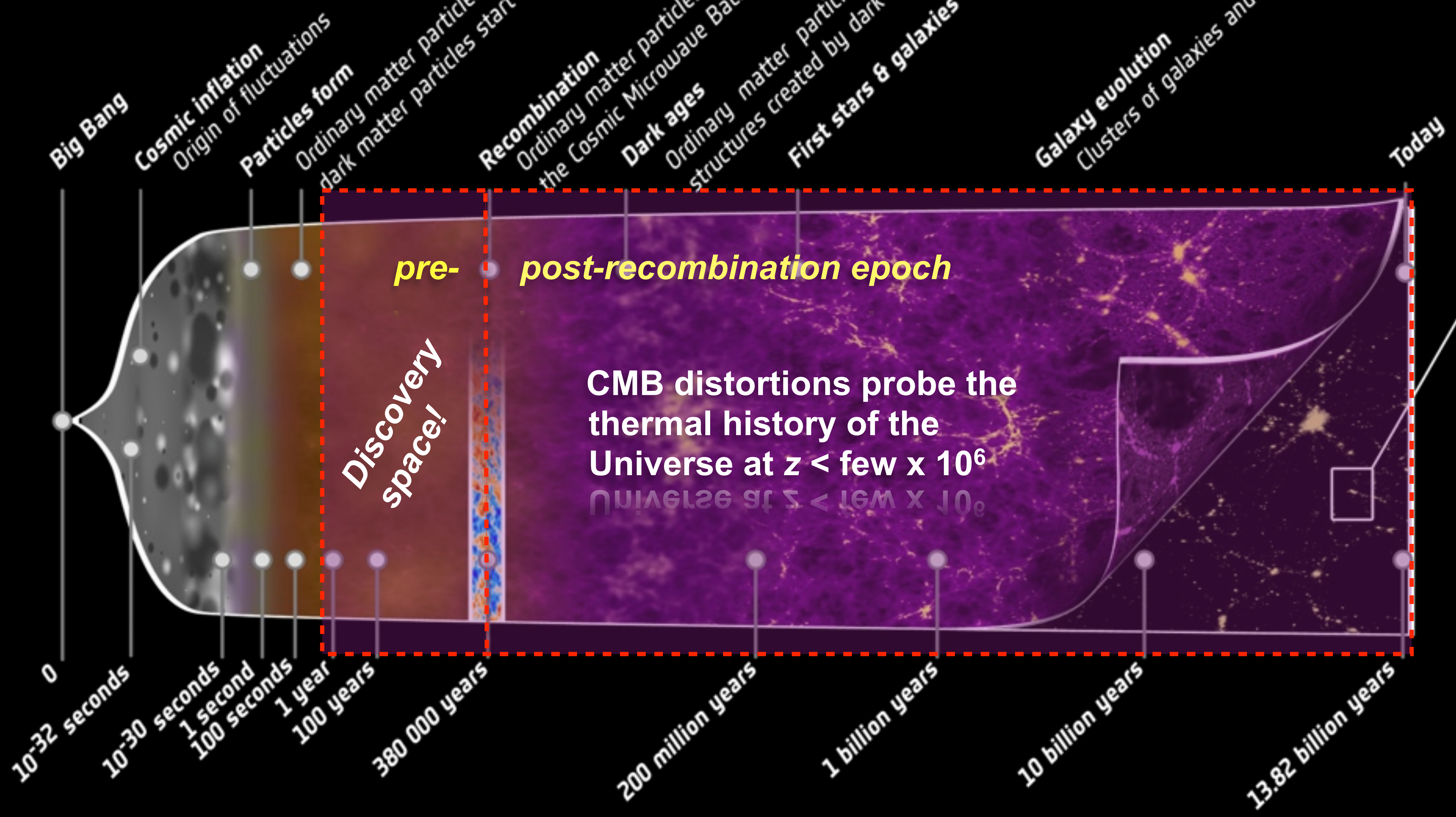
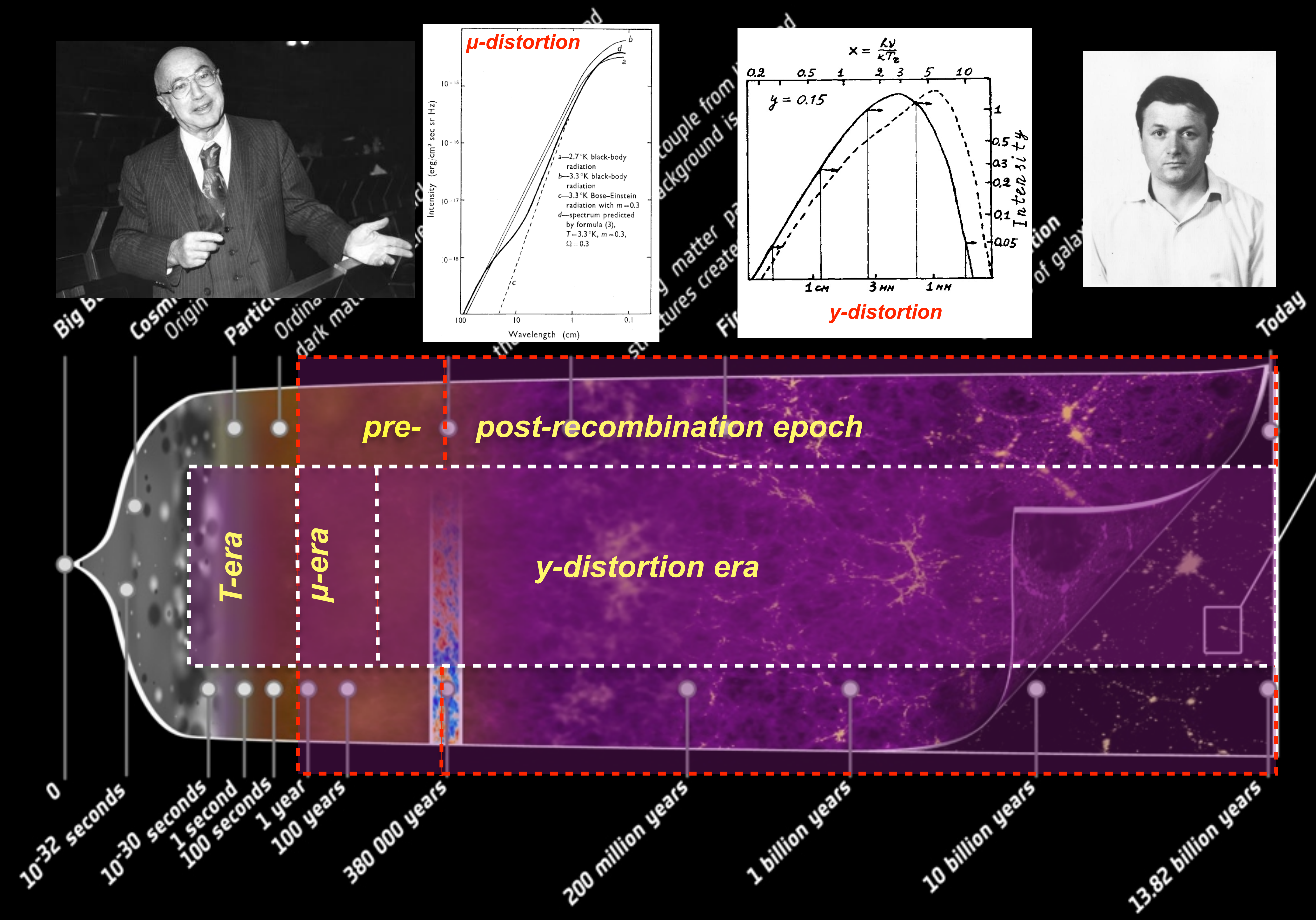
Measurements of CMB spectrum will open a new unexplored window to the early Universe!




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
x = hν/kT_e
y = 0.15
Intensity
y-distortion
Today
pre-
post-recombination epoch
T-era
μ-era
y-distortion era
0
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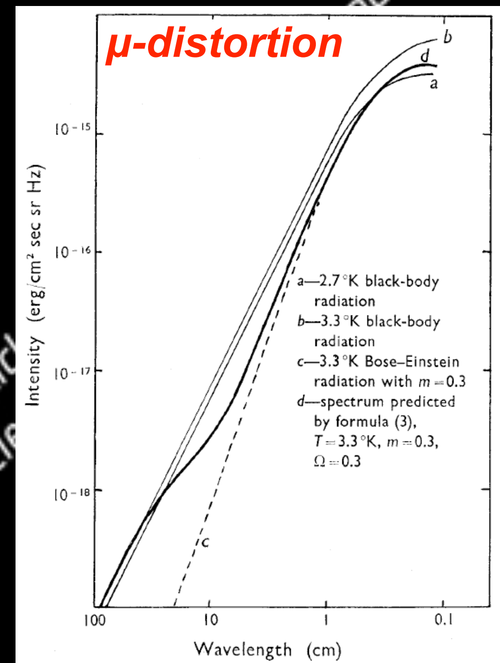
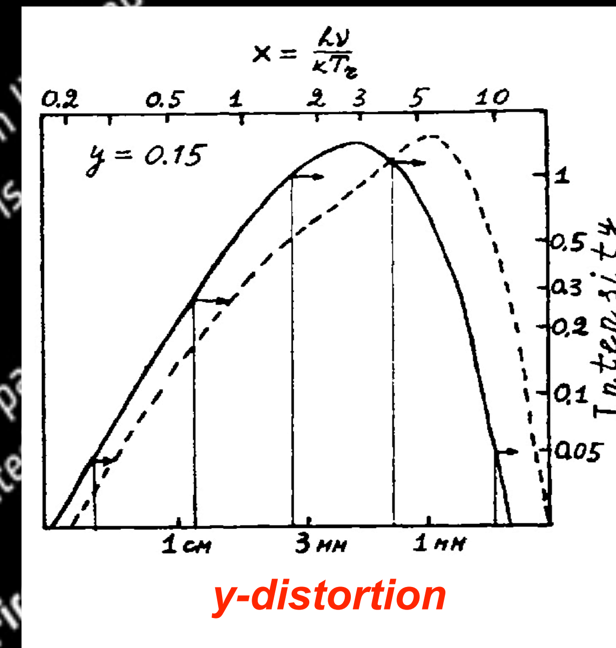
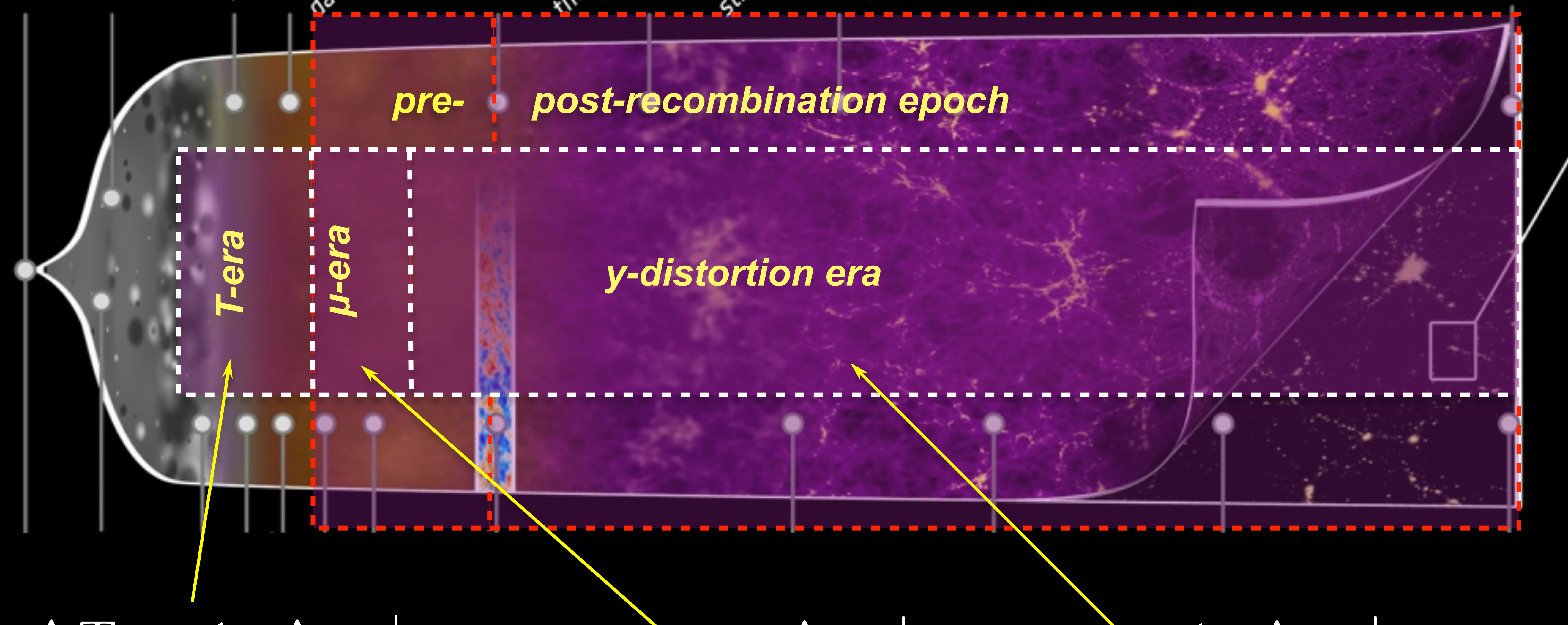
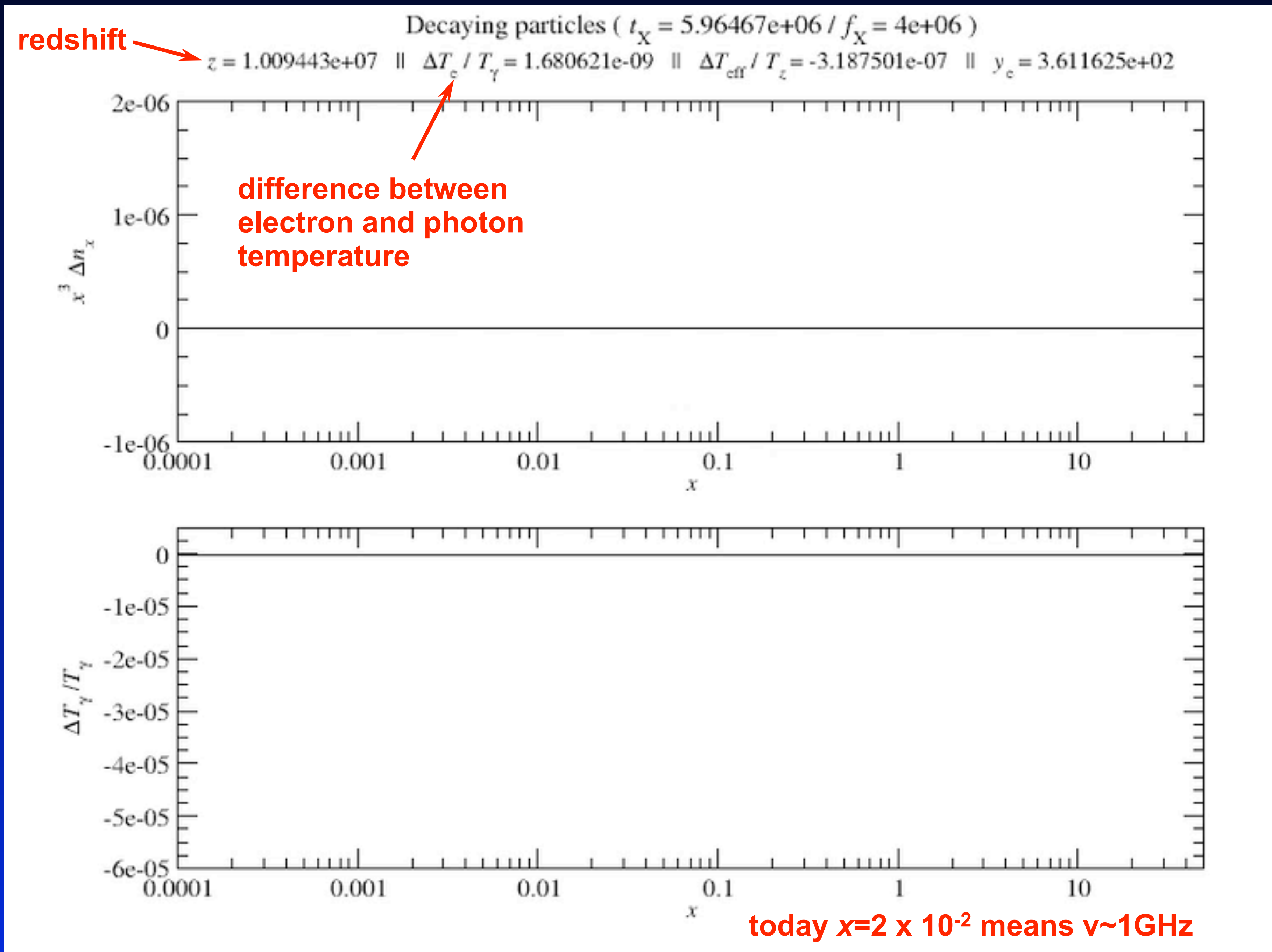






$$\frac{\Delta T}{T} \simeq \frac{1}{4} \left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_T \qquad \mu \simeq 1.4 \left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_\mu \qquad y \simeq \frac{1}{4} \left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_y$$

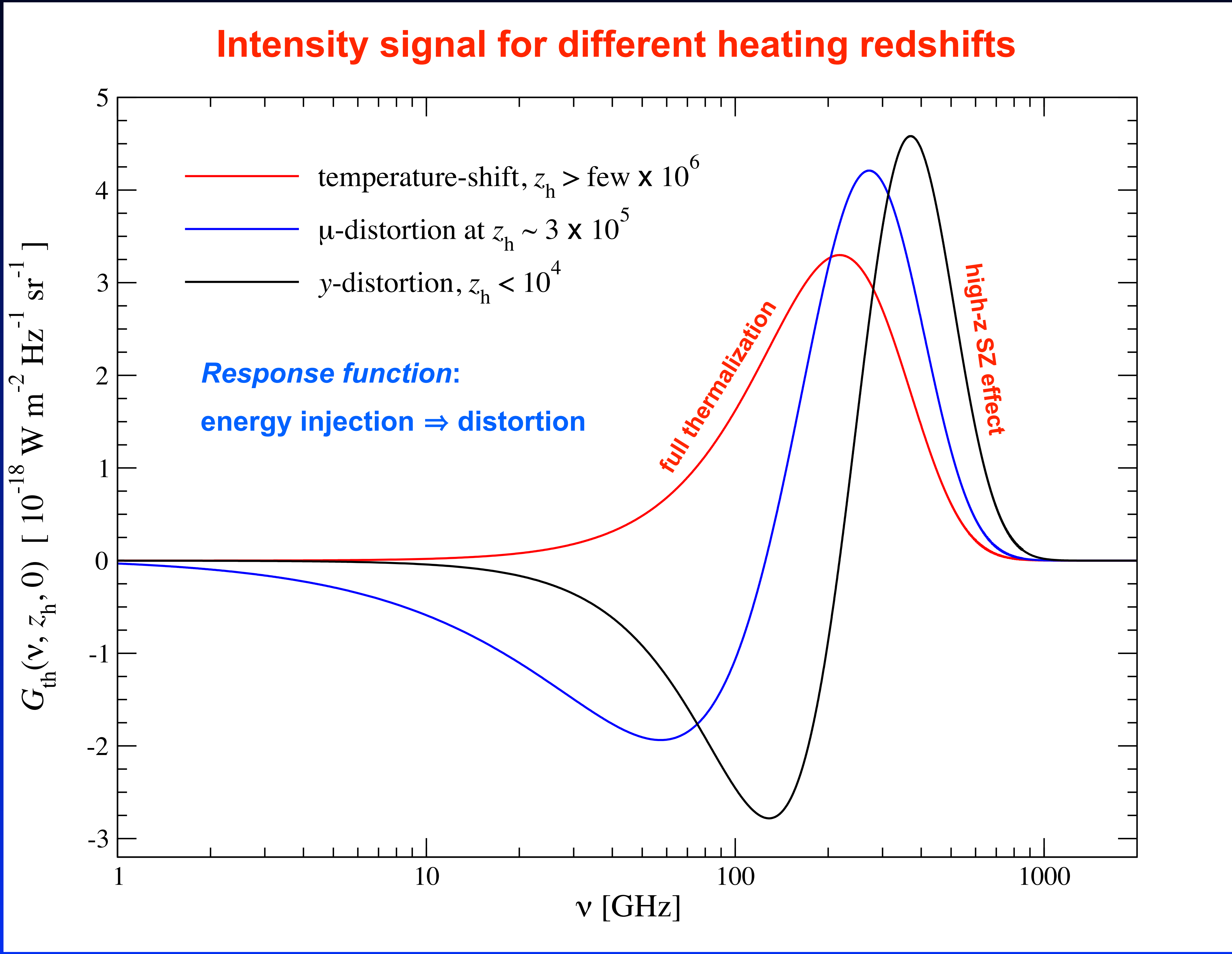
Example: *Energy release by decaying relict particle*



- initial condition: *full equilibrium*
- total energy release: $\Delta\rho/\rho \sim 1.3\times10^{-6}$
- most of energy released around: $z_X \sim 2\times10^{6}$
- positive μ-distortion
- high frequency distortion frozen around $z \simeq 5\times10^{5}$
- 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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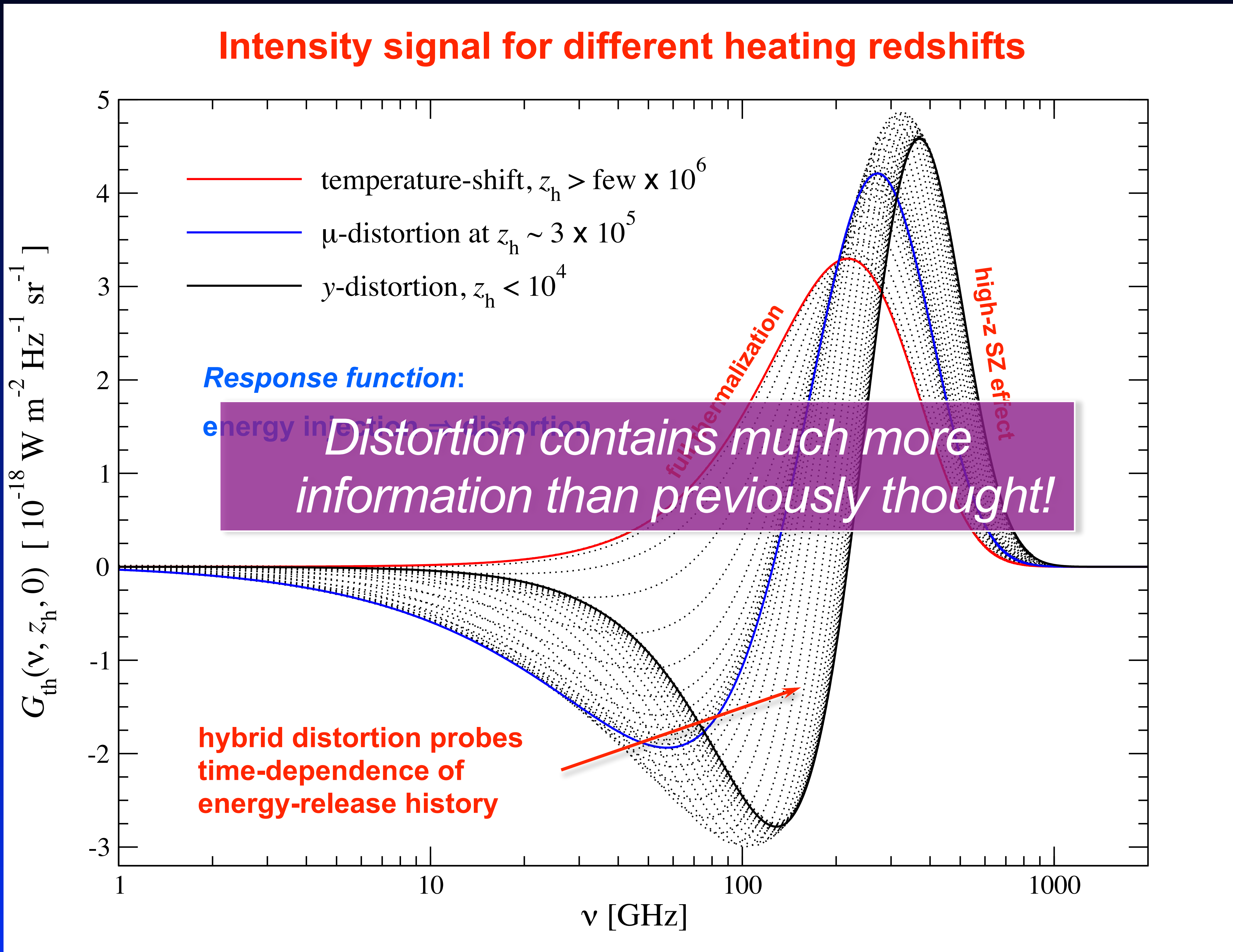

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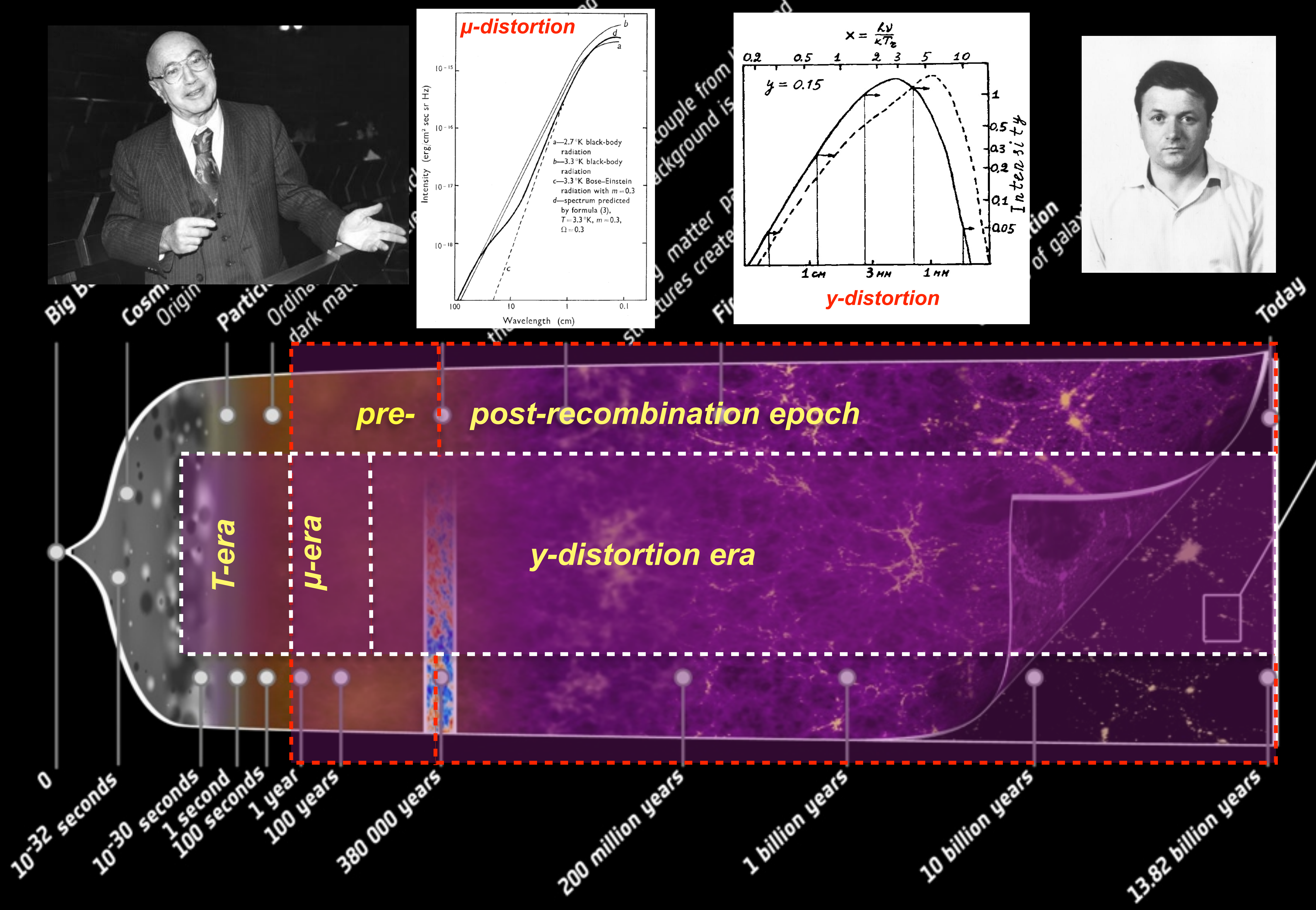
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1 cm
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y-distortion
Today
pre-
post-recombination epoch
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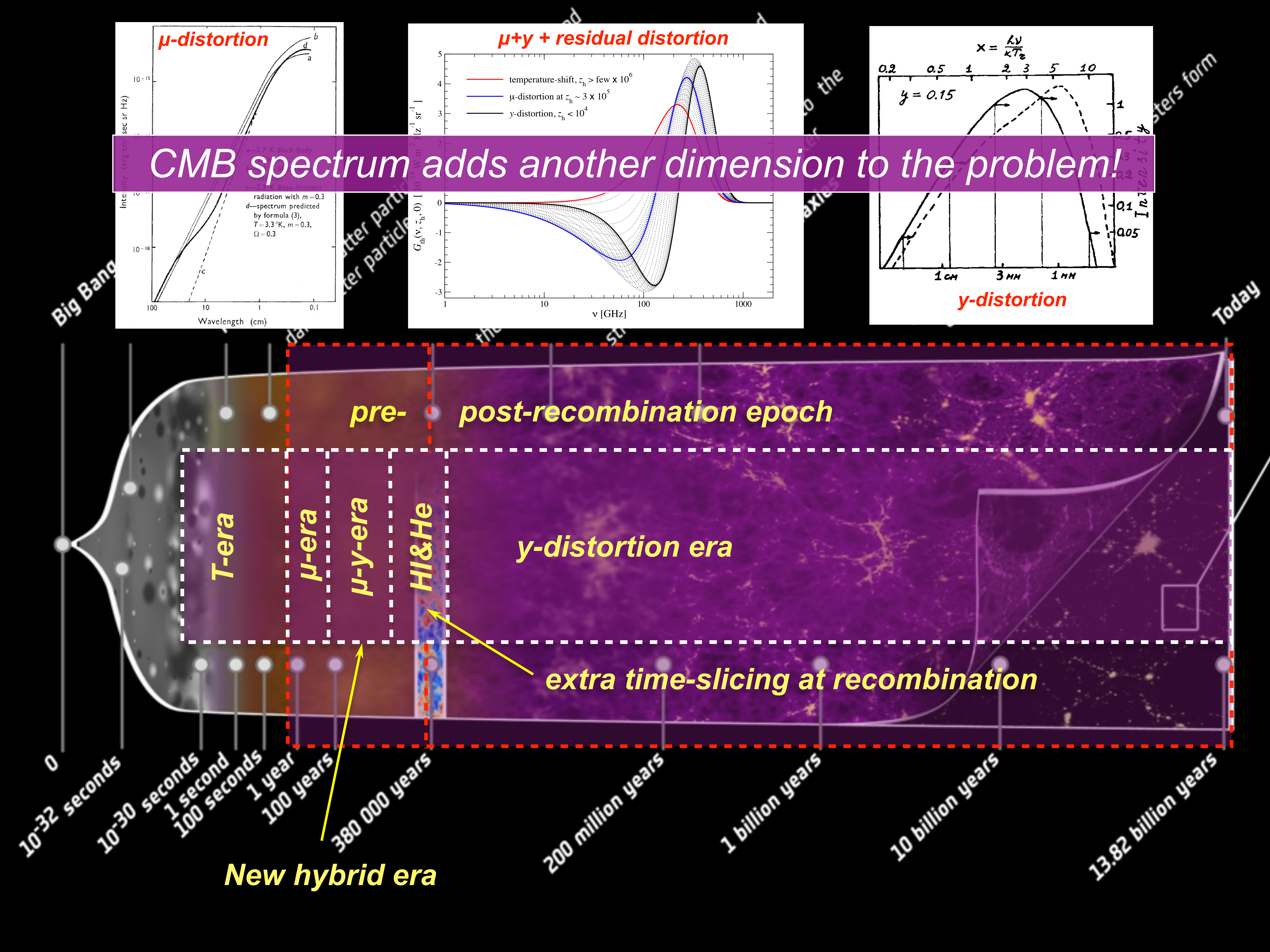
CMB spectrum adds another dimension to the problem!
μ-distortion
Wavelength (cm)
μ+y + residual distortion
temperature-shift, z_h > few x 10^6
μ-distortion at $z_h \sim 3 \times 10^5$
y-distortion, $z_h < 10^4$
ν [GHz]
y-distortion
$x = \frac{h\nu}{kT_e}$
y = 0.15
Big Bang
Today
pre-
post-recombination epoch
T-era
μ-era
μ-y-era
HI&He
y-distortion era
extra time-slicing at recombination
New hybrid era
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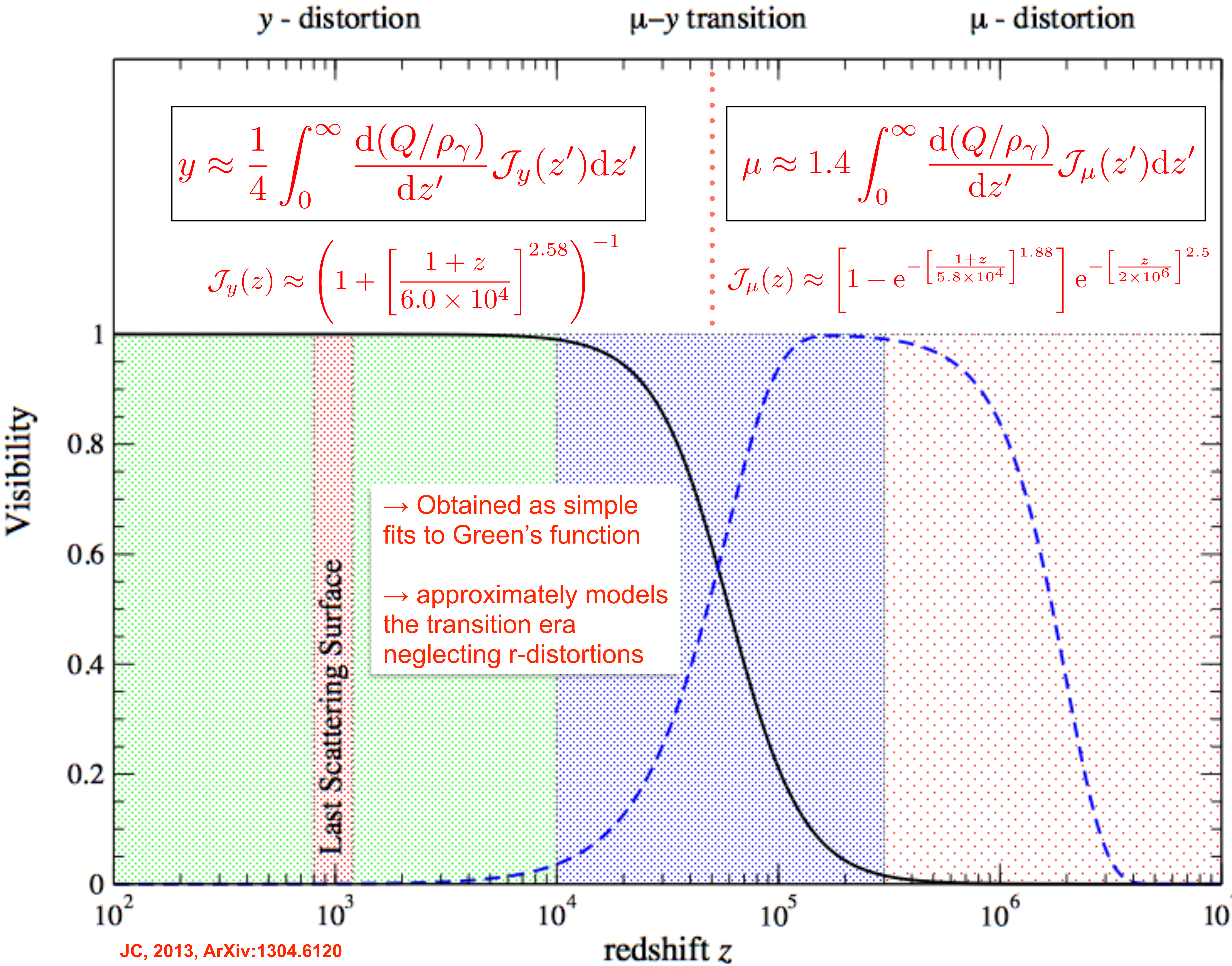

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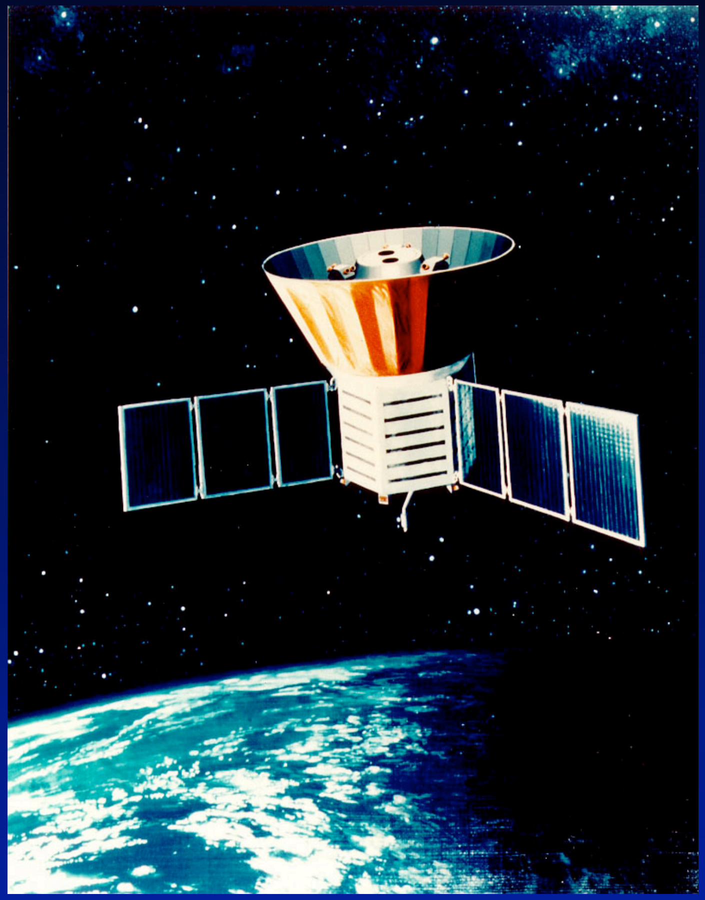
COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)



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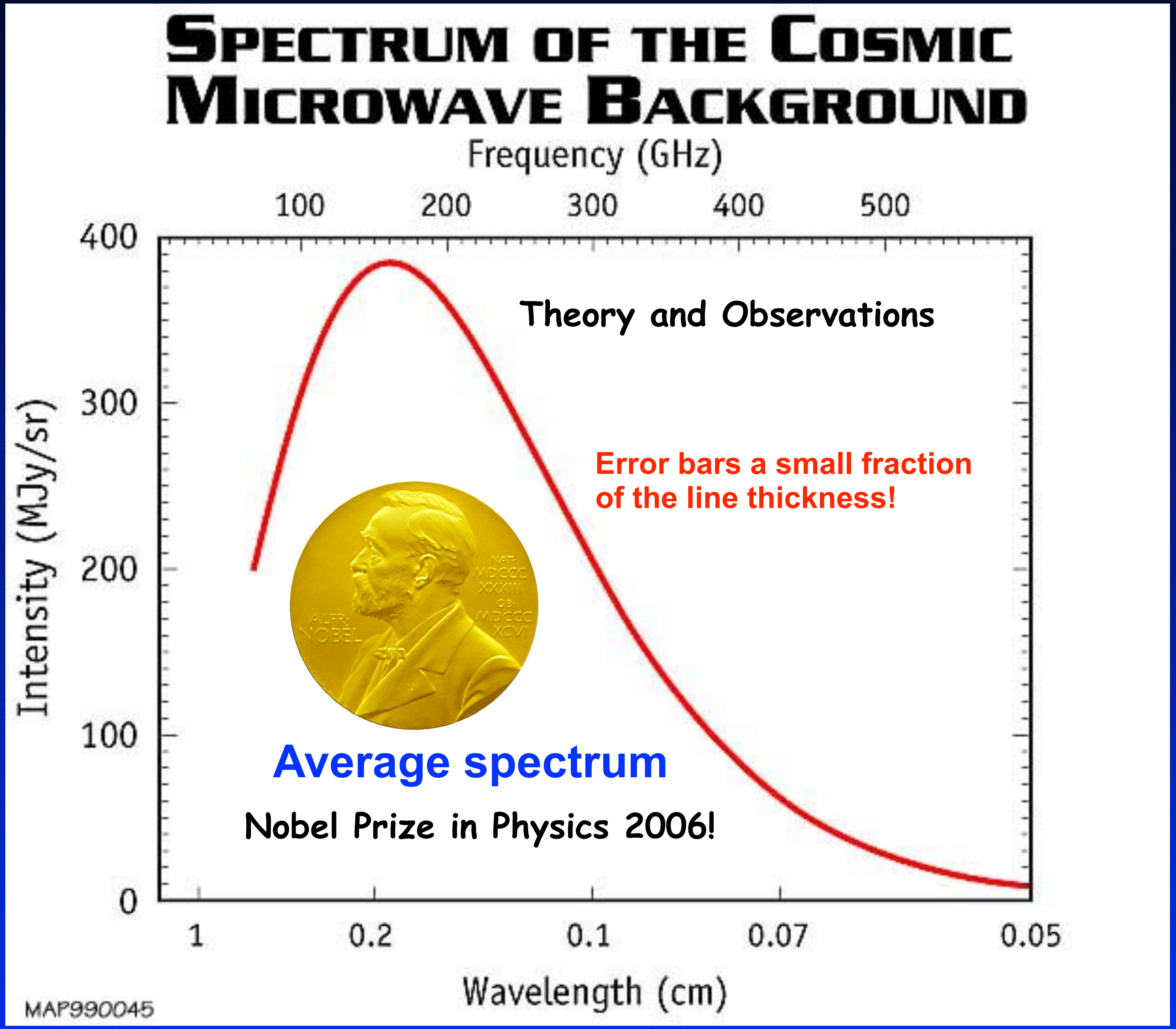

Only very small distortions of CMB spectrum are still allowed!

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)

„high“ redshifts

pre-recombination epoch

„low“ redshifts

post-recombination

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

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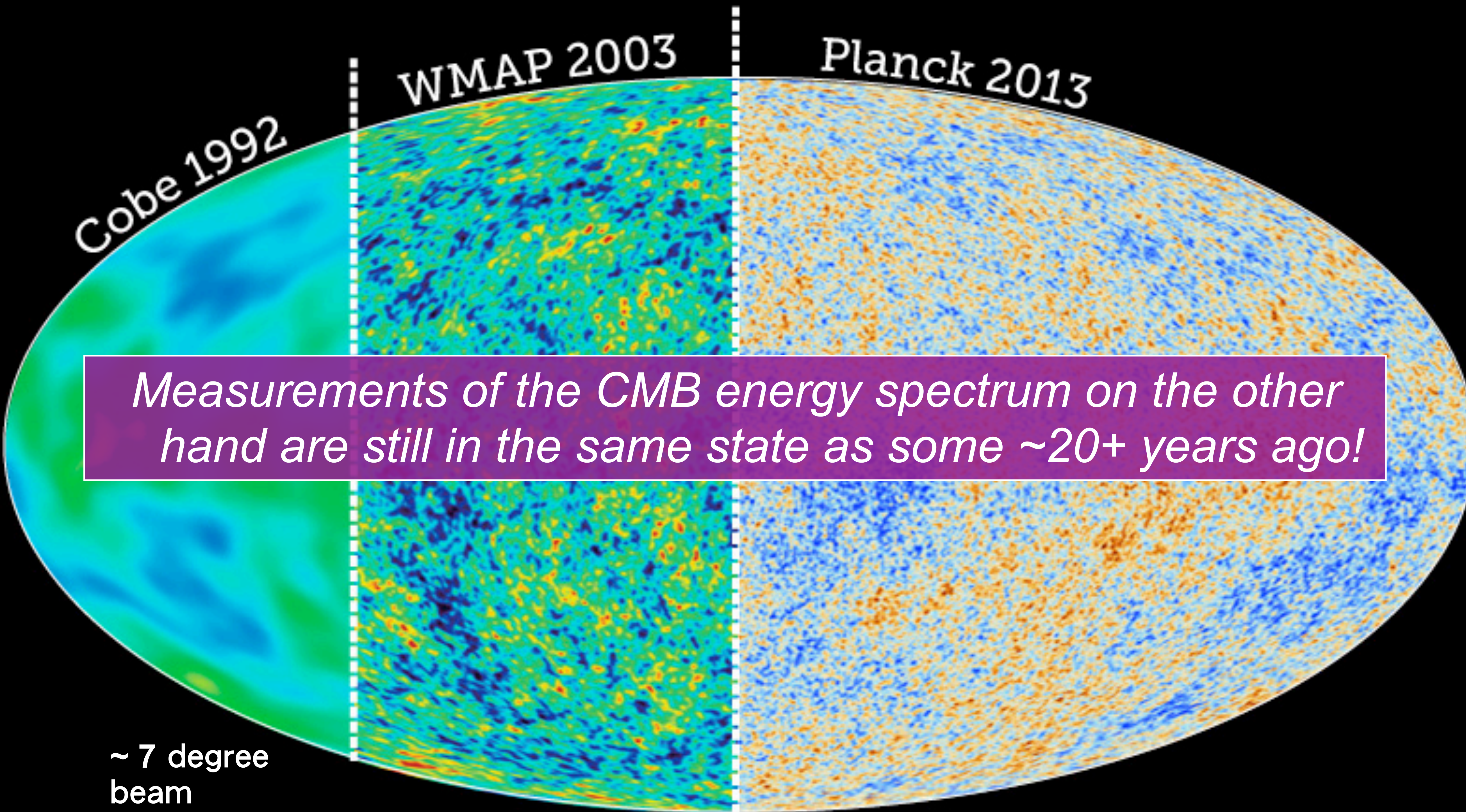
post-recombination

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



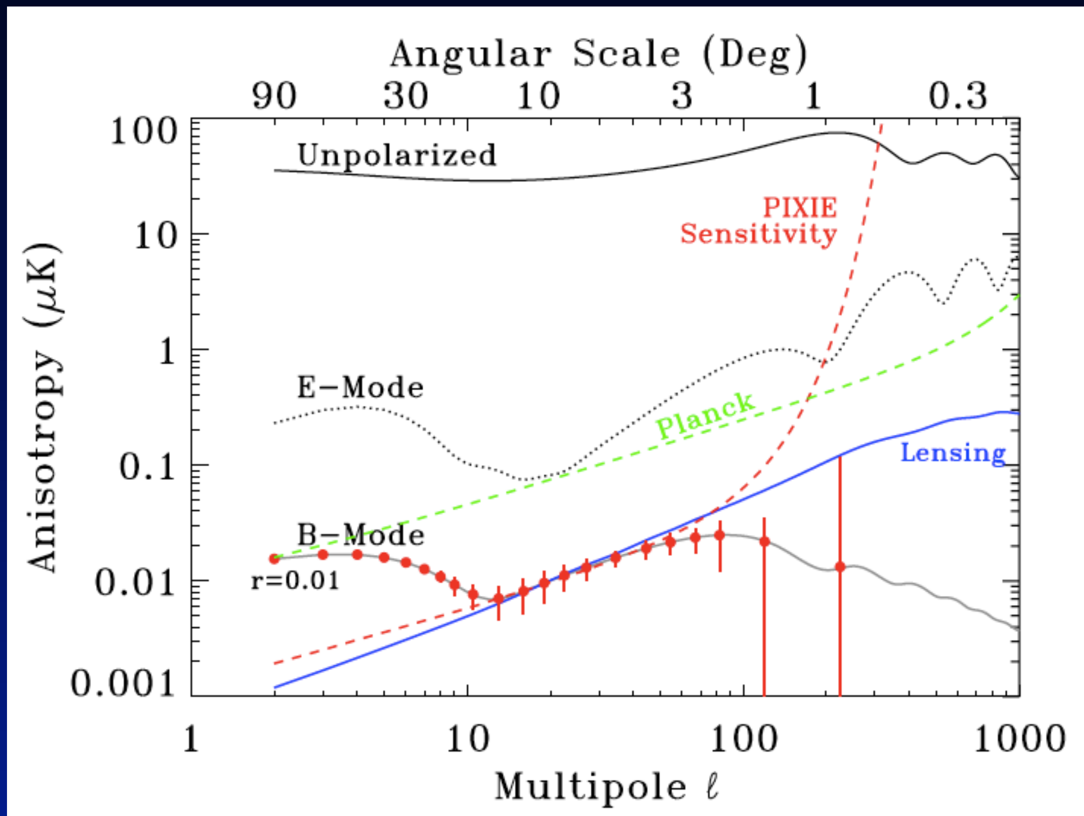
Measurements of the CMB energy spectrum on the other hand are still in the same state as some ~20+ years ago!

~ 7 degree beam

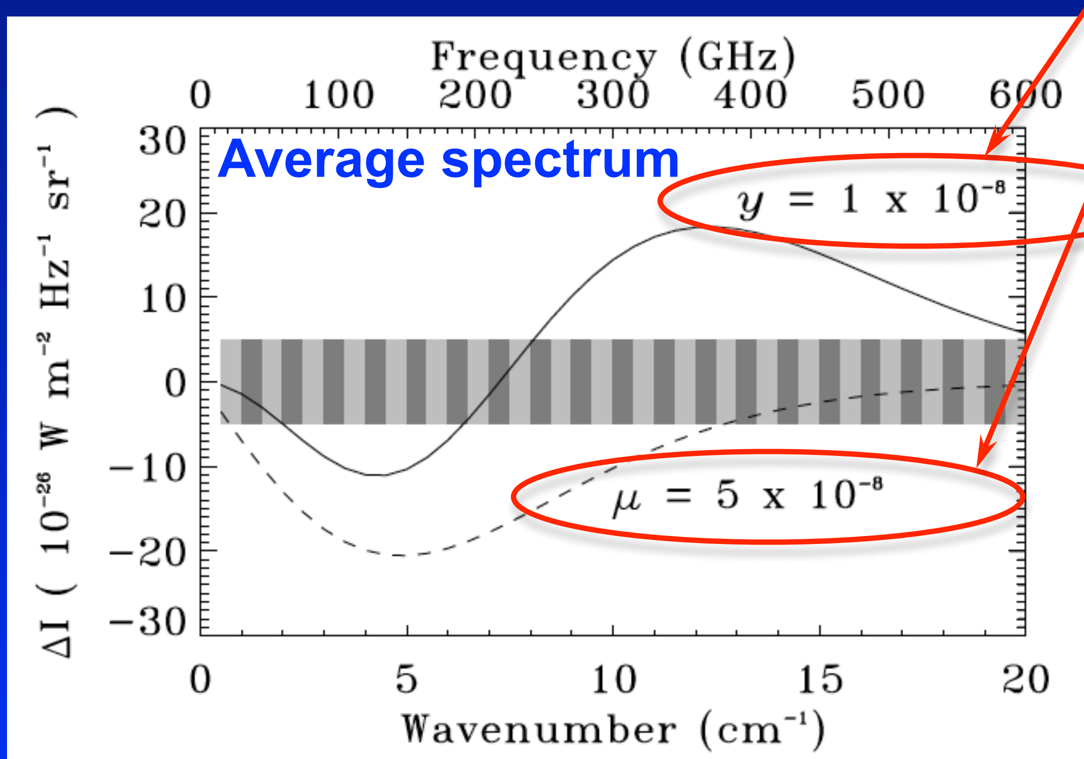
~ 0.3 degree beam

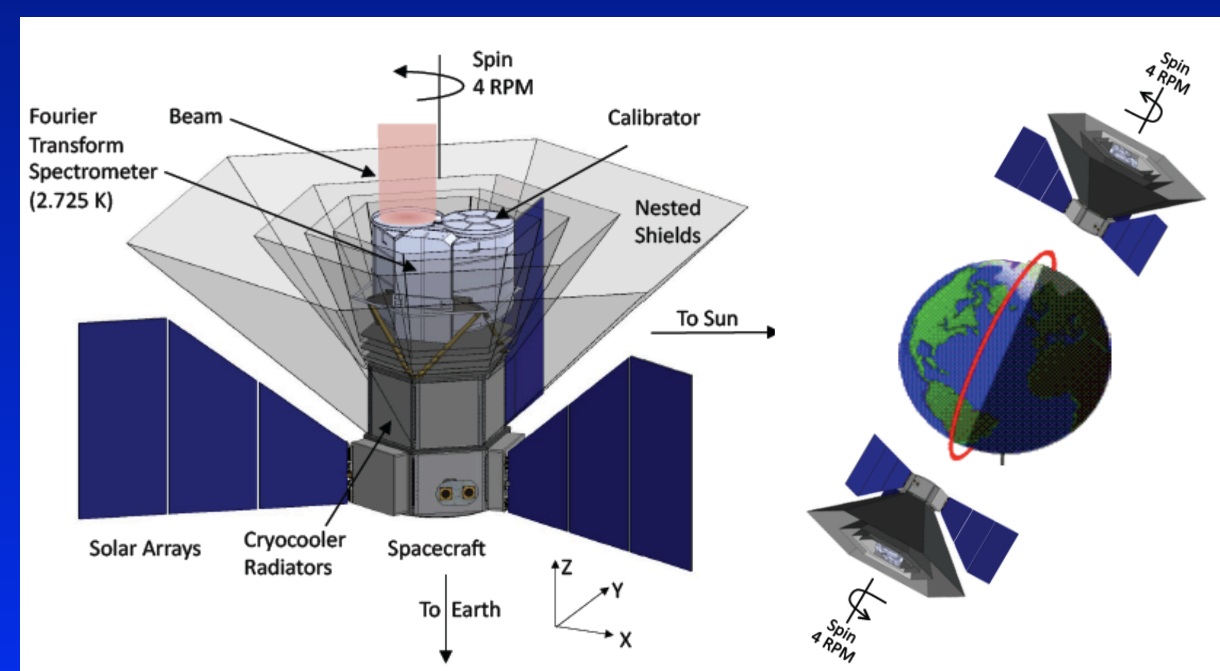
~ 0.08 degree beam

PIXIE: Primordial Inflation Explorer

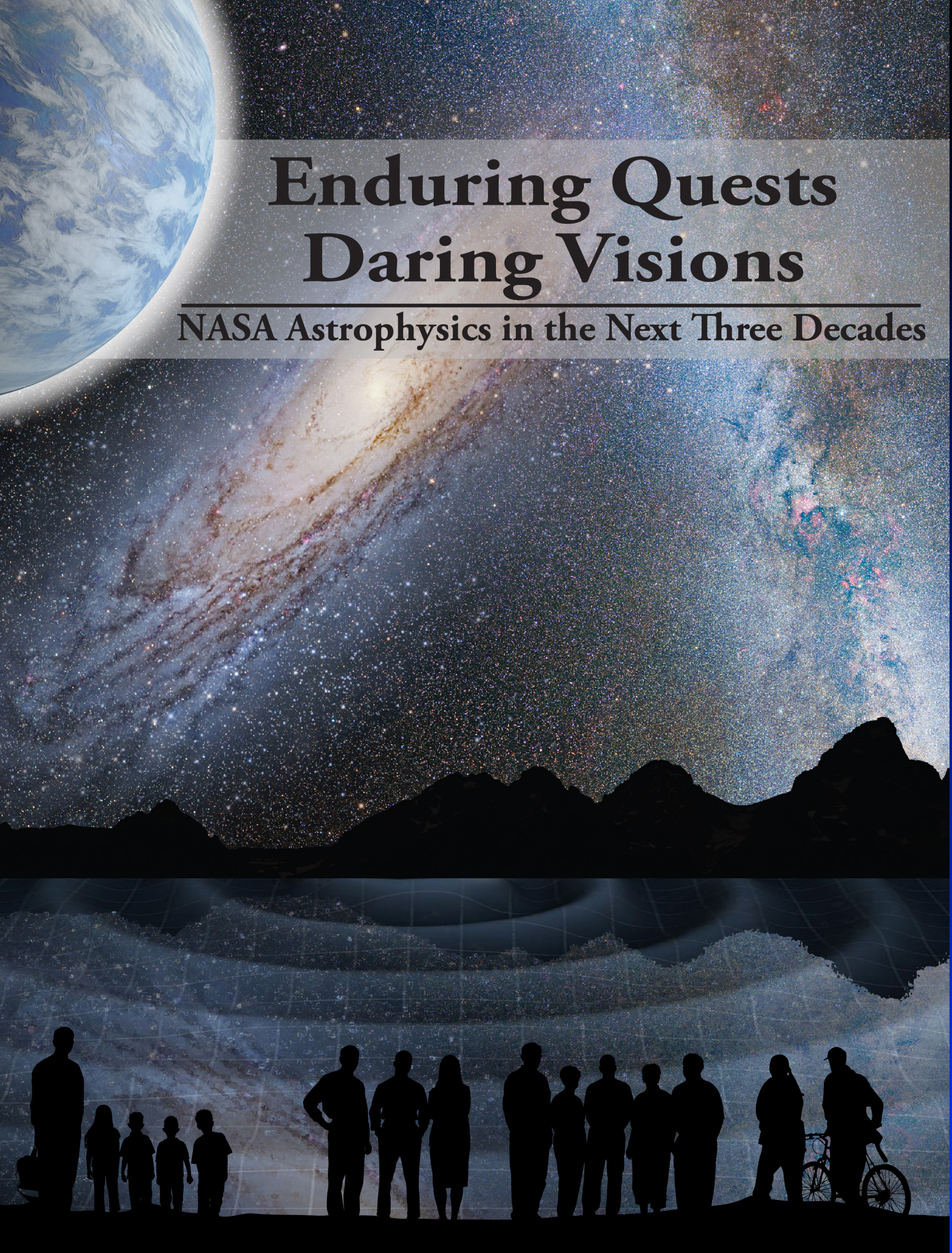


- 400 spectral channel in the frequency range 30 GHz and 6THz (Δν ~ 15GHz)
- about 1000 (!!!) times more sensitive than COBE/FIRAS
- B-mode polarization from inflation ($r \approx 10^{-3}$)
- improved limits on μ and y
- was proposed 2011 as NASA EX mission (i.e. cost ~ 200 M$)





Kogut et al, JCAP, 2011, arXiv:1105.2044



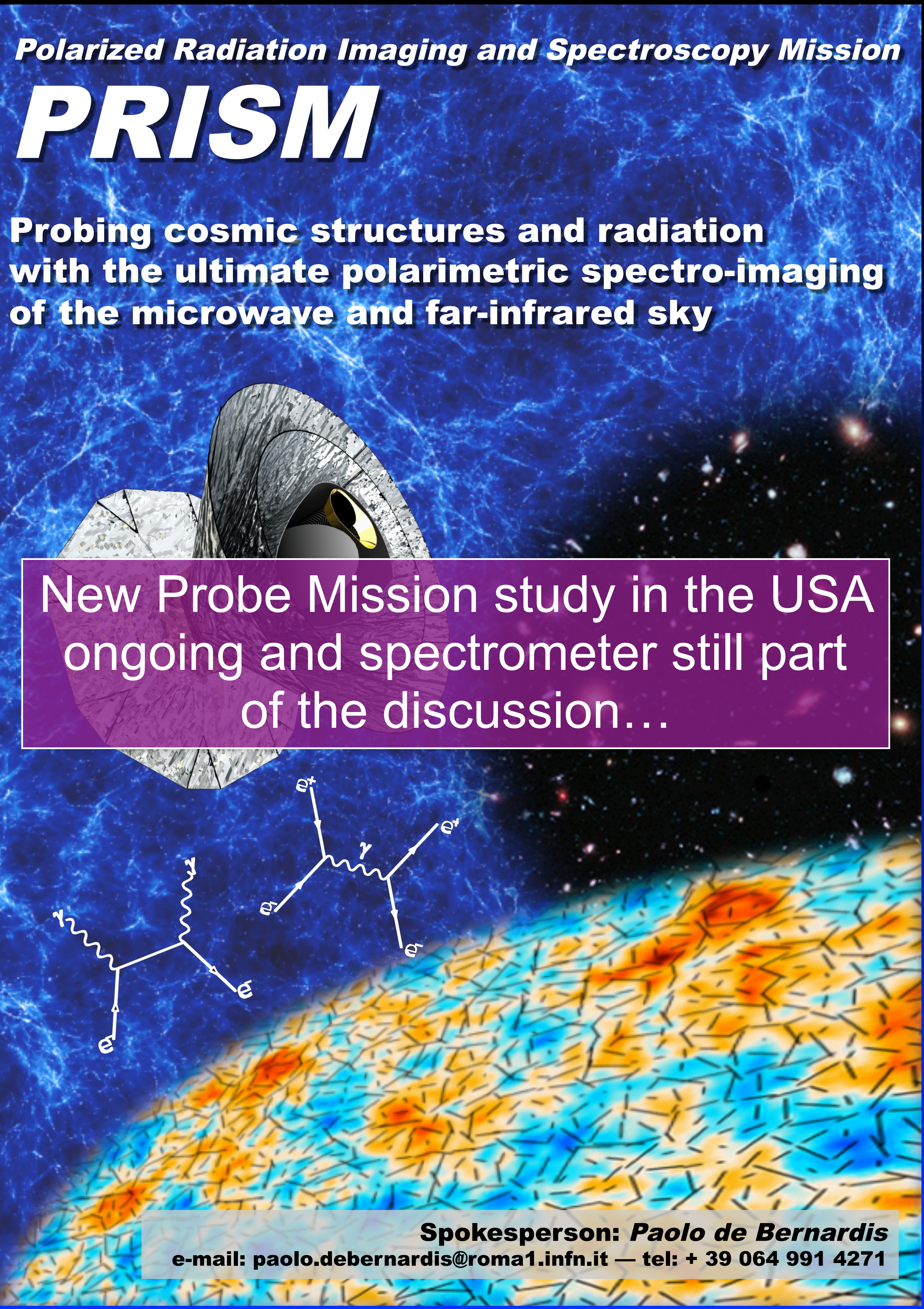
NASA 30-yr Roadmap Study

(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. Sadly not selected :(:(



New Probe Mission study in the USA ongoing and spectrometer still part of the discussion…

Instruments:

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

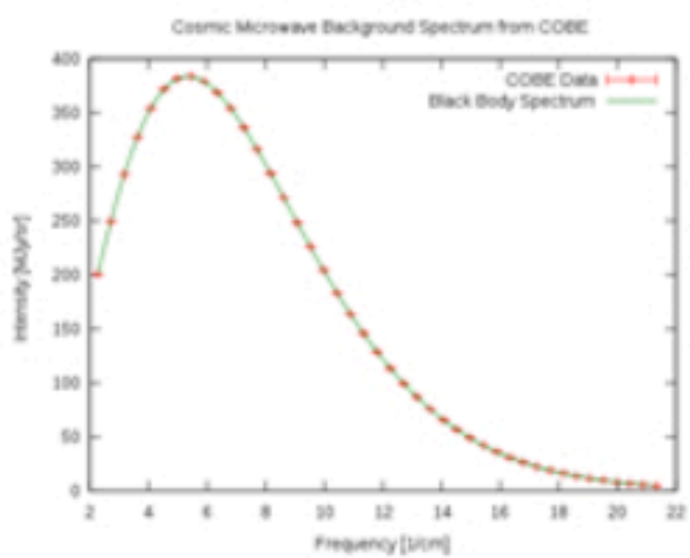
Some of the science goals:

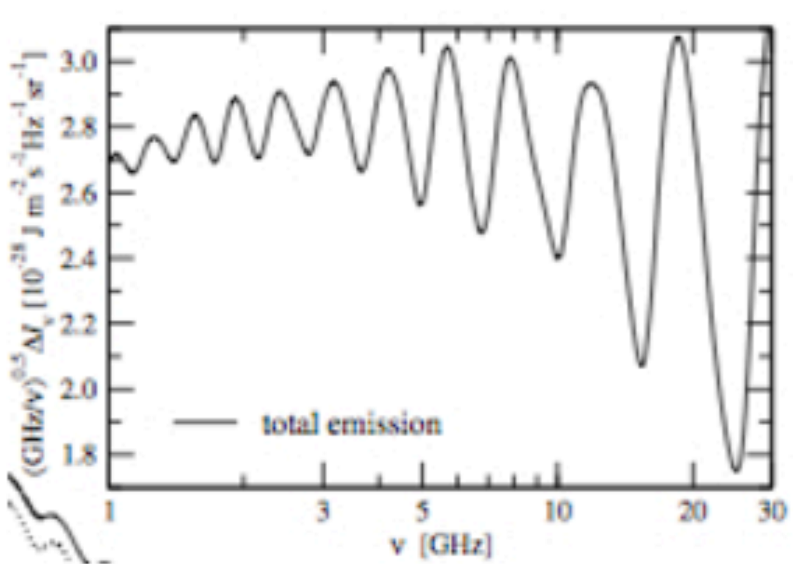
- B-mode polarization from inflation ($r \approx 5 \times 10^{-4}$)
- count all SZ clusters $>10^{14}$ M_{sun}
- CIB/large scale structure
- Galactic science
- *CMB spectral distortions*

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.

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  (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

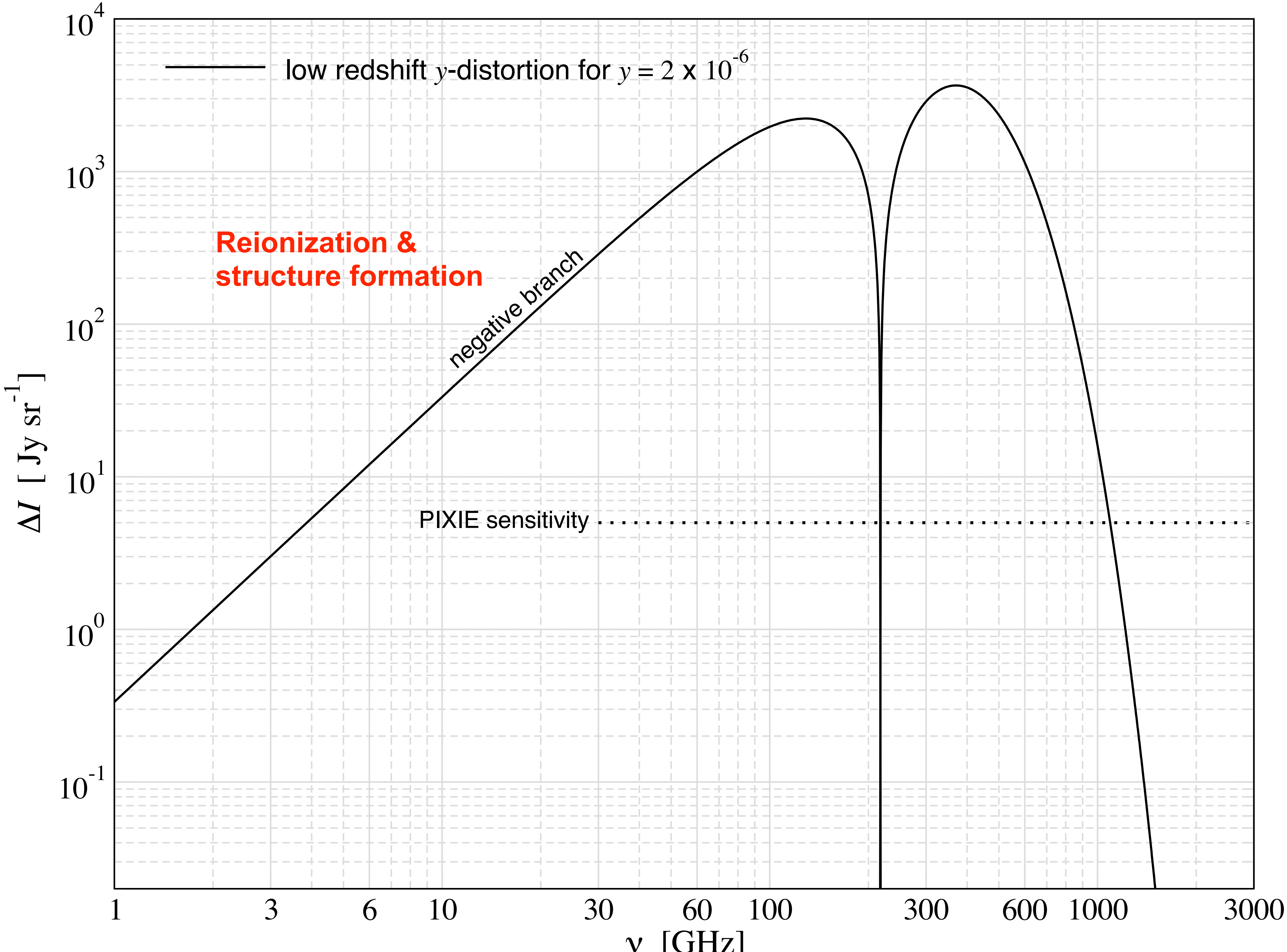
„high“ redshifts

„low“ redshifts

post-recombination

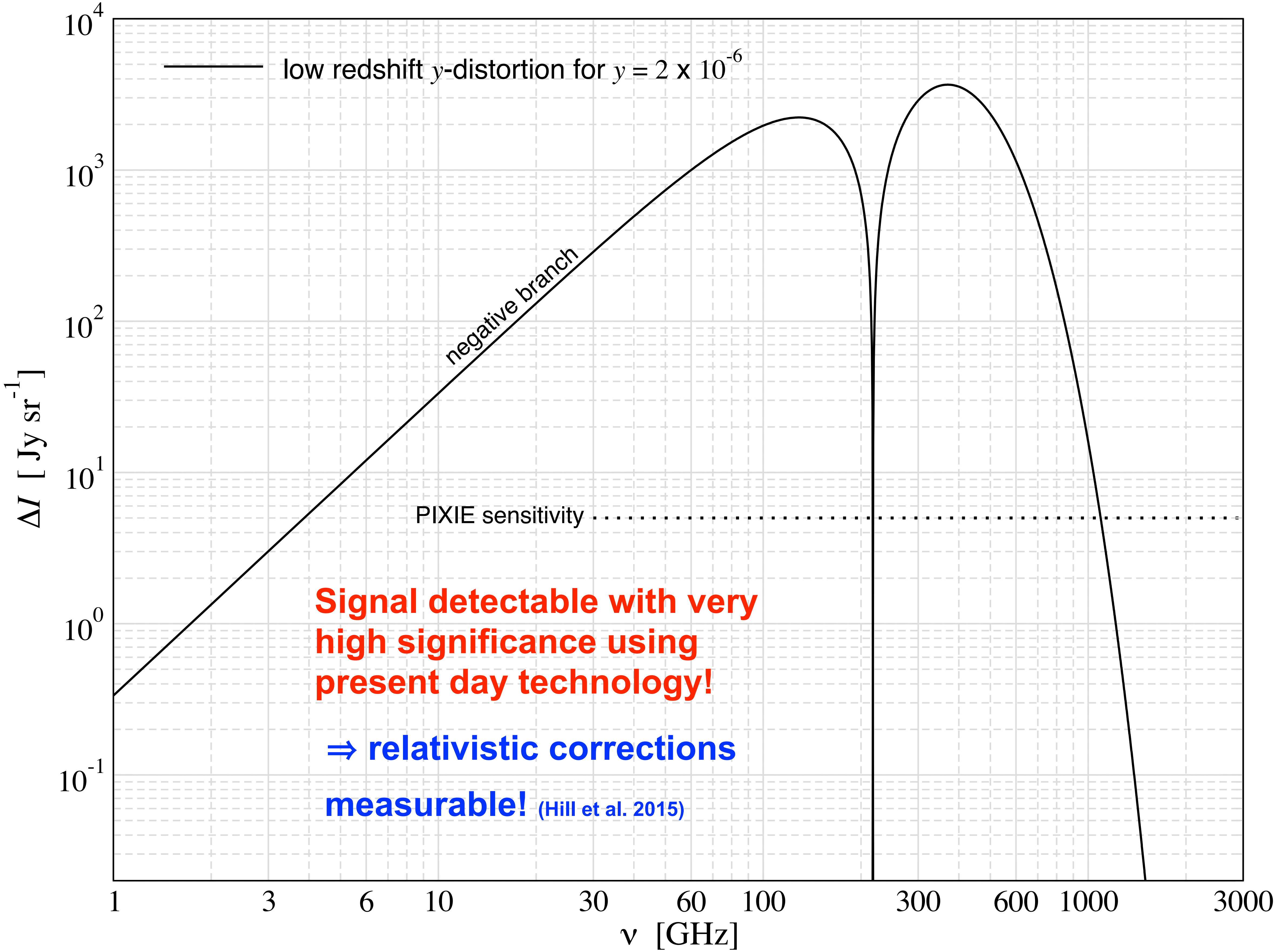
- Signatures due to first supernovae and their remnants
  (Oh, Cooray & Kamionkowski, 2003)
- Shock waves arising due to large-scale structure formation
  (Sunyaev & Zeldovich, 1972; Cen & Ostriker, 1999)
- SZ-effect from clusters; effects of reionization
  (Refregier et al., 2003; Zhang et al. 2004;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

Average CMB spectral distortions

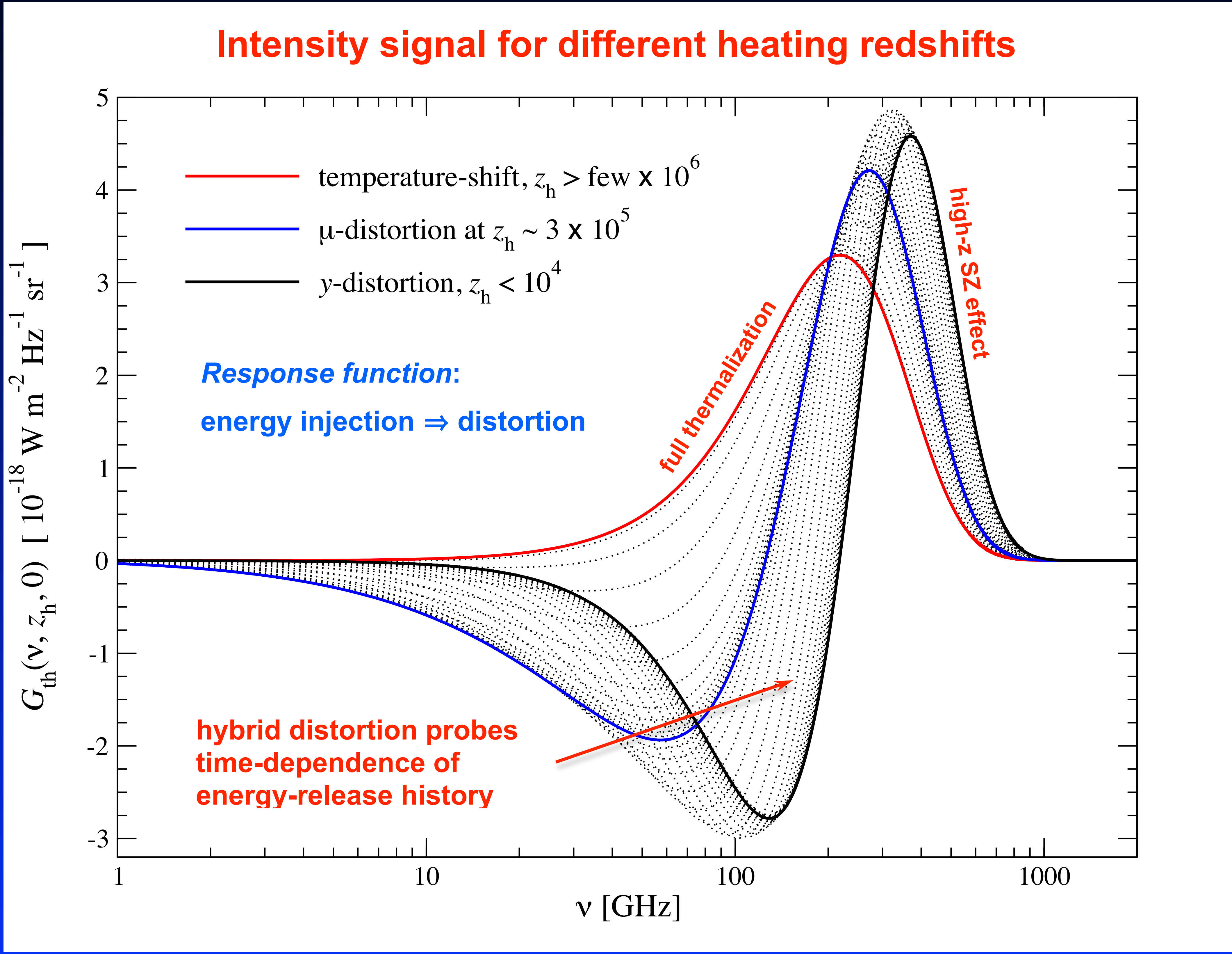


JC, 2016, MNRAS (ArXiv:1603.02496)

Average CMB spectral distortions



What does the spectrum look like after energy injection?



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

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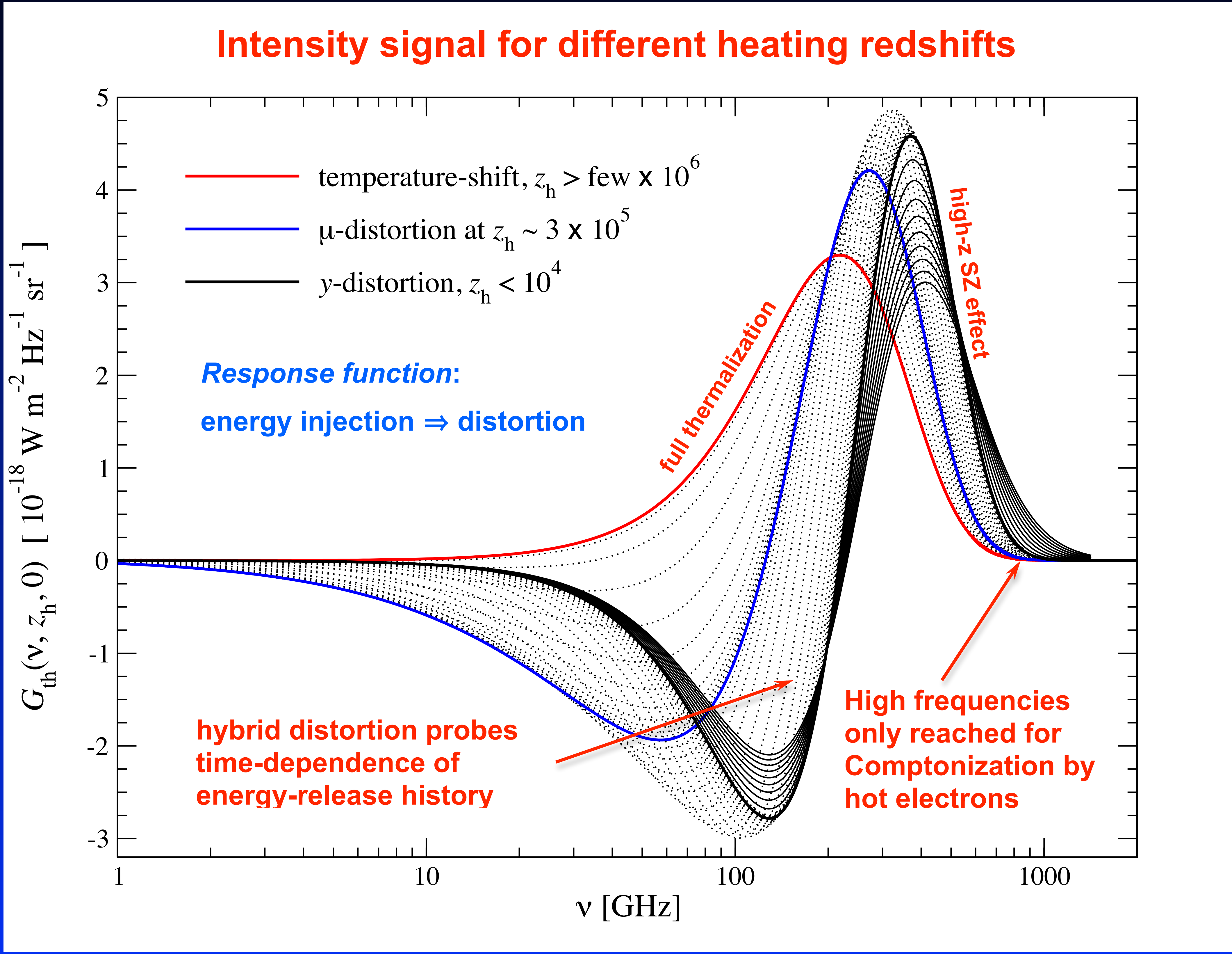

JC & Sunyaev, 2012, ArXiv:1109.6552
JC, 2013, ArXiv:1304.6120

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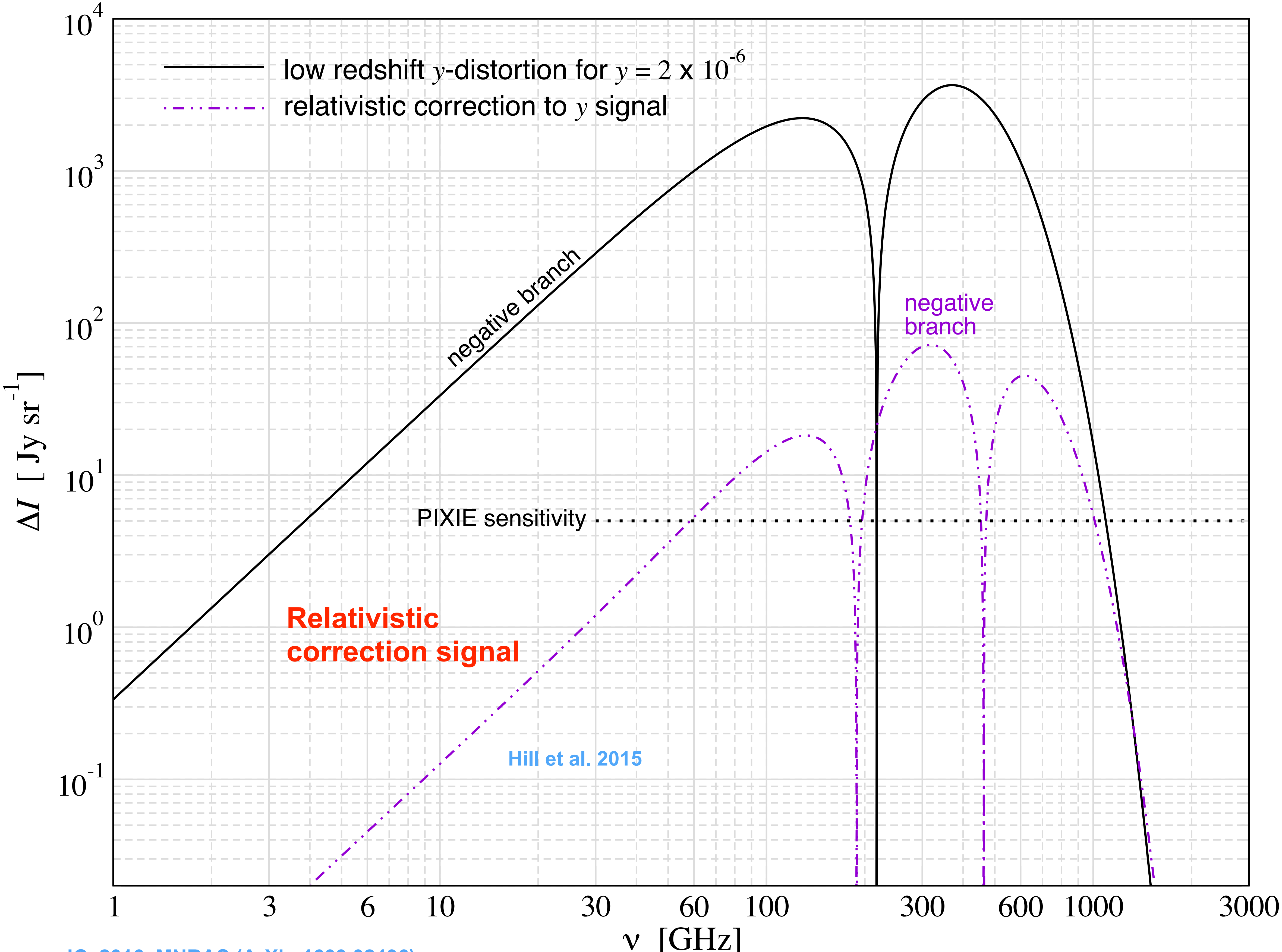
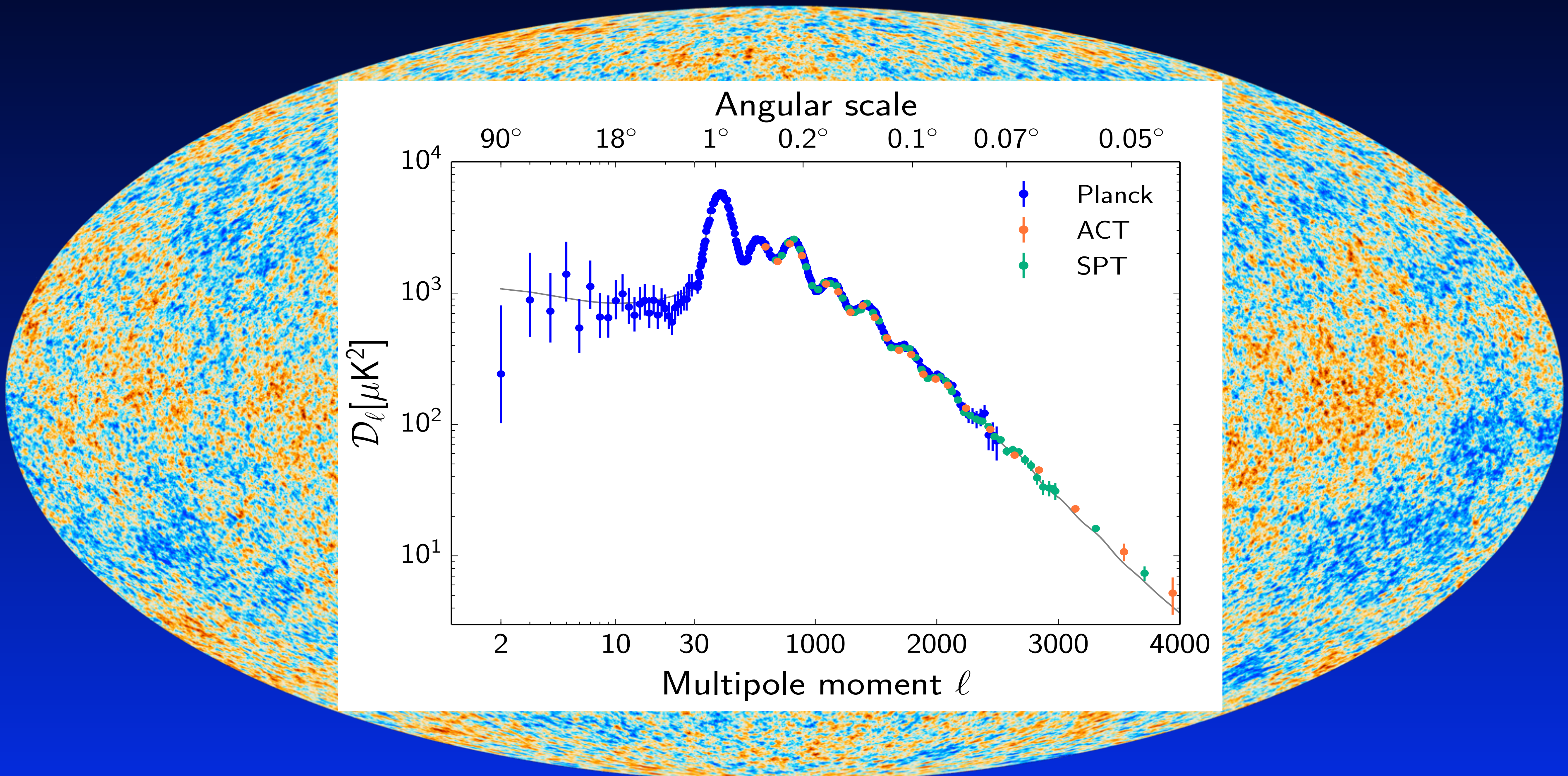
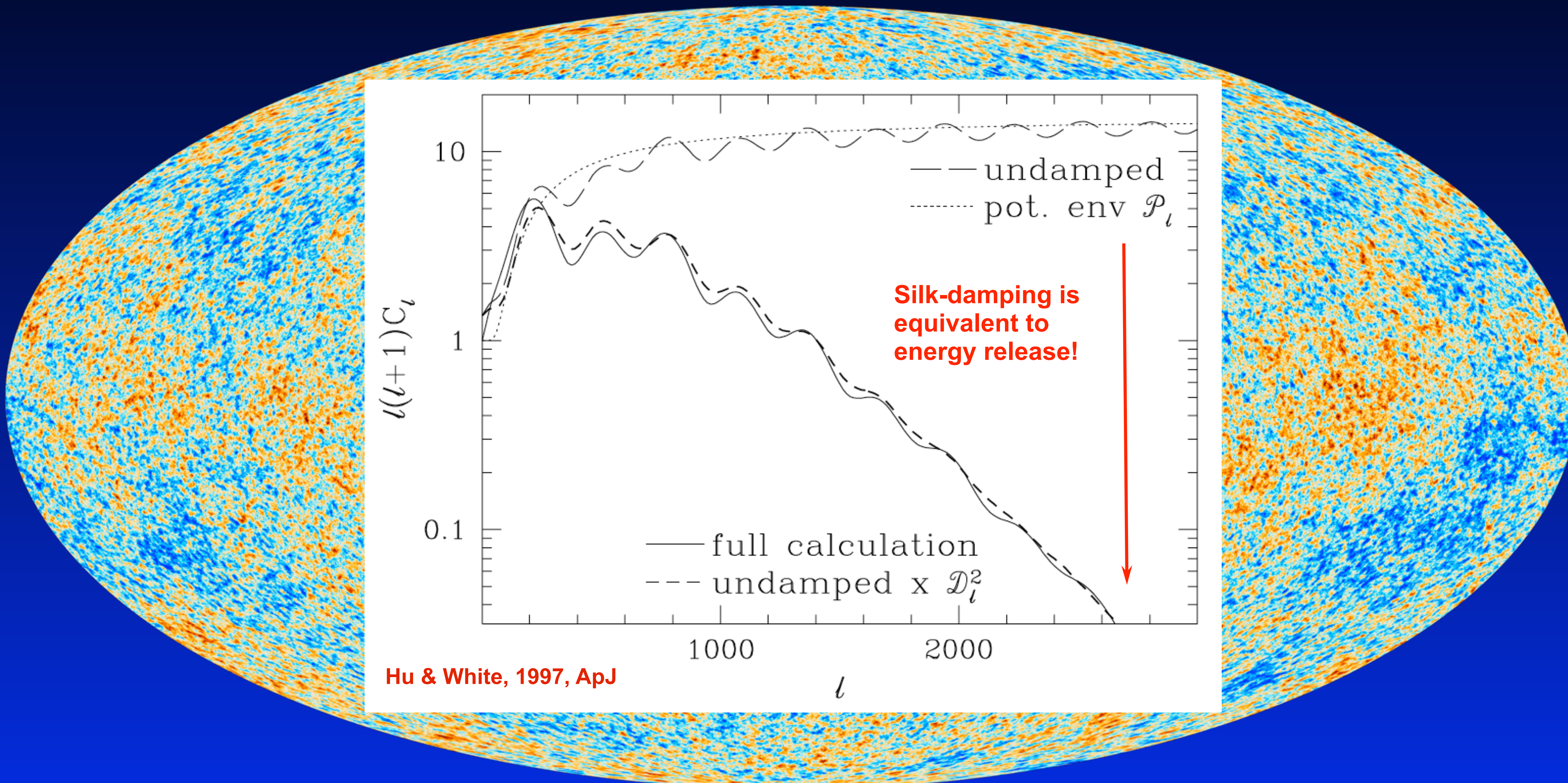


JC, 2016, MNRAS (ArXiv:1603.02496)

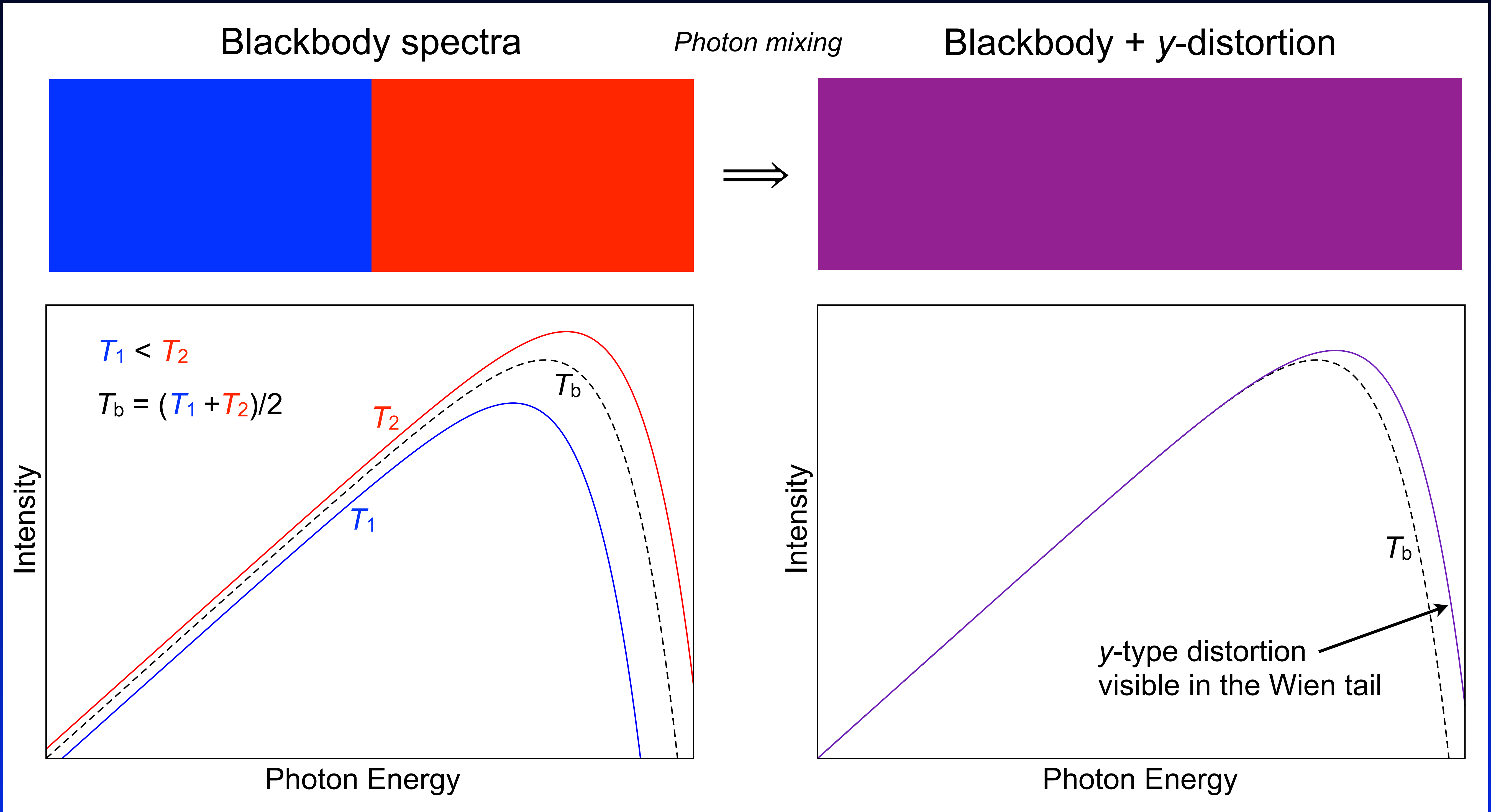
Dissipation of small-scale acoustic modes



Dissipation of small-scale acoustic modes



Distortion due to mixing of blackbodies



JC, Hamann & Patil, 2015

Early power spectrum constraints from FIRAS

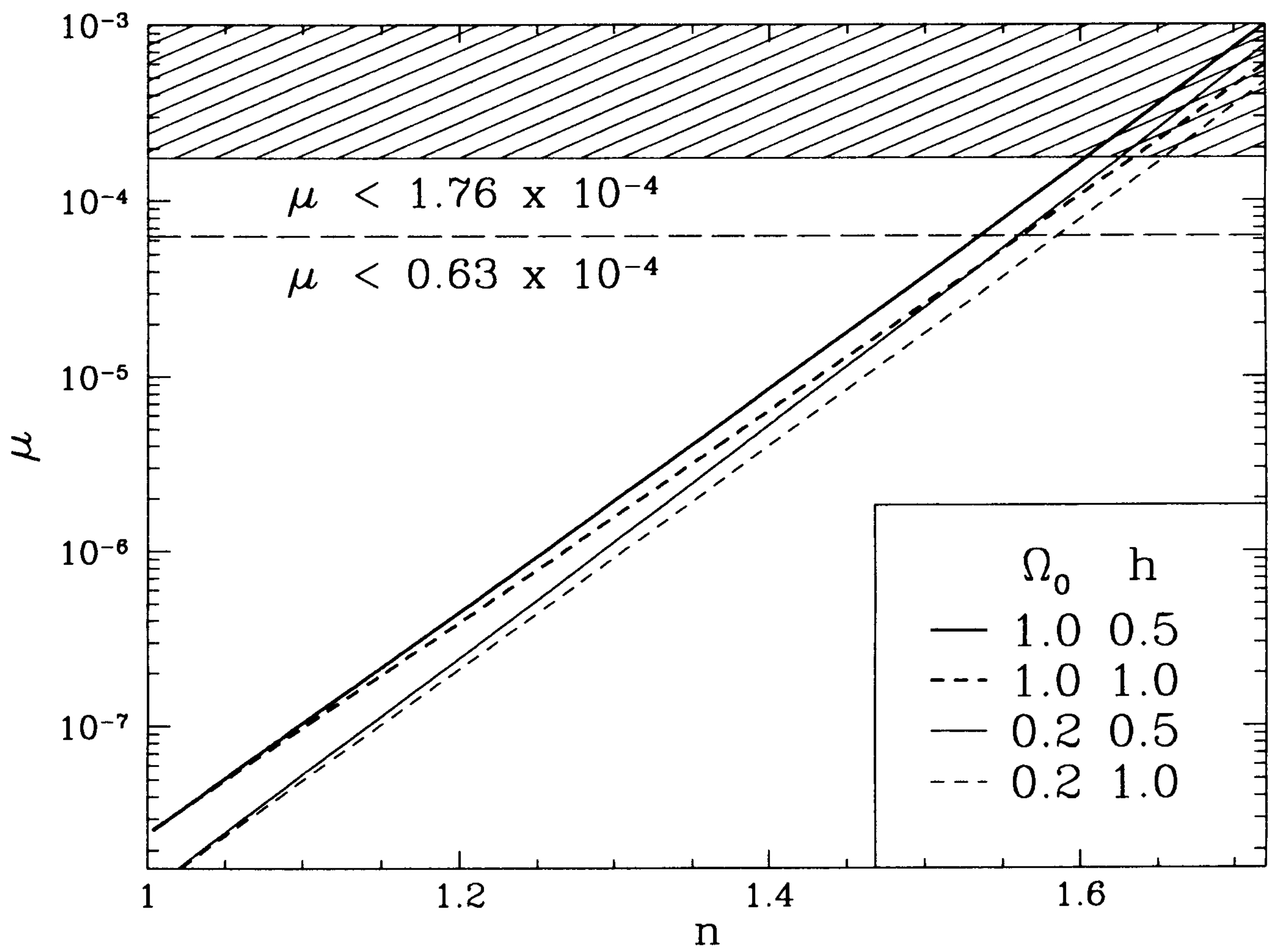


FIG. 1.—Spectral distortion μ, predicted from the full eq. (11), as a function of the power index n for a normalization at the mean of the *COBE* DMR detection $(\Delta T/T)_{10^\circ} = 1.12 \times 10^{-5}$. With the uncertainties on *both* the DMR and FIRAS measurements, the conservative 95% upper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

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

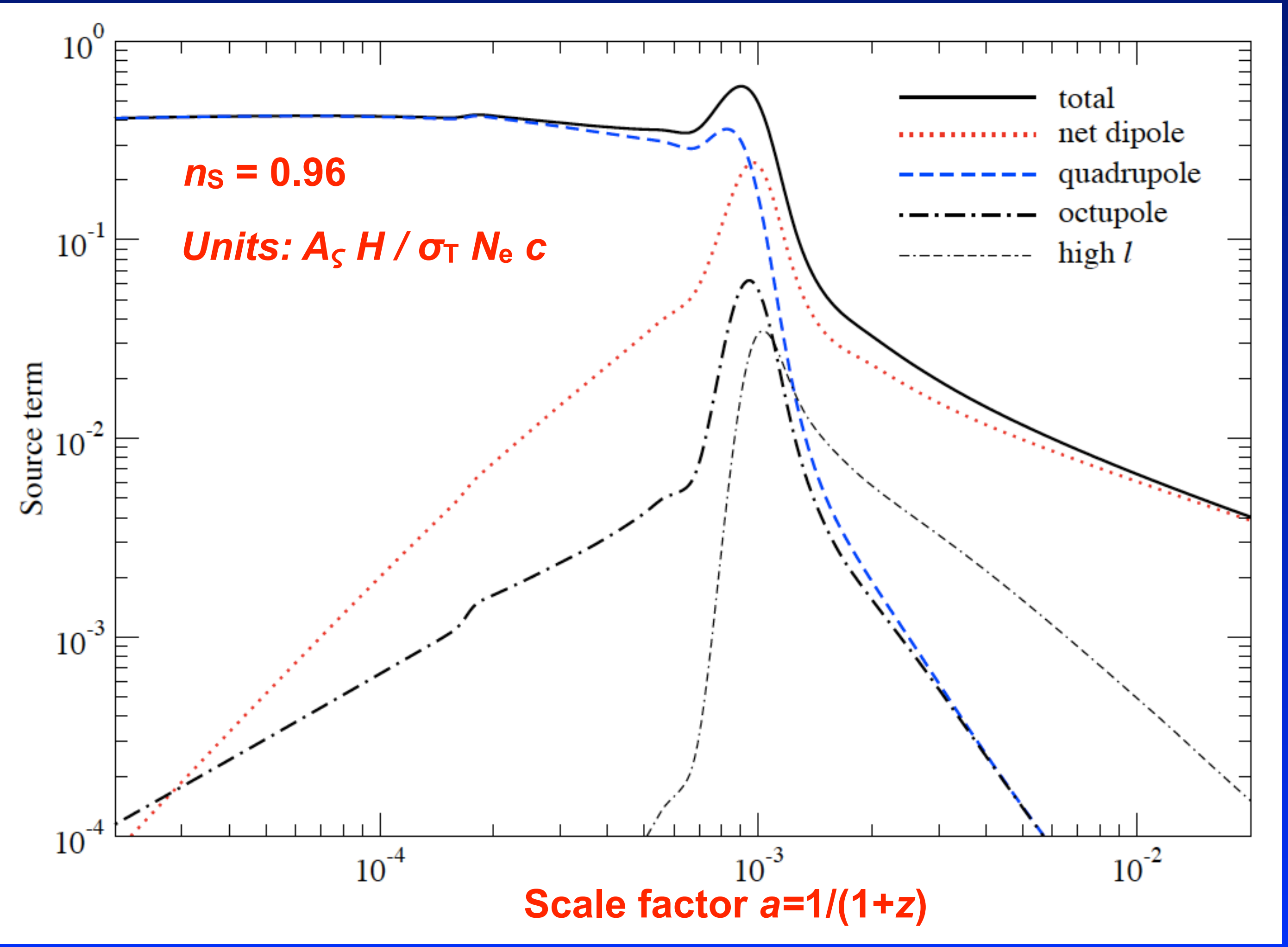
$$\Theta_\ell = \frac{1}{2}\int \Theta(\mu) P_\ell(\mu)\mathrm{d}\mu$$

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

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

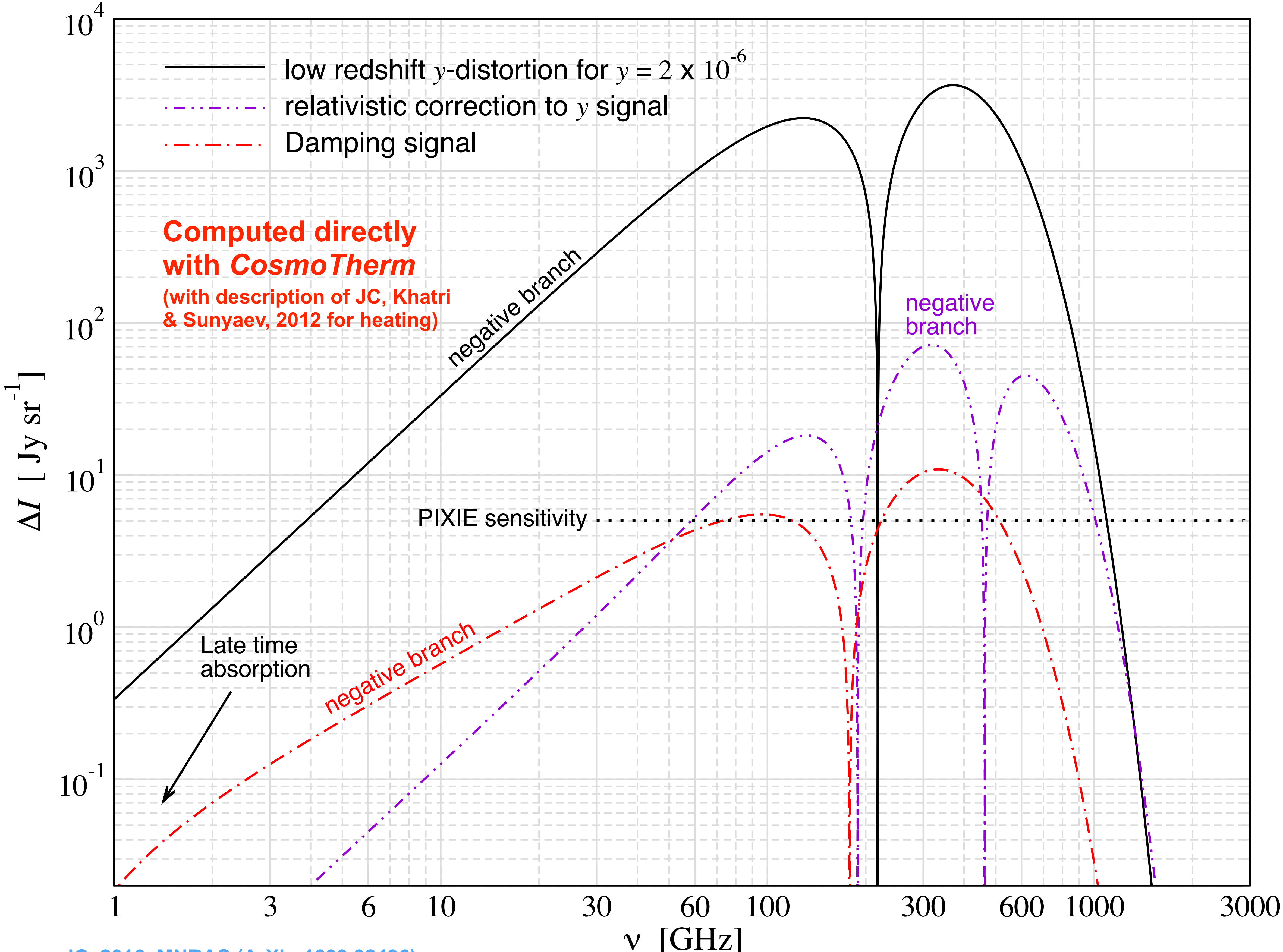
Primordial power spectrum

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



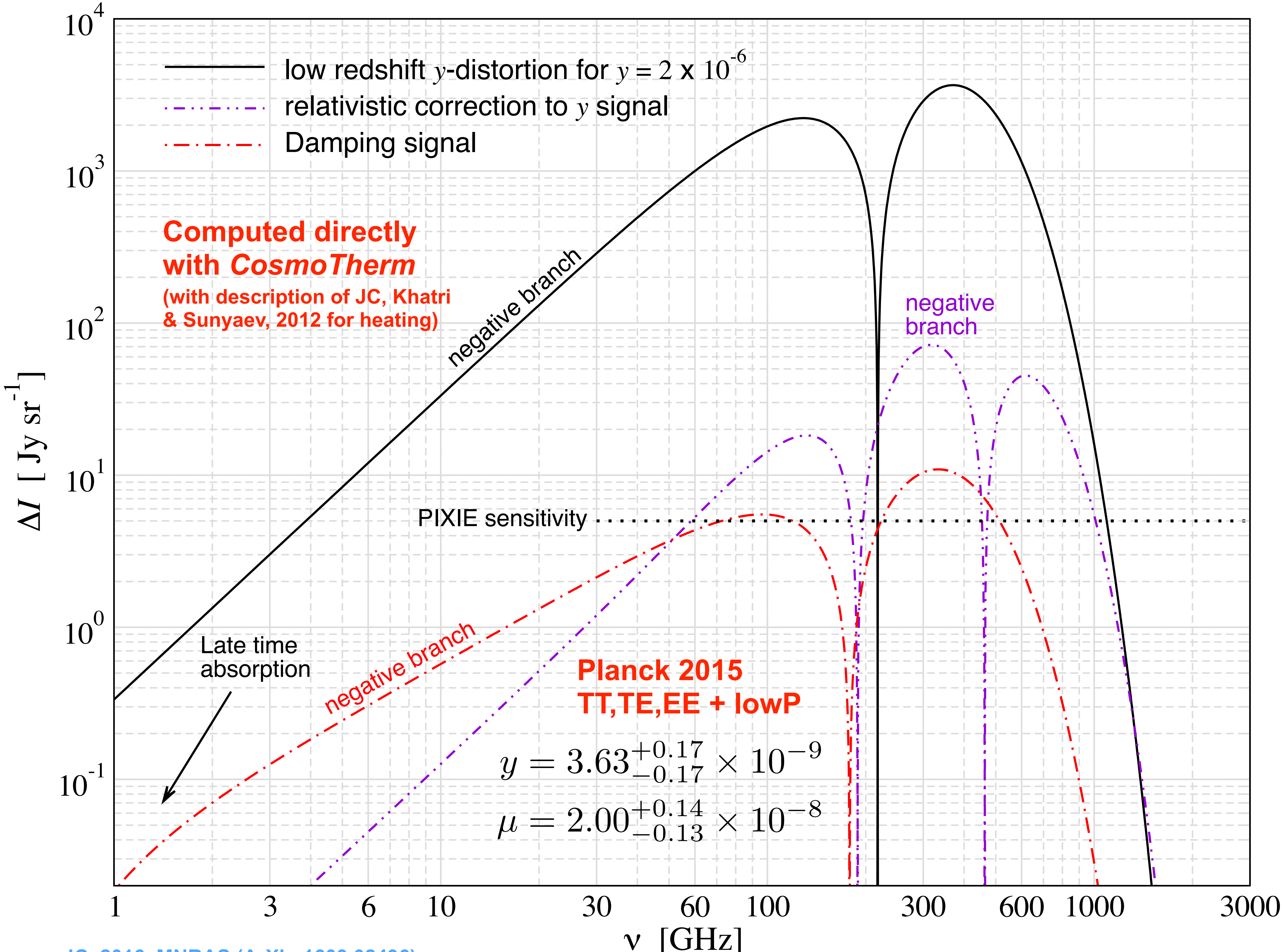
JC, Khatri & Sunyaev, 2012

Average CMB spectral distortions



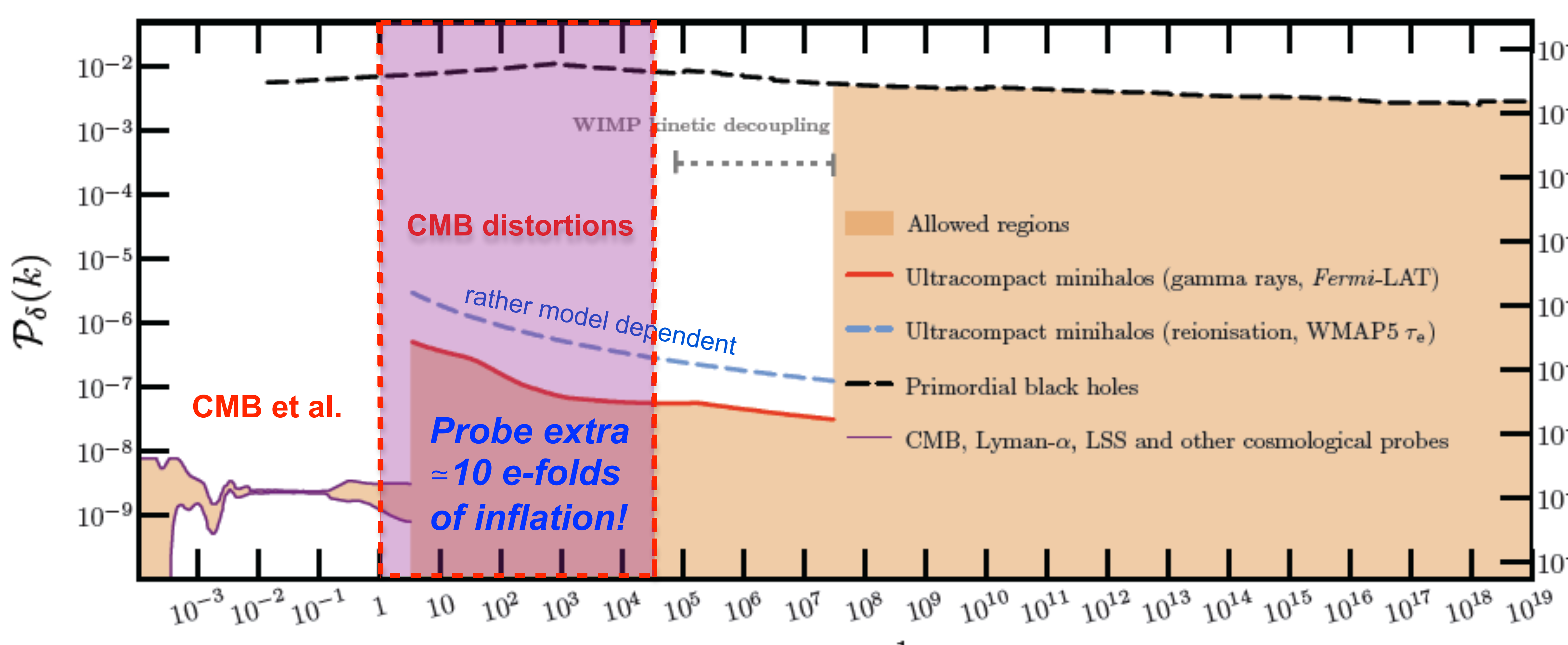
JC, 2016, MNRAS (ArXiv:1603.02496)

Average CMB spectral distortions



JC, 2016, MNRAS (ArXiv:1603.02496)

Distortions provide general power spectrum constraints!

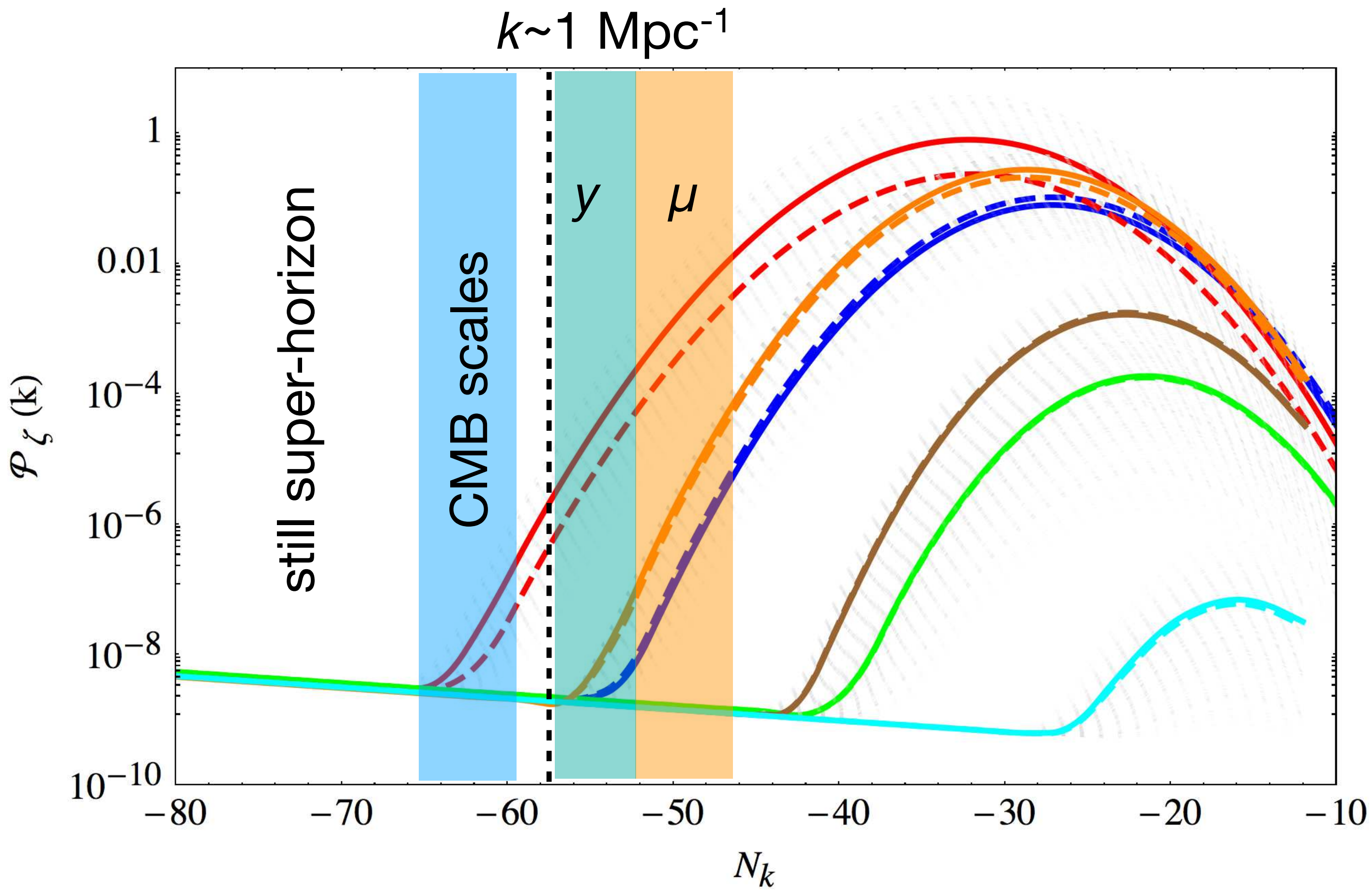


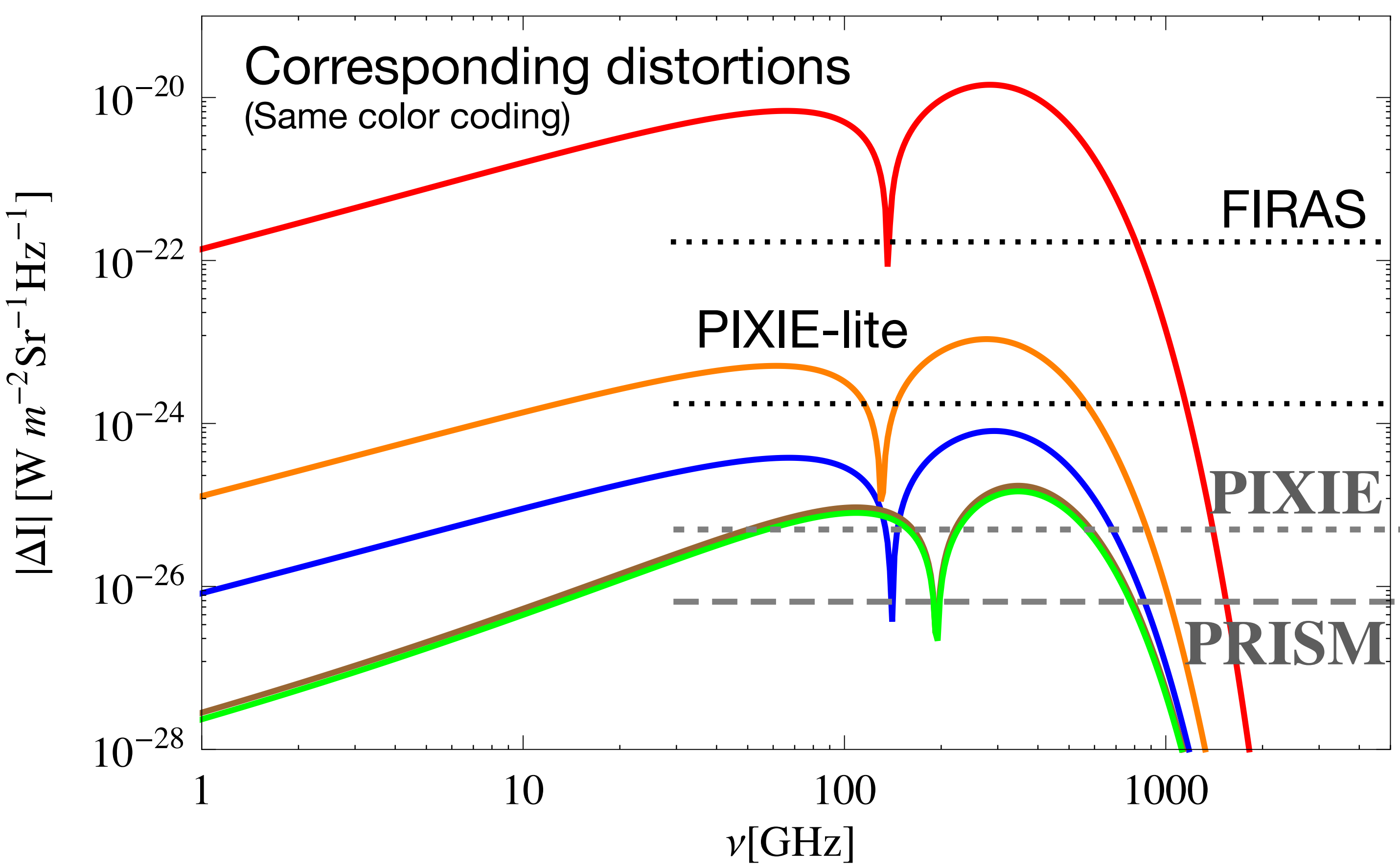
Bringmann, Scott & Akrami, 2011, ArXiv:1110.2484

- 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

Enhanced small-scale power in hybrid inflation



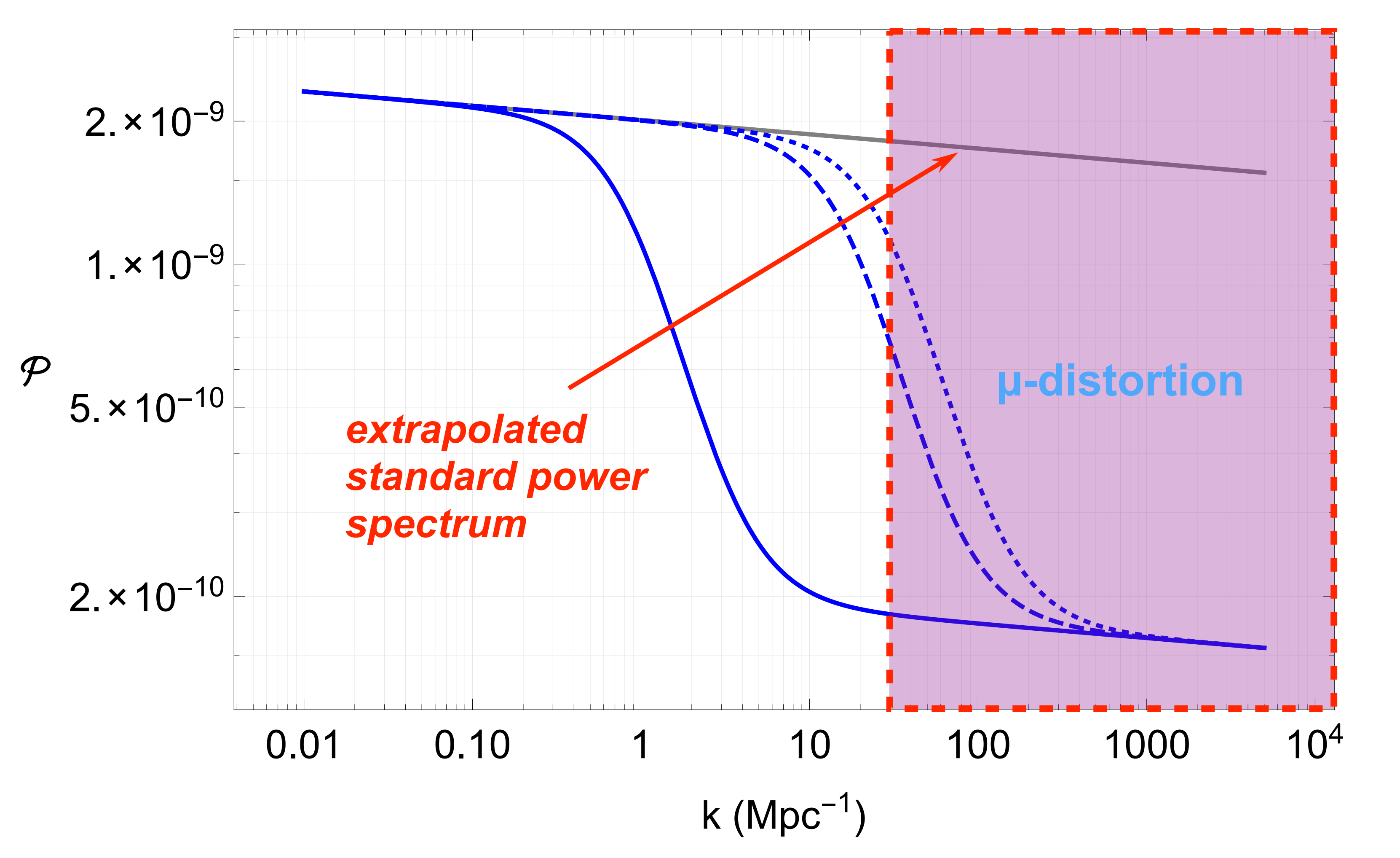


Old forecast without foreground penalty

- Hybrid Inflation models cause enhanced small scale power
- Motivated to explain seeds of supermassive blackholes seen in basically all galaxies
- μ and y distortions sensitive to enhancement at scales $1\ \mathrm{Mpc}^{-1} \lesssim k \lesssim 2\times10^4\ \mathrm{Mpc}^{-1}$
- Can constrain cases that are unconstrained by CMB measurements at large scales
- Possible link to BH mergers seen by LIGO??
- Figure: case with red line already ruled out by FIRAS and today's (!) CMB; distortions sensitive to orange and blue case; other cases PIXIE-lite is not sensitive to

Figures adapted from Clesse & Garcia-Bellido, 2015

Shedding Light on the ‘Small-Scale Crisis’



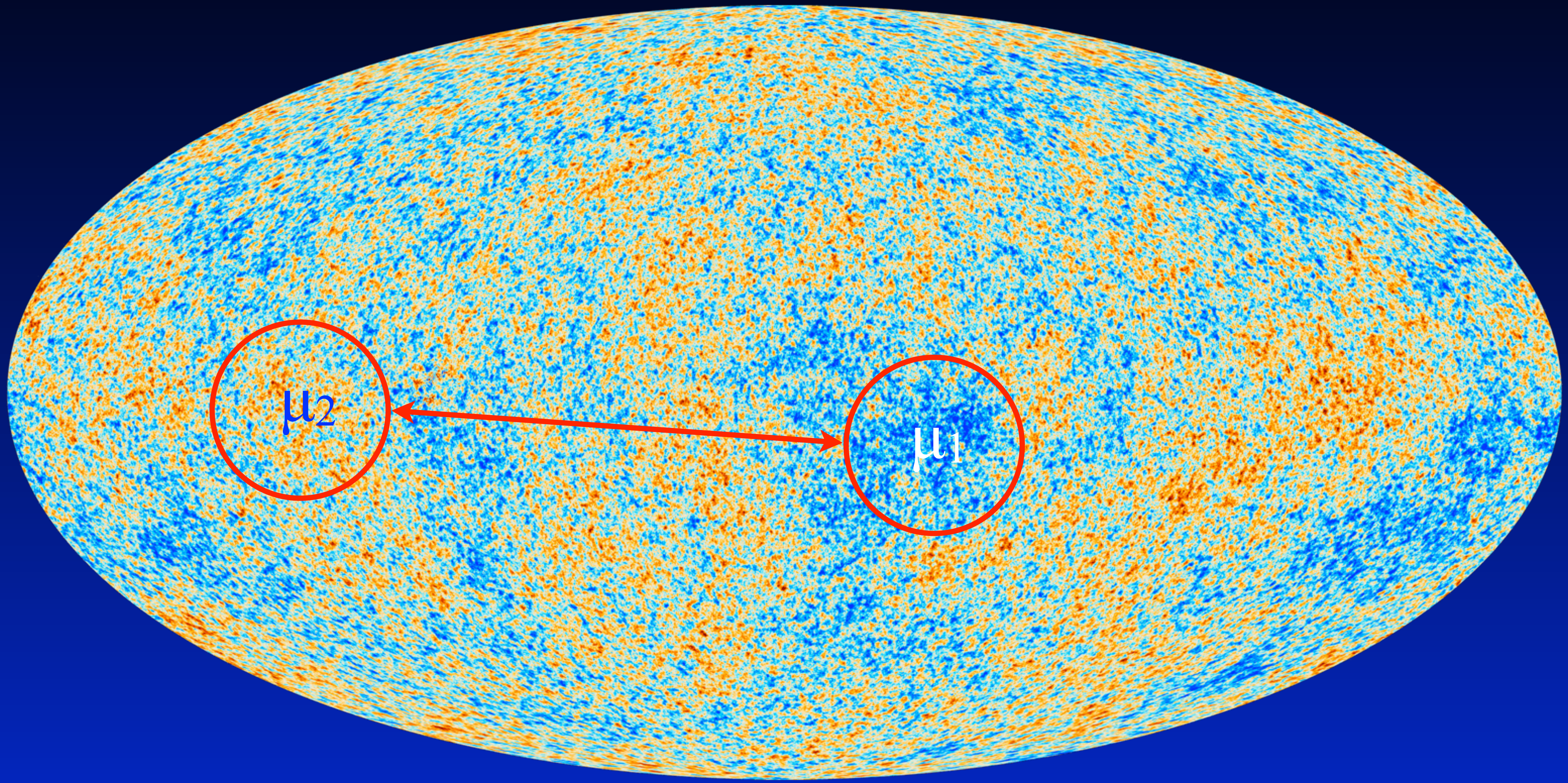
- ‘missing satellite’ problem
- ‘too-big-to-fail’
- Cusp-vs-core problem

$\Rightarrow$ Are these caused by a *primordial* or *late-time* suppression?

- A primordial suppression would result in a very small μ-distortions
- Spectral distortion measurements might be able to test this question

Nakama, JC & Kamionkowski, ArXiv:1703.10559

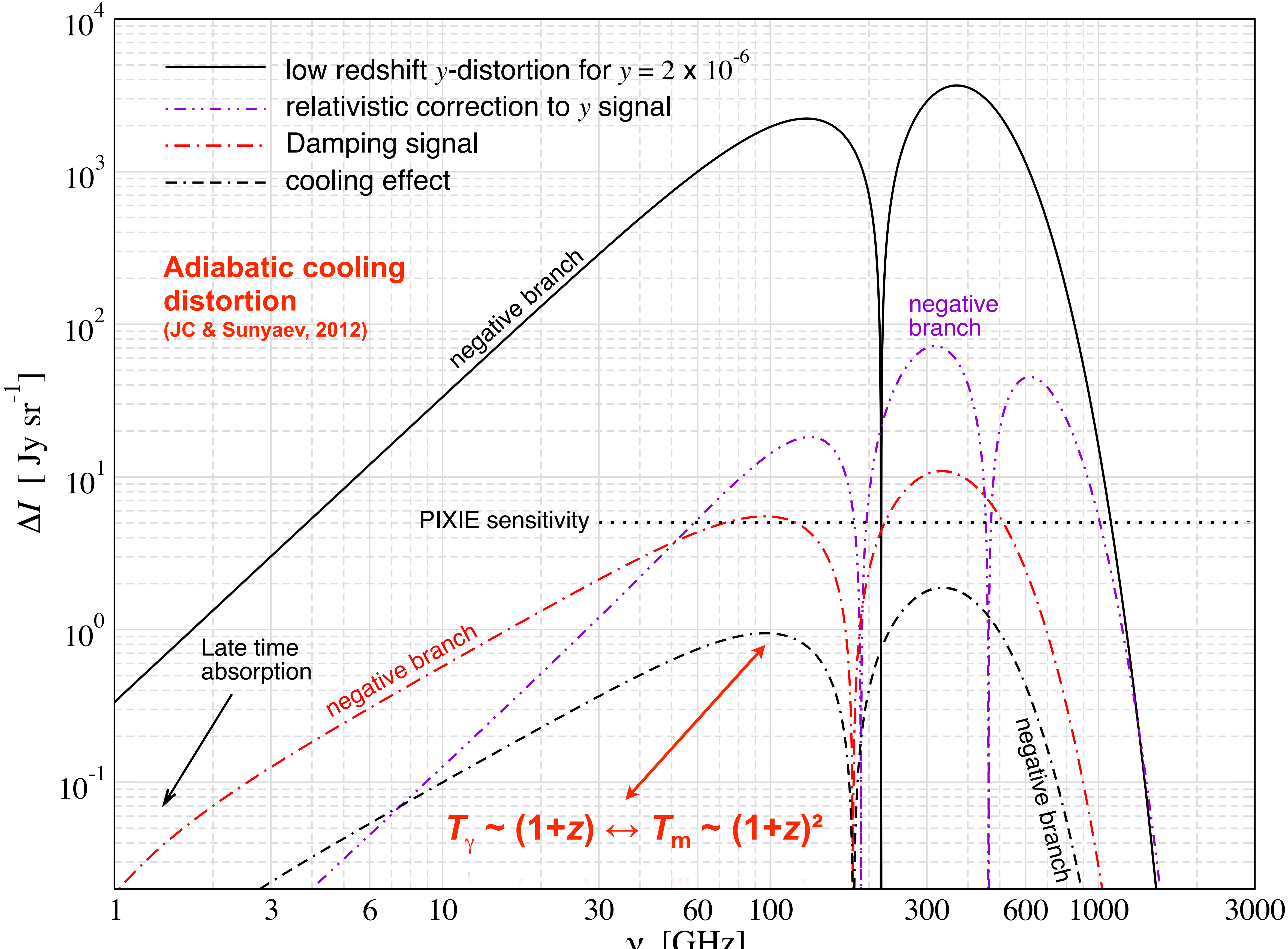
Spatially varying heating and dissipation of acoustic modes for non-Gaussian perturbations



- 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

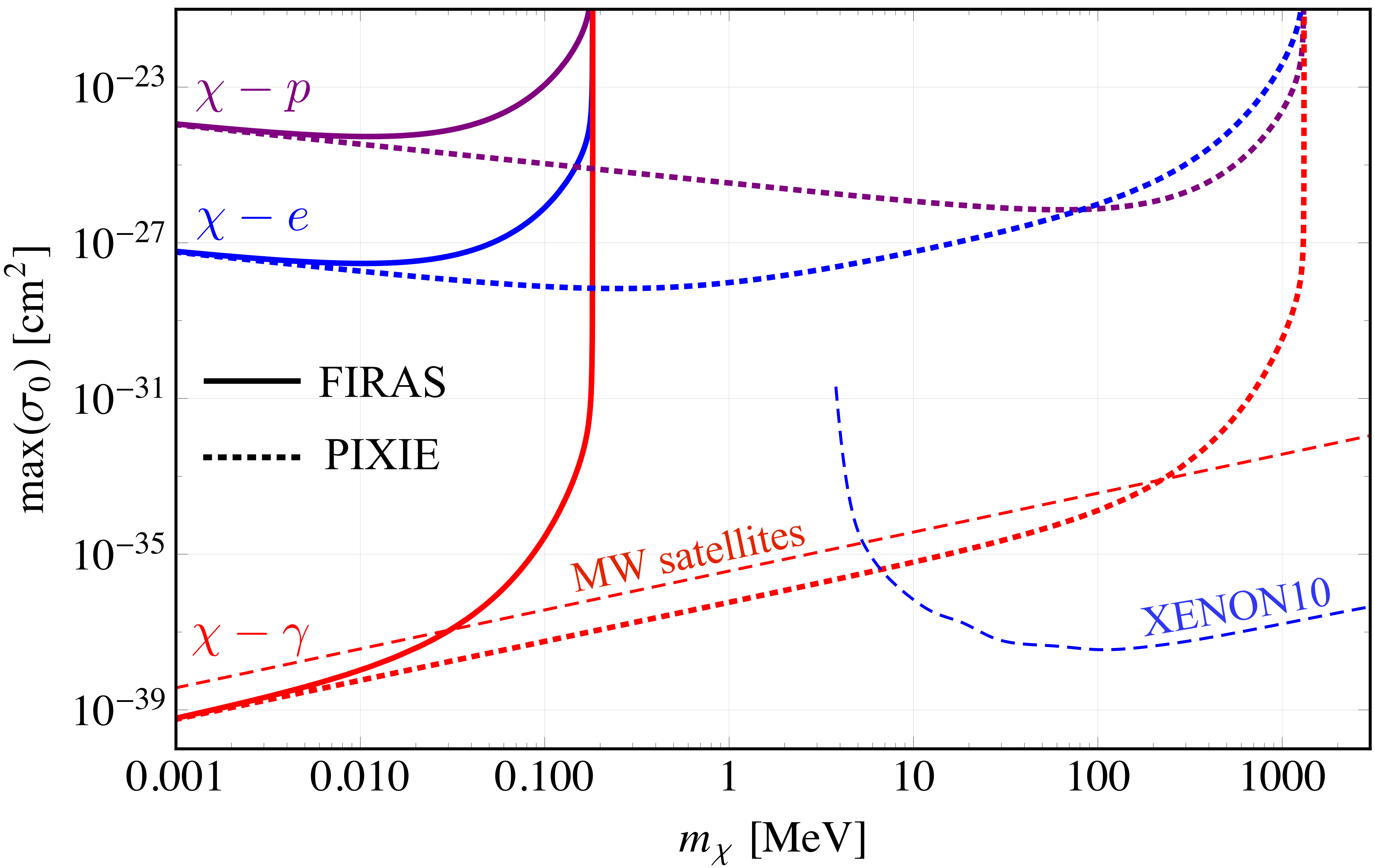
Pajer & Zaldarriaga, 2012; Ganc & Komatsu, 2012; Biagetti et al., 2013; JC et al., 2016

Average CMB spectral distortions



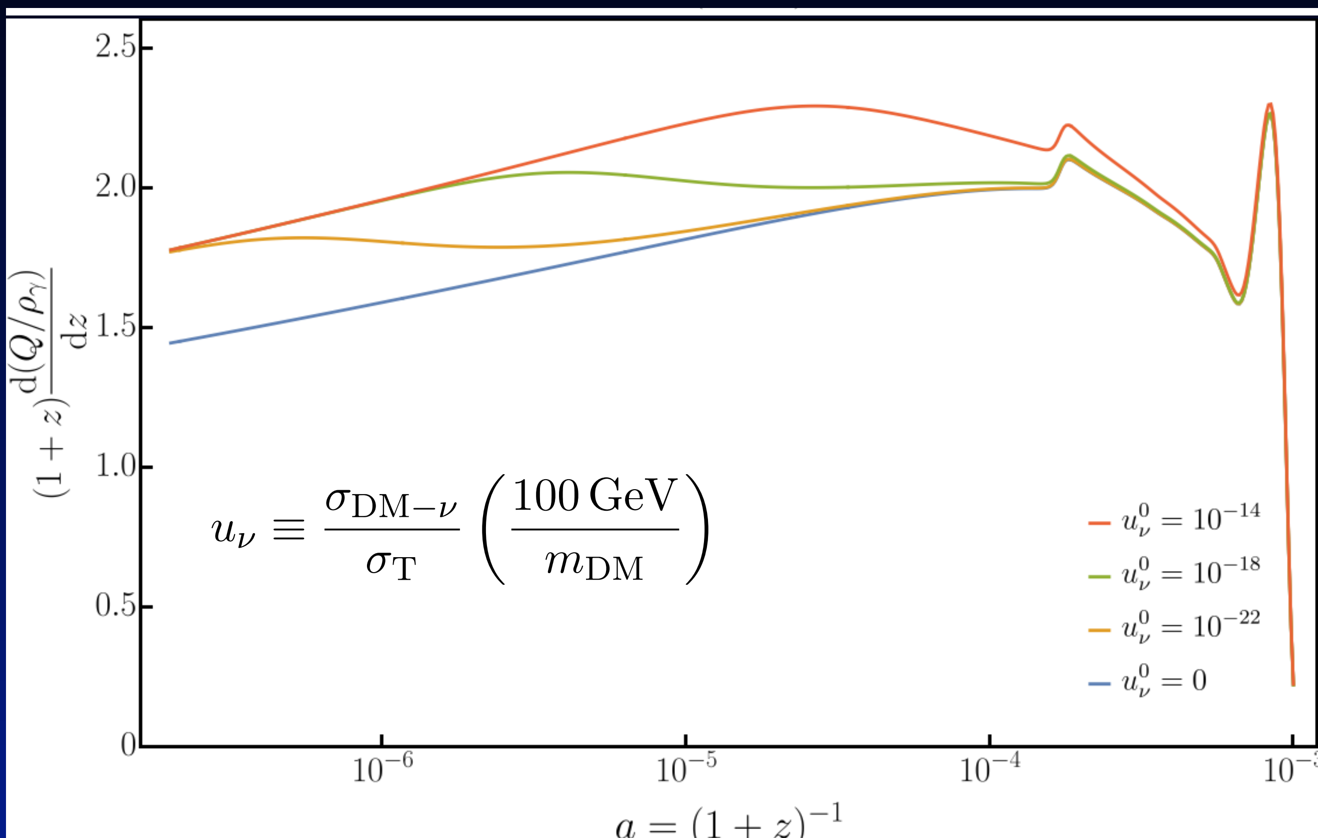
JC, 2016, MNRAS (ArXiv:1603.02496)

Distortion constraints on DM interactions through adiabatic cooling effect

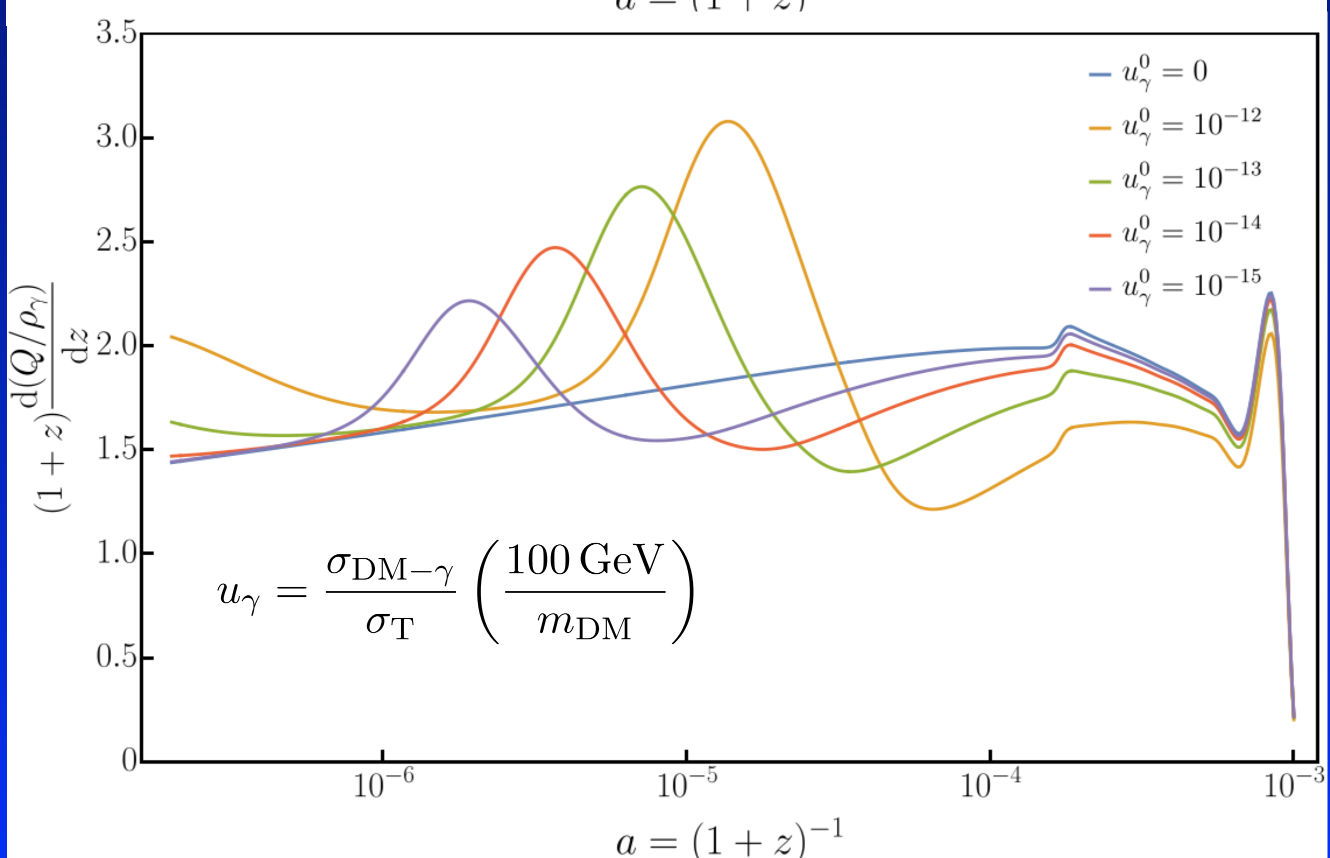


Ali-Haimoud, JC & Kamionkowski, 2015

Constrain interactions of DM with neutrinos/photons



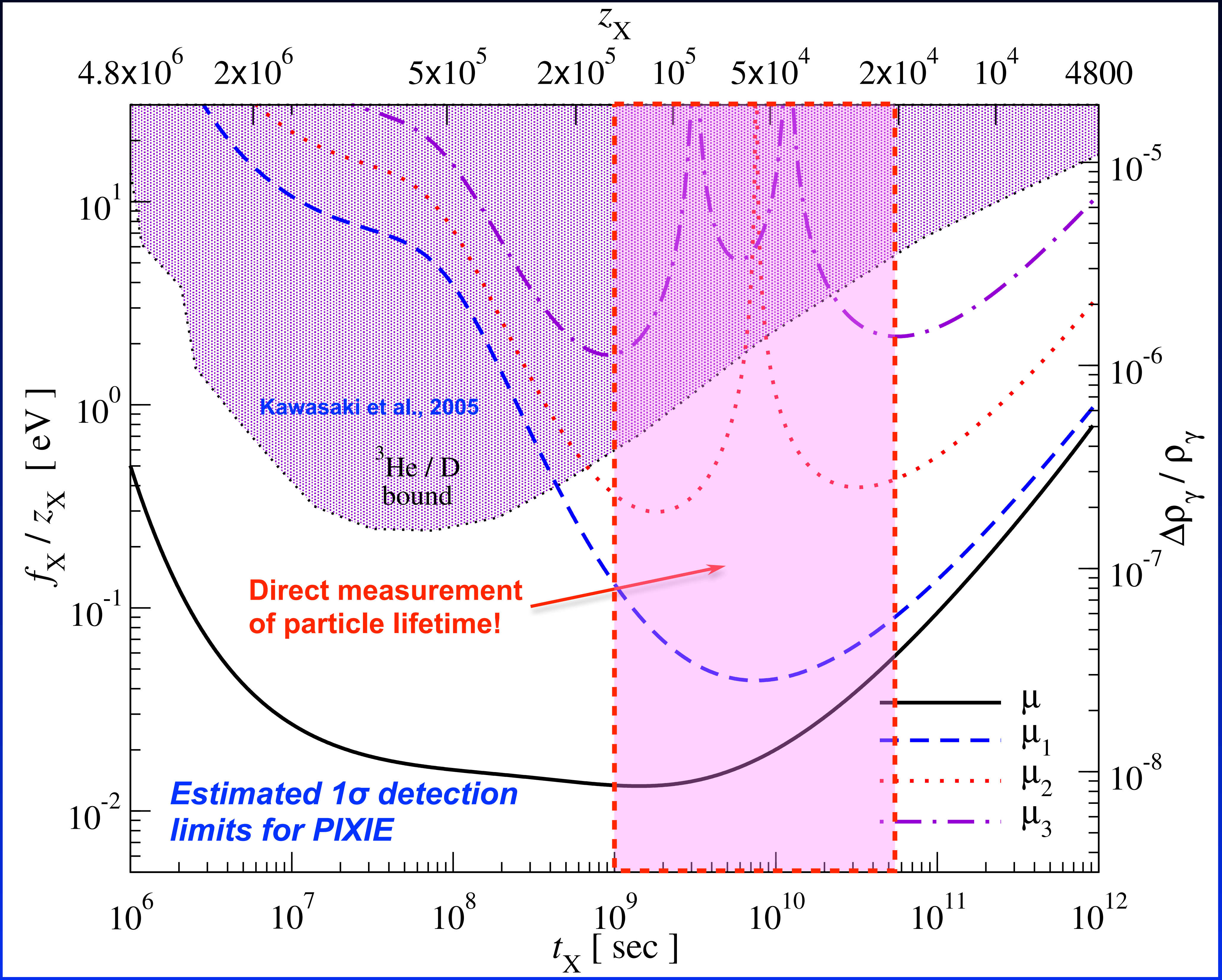
- Dissipation is increased
- Enhances μ distortion
- Interesting complementary probe



- Early-time dissipation enhanced → larger μ
- Later, modes already gone, so less heating
- Dissipation scale larger early on

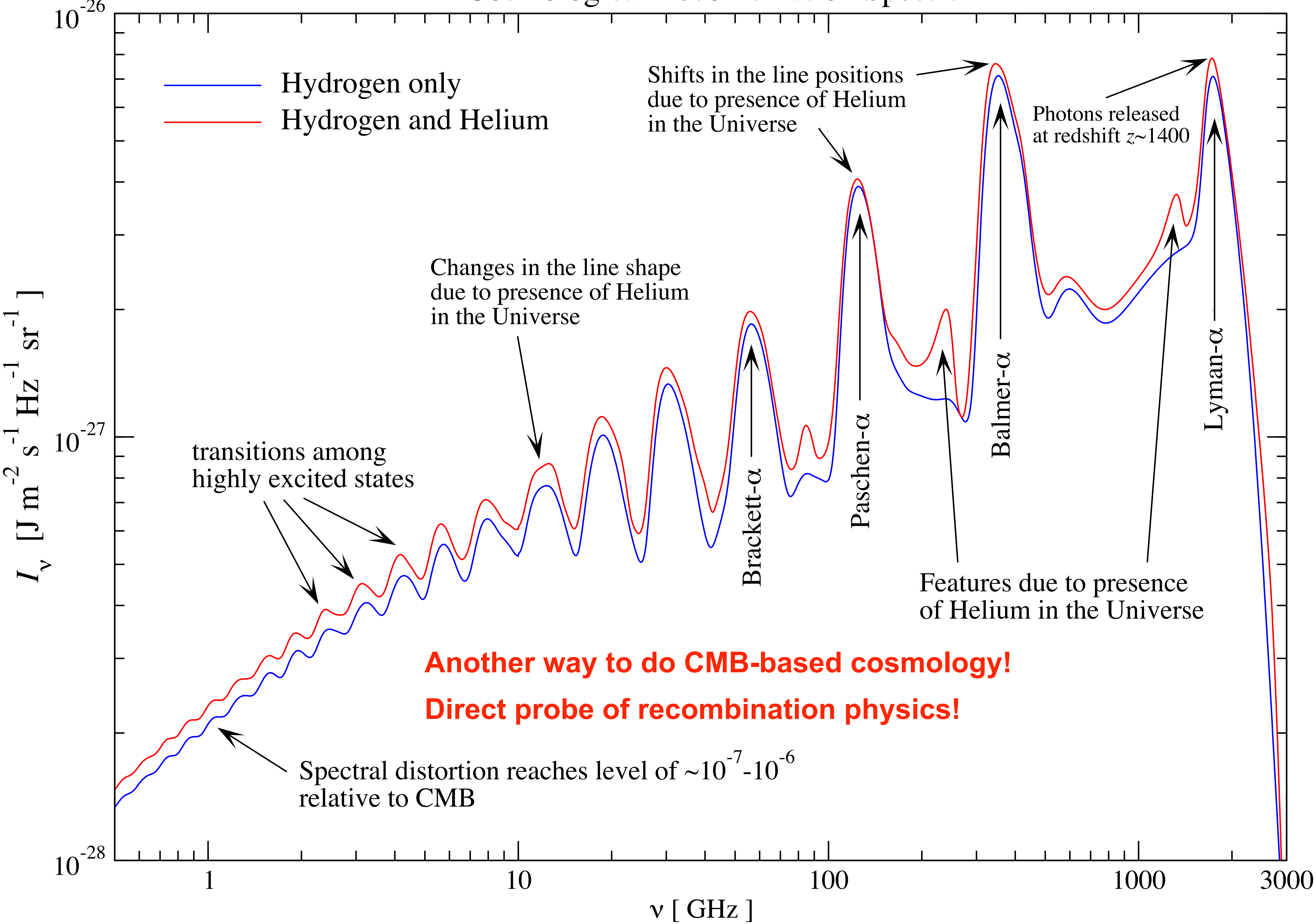
Diacoumis & Wong, 2017, 1707.07050

Distortions could shed light on decaying (DM) particles!



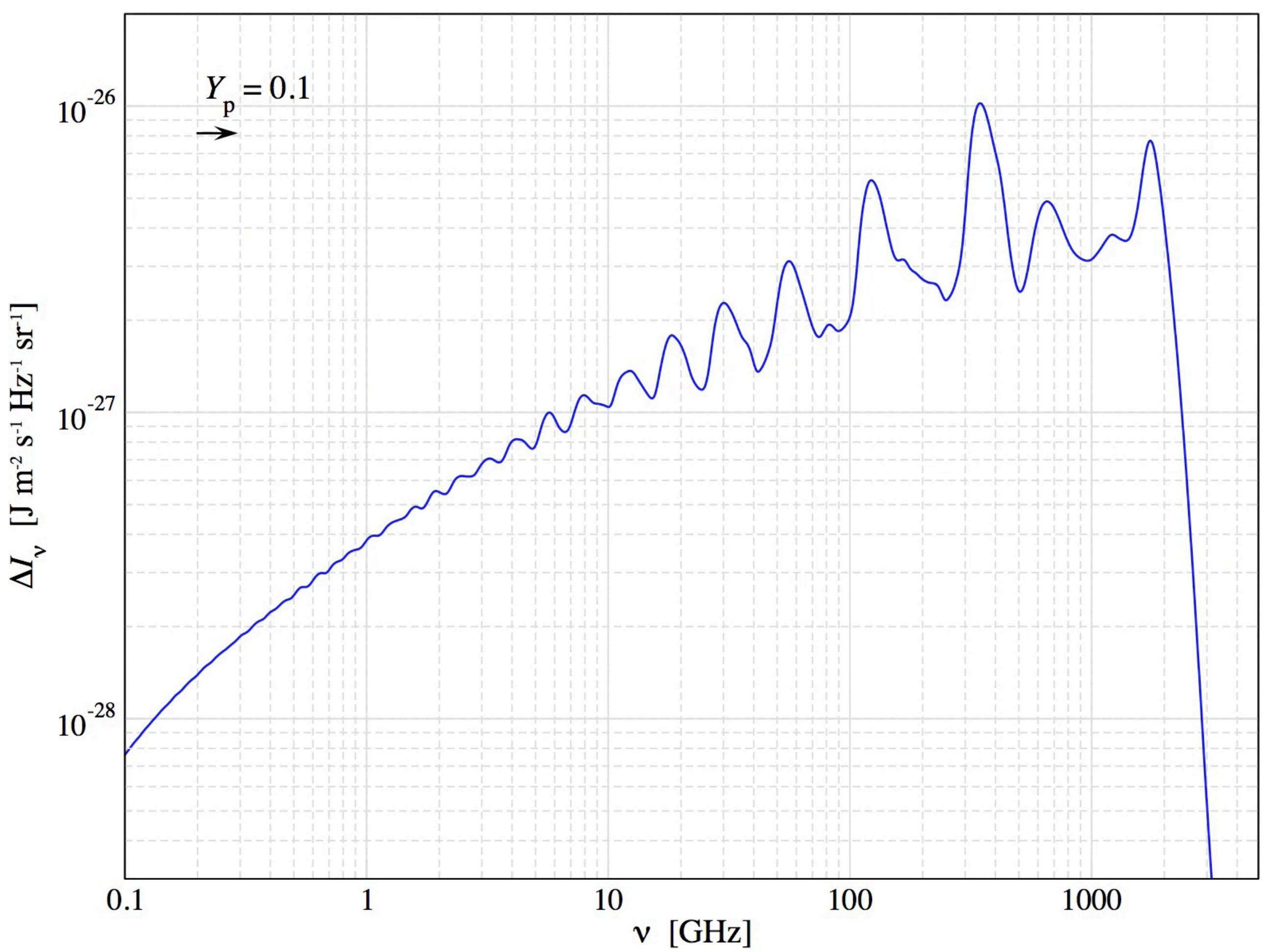
JC & Jeong, 2013

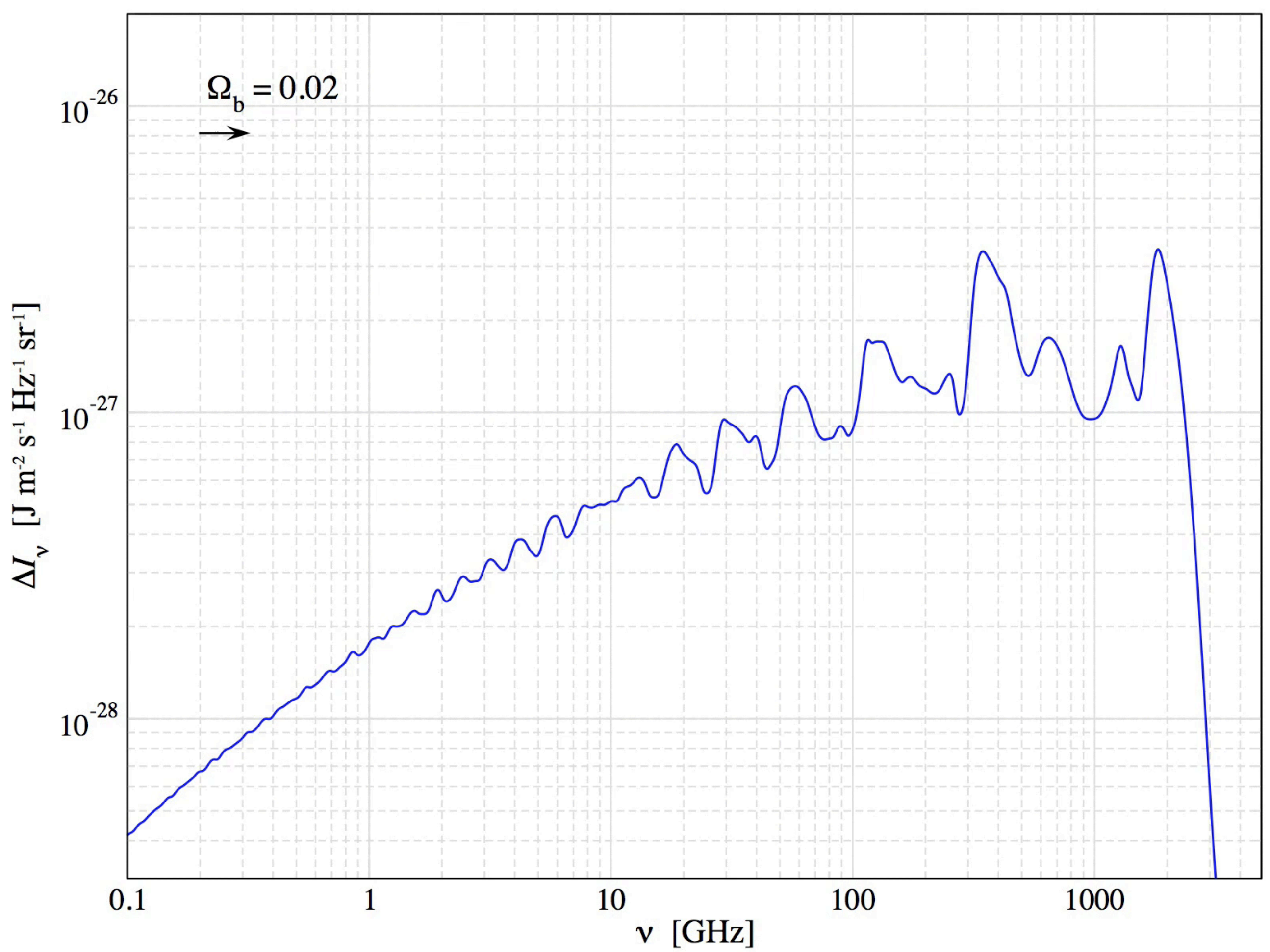
Cosmological Recombination Spectrum



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

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.)

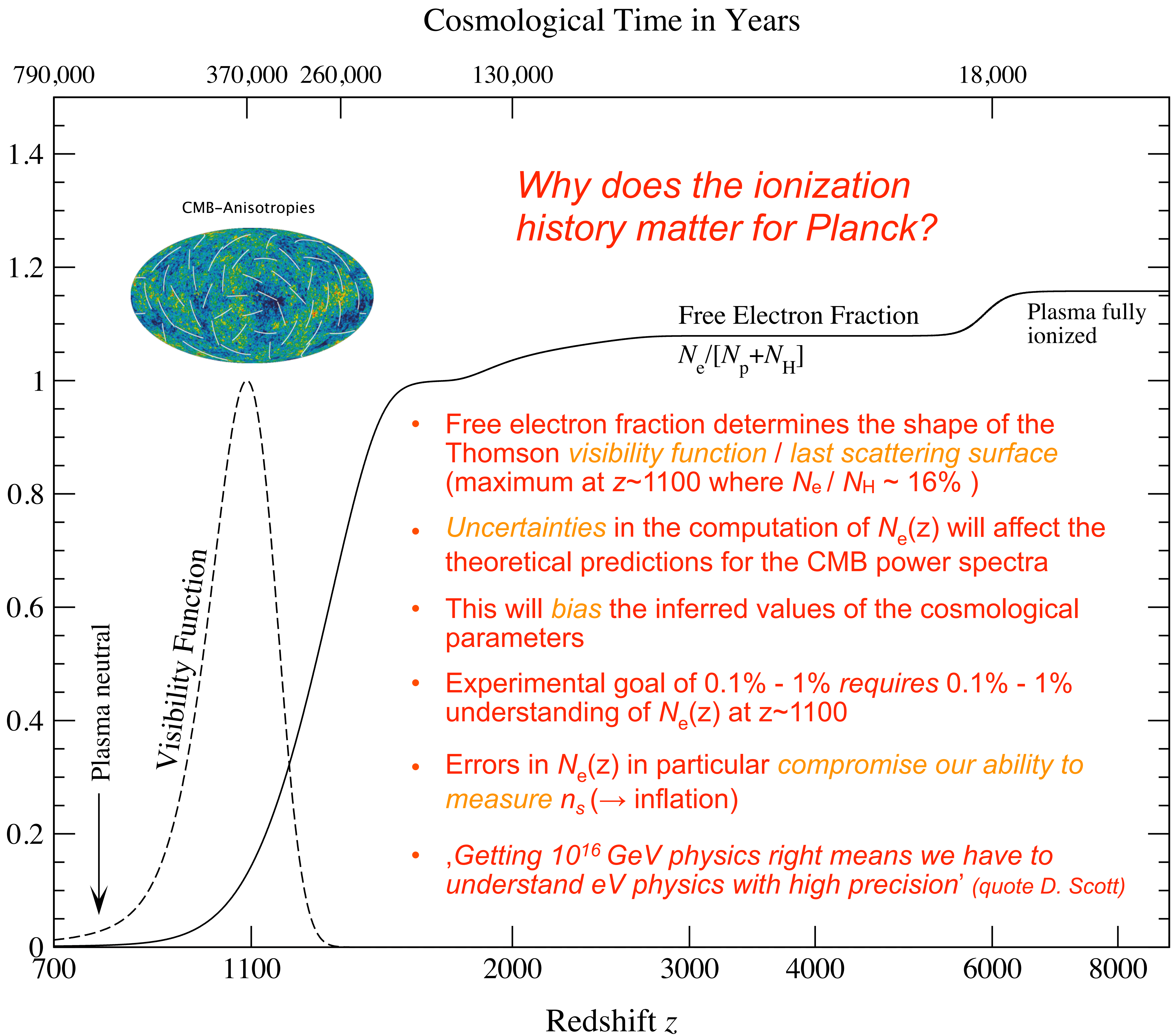
CosmoSpec will be available here:

www.Chluba.de/CosmoSpec

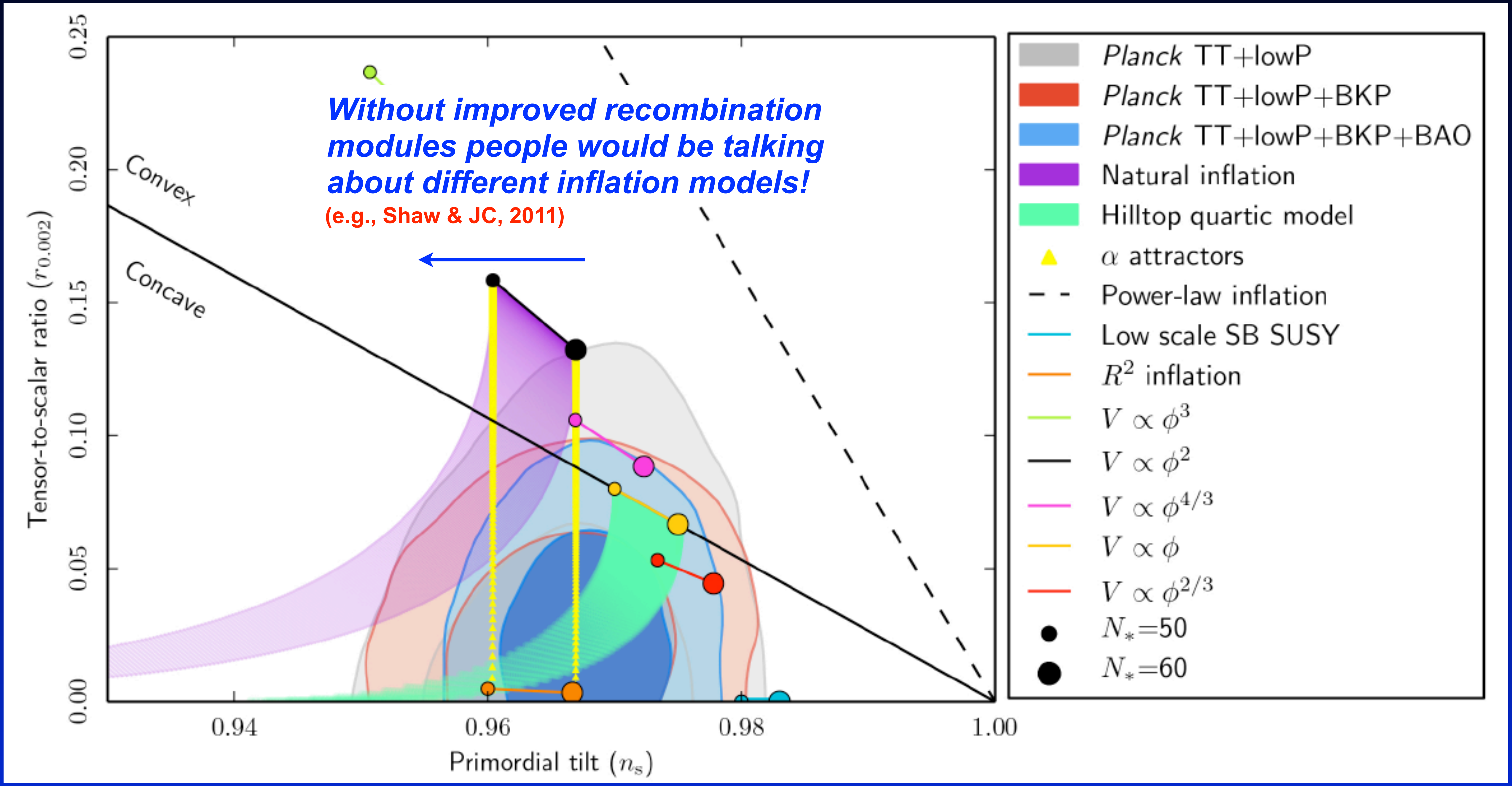
JC & Ali-Haimoud, arXiv:1510.03877

Why does the ionization history matter for Planck?

- Free electron fraction determines the shape of the Thomson *visibility function / last scattering surface* (maximum at $z \sim 1100$ where $N_e / N_H \sim 16\%$)
- *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 $z \sim 1100$
- 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)*



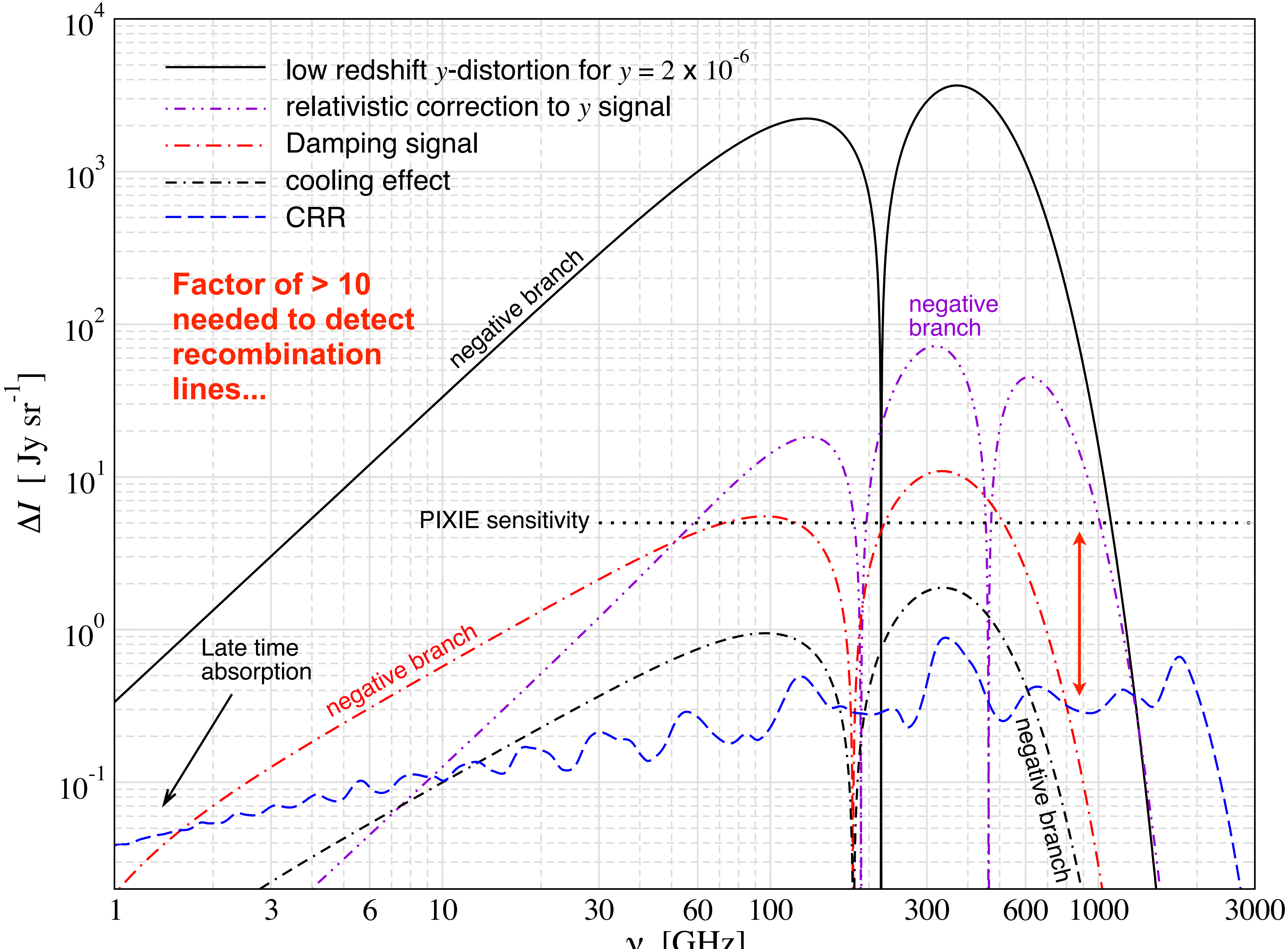
Importance of recombination for inflation constraints



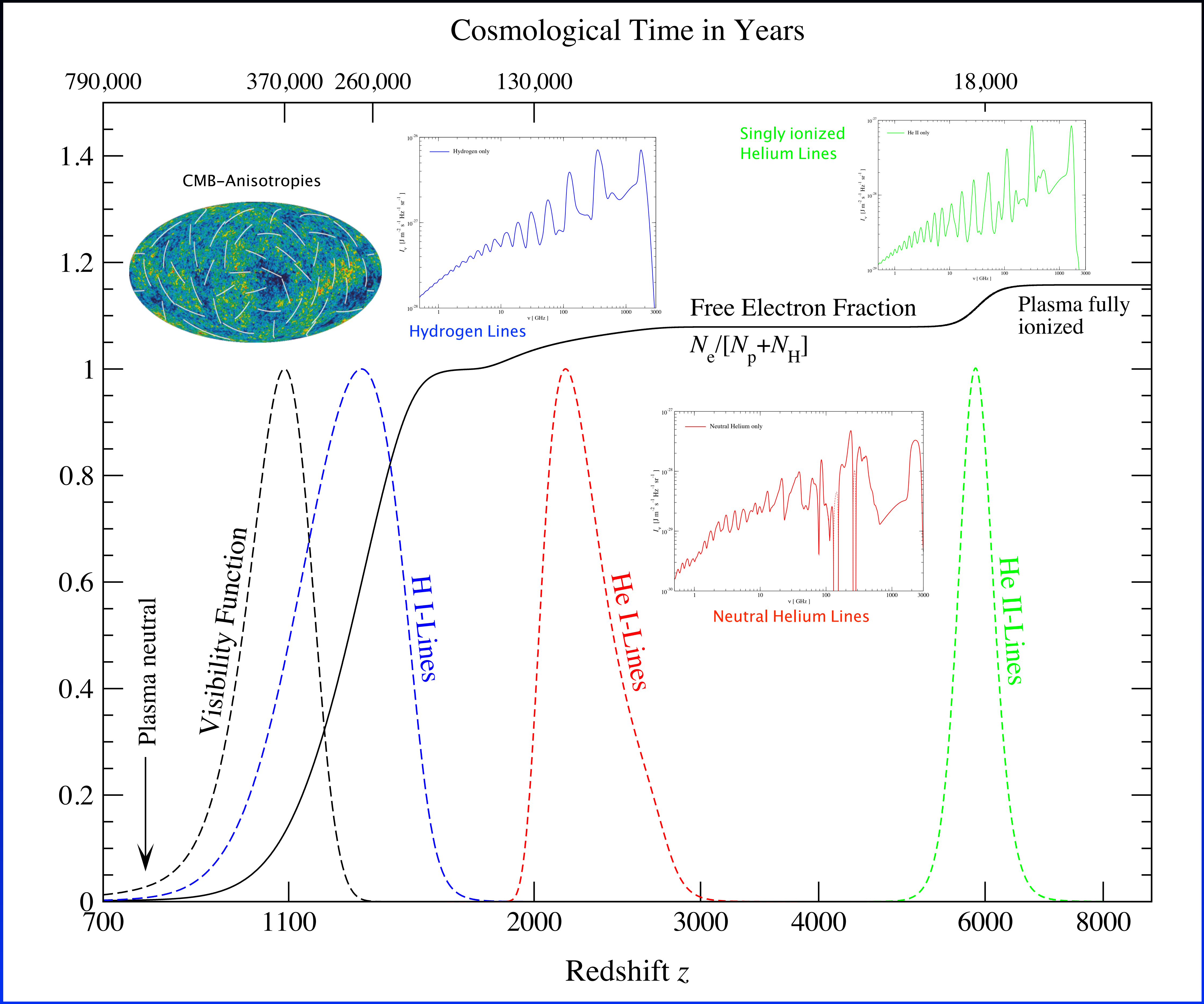
Planck Collaboration, 2015, paper XX

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

Average CMB spectral distortions



JC, 2016, MNRAS (ArXiv:1603.02496)

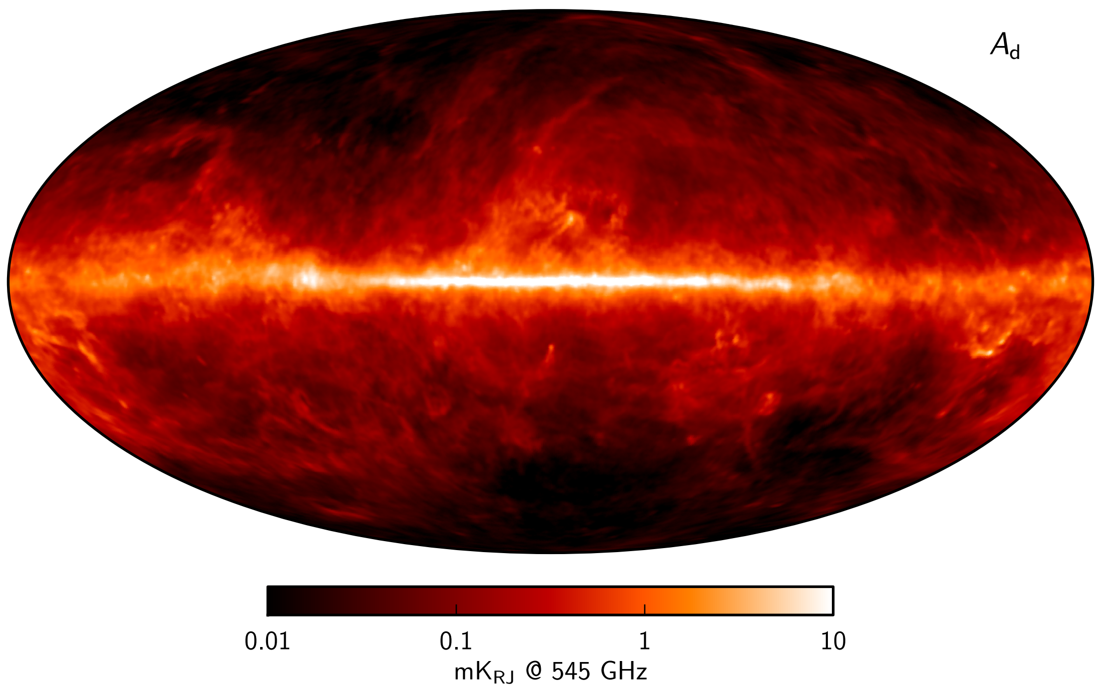

Cosmological Time in Years
790,000
370,000
260,000
130,000
18,000
CMB–Anisotropies
Hydrogen Lines
Singly ionized
Helium Lines
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully
ionized
Neutral Helium Lines
Plasma neutral
Visibility Function
H I-Lines
He I-Lines
He II-Lines
1.4
1.2
1
0.8
0.6
0.4
0.2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

Foreground problem for CMB spectral distortions

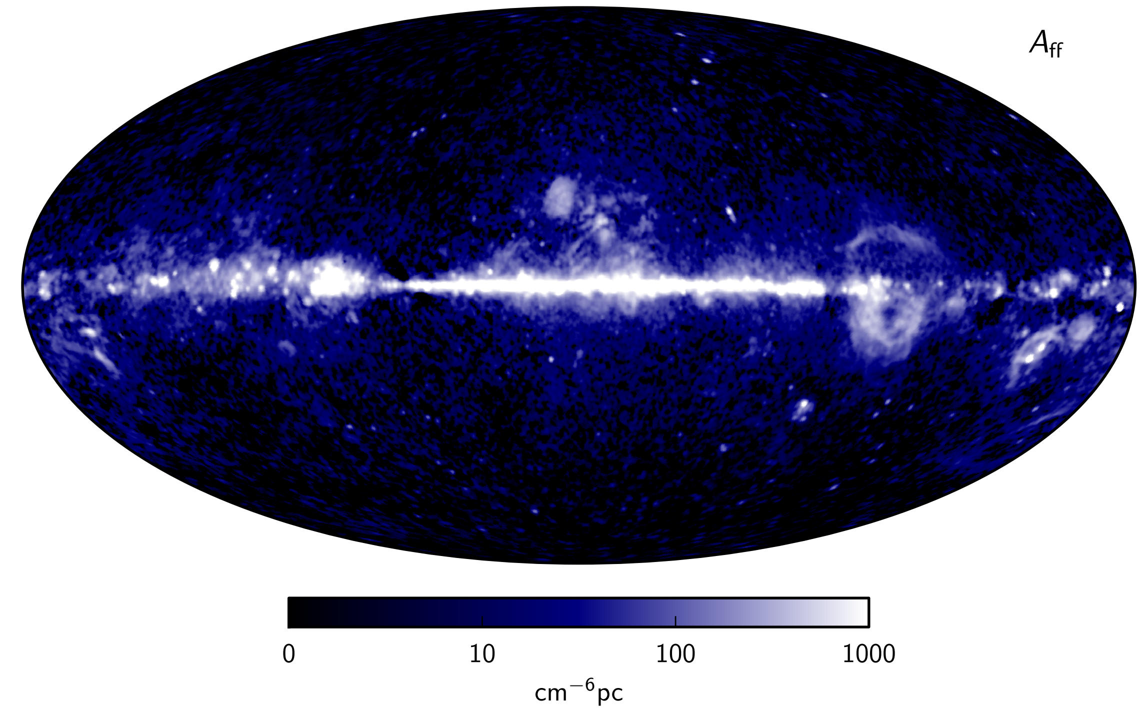
- Distortion signals *quite* small even if spectrally different
- spatially varying foreground signals across the sky
  - Introduces new spectral shapes (*superposition of power-laws, etc.*)
  - Scale-dependent SED
  - Similar problem for B-mode searches
- New foreground parametrization required
  - 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

Some of the foregrounds and their spatial variation

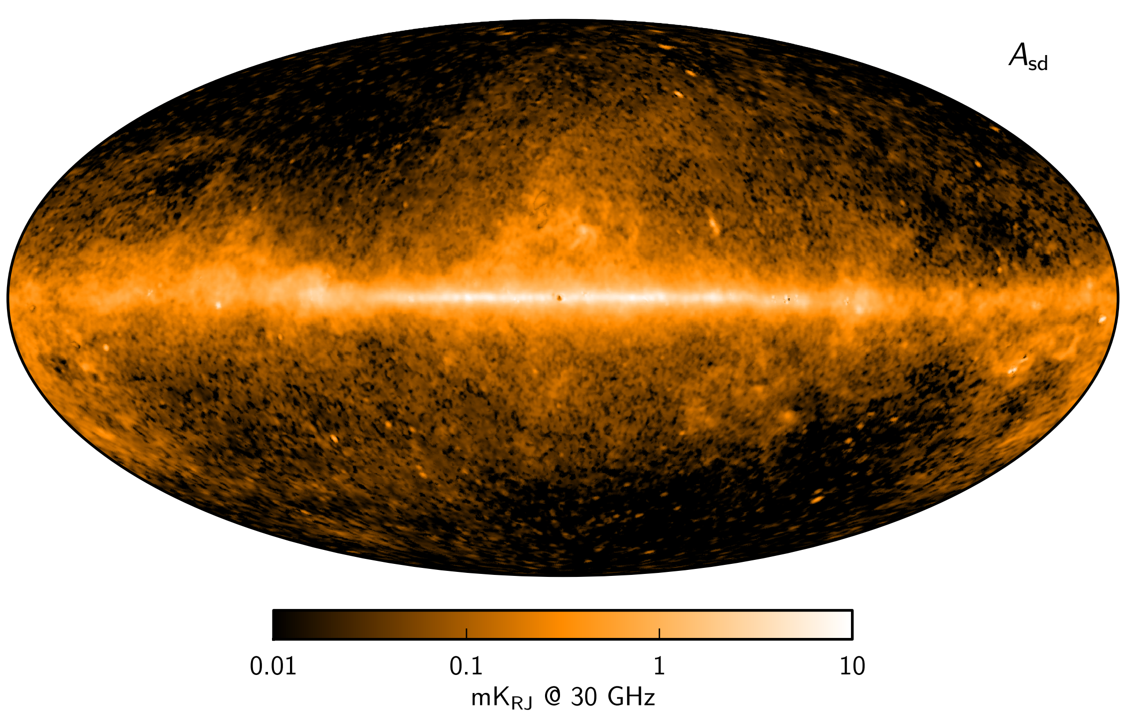
Thermal dust



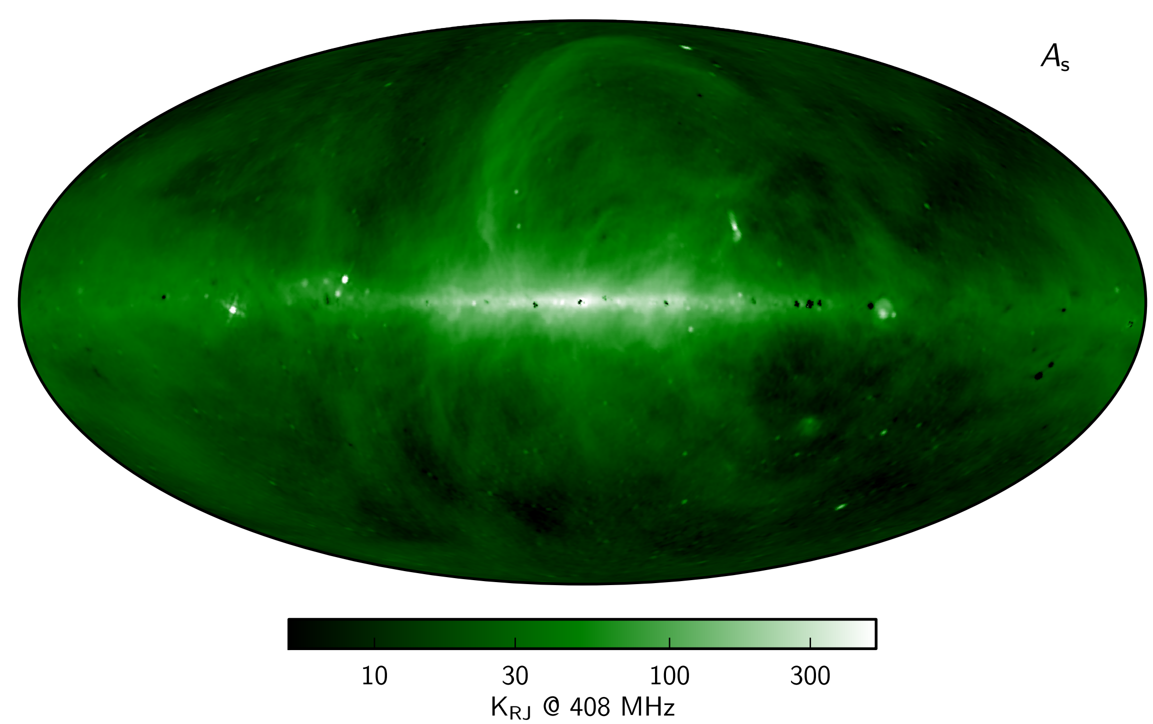
free-free emission



Spinning dust



Synchrotron



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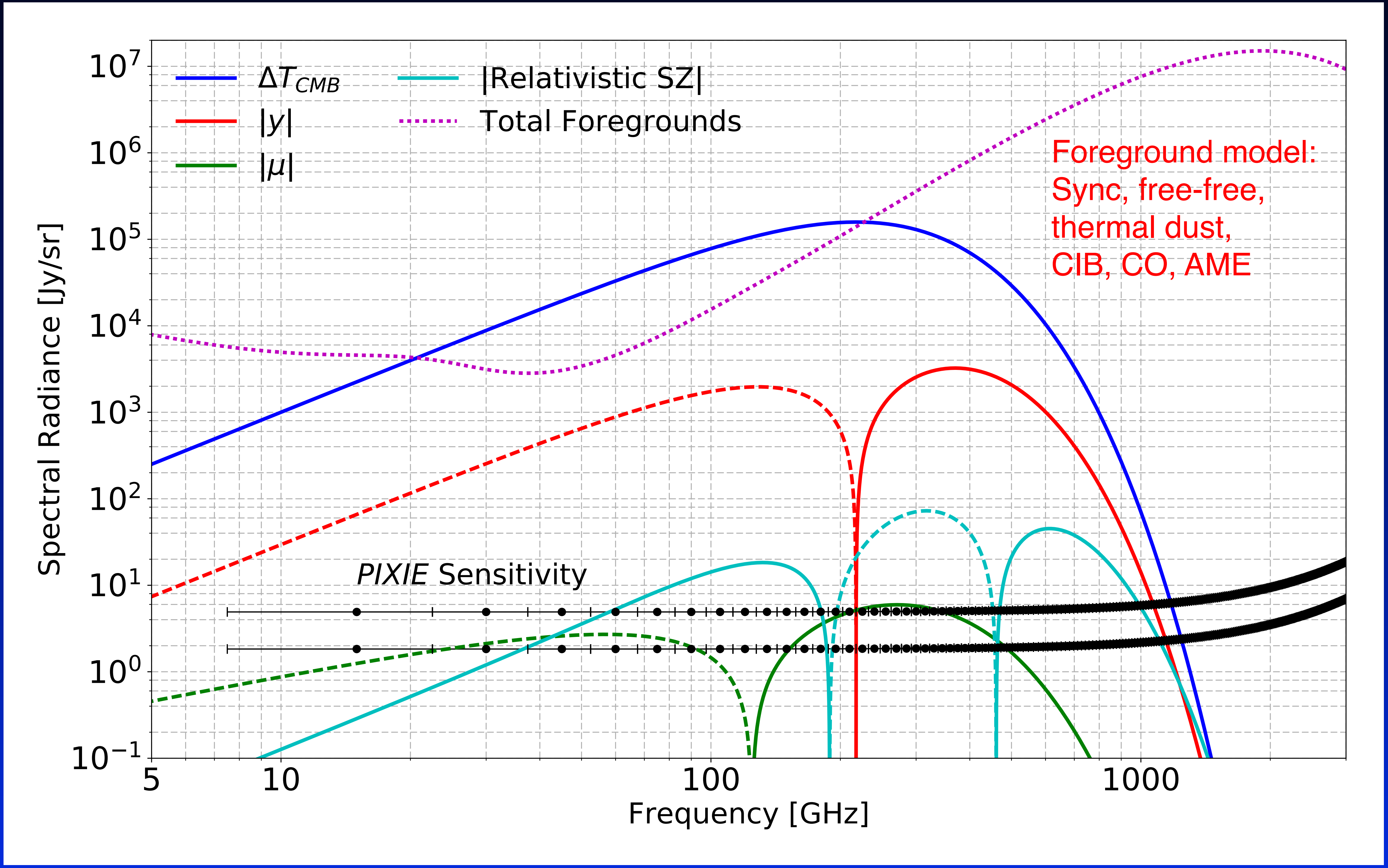
Comparison of distortion signals with foregrounds



Abitbol, JC & Hill, 1705.01534

Forecasted sensitivities for PIXIE

Sky Model	CMB (baseline)	CMB	Dust, CO	Sync, FF, AME	Sync, FF, Dust	Dust, CIB, CO	Sync, FF, Dust, CIB	Sync, FF, AME Dust, CIB, CO
# of parameters	4	4	8	9	11	11	14	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)

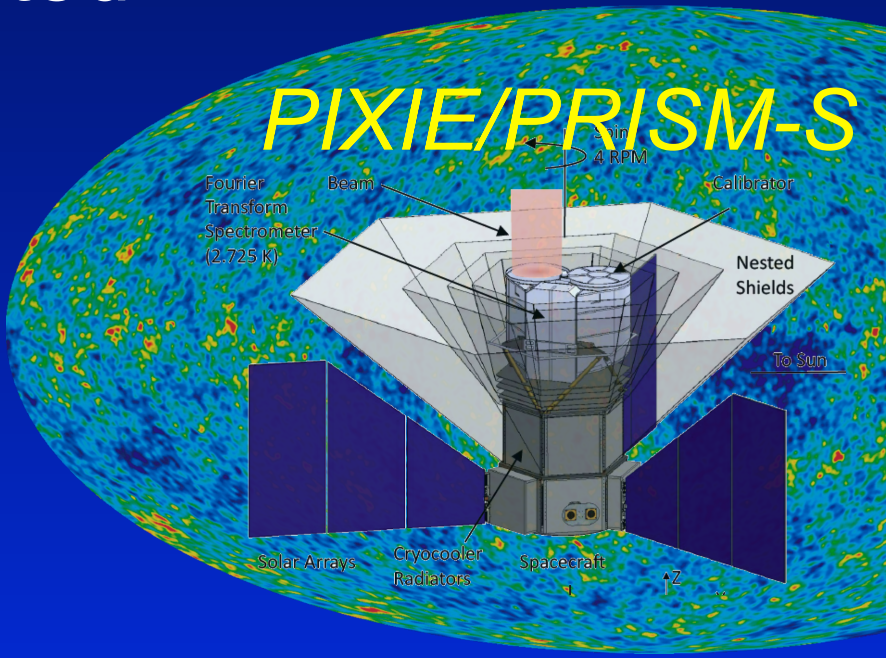
Parameter	1% / −−	10% / 10%	1% / 1%	none (no μ)	10% / 10% (no μ)	1% / 1% (no μ)
$\sigma_{\Delta_T}[10^{-9}]$	194 (619σ)	75 (1600σ)	18 (6500σ)	17 (7200σ)	4.4 (27000σ)	3.7 (33000σ)
$\sigma_y[10^{-9}]$	32 (55σ)	14 (130σ)	5.9 (300σ)	9.1 (194σ)	4.6 (380σ)	4.6 (390σ)
$\sigma_{kT_{\rm eSZ}}[10^{-2}$ keV]	23 (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, 1705.01534

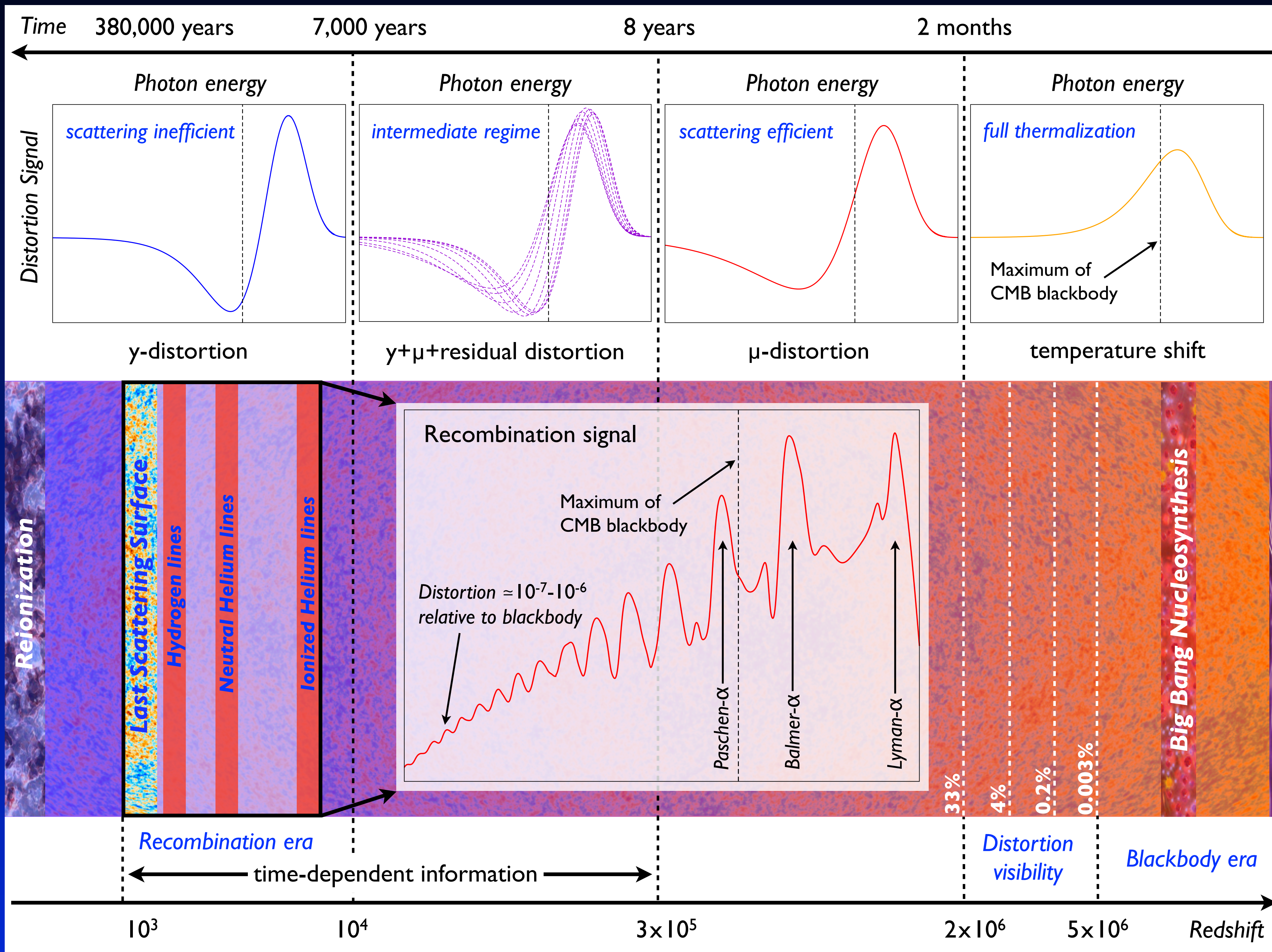
What can CMB spectral distortions add?

- 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!!!

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