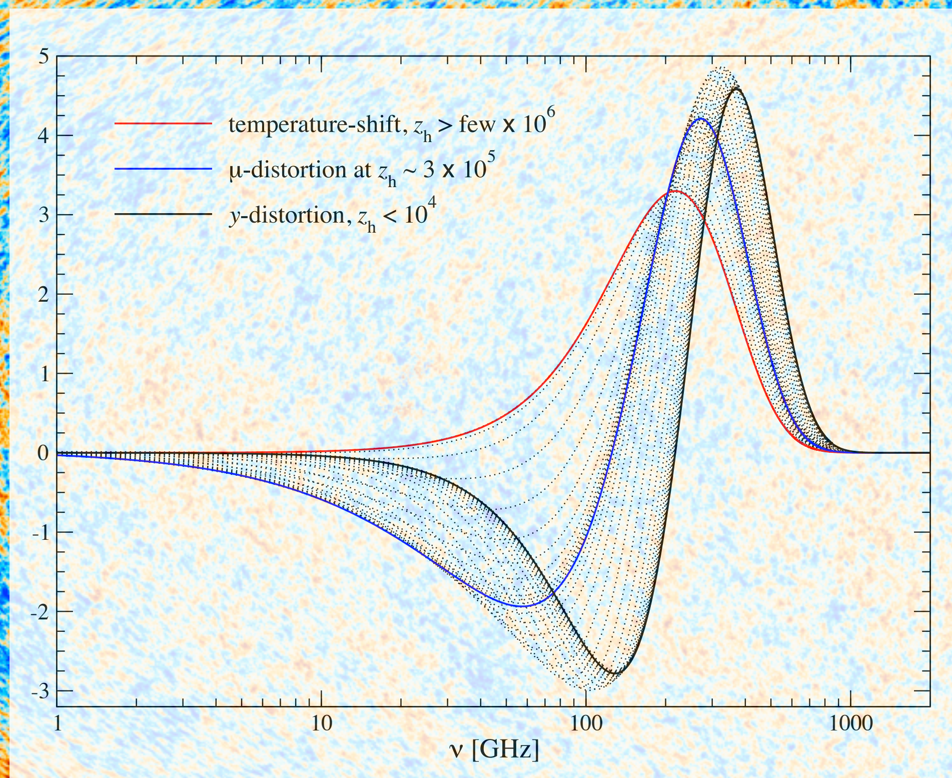
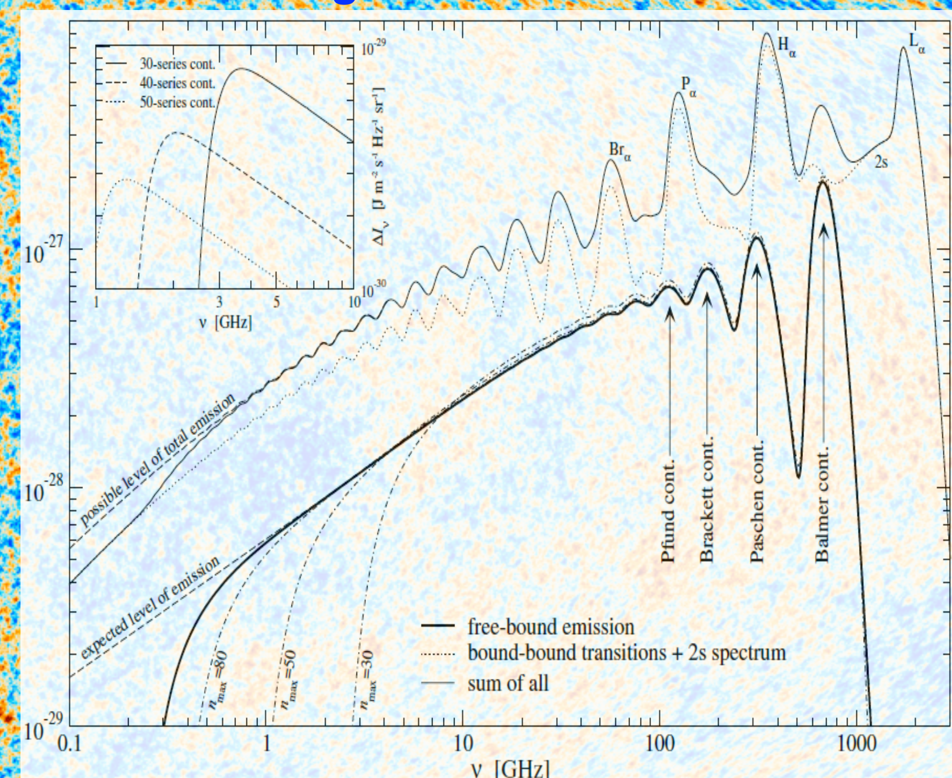
CMB Cosmology beyond thermal equilibrium

Primordial Distortions



Cosmological Recombination lines



MANCHESTER 1824
The University of Manchester

Jens Chluba

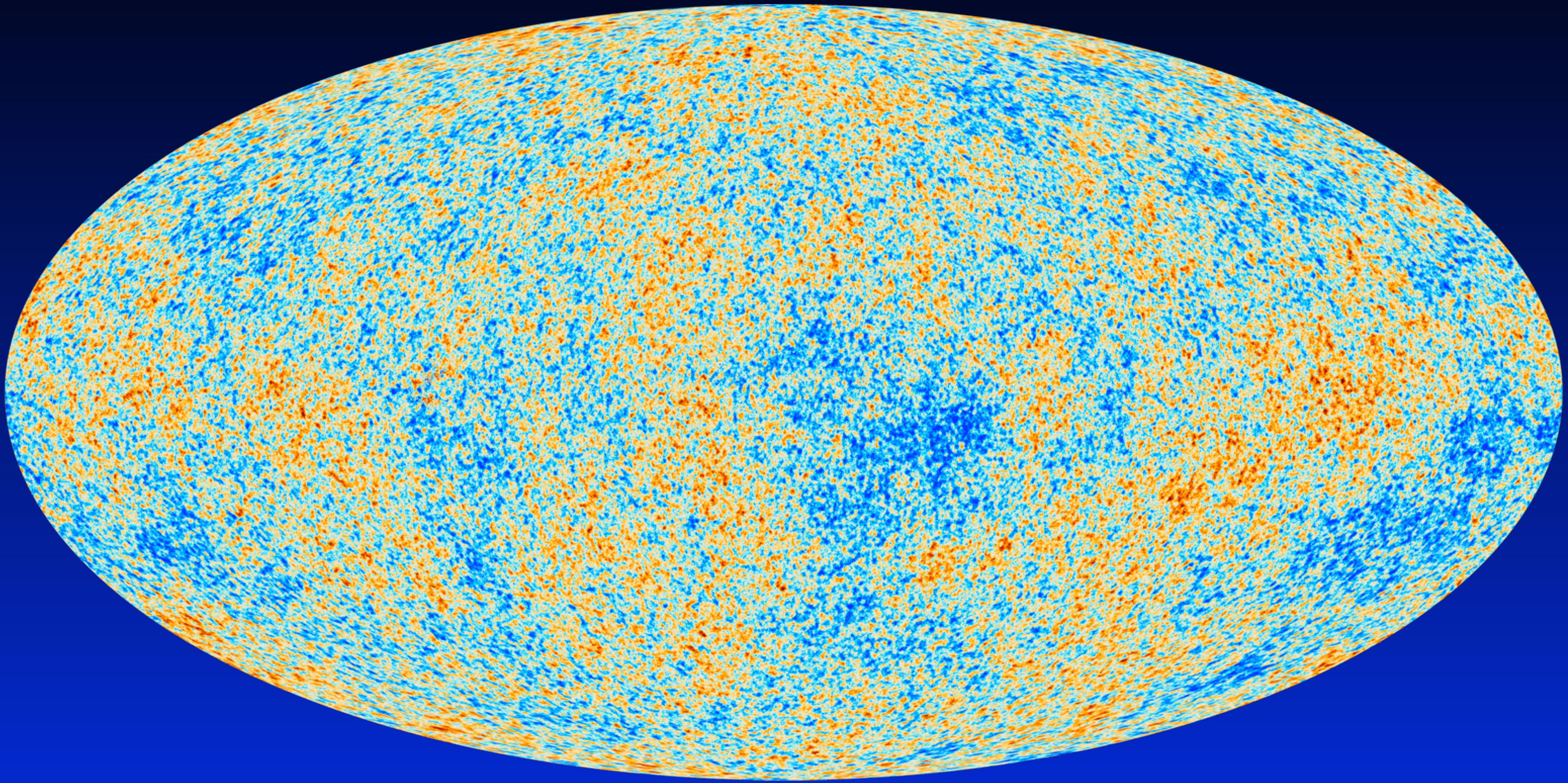
Windows on the Universe, ICISE

Quy Nhon, 06 - 11 June 2018

erc

THE ROYAL SOCIETY

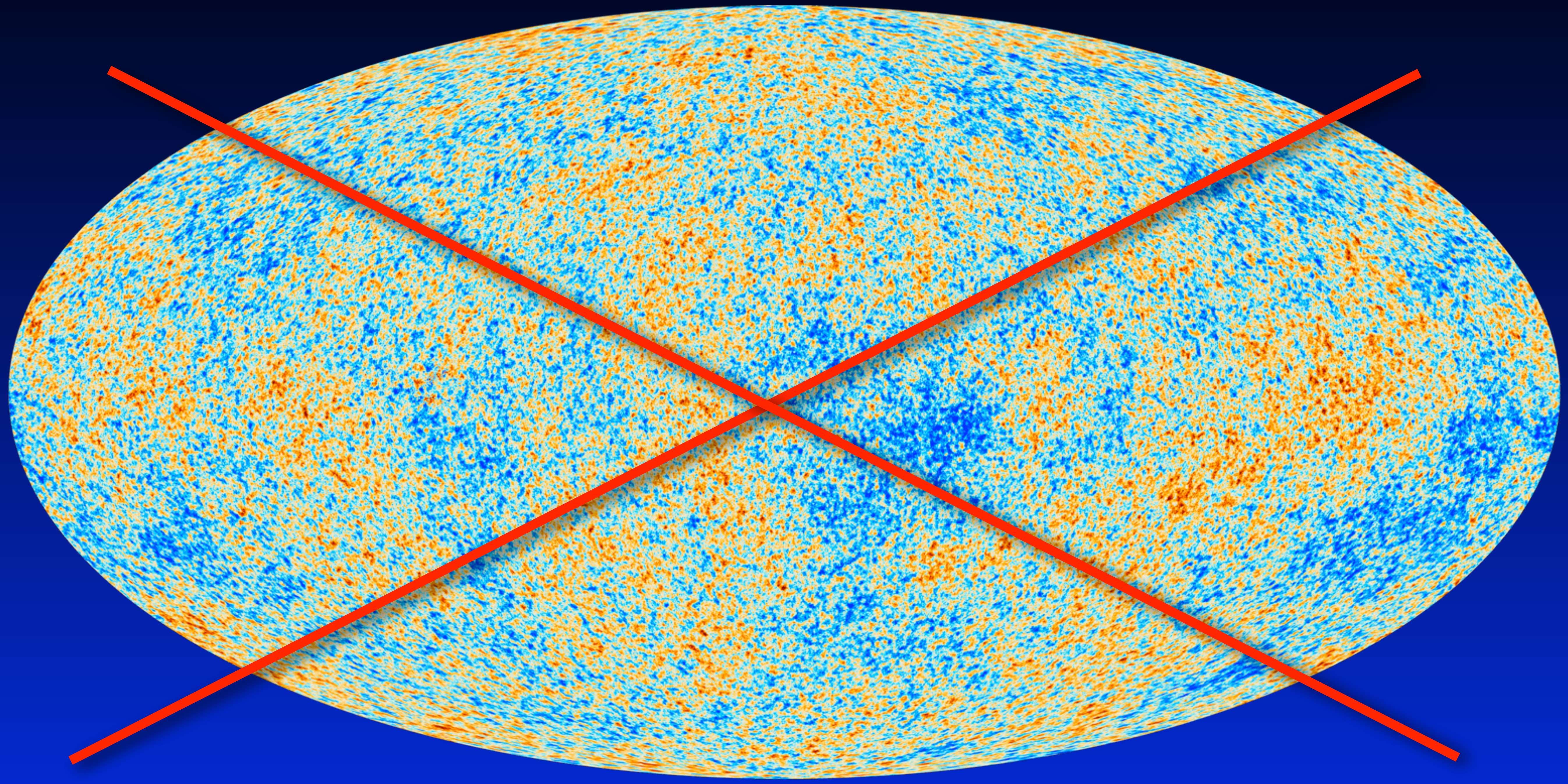
Cosmic Microwave Background Anisotropies



Planck all-sky temperature map

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

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

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

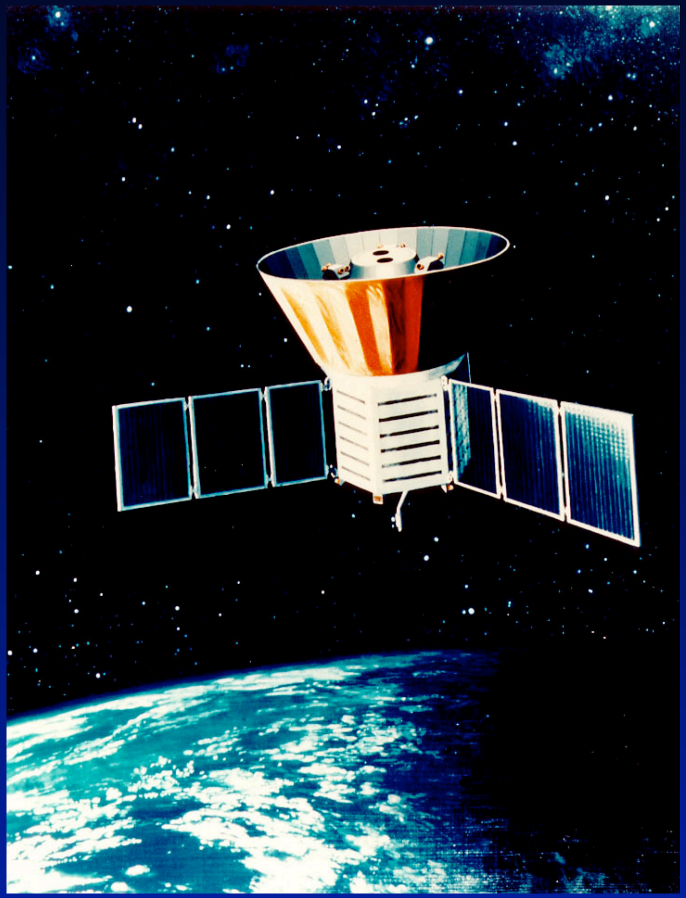
Absolute measurement required!

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)

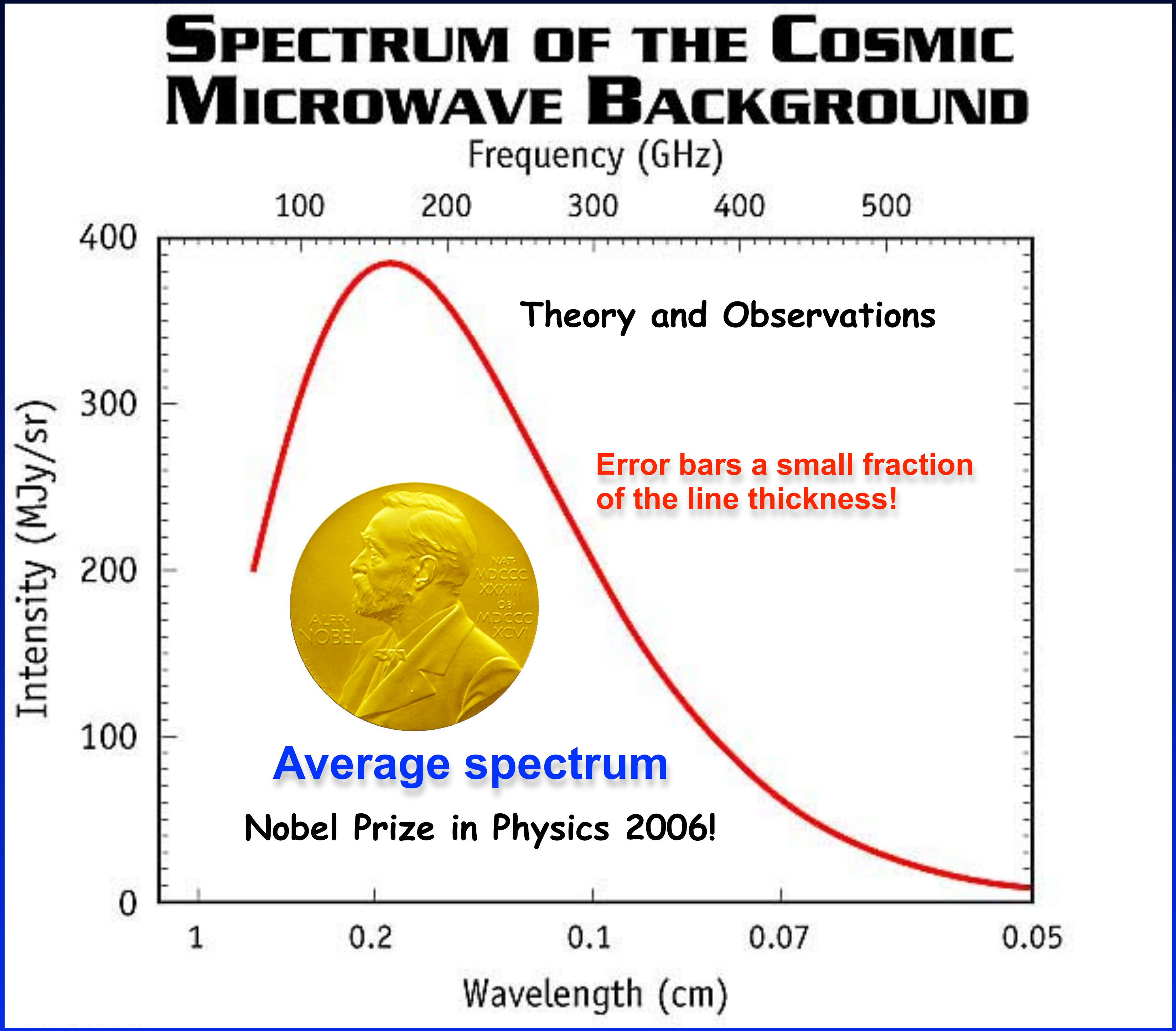


$$T_0 = 2.725 \pm 0.001\,\mathrm{K}$$

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

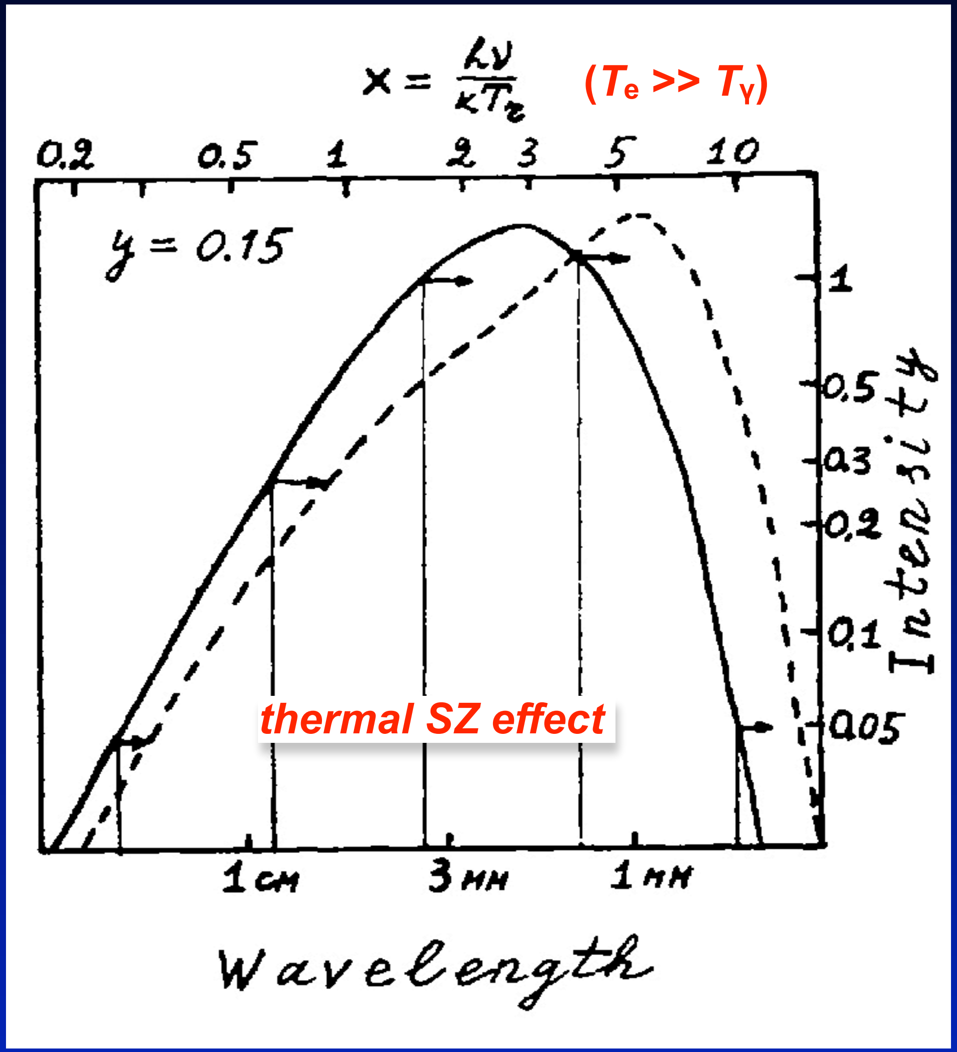
$$|\mu| \leq 9 \times 10^{-5}$$

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



Standard types of primordial CMB distortions

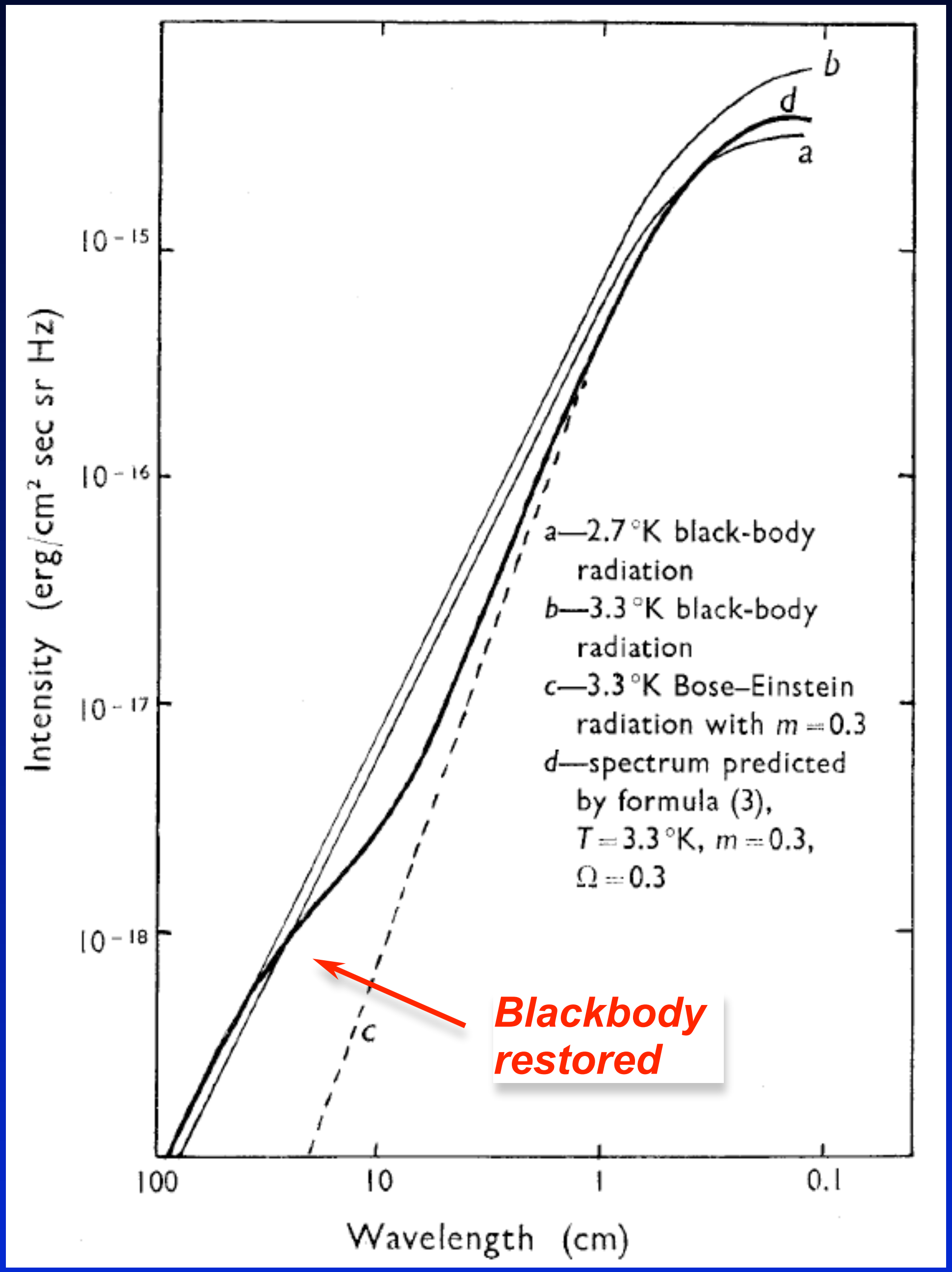
Compton y-distortion



Sunyaev & Zeldovich, 1980, ARAA, 18, 537

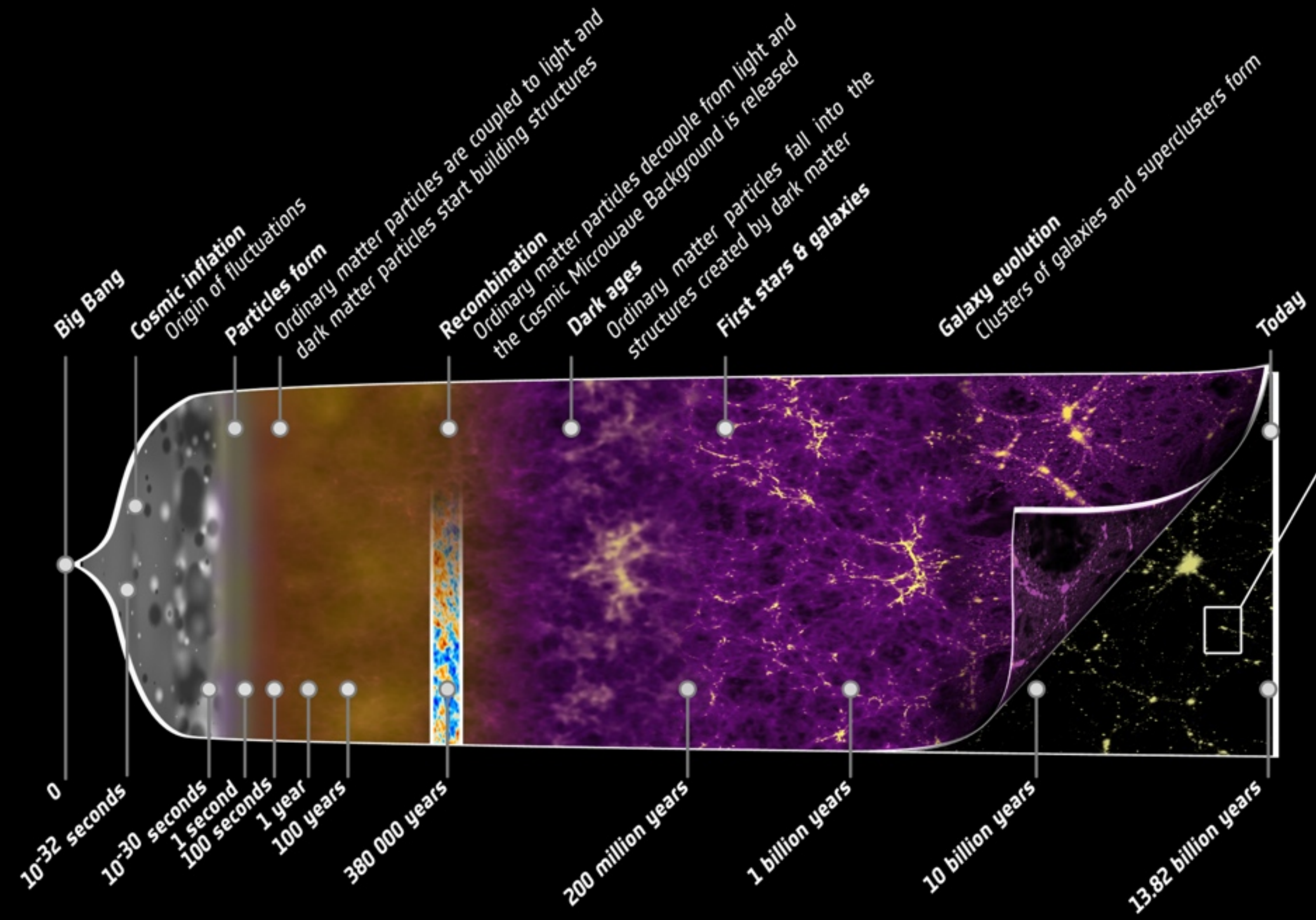
- also known from thSZ effect
- up-scattering of CMB photon
- important at late times (z<50000)
- scattering `inefficient'

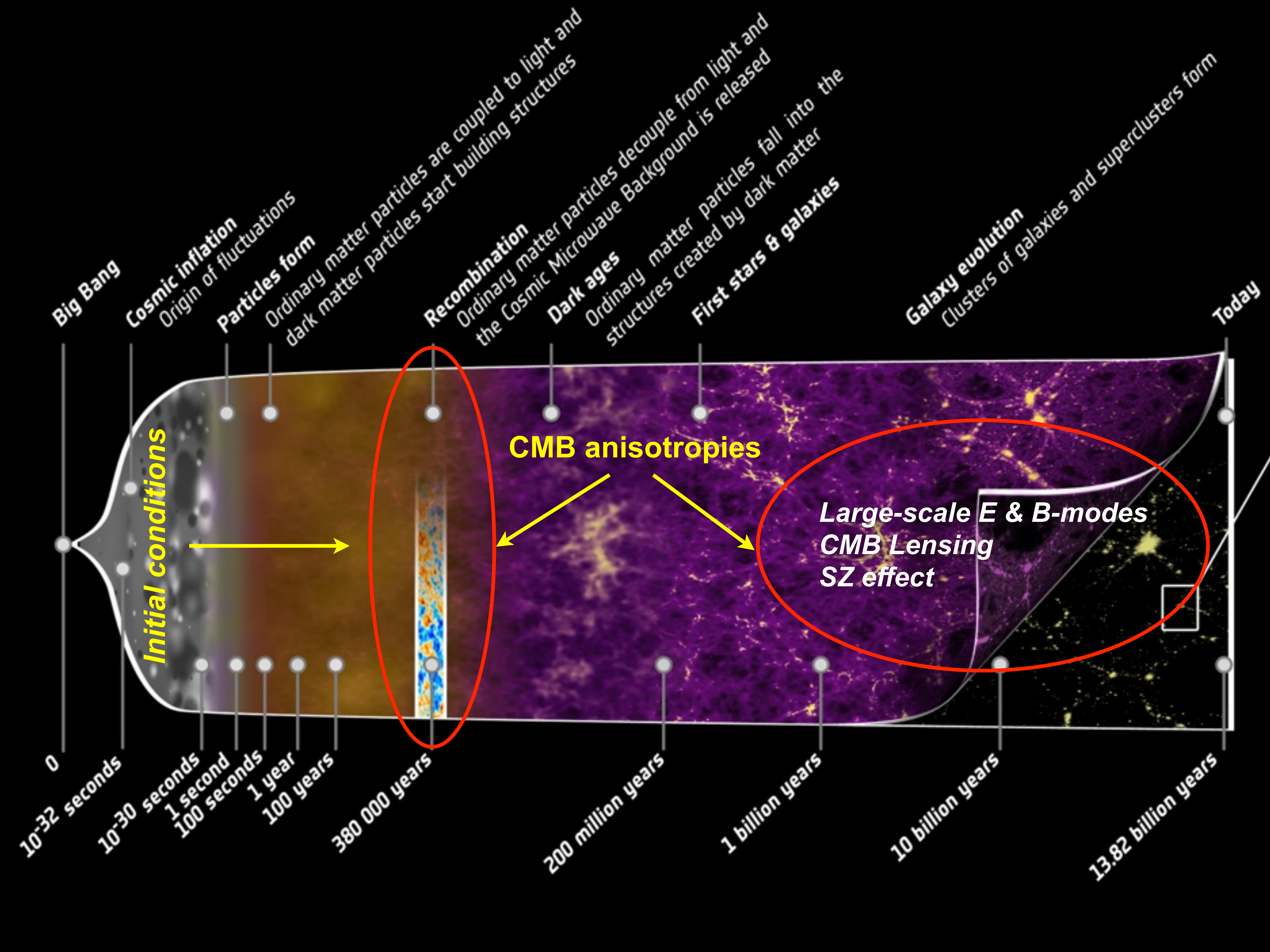
Chemical potential μ-distortion



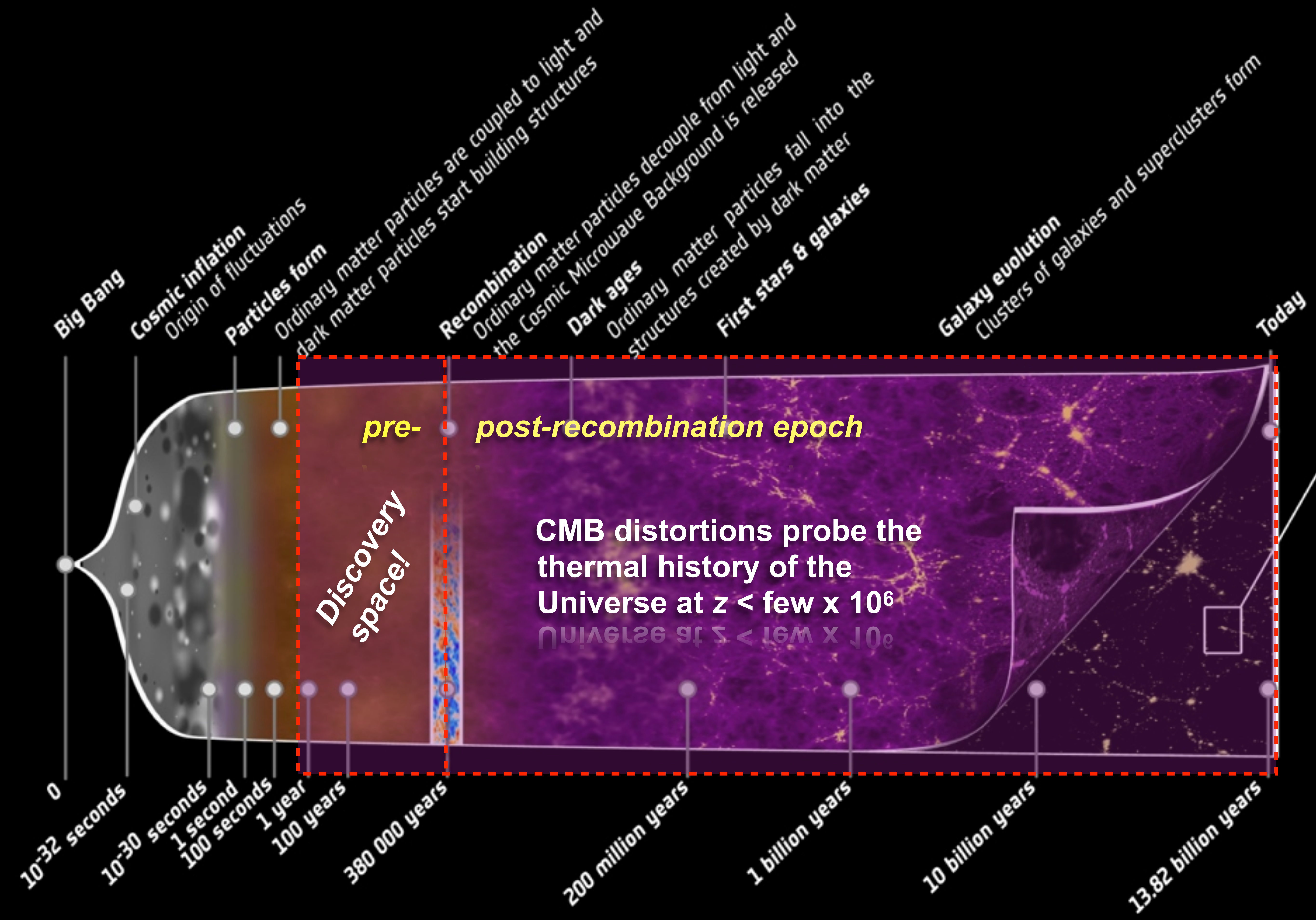
Sunyaev & Zeldovich, 1970, ApSS, 2, 66

- 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

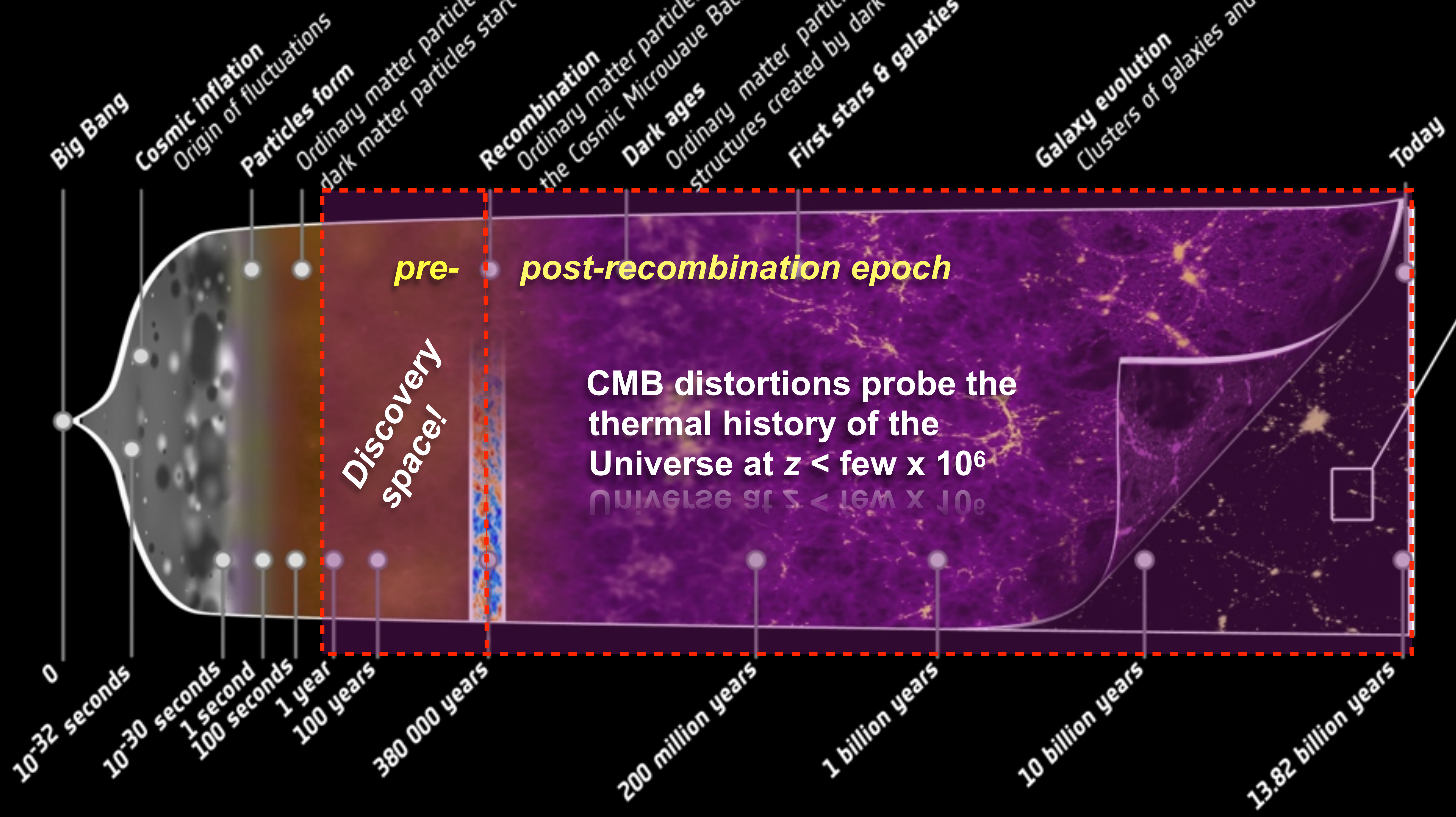


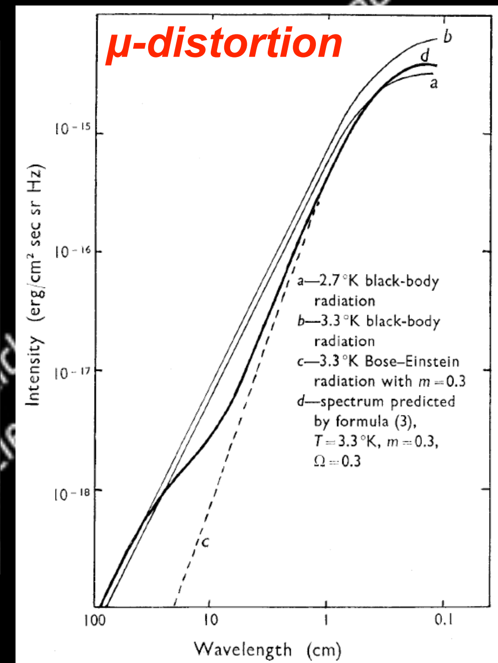
Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
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
200 million years
1 billion years
10 billion years
13.82 billion years

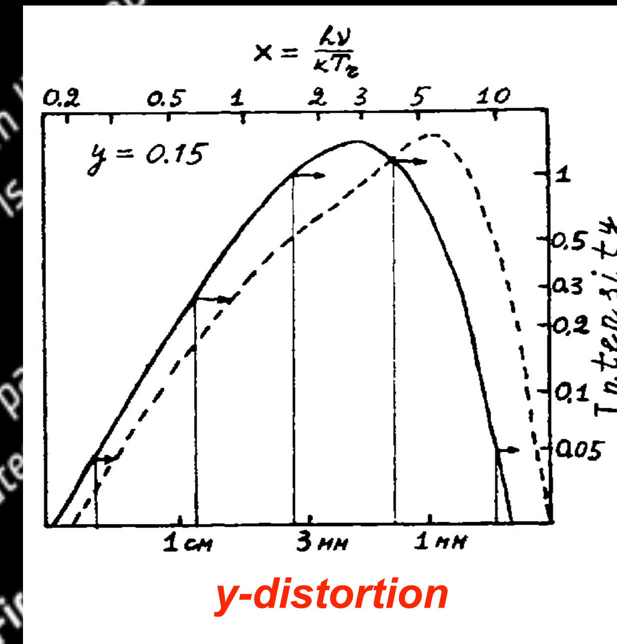


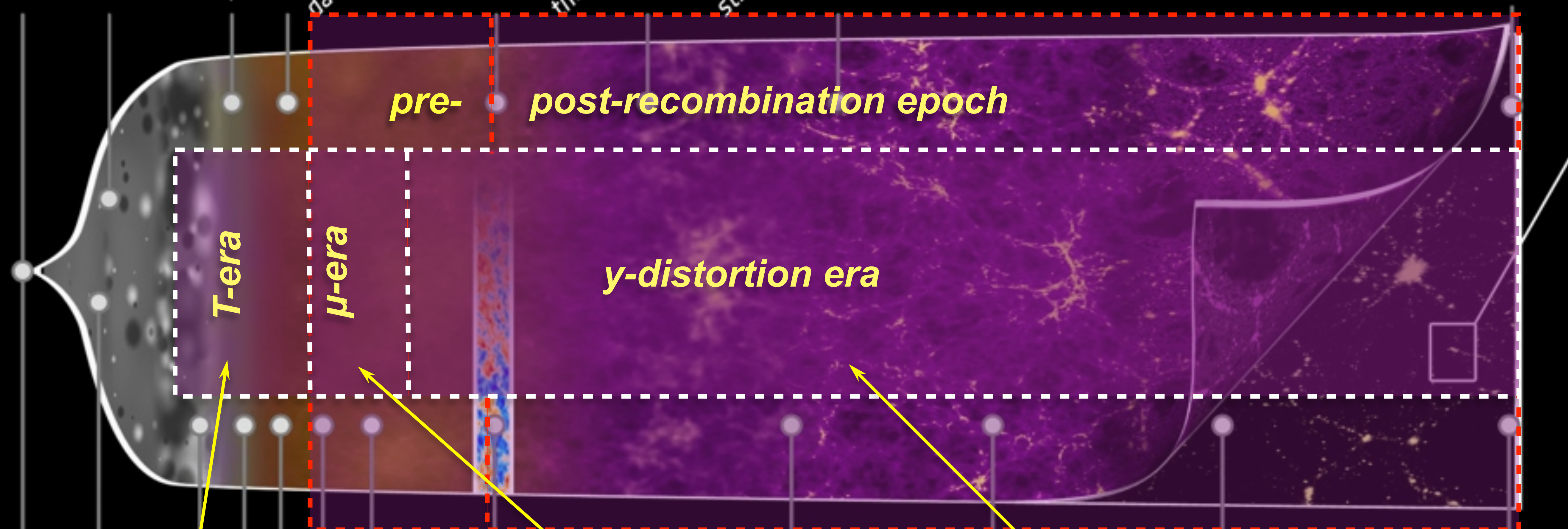
Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
pre-
post-recombination epoch
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
200 million years
1 billion years
10 billion years
13.82 billion years

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



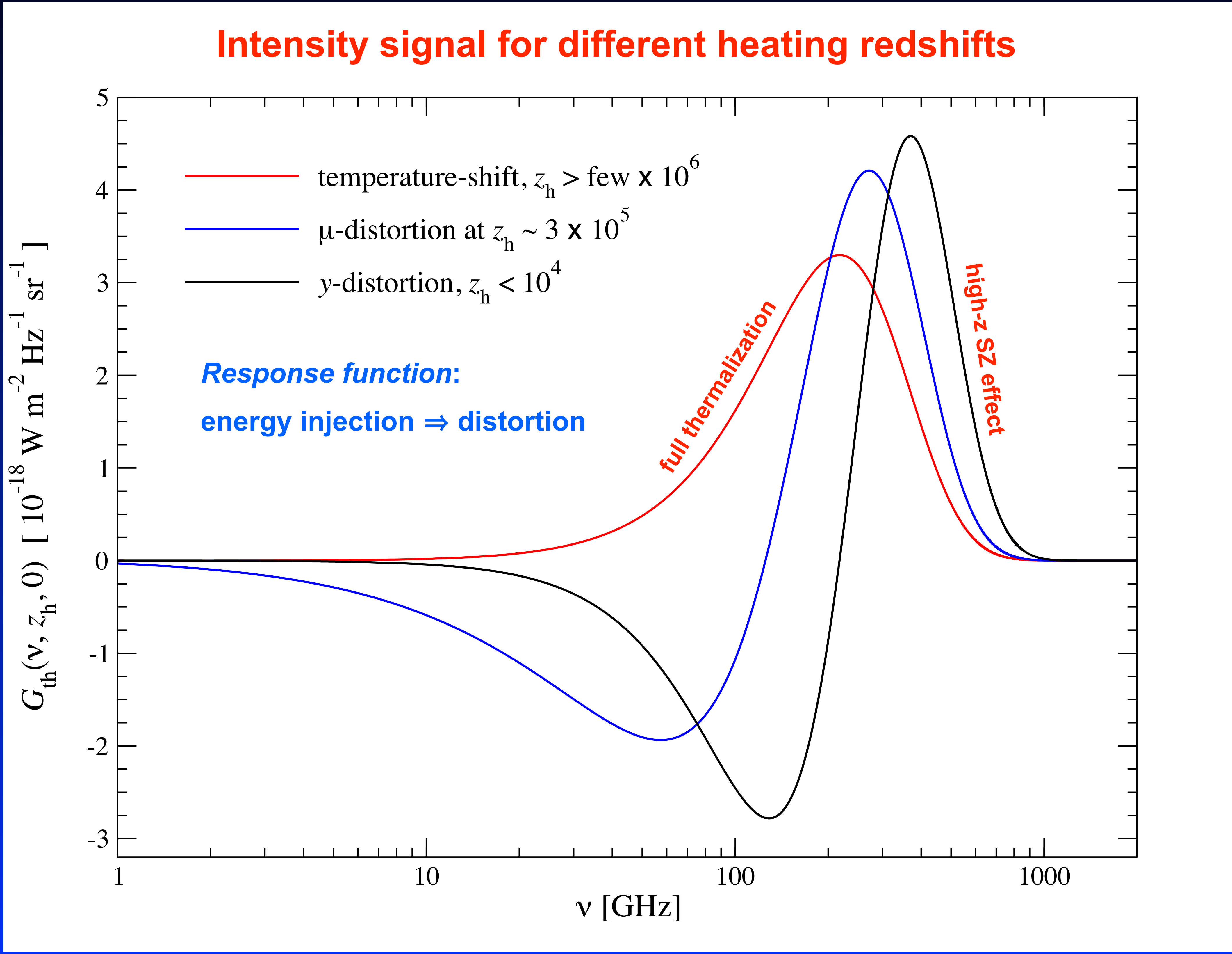






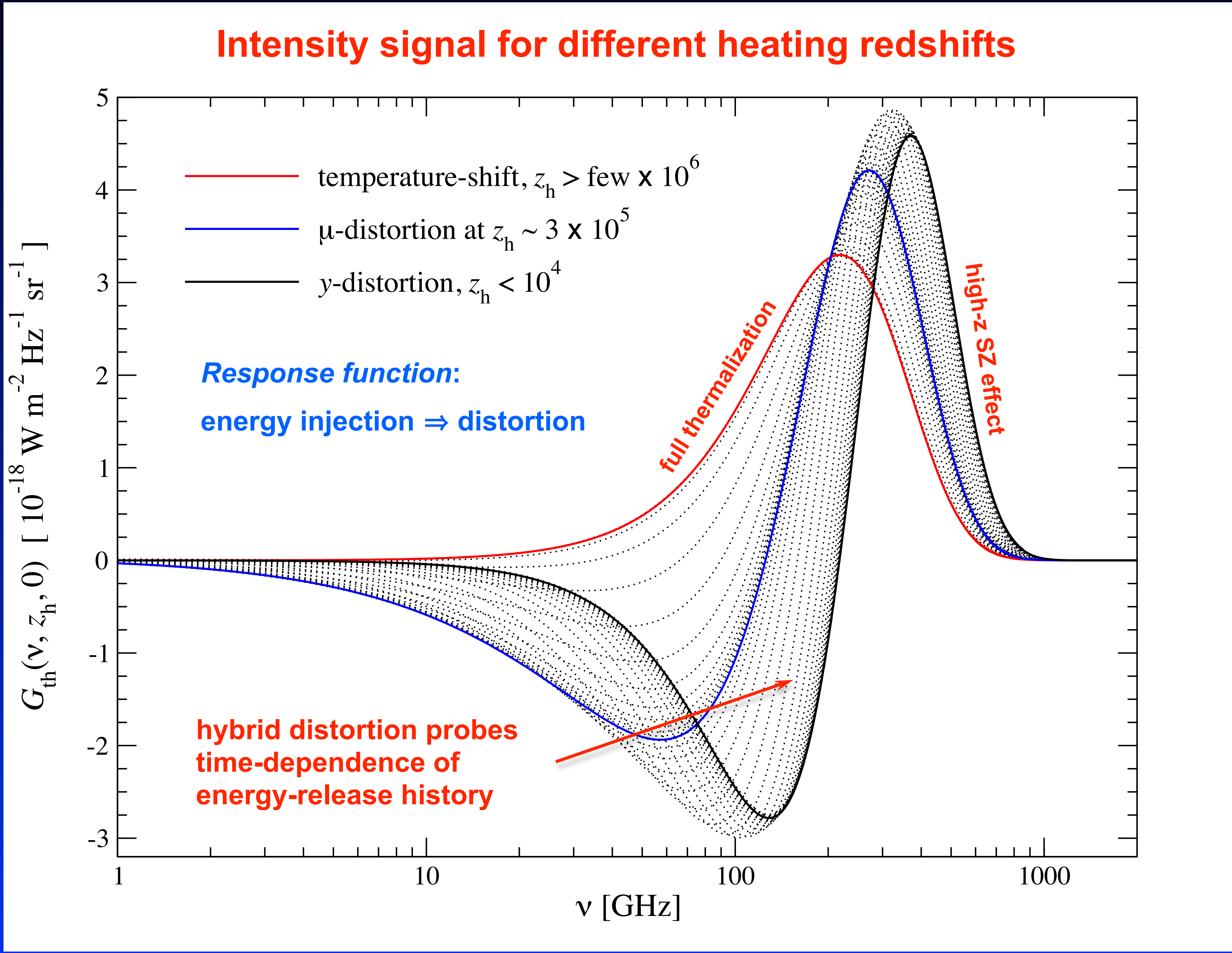
$$\frac{\Delta T}{T} \simeq \frac{1}{4} \left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_T \qquad \mu \simeq 1.4 \left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_\mu \qquad y \simeq \frac{1}{4} \left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_y$$

What does the spectrum look like after energy injection?



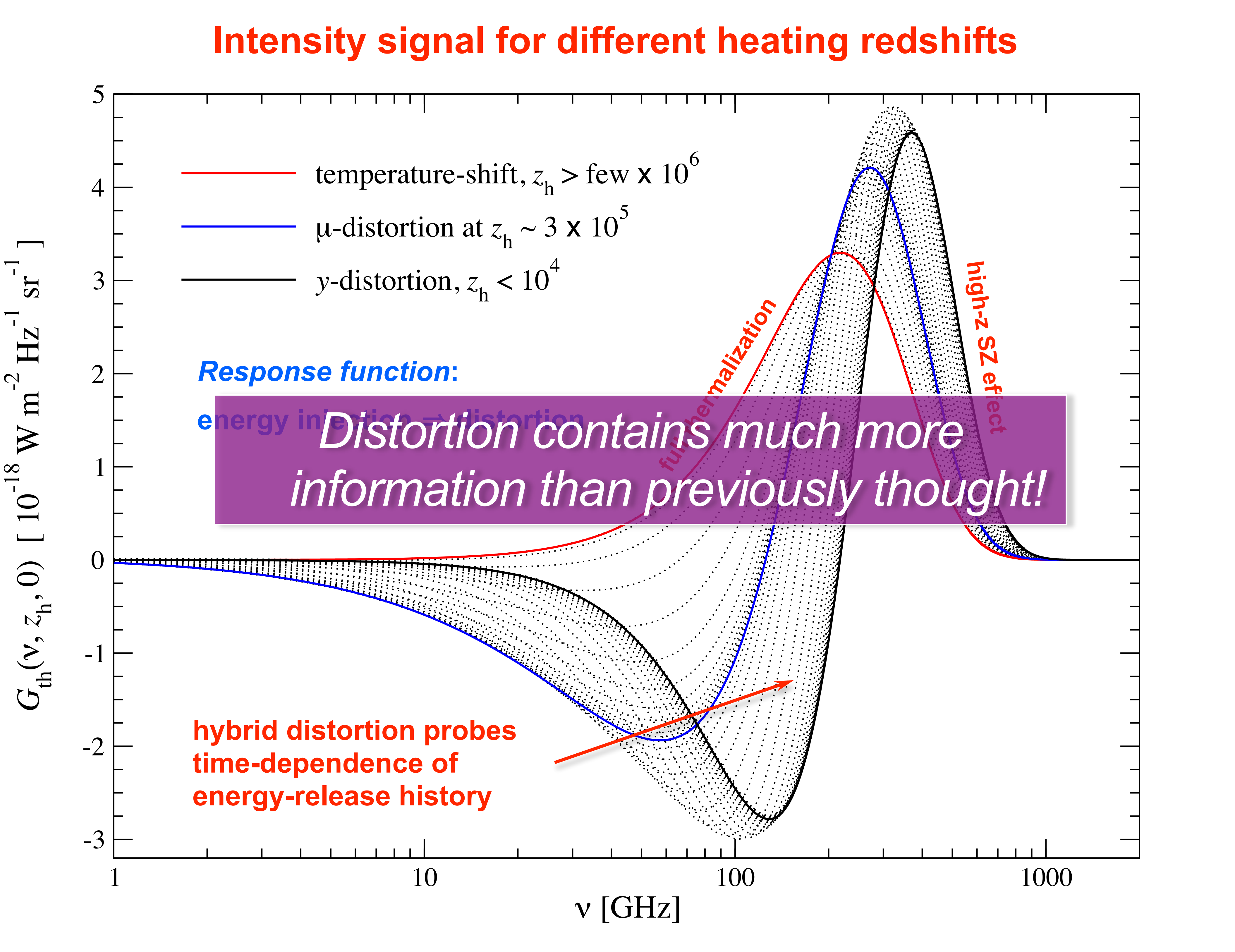
JC & Sunyaev, 2012, ArXiv:1109.6552
JC, 2013, ArXiv:1304.6120

What does the spectrum look like after energy injection?



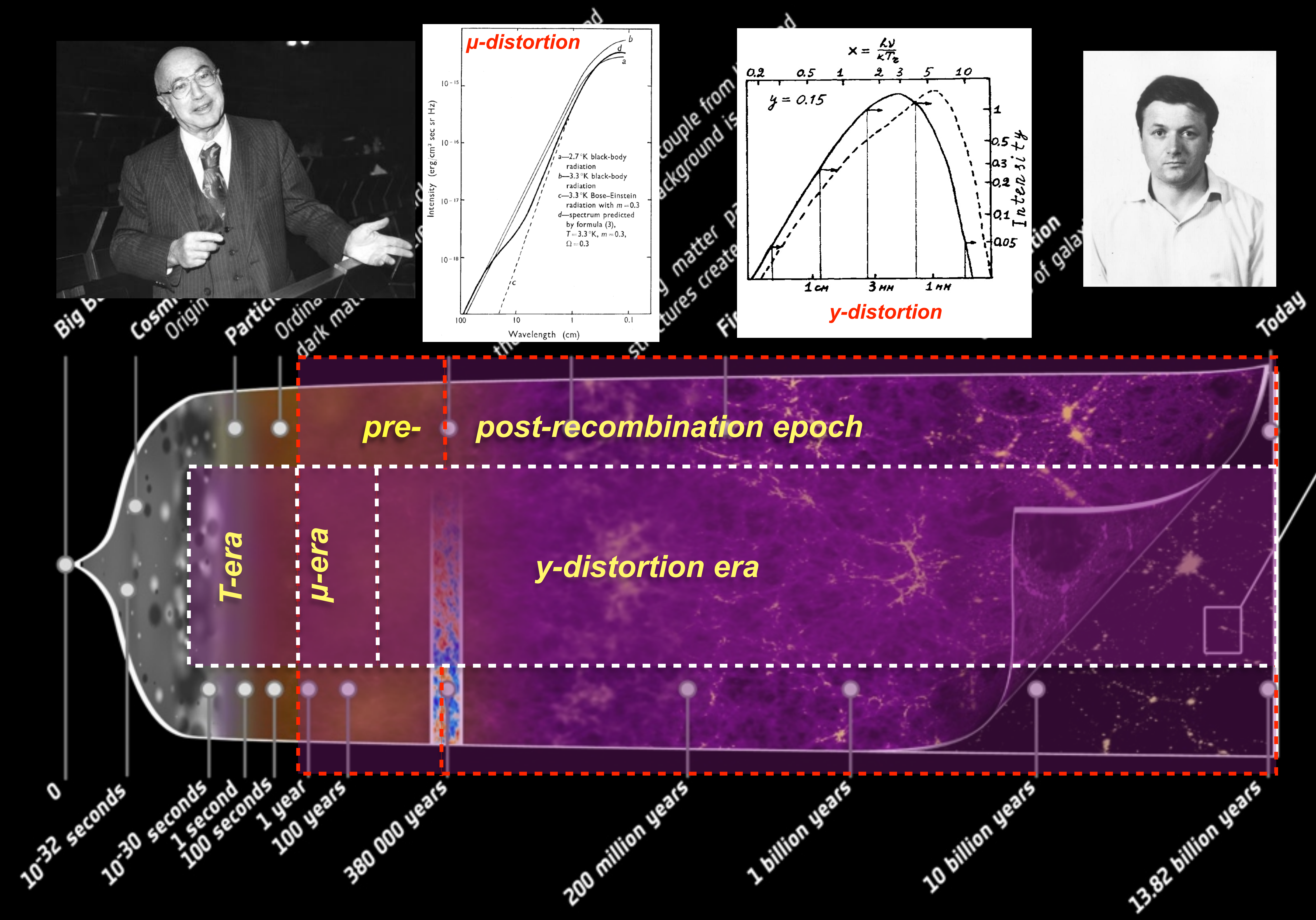
JC & Sunyaev, 2012, ArXiv:1109.6552
JC, 2013, ArXiv:1304.6120

What does the spectrum look like after energy injection?

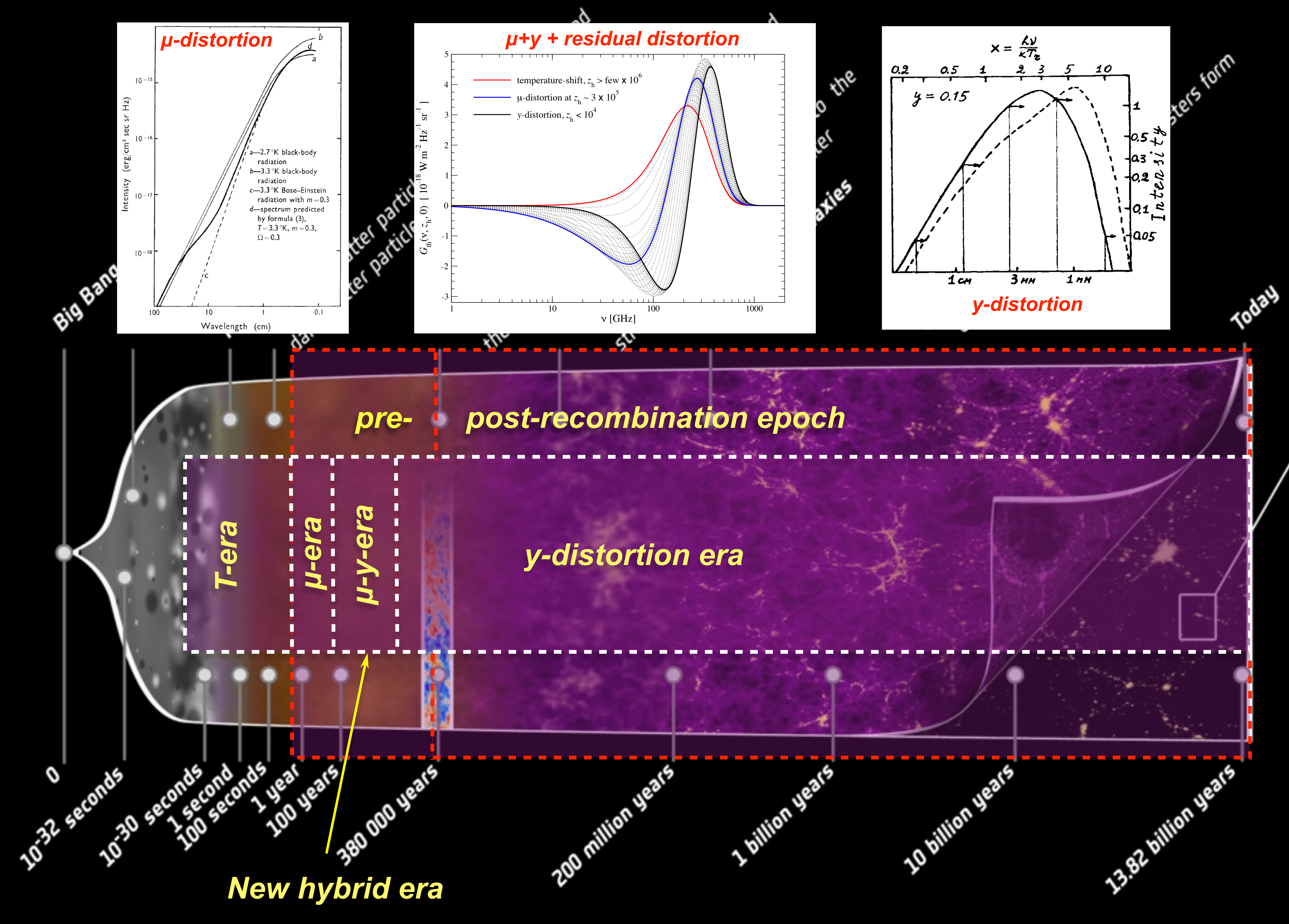


Distortion contains much more information than previously thought!

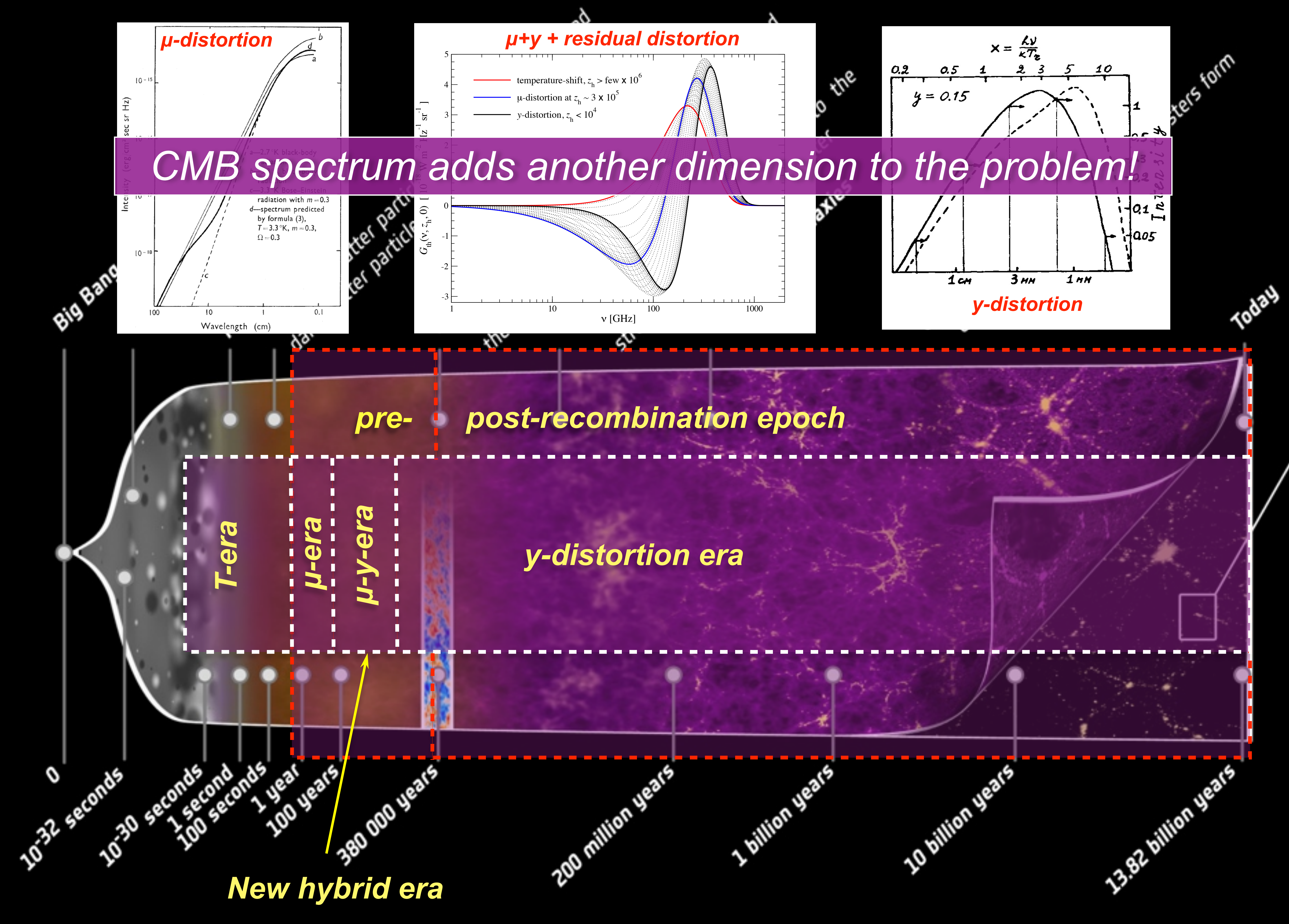
JC & Sunyaev, 2012, ArXiv:1109.6552
JC, 2013, ArXiv:1304.6120



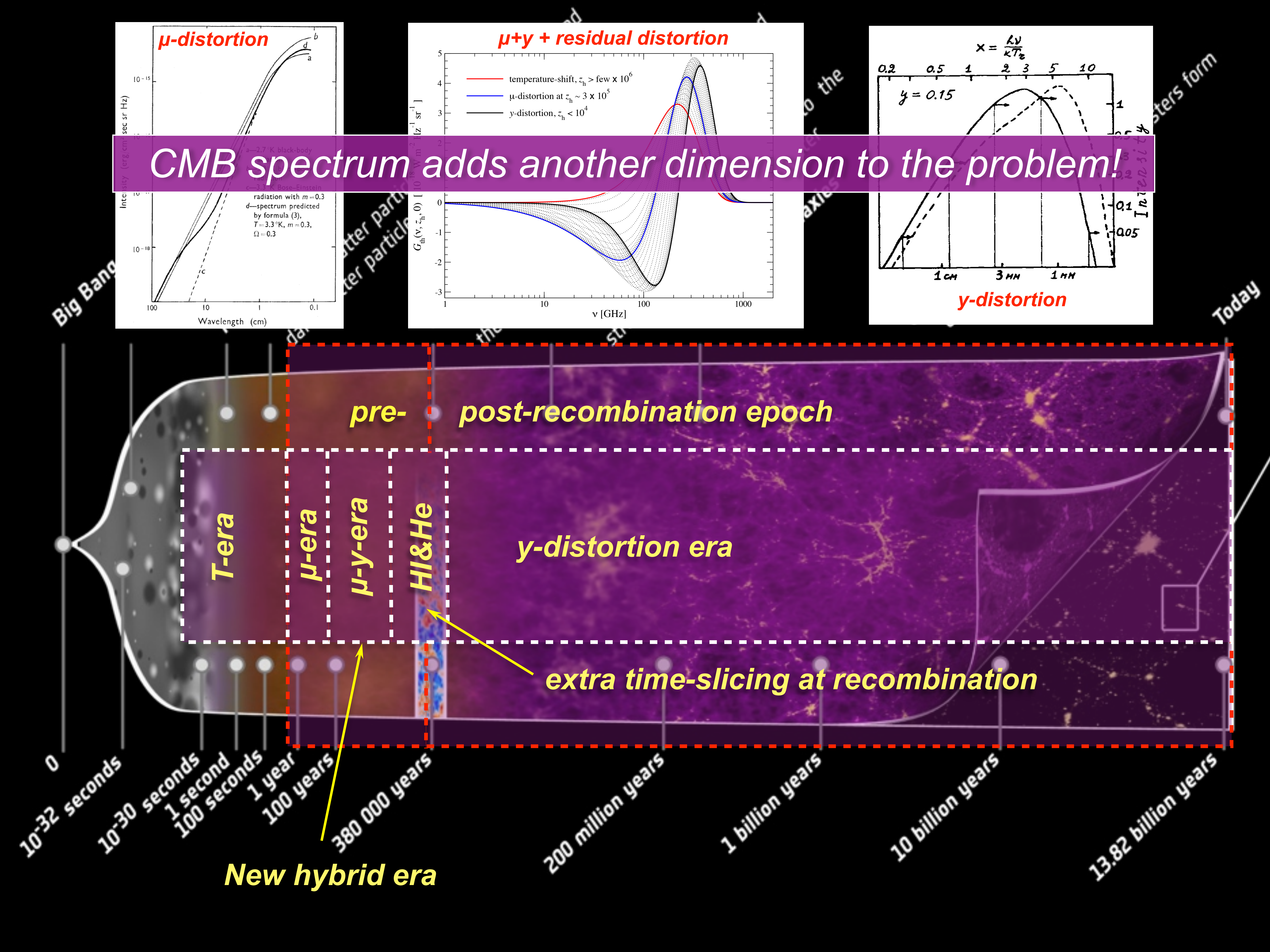
μ-distortion
Intensity (erg/cm² sec sr Hz)
Wavelength (cm)
a—2.7°K black-body radiation
b—3.3°K black-body radiation
c—3.3°K Bose–Einstein radiation with m=0.3
d—spectrum predicted by formula (3), T=3.3°K, m=0.3, Ω=0.3
x = hν/kT_e
y = 0.15
Intensity
1 cm
3 mm
1 mm
y-distortion
Today
pre-
post-recombination epoch
T-era
μ-era
y-distortion era
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years



μ-distortion
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
Intensity (erg cm² 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 = 0.15
Intensity
y-distortion
Big Bang
Today
pre-
post-recombination epoch
T-era
μ-era
μ-y-era
y-distortion era
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years
New hybrid era

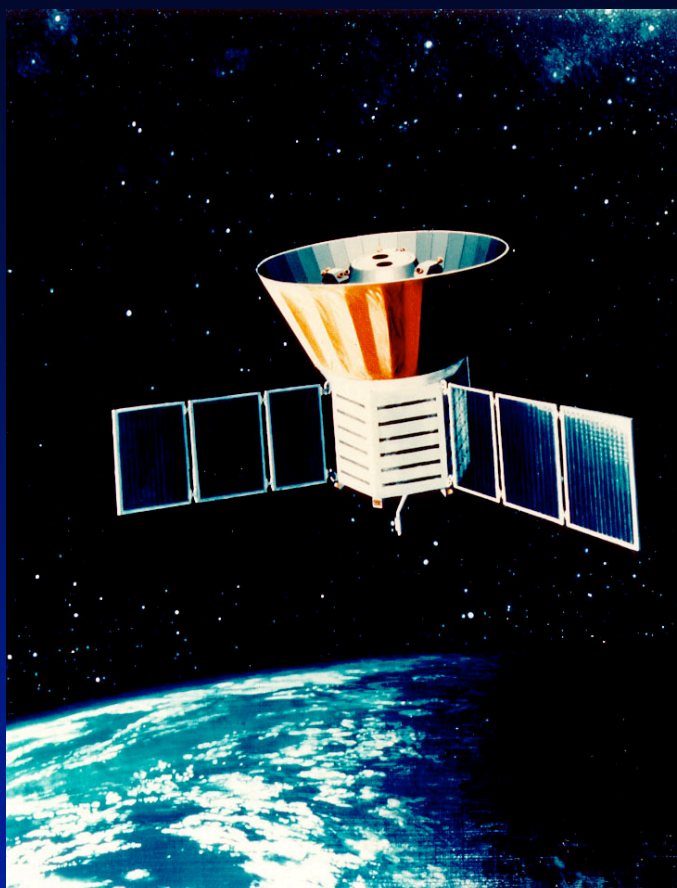


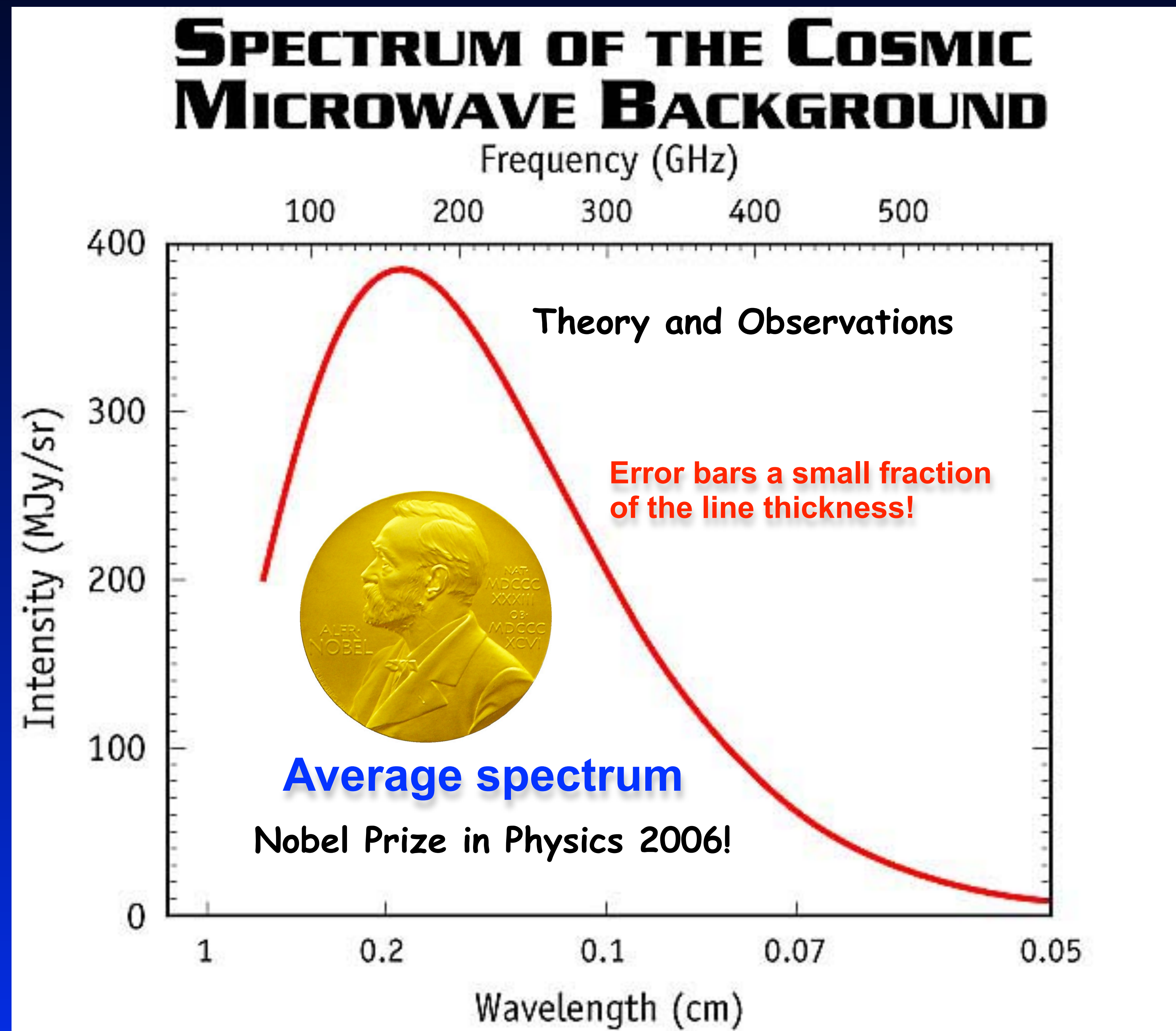
CMB spectrum adds another dimension to the problem!
μ-distortion
μ+y + residual distortion
temperature-shift, z_h > few x 10^6
μ-distortion at $z_h \sim 3 \times 10^5$
y-distortion, $z_h < 10^4$
ν [GHz]
y-distortion
Wavelength (cm)
pre-
post-recombination epoch
T-era
μ-era
μ-y-era
y-distortion era
New hybrid era
Big Bang
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



μ-distortion
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]
Wavelength (cm)
y = 0.15
y-distortion
CMB spectrum adds another dimension to the problem!
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
200 million years
1 billion years
10 billion years
13.82 billion years
New hybrid era

COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)





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

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

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

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

- *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)

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

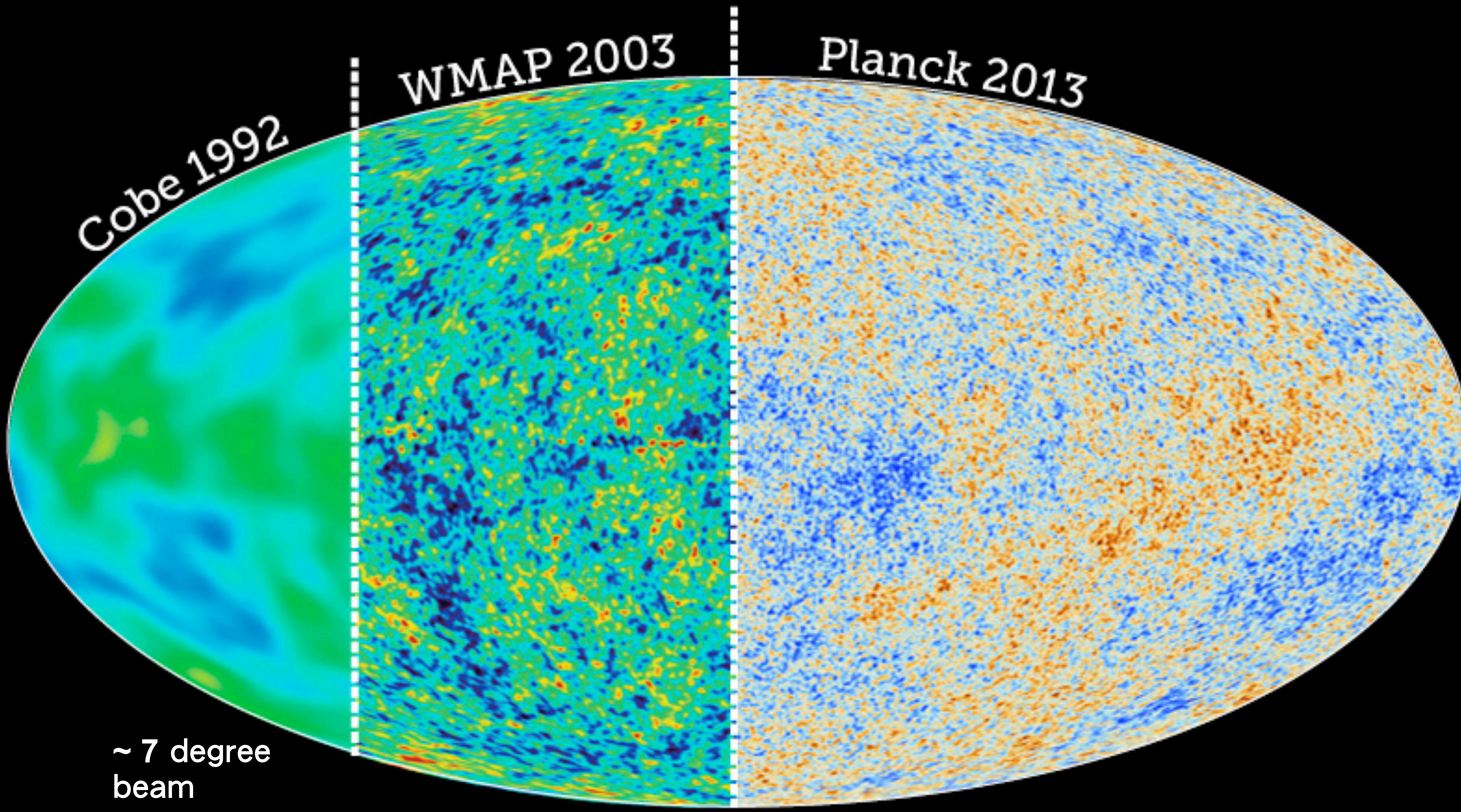
„high“ redshifts

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

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

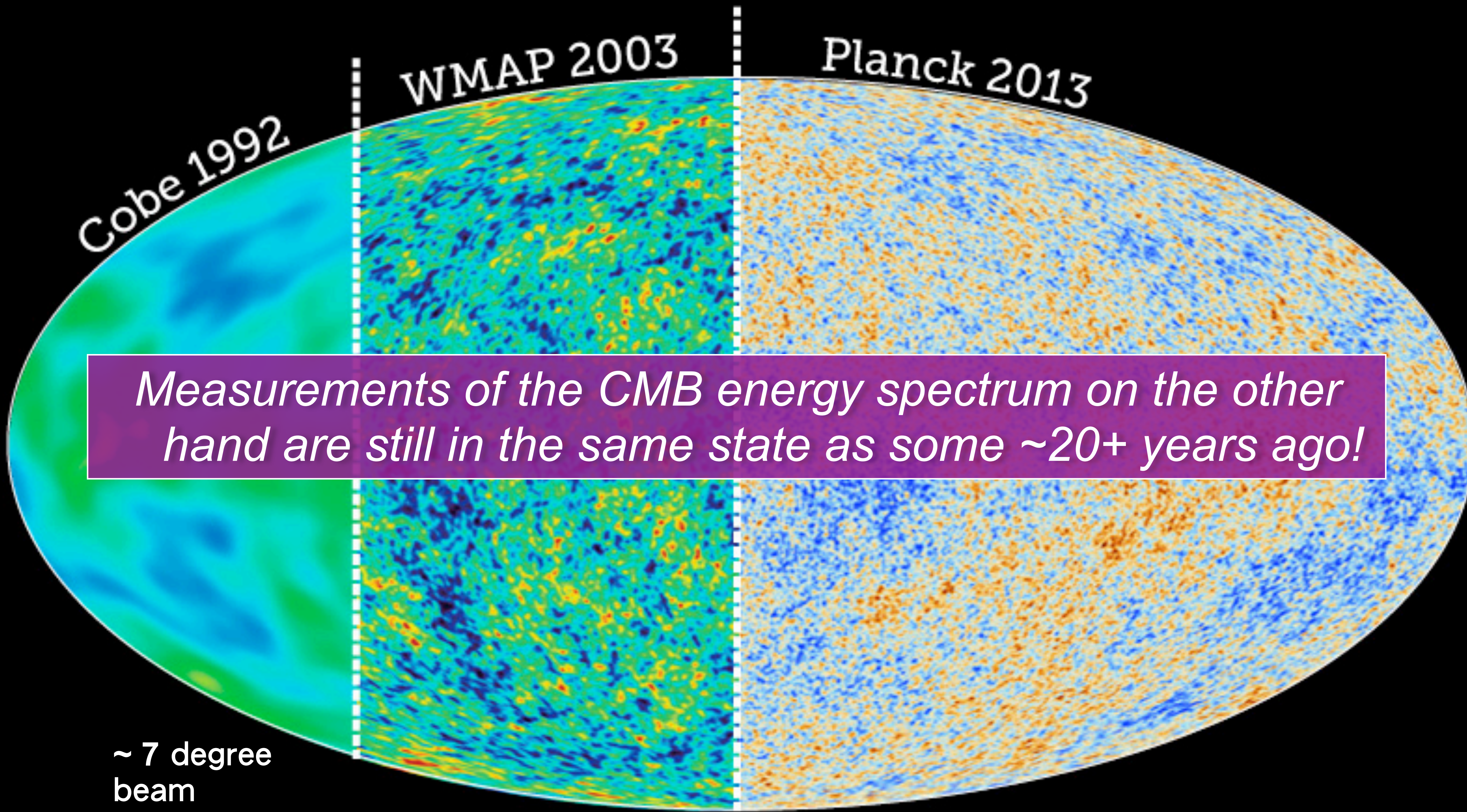


~ 7 degree beam

~ 0.3 degree beam

~ 0.08 degree beam

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



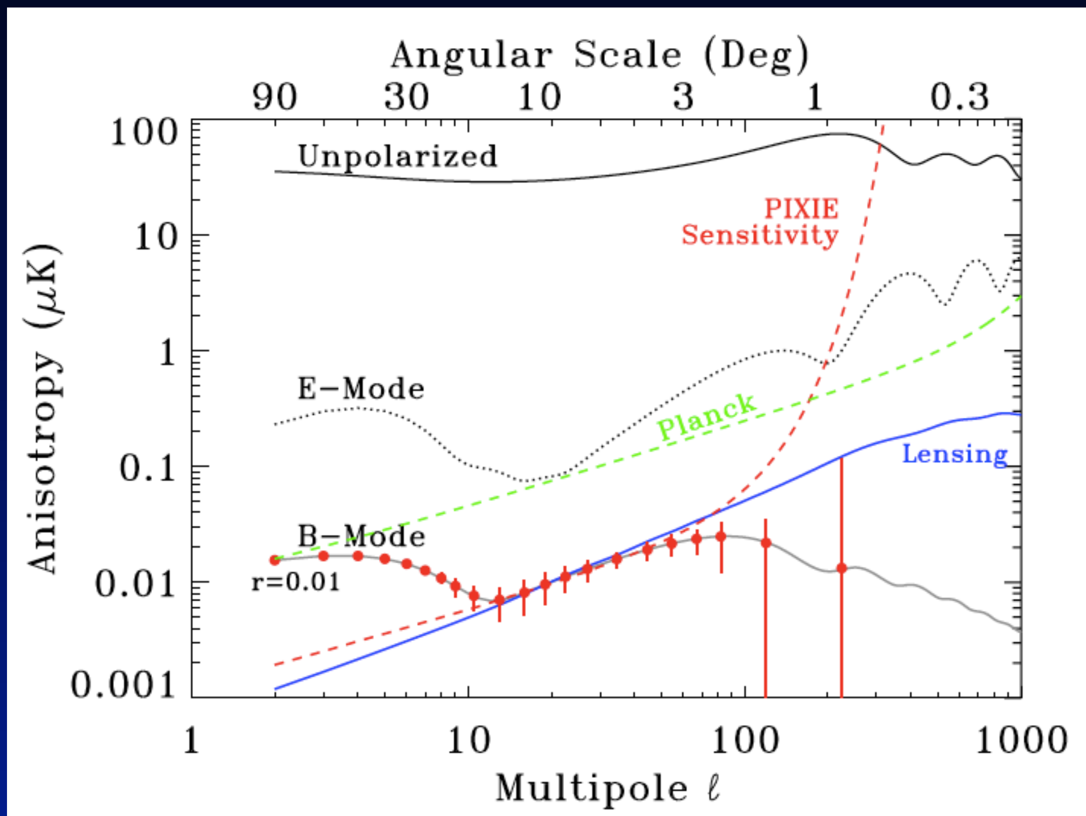
Measurements of the CMB energy spectrum on the other hand are still in the same state as some ~20+ years ago!

~ 7 degree beam

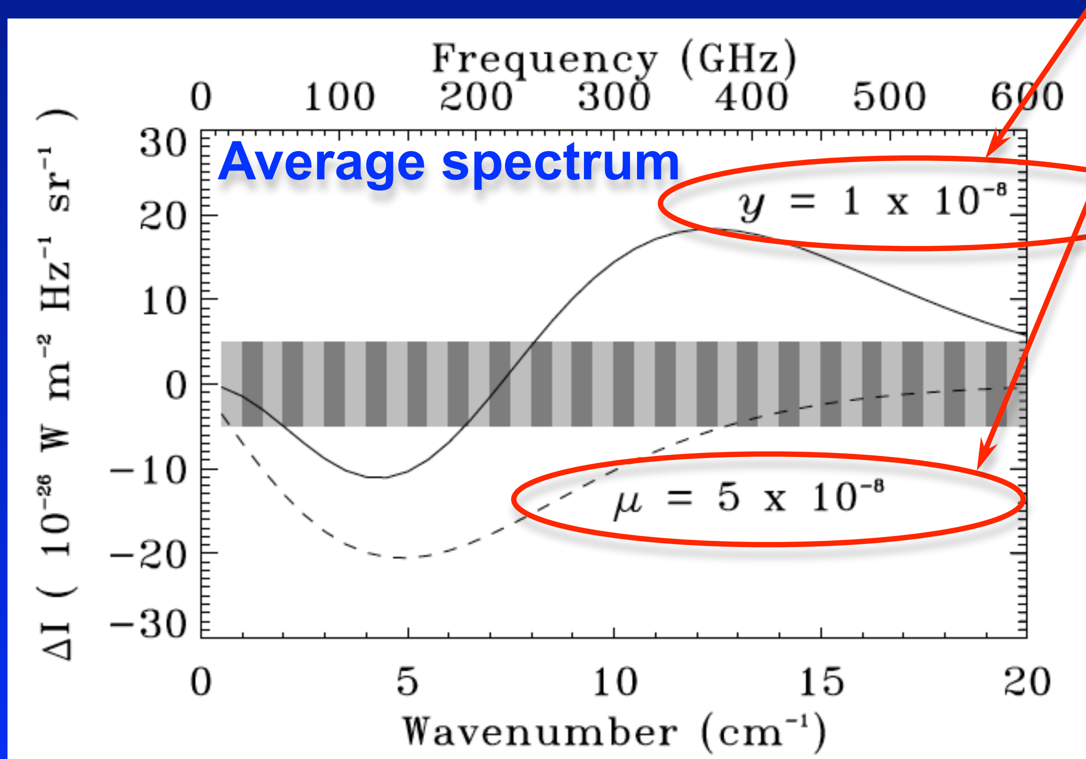
~ 0.3 degree beam

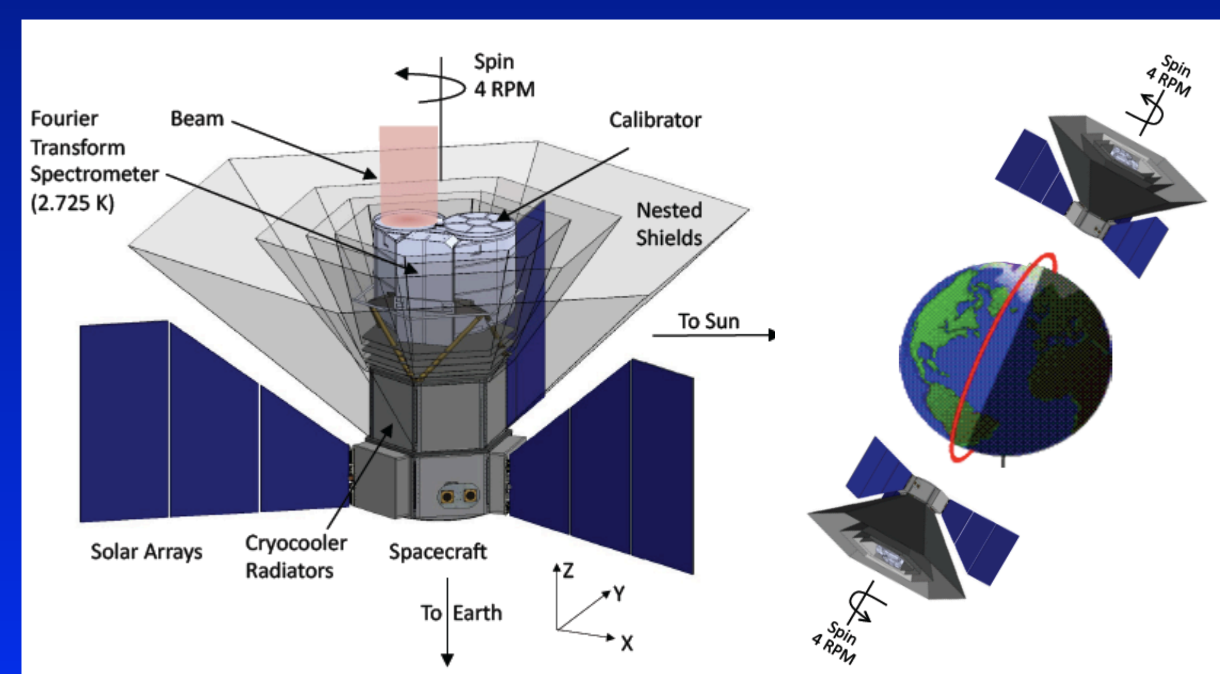
~ 0.08 degree beam

PIXIE: Primordial Inflation Explorer

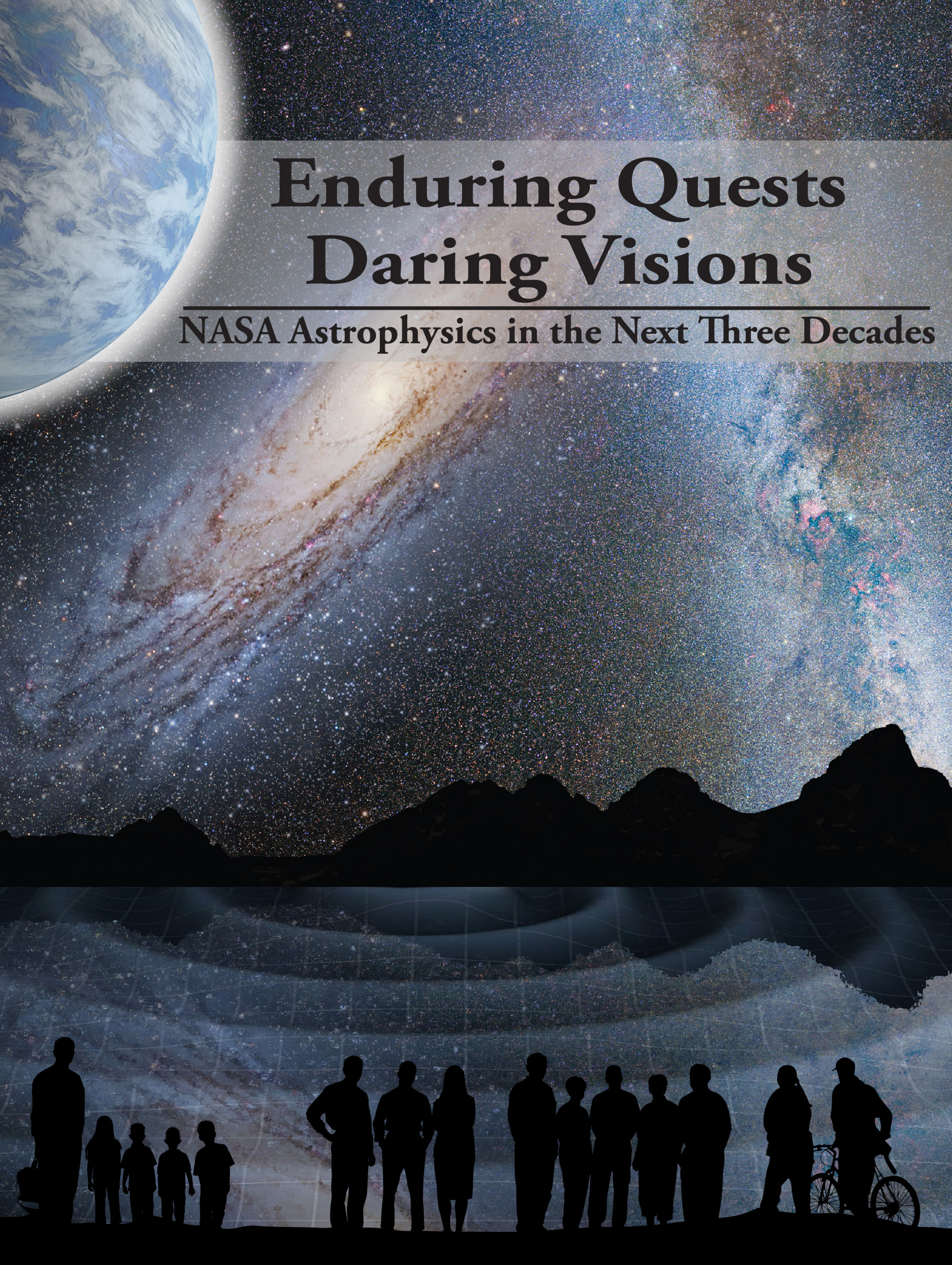


- 400 spectral channel in the frequency range 30 GHz and 6THz (Δv ~ 15GHz)
- about 1000 (!!!) times more sensitive than COBE/FIRAS
- B-mode polarization from inflation ($r \approx 10^{-3}$)
- improved limits on μ and y
- was proposed 2011 & 2016 as NASA EX mission (i.e. cost ~ 200-250 M$)





Kogut et al, JCAP, 2011, arXiv:1105.2044

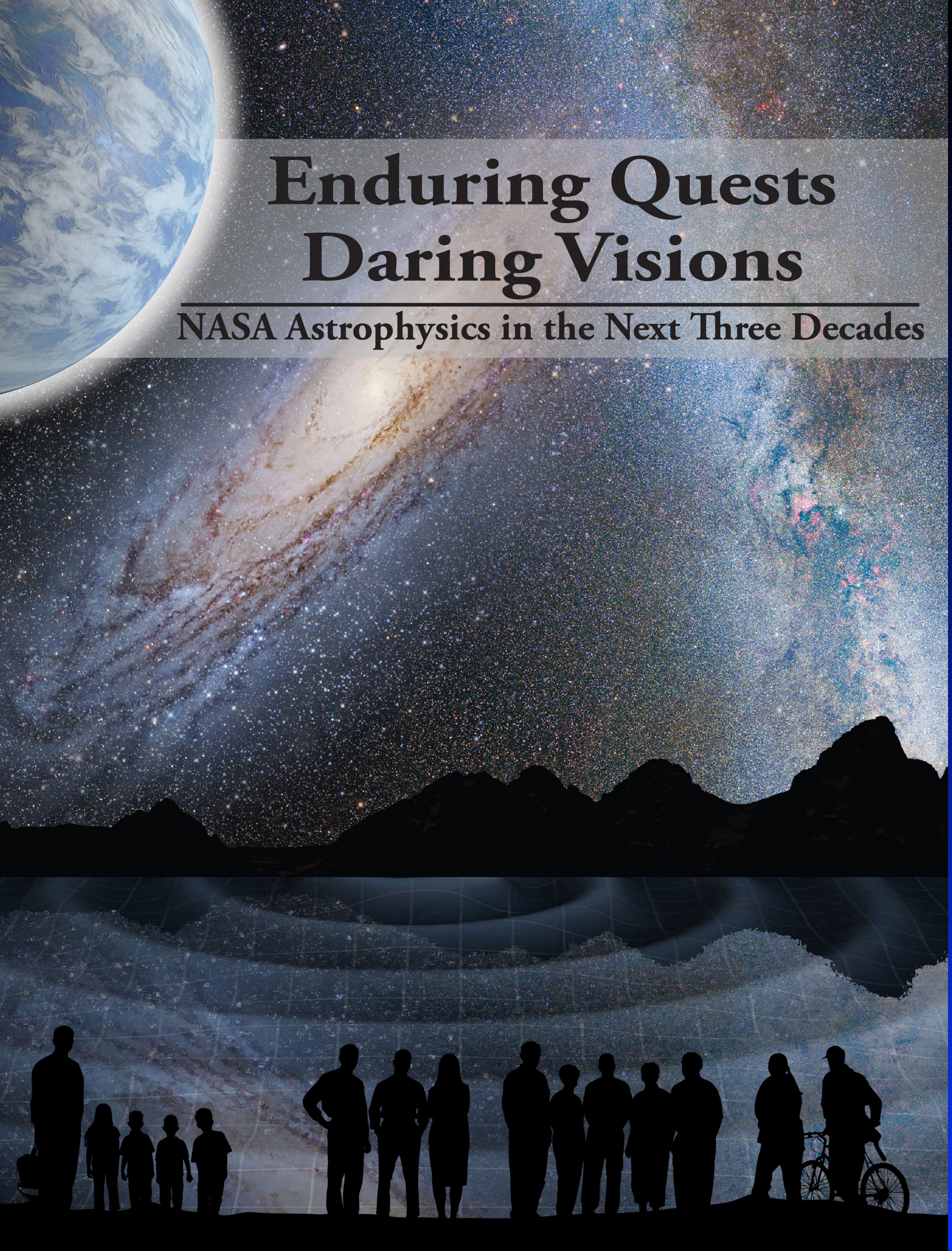


NASA 30-yr Roadmap Study

(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."



NASA 30-yr Roadmap Study

(published Dec 2013)

How does the Universe work?

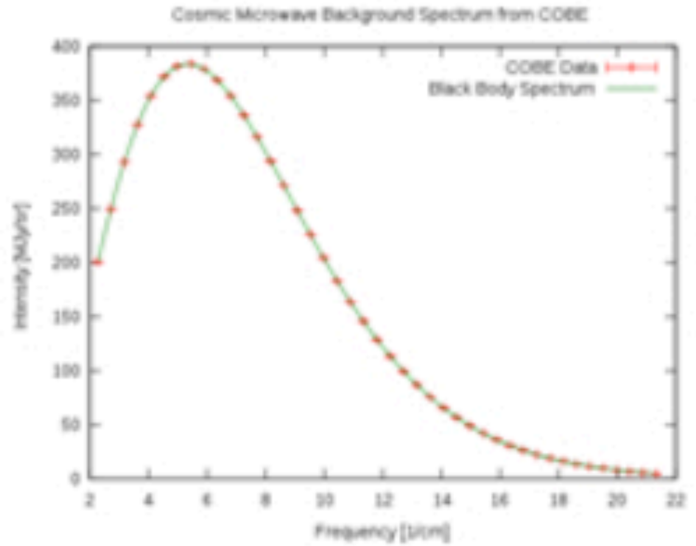
"Measure the spectrum of the CMB with precision several orders of magnitude higher than COBE FIRAS, from a moderate-scale mission or an instrument on CMB Polarization Surveyor."

New mission concepts:

PRISTINE (France)
CMB-Bharat (India)

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.

COSMO at Dome C

COSmological Monopole Observer

SAPIENZA
UNIVERSITÀ DI ROMA

Taken from a talk by Elia Battistelli

SAPIENZA UNIVERSITÀ DI ROMA

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

CNR IFN Istituto di Fotonica e Nanotecnologie

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

ASU ARIZONA STATE UNIVERSITY

PROGRAMMA NAZIONALE DI RICERCHE IN ANTARTIDE — ITALIANTARTIDE

Probing fundamental physics with CMB spectral distortions

12 Mar 2018, 00:30 → 16 Mar 2018, 19:00 Europe/Zurich

503-1-001 - Council Chamber (CERN)

Physical mechanisms that lead to spectral distortions

Standard sources of distortions

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

pre-recombination epoch

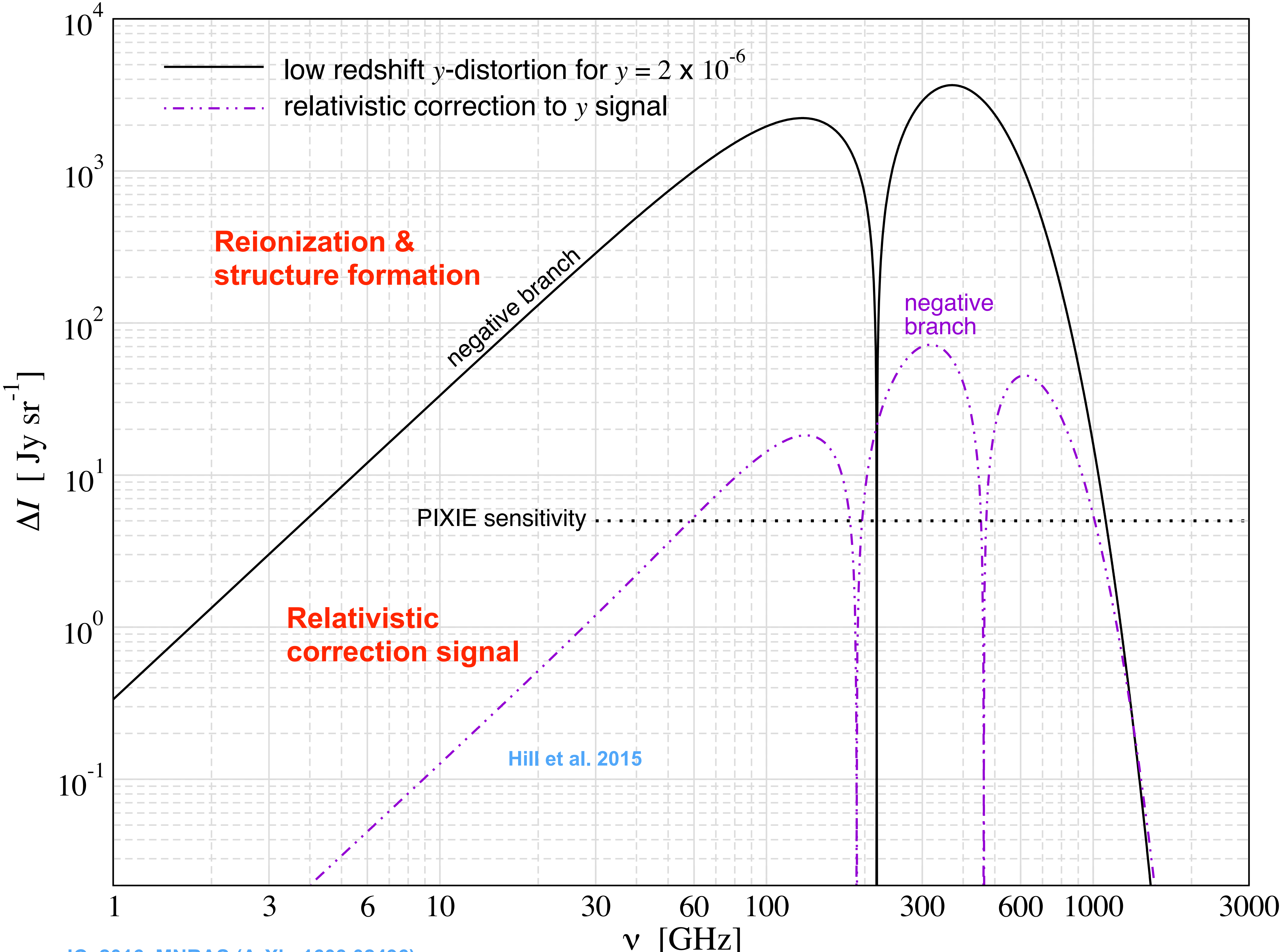
„high" redshifts

„low" redshifts

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

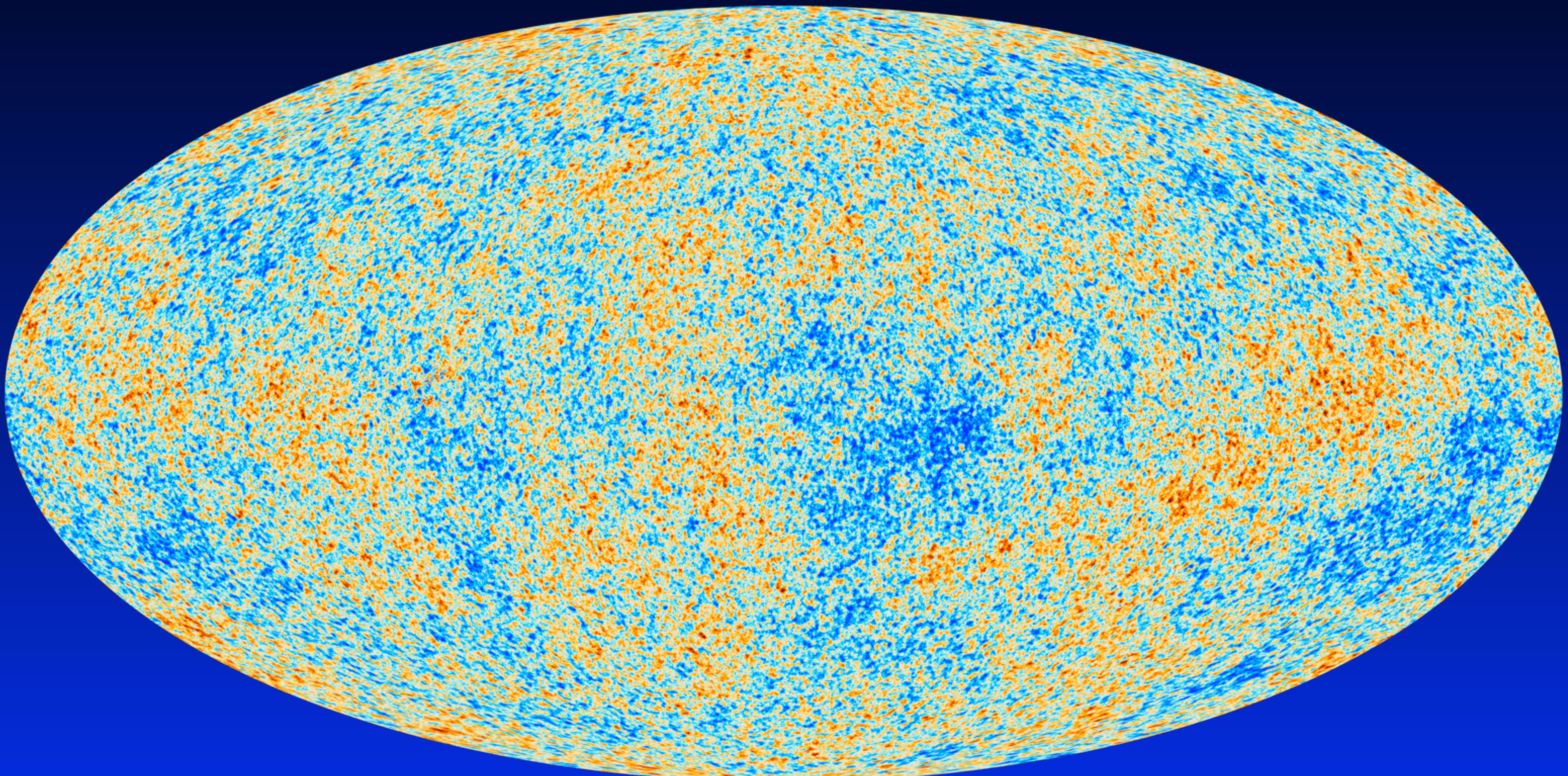
post-recombination

Average CMB spectral distortions

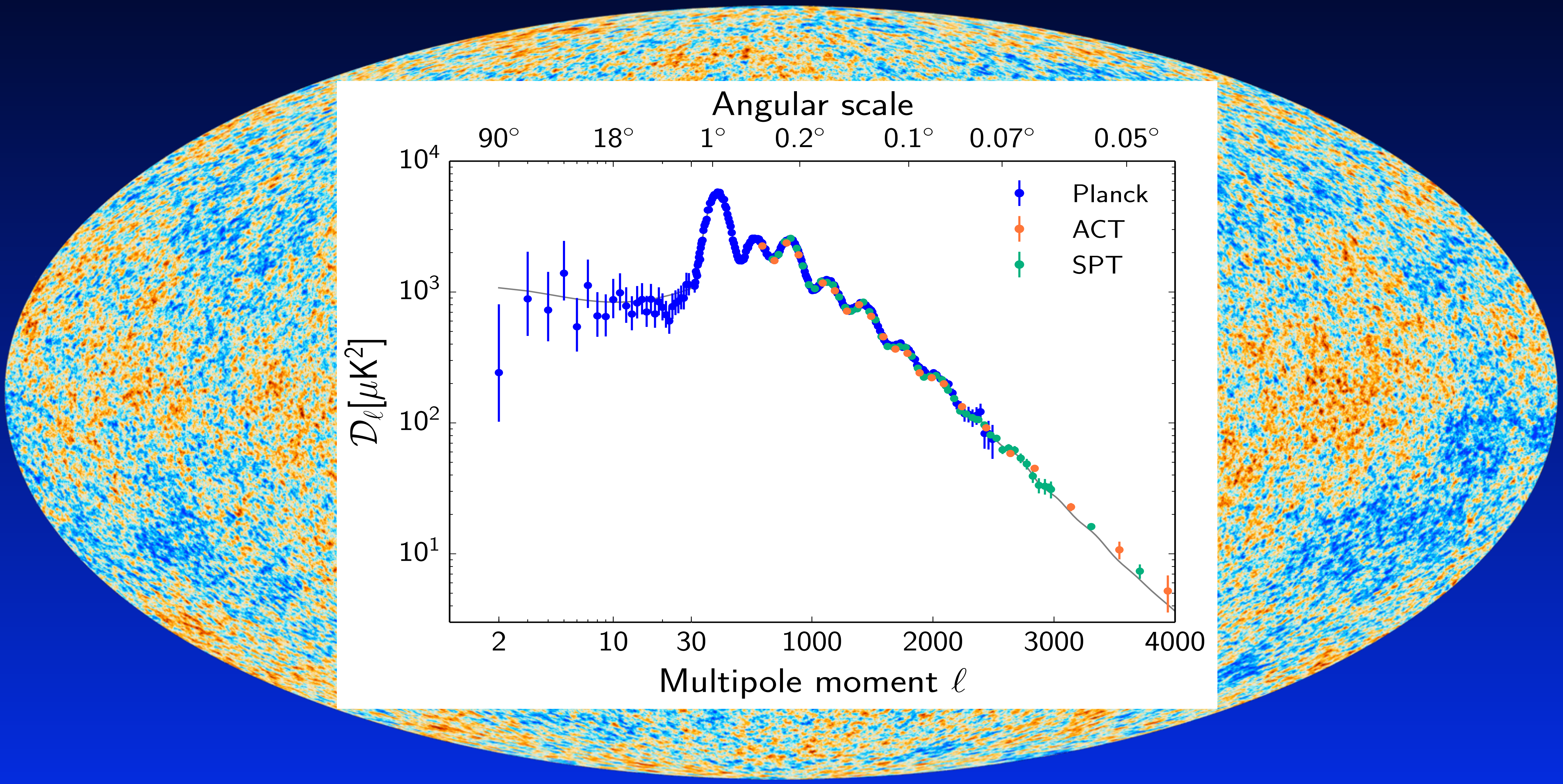


JC, 2016, MNRAS (ArXiv:1603.02496)

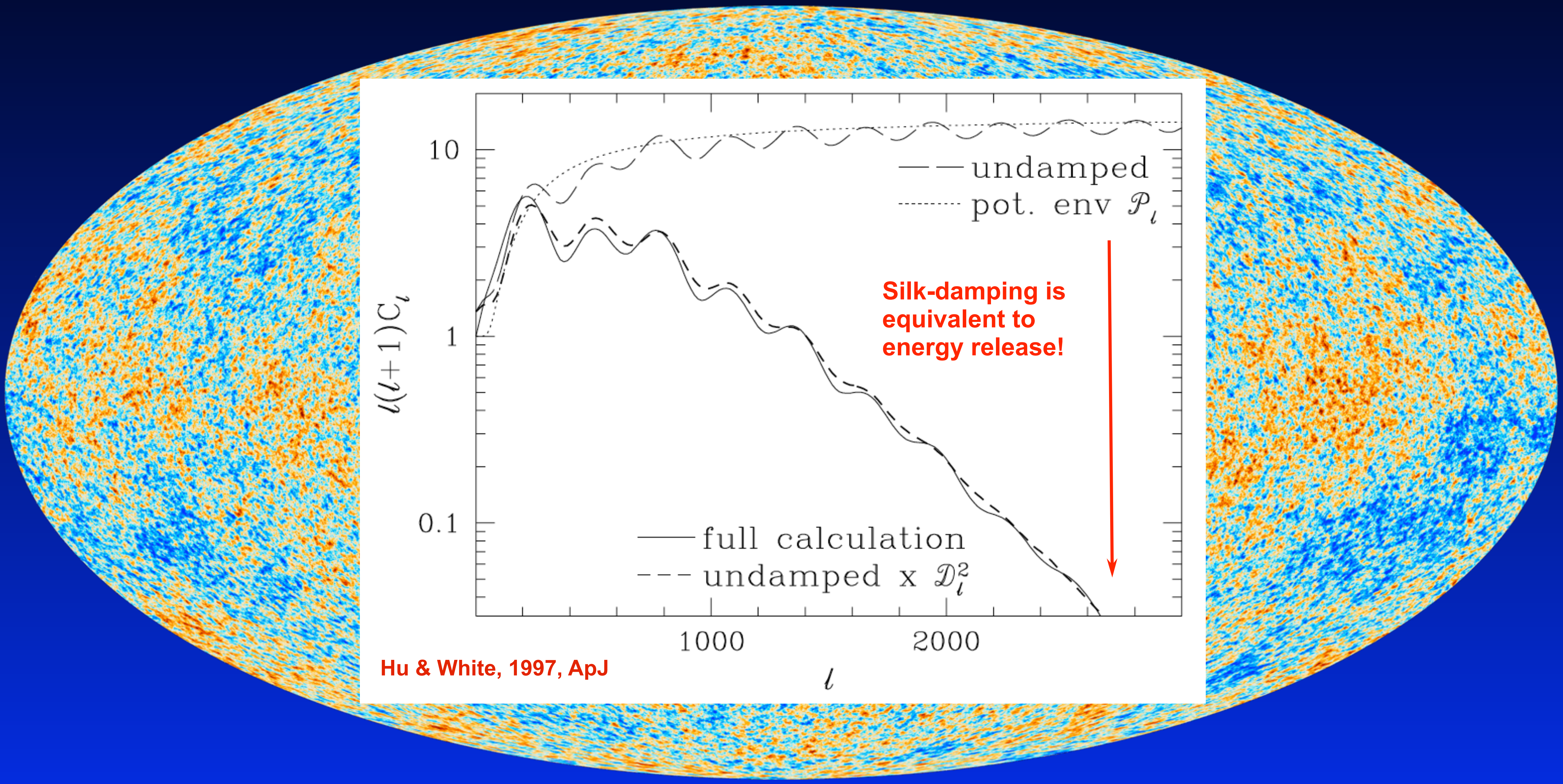
Dissipation of small-scale acoustic modes



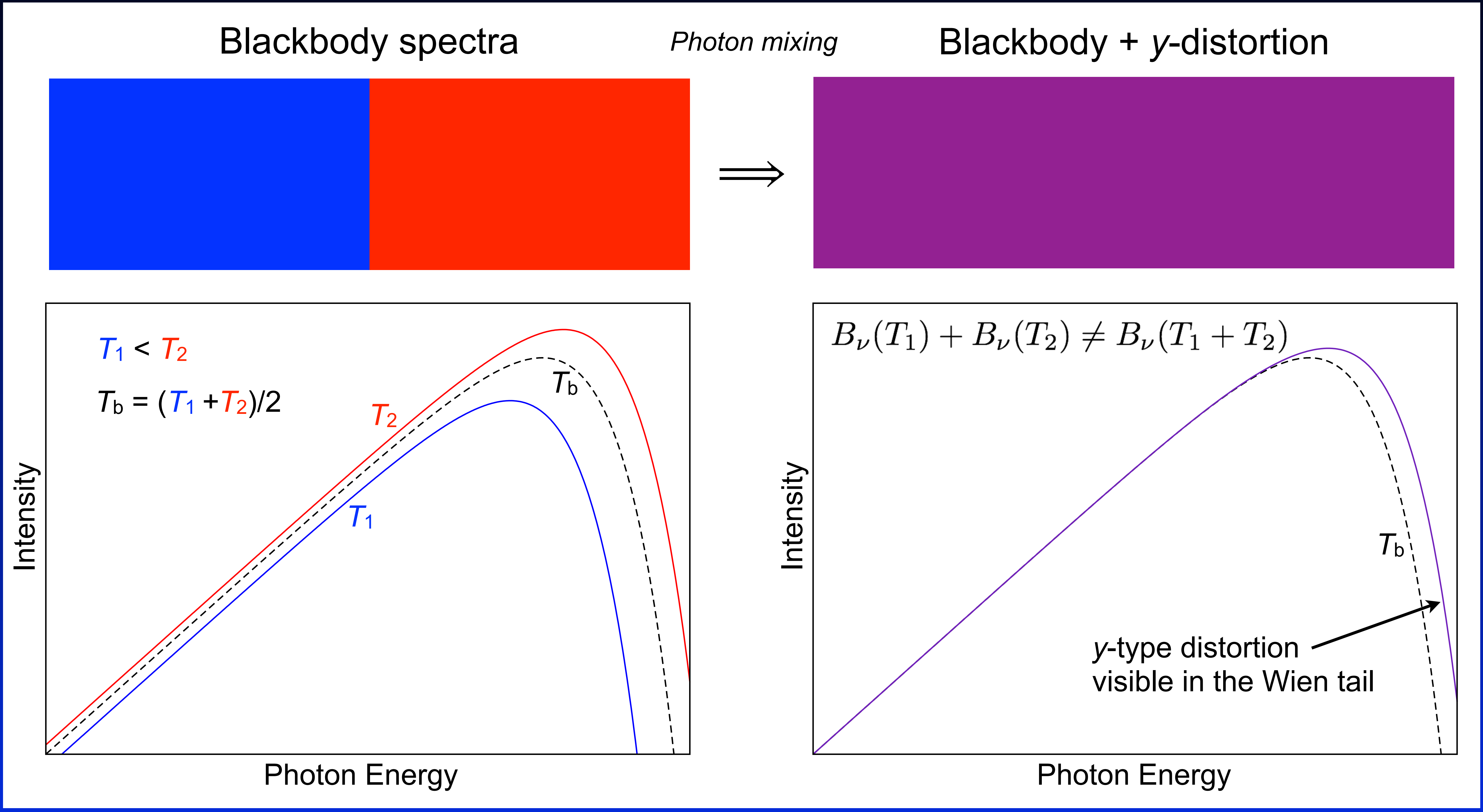
Dissipation of small-scale acoustic modes



Dissipation of small-scale acoustic modes



Distortion due to mixing of blackbodies



JC, Hamann & Patil, 2015

Mixing is mediated by Thomson scattering ⇒ Silk damping

Early power spectrum constraints from FIRAS

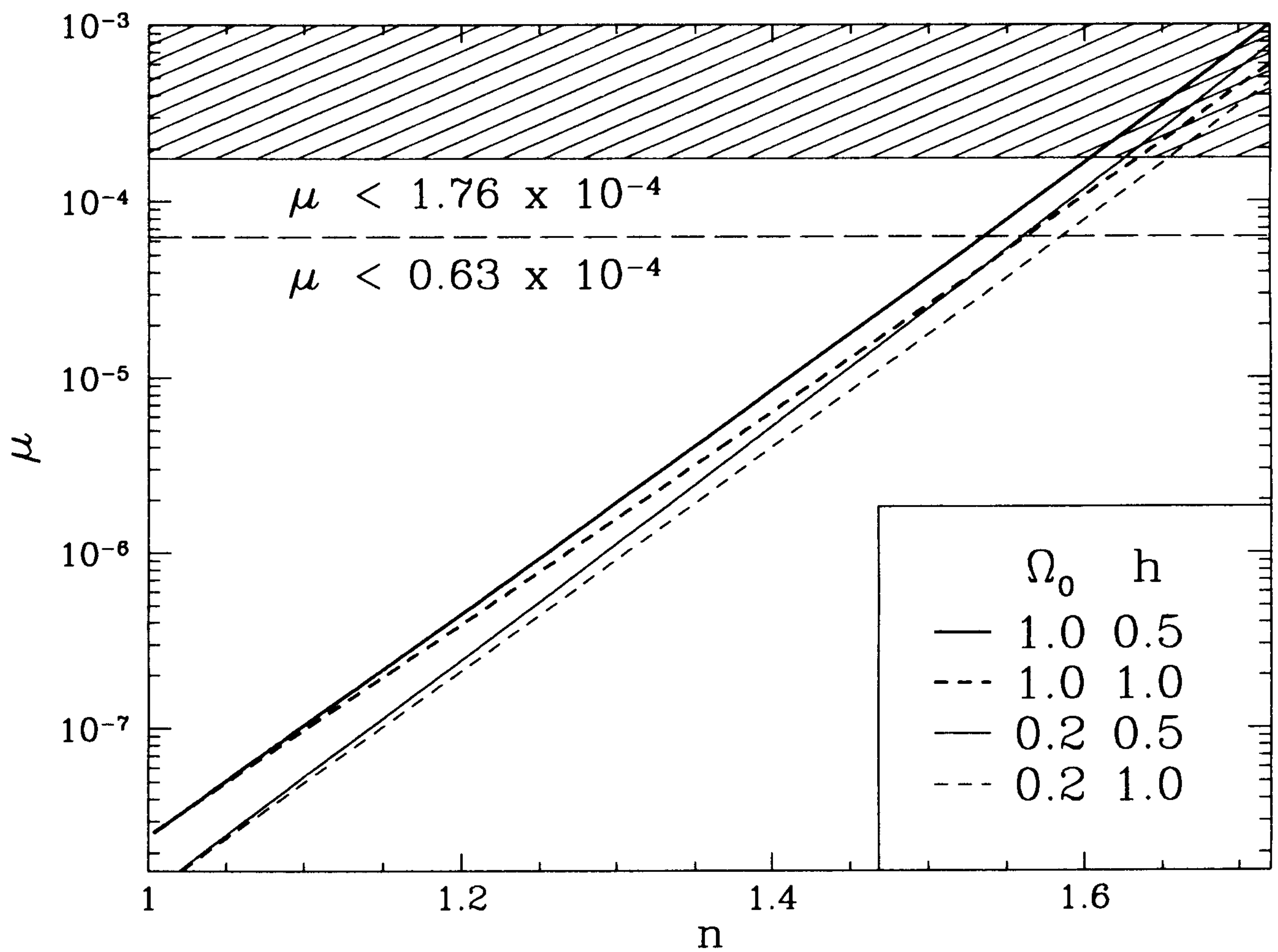
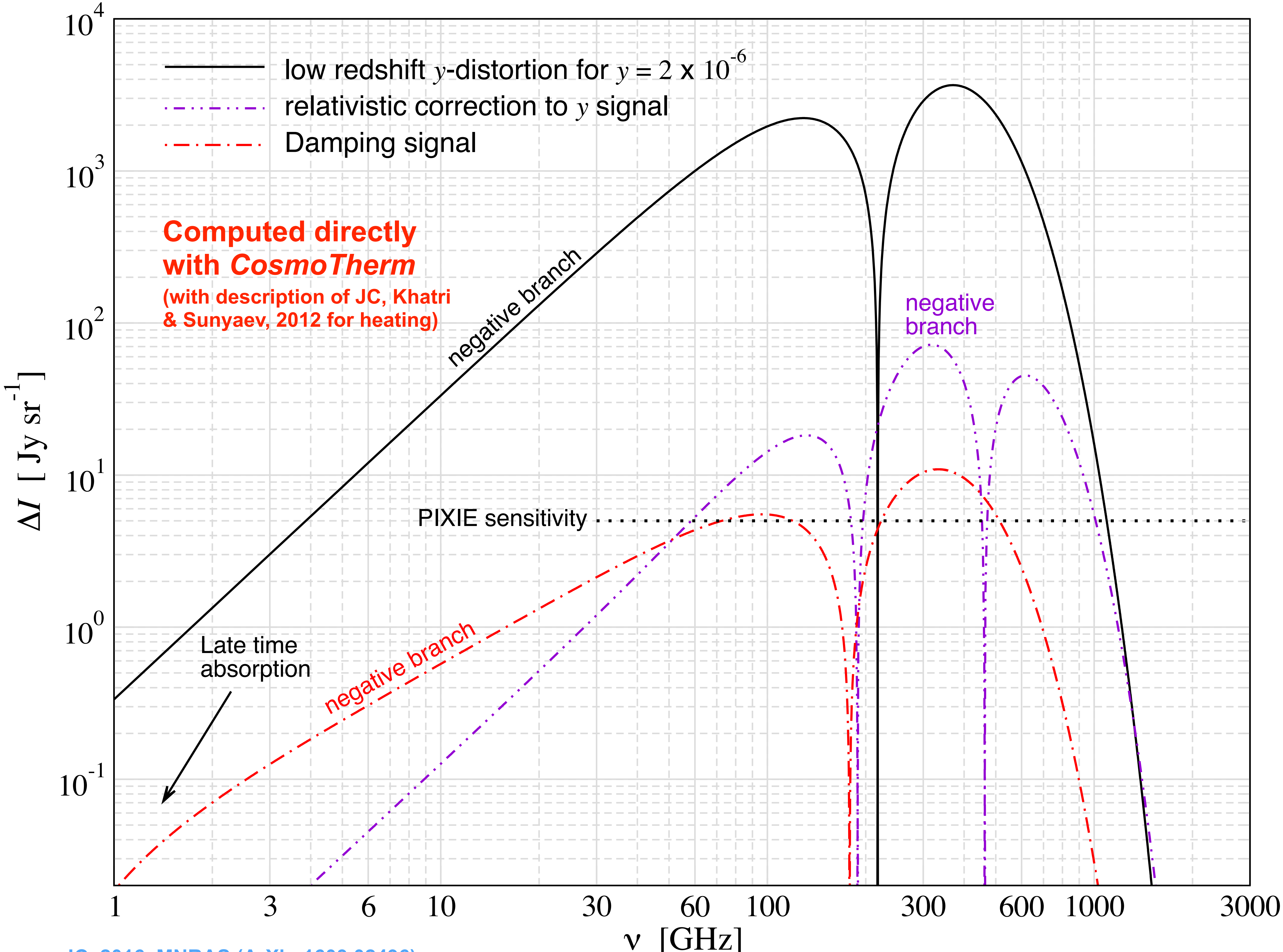


FIG. 1.—Spectral distortion μ, predicted from the full eq. (11), as a function of the power index n for a normalization at the mean of the *COBE* DMR detection $(\Delta T/T)_{10^\circ} = 1.12 \times 10^{-5}$. With the uncertainties on *both* the DMR and FIRAS measurements, the conservative 95% upper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

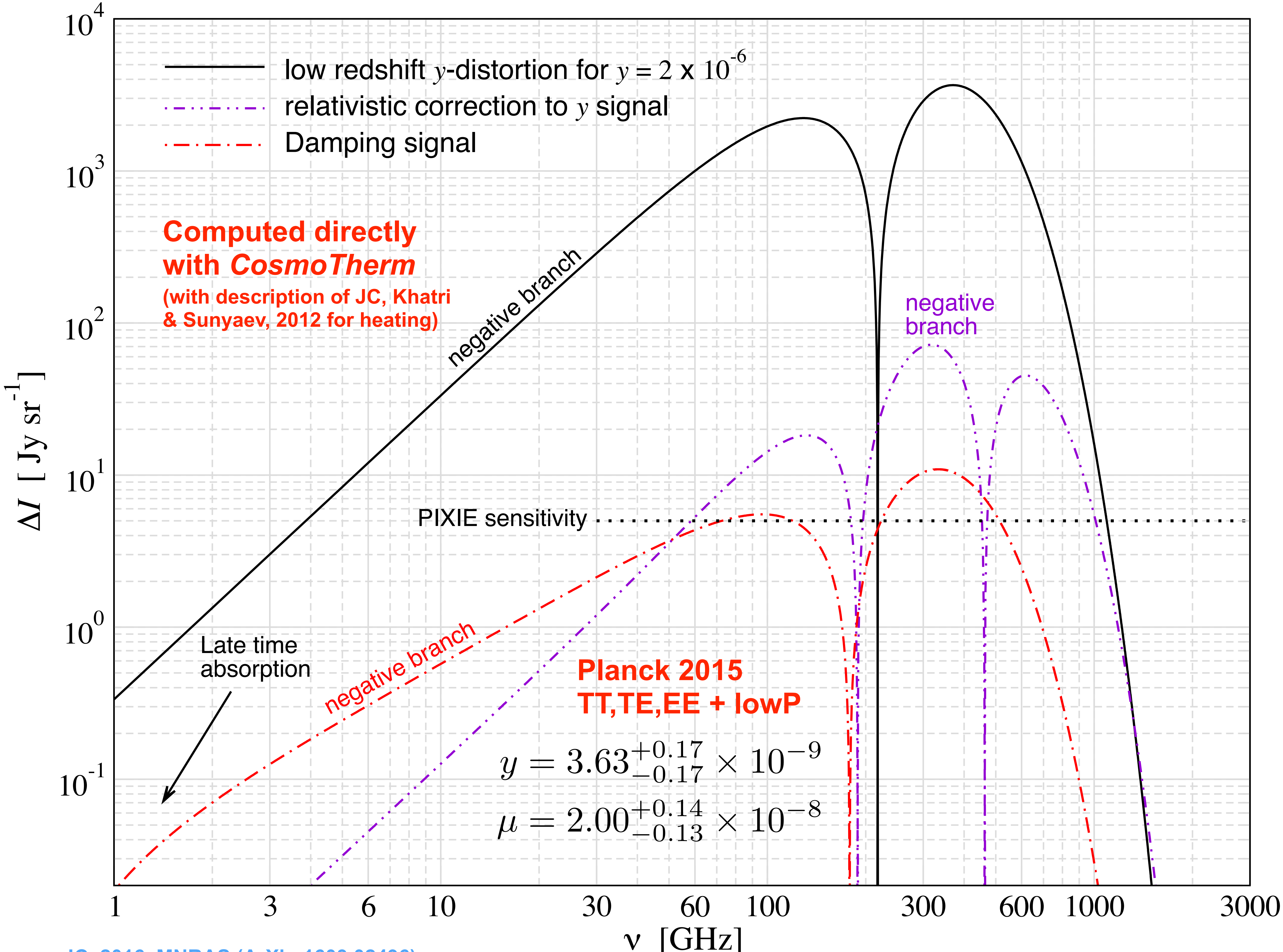
Hu, Scott & Silk, 1994

Average CMB spectral distortions



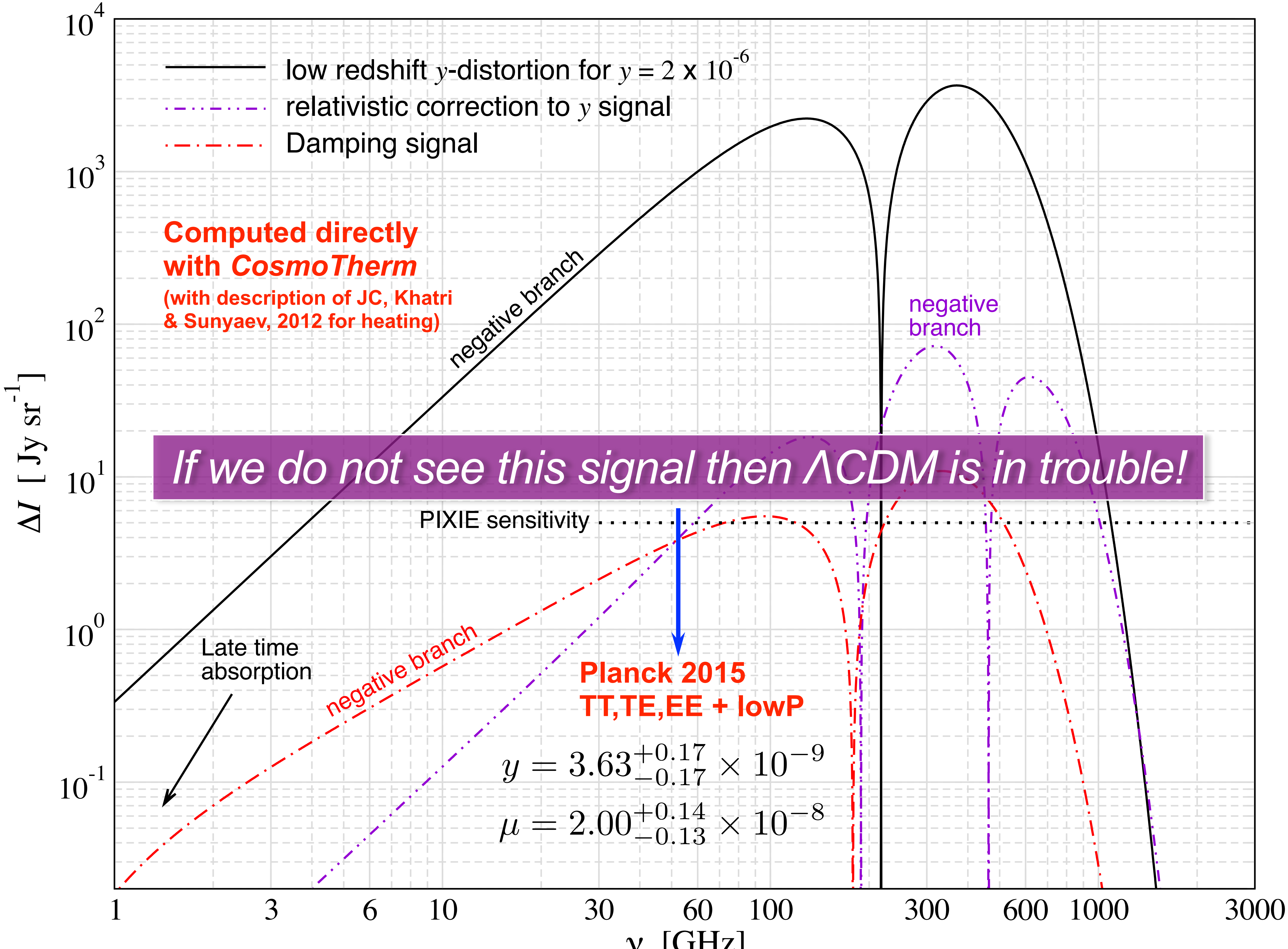
JC, 2016, MNRAS (ArXiv:1603.02496)

Average CMB spectral distortions



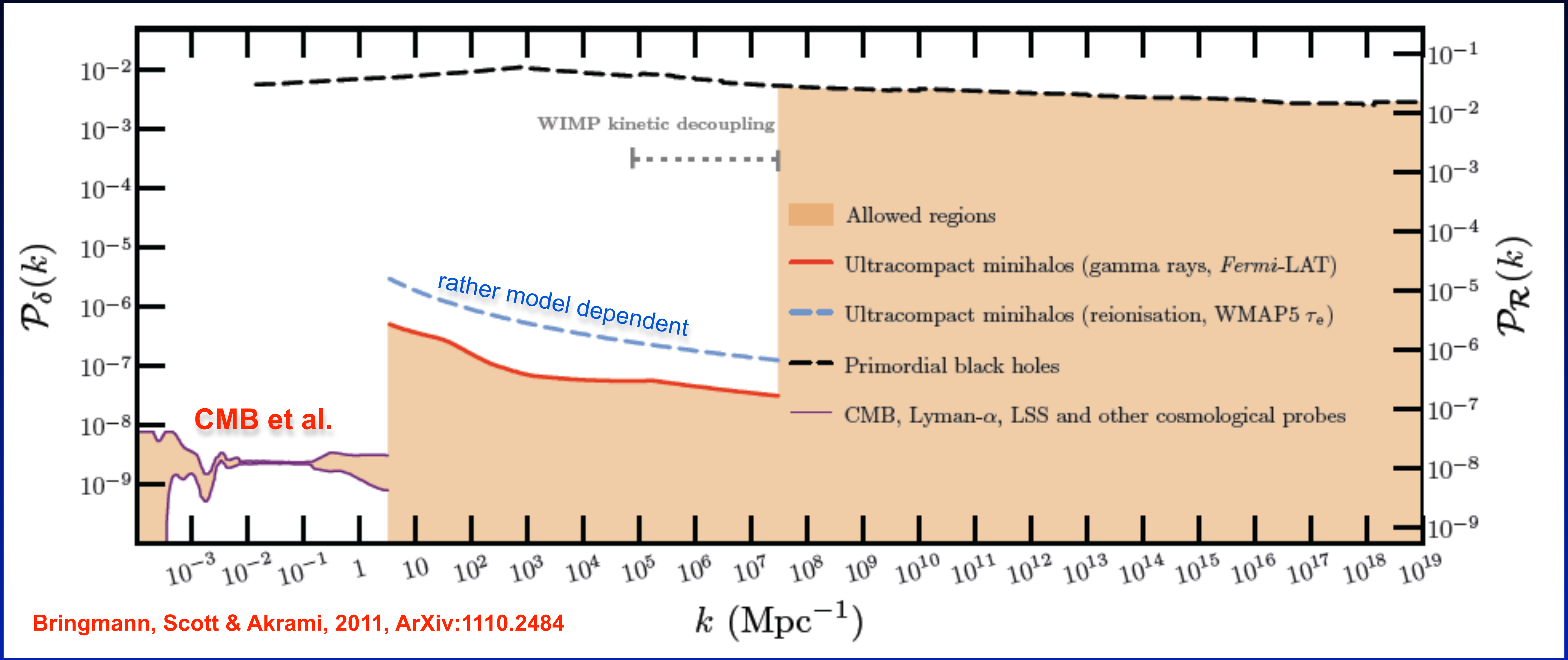
JC, 2016, MNRAS (ArXiv:1603.02496)

Average CMB spectral distortions



JC, 2016, MNRAS (ArXiv:1603.02496)

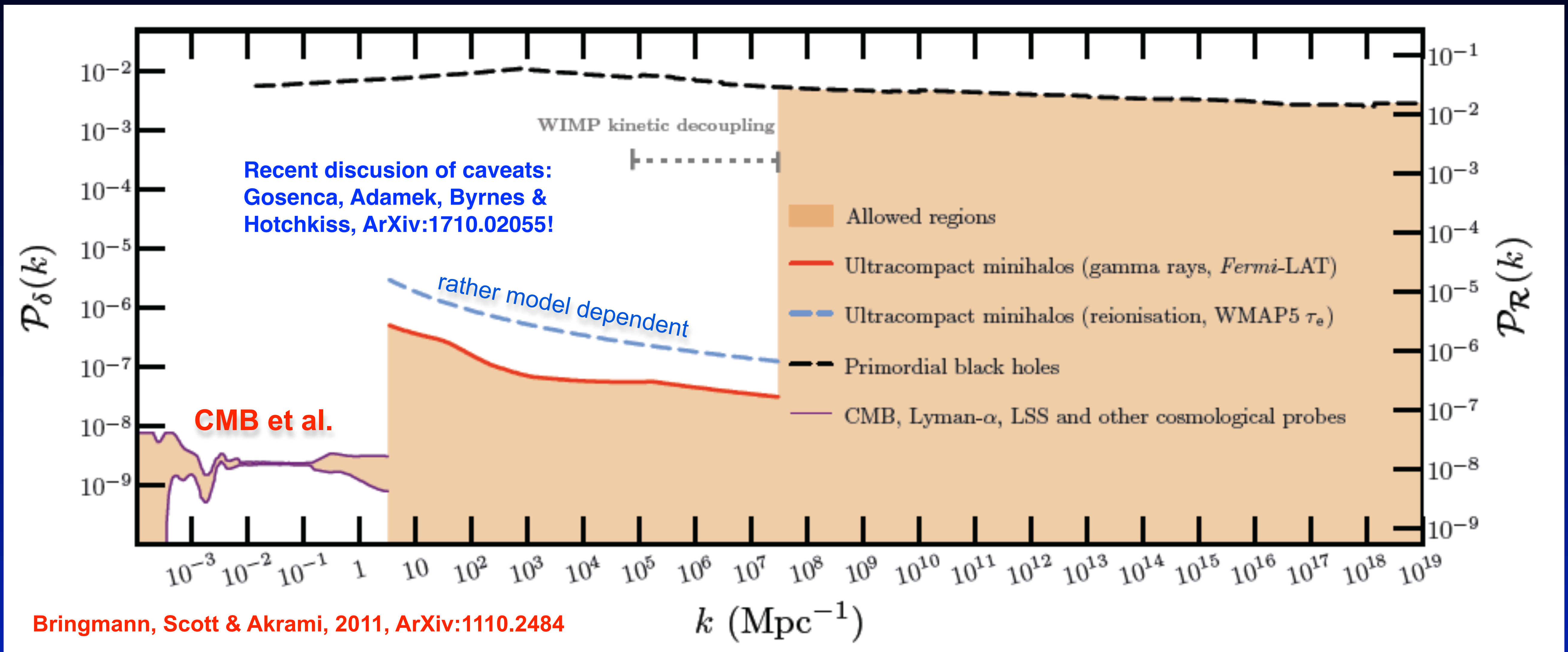
Distortions provide new power spectrum constraints!



- 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

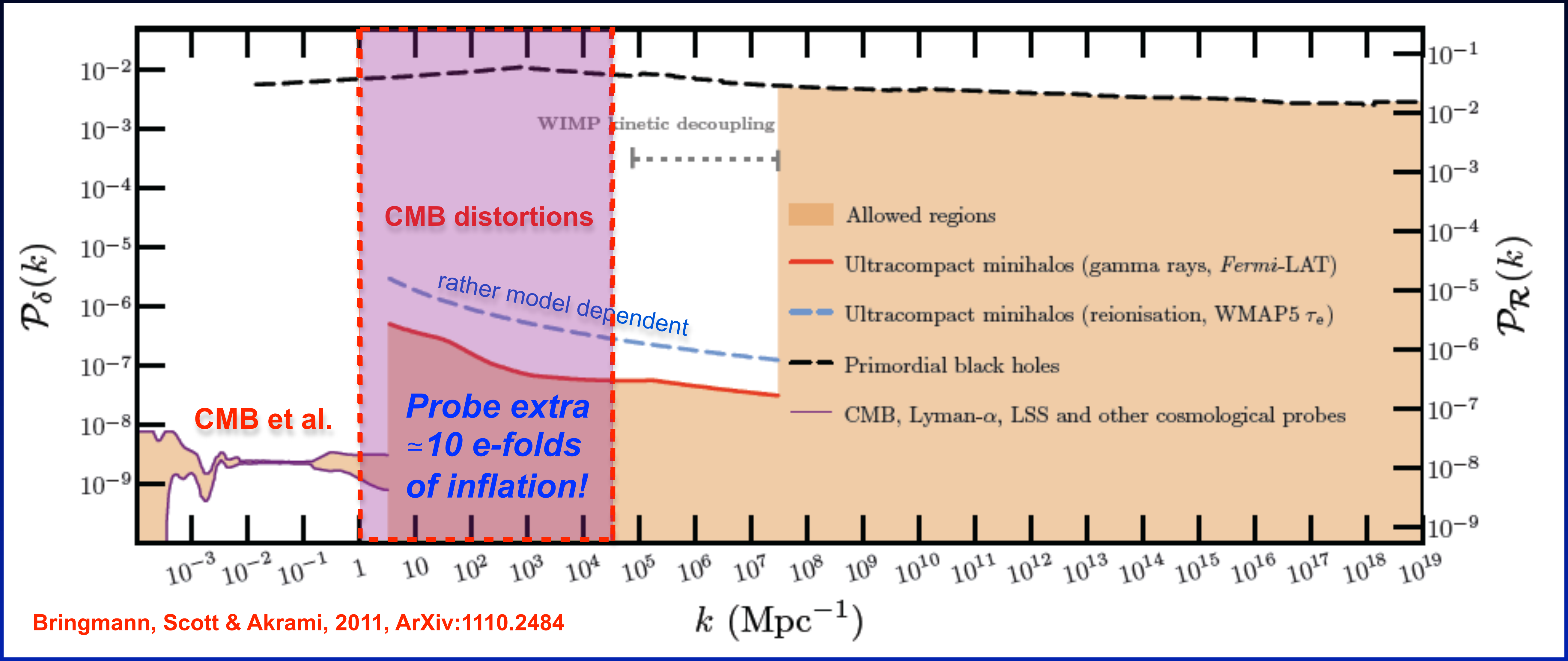
Distortions provide new power spectrum constraints!



- 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

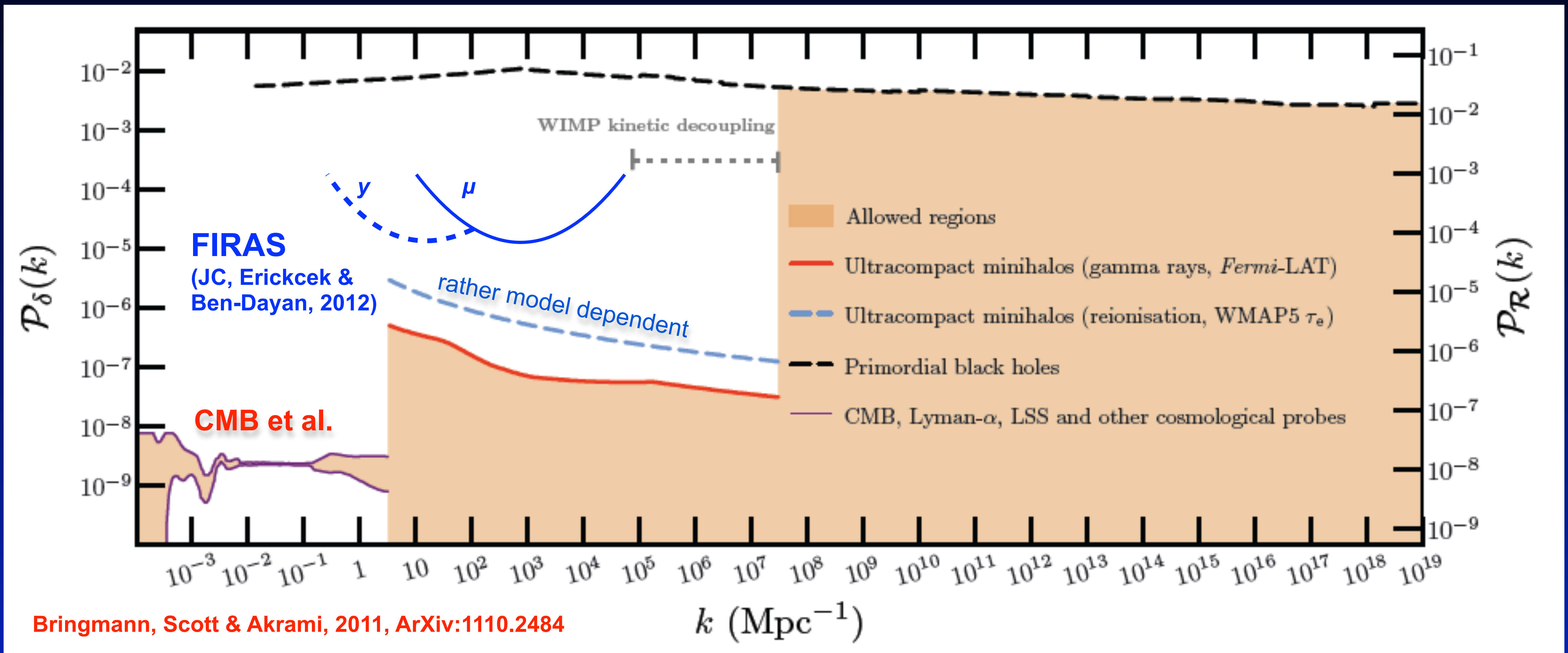
Distortions provide new power spectrum constraints!



- 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 $k \sim 10^4$ 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

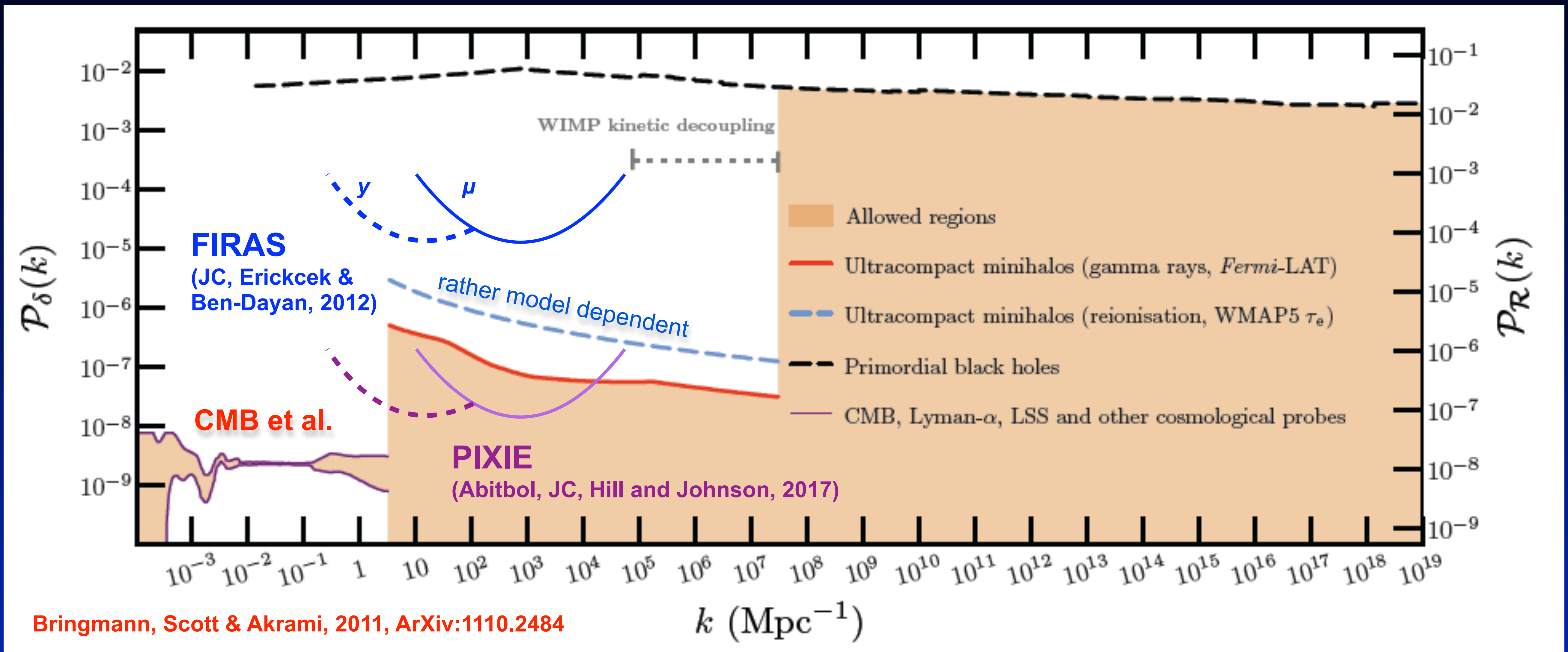
Distortions provide new power spectrum constraints!



- 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 $k \sim 10^4$ 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

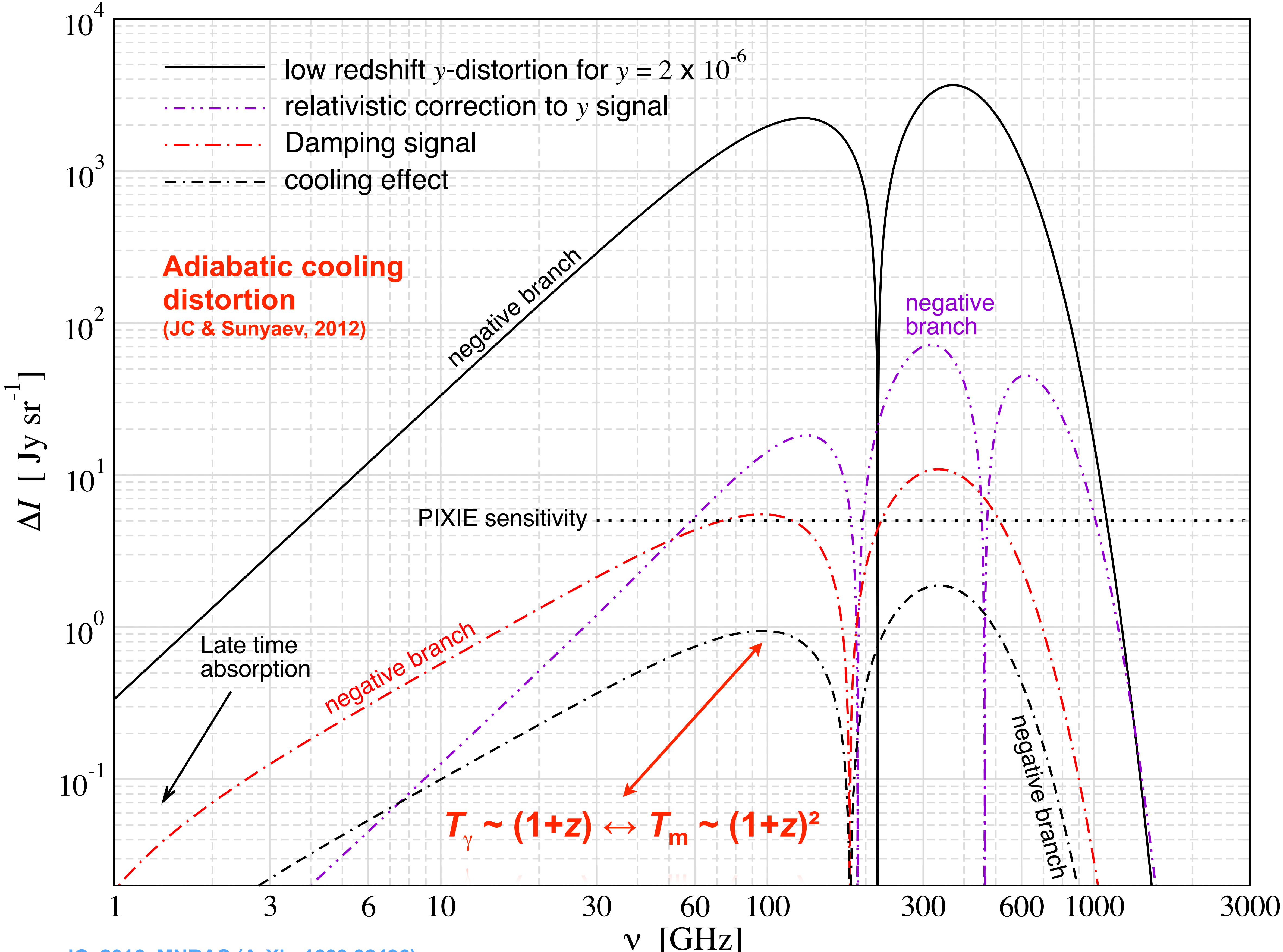
Distortions provide new power spectrum constraints!



- 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 $k \sim 10^4$ 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

Average CMB spectral distortions



JC, 2016, MNRAS (ArXiv:1603.02496)

Decaying and annihilating particles and test of Dark matter physics

Why are decaying/annihilating particles still interesting?

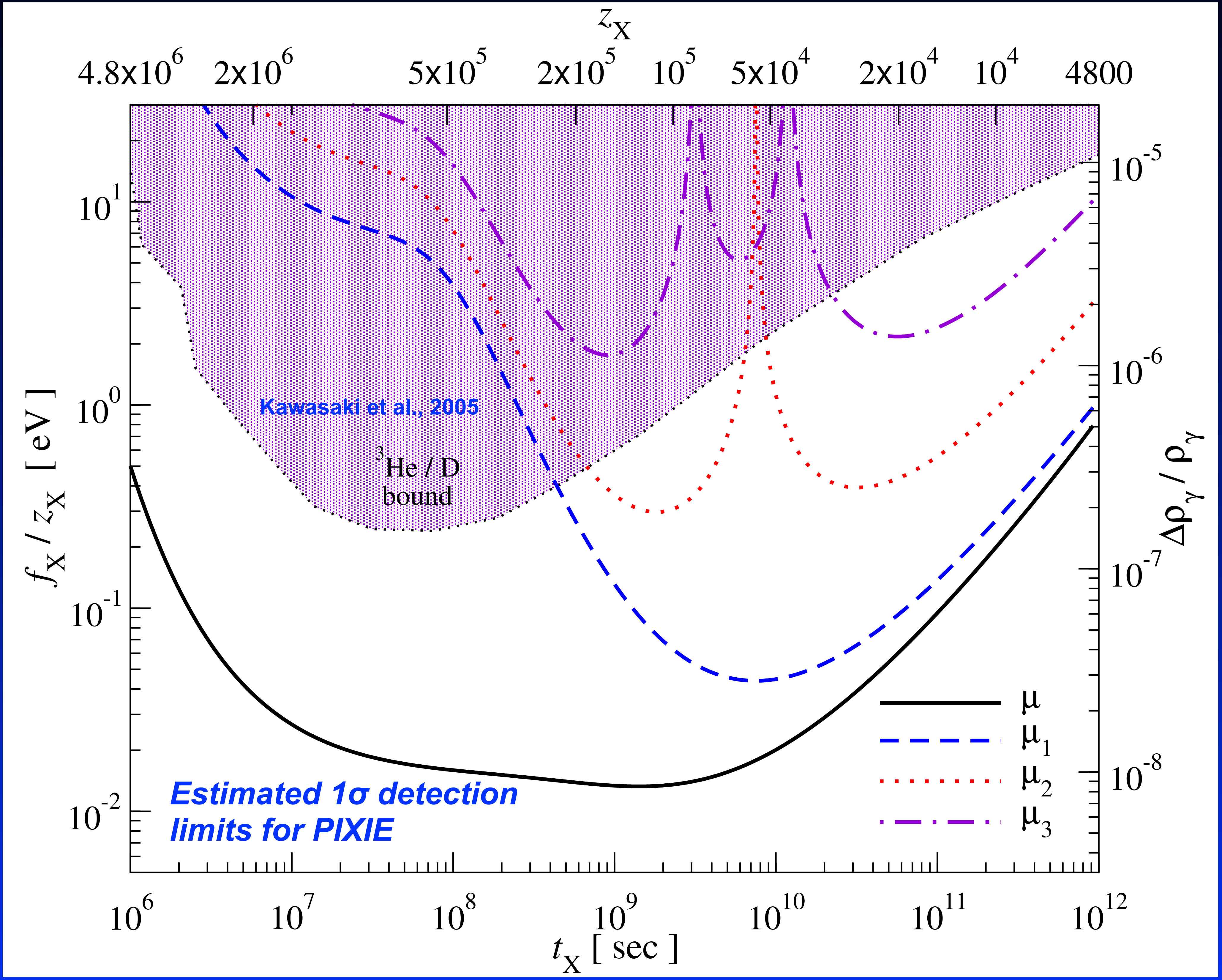
- A priori no specific particle in mind
- *But:* we do not know what dark matter is and where it really came from!
- Was dark matter thermally produced or as a decay product of some heavy particle?
- is dark matter structureless or does it have internal (excited) states?
- sterile neutrinos? Axions?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

Why are decaying/annihilating particles still interesting?

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

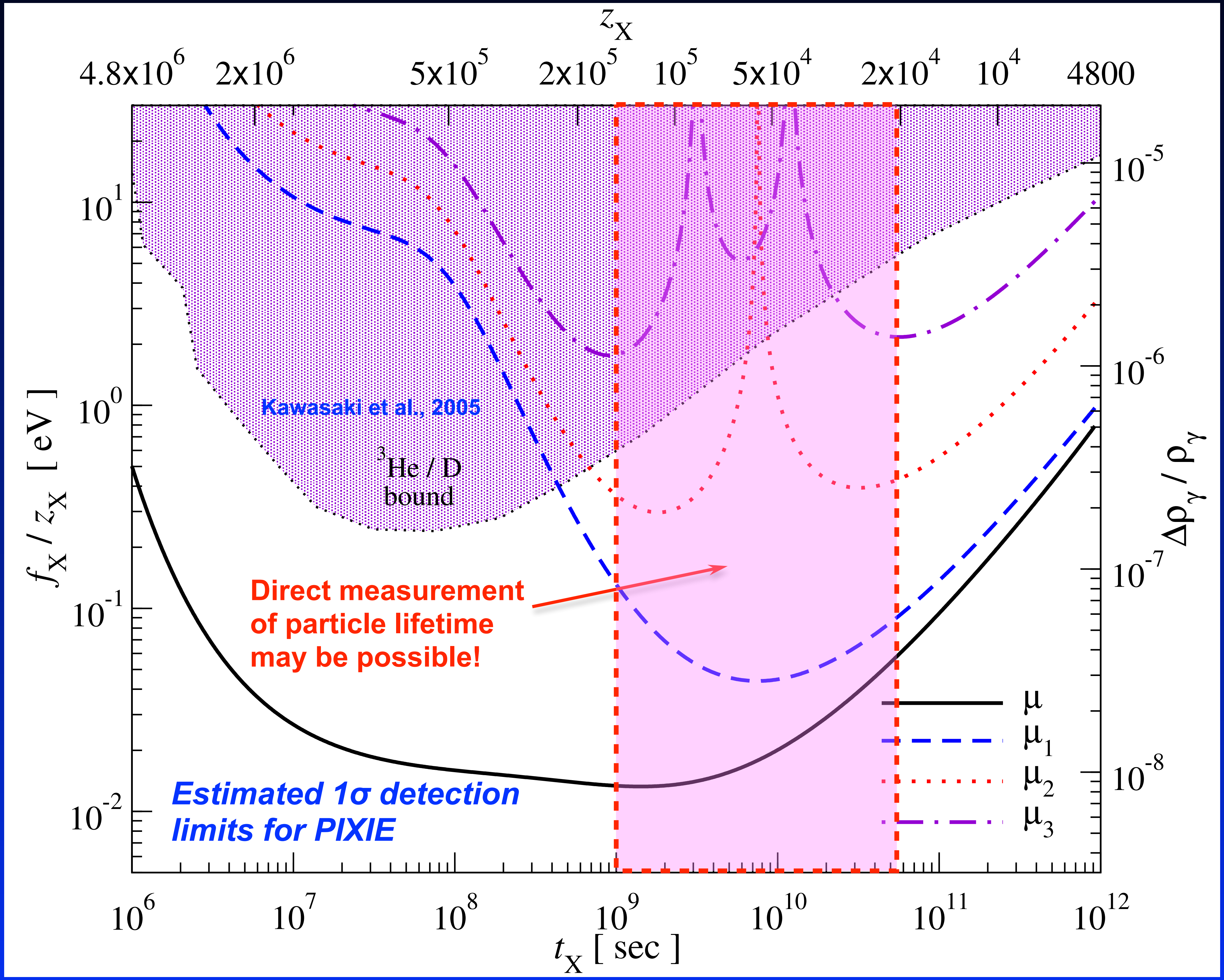
CMB spectral distortions offer a new independent way to constrain these kind of models

Distortions could shed light on decaying (DM) particles!



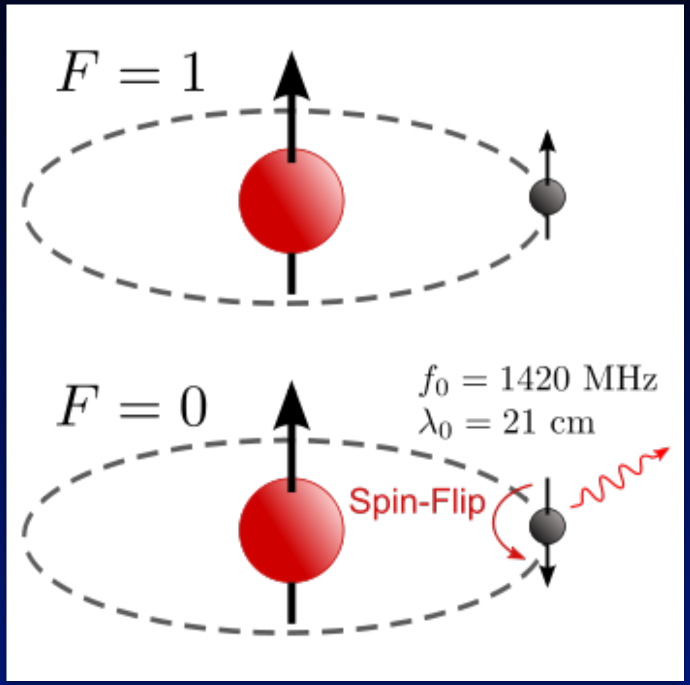
JC & Jeong, 2013

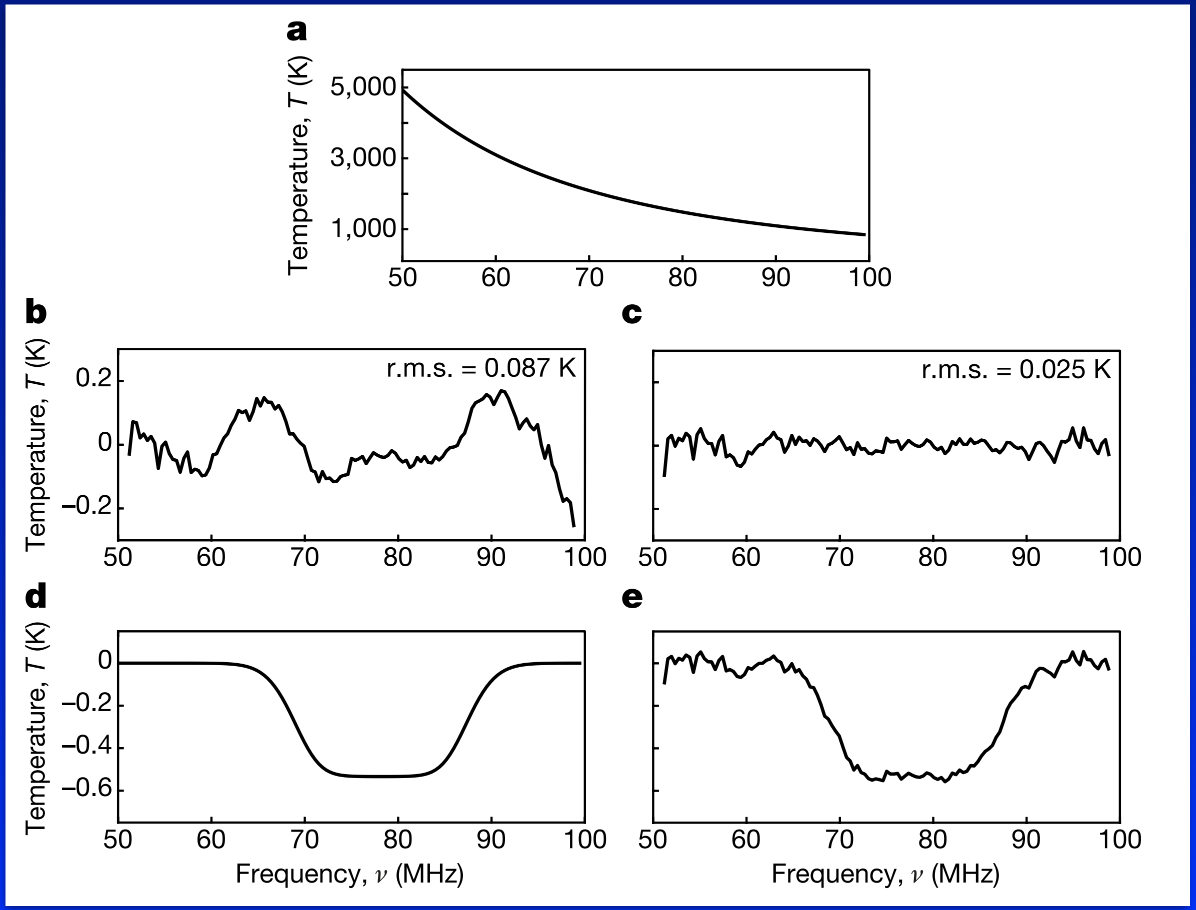
Distortions could shed light on decaying (DM) particles!



JC & Jeong, 2013

EDGES detection of cosmological 21cm absorption?

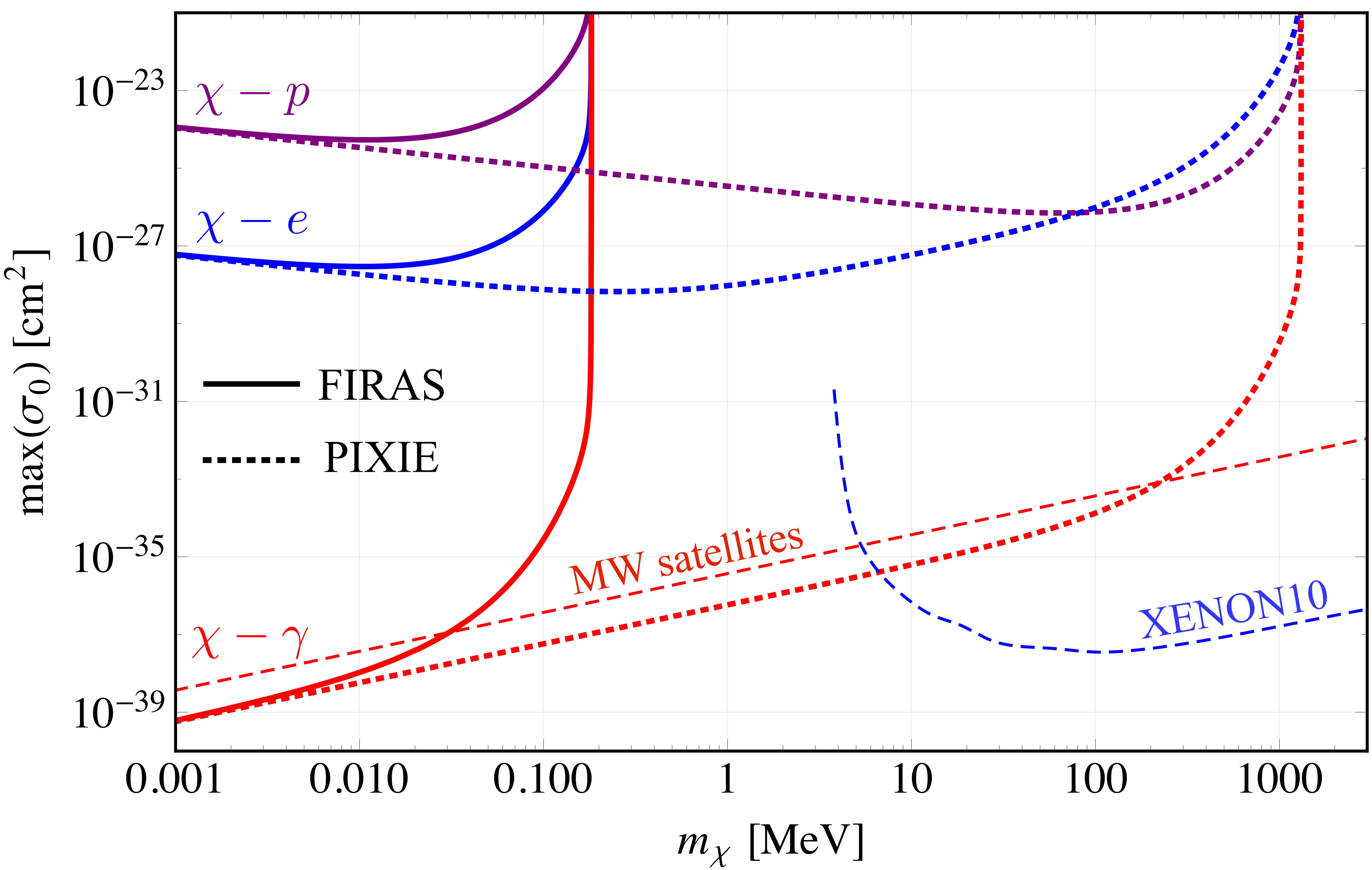




- Stimulated lots of discussion
- Signal much larger than expected in standard scenario
- Possible connection to DM physics / interactions?

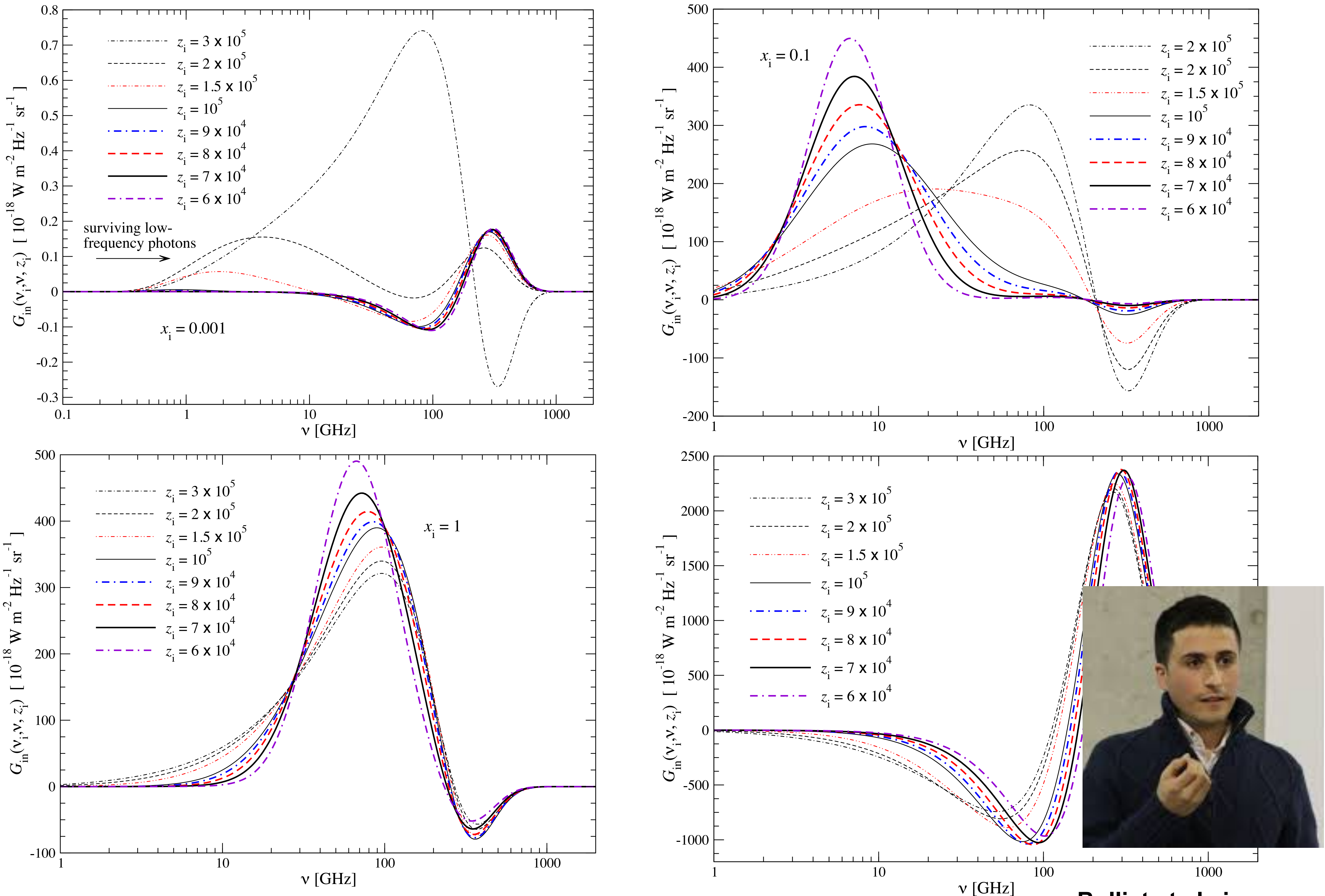
Bowman et al., Nature, 2018

Distortion constraints on DM interactions through adiabatic cooling effect



Ali-Haimoud, JC & Kamionkowski, 2015

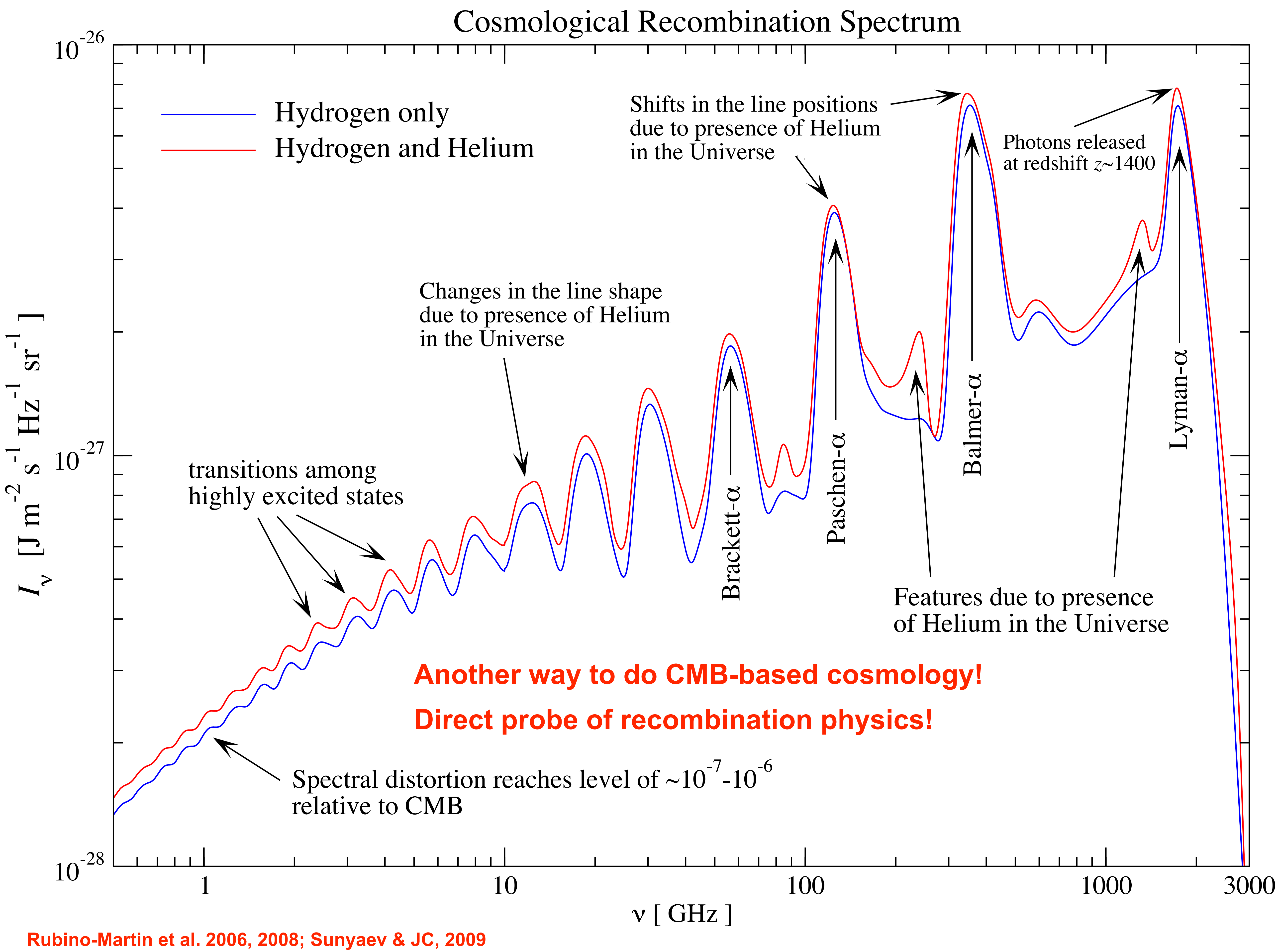
Rich phenomenology of photon injection distortions



JC 2015, ArXiv:1506.06582

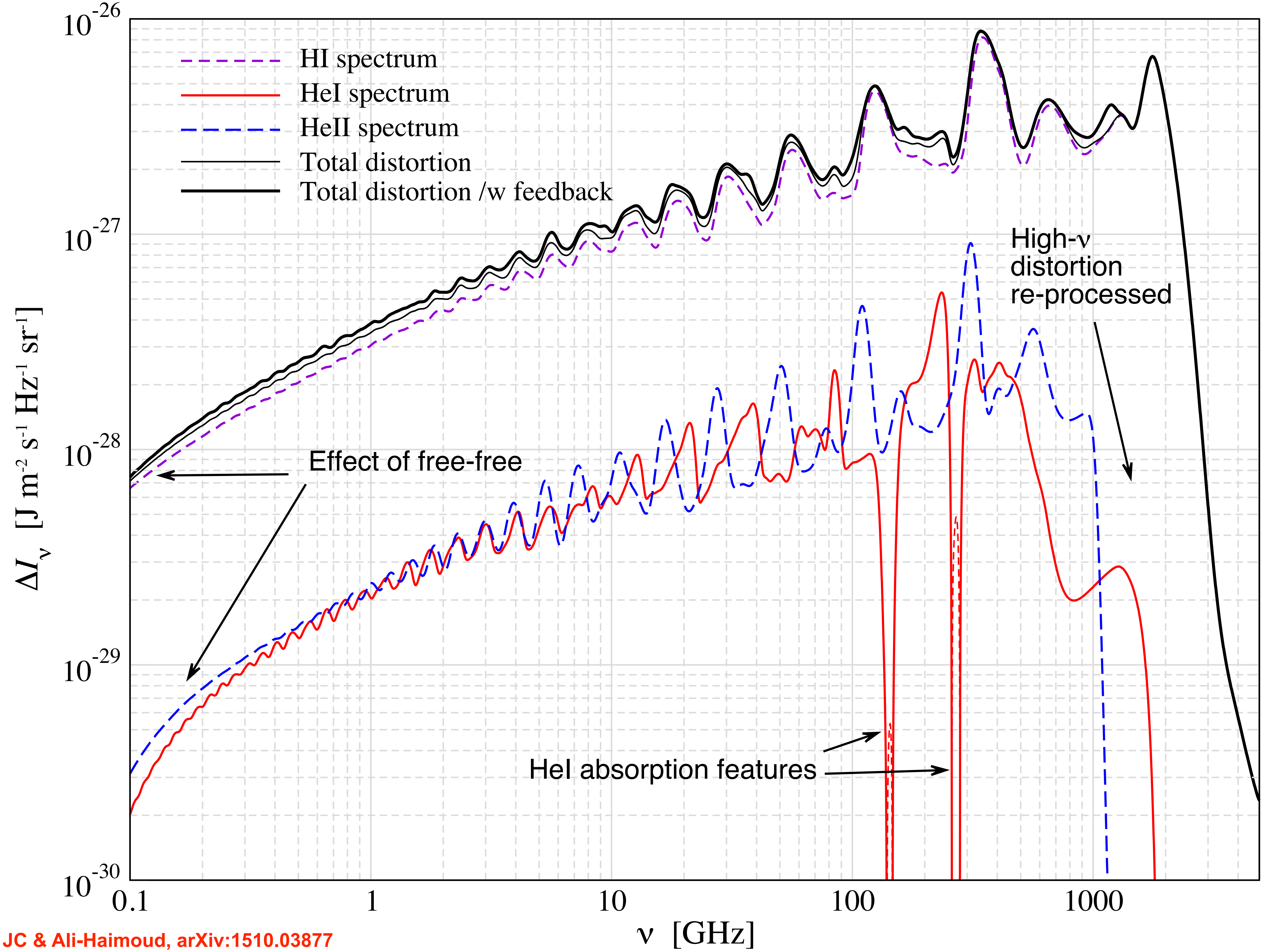
Bolliet et al., in prep

The cosmological recombination radiation



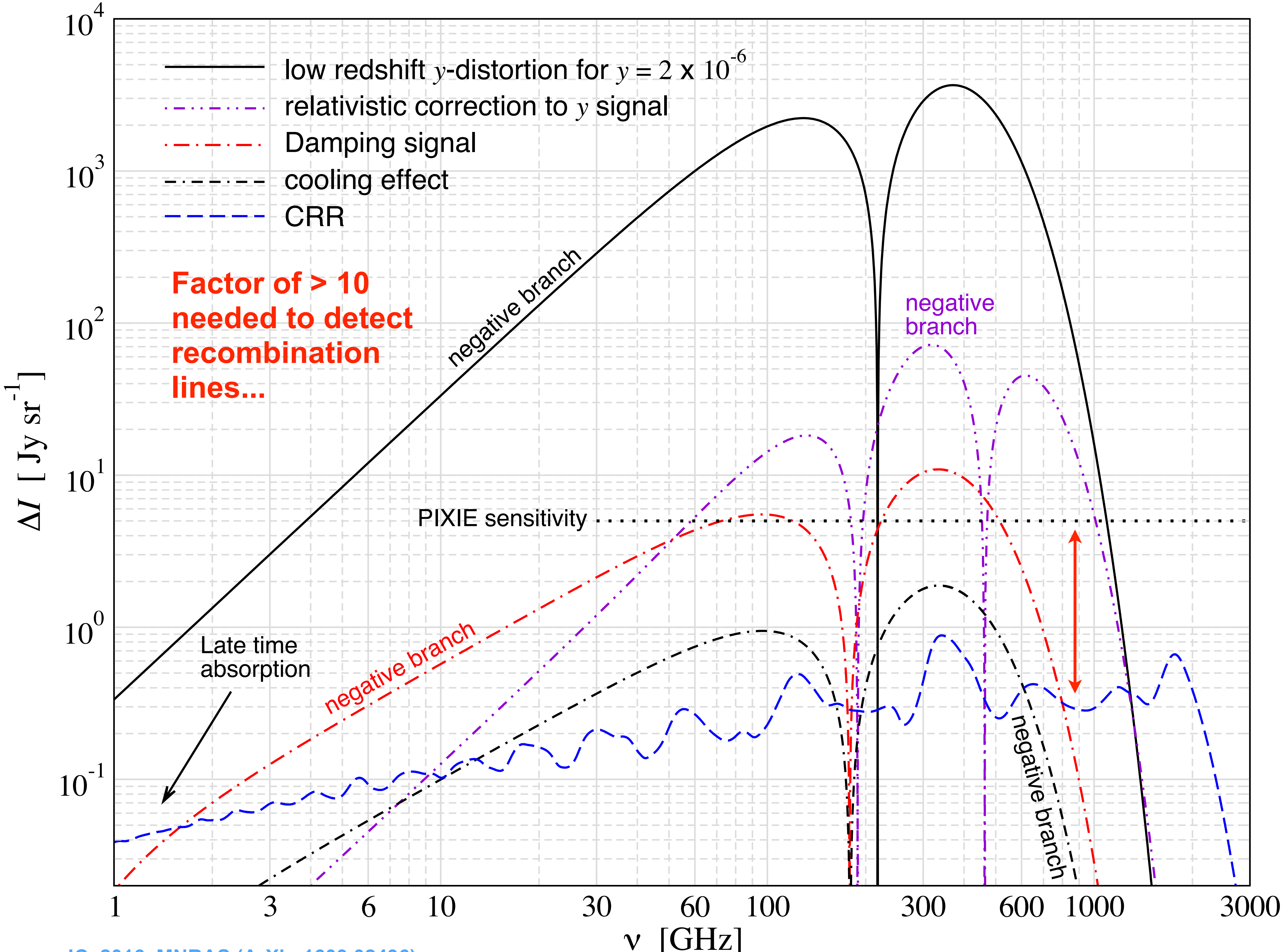
Cosmological Recombination Spectrum
Hydrogen only
Hydrogen and Helium
Shifts in the line positions due to presence of Helium in the Universe
Photons released at redshift z~1400
Changes in the line shape due to presence of Helium in the Universe
transitions among highly excited states
Brackett-α
Paschen-α
Balmer-α
Lyman-α
Features due to presence of Helium in the Universe
Another way to do CMB-based cosmology!
Direct probe of recombination physics!
Spectral distortion reaches level of ~10^-7-10^-6 relative to CMB
I_ν [J m^-2 s^-1 Hz^-1 sr^-1]
ν [GHz]
10^-26
10^-27
10^-28
1
10
100
1000
3000
Rubino-Martin et al. 2006, 2008; Sunyaev & JC, 2009

New detailed and fast computation!

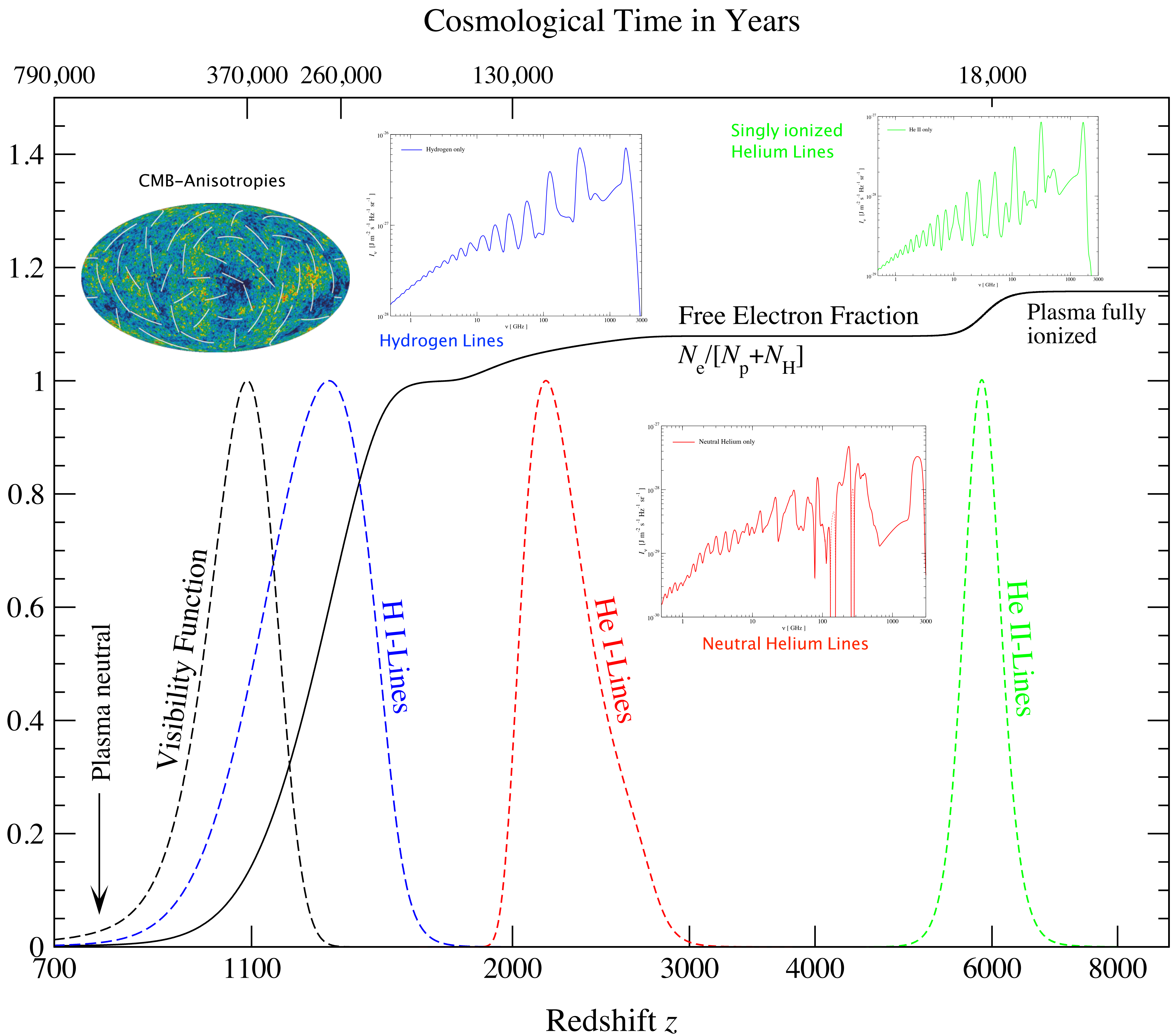


JC & Ali-Haimoud, arXiv:1510.03877

Average CMB spectral distortions



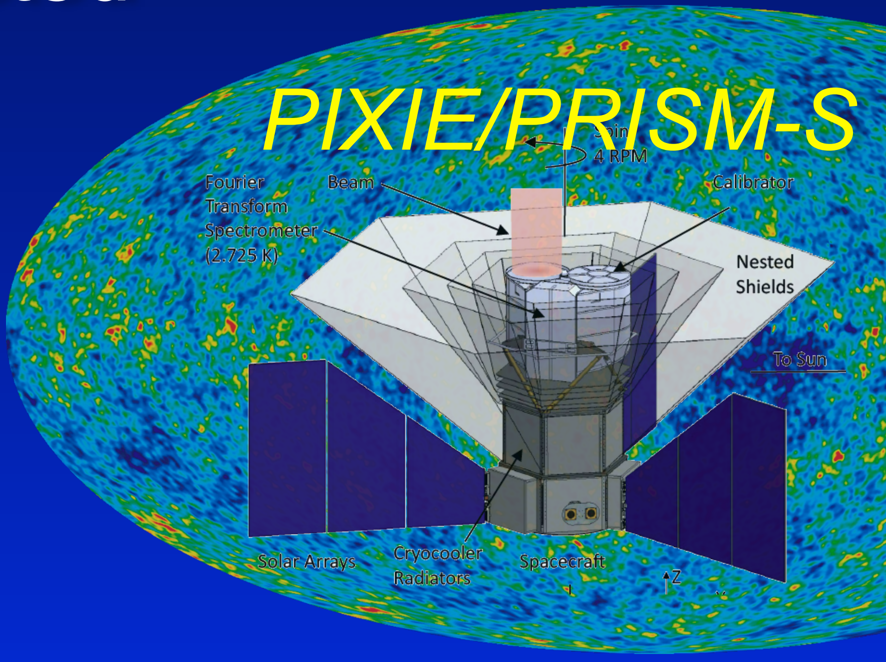
JC, 2016, MNRAS (ArXiv:1603.02496)



Cosmological Time in Years
790,000
370,000
260,000
130,000
18,000
1.4
1.2
1
0.8
0.6
0.4
0.2
0
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

What can CMB spectral distortions teach us?

- 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



Let us make use of this source of information!