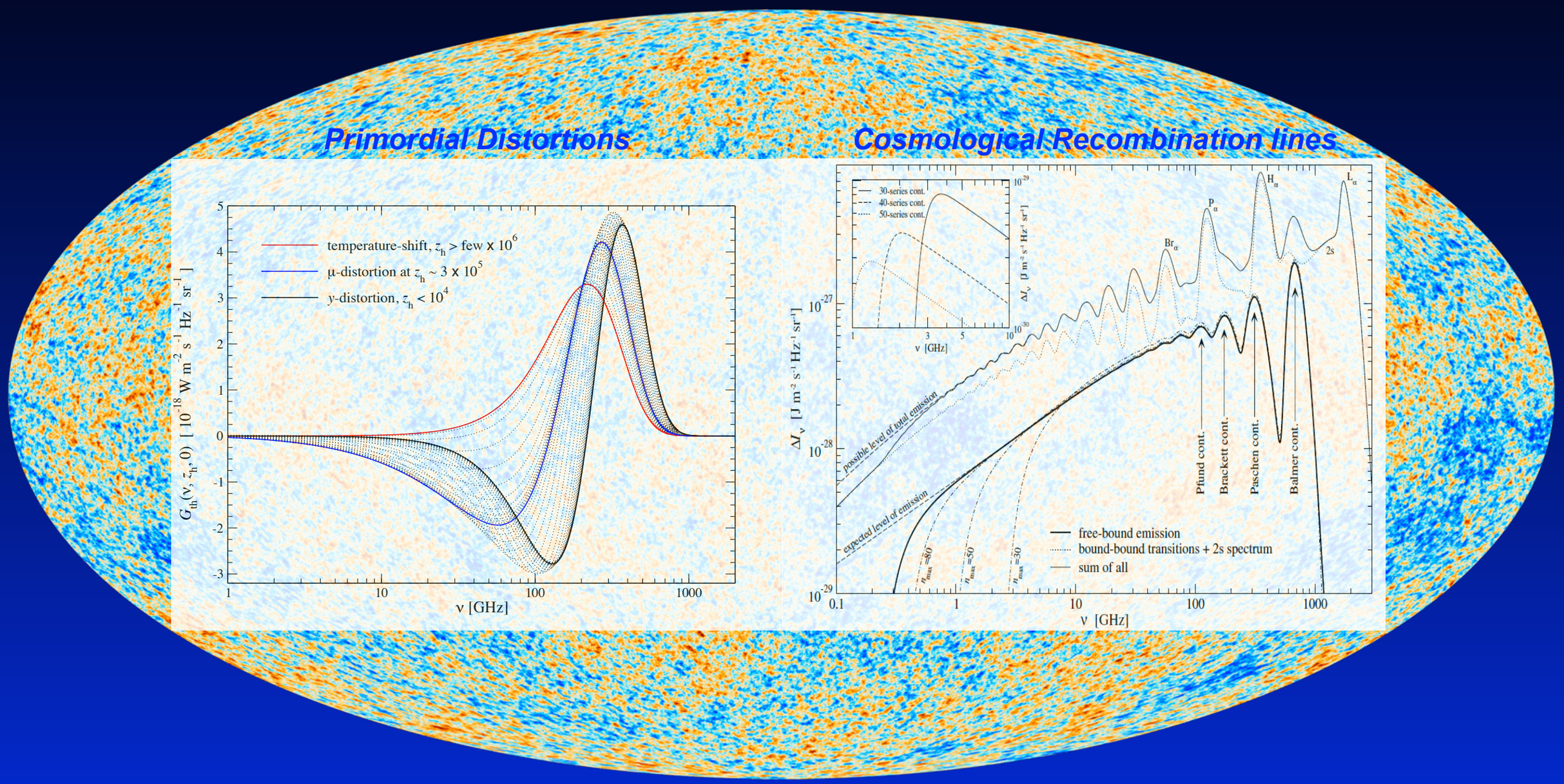
Cosmology Beyond Thermal Equilibrium:

Future Steps with CMB spectral distortions*



MANCHESTER 1824
The University of Manchester

Jens Chluba

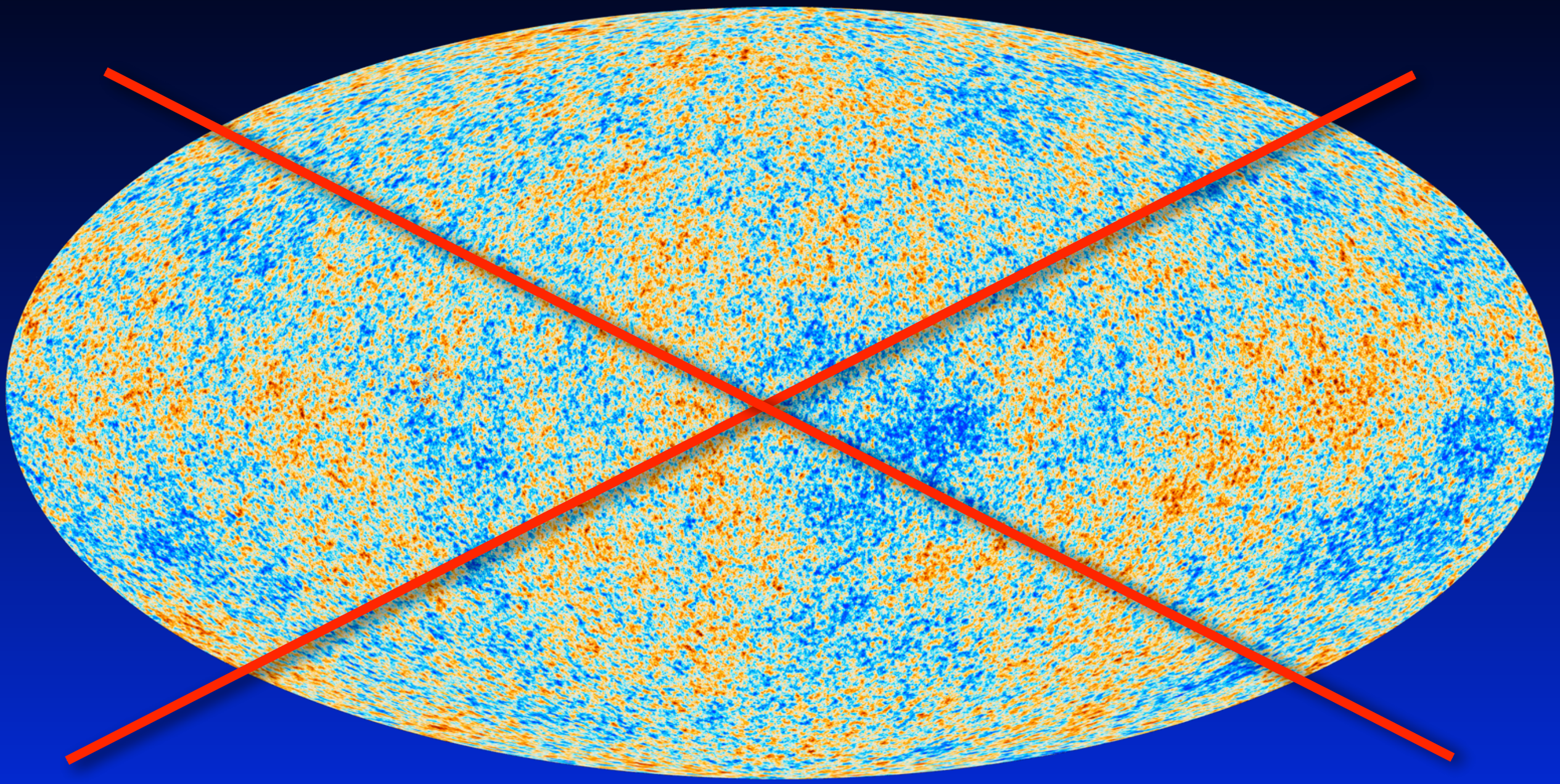
DESY Theory Workshop

Hamburg, Sept 28th, 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 $\Delta T/T \sim 10^{-5}$

… more in Julien's and Raphael's talks

CMB provides another independent piece of information!

COBE/FIRAS

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

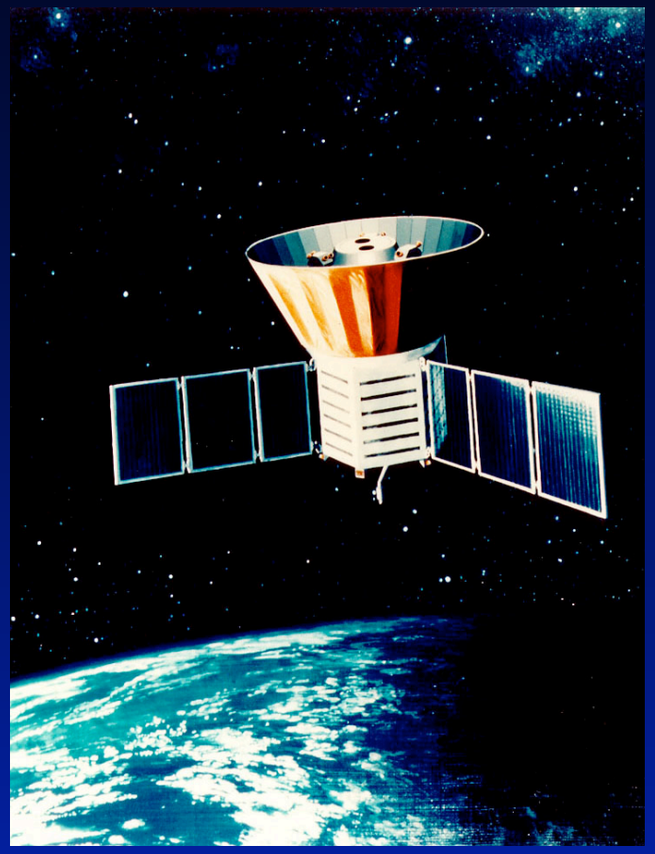
Absolute measurement required!

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)



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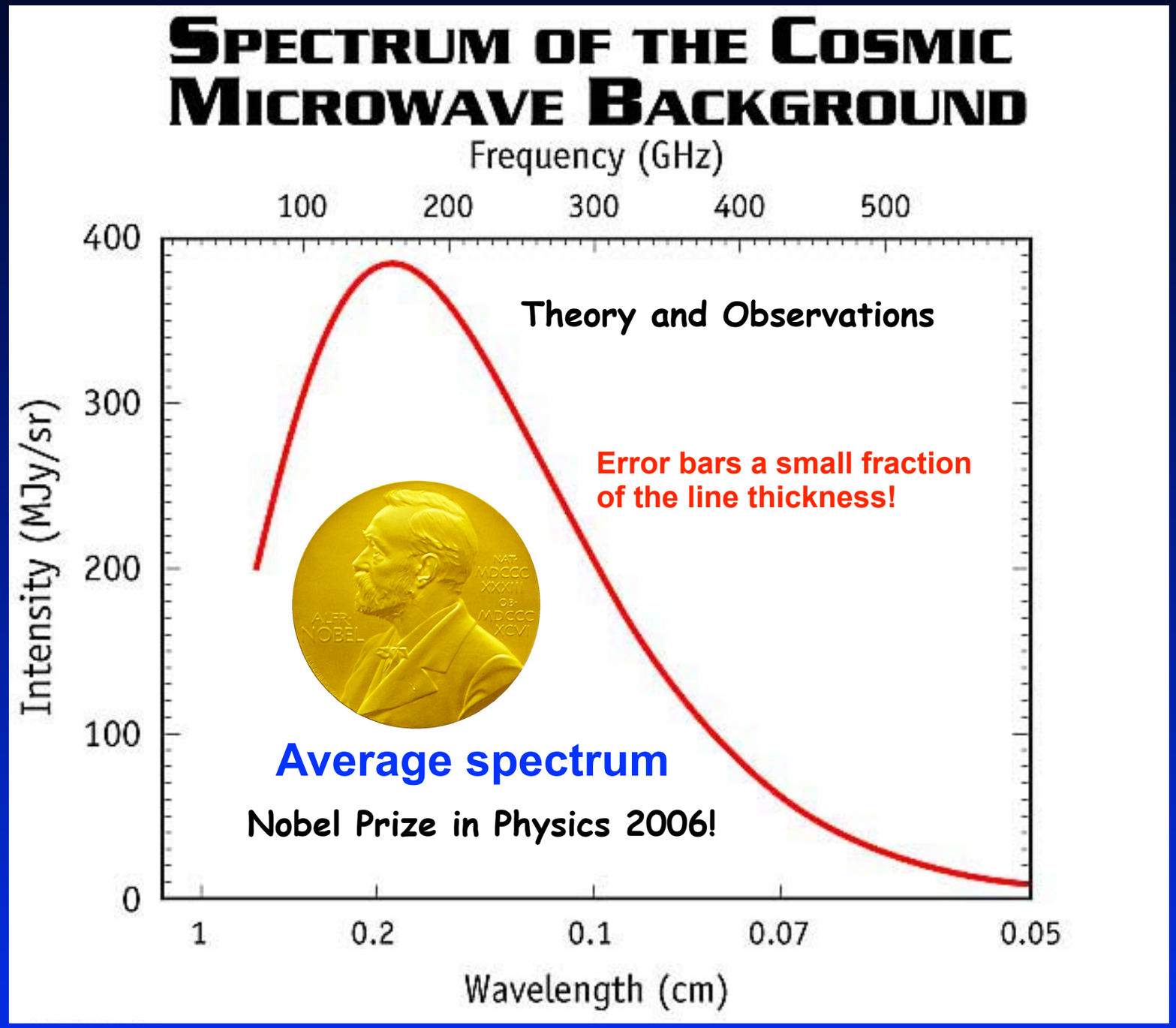
$$|y| \leq 1.5\times10^{-5}$$

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



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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

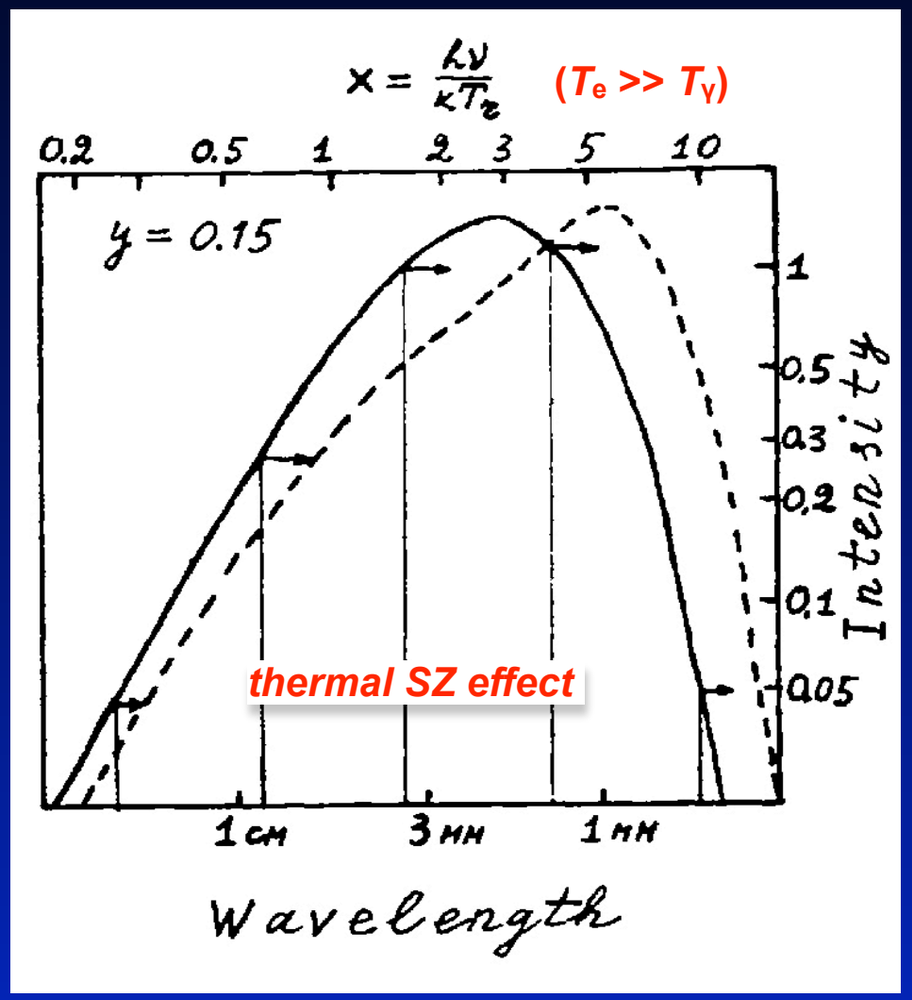
→ thermalization process (partially) erases distortions

(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

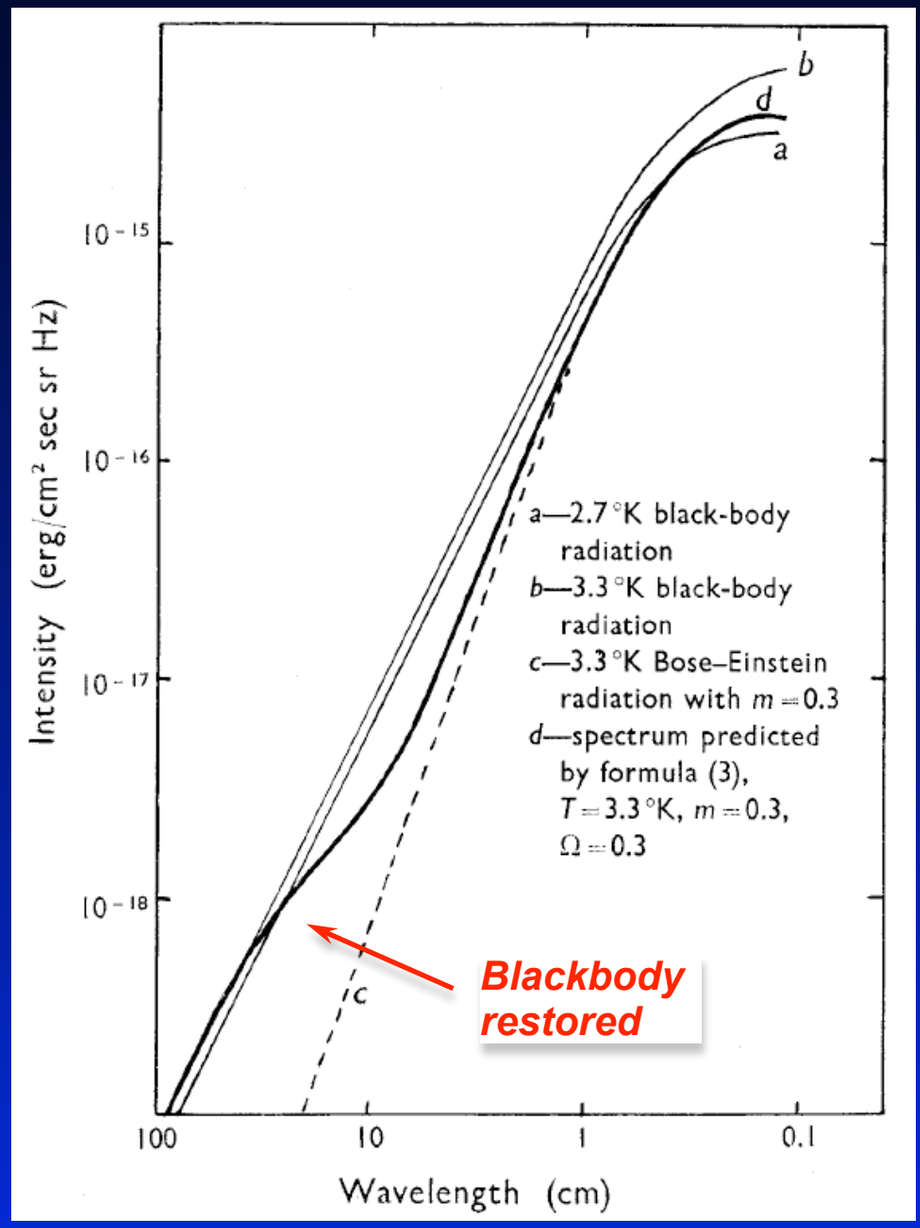
Compton y-distortion



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'

Big Bang
0

Cosmic inflation
Origin of fluctuations
10^{-32} seconds

Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
10^{-30} seconds

Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
1 second
100 seconds
1 year
100 years
380 000 years

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

First stars & galaxies
1 billion years

Galaxy evolution
Clusters of galaxies and superclusters form
10 billion years

Today
13.82 billion years

Big Bang

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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
200 million years
1 billion years
10 billion years
13.82 billion years

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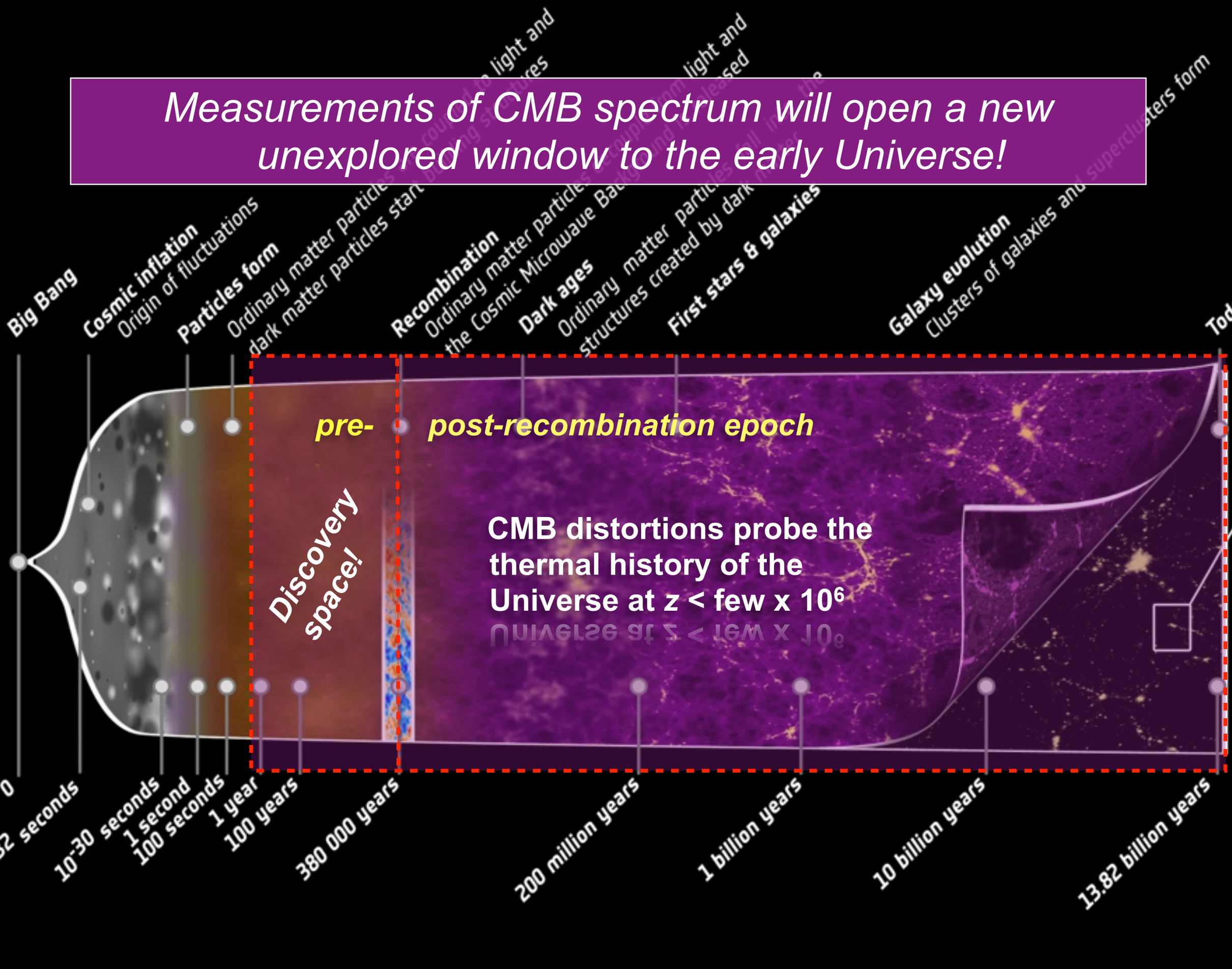
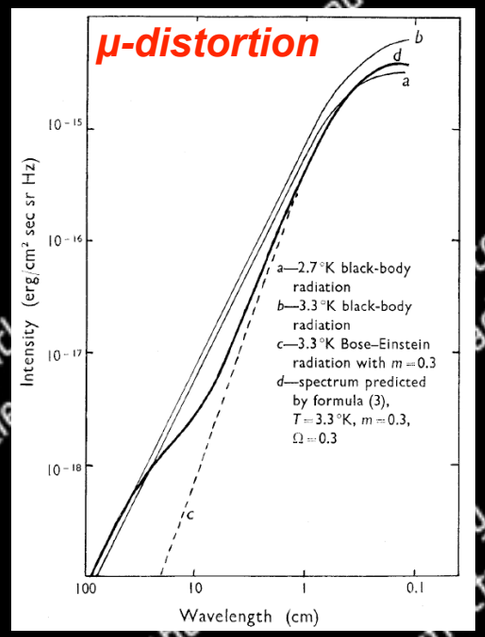
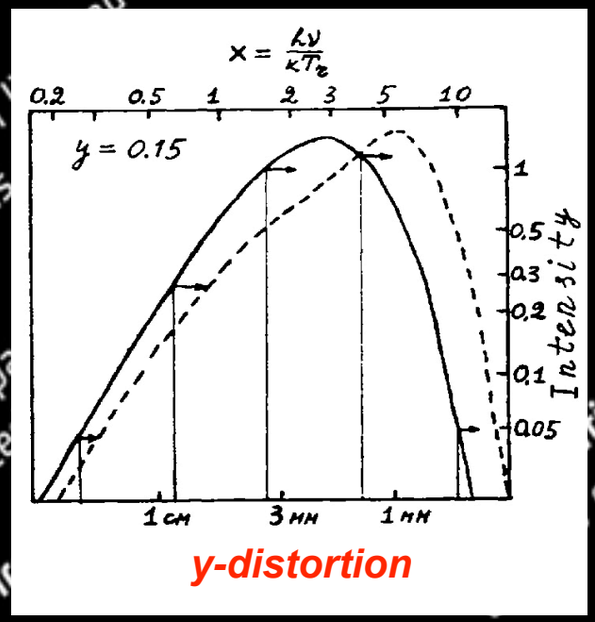
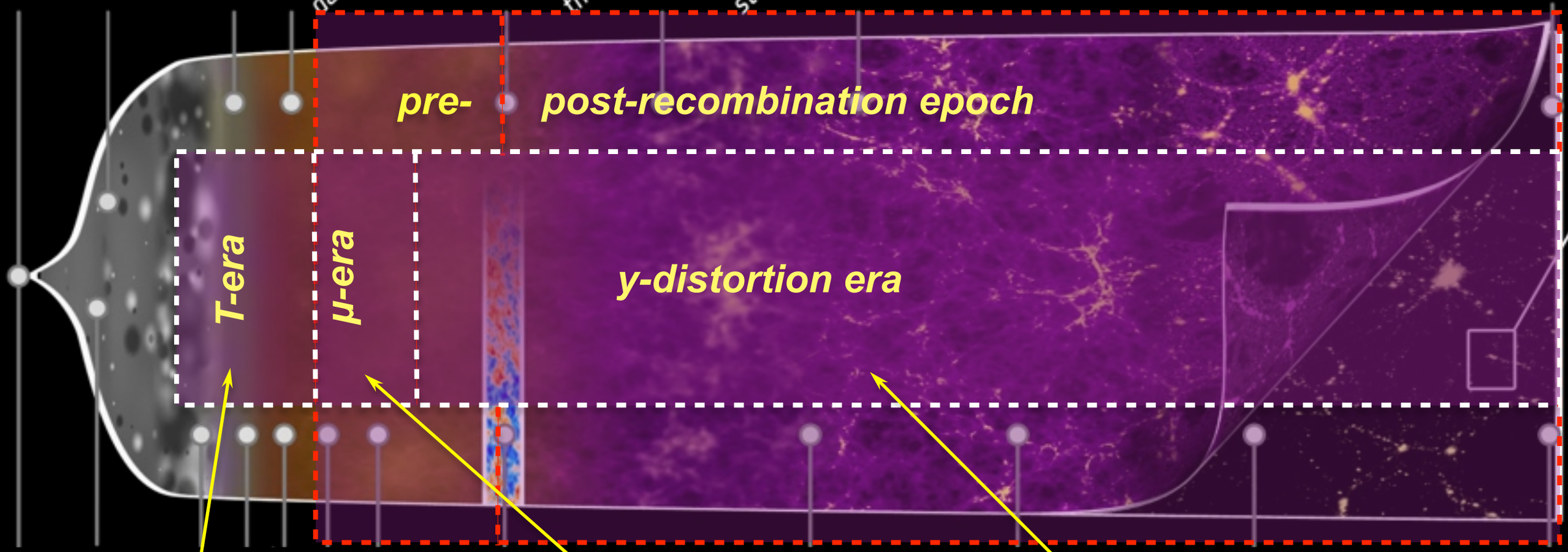
Measurements of CMB spectrum will open a new unexplored window to the early Universe!







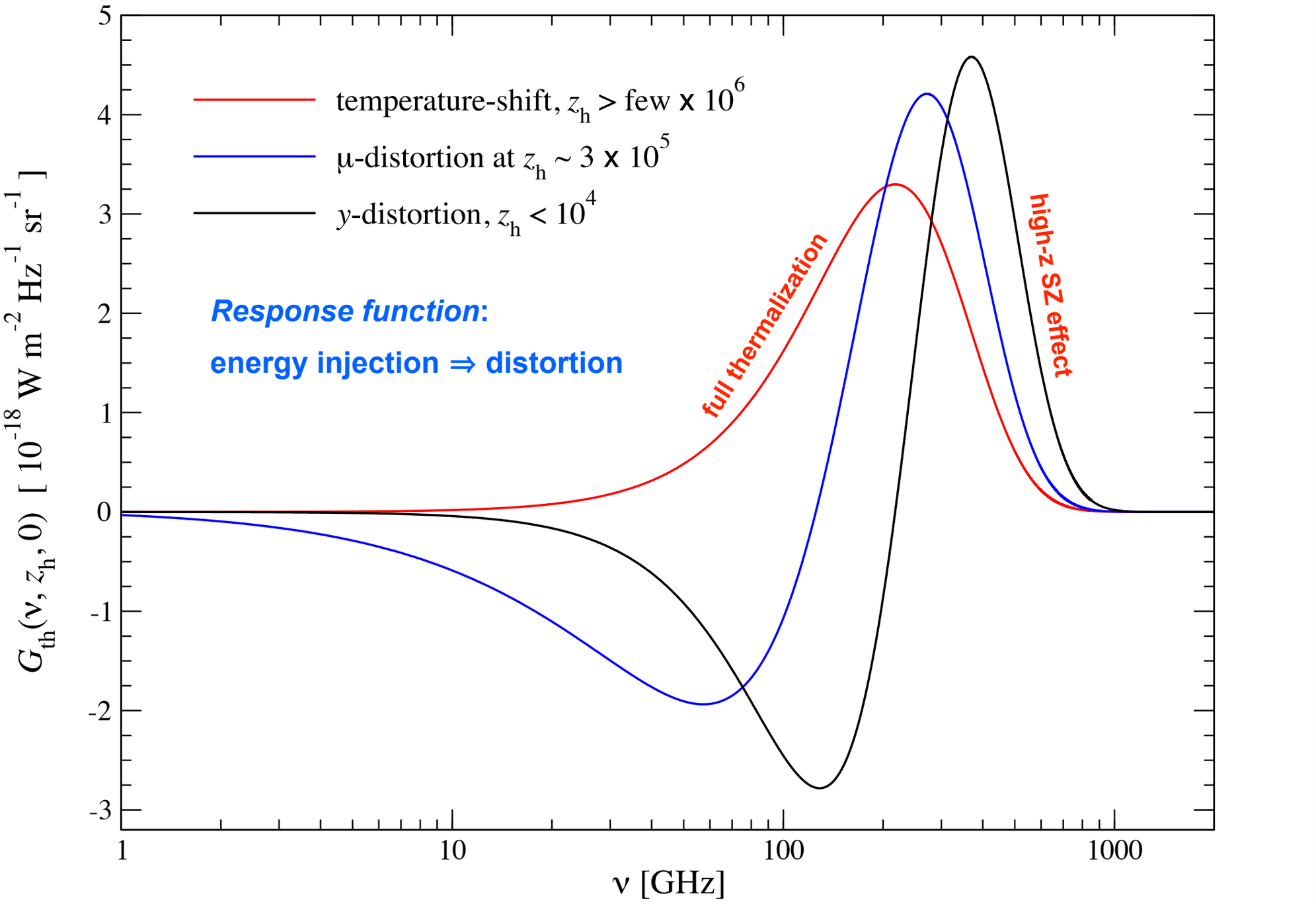
Big B… Cosm… Origin… Partic… Ordina… dark mat… couple from … background is … g matter pa… structures create… Fi… …tion of galax… Today



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

What does the spectrum look like after energy injection?

Intensity signal for different heating redshifts



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

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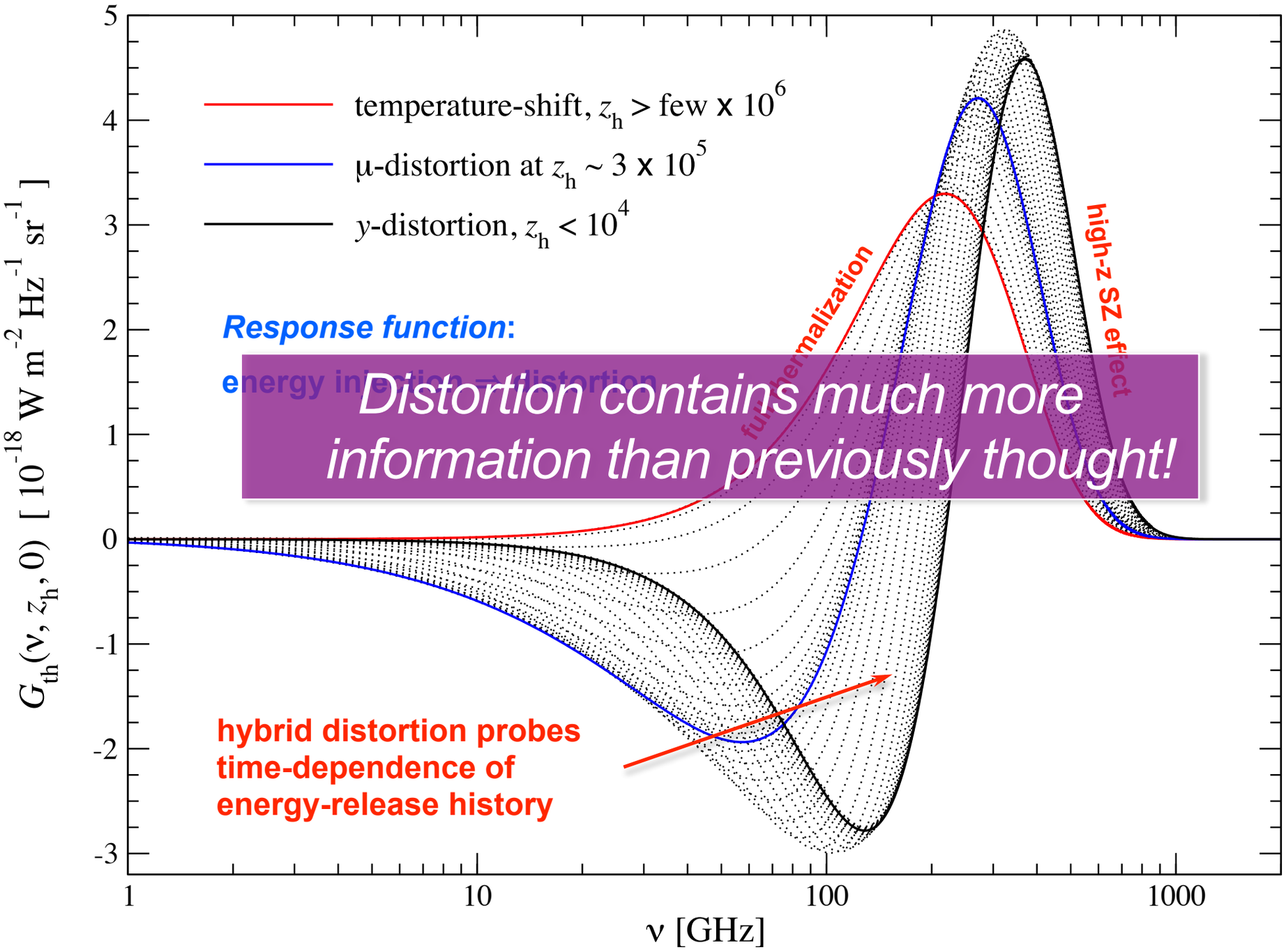

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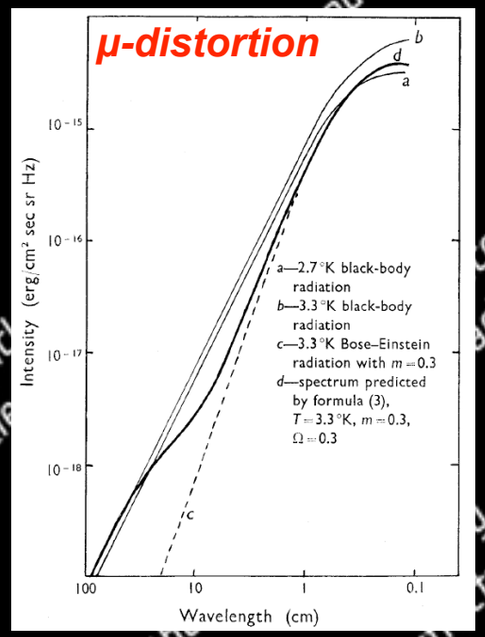

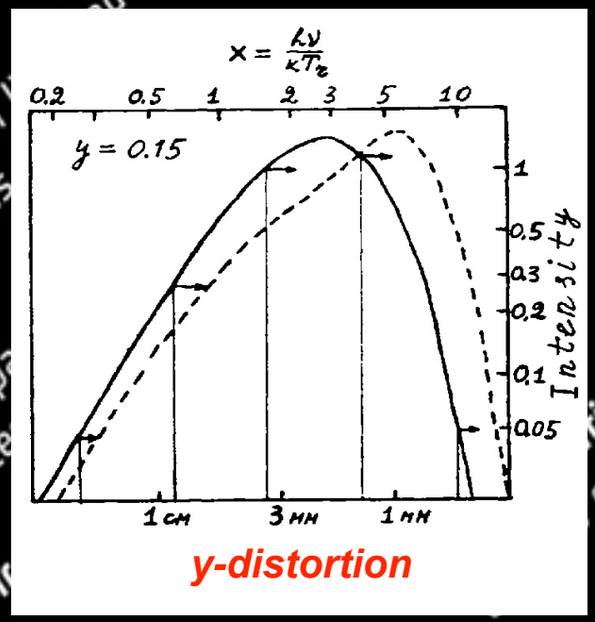

Big Bang
Cosmic Origin
Particle
Ordinary + dark matter
Today

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
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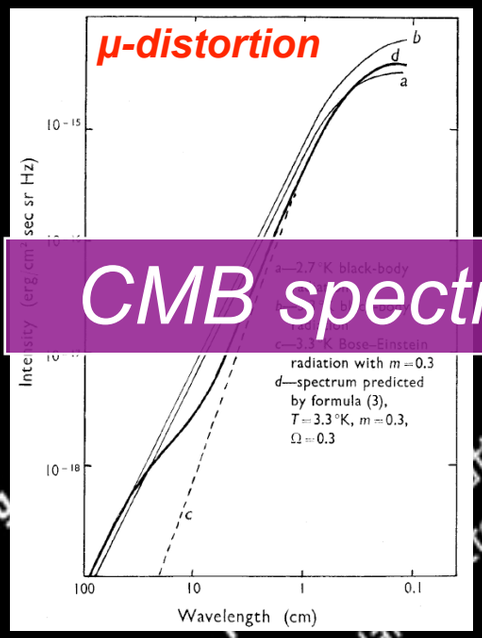
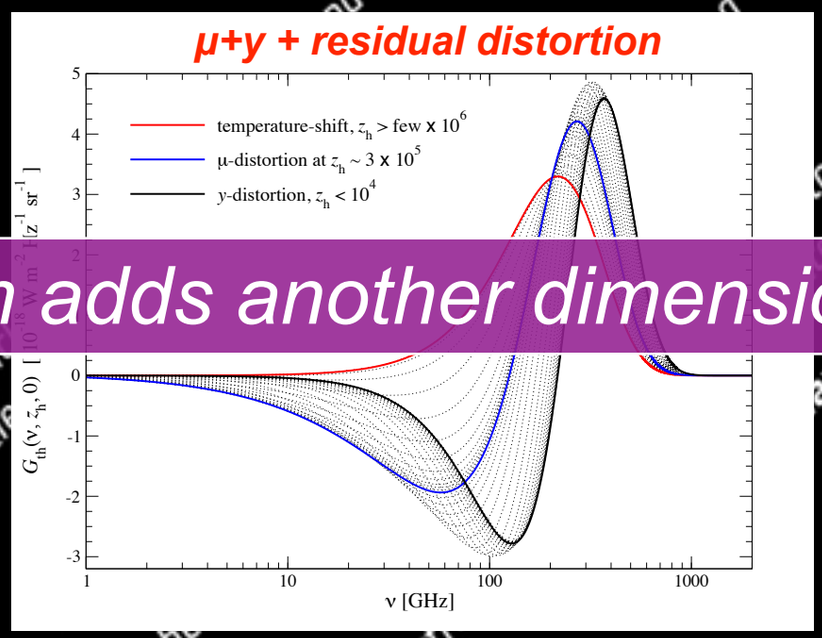
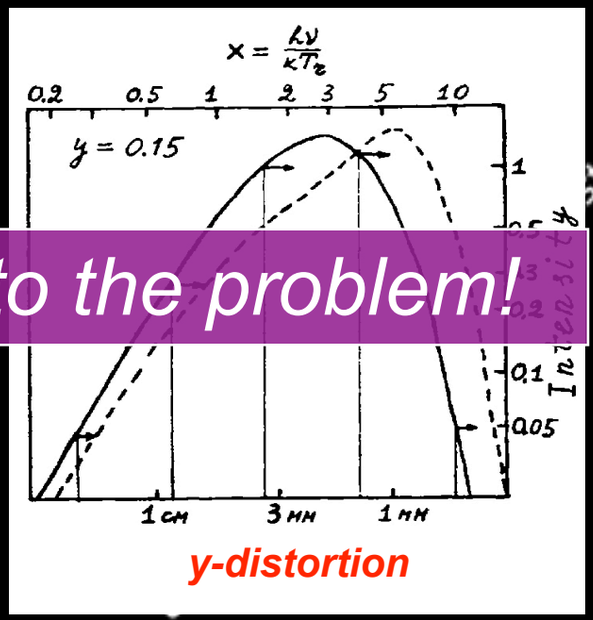
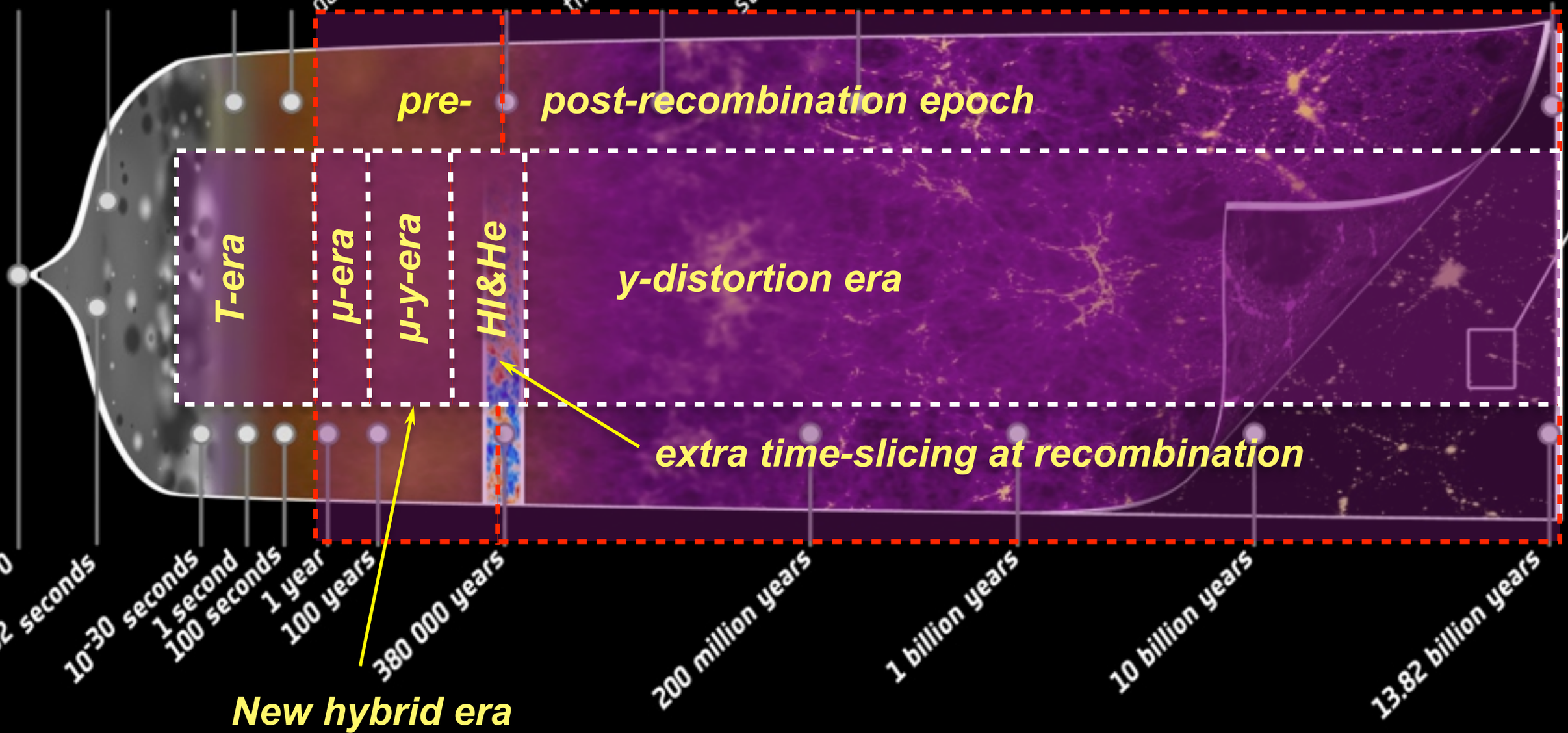


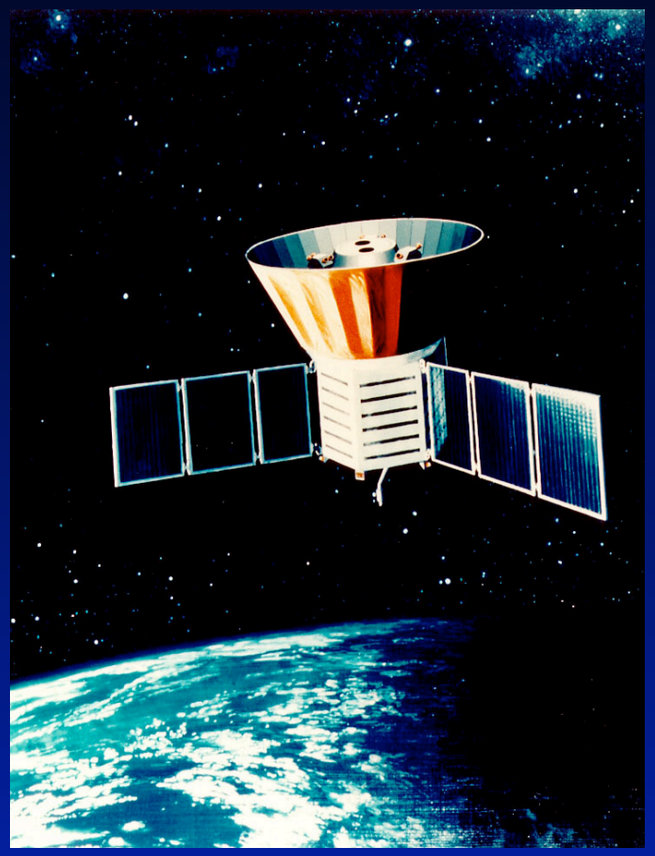




CMB spectrum adds another dimension to the problem!



COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)



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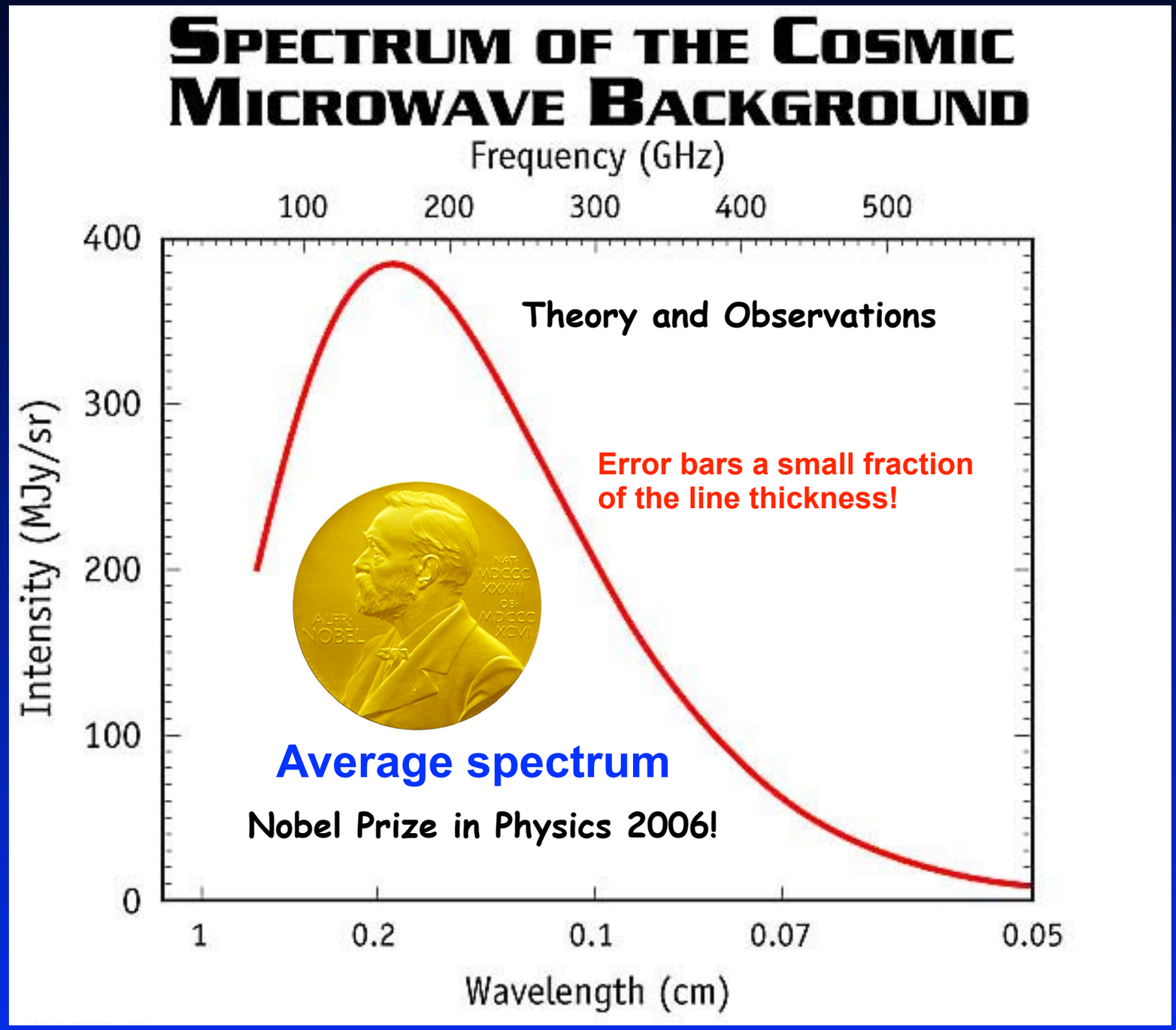

Only very small distortions of CMB spectrum are still allowed!

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
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„high“ redshifts

pre-recombination epoch

„low“ redshifts

post-recombination

- Signatures due to first supernovae and their remnants
  (Oh, Cooray & Kamionkowski, 2003)
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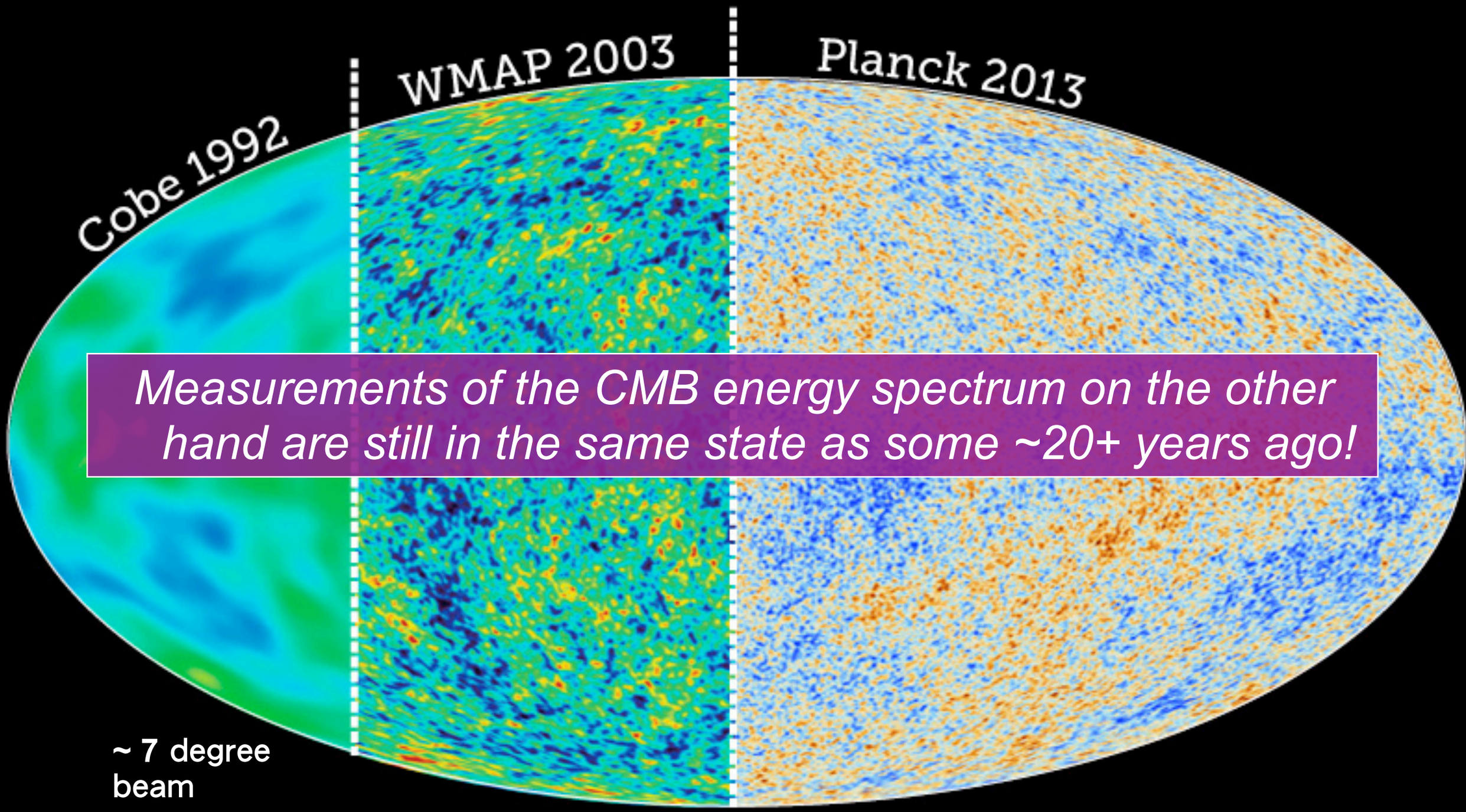
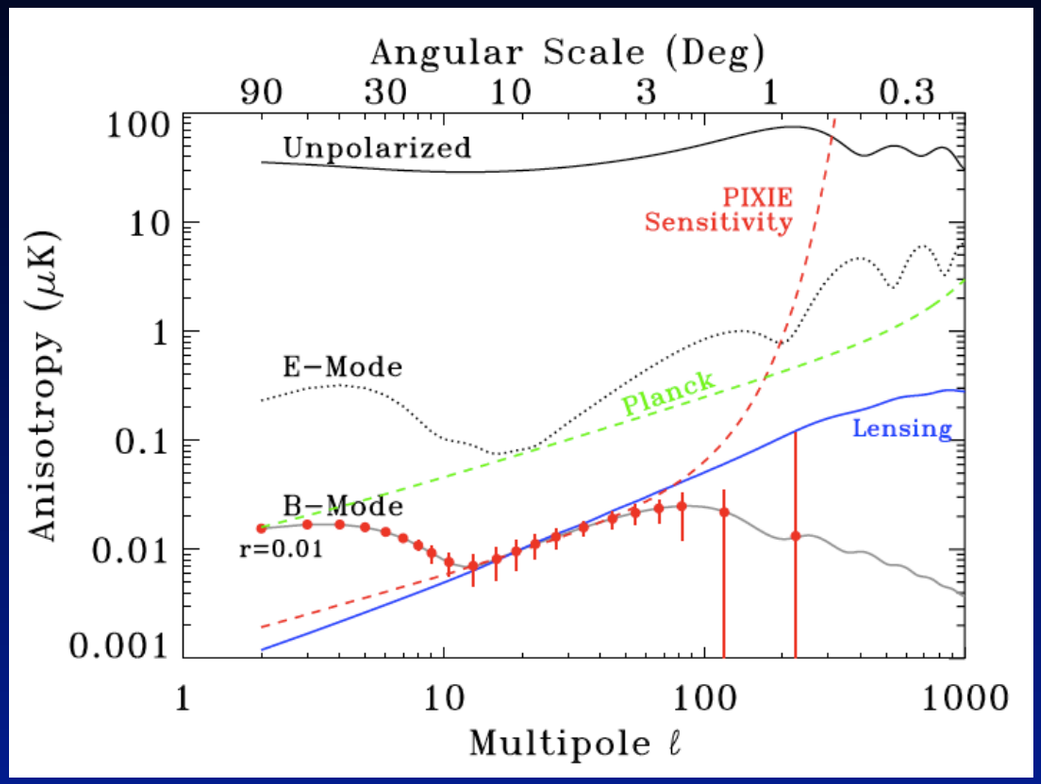
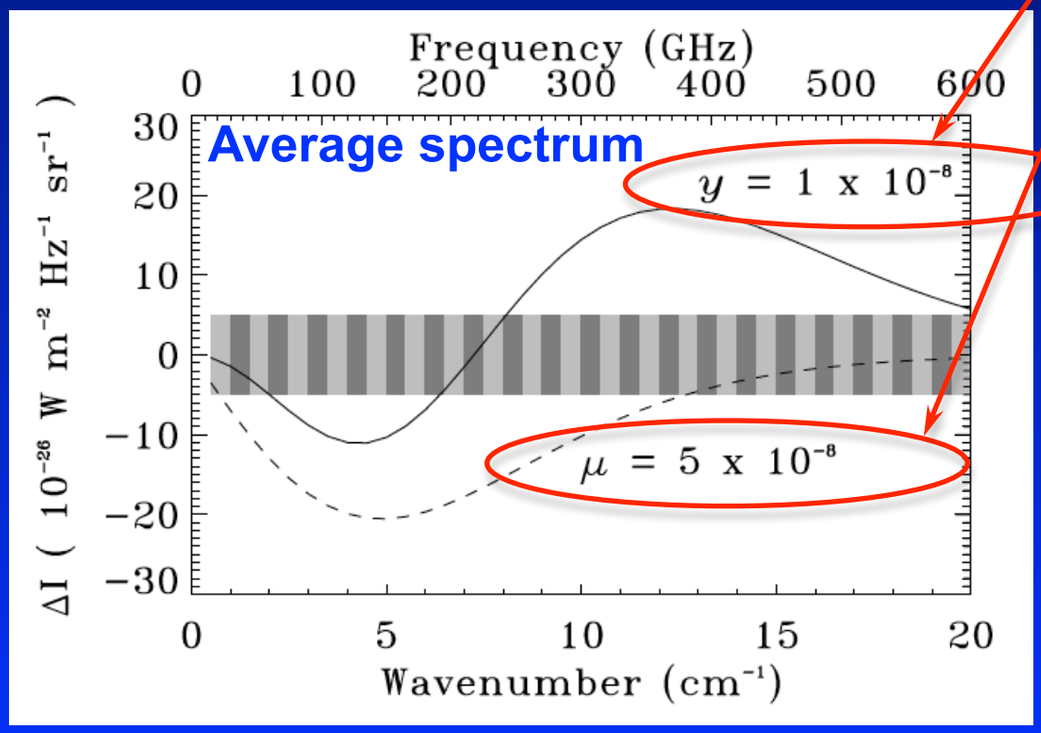
Dramatic improvements in angular resolution and sensitivity over the past decades!



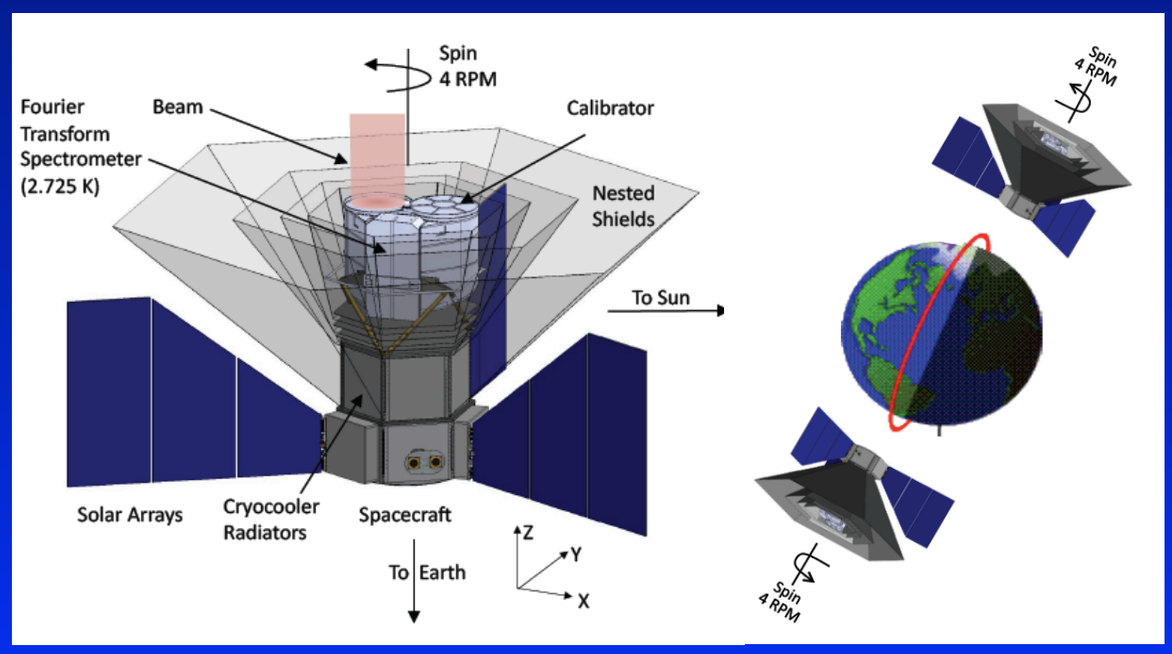
Measurements of the CMB energy spectrum on the other hand are still in the same state as some ~20+ years ago!

PIXIE: Primordial Inflation Explorer

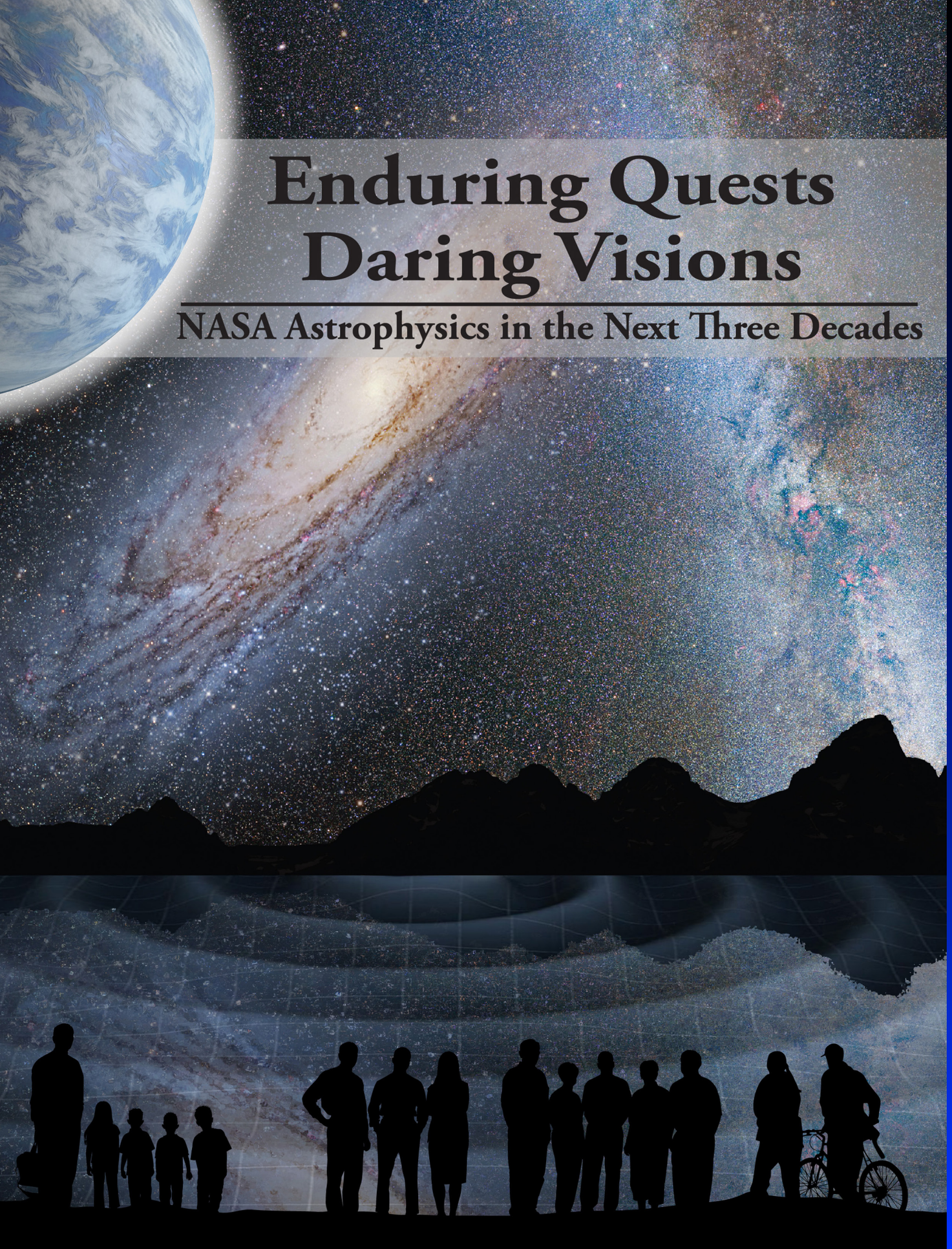




- 400 spectral channel in the frequency range 30 GHz and 6THz (Δv ~ 15GHz)
- about 1000 (!!!) times more sensitive than COBE/FIRAS
- B-mode polarization from inflation ($r \approx 10^{-3}$)
- improved limits on μ and y
- was proposed 2011 as NASA EX mission (i.e. cost ~ 200 M$)



Kogut et al, JCAP, 2011, arXiv:1105.2044



NASA 30-yr Roadmap Study

(published Dec 2013)

How does the Universe work?

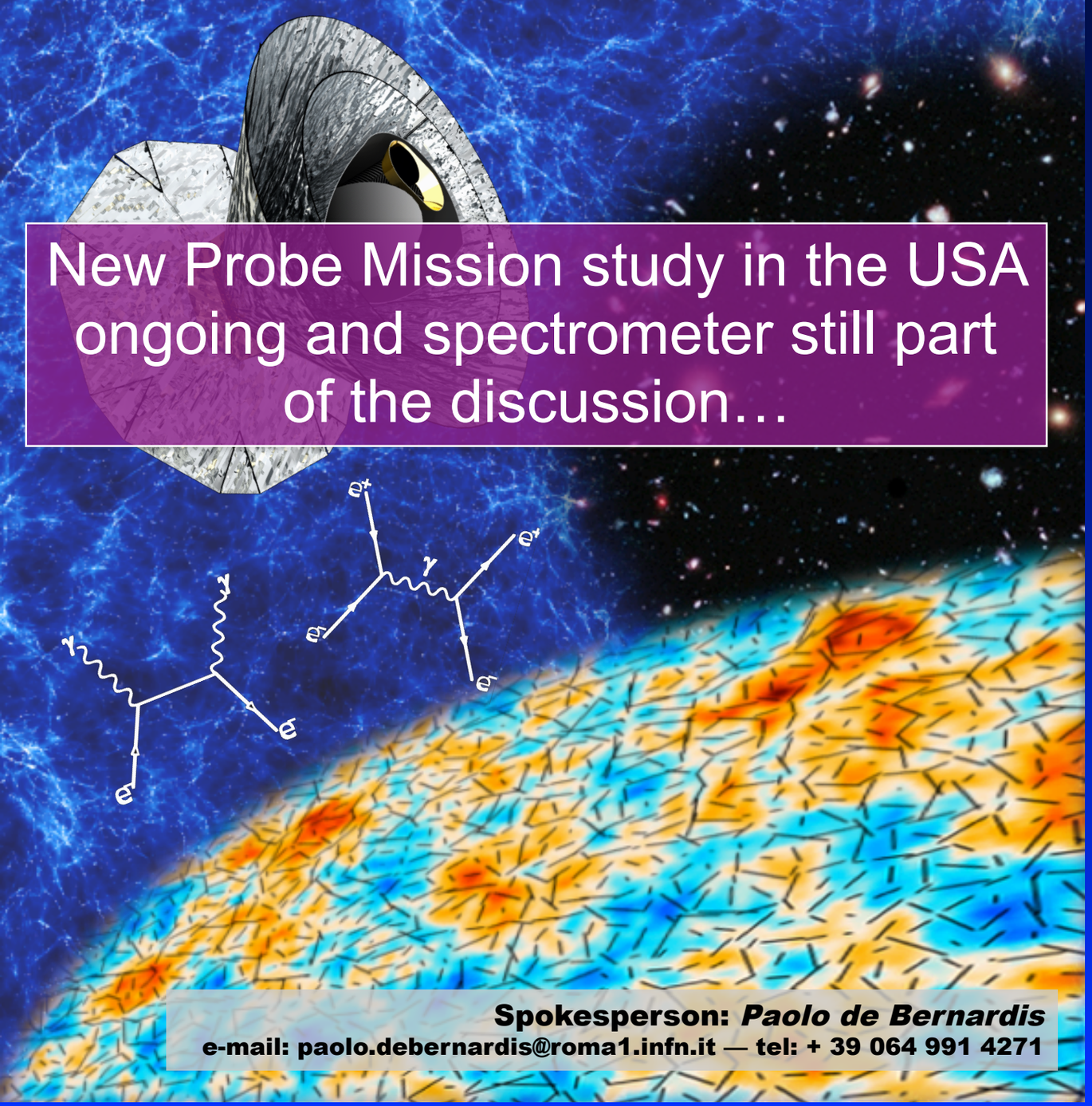
"Measure the spectrum of the CMB with precision several orders of magnitude higher than COBE FIRAS, from a moderate-scale mission or an instrument on CMB Polarization Surveyor."

PIXIE was proposed to NASA in Dec 2016. Sadly not selected :(:(

Polarized Radiation Imaging and Spectroscopy Mission

PRISM

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



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

Spokesperson: ***Paolo de Bernardis***
e-mail: paolo.debernardis@roma1.infn.it — tel: + 39 064 991 4271

Instruments:

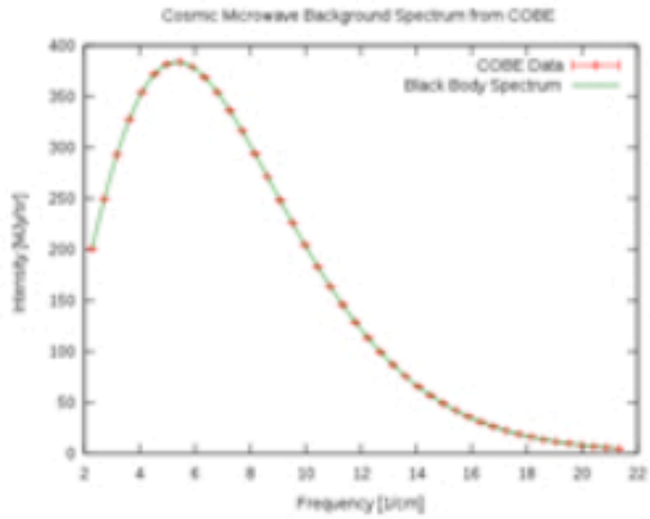
- L-class ESA mission
- White paper, May 24th, 2013
- Imager:
  - polarization sensitive
  - 3.5m telescope [arcmin resolution at highest frequencies]
  - 30GHz-6THz [30 broad ($\Delta\nu/\nu$~25%) and 300 narrow ($\Delta\nu/\nu$~2.5%) bands]
- Spectrometer:
  - FTS similar to PIXIE
  - 30GHz-6THz ($\Delta\nu$~15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

Some of the ~~science~~ goals:

- B-mode polarization from inflation ($r \approx 5\times10^{-4}$)
- 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



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


Concordia station at Dome-C

Taken from a talk by Elia Battistelli

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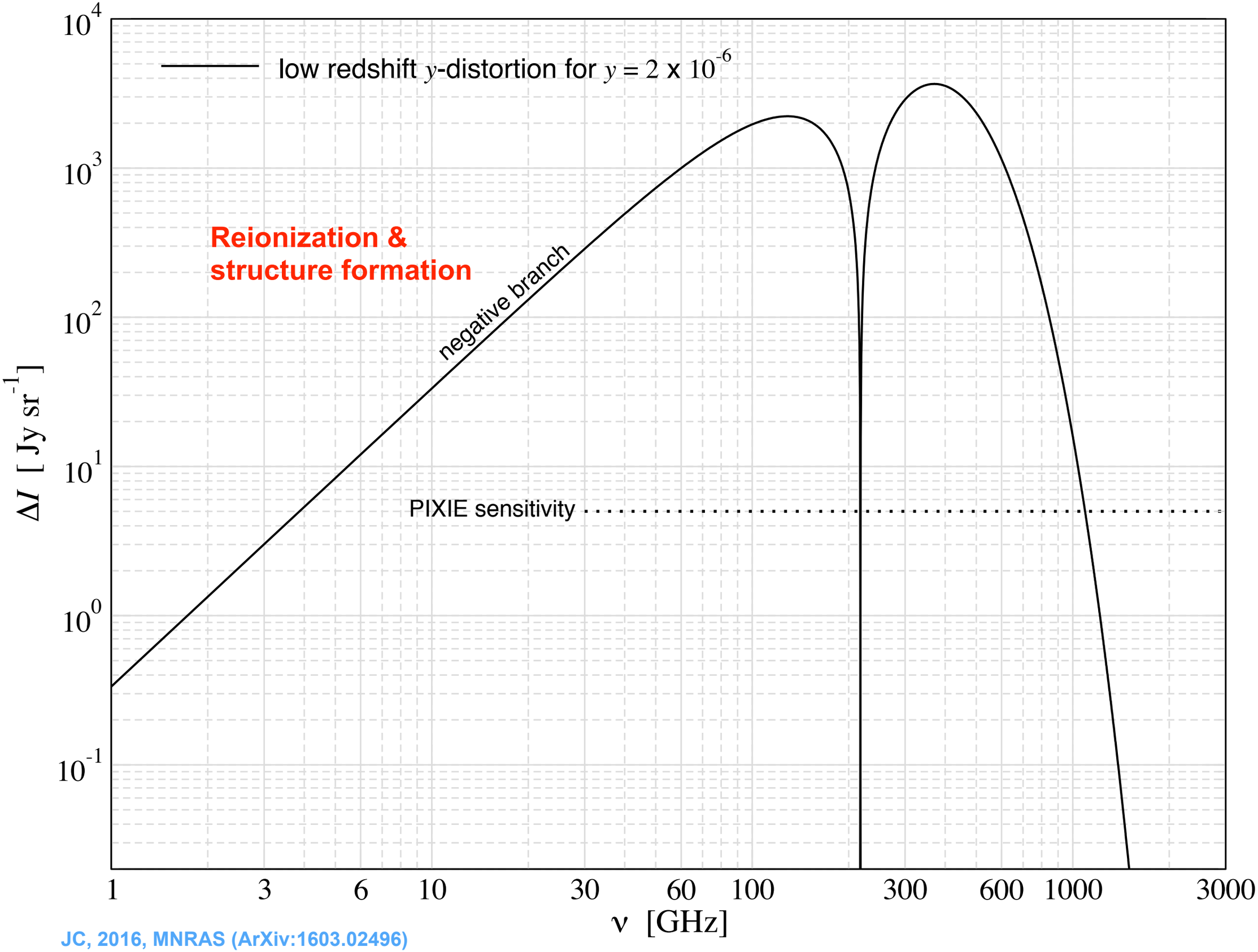
Average CMB spectral distortions



JC, 2016, MNRAS (ArXiv:1603.02496)

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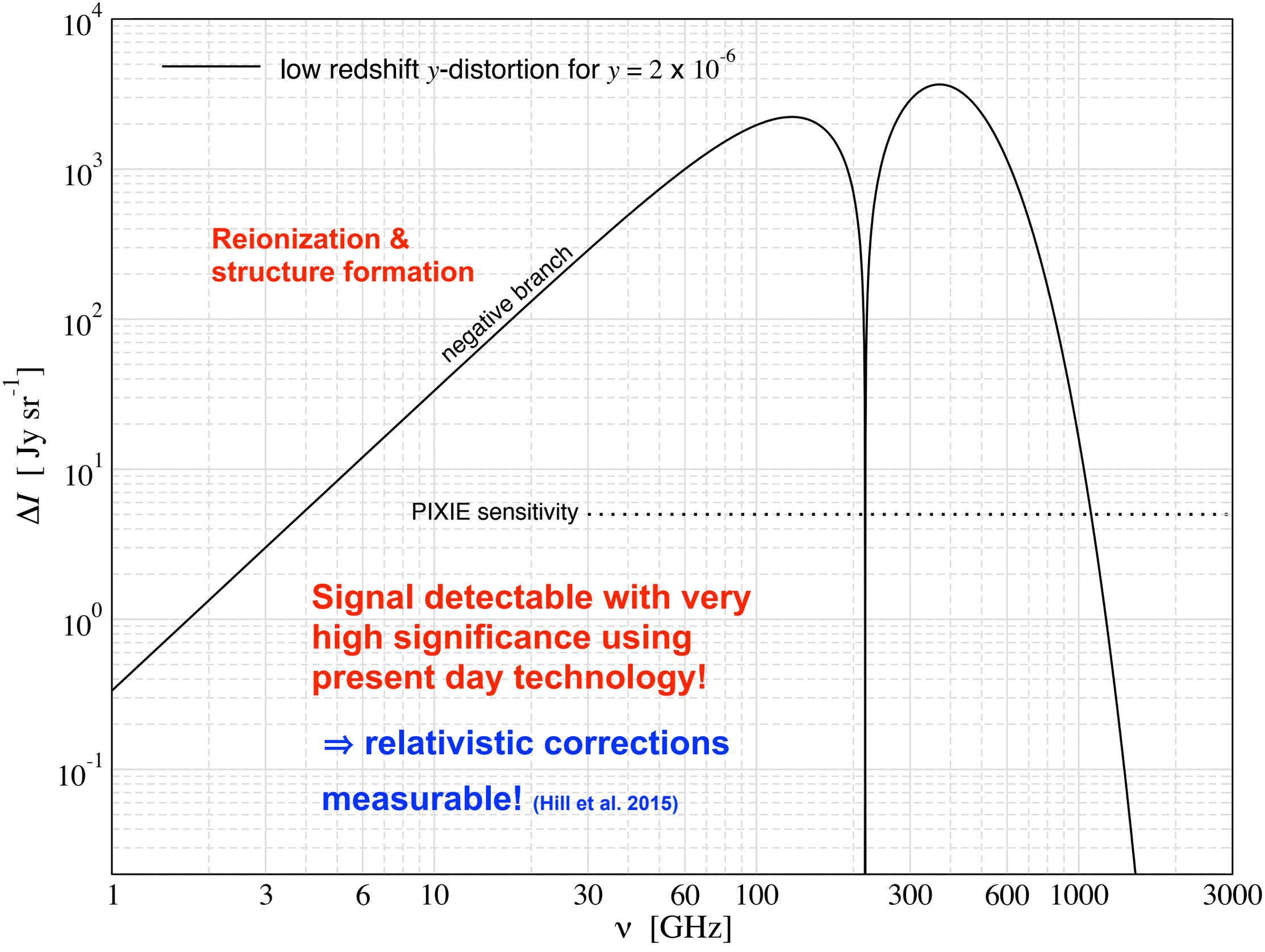

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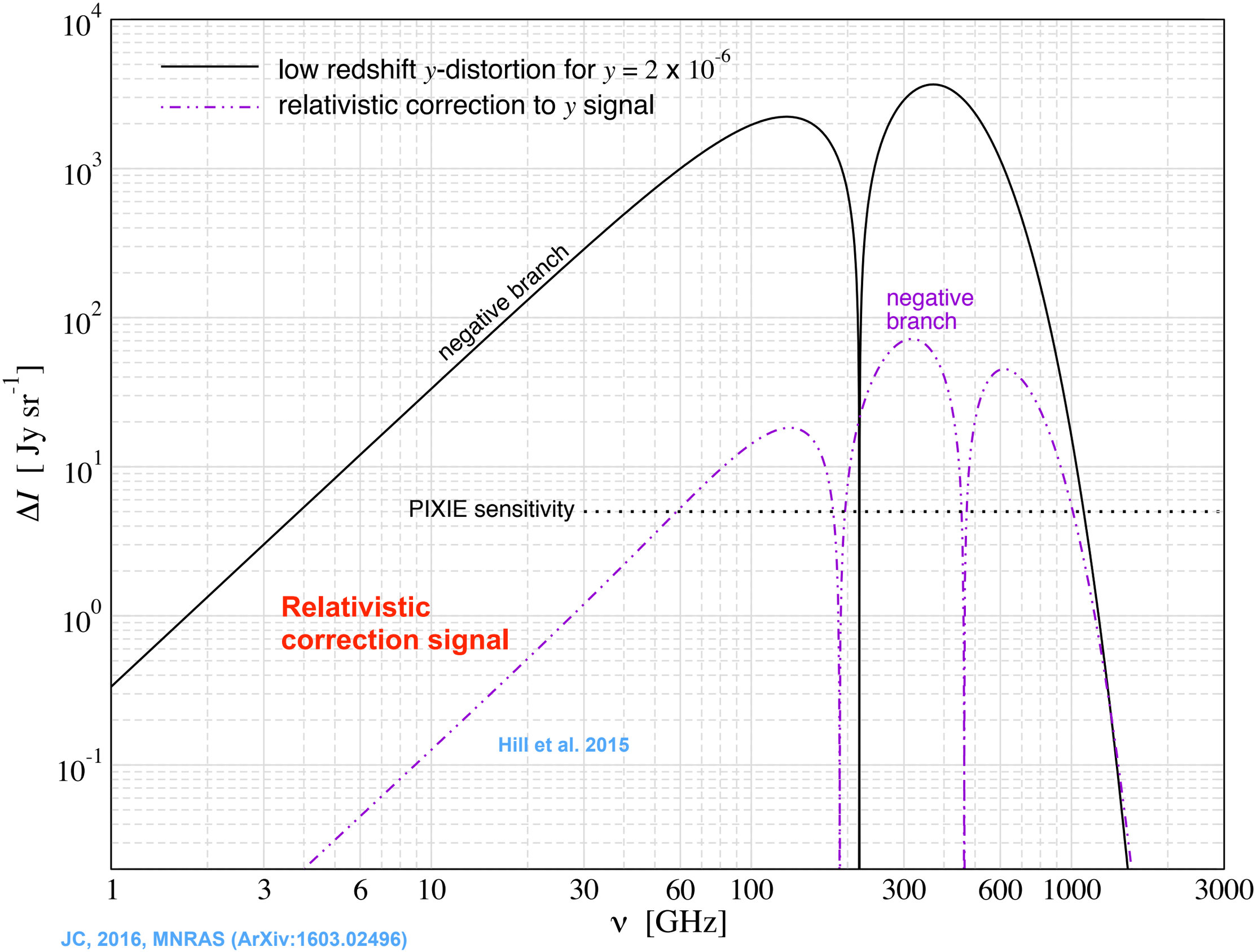

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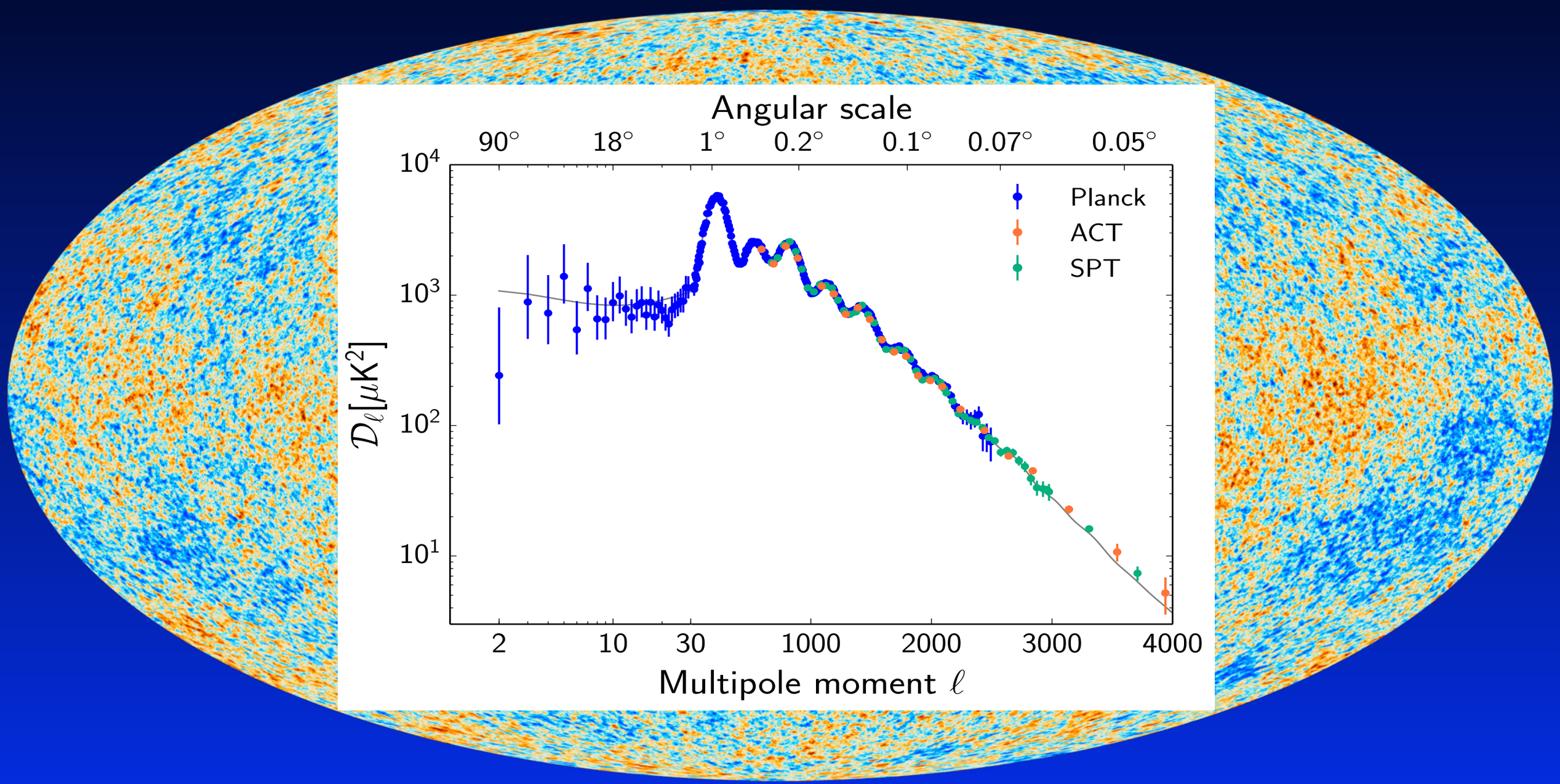
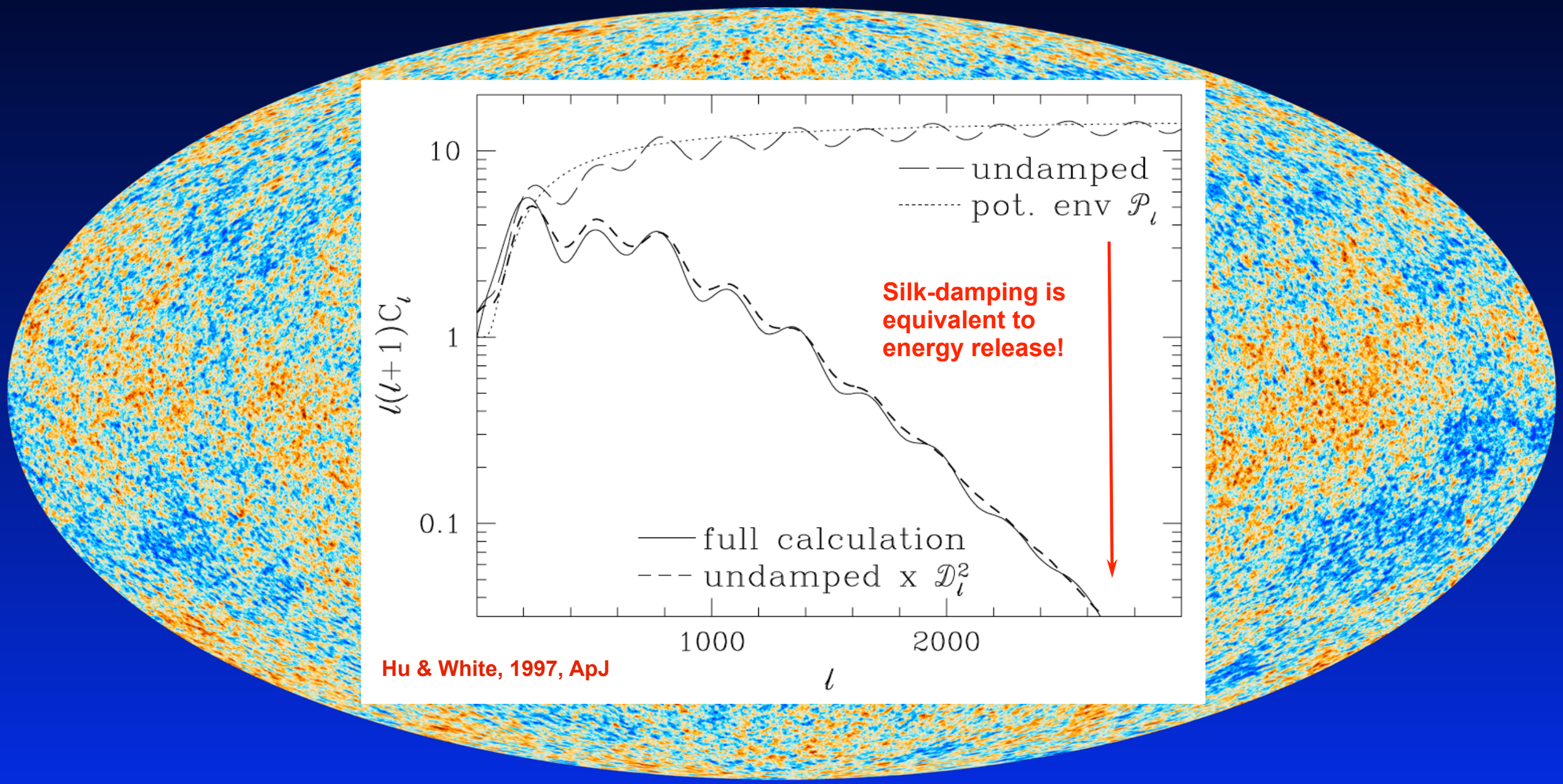
Dissipation of small-scale acoustic modes



Dissipation of small-scale acoustic modes



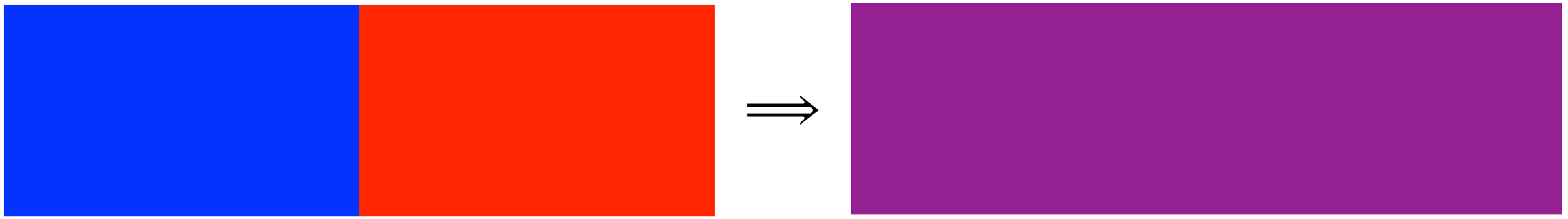
Hu & White, 1997, ApJ

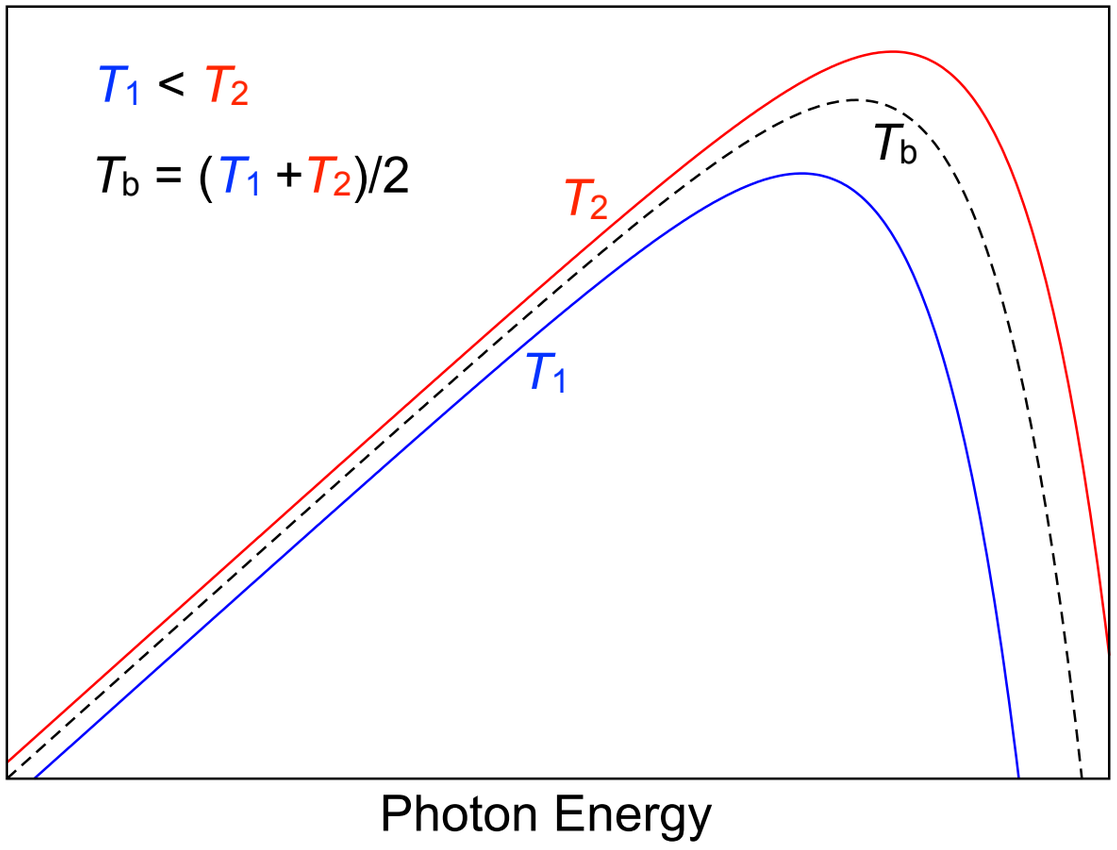
Distortion due to mixing of blackbodies

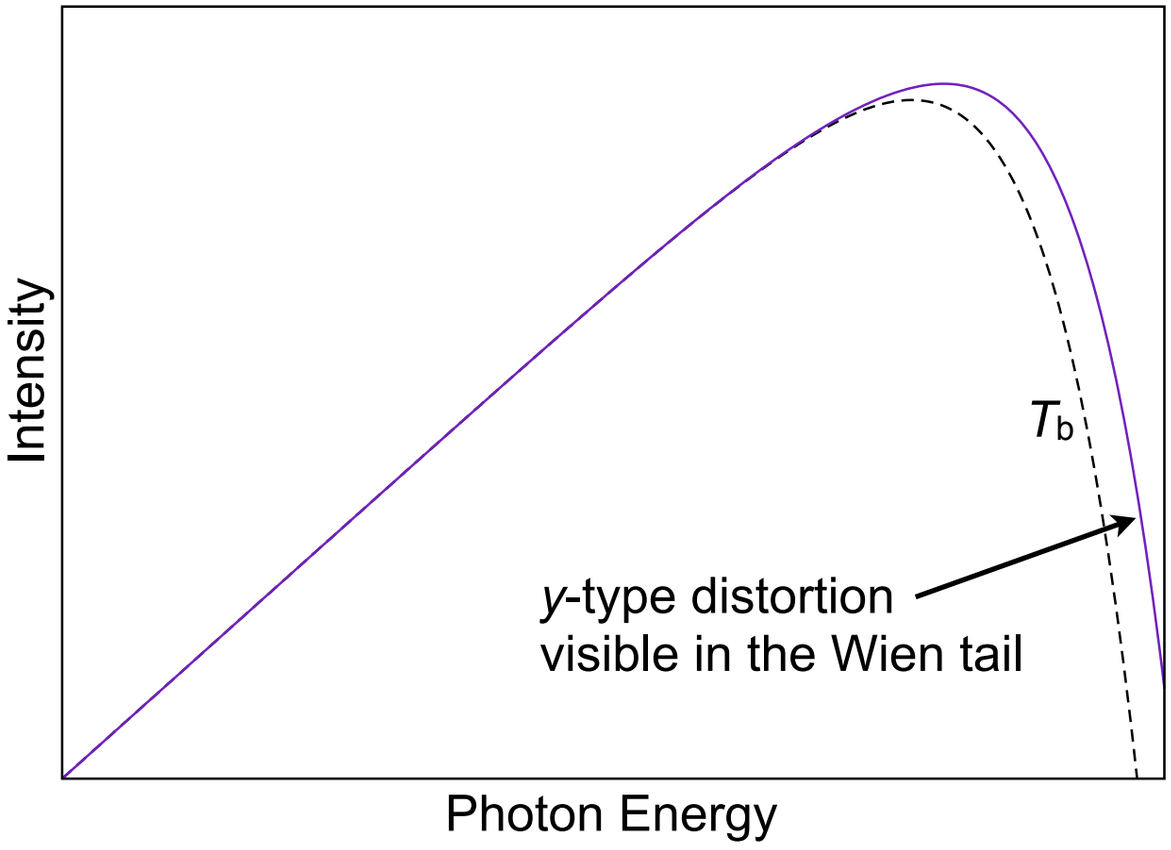
Blackbody spectra

Photon mixing

Blackbody + *y*-distortion







JC, Hamann & Patil, 2015

Mixing is mediated by Thomson scattering ⇒ Silk damping

Early power spectrum constraints from FIRAS

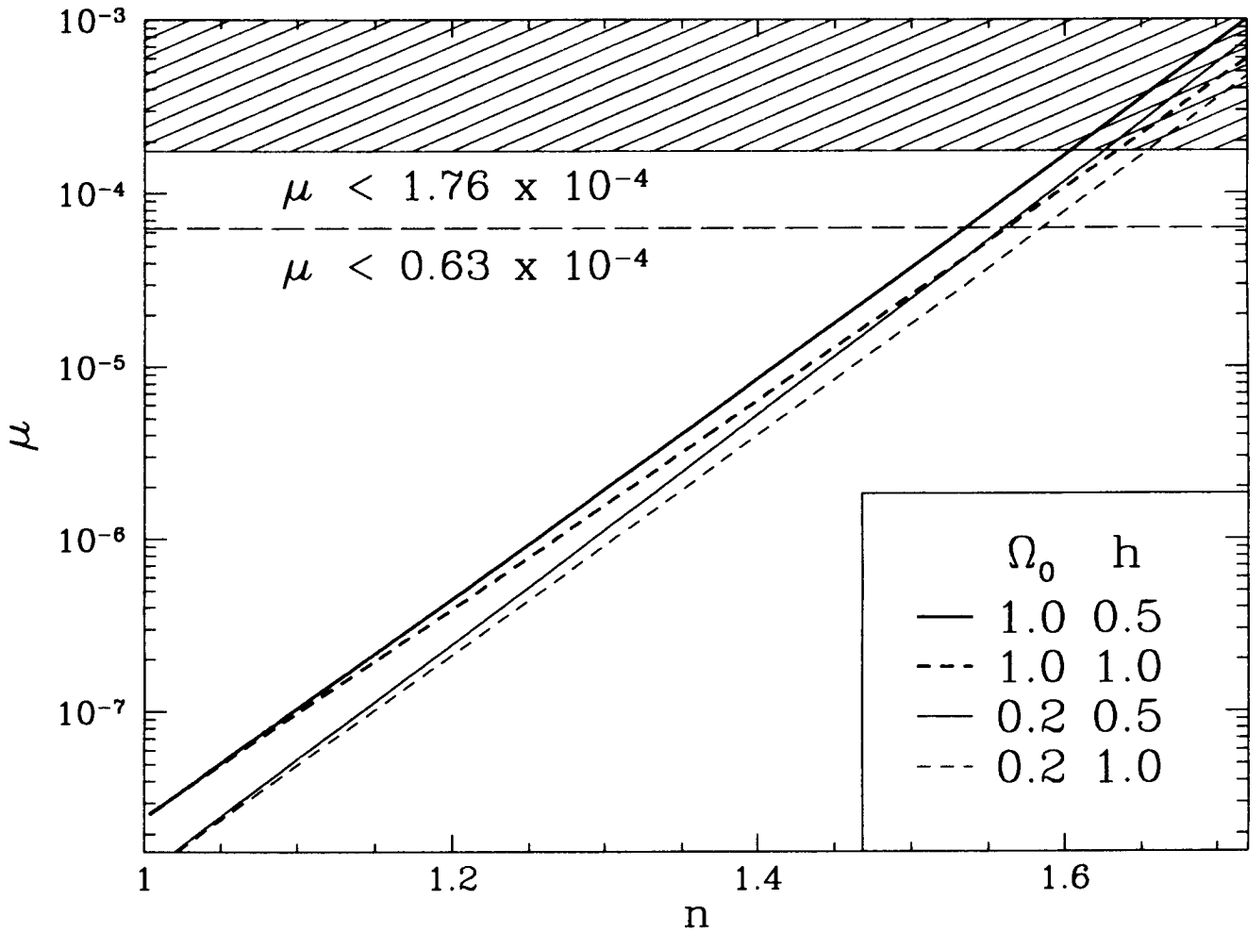


FIG. 1.—Spectral distortion μ, predicted from the full eq. (11), as a function of the power index n for a normalization at the mean of the *COBE* DMR detection $(\Delta T/T)_{10^\circ} = 1.12 \times 10^{-5}$. With the uncertainties on *both* the DMR and FIRAS measurements, the conservative 95% upper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

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

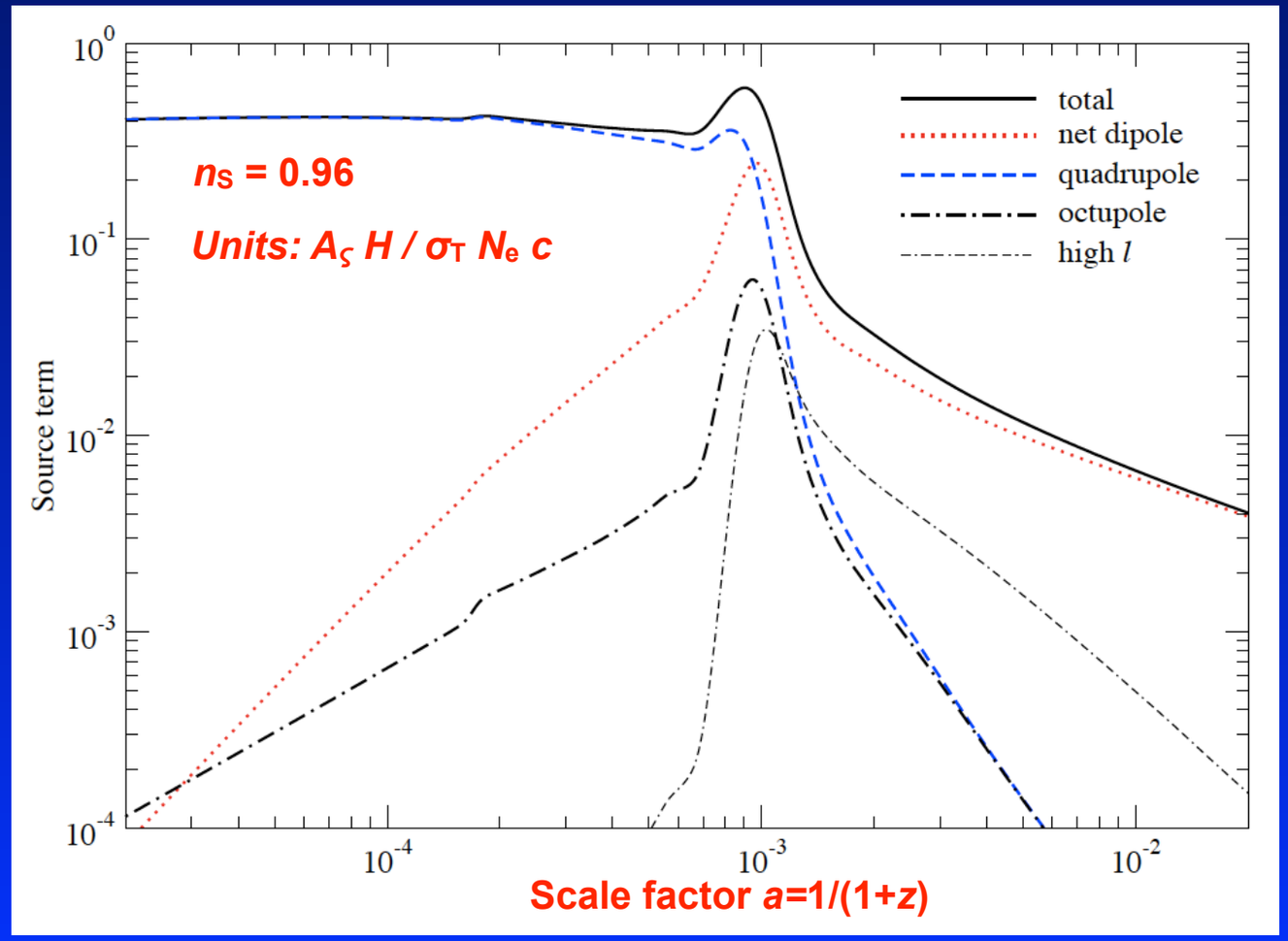
$$\Theta_\ell = \frac{1}{2}\int \Theta(\mu)P_\ell(\mu)\mathrm{d}\mu$$

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

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

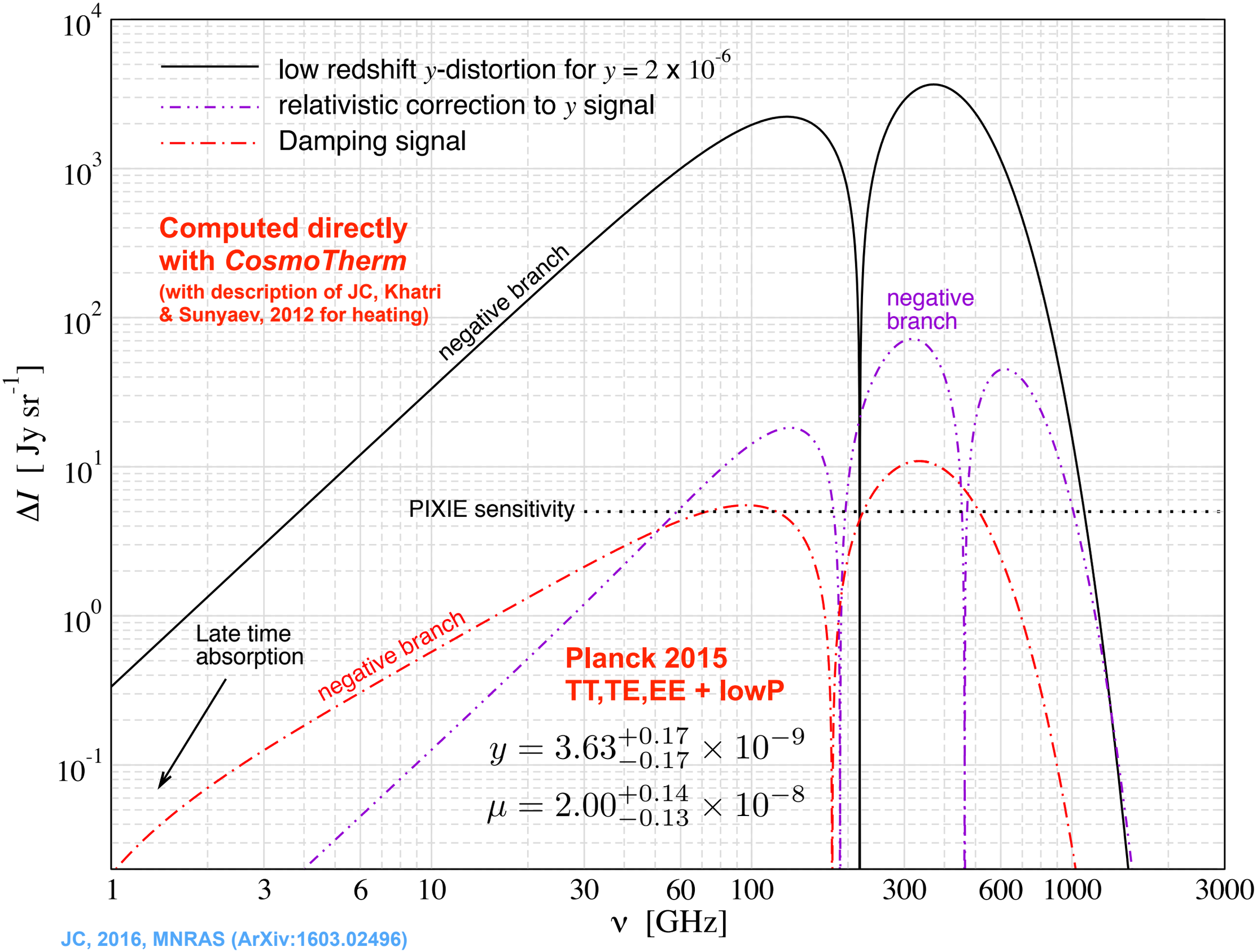
Primordial power spectrum

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



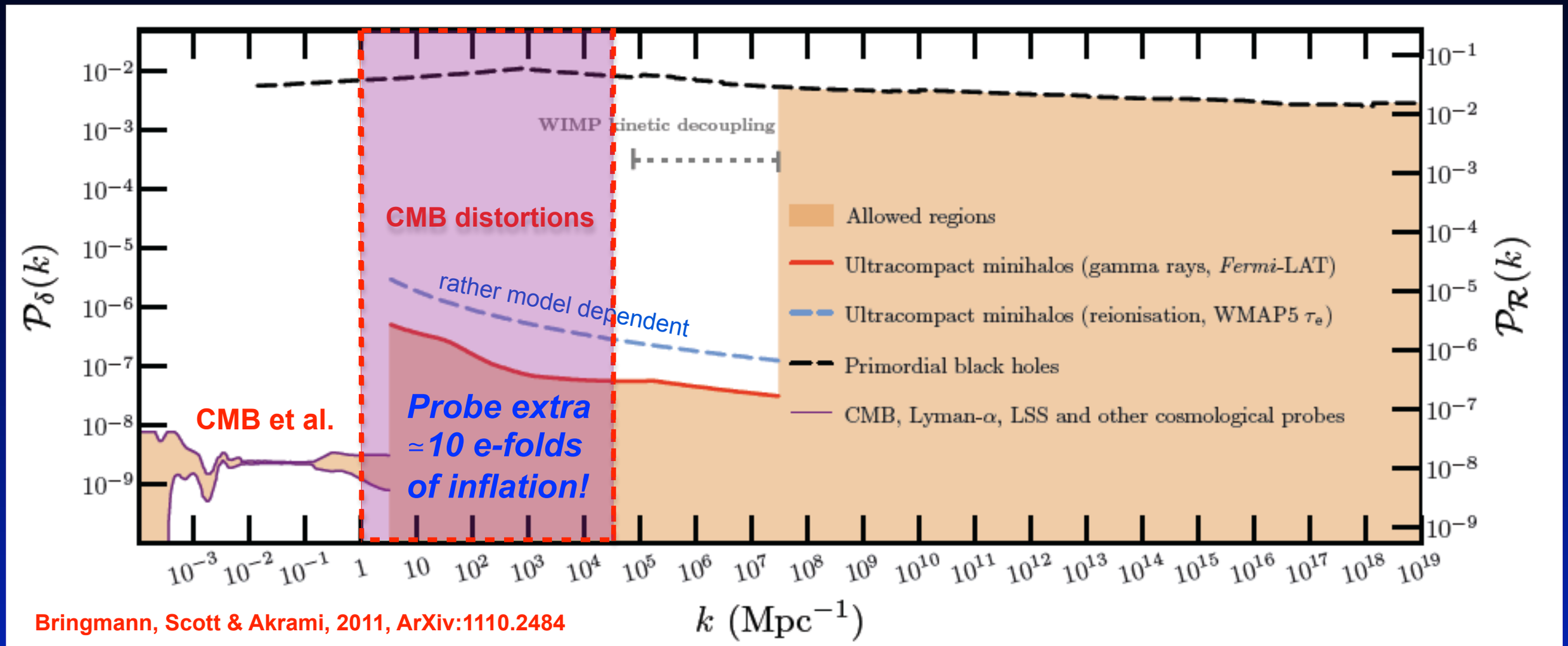
JC, Khatri & Sunyaev, 2012

Average CMB spectral distortions



JC, 2016, MNRAS (ArXiv:1603.02496)

Distortions provide general power spectrum constraints!

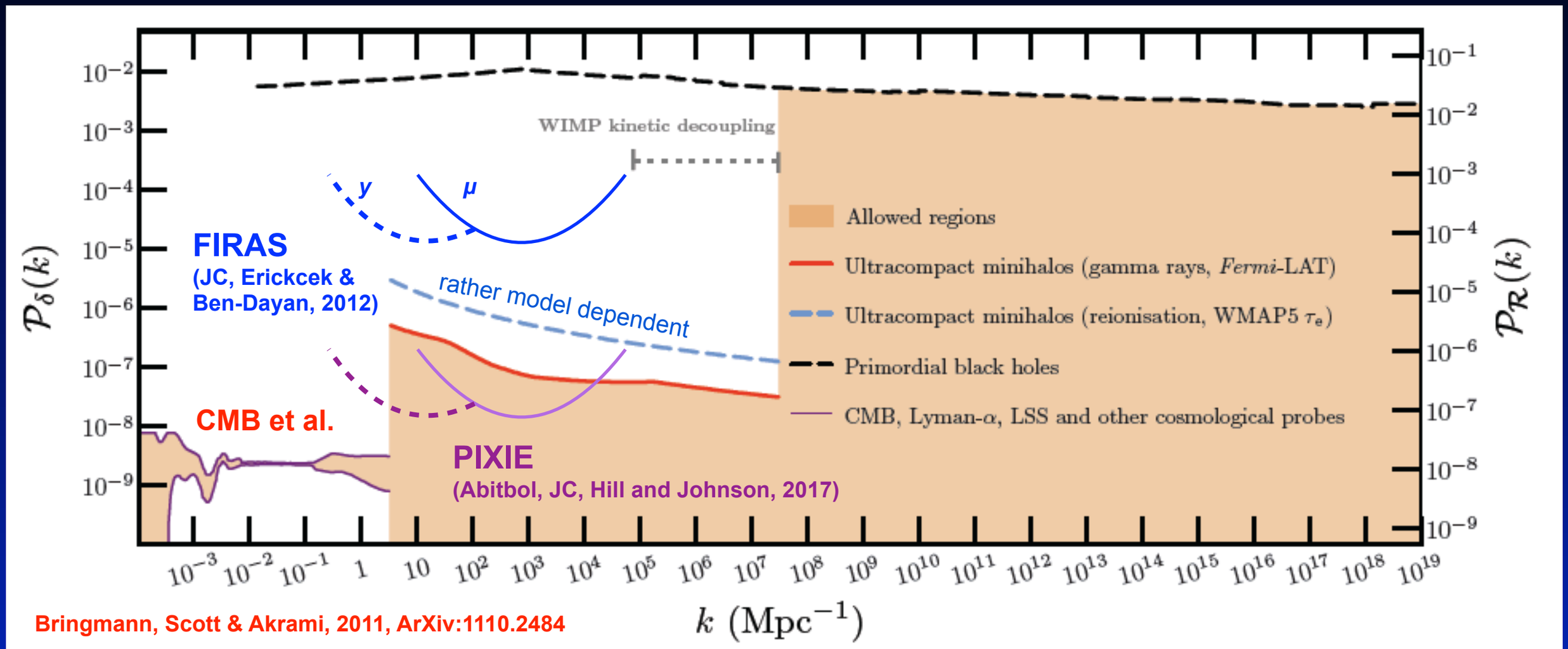


Bringmann, Scott & Akrami, 2011, ArXiv:1110.2484

- 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

Distortions provide general power spectrum constraints!



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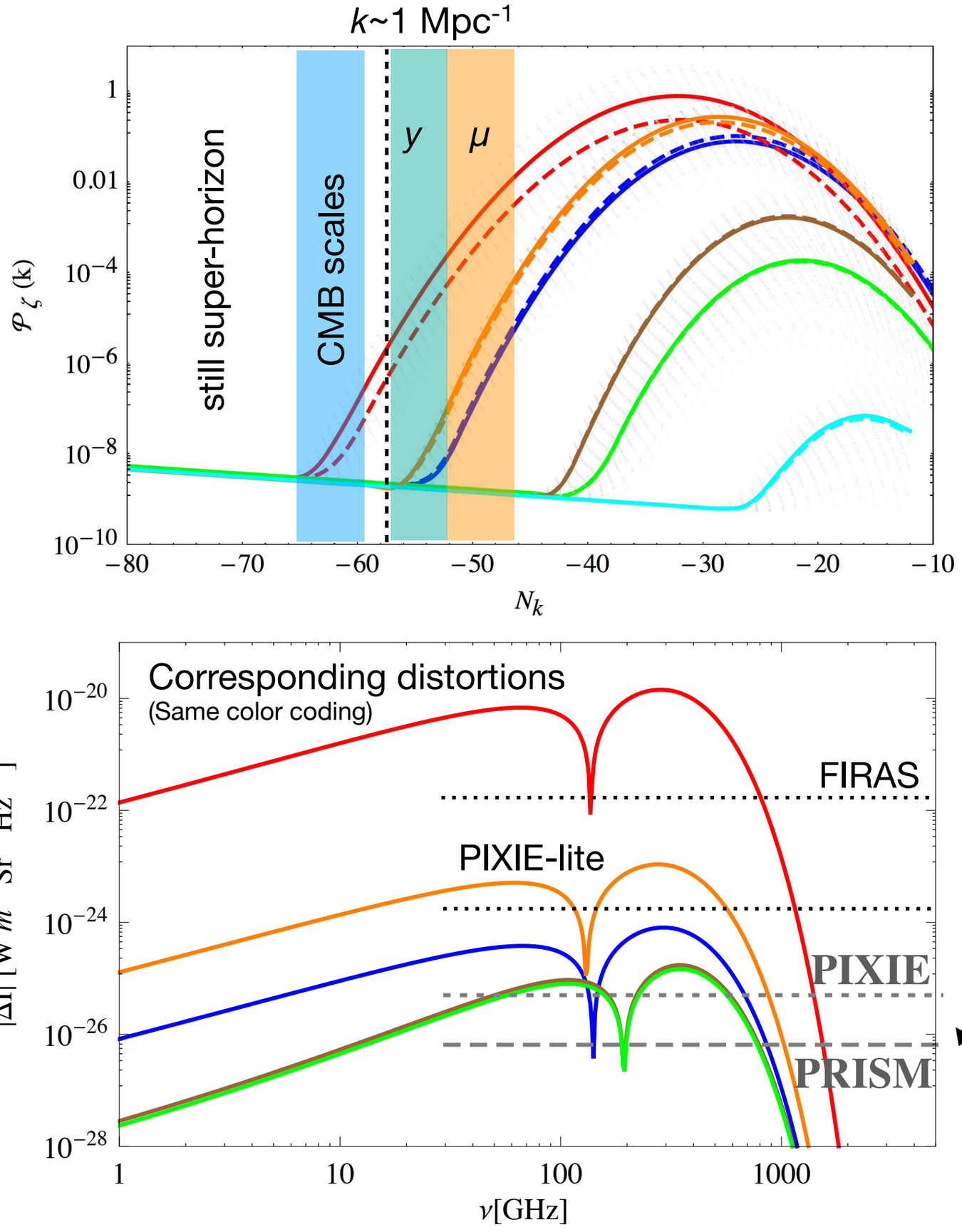
Enhanced small-scale power in hybrid inflation

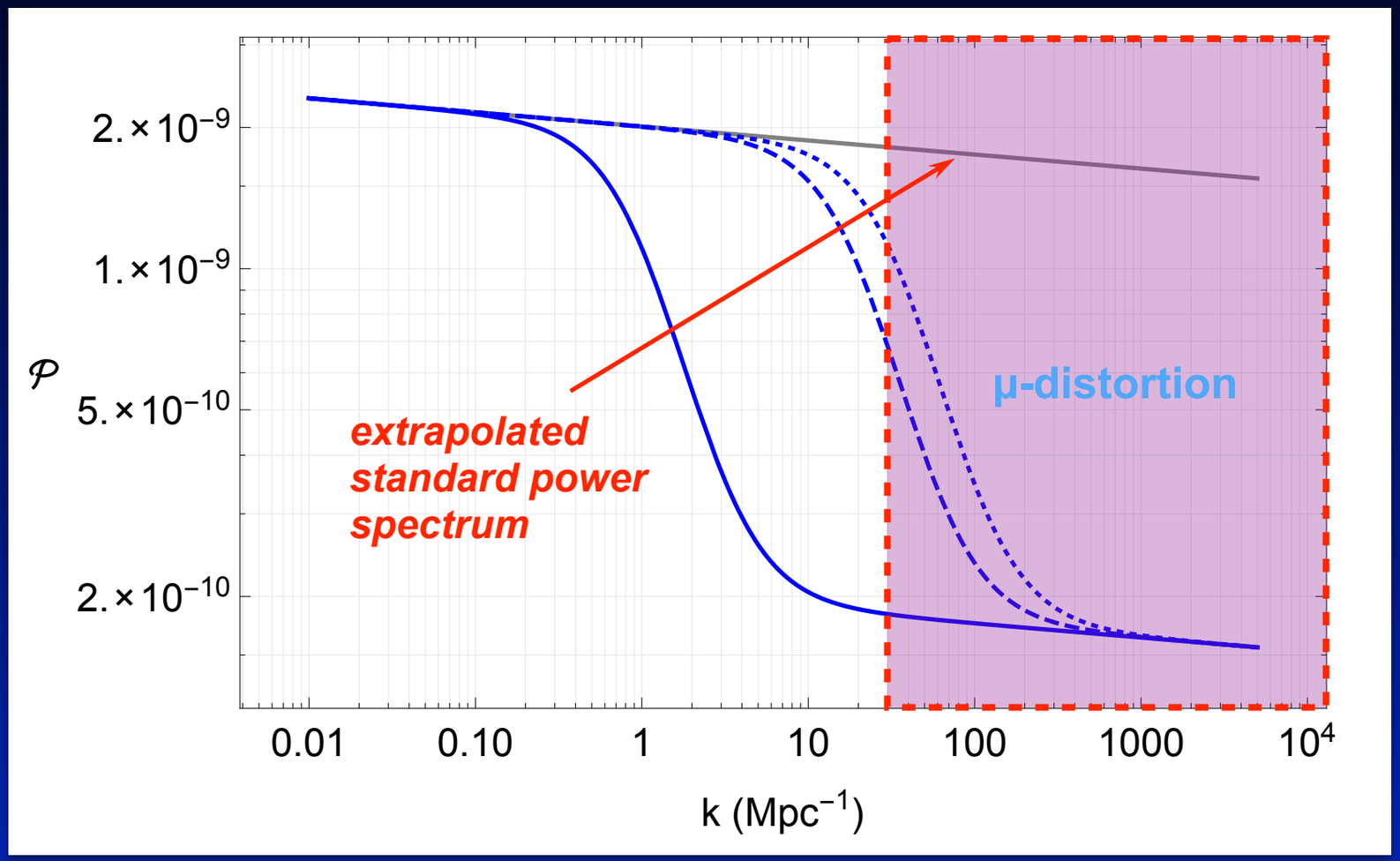


- Hybrid Inflation models cause enhanced small-scale power
- Motivated to explain seeds of supermassive blackholes seen in basically all galaxies
- μ and y distortions sensitive to enhancement at scales $1\ \mathrm{Mpc}^{-1} \lesssim k \lesssim 2\times10^{4}\ \mathrm{Mpc}^{-1}$
- Can constrain cases 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

Old forecast without foreground penalty

Figures adapted from Clesse & Garcia-Bellido, 2015

Shedding Light on the ‘Small-Scale Crisis’



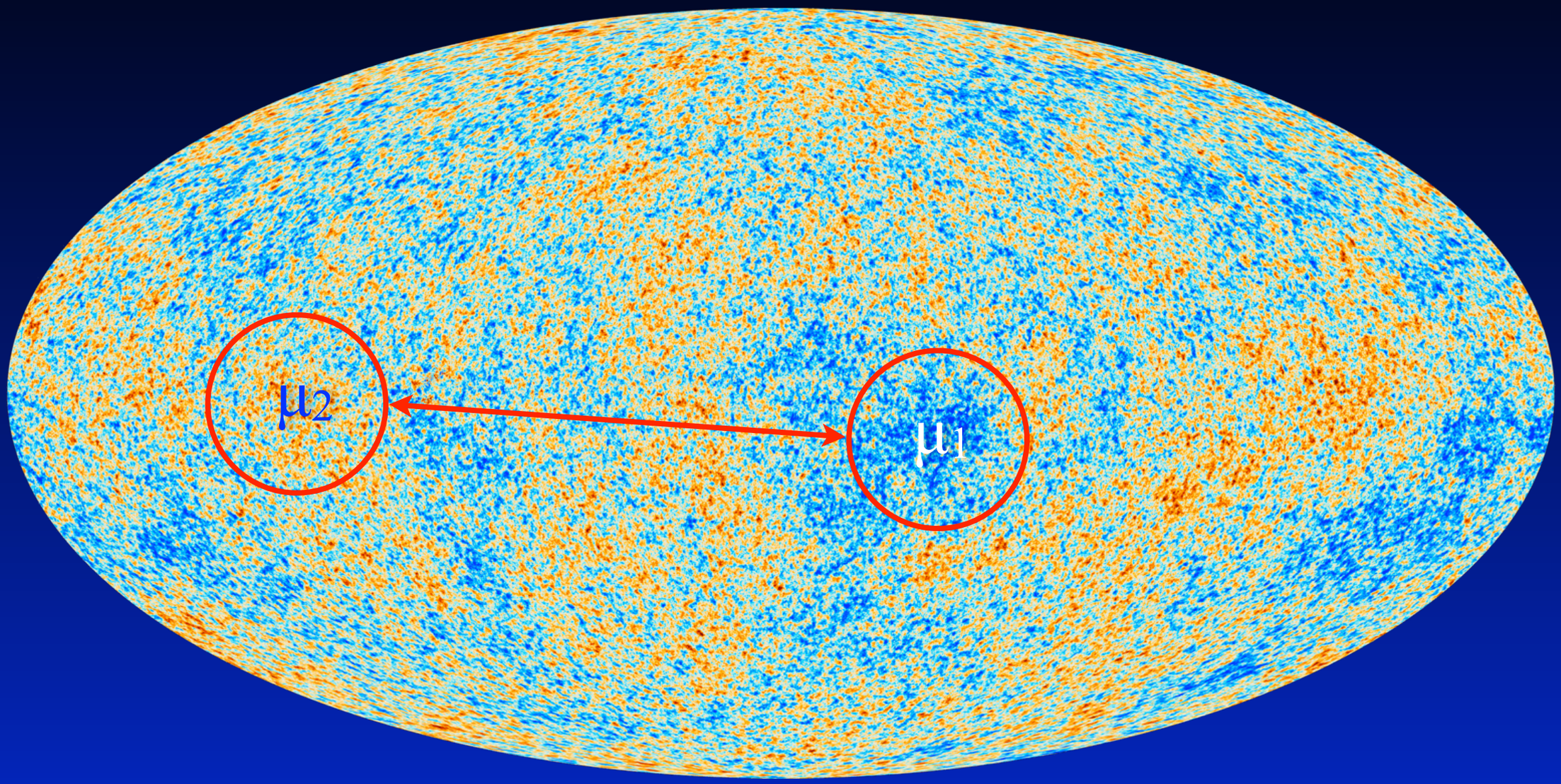
- ‘missing satellite’ problem
- ‘too-big-to-fail’
- Cusp-vs-core problem

⇒ 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

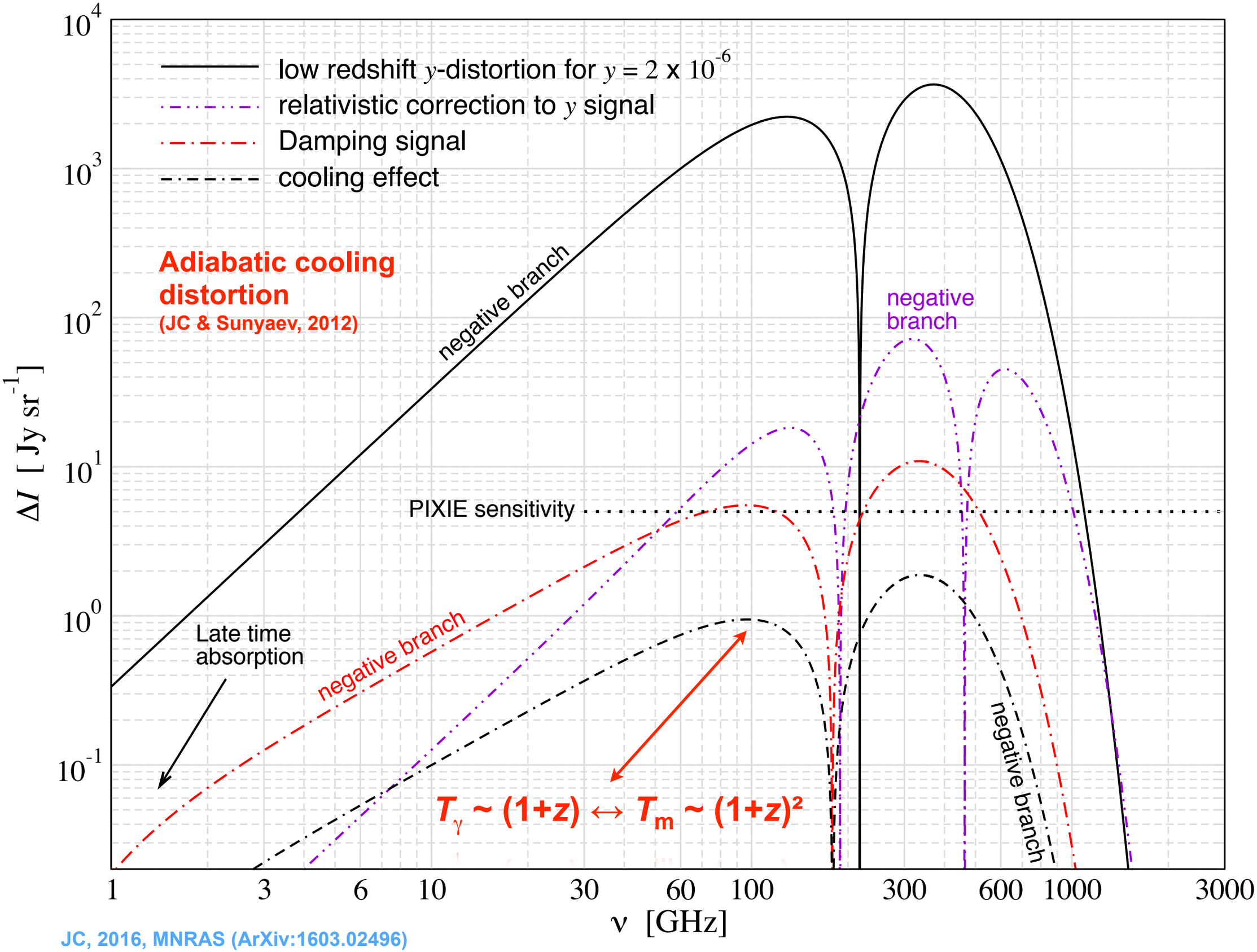
Spatially varying heating and dissipation of acoustic modes for non-Gaussian perturbations



- 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
  → probe of *scale-dependent* non-Gaussianity at k~10 Mpc^{-1} and ~750 Mpc^{-1}

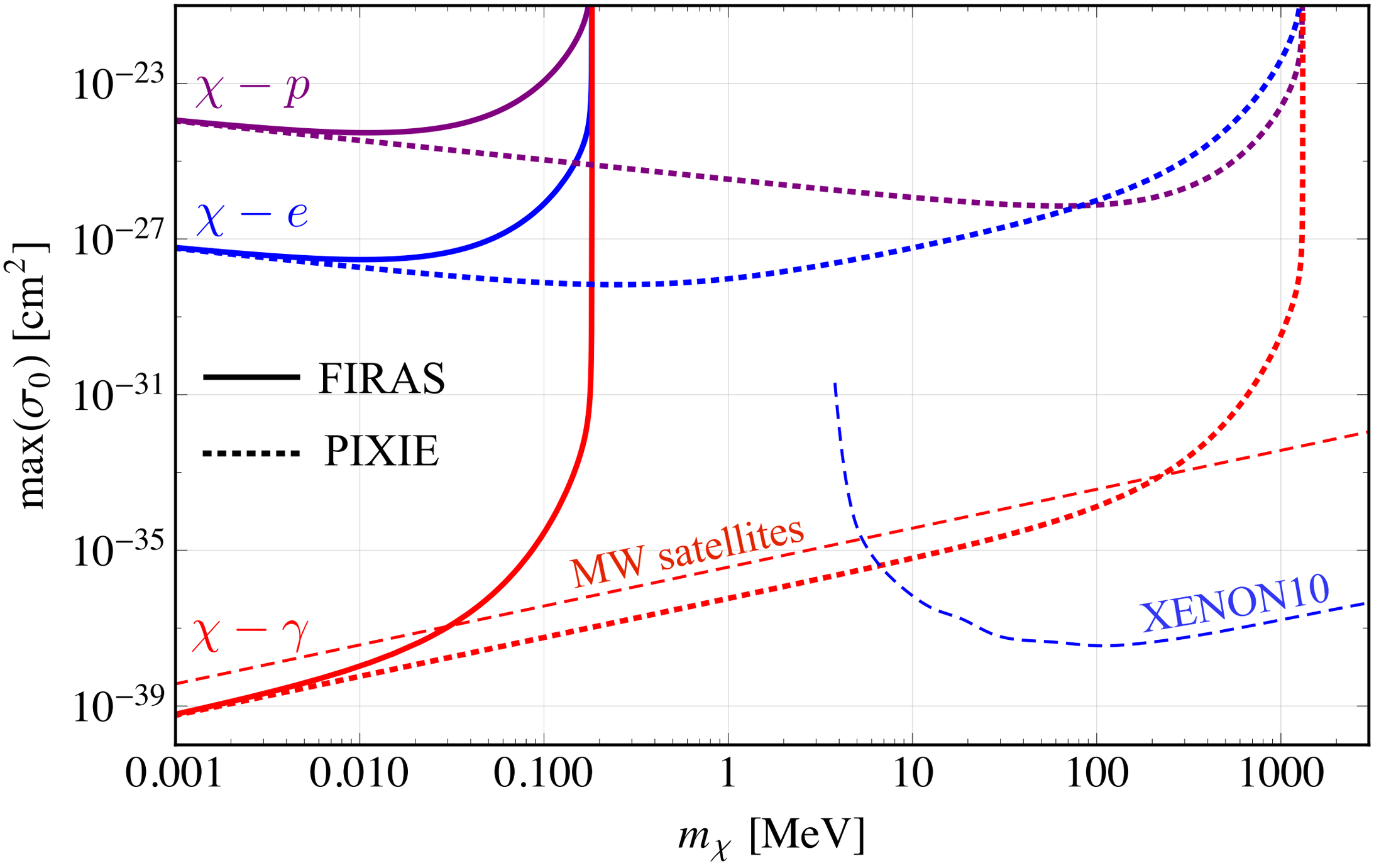
Pajer & Zaldarriaga, 2012; Ganc & Komatsu, 2012; Biagetti et al., 2013; JC et al., 2016

Average CMB spectral distortions



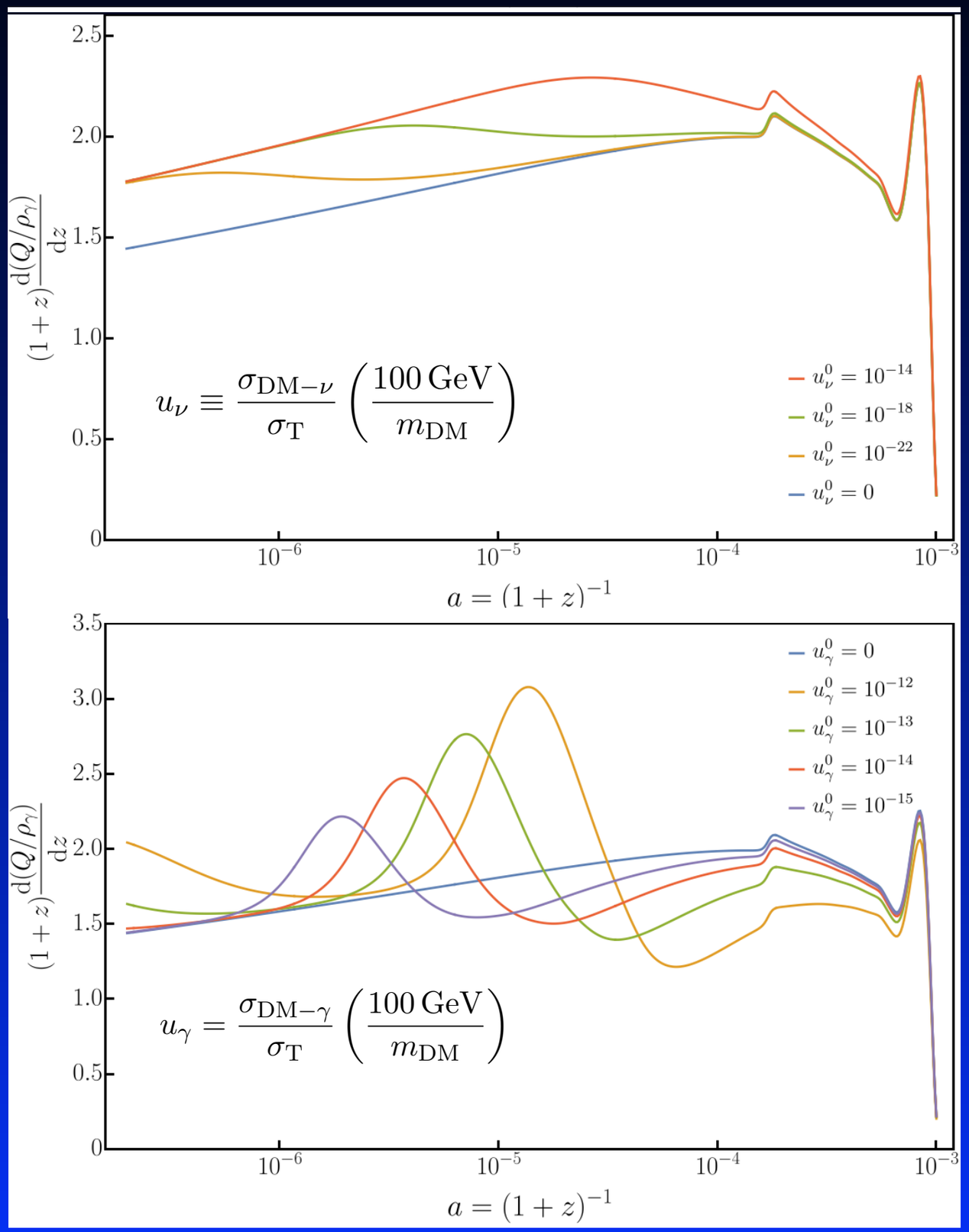
JC, 2016, MNRAS (ArXiv:1603.02496)

Distortion constraints on DM interactions through adiabatic cooling effect



Ali-Haimoud, JC & Kamionkowski, 2015

Constrain interactions of DM with neutrinos/photons

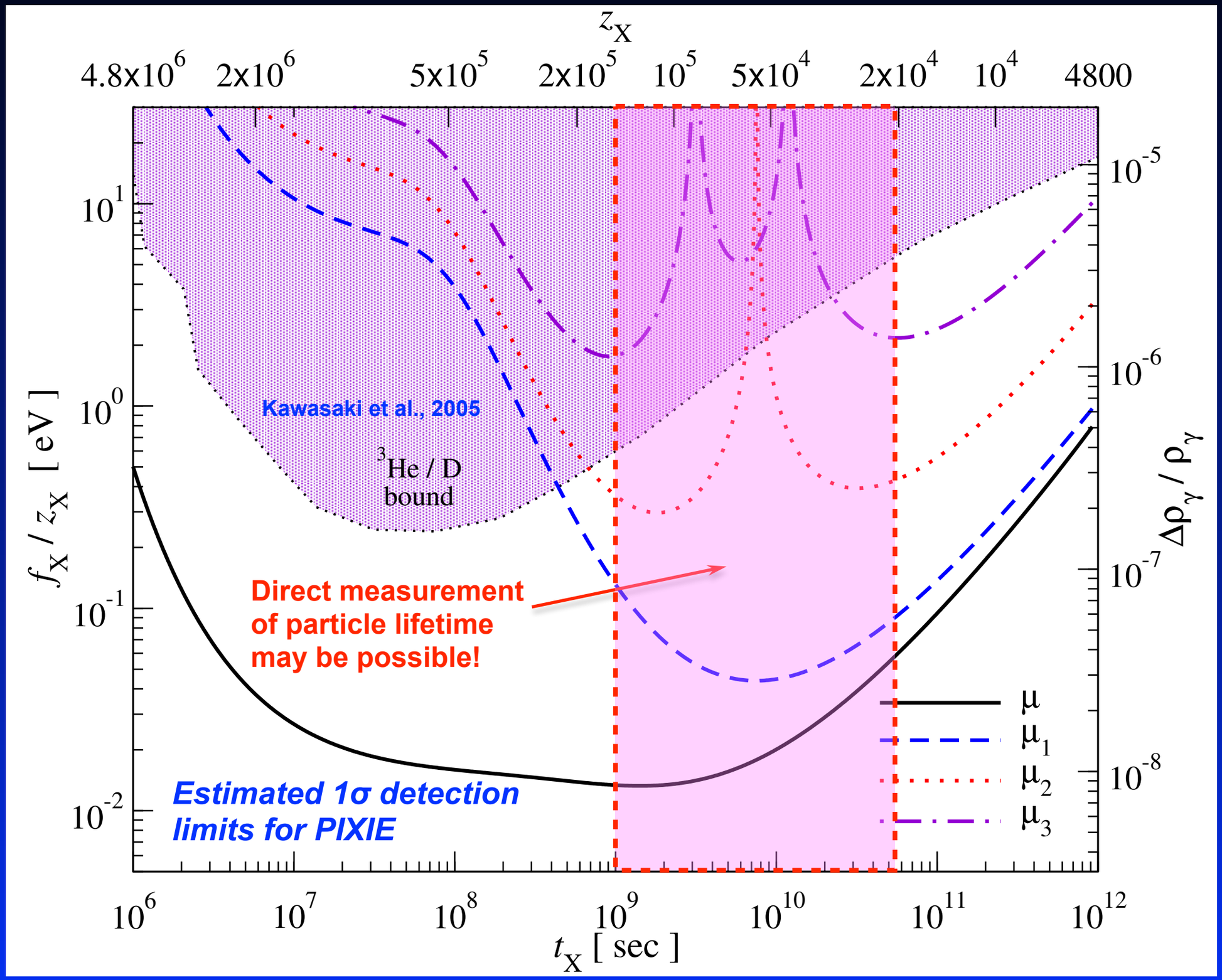


- Dissipation is increased
- Enhances μ distortion
- Interesting complementary probe

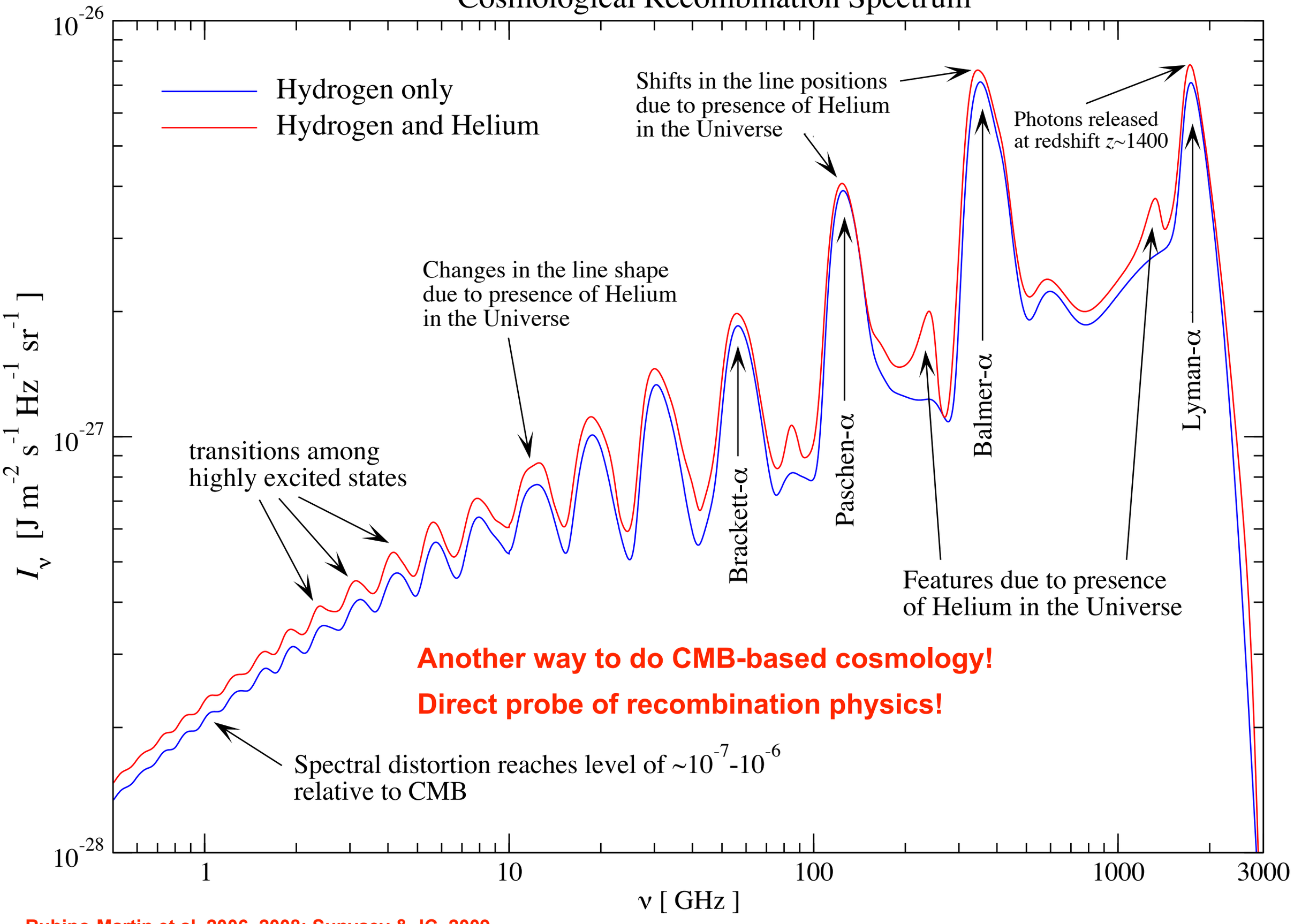
- Early-time dissipation enhanced → larger μ
- Later, modes already gone, so less heating
- Dissipation scale larger early on

Diacoumis & Wong, 2017, 1707.07050

Distortions could shed light on decaying (DM) particles!

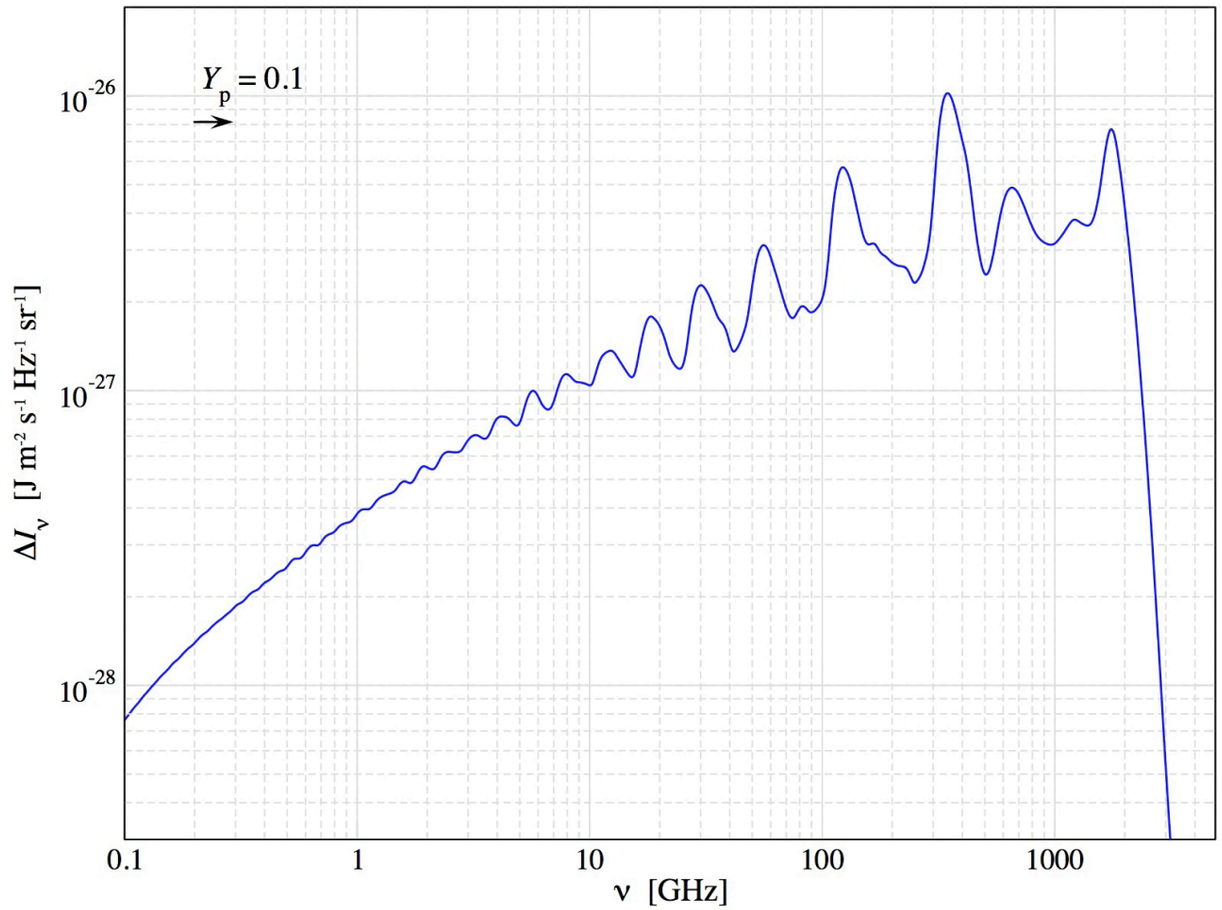


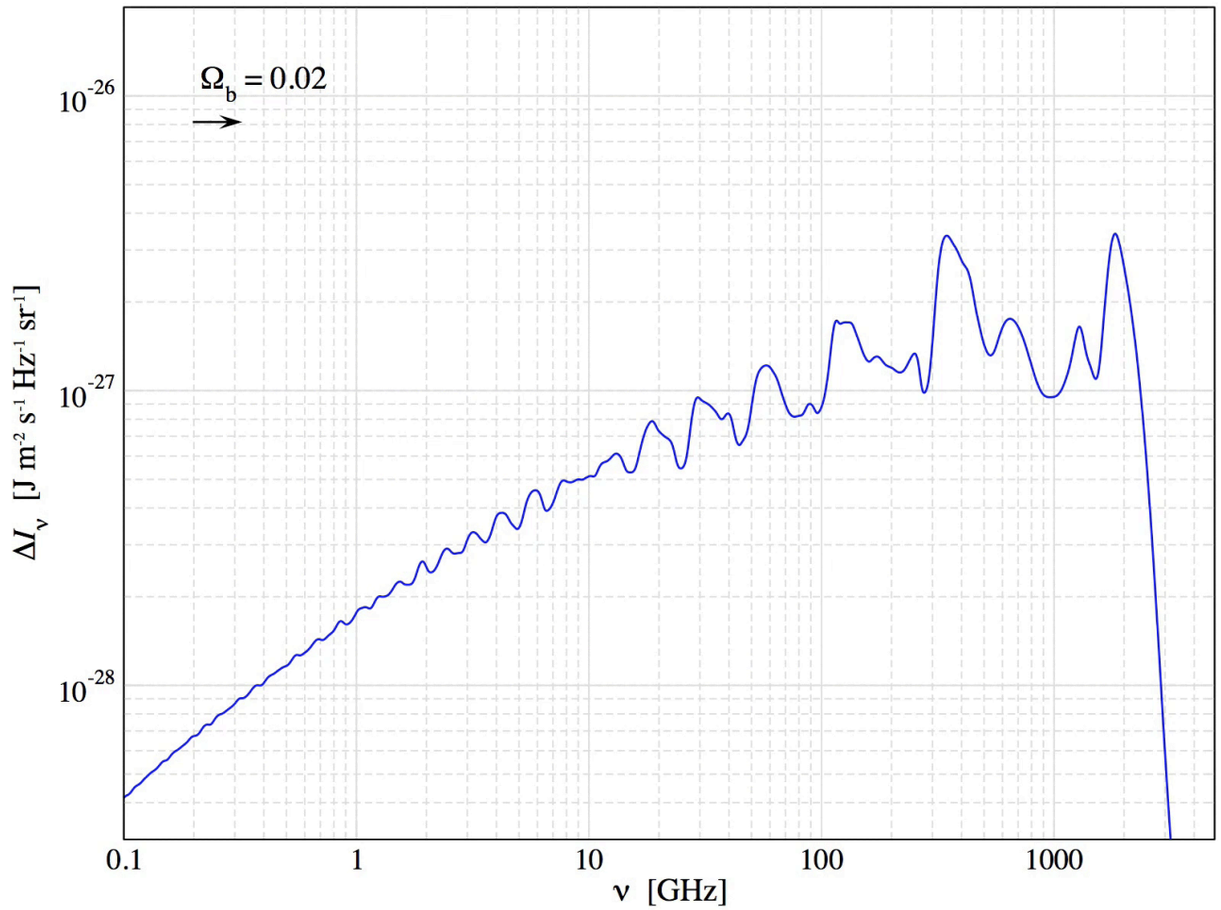
JC & Jeong, 2013



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.)

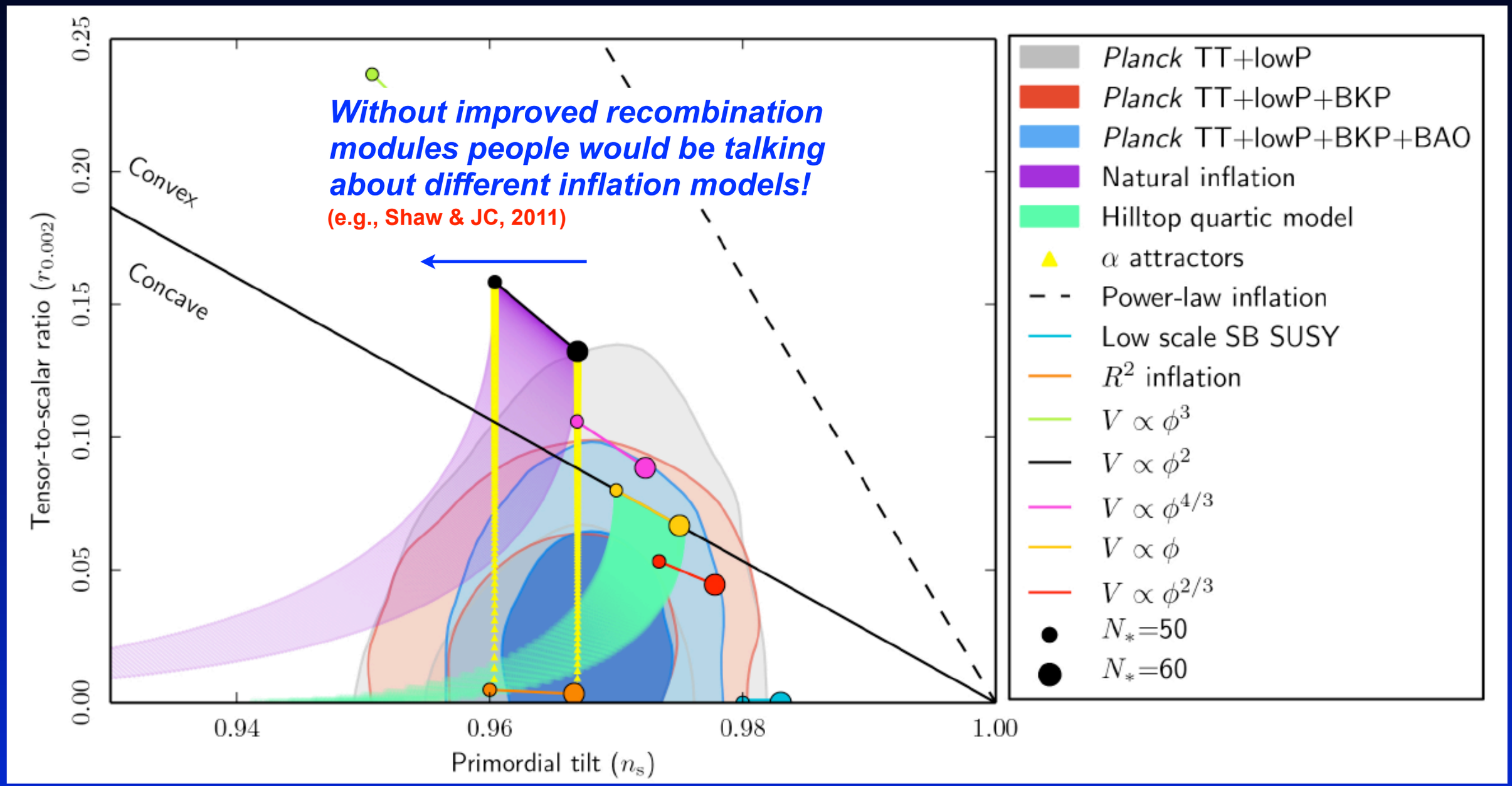
CosmoSpec will be available here:

www.Chluba.de/CosmoSpec

JC & Ali-Haimoud, arXiv:1510.03877

** Cosmological Recombination Radiation*

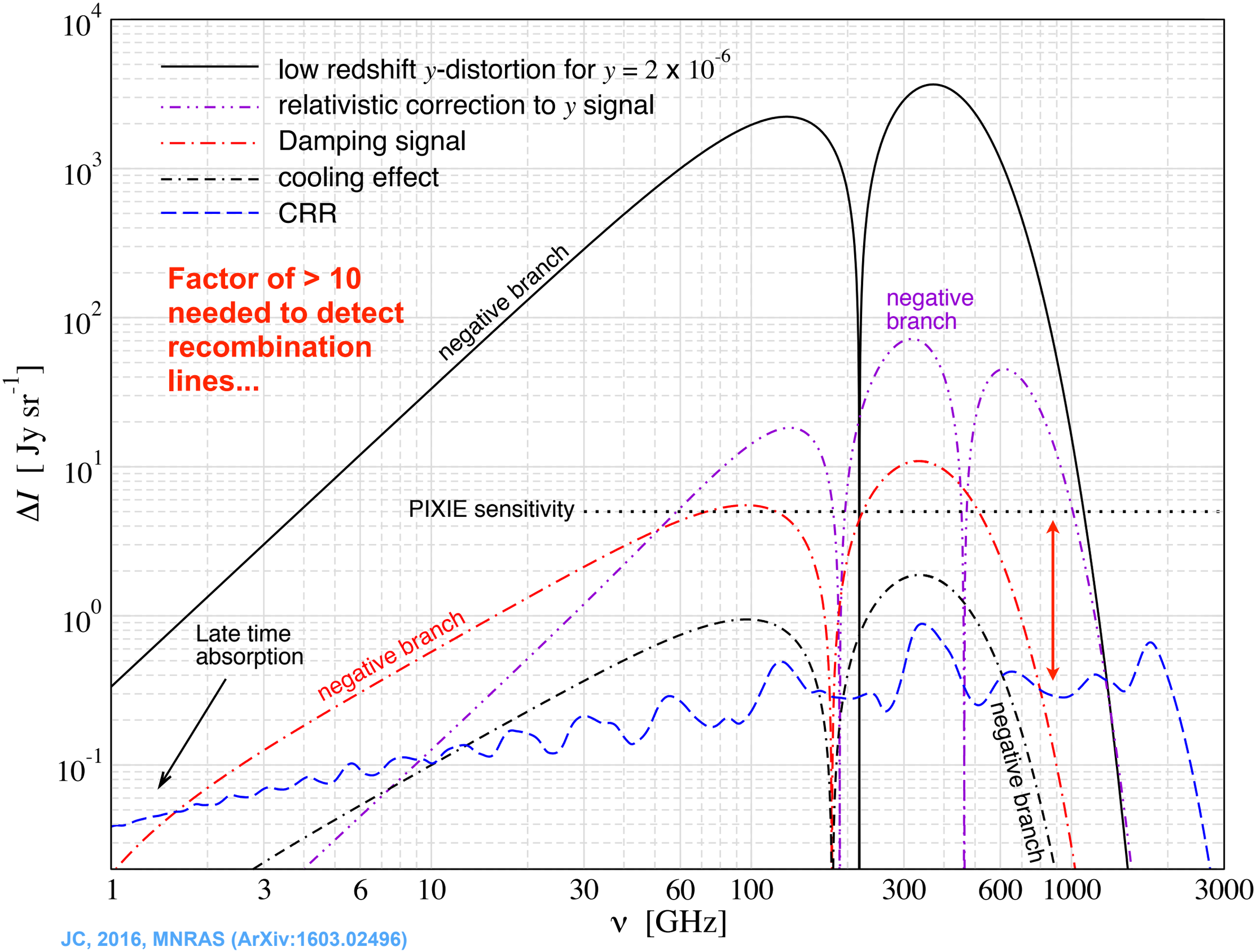
Importance of recombination for inflation constraints



Planck Collaboration, 2015, paper XX

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

Average CMB spectral distortions

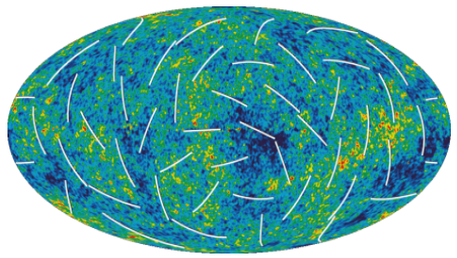


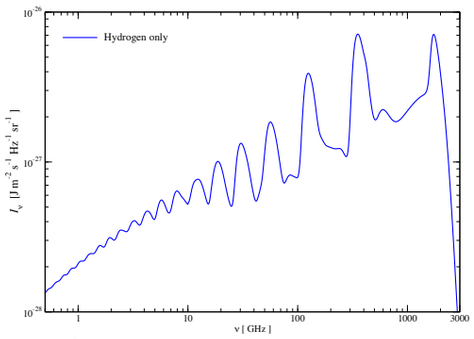
JC, 2016, MNRAS (ArXiv:1603.02496)

Cosmological Time in Years

790,000 370,000 260,000 130,000 18,000

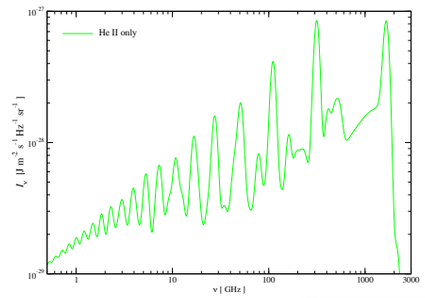
CMB-Anisotropies





Hydrogen Lines

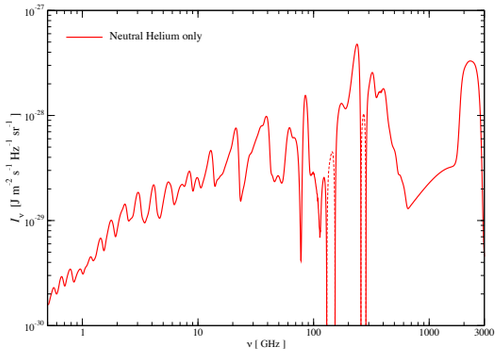
Singly ionized Helium Lines



Free Electron Fraction

$N_e/[N_p+N_H]$

Plasma fully ionized



Neutral Helium Lines

Visibility Function

Plasma neutral

H I-Lines

He I-Lines

He II-Lines

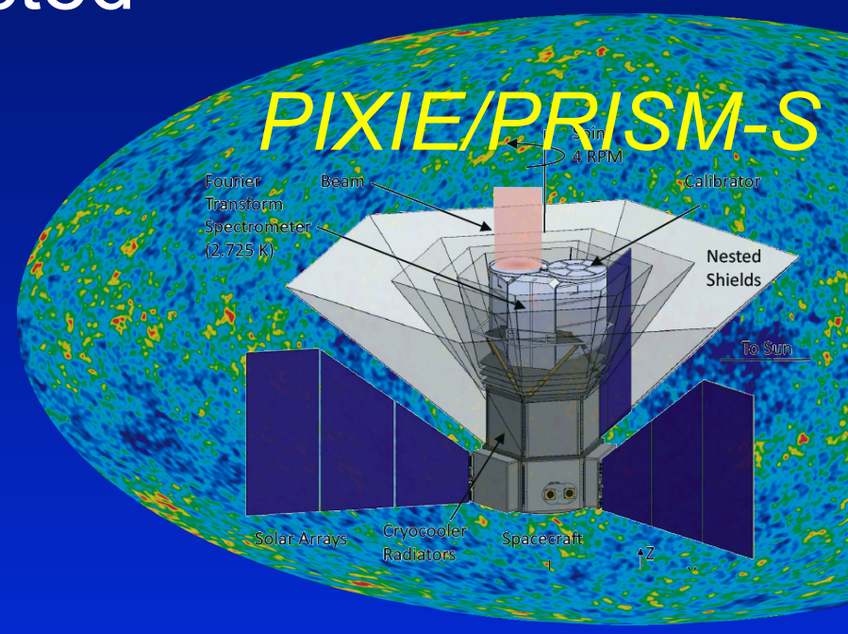
1.4 1.2 1 0.8 0.6 0.4 0.2 0

700 1100 2000 3000 4000 6000 8000

Redshift z

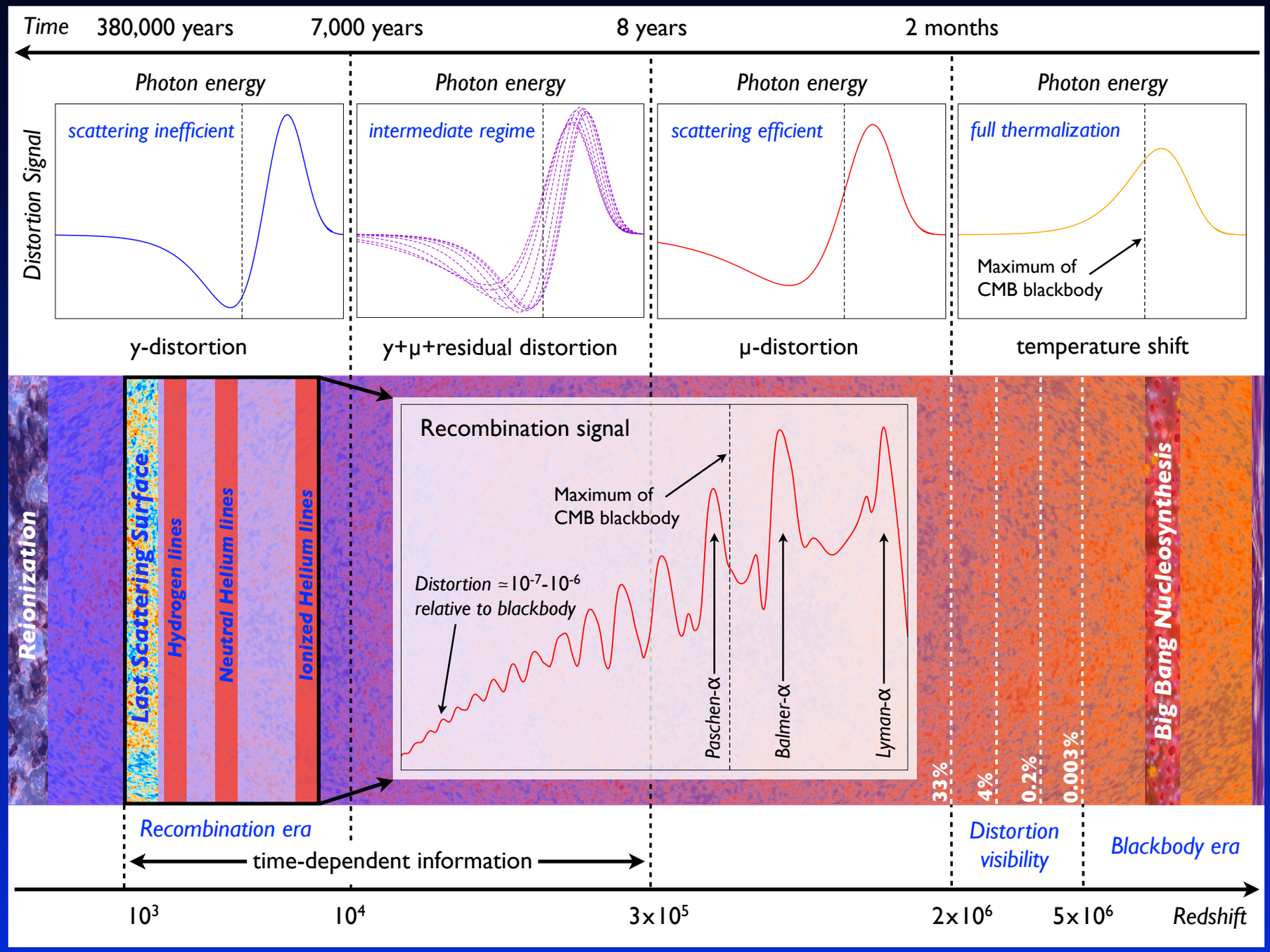
What can CMB spectral distortions add?

- 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