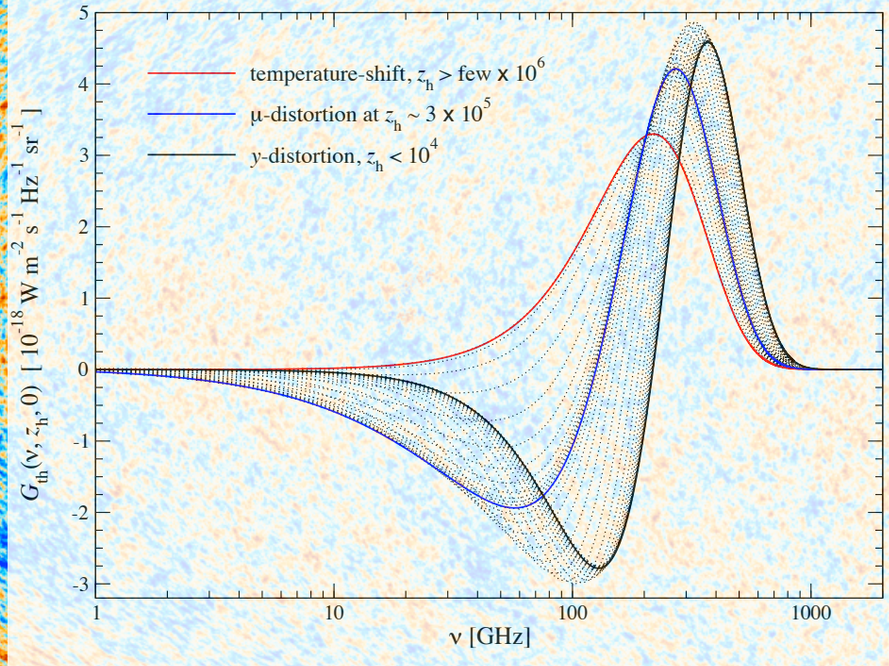
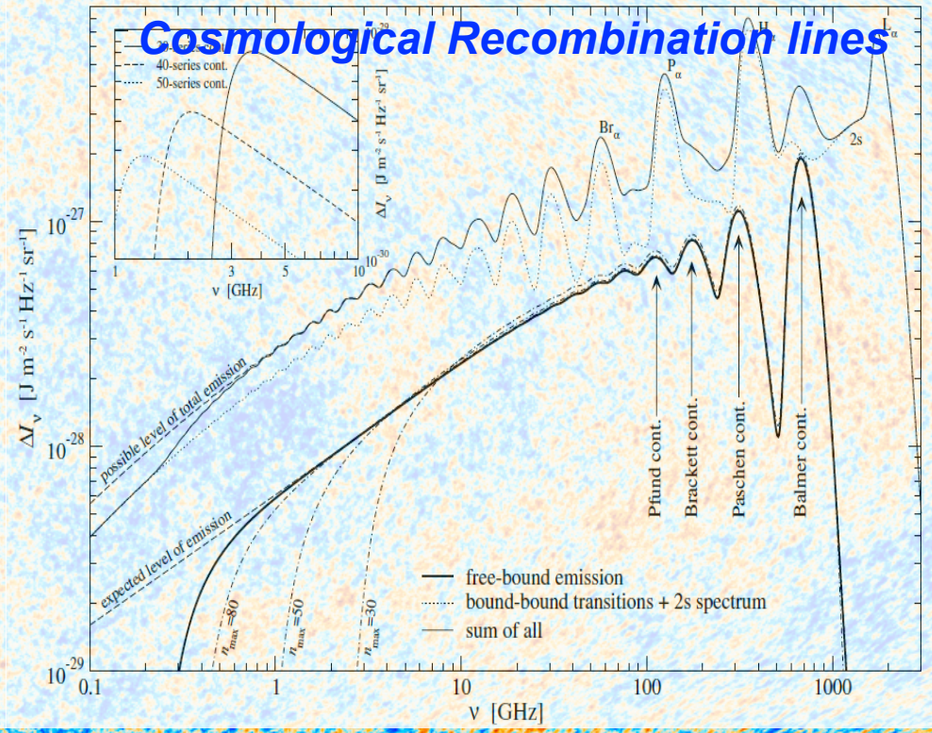
Absolute spectrometer or not?

Primordial Distortions



Cosmological Recombination lines

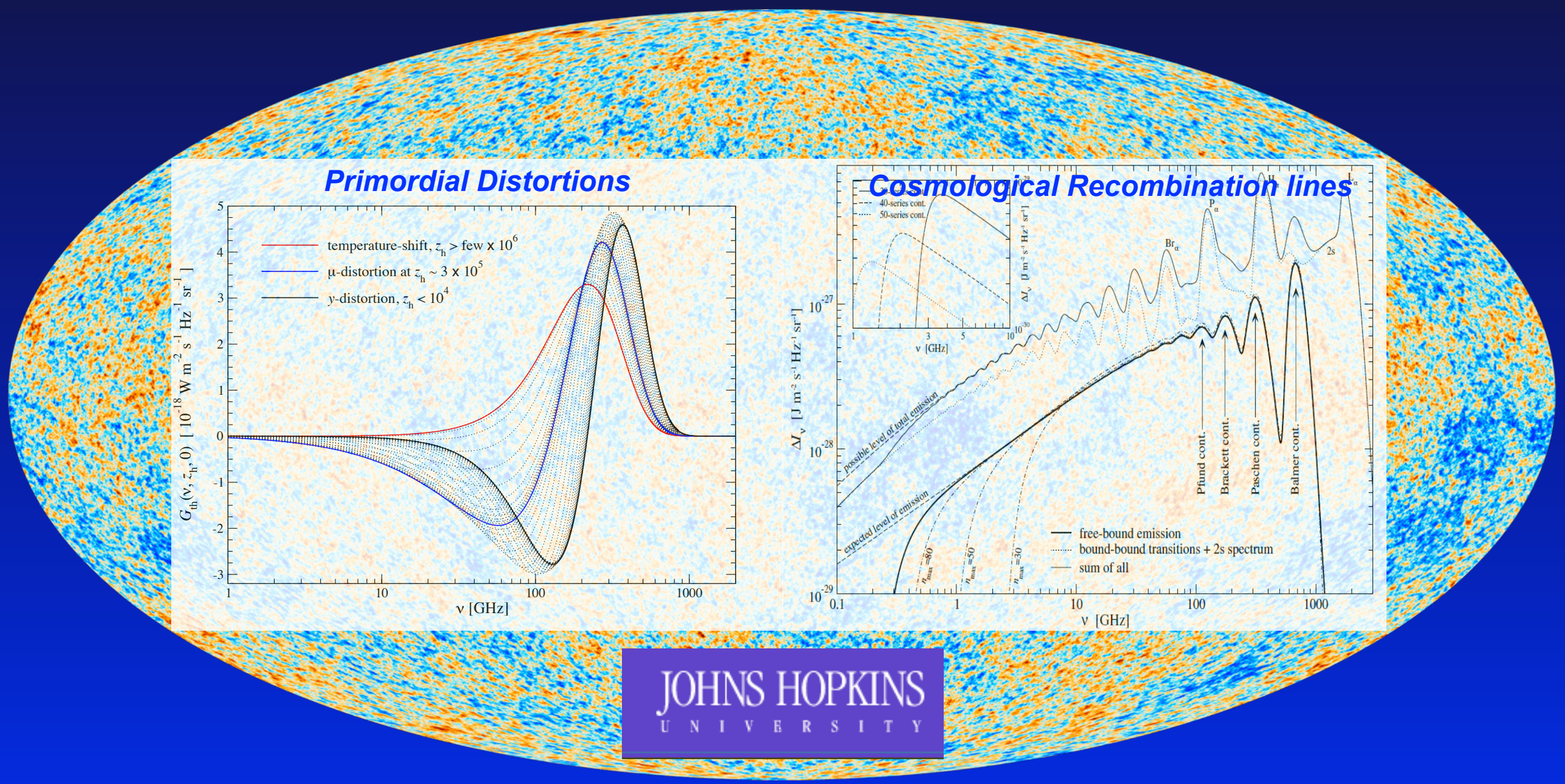


JOHNS HOPKINS UNIVERSITY

Jens Chluba

Paris, France, Feb 11th, 2014

Why we should have a spectrometer on the next CMB space mission



Primordial Distortions

Cosmological Recombination lines

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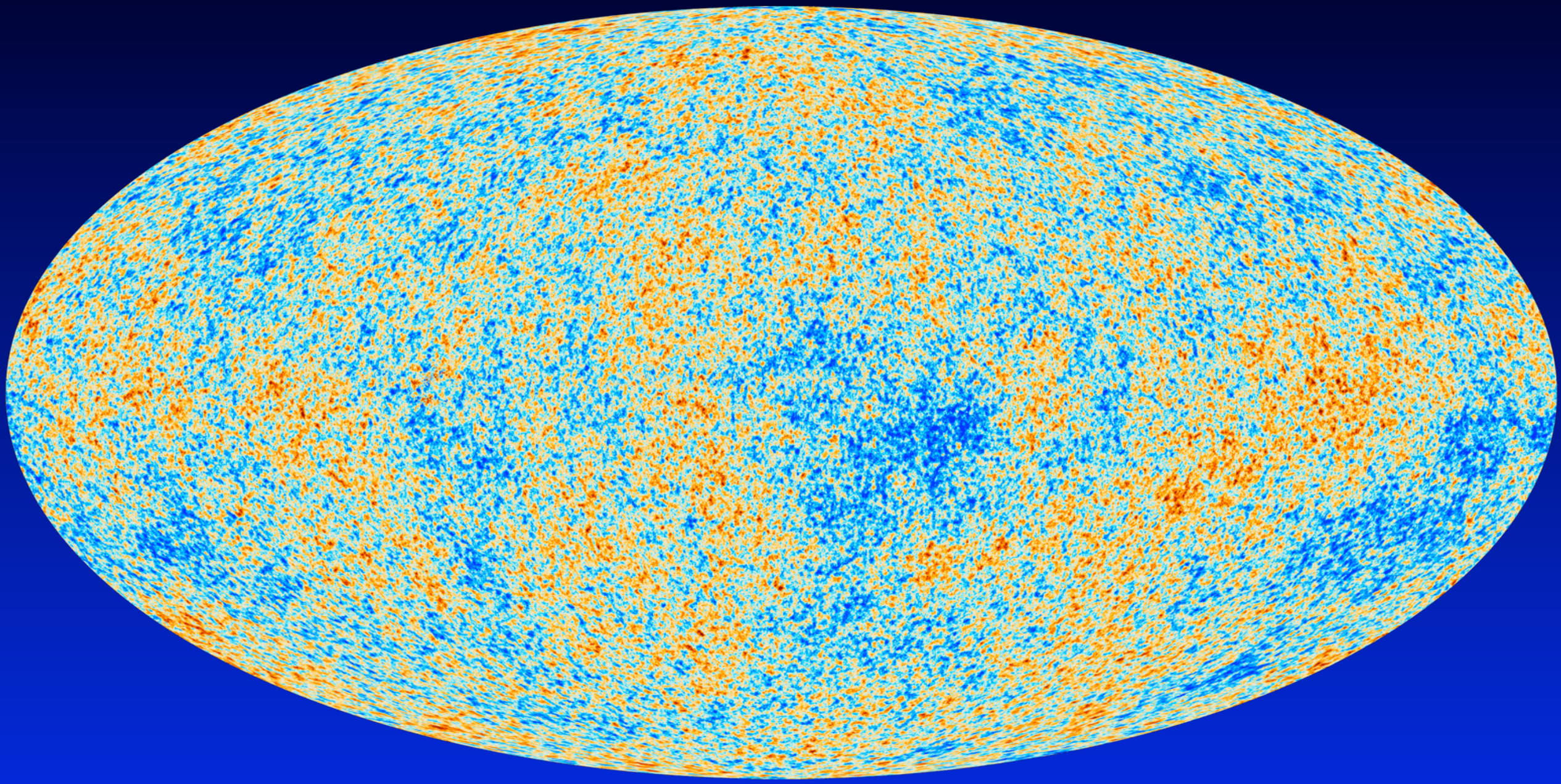
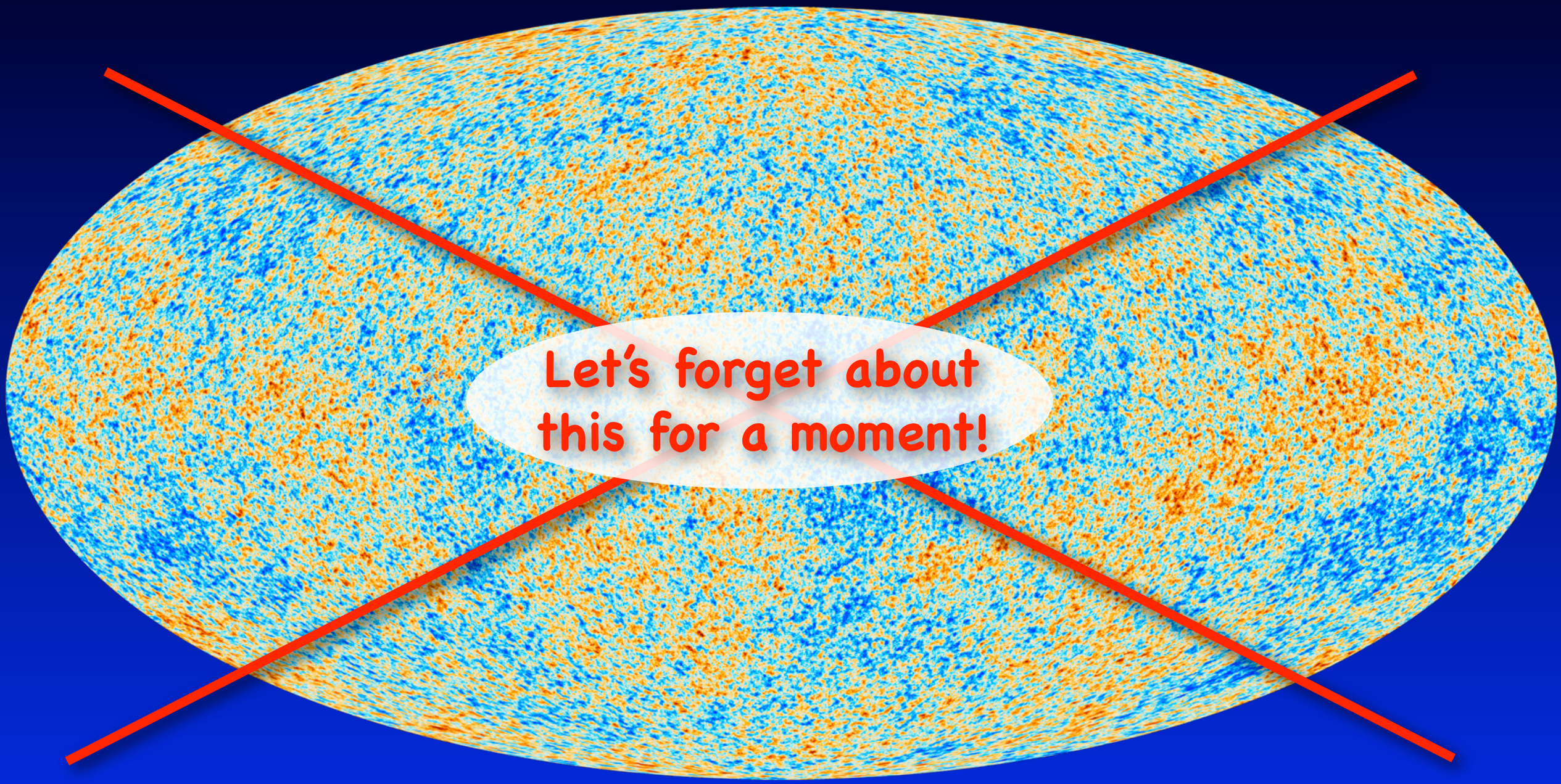
Cosmic Microwave Background Anisotropies



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

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

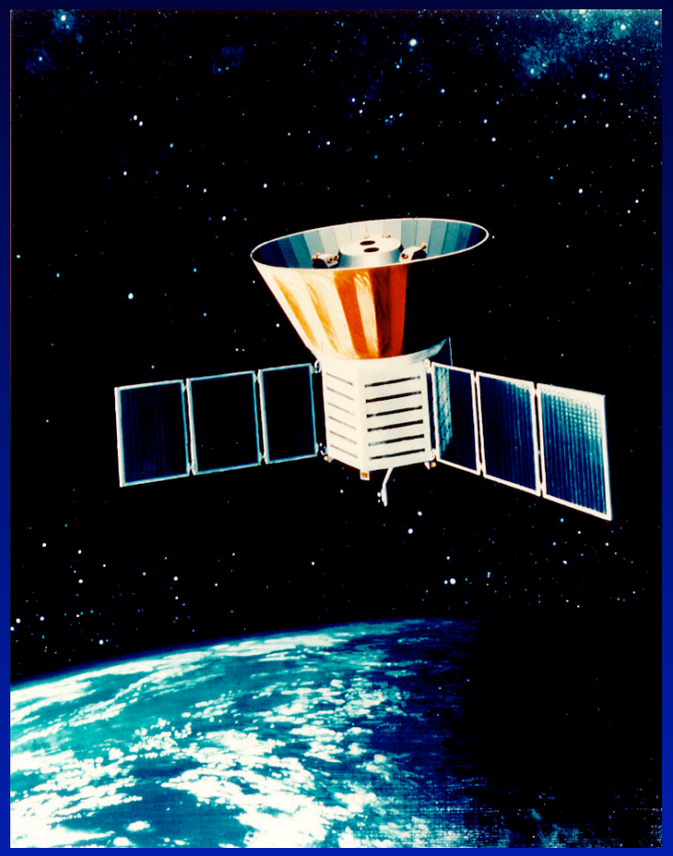
Absolute measurement required!

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

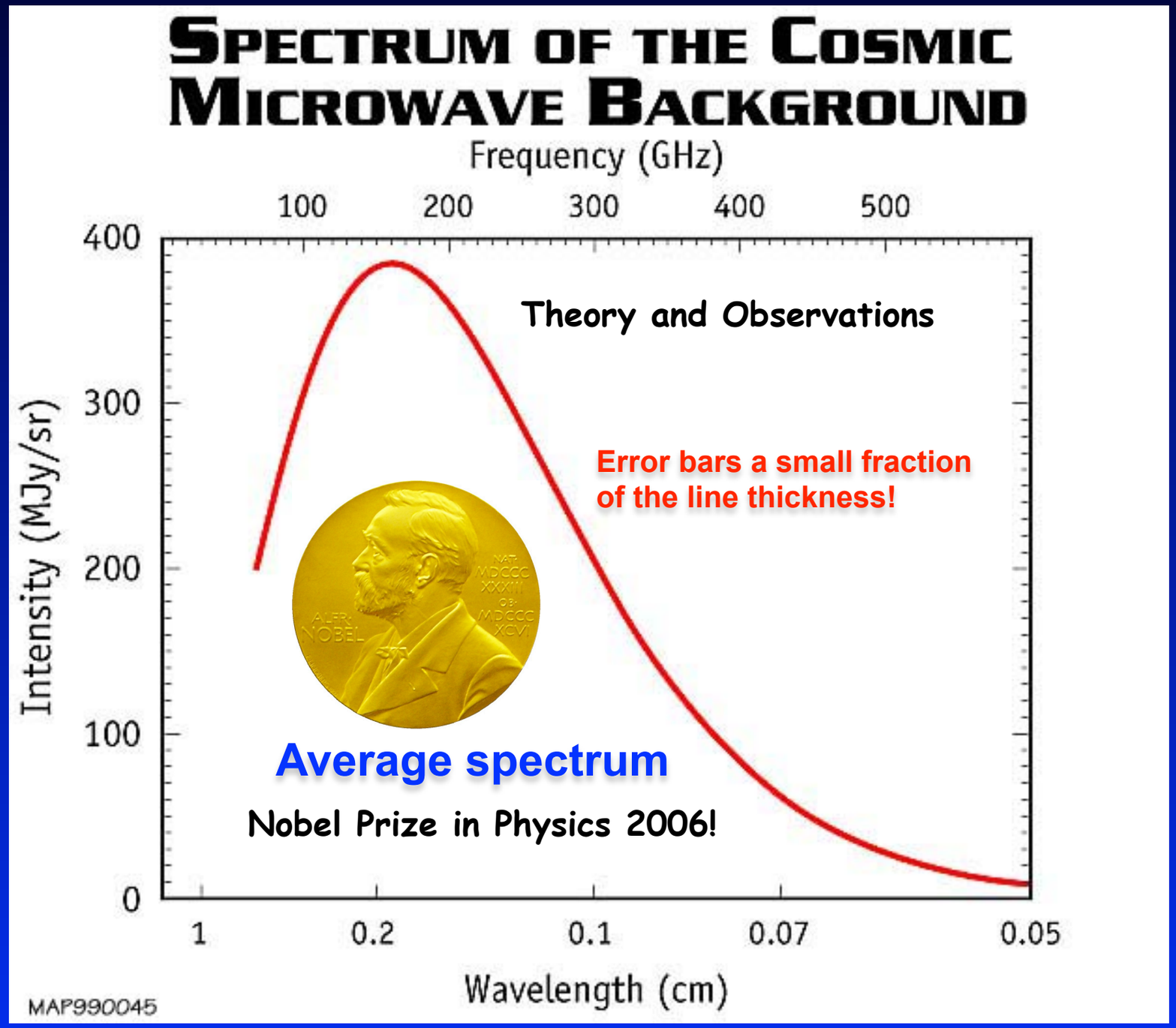
COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)



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

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

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



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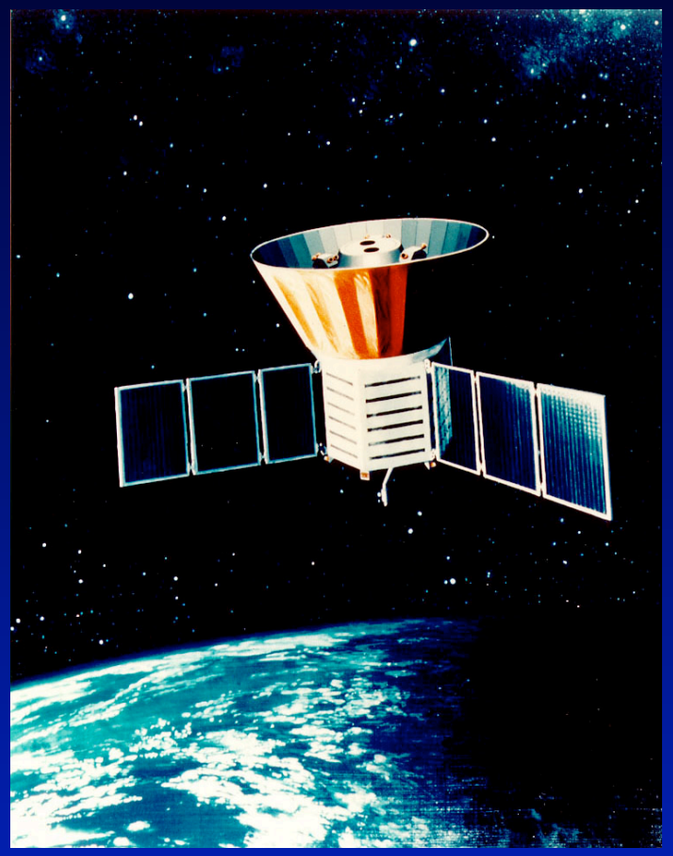

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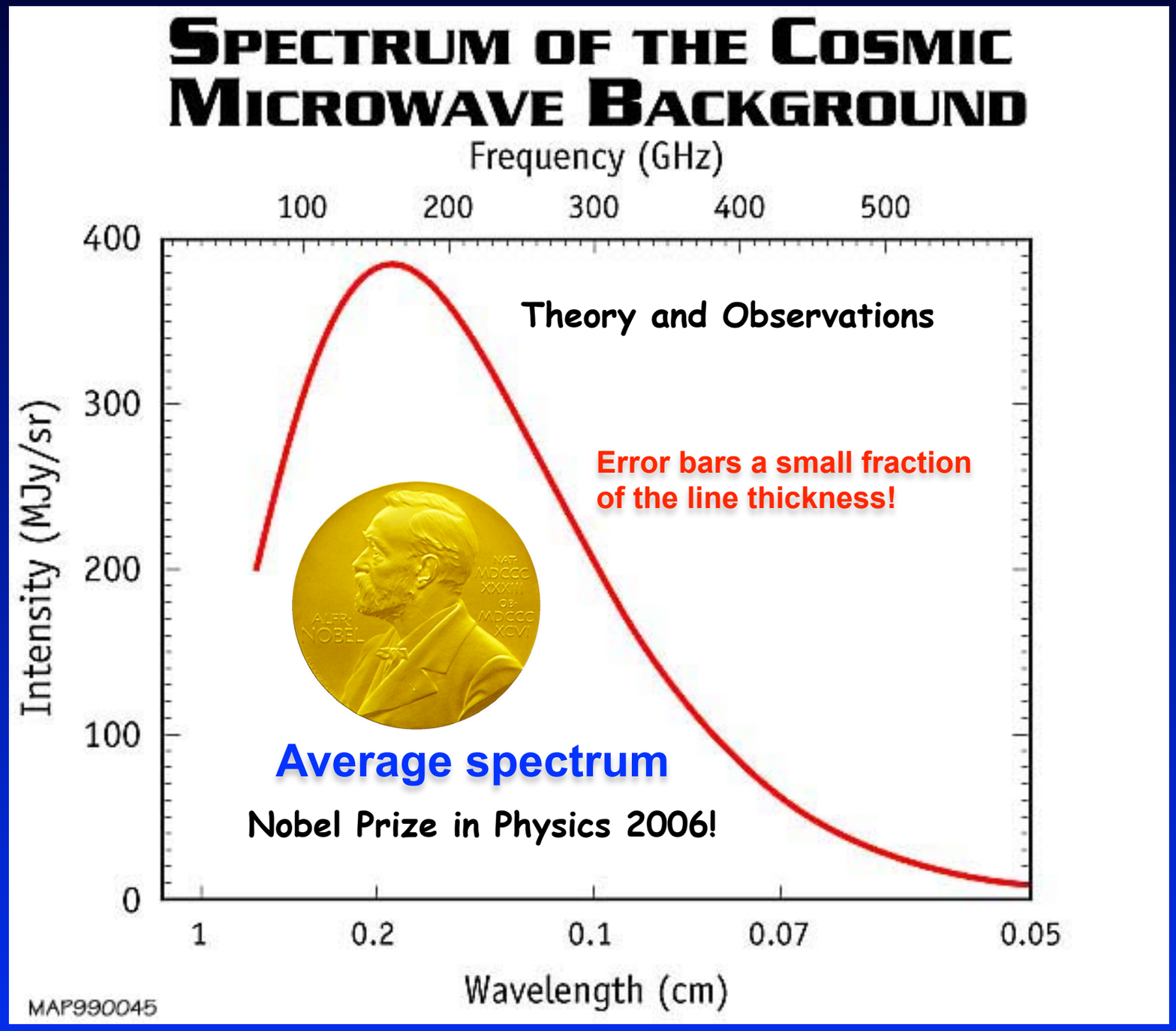


Only very small distortions of CMB spectrum are still allowed!

No primordial distortion found so far!? Why are we at all thinking about this then?

Physical mechanisms that lead to spectral distortions

- *Cooling by adiabatically expanding ordinary matter*: $T_\gamma \sim (1+z) \leftrightarrow T_m \sim (1+z)^2$
  (JC, 2005; JC & Sunyaev 2011; Khatri, Sunyaev & JC, 2011)
  - continuous *cooling* of photons until redshift $z \sim 150$ via Compton scattering
  - due to huge heat capacity of photon field distortion very small ($\Delta\rho/\rho \sim 10^{-10}$-$10^{-9}$)

Standard sources of distortions

- Heating by *decaying* or *annihilating* relic particles
  - How is energy transferred to the medium?
  - lifetimes, decay channels, neutrino fraction, (at low redshifts: environments), ...
- *Evaporation of primordial black holes & superconducting strings*
  (Carr et al. 2010; Ostriker & Thompson, 1987; Tashiro et al. 2012)
  - rather fast, quasi-instantaneous but also extended energy release
- *Dissipation of primordial acoustic modes & magnetic fields*
  (Sunyaev & Zeldovich, 1970; Daly 1991; Hu et al. 1994; Jedamzik et al. 2000)
- *Cosmological recombination*

pre-recombination epoch

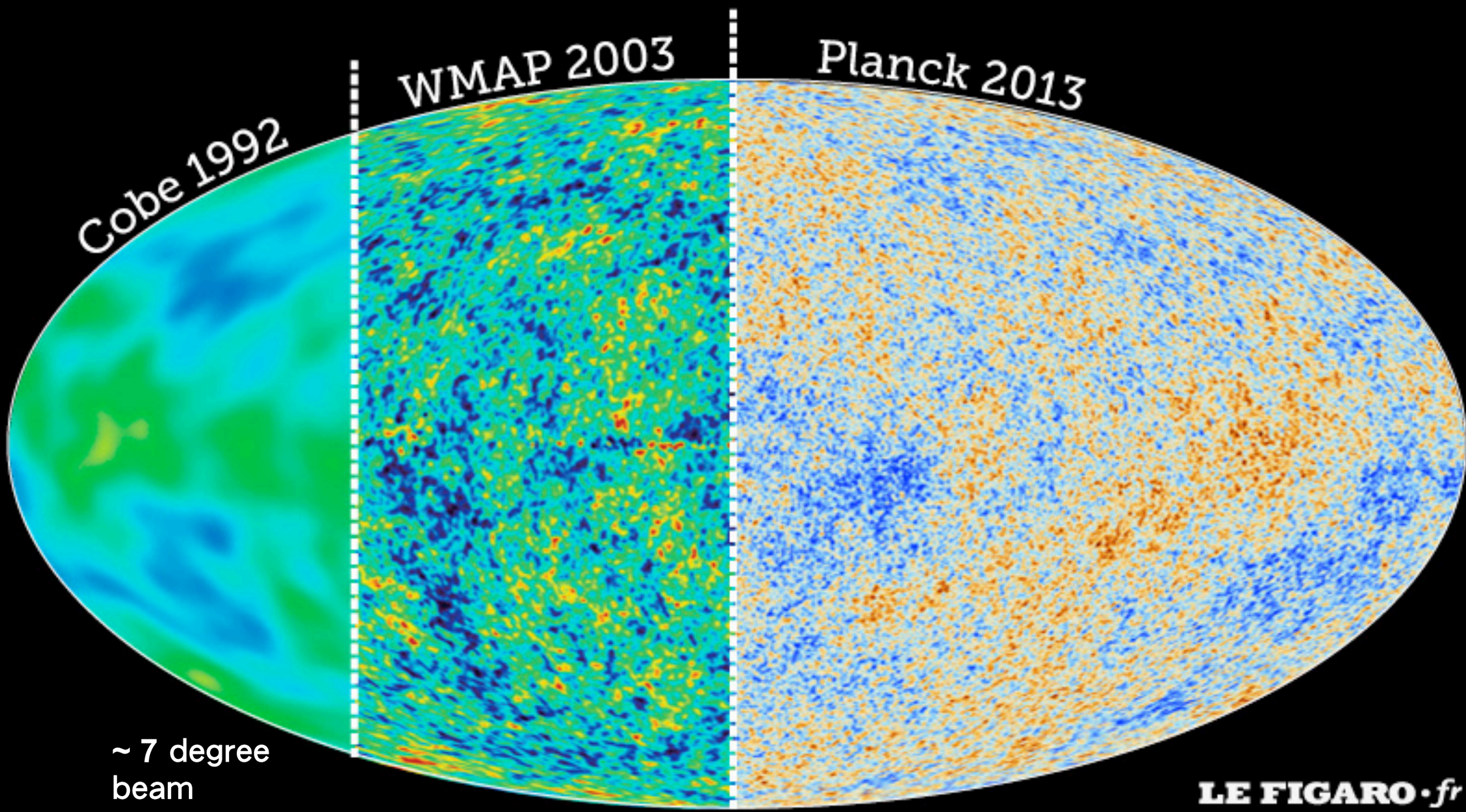
„high“ redshifts

„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 (Heating of medium by X-Rays, Cosmic Rays, etc)

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



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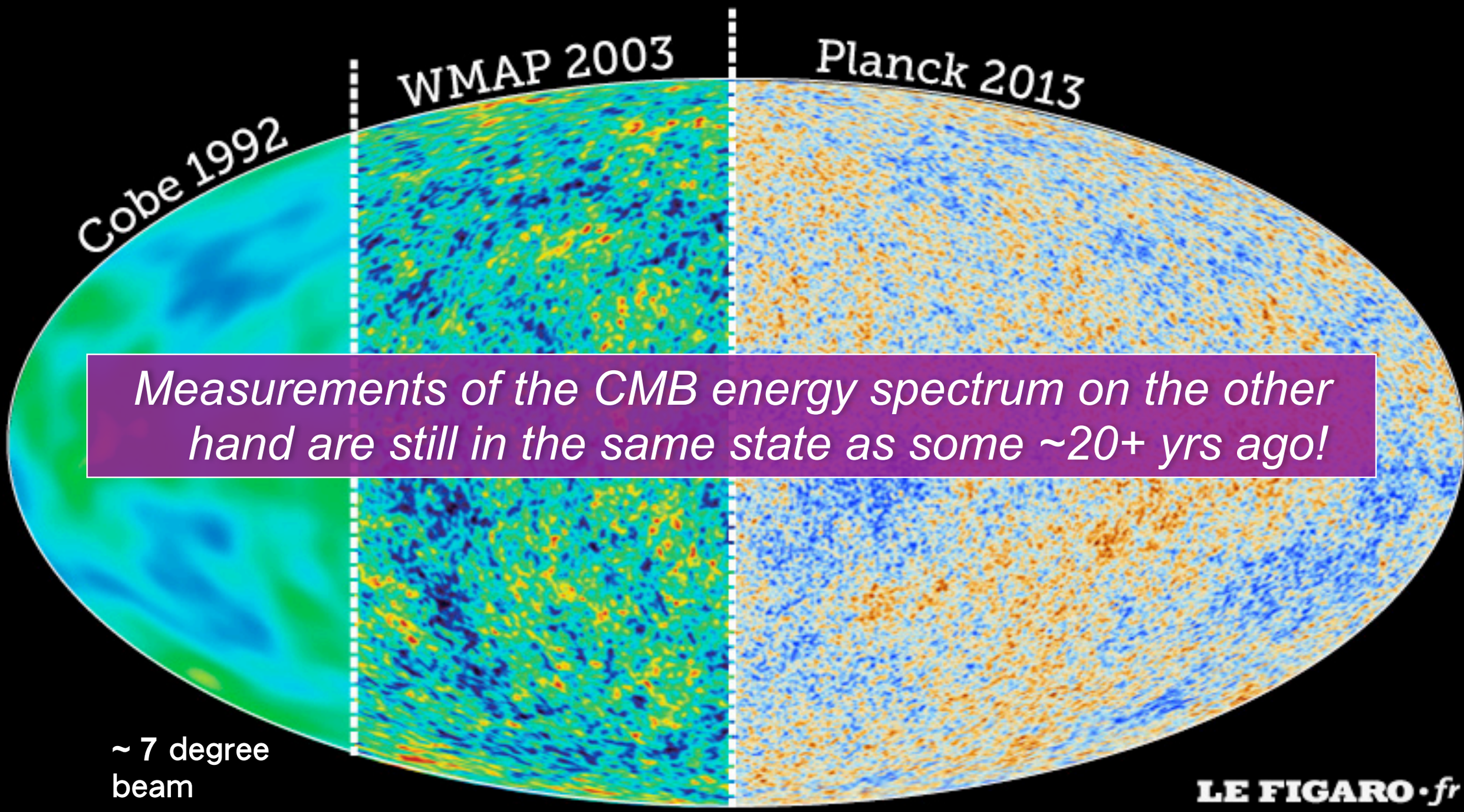
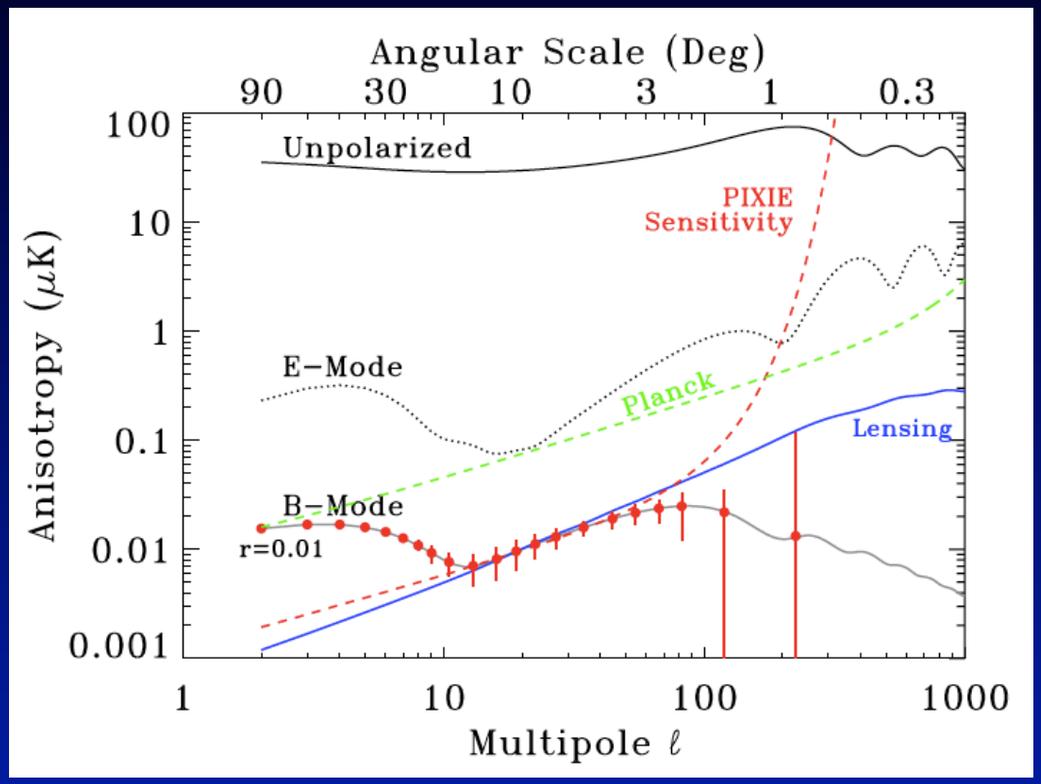
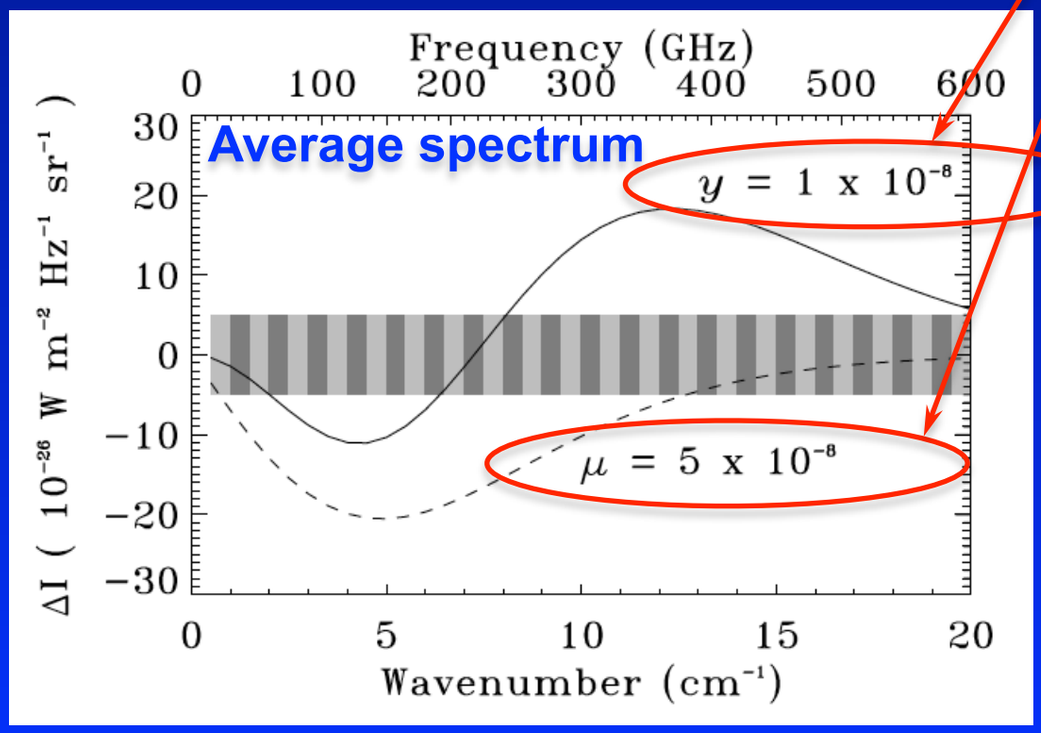


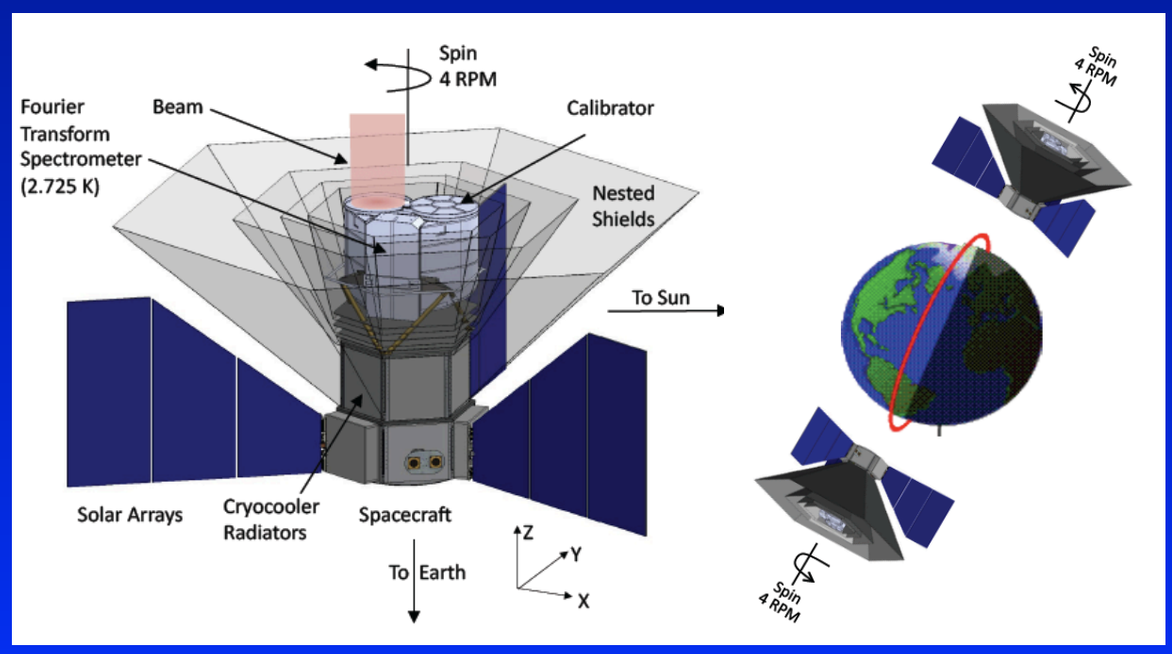
Measurements of the CMB energy spectrum on the other hand are still in the same state as some ~20+ yrs ago!

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$)



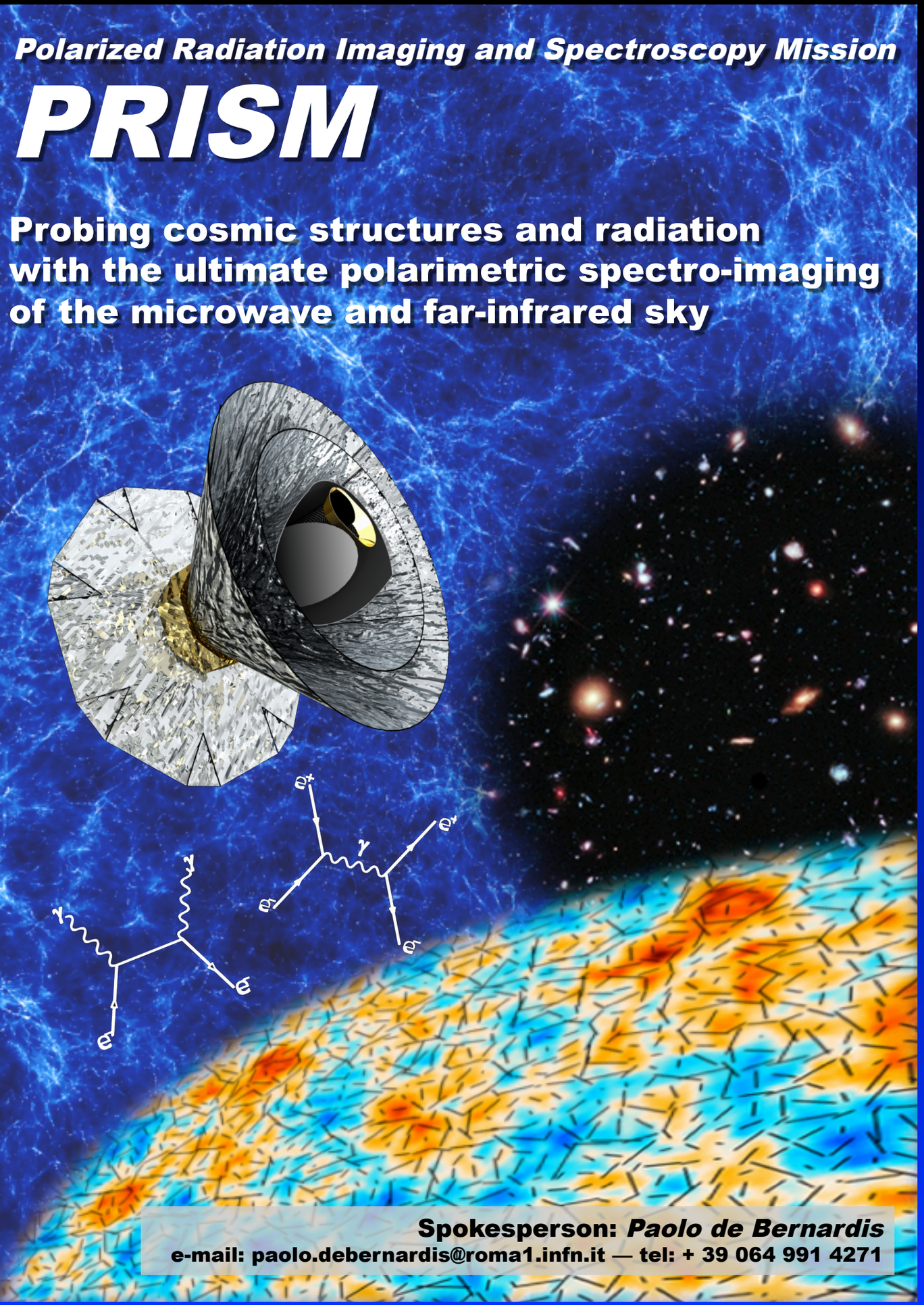


Kogut et al, JCAP, 2011, arXiv:1105.2044

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



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

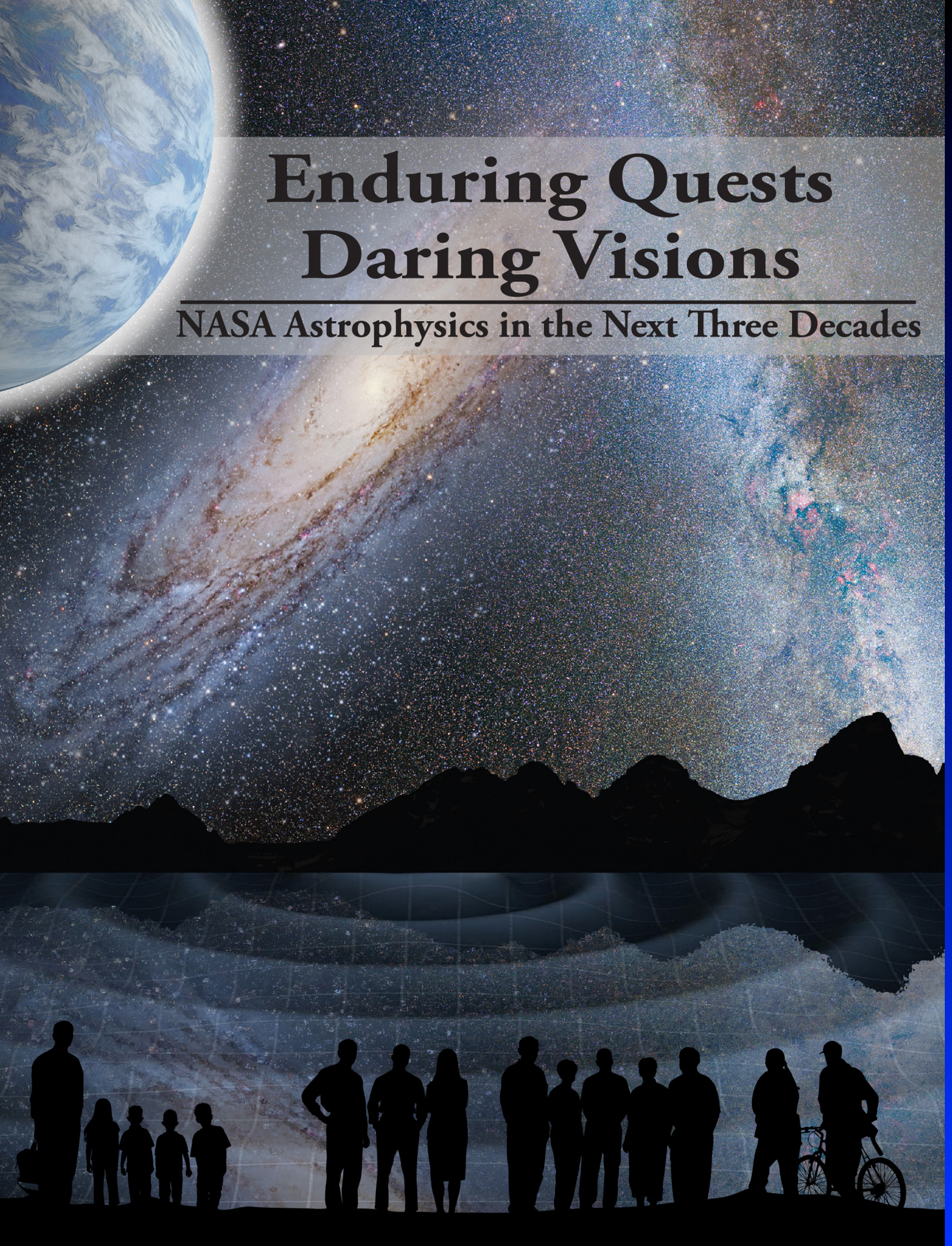
Instruments:

- 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 information at:
http://www.prism-mission.org/

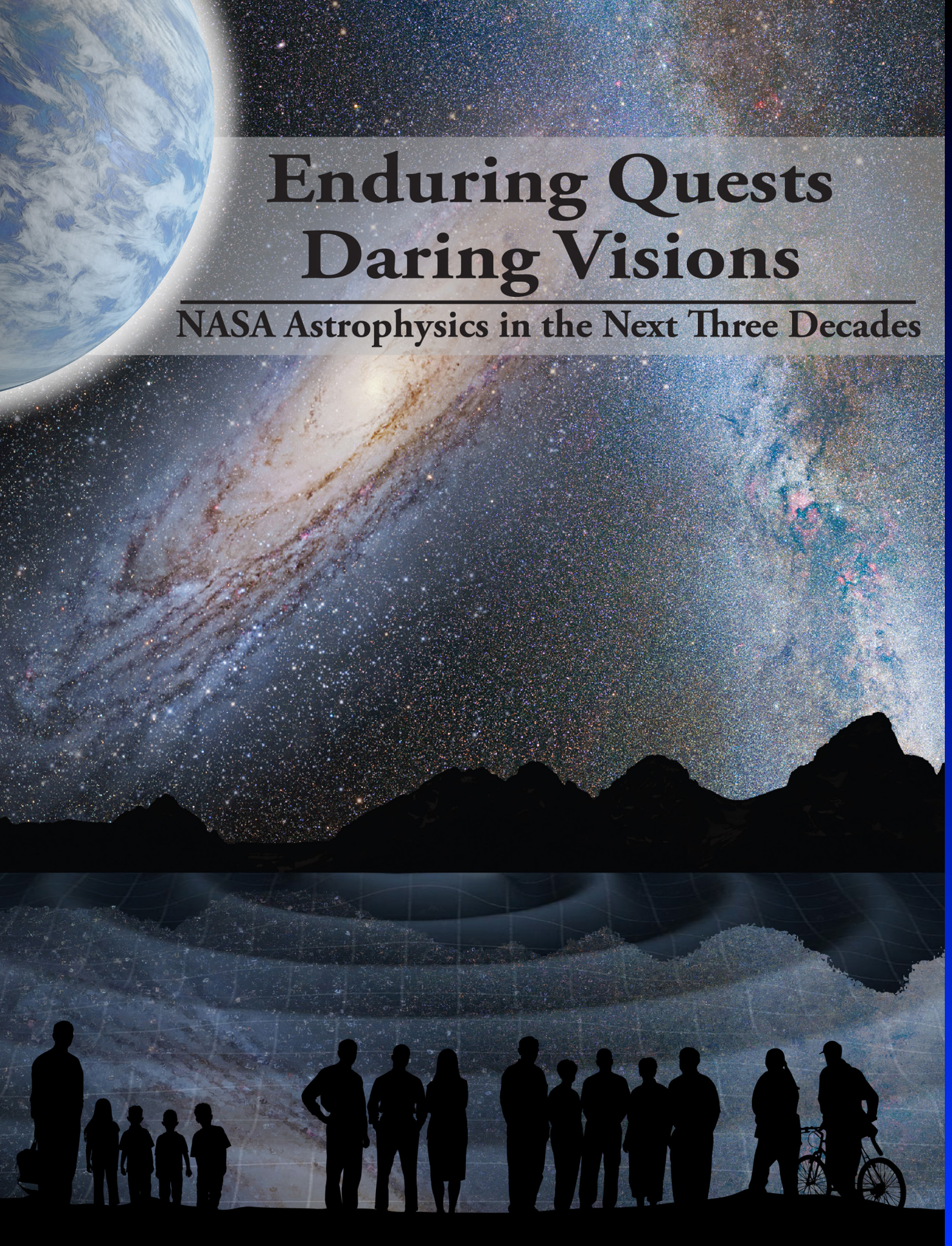


NASA 30-yr Roadmap Study

(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."



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CMB spectral distortions will be measured at some point and one should probably make sure to get a piece of the cake!

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
1 second
100 seconds

Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
1 year

Dark ages
Ordinary matter particles fall into the structures created by dark matter
100 years
380 000 years
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

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pre-

post-recombination epoch

Discovery space!

CMB distortions probe the thermal history of the Universe at $z <$ few x 10^6

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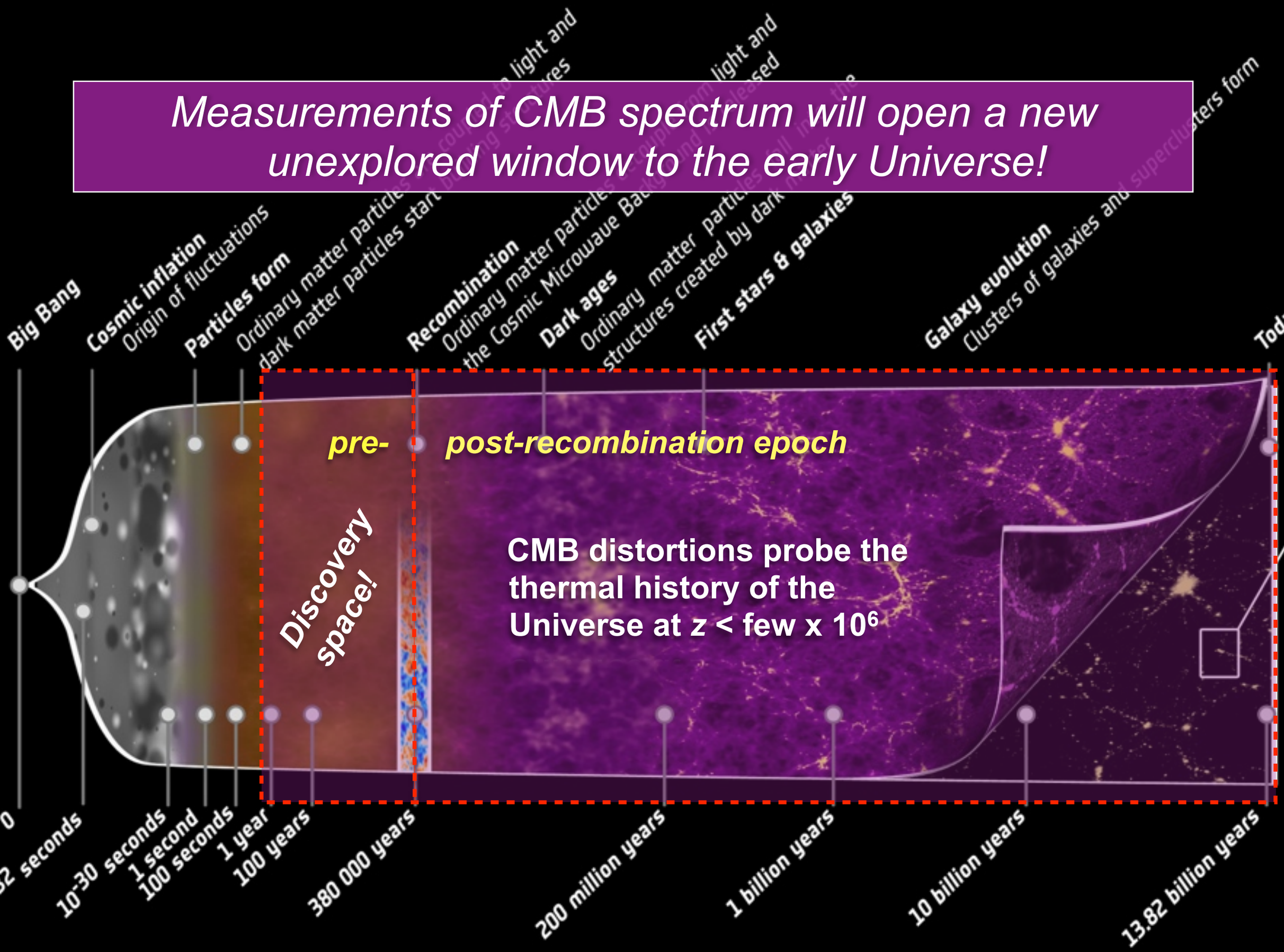
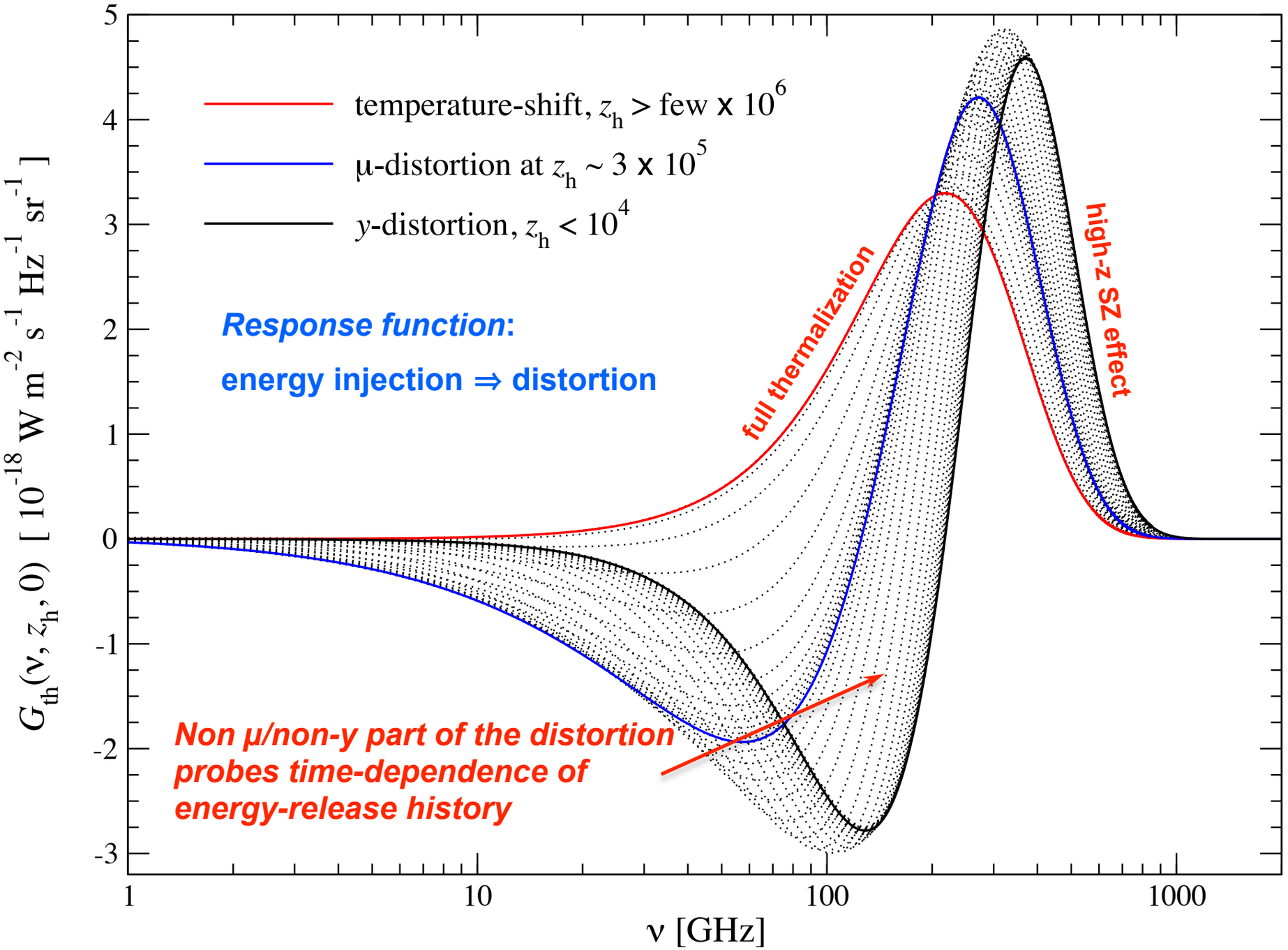
Measurements of CMB spectrum will open a new unexplored window to the early Universe!



CMB distortion signal contains much more information!

Intensity signal for different heating redshifts



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

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μ-era

μ-y-era

y-distortion era

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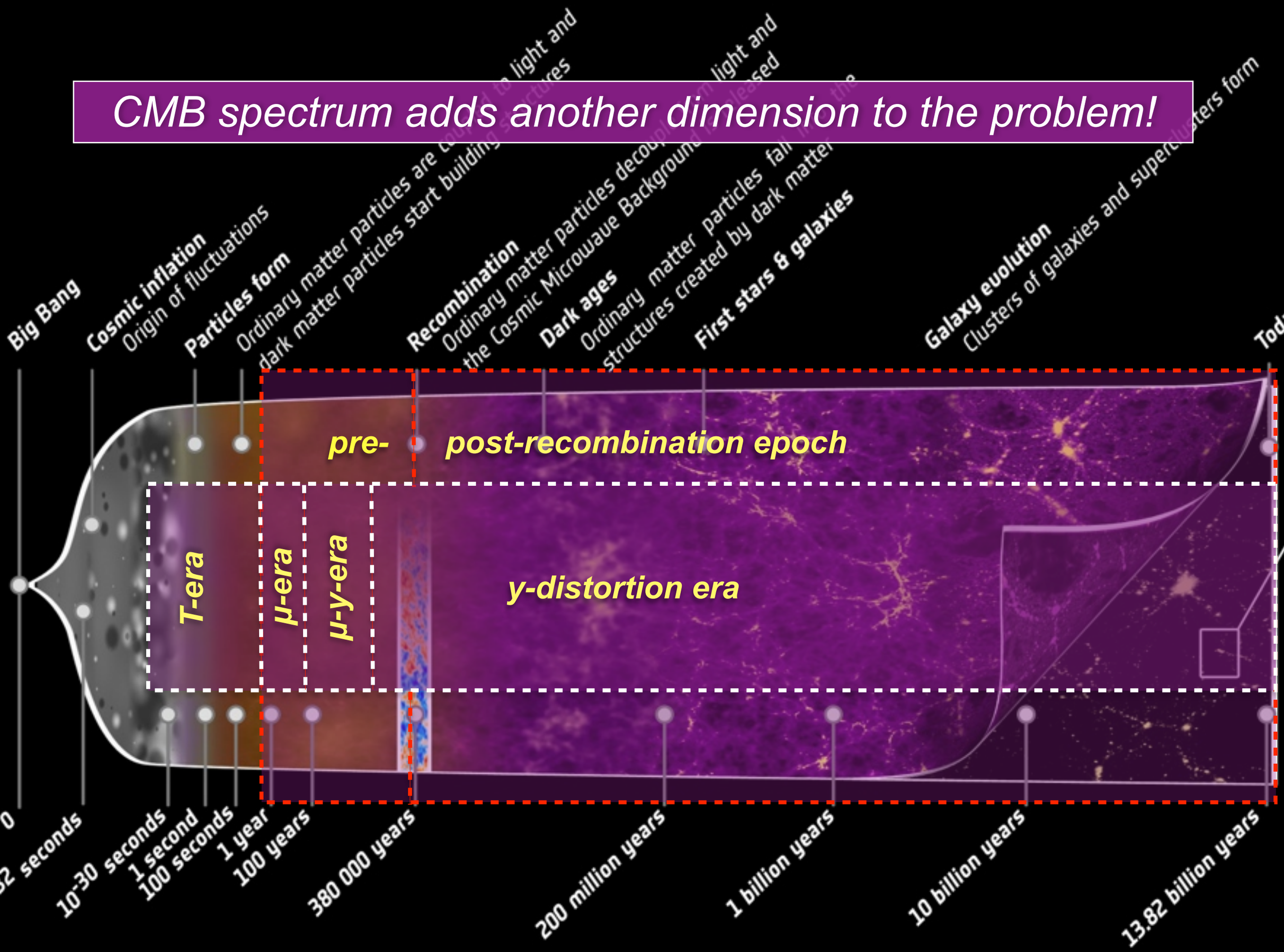
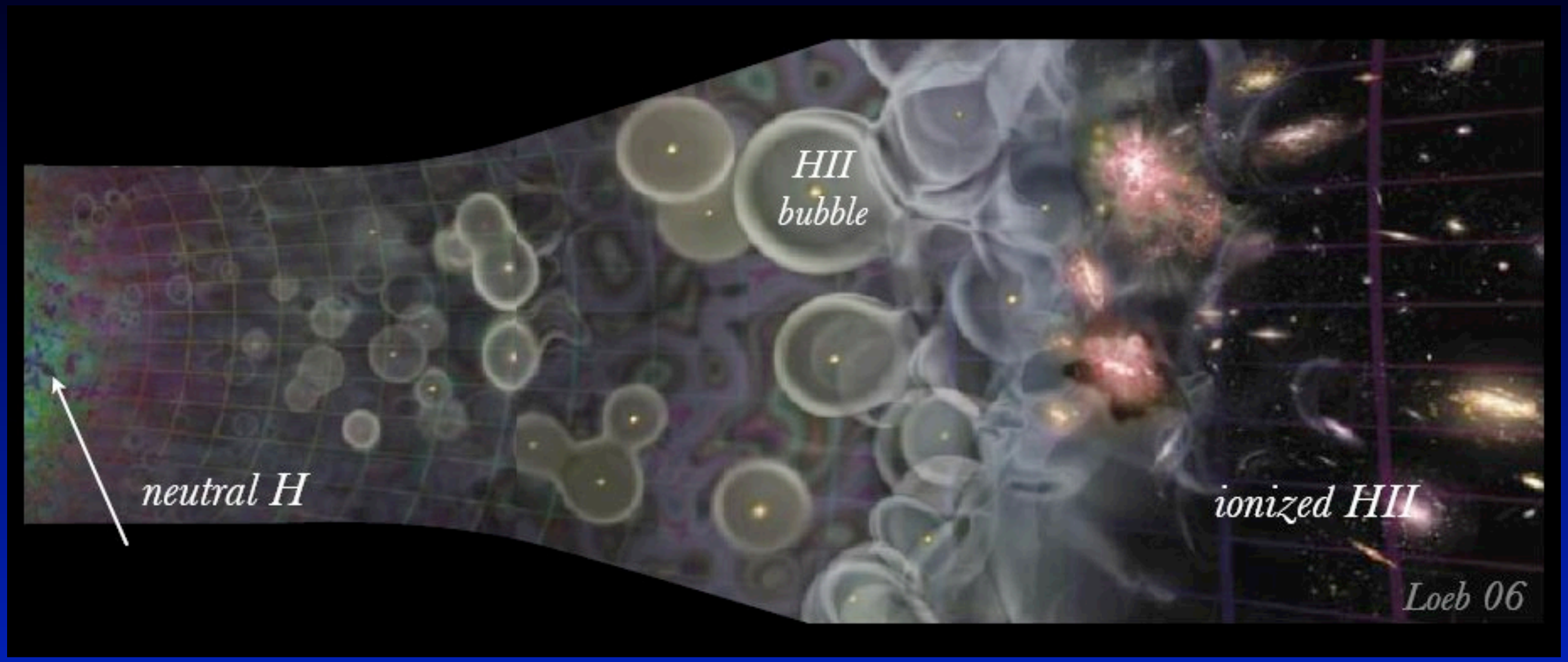
CMB spectrum adds another dimension to the problem!



Some of the cool things we will miss out on without absolute measurement!

Average y-distortion from reionization

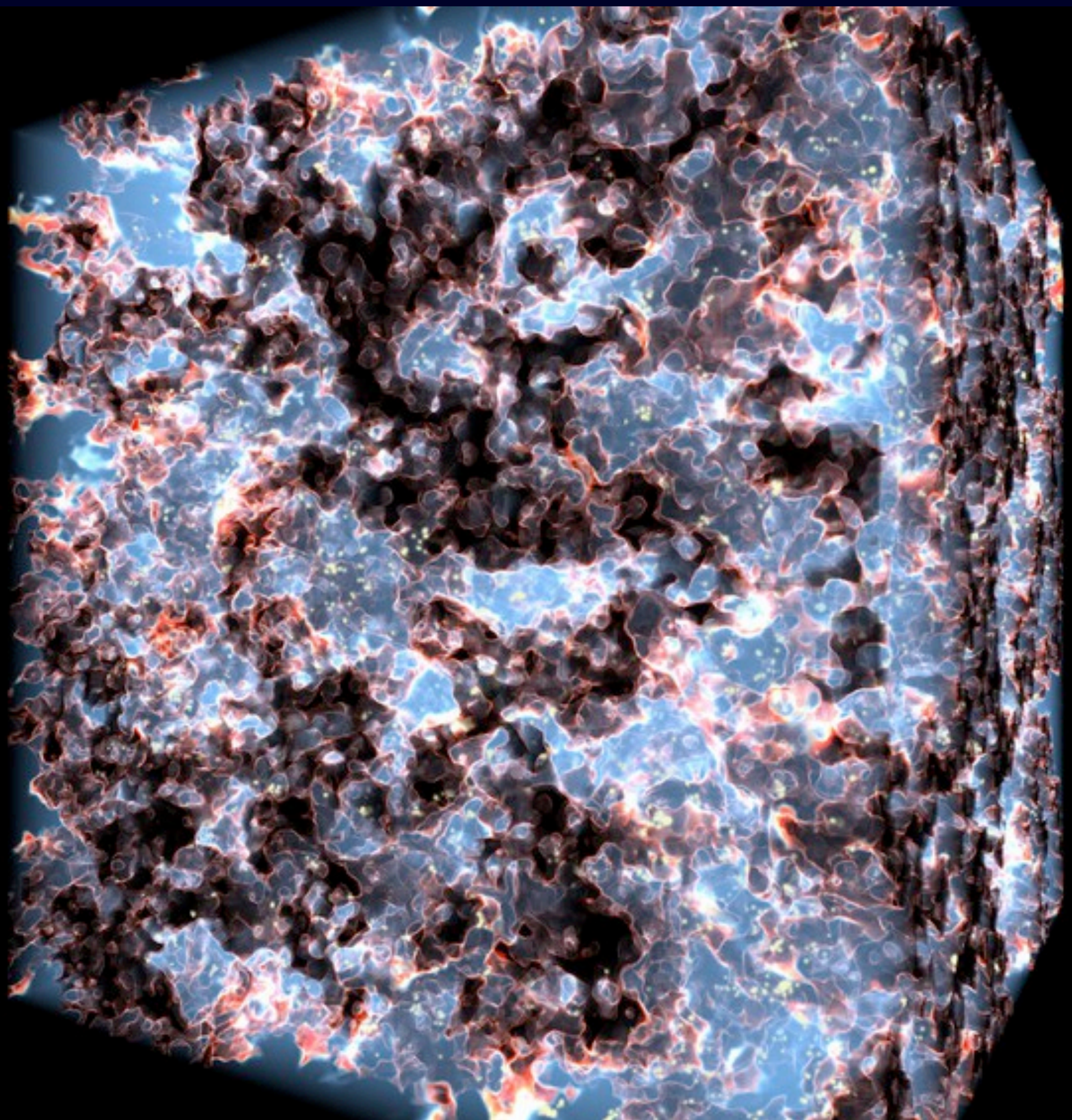


- Gas temperature T ≃ 10^4 K
- Thomson optical depth $\tau \simeq 0.1$

$$\Longrightarrow \quad y \simeq \frac{kT_{\rm e}}{m_{\rm e}c^2} \simeq 2 \times 10^{-7}$$

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

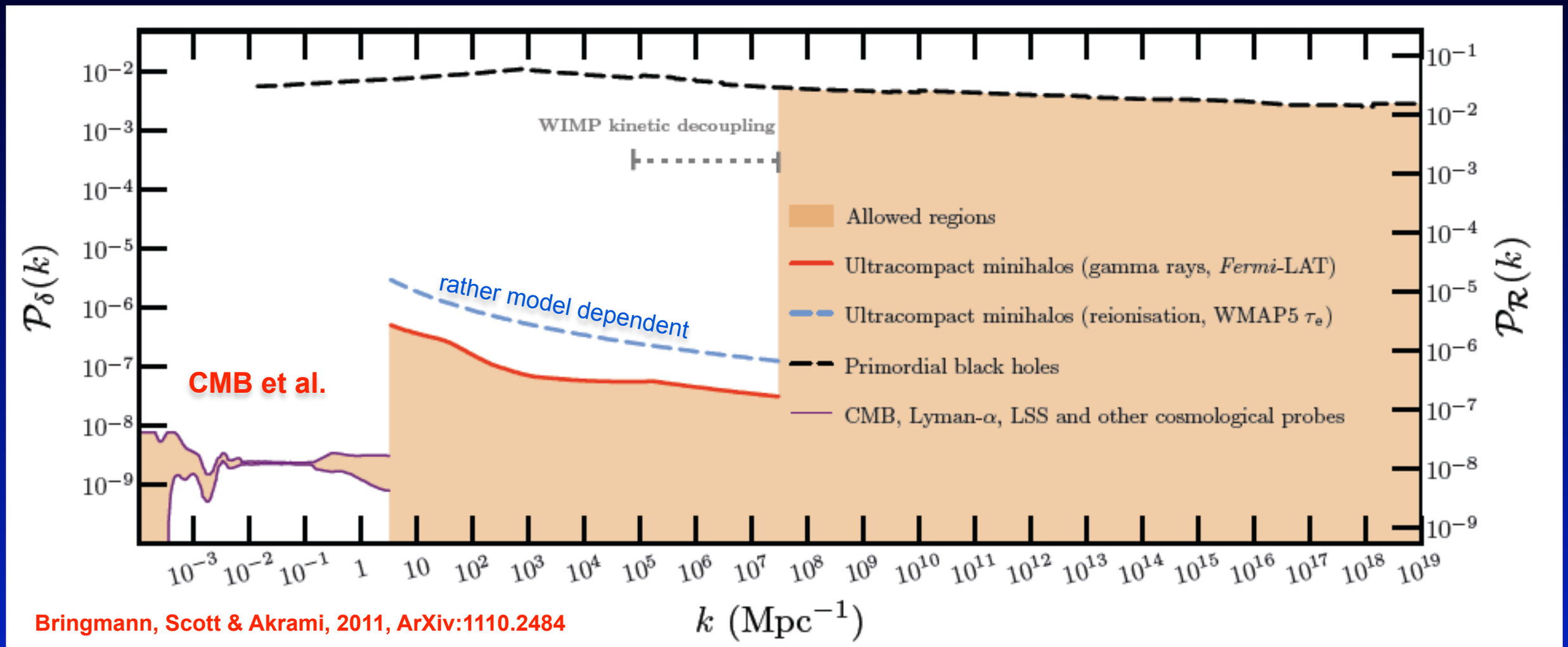
Fluctuations of the y-parameter at large scales



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

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

Distortions provide additional 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*

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

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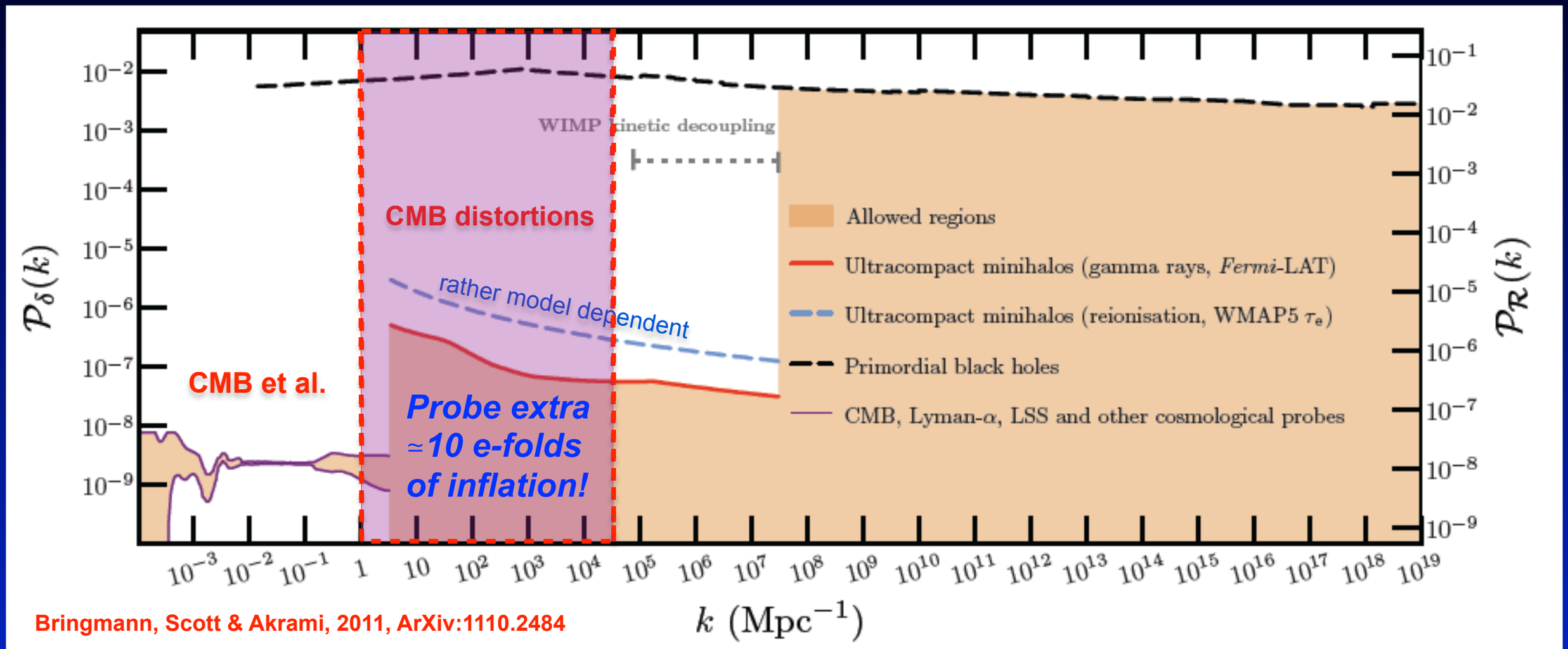

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- Amplitude of power spectrum rather uncertain at $k > 3$ Mpc^{-1}
- improved limits at smaller scales can *rule out* many *inflationary models*
- CMB spectral distortions would *extend* our *lever arm* to $k \sim 10^4$ Mpc^{-1}
- very *complementary*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

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

Spectral distortions could address additional small-scale power-spectrum questions

- *primordial non-Gaussianity* in the ultra-squeezed limit
  (Pajer & Zaldarriaga, 2012; Ganc & Komatsu, 2012; Biagetti et al., 2013)

- *Type* of the perturbations (adiabatic ↔ isocurvature)
  (Barrow & Coles, 1991; Hu et al., 1994; Dent et al, 2012, JC & Grin, 2012)

- *Theoretical link* between B-modes and small-scale power spectrum?

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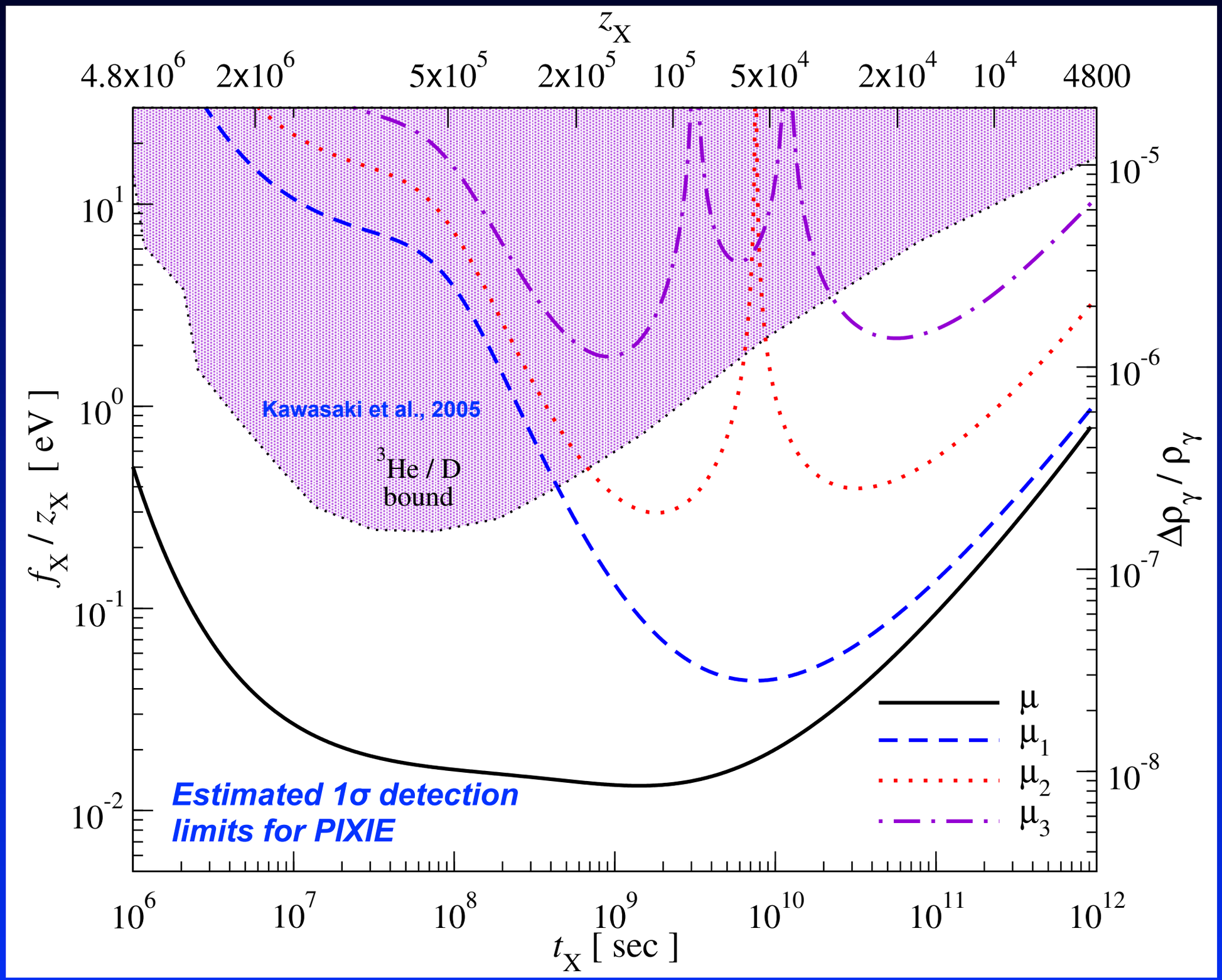
CMB Spectral distortions could add additional numbers beyond 'just' the tensor-to-scalar ratio from B-modes!

Distortions could shed light on decaying (DM) particles!



JC & Jeong, 2013

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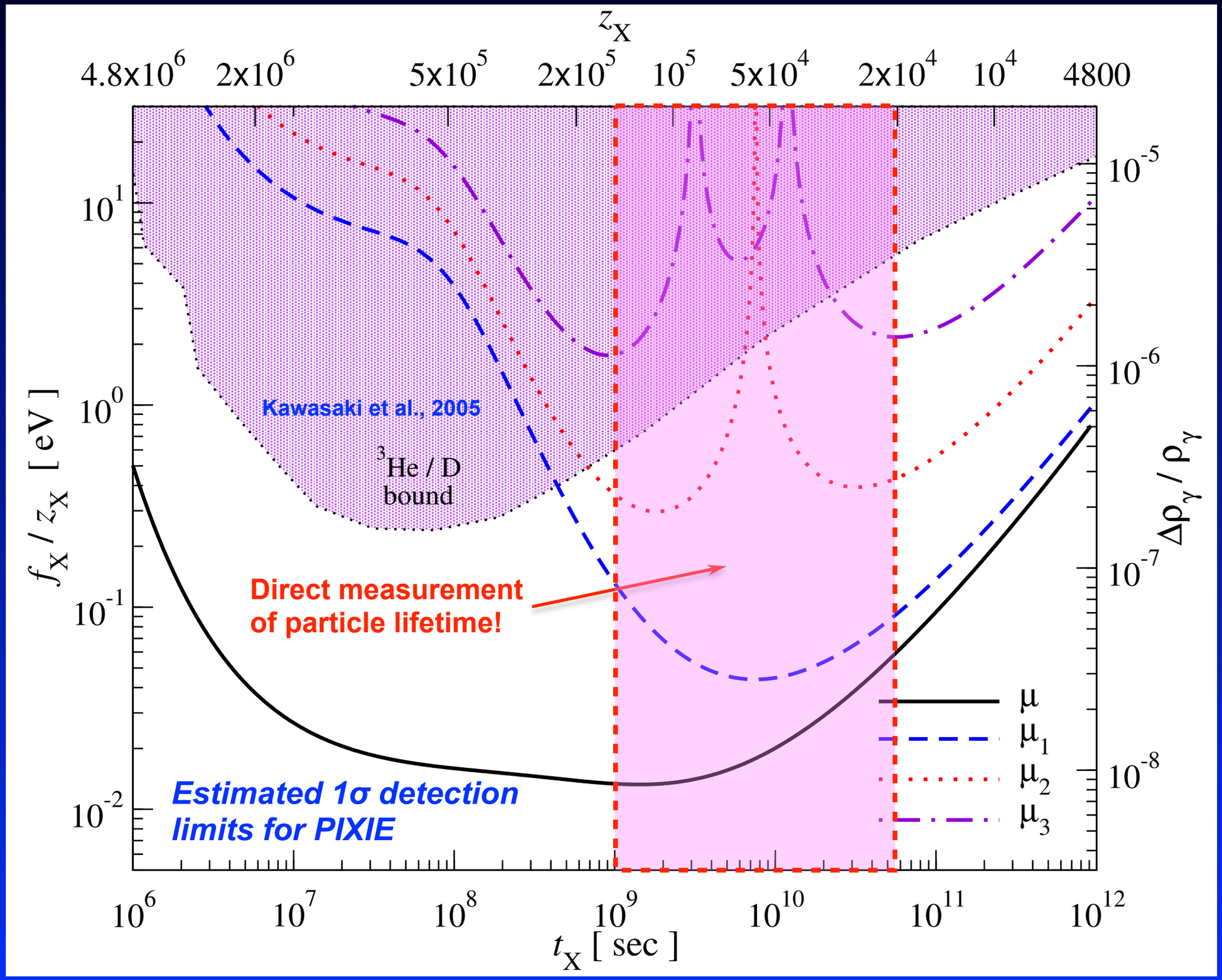
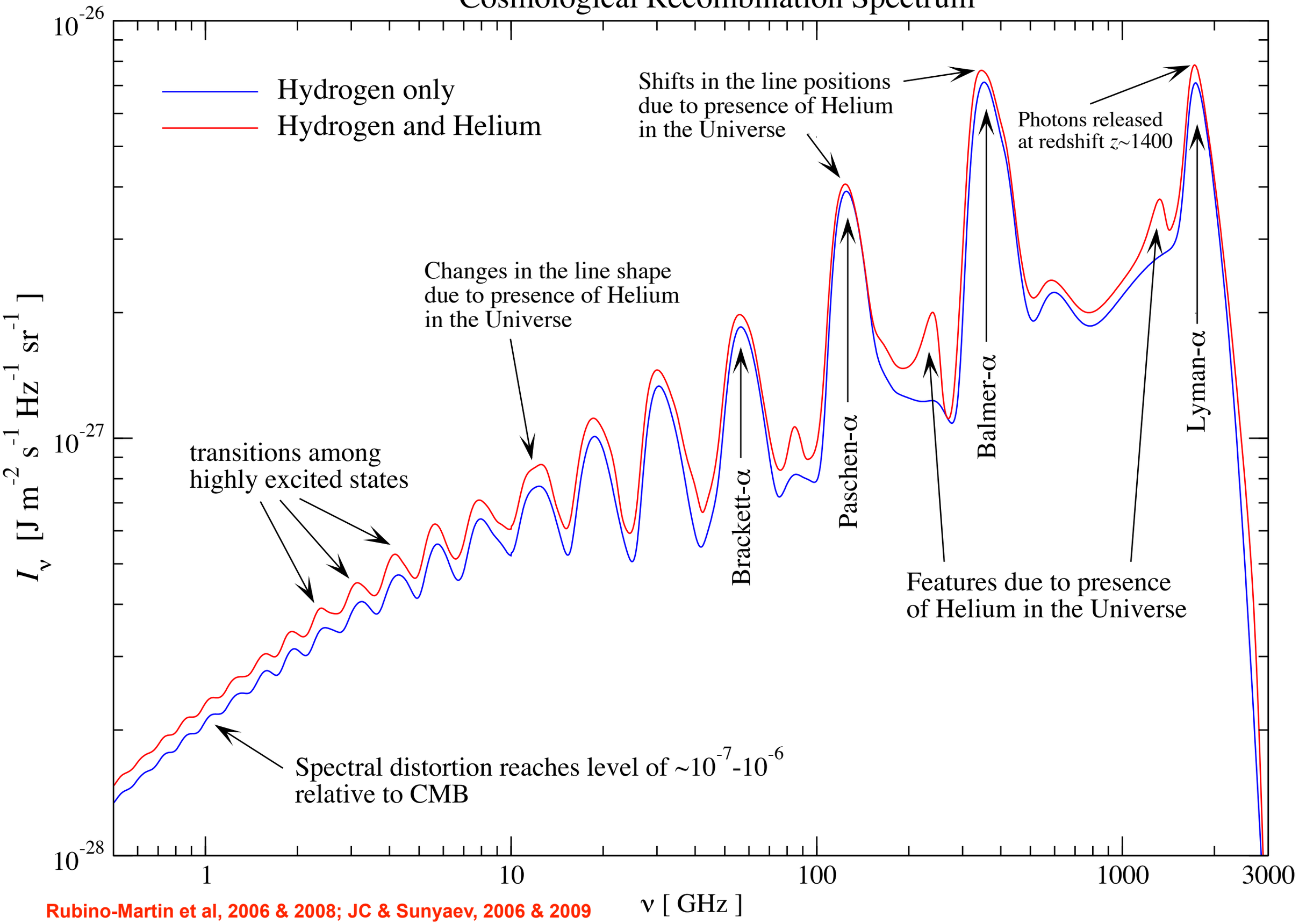


JC & Jeong, 2013

Cosmological Recombination Spectrum



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

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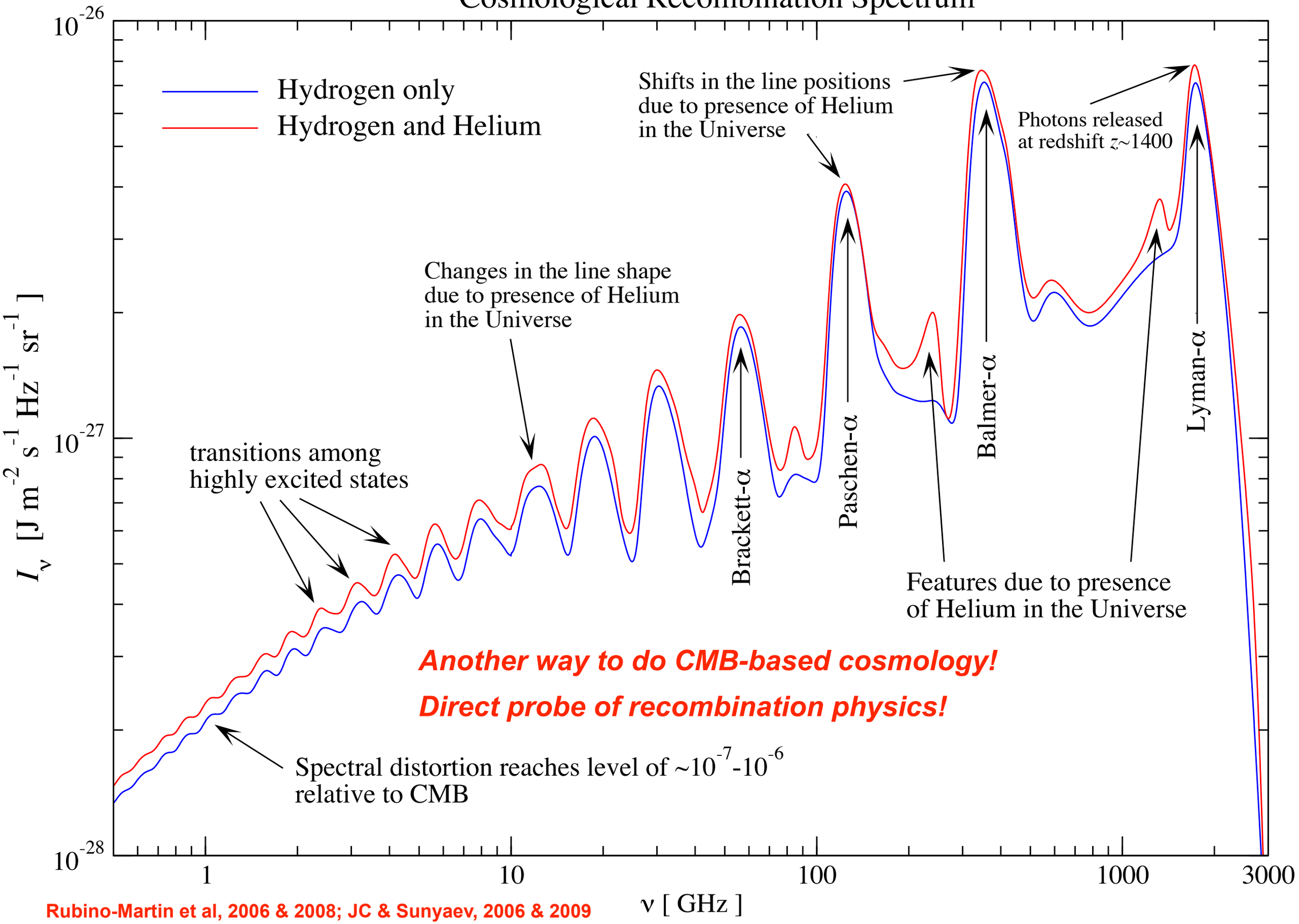
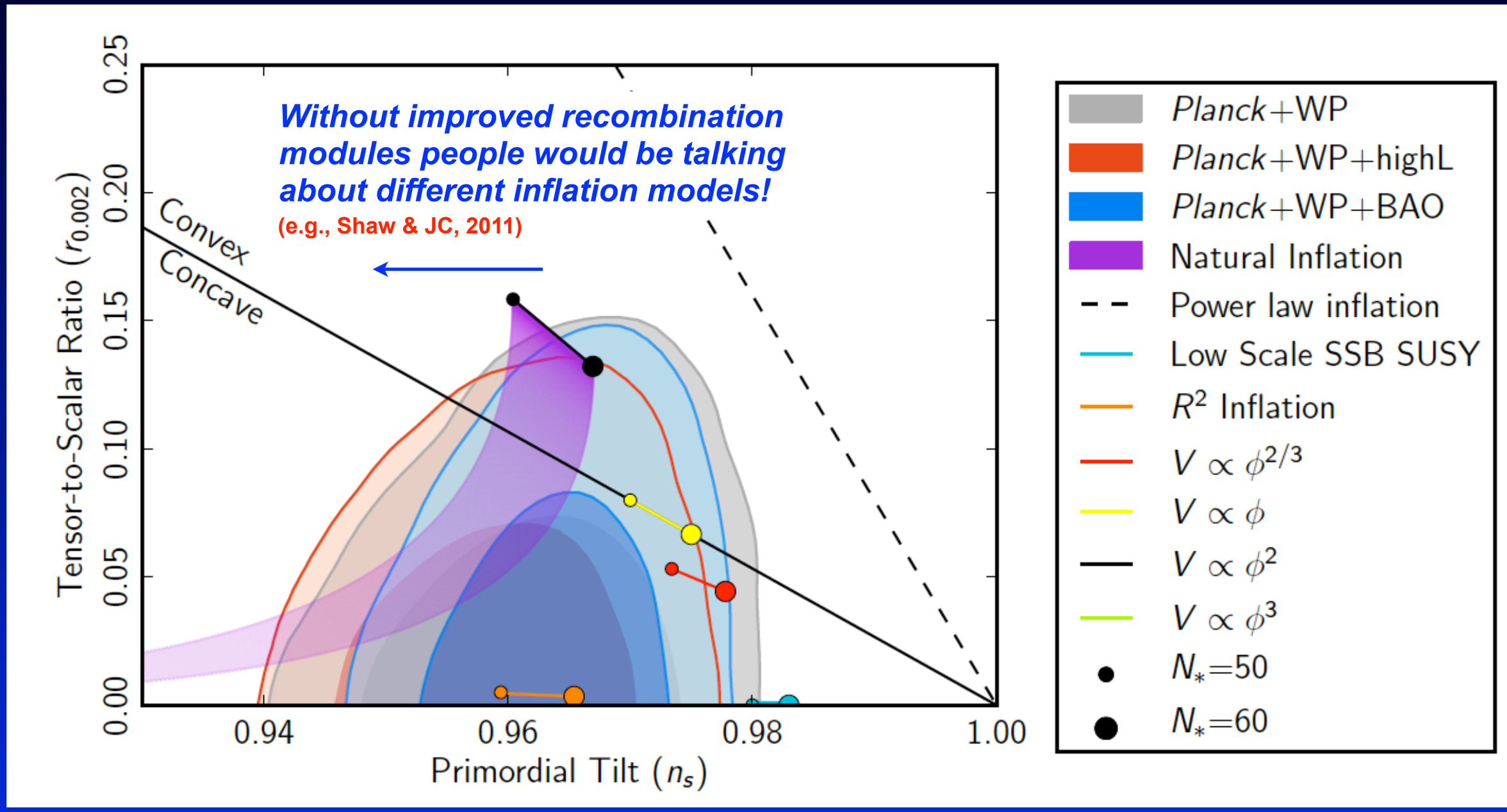


Rubino-Martin et al, 2006 & 2008; JC & Sunyaev, 2006 & 2009

Importance of recombination for inflation constraints



Planck Collaboration, 2013, paper XXII

- Analysis uses refined recombination model (CosmoRec/HyRec)

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Cosmic inflation
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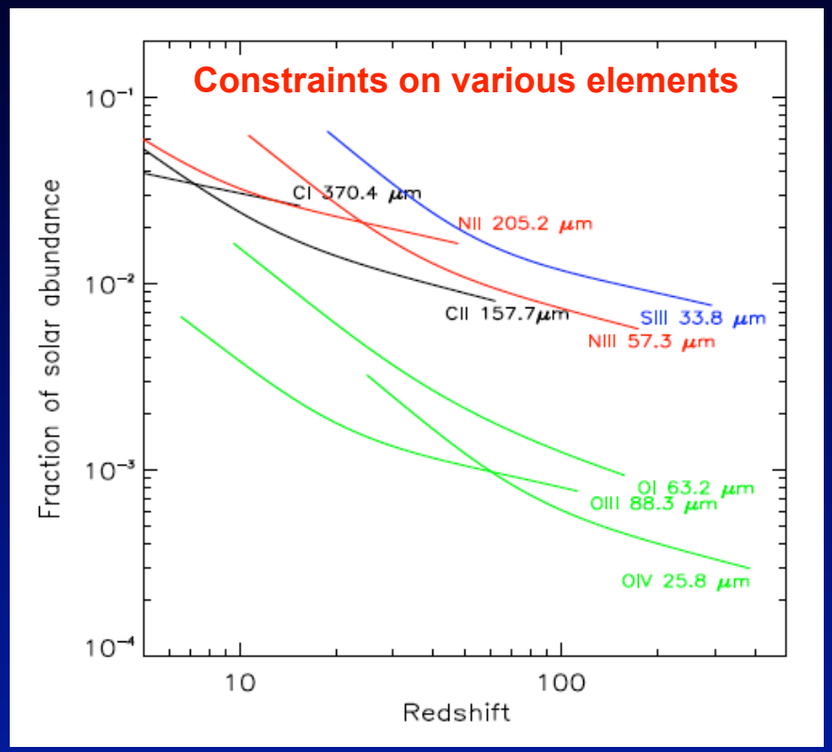
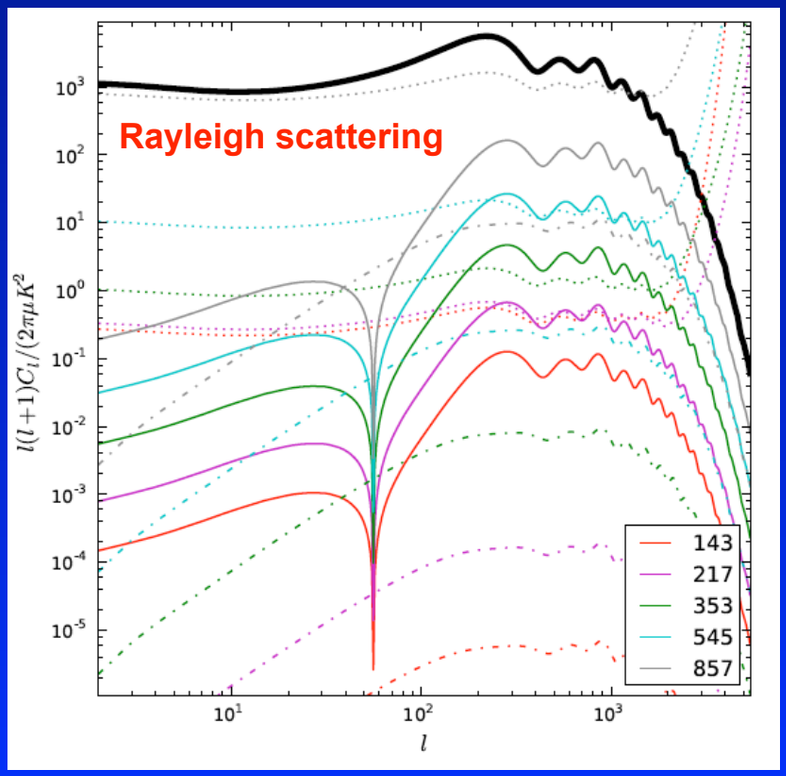
Other extremely interesting new signals

- Scattering signals from the dark ages
  (e.g., Basu et al., 2004; Hernandez-Monteagudo et al., 2007; Schleicher et al., 2009)
  - constrain abundances of chemical elements at high redshift
  - learn about star formation history
- Rayleigh / HI scattering signals
  (e.g., Yu et al., 2001; Rubino-Martin et al., 2005; Lewis 2013)
  - provides way to constrain recombination history
  - important when asking questions about $N_{\rm eff}$ and $Y_{\rm p}$
- Free-free signals from reionization
  (e.g., Burigana et al. 1995; Trombetti & Burigana, 2013)
  - constrains reionization history
  - depends on clumpiness of the medium





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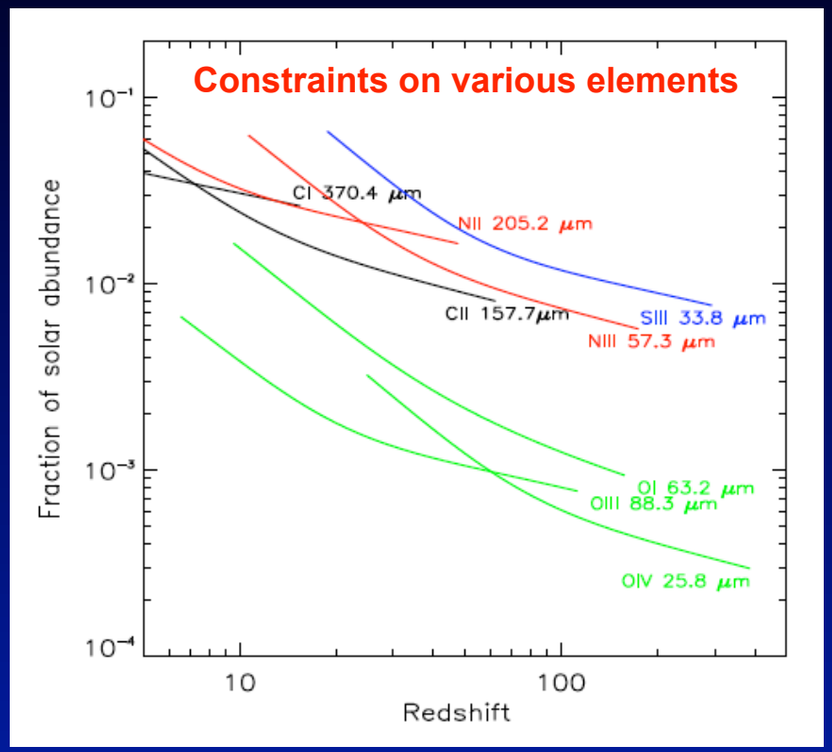
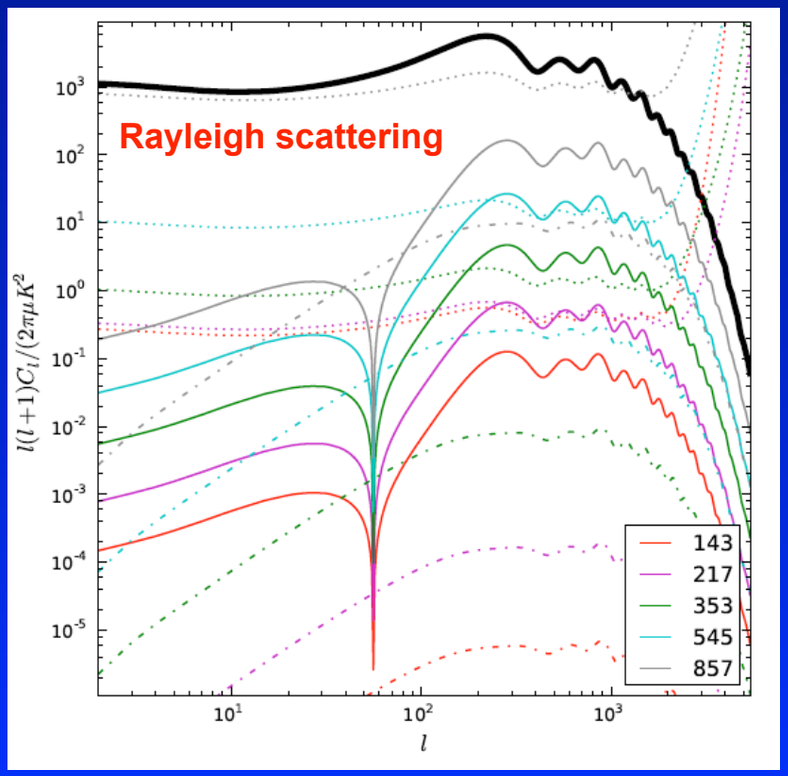
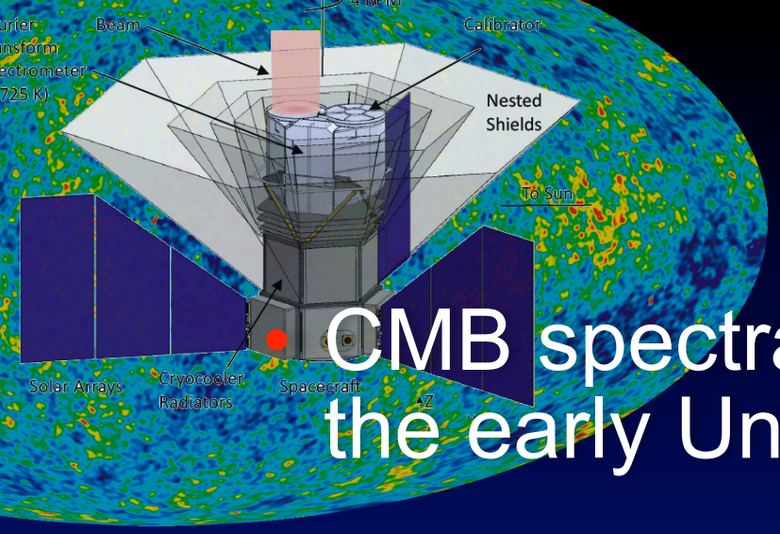
- Rayleigh / HI scattering signals
  (e.g., Yu et al., 2001; Rubino-Martin et al., 2005; Lewis 2013)
  - provides way to constrain recombination history
  - important when asking questions about $N_{\rm eff}$ and $Y_{\rm p}$
- Free-free signals from reionization
  (e.g., Burigana et al. 1995; Trombetti & Burigana, 2013)
  - constrains reionization history
  - depends on clumpiness of the medium

Although all these effects give spectral-spatial signals, an absolute spectrometer will help with channel cross calibration!

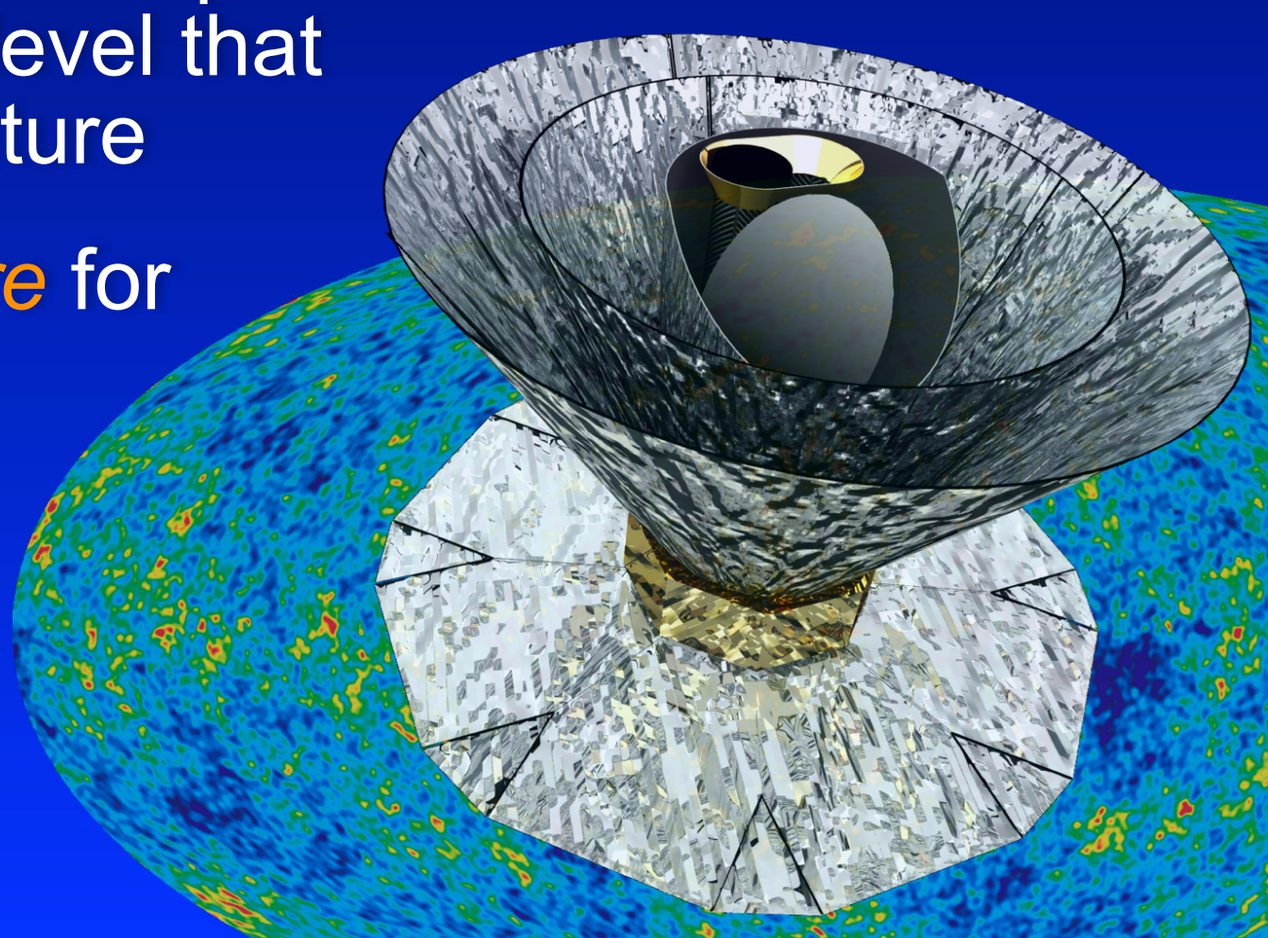


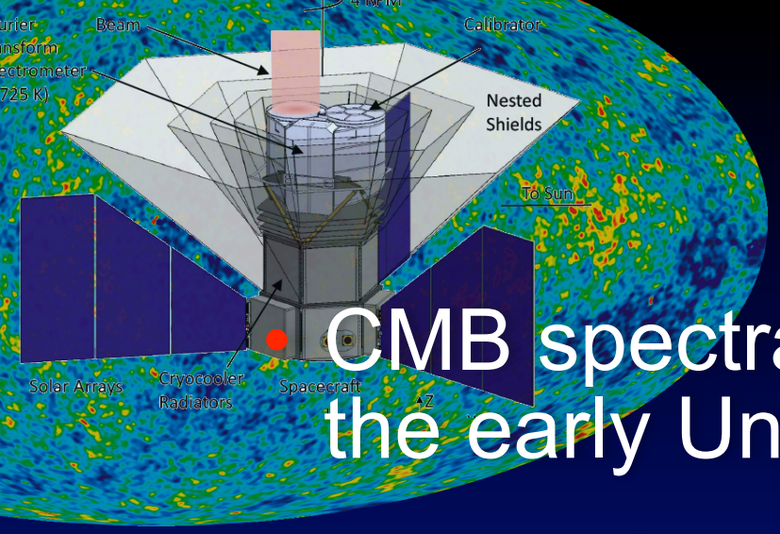




Conclusions

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





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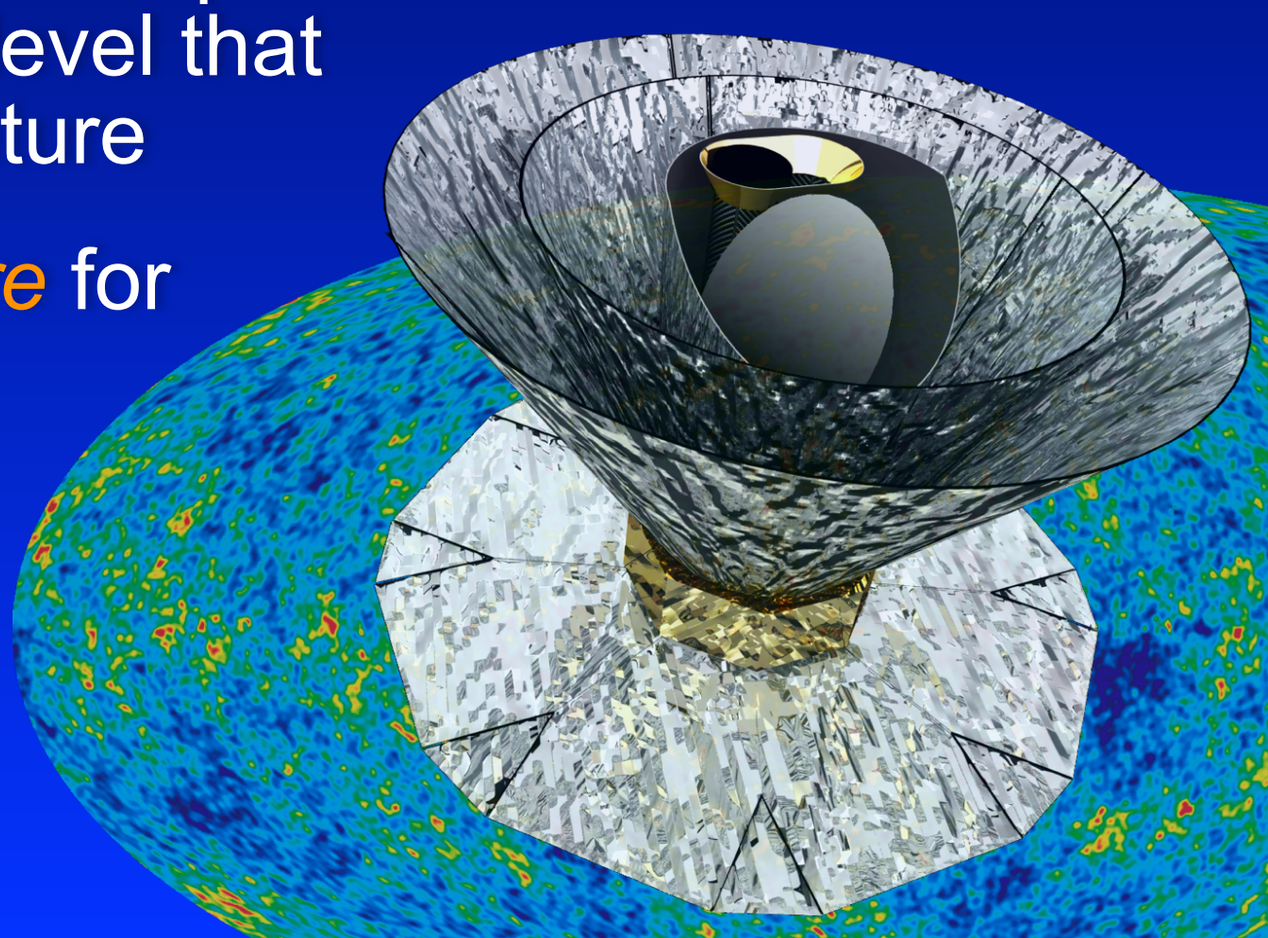
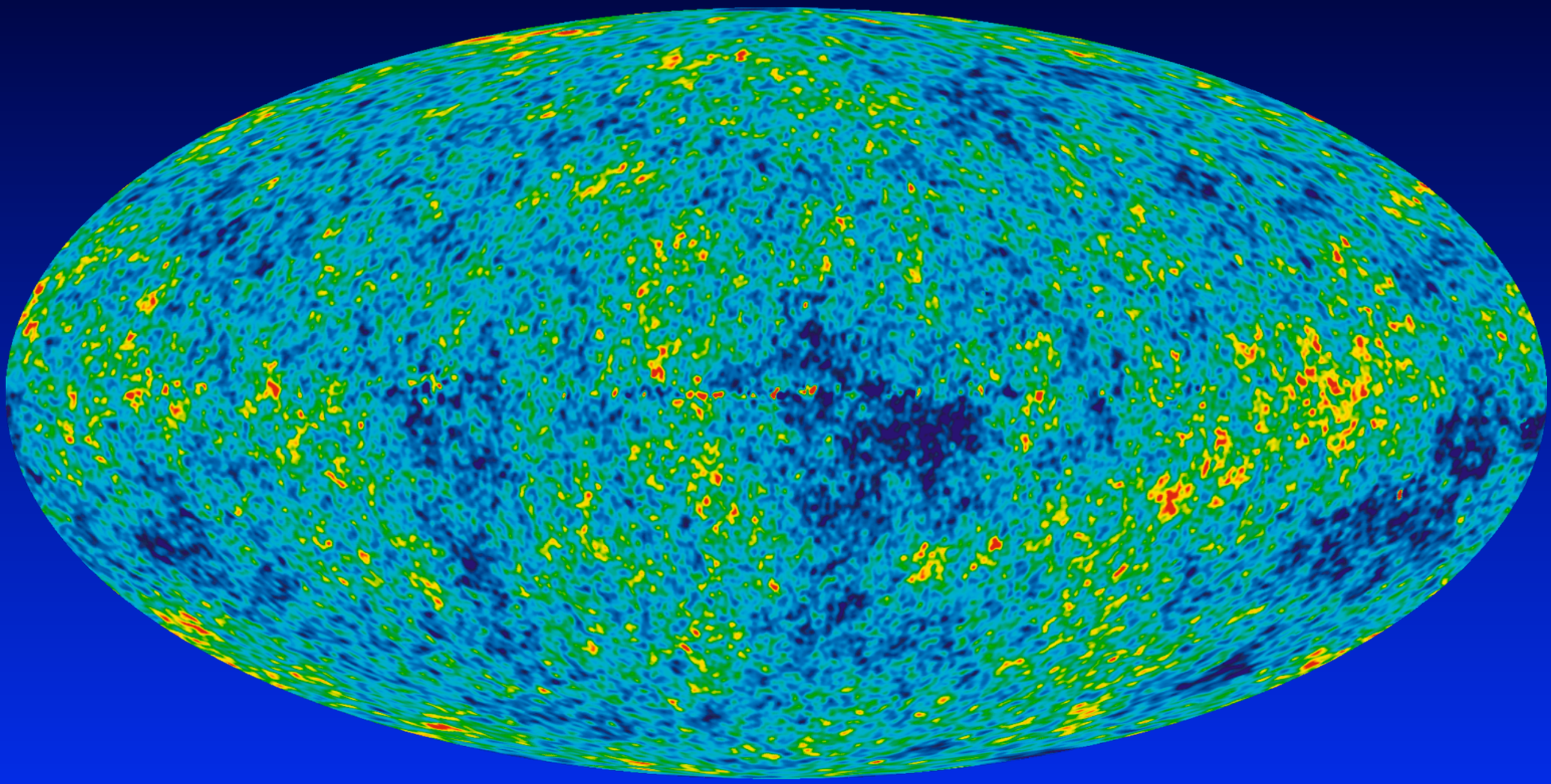
We should make use of all this information!



Comments for the discussion

- Main competition really only is PIXIE-2
- How will low angular resolution compromise their ability to reach the spectral sensitivity?
- Importance of high frequency channels for foreground modeling?
- If the spectrometer becomes part of CORE++ more detailed studies to determine the best spectral coverage will be needed
- need a working group on spectral-spatial distortion signals: these are also possible with just inter-channel calibration

Dissipation of small-scale acoustic modes



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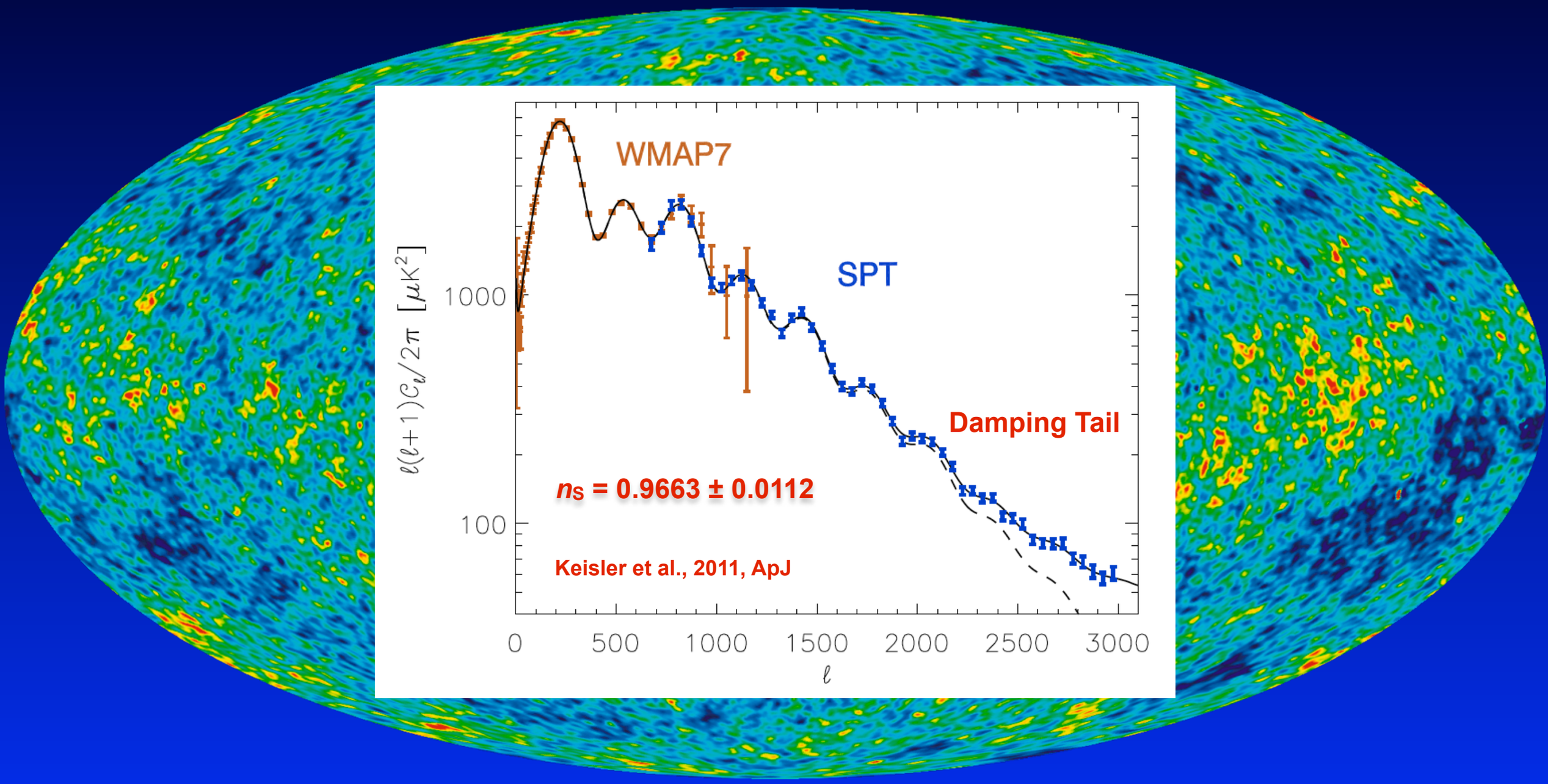

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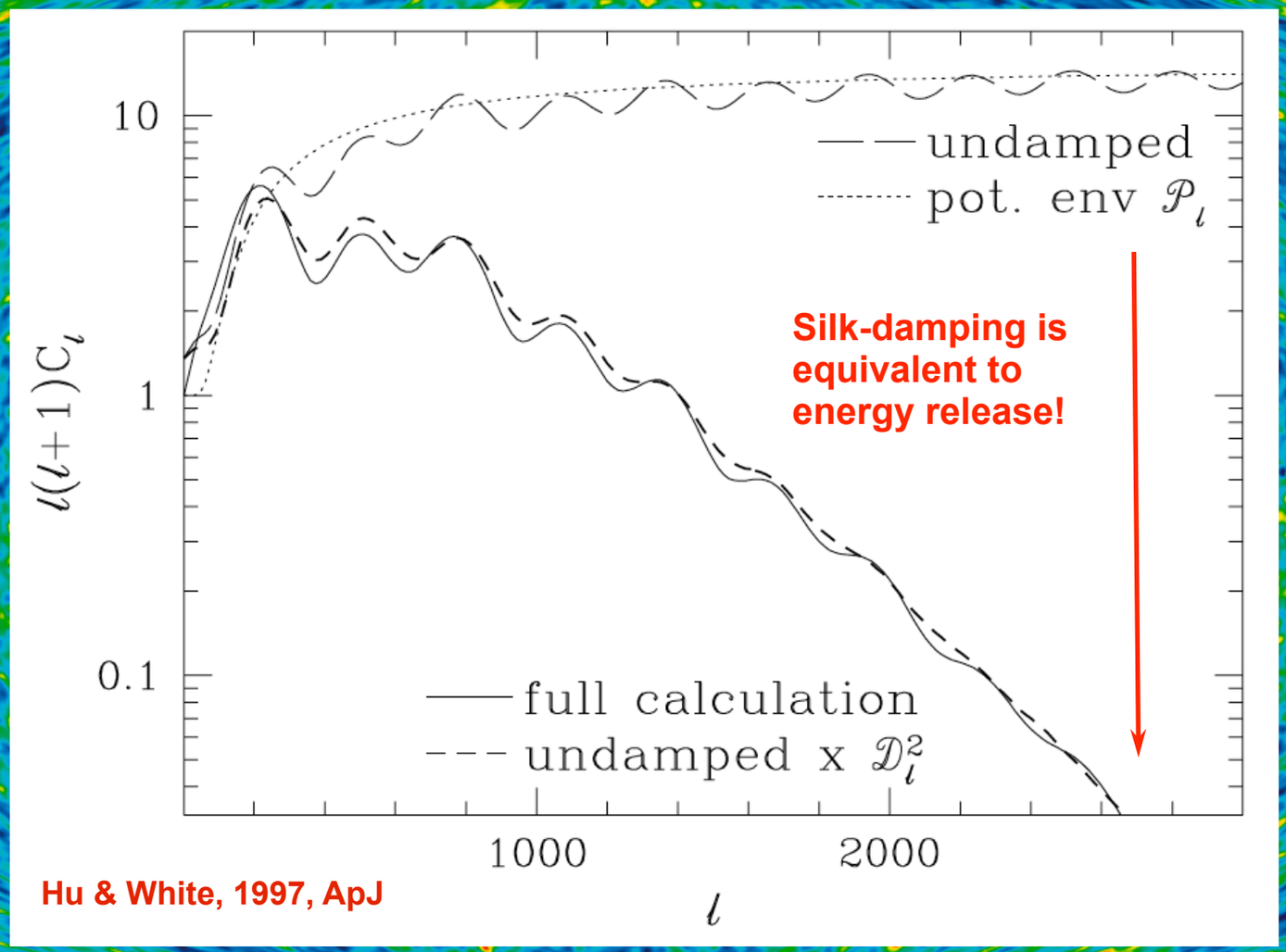

Hu & White, 1997, ApJ

Energy release caused by dissipation process

‘Obvious’ dependencies:

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

not so ‘obvious’ dependencies:

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

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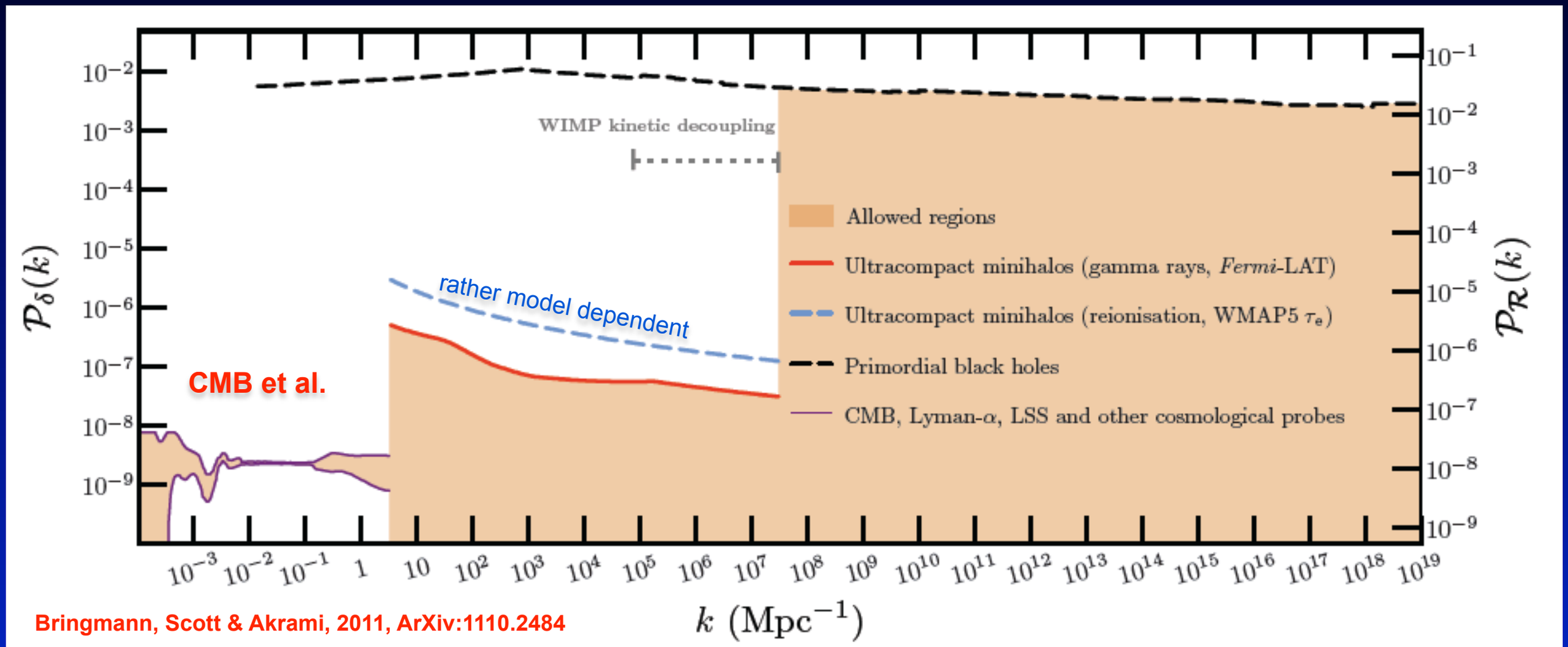
CMB Spectral distortions provide probe of Inflation physics!!!

Distortions provide additional power spectrum constraints!



Bringmann, Scott & Akrami, 2011, ArXiv:1110.2484

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

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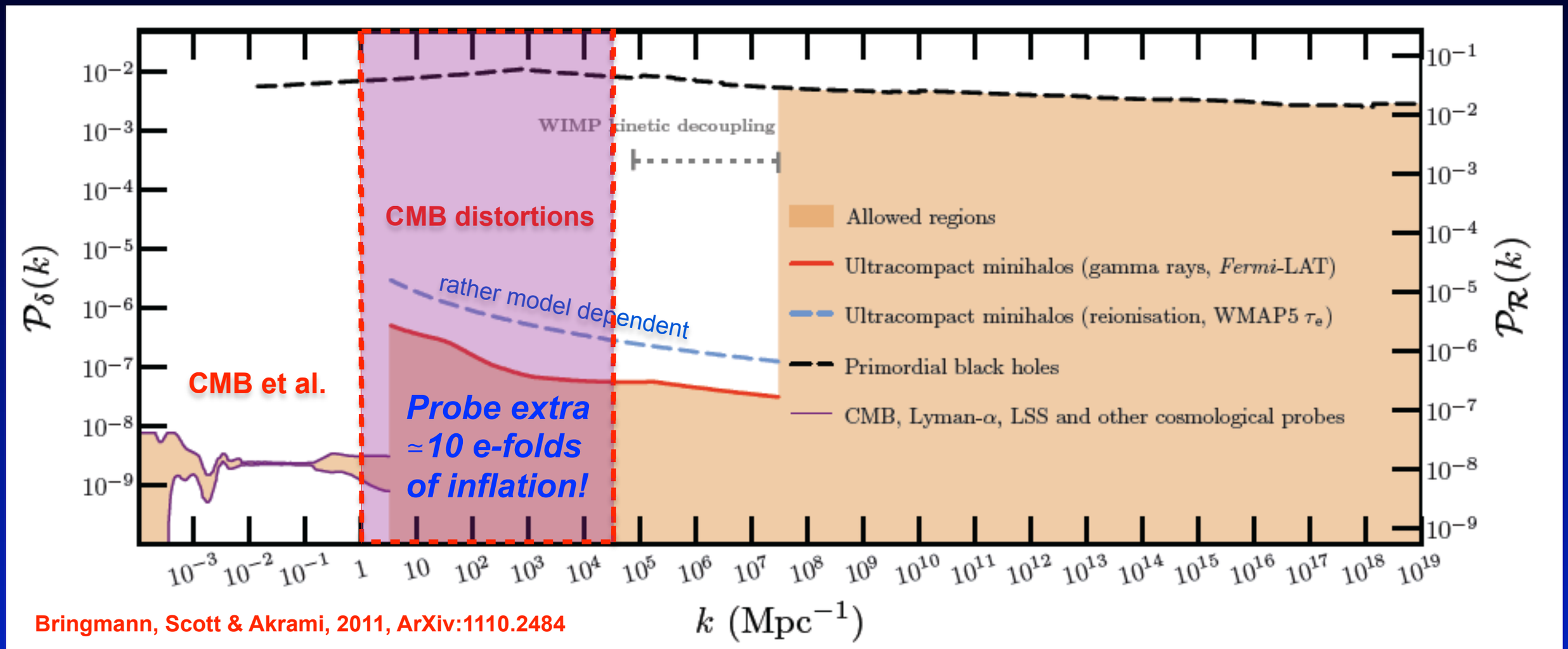

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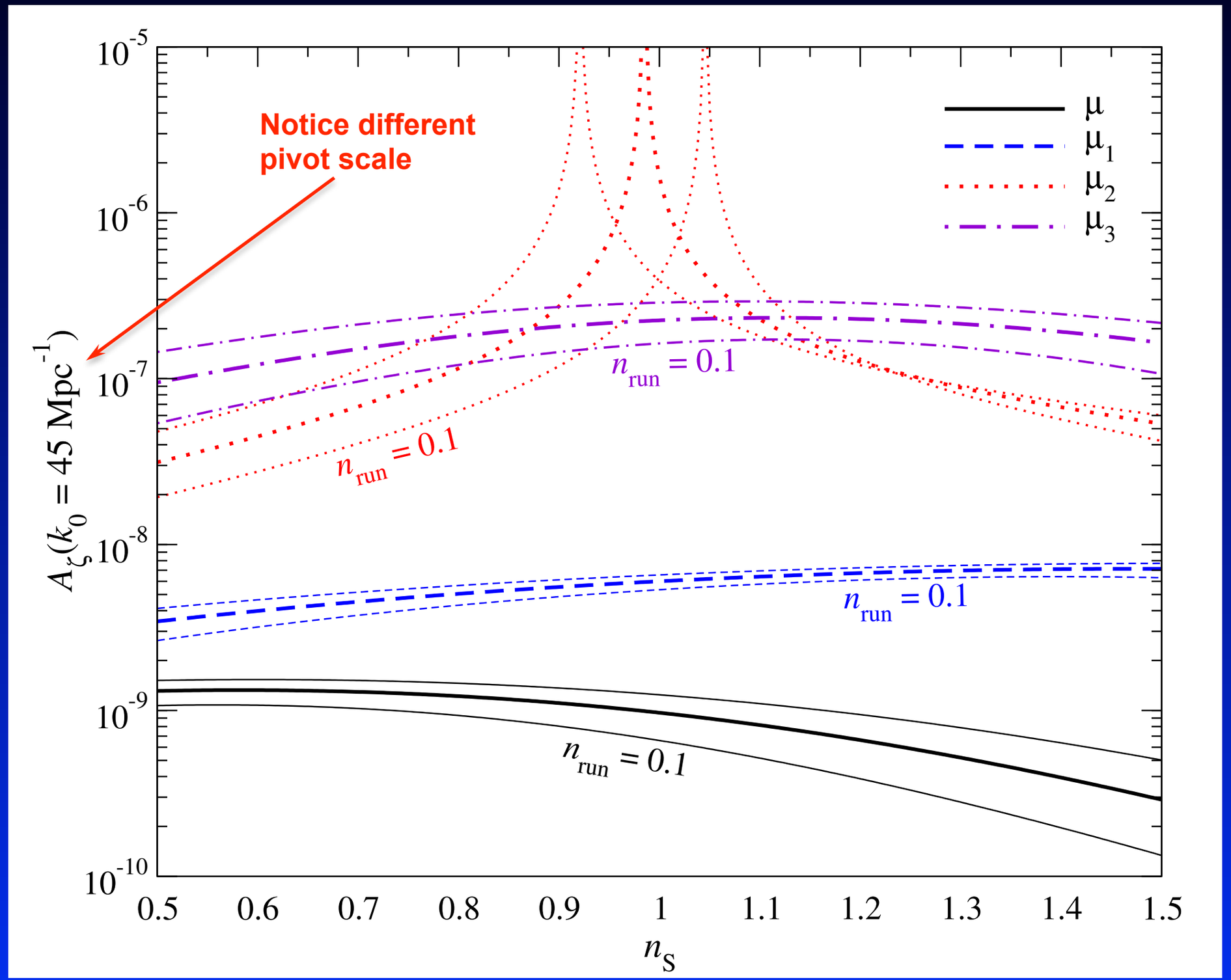
- improving limits at smaller scales would *rule out* many *inflationary models*
- CMB spectral distortions would *extend* our *lever arm* to $k \sim 10^4$ Mpc^{-1}
- very *complementary* piece of information about inflation physics

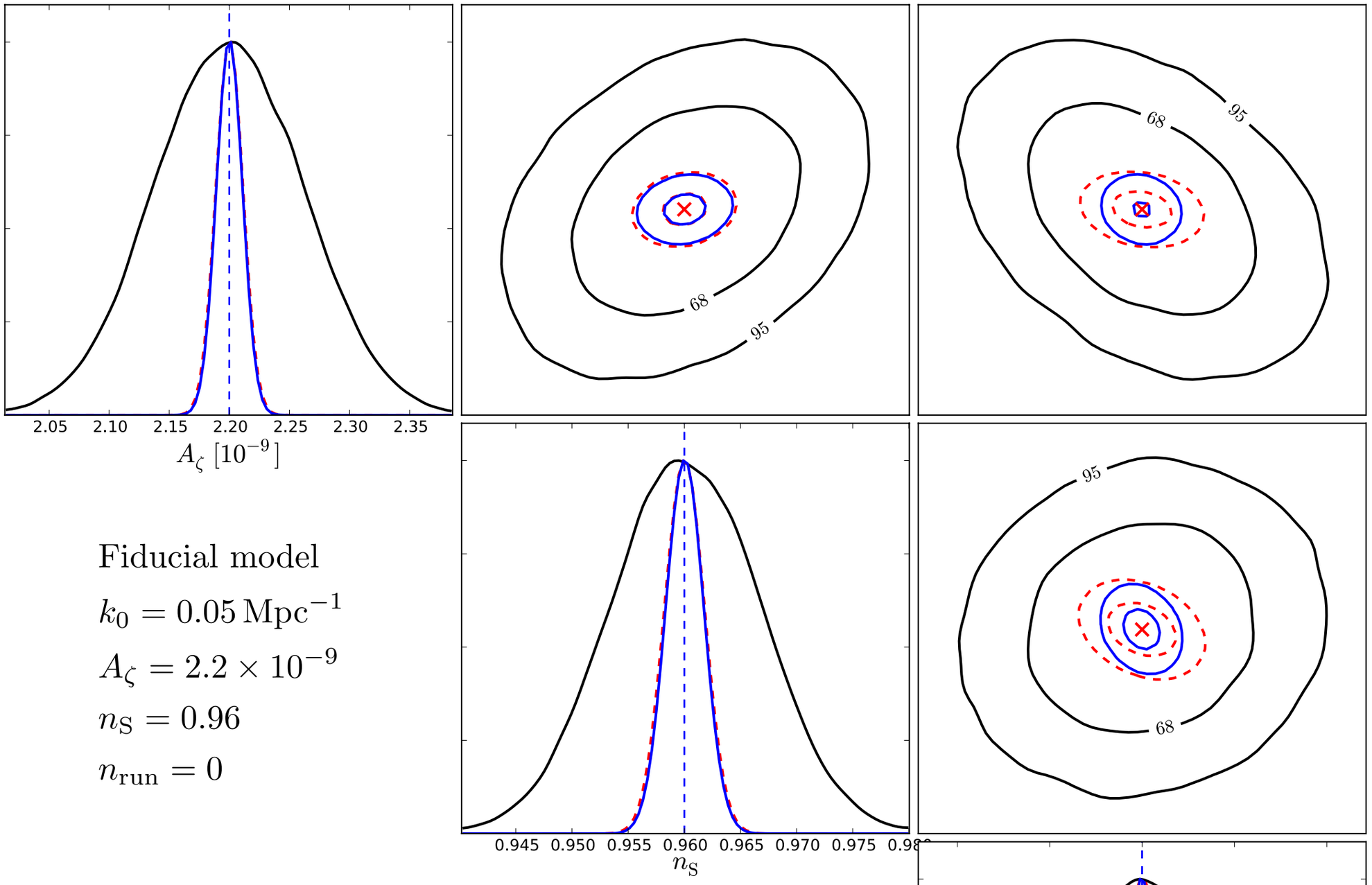
JC, Khatri & Sunyaev, 2012; JC, Erickcek & Ben-Dayan, 2012; JC & Jeong, 2013

Dissipation scenario: 1σ-detection limits for PIXIE



JC & Jeong, 2013

$$P_\zeta(k) = 2\pi^2 A_\zeta k^{-3} (k/k_0)^{n_S - 1 + \frac{1}{2} n_{\mathrm{run}} \ln(k/k_0)}$$



Fiducial model

$k_0 = 0.05\,\mathrm{Mpc}^{-1}$

$A_\zeta = 2.2 \times 10^{-9}$

$n_{\rm S} = 0.96$

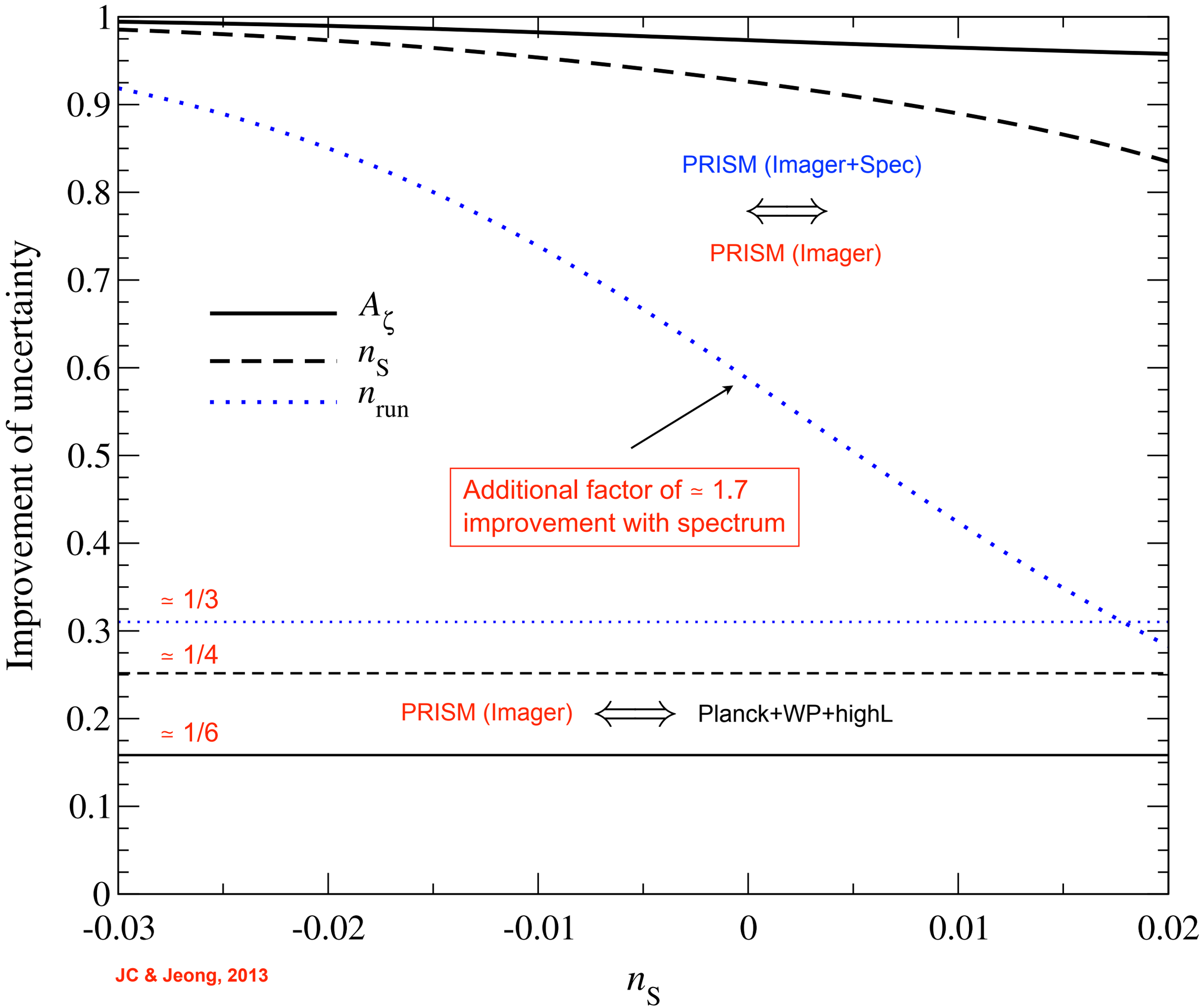
$n_{\rm run} = 0$

Planck+WP+highL

PRISM (Imager)

PRISM (Imager+Spec)

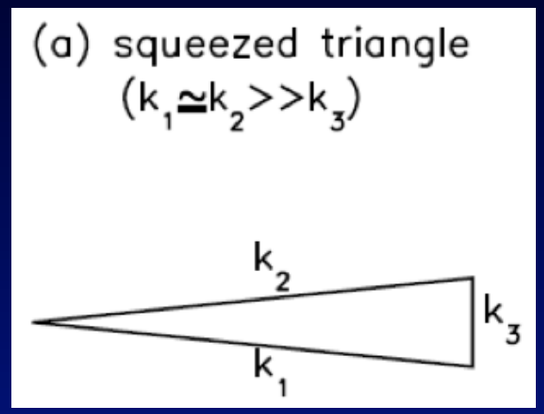
JC & Jeong, 2013



JC & Jeong, 2013

Modified μ-distortion in the squeezed limit

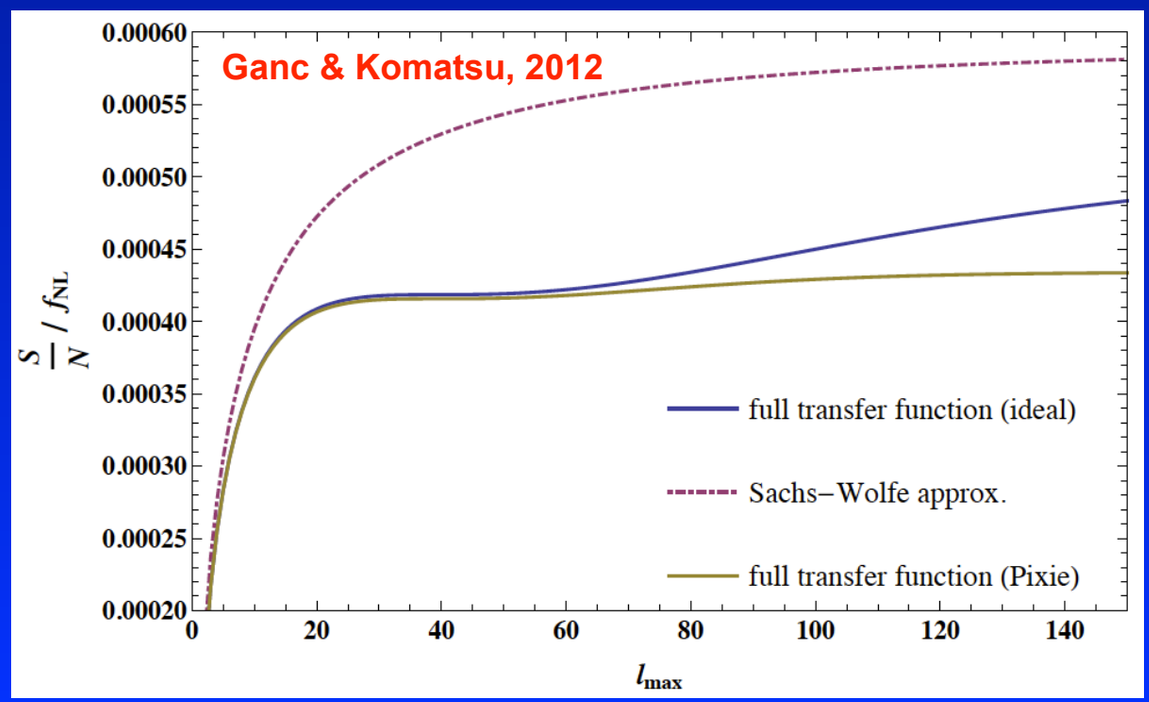
- Modes that dissipate energy have $k_1 \approx k_2 >> k_3$
- Non-Gaussian power spectrum → presence of positive long-wavelength mode enhances small-scale power
- More small-scale power → larger μ-distortion
- → Spatially varying μ-distortion caused by non-Gaussianity!
  (Pajer & Zaldarriaga, 2012; Ganc & Komatsu, 2012)



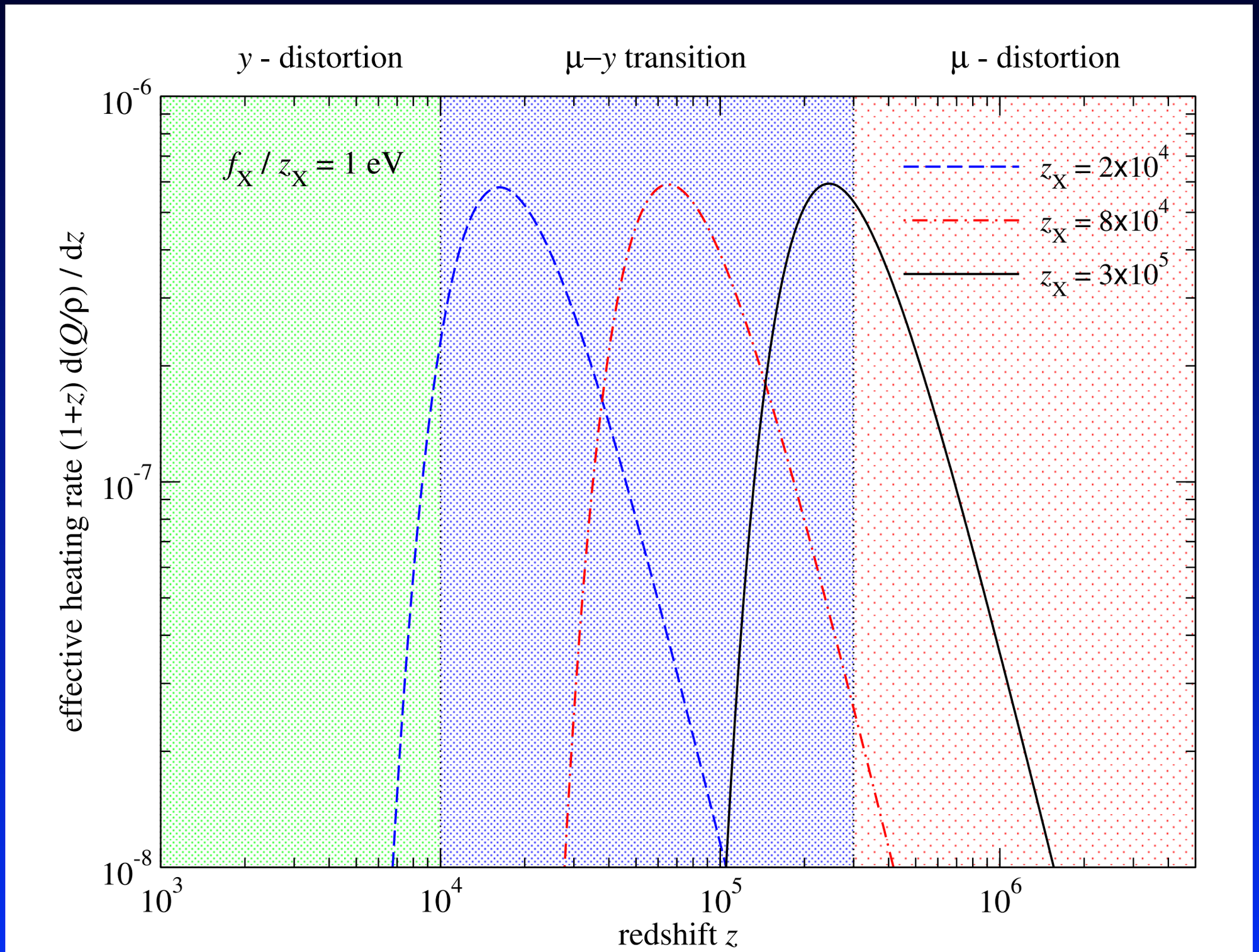
- Non-vanishing μ-T correlation at large scales
- Might be detectable with PIXIE-type experiment for $f_{NL} > 10^3$

Requirements

- precise cross-calibration of frequency channels
- higher angular resolution does not improve cumulative S/N



Decaying particle scenarios



JC & Sunyaev, 2011, Arxiv:1109.6552
JC, 2013, Arxiv:1304.6120

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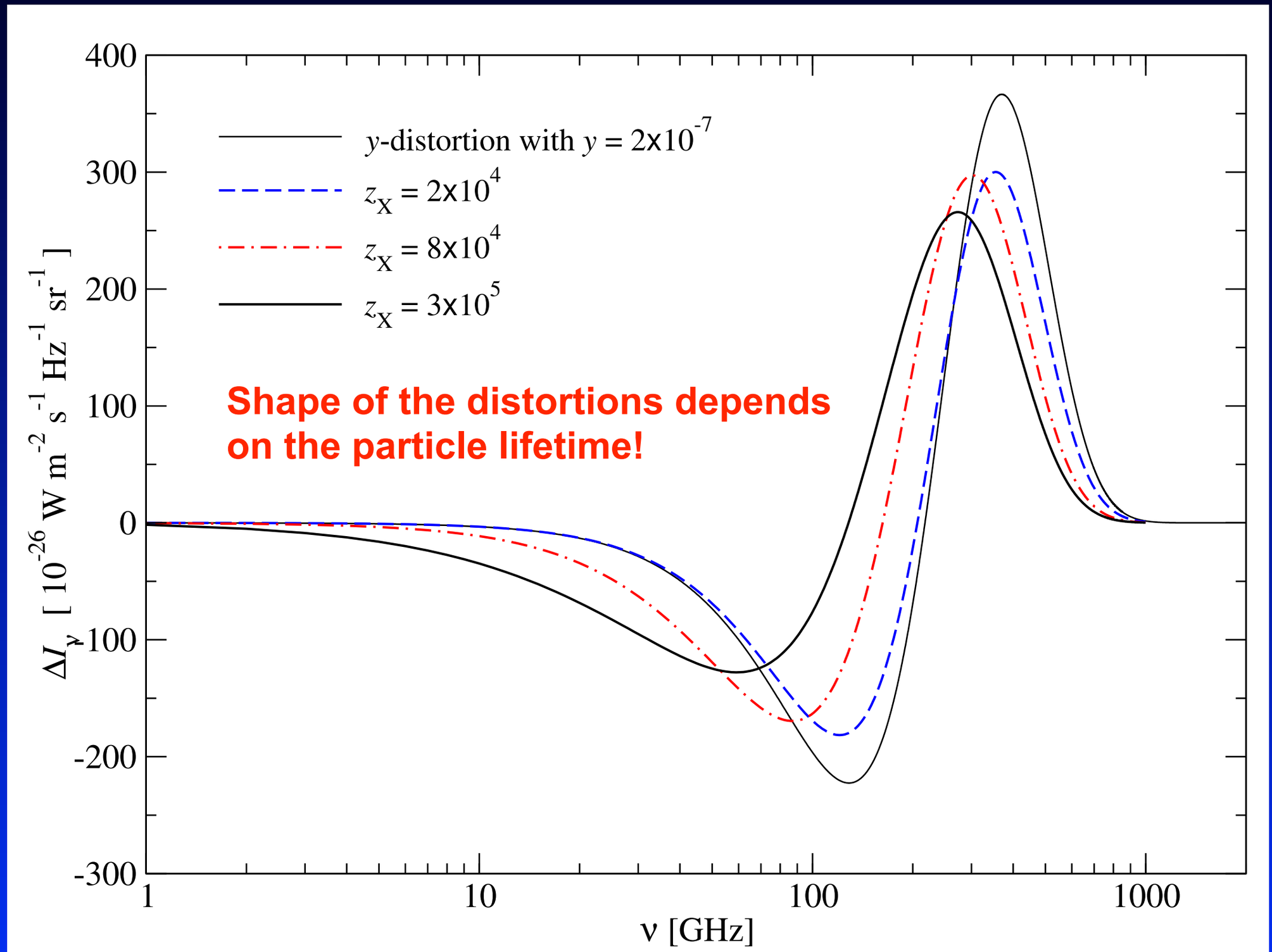

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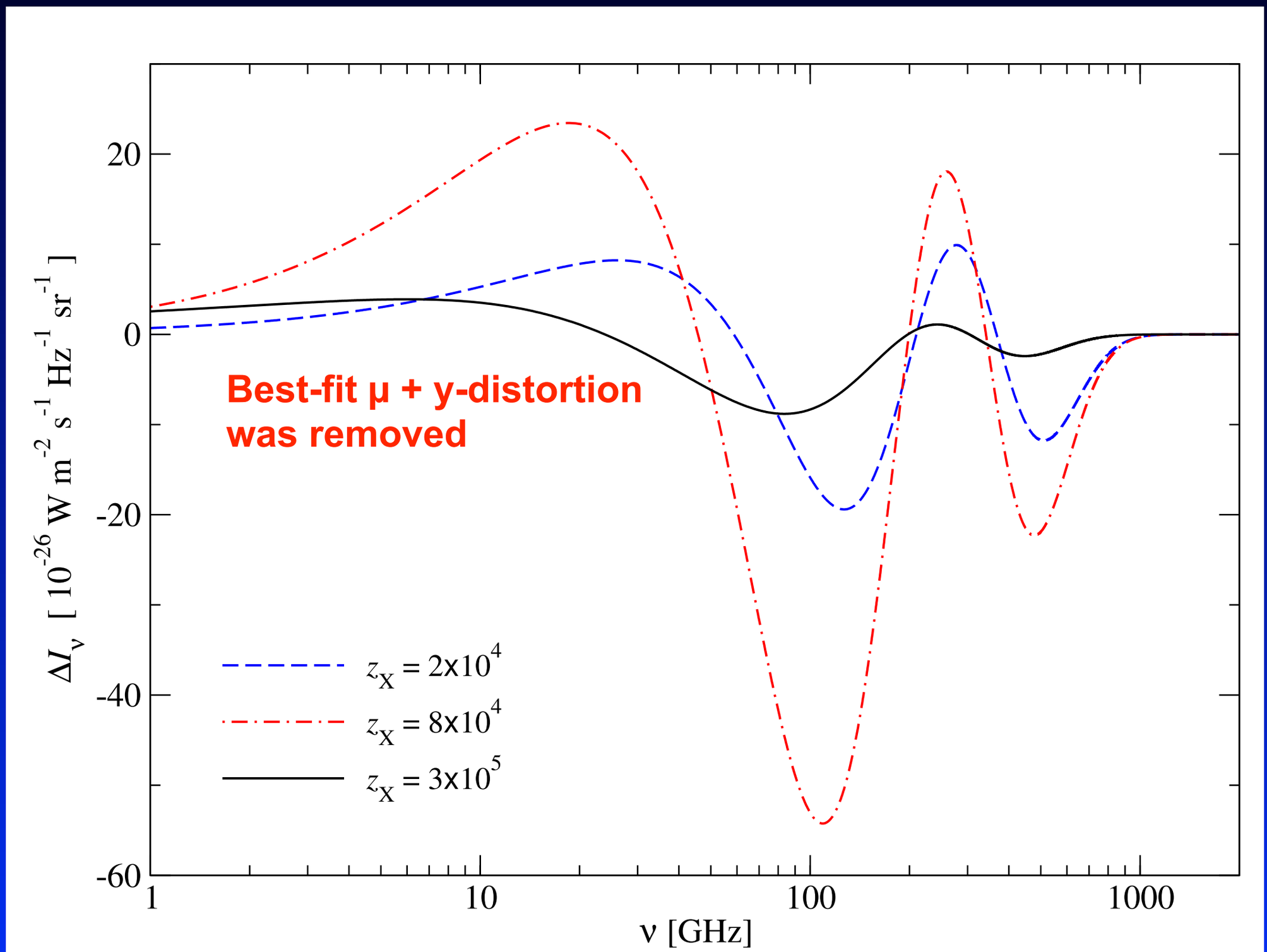
Decaying particle scenarios (information in residual)



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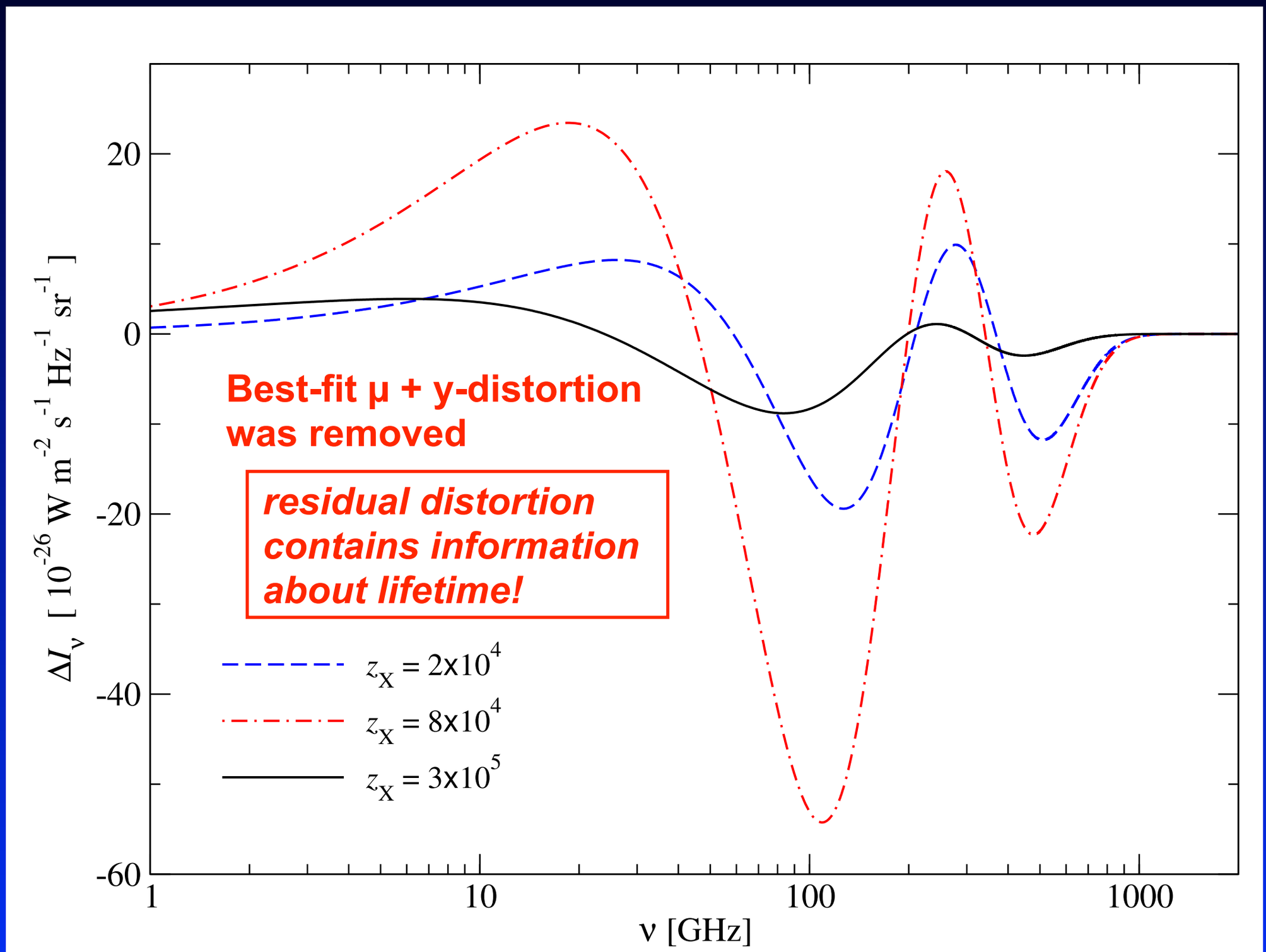

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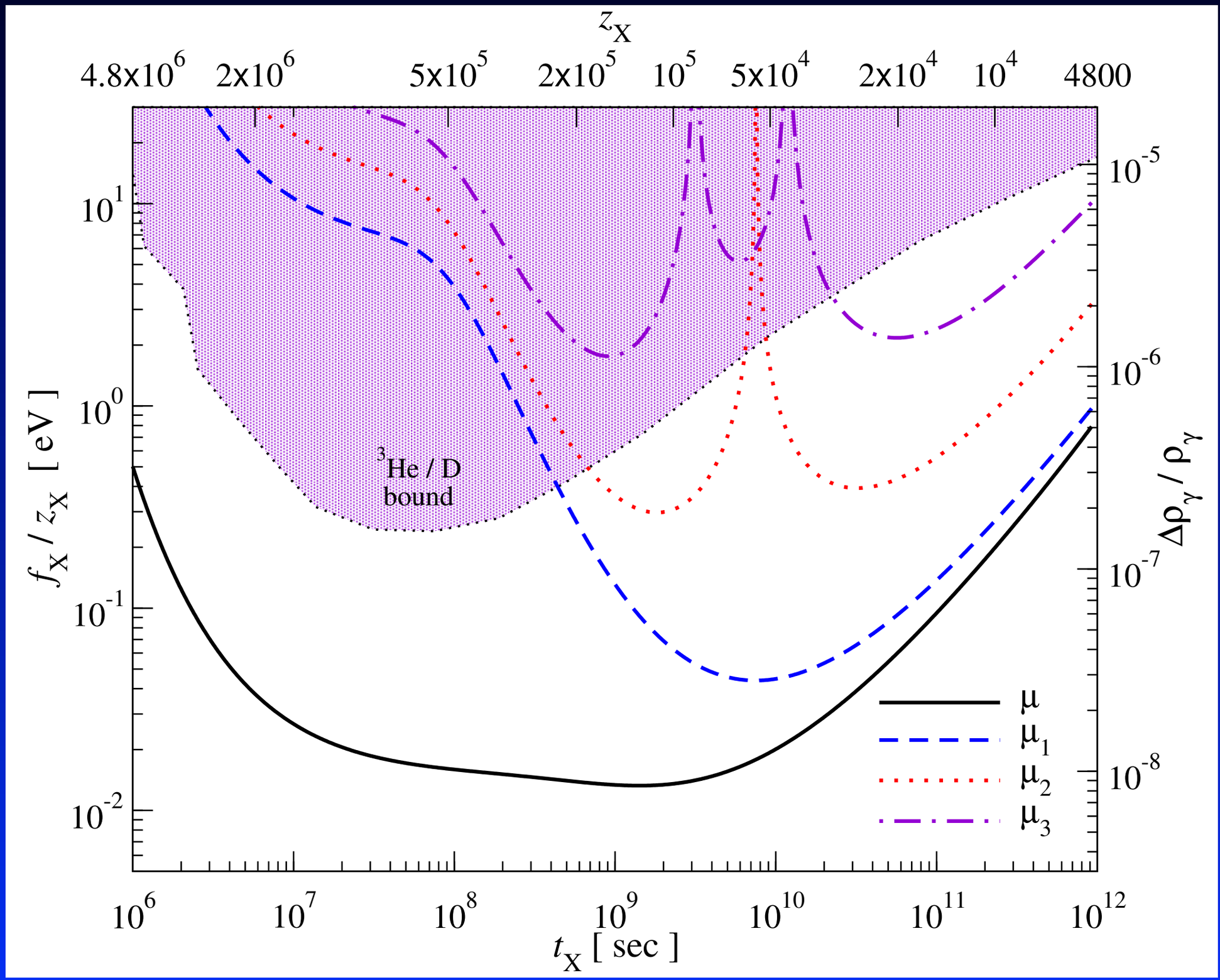
Decaying particle 1σ-detection limits for PIXIE



JC & Jeong, 2013

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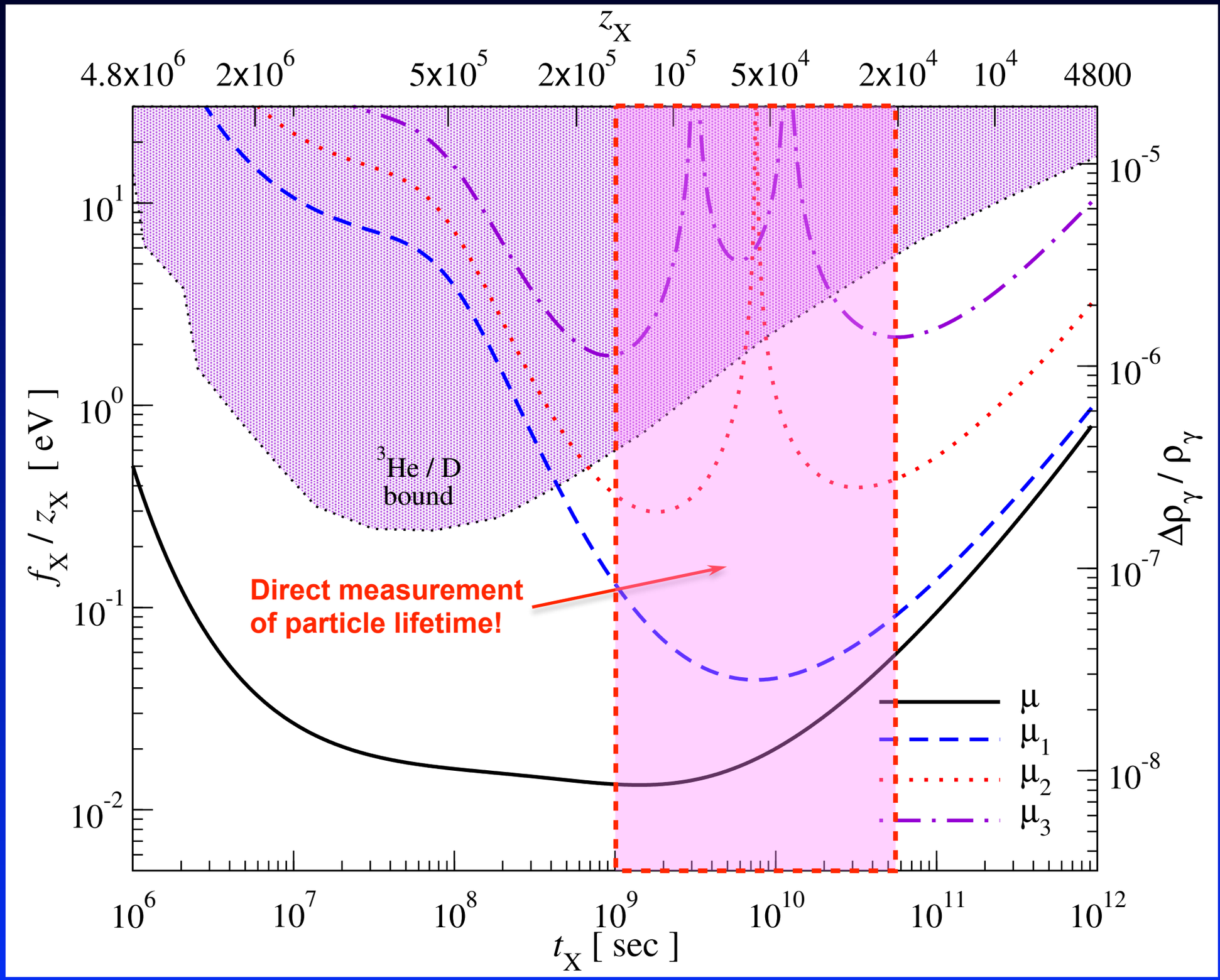
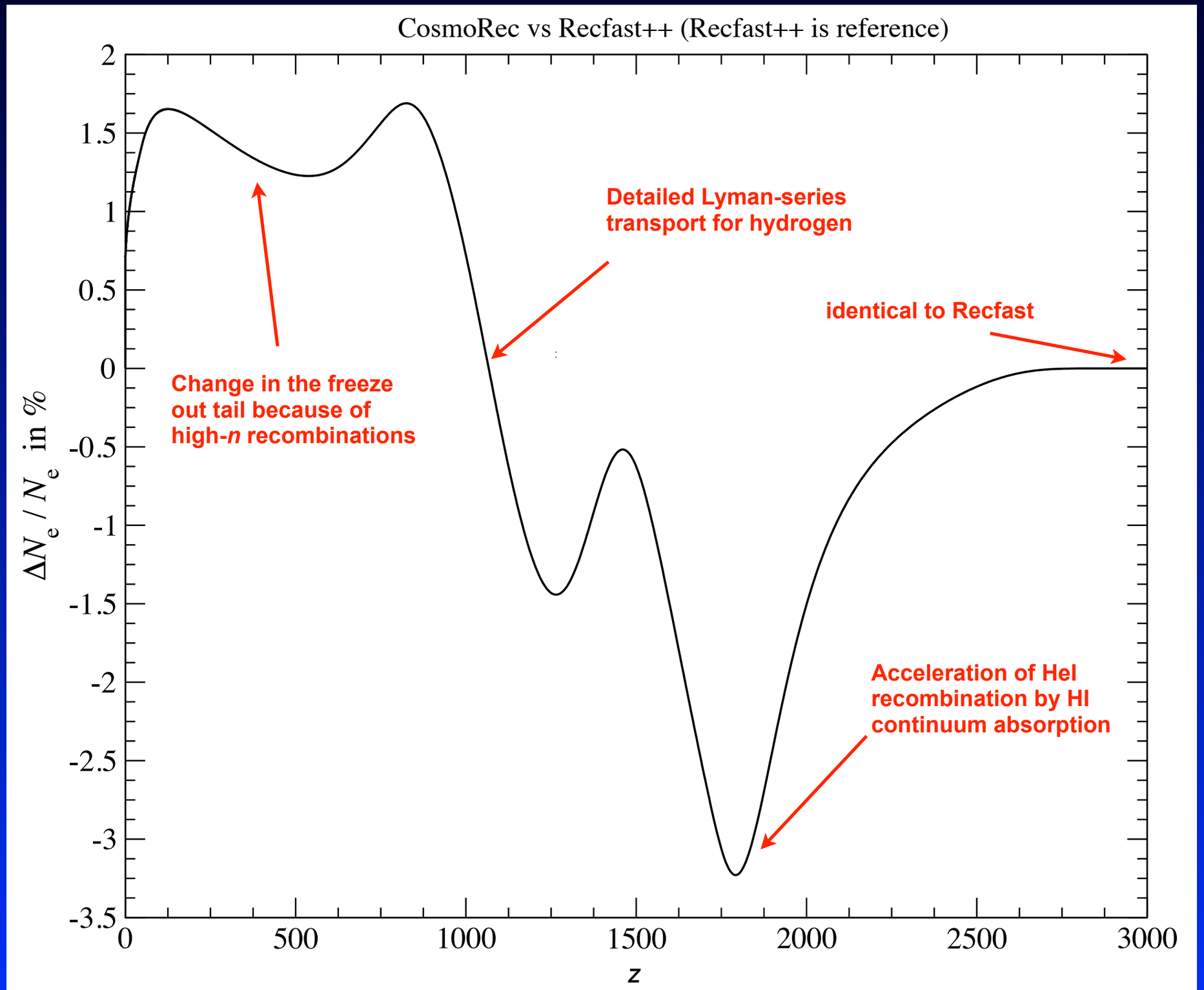


JC & Jeong, 2013

Cumulative Changes to the Ionization History



JC & Thomas, MNRAS, 2010; Shaw & JC, MNRAS, 2011

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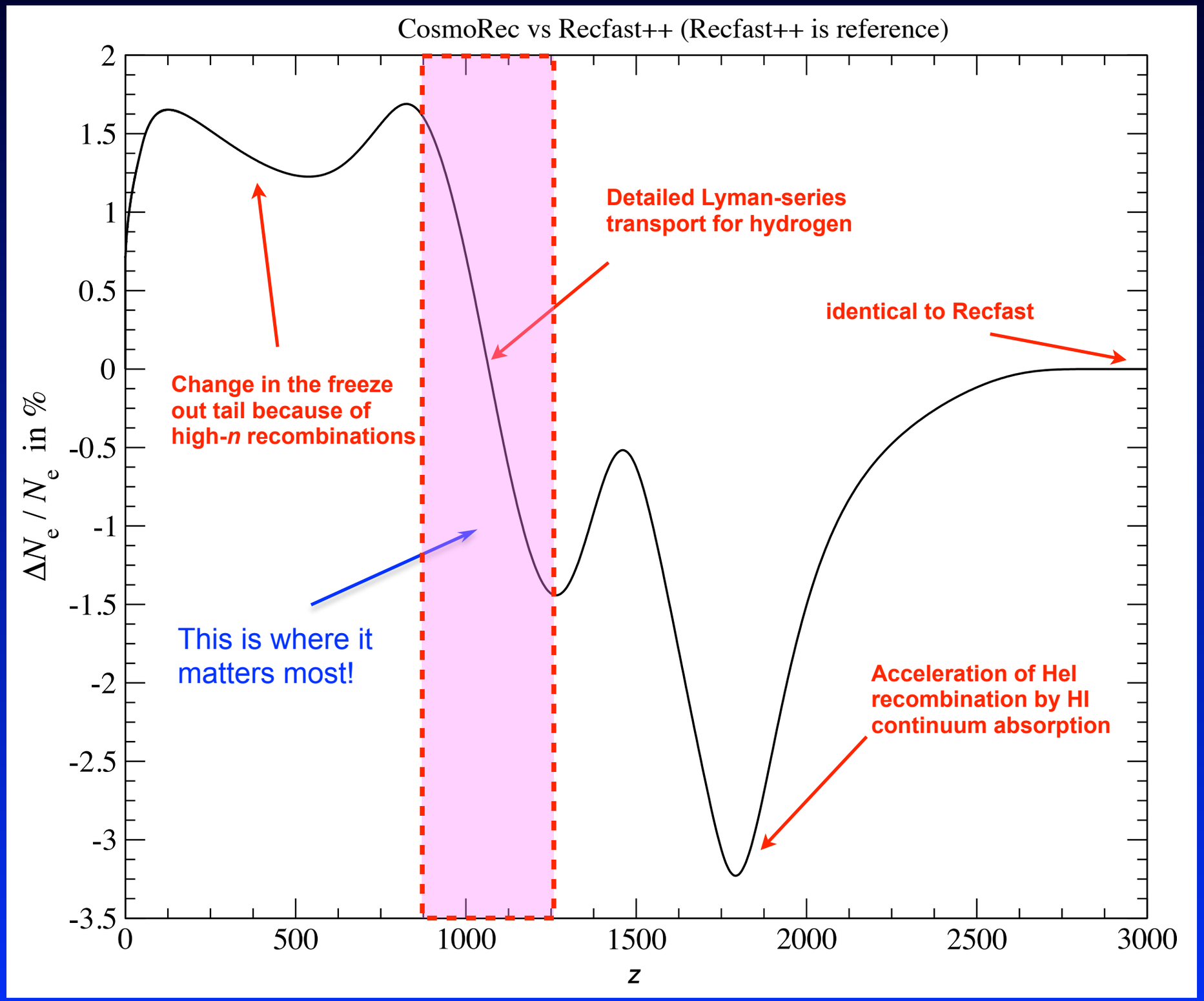
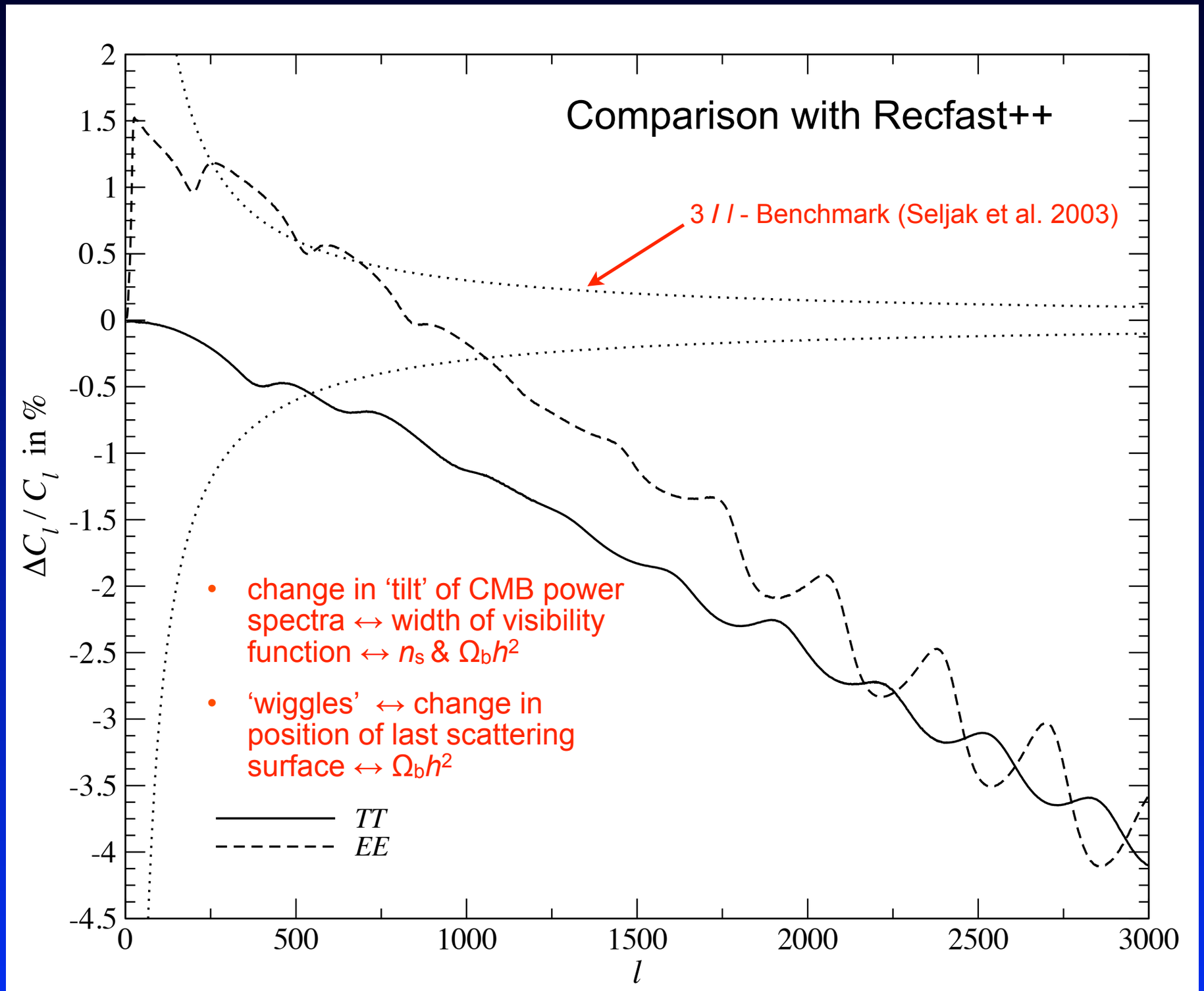


JC & Thomas, MNRAS, 2010; Shaw & JC, MNRAS, 2011

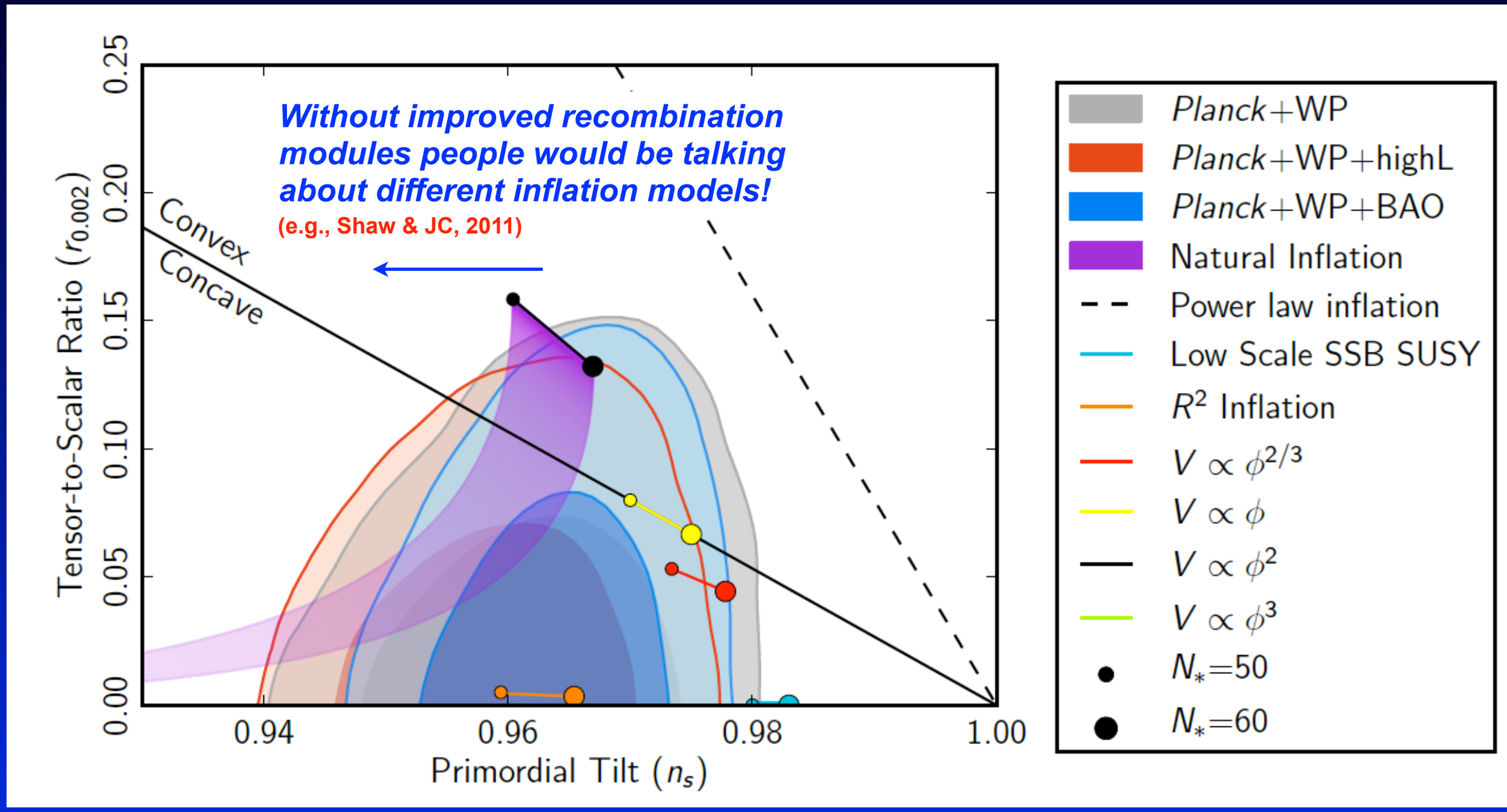
Cumulative Change in the CMB Power Spectra



CITA ICAT Canadian Institute for Theoretical Astrophysics / L'institut canadien d'astrophysique théorique

Shaw & JC, MNRAS, 2011

Importance of recombination for inflation constraints



Planck Collaboration, 2013, paper XXII

- Analysis uses refined recombination model (CosmoRec/HyRec)

What would we actually learn by doing such hard job?

Cosmological Recombination Spectrum opens a way to measure:

→ **the specific *entropy* of our universe (related to $\Omega_b h^2$)**

→ **the CMB *monopole* temperature T_0**

→ ***the pre-stellar abundance of helium Y_p***

→ ***If recombination occurs as we think it does, then the lines can be predicted with very high accuracy!***

→ ***In principle allows us to directly check our understanding of the standard recombination physics***

If something unexpected or non-standard happened:

→ ***non-standard thermal histories should leave some measurable traces***

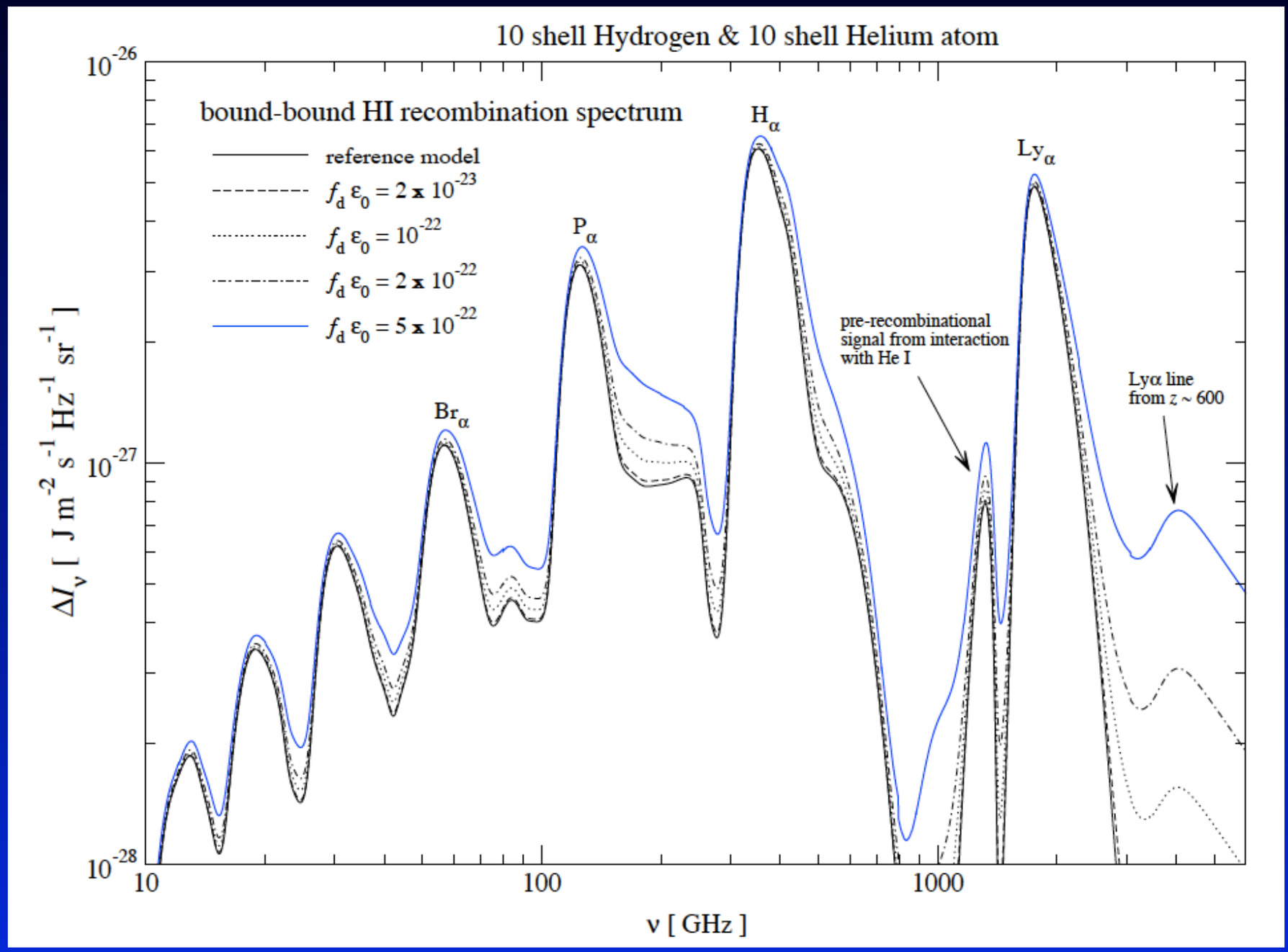
→ ***direct way to measure/reconstruct the recombination history!***

→ **possibility to distinguish *pre-* and *post-recombination y*-type distortions**

→ ***sensitive to energy release during recombination***

→ **variation of fundamental constants**

Dark matter annihilations / decays



JC, 2009, arXiv:0910.3663

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