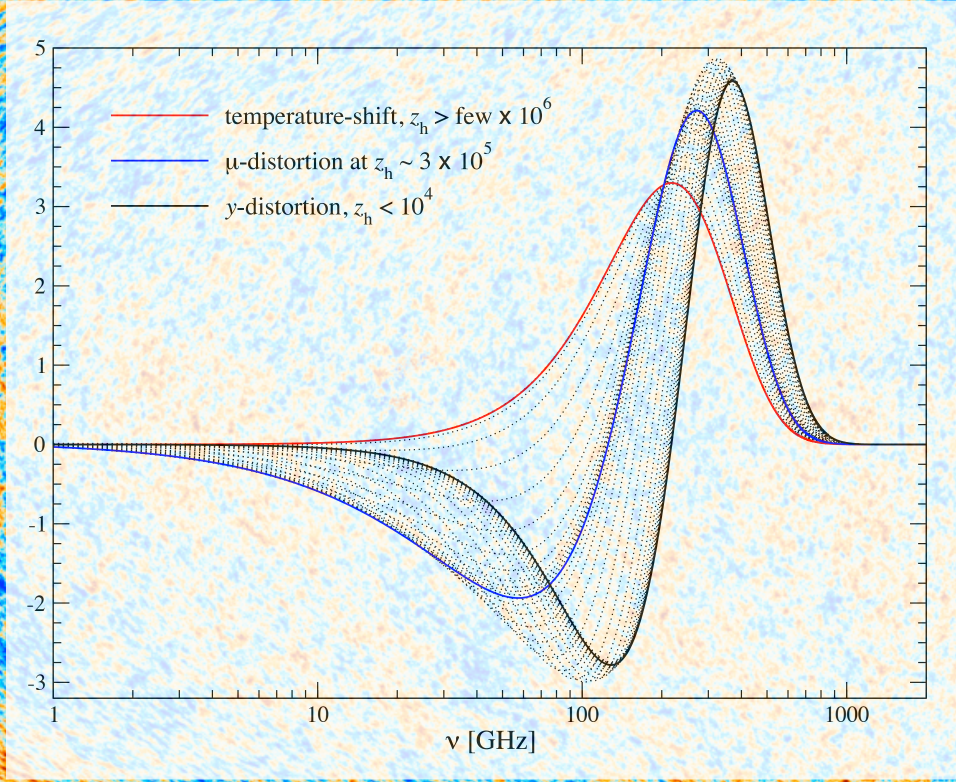
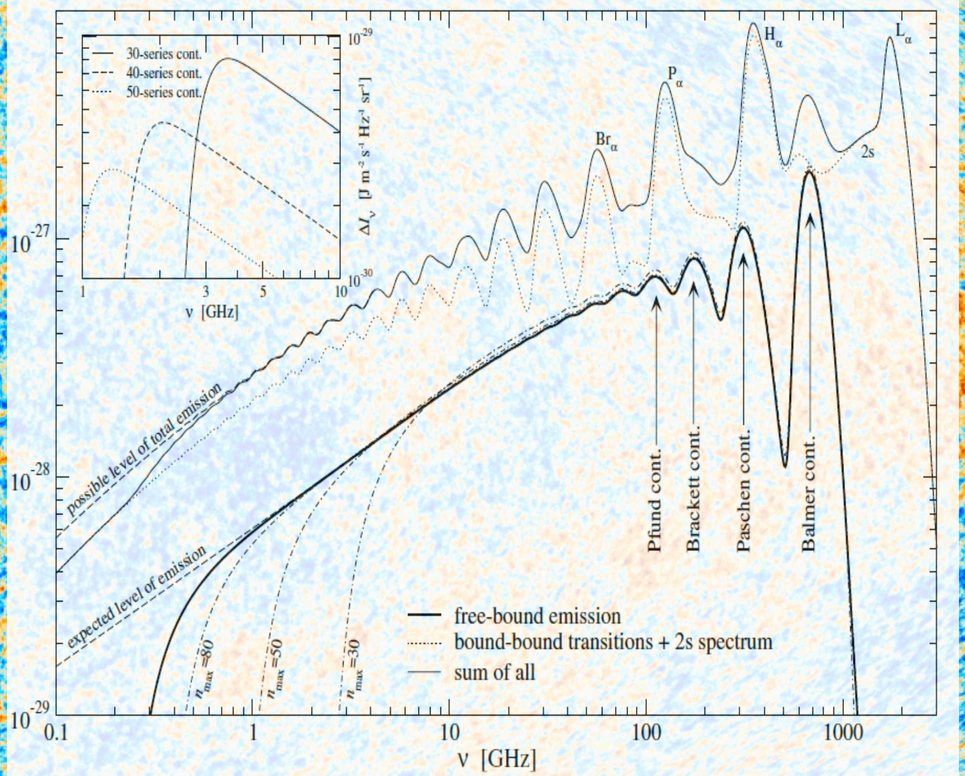
CMB Spectroscopy: What Spectral Distortions Could Add

Primordial Distortions



Cosmological Recombination lines



Jens Chluba

Towards a European Coordination of the CMB Program

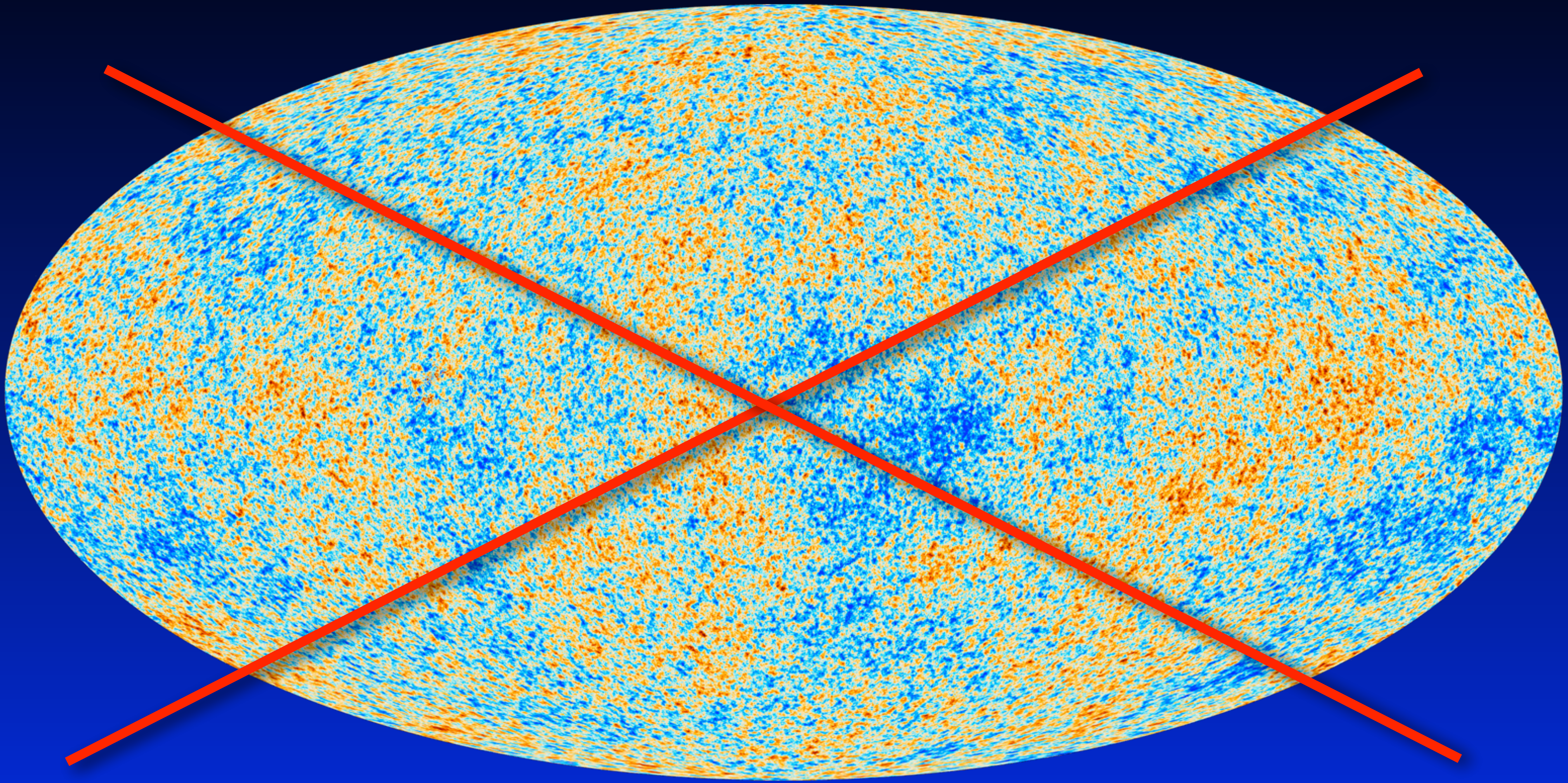
Florence, 20-21 September 2018

MANCHESTER 1824
The University of Manchester

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 $\Delta T/T \sim 10^{-5}$

CMB provides another independent piece of information!

COBE/FIRAS

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

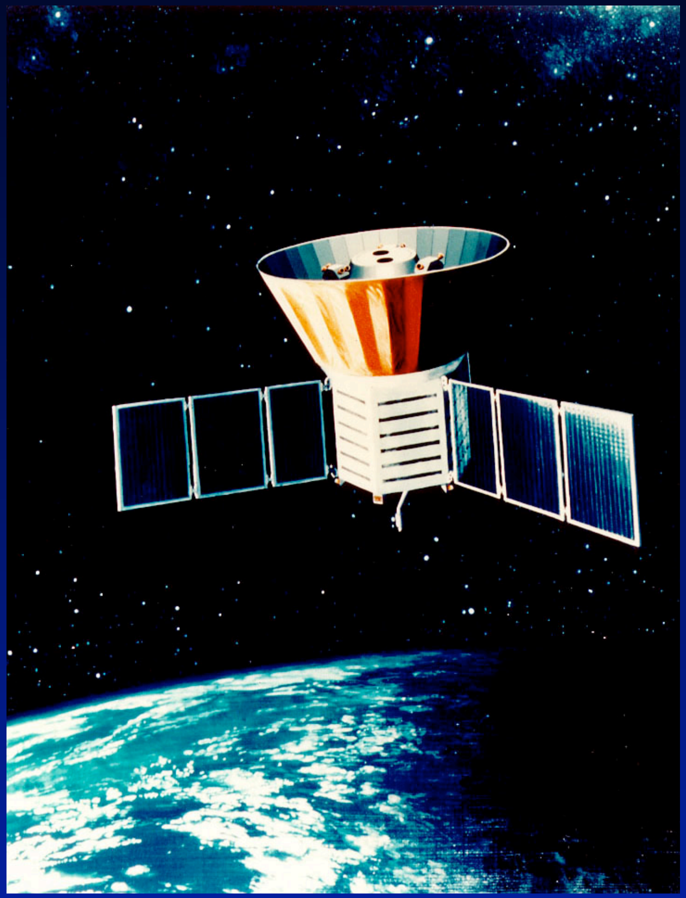
Absolute measurement required!

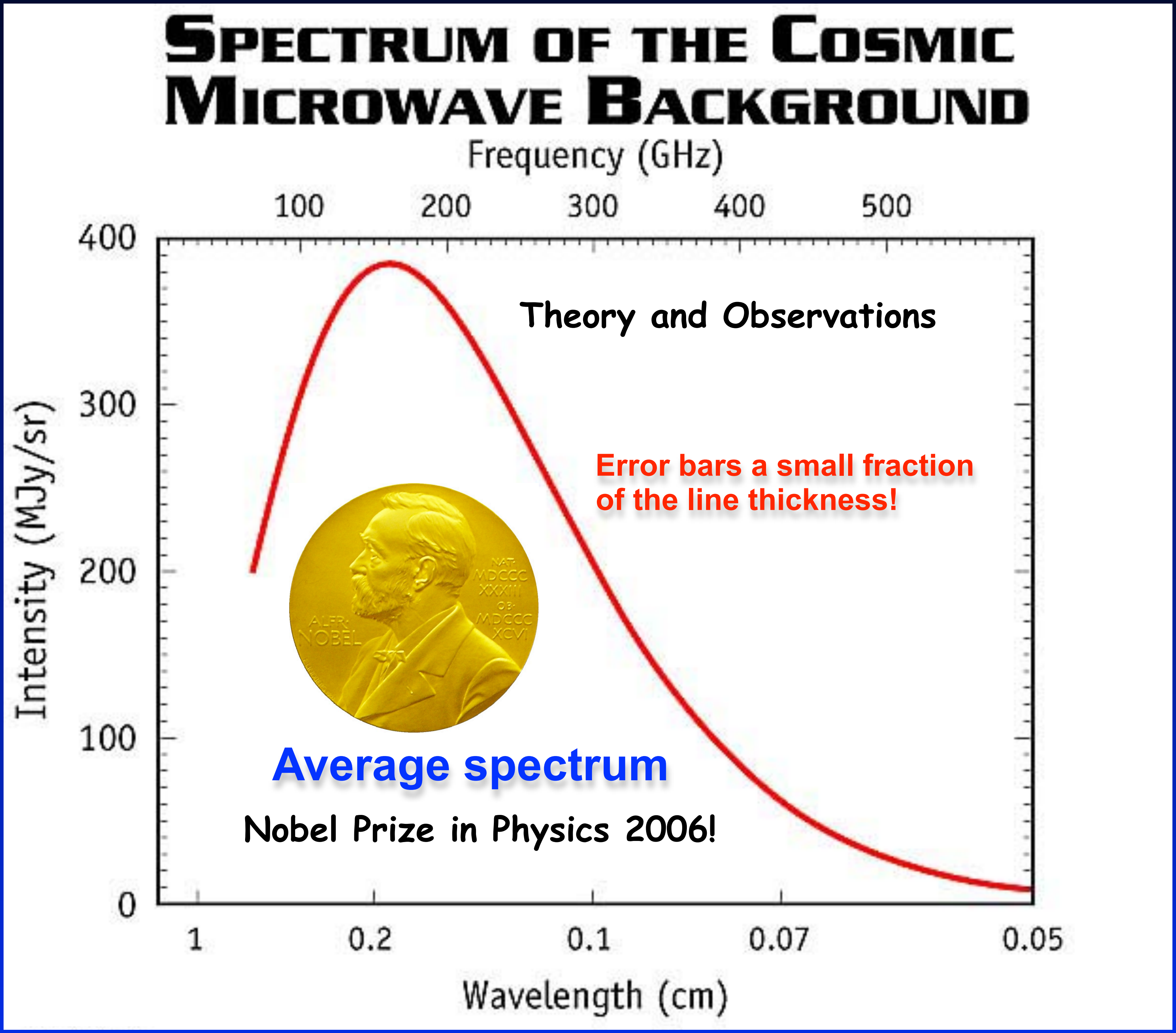
(One has to go to space...)

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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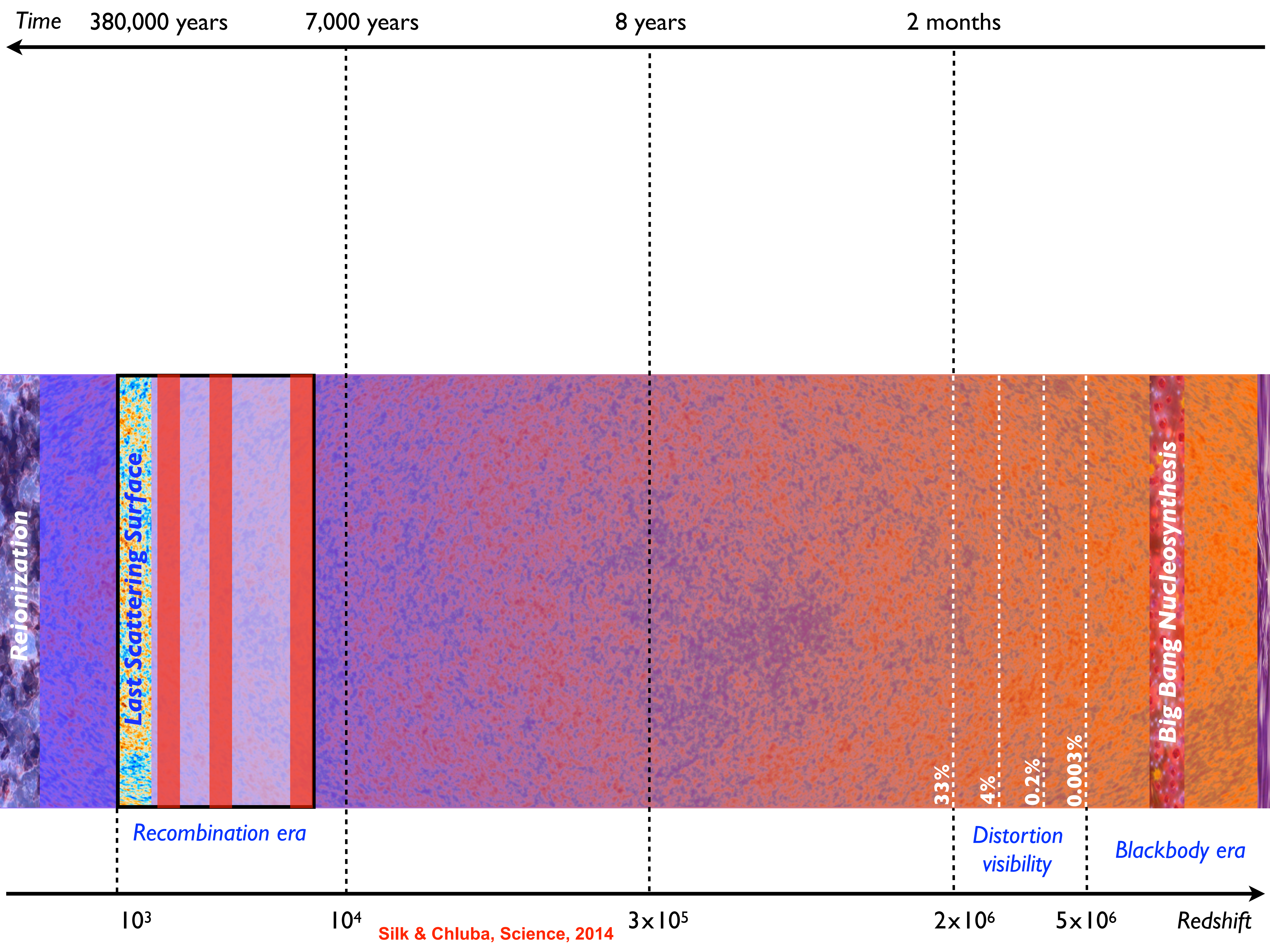
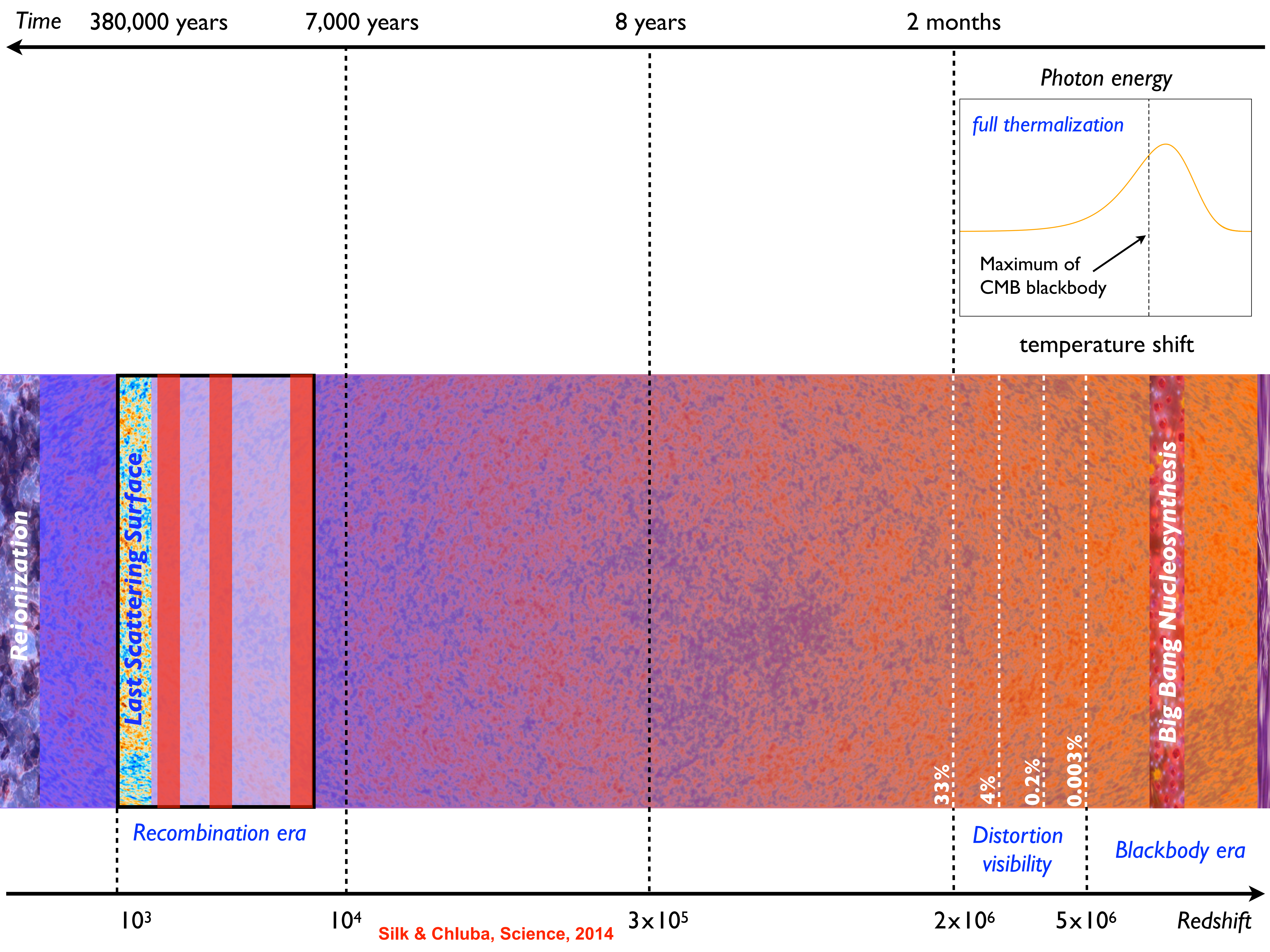


Time
380,000 years
7,000 years
8 years
2 months
Reionization
Last Scattering Surface
33%
4%
0.2%
0.003%
Big Bang Nucleosynthesis
Recombination era
Distortion visibility
Blackbody era
10^3
10^4
3×10^5
2×10^6
5×10^6
Redshift
Silk & Chluba, Science, 2014



Time
380,000 years
7,000 years
8 years
2 months
Photon energy
full thermalization
Maximum of
CMB blackbody
temperature shift
Reionization
Last Scattering Surface
33%
4%
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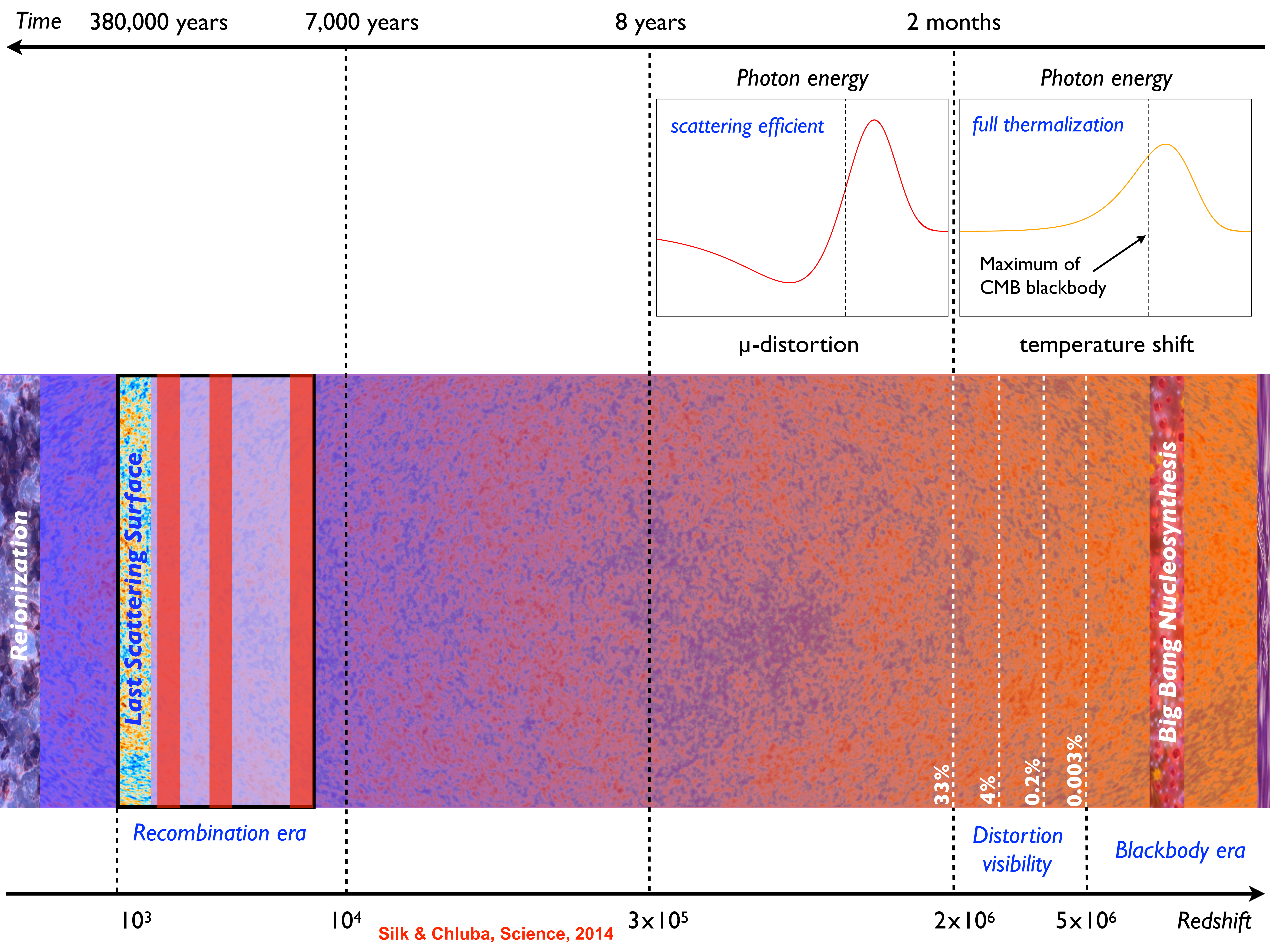
Time
380,000 years
7,000 years
8 years
2 months
Photon energy
scattering efficient
μ-distortion
Photon energy
full thermalization
Maximum of CMB blackbody
temperature shift
Reionization
Last Scattering Surface
33%
4%
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Big Bang Nucleosynthesis
Recombination era
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10³
10⁴
3x10⁵
2x10⁶
5x10⁶
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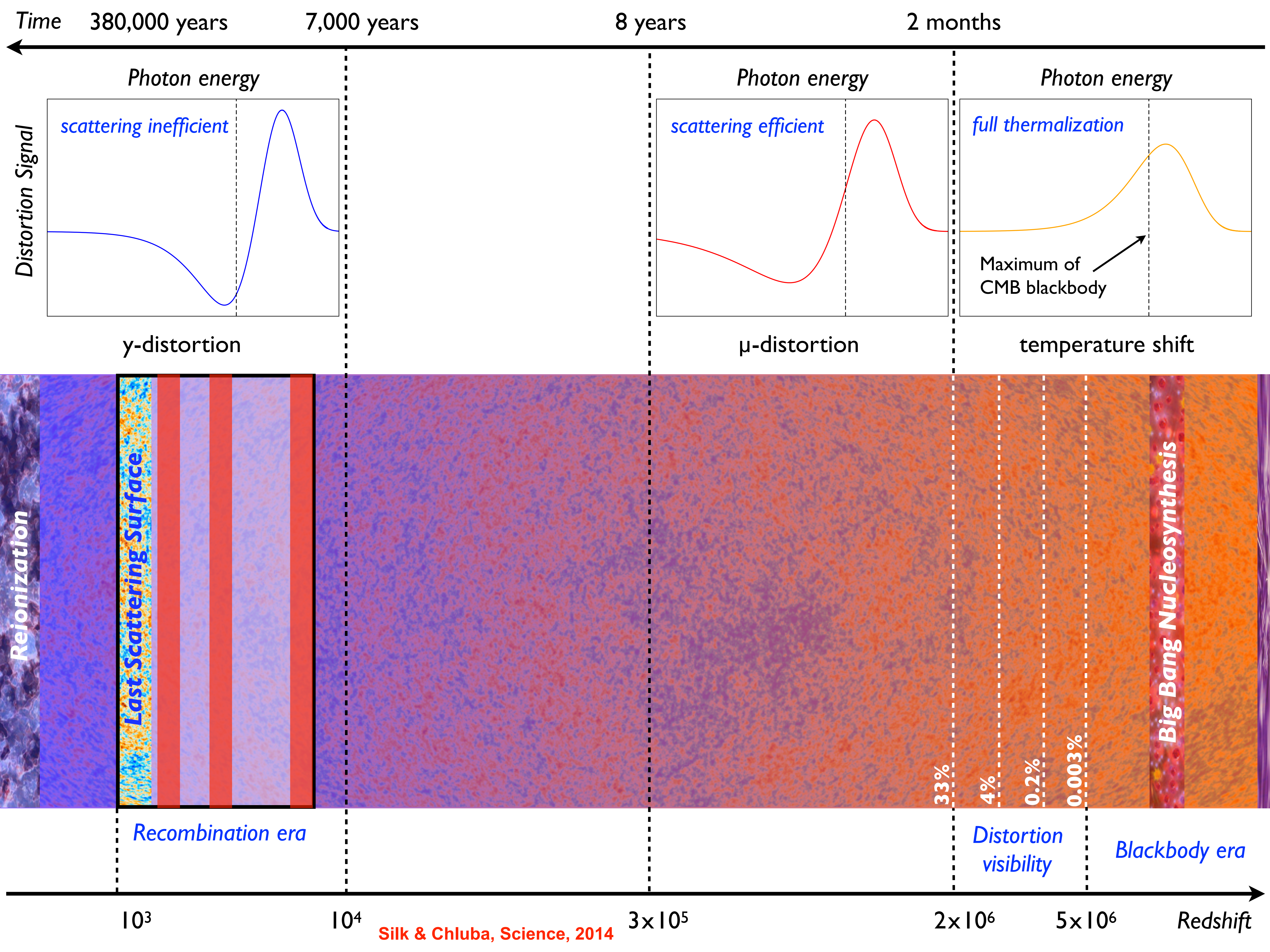
Silk & Chluba, Science, 2014



Time
380,000 years
7,000 years
8 years
2 months
Photon energy
Photon energy
Photon energy
Distortion Signal
scattering inefficient
scattering efficient
full thermalization
Maximum of
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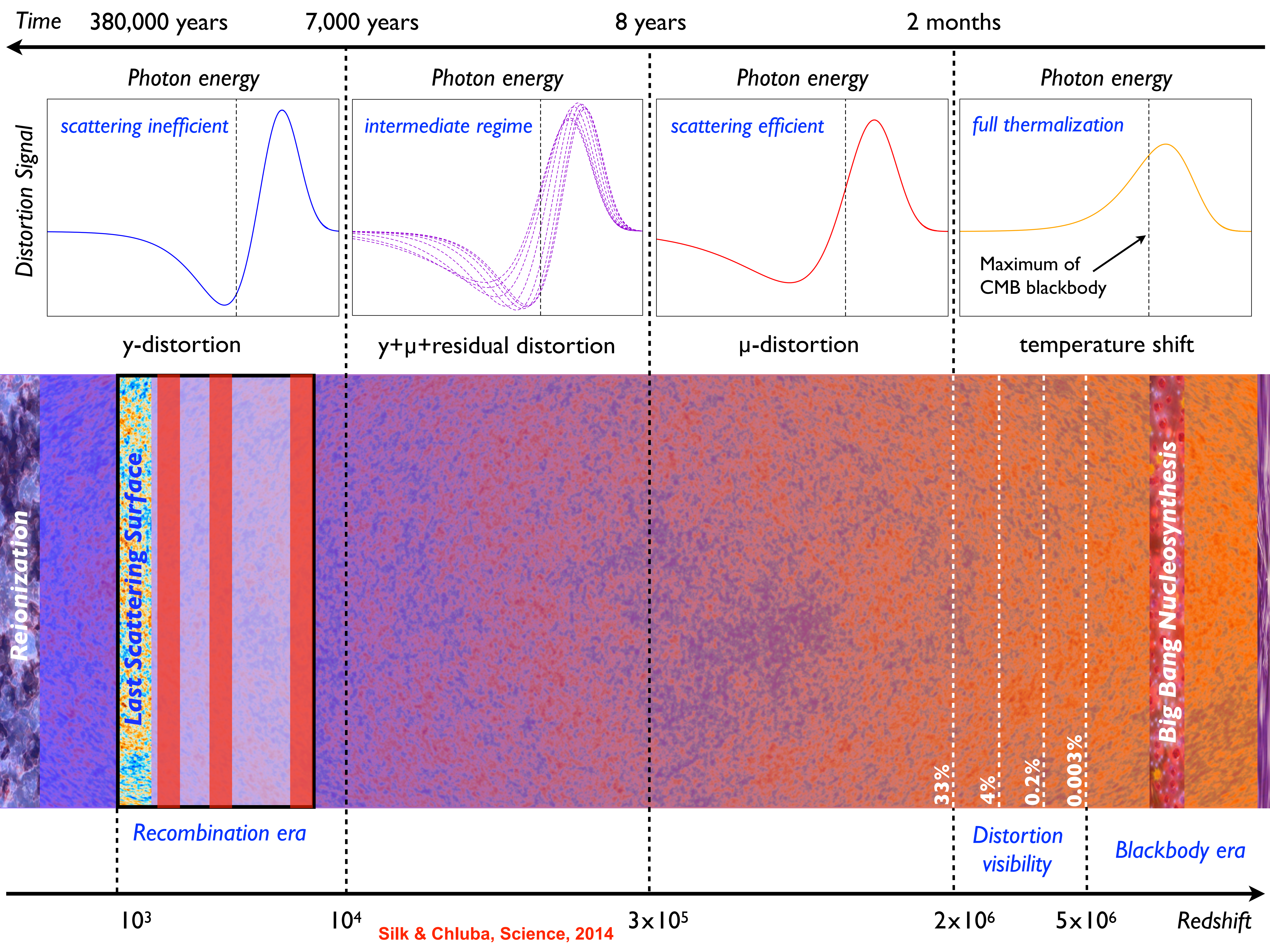

Time
380,000 years
7,000 years
8 years
2 months
Photon energy
Photon energy
Photon energy
Photon energy
Distortion Signal
scattering inefficient
intermediate regime
scattering efficient
full thermalization
Maximum of
CMB blackbody
y-distortion
y+μ+residual distortion
μ-distortion
temperature shift
Reionization
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Big Bang Nucleosynthesis
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10^3
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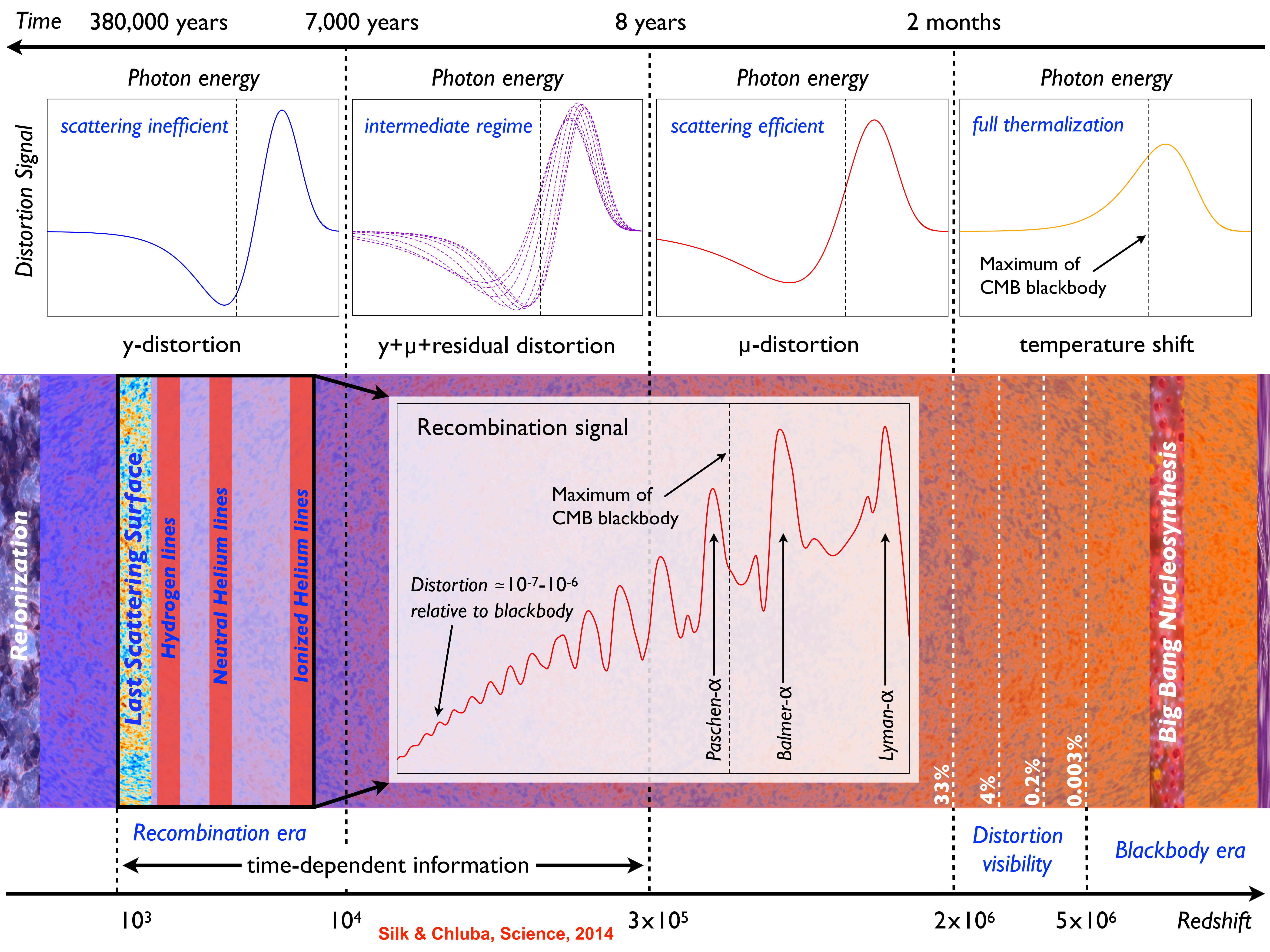

Time
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7,000 years
8 years
2 months
Distortion Signal
Photon energy
scattering inefficient
y-distortion
Photon energy
intermediate regime
y+μ+residual distortion
Photon energy
scattering efficient
μ-distortion
Photon energy
full thermalization
Maximum of CMB blackbody
temperature shift
Reionization
Last Scattering Surface
Hydrogen lines
Neutral Helium lines
Ionized Helium lines
Recombination signal
Maximum of CMB blackbody
Distortion ≃10^-7-10^-6 relative to blackbody
Paschen-α
Balmer-α
Lyman-α
33%
4%
0.2%
0.003%
Big Bang Nucleosynthesis
Recombination era
time-dependent information
Distortion visibility
Blackbody era
10^3
10^4
3x10^5
2x10^6
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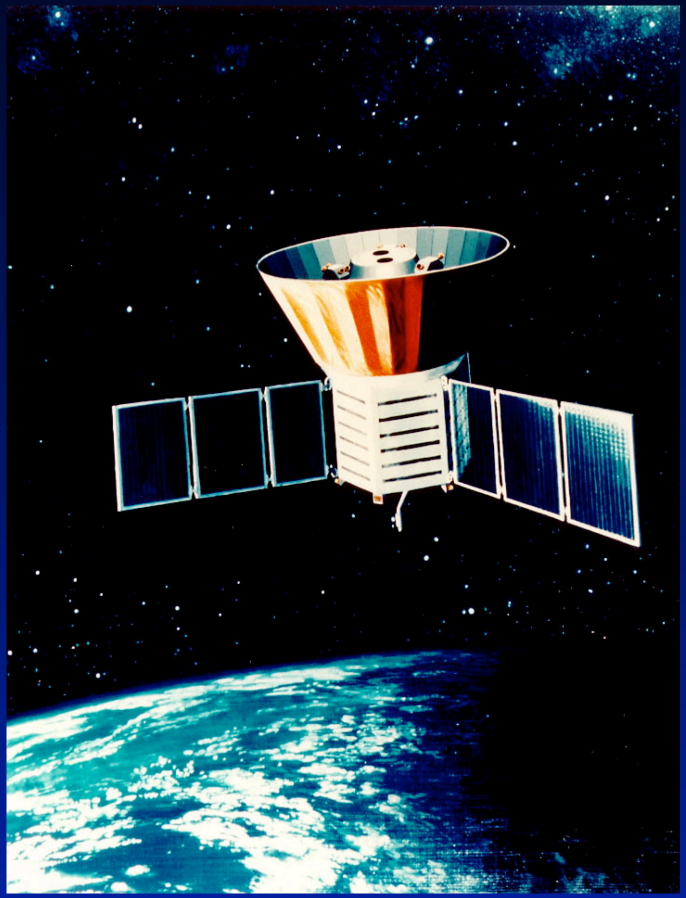
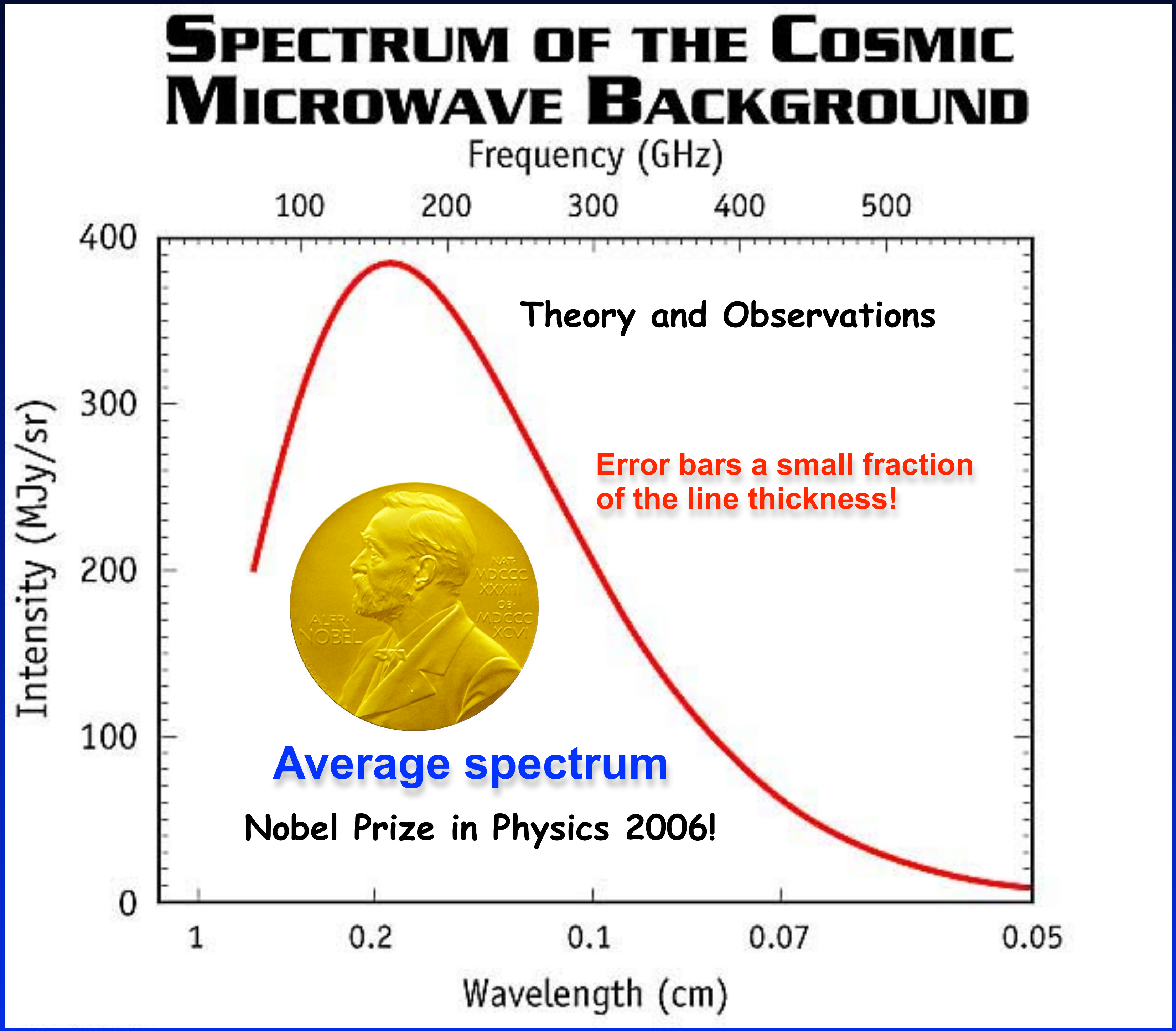
Redshift
Silk & Chluba, Science, 2014

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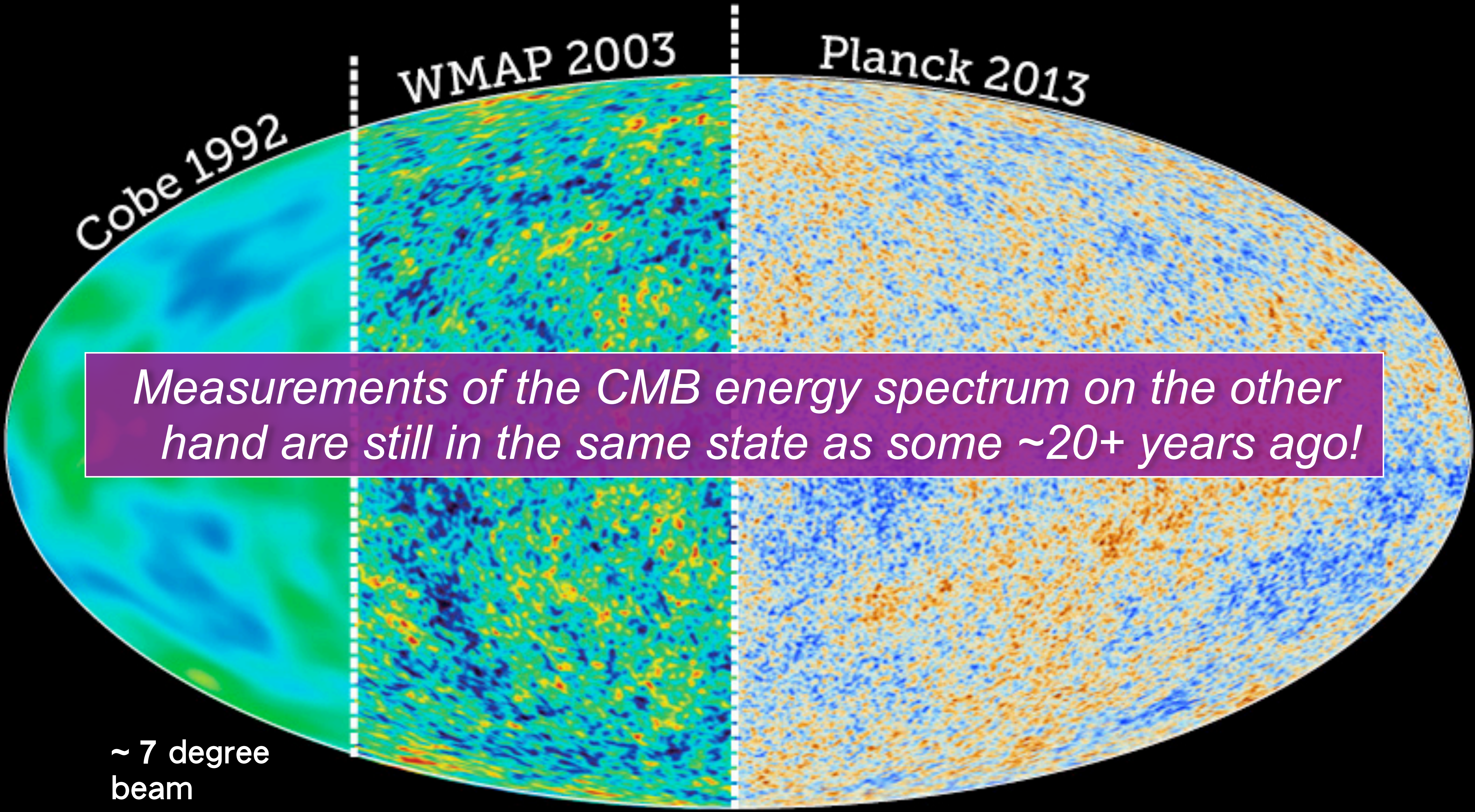
Dramatic improvements in angular resolution and sensitivity over the past decades!



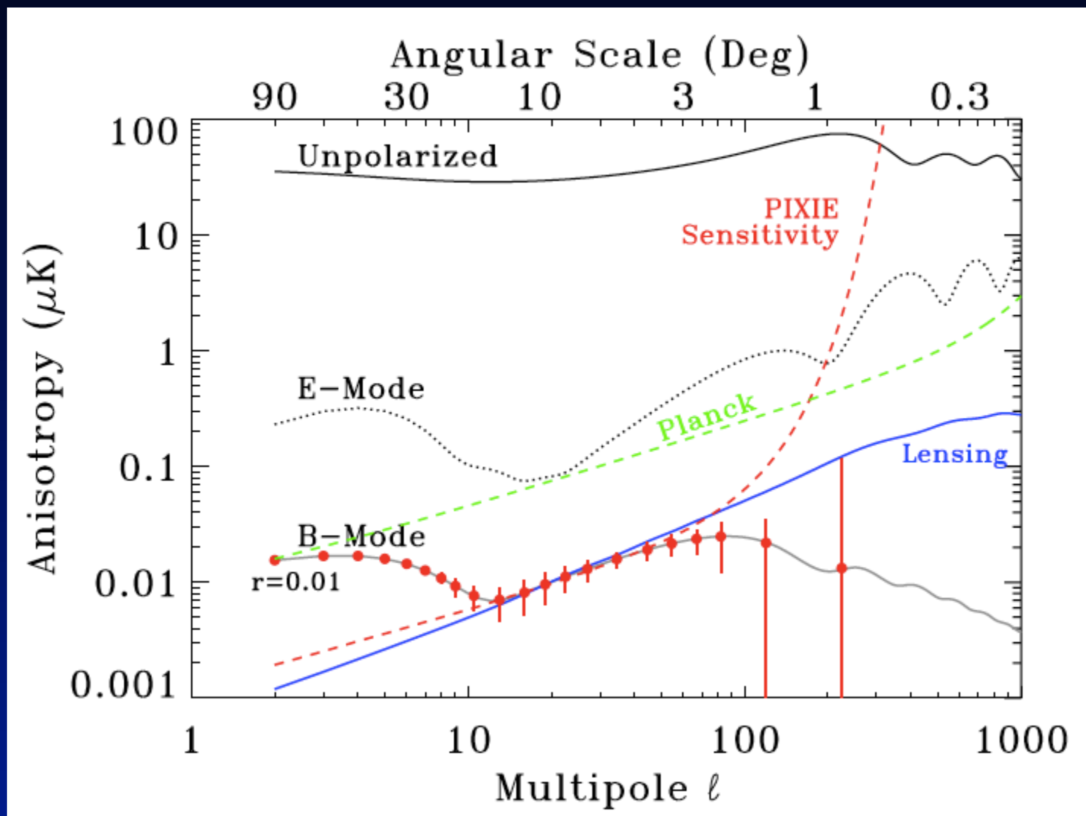
Measurements of the CMB energy spectrum on the other hand are still in the same state as some ~20+ years ago!

~ 7 degree beam

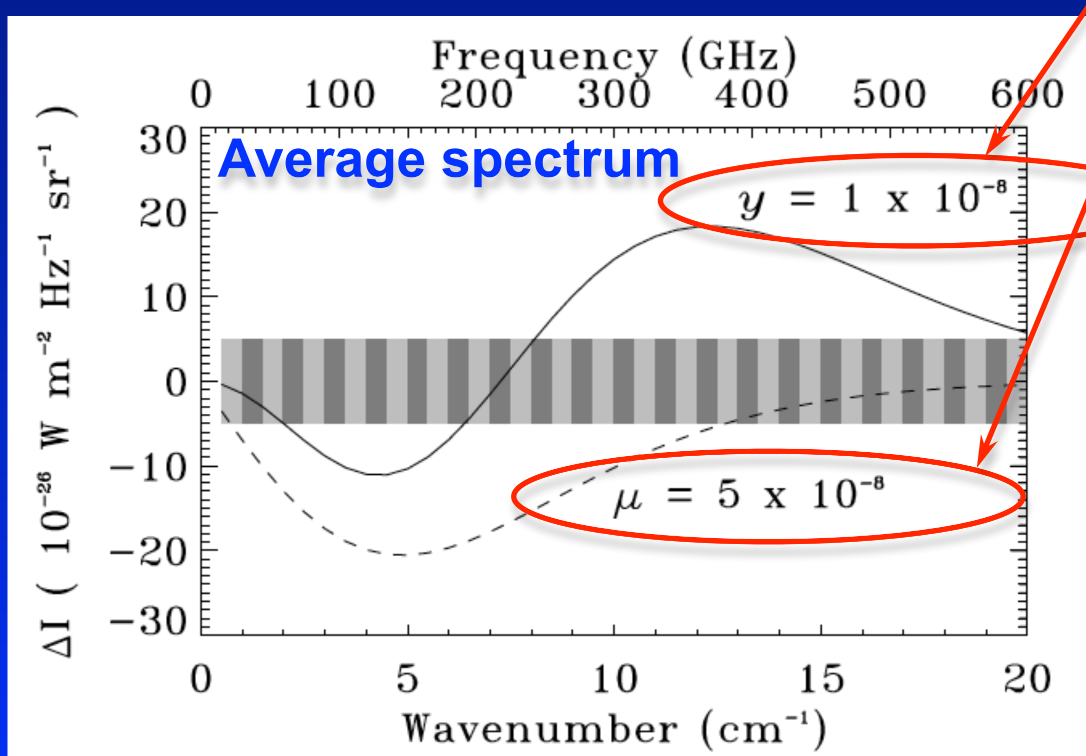
~ 0.3 degree beam

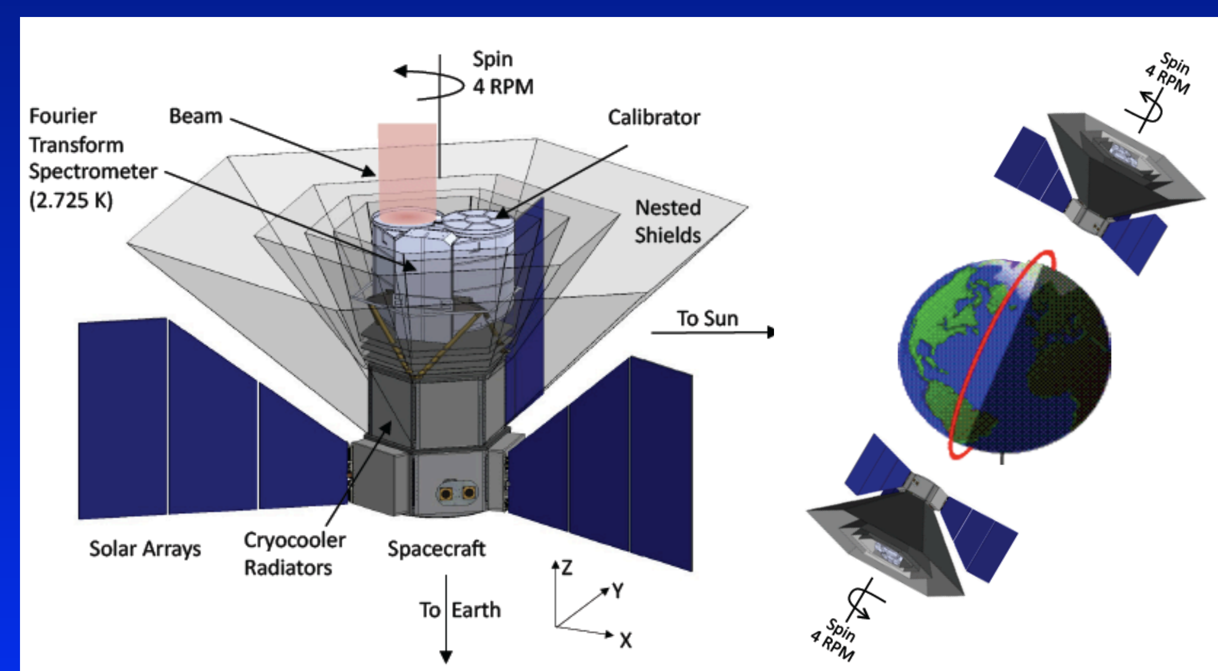
~ 0.08 degree beam

PIXIE: Primordial Inflation Explorer

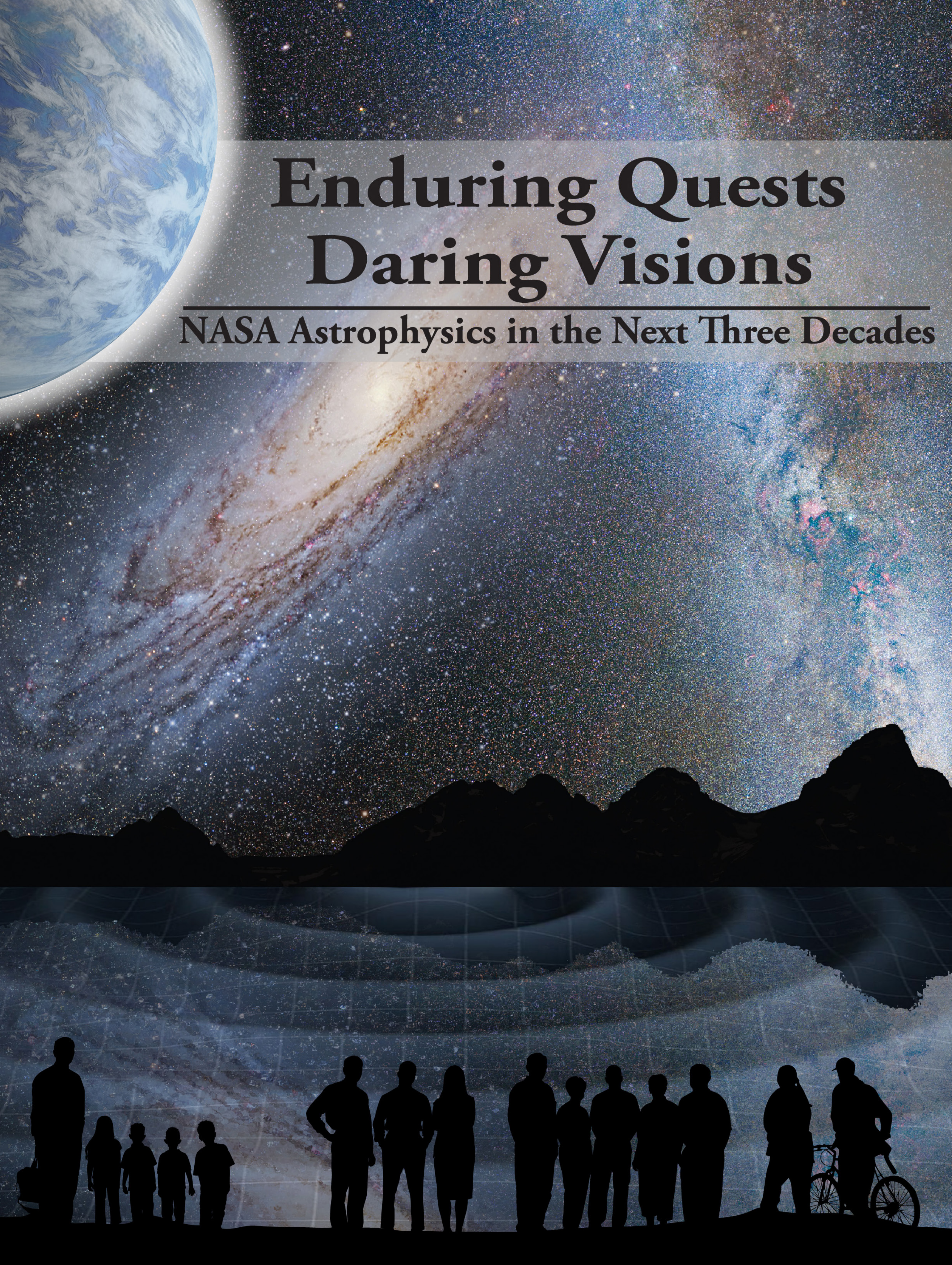


- 400 spectral channel in the frequency range 30 GHz and 6THz (Δv ~ 15GHz)
- about 1000 (!!!) times more sensitive than COBE/FIRAS
- B-mode polarization from inflation ($r \approx 10^{-3}$)
- improved limits on μ and y
- was proposed 2011 & 2016 as NASA EX mission (i.e. cost ~ 200-250 M$)





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."

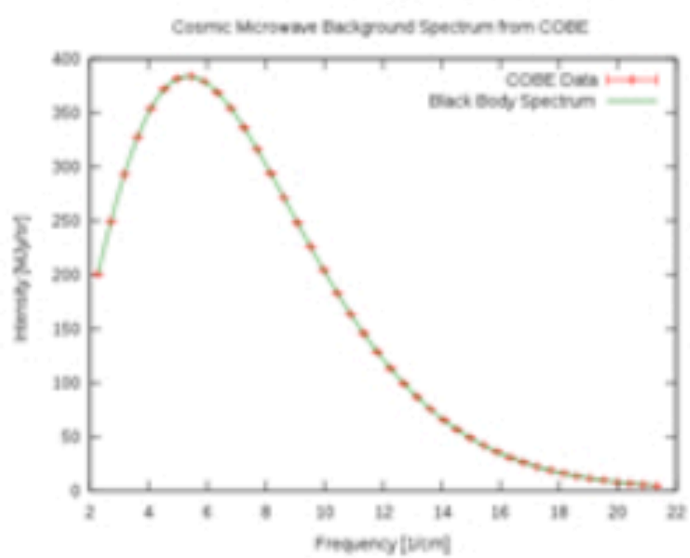
New mission concepts:

PRISTINE (France)
CMB-Bharat (India)

Decadal Survey

White papers for Jan 2019

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.

Details in Rao et al., ArXiv:1501.07191

COSMO at Dome C

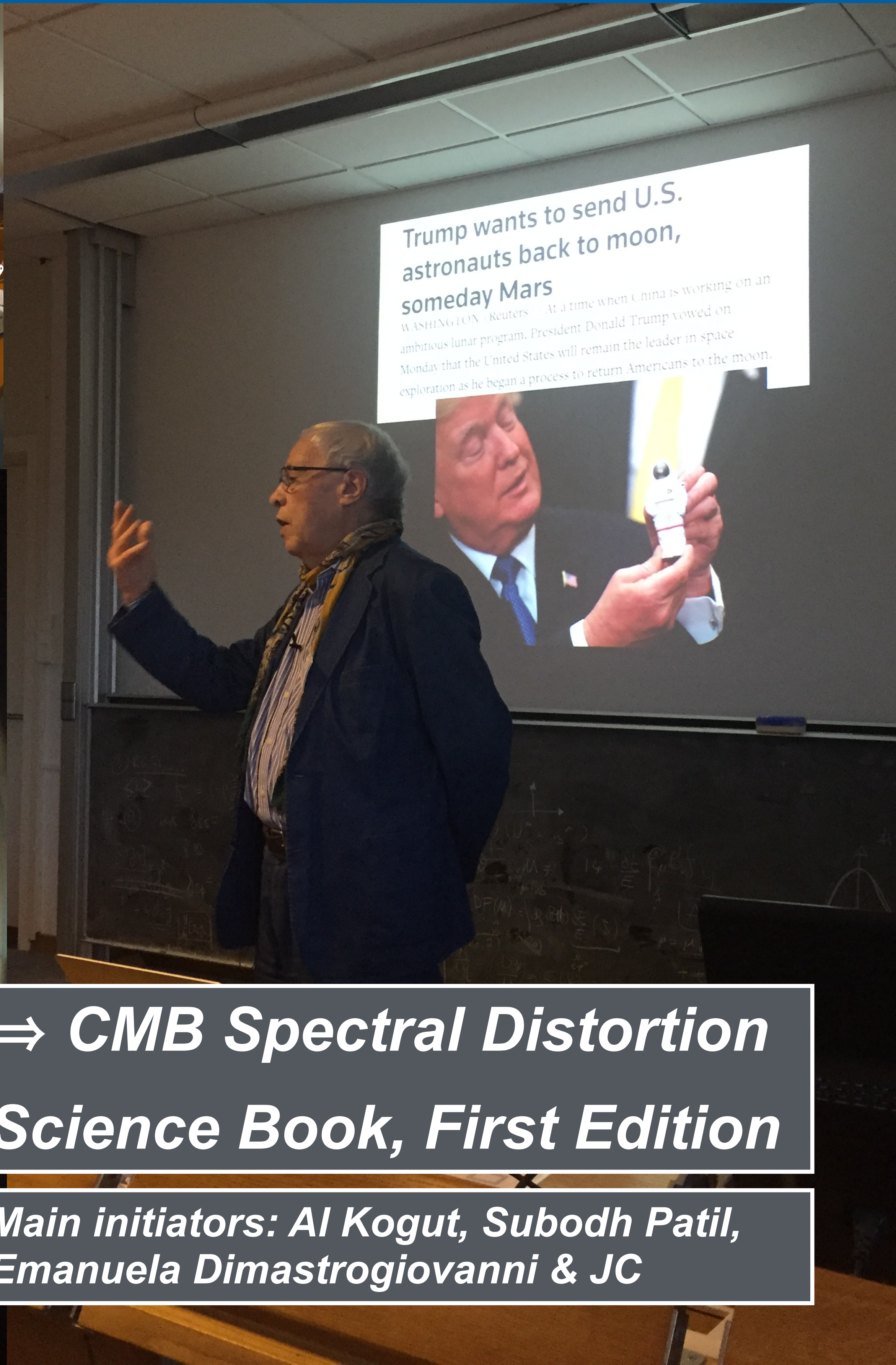
COSmological **M**onopole **O**bserver

Taken from a talk by Elia Battistelli

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)



⇒ *CMB Spectral Distortion Science Book, First Edition*

Main initiators: Al Kogut, Subodh Patil, Emanuela Dimastrogiovanni & JC

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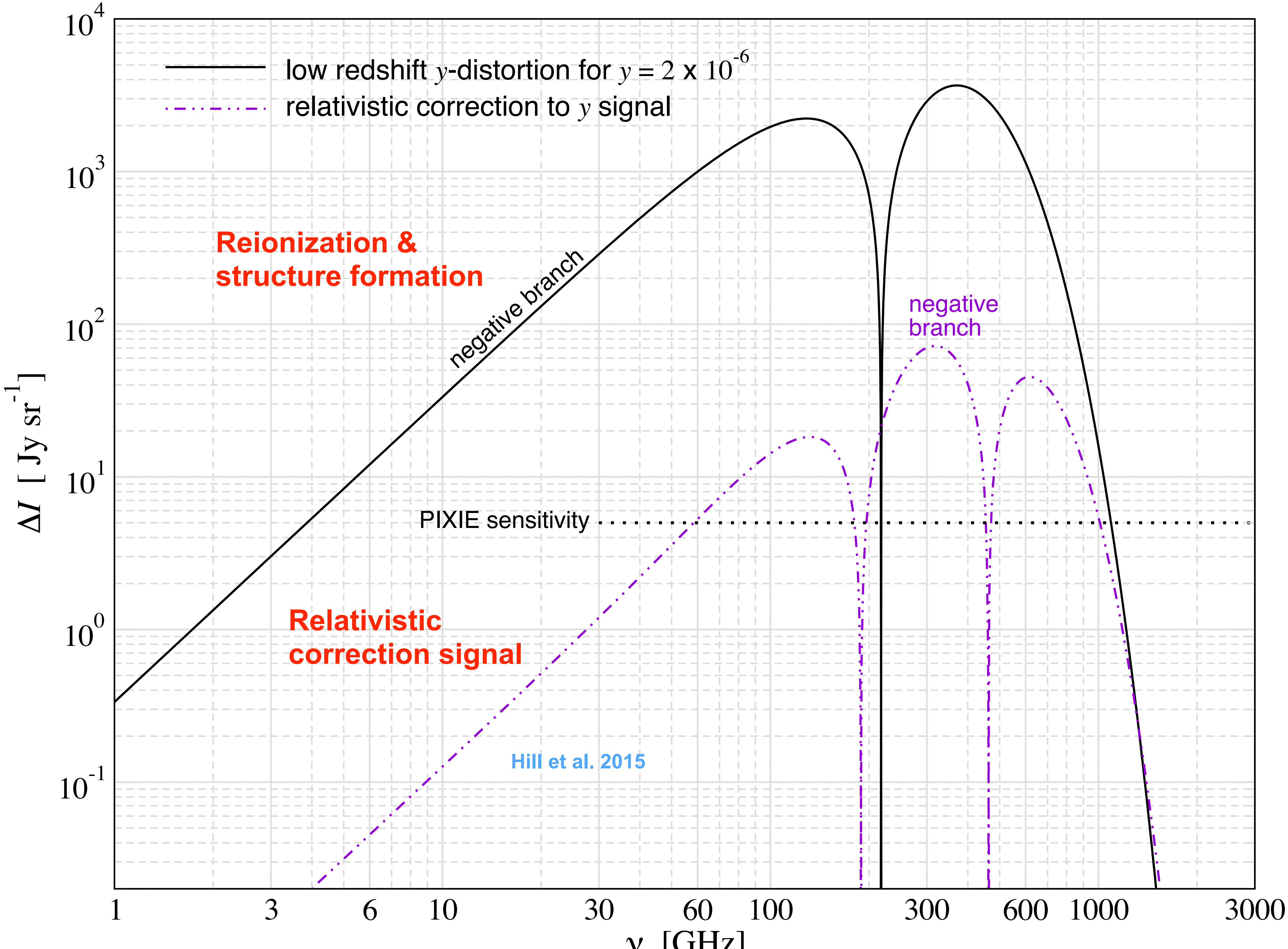
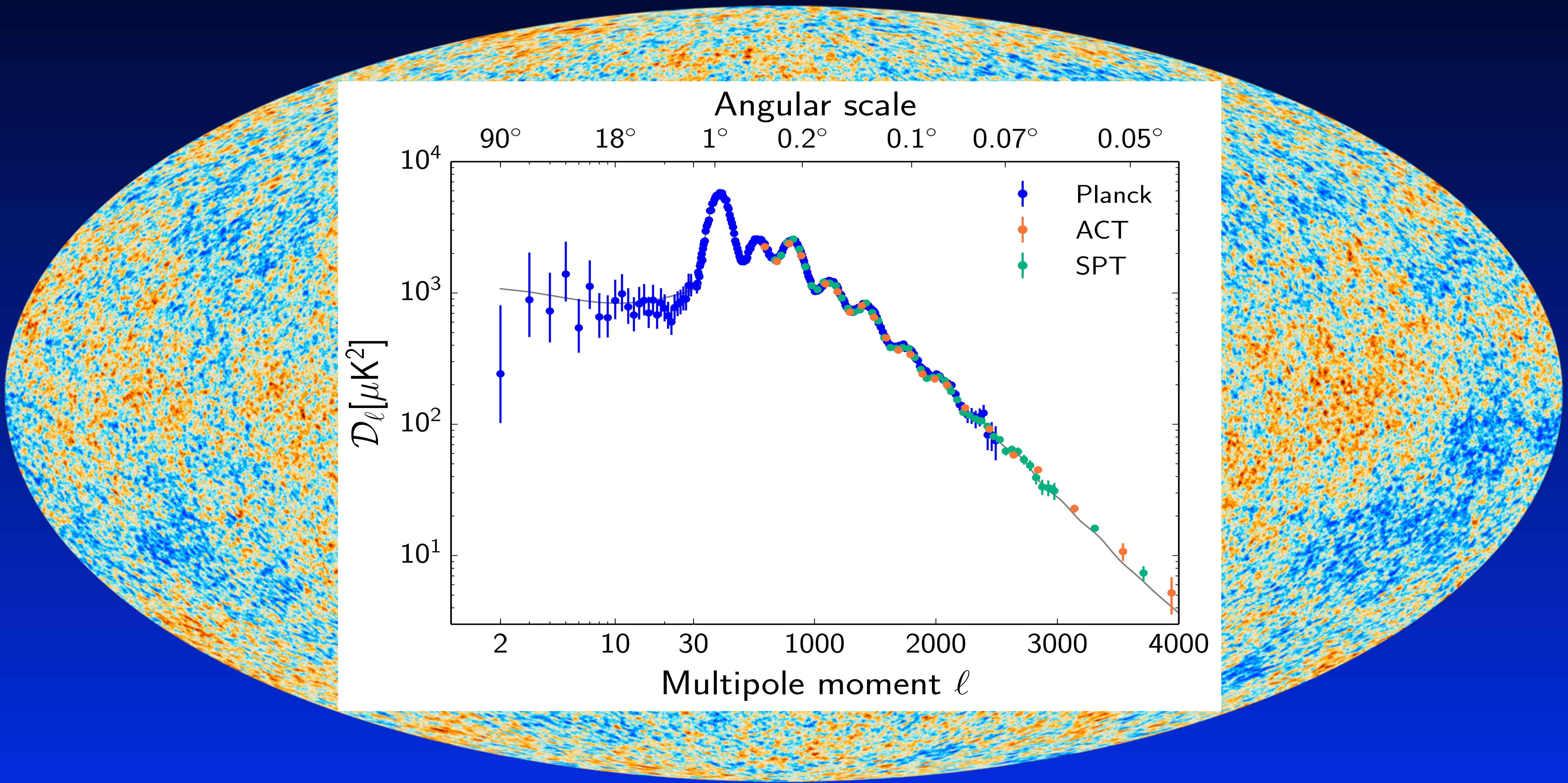
Average CMB spectral distortions



JC, 2016, MNRAS (ArXiv:1603.02496)

Dissipation of small-scale acoustic modes



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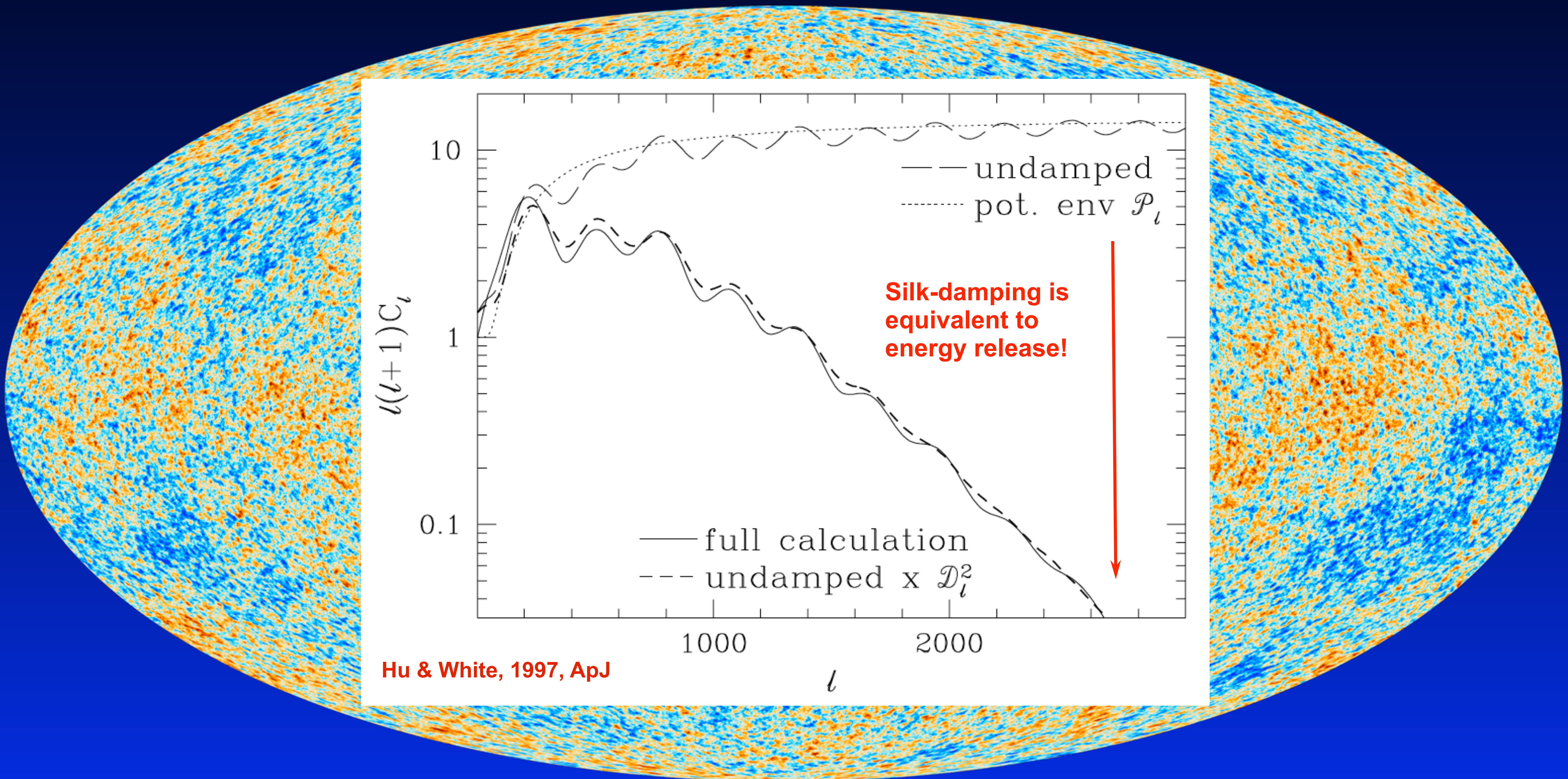
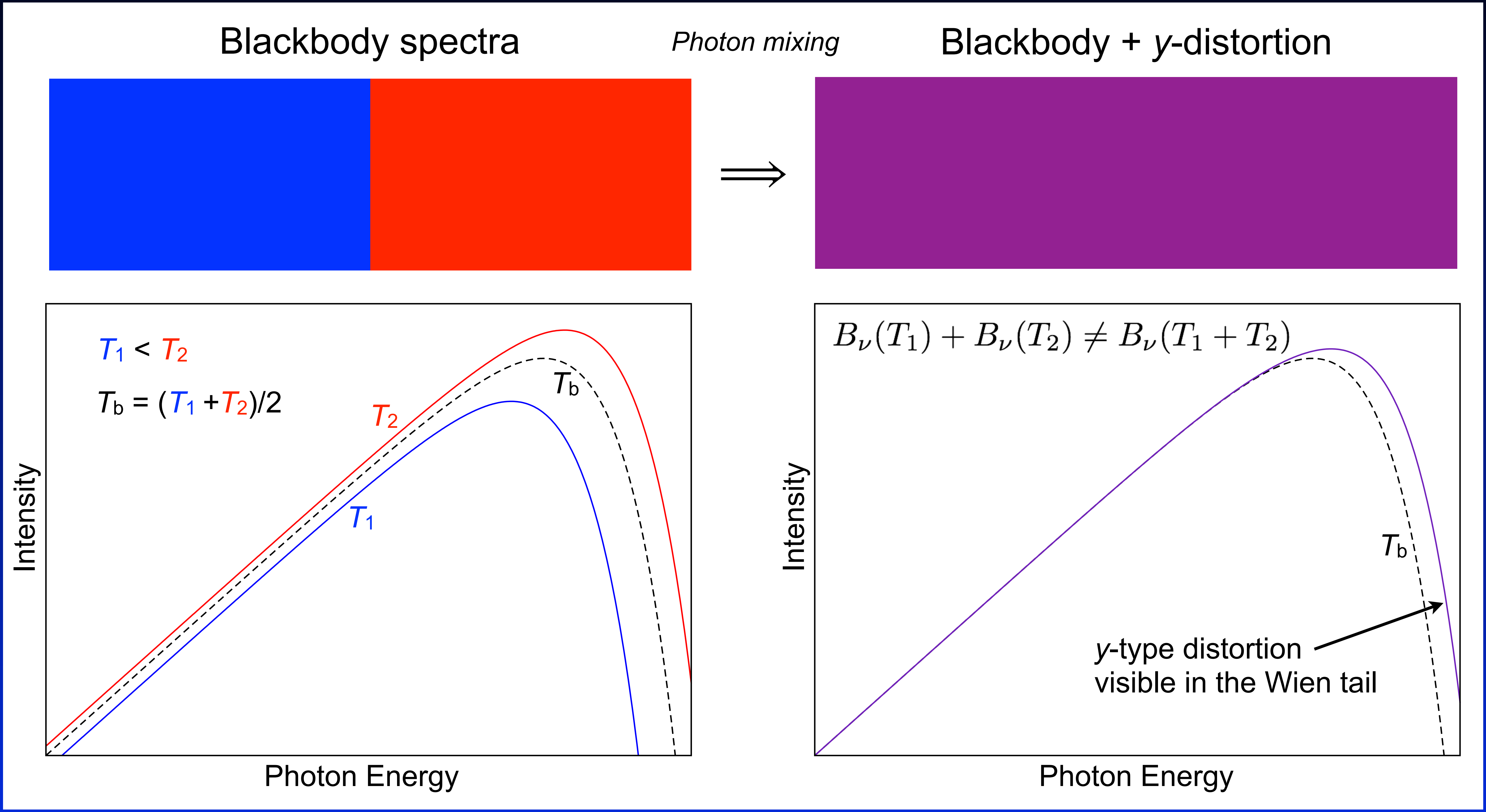


Distortion due to mixing of blackbodies



JC, Hamann & Patil, 2015

Mixing is mediated by Thomson scattering ⇒ Silk damping

Early power spectrum constraints from FIRAS

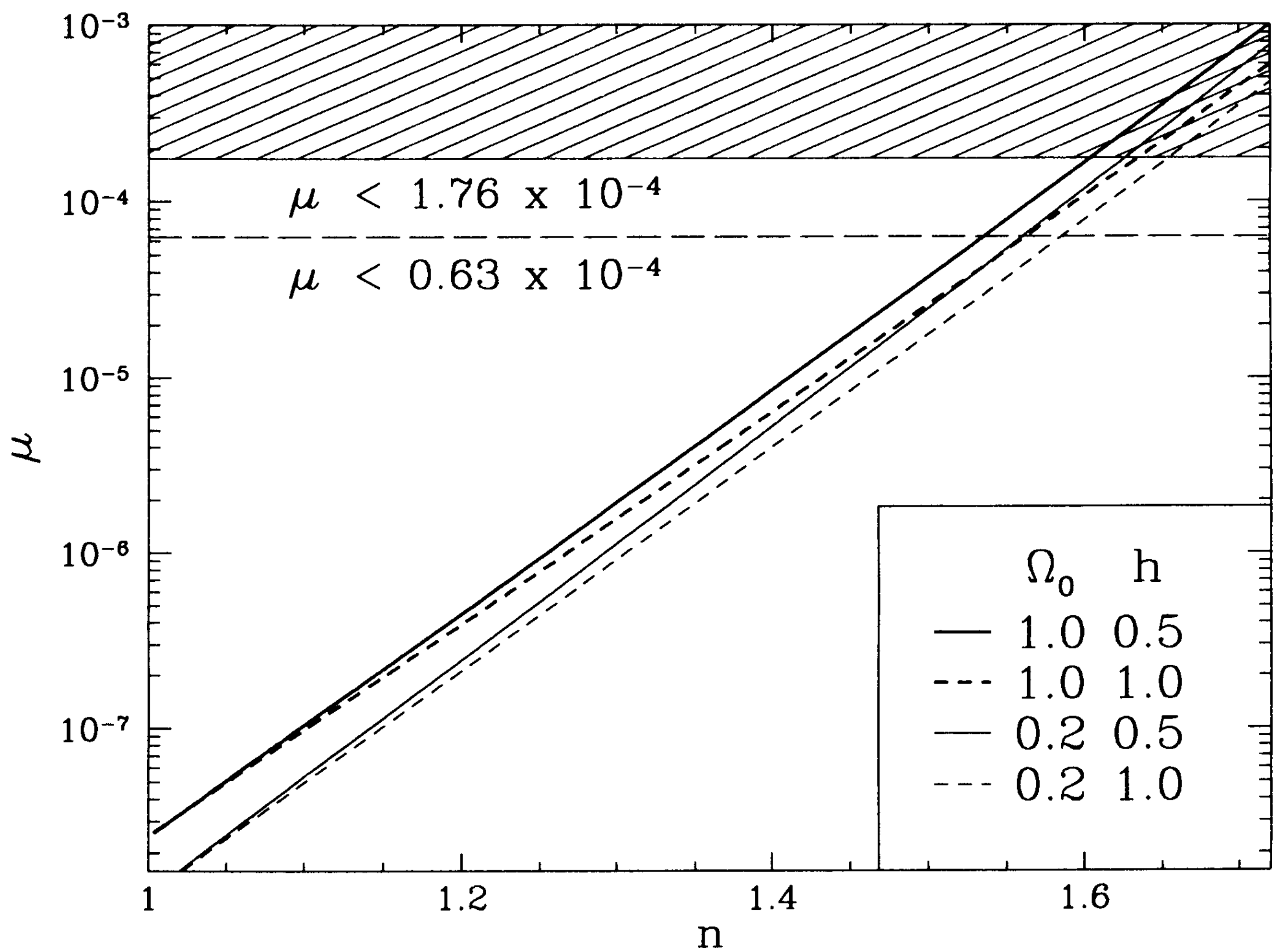
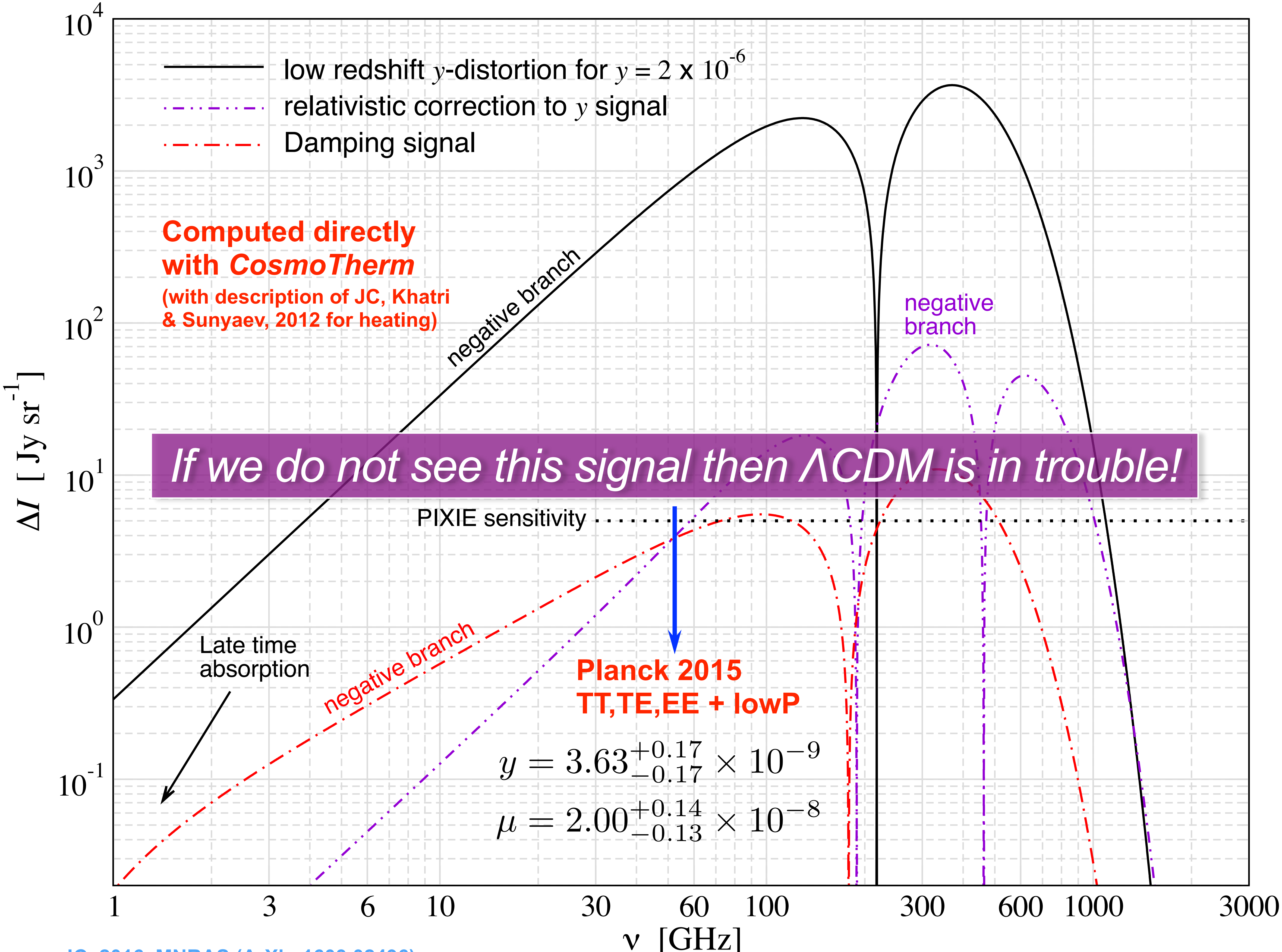


FIG. 1.—Spectral distortion μ, predicted from the full eq. (11), as a function of the power index n for a normalization at the mean of the *COBE* DMR detection $(\Delta T/T)_{10^\circ} = 1.12 \times 10^{-5}$. With the uncertainties on *both* the DMR and FIRAS measurements, the conservative 95% upper 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
- *μ~10^{-8} for scale-invariant power spectrum*
- $n_S \lesssim 1.6$

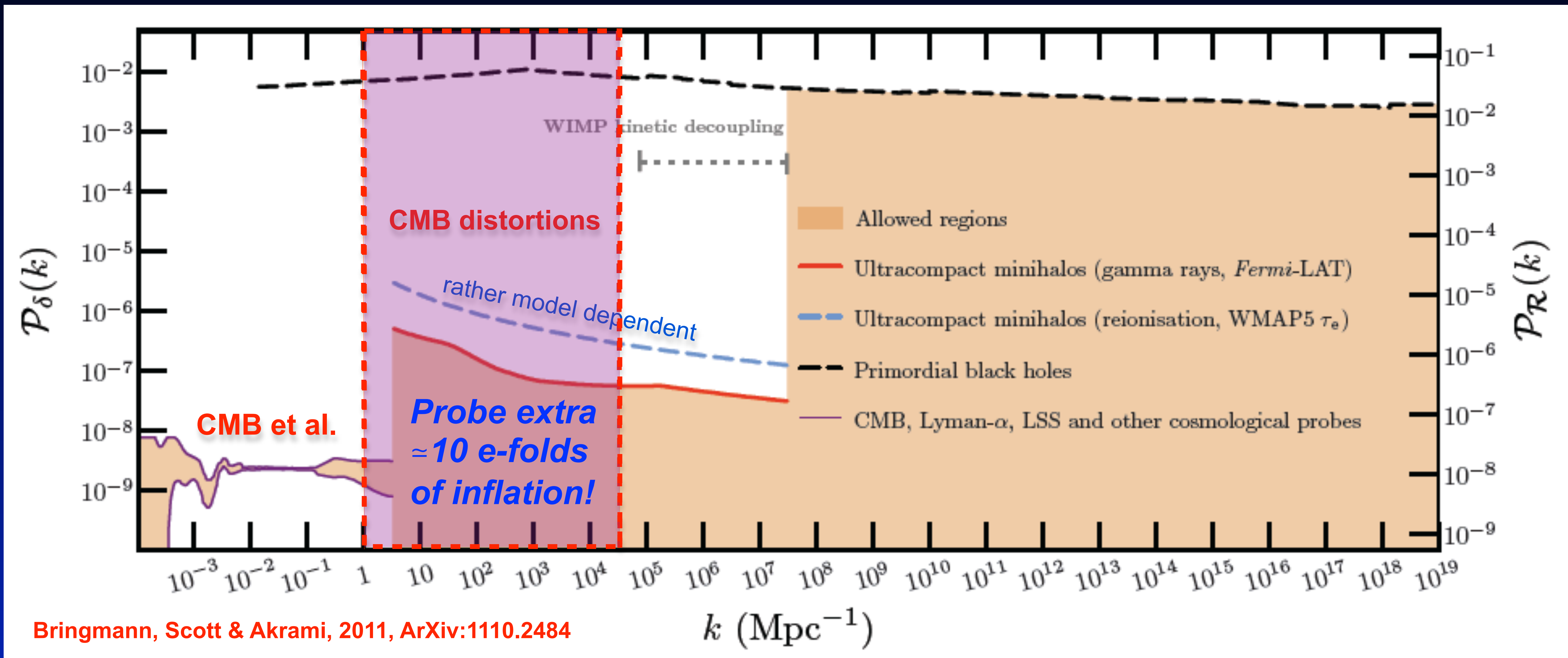
Hu, Scott & Silk, 1994

Average CMB spectral distortions



JC, 2016, MNRAS (ArXiv:1603.02496)

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}
- *complementary* piece of information about early-universe physics

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

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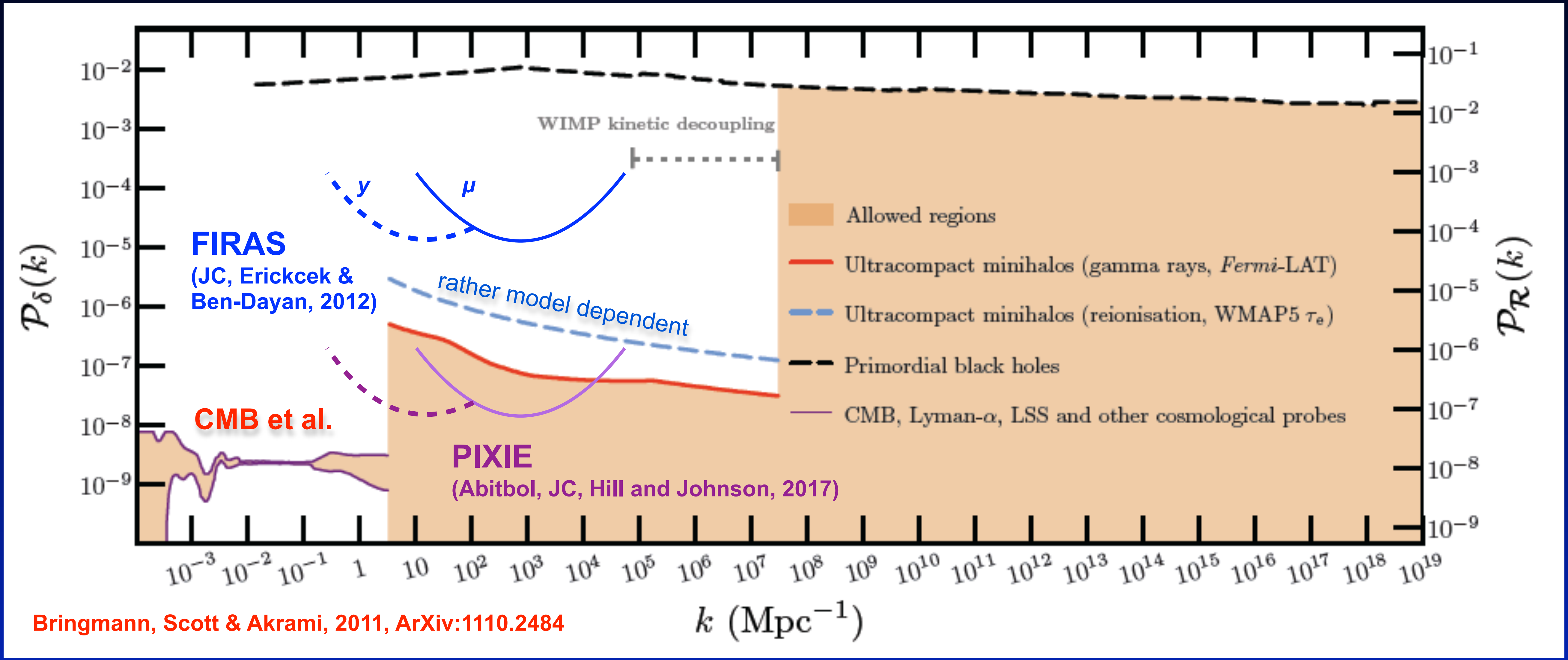

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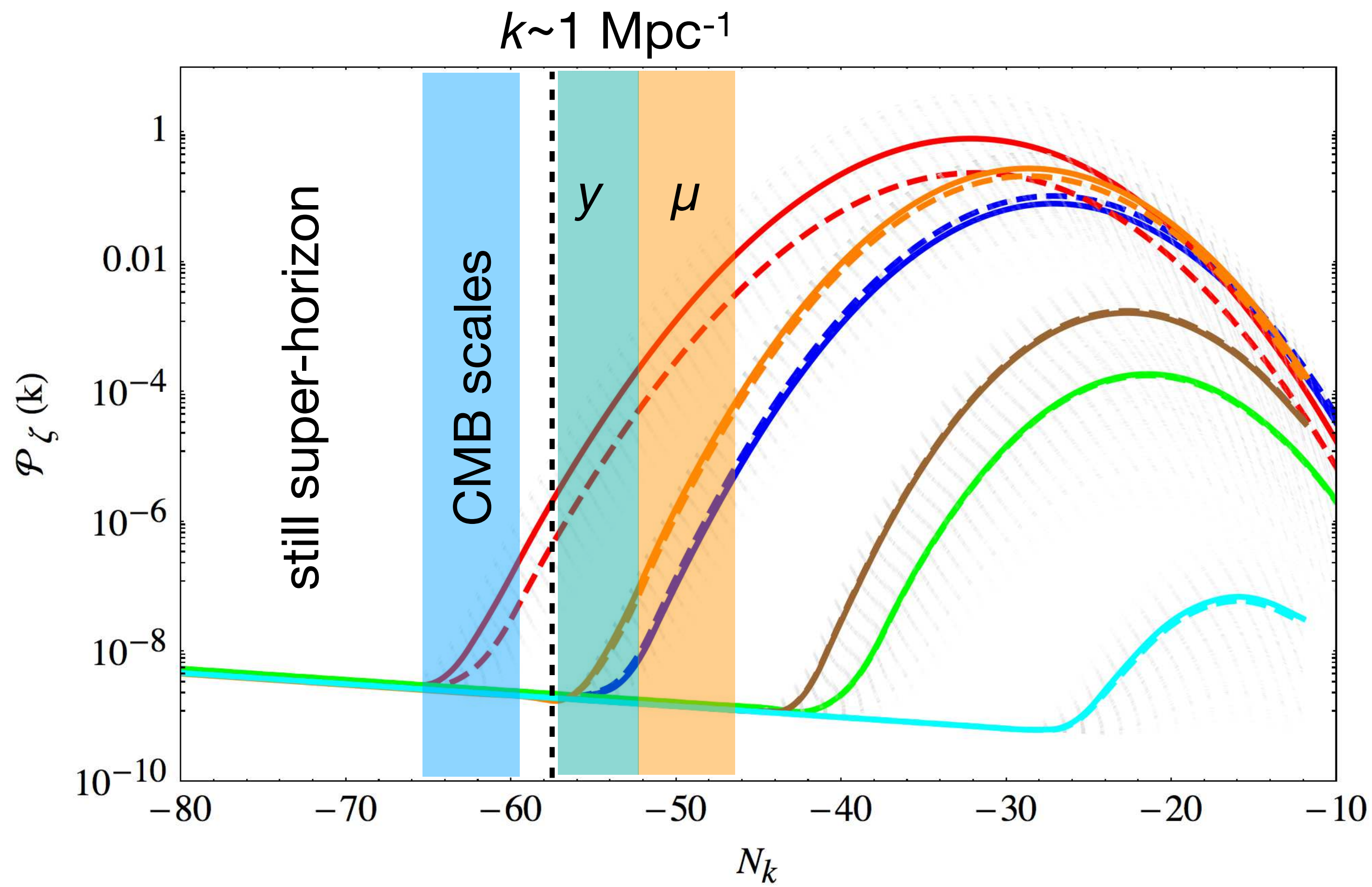
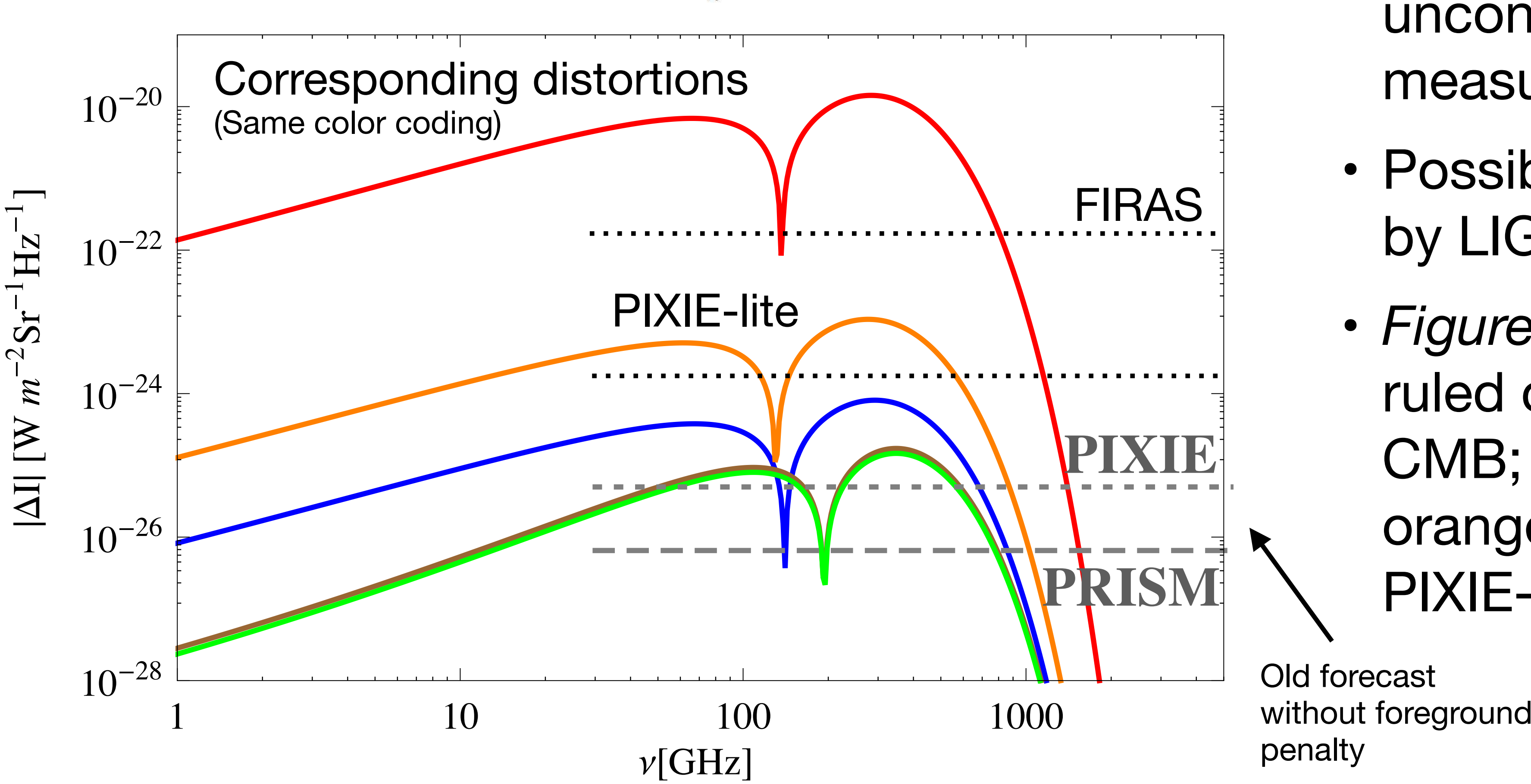
Enhanced small-scale power in hybrid inflation

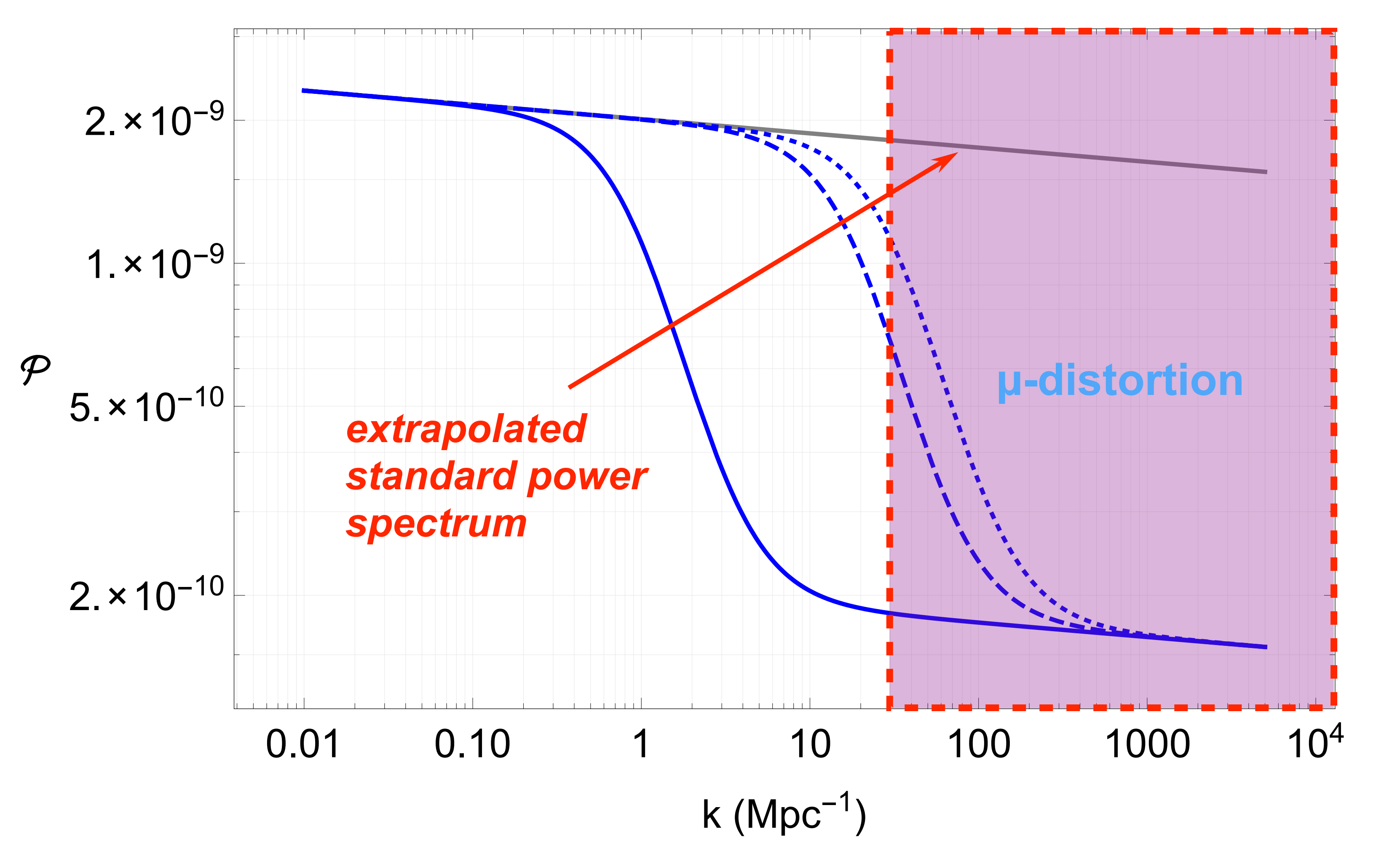




- Hybrid Inflation models cause enhanced small-scale power
- Motivated to explain seeds of supermassive blackholes seen in basically all galaxies
- μ and y distortions sensitive to enhancement at scales 1 Mpc^{-1} ≲ k ≲ 2x10^{4} Mpc^{-1}
- Can constrain cases that are unconstrained by CMB measurements at large scales
- Possible link to BH mergers seen by LIGO??
- *Figure*: case with red line already ruled out by FIRAS (!) and today's CMB; distortions sensitive to orange and blue case; other cases PIXIE-lite is not sensitive to

Figures adapted from Clesse & Garcia-Bellido, 2015

Shedding Light on the 'Small-Scale Crisis'



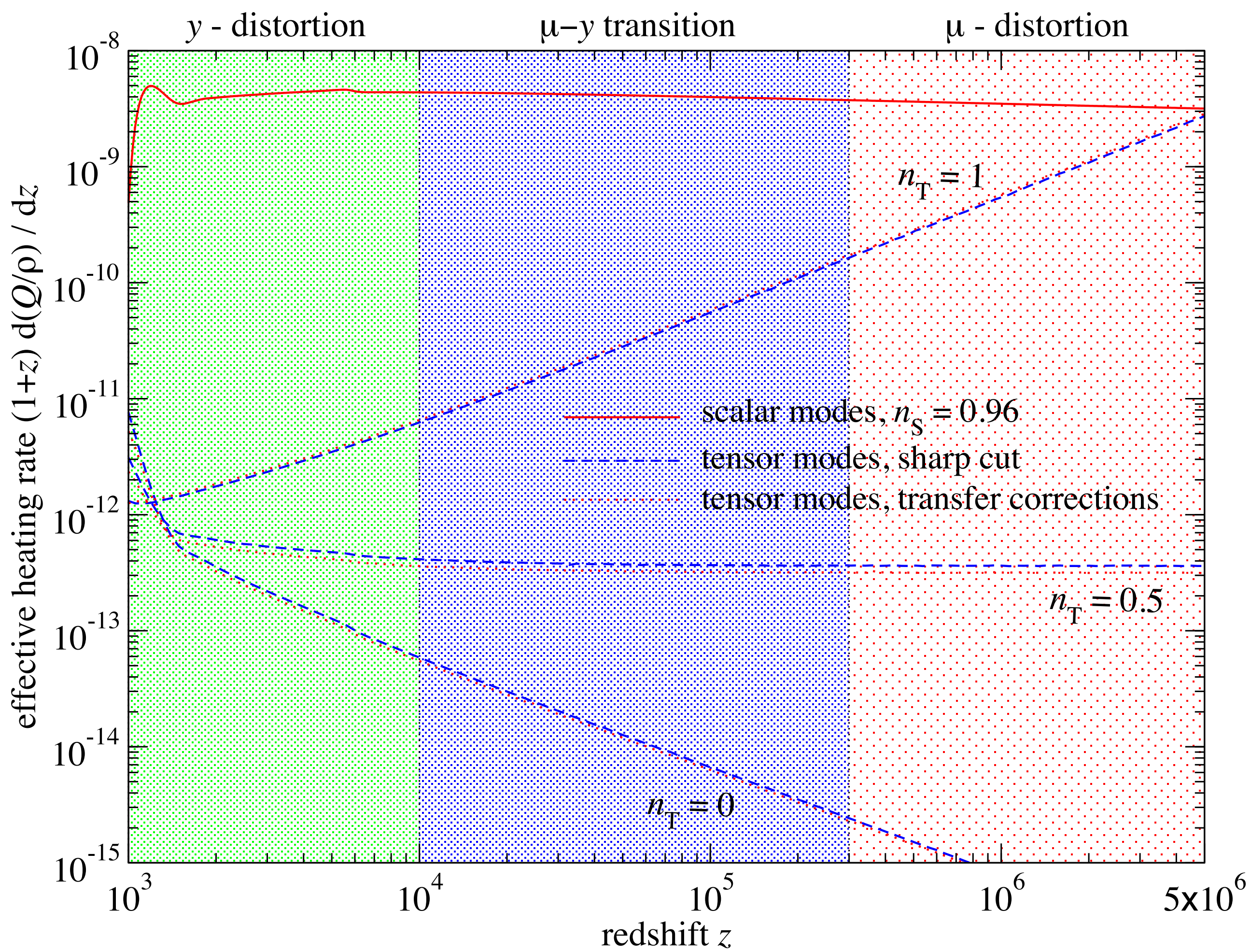
- 'missing satellite' problem
- 'too-big-to-fail'
- Cusp-vs-core problem

⇒ Are these caused by a *primordial* or *late-time* suppression?

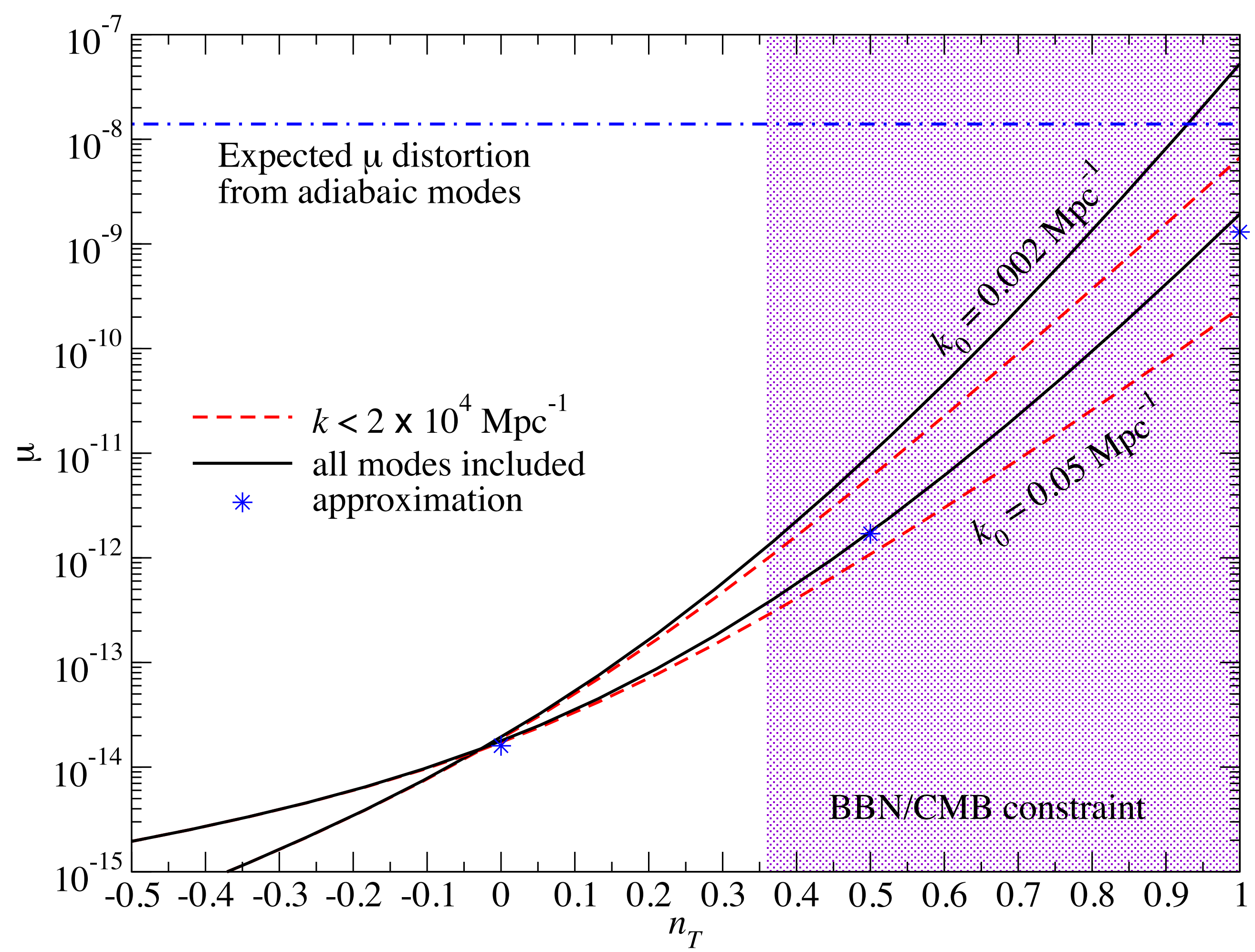
- A primordial suppression would result in a very small μ-distortions
- Spectral distortion measurements might be able to test this question

Nakama, JC & Kamionkowski, ArXiv:1703.10559

Dissipation of tensor perturbations



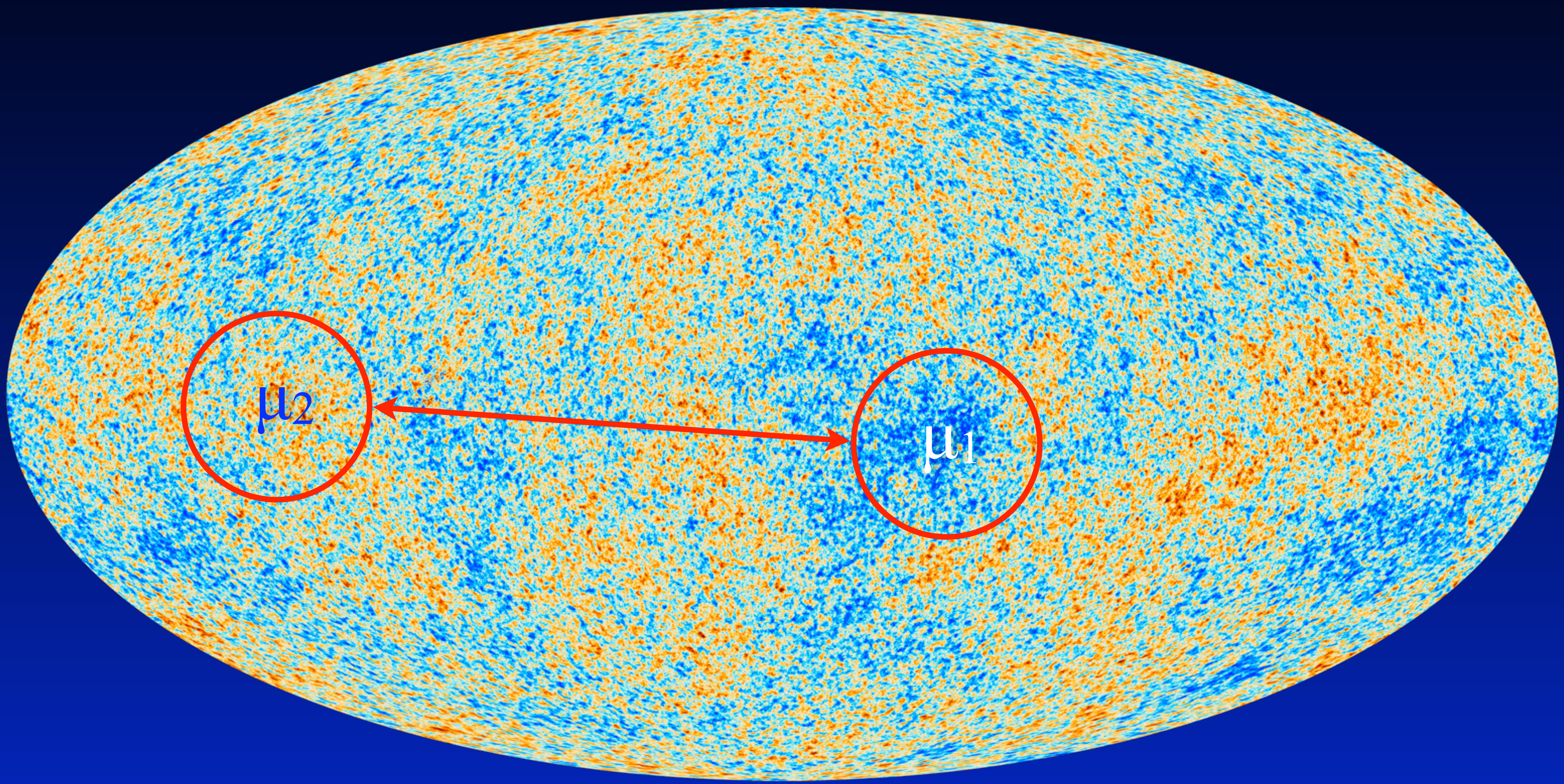
- distortion signal very small compared to adiabatic modes
- no severe *contamination* in simplest cases
- models with 'large' distortion already constrained by BBN/CMB



- heating rate can be computed similar to adiabatic modes
- heating rate much smaller than for scalar perturbations
- roughly constant per dlnz for n_T~0.5

JC, Dai, Grin et al., 2014, ArXiv:1407.3653

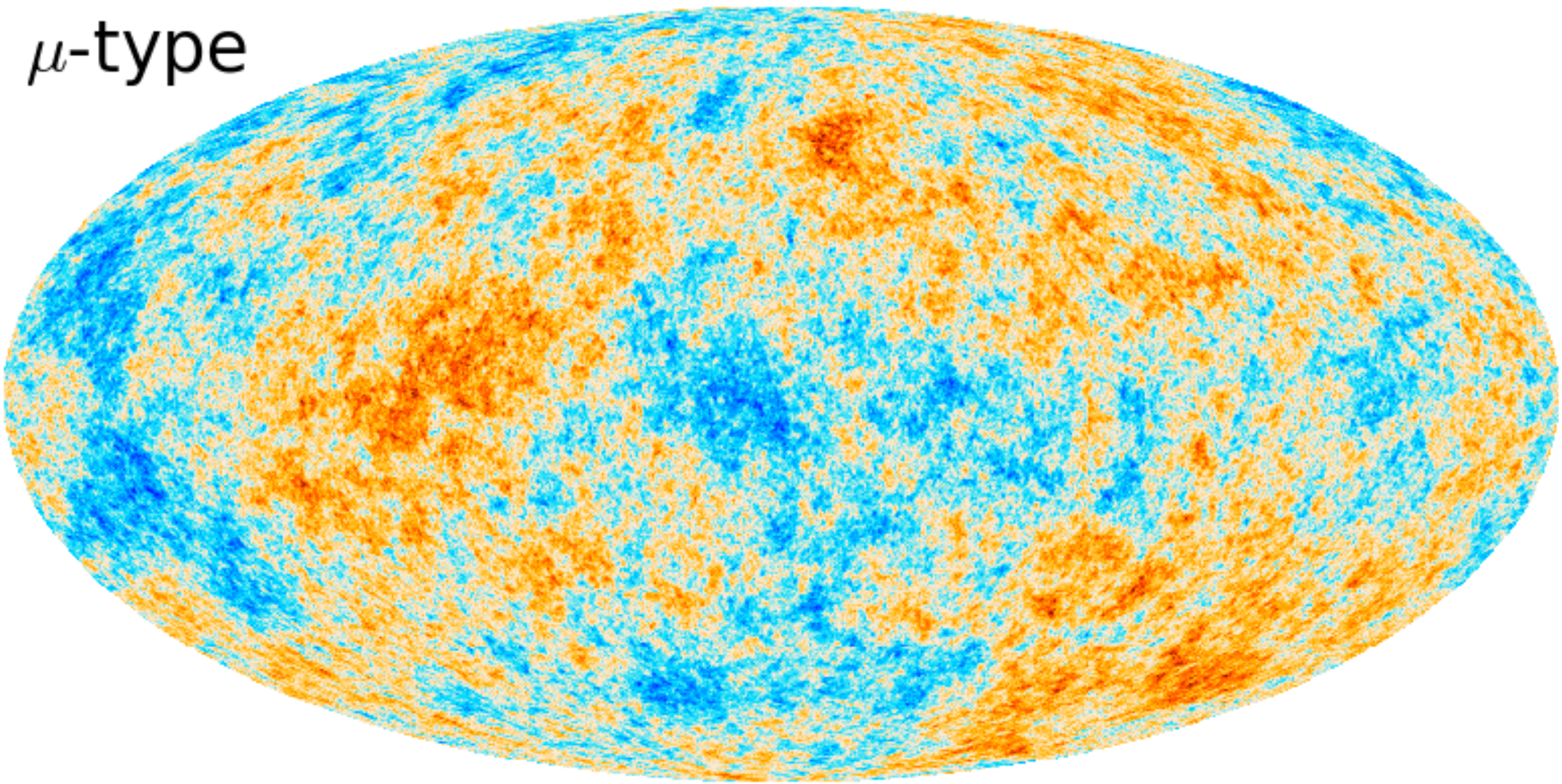
Spatially varying heating and dissipation of acoustic modes for non-Gaussian perturbations



- 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 *squeezed limit non-Gaussianity*)
  → 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

Simulated μ-map for $f_{\rm NL}$=4500

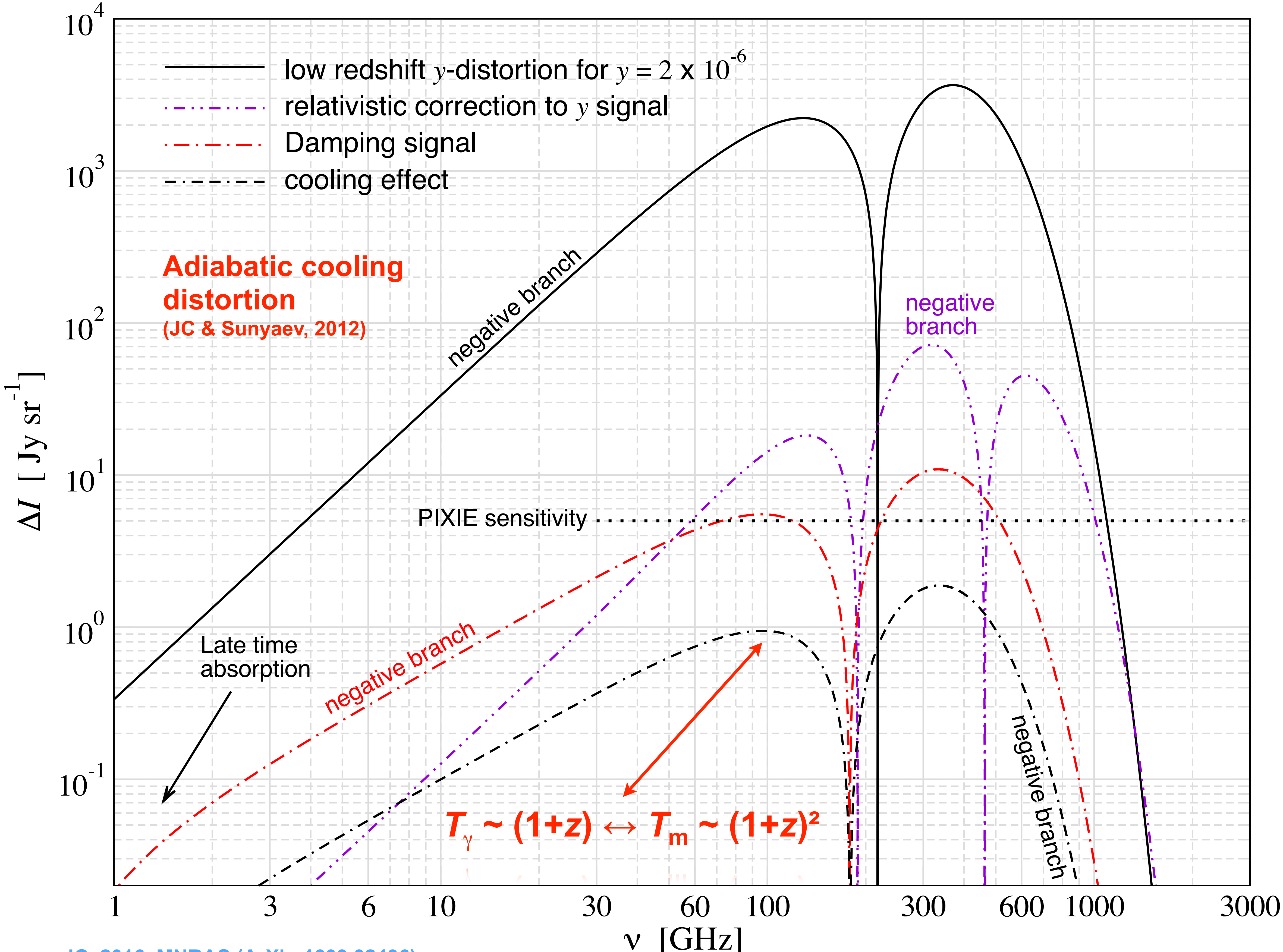


$$C_\ell^{\mu\times T} = 12\, C_\ell^{TT,\,\rm SW}\, \rho(\ell)\, f_{\rm NL}\, \langle\mu\rangle$$

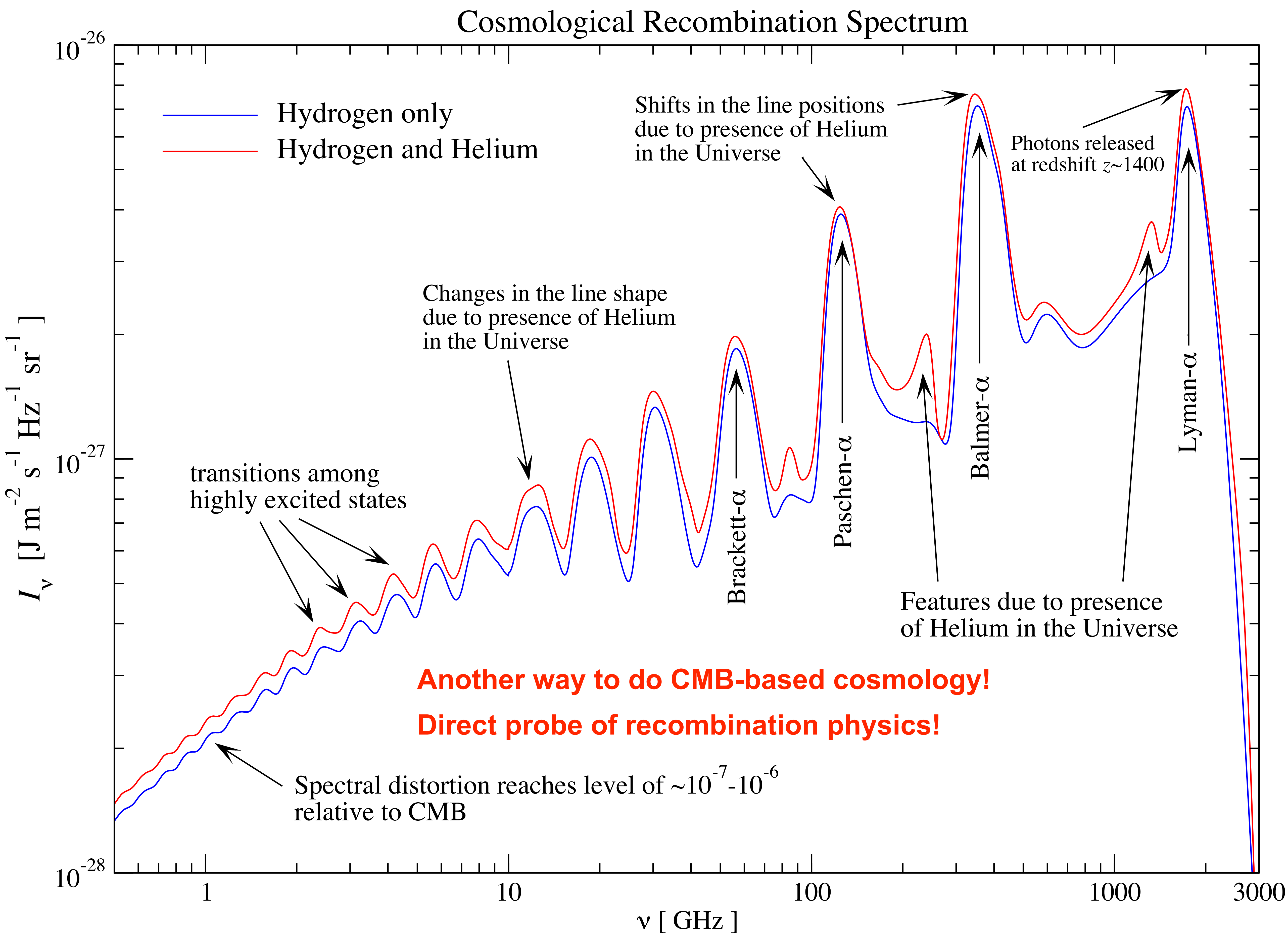
Remazeilles & JC, 2018, MNRAS (ArXiv:1802.10101)

- Signals could be detectable by future CMB anisotropy experiments (e.g., Litebird, CORE, PICO, CMB-Bharat)
- Additional information from yT, μE, yE (Ravenni et al., 2017)

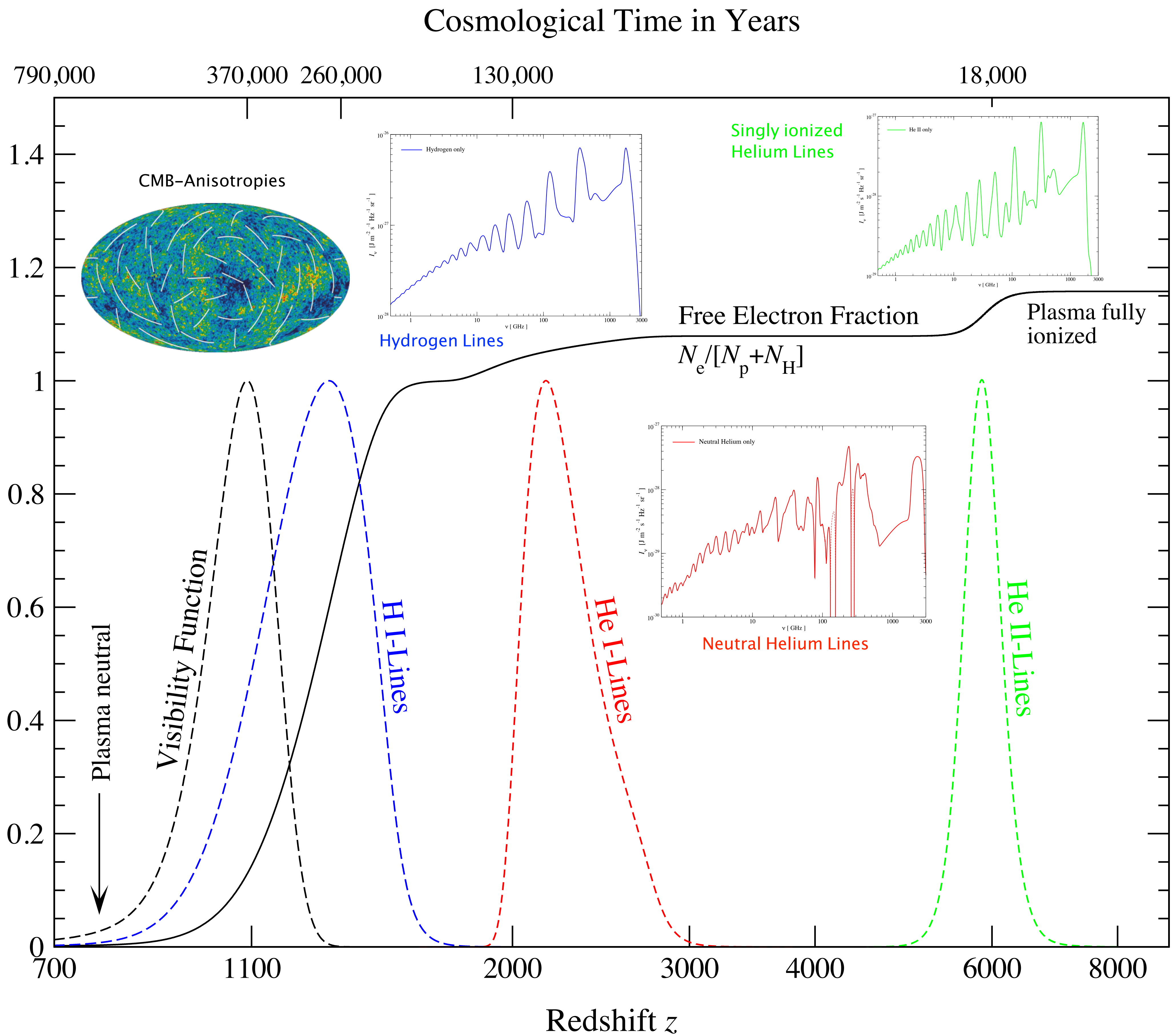
Average CMB spectral distortions



JC, 2016, MNRAS (ArXiv:1603.02496)

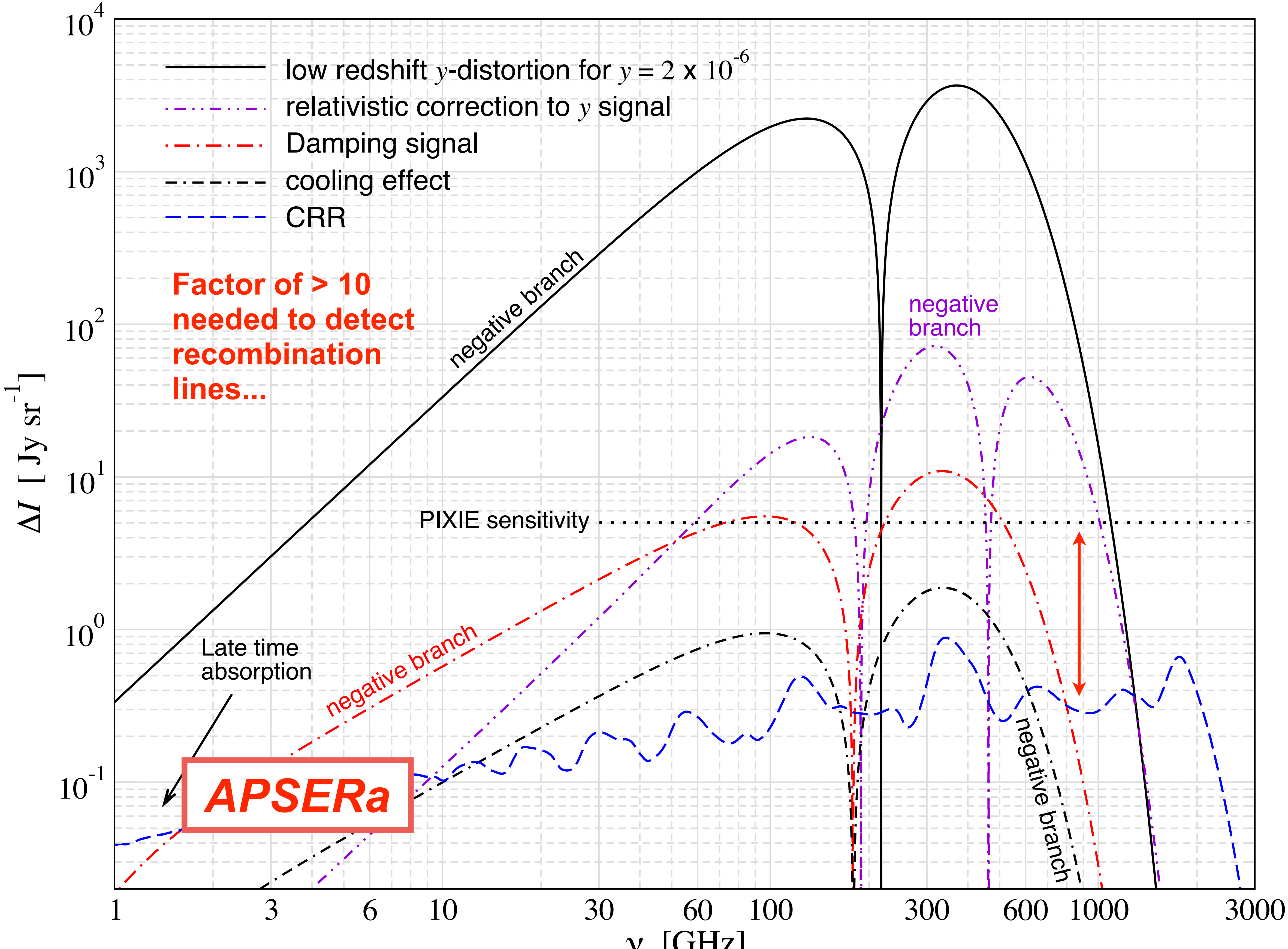


Rubino-Martin et al. 2006, 2008; Sunyaev & JC, 2009



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

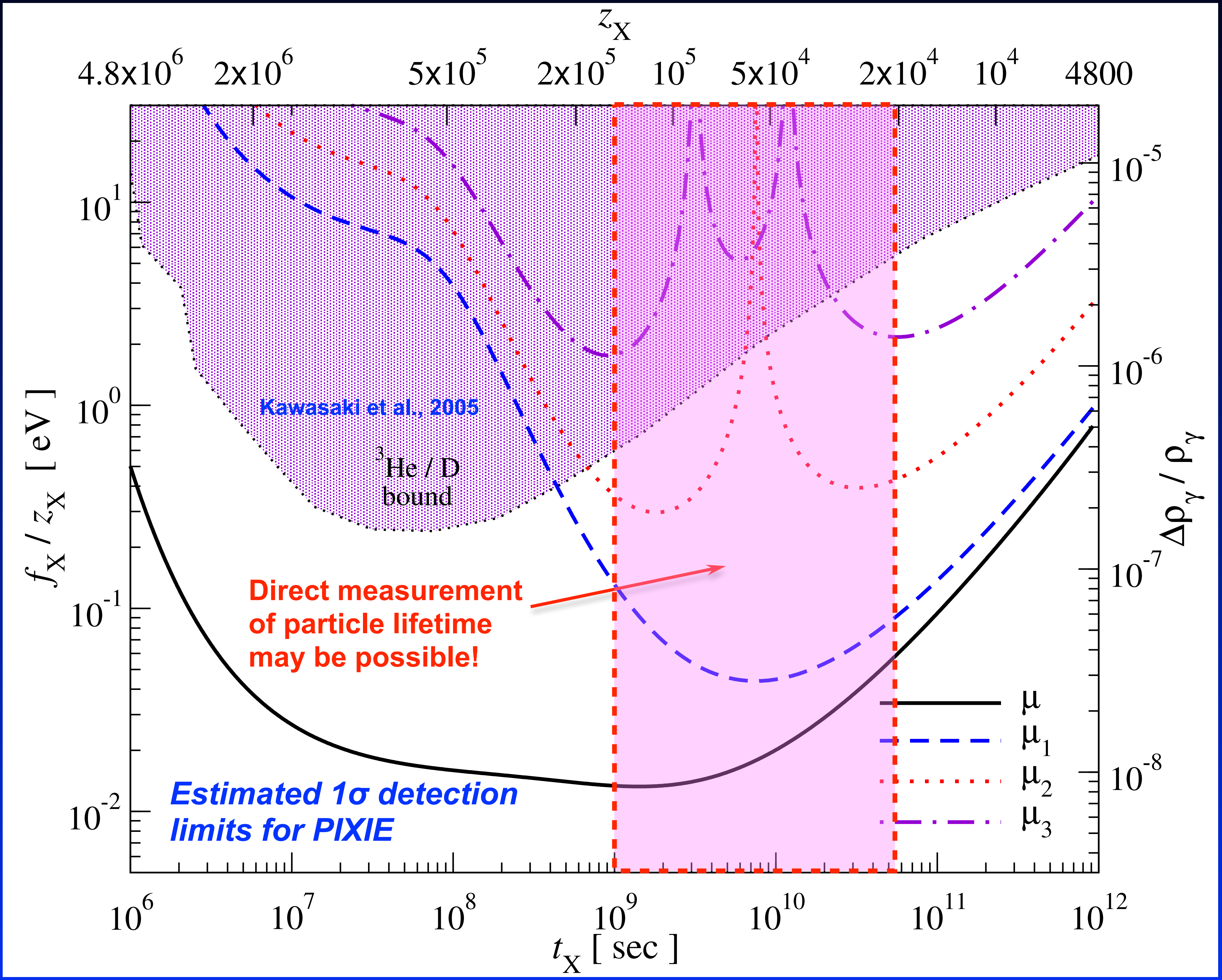
Average CMB spectral distortions



JC, 2016, MNRAS (ArXiv:1603.02496)

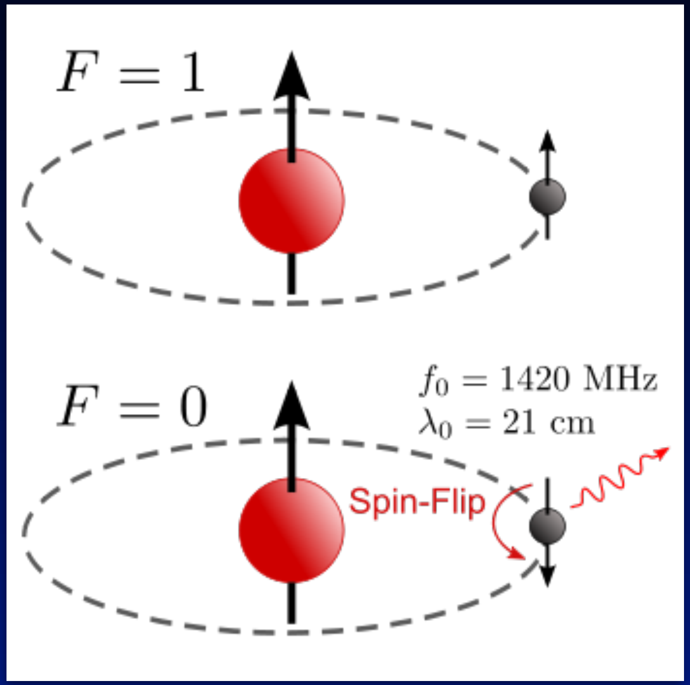
Some non-standard distortion signals

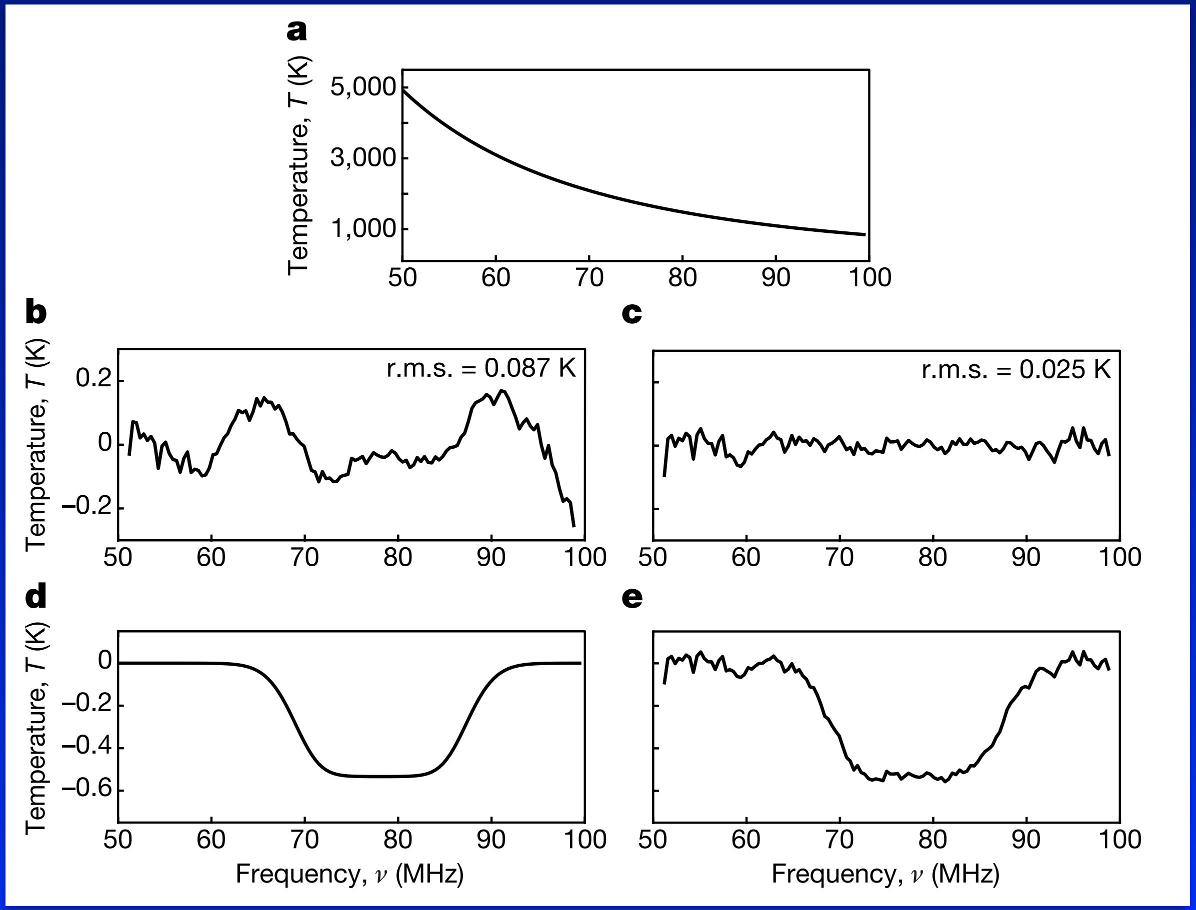
Distortions could shed light on decaying (DM) particles



JC & Jeong, 2013

EDGES detection of cosmological 21cm absorption?

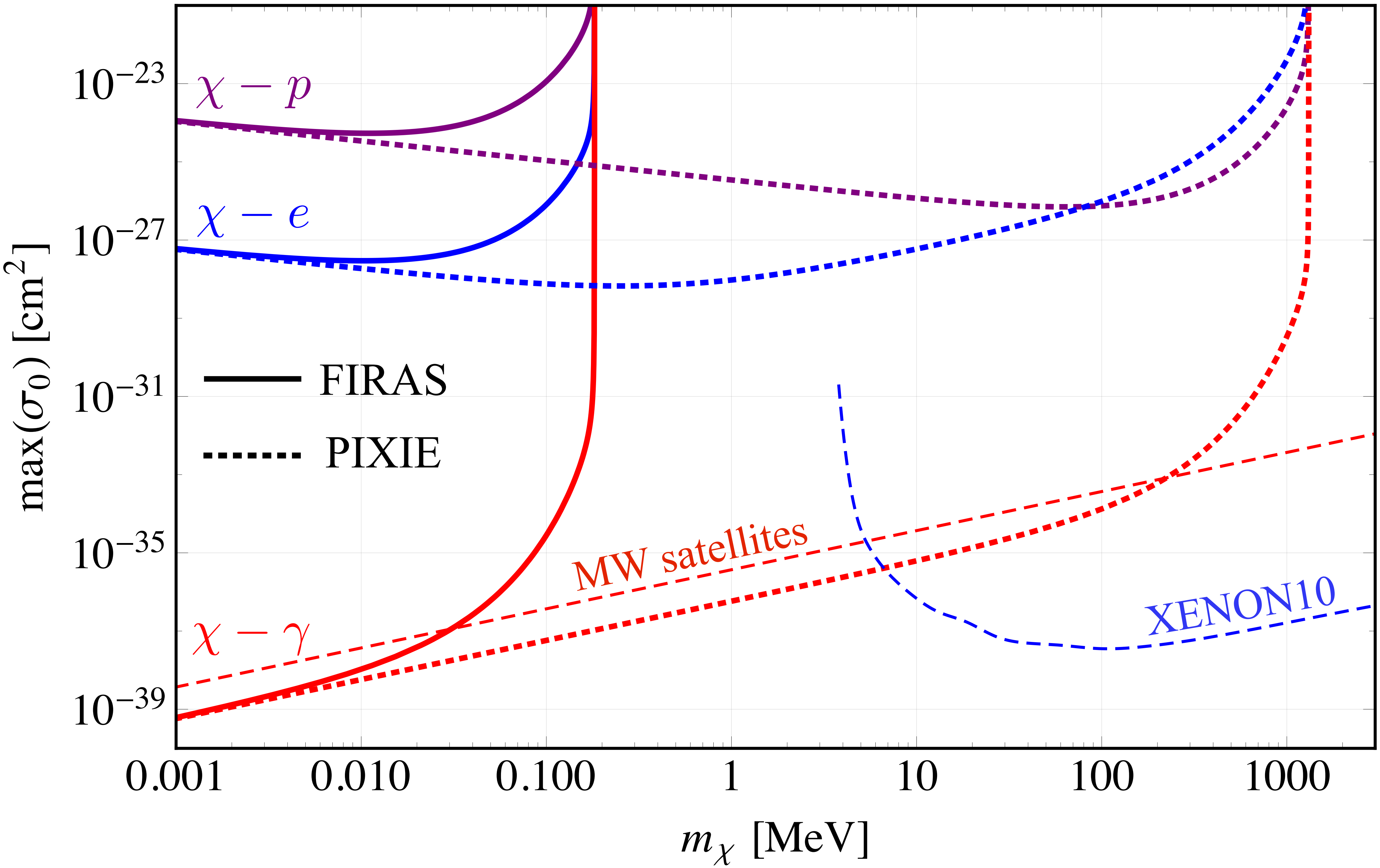




- Stimulated lots of discussion
- Signal much larger than expected in standard scenario
- Possible connection to DM physics / interactions?

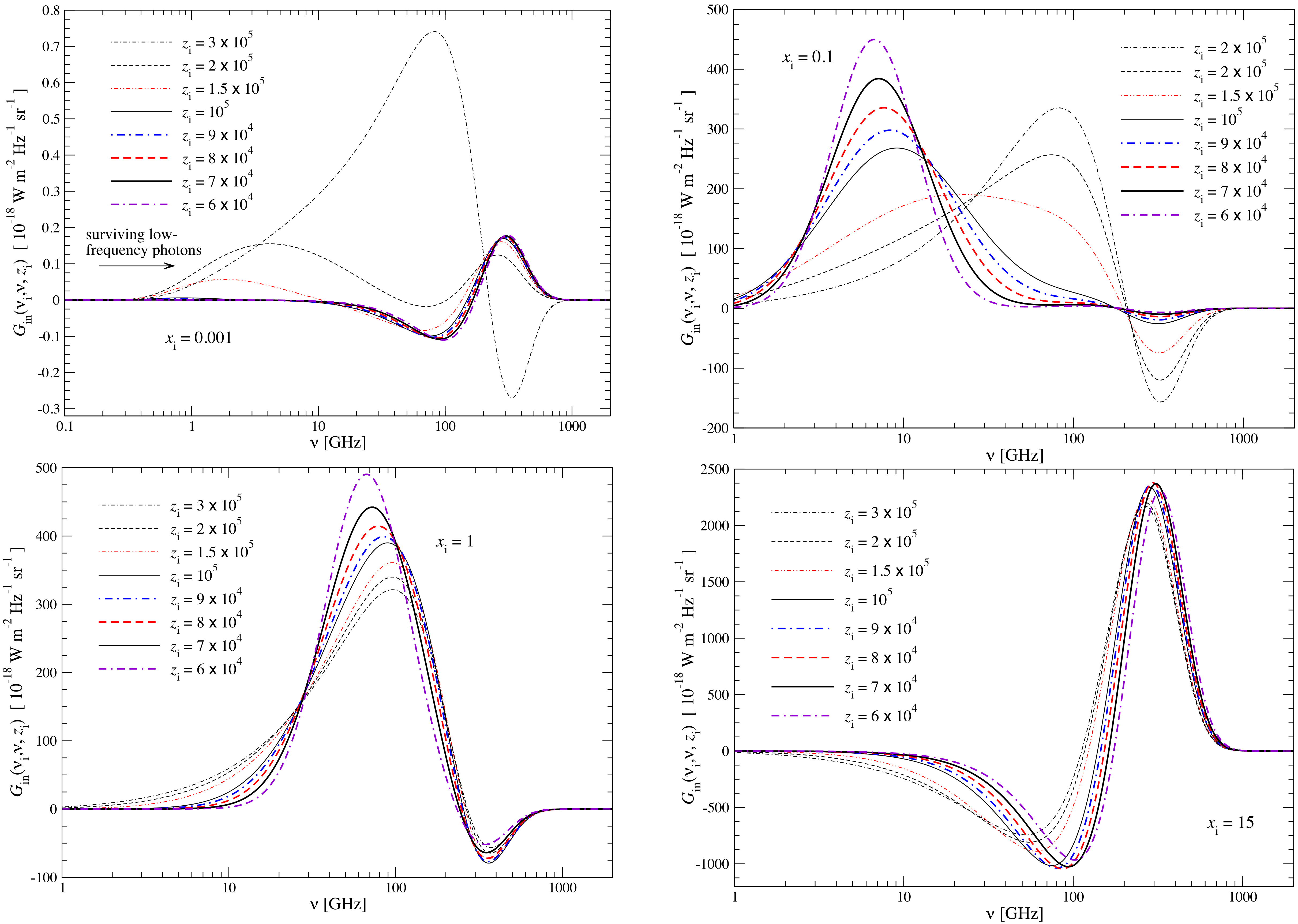
Bowman et al., Nature, 2018

Distortion constraints on DM interactions through adiabatic cooling effect



Ali-Haimoud, JC & Kamionkowski, 2015

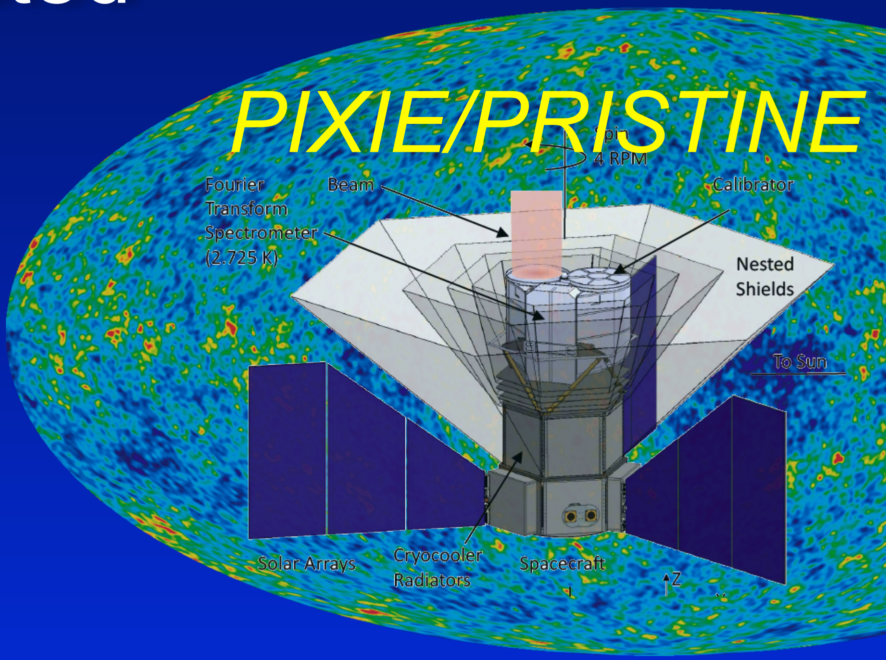
Rich phenomenology of photon injection distortions



JC 2015, ArXiv:1506.06582

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 CMB 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



We should really make use of this information!

What are the opportunities for Europe?

Steps forward on CMB spectral distortions

- *Pioneering* work from the ground
  - Improved constraints on μ and *y*
  - Possible detection of average late-time *y*-distortion
  - Discovery potential (e.g., ARCADE excess, EDGES)

  ➡ COSMO at Dome-C and APSERa

- *Low-frequency foregrounds*
  - One of the main problems for distortions (Abitbol, JC, Hill and Johnson, 2017)
  - Capitalize on *existing experience* (e.g., C-Bass, Quijote)
  - One of the *important inputs* for B-mode searches

- Advancing the frontier from *space*
  - Probe of *inflation* and early-Universe physics
  - Complementary science to B-modes & guaranteed signals
  - Absolutely calibrated multi-frequency maps incredibly valuable (e.g., calibration issues, foreground separation)

  ➡ PRISTINE, PIXIE-prime, CMB-Bharat

What is PRISTINE?

Aims, boundary conditions and collaboration

- Measure both CMB polarisation and distortions
- From design of COBE/FIRAS and PIXIE optimise and adapt the science case and instrument deign for a small mission
  - y-type distortions
  - Do from space what can only be done from space
  - Complementarity with other missions and ground based projects
  - Do not have the ambition of a definitive CMB mission

European and US Consortium

Max Abitbol
Nabila Aghanim
Jonathan Aumont
François Bouchet
Jens Chluba
Hervé Dole
Marian Douspis
Josquin Errard
Ken Ganga
Julien Grain
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Jean-Pierre Maillard
Anna Mangilli
Luca Pagano
Etienne Pointecouteau
Jean-Loup Puget
Mathieu Remazeilles
Louis Rodriguez
Gérard Rouillé
Abdellah Roussafi
Giorgio Savini
Jean-Luc Starck
Valentin Sauvage
Andrea Tartari
Neil Trappe
Sébastien Triqueneaux
Gérard Vermeulen
Al Kogut
Dale Fixsen

Courtesy: Bruno Maffei

Instrument Philosophy

Optimised imaging polarised FT Spectro. based on PIXIE concept

- Two telescopes of 36 cm each
- Frequency range 90 to 2000 GHz
  - 2 THz decreases largely the noise contribution from dust and mitigates degeneracy with CIB, and correlation with synchrotron
  - 90 GHz improves spatial resolution and constraints size of optical elements
- Spectral resolution of 5 GHz
  - Mitigates contamination from lines and optimises legacy ISM & galaxies
- Spatial resolution 0.75 deg equivalent Gaussian
- Array of 7 dual polarised pixels (x 2, one for each output port)
- Sensitivity similar to PIXIE
- Internal absolute photometric calibrator
- Try to reduce risks and have high TRL
- Slow spinning

Forecasts by Max Abitbol:

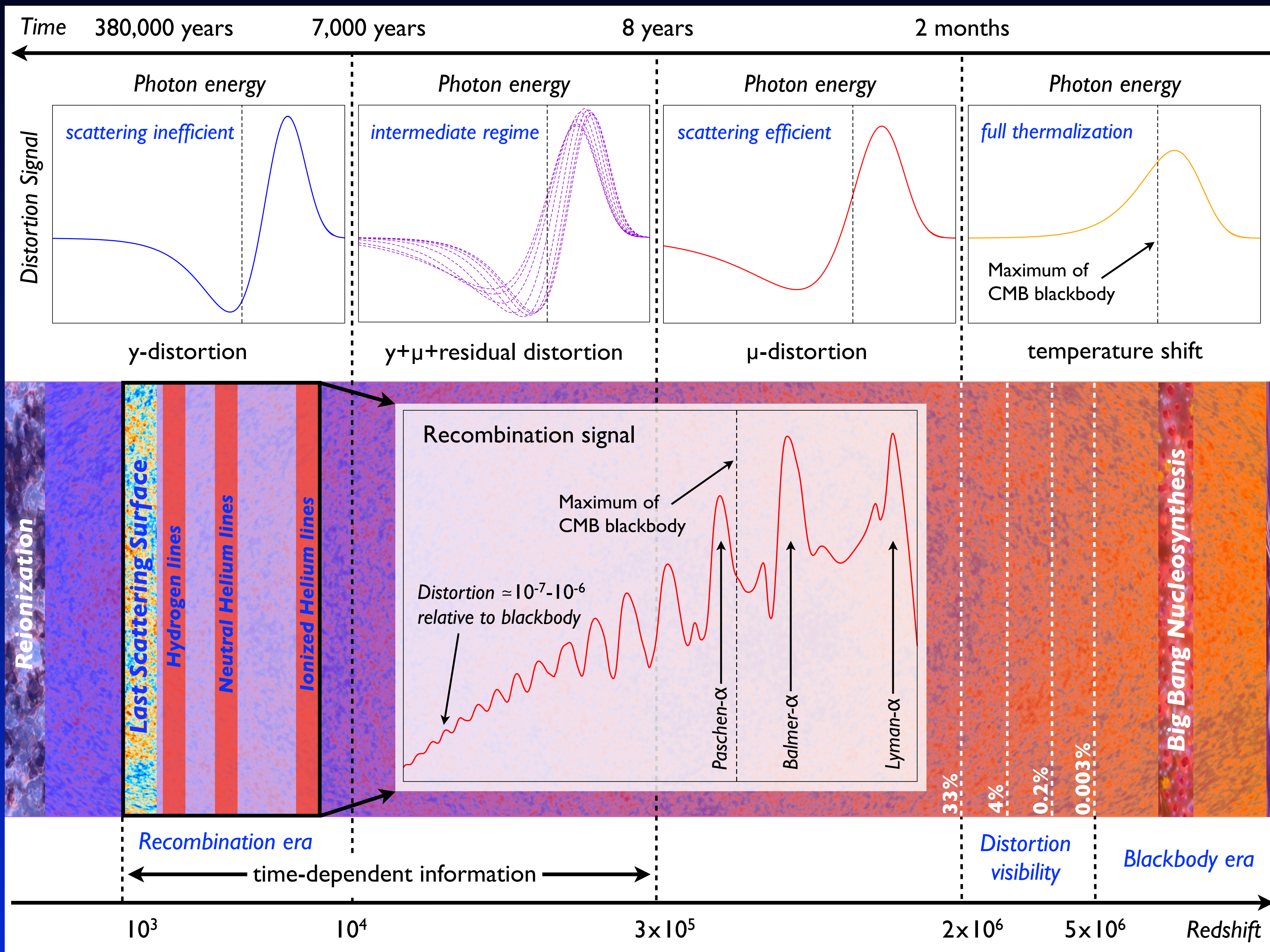
➡ Significant detection of y

➡ Close to detecting average rel. thSZ

Proposal to be submitted to ESA (F-class)

Courtesy: Bruno Maffei

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

PRISTINE
COSMO
CMB-Bharat