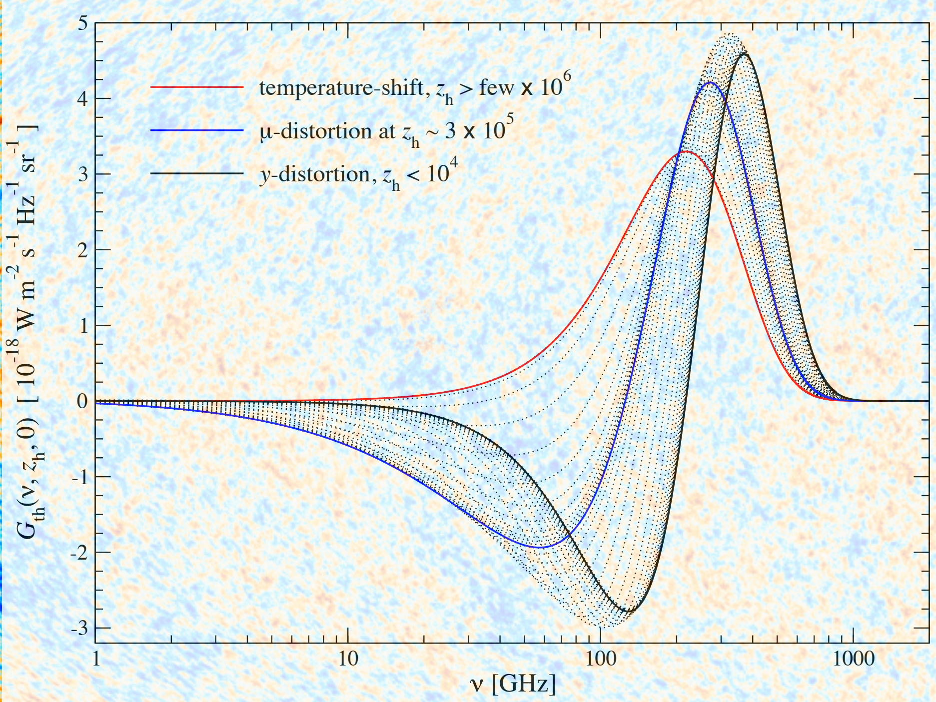
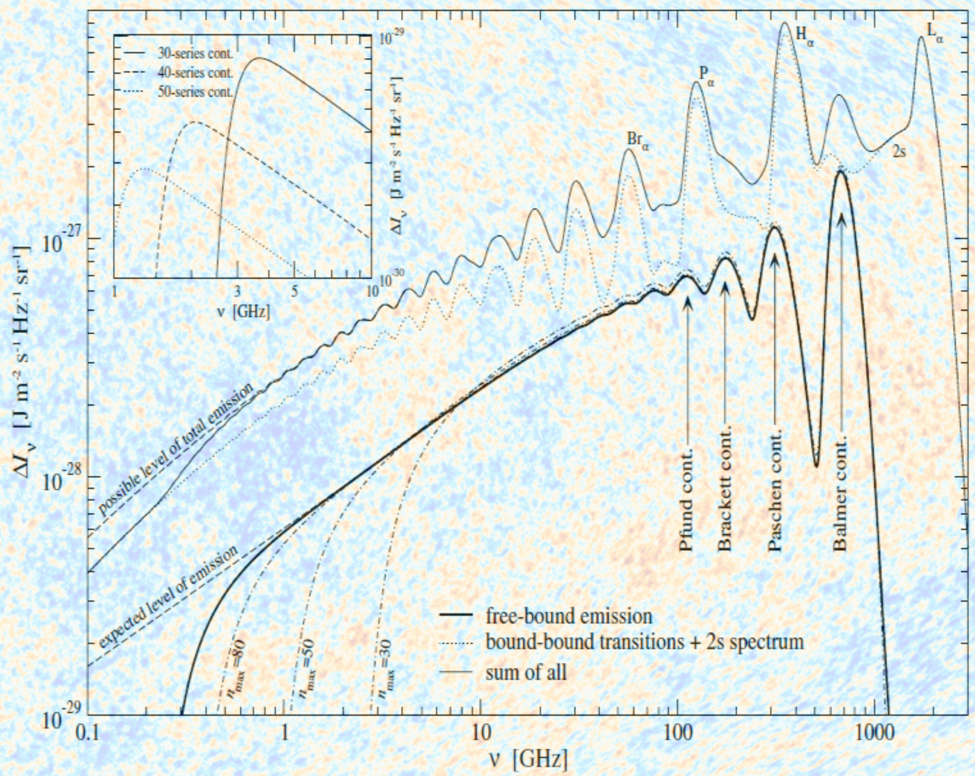
Why CMB spectral distortions are so cool

Primordial Distortions



Cosmological Recombination lines



Jens Chluba

CMB/LSS/21cm Workshop

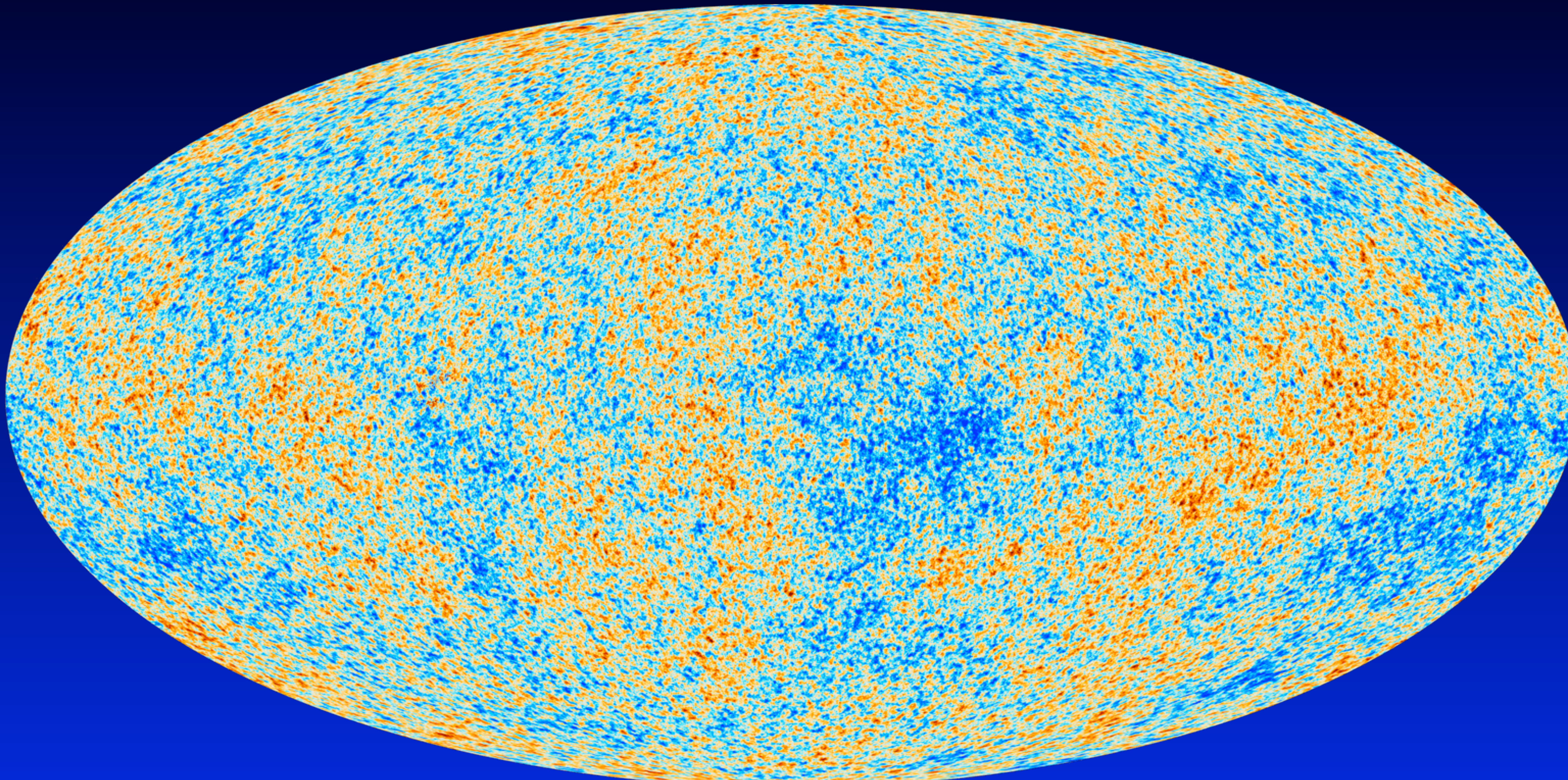
IFT Madrid, June 17th, 2016

MANCHESTER 1824

The University of Manchester

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

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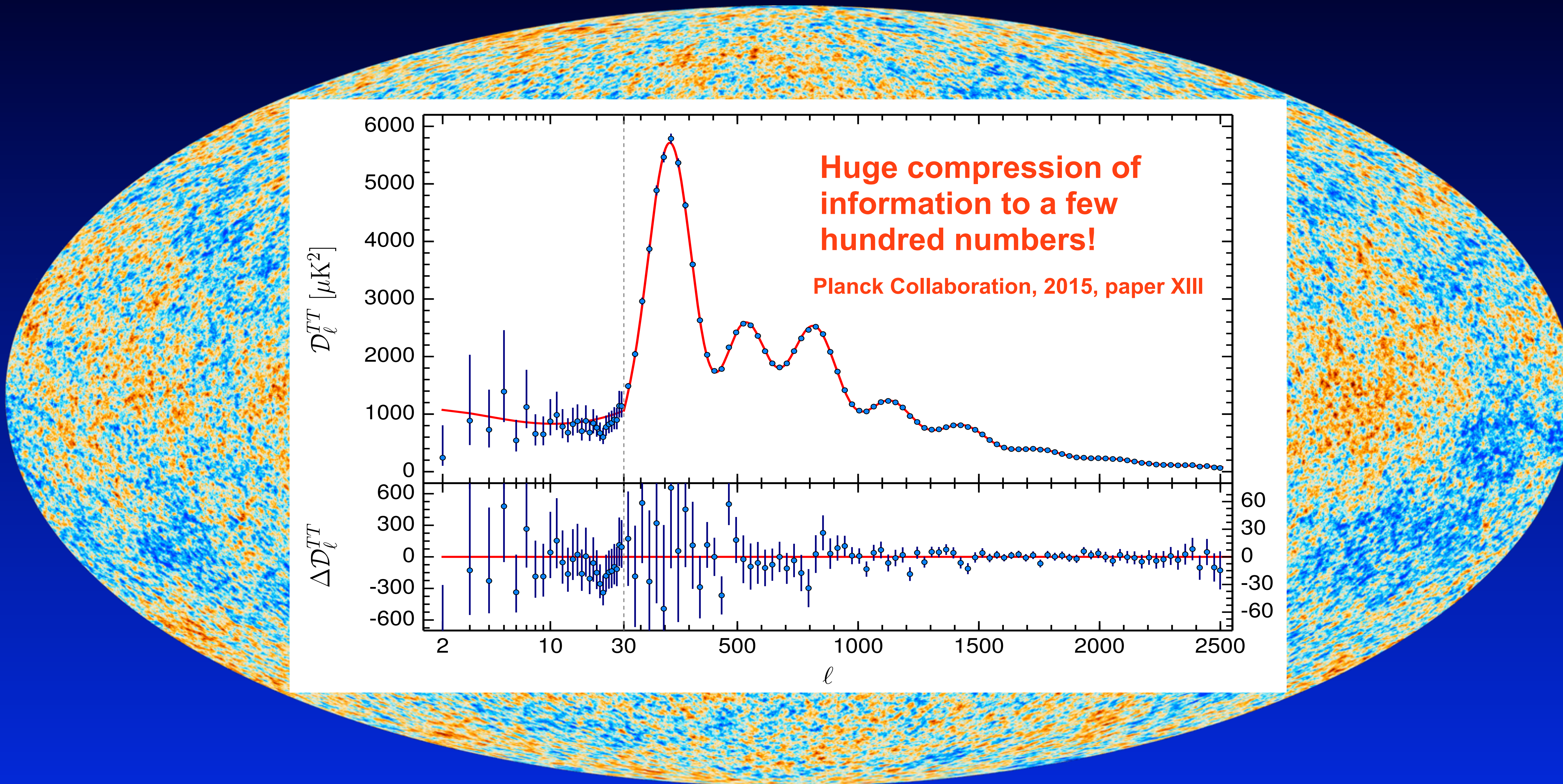

Planck all-sky temperature map

- CMB has a blackbody spectrum in every direction
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CMB provides another independent piece of information!

COBE/FIRAS

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

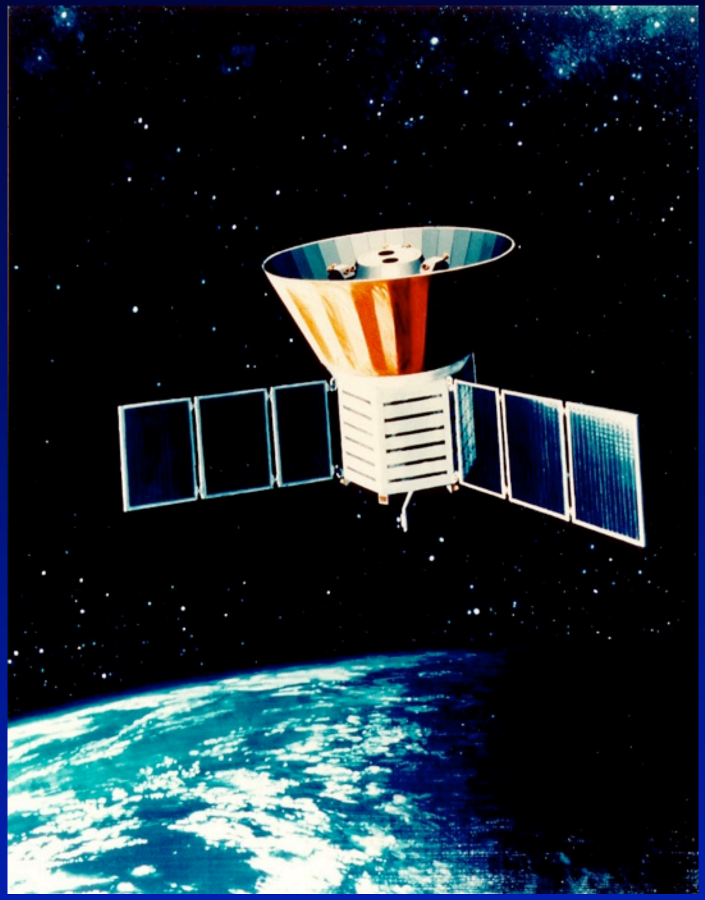
Absolute measurement required!

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

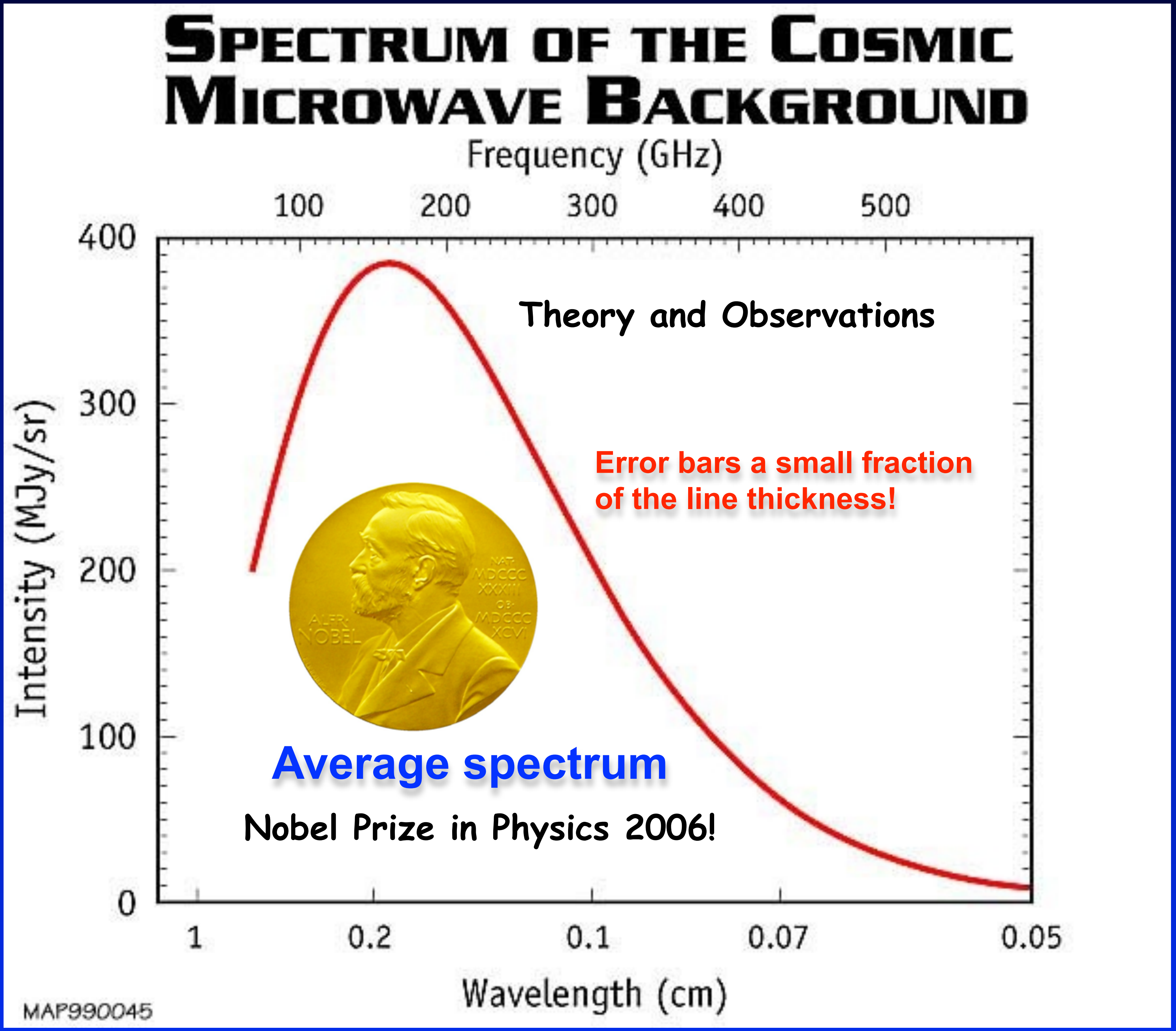
COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)



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

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

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



Mather et al., 1994, ApJ, 420, 439
Fixsen et al., 1996, ApJ, 473, 576
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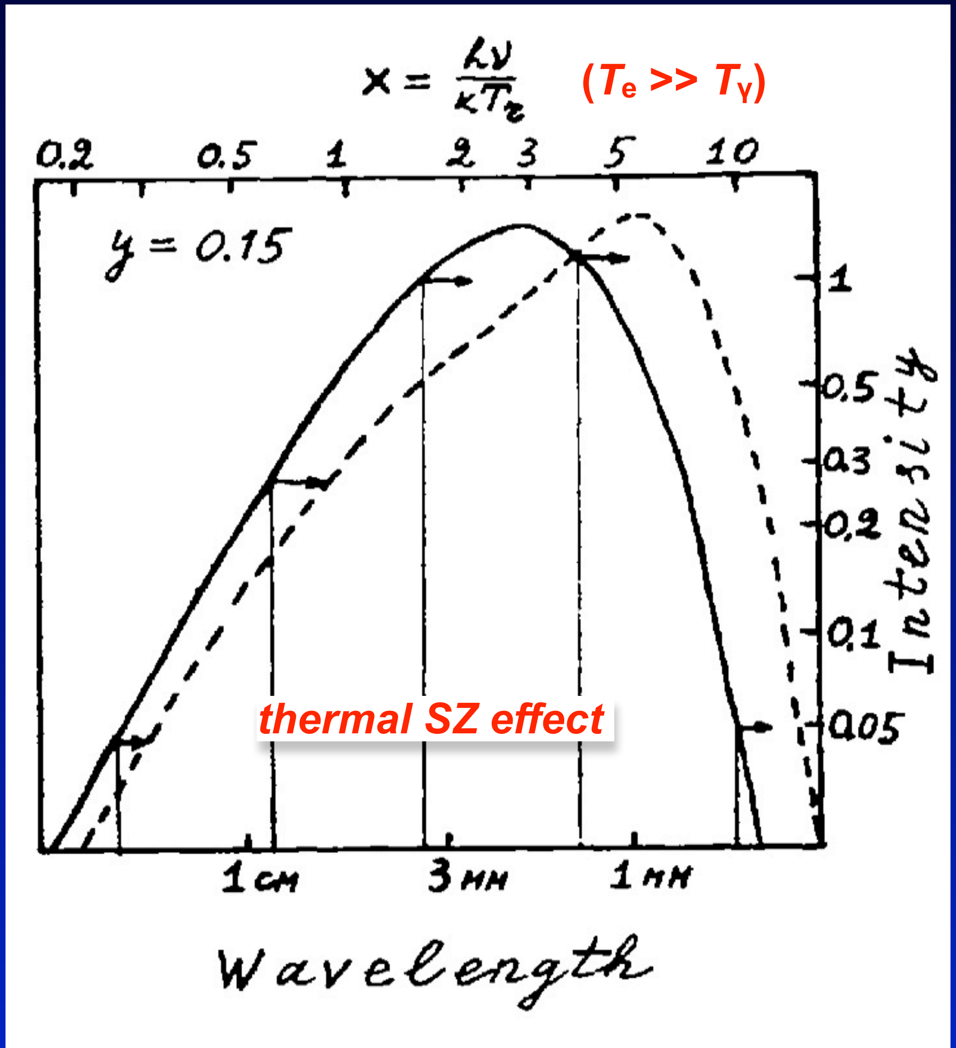
Standard types of primordial CMB distortions

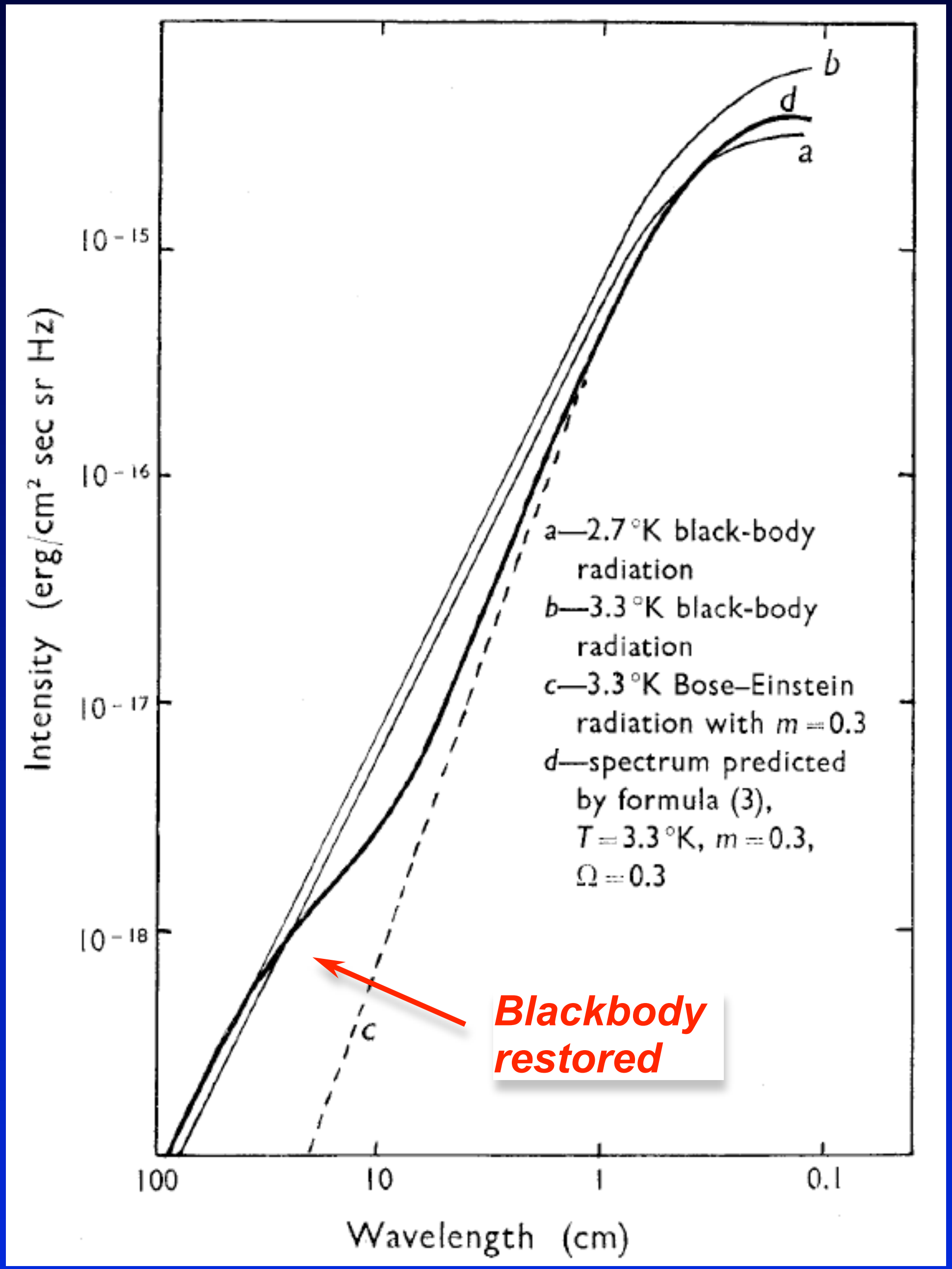
Compton y-distortion



Sunyaev & Zeldovich, 1980, ARAA, 18, 537

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

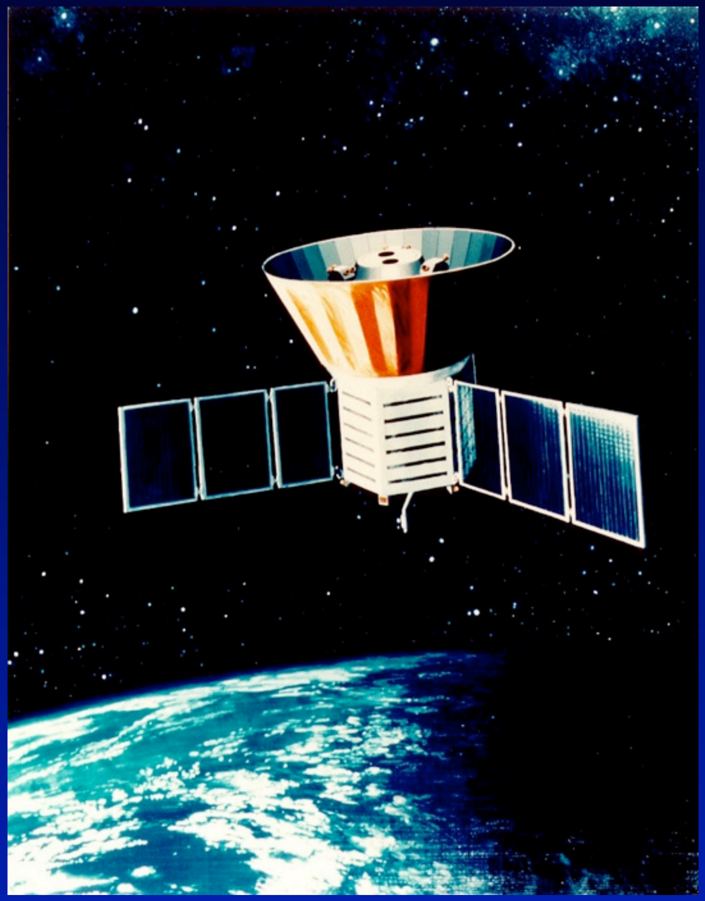
Chemical potential μ-distortion

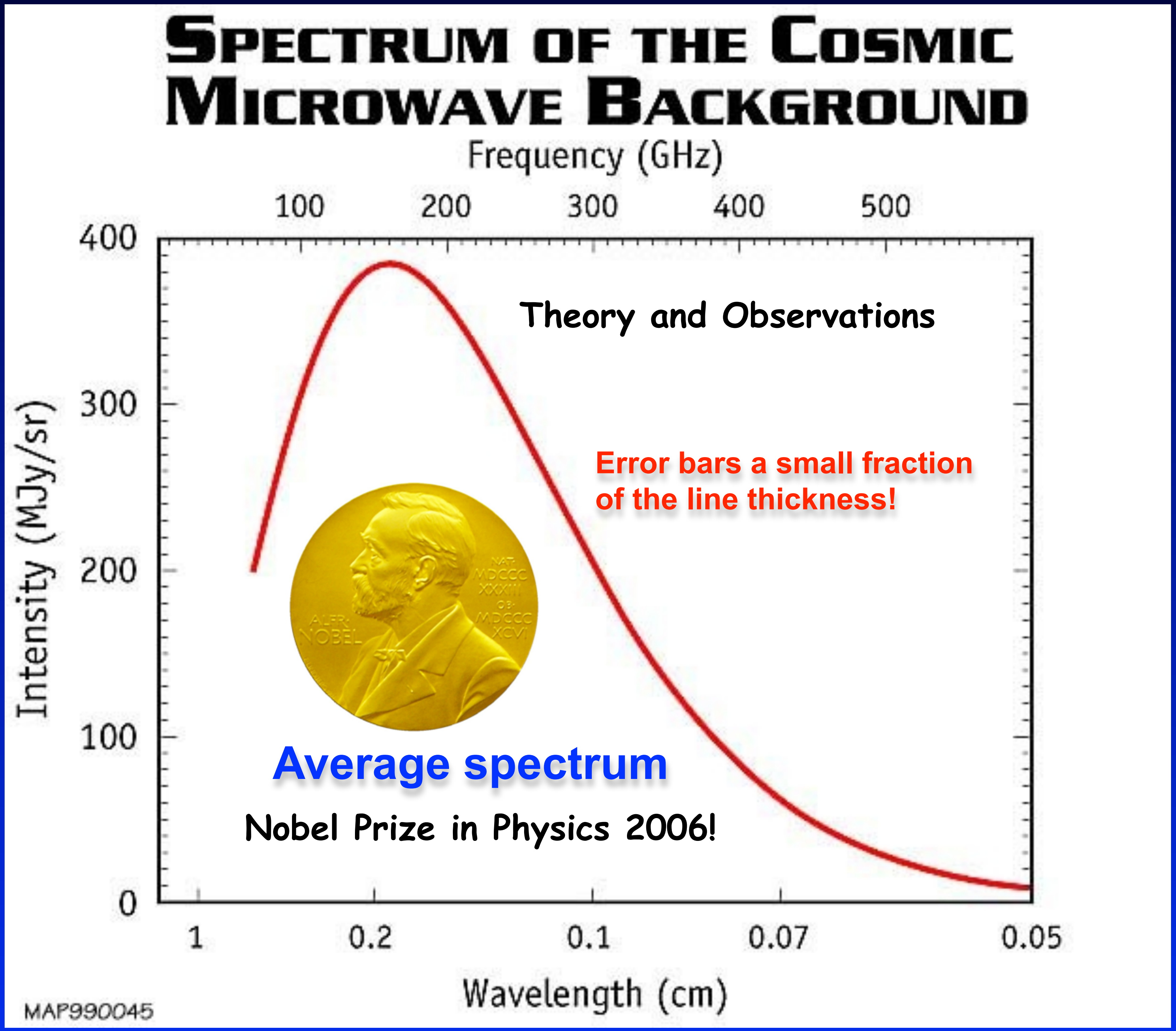


Sunyaev & Zeldovich, 1970, ApSS, 2, 66

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

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)
- Shock waves arising due to large-scale structure formation
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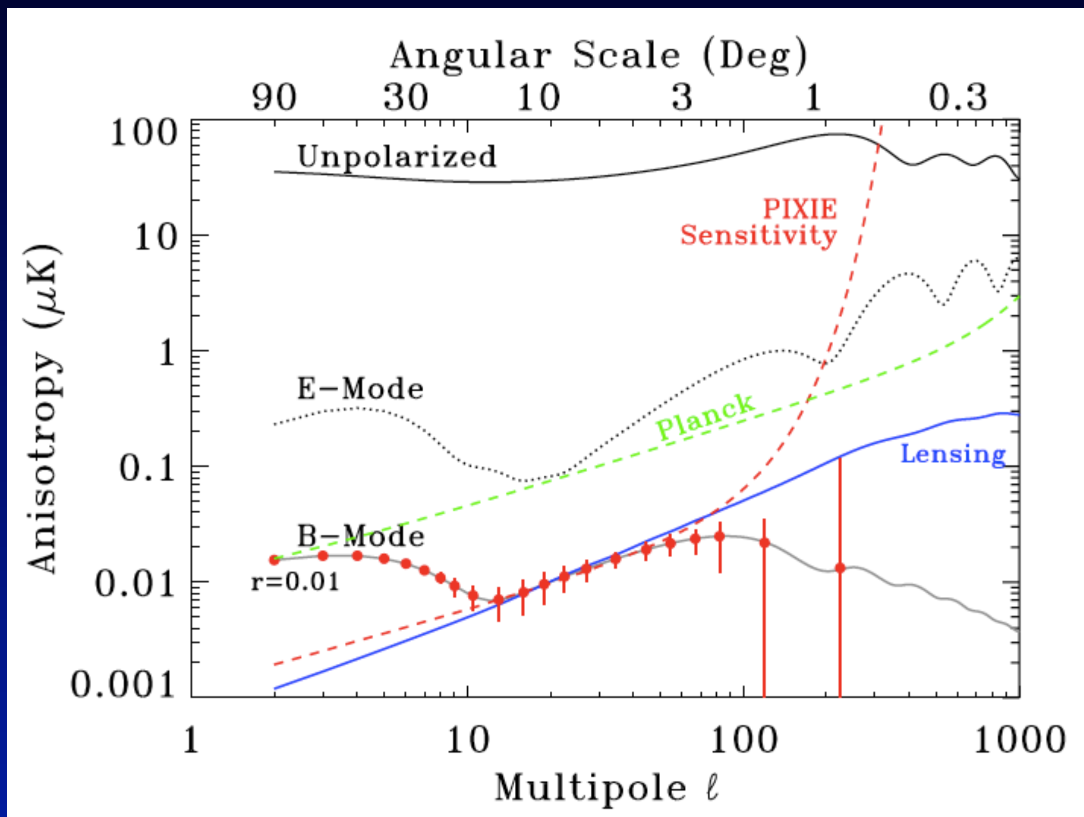
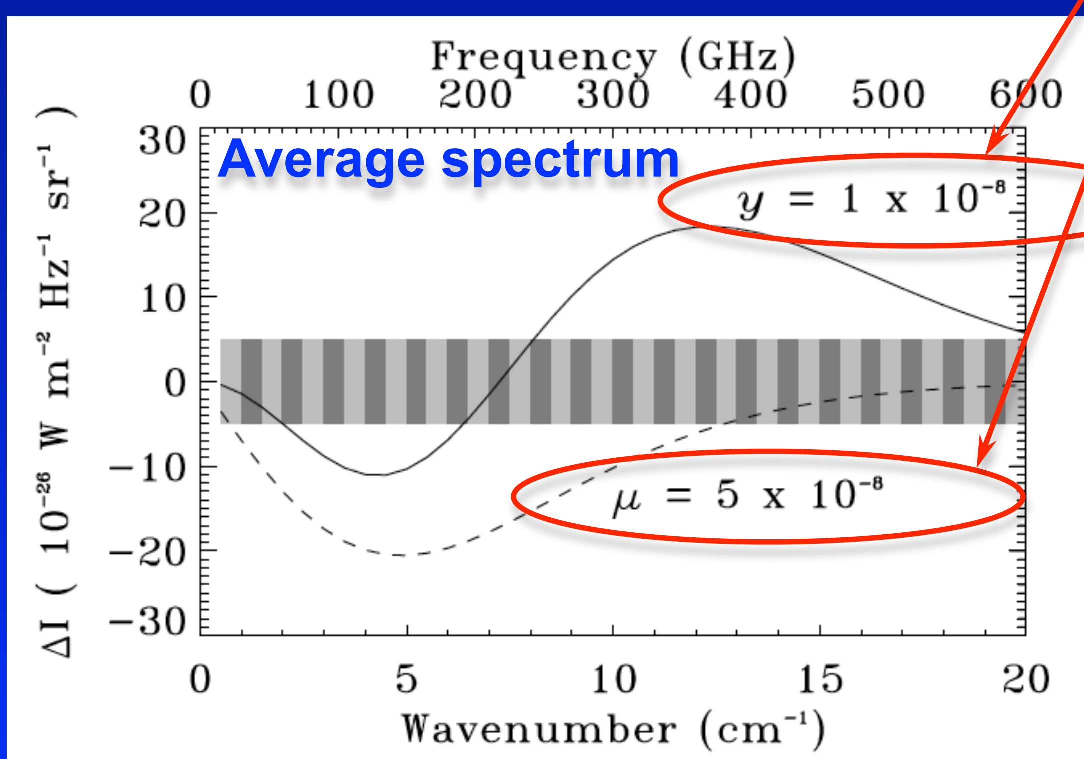
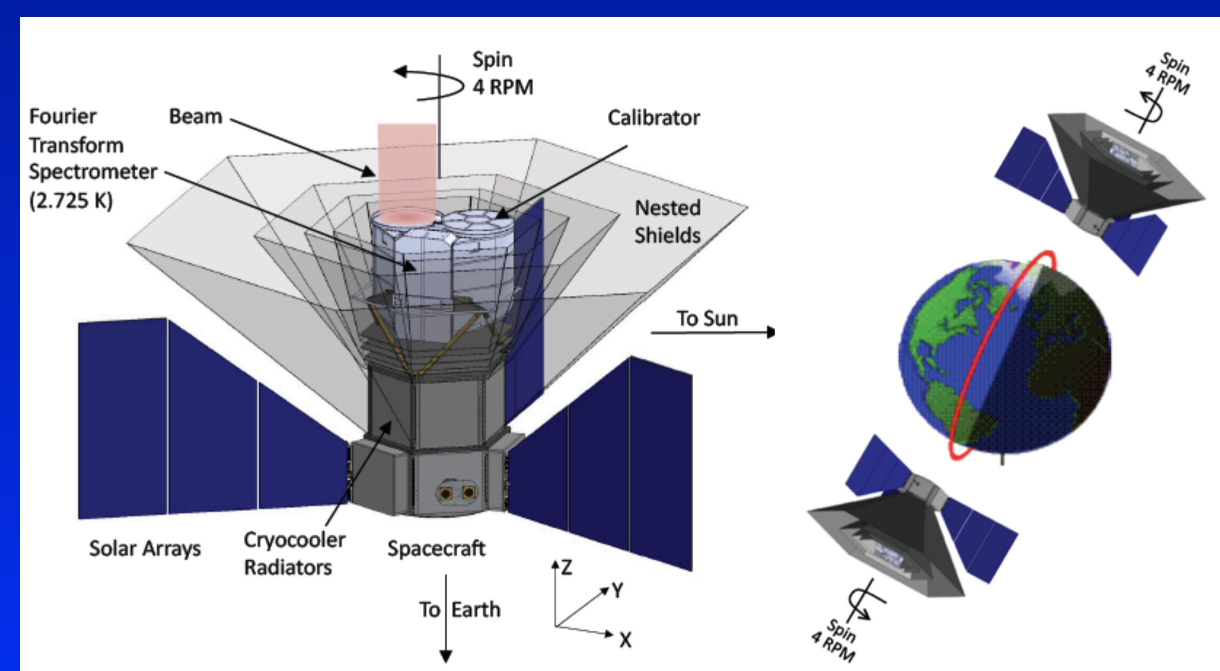
PIXIE: Primordial Inflation Explorer

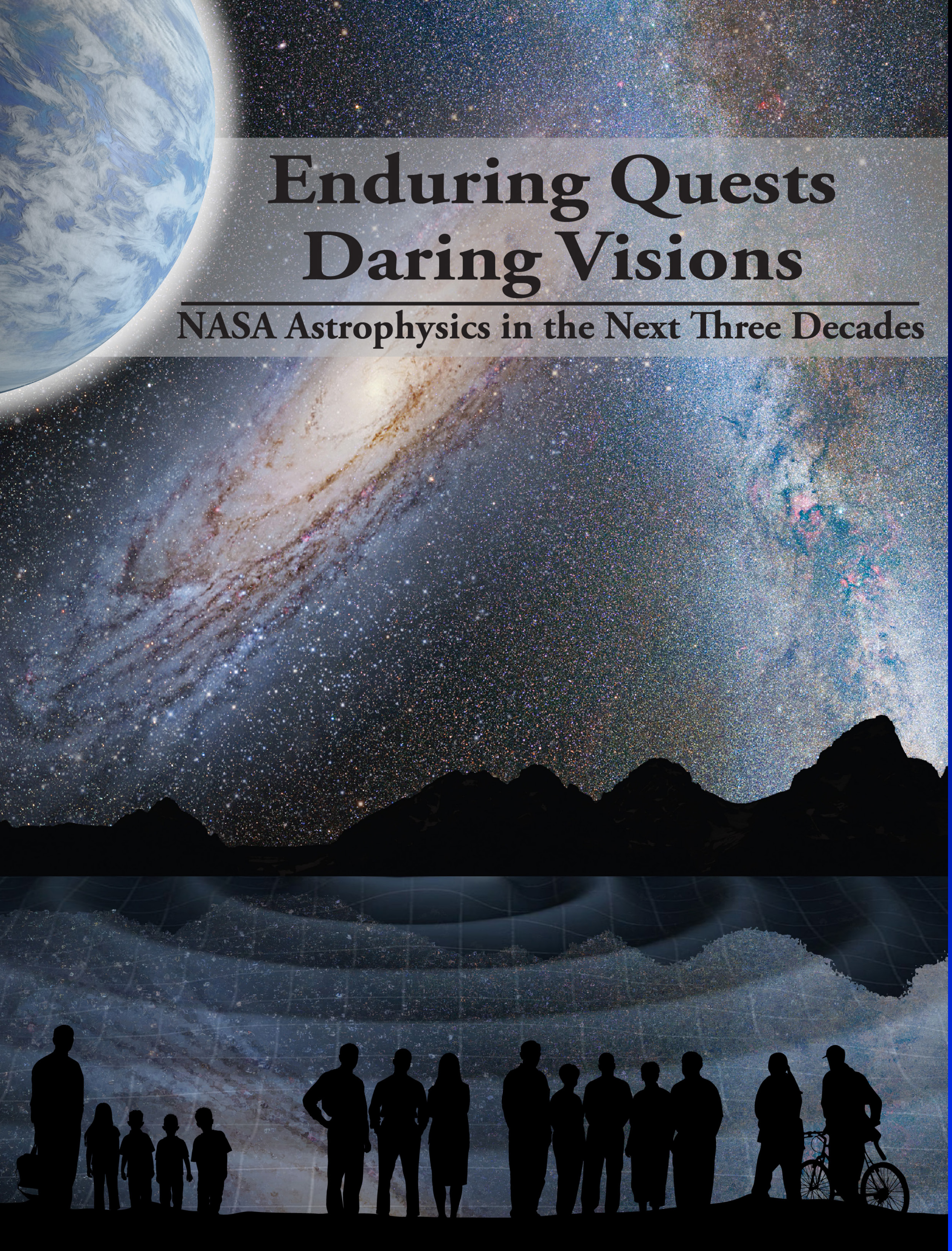


- 400 spectral channel in the frequency range 30 GHz and 6THz (Δv ~ 15GHz)
- about 1000 (!!!) times more sensitive than COBE/FIRAS
- B-mode polarization from inflation ($r \approx 10^{-3}$)
- improved limits on μ and y
- was proposed 2011 as NASA EX mission (i.e. cost ~ 200 M$)





Kogut et al, JCAP, 2011, arXiv:1105.2044



NASA 30-yr Roadmap Study

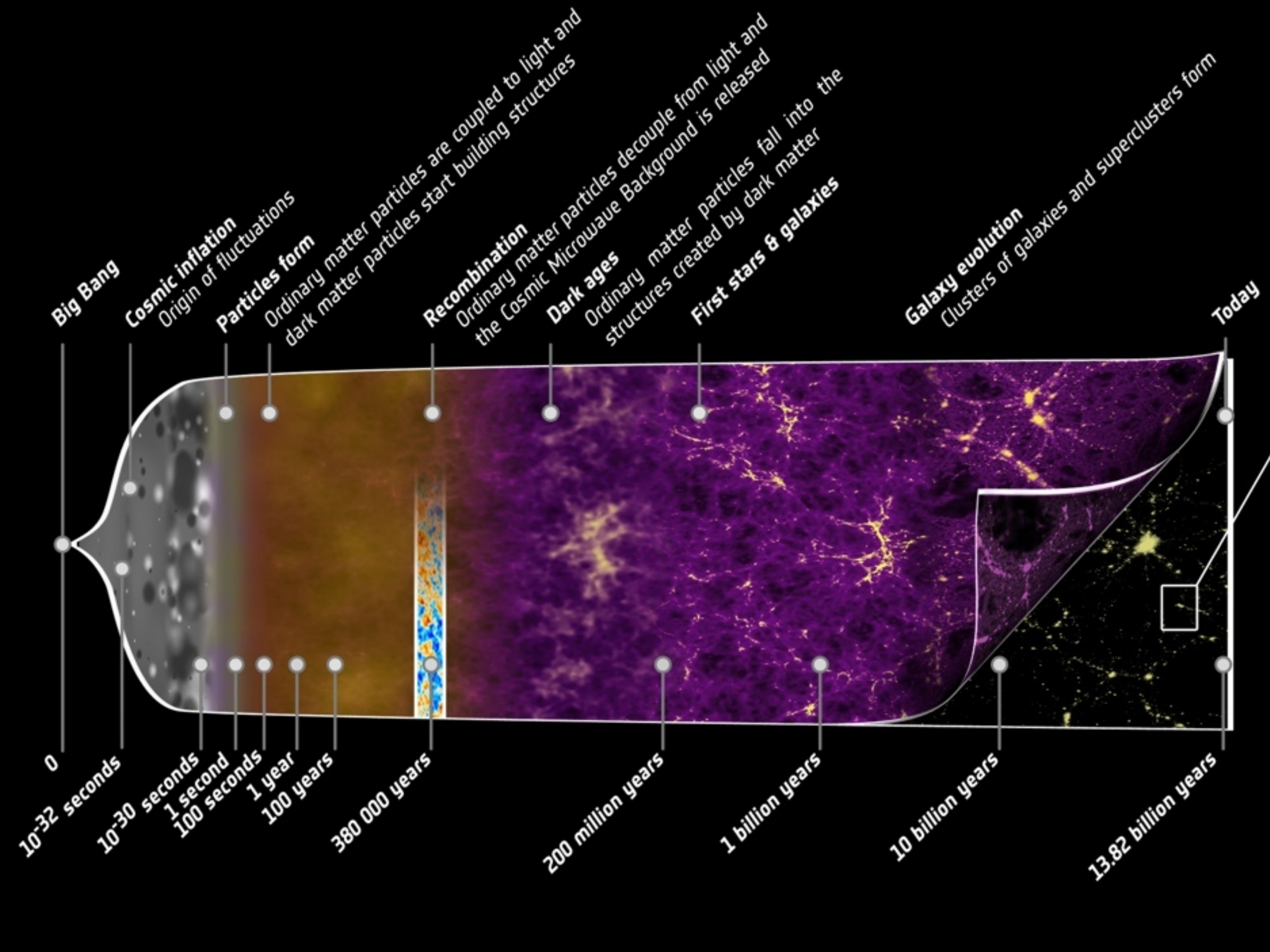
(published Dec 2013)

How does the Universe work?

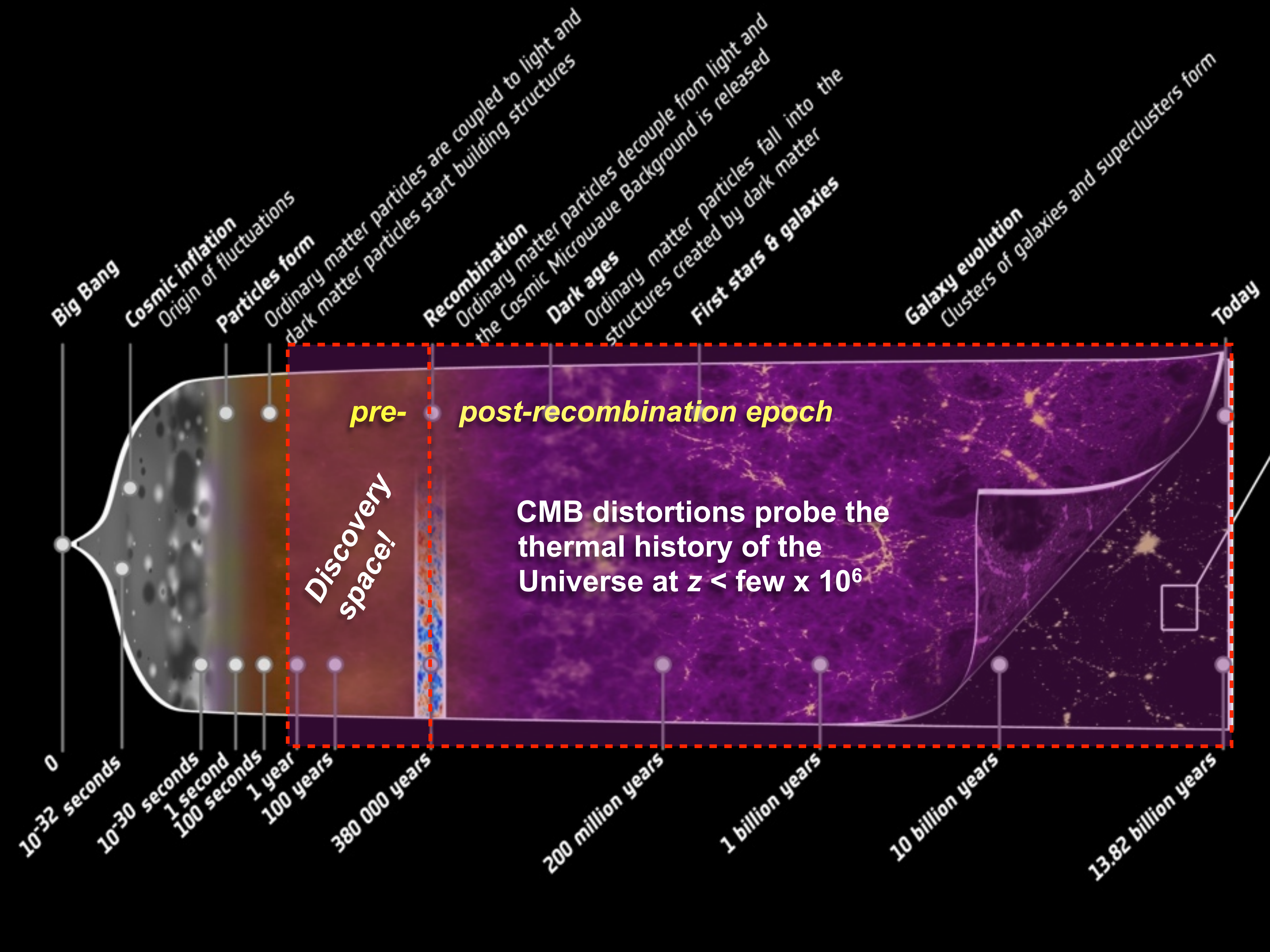
"Measure the spectrum of the CMB with precision several orders of magnitude higher than COBE FIRAS, from a moderate-scale mission or an instrument on CMB Polarization Surveyor."

New call from NASA expected end 2016

Energy release distortions primer



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
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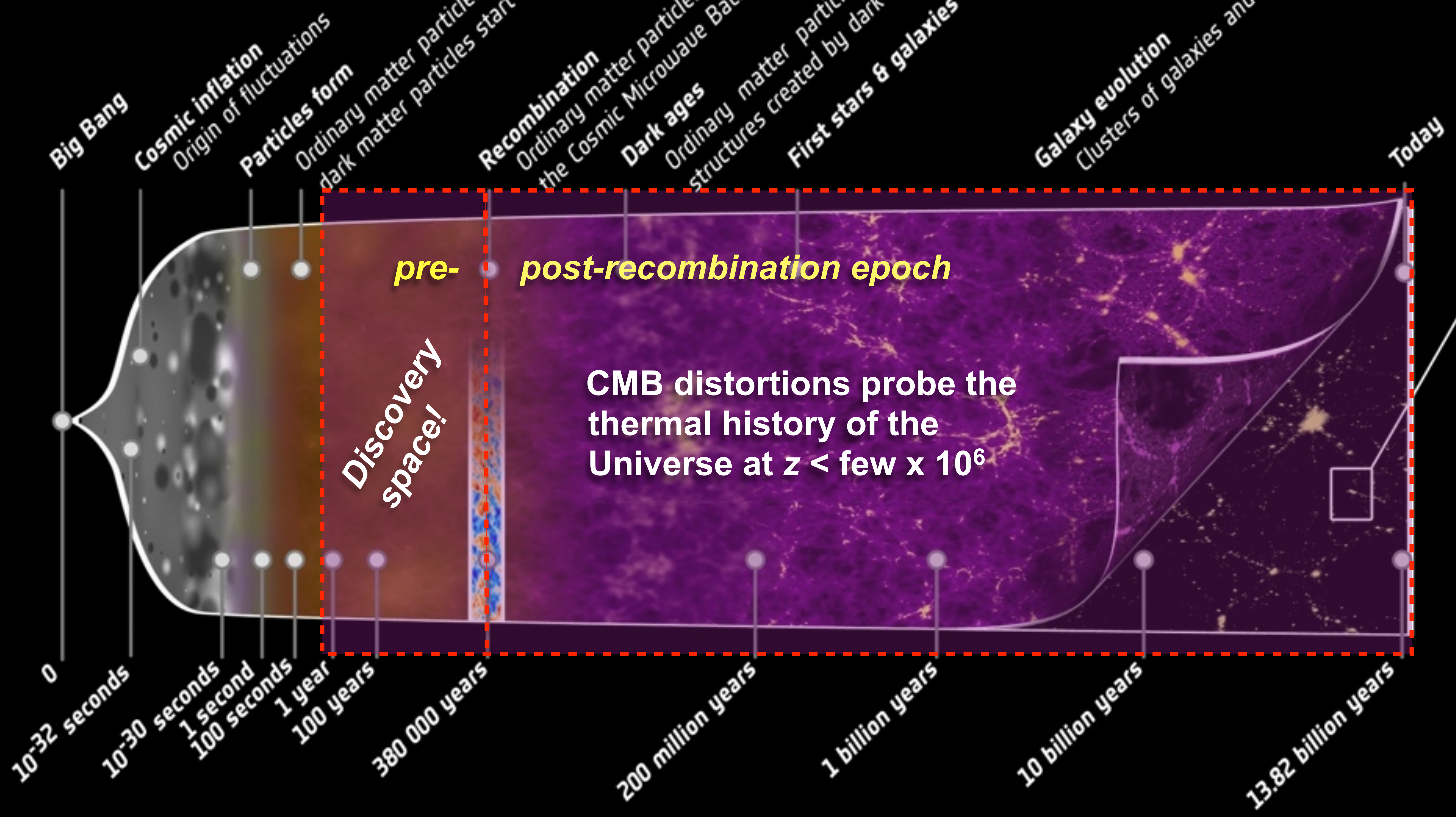
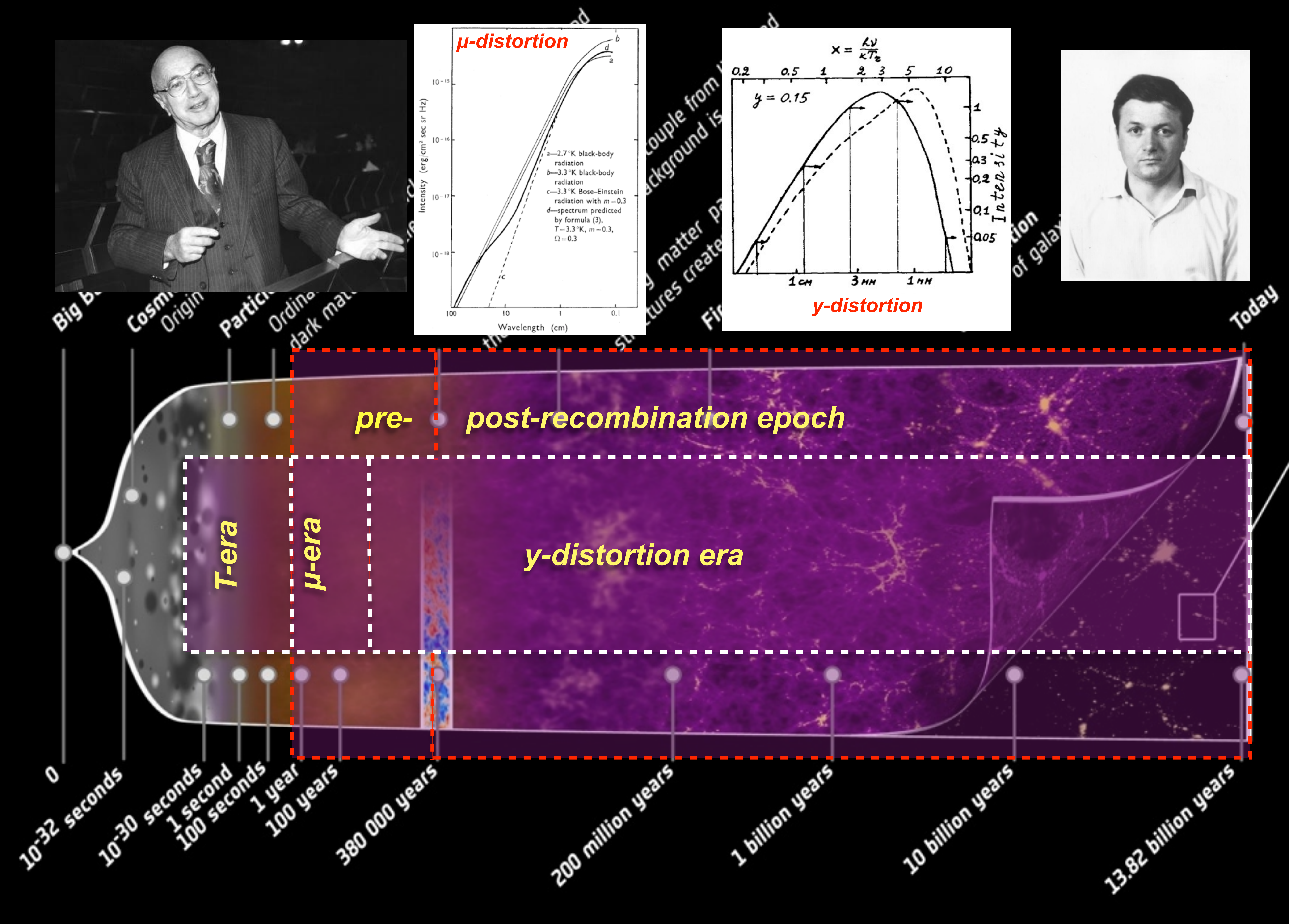
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
pre-
post-recombination epoch
Discovery 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!




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
y-distortion
y = 0.15
Intensity
pre-
post-recombination epoch
T-era
μ-era
y-distortion era
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

Simple estimates for the distortion μ- and y-parameters caused by energy release

- Generalization of classical approximations:

$$y = \frac{1}{4}\left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_y = \frac{1}{4}\int_0^\infty \mathcal{J}_y(z')\,\frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z'}\,\mathrm{d}z'$$

$$\mu = 1.401\left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_\mu = 1.401\int_0^\infty \mathcal{J}_\mu(z')\,\frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z'}\,\mathrm{d}z'$$

Energy release history

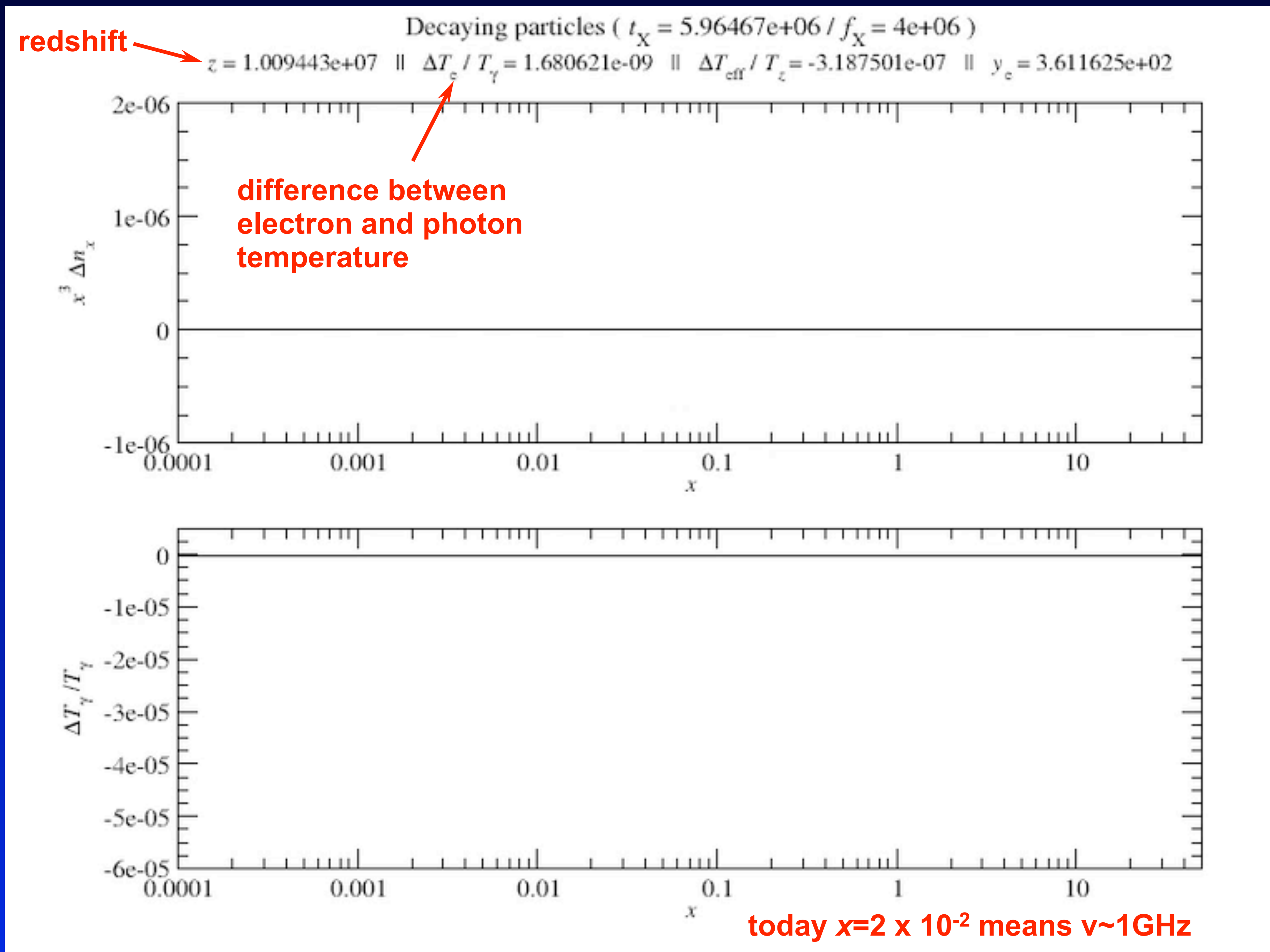
- Differences in the approximations are due to *visibility functions*
- An overview can be found in ArXiv:1603.02496
- One *commonly* used approximation (e.g., see Hu&Silk, 1993):

$$\mathcal{J}_y(z) = \begin{cases} 1 & \text{for } z_{\rm rec} \le z \le z_{\mu y} \\ 0 & \text{otherwise} \end{cases}$$

$$\mathcal{J}_\mu(z) = \begin{cases} \mathcal{J}_{\rm bb}(z) & \text{for } z_{\mu y} \le z \\ 0 & \text{otherwise.} \end{cases}$$

- step-function transition between μ and *y* around $z_{\mu y} \simeq 5\times 10^4$
- accounts for thermalization efficiency with *distortion visibility*
  $\mathcal{J}_{\rm bb}(z) \approx \mathrm{e}^{-(z/z_{\rm th})^{5/2}}$ $z_{\rm th} \approx 1.98\times 10^6$

Example: *Energy release by decaying relict particle*



- initial condition: *full equilibrium*
- total energy release:
  $\Delta\rho/\rho \sim 1.3 \times 10^{-6}$
- most of energy release around:
  $z_X \sim 2 \times 10^6$
- positive μ-distortion
- high frequency distortion frozen around $z \simeq 5 \times 10^5$
- late ($z < 10^3$) free-free absorption at very low frequencies ($T_e < T_\gamma$)

Computation carried out with *CosmoTherm* (JC & Sunyaev 2012)

Quasi-Exact Treatment of the Thermalization Problem

- *For real forecasts of future prospects a precise & fast method for computing the spectral distortion is needed!*
- *Case-by-case computation of the distortion (e.g., with CosmoTherm, JC & Sunyaev, 2012, ArXiv:1109.6552) still rather time-consuming*
- *But: distortions are small ⇒ thermalization problem becomes linear!*
- *Simple solution: compute "response function" of the thermalization problem ⇒ Green's function approach (JC, 2013, ArXiv:1304.6120)*
- *Final distortion for fixed energy-release history given by*

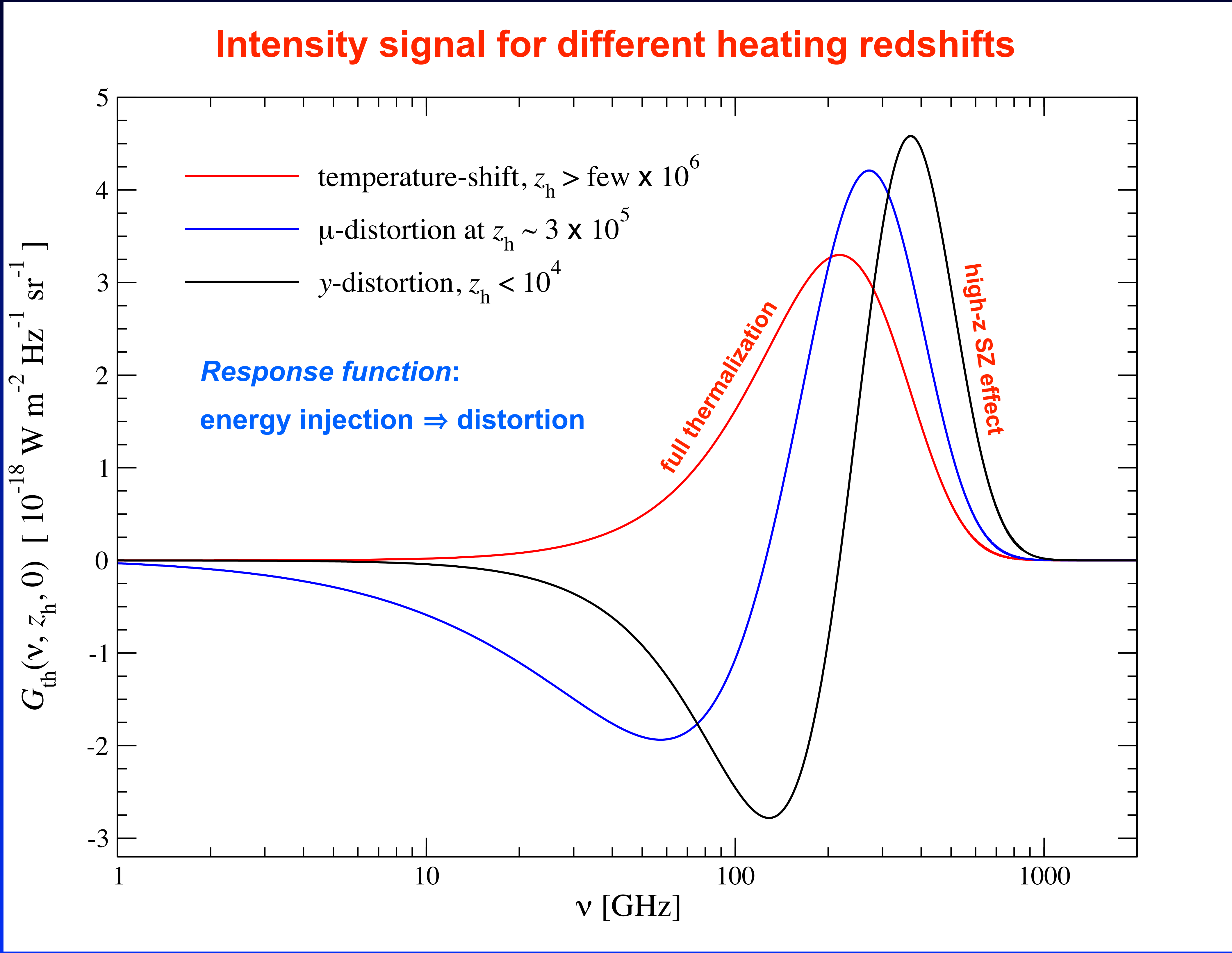
$$\Delta I_\nu \approx \int_0^\infty G_{\rm th}(\nu, z') \frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'} {\rm d}z'$$

Thermalization Green's function

- *Fast and quasi-exact! No additional approximations!*

CosmoTherm available at: www.Chluba.de/CosmoTherm

Distortion Green's function for energy release



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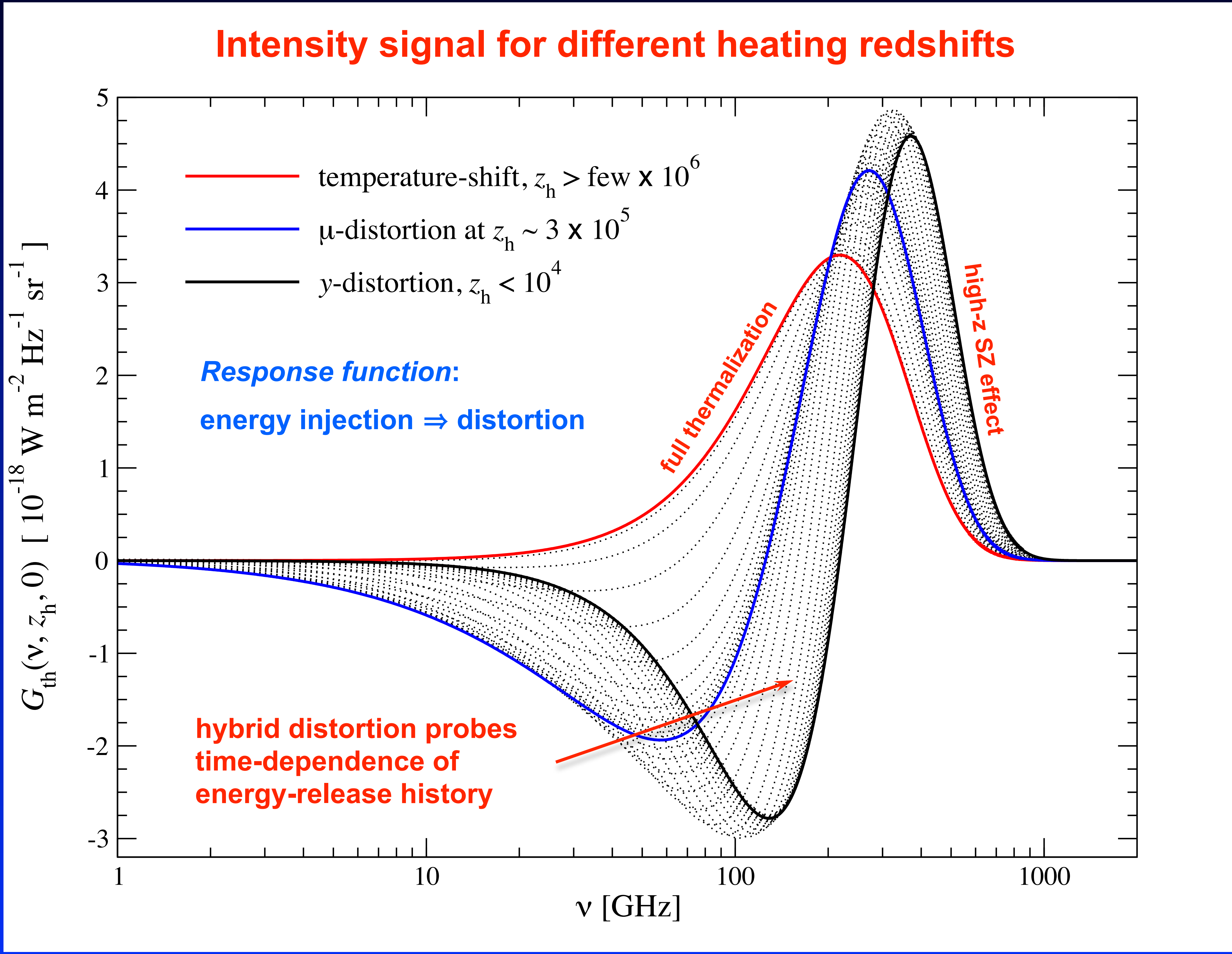

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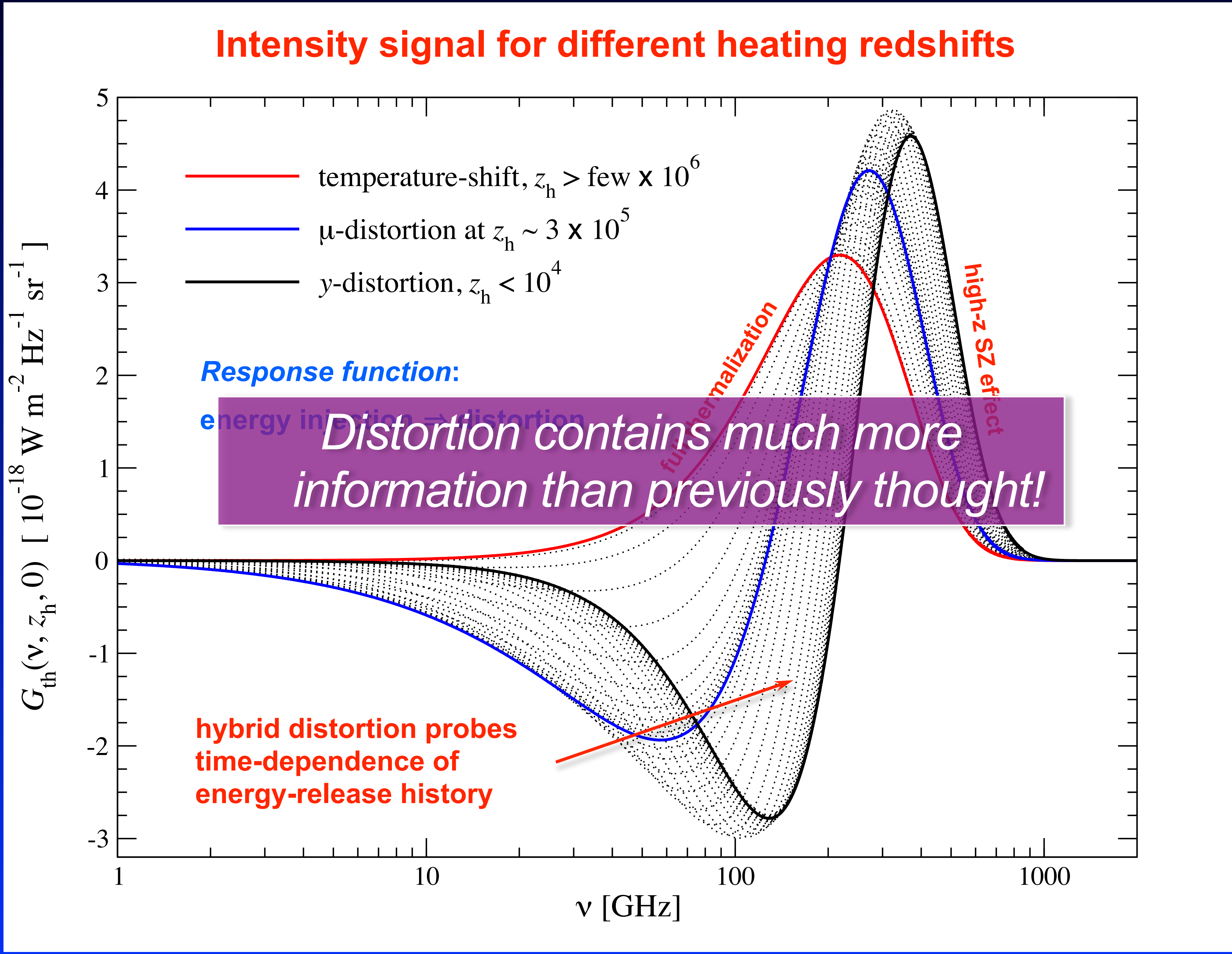

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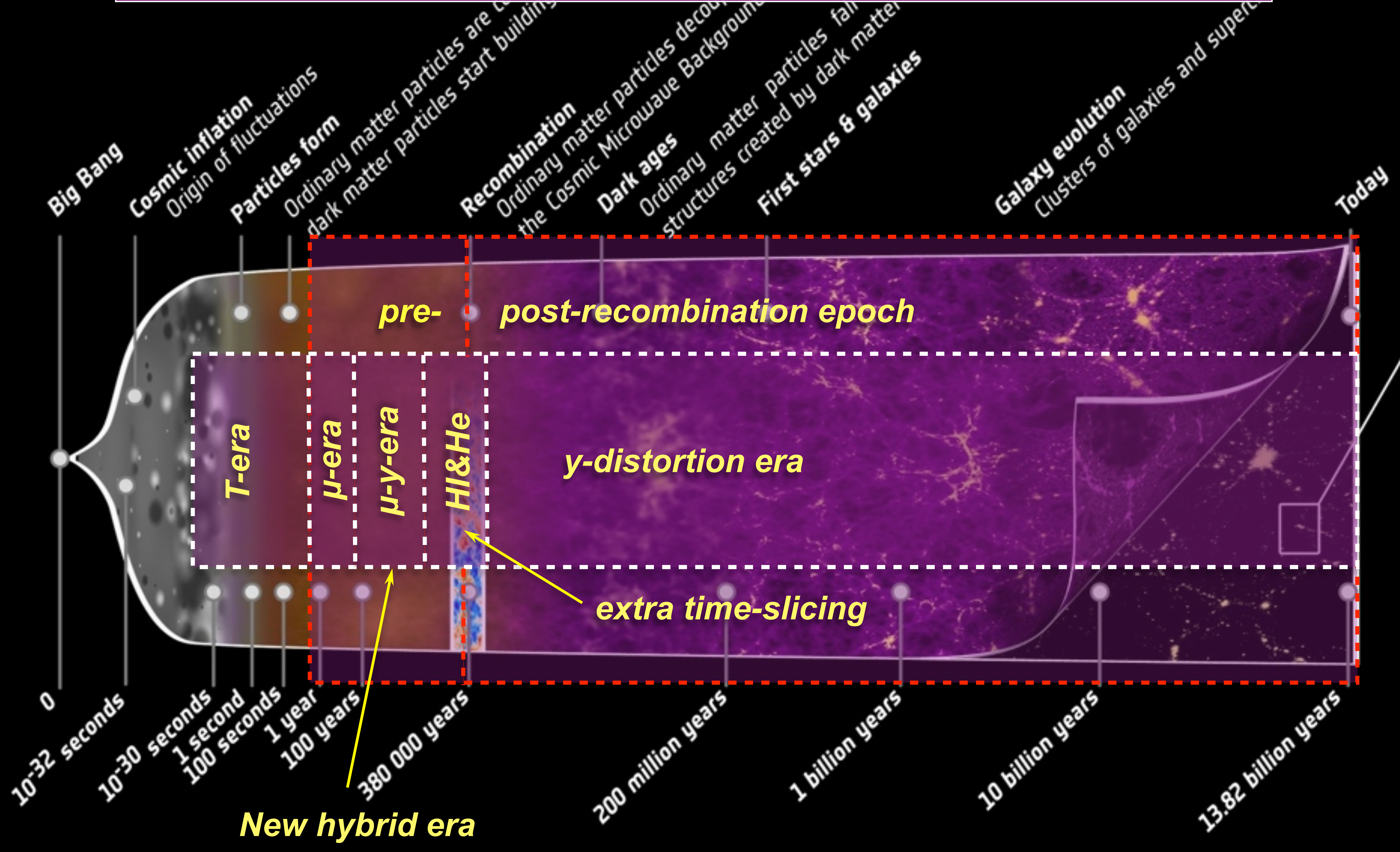
CMB spectrum adds another dimension to the problem!



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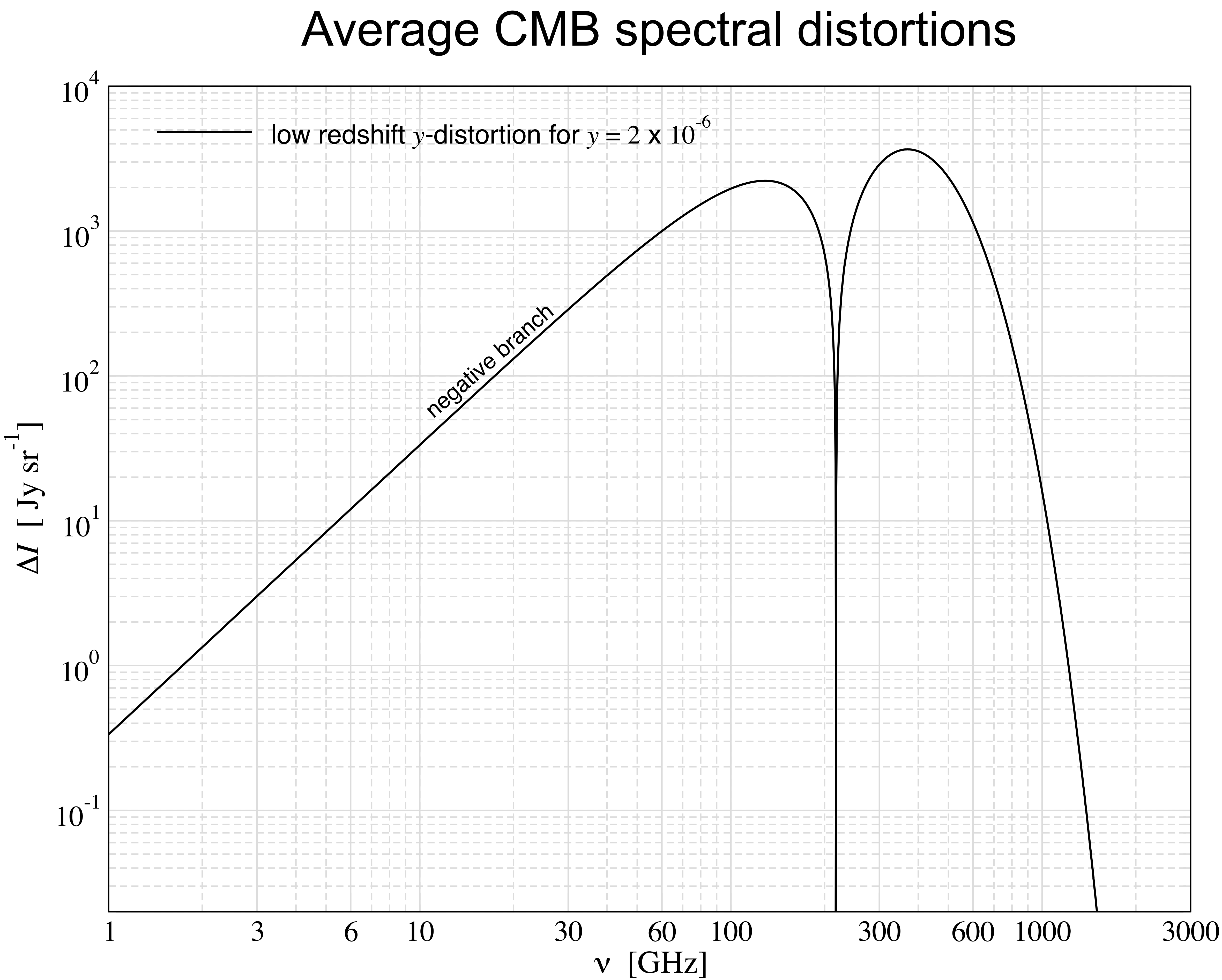
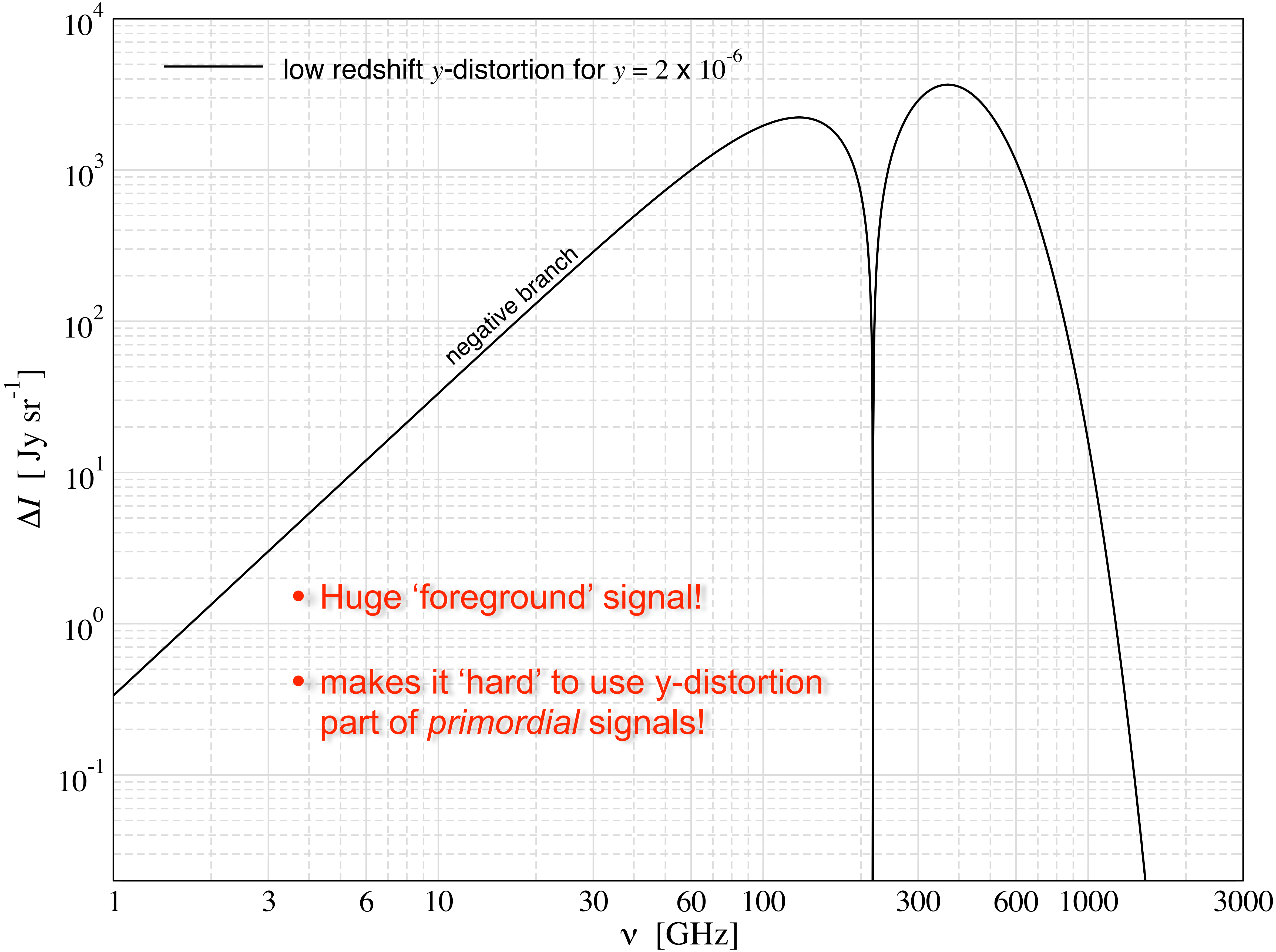
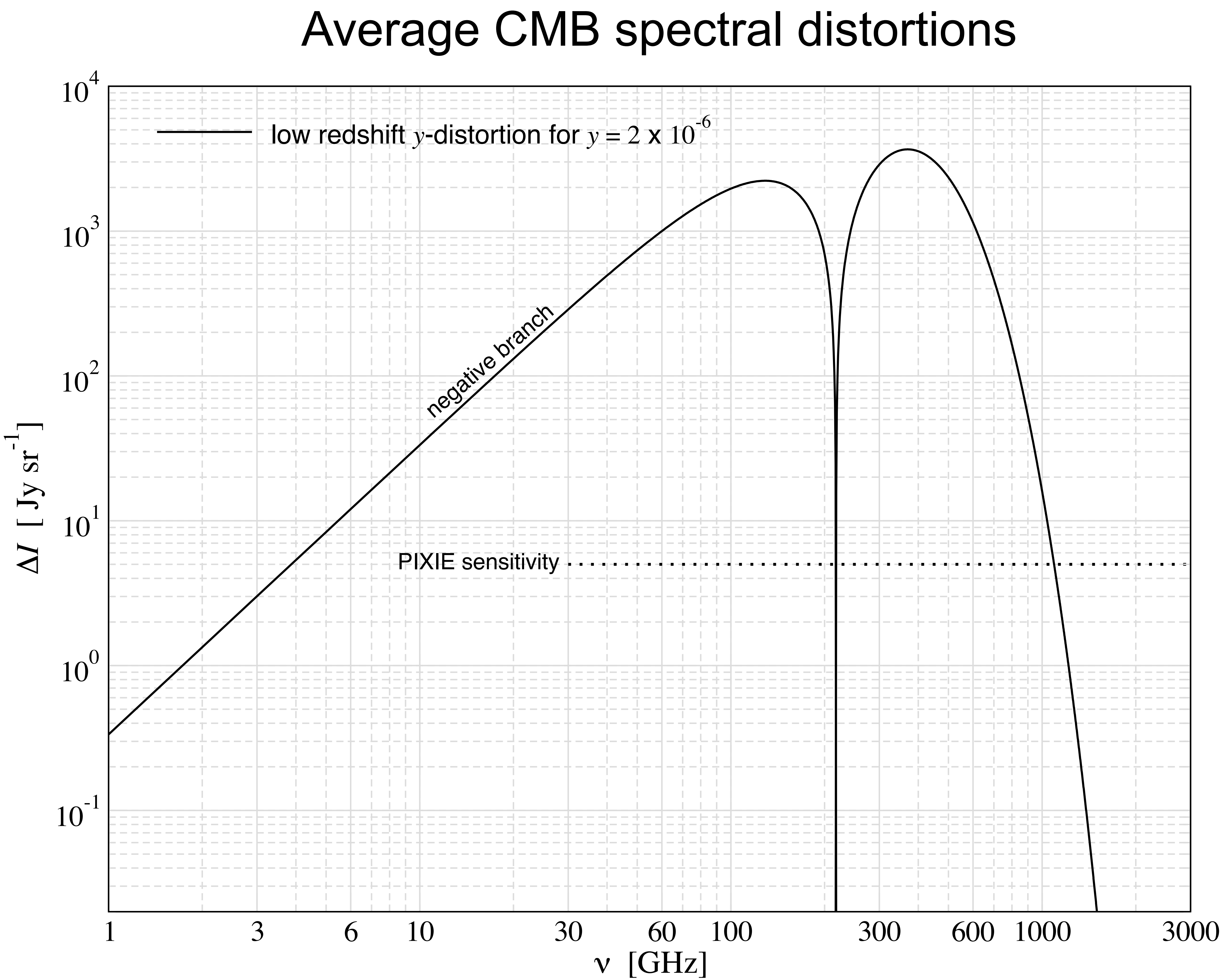

Average CMB spectral distortions
low redshift y-distortion for y = 2 x 10^-6
negative branch
ΔI [Jy sr^-1]
10^4
10^3
10^2
10^1
10^0
10^-1
1
3
6
10
30
60
100
300
600
1000
3000
ν [GHz]

Average CMB spectral distortions





Average CMB spectral distortions
low redshift y-distortion for $y = 2 \times 10^{-6}$
negative branch
PIXIE sensitivity
ΔI [Jy sr^{-1}]
ν [GHz]
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
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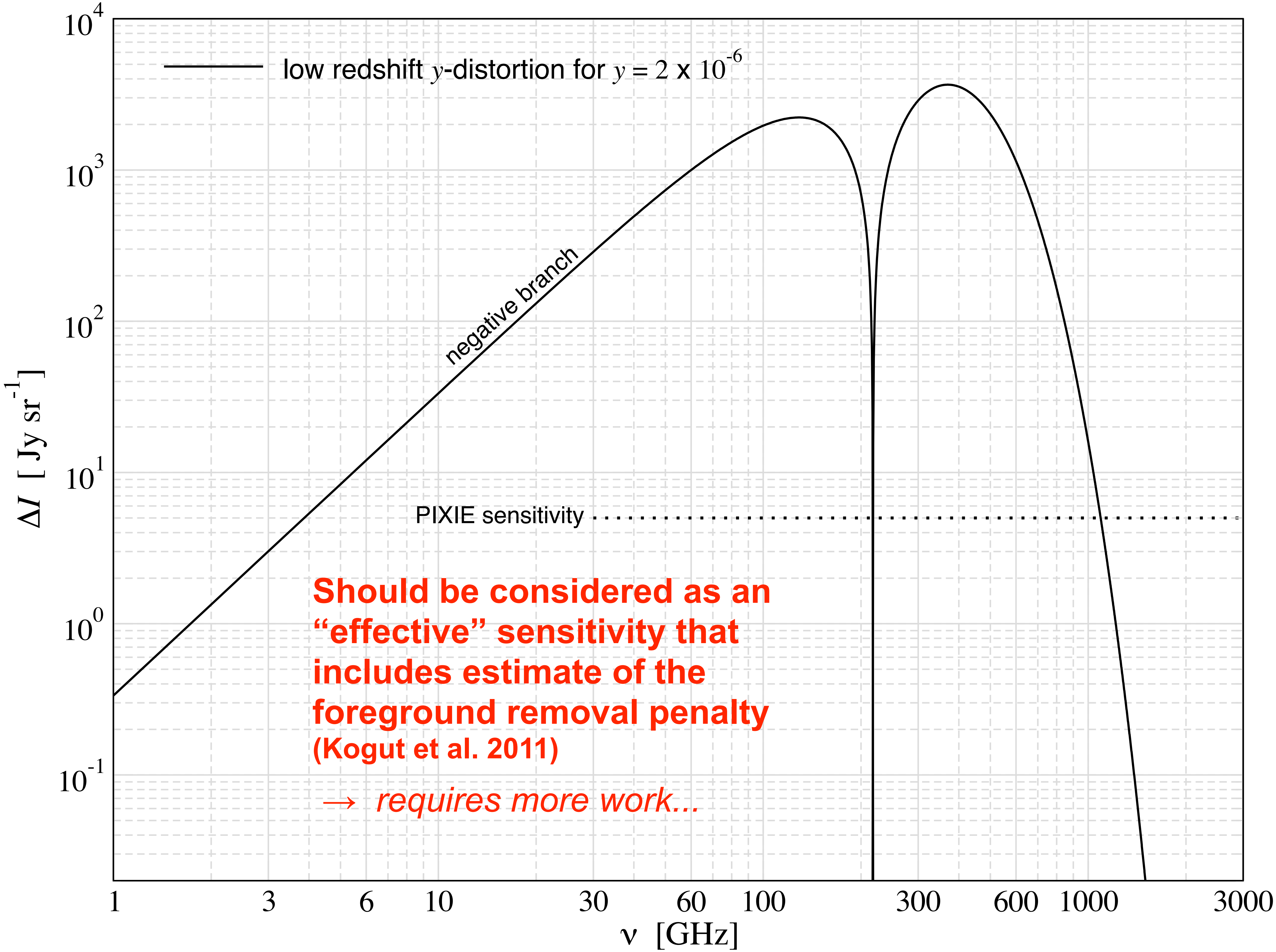

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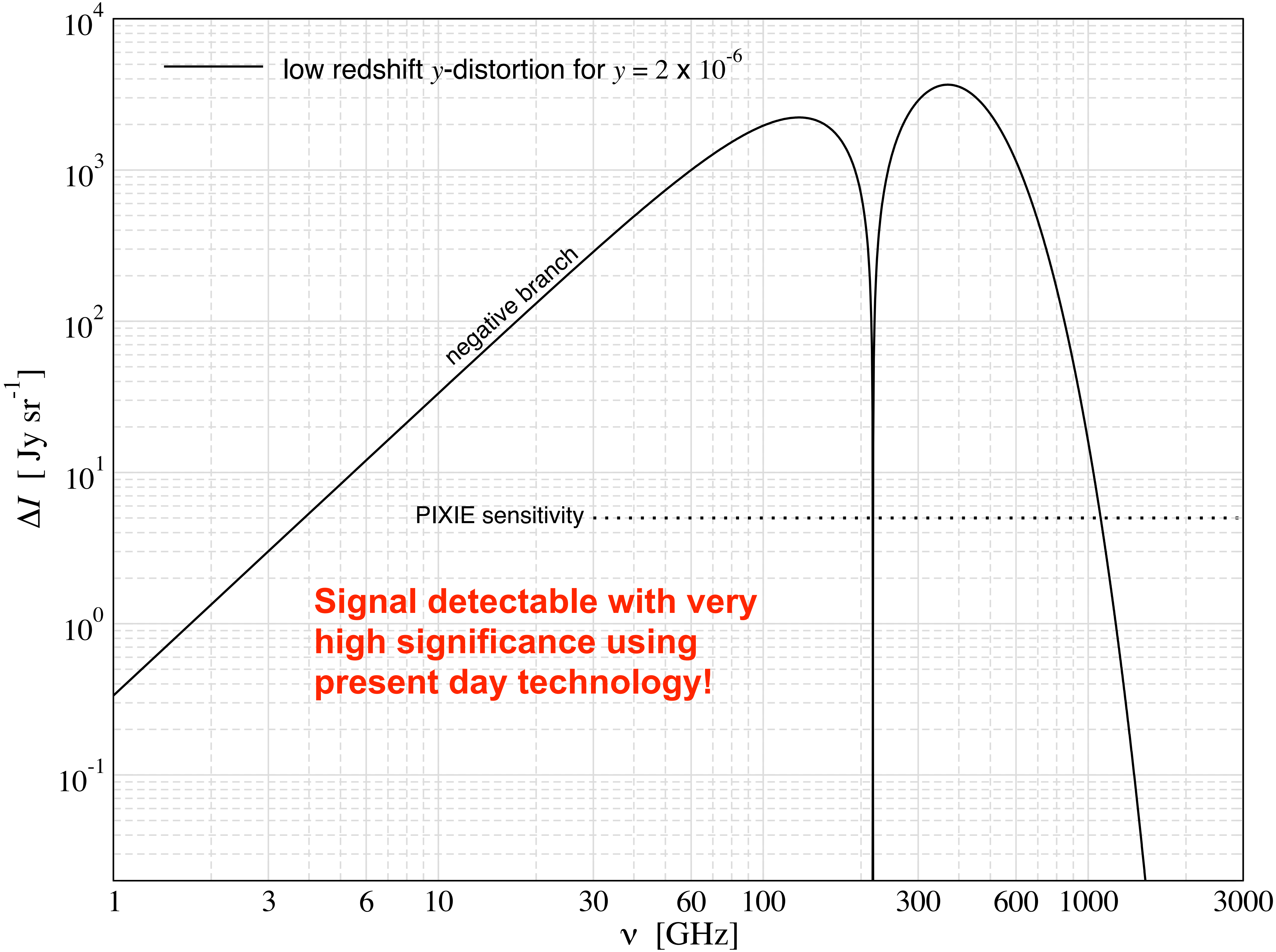

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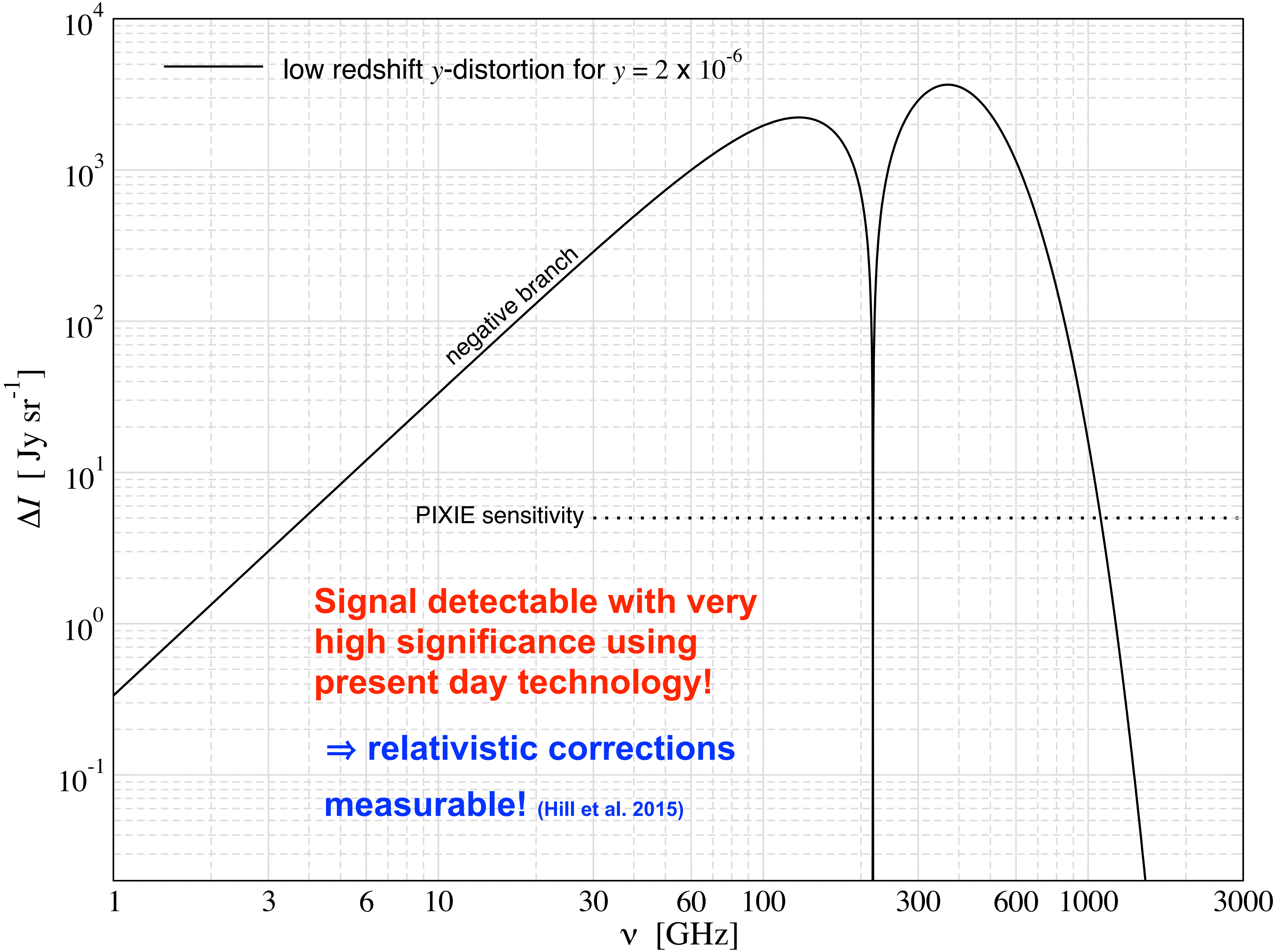

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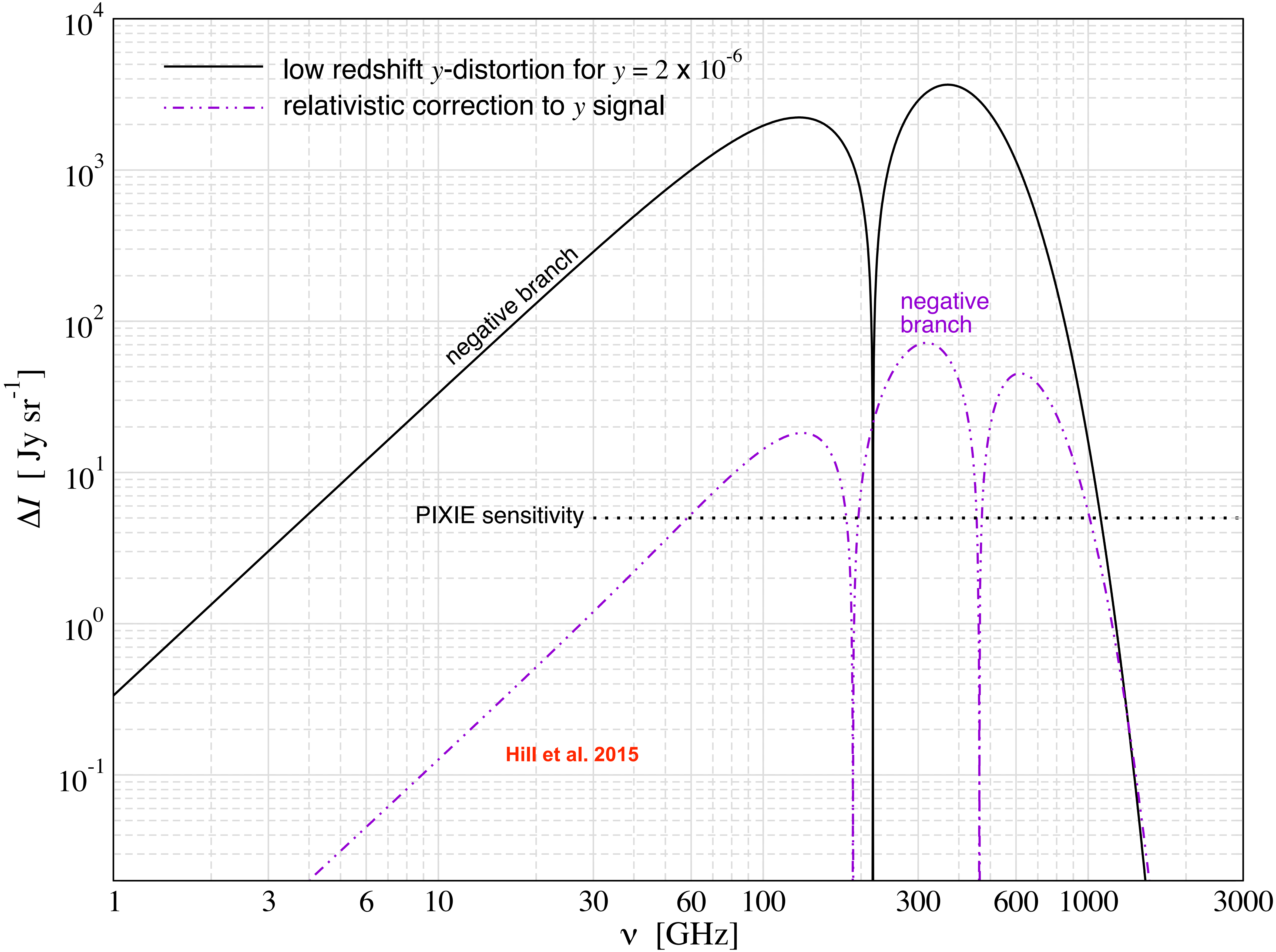

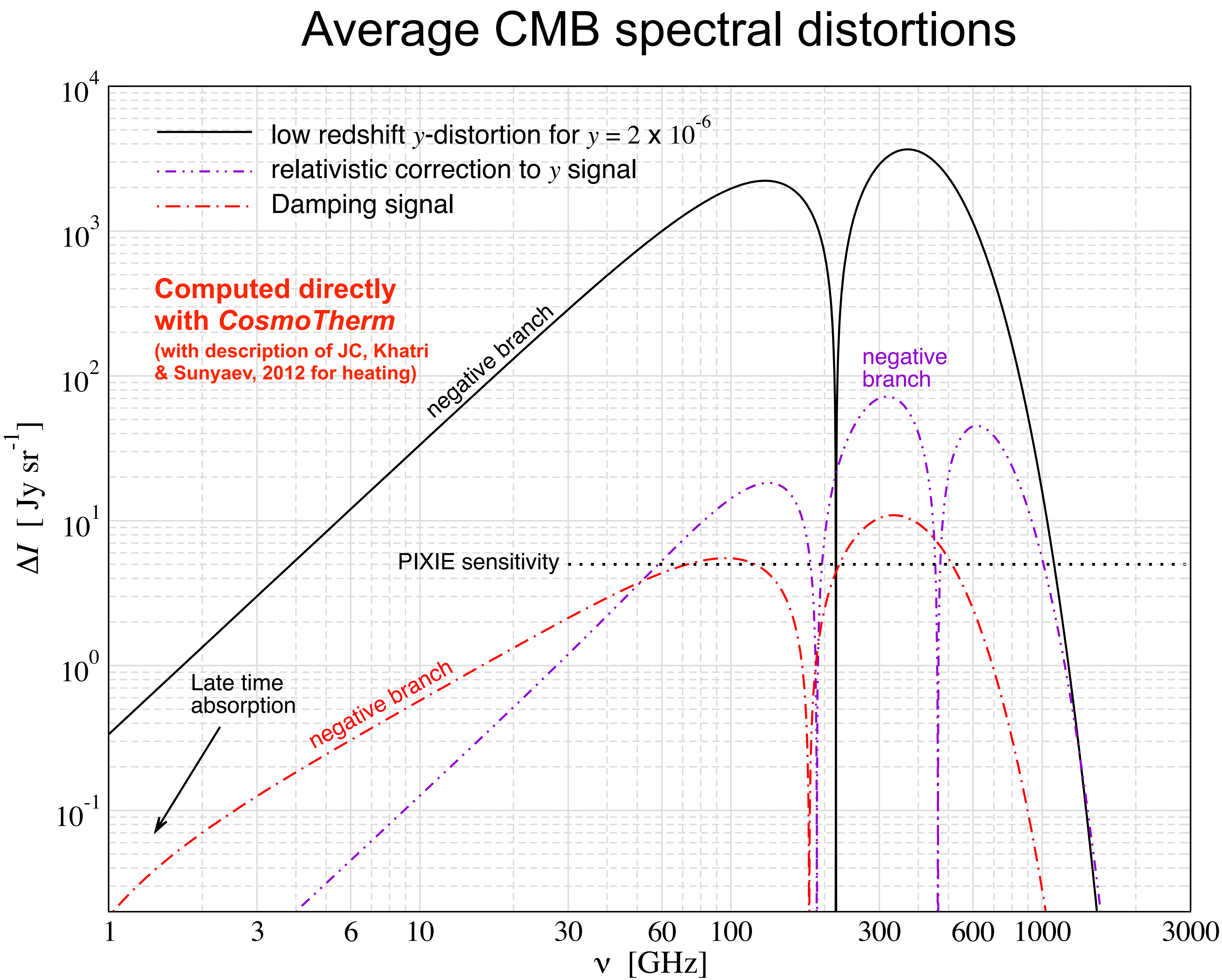
Average CMB spectral distortions
low redshift y-distortion for y = 2 x 10^-6
relativistic correction to y signal
Damping signal
Computed directly
with CosmoTherm
(with description of JC, Khatri
& Sunyaev, 2012 for heating)
negative branch
negative branch
negative branch
PIXIE sensitivity
Late time
absorption
ΔI [Jy sr^-1]
ν [GHz]
10^4
10^3
10^2
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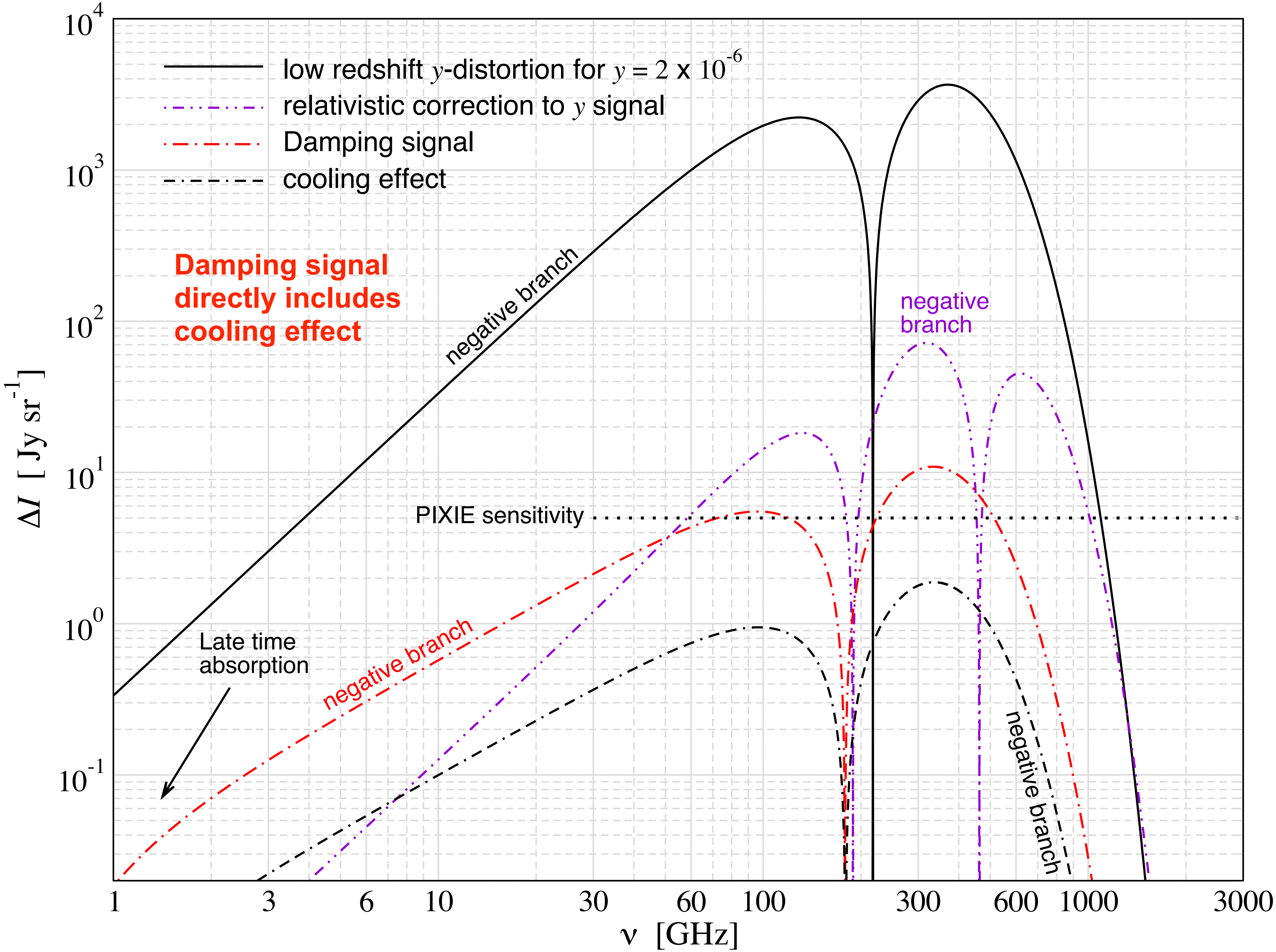
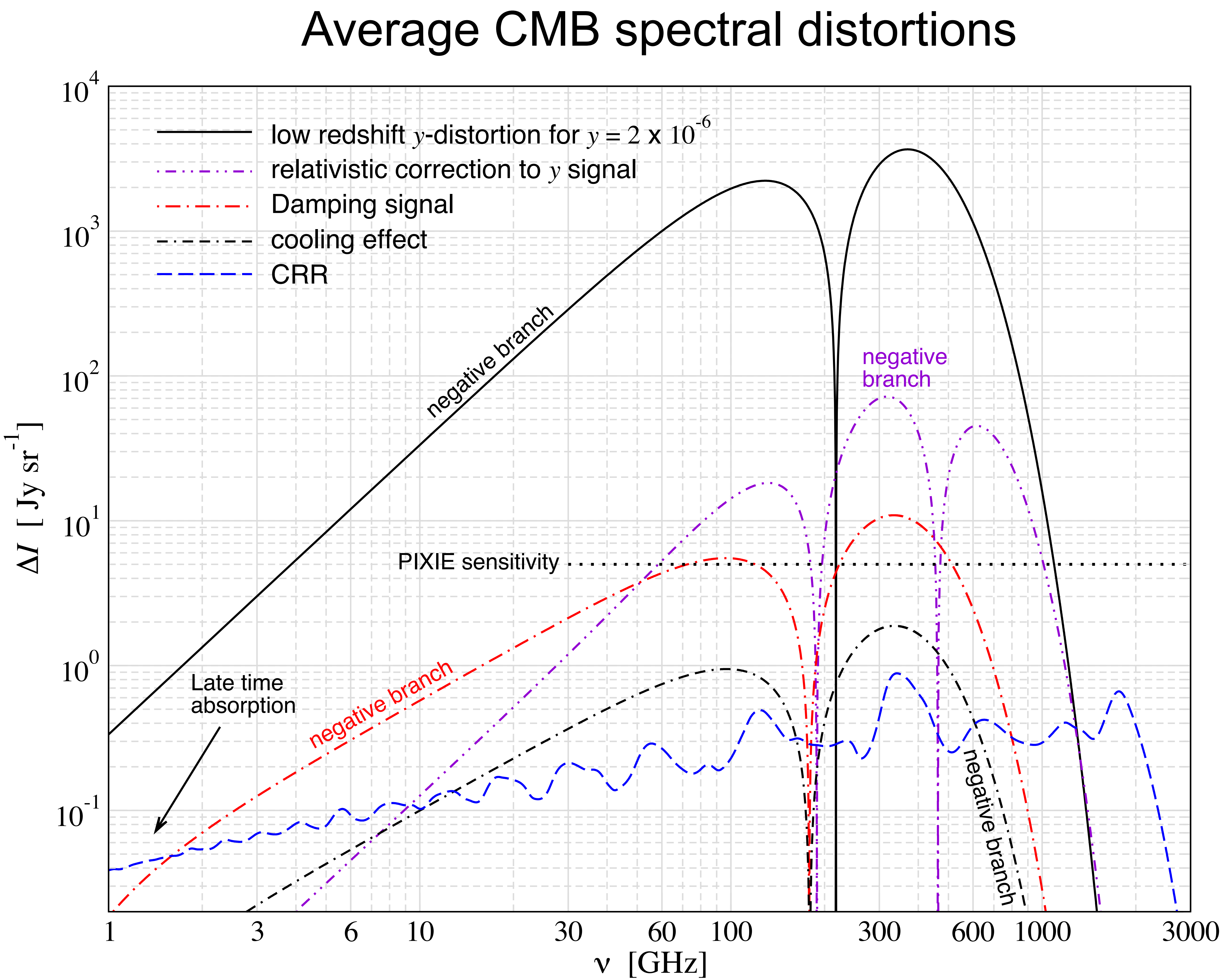
Average CMB spectral distortions





Average CMB spectral distortions
low redshift y-distortion for y = 2 x 10^-6
relativistic correction to y signal
Damping signal
cooling effect
CRR
negative branch
negative branch
negative branch
negative branch
PIXIE sensitivity
Late time absorption
ΔI [Jy sr^-1]
ν [GHz]
10^4
10^3
10^2
10^1
10^0
10^-1
1
3
6
10
30
60
100
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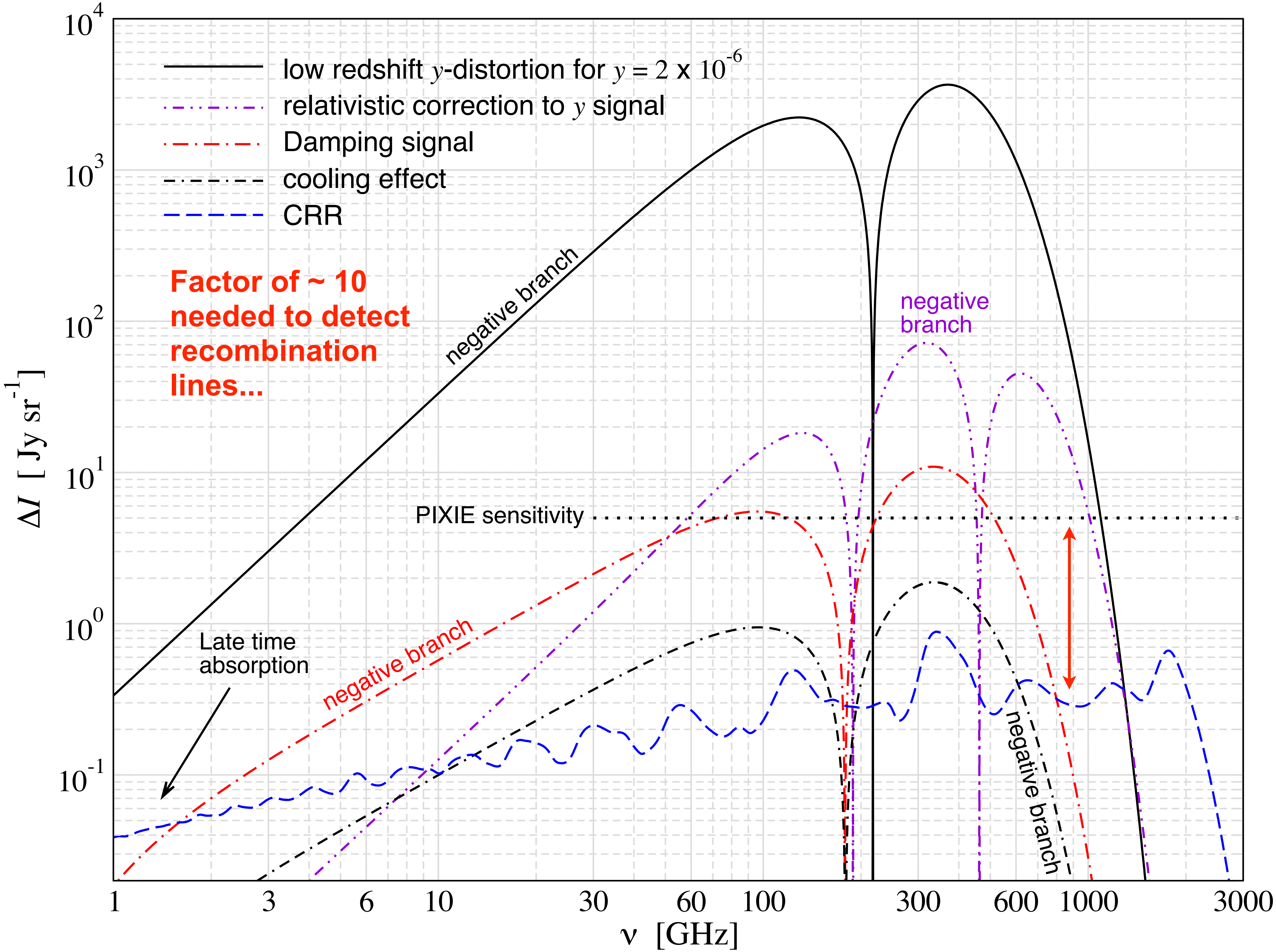
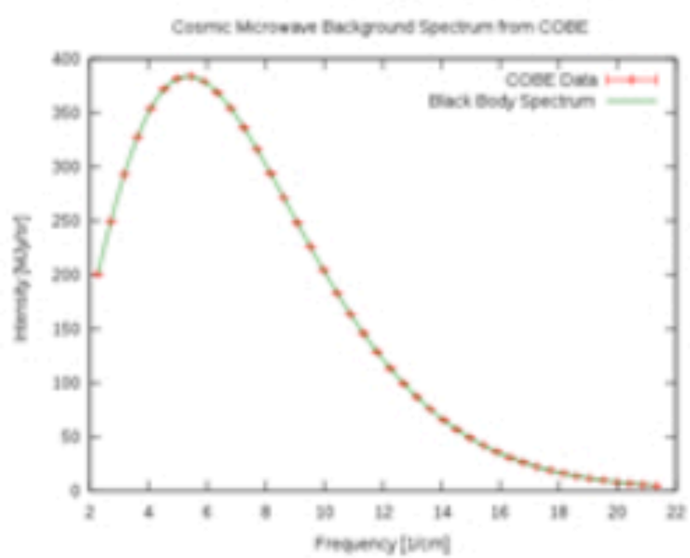
600
1000
3000

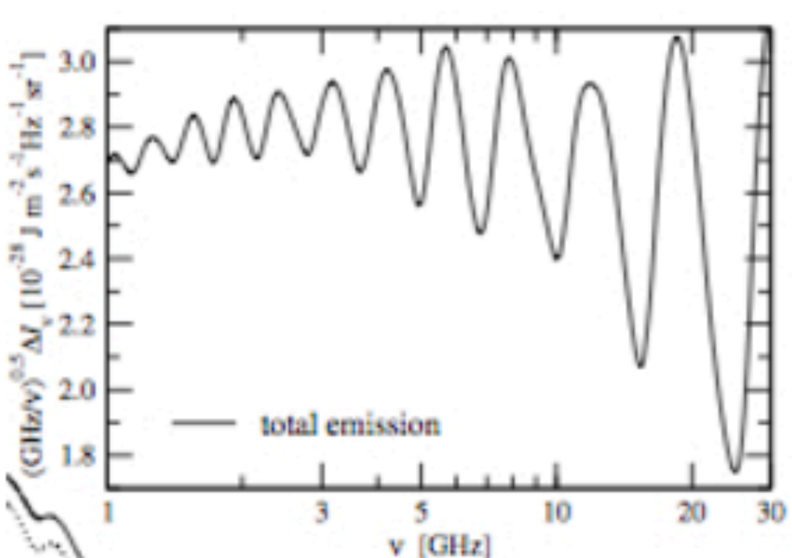
Average CMB spectral distortions



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.

CMB SPECTRAL DISTORTIONS FROM COSMIC BARYON EVOLUTION

RAMAN RESEARCH INSTITUTE, BANGALORE
July 11-16, 2016

Main

Poster

Programme

Logistics

Accommodation

Venue: Raman Research Institute, Bangalore, India

This joint discussion forum aims to bring together theorists and experimentalists, both ground based and space based, working on the theory and detection of spectral distortions in the CMB, including those from recombination and reionization.

The scope of the forum is primarily all-sky or global or monopole component spectral distortions in the CMB of

1. mu, y and free-free types arising from standard and non-standard (e.g. particle decay, primordial magnetic fields) models for cosmology and structure formation,
2. spectral distortions from cosmological Helium and Hydrogen recombination,
3. redshifted 21-cm distortions expected from Dark Ages and Cosmic Dawn all the way down to the end of reionization.

However, we do expect some talks on the spatial structure in these distortions, particularly when detection of the spatial distribution is necessary for decomposing the global into components from different origins, and when detection of the global is of significance to the understanding of detections of spatial fluctuations.

The plan is to review the theory, discuss experimental methods and have presentations on proposals and on-going experiments. The goal is to encourage collaborations between experimentalists with complementary strengths, and better align the configurations and products of experiments to be motivated by realistic and plausible theoretical models, which are based on and consistent with current understanding of cosmology and galaxy formation and evolution.

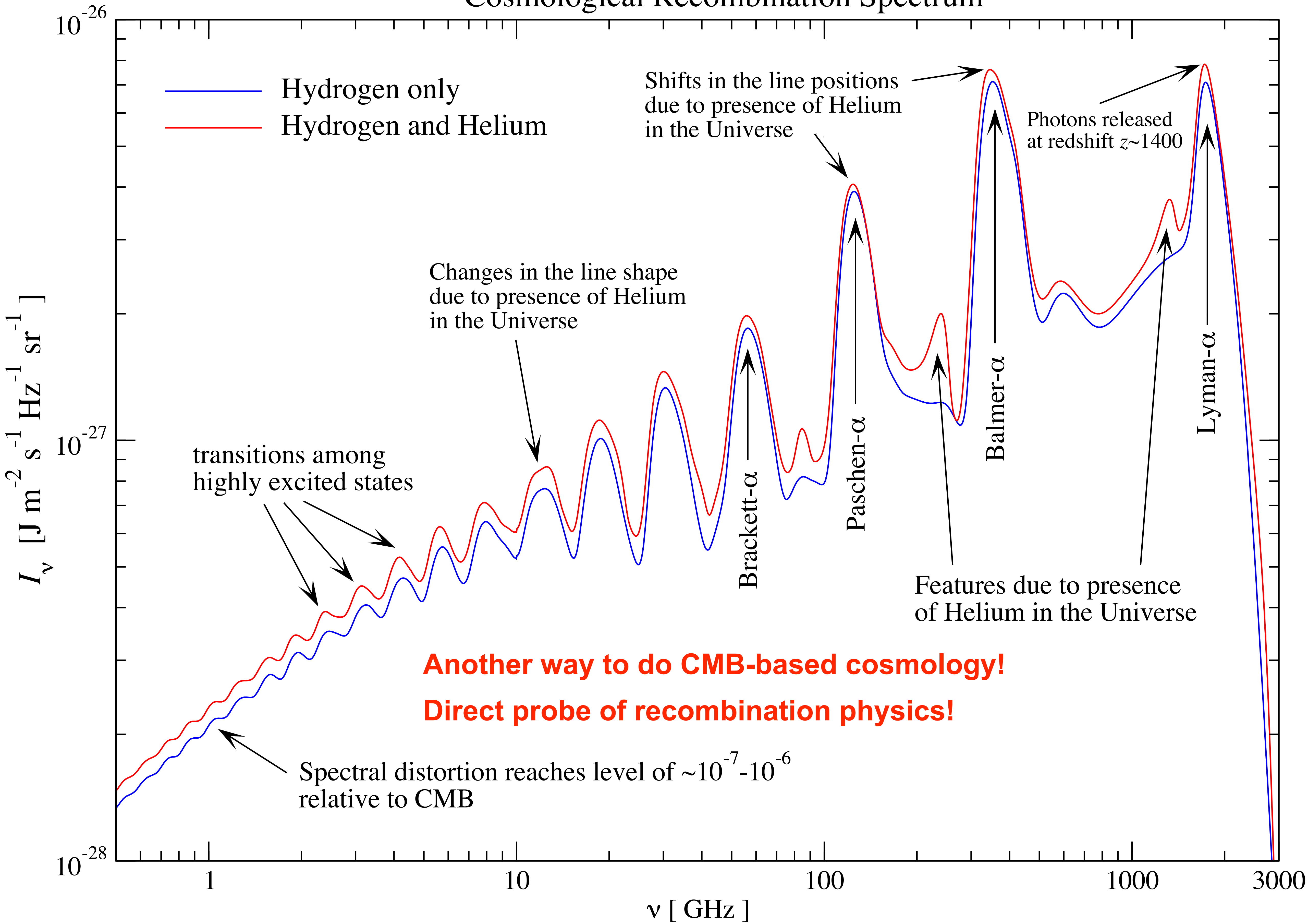
The space physics group of the Indian Space Research Organization (ISRO)

List of participants:

If you wish to participate but do not find your name listed below please contact one of the SOC members.

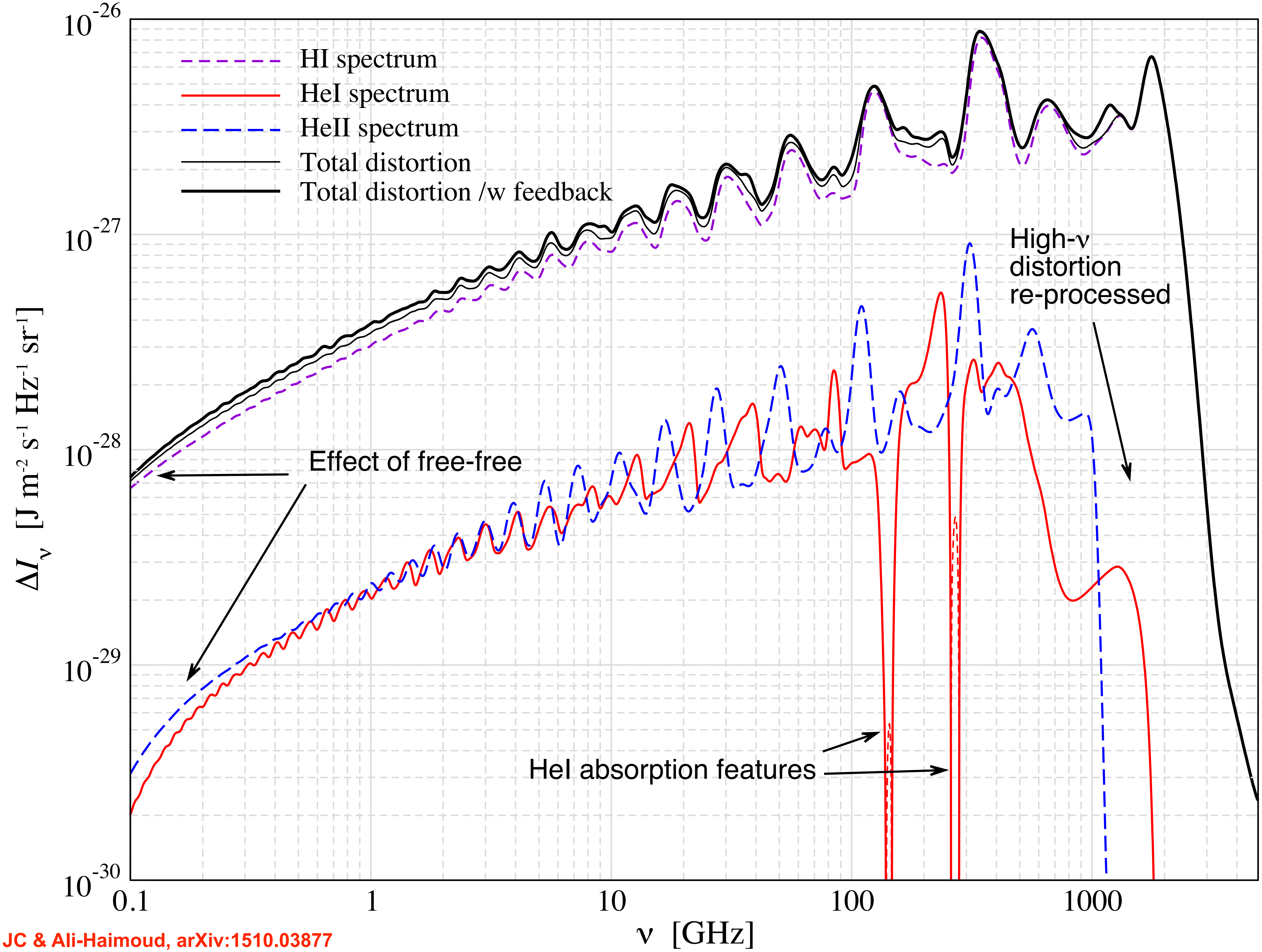
- Eric Switzer (Goddard)
- Chris Sheehy (Chicago)
- James Colin Hill (Columbia)
- Daniel Grin (Kavli Institute, Chicago)
- José-Alberto Rubiño-Martín (IAC, Tenerife, Spain)
- Yacine Ali-Haimoud (Johns Hopkins)
- Rishi Khatri (TIFR, Mumbai)
- Anastasia Fialkov (Harvard)
- Harish Vedantham (Caltech)
- Jeffrey Peterson (Carnegie Mellon)
- Joseph Lazio (NASA) TBC
- Lincoln J. Greenhill (Harvard)
- Jonathan Pritchard (Imperial College, London)
- Subir Sarkar (Oxford/NBI, Copenhagen)
- Mathieu Remazeilles (Manchester)
- Aaron Chippendale (CASS)
- Jack Singal (Richmond University)
- Francois Bouchet (IAP)
- Leon Koopmans (Kapteyn Astronomical Institute)
- Tzu-Ching Chang (ASIAA)
- Suzanne Staggs (Princeton)
- Raul Monsalve (Arizona State University)
- Nipanjana Patra (UCB)
- Xuelei Chen (NAOC)
- Rennan Barkana (Tel-Aviv University)
- Nithyanandan Thyagarajan (Arizona State University)

Cosmological Recombination Spectrum



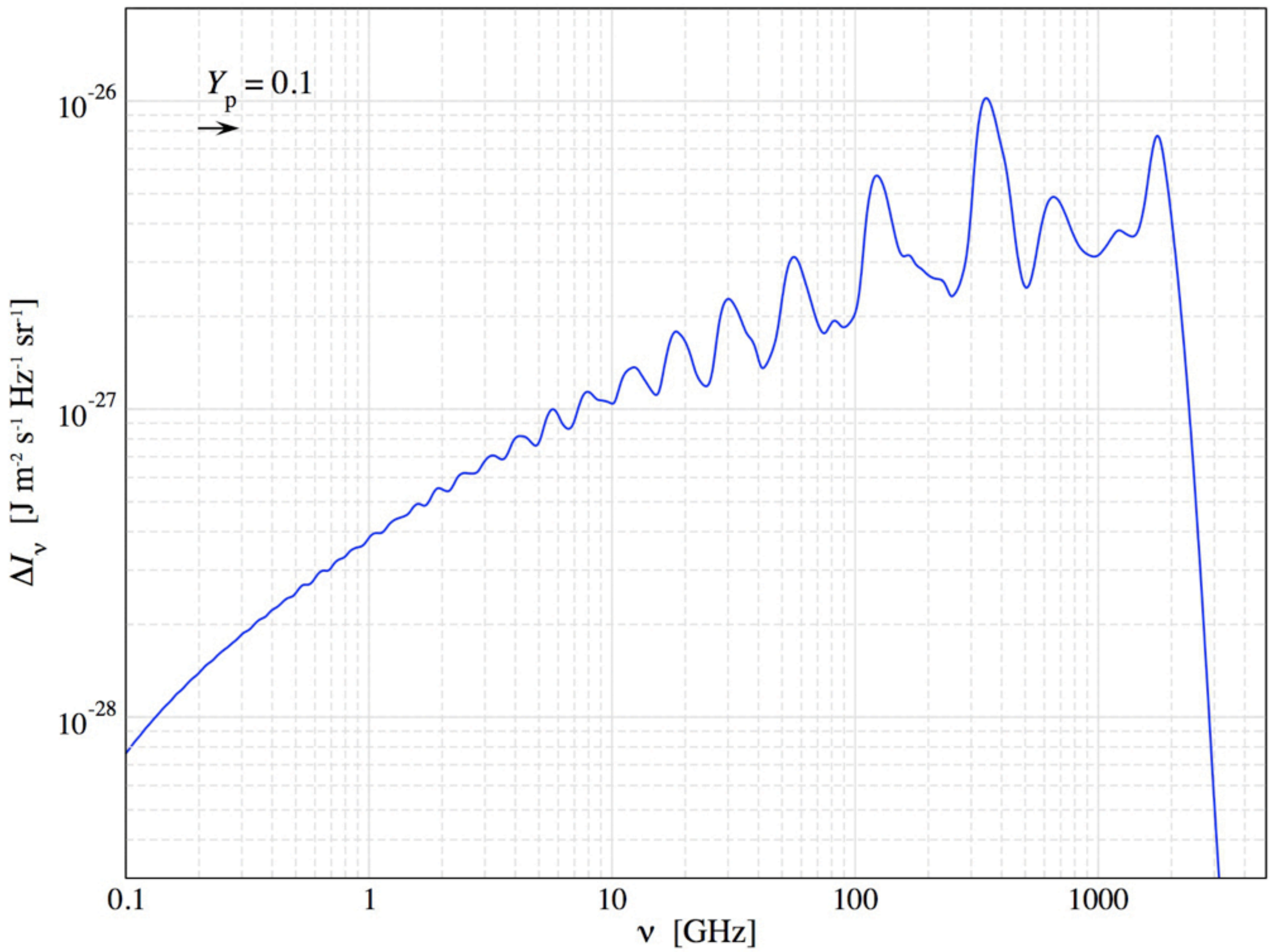
Rubino-Martin et al. 2006, 2008; Sunyaev & JC, 2009

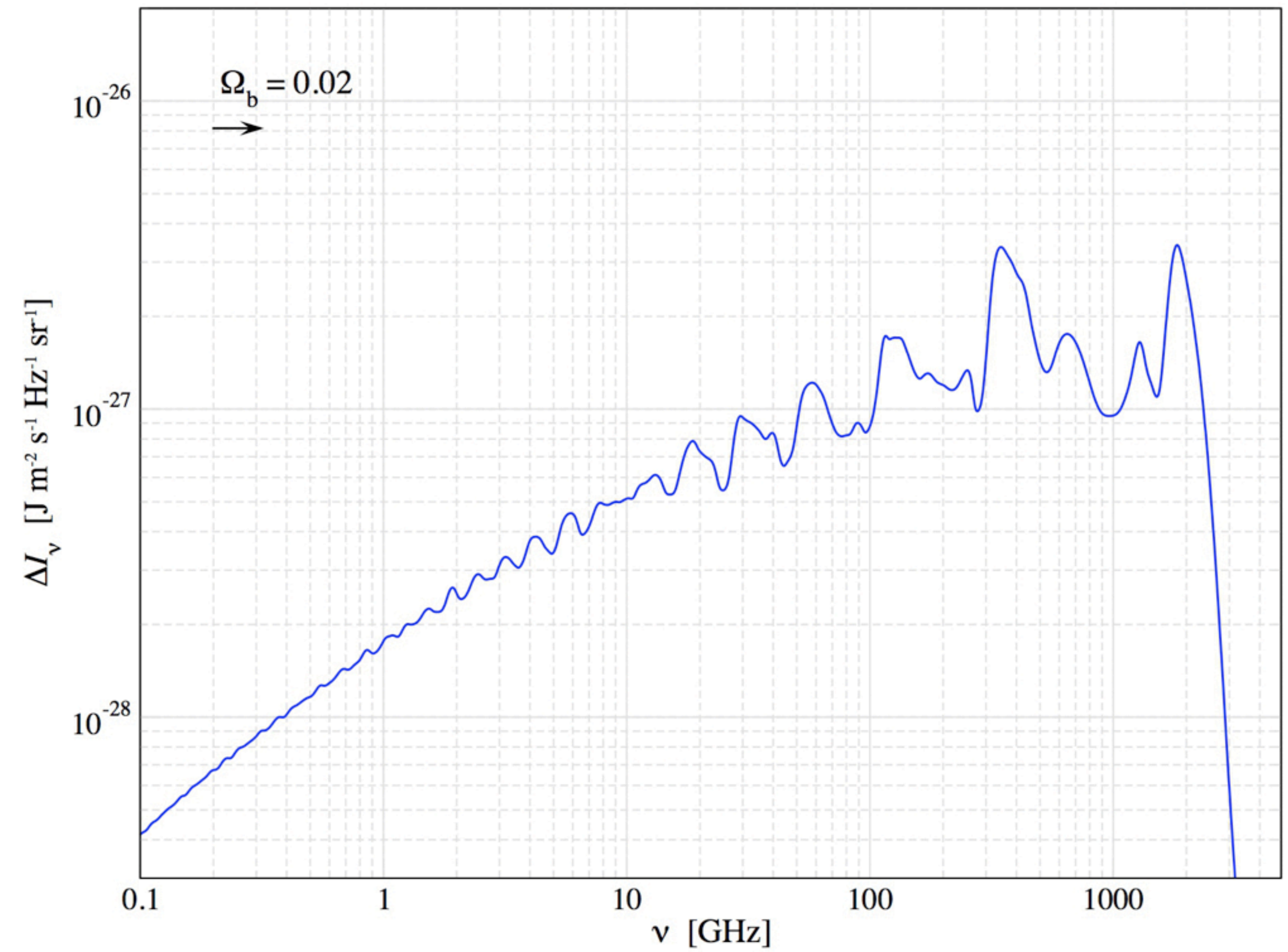
New detailed and fast computation!



JC & Ali-Haimoud, arXiv:1510.03877

CosmoSpec: fast and accurate computation of the CRR



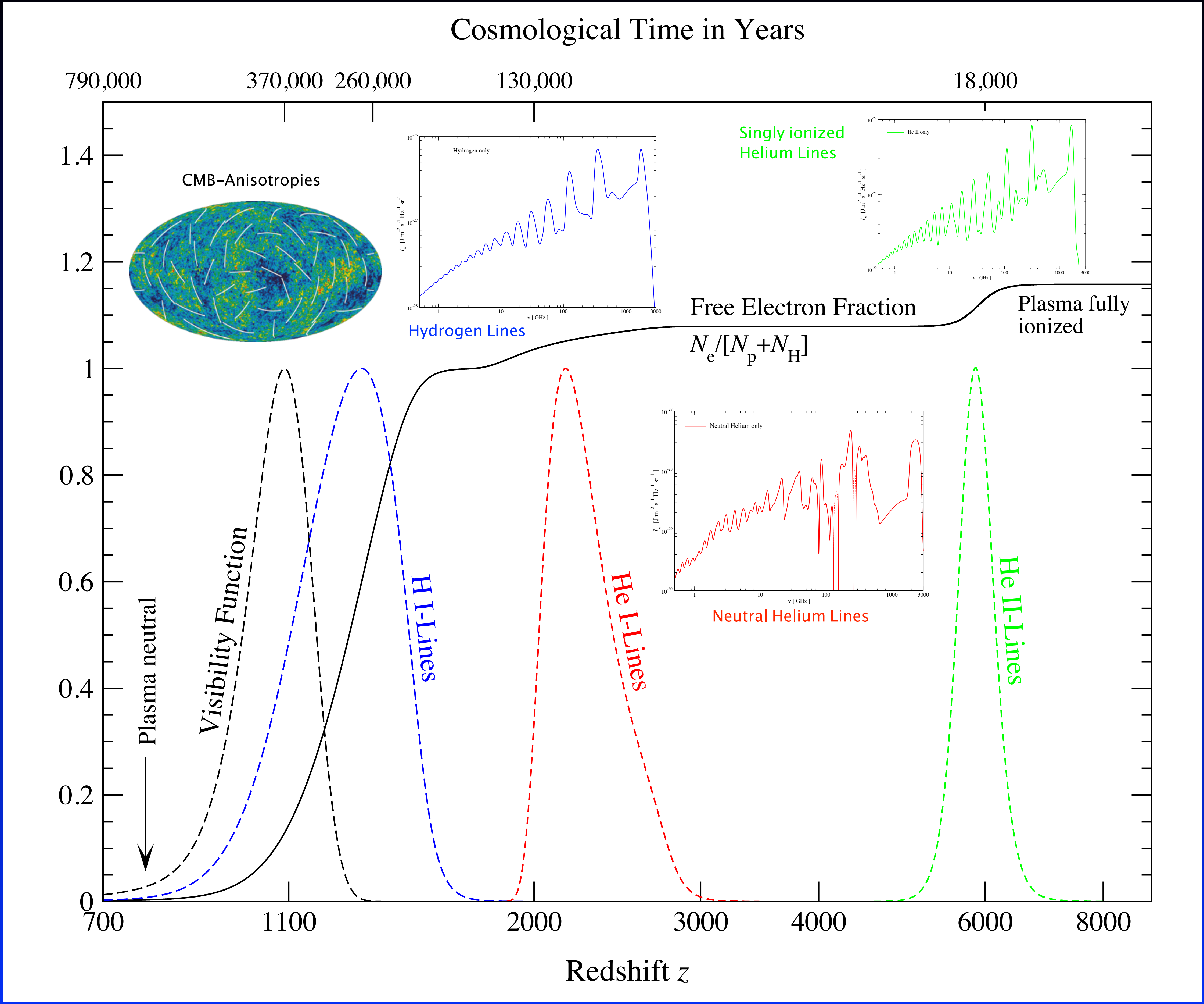


- Like in old days of CMB anisotropies!
- detailed forecasts and feasibility studies
- non-standard physics (variation of α, energy injection etc.)

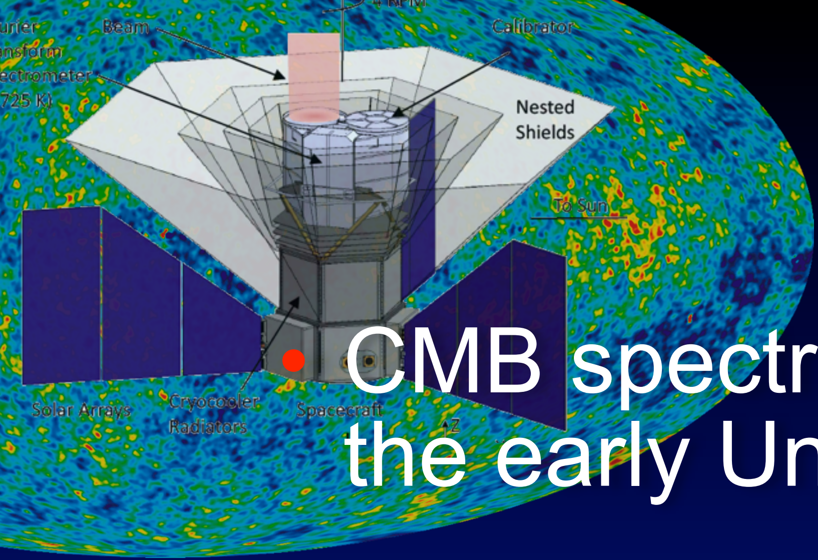
CosmoSpec will be available here:

www.Chluba.de/CosmoSpec

JC & Ali-Haimoud, arXiv:1510.03877



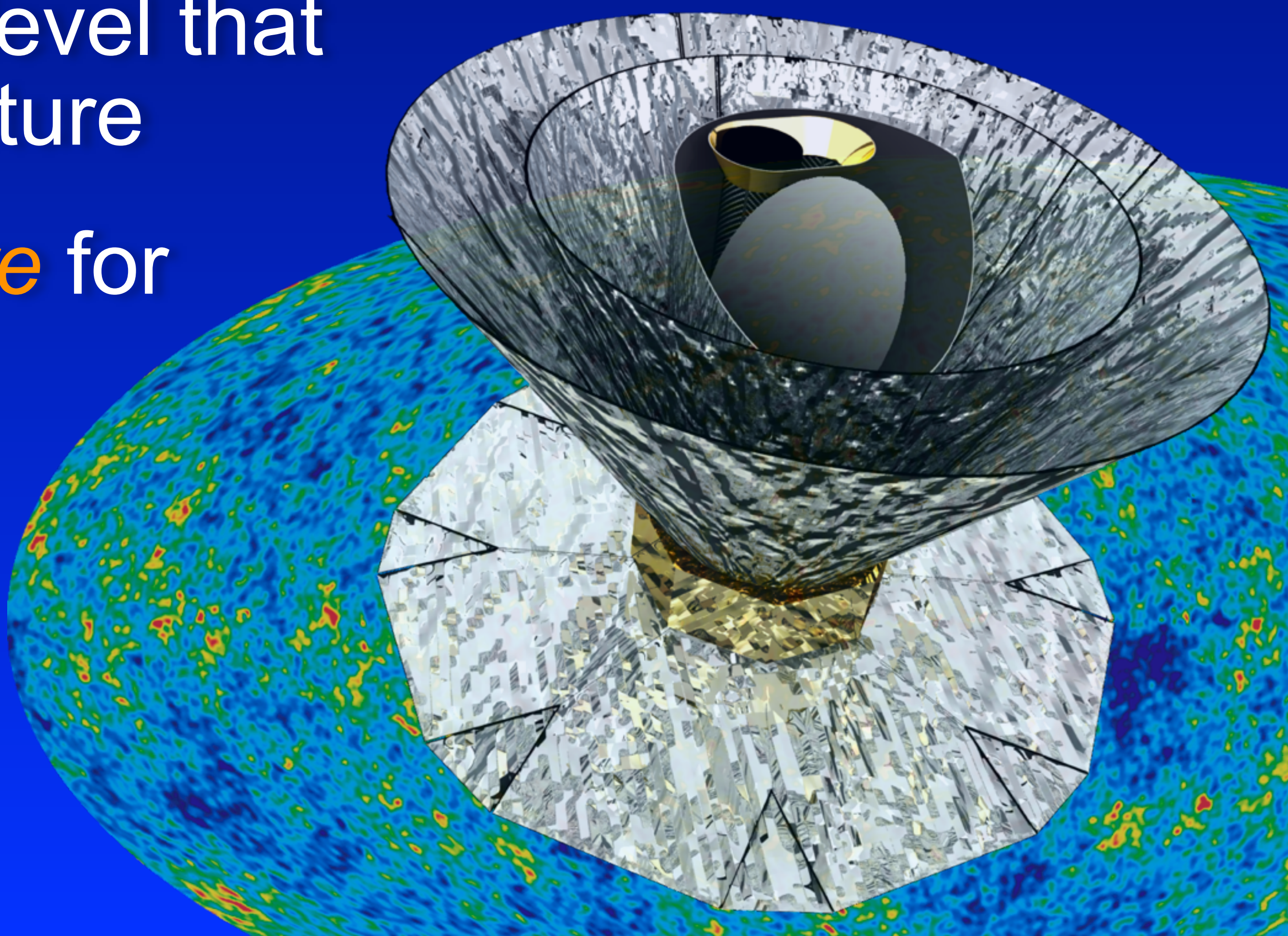
Cosmological Time in Years
790,000
370,000
260,000
130,000
18,000
CMB-Anisotropies
Hydrogen Lines
Singly ionized Helium Lines
Neutral Helium Lines
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully ionized
Plasma neutral
Visibility Function
H I-Lines
He I-Lines
He II-Lines
Hydrogen only
He II only
Neutral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

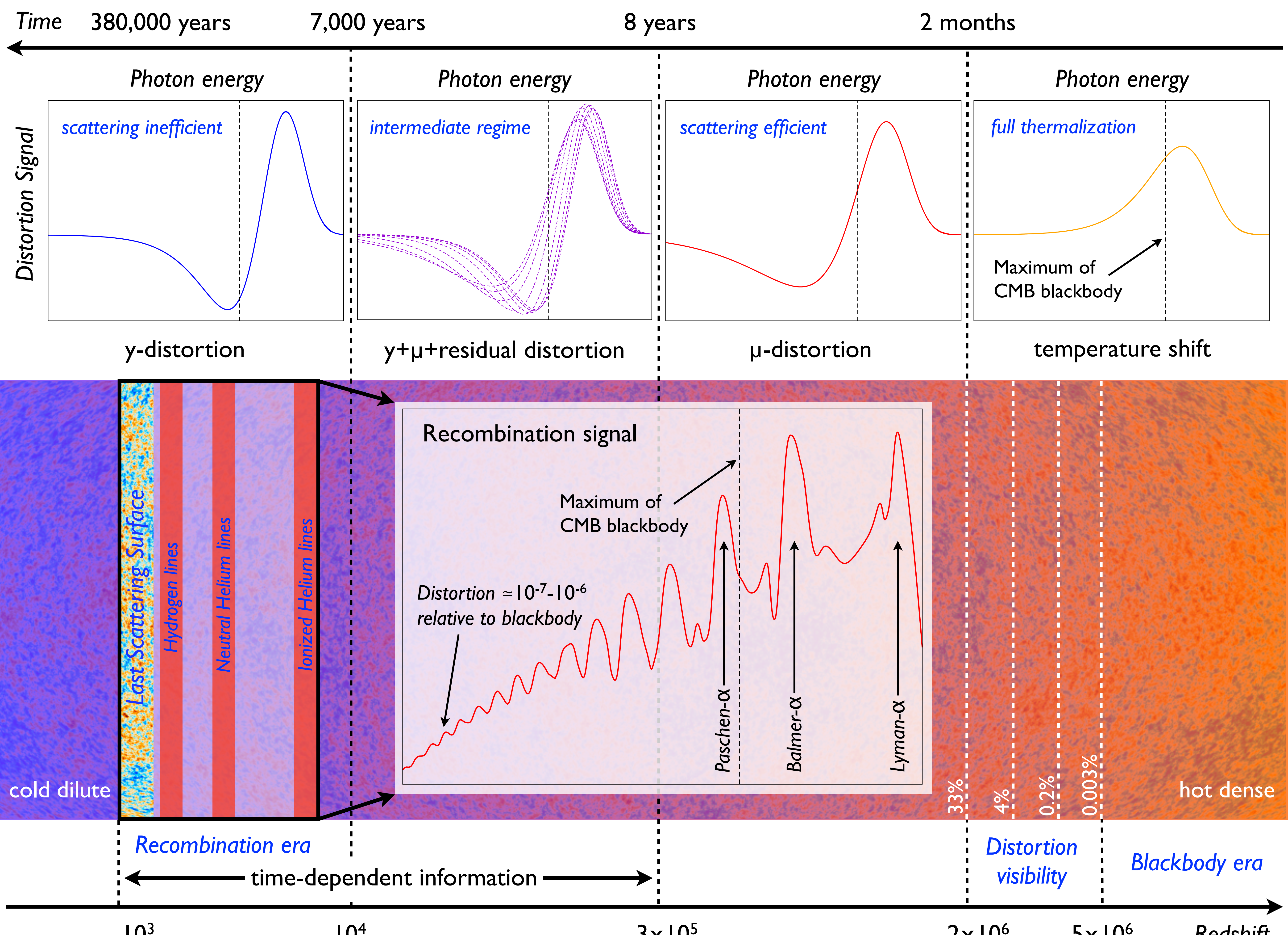


Conclusions

- 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 *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!

We should make use of all this information!





Silk & Chluba, Science, 2014