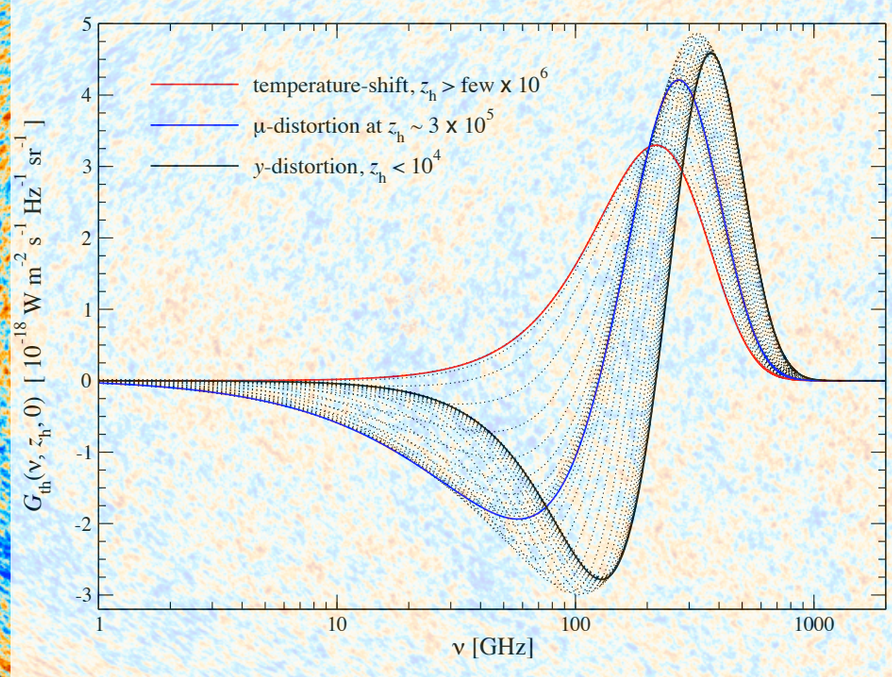
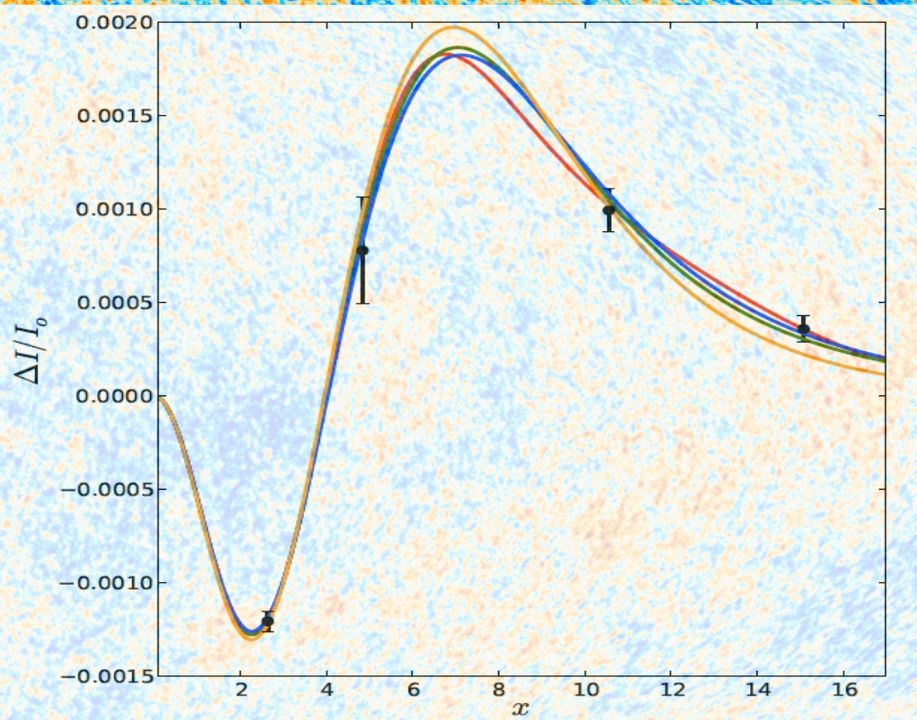
CMB Spectral Distortion Computations using ***CosmoTherm*** and ***SZpack***

Primordial Distortions



Sunyaev-Zeldovich effect



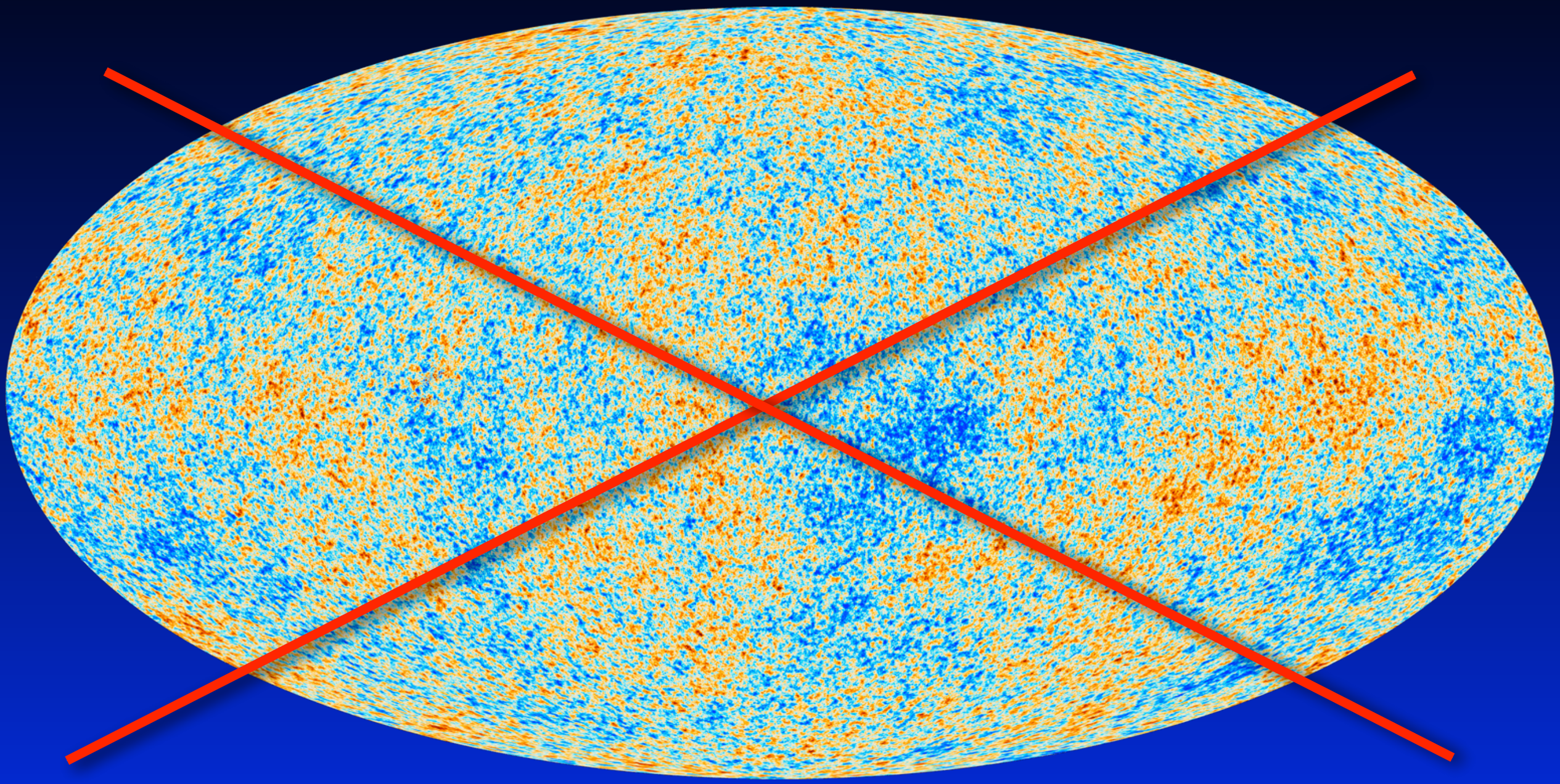
Jens Chluba

2nd IFT School on Cosmological Tools

Madrid, Spain, March 13th - 17th, 2017

MANCHESTER 1824
The University of Manchester

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

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

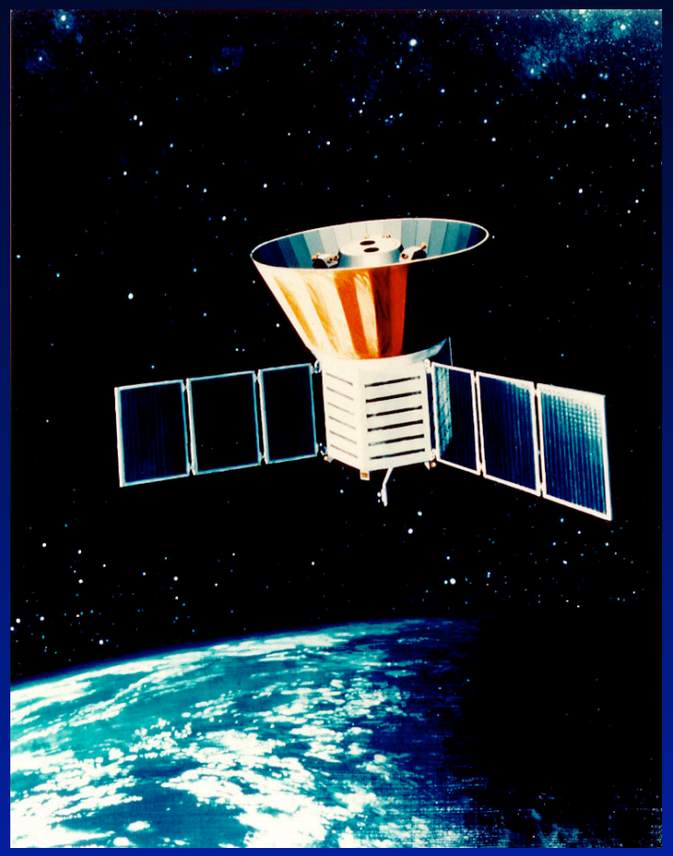
Absolute measurement required!

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)



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

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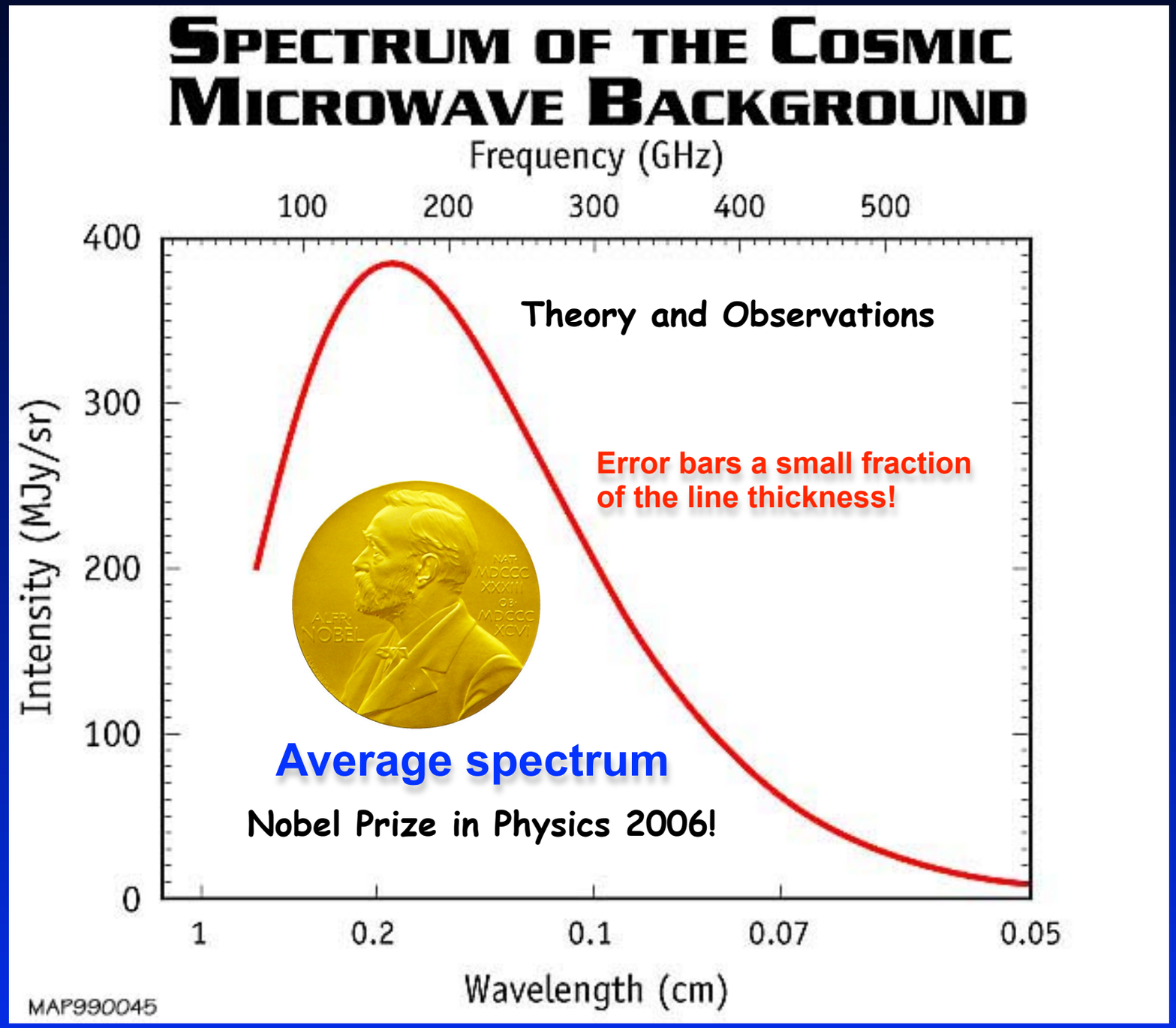
$$|\mu| \leq 9\times10^{-5}$$



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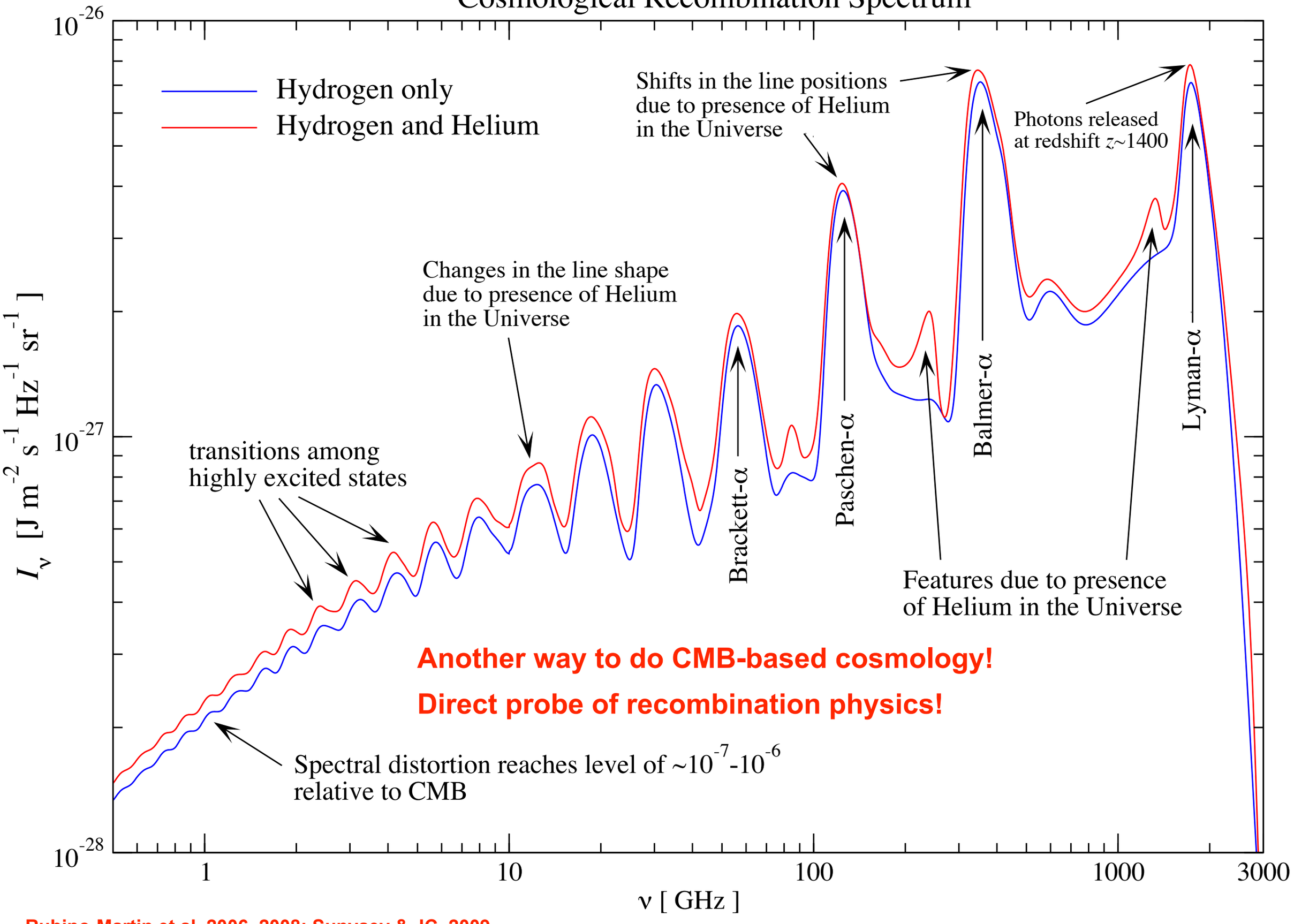


Rubino-Martin et al. 2006, 2008; Sunyaev & JC, 2009

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

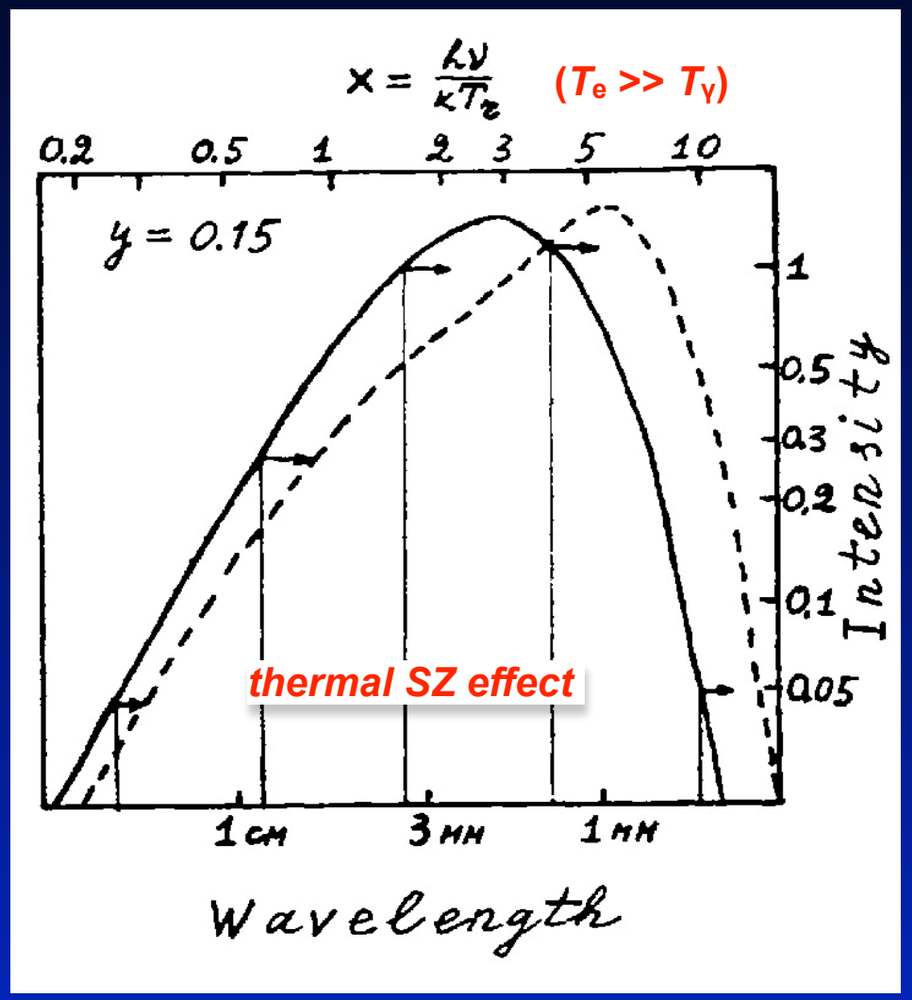
→ thermalization process (partially) erases distortions

(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

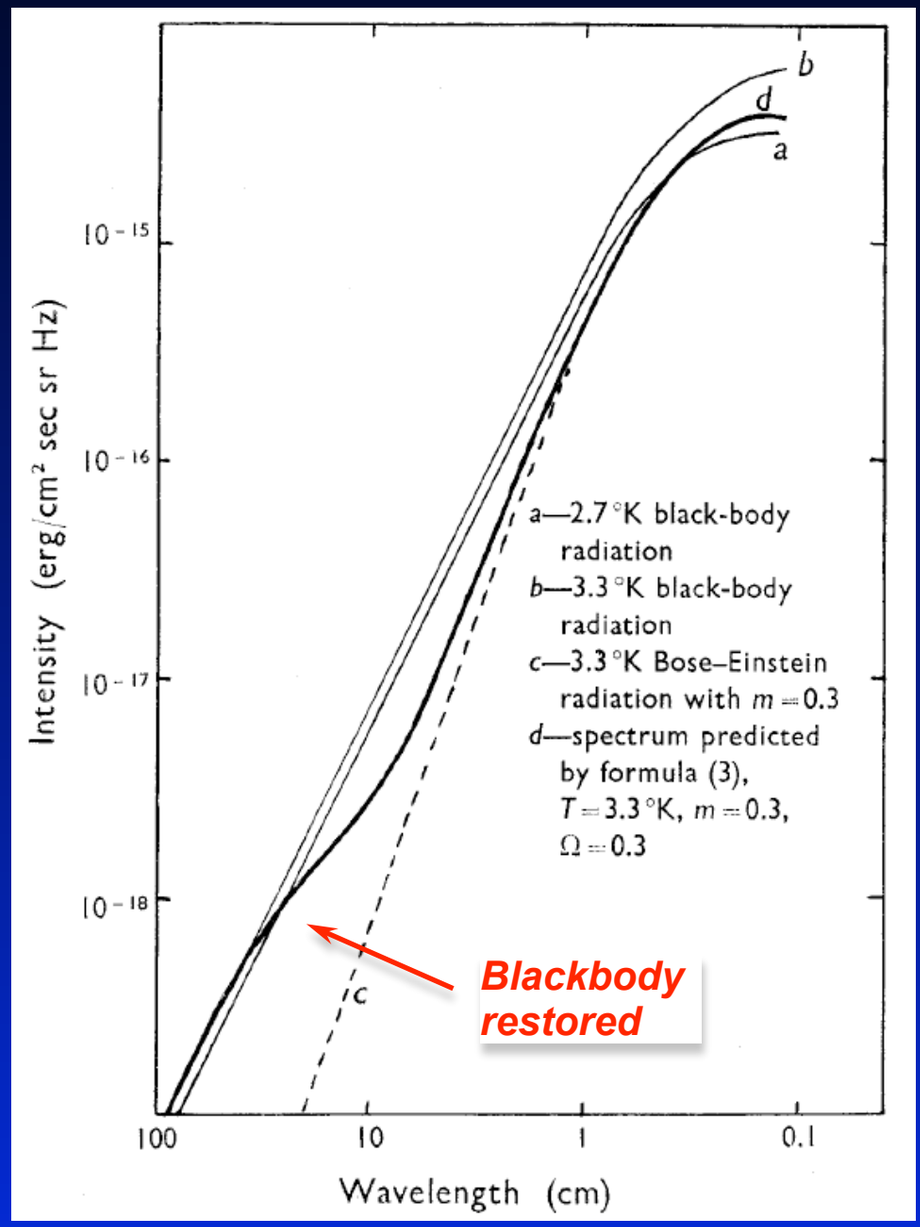
Compton y-distortion



Sunyaev & Zeldovich, 1980, ARAA, 18, 537

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

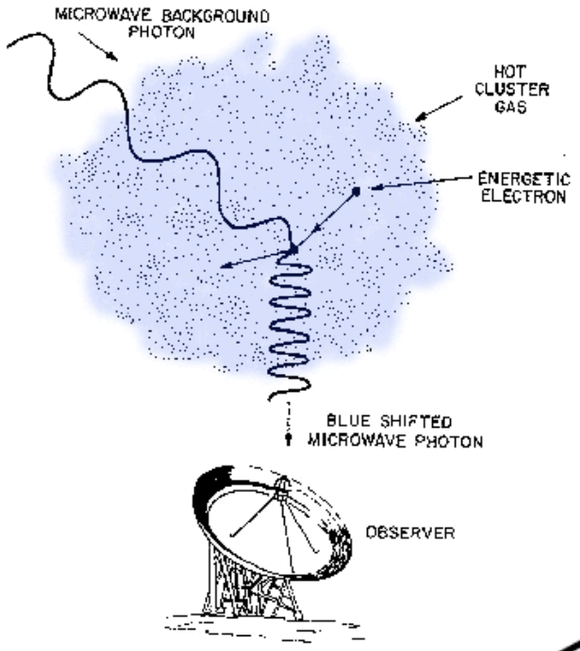
Chemical potential μ-distortion

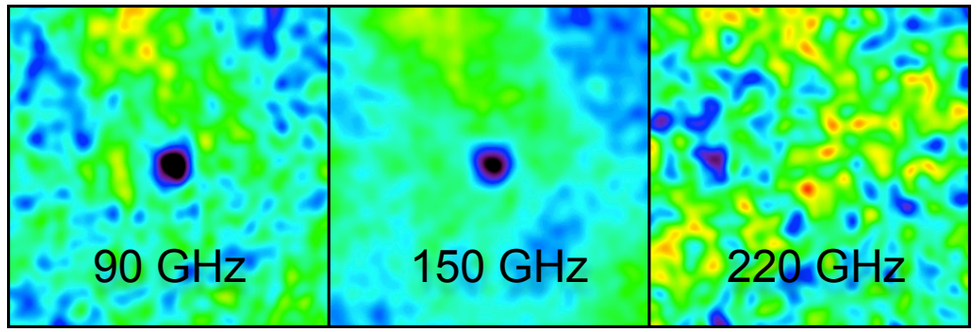


Sunyaev & Zeldovich, 1970, ApSS, 2, 66

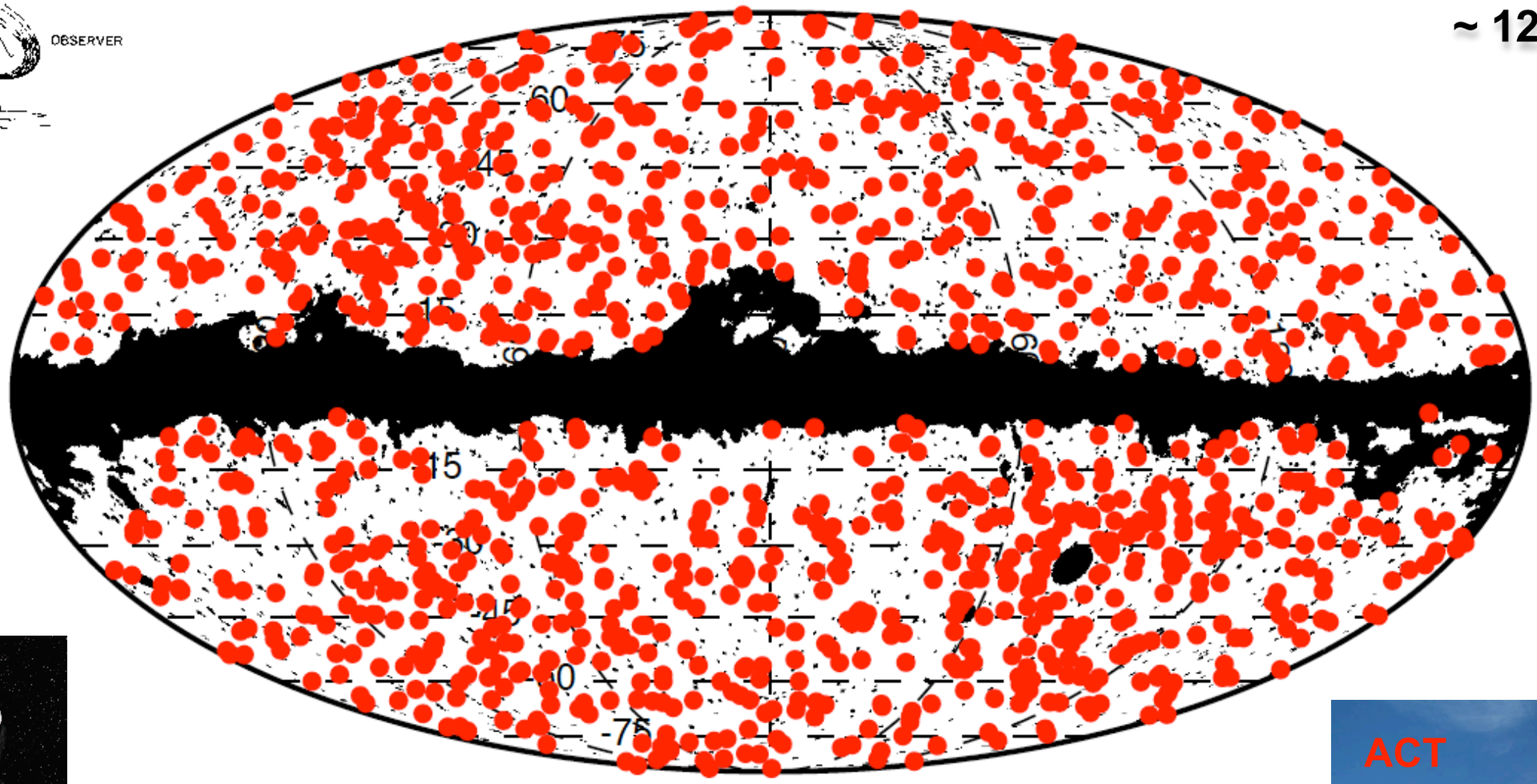
- important at very times (z>50000)
- scattering very efficient

Thermal SZ effect is now routinely observed!

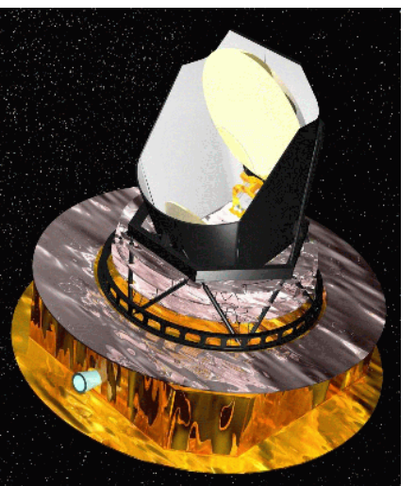




~ 1230 objects



Planck Collaboration, 2013, paper XXIV



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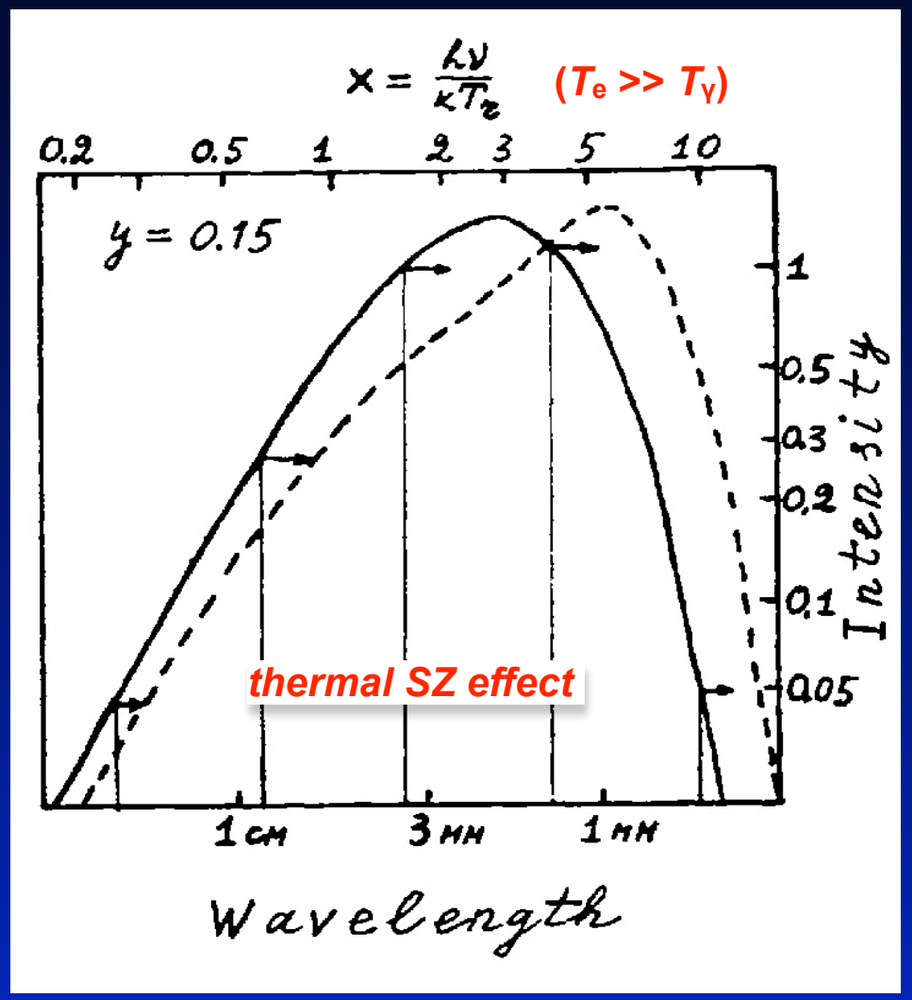

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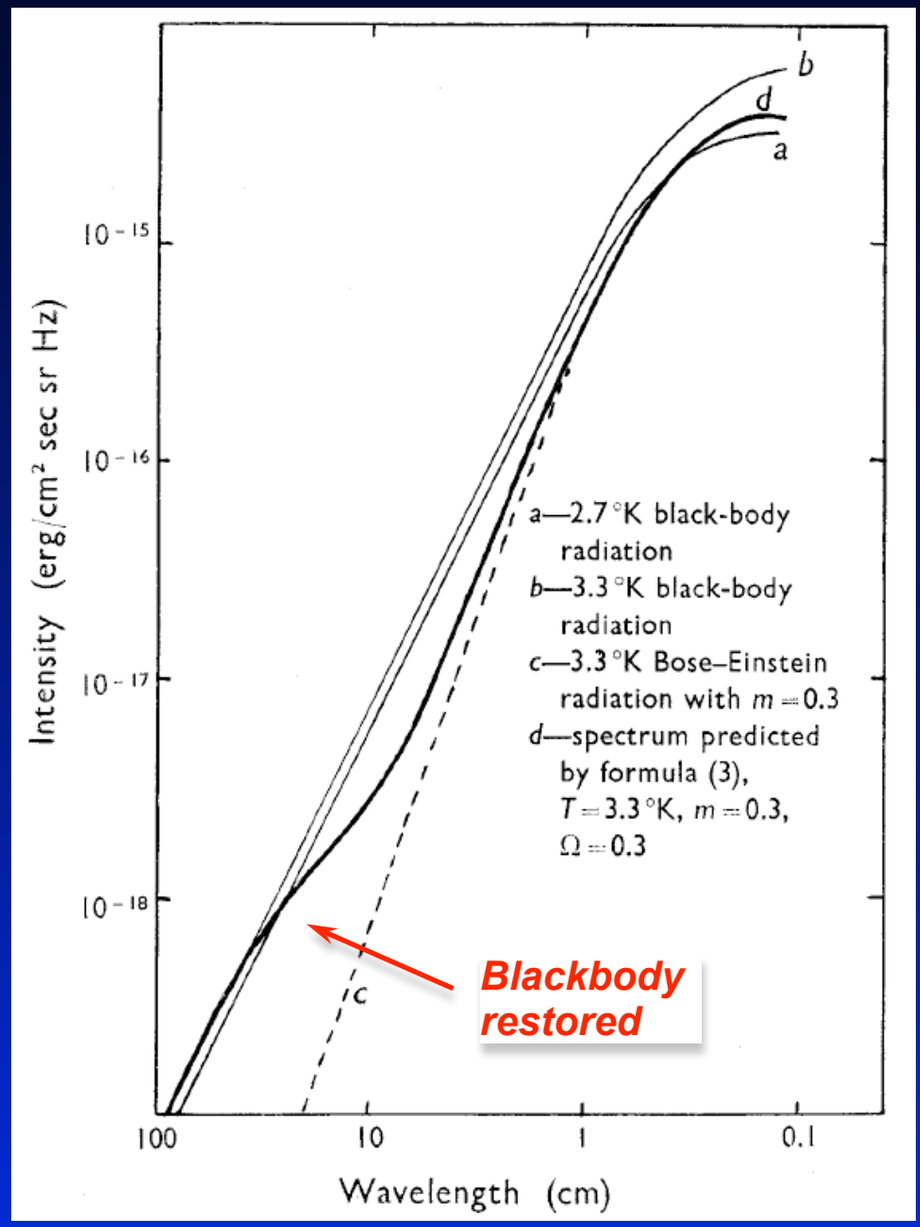

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Big Bang
0

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

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Initial conditions

CMB anisotropies

Large-scale E & B-modes
CMB Lensing
SZ effect

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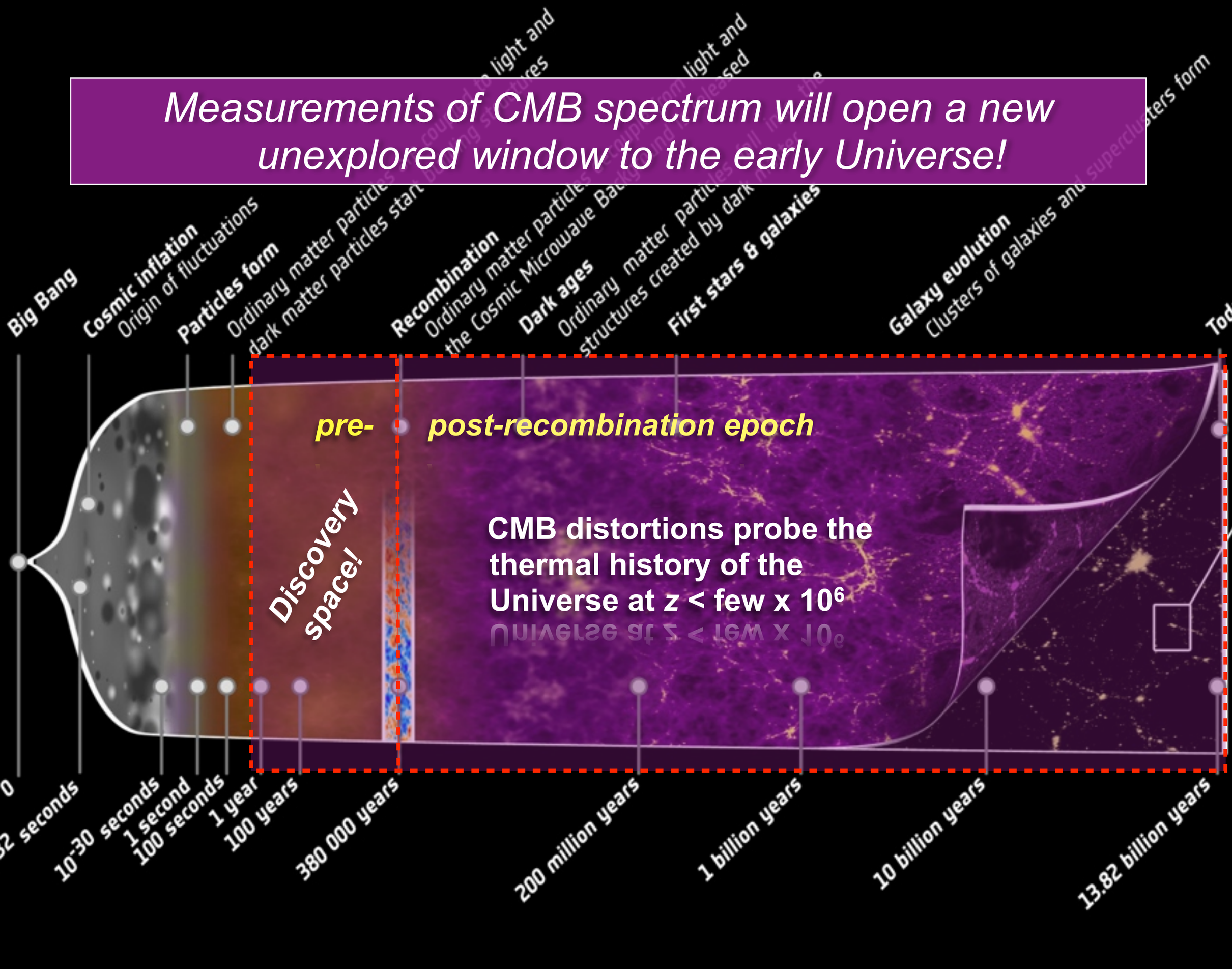
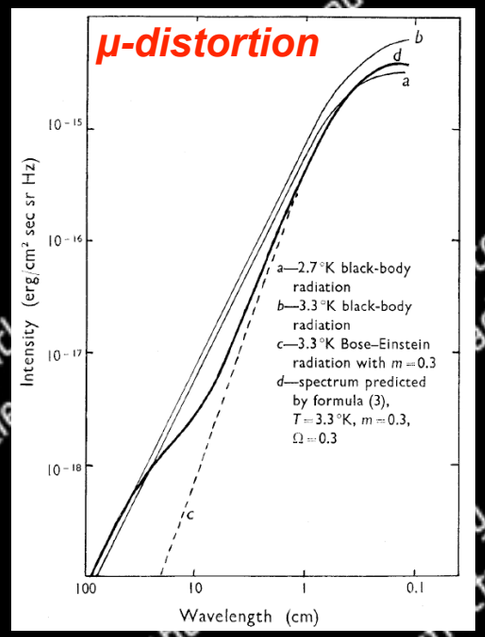
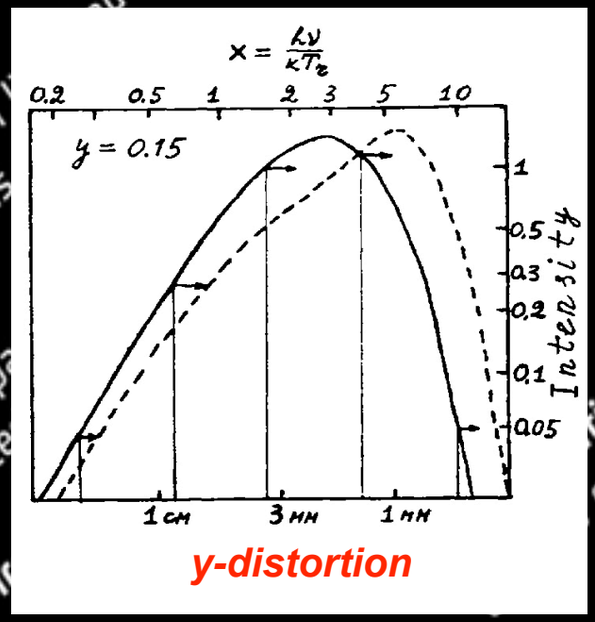
Measurements of CMB spectrum will open a new unexplored window to the early Universe!







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

pre- post-recombination epoch

T-era

μ-era

y-distortion era

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10^{-32} seconds

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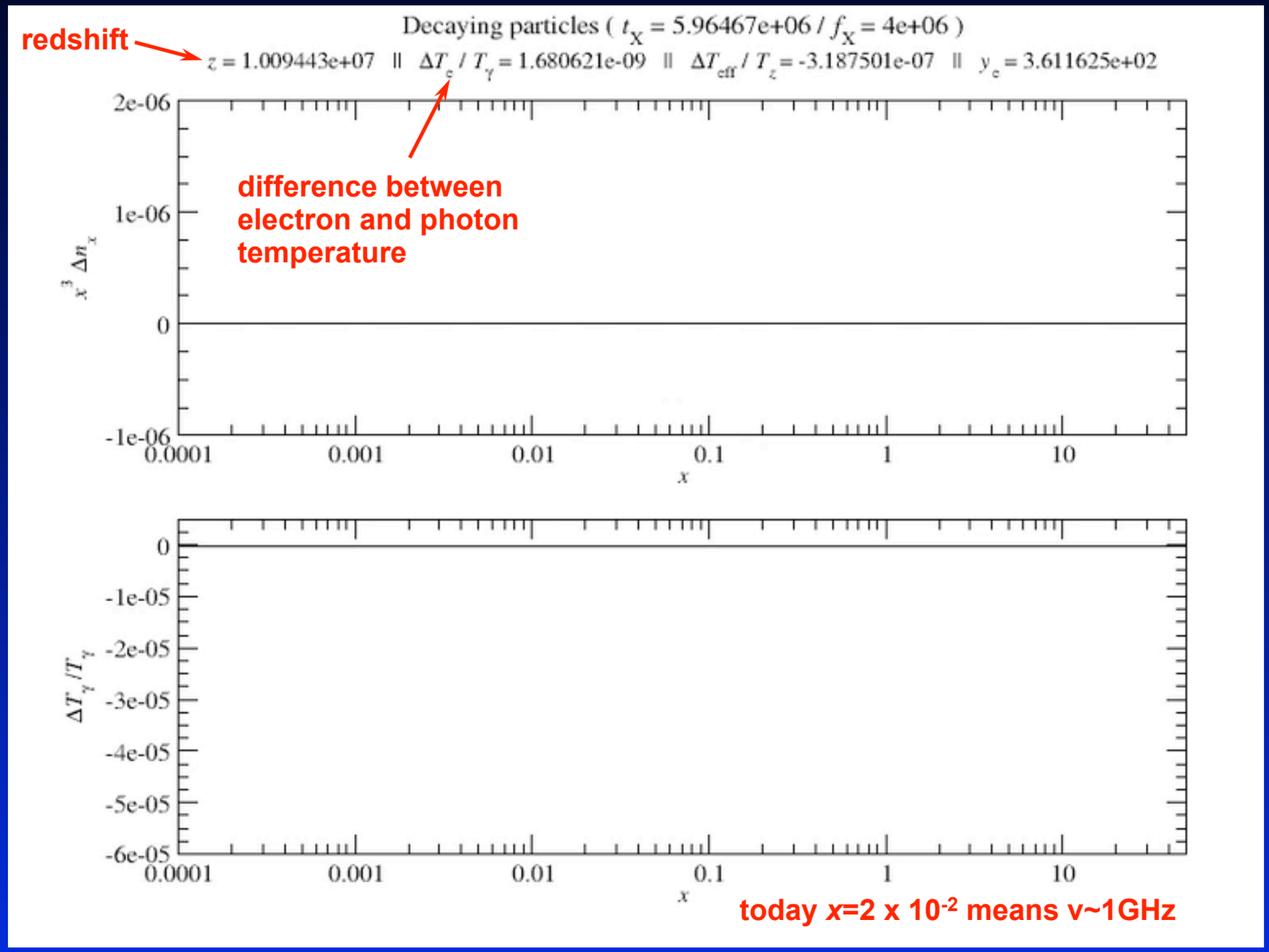
Example: *Energy release by decaying relict particle*



- 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

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*

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

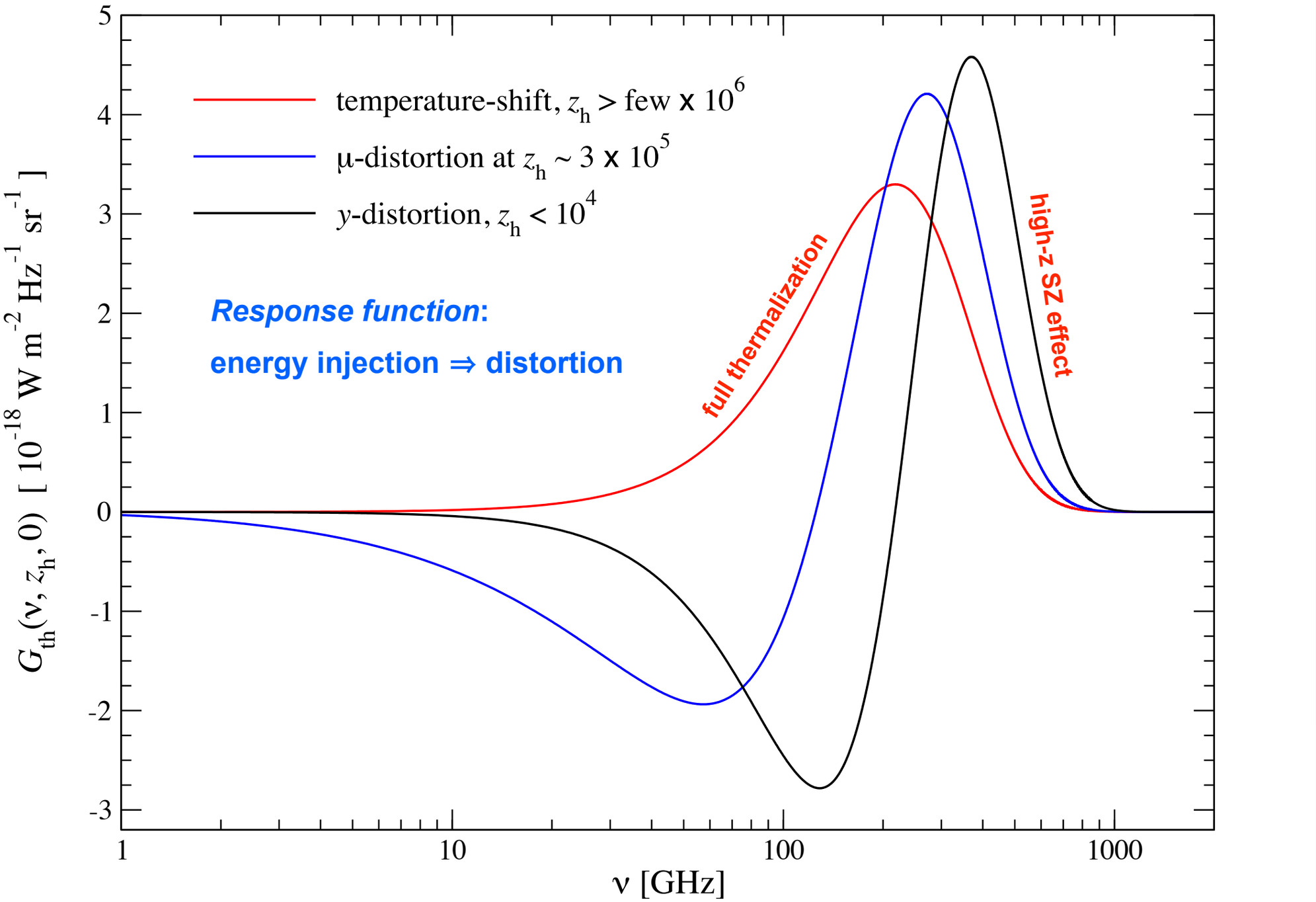
Thermalization Green's function

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

CosmoTherm available at: www.Chluba.de/CosmoTherm

What does the spectrum look like after energy injection?

Intensity signal for different heating redshifts



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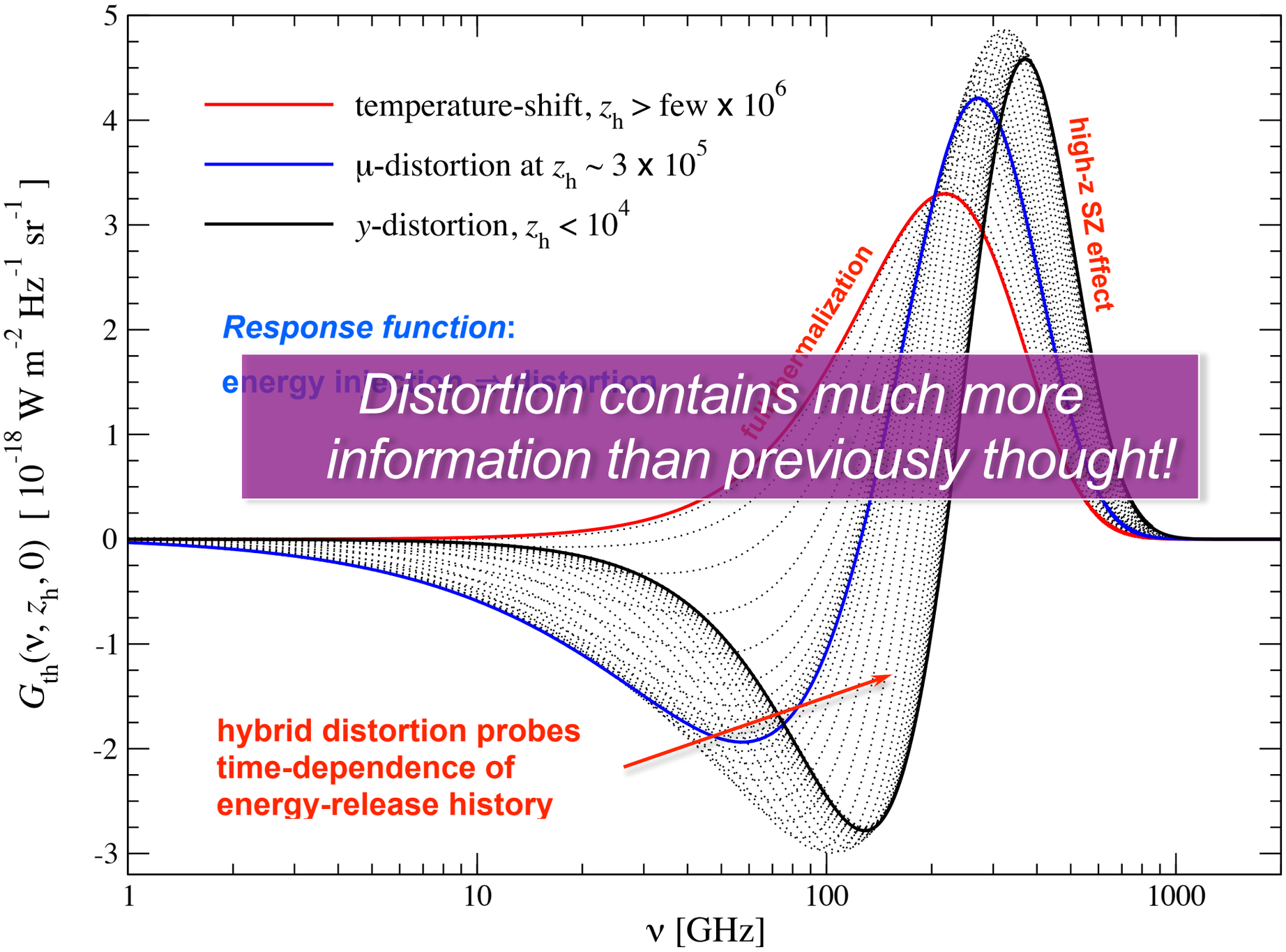

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Transition from y-distortion → μ-distortion

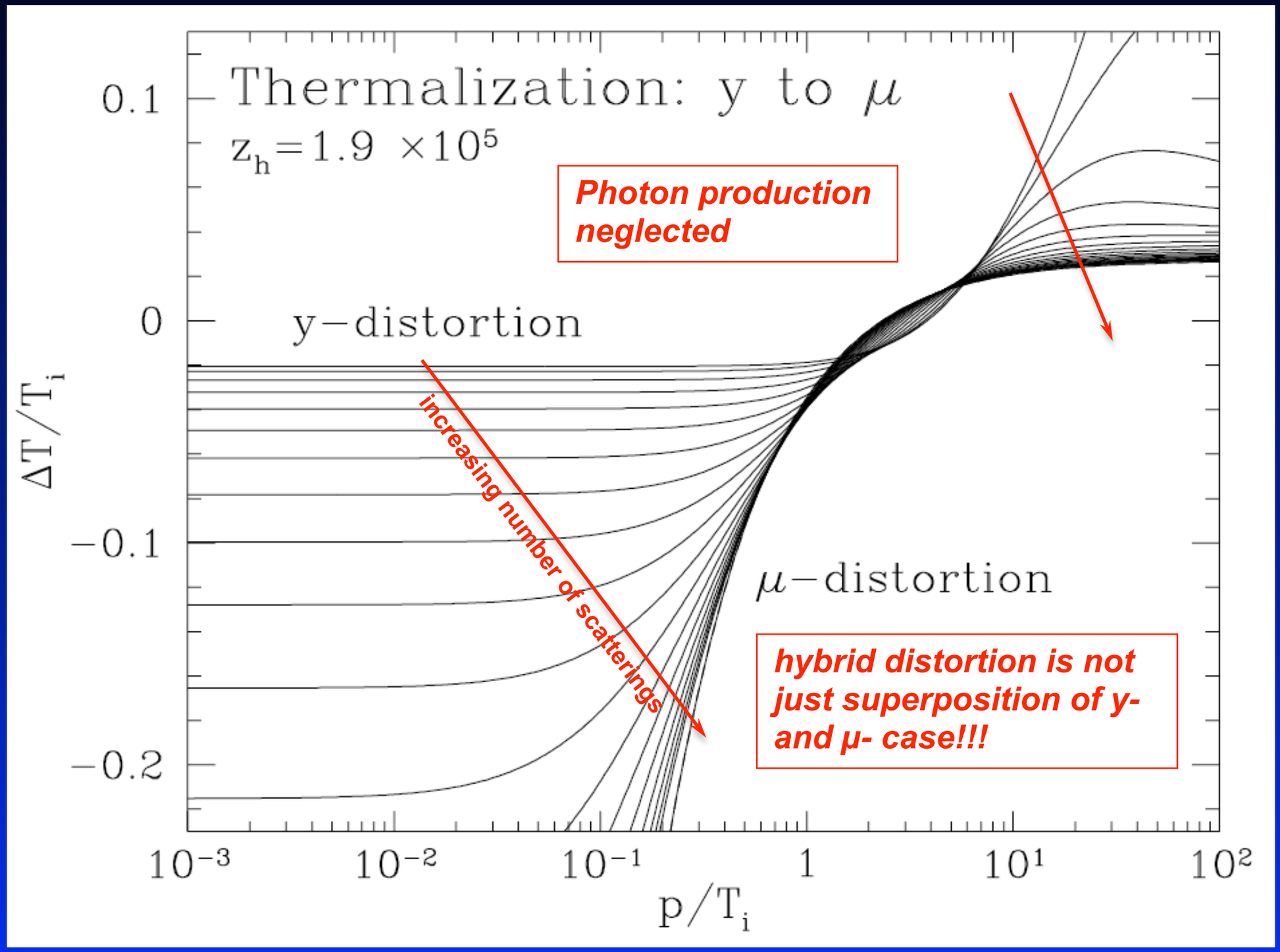
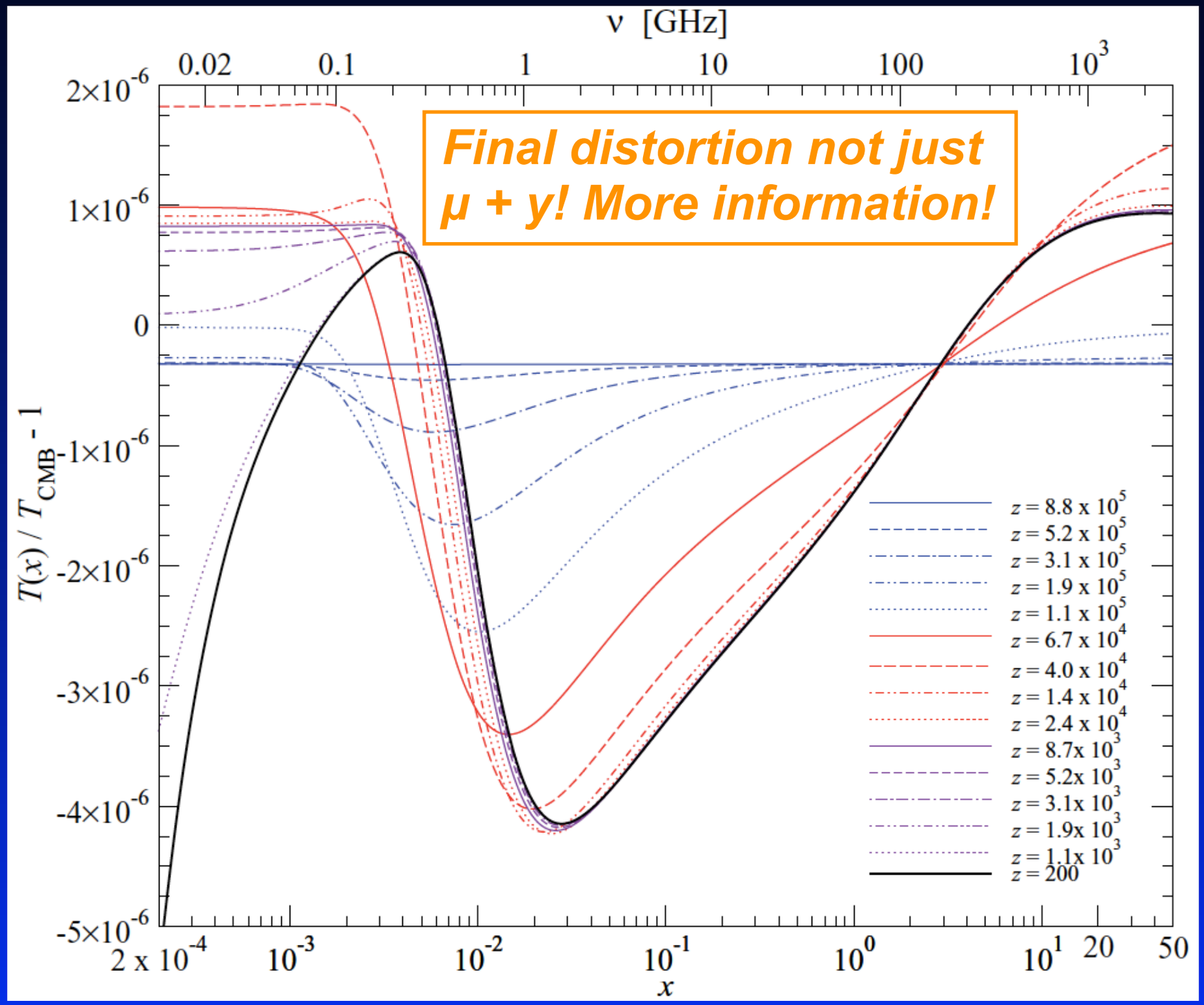


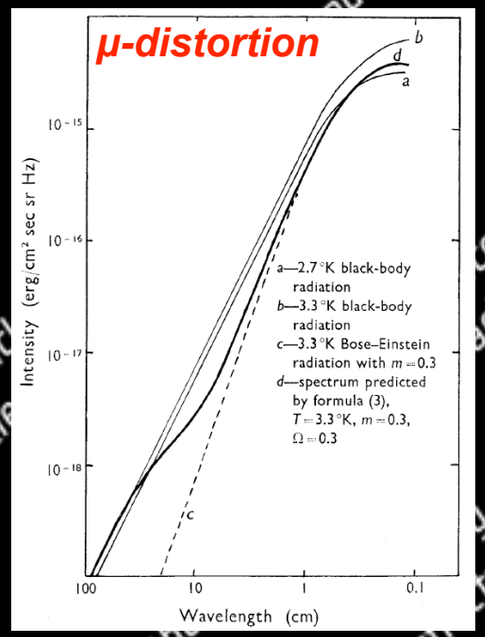
Figure from Wayne Hu's PhD thesis, 1995, but see also discussion in Burigana, 1991

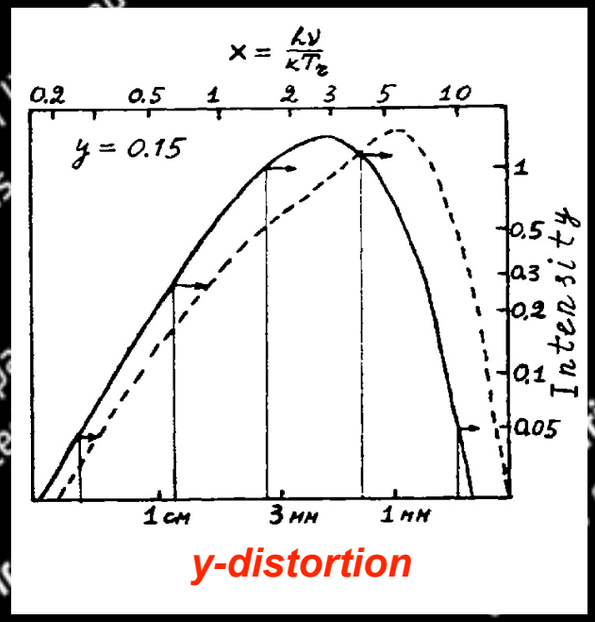
Distortion *not* just superposition of *μ* and *y*-distortion!



Computation carried out with *CosmoTherm*
(JC & Sunyaev 2011)

First explicit calculation that showed that there is more!





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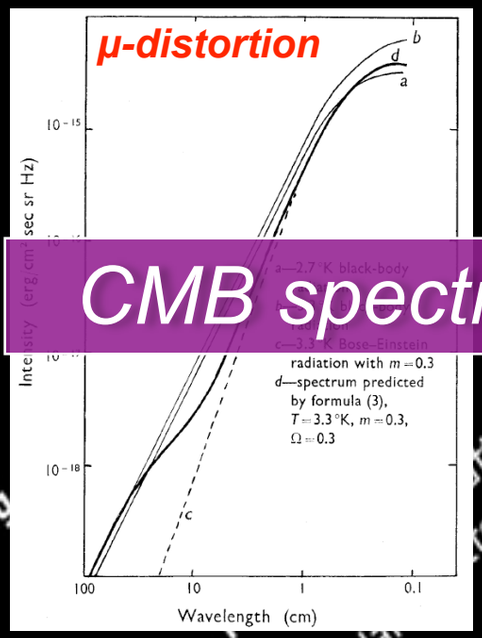
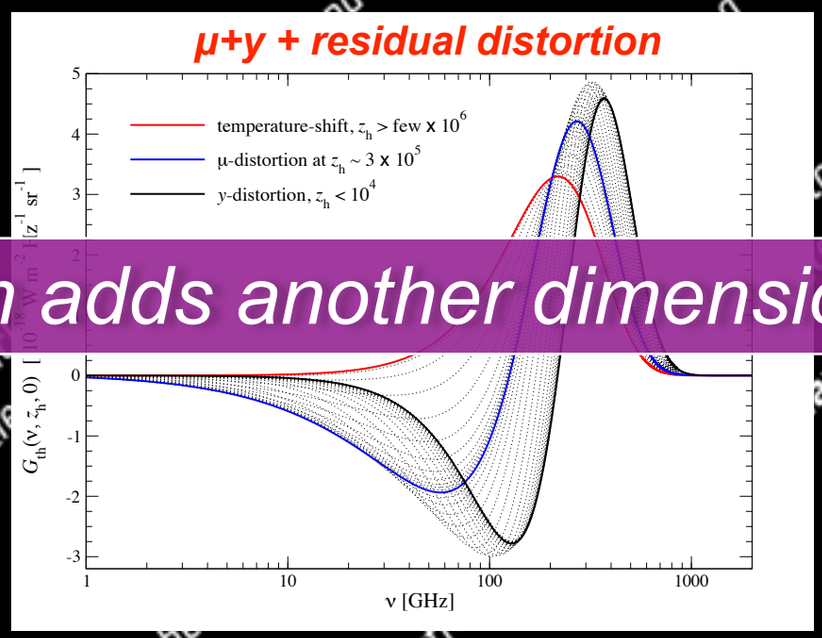
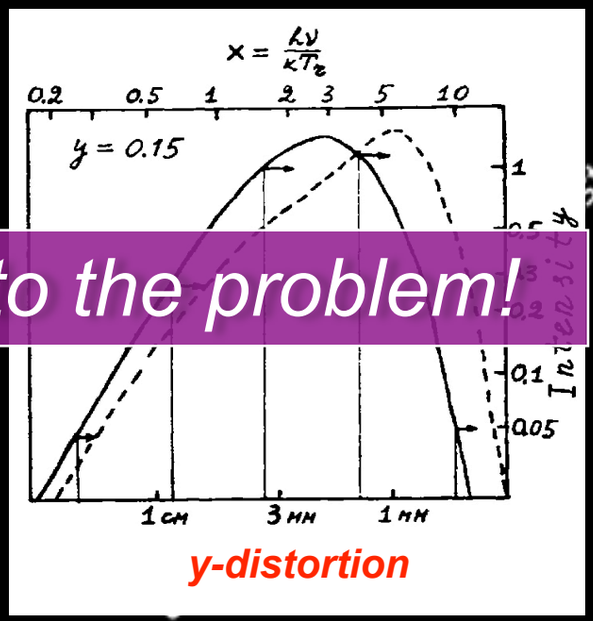
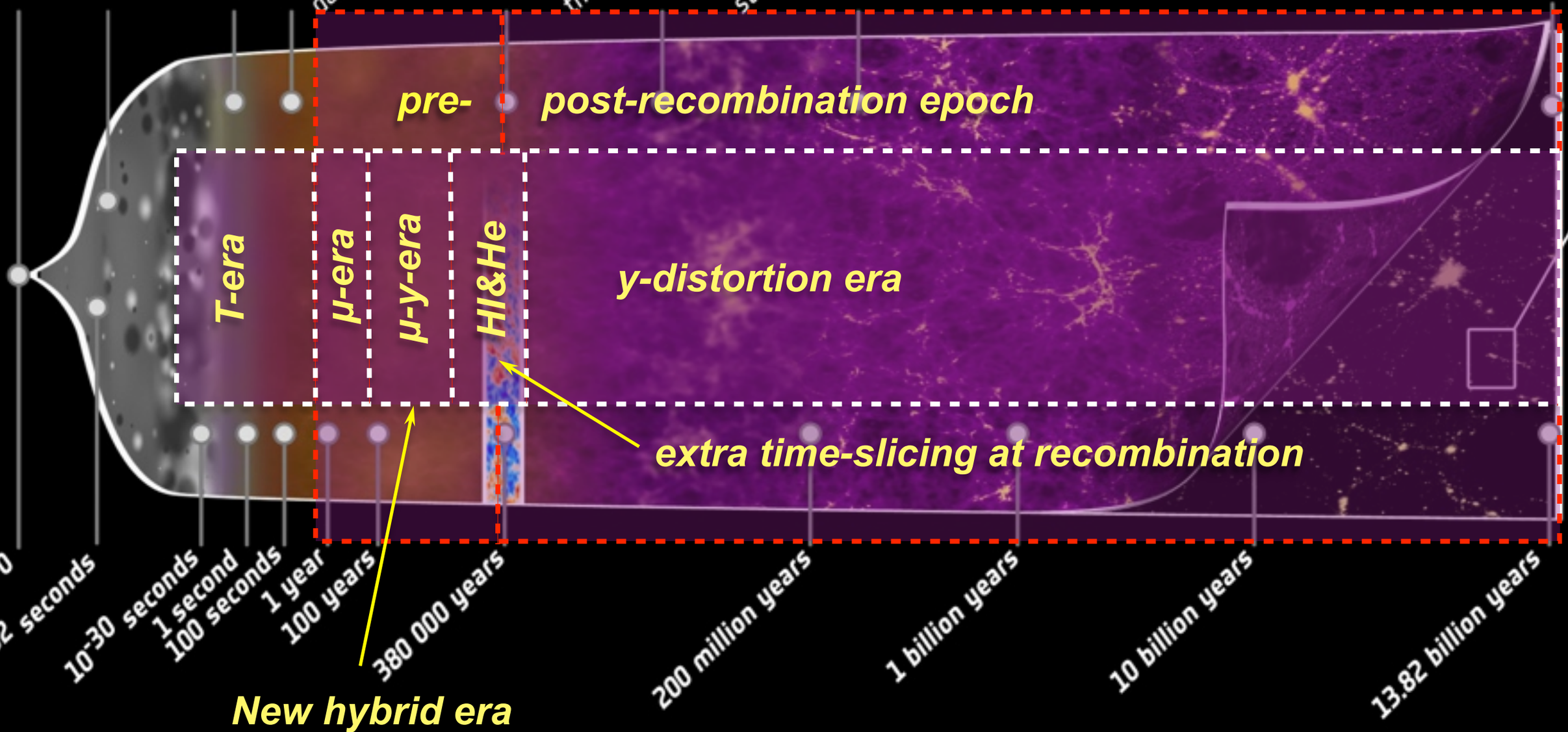


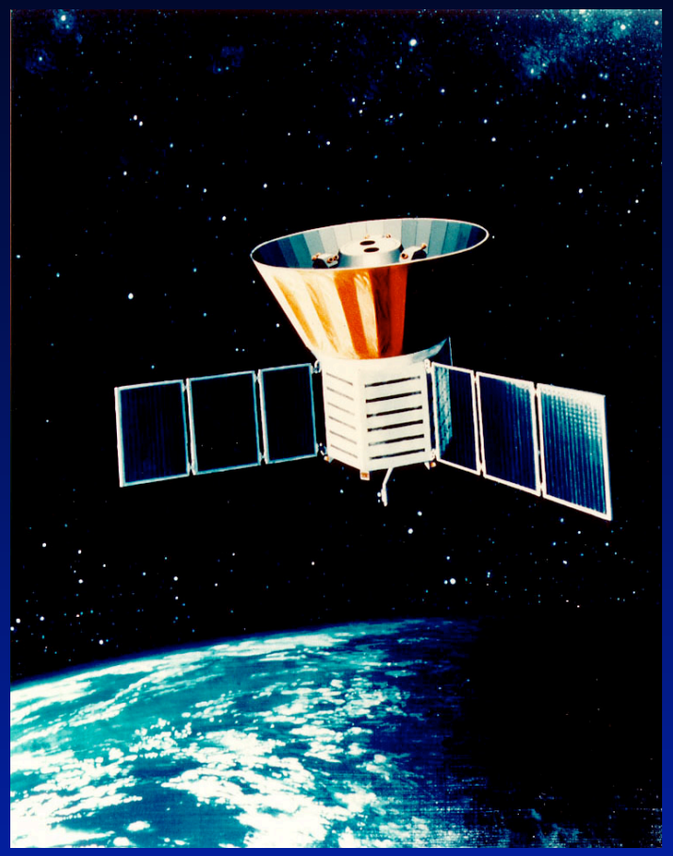




CMB spectrum adds another dimension to the problem!



COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)



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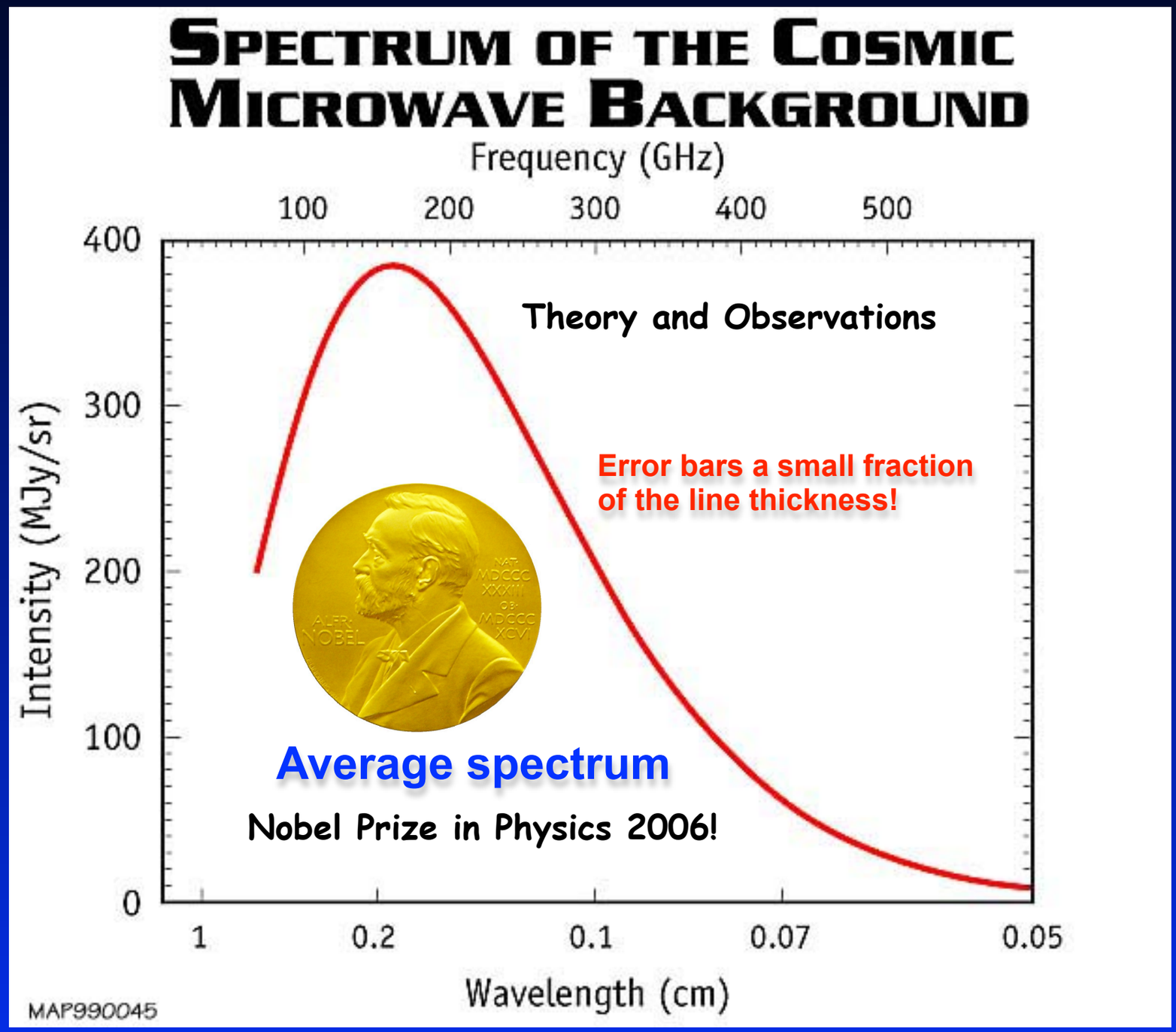

Only very small distortions of CMB spectrum are still allowed!

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

pre-recombination epoch

„high“ redshifts

„low“ redshifts

post-recombination

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

Physical mechanisms that lead to spectral distortions

Standard sources of distortions

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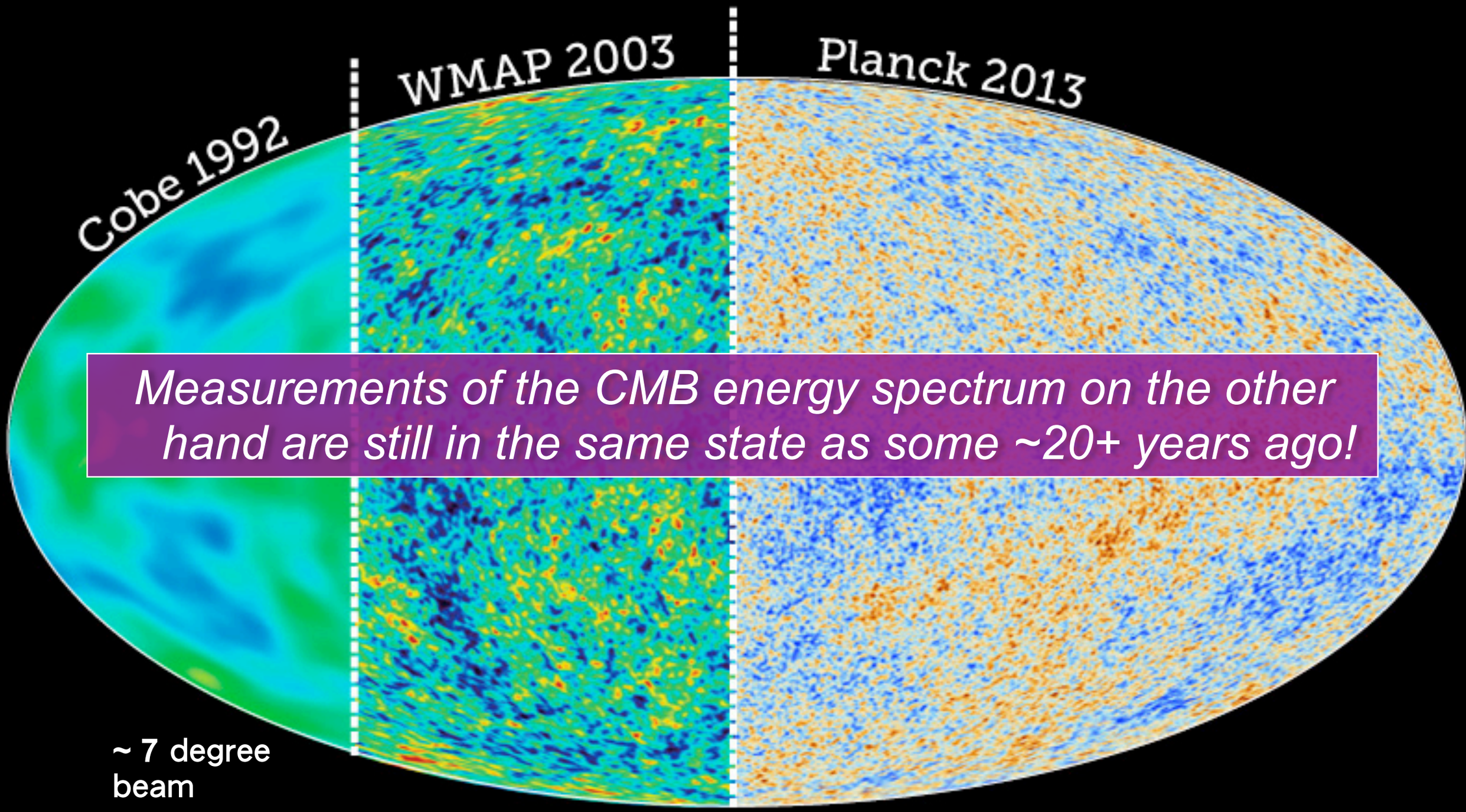
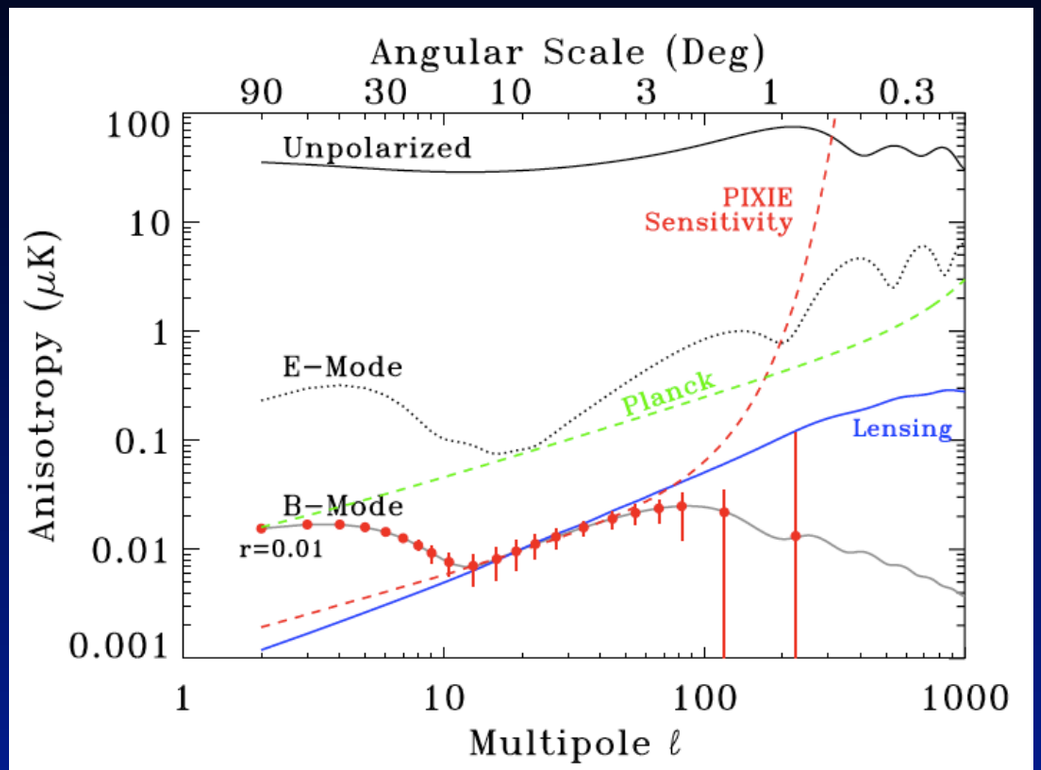
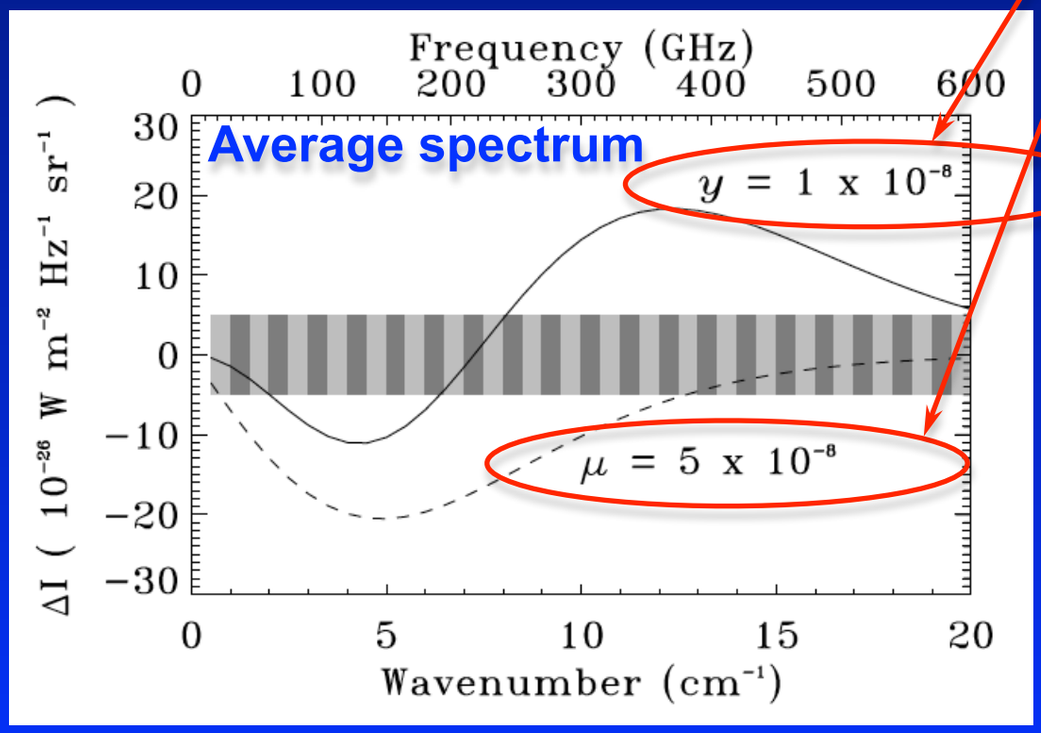
Dramatic improvements in angular resolution and sensitivity over the past decades!



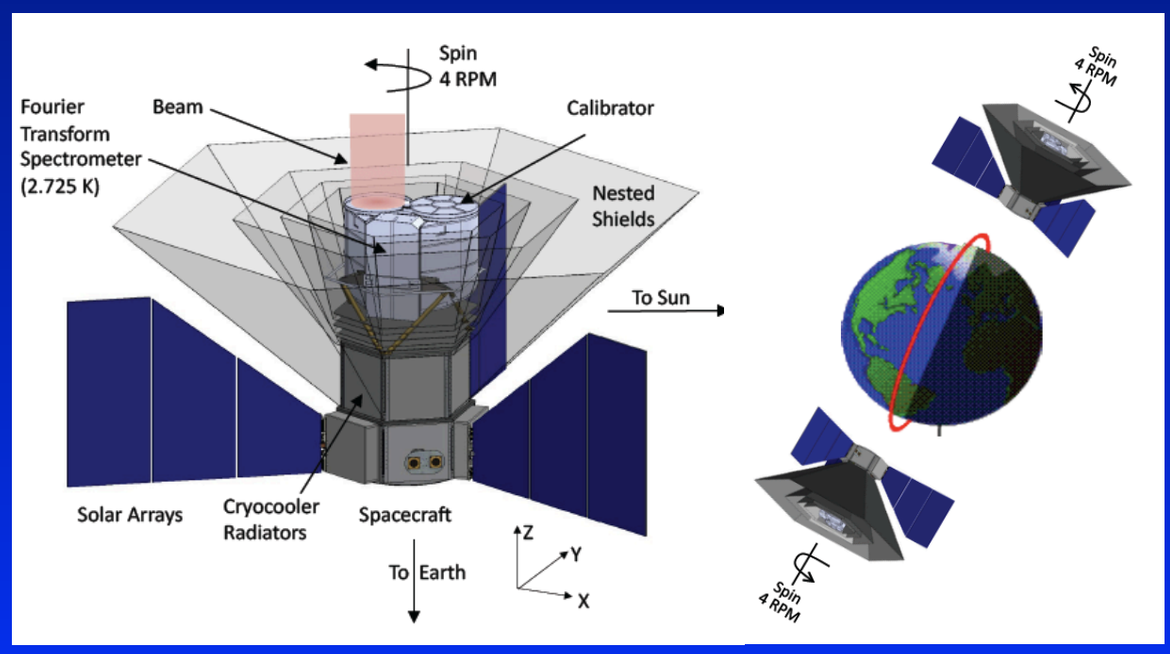
Measurements of the CMB energy spectrum on the other hand are still in the same state as some ~20+ years ago!

PIXIE: Primordial Inflation Explorer

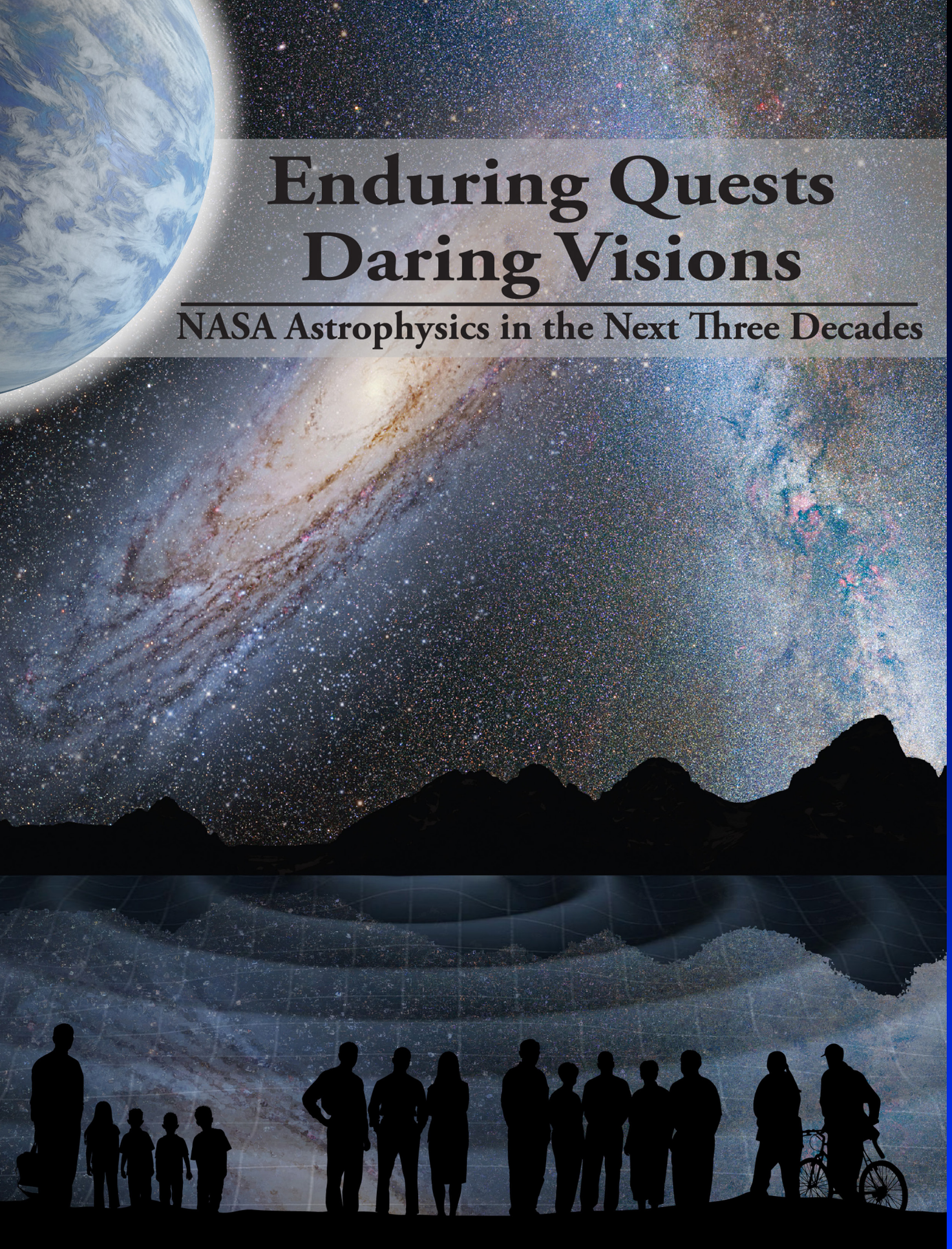




- 400 spectral channel in the frequency range 30 GHz and 6THz (Δv ~ 15GHz)
- about 1000 (!!!) times more sensitive than COBE/FIRAS
- B-mode polarization from inflation ($r \approx 10^{-3}$)
- improved limits on μ and y
- was proposed 2011 as NASA EX mission



Kogut et al, JCAP, 2011, arXiv:1105.2044



NASA 30-yr Roadmap Study

(published Dec 2013)

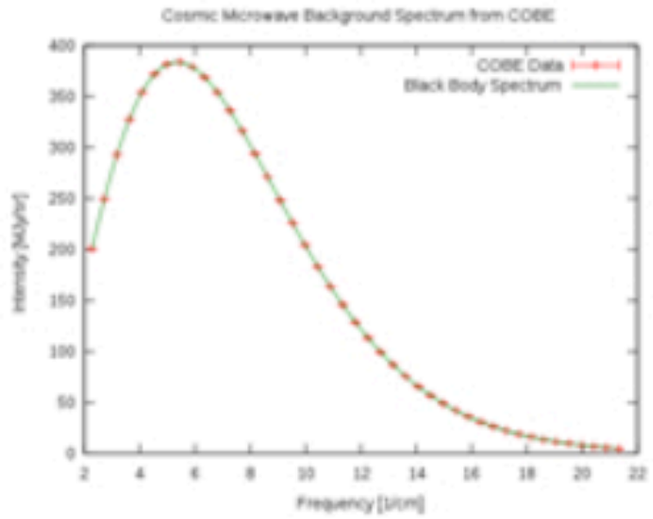
How does the Universe work?

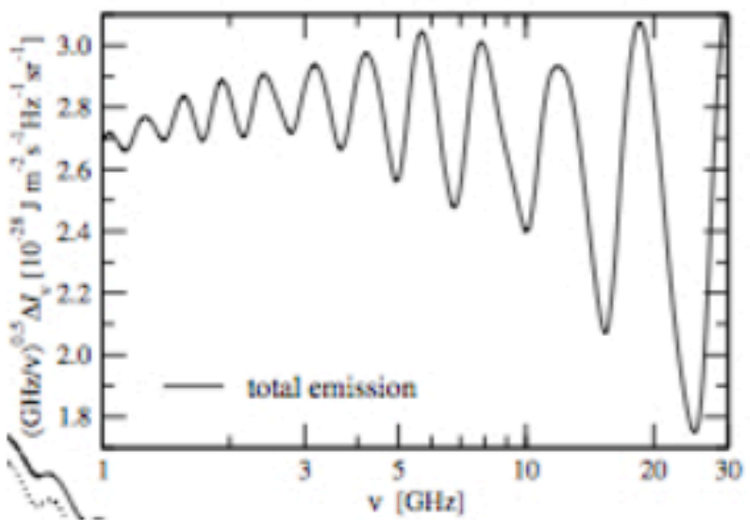
"Measure the spectrum of the CMB with precision several orders of magnitude higher than COBE FIRAS, from a moderate-scale mission or an instrument on CMB Polarization Surveyor."

PIXIE was proposed to NASA in Dec 2016. Decision this year!

Array of Precision Spectrometers for detecting spectral ripples from the Epoch of RecombinAtion

HOME PEOPLE



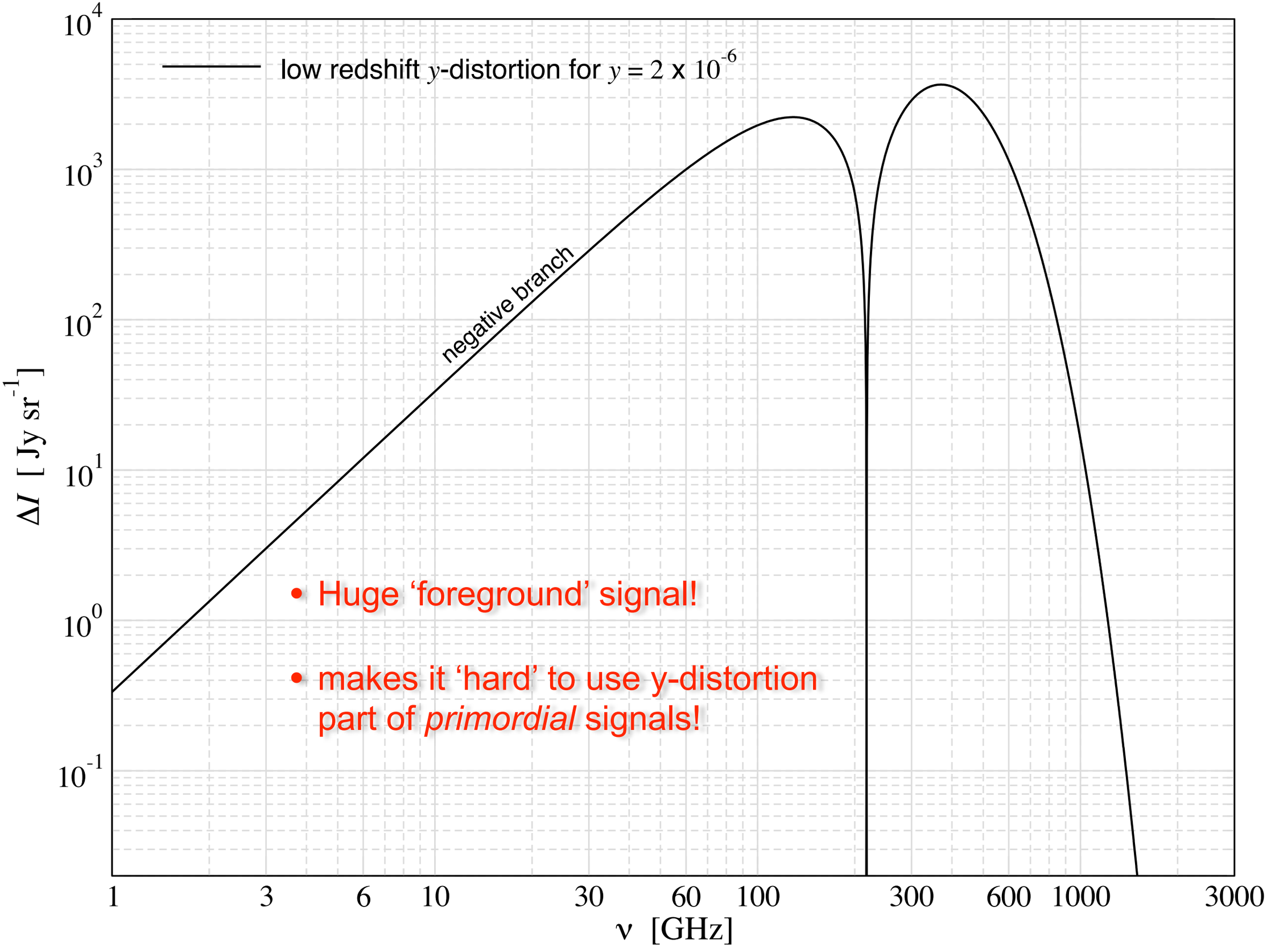


About APSERa

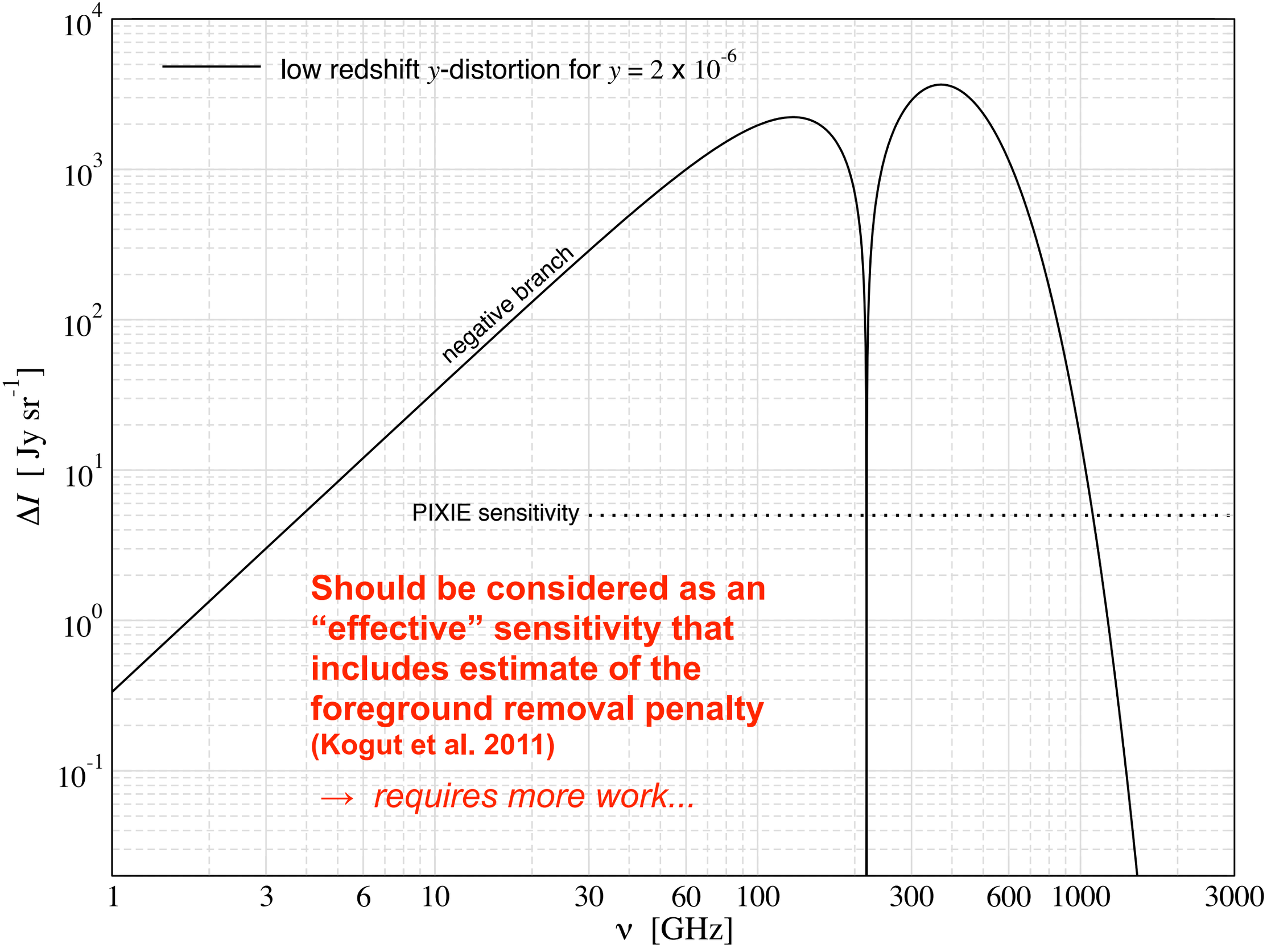
The Array of Precision Spectrometers for the Epoch of RecombinAtion - APSERa - is a venture to detect recombination lines from the Epoch of Cosmological Recombination. These are predicted to manifest as 'ripples' in wideband spectra of the cosmic radio background (CRB) since recombination of the primeval 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.

Average CMB spectral distortions



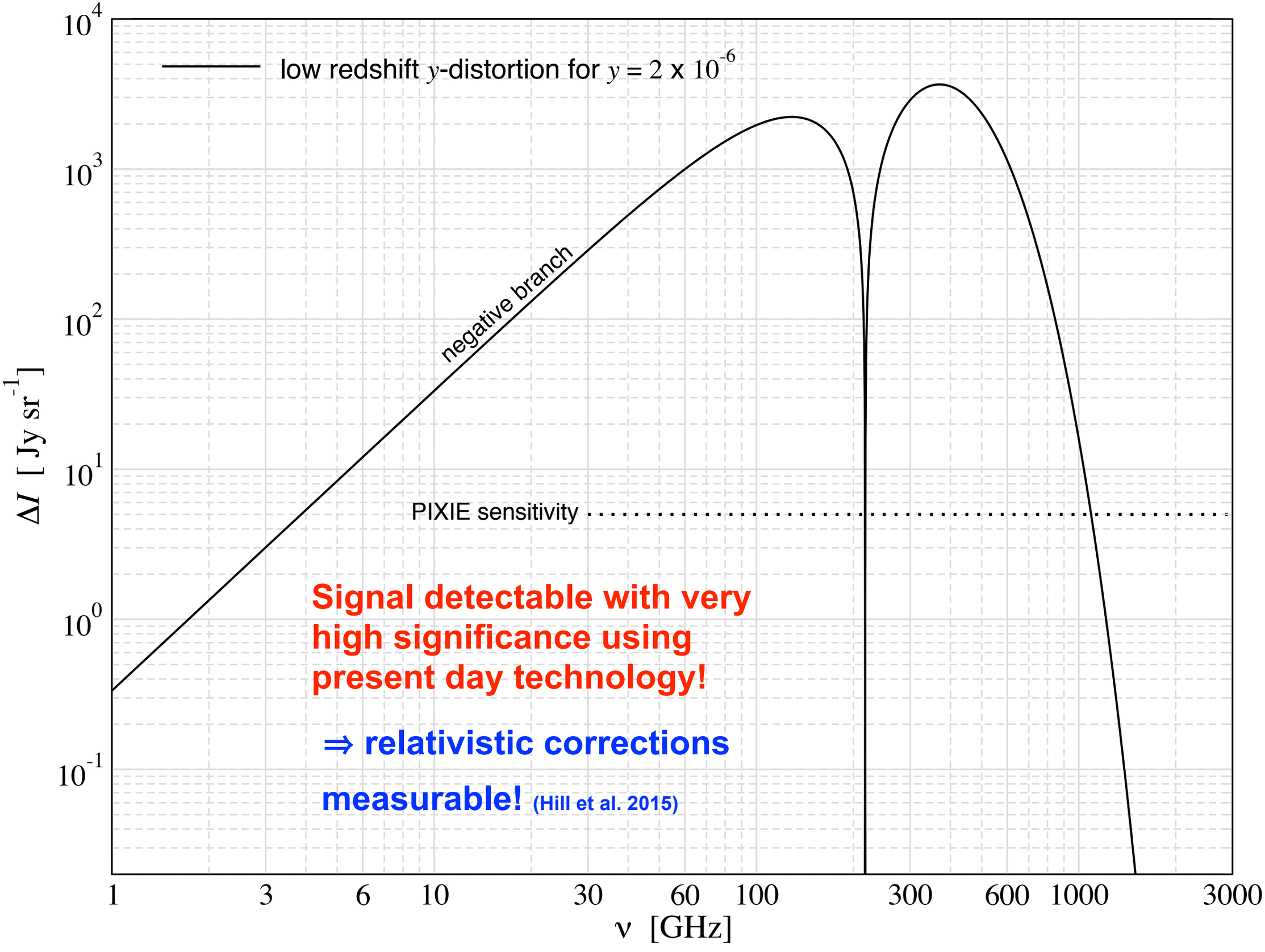
Average CMB spectral distortions



Should be considered as an "effective" sensitivity that includes estimate of the foreground removal penalty
(Kogut et al. 2011)

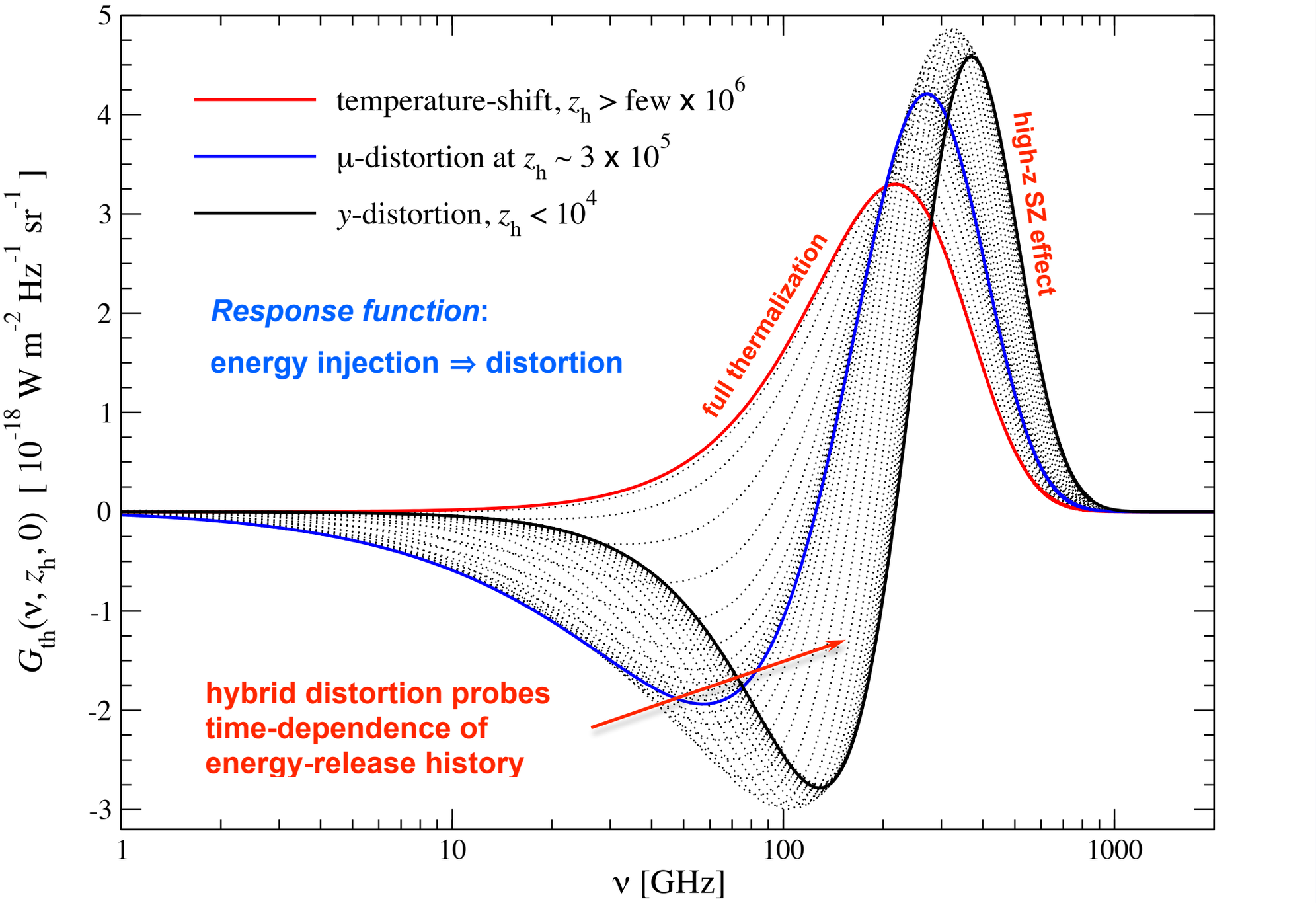
→ *requires more work...*

Average CMB spectral distortions



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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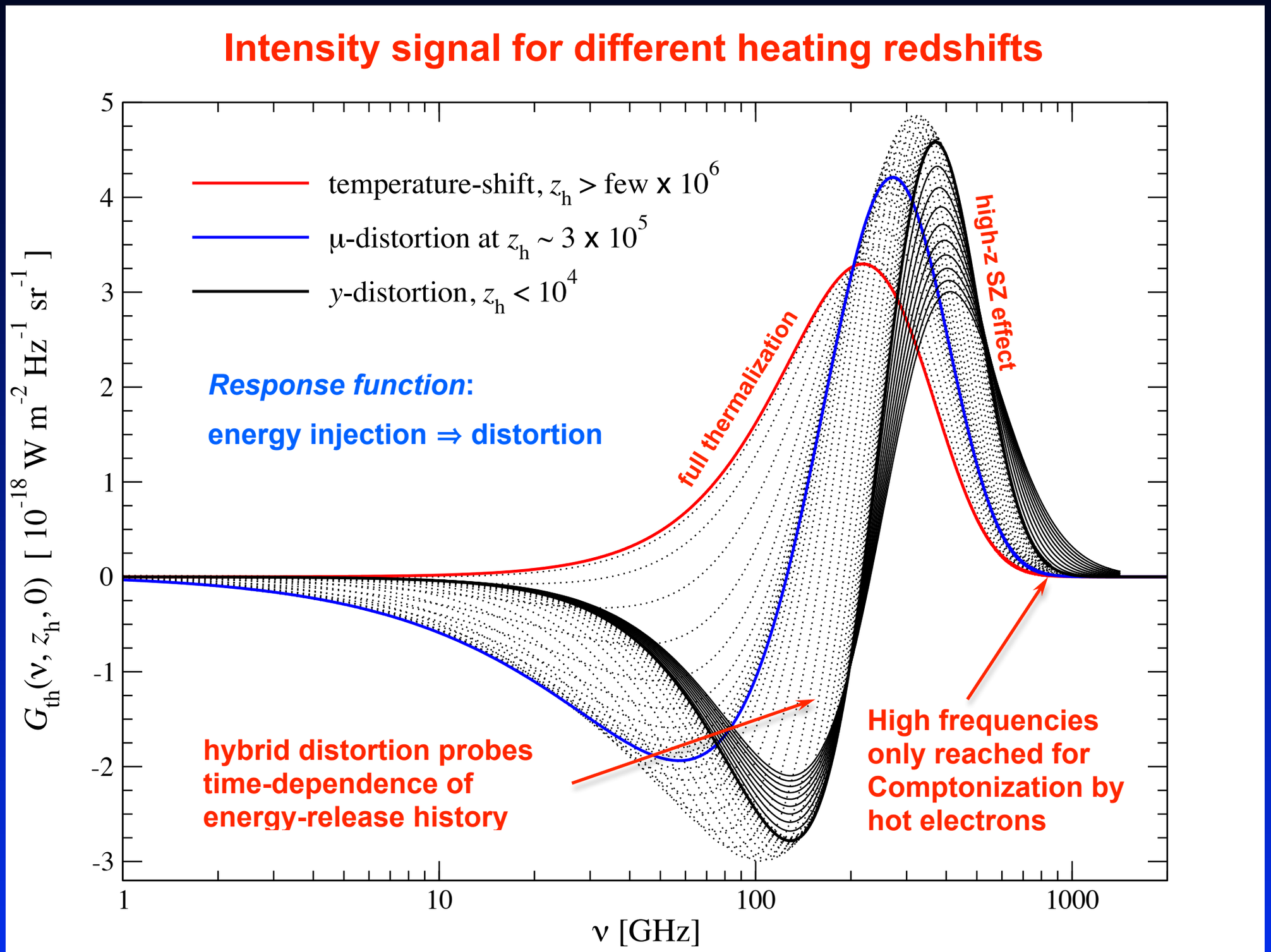

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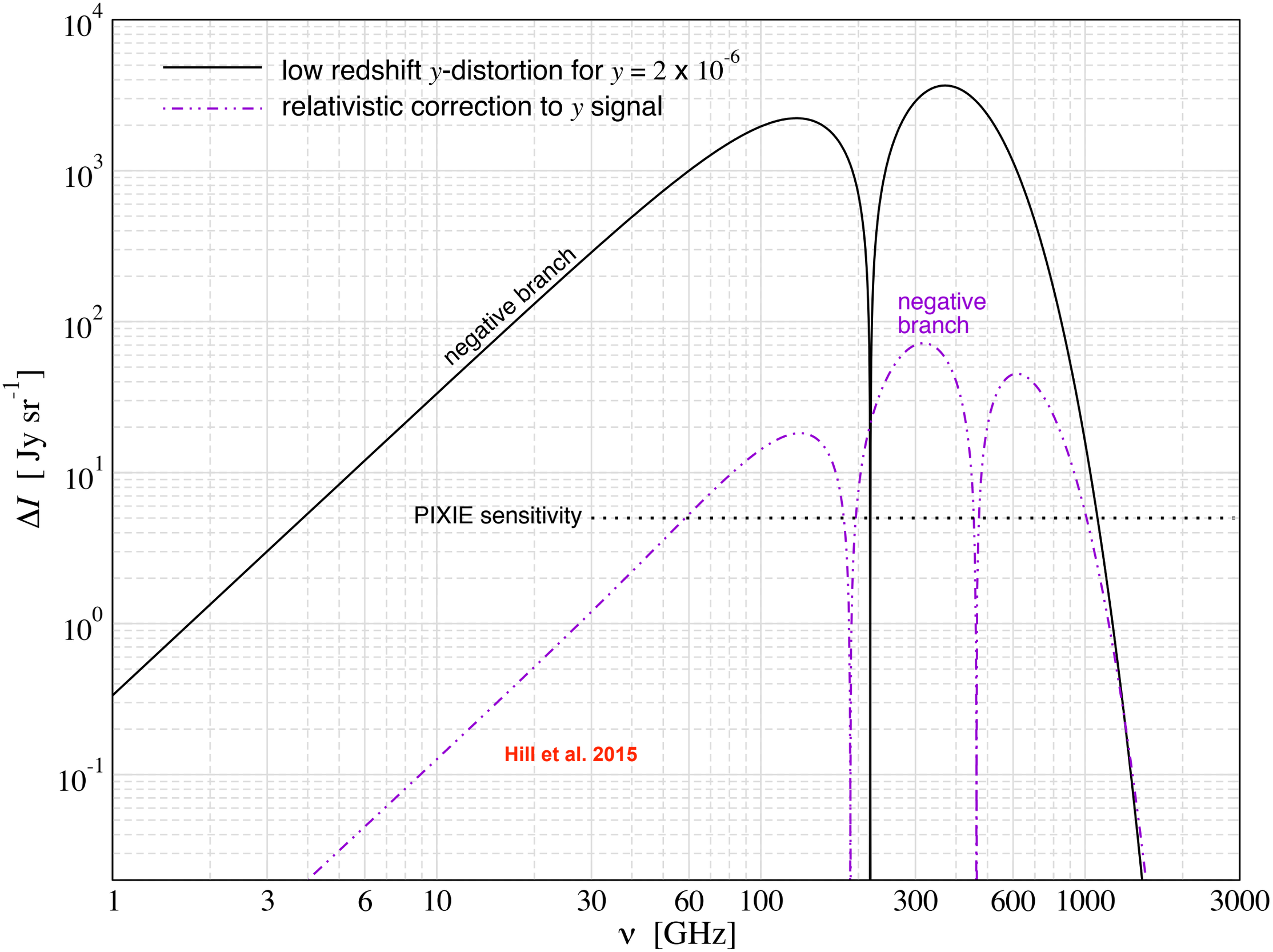

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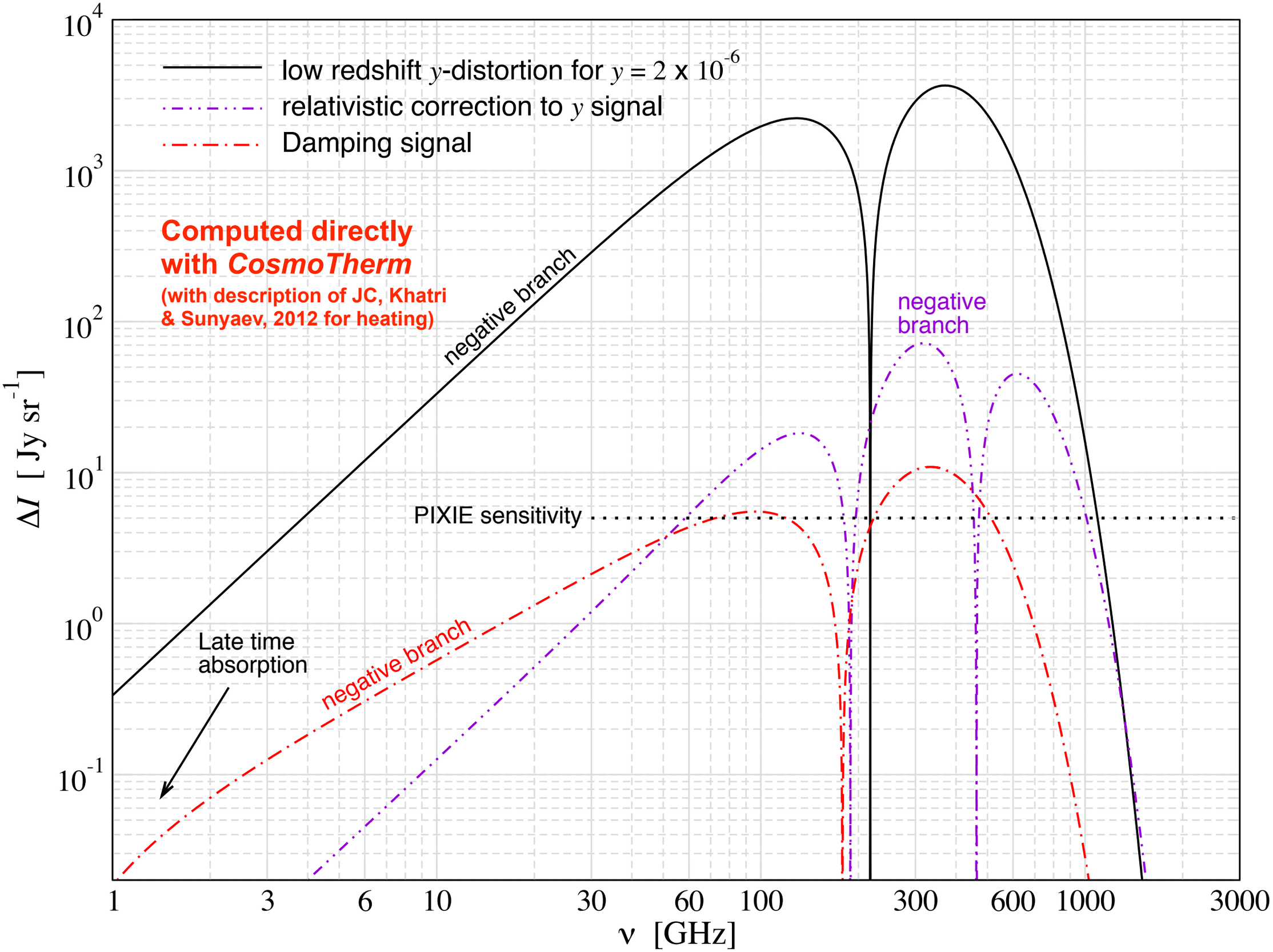

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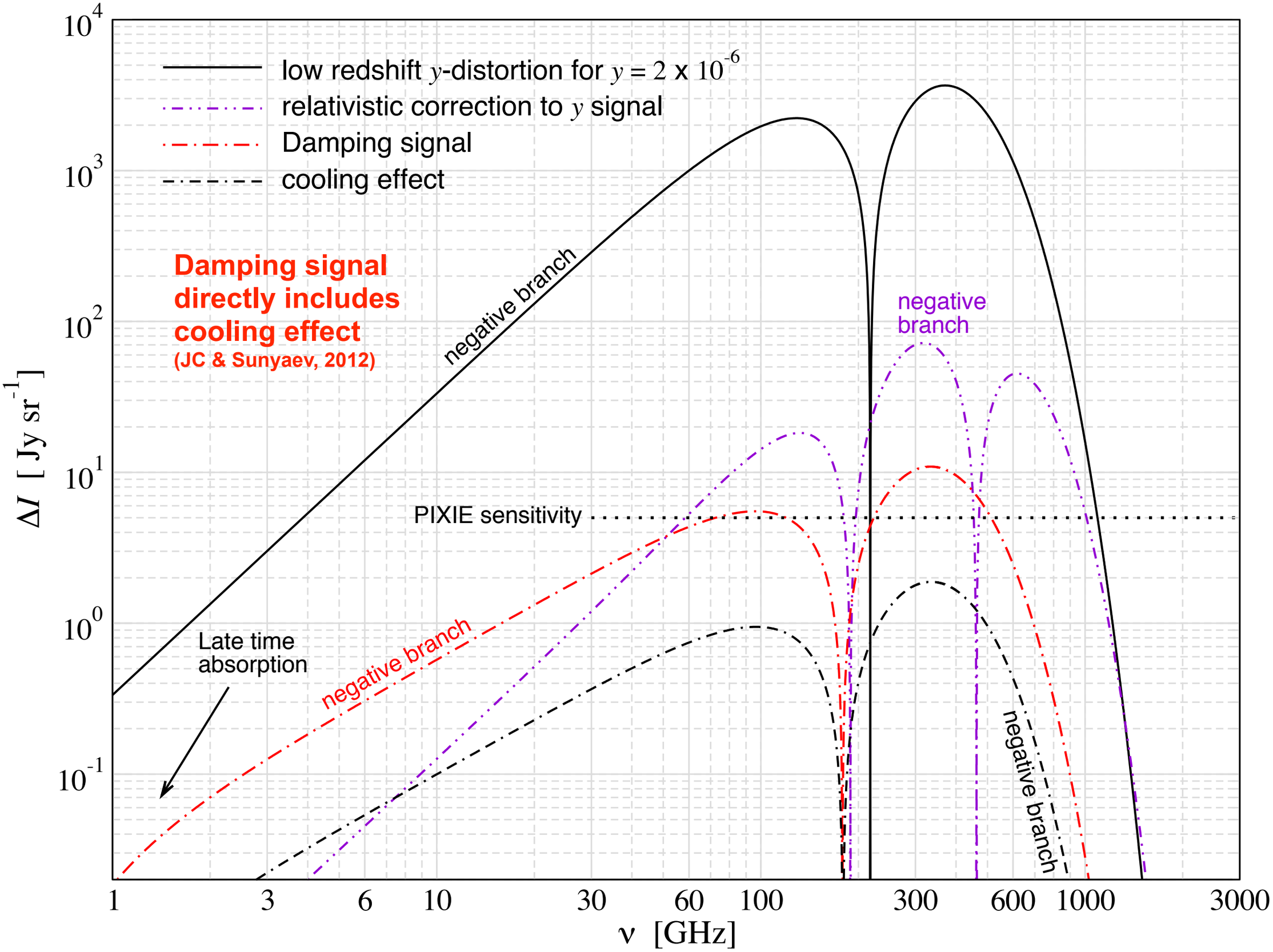
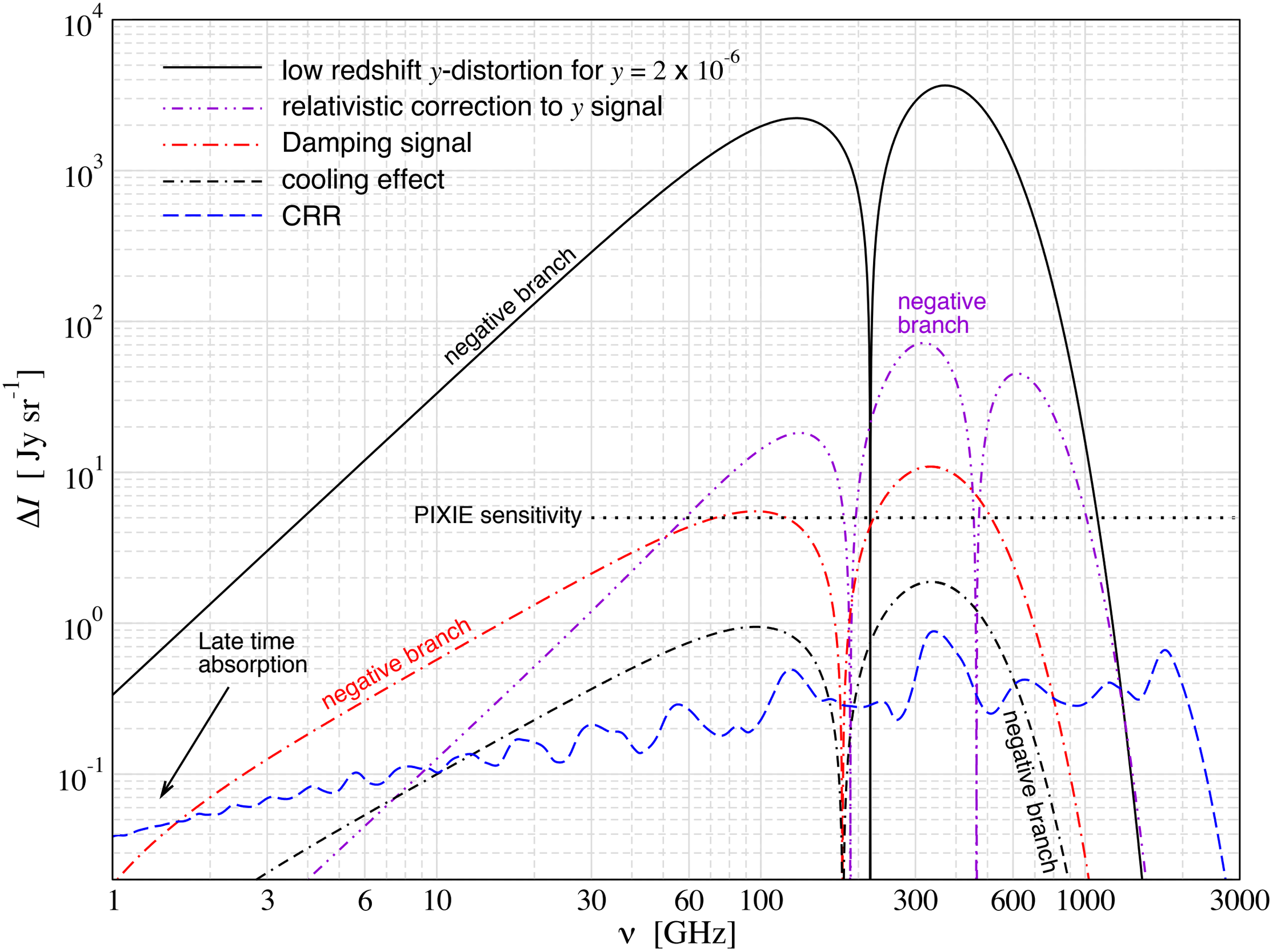
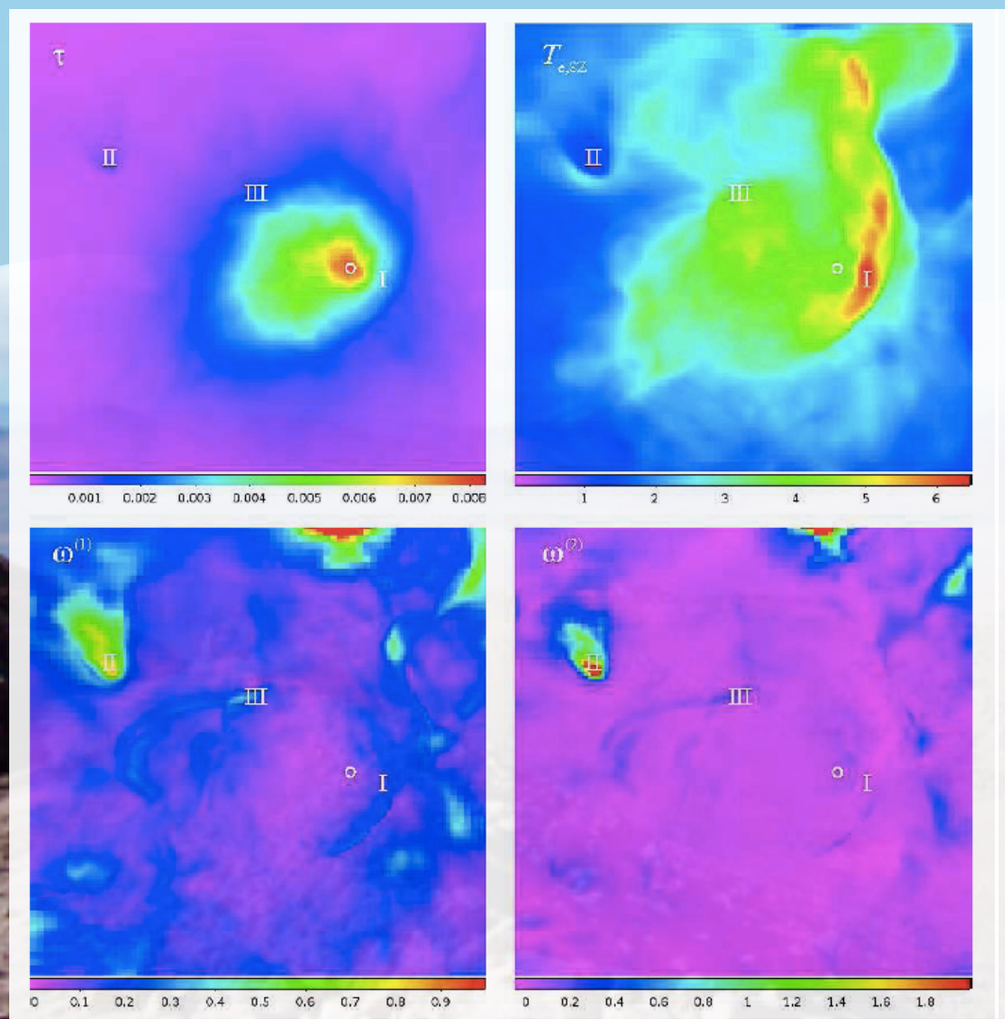
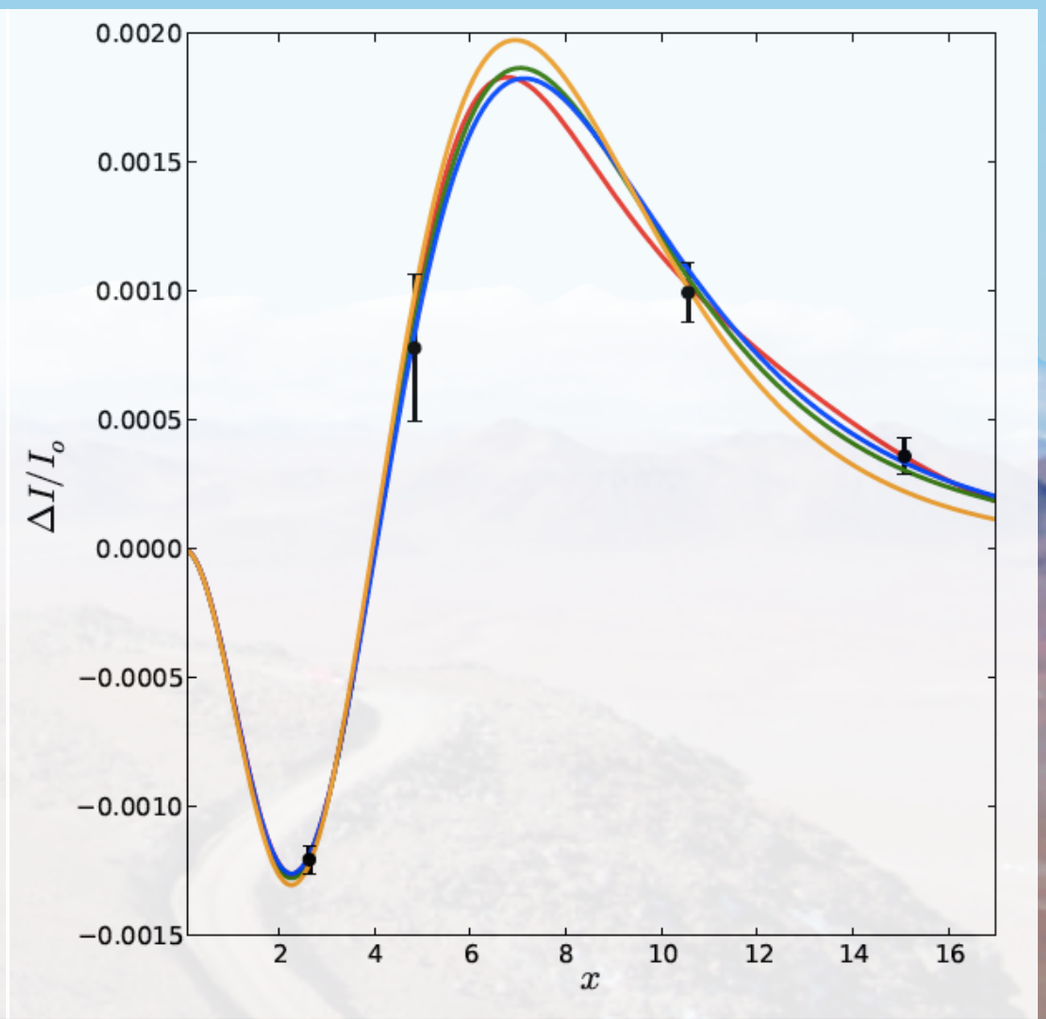


Average CMB spectral distortions in ΛCDM

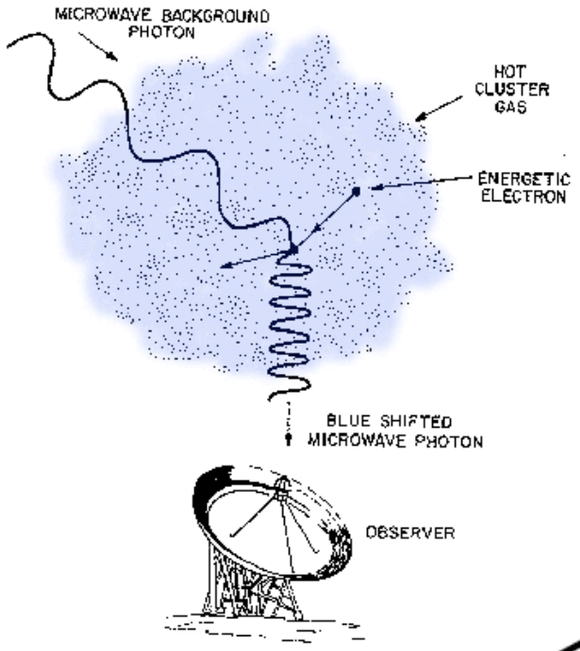


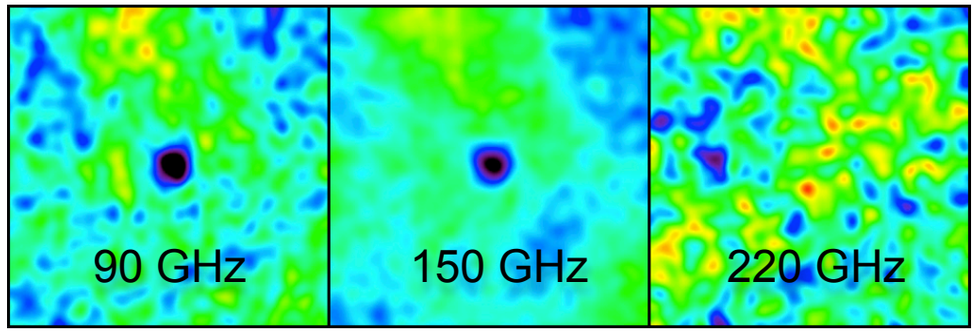
SZpack: fast computation of the SZ-effect using temperature and velocity moments



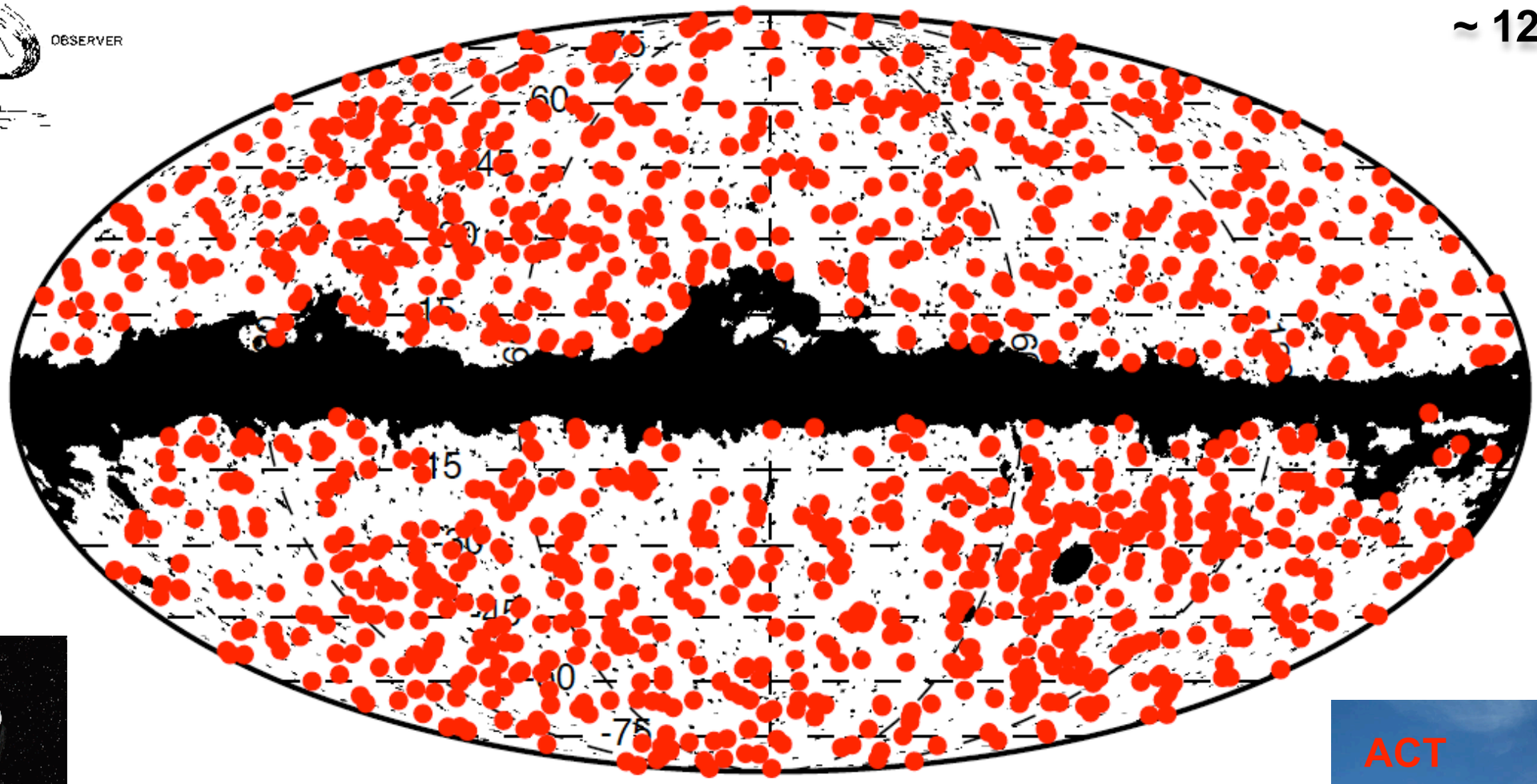


Thermal SZ effect is now routinely observed!

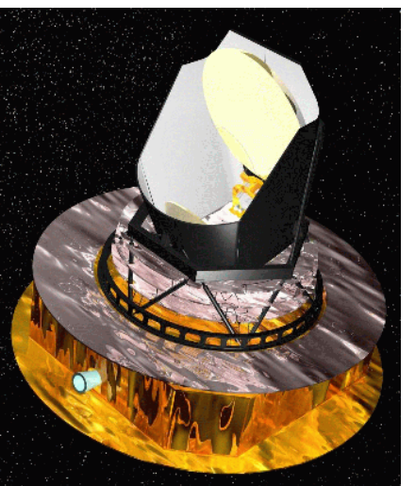




~ 1230 objects



Planck Collaboration, 2013, paper XXIV



What is the problem?

- Future high resolution & high sensitivity SZ observations

  → will allow us to address detailed questions about the state of the ICM

  → require accurate model for the SZ signal (*along different lines of sight...*)

  → which parameters actually determine it?

SZpack available at: www.Chluba.de/SZpack

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- Future high resolution & high sensitivity SZ observations

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  → which parameters actually determine it?

- Computation of the SZ signal (*e.g., from a simulation or in analysis*)

  → depends on the electron number density, temperature and velocity structure

  → *brute force* calculation pretty expensive & link to parameters complicated

  → previous analytic approximations have *limited applicability*

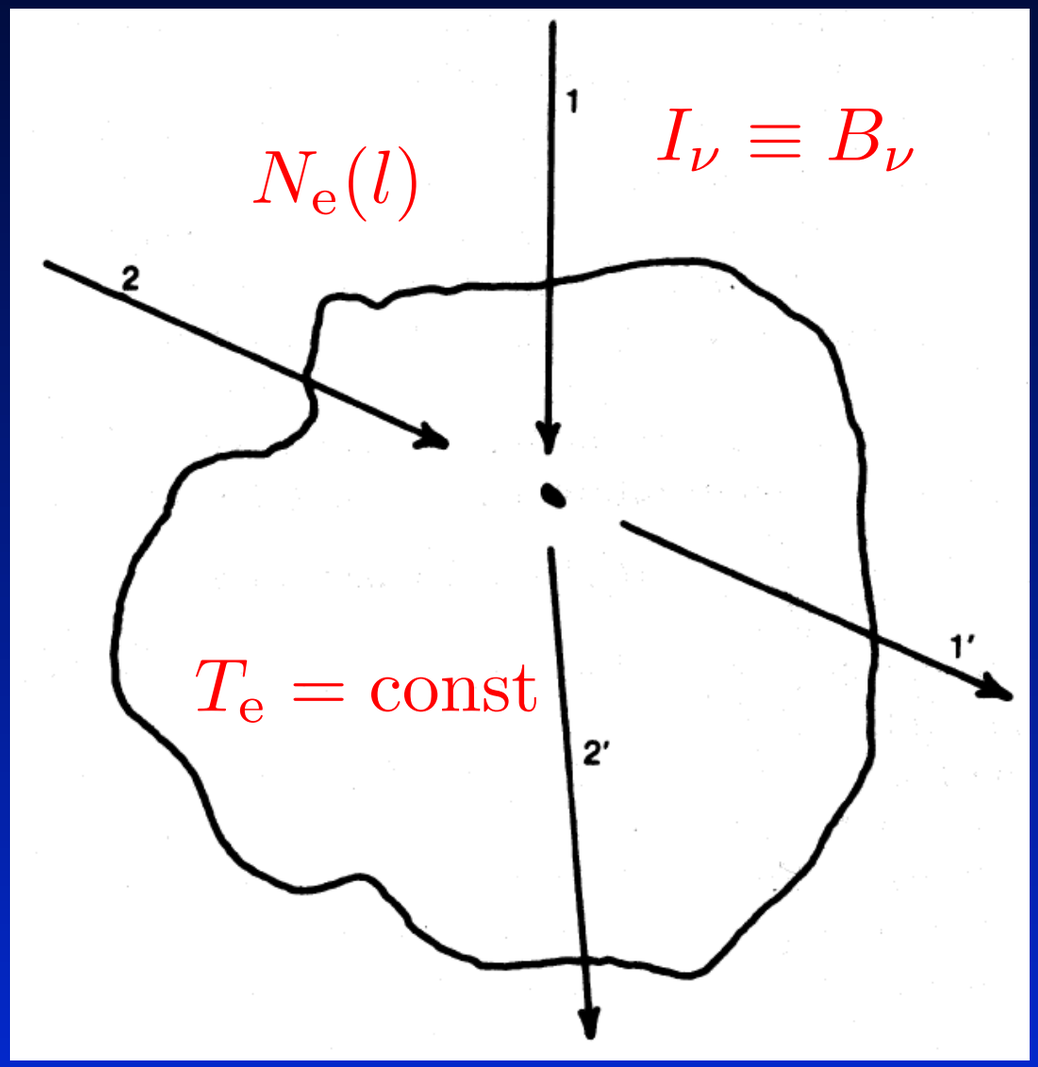
  → *variations* of the temperature and velocity structure not accounted for

  → previous treatment of multiple scattering correction too simplistic...

SZpack overcomes all these problems!

SZpack available at: www.Chluba.de/SZpack

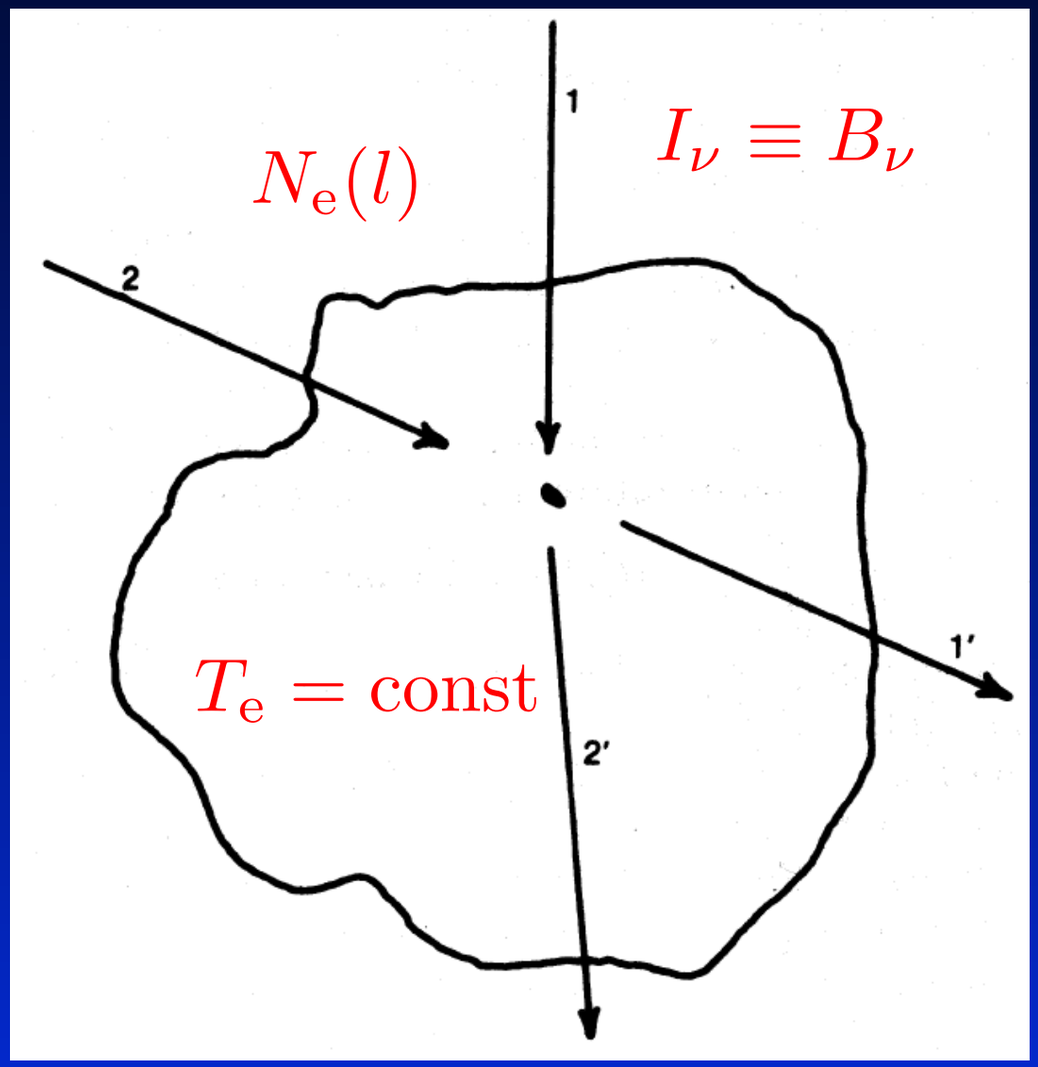
Thermal SZ effect for isothermal cluster



Scattering physics

- SZ signal depends on # of photons scattering *in* and *out* of the line-of-sight
- optically thin case $\Delta I_\nu \sim \tau\, S(\nu, T_{\rm e})$
- computation of $S(\nu, T_{\rm e})$ demanding

Thermal SZ effect for isothermal cluster



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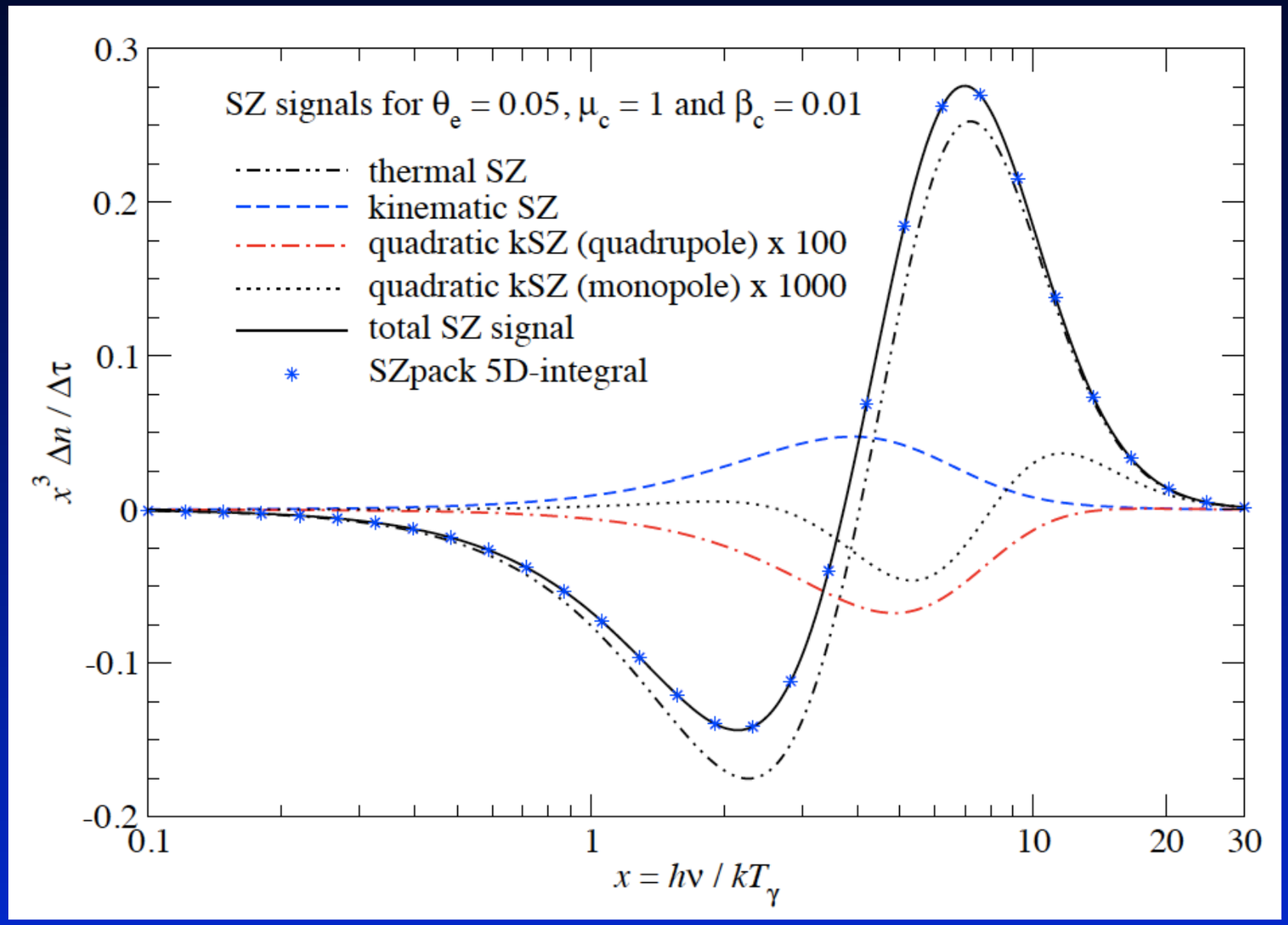
asymptotic expansion (e.g., *Itoh et al 1998*)

- assumption $kT_e << mc^2$ and $\Delta\nu/\nu << 1$
- $\Rightarrow$ convergence issues at high frequencies for $kT_e > 8$ keV

Thermal and kinematic SZ effect for isothermal cluster



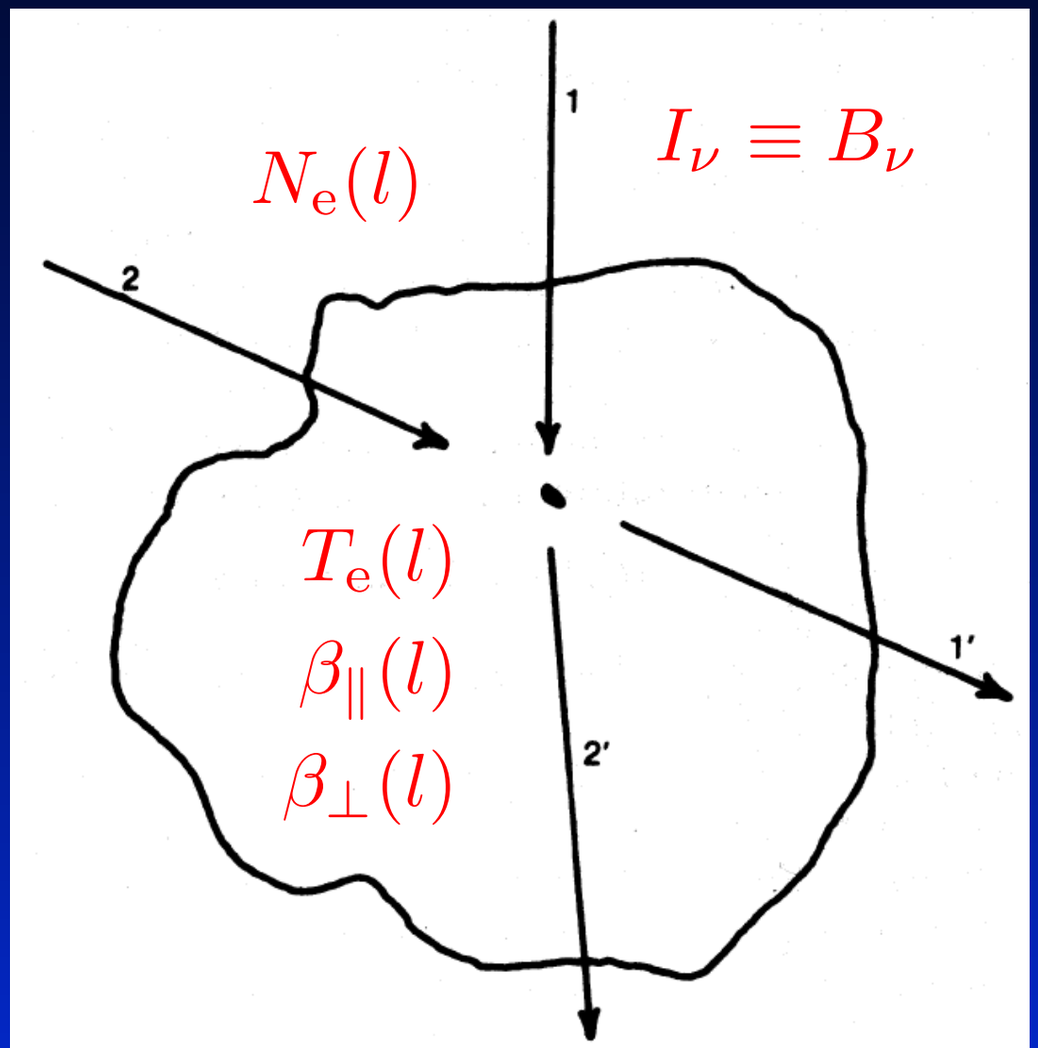
JC, Nagai, Sazonov & Nelson, 2012

SZpack approach

- T_e derivatives analytically
- collision integral numerically for given reference temperature
- set of smooth basis functions that is motivated by scattering physics
- excellent convergence properties
- precise representation of SZ signal for $kT_e < 75$ keV and $x<30$

SZpack available at: www.Chluba.de/SZpack

Non-isothermality and effect of internal motions



- SZ signal given by additional integral over line-of-sight
- problem becomes very demanding
- *Question*: what are the real parameters/observables?

Simple Solution:

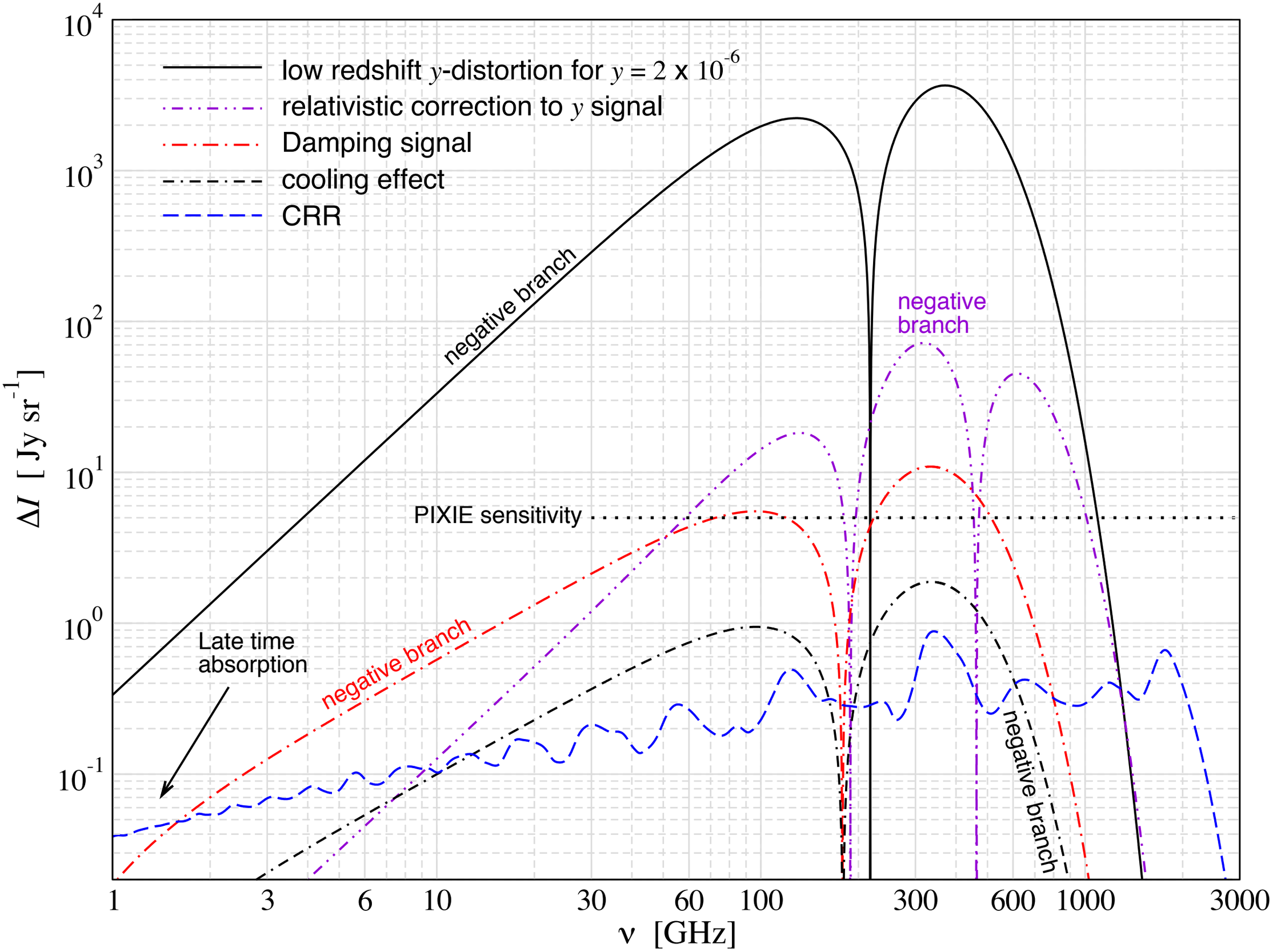
- perform expansion around mean values of main variables!
- *temperature-velocity moments* define new set of parameters:

$$p = \{\tau, T_{\rm e}, \omega^{(k)}, \sigma^{(k)}, \kappa^{(k)}, \beta_\parallel, \beta_\perp^2\}$$

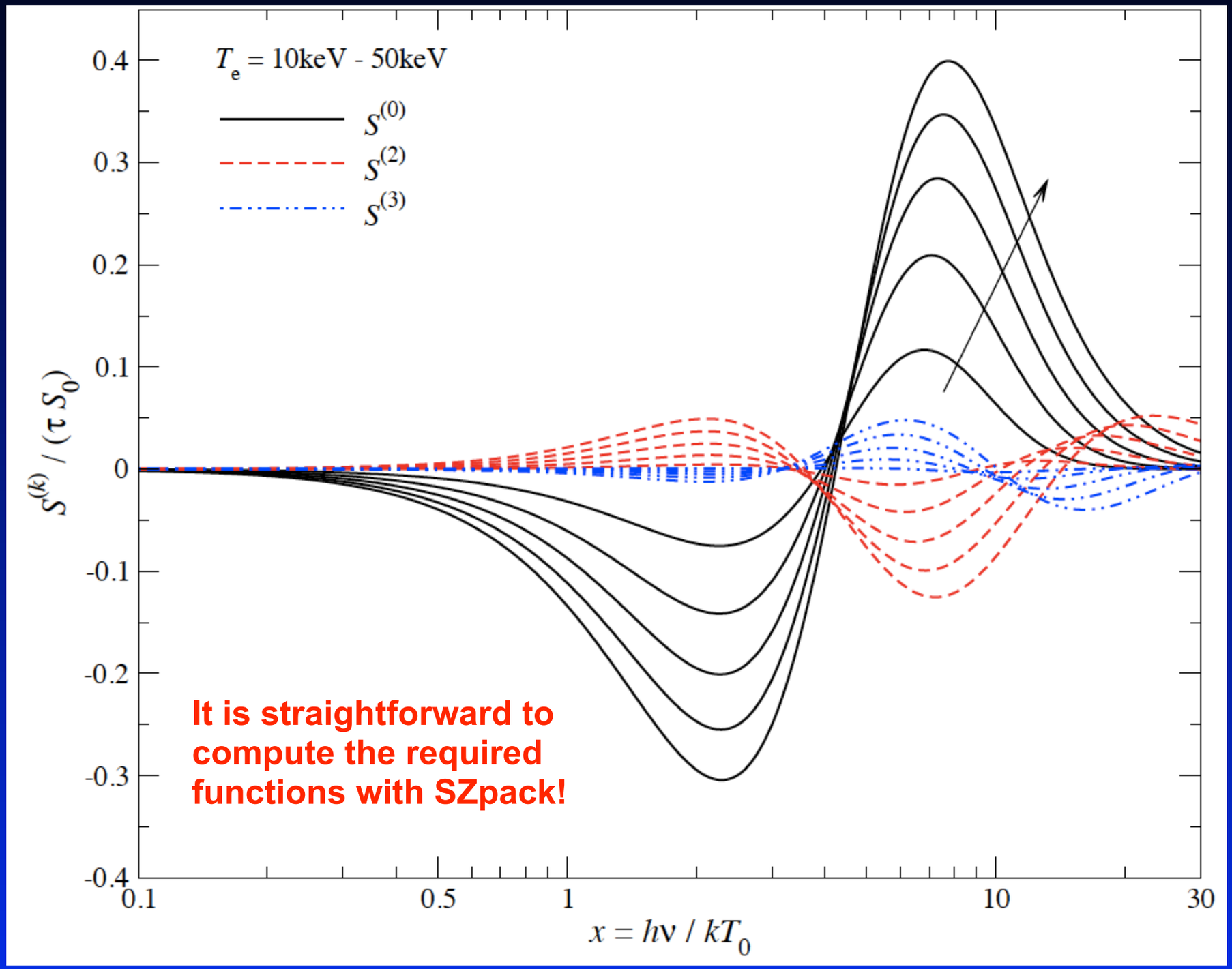
$$S \approx S_{\rm iso}^{(0)} + S_{\rm iso}^{(2)}\,\omega^{(1)} + C_{\rm iso}^{(1)}\,\sigma^{(1)} + D_{\rm iso}^{(2)}\,\kappa^{(1)} + E_{\rm iso}^{(2)}\,\beta_{\rm c,\perp,SZ}^2 + \ldots,$$

all functions of $T_{\rm e}$, τ and $\beta_\parallel$

Average CMB spectral distortions in ΛCDM

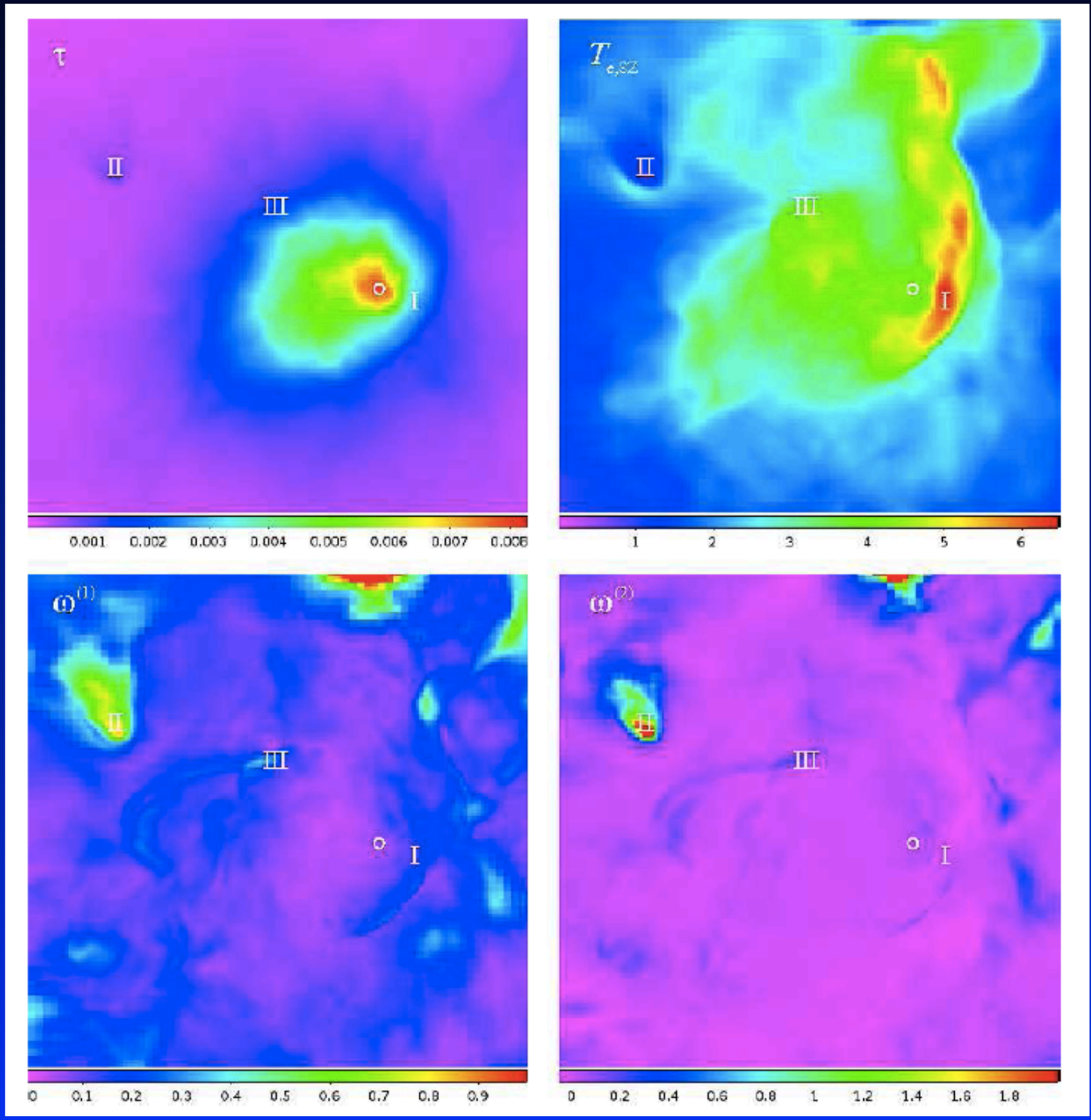


Basis functions to include non-isothermality



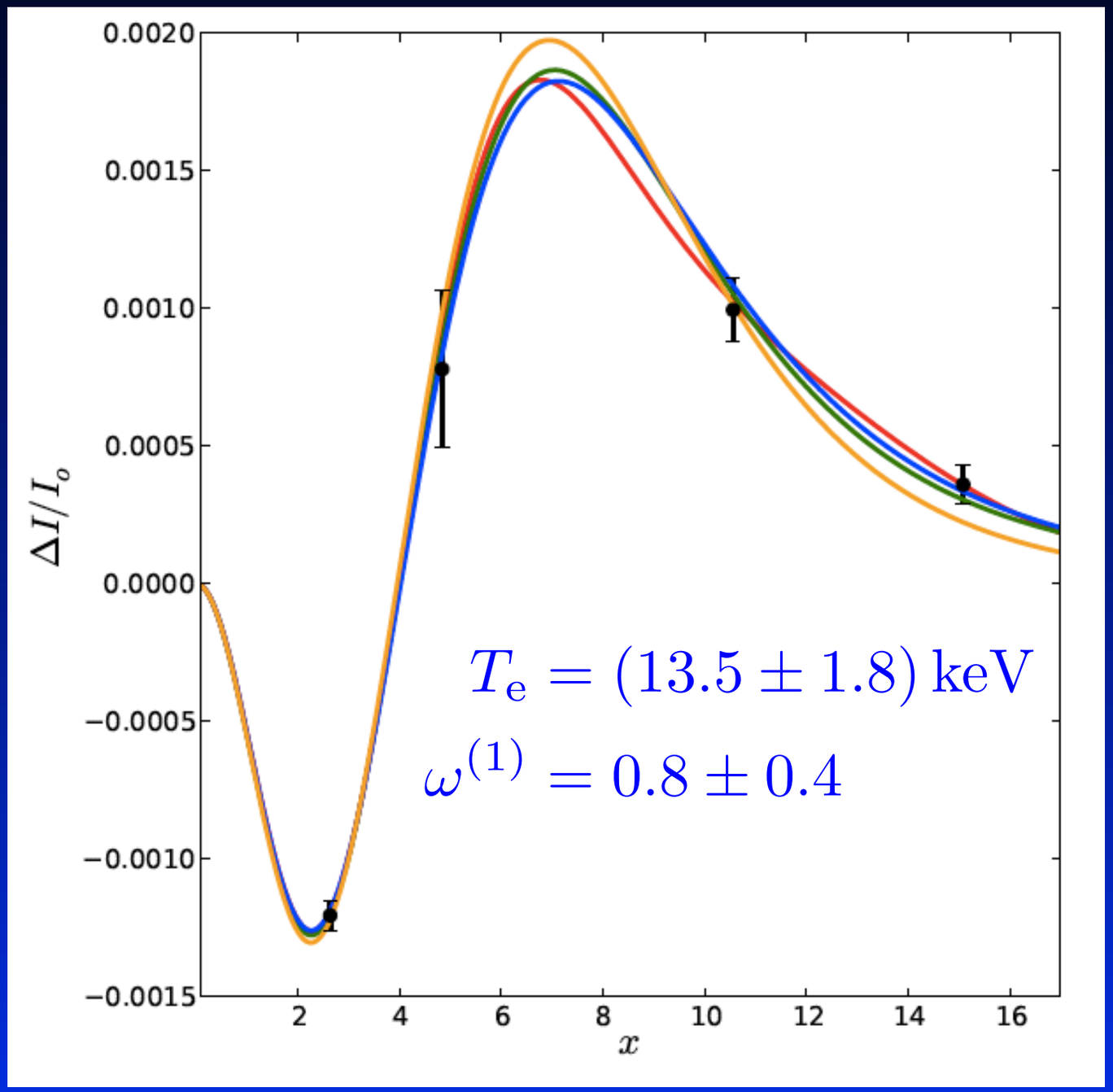
JC, Switzer, Nagai & Nelson, 2012

Can be directly used to compute signal morphologies



JC, Switzer, Nagai & Nelson, 2012

Analysis of Bullet cluster data (Prokhorov et al)



- MCMC analysis with extended set of parameters
- consistent analysis for mean and dispersion
- isothermal model in tension with data (orange)
- two-temperature (green) and simple dispersion (blue) models indistinguishable
- high frequency spectrum very important
- Itoh expansion (red) in this case not meaningful although at current level of precision consistent with data...

JC, Switzer, Nagai & Nelson, 2012