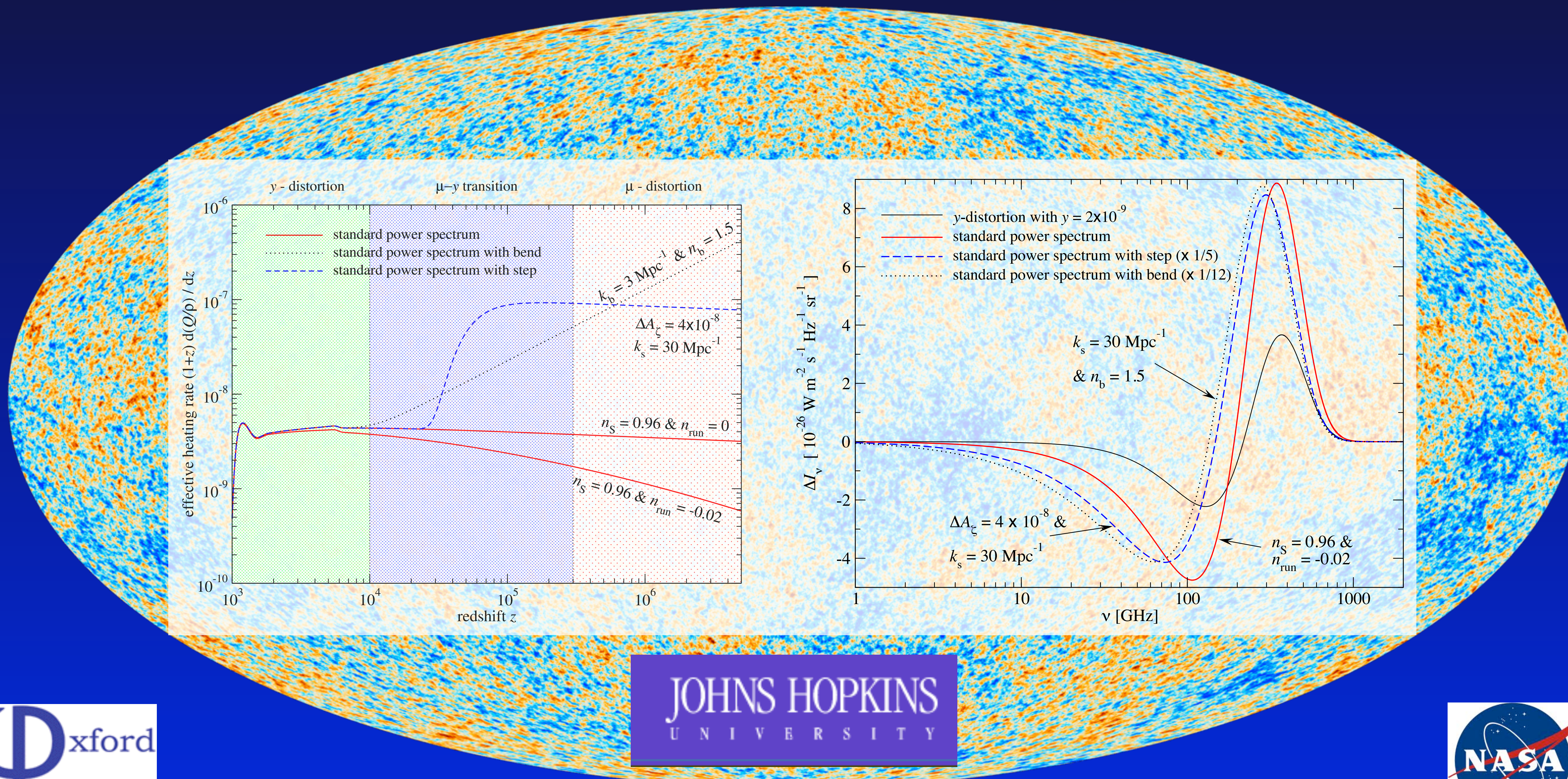
Spectral distortions of the CMB: a new window to early universe physics



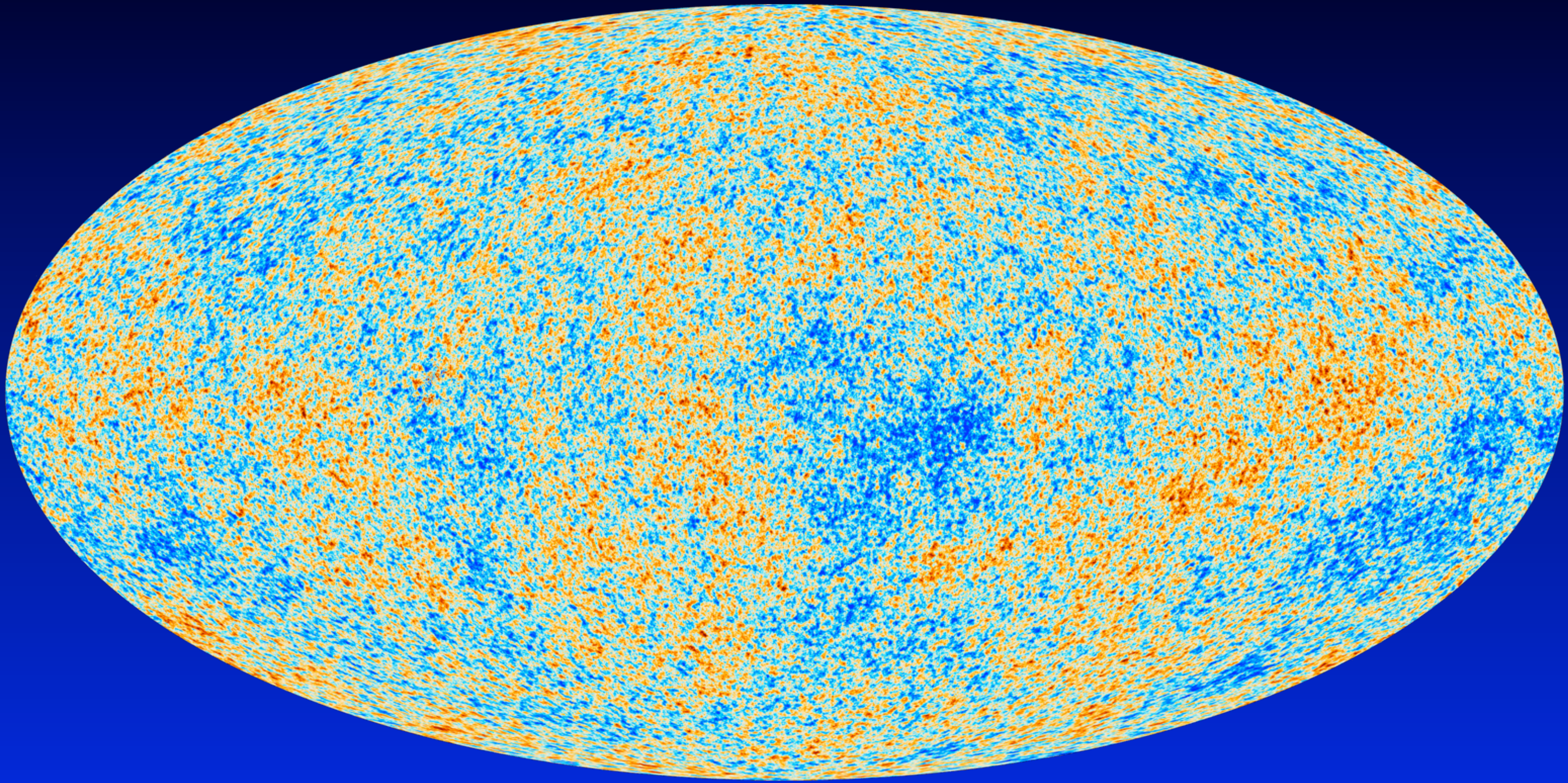
Jens Chluba

NASA Astrophysics Roadmap Town Hall Meeting

May 6-7, 2013

Collaborators: ***D.J. Fixsen, M. Kamionkowski, R. Khatri, A. Kogut, J.C. Mather, M.D. Niemack, J. Silk, R.A. Sunyaev and E.J. Wollack***

Cosmic Microwave Background Anisotropies



Planck all sky 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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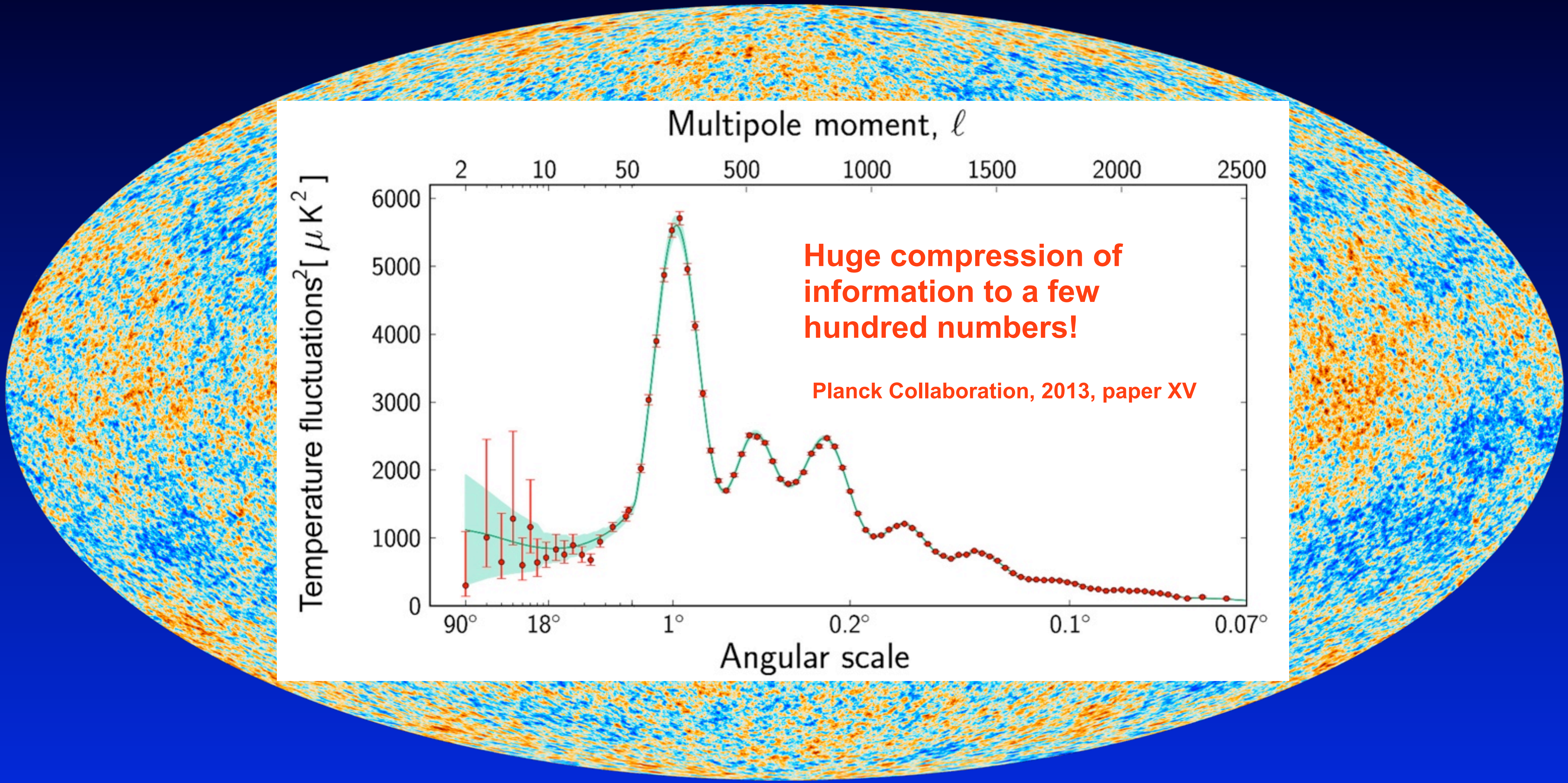

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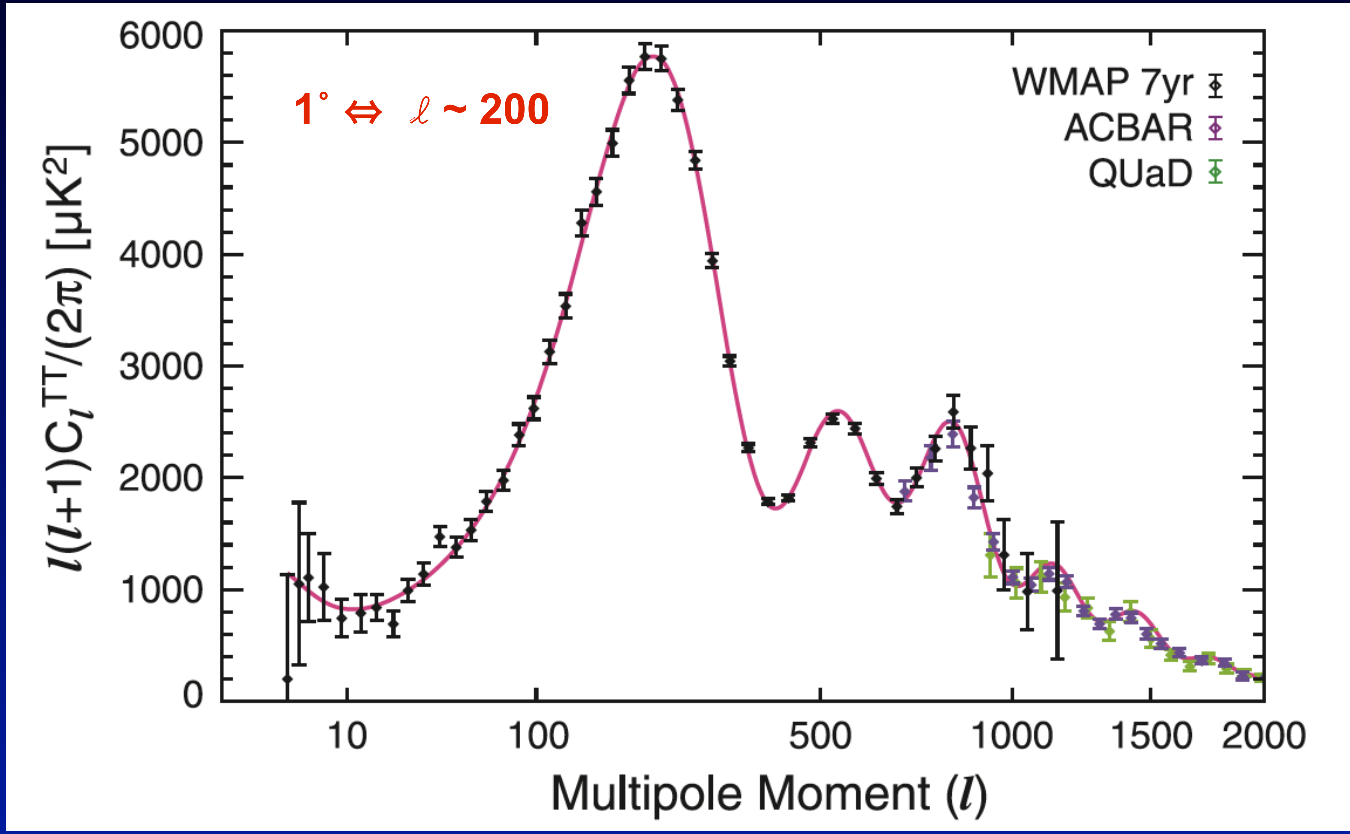
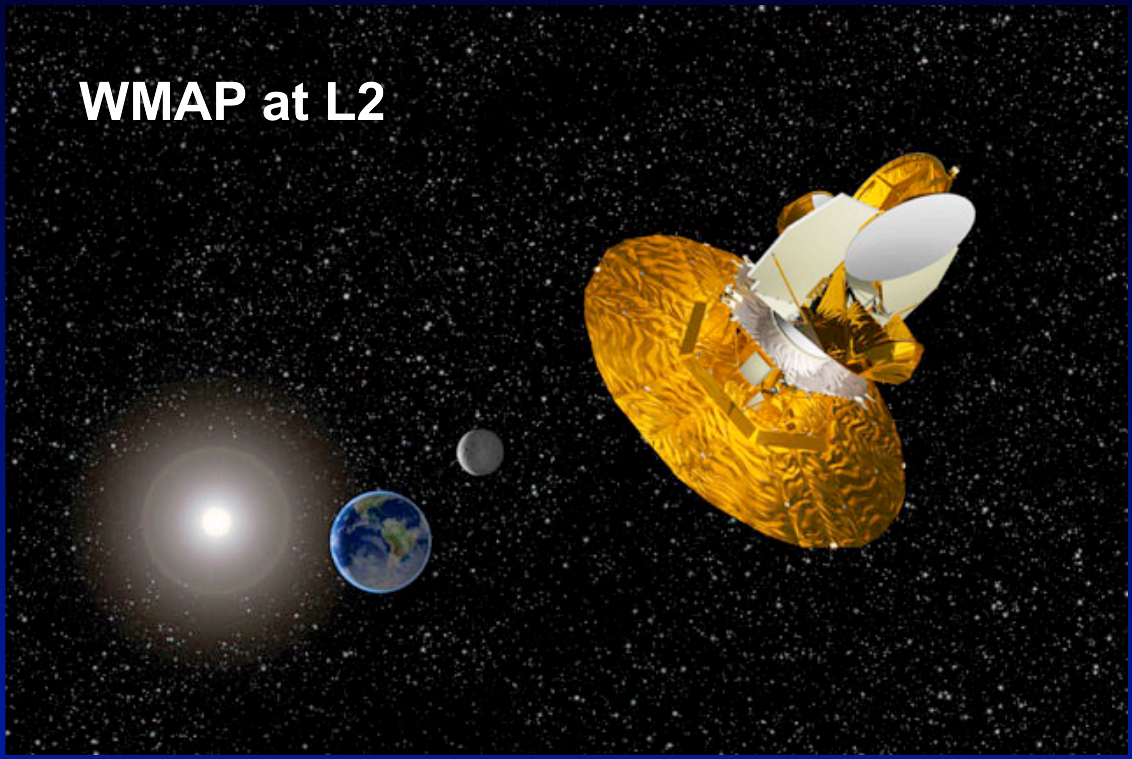
CMB anisotropies clearly taught us a lot about the Universe we live in!





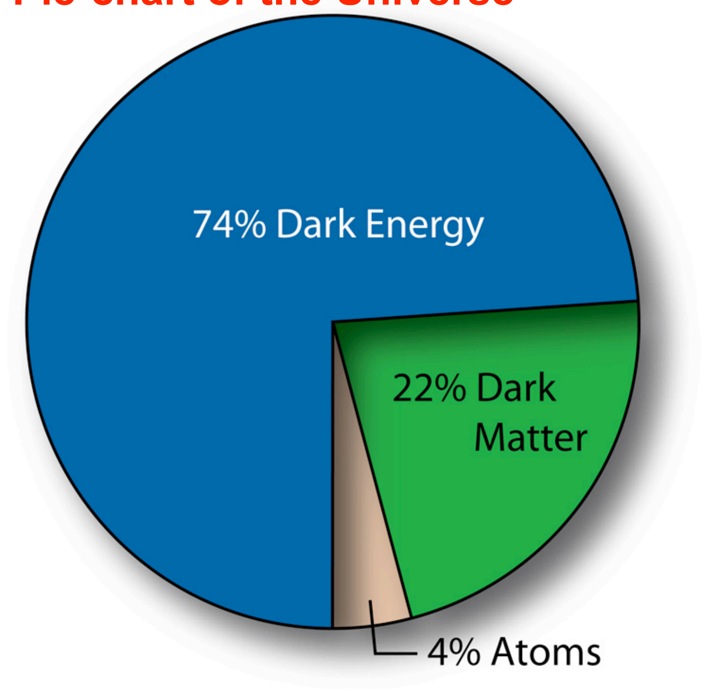
Precision cosmology **Tiny error bars!**

TABLE 1
SUMMARY OF THE COSMOLOGICAL PARAMETERS OF ΛCDM MODEL

Class	Parameter	*WMAP* 7-year ML[a]	*WMAP*+BAO+H_0 ML	*WMAP* 7-year Mean[b]	*WMAP*+BAO+H_0 Mean
Primary	$100\Omega_b h^2$	2.270	2.246	$2.258^{+0.057}_{-0.056}$	2.260 ± 0.053
	$\Omega_c h^2$	0.1107	0.1120	0.1109 ± 0.0056	0.1123 ± 0.0035
	Ω_Λ	0.738	0.728	0.734 ± 0.029	$0.728^{+0.015}_{-0.016}$
	n_s	0.969	0.961	0.963 ± 0.014	0.963 ± 0.012
	τ	0.086	0.087	0.088 ± 0.015	0.087 ± 0.014
	$\Delta^2_{\mathcal{R}}(k_0)$[c]	2.38×10^{-9}	2.45×10^{-9}	$(2.43 \pm 0.11) \times 10^{-9}$	$(2.441^{+0.088}_{-0.092}) \times 10^{-9}$
Derived	σ_8	0.803	0.807	0.801 ± 0.030	0.809 ± 0.024
	H_0	71.4 km/s/Mpc	70.2 km/s/Mpc	71.0 ± 2.5 km/s/Mpc	$70.4^{+1.3}_{-1.4}$ km/s/Mpc
	Ω_b	0.0445	0.0455	0.0449 ± 0.0028	0.0456 ± 0.0016
	Ω_c	0.217	0.227	0.222 ± 0.026	0.227 ± 0.014
	$\Omega_m h^2$	0.1334	0.1344	$0.1334^{+0.0056}_{-0.0055}$	0.1349 ± 0.0036
	$z_{\rm reion}$[d]	10.3	10.5	10.5 ± 1.2	10.4 ± 1.2
	t_0[e]	13.71 Gyr	13.78 Gyr	13.75 ± 0.13 Gyr	13.75 ± 0.11 Gyr

[a] Larson et al. (2010). "ML" refers to the Maximum Likelihood parameters.
[b] Larson et al. (2010). "Mean" refers to the mean of the posterior distribution of each parameter. The quoted errors show the 68% confidence levels (CL).
[c] $\Delta^2_{\mathcal{R}}(k) = k^3 P_{\mathcal{R}}(k)/(2\pi^2)$ and $k_0 = 0.002$ Mpc^{-1}.
[d] "Redshift of reionization," if the universe was reionized instantaneously from the neutral state to the fully ionized state at $z_{\rm reion}$. Note that these values are somewhat different from those in Table 1 of Komatsu et al. (2009b), largely because of the changes in the treatment of reionization history in the Boltzmann code CAMB (Lewis 2008).
[e] The present-day age of the universe.

Pie-chart of the Universe



e.g. Komatsu et al., 2011, ApJ, arXiv:1001.4538
Dunkley et al., 2011, ApJ, arXiv:1009.0866

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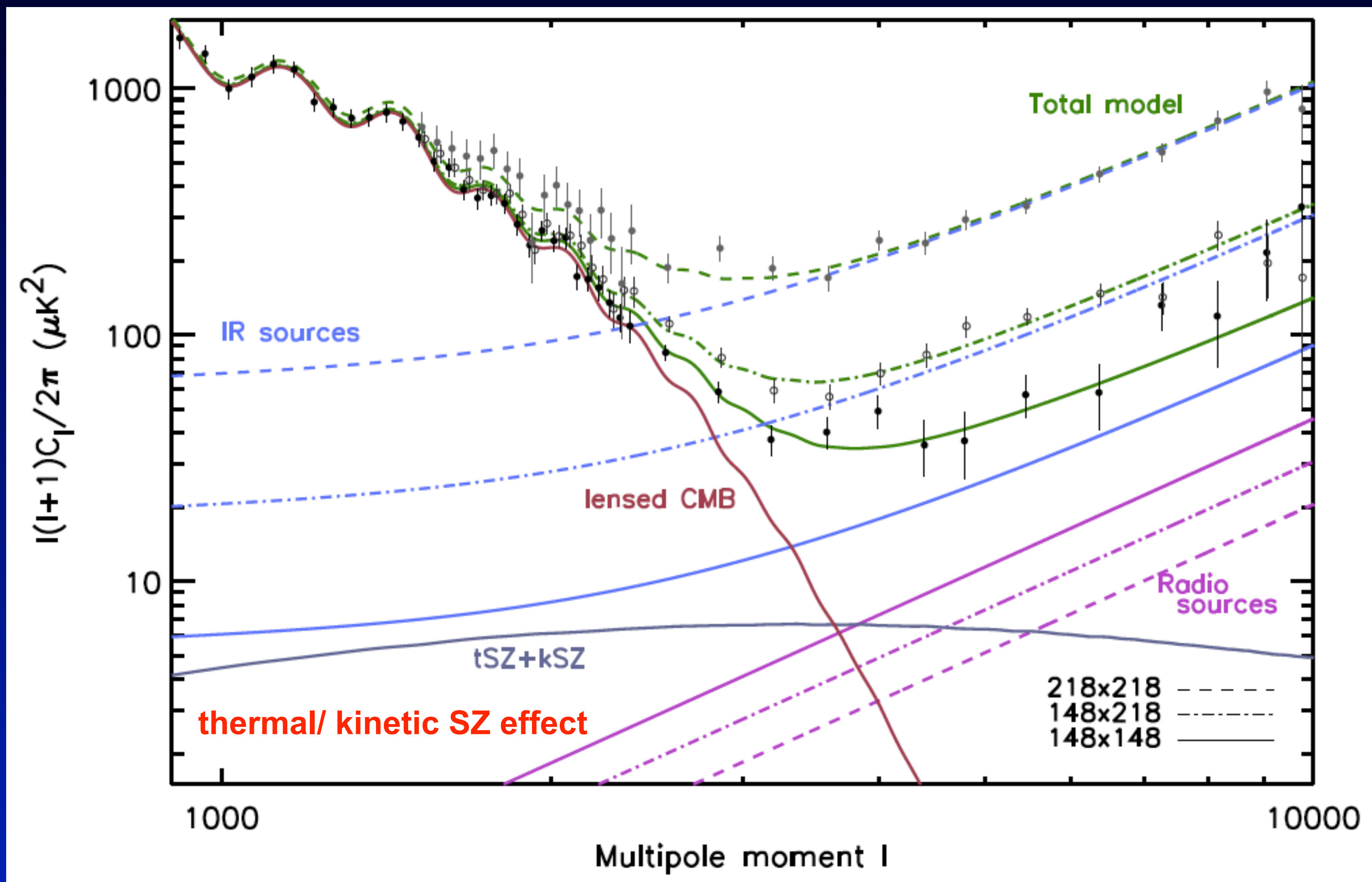

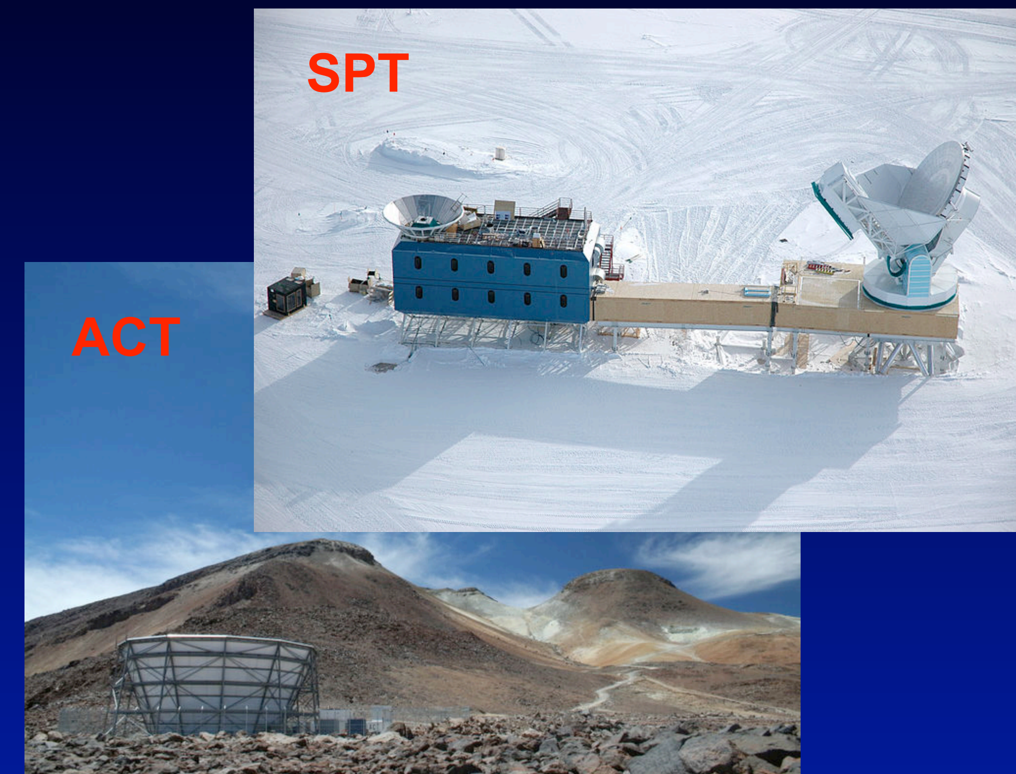

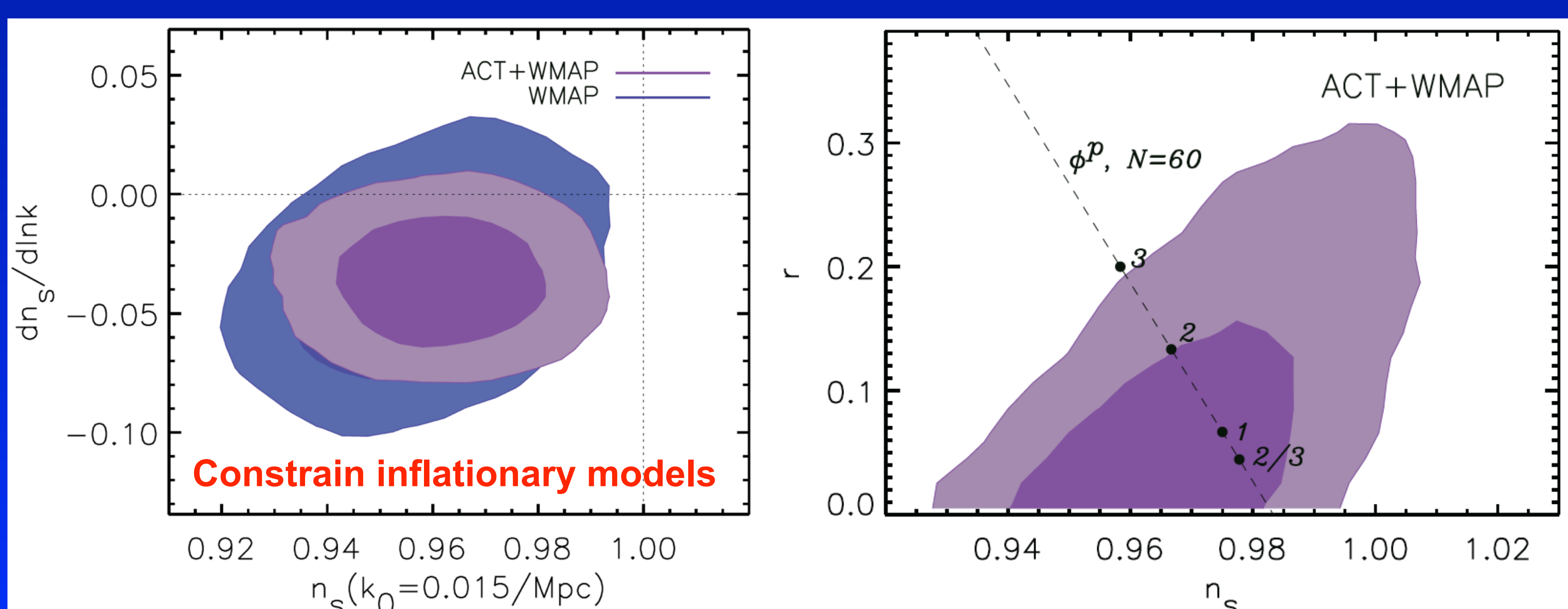

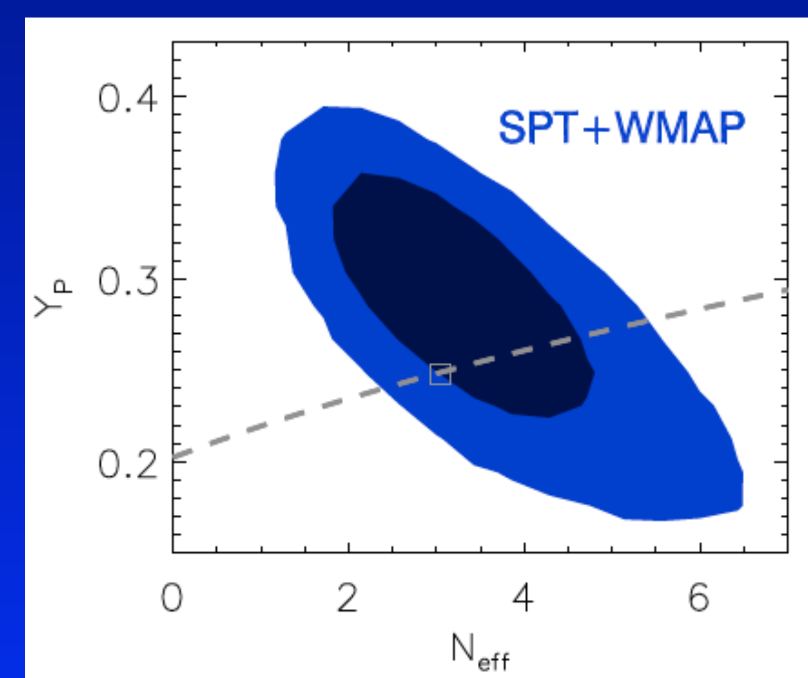

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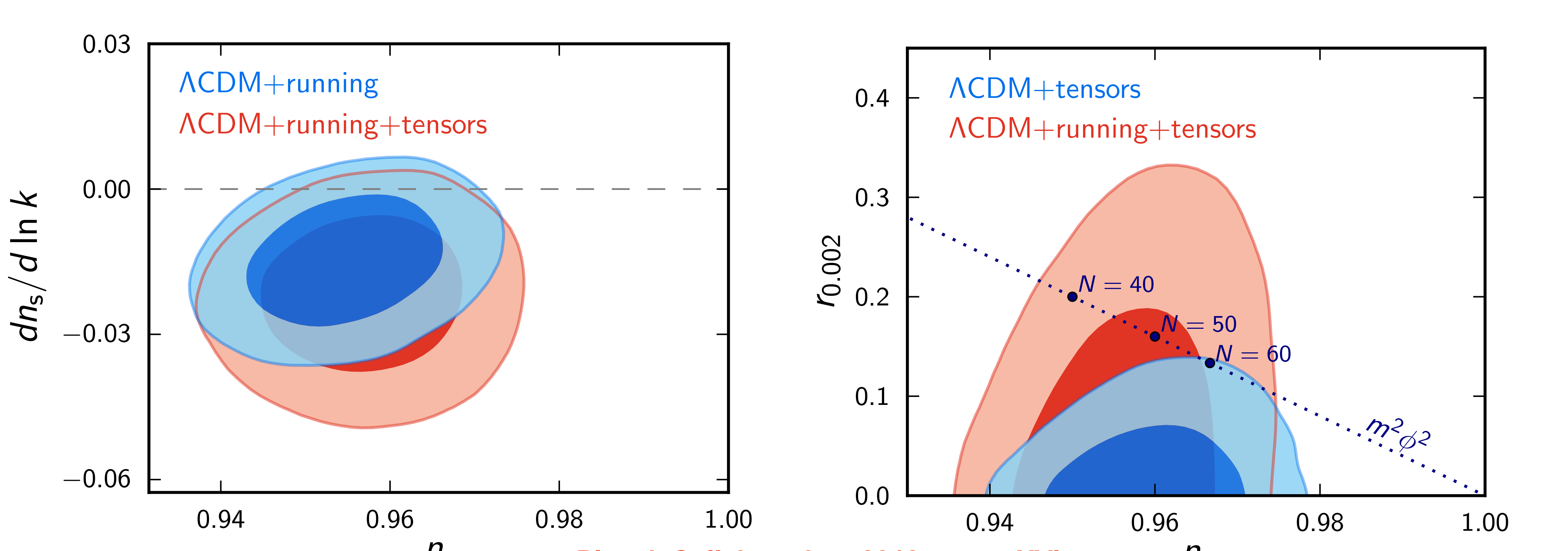
CMB anisotropies as probe of Inflation

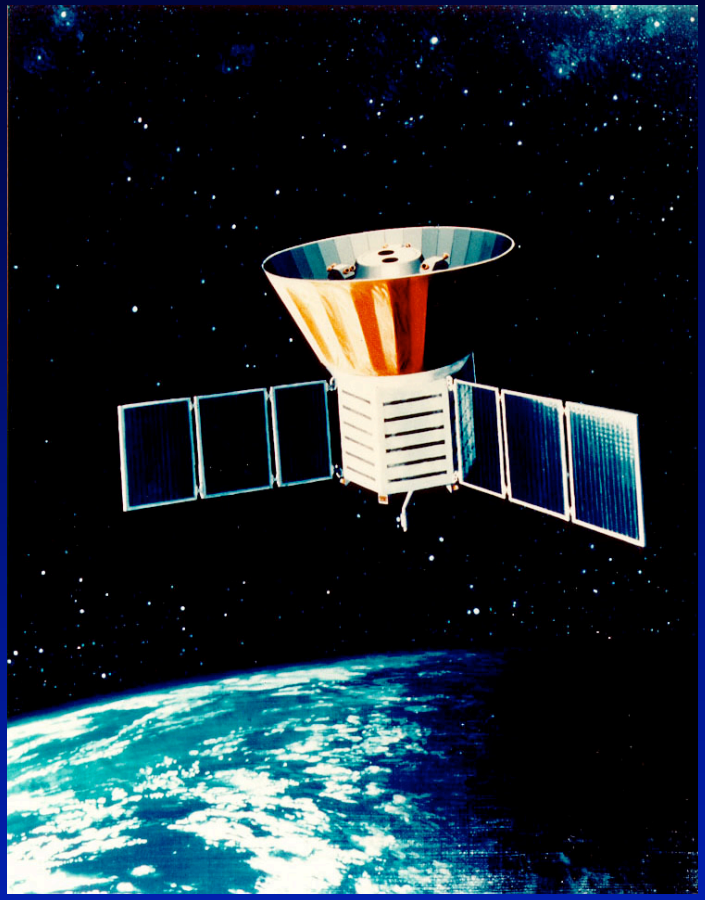


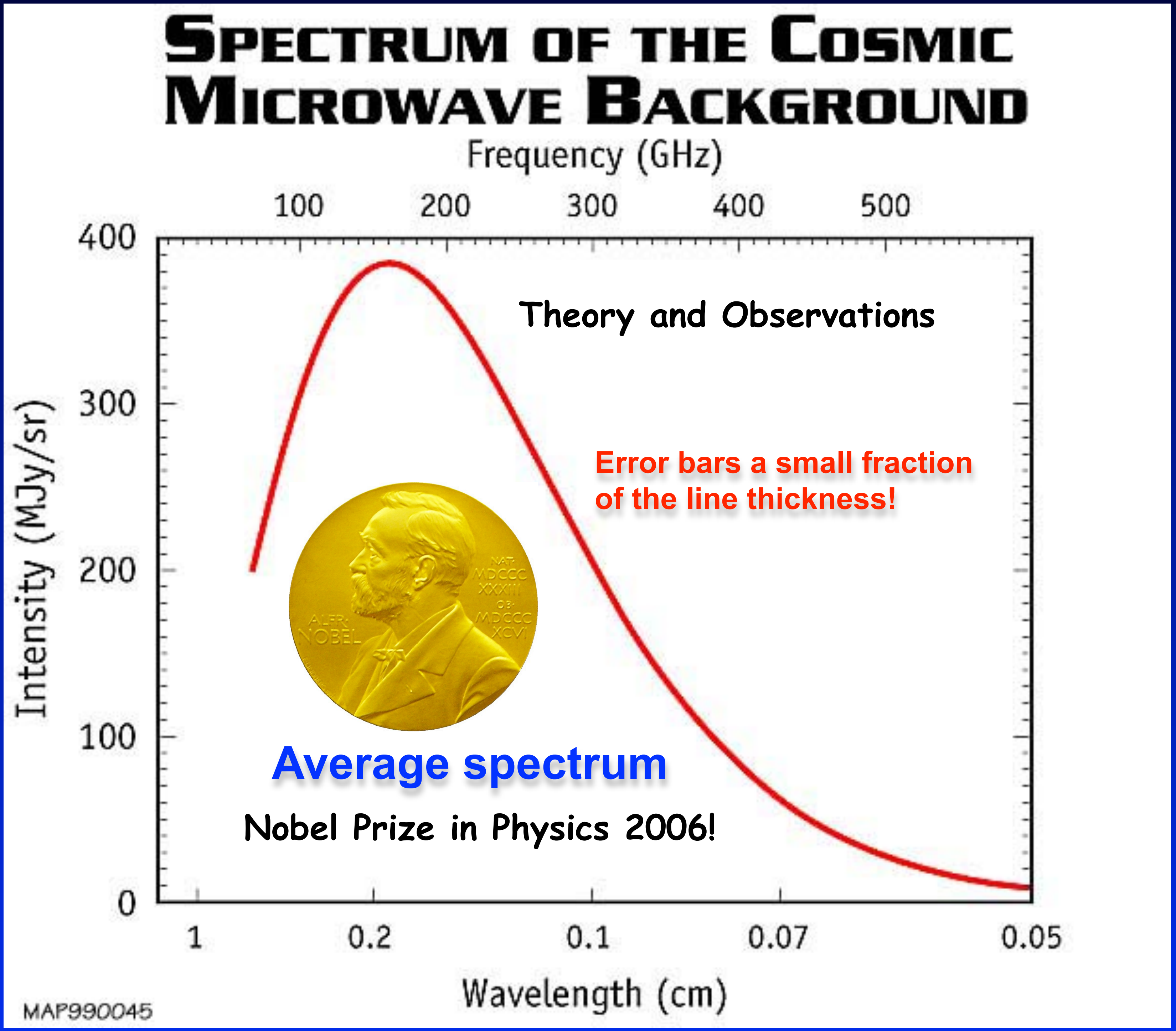
Planck Collaboration, 2013, paper XVI

- *Big goal/hope:* detection of B-polarization
- Plenty of progress over the next few years:

  ground/balloon: SPTpol, ACTpol, Spider, ...
  space: Planck, LiteBIRD, PIXIE, COrE, ...?

COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)





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

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

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

Only very small distortions of CMB spectrum are still allowed!

Mather et al., 1994, ApJ, 420, 439
Fixsen et al., 1996, ApJ, 473, 576
Fixsen et al., 2003, ApJ, 594, 67

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
    - $T_\gamma \sim 2.725\,(1+z)$ K
    - $N_\gamma \sim 411\ \mathrm{cm}^{-3}\,(1+z)^3 \sim 2\times10^9\,N_\mathrm{b}$
    - $\rho_\gamma \sim 5.1\times10^{-7}\,m_\mathrm{e}c^2\ \mathrm{cm}^{-3}\,(1+z)^4 \sim \rho_\mathrm{b}$ x $(1+z)$ / 925

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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)

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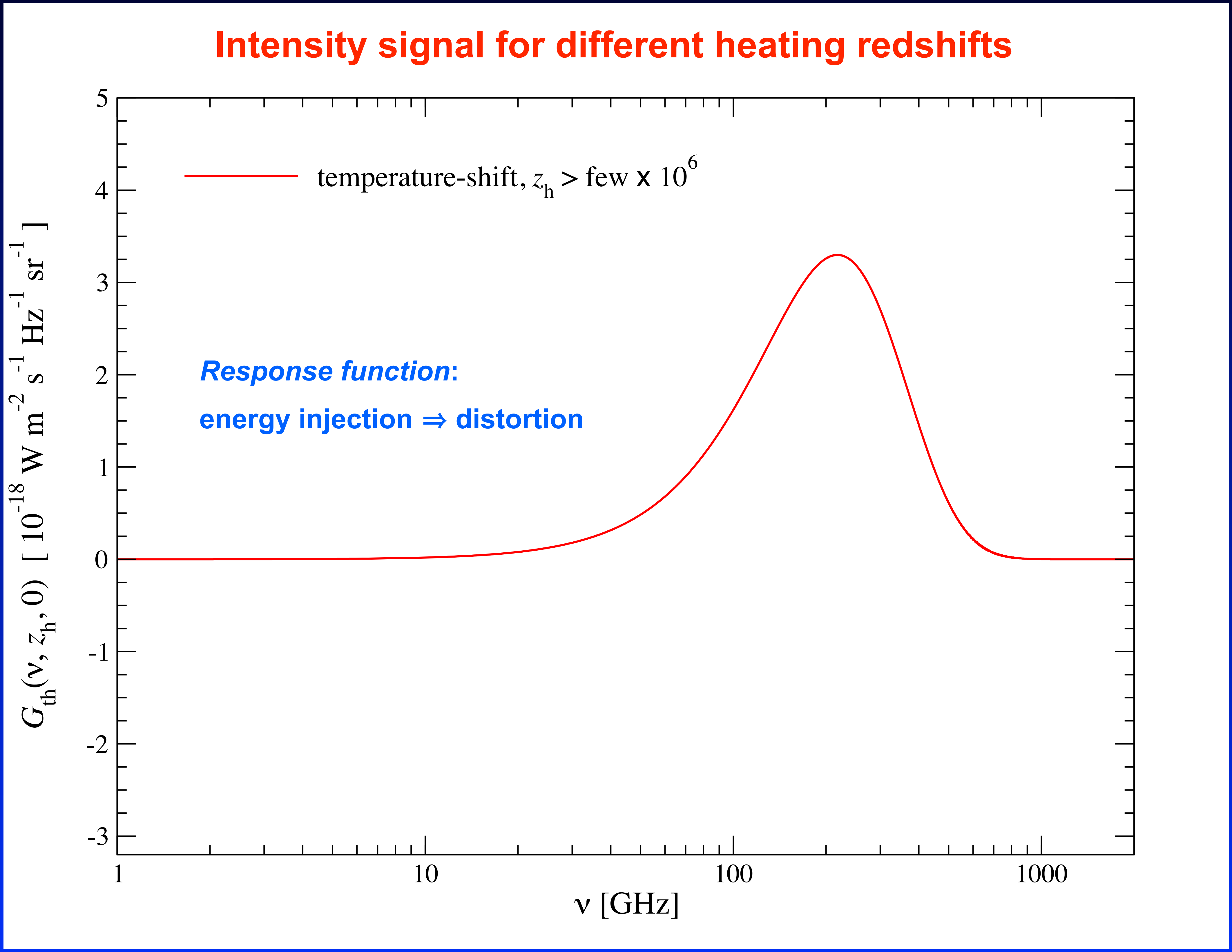
Measurements of CMB spectrum place tight constraints on the thermal history of our Universe!

What does the distortion look like?



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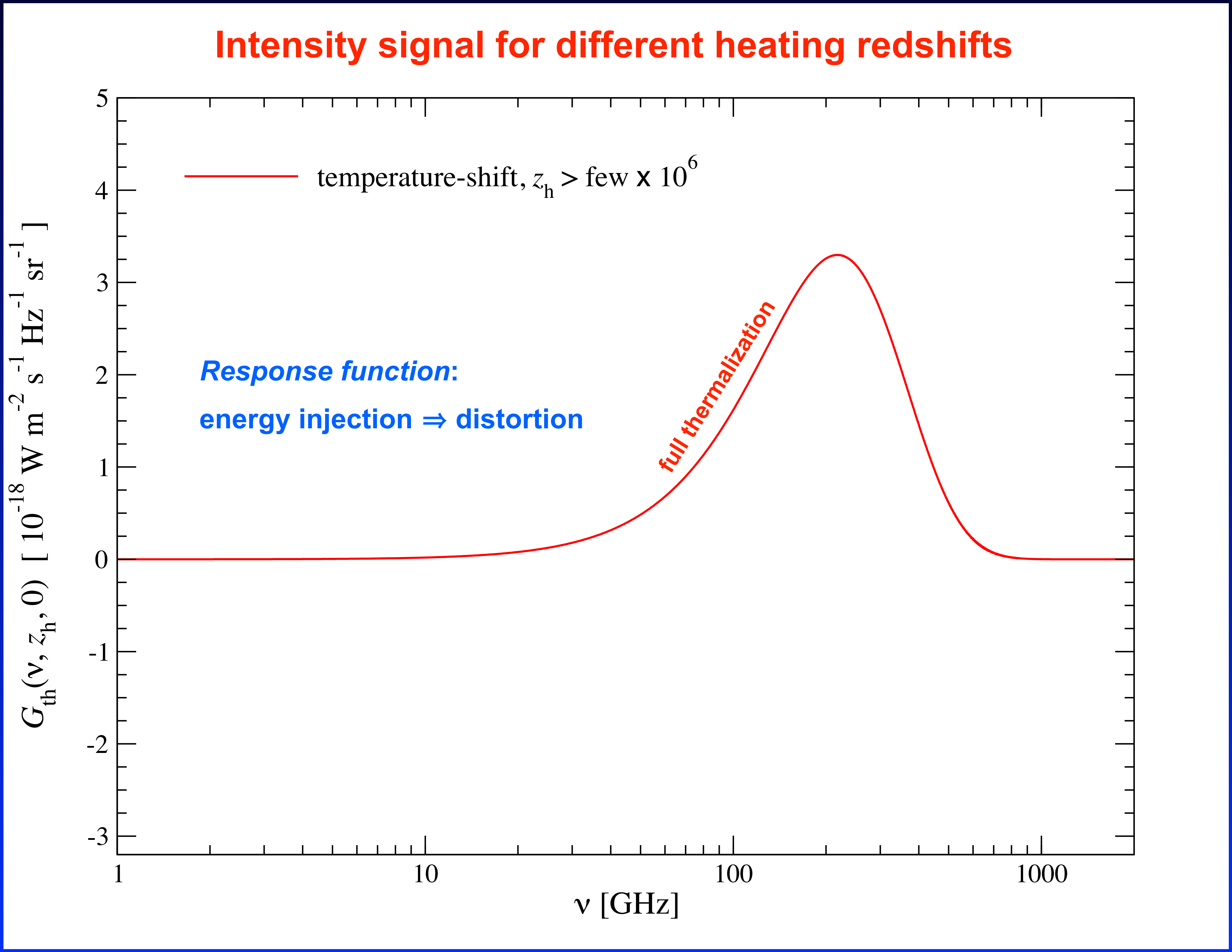

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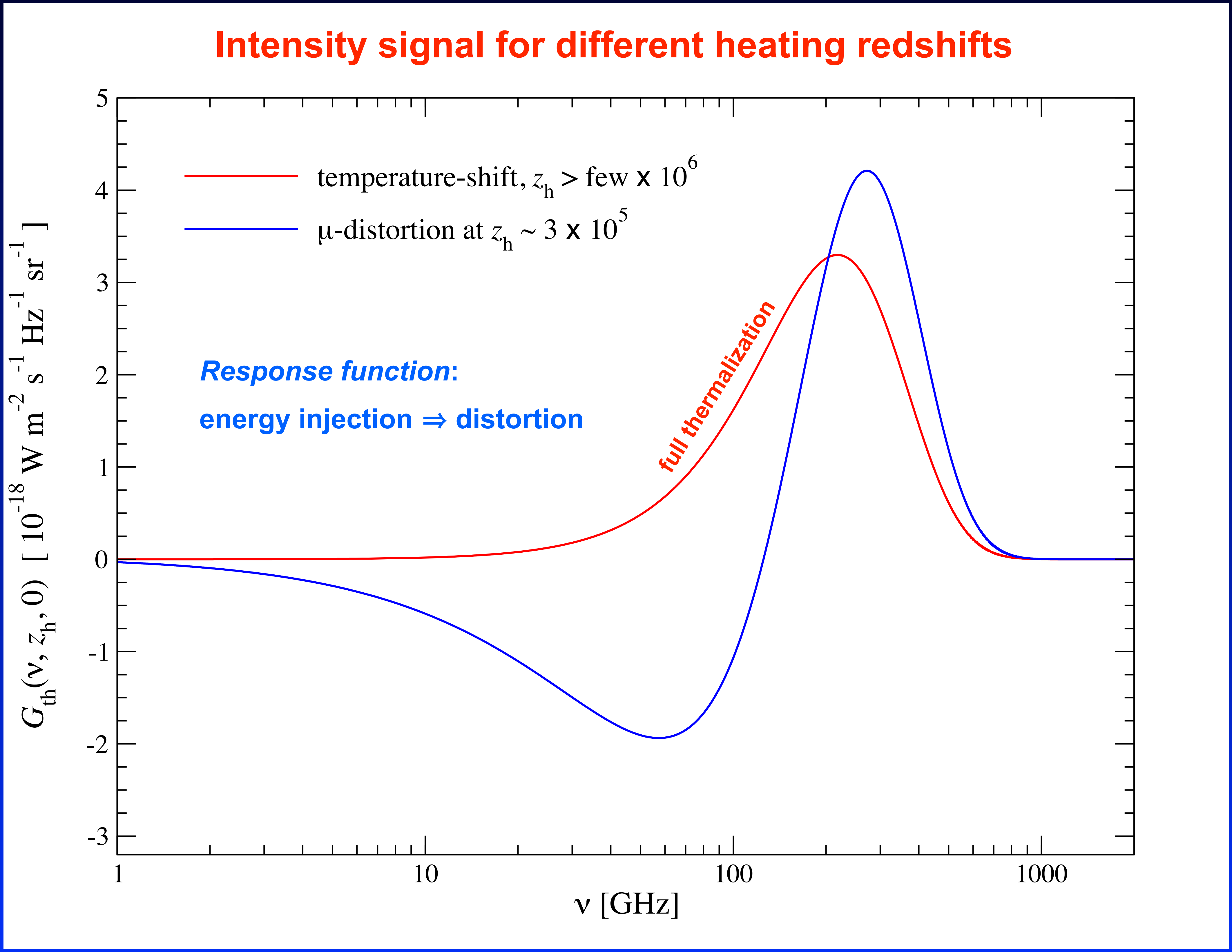

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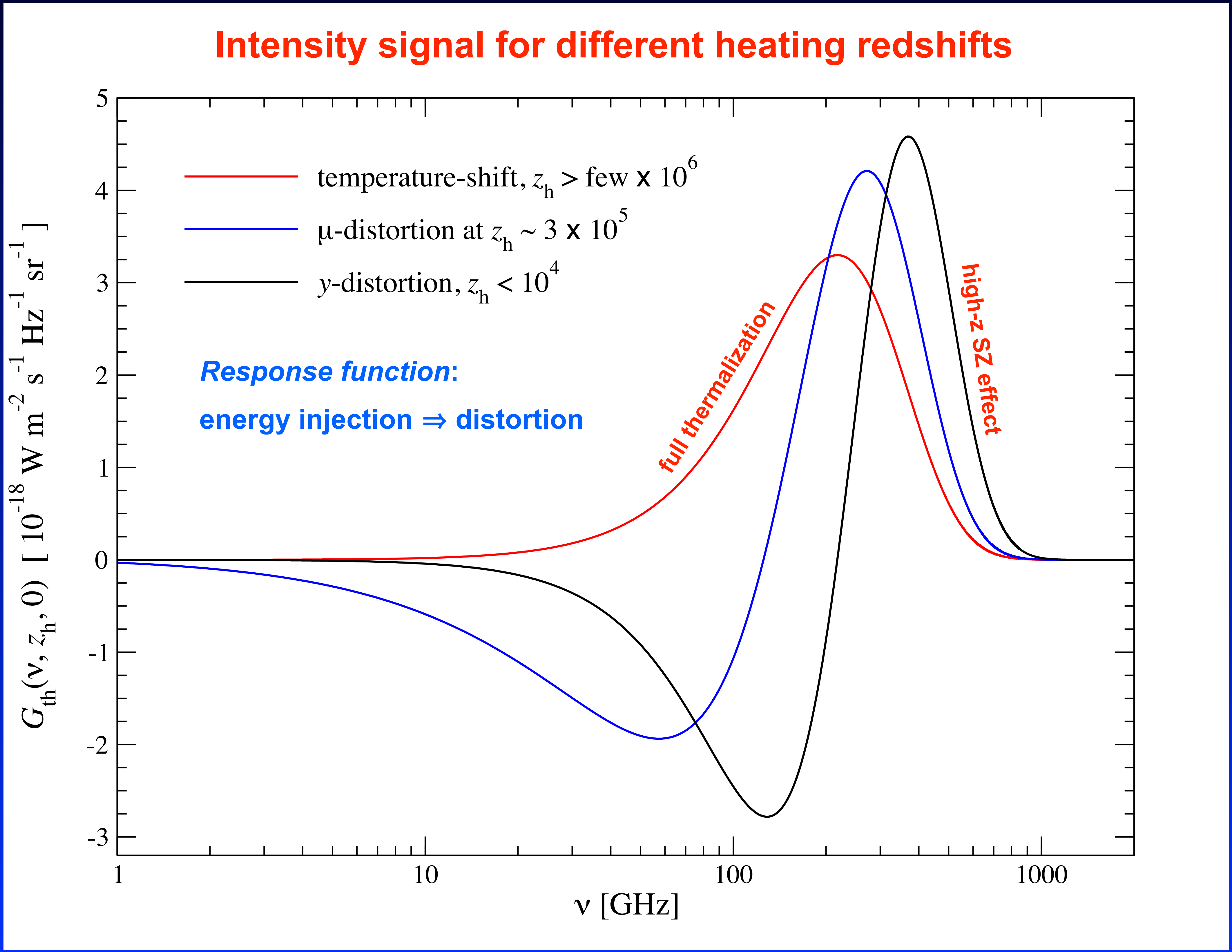

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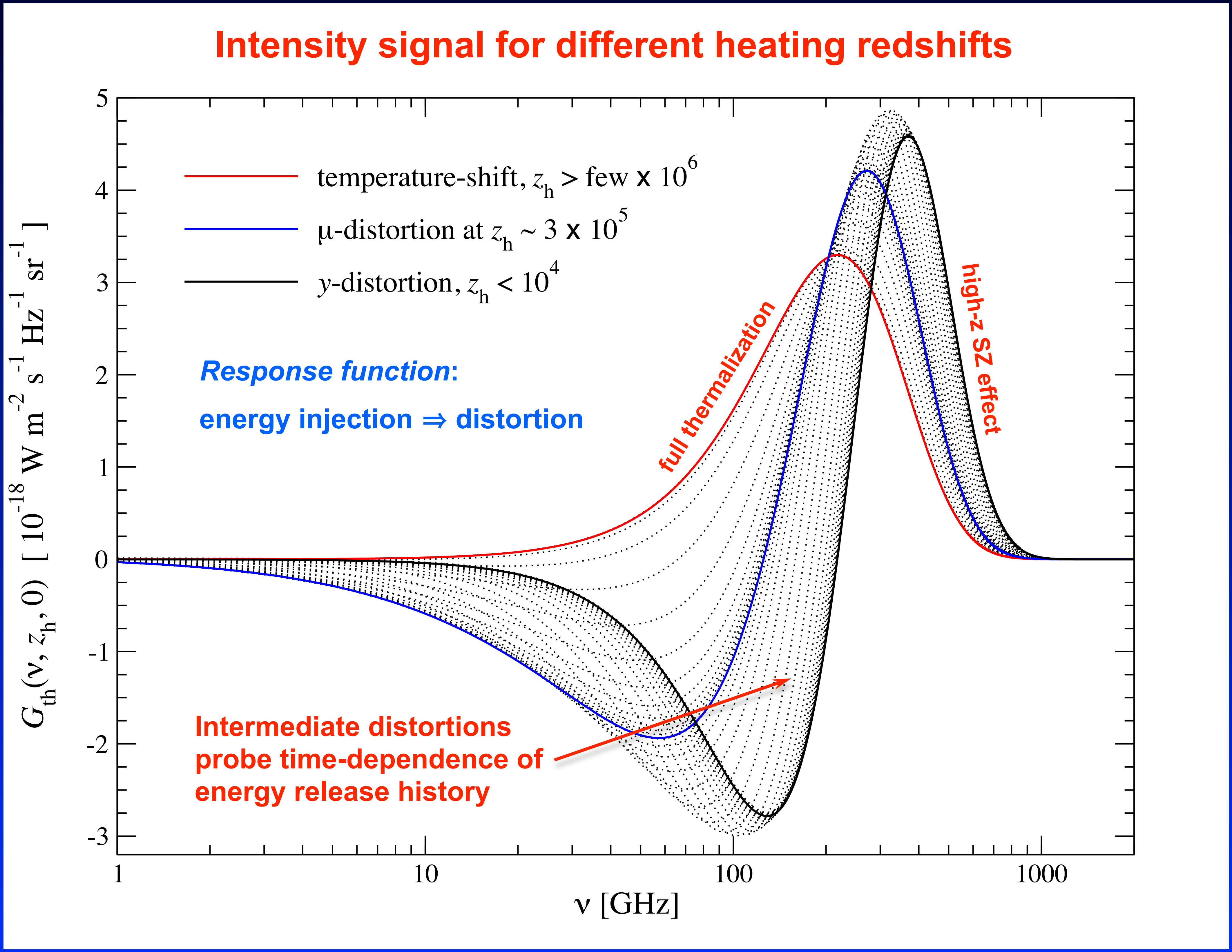
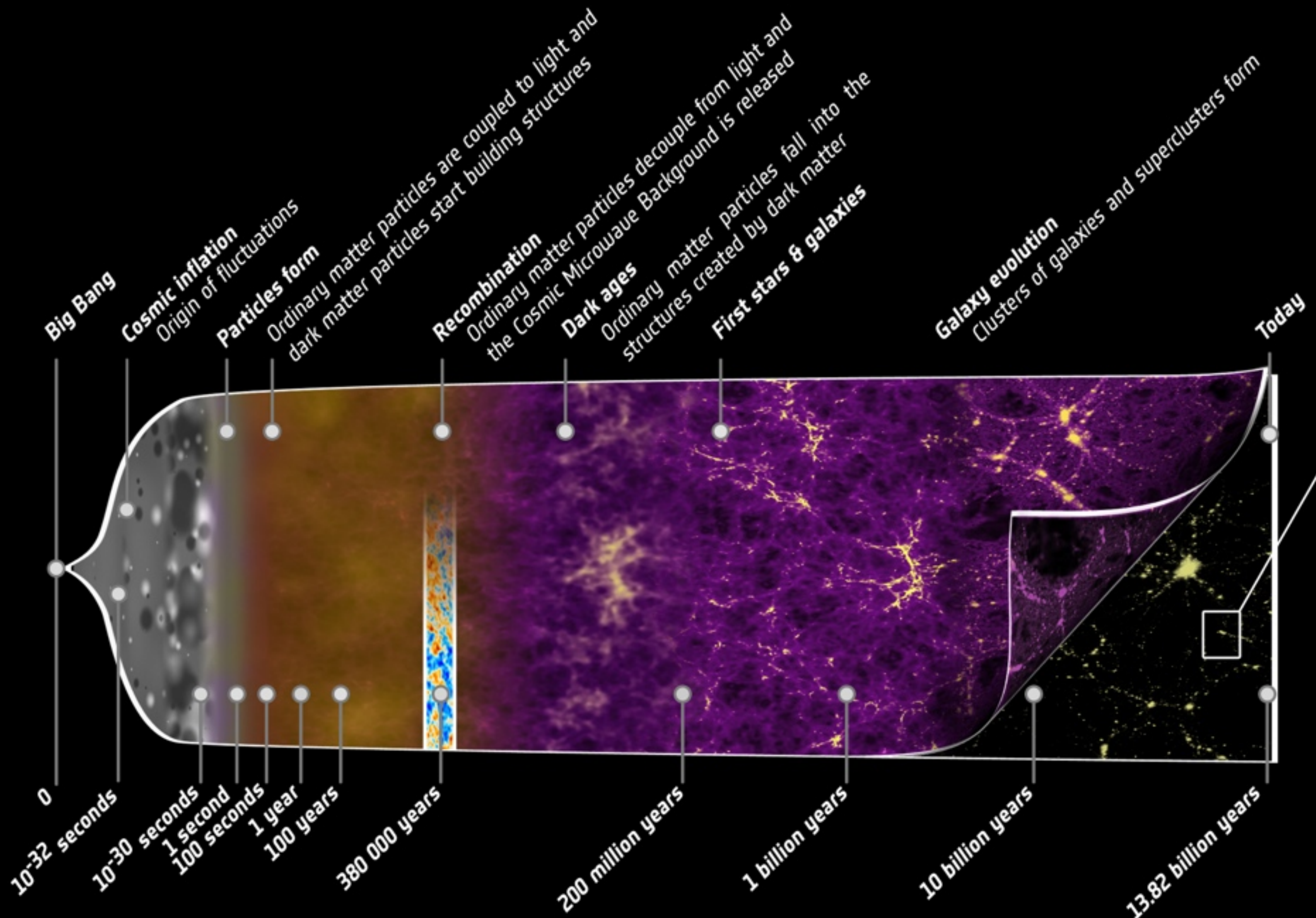
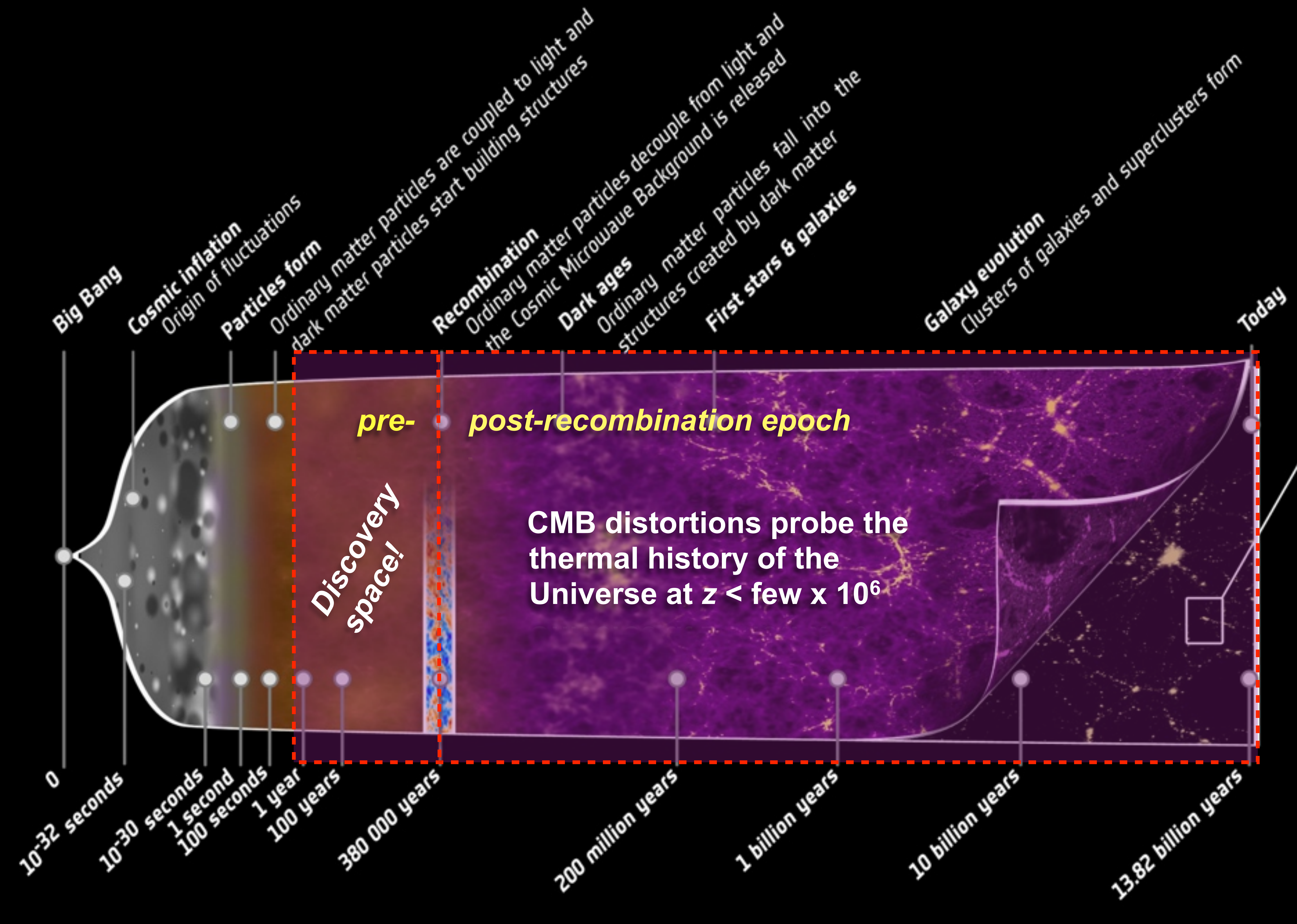



Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles 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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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

Physical mechanisms that lead to release of energy

- *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 ($\Delta\rho/\rho \sim 10^{-10}$-$10^{-9}$)
- 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 energy release
- *Dissipation of primordial acoustic modes & magnetic fields*
  (Sunyaev & Zeldovich, 1970; Daly 1991; Hu et al. 1994; Jedamzik et al. 2000)
- *Cosmological recombination*

„high“ redshifts

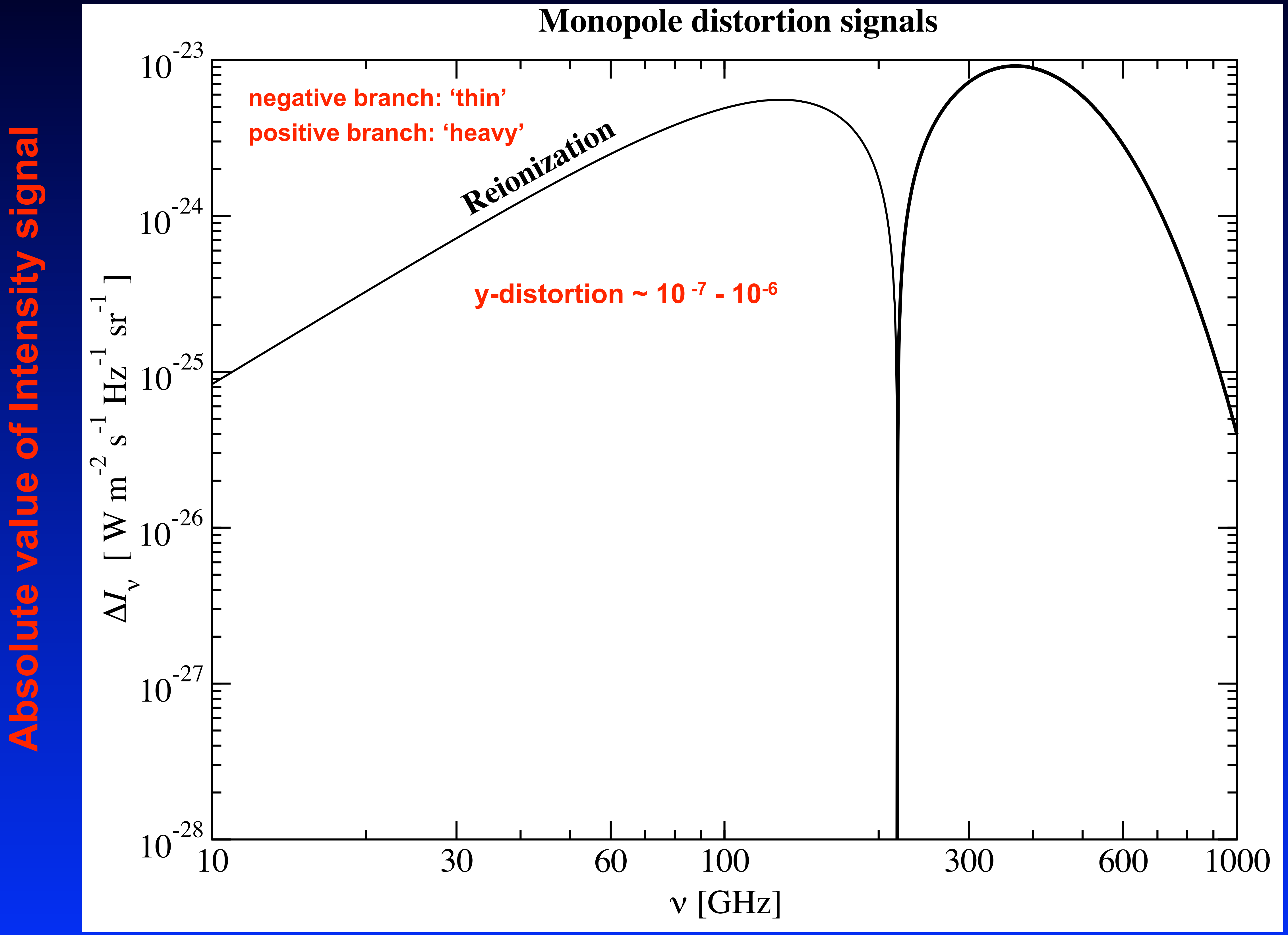
pre-recombination epoch

„low“ redshifts

post-recombination

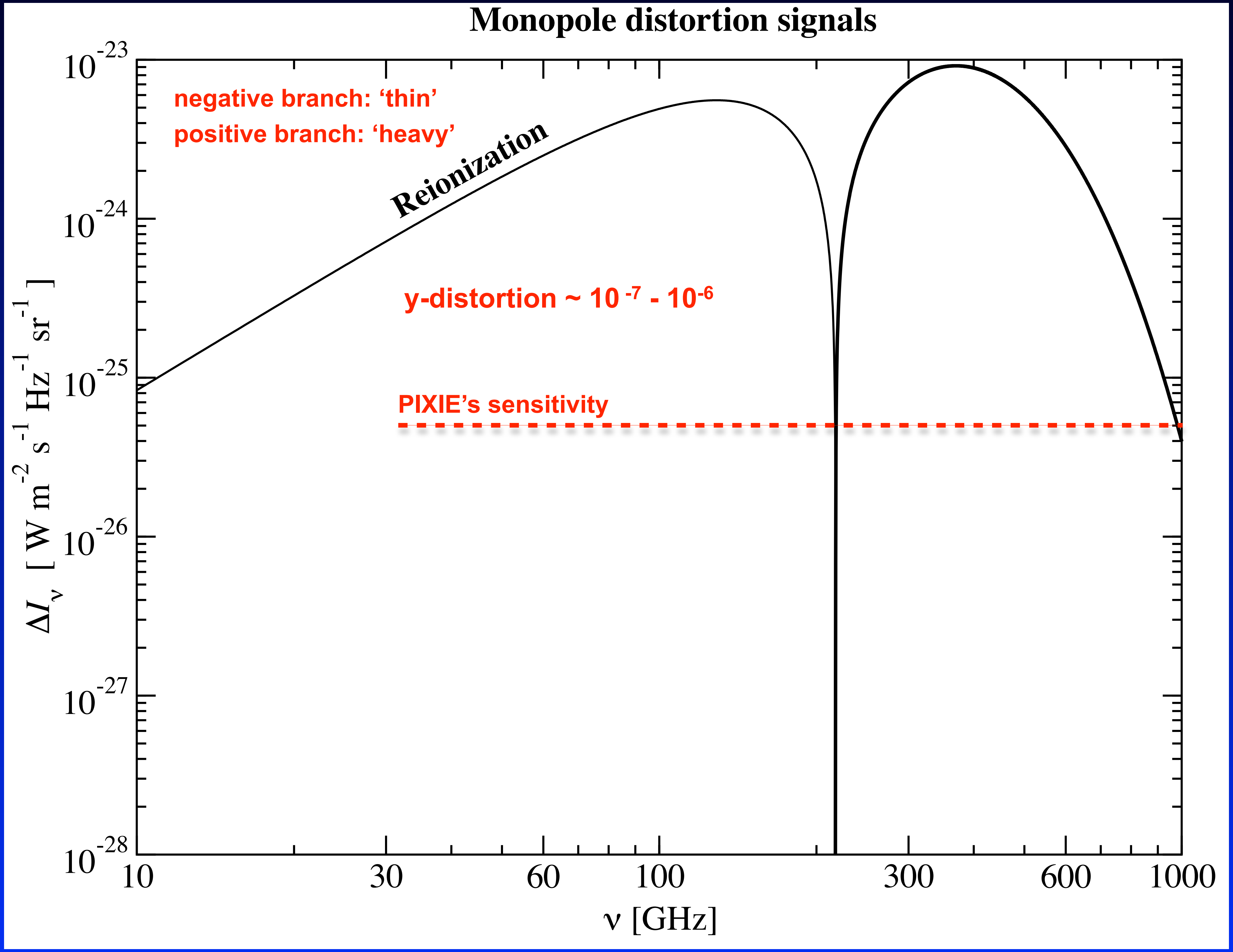
- Signatures due to first supernovae and their remnants
  (Oh, Cooray & Kamionkowski, 2003)
- Shock waves arising due to large-scale structure formation
  (Sunyaev & Zeldovich, 1972; Cen & Ostriker, 1999)
- SZ-effect from clusters; effects of reionization (Heating of medium by X-Rays, Cosmic Rays, etc)

Average CMB spectral distortions



Average CMB spectral distortions

Absolute value of Intensity signal



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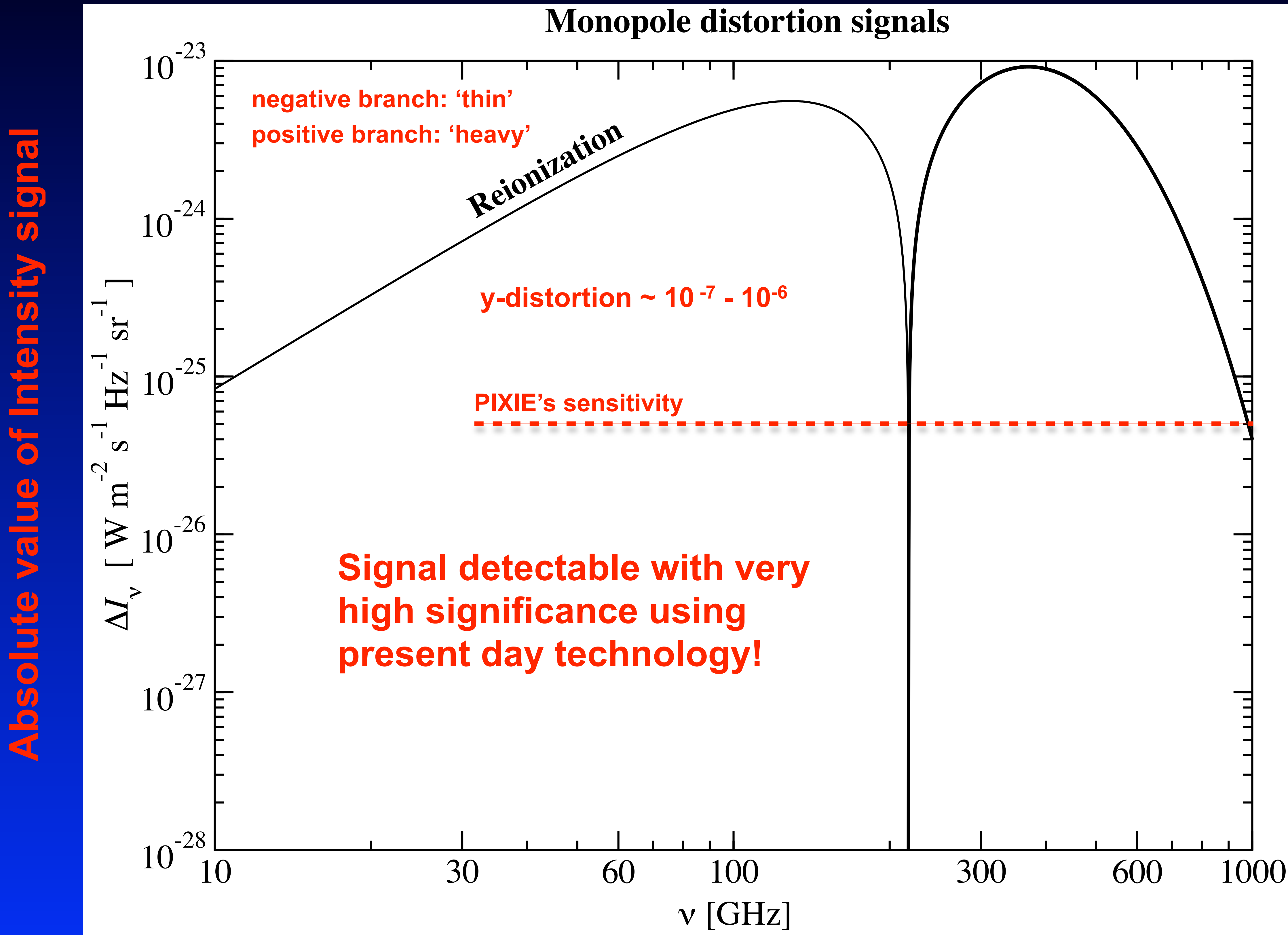

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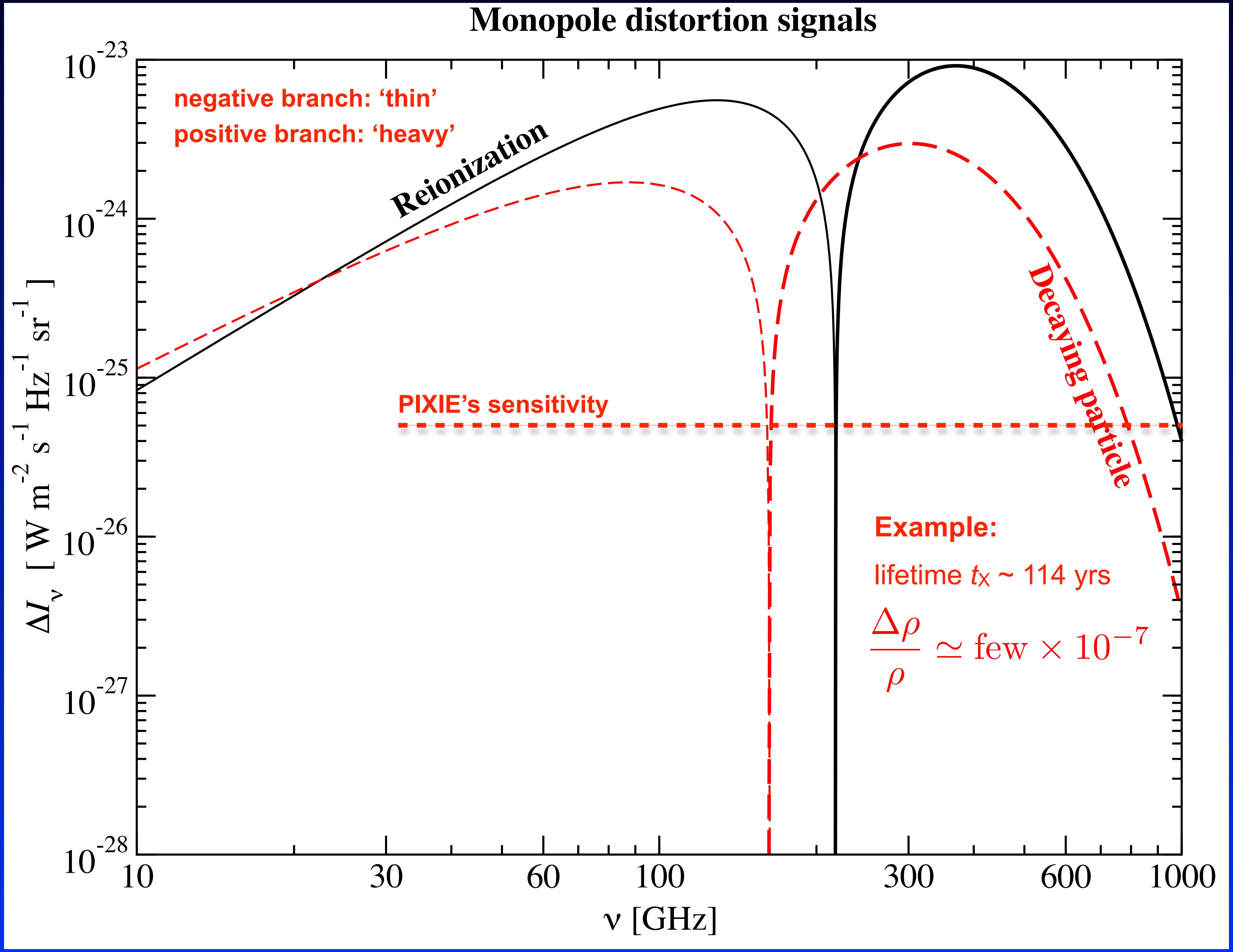

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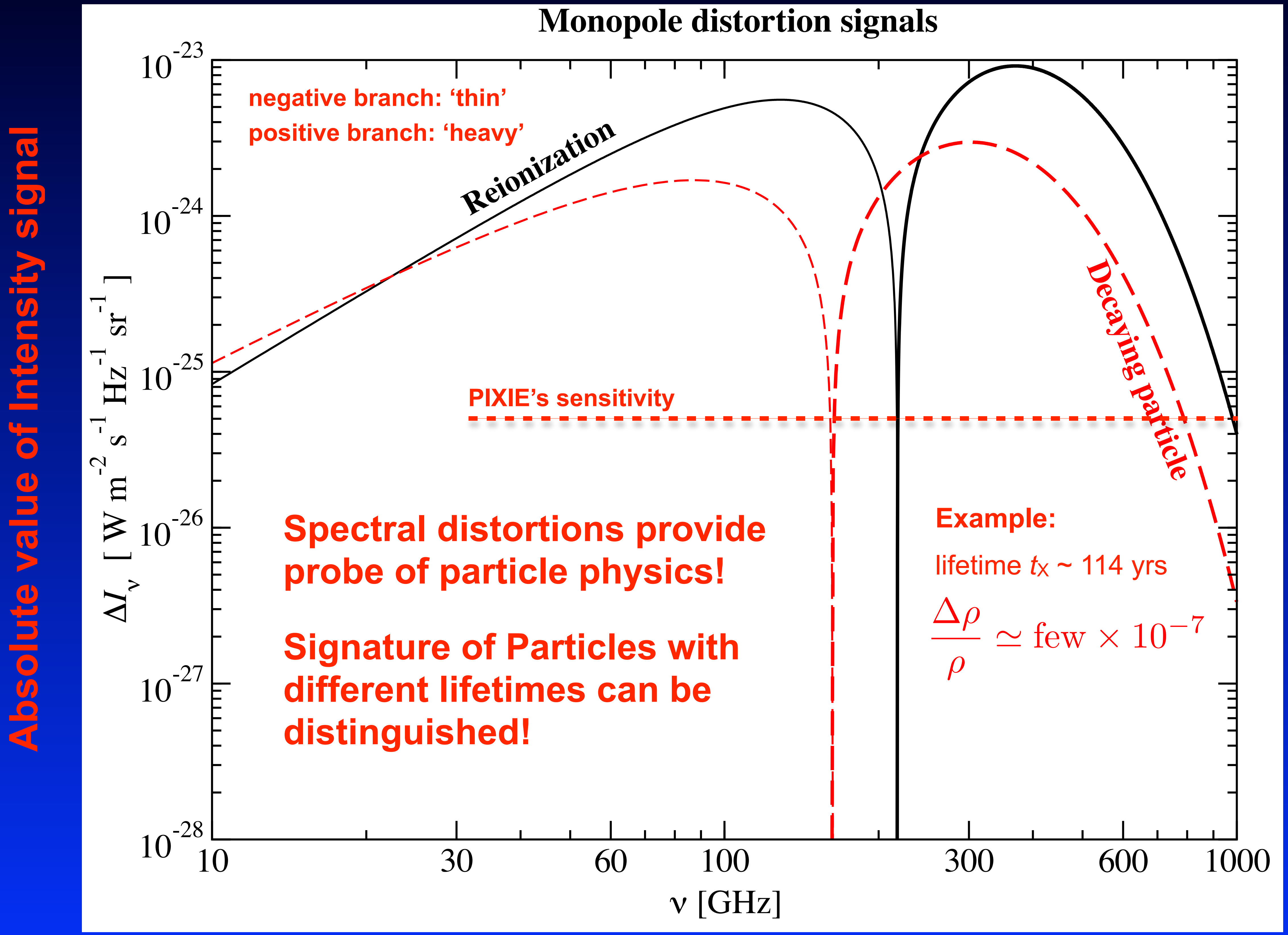
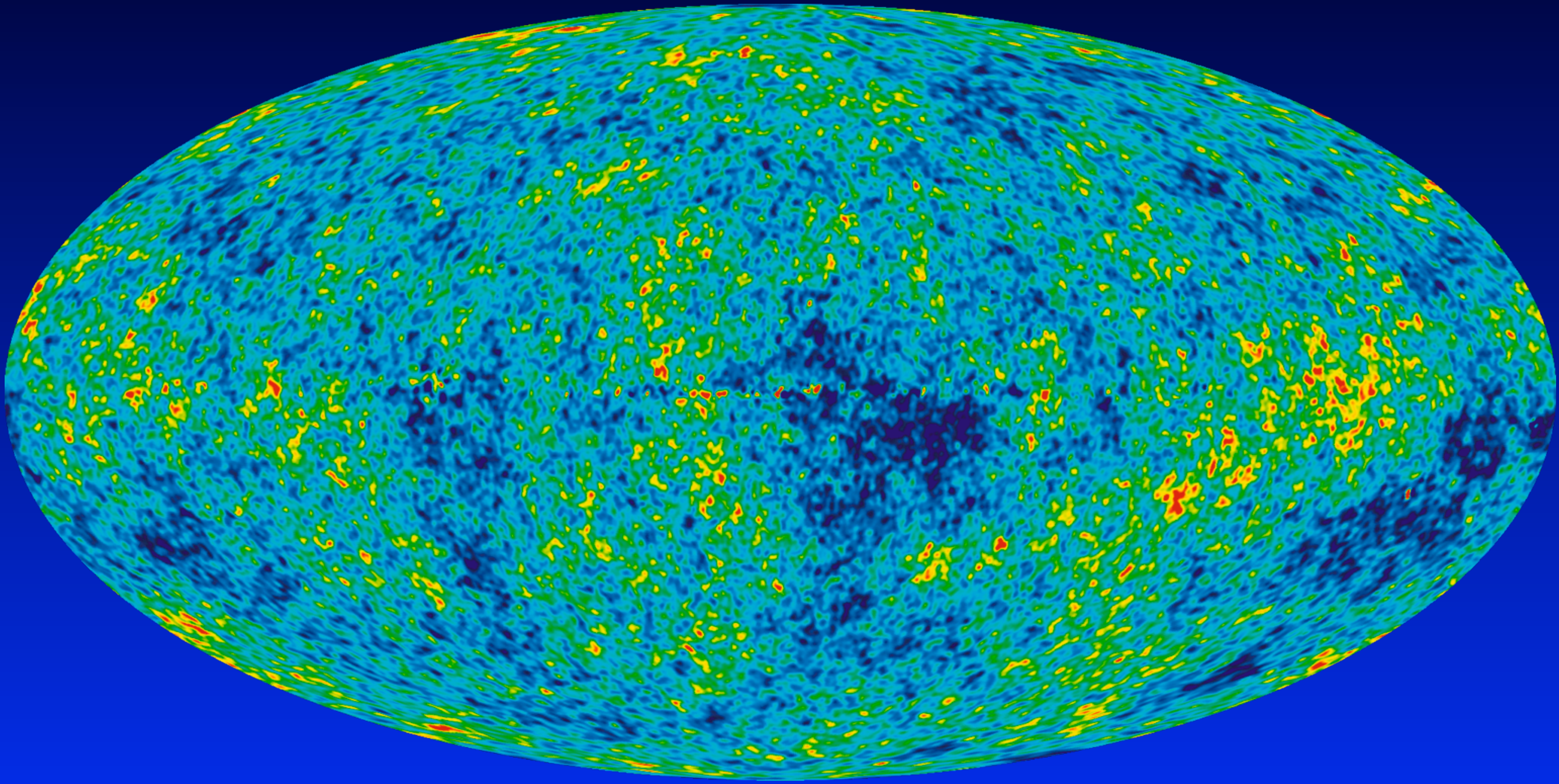


Dissipation of small-scale acoustic modes



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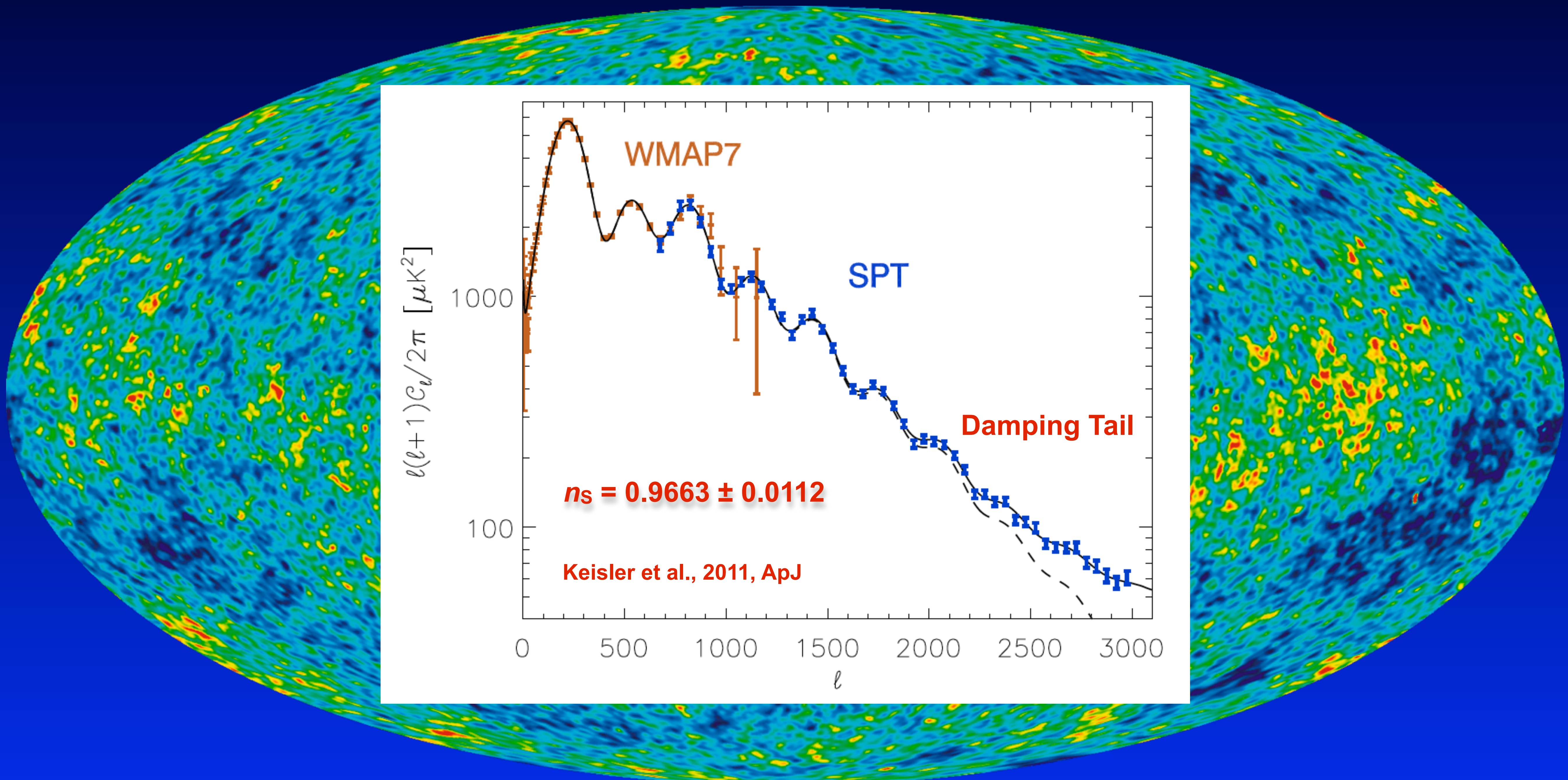

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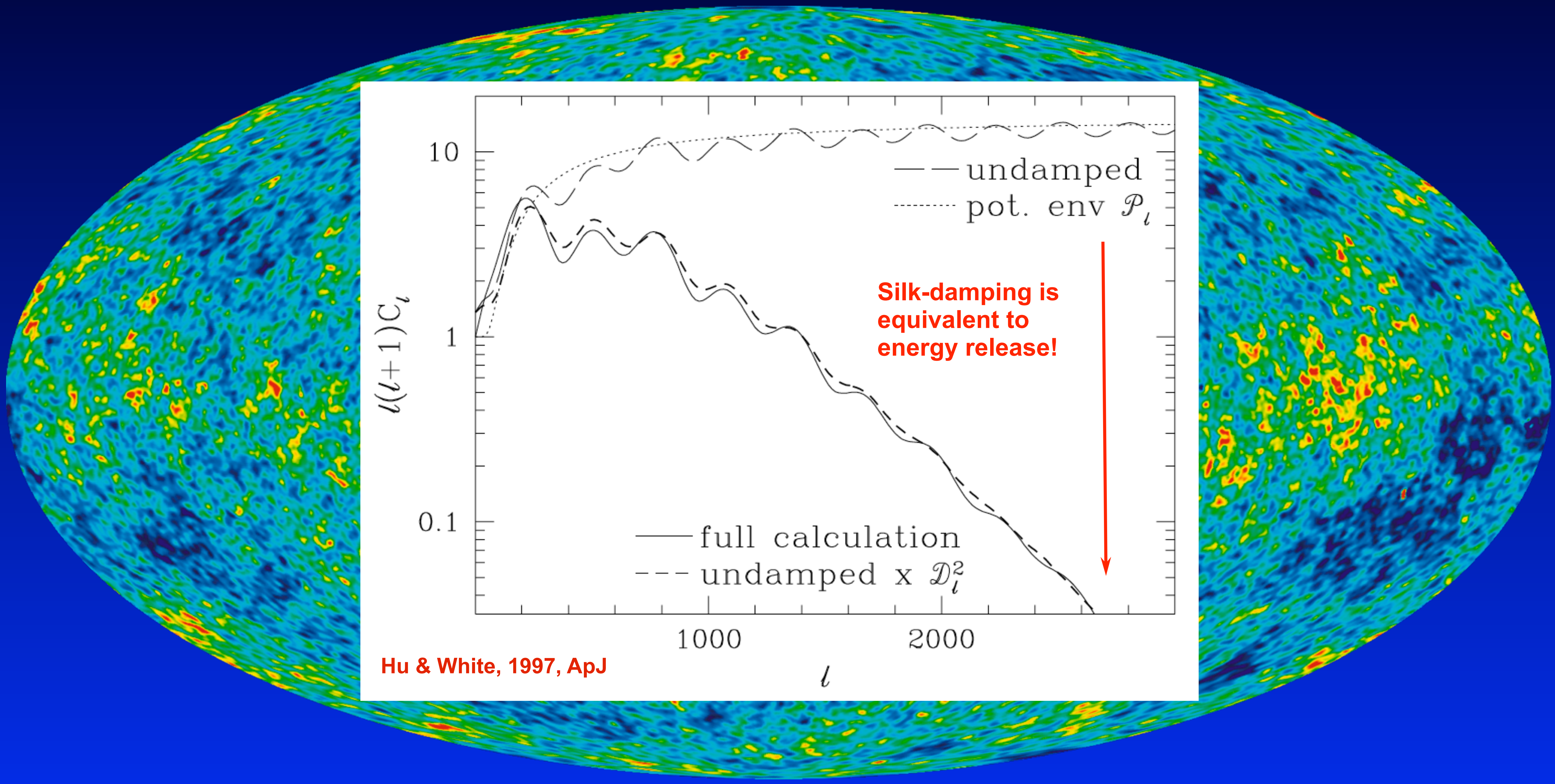

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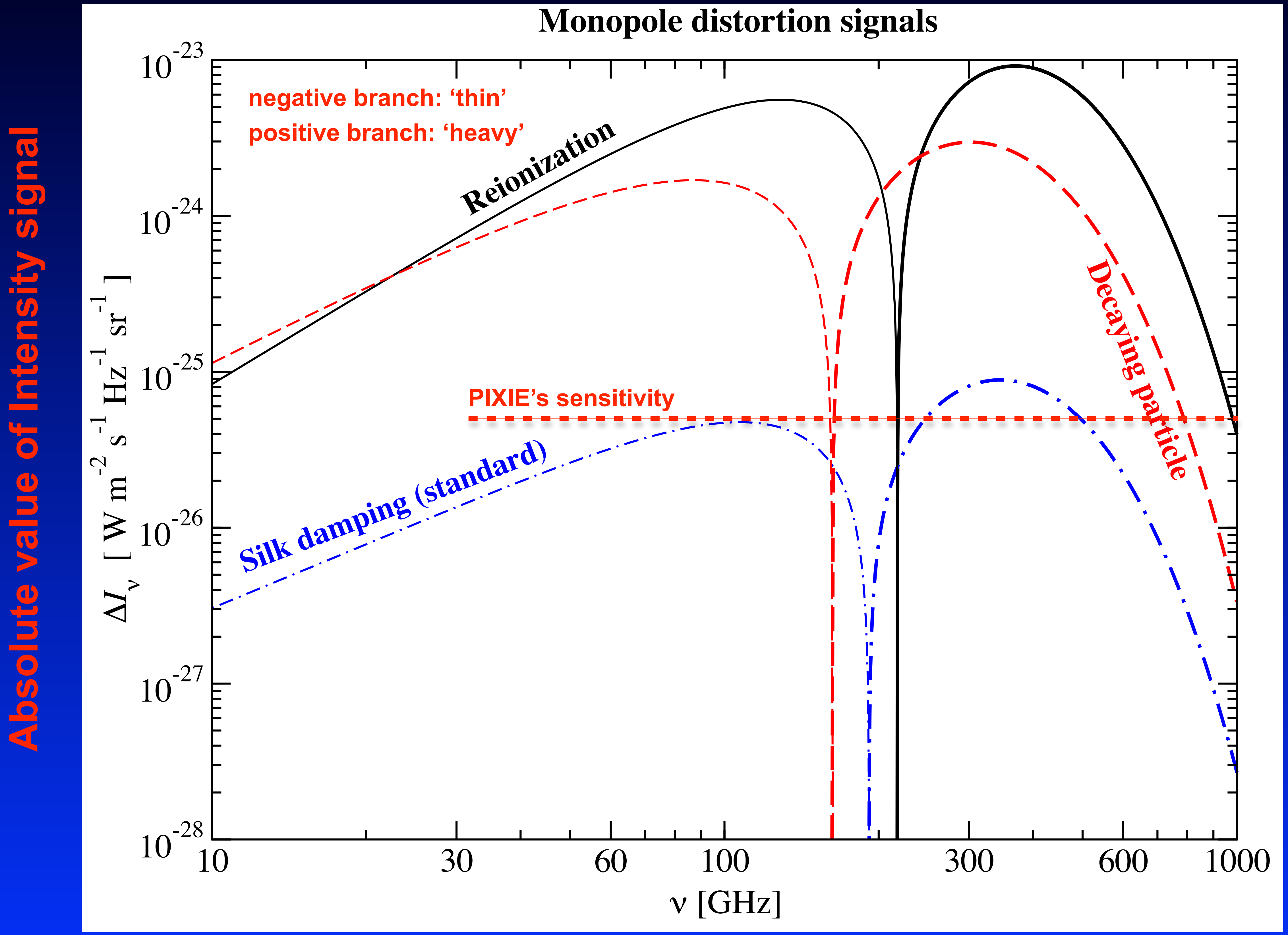

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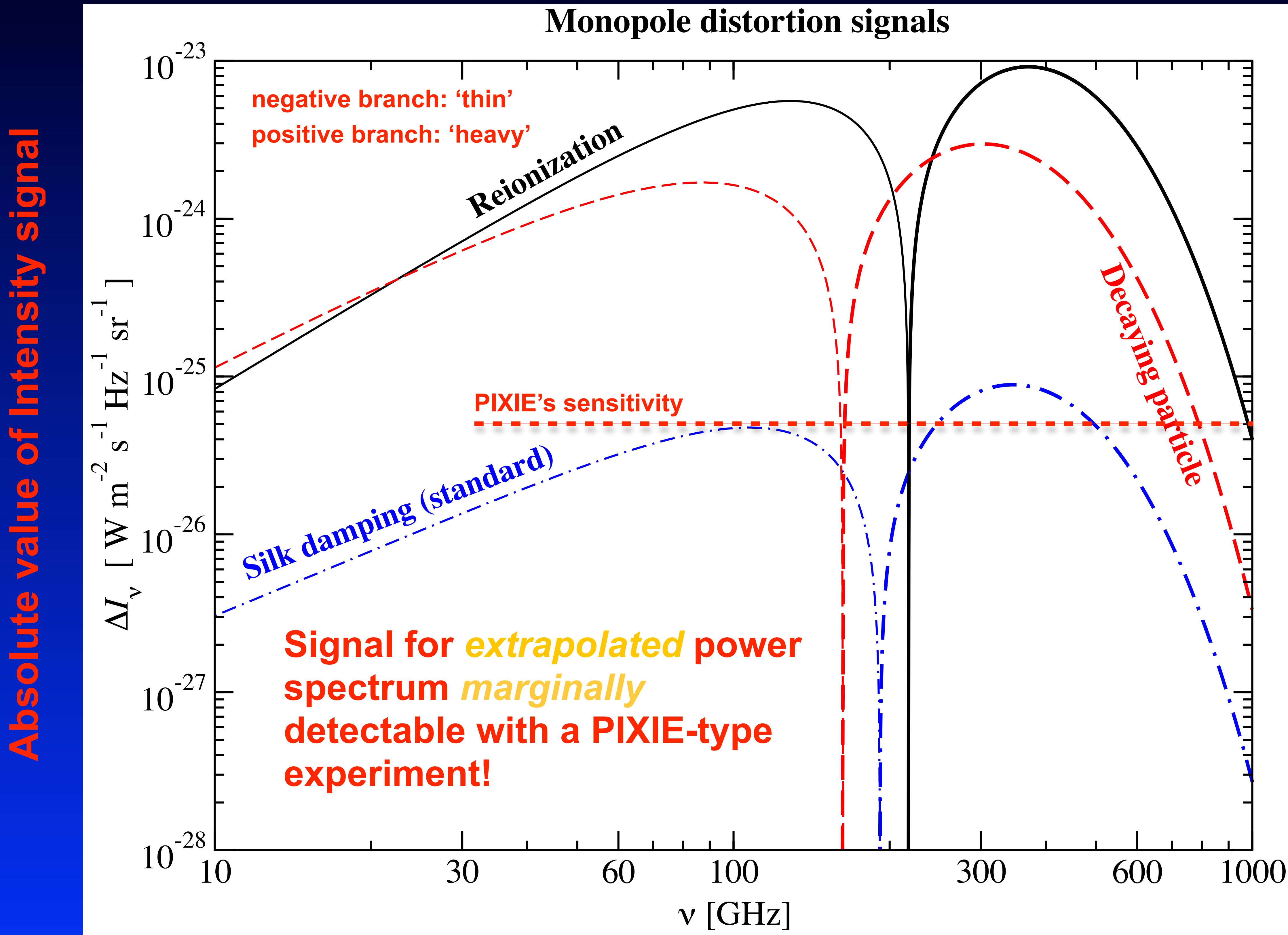
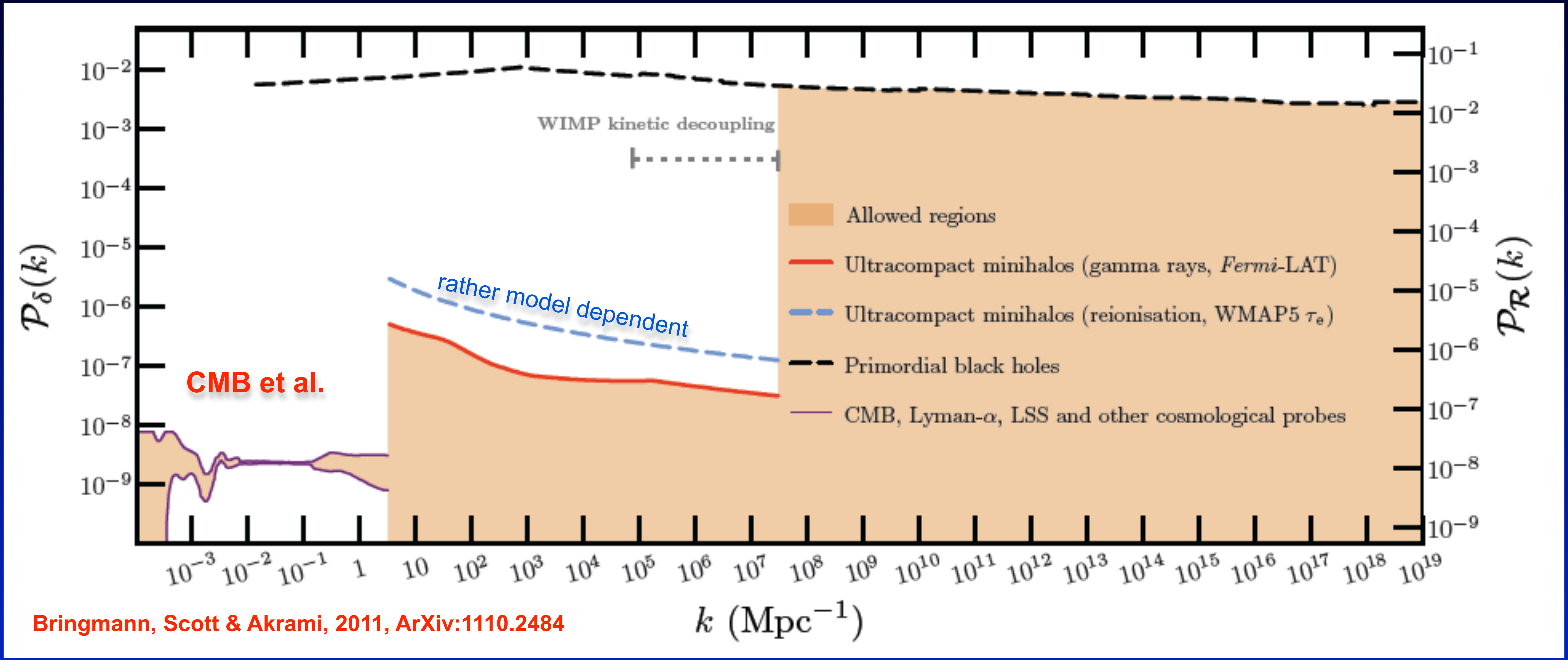


Power spectrum constraints



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- improving limits at smaller scales would constrain inflationary models

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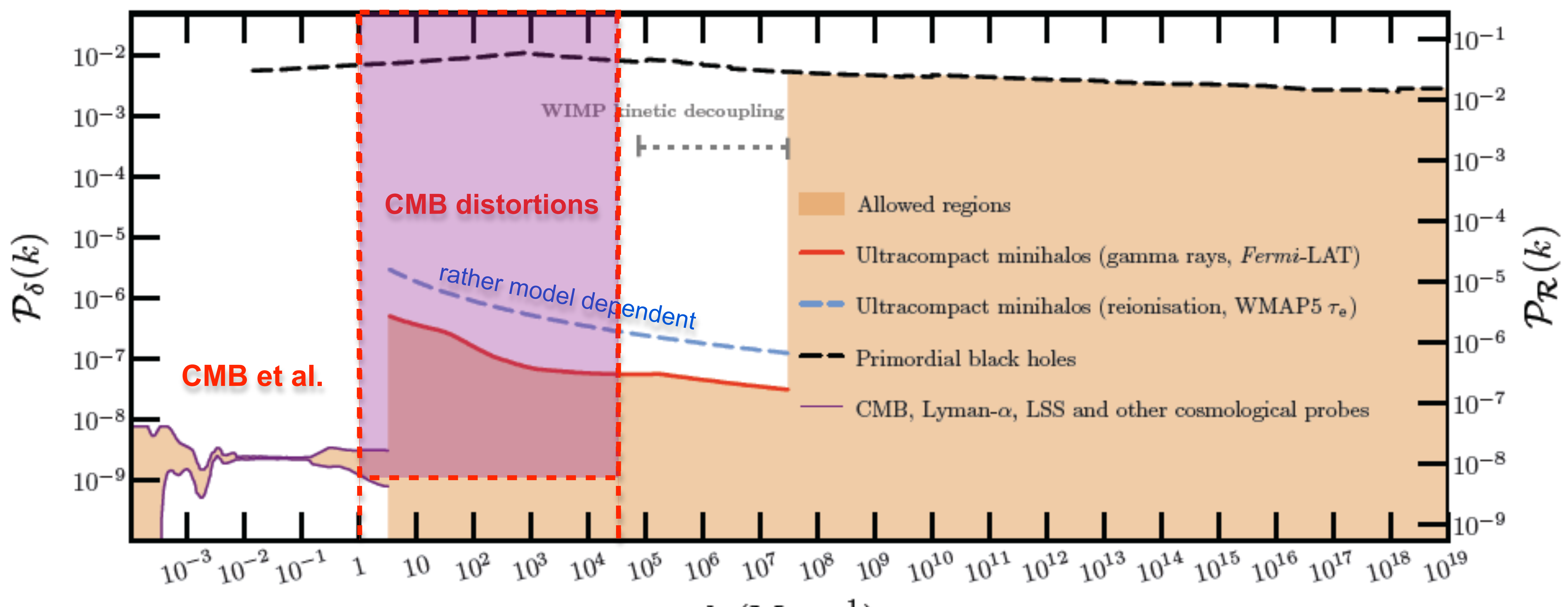
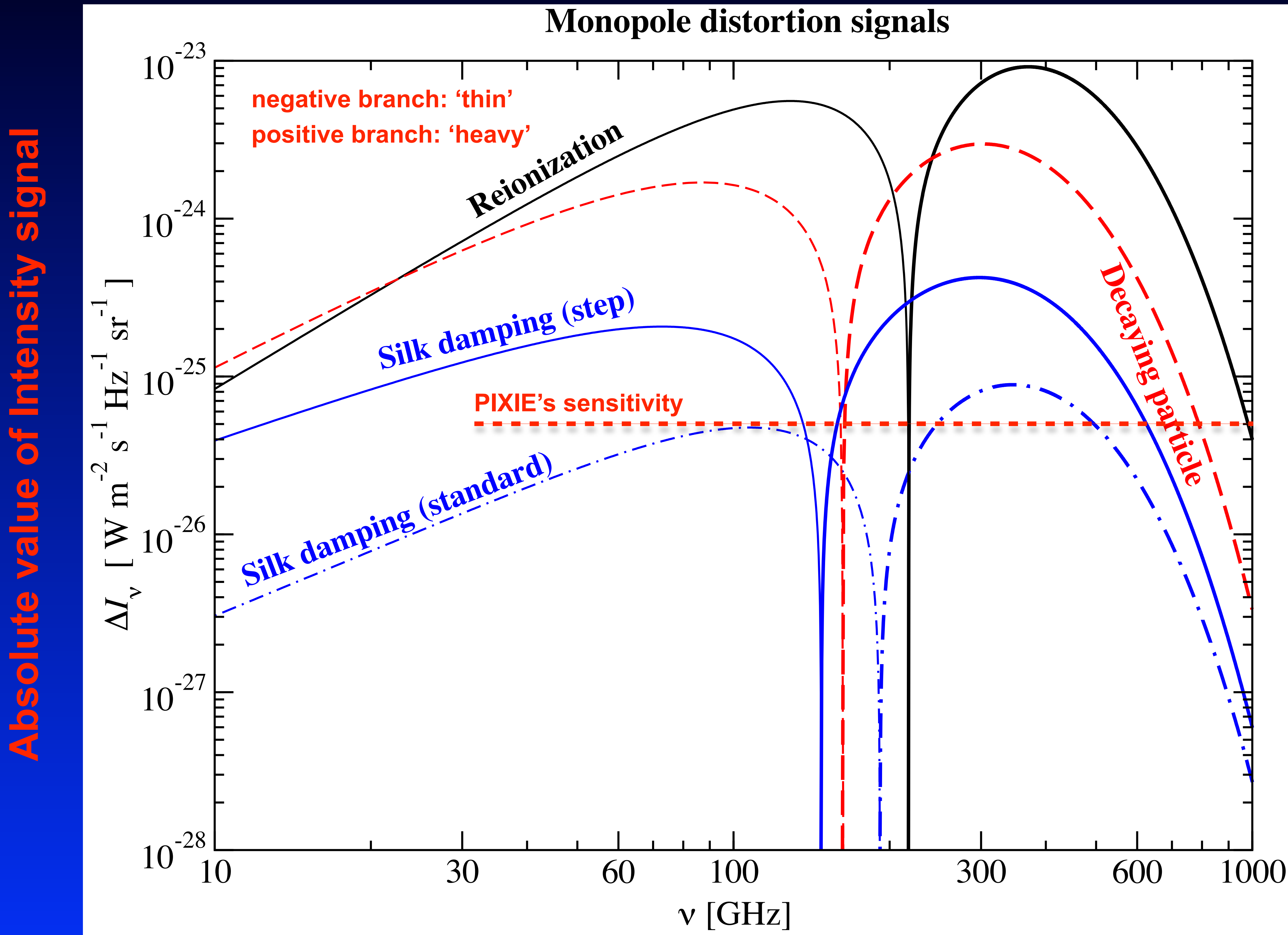


Bringmann, Scott & Akrami, 2011, ArXiv:1110.2484

- Amplitude of power spectrum rather uncertain at $k > 3$ Mpc^{-1}
- improving limits at smaller scales would constrain inflationary models
- CMB spectral distortions could allow extending our lever arm to $k \sim 10^4$ Mpc^{-1}
- See JC, Erickcek & Ben-Dayan, 2012 for constraints on more general P(k)

Average CMB spectral distortions



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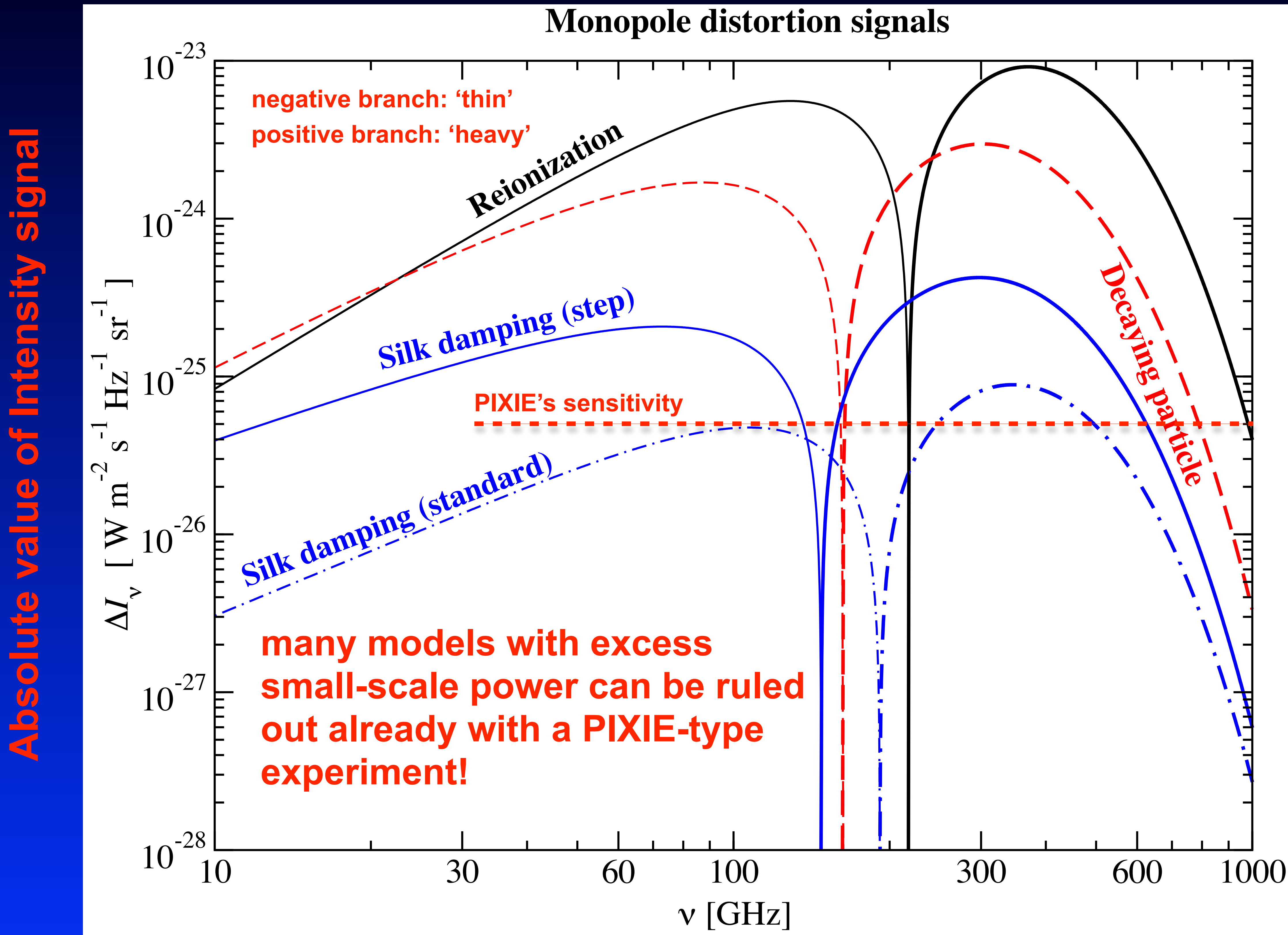
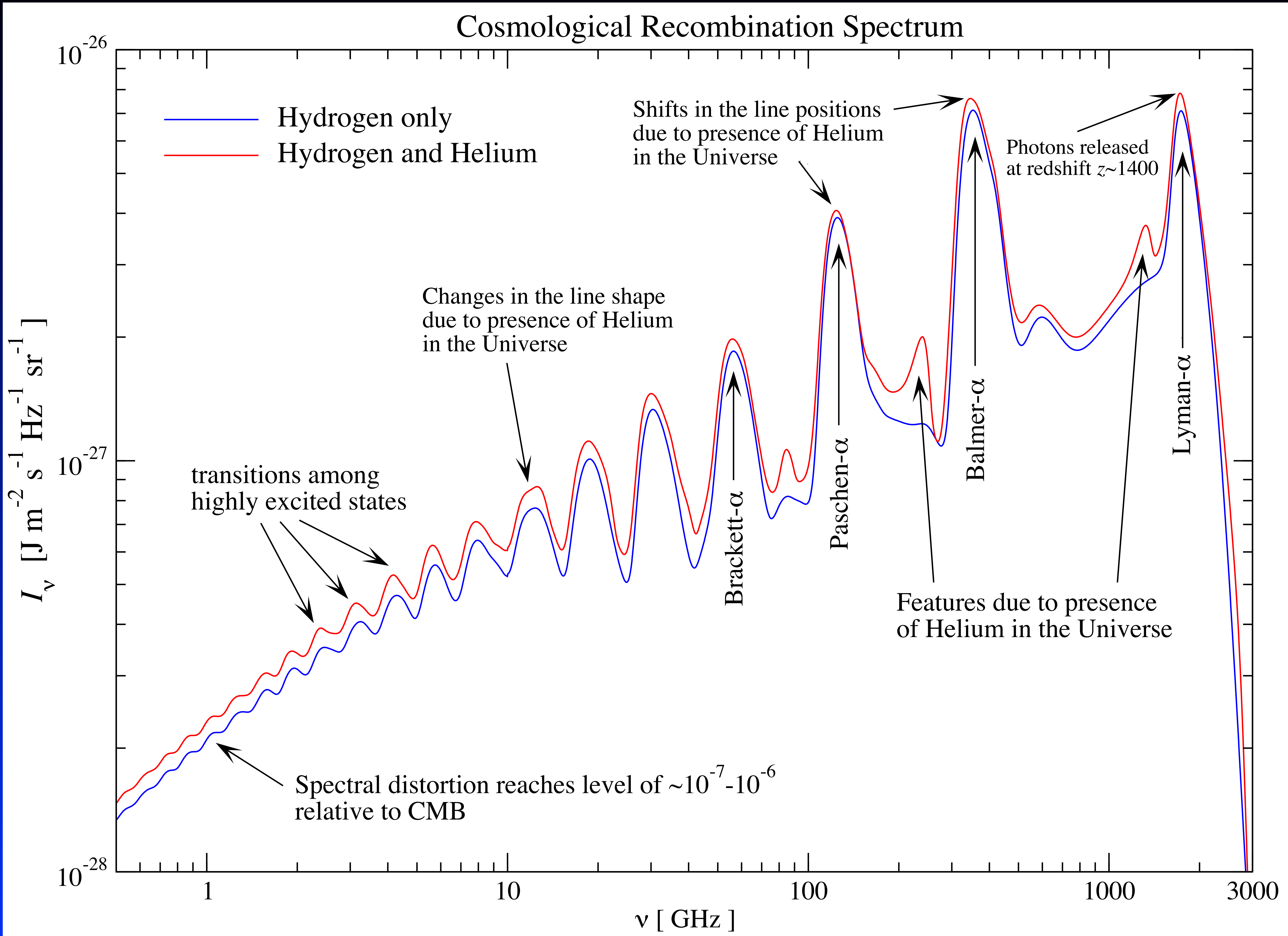
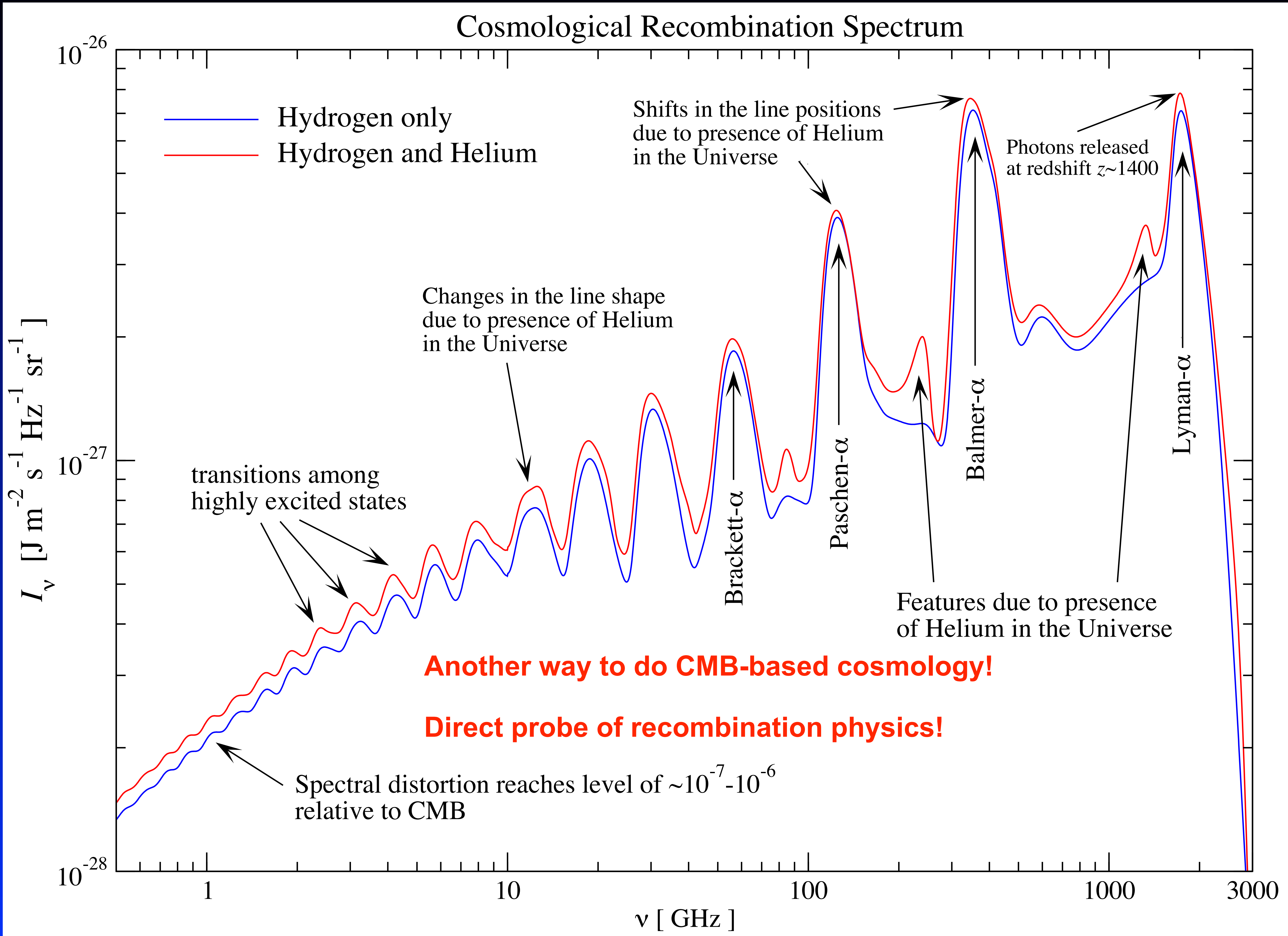



Cosmological Recombination Spectrum
Hydrogen only
Hydrogen and Helium
Shifts in the line positions due to presence of Helium in the Universe
Photons released at redshift z~1400
Changes in the line shape due to presence of Helium in the Universe
transitions among highly excited states
Brackett-α
Paschen-α
Balmer-α
Lyman-α
Features due to presence of Helium in the Universe
Spectral distortion reaches level of ~10^-7-10^-6 relative to CMB
I_ν [J m^-2 s^-1 Hz^-1 sr^-1]
ν [GHz]
10^-26
10^-27
10^-28
1
10
100
1000
3000



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Features due to presence of Helium in the Universe
Another way to do CMB-based cosmology!
Direct probe of recombination physics!
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I_ν [J m^-2 s^-1 Hz^-1 sr^-1]
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Average CMB spectral distortions

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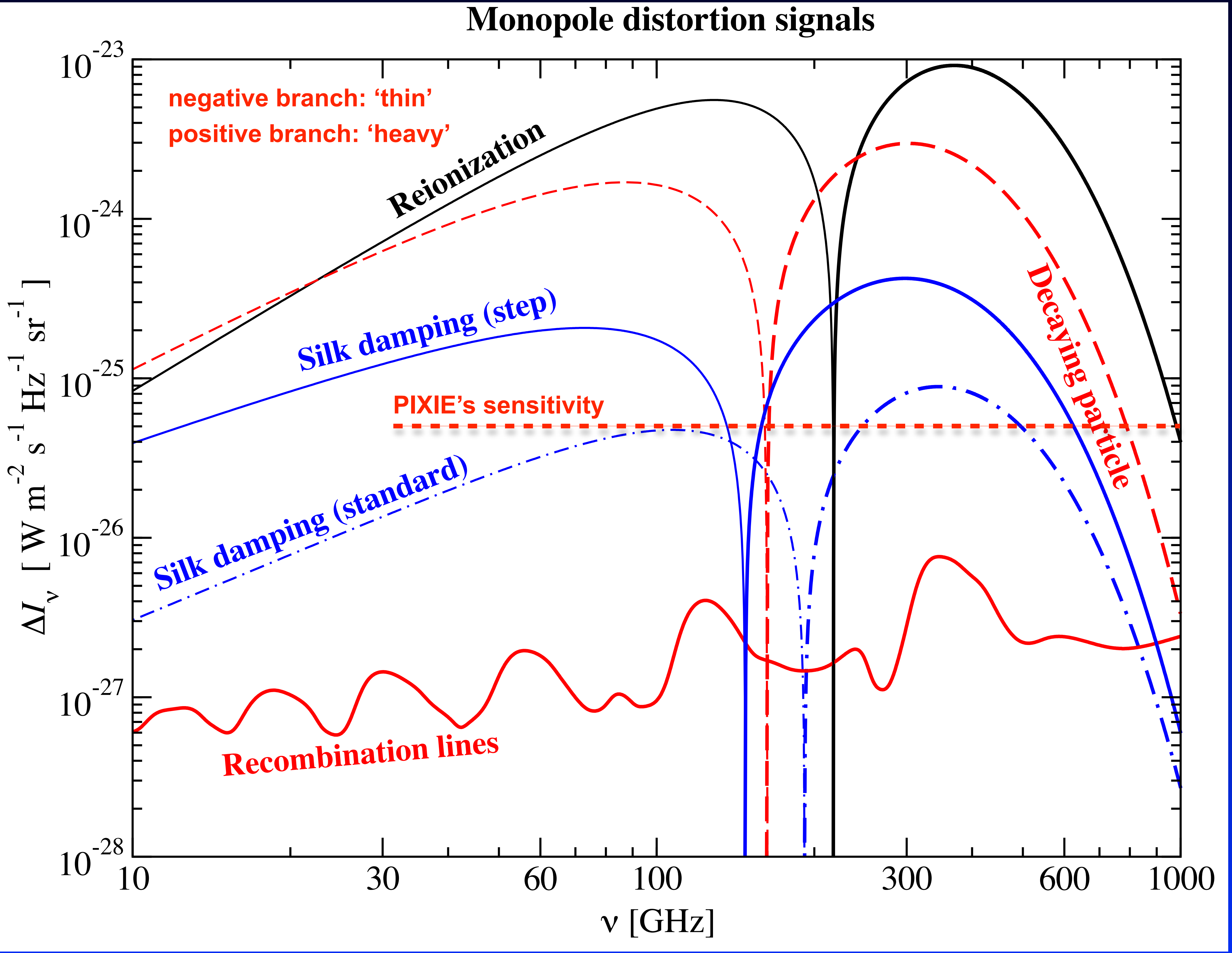

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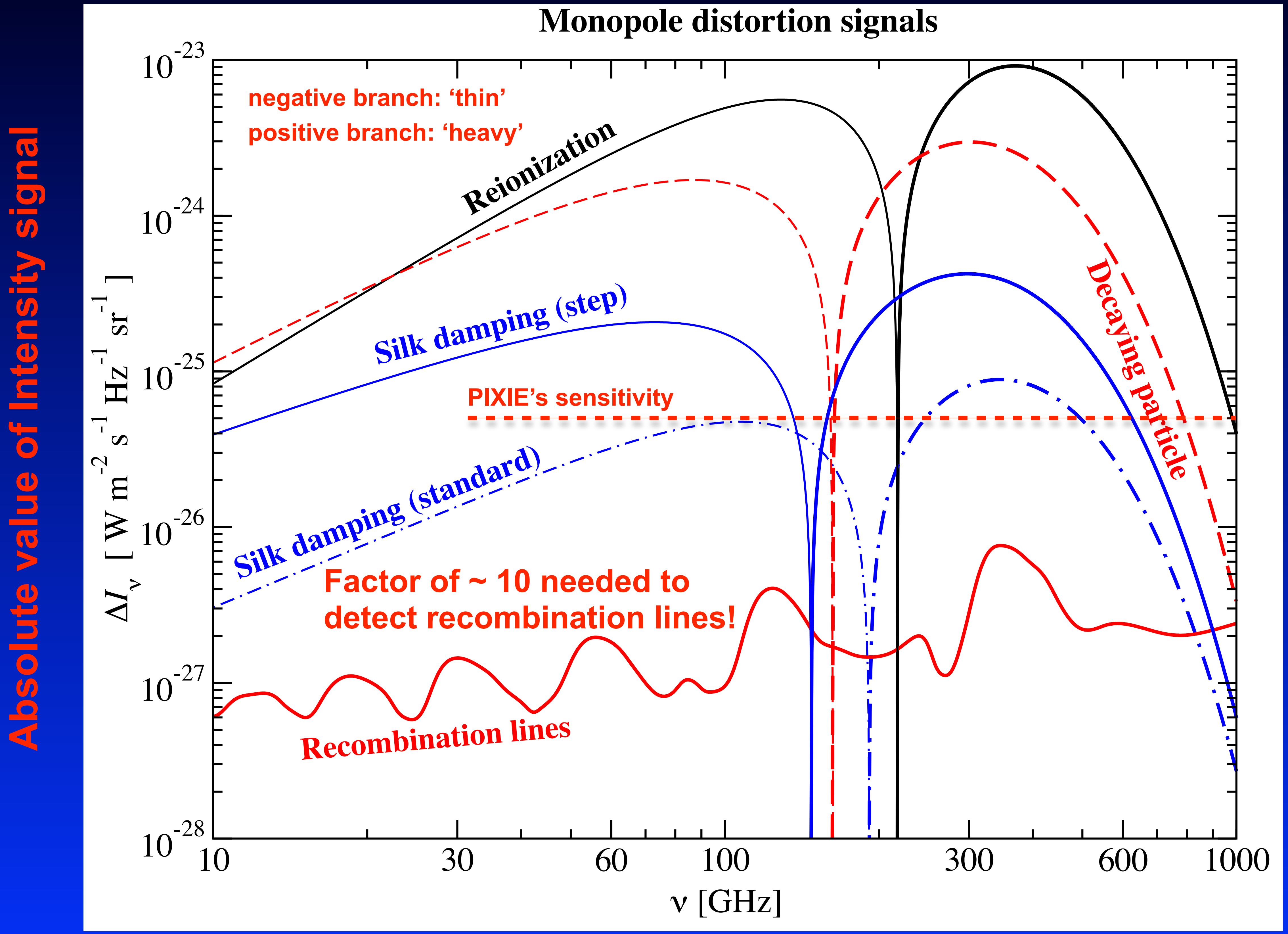

The 30 year Roadmap

5-10 years from now (*PIXIE-type experiment*):

- average y-distortion from *reionization* with sub 1% precision
- Tight constraints on *decaying particles* with lifetimes $t_X \sim 10^8$ - 10^{11} sec
- Tight constraints on inflation models that produce excess small-scale power

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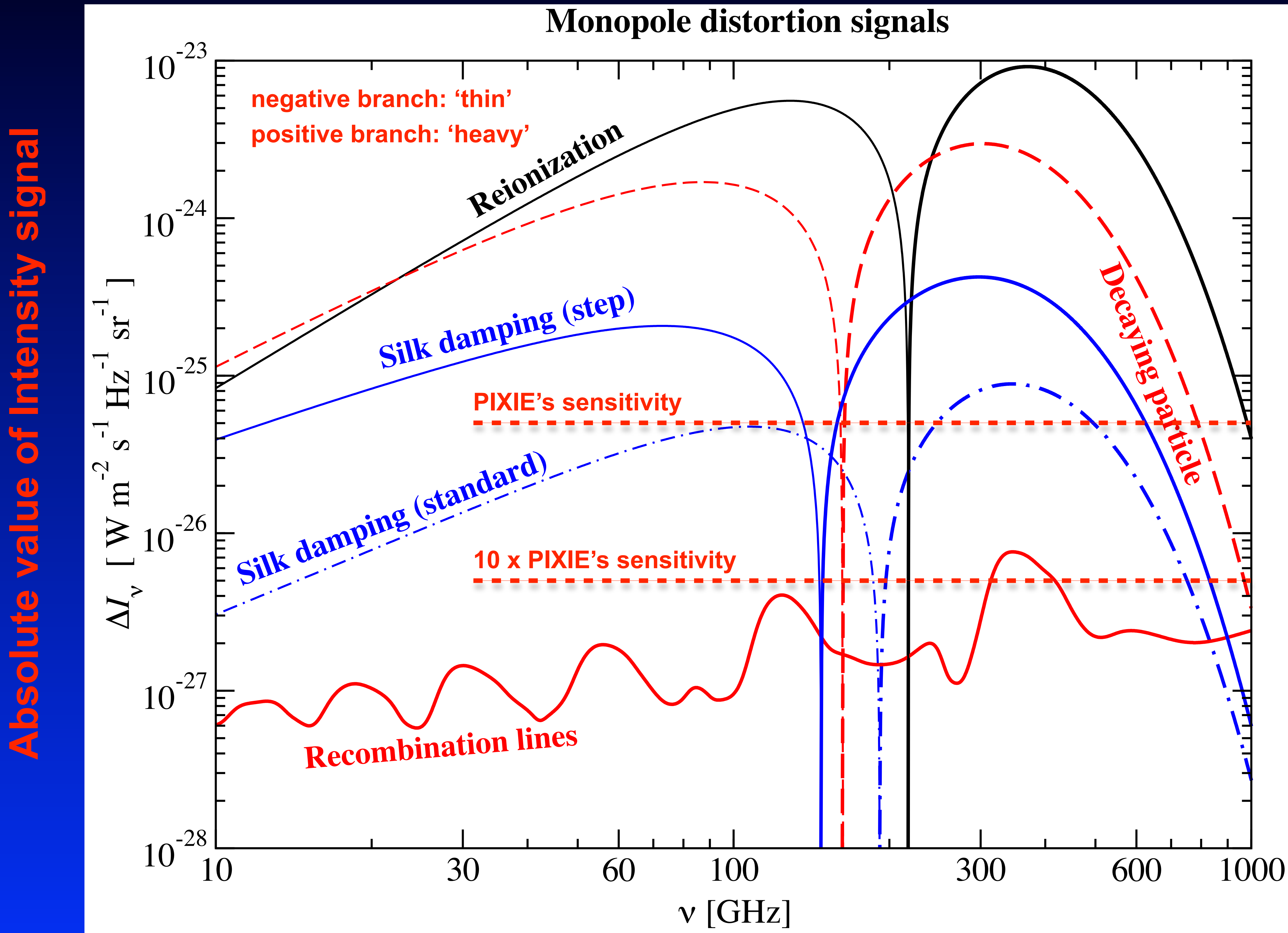

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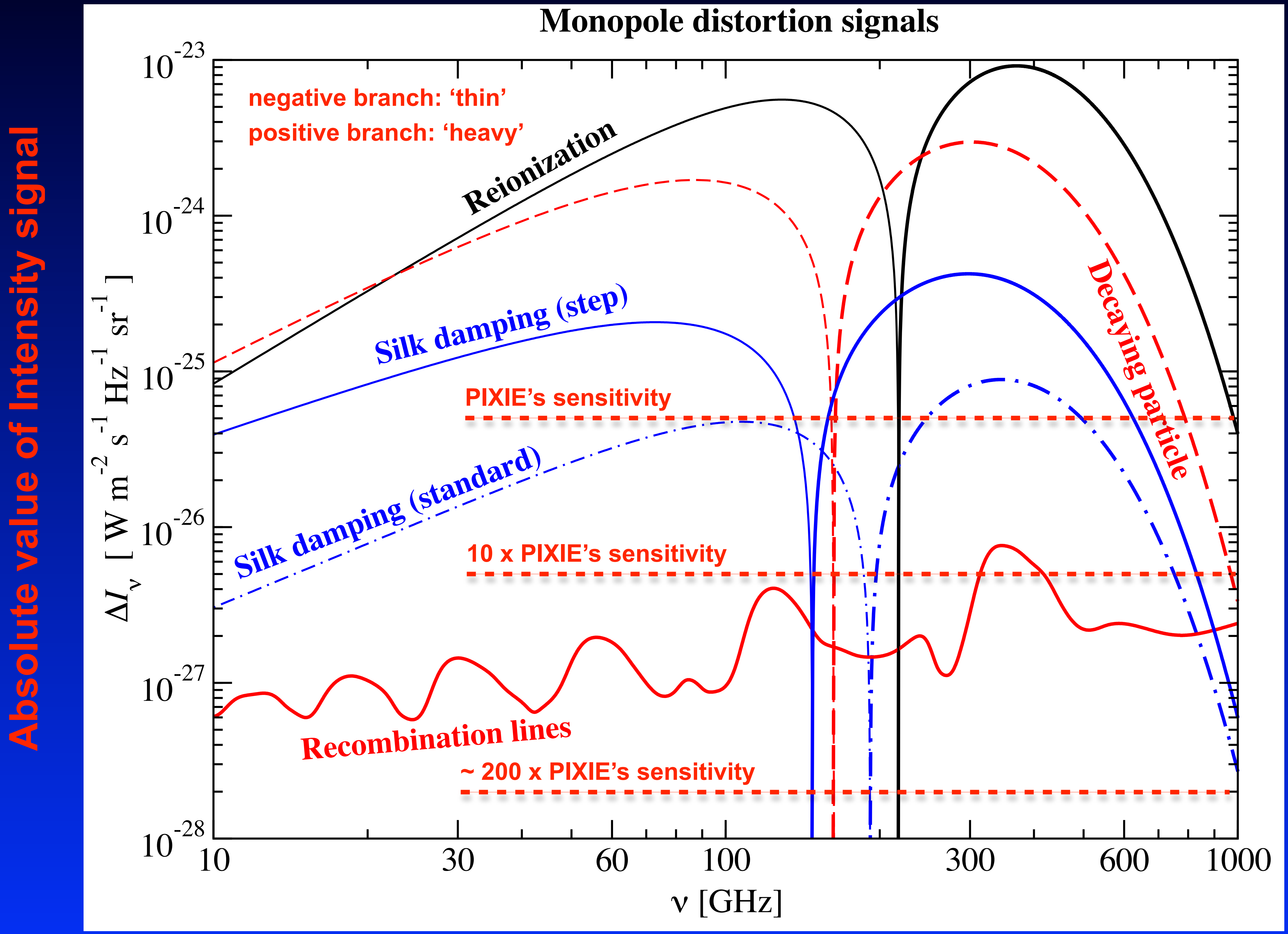
10-20 years from now (~10-20 times *PIXIE sensitivity*):

- spatially varying y-distortion from *WHIM*
- even tighter constraints on *decaying particles*
- significant *detection* of signal from Silk-damping *even* in standard case
- first *detection* of recombination signal

Combination with very high sensitivity B-polarization experiment to probe both large and small-scale CMB

Average CMB spectral distortions



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- Tight constraints on *decaying particles* with lifetimes $t_X \sim 10^8 - 10^{11}$ sec
- Tight constraints on inflation models that produce excess small-scale power

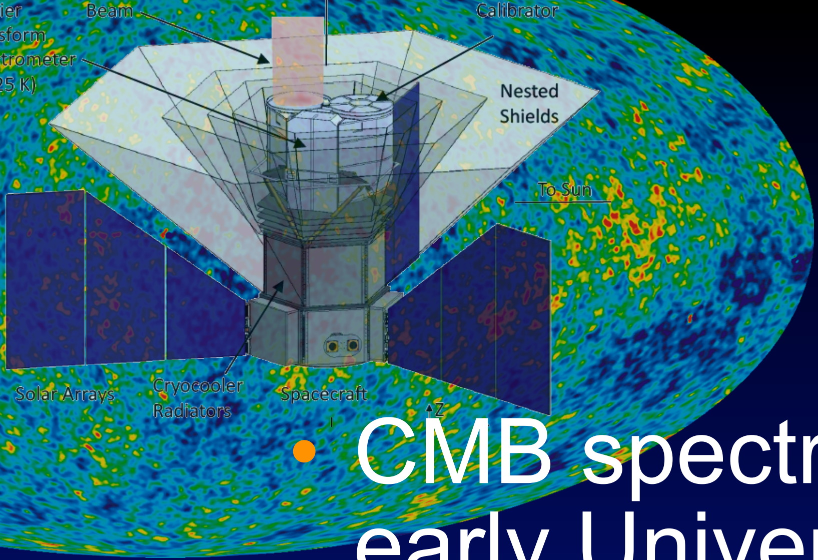
10-20 years from now (~10-20 times *PIXIE sensitivity*):

- spatially varying y-distortion from *WHIM*
- even tighter constraints on *decaying particles*
- significant *detection* of signal from Silk-damping *even* in standard case
- first *detection* of recombination signal

Combination with very high sensitivity B-polarization experiment to probe both large and small-scale CMB

30 years from now (~ 200 times *PIXIE sensitivity*):

- cosmology based on recombination lines (*pre-stellar helium abundance!*)
- direct test of recombination physics (interpretation of $N_{\rm eff} > 3.046$)
- very sensitive measurement of the primordial power spectrum to $k \sim 10^4\ {\rm Mpc}^{-1}$



Conclusions

- CMB spectral distortions open a *new window* to the early Universe and inflationary epoch
- *complementary* and *independent* source of information about our Universe *not* just confirmation
- simplicity of thermalization physics allows making very *precise predictions* for the distortions caused by different heating mechanisms
- 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!