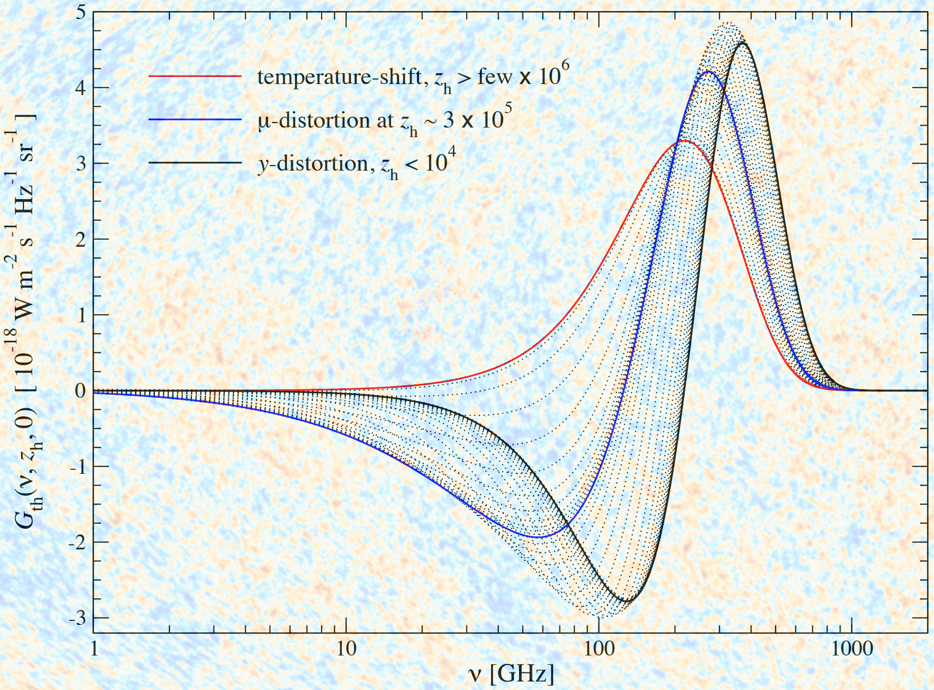
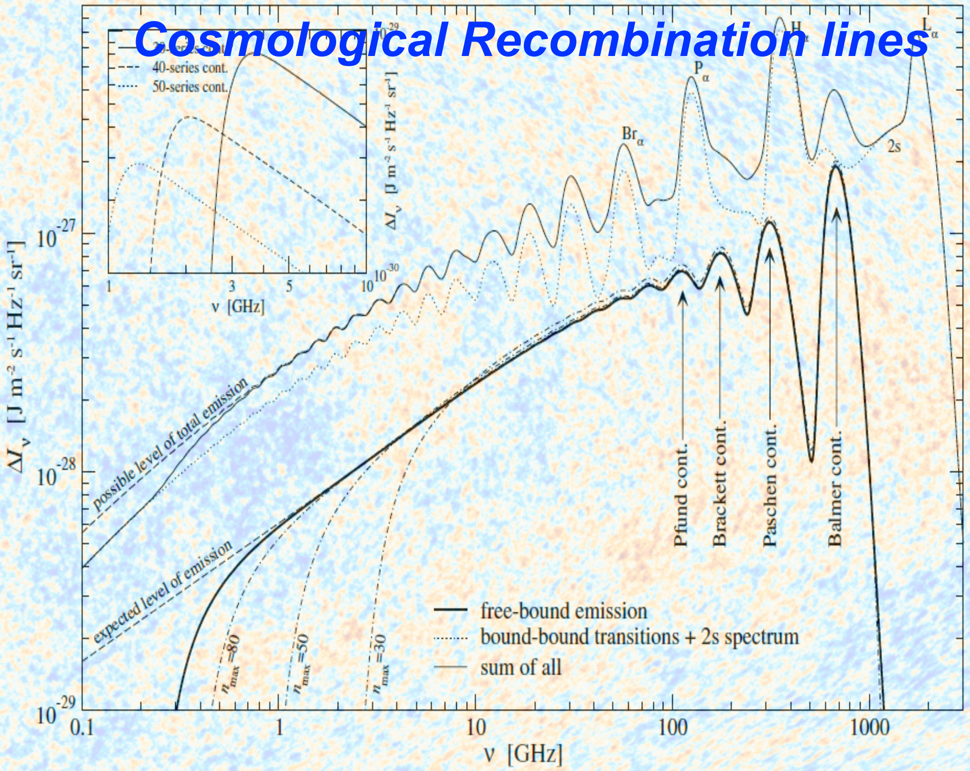
Parametrization of distortions, the cosmological recombination radiation and what we can learn



Primordial Distortions



Cosmological Recombination lines

KICC

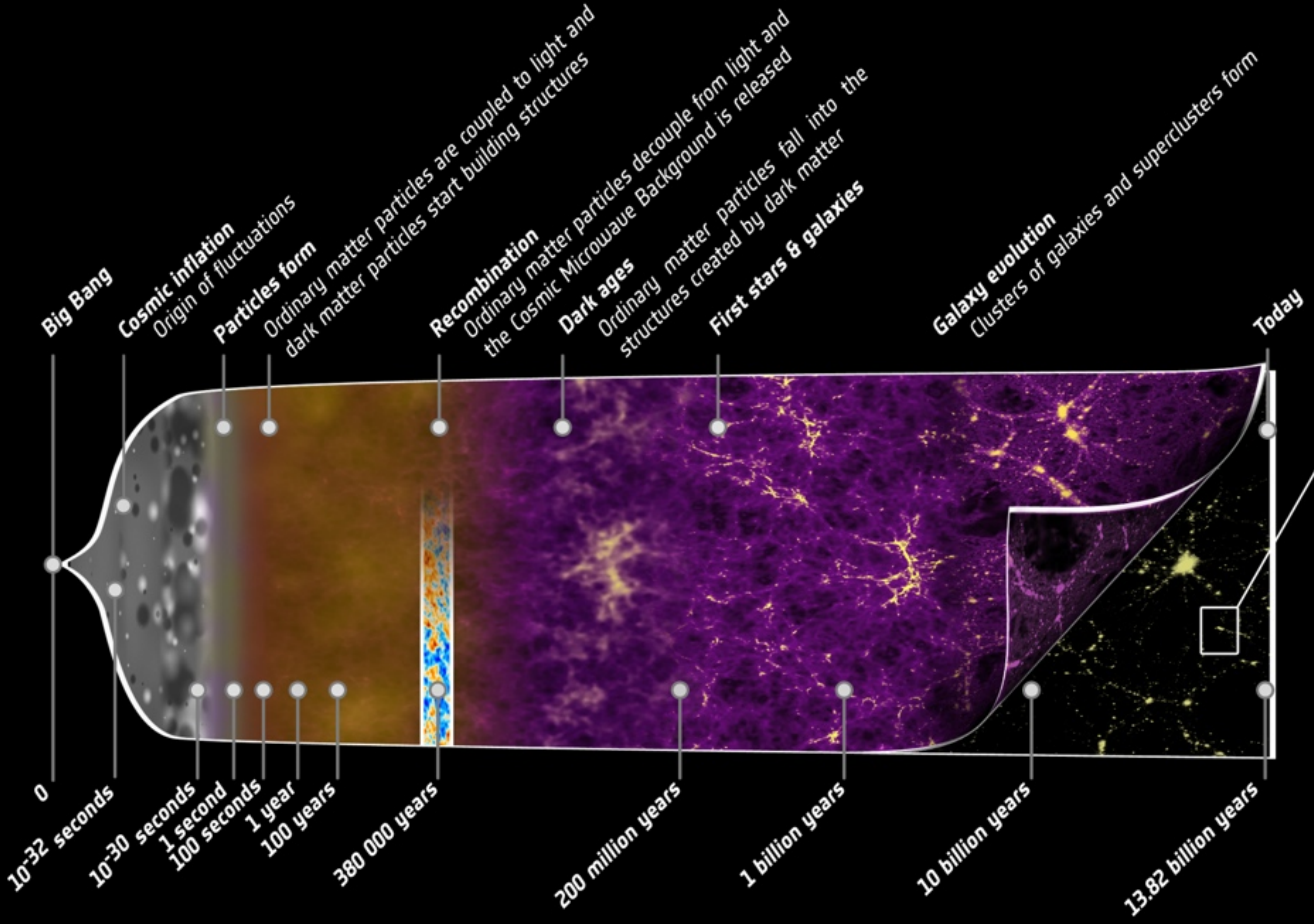
ioa

THE ROYAL SOCIETY

Jens Chluba

CMB Distortion Workshop at KICP

Chicago, May 18th-20th, 2015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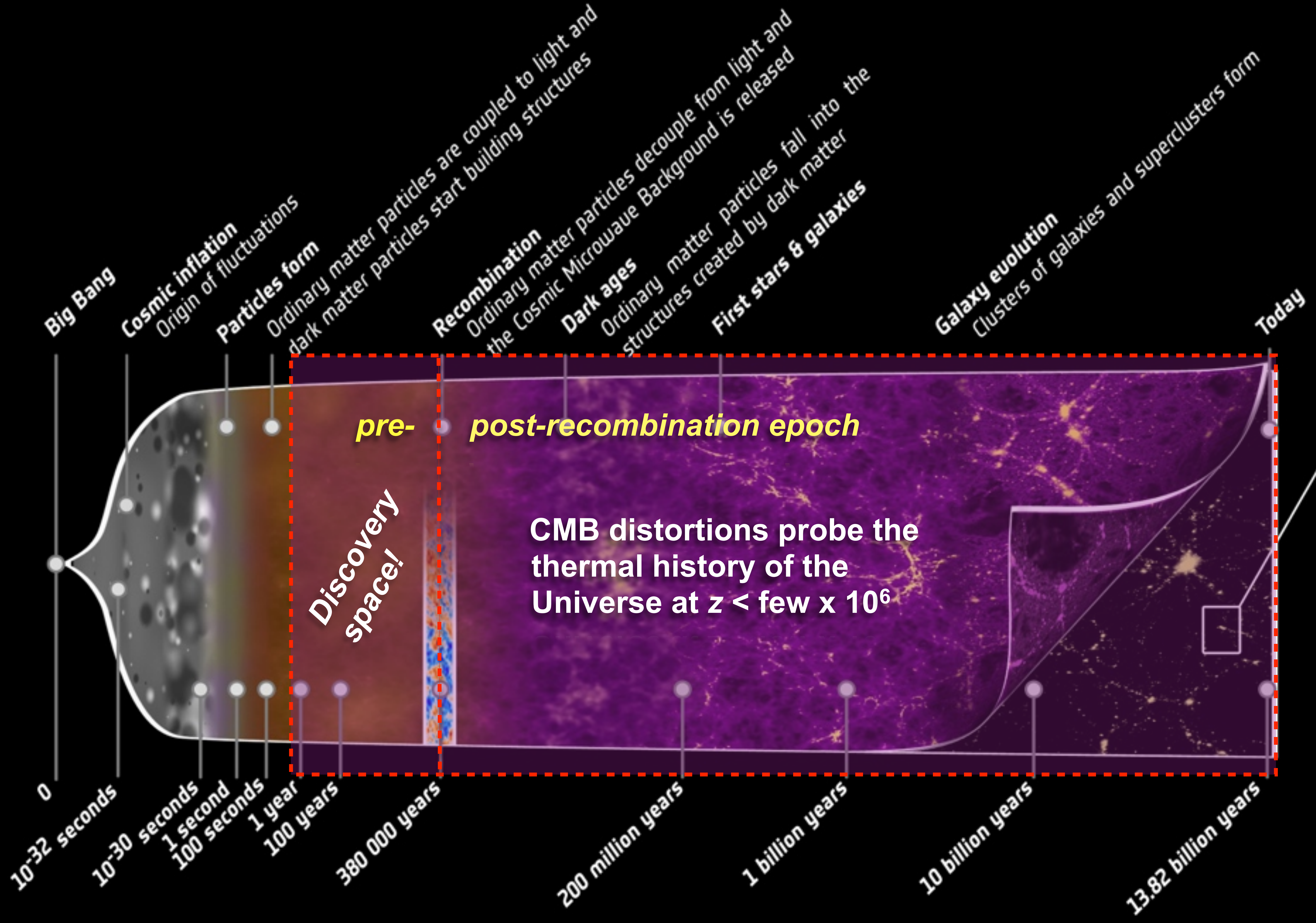
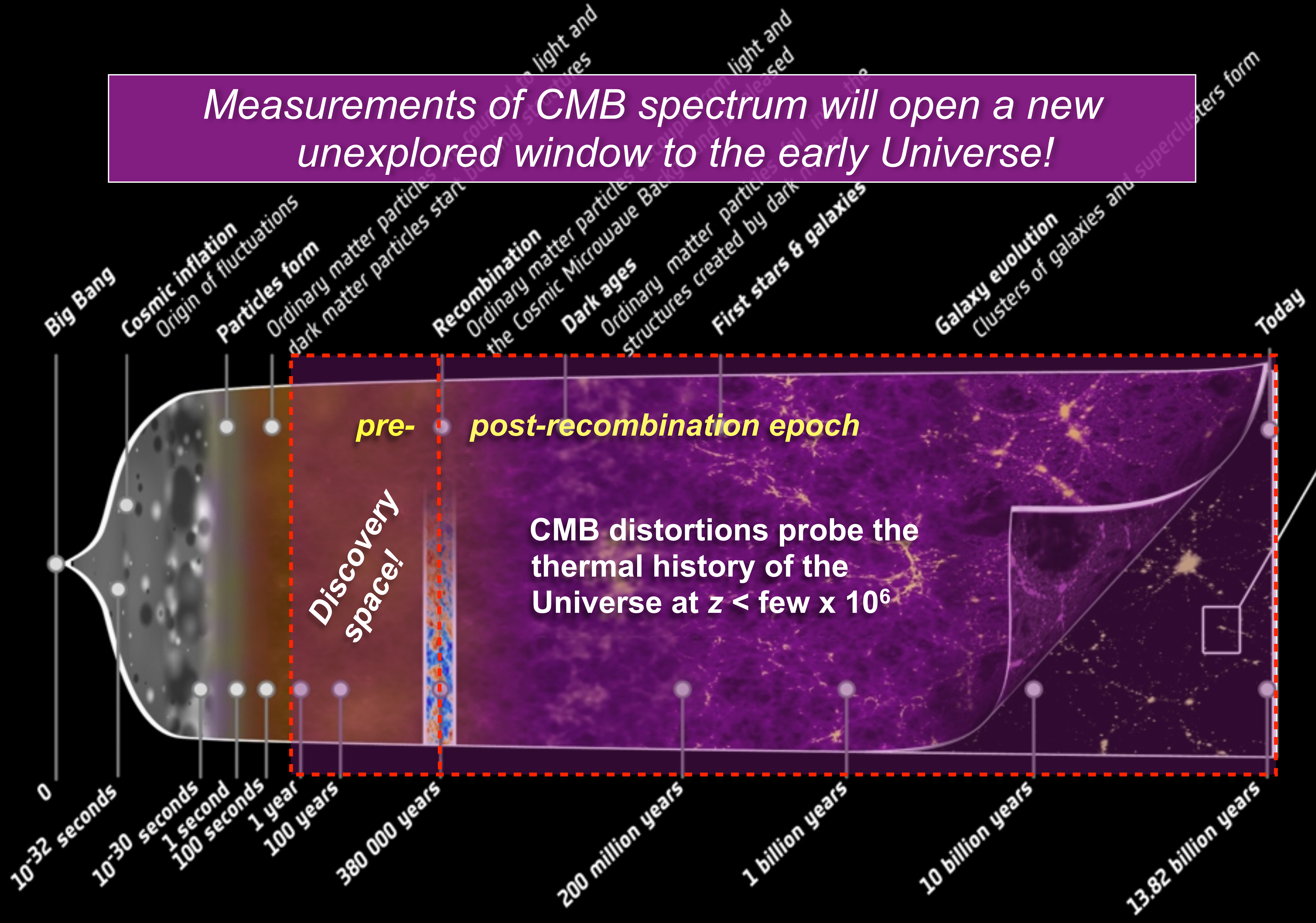


pre- post-recombination epoch

Discovery space!

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

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



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Physical mechanisms that lead to spectral distortions

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„high" redshifts

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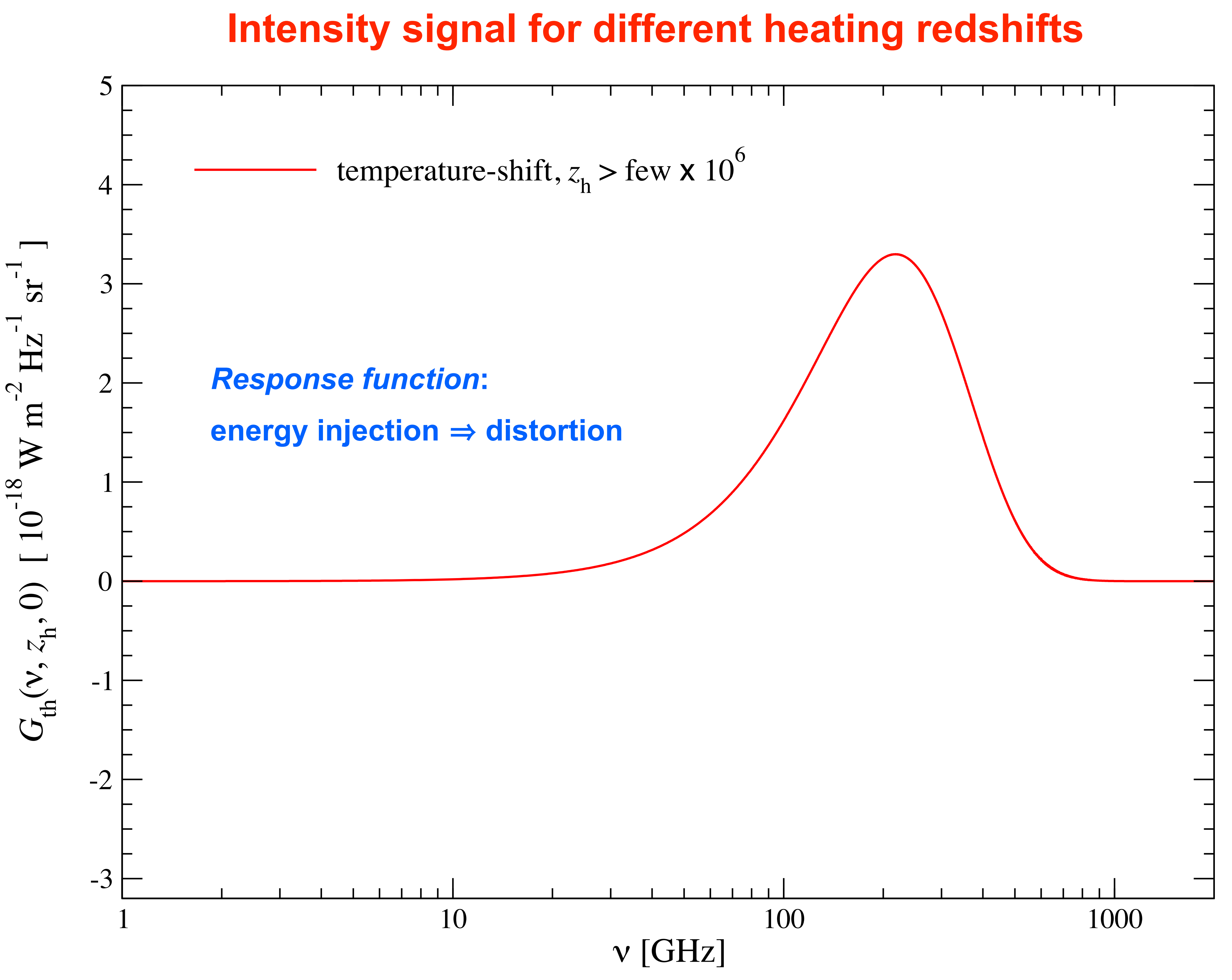

Intensity signal for different heating redshifts

***Response function*:**

energy injection ⇒ distortion

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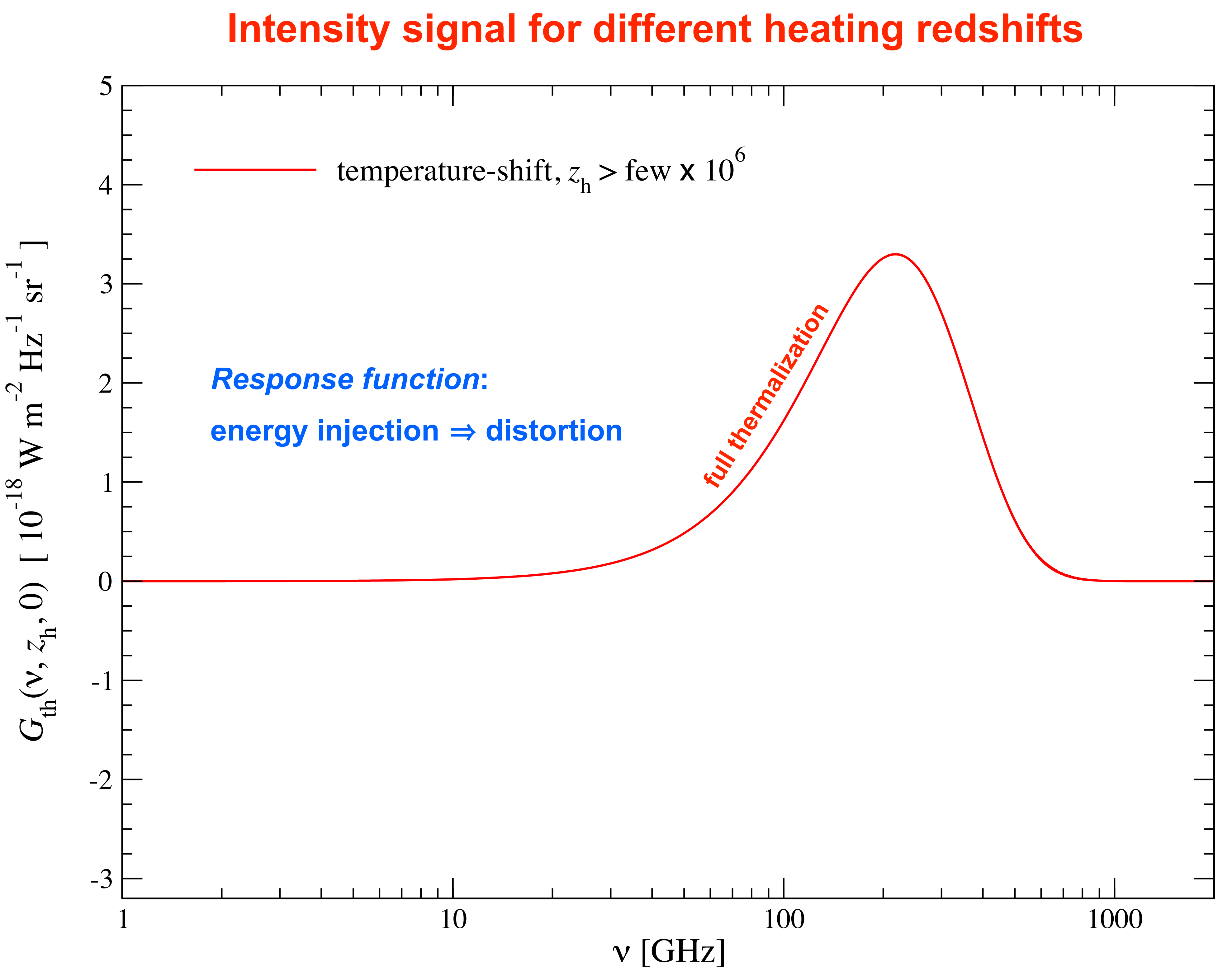

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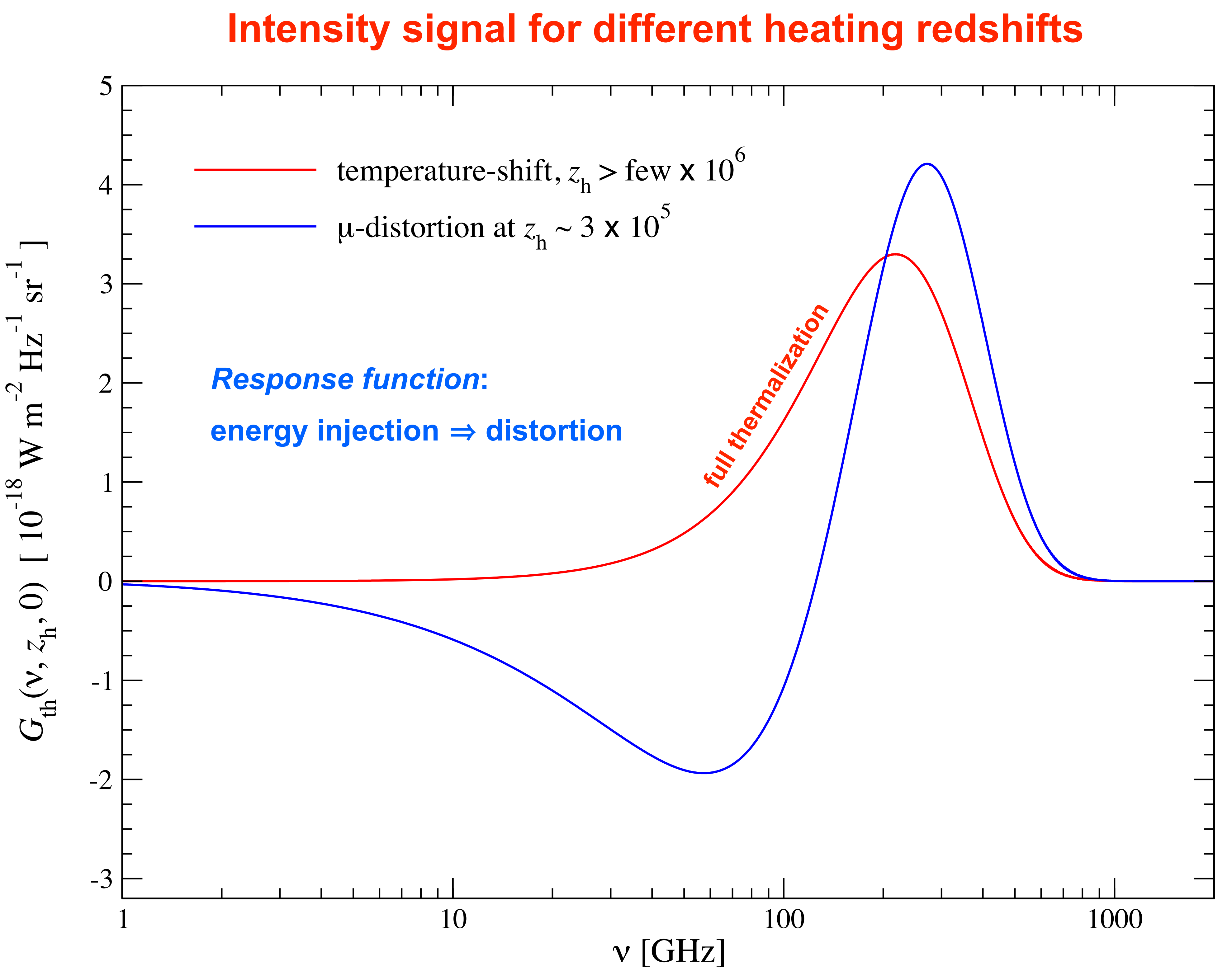

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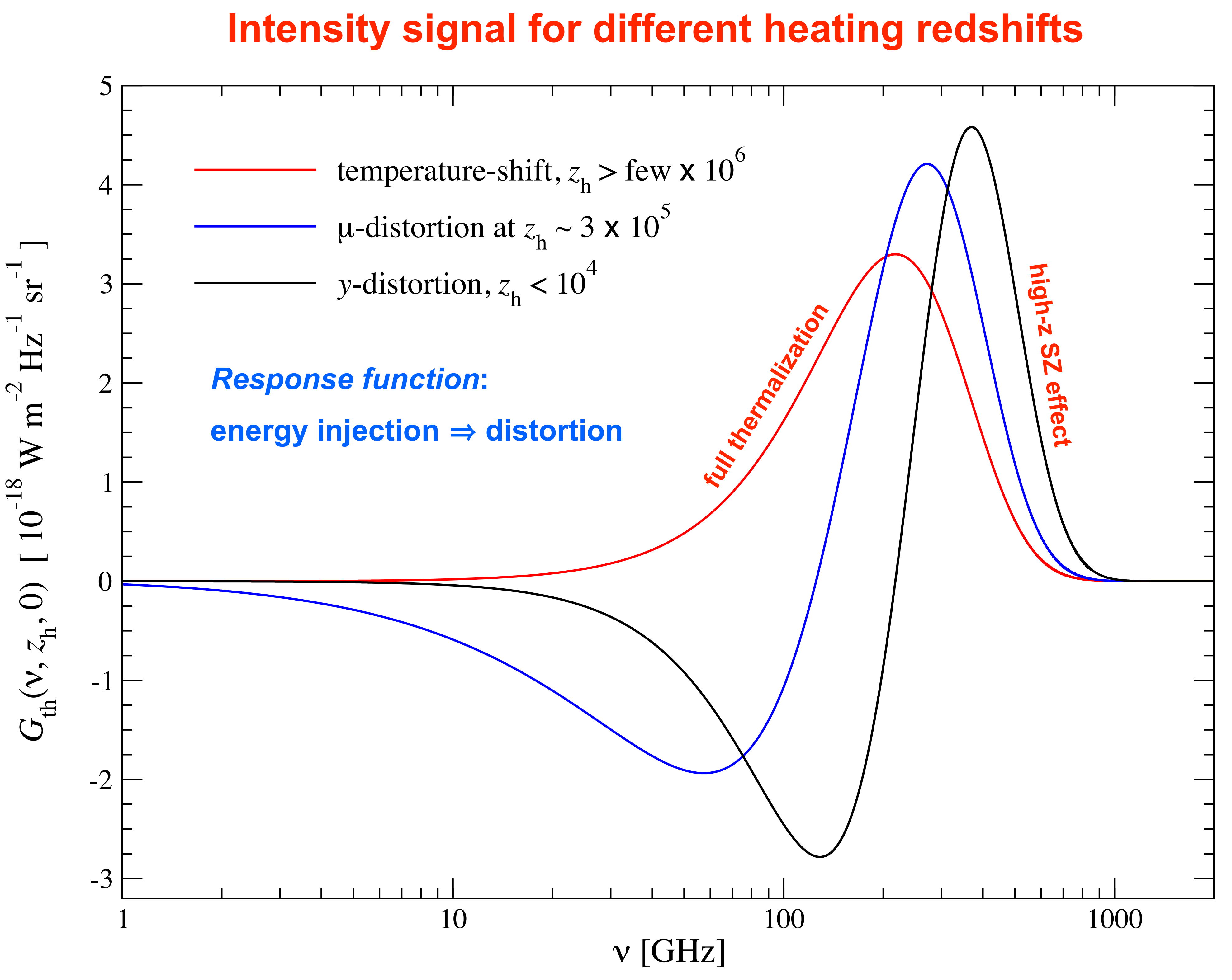

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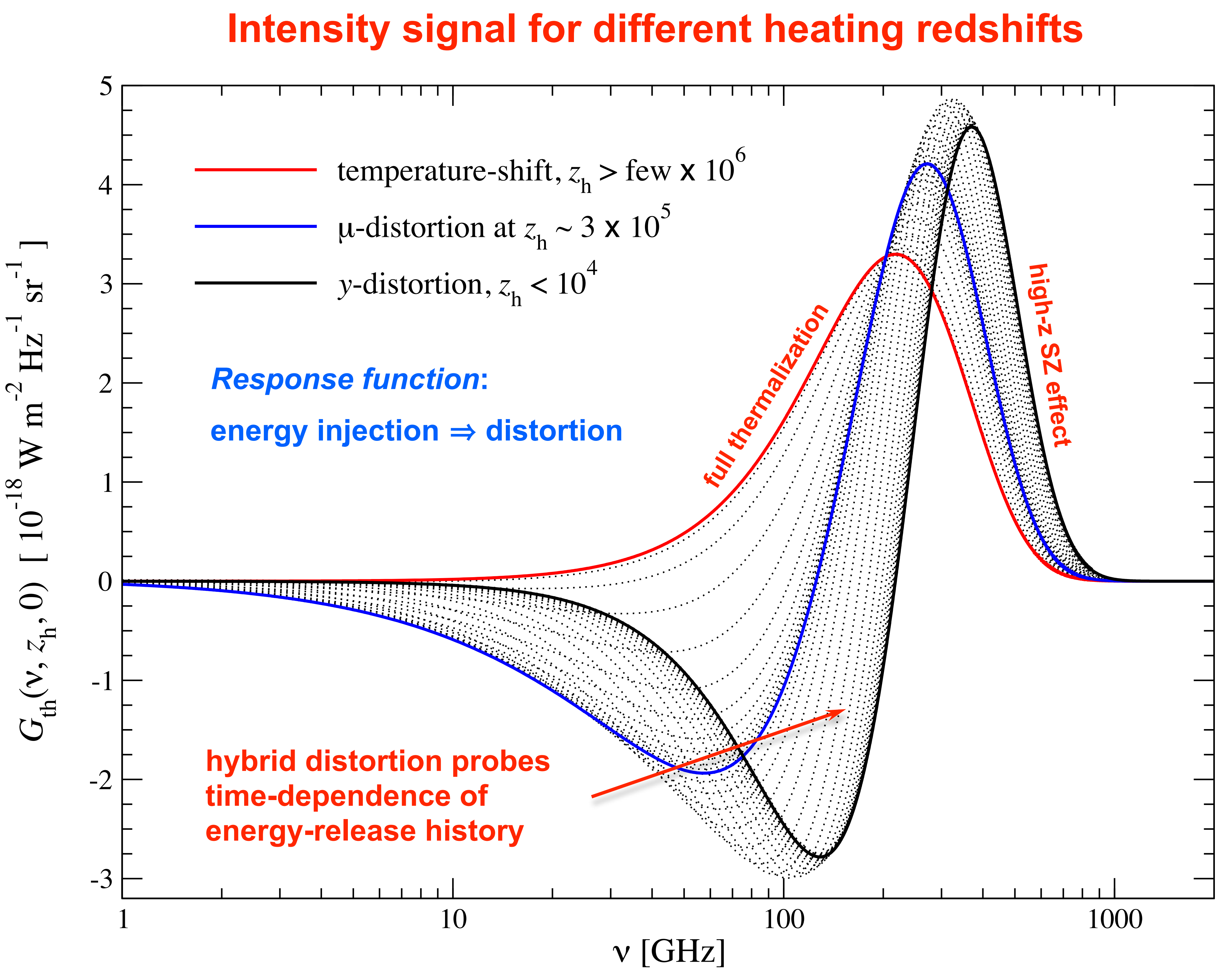
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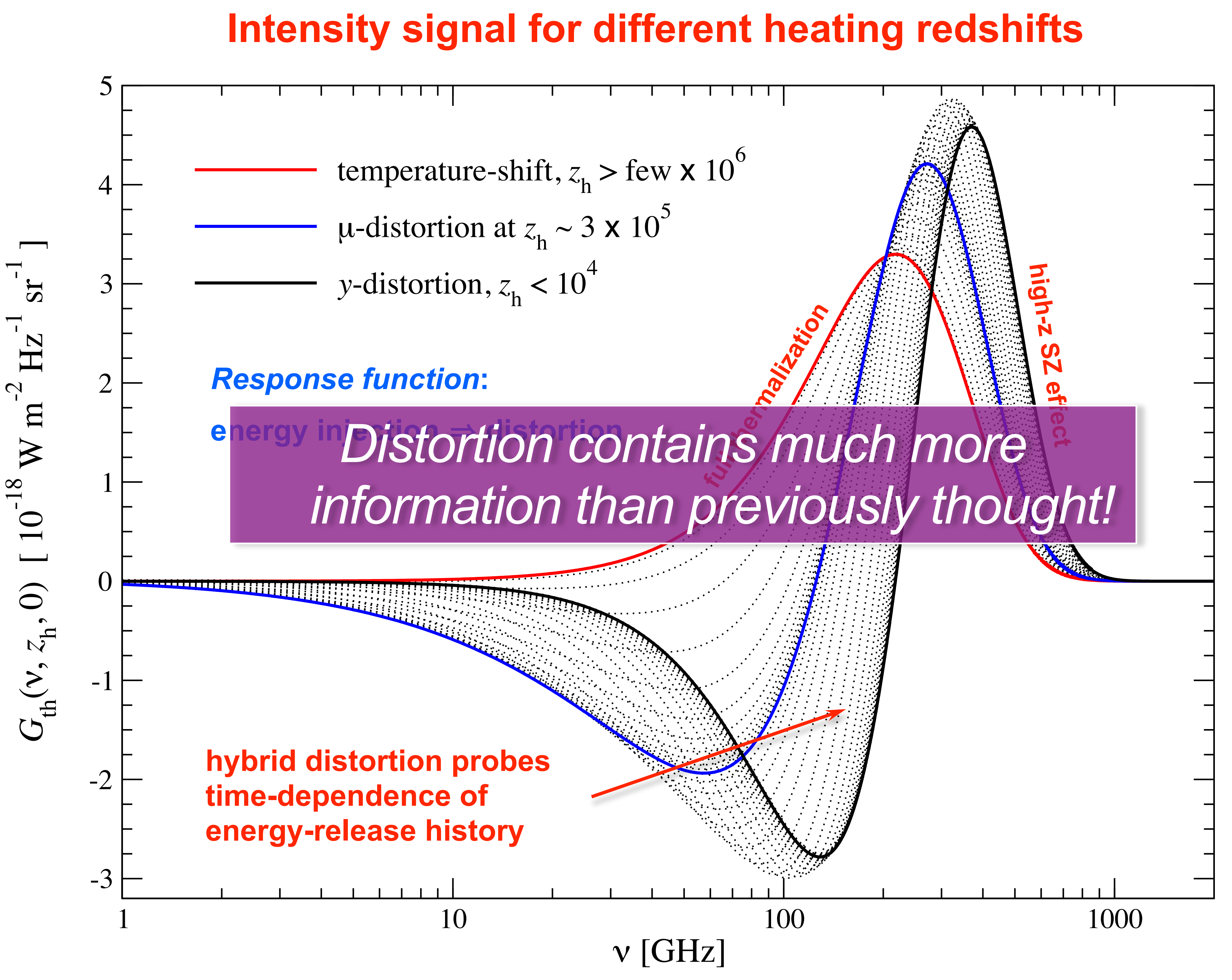

Intensity signal for different heating redshifts

Response function:

energy injection ⇒ distortion

Distortion contains much more information than previously thought!

hybrid distortion probes time-dependence of energy-release history

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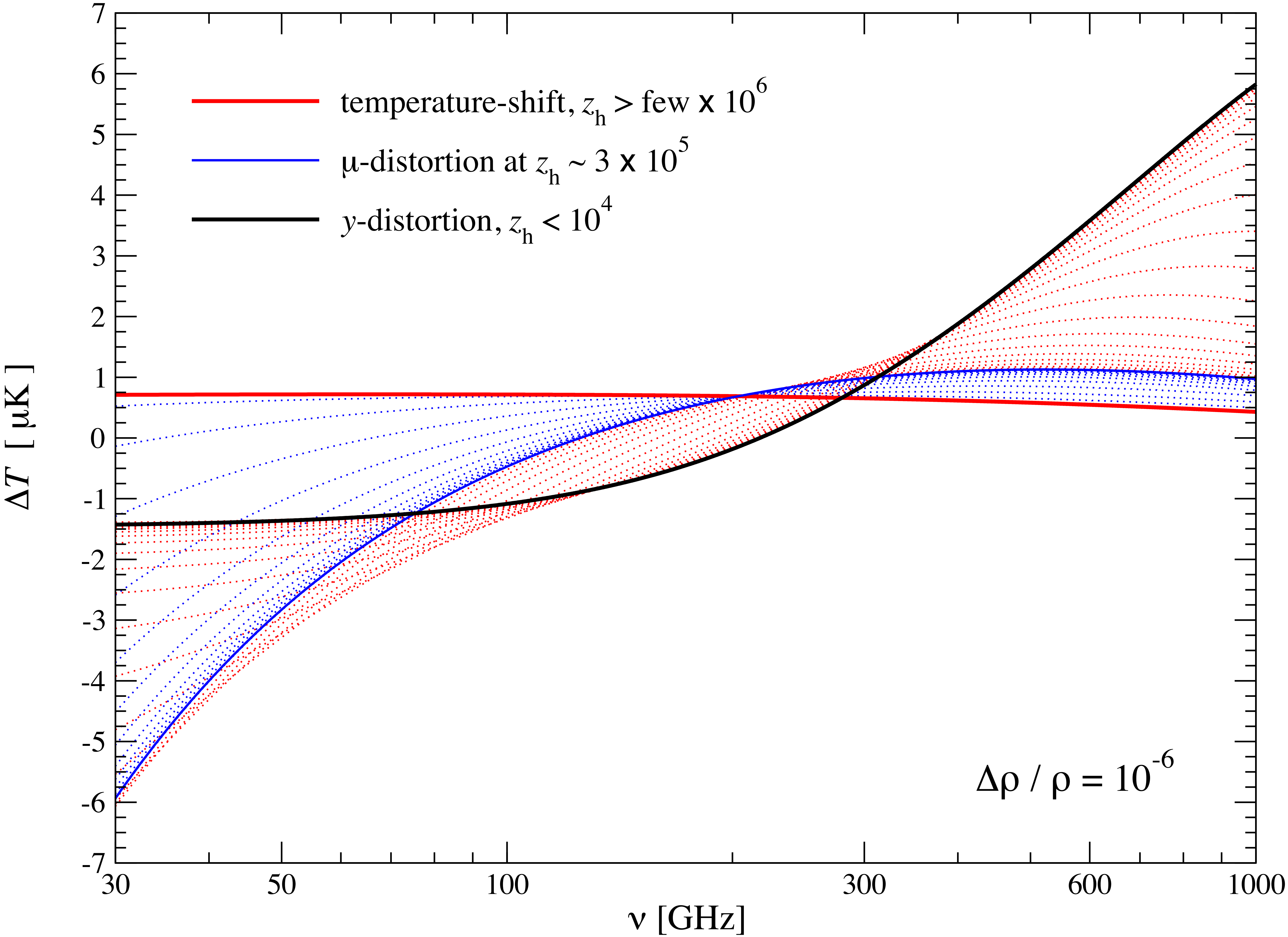
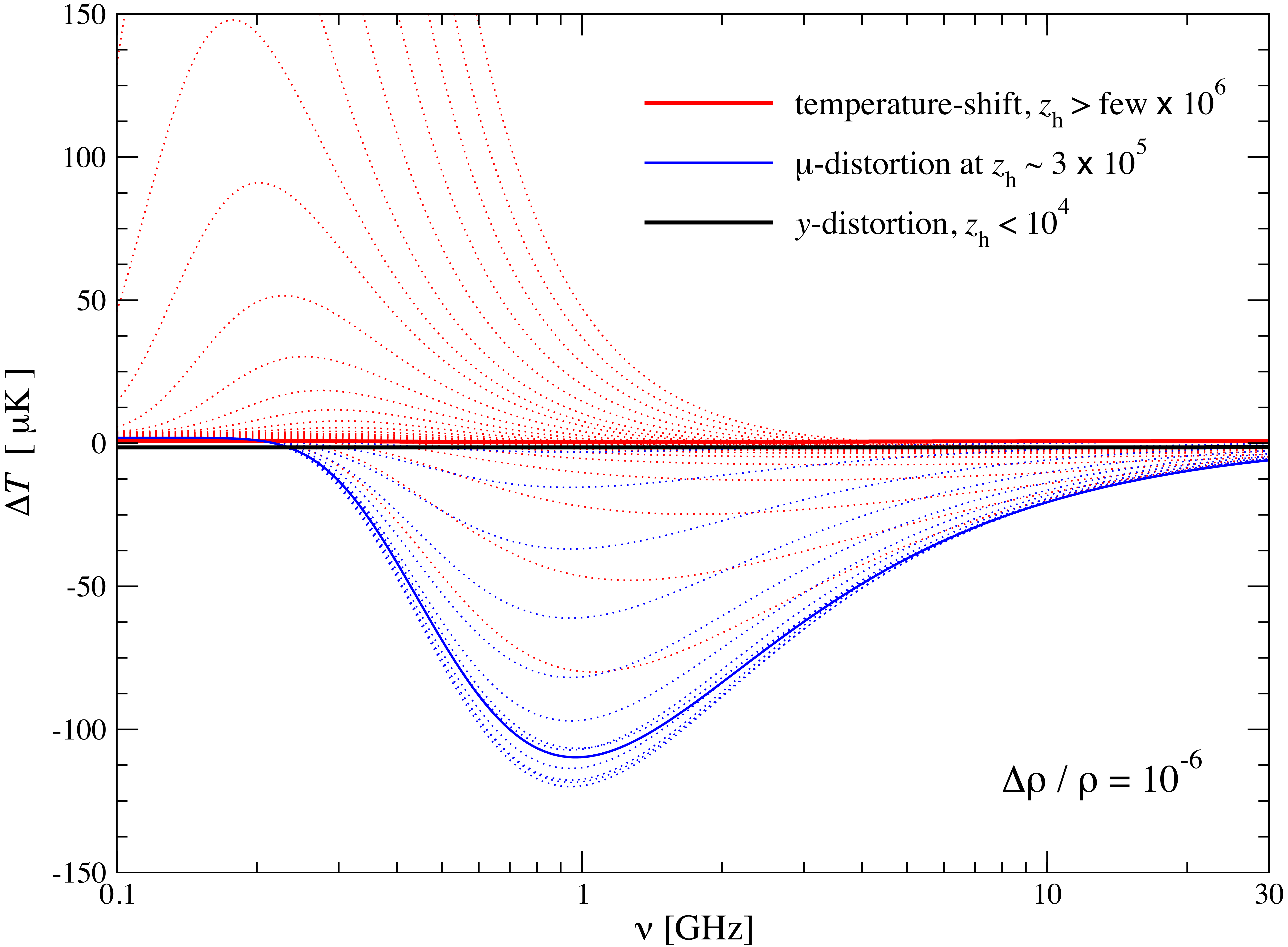

temperature-shift, z_h > few x 10^6
μ-distortion at $z_h \sim 3 \times 10^5$
y-distortion, $z_h < 10^4$
$\Delta\rho / \rho = 10^{-6}$
ΔT [μK]
ν [GHz]
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
30
50
100
300
600
1000



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ν [GHz]
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100
50
0
-50
-100
-150
0.1
1
10
30

Transition from y-distortion → μ-distortion

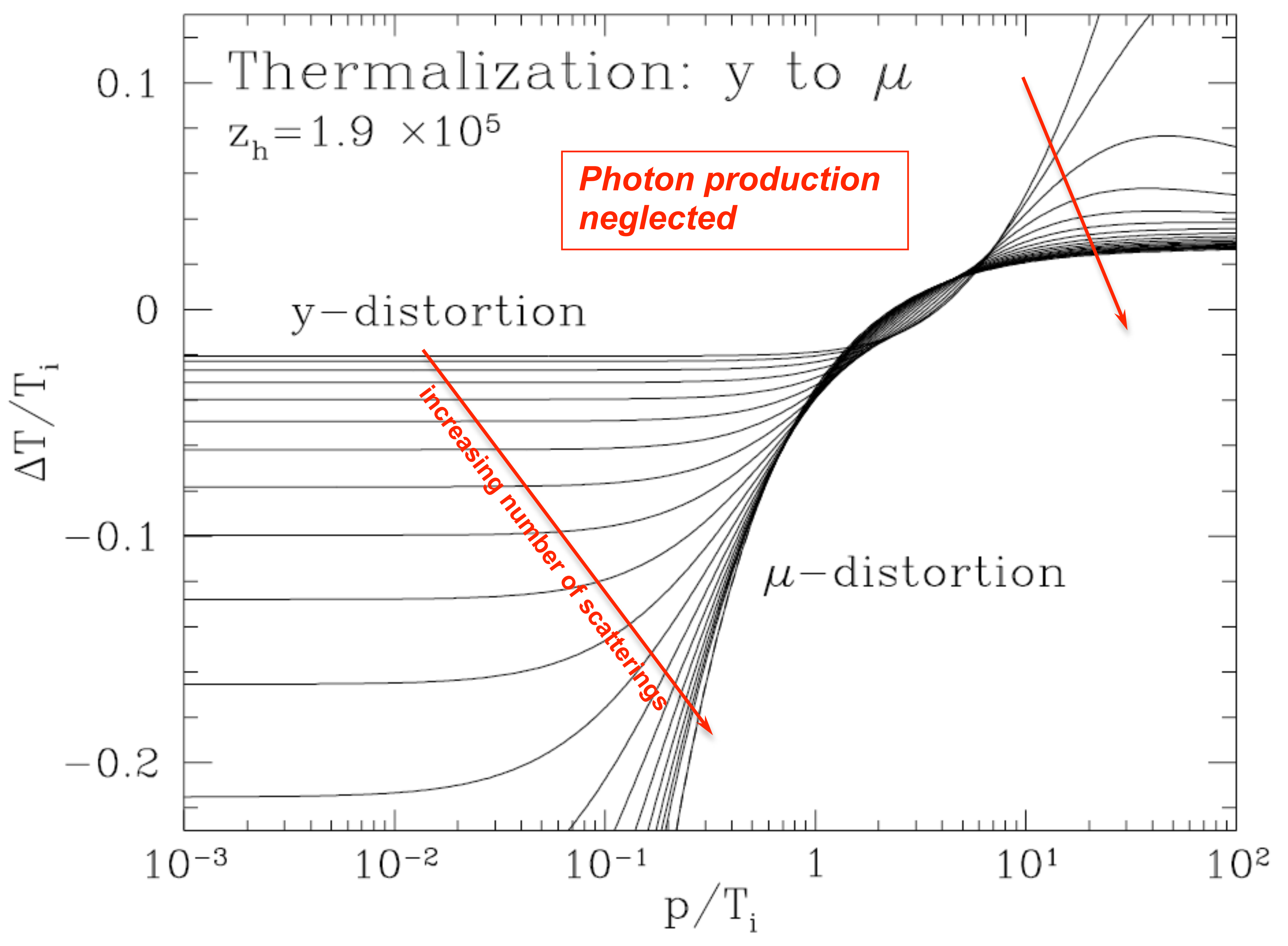
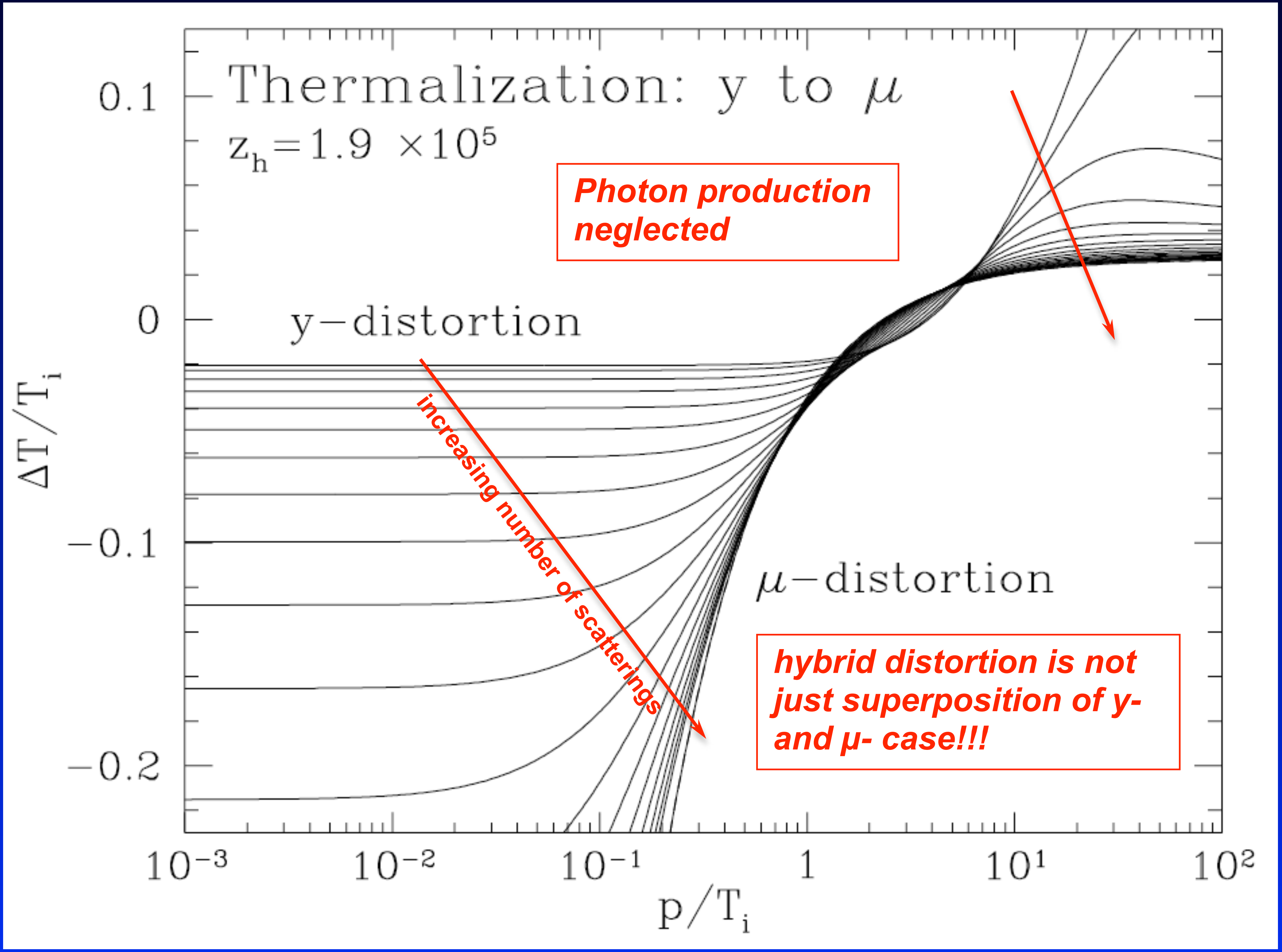


Figure from Wayne Hu's PhD thesis, 1995

Transition from y-distortion → μ-distortion



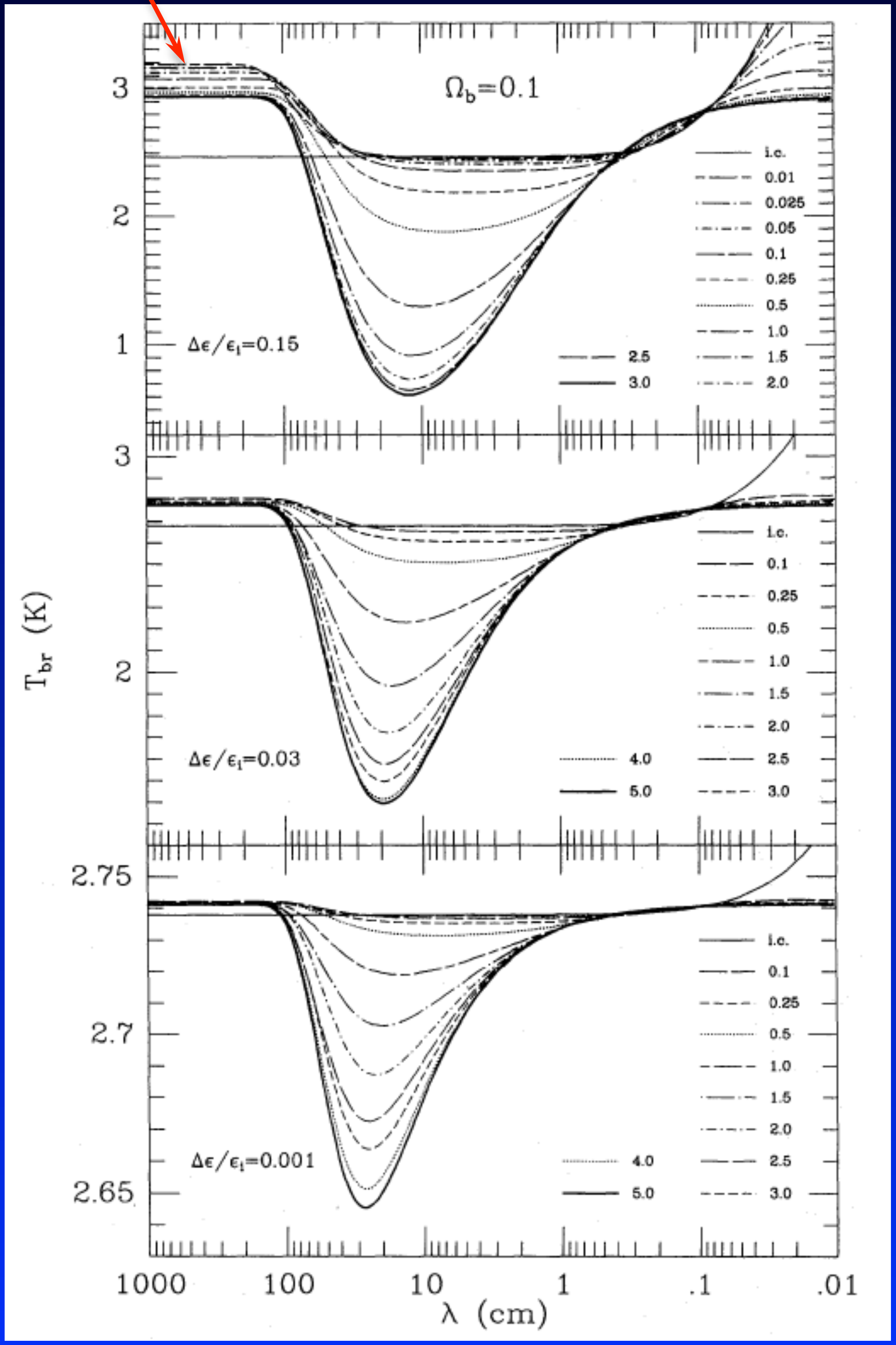
Photon production neglected

hybrid distortion is not just superposition of y- and μ- case!!!

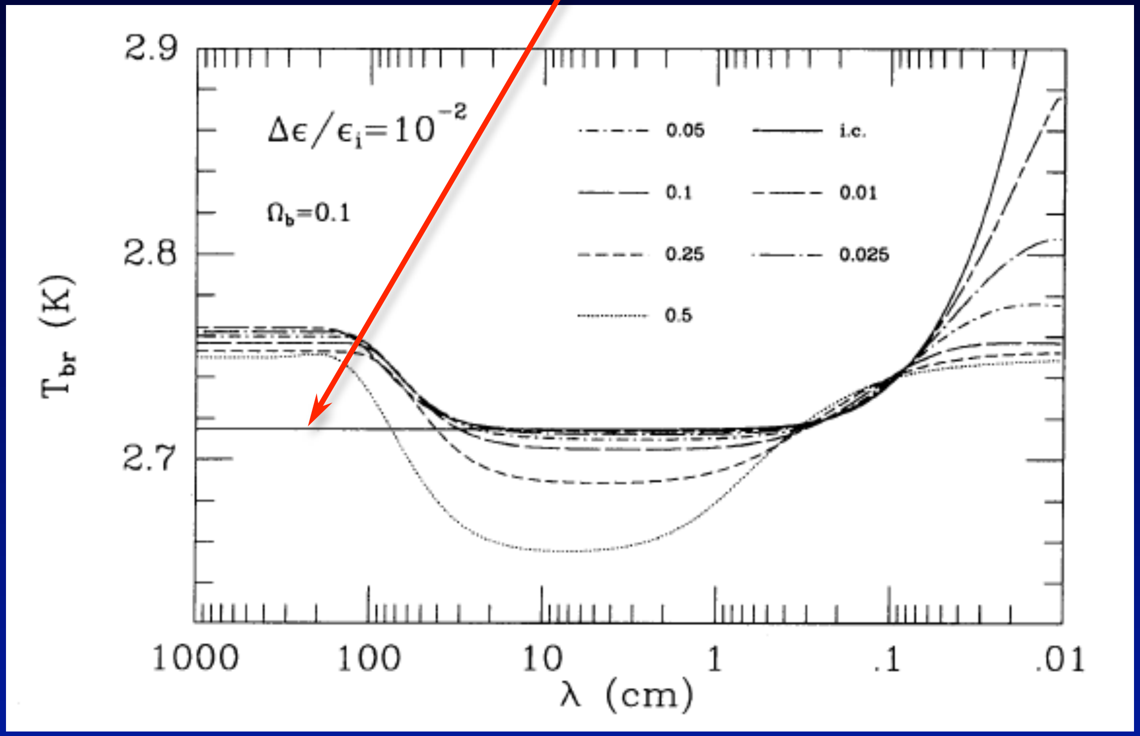
Figure from Wayne Hu's PhD thesis, 1995

Thermalization from $y \rightarrow \mu$ *at low frequencies*

Effect of photon production!



All calculations start with y-distortion here



- amount of energy

  ↔ amplitude of distortion

  ↔ position of 'dip'

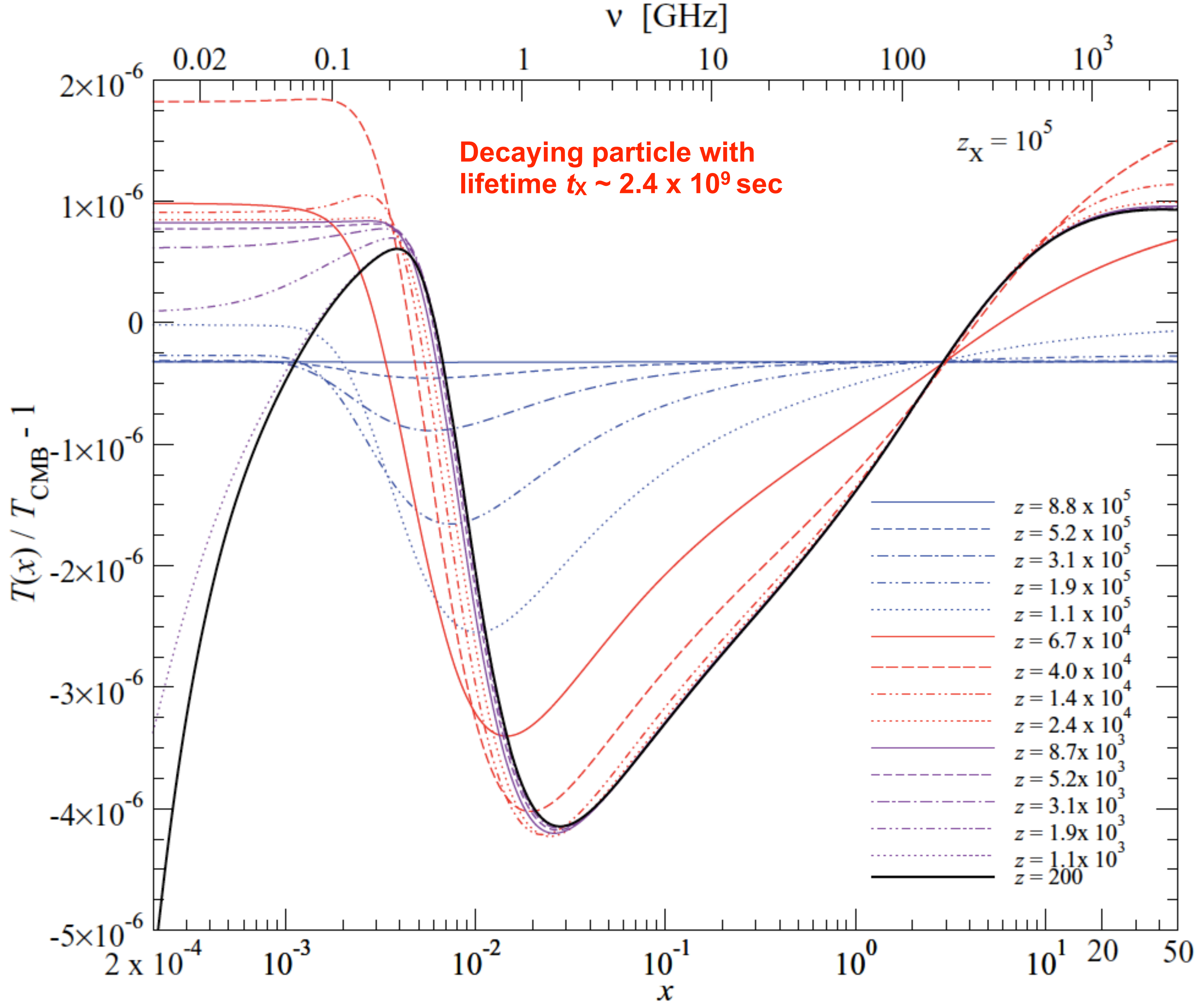
- hydrid case ($3\times10^5 \geq z \geq 10000$)

  ⇒ superposition between μ & y + *residual*

- details at very low frequencies change

Burigana, De Zotti & Danese, 1991, ApJ
Burigana, Danese & De Zotti, 1991, A&A

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

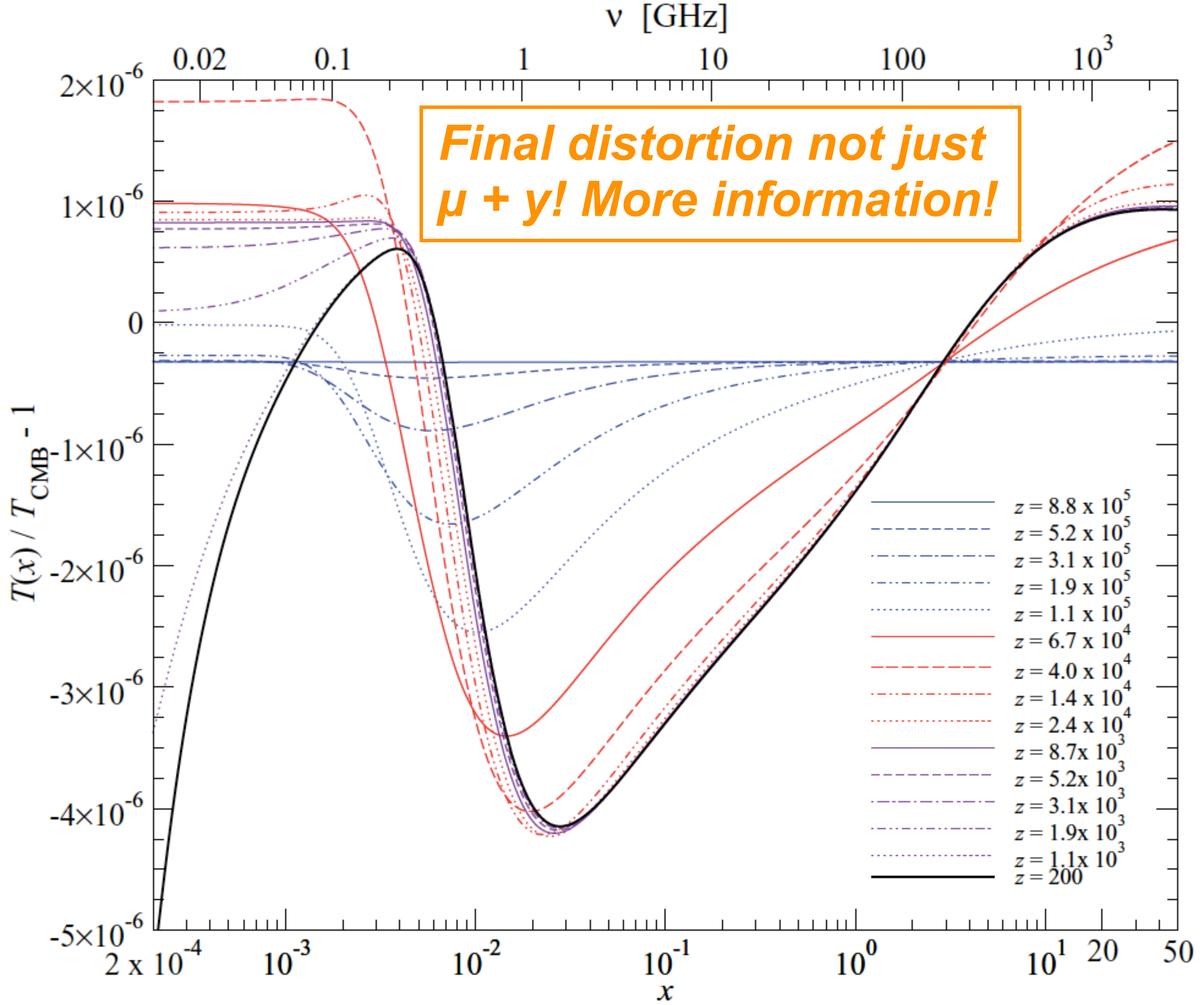


Decaying particle with lifetime t_X ~ 2.4 x 10^9 sec

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

- Explicit calculation that emphasized that there is more

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



Final distortion not just μ + y! More information!

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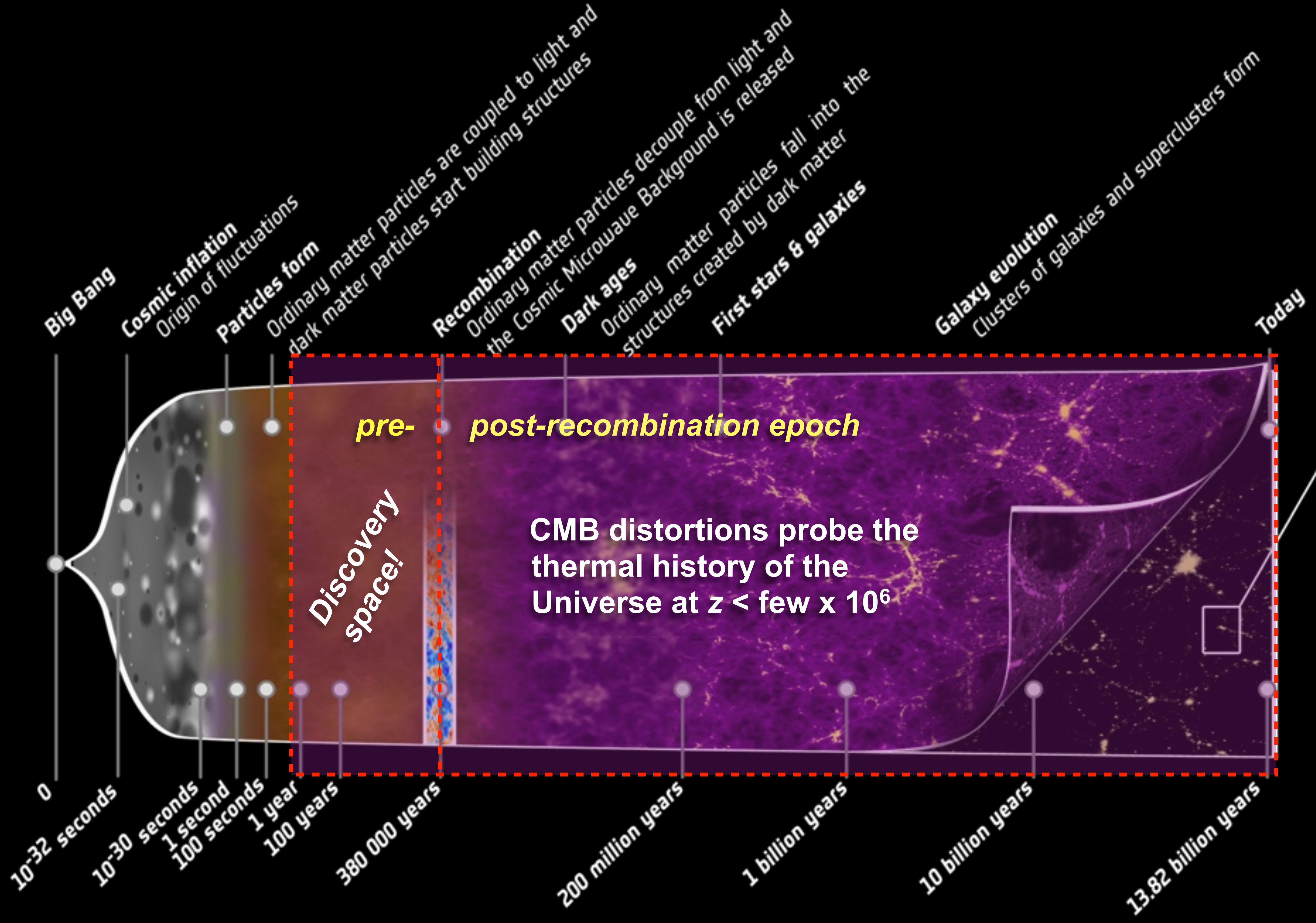

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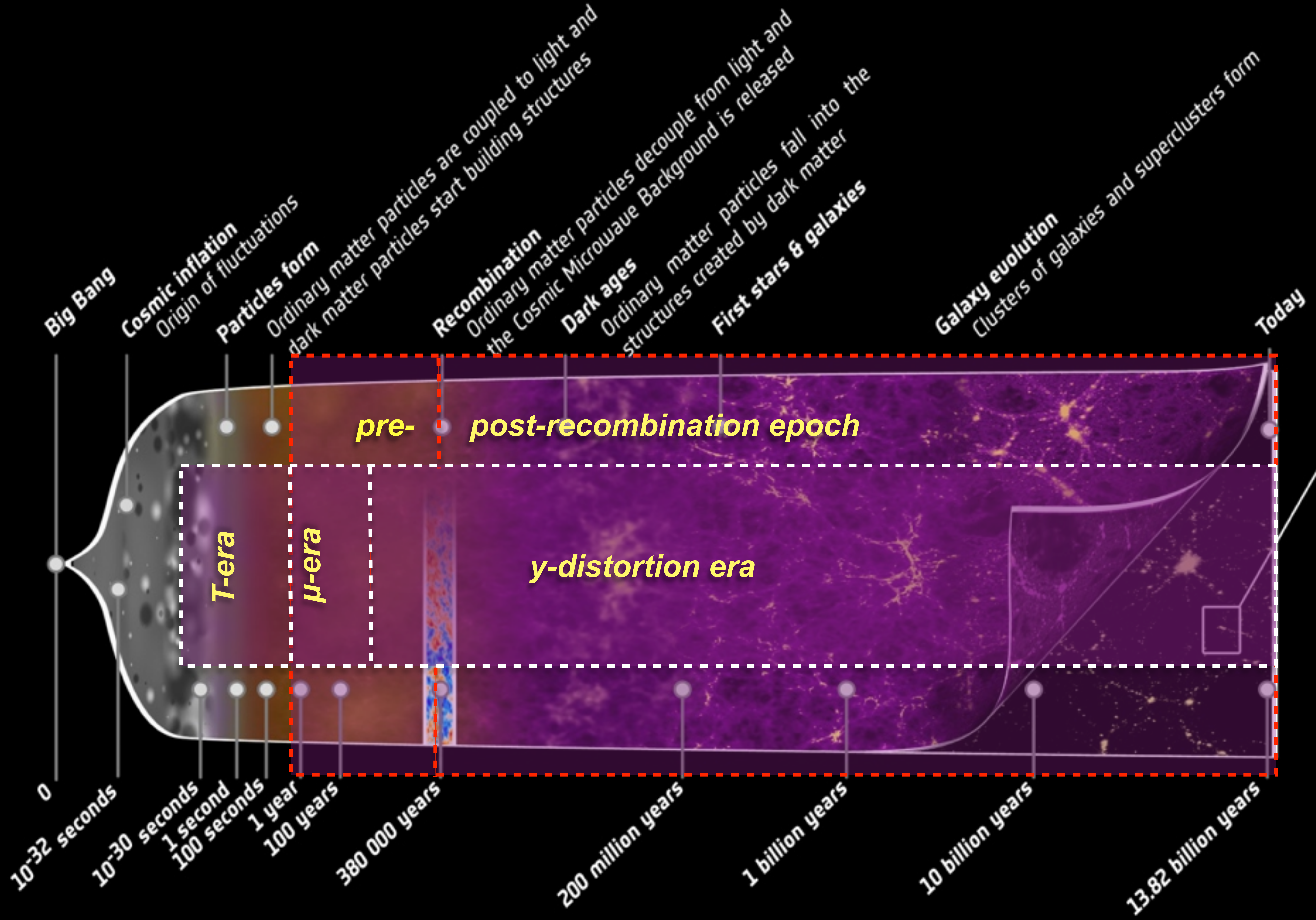
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pre-
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μ-era
y-distortion era
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10^{-32} seconds
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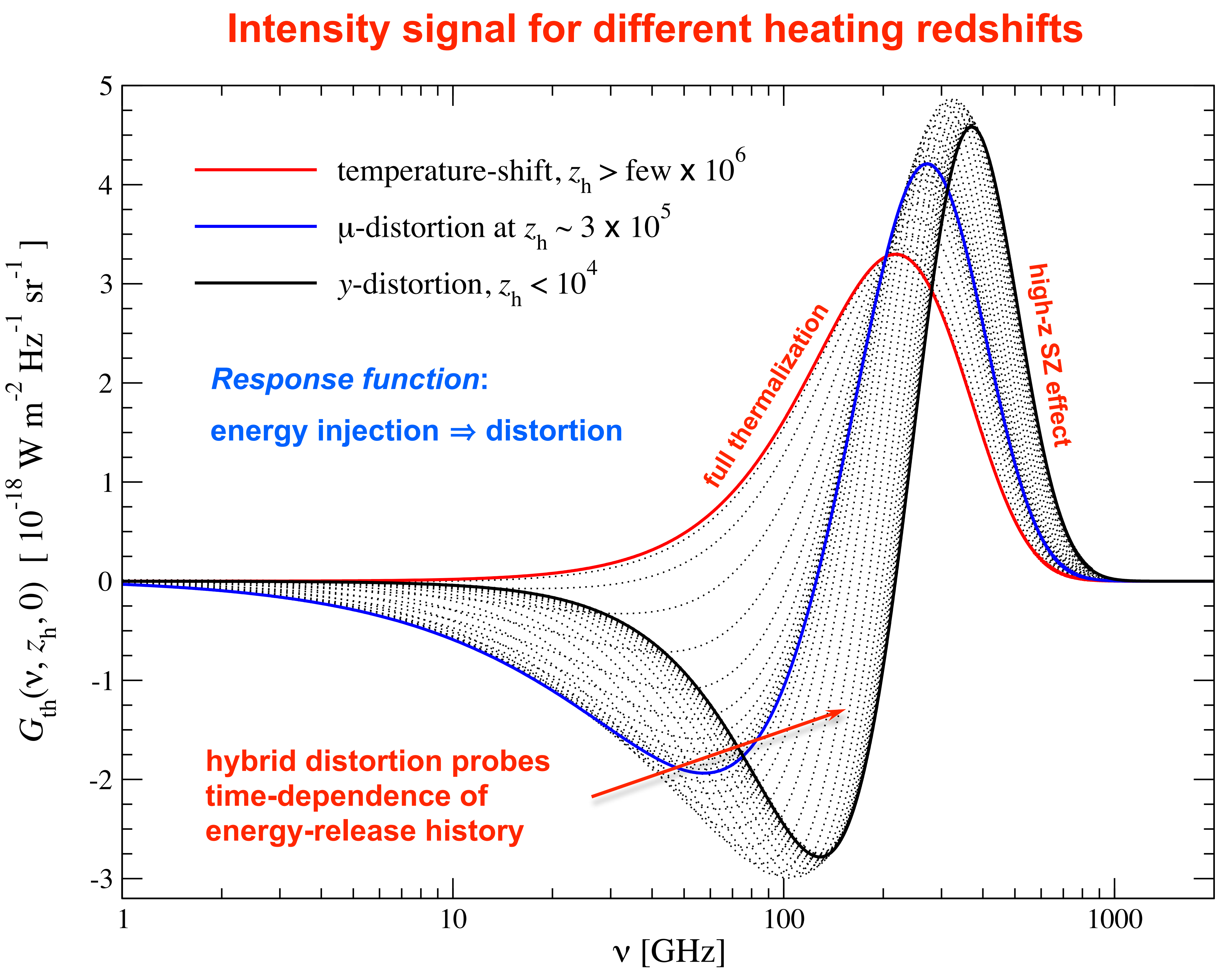

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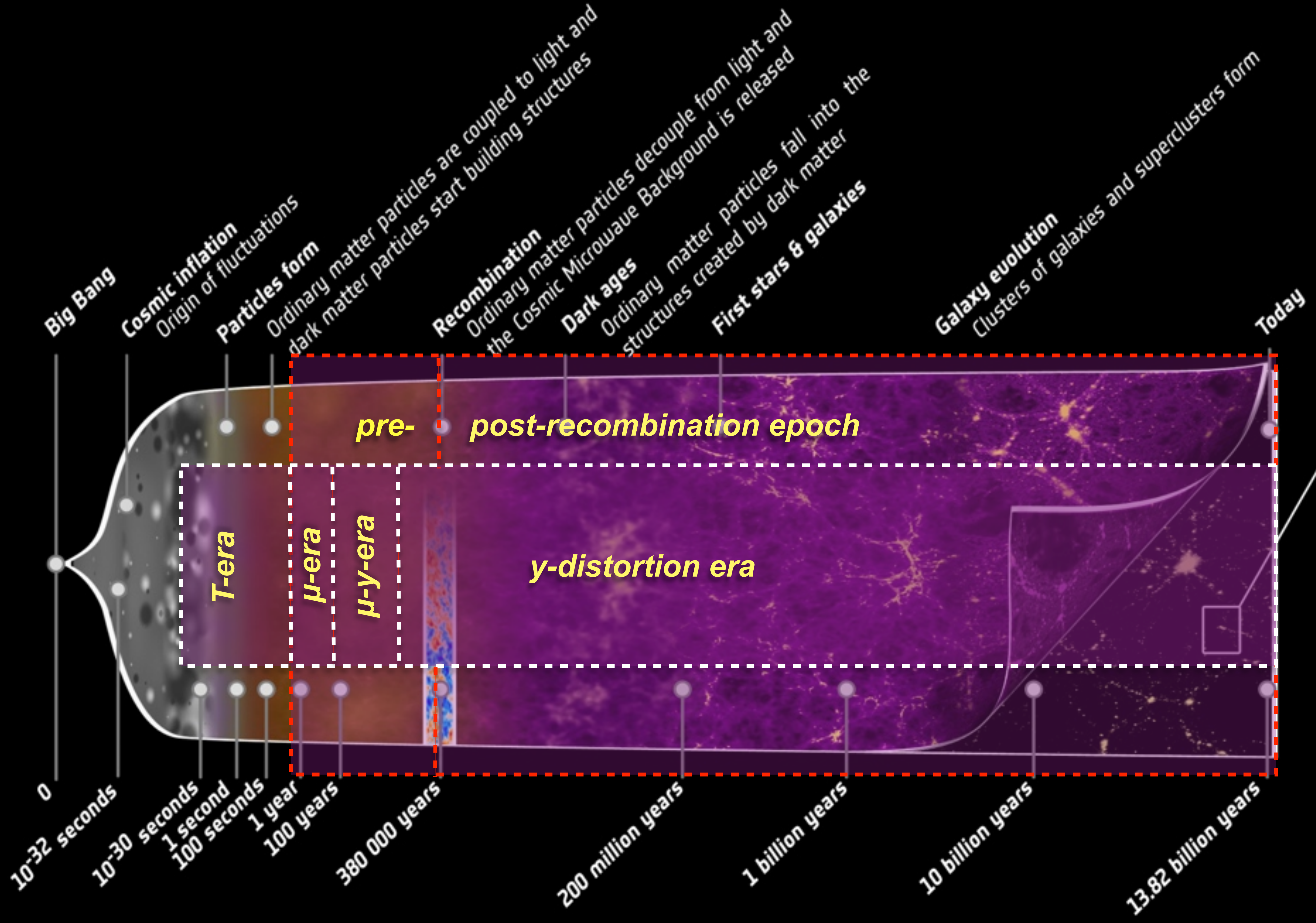
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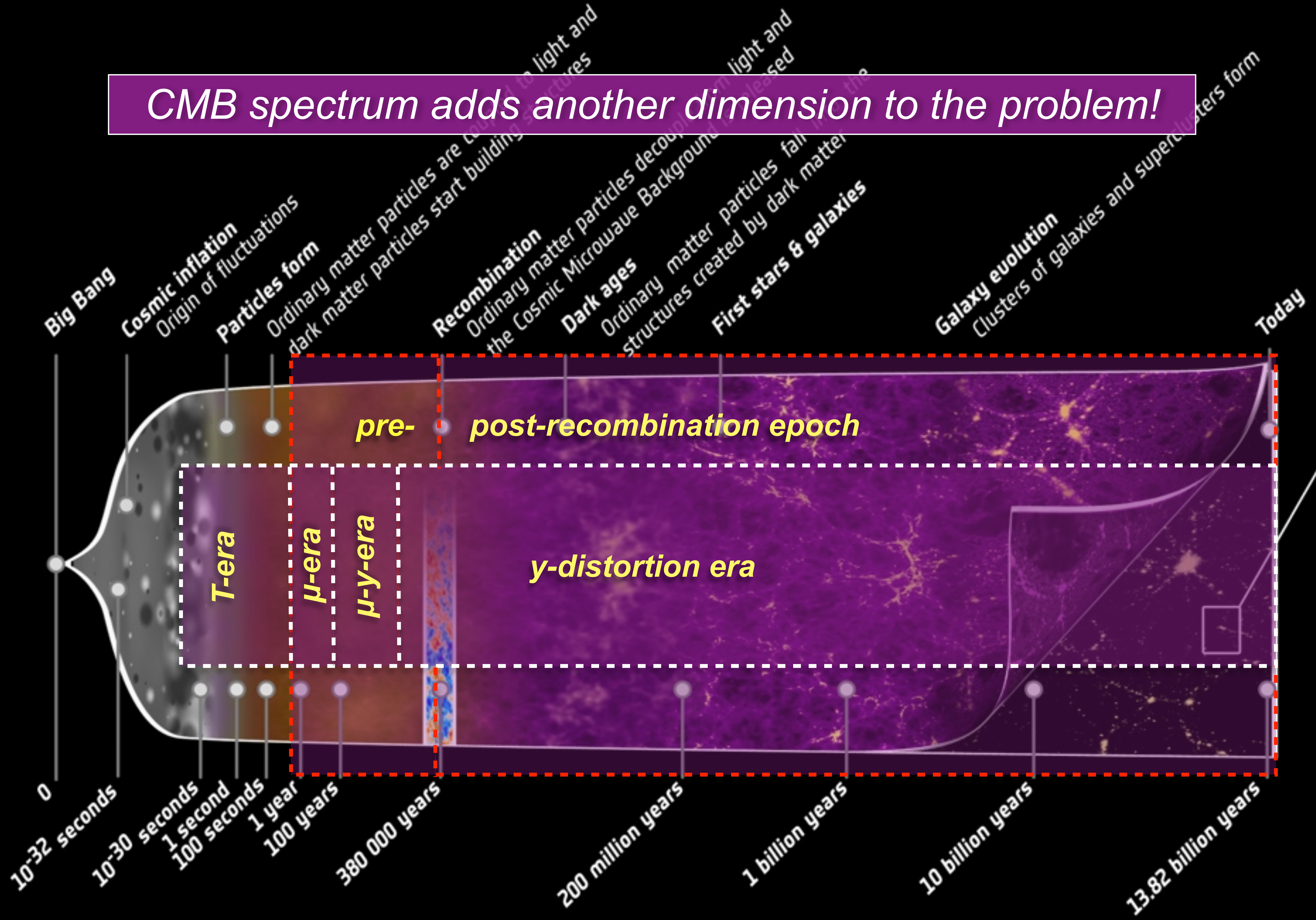
CMB spectrum adds another dimension to the problem!



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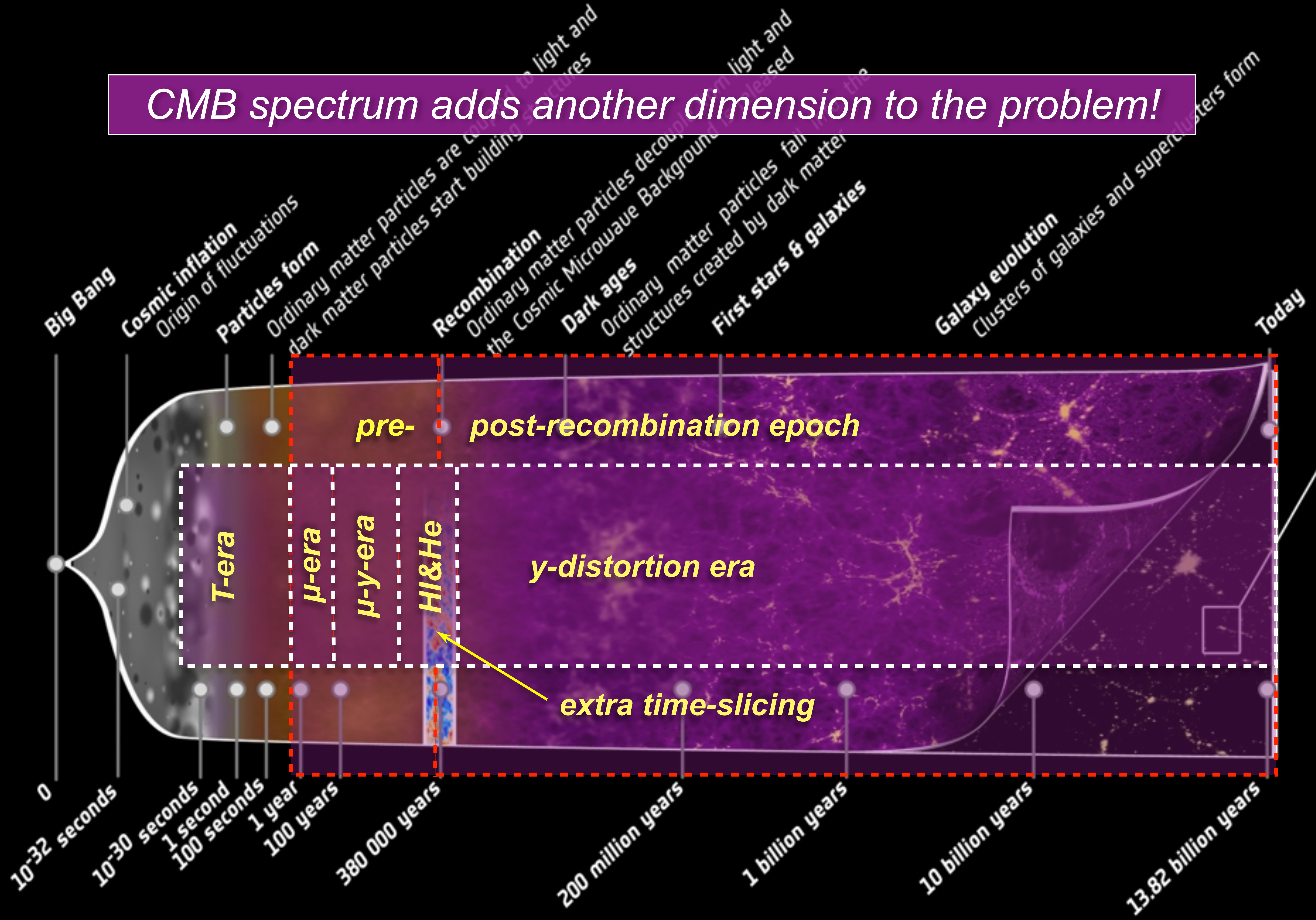

pre-

post-recombination epoch

T-era

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μ-y-era

HI&He

y-distortion era

extra time-slicing

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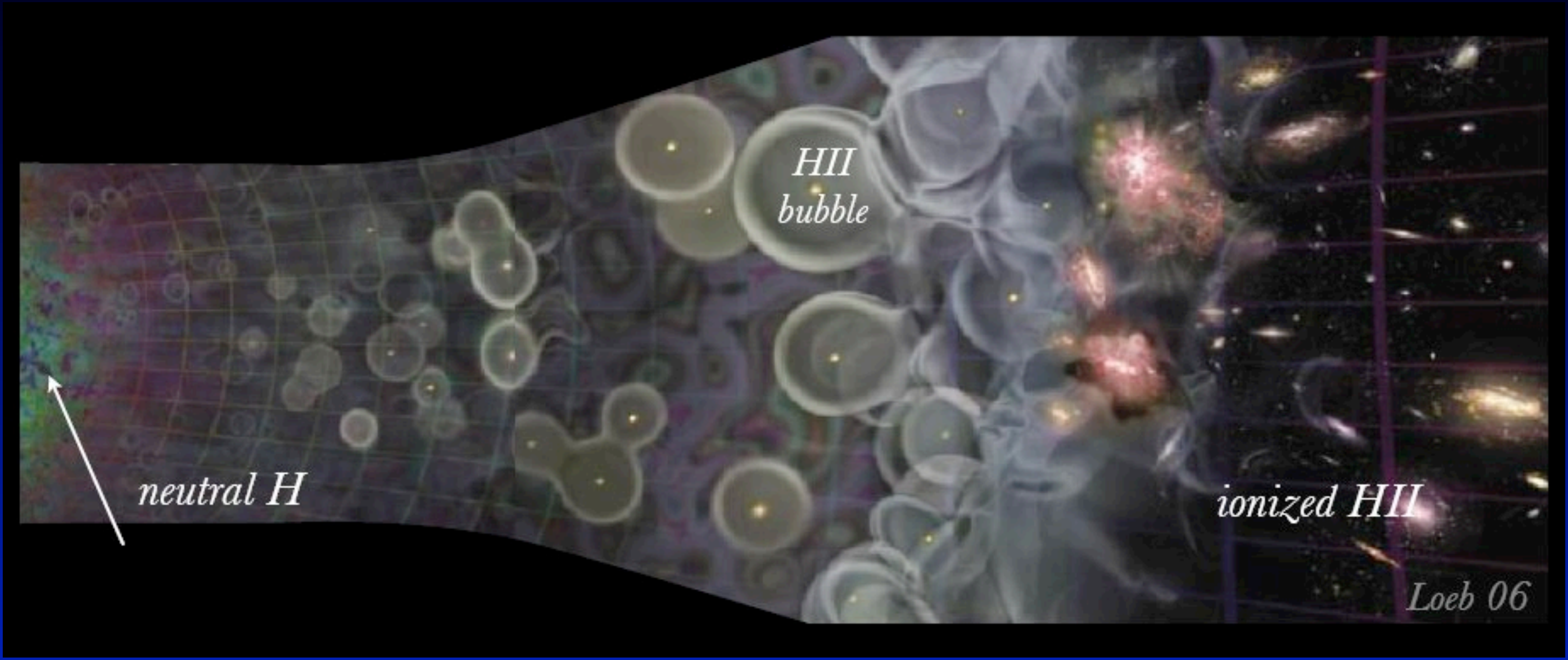
Reionization and structure formation

Simple estimates for the distortion



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

$$\Longrightarrow \quad y \simeq \frac{kT_{\rm e}}{m_{\rm e}c^2}\,\tau \approx 2\times10^{-7}$$

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

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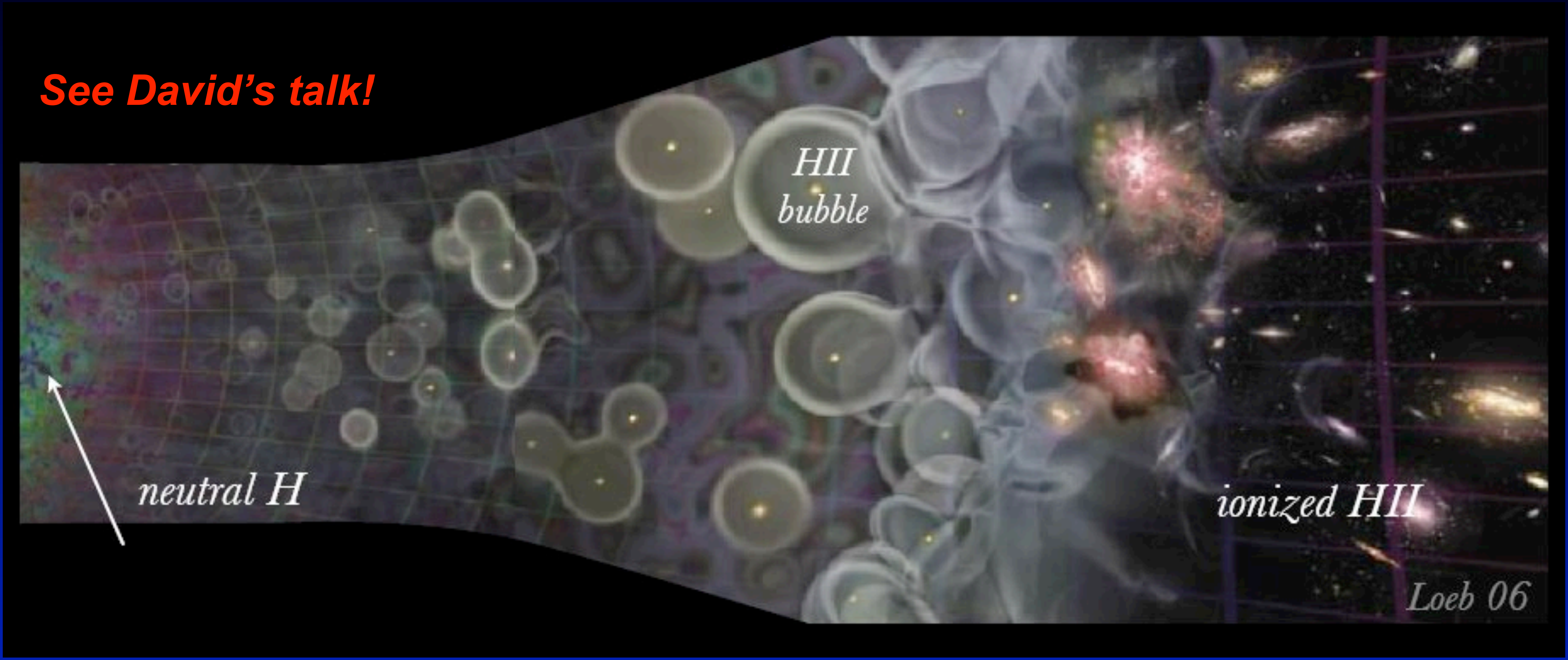

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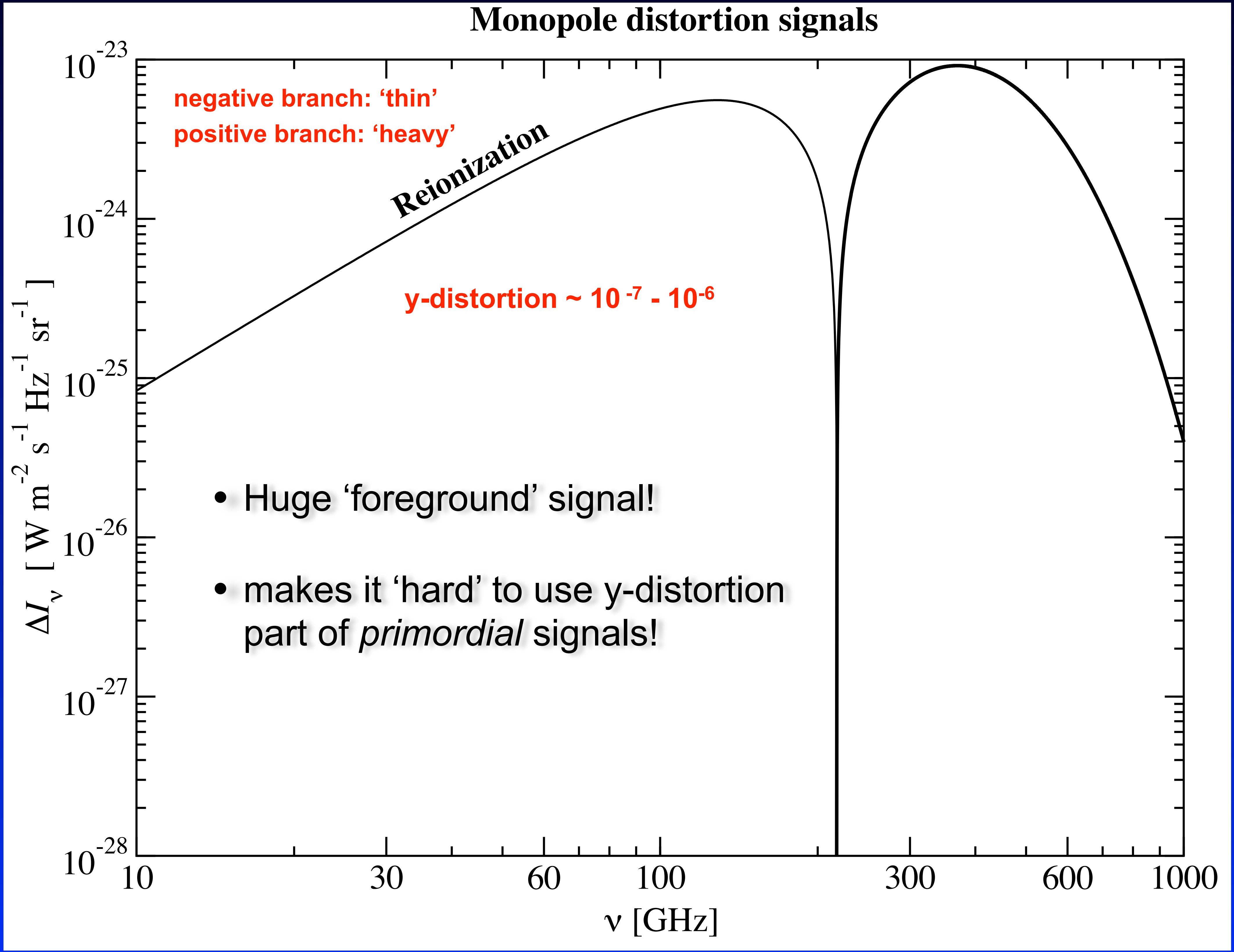


Monopole distortion signals

Absolute value of Intensity signal

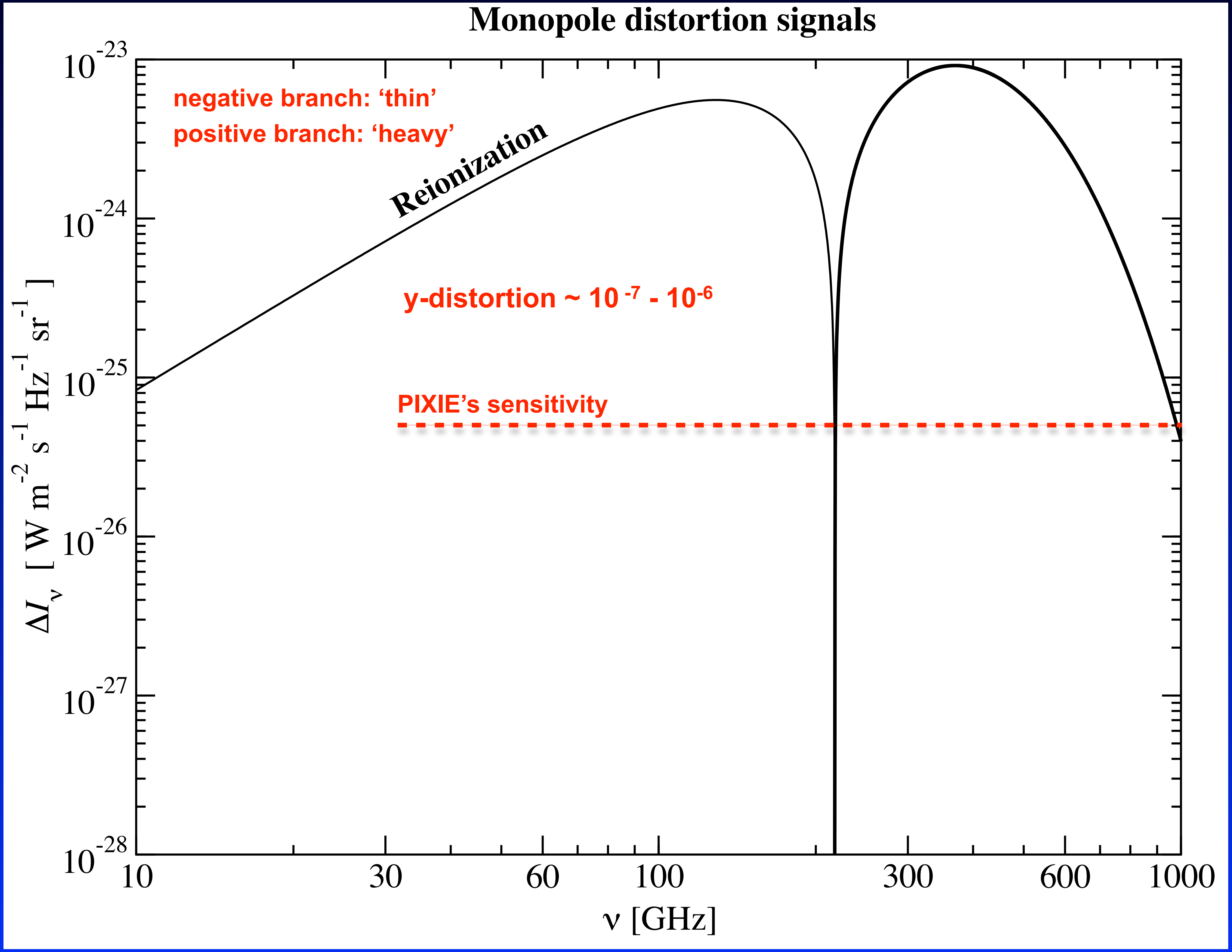
negative branch: ‘thin’

positive branch: ‘heavy’

y-distortion ~ 10^{-7} - 10^{-6}

- Huge ‘foreground’ signal!
- makes it ‘hard’ to use y-distortion part of *primordial* signals!

Average CMB spectral distortions



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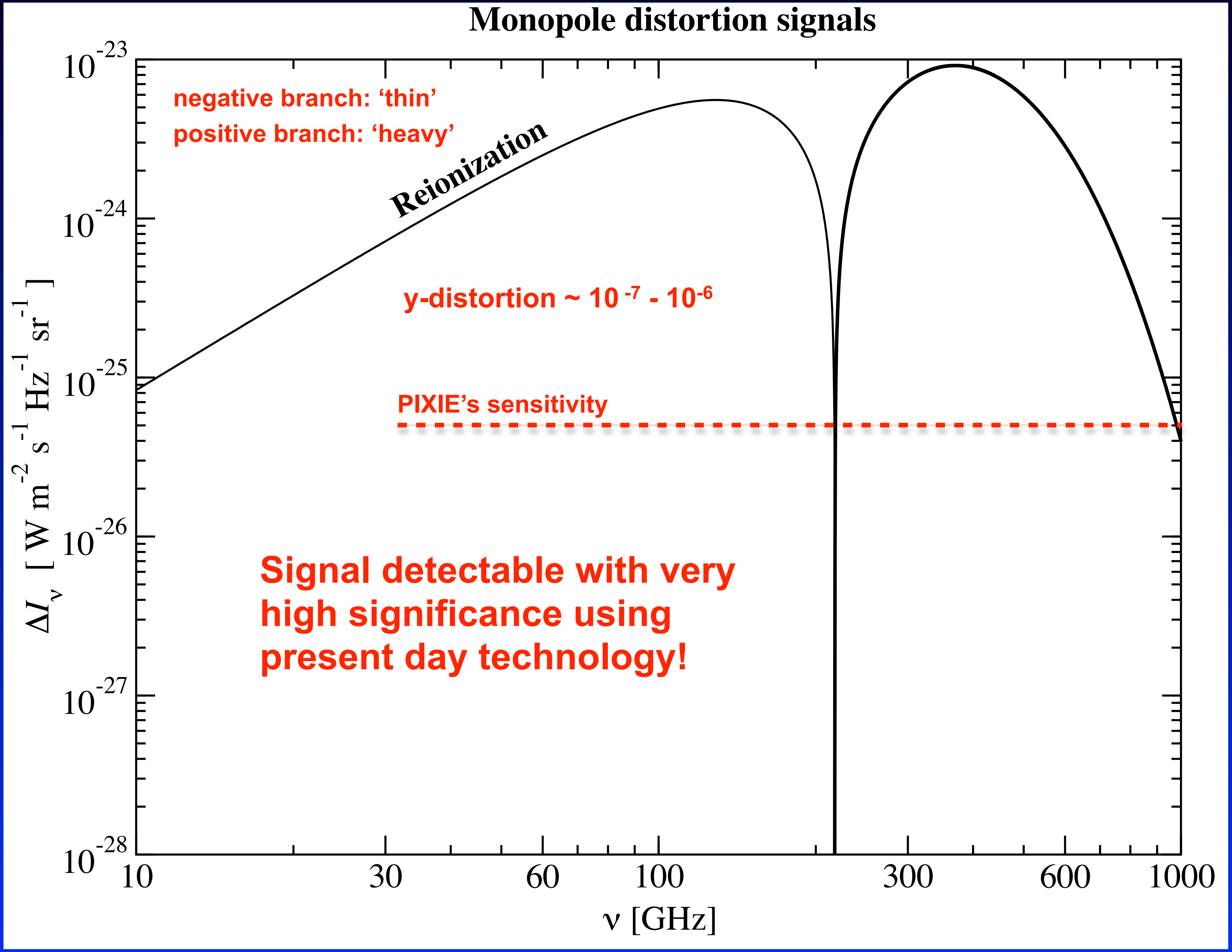

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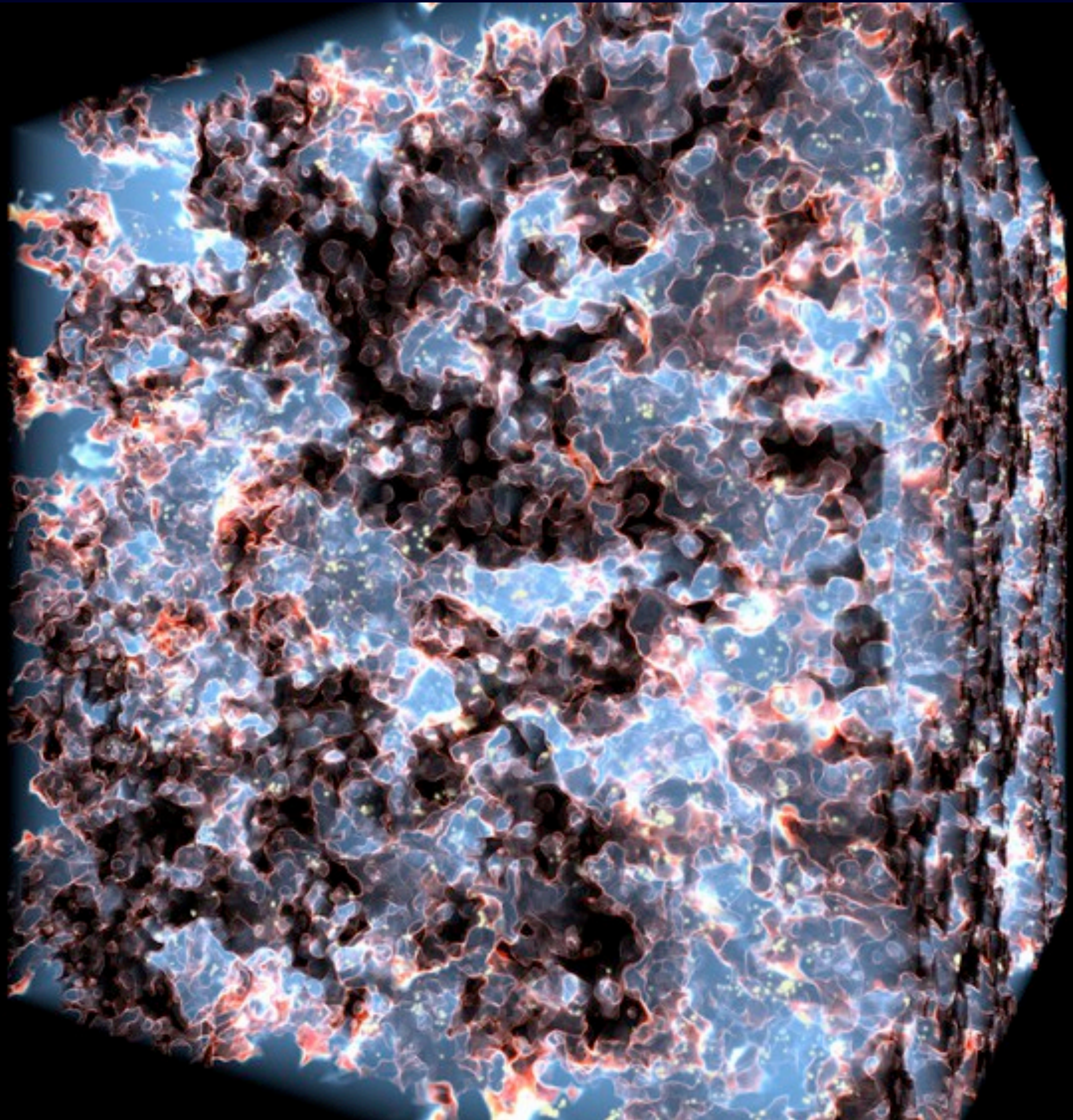
y-distortion ~ 10^{-7} - 10^{-6}

PIXIE’s sensitivity

Signal detectable with very high significance using present day technology!

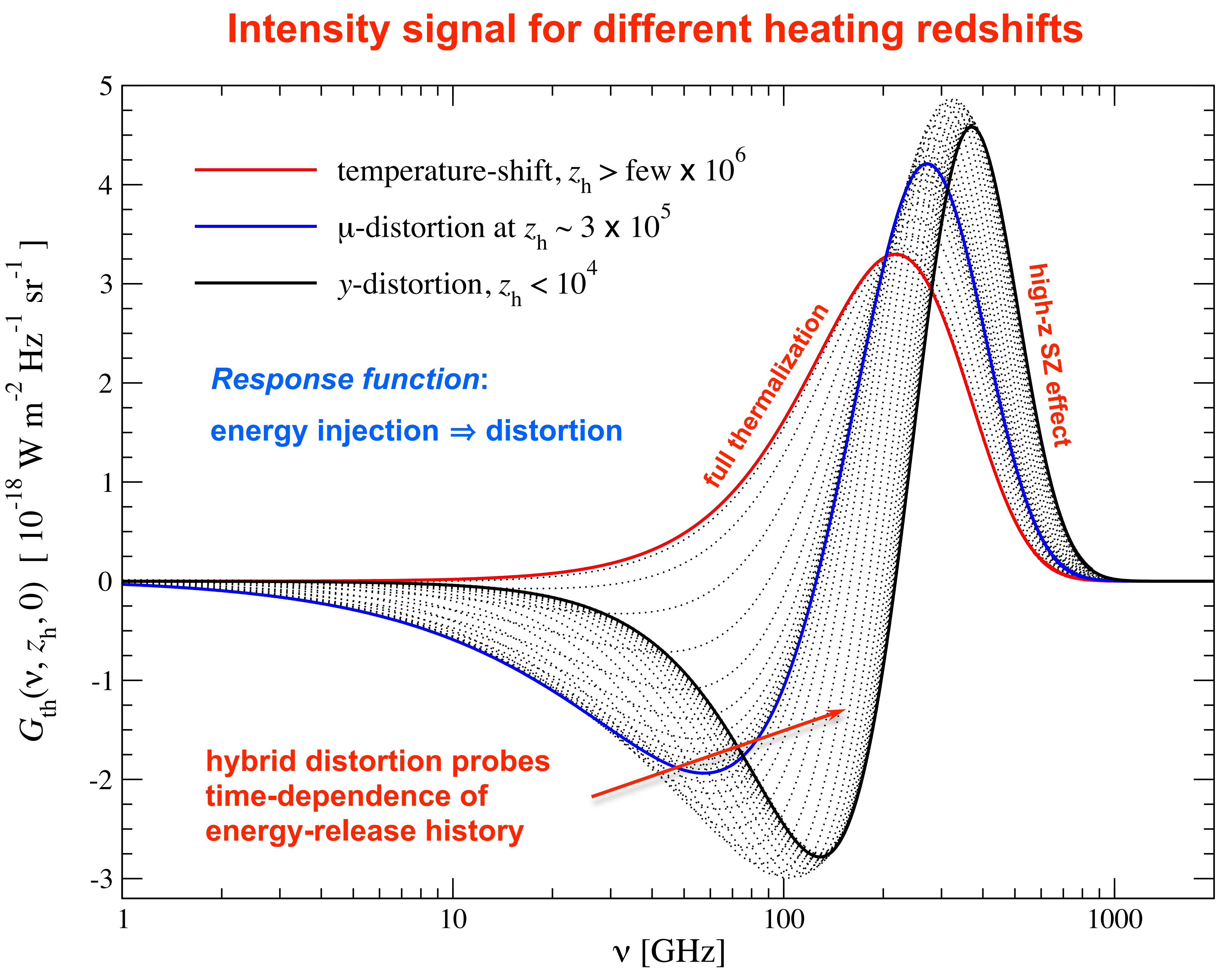
Fluctuations of the y-parameter at large scales



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

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

What does the spectrum look like after energy injection?



Intensity signal for different heating redshifts

Response function:

energy injection ⇒ distortion

hybrid distortion probes time-dependence of energy-release history

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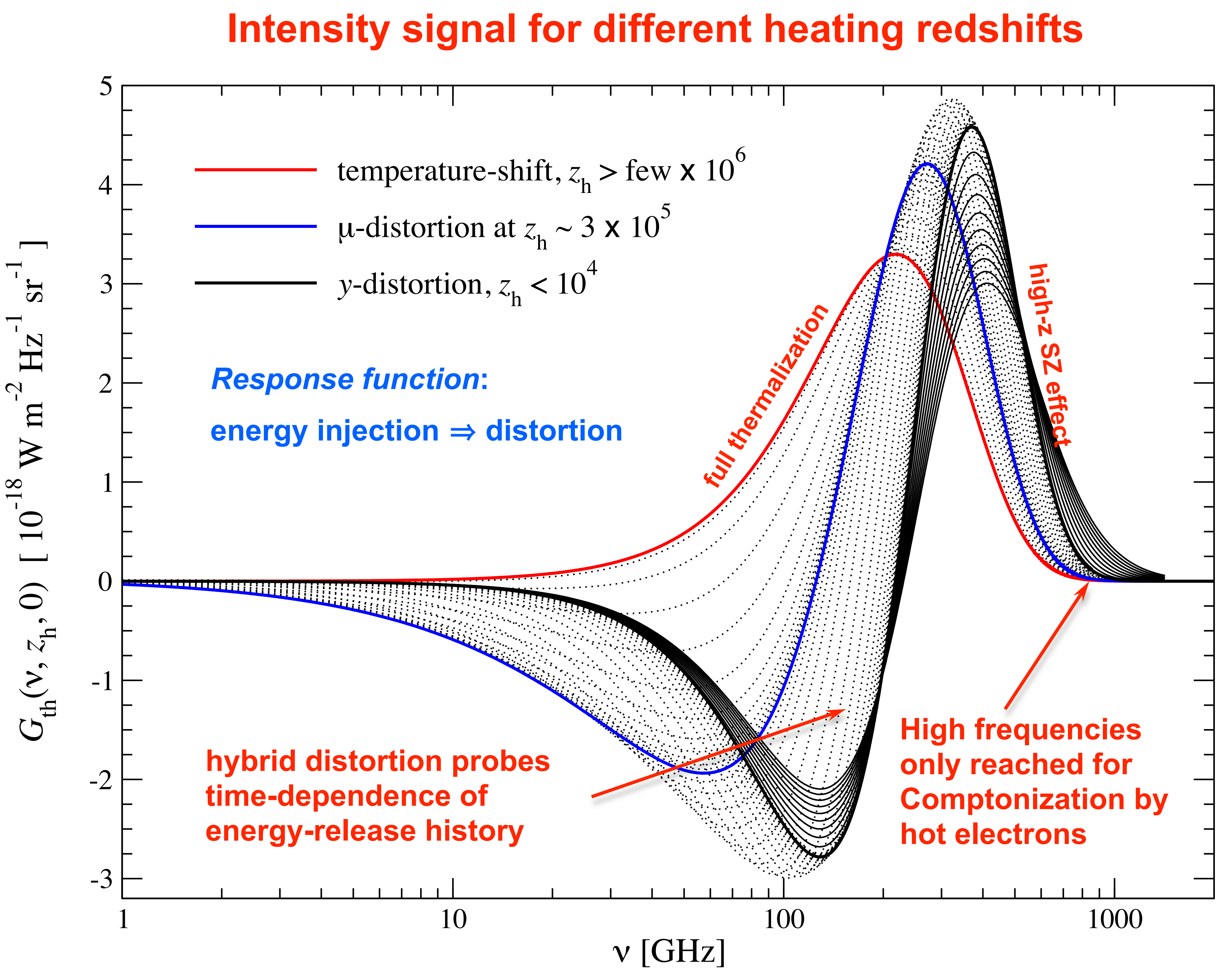

Intensity signal for different heating redshifts

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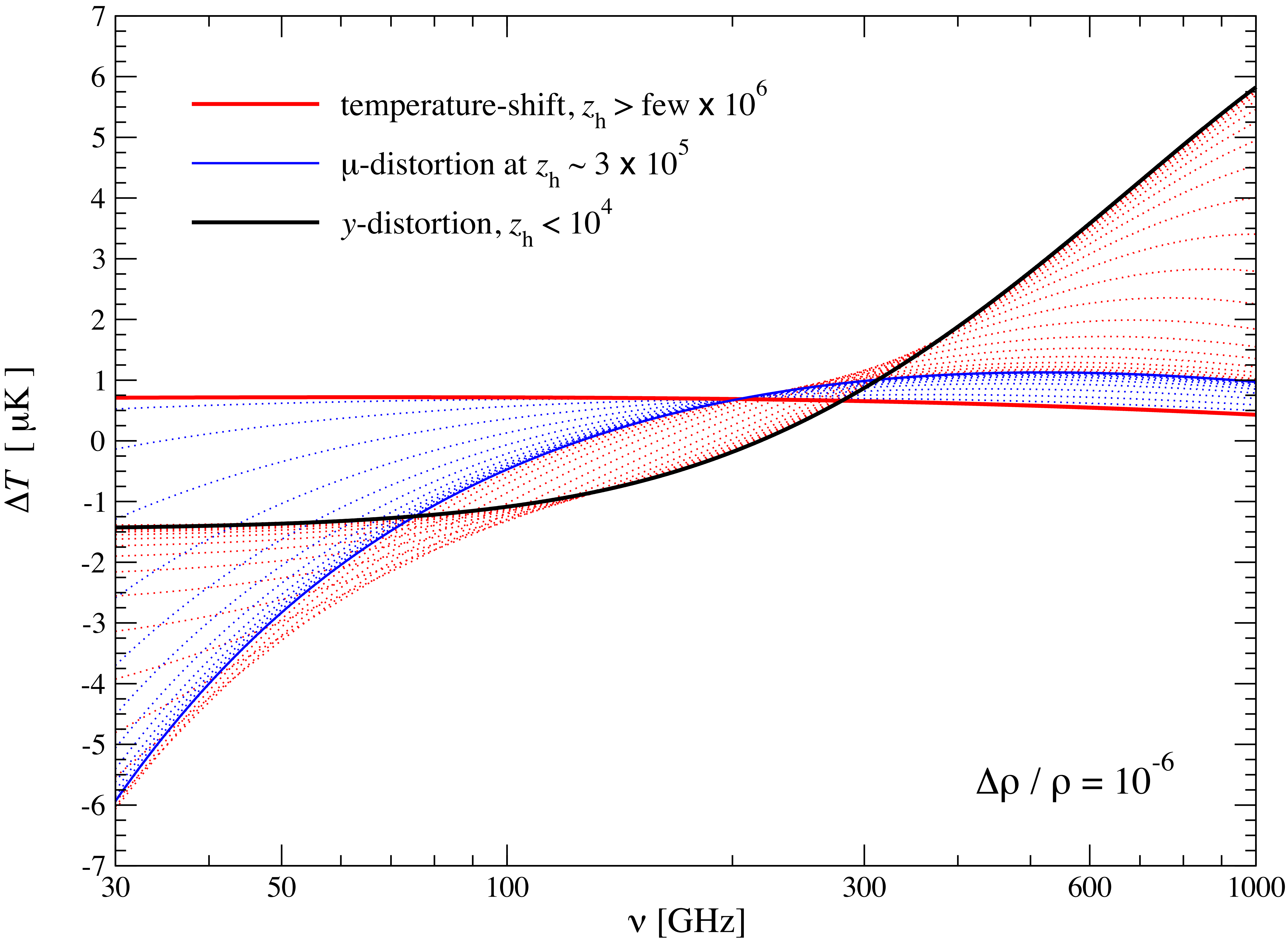
High frequencies only reached for Comptonization by hot electrons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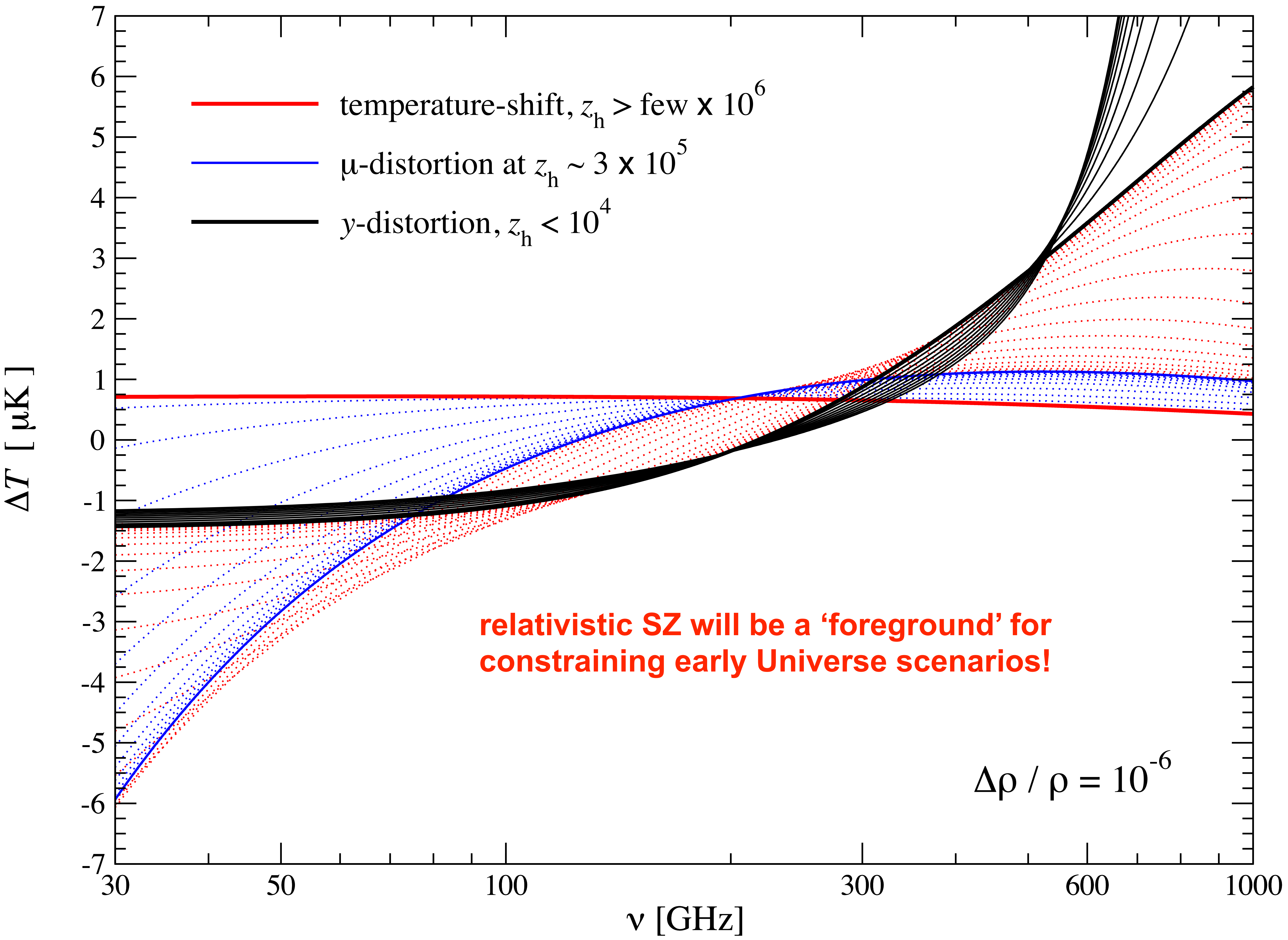
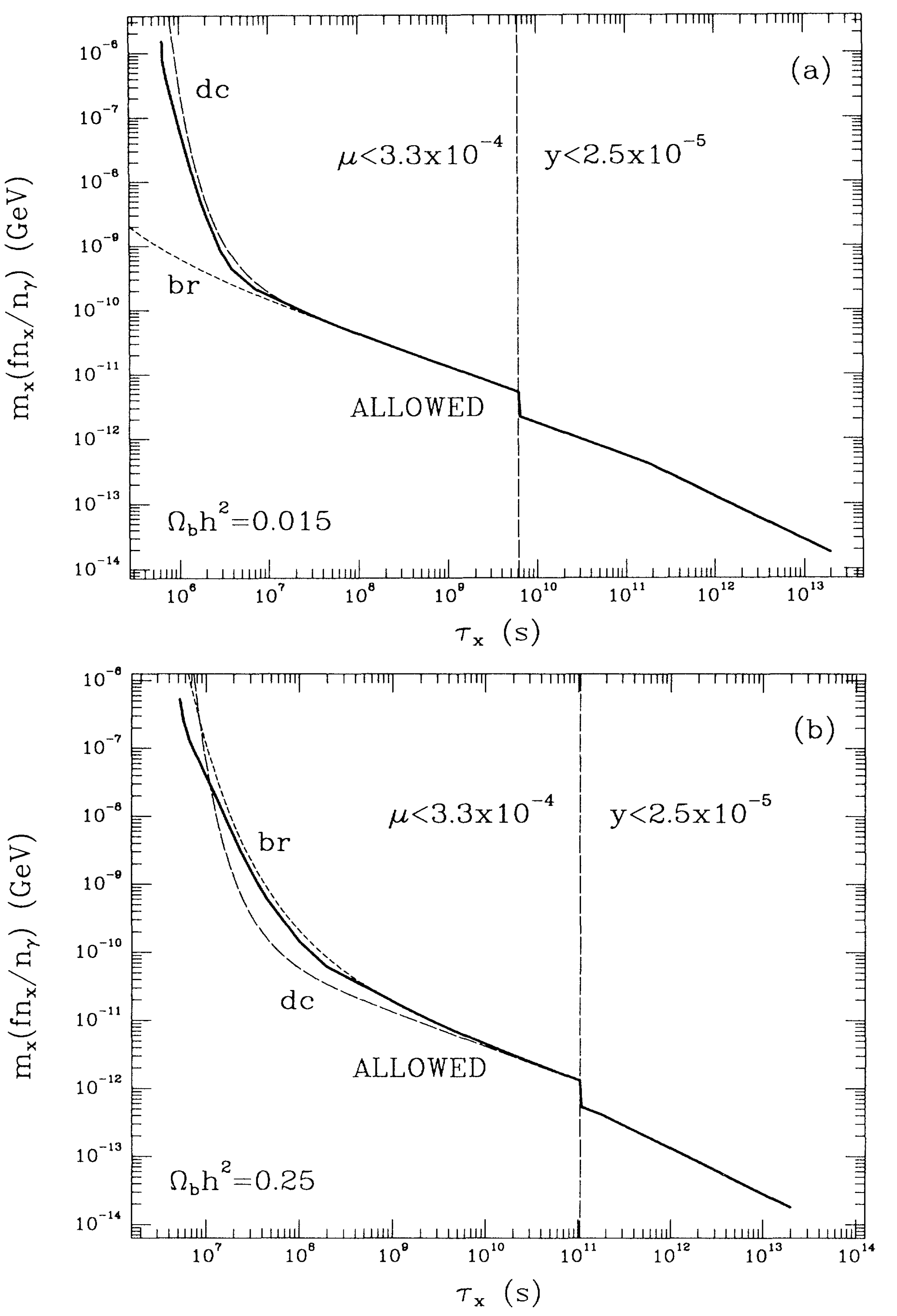


relativistic SZ will be a 'foreground' for constraining early Universe scenarios!

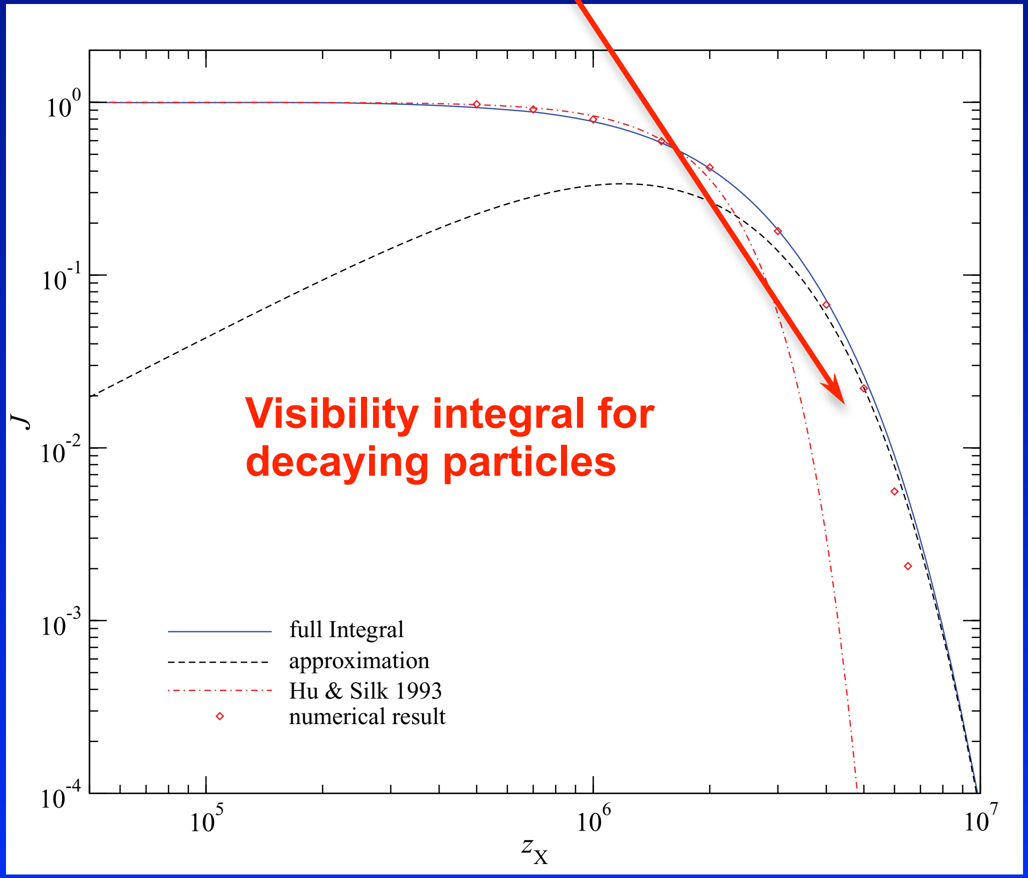
Decaying (dark matter) particles

Early constraints from CMB measurements



Hu & Silk, 1993

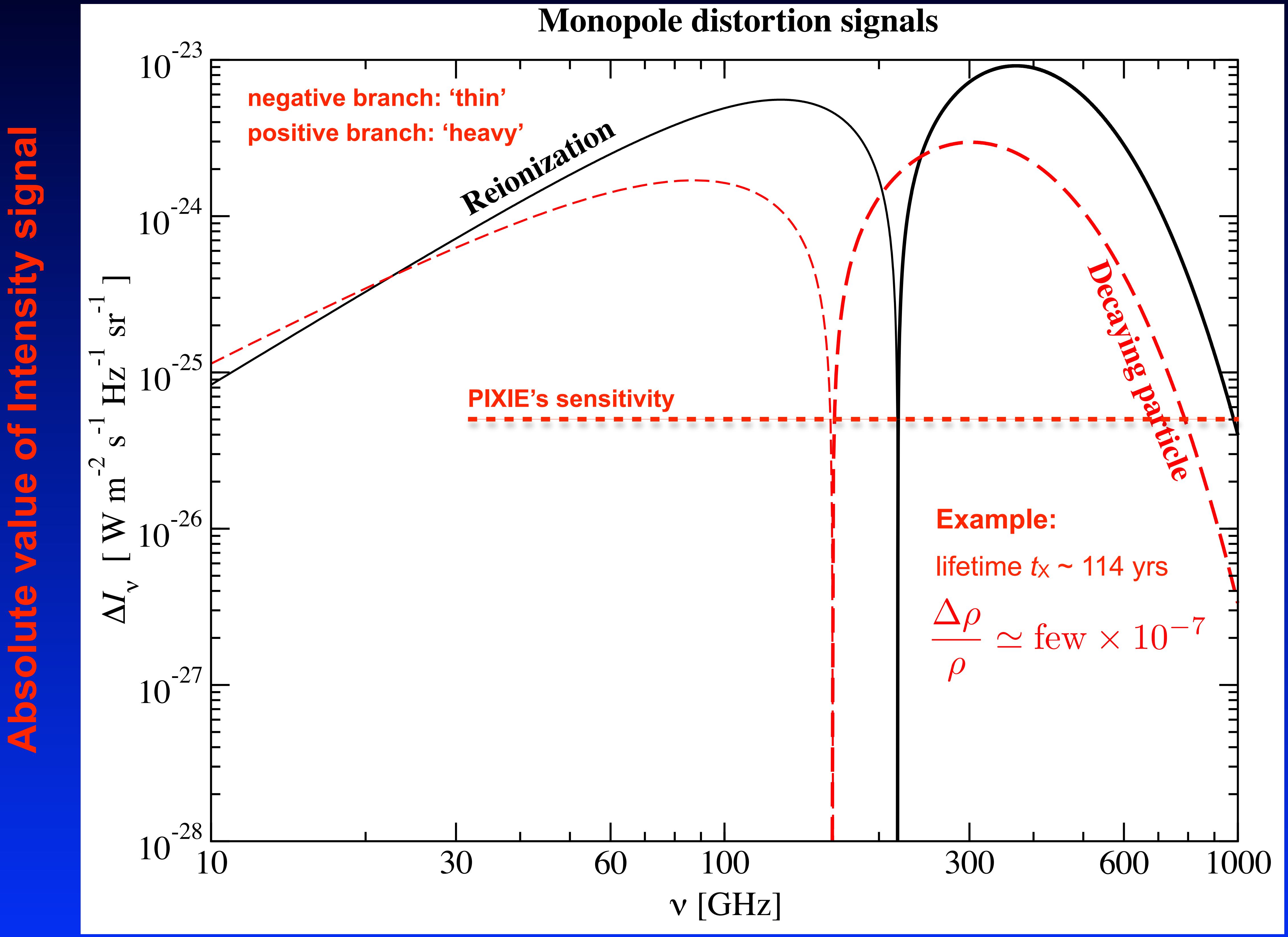
- Simple estimates for μ and y-distortion from energy arguments just like we discussed above
- Early COBE/FIRAS limits
- constraint a little tighter for short lifetimes than estimated...



Visibility integral for decaying particles

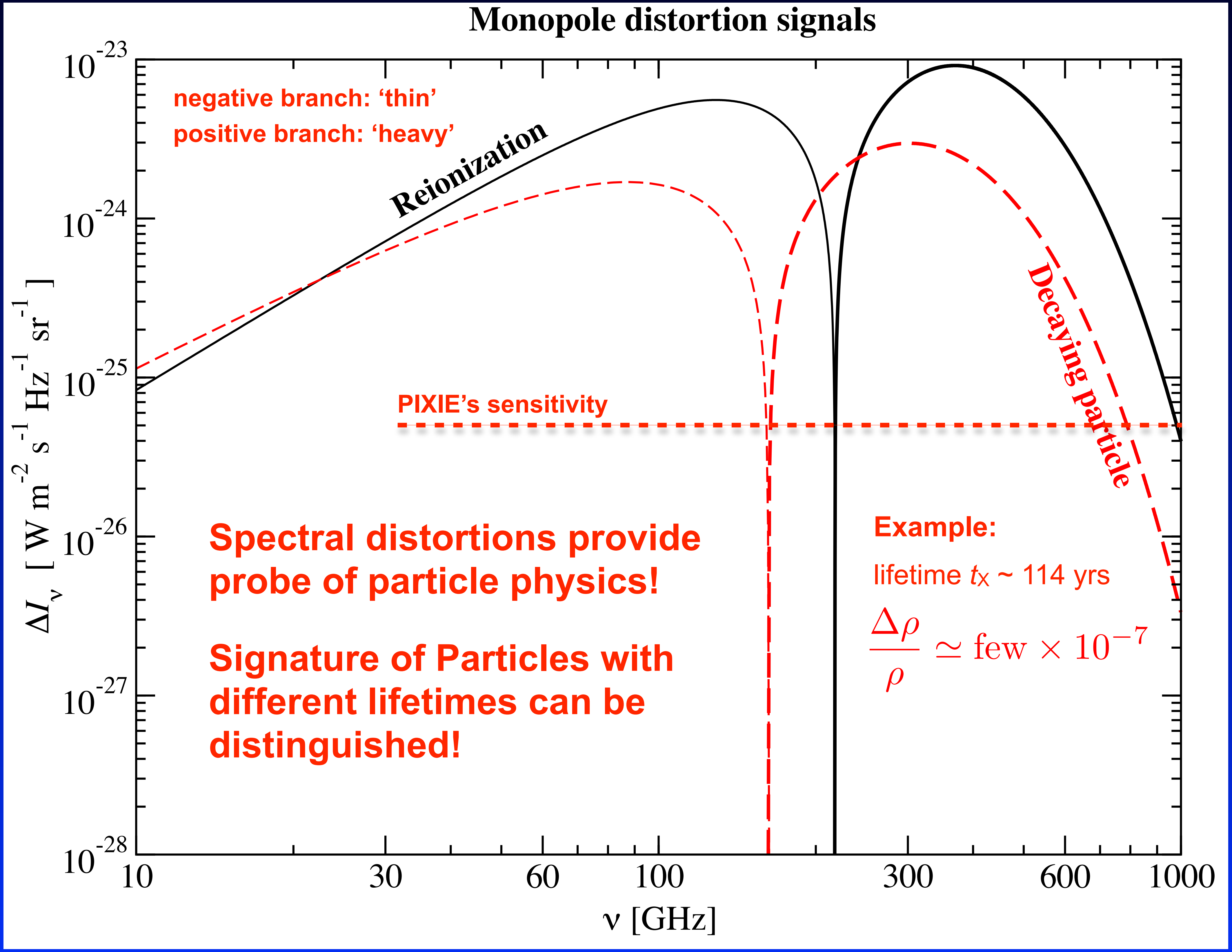
JC, 2005; JC & Sunyaev, 2012

Average CMB spectral distortions



Average CMB spectral distortions

Absolute value of Intensity signal



Spectral distortions provide probe of particle physics!

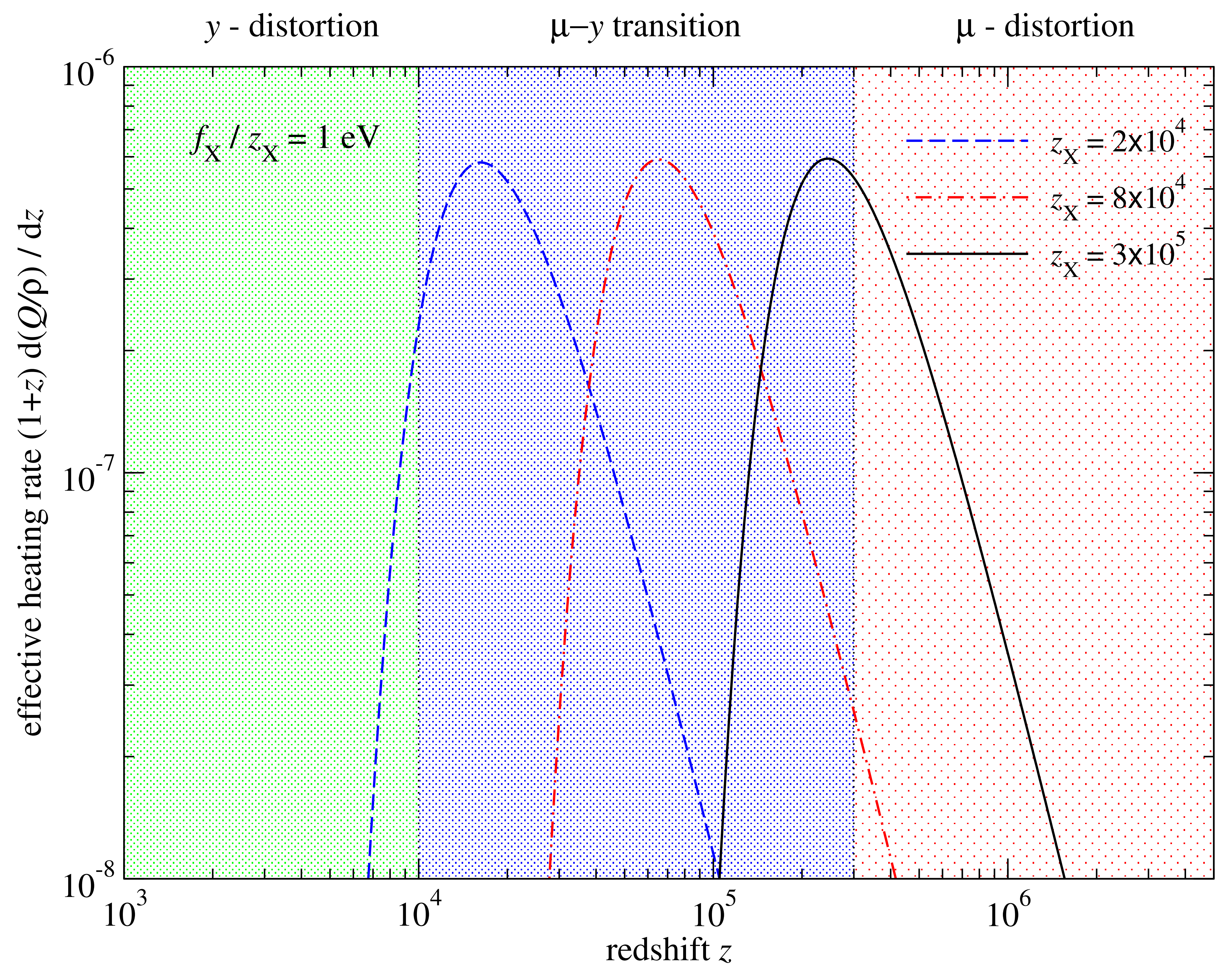
Signature of Particles with different lifetimes can be distinguished!

Example:

lifetime t_X ~ 114 yrs

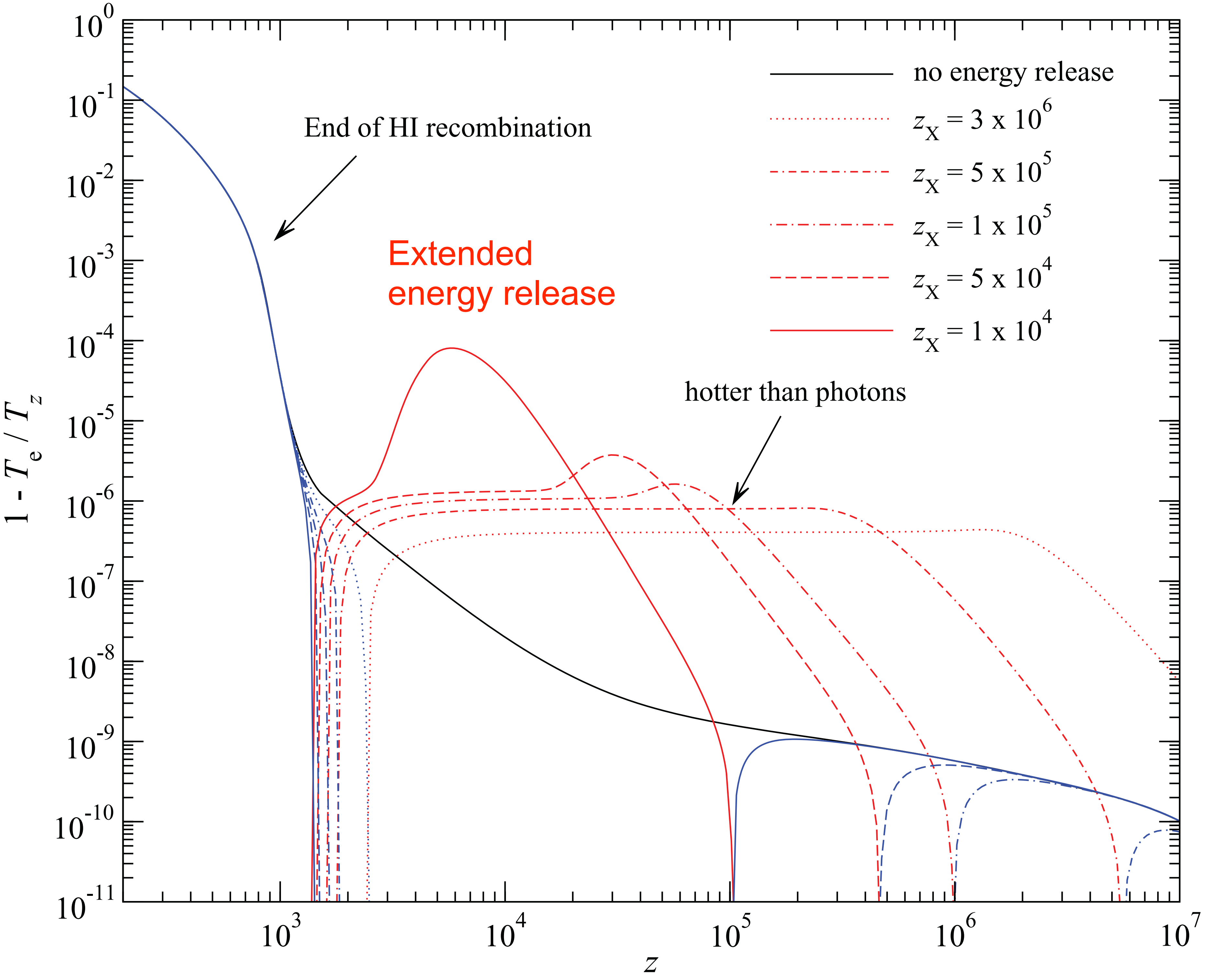
$$\frac{\Delta\rho}{\rho} \simeq \text{few} \times 10^{-7}$$

Decaying particle scenarios



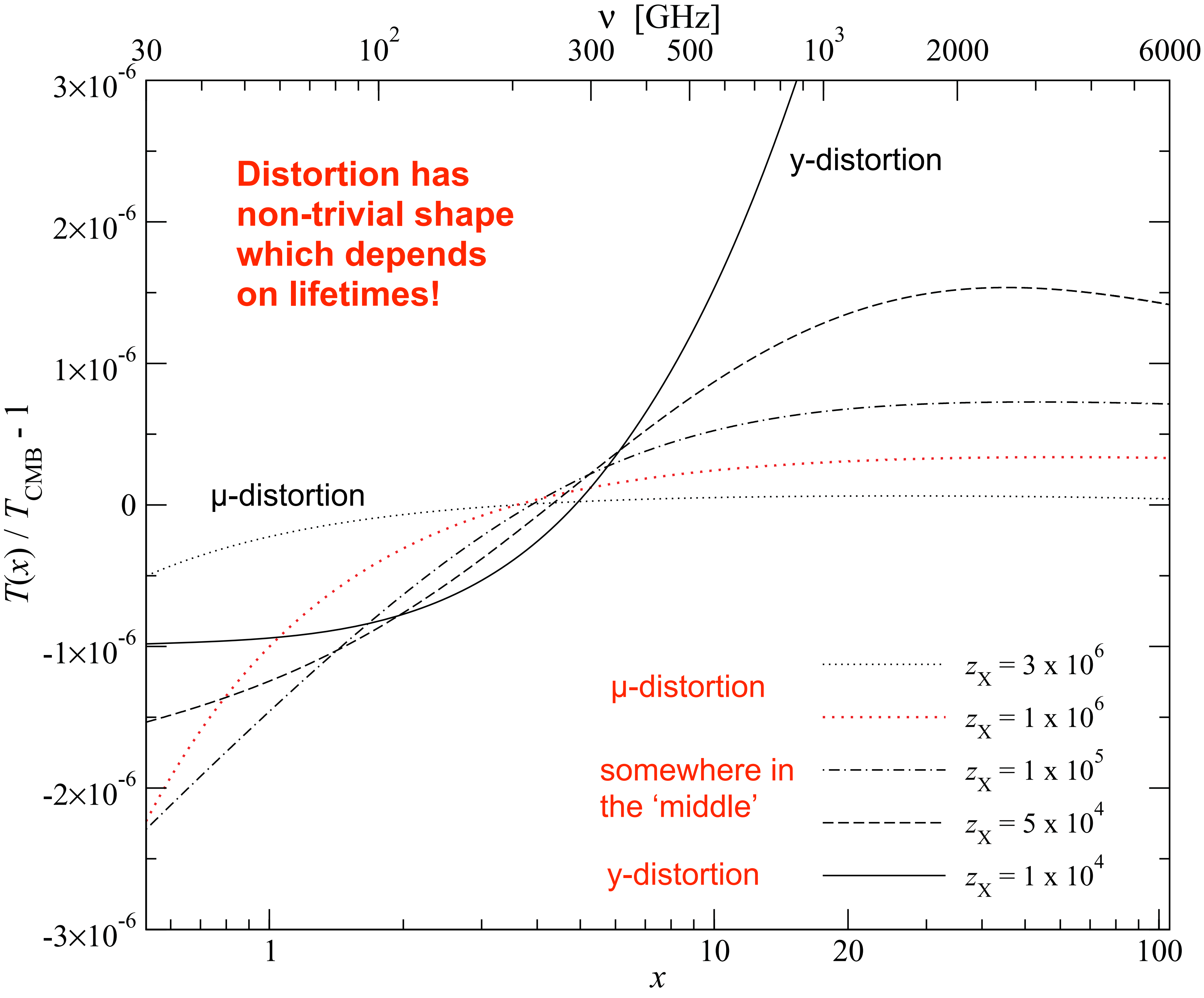
JC & Sunyaev, 2011, Arxiv:1109.6552
JC, 2013, Arxiv:1304.6120

Electron temperature evolution for decaying particle scenarios



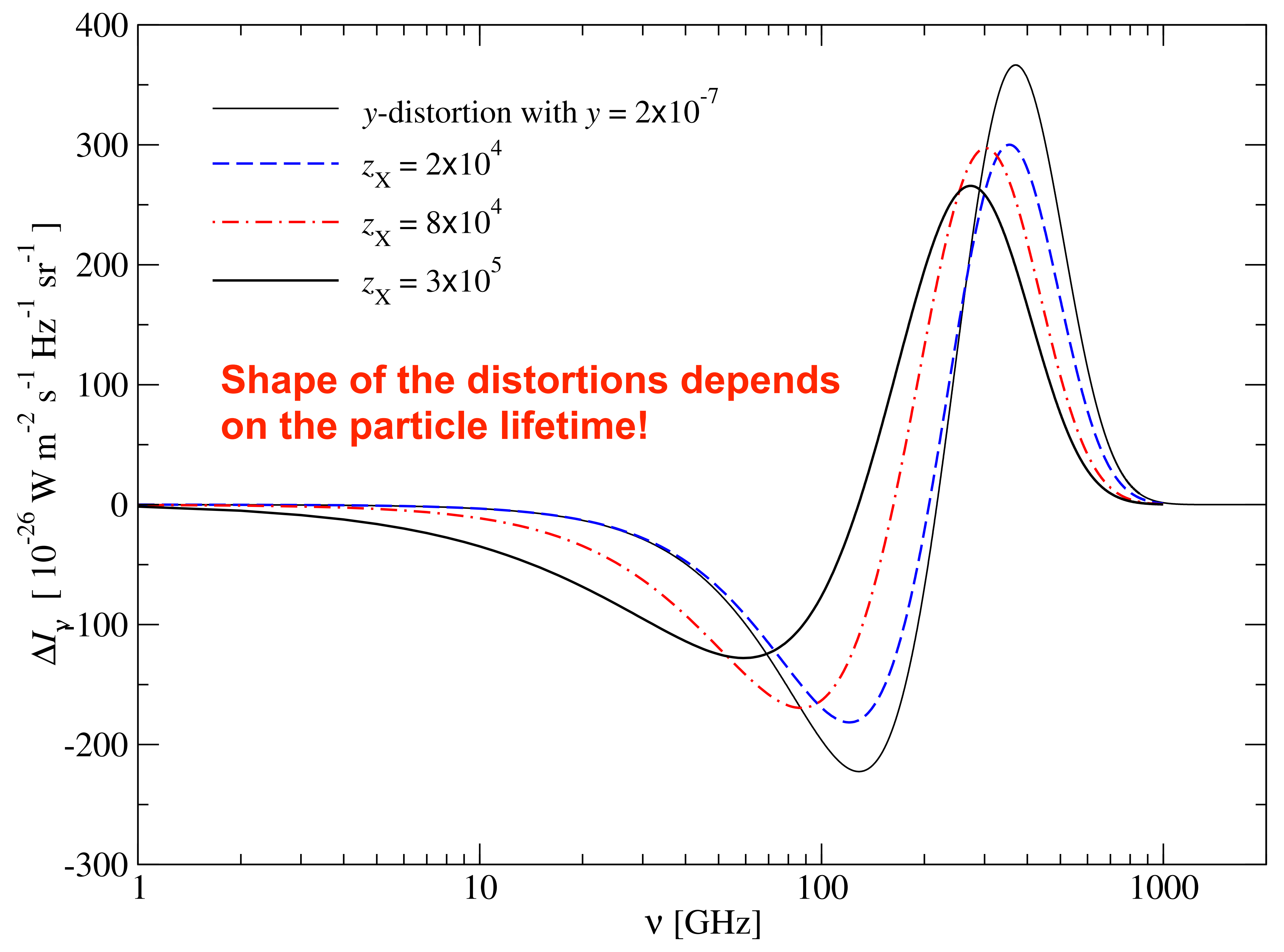
JC & Sunyaev, 2012

High frequency distortion for decaying particle scenarios



JC & Sunyaev, 2012

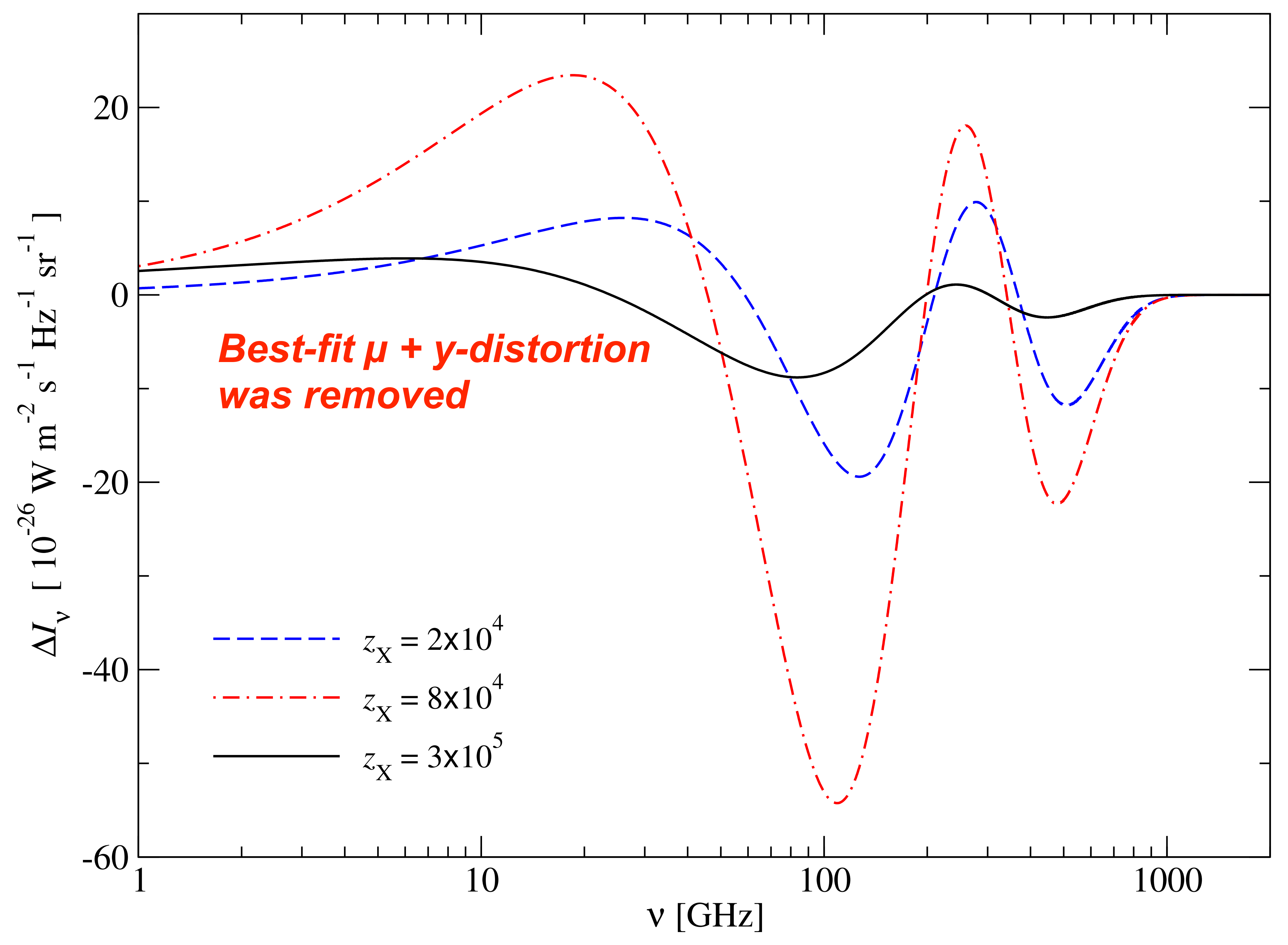
Decaying particle scenarios



Shape of the distortions depends on the particle lifetime!

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

Decaying particle scenarios (information in residual)



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

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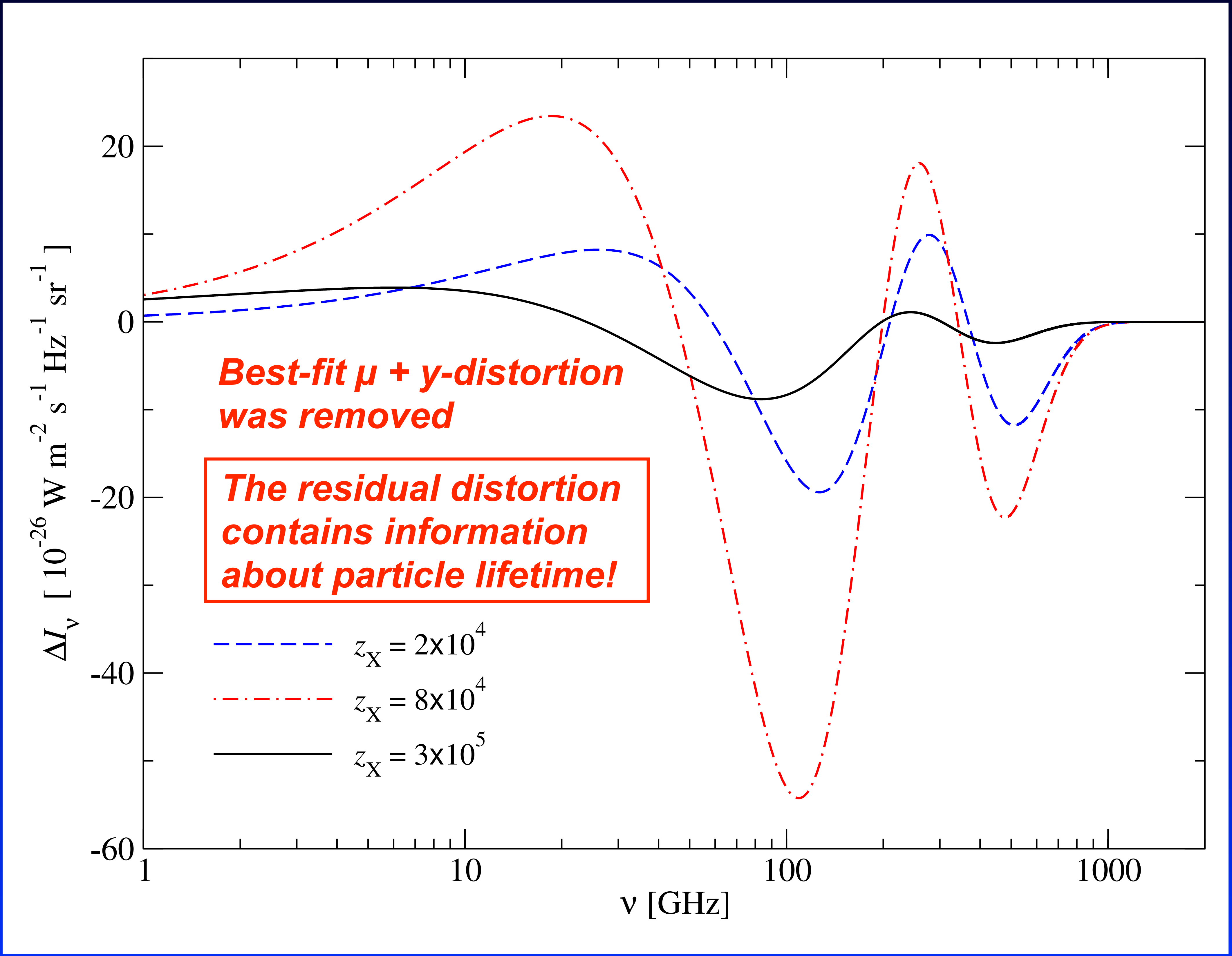
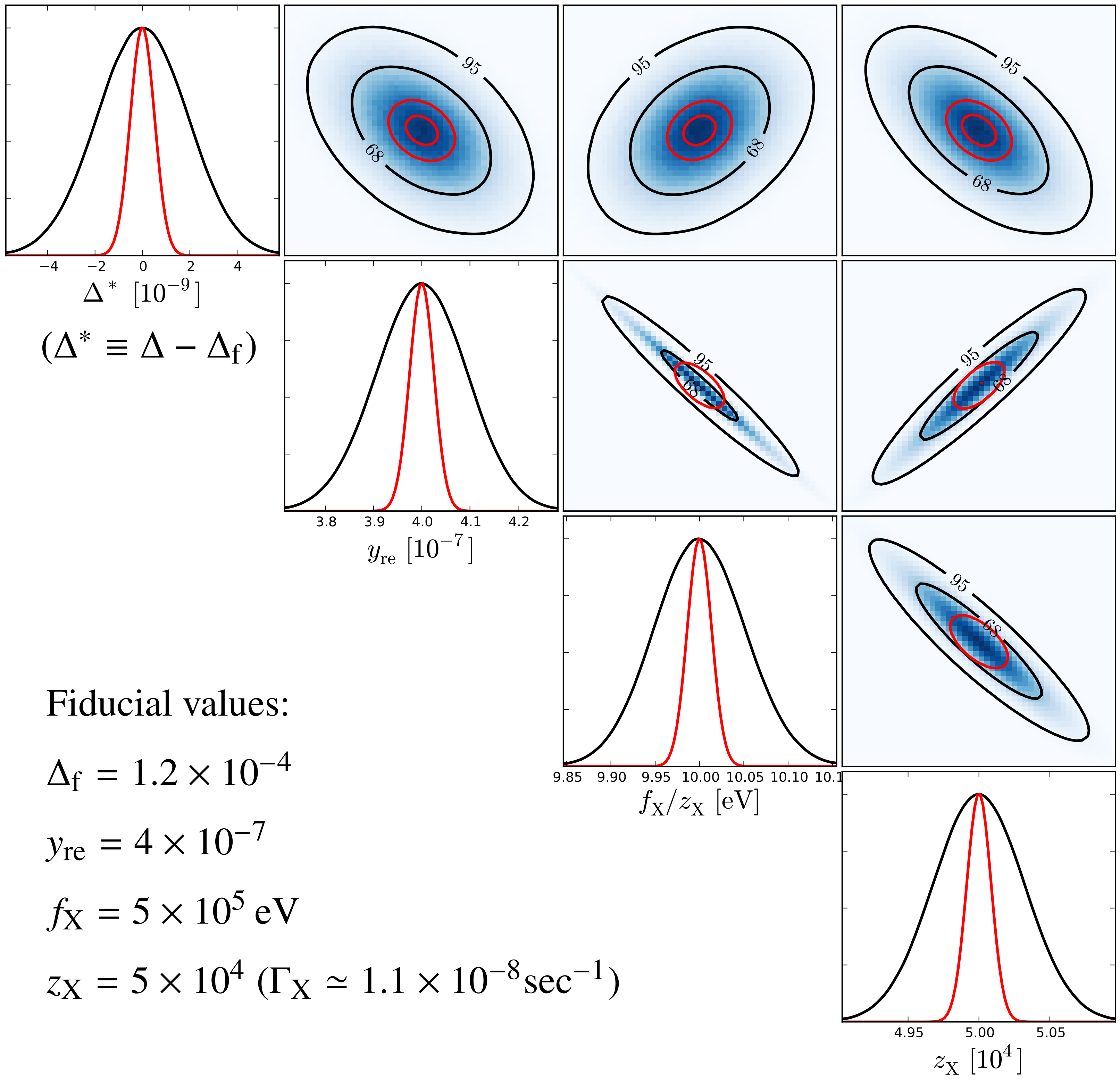


Best-fit μ + y-distortion was removed

The residual distortion contains information about particle lifetime!

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

Decaying particle scenarios



$(\Delta^* \equiv \Delta - \Delta_{\rm f})$

Fiducial values:

$\Delta_{\rm f} = 1.2 \times 10^{-4}$

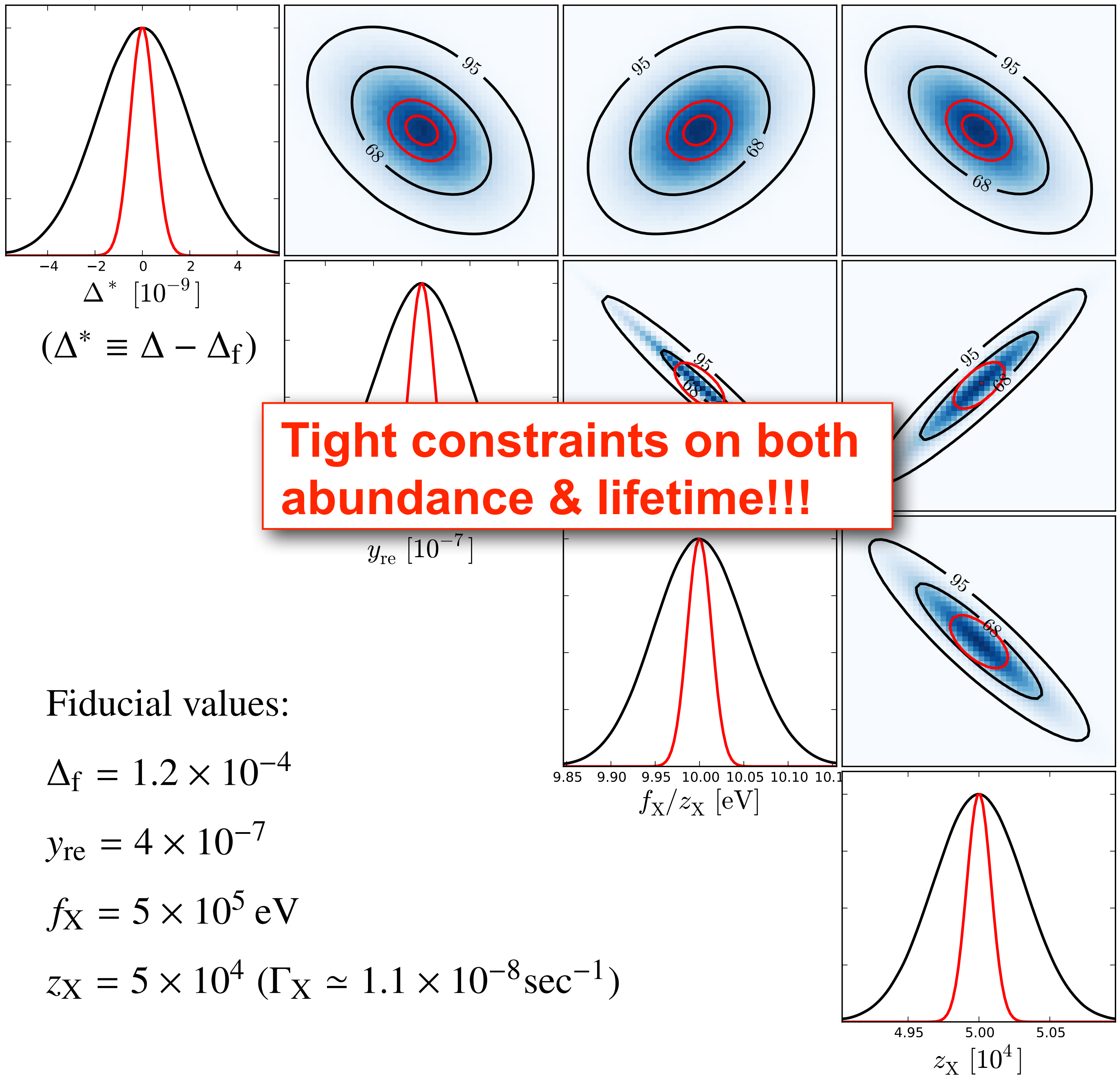
$y_{\rm re} = 4 \times 10^{-7}$

$f_{\rm X} = 5 \times 10^5$ eV

$z_{\rm X} = 5 \times 10^4$ $(\Gamma_{\rm X} \simeq 1.1 \times 10^{-8} {\rm sec}^{-1})$

JC, 2013, ArXiv:1304.6120

Decaying particle scenarios



$(\Delta^* \equiv \Delta - \Delta_f)$

Tight constraints on both abundance & lifetime!!!

Fiducial values:

$\Delta_f = 1.2 \times 10^{-4}$

$y_{\mathrm{re}} = 4 \times 10^{-7}$

$f_X = 5 \times 10^5$ eV

$z_X = 5 \times 10^4$ $(\Gamma_X \simeq 1.1 \times 10^{-8} \mathrm{sec}^{-1})$

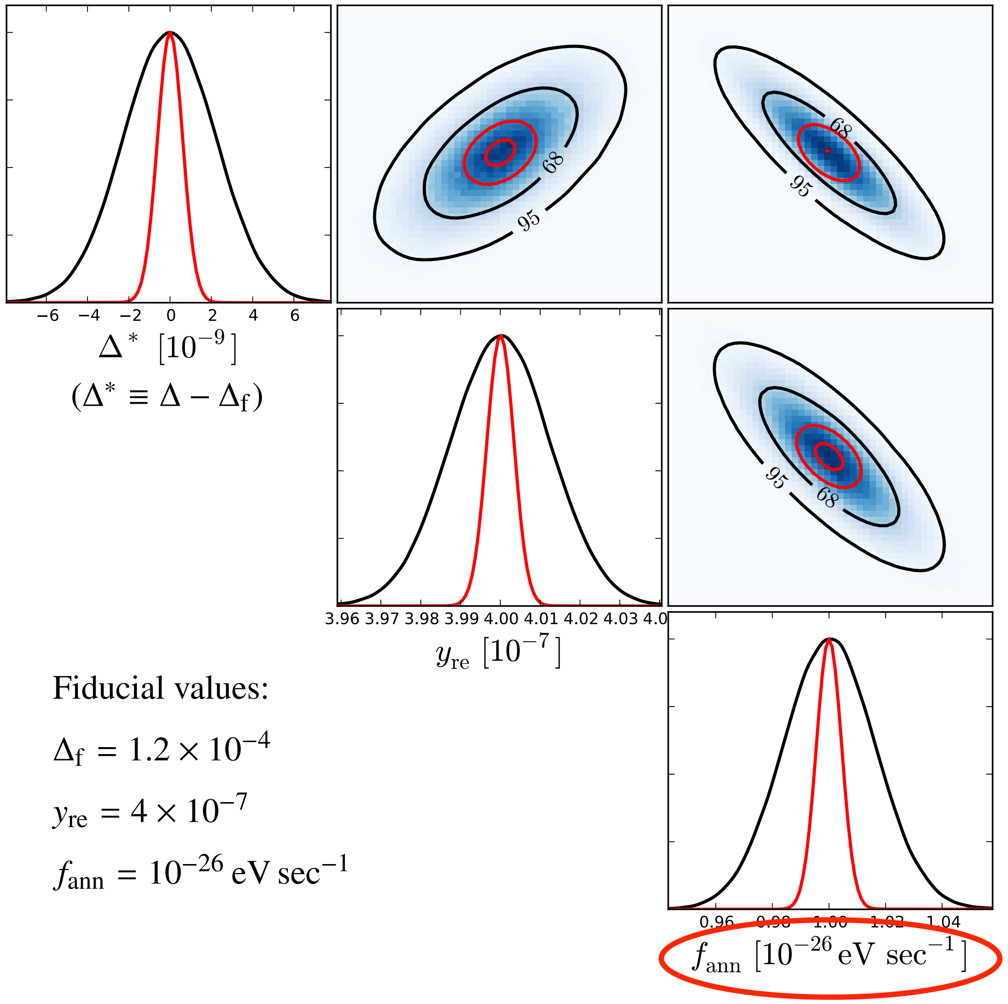
JC, 2013, ArXiv:1304.6120

Compressing the information of the distortion signal

Why model-independent approach to distortion signal

- Model-dependent analysis makes model-selection non-trivial
- Real information in the distortion signal limited by sensitivity and foregrounds
- *Principle Component Analysis* (PCA) can help optimizing this!
- useful for optimizing experimental designs (*frequencies; sensitivities,* ...)!

Annihilation scenario



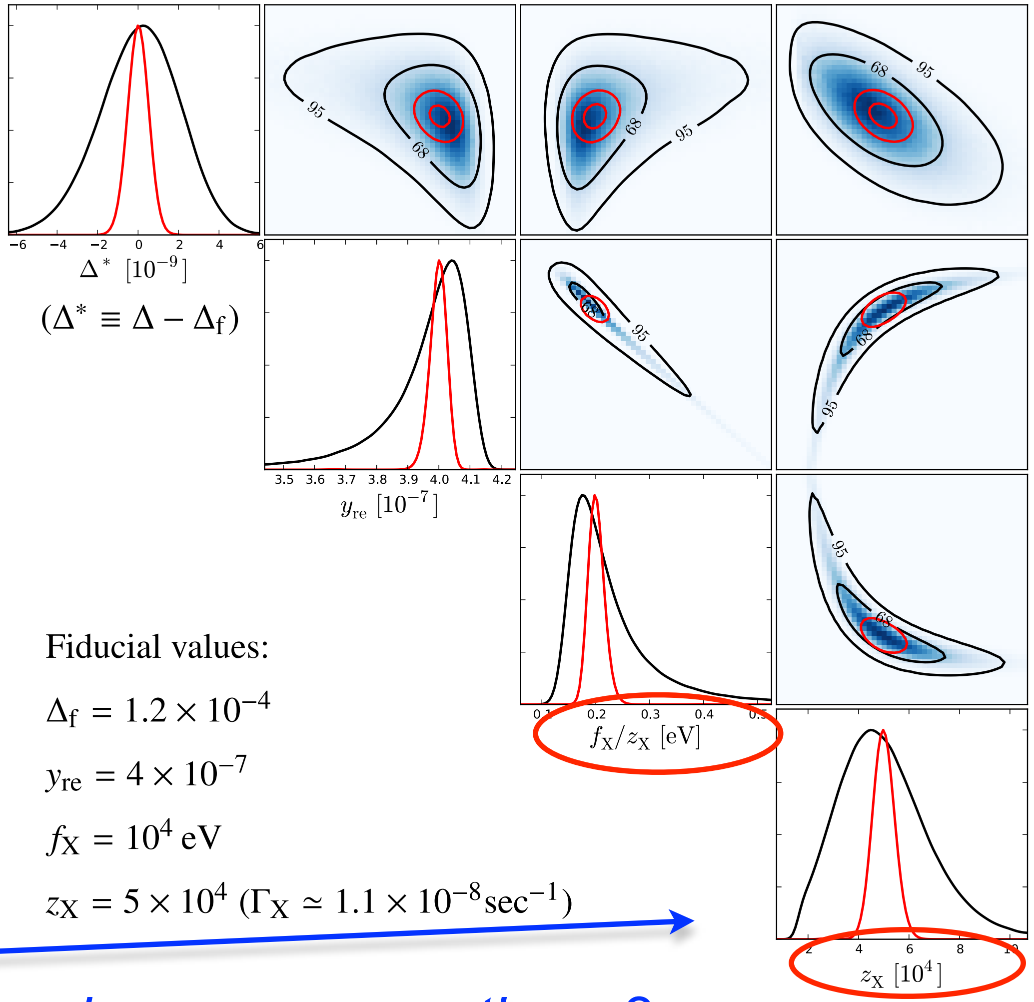
Fiducial values:

$\Delta_\mathrm{f} = 1.2 \times 10^{-4}$

$y_\mathrm{re} = 4 \times 10^{-7}$

$f_\mathrm{ann} = 10^{-26}\,\mathrm{eV\,sec}^{-1}$

Decaying particle scenario



Fiducial values:

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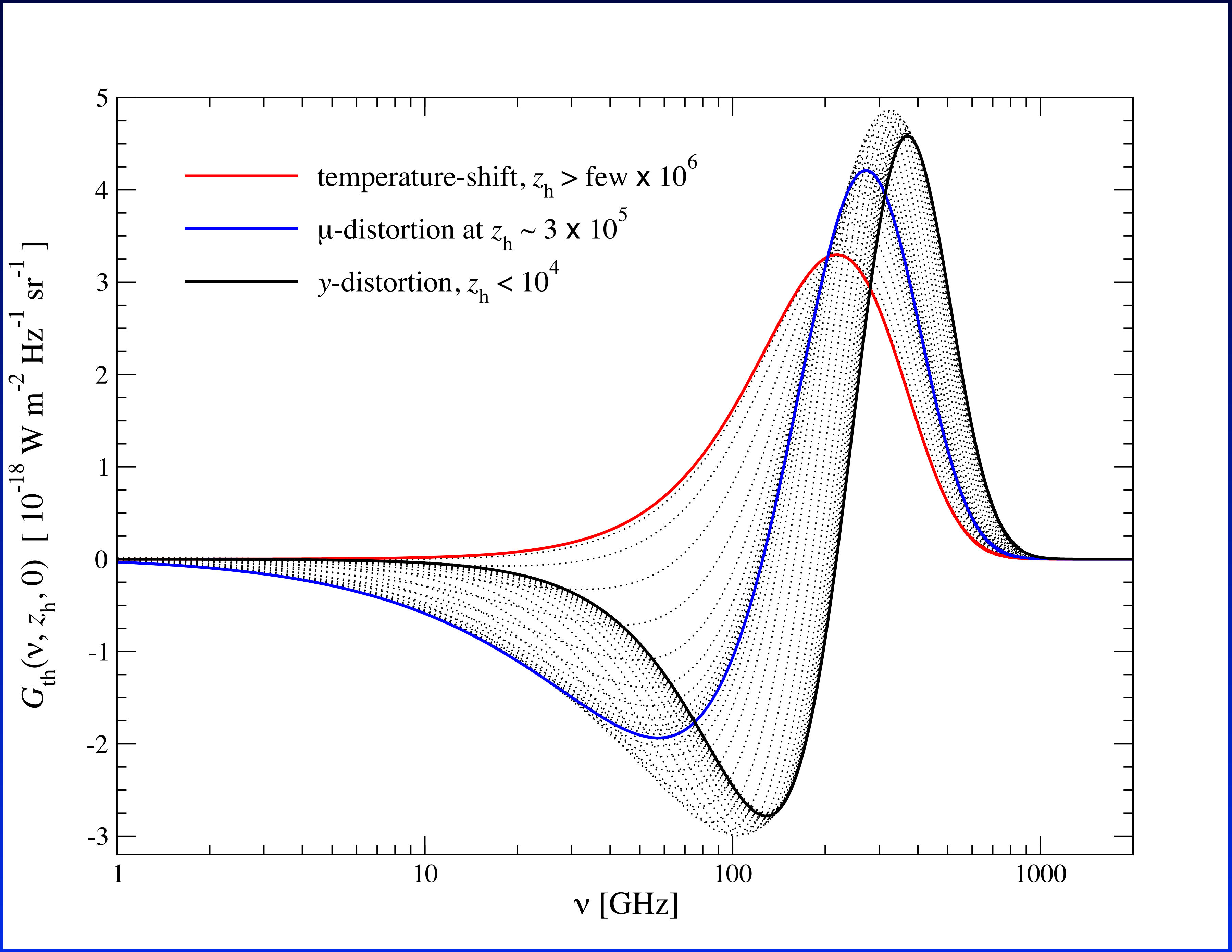
$f_\mathrm{X} = 10^4\,\mathrm{eV}$

$z_\mathrm{X} = 5 \times 10^4$ $(\Gamma_\mathrm{X} \simeq 1.1 \times 10^{-8}\mathrm{sec}^{-1})$

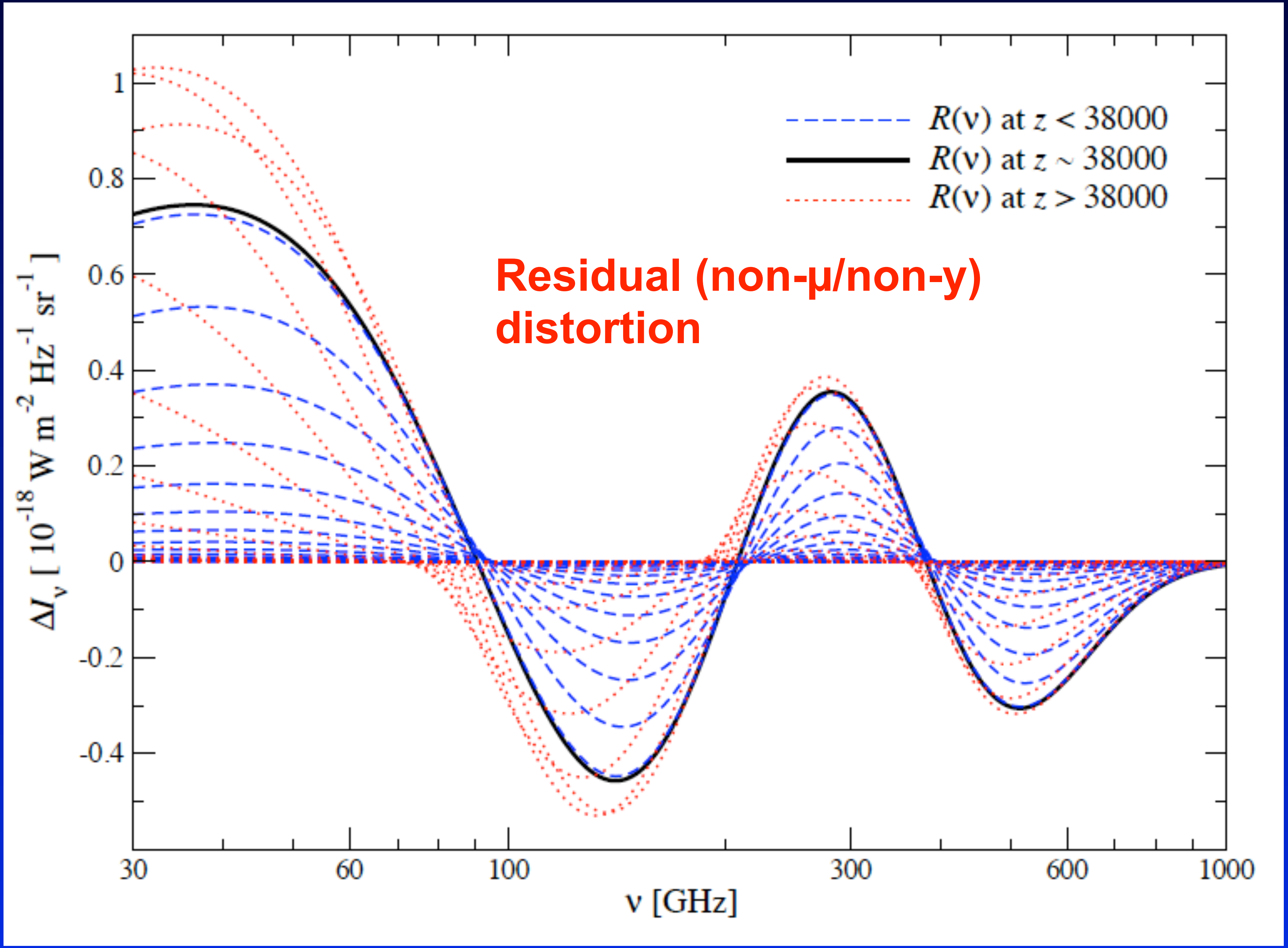
How do we compare these?

Using signal eigenmodes to compress the distortion data



- *Principle component decomposition* of the distortion signal
- compression of the useful information given instrumental settings

Using signal eigenmodes to compress the distortion data



JC & Jeong, 2013

- *Principle component decomposition* of the distortion signal
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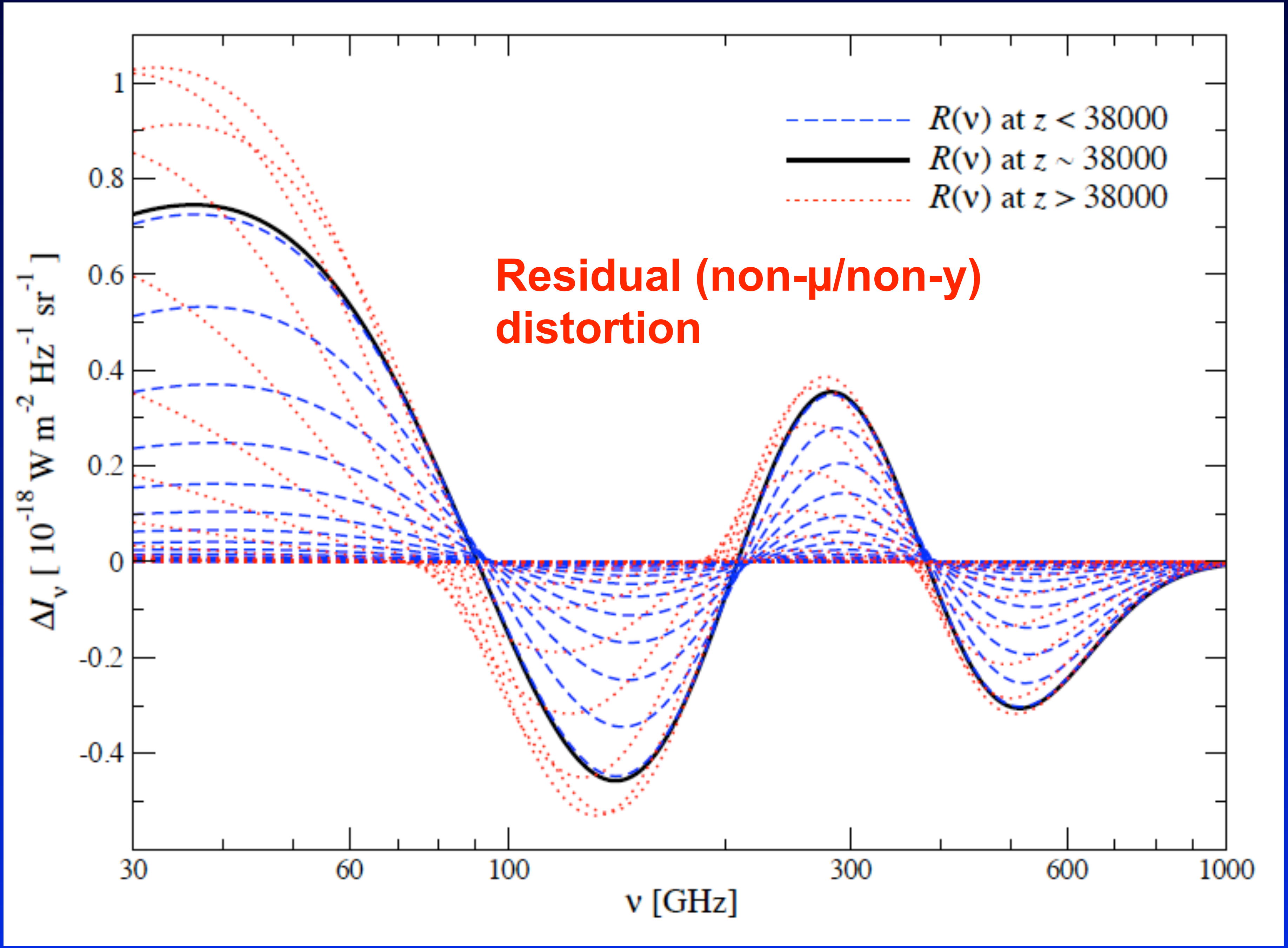
Using signal eigenmodes to compress the distortion data



JC & Jeong, 2013

- *Principle component decomposition* of the distortion signal
- compression of the useful information given instrumental settings
- new set of observables

  $p = \{y, \mu, \mu_1, \mu_2, ...\}$
- model-comparison + forecasts of errors very simple!

Residual distortion dependents on settings

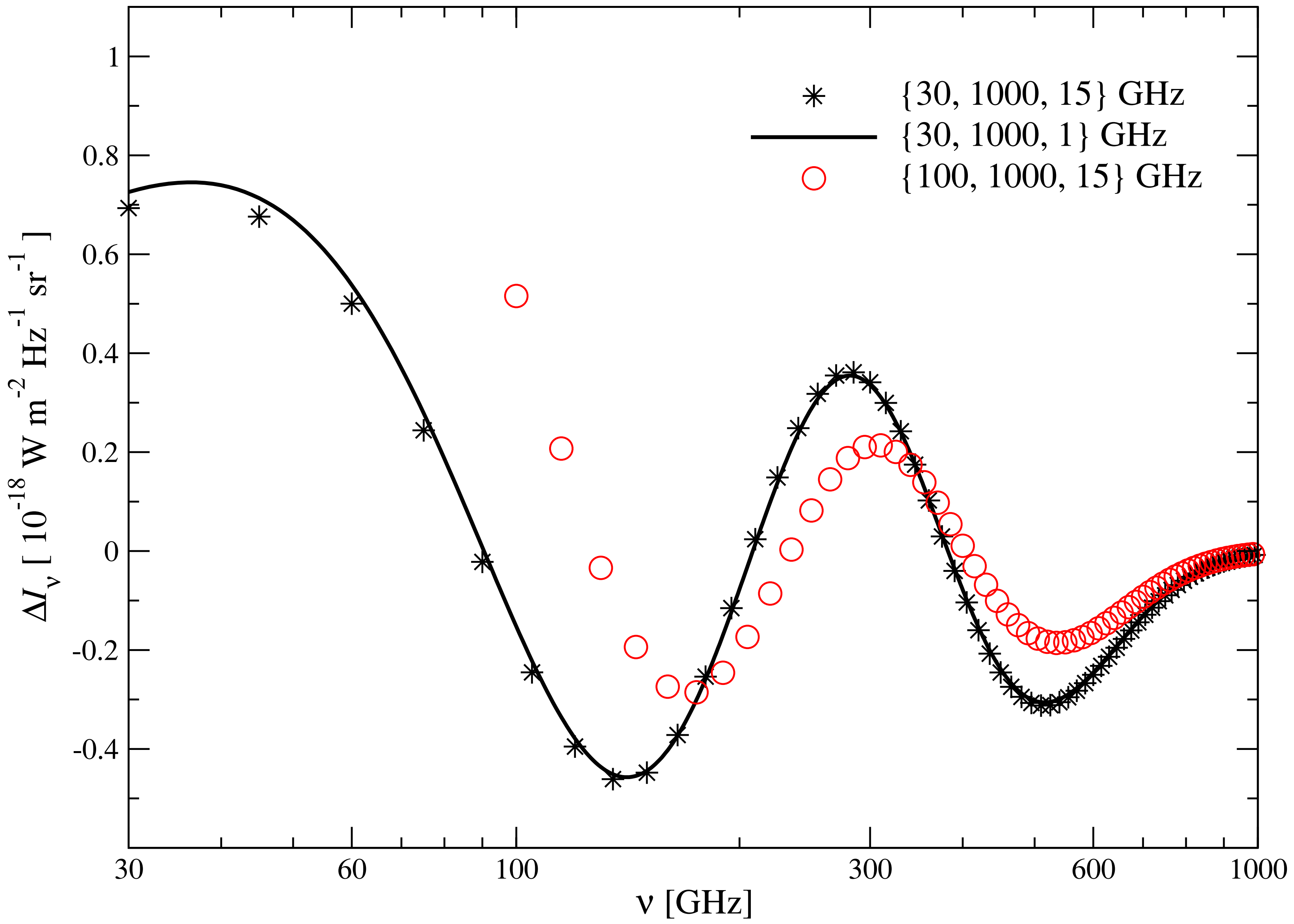


Figure 3. Residual function at redshift $z \simeq 38\,000$ but for different instrumental settings. The annotated values are $\{\nu_{\rm min}, \nu_{\rm max}, \Delta\nu_{\rm s}\}$ and we assumed diagonal noise covariance.

JC & Jeong, 2013

Eigenmodes for a PIXIE-type experiment

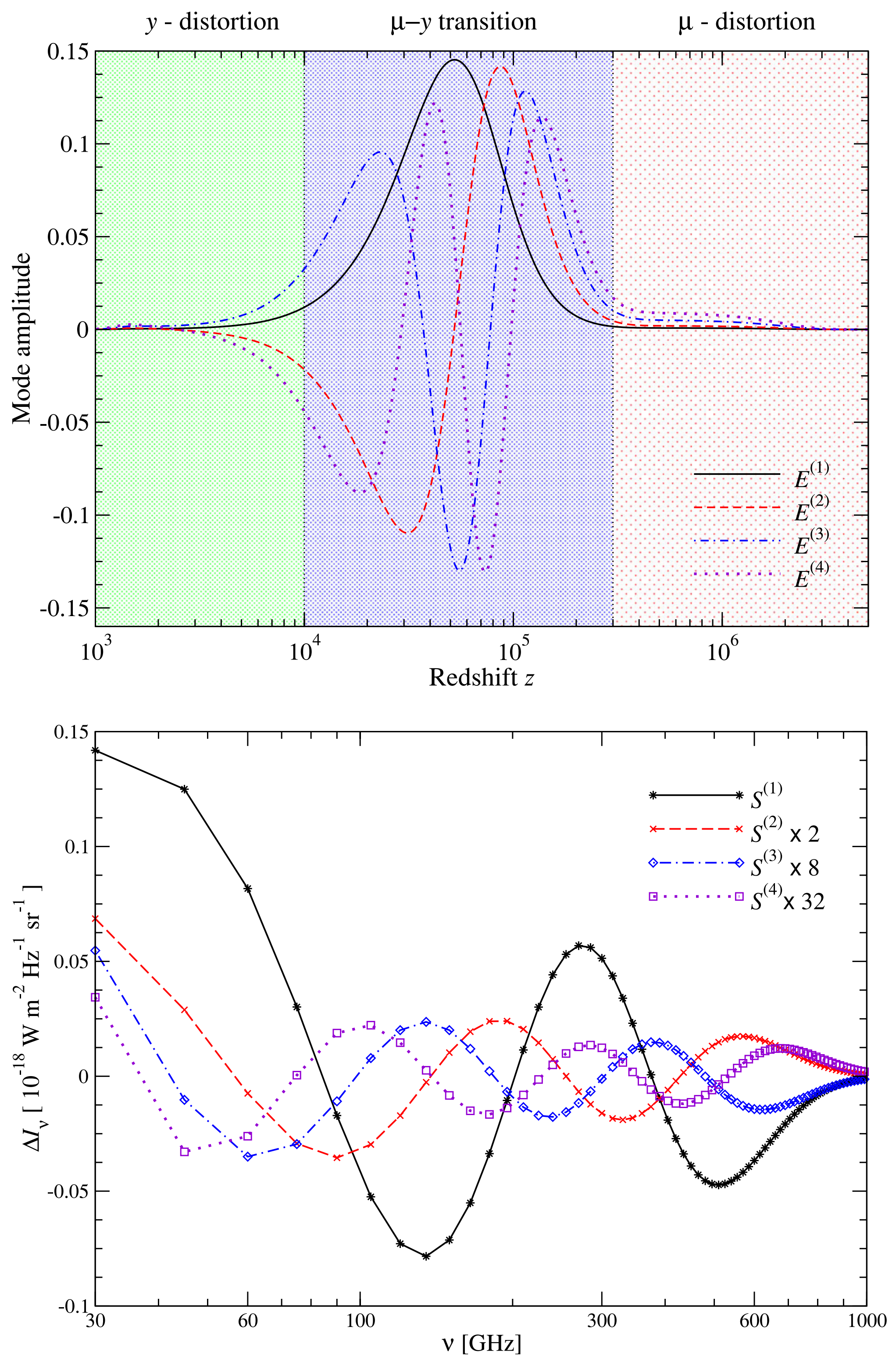


Figure 4. First few eigenmodes $\boldsymbol{E}^{(k)}$ and $\boldsymbol{S}^{(k)}$ for *PIXIE*-type settings ($\nu_{\rm min} = 30\,{\rm GHz}$, $\nu_{\rm max} = 1000\,{\rm GHz}$ and $\Delta\nu_{\rm s} = 15\,{\rm GHz}$). In the mode construction, we assumed that energy release only occurred at $10^3 \leq z \leq 5\times10^6$.

Estimated error bars

(under idealistic assumptions...)

$$\frac{\Delta T}{T} \simeq 2\,{\rm nK}\left(\frac{\Delta I_{\rm c}}{5\,{\rm Jy\,sr^{-1}}}\right)$$

$$\Delta y \simeq 1.2\times10^{-9}\left(\frac{\Delta I_{\rm c}}{5\,{\rm Jy\,sr^{-1}}}\right)$$

$$\Delta \mu \simeq 1.4\times10^{-8}\left(\frac{\Delta I_{\rm c}}{5\,{\rm Jy\,sr^{-1}}}\right)$$

Table 1. Forecasted 1σ errors of the first six eigenmode amplitudes, $\boldsymbol{E}^{(k)}$. We also give $\varepsilon_k = 4\sum_i S_i^{(k)}/\sum_i G_{i,T}$, and the scalar products $\boldsymbol{S}^{(k)}\cdot\boldsymbol{S}^{(k)}$ (in units of $[10^{-18}\,{\rm W\,m^{-2}\,Hz^{-1}\,sr^{-1}}]^2$). The fraction of energy release to the residual distortion and its uncertainty are given by $\varepsilon \approx \sum_k \varepsilon_k\,\mu_k$ and $\Delta\varepsilon \approx (\sum_k \varepsilon_k^2 \Delta\mu_k^2)^{1/2}$, respectively. For the mode construction we used *PIXIE*-settings $(\{\nu_{\rm min},\ \nu_{\rm max},\ \Delta\nu_{\rm s}\} = \{30,\ 1000,\ 15\}\,{\rm GHz}$ and channel sensitivity $\Delta I_{\rm c} = 5\times10^{-26}\,{\rm W\,m^{-2}\,Hz^{-1}\,sr^{-1}}$). The errors roughly scale as $\Delta\mu_k \propto \Delta I_{\rm c}/\sqrt{\Delta\nu_{\rm s}}$.

k	$\Delta\mu_k$	$\Delta\mu_k/\Delta\mu_1$	ε_k	$\boldsymbol{S}^{(k)}\cdot\boldsymbol{S}^{(k)}$
1	1.48×10^{-7}	1	-6.98×10^{-3}	1.15×10^{-1}
2	7.61×10^{-7}	5.14	2.12×10^{-3}	4.32×10^{-3}
3	3.61×10^{-6}	24.4	-3.71×10^{-4}	1.92×10^{-4}
4	1.74×10^{-5}	1.18×10^{2}	8.29×10^{-5}	8.29×10^{-6}
5	8.52×10^{-5}	5.76×10^{2}	-1.55×10^{-5}	3.45×10^{-7}
6	4.24×10^{-4}	2.86×10^{3}	2.75×10^{-6}	1.39×10^{-8}

JC & Jeong, 2013

Partial recovery of energy release history

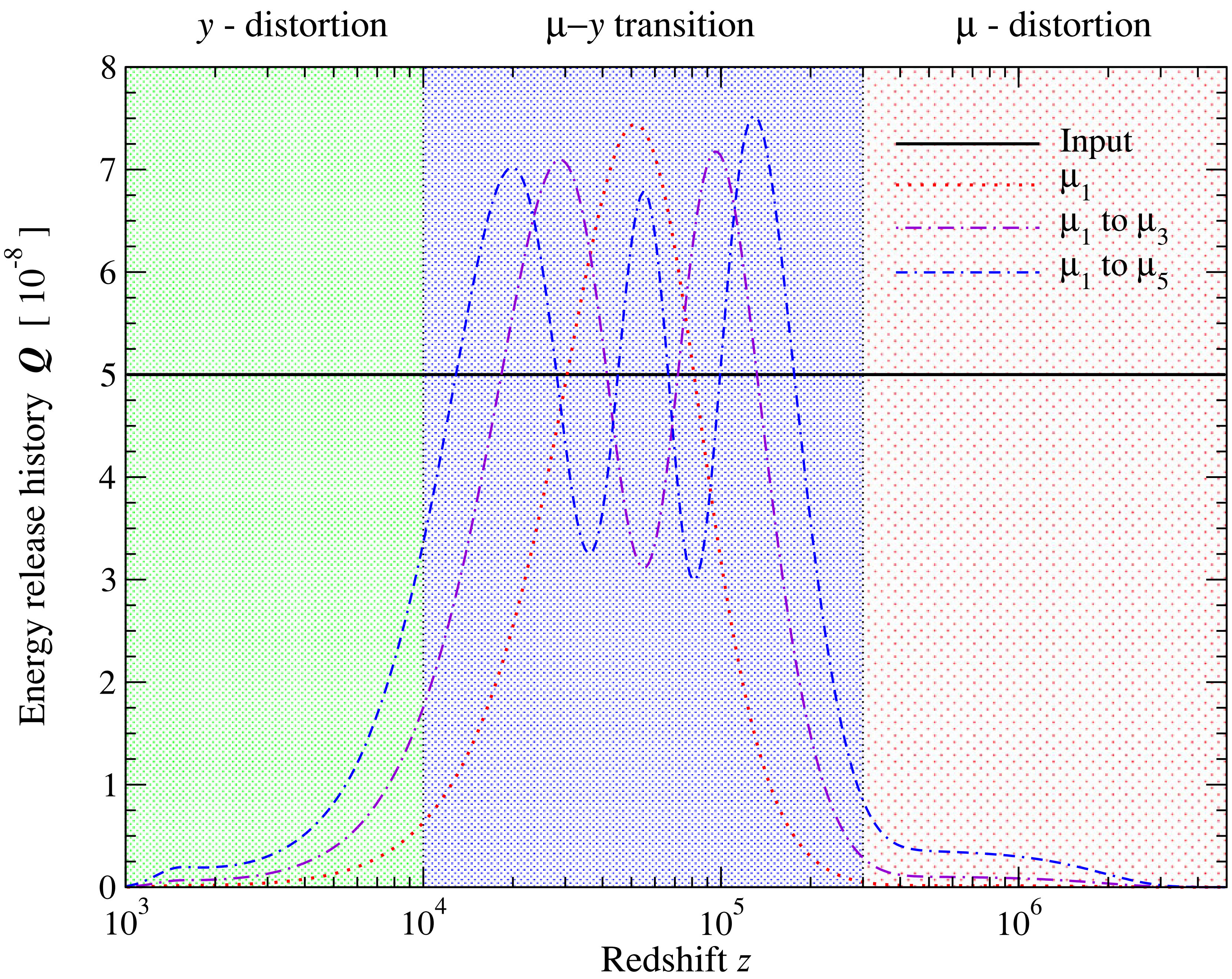
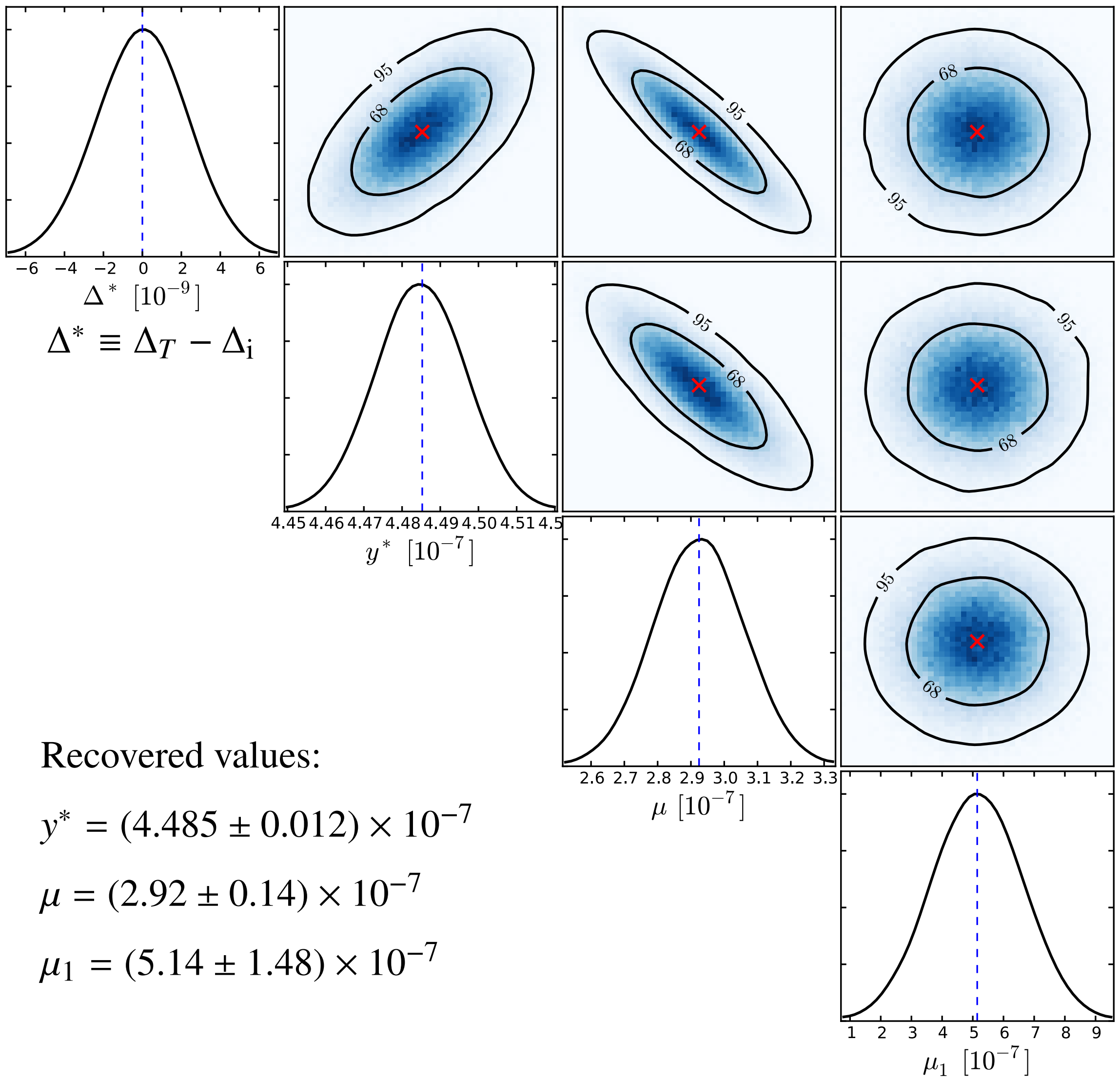


Figure 6. Partial recovery of the input energy-release history, $\mathcal{Q} = 5 \times 10^{-8}$.

- 'wiggly' recovery of input thermal history possible
- redshift resolution depends on sensitivity and distortion amplitude

JC & Jeong, 2013

Signal eigenmodes are uncorrelated by construction



Recovered values:

$y^* = (4.485 \pm 0.012) \times 10^{-7}$

$\mu = (2.92 \pm 0.14) \times 10^{-7}$

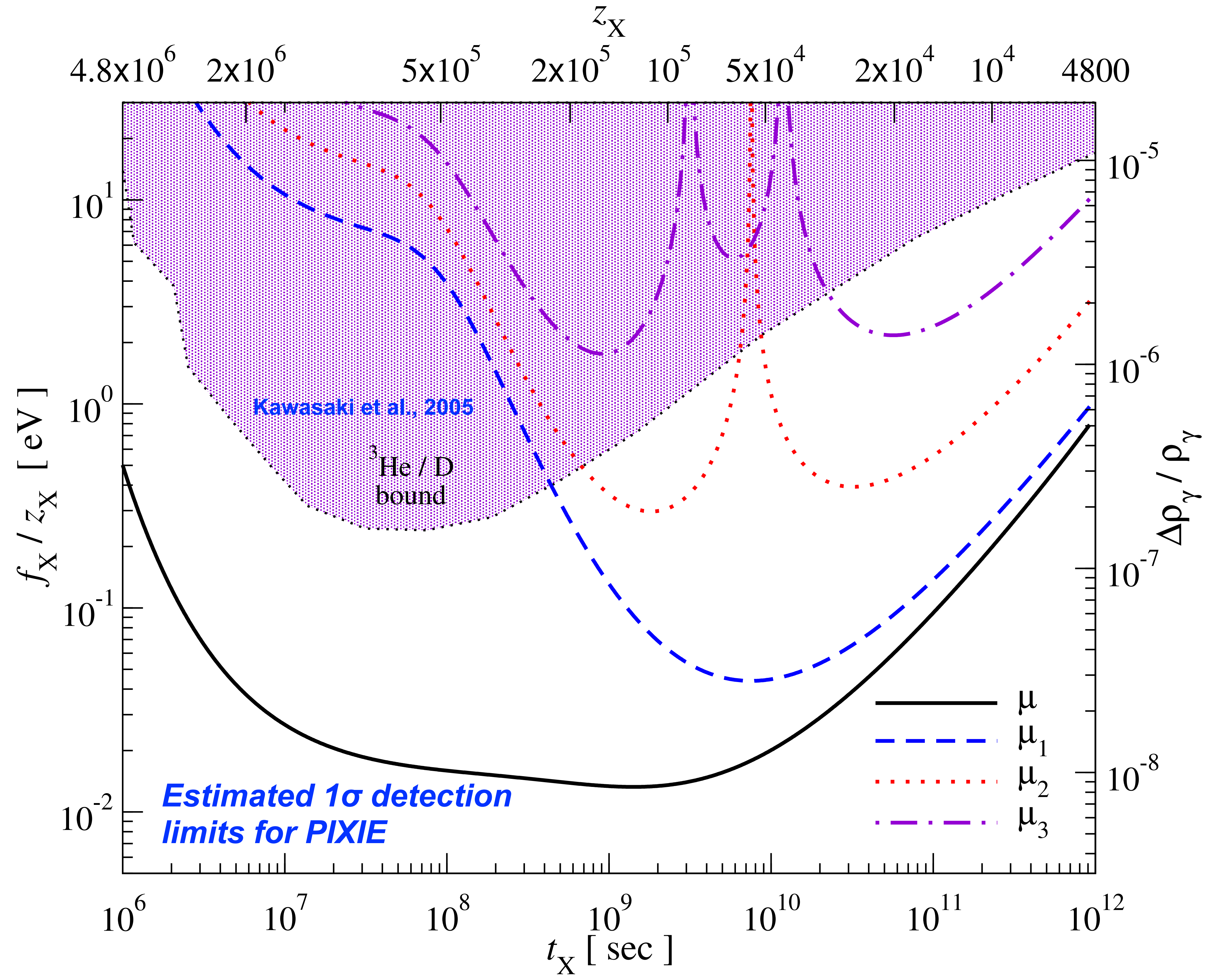
$\mu_1 = (5.14 \pm 1.48) \times 10^{-7}$

Figure 5. Analysis of energy-release history with $\mathcal{Q}(z) = 5 \times 10^{-8}$ in the redshift interval $10^3 < z < 5 \times 10^6$ using signal eigenmode, $\boldsymbol{S}^{(1)}$ (Fig. 4). We assumed $\{\nu_\mathrm{min}, \nu_\mathrm{max}, \Delta\nu_\mathrm{s}\} = \{30, 1000, 15\}$ GHz and channel sensitivity $\Delta I_\mathrm{c} = 5 \times 10^{-26}\,\mathrm{W\,m^{-2}\,Hz^{-1}\,sr^{-1}}$. The dashed blue lines and red crosses indicate the expected recovered values. Contours are for 68 per cent and 95 per cent confidence levels. All errors and recovered values agree with the Fisher estimates. We shifted Δ_T by $\Delta_\mathrm{i} = \Delta_\mathrm{f} + \Delta_\mathrm{prim}$ with $\Delta_\mathrm{f} = 1.2 \times 10^{-4}$ and $\Delta_\mathrm{prim} \simeq -8.46 \times 10^{-9}$, where Δ_prim is the primordial contribution.

- Adding more modes does not affect error bars
- optimal for given experiment
- *Even non-optimal modes can be used to parametrize distortions!*
- *in this case errors will generally be correlated*

JC & Jeong, 2013

Distortions could shed light on decaying (DM) particles!



JC & Jeong, 2013

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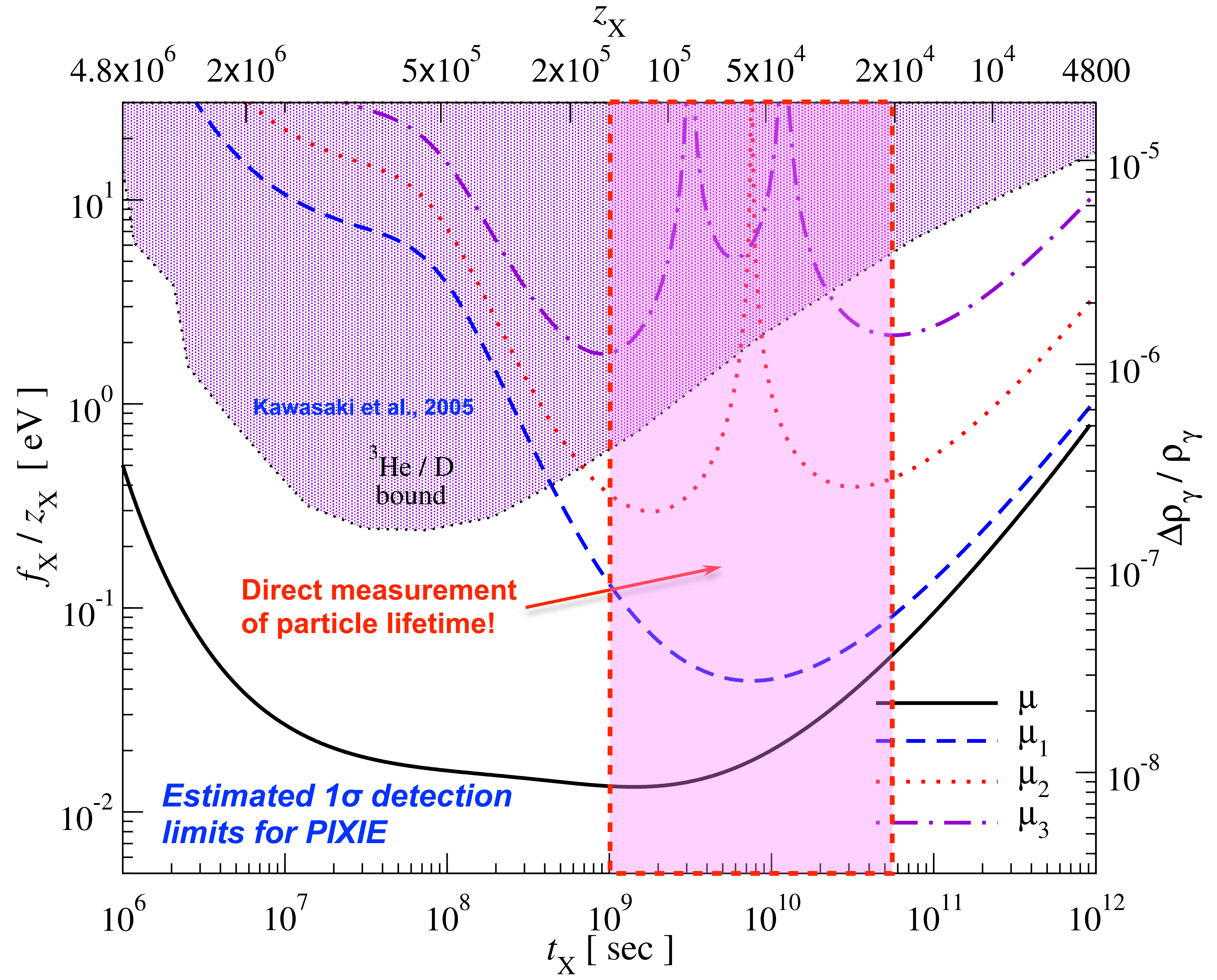

JC & Jeong, 2013

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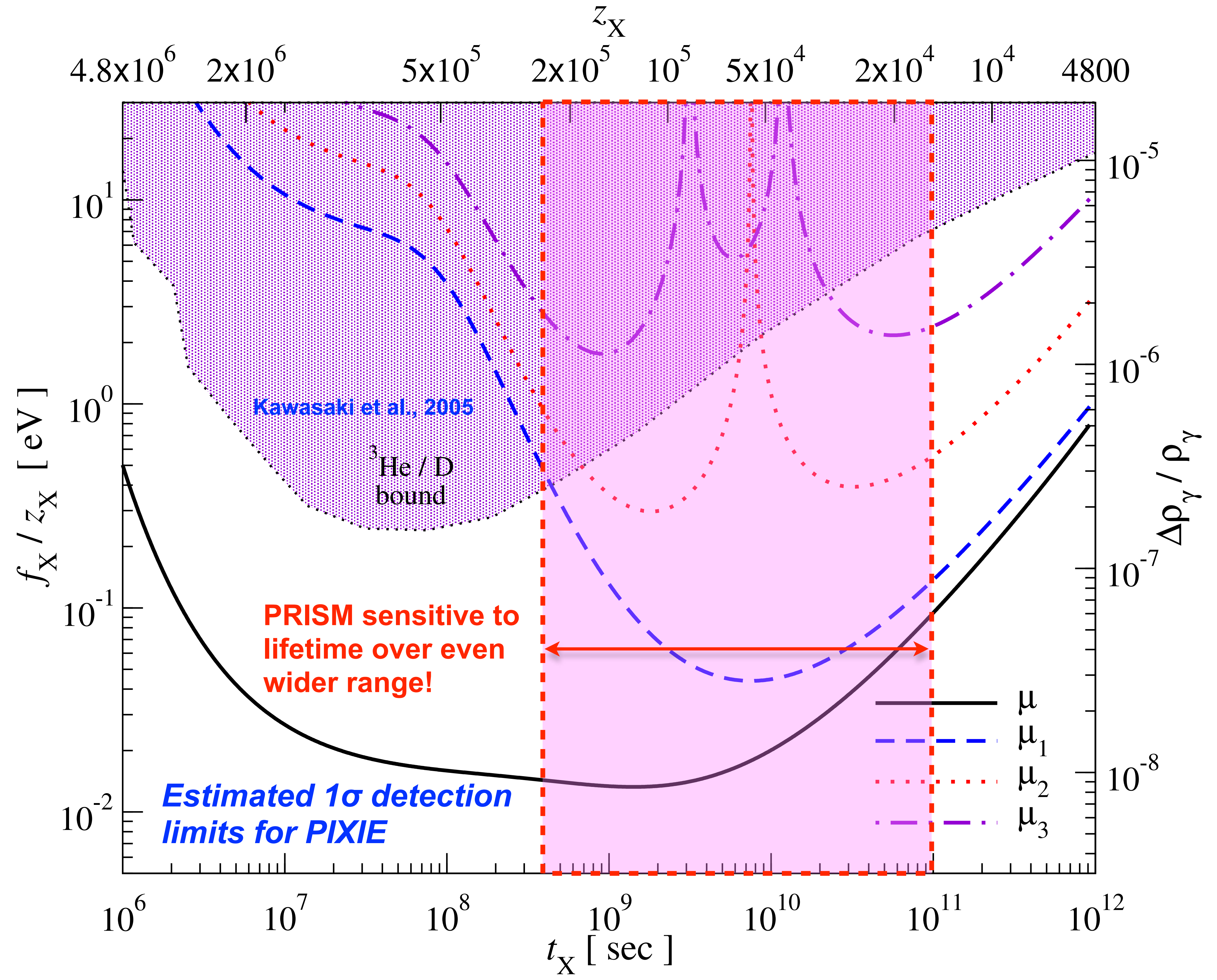

PRISM sensitive to lifetime over even wider range!

Estimated 1σ detection limits for PIXIE

JC & Jeong, 2013

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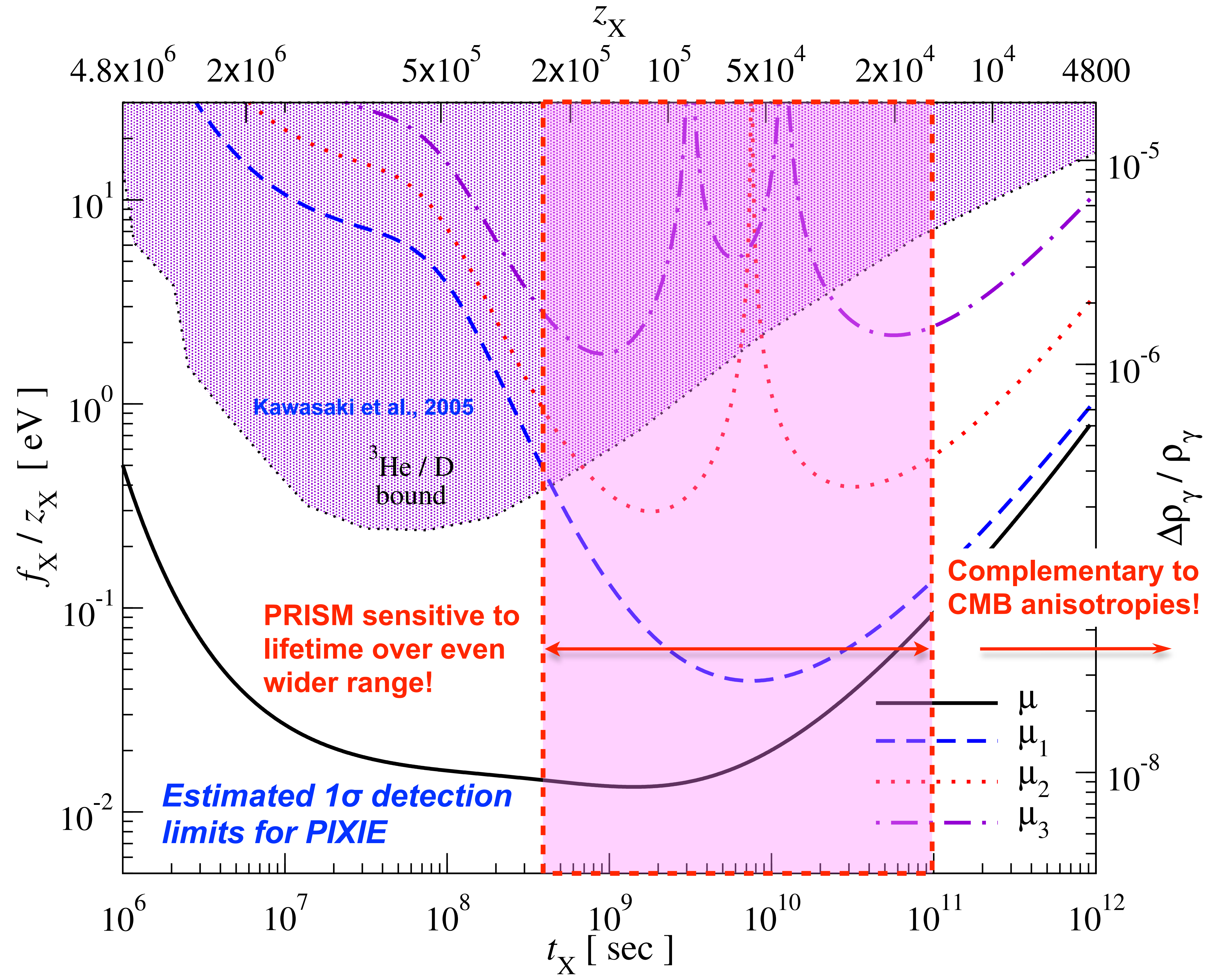


PRISM sensitive to lifetime over even wider range!

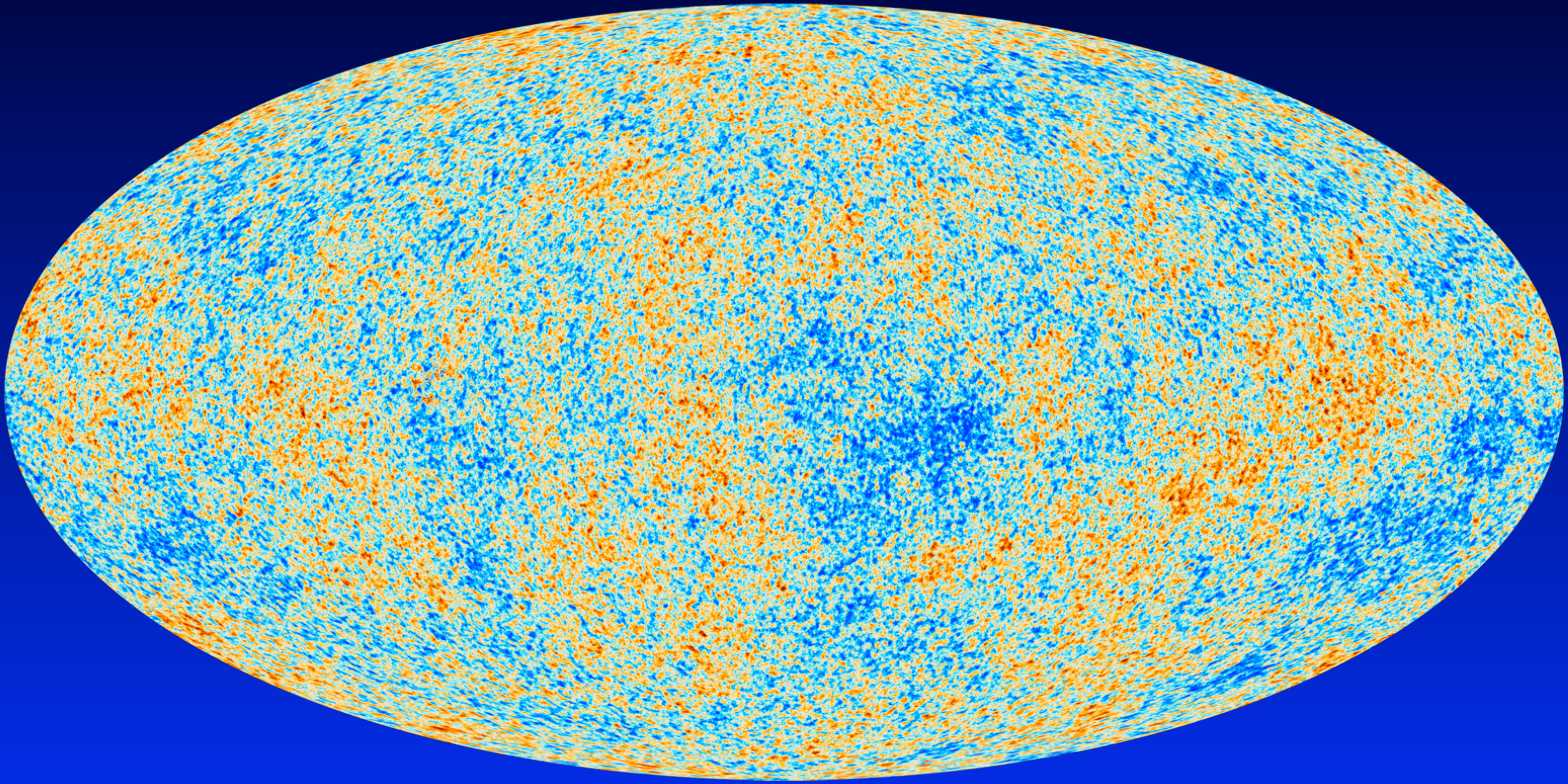
Complementary to CMB anisotropies!

Estimated 1σ detection limits for PIXIE

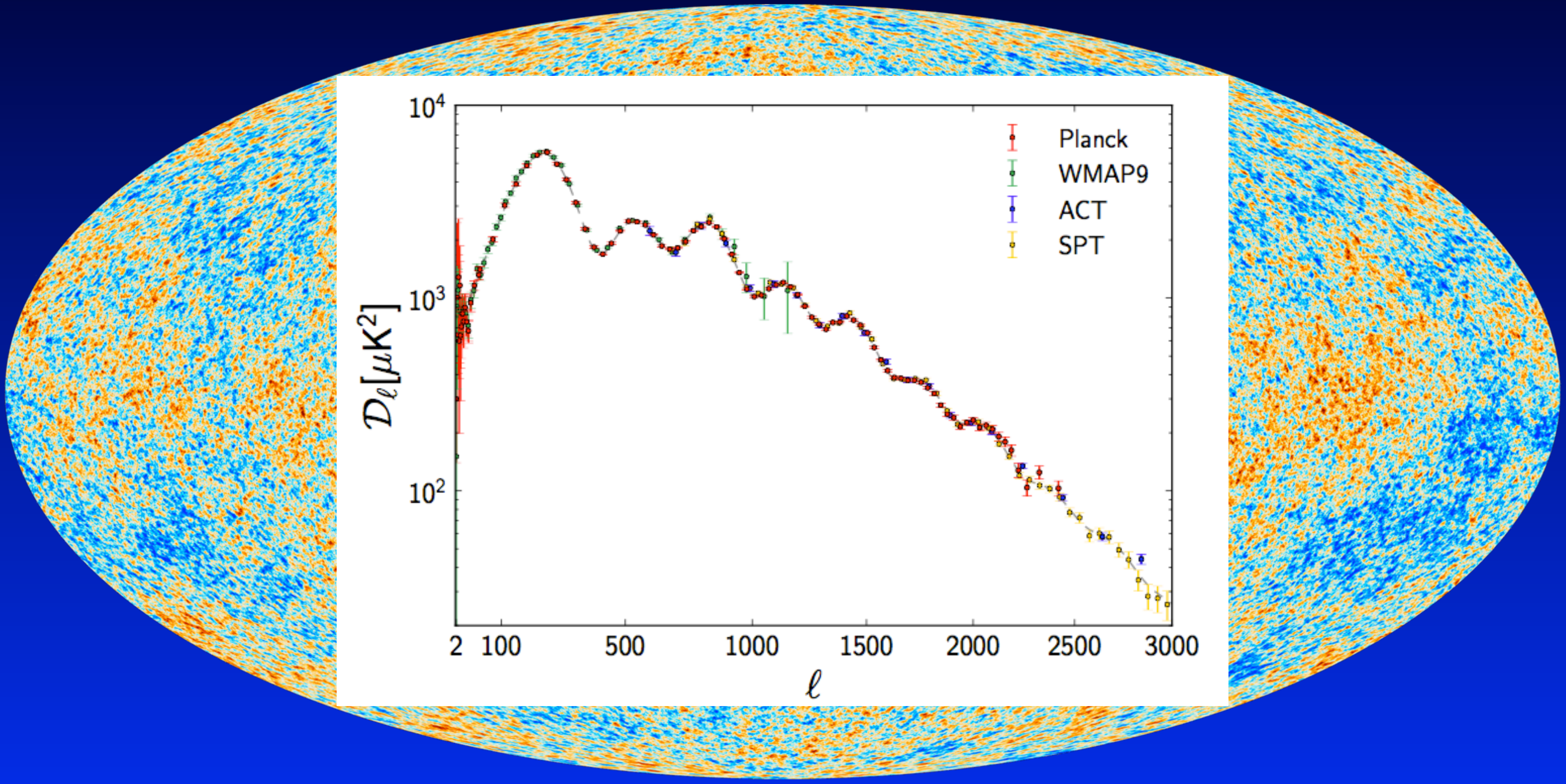
JC & Jeong, 2013

The dissipation of small-scale acoustic modes

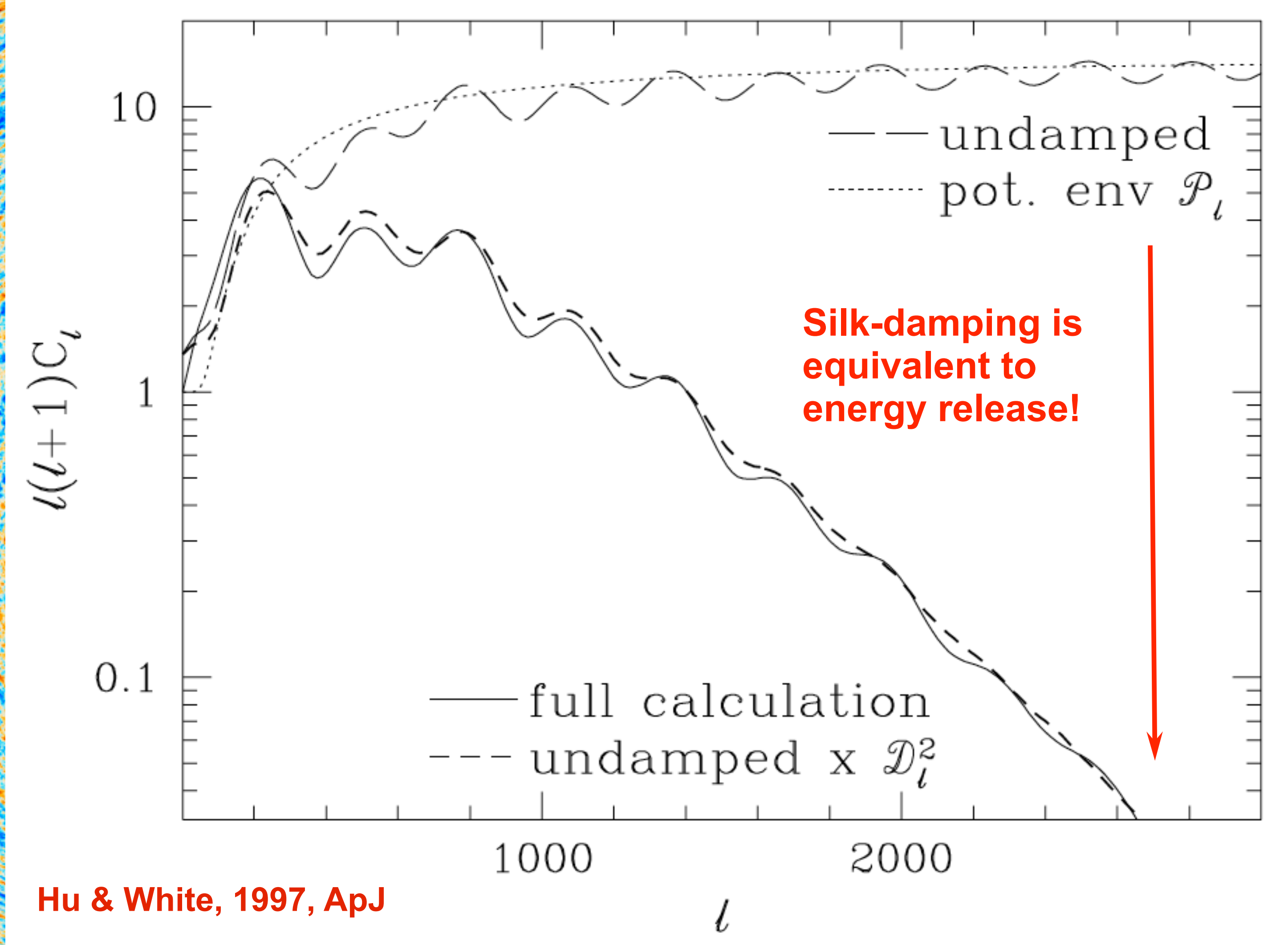
Dissipation of small-scale acoustic modes



Dissipation of small-scale acoustic modes



Dissipation of small-scale acoustic modes



Silk-damping is equivalent to energy release!

Hu & White, 1997, ApJ

Energy release caused by dissipation process

‘Obvious’ dependencies:

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

not so ‘obvious’ dependencies:

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

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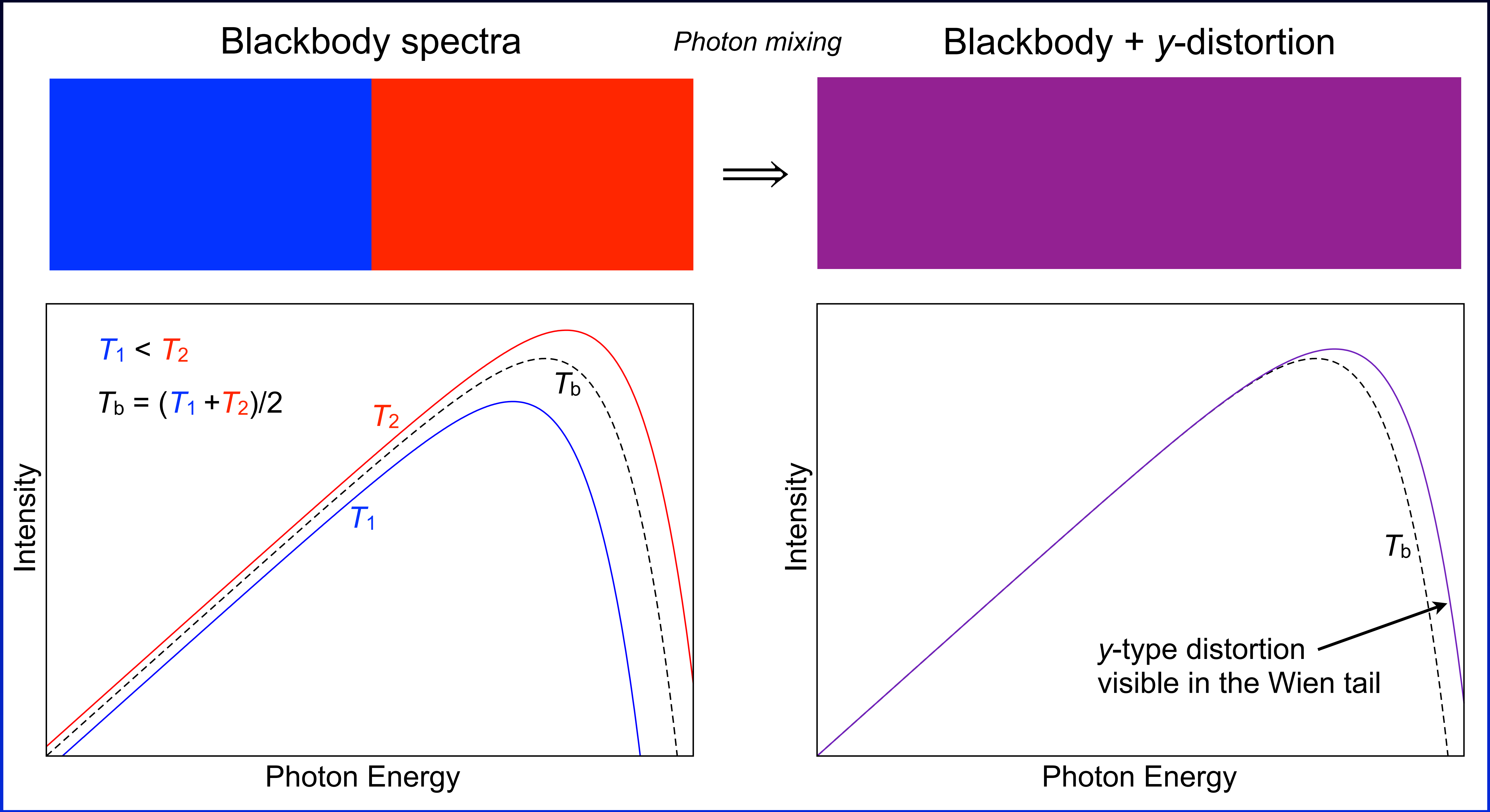
CMB Spectral distortions could add additional numbers beyond ‘just’ the tensor-to-scalar ratio from B-modes!

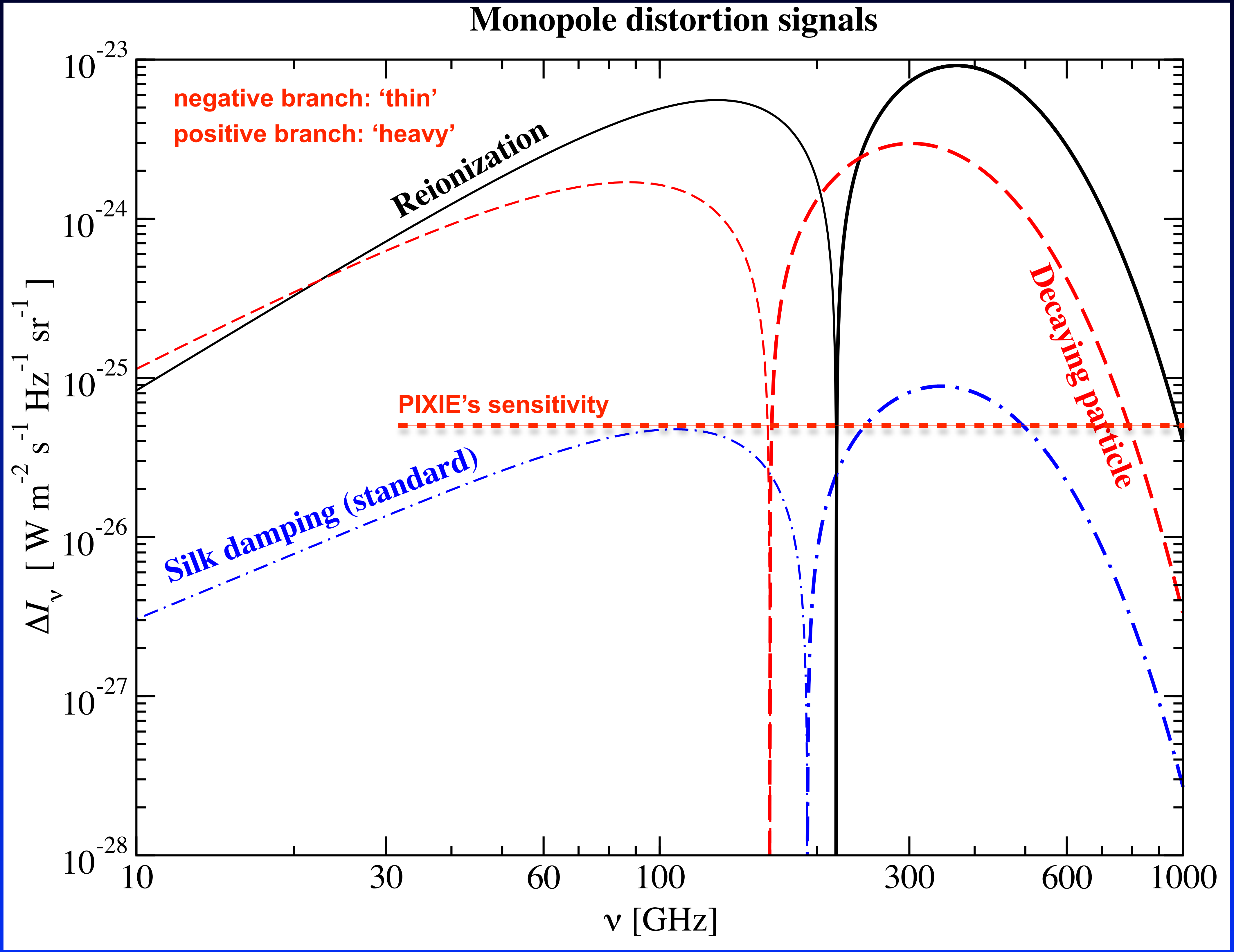
Distortion due to mixing of blackbodies



JC, Hamann & Patil, 2015

Average CMB spectral distortions

Absolute value of Intensity signal



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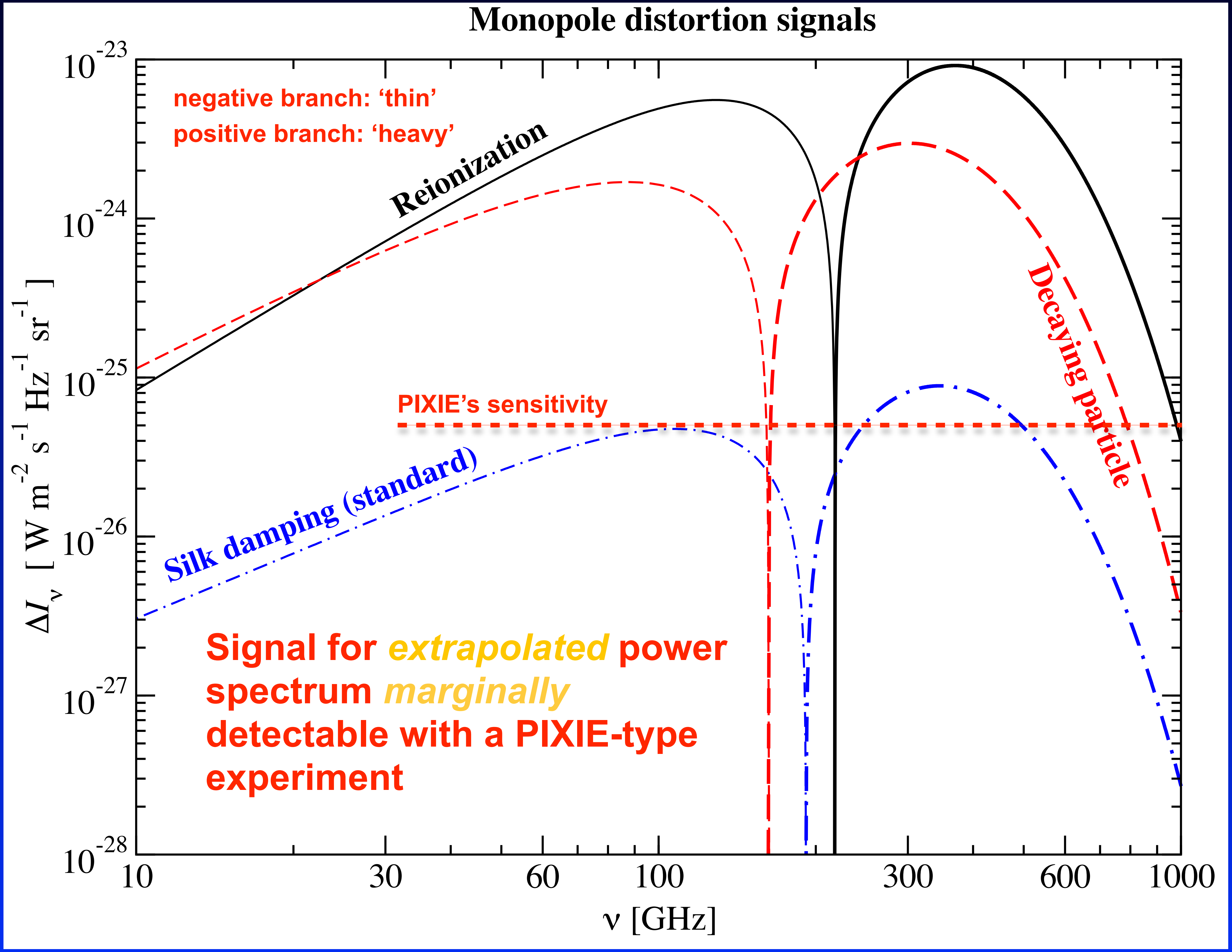
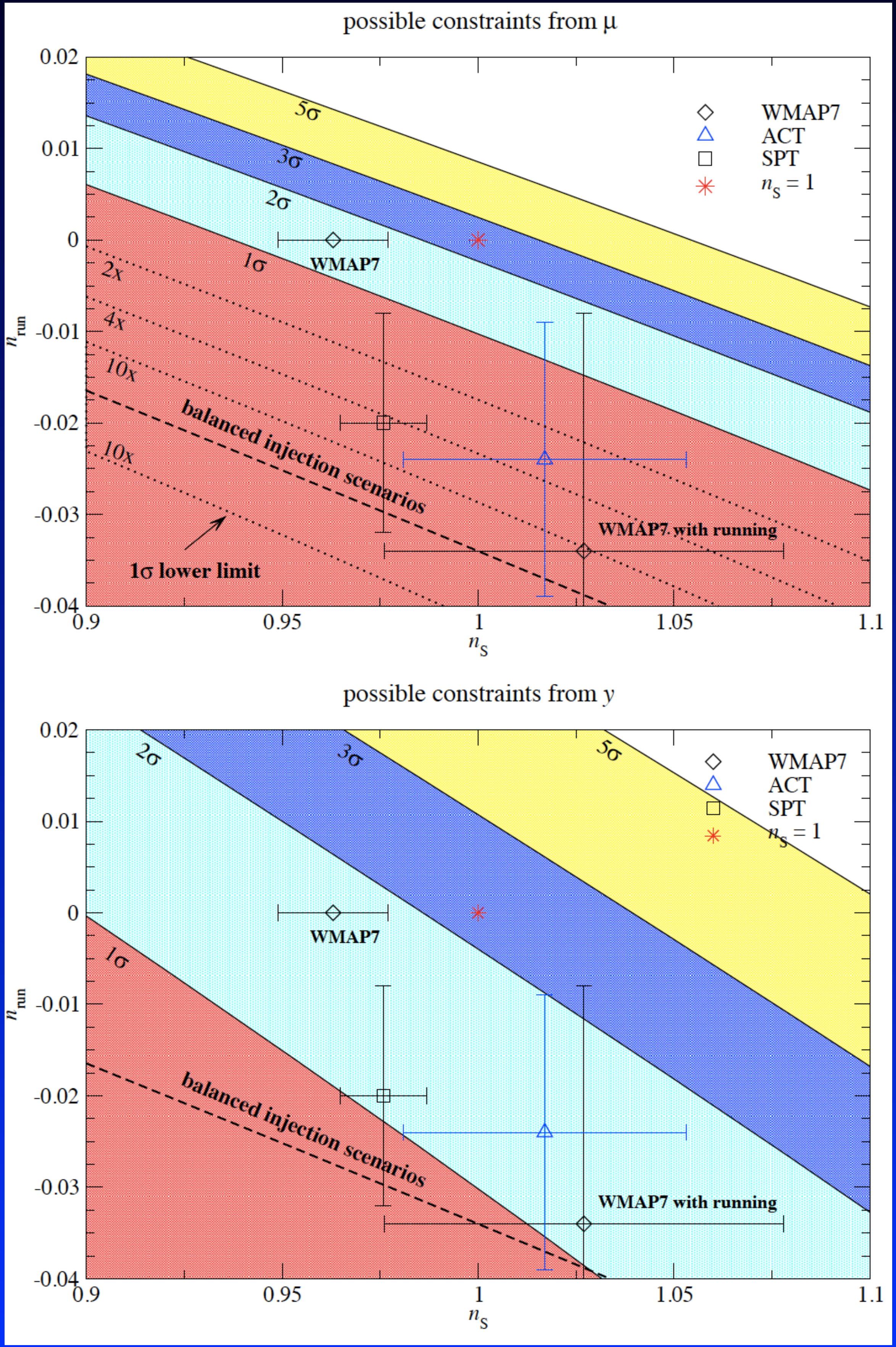


Signal for *extrapolated* power spectrum *marginally* detectable with a PIXIE-type experiment

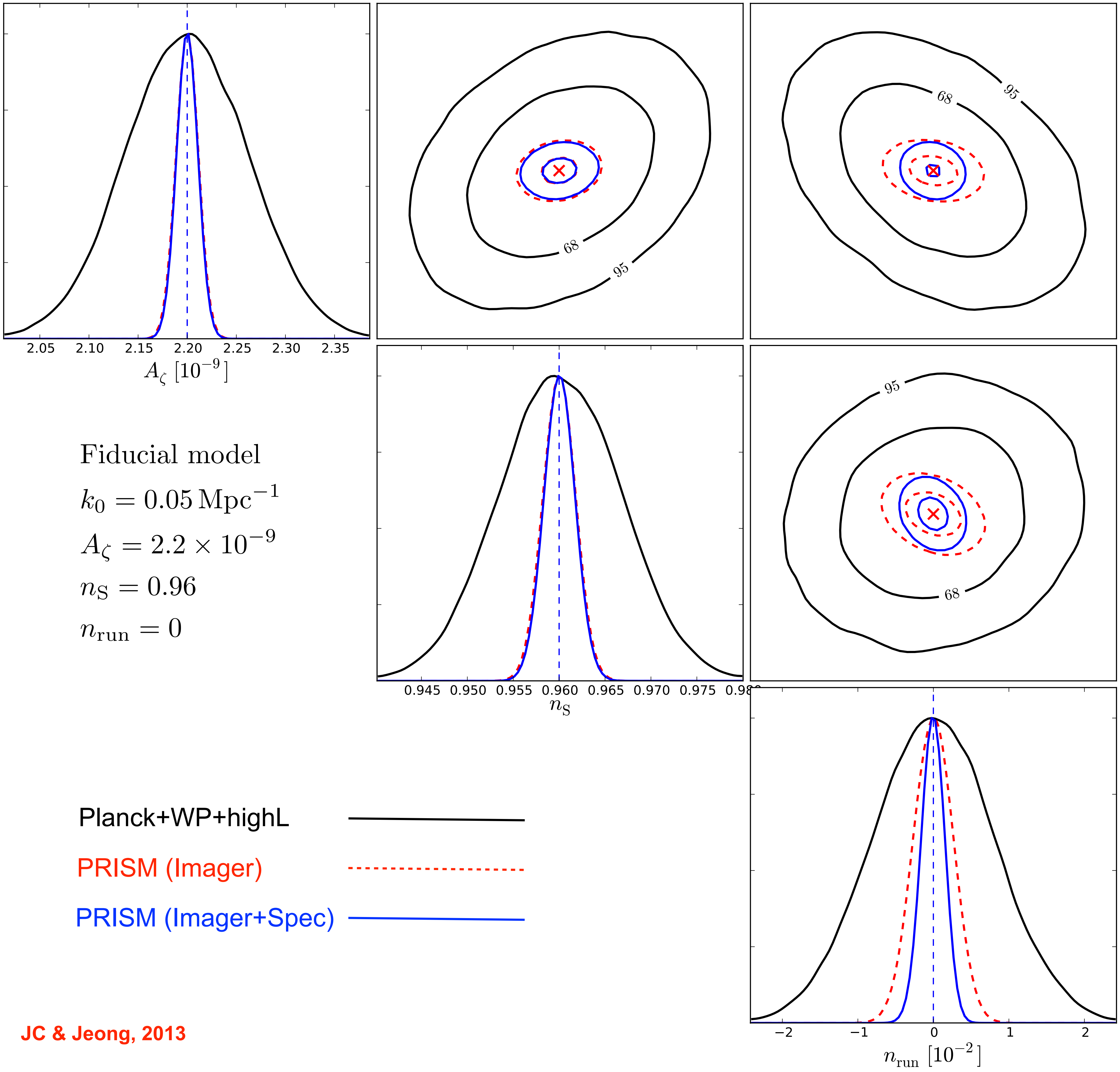
Constraints on the standard primordial power spectrum



- For *any* given power spectrum very precise predictions are possible!
- The *physics* going into the computation are *well understood*
- For the standard power spectrum PIXIE might detect the μ-distortion caused by acoustic damping at ~ 1.5σ level
- PIXIE could *independently* rule out a scale-invariant power spectrum at ~ 2.5σ level
- *y*-distortion will be harder to measure, since many *other astrophysical processes* cause *y*-distortions at low redshift

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

JC, Khatri & Sunyaev, 2012



Fiducial model

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

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

$n_\mathrm{S} = 0.96$

$n_\mathrm{run} = 0$

Planck+WP+highL

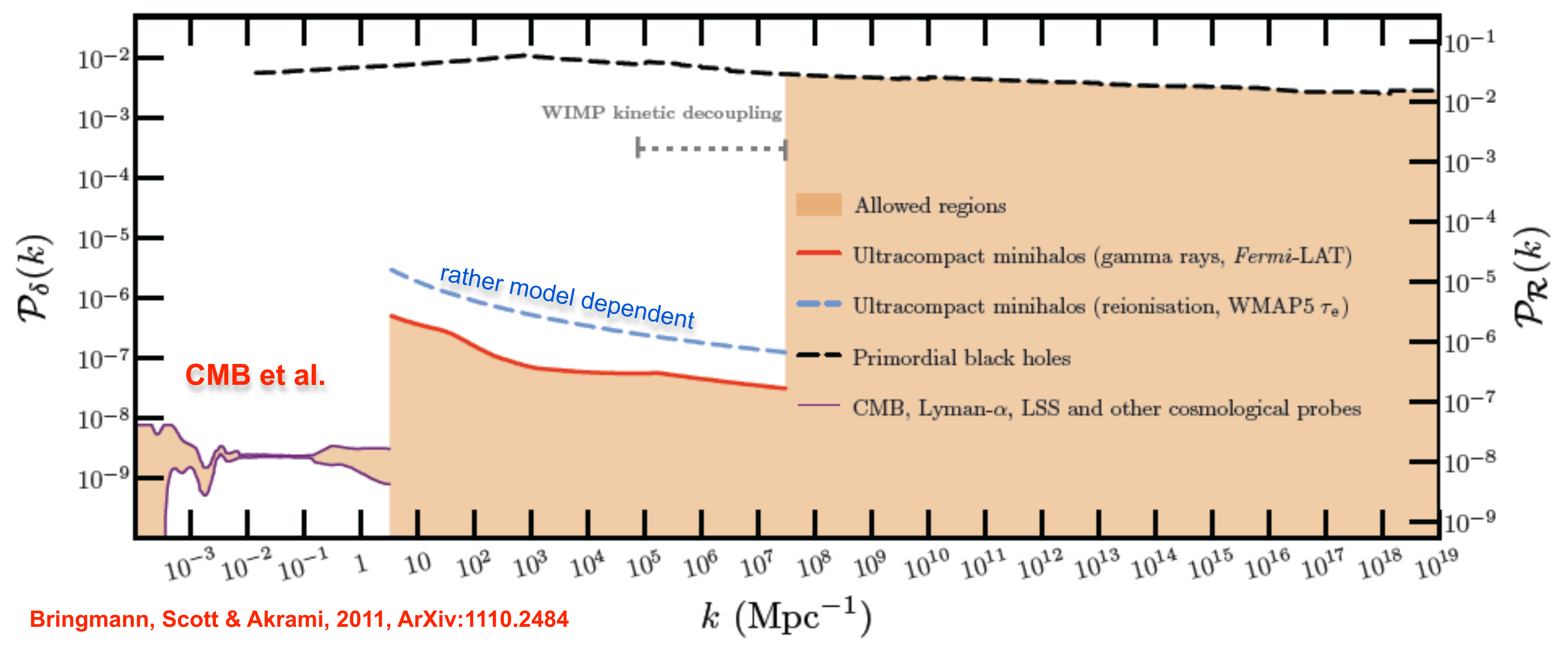
PRISM (Imager)

PRISM (Imager+Spec)

JC & Jeong, 2013

But this is not all that one could look at !!!

Distortions provide additional power spectrum constraints!



Bringmann, Scott & Akrami, 2011, ArXiv:1110.2484

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

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

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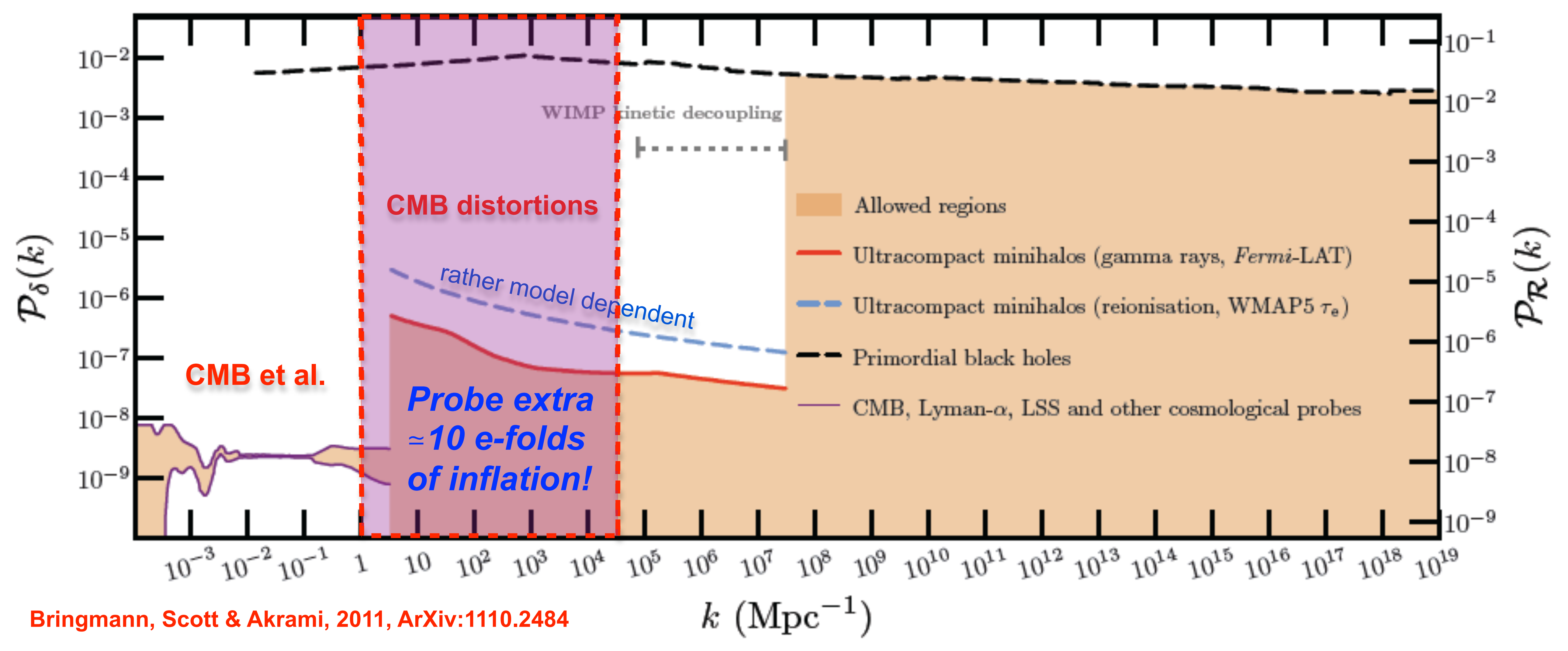
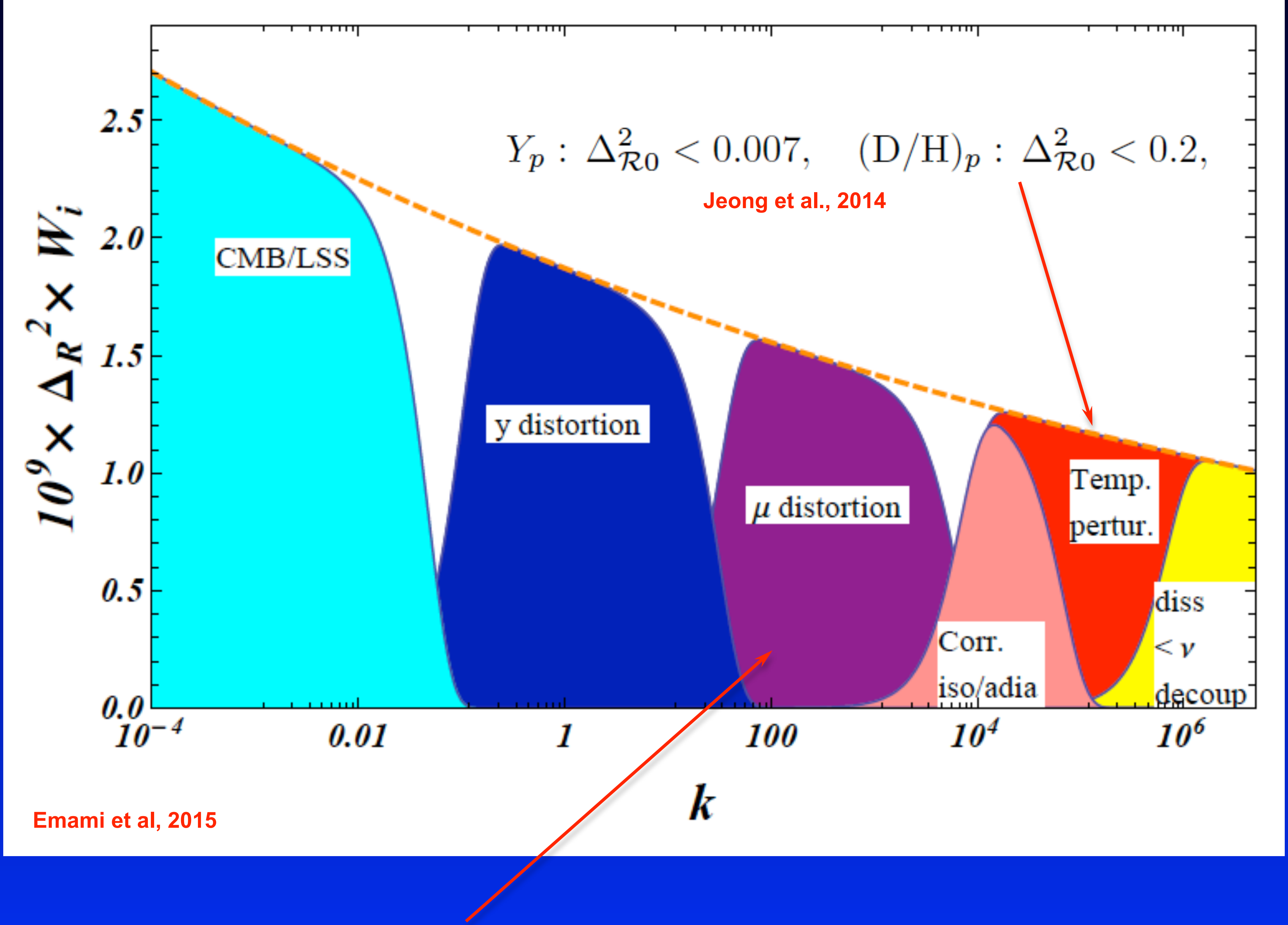


Bringmann, Scott & Akrami, 2011, ArXiv:1110.2484

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

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

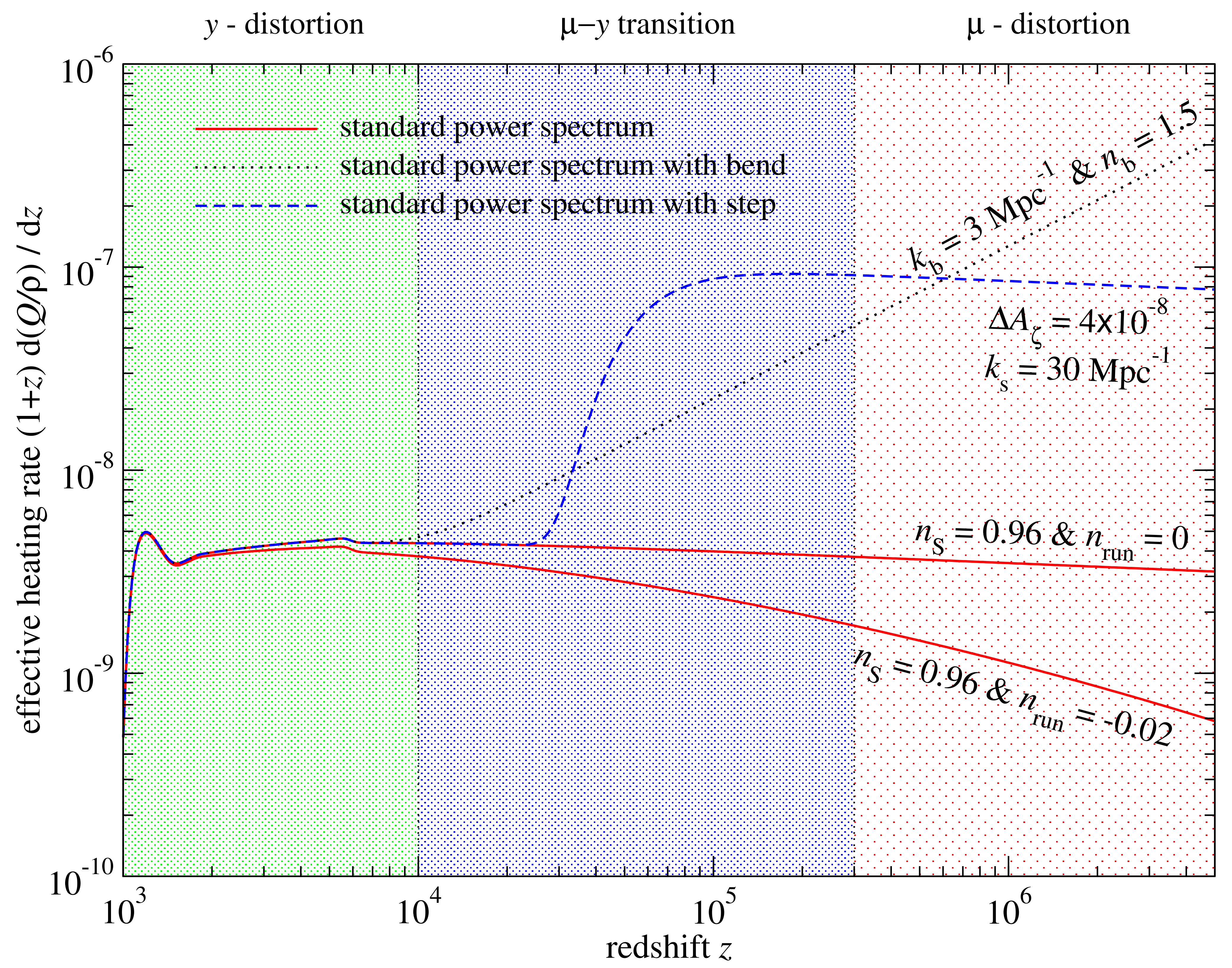


Jeong et al., 2014

Emami et al, 2015

- *Ultra-squeezed limit non-Gaussianity* (Pajer & Zaldarriaga, 2012; Ganc & Komatsu, 2012)

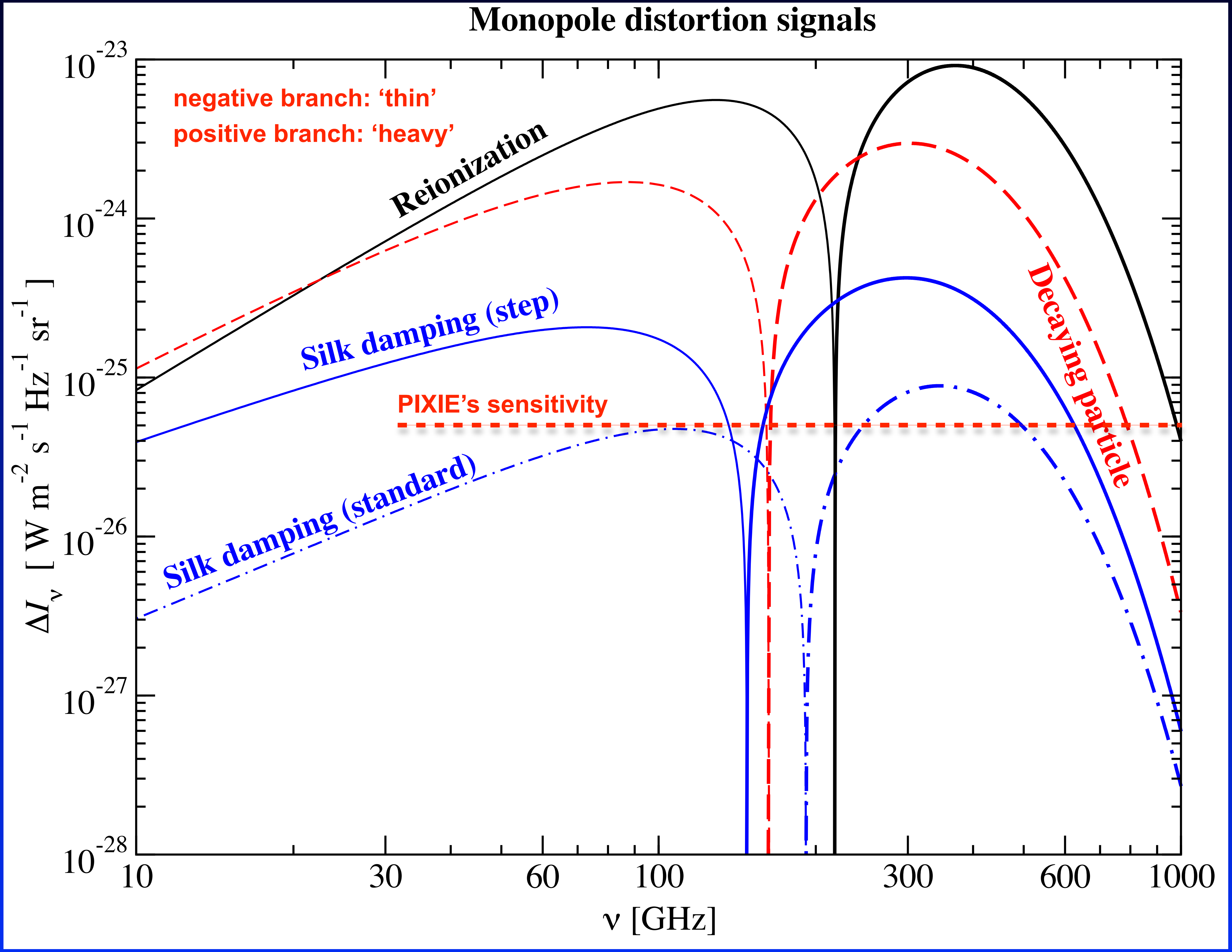
Probing the small-scale power spectrum



JC, 2013, Arxiv:1304.6120

Average CMB spectral distortions

Absolute value of Intensity signal



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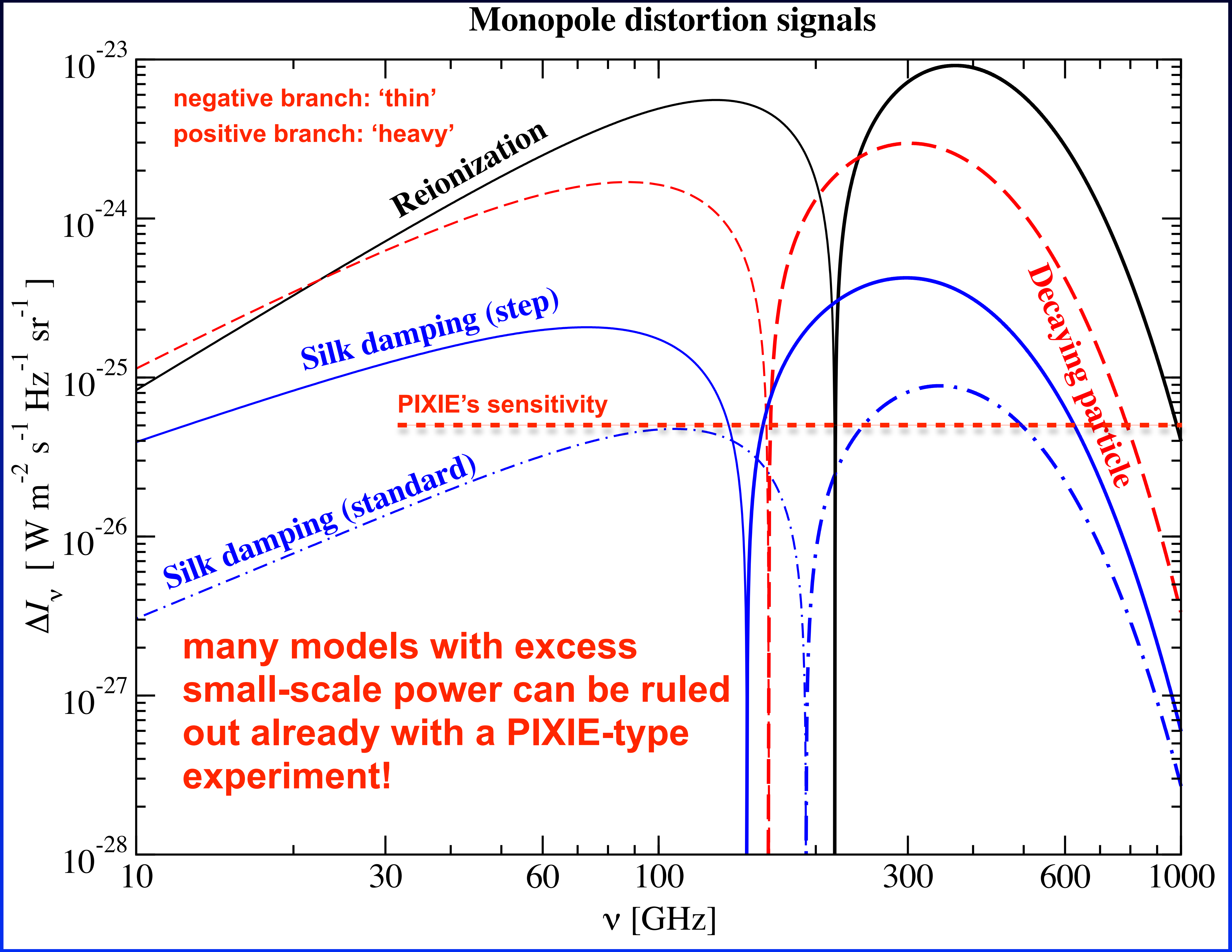
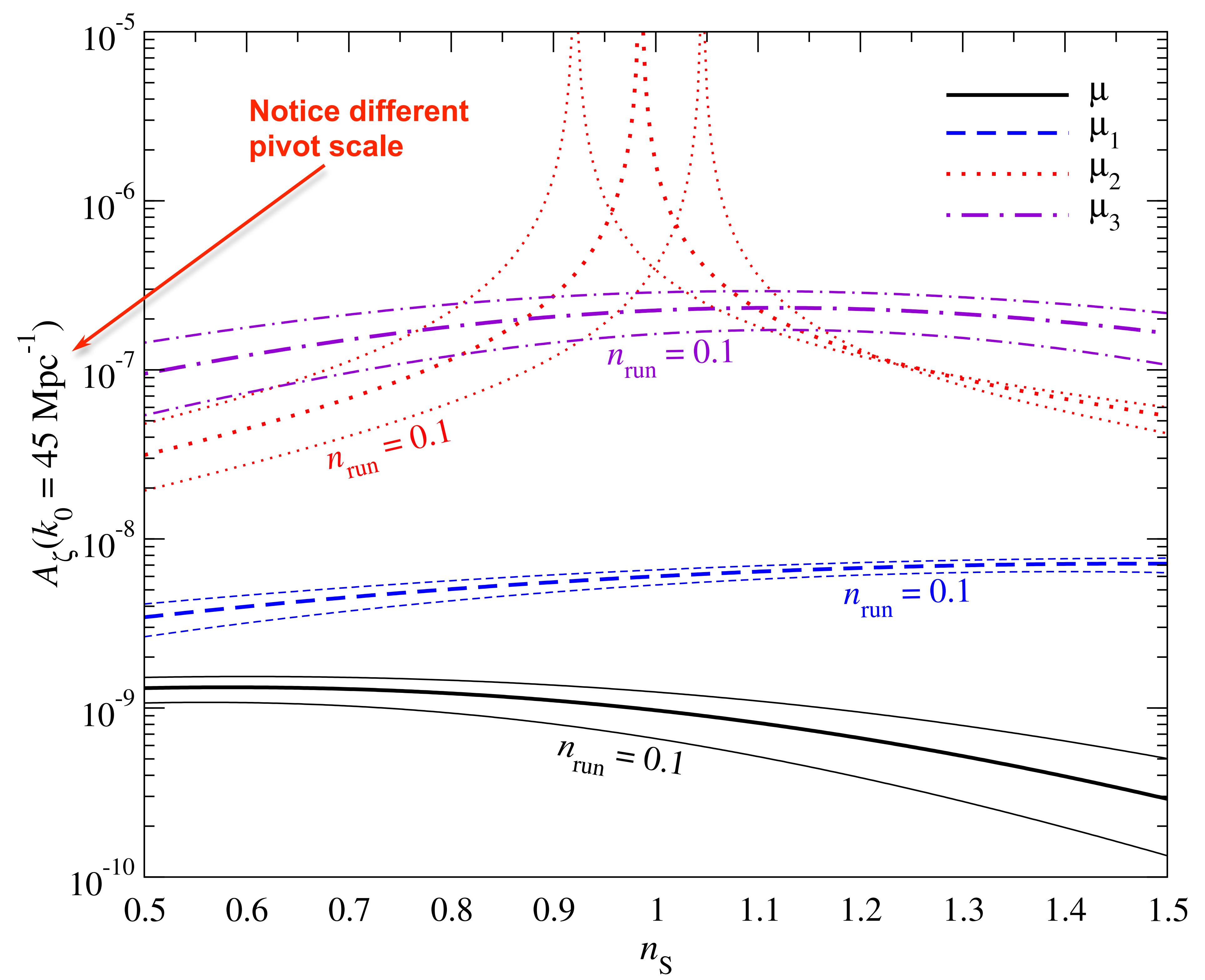


many models with excess small-scale power can be ruled out already with a PIXIE-type experiment!

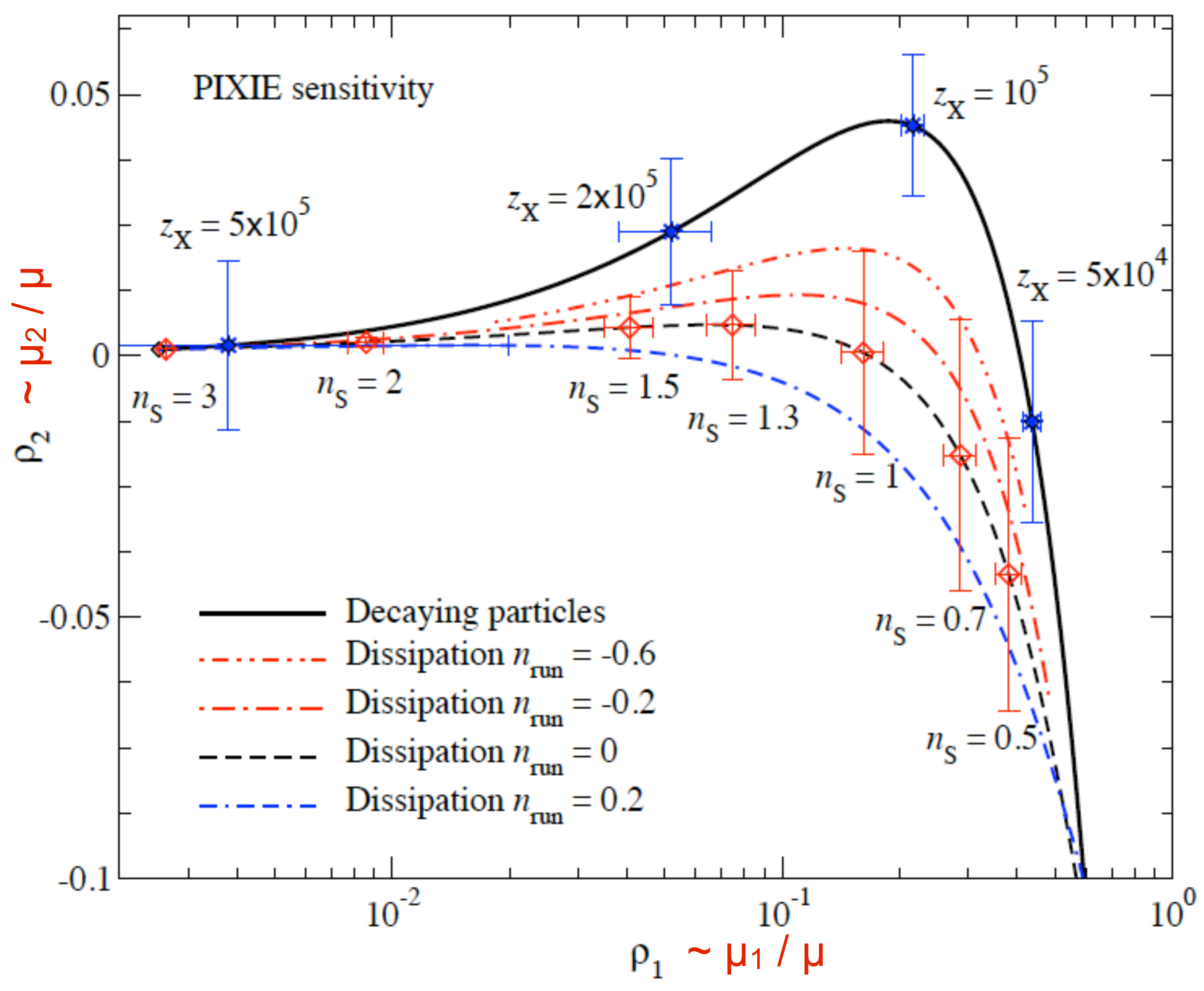
Dissipation scenario: 1σ-detection limits for PIXIE



JC & Jeong, 2013

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

Distinguishing dissipation and decaying particle scenarios

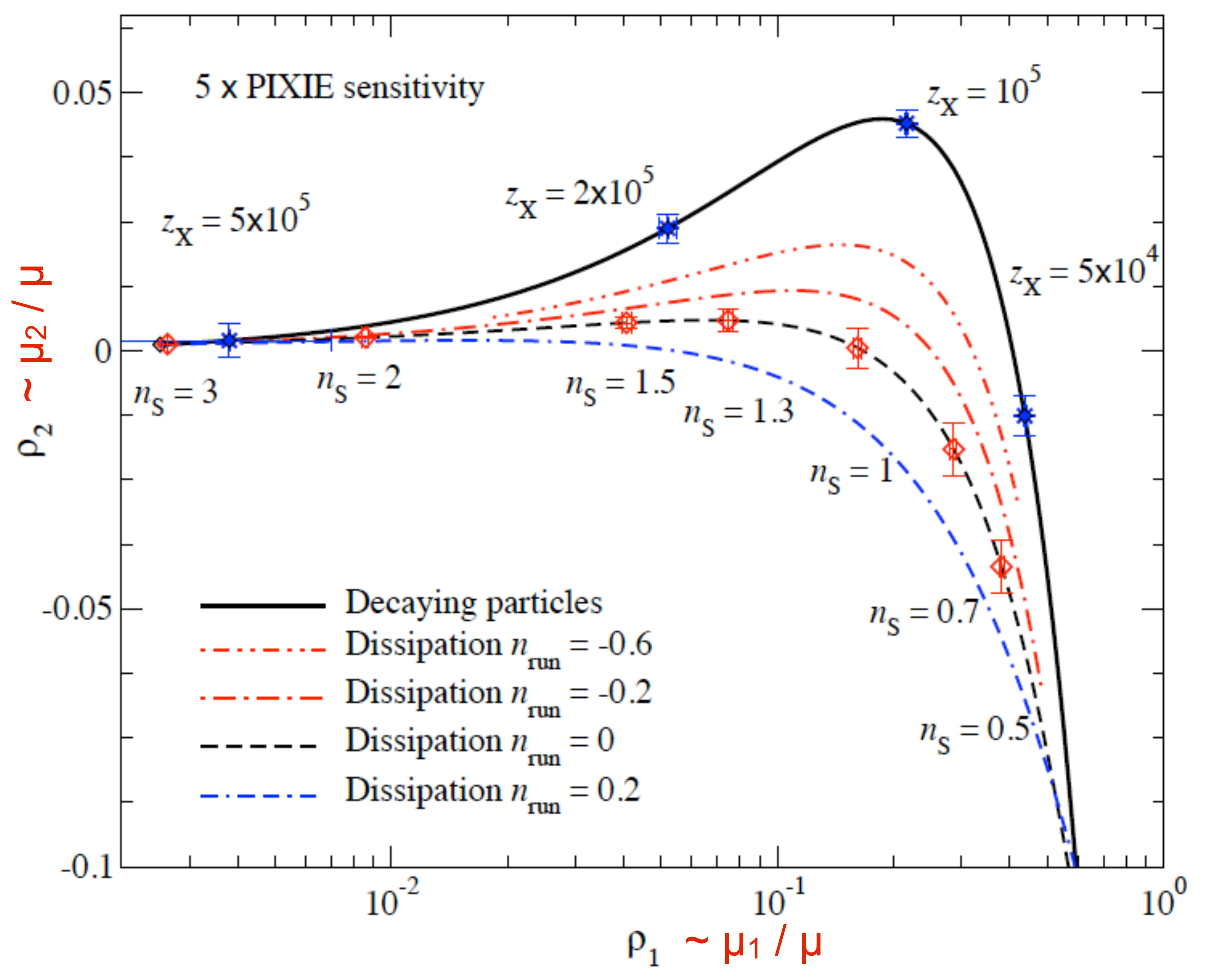


- measurement of μ, μ_1 & μ_2
- trajectories of decaying particle and dissipation scenarios differ!
- scenarios can in principle be distinguished

$$A_\zeta = 5 \times 10^{-8}$$

JC & Jeong, 2013

Distinguishing dissipation and decaying particle scenarios

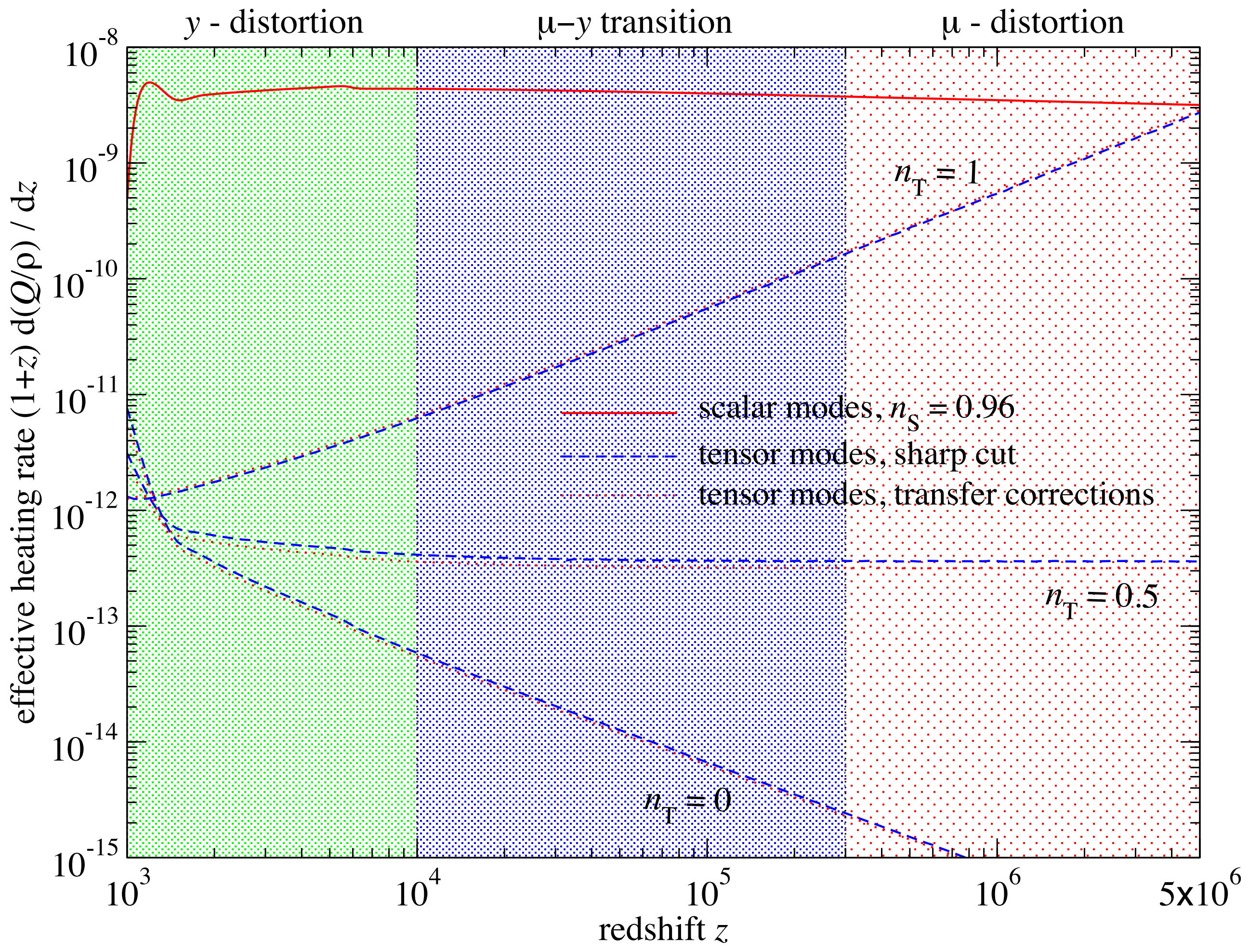


- measurement of μ, μ_1 & μ_2
- trajectories of decaying particle and dissipation scenarios differ!
- scenarios can in principle be distinguished

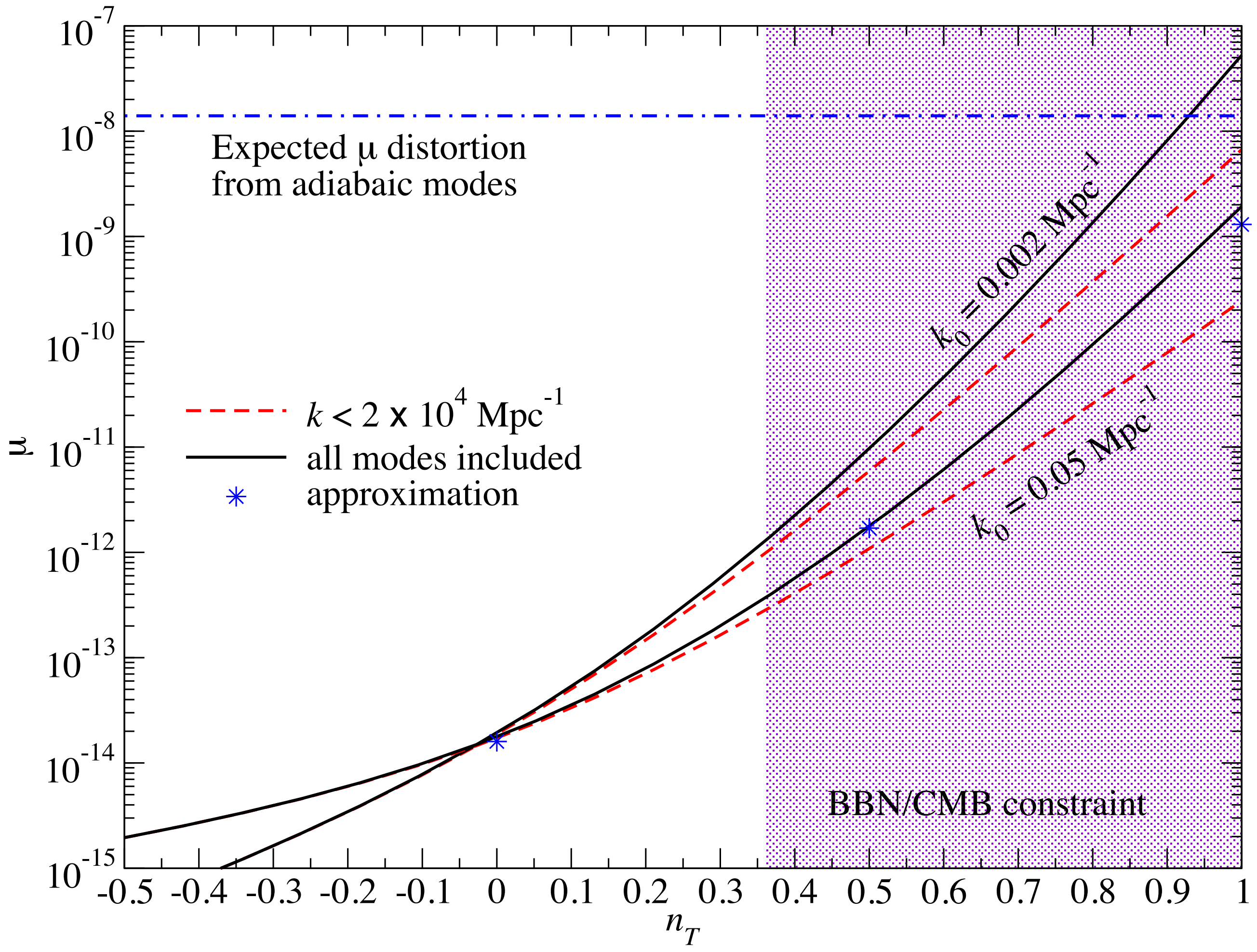
$$A_\zeta = 5 \times 10^{-8}$$

JC & Jeong, 2013

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 et al., 2014, ArXiv:1407.3653

The cosmological recombination radiation

Simple estimates for hydrogen recombination

Hydrogen recombination:

- per recombined hydrogen atom an energy of ~ 13.6 eV in form of photons is released
- at z ~ 1100 → $\Delta\varepsilon/\varepsilon \sim 13.6\ \mathrm{eV}\ N_b / (N_\gamma\, 2.7kT_r) \sim 10^{-9} - 10^{-8}$

→ recombination occurs at redshifts $z < 10^4$

→ At that time the *thermalization* process doesn't work anymore!

→ There should be some *small* spectral distortion due to additional Ly-α and 2s-1s photons!
(Zeldovich, Kurt & Sunyaev, 1968, ZhETF, 55, 278; Peebles, 1968, ApJ, 153, 1)

→ In 1975 ***Viktor Dubrovich*** emphasized the possibility to observe the recombinational lines from n > 3 and Δn << n!

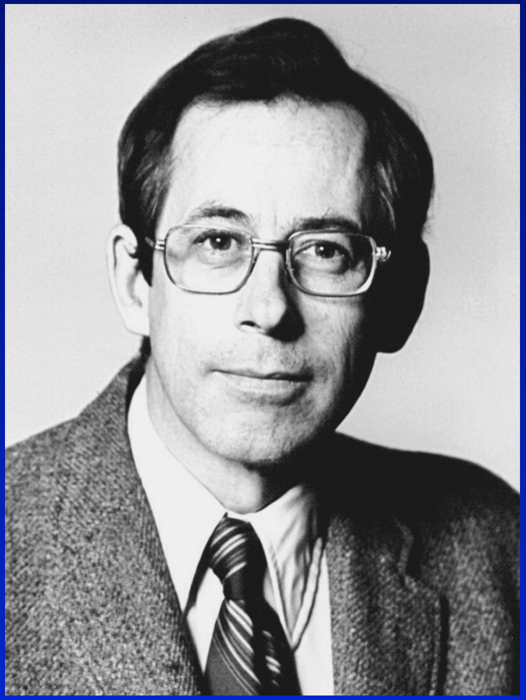
First recombination computations completed in 1968!

Yakov Zeldovich

Moscow

Princeton

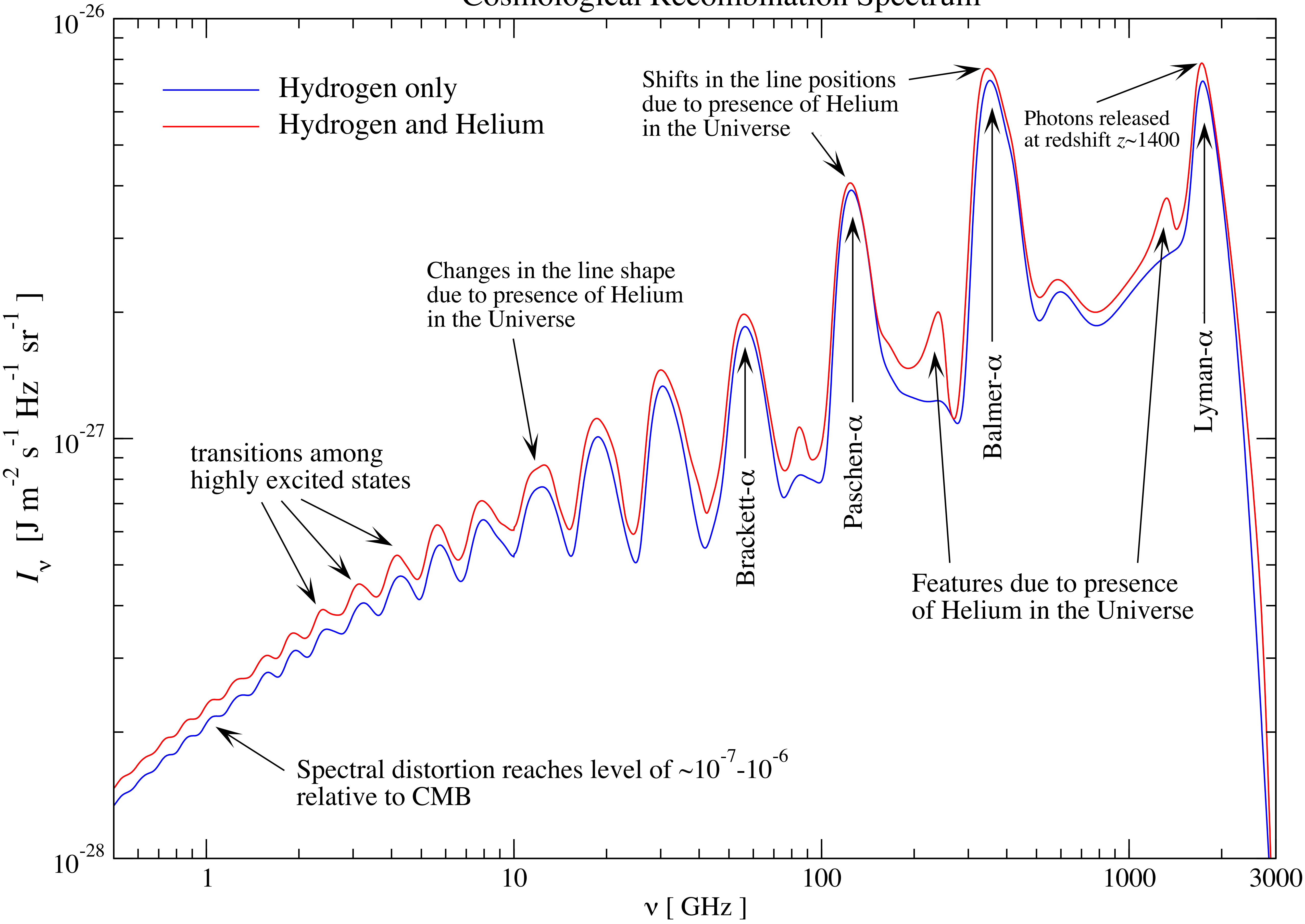
Rashid Sunyaev



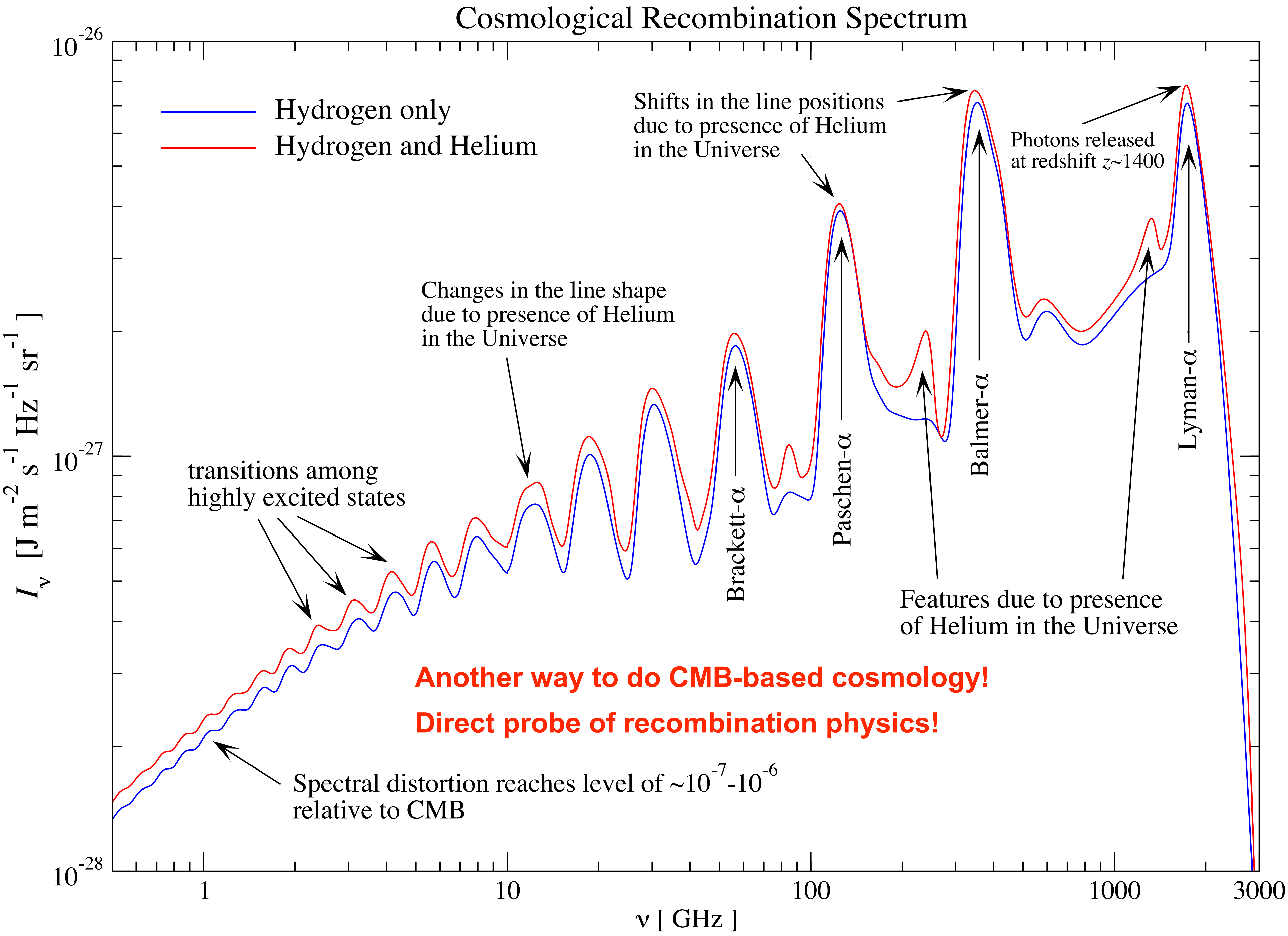
Jim Peebles

Vladimir Kurt
(UV astronomer)

Cosmological Recombination Spectrum



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

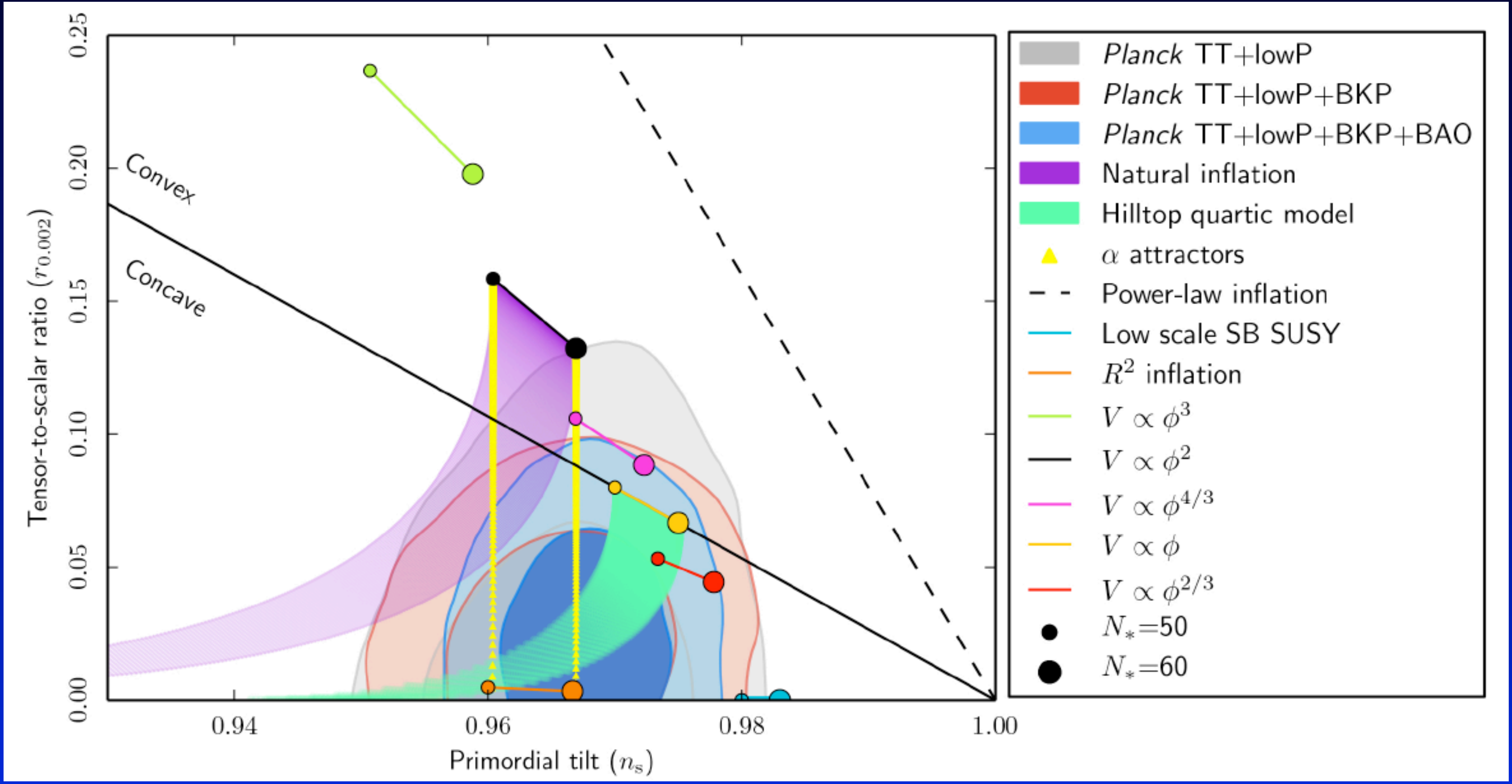


Another way to do CMB-based cosmology!

Direct probe of recombination physics!

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

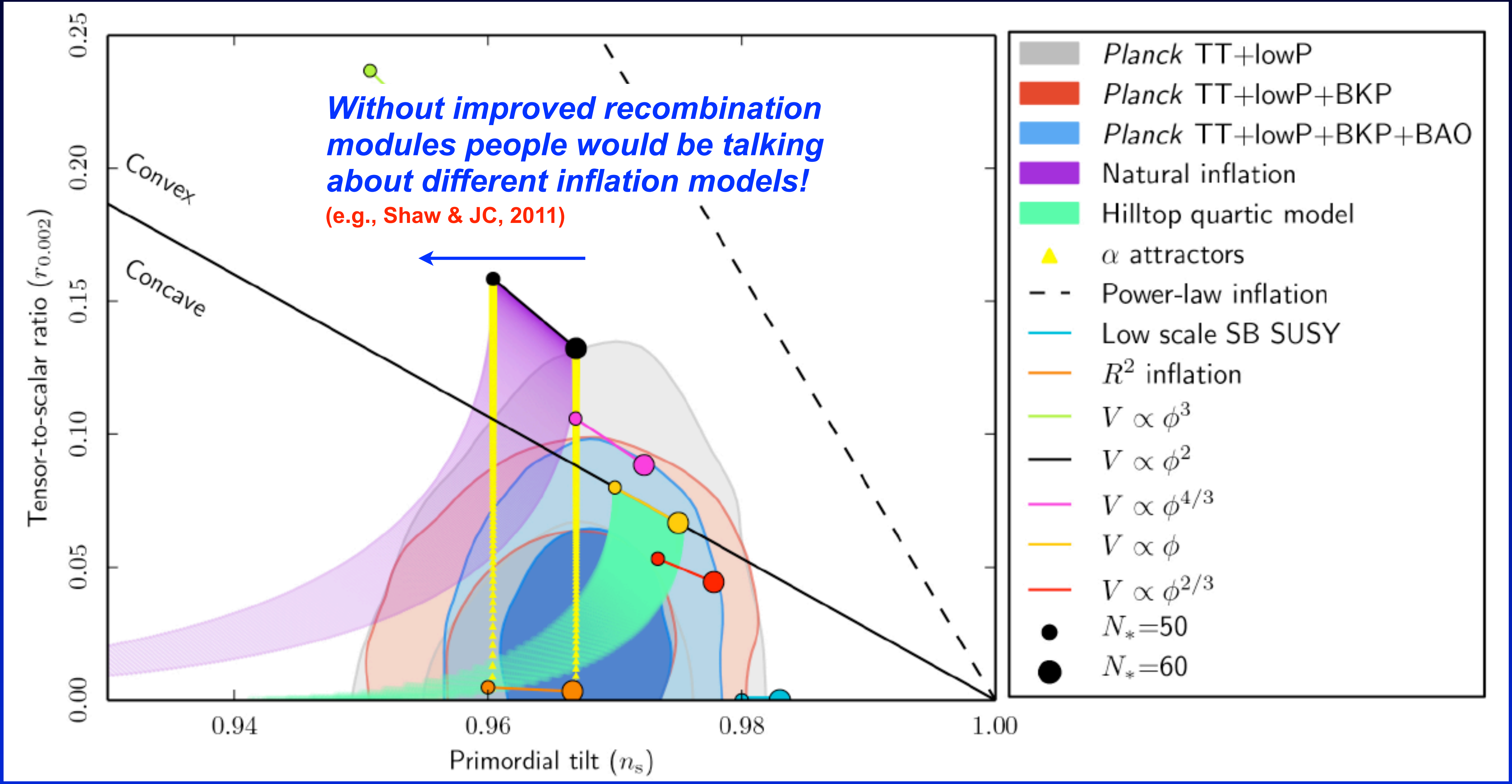
Importance of recombination for inflation constraints



Planck Collaboration, 2015, paper XX

- Analysis uses refined recombination model (CosmoRec/HyRec)

Importance of recombination for inflation constraints

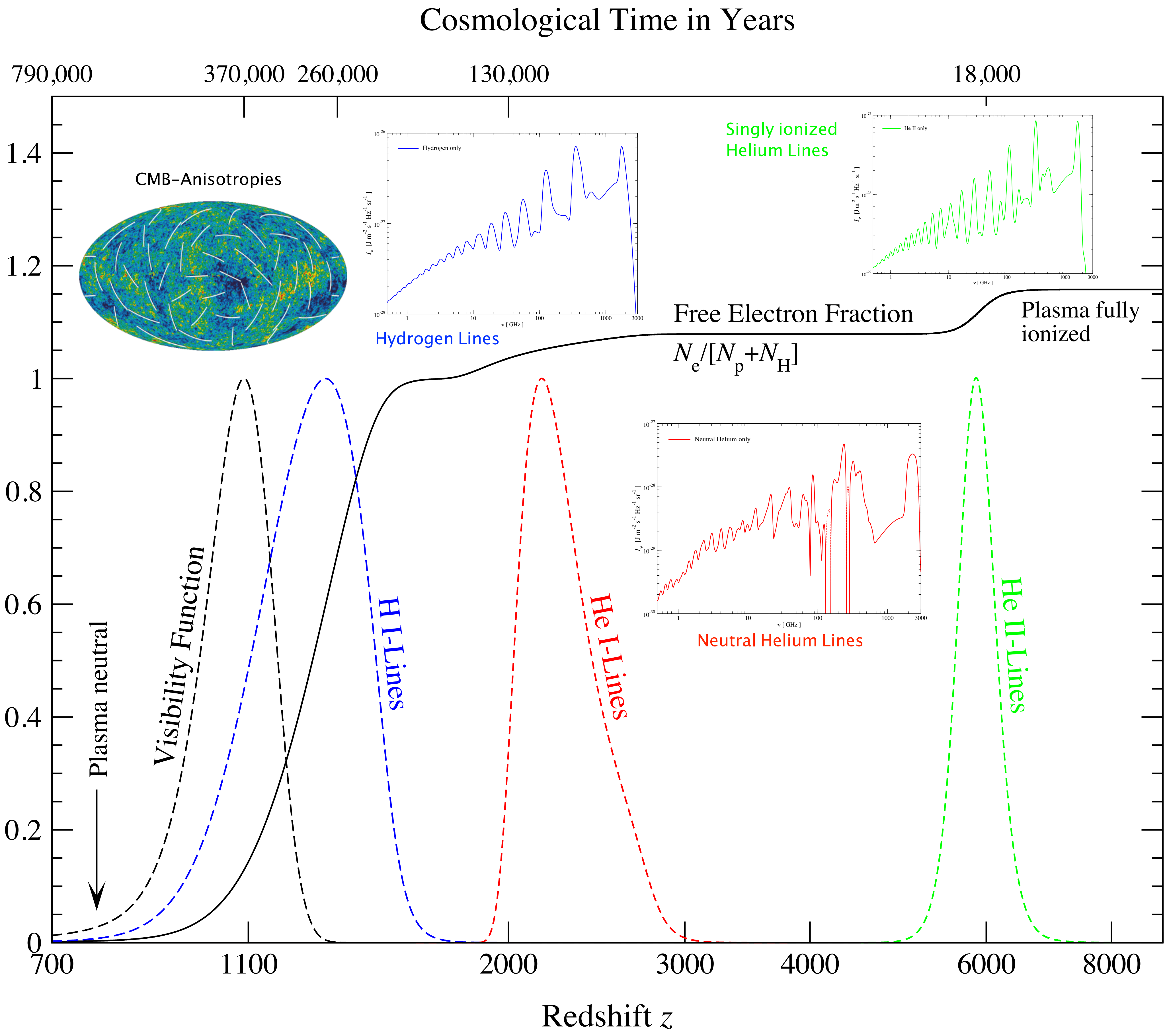


Without improved recombination modules people would be talking about different inflation models!

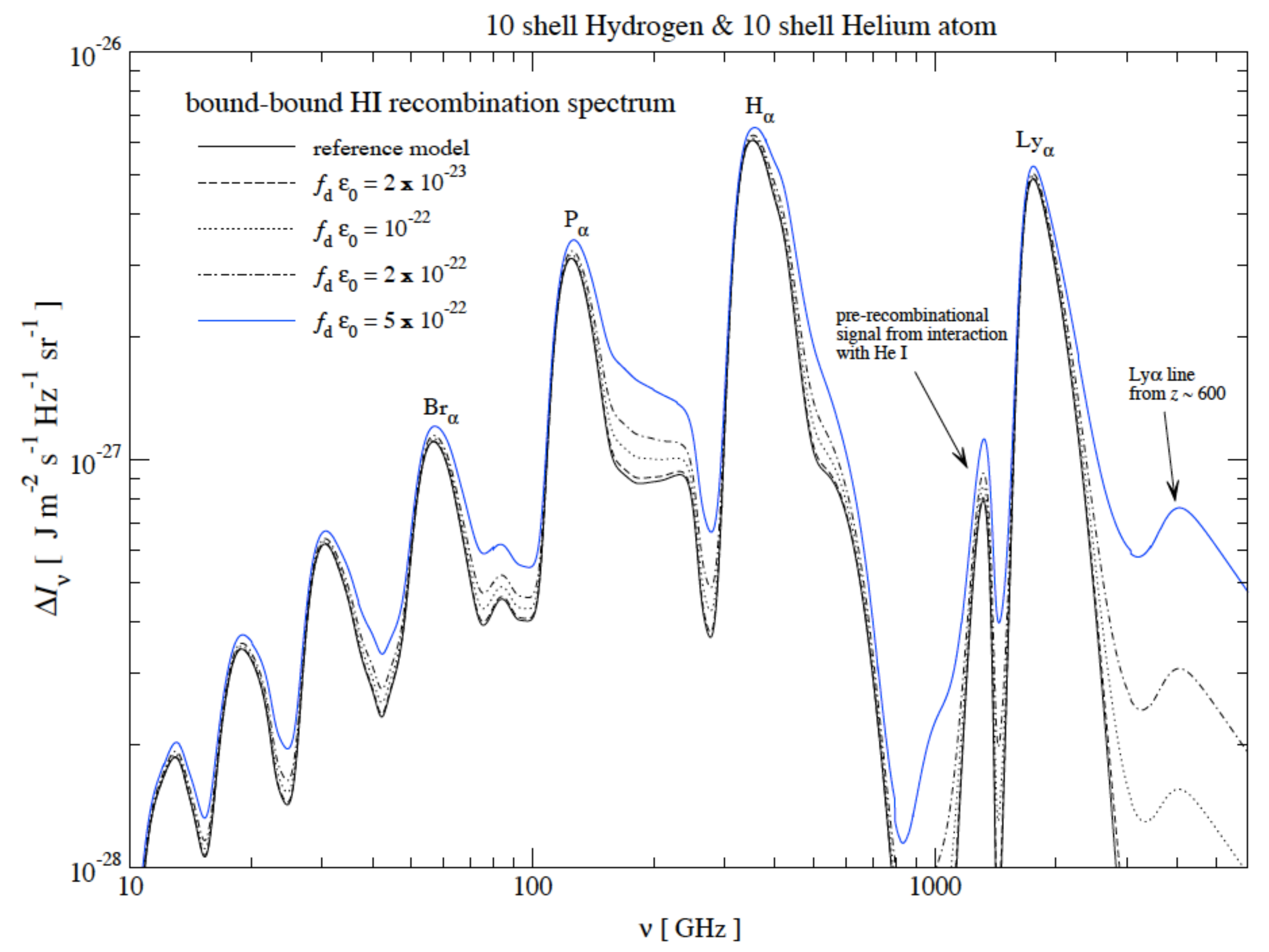
(e.g., Shaw & JC, 2011)

Planck Collaboration, 2015, paper XX

- Analysis uses refined recombination model (CosmoRec/HyRec)


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
700
1100
2000
3000
4000
6000
8000
Redshift z
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
ν [GHz]
Plasma neutral
Visibility Function
H I-Lines
He I-Lines
He II-Lines

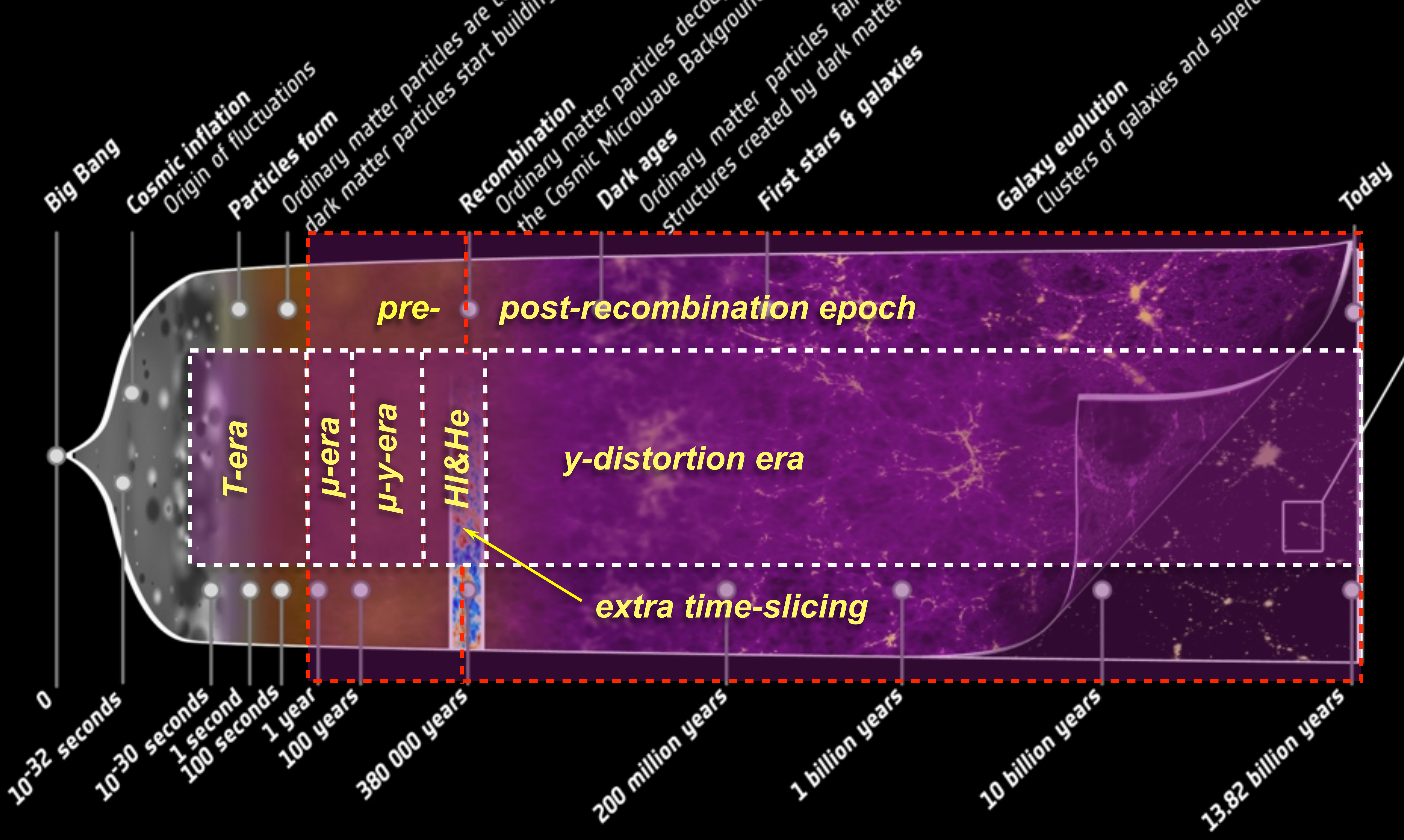
Dark matter annihilations / decays



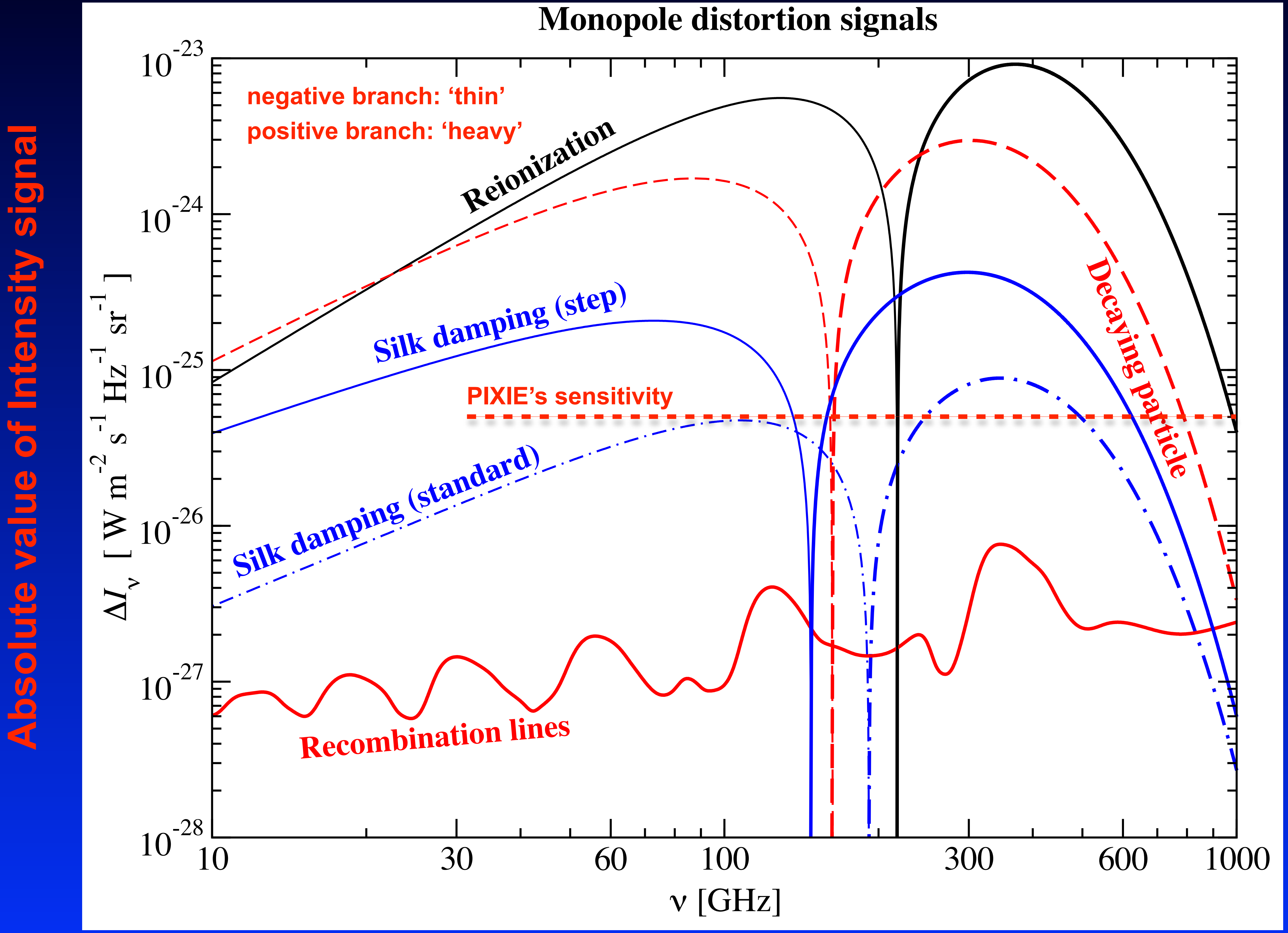
JC, 2009, arXiv:0910.3663

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

CMB spectrum adds another dimension to the problem!

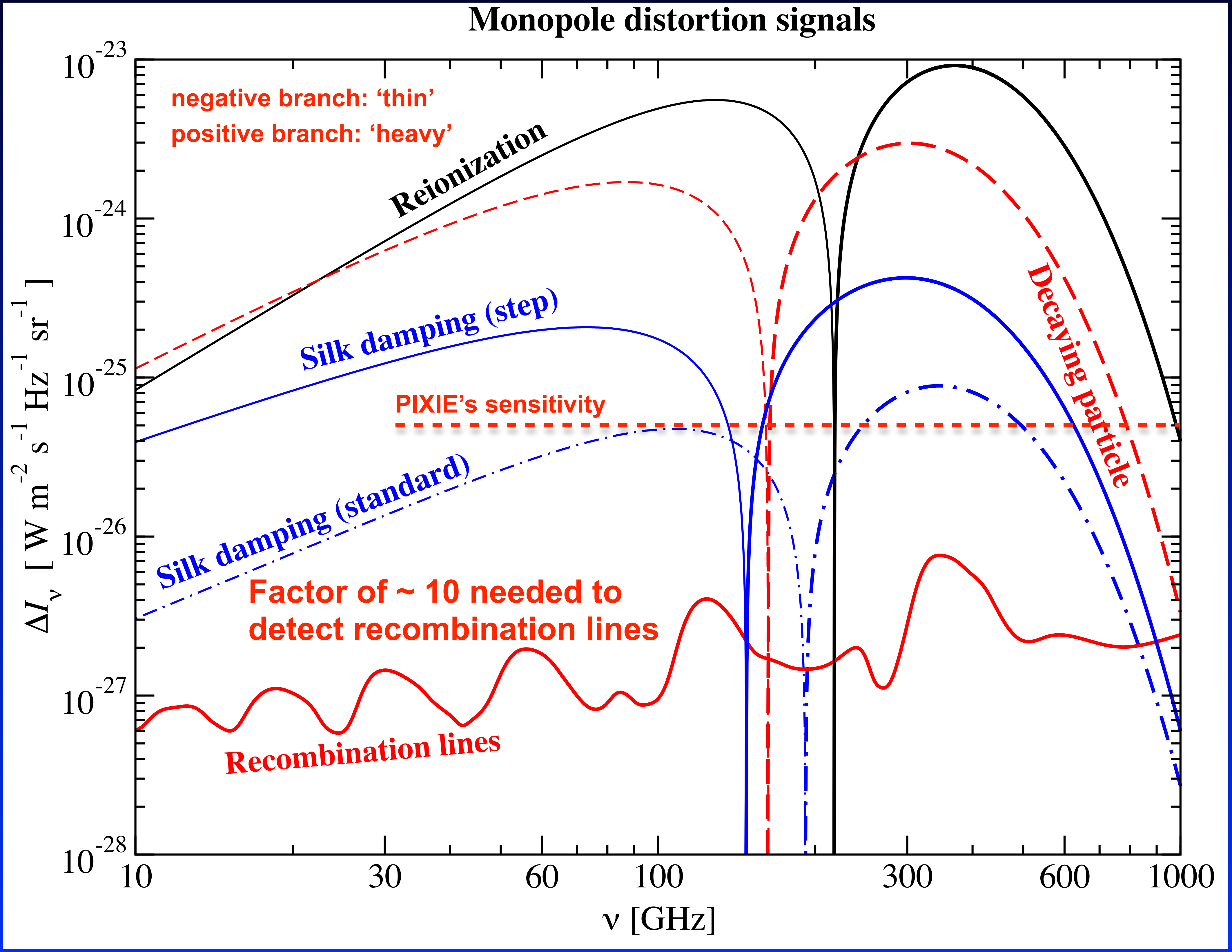


Average CMB spectral distortions

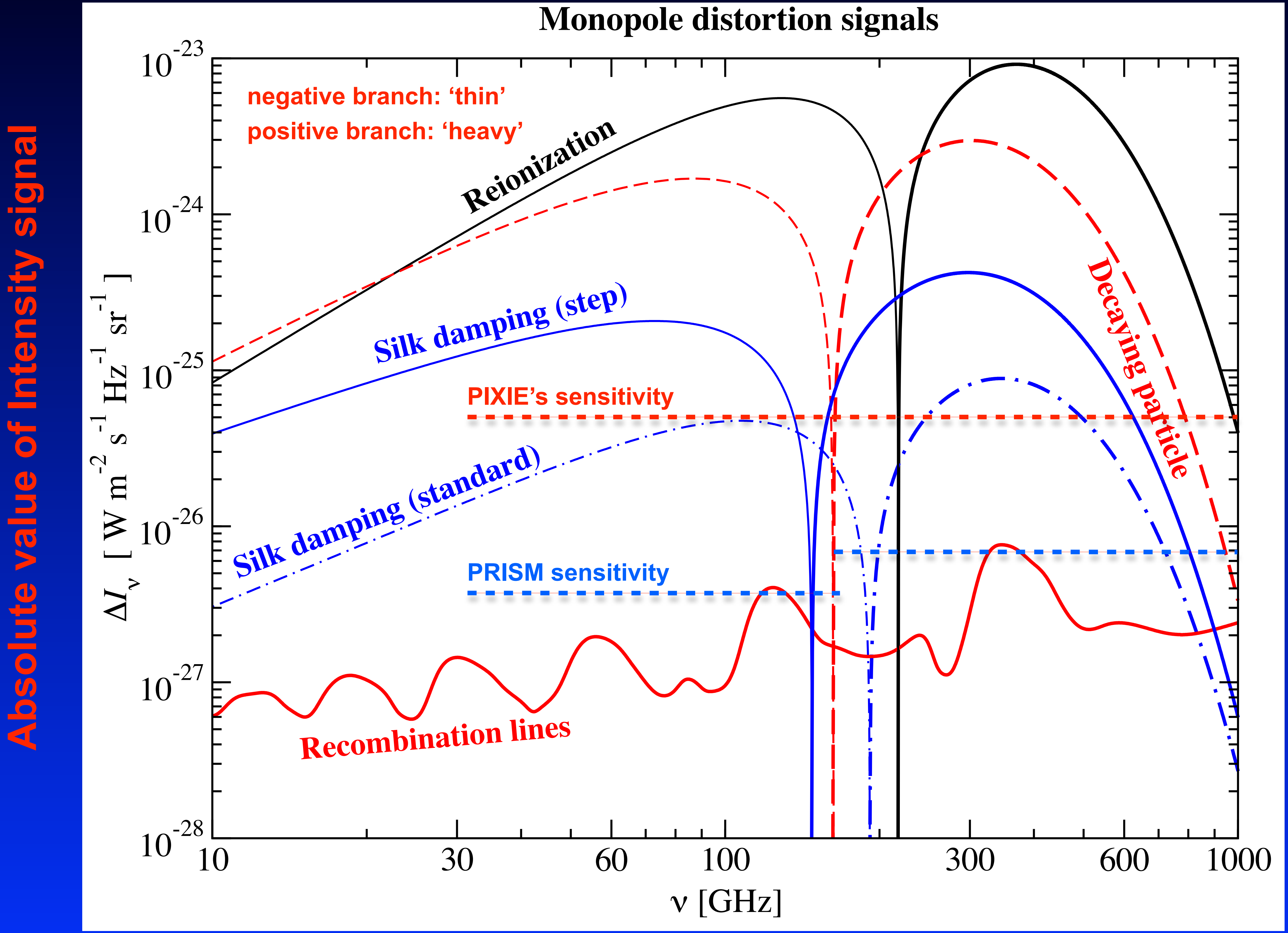


Average CMB spectral distortions

Absolute value of Intensity signal



Average CMB spectral distortions



What would we actually learn by doing such hard job?

Cosmological Recombination Spectrum opens a way to measure:

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

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

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

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

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

computations prepared by Chad Fendt
in 2009 using detailed recombination code

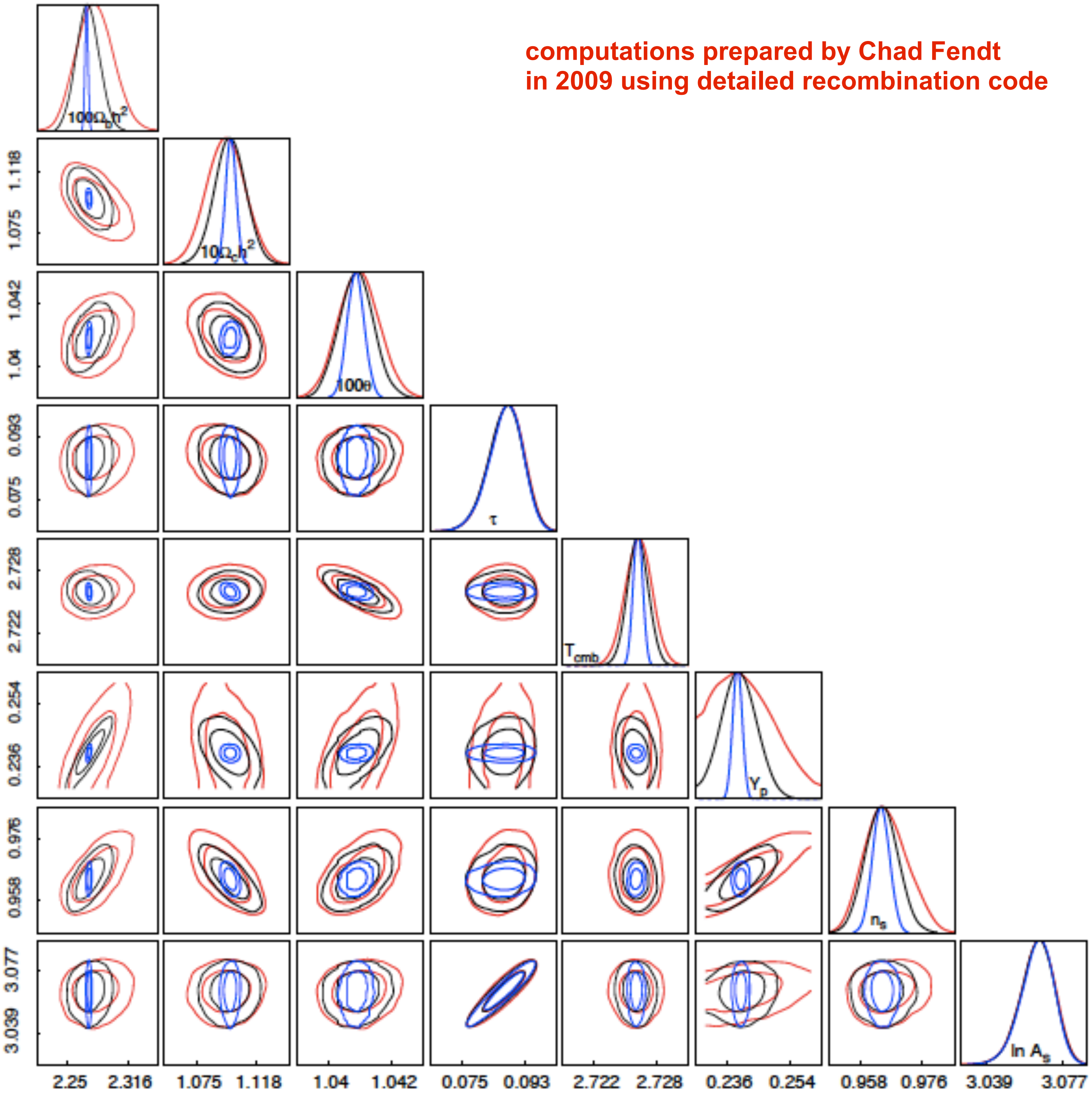


Figure 7.3: The 1 and 2 dimensional marginalized parameter posterior using the CMB spectral distortions. All three cases constrain the CMB power spectrum using a Gaussian likelihood based on Planck noise levels. The black line adds constraints due to a 10% measurement of the spectral distortions, while the blue line assumes a 1% measurement. The red line does not include the data from the spectral distortions.

- CMB based cosmology alone
- Spectrum helps to break some of the parameter degeneracies
- Planning to provide a module that computes the recombination spectrum in a fast way
- detailed forecasts: which lines to measure; how important is the absolute amplitude; how accurately one should measure; best frequency resolution;

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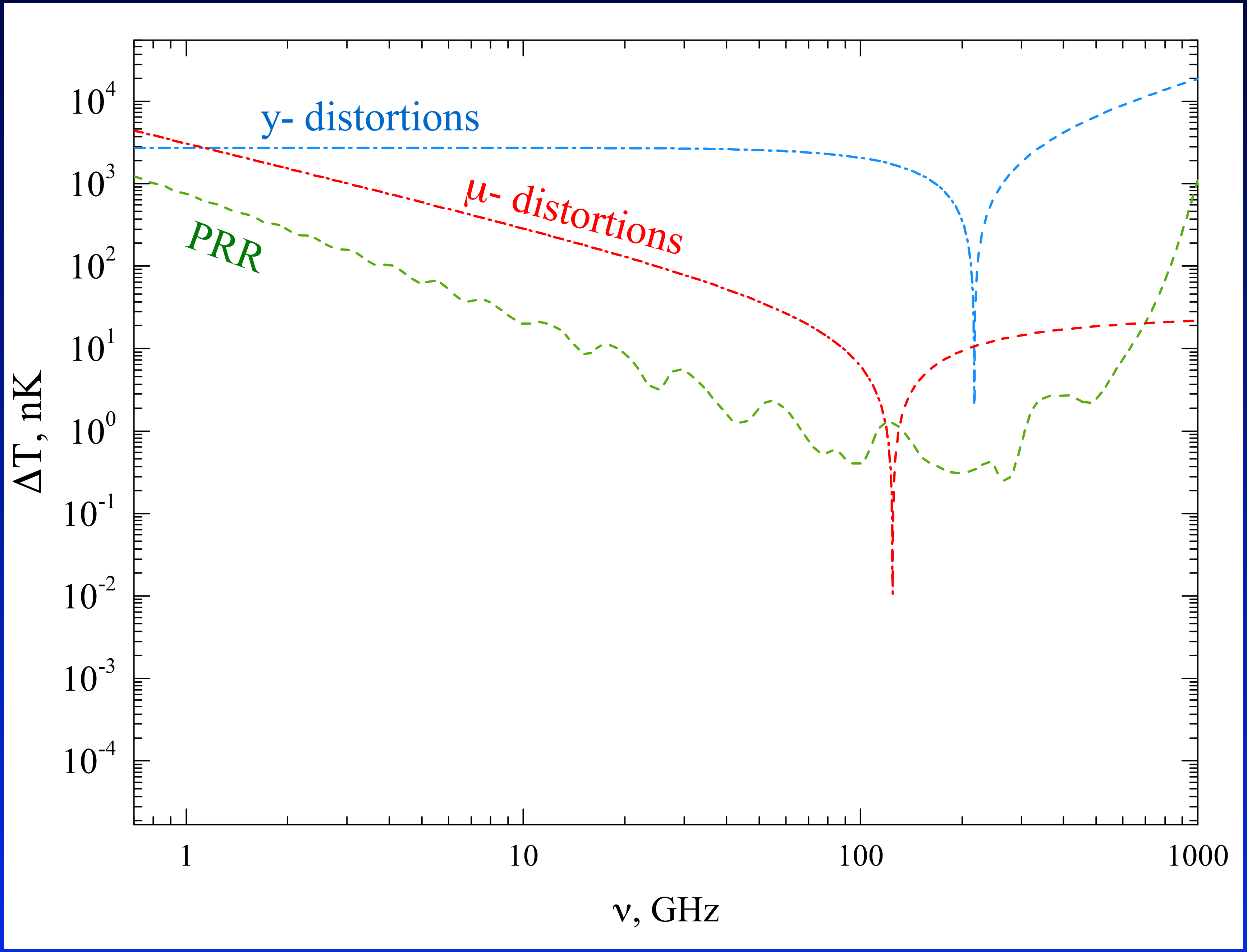
If something unexpected or non-standard happened:

→ ***non-standard thermal histories should leave some measurable traces***
→ ***direct way to measure/reconstruct the recombination history!***
→ **possibility to distinguish *pre-* and *post-recombination* y-type distortions**
→ ***sensitive to energy release during recombination***
→ **variation of fundamental constants**

Spectral distortions of the CMB dipole



- motion with respect to CMB blackbody monopole

⇒ *CMB temperature dipole*

- including primordial distortions of the CMB

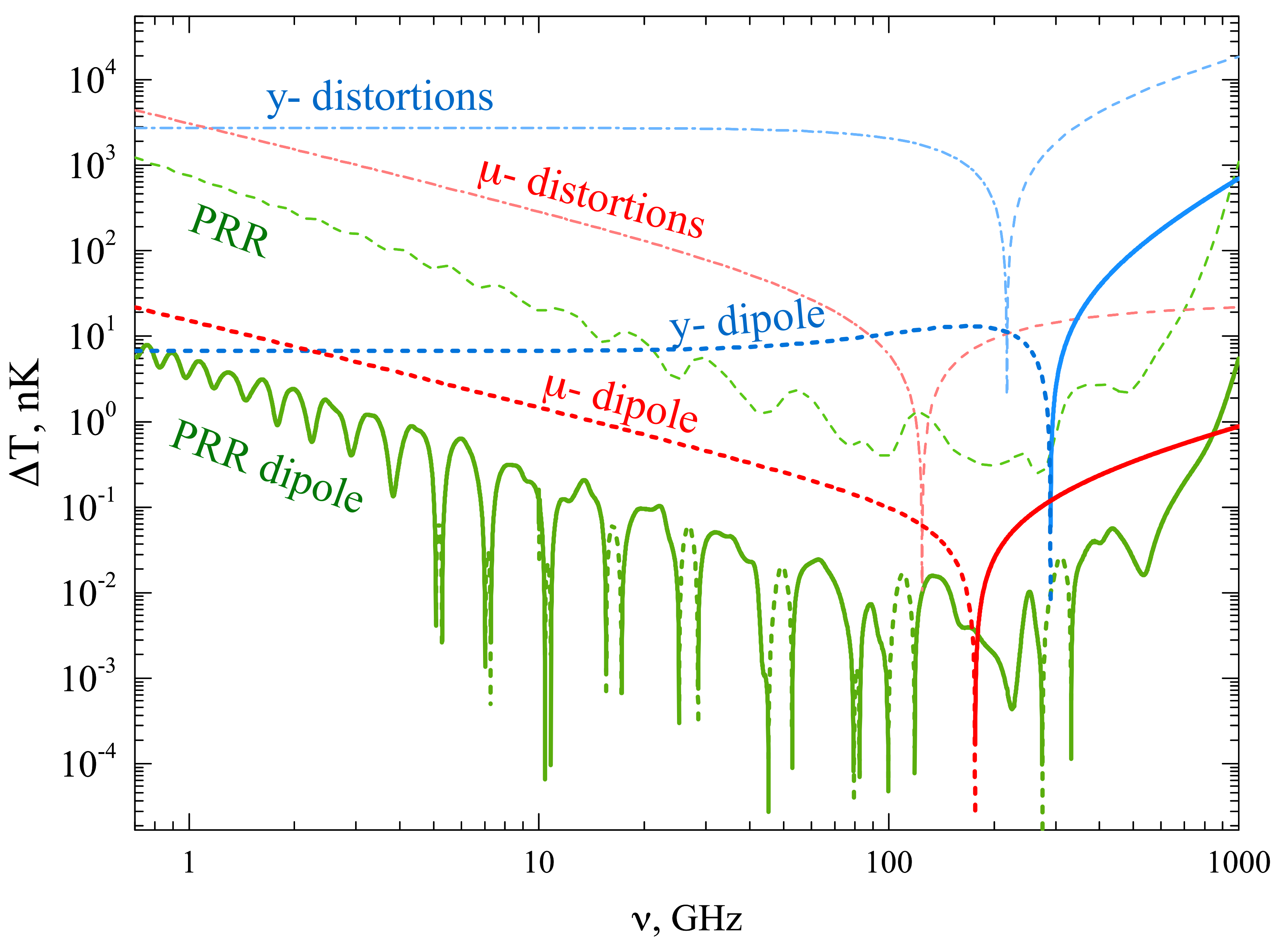
⇒ *CMB dipole is distorted*

$$\eta_{\rm d}(\nu, \mathbf{n}) \approx -\nu \partial_\nu \eta_{\rm m}(\nu)\, \beta \cos\Theta$$

- spectrum of the dipole is sensitive to the *derivative* of the monopole spectrum
- anisotropy does not need *absolute* calibration but just *inter-channel* calibration
- *but* signal is ~1000 times smaller...
- foregrounds will also leak into the dipole in this way

Balashev, Kholupenko, JC, Ivanchik & Varshalovich, 2015, in prep.

Spectral distortions of the CMB dipole



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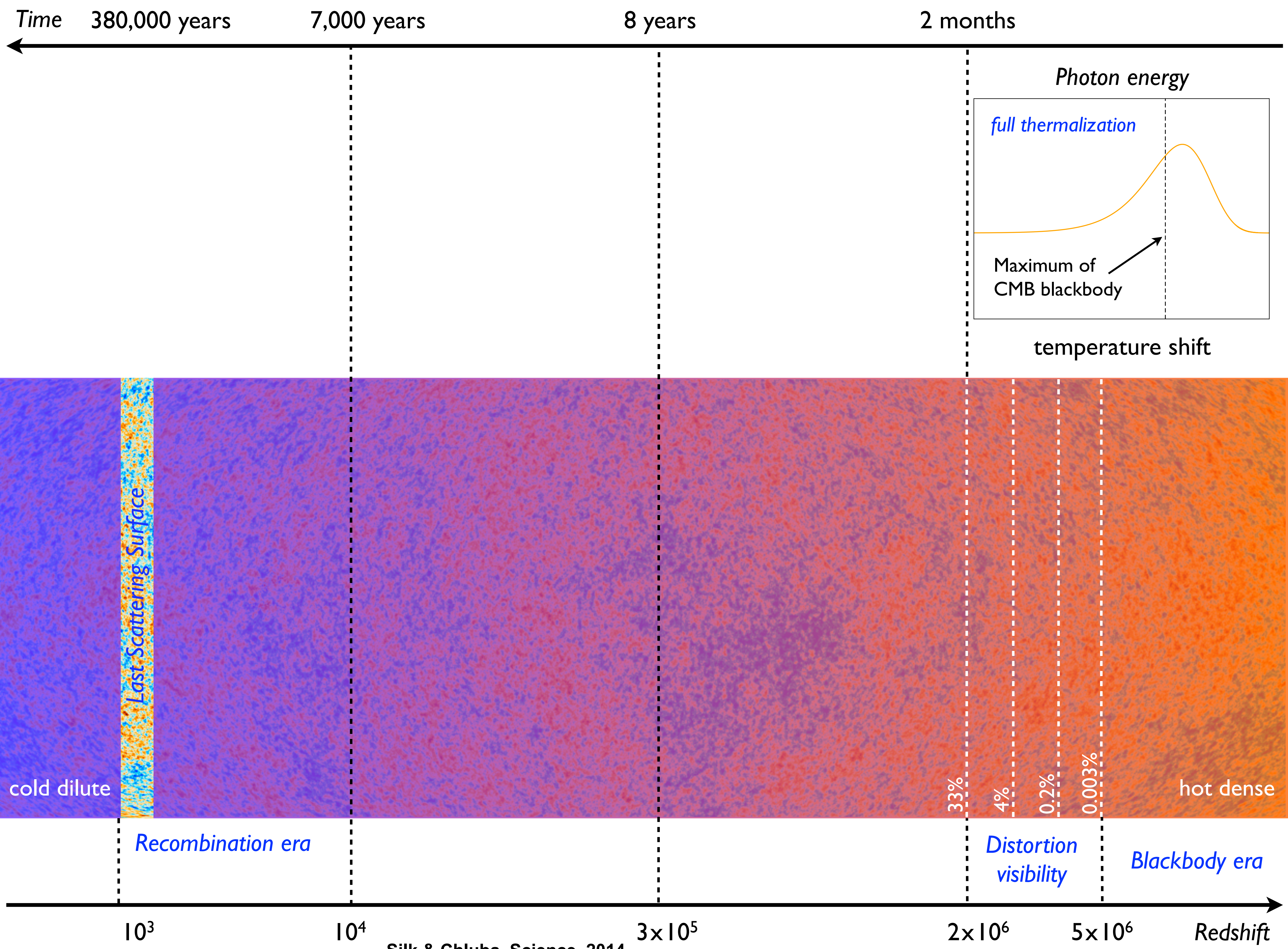
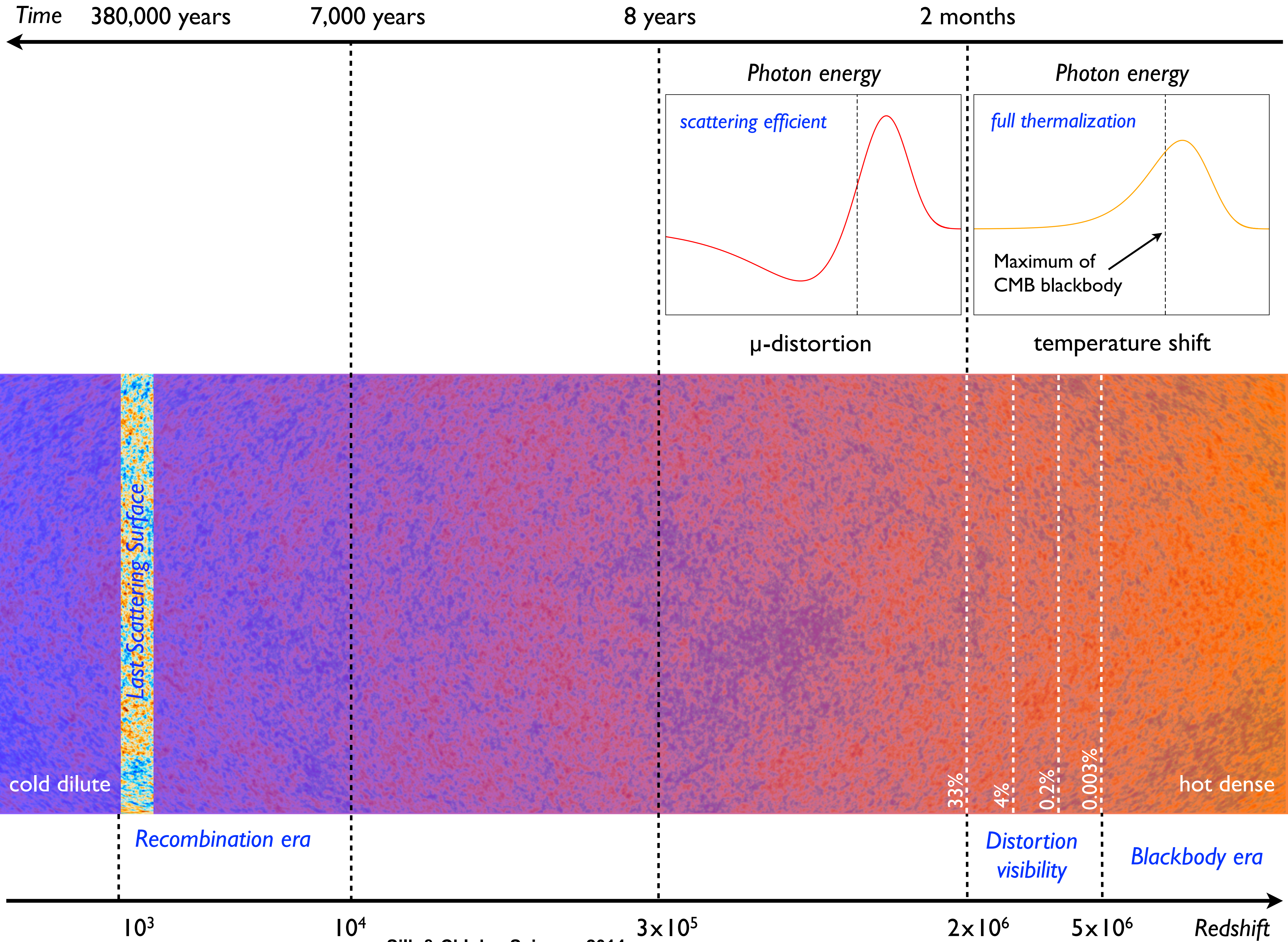


Silk & Chluba, Science, 2014



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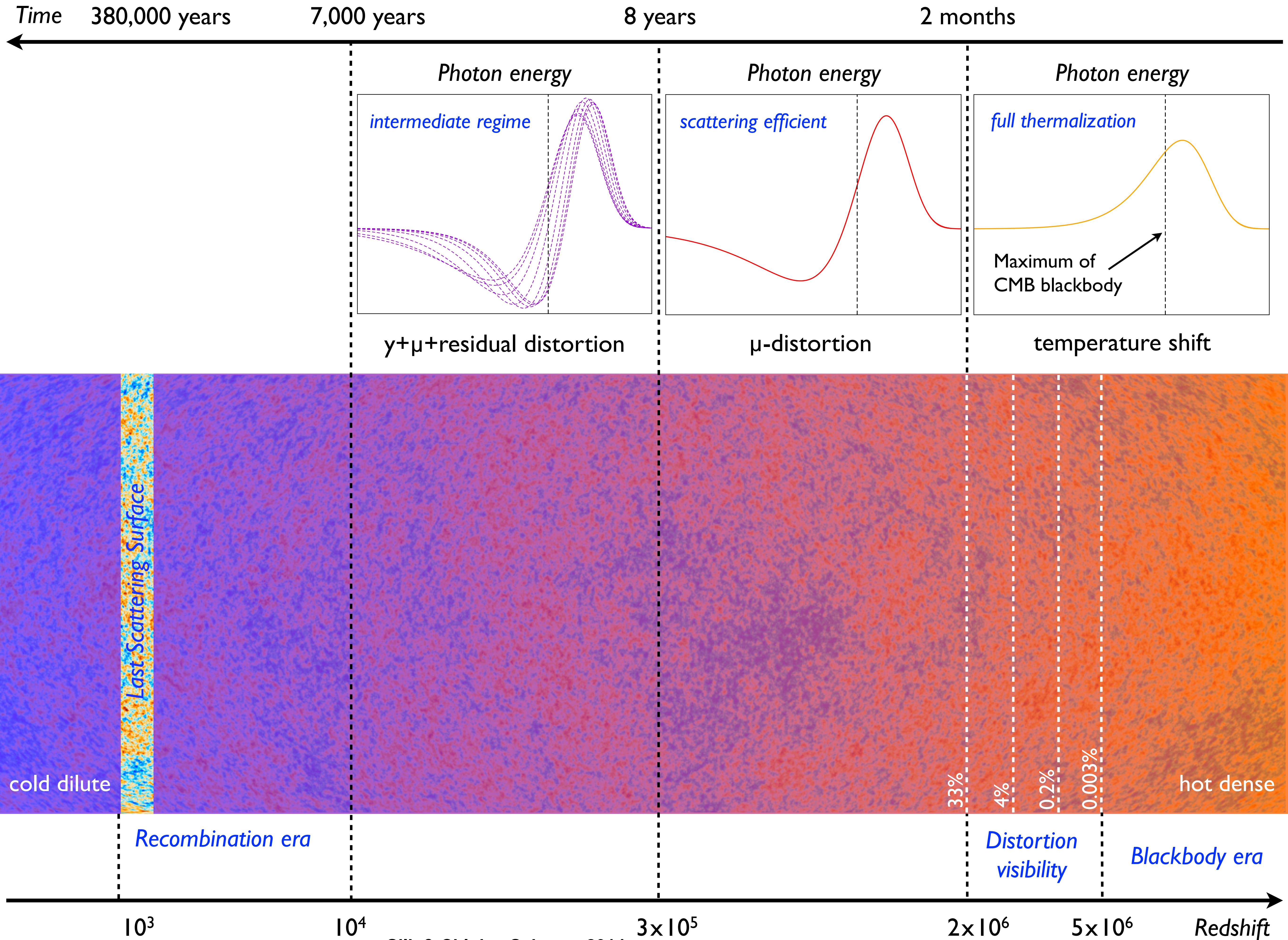

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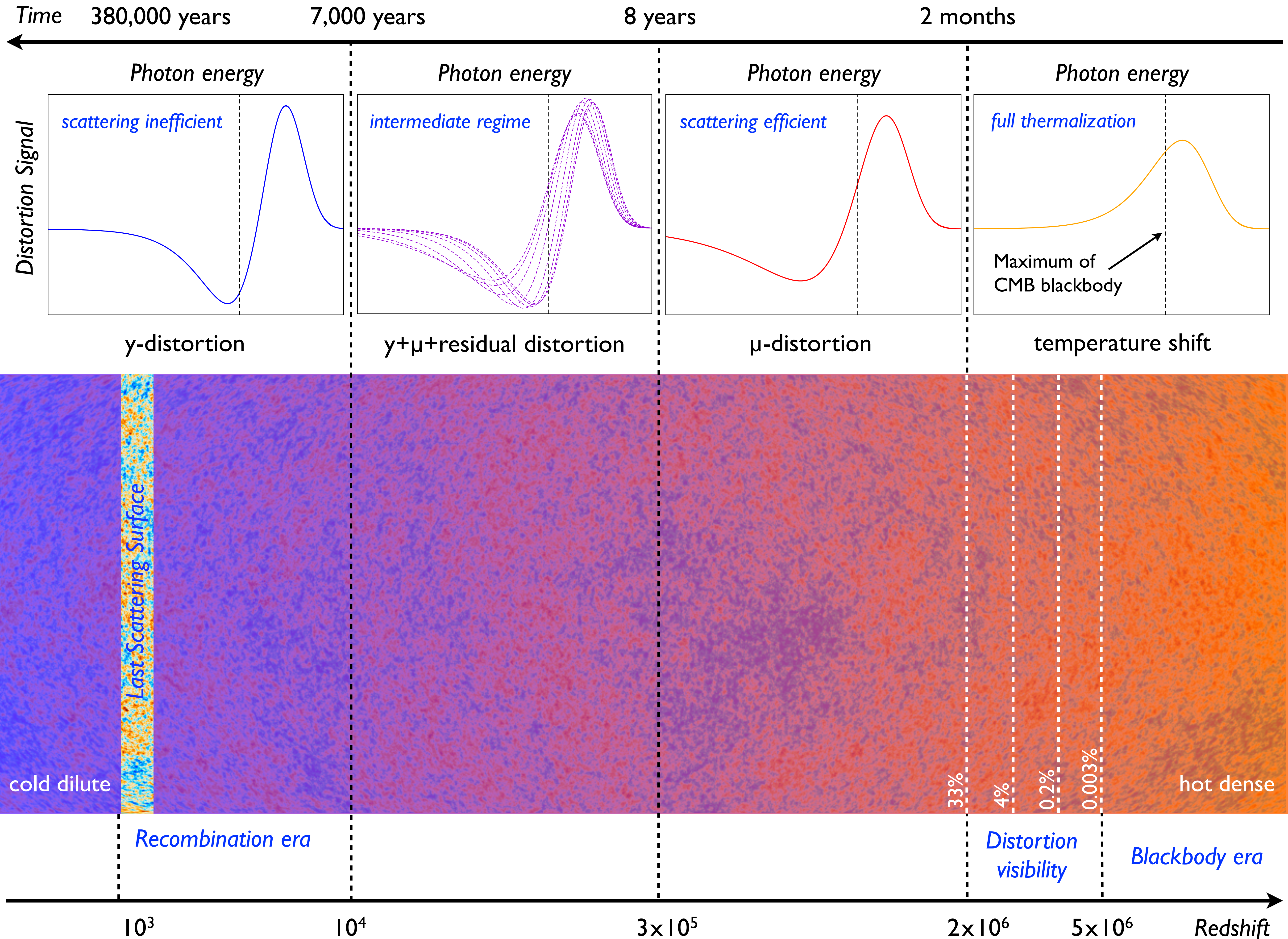

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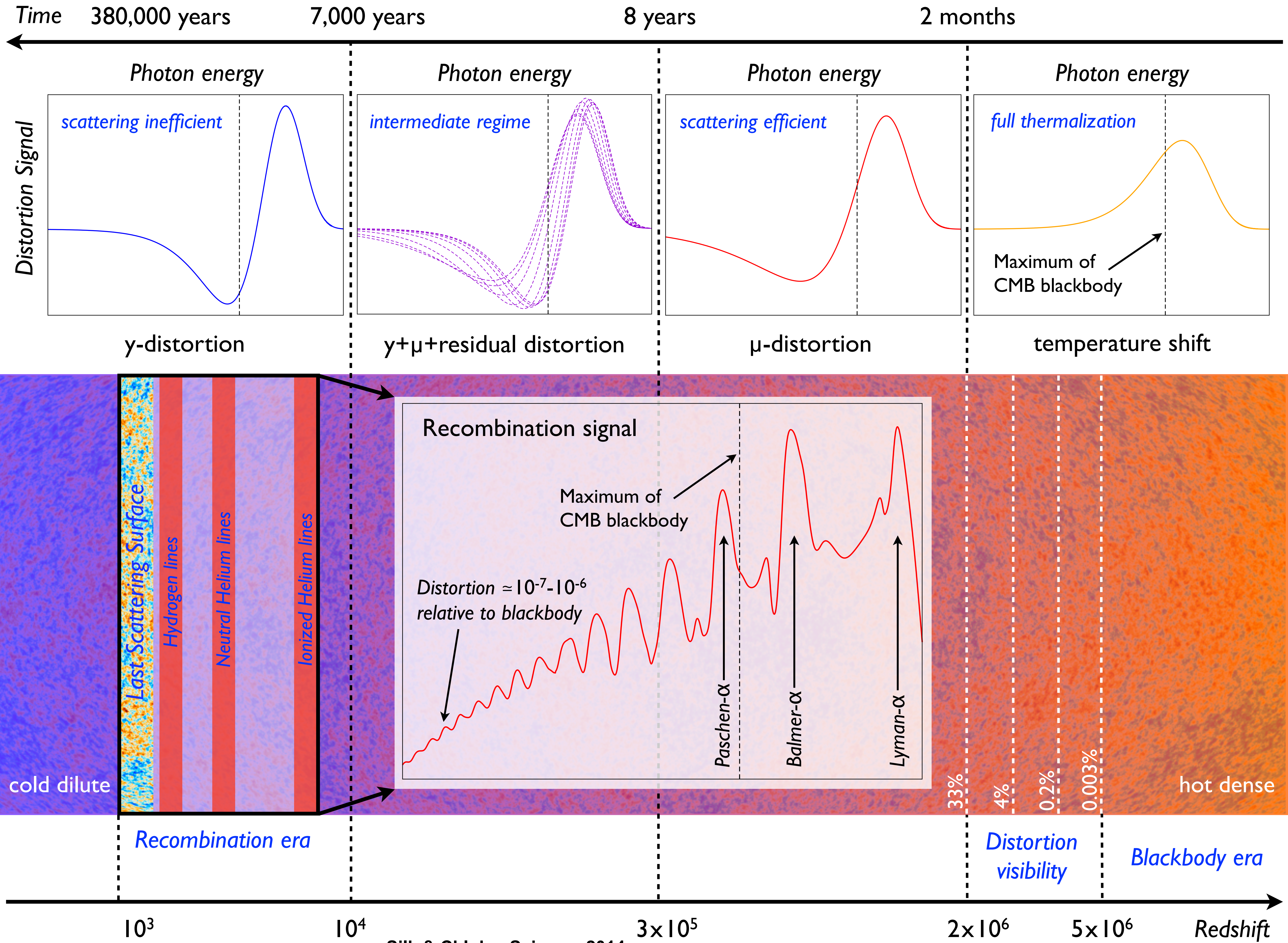

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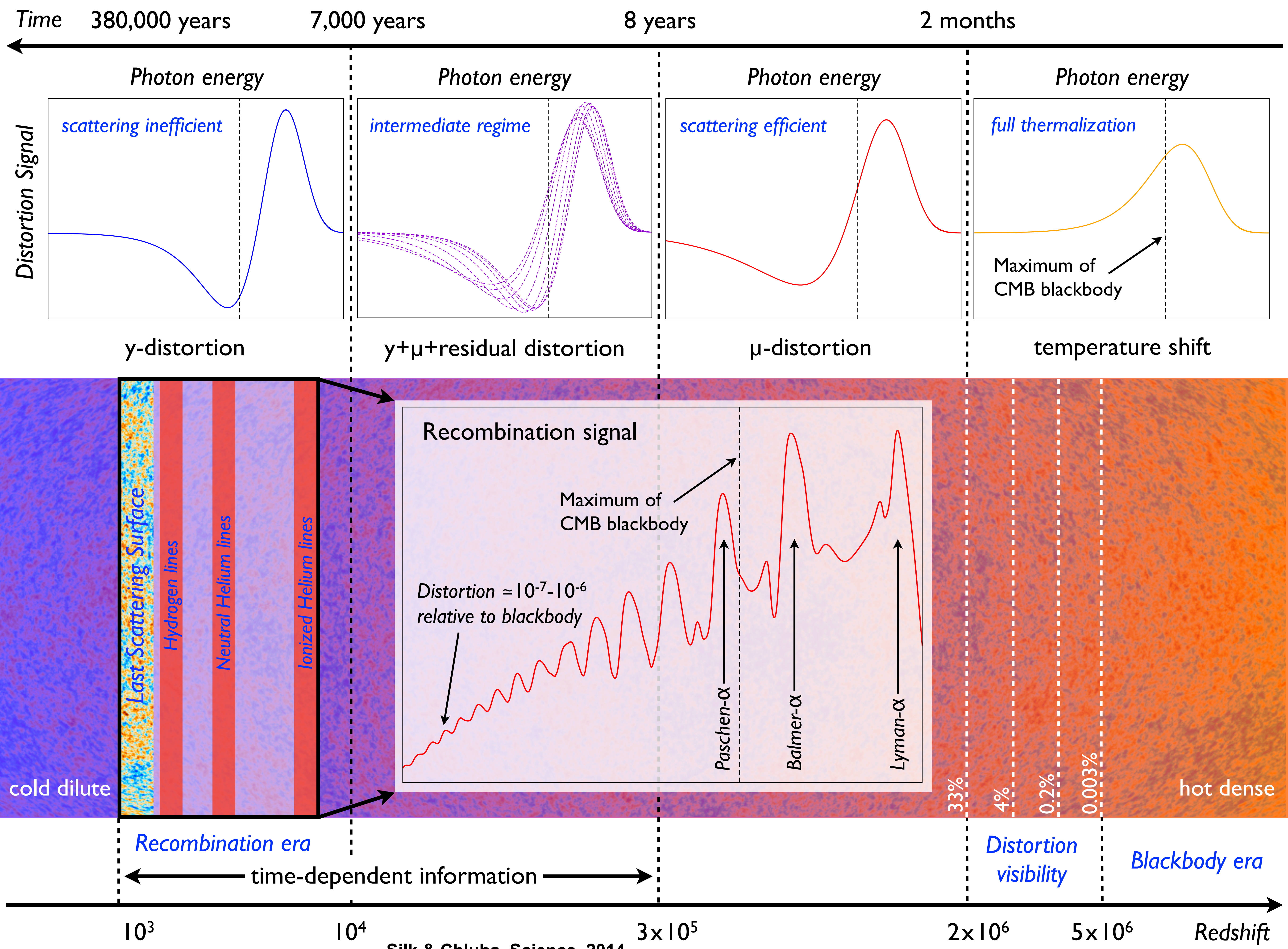

Silk & Chluba, Science, 2014