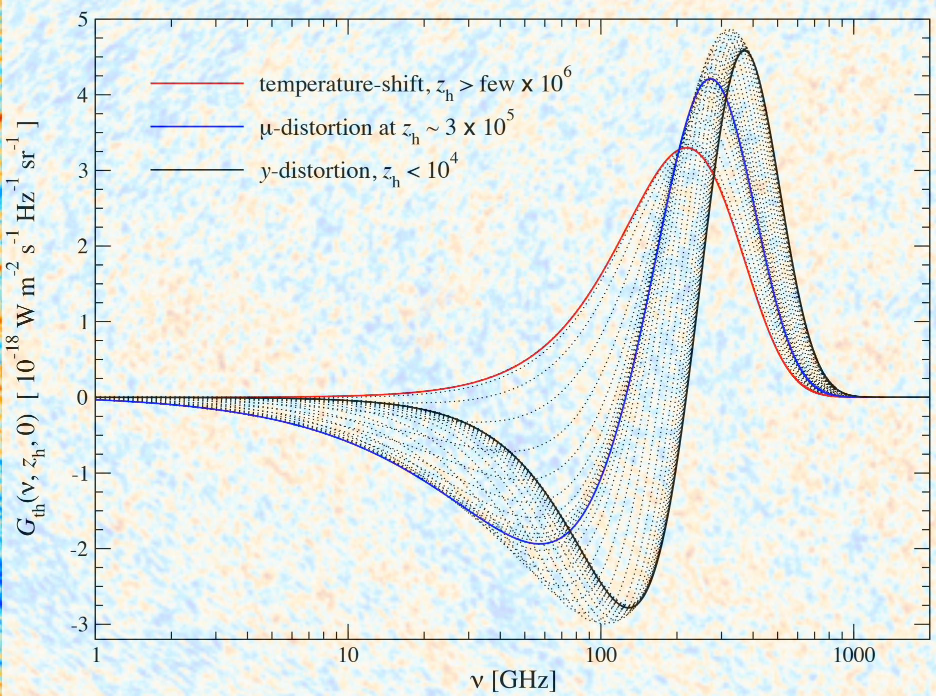
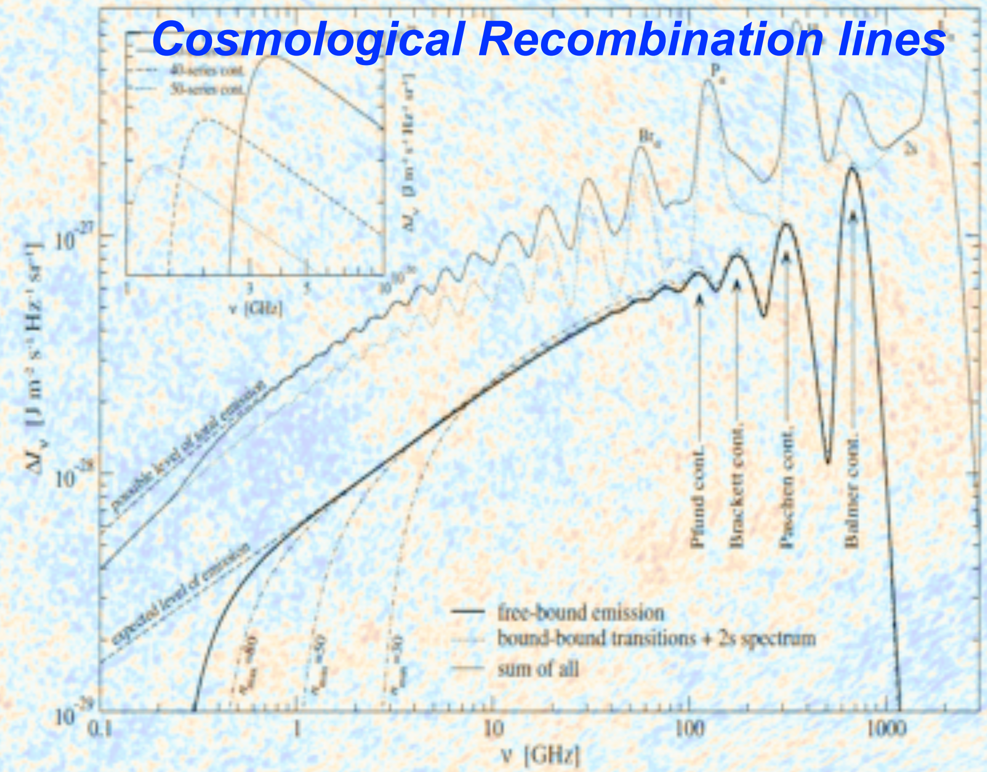
Science with Spectral Distortions of the CMB - III

Primordial Distortions



Cosmological Recombination lines



JOHNS HOPKINS UNIVERSITY

Jens Chluba

CUSO Doctoral Program in Physics

Lausanne, October 30th, 2014

CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut canadien d'astrophysique theorique

Structure of the Lectures *(at least in theory)*

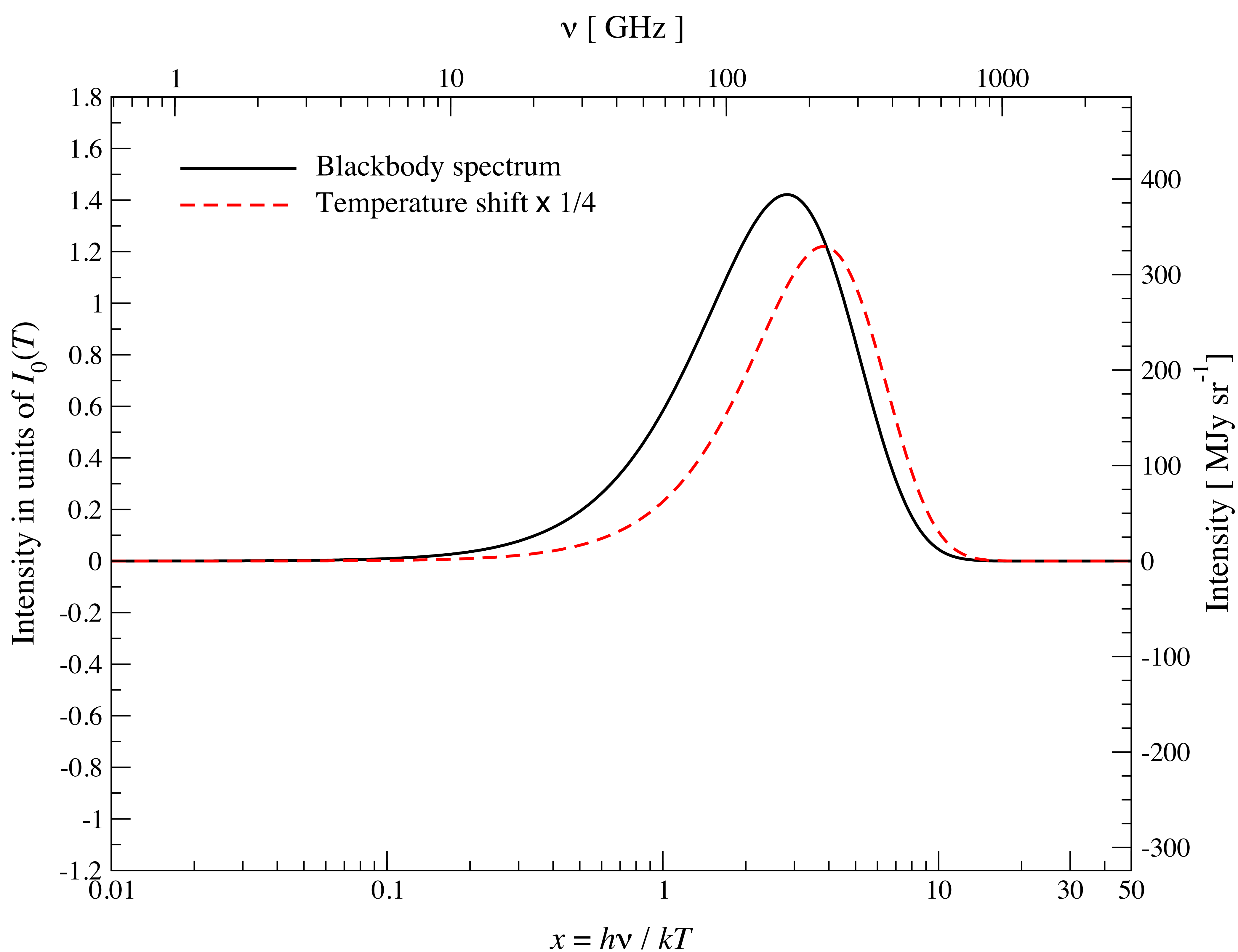
Lecture I:

- Overview and motivation
- Simple blackbody radiation warm-ups
- Formulation of the thermalization problem

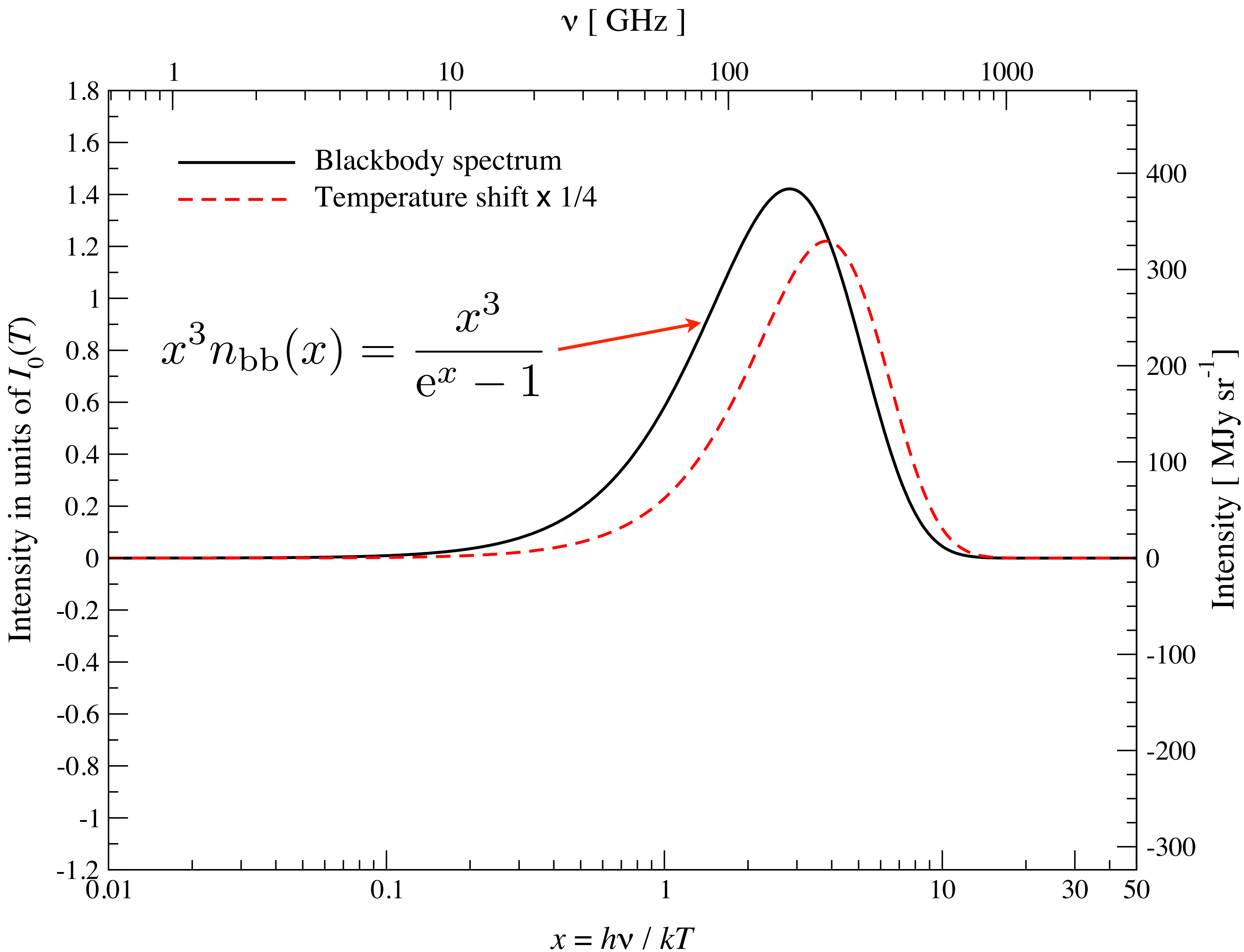
Lecture II:

- Analytic description of the distortions
- Distortion visibility function
- Fast computation of the distortions

Spectral Signals that we already understand



$$I_0 = (2h/c^2)(kT_0/h)^3 \approx 270\,\mathrm{MJy\,sr^{-1}}$$



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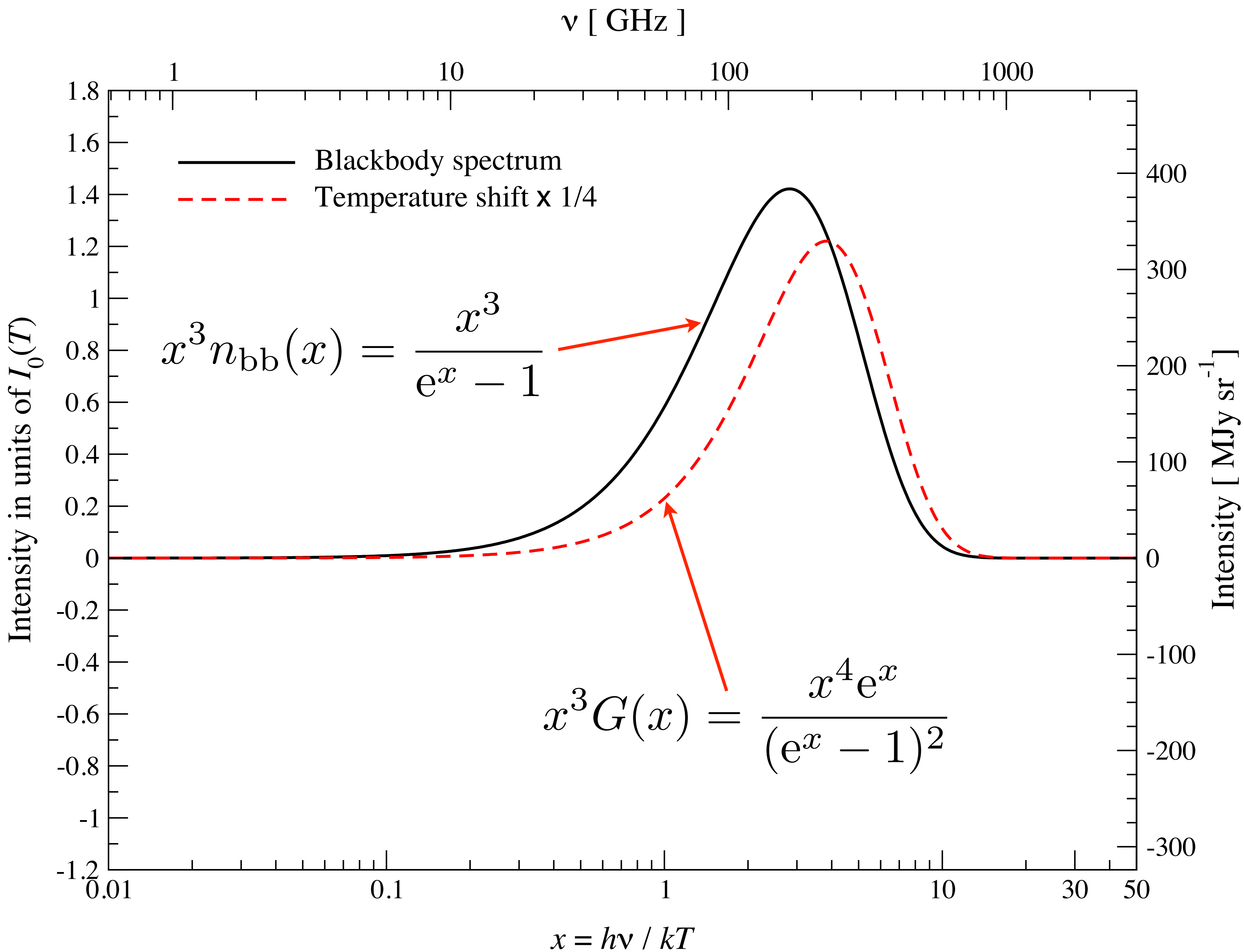

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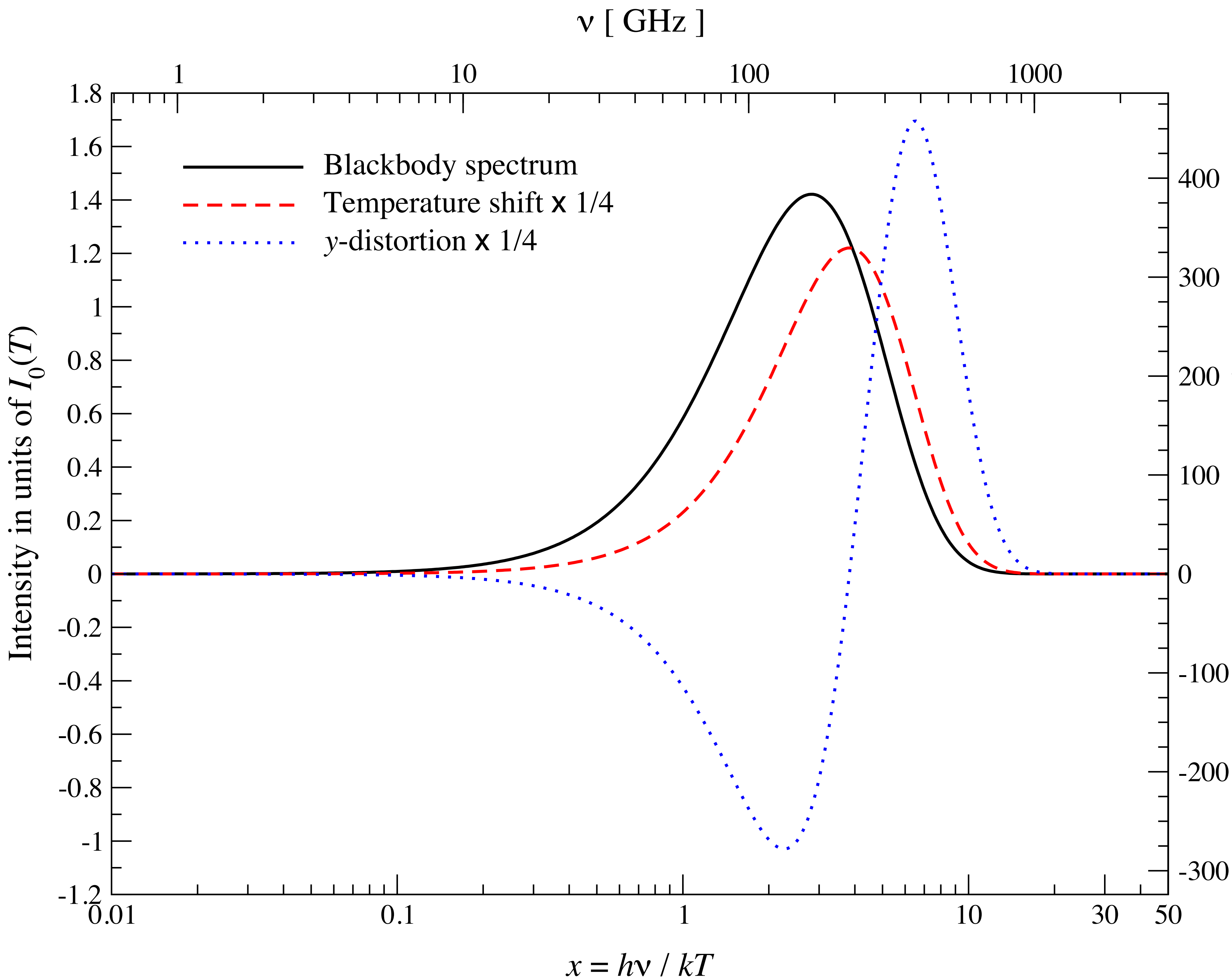

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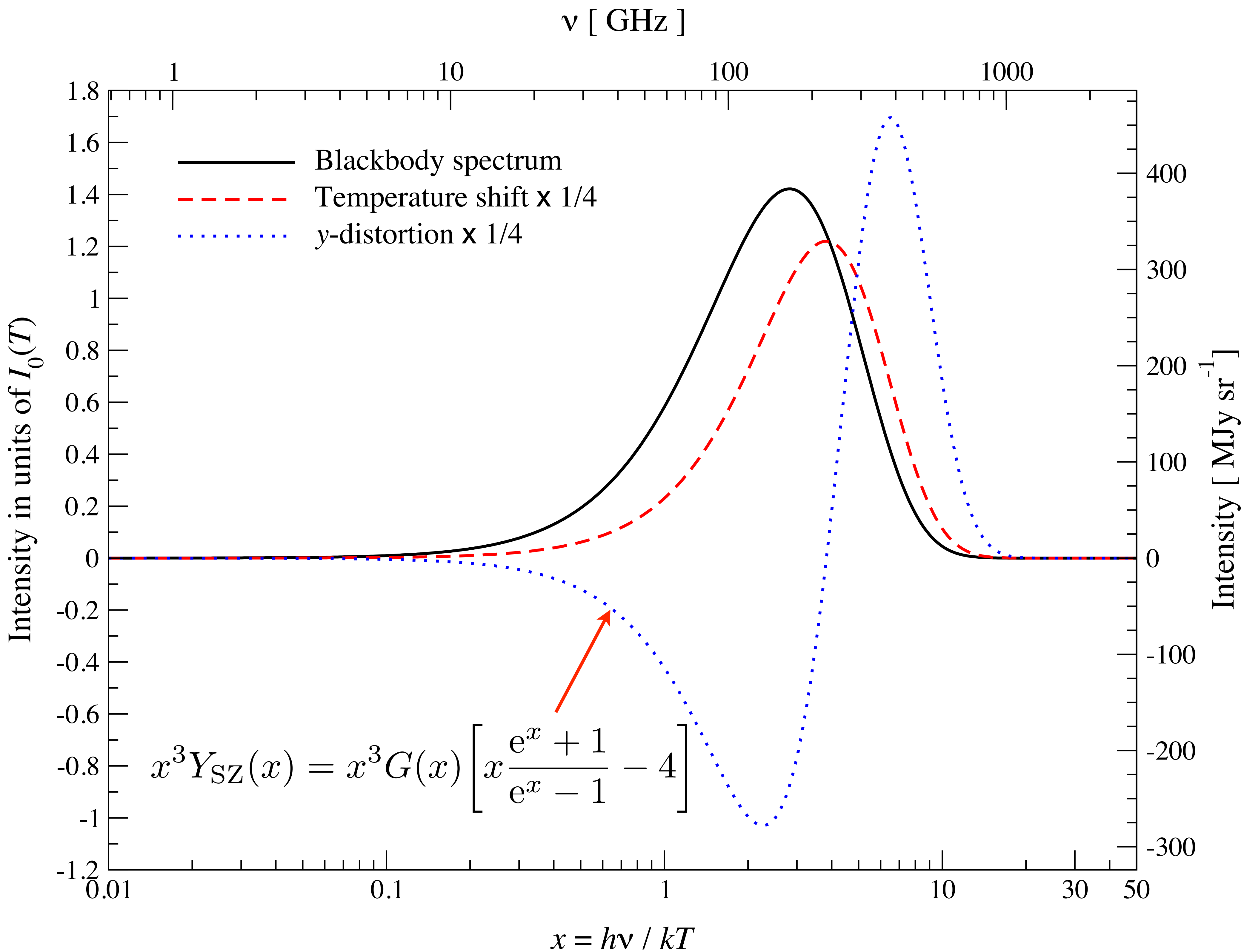

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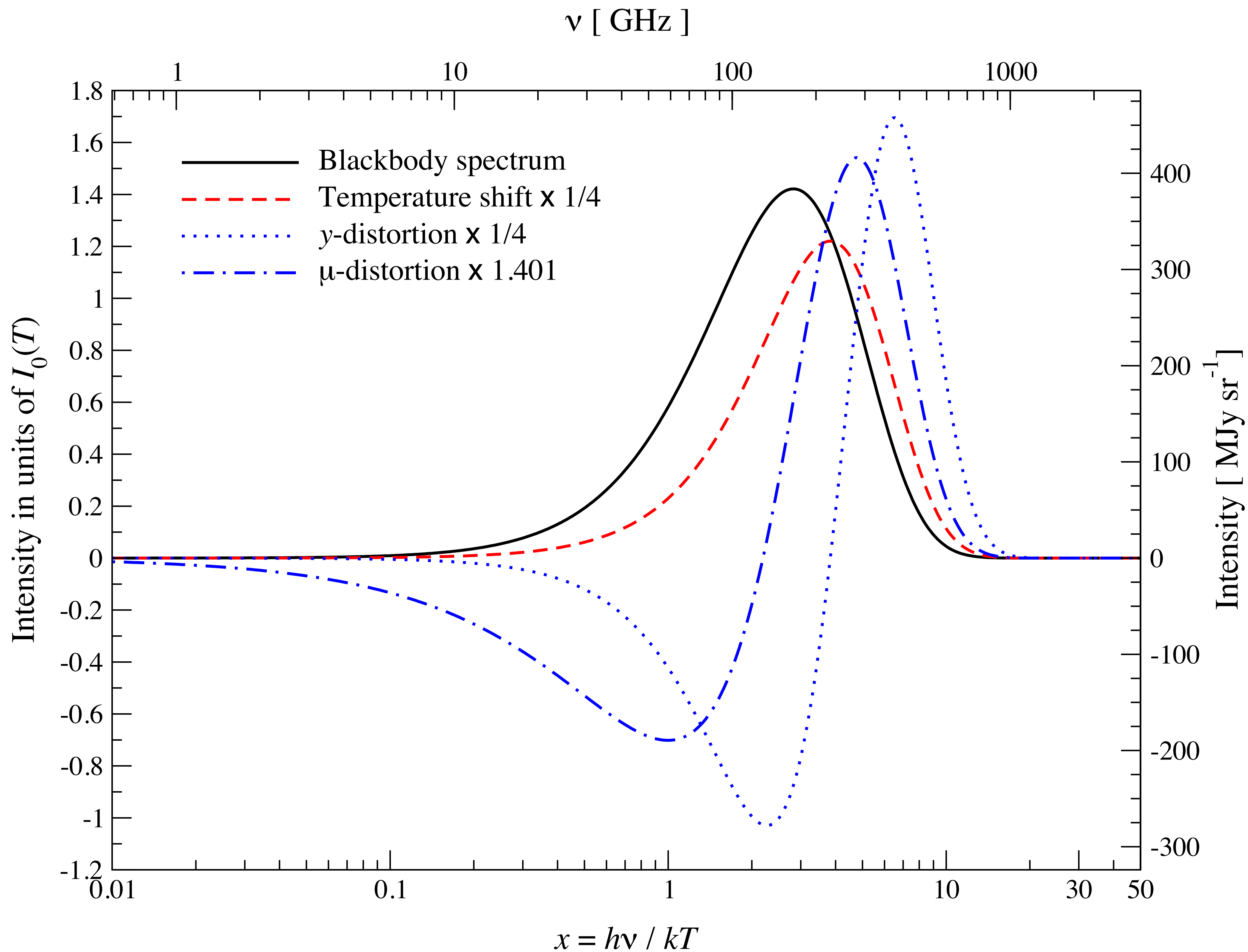

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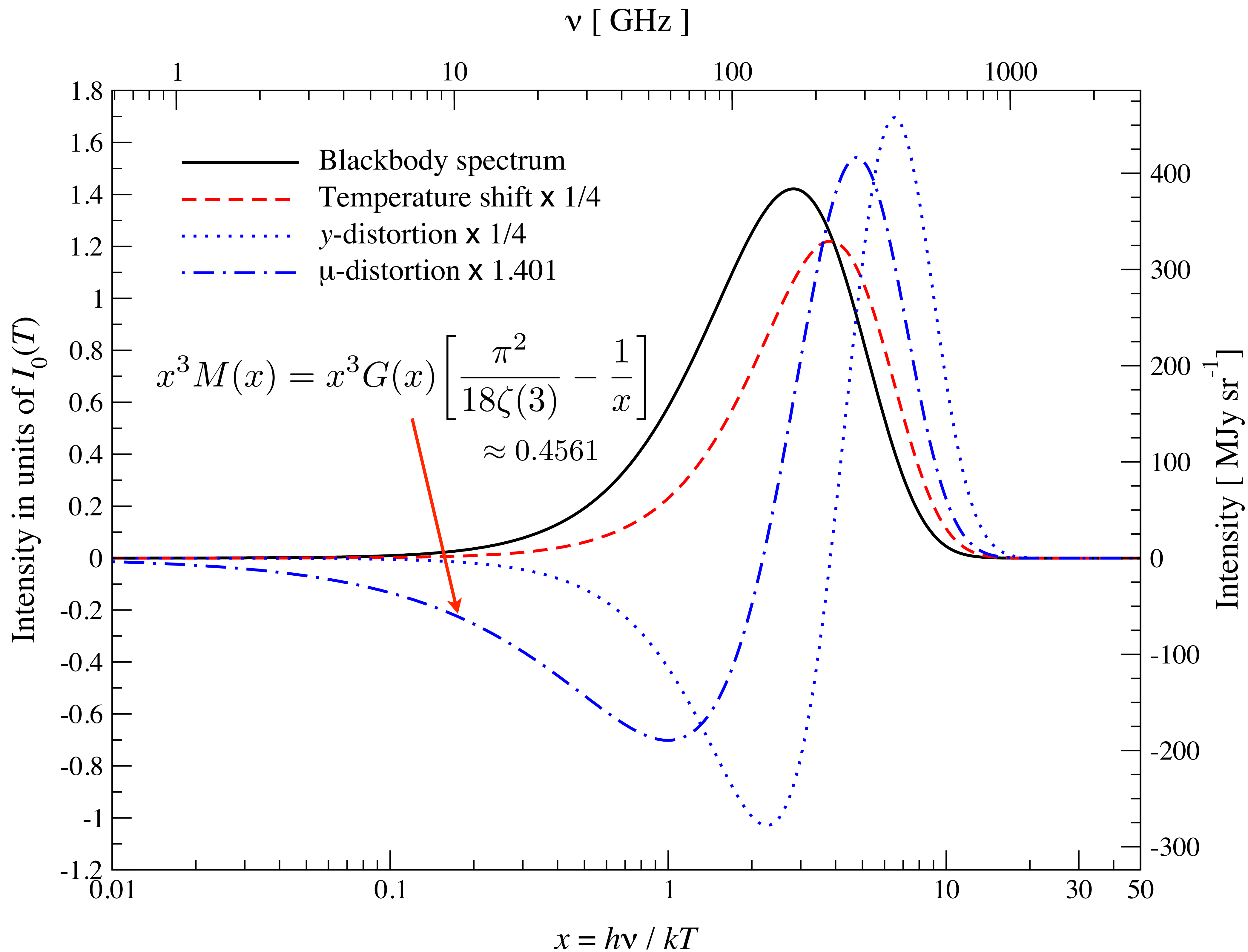
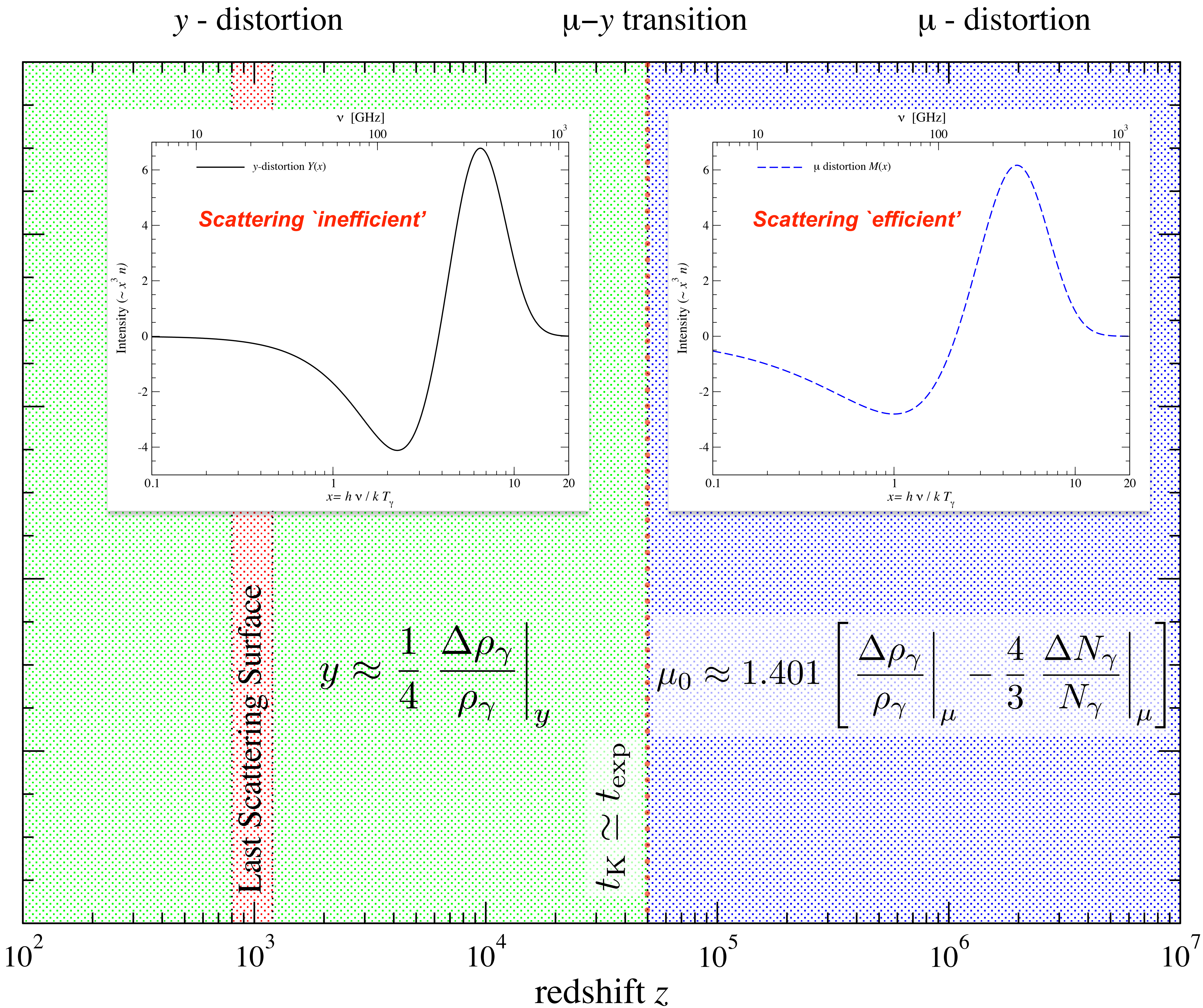


$$I_0 = (2h/c^2)(kT_0/h)^3 \approx 270\,\mathrm{MJy\,sr^{-1}}$$

Simplest picture for the formation of distortions



y - distortion
μ−y transition
μ - distortion
ν [GHz]
10
100
10^3
y-distortion Y(x)
Scattering `inefficient'
Intensity (~ x^3 n)
6
4
2
0
-2
-4
0.1
1
10
20
x= h ν / k T_γ
μ distortion M(x)
Scattering `efficient'
Last Scattering Surface
$y \approx \frac{1}{4} \left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_y$
$\mu_0 \approx 1.401 \left[\left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_\mu - \frac{4}{3} \left.\frac{\Delta N_\gamma}{N_\gamma}\right|_\mu \right]$
$t_K \simeq t_{\rm exp}$
10^2
10^3
10^4
10^5
10^6
10^7
redshift z

Approximate analytic solutions for photon injection

(useful for computations in the y-era)

Doppler-dominated scattering

$$\left.\frac{\partial f}{\partial \tau}\right|_{\rm CS} \approx \frac{\theta_{\rm e}}{x^2}\frac{\partial}{\partial x} x^4 \frac{\partial}{\partial x} f$$

Zeldovich & Sunyaev, 1969

$$y_{\rm e} = \int \theta_{\rm e}\,{\rm d}\tau$$

$$f(y_{\rm e}, x) = \int f(0, x')\, G_{\rm D}(y_{\rm e}, x' \rightarrow x)\,{\rm d}x'$$

$$G_{\rm D}(y_{\rm e}, x' \rightarrow x) = \frac{x'^3}{x^3}\,\frac{{\rm e}^{-\frac{(\ln[x/x'] - 3y_{\rm e})^2}{4y_{\rm e}}}}{\sqrt{4\pi y_{\rm e}}\,x'}$$

Recoil-dominated scattering

$$\left.\frac{\partial f}{\partial \tau}\right|_{\rm CS} \approx \frac{1}{\omega^2}\frac{\partial}{\partial \omega}\omega^4 f$$

$$f(\tau, \omega) = \frac{f\left(0, \frac{\omega}{1-\omega\tau}\right)}{[1-\omega\tau]^4} \qquad \omega = h\nu/m_{\rm e}c^2$$

$$\omega_0(\tau) = \omega_0/(1+\omega_0\tau)$$

Blackbody-induced scattering

$$\left.\frac{\partial \Delta f}{\partial \tau}\right|_{\rm CS} \approx \frac{\theta_\gamma}{x^2}\frac{\partial}{\partial x} x^4 \left[\frac{\partial}{\partial x}\Delta f + \frac{2}{x}\Delta f\right]$$

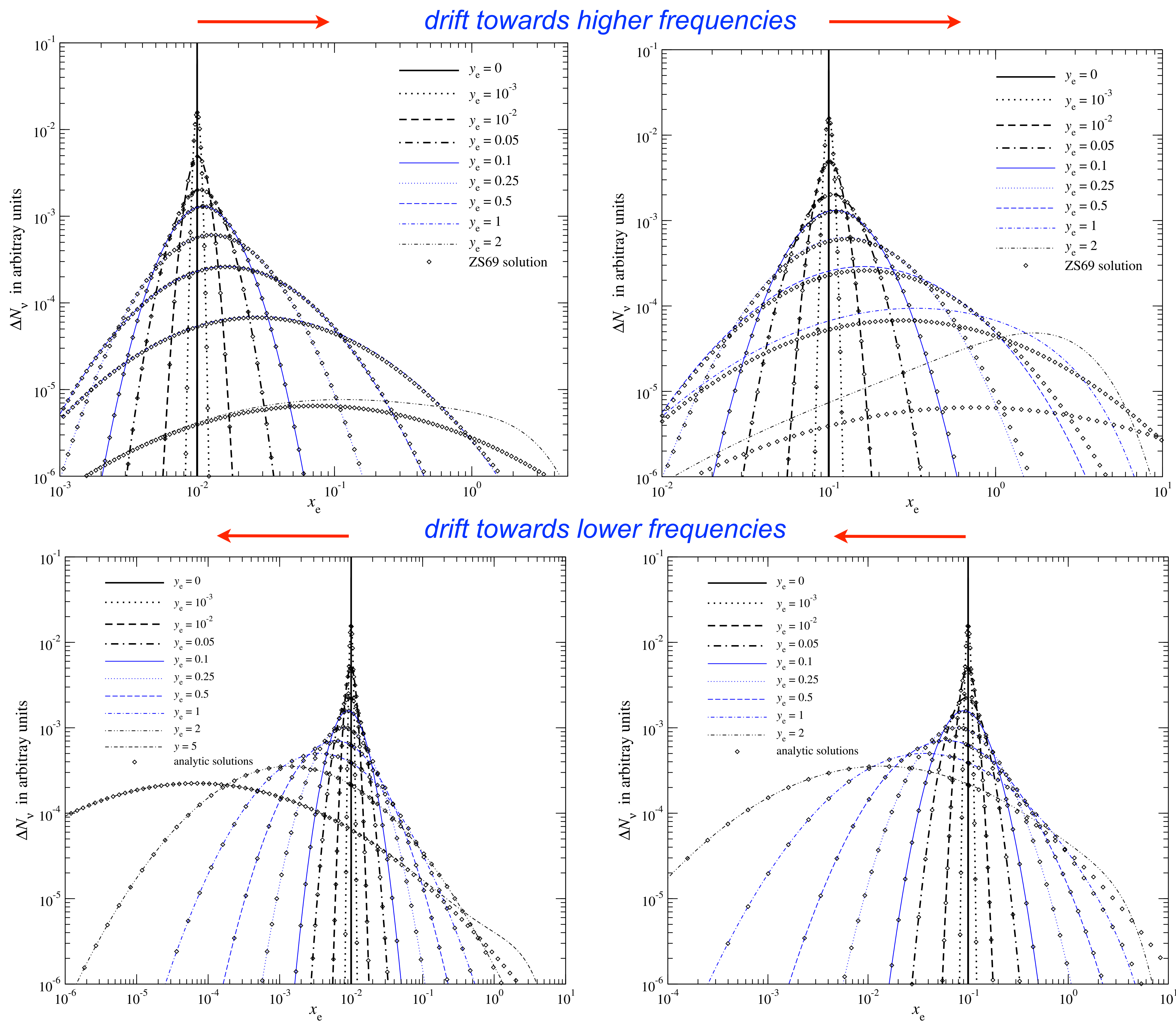
JC & Sunyaev, 2008

$$y_\gamma = \int \theta_\gamma\,{\rm d}\tau$$

$$f(y_\gamma, x) = \int f(0, x')\, G_{\rm B}(y_\gamma, x' \rightarrow x)\,{\rm d}x'$$

$$G_{\rm B}(y_\gamma, x' \rightarrow x) = \frac{x'^3}{x^3}\,\frac{{\rm e}^{-\frac{(\ln[x/x'] - y_\gamma)^2}{4y_\gamma}}}{\sqrt{4\pi y_\gamma}\,x'}$$

Difference between ZS69 and CS08 solutions



Effect of photon production by DC and BR

Evolution of chemical potential amplitude

$$\mu_0 \approx 1.401 \left[\left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_\mu - \frac{4}{3} \left.\frac{\Delta N_\gamma}{N_\gamma}\right|_\mu \right]$$

'Take time-derivative'

Evolution of chemical potential amplitude

$$\Longrightarrow \qquad \frac{\mathrm{d}\mu_0}{\mathrm{d}\tau} \approx \frac{3}{\kappa^{\mathrm{c}}} \frac{\mathrm{d}\ln a^4 \rho_\gamma}{\mathrm{d}\tau} - \frac{4}{\kappa^{\mathrm{c}}} \frac{\mathrm{d}\ln a^3 N_\gamma}{\mathrm{d}\tau} \qquad \kappa^{\mathrm{c}} \approx 2.1419$$

heating of electrons / photon injection

DC & BR process / photon injection

Evolution of chemical potential amplitude

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heating of electrons / photon injection

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- *Need solution for low frequency spectrum to compute DC & BR production term!*

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- *Need solution for low frequency spectrum to compute DC & BR production term!*

Sunyaev & Zeldovich, 1970: *critical frequency*

$$0 \approx \partial_x x^2 \partial_x \mu - \frac{x_{\mathrm{c}}^2}{x^2}\,\mu \qquad \Lambda(t,x) \approx \Lambda(t,x_{\mathrm{c}}) \approx \theta_\gamma x_{\mathrm{c}}^2 \qquad \Lambda(x,T_\gamma) = K_{\mathrm{BR}}(x,T_\gamma) + K_{\mathrm{DC}}(x,T_\gamma)\,\mathrm{e}^{-x}$$

Evolution of chemical potential amplitude

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$$\Longrightarrow \quad \mu(t,x) \approx \mu_0(t)\,\mathrm{e}^{-x_{\rm c}(t)/x}$$

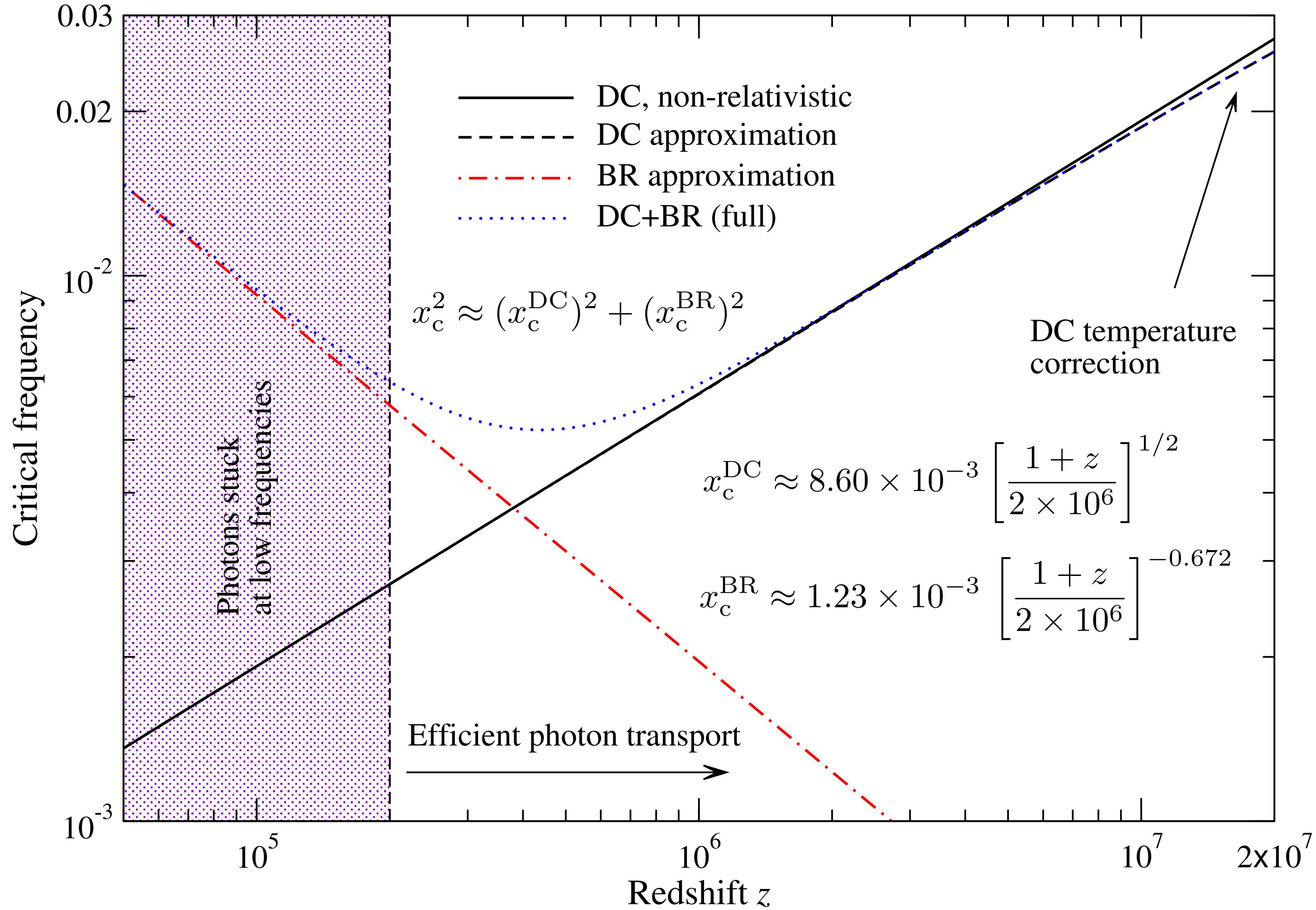

Figure 4.8: Critical frequency, x_c as a function of z. Photon transport is inefficient below $z \simeq 2 \times 10^5$ so that the distortion visibility function quickly approaches unity. DC temperature corrections become noticeable at $z \gtrsim 10^6$. The approximations are from Eq. (4.38) and (4.39). The figure is taken from Chluba [10].

Evolution of chemical potential amplitude

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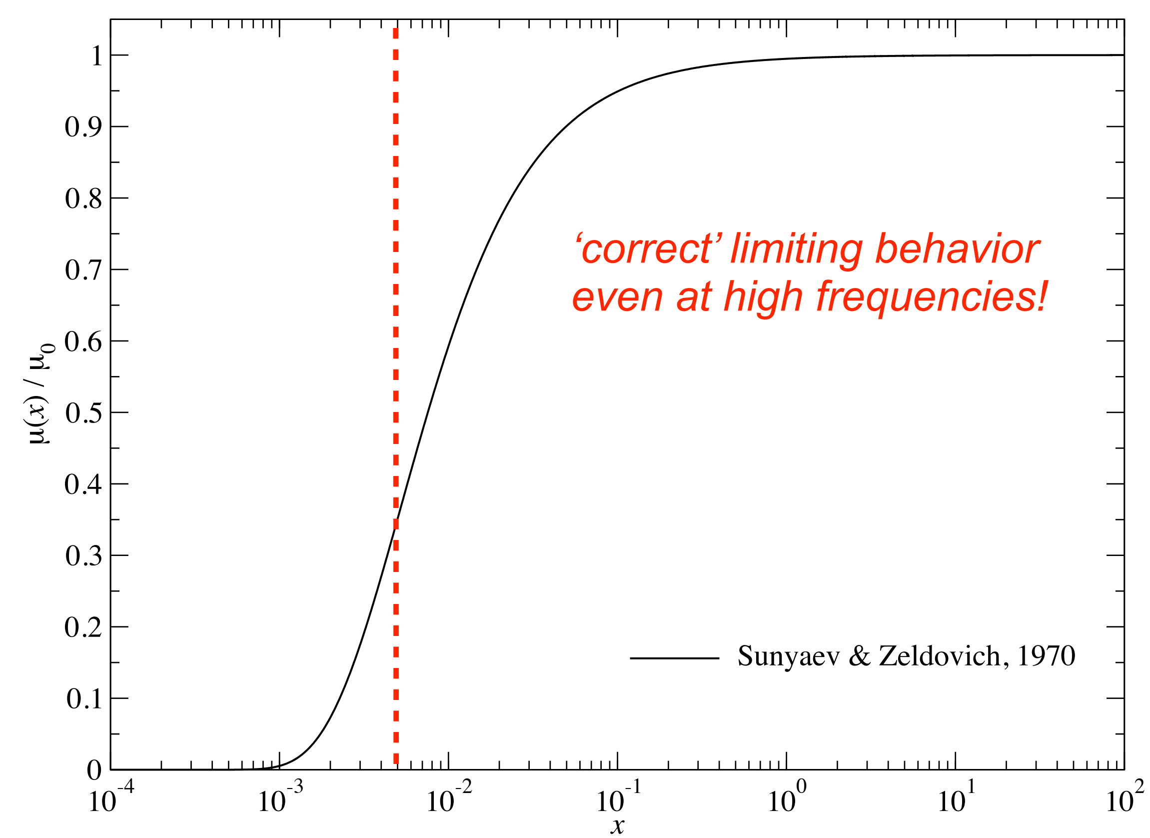

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heating of electrons / photon injection *DC & BR process / photon injection*

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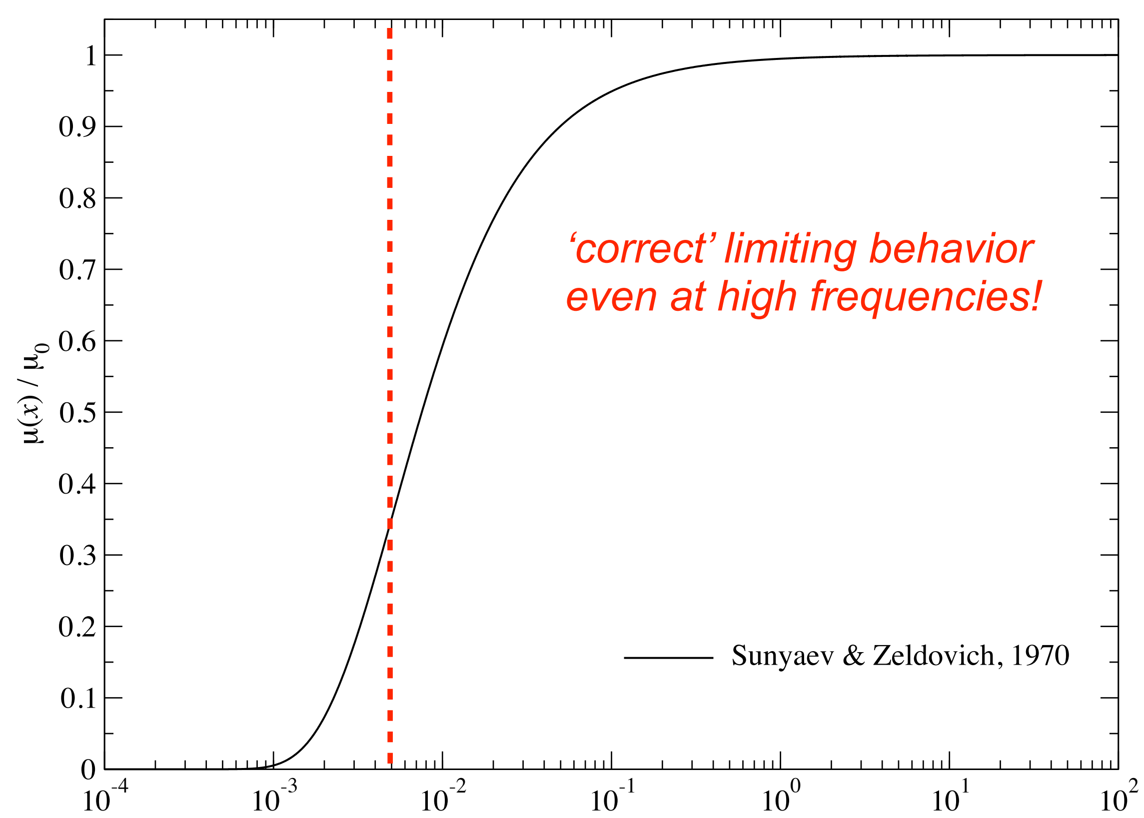
$$\Longrightarrow \quad \mu(t,x) \approx \mu_0(t)\,\mathrm{e}^{-x_{\mathrm{c}}(t)/x}$$

$$\Longrightarrow \quad \frac{\mathrm{d}\ln a^3 N_\gamma}{\mathrm{d}\tau} \approx \frac{\theta_\gamma x_{\mathrm{c}}}{G_2^{\mathrm{Pl}}}\,\mu_0(\tau)$$



Evolution of chemical potential amplitude

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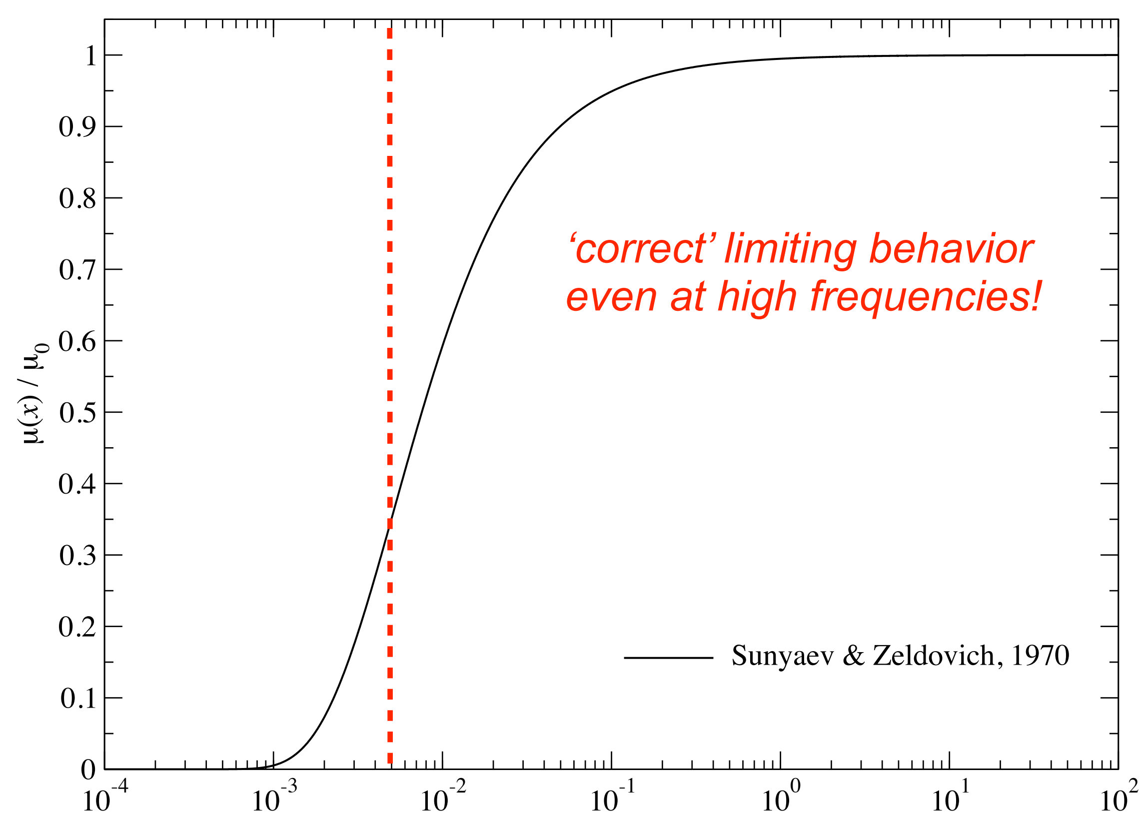
$$\Longrightarrow \quad \frac{4}{\kappa^{\mathrm{c}}}\frac{\mathrm{d}\ln a^3 N_\gamma}{\mathrm{d}\tau} \approx 0.7769\,\theta_\gamma x_{\mathrm{c}}\,\mu_0$$



Solution with photon production & distortion visibility function

Putting things together (no extra photon source term)

$$\Longrightarrow \quad \frac{\mathrm{d}\mu_0}{\mathrm{d}\tau} \approx 1.401\,\frac{\dot{Q}_{\mathrm{e}}^{*}}{\rho_\gamma} - 0.7769\,\theta_\gamma x_{\mathrm{c}}\,\mu_0$$

electron (+matter) heating term

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electron (+matter) heating term

Thermalization optical depth

$$\tau_\mu(z) \approx 0.7769 \int_0^z \theta_\gamma x_\mathrm{c} \frac{\sigma_\mathrm{T} N_\mathrm{e} c\,\mathrm{d}z'}{H(1+z')}$$

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$$\tau_\mu(z, z') = \tau_\mu(z) - \tau_\mu(z')$$

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$$\tau_\mu(z, z') = \tau_\mu(z) - \tau_\mu(z')$$

$$\Longrightarrow \quad \mathcal{J}(z, z') = \mathrm{e}^{-\tau_\mu(z,z')}$$

Distortion visibility function between z and z’

Solution with photon production & distortion visibility function

Putting things together (no extra photon source term)

$$\Longrightarrow \quad \frac{\mathrm{d}\mu_0}{\mathrm{d}\tau} \approx 1.401 \frac{\dot{Q}_\mathrm{e}^*}{\rho_\gamma} - 0.7769\, \theta_\gamma x_\mathrm{c}\, \mu_0$$

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Distortion visibility function between z and z'

- *Shape depends on the photon production process (which defines τ integral)*

Solution with photon production & distortion visibility function

Putting things together (no extra photon source term)

$$\Longrightarrow \quad \frac{\mathrm{d}\mu_0}{\mathrm{d}\tau} \approx 1.401 \frac{\dot{Q}_\mathrm{e}^*}{\rho_\gamma} - 0.7769\,\theta_\gamma x_\mathrm{c}\,\mu_0$$

electron (+matter) heating term

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$$\tau_\mu(z, z') = \tau_\mu(z) - \tau_\mu(z')$$

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Distortion visibility function between z and z'

- *Shape depends on the photon production process (which defines τ integral)*
- *Determines what fraction of the released energy remains visible as a distortion*

Solution with photon production & distortion visibility function

Putting things together (no extra photon source term)

$$\Longrightarrow \quad \frac{\mathrm{d}\mu_0}{\mathrm{d}\tau} \approx 1.401\,\frac{\dot{Q}^*_{\mathrm{e}}}{\rho_\gamma} - 0.7769\,\theta_\gamma x_{\mathrm{c}}\,\mu_0$$

electron (+matter) heating term

Thermalization optical depth

$$\tau_\mu(z) \approx 0.7769 \int_0^z \theta_\gamma x_{\mathrm{c}} \frac{\sigma_{\mathrm{T}} N_{\mathrm{e}} c\,\mathrm{d}z'}{H(1+z')}$$

$$\mu_0(z) \approx 1.401 \int_z^\infty \frac{\dot{Q}^*_{\mathrm{e}}}{\rho_\gamma} \frac{\mathrm{e}^{-\tau_\mu(z',z)}\,\mathrm{d}z'}{H(1+z')}$$

$$\tau_\mu(z,z') = \tau_\mu(z) - \tau_\mu(z')$$

$$\Longrightarrow \quad \mathcal{J}(z,z') = \mathrm{e}^{-\tau_\mu(z,z')}$$

Distortion visibility function between z and z'

- *Shape depends on the photon production process (which defines τ integral)*
- *Determines what fraction of the released energy remains visible as a distortion*
- *Fraction of energy that is fully thermalized:*

$$\mathcal{J}_{\mathrm{th}}(z,z') = 1 - \mathcal{J}(z,z')$$

Distortion visibility function for DC and BR only

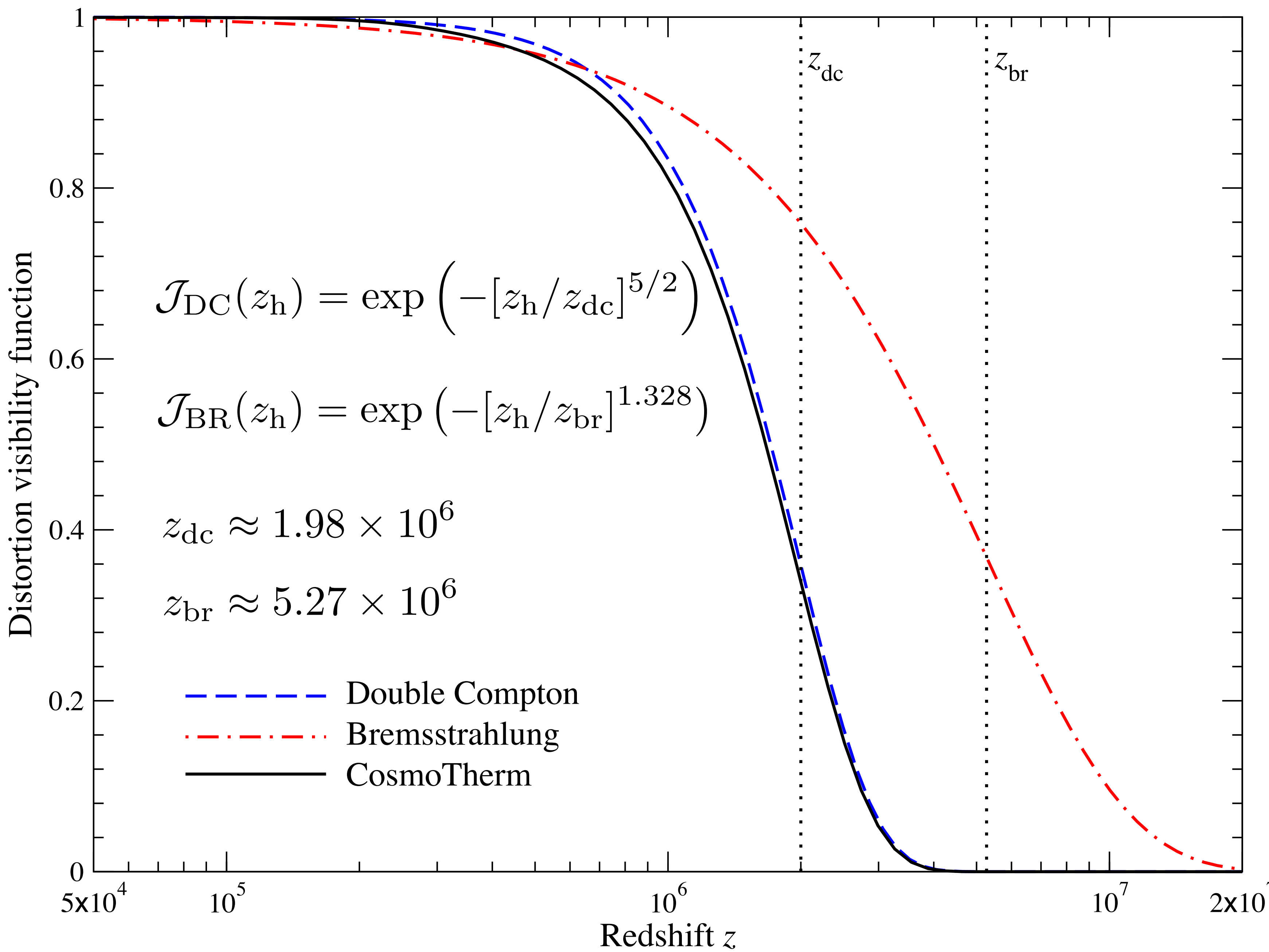
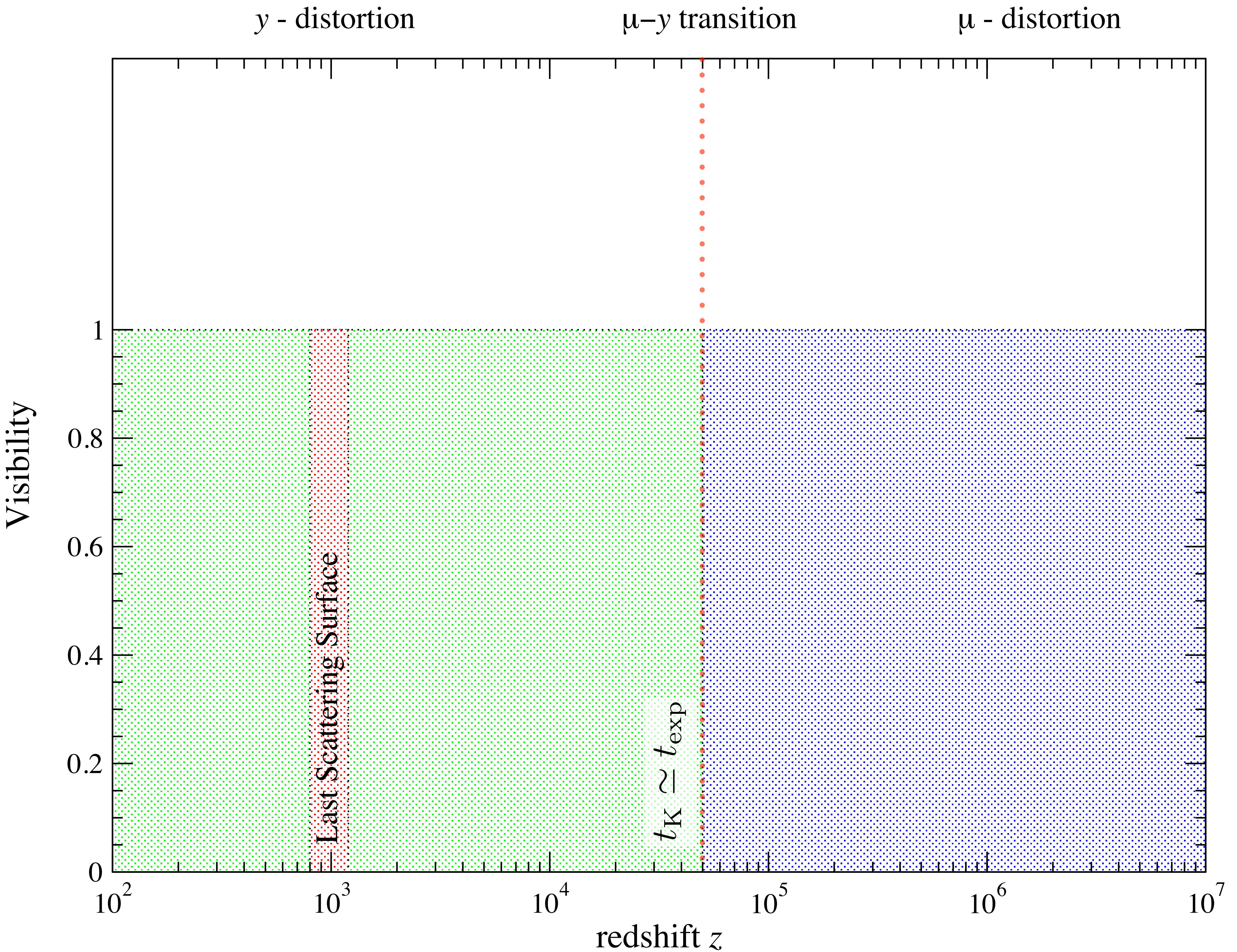
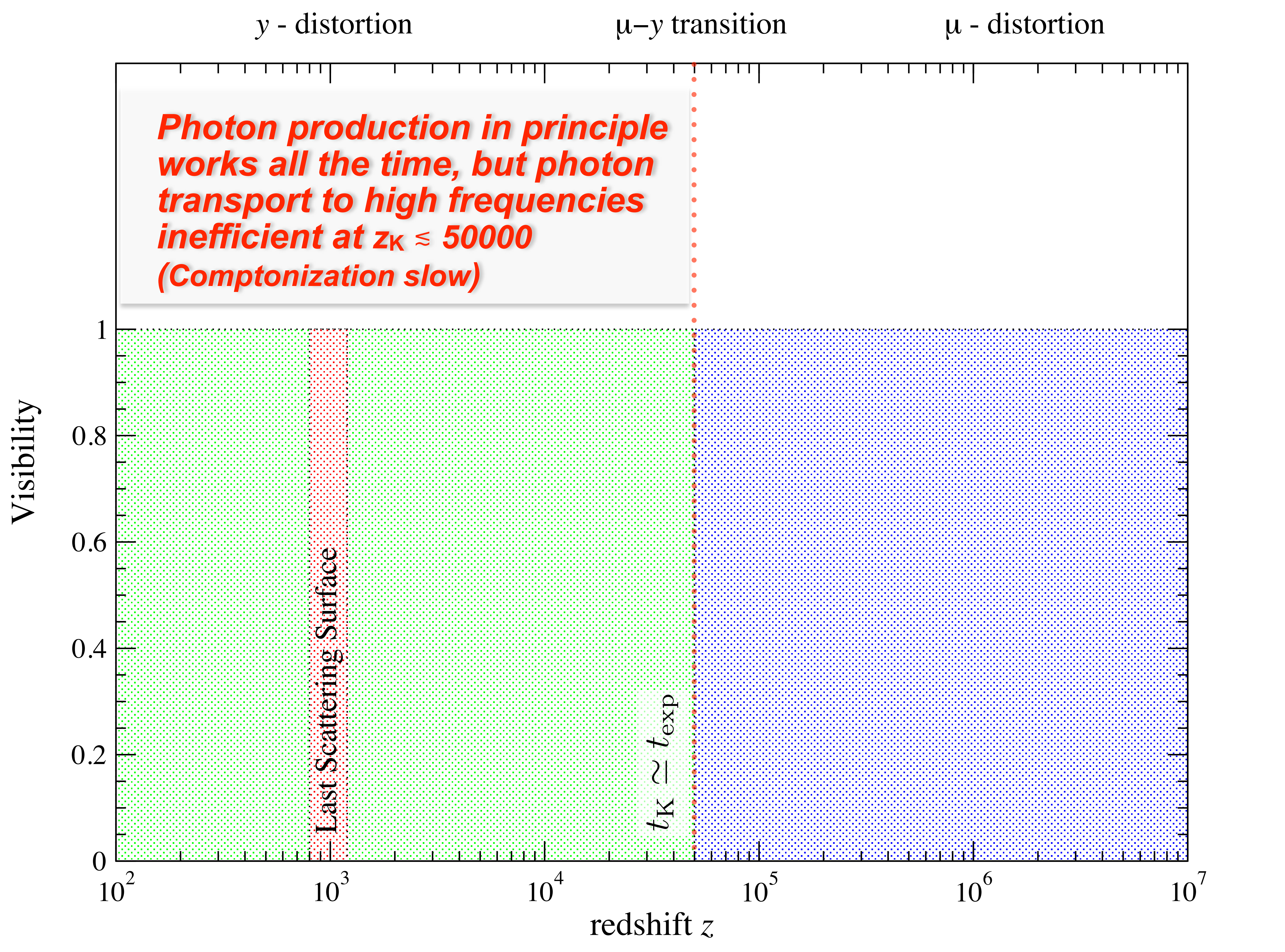


Figure 4.9: Distortion visibility function. We compare $\mathcal{J}_{\rm DC}(z_{\rm h})$, $\mathcal{J}_{\rm BR}(z_{\rm h})$ and the numerical result obtained with CosmoTherm. DC emission significantly change the thermalization efficiency. Deviations from the numerical result can be captured by adding several effects, as discussed in Sect. 4.6.

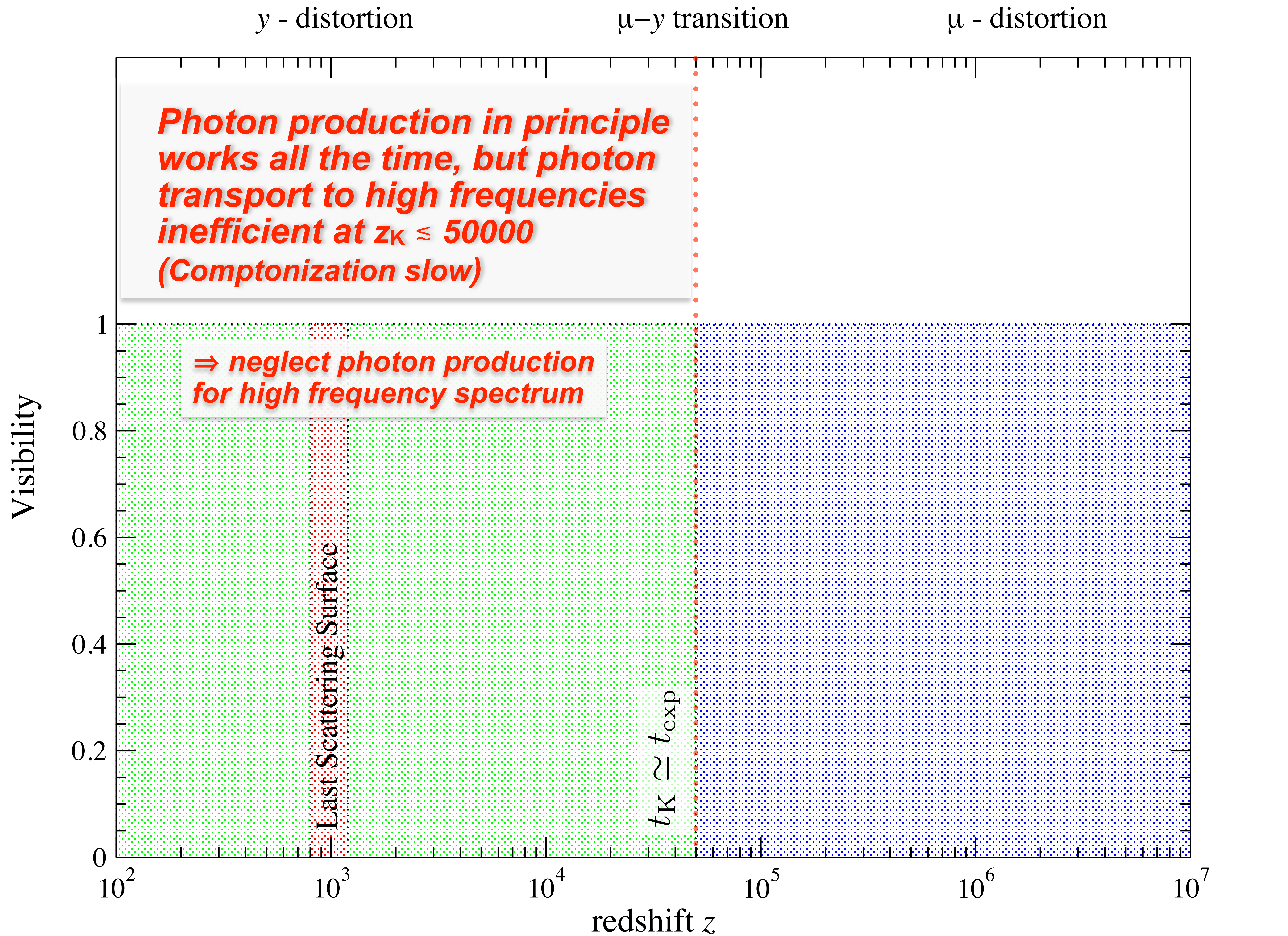
Improved picture for the formation of distortions

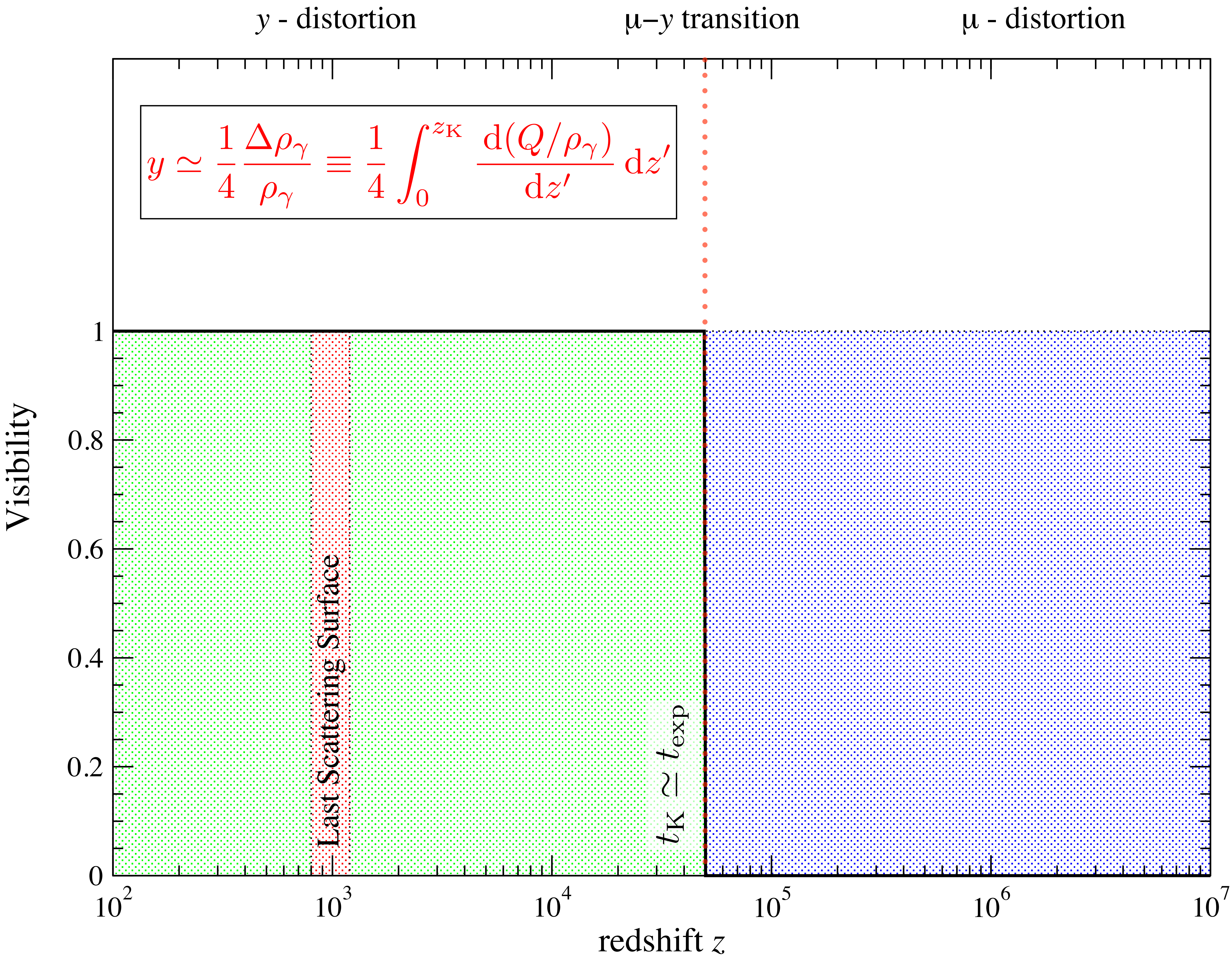


y - distortion
μ–y transition
μ - distortion
Visibility
Last Scattering Surface
$t_K \simeq t_{exp}$
redshift z

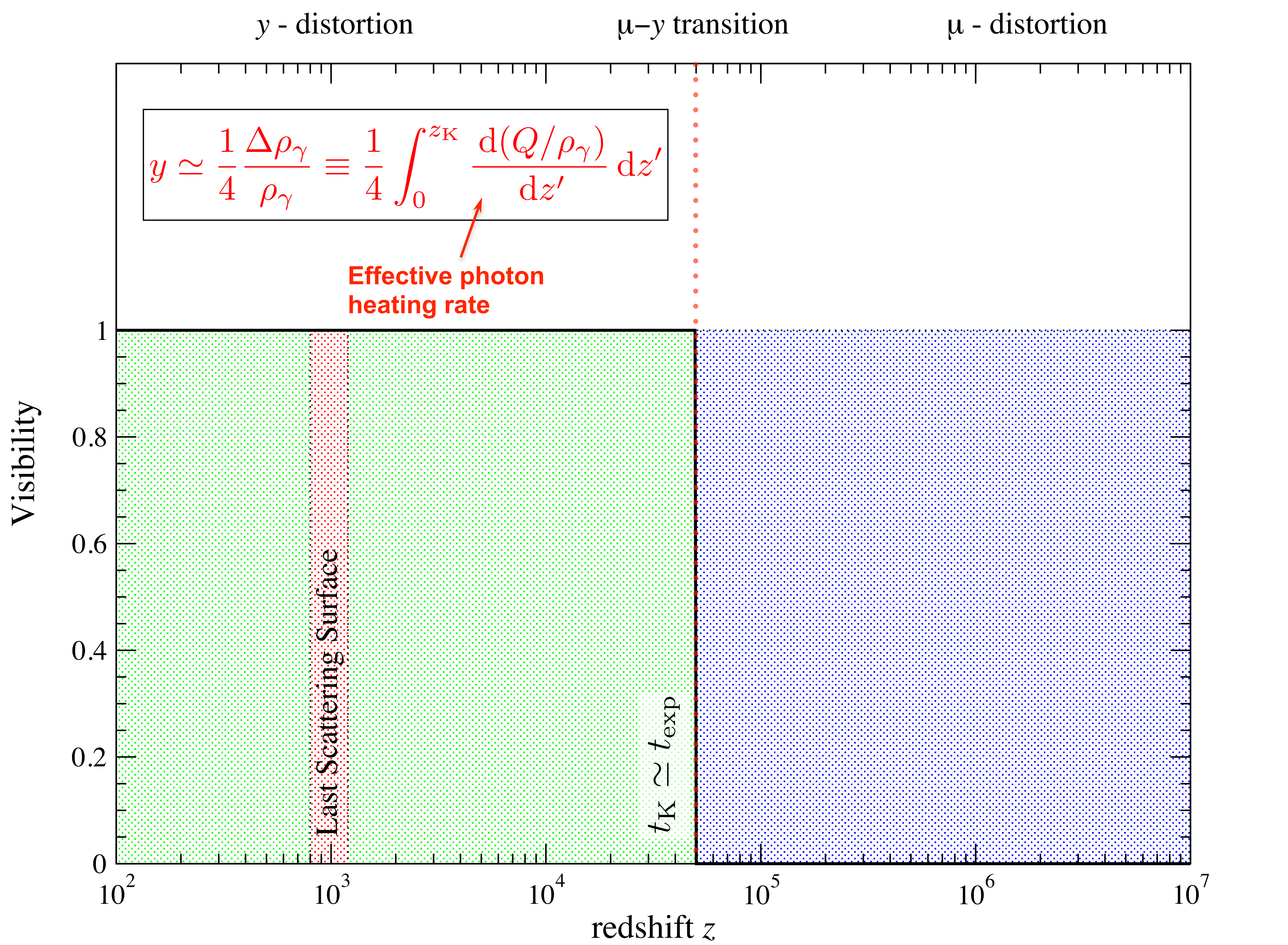


y - distortion
μ−y transition
μ - distortion
Photon production in principle works all the time, but photon transport to high frequencies inefficient at zK ≲ 50000 (Comptonization slow)
Visibility
1
0.8
0.6
0.4
0.2
0
Last Scattering Surface
tK ≃ texp
10^2
10^3
10^4
10^5
10^6
10^7
redshift z

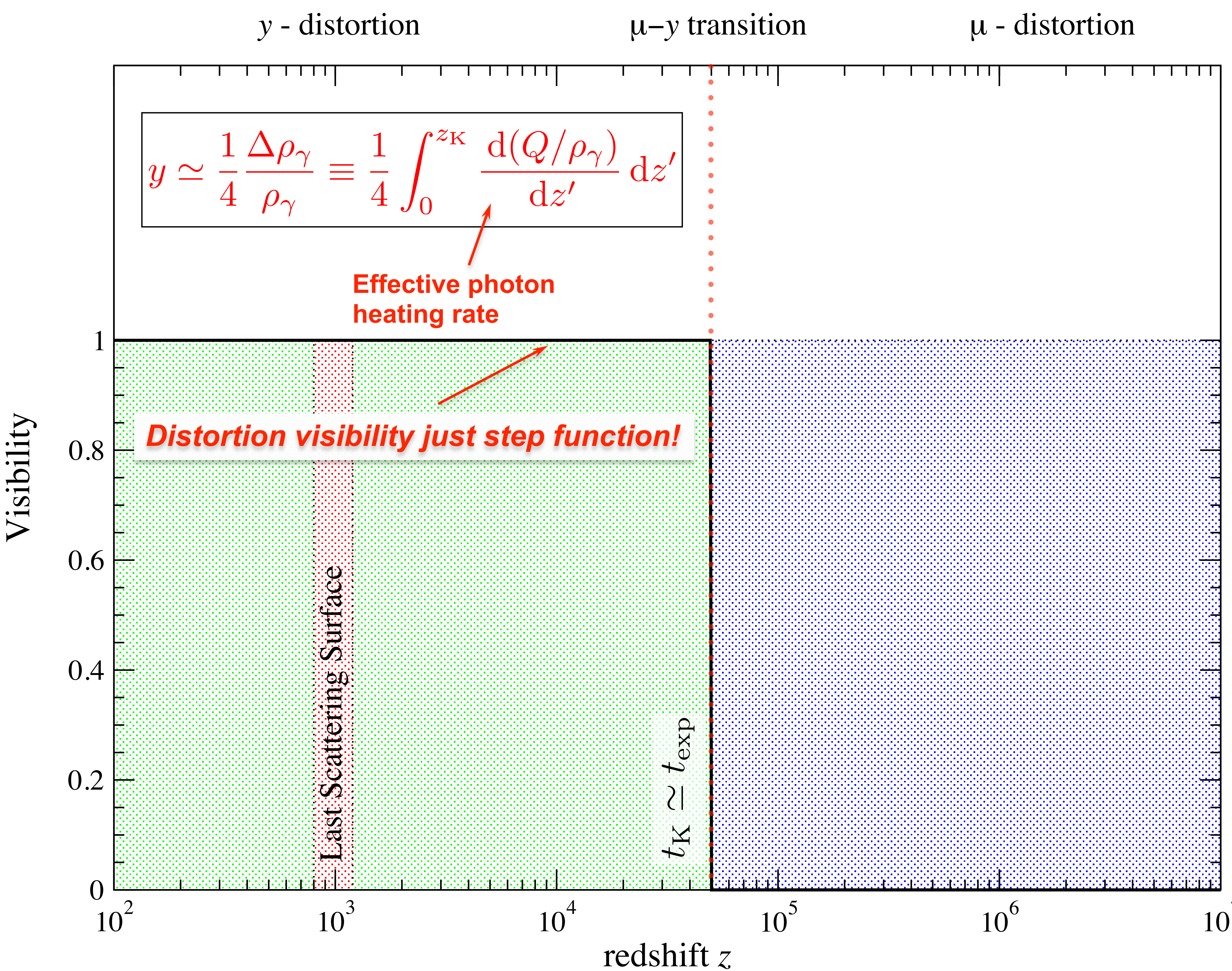

y - distortion
μ–y transition
μ - distortion
Photon production in principle works all the time, but photon transport to high frequencies inefficient at zK ≲ 50000 (Comptonization slow)
⇒ neglect photon production for high frequency spectrum
Last Scattering Surface
tK ≃ texp
Visibility
1
0.8
0.6
0.4
0.2
0
10^2
10^3
10^4
10^5
10^6
10^7
redshift z



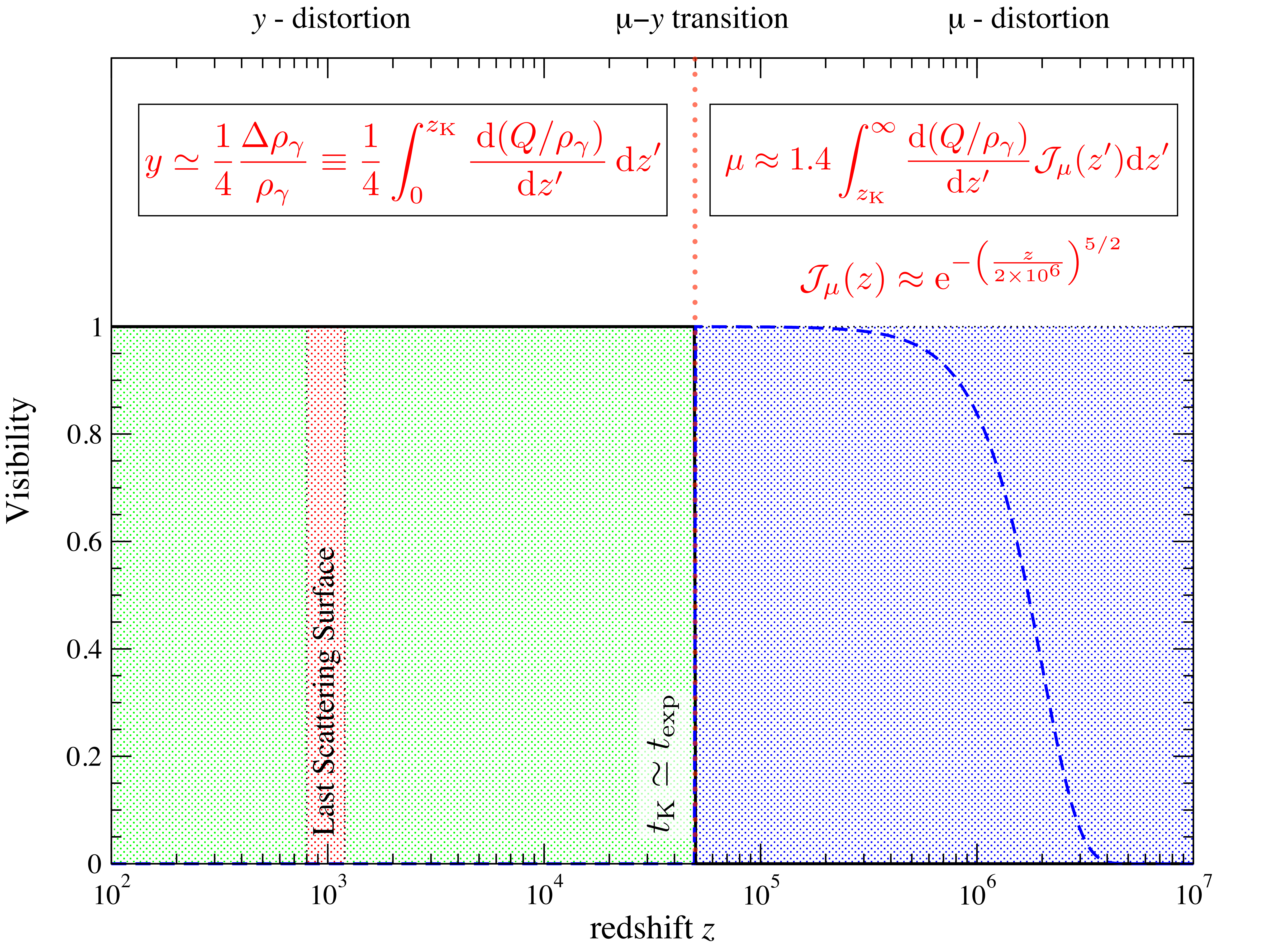
y - distortion
μ–y transition
μ - distortion
$y \simeq \frac{1}{4}\frac{\Delta\rho_\gamma}{\rho_\gamma} \equiv \frac{1}{4}\int_0^{z_K} \frac{d(Q/\rho_\gamma)}{dz'}\,dz'$
Visibility
Last Scattering Surface
$t_K \simeq t_{exp}$
redshift z



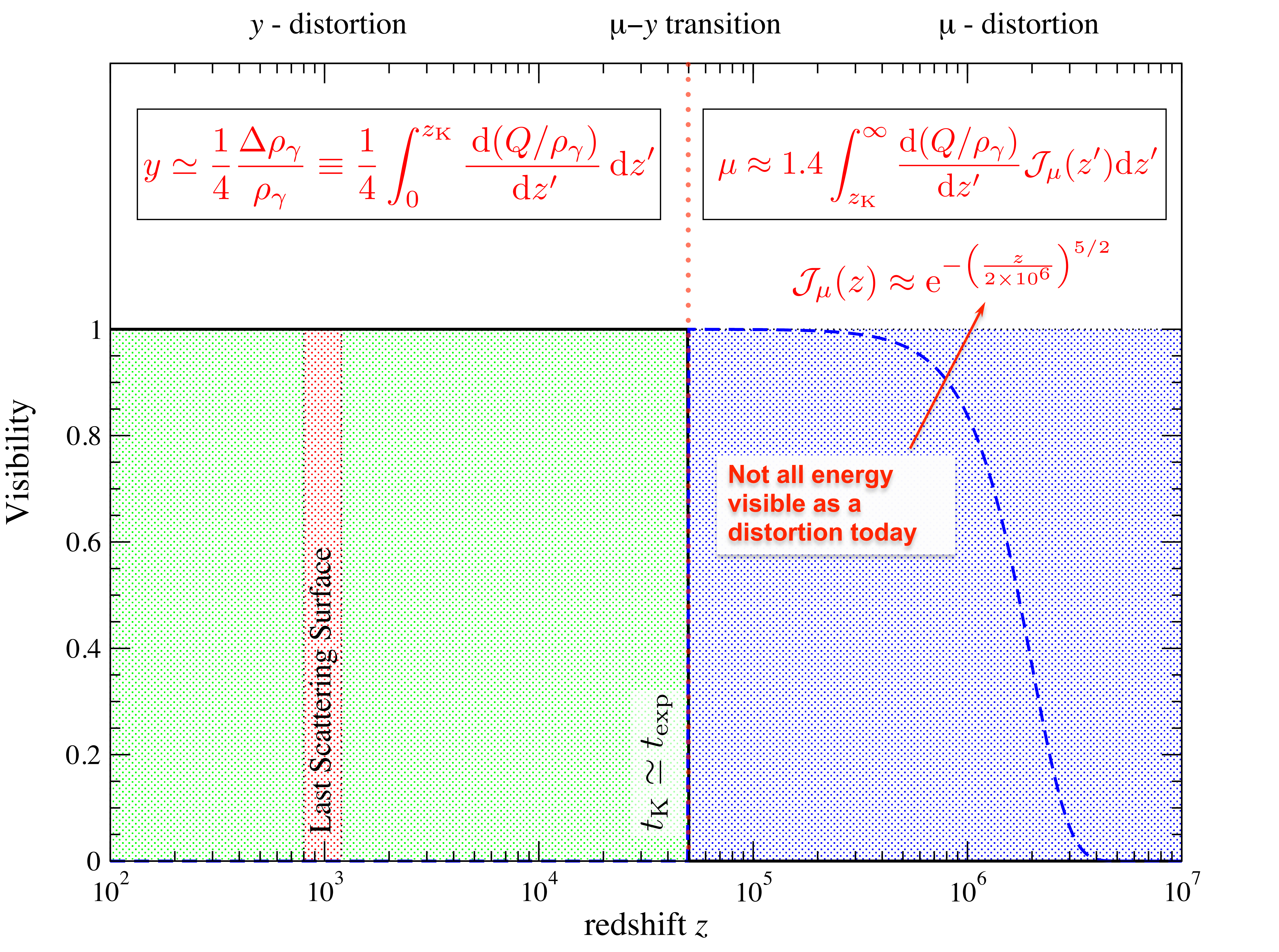
y - distortion
μ–y transition
μ - distortion
$y \simeq \frac{1}{4}\frac{\Delta\rho_\gamma}{\rho_\gamma} \equiv \frac{1}{4}\int_0^{z_{\rm K}} \frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'}\,{\rm d}z'$
Effective photon heating rate
Last Scattering Surface
$t_{\rm K} \simeq t_{\rm exp}$
Visibility
redshift z



y - distortion
μ–y transition
μ - distortion
$y \simeq \frac{1}{4}\frac{\Delta\rho_\gamma}{\rho_\gamma} \equiv \frac{1}{4}\int_0^{z_K} \frac{d(Q/\rho_\gamma)}{dz'}\,dz'$
Effective photon heating rate
Distortion visibility just step function!
Last Scattering Surface
$t_K \simeq t_{exp}$
Visibility
0
0.2
0.4
0.6
0.8
1
10^2
10^3
10^4
10^5
10^6
10^7
redshift z



y - distortion
μ–y transition
μ - distortion
$y \simeq \frac{1}{4}\frac{\Delta\rho_\gamma}{\rho_\gamma} \equiv \frac{1}{4}\int_0^{z_\mathrm{K}} \frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z'}\,\mathrm{d}z'$
$\mu \approx 1.4\int_{z_\mathrm{K}}^{\infty} \frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z'}\mathcal{J}_\mu(z')\mathrm{d}z'$
$\mathcal{J}_\mu(z) \approx \mathrm{e}^{-\left(\frac{z}{2\times10^6}\right)^{5/2}}$
Last Scattering Surface
$t_\mathrm{K} \simeq t_\mathrm{exp}$
Visibility
redshift z



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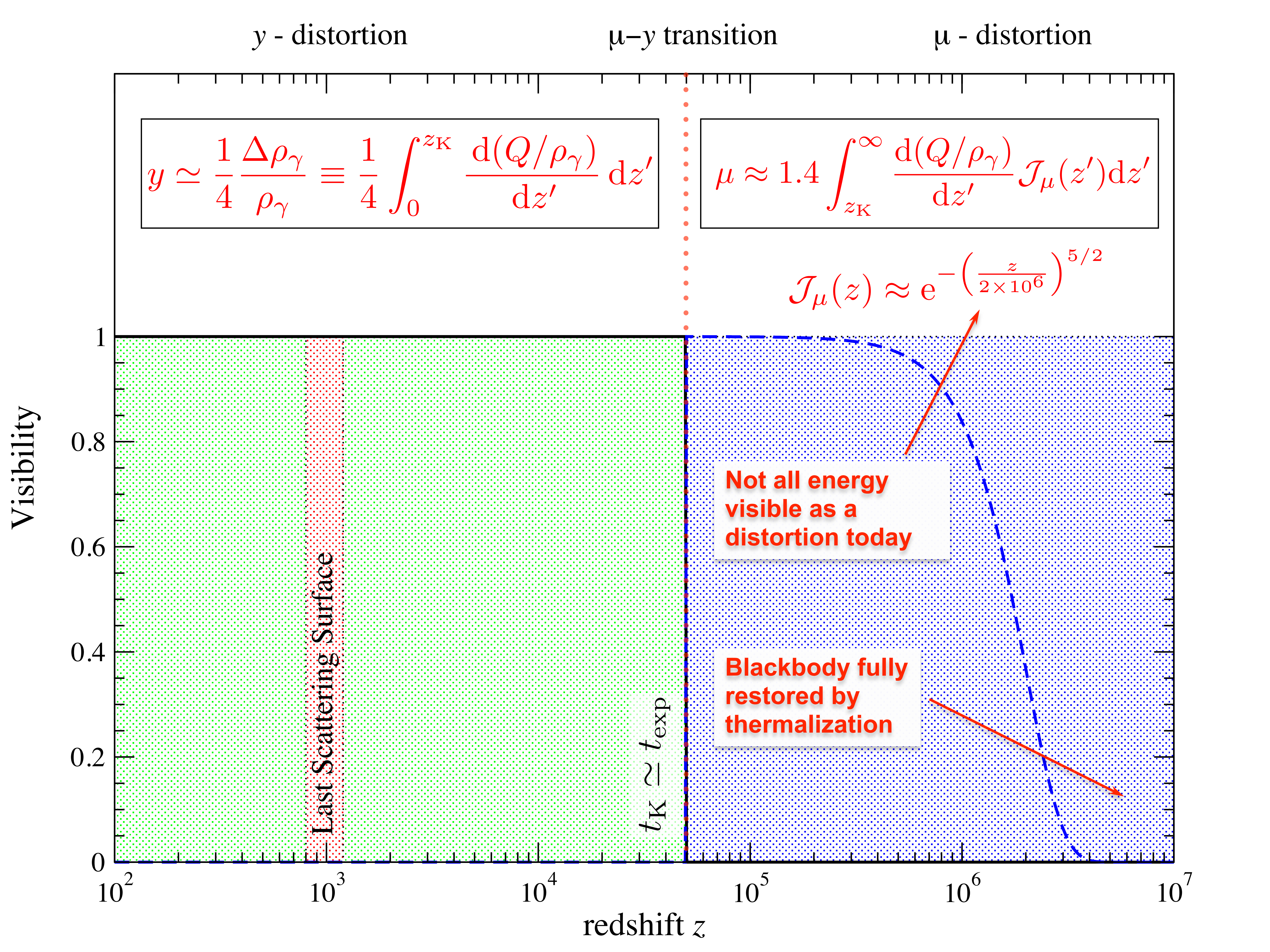
$\mathcal{J}_\mu(z) \approx e^{-\left(\frac{z}{2\times10^6}\right)^{5/2}}$
Not all energy visible as a distortion today
Last Scattering Surface
$t_K \simeq t_{exp}$
Visibility
redshift z
0
0.2
0.4
0.6
0.8
1
10^2
10^3
10^4
10^5
10^6
10^7



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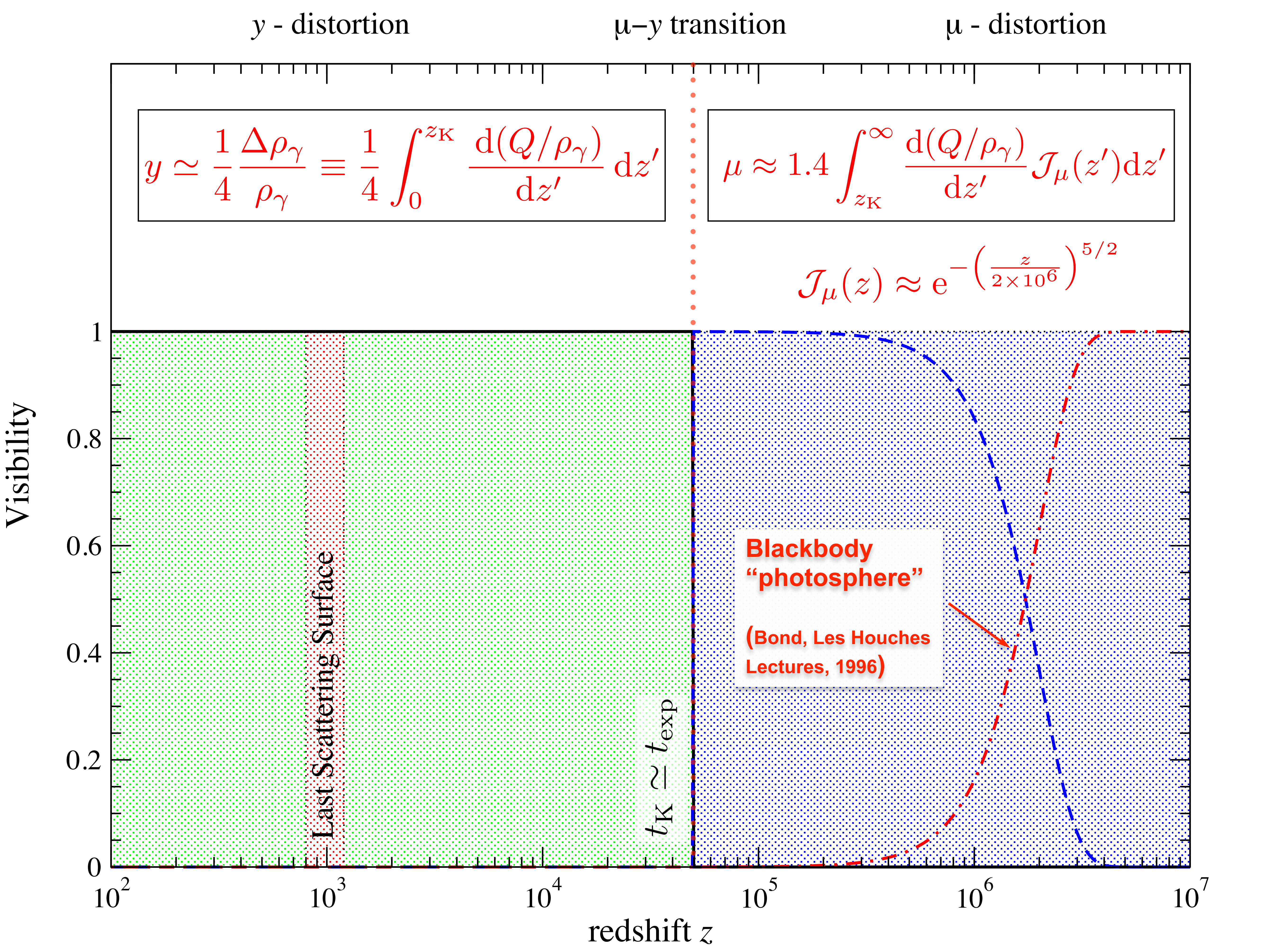
$\mathcal{J}_\mu(z) \approx e^{-\left(\frac{z}{2\times10^6}\right)^{5/2}}$
Not all energy visible as a distortion today
Blackbody fully restored by thermalization
Last Scattering Surface
$t_K \simeq t_{exp}$
Visibility
redshift z



y - distortion
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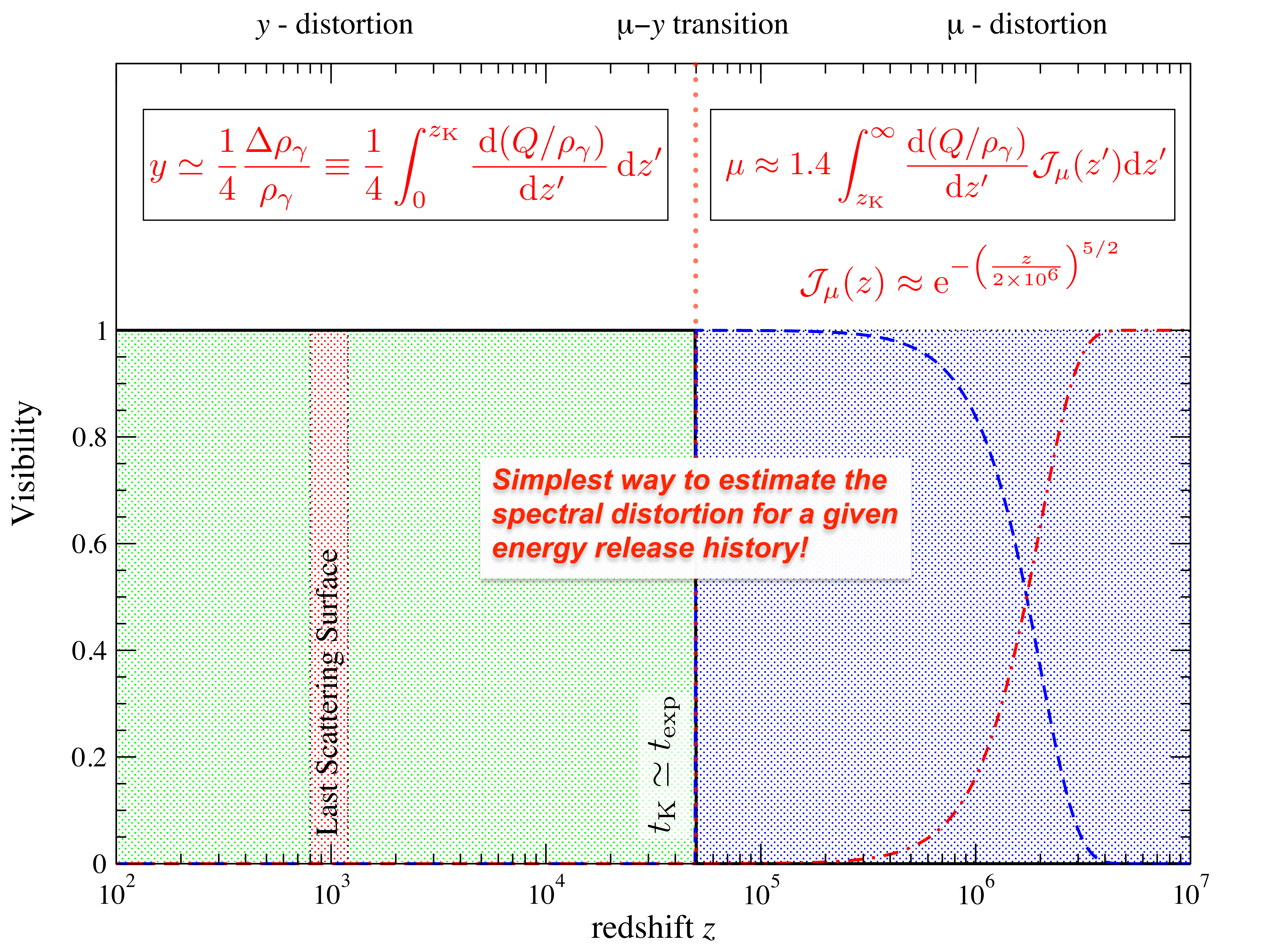
$\mathcal{J}_\mu(z) \approx \mathrm{e}^{-\left(\frac{z}{2\times10^6}\right)^{5/2}}$
Visibility
Last Scattering Surface
$t_\mathrm{K} \simeq t_\mathrm{exp}$
Blackbody "photosphere"
(Bond, Les Houches Lectures, 1996)
redshift z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$\mathcal{J}_\mu(z) \approx e^{-\left(\frac{z}{2\times10^6}\right)^{5/2}}$
Simplest way to estimate the spectral distortion for a given energy release history!
Last Scattering Surface
$t_K \simeq t_{exp}$
Visibility
redshift z
0
0.2
0.4
0.6
0.8
1
10^2
10^3
10^4
10^5
10^6
10^7

Refined computation of the distortion visibility

(JC 2014, ArXiv:1312.6030)

Can we improve the agreement with CosmoTherm?

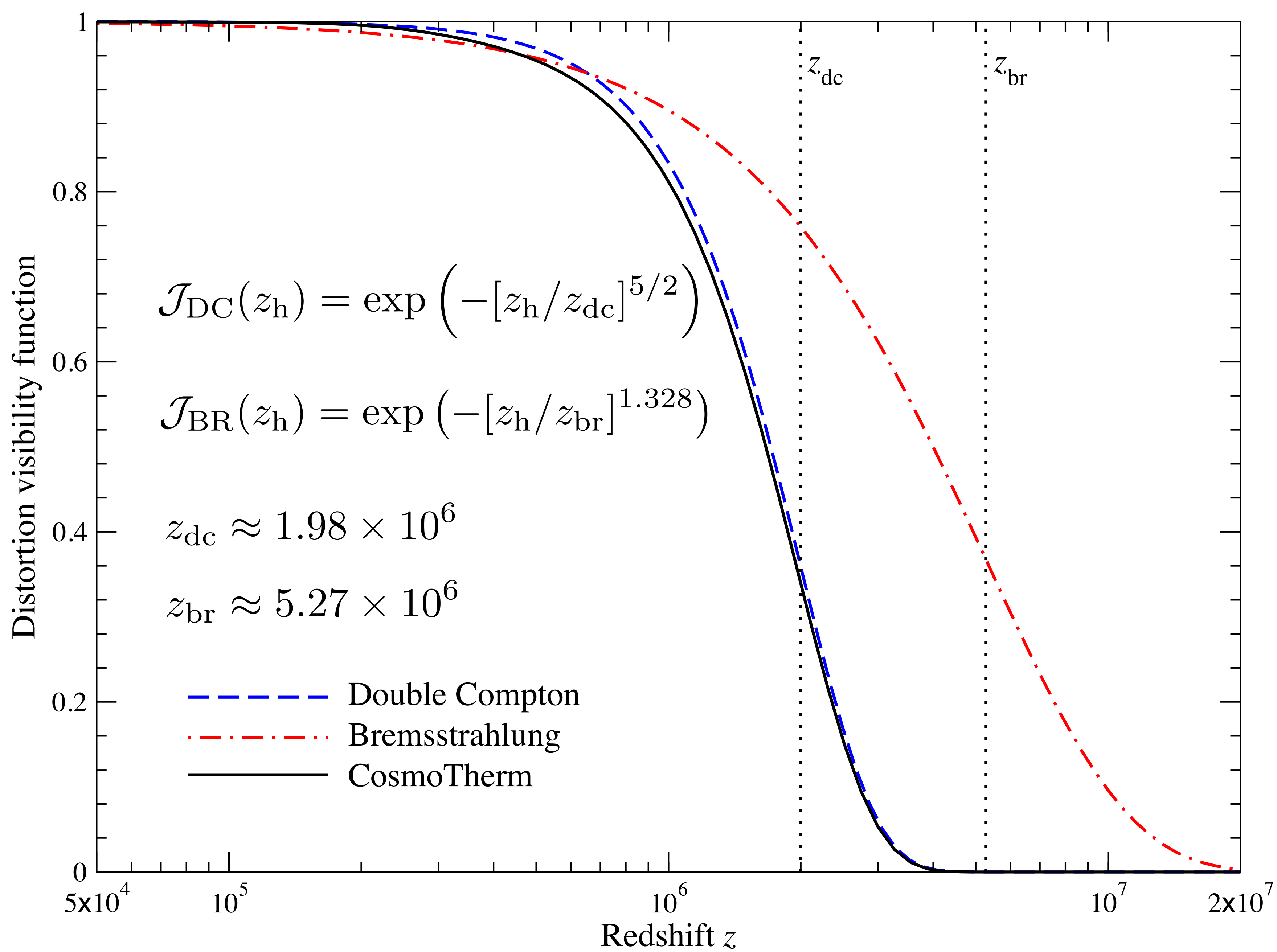
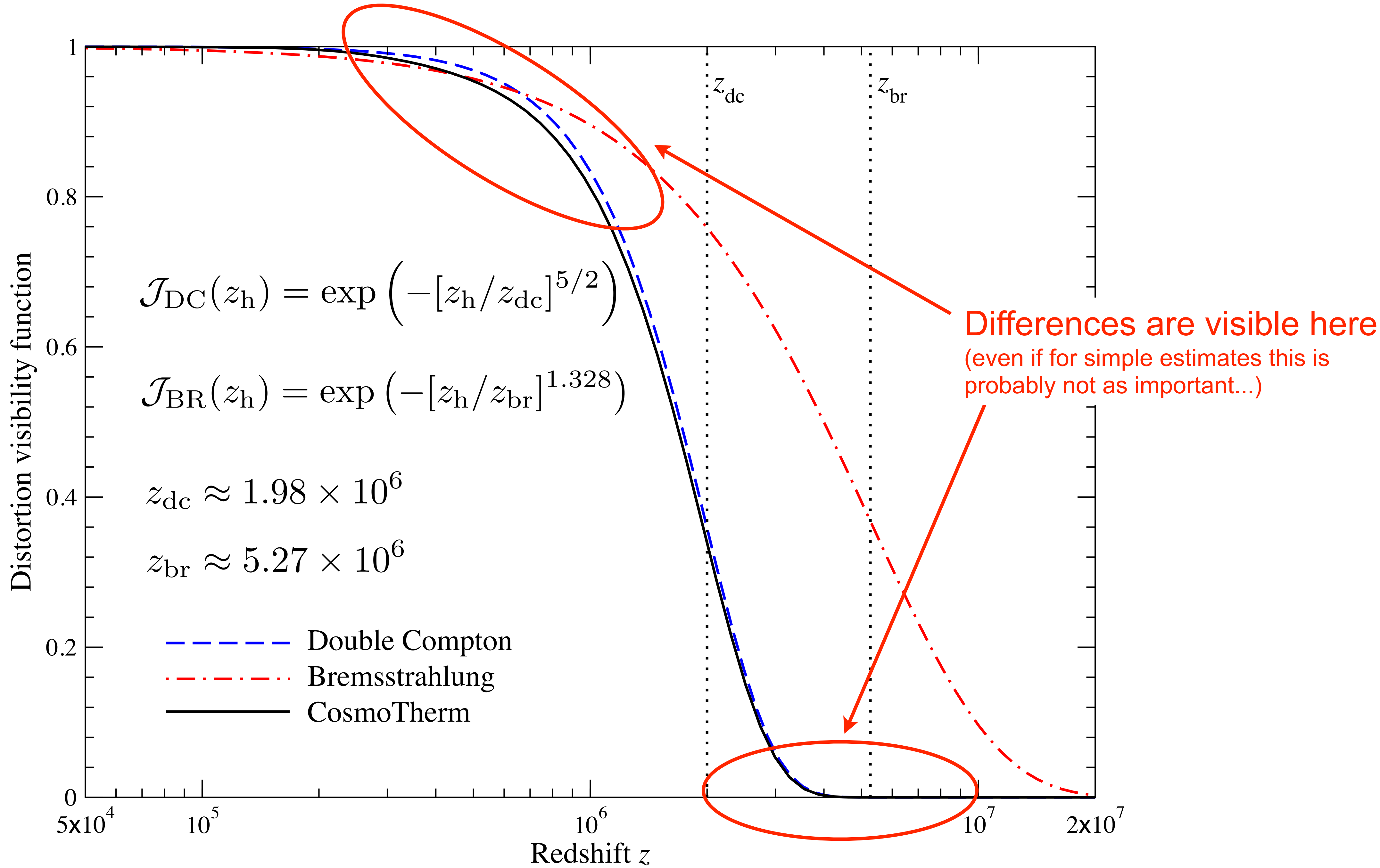


Figure 4.9: Distortion visibility function. We compare $\mathcal{J}_{\rm DC}(z_{\rm h})$, $\mathcal{J}_{\rm BR}(z_{\rm h})$ and the numerical result obtained with CosmoTherm. DC emission significantly change the thermalization efficiency. Deviations from the numerical result can be captured by adding several effects, as discussed in Sect. 4.6.

Can we improve the agreement with CosmoTherm?



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What do we need to do to improve this?

(i) improve computation of emission integral

- optical depth
- numerical evaluation of integral

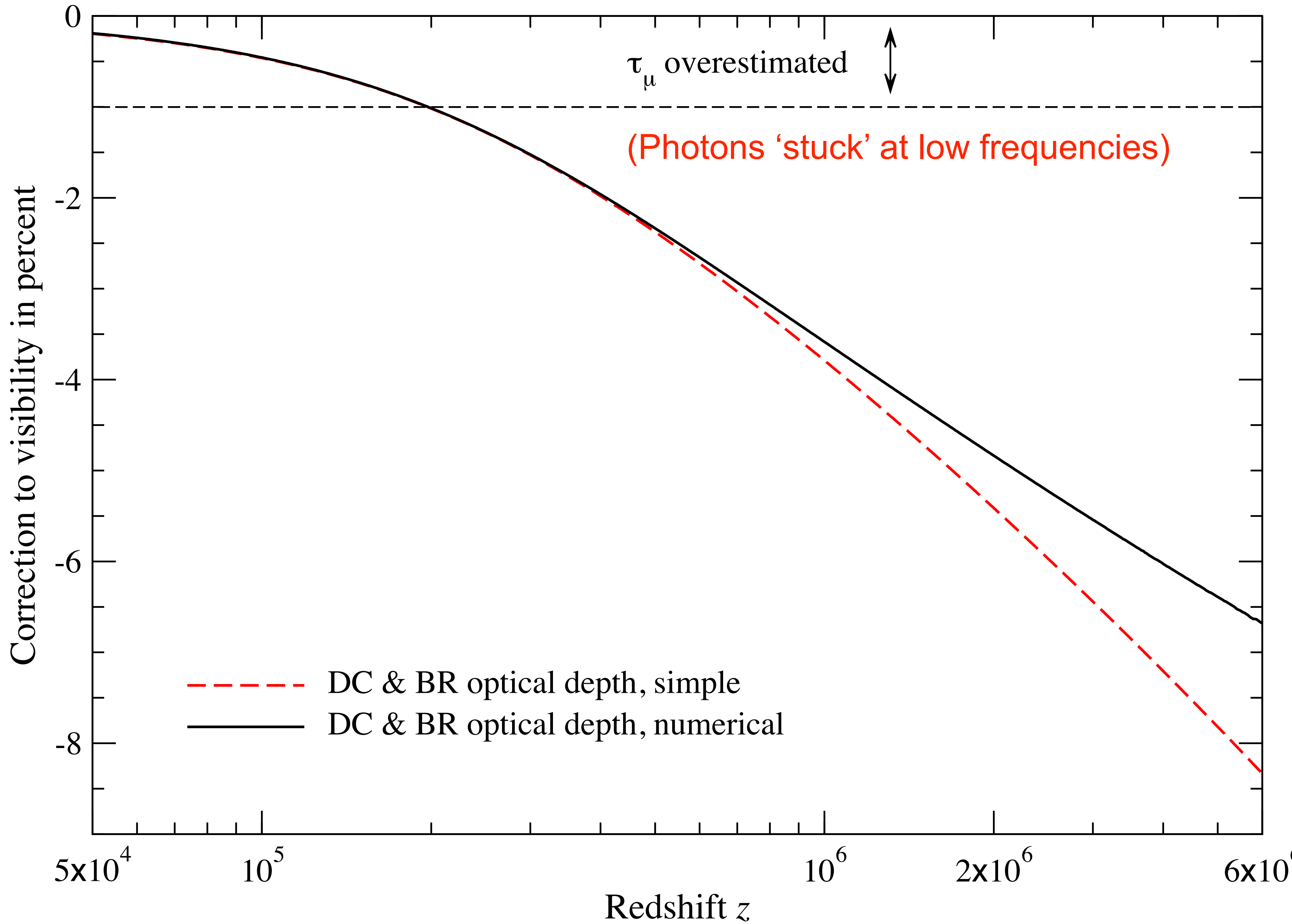
(ii) improve approximation for μ

- beyond the low frequency limit
- add time-dependent corrections
- corrections to emission and scattering terms

First improvements by Khatri & Sunyaev, 2012

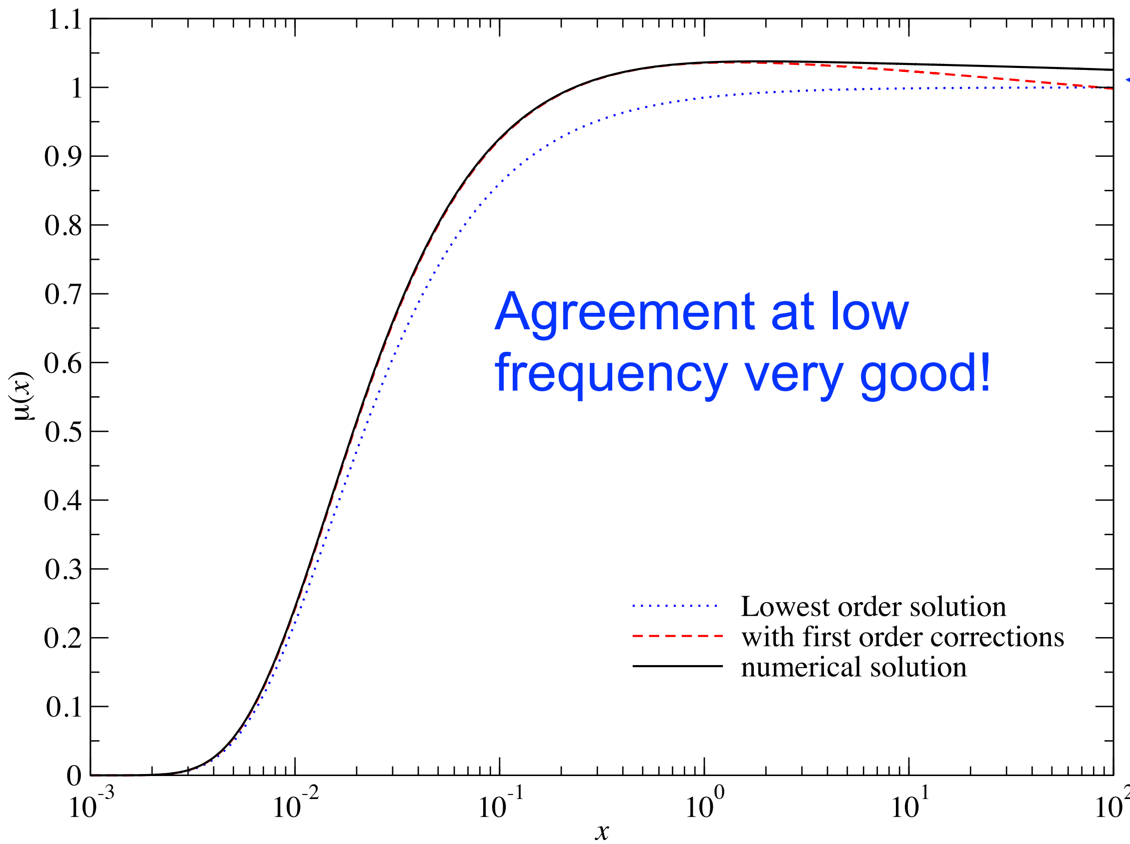
Perturbative study by JC 2014, ArXiv: 1312.6030

Computing the thermalization optical depth better

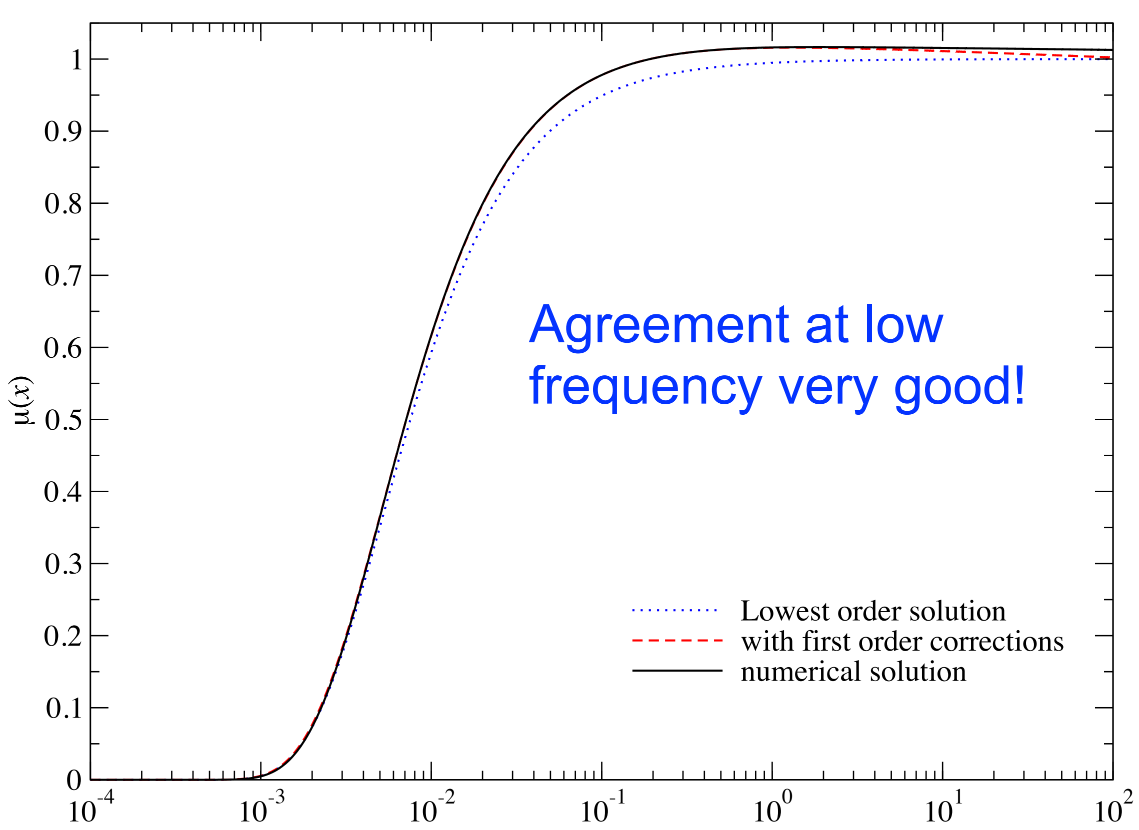


JC 2014, ArXiv:1312.6030

Correction to the shape of μ



Differences can be avoided by matching with high-frequency solution (see below...)



Time-dependence of μ

Determined using energy argument

(similar to Khatri & Sunyaev, 2012)

$$\hat{\mu}^{(1)} \approx C_1\, e^{-x_c/x} + \ln(x/x_c)\, e^{-x_c/x} \partial_y \ln \mu_\infty^{(0)} + D_\mu(x_c/x)\left[\partial_y \ln \mu_\infty^{(0)} + \frac{1}{2}\partial_y \ln x_c\right] + D_{\rm em}(x_c, x_c/x)\, x_c$$

Time-dependence of μ and x_c

Correction to emission term

- *Spectral functions simple expressions*

JC 2014, ArXiv:1312.6030

Correction to the photon production integral

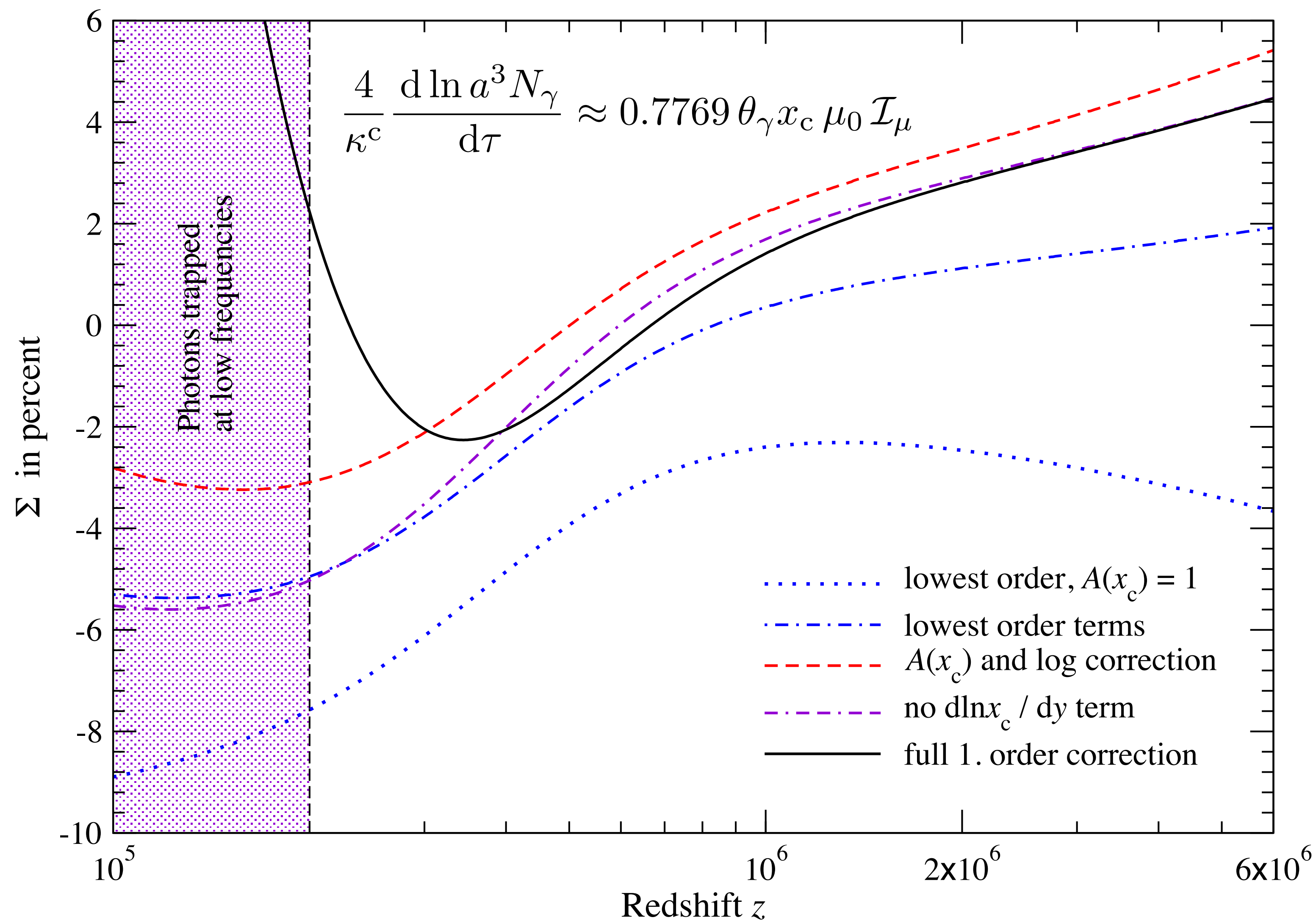
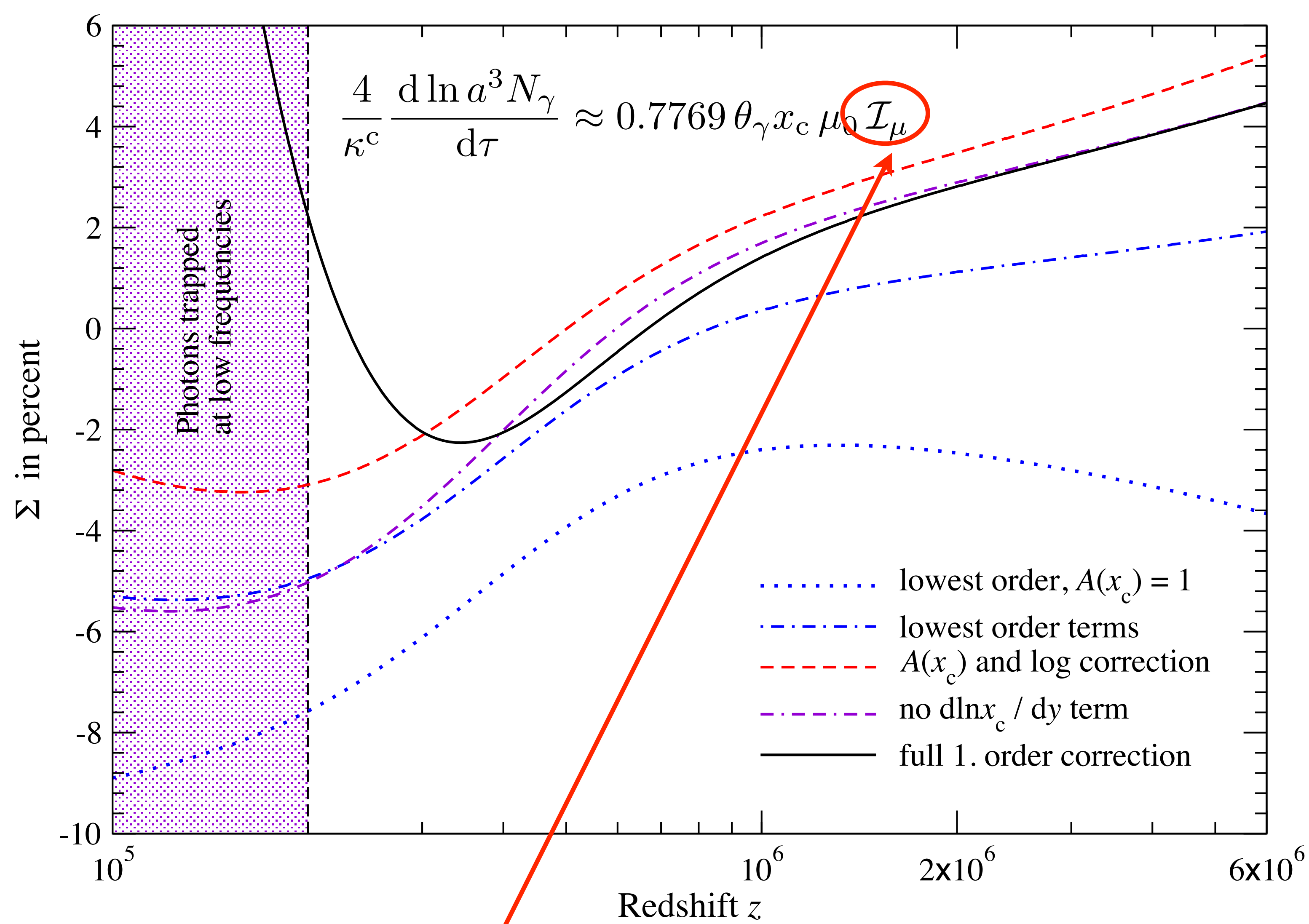


Figure 7. Changes of $\Sigma = \mathcal{I}_{\hat{\mu}} - 1$ for different approximations of $\hat{\mu}$ discussed in Sect. 5.3.2. For the lowest order solution, we used $\hat{\mu} = A(x_c)\,\mathrm{e}^{-x_c/x}$ with $A(x_c) = 1$ and $A(x_c) = A_0(x_c)$ defined by Eq. (57). For the dashed red line, we used $\hat{\mu} = A(x_c)\mathrm{e}^{-x_c/x} + \ln(x/x_c)\,\mathrm{e}^{-x_c/x}\partial_y \ln \mu_\infty^{(0)}$, while for the solid black line we used the full first-order expression, Eq. (54), each with their corresponding normalization constants, $A(x_c)$. The double-dash dotted curve also gives the result using Eq. (54), but when neglecting the contribution from $\partial_y \ln x_c$, which becomes large at low redshifts. The shaded region indicates where the high-frequency photon number freezes out.

JC 2014, ArXiv:1312.6030

Correction to the photon production integral



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JC 2014, ArXiv:1312.6030

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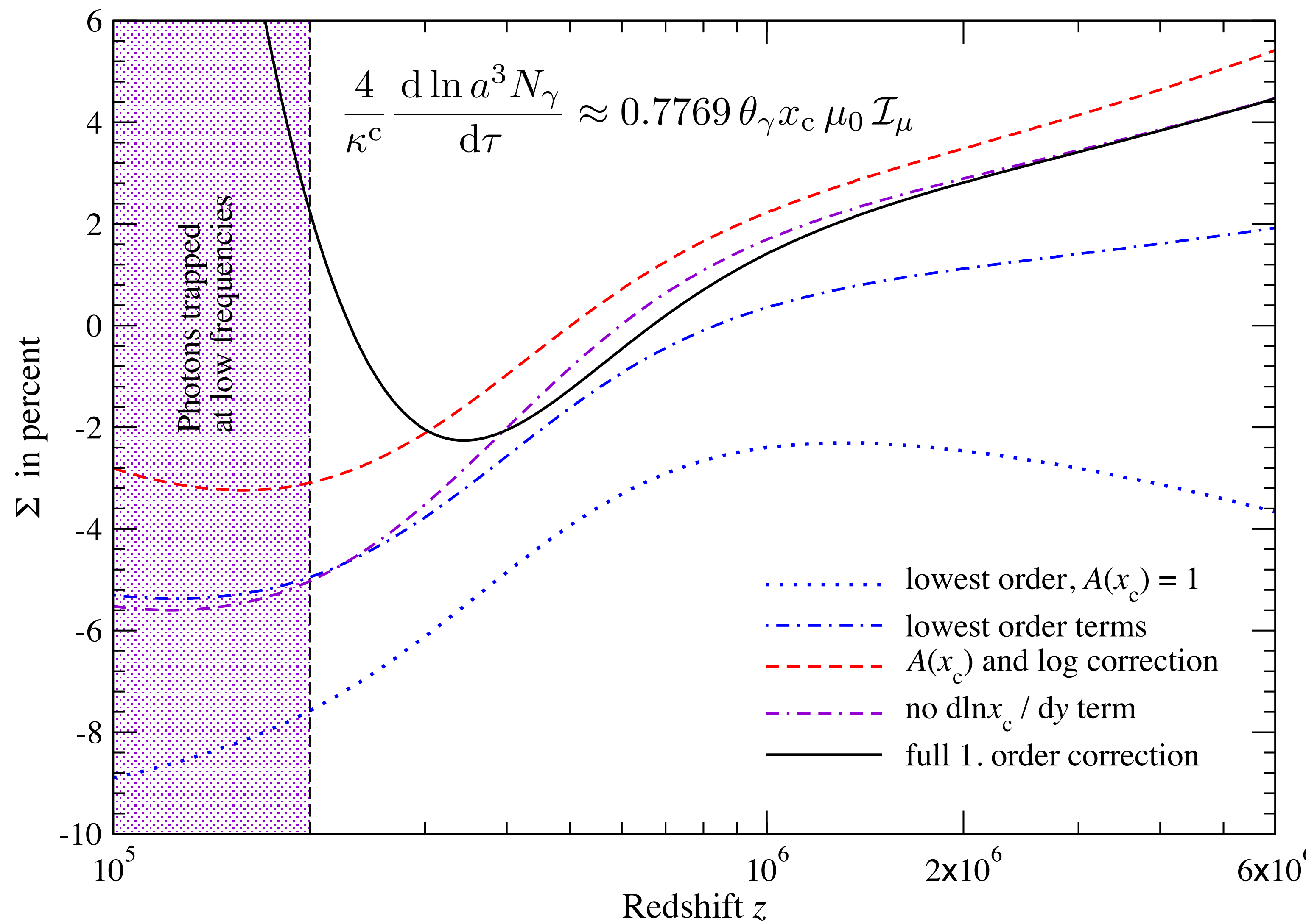

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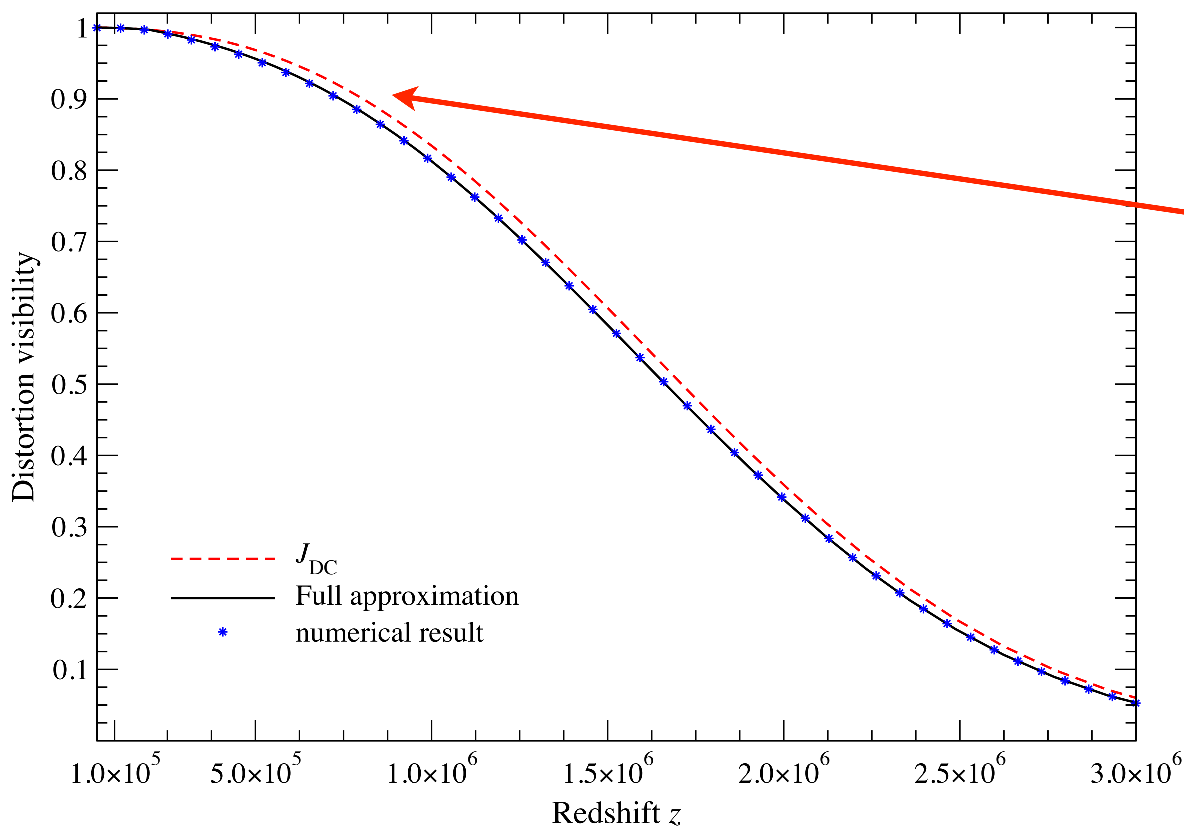
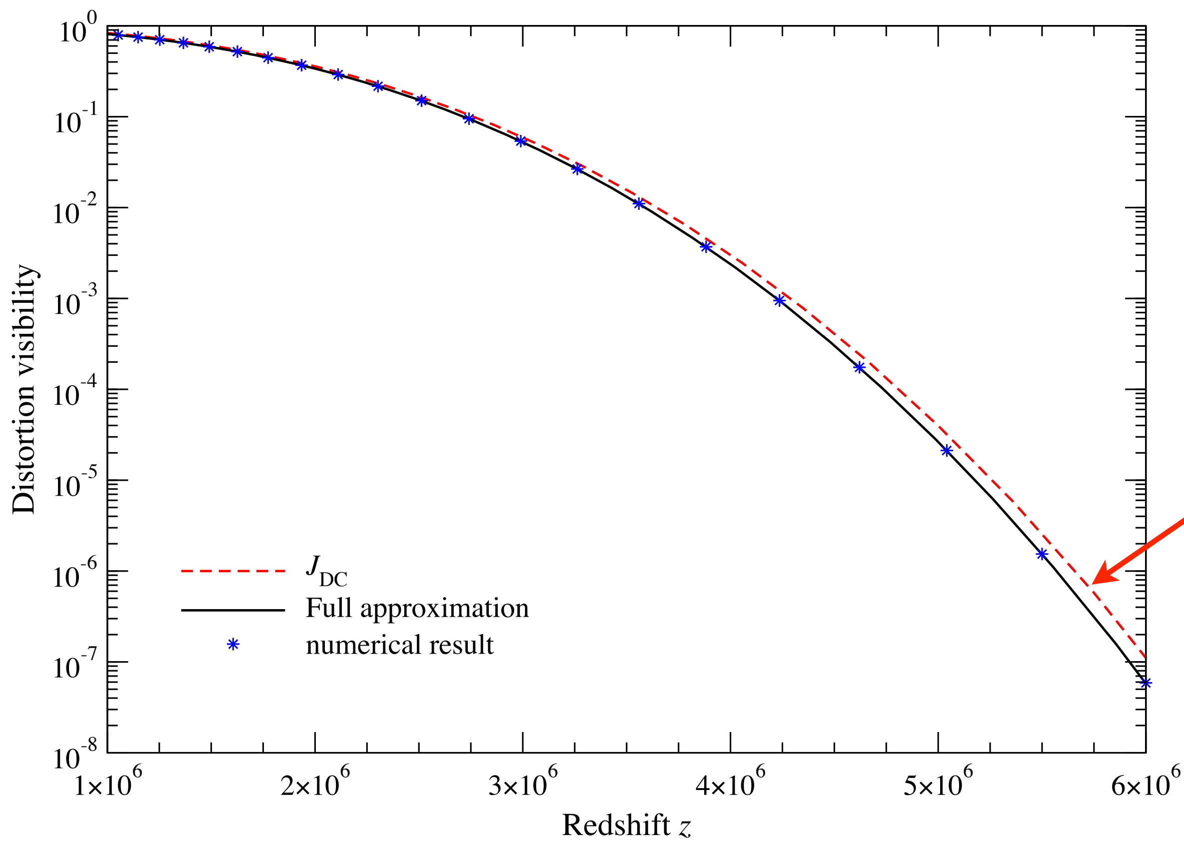
JC 2014, ArXiv:1312.6030

Final approximation for the visibility function



τ correction from photons being stuck at low frequencies important here

(Not included by KS12)



- Approximation given in terms of simple integrals
- Evaluation very fast and precise
- will be available as part of the *CosmoTherm* package

DC visibility is off by a factor of ~2

JC 2014, ArXiv:1312.6030

Contributions from different terms

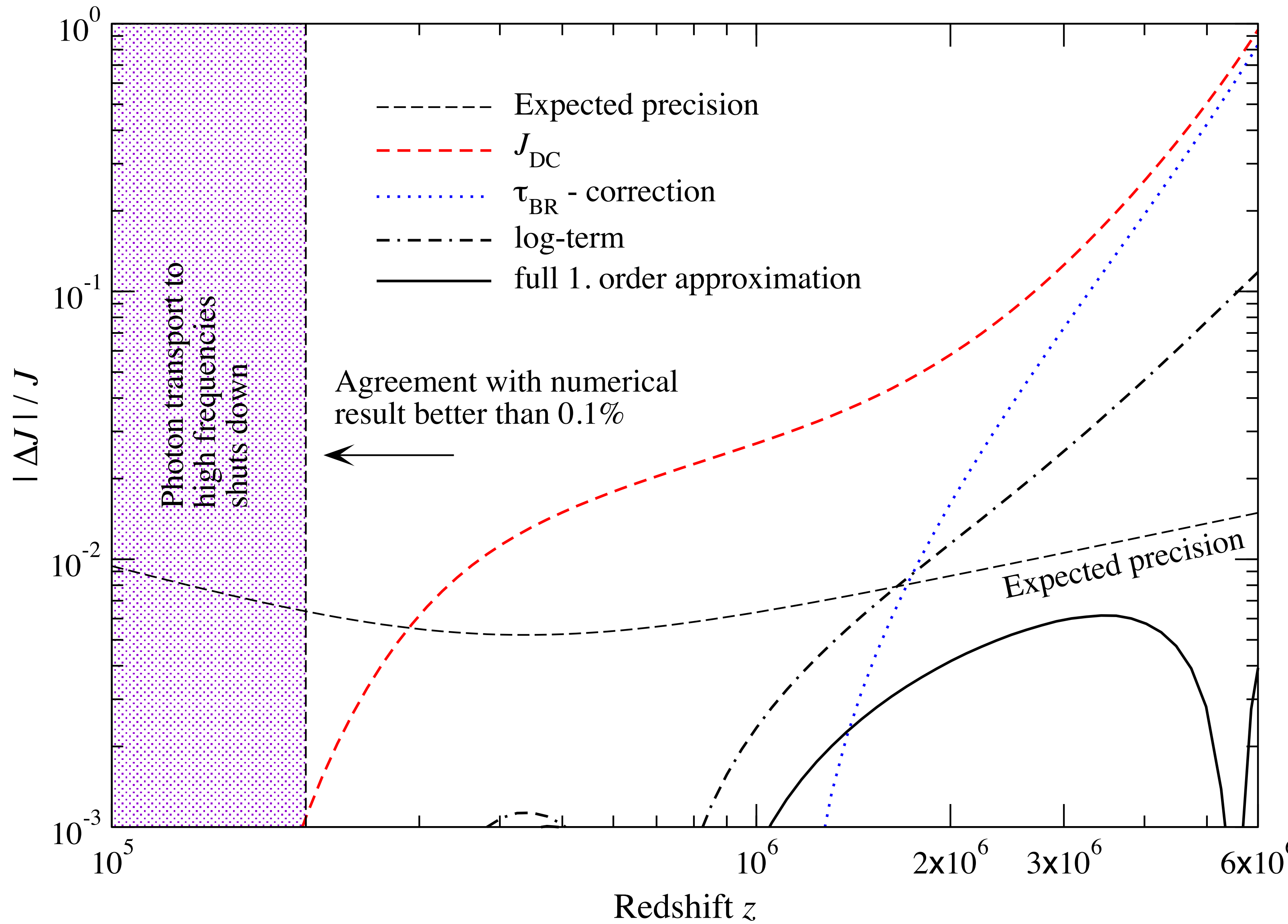


Figure 9. Corrections to the distortion visibility function at different redshifts. For all curves, the numerical result obtained using CosmoTherm was used as reference. The dashed red line shows $\mathcal{J}_{\rm DC} = e^{-(z/z_{\rm dc})^{5/2}}$ with $z_{\rm dc} = 1.98\times10^6$. When only including the BR correction to the optical depth (Sect. 5.2), we obtain the dotted blue line. Only adding the $\ln(x/x_{\rm c})e^{-x_{\rm c}/x}$ term, we improve the agreement at early times. The solid black line gives our approximation based on Eq. (54), with all terms included, showing precision below the level expected in terms of perturbation order $\simeq x_{\rm c}$.

JC 2014, ArXiv:1312.6030

Comparison with Kharti & Sunyaev, 2012

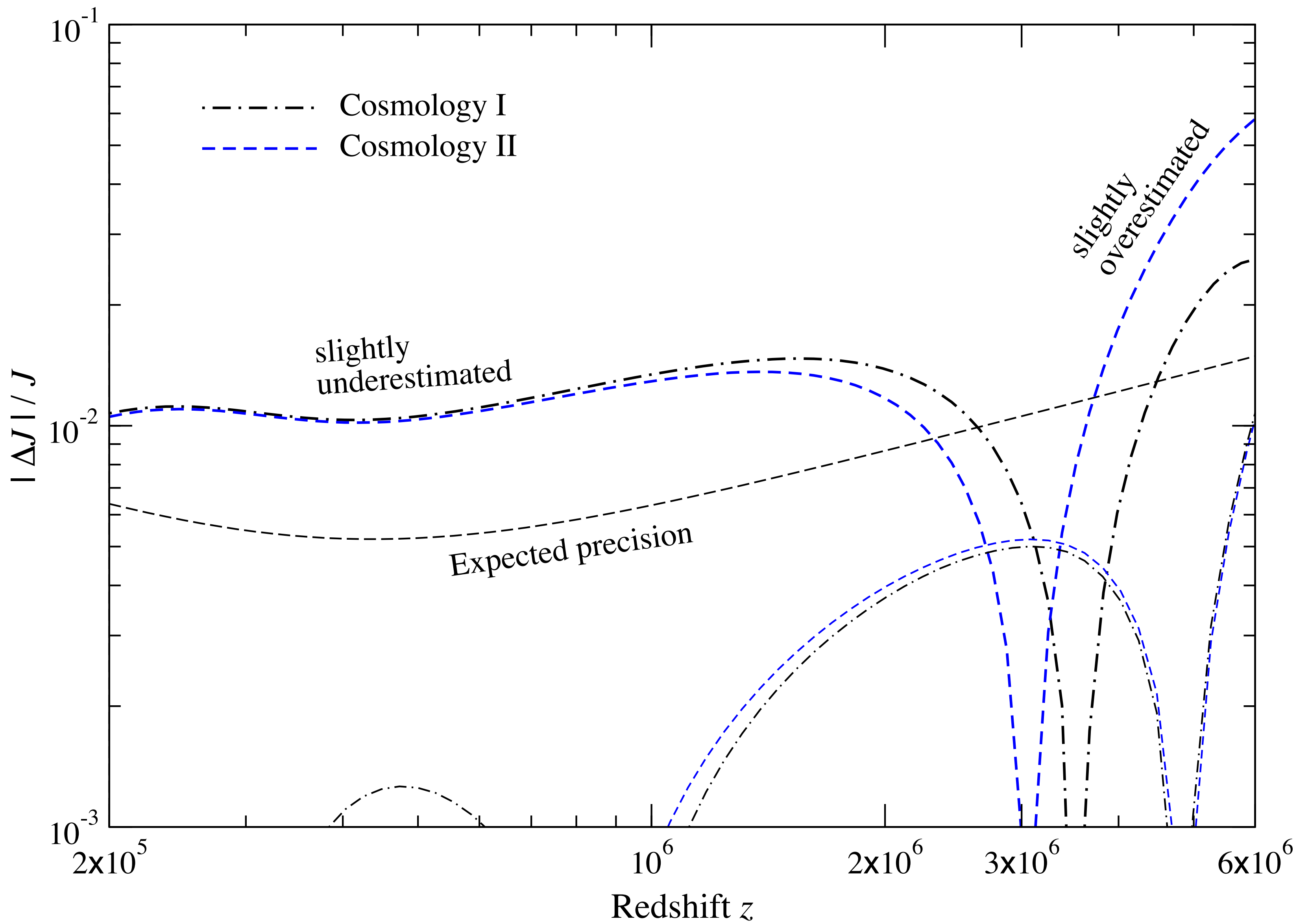


Figure 10. Comparison of the approximation given by KS12 with our numerical result from CosmoTherm. We compare for the cosmology used in KS12 (blue dashed) and the one used here (black dash-dotted). Their simple expression (heavy lines) works very well overall. Our approximation (thin lines) represents our numerical result below the expected precision $\simeq x_c$ at all redshifts and giving $\lesssim 0.1\%$ precision at $z \lesssim 10^6$. In Sect. 5.4.1, we briefly discuss the possible explanations for difference with KS12.

JC 2014, ArXiv:1312.6030

DC and CS relativistic corrections

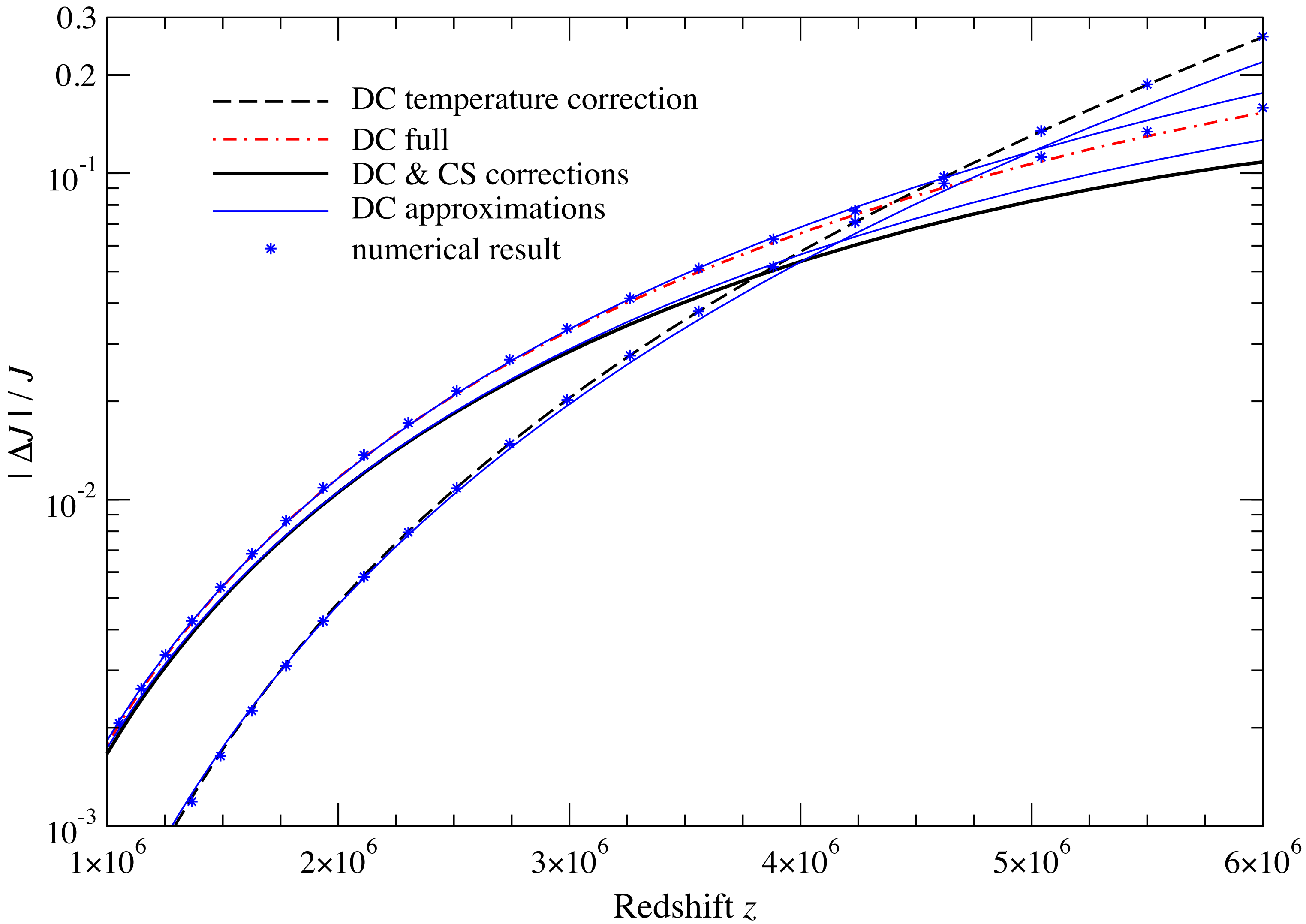


Figure 13. DC and CS corrections to the distortion visibility function. The full non-relativistic result is used as a reference. The thin solid blue lines give the simple approximations discussed in Sect. 6, while the other lines were obtained by modifying our perturbation expansion, Eq. (54), accordingly. For the DC corrections, we also show the full numerical result for the correction obtained with CosmoTherm.

DC temperature correction

$$\Delta\tau_\mu^{\rm DC}(z,0) \approx -5.06\,\theta_\gamma\,(z/z_{\rm dc})^{5/2}$$

DC frequency correction

$$\Delta\tau_\mu^{\rm DC}(z,0) \approx [3.70\times10^{-3} + 1.43x_{\rm c}^{\rm DC,0}]\,(z/z_{\rm dc})^{5/2}$$

CS correction

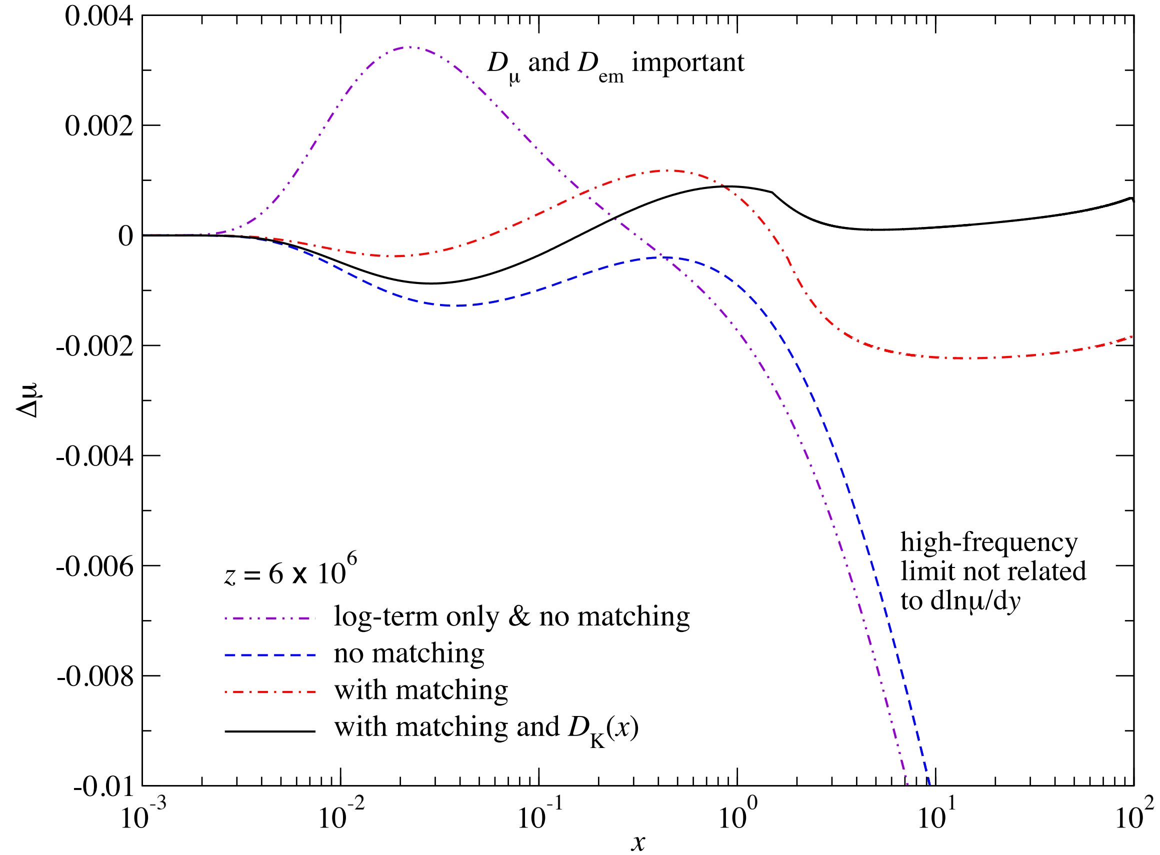
$$\Delta\tau_\mu^{\rm CS}(z,0) \approx -1.23\theta_\gamma\,(z/z_{\rm dc})^{5/2}$$

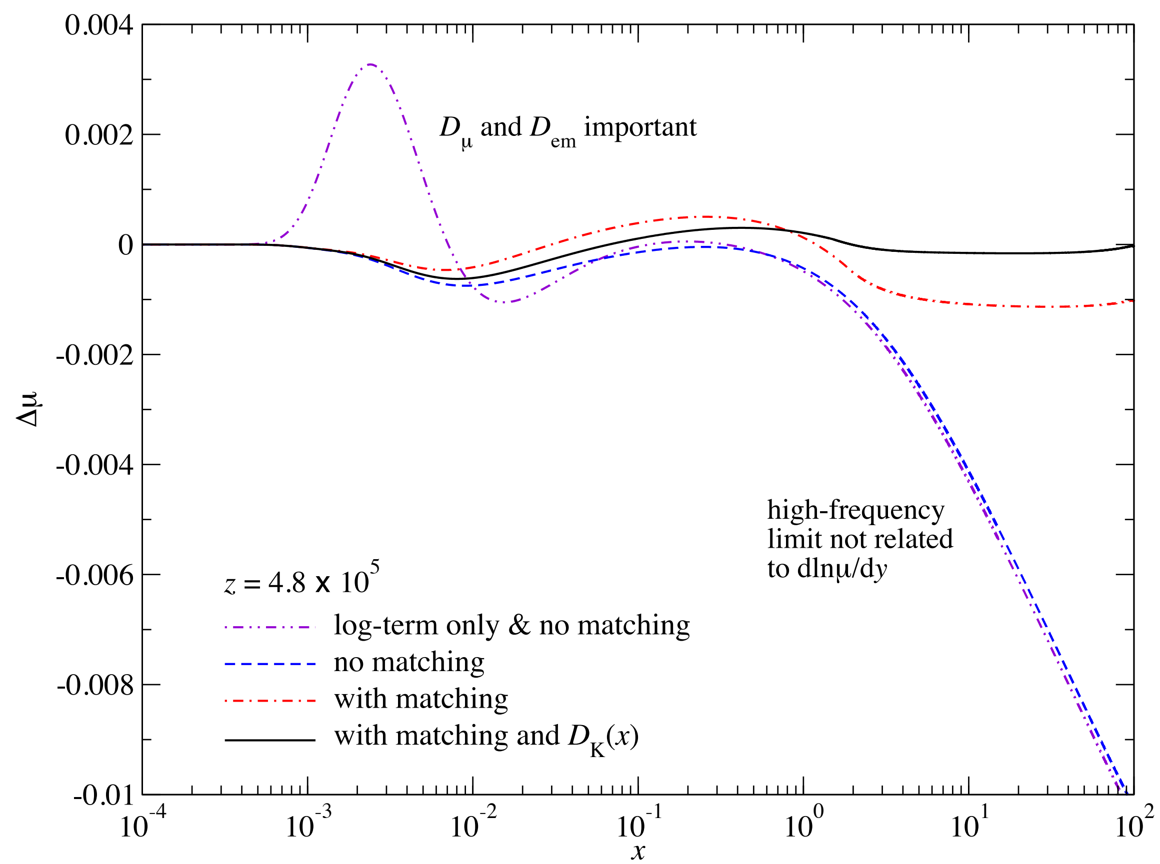
- individual effects as large as ~20-30%

- cancelation leaves only a ~10% effect

JC, 2005, PhD; JC 2014, ArXiv:1312.6030

Solution at high frequencies





Evolution equation at $x \gg 1$

$$\partial_y \mu - x\,\partial_y(T_e/T_\gamma) \approx x^2\mu'' + (4-x)x\mu'$$

Lowest order solution

$$\mu_{\rm high}(x) \approx C_{\rm high} + \ln(x)\,\partial_y(T_e^{(0)}/T_\gamma)$$

$$\Longrightarrow n(t, x_e) \simeq \alpha(t) x_e^{\gamma}(t)\, e^{-x_e}$$

First order correction in x

Compton corrections

$$\hat{\mu}_{\rm high}(x) \approx C_{\rm high} + \ln(x)\,\frac{\partial_y(T_e^{(0)}/T_\gamma)}{\mu_\infty^{(0)}} + \left(\partial_y \ln\mu_\infty^{(0)} - 3\,\frac{\partial_y(T_e^{(0)}/T_\gamma)}{\mu_\infty^{(0)}}\right)\frac{1+\frac{1}{x}+\frac{2}{3x}}{x}$$

(Not captured by Khatri & Sunyaev 2012 solution...)

JC 2014, ArXiv:1312.6030

Numerical solution of the thermalization problem

Final Set of evolution equations

Photon field

$$\frac{\partial f}{\partial \tau} \approx \frac{\theta_{\rm e}}{x^2}\frac{\partial}{\partial x}x^4\left[\frac{\partial}{\partial x}f + \frac{T_\gamma}{T_{\rm e}}\,f(1+f)\right] + \frac{K_{\rm BR}\,{\rm e}^{-x_{\rm e}}}{x_{\rm e}^3}[1-f\,({\rm e}^{x_{\rm e}}-1)] + \frac{K_{\rm DC}\,{\rm e}^{-2x}}{x^3}[1-f\,({\rm e}^{x_{\rm e}}-1)] + S(\tau,x)$$

$$K_{\rm BR} = \frac{\alpha}{2\pi}\frac{\lambda_{\rm e}^3}{\sqrt{6\pi}\,\theta_{\rm e}^{7/2}}\sum_i Z_i^2 N_i\,\bar{g}_{\rm ff}(Z_i, T_{\rm e}, T_\gamma, x_{\rm e}), \qquad K_{\rm DC} = \frac{4\alpha}{3\pi}\,\theta_\gamma^2\,I_{\rm dc}\,g_{\rm dc}(T_{\rm e}, T_\gamma, x)$$

$$\bar{g}_{\rm ff}(x_{\rm e}) \approx \begin{cases} \frac{\sqrt{3}}{\pi}\ln\left(\frac{2.25}{x_{\rm e}}\right) & \text{for} \quad x_{\rm e} \le 0.37 \\ 1 & \text{otherwise} \end{cases}, \qquad g_{\rm dc} \approx \frac{1+\frac{3}{2}x+\frac{29}{24}x^2+\frac{11}{16}x^3+\frac{5}{12}x^4}{1+19.739\theta_\gamma - 5.5797\theta_{\rm e}}.$$

$$I_{\rm dc} = \int x^4 f(1+f)\,{\rm d}x \approx 4\pi^4/15$$

Ordinary matter temperature

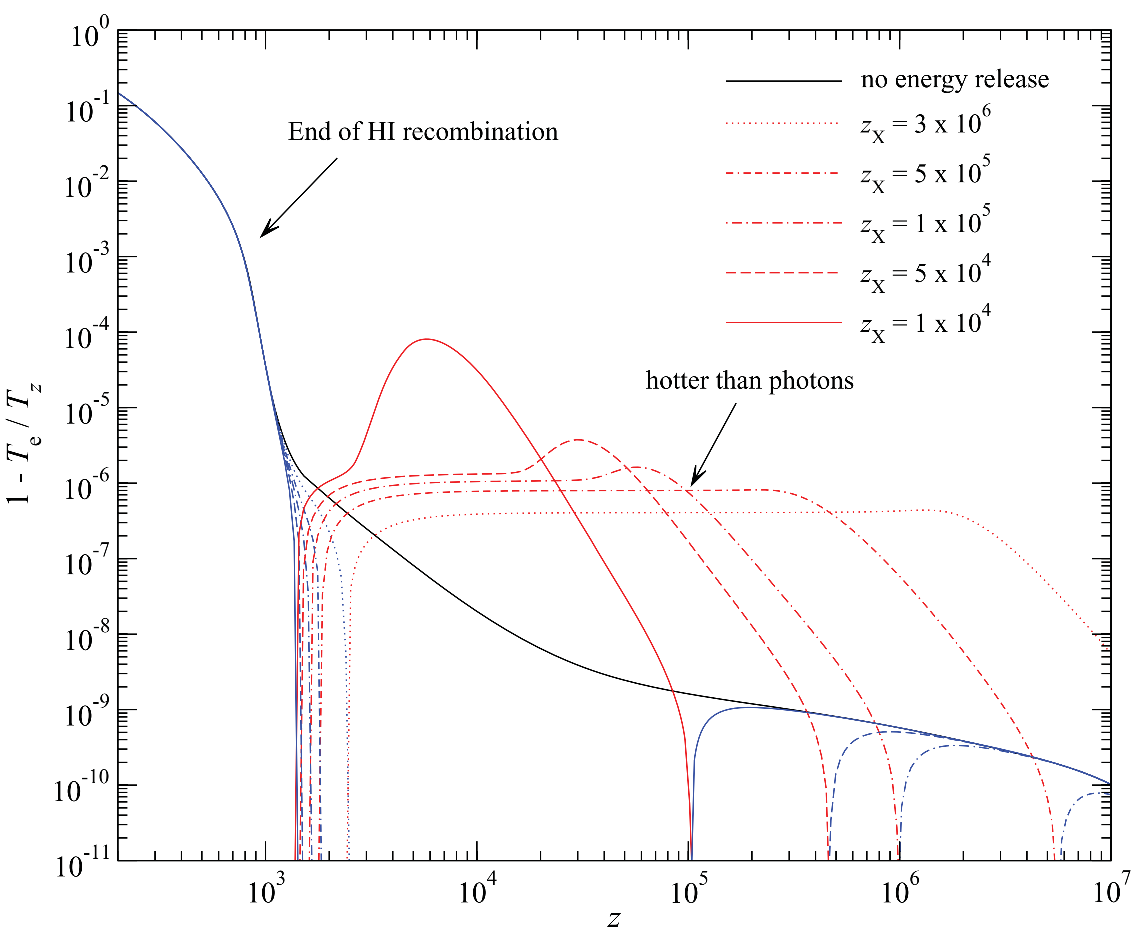
$$\frac{{\rm d}\rho_{\rm e}}{{\rm d}\tau} = \frac{{\rm d}(T_{\rm e}/T_\gamma)}{{\rm d}\tau} = \frac{t_{\rm T}\dot{Q}}{\alpha_{\rm h}\theta_\gamma} + \frac{4\tilde{\rho}_\gamma}{\alpha_{\rm h}}[\rho_{\rm e}^{\rm eq} - \rho_{\rm e}] - \frac{4\tilde{\rho}_\gamma}{\alpha_{\rm h}}\mathcal{H}_{\rm DC,BR}(\rho_{\rm e}) - H\,t_{\rm T}\,\rho_{\rm e}.$$

$$k\alpha_{\rm h} = \frac{3}{2}k[N_{\rm e}+N_{\rm H}+N_{\rm He}] = \frac{3}{2}kN_{\rm H}[1+f_{\rm He}+X_{\rm e}] \qquad \rho_{\rm e}^{\rm eq} = T_{\rm e}^{\rm eq}/T_\gamma$$

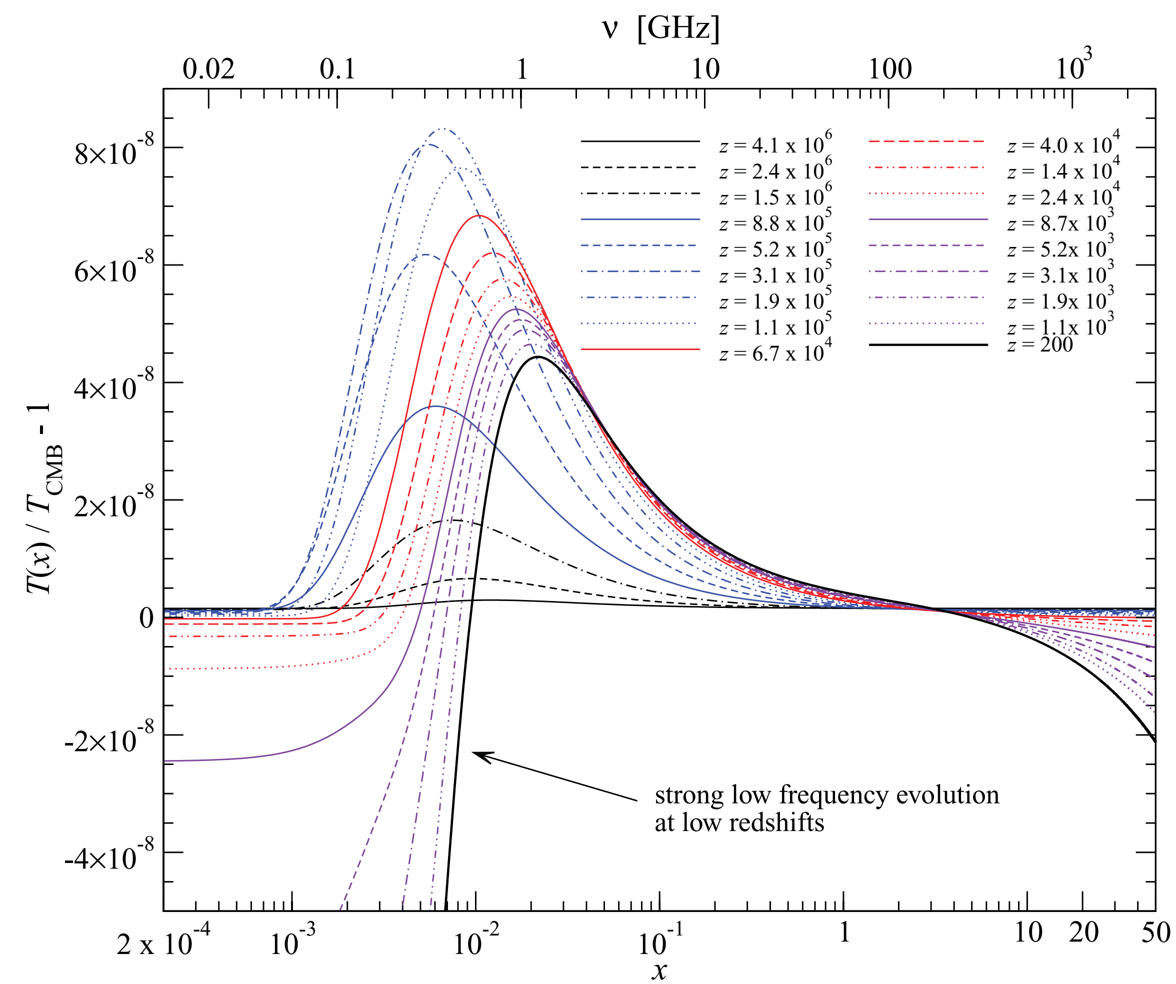
$$\tilde{\rho}_\gamma = \rho_\gamma/m_{\rm e}c^2 \qquad T_{\rm e}^{\rm eq} = T_\gamma\frac{\int x^4 f(1+f)\,{\rm d}x}{4\int x^3 f\,{\rm d}x} \equiv \frac{h}{k}\frac{\int \nu^4 f(1+f)\,{\rm d}\nu}{4\int \nu^3 f\,{\rm d}\nu}$$

CosmoTherm: a new flexible thermalization code

- Solve the thermalization problem for a *wide range* of energy release histories
- several scenarios already implemented *(decaying particles, damping of acoustic modes)*
- first explicit solution of time-dependent energy release scenarios
- open source code
- will be available at *www.Chluba.de/CosmoTherm/*
- Main reference: JC & Sunyaev, MNRAS, 2012 (arXiv:1109.6552)



Electron temperature evolution



Evolution of distortion

Example: *Energy release by decaying relict particle*

redshift

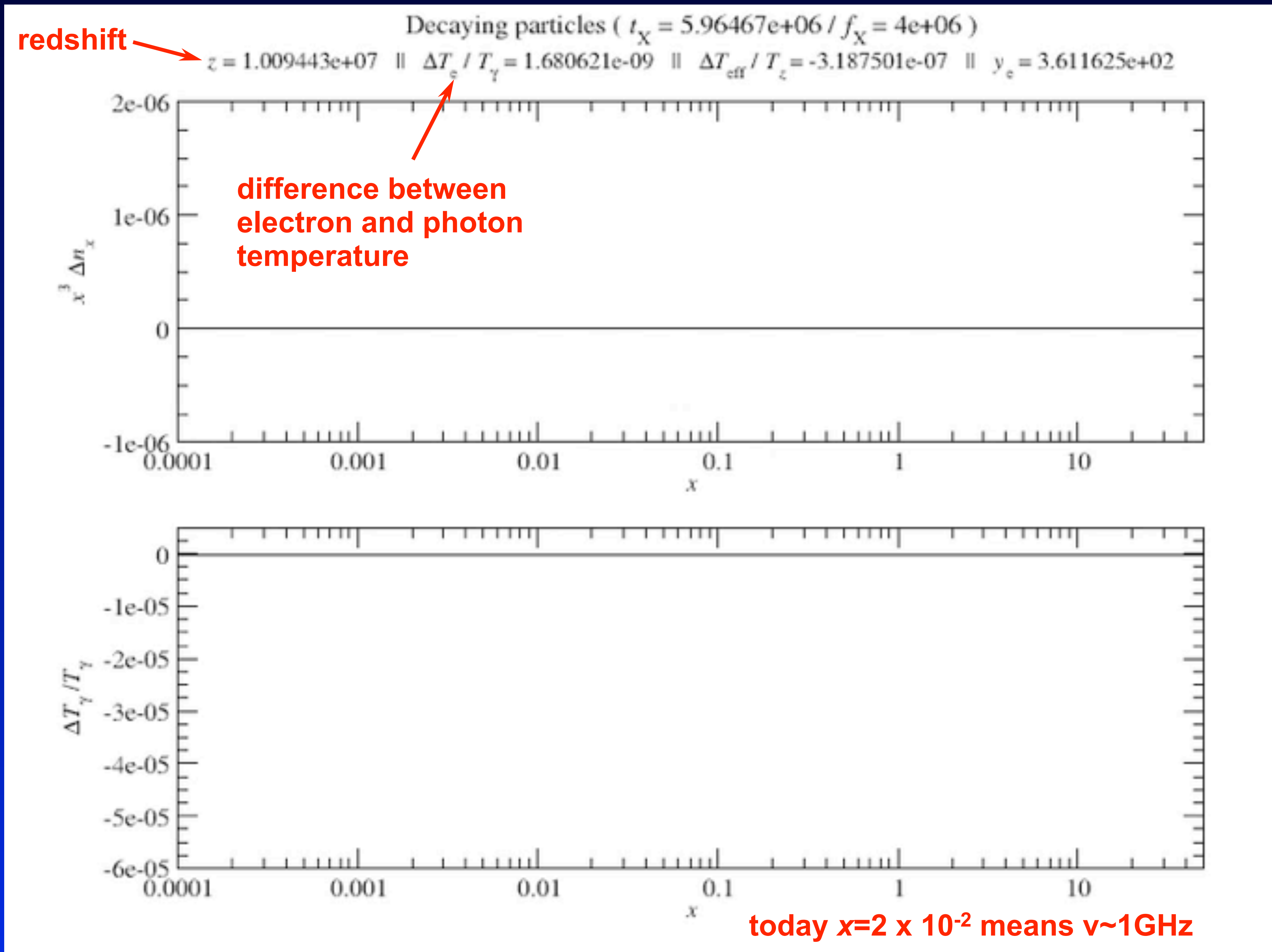
difference between electron and photon temperature

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

today x=2 x 10^{-2} means ν~1GHz

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

Example: *Energy release by decaying relict particle*



- initial condition: *full equilibrium*
- total energy release:

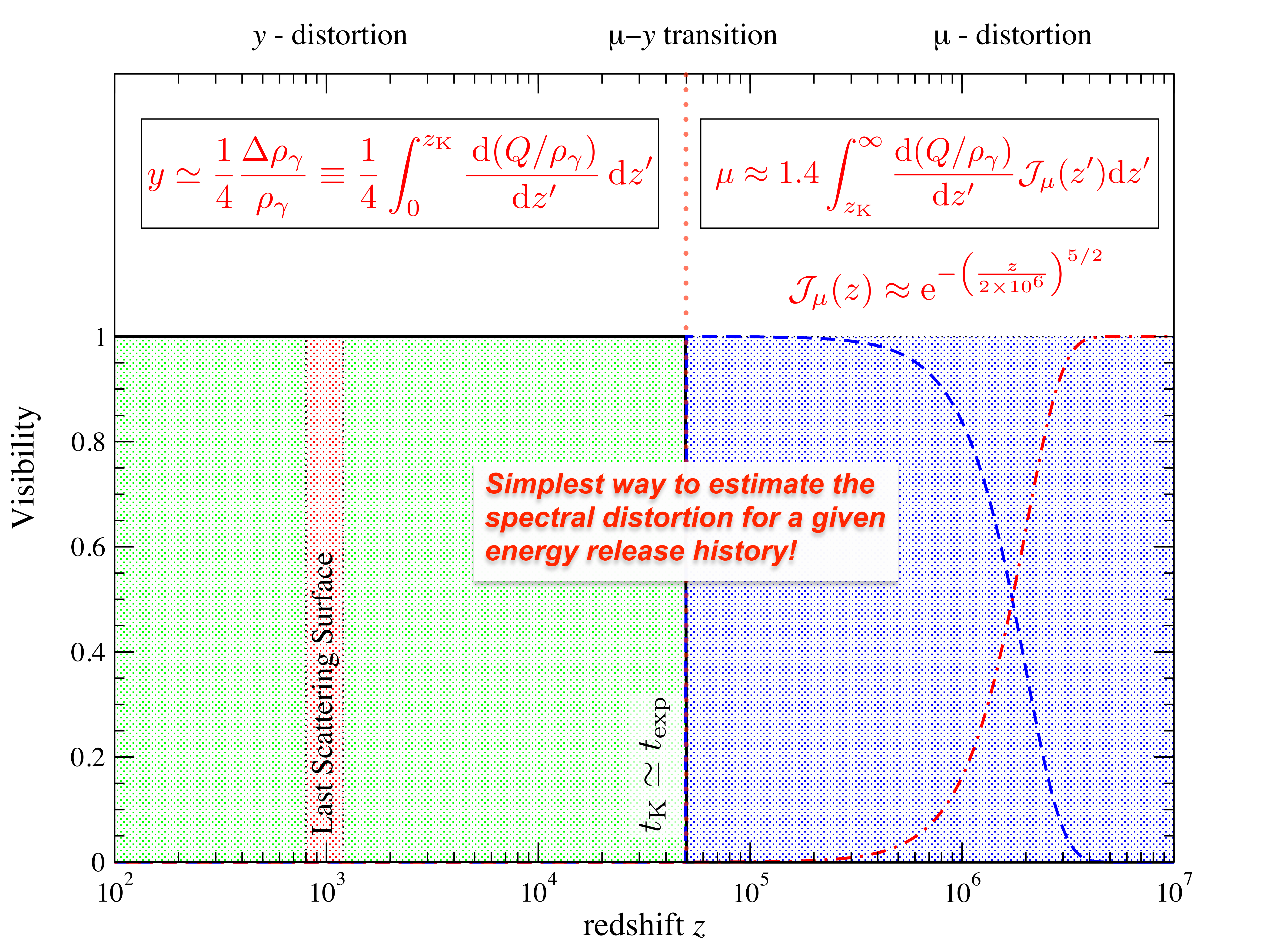
  $\Delta\rho/\rho \sim 1.3 \times 10^{-6}$
- most of energy release around:

  $z_X \sim 2 \times 10^6$
- positive μ-distortion
- high frequency distortion frozen around $z \simeq 5 \times 10^5$
- late ($z < 10^3$) free-free absorption at very low frequencies ($T_e < T_\gamma$)

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

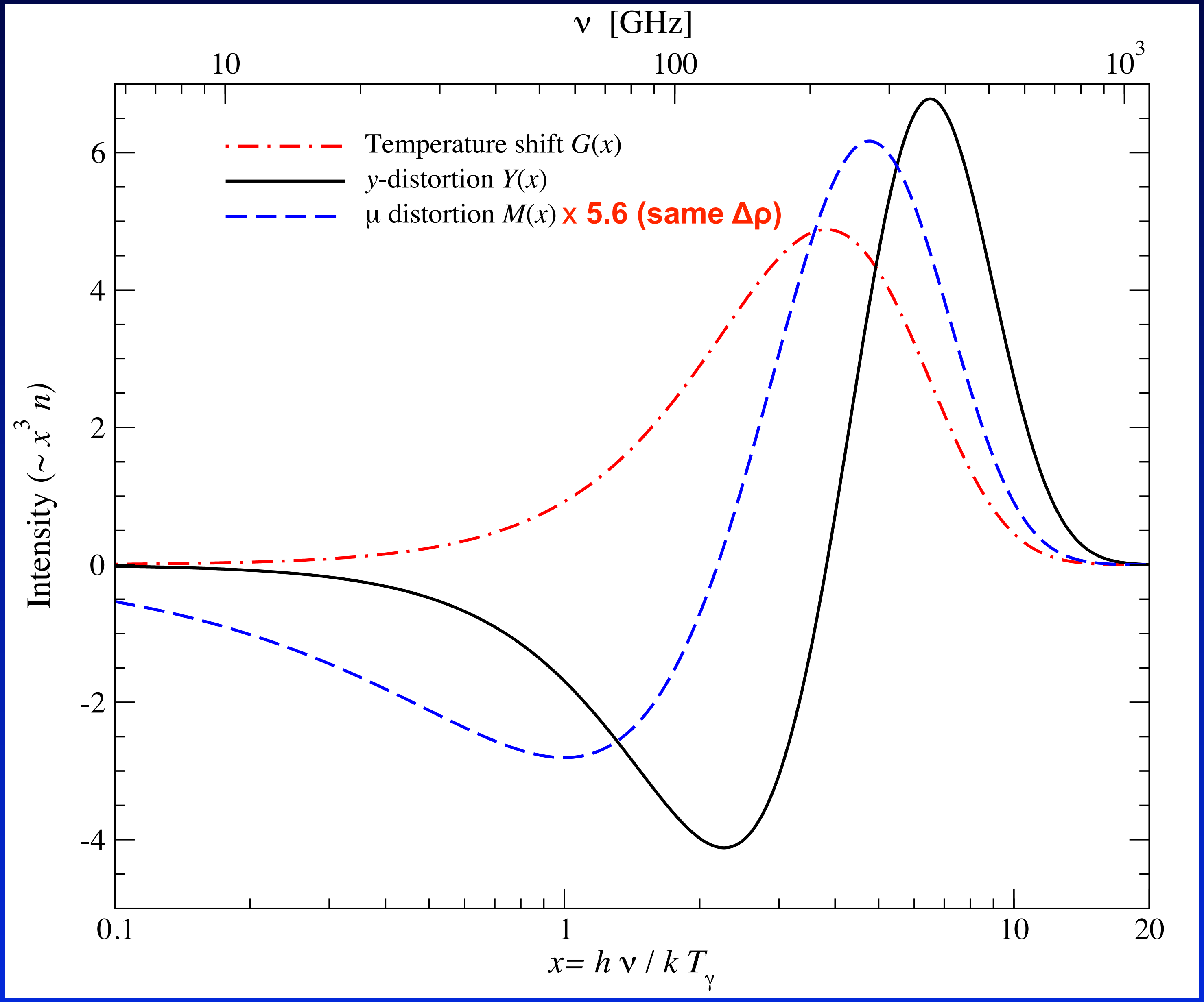
What about the μ-y transition regime?

Is the transition really as abrupt?

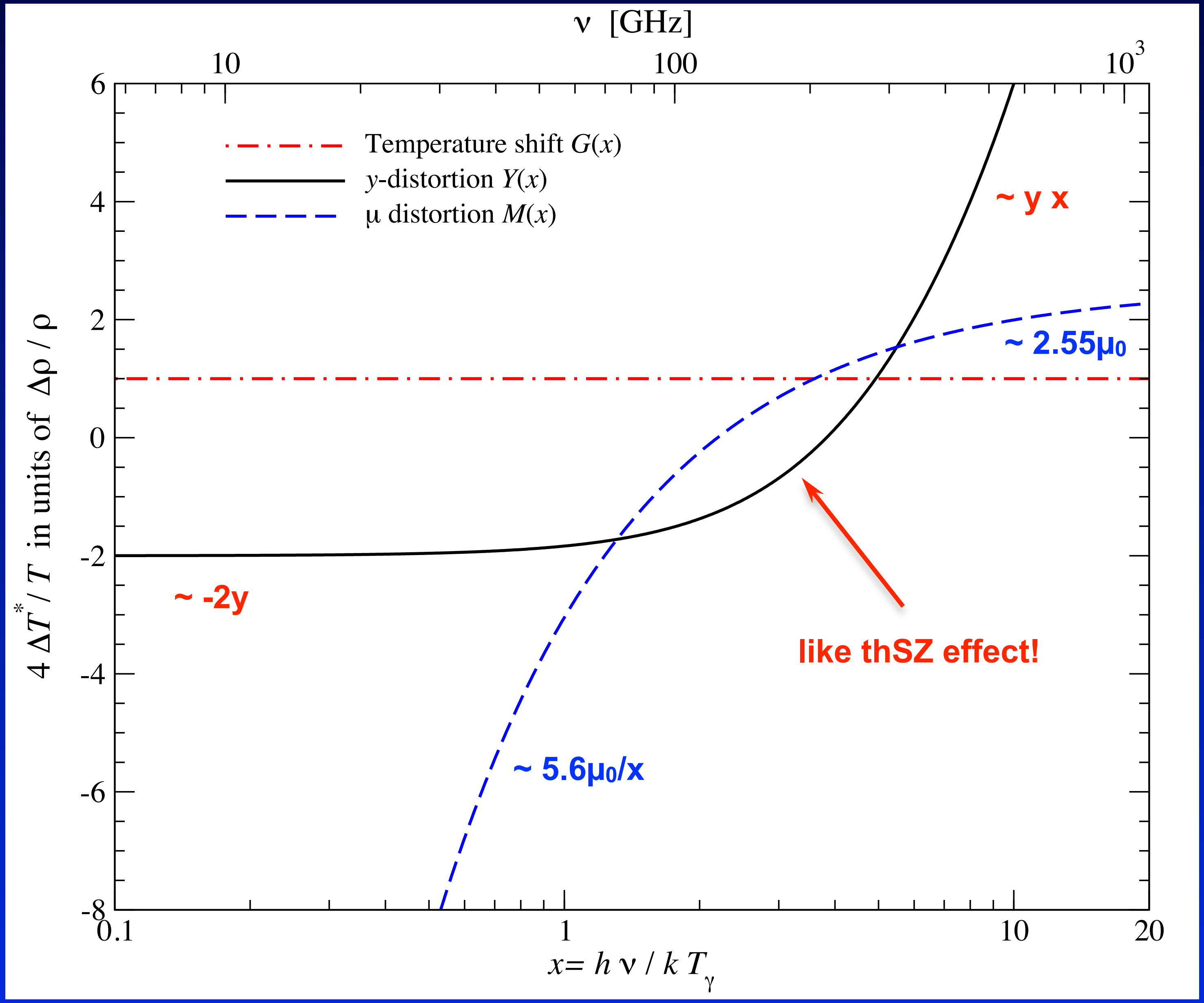


y - distortion
μ–y transition
μ - distortion
$y \simeq \frac{1}{4}\frac{\Delta\rho_\gamma}{\rho_\gamma} \equiv \frac{1}{4}\int_0^{z_{\rm K}} \frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'}\,{\rm d}z'$
$\mu \approx 1.4 \int_{z_{\rm K}}^{\infty} \frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'}\,\mathcal{J}_\mu(z')\,{\rm d}z'$
$\mathcal{J}_\mu(z) \approx {\rm e}^{-\left(\frac{z}{2\times10^6}\right)^{5/2}}$
Simplest way to estimate the spectral distortion for a given energy release history!
Last Scattering Surface
$t_{\rm K} \simeq t_{\rm exp}$
Visibility
redshift z

Temperature shift ↔ y-distortion ↔ μ-distortion



Temperature shift ↔ y-distortion ↔ μ-distortion



Same as before but as effective temperature

$$\frac{\Delta T^*}{T} \approx \frac{\Delta n(x)}{G(x)}$$

Transition from y-distortion → μ-distortion

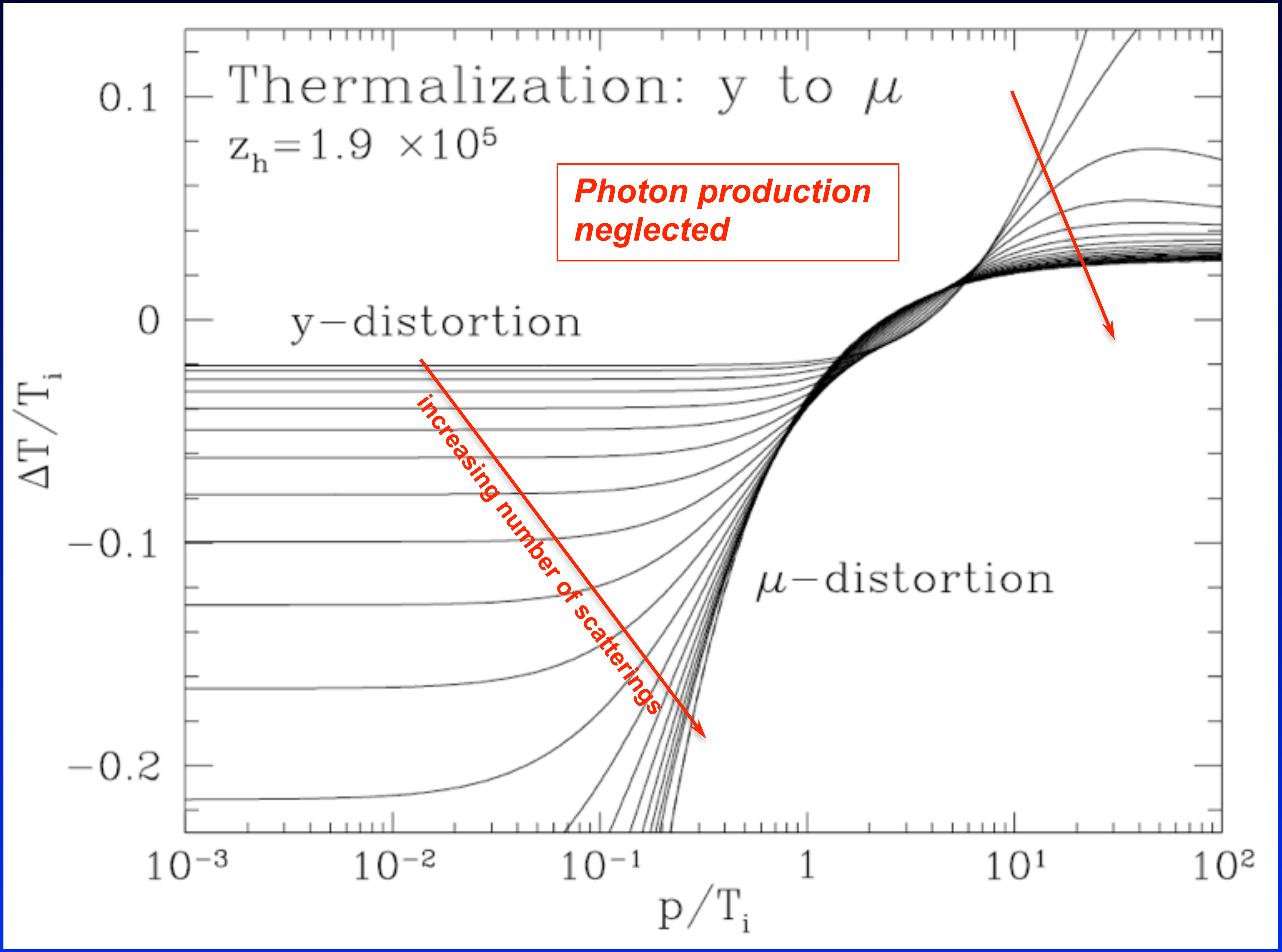


Figure from Wayne Hu's PhD thesis, 1995, but see also discussion in Burigana, 1991

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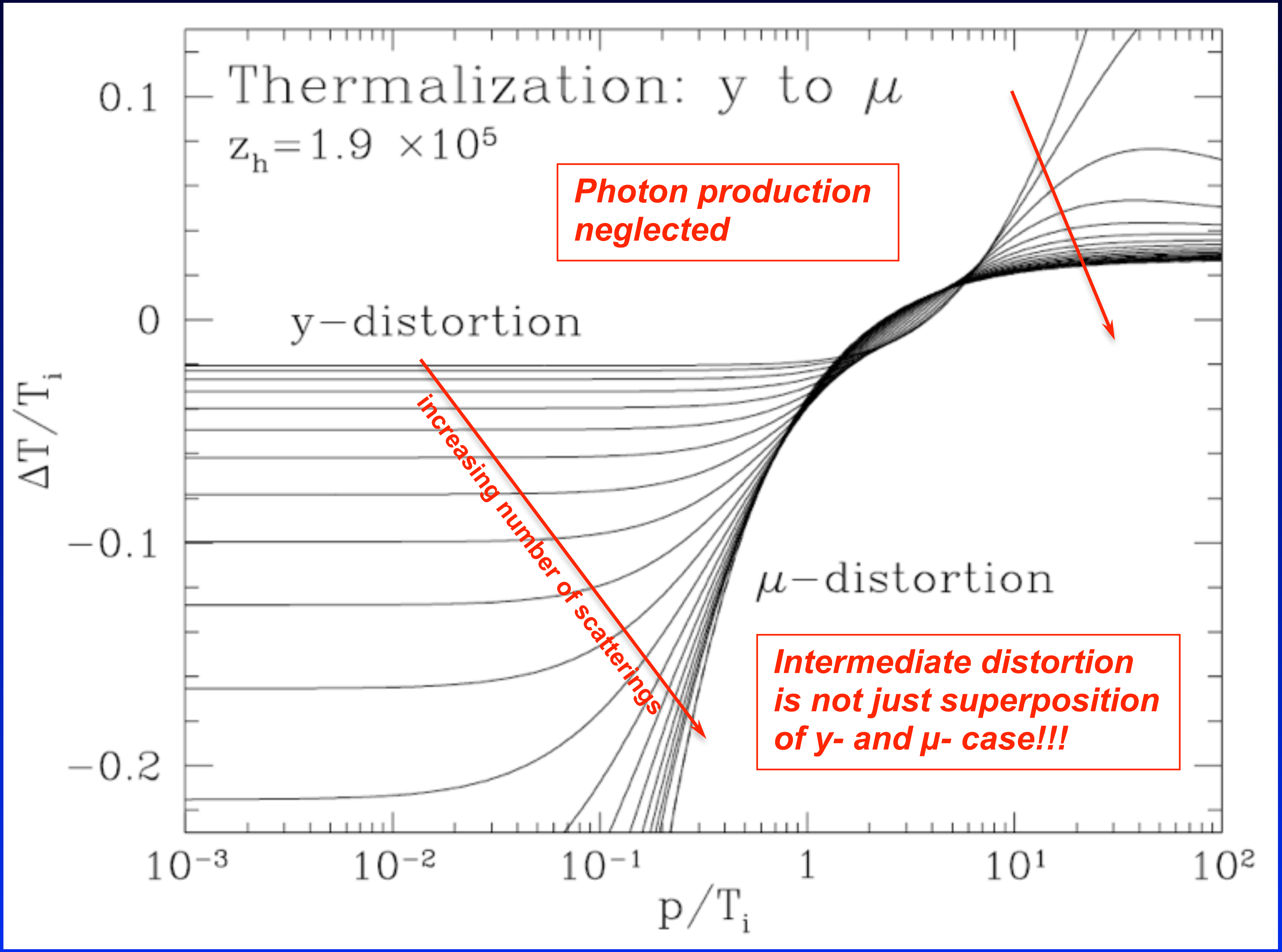
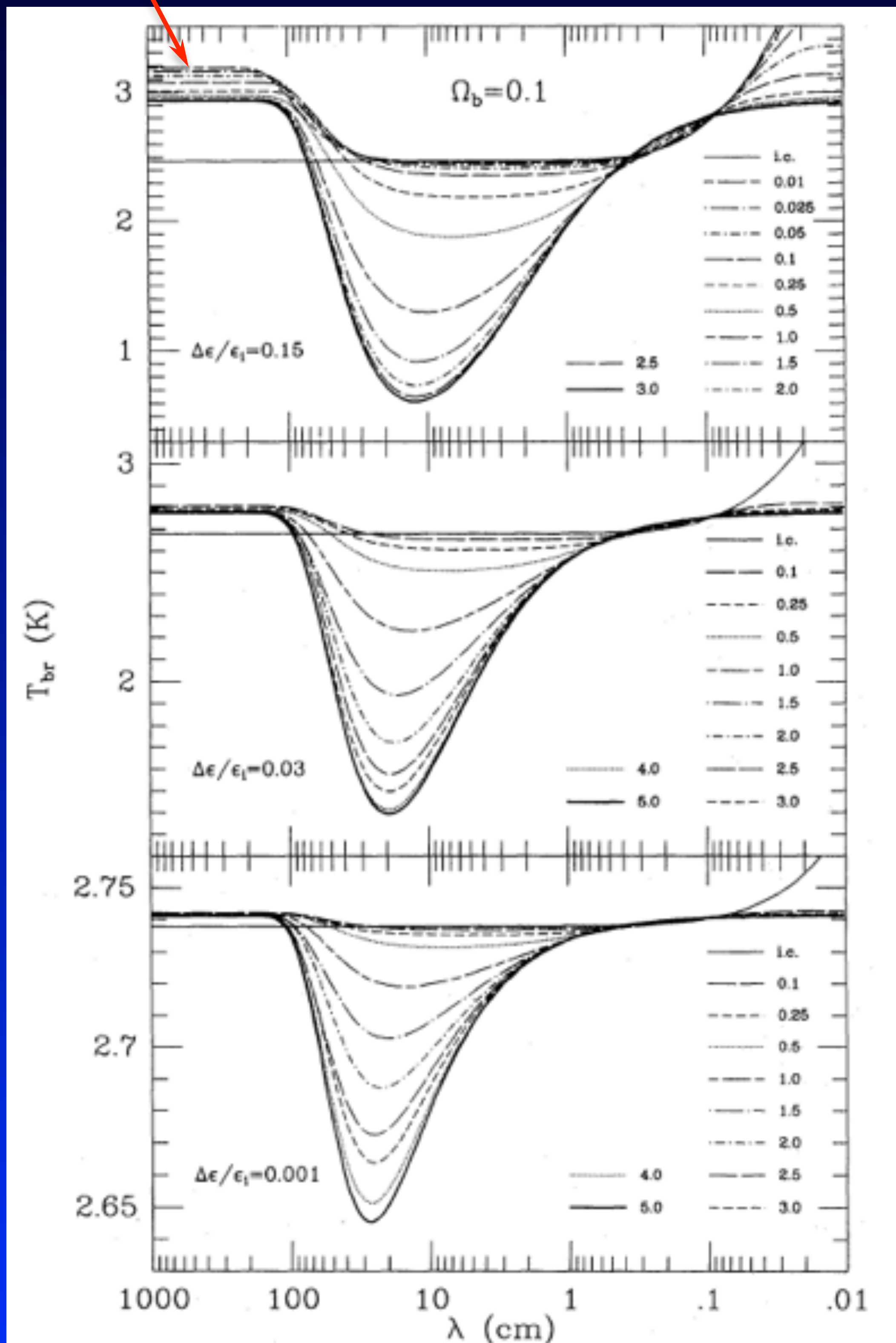


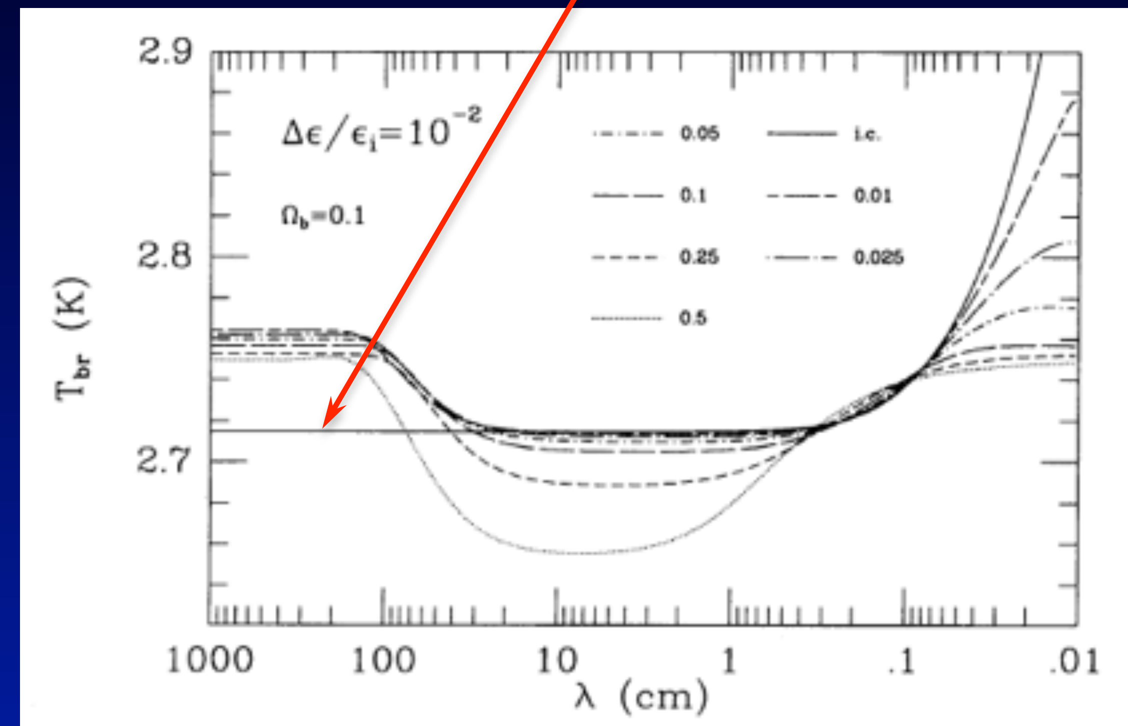
Figure from Wayne Hu's PhD thesis, 1995, but see also discussion in Burigana, 1991

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'

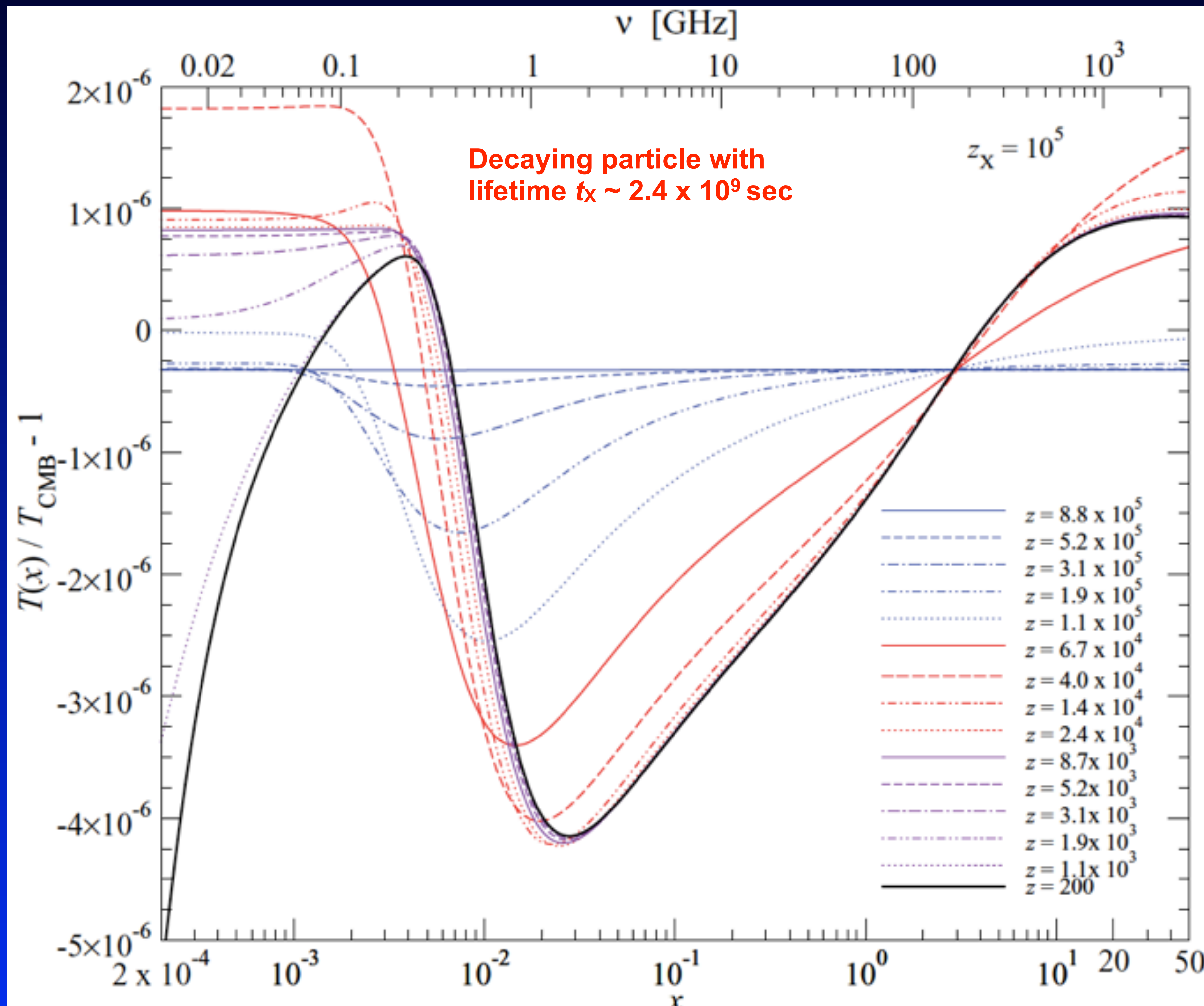
- Intermediate case ($3 \times 10^5 \geq z \geq 10000$)

  ⇒ mixture 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!



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

- First explicit calculation that showed that there is more!

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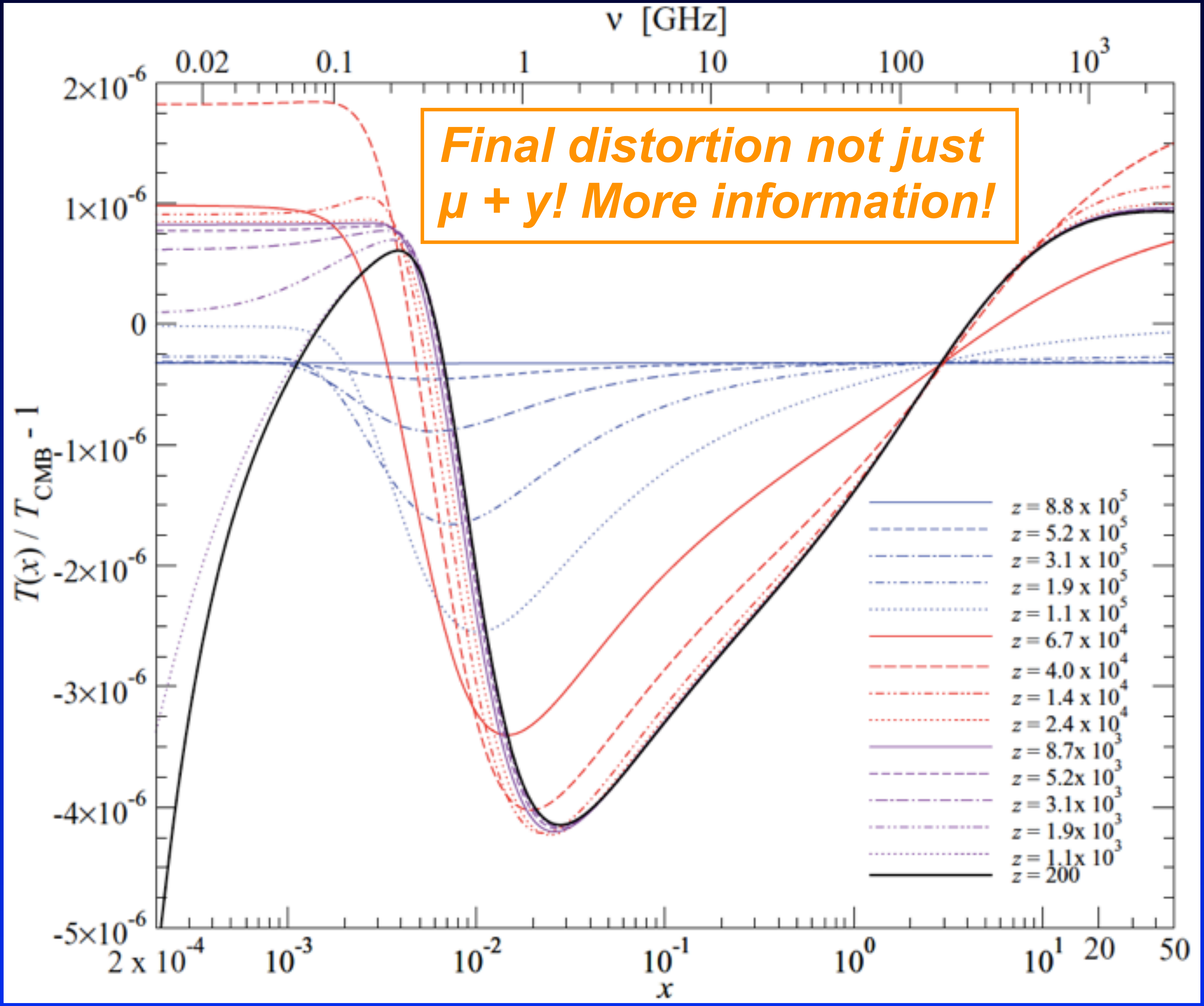

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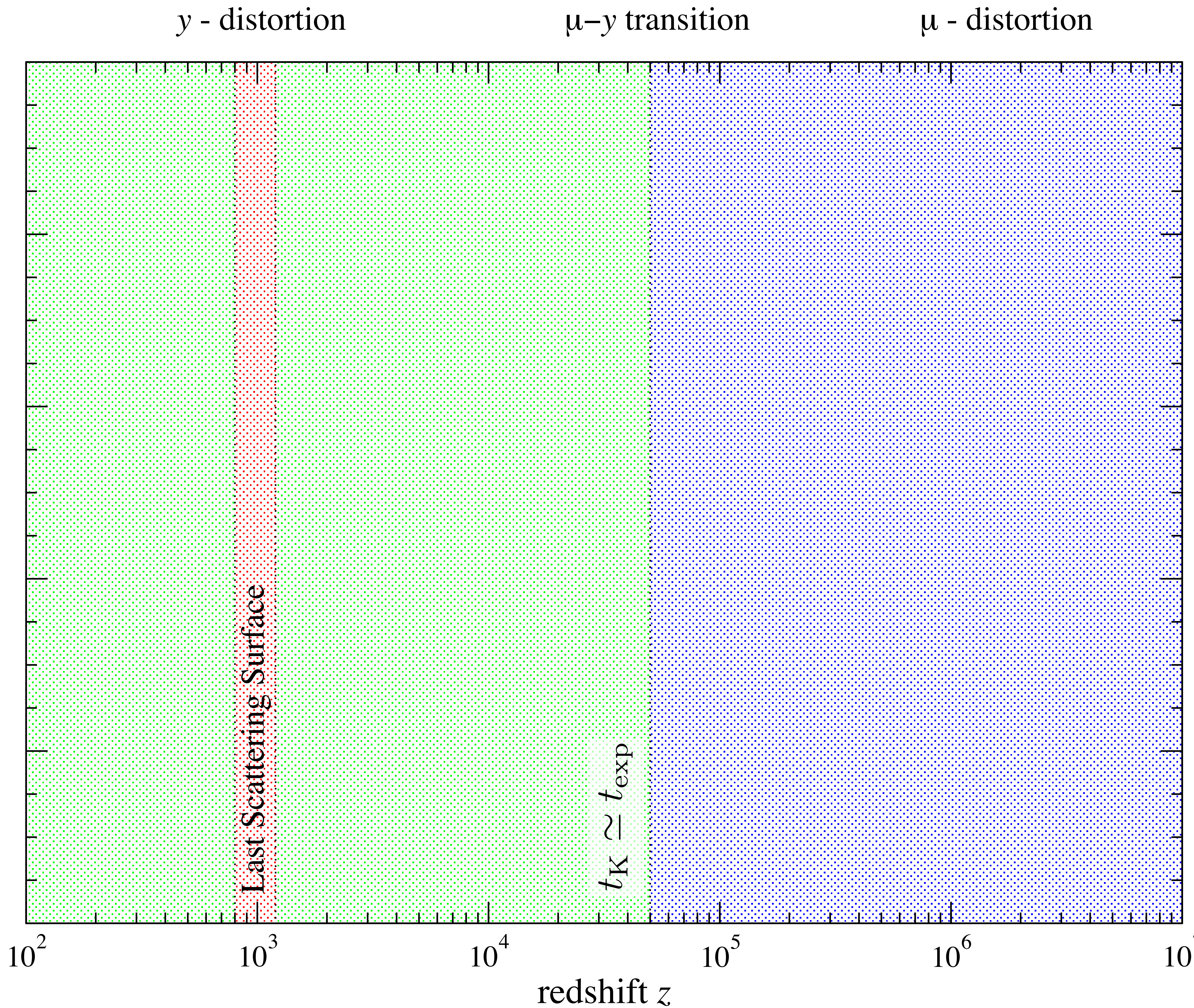
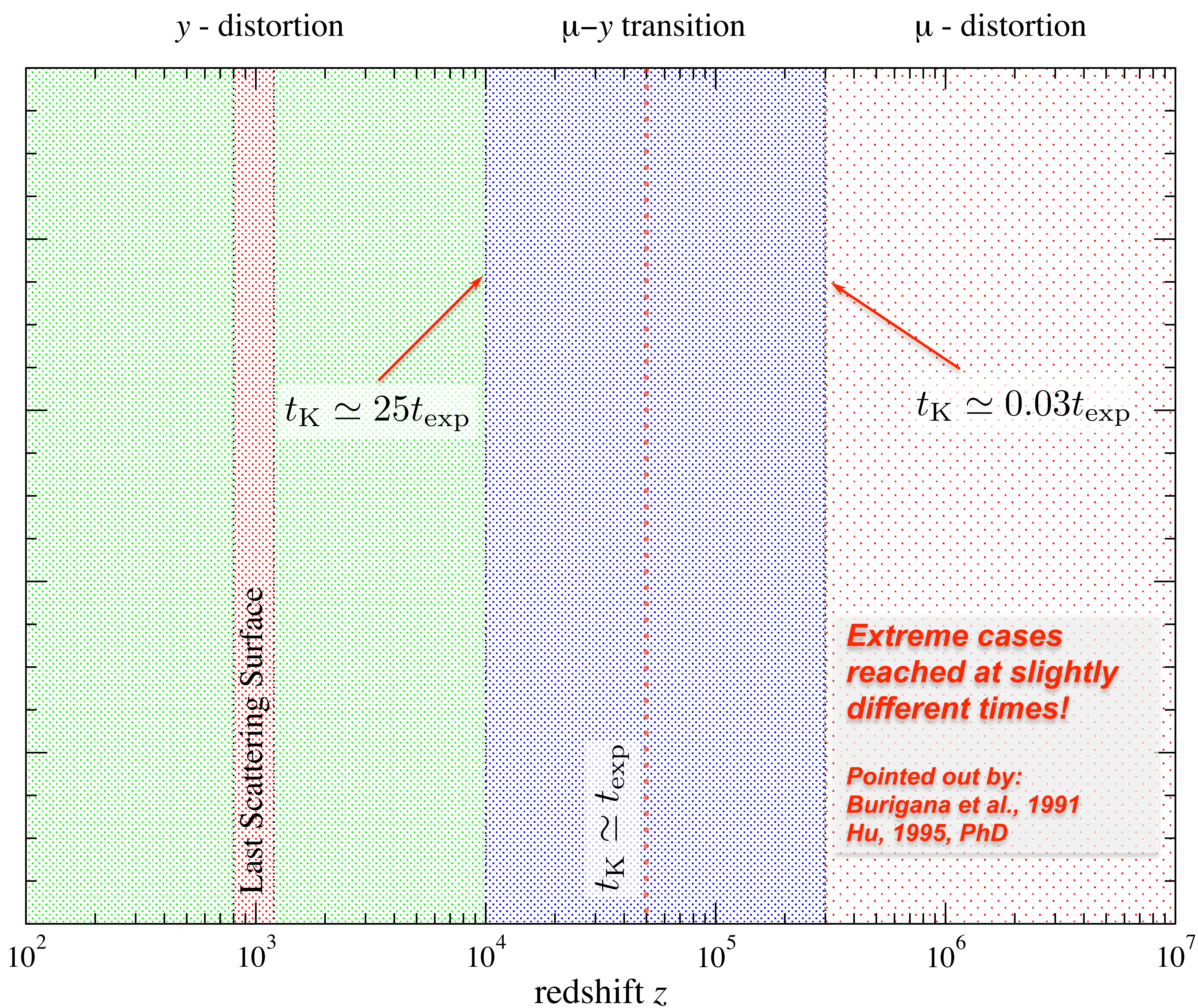
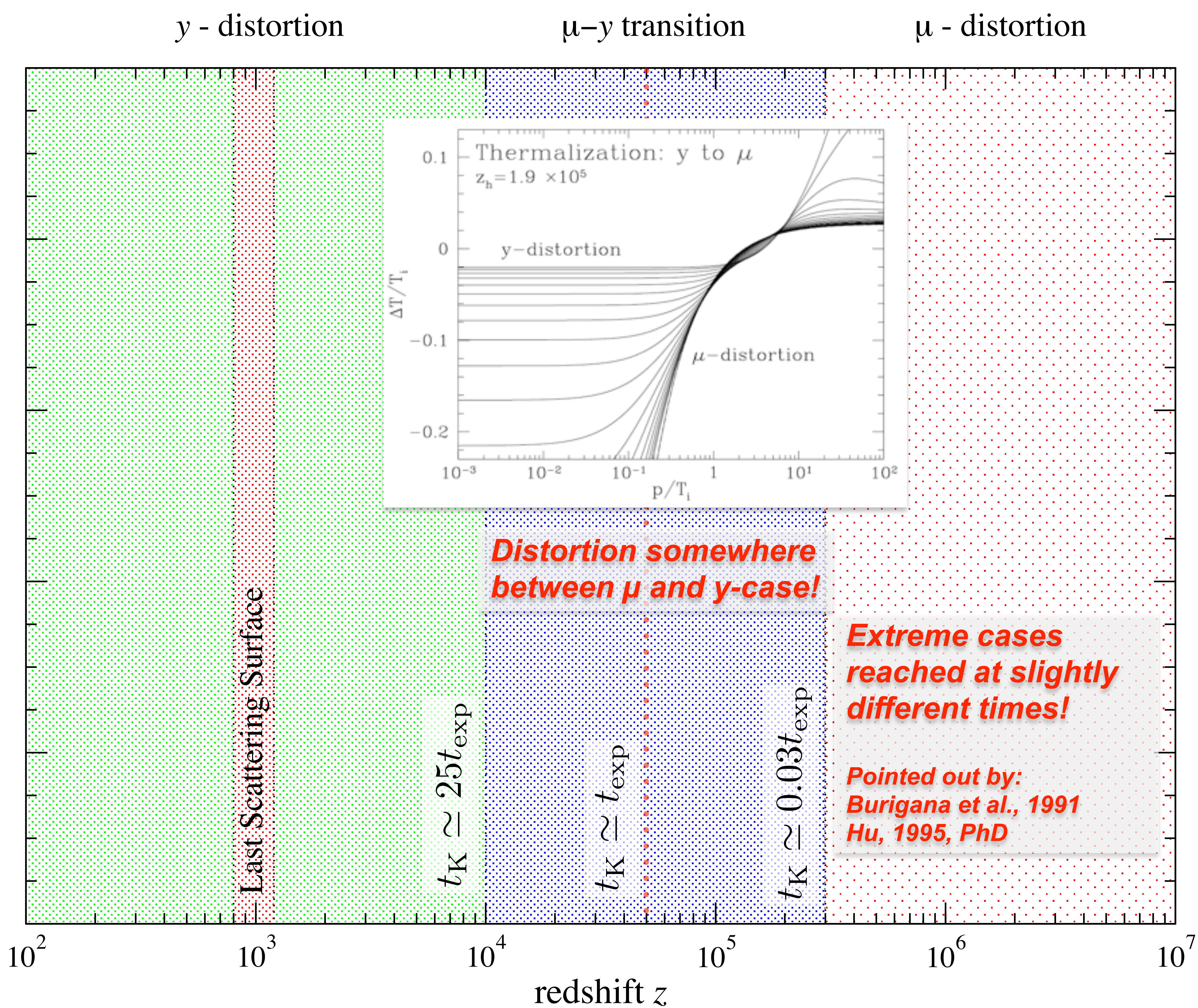


y - distortion
μ–y transition
μ - distortion
Last Scattering Surface
$t_{\rm K} \simeq t_{\rm exp}$
10^2
10^3
10^4
10^5
10^6
10^7
redshift z



y - distortion
μ–y transition
μ - distortion
$t_{\rm K} \simeq 25 t_{\rm exp}$
$t_{\rm K} \simeq 0.03 t_{\rm exp}$
$t_{\rm K} \simeq t_{\rm exp}$
Last Scattering Surface
Extreme cases reached at slightly different times!
Pointed out by:
Burigana et al., 1991
Hu, 1995, PhD
10^2 10^3 10^4 10^5 10^6 10^7
redshift z



y - distortion
μ–y transition
μ - distortion
Thermalization: y to μ
z_h=1.9 ×10^5
y−distortion
μ−distortion
ΔT/T_i
p/T_i
Distortion somewhere between μ and y-case!
Extreme cases reached at slightly different times!
Pointed out by:
Burigana et al., 1991
Hu, 1995, PhD
Last Scattering Surface
t_K ≃ 25t_exp
t_K ≃ t_exp
t_K ≃ 0.03t_exp
redshift z

How can we include this efficiently into the picture?

Quasi-Exact Treatment: Thermalization Green’s Function

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

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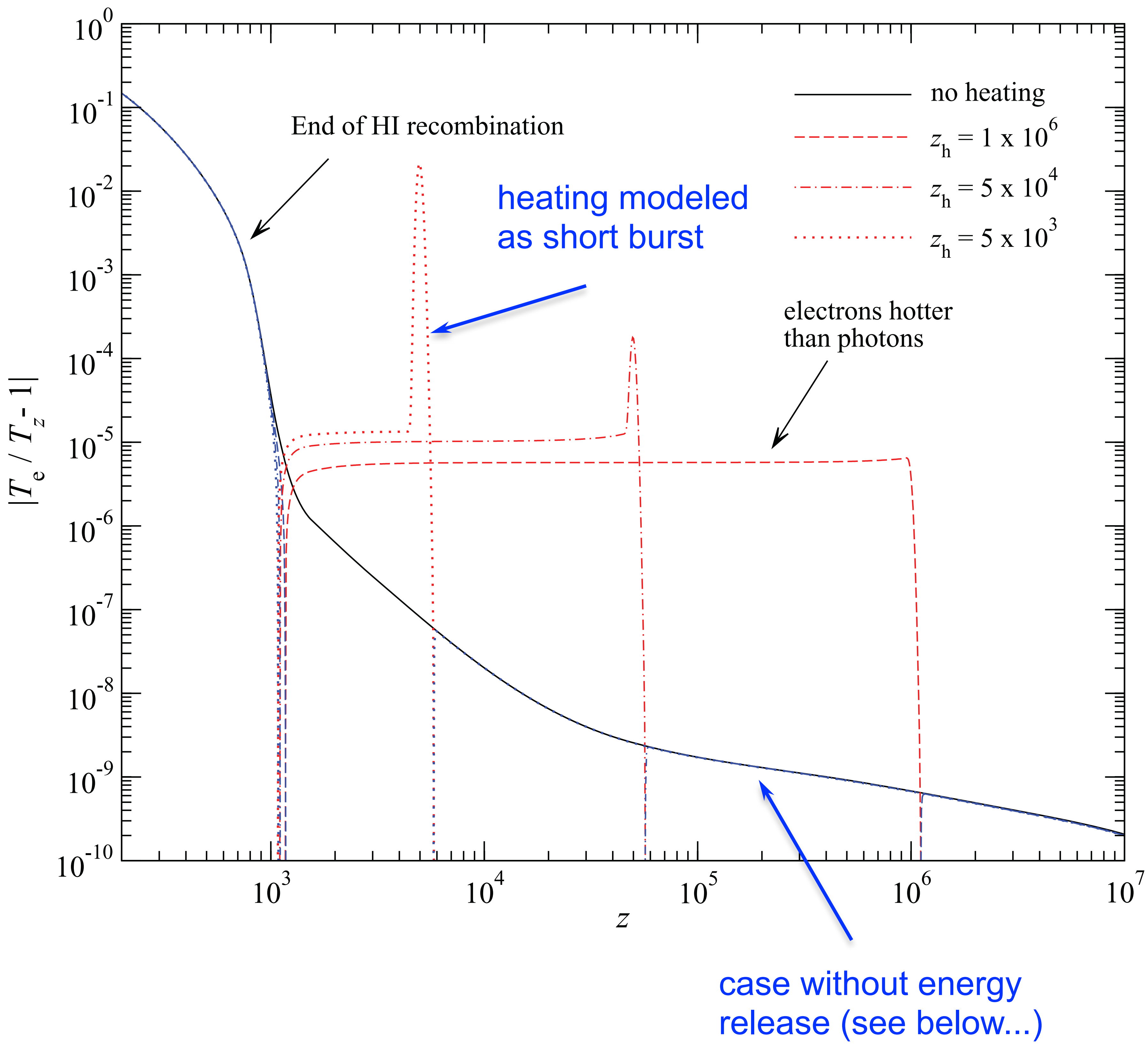
Thermalization Green's function

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

Electron temperature evolution for single energy release



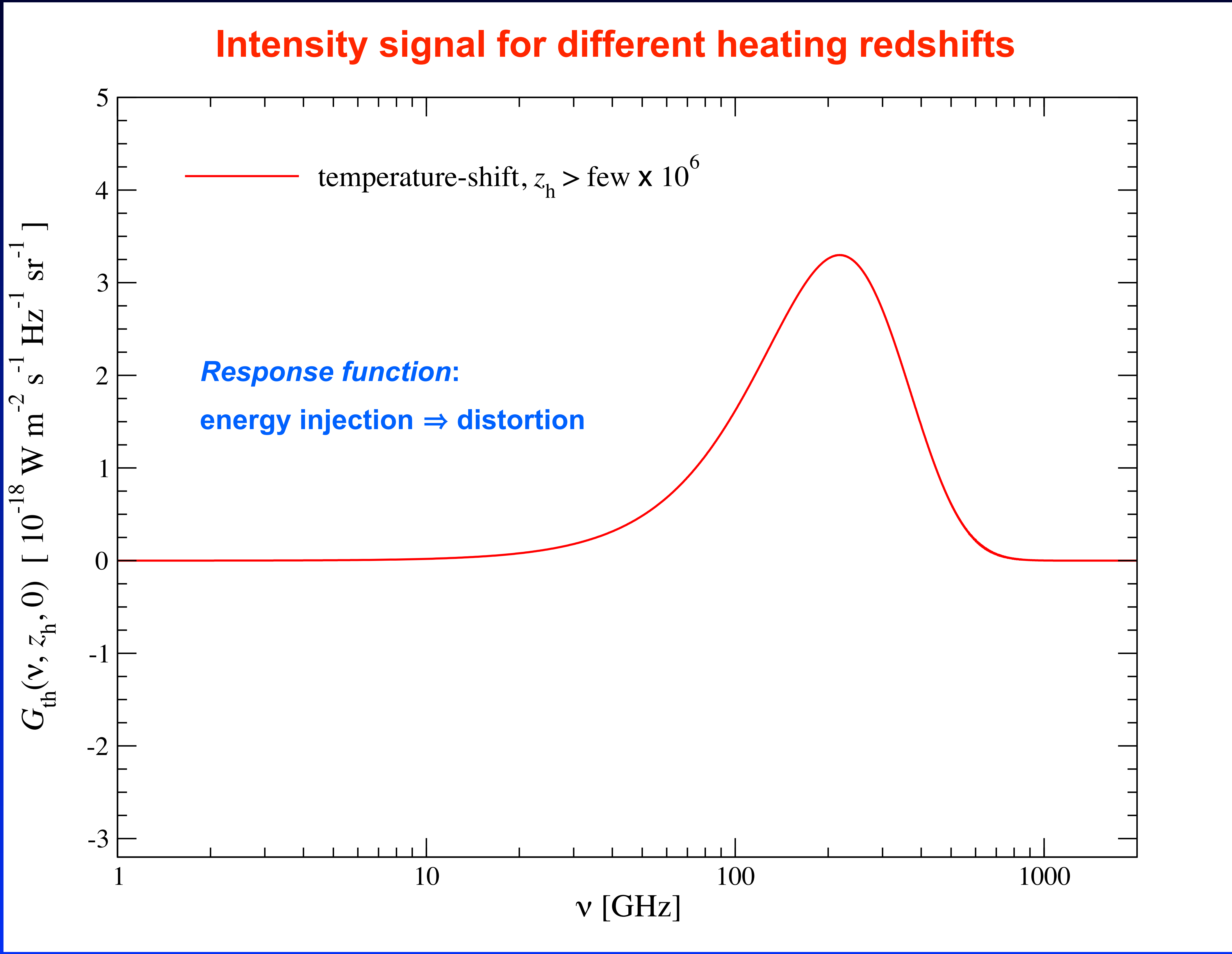
- injected energy

$$\frac{\Delta\rho_\gamma}{\rho_\gamma} = 10^{-5}$$

- need to worry about 'width' of burst
- explicitly done with *CosmoTherm*

JC & Sunyaev, 2012

What does the spectrum look like after energy injection?



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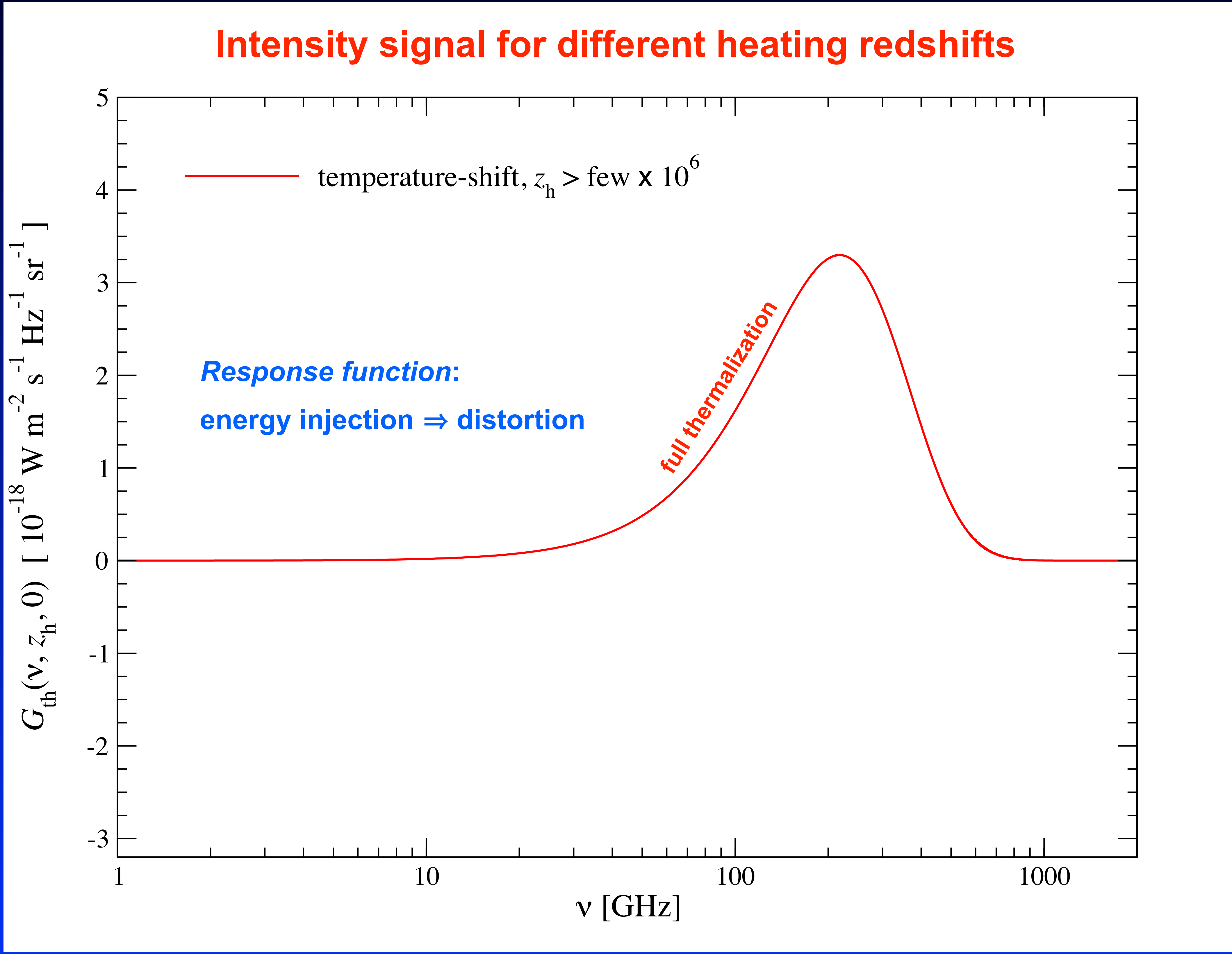

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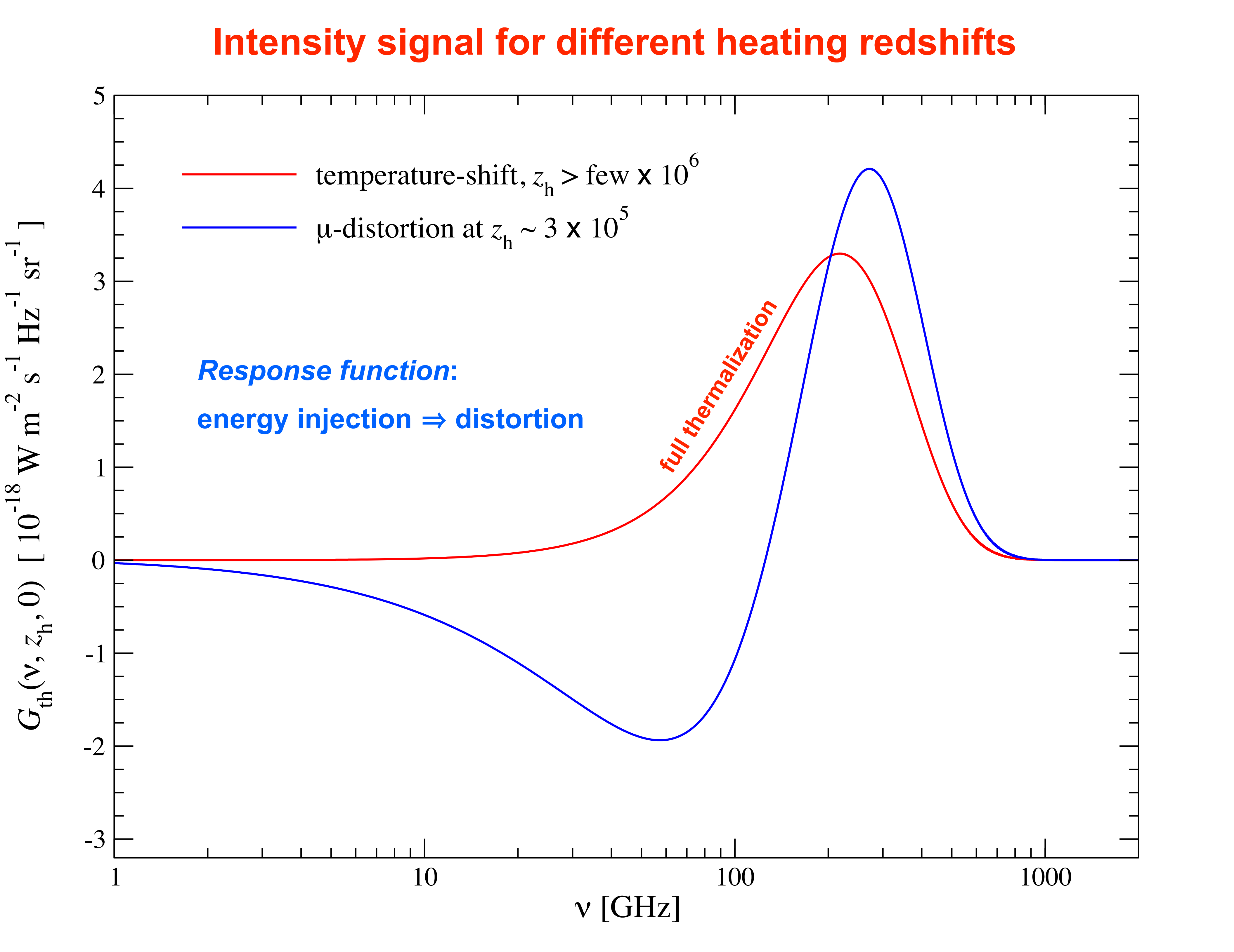

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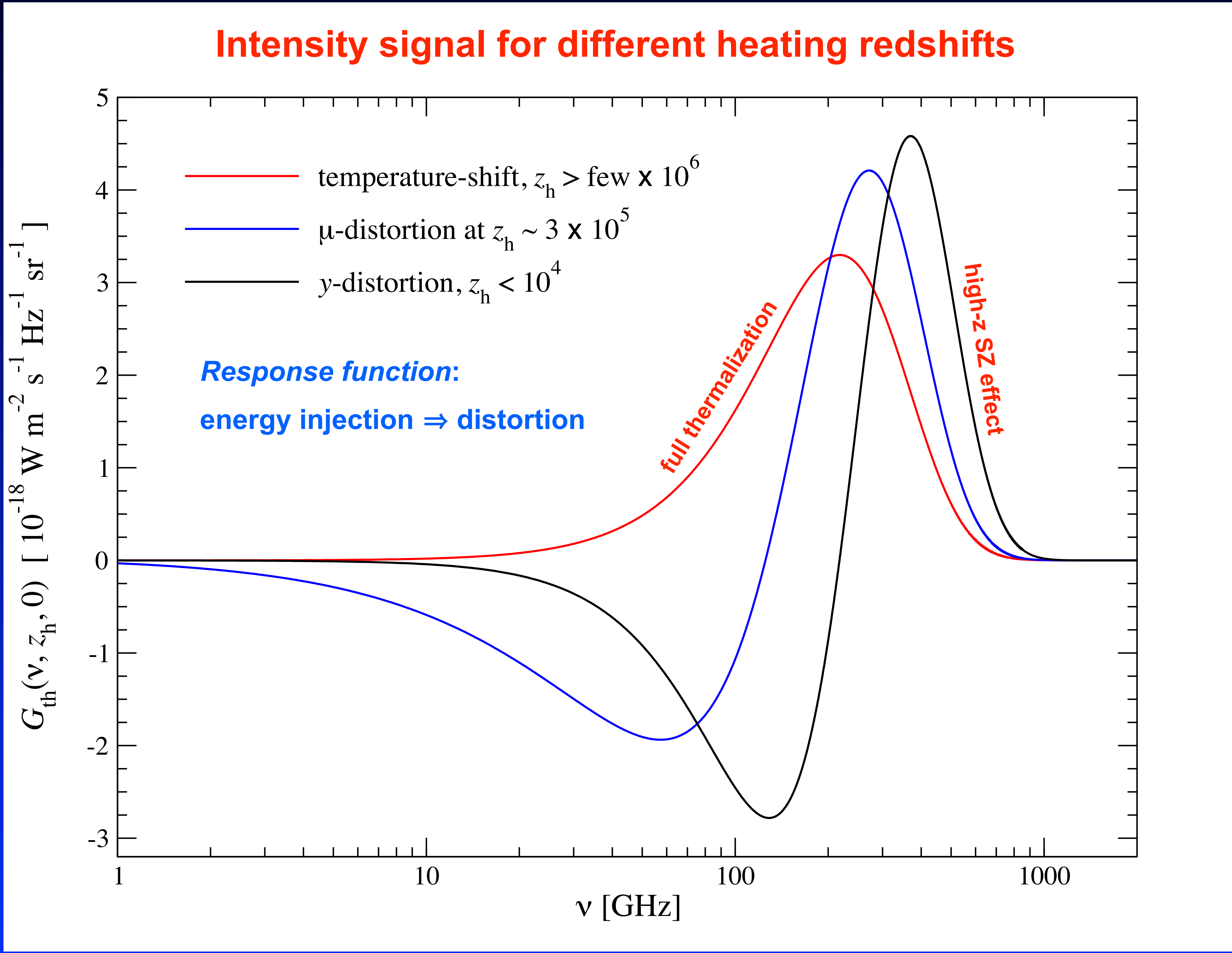

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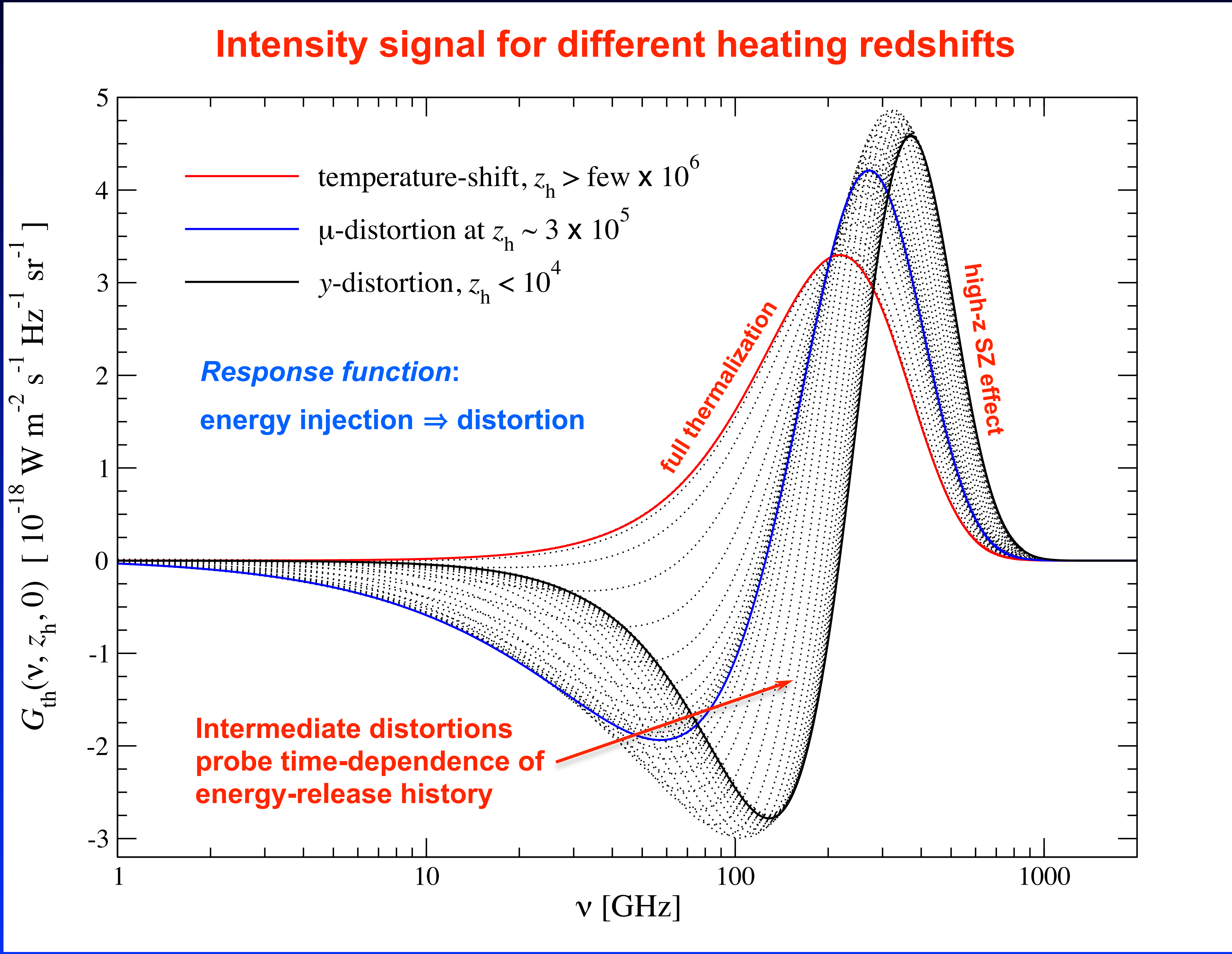

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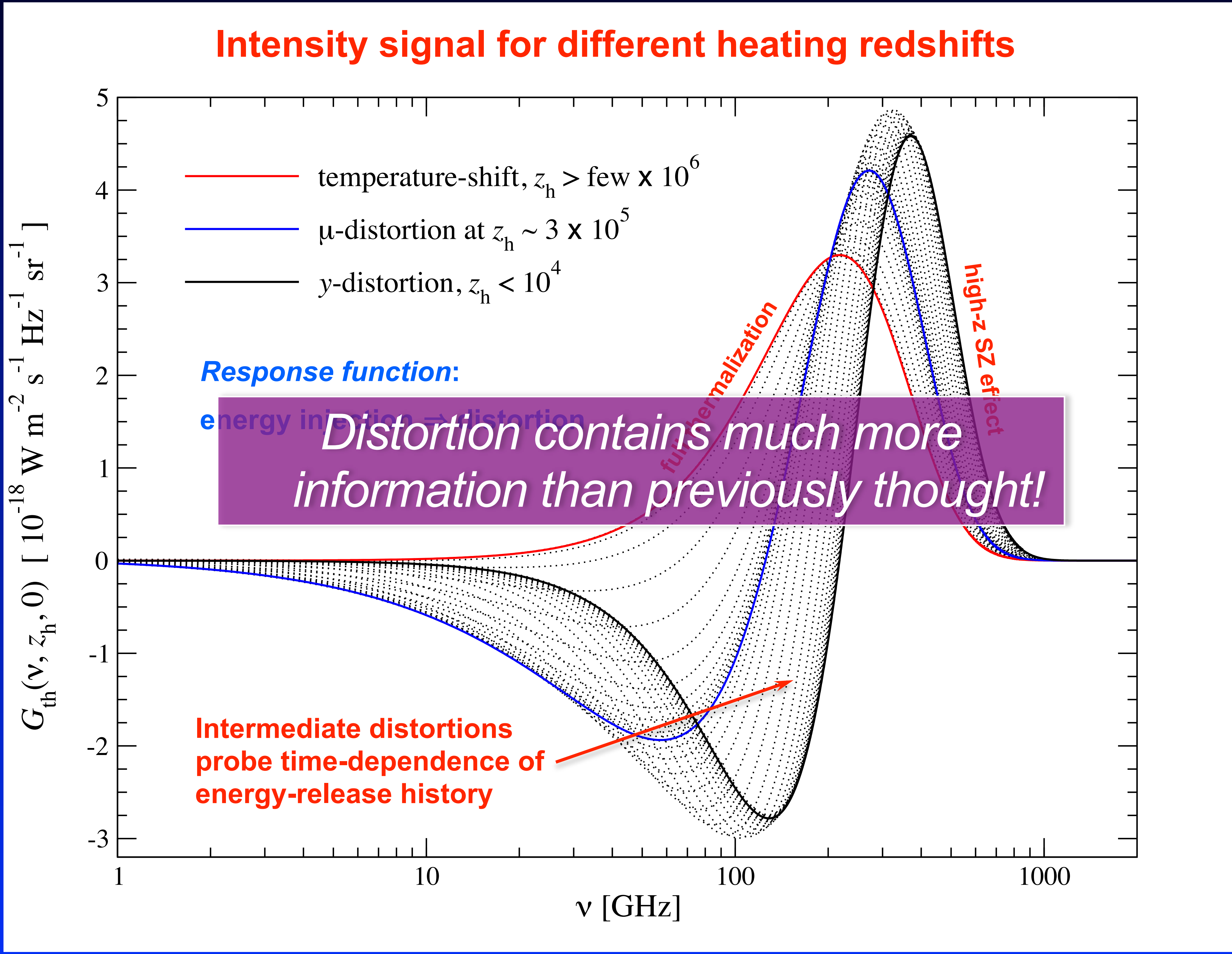
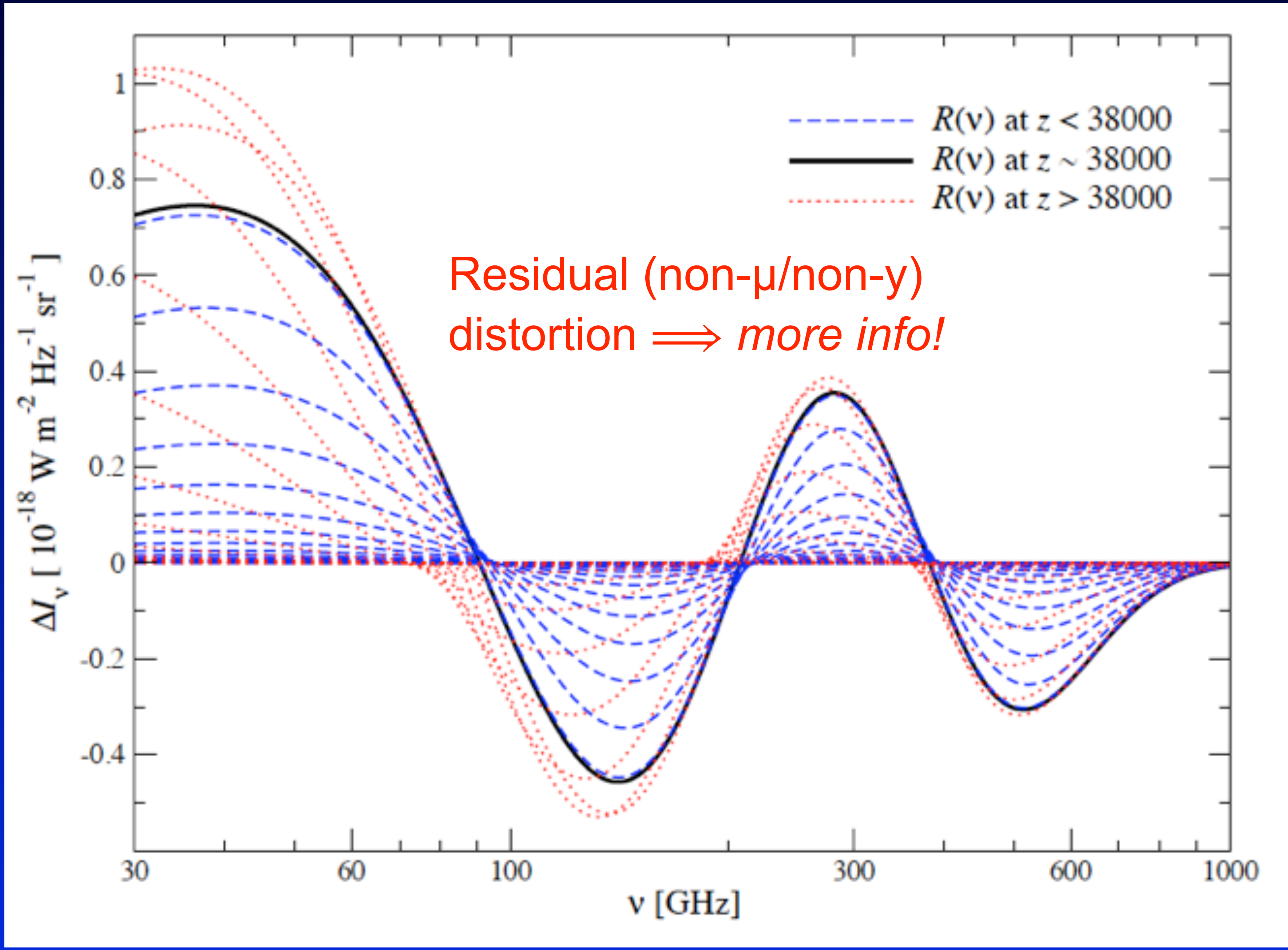


JC & Sunyaev, 2012, ArXiv:1109.6552
JC, 2013, ArXiv:1304.6120

Explicitly taking out the superposition of μ & y distortion

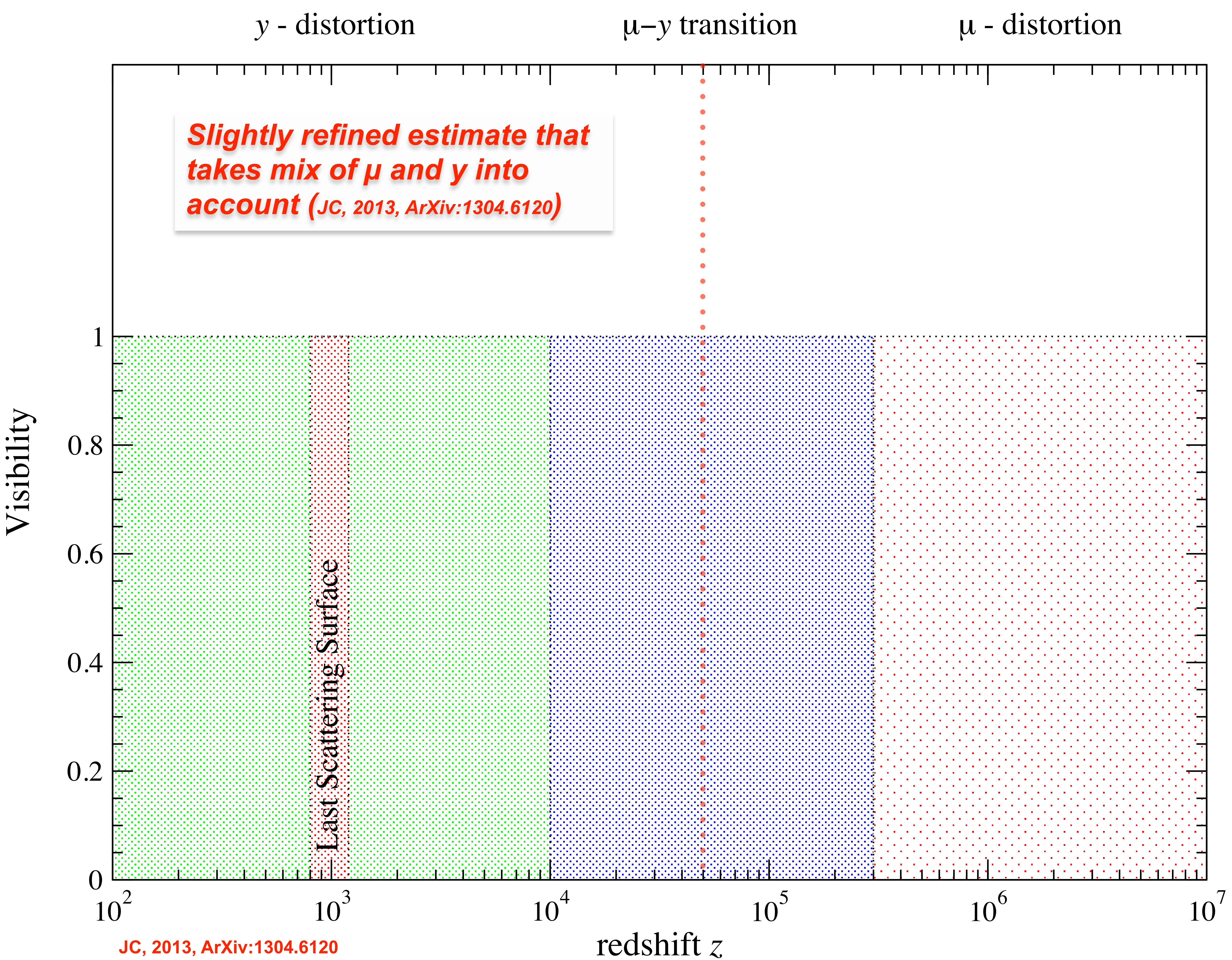


- *Allows us to distinguish different energy release scenarios!*

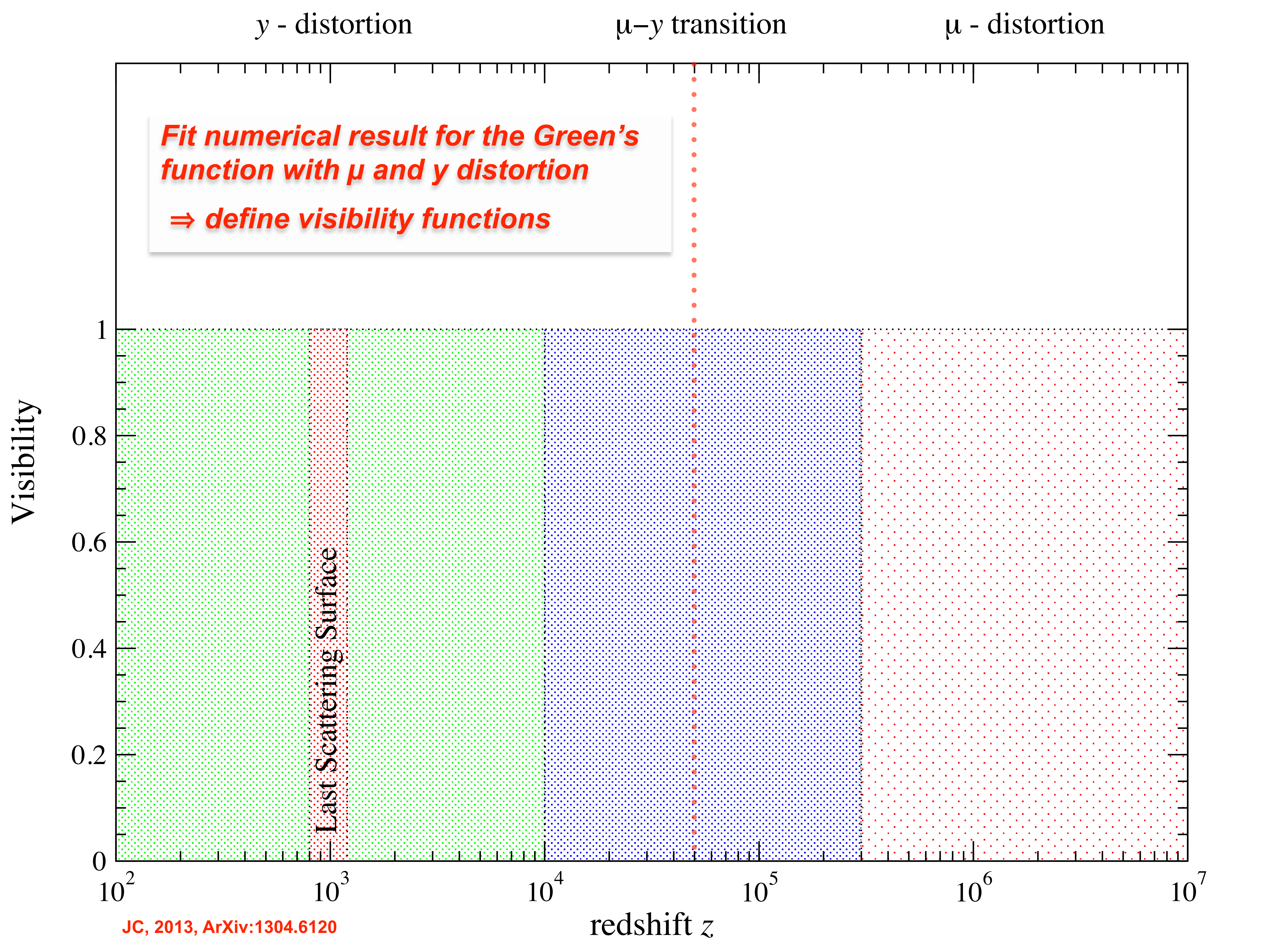
JC & Sunyaev, 2012, ArXiv:1109.6552
JC, 2013, ArXiv:1304.6120; JC, 2013, ArXiv:1304.6121; JC & Jeong, 2013

Approximate modeling of the μ - y transition

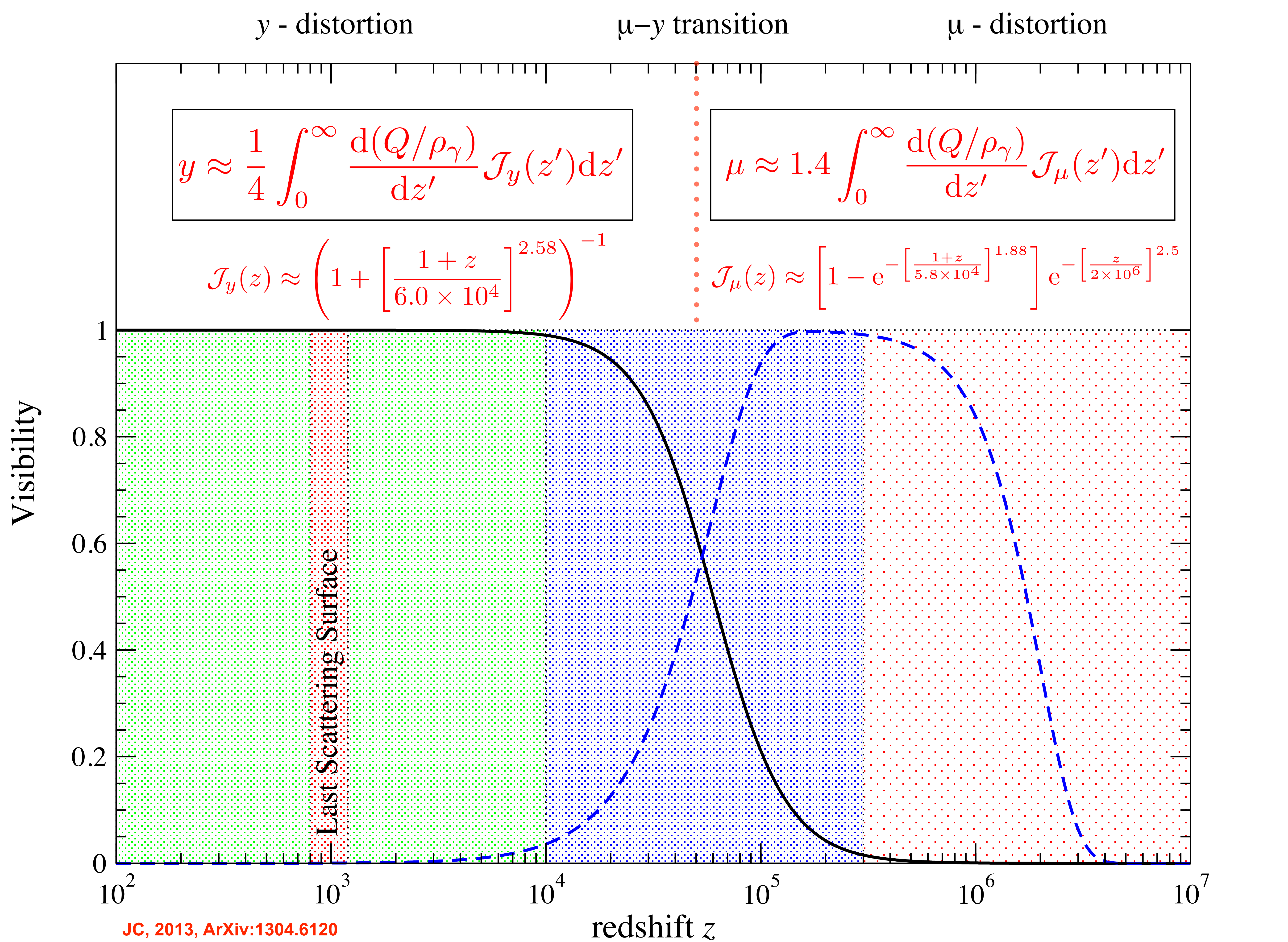
(without the residual distortion though...)



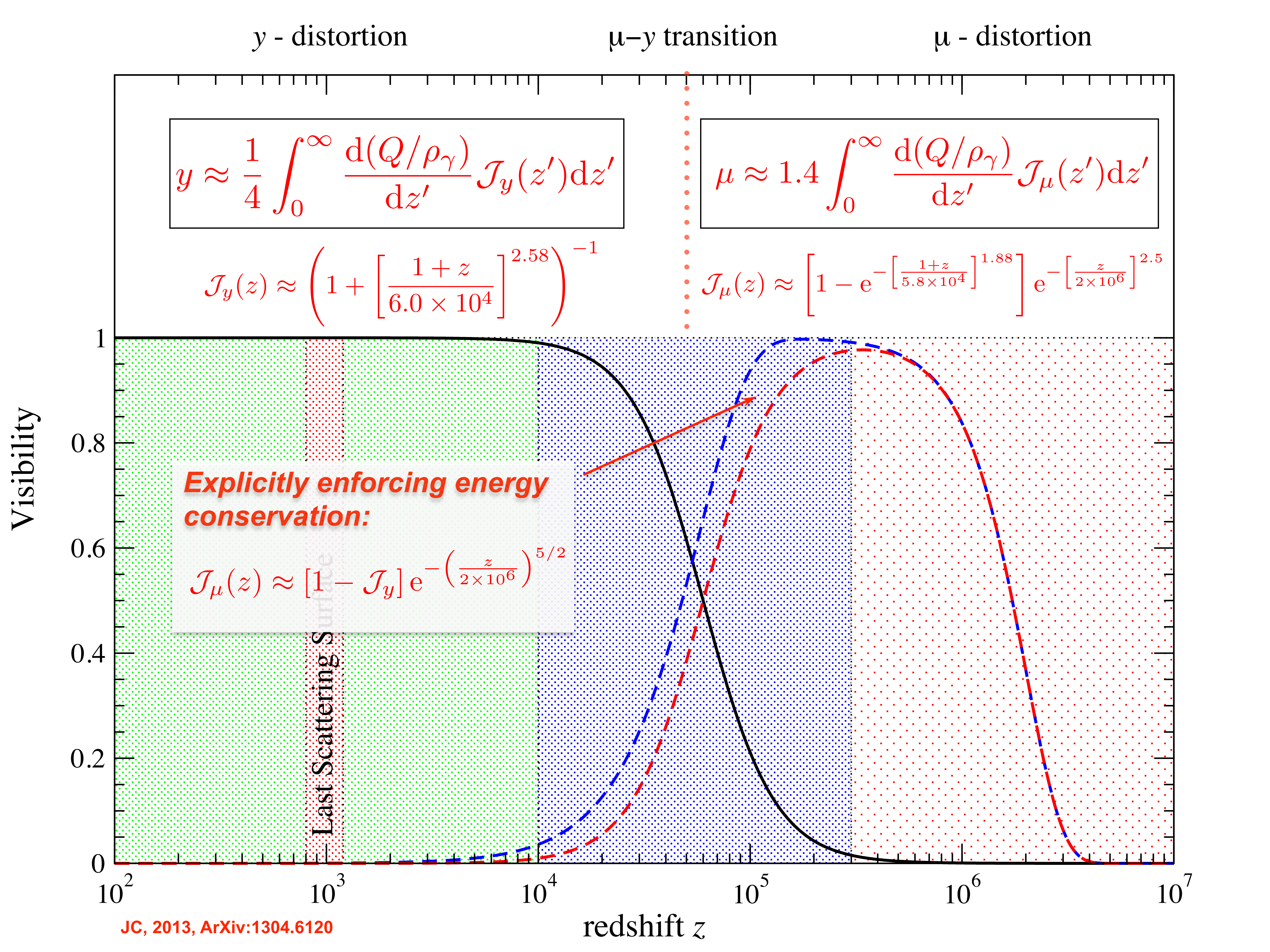
y - distortion
μ−y transition
μ - distortion
Slightly refined estimate that takes mix of μ and y into account (JC, 2013, ArXiv:1304.6120)
Visibility
1
0.8
0.6
0.4
0.2
0
Last Scattering Surface
10^2
10^3
10^4
10^5
10^6
10^7
redshift z
JC, 2013, ArXiv:1304.6120



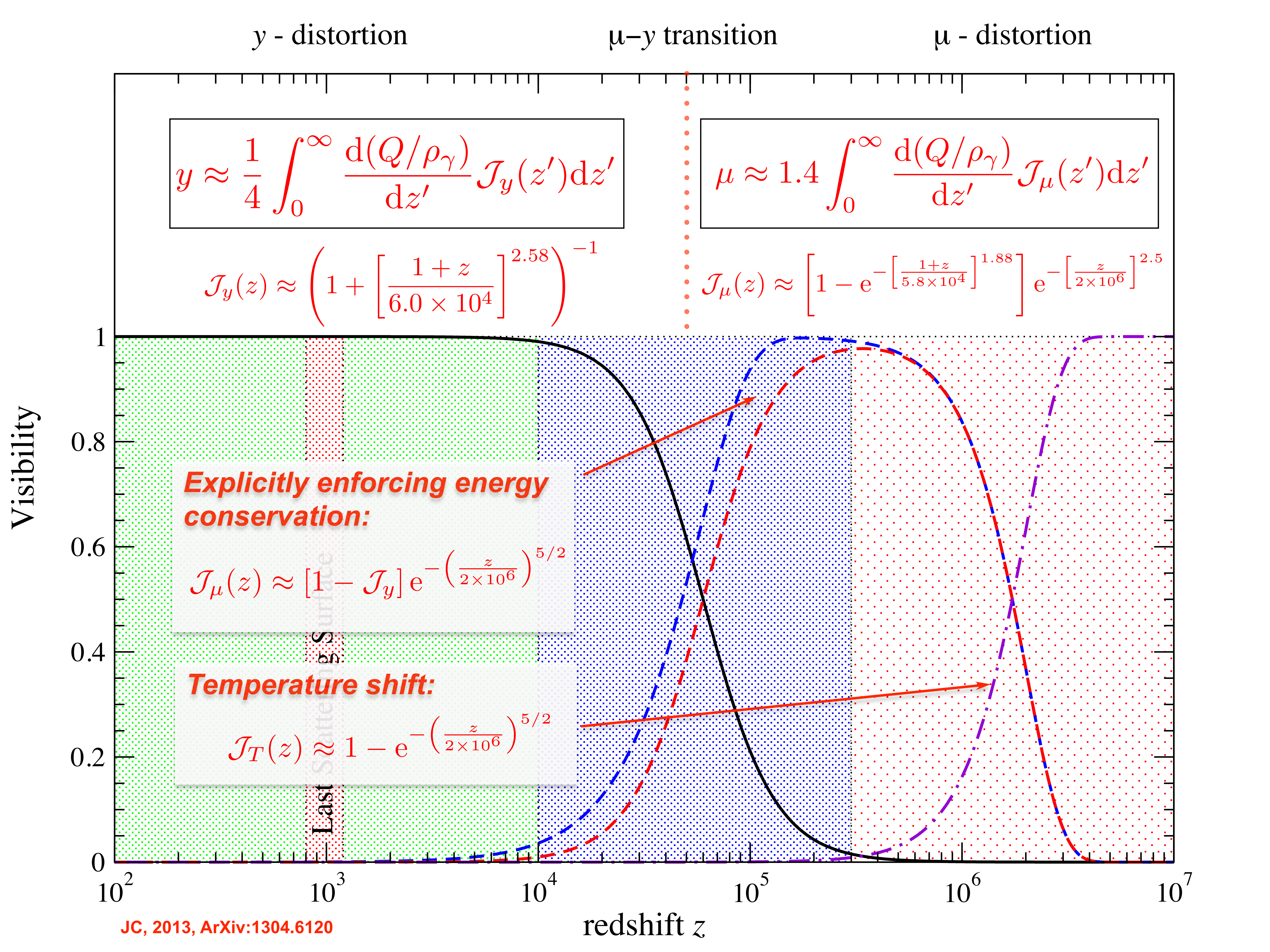
y - distortion
μ−y transition
μ - distortion
Fit numerical result for the Green's function with μ and y distortion
⇒ define visibility functions
Visibility
Last Scattering Surface
0
0.2
0.4
0.6
0.8
1
10^2
10^3
10^4
10^5
10^6
10^7
redshift z
JC, 2013, ArXiv:1304.6120



y - distortion
μ–y transition
μ - distortion
$y \approx \frac{1}{4}\int_0^\infty \frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z'}\mathcal{J}_y(z')\mathrm{d}z'$
$\mu \approx 1.4\int_0^\infty \frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z'}\mathcal{J}_\mu(z')\mathrm{d}z'$
$\mathcal{J}_y(z) \approx \left(1+\left[\frac{1+z}{6.0\times10^4}\right]^{2.58}\right)^{-1}$
$\mathcal{J}_\mu(z) \approx \left[1-\mathrm{e}^{-\left[\frac{1+z}{5.8\times10^4}\right]^{1.88}}\right]\mathrm{e}^{-\left[\frac{z}{2\times10^6}\right]^{2.5}}$
Visibility
Last Scattering Surface
redshift z
JC, 2013, ArXiv:1304.6120



y - distortion
μ−y transition
μ - distortion
$y \approx \frac{1}{4}\int_0^\infty \frac{d(Q/\rho_\gamma)}{dz'}\mathcal{J}_y(z')dz'$
$\mu \approx 1.4\int_0^\infty \frac{d(Q/\rho_\gamma)}{dz'}\mathcal{J}_\mu(z')dz'$
$\mathcal{J}_y(z) \approx \left(1+\left[\frac{1+z}{6.0\times10^4}\right]^{2.58}\right)^{-1}$
$\mathcal{J}_\mu(z) \approx \left[1-e^{-\left[\frac{1+z}{5.8\times10^4}\right]^{1.88}}\right]e^{-\left[\frac{z}{2\times10^6}\right]^{2.5}}$
Explicitly enforcing energy conservation:
$\mathcal{J}_\mu(z) \approx [1-\mathcal{J}_y]\,e^{-\left(\frac{z}{2\times10^6}\right)^{5/2}}$
Last Scattering Surface
Visibility
redshift z
JC, 2013, ArXiv:1304.6120



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μ–y transition
μ - distortion
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$\mathcal{J}_y(z) \approx \left(1+\left[\frac{1+z}{6.0\times10^4}\right]^{2.58}\right)^{-1}$
$\mu \approx 1.4\int_0^\infty \frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z'}\mathcal{J}_\mu(z')\mathrm{d}z'$
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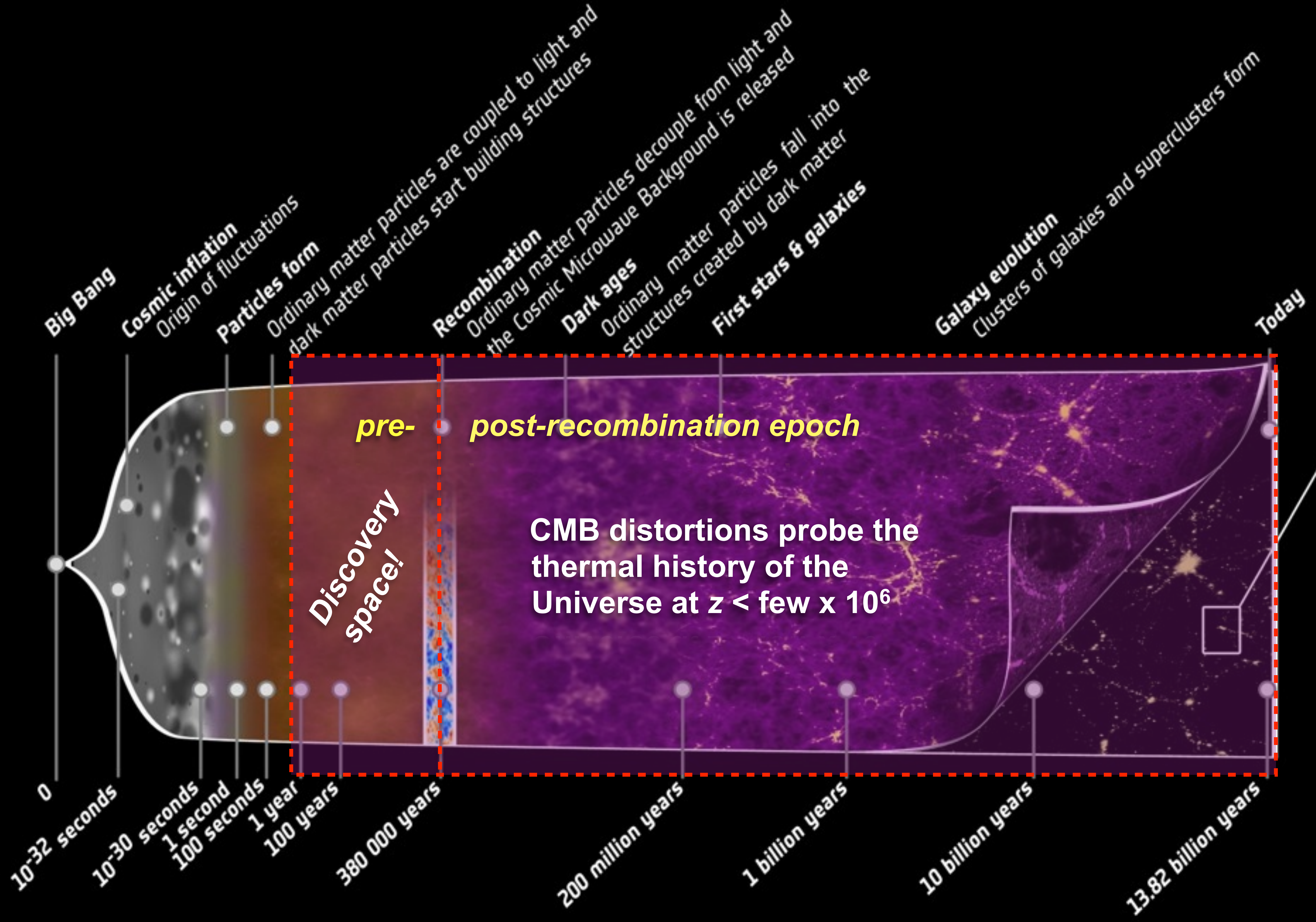
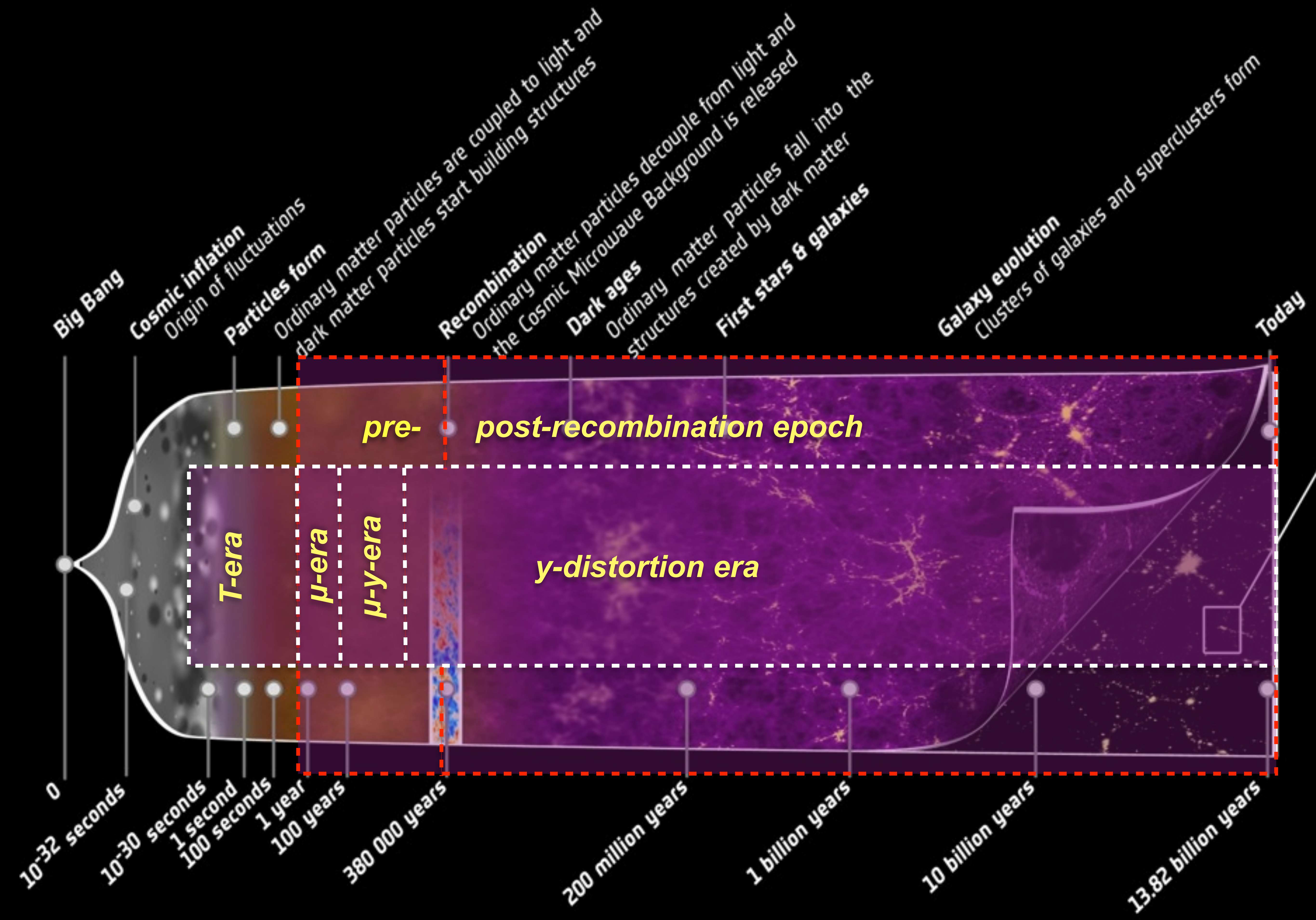
Explicitly enforcing energy conservation:
$\mathcal{J}_\mu(z) \approx [1-\mathcal{J}_y]\,\mathrm{e}^{-\left(\frac{z}{2\times10^6}\right)^{5/2}}$
Temperature shift:
$\mathcal{J}_T(z) \approx 1-\mathrm{e}^{-\left(\frac{z}{2\times10^6}\right)^{5/2}}$
Last Scattering Surface
Visibility
0
0.2
0.4
0.6
0.8
1
10^2
10^3
10^4
10^5
10^6
10^7
redshift z
JC, 2013, ArXiv:1304.6120



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
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



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Today
pre-
post-recombination epoch
T-era
μ-era
μ-y-era
y-distortion era
0
10-32 seconds
10-30 seconds
1 second
100 seconds
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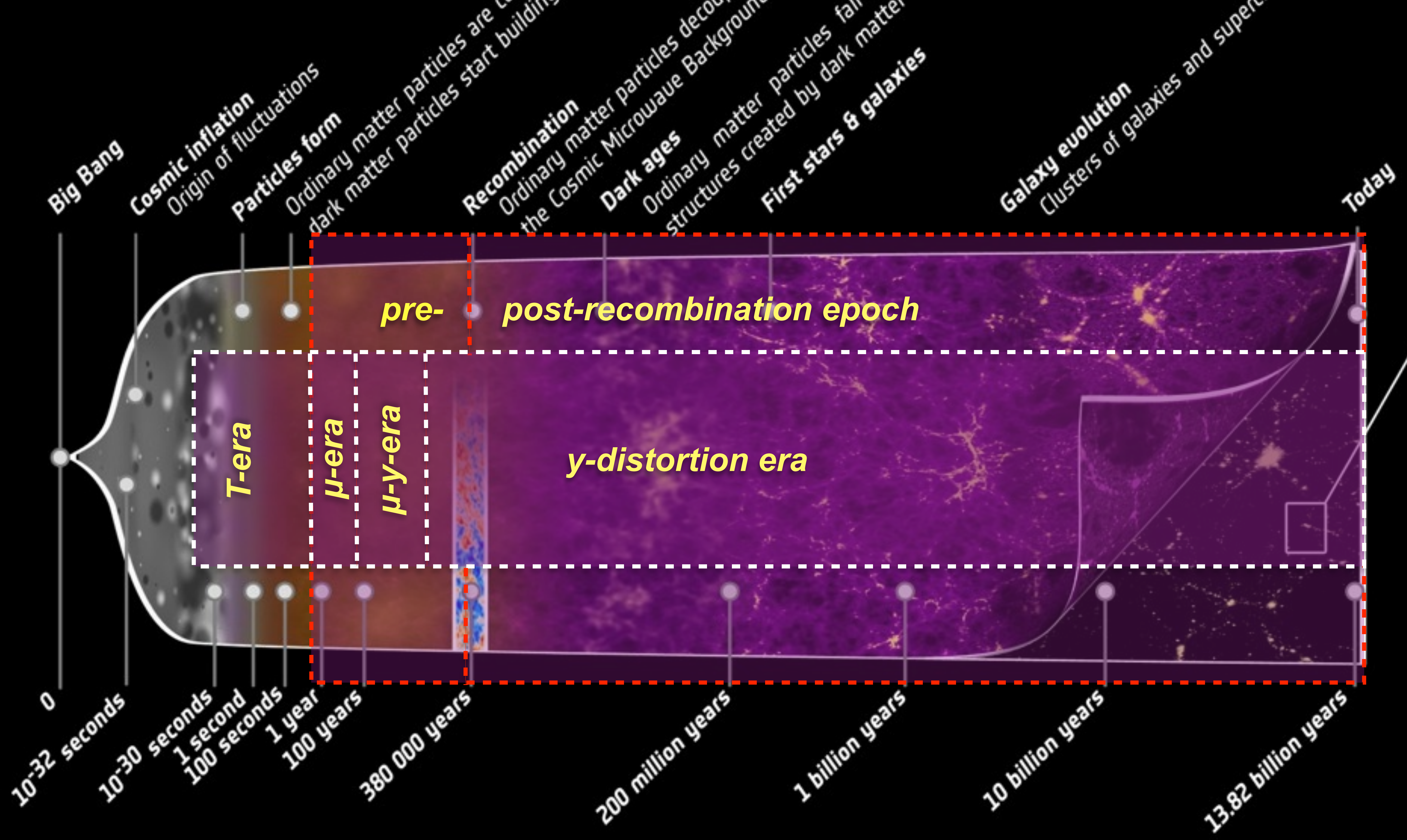
CMB spectrum adds another dimension to the problem!



Structure of the Lectures (cont.)

Lecture III:

- Overview of different sources of distortions
- Decaying particles
- Dissipation of acoustic modes

Physical mechanisms that lead to spectral distortions

Standard sources of 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

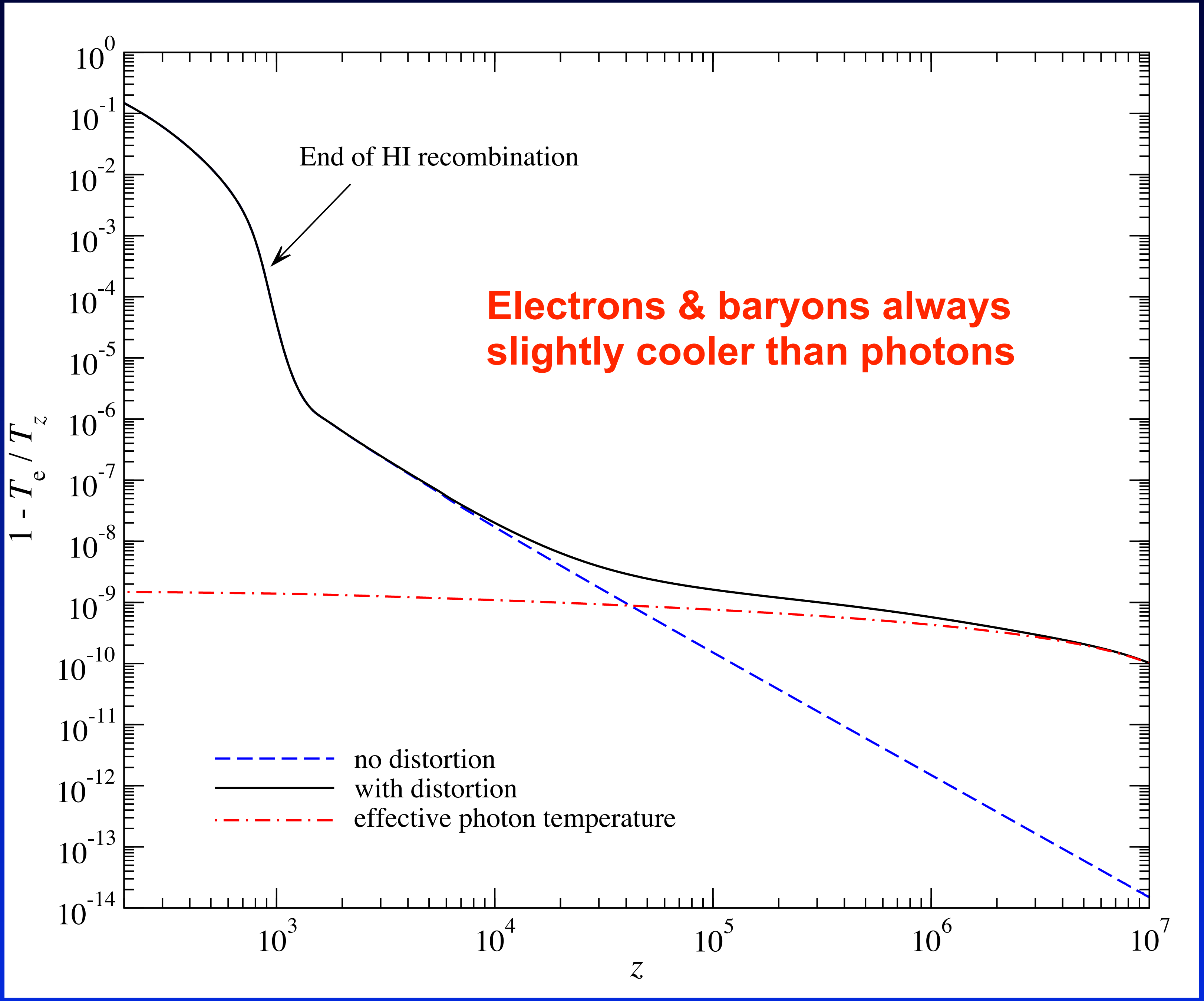
„low“ redshifts

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)

Adiabatic cooling of ordinary matter

Spectral distortion caused by the cooling of ordinary matter



- adiabatic expansion

$\Rightarrow$ $T_\gamma \sim (1+z) \leftrightarrow T_m \sim (1+z)^2$

- photons continuously *cooled* / *down-scattered* since day one of the Universe!
- Compton heating balances adiabatic cooling

$$\Rightarrow \frac{\mathrm{d}a^4\rho_\gamma}{a^4\mathrm{d}t} \simeq -Hk\alpha_\mathrm{h}T_\gamma \propto (1+z)^6$$

- at high redshift same scaling as *annihilation* ($\propto N_X^2$) and *acoustic mode damping*

$\Rightarrow$ *cancellation* possible

JC, 2005; JC & Sunyaev, 2012
Khatri, Sunyaev & JC, 2012

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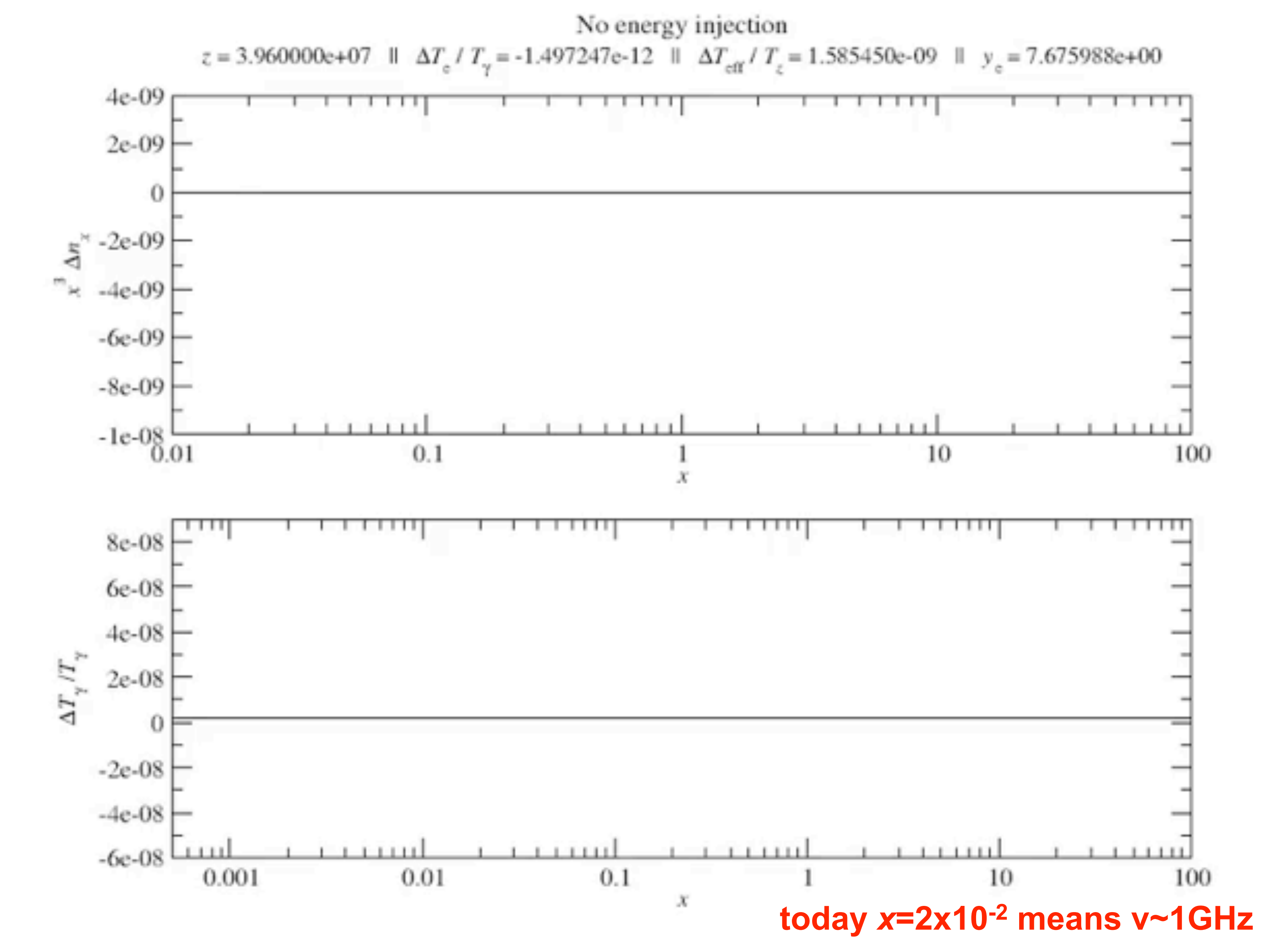
- at high redshift same scaling as *annihilation* ($\propto N_X^2$) and *acoustic mode damping*

$\Rightarrow$ *cancellation* possible

today x=2x10^{-2} means ν~1GHz

JC, 2005; JC & Sunyaev, 2012
Khatri, Sunyaev & JC, 2012

Spectral distortion caused by the cooling of ordinary matter



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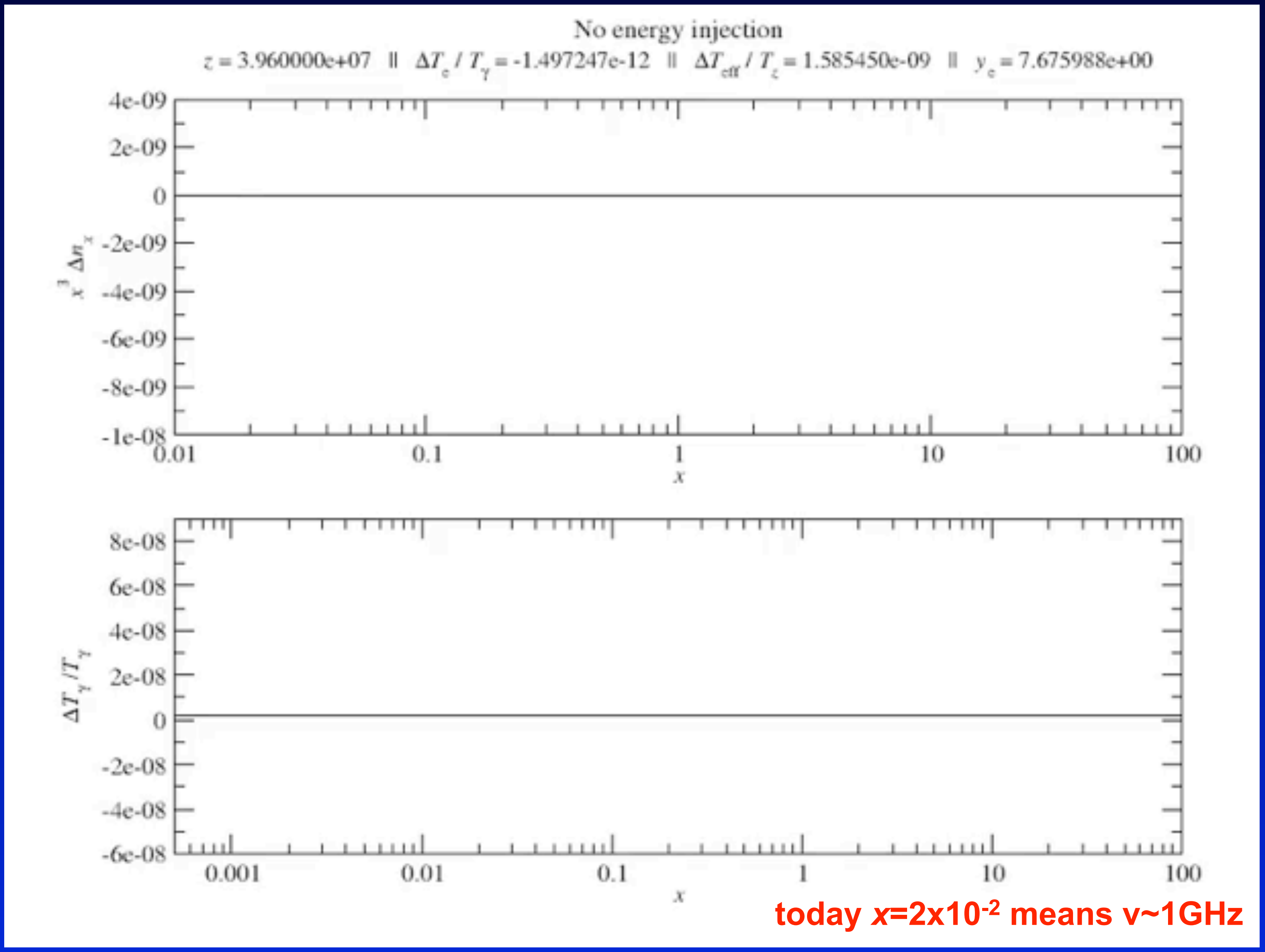
Spectral distortion caused by the cooling of ordinary matter



$$\mu \simeq 1.4 \left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_\mu \approx -3\times10^{-9} \qquad y \simeq \frac{1}{4}\left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_y \approx -6\times10^{-10}$$

- adiabatic expansion

$\Rightarrow$ $T_\gamma \sim (1+z) \leftrightarrow T_m \sim (1+z)^2$

- photons continuously *cooled* / *down-scattered* since day one of the Universe!
- Compton heating balances adiabatic cooling

$$\Rightarrow \frac{\mathrm{d}a^4\rho_\gamma}{a^4\mathrm{d}t} \simeq -Hk\alpha_\mathrm{h}T_\gamma \propto (1+z)^6$$

- at high redshift same scaling as *annihilation* ($\propto N_X^2$) and *acoustic mode damping*

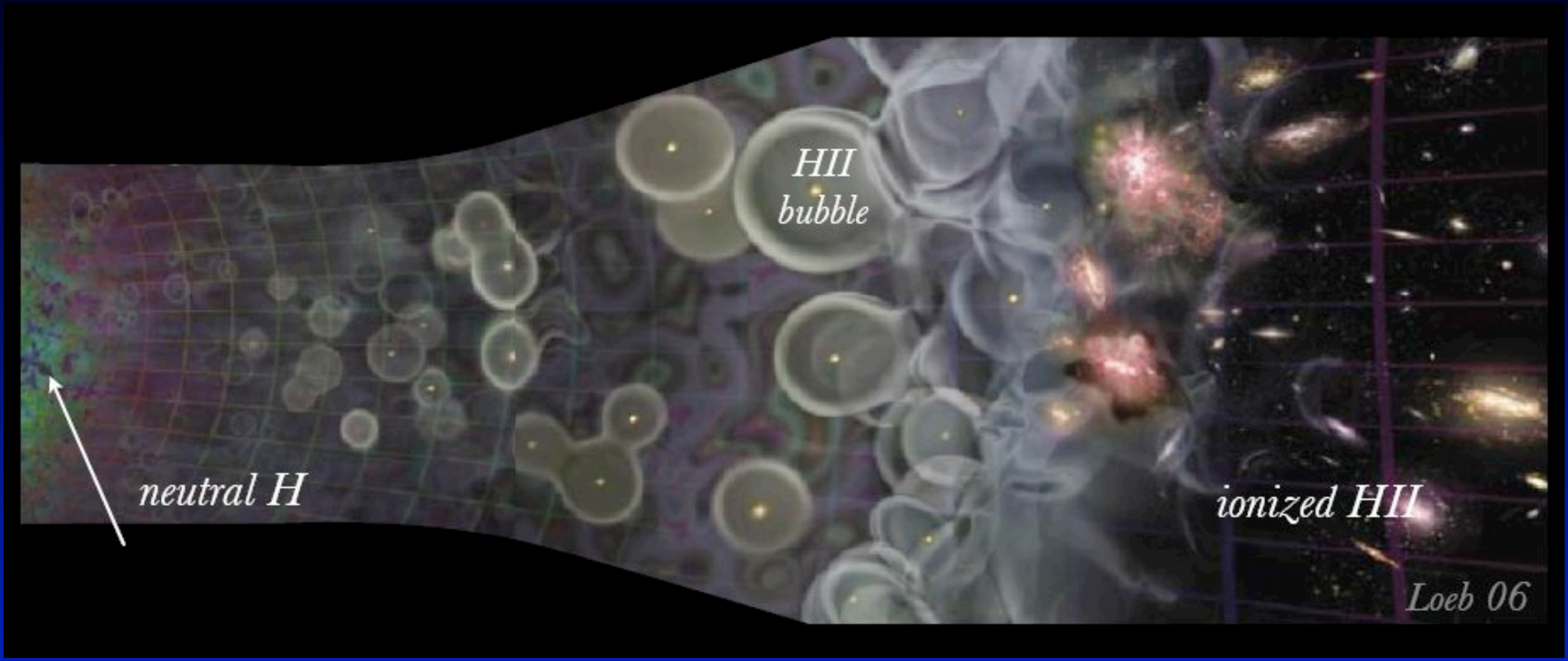
$\Rightarrow$ *cancellation* possible

- *negative* μ and y distortion
- late free-free absorption at very low frequencies
- Distortion a few times below PIXIE's sensitivity

JC, 2005; JC & Sunyaev, 2012
Khatri, Sunyaev & JC, 2012

Reionization and structure formation

Simple estimates for the distortion

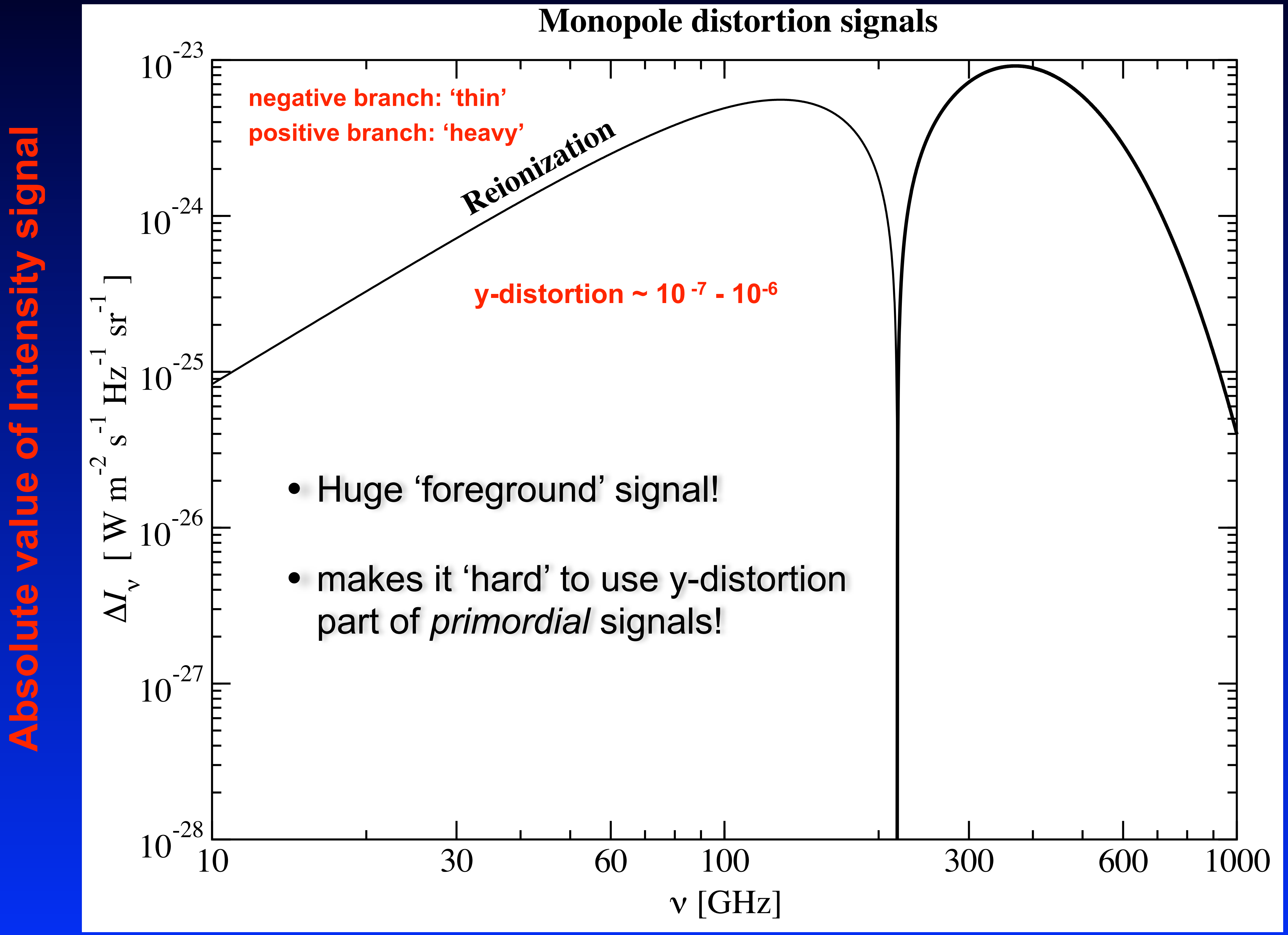


- Gas temperature T ≃ 10^4 K
- Thomson optical depth $\tau \simeq 0.1$

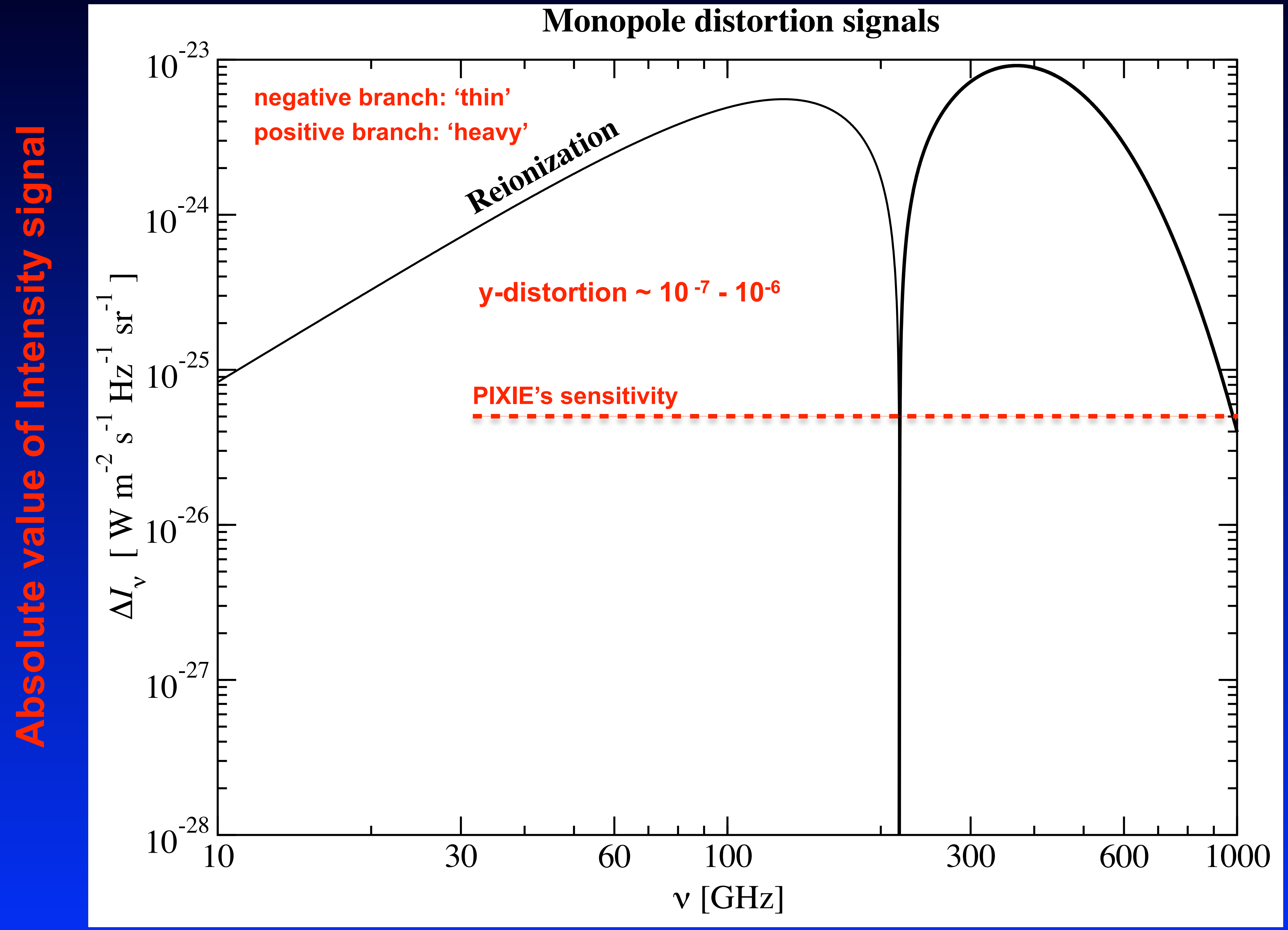
$$\Longrightarrow \quad y \simeq \frac{kT_{\rm e}}{m_{\rm e}c^2}\,\tau \approx 2\times10^{-7}$$

- 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}

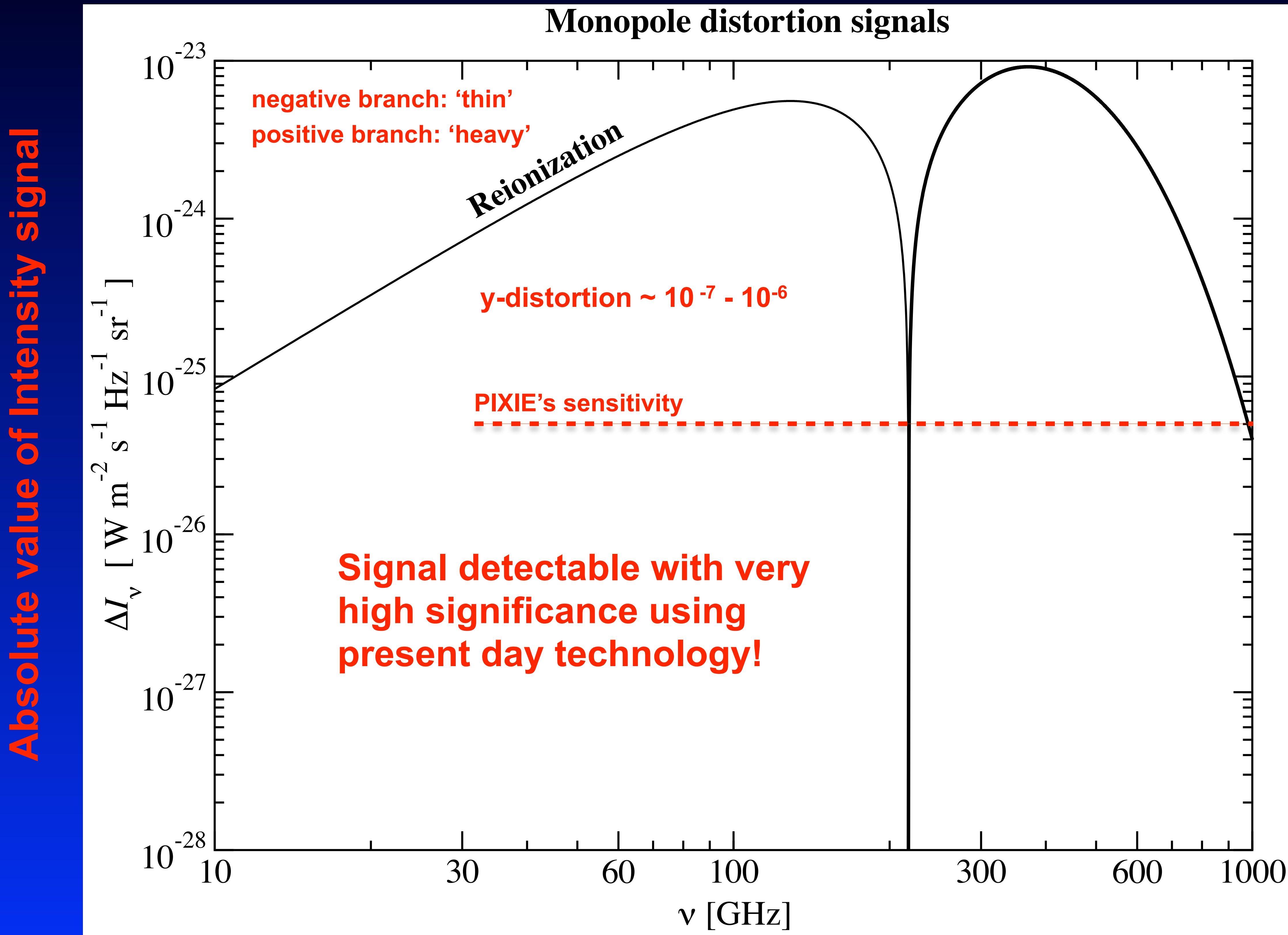
Average CMB spectral distortions



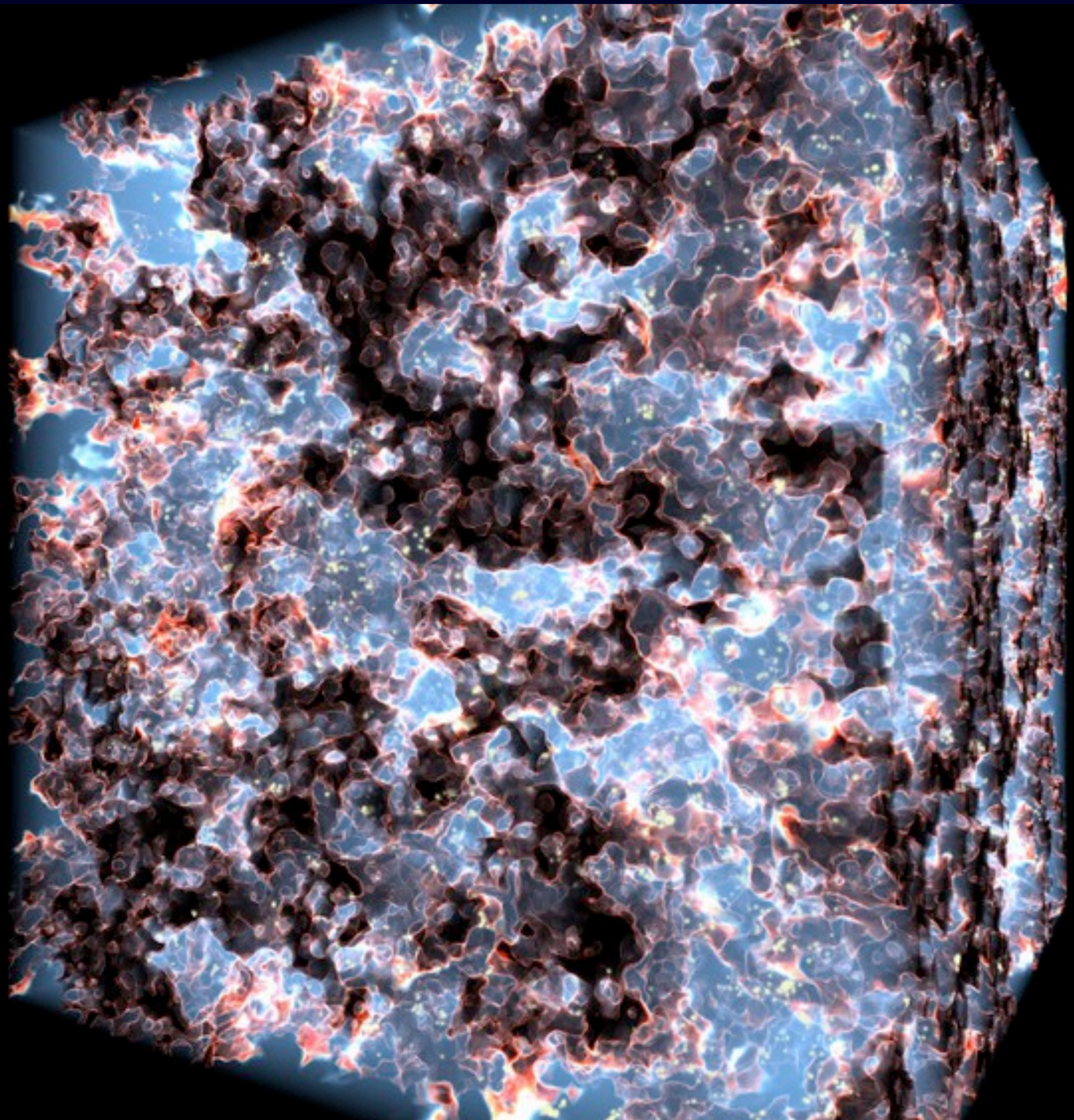
Average CMB spectral distortions



Average CMB spectral distortions



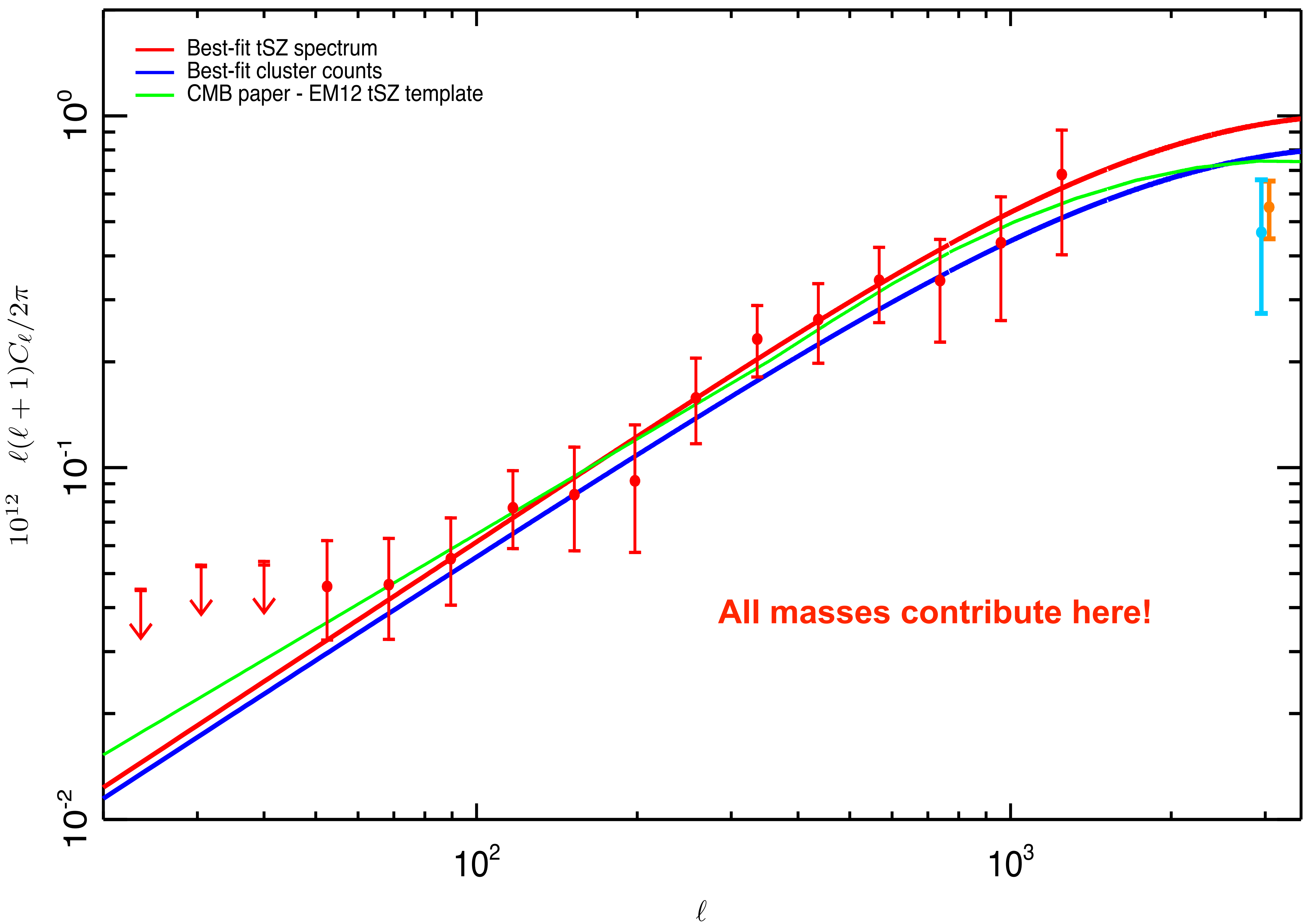
Fluctuations of the y-parameter at large scales



- 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*

Measured power spectrum for y-parameter



Planck Collaboration, 2013, XXI

Decaying particles

Why is this interesting?

- A priori no specific particle in mind
- *But:* we do not know what dark matter is and where it really came from!
- Was dark matter thermally produced or as a decay product of some heavy particle?
- is dark matter structureless or does it have internal (excited) states?
- sterile neutrinos? moduli? Some other relic particle?
- From the theoretical point of view really no shortage of particles to play with...

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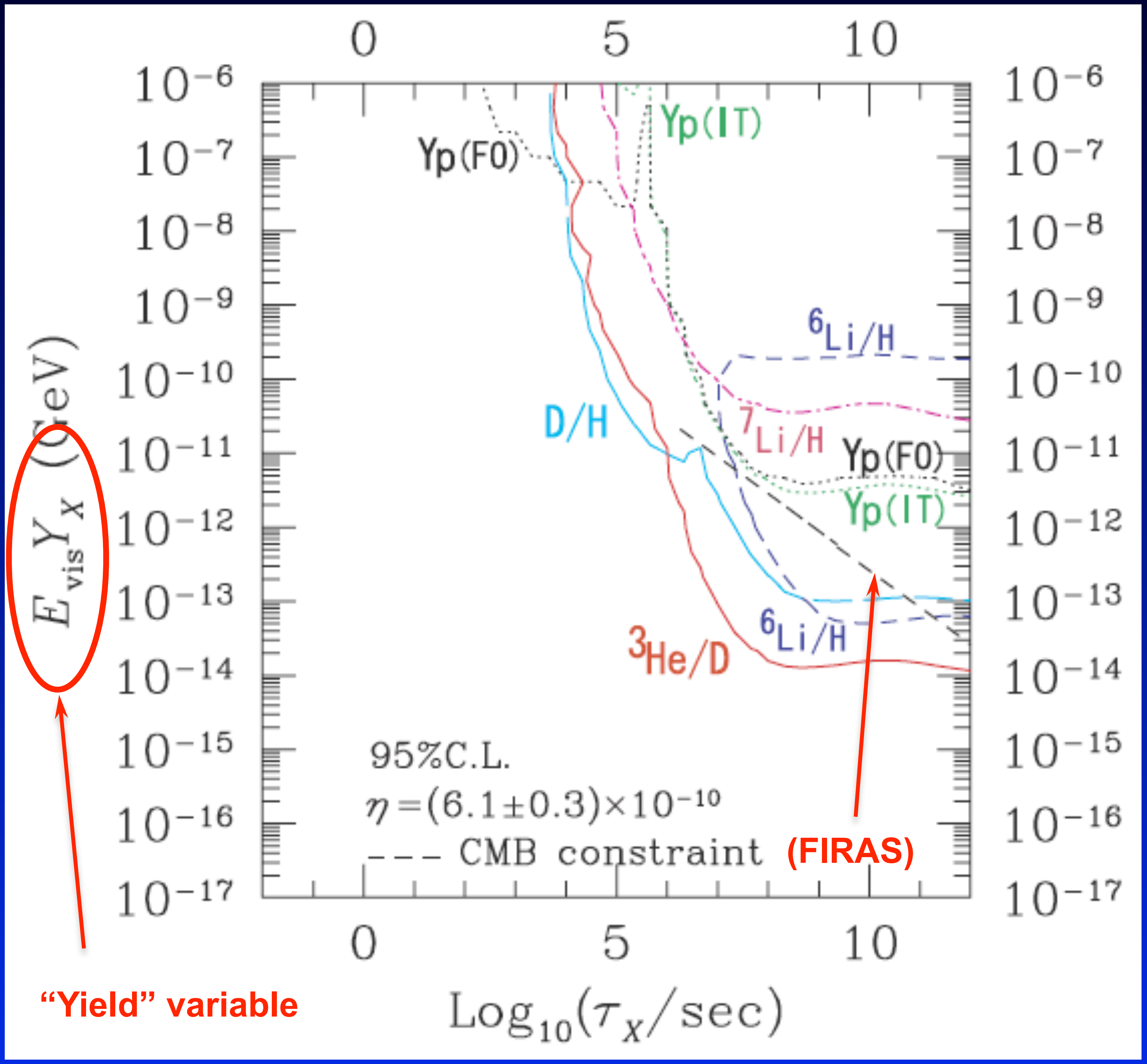
CMB spectral distortions offer a new independent way to constrain these kind of models

Constraints from measurements of light elements



from Kawasaki et al, 2005

- Yield variable ⇒

  parametrizes the total energy release relative to total entropy density of the Universe

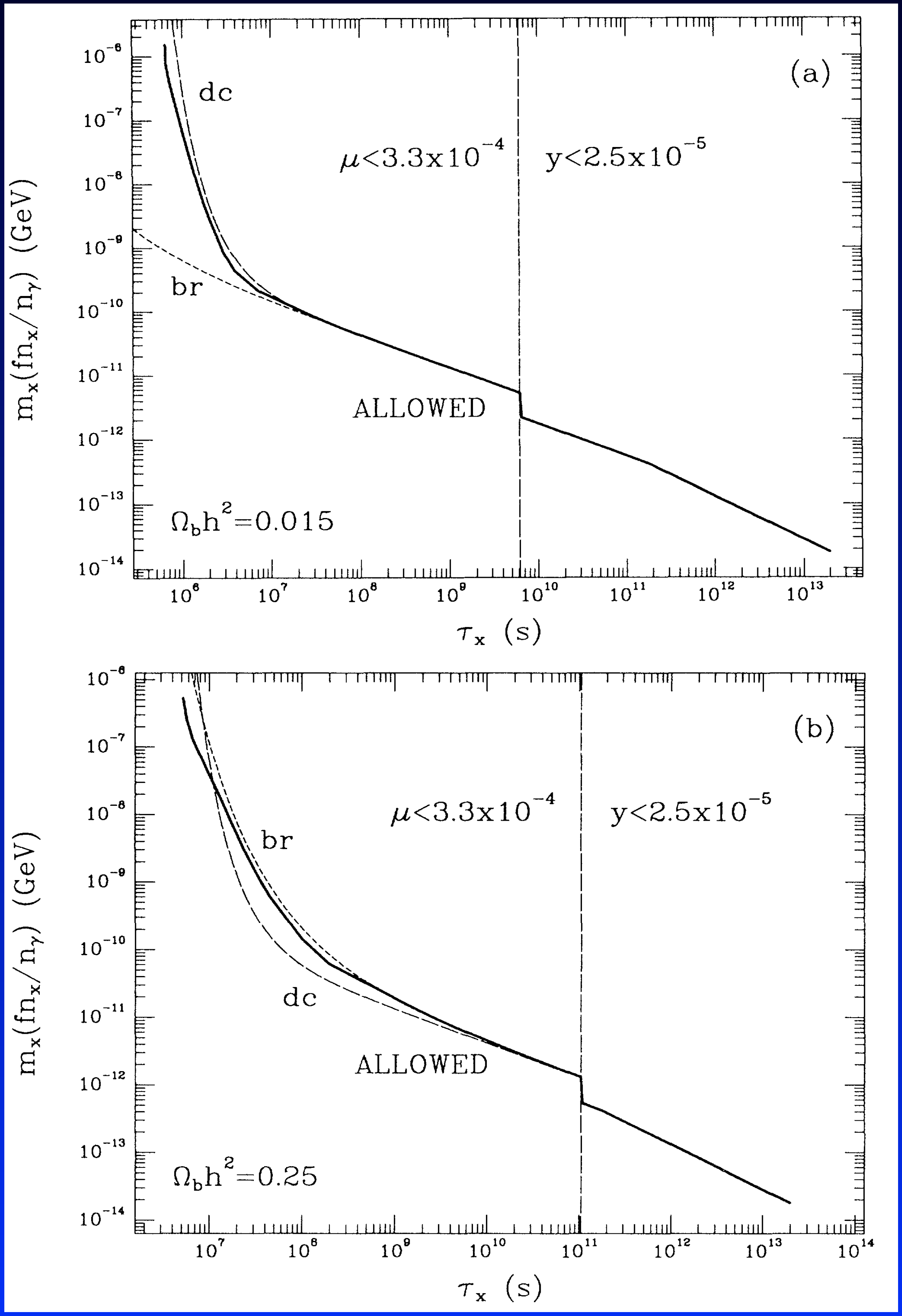
  $$Y_X \simeq N_X/S$$

- energy release *destroys* light elements
- E_{vis} hides physics of energy deposition

  (decay channels, neutrino fraction, etc.)

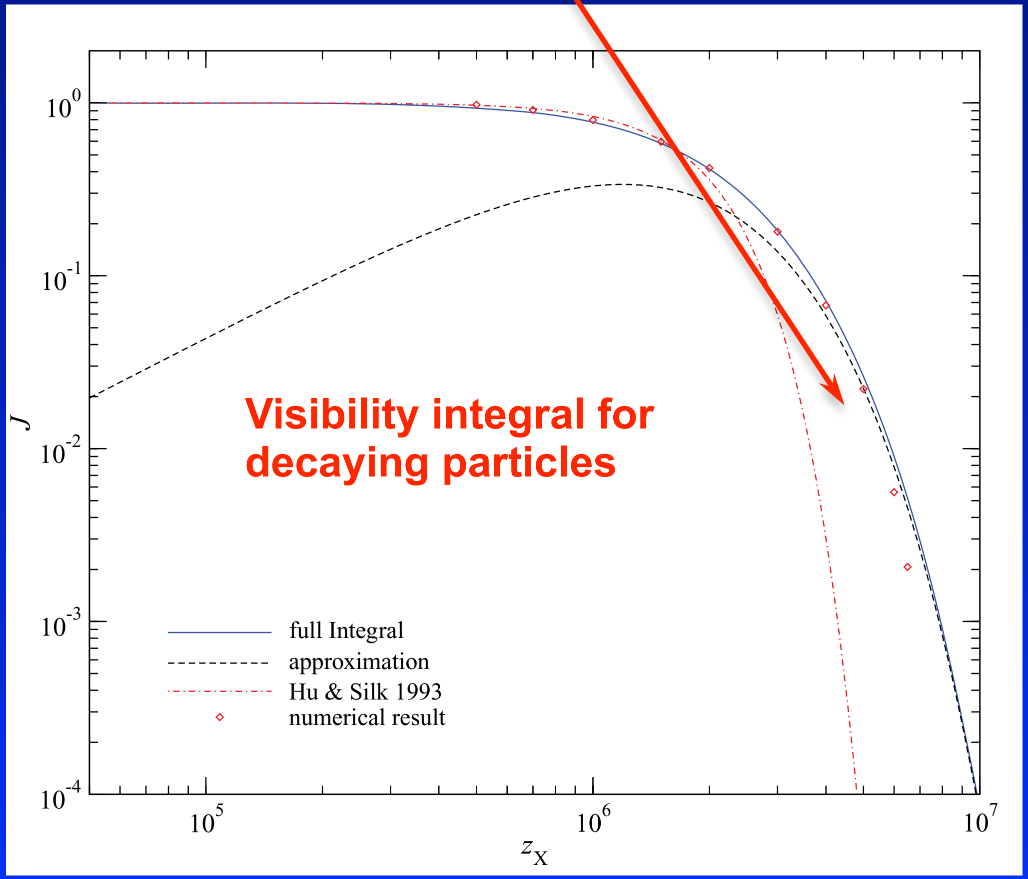
- current CMB limit rather weak in comparison....

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...



JC, 2005; JC & Sunyaev, 2012

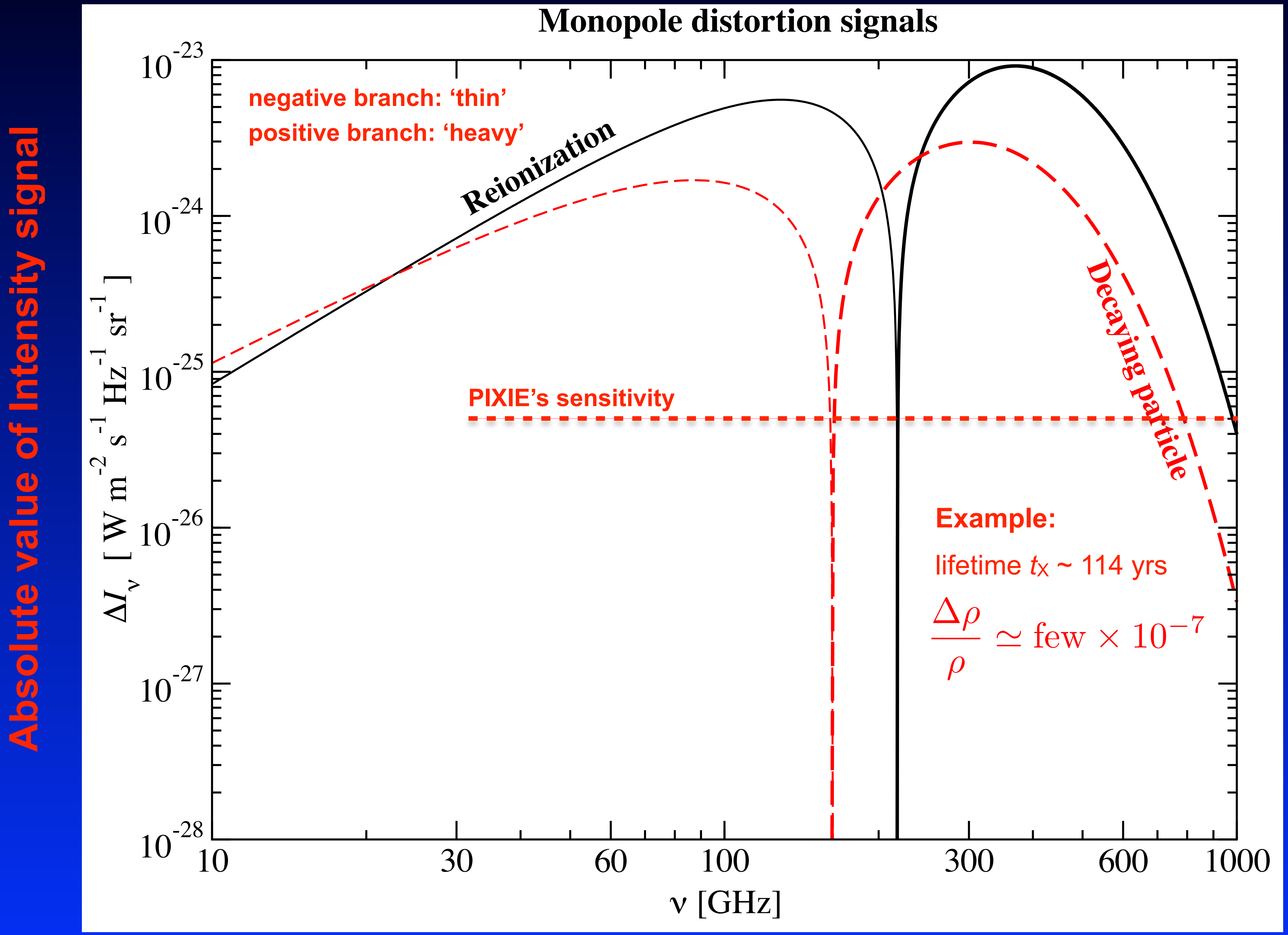
Energy release by decaying particles

- Energy release rate $$\frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z} \approx \frac{f^* M_\mathrm{X} c^2}{H(z)(1+z)} \frac{N_\mathrm{X}(z)}{\rho_\gamma(z)} \Gamma_\mathrm{X} \mathrm{e}^{-\Gamma_\mathrm{X} t}$$
- *For computations*: $f_\mathrm{X} = f^* M_\mathrm{X} c^2 N_\mathrm{X}/N_\mathrm{H}$ and $\varepsilon_\mathrm{X} = \dfrac{f_\mathrm{X}}{z_\mathrm{X}}$
- Efficiency factor f^* contains all the physics describing the cascade of decay products
- At high redshift deposited energy goes all into heat
- Around recombination and after things become more complicated **(Slatyer et al. 2009; Cirelli et al. 2009; Huetsi et al. 2009; Slatyer et al. 2013)**

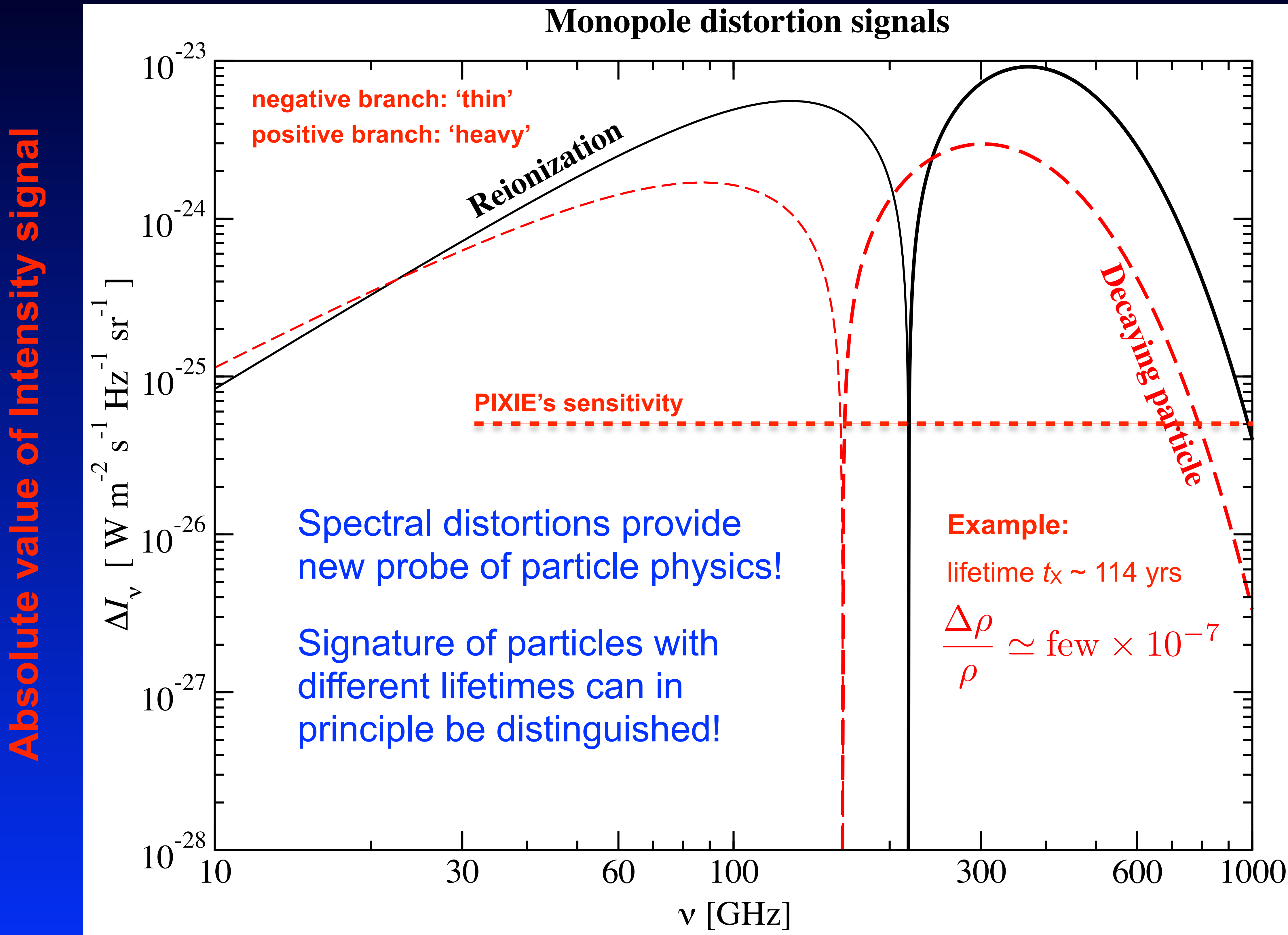
  $\Longrightarrow$ *branching ratios into heat, ionizations, and atomic excitation*

  $\Longrightarrow$ *details would be important for y-distortion part*

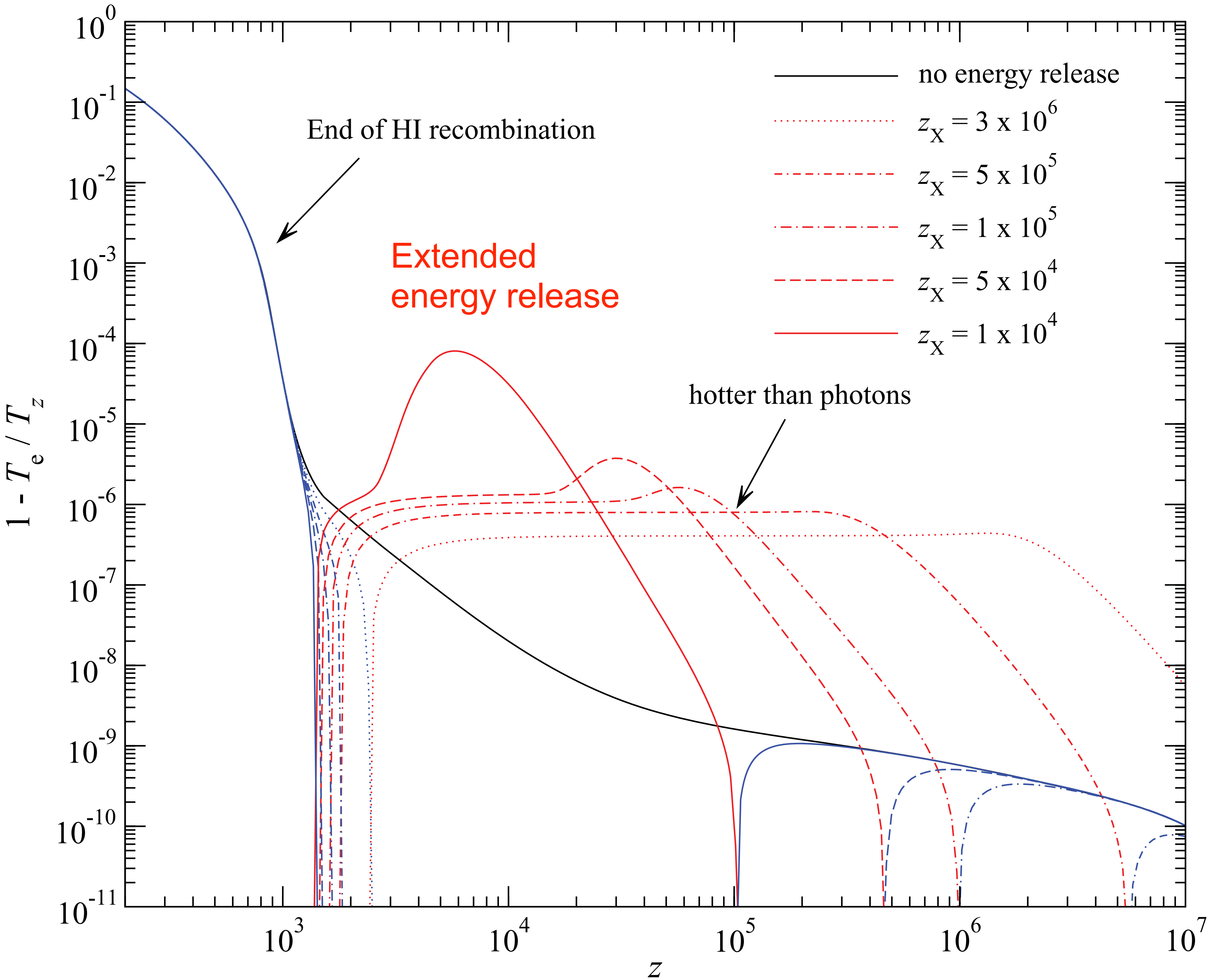
Average CMB spectral distortions



Average CMB spectral distortions

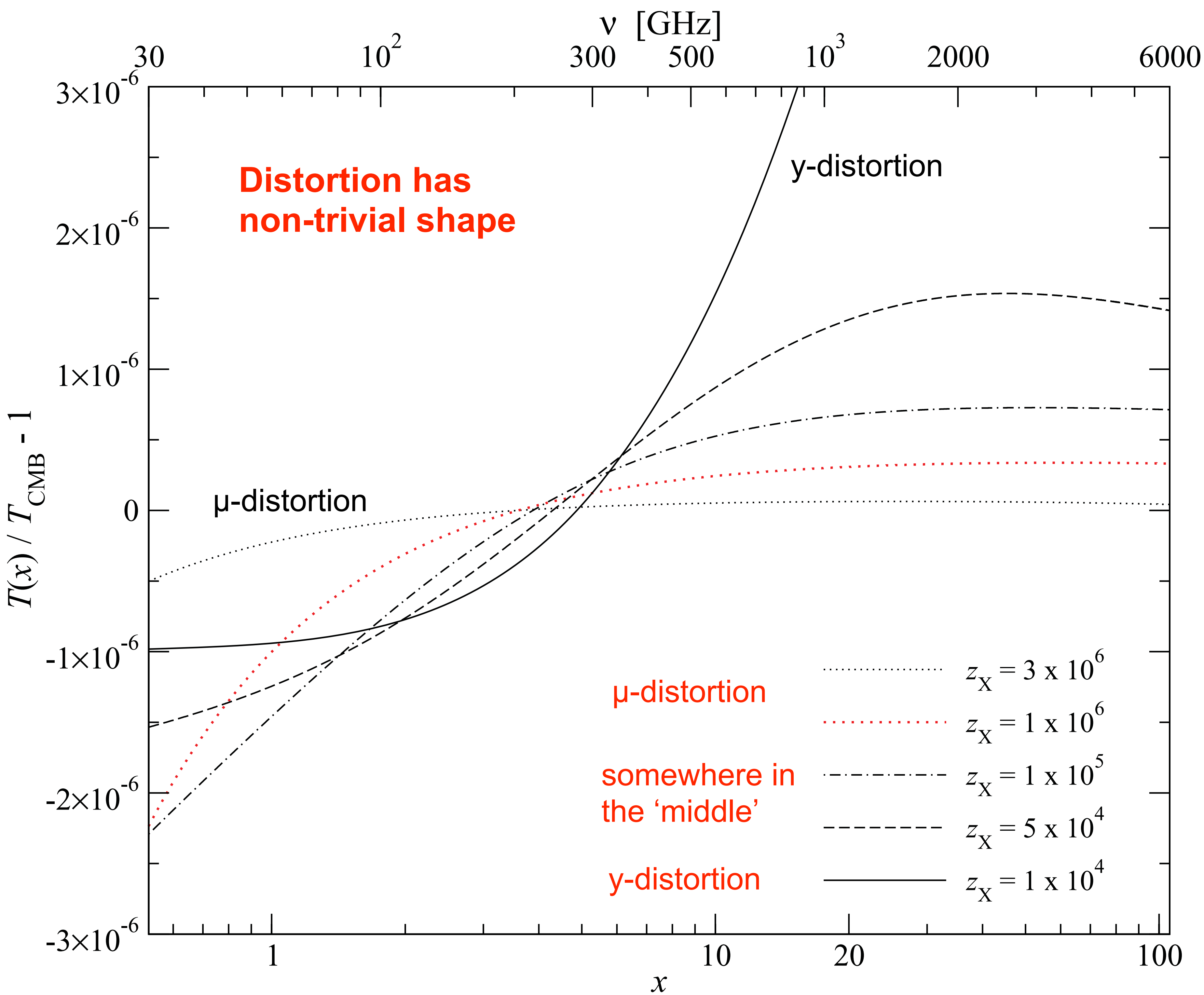


Electron temperature evolution for decaying particle scenarios



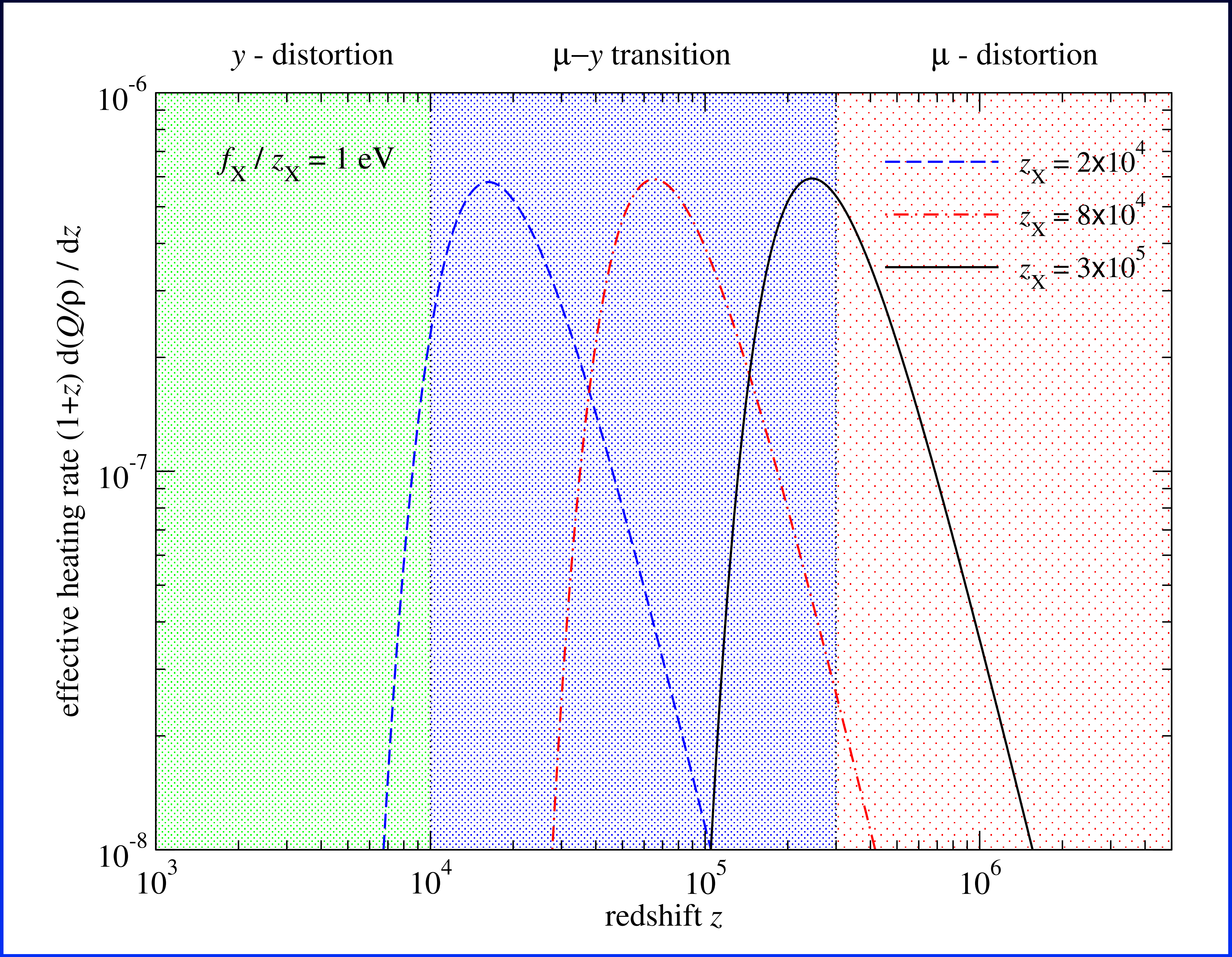
JC & Sunyaev, 2012

High frequency distortion for decaying particle scenarios



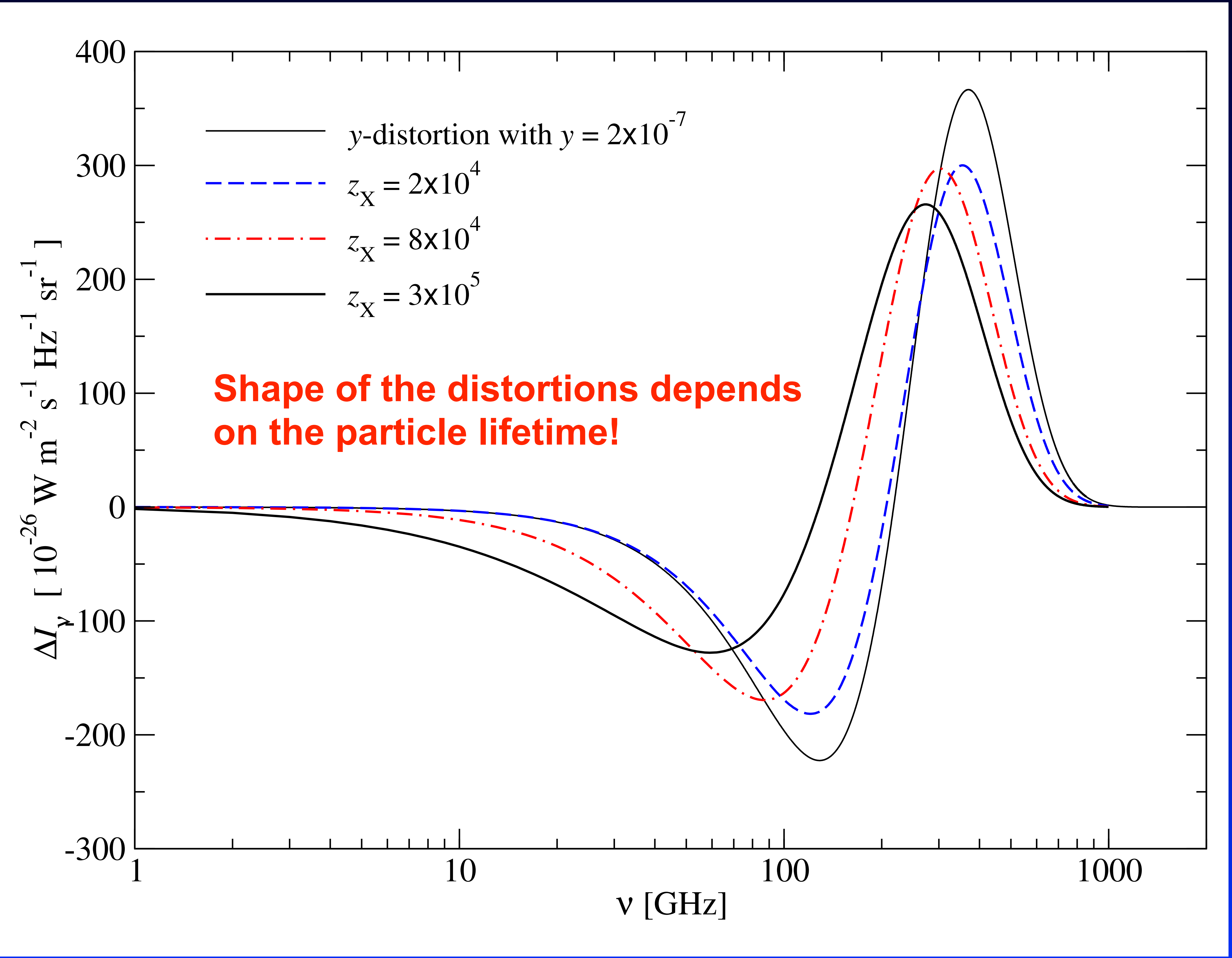
JC & Sunyaev, 2012

Decaying particle scenarios



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

Decaying particle scenarios



JC & Sunyaev, 2011, Arxiv:1109.6552
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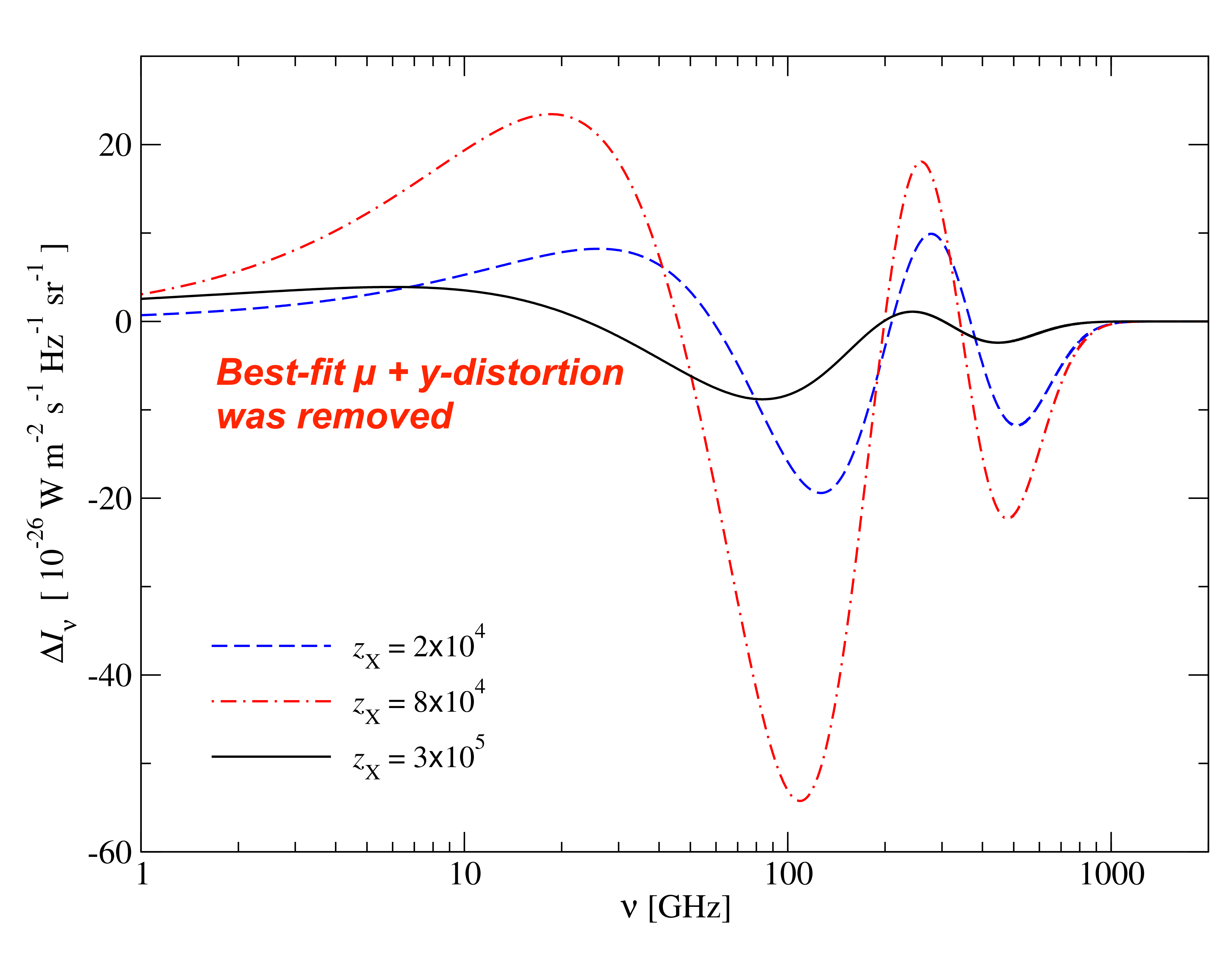
Decaying particle scenarios (information in residual)



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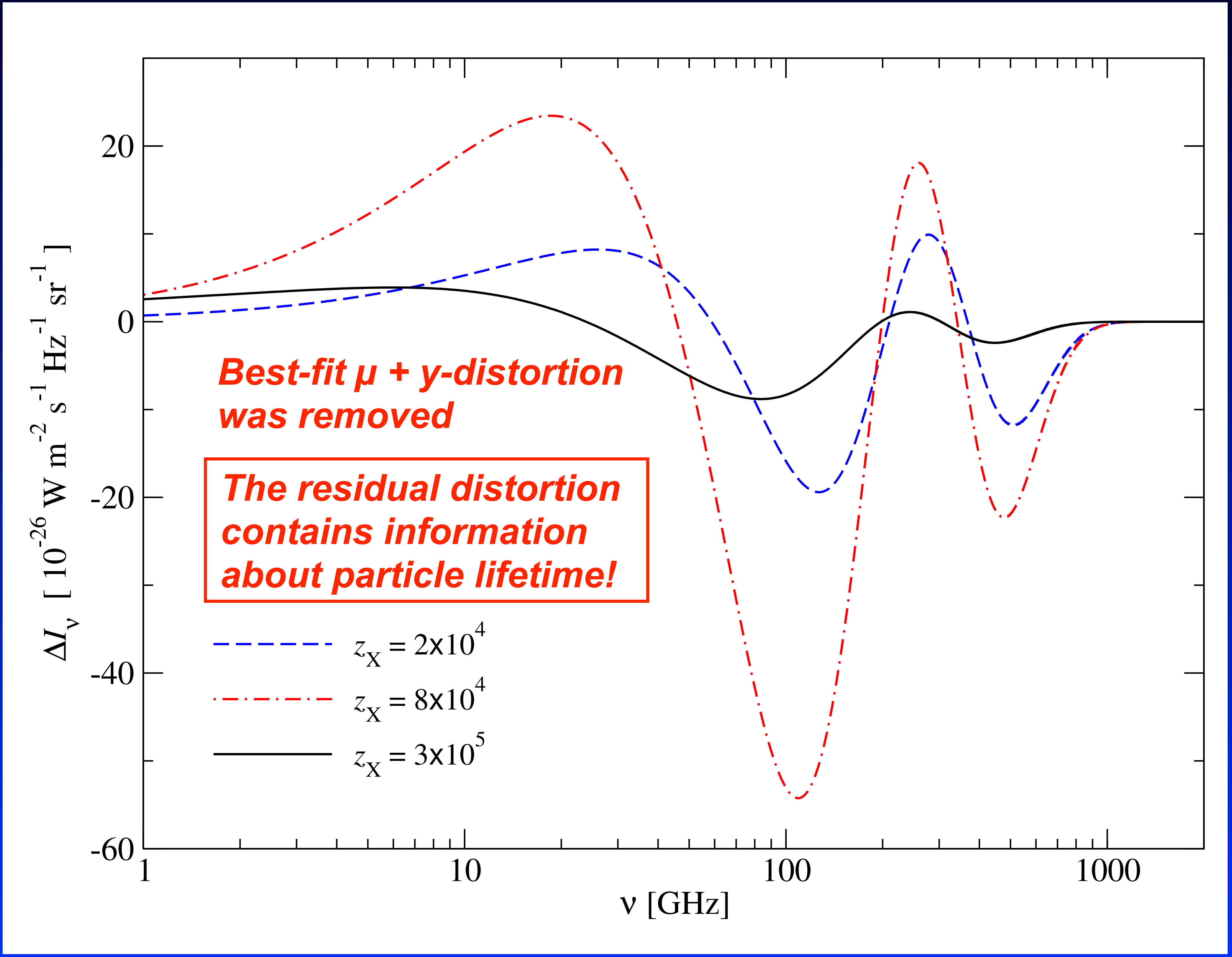

JC & Sunyaev, 2011, Arxiv:1109.6552
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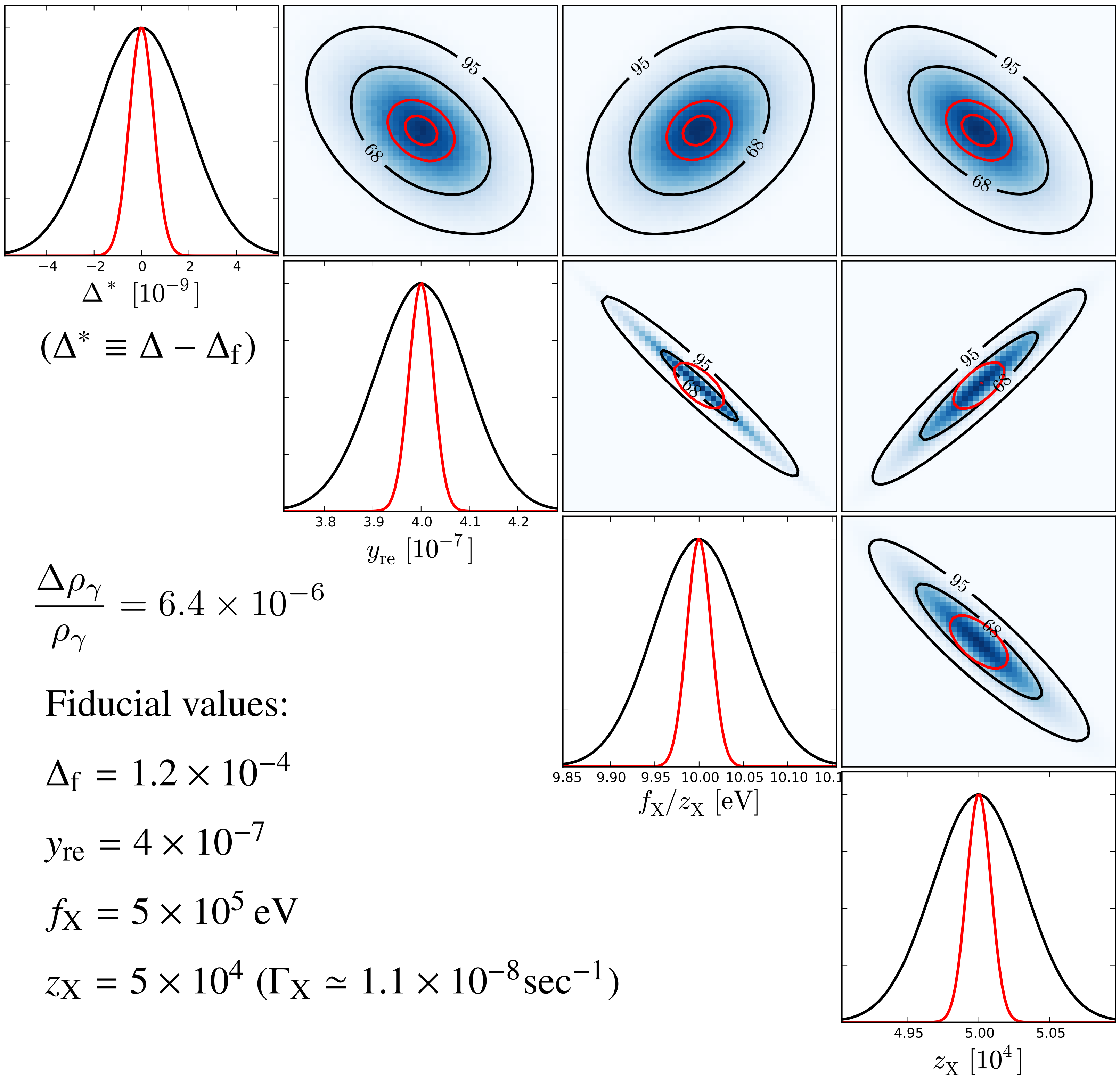
Decaying particle scenarios



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

$$\frac{\Delta\rho_\gamma}{\rho_\gamma} = 6.4 \times 10^{-6}$$

Fiducial values:

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

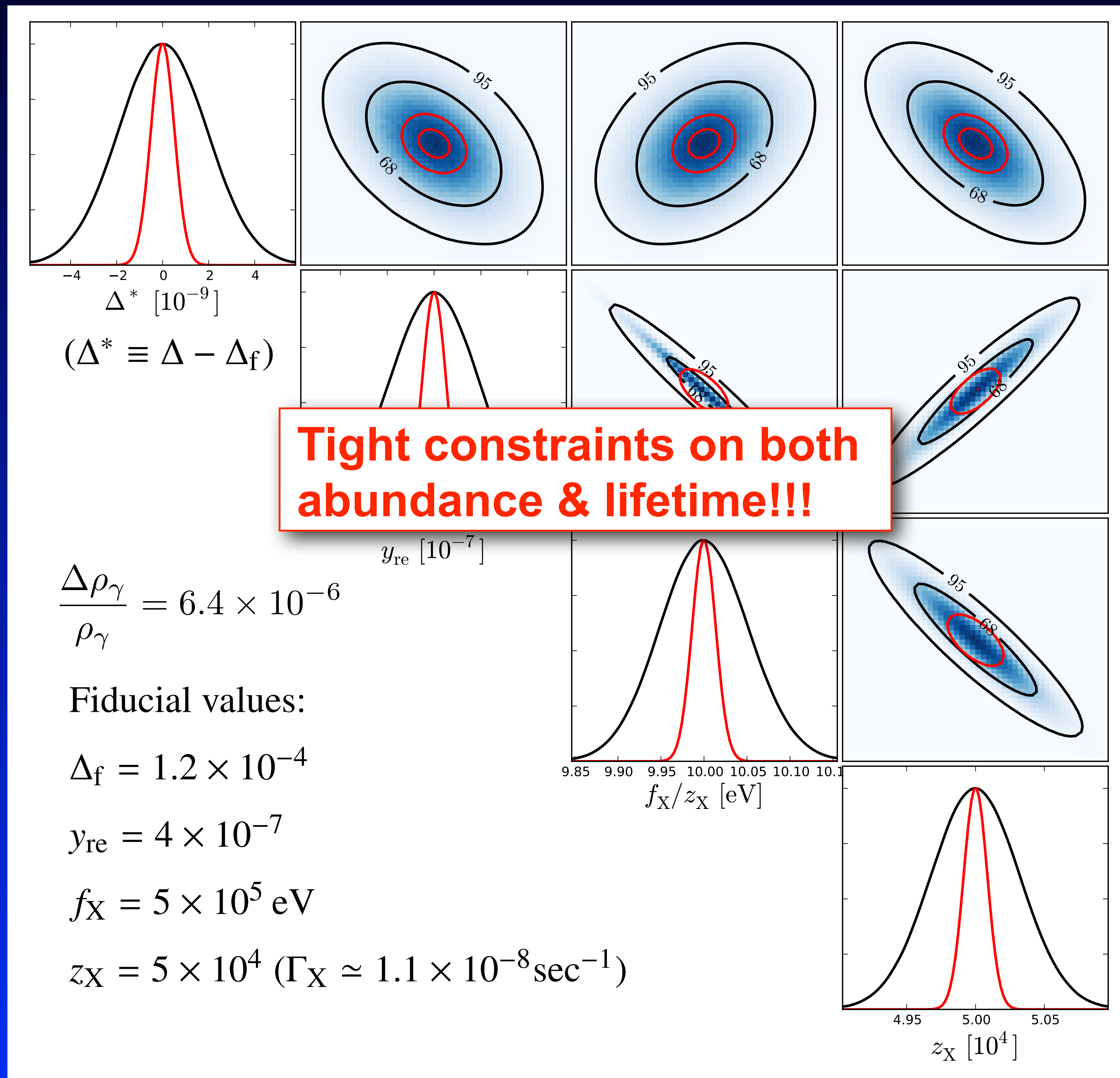
$y_{\rm re} = 4 \times 10^{-7}$

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

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

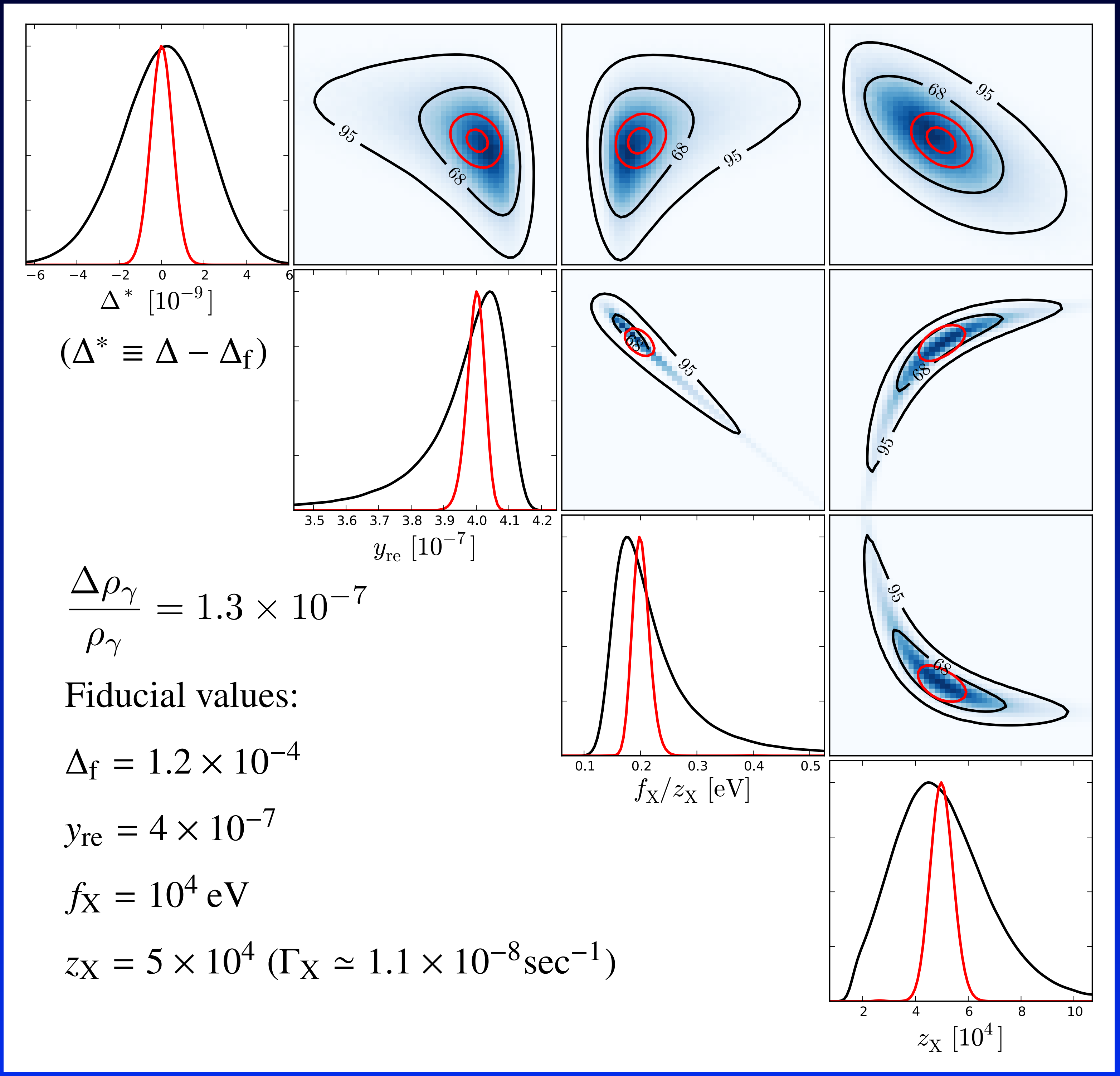
JC, 2013, ArXiv:1304.6120

Decaying particle scenarios



JC, 2013, ArXiv:1304.6120

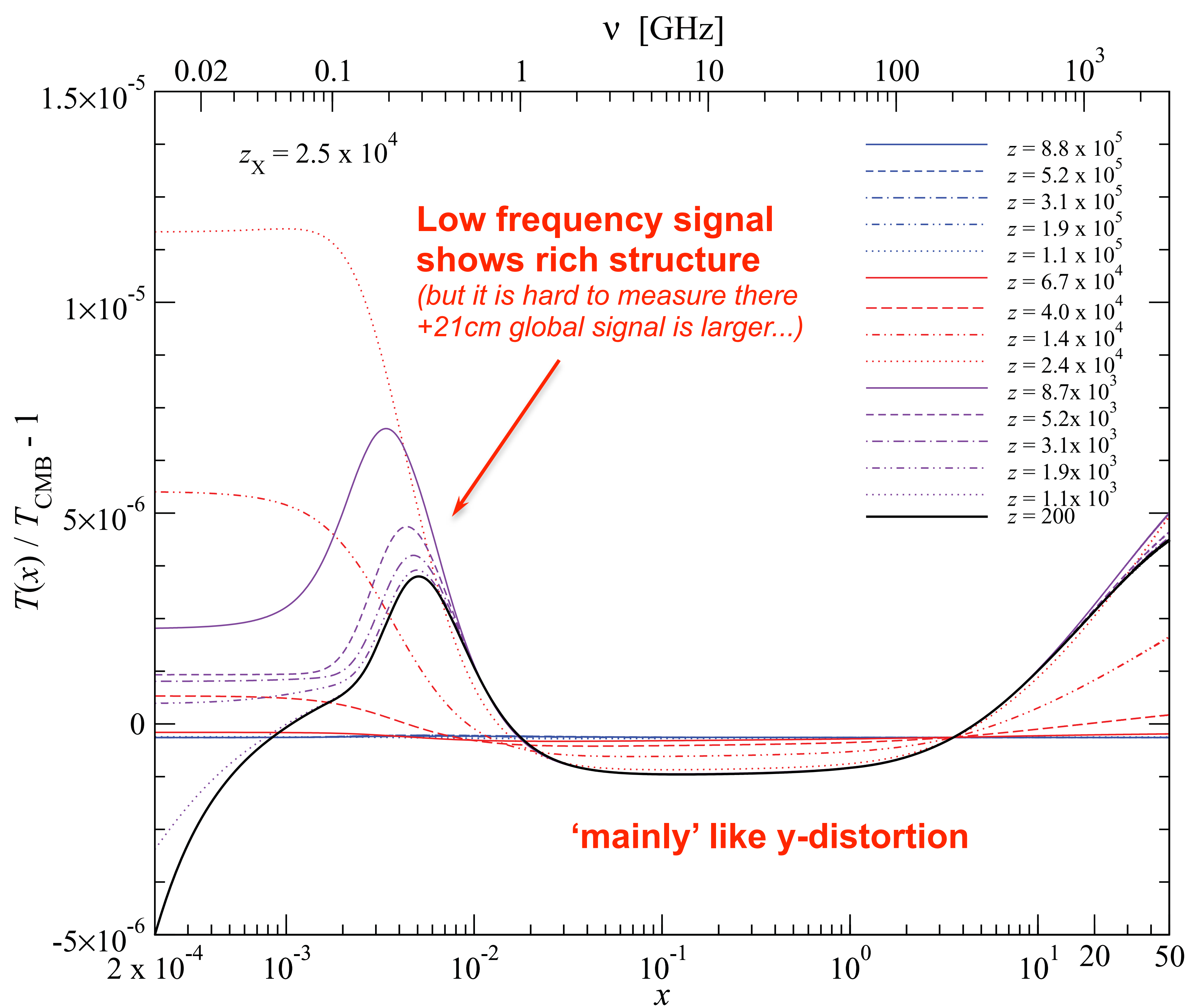
Decaying particle scenario close to detection limit



- Parameters more degenerate close to detection limit
- Non-Gaussian contours
- big improvement with sensitivity

JC, 2013, ArXiv:1304.6120

Distortion for late particle decay



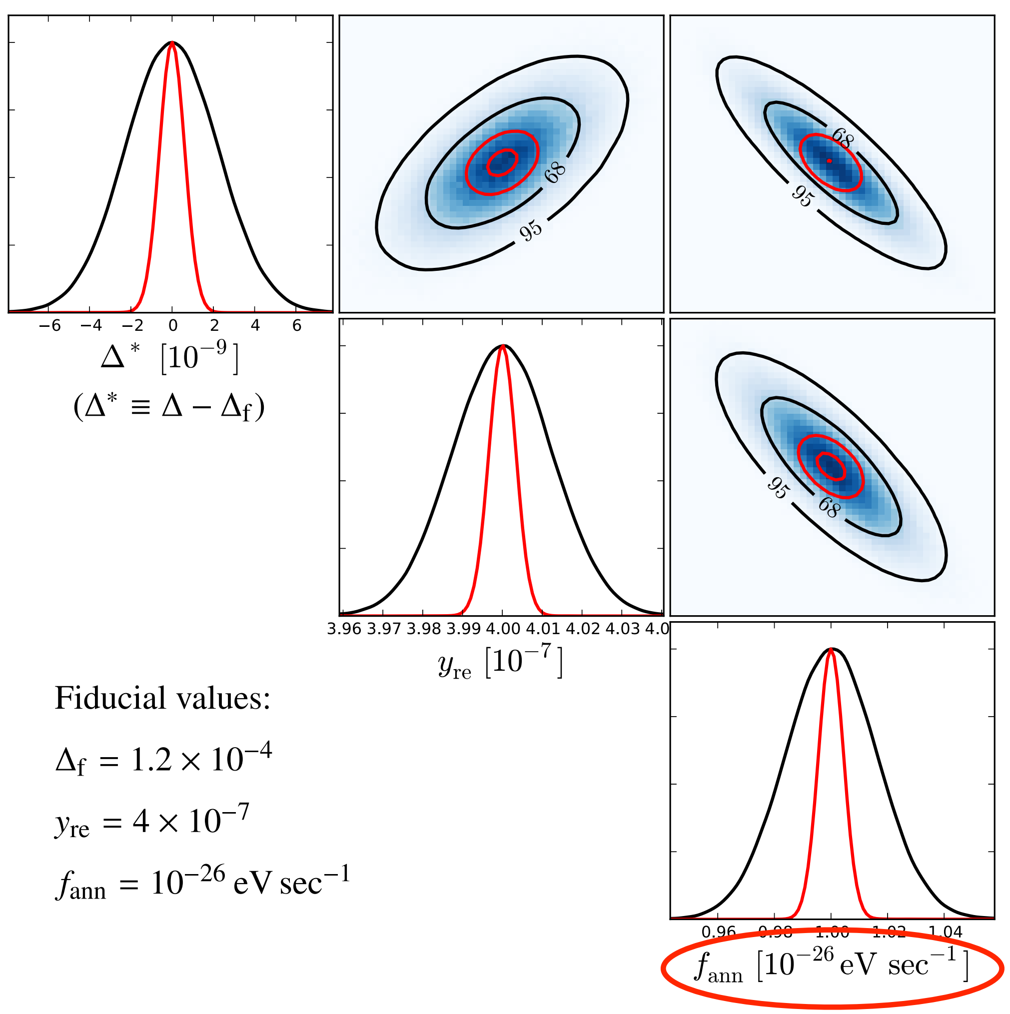
JC & Sunyaev, 2012

Compressing the information of the distortion signal

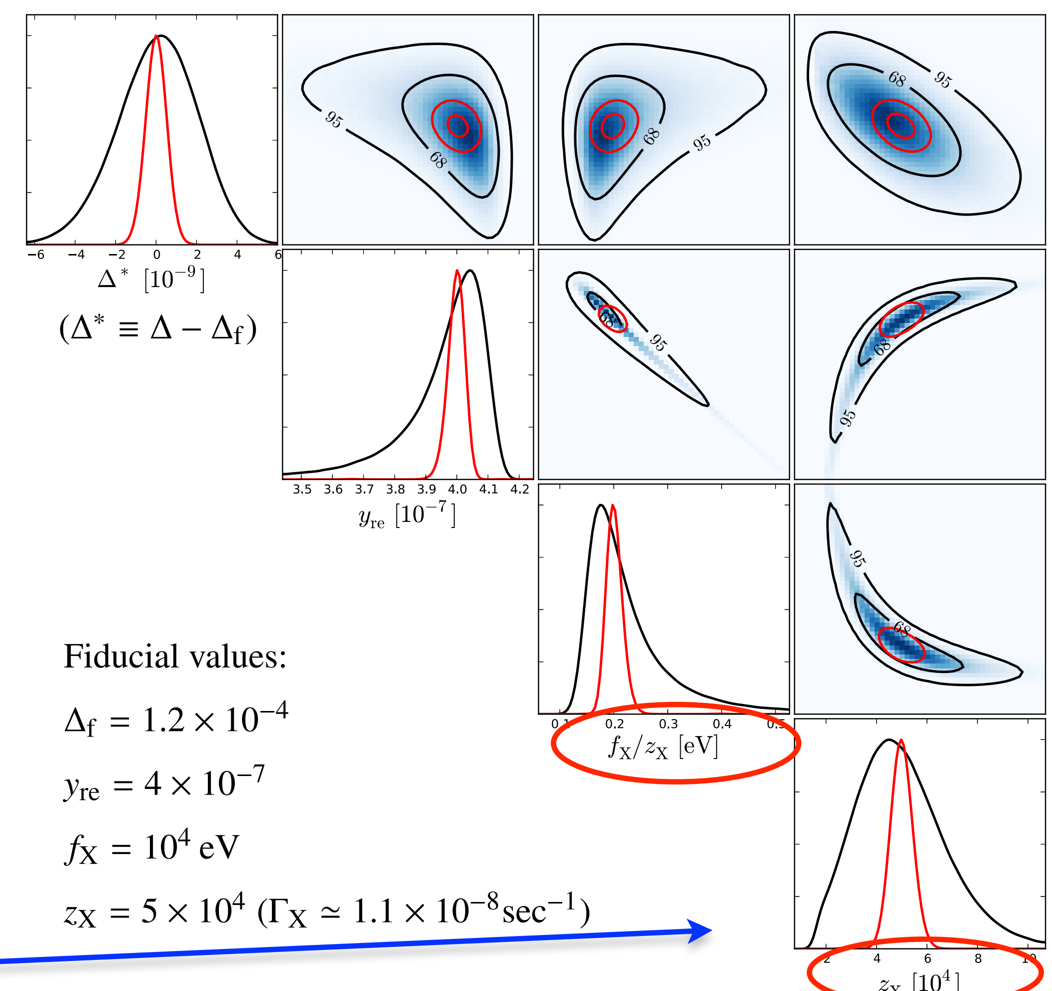
Why model-independent approach to distortion signal

- 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

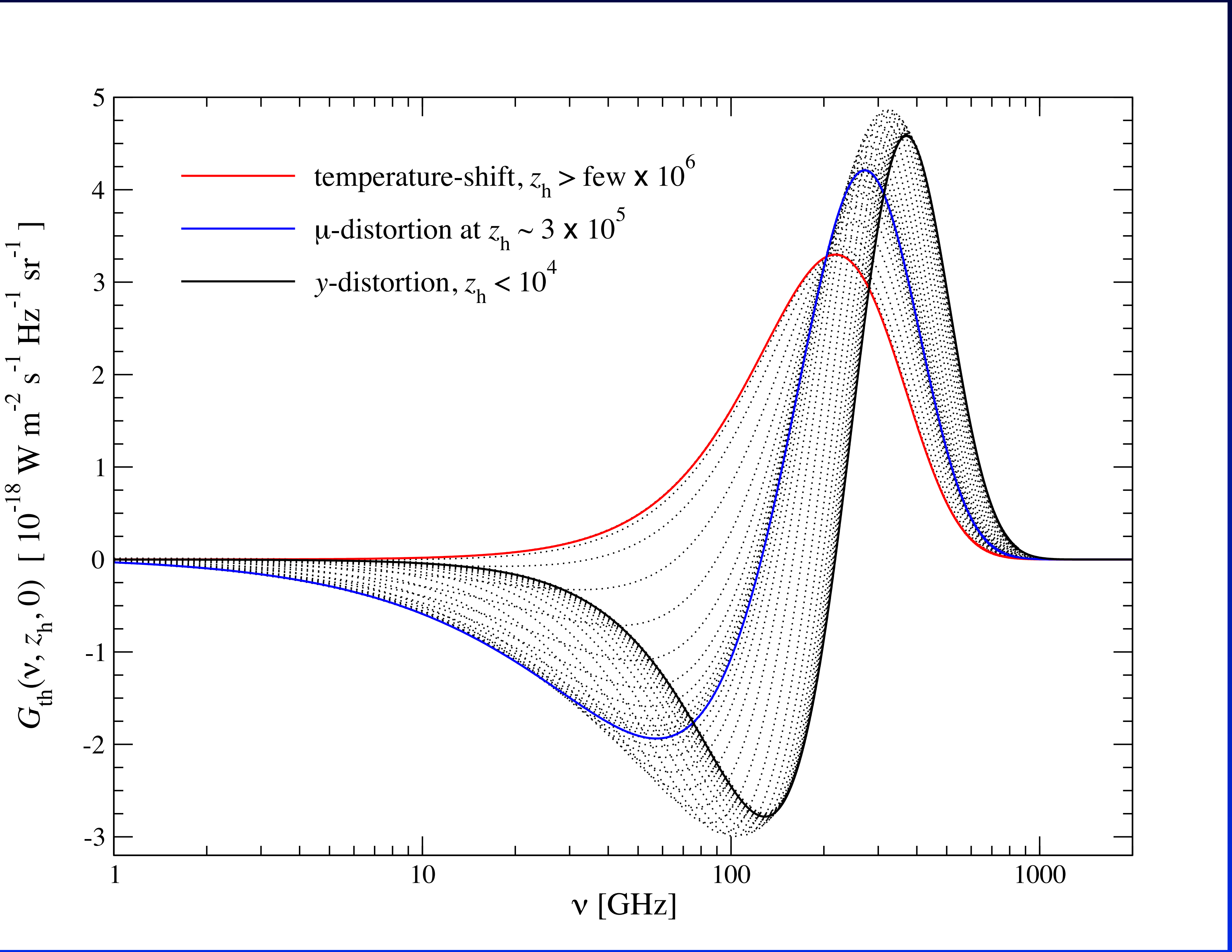


Decaying particle scenario



How do we compare these?

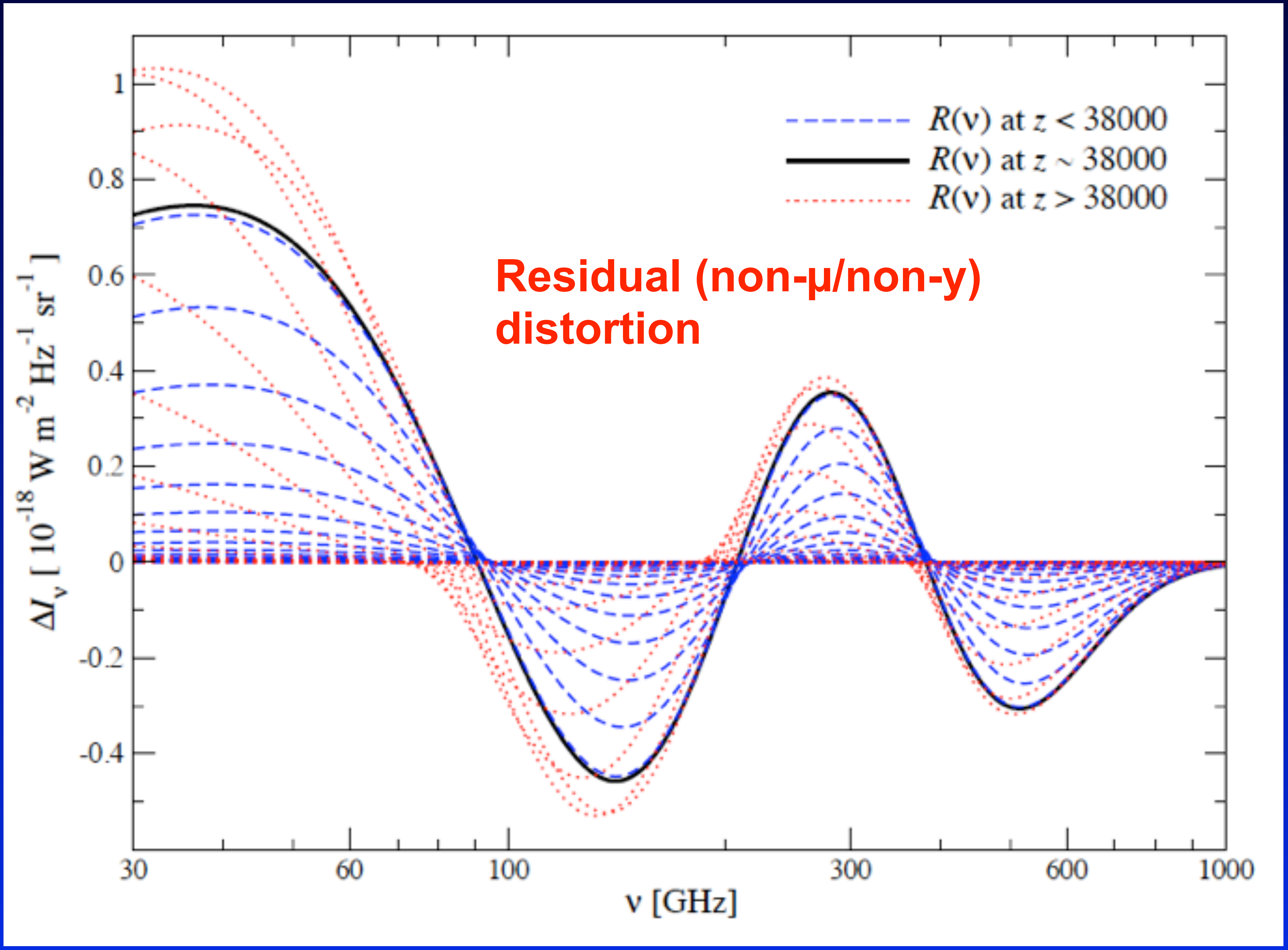
Using signal eigenmodes to compress the distortion data



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

JC & Jeong, 2013

Using signal eigenmodes to compress the distortion data



JC & Jeong, 2013

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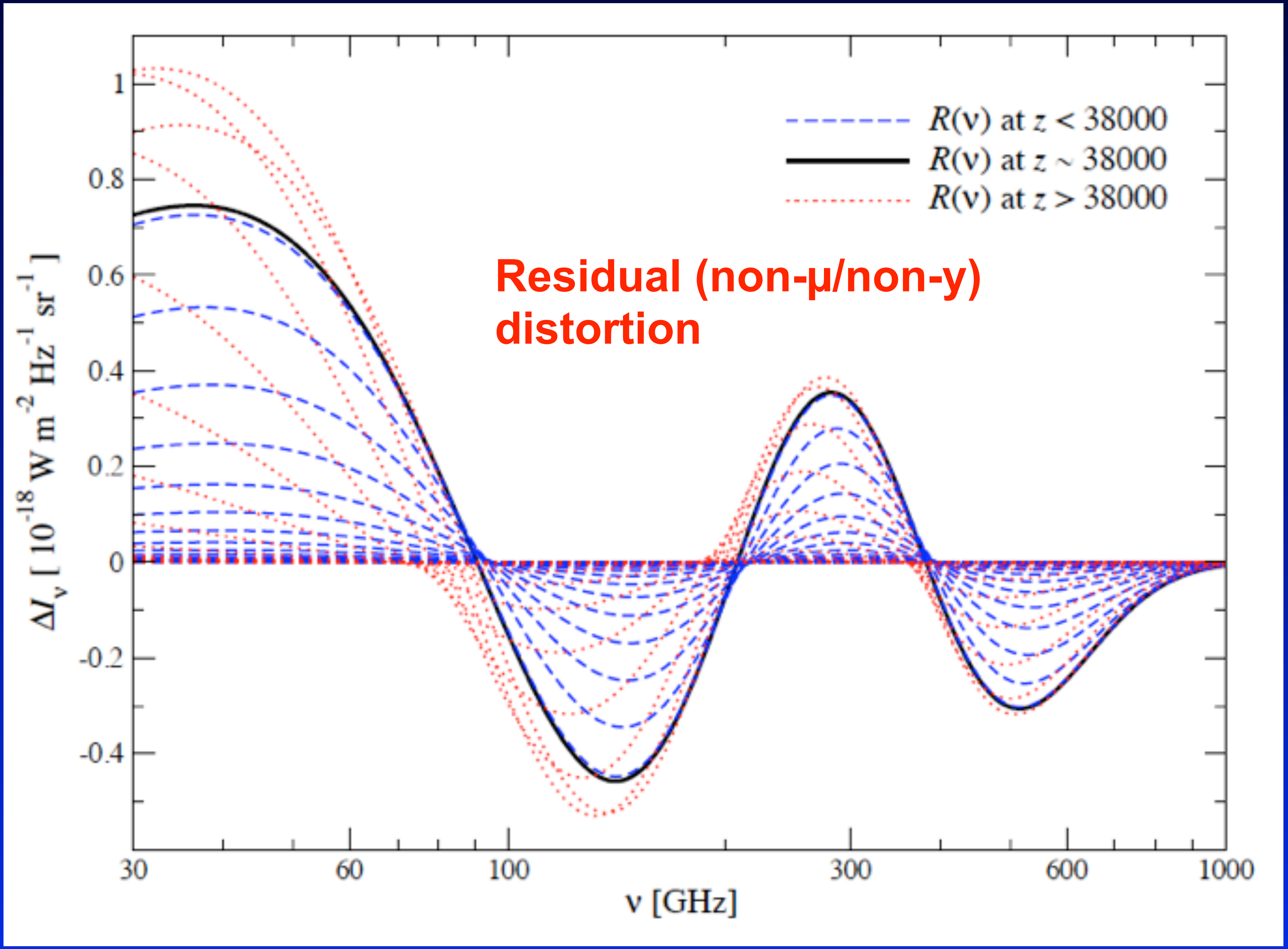
Using signal eigenmodes to compress the distortion data



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

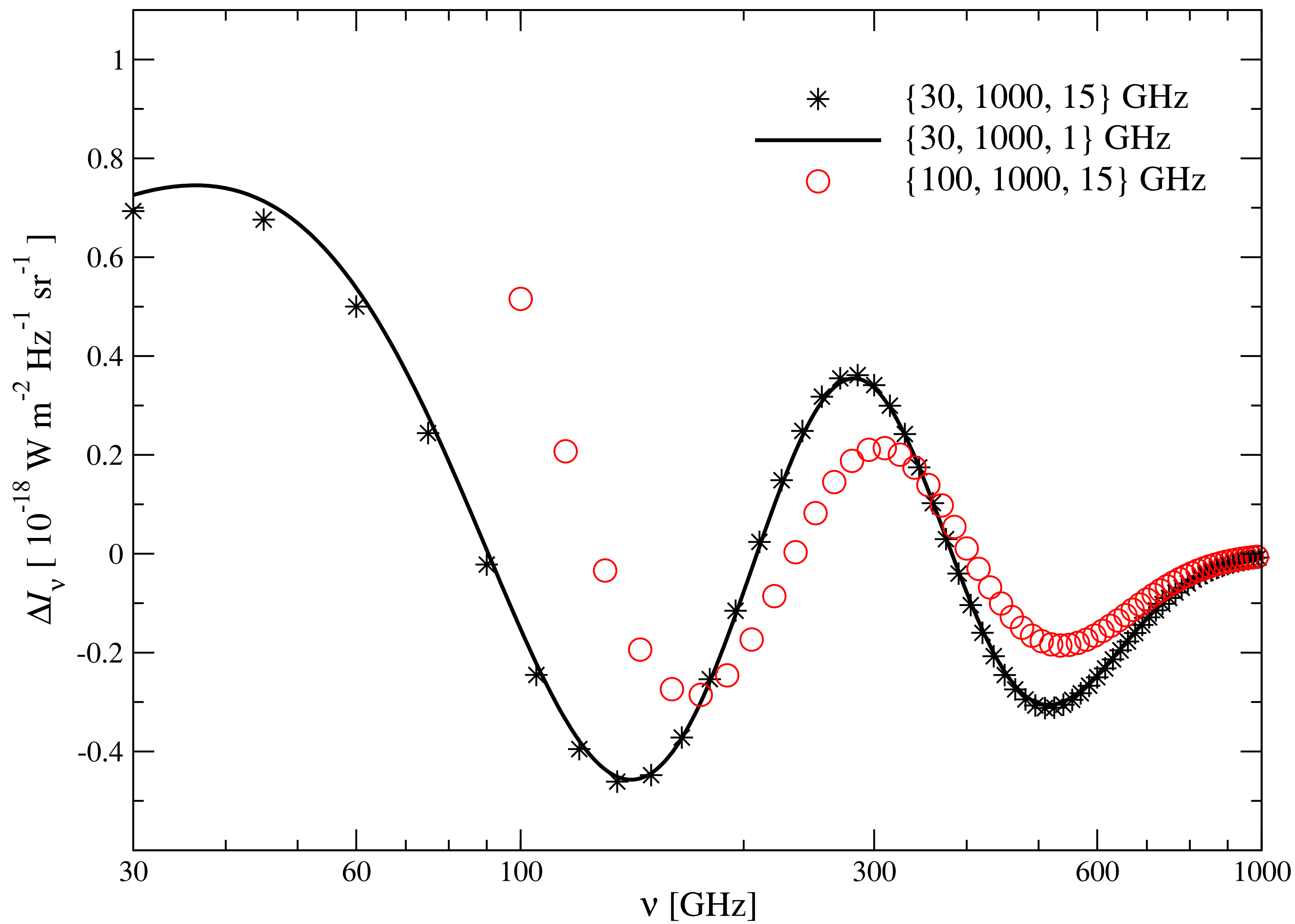
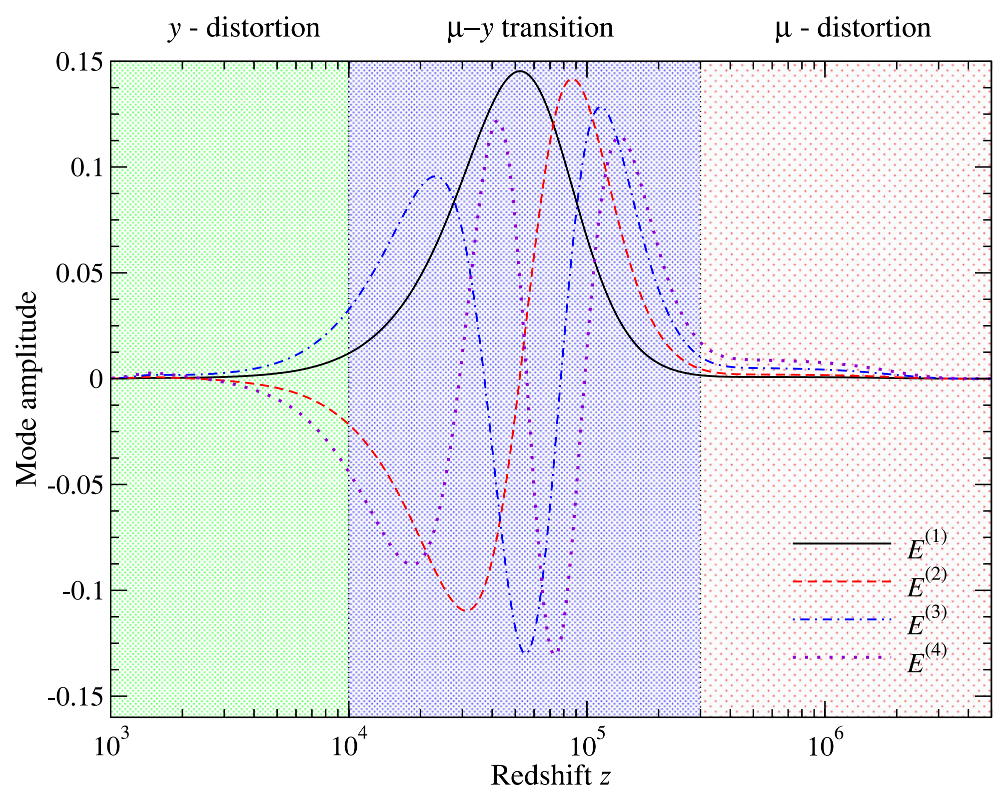


Figure 3. Residual function at redshift $z \simeq 38\,000$ but for different instrumental settings. The annotated values are $\{\nu_{\rm min}, \nu_{\rm max}, \Delta\nu_{\rm s}\}$ and we assumed diagonal noise covariance.

JC & Jeong, 2013

Eigenmodes for a PIXIE-type experiment



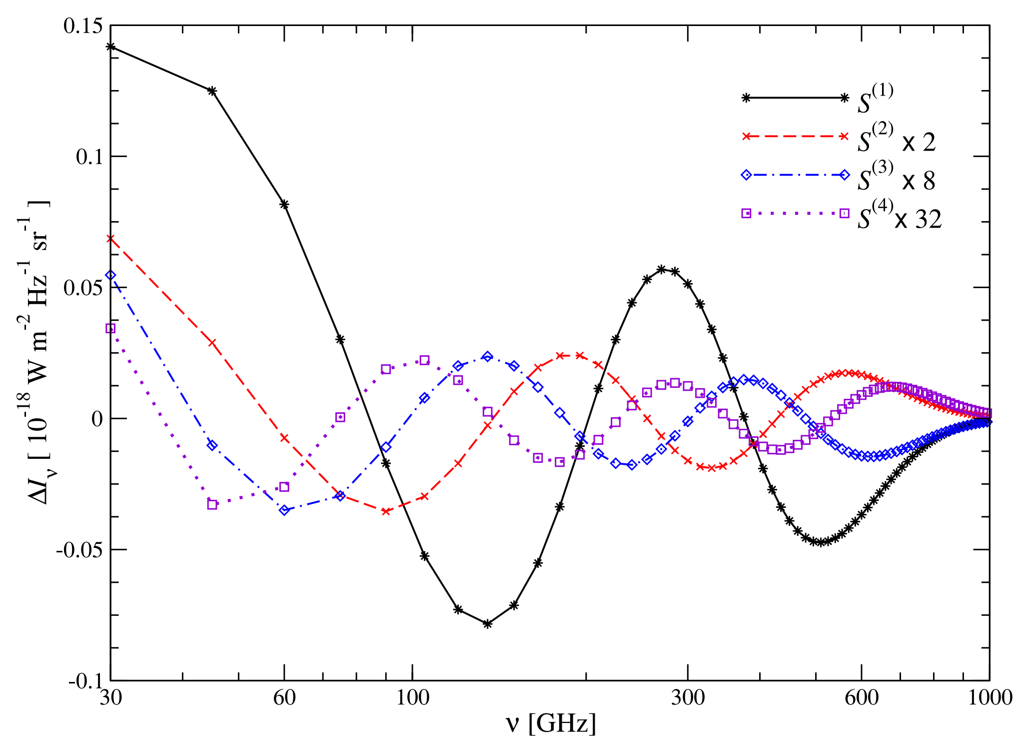


Figure 4. First few eigenmodes $\boldsymbol{E}^{(k)}$ and $\boldsymbol{S}^{(k)}$ for *PIXIE*-type settings ($\nu_{\rm min} = 30\,$GHz, $\nu_{\rm max} = 1000\,$GHz and $\Delta\nu_{\rm s} = 15\,$GHz). In the mode construction, we assumed that energy release only occurred at $10^3 \leq z \leq 5 \times 10^6$.

Estimated error bars

(under idealistic assumptions...)

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

$$\Delta y \simeq 1.2 \times 10^{-9}\left(\frac{\Delta I_{\rm c}}{5\,\mathrm{Jy\,sr^{-1}}}\right)$$

$$\Delta \mu \simeq 1.4 \times 10^{-8}\left(\frac{\Delta I_{\rm c}}{5\,\mathrm{Jy\,sr^{-1}}}\right)$$

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 $[10^{-18}\,\mathrm{W\,m^{-2}\,Hz^{-1}\,sr^{-1}}]^2$). 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 ($\{\nu_{\rm min}, \nu_{\rm max}, \Delta\nu_{\rm s}\} = \{30, 1000, 15\}\,$GHz and channel sensitivity $\Delta I_{\rm c} = 5 \times 10^{-26}\,\mathrm{W\,m^{-2}\,Hz^{-1}\,sr^{-1}}$). 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

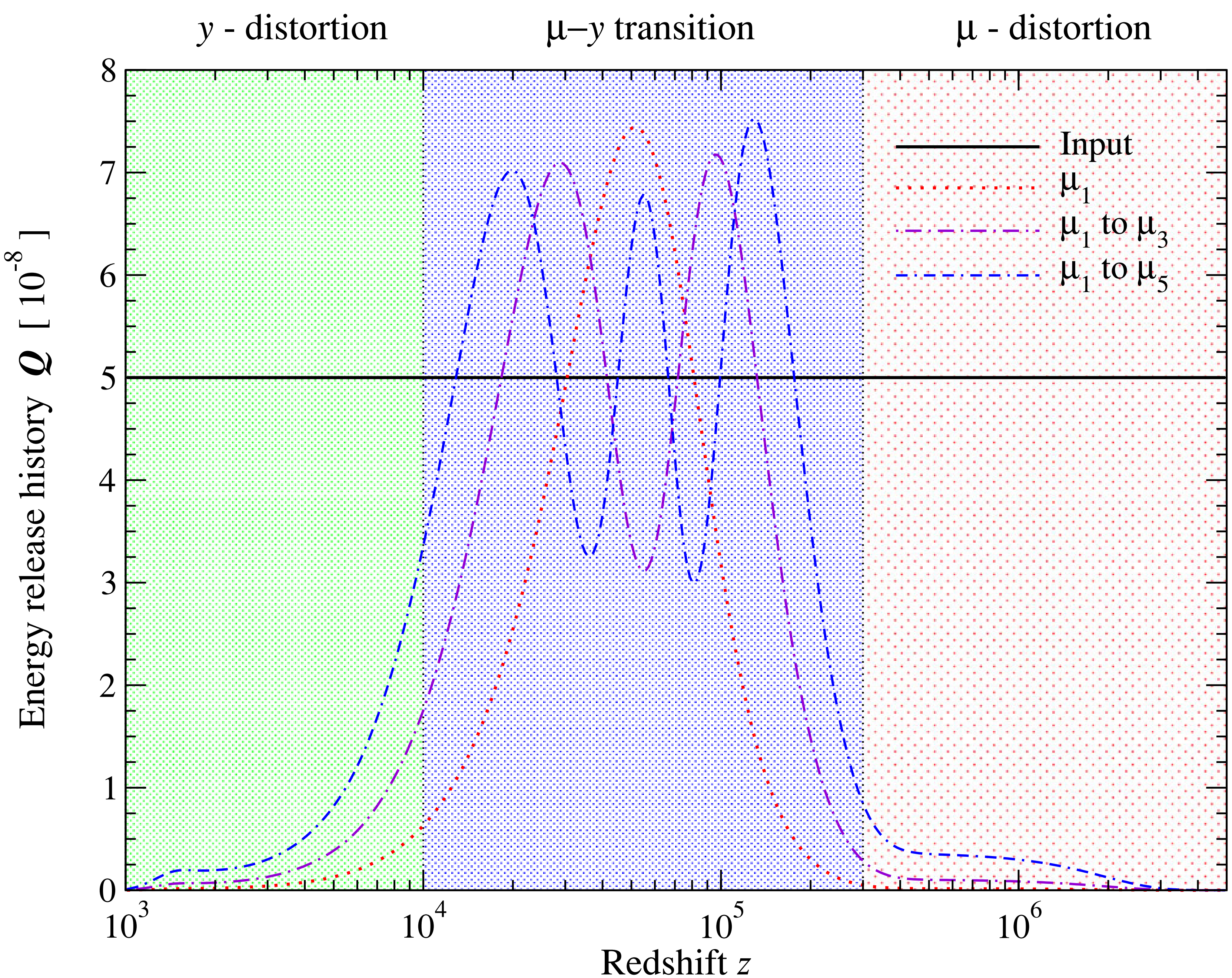


Figure 6. Partial recovery of the input energy-release history, $\mathcal{Q} = 5 \times 10^{-8}$.

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

JC & Jeong, 2013

Signal eigenmodes are uncorrelated by construction

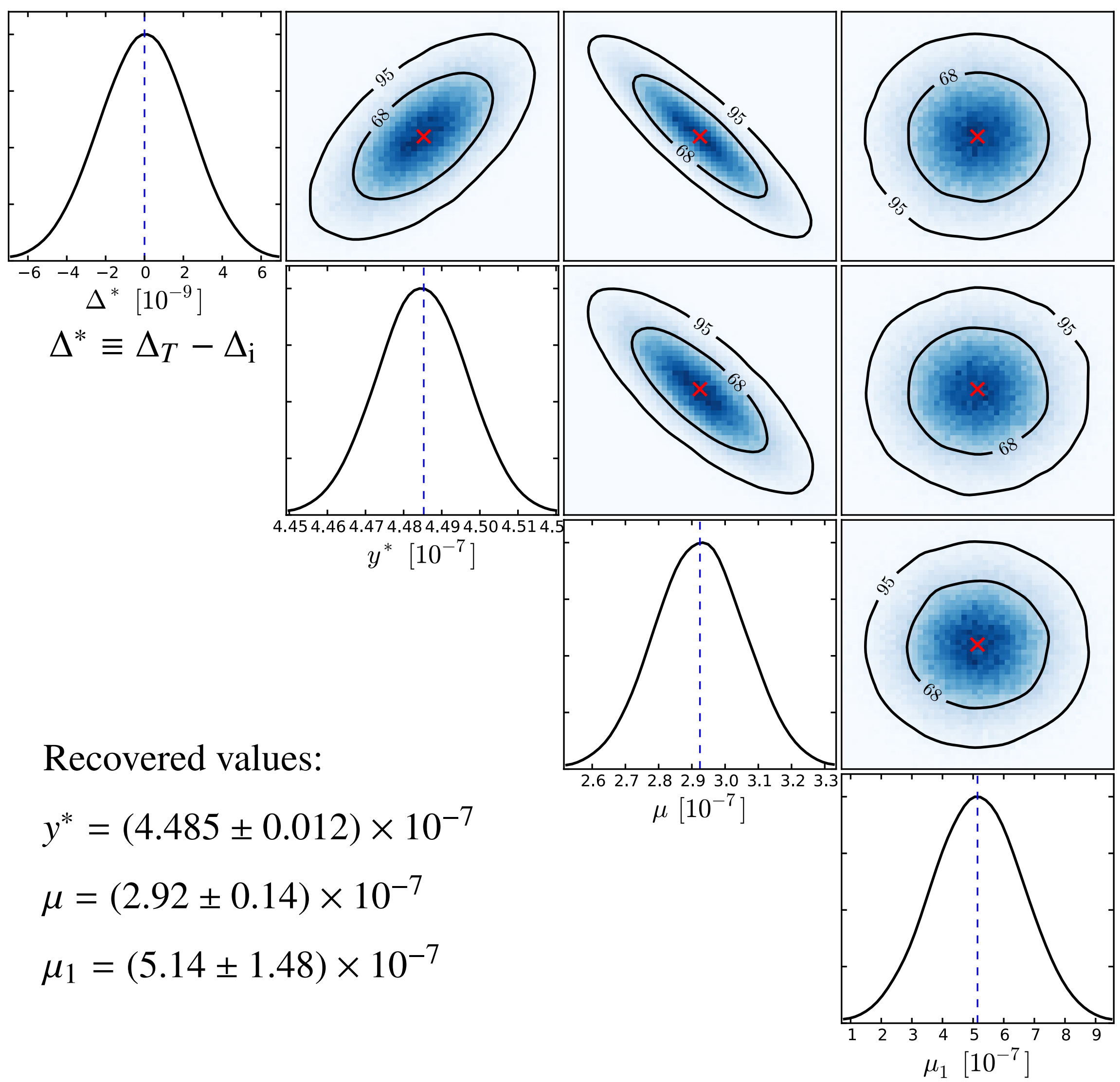
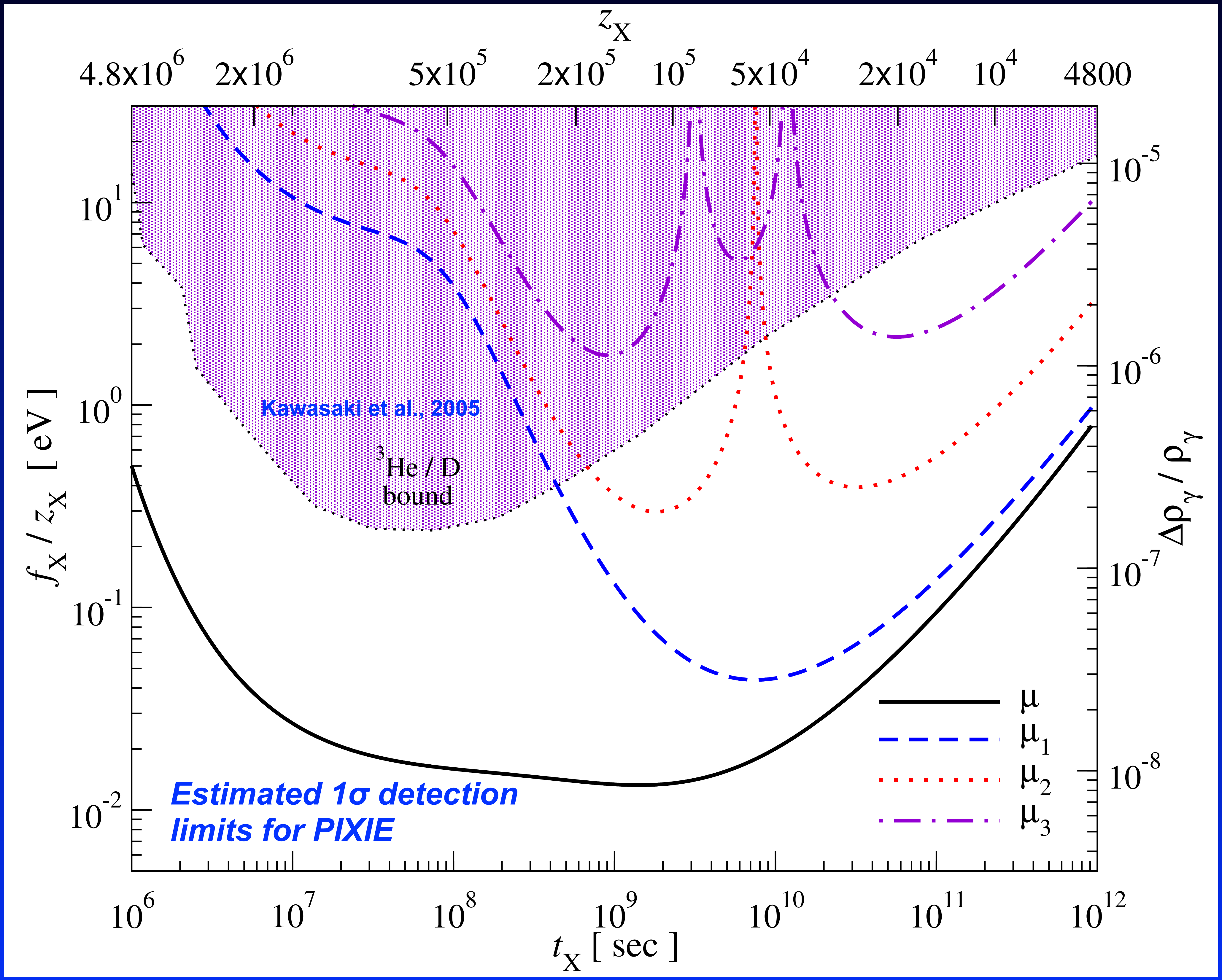


Figure 5. Analysis of energy-release history with $\mathcal{Q}(z) = 5 \times 10^{-8}$ in the redshift interval $10^3 < z < 5 \times 10^6$ using signal eigenmode, $\boldsymbol{S}^{(1)}$ (Fig. 4). We assumed $\{\nu_\mathrm{min}, \nu_\mathrm{max}, \Delta\nu_\mathrm{s}\} = \{30, 1000, 15\}$ GHz and channel 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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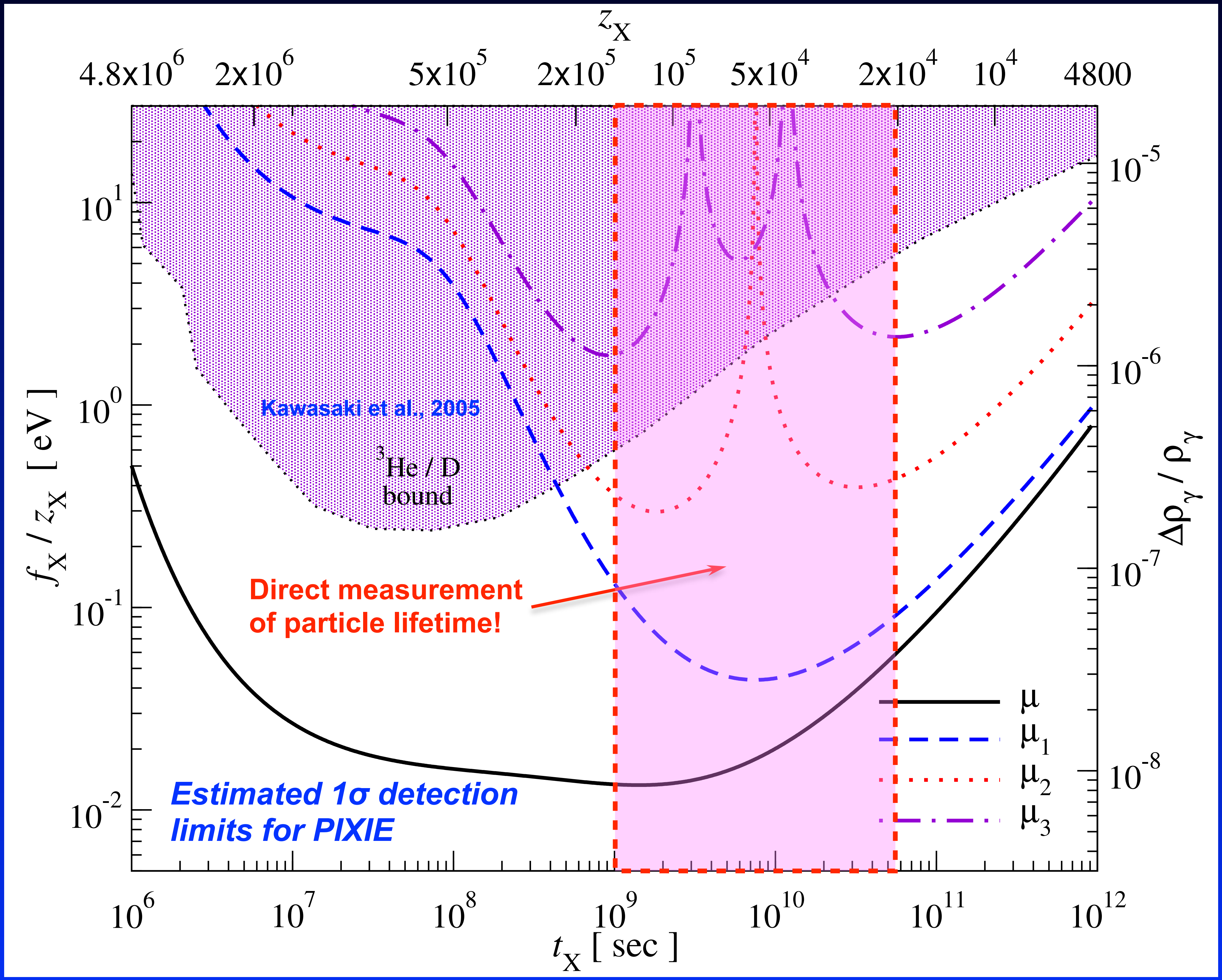

JC & Jeong, 2013

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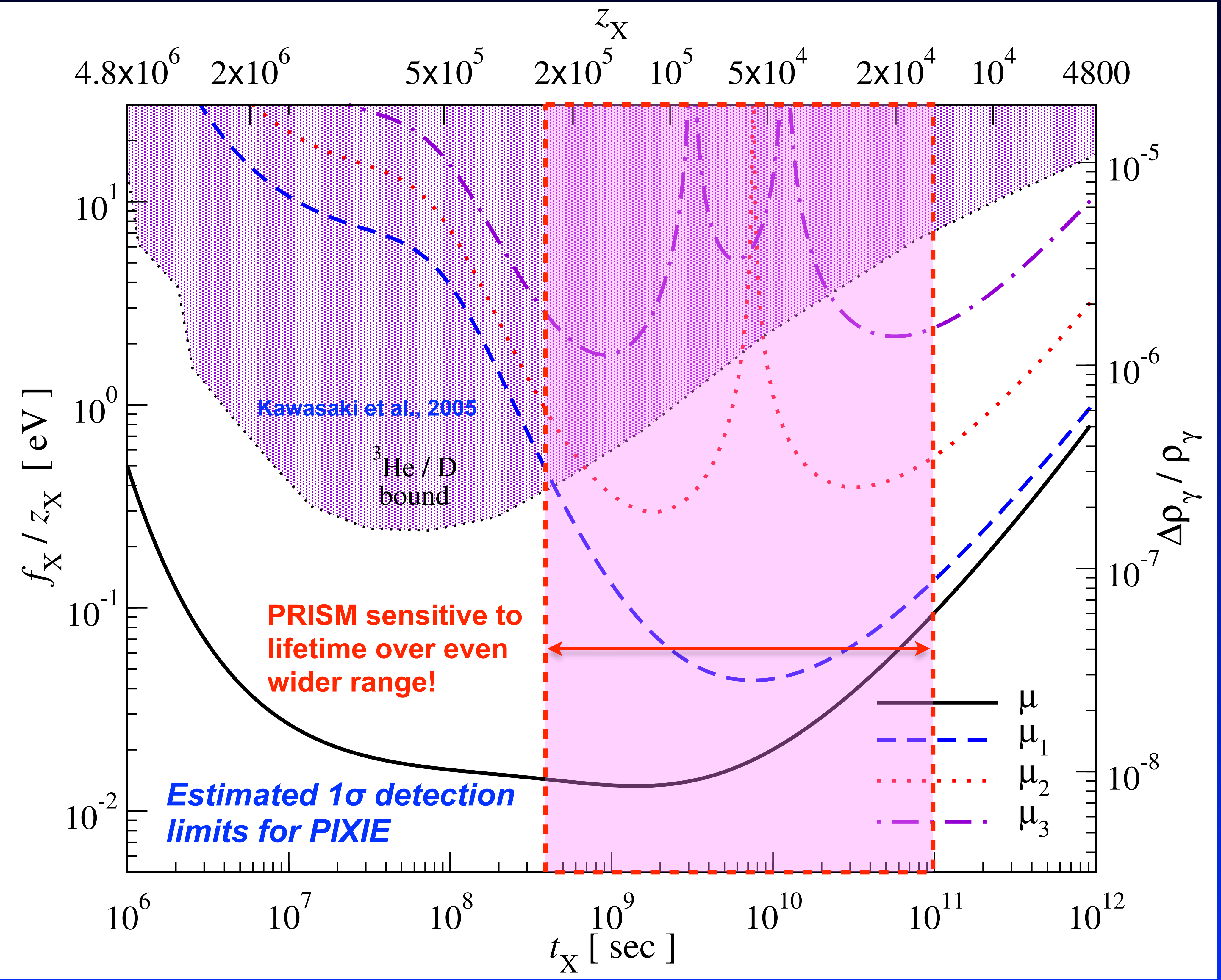
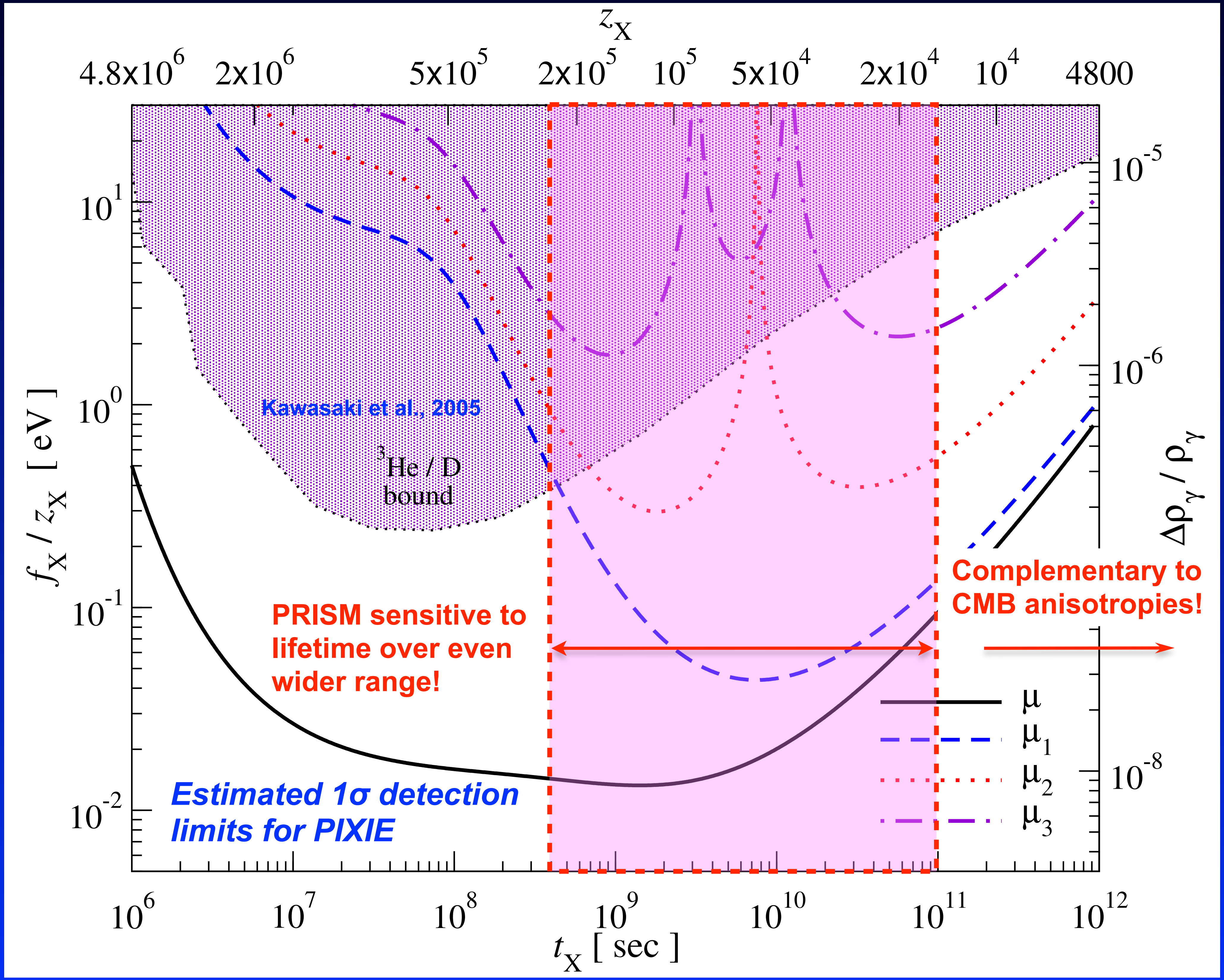


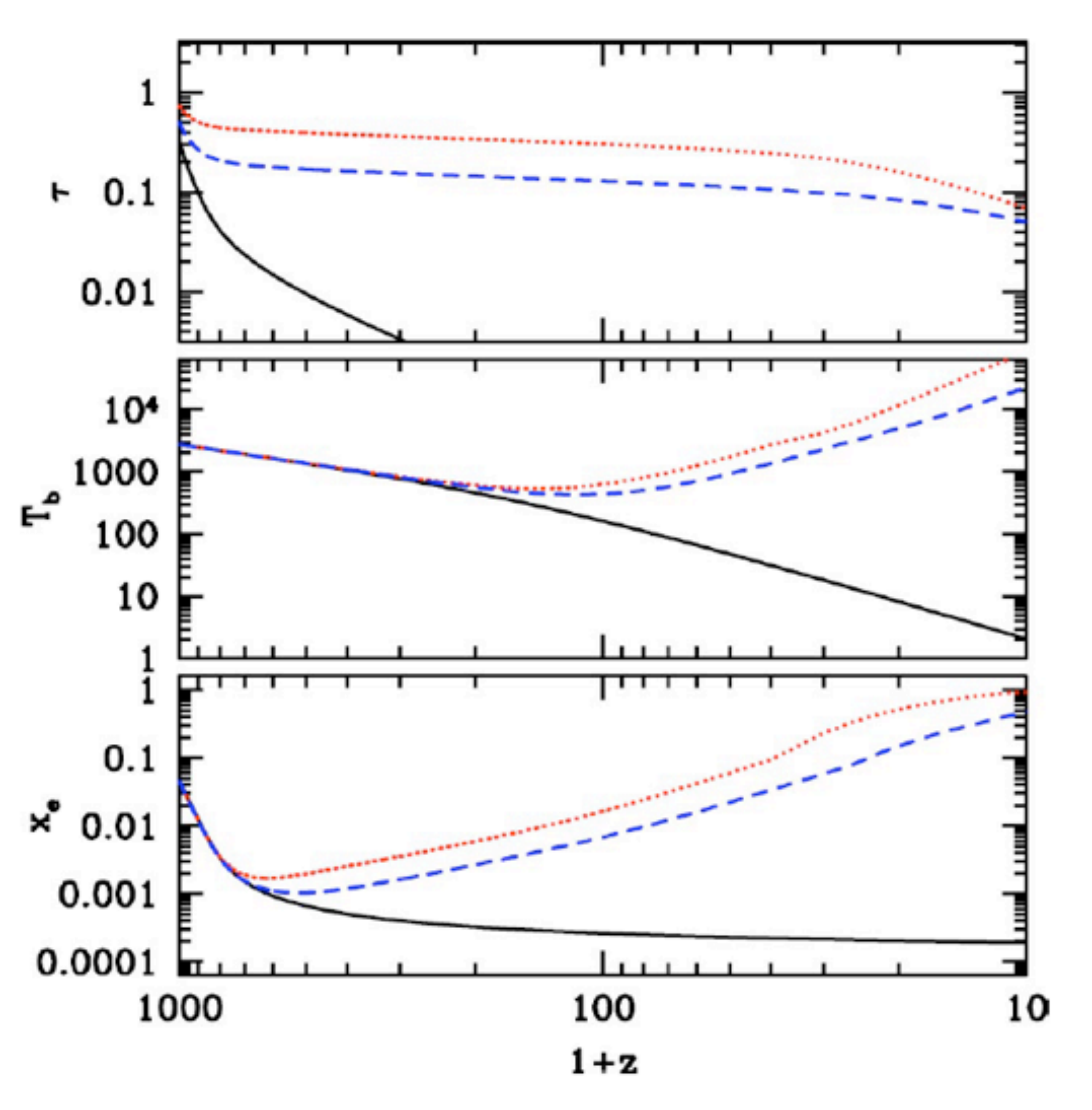
JC & Jeong, 2013

Distortions could shed light on decaying (DM) particles!



JC & Jeong, 2013

Decaying particle during & after recombination

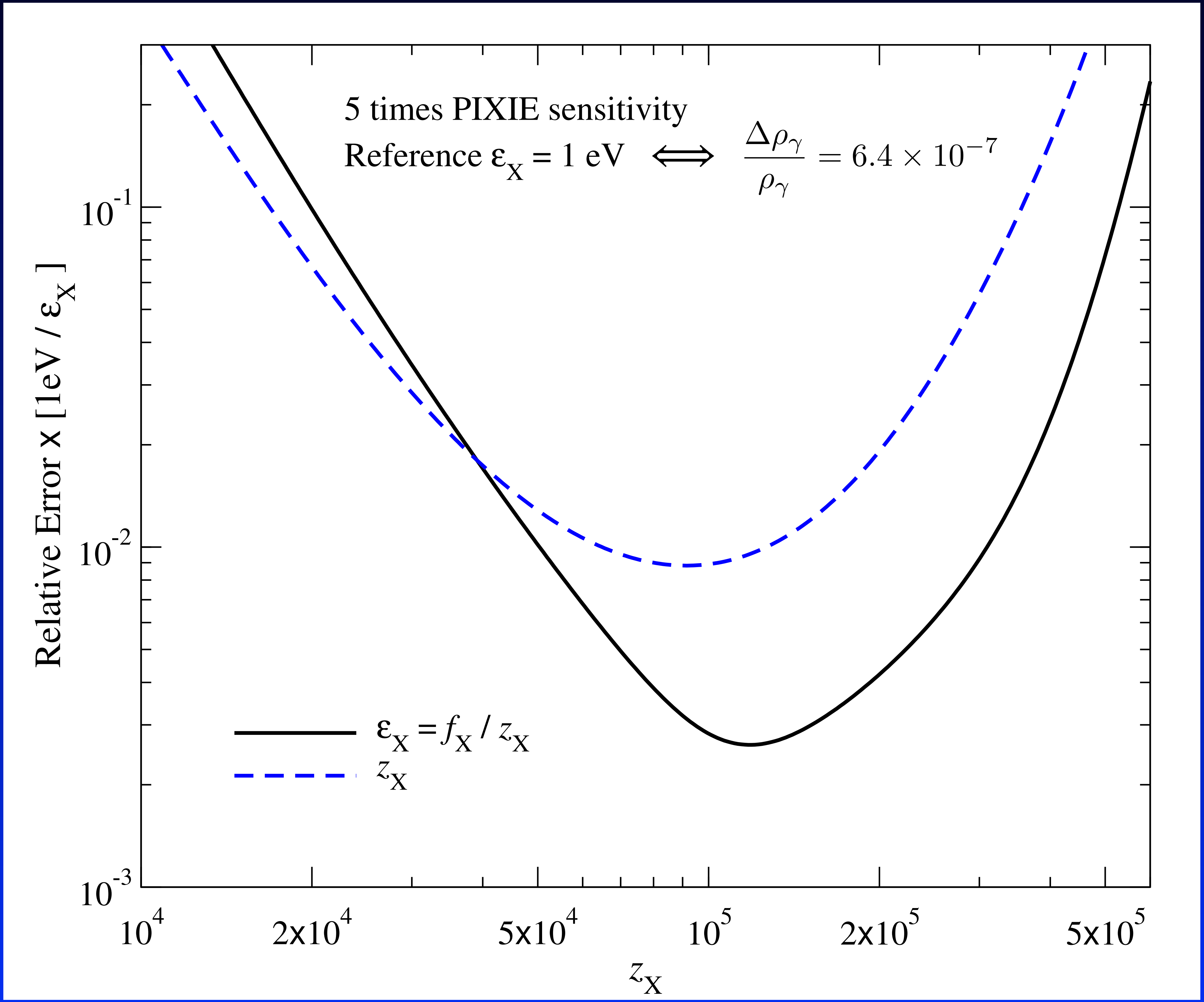


Chen & Kamionkowski, 2004

- Modify recombination history
- this changes Thomson visibility function and thus the CMB temperature and polarization power spectra
- ⇒ CMB anisotropies allow

  probing particles with lifetimes ≳ 10^{12} sec
- CMB spectral distortions provide complementary probe!

Decaying particle forecasted error



JC & Jeong, 2013

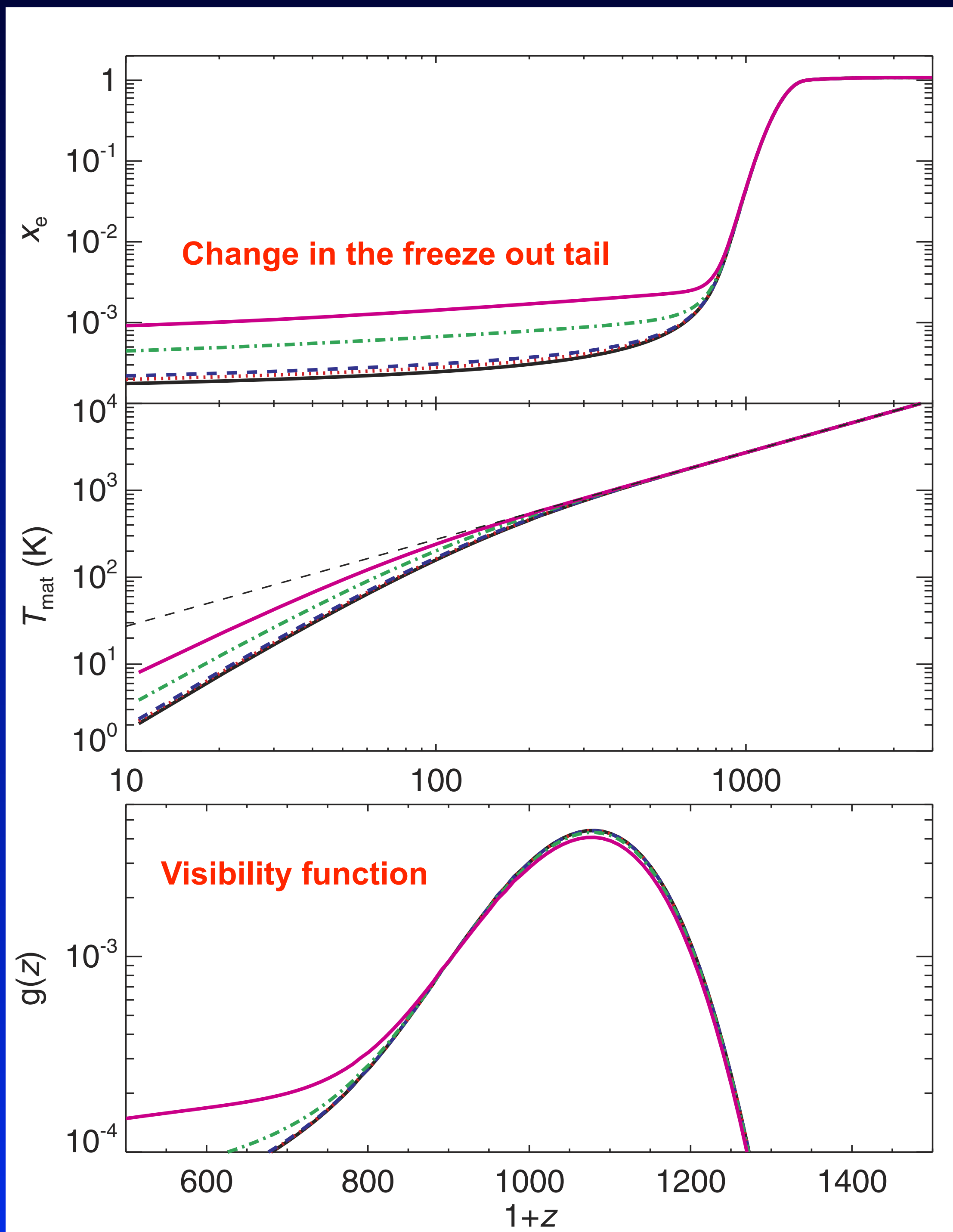
Annihilating particles / dark matter

Why is this interesting and what are the questions

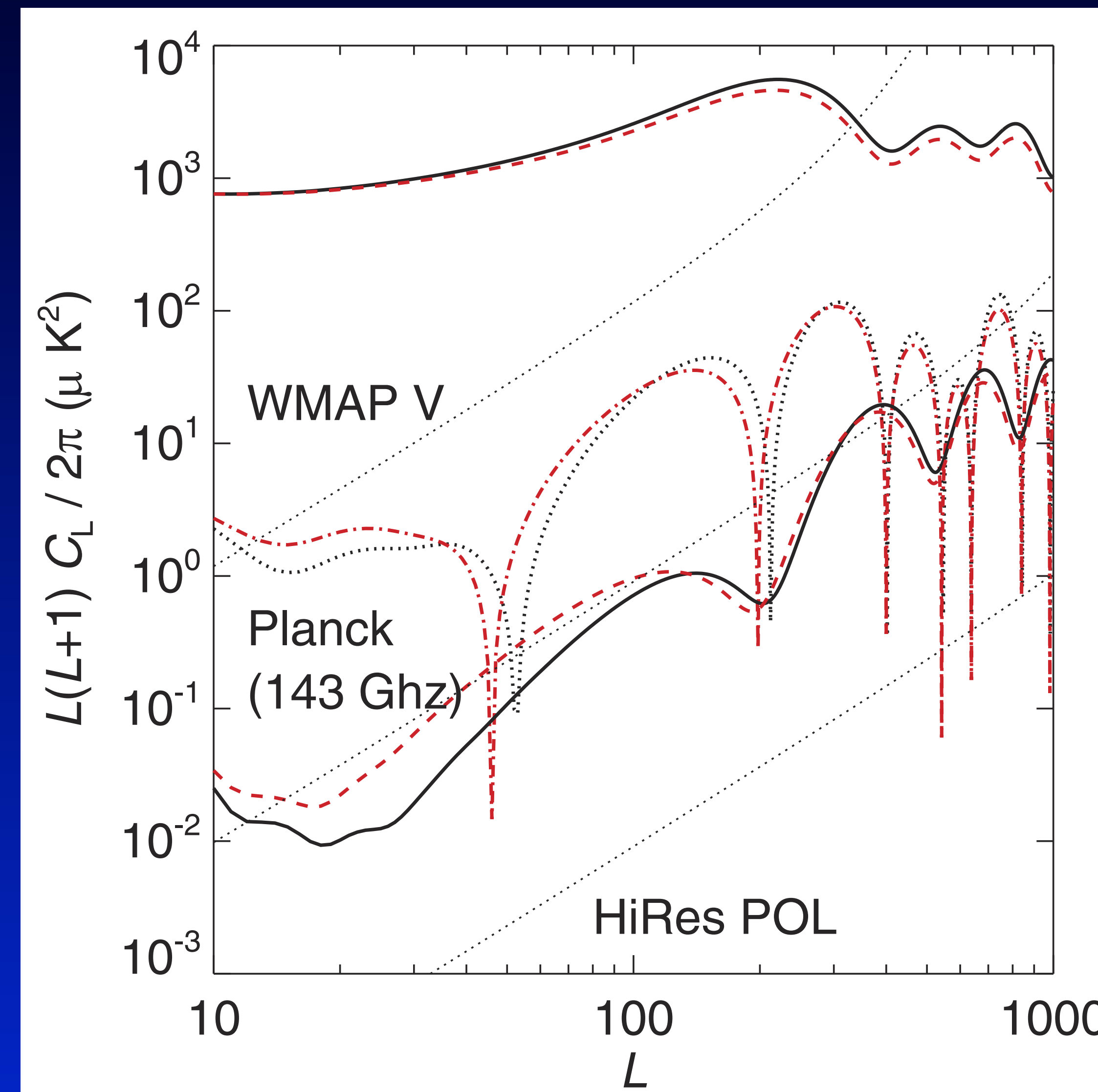
- Thermally produced WIMP should naturally annihilate even today
- CMB anisotropy and X-ray / γ-ray constraints complementary
- s- and p-wave annihilation $\Longrightarrow \langle \sigma v \rangle \propto T^n$
- Sommerfeld enhanced cross sections
- Boost by structure formation since $\langle N_X \rangle^2 \lesssim \langle N_X^2 \rangle$
- Computation is limited by particle physics (annihilation channels; energy transfer efficiencies, etc.)
- CMB spectral distortions can be used to as a consistency test
- CMB anisotropies insensitive to p-wave annihilation
- Recombination spectrum also affected (see next lecture)

Changes of CMB anisotropies by annihilating particles

95% c.l.



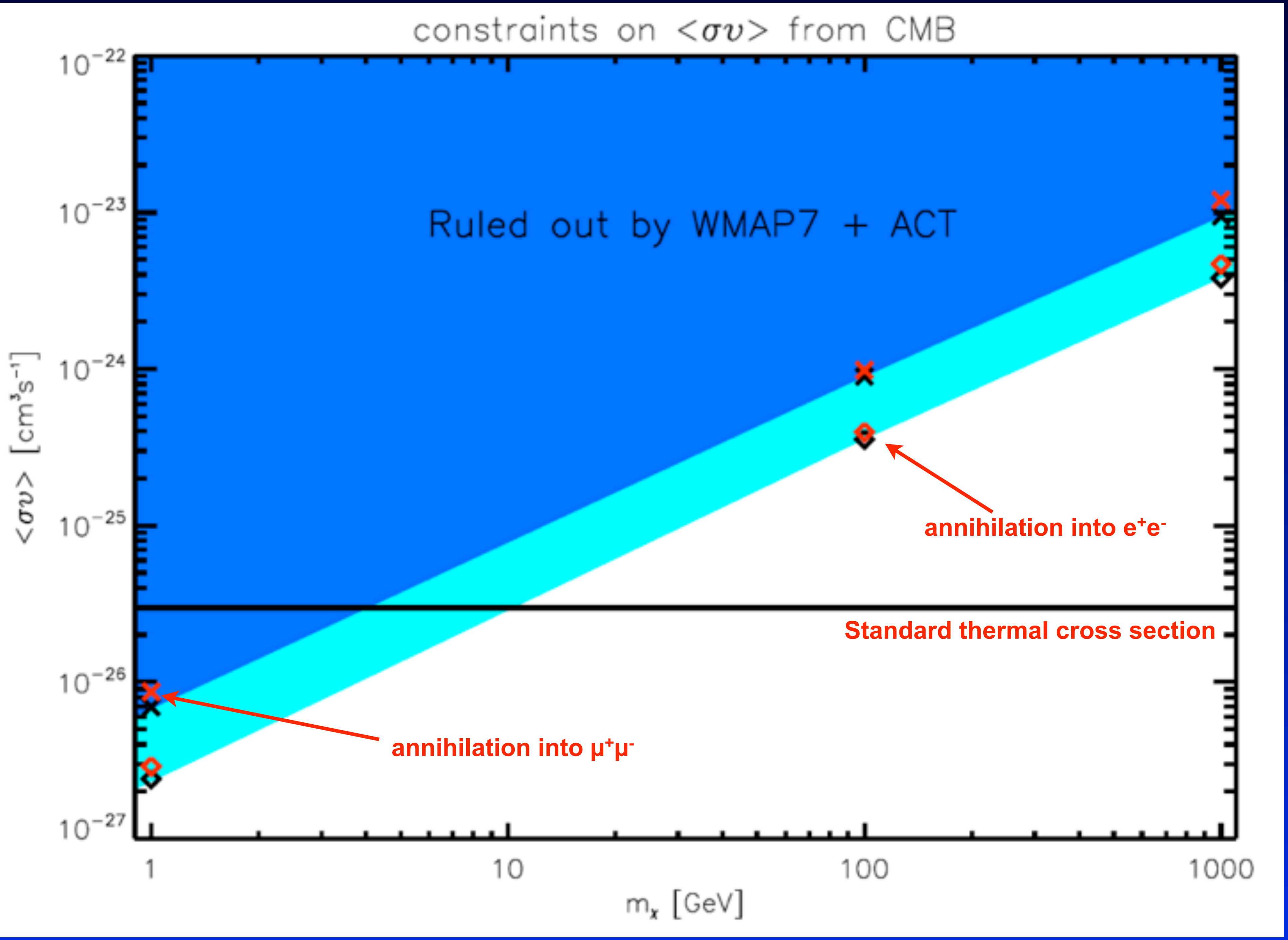
Padmanabhan & Finkbeiner, 2005



- more damping because τ increases
- change close to visibility maximum → shift in peak positions

CMB limits on annihilation cross section

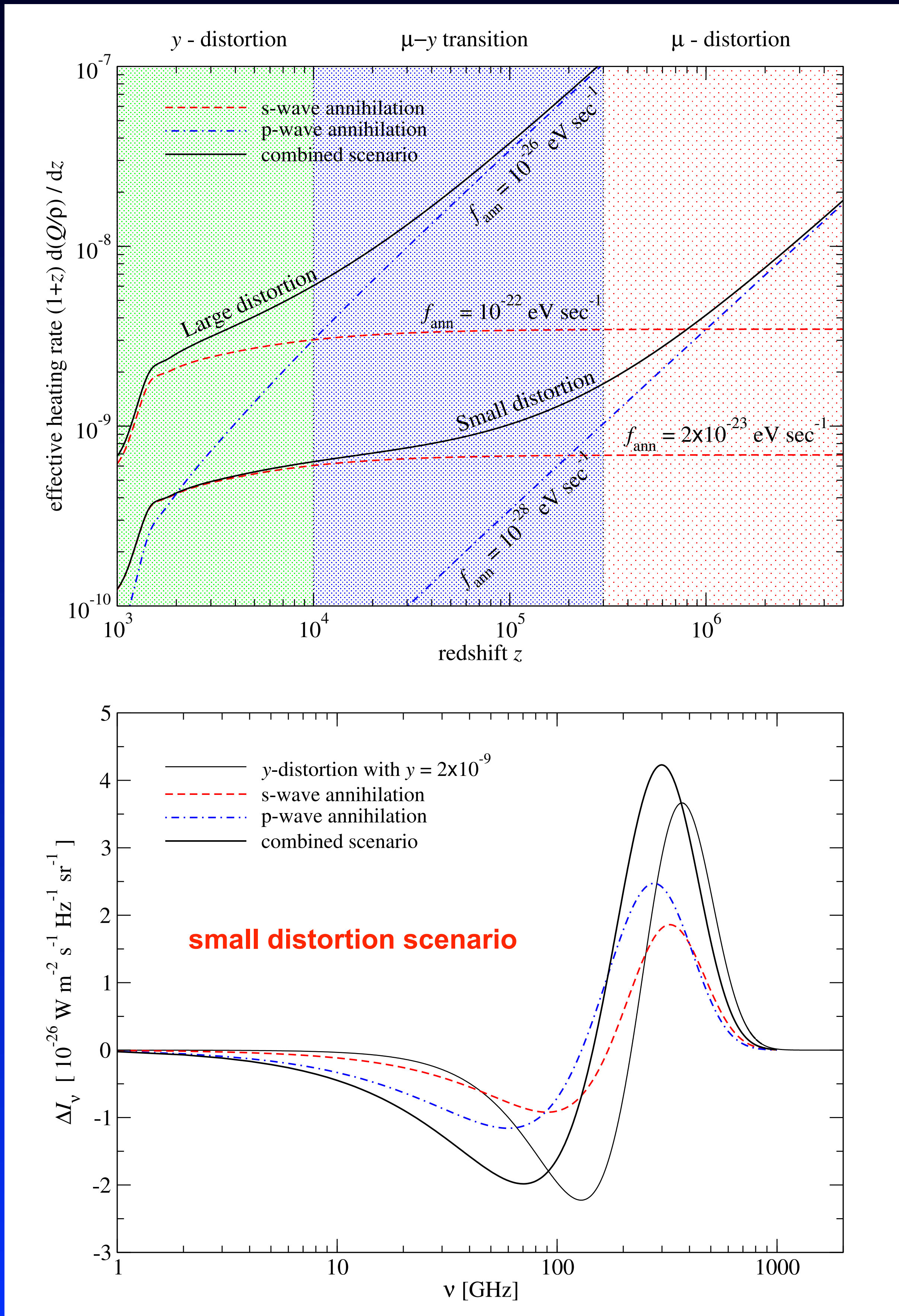
95% c.l.



- s-wave annihilation
- Planck limits still not as tight (polarization data)
- in the future factor of ~ 5-10 improvement possible
- constraints depend on DM model

Galli et al, 2011 (similar to Huetsi et al, 2011)

Examples of annihilating particle scenarios

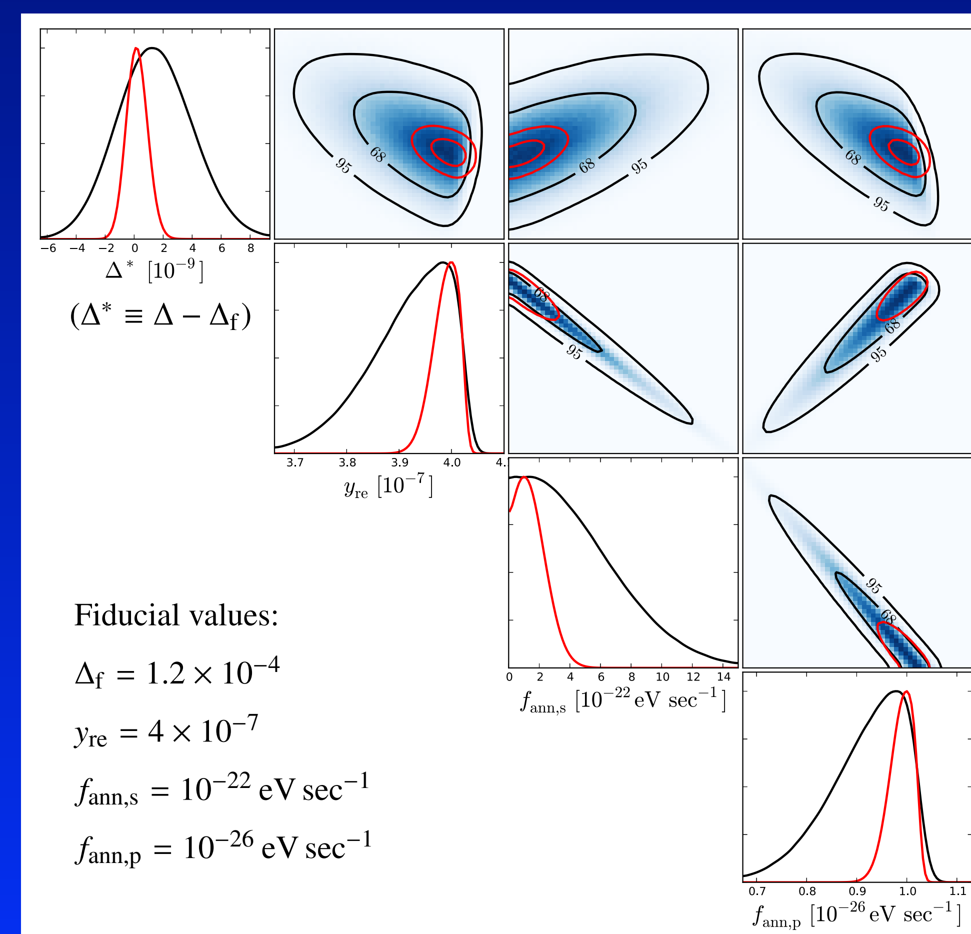


- $f_{\rm ann}$ ≡ annihilation efficiency
  (Padmanabhan & Finkbeiner, 2005; JC 2010)
- CMB anisotropy constraint

$$f_{\rm ann} \lesssim 2\times10^{-23}\,{\rm eV s^{-1}}$$

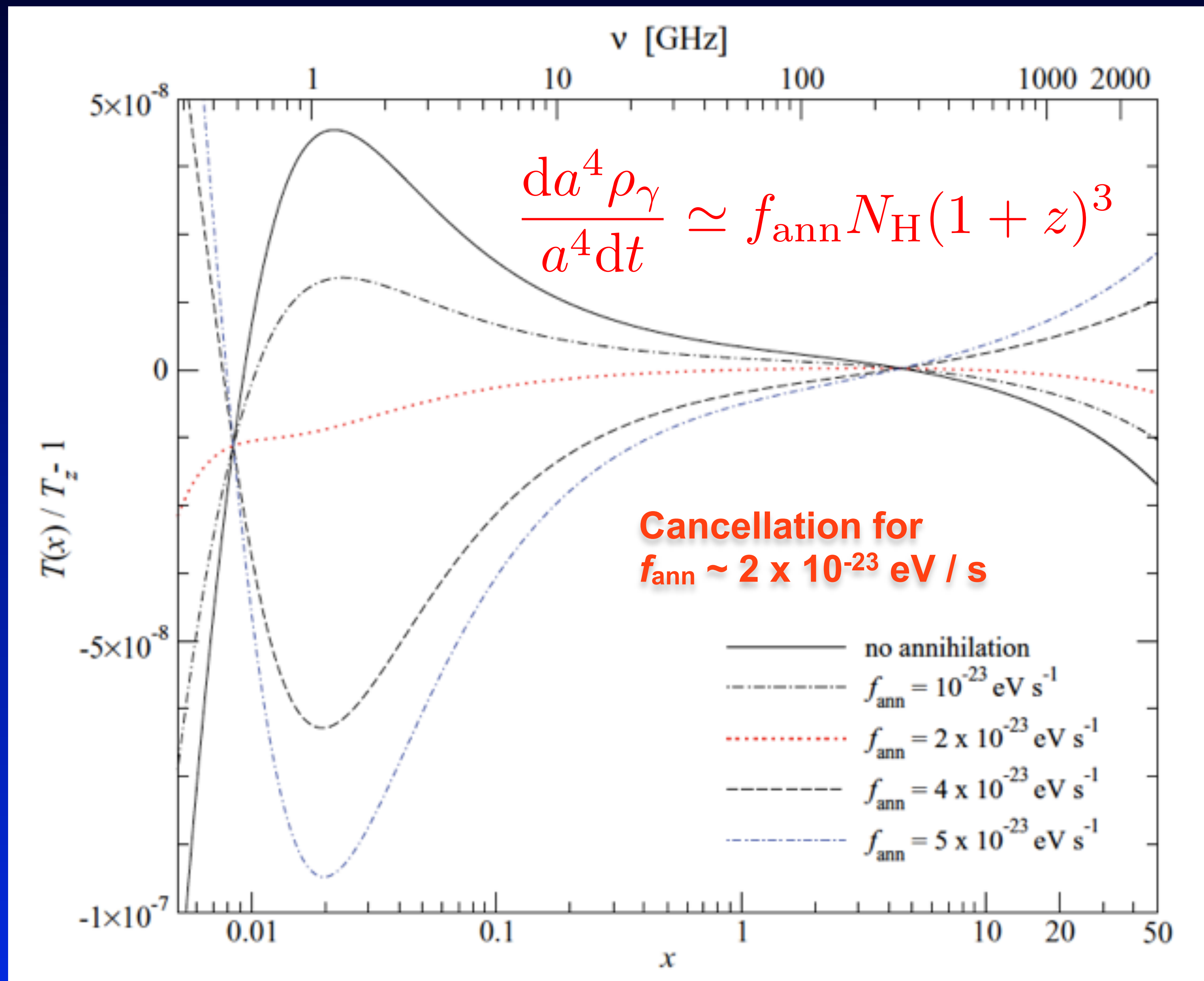
(Galli et al., 2009; Slatyer et al., 2009; Huetsi et al., 2009, 2011)

$$\frac{{\rm d}E}{{\rm d}t} = f_{\rm ann} N_{\rm H} (1+z)^{3+n}$$



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

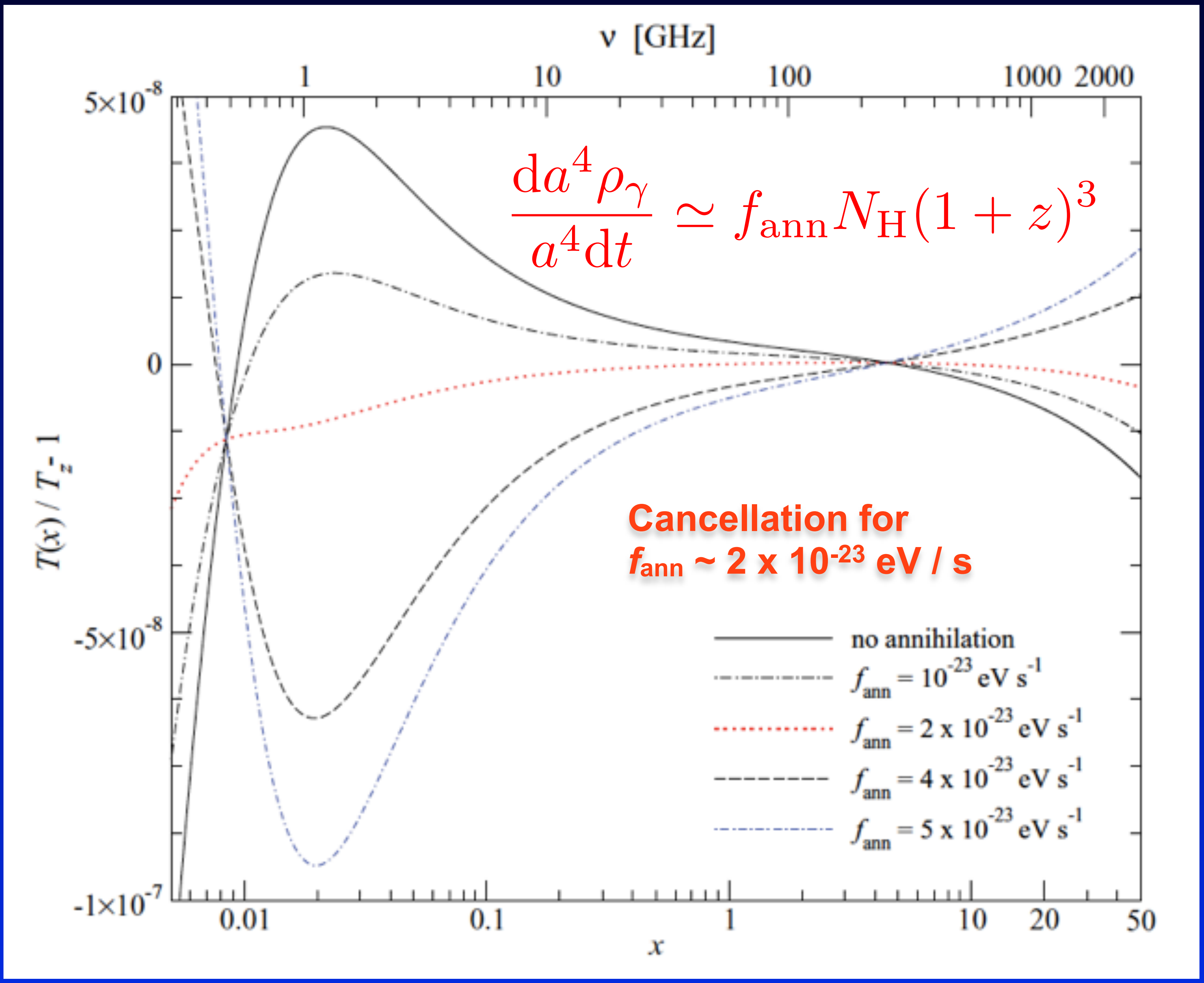
Cancellation of cooling by heating from annihilation



JC & Sunyaev, 2012

$$f_{\rm ann} = 1.1 \times 10^{-24} \, \frac{100\mathrm{GeV}}{M_X c^2} \left[\frac{\Omega_X h^2}{0.11}\right]^2 \frac{\langle \sigma v \rangle}{3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}}$$

Cancellation of cooling by heating from annihilation



- f_{ann} ≡ annihilation efficiency
  (Padmanabhan & Finkbeiner, 2005; JC 2010)
- CMB anisotropy constraint

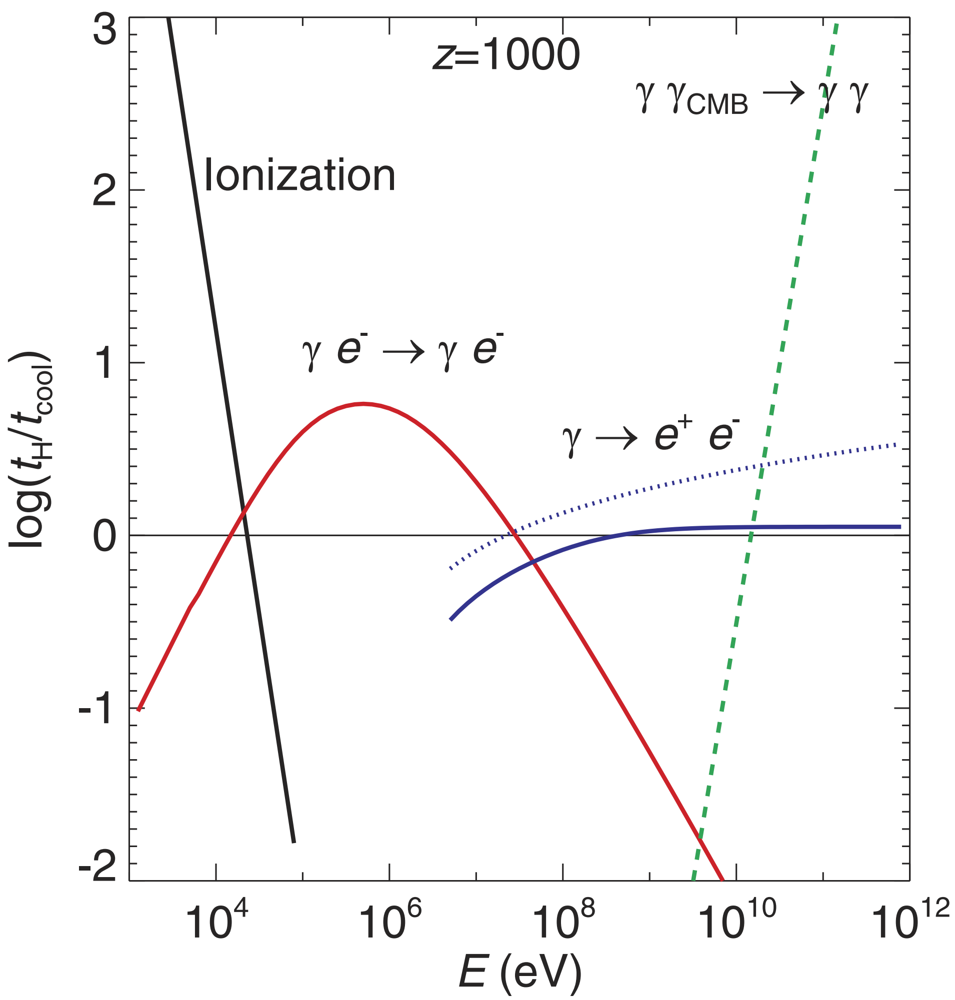
$$f_\mathrm{ann} \lesssim 2\times10^{-23}\mathrm{eV}\mathrm{s}^{-1}$$

(Galli et al., 2009; Slatyer et al., 2009; Huetsi et al., 2009, 2011)

- Limit from Planck satellite will be roughly *6 times stronger* → more precise prediction for the distortion will be possible
- uncertainty dominated by particle physics
- limits from PIXIE/PRISM several times weaker, *but* independent

JC & Sunyaev, 2012

$$f_\mathrm{ann} = 1.1\times10^{-24}\,\frac{100\mathrm{GeV}}{M_X c^2}\left[\frac{\Omega_X h^2}{0.11}\right]^2\frac{\langle\sigma v\rangle}{3\times10^{-26}\mathrm{cm}^3/\mathrm{s}}$$


z=1000
γ γ_CMB → γ γ
Ionization
γ e⁻ → γ e⁻
γ → e⁺ e⁻
log(t_H/t_cool)
3
2
1
0
-1
-2
10^4
10^6
10^8
10^10
10^12
E (eV)