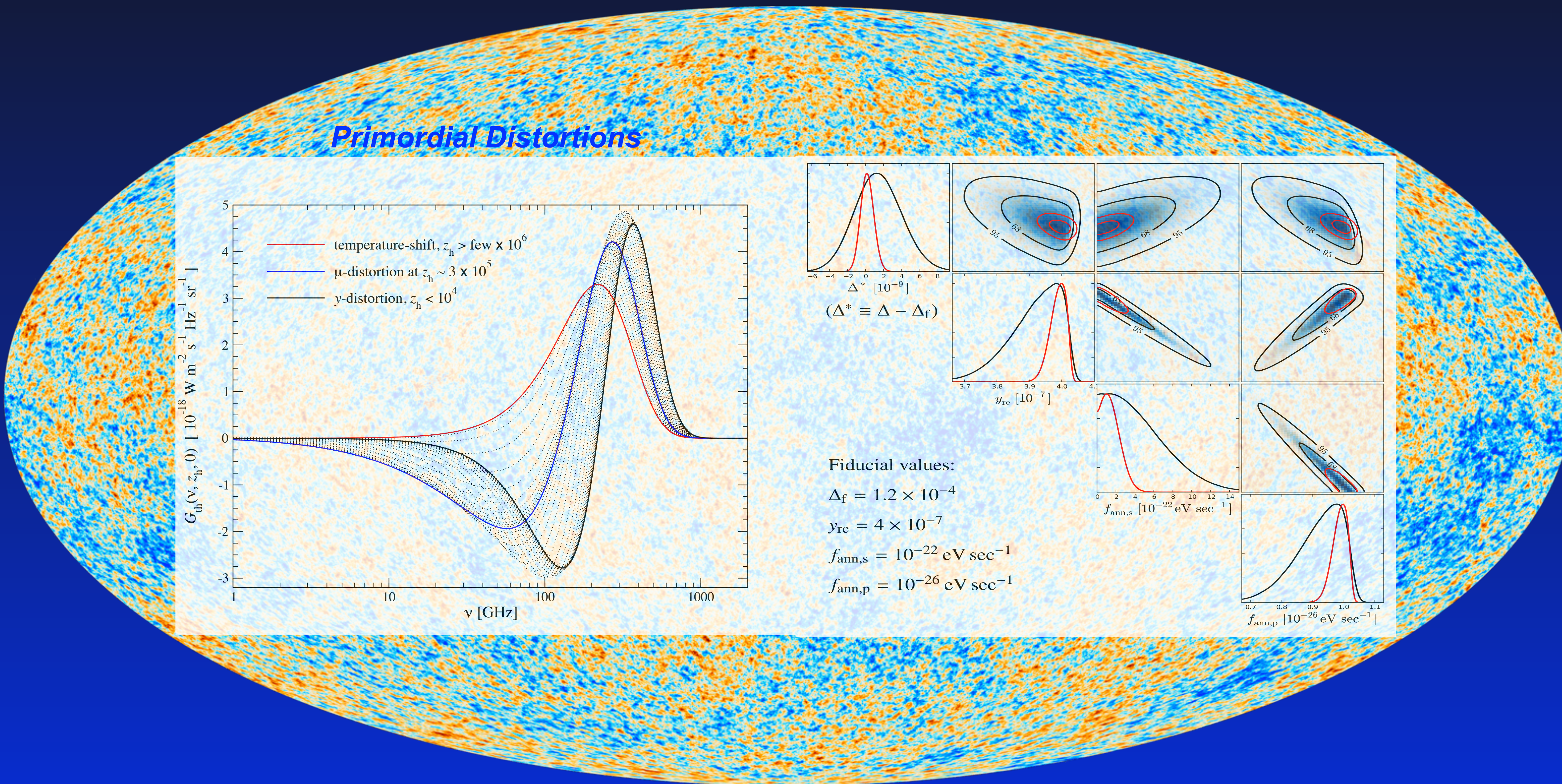
CMB Spectral Distortion Computations using the Green's function package of *CosmoTherm*



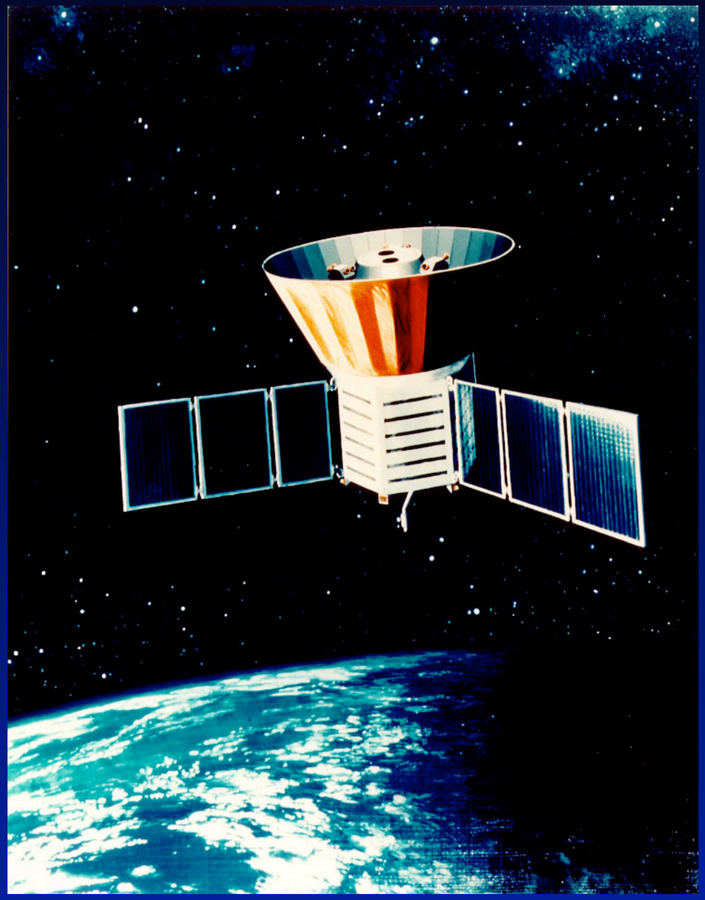
MANCHESTER 1824
The University of Manchester

Jens Chluba

Cosmology School in the Canary Islands

Fuerteventura, Sept 21st, 2017

COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)

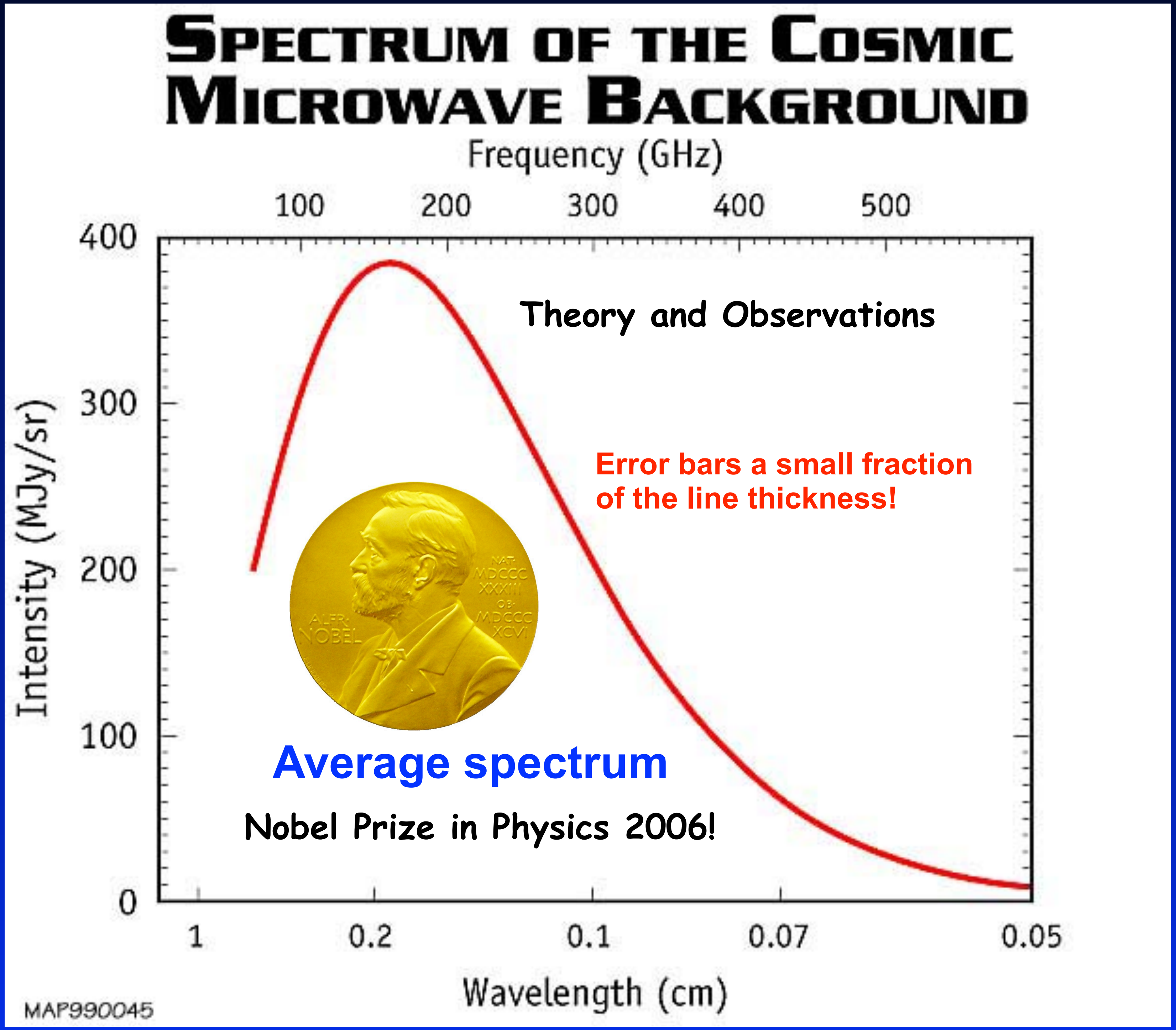


$$T_0 = 2.725 \pm 0.001\,\mathrm{K}$$

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

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

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



Only very small distortions of CMB spectrum are still allowed!

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)

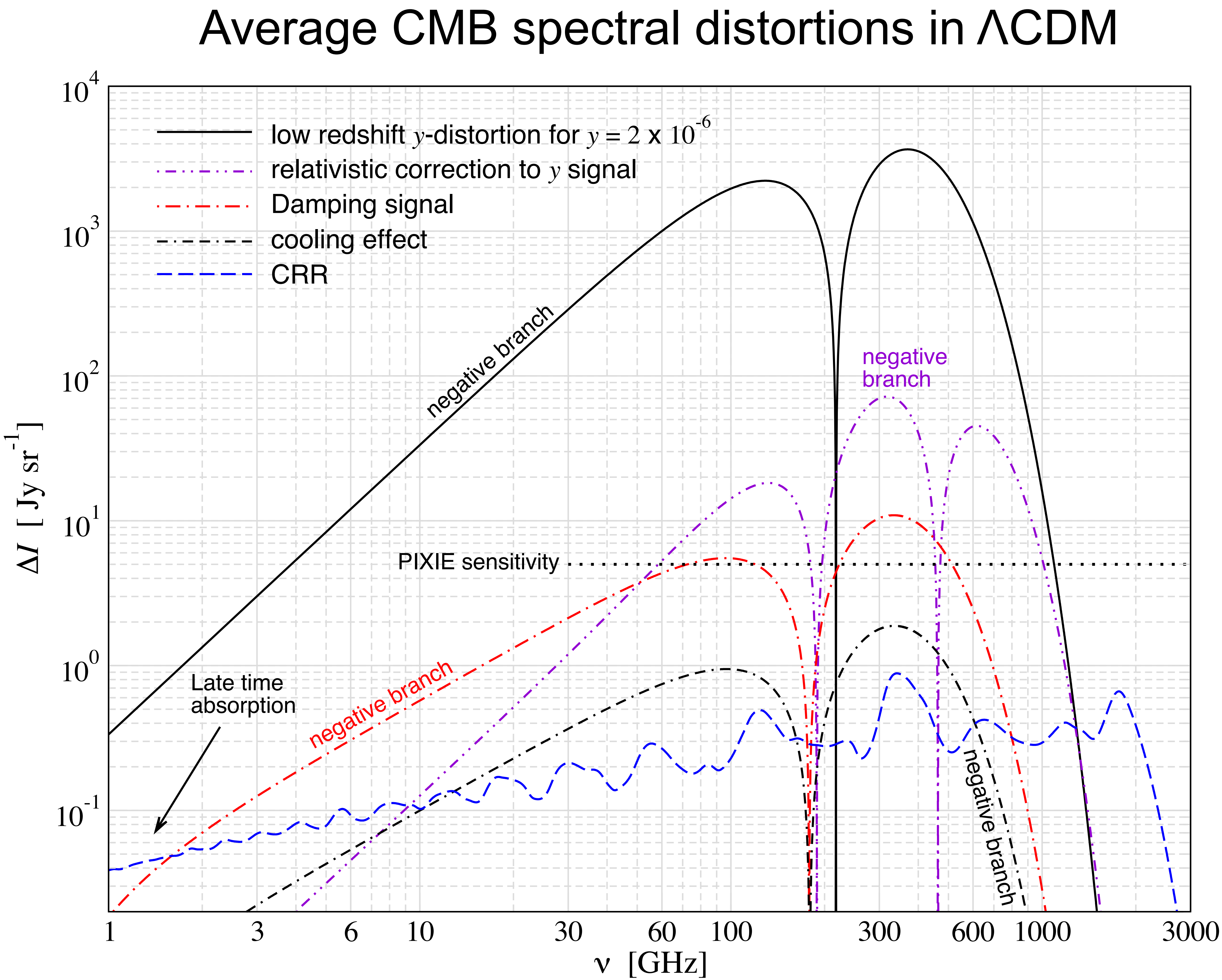
„high“ redshifts

pre-recombination epoch

„low“ redshifts

post-recombination

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


Average CMB spectral distortions in ΛCDM
low redshift y-distortion for y = 2 x 10^-6
relativistic correction to y signal
Damping signal
cooling effect
CRR
negative branch
negative branch
negative branch
negative branch
PIXIE sensitivity
Late time absorption
ΔI [Jy sr^-1]
ν [GHz]
10^4
10^3
10^2
10^1
10^0
10^-1
1
3
6
10
30
60
100
300
600
1000
3000

Set of evolution equations for distortions

Photon field

$$x = \frac{h\nu}{kT_\gamma} \qquad \theta_{\rm e} = \frac{kT_{\rm e}}{m_{\rm e}c^2}$$

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

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

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

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

Ordinary matter temperature

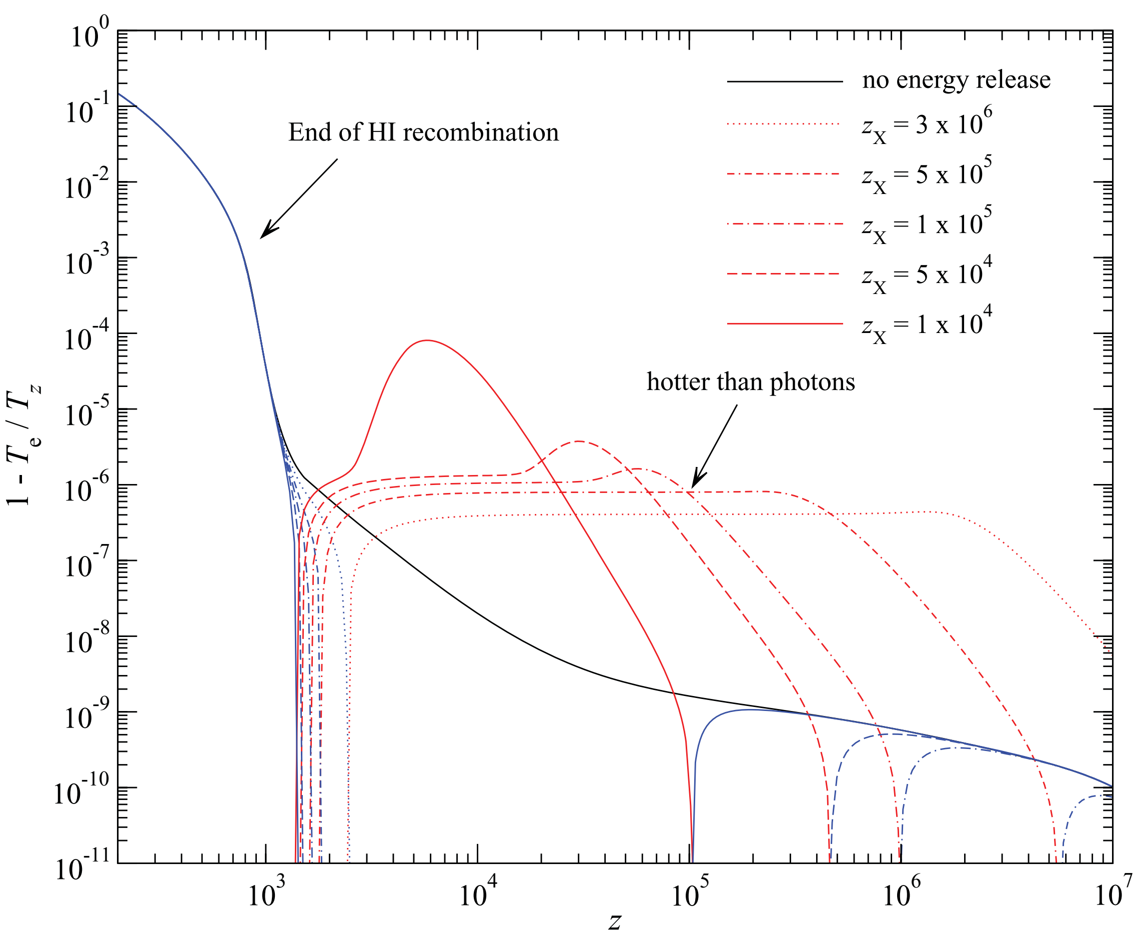
$$\frac{{\rm d}\rho_{\rm e}}{{\rm d}\tau} = \frac{{\rm d}(T_{\rm e}/T_\gamma)}{{\rm d}\tau} = \frac{t_{\rm T}\dot{Q}}{\alpha_{\rm h}\theta_\gamma} + \frac{4\tilde{\rho}_\gamma}{\alpha_{\rm h}}[\rho_{\rm e}^{\rm eq} - \rho_{\rm e}] - \frac{4\tilde{\rho}_\gamma}{\alpha_{\rm h}}\mathcal{H}_{\rm DC,BR}(\rho_{\rm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

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

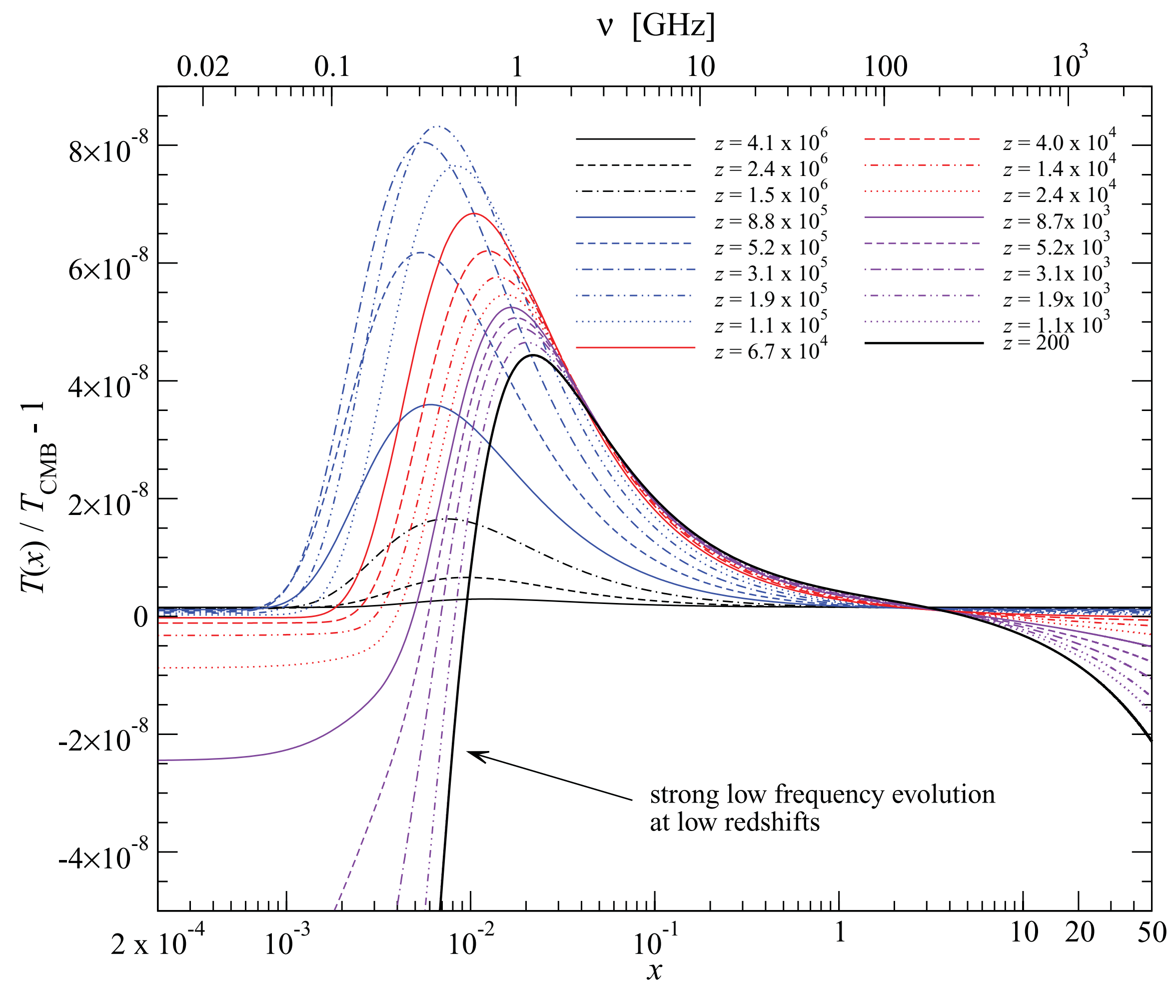
$$\tilde{\rho}_\gamma = \rho_\gamma/m_{\rm e}c^2 \qquad T_{\rm e}^{\rm eq} = T_\gamma\frac{\int x^4 f(1+f)\,{\rm d}x}{4\int x^3 f\,{\rm d}x} \equiv \frac{h}{k}\frac{\int \nu^4 f(1+f)\,{\rm d}\nu}{4\int \nu^3 f\,{\rm d}\nu}$$

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)

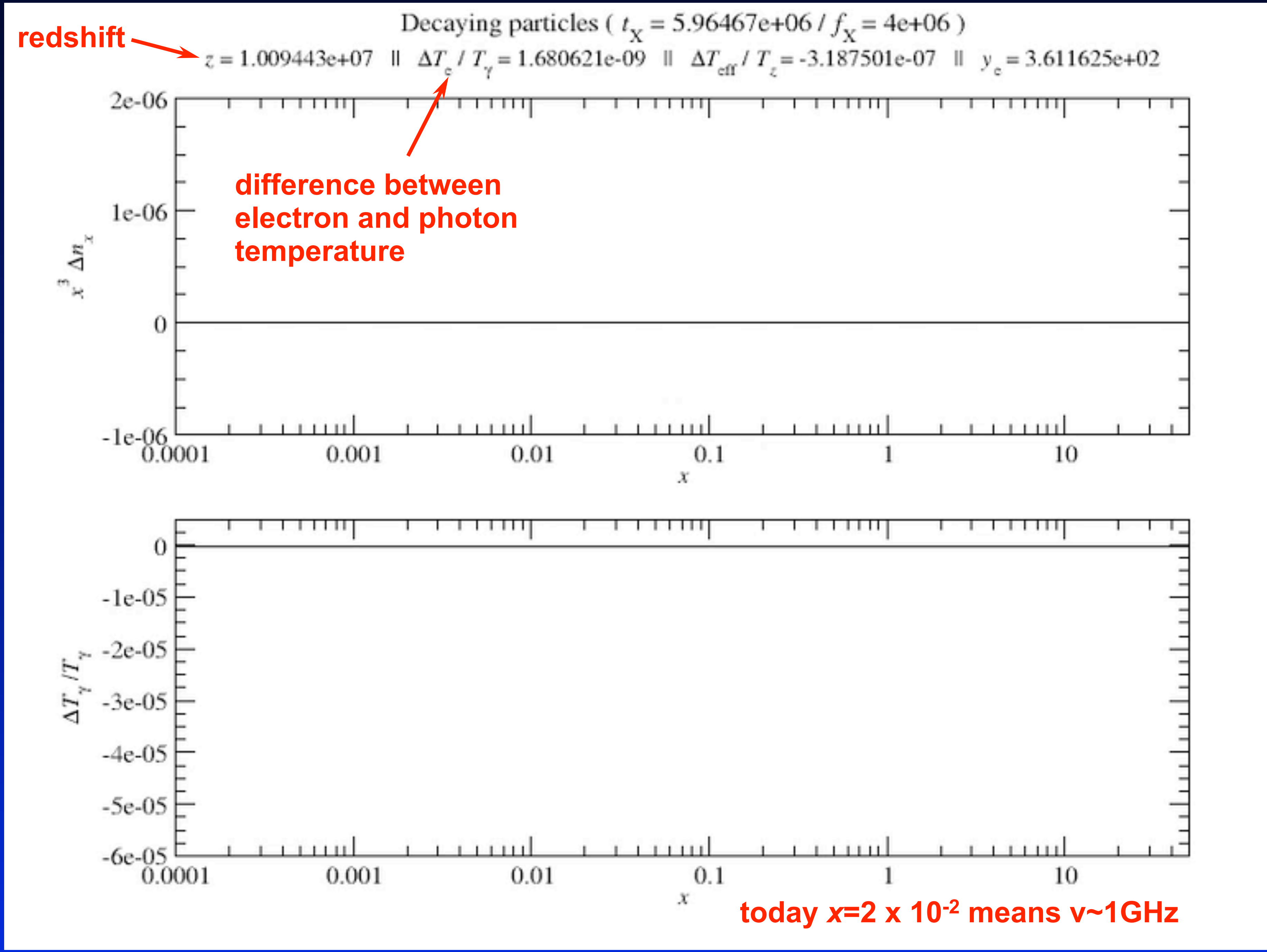


Electron temperature evolution



Evolution of distortion

Example: *Energy release by decaying relict particle*



- initial condition: *full equilibrium*
- total energy release: $\Delta\rho/\rho \sim 1.3\times10^{-6}$
- most of energy released around: $z_X \sim 2\times10^{6}$
- positive μ-distortion
- high frequency distortion frozen around $z \simeq 5\times10^{5}$
- late ($z<10^3$) free-free absorption at very low frequencies ($T_e < T_\gamma$)

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

Quasi-Exact Treatment of the Thermalization Problem

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

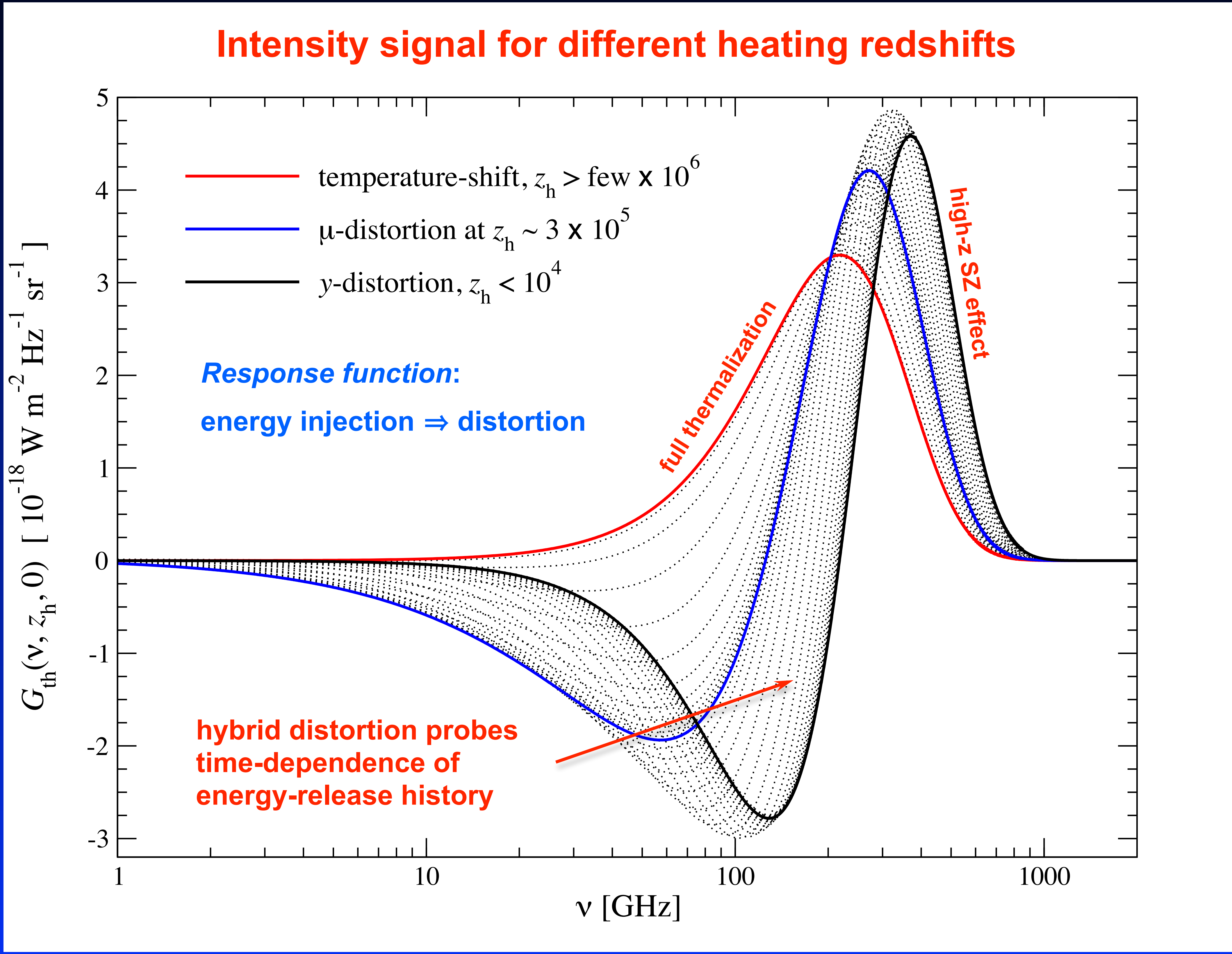
$$\Delta I_\nu \approx \int_0^\infty G_{\rm th}(\nu, z') \frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'} {\rm d}z'$$

Thermalization Green's function

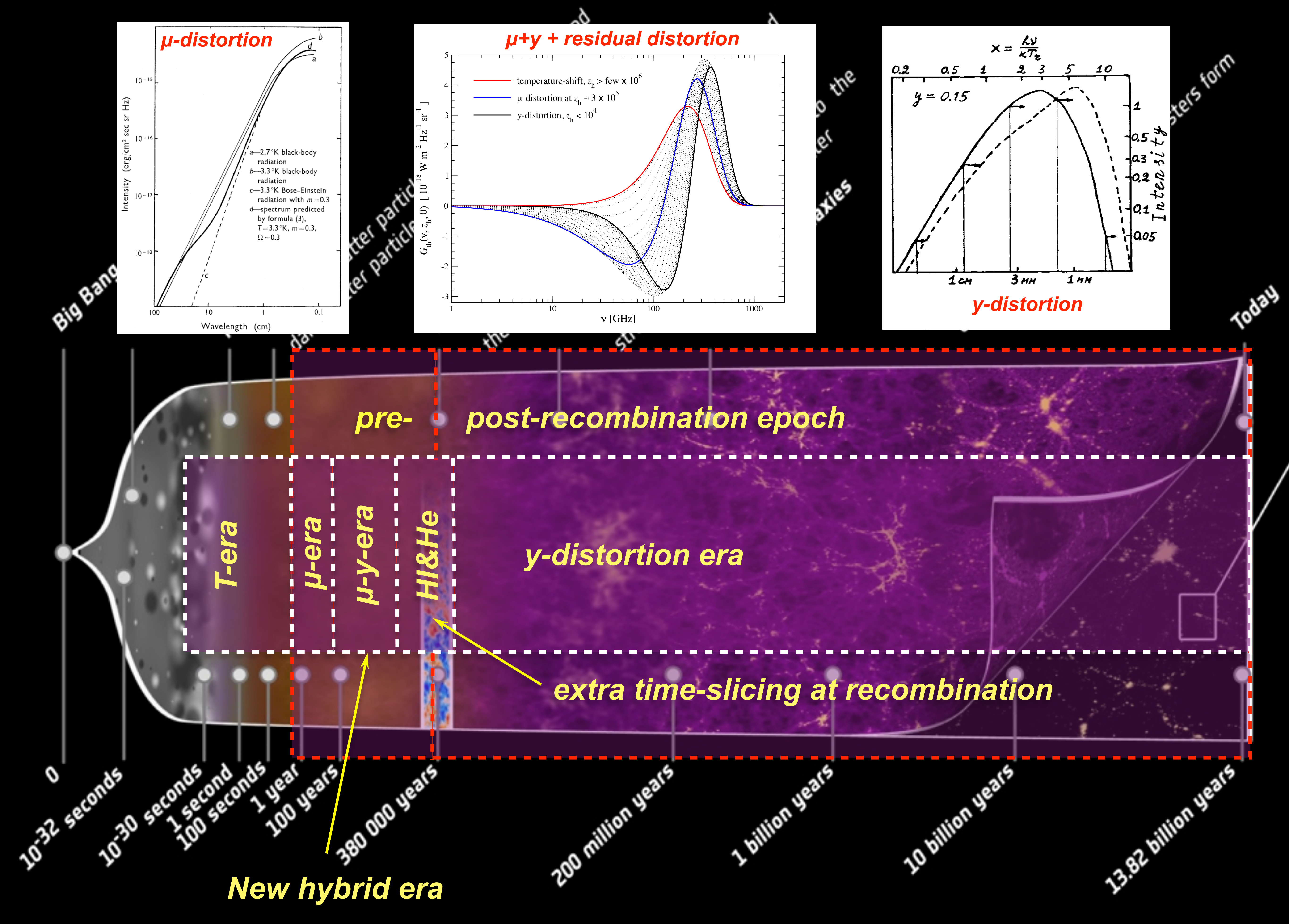
- *Fast and quasi-exact! No additional approximations!*

CosmoTherm available at: www.Chluba.de/CosmoTherm

What does the spectrum look like after energy injection?



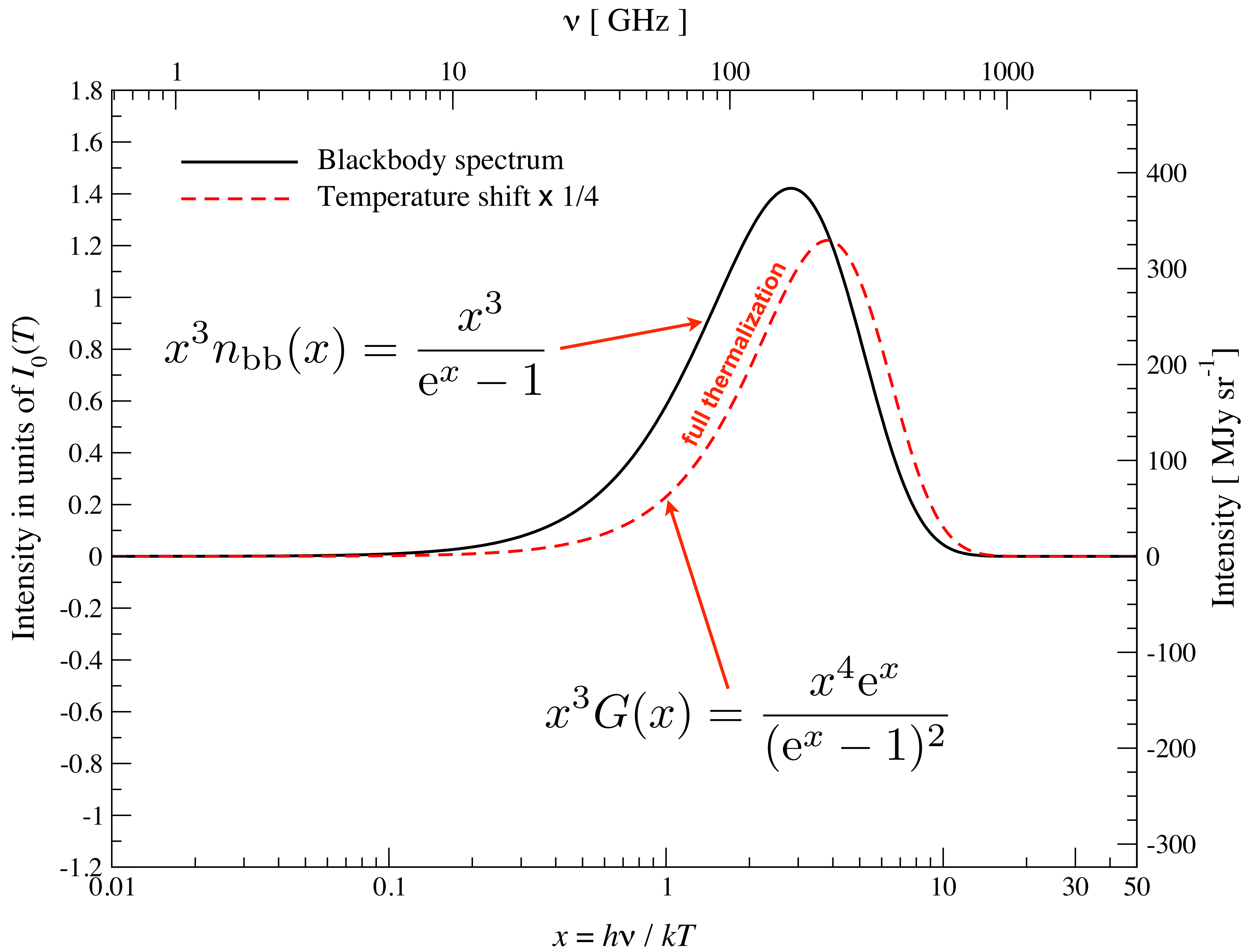
JC & Sunyaev, 2012, ArXiv:1109.6552
JC, 2013, ArXiv:1304.6120



μ-distortion
μ+y + residual distortion
temperature-shift, z_h > few x 10^6
μ-distortion at $z_h \sim 3 \times 10^5$
y-distortion, $z_h < 10^4$
ν [GHz]
$G_{th}(\nu, z_h, 0)$ [10^{-18} W m^{-2} Hz^{-1} sr^{-1}]
y-distortion
$x = \frac{h\nu}{kT_e}$
y = 0.15
Intensity
Wavelength (cm)
Intensity (erg cm^2 sec sr Hz)
a—2.7°K black-body radiation
b—3.3°K black-body radiation
c—3.3°K Bose-Einstein radiation with m = 0.3
d—spectrum predicted by formula (3), T = 3.3°K, m = 0.3, Ω = 0.3
Big Bang
Today
pre-
post-recombination epoch
T-era
μ-era
μ-y-era
HI&He
y-distortion era
extra time-slicing at recombination
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
New hybrid era

Exercises for simple spectral shapes

Simplest spectral shapes



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

Exercises for y and μ-distortion

Starting from Kompaneets Equation:

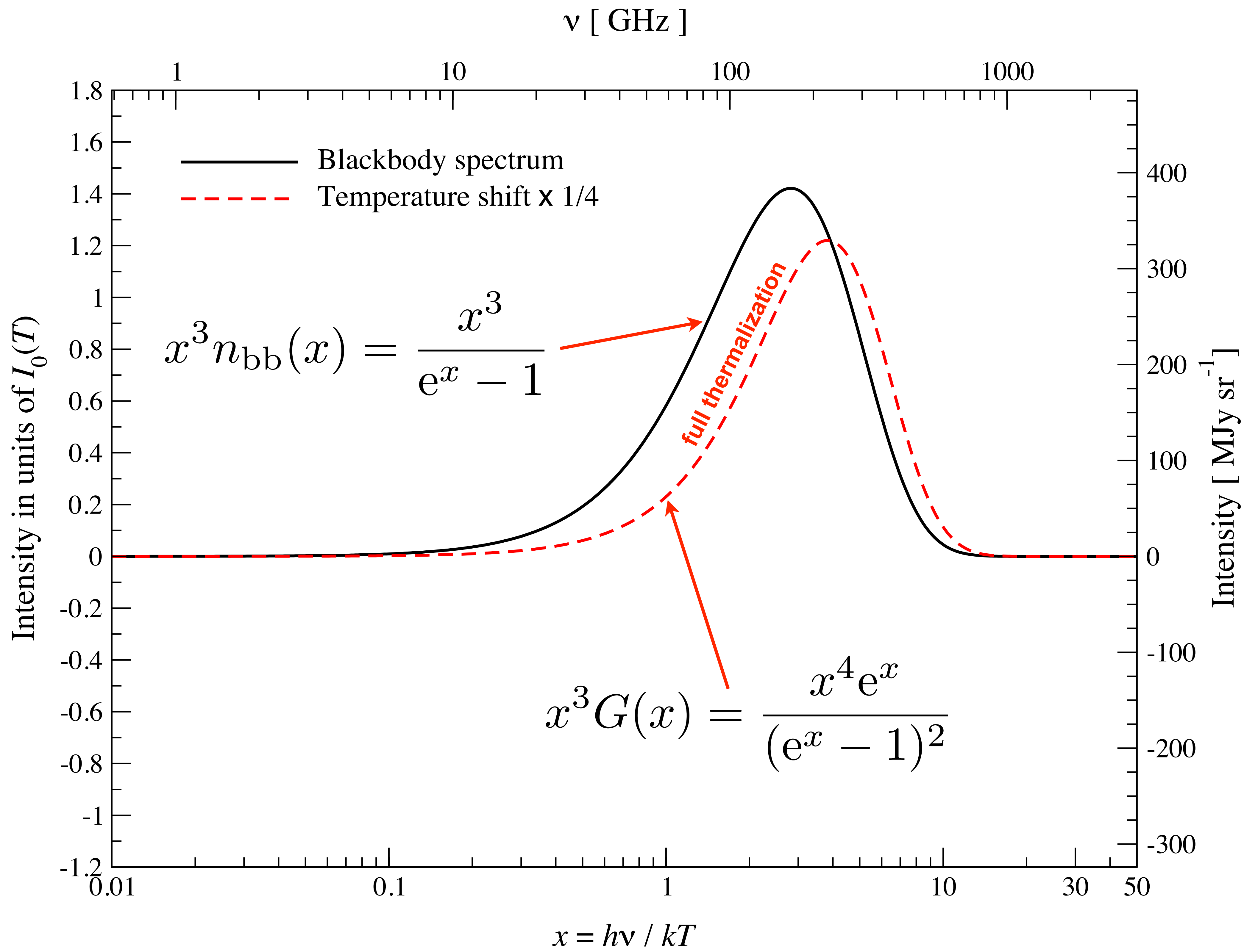
$$\frac{\partial f}{\partial \tau} \approx \frac{\theta_{\rm e}}{x^2} \frac{\partial}{\partial x} x^4 \left[\frac{\partial}{\partial x} f + \frac{T_\gamma}{T_{\rm e}} f(1+f) \right]$$

1. Derive the spectrum of a y-type distortion by inserting a CMB blackbody $f_0 = \frac{1}{{\rm e}^x - 1}$ *and writing* $\Delta f \approx \Delta\tau \, {\rm C}[f_0]$

2a. Determine which photon occupation number makes the Compton collision term vanish (Hint: write the occupation number as $f(x) = [{\rm e}^{x+\mu(x)} - 1]^{-1}$ *)*

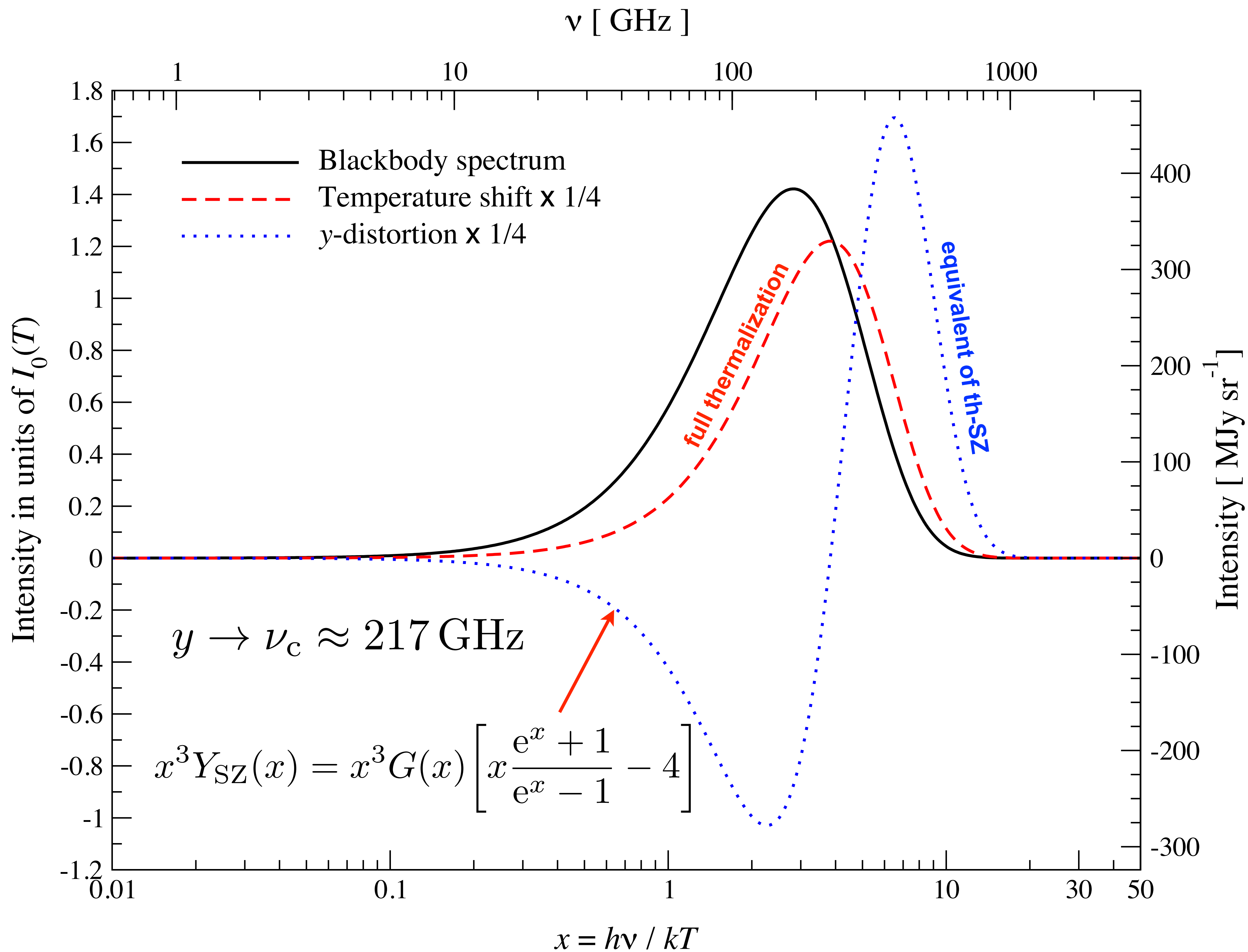
2b. What happens if you neglect simulated scattering terms?

Simplest spectral shapes



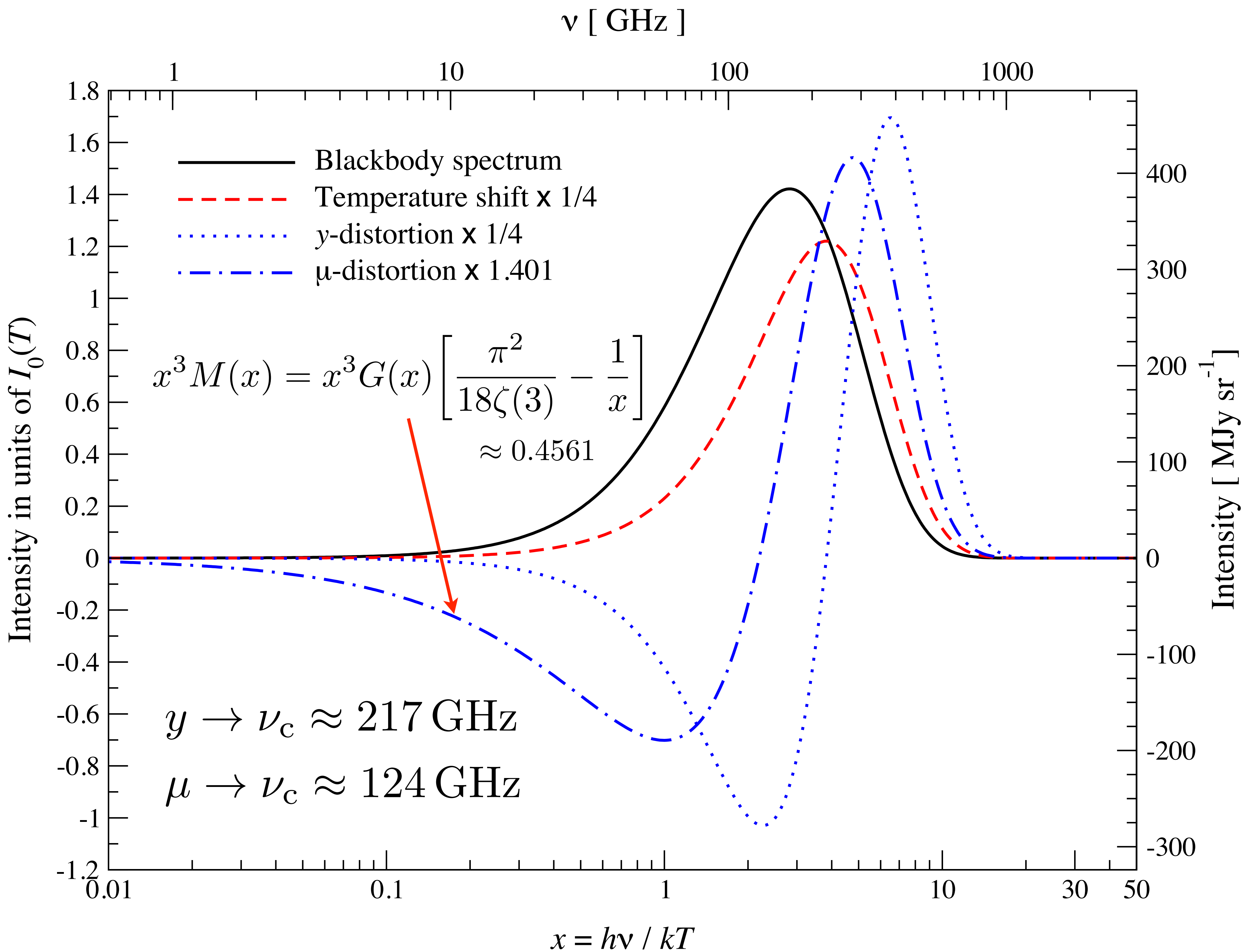
$$I_0 = (2h/c^2)(kT_0/h)^3 \approx 270\,\mathrm{MJy\,sr}^{-1}$$

Simplest spectral shapes



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

Simplest spectral shapes



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

Energy release histories

Energy release histories for some cases

Adiabatic cooling

$$\frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z} = -\frac{3}{2}\,\frac{N_{\rm tot} k T_\gamma}{\rho_\gamma (1+z)}$$

$$\approx -\frac{5.71\times 10^{-10}}{(1+z)}\left[\frac{(1-Y_{\rm p})}{0.7533}\right]\left[\frac{\Omega_{\rm b} h^2}{0.02225}\right] \times \left[\frac{(1+f_{\rm He}+X_{\rm e})}{2.246}\right]\left[\frac{T_0}{2.726\,{\rm K}}\right]^{-3}$$

Annihilation

$$\frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z} = f_{\rm ann}\,\frac{N_{\rm H}(z)(1+z)^{2+\lambda}}{H(z)\,\rho_\gamma(z)}$$

Decay

$$\left.\frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z}\right|_{\rm dec} \approx \epsilon_{\rm X}\,\frac{N_{\rm H}(z)(1+z_{\rm X})\Gamma_{\rm X}}{H(z)\rho_\gamma(z)\,(1+z)}\,\exp\left(-\Gamma_{\rm X}\, t\right)$$

Dissipation of acoustic modes

$$\frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z} \approx 4A^2 \partial_z k_{\rm D}^{-2}\int_{k_{\rm min}}^{\infty}\frac{k^4\,\mathrm{d}k}{2\pi^2}P_\zeta(k)\,\mathrm{e}^{-2k^2/k_{\rm D}^2}$$

$$A^2 \approx (1+4R_\nu/15)^{-2} \approx 0.813$$

$$k_{\rm D} \approx 4.048\times 10\,(1+z)^{3/2}{\rm Mpc}^{-1}$$

$$k_{\rm min} \approx 0.12\,{\rm Mpc}^{-1}$$

Exercises for energy release histories

3a. Explain the parametrization for the energy release history of a decaying particle

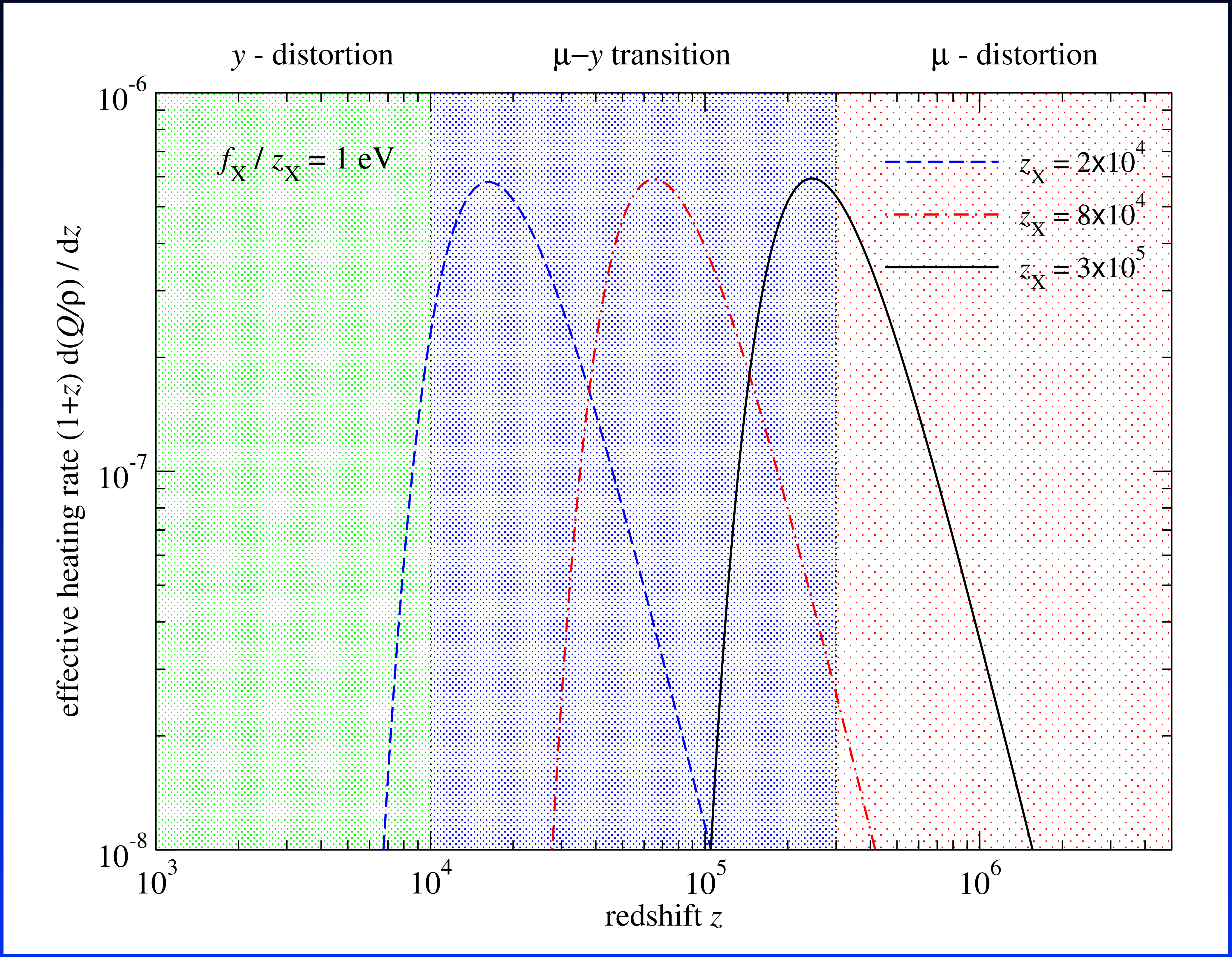
$$\left.\frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z}\right|_{\rm dec} \approx \epsilon_{\rm X}\,\frac{N_{\rm H}(z)(1+z_{\rm X})\Gamma_{\rm X}}{H(z)\rho_\gamma(z)\,(1+z)}\,\exp\left(-\Gamma_{\rm X}\,t\right)$$

3b. How does this energy release history scale before and after $t_{\rm X} = \Gamma_{\rm X}^{-1}$ *?*

4. Can you qualitatively explain the adiabatic cooling term?

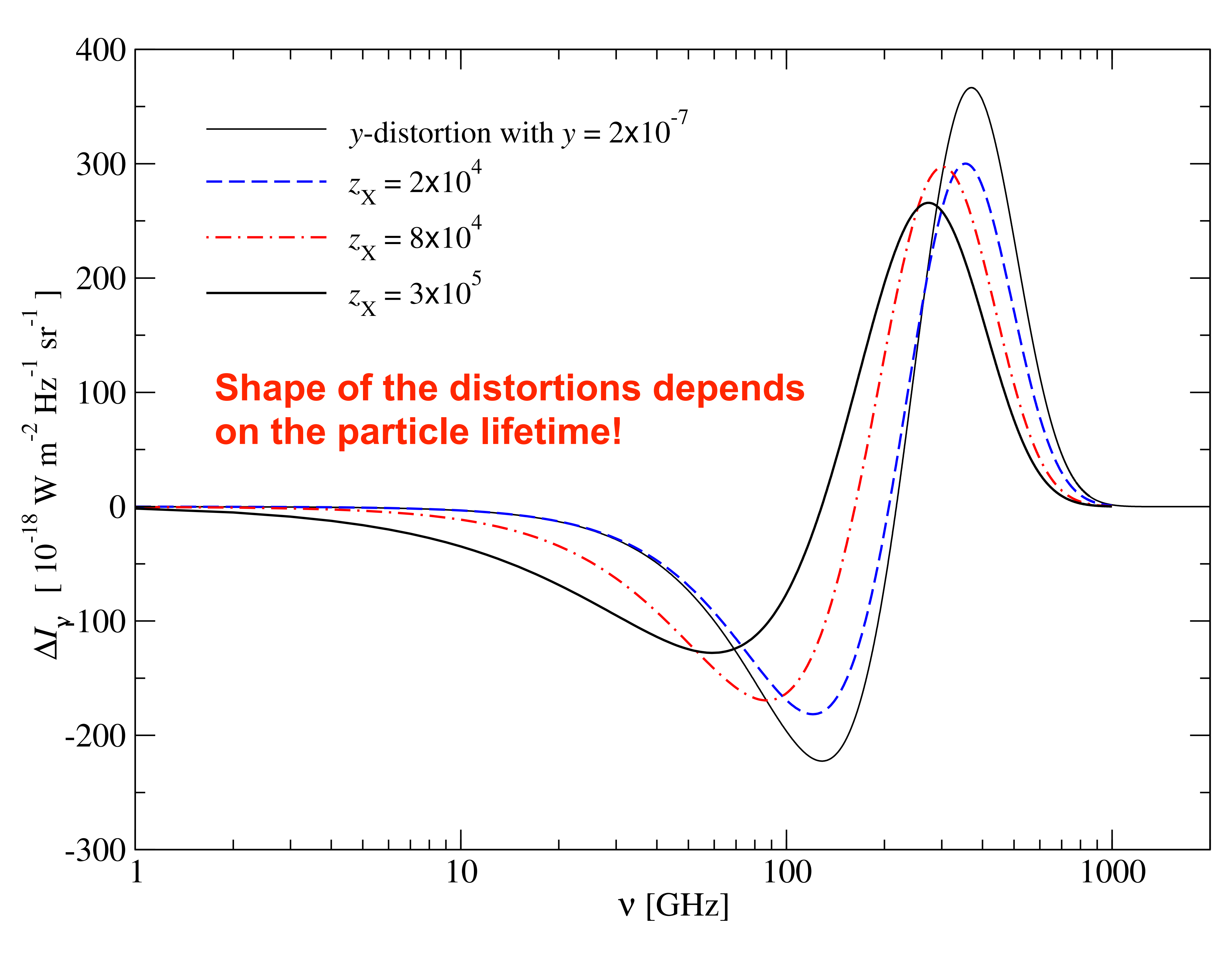
$$\frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z} = -\frac{3}{2}\,\frac{N_{\rm tot}kT_\gamma}{\rho_\gamma(1+z)}$$

Decaying particle scenarios



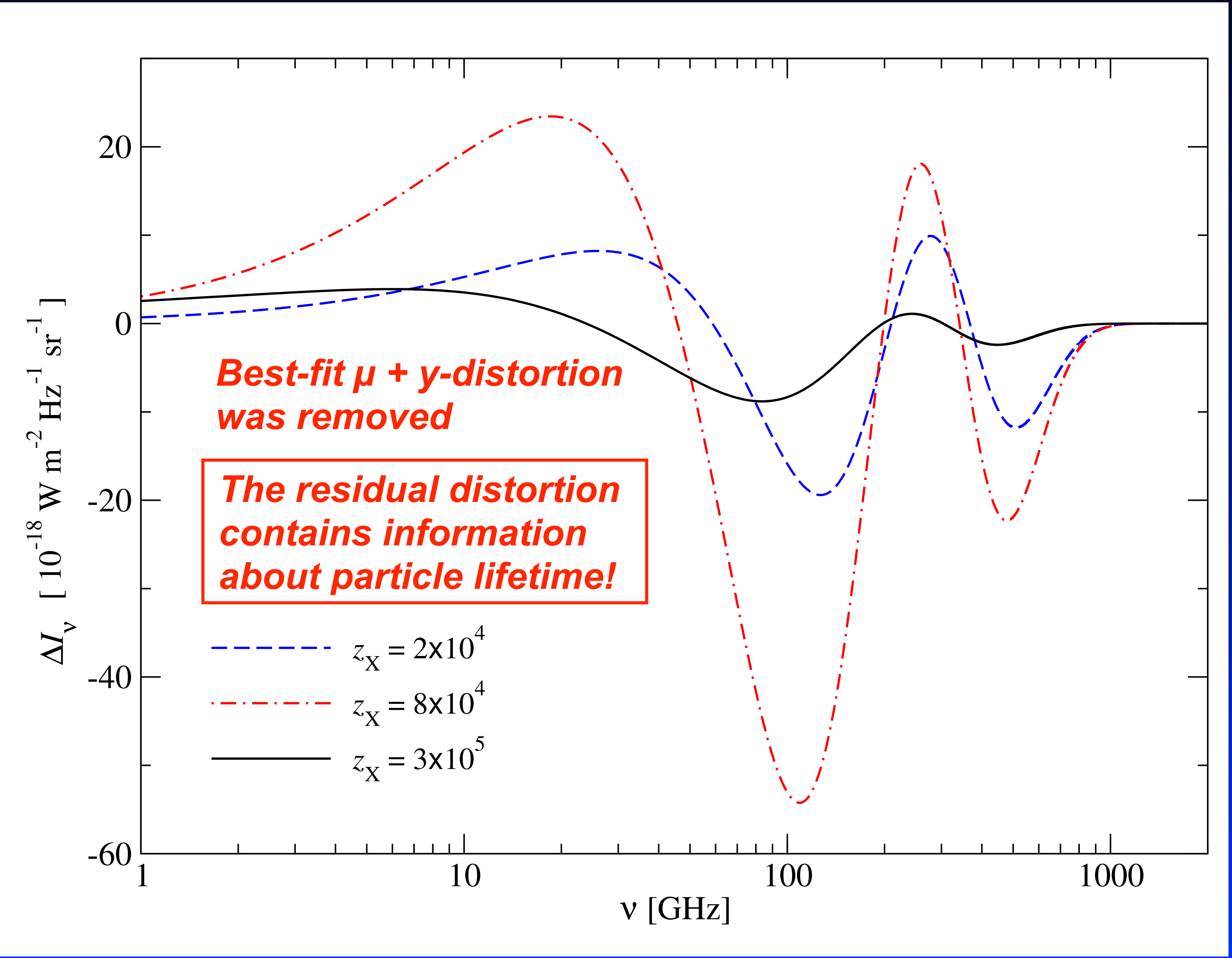
JC & Sunyaev, 2011, Arxiv:1109.6552
JC, 2013, Arxiv:1304.6120

Decaying particle scenarios



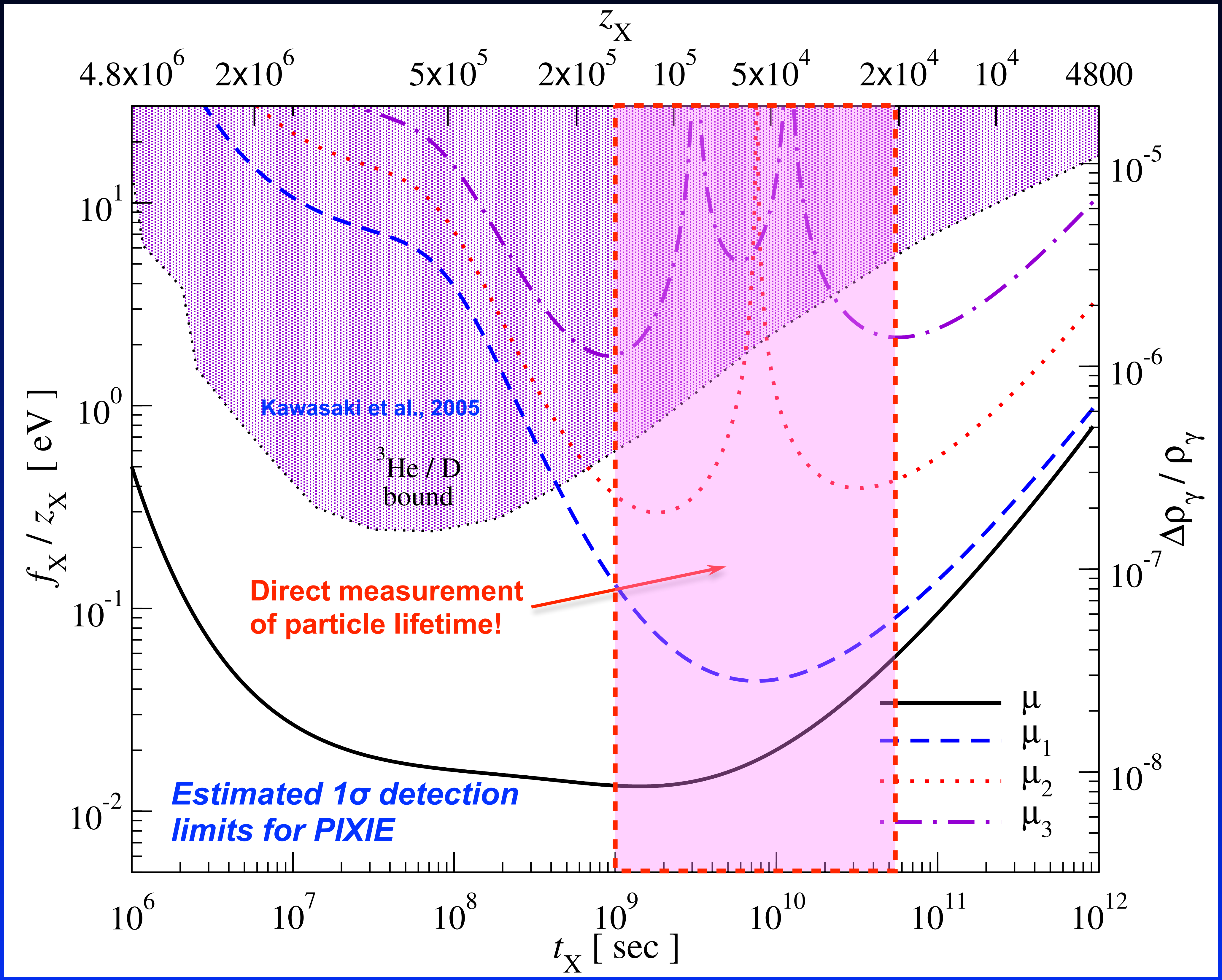
JC & Sunyaev, 2011, Arxiv:1109.6552
JC, 2013, Arxiv:1304.6120

Decaying particle scenarios (information in residual)



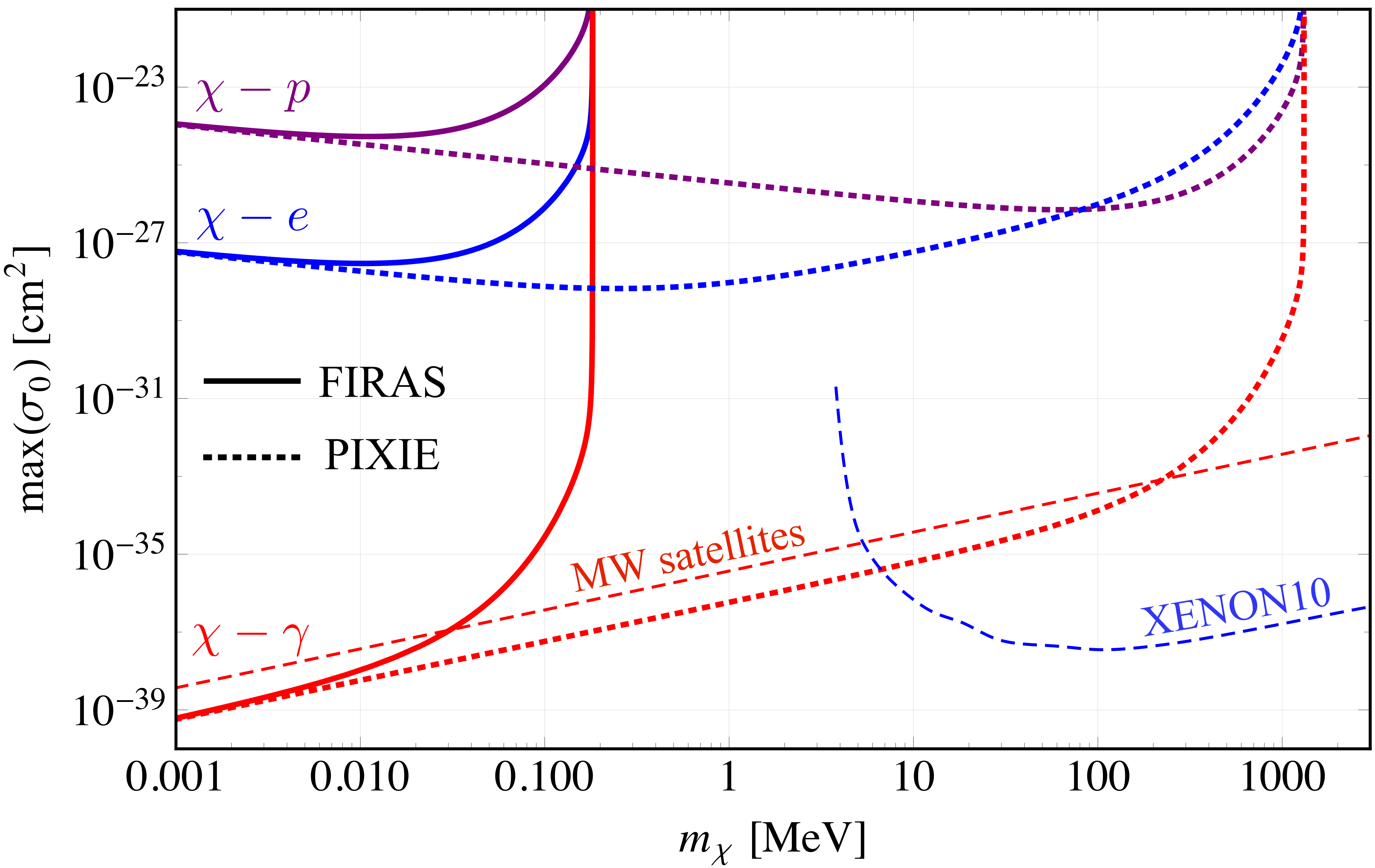
JC & Sunyaev, 2011, Arxiv:1109.6552
JC, 2013, Arxiv:1304.6120

Distortions could shed light on decaying (DM) particles!



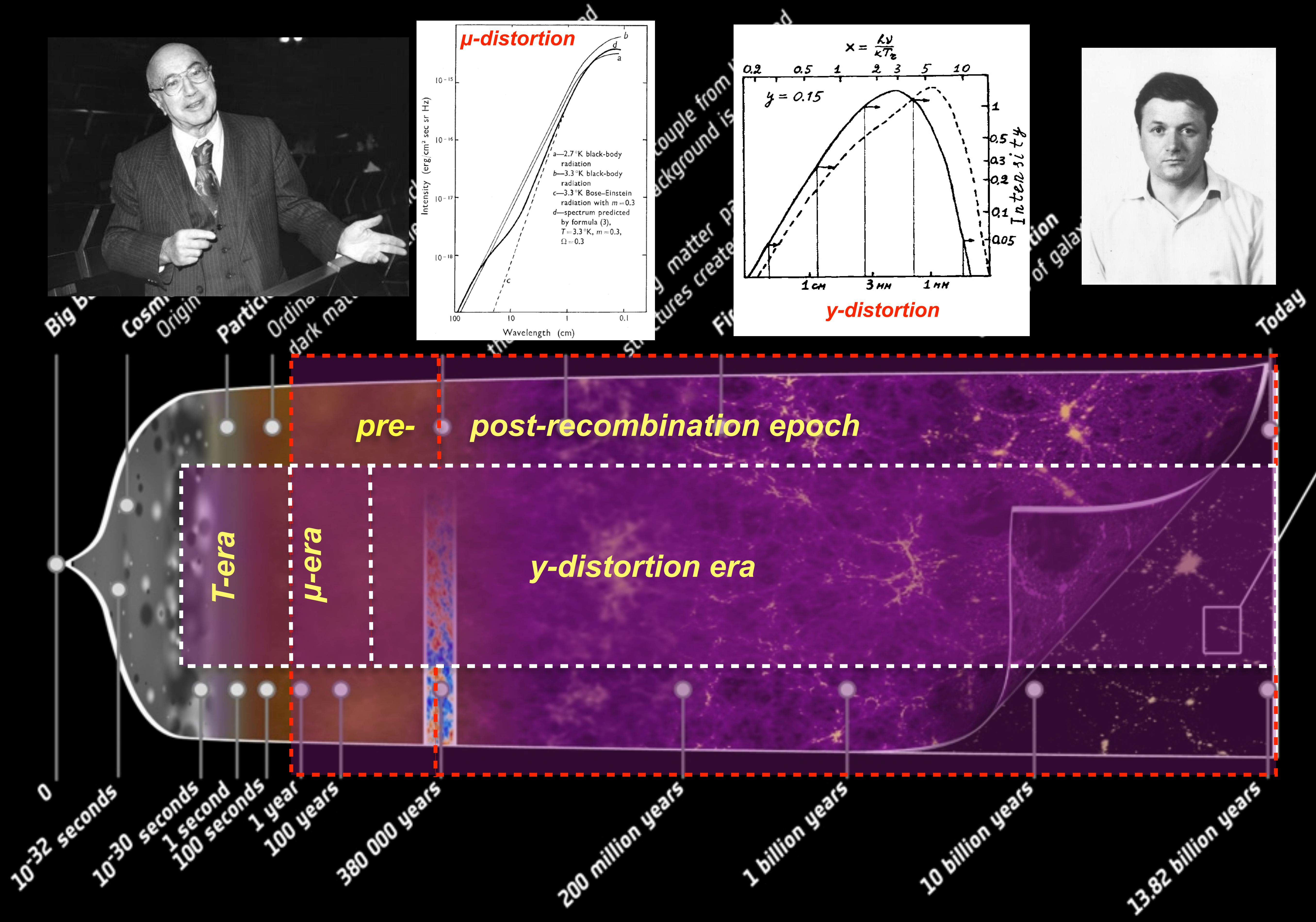
JC & Jeong, 2013

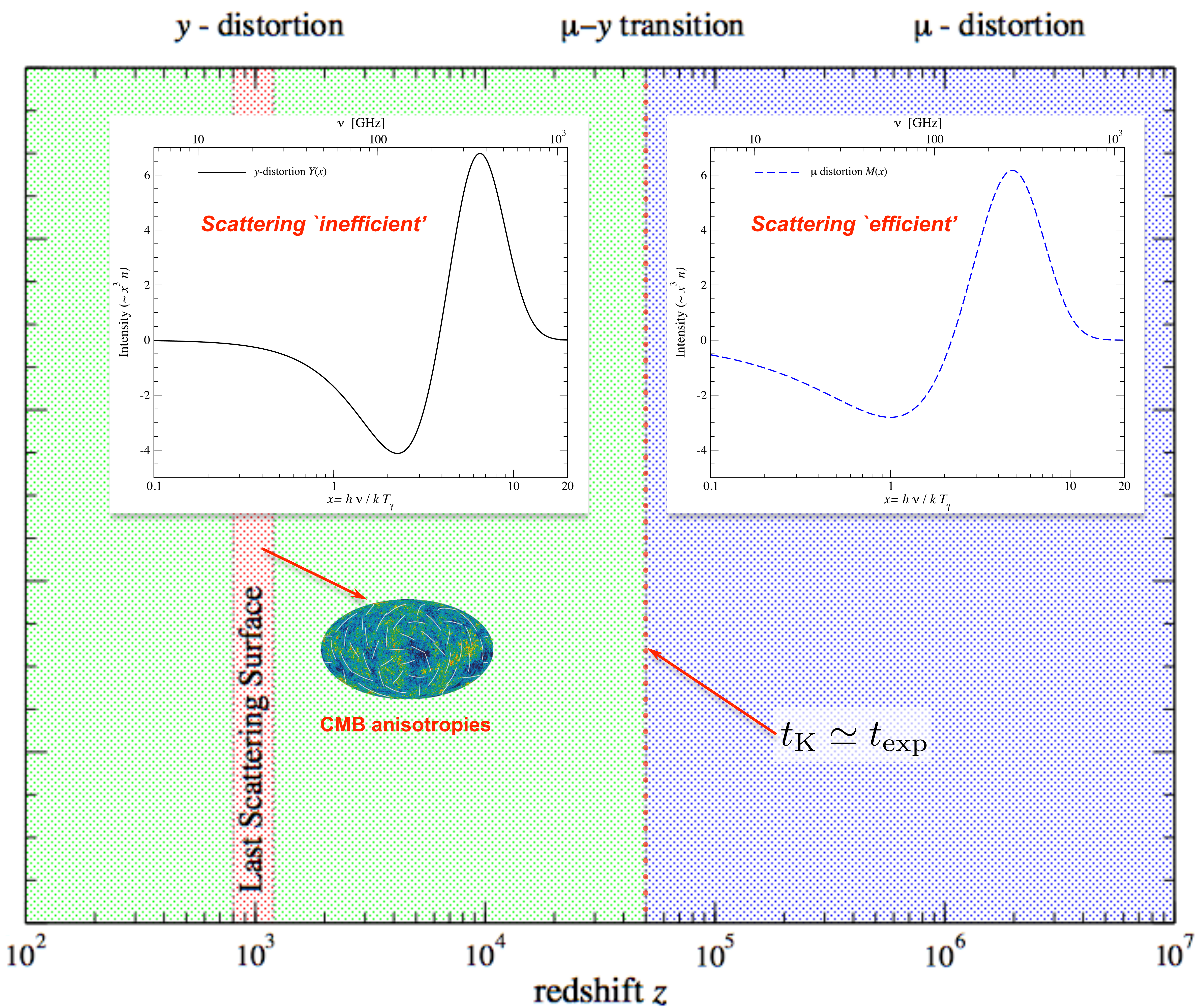
Distortion constraints on DM interactions through adiabatic cooling effect



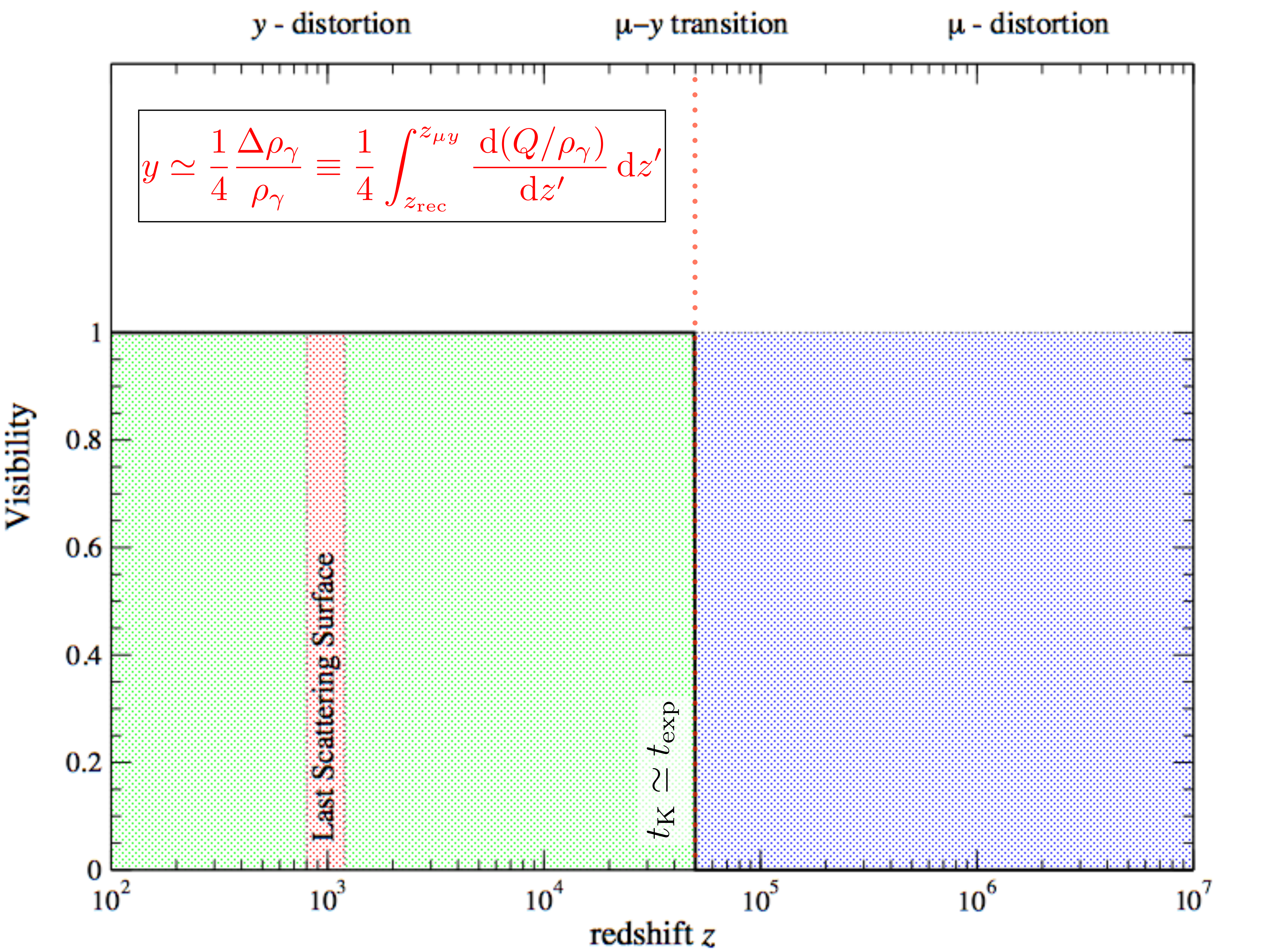
Ali-Haimoud, JC & Kamionkowski, 2015

Simple analytic approximations for estimates

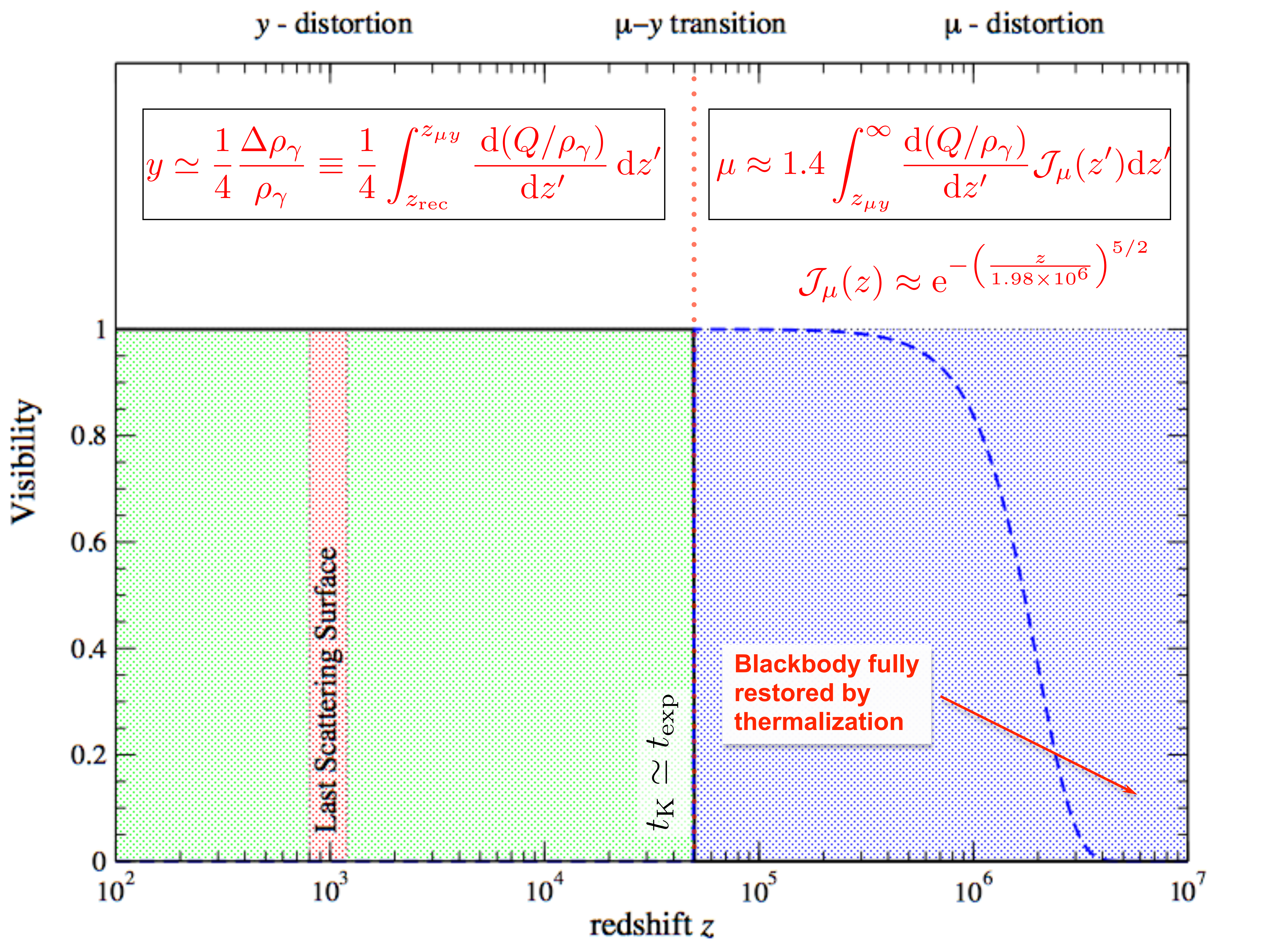

μ-distortion
Intensity (erg/cm² sec sr Hz)
Wavelength (cm)
a—2.7 °K black-body radiation
b—3.3 °K black-body radiation
c—3.3 °K Bose-Einstein radiation with m = 0.3
d—spectrum predicted by formula (3), T = 3.3 °K, m = 0.3, Ω = 0.3
y-distortion
y = 0.15
Intensity
1 см
3 мм
1 мм
Big Bang
Today
pre-
post-recombination epoch
T-era
μ-era
y-distortion era
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



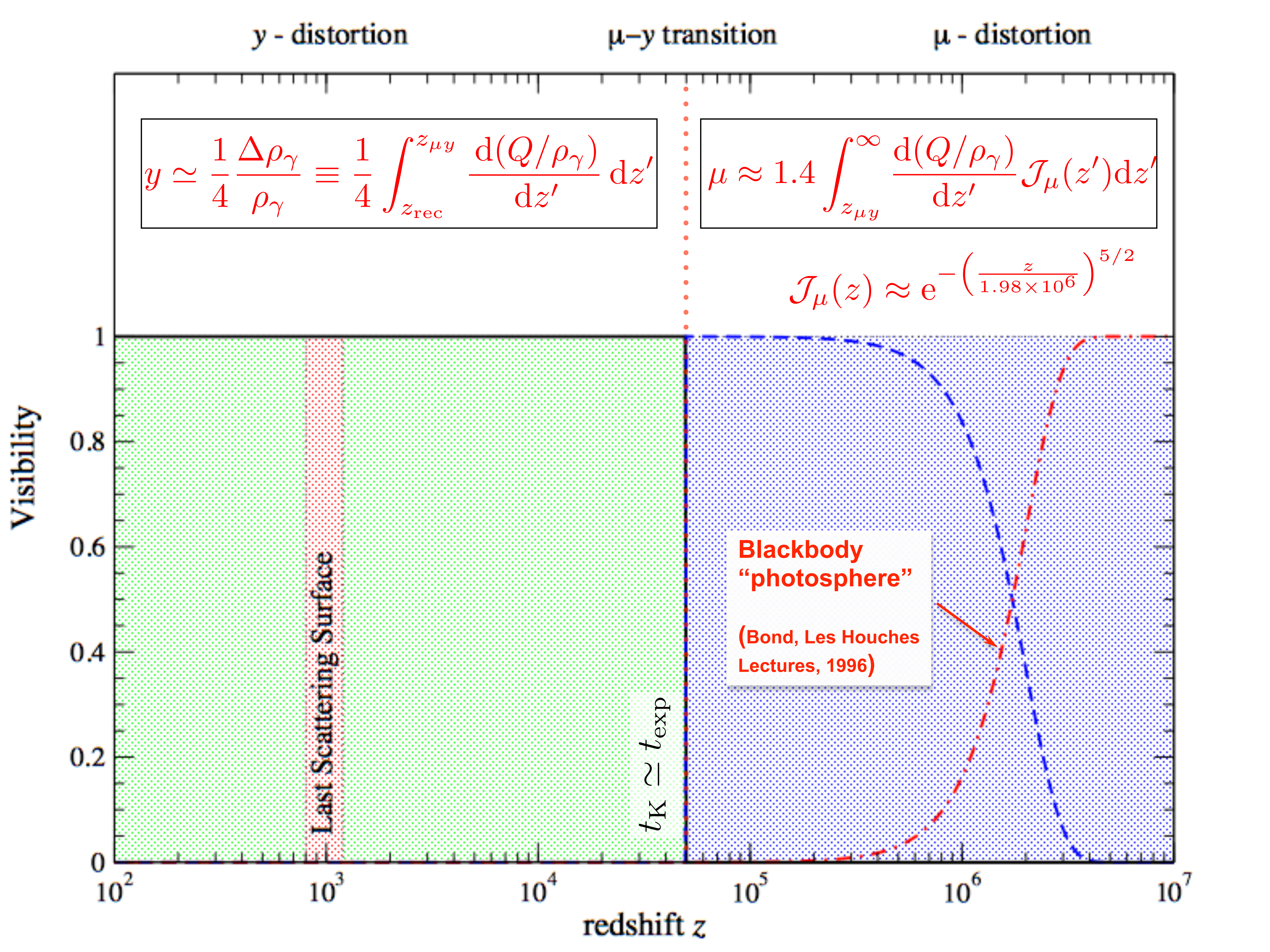
y - distortion
μ–y transition
μ - distortion
ν [GHz]
y-distortion Y(x)
Scattering `inefficient'
Intensity (~ x^3 n)
x= h ν / k T_γ
ν [GHz]
μ distortion M(x)
Scattering `efficient'
Intensity (~ x^3 n)
x= h ν / k T_γ
Last Scattering Surface
CMB anisotropies
$t_K \simeq t_{exp}$
redshift z



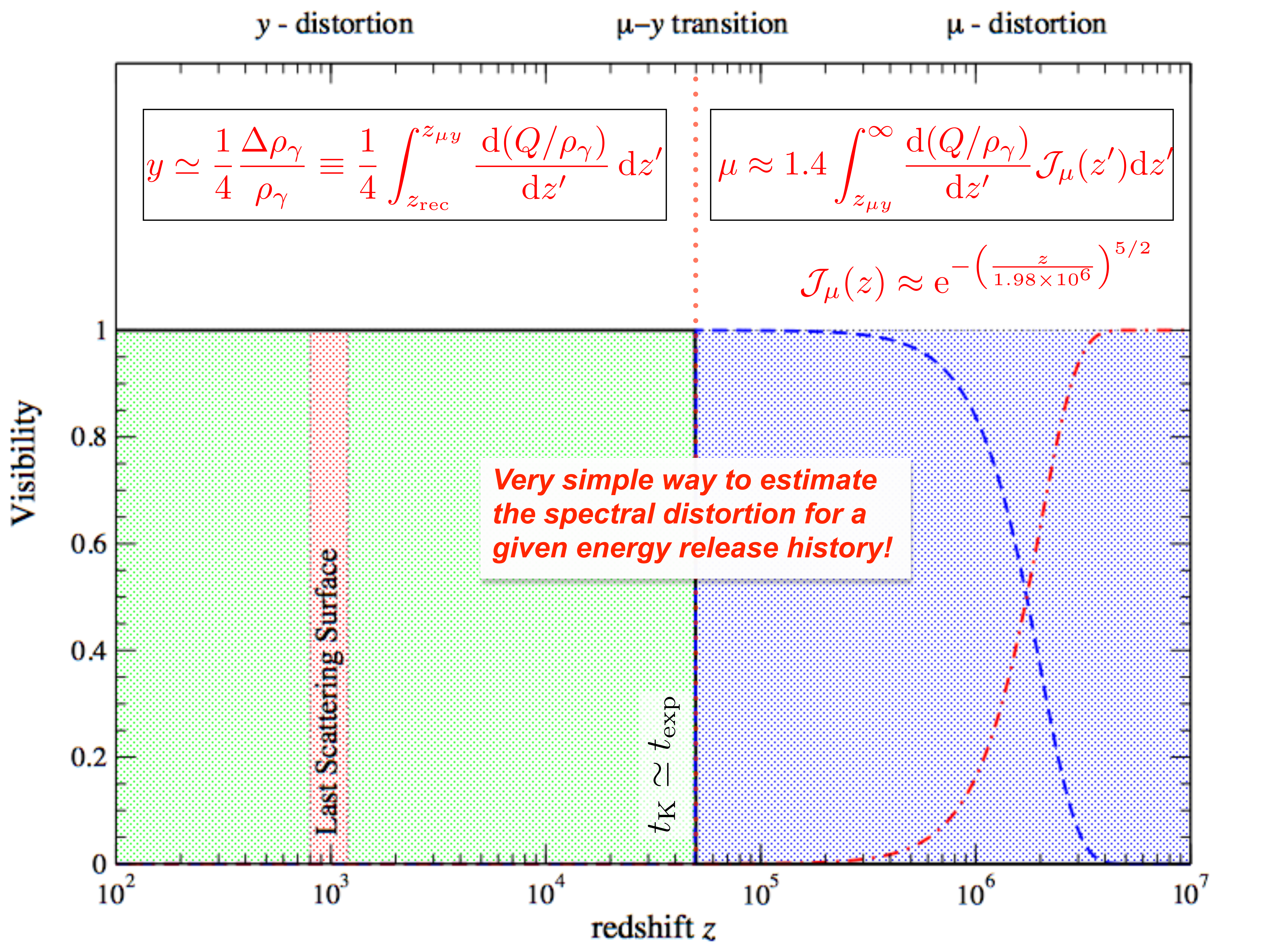
y - distortion
μ–y transition
μ - distortion
$y \simeq \frac{1}{4}\frac{\Delta\rho_\gamma}{\rho_\gamma} \equiv \frac{1}{4}\int_{z_{\rm rec}}^{z_{\mu y}} \frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'}\,{\rm d}z'$
Visibility
Last Scattering Surface
$t_{\rm K} \simeq t_{\rm exp}$
redshift z

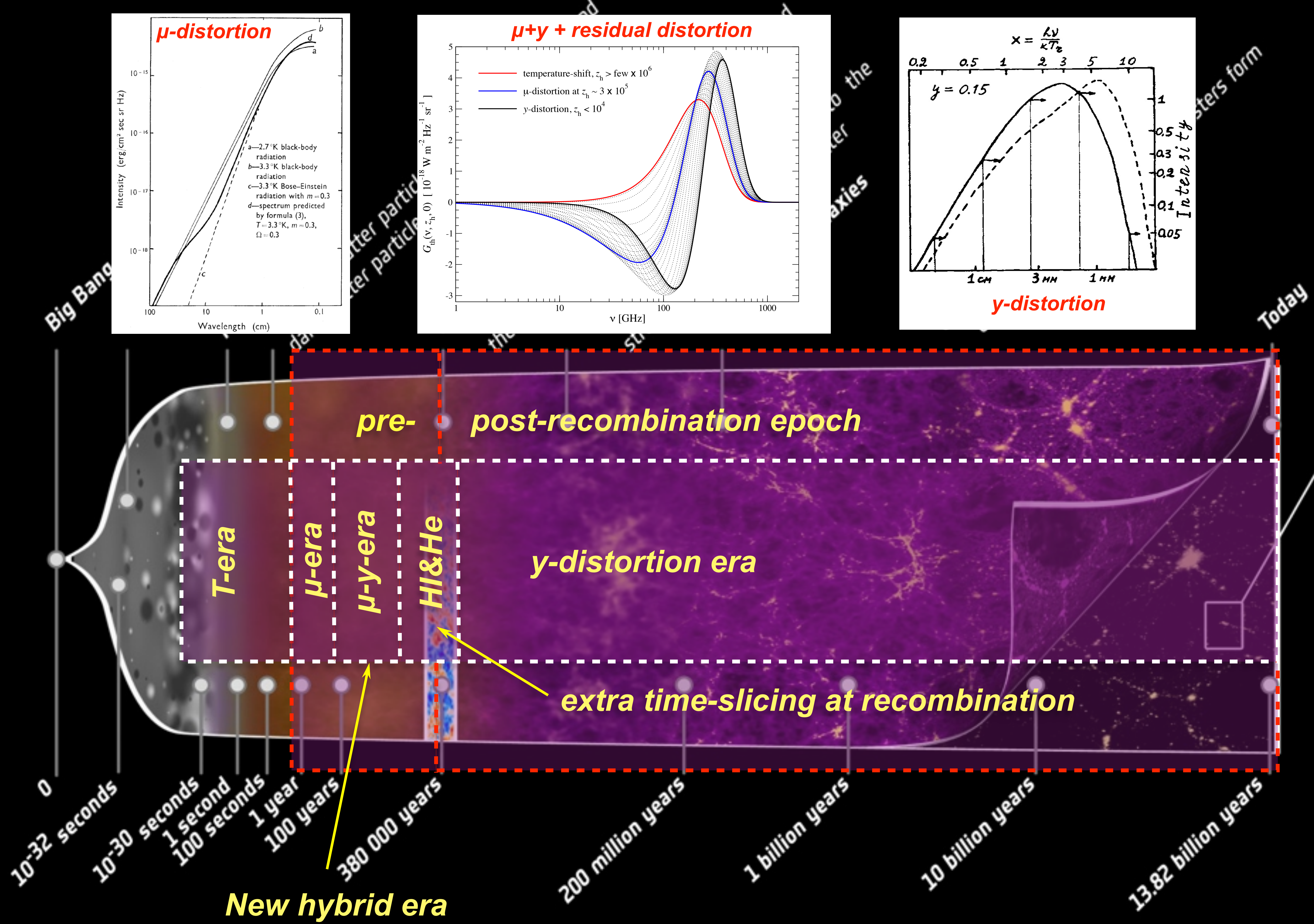


y - distortion
μ–y transition
μ - distortion
$y \simeq \frac{1}{4}\frac{\Delta\rho_\gamma}{\rho_\gamma} \equiv \frac{1}{4}\int_{z_{\rm rec}}^{z_{\mu y}} \frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'}\,{\rm d}z'$
$\mu \approx 1.4\int_{z_{\mu y}}^{\infty} \frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'}\mathcal{J}_\mu(z')\,{\rm d}z'$
$\mathcal{J}_\mu(z) \approx {\rm e}^{-\left(\frac{z}{1.98\times10^6}\right)^{5/2}}$
Visibility
1
0.8
0.6
0.4
0.2
0
Last Scattering Surface
$t_{\rm K} \simeq t_{\rm exp}$
Blackbody fully restored by thermalization
10^2
10^3
10^4
10^5
10^6
10^7
redshift z

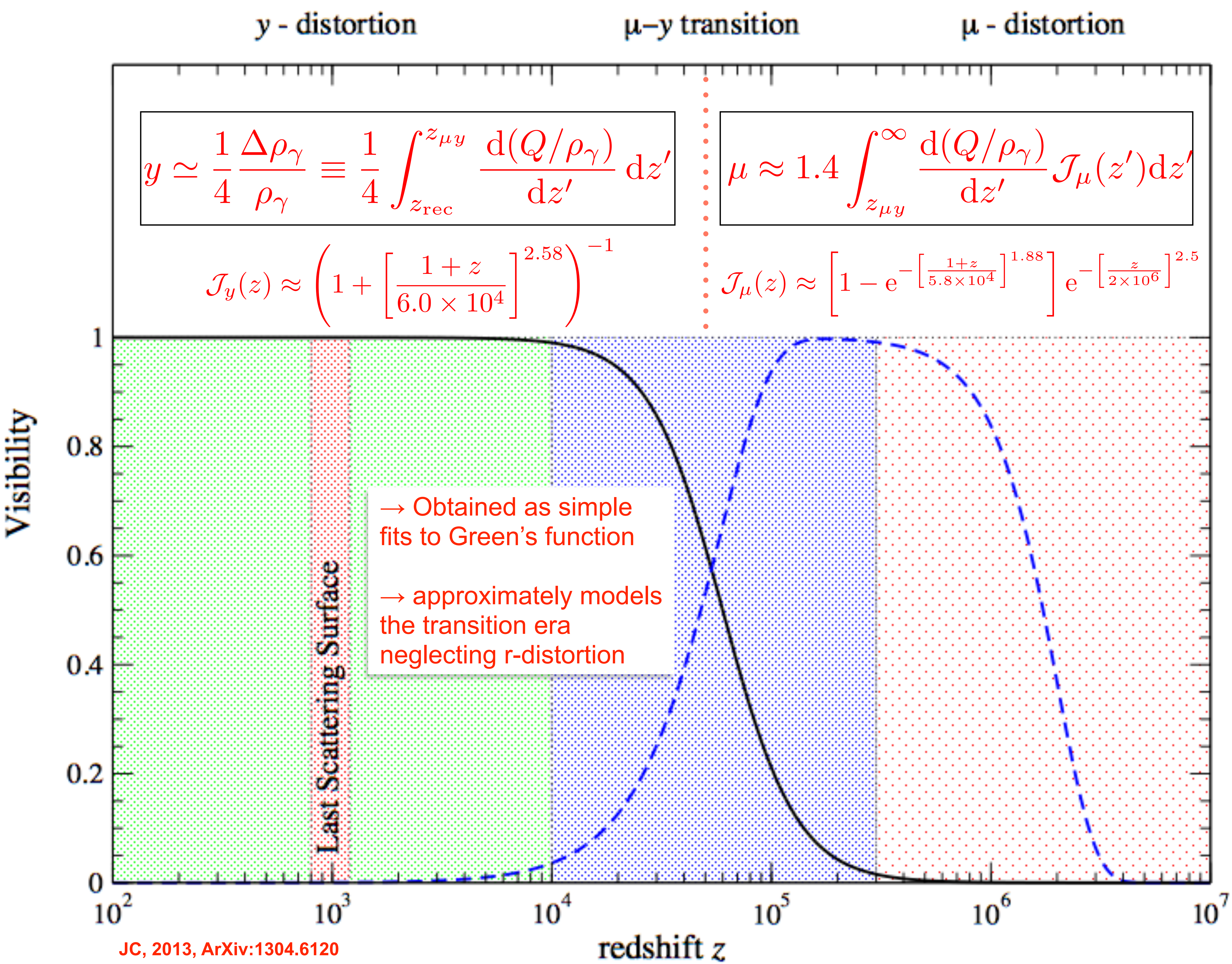


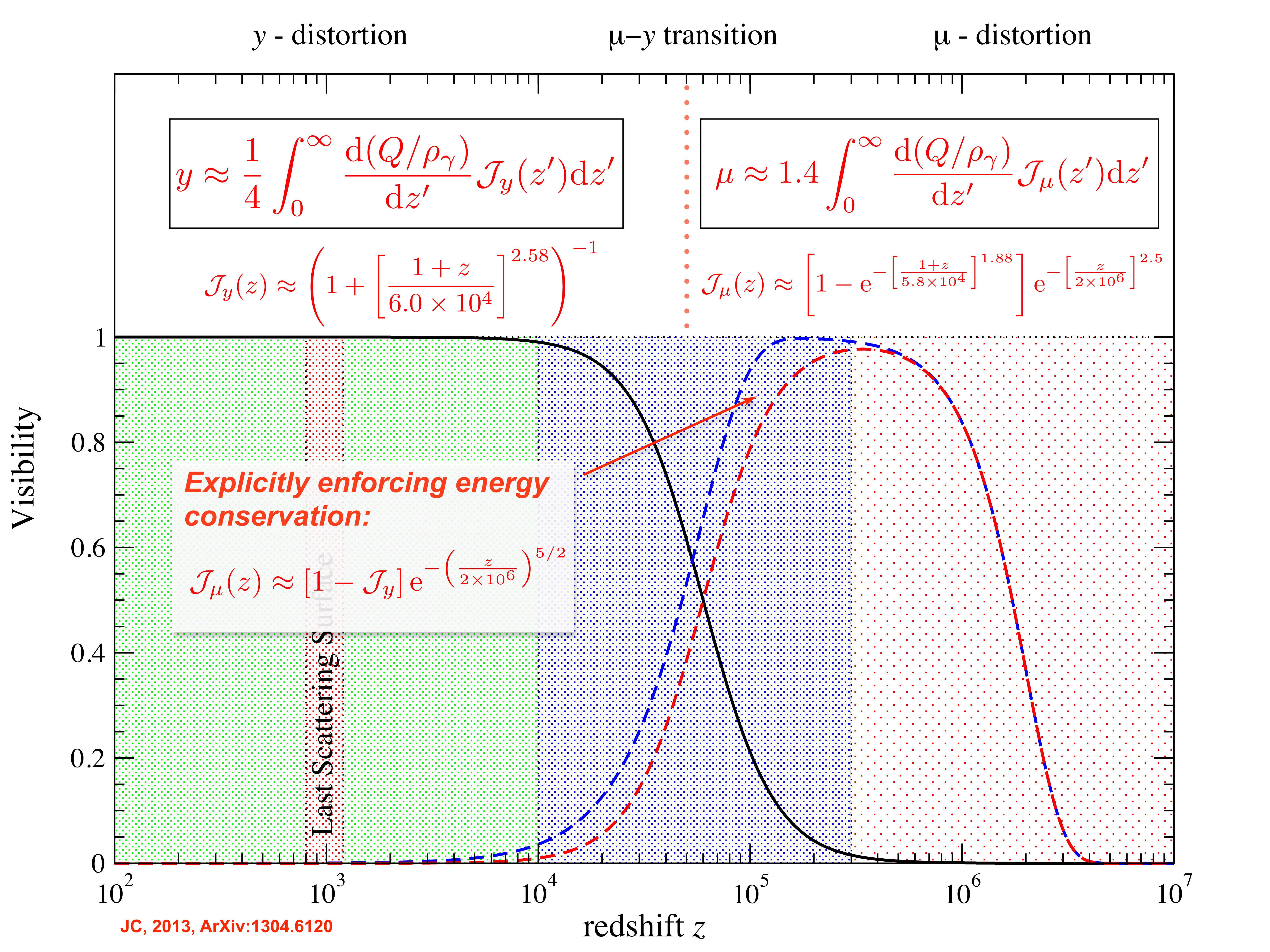
y - distortion
μ–y transition
μ - distortion
$y \simeq \frac{1}{4}\frac{\Delta\rho_\gamma}{\rho_\gamma} \equiv \frac{1}{4}\int_{z_{\rm rec}}^{z_{\mu y}} \frac{d(Q/\rho_\gamma)}{dz'}\,dz'$
$\mu \approx 1.4\int_{z_{\mu y}}^{\infty} \frac{d(Q/\rho_\gamma)}{dz'}\mathcal{J}_\mu(z')dz'$
$\mathcal{J}_\mu(z) \approx e^{-\left(\frac{z}{1.98\times10^6}\right)^{5/2}}$
Visibility
Last Scattering Surface
$t_K \simeq t_{\rm exp}$
Blackbody "photosphere"
(Bond, Les Houches Lectures, 1996)
redshift z


y - distortion
μ–y transition
μ - distortion
$y \simeq \frac{1}{4}\frac{\Delta\rho_\gamma}{\rho_\gamma} \equiv \frac{1}{4}\int_{z_{\rm rec}}^{z_{\mu y}} \frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'}\,{\rm d}z'$
$\mu \approx 1.4 \int_{z_{\mu y}}^{\infty} \frac{{\rm d}(Q/\rho_\gamma)}{{\rm d}z'}\mathcal{J}_\mu(z'){\rm d}z'$
$\mathcal{J}_\mu(z) \approx {\rm e}^{-\left(\frac{z}{1.98\times10^6}\right)^{5/2}}$
Very simple 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
0
0.2
0.4
0.6
0.8
1
10^2
10^3
10^4
10^5
10^6
10^7

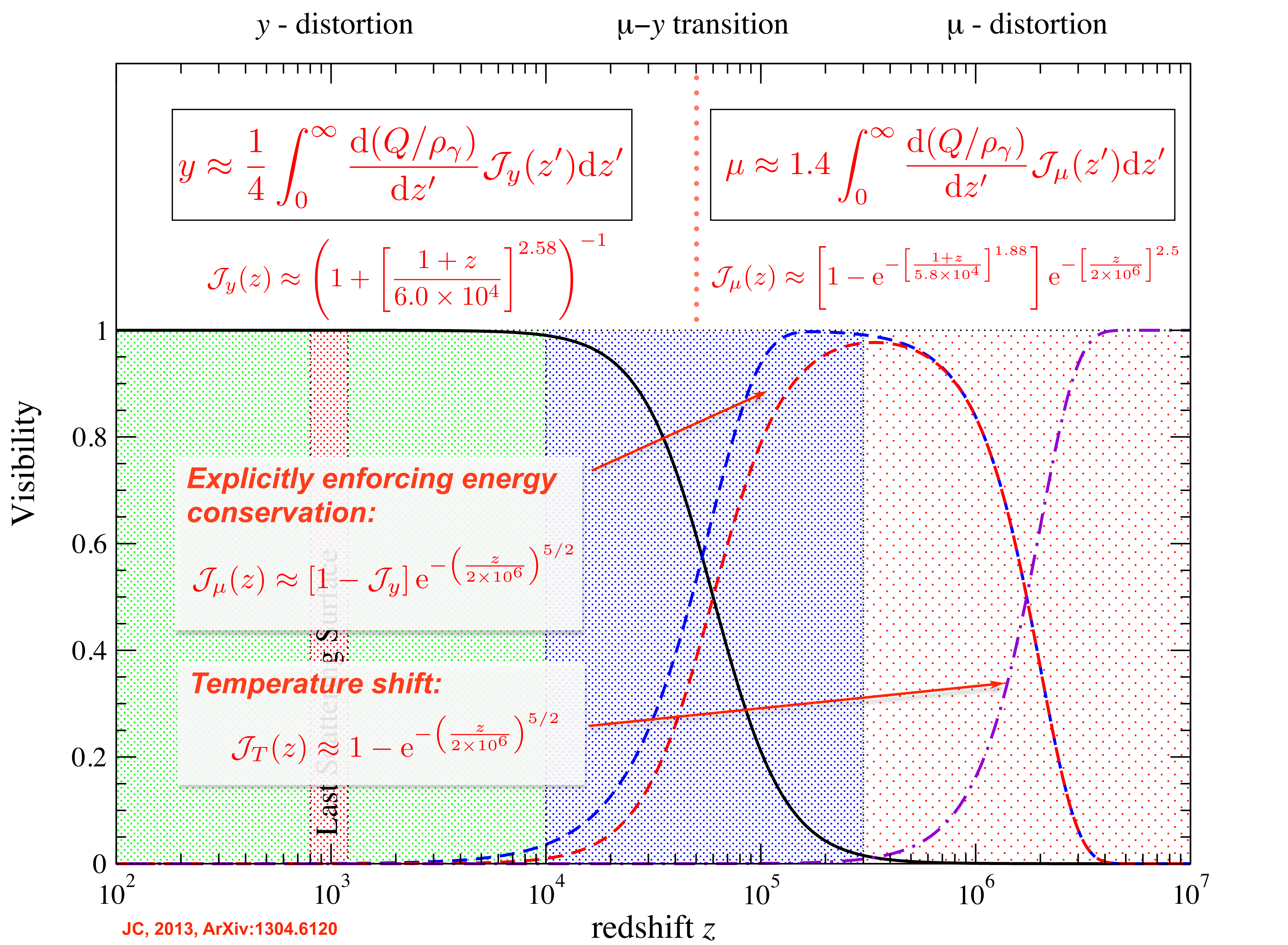


μ-distortion
Intensity (erg cm² sec sr Hz)
Wavelength (cm)
a—2.7°K black-body radiation
b—3.3°K black-body radiation
c—3.3°K Bose-Einstein radiation with m = 0.3
d—spectrum predicted by formula (3), T = 3.3°K, m = 0.3, Ω = 0.3
μ+y + residual distortion
temperature-shift, z_h > few x 10^6
μ-distortion at z_h ~ 3 x 10^5
y-distortion, z_h < 10^4
ν [GHz]
y-distortion
y = 0.15
Intensity
1 cm
3 mm
1 mm
Big Bang
Today
pre-
post-recombination epoch
T-era
μ-era
μ-y-era
HI&He
y-distortion era
extra time-slicing at recombination
New hybrid era
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


y - distortion
μ–y transition
μ - distortion
$y \simeq \frac{1}{4}\frac{\Delta\rho_\gamma}{\rho_\gamma} \equiv \frac{1}{4}\int_{z_{\rm rec}}^{z_{\mu y}} \frac{d(Q/\rho_\gamma)}{dz'}\,dz'$
$\mu \approx 1.4 \int_{z_{\mu y}}^{\infty} \frac{d(Q/\rho_\gamma)}{dz'}\mathcal{J}_\mu(z')dz'$
$\mathcal{J}_y(z) \approx \left(1 + \left[\frac{1+z}{6.0\times10^4}\right]^{2.58}\right)^{-1}$
$\mathcal{J}_\mu(z) \approx \left[1 - e^{-\left[\frac{1+z}{5.8\times10^4}\right]^{1.88}}\right] e^{-\left[\frac{z}{2\times10^6}\right]^{2.5}}$
Visibility
Last Scattering Surface
→ Obtained as simple fits to Green's function
→ approximately models the transition era neglecting r-distortion
redshift z
JC, 2013, ArXiv:1304.6120



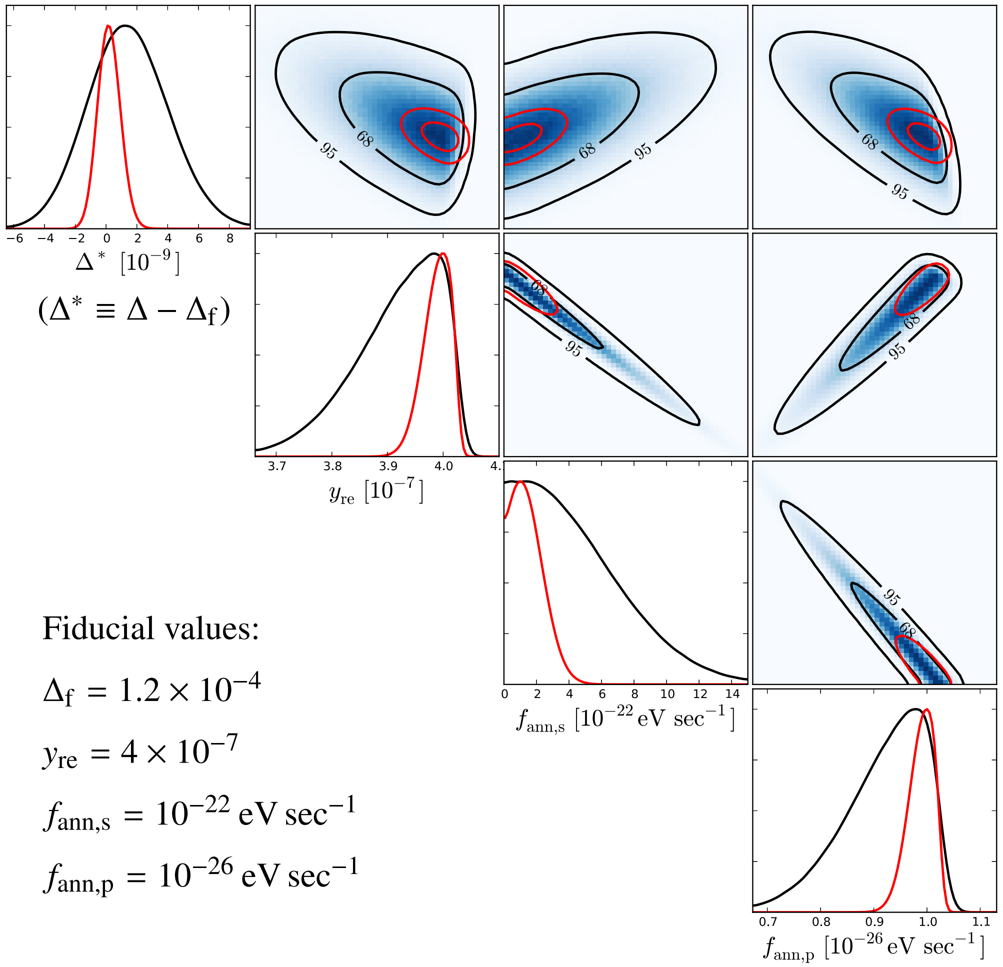
y - distortion
μ–y transition
μ - distortion
$y \approx \frac{1}{4}\int_0^\infty \frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z'}\mathcal{J}_y(z')\mathrm{d}z'$
$\mathcal{J}_y(z) \approx \left(1+\left[\frac{1+z}{6.0\times10^4}\right]^{2.58}\right)^{-1}$
$\mu \approx 1.4\int_0^\infty \frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z'}\mathcal{J}_\mu(z')\mathrm{d}z'$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



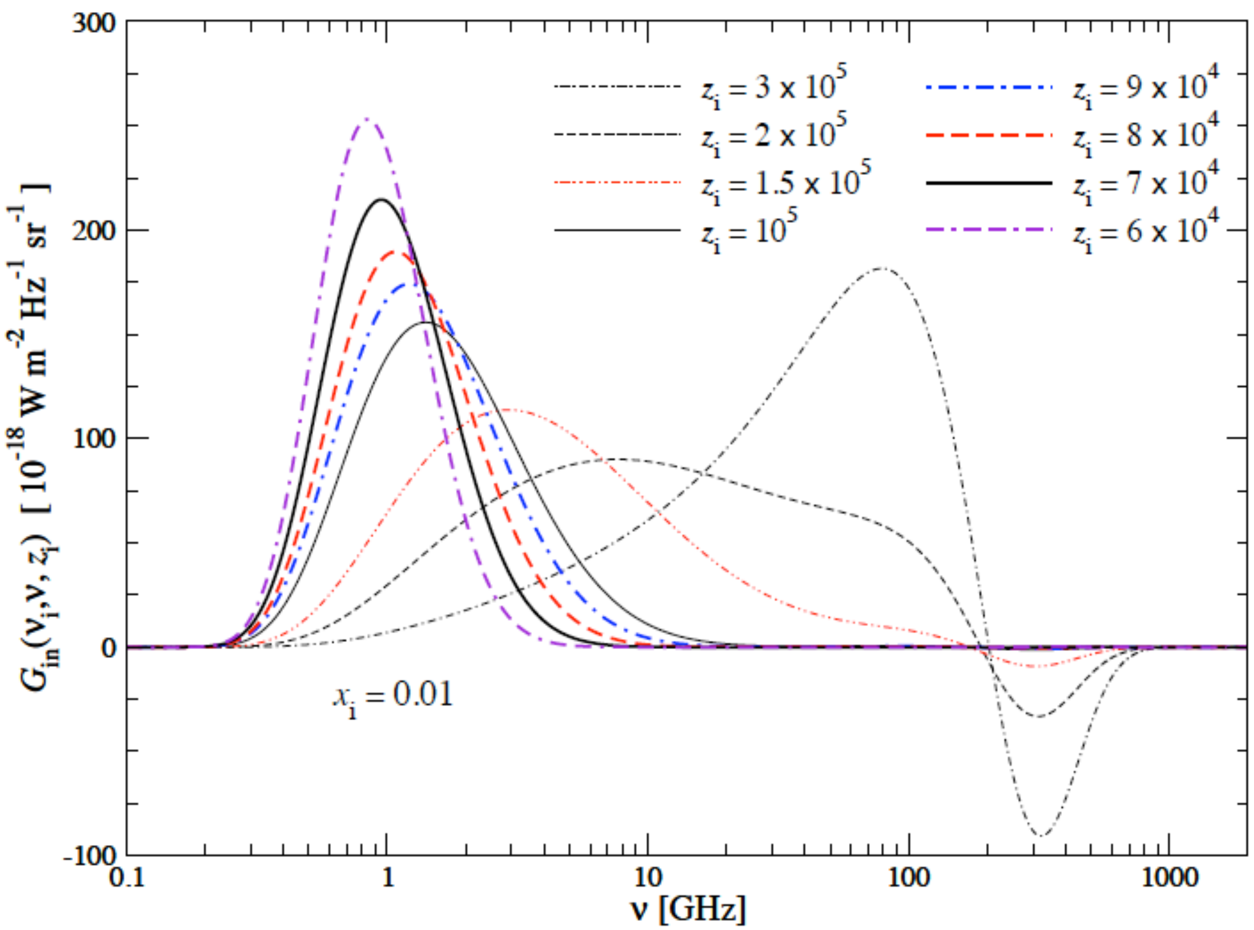
y - distortion
μ–y transition
μ - distortion
$y \approx \frac{1}{4} \int_0^\infty \frac{d(Q/\rho_\gamma)}{dz'} \mathcal{J}_y(z') dz'$
$\mathcal{J}_y(z) \approx \left(1 + \left[\frac{1+z}{6.0 \times 10^4}\right]^{2.58}\right)^{-1}$
$\mu \approx 1.4 \int_0^\infty \frac{d(Q/\rho_\gamma)}{dz'} \mathcal{J}_\mu(z') dz'$
$\mathcal{J}_\mu(z) \approx \left[1 - e^{-\left[\frac{1+z}{5.8\times10^4}\right]^{1.88}}\right] e^{-\left[\frac{z}{2\times10^6}\right]^{2.5}}$
Explicitly enforcing energy conservation:
$\mathcal{J}_\mu(z) \approx [1 - \mathcal{J}_y] e^{-\left(\frac{z}{2\times10^6}\right)^{5/2}}$
Temperature shift:
$\mathcal{J}_T(z) \approx 1 - e^{-\left(\frac{z}{2\times10^6}\right)^{5/2}}$
Last Scattering Surface
Visibility
redshift z
JC, 2013, ArXiv:1304.6120

Using the Green's function package

- Green's function package available at `www.Chluba.de/CosmoTherm/`
- Depends on GSL library
- Has python interface and python packages
- PCA methods (not added yet…)
- Green's function method for photon injection too (JC 2015, ArXiv:1506.06582)



JC 2013, ArXiv:1304.6121



JC 2015, ArXiv:1506.06582

Some useful commands

Making and cleaning

```
> make
> make py
> make clean
> make tidy
```

Execute Greens-package like

`./run_Greens runfiles/parameters.dat` **(default computation)**

Some other runmodes…

`./run_Greens Greens runfiles/parameters.dat` **(Greens function output)**

`./run_Greens Mock runfiles/parameters.dat` **(band average for mock)**

Green’s function specific parameters

./runfiles/parameters.dat

```
//==============================================================================
// the above parameters are (default values are given as examples)
//==============================================================================
0           == error in the reference blackbody assumed to be T0=2.726 K

1.0e-23     == fann*=fann(1-fnu) typically f_ann<~2.0e-23 eV s^-1 [set ==0 to deactivate]
0           == s (==0) or p (==1)-wave annihilation cross section

2.4e-9      == Amplitude of adiabatic mode [set ==0 to deactivate 'all' dissipation parts]
0.002       == pivot scale k0 in Mpc^-1
1.0         == spectral index nS
0.0         == running n_run

4.0e-8      == Amplitude of the power spectrum step [set ==0 to deactivate]
30.0        == ks in Mpc^-1
0.96        == spectral index nS' after step

3.0         == kbend in Mpc^-1 [set ==1.0e+10 to deactivate]
1.5         == spectral index nS' after bend

5e+4        == z_X which determines lifetime of particle by Gamma_X=1/t(z_X)
2.0e+3      == f_X'=f_X(1-fnu) typically f_X <~10^6 eV for z_X~5x10^4
               [set ==0 to deactivate]

4.0e-9      == Amplitude for particle production feature [set ==0 to deactivate]
20.0        == position of particle production feature in k

4.0e-7      == y-parameter from reionization

./outputs/  == path for output
.dat        == addition to name of files at the very end

//==============================================================================
```

Execute Greens-package like

```
./run_Greens MODE runfiles/parameters.dat
```