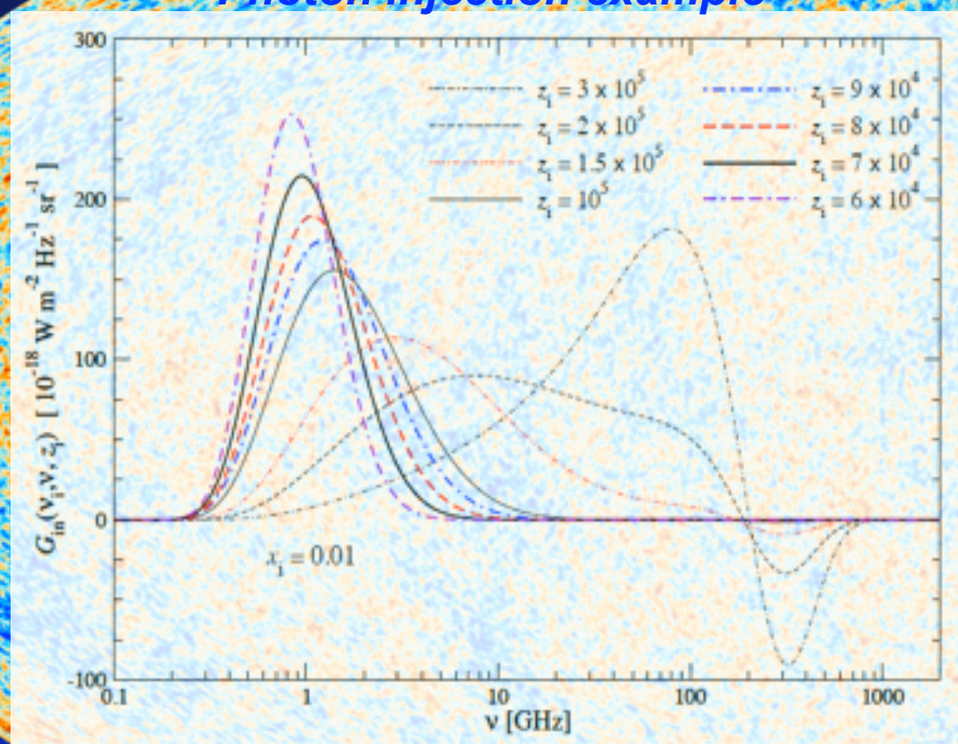
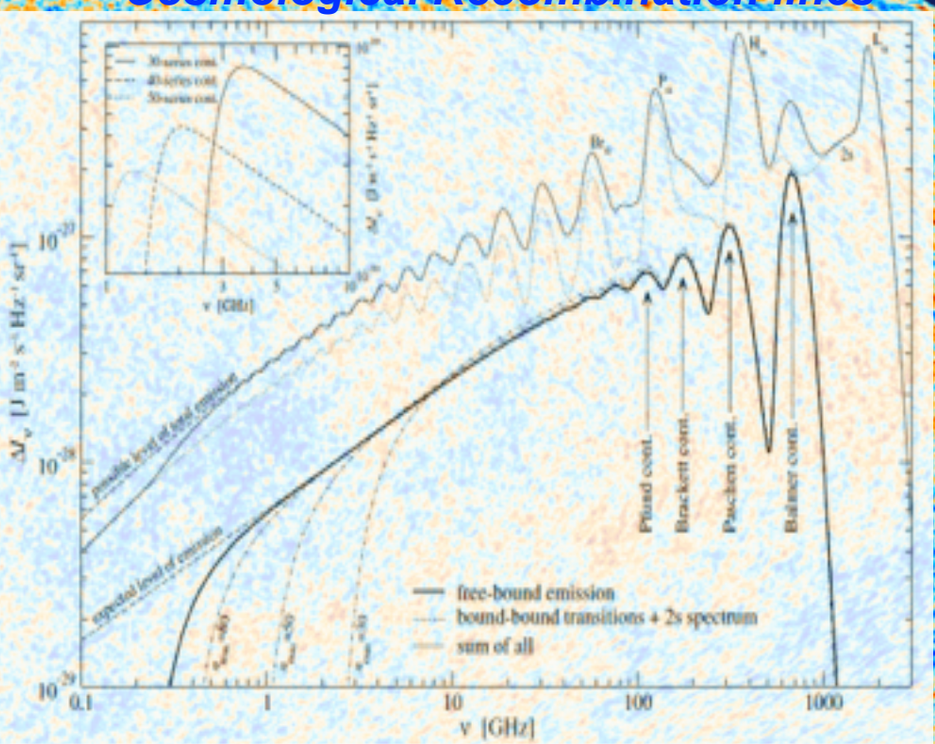
# CMB Spectral Distortions: Energy Release Versus Photon Injection

***Photon injection example***




***Cosmological Recombination lines***



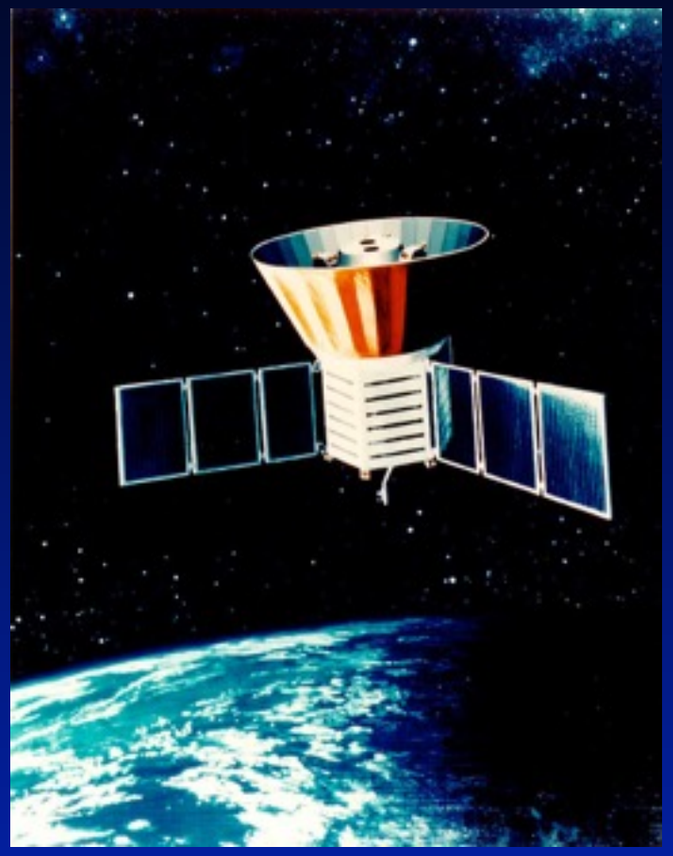


**Jens Chluba**


**28th Texas Symposium on Relativistic Astrophysics**

**Geneva, December 13th-18th, 2015**

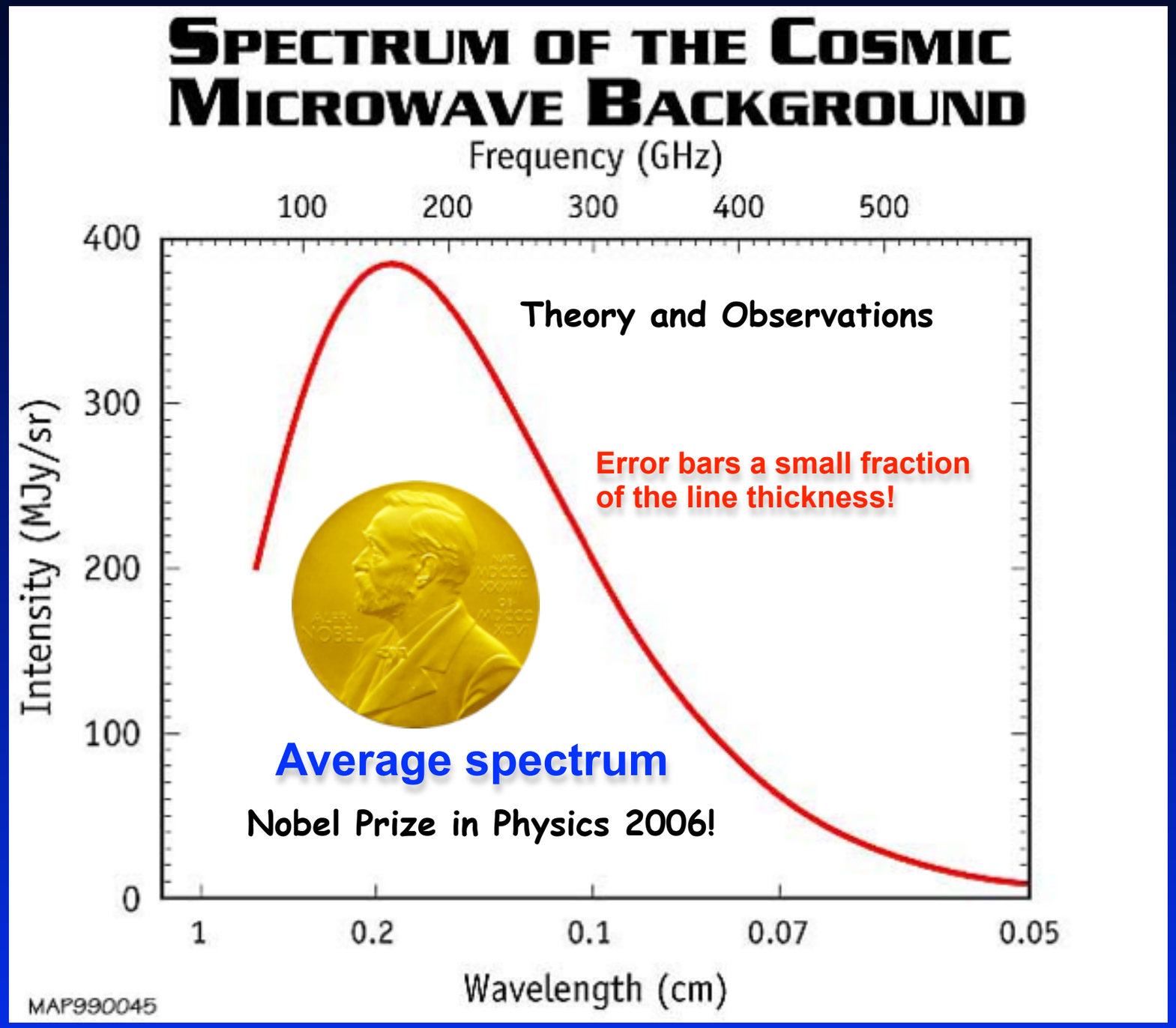
# COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)



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

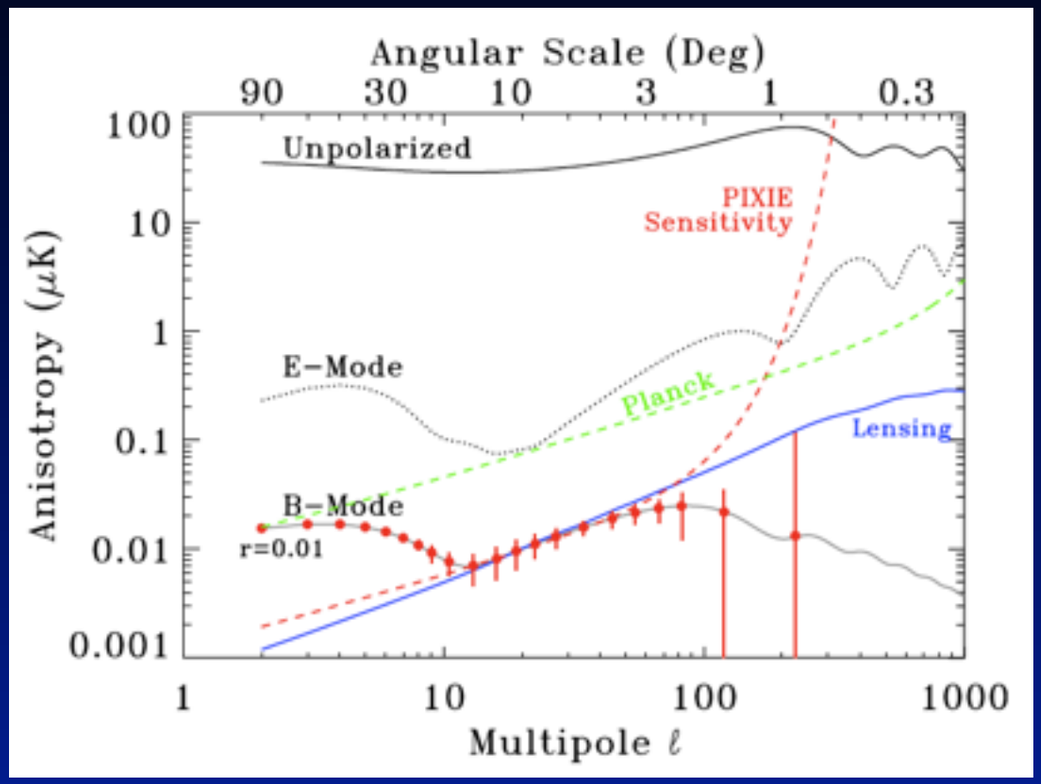
$$|y| \leq 1.5\times10^{-5}$$

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

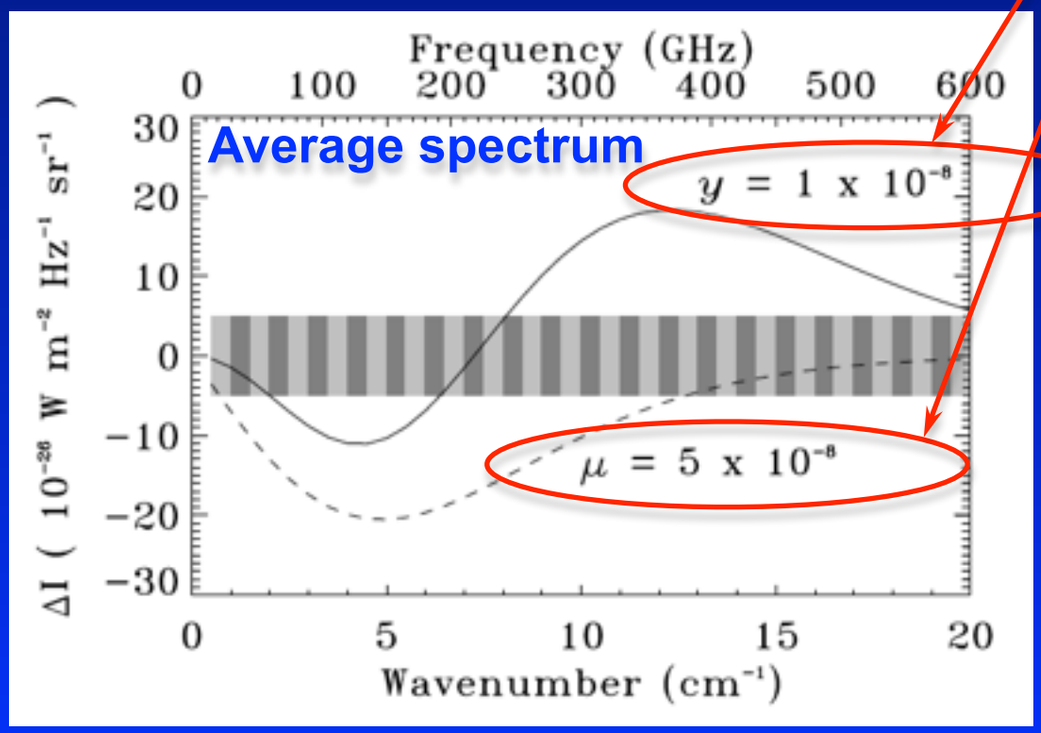


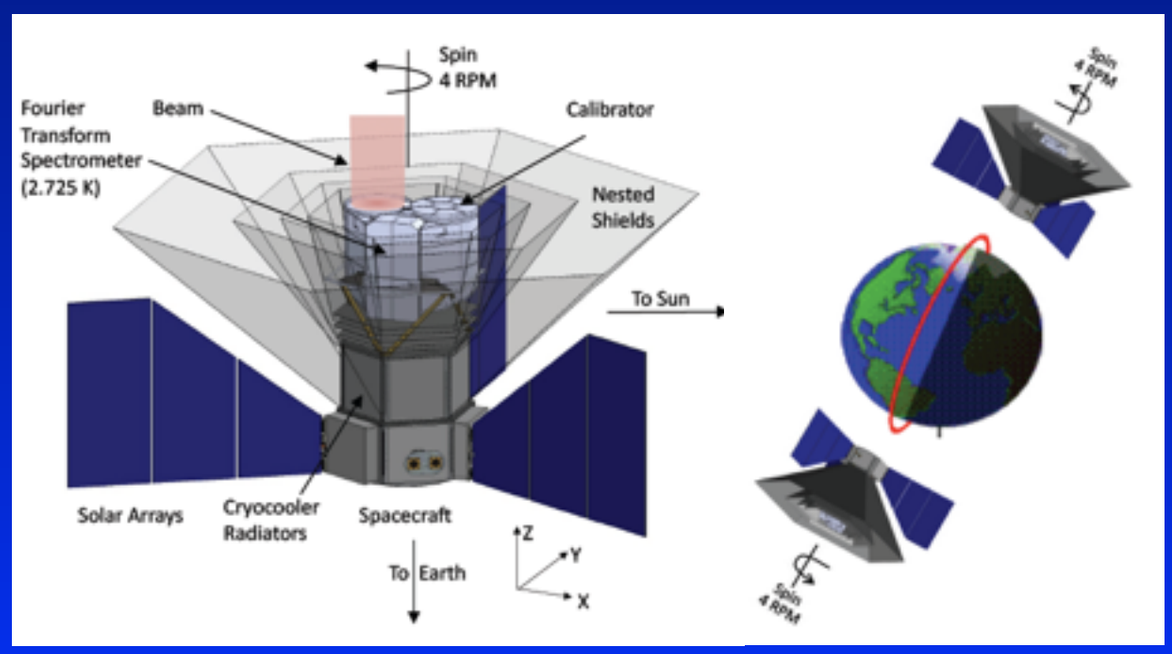

Mather et al., 1994, ApJ, 420, 439
Fixsen et al., 1996, ApJ, 473, 576
Fixsen et al., 2003, ApJ, 594, 67

# PIXIE: Primordial Inflation Explorer




- 400 spectral channel in the frequency range 30 GHz and 6THz (Δv ~ 15GHz)
- about 1000 (!!!) times more sensitive than COBE/FIRAS
- B-mode polarization from inflation ($r \approx 10^{-3}$)
- improved limits on $\mu$ and $y$
- was proposed 2011 as NASA EX mission (i.e. cost ~ 200 M$)




Kogut et al, JCAP, 2011, arXiv:1105.2044

Time

380,000 years

7,000 years

8 years

2 months

Last Scattering Surface

cold dilute

hot dense

33%

4%

0.2%

0.003%

Recombination era

Distortion visibility

Blackbody era

$10^3$

$10^4$

$3\times10^5$

$2\times10^6$

$5\times10^6$

Redshift

Silk & Chluba, Science, 2014

Time 380,000 years 7,000 years 8 years 2 months

Photon energy

full thermalization

Maximum of CMB blackbody

temperature shift

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Photon energy

scattering efficient

μ-distortion

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intermediate regime

y+μ+residual distortion

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# Physical mechanisms that lead to spectral distortions

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

„high“ redshifts

---

„low“ redshifts

- 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)

*pre-recombination epoch*

*post-recombination*

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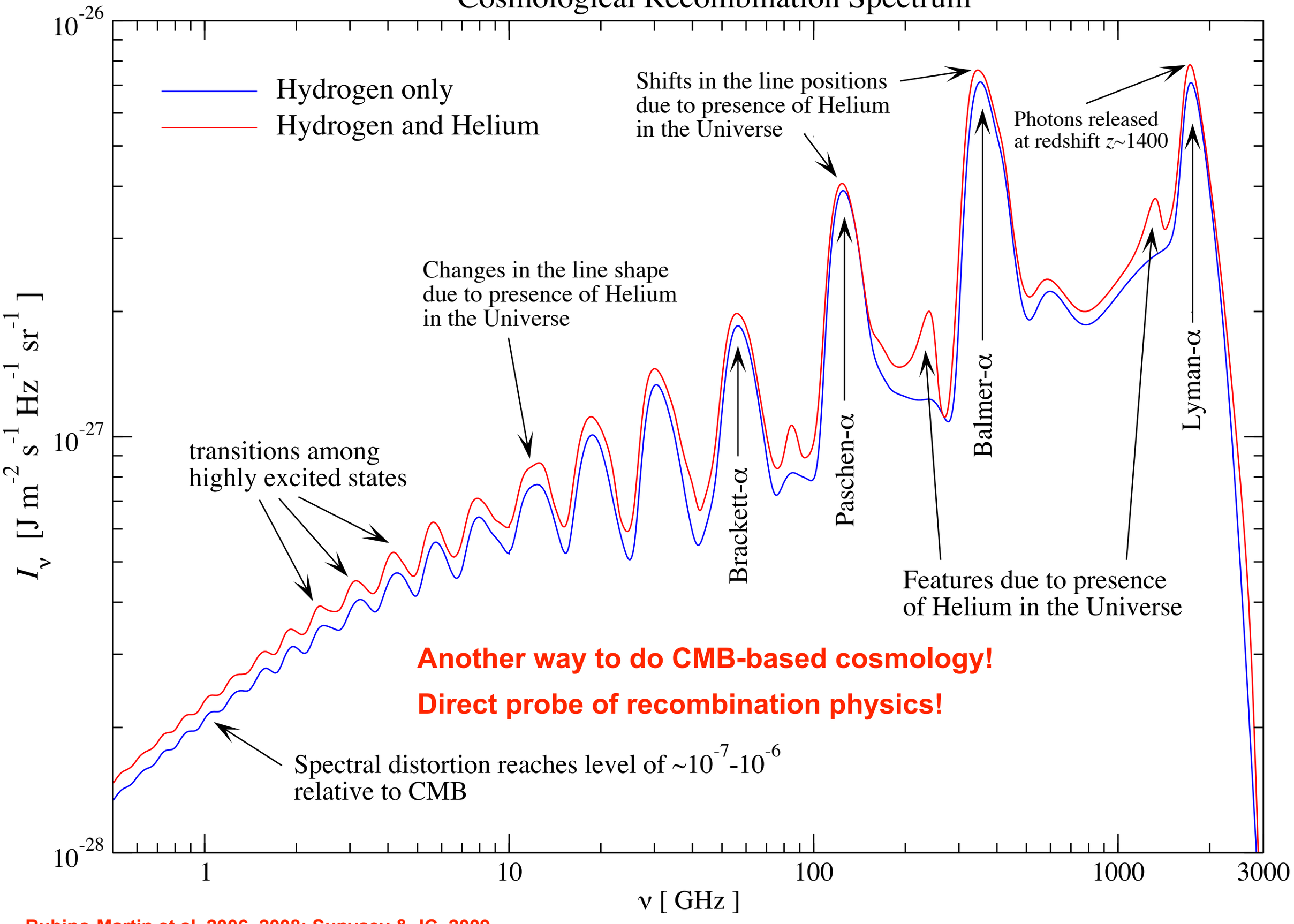


Rubino-Martin et al. 2006, 2008; Sunyaev & JC, 2009

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Distortion Signal

scattering inefficient

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Hydrogen lines

Neutral Helium lines

Ionized Helium lines

Recombination signal

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Distortion ≃$10^{-7}$-$10^{-6}$
relative to blackbody

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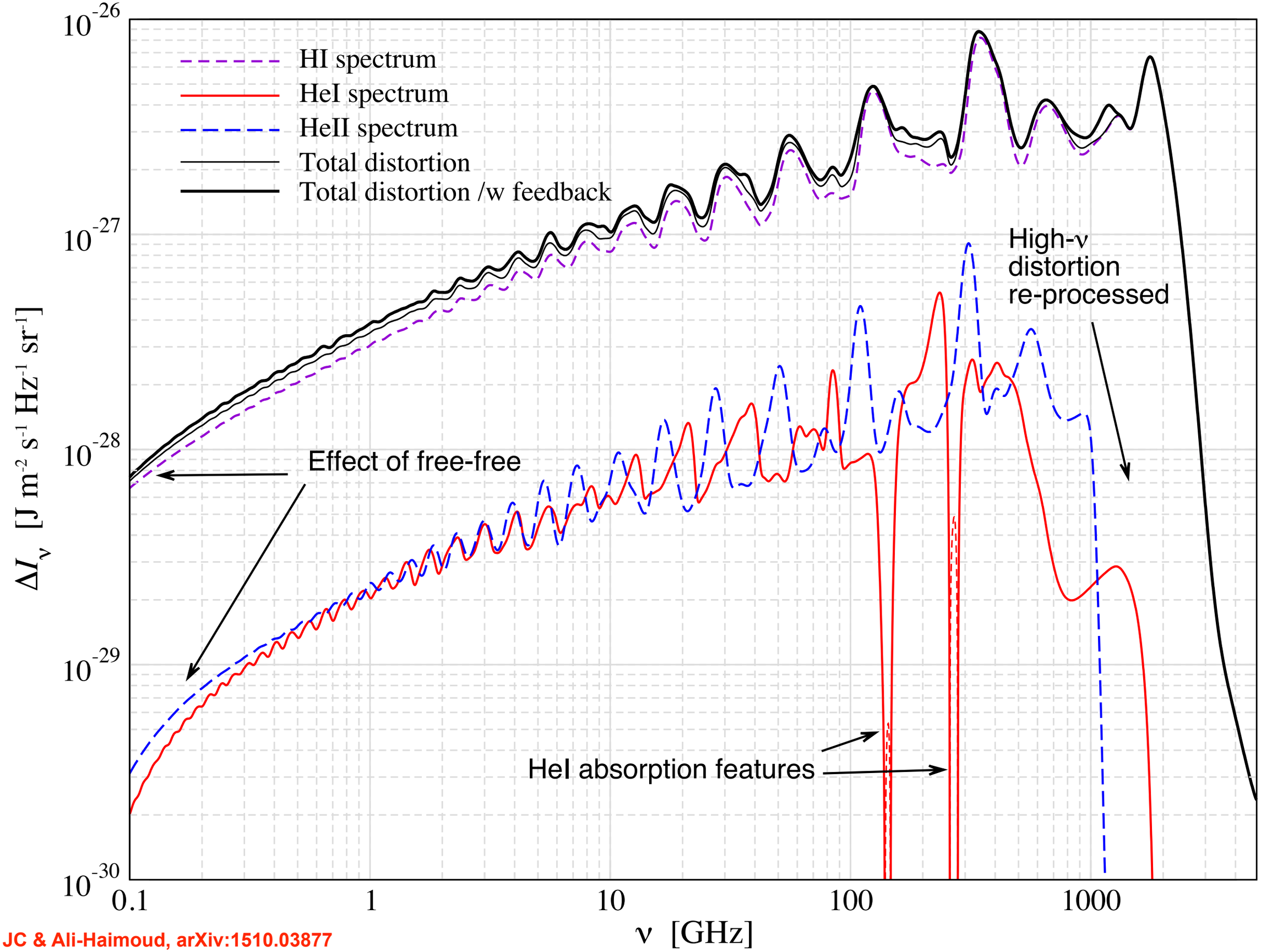
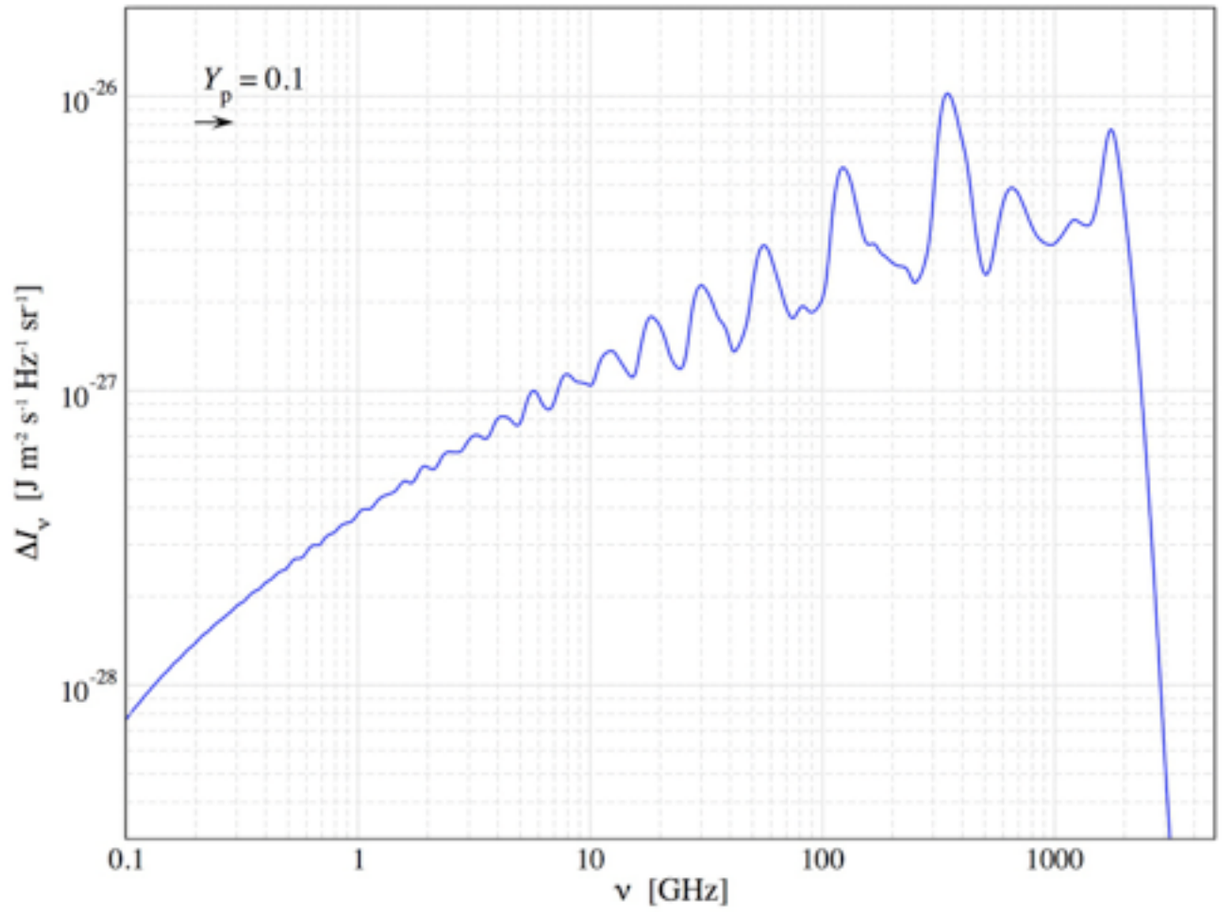
Silk & Chluba, Science, 2014

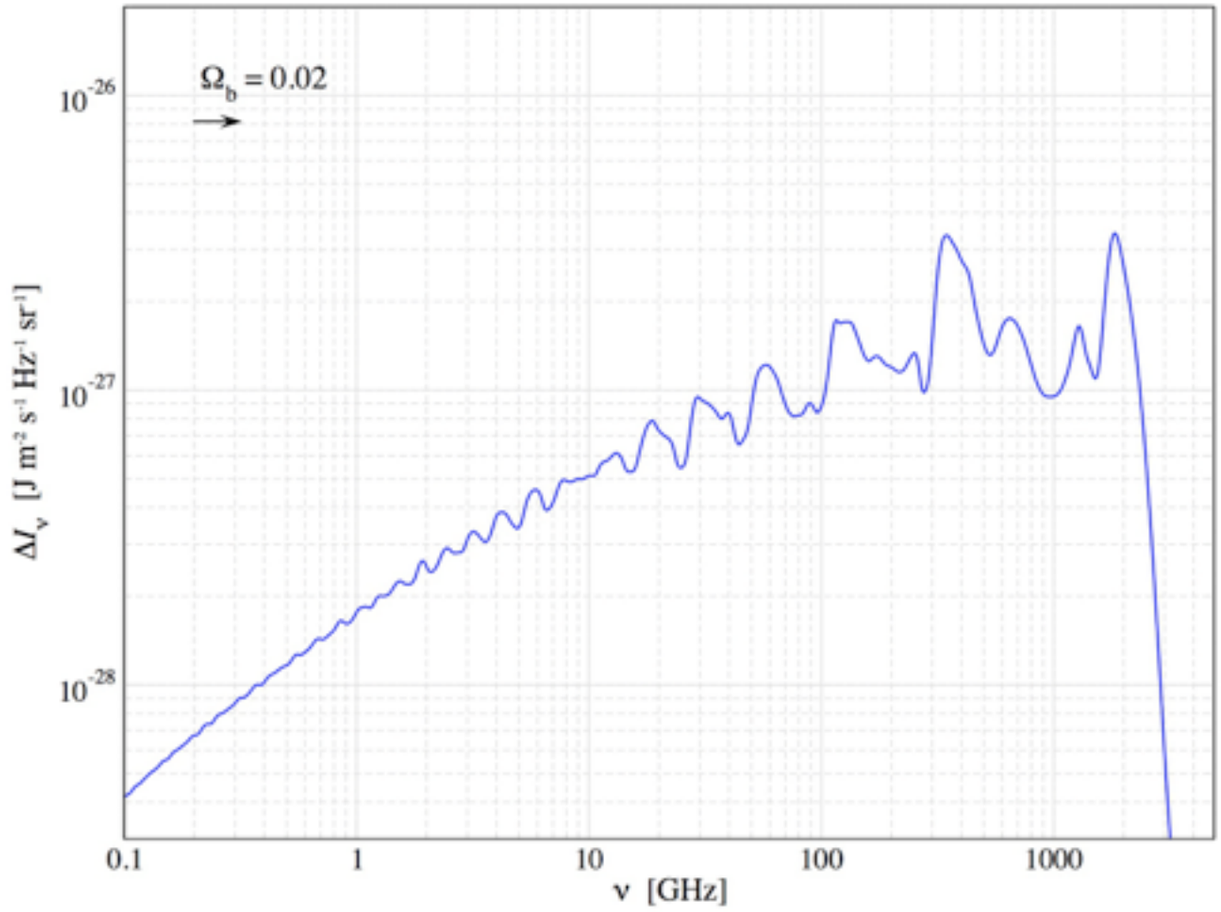
# New detailed and fast computation!




JC & Ali-Haimoud, arXiv:1510.03877

# *CosmoSpec*: fast and accurate computation of the CRR




- Like in old days of CMB anisotropies!
- detailed forecasts and feasibility studies
- non-standard physics (variation of α, energy injection etc.)

*CosmoSpec* will be available here:

**www.Chluba.de/CosmoSpec**

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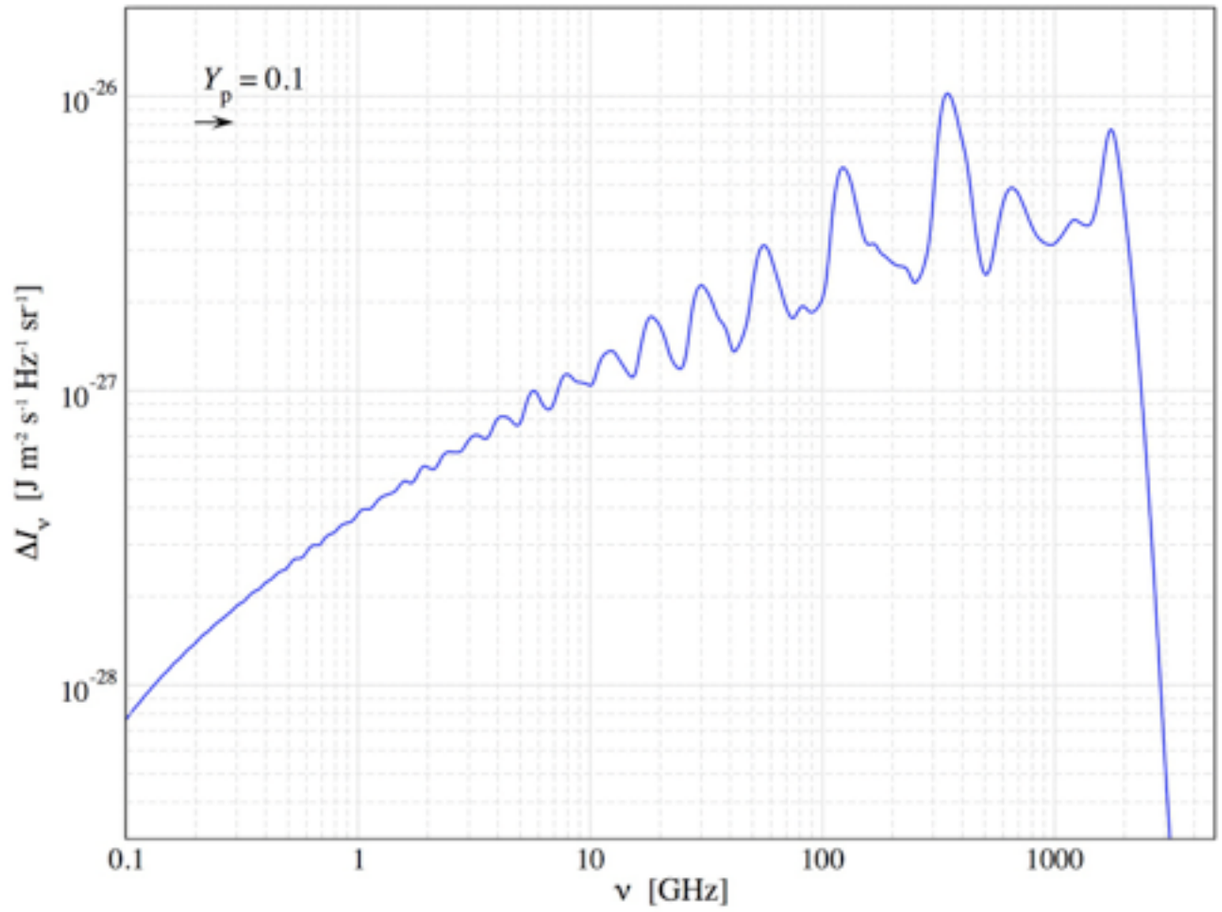


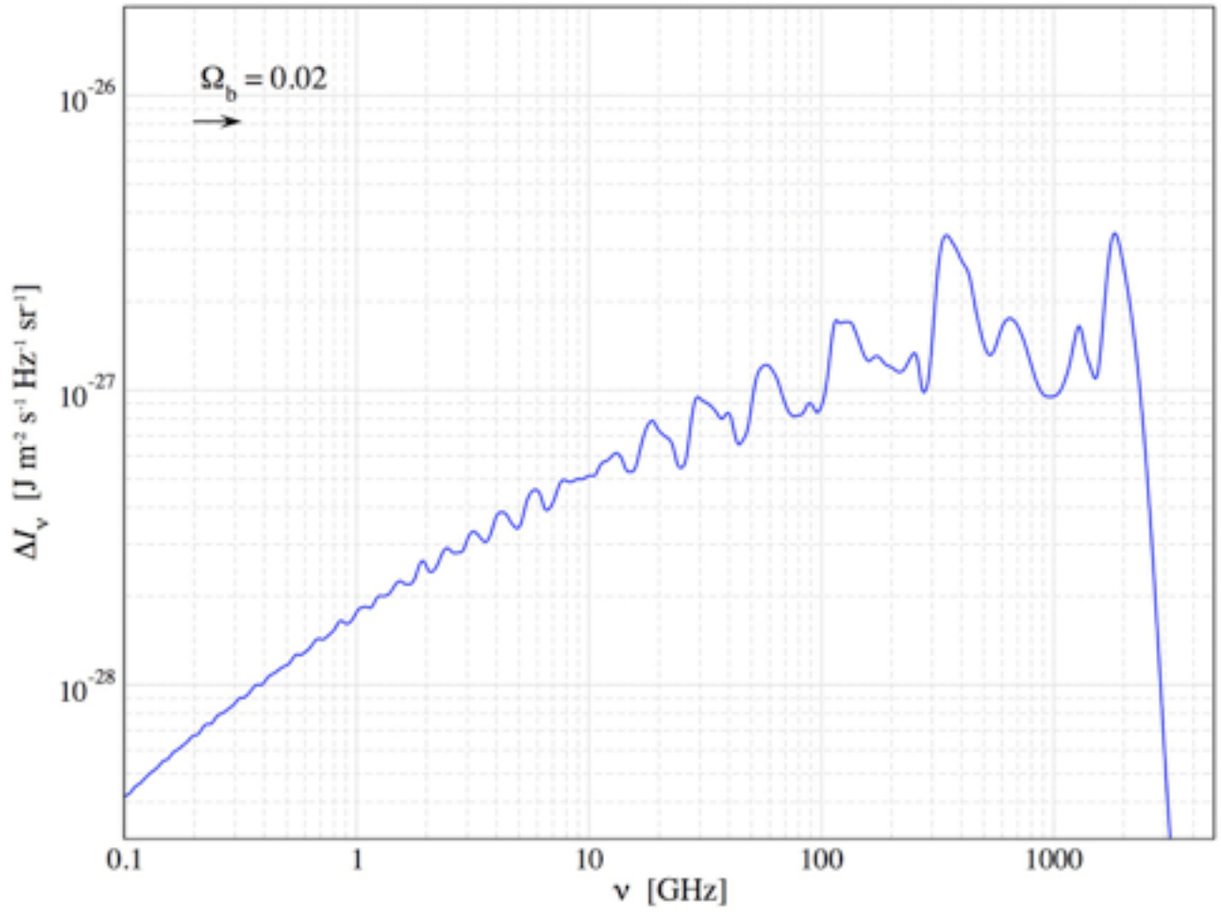


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Low redshift: *rich spectral shape*
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Low redshift: (inefficient Comptonization) *rich spectral shape* High redshift: (efficient Comptonization) $\mu \approx 1.4\left[\frac{\Delta\rho_\gamma}{\rho_\gamma} - \frac{4}{3}\frac{\Delta N_\gamma}{N_\gamma}\right]$

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*Narrow line:*

$$\frac{\Delta\rho_\gamma}{\rho_\gamma} \approx 0.37\, x_{\rm i}\, \frac{\Delta N_\gamma}{N_\gamma}$$

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Low redshift: (inefficient Comptonization) *rich spectral shape*

High redshift: (efficient Comptonization) $\mu \approx 0.52\,[x_\mathrm{i} - 3.60]\,\frac{\Delta N_\gamma}{N_\gamma}$

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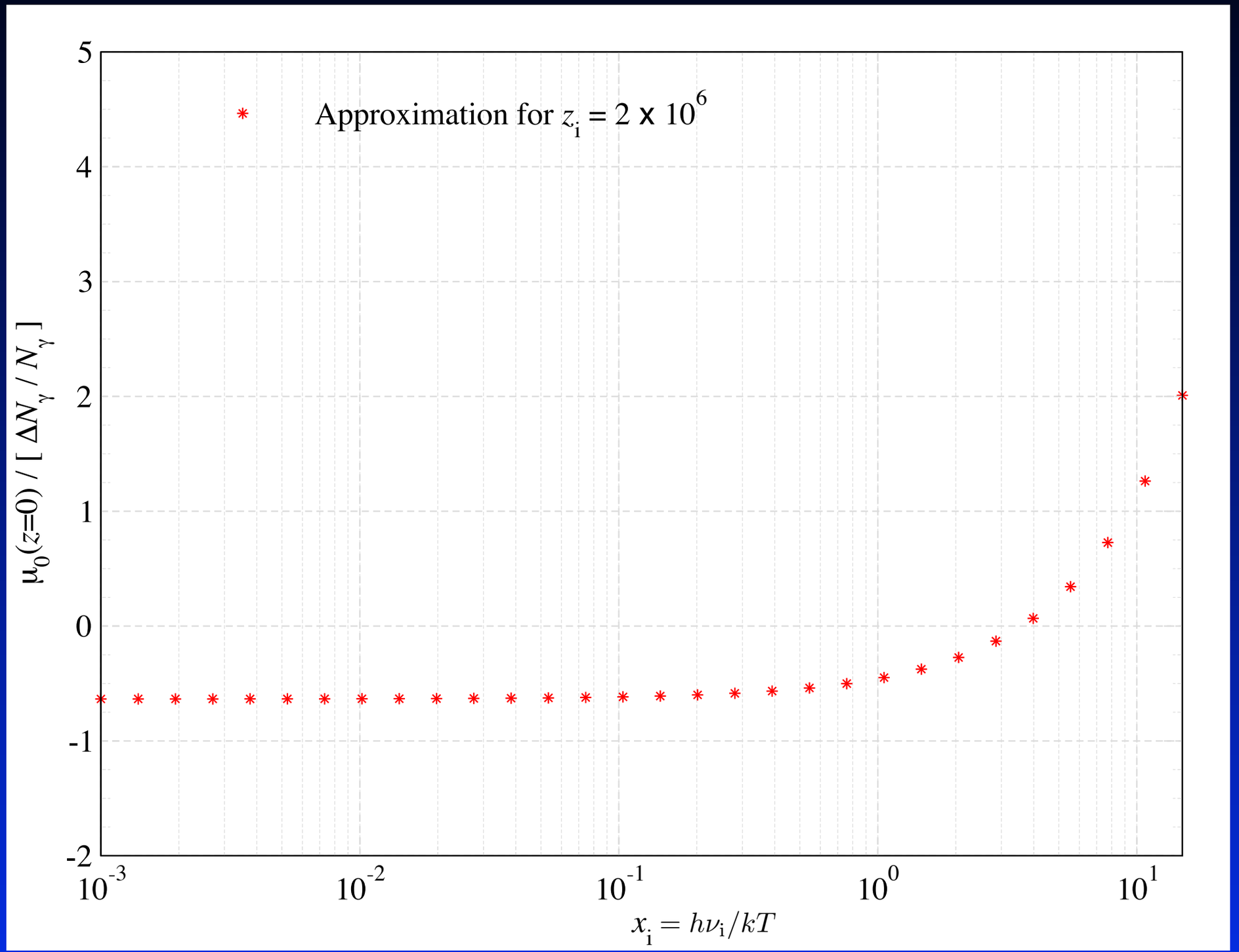
*Net μ-distortion can vanish or be negative!*

# Photon injection in the μ-era

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JC 2015, ArXiv:1506.06582

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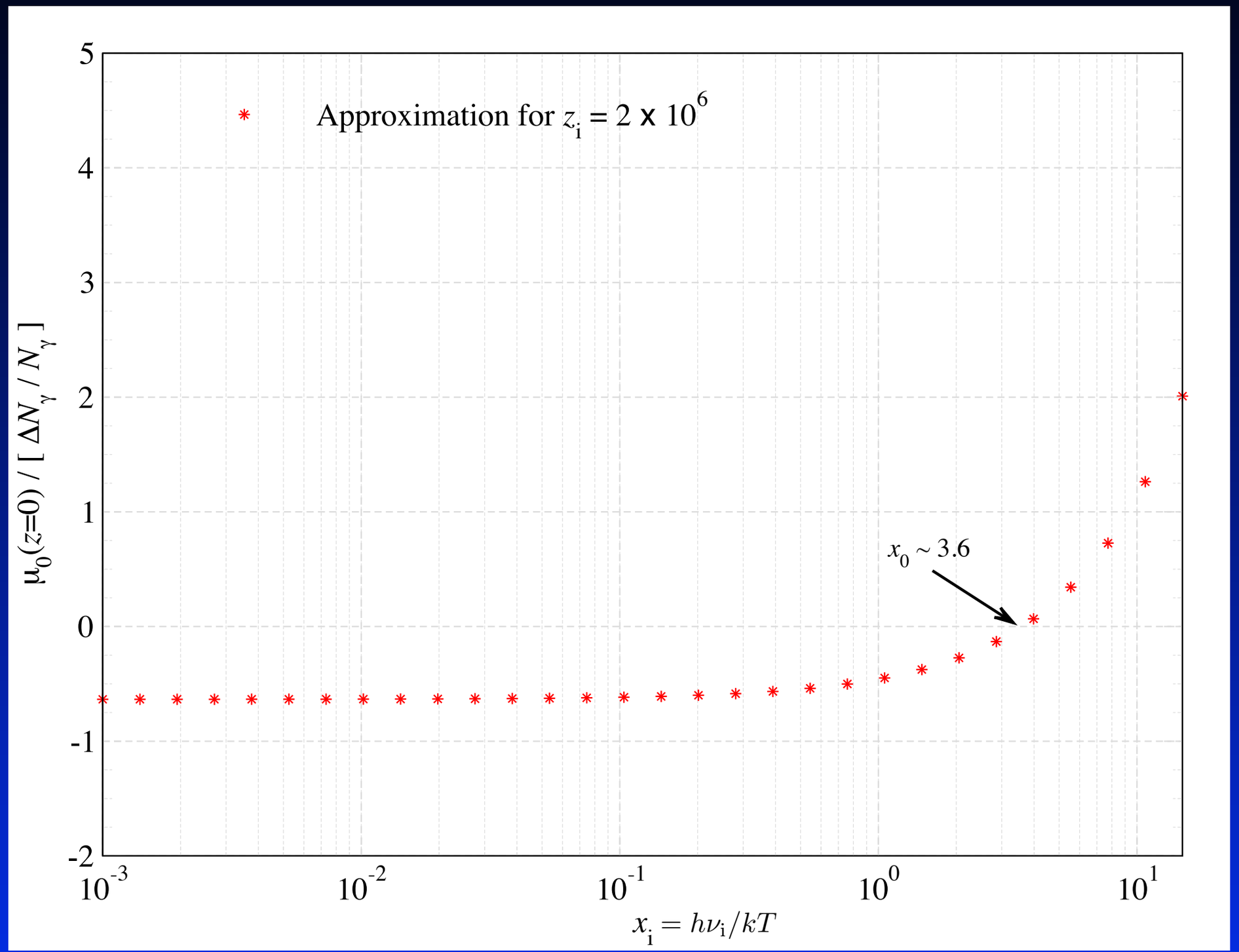


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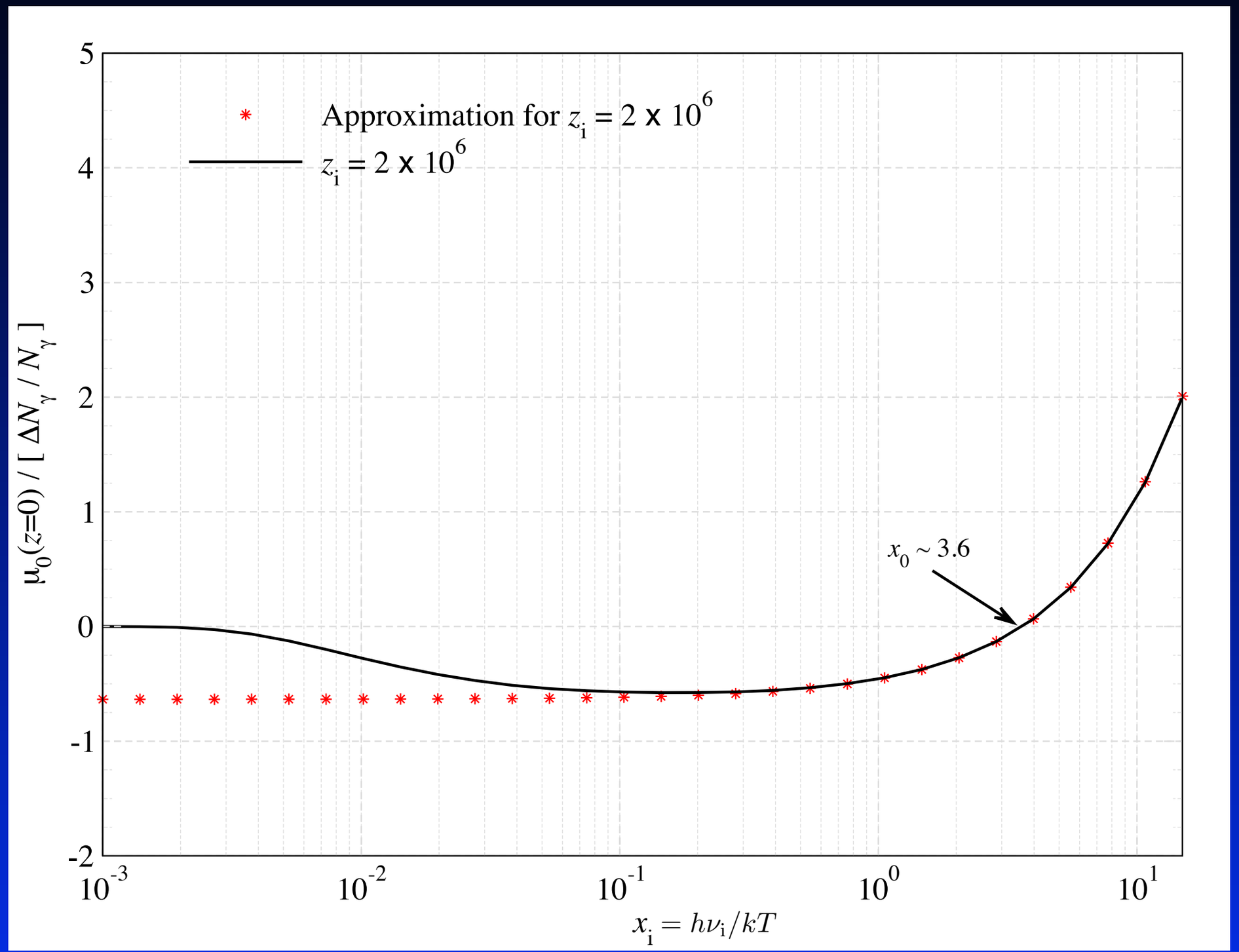


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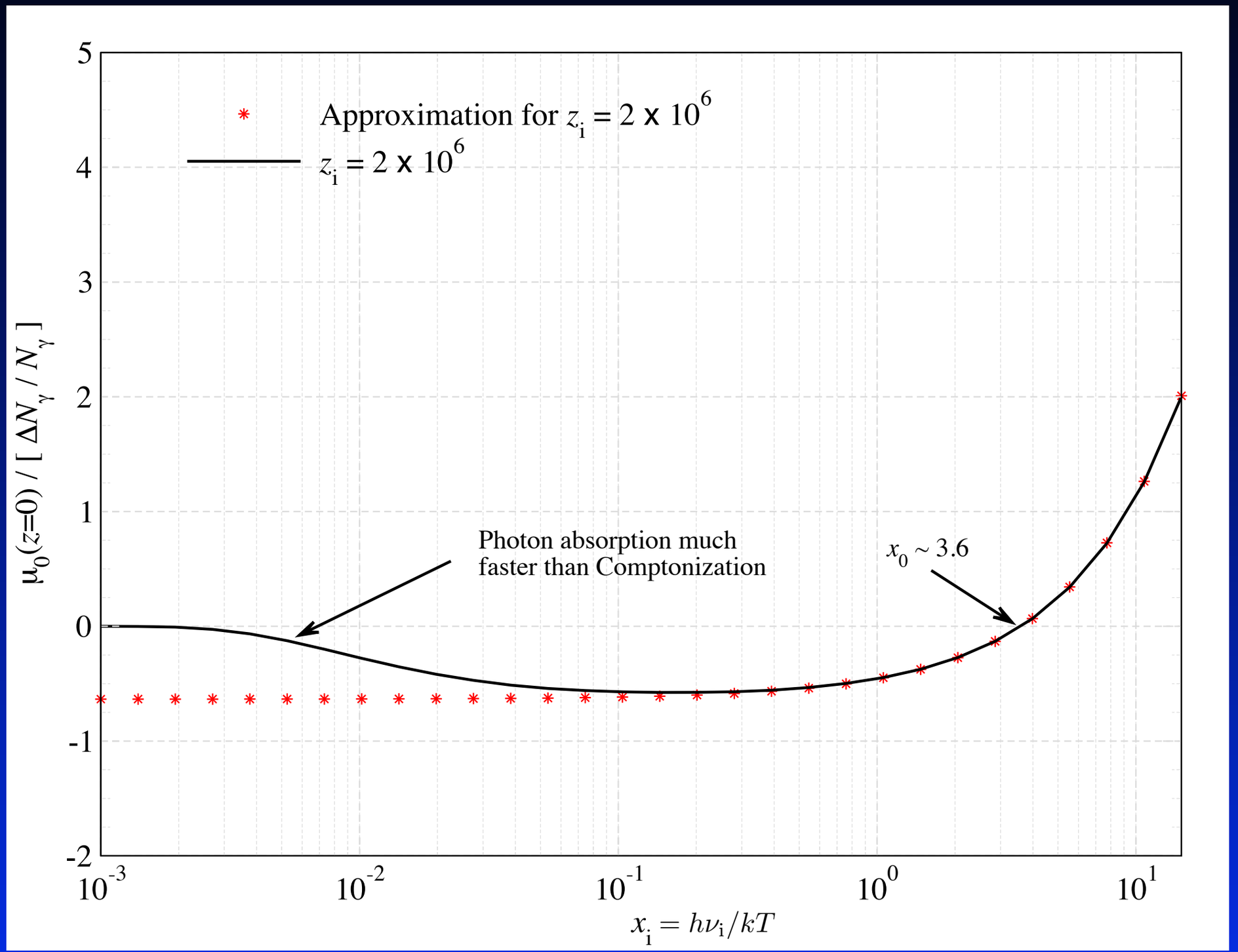


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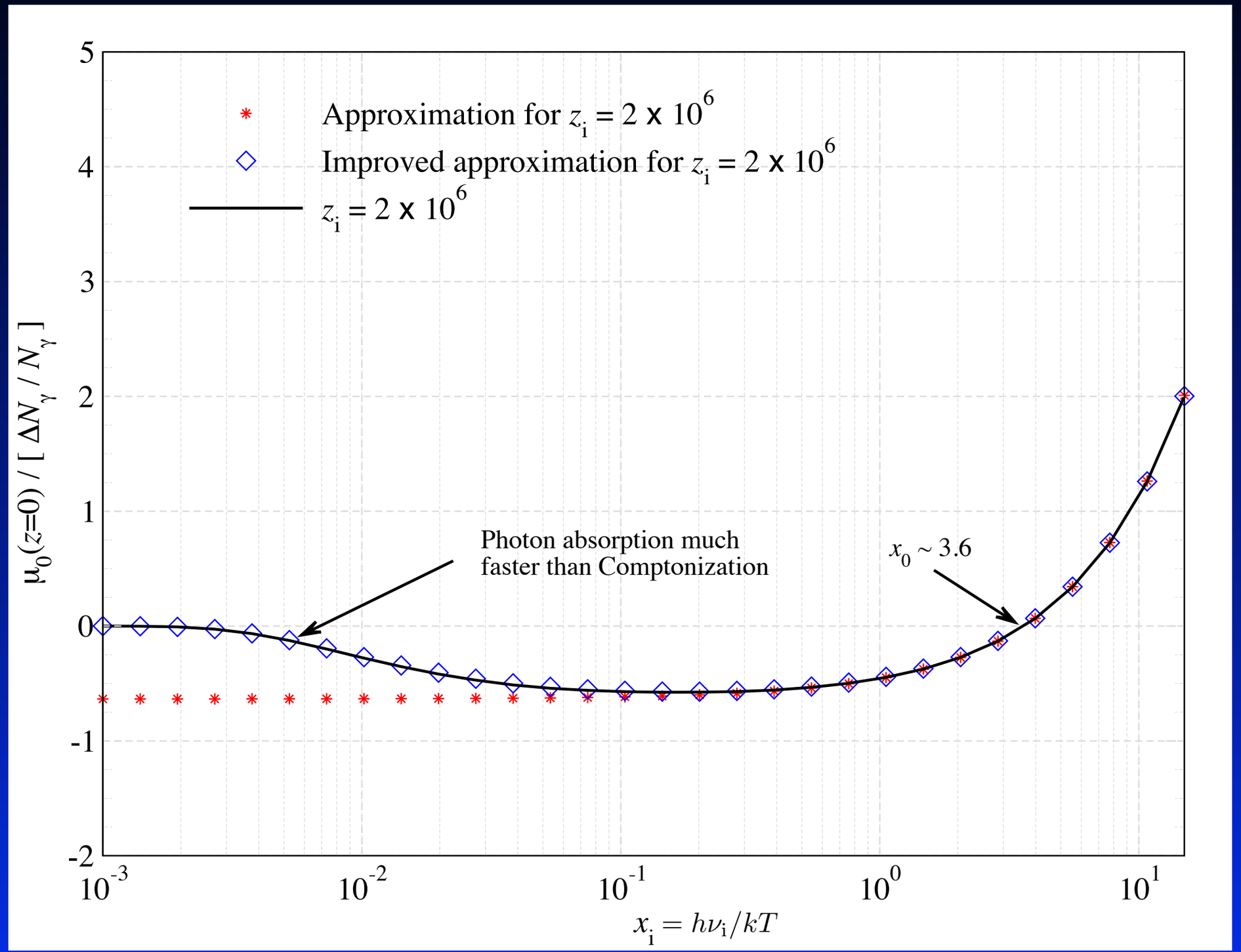


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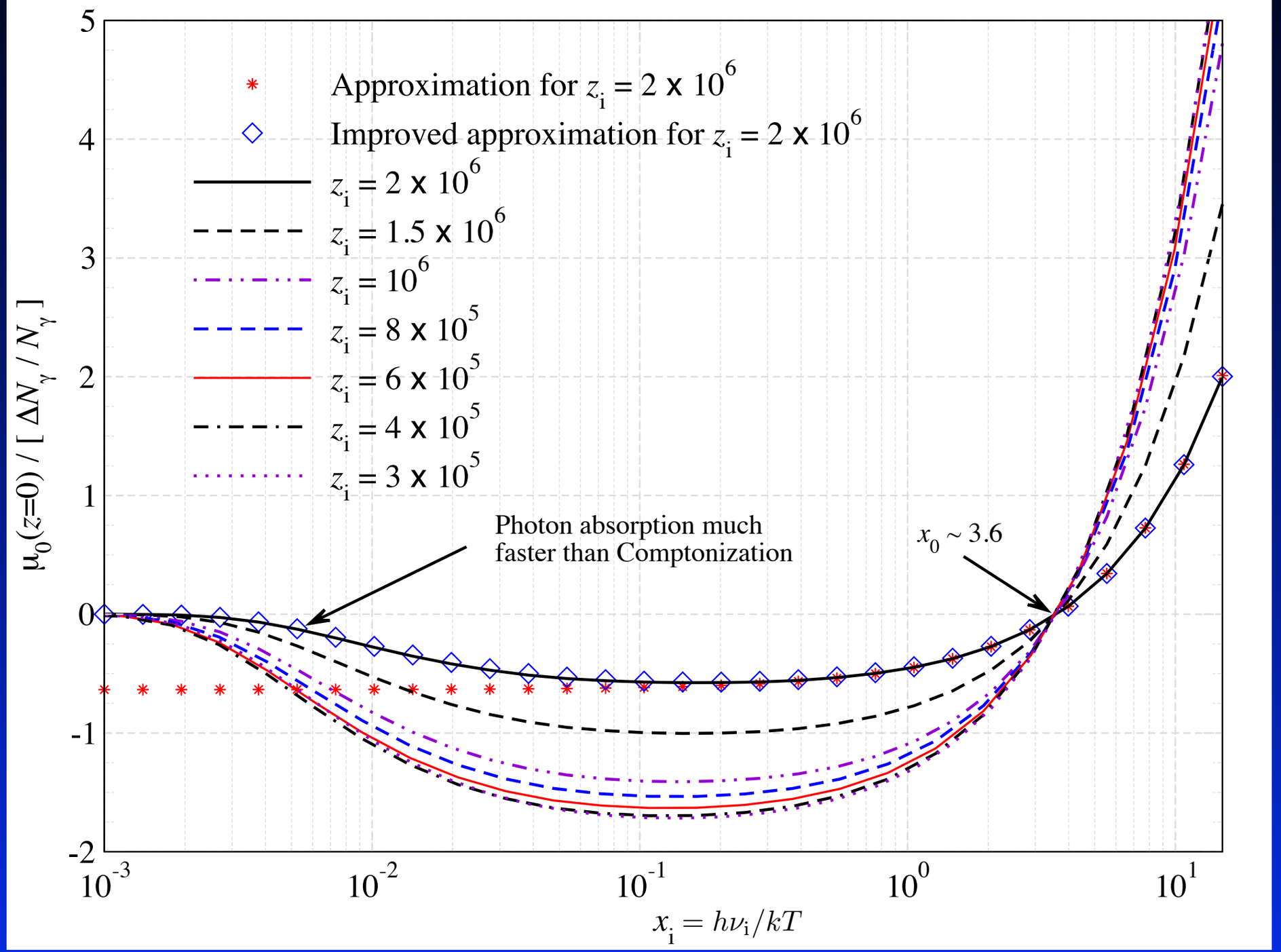


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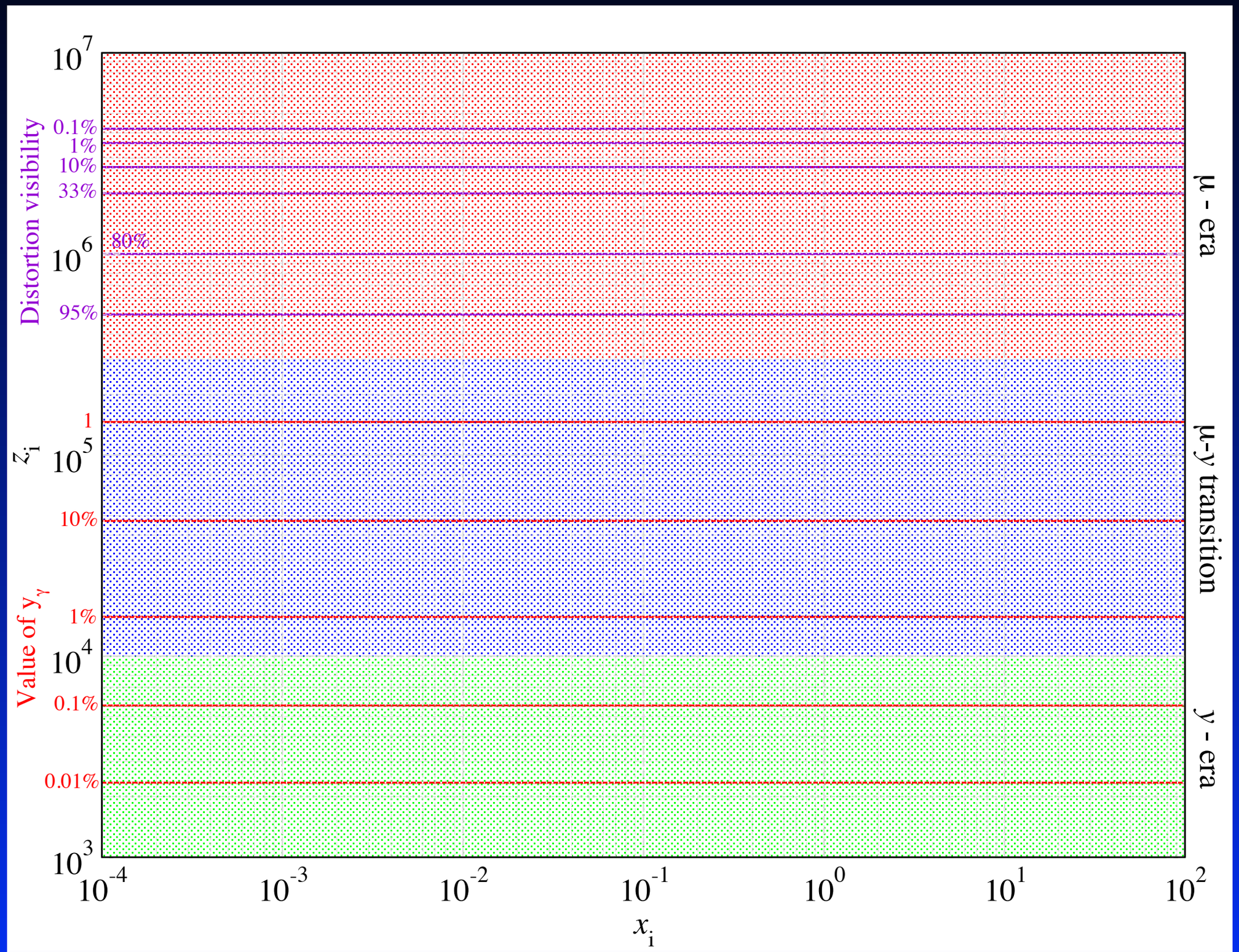
JC 2015, ArXiv:1506.06582

# Different regimes for photon injection

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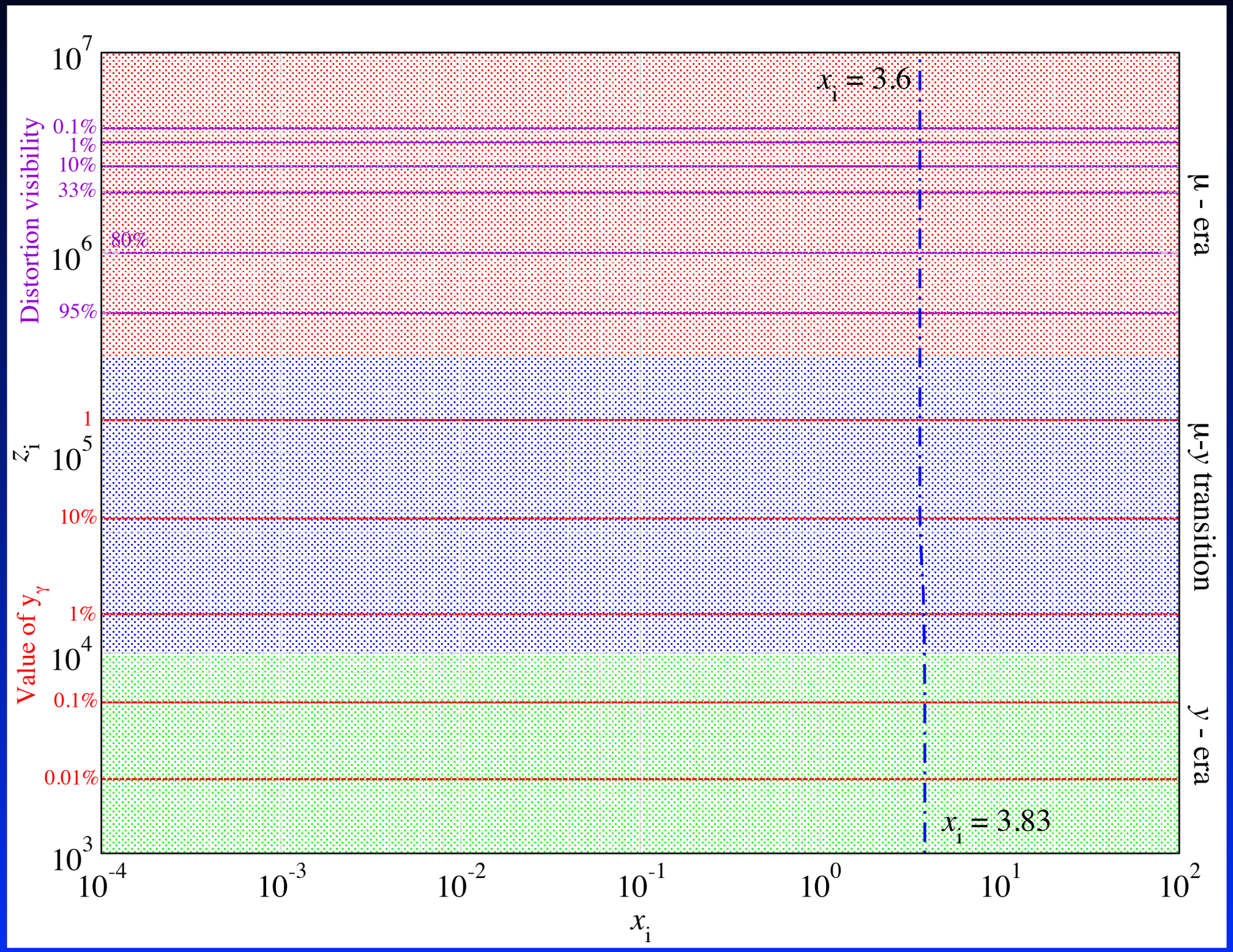


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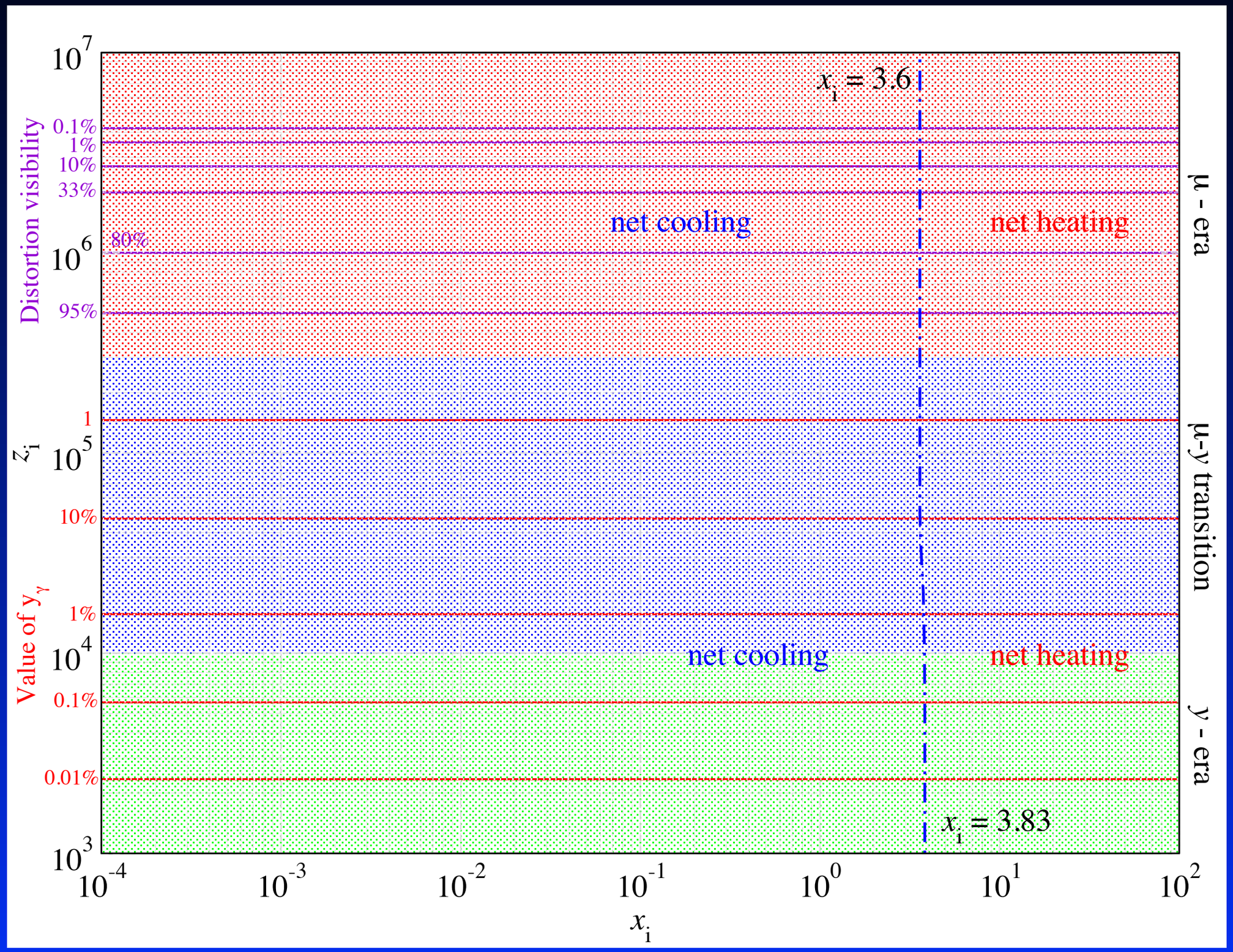


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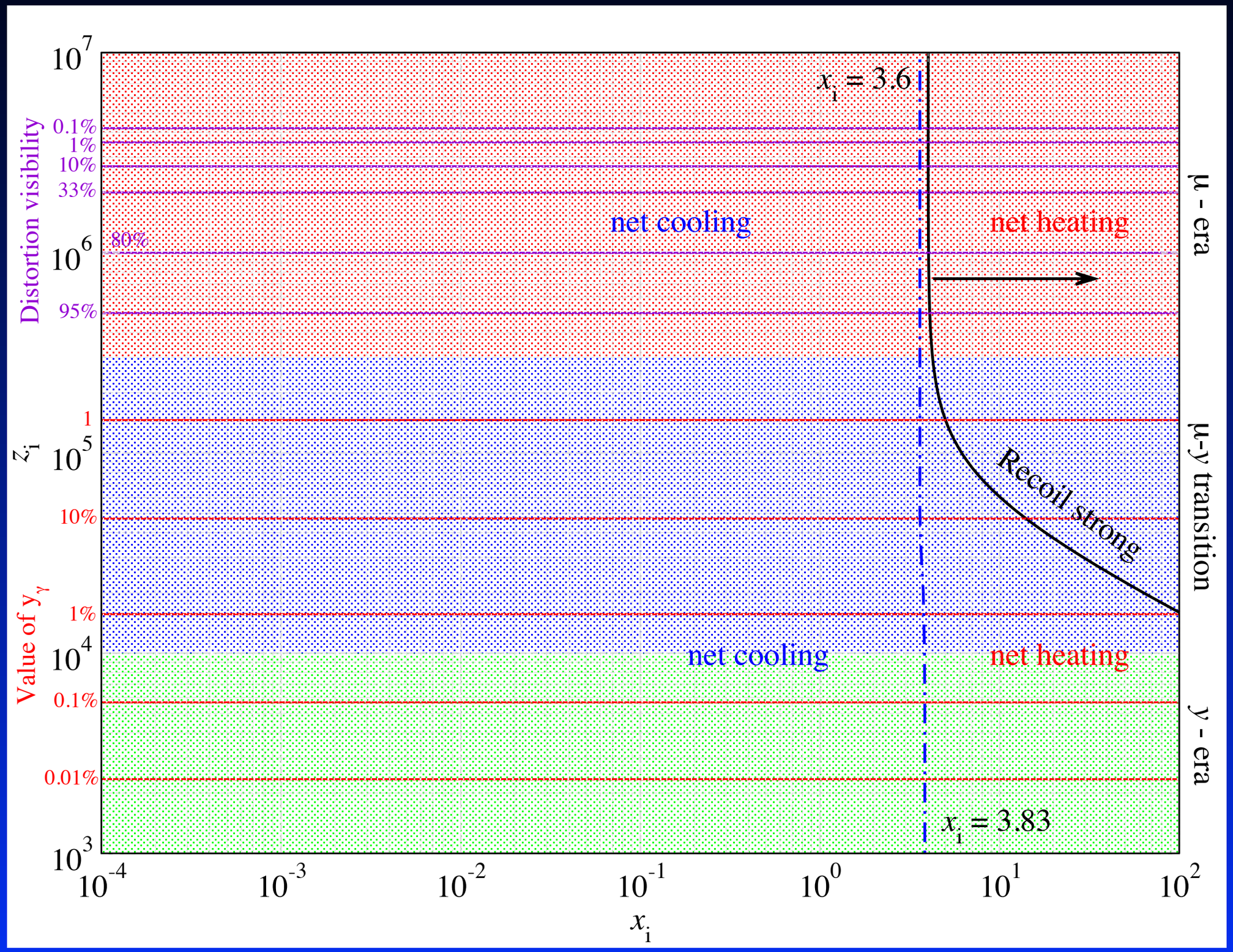


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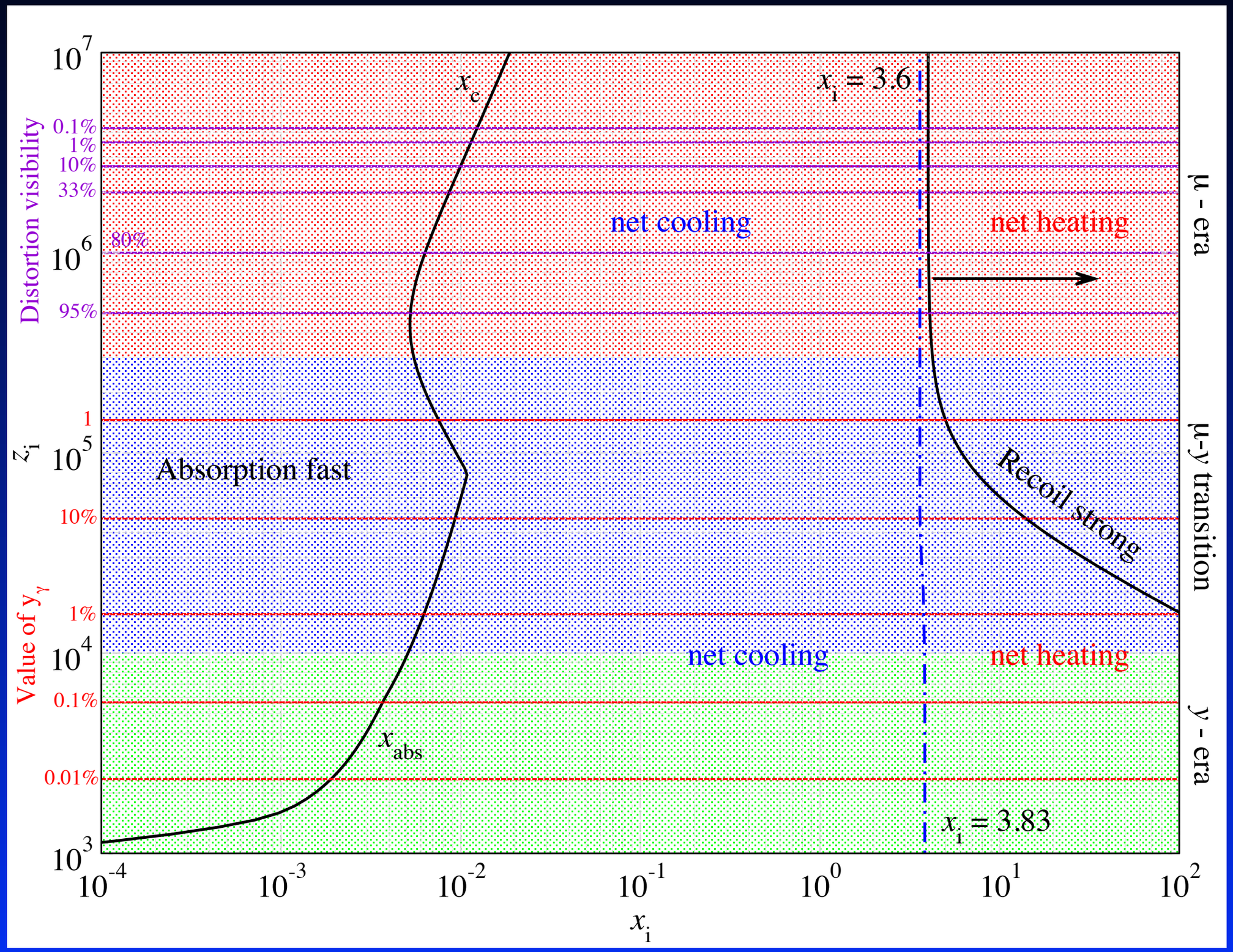


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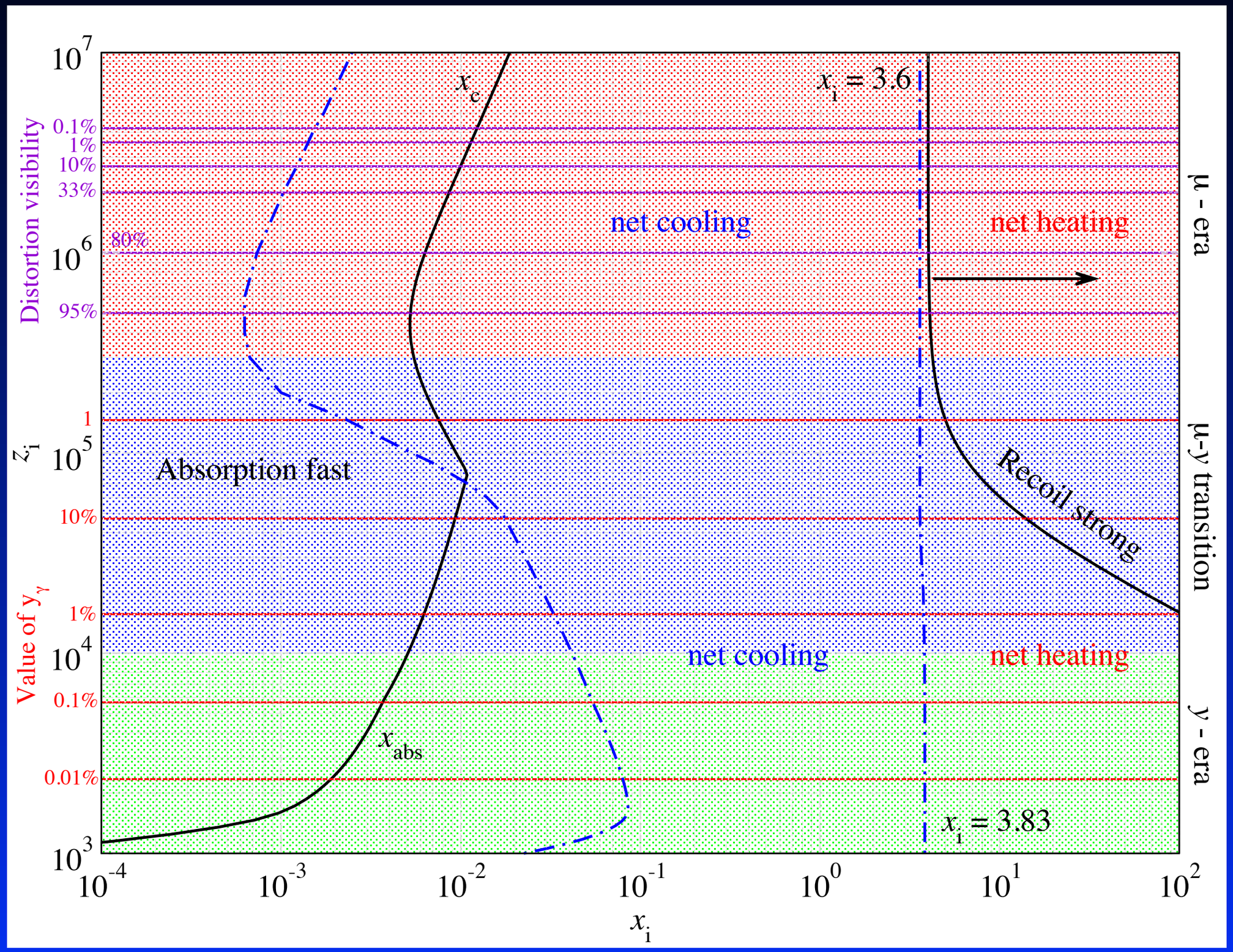


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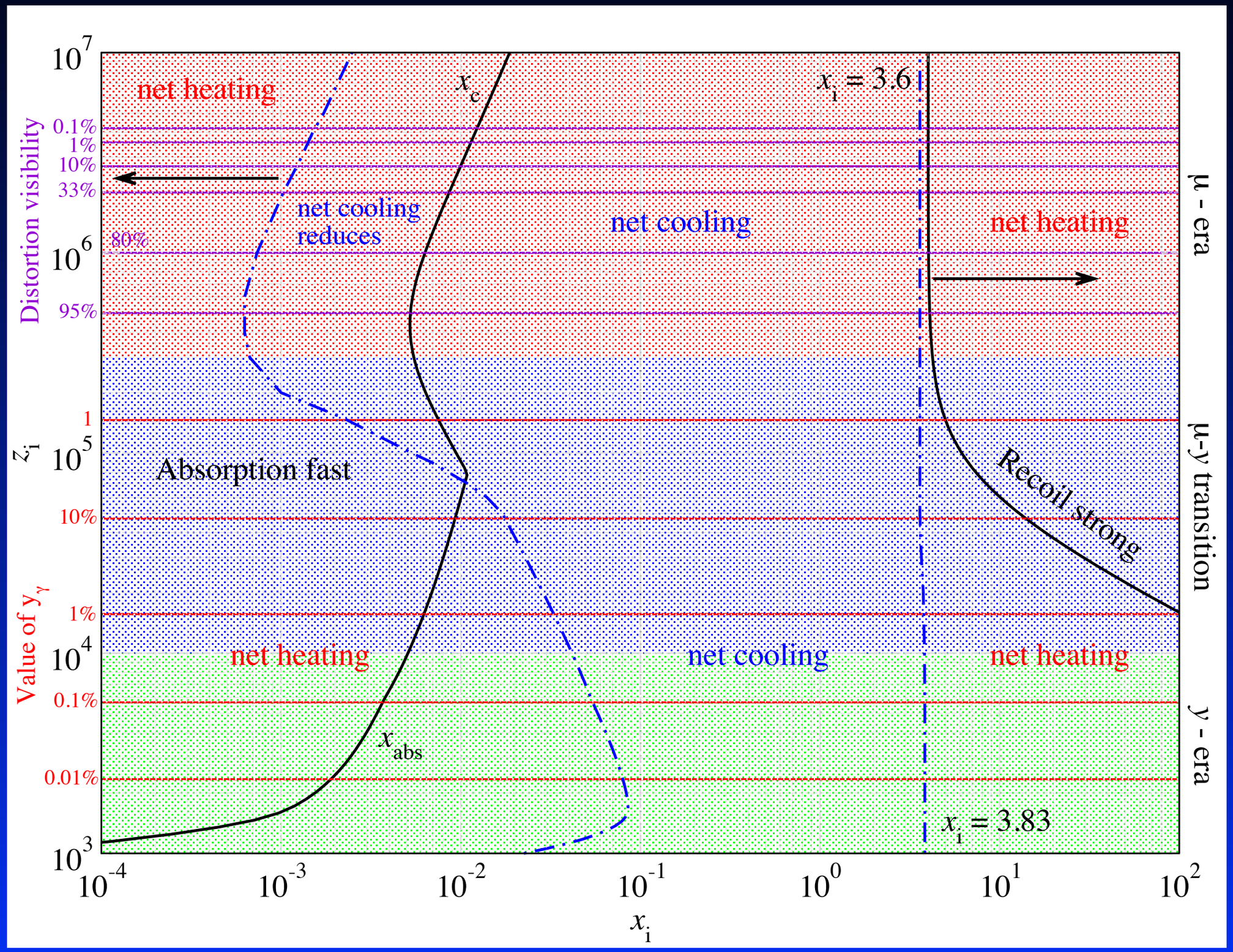


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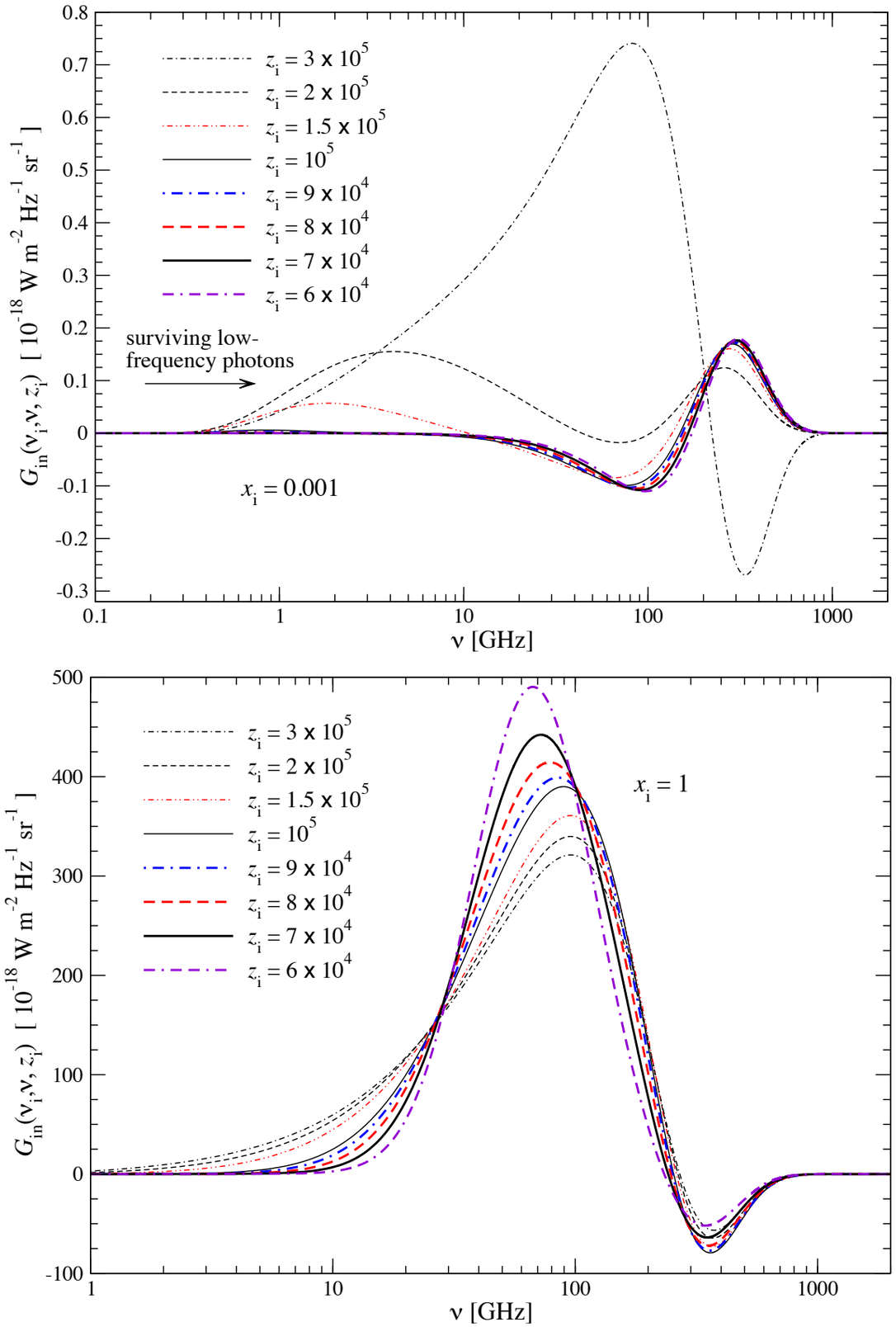
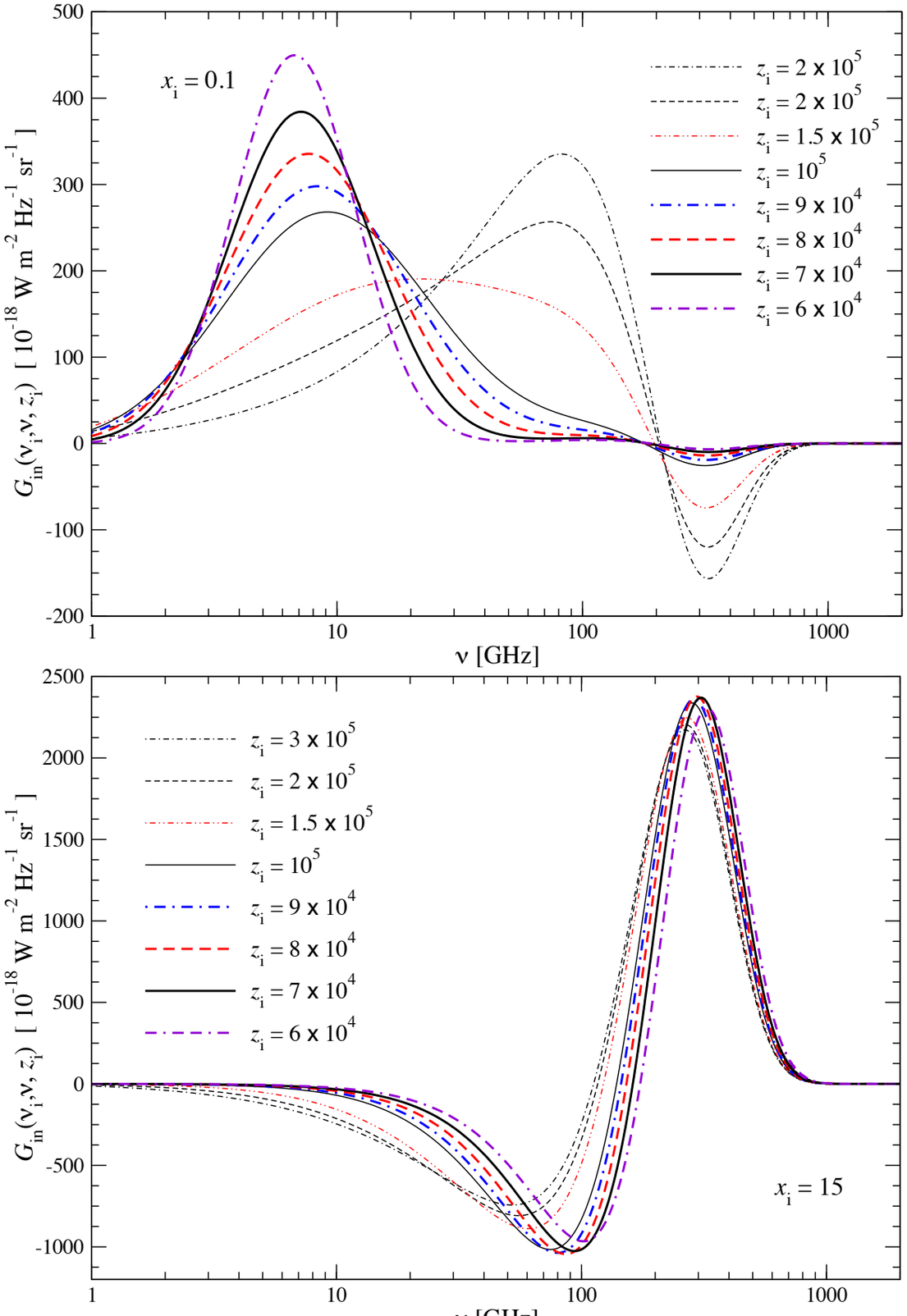
# Photon injection at later times







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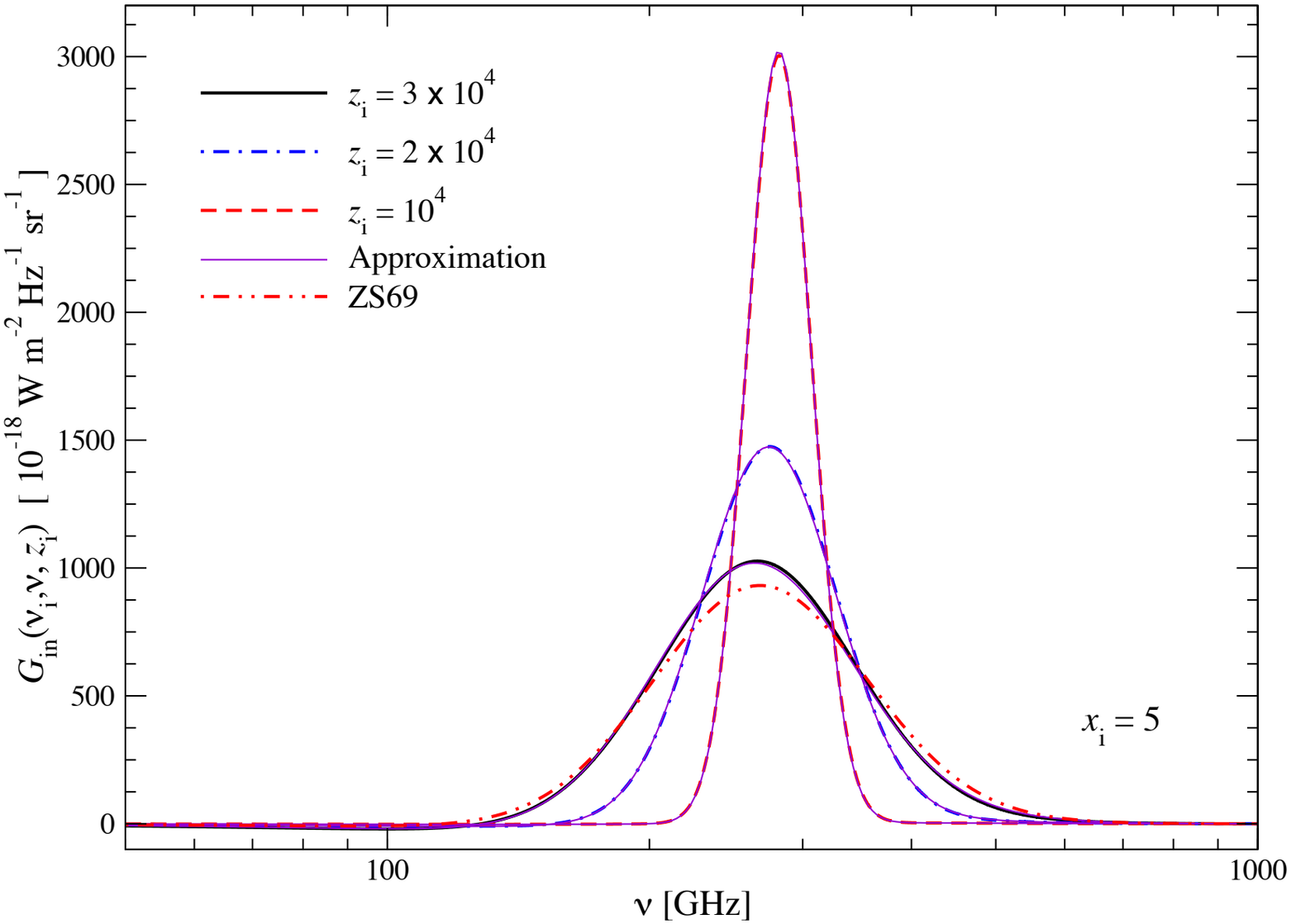
# Regime with very few scatterings




**Classical solution by Zeldovich & Sunyaev, 1969**

$$\Delta n(x, y) = \frac{A}{\sqrt{4\pi y}} \frac{e^{-[\ln(x/x_i)-3y]^2/4y}}{x^3}$$

**Improved solution capturing recoil and stimulated scattering**

$$\Delta n^*(x, y) = \frac{A}{\sqrt{4\pi y\, \beta(x_i, y)}} \frac{e^{-\left[\ln(x/x_i)-\alpha(x_i,y)\, y+\ln(1+x_i y)\right]^2/4y\beta(x_i,y)}}{x^3}$$

$$\alpha = [3 - 2f(x_i)]/\sqrt{1 + x_i y} \qquad f(x_i) = e^{-x_i}(1 + x_i^2/2)$$

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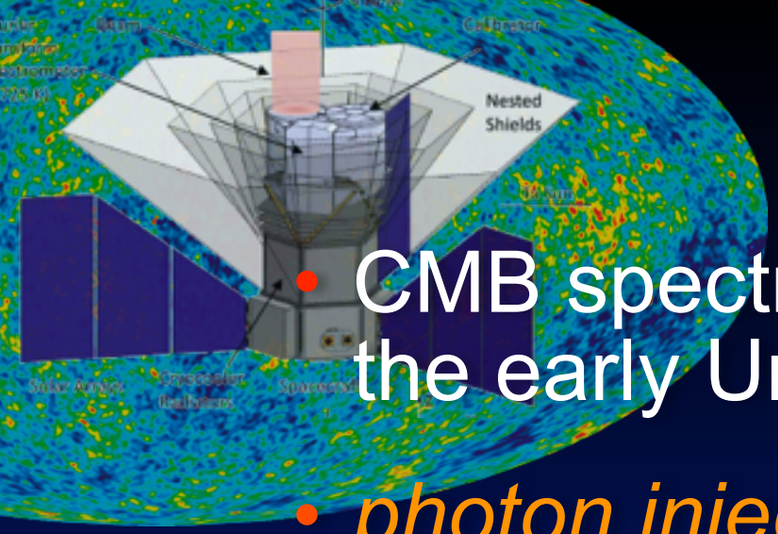
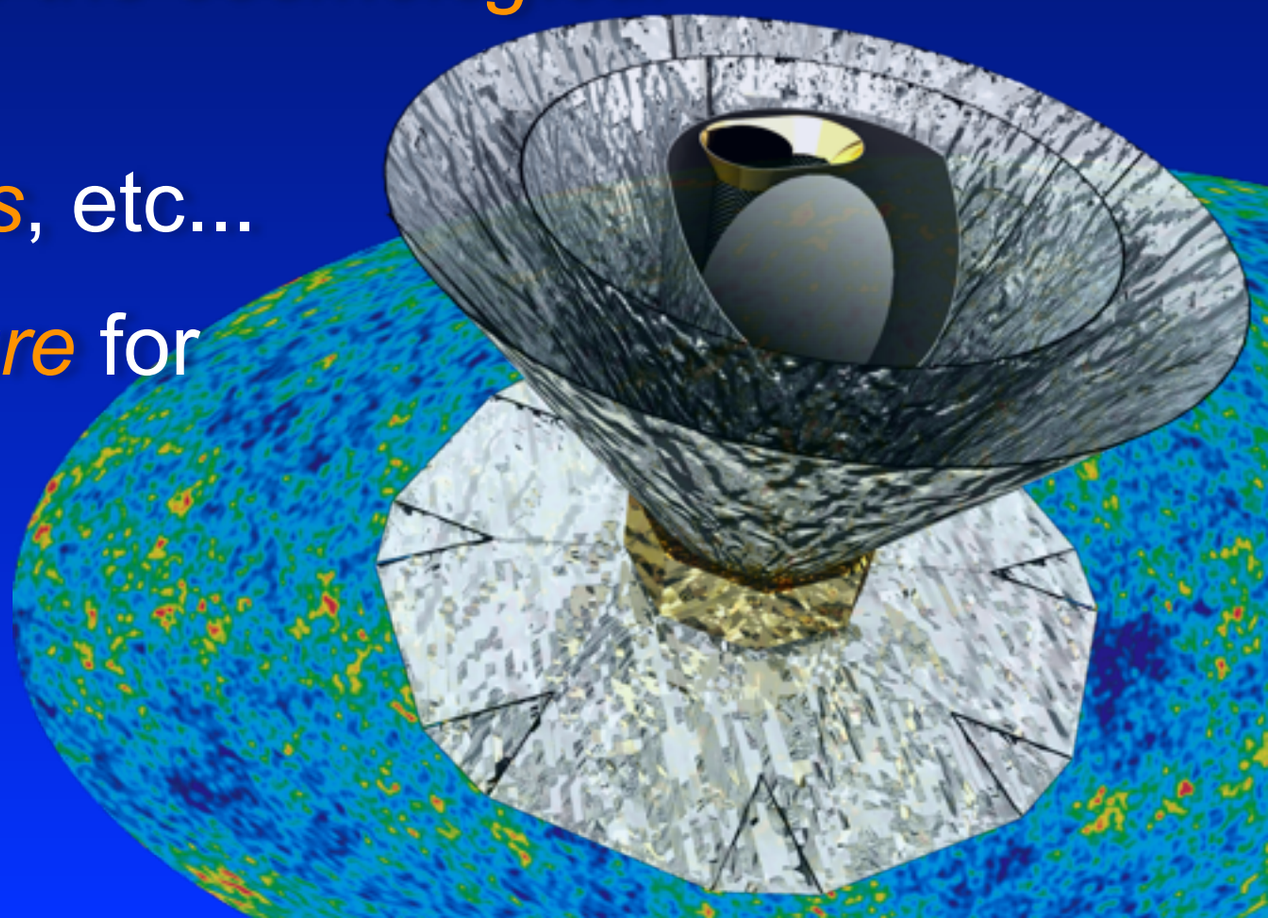
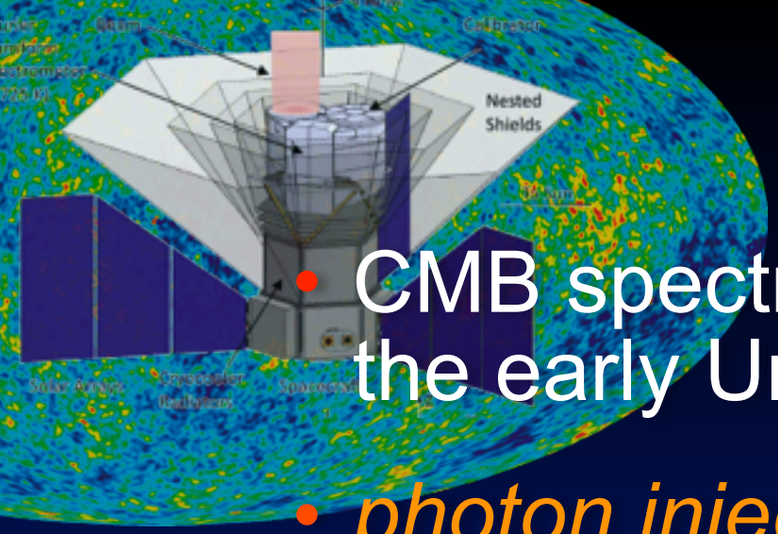



# Conclusions

- CMB spectral distortions *will* open a *new window* to the early Universe
- *photon injection scenarios* show a very rich spectral phenomenology
- *additional information* about the underlying process which could help to *distinguish scenarios*
- one important example is the *cosmological recombination radiation*
- *decaying particles, axions*, etc...
- extremely interesting *future* for CMB-based science!



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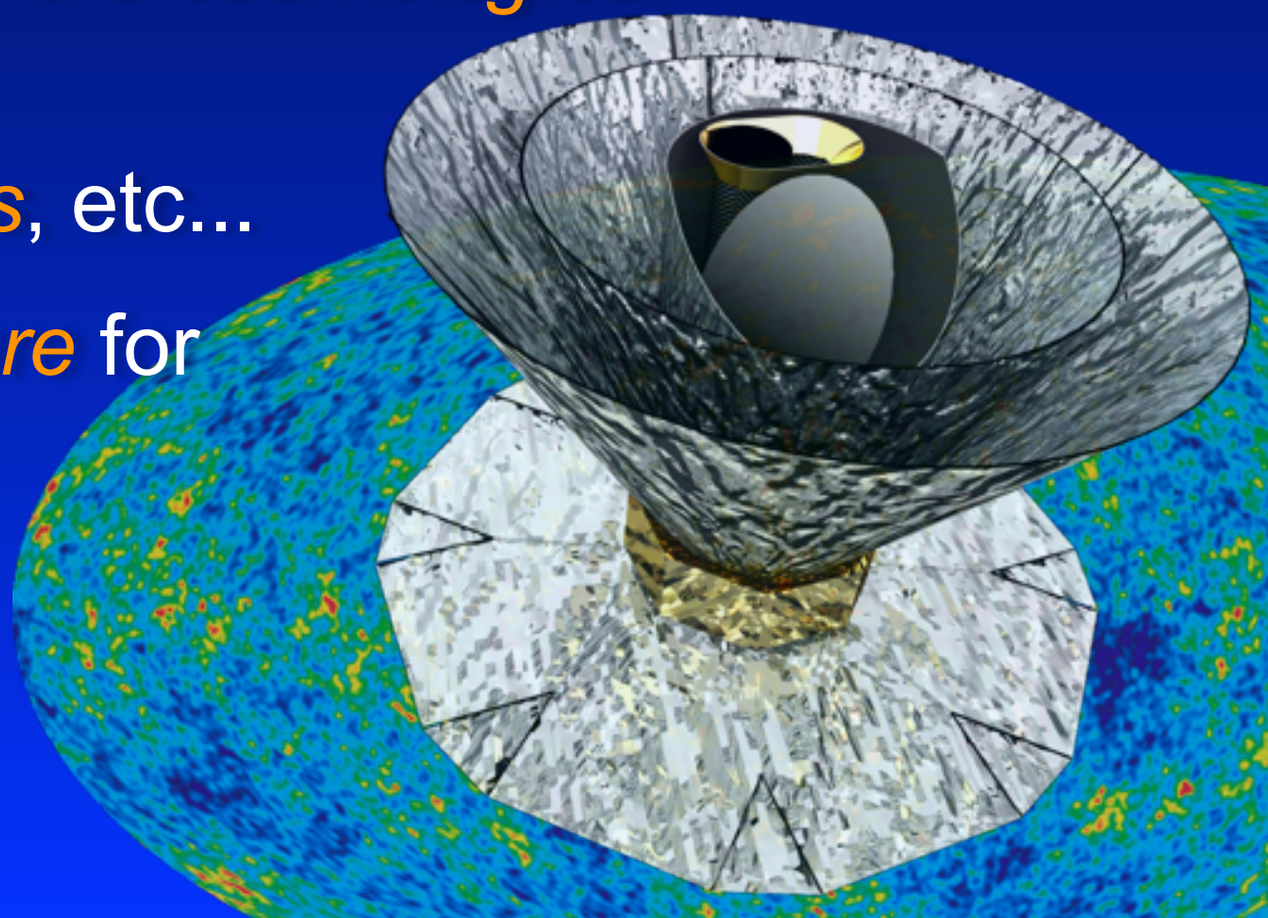
*We should make use of all this information!*



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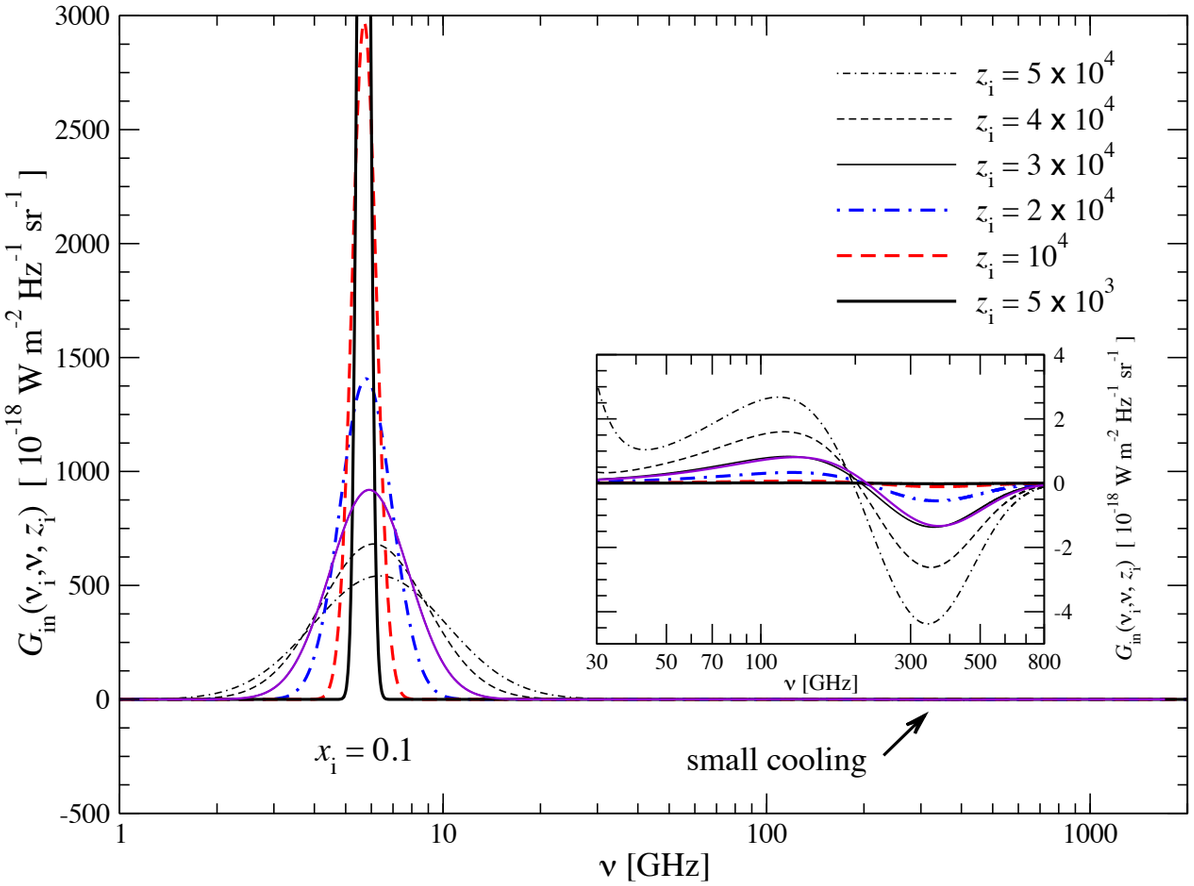


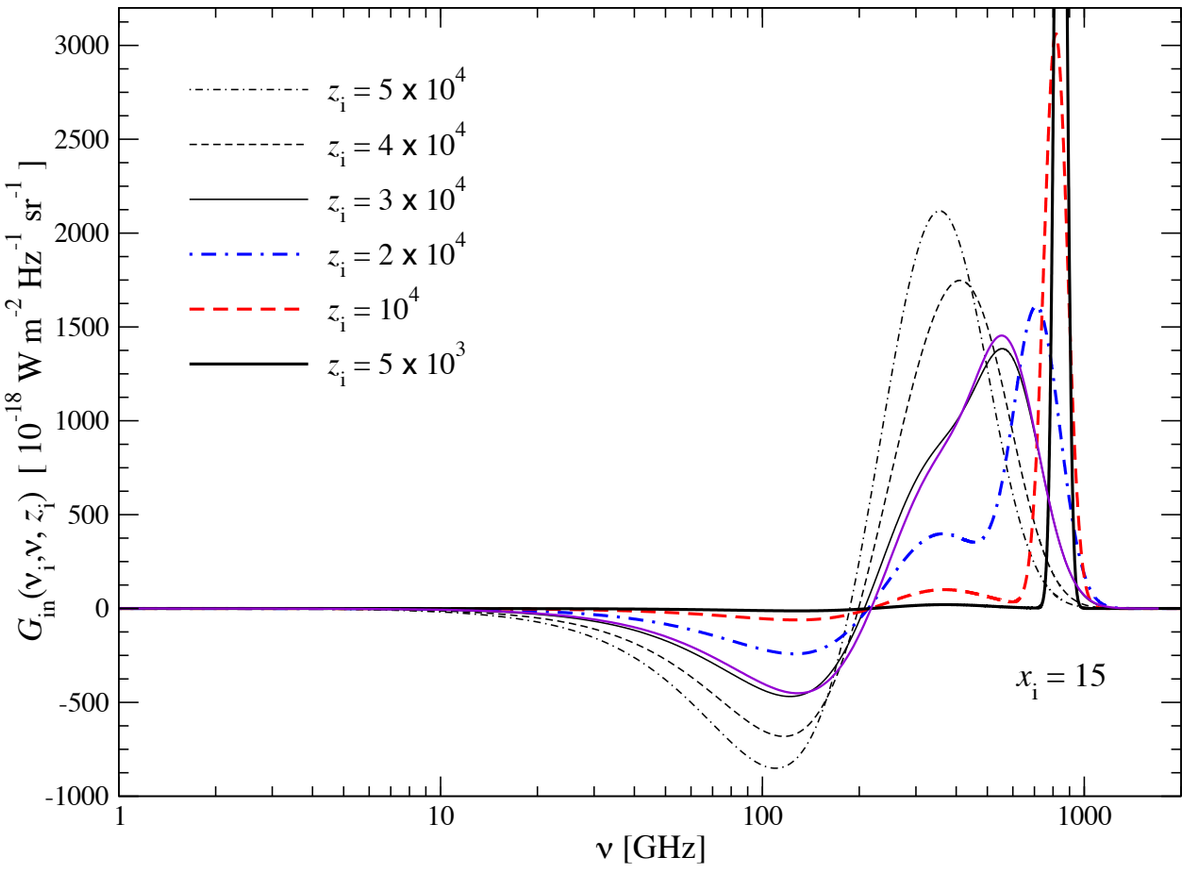


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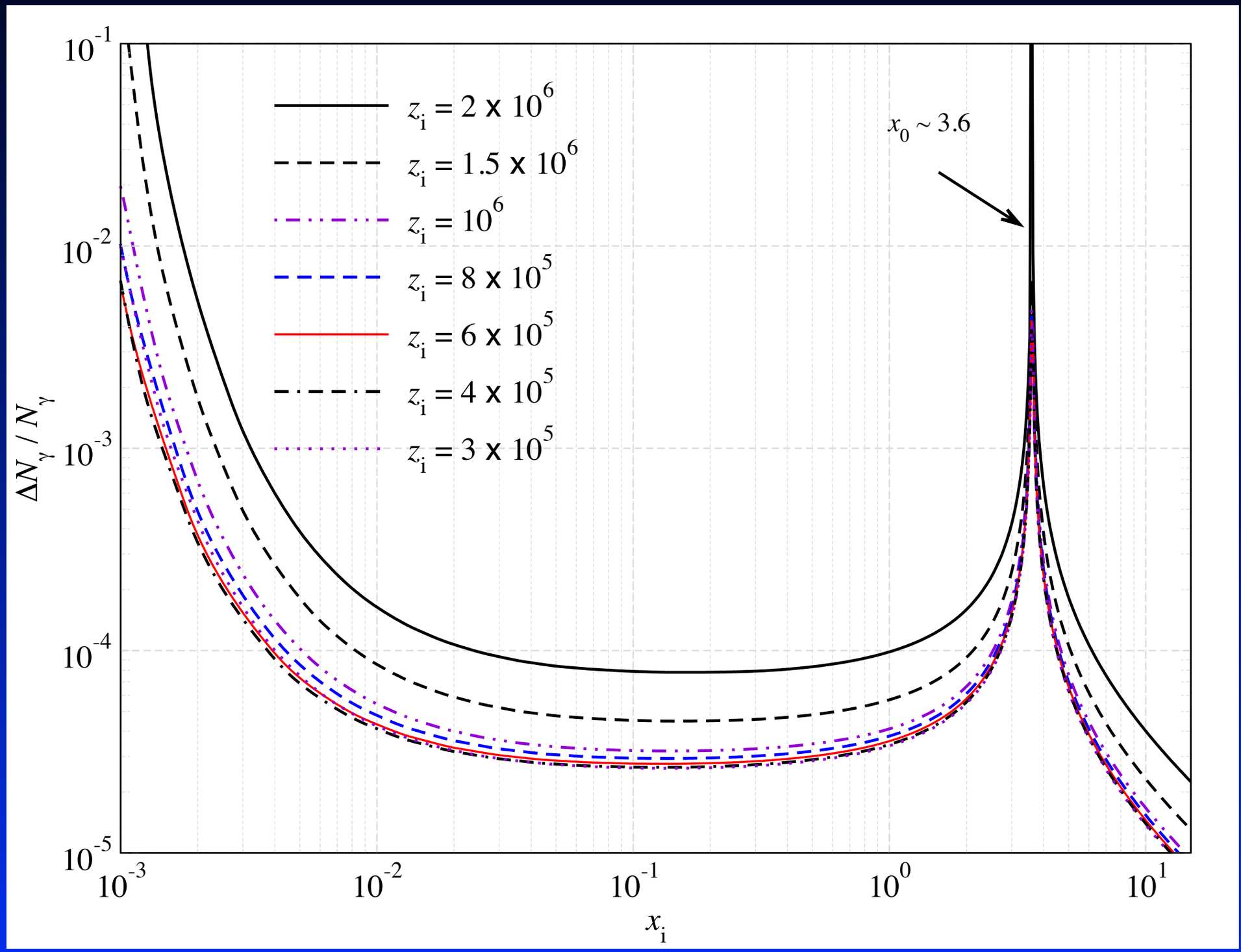
# Limits on photon injection from COBE/FIRAS

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