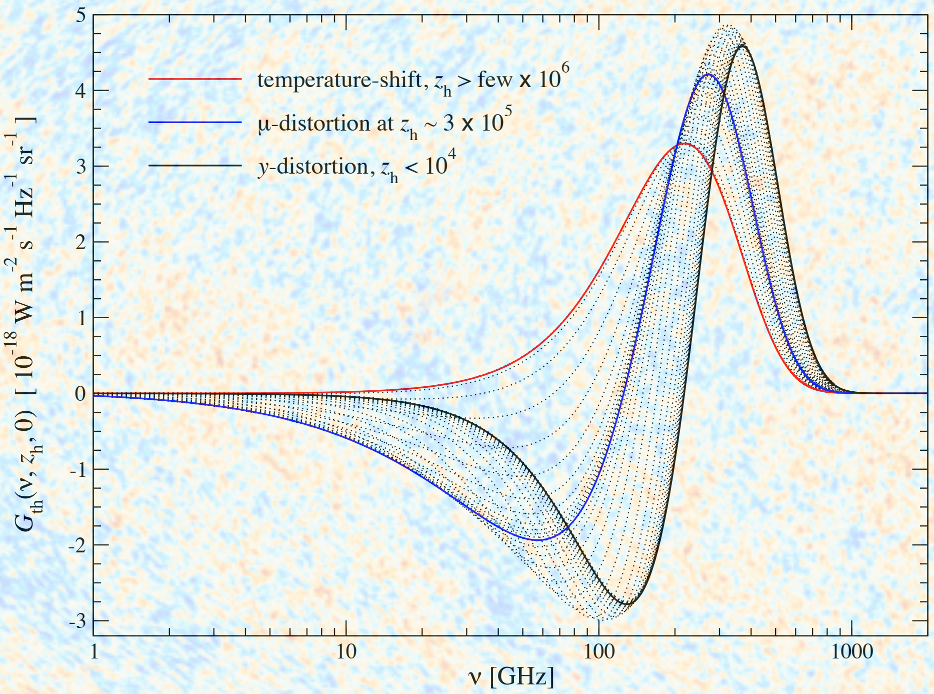
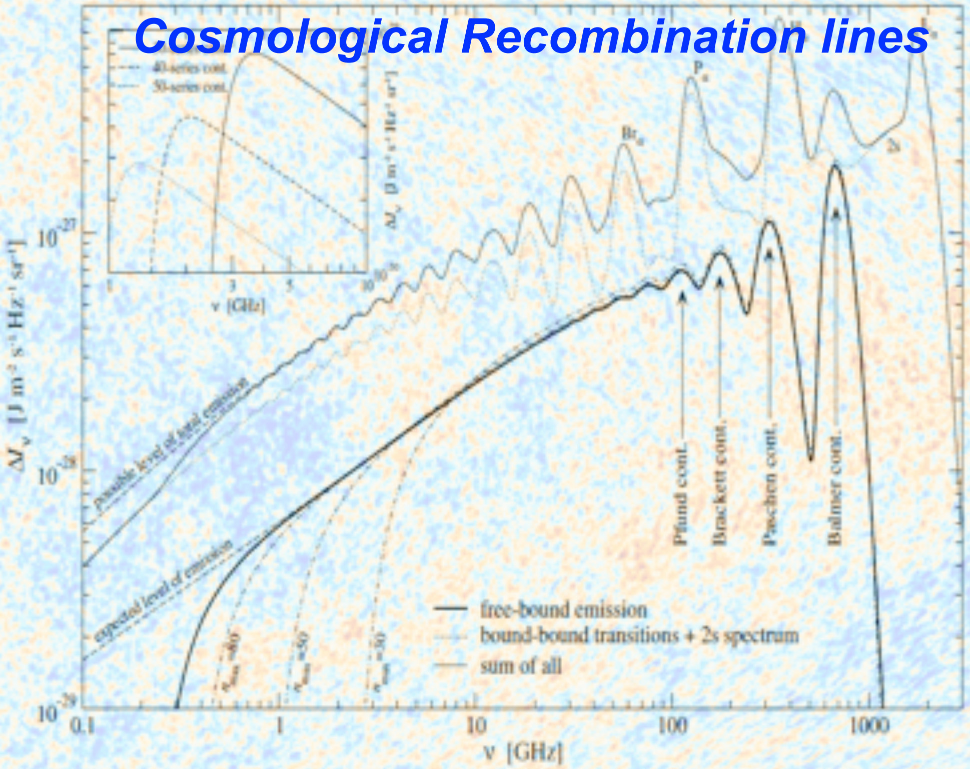
Science with Spectral Distortions of the CMB - IV



Primordial Distortions



Cosmological Recombination lines

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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)

Quasi-Exact Treatment: Thermalization Green's Function

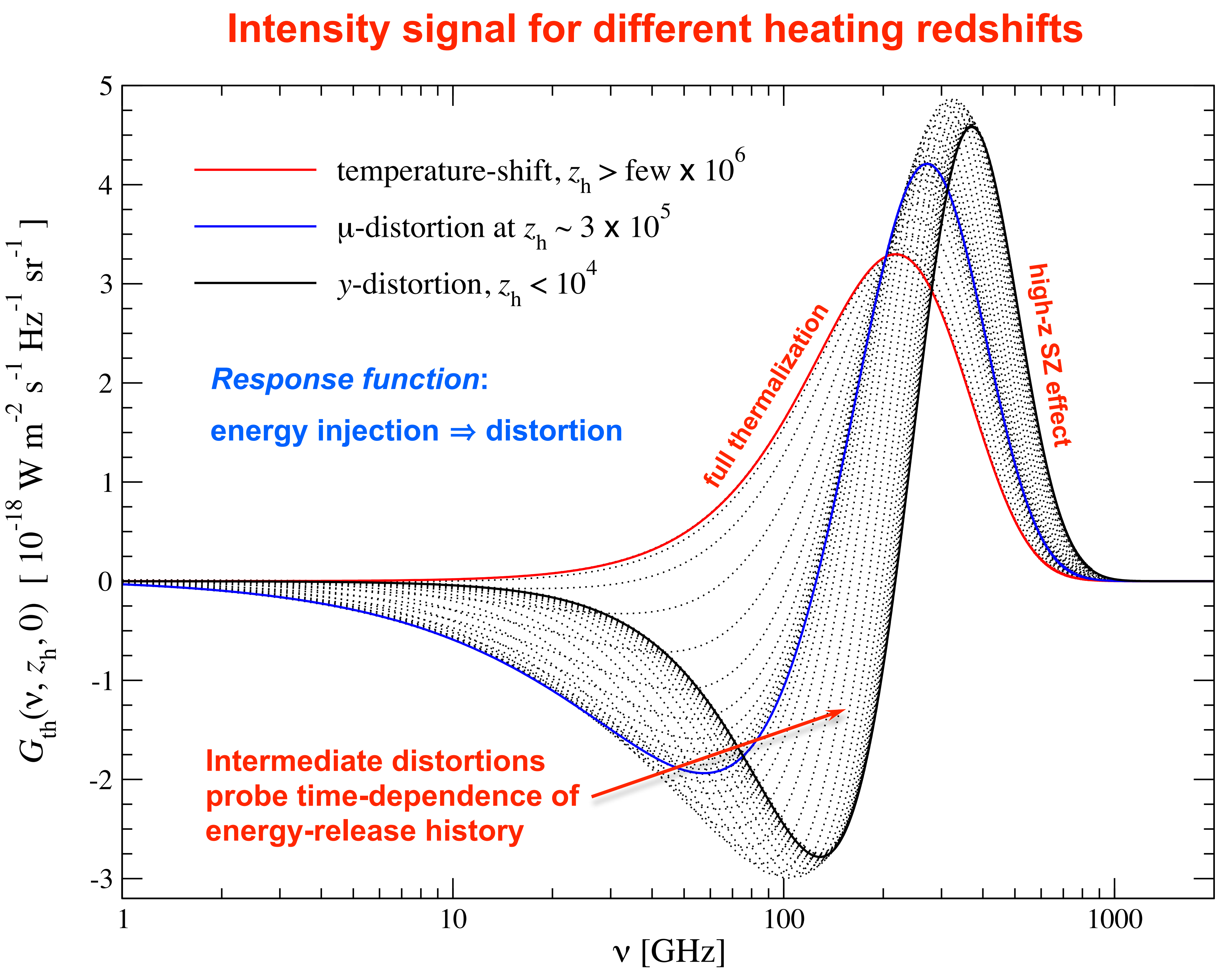
- *For real forecasts of future prospects a precise & fast method for computing the spectral distortion is needed!*
- *Case-by-case computation of the distortion (e.g., with CosmoTherm, JC & Sunyaev, 2012, ArXiv:1109.6552) still rather time-consuming*
- *But: distortions are small ⇒ thermalization problem 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

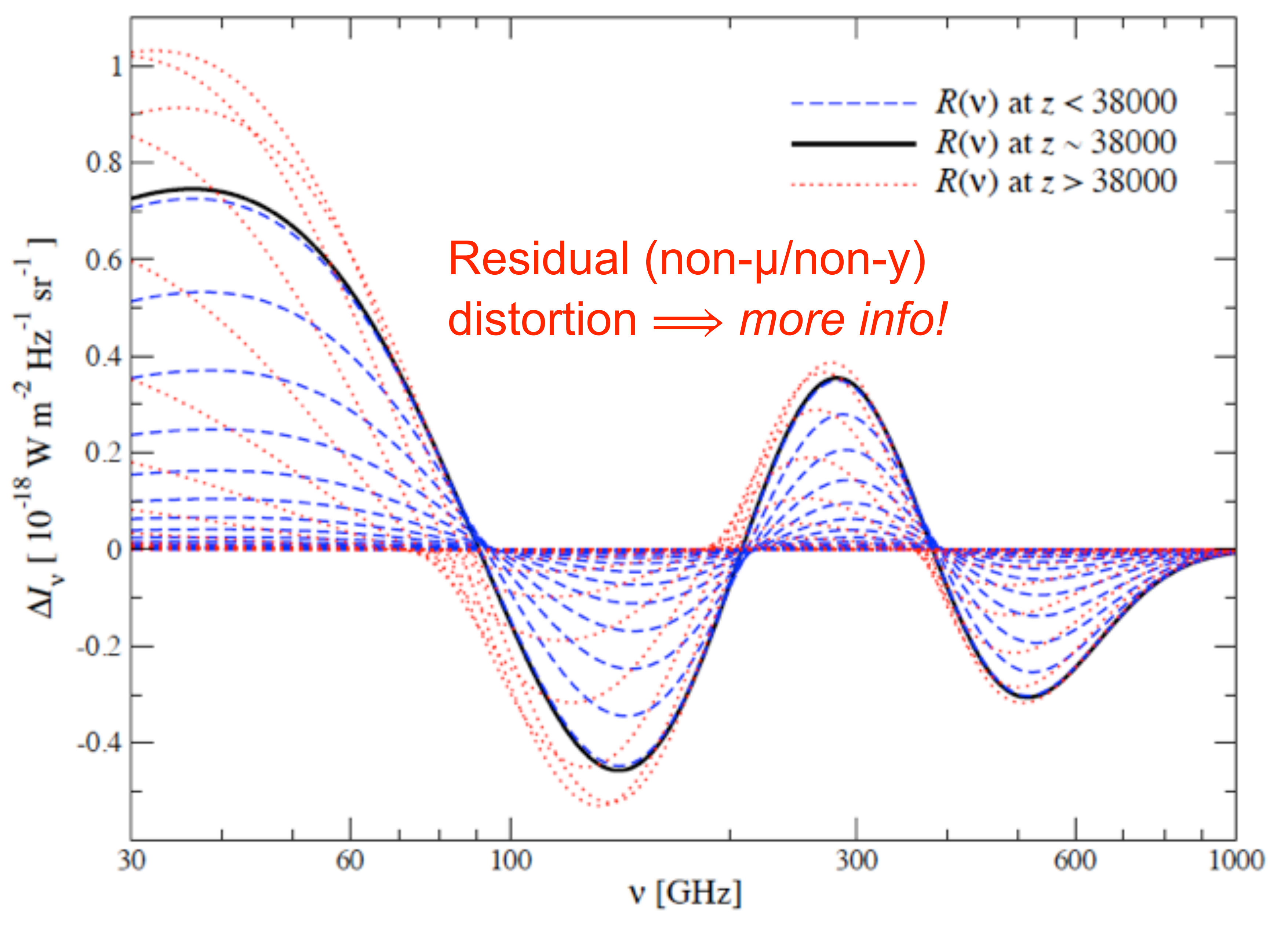
- *Fast and quasi-exact! No additional approximations!*

What does the spectrum look like after energy injection?



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

Explicitly taking out the superposition of μ & y distortion

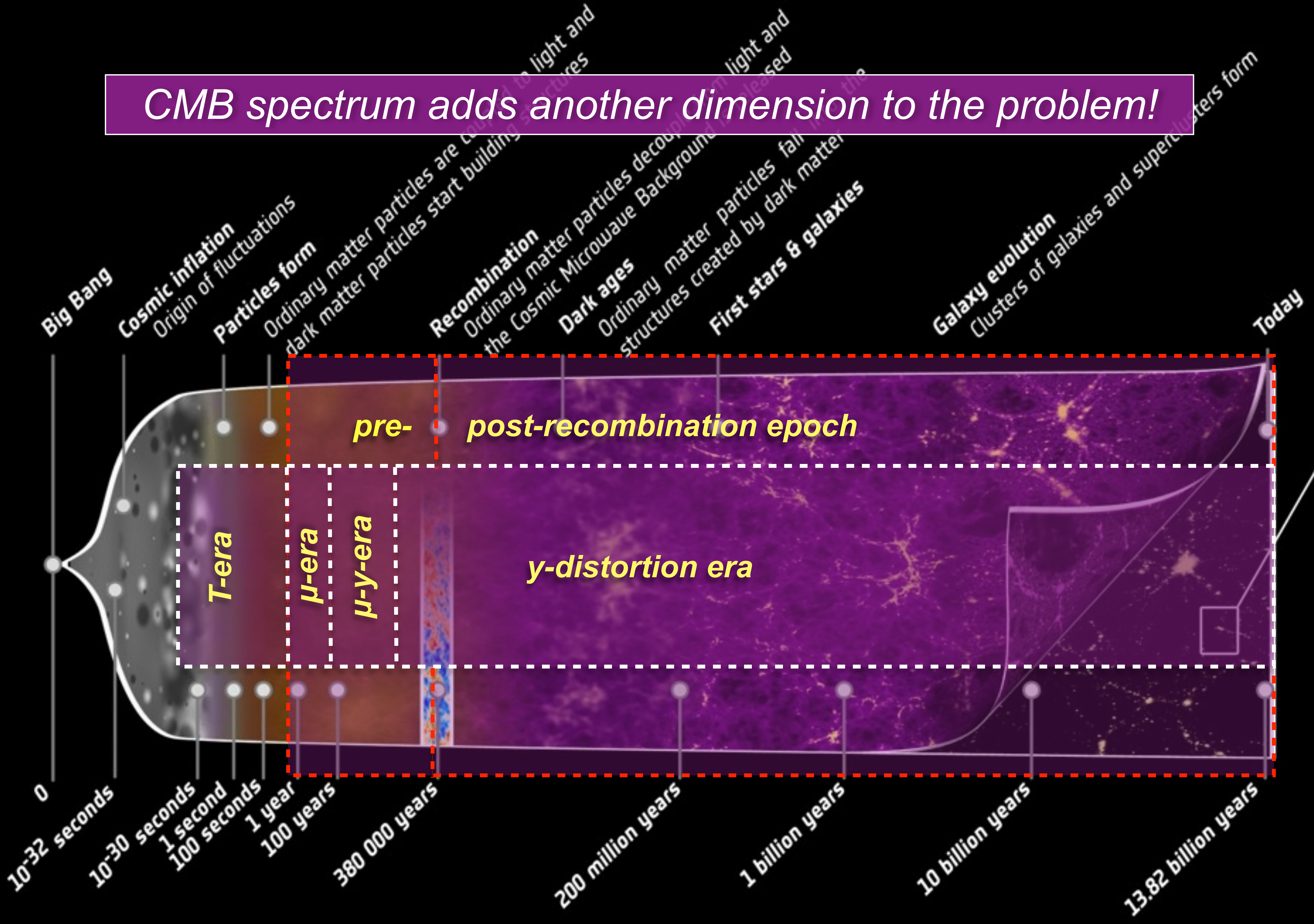


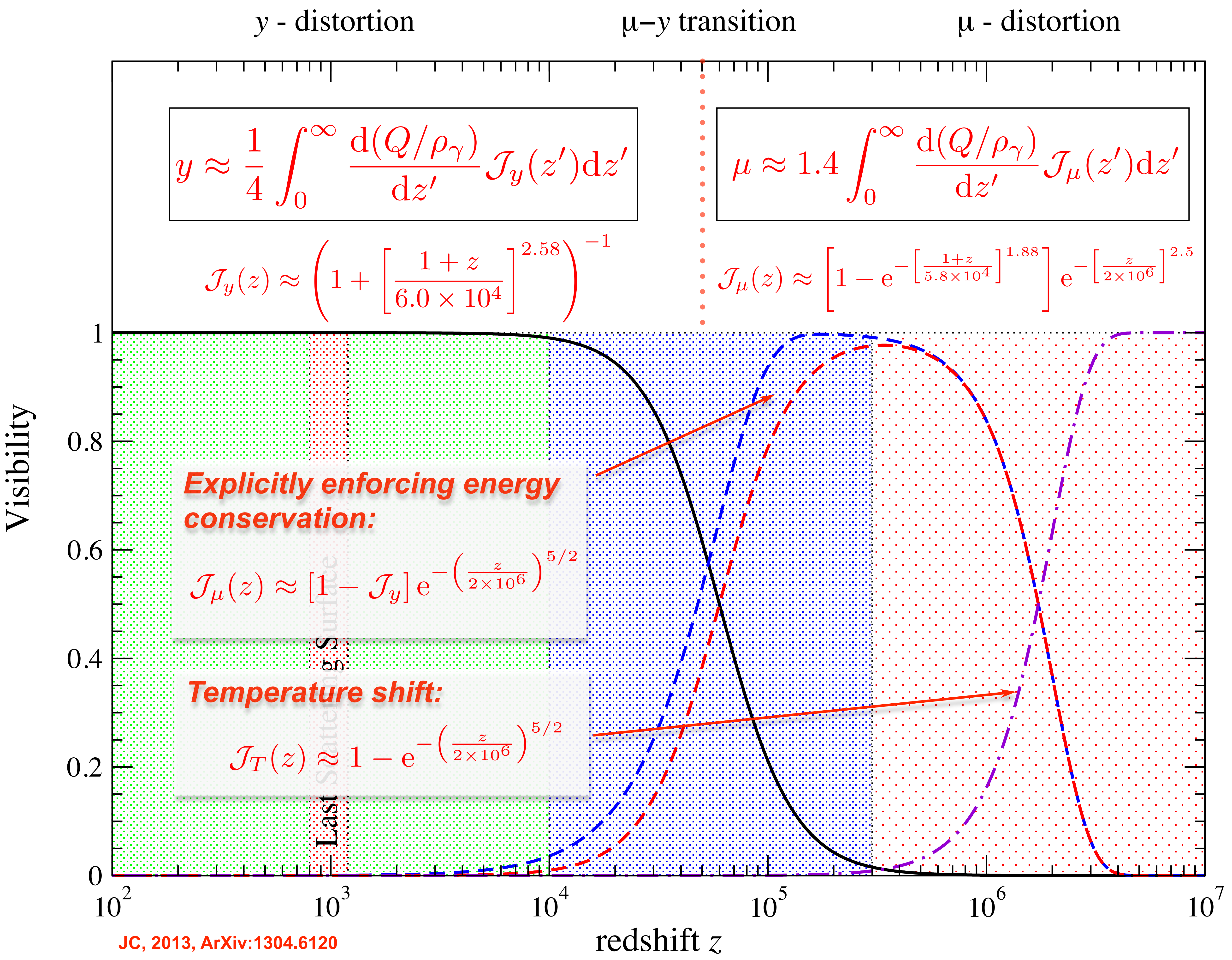
Residual (non-μ/non-y) distortion $\Longrightarrow$ *more info!*

- *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

CMB spectrum adds another dimension to the problem!





$$y \approx \frac{1}{4}\int_0^\infty \frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z'}\mathcal{J}_y(z')\mathrm{d}z'$$

$$\mathcal{J}_y(z) \approx \left(1+\left[\frac{1+z}{6.0\times10^4}\right]^{2.58}\right)^{-1}$$

$$\mu \approx 1.4\int_0^\infty \frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z'}\mathcal{J}_\mu(z')\mathrm{d}z'$$

$$\mathcal{J}_\mu(z) \approx \left[1-\mathrm{e}^{-\left[\frac{1+z}{5.8\times10^4}\right]^{1.88}}\right]\mathrm{e}^{-\left[\frac{z}{2\times10^6}\right]^{2.5}}$$

Explicitly enforcing energy conservation:

$$\mathcal{J}_\mu(z) \approx [1-\mathcal{J}_y]\,\mathrm{e}^{-\left(\frac{z}{2\times10^6}\right)^{5/2}}$$

Temperature shift:

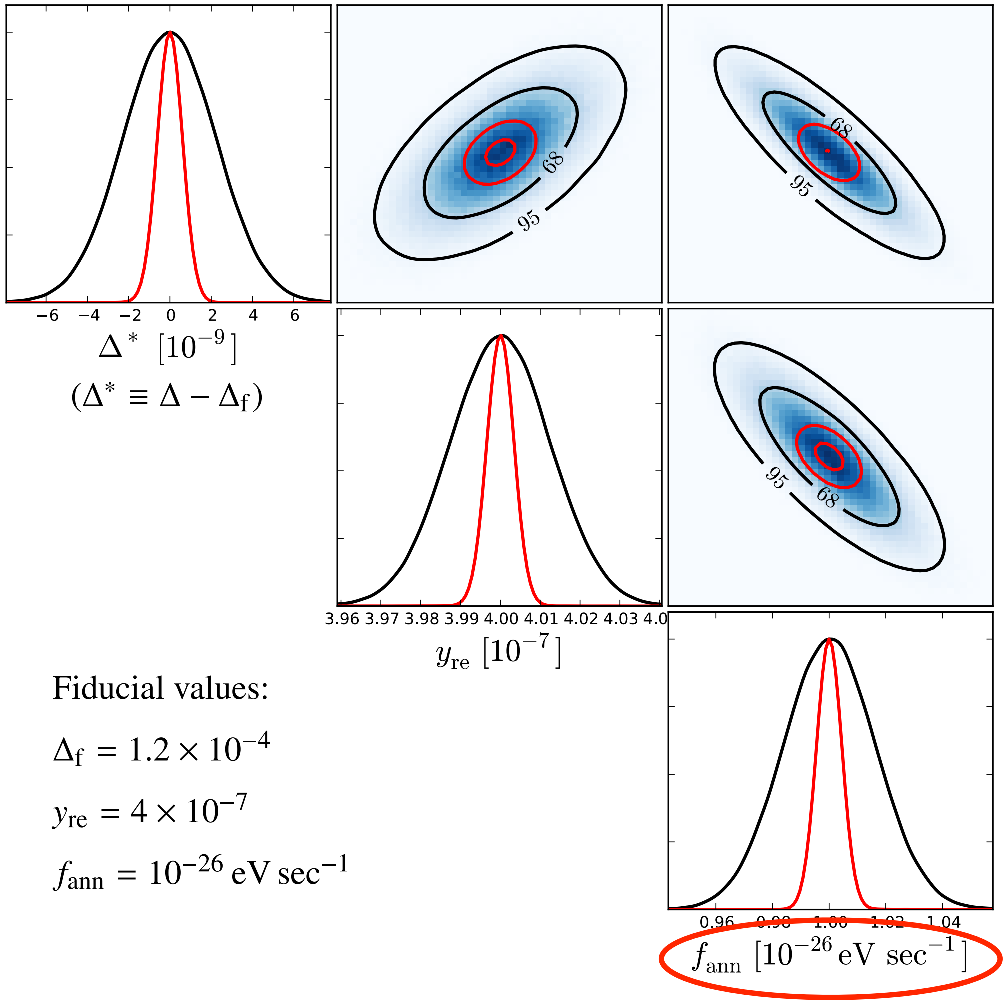
$$\mathcal{J}_T(z) \approx 1-\mathrm{e}^{-\left(\frac{z}{2\times10^6}\right)^{5/2}}$$

JC, 2013, ArXiv:1304.6120

Why model-independent approach to distortion signal

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

Annihilation scenario



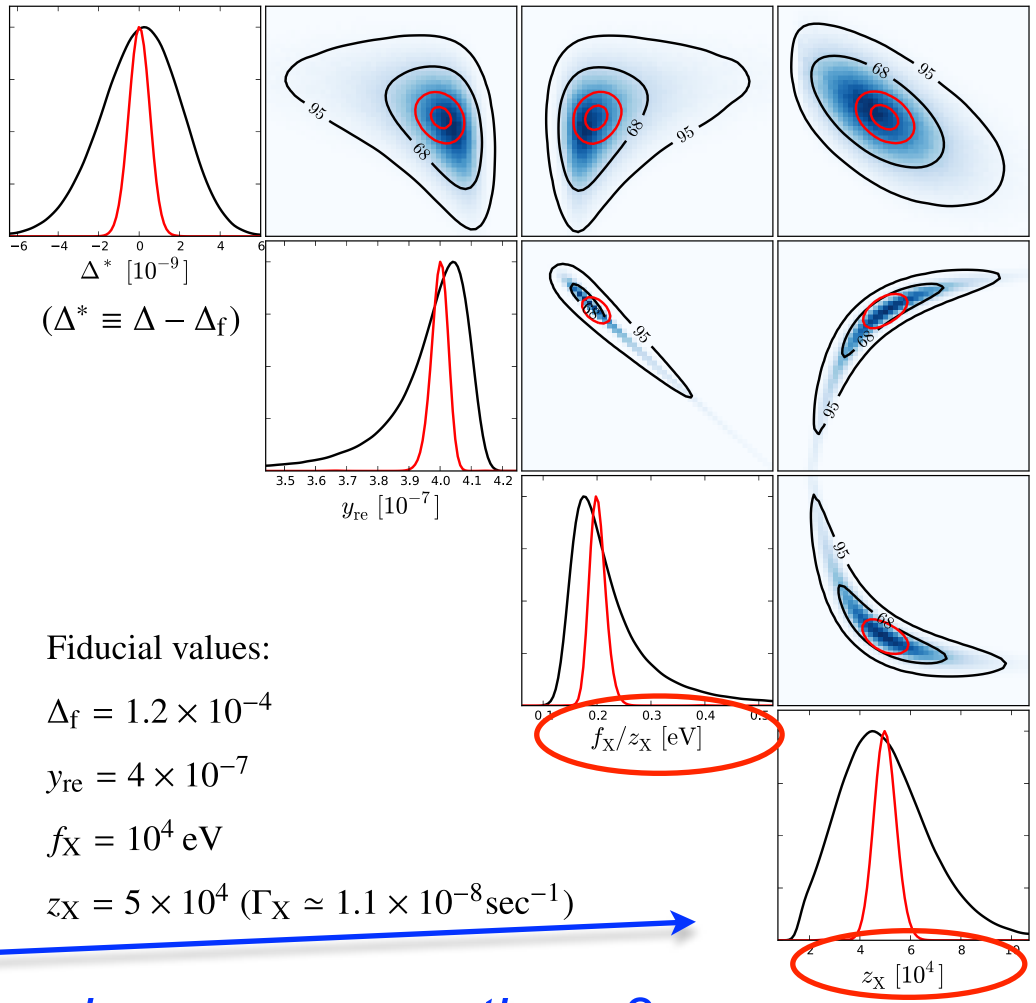
Fiducial values:

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

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

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

Decaying particle scenario



Fiducial values:

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

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

$f_X = 10^4\ \mathrm{eV}$

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

How do we compare these?

Eigenmodes for a PIXIE-type experiment

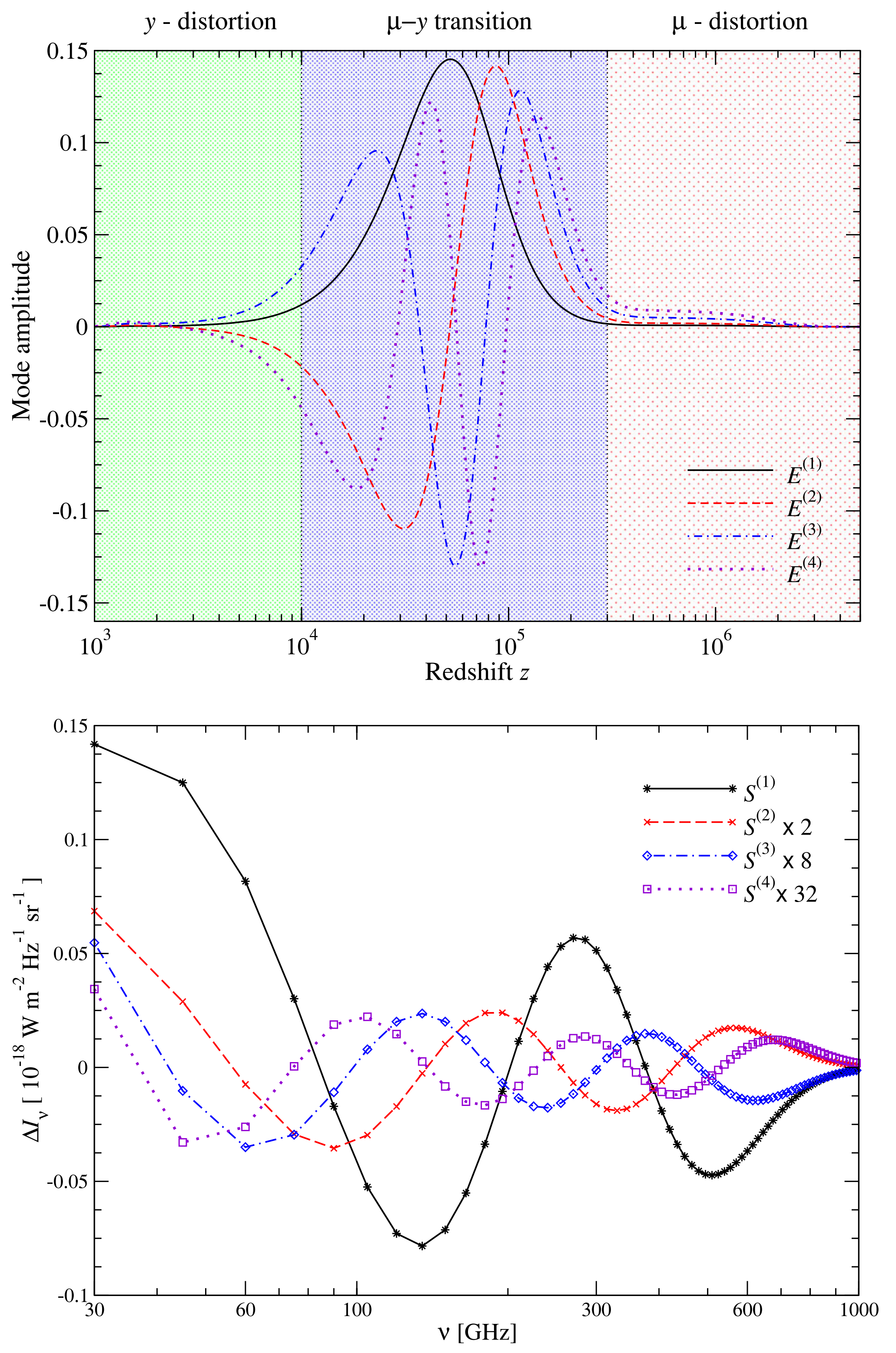


Figure 4. First few eigenmodes $\boldsymbol{E}^{(k)}$ and $\boldsymbol{S}^{(k)}$ for *PIXIE*-type settings ($\nu_{\rm min} = 30\,{\rm GHz}$, $\nu_{\rm max} = 1000\,{\rm GHz}$ and $\Delta\nu_{\rm s} = 15\,{\rm GHz}$). In the mode construction, we assumed that energy release only occurred at $10^3 \leq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

Estimated error bars

(under idealistic assumptions...)

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

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

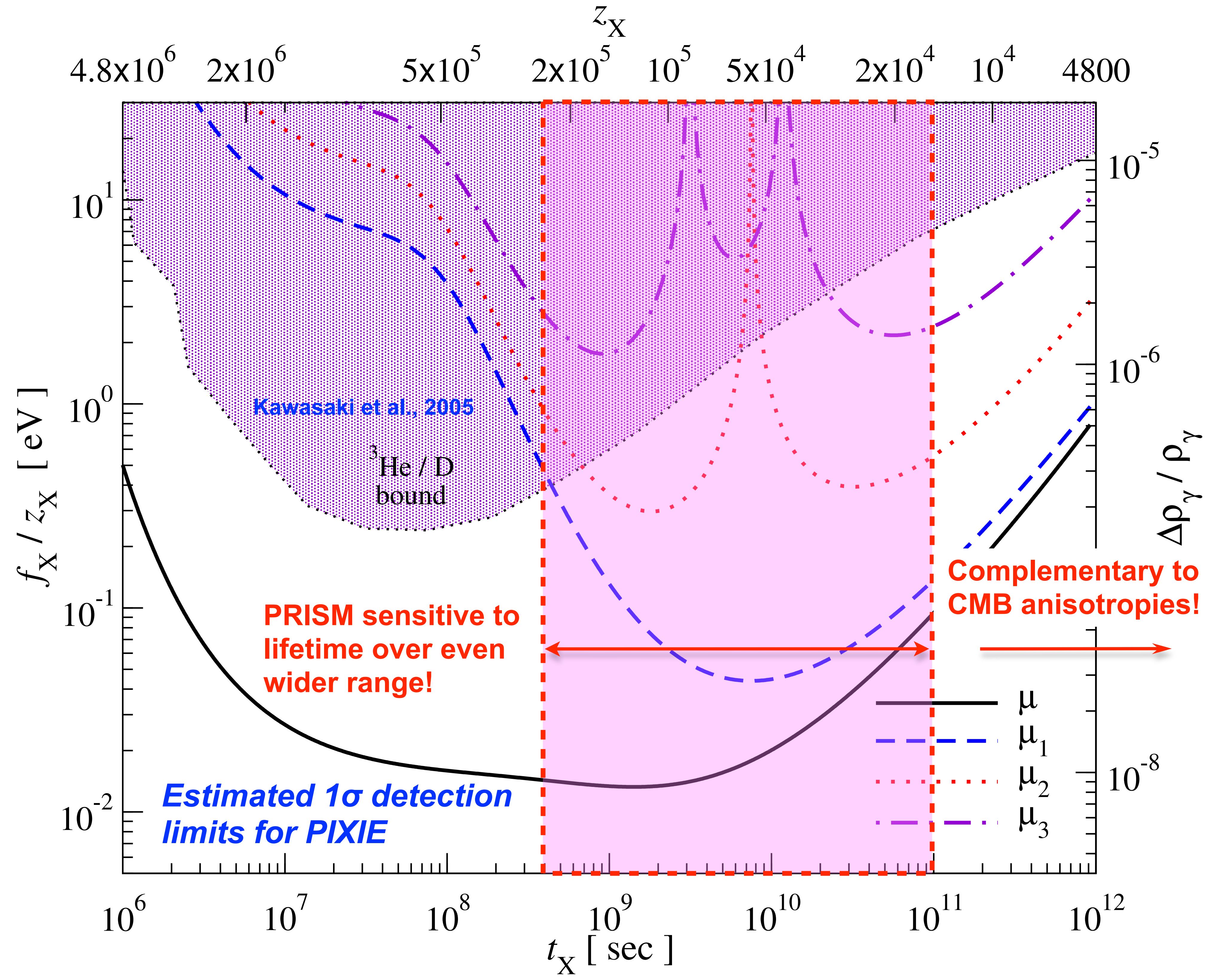
$$\Delta \mu \simeq 1.4 \times 10^{-8} \left(\frac{\Delta I_{\rm c}}{5\,{\rm Jy\,sr^{-1}}}\right)$$

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

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

JC & Jeong, 2013

Distortions could shed light on decaying (DM) particles!



PRISM sensitive to lifetime over even wider range!

Complementary to CMB anisotropies!

Estimated 1σ detection limits for PIXIE

JC & Jeong, 2013

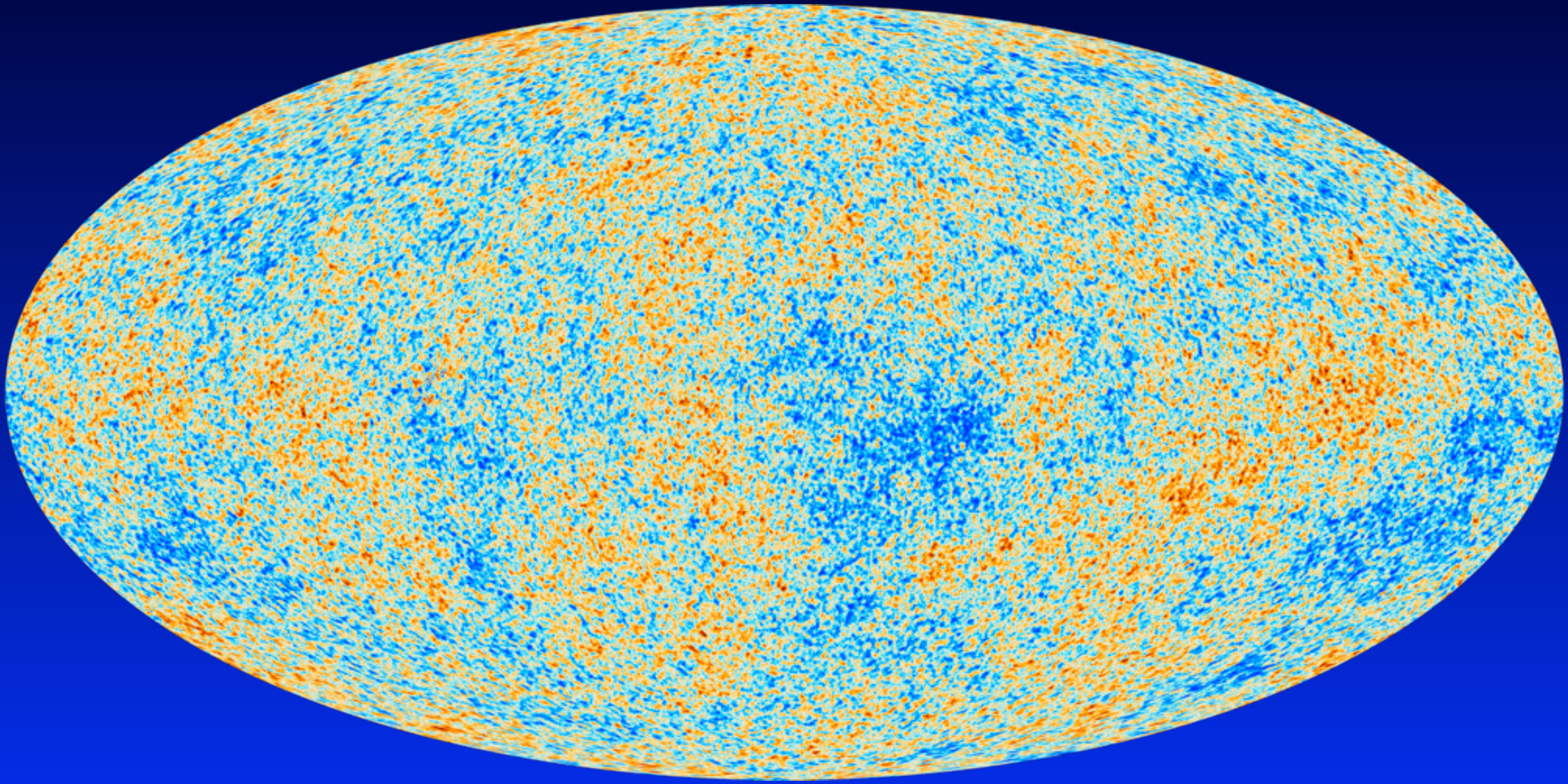
Structure of the Lectures (cont.)

Lecture III:

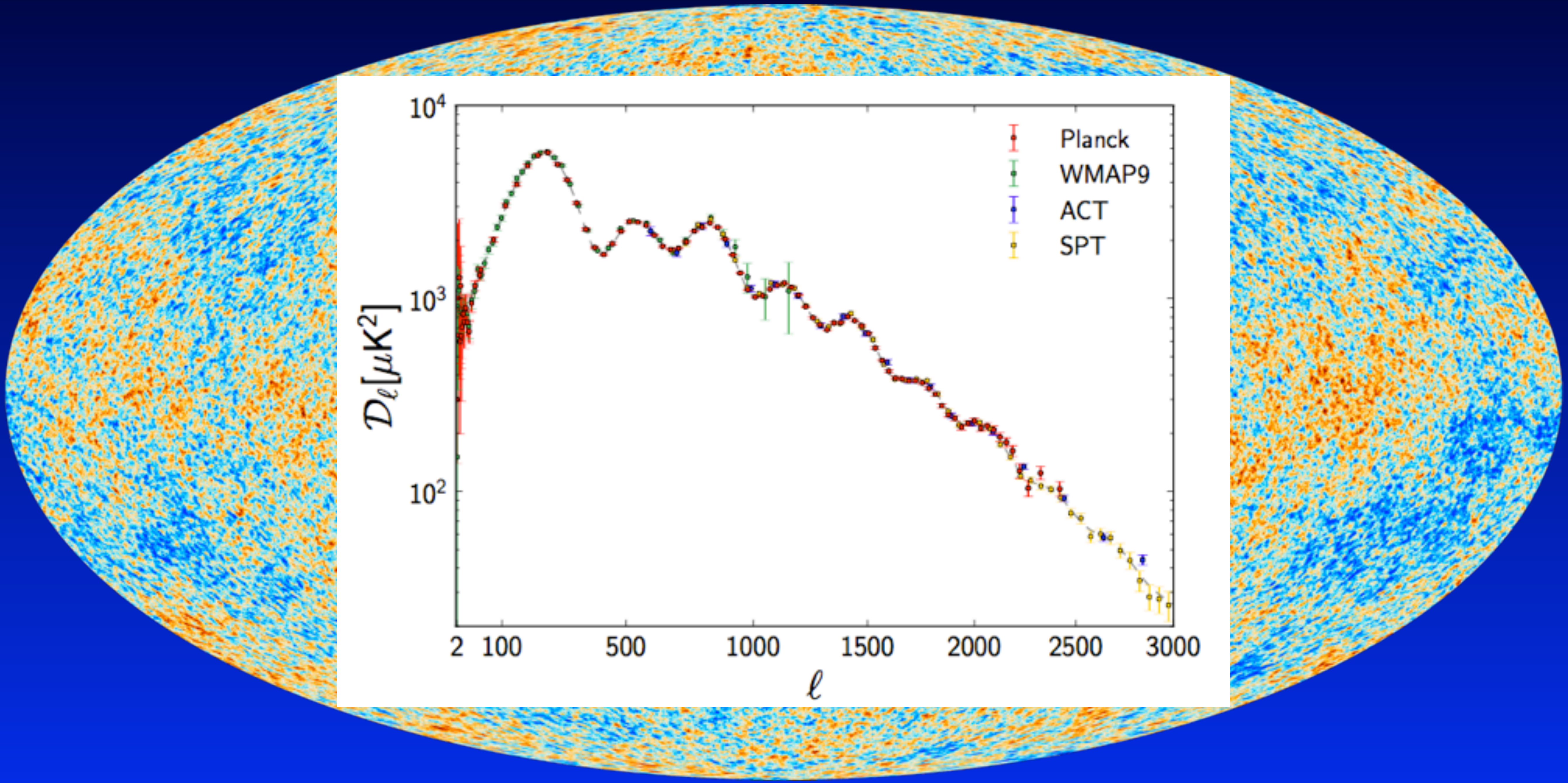
- Overview of different sources of distortions
- Decaying particles
- Dissipation of acoustic modes

The dissipation of small-scale acoustic modes

Dissipation of small-scale acoustic modes



Dissipation of small-scale acoustic modes



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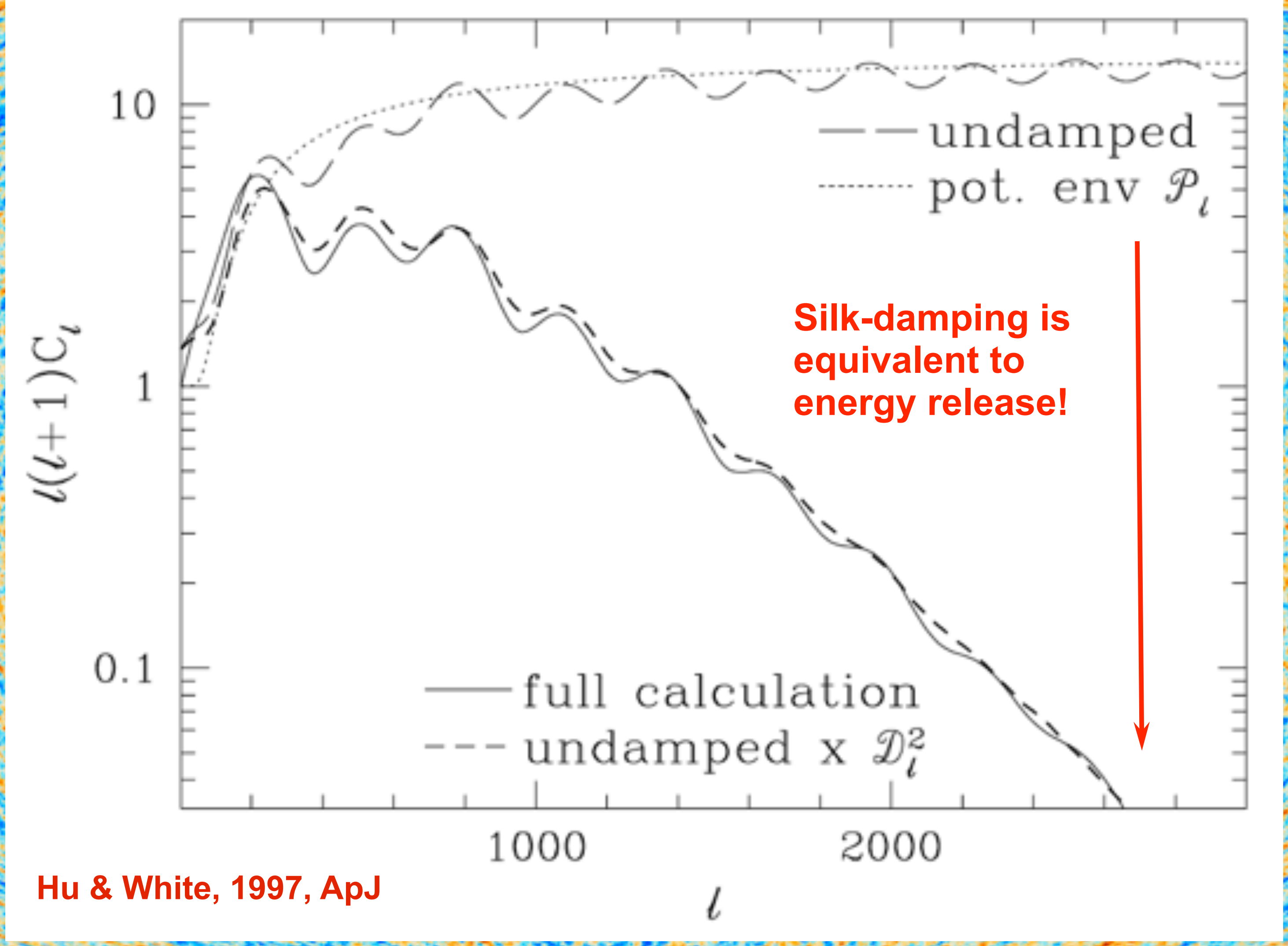

Silk-damping is equivalent to energy release!

Hu & White, 1997, ApJ

Energy release caused by dissipation process

‘Obvious’ dependencies:

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

not so ‘obvious’ dependencies:

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

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

Handwavy derivation of the heating rate

Dissipation of acoustic modes: ‘classical treatment’

- energy stored in plane sound waves

  Landau & Lifshitz, ‘Fluid Mechanics‘, § 65 ⇒ $Q \sim c_s^2\, \rho\, (\delta\rho/\rho)^2$

- expression for normal ideal gas where ρ is ‘*mass density*’ and c_s denotes ‘*sounds speed*’

Sunyaev & Zeldovich, 1970
Hu, Scott & Silk, 1994, ApJ

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- photon-baryon fluid with baryon loading $R << 1$

  $(c_s/c)^2 = [\, 3\,(1+R)\,]^{-1} \sim 1/3$

  $\rho \longrightarrow \rho_\gamma \; = a_R\, T^4$

  $\delta\rho/\rho \longrightarrow 4(\delta T_0/T) \equiv 4\Theta_0 \longleftarrow$ **only perturbation in the monopole accounted for**

Sunyaev & Zeldovich, 1970
Hu, Scott & Silk, 1994, ApJ

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- photon-baryon fluid with baryon loading $R \ll 1$

‘minus’ because *decrease* of Θ at small scales means *increase* for average spectrum

$$(c_s/c)^2 = [\,3\,(1+R)\,]^{-1} \sim 1/3$$

$$\rho \rightarrow \rho_\gamma \;= a_R\, T^4 \qquad \Rightarrow \quad (a^4\rho_\gamma)^{-1}\, da^4Q_{ac}/dt = -16/3\; d\langle\Theta_0{}^2\rangle/dt$$

$$\delta\rho/\rho \rightarrow 4(\delta T_0/T) \equiv 4\Theta_0$$

can be calculated using first order perturbation theory

Sunyaev & Zeldovich, 1970
Hu, Scott & Silk, 1994, ApJ

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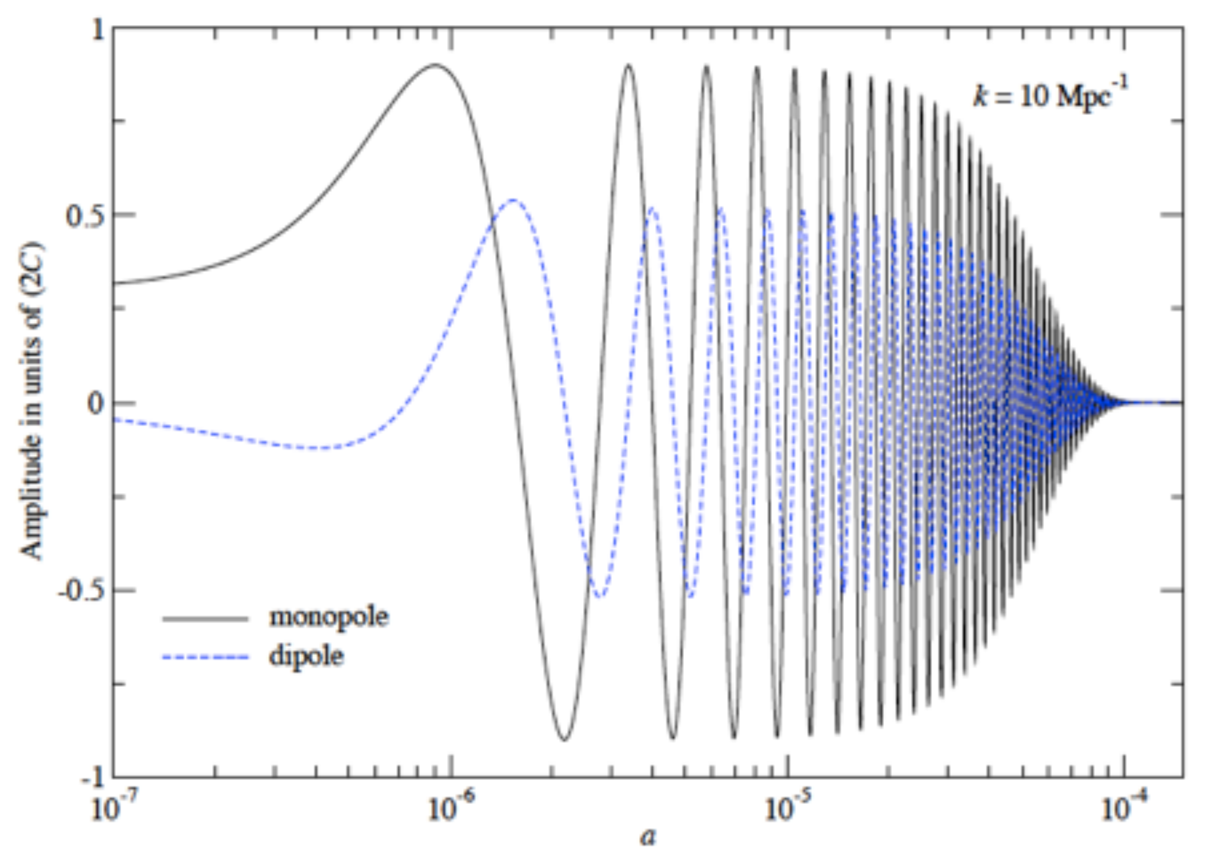

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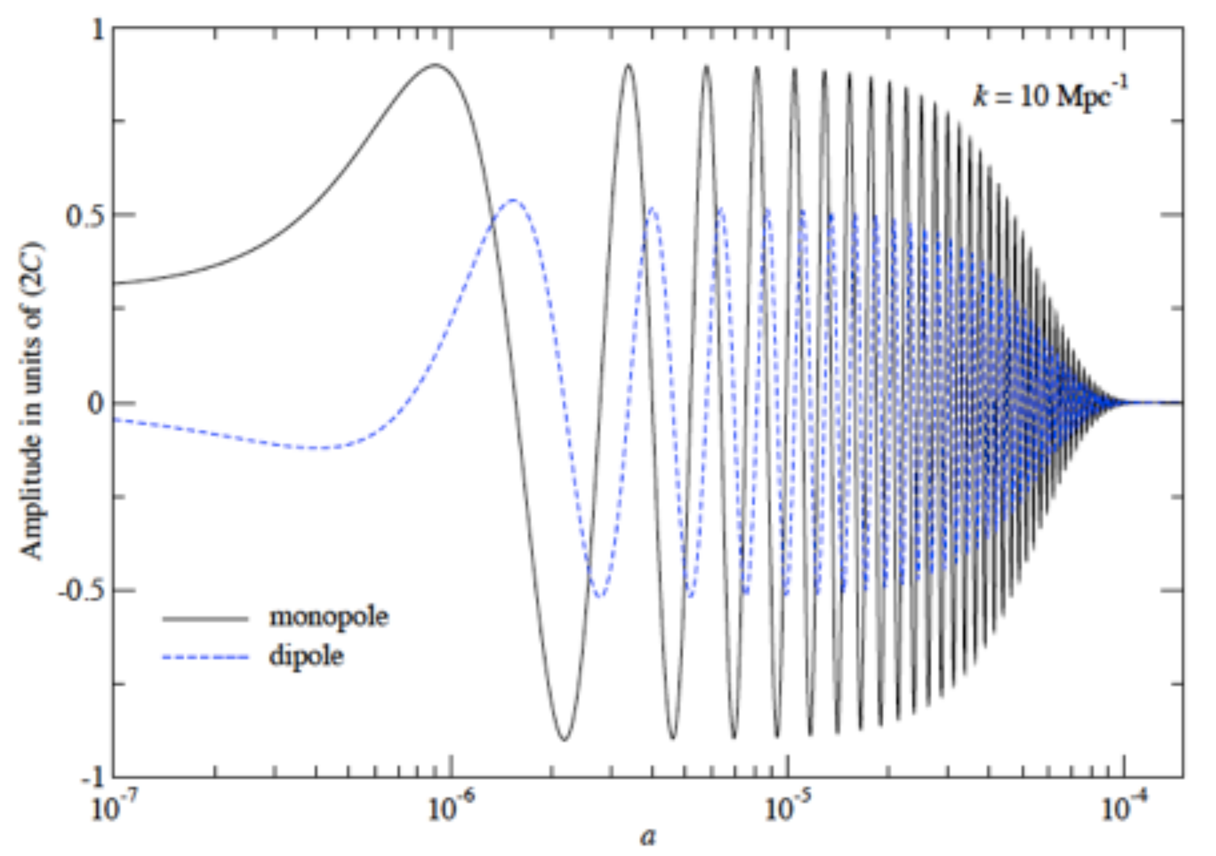
  $\delta\rho/\rho \rightarrow 4(\delta T_0/T) \equiv 4\Theta_0$

- Simple estimate does *not* capture all the physics of the problem:
  (JC, Khatri & Sunyaev, 2012)
  - *total energy release is 9/4 ~ 2.25 times larger!*
  - *only 1/3 of the released energy goes into distortions*



Sunyaev & Zeldovich, 1970
Hu, Scott & Silk, 1994, ApJ

Early power spectrum constraints from FIRAS

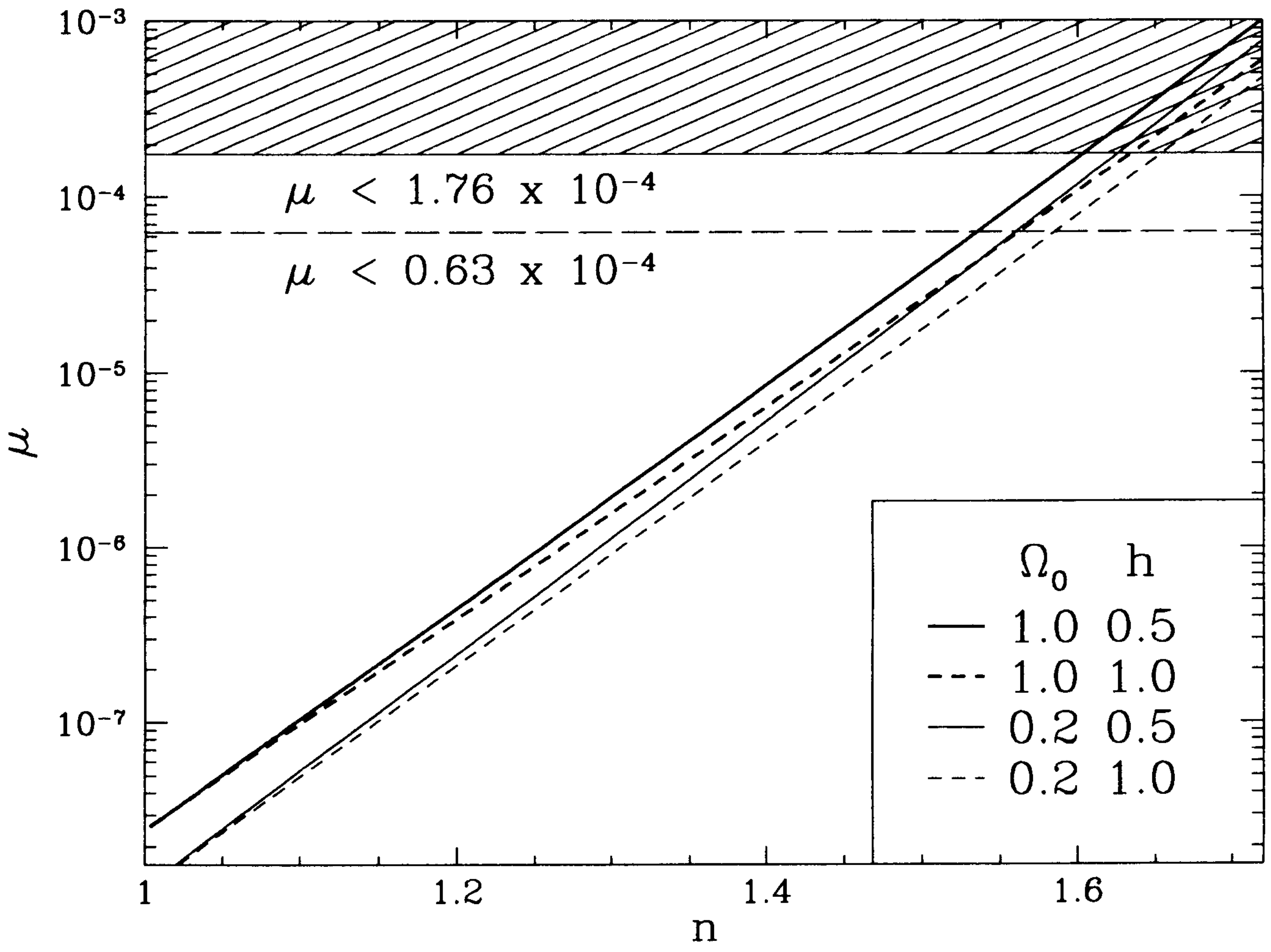


FIG. 1.—Spectral distortion μ, predicted from the full eq. (11), as a function of the power index n for a normalization at the mean of the *COBE* DMR detection $(\Delta T/T)_{10^\circ} = 1.12 \times 10^{-5}$. With the uncertainties on *both* the DMR and FIRAS measurements, the conservative 95% upper limit is effectively $\mu < 1.76 \times 10^{-4}$ (see text). The corresponding constraint on n is relatively weakly dependent on cosmological parameters: $n < 1.60$ $(h = 0.5)$ and $n < 1.63$ $(h = 1.0)$ for $\Omega_0 = 1$ and quite similar for $0.2 < \Omega_0 = 1 - \Omega_\Lambda < 1$ universes. These limits are nearly independent of Ω_B. We have also plotted the optimistic 95% upper limit on $\mu < 0.63 \times 10^{-4}$ for comparison as discussed in the text.

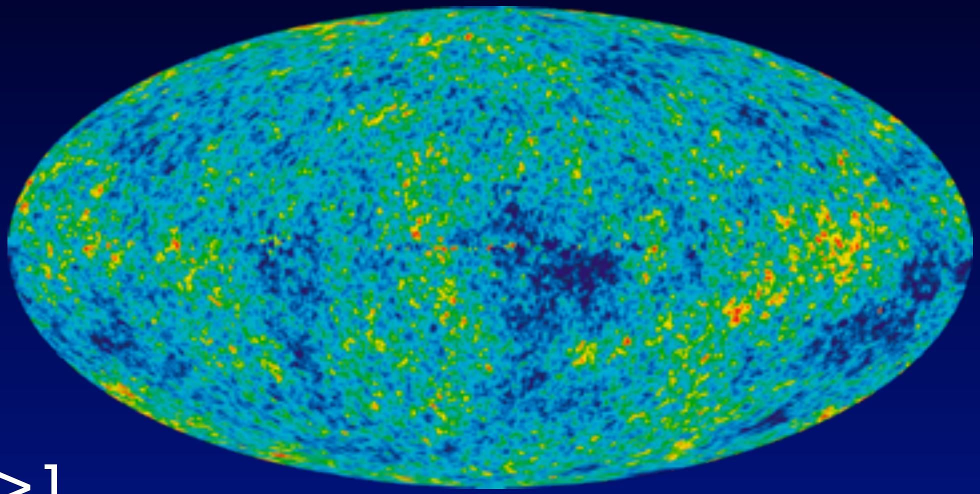
- based on classical estimate for heating rate
- Tightest / cleanest constraint at that point!
- simple power-law spectrum assumed
- *$\mu \sim 10^{-8}$ for scale-invariant power spectrum*
- $n_S \lesssim 1.6$

Hu, Scott & Silk, 1994

Dissipation of acoustic modes: ‘microscopic picture’

- after inflation: photon field has spatially varying temperature *T*
- average energy stored in photon field at any given moment

$$\langle \rho_\gamma \rangle = a_R \langle T^4 \rangle \approx a_R \langle T \rangle^4 \left[1 + 4\underbrace{\langle \Theta \rangle}_{== 0} + 6\langle \Theta^2 \rangle\right]$$



E.g., our **snapshot at *z*=0**

JC, Khatri & Sunyaev, 2012

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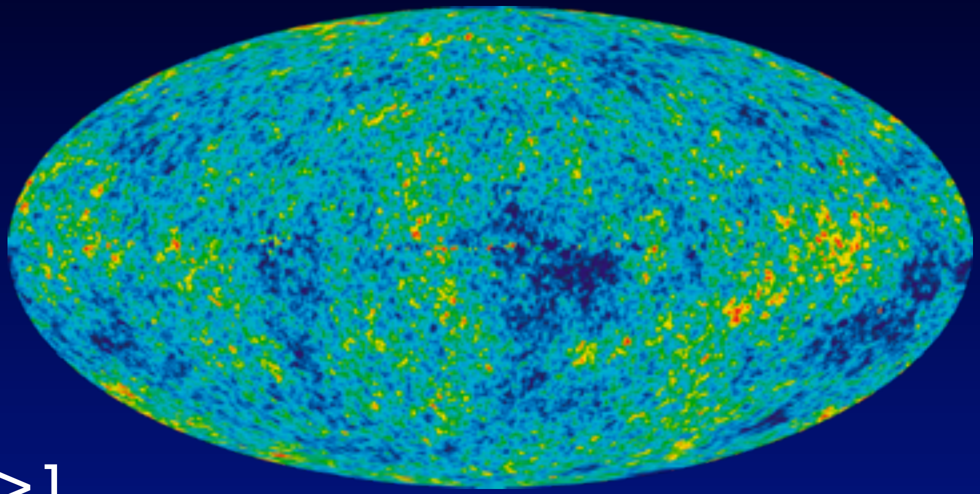

E.g., our snapshot at z=0

- after inflation: photon field has spatially varying temperature T
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$$< \rho_\gamma > = a_R <T^4> \approx a_R <T>^4 [1 + 4\underbrace{<\Theta>}_{== 0} + 6<\Theta^2>]$$

$$\Rightarrow \quad (a^4\rho_\gamma)^{-1} \, da^4 Q_{ac}/dt = -6 \, d<\Theta^2>/dt$$

- Monopole actually drops out of the equation!
- In principle *all* higher multipoles contribute to the energy release

JC, Khatri & Sunyaev, 2012

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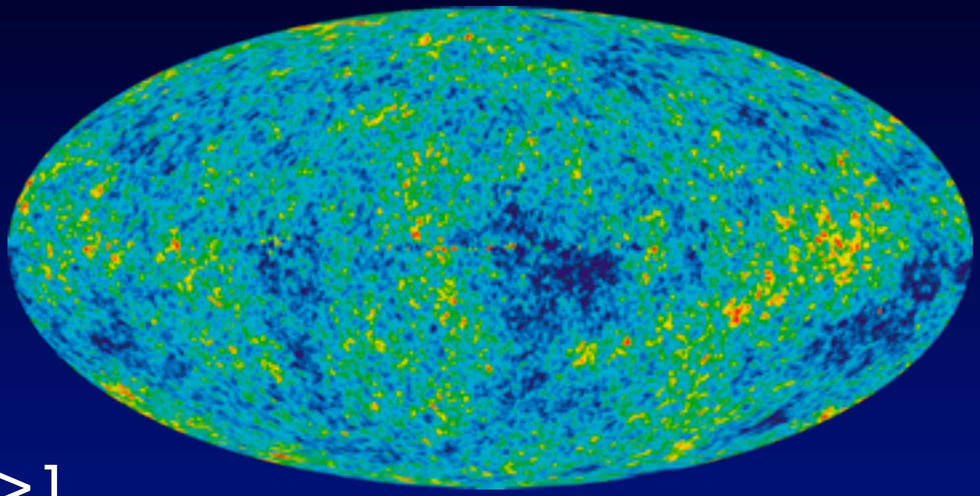

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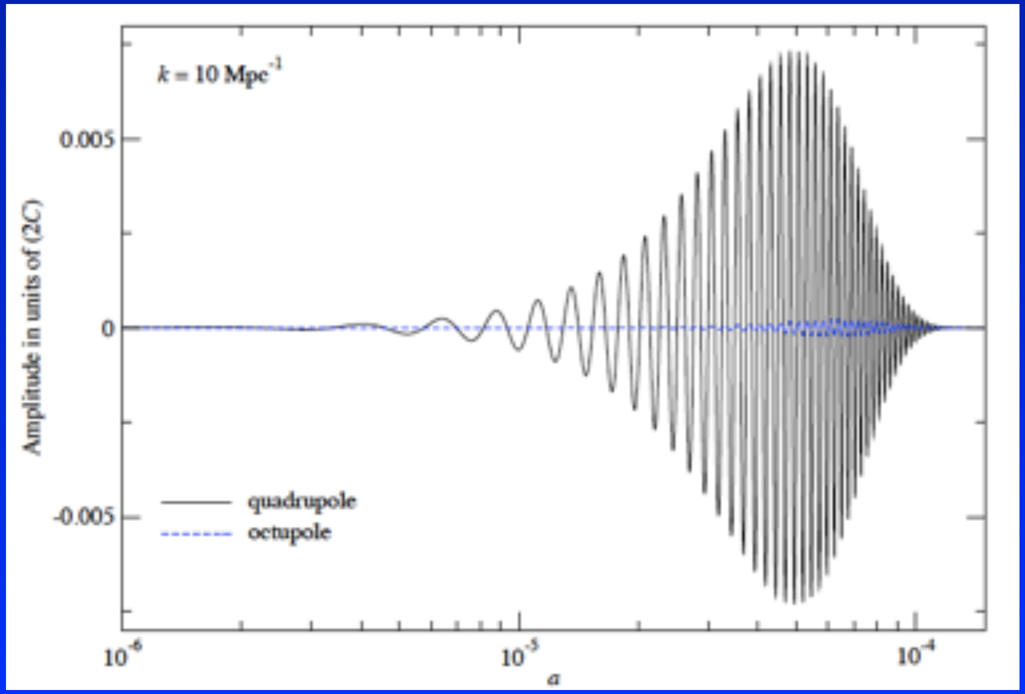
- Monopole actually drops out of the equation!
- In principle *all* higher multipoles contribute to the energy release
- At high redshifts ($z \geq 10^4$):
  - *net (gauge-invariant) dipole and contributions from higher multipoles are negligible*
  - *dominant term caused by quadrupole anisotropy*

$$\Rightarrow \quad (a^4 \rho_\gamma)^{-1} \, d a^4 Q_{ac}/dt \approx -12 \, d<\Theta_0^2>/dt$$

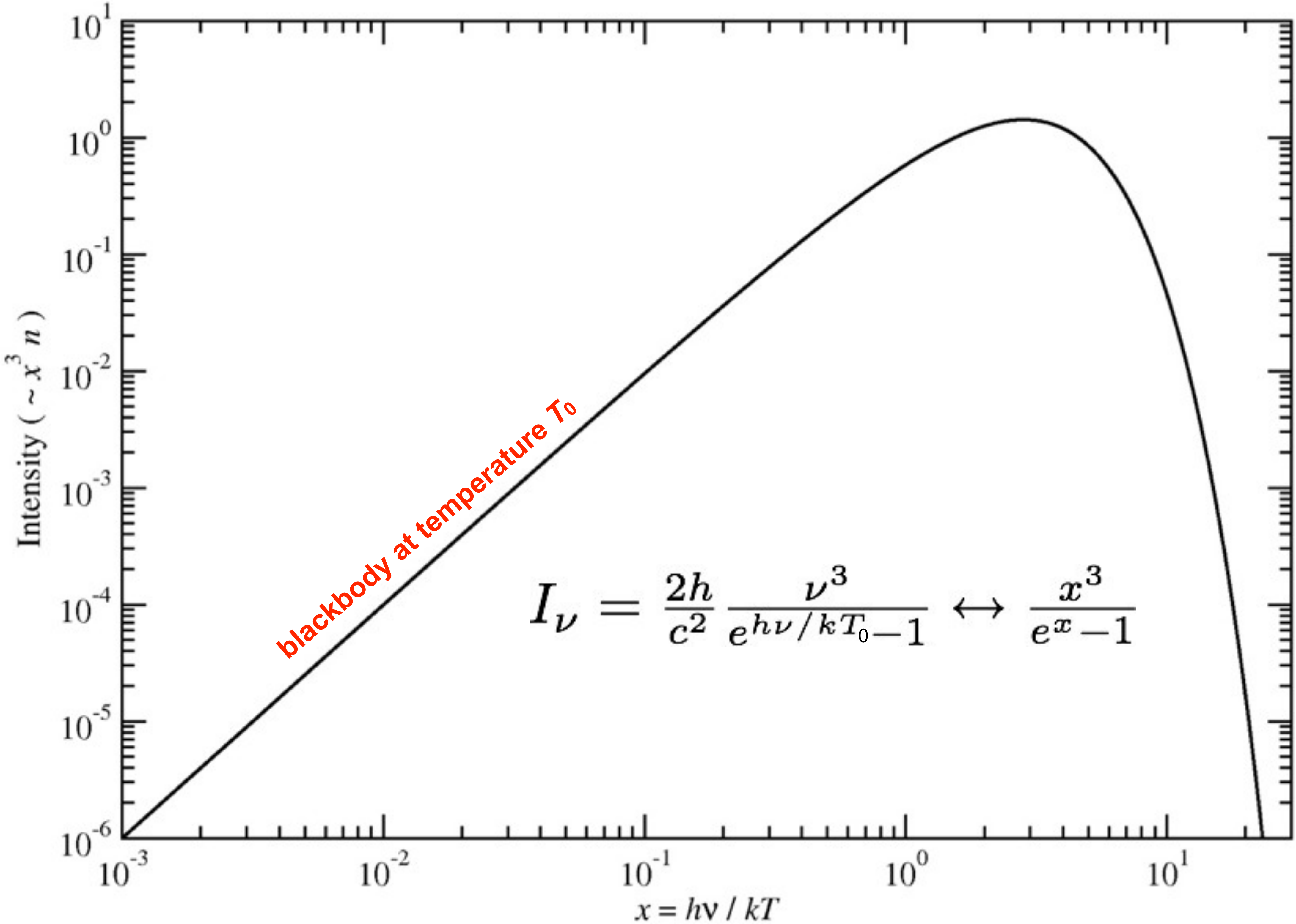
9/4 larger than classical estimate



JC, Khatri & Sunyaev, 2012

Where does the 2:1 ratio come from?

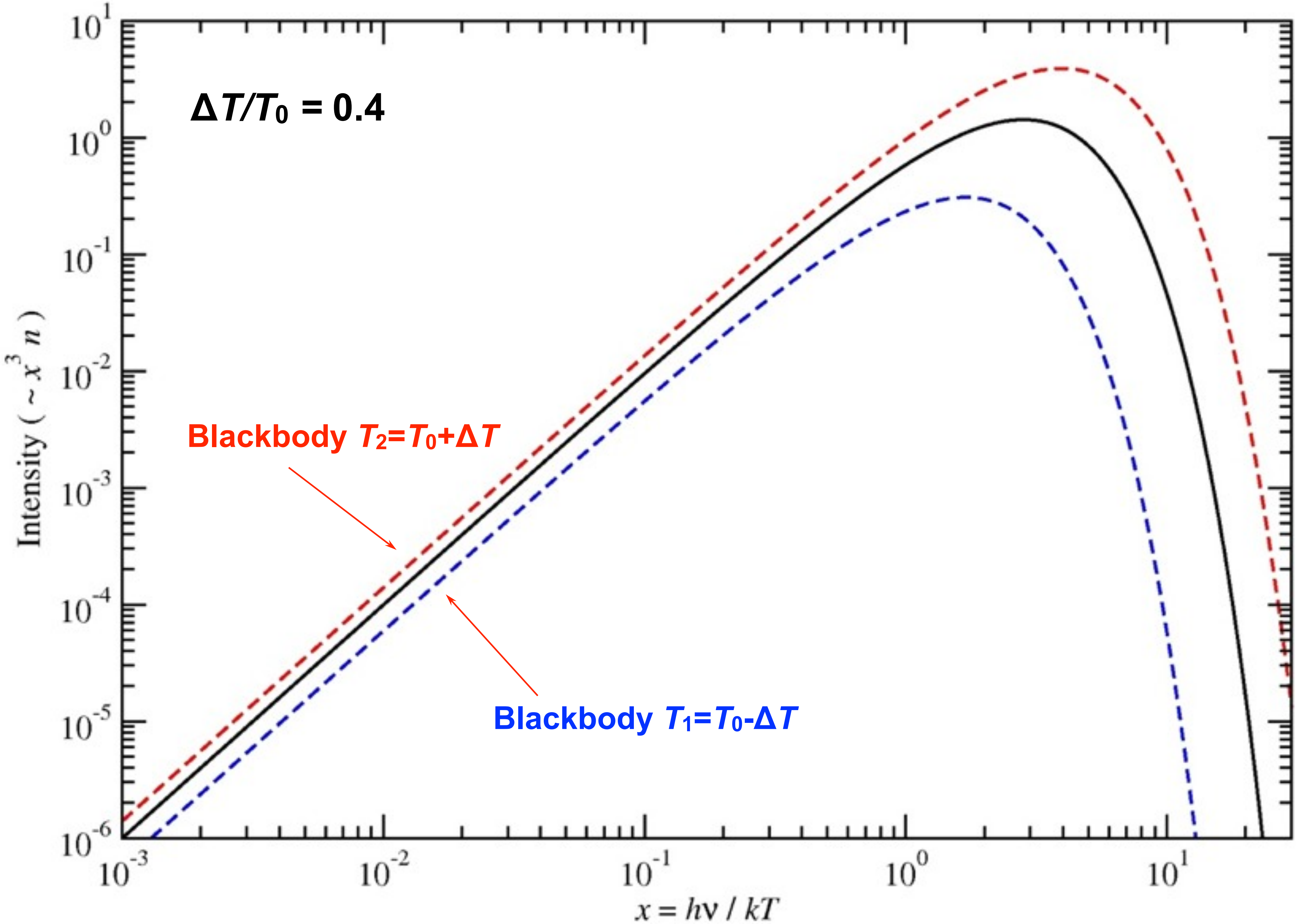
Superpositions of blackbody spectra



$$I_\nu = \frac{2h}{c^2} \frac{\nu^3}{e^{h\nu/kT_0} - 1} \leftrightarrow \frac{x^3}{e^x - 1}$$

Zeldovich, Illarionov & Sunyaev, 1972
JC & Sunyaev 2004

Superpositions of blackbody spectra



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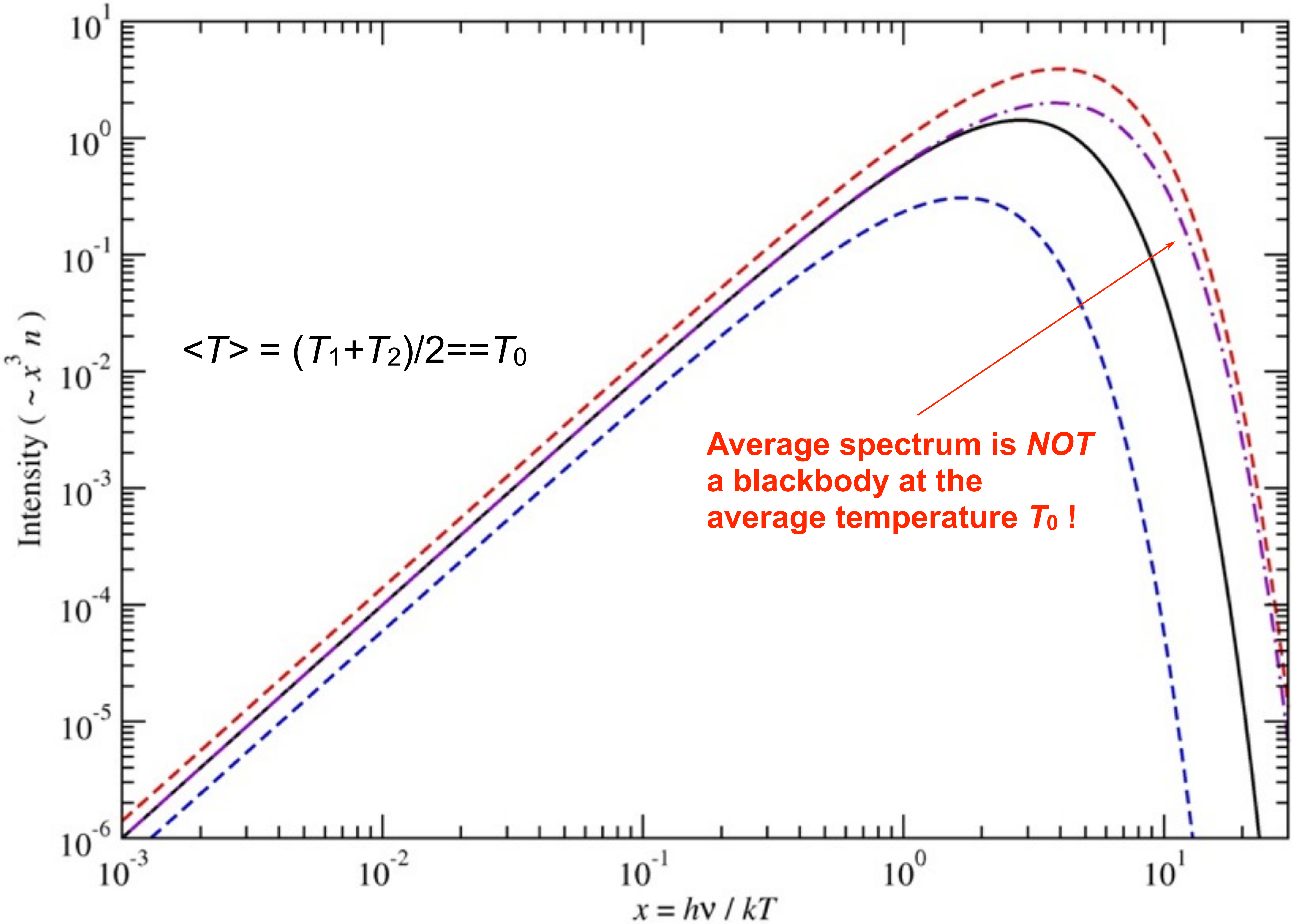

$\langle T\rangle = (T_1+T_2)/2 == T_0$

Average spectrum is *NOT* a blackbody at the average temperature T_0 !

Zeldovich, Illarionov & Sunyaev, 1972
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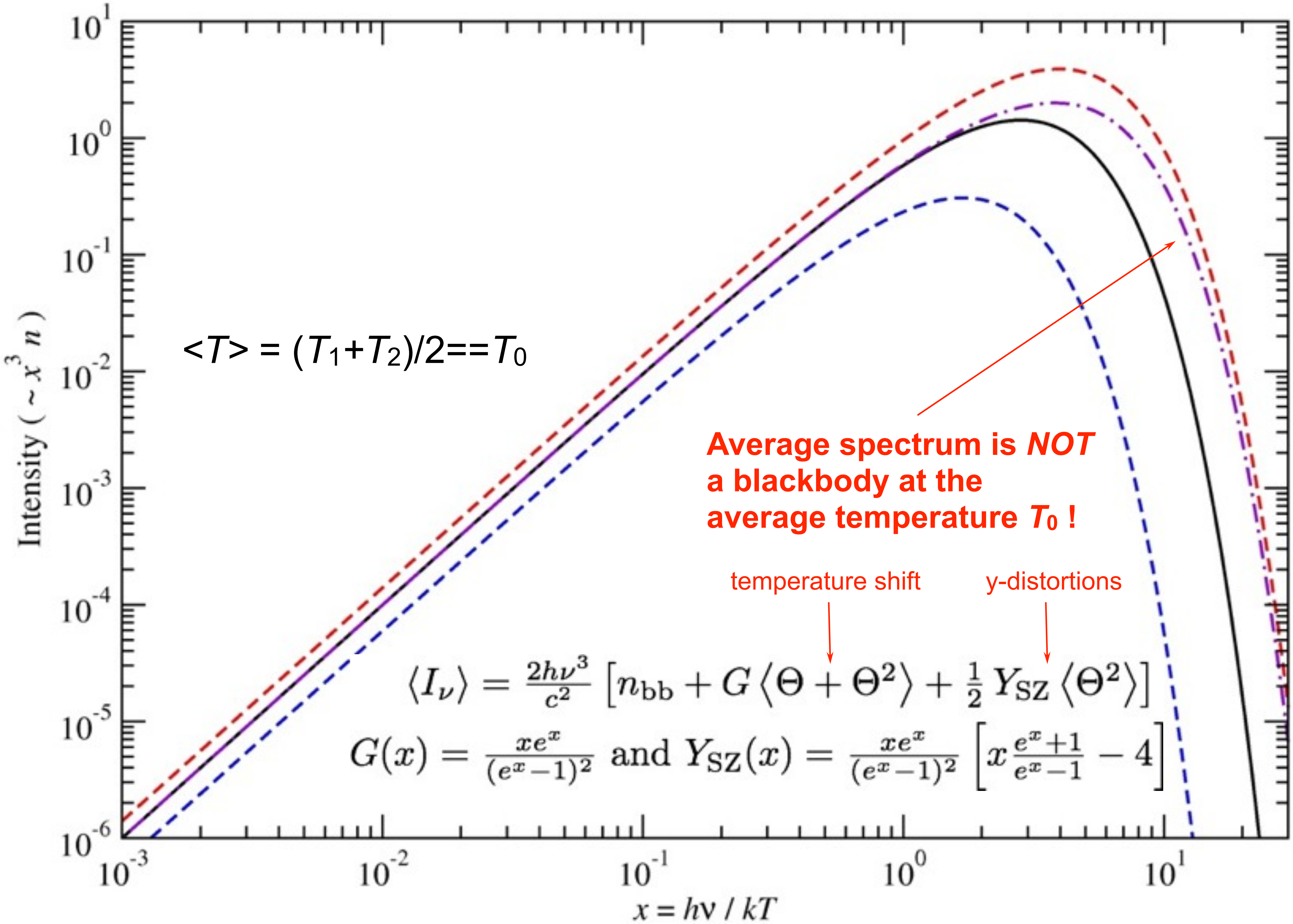

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Average spectrum is *NOT* a blackbody at the average temperature T_0 !

temperature shift

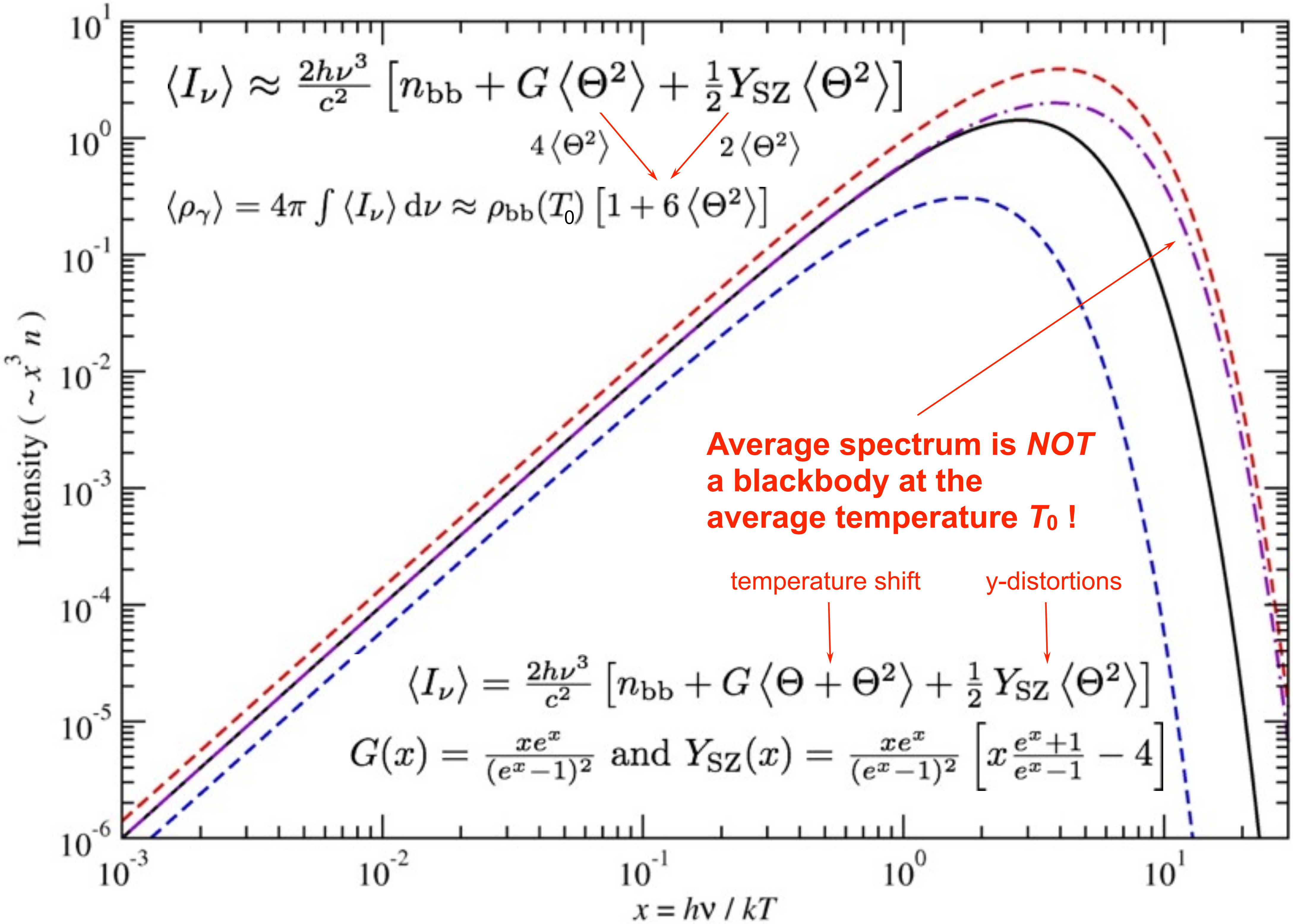
y-distortions

$$\langle I_\nu \rangle = \frac{2h\nu^3}{c^2}\left[n_{\rm bb} + G\,\langle \Theta + \Theta^2\rangle + \frac{1}{2}\,Y_{\rm SZ}\,\langle\Theta^2\rangle\right]$$

$$G(x) = \frac{xe^x}{(e^x-1)^2} \quad \text{and} \quad Y_{\rm SZ}(x) = \frac{xe^x}{(e^x-1)^2}\left[x\,\frac{e^x+1}{e^x-1} - 4\right]$$

Zeldovich, Illarionov & Sunyaev, 1972
JC & Sunyaev 2004

Superpositions of blackbody spectra



$$\langle I_\nu \rangle \approx \frac{2h\nu^3}{c^2}\left[n_{\rm bb} + G\left\langle\Theta^2\right\rangle + \tfrac{1}{2}Y_{\rm SZ}\left\langle\Theta^2\right\rangle\right]$$

$4\left\langle\Theta^2\right\rangle$ $2\left\langle\Theta^2\right\rangle$

$$\langle\rho_\gamma\rangle = 4\pi\int\langle I_\nu\rangle\,\mathrm{d}\nu \approx \rho_{\rm bb}(T_0)\left[1+6\left\langle\Theta^2\right\rangle\right]$$

Average spectrum is *NOT* a blackbody at the average temperature *T*₀ !

temperature shift

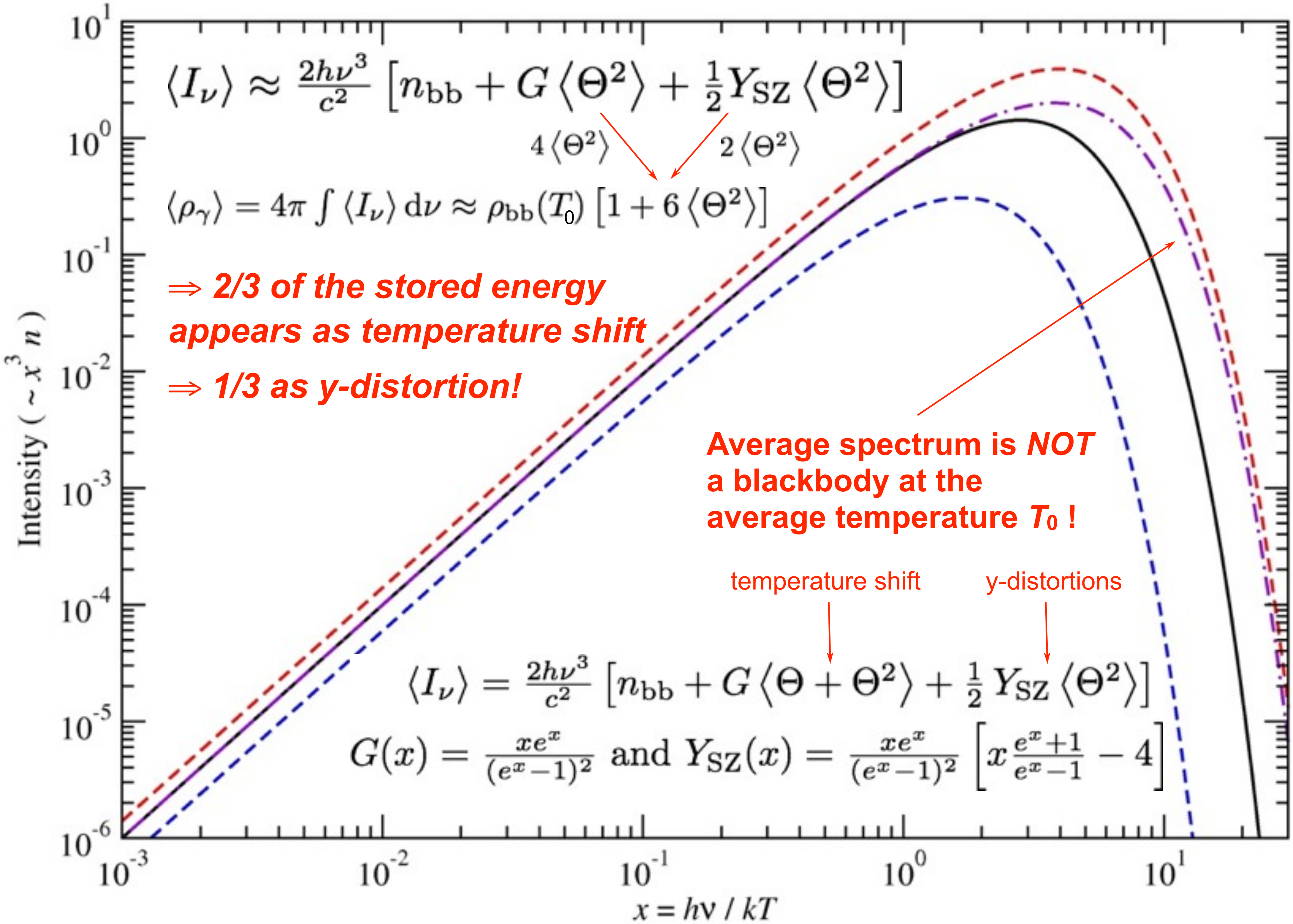
y-distortions

$$\langle I_\nu \rangle = \frac{2h\nu^3}{c^2}\left[n_{\rm bb} + G\left\langle\Theta+\Theta^2\right\rangle + \tfrac{1}{2}\,Y_{\rm SZ}\left\langle\Theta^2\right\rangle\right]$$

$$G(x) = \frac{xe^x}{(e^x-1)^2} \text{ and } Y_{\rm SZ}(x) = \frac{xe^x}{(e^x-1)^2}\left[x\,\frac{e^x+1}{e^x-1} - 4\right]$$

Zeldovich, Illarionov & Sunyaev, 1972
JC & Sunyaev 2004

Superpositions of blackbody spectra



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$$\langle\rho_\gamma\rangle = 4\pi\int\langle I_\nu\rangle\,{\rm d}\nu \approx \rho_{\rm bb}(T_0)\left[1+6\left\langle\Theta^2\right\rangle\right]$$

⇒ 2/3 of the stored energy appears as temperature shift

⇒ 1/3 as y-distortion!

Average spectrum is *NOT* a blackbody at the average temperature *T*₀ !

temperature shift y-distortions

$$\langle I_\nu \rangle = \frac{2h\nu^3}{c^2}\left[n_{\rm bb} + G\left\langle\Theta + \Theta^2\right\rangle + \frac{1}{2}\,Y_{\rm SZ}\left\langle\Theta^2\right\rangle\right]$$

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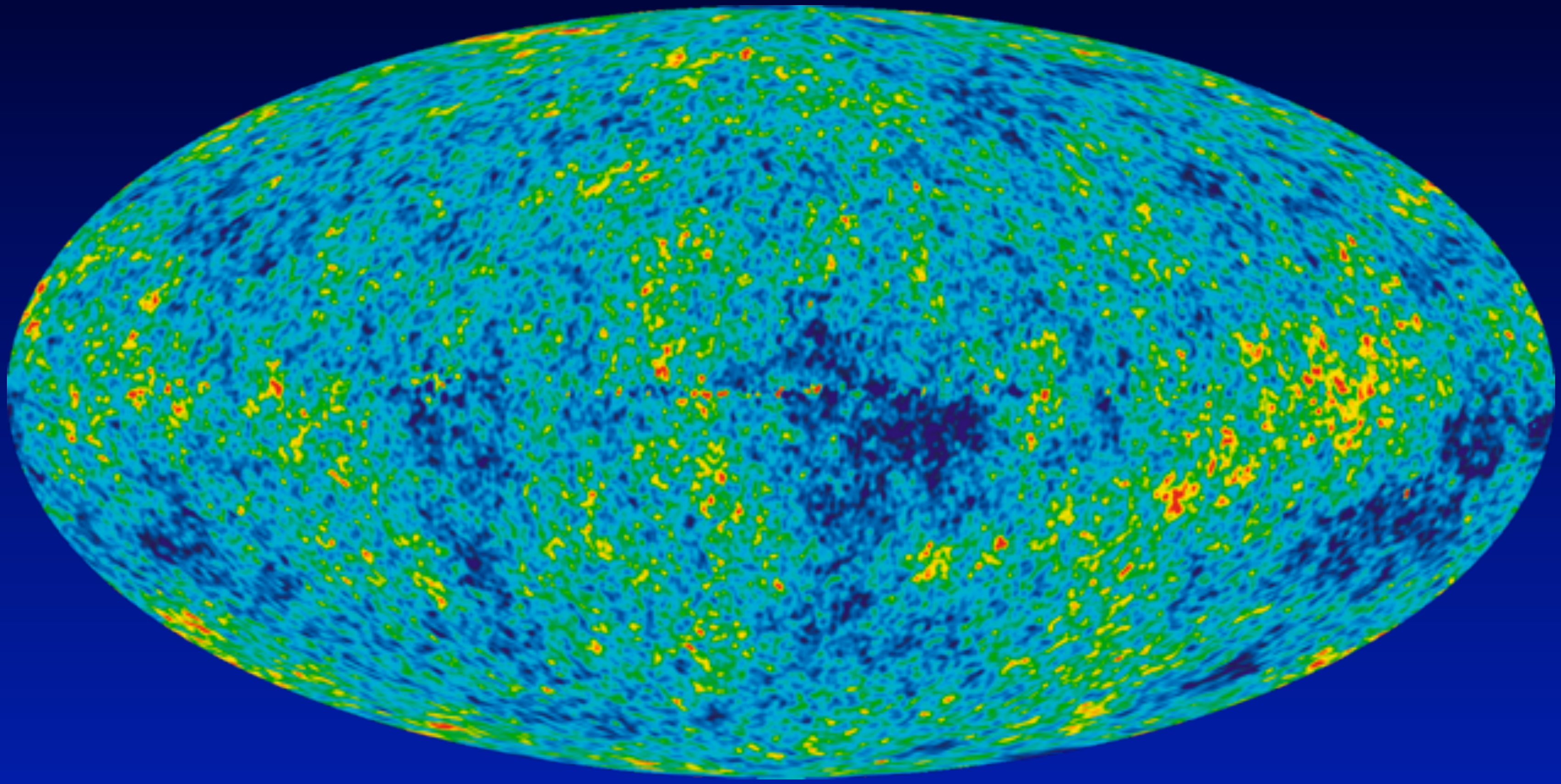
Zeldovich, Illarionov & Sunyaev, 1972
JC & Sunyaev 2004

Distortions caused by superposition of blackbodies



- average spectrum

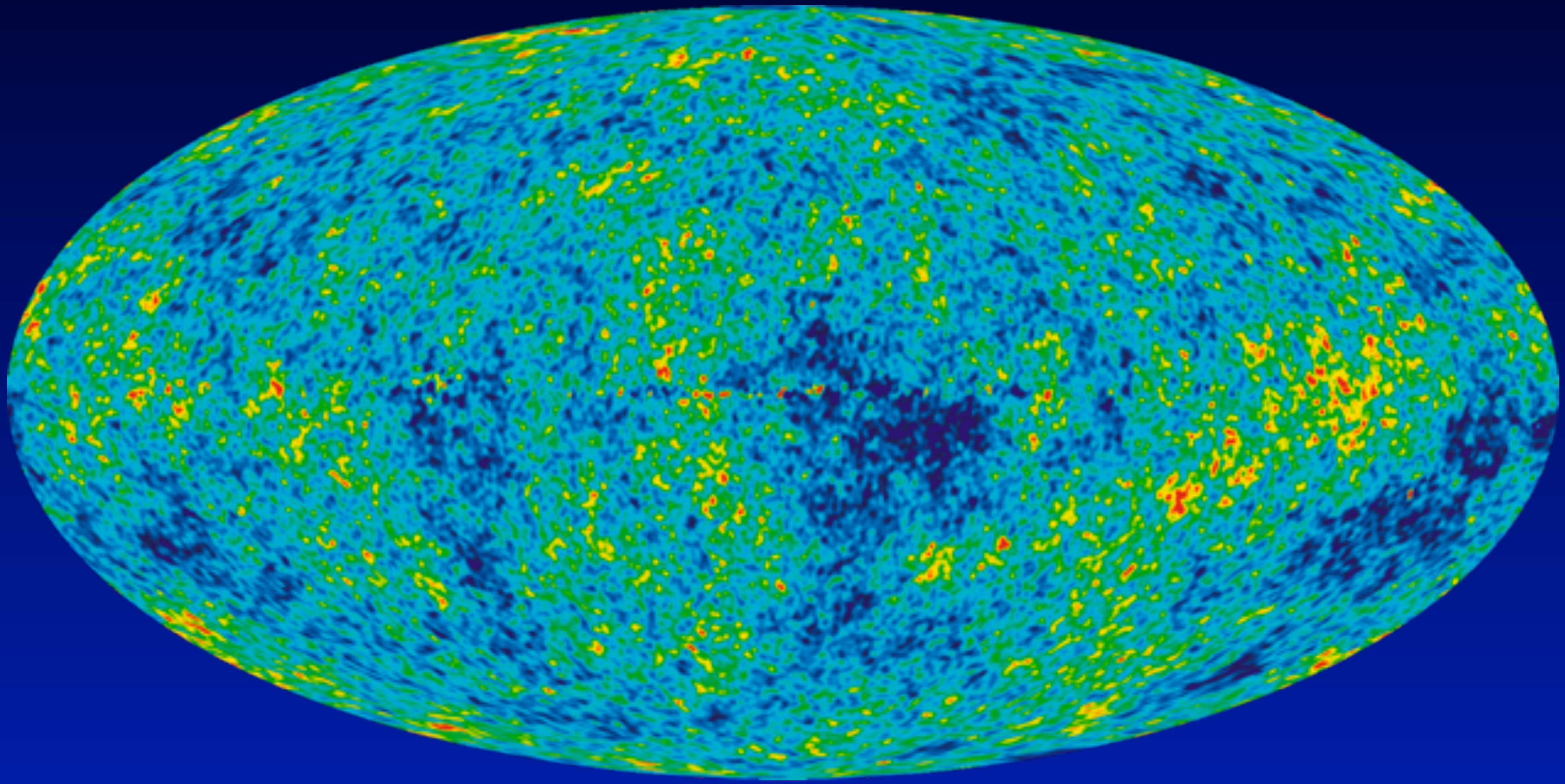
$$\Rightarrow \; y \simeq \frac{1}{2}\left\langle\left(\frac{\Delta T}{T}\right)^2\right\rangle \approx 8\times10^{-10}$$

$$\Delta T_{\rm sup} \simeq T\left\langle\left(\frac{\Delta T}{T}\right)^2\right\rangle \approx 4.4{\rm nK}$$

- known with very high precision

JC & Sunyaev, 2004
JC, Khatri & Sunyaev, 2012

Distortions caused by superposition of blackbodies



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$$\Delta T_{\rm sup} \simeq T\left\langle\left(\frac{\Delta T}{T}\right)^2\right\rangle \approx 4.4{\rm nK}$$

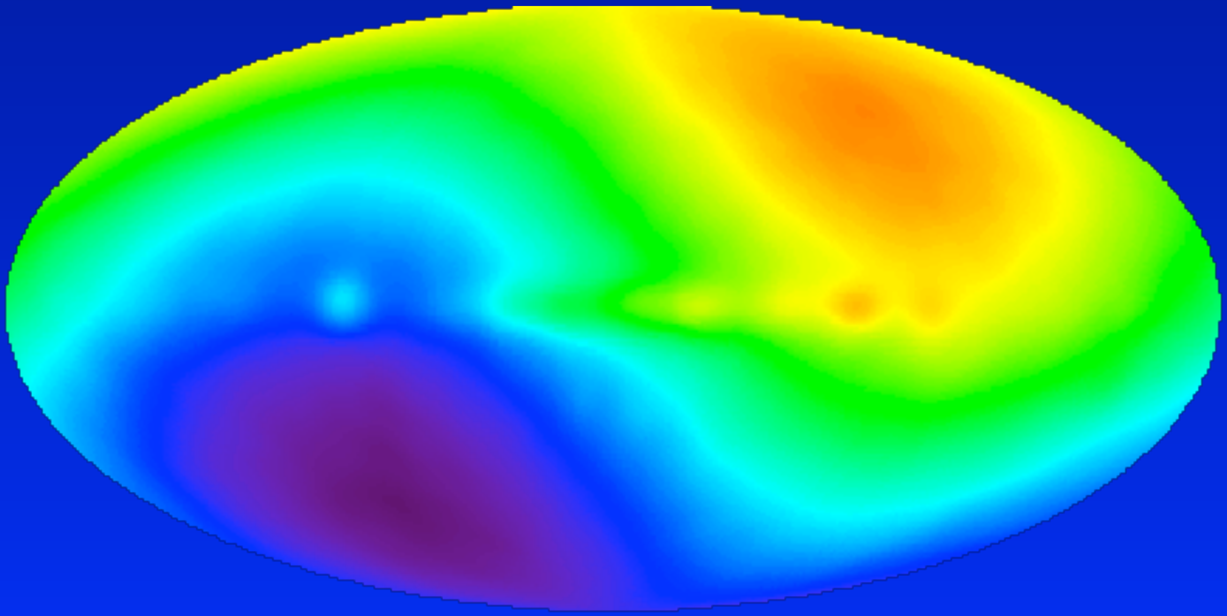
- known with very high precision

- *CMB dipole* ($\beta_c \sim 1.23\times10^{-3}$)

$$\Rightarrow \qquad y \simeq \frac{\beta_{\rm c}^2}{6} \approx 2.6\times10^{-7}$$

$$\Delta T_{\rm sup} \simeq T\,\frac{\beta_{\rm c}^2}{3} \approx 1.4\mu{\rm K}$$

- electrons are up-scattered
- can be taken out at the level of ~ 10^{-9}



COBE/DMR: ΔT = 3.353 mK

JC & Sunyaev, 2004
JC, Khatri & Sunyaev, 2012

Effective energy release caused by damping effect

- Effective heating rate from full 2x2 Boltzmann treatment **(JC, Khatri & Sunyaev, 2012)**

$$\frac{1}{a^4\rho_\gamma}\frac{\mathrm{d}a^4Q_{\rm ac}}{\mathrm{d}t} = 4\sigma_{\rm T}N_{\rm e}c\left\langle \frac{(3\Theta_1-\beta)^2}{3} + \frac{9}{2}\Theta_2^2 - \frac{1}{2}\Theta_2(\Theta_0^{\rm P}+\Theta_2^{\rm P}) + \sum_{l\geq 3}(2l+1)\Theta_\ell^2\right\rangle$$

$$\Theta_\ell = \frac{1}{2}\int \Theta(\mu)P_\ell(\mu)\mathrm{d}\mu$$

gauge-independent dipole **effect of polarization** **higher multipoles**

$$\langle XY\rangle = \int \frac{k^2\mathrm{d}k}{2\pi^2}P(k)X(k)Y(k)$$

Primordial power spectrum

Effective energy release caused by damping effect

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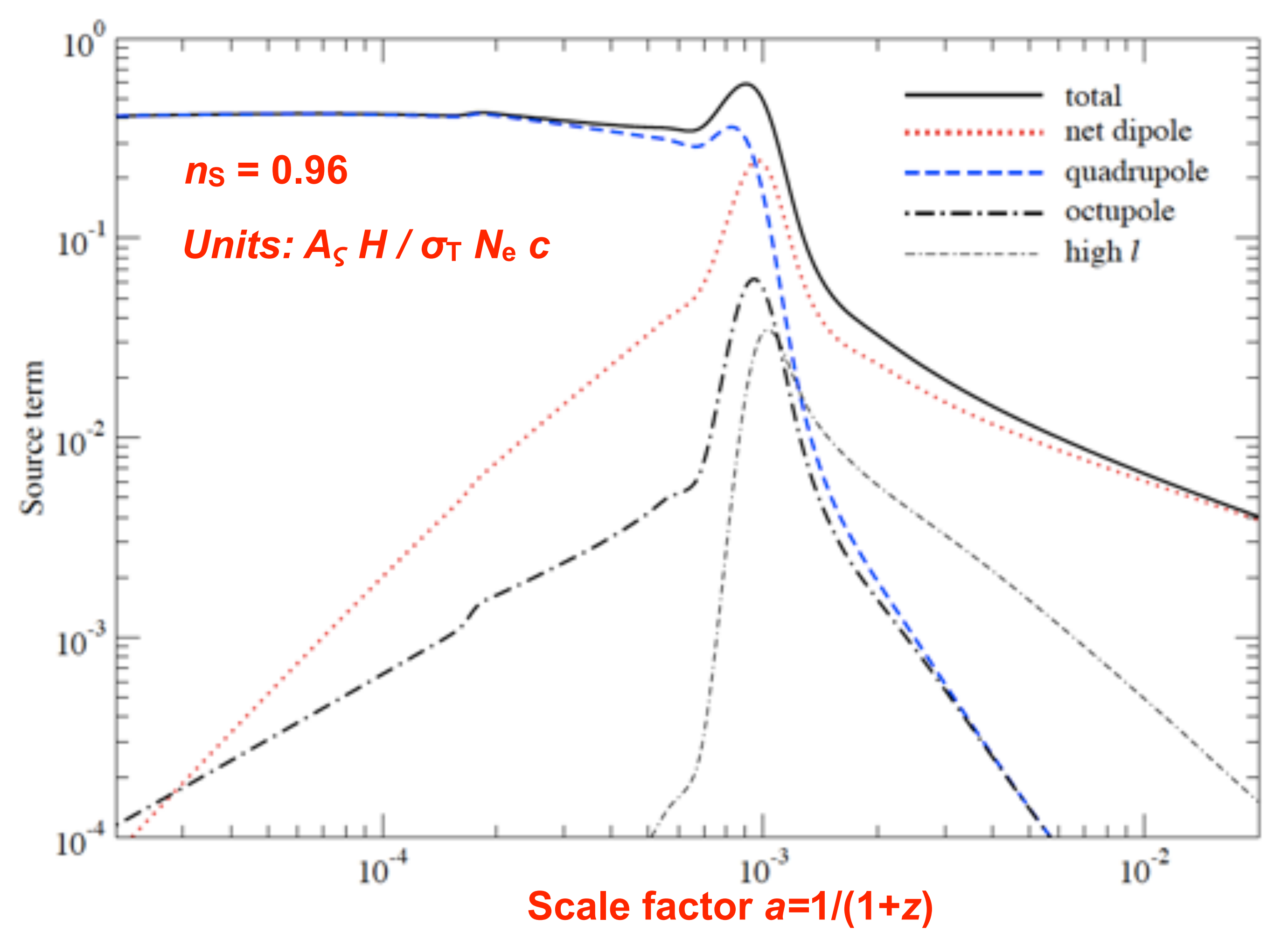
gauge-independent dipole **effect of polarization** **higher multipoles**

$$\langle XY\rangle = \int \frac{k^2\mathrm{d}k}{2\pi^2}P(k)X(k)Y(k)$$

Primordial power spectrum

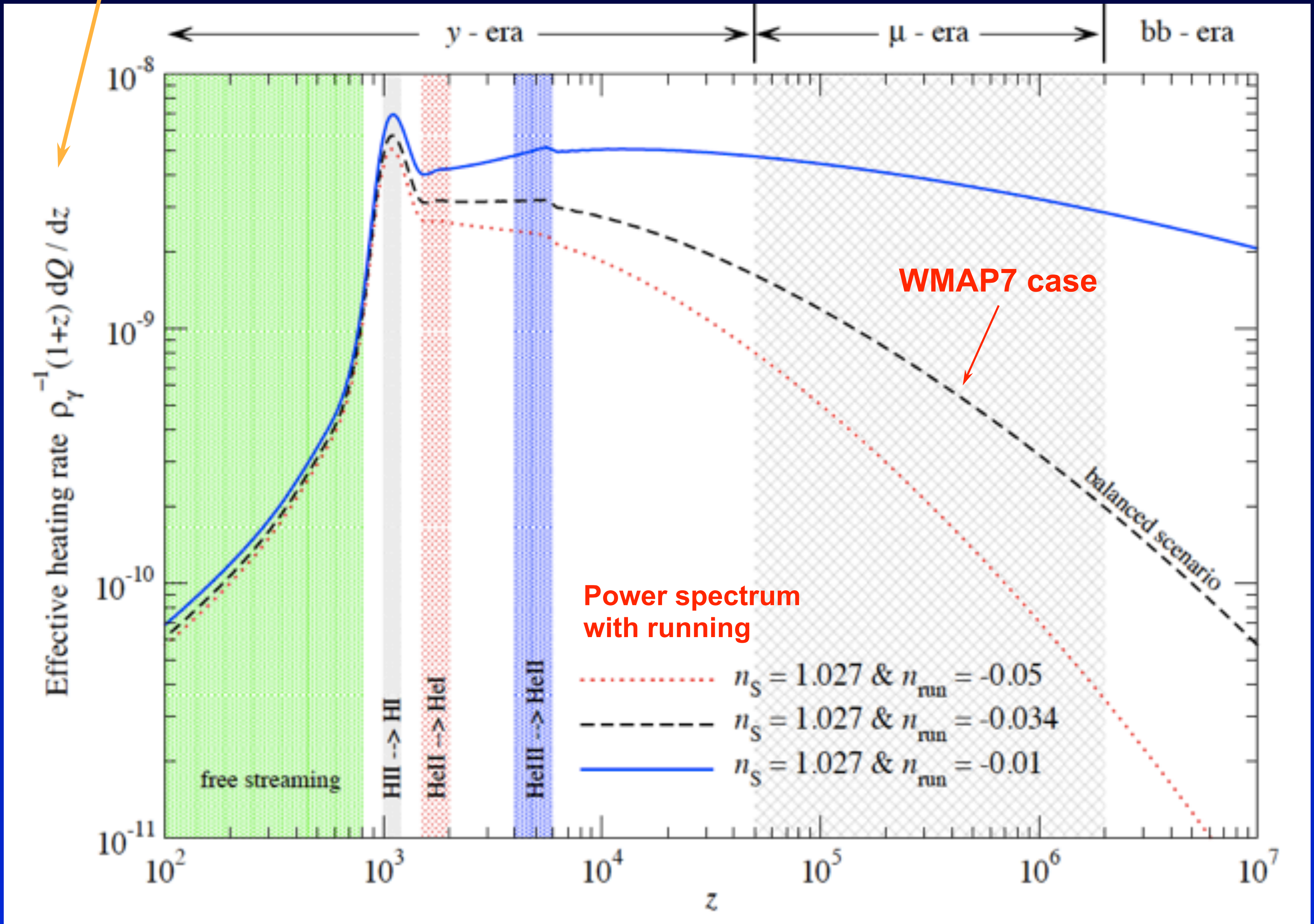
- *quadrupole* dominant at high *z*
- *net dipole* important only at low redshifts
- polarization ~5% effect
- contribution from higher multipoles rather small



JC, Khatri & Sunyaev, 2012

Our computation for the effective energy release

scaled such that constant for $n_S = 1$



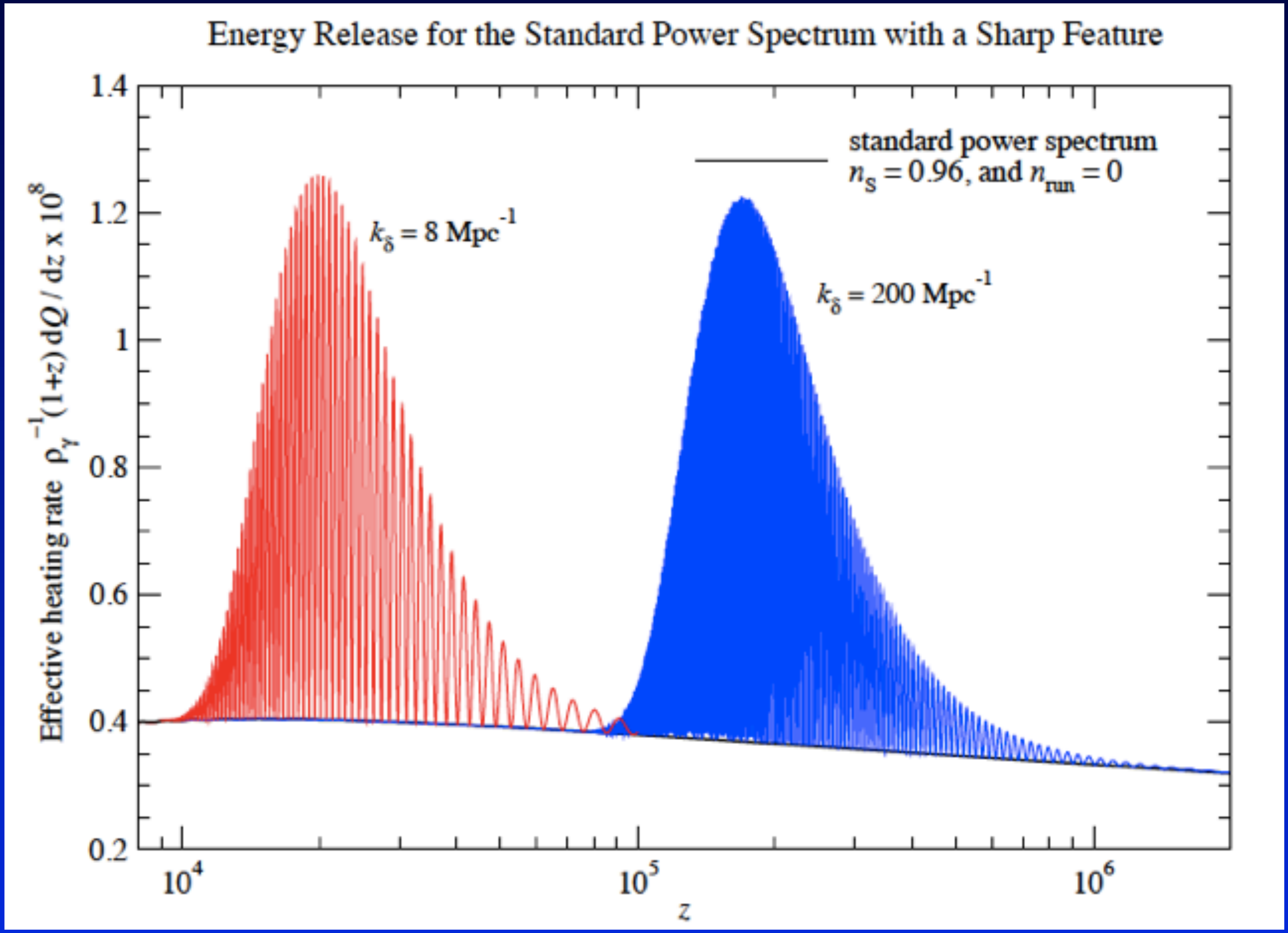
- Our 2. order perturbation calculation showed that the *classical* picture was slightly inconsistent
- Amplitude of the distortion depends on the small-scale power spectrum
- **Computation carried out with *CosmoTherm***
  (JC & Sunyaev 2011)

JC, Khatri & Sunyaev, 2012

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

Primordial power spectrum of curvature perturbations is input for the calculation

Which modes dissipate in the μ and y-eras?



JC, Erickcek & Ben-Dayan, 2012

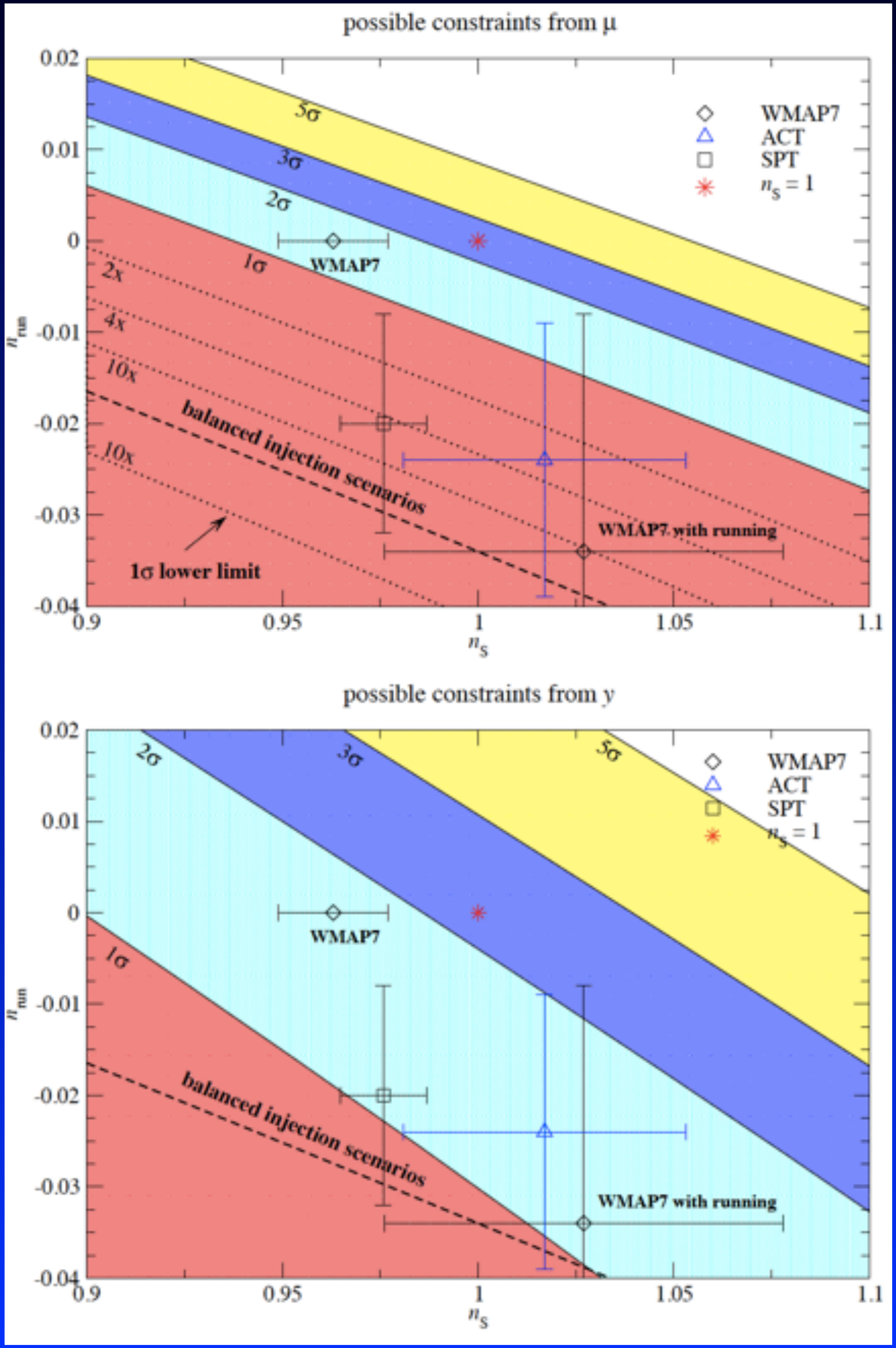
- Single mode with wavenumber *k* dissipates its energy at

$z_d \sim 4.5\times10^5(k\ \mathrm{Mpc}/10^3)^{2/3}$

- Modes with wavenumber $50\ \mathrm{Mpc}^{-1} < k < 10^4\ \mathrm{Mpc}^{-1}$ dissipate their energy during the *μ*-era

- Modes with $k < 50\ \mathrm{Mpc}^{-1}$ cause *y*-distortion

Constraints on the standard primordial power spectrum

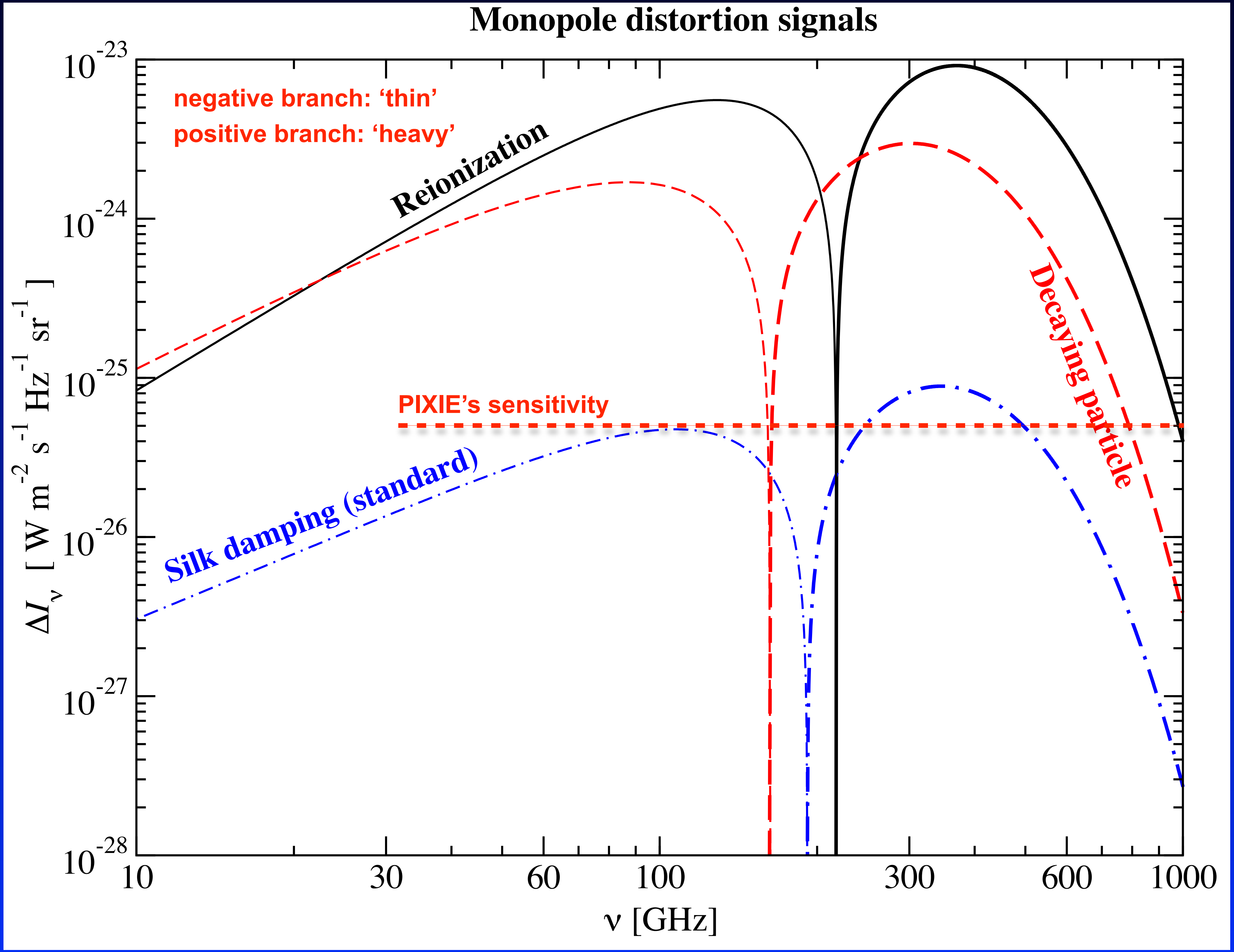


- For *any* given power spectrum very precise predictions are possible!
- The *physics* going into the computation are *well understood*
- For the standard power spectrum PIXIE might detect the *μ*-distortion caused by acoustic damping at ~ 1.5σ level
- PIXIE could *independently* rule out a scale-invariant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

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

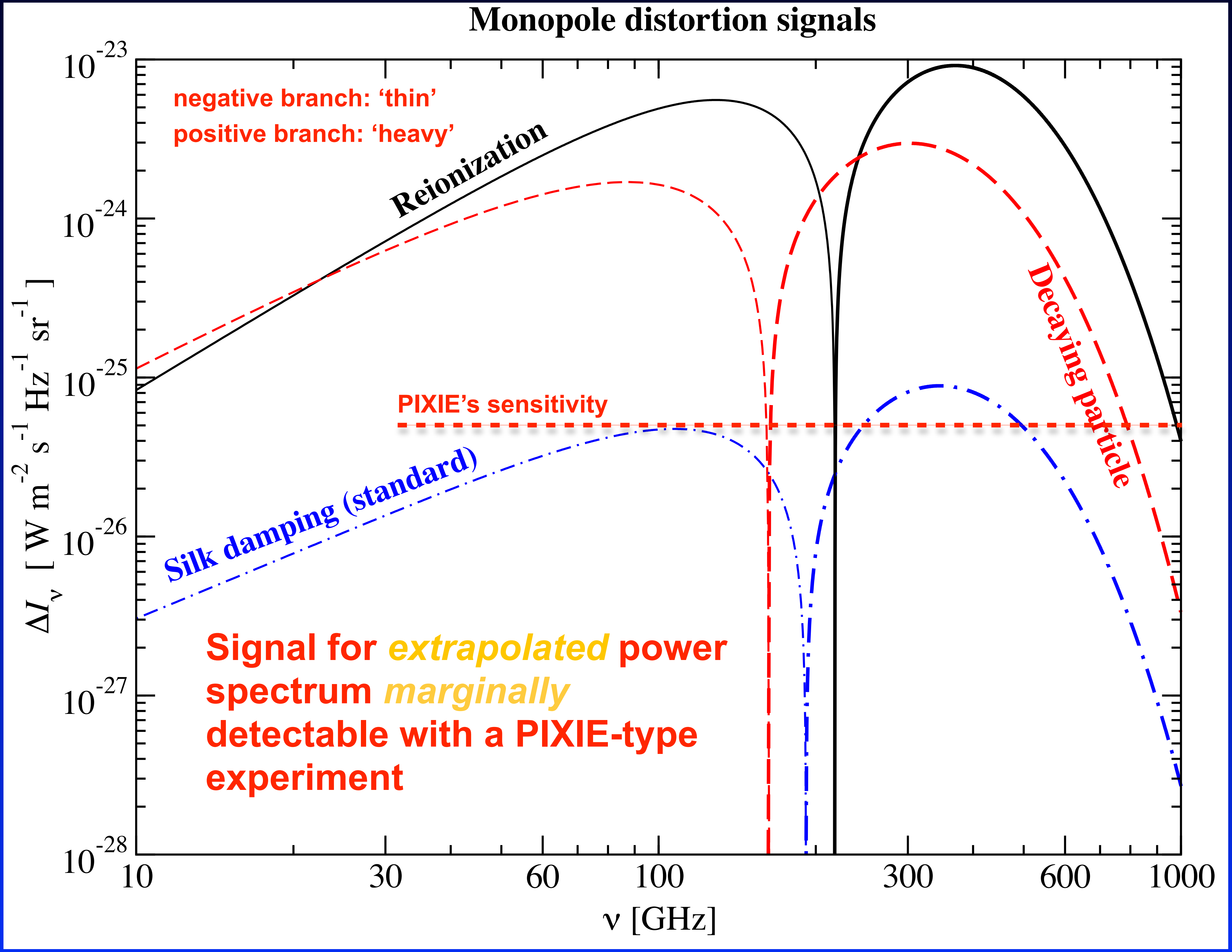
JC, Khatri & Sunyaev, 2012

Average CMB spectral distortions



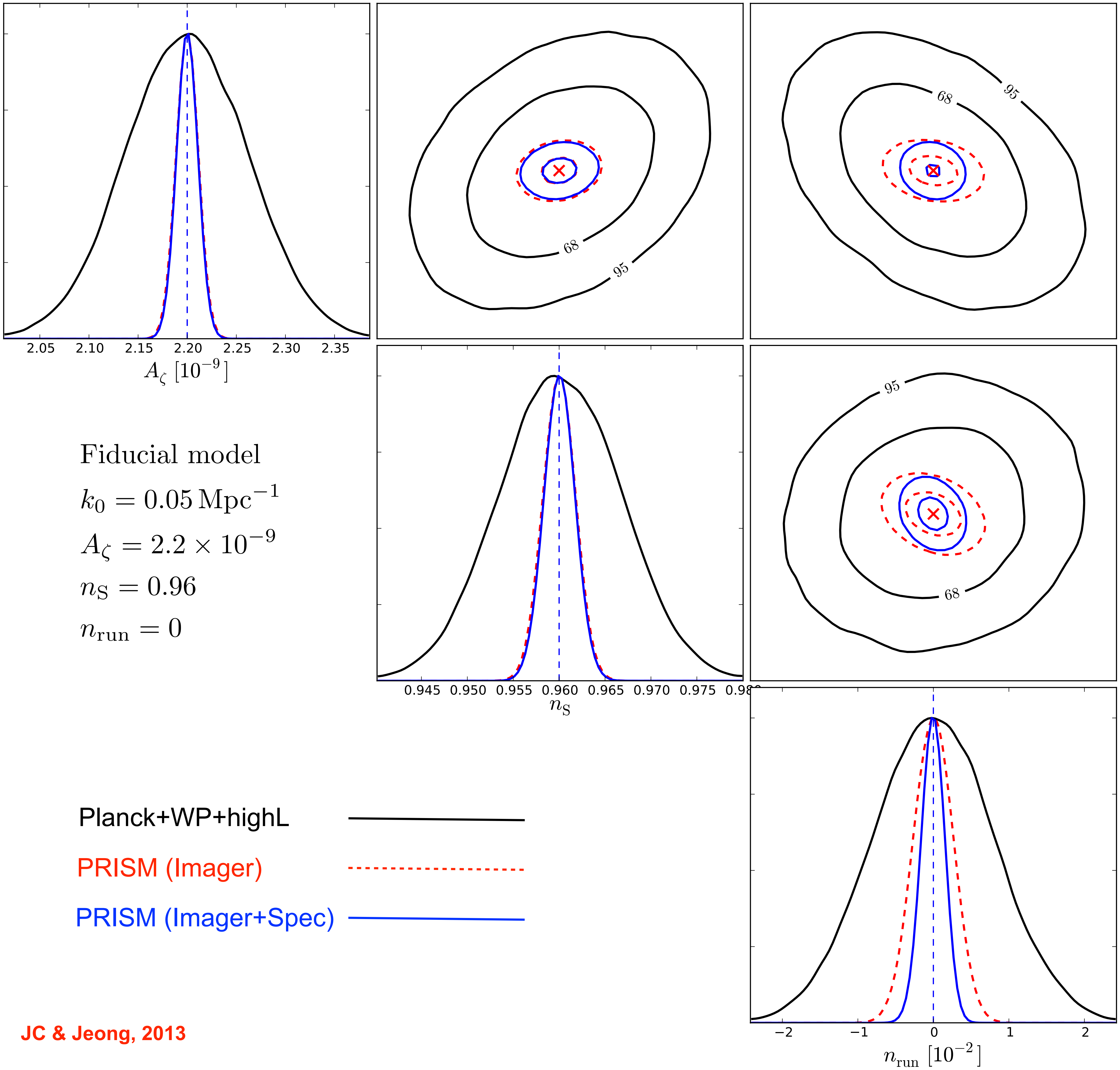
Absolute value of Intensity signal

Average CMB spectral distortions



Absolute value of Intensity signal

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



Fiducial model

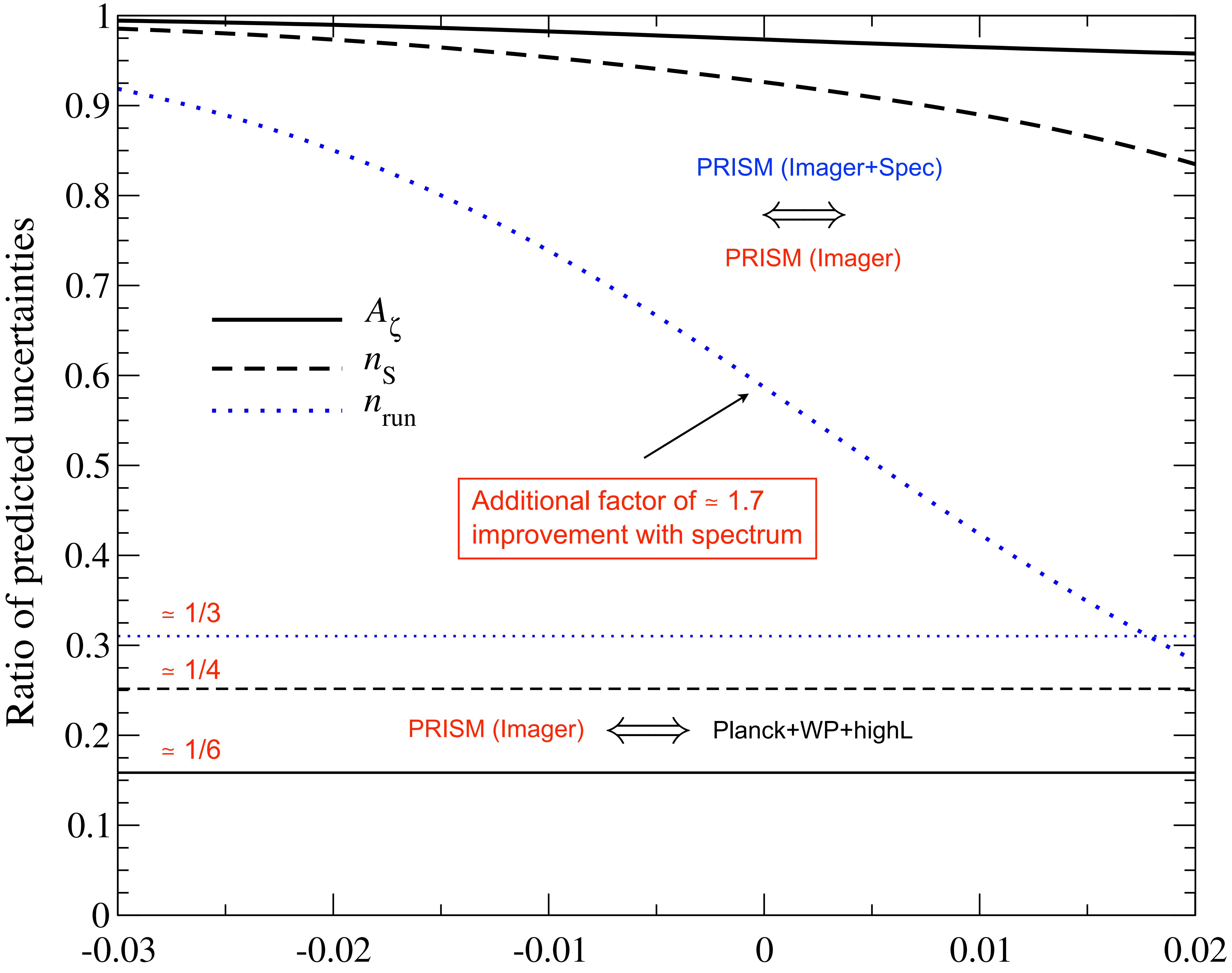
$k_0 = 0.05\,\mathrm{Mpc}^{-1}$

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

$n_\mathrm{S} = 0.96$

$n_\mathrm{run} = 0$

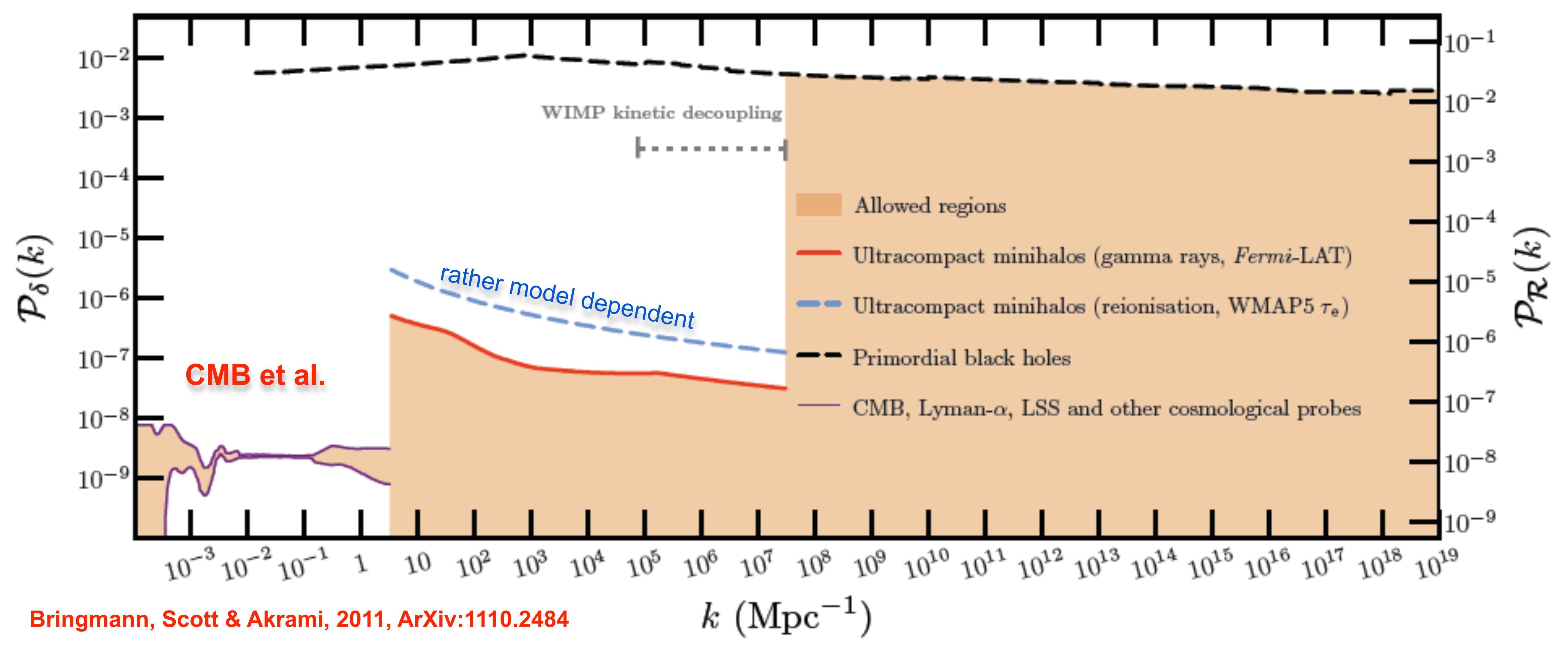
JC & Jeong, 2013



JC & Jeong, 2013

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

Distortions provide additional power spectrum constraints!

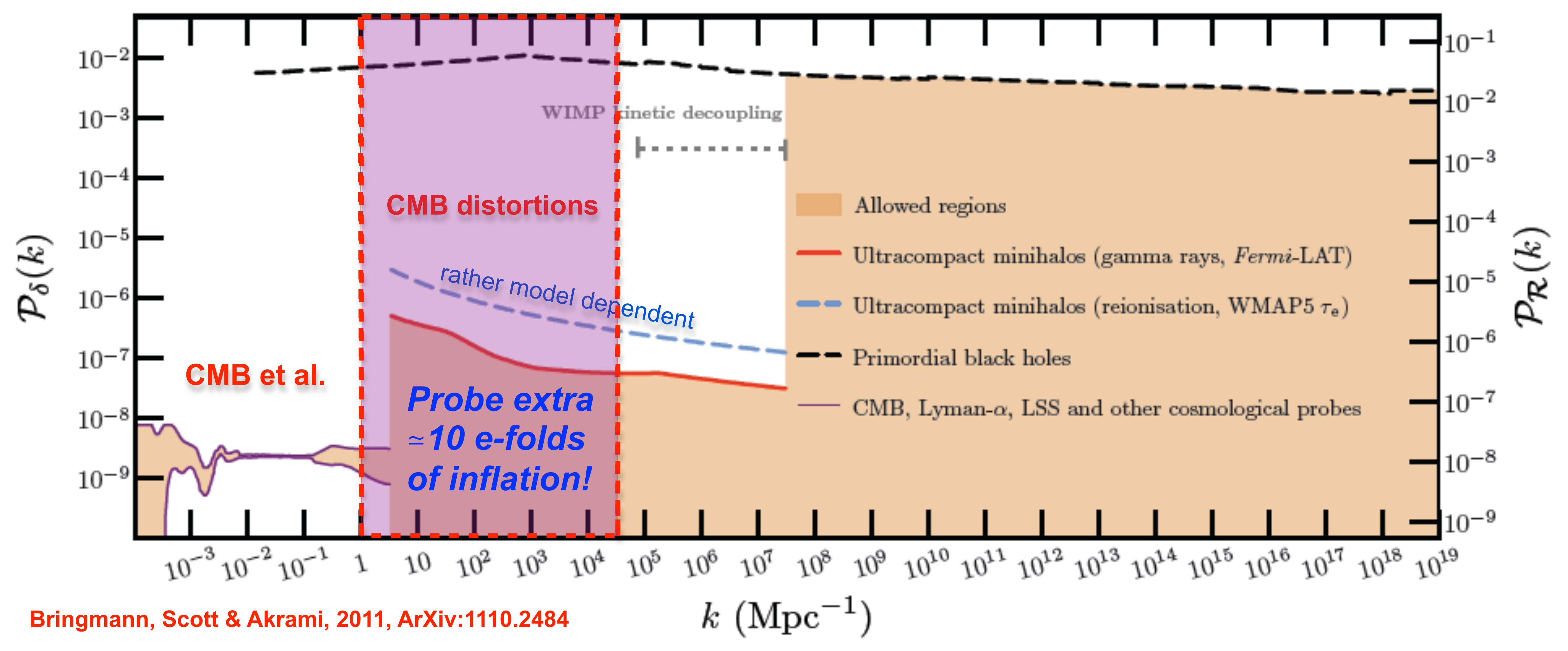


Bringmann, Scott & Akrami, 2011, ArXiv:1110.2484

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

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

Distortions provide additional power spectrum constraints!



CMB distortions

rather model dependent

CMB et al.

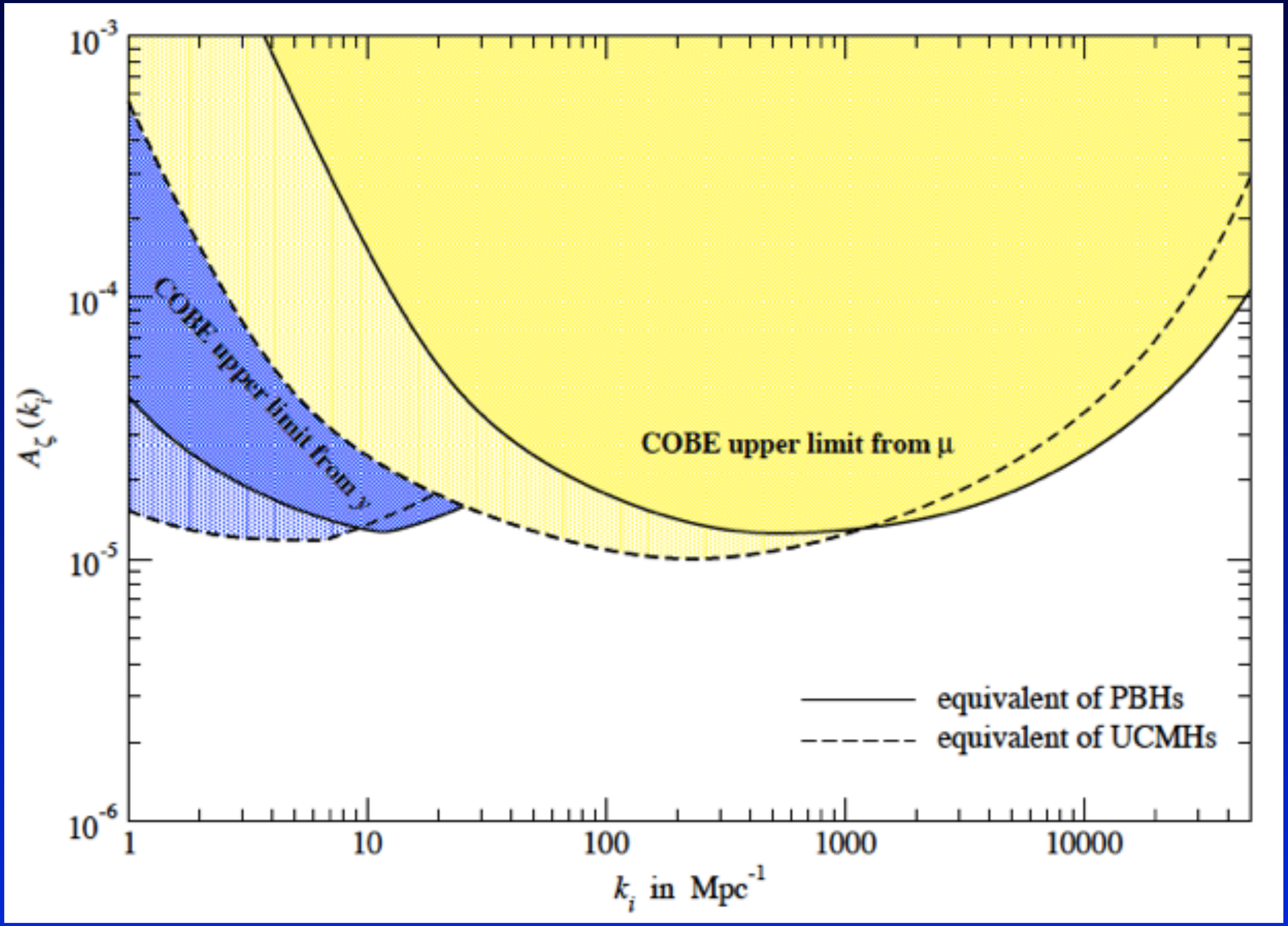
Probe extra ≃10 e-folds of inflation!

Bringmann, Scott & Akrami, 2011, ArXiv:1110.2484

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

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

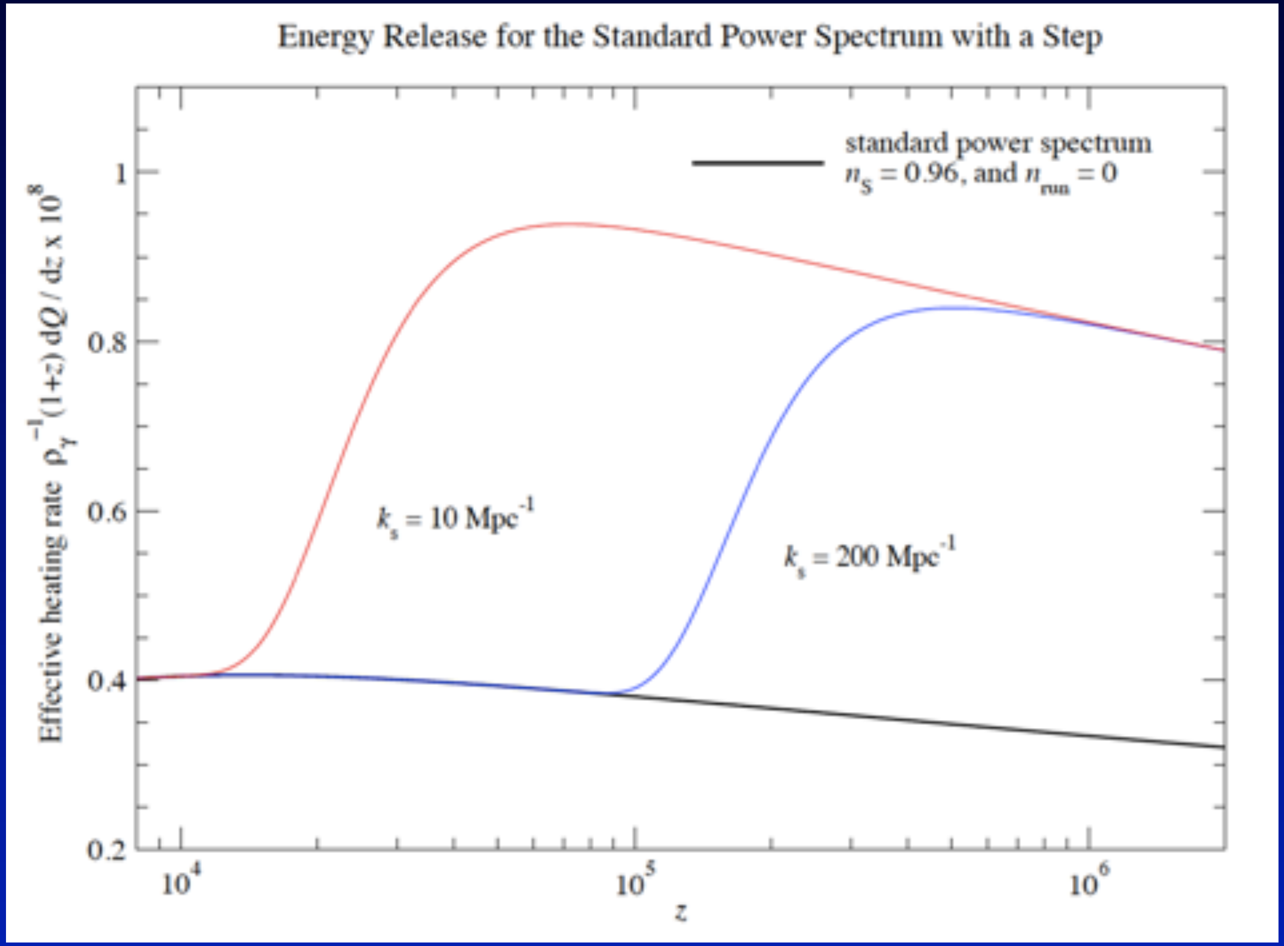
COBE/FIRAS limits on the amplitude of the small-scale power spectrum

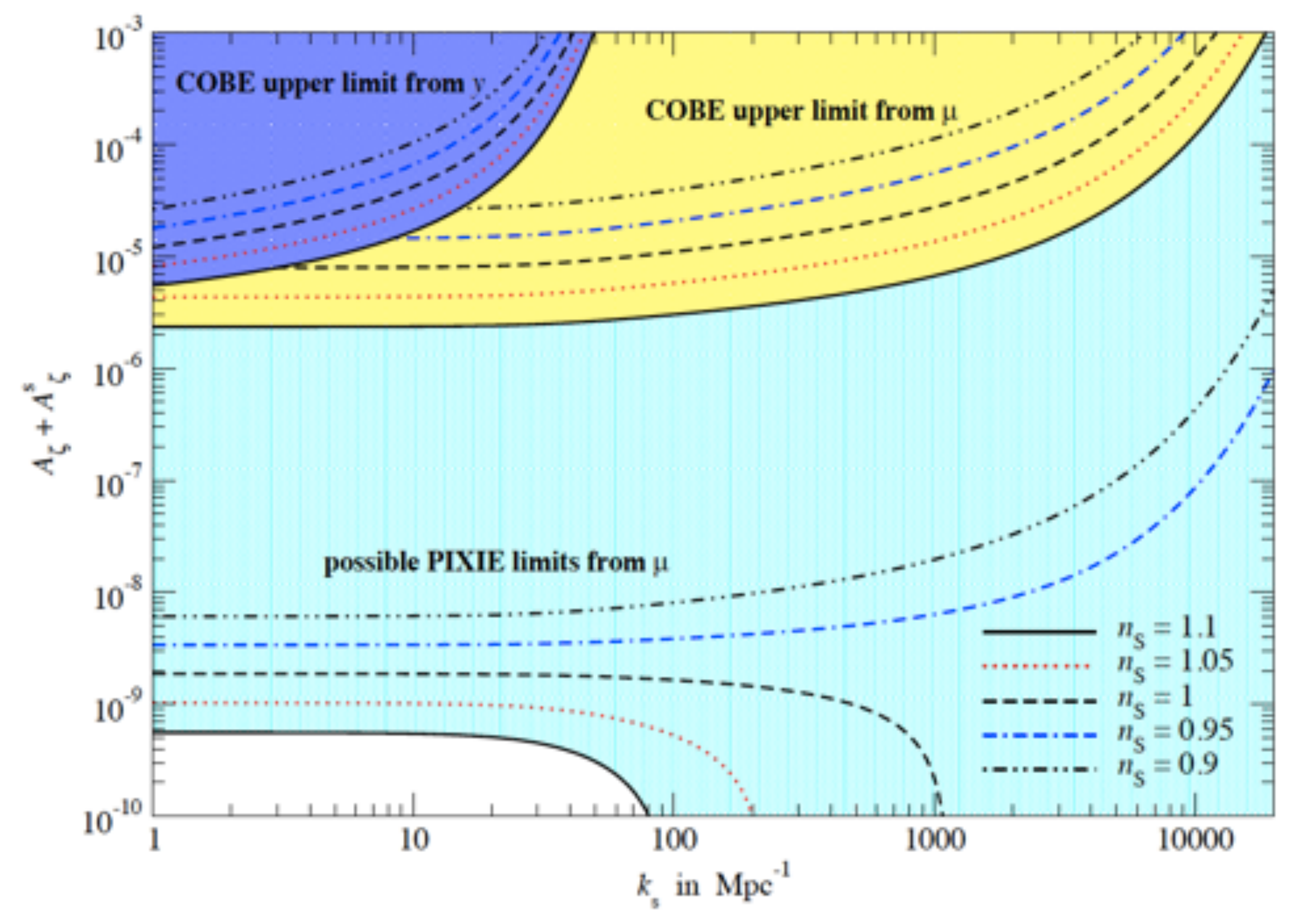


- ‘optimistic’ limit $P(k) < 8.4 \times 10^{-6}$
- Conservative constraint
- ~10^3 stronger that PBHs limit
- UCMHs limit still ~10 times stronger but more uncertain
- PIXIE could improve limit to $P(k) < 10^{-8}$
- constant power limit even $P(k) < 10^{-9}$

JC, Erickcek & Ben-Dayan, 2012

Primordial power spectra with ‘step’ at small scales





$$\mu \approx 2.2 \int_{k_{\min}}^{\infty} \mathcal{P}_\zeta(k) \left[\exp\left(-\frac{\hat{k}}{5400}\right) - \exp\left(-\left[\frac{\hat{k}}{31.6}\right]^2\right)\right] \mathrm{d}\ln k$$

$$y \approx 0.4 \int_{k_{\min}}^{\infty} \mathcal{P}_\zeta(k) \exp\left(-\left[\frac{\hat{k}}{31.6}\right]^2\right) \mathrm{d}\ln k,$$

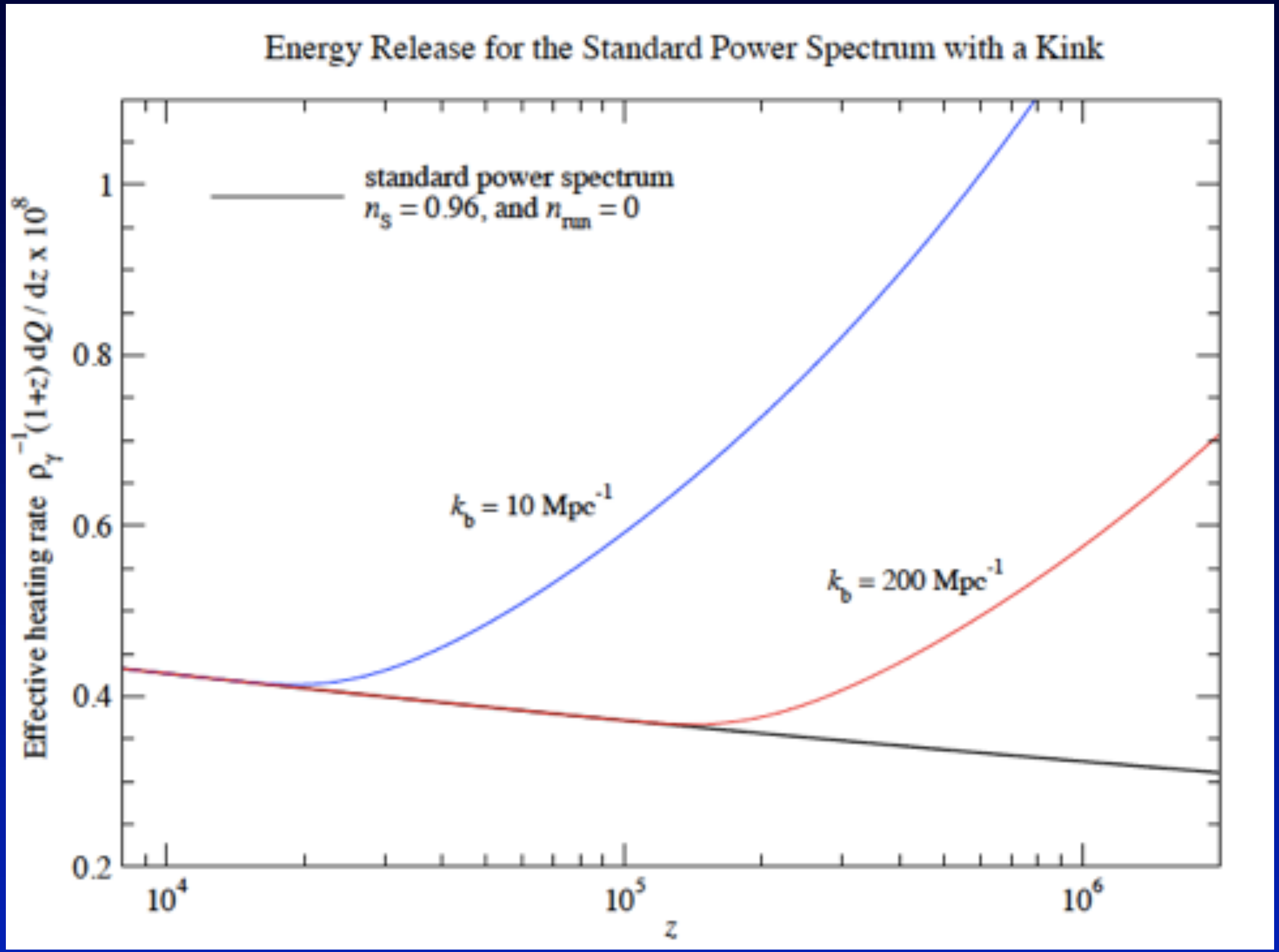
Integral constraint on small-scale power

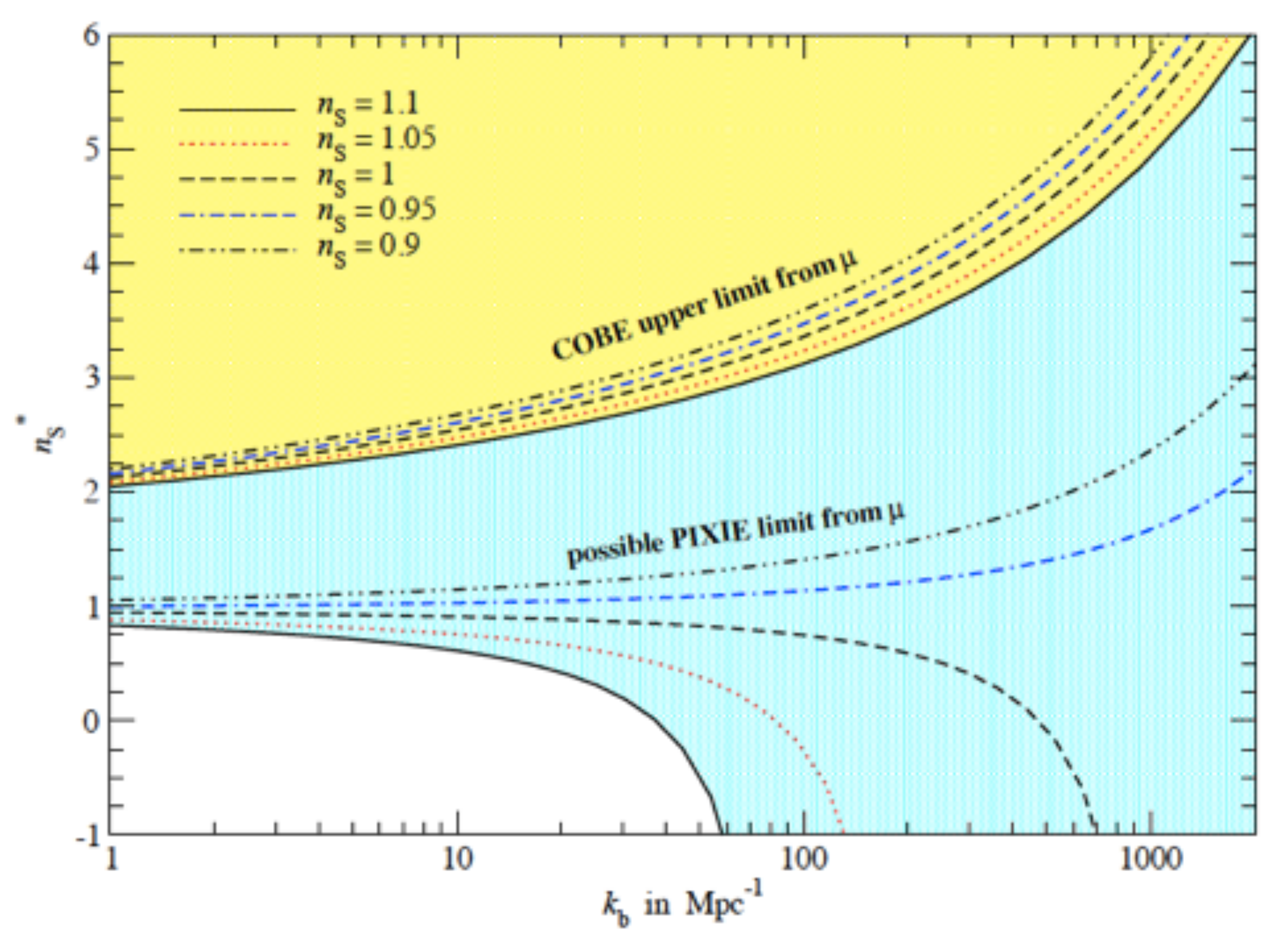
- simple formula to compute the effective *μ* and *y*-parameter
- COBE/FIRAS ⇒ amplitude of the

  small-scale power spectrum can’t change by more than ~2x10^{-6} at wavenumber k ~ 1 Mpc^{-1}

JC, Erickcek & Ben-Dayan, 2012

Primordial power spectra with ‘bend’ at small scales





$$\mu \approx 2.2 \int_{k_{\rm min}}^{\infty} \mathcal{P}_\zeta(k) \left[\exp\left(-\frac{\hat{k}}{5400}\right) - \exp\left(-\left[\frac{\hat{k}}{31.6}\right]^2\right)\right] \mathrm{d}\ln k$$

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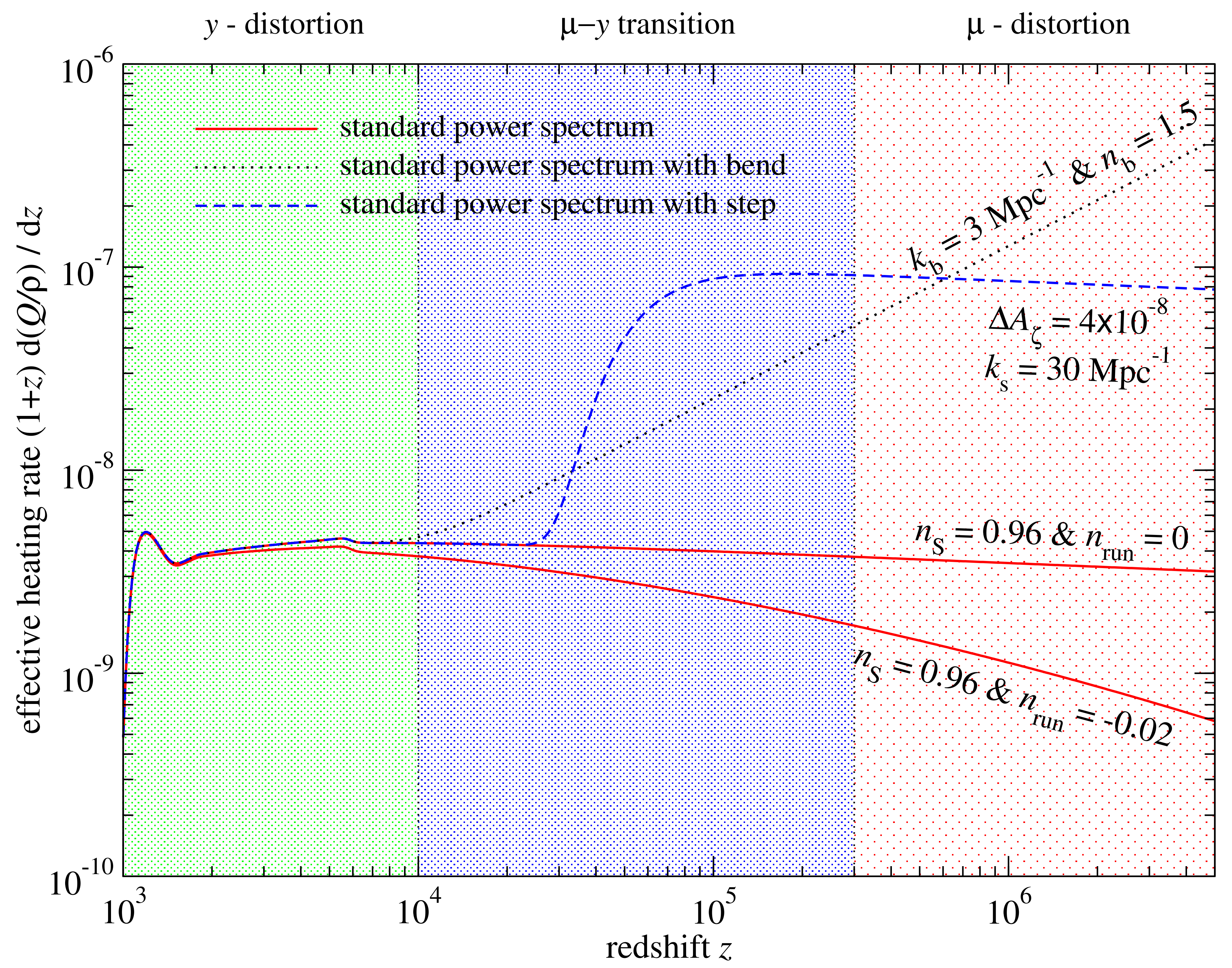
Integral constraint on small-scale power

- COBE/FIRAS ⇒ spectral index at $k \sim 1\,\mathrm{Mpc}^{-1}$ cannot change by more than Δn~1
- PIXIE will place very tight constraints on such models

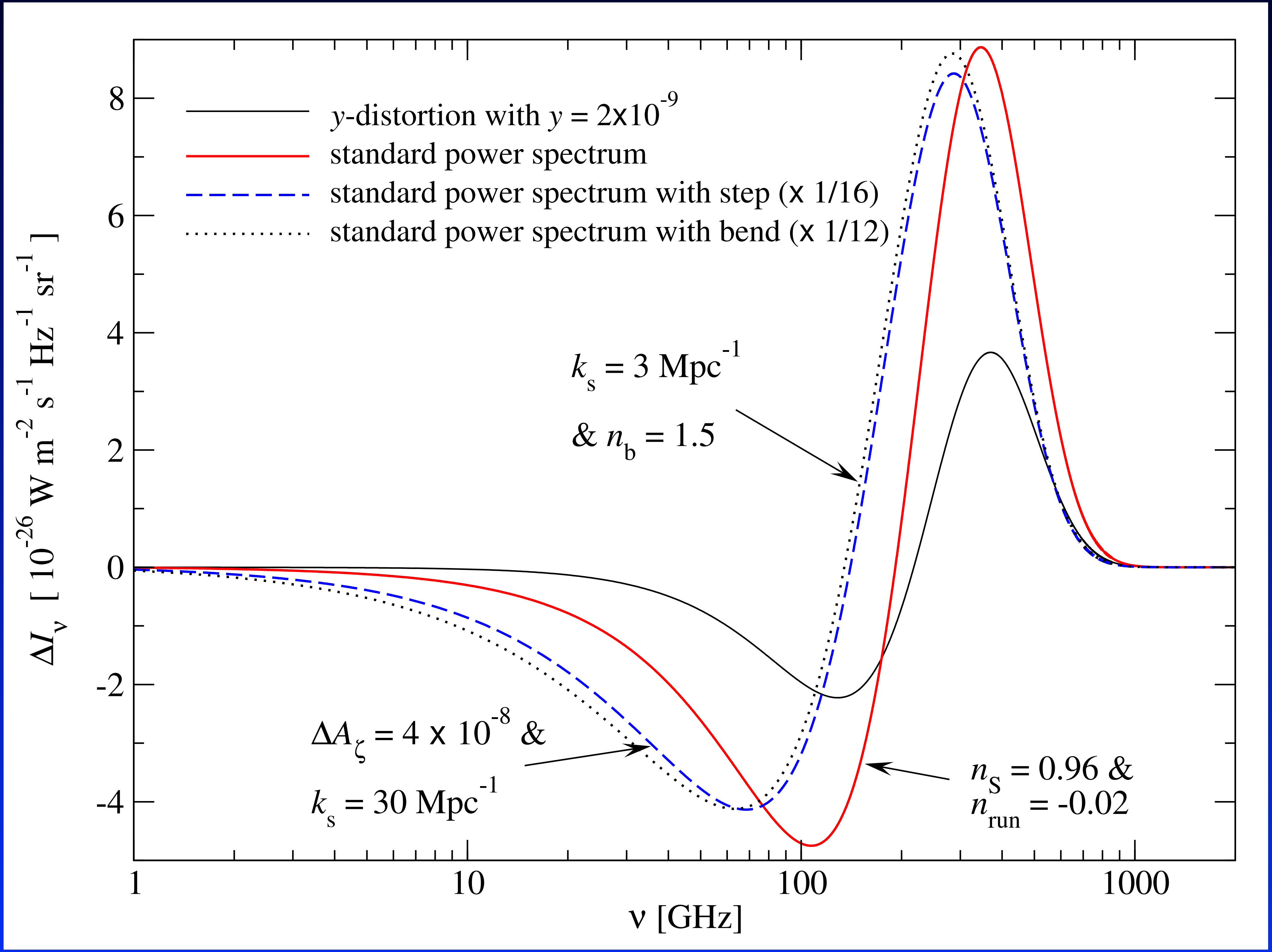
JC, Erickcek & Ben-Dayan, 2012

Probing the small-scale power spectrum



JC, 2013, Arxiv:1304.6120

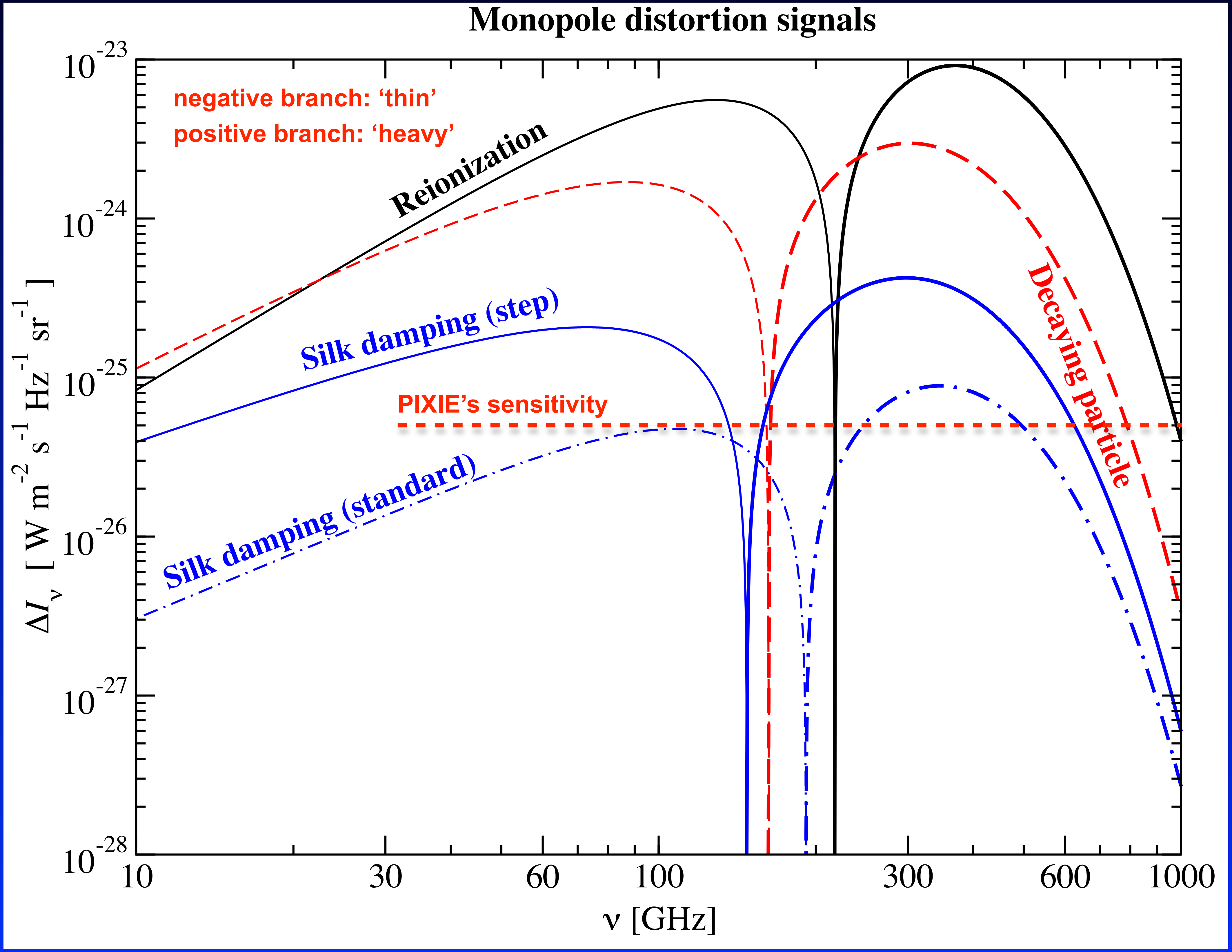
Probing the small-scale power spectrum



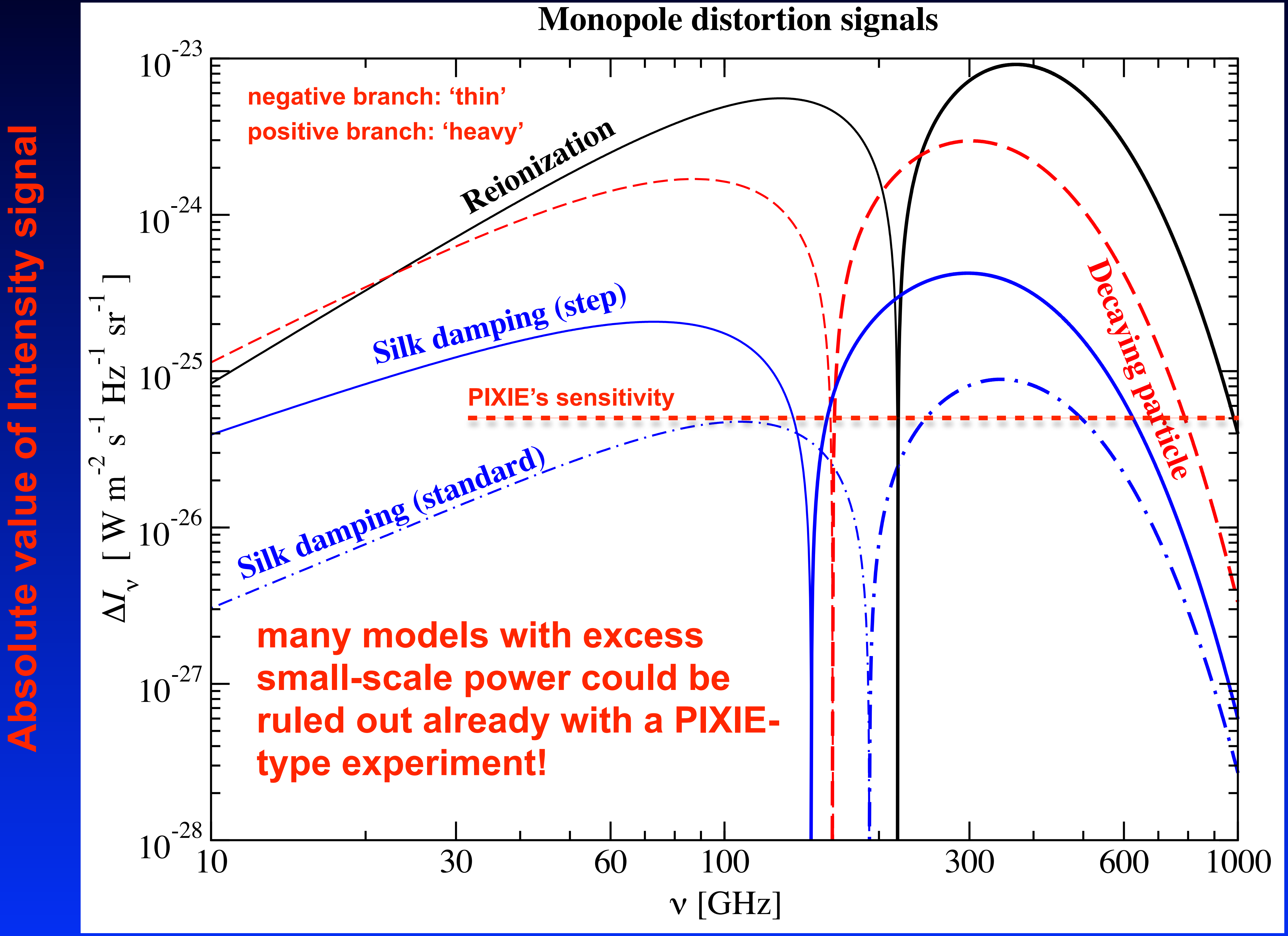
JC, 2013, Arxiv:1304.6120

Average CMB spectral distortions

Absolute value of Intensity signal

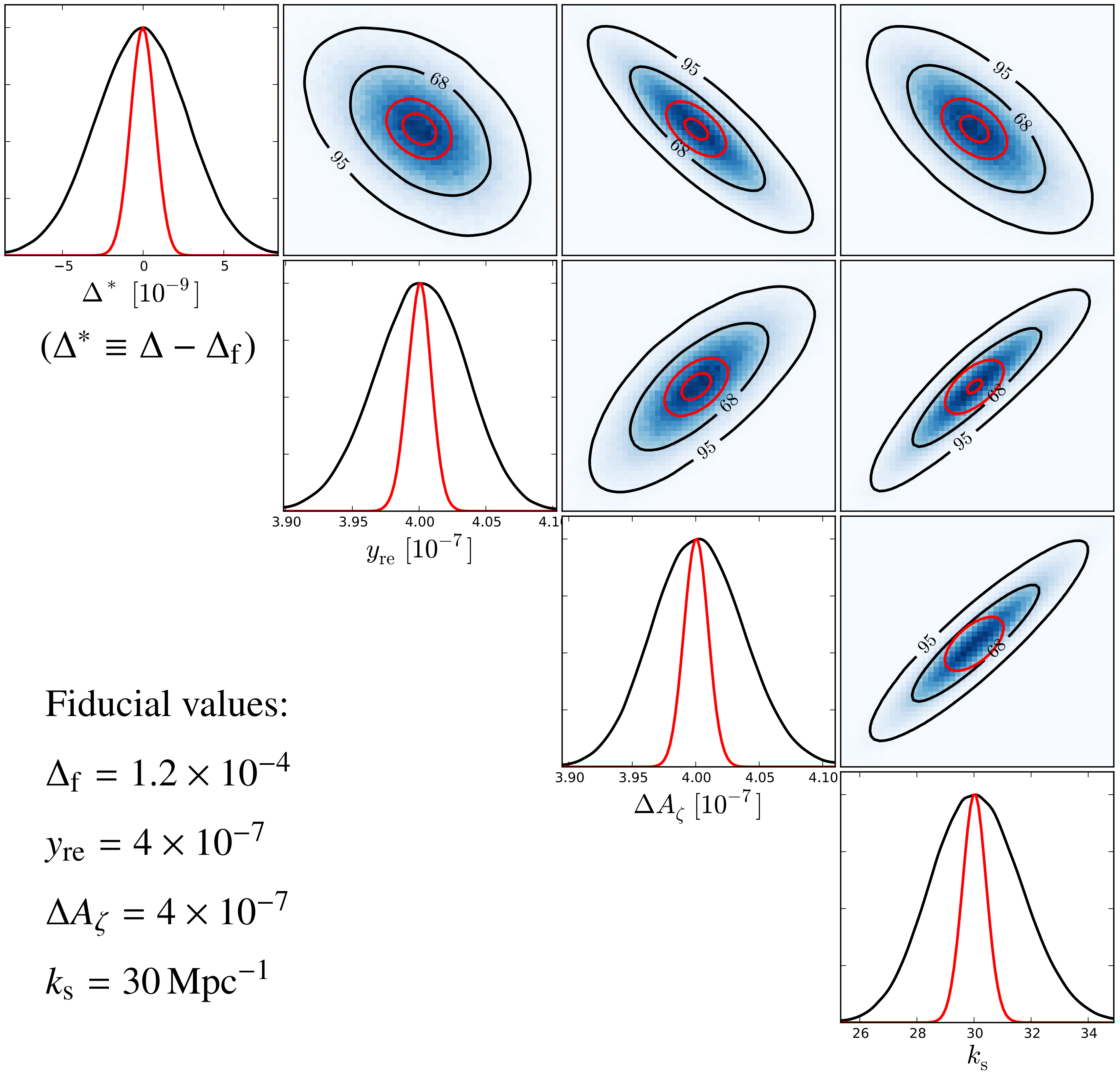


Average CMB spectral distortions



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

Probing the small-scale power spectrum



Fiducial values:

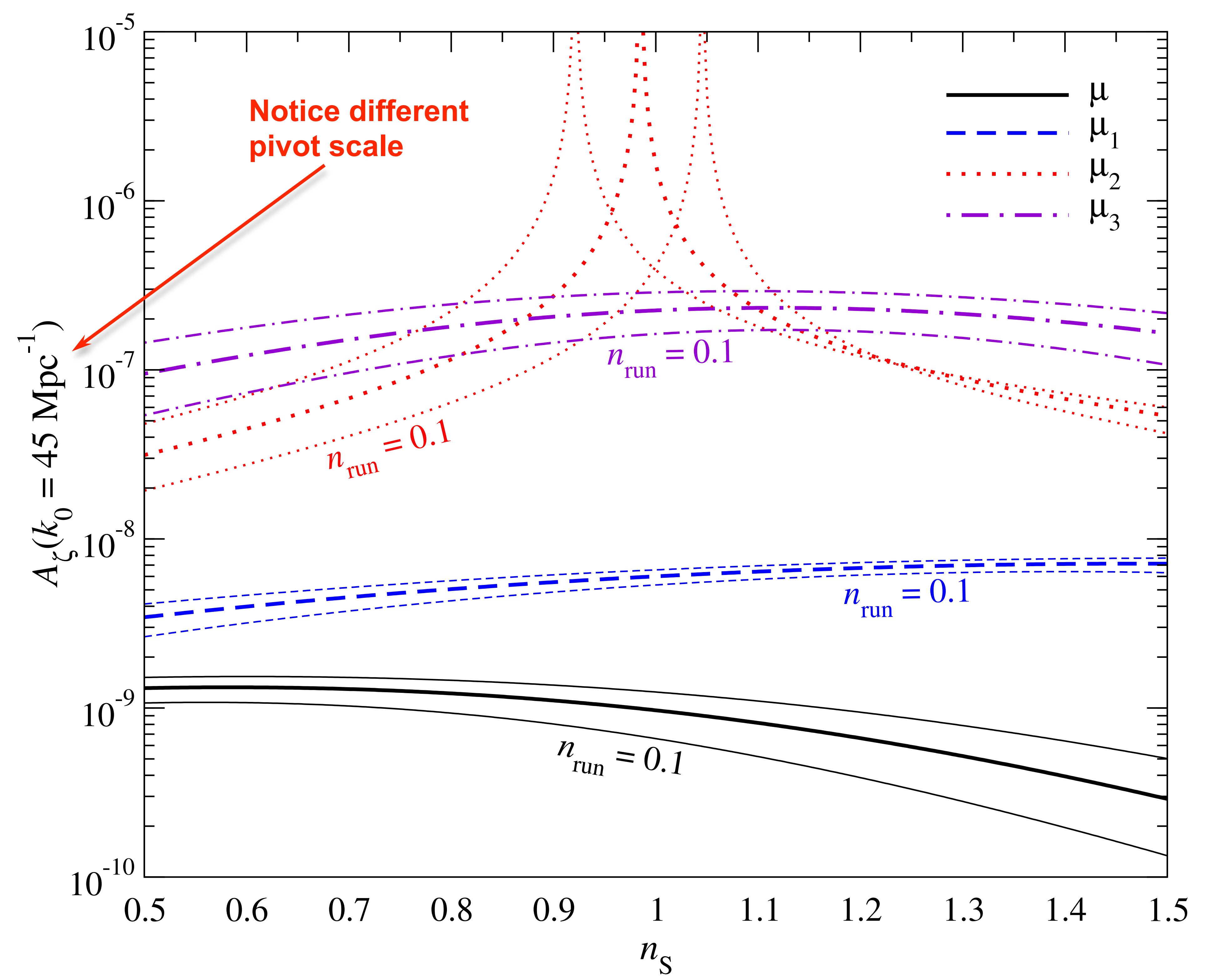
$\Delta_\mathrm{f} = 1.2 \times 10^{-4}$

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

$\Delta A_\zeta = 4 \times 10^{-7}$

$k_\mathrm{s} = 30\,\mathrm{Mpc}^{-1}$

Dissipation scenario: 1σ-detection limits for PIXIE

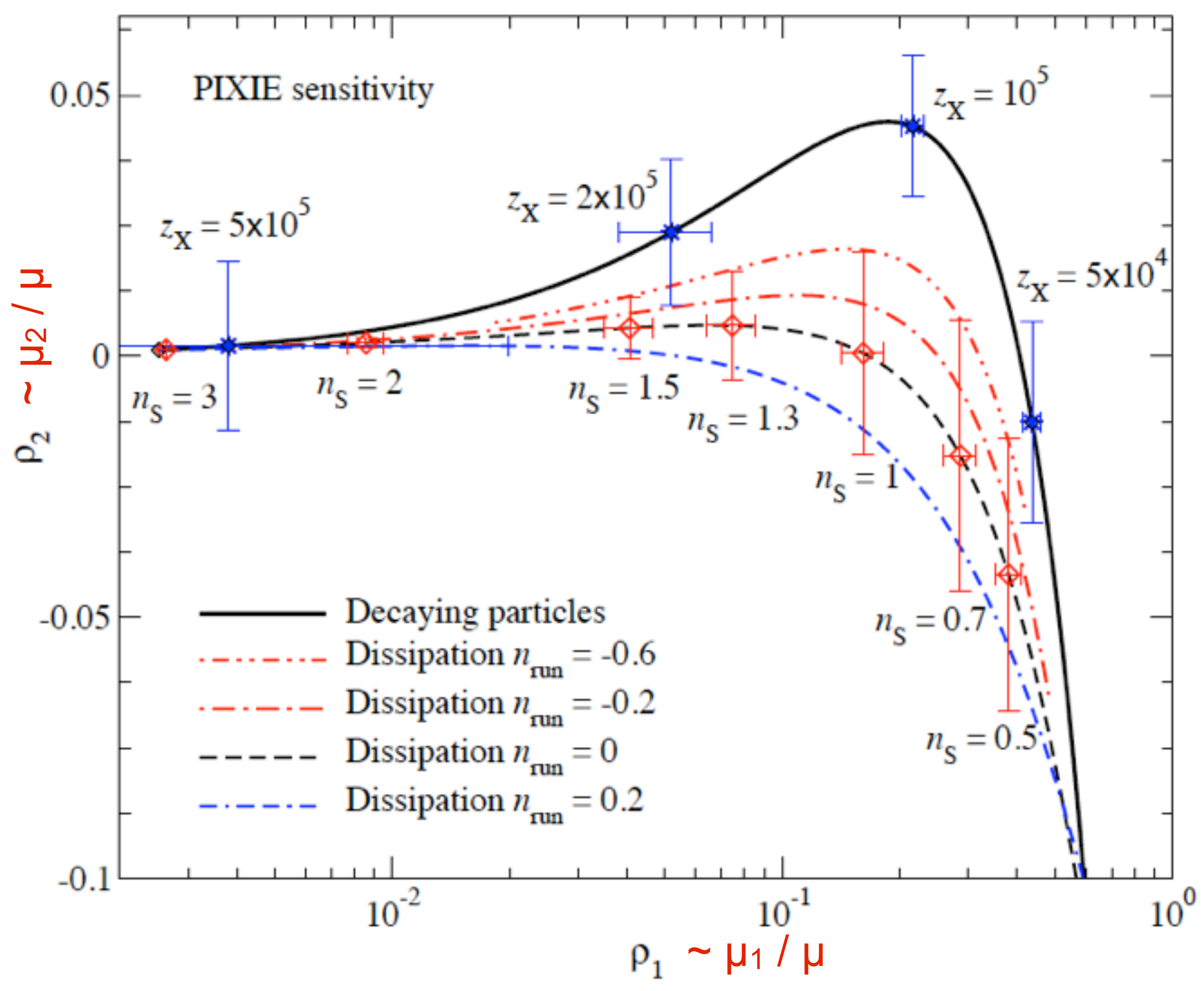


Notice different pivot scale

JC & Jeong, 2013

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

Distinguishing dissipation and decaying particle scenarios

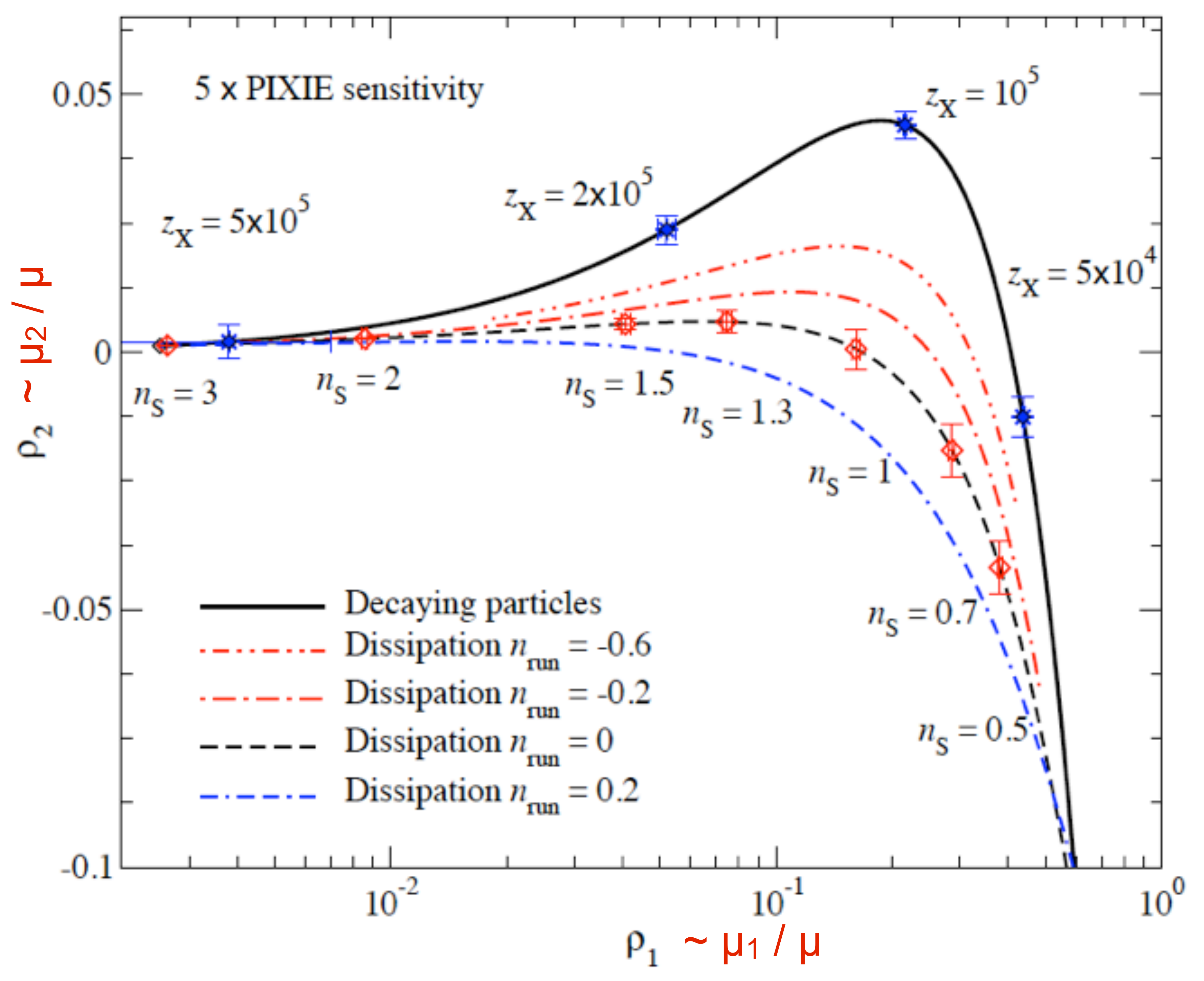


- measurement of μ, μ_1 & μ_2
- trajectories of decaying particle and dissipation scenarios differ!
- scenarios can in principle be distinguished

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

JC & Jeong, 2013

Distinguishing dissipation and decaying particle scenarios



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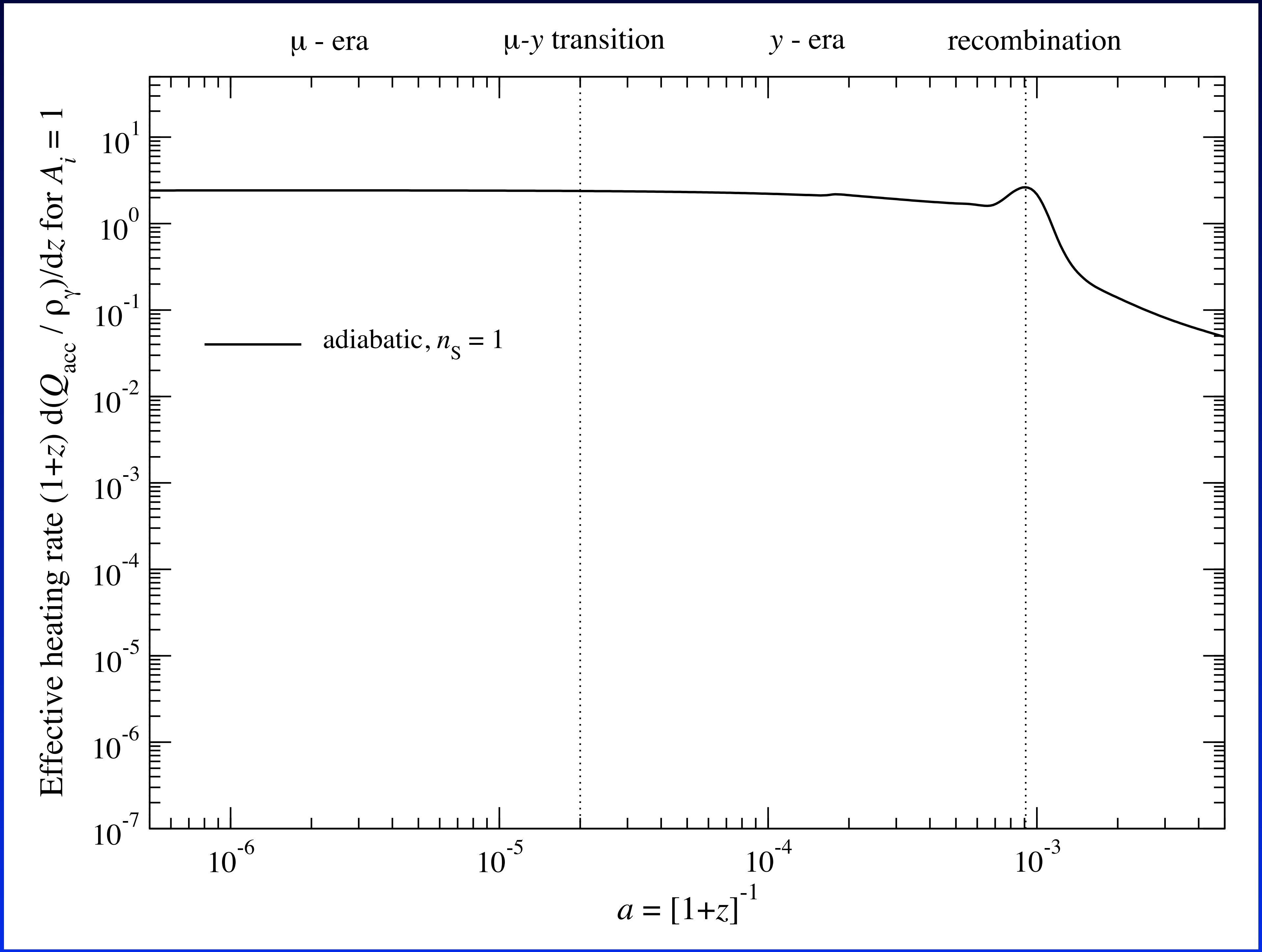
JC & Jeong, 2013

Dependence of heating rate on the perturbation type

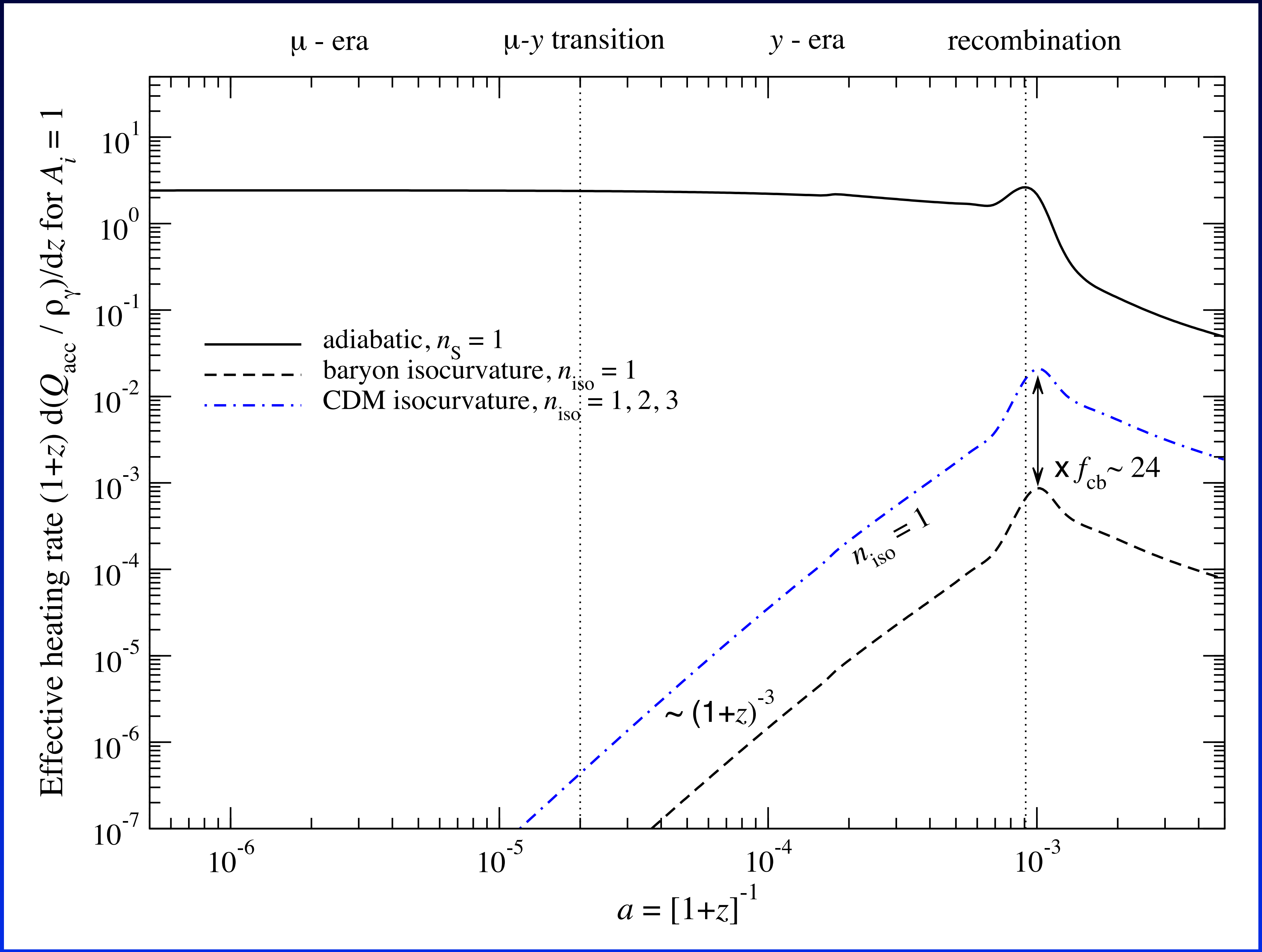


- Adiabatic modes: heating rate ~ 1/z at high z

JC & Grin, 2013

$$P_i(k) = 2\pi^2 A_i k^{-3} (k/k_0)^{n_i - 1}$$

Dependence of heating rate on the perturbation type



- Adiabatic modes: heating rate ~ $1/z$ at high z
- baryon/CDM iso-curvature modes:

  $A \sim k/k_{\rm eq}$

  during radiation dominated epoch

JC & Grin, 2013

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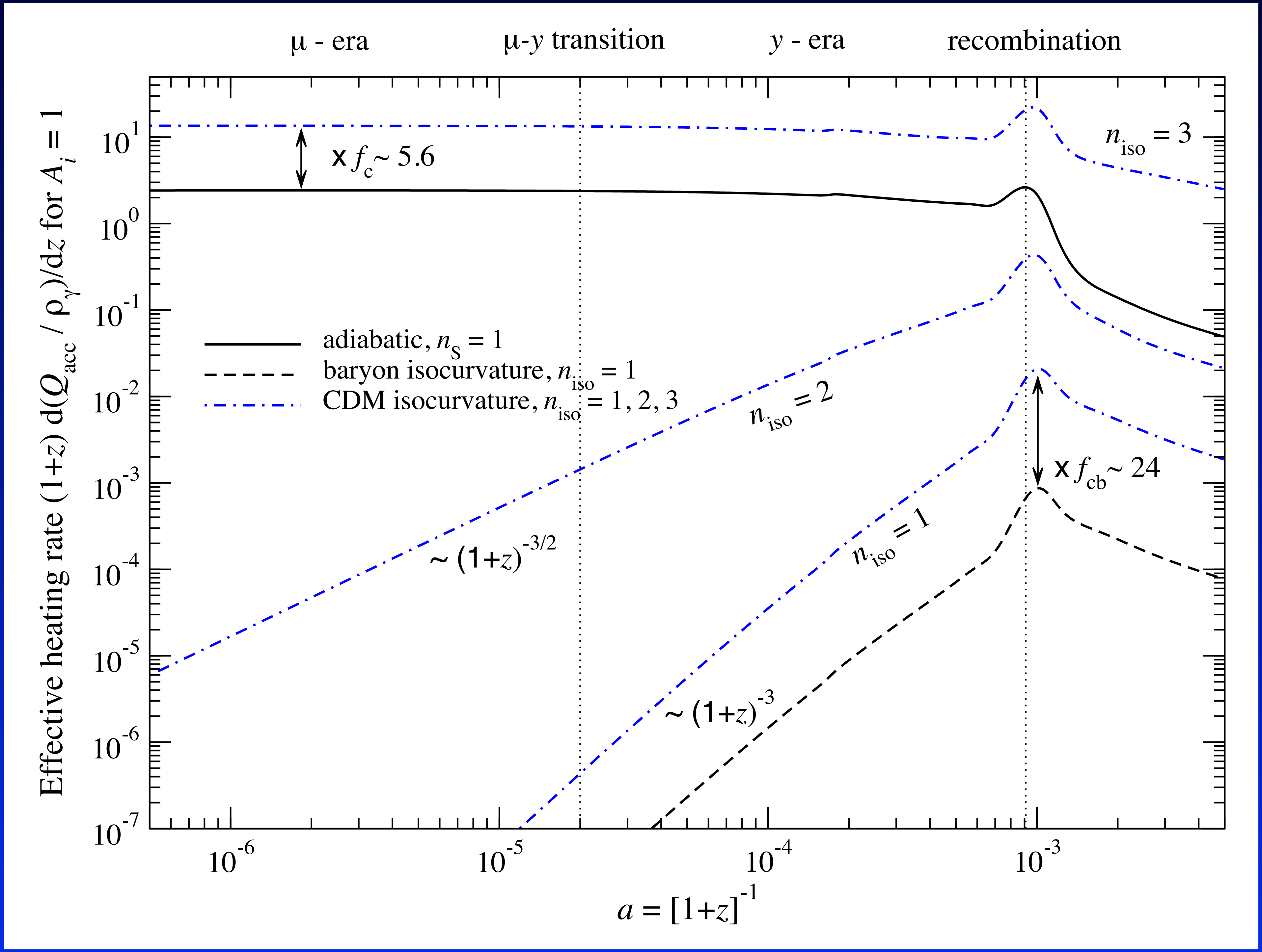
Dependence of heating rate on the perturbation type



- Adiabatic modes: heating rate ~ 1/*z* at high *z*
- baryon/CDM iso-curvature modes:

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  during radiation dominated epoch
- $n_{iso} \sim 3 \Rightarrow$ heating rate ~ 1/*z*

JC & Grin, 2013

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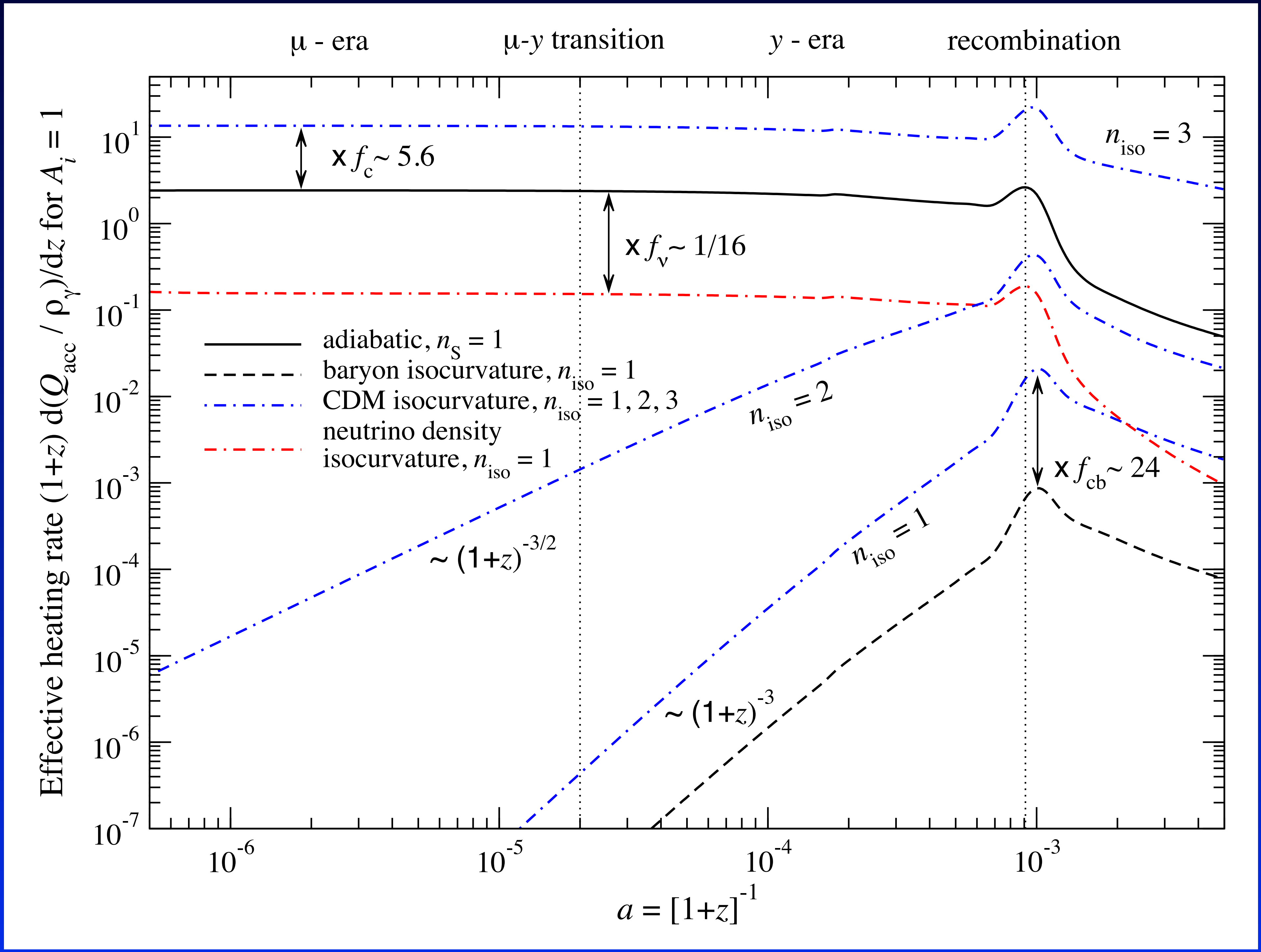
Dependence of heating rate on the perturbation type



- Adiabatic modes: heating rate ~ 1/z at high z
- baryon/CDM isocurvature modes:

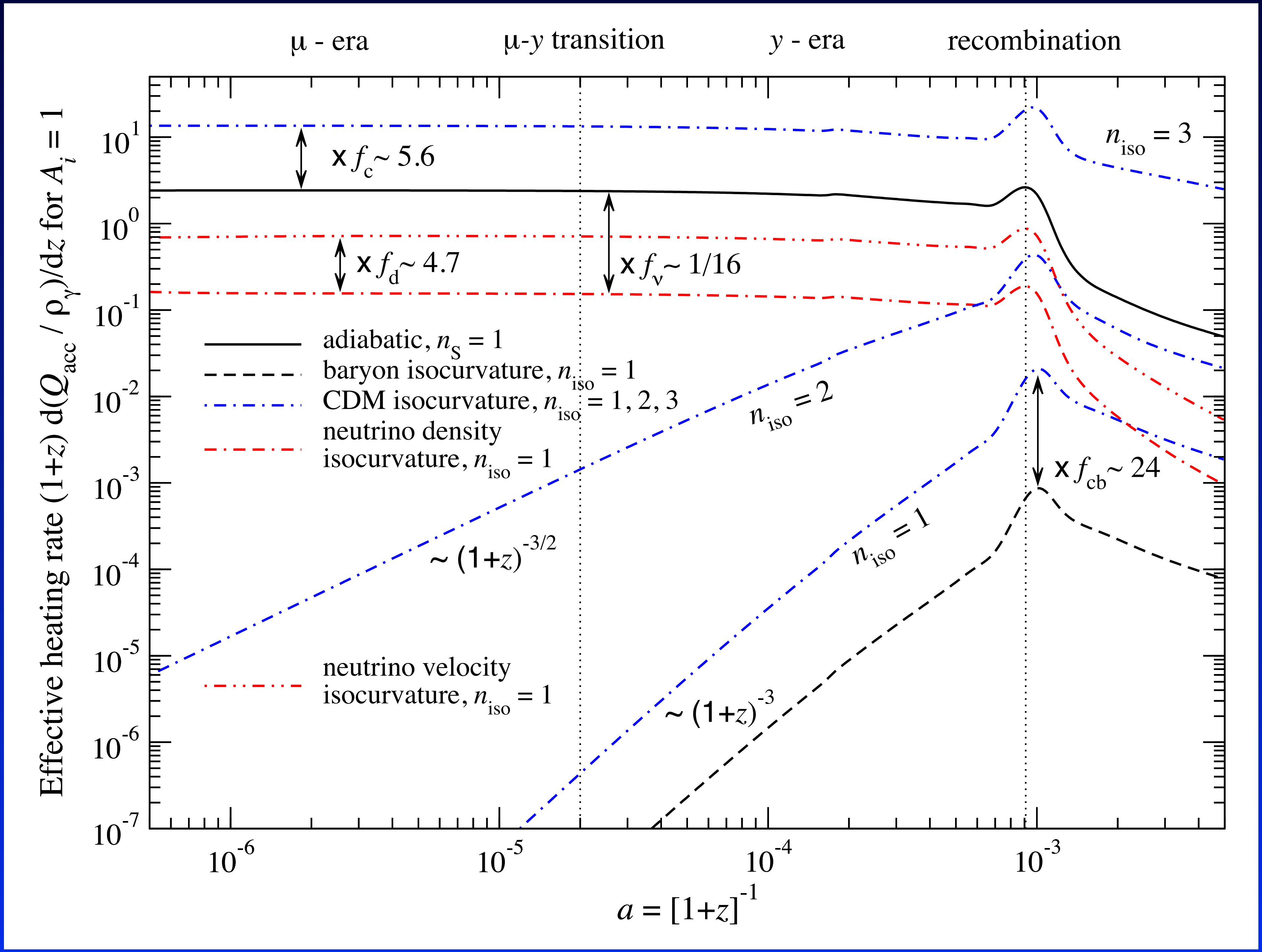
  $A \sim k/k_{\rm eq}$

  during radiation dominated epoch
- $n_{\rm iso} \sim 3 \Rightarrow$ heating rate ~ 1/z
- neutrino isocurvature modes very similar to adiabatic modes

JC & Grin, 2013

$$P_i(k) = 2\pi^2 A_i k^{-3} (k/k_0)^{n_i - 1}$$

Dependence of heating rate on the perturbation type



- Adiabatic modes: heating rate ~ 1/*z* at high *z*
- baryon/CDM iso-curvature modes:

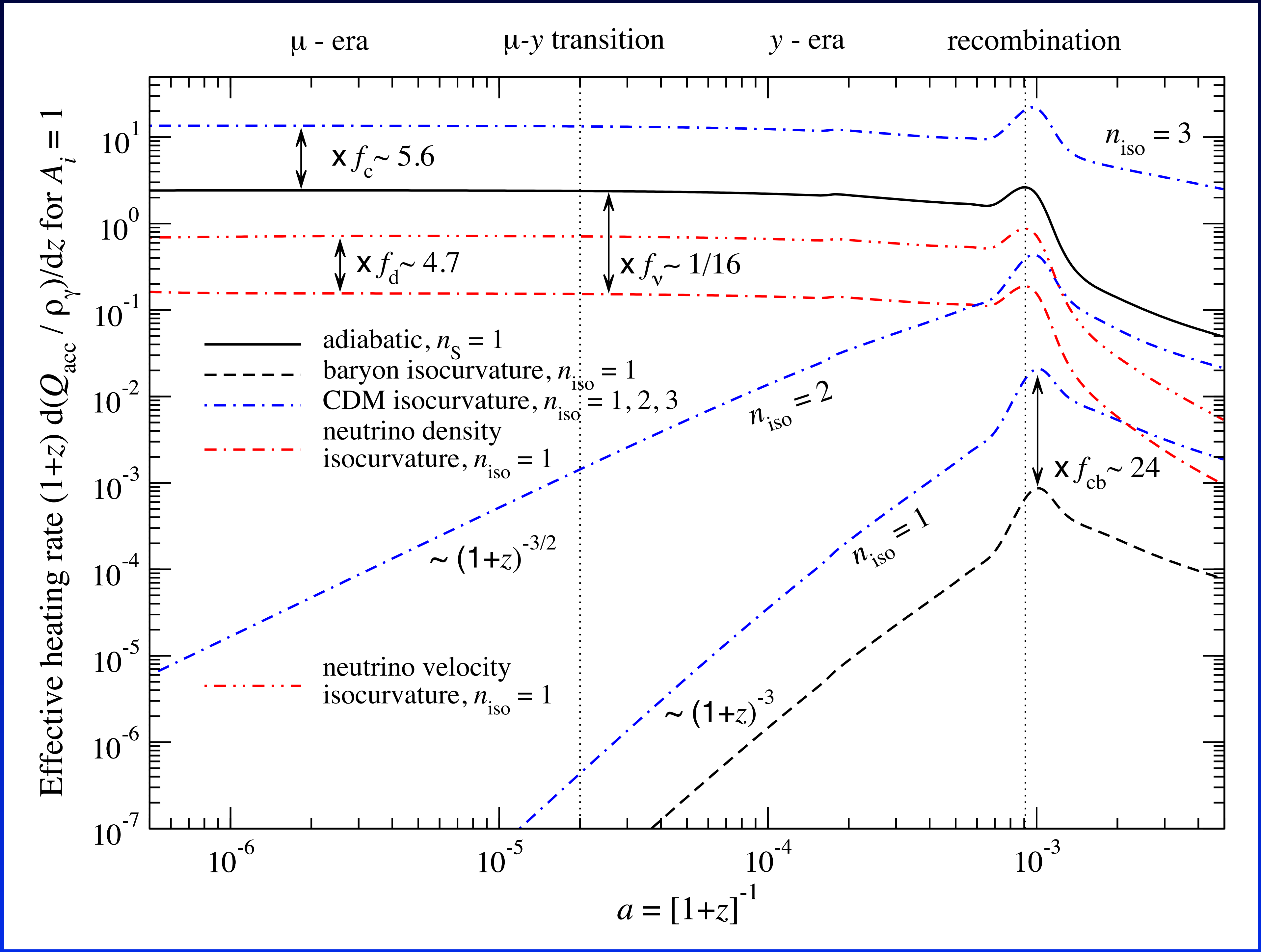
  A ~ *k*/k_{eq}

  during radiation dominated epoch
- n_{iso} ~ 3 ⇒ heating rate ~ 1/*z*
- neutrino iso-curvature modes very similar to adiabatic modes

JC & Grin, 2013

$$P_i(k) = 2\pi^2 A_i k^{-3} (k/k_0)^{n_i - 1}$$

Dependence of heating rate on the perturbation type



- Adiabatic modes: heating rate ~ 1/*z* at high *z*
- baryon/CDM iso-curvature modes:

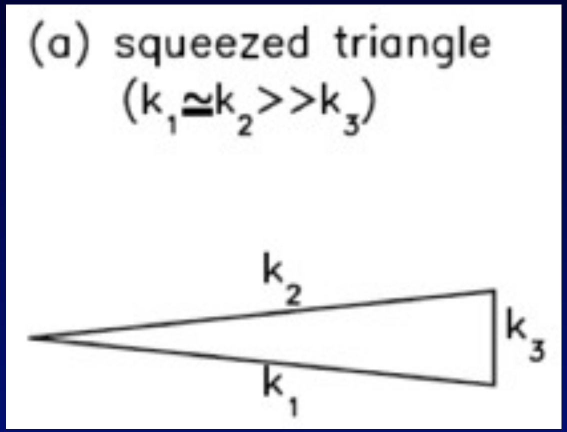
  $A \sim k/k_{\rm eq}$

  during radiation dominated epoch
- $n_{\rm iso} \sim 3 \Rightarrow$ heating rate ~ 1/*z*
- neutrino iso-curvature modes very similar to adiabatic modes
- compensated isocurvature modes: *practically no heating*

JC & Grin, 2013

$$P_i(k) = 2\pi^2 A_i k^{-3} (k/k_0)^{n_i - 1}$$

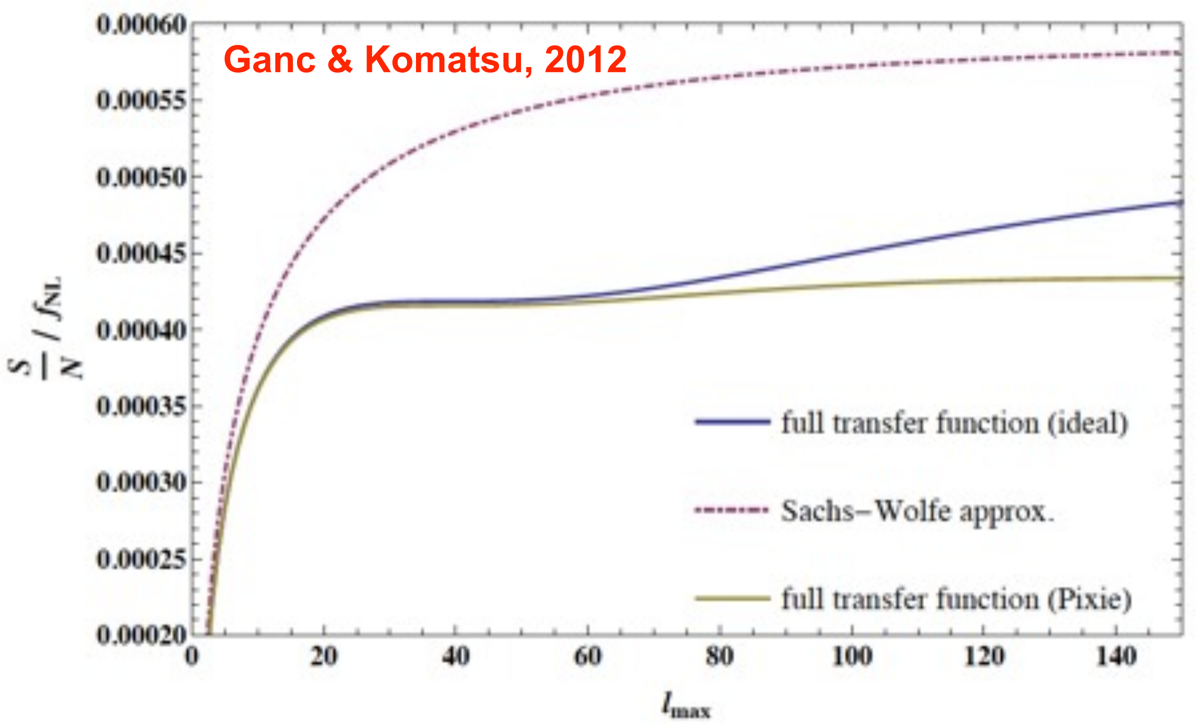
Anisotropic μ-distortions from non-Gaussianity



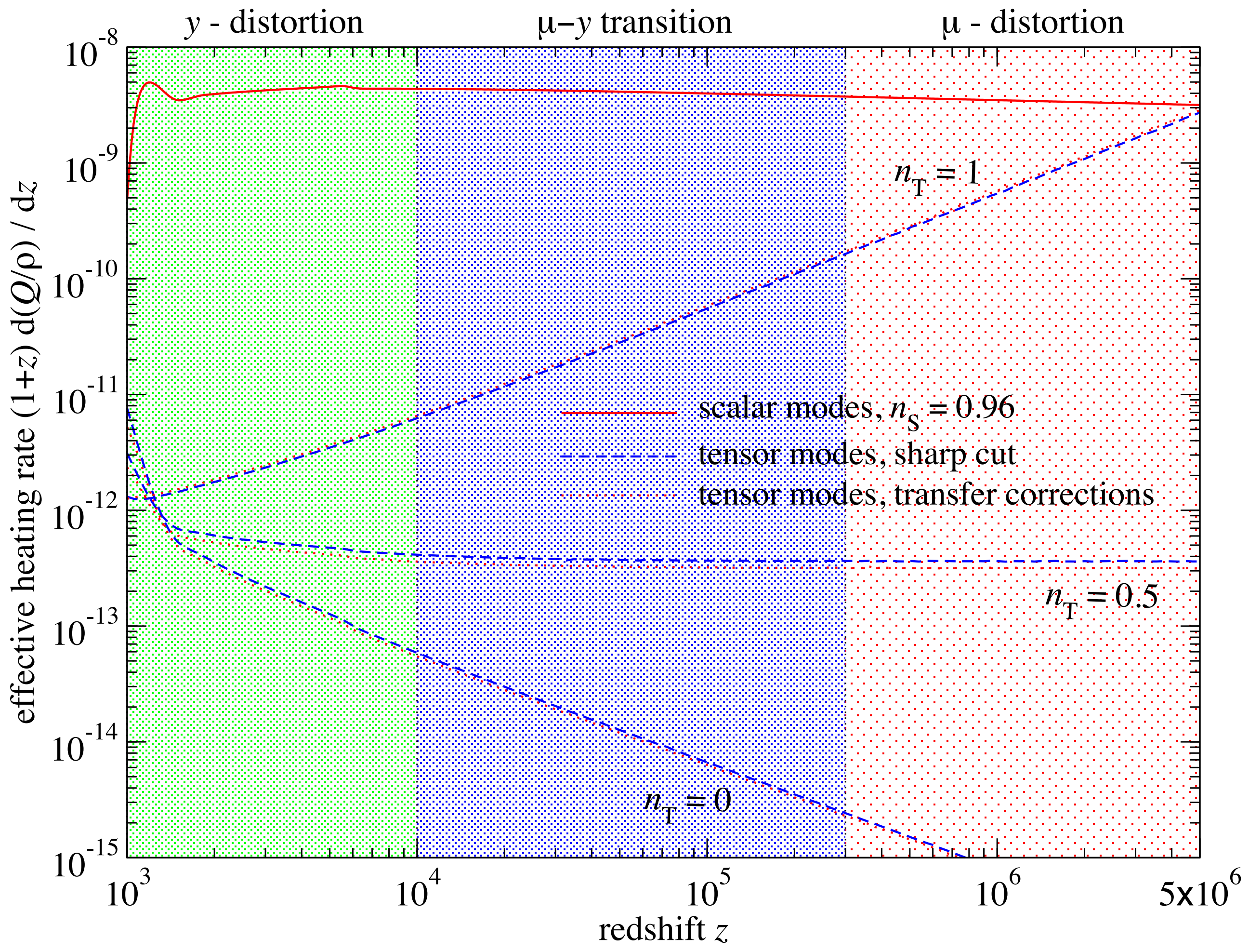
- Modes that dissipate energy have $k_1 \approx k_2 >> k_3$
- Non-Gaussian power spectrum → presence of positive long-wavelength mode enhances small-scale power
- More small-scale power → larger μ-distortion
- → Spatially varying μ-distortion caused by non-Gaussianity!
  (Pajer & Zaldarriaga, 2012; Ganc & Komatsu, 2012)
- Non-vanishing μ-T correlation at large scales
- Might be detectable with PIXIE-type experiment for $f_{NL} > 10^3$

Requirements

- precise cross-calibration of frequency channels
- higher angular resolution does not improve cumulative S/N

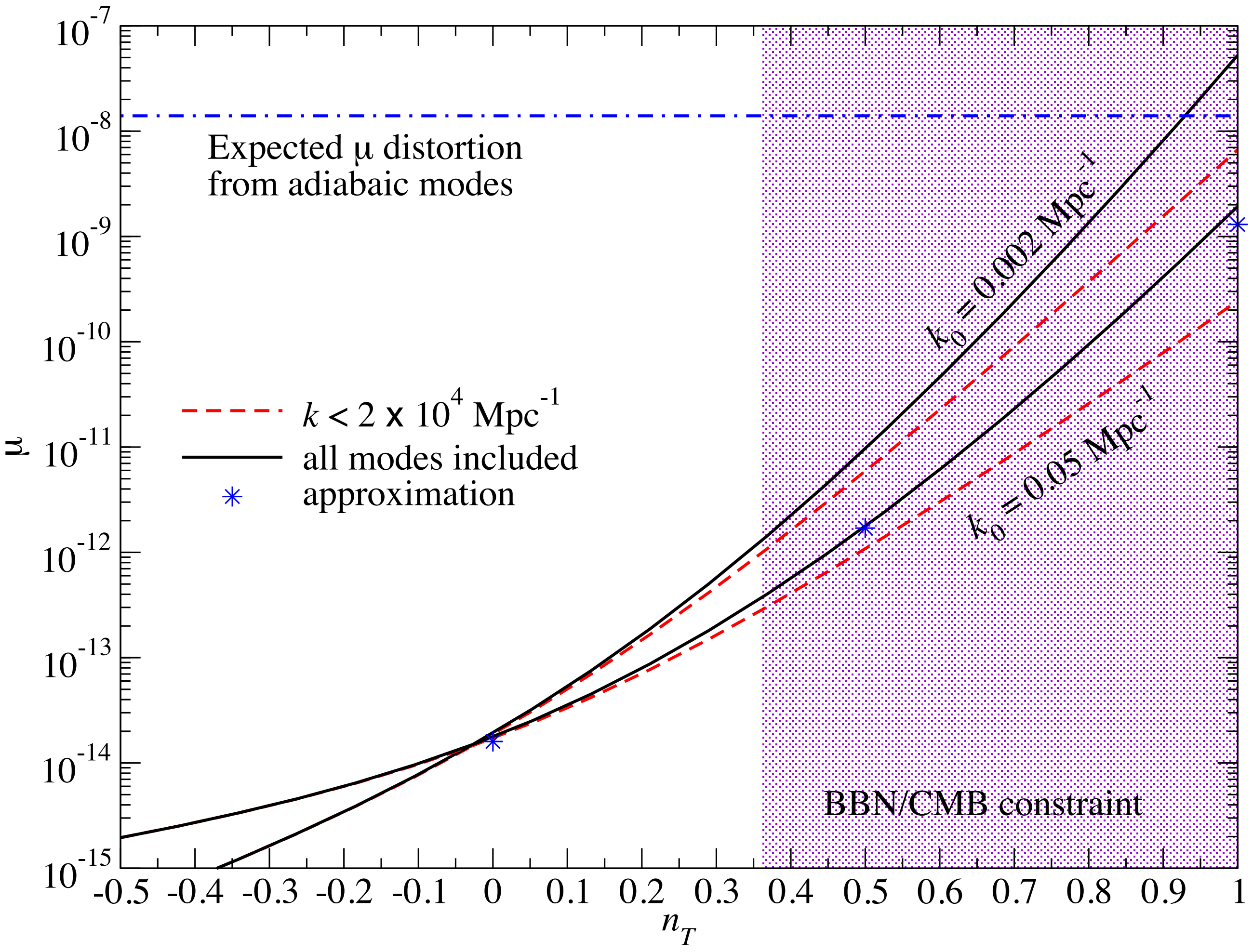

Ganc & Komatsu, 2012

Dissipation of tensor perturbations



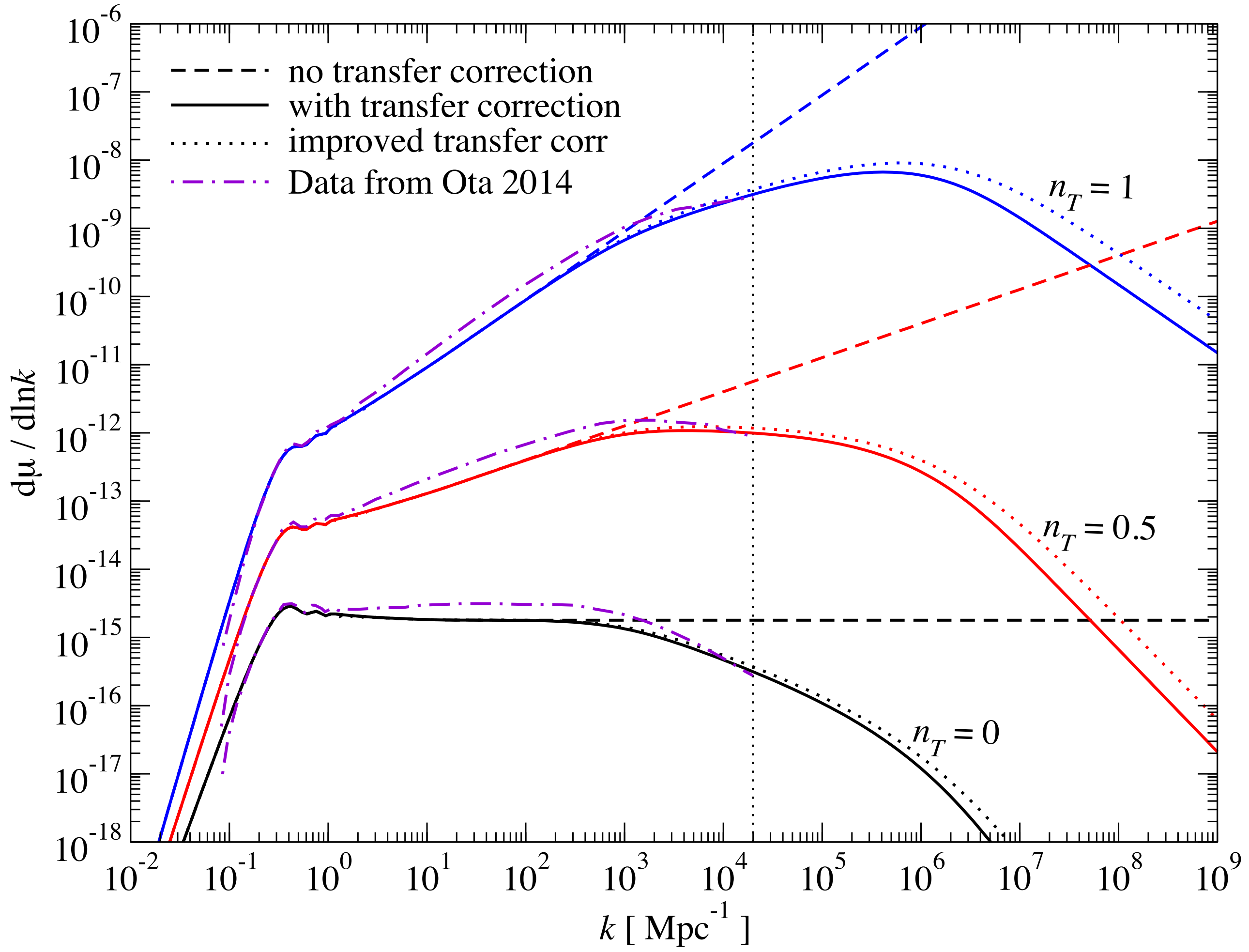
- distortion signal very small compared to adiabatic modes
- no severe contamination in simplest cases
- models with ‘large’ distortion already constrained by BBN/CMB

- heating rate can be computed similar to adiabatic modes
- heating rate much smaller than for scalar perturbations
- roughly constant per dlnz for n_T~0.5

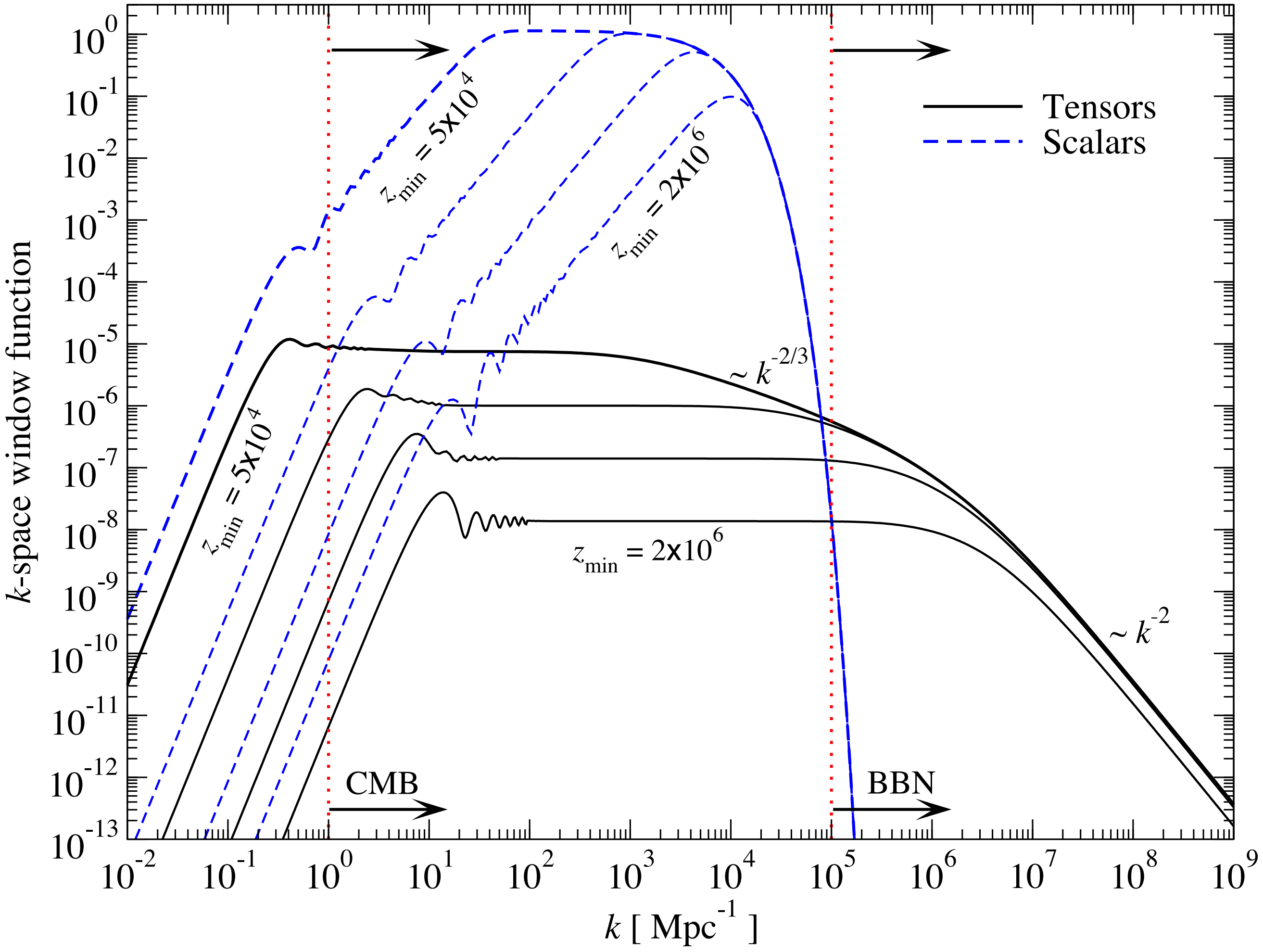


JC et al., 2014, ArXiv:1407.3653

Comparison of the distortion window functions



- adiabatic modes sensitive to a smaller range of scales
- tensors even have contributions from close to the horizon scale
- power-law decay at small scales

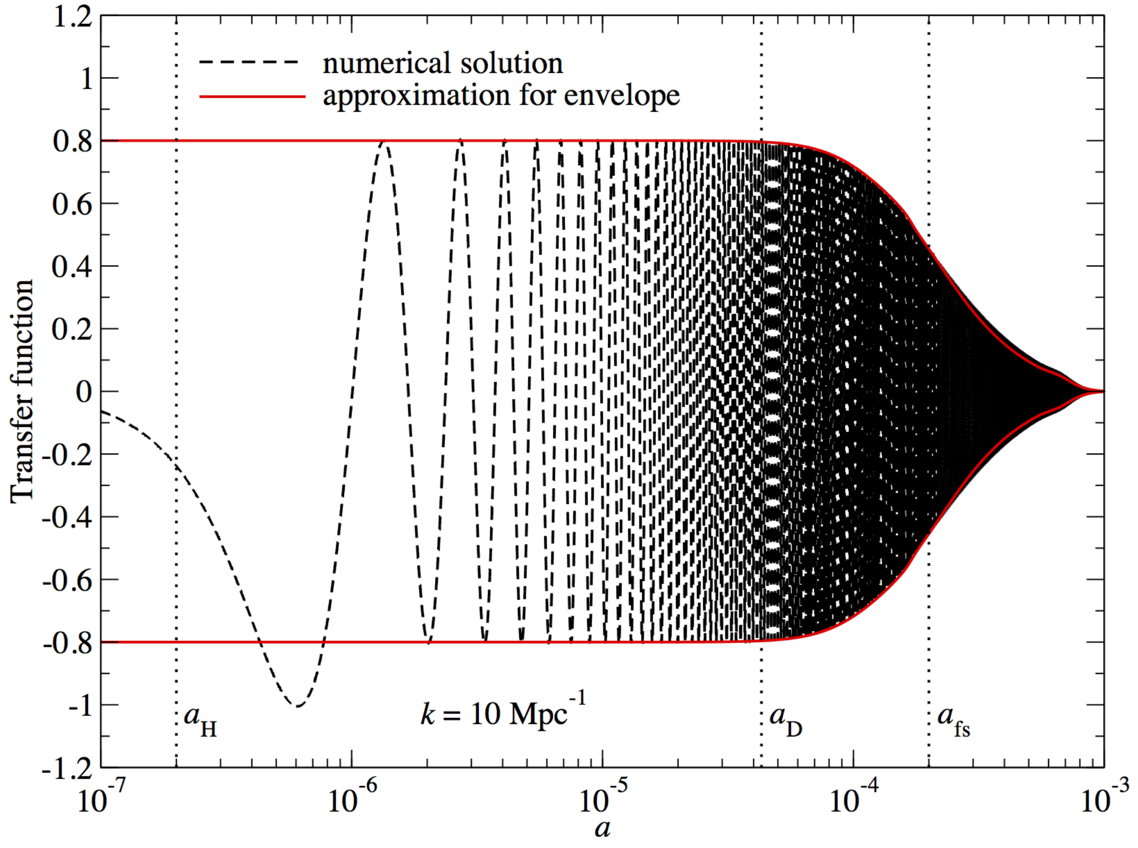


- small-scale modes important for blue tensor power spectra
- Ota et al. underestimated distortion in this case ~7 times

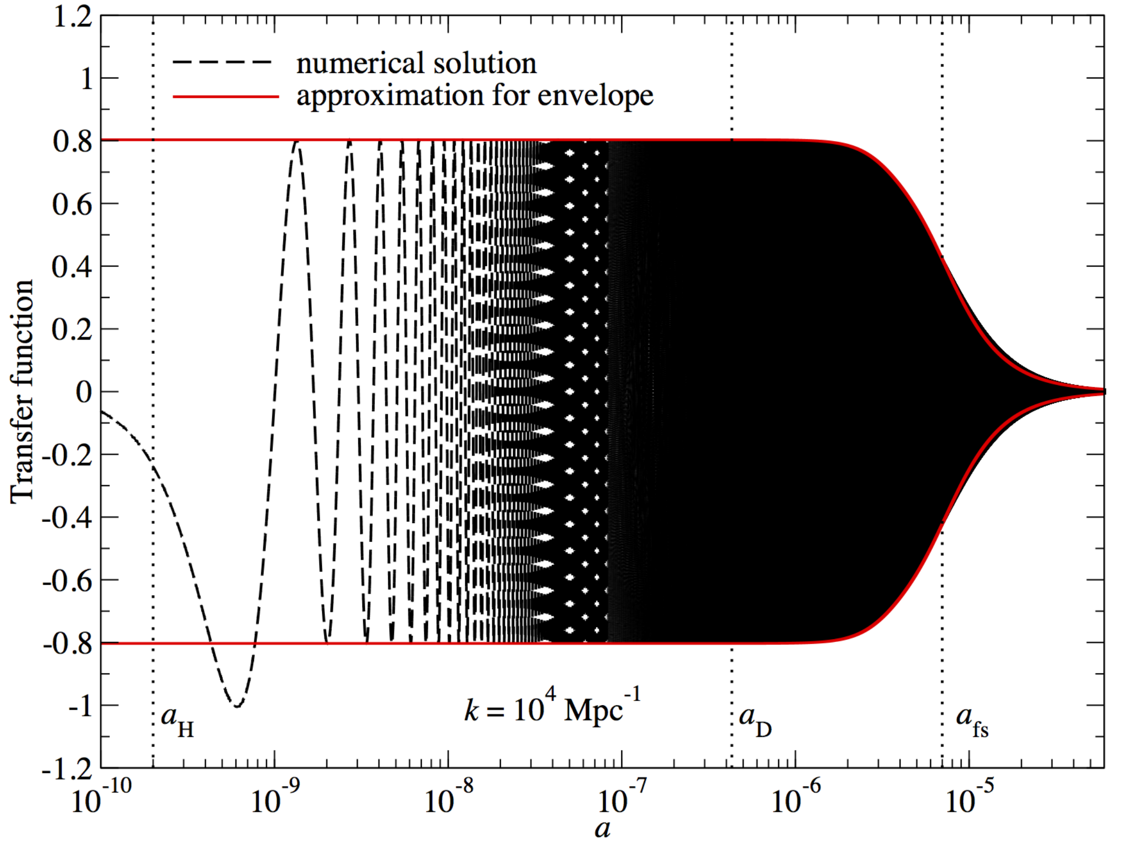
$$\mu_i \approx \int_0^\infty \frac{k^2 \mathrm{d}k}{2\pi^2} P_i(k) W_i(k)$$

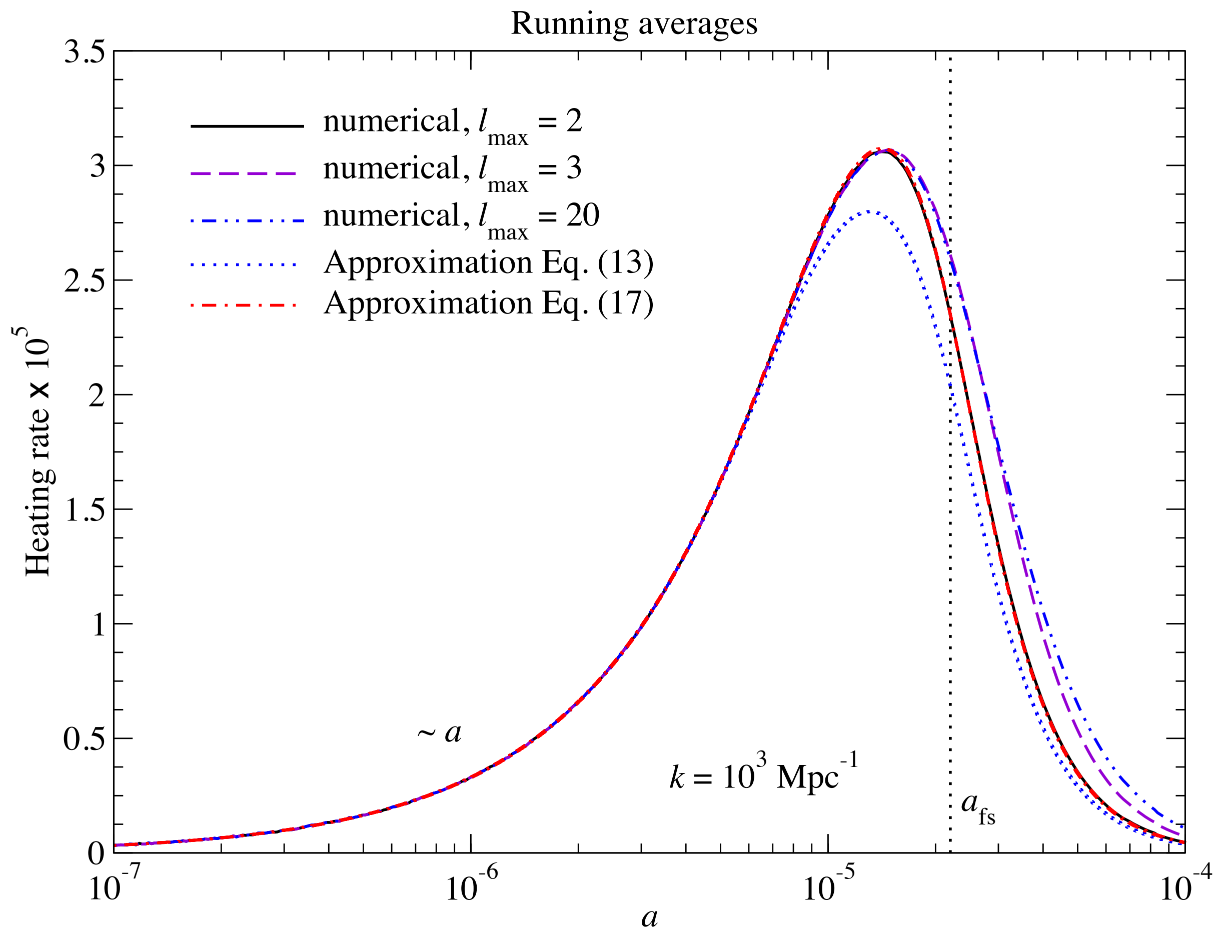
JC et al., 2014, ArXiv:1407.3653

Small-scale photon transfer function for tensors



- simple analytic expressions for the envelope and phase
- tensors never really disappear at small scales
- decay of amplitude only power-law instead of exponential as for adiabatic modes





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Structure of the Lectures (cont.)

Lecture III:

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

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- Sunyaev-Zeldovich effect and what the signals could tell us

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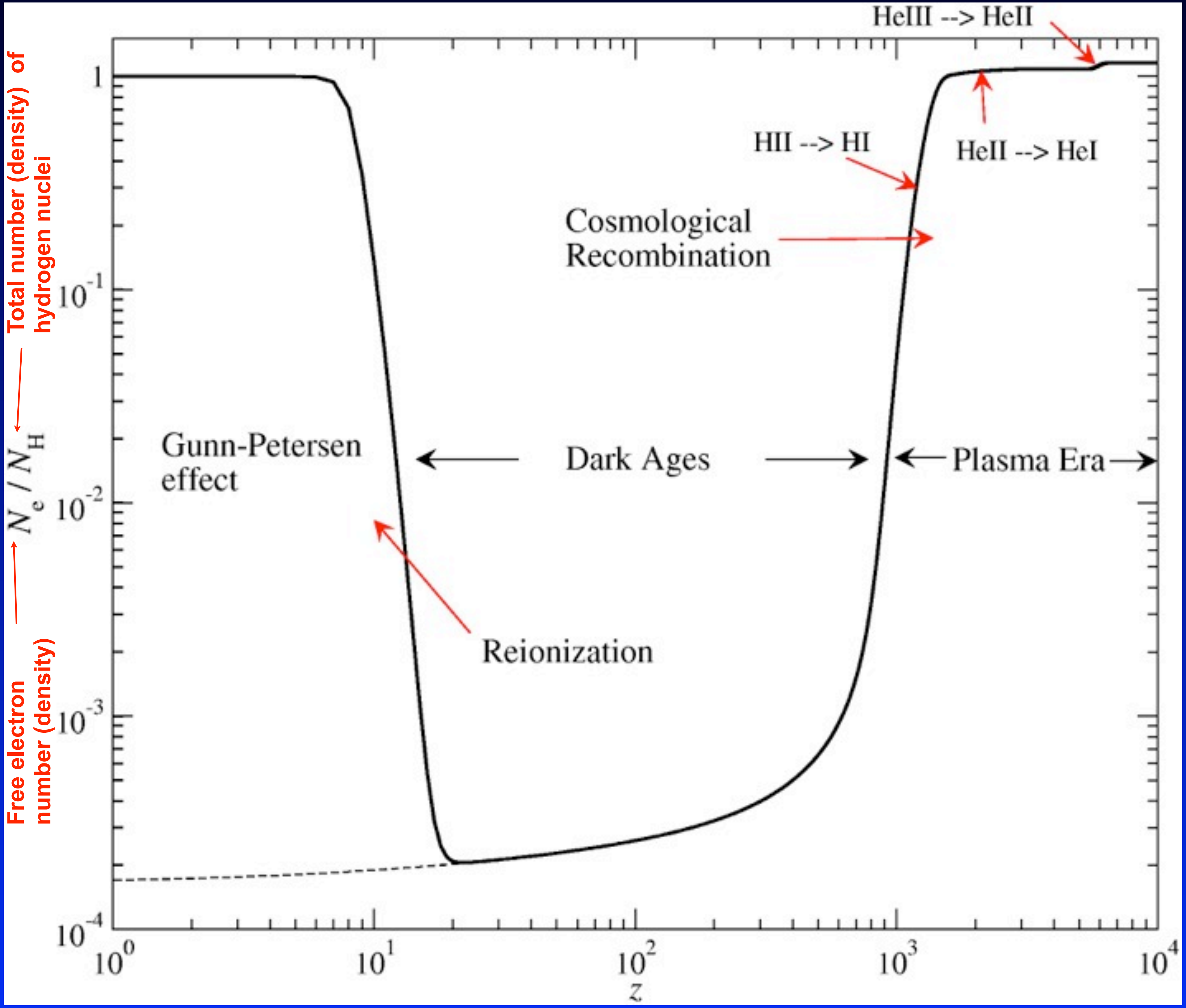
Sadly we won’t have time for this...

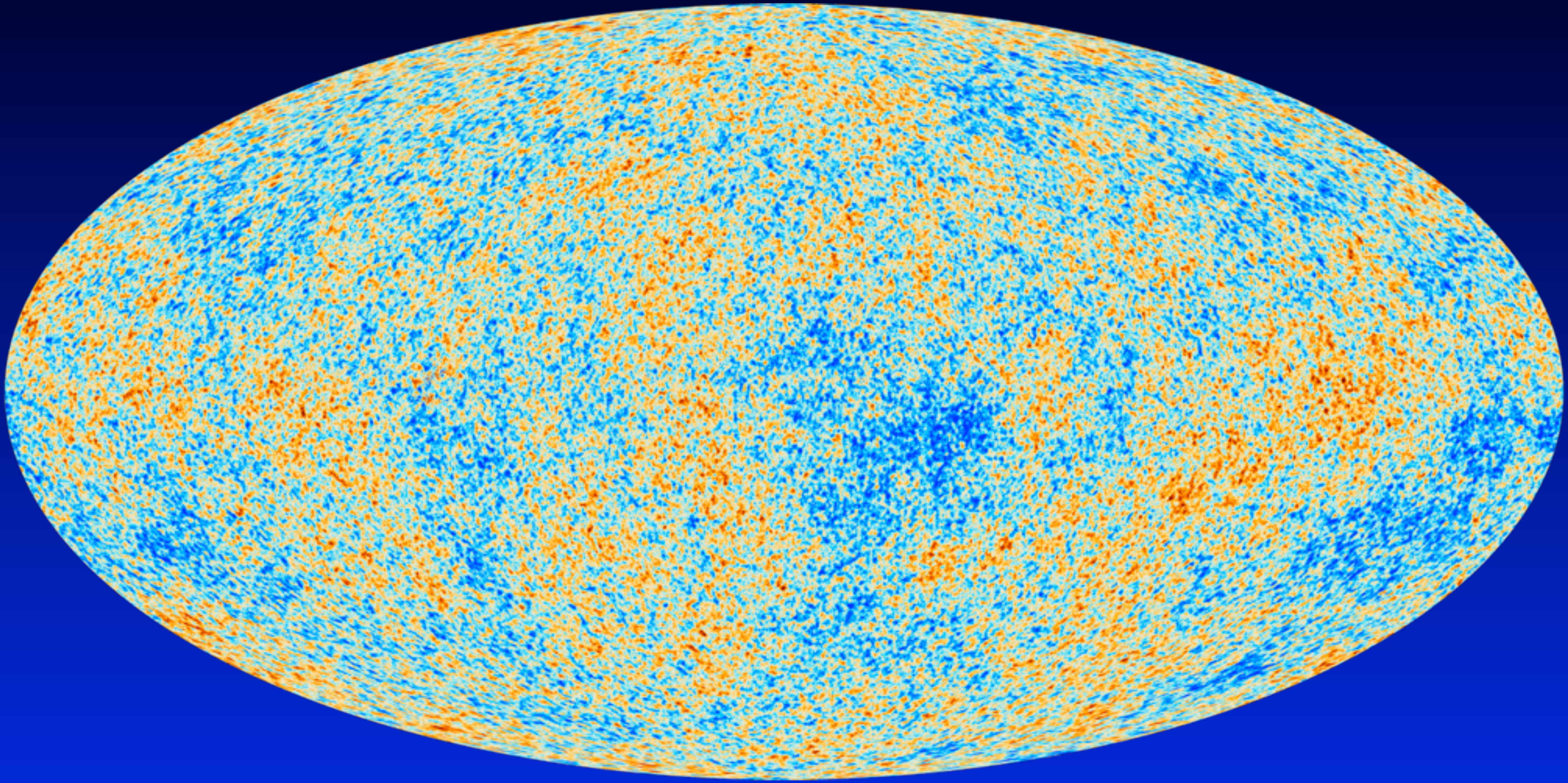
The cosmological recombination radiation & ionization history and why they are so important

Sketch of the Cosmic Ionization History



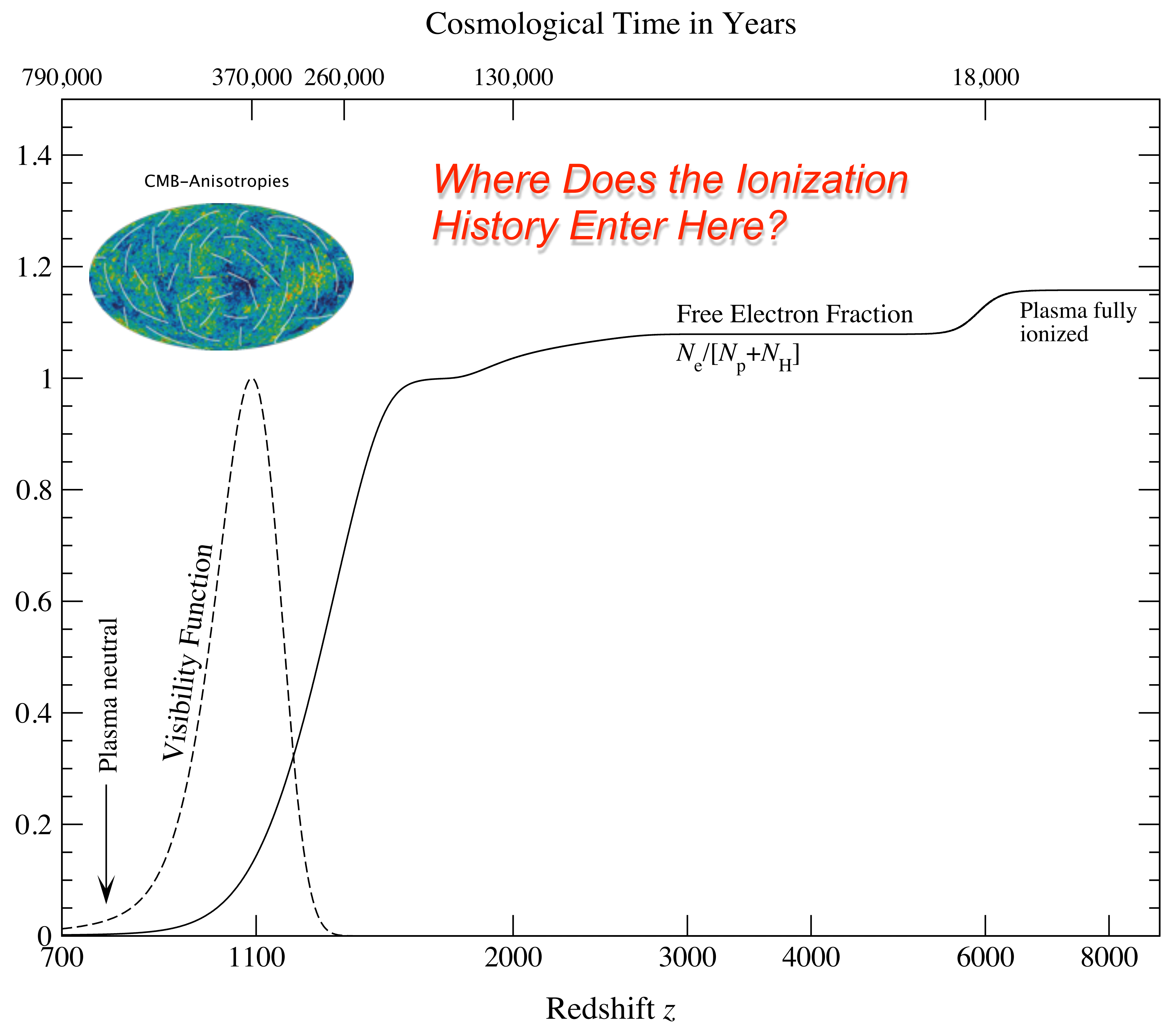
- **at redshifts higher than ~10^4 Universe → *fully ionized***
- **$z \geq 10^4$ → *free electron fraction* N_e/N_H ~ 1.16** (Helium has 2 electrons and abundance ~ 8%)
- **HeIII → HeII recombination at z~6000**
- **HeII → HeI recombination at z~2000**
- **HII → HI recombination at z~1000**

Cosmic Microwave Background Anisotropies



Planck all sky map

- CMB has a blackbody spectrum in every direction
- tiny variations of the CMB temperature $\Delta T/T \sim 10^{-5}$



Where Does the Ionization History Enter Here?

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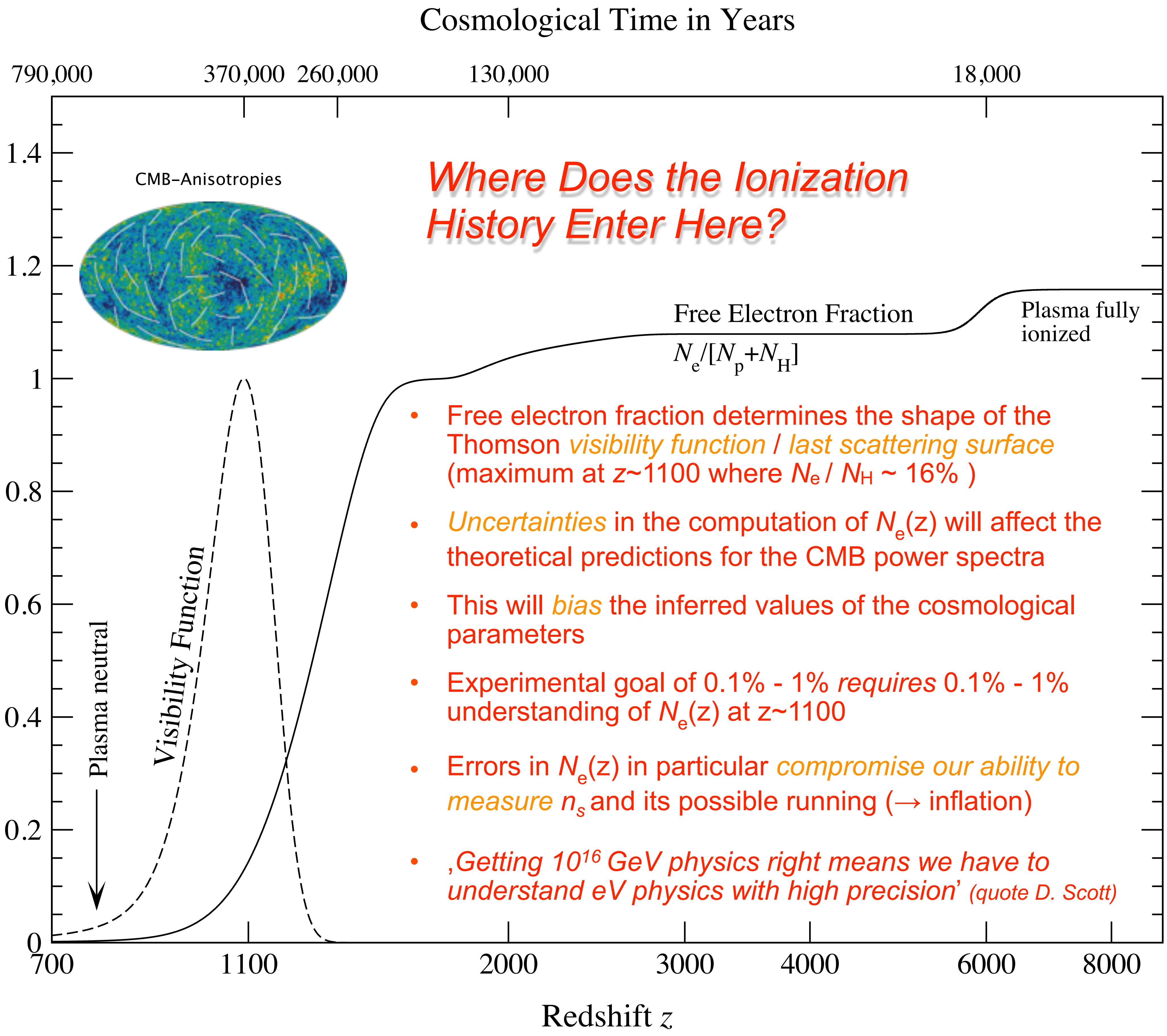
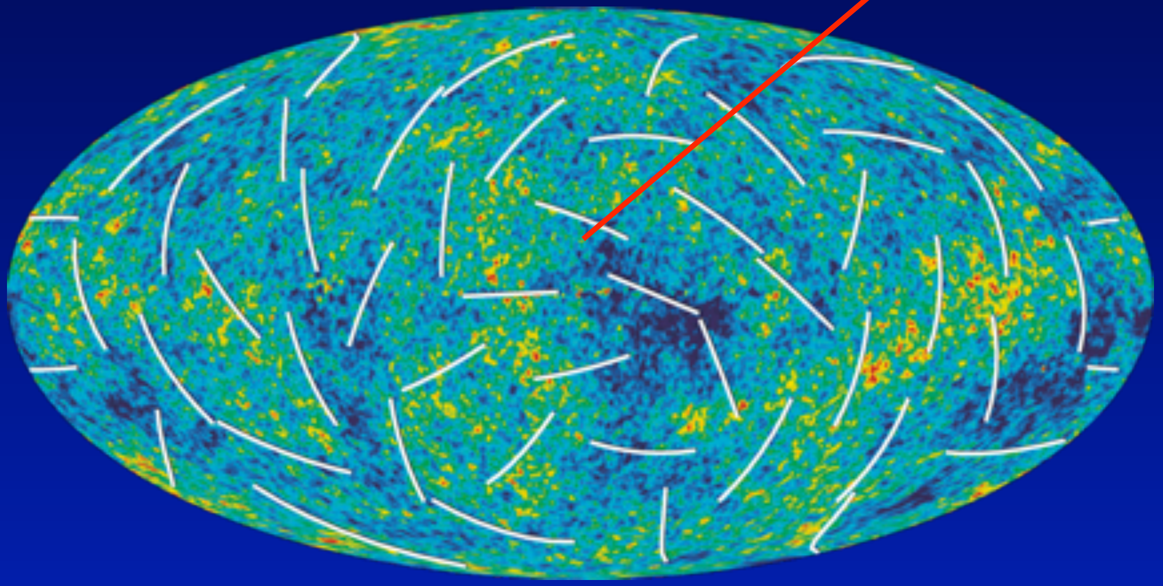


- Free electron fraction determines the shape of the Thomson *visibility function* / *last scattering surface* (maximum at $z\sim1100$ where $N_e / N_H \sim 16\%$)
- *Uncertainties* in the computation of $N_e(z)$ will affect the theoretical predictions for the CMB power spectra
- This will *bias* the inferred values of the cosmological parameters
- Experimental goal of 0.1% - 1% *requires* 0.1% - 1% understanding of $N_e(z)$ at $z\sim1100$
- Errors in $N_e(z)$ in particular *compromise our ability to measure* n_s and its possible running (→ inflation)
- *‚Getting 10^{16} GeV physics right means we have to understand eV physics with high precision‘* *(quote D. Scott)*

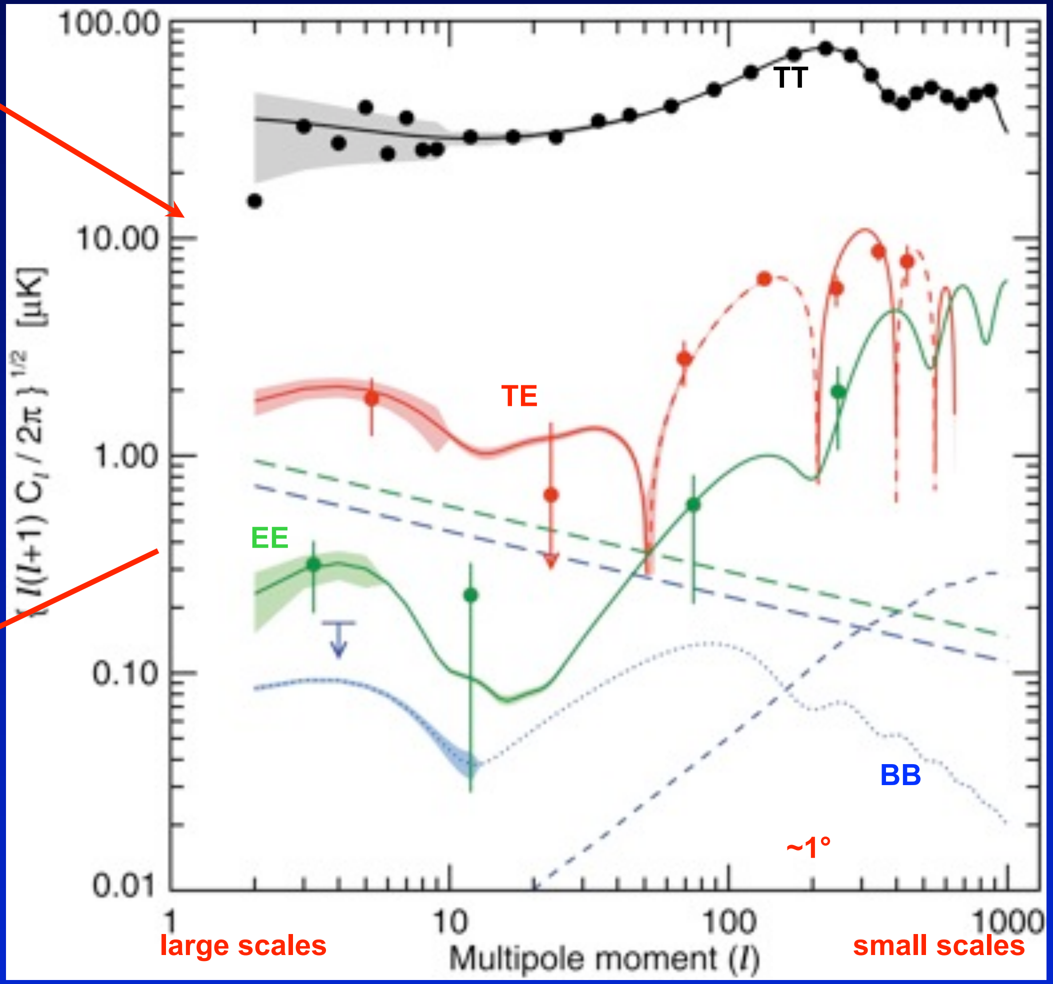
CMB Sky → Cosmology

WMAP CMB Sky



a_{lm}

Power spectra



(Joint) analysis

Cosmological Parameters

Ω_{tot}, Ω_m, Ω_b, Ω_Λ, h, τ, n_s,...

Other cosmological Dataset:

small-scale CMB, Supernovae, large-scale structure/ BAO, Lyman-α forest, lensing, ...

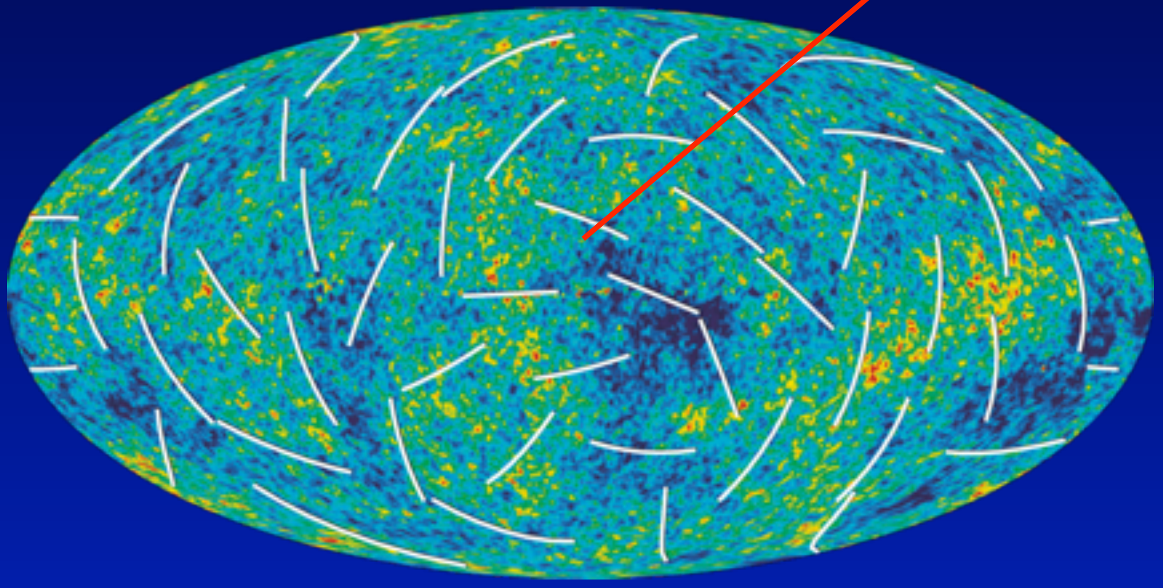
CMB Sky → Cosmology

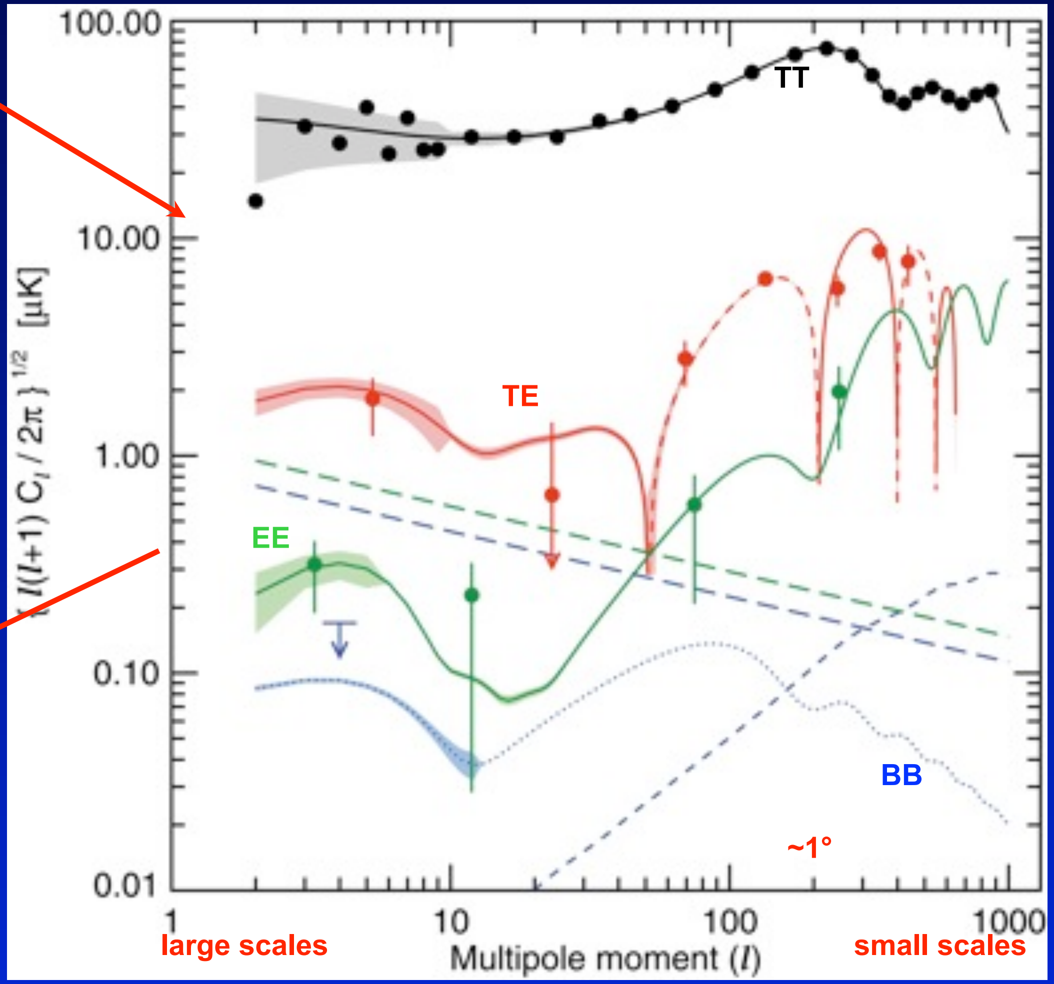
$N_e(z)$ is a *crucial* input

a_{lm}

Power spectra

WMAP CMB Sky





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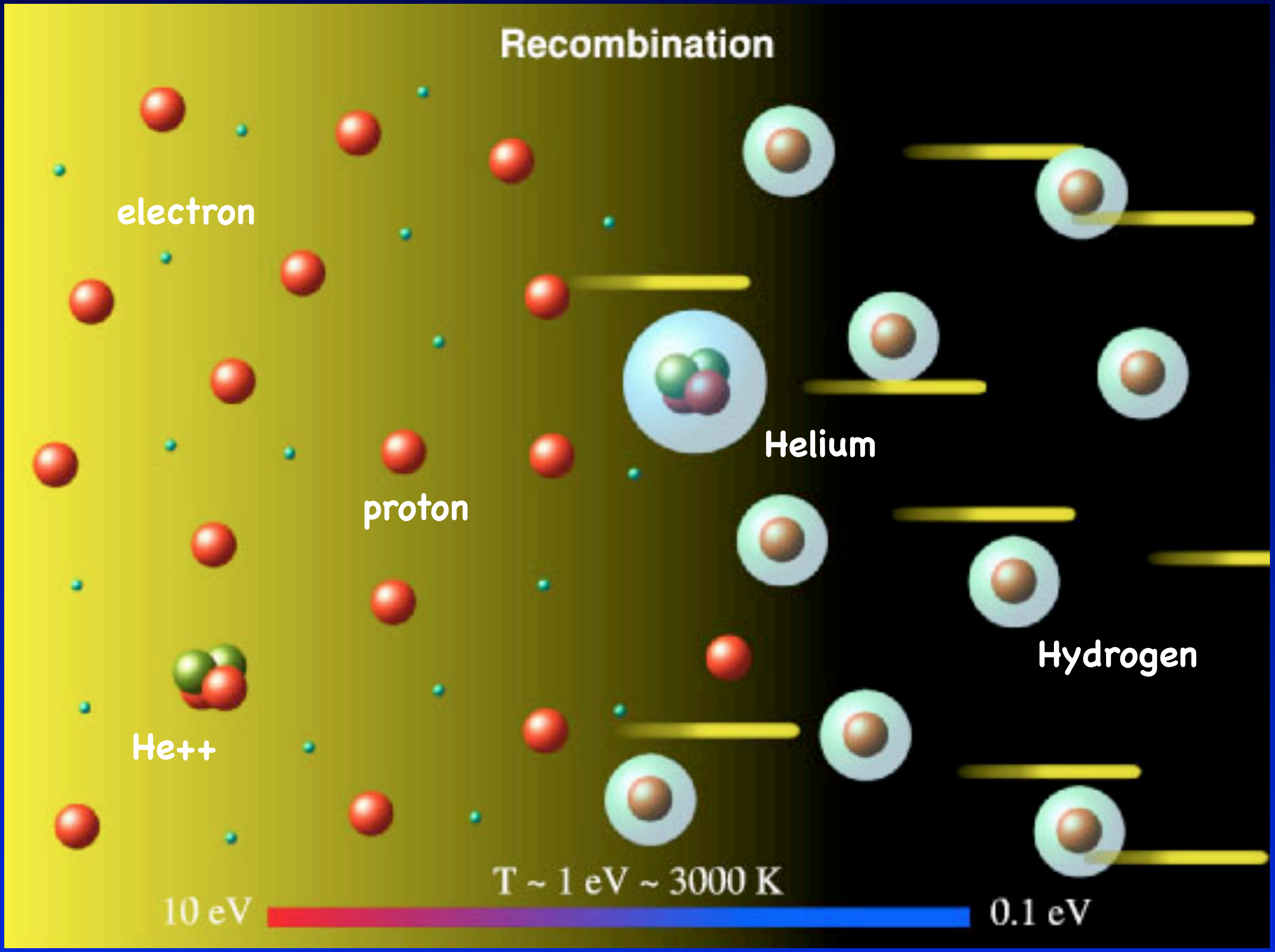
Why are the ionization history and recombination radiation connected?

- To interpret high-precision CMB data we need to understand the *ionization history* very well!
- The recombination radiation is a direct *record* of the recombination process
- measuring the recombination radiation allows us to directly *check our understanding* of the recombination process!
- *High-frequency distortion* actually *controls* recombination dynamics, so we need to understand both well!

How does cosmological recombination work?

What is the recombination problem about?



- coupled system describing the interaction of *matter* with the ambient CMB *photon* field
- atoms can be in different excitation states

  $\Longrightarrow$ *lots of levels to worry about*
- recombination process changes Wien tail of CMB and this affects the recombination dynamics

  $\Longrightarrow$ *radiative transfer problem*

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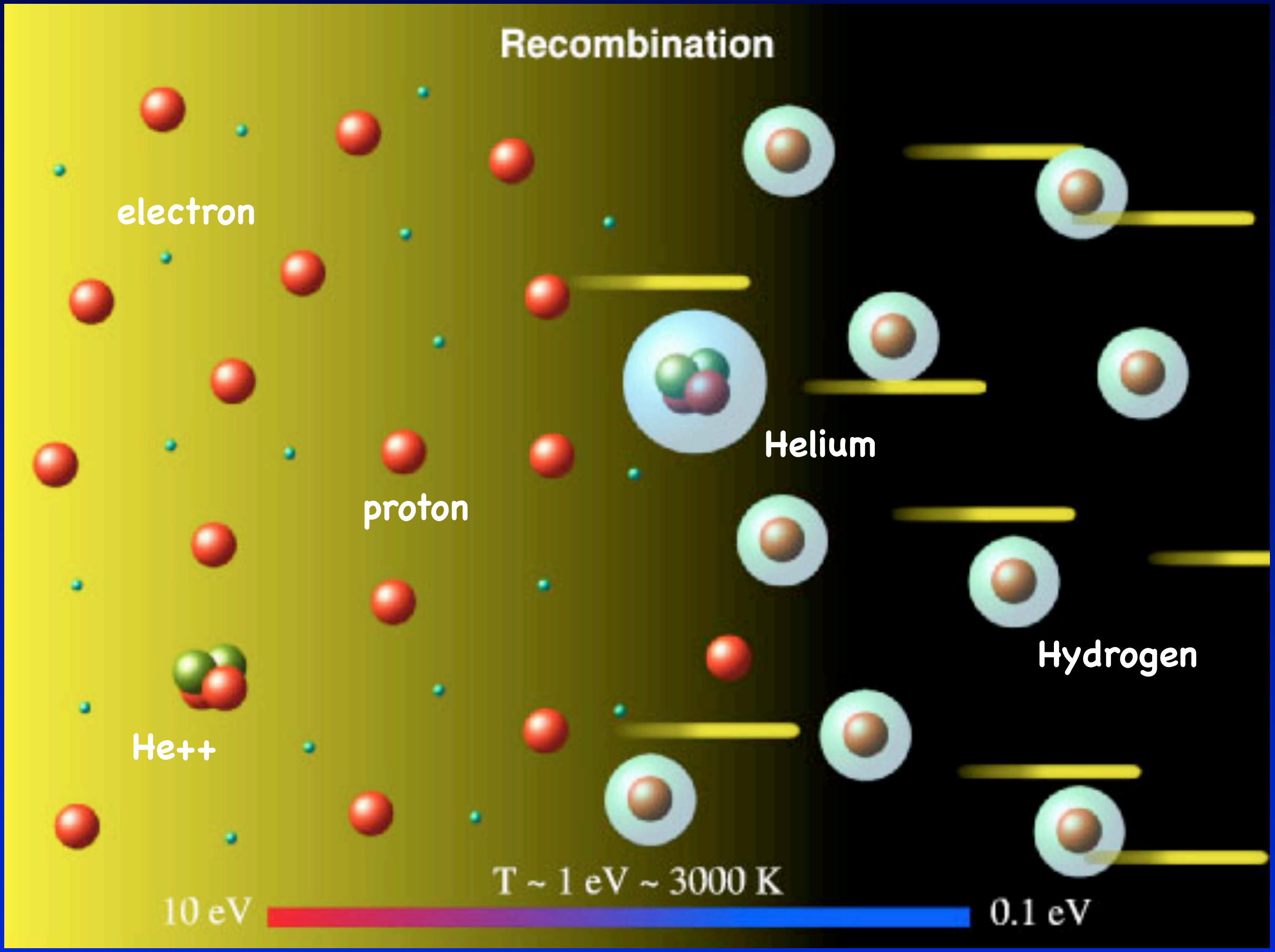

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Have to follow evolution of: $N_{\rm e}, T_{\rm e}, N_{\rm p}, N_i$ and ΔI_ν

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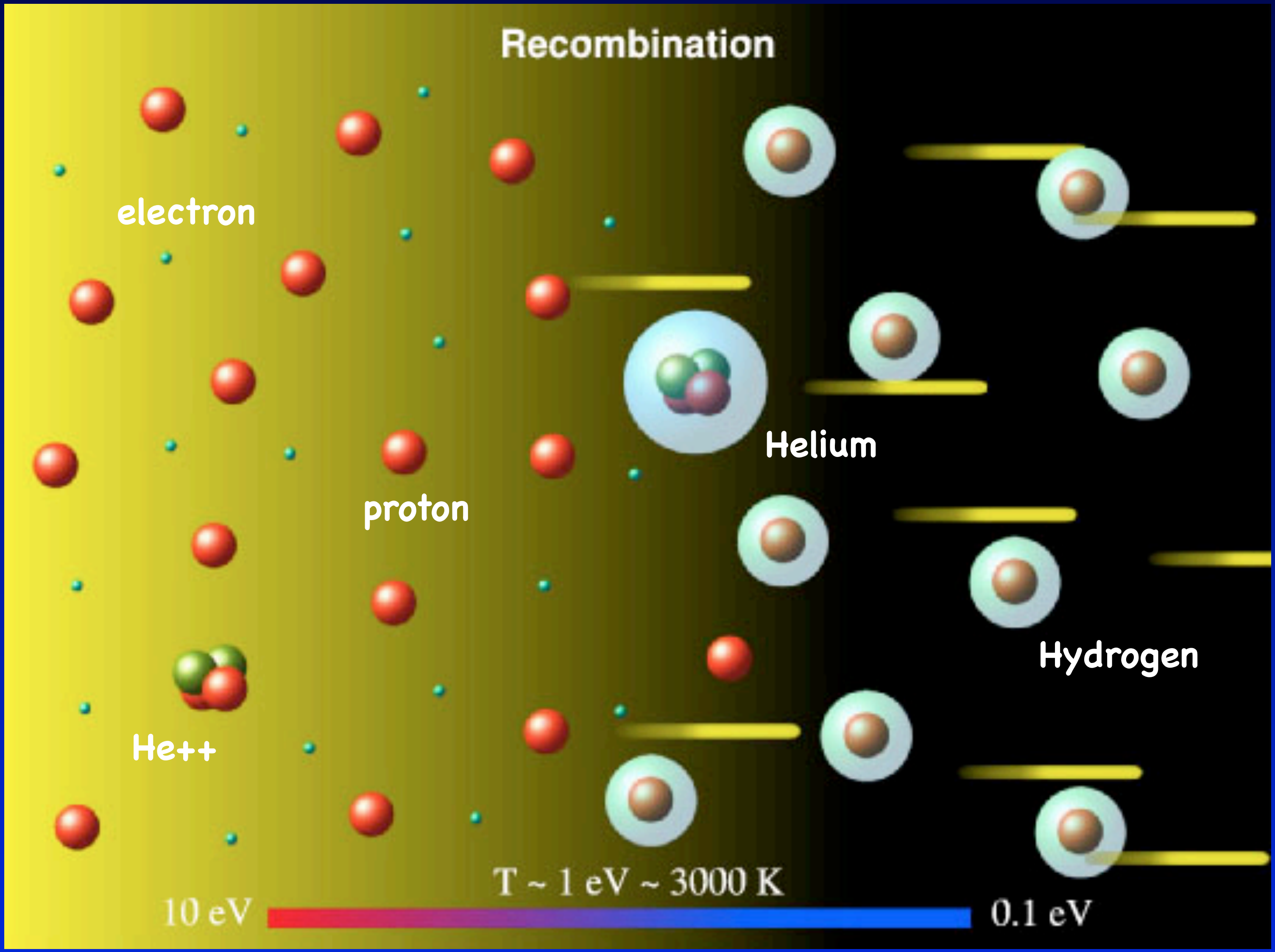

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electron temperature

Have to follow evolution of: $N_{\rm e}, T_{\rm e}, N_{\rm p}, N_i$ and ΔI_ν

number densities

non-thermal photons

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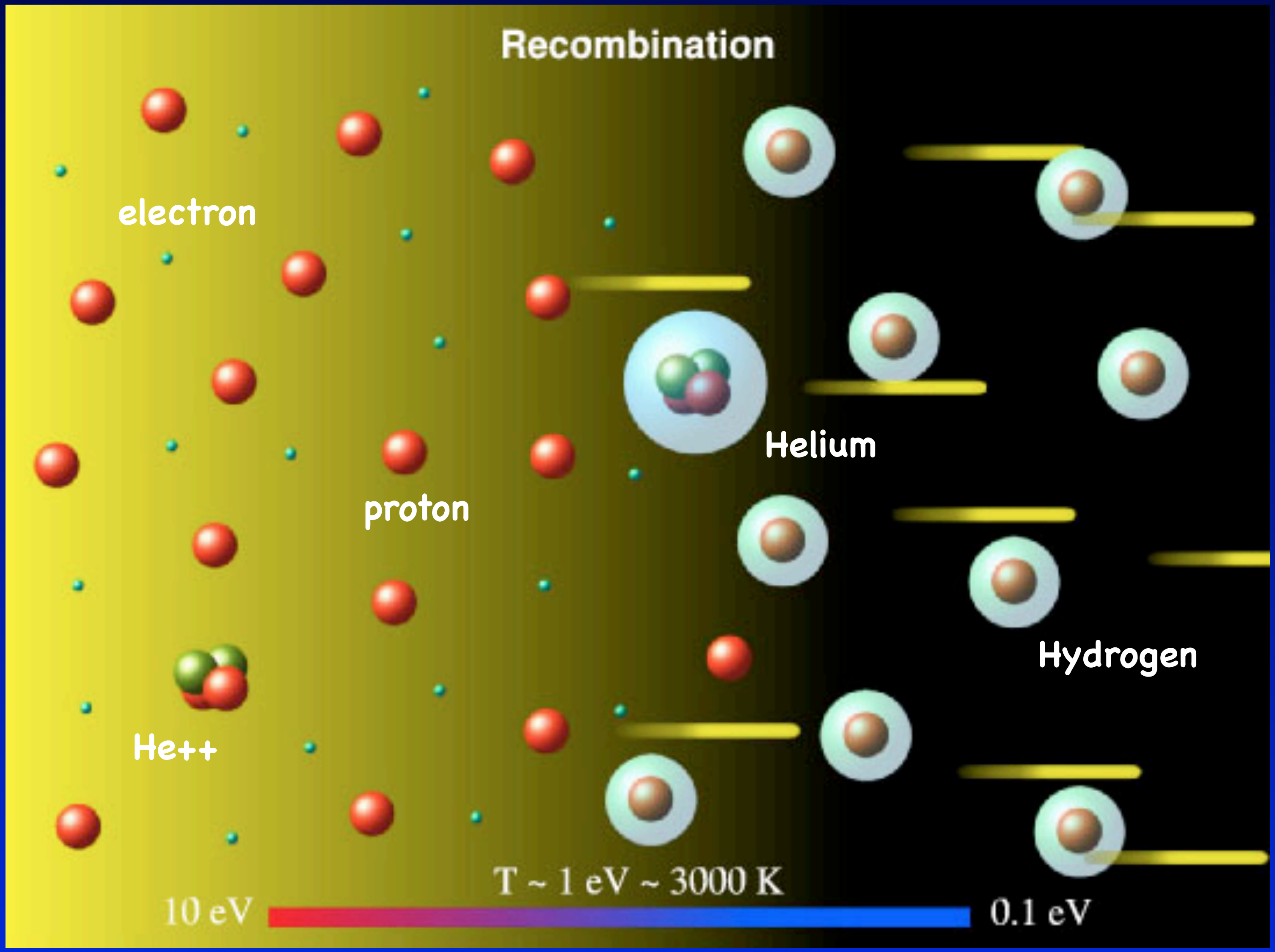

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Only problem in time!

electron temperature

Have to follow evolution of: $N_{\rm e}, T_{\rm e}, N_{\rm p}, N_i$ and ΔI_ν

number densities

non-thermal photons

Physical Conditions during Recombination

- Temperature T_γ ~ 2.725 (1+z) K ~ 3000 K
- Baryon number density N_b ~ 2.5x10^{-7}cm^{-3} (1+z)^3 ~ 330 cm^{-3}
- Photon number density N_γ ~ 410 cm^{-3} (1+z)^3 ~ 2×10^9 N_b

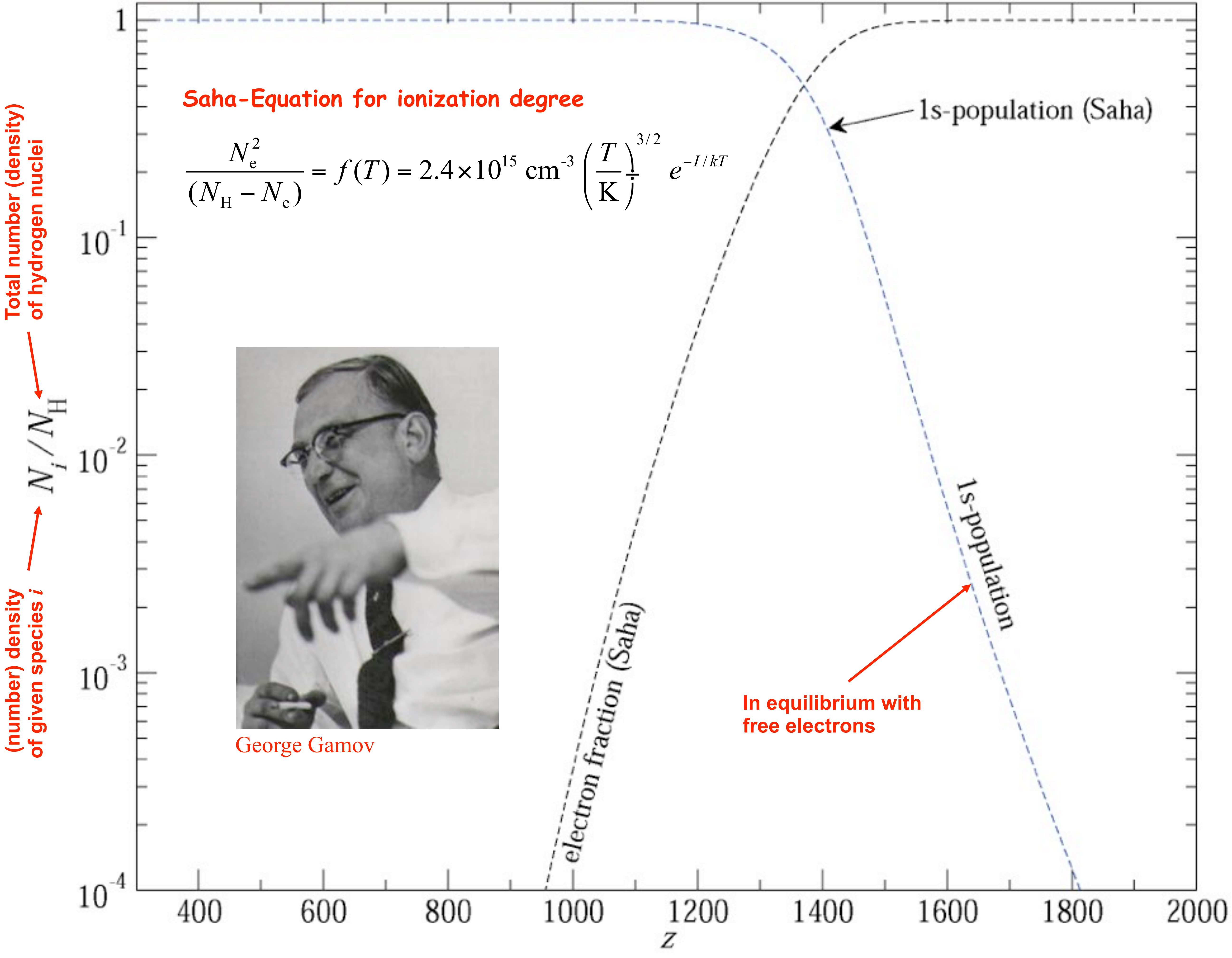
⇒ *photons in very distant Wien tail of blackbody spectrum can keep hydrogen ionized until* $h\nu_\alpha \sim 40\ kT_\gamma \iff T_\gamma \sim 0.26$ eV

- Collisional processes negligible (*completely different in stars!!!*)
- Rates dominated by radiative processes

  (*e.g. stimulated emission & stimulated recombination*)
- Compton interaction couples electrons very tightly to photons until z ~ 200 ⇒ $T_\gamma \sim T_e \sim T_m$

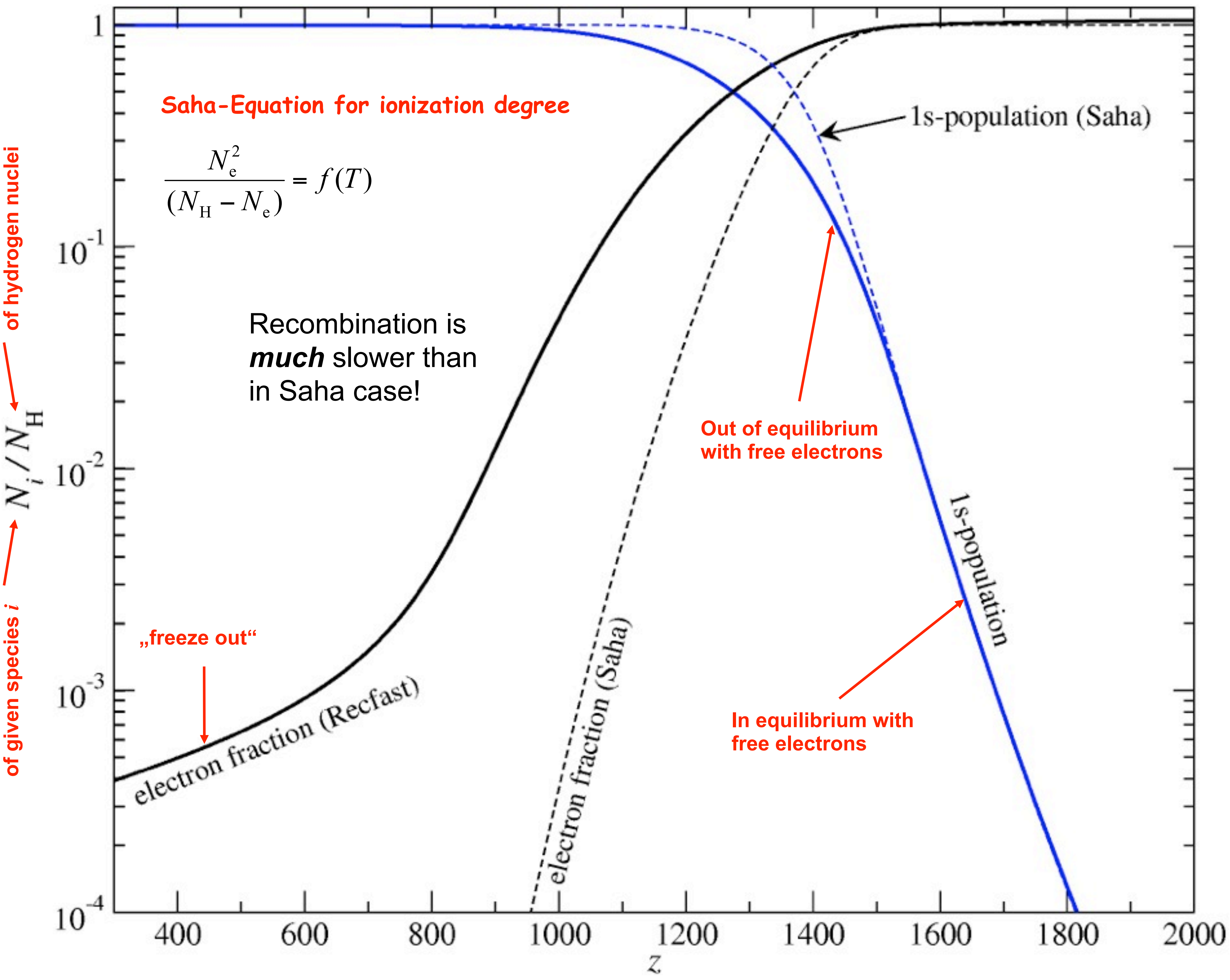
Saha-Equation for ionization degree

$$\frac{N_e^2}{(N_H - N_e)} = f(T) = 2.4 \times 10^{15}\ \mathrm{cm}^{-3} \left(\frac{T}{K}\right)^{3/2} e^{-I/kT}$$



George Gamov

In equilibrium with free electrons



Saha-Equation for ionization degree

$$\frac{N_e^2}{(N_H - N_e)} = f(T)$$

Recombination is ***much*** slower than in Saha case!

Total number (density) of hydrogen nuclei

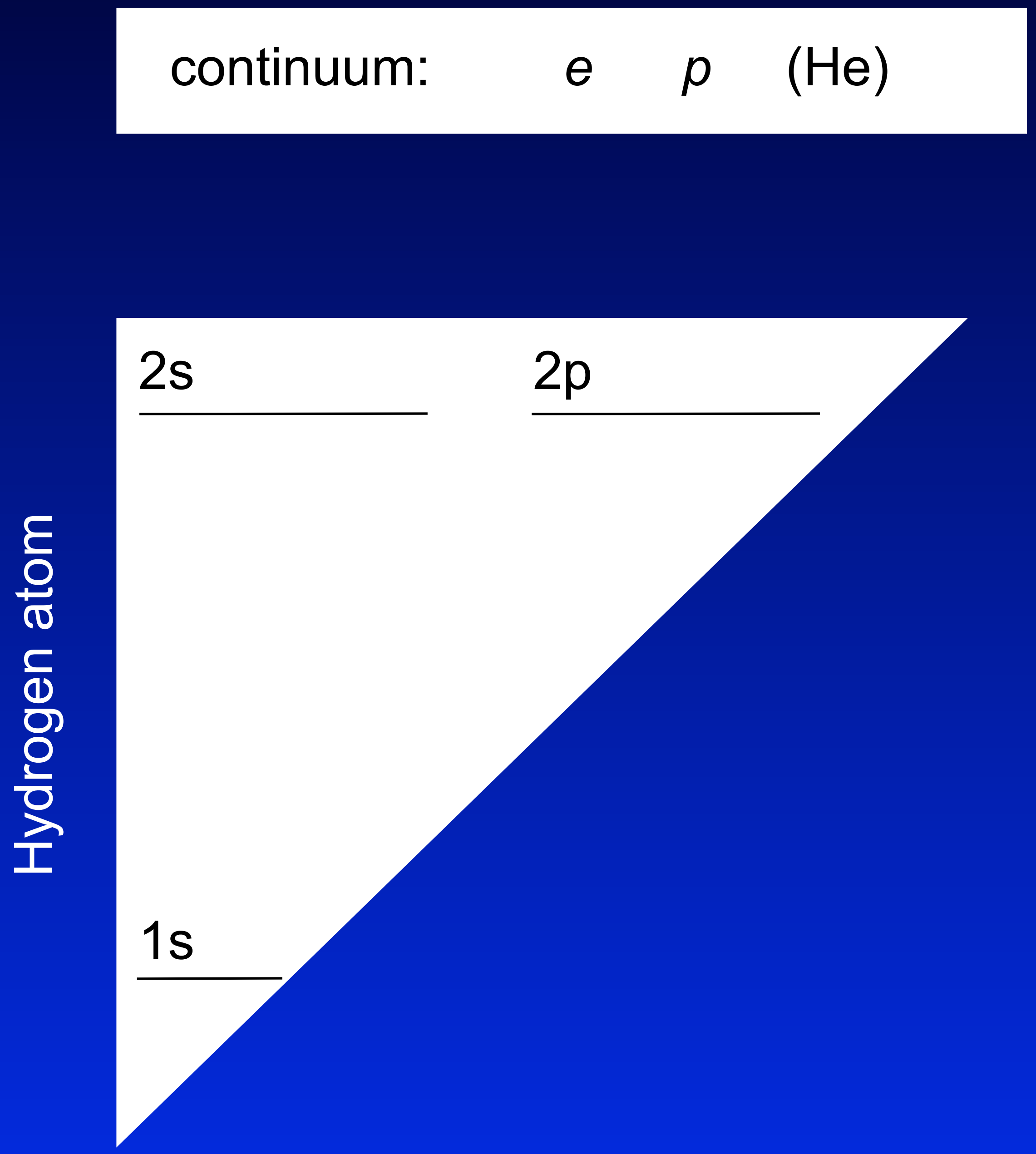
(number) density of given species *i*

„freeze out“

Out of equilibrium with free electrons

In equilibrium with free electrons

3-level Hydrogen Atom and Continuum



continuum: *e* *p* (He)

2s

2p

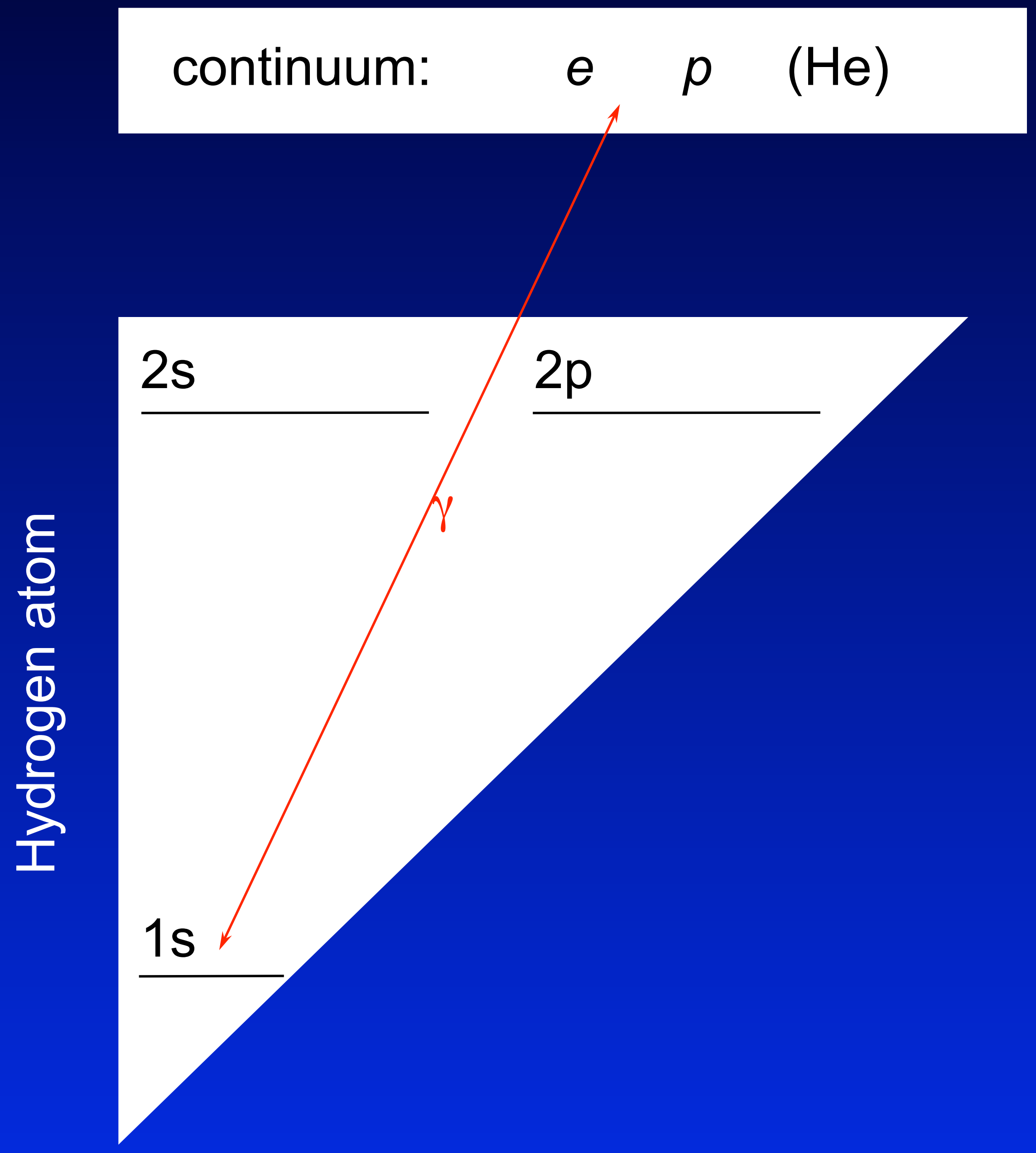
1s

Hydrogen atom

Zeldovich, Kurt & Sunyaev, 1968, ZhETF, 55, 278
Peebles, 1968, ApJ, 153, 1

Routes to the ground state ?

3-level Hydrogen Atom and Continuum



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- **direct recombination to 1s**
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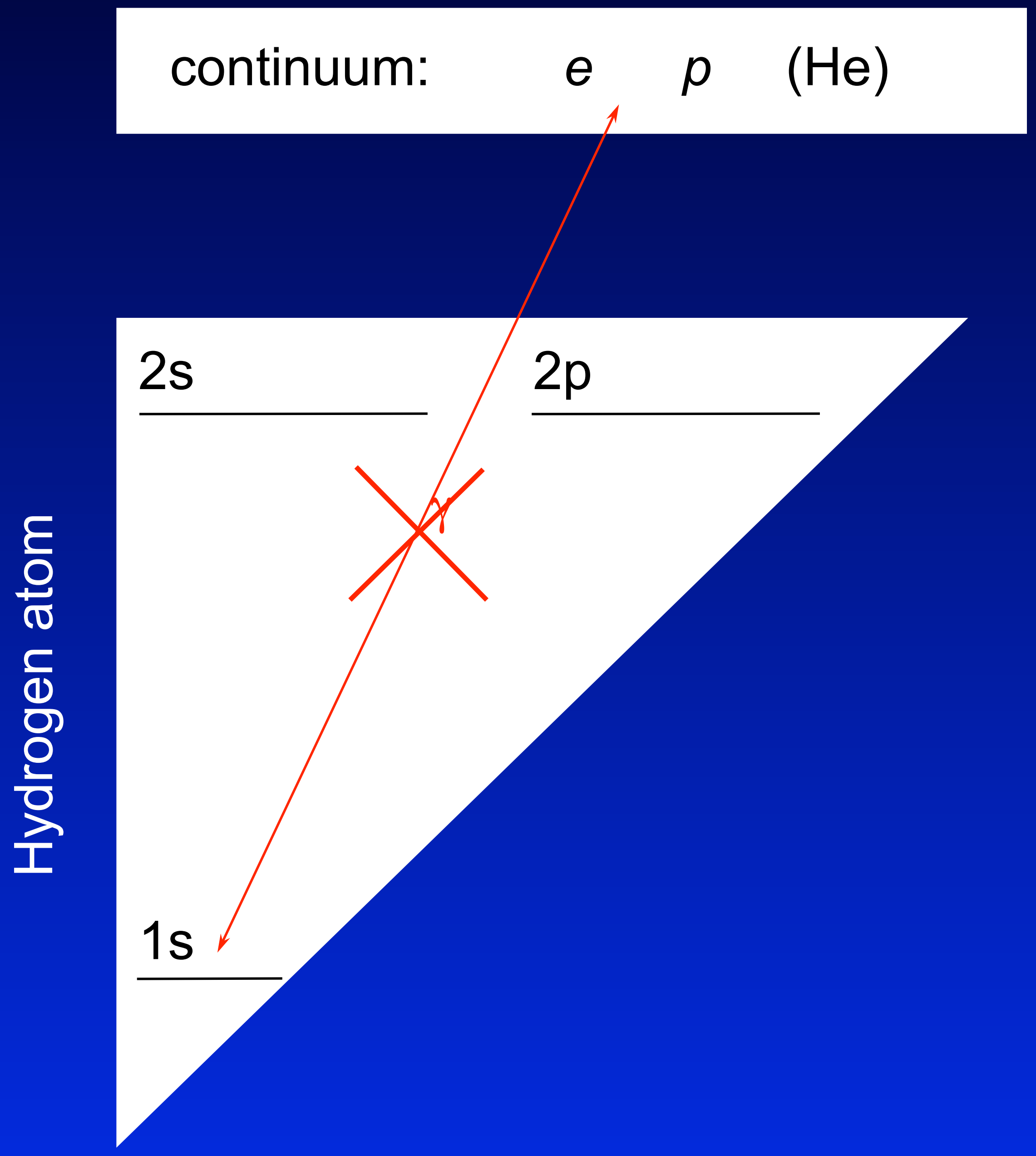

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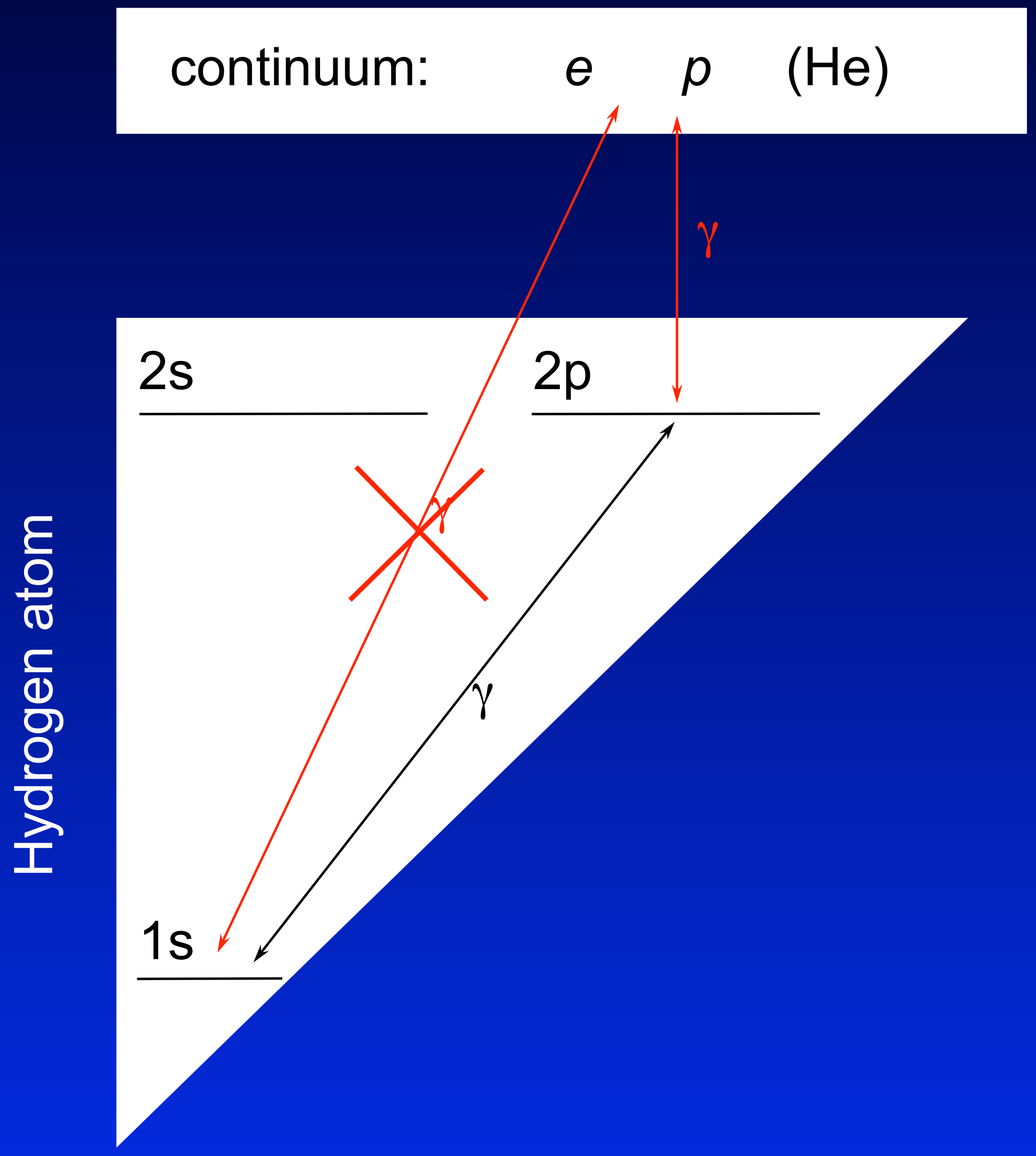

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  - **many resonant scatterings**
  - **escape very hard ($p \sim 10^{-9}$ @ $z \sim 1100$)**

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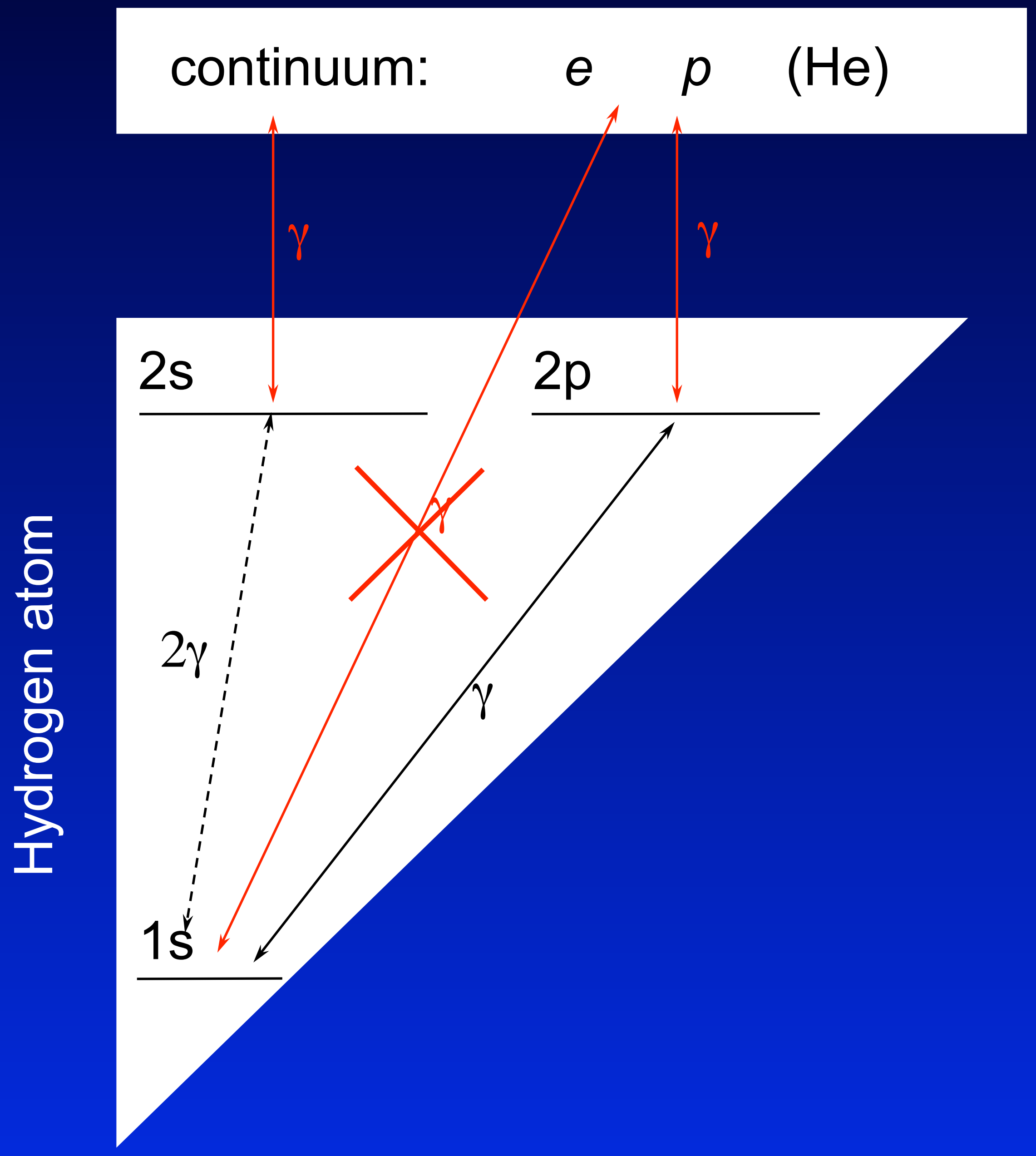

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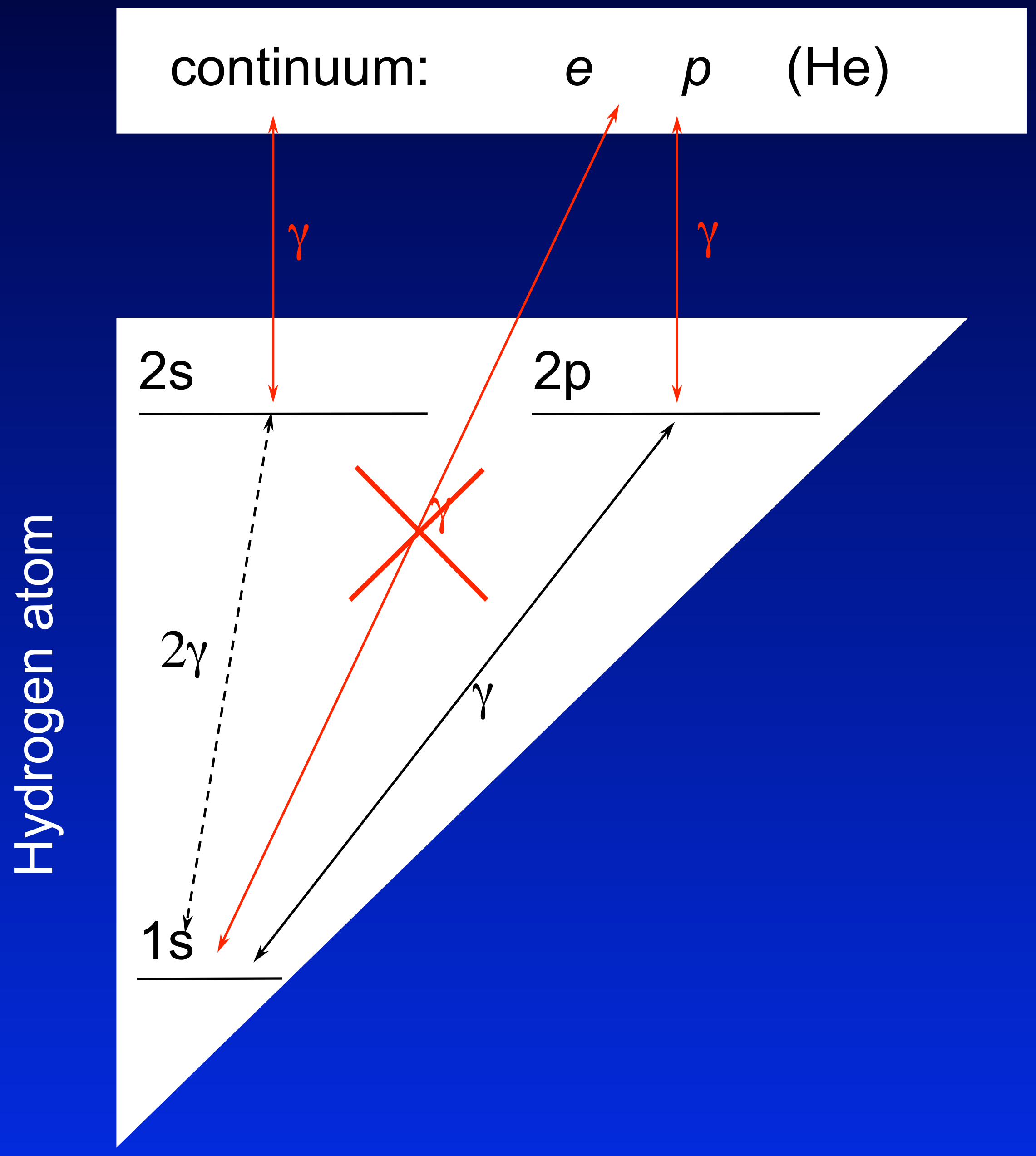

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~ 57%

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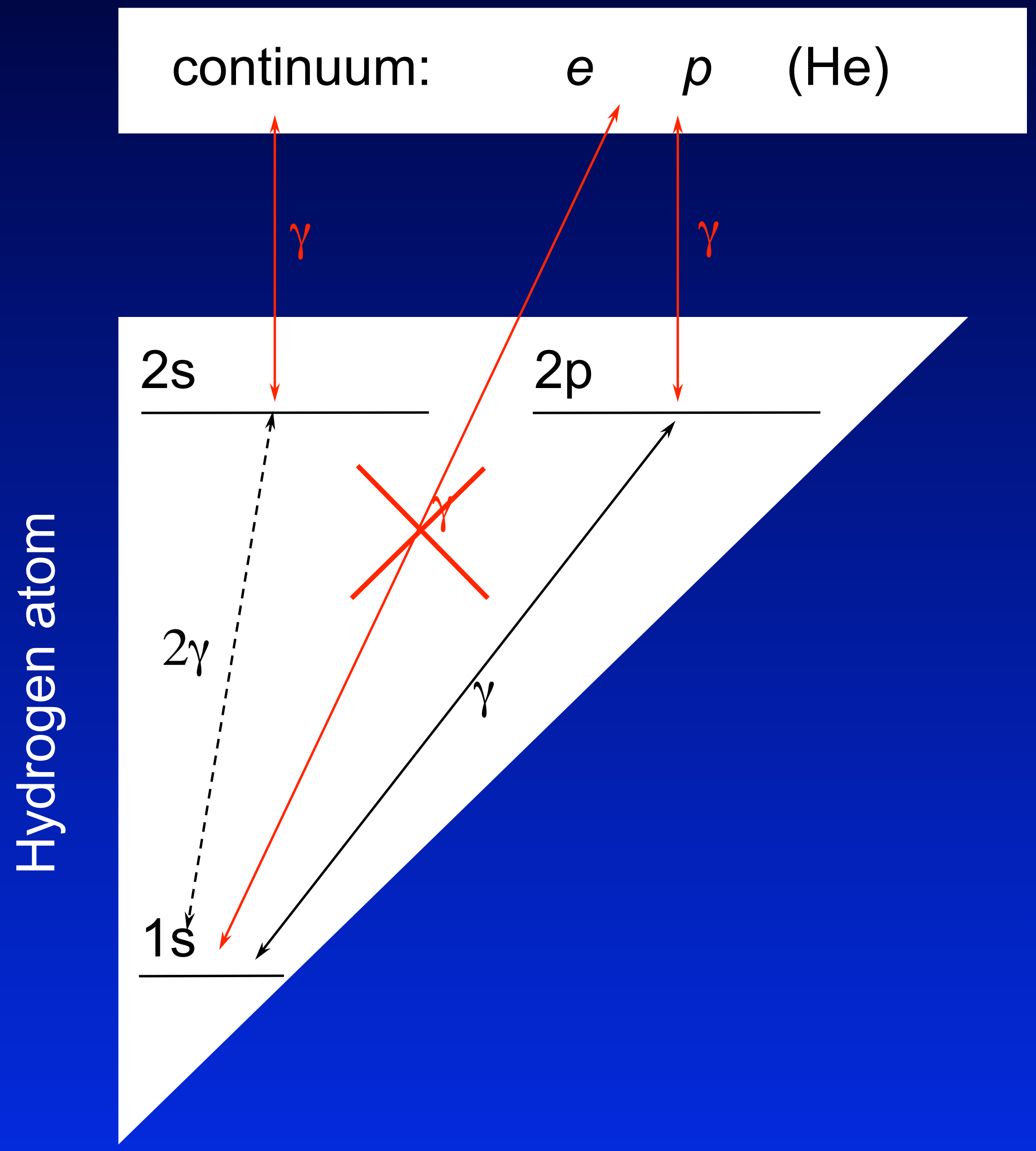

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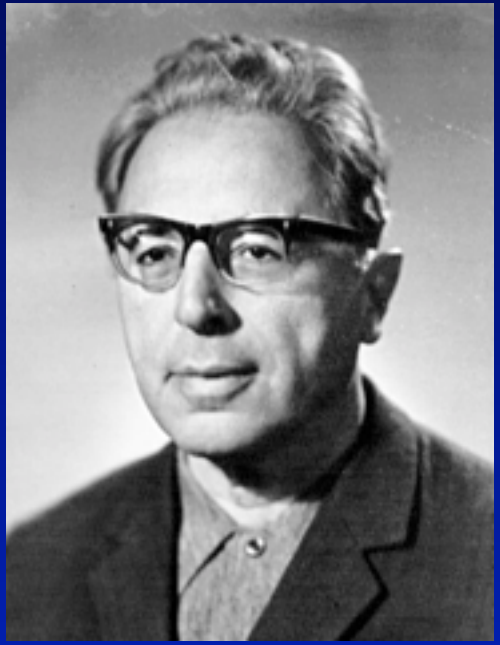
$\Delta N_e\ /\ N_e \sim 10\% - 20\%$

These first computations were completed in 1968!

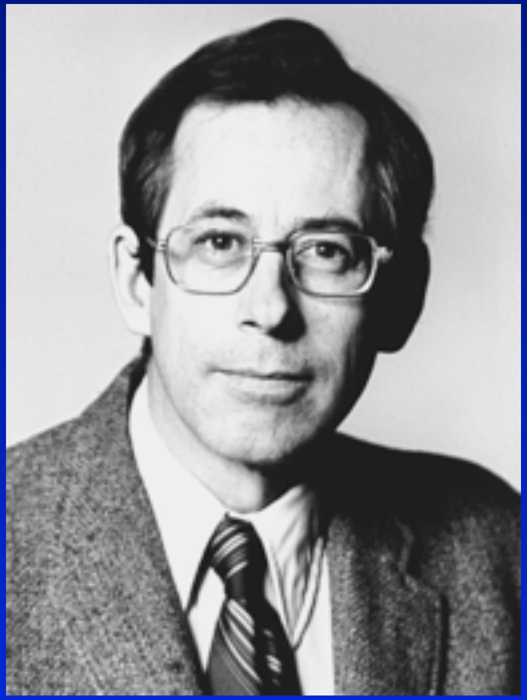
Moscow

Yakov Zeldovich



Iosif Shklovskii

Princeton

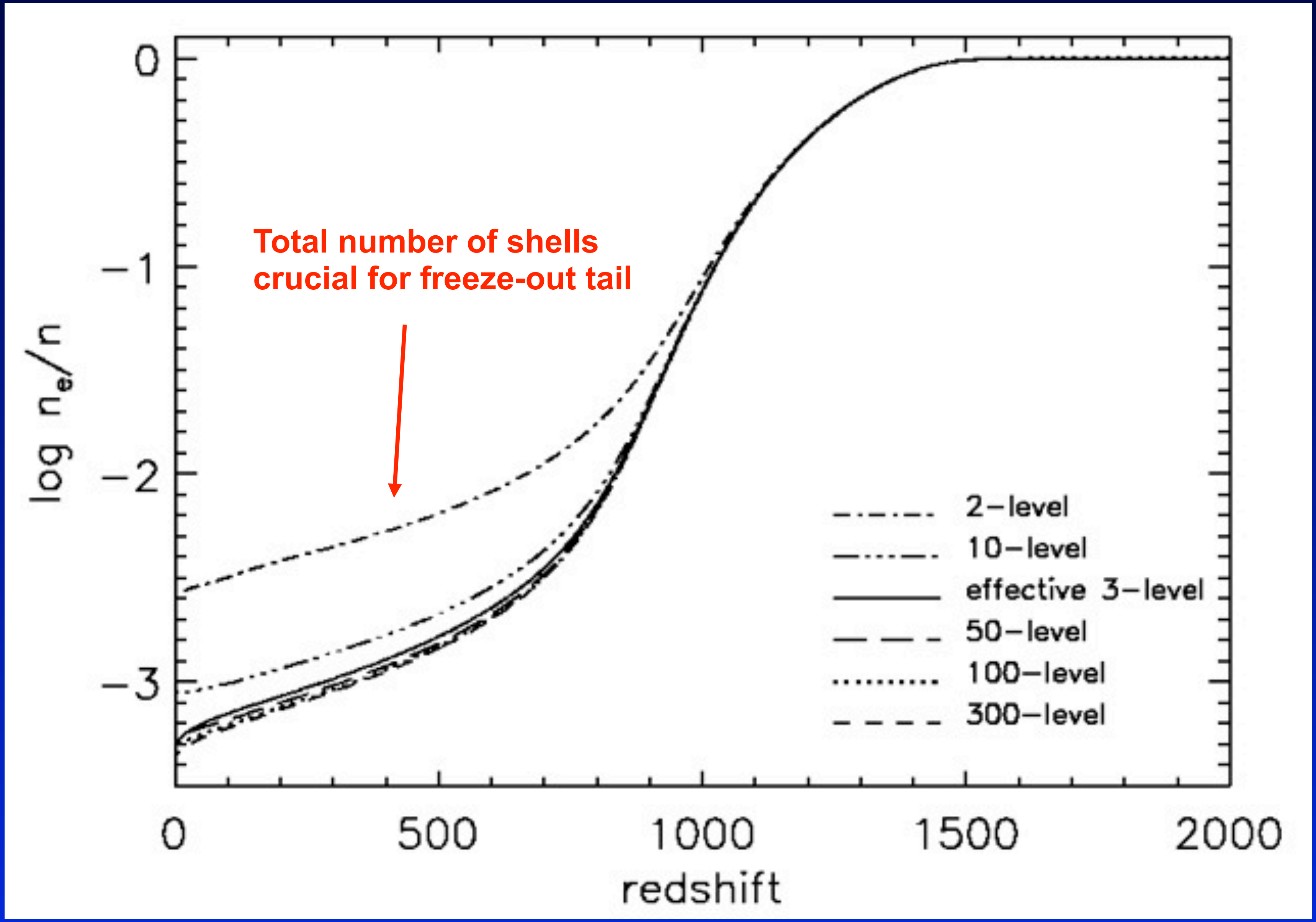


Jim Peebles

Vladimir Kurt
(UV astronomer)

Rashid Sunyaev

Multi-level Atom ⟺ Recfast-Code



Seager, Sasselov & Scott, 1999, ApJL, 523, L1
Seager, Sasselov & Scott, 2000, ApJS, 128, 407

Output of N_e/N_H

Hydrogen:

- up to 300 levels (shells)
- $n \geq 2$ → full SE for l-sub-states

Helium:

- HeI 200-levels (*z* ~ 1400-1500)
- HeII 100-levels (*z* ~ 6000-6500)
- HeIII 1 equation

Low Redshifts:

- H chemistry (only at low z)
- cooling of matter (Bremsstrahlung, collisional cooling, line cooling)

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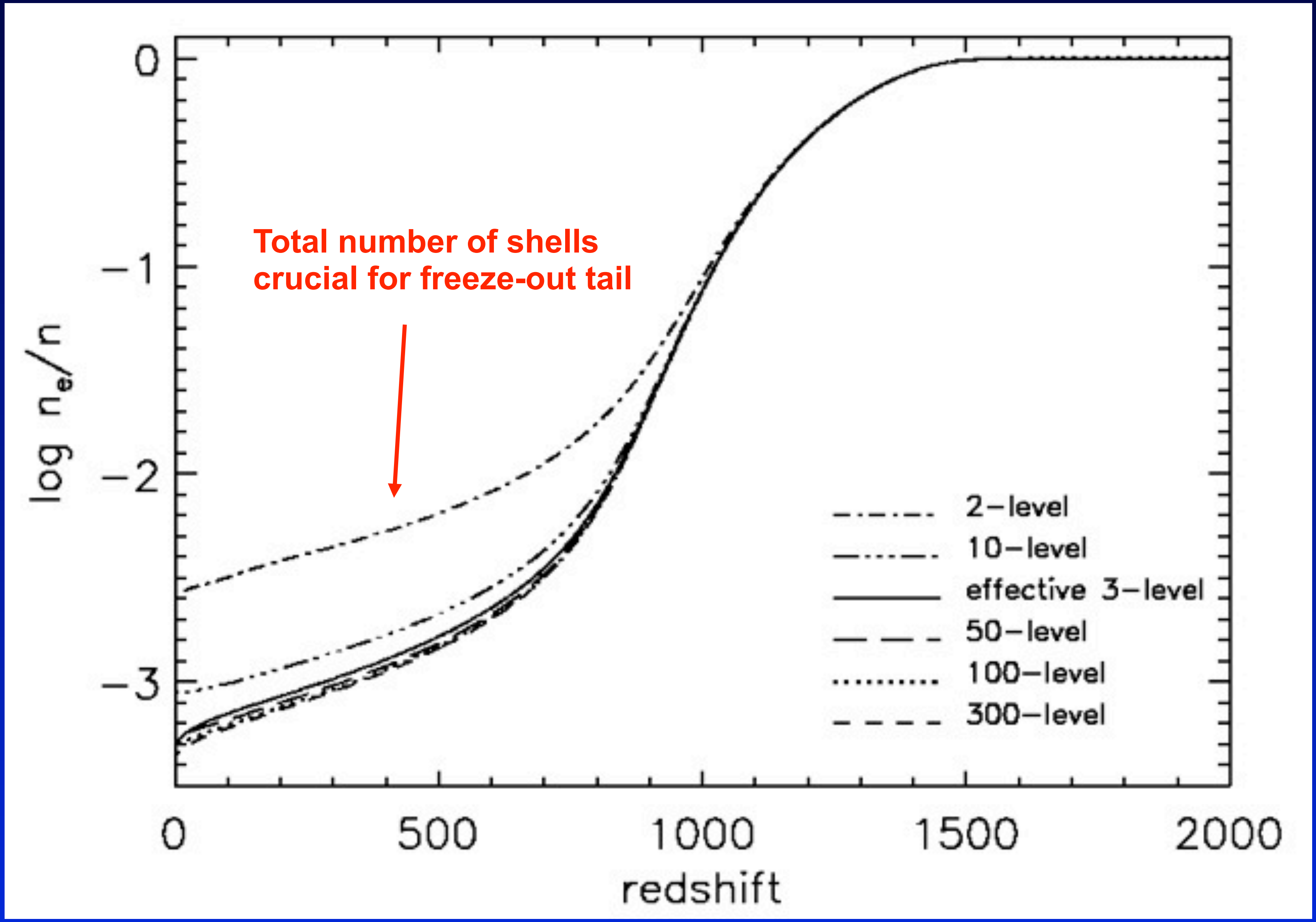

Total number of shells crucial for freeze-out tail

Seager, Sasselov & Scott, 1999, ApJL, 523, L1
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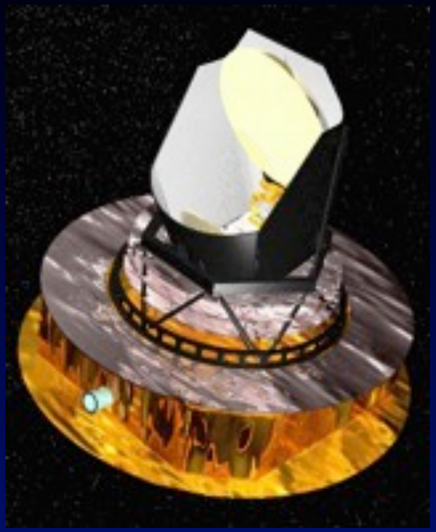
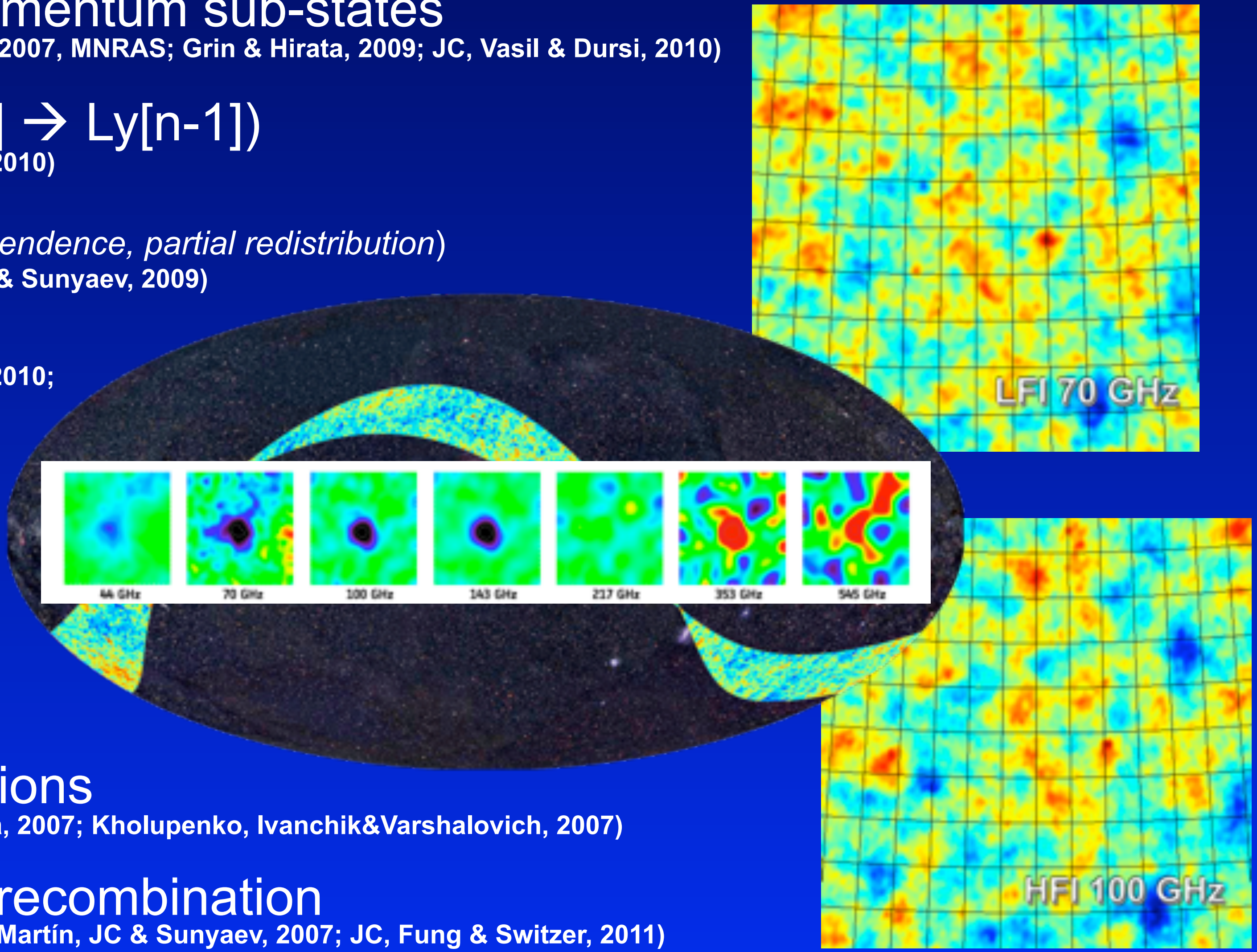
$\Delta N_e \,/\, N_e \sim 1\% - 3\%$

Getting the job done for Planck



Hydrogen recombination

- Two-photon decays from higher levels
  (Dubrovich & Grachev, 2005, Astr. Lett., 31, 359; Wong & Scott, 2007; JC & Sunyaev, 2007; Hirata, 2008; JC & Sunyaev 2009)
- Induced 2s two-photon decay for hydrogen
  (JC & Sunyaev, 2006, A&A, 446, 39; Hirata 2008)
- Feedback of the Lyman-α distortion on the 1s-2s two-photon absorption rate
  (Kholupenko & Ivanchik, 2006, Astr. Lett.; Fendt et al. 2008; Hirata 2008)
- Non-equilibrium effects in the angular momentum sub-states
  (Rubiño-Martín, JC & Sunyaev, 2006, MNRAS; JC, Rubiño-Martín & Sunyaev, 2007, MNRAS; Grin & Hirata, 2009; JC, Vasil & Dursi, 2010)
- Feedback of Lyman-series photons (Ly[n] → Ly[n-1])
  (JC & Sunyaev, 2007, A&A; Kholupenko et al. 2010; Haimoud, Grin & Hirata, 2010)
- Lyman-α escape problem (*atomic recoil, time-dependence, partial redistribution*)
  (Dubrovich & Grachev, 2008; JC & Sunyaev, 2008; Forbes & Hirata, 2009; JC & Sunyaev, 2009)
- Collisions and Quadrupole lines
  (JC, Rubiño-Martín & Sunyaev, 2007; Grin & Hirata, 2009; JC, Vasil & Dursi, 2010; JC, Fung & Switzer, 2011)
- Raman scattering
  (Hirata 2008; JC & Thomas , 2010; Haimoud & Hirata, 2010)



Helium recombination

- Similar list of processes as for hydrogen
  (Switzer & Hirata, 2007a&b; Hirata & Switzer, 2007)
- Spin forbidden 2p-1s triplet-singlet transitions
  (Dubrovich & Grachev, 2005, Astr. Lett.; Wong & Scott, 2007; Switzer & Hirata, 2007; Kholupenko, Ivanchik&Varshalovich, 2007)
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- Detailed feedback of helium photons
  (Switzer & Hirata, 2007a; JC & Sunyaev, 2009, MNRAS; JC, Fung & Switzer, 2011)

$\Delta N_e \;/\; N_e \sim 0.1\,\%$

Solving the problem for the Planck Collaboration was a common effort!

Recombination Physics Meeting in Orsay 2008

see: http://www.b-pol.org/RecombinationConference/

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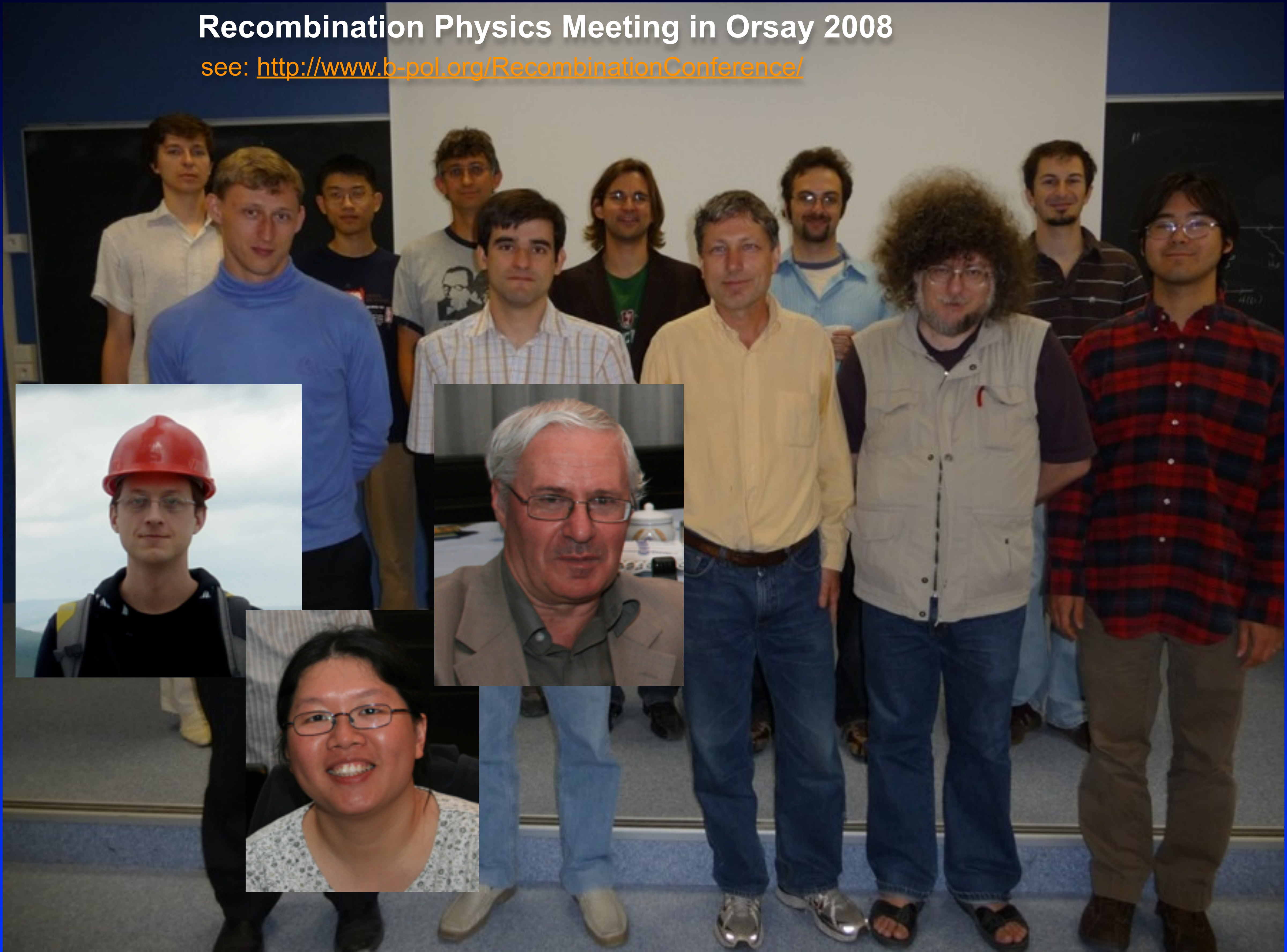

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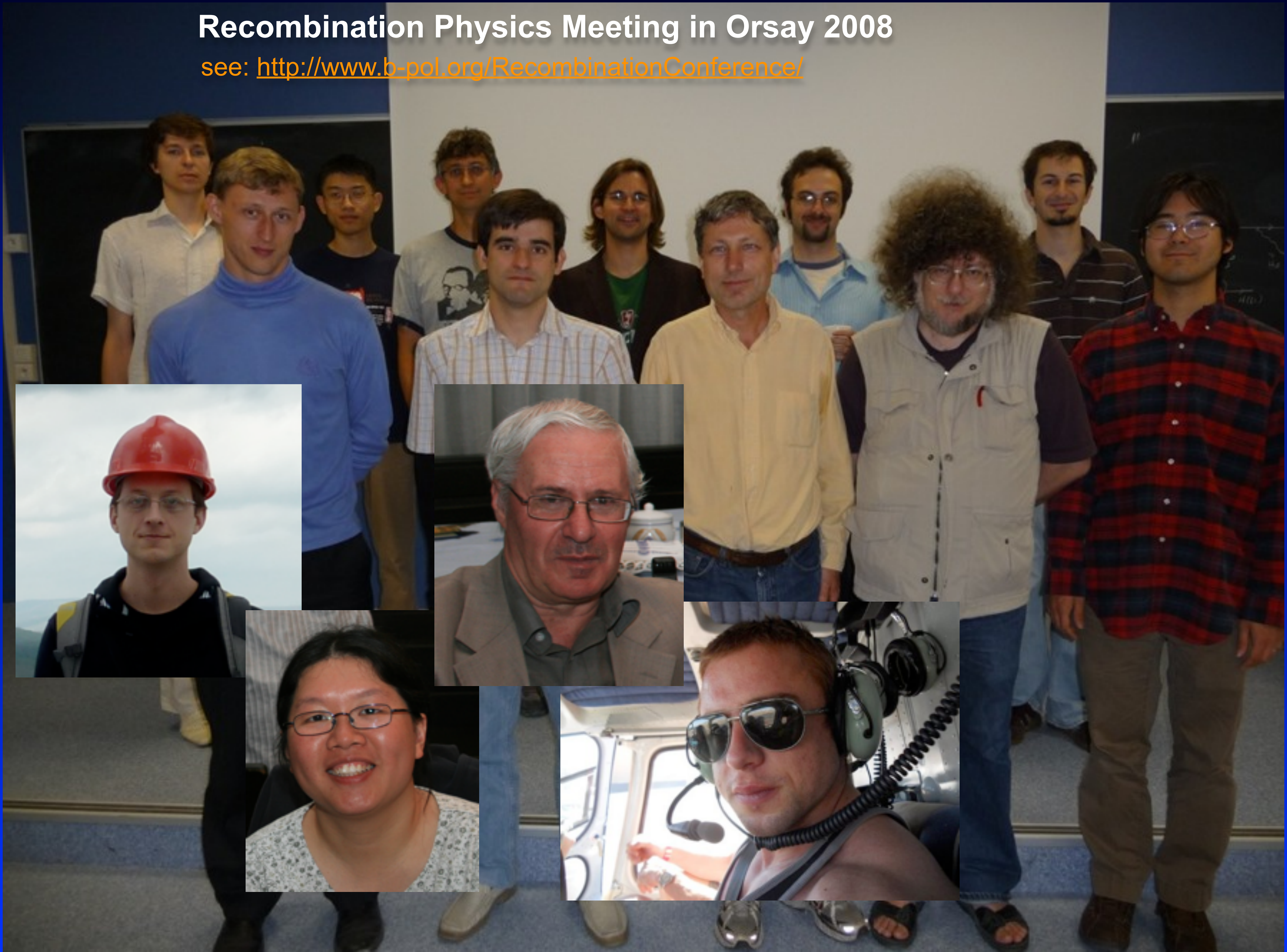

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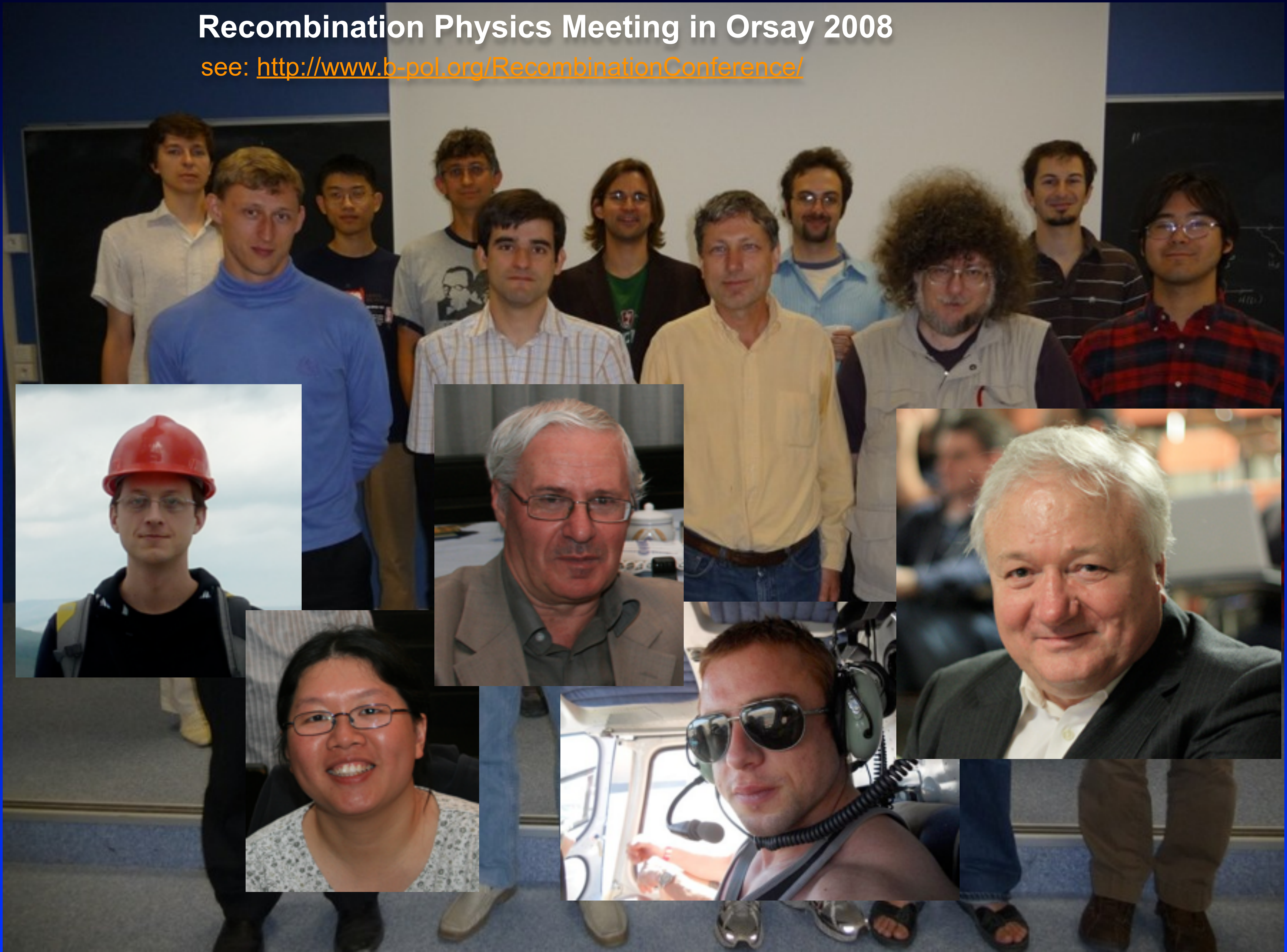

Recombination Physics Meeting in Orsay 2008

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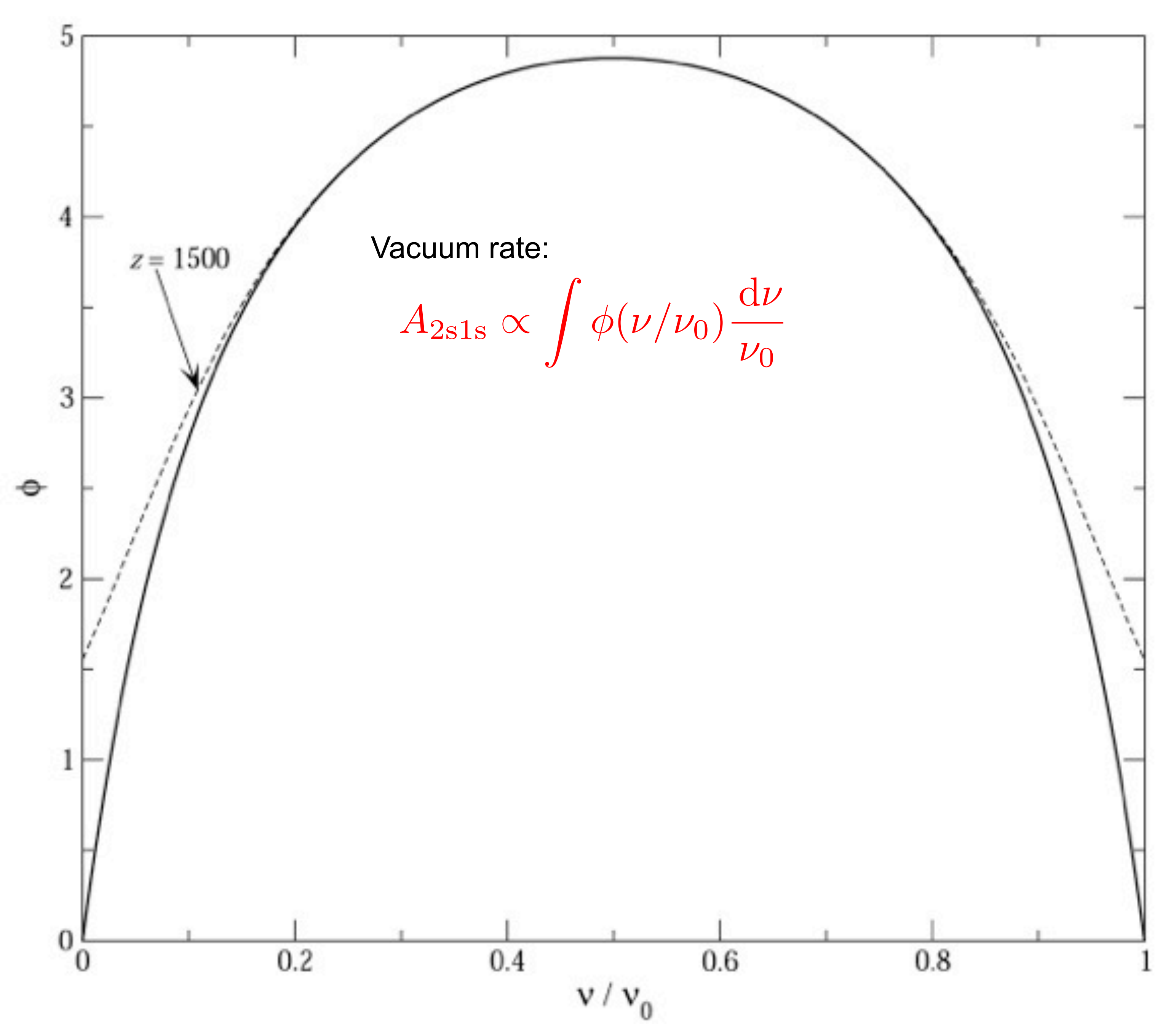
Simple example: stimulated 2s →1s decay



Vacuum rate:

$$A_{2s1s} \propto \int \phi(\nu/\nu_0)\,\frac{d\nu}{\nu_0}$$

2s-1s emission profile

Transition rate in vacuum

→ A_{2s1s}~ 8.22 sec^{-1}

CMB ambient photons field

→ A_{2s1s} increased by ~1%-2%

→ HI - recombination faster by $\Delta N_e/N_e$ ~ 1.3%

JC & Sunyaev, 2006, A&A

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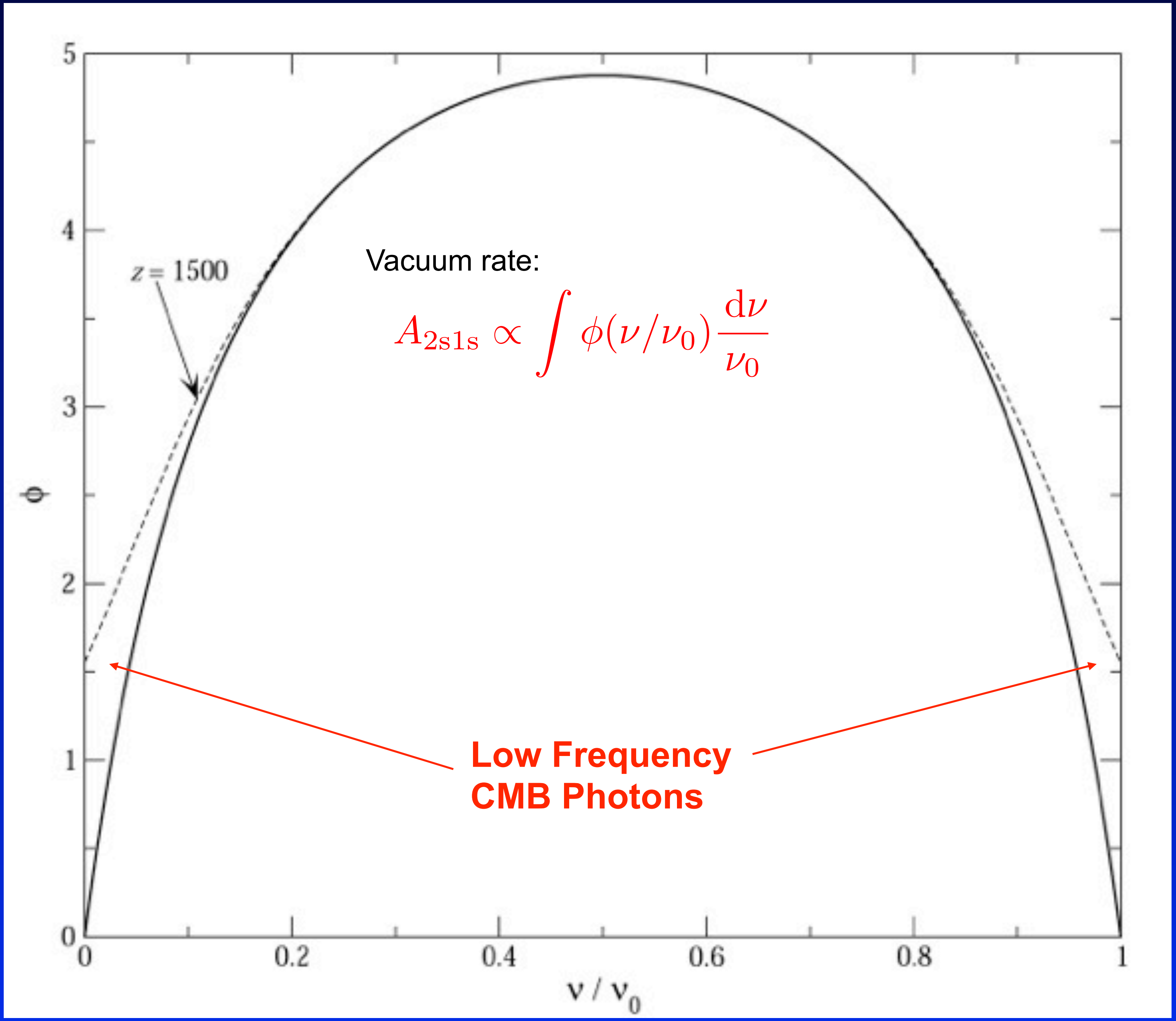

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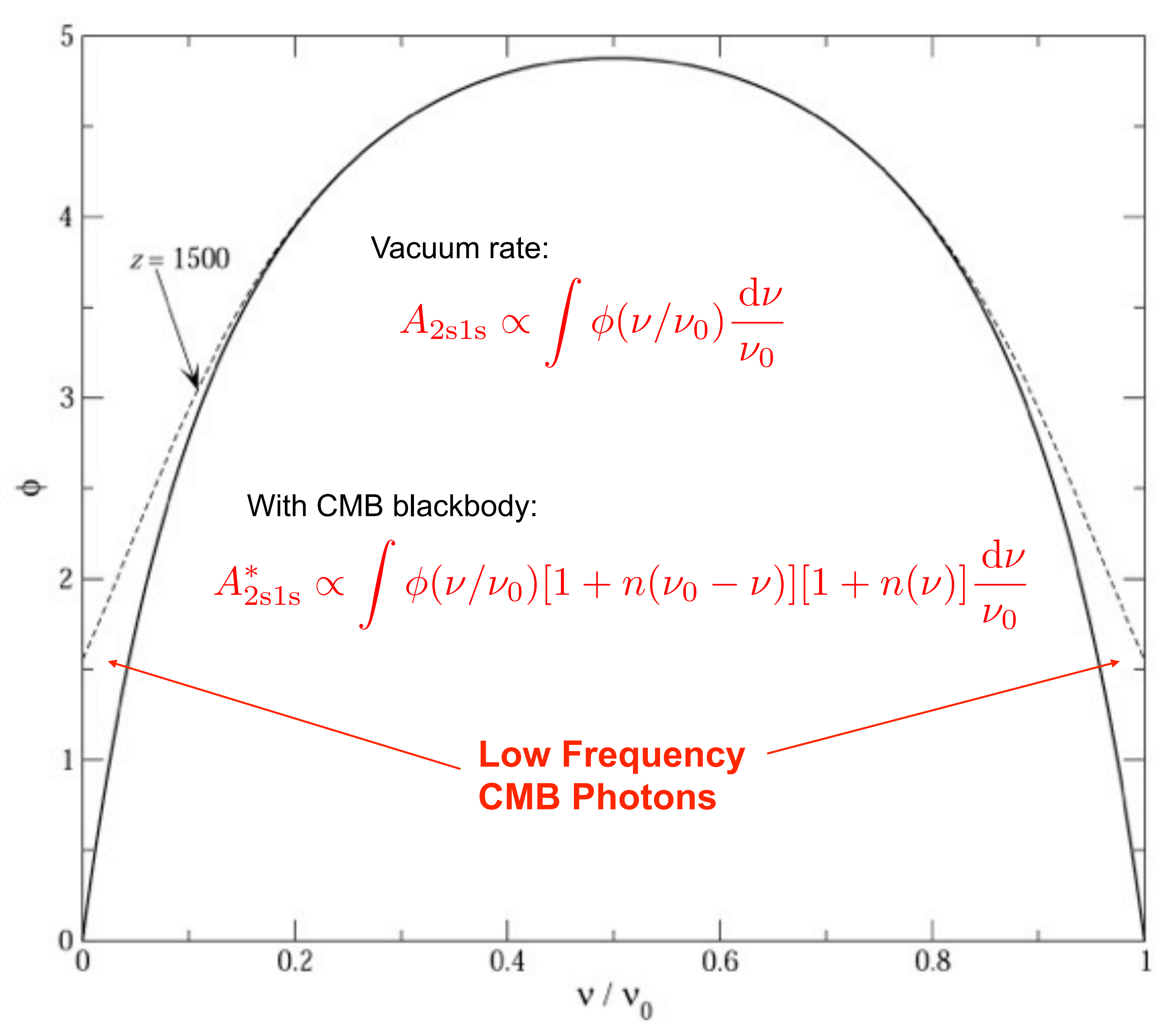

Vacuum rate:

$$A_{2\mathrm{s}1\mathrm{s}} \propto \int \phi(\nu/\nu_0)\, \frac{\mathrm{d}\nu}{\nu_0}$$

With CMB blackbody:

$$A^*_{2\mathrm{s}1\mathrm{s}} \propto \int \phi(\nu/\nu_0)[1 + n(\nu_0 - \nu)][1 + n(\nu)]\, \frac{\mathrm{d}\nu}{\nu_0}$$

Low Frequency CMB Photons

2s-1s emission profile

Transition rate in vacuum

→ A_{2s1s}~ 8.22 sec^{-1}

CMB ambient photons field

→ A_{2s1s} increased by ~1%-2%

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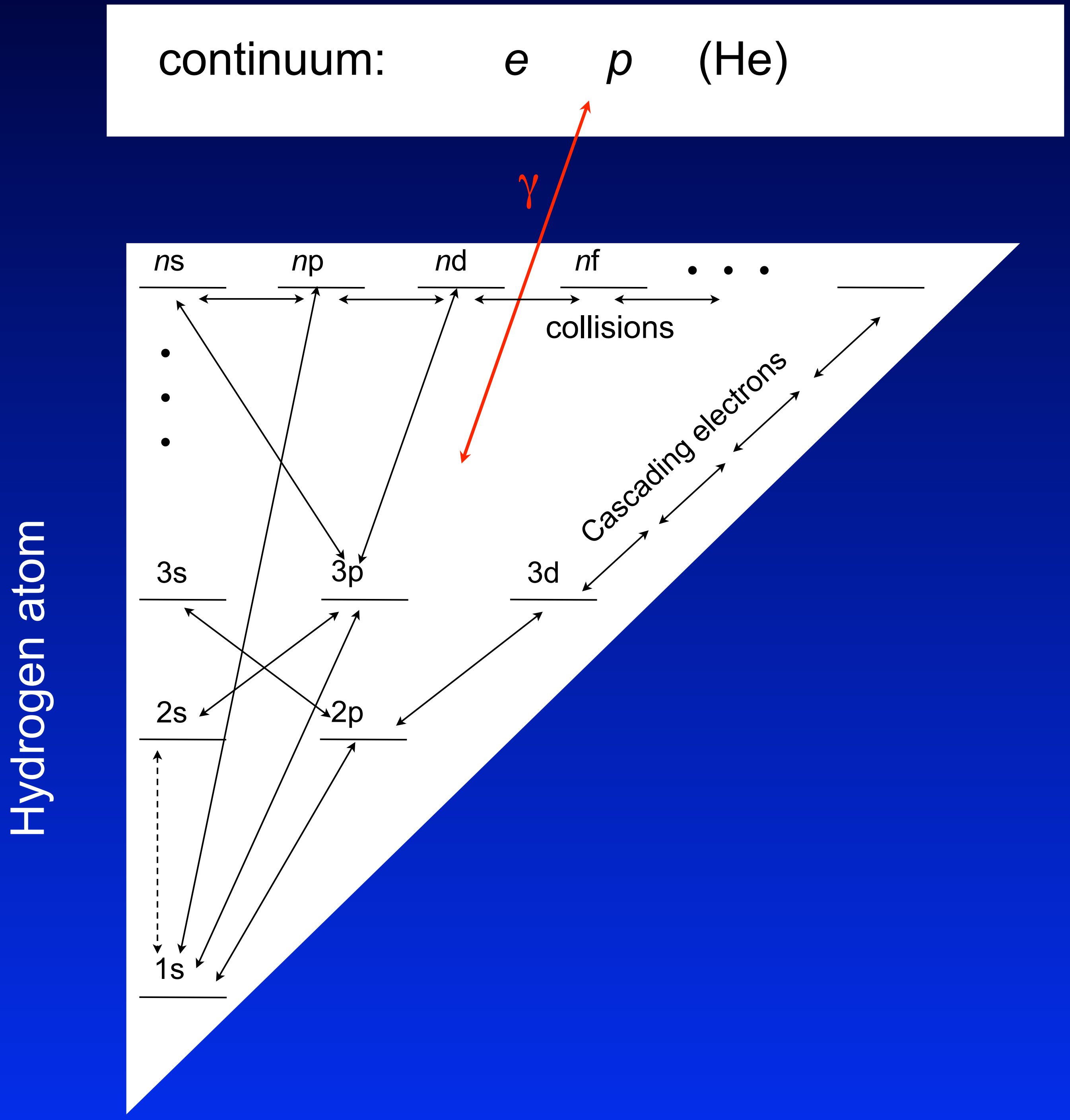
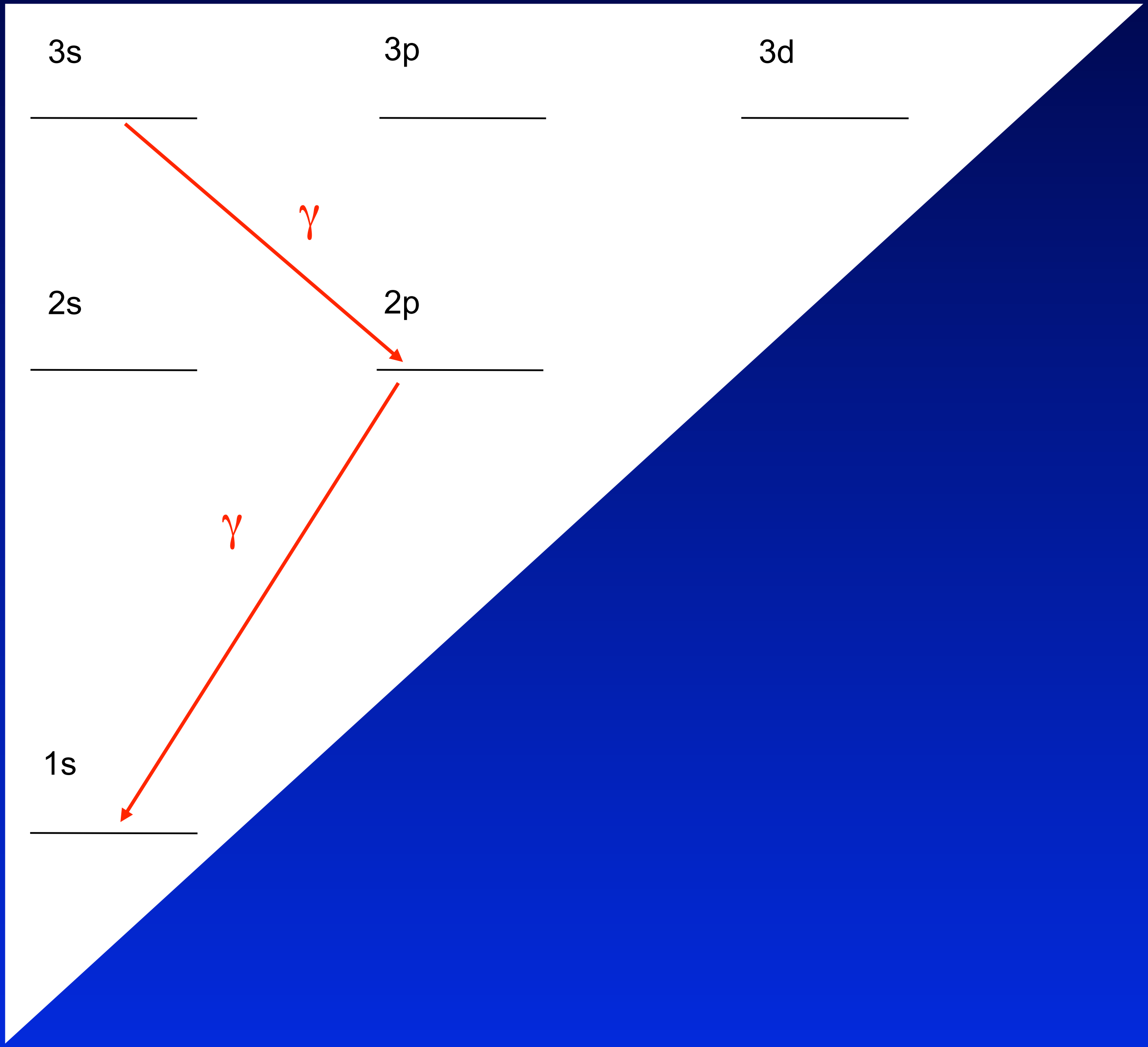
JC & Sunyaev, 2006, A&A

Processes for the upper levels



- recombination & photoionization
  - *n* small → *l*-dependence not drastic
  - high shells → more likely to *l*<<*n*
  - large *n* → *induced* recombination
- many radiative dipole transitions
  - Lyman-series optically thick
  - $\Delta l = \pm 1$ restriction (electron cascade)
  - large *n* & small Δn → *induced* emission
- *l*-changing collisions
  - help to establish full SE within the shell
  - only effective for *n* > 25-30
- *n*-changing collisions
- Collisional photoionization
- Three-body-recombination

Two-photon emission profile



Seaton cascade (1+1 photon)

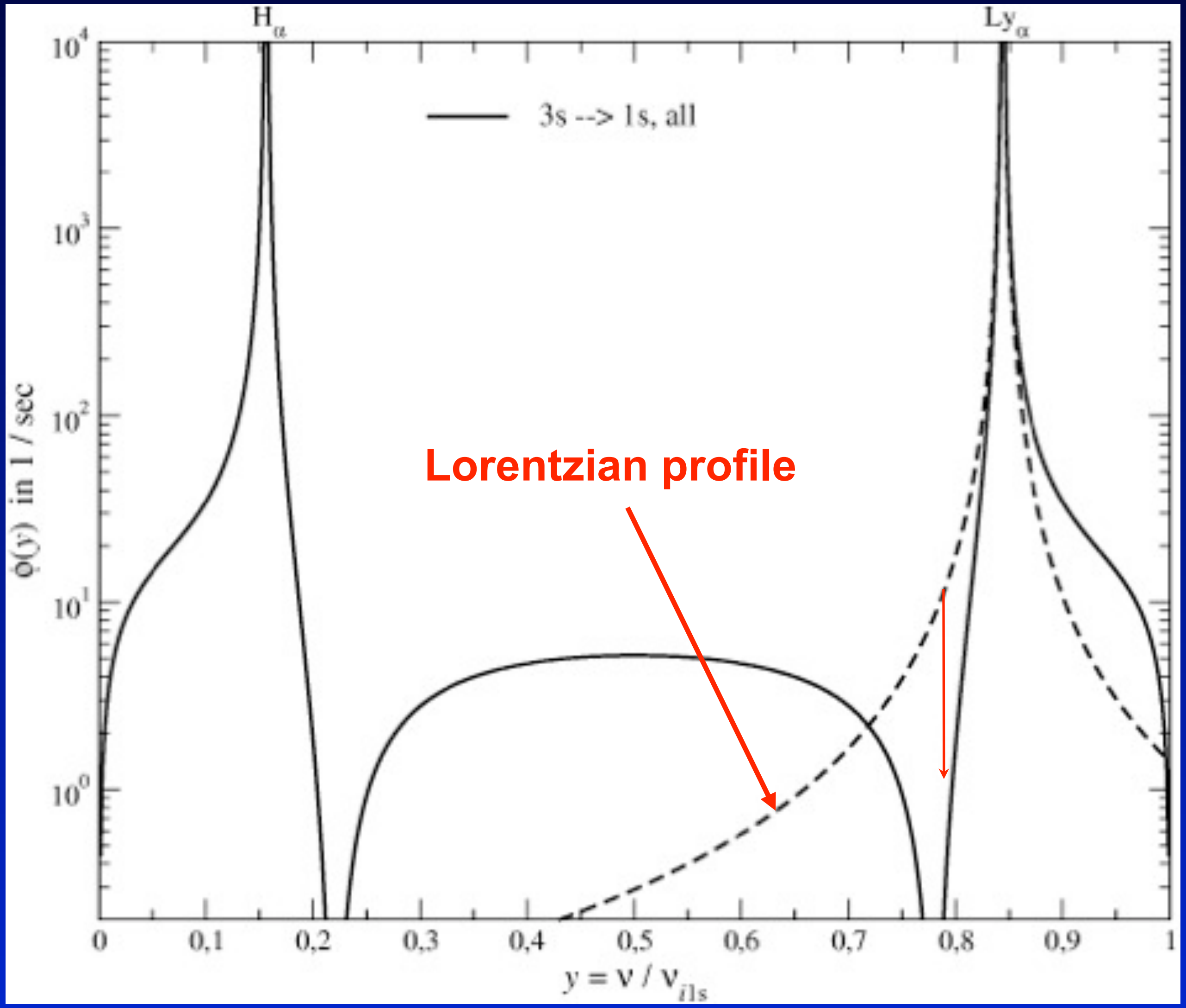
No collisions → two photons (mainly H-α and Ly-α) are emitted!

Maria-Göppert-Mayer (1931): description of two-photon emission as single process in Quantum Mechanics

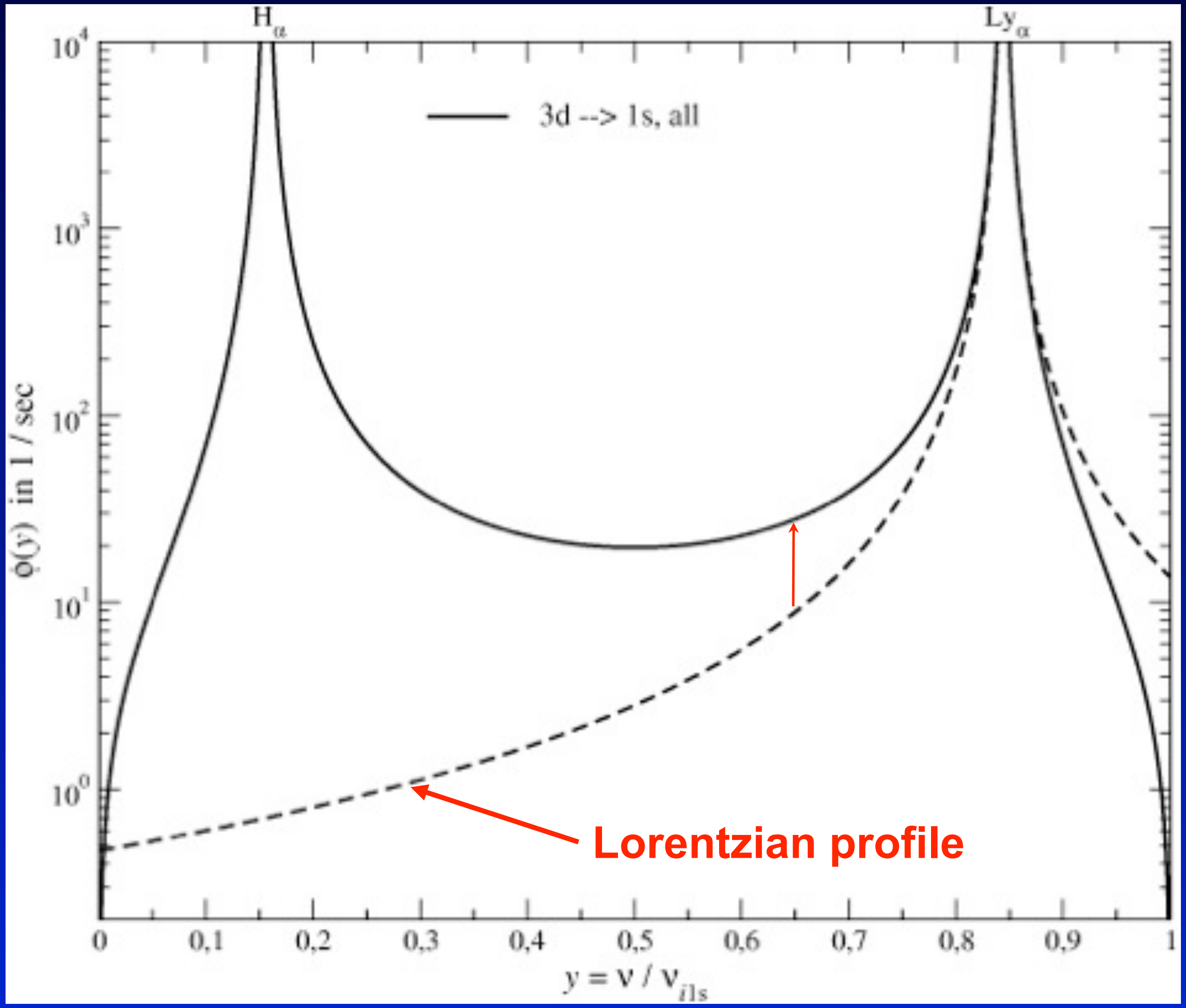
→Deviations of the *two-photon line profile* from the Lorentzian in the damping wings

→Changes in the optically thin (below ~500-5000 Doppler width) parts of the line spectra

3s and 3d two-photon decay spectrum



Lorentzian profile



Lorentzian profile

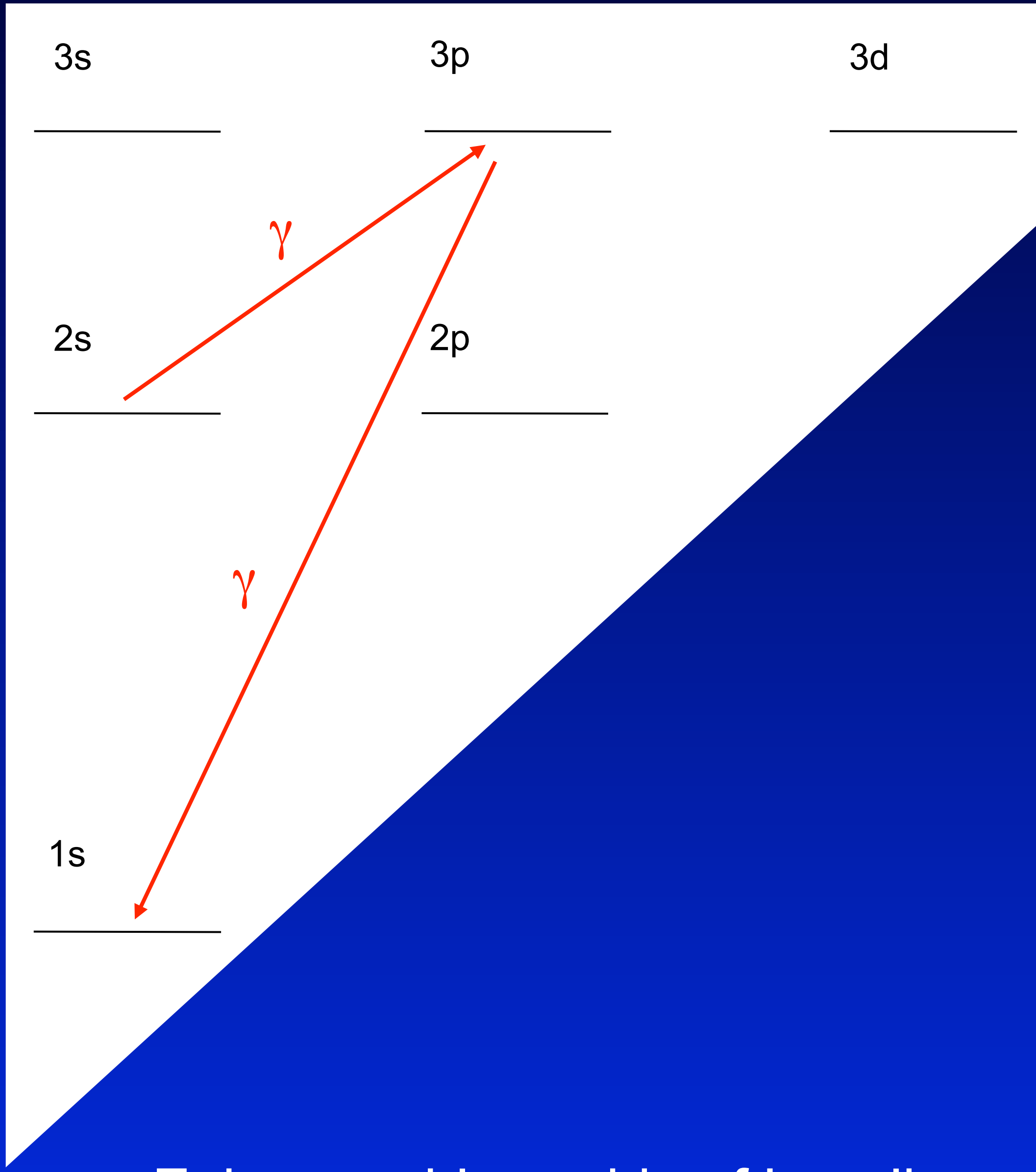
Direct Escape in optically thin regions:

→ HI -recombination is a bit *slower* due to 2γ-transitions from s-states

→ HI -recombination is a bit *faster* due to 2γ-transitions from d-states

JC & Sunyaev, A&A, 2008

2s-1s Raman scattering



- Computation similar to two-photon decay profiles
- collisions weak $\Longrightarrow$ *process needs to be modeled as single quantum act*

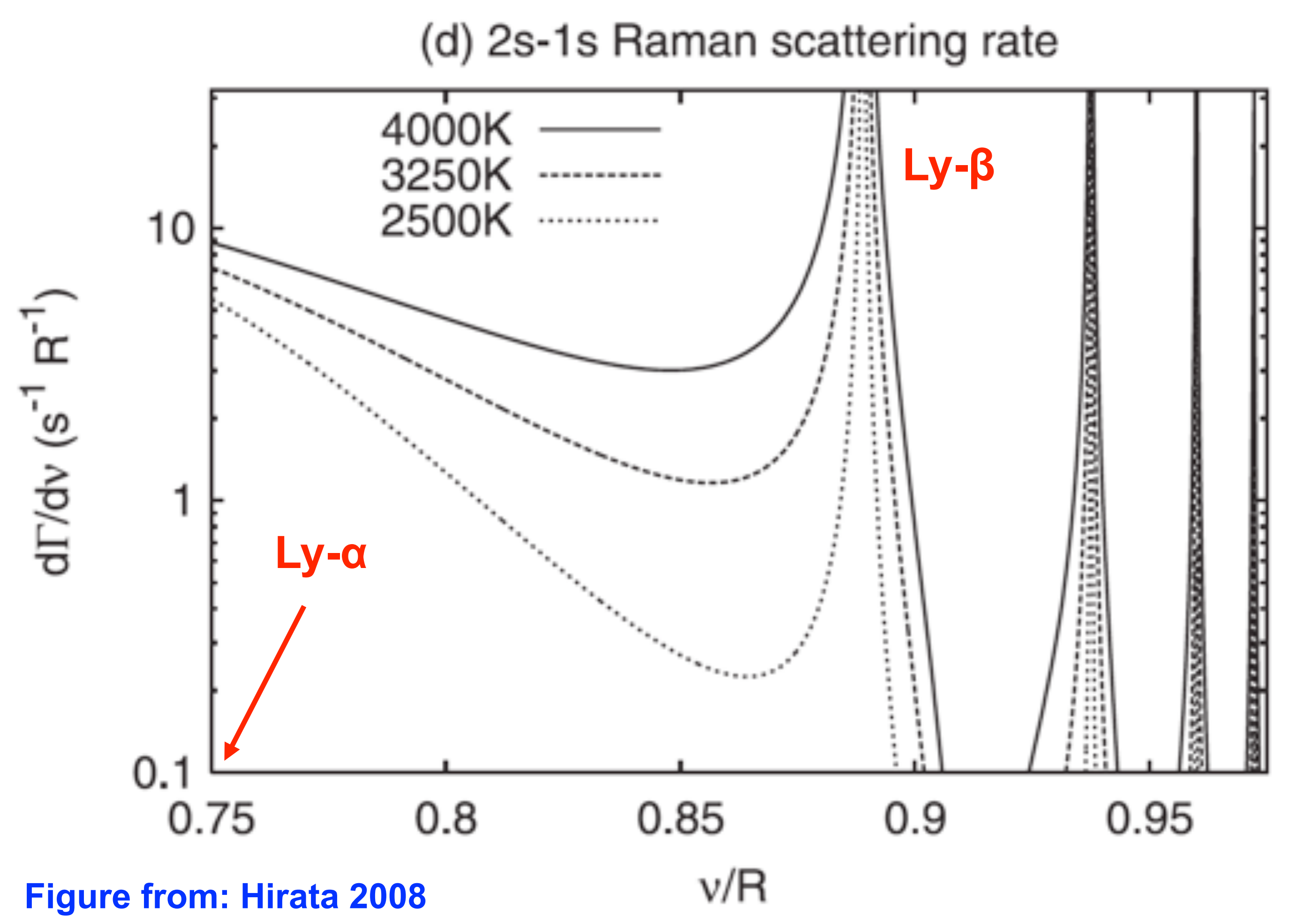
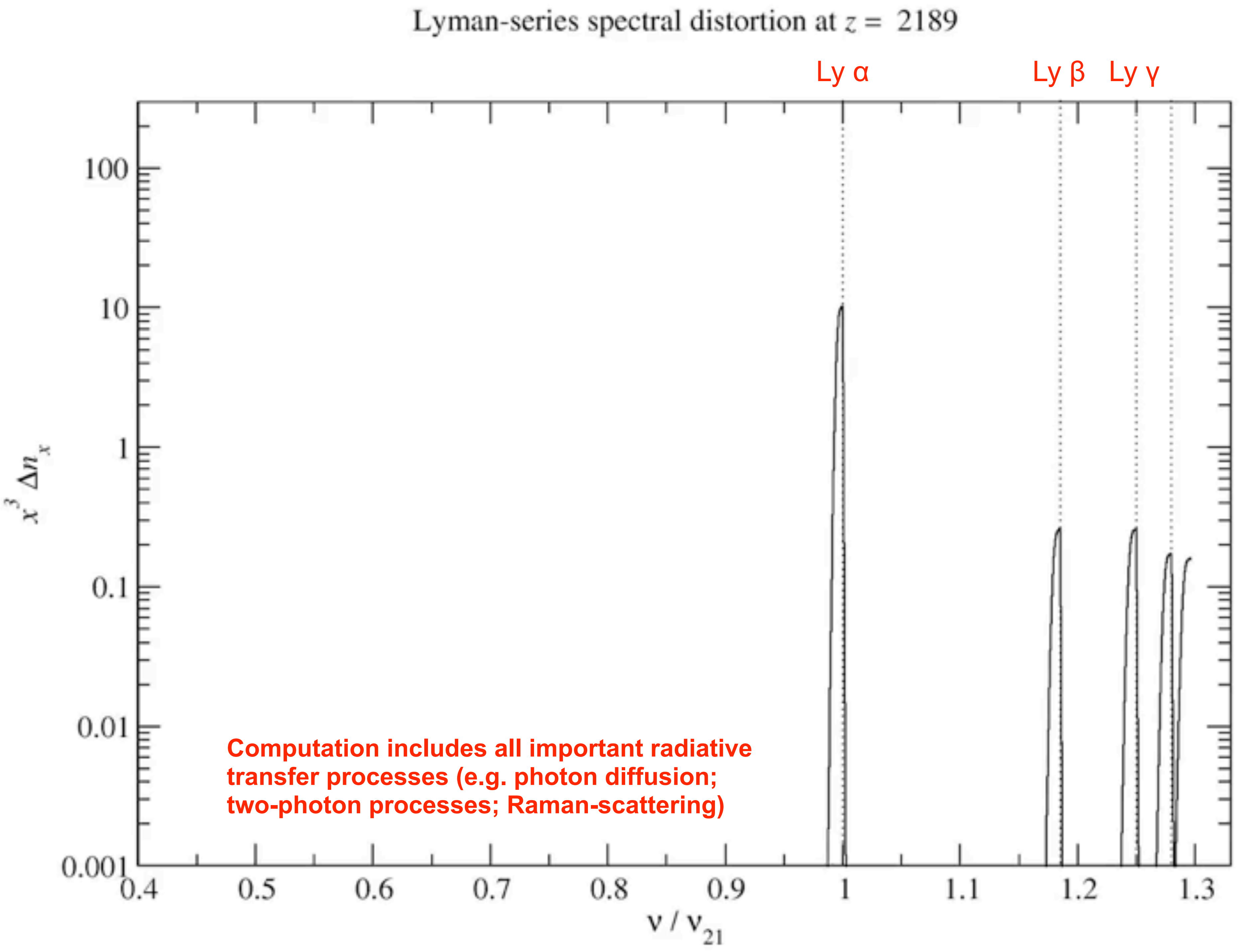


Figure from: Hirata 2008

- Enhances blues side of Ly-α line
- associated feedback delays recombination around z~900

Hirata 2008
JC & Thomas, 2010

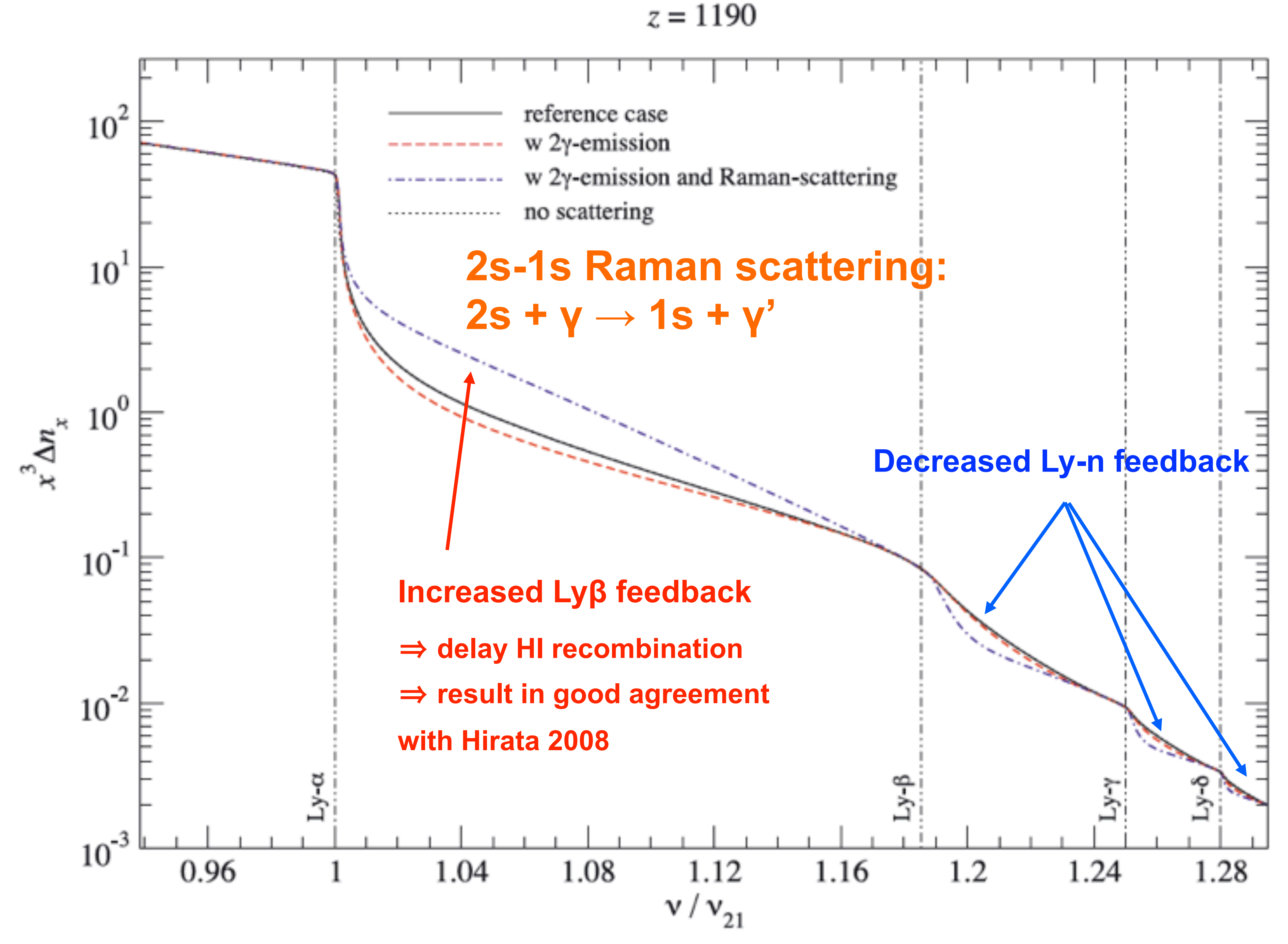
Evolution of the HI Lyman-series distortion



Computation includes all important radiative transfer processes (e.g. photon diffusion; two-photon processes; Raman-scattering)

JC & Thomas, MNRAS, 2010

Effect of Raman scattering and 2γ decays



2s-1s Raman scattering:
$2s + \gamma \rightarrow 1s + \gamma'$

Decreased Ly-n feedback

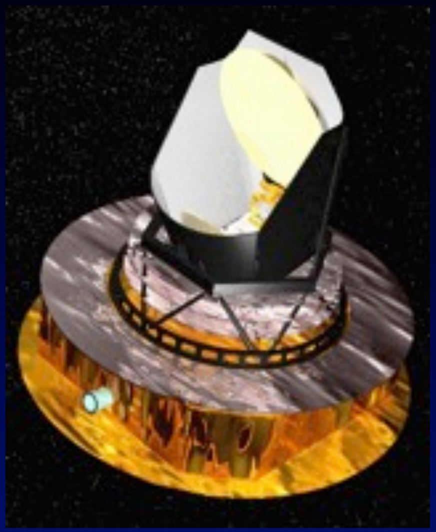
Increased Lyβ feedback

⇒ delay HI recombination

⇒ result in good agreement with Hirata 2008

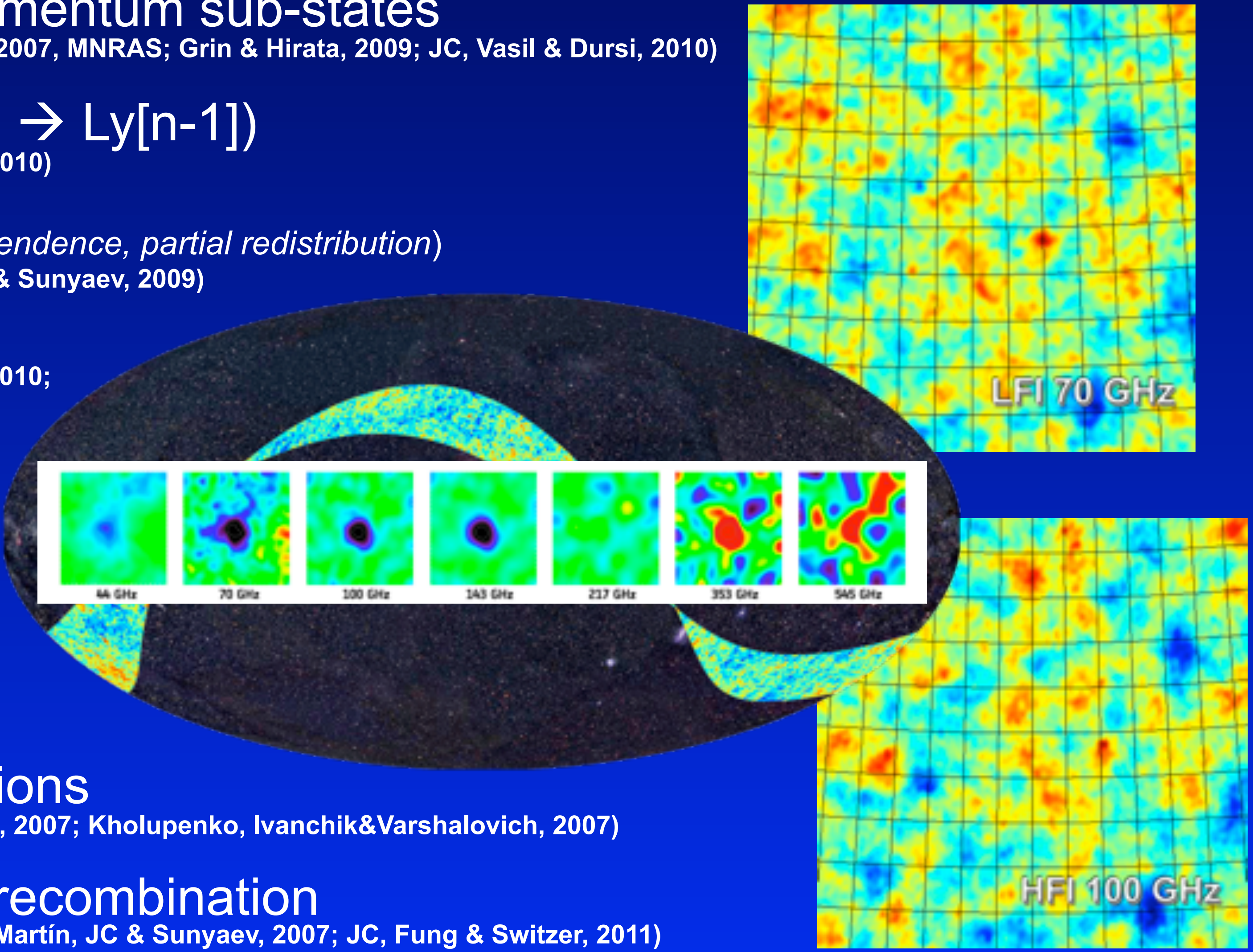
JC & Thomas, MNRAS, 2010

Getting Ready for Planck



Hydrogen recombination

- Two-photon decays from higher levels
  (Dubrovich & Grachev, 2005, Astr. Lett., 31, 359; Wong & Scott, 2007; JC & Sunyaev, 2007; Hirata, 2008; JC & Sunyaev 2009)
- Induced 2s two-photon decay for hydrogen
  (JC & Sunyaev, 2006, A&A, 446, 39; Hirata 2008)
- Feedback of the Lyman-α distortion on the 1s-2s two-photon absorption rate
  (Kholupenko & Ivanchik, 2006, Astr. Lett.; Fendt et al. 2008; Hirata 2008)
- Non-equilibrium effects in the angular momentum sub-states
  (Rubiño-Martín, JC & Sunyaev, 2006, MNRAS; JC, Rubiño-Martín & Sunyaev, 2007, MNRAS; Grin & Hirata, 2009; JC, Vasil & Dursi, 2010)
- Feedback of Lyman-series photons (Ly[n] → Ly[n-1])
  (JC & Sunyaev, 2007, A&A; Kholupenko et al. 2010; Haimoud, Grin & Hirata, 2010)
- Lyman-α escape problem (*atomic recoil, time-dependence, partial redistribution*)
  (Dubrovich & Grachev, 2008; JC & Sunyaev, 2008; Forbes & Hirata, 2009; JC & Sunyaev, 2009)
- Collisions and Quadrupole lines
  (JC, Rubiño-Martín & Sunyaev, 2007; Grin & Hirata, 2009; JC, Vasil & Dursi, 2010; JC, Fung & Switzer, 2011)
- Raman scattering
  (Hirata 2008; JC & Thomas , 2010; Haimoud & Hirata, 2010)



Helium recombination

- Similar list of processes as for hydrogen
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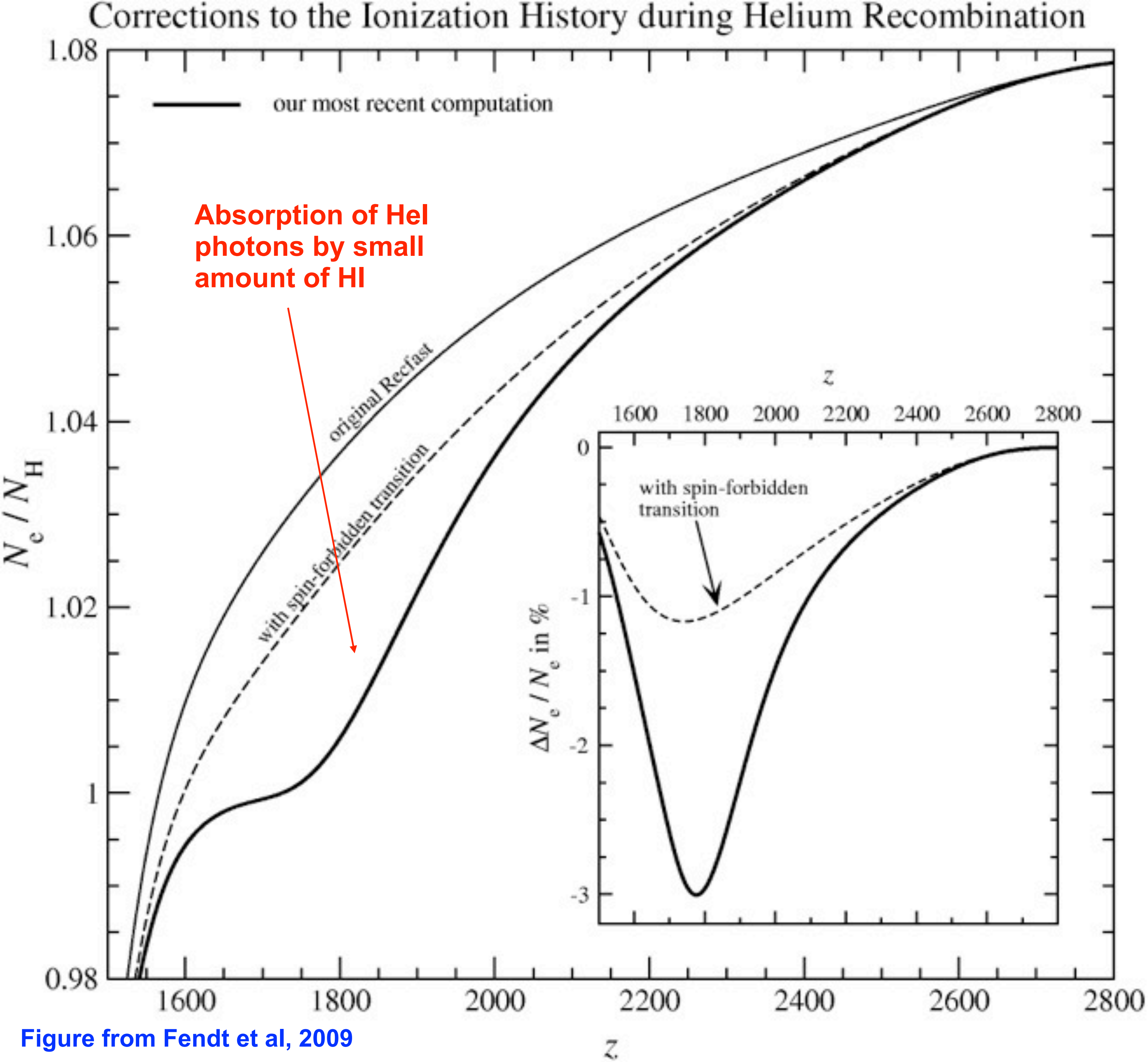
- Detailed feedback of helium photons
  (Switzer & Hirata, 2007a; JC & Sunyaev, 2009, MNRAS; JC, Fung & Switzer, 2011)

$\Delta N_e \;/\; N_e \sim 0.1\ \%$

Main corrections during HeI Recombination

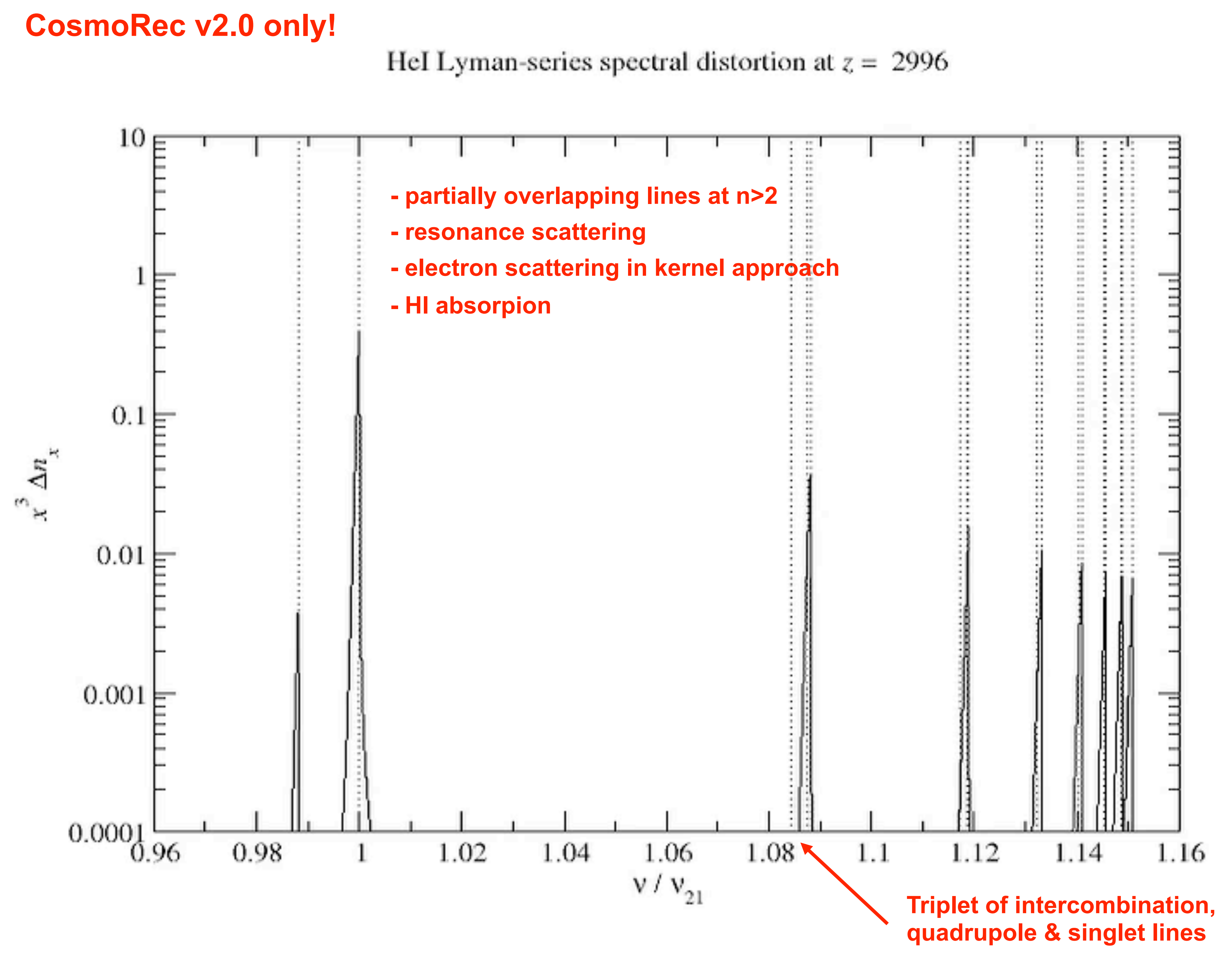


Absorption of HeI photons by small amount of HI

Figure from Fendt et al, 2009

Kholupenko et al, 2007
Switzer & Hirata, 2007

Evolution of the HeI high frequency distortion



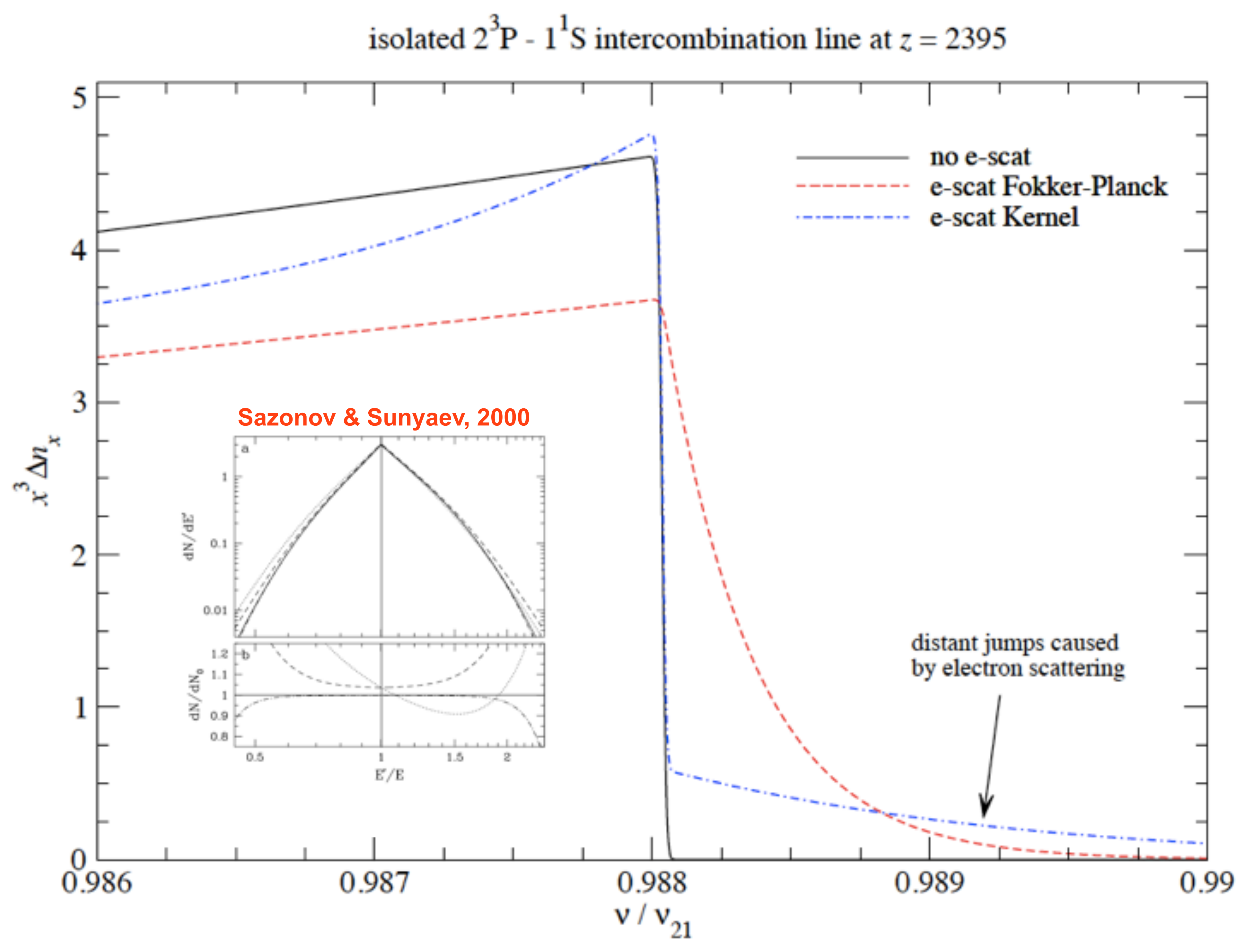
CosmoRec v2.0 only!

- partially overlapping lines at n>2
- resonance scattering
- electron scattering in kernel approach
- HI absorption

Triplet of intercombination, quadrupole & singlet lines

JC, Fung & Switzer, 2011

Effect of electron scattering during HeI recombination



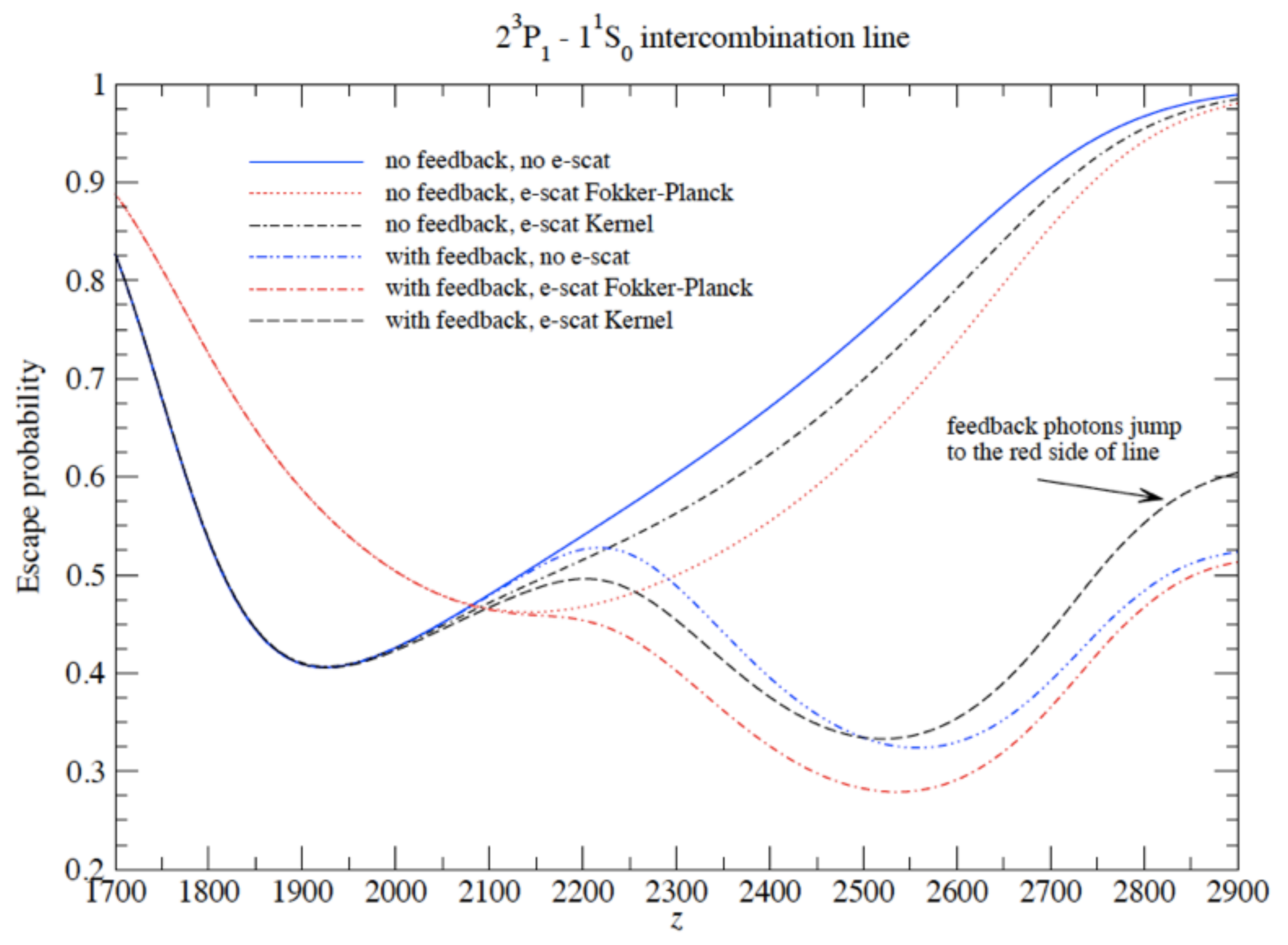
isolated 2^3P - 1^1S intercombination line at $z = 2395$

Sazonov & Sunyaev, 2000

distant jumps caused by electron scattering

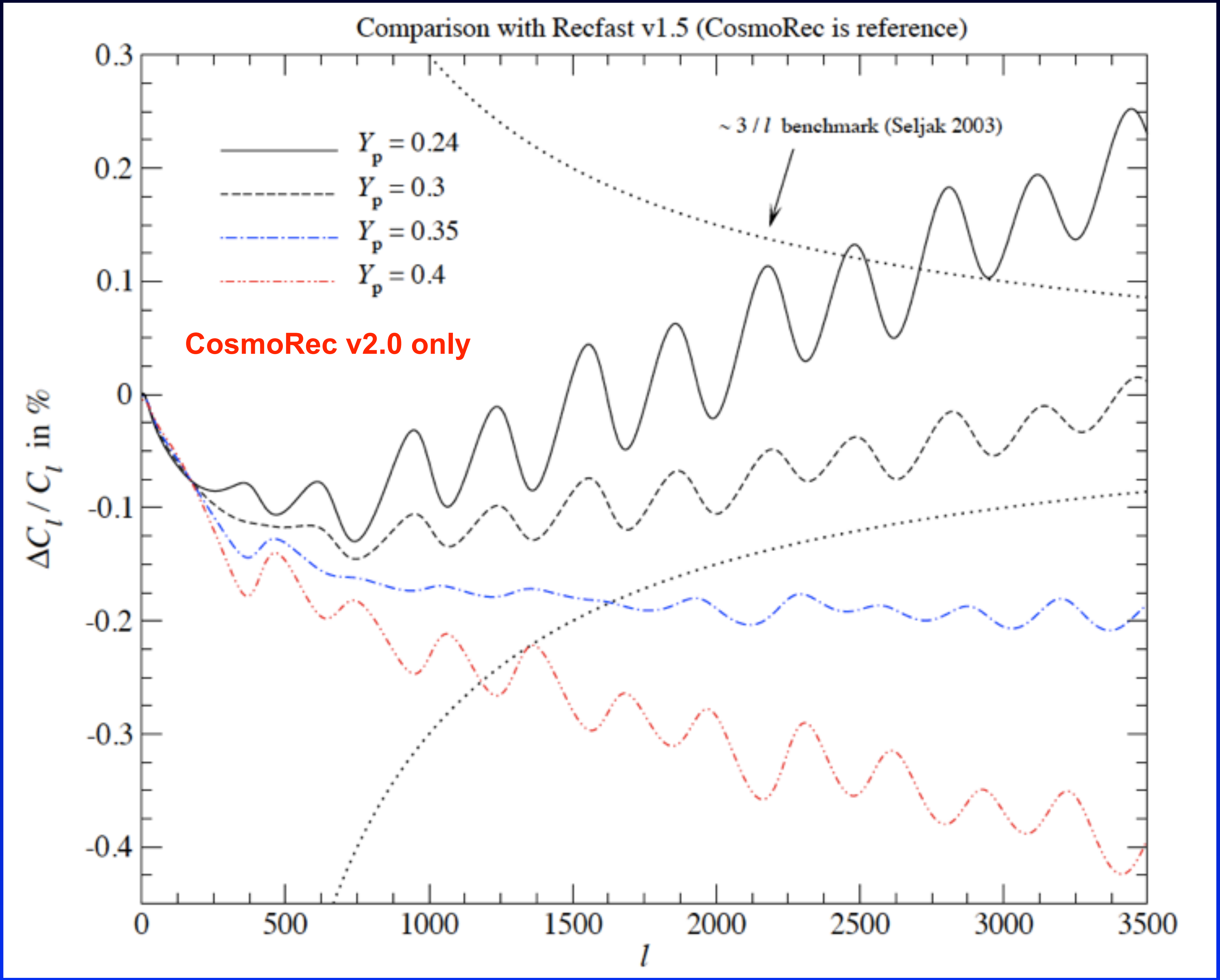
JC, Fung & Switzer, 2011

Effect of electron scattering during HeI recombination



JC, Fung & Switzer, 2011

Overall effect of detailed HeI radiative transfer

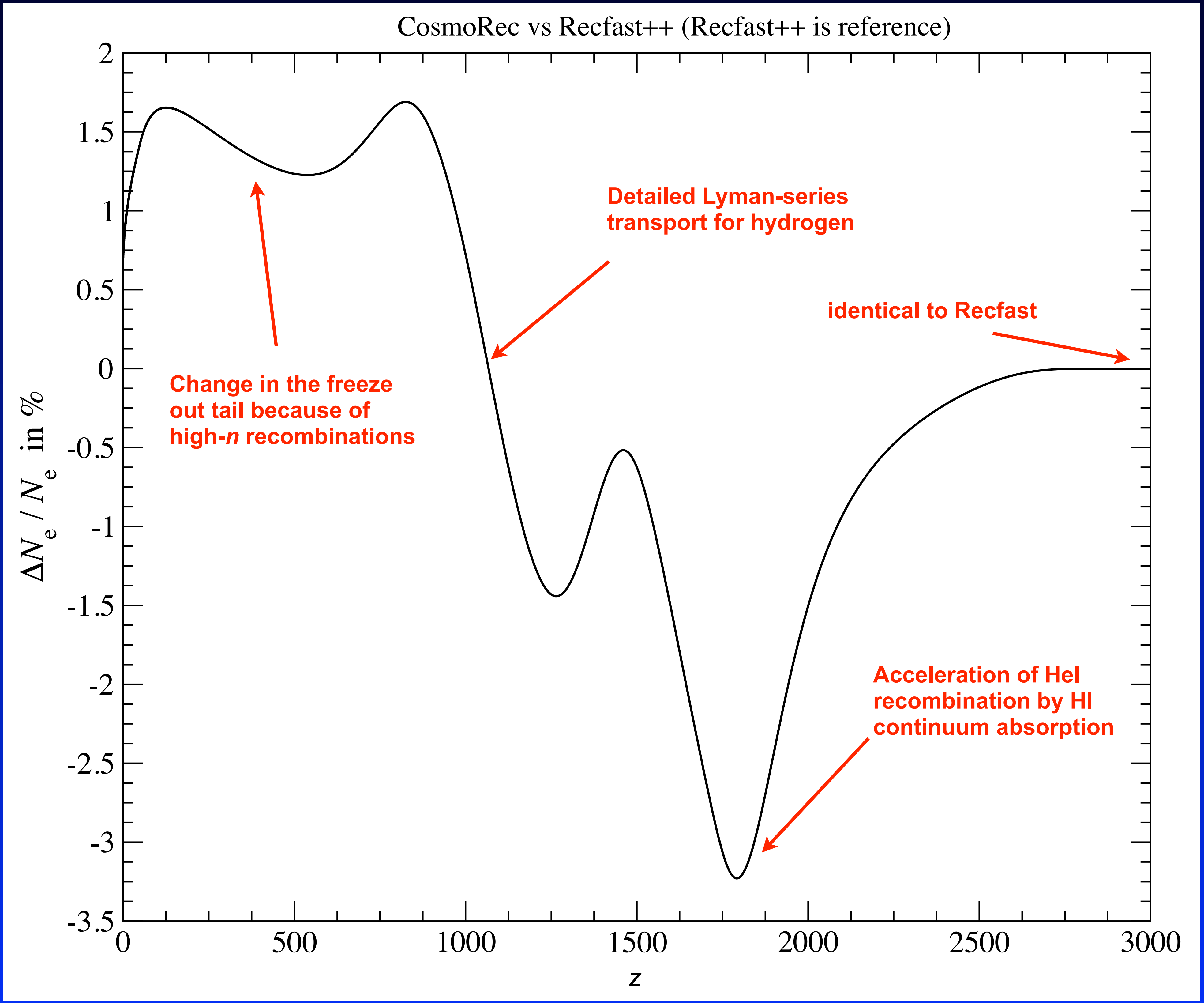


JC, Fung & Switzer, 2011

Cosmological Recombination Code: *CosmoRec*

- uses an effective multi-level approach *(Haimoud & Hirata, 2010)*
- very *accurate* and *fast* (for ‘default’ setting ~1.3 sec per model!)
- solves the detailed radiative transfer problem for Ly-*n*
- no *fudging* *(Recfast)* or *multi-dimensional interpolation* *(RICO)*
- different *runmodes/accuracies* implemented
- easily *extendable* (effect of dark matter annihilation already included)
- was already tested in a wide range of cosmologies
- now runs smoothly with CAMB/CosmoMC **(Shaw & JC, MNRAS, 2011)**
- *CosmoRec* is available at: www.Chluba.de/CosmoRec

Cumulative Changes to the Ionization History



Change in the freeze out tail because of high-*n* recombinations

Detailed Lyman-series transport for hydrogen

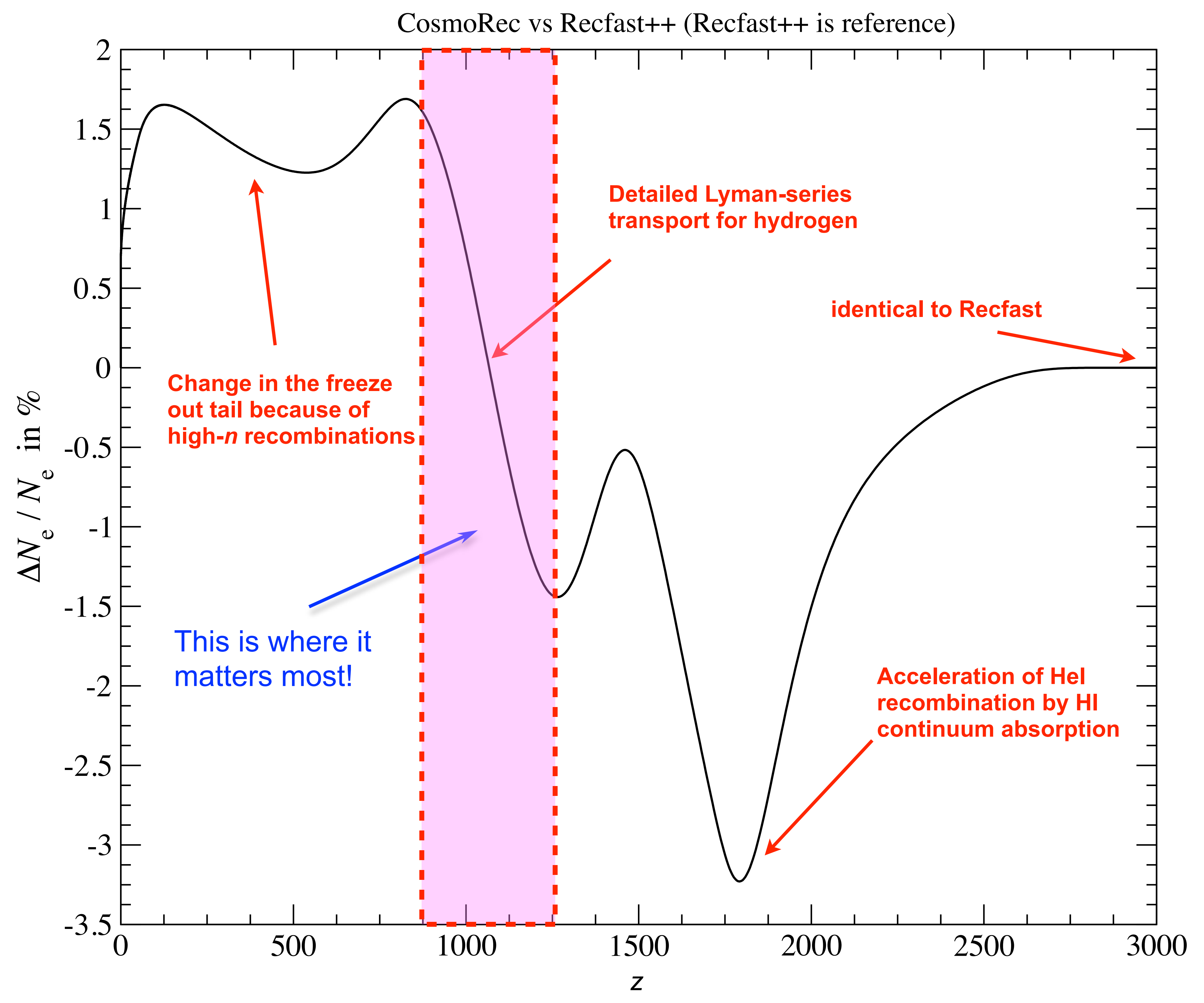
identical to Recfast

Acceleration of HeI recombination by HI continuum absorption

CITA ICAT

JC & Thomas, MNRAS, 2010; Shaw & JC, MNRAS, 2011

Cumulative Changes to the Ionization History



Change in the freeze out tail because of high-*n* recombinations

Detailed Lyman-series transport for hydrogen

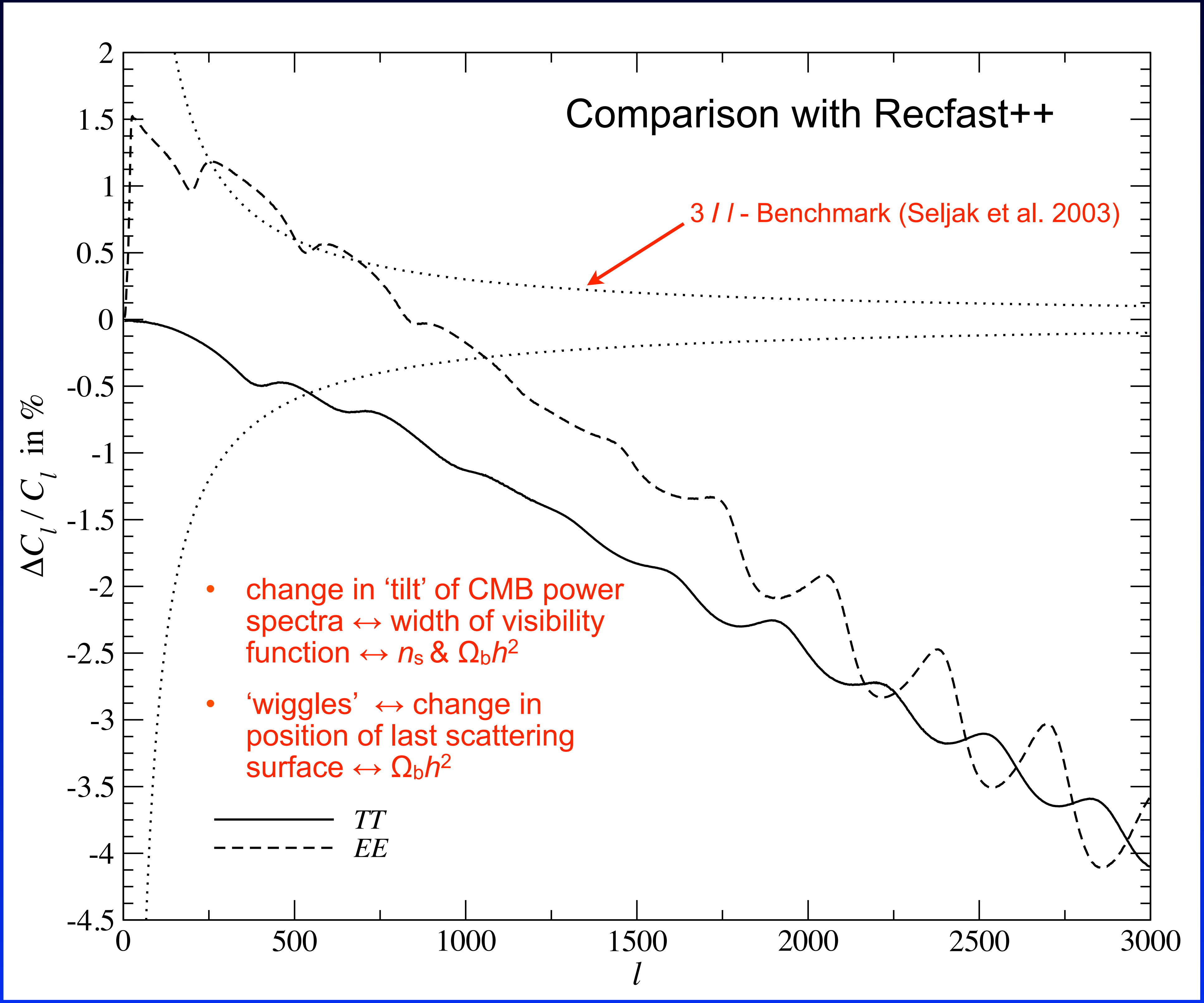
identical to Recfast

This is where it matters most!

Acceleration of HeI recombination by HI continuum absorption

JC & Thomas, MNRAS, 2010; Shaw & JC, MNRAS, 2011

Cumulative Change in the CMB Power Spectra

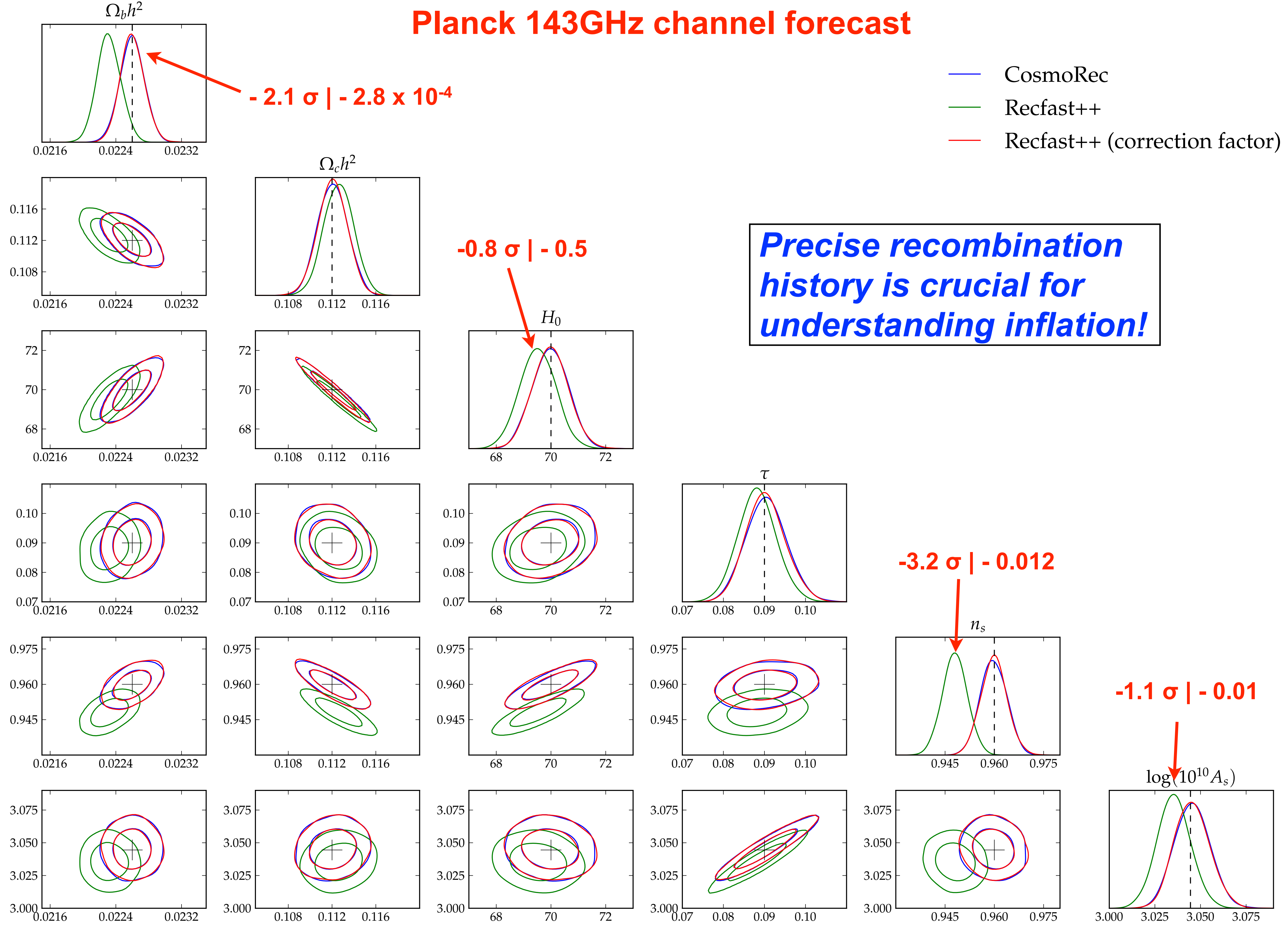


$3\,/\,l$ - Benchmark (Seljak et al. 2003)

- change in 'tilt' of CMB power spectra ↔ width of visibility function ↔ n_s & $\Omega_b h^2$
- 'wiggles' ↔ change in position of last scattering surface ↔ $\Omega_b h^2$

Shaw & JC, MNRAS, 2011

Importance of recombination for inflation



Planck 143GHz channel forecast

- 2.1 σ | - 2.8 x 10^{-4}

-0.8 σ | - 0.5

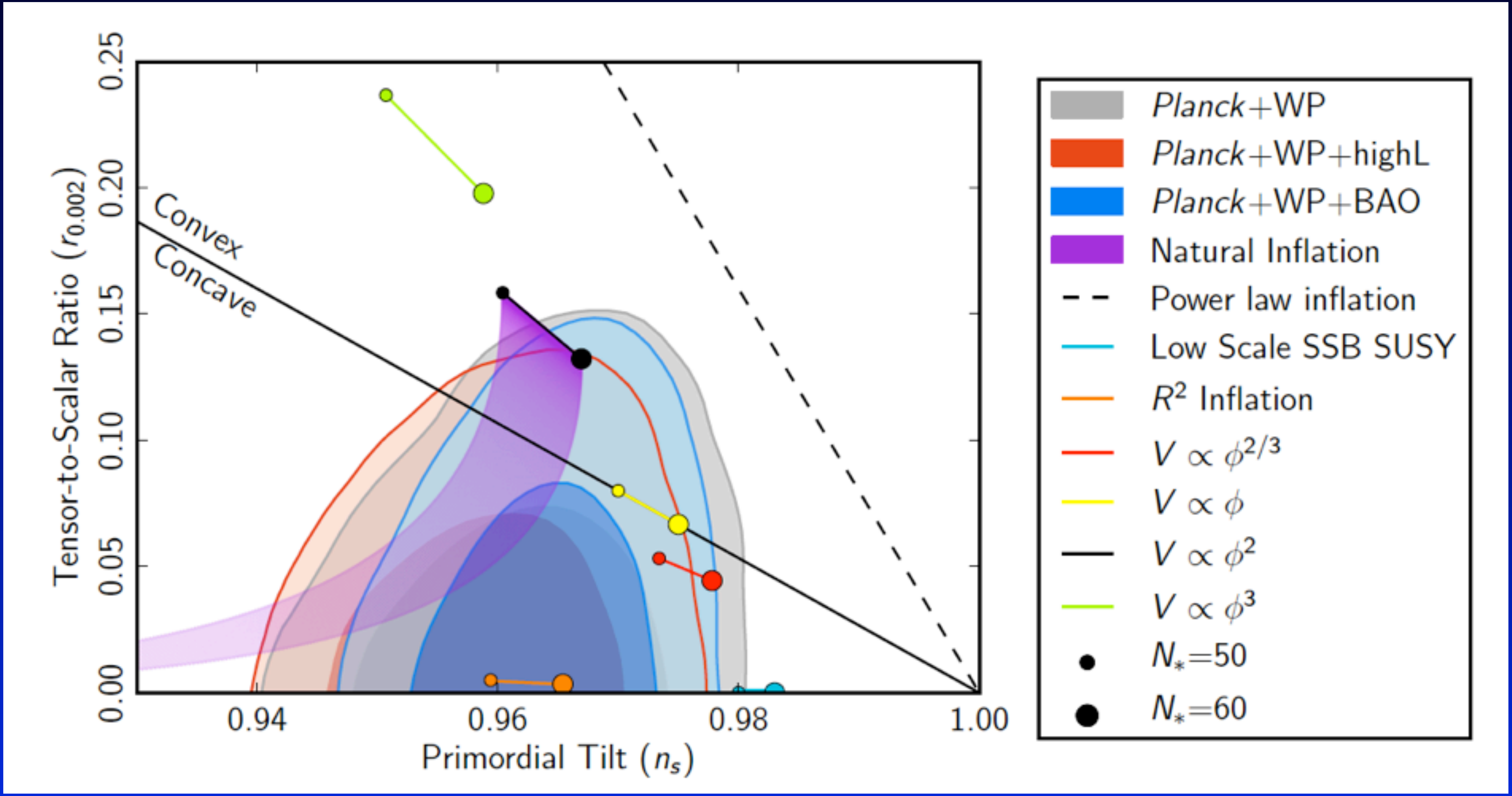
-3.2 σ | - 0.012

-1.1 σ | - 0.01

Precise recombination history is crucial for understanding inflation!

Shaw & JC, 2011, and references therein

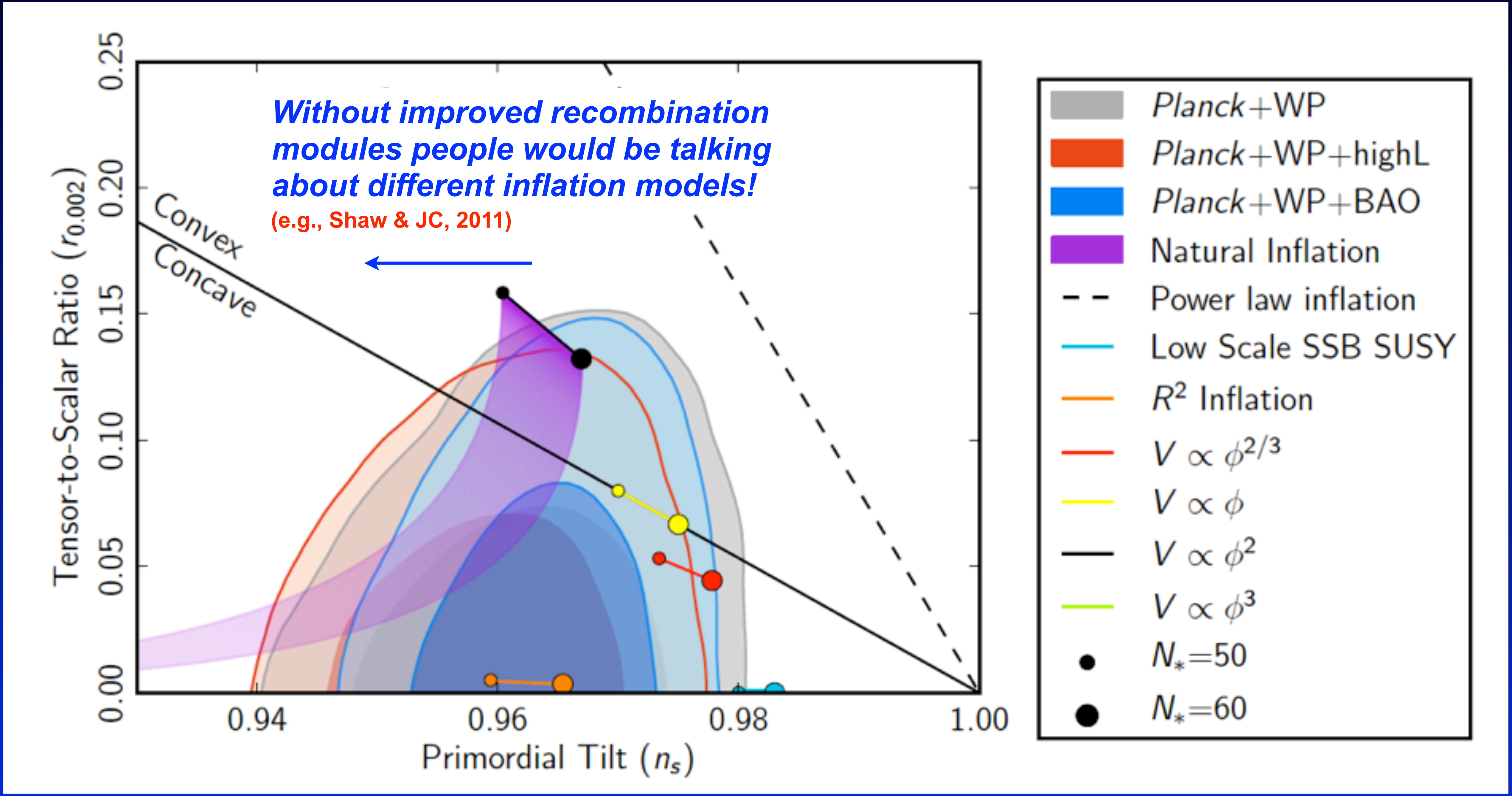
Importance of recombination for inflation constraints



Planck Collaboration, 2013, paper XXII

- Analysis uses refined recombination model (CosmoRec/HyRec)

Importance of recombination for inflation constraints



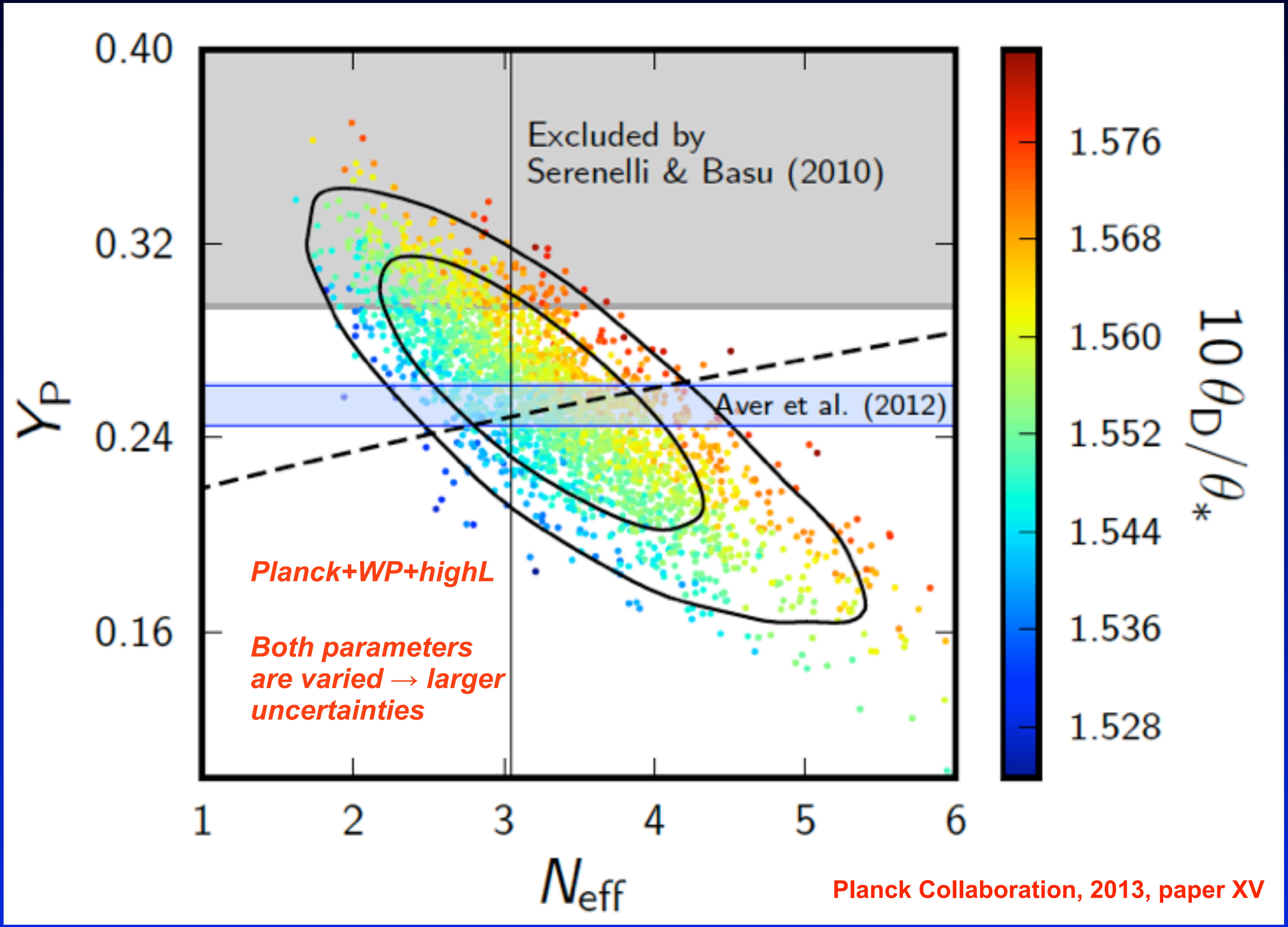
Without improved recombination modules people would be talking about different inflation models!

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

Planck Collaboration, 2013, paper XXII

- Analysis uses refined recombination model (CosmoRec/HyRec)

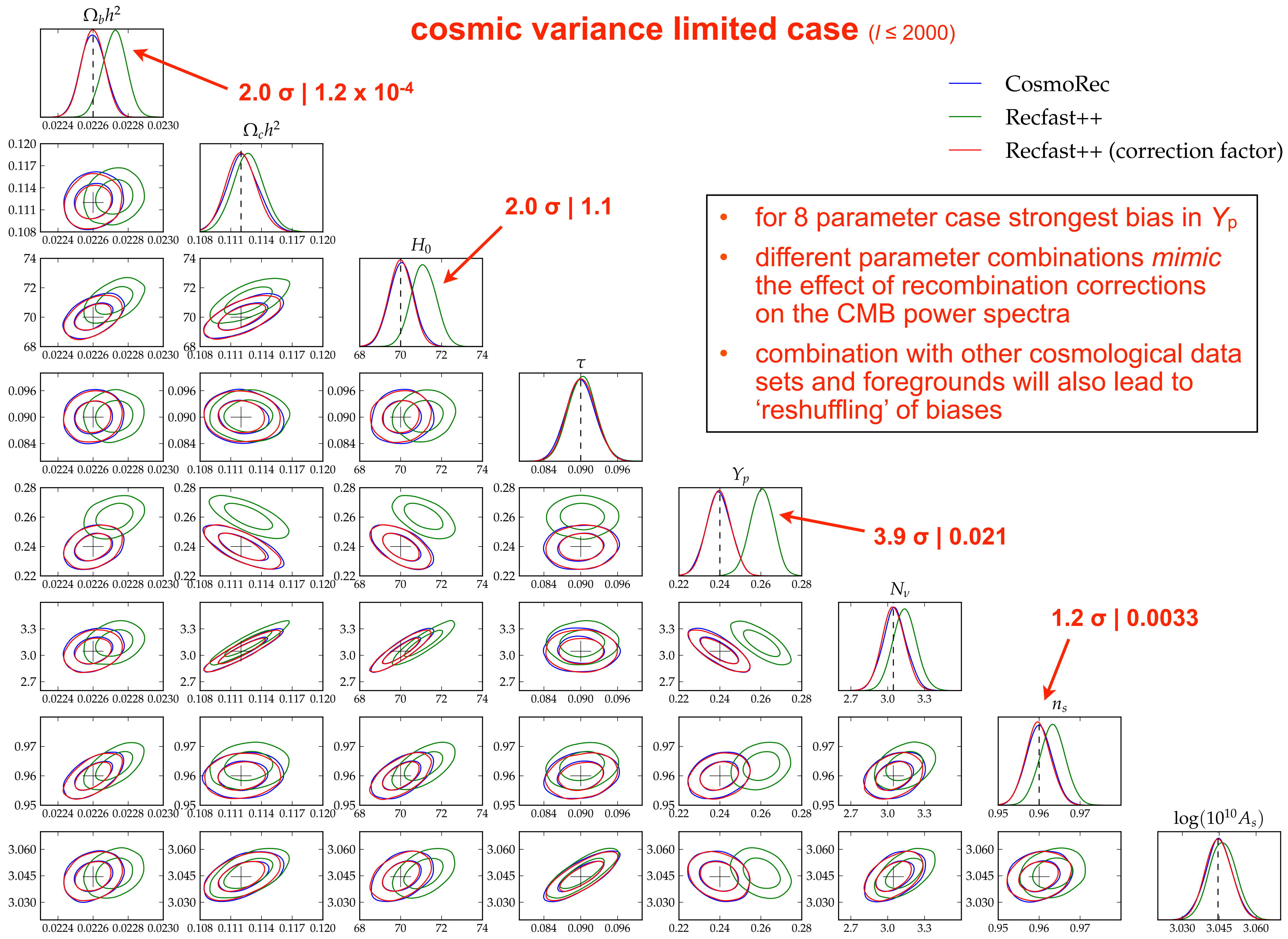
CMB constraints on N_{eff} and Y_p



Planck Collaboration, 2013, paper XV

- *Consistent with SBBN and standard value for N_{eff}*
- *Future CMB constraints (SPTPol & ACTPol) on Y_p will reach 1% level*

Importance of recombination for measuring helium



cosmic variance limited case ($l \leq 2000$)

2.0 σ | 1.2 x 10^{-4}

2.0 σ | 1.1

3.9 σ | 0.021

1.2 σ | 0.0033

- for 8 parameter case strongest bias in Y_p
- different parameter combinations *mimic* the effect of recombination corrections on the CMB power spectra
- combination with other cosmological data sets and foregrounds will also lead to 'reshuffling' of biases

Shaw & JC, 2011, and references therein

How does the cosmological recombination radiation look and how can it help us?

Simple estimates for hydrogen recombination

Hydrogen recombination:

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

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

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

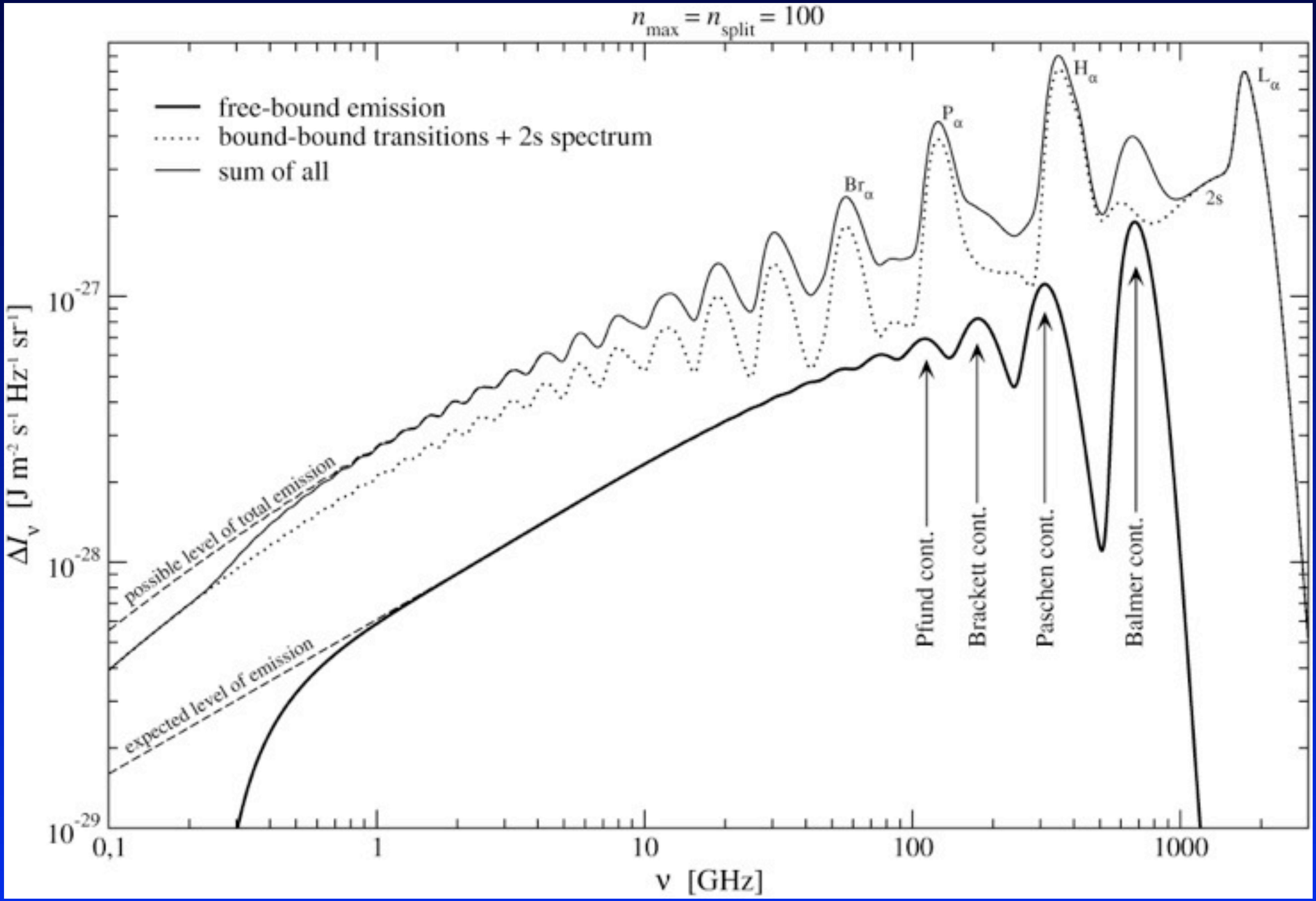
→ There should be some *small* spectral distortion due to additional Ly-α and 2s-1s photons!

(Zeldovich, Kurt & Sunyaev, 1968, ZhETF, 55, 278; Peebles, 1968, ApJ, 153, 1)

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

100-shell hydrogen atom and continuum

CMB spectral distortions



JC & Sunyaev, 2006, A&A, 458, L29 (astro-ph/0608120)

bound-bound & 2s:

- at ν > 1GHz: distinct features
- slope ~ 0.46

free-bound:

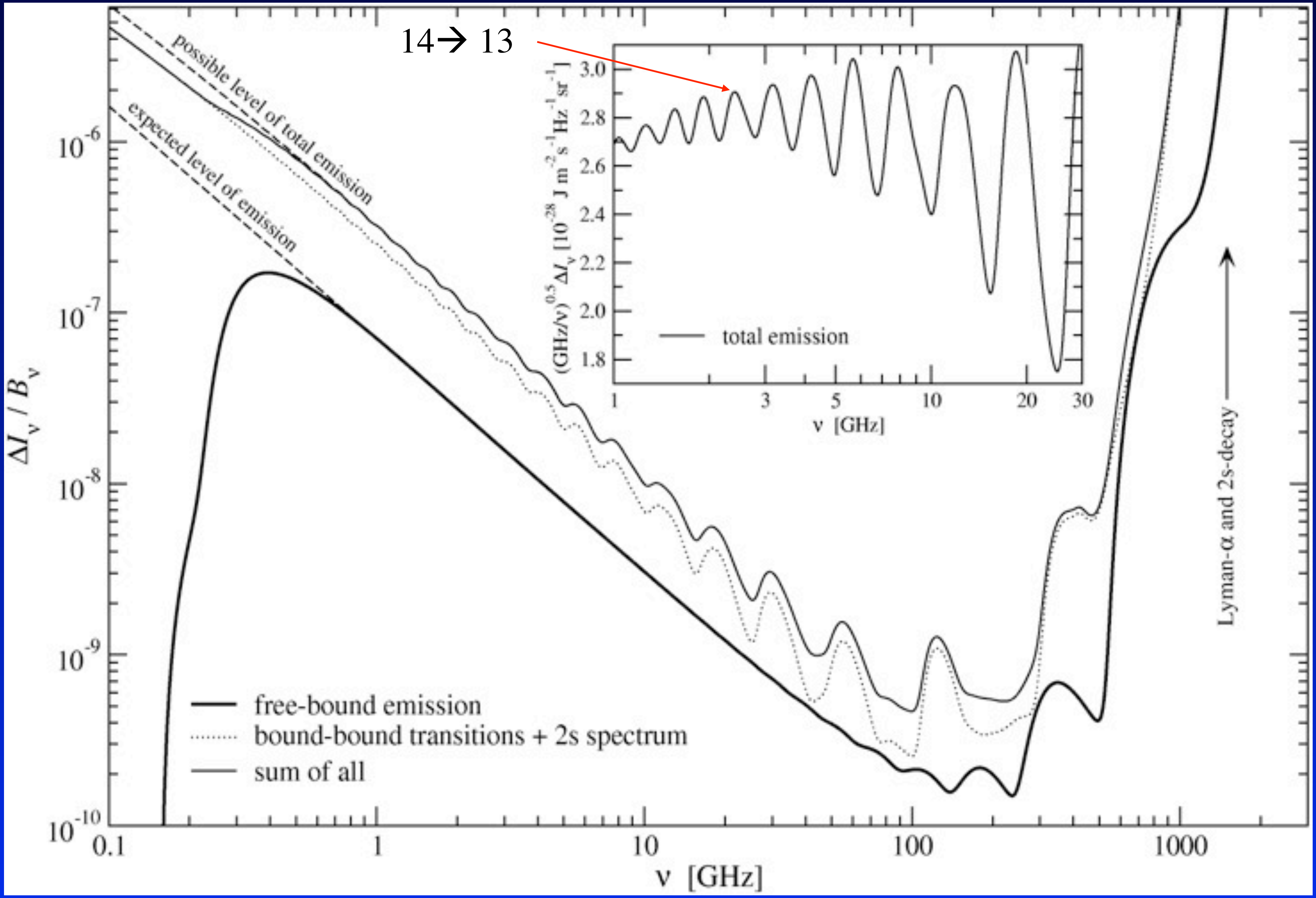
- only a few features distinguishable
- slope ~ 0.6

Total:

- f-b contributes ~ 30% and more
- Balmer cont. ~ 90%
- Balmer: 1γ per HI
- in total 5γ per HI

100-shell hydrogen atom and continuum

Relative distortions



JC & Sunyaev, 2006, A&A, 458, L29 (astro-ph/0608120)

Wien-region:

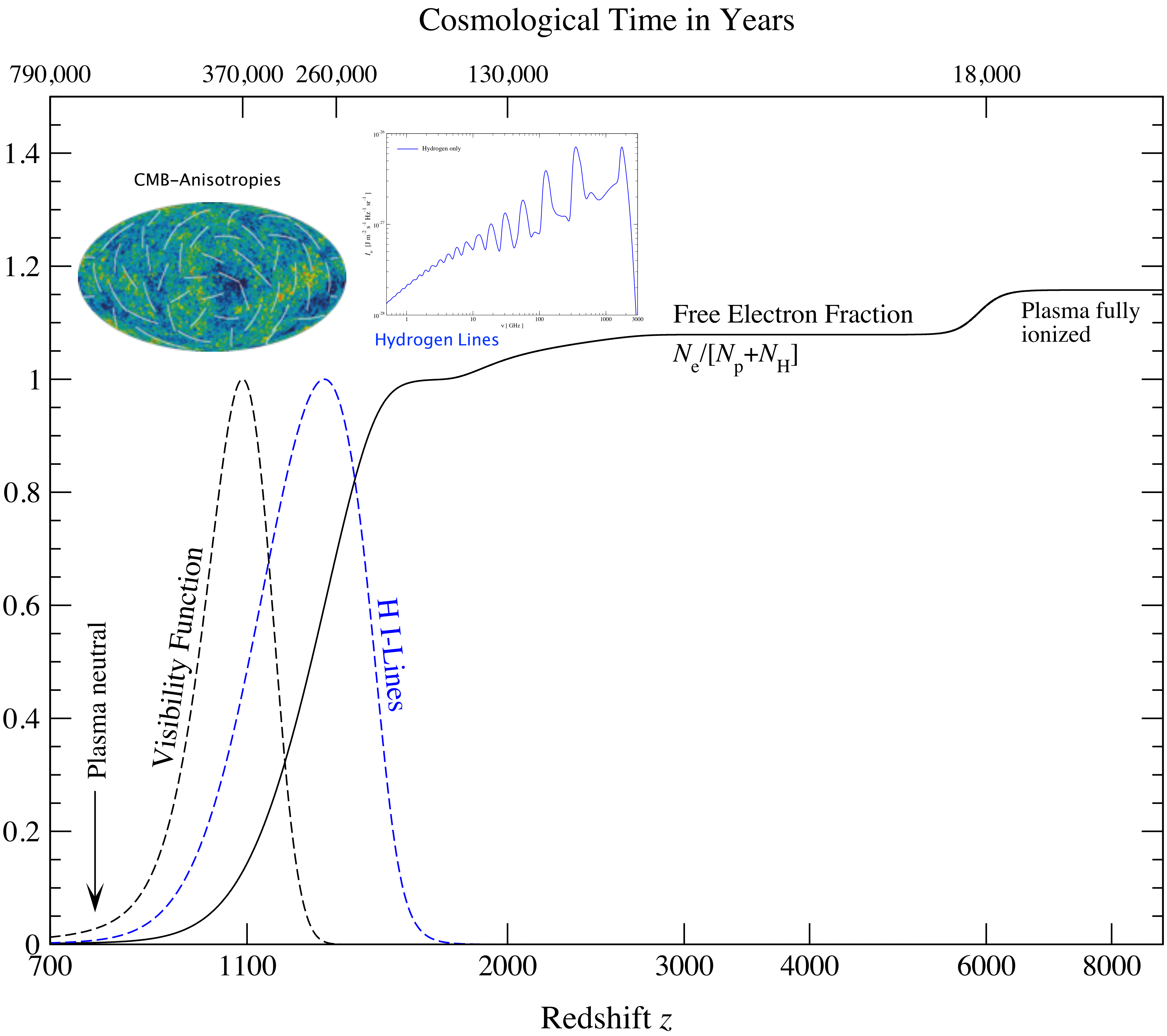
- L $_\alpha$ and 2s distortions are very strong
- but CIB more dominant

@ CMB maximum:

- relative distortions extremely small
- strong ν-dependence

RJ-region:

- relative distortion exceeds level of ~ 10^{-7} below ν ~ 1-2 GHz
- oscillatory frequency dependence with ~ 1-10 percent-level amplitude:
- *hard to mimic by known foregrounds or systematics*


Cosmological Time in Years
790,000
370,000
260,000
130,000
18,000
1.4
1.2
1
0.8
0.6
0.4
0.2
0
CMB–Anisotropies
Hydrogen only
10^{-26}
10^{-27}
10^{-28}
I_ν [J m^{-2} s^{-1} Hz^{-1} sr^{-1}]
1
10
100
1000
3000
ν [GHz]
Hydrogen Lines
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully ionized
Visibility Function
H I-Lines
Plasma neutral
700
1100
2000
3000
4000
6000
8000
Redshift z

What about the contributions from helium recombination?

- Nuclear reactions: Y_p~0.24 ←→ N_{HeI} / N_H ~8 %

  → expected photon number rather small

- ***BUT:***

  (*i*) *two* epochs of He recombination
  HeIII→HeII at *z*~6000 and HeII→HeI at *z*~2500

  (*ii*) Helium recombinations faster

  → more *narrow* features with *larger* amplitude

  (*iii*) non-trivial superposition

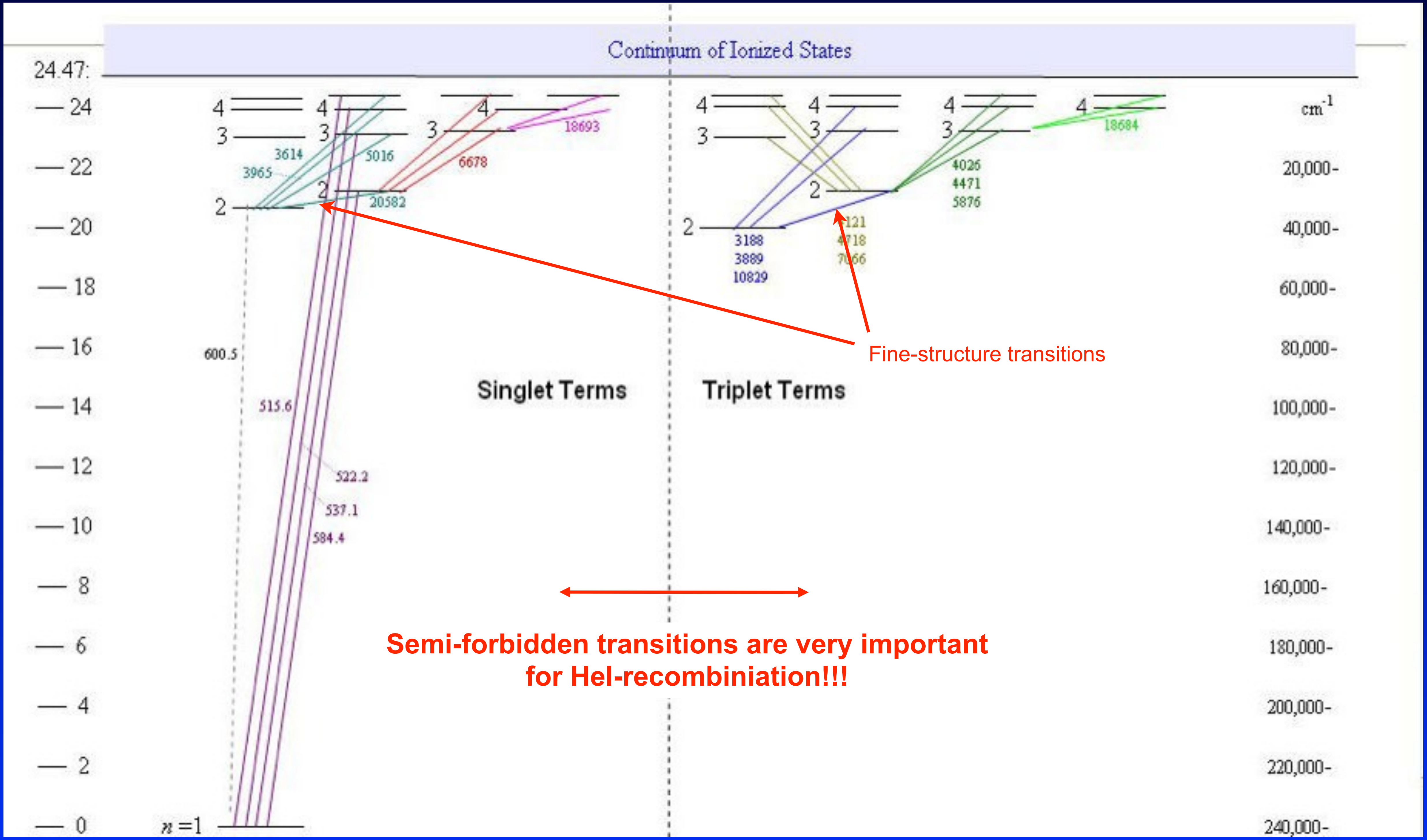
  → local amplification possible

  (*iv*) reprocessing of HeII & HeI photons by HeI and HI

  → increases the number of helium-related photons

→ May opens a way to ***directly*** measure the primordial (pre-stellar!!!) helium abundance!

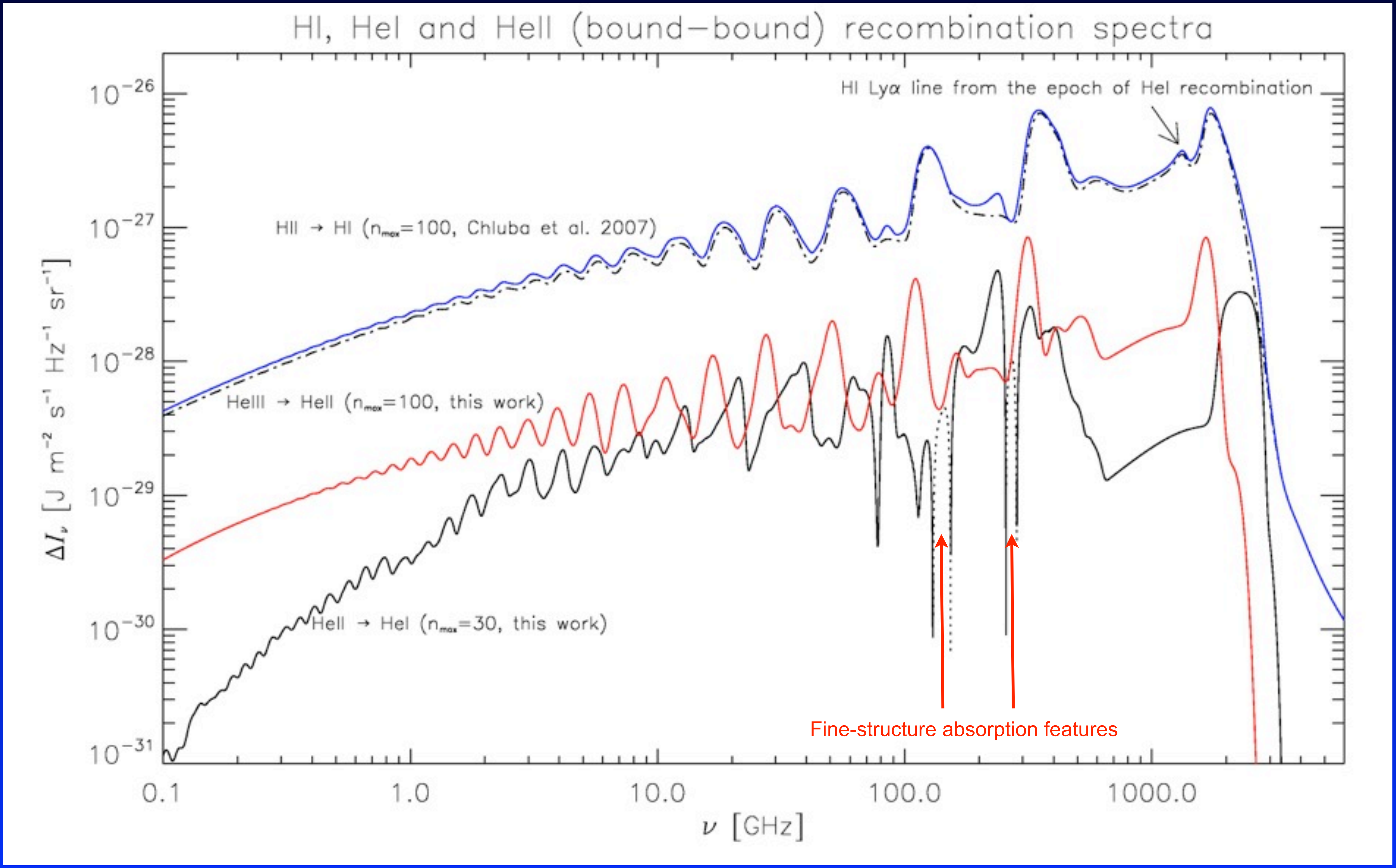
Grotrian diagram for neutral helium



Fine-structure transitions

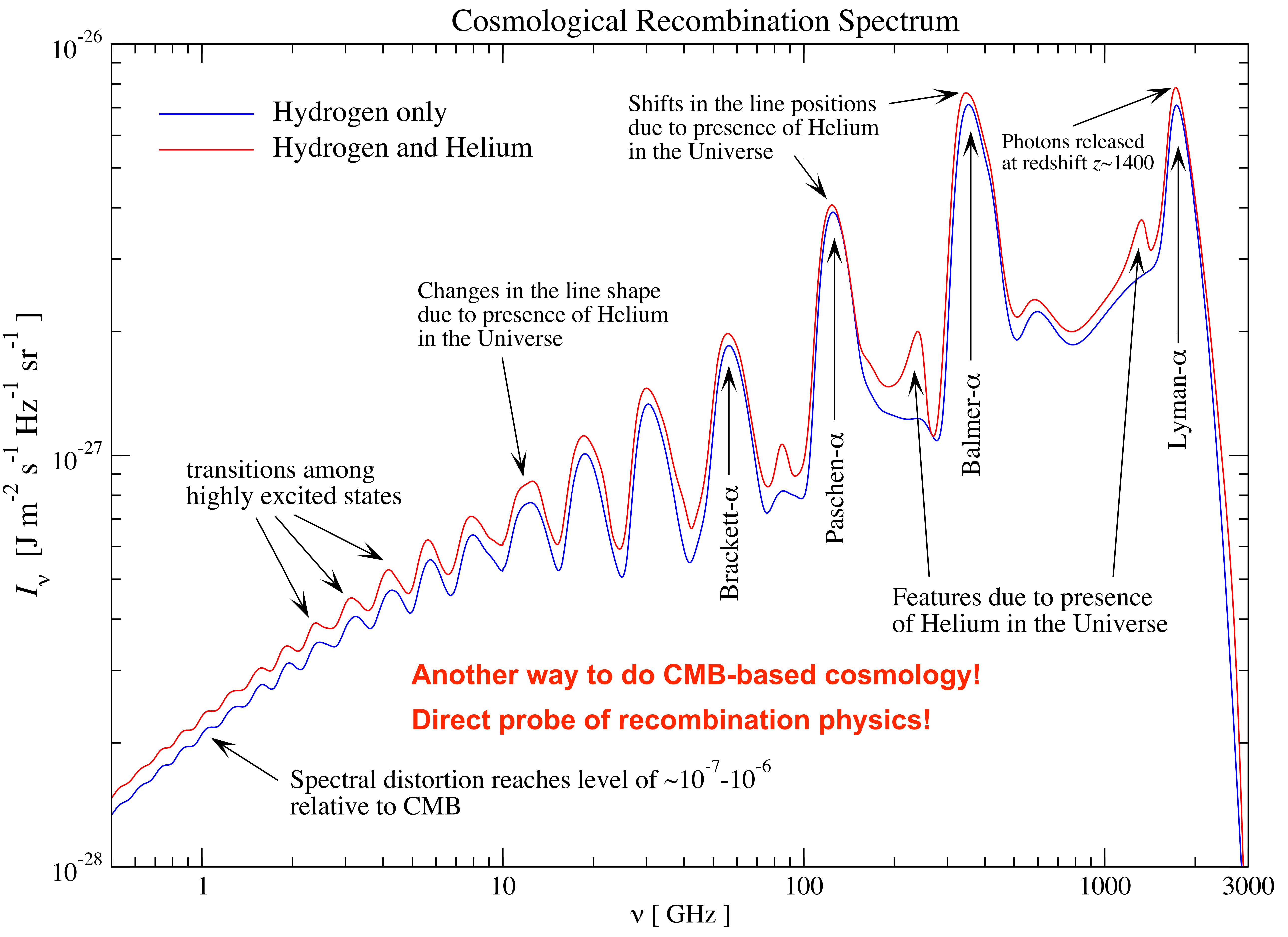
Semi-forbidden transitions are very important for HeI-recombiniation!!!

Helium contributions to the cosmological recombination spectrum



Fine-structure absorption features

Rubino-Martin, JC & Sunyaev, 2008



Shifts in the line positions due to presence of Helium in the Universe

Photons released at redshift z~1400

Changes in the line shape due to presence of Helium in the Universe

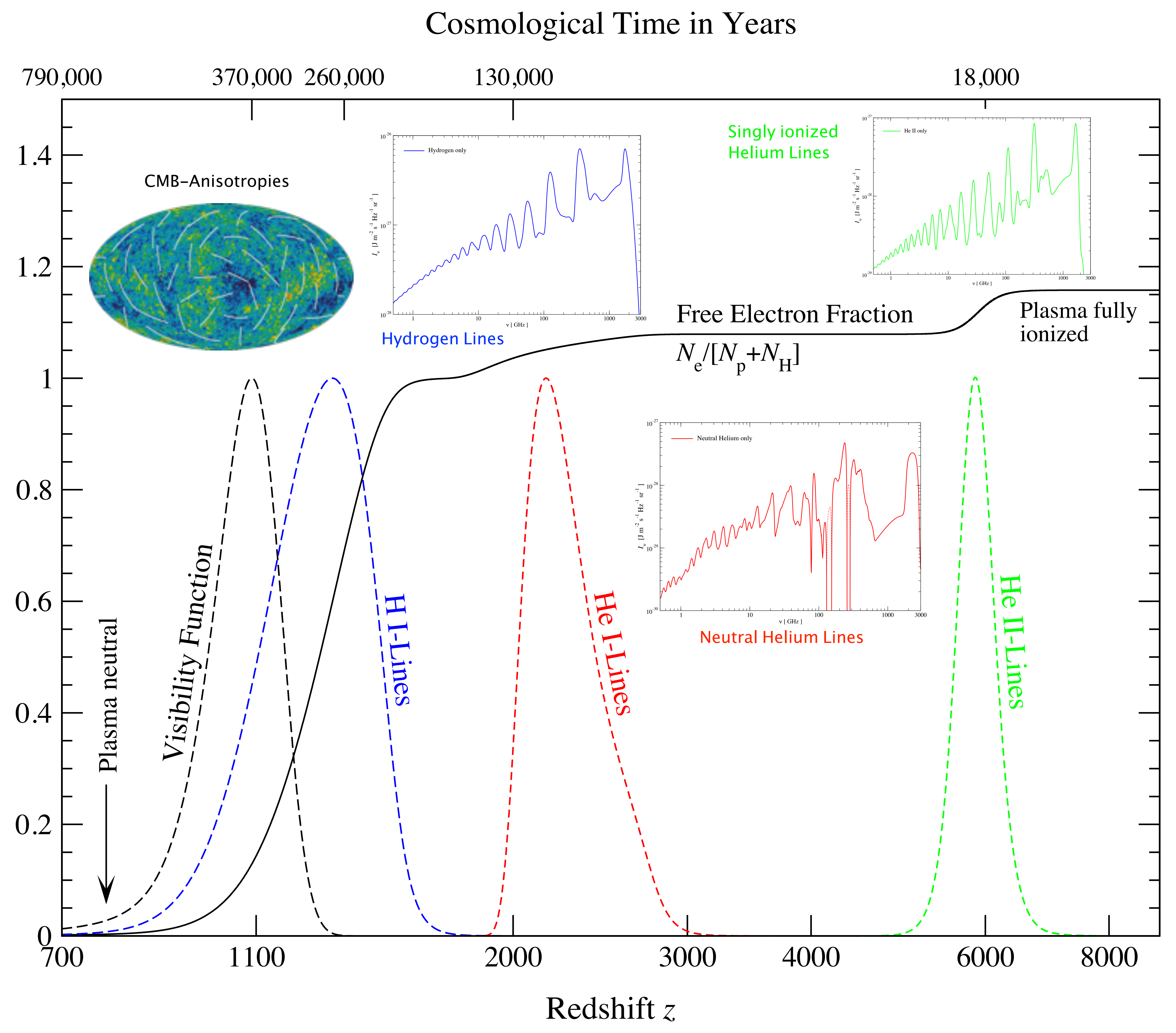
transitions among highly excited states

Features due to presence of Helium in the Universe

Spectral distortion reaches level of ~10^{-7}-10^{-6} relative to CMB

Another way to do CMB-based cosmology!

Direct probe of recombination physics!

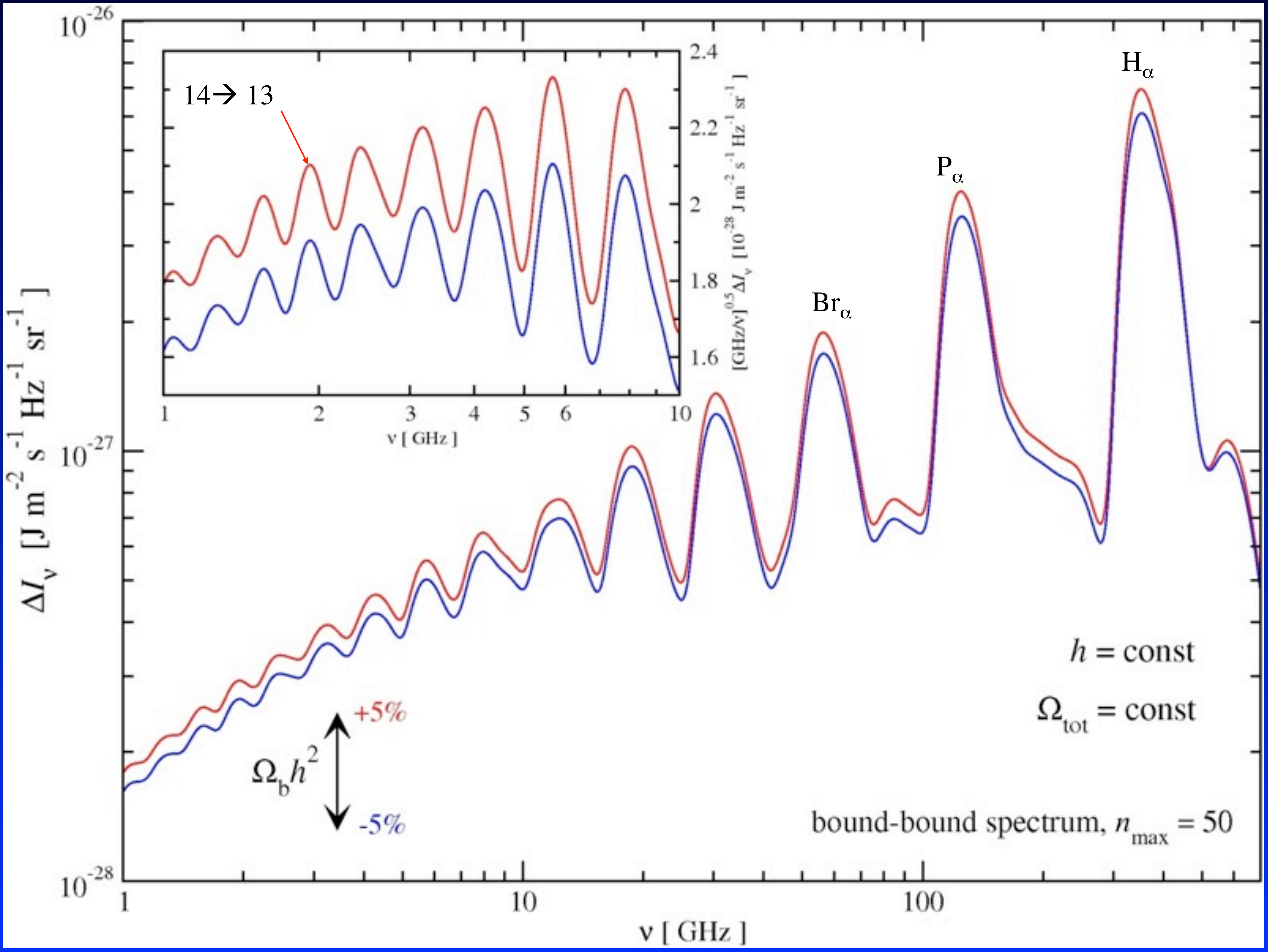

Cosmological Time in Years
790,000
370,000
260,000
130,000
18,000
CMB–Anisotropies
Hydrogen only
Hydrogen Lines
Singly ionized Helium Lines
He II only
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully ionized
Neutral Helium only
Neutral Helium Lines
Plasma neutral
Visibility Function
H I-Lines
He I-Lines
He II-Lines
1.4
1.2
1
0.8
0.6
0.4
0.2
0
700
1100
2000
3000
4000
6000
8000
Redshift z

What would we actually learn by doing such hard job?

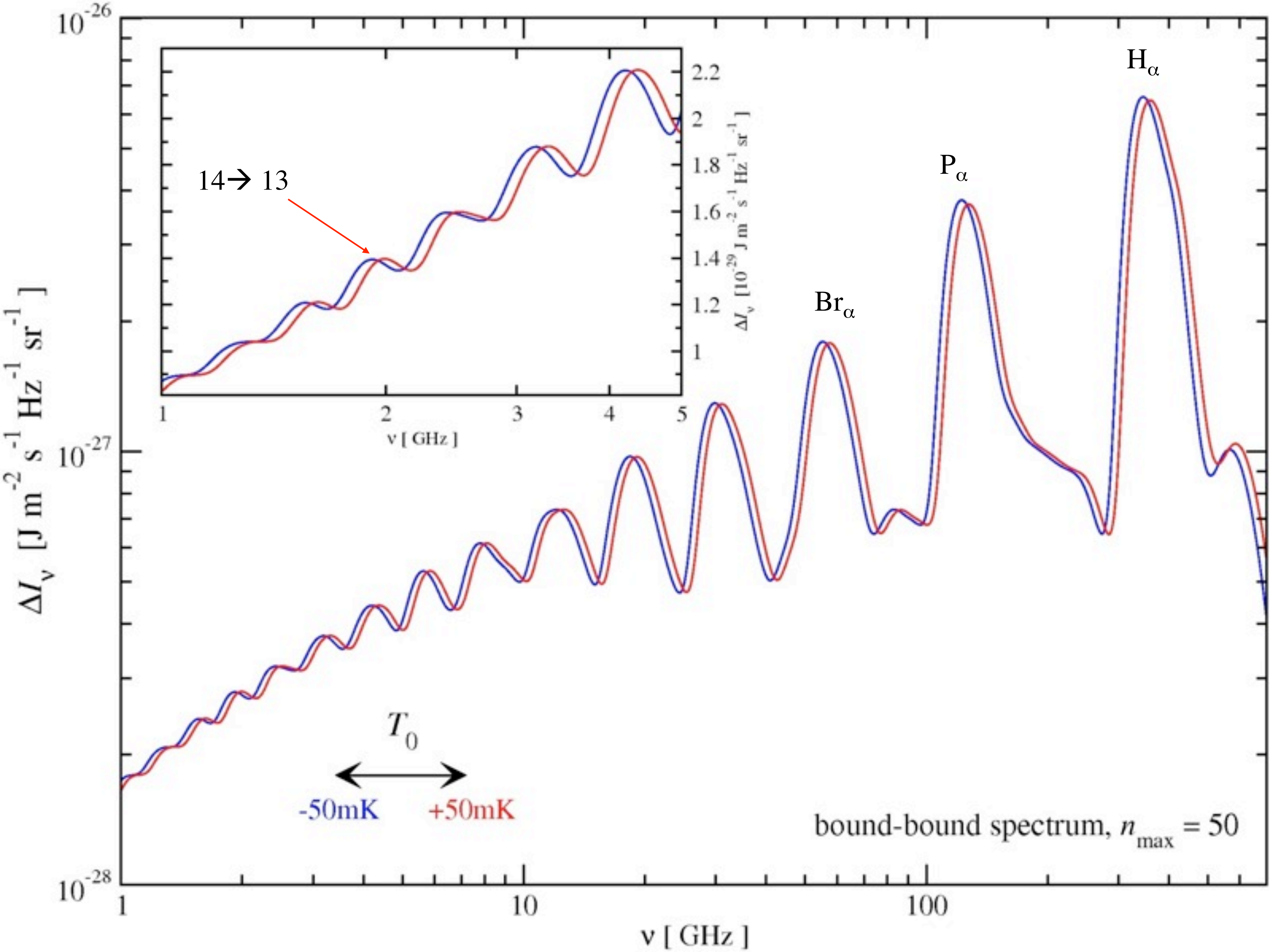
Cosmological Recombination Spectrum opens a way to measure:

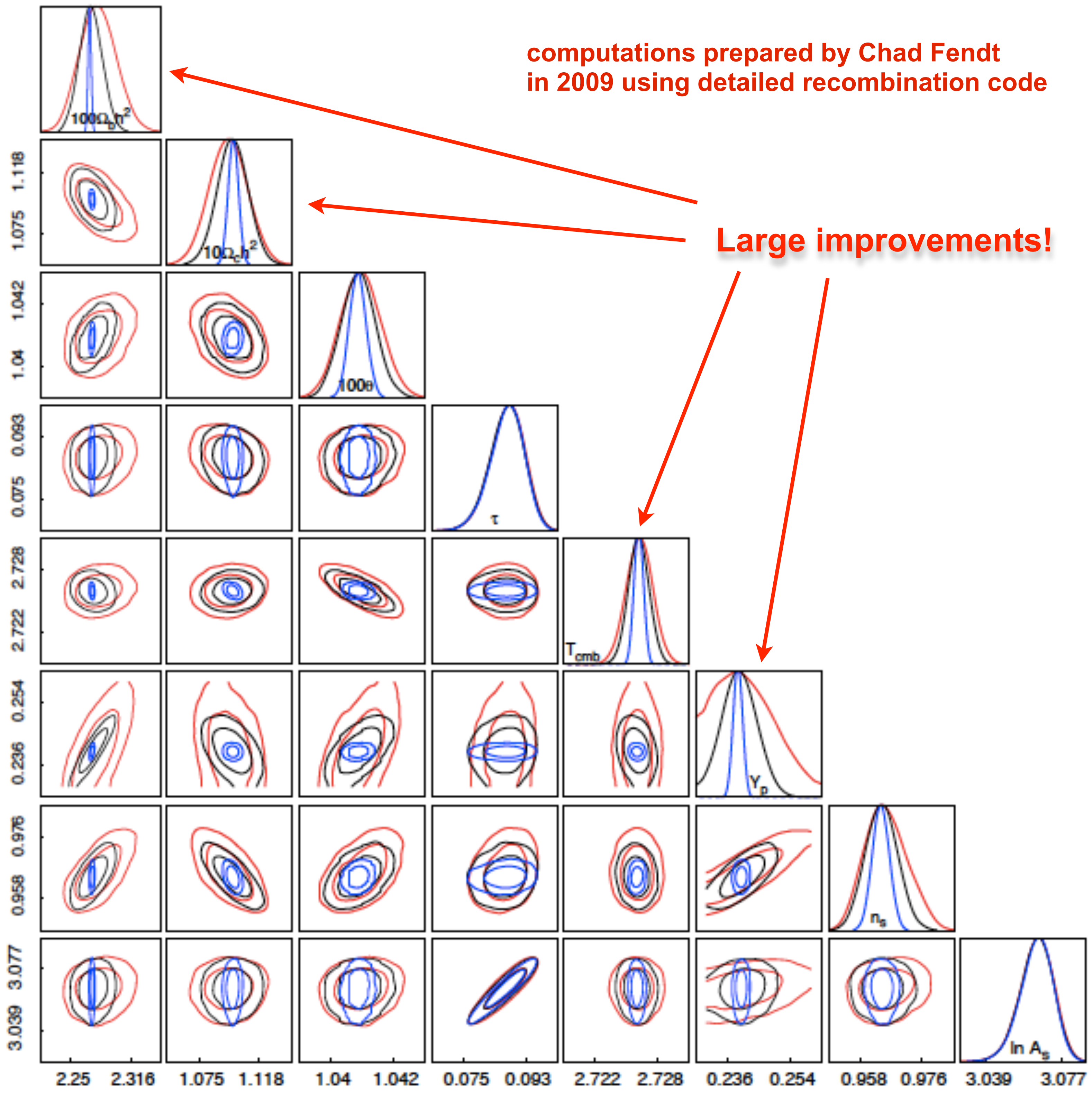
- → **the specific *entropy* of our universe (related to $\Omega_b h^2$)**
- → **the CMB *monopole* temperature T_0**
- → ***the pre-stellar abundance of helium Y_p***

Hydrogen recombination spectrum:
dependence on $\Omega_b h^2$



Hydrogen recombination spectrum: *dependence on T_0*





computations prepared by Chad Fendt
in 2009 using detailed recombination code

Large improvements!

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

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

What would we actually learn by doing such hard job?

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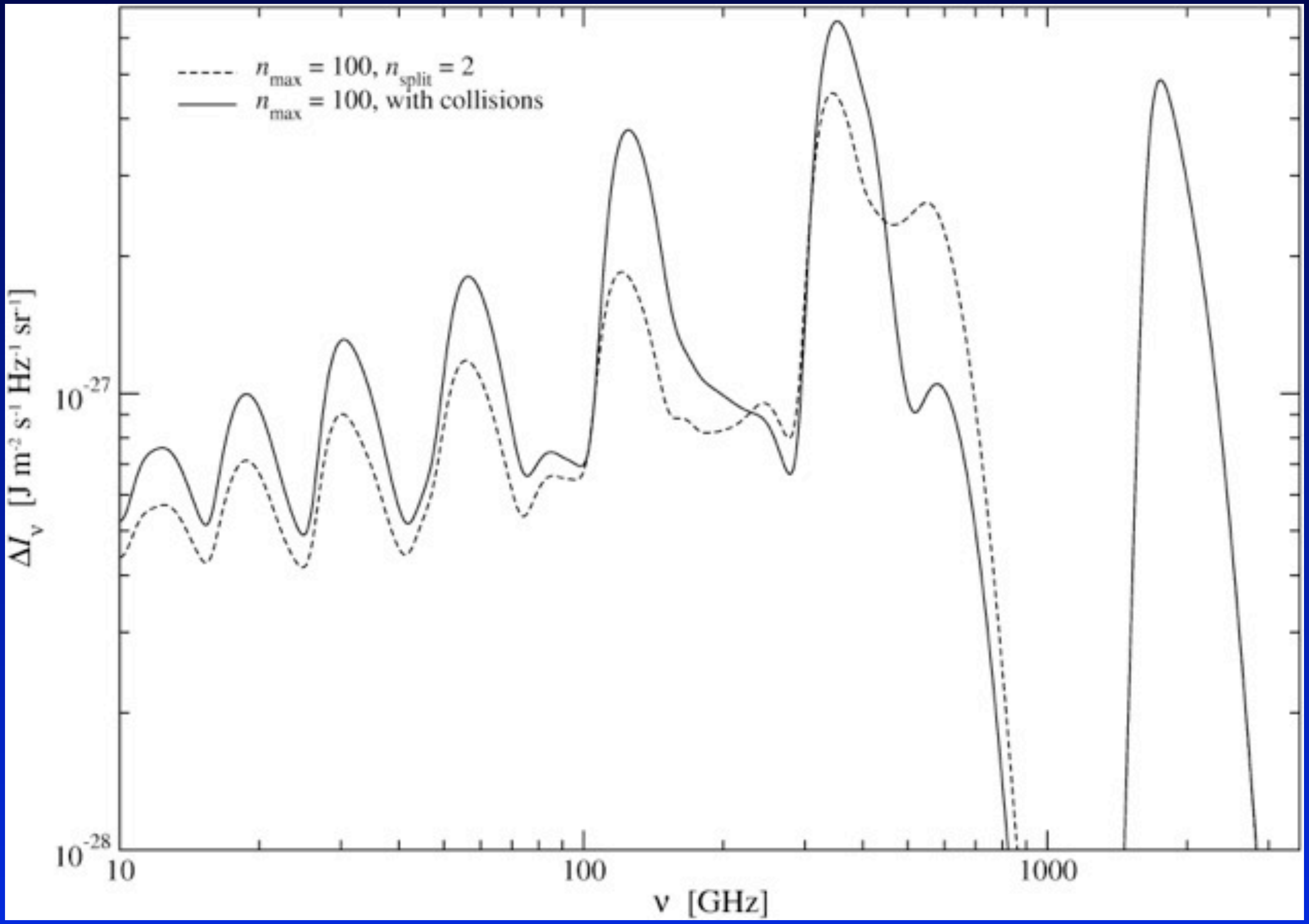
- → ***In principle allows us to directly check our understanding of the standard recombination physics***

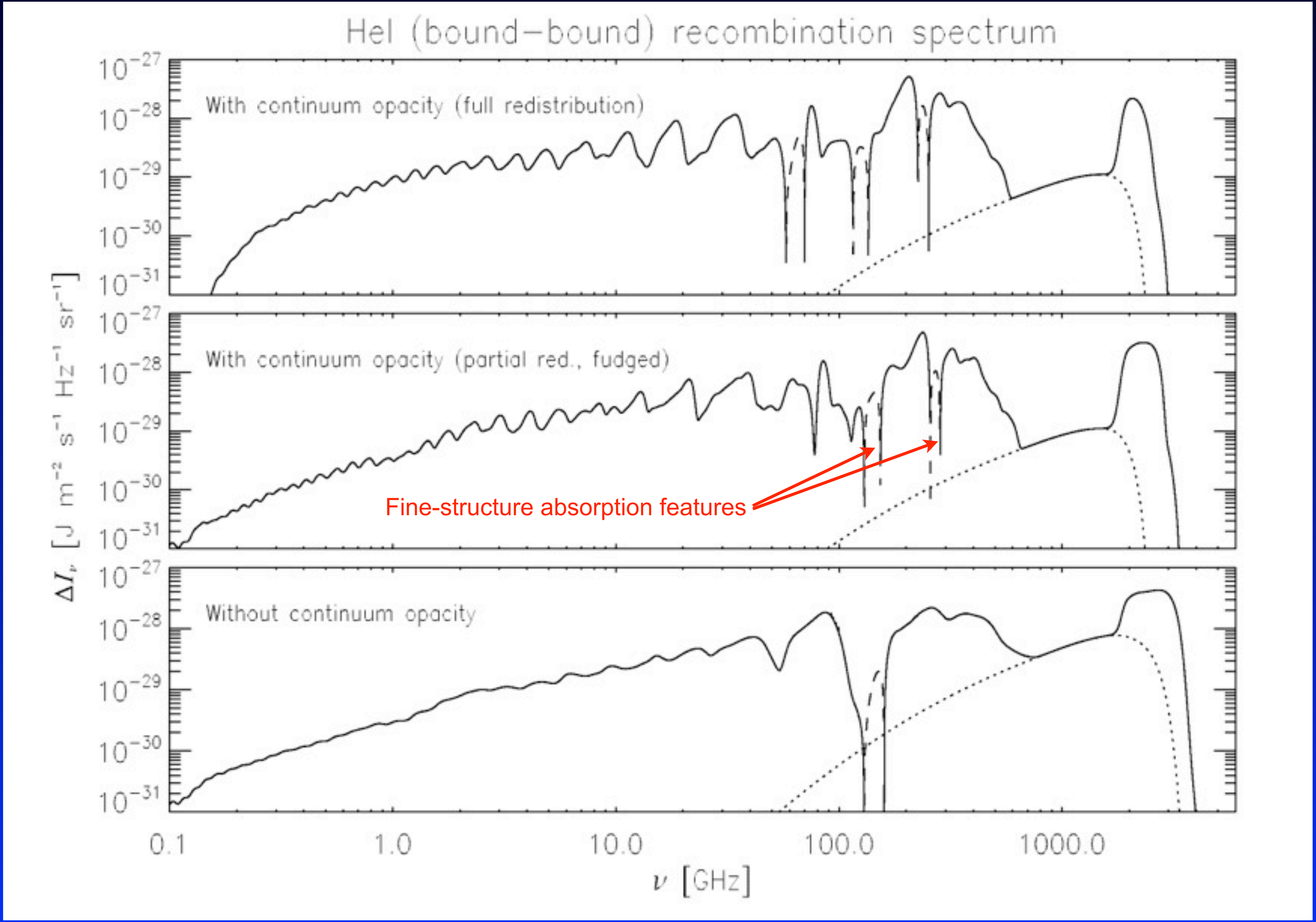
Difference in the hydrogen spectrum if collisions were more efficient



- Lyman- α unchanged
- Balmer-series:
  - B $_\alpha$ lower for n_{split}=2
  - for n_{split}=2 second peak more than 2 times higher
  - ratio first to second peak decreases from 6 → 2
- higher series:
  - n_{split}=2 → emission lower

Rubiño-Martín, JC & Sunyaev, 2006, astro-ph/0607373
JC, Rubiño-Martín & Sunyaev, 2006, astro-ph/0608242

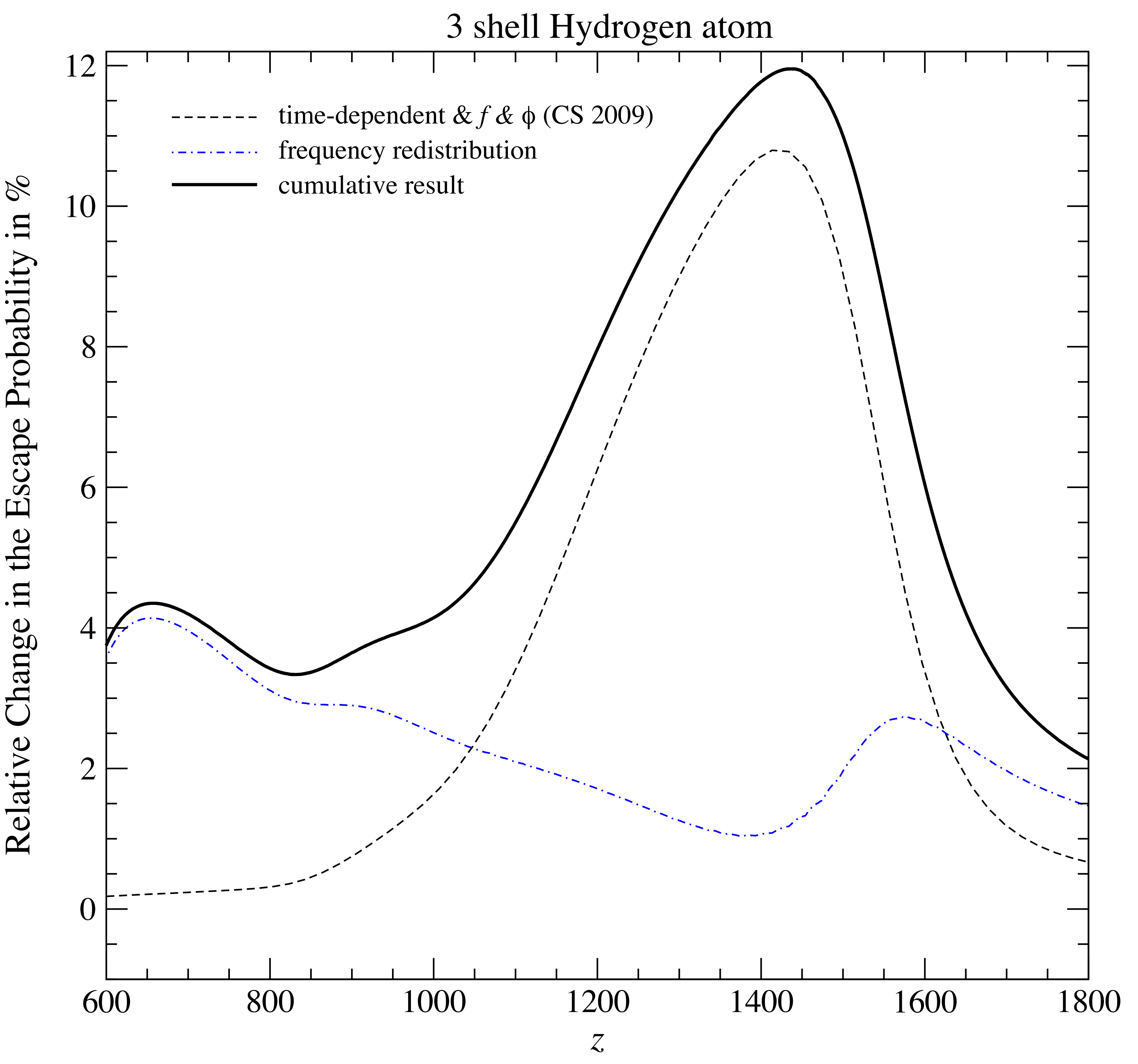
The importance of HI continuum absorption



Fine-structure absorption features

Rubino-Martin, JC & Sunyaev, A&A, 2008

Changes in the Lyman α escape probability



- Changes in Ly α escape probability *directly* translate into changes of the CMB Ly α distortion
- $\Delta P/P$=10% ⇒ $\Delta I_\nu/I_\nu$=10%
- Since Ly α line controls dynamics of recombination also all other lines will be affected by this process

What would we actually learn by doing such hard job?

Cosmological Recombination Spectrum opens a way to measure:

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

→ the CMB *monopole* temperature T_0

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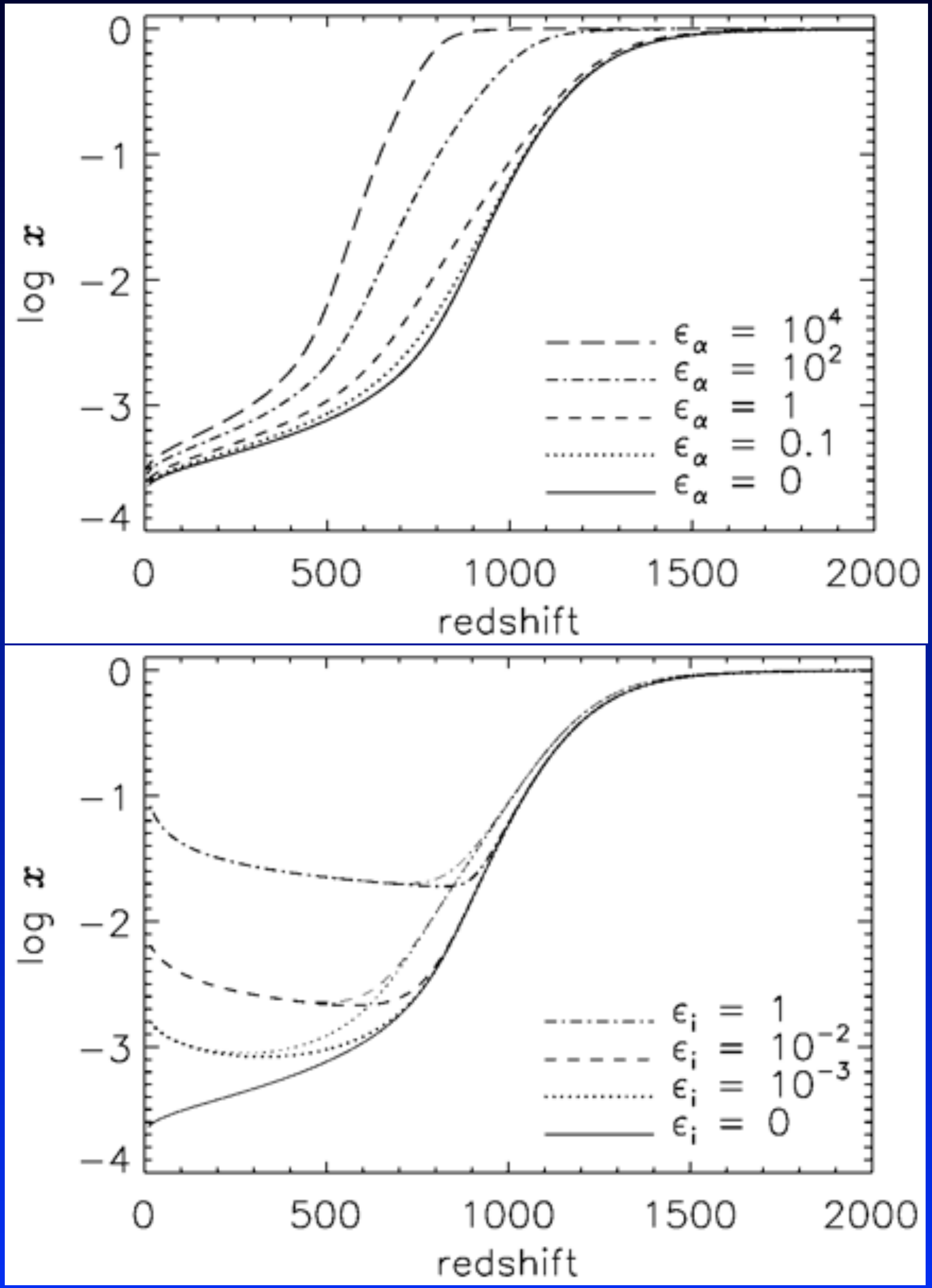
If something unexpected or non-standard happened:

Extra Sources of Ionizations or Excitations

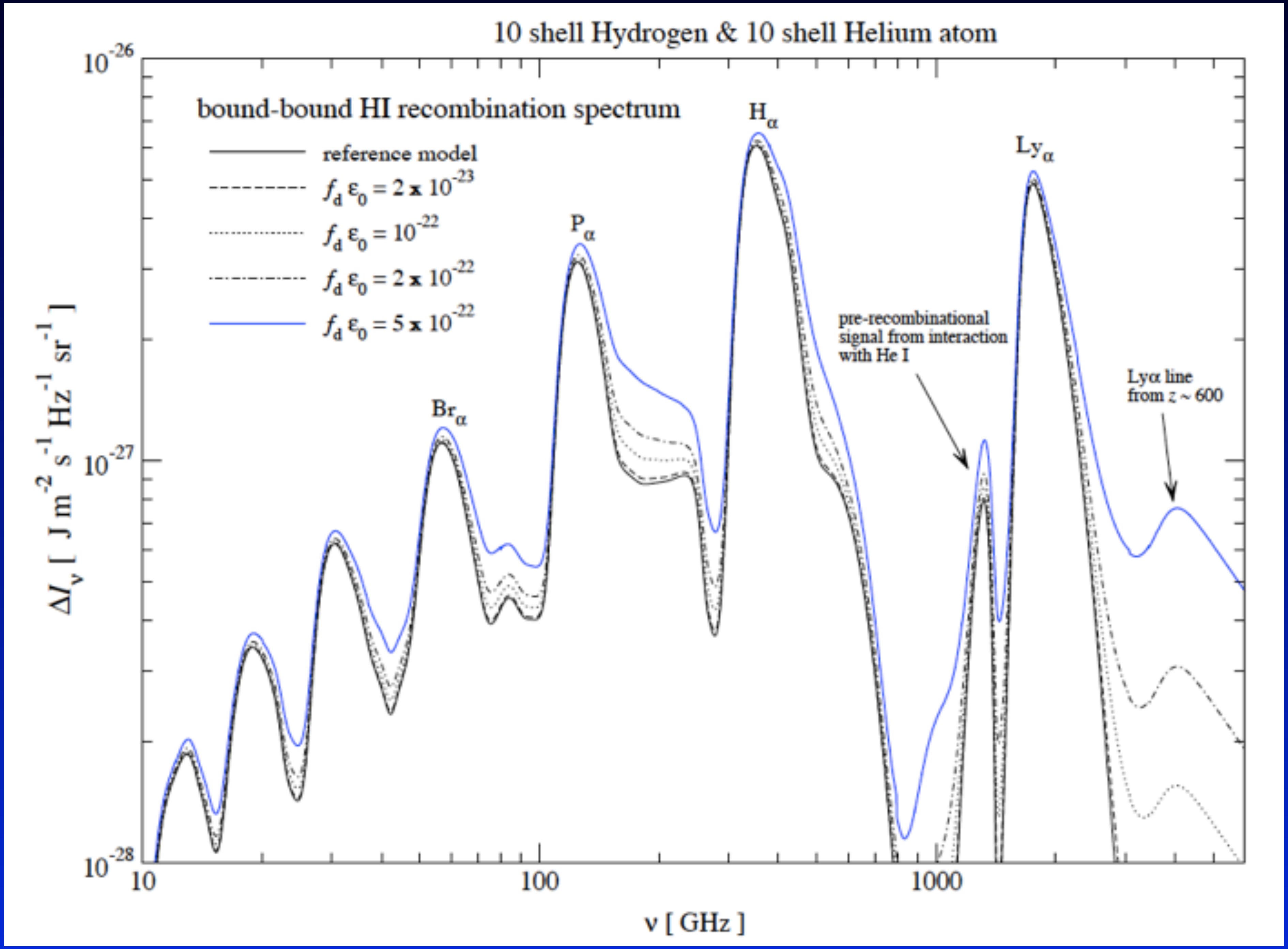


- ‚Hypothetical' source of extra photons parametrized by ε_α & ε_i
- Extra excitations ⇒ delay of Recombination
- Extra ionizations ⇒ affect 'freeze out' tail
- This affects the Thomson visibility function
- From WMAP ⇒ $\varepsilon_\alpha < 0.39$ & $\varepsilon_i < 0.058$ at 95% confidence level (Galli et al. 2008)

- Extra ionizations & excitations should also lead to additional photons in the recombination radiation!!!
- This in principle should allow us to check for such sources at z~1000

Peebles, Seager & Hu, ApJ, 2000

Dark matter annihilations / decays



JC, 2009, arXiv:0910.3663

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

Energy injection ⇒ CMB Spectral Distortions

How easy is it actually to learn something interesting about the thermal history?

- CMB distortion can be predicted for different energy injection histories and mechanisms (e.g. Hu & Silk,1993a&b; Burigana & Salvaterra, 2003)

  → Spectral distortions are *broad* and *featureless*

  → Absolute (COBE-type) measurements are required

- Different injection histories yield very similar spectral distortion!

  Simplest example: *pre-* and *post-recombinational y-type distortions*

  - energy release at redshifts $1000 < z < 50000$
  - SZ-effect e.g. due to unresolved clusters, supernova remnants, shockwaves, etc.

  $\Bigg\} \Rightarrow$ y-distortion

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  ⇒ *y*-distortion

Absence of *narrow spectral features* makes it very hard to understand real details!!!

Pre-recombinational atomic transitions after possible early energy release

- pure blackbody CMB

  → *no net emission or absorption of photons before recombination epoch!*

- non-blackbody CMB
  (Lyubarsky & Sunyaev, 1983)

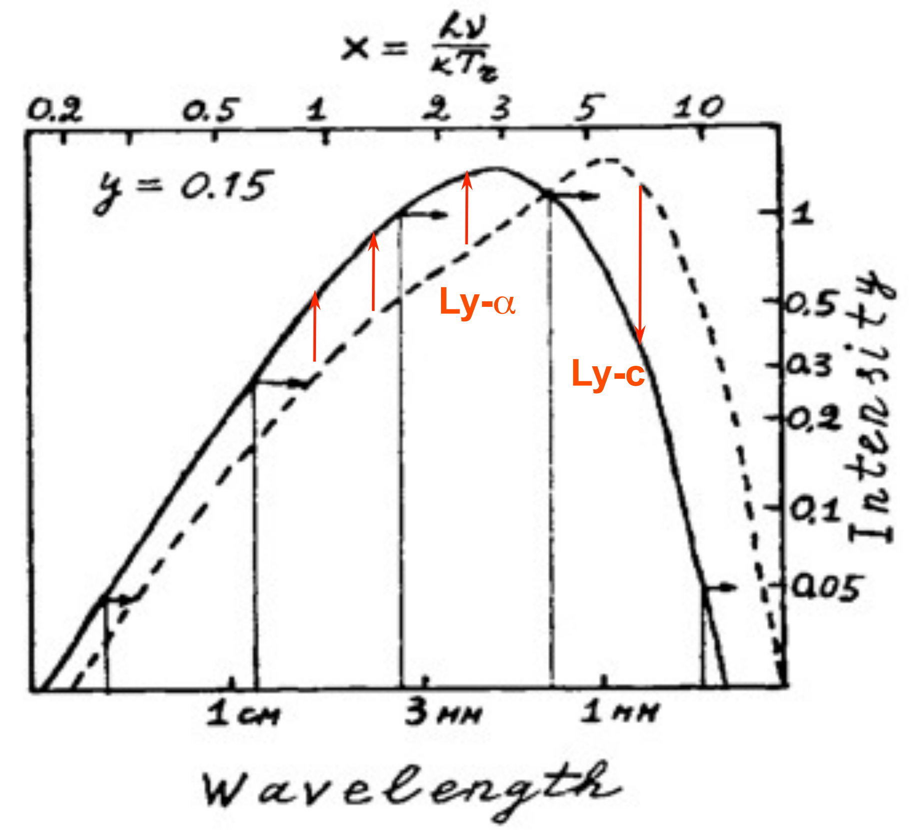
  → atoms "try" to restore full equilibrium

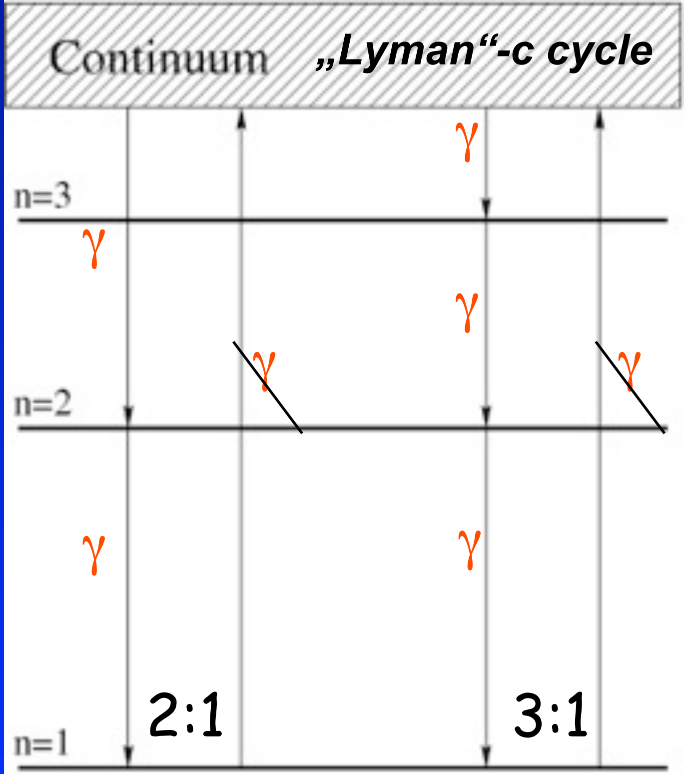
  → *atomic loops* develop (cont.→ bound → cont.)

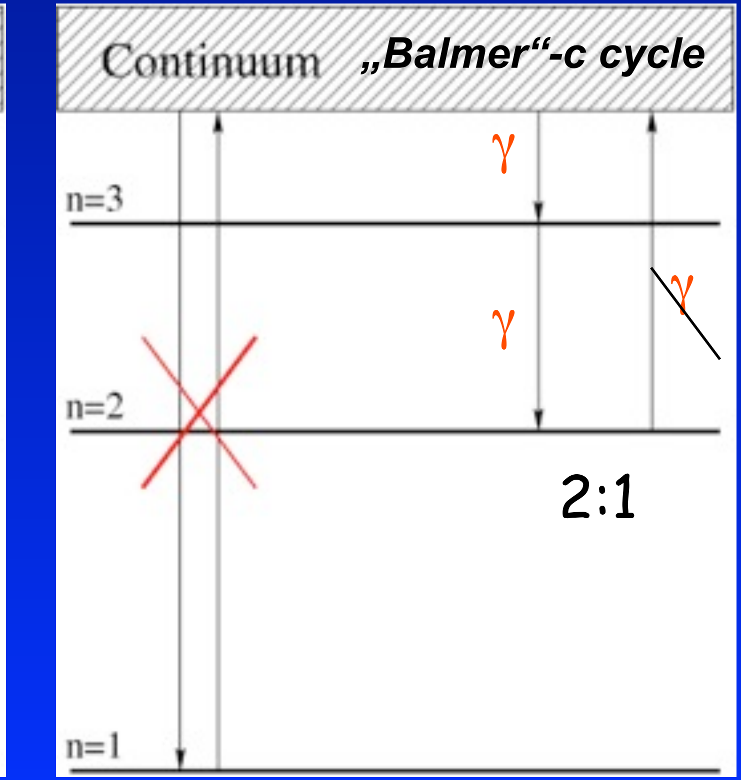
  → "splitting" of photons

  → cycles mainly end in Lyman-continuum

  → Balmer-cont. cycles work just before recombination



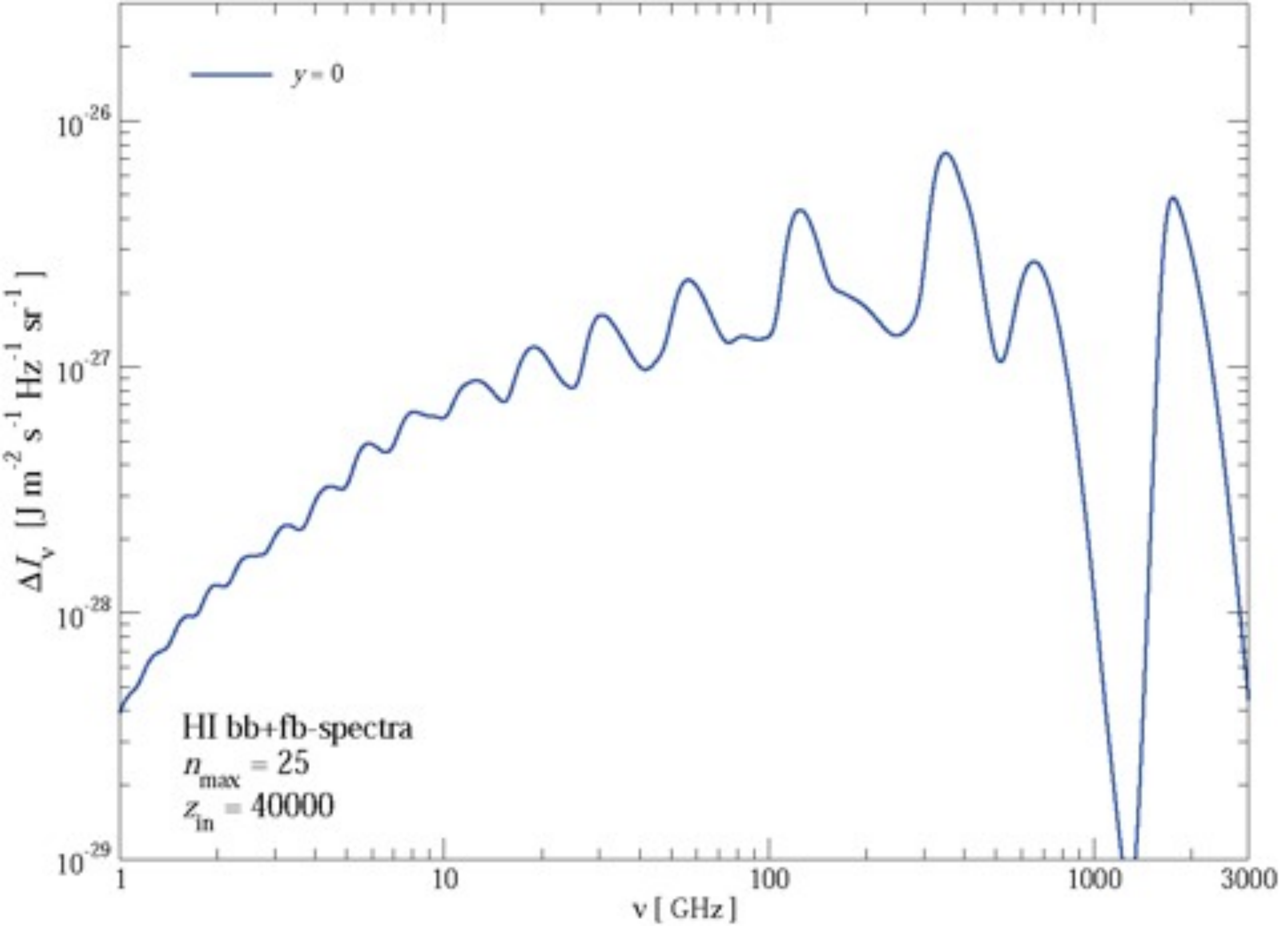




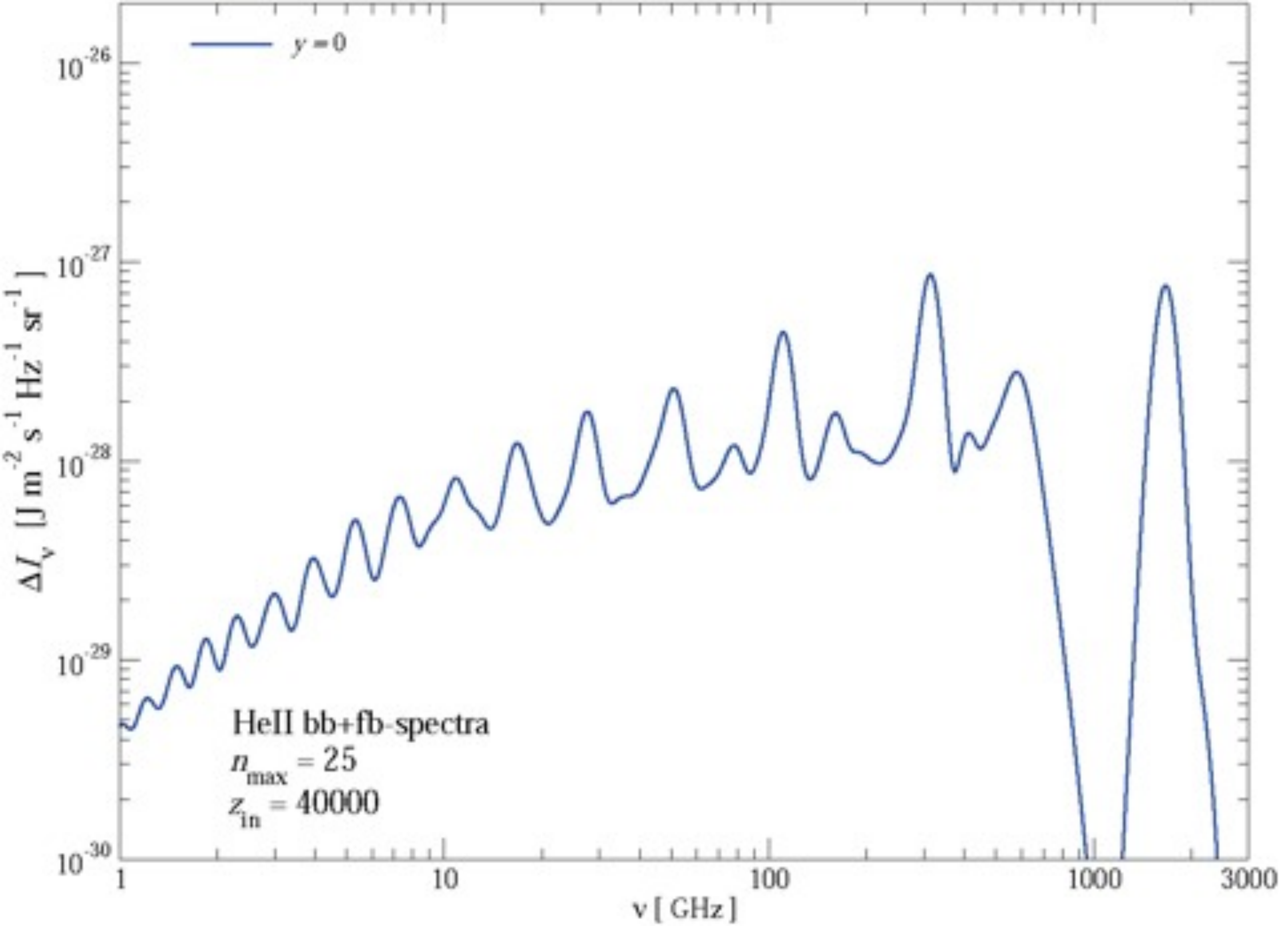
CMB spectral distortions after single energy release

25 shell HI and HeII bb&fb spectra: dependence on y

Hydrogen



Helium +



JC & Sunyaev, 2008, astro-ph/0803.3584

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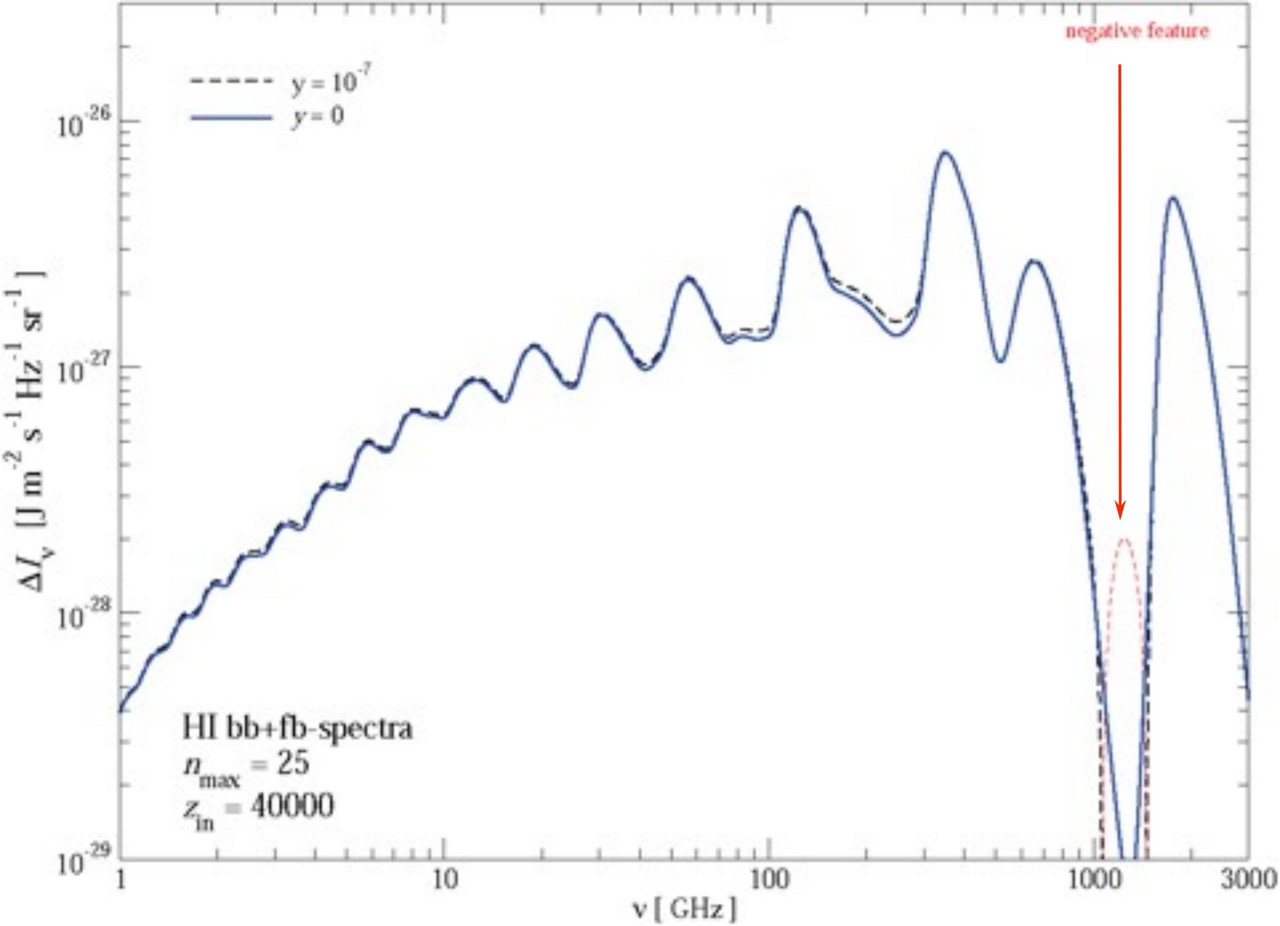

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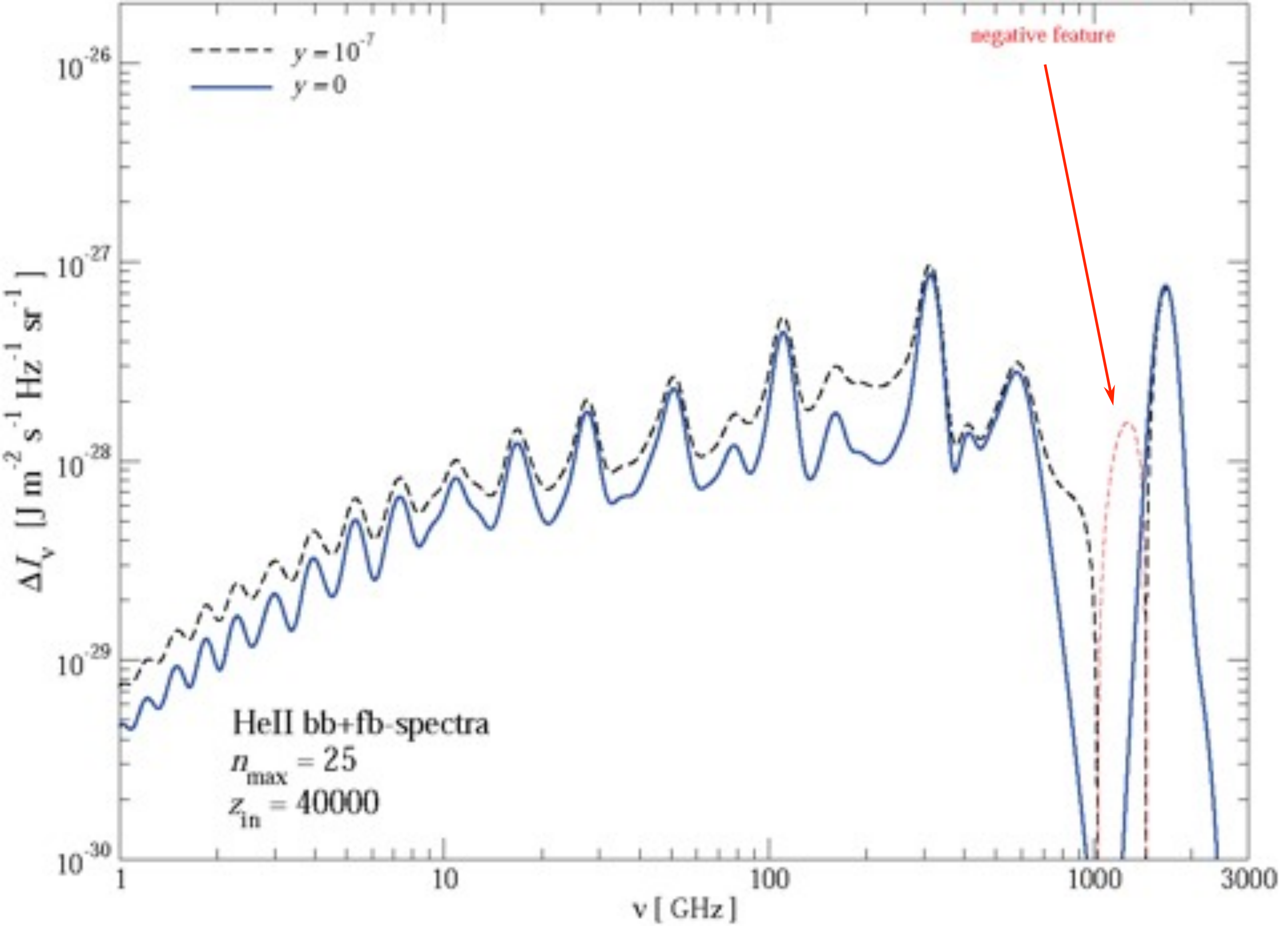

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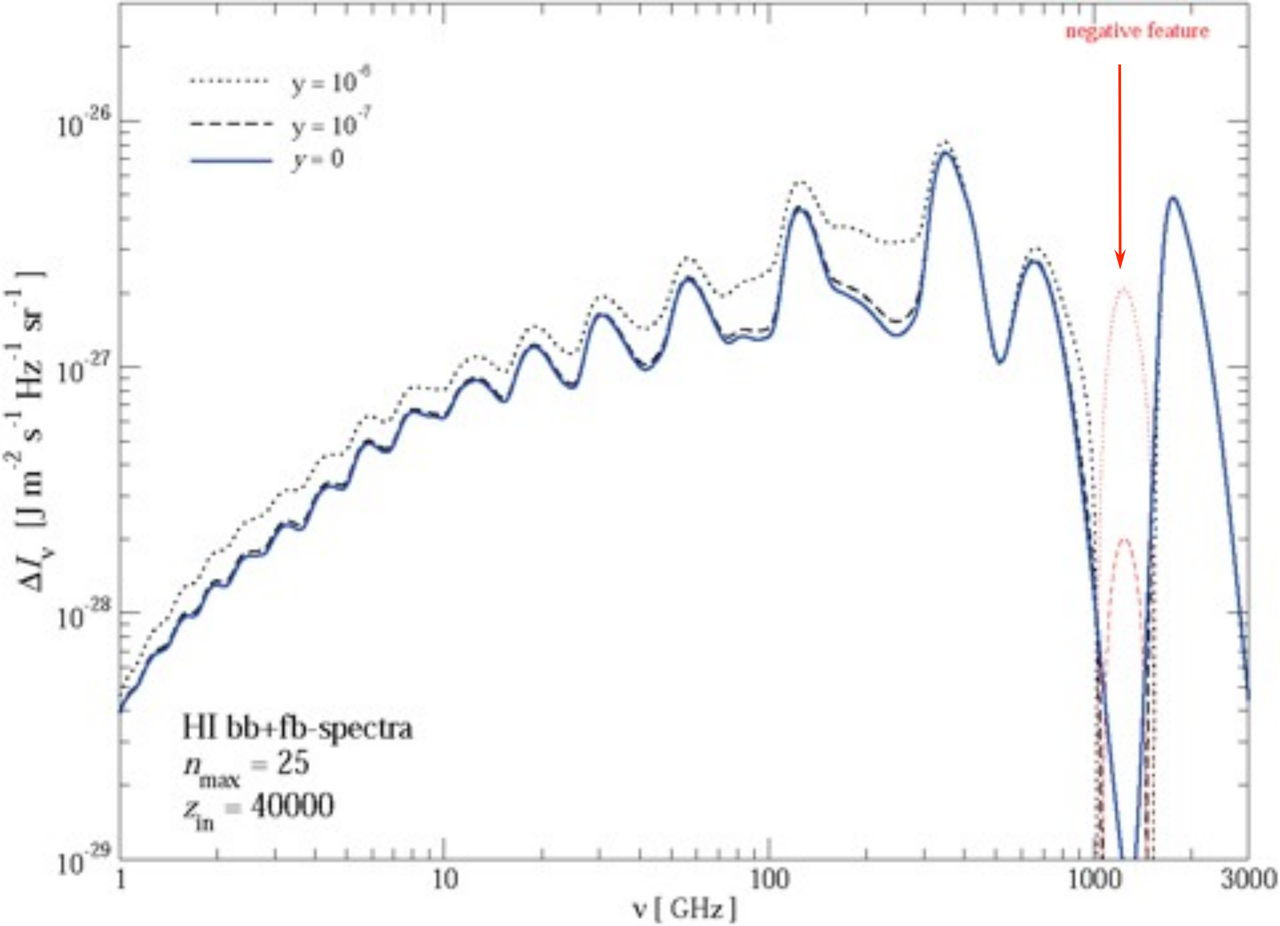

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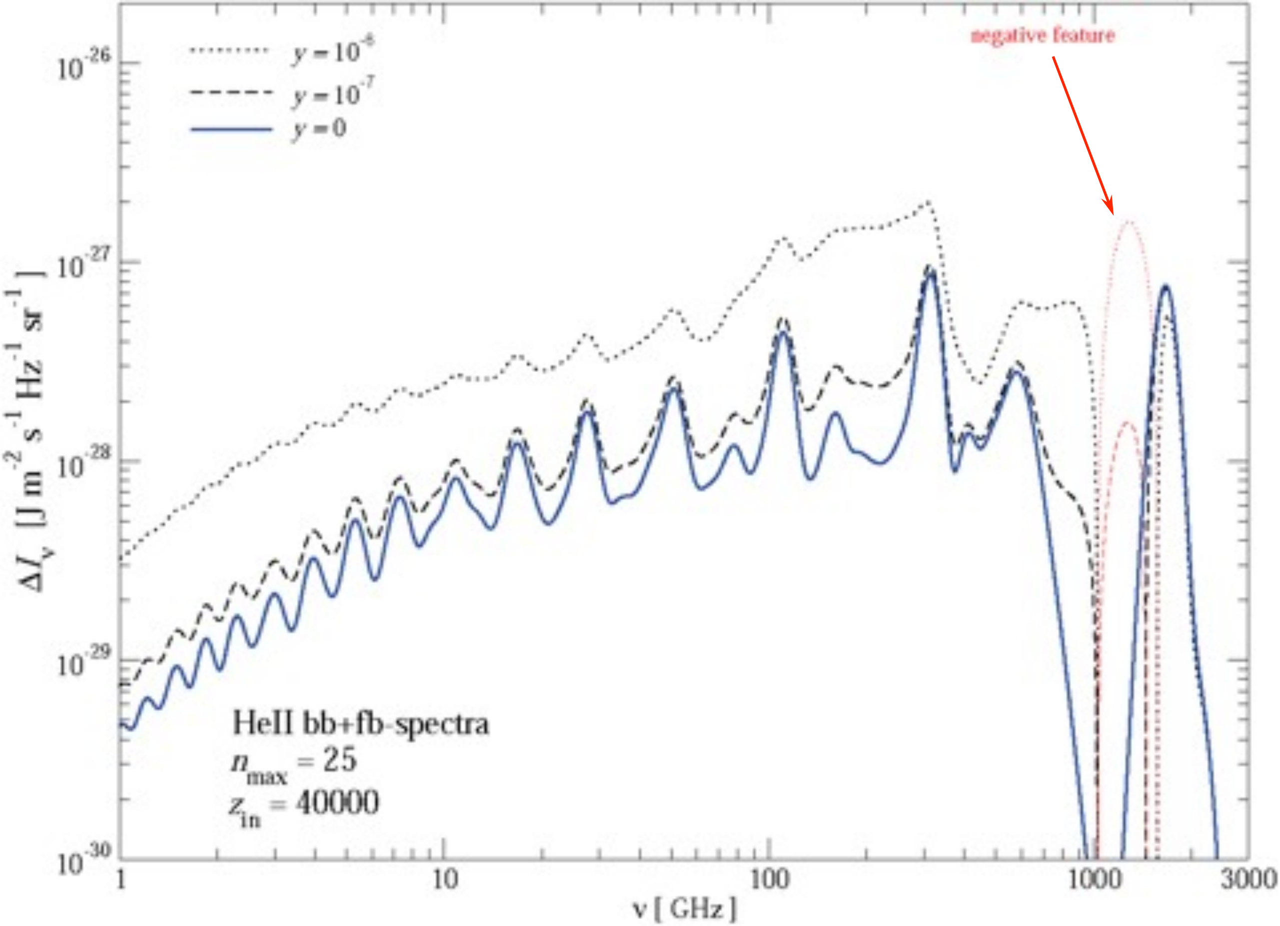

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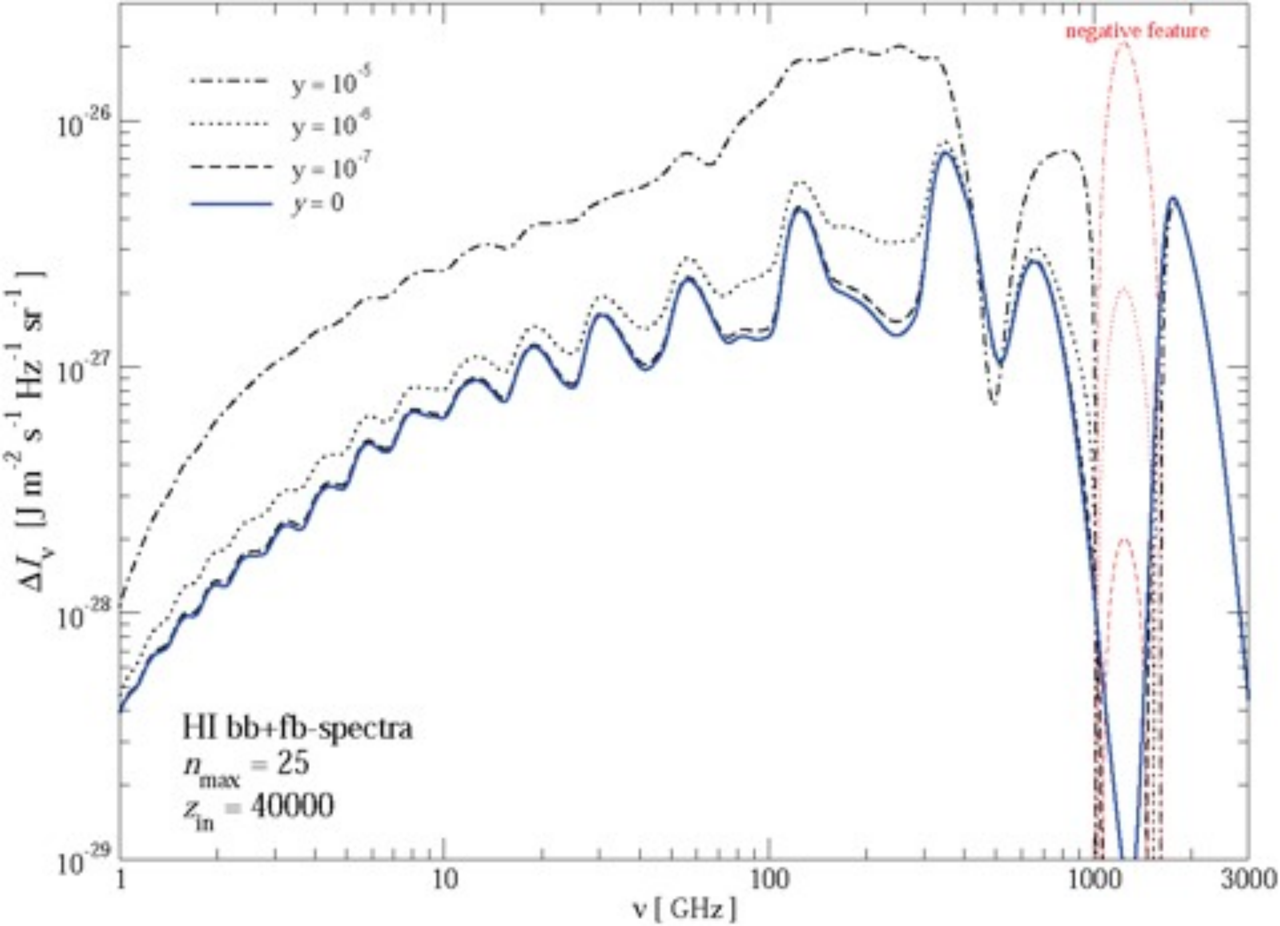
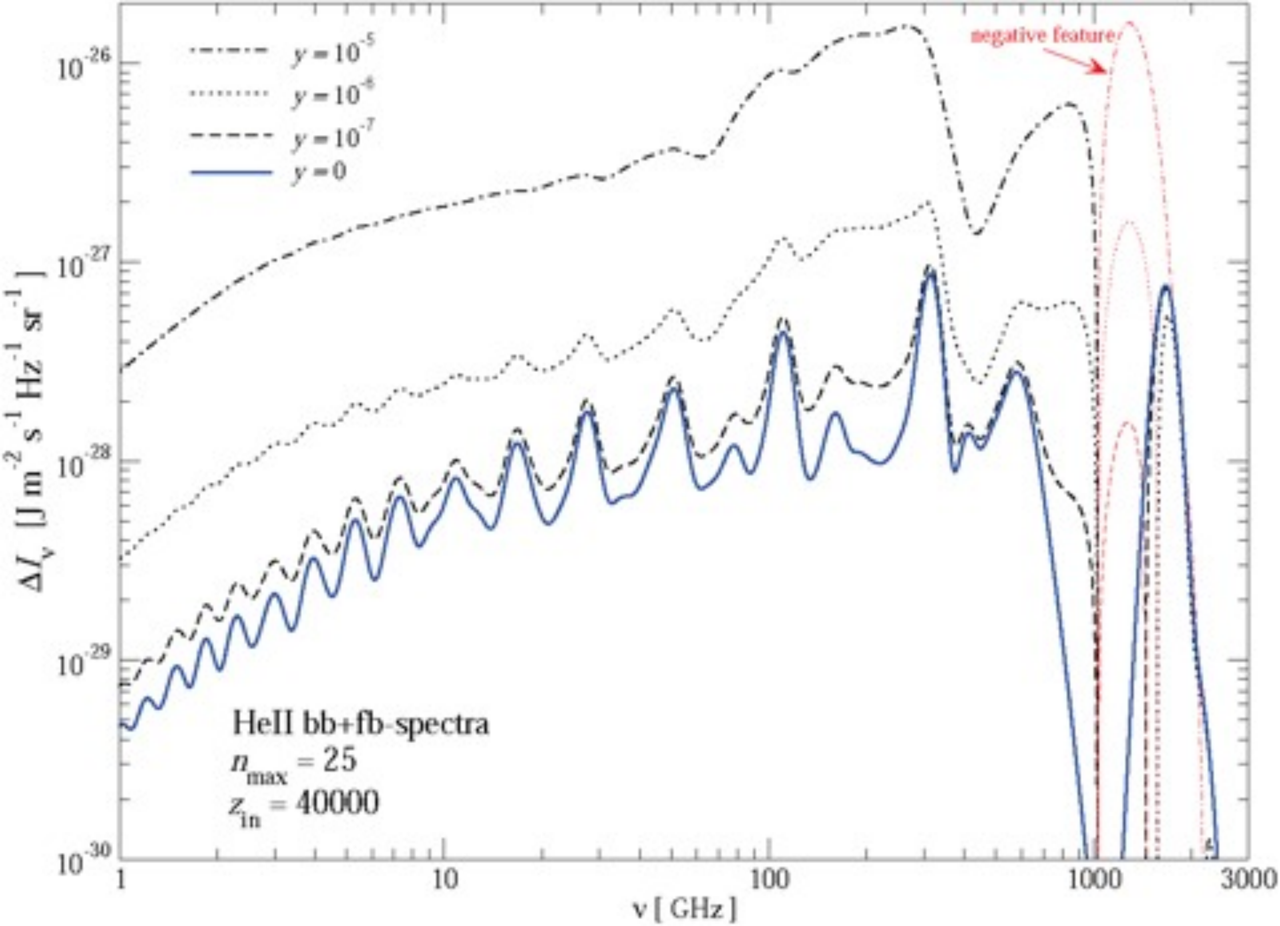


Helium +



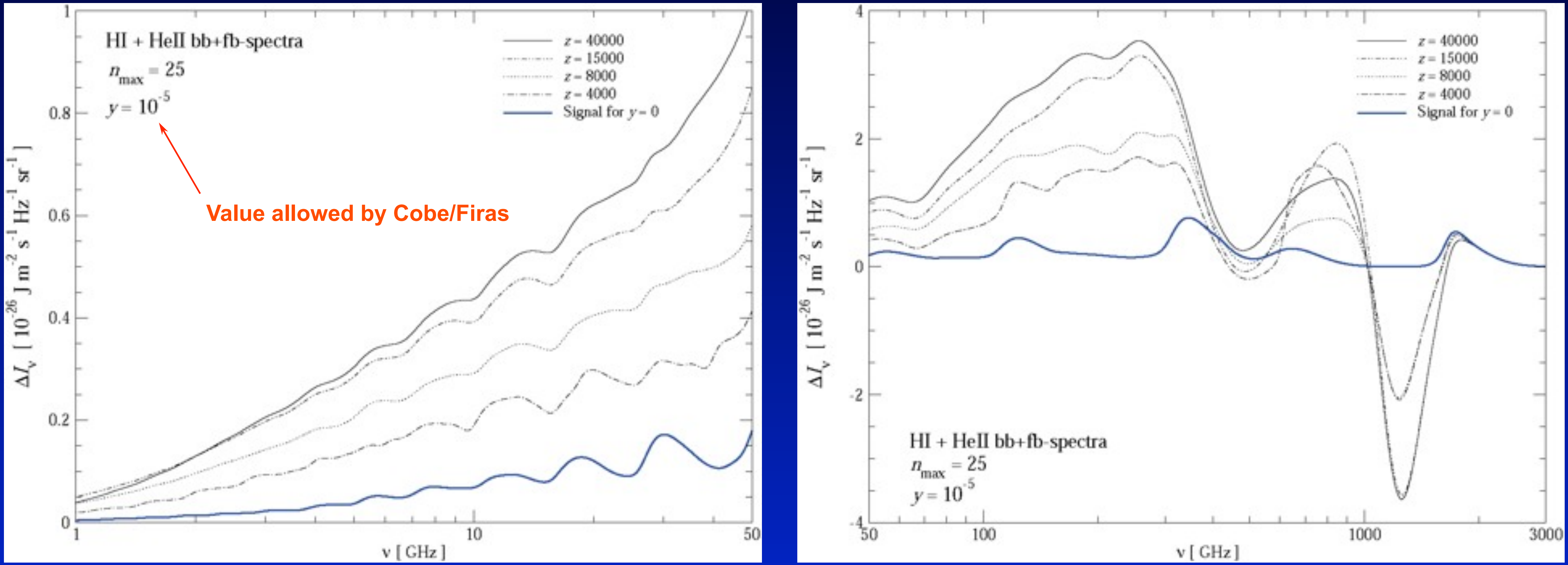
JC & Sunyaev, 2008, astro-ph/0803.3584

- Large increase in the total amplitude of the distortions with value of *y*!
- Strong emission-absorption feature in the Wien-part of CMB (absent for *y*=0!!!)
- HeII contribution to the pre-recombinational emission as strong as the one from Hydrogen alone !

CMB spectral distortions after single energy release

25 shell HI and HeII bb&fb spectra: dependence on z

Hydrogen and Helium +



Value allowed by Cobe/Firas

JC & Sunyaev, 2008, astro-ph/0803.3584

- Large increase in the total amplitude of the distortions with injection redshift!
- Number of spectral features depends on injection redshift!
- Emission-Absorption feature increases ~2 for energy injection z ⇒11000

What would we actually learn by doing such hard job?

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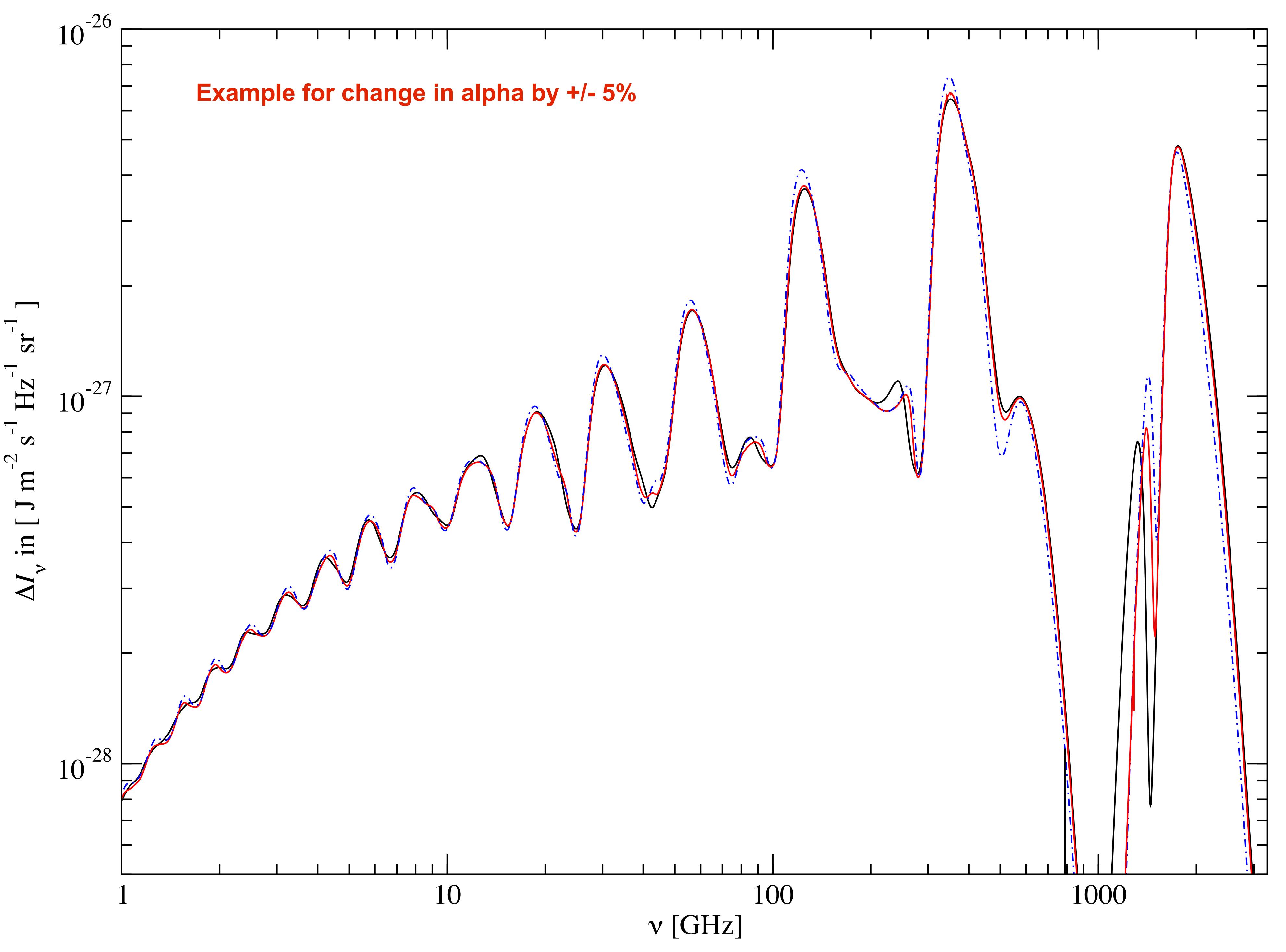
If something unexpected or non-standard happened:

- → ***non-standard thermal histories should leave some measurable traces***
- → **possibility to distinguish *pre-* and *post-recombinational y*-type distortions**
- → ***sensitive to energy release during recombination epochs***

Change of HI distortion because of difference in α



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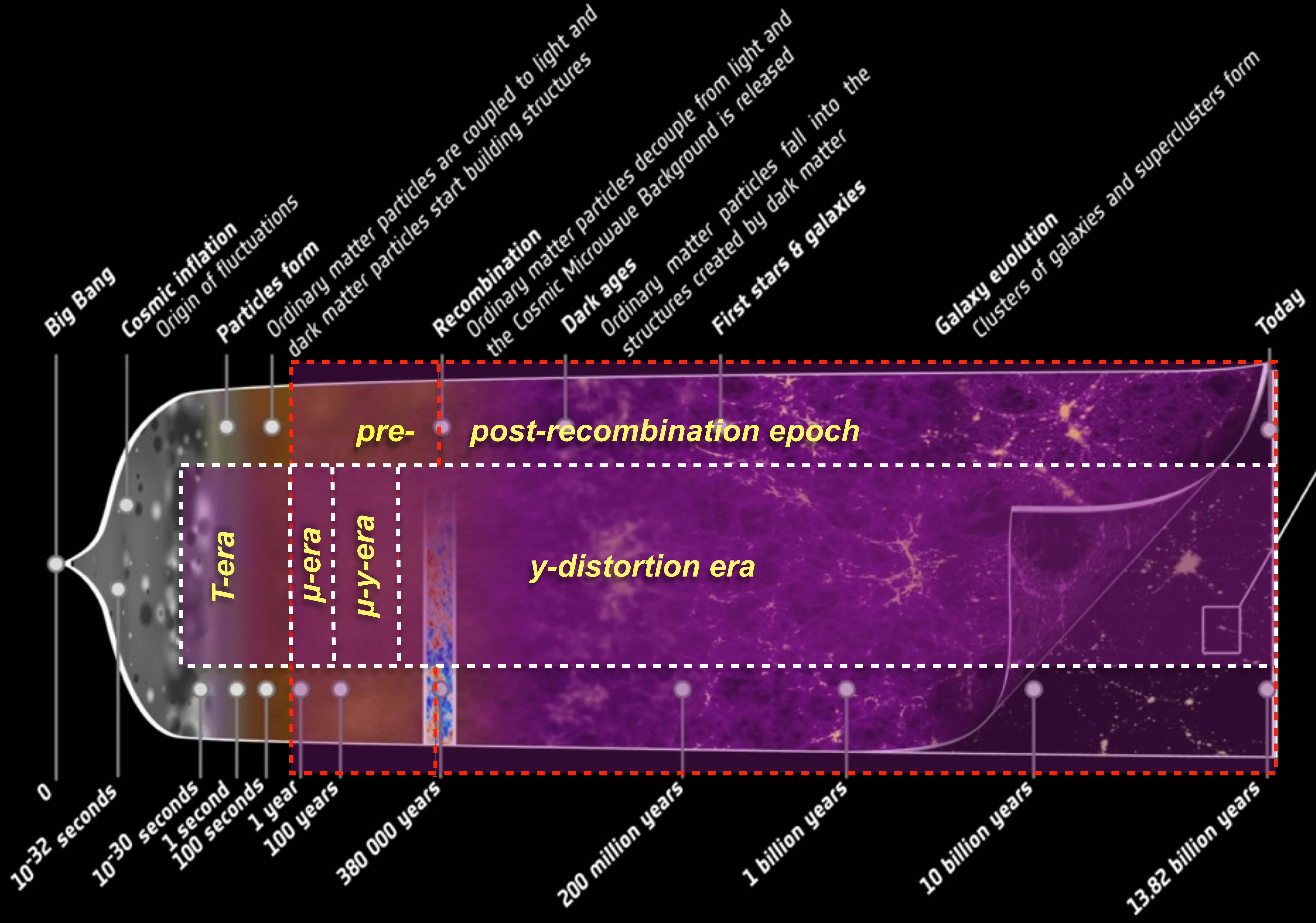
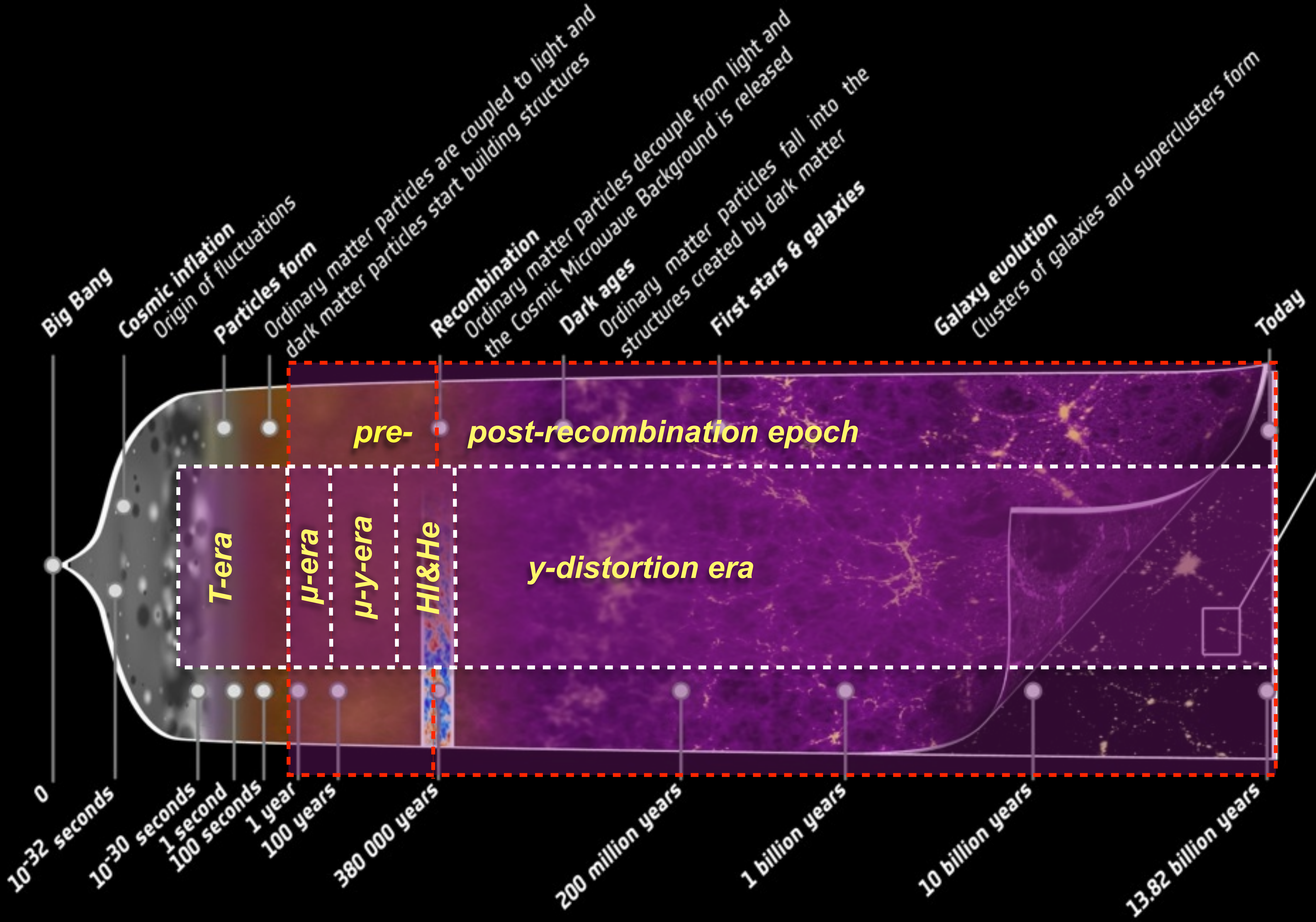
This would open a new way to constrain cosmological models


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
T-era
μ-era
μ-y-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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10^{-30} seconds
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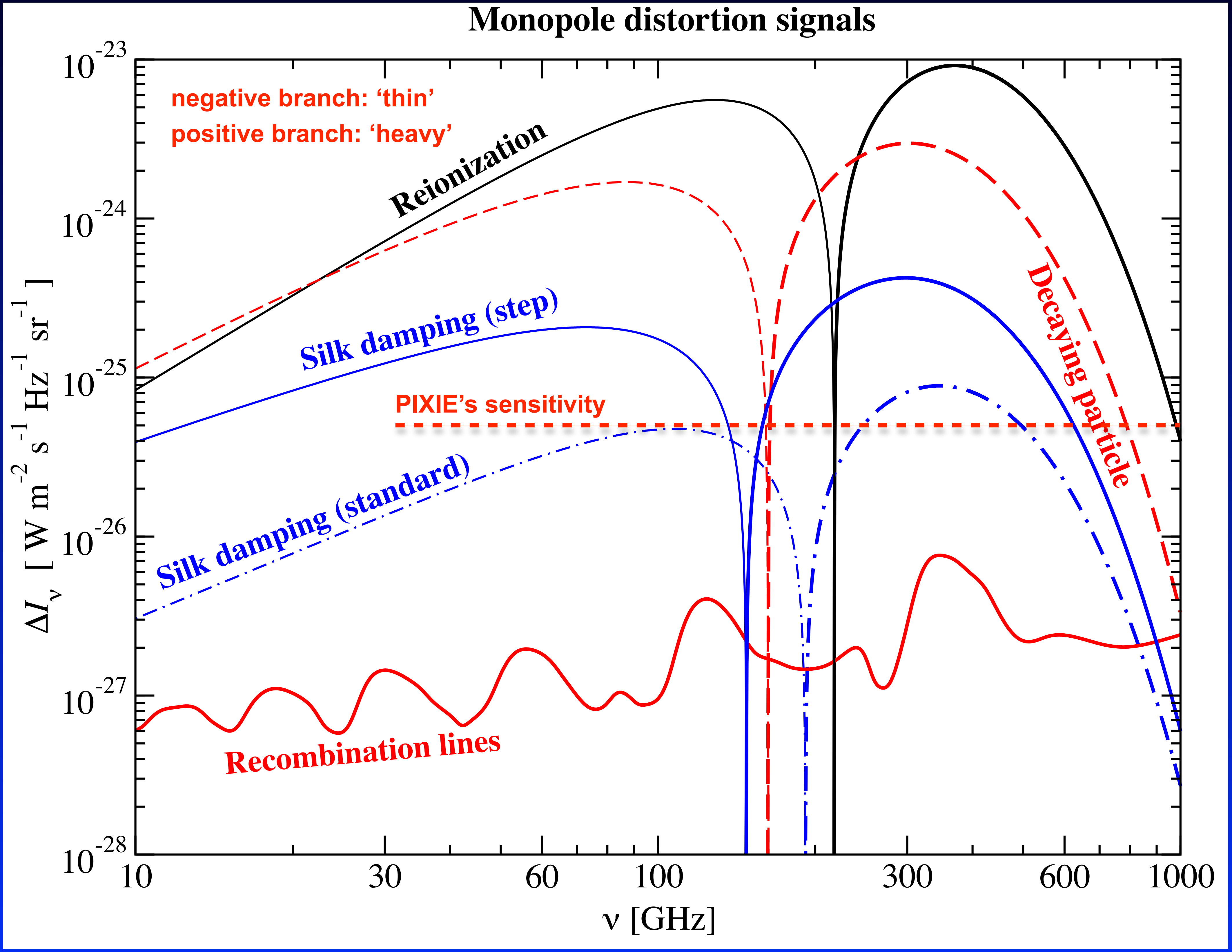
10 billion years
13.82 billion years

Average CMB spectral distortions

Absolute value of Intensity signal



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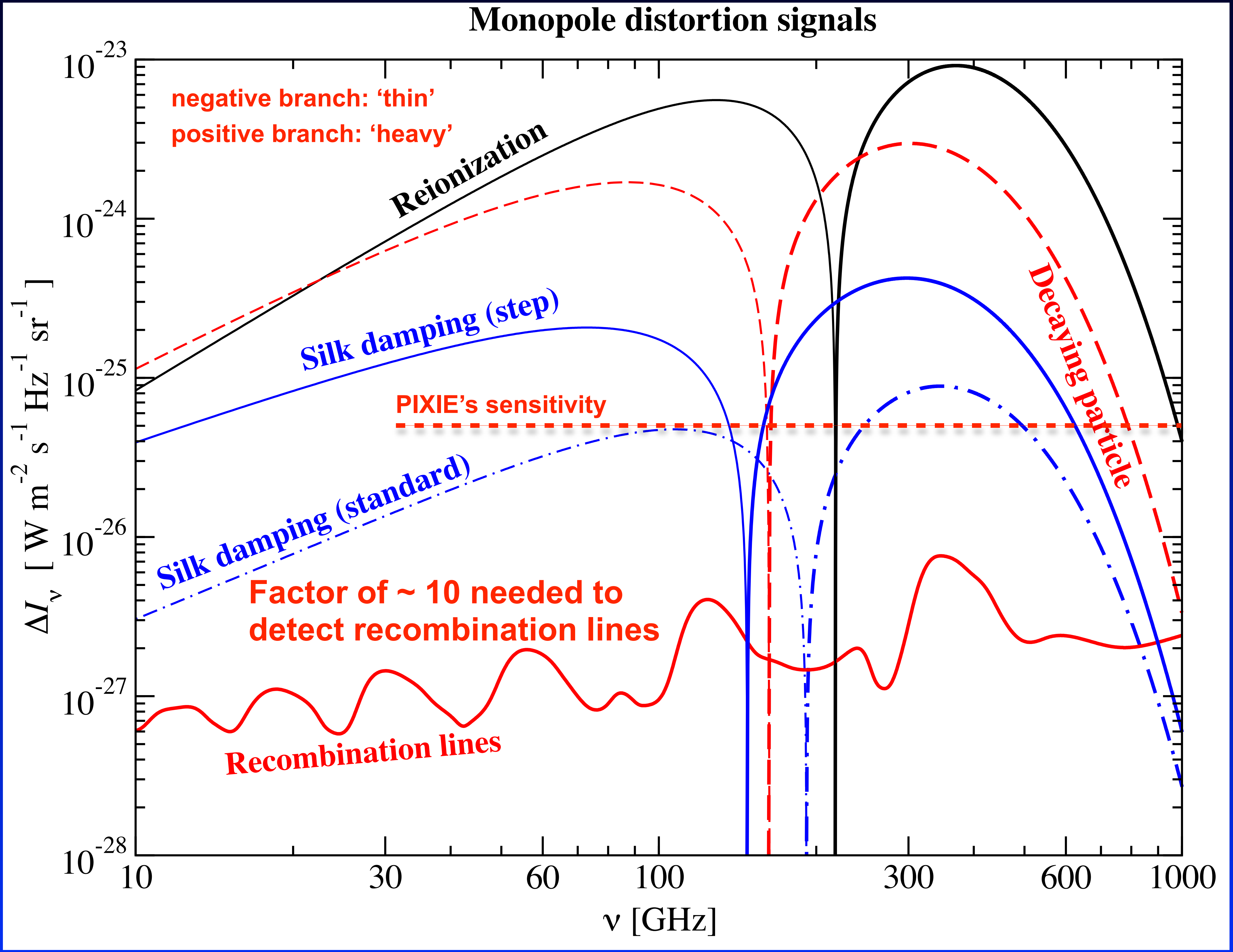

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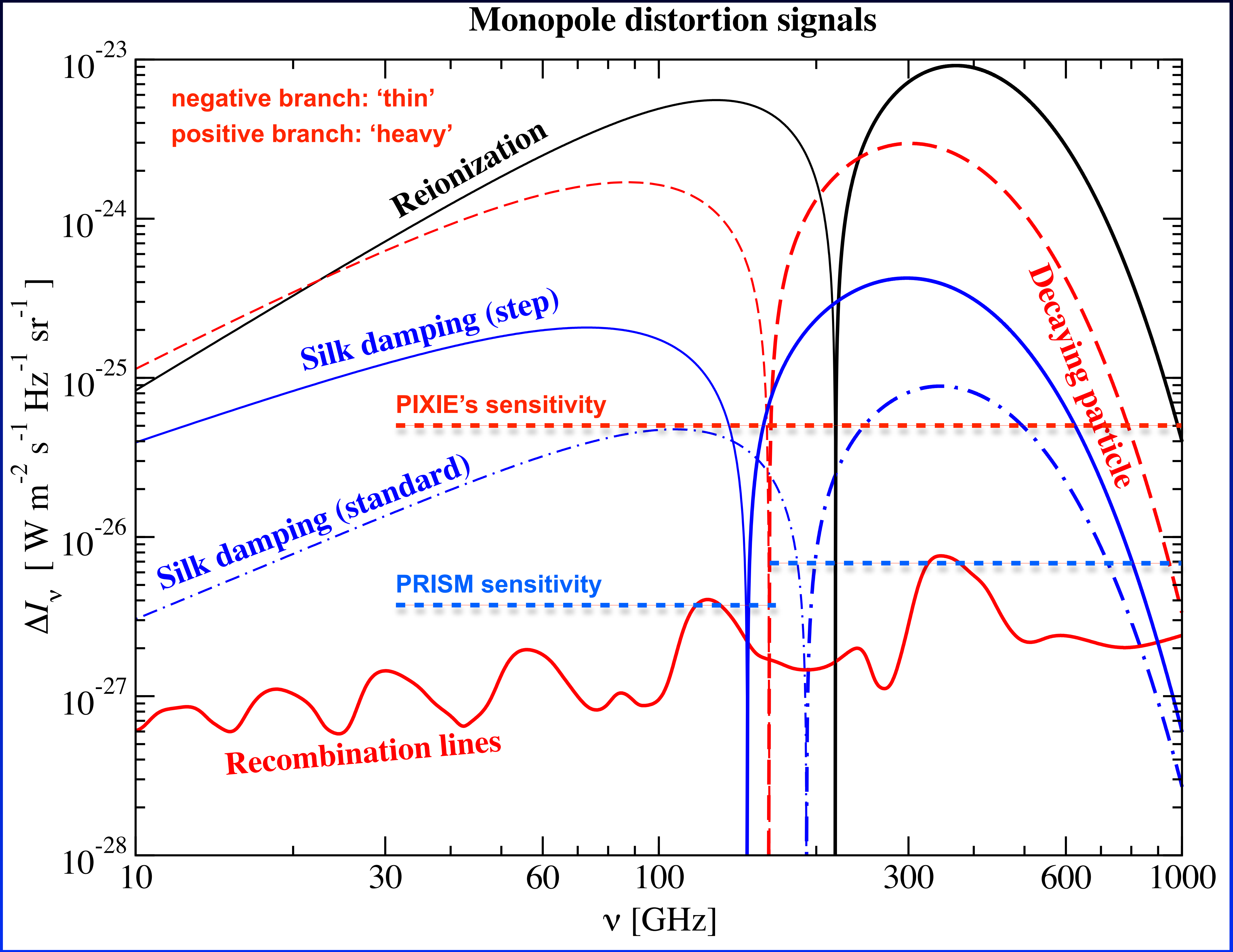
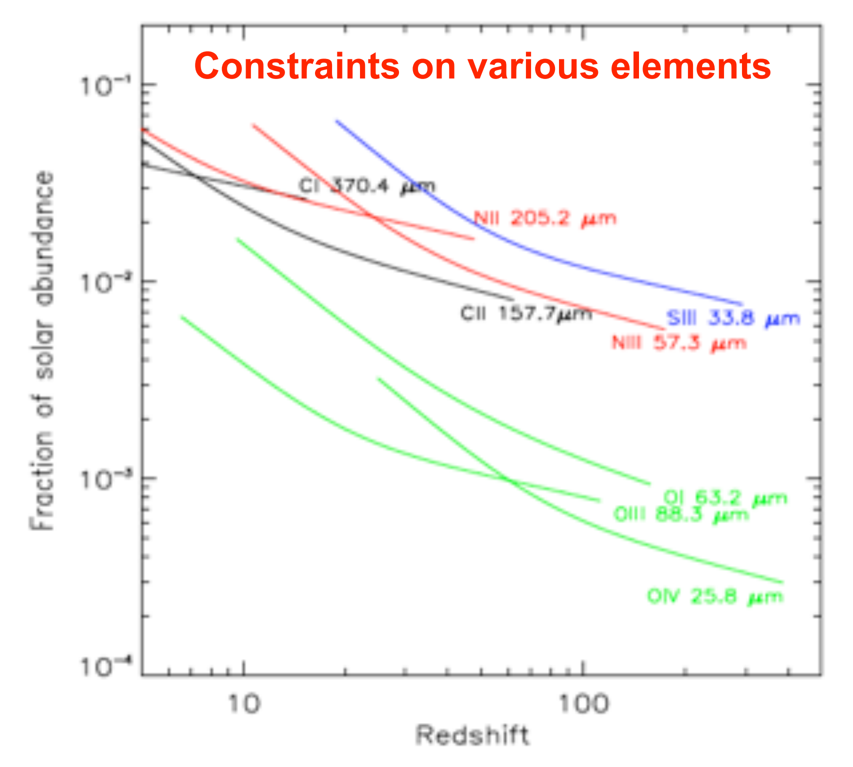
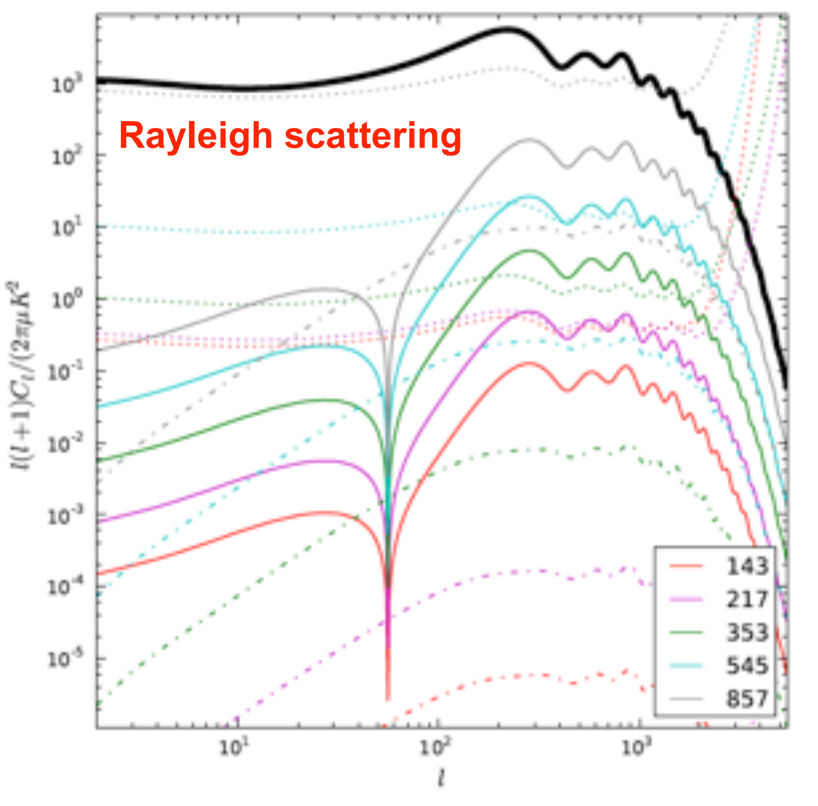


Other extremely interesting new signals

- Scattering signals from the dark ages
  (e.g., Basu et al., 2004; Hernandez-Monteagudo et al., 2007; Schleicher et al., 2009)
  - constrain abundances of chemical elements at high redshift
  - learn about star formation history
- Rayleigh / HI scattering signals
  (e.g., Yu et al., 2001; Rubino-Martin et al., 2005; Lewis 2013)
  - provides way to constrain recombination history
  - important when asking questions about N_{eff} and Y_{p}
- Free-free signals from reionization
  (e.g., Burigana et al. 1995; Trombetti & Burigana, 2013)
  - constrains reionization history
  - depends on clumpiness of the medium

> *All these effects give spectral-spatial signals, and an absolute spectrometer will help with channel cross calibration!*





Physical mechanisms that lead to spectral distortions

Standard sources of distortions

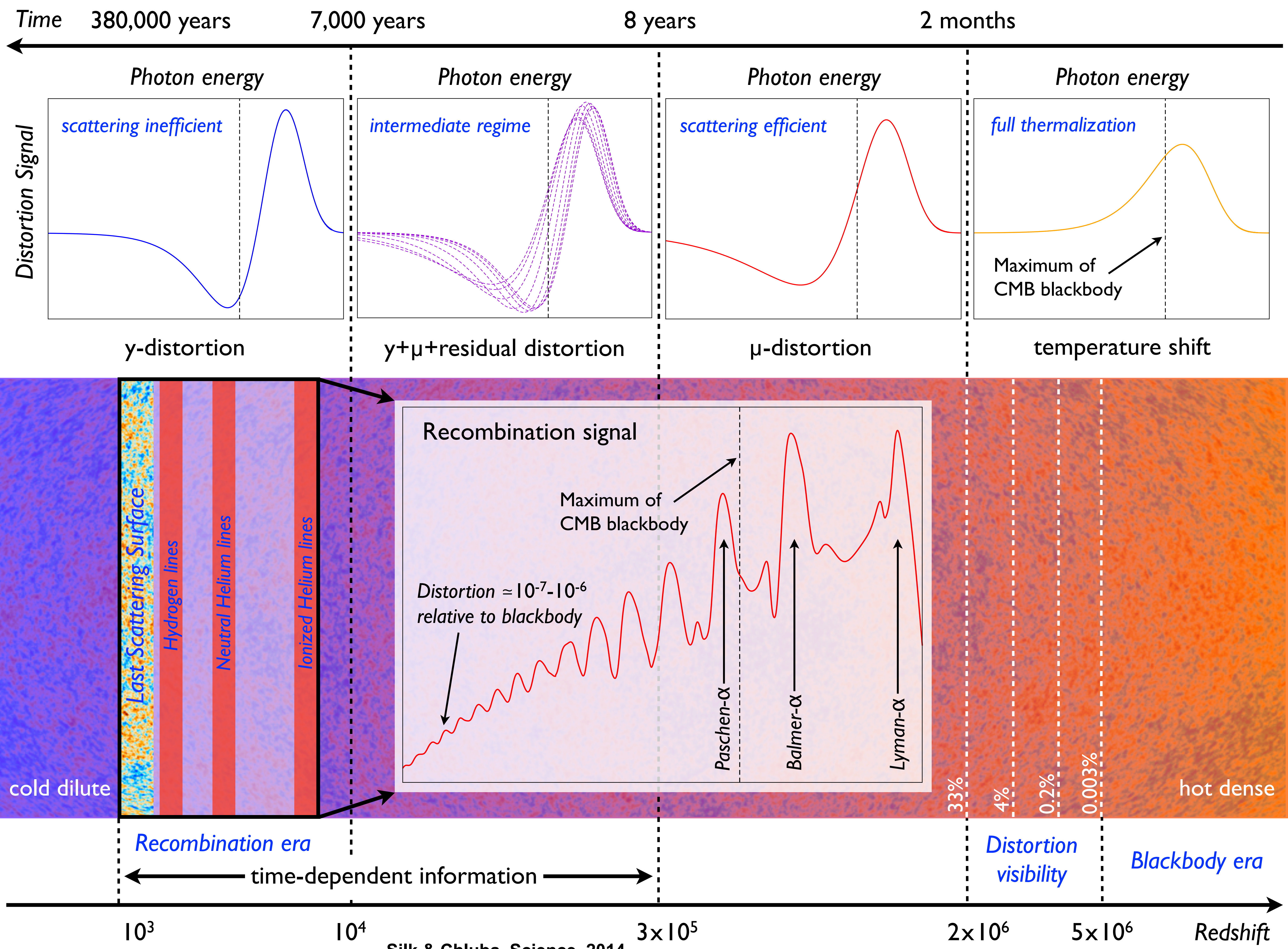
- *Cooling by adiabatically expanding ordinary matter*
  (JC, 2005; JC & Sunyaev 2011; Khatri, Sunyaev & JC, 2011)
- Heating by *decaying* or *annihilating* relic particles
  (Kawasaki et al., 1987; Hu & Silk, 1993; McDonald et al., 2001; JC, 2005; JC & Sunyaev, 2011; JC, 2013; JC & Jeong, 2013)
- *Evaporation 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***

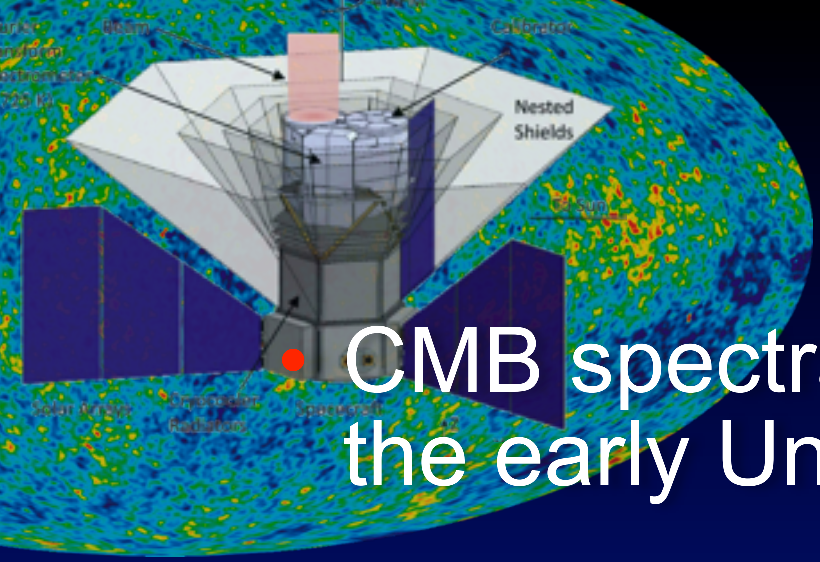
- -

„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)



Silk & Chluba, Science, 2014



Conclusions

- CMB spectral distortions *will* open a *new window* to the early Universe
- new probe of the *inflation epoch* and *particle physics*
- *complementary* and *independent* source of information *not* just confirmation
- in *standard cosmology* several processes lead to *early energy release* at a level that will be detectable in the future
- extremely interesting *future* for CMB-based science!

We should make use of all this information!