Science with CMB Spectral Distortions

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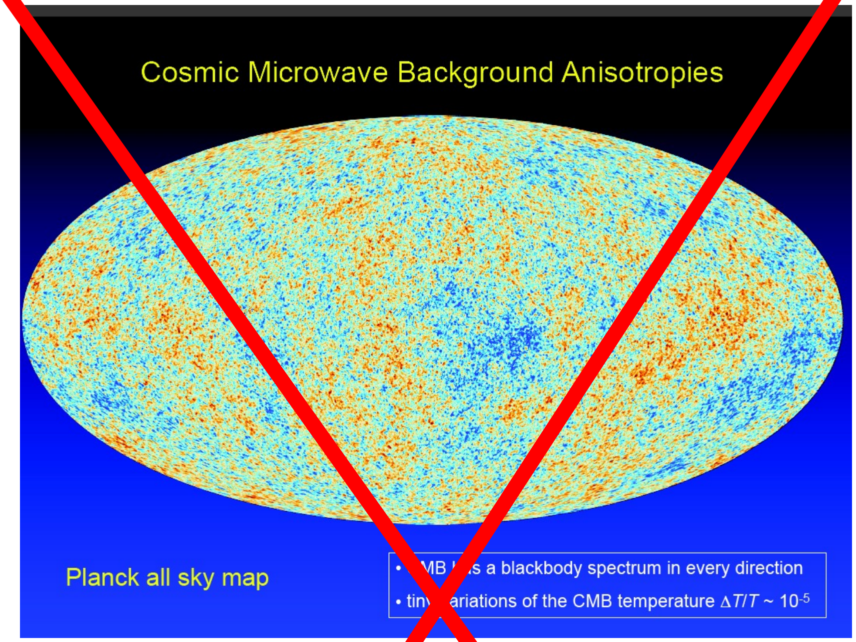
Astro-ph 1405.6938

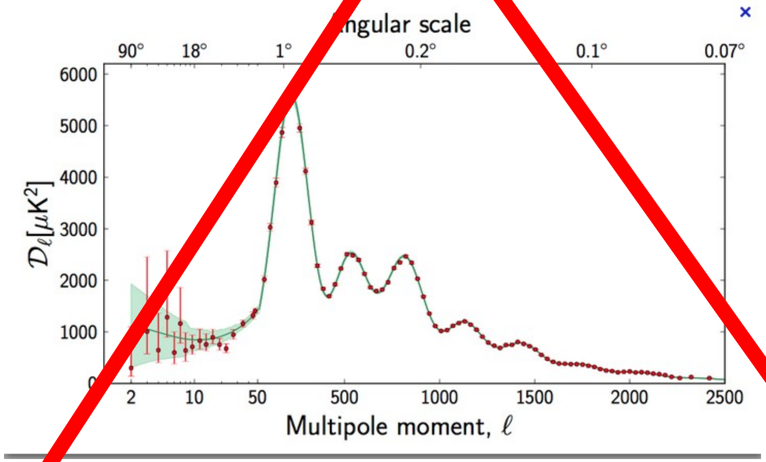
TODAY



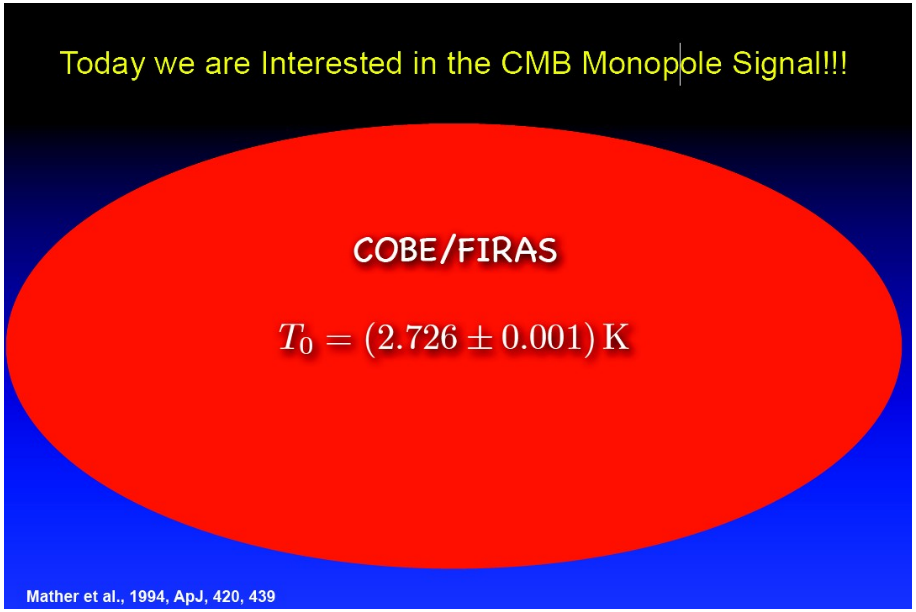
Cosmic Microwave Background Anisotropies

Planck all sky map

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



Spatial anisotropies



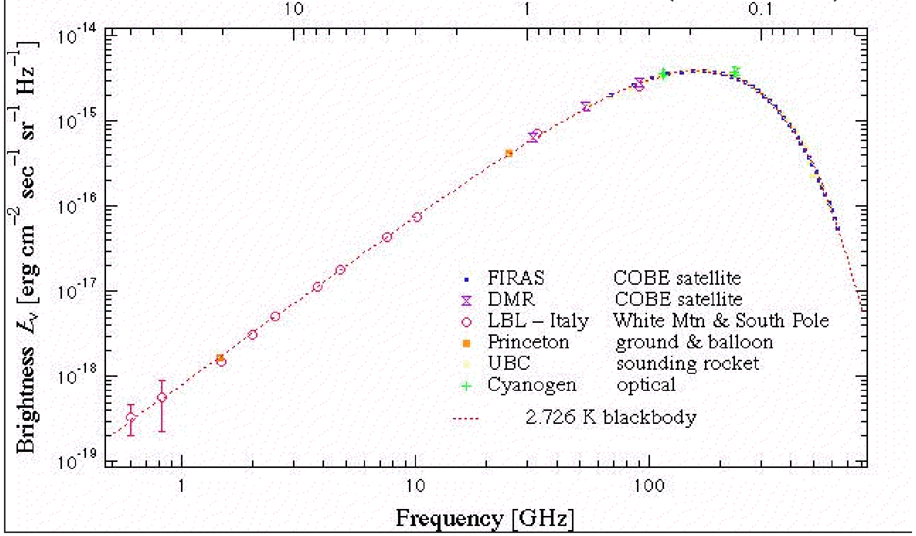
Today we are Interested in the CMB Monopole Signal!!!

COBE/FIRAS

$$T_0 = (2.726 \pm 0.001)\,\mathrm{K}$$

Mather et al., 1994, ApJ, 420, 439

$$\Delta I_\nu \lesssim 10^{-5}\, I_\nu(peak)$$



Spectral shape

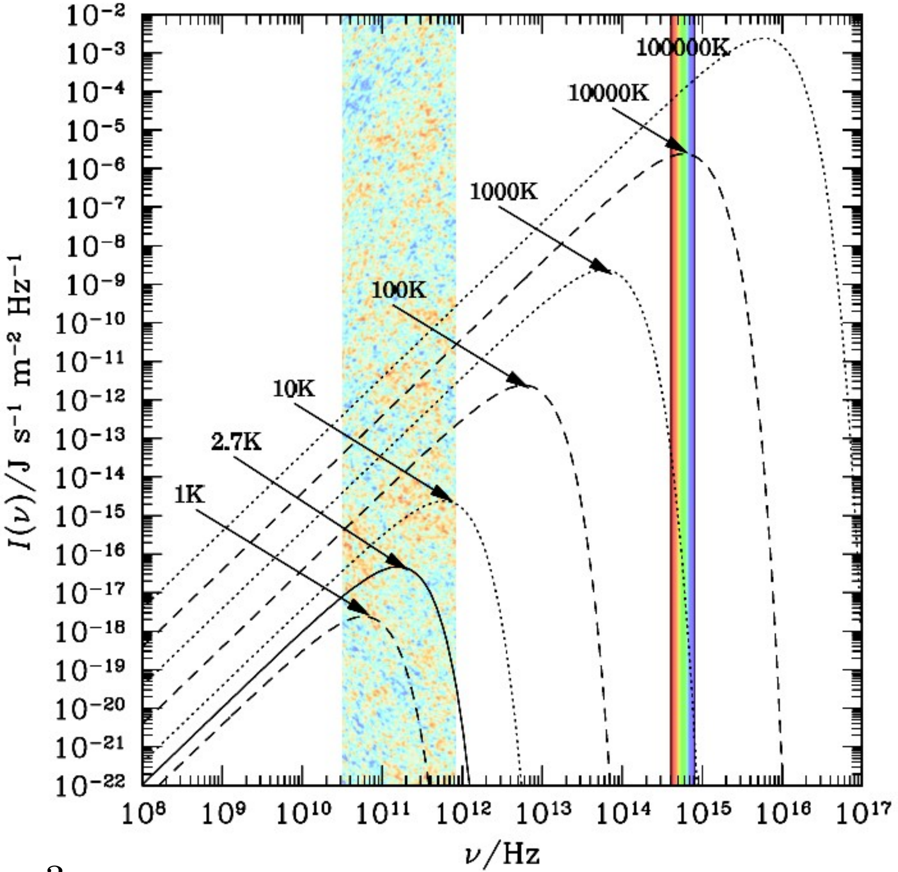
Blackbody radiation

$$x = \frac{h\nu}{kT}$$

Rayleigh-Jeans

$x \ll 1$

$$B_\nu(T) \propto x^2 T$$



Wien

$x \gg 1$

$$B_\nu(T) \propto x^3\, e^{-x}$$

Planck $$B_\nu(T) \propto \frac{x^3}{e^x - 1}$$

Specific Intensity $$dE = I_\nu \; (W/m^{-2}/Hz/sr)\; dt\; dA\; d\Omega\; d\nu$$

$$\nu_{max} \simeq 58.8\, T\, GHz \;\; \longrightarrow \; 160\; GHz\; @2.726\; K \;\; (I_{\nu_{max}} = 3.8\; 10^{-18}\; W/m^2/Hz/sr)$$

Energy injection in BB

- *(remember: uniform adiabatic expansion of the Universe leaves BB unchanged)*
- Just add energy to photon field (ex: shift the frequency) $\frac{\Delta T}{T} \sim \frac{1}{4} \, \frac{\Delta \rho_\gamma}{\rho_\gamma}$
- Keeping the BB need to change the number of photons such that

$$\frac{\Delta T}{T} \sim \frac{1}{3} \, \frac{\Delta n_\gamma}{n_\gamma} \qquad \longrightarrow \qquad \frac{\Delta n_\gamma}{n_\gamma} = \frac{3}{4} \, \frac{\Delta \rho_\gamma}{\rho_\gamma}$$

- Necessary but not sufficient: need to specify how the added/missing photons are distributed in energy
- Keeping BB after energy injection need:
  - Changing the photon number + Redistributing photon energy
- In the early universe this is done by :
  - Compton scattering with e- (energy redistribution,, Thompson just isotropize)
  - Double compton + Bremsstrahlung (changing photon number)

Was enough time from the creation of the distortion until today to fully restore the BB shape below any observable level

How does it work ?   Boltzmann eq.

$$\frac{\partial f}{\partial t} = C_{\mathrm{K}} + C_{\mathrm{DC}} + C_{\mathrm{BR}} + x\frac{\partial f}{\partial x}\frac{\partial}{\partial t}\left[\ln\left(\frac{T_e}{T_{\gamma 0}(1+z)}\right)\right]$$

Compton scatterring

Double compton scatterring

Bremsstrahlung

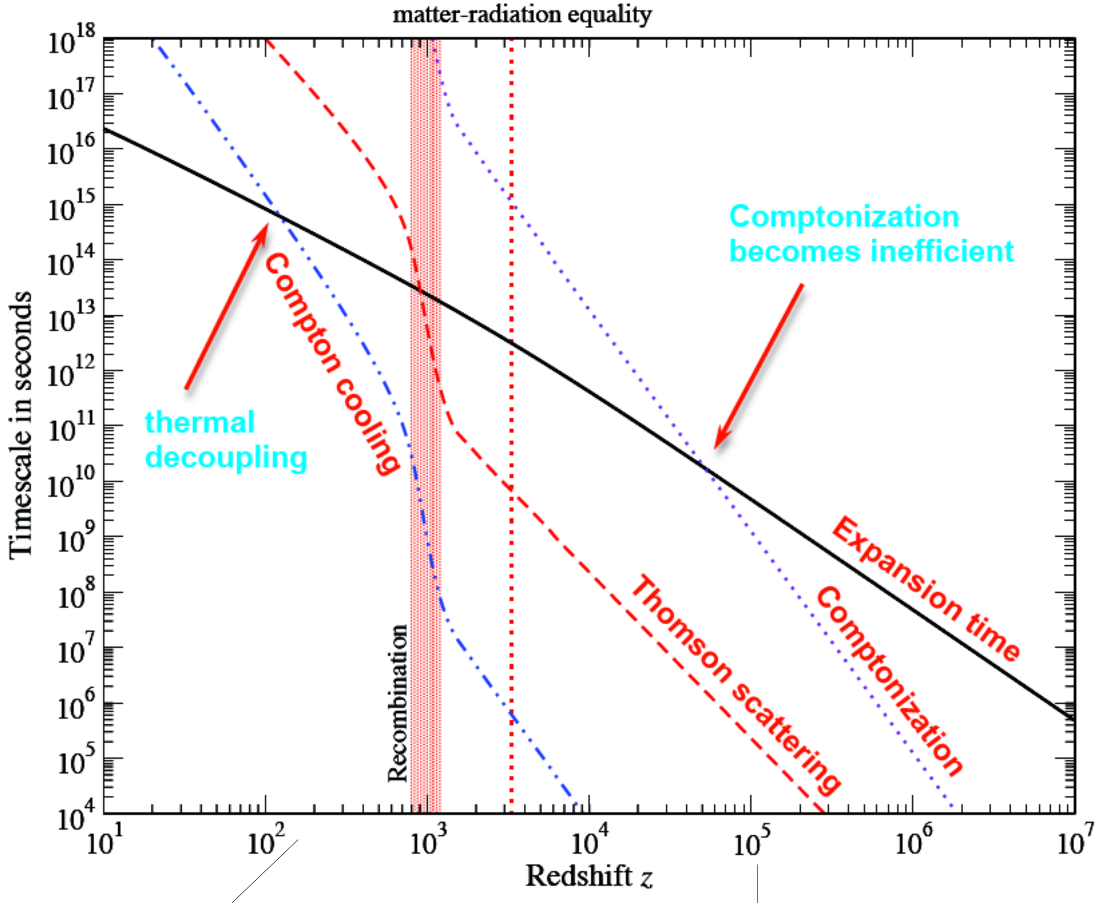
Te evolves with time

$$\frac{dT_e}{dt} = -2HT_e - \frac{4\sigma_{\mathrm{T}}\rho_\gamma}{3m_e f_*}\left(T_e - \frac{1}{\rho_\gamma \pi^2}\int dp\, p^4 f(1+f)\right)$$

Adiabatic cooling (expansion)

Compton cooling
e- cool (1+z)^2 , photons (1+z)
but photons heat e- (10^9 ph/e-)
Dominant for z>200

f*(Ne,Yp) : correction due to rapid thermalization of baryons and e- by Coulomb scattering



$$z_{dc}, z_{br} \sim 2\ 10^6$$

$$t_{cc} \sim t_H$$

$$z_{cc} \sim 200$$

$$t_K \sim t_H$$

~~$z_k \sim 5\ 10^4$~~

$$z_{fr} \sim 2\ 10^5$$

$$z_{bb} \sim 2\ 10^6$$

Inject energy at z

e- cool

$T_e \propto (1+z)^2$

No more K
y-type distortions

K works
ph+e- interact
Photon is BE
µ-type distortions

DC+BR works
Photons is BB
Just a T increase

y–type, μ-type and I-type distortions

- 2 E5 < z < 2 E6 : photons and electrons in thermal equilibrium
  - Photon BE with a x dependant chemical potential: $f(x) \sim \frac{1}{e^{x-\mu(x)}-1}$
  - Because DC and BR decoupling times depend on photon energy

$$t_{dc} = t_H \longrightarrow x_{H,dc} \simeq 6\ 10^{-11}\ (1+z)^{3/2} \longrightarrow z_{dc}(x)$$

  - For low energy photons x<<1 , a blackbody is quickly established
  - While for high energy photons x>>1 , the photon spectrum stays BE
  - Approx: $\mu \propto 3\frac{\delta\rho_\gamma}{\rho_\gamma} - 4\frac{\delta n_\gamma}{n_\gamma}$
- 200 < z < 1.5 E 4 : injected energy is not thermalized, just transfert energy between photons and electrons via CC (SZ distortion at low z, high Te)
  - $y = \int dt x_e n_e \sigma_T \frac{T_e - T}{m_e}$
  - Also generated by BB mixing: $T' = T\,[1+ <\Delta T>^2/T^2]\ ,\ y = \frac{1}{2}\frac{<\Delta T>^2}{T^2}$
- But there is no sharp transition, but a spectral distortion will depend on the “amount” of comptonization (compton parameter): 1.5 E4 < z < 2 E5

$$y_\gamma = -\int_{z_{inject}}^{z} dz \frac{k_B \sigma_T}{m_e c}\frac{n_e T_\gamma}{H(1+z)}$$

$$y_\gamma \ll 1 \longrightarrow y - type$$

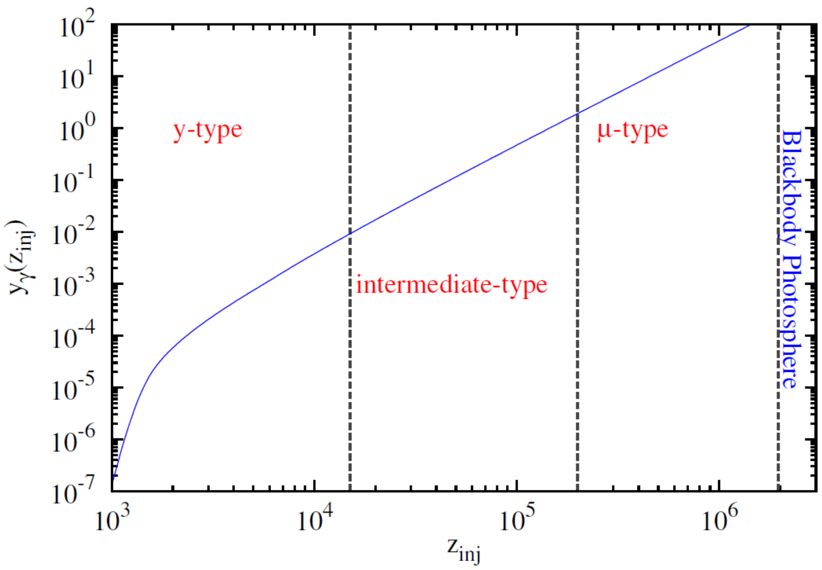
$$y_\gamma \gg 1 \longrightarrow \mu - type$$

Spectral shape

COBE 95% CL

$$|\, y \,| < \; 1.5\; 10^{-5}$$

$$|\, \mu \,| < \; 9.0\; 10^{-5}$$



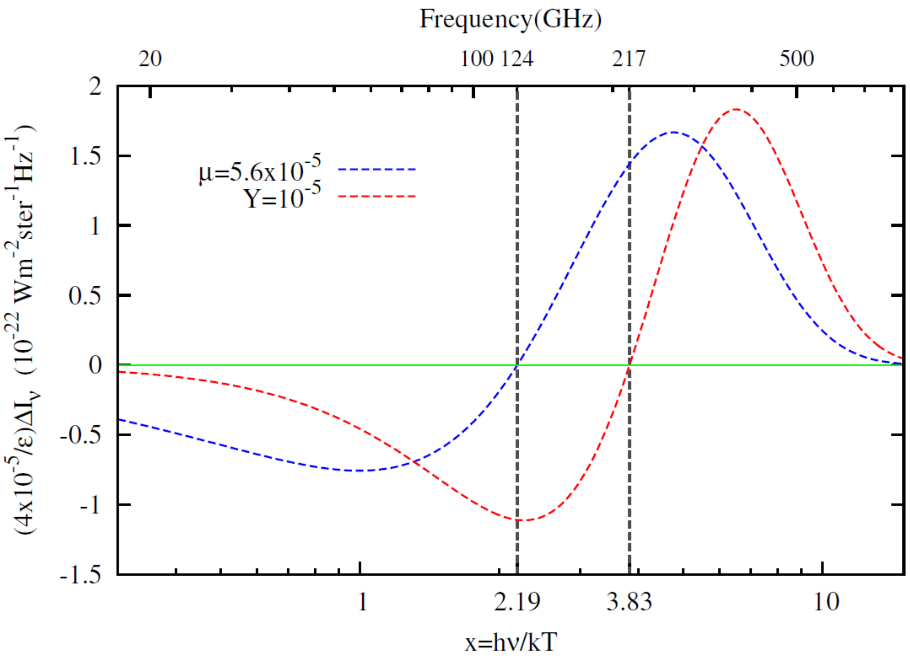
PIXIE, PRISM(?)

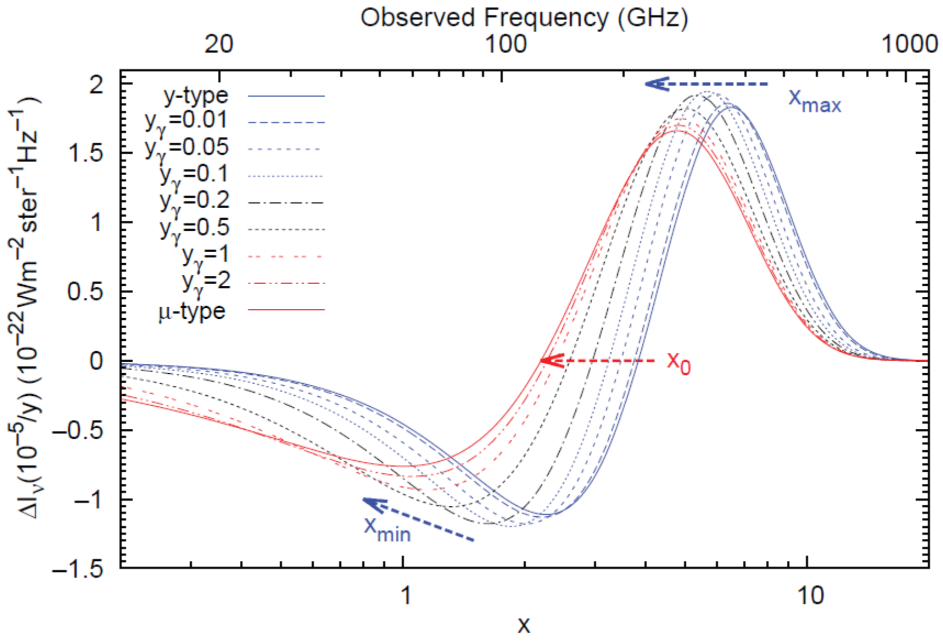
$$30\; GHz \;\rightarrow\; 6\; THz$$

$$\Delta\, I_\nu \;=\; 5\; 10^{-26}\; Wm^{-2} sr^{-1} Hz^{-1}$$

$$y \;=\; 10^{-8} \qquad (5\sigma)$$

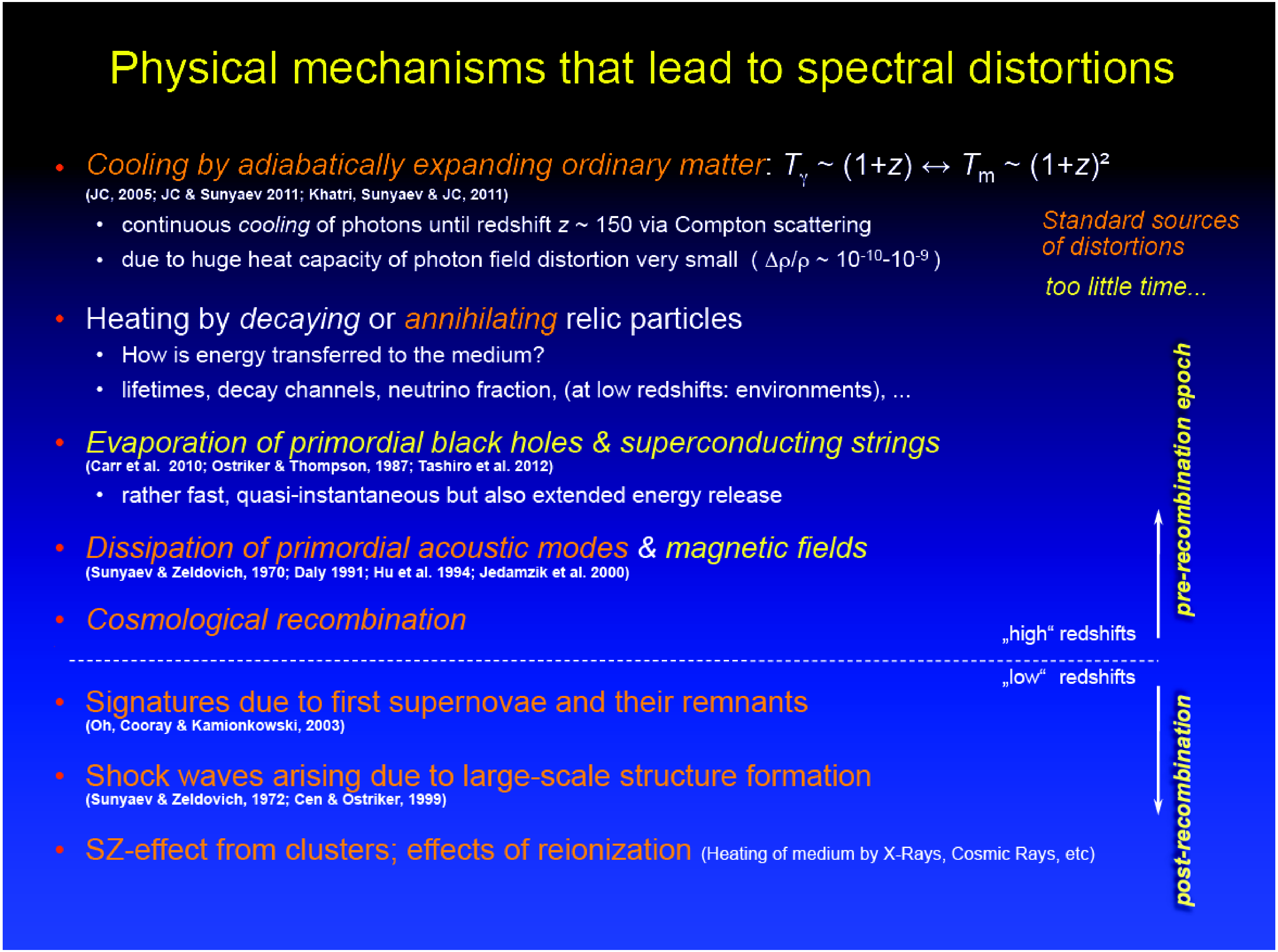
$$\mu \;=\; 5\; 10^{-8} \qquad (5\sigma)$$





$$I_\nu(peak) \;\sim\; 10^{-18}\; Wm^{-2} sr^{-1} Hz^{-1}$$

Physical mechanisms that lead to spectral distortions



Physical mechanisms that lead to spectral distortions

- *Cooling by adiabatically expanding ordinary matter*: $T_\gamma \sim (1+z) \leftrightarrow T_m \sim (1+z)^2$
  (JC, 2005; JC & Sunyaev 2011; Khatri, Sunyaev & JC, 2011)
  - continuous *cooling* of photons until redshift $z \sim 150$ via Compton scattering
  - due to huge heat capacity of photon field distortion very small ($\Delta\rho/\rho \sim 10^{-10}\text{-}10^{-9}$)
- Heating by *decaying* or *annihilating* relic particles
  - How is energy transferred to the medium?
  - lifetimes, decay channels, neutrino fraction, (at low redshifts: environments), ...
- *Evaporation of primordial black holes & superconducting strings*
  (Carr et al. 2010; Ostriker & Thompson, 1987; Tashiro et al. 2012)
  - rather fast, quasi-instantaneous but also extended energy release
- *Dissipation of primordial acoustic modes* & *magnetic fields*
  (Sunyaev & Zeldovich, 1970; Daly 1991; Hu et al. 1994; Jedamzik et al. 2000)
- *Cosmological recombination*

Standard sources of distortions

too little time...

pre-recombination epoch

„high“ redshifts

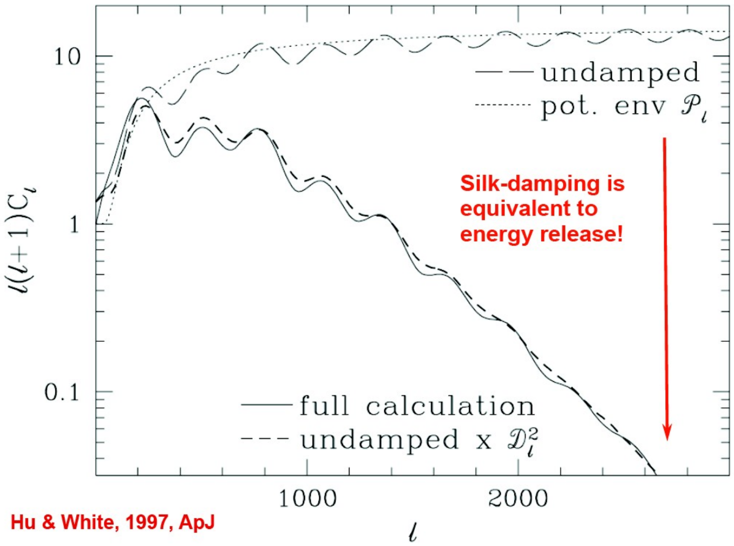
„low“ redshifts

post-recombination epoch

- 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 (Heating of medium by X-Rays, Cosmic Rays, etc)

Dissipation of small-scale perturbations

Photon free streaming smooths small wavelength acoustic waves (Silk damping)

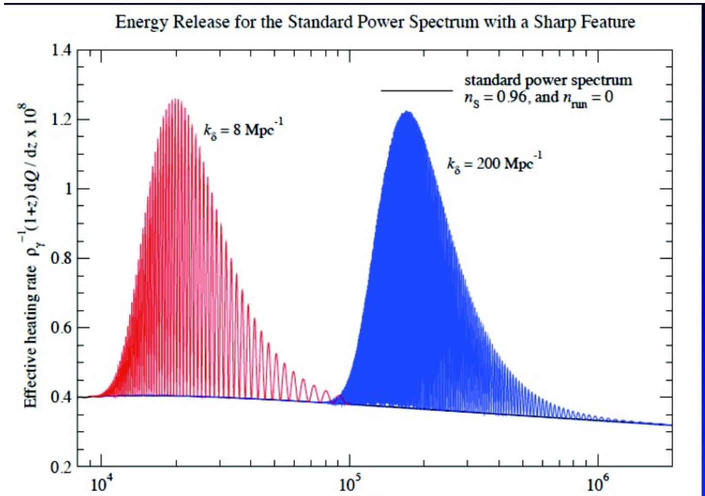


Silk-damping is equivalent to energy release!

Hu & White, 1997, ApJ

$$\mathcal{P}_\zeta(k) \equiv A_\zeta\,(k/k_0)^{n_S-1+\frac{1}{2}n_{\rm run}\ln(k/k_0)}$$

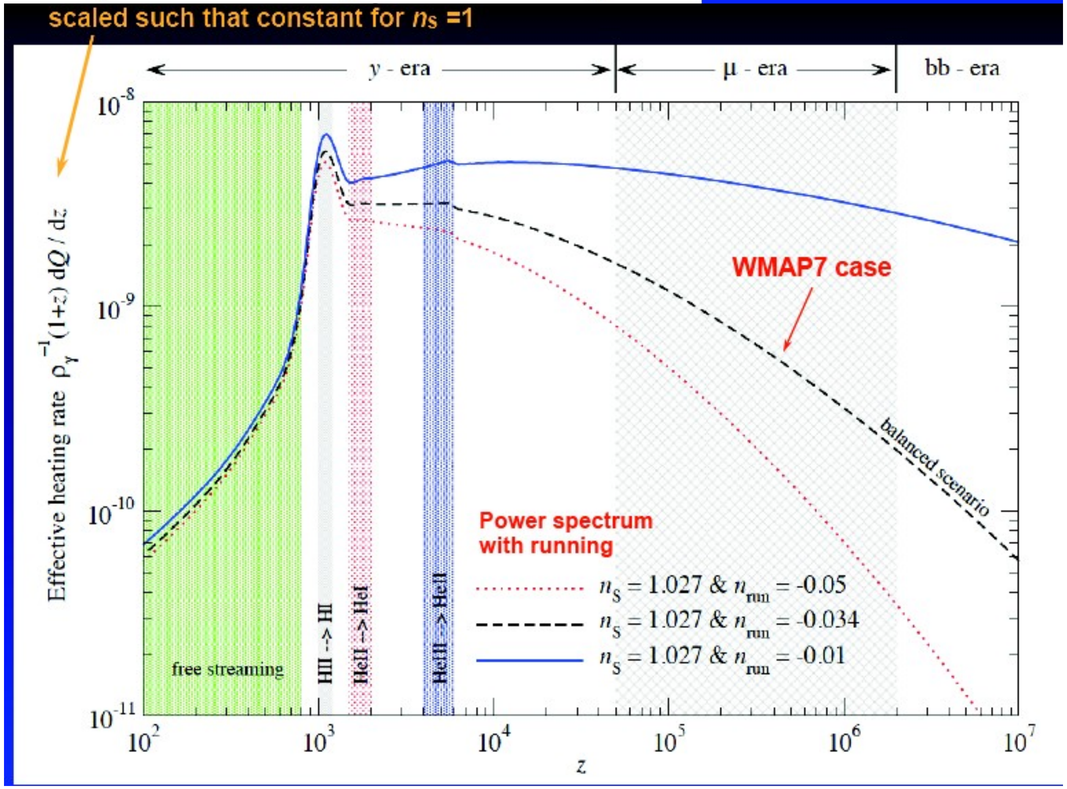
$$\left.\frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z}\right|_{\rm ac} \approx 2D^2\int_{k_{\rm cut}}^{\infty} \mathcal{P}_\zeta(k)\,\partial_z \mathrm{e}^{-2k^2/k_{\rm D}^2}\,\mathrm{d}\ln k$$



- 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

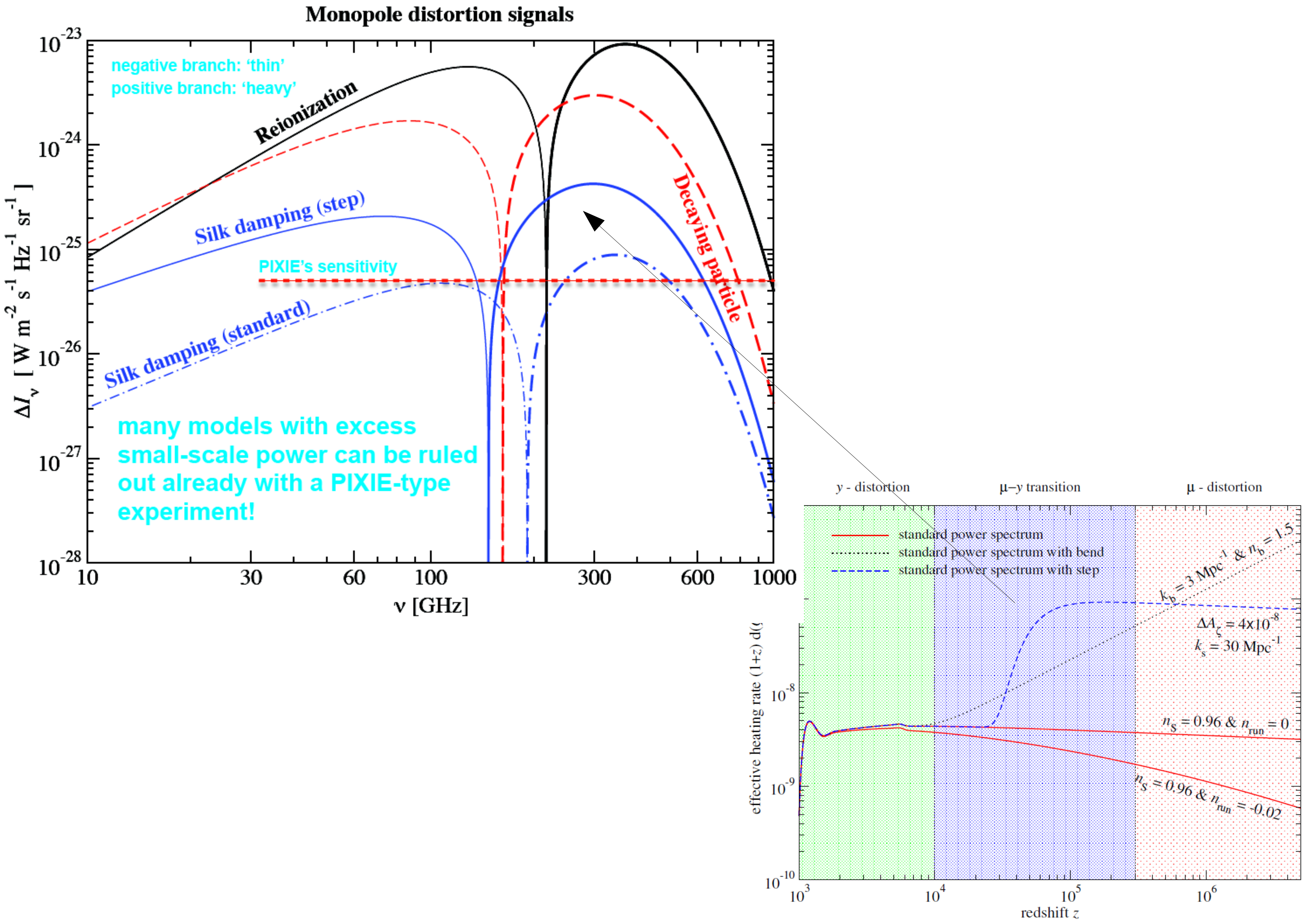


scaled such that constant for n_S =1

WMAP7 case

Power spectrum with running

Dissipation of small-scale perturbations



negative branch: ‘thin’
positive branch: ‘heavy’

PIXIE's sensitivity

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

Energy release by decaying particles

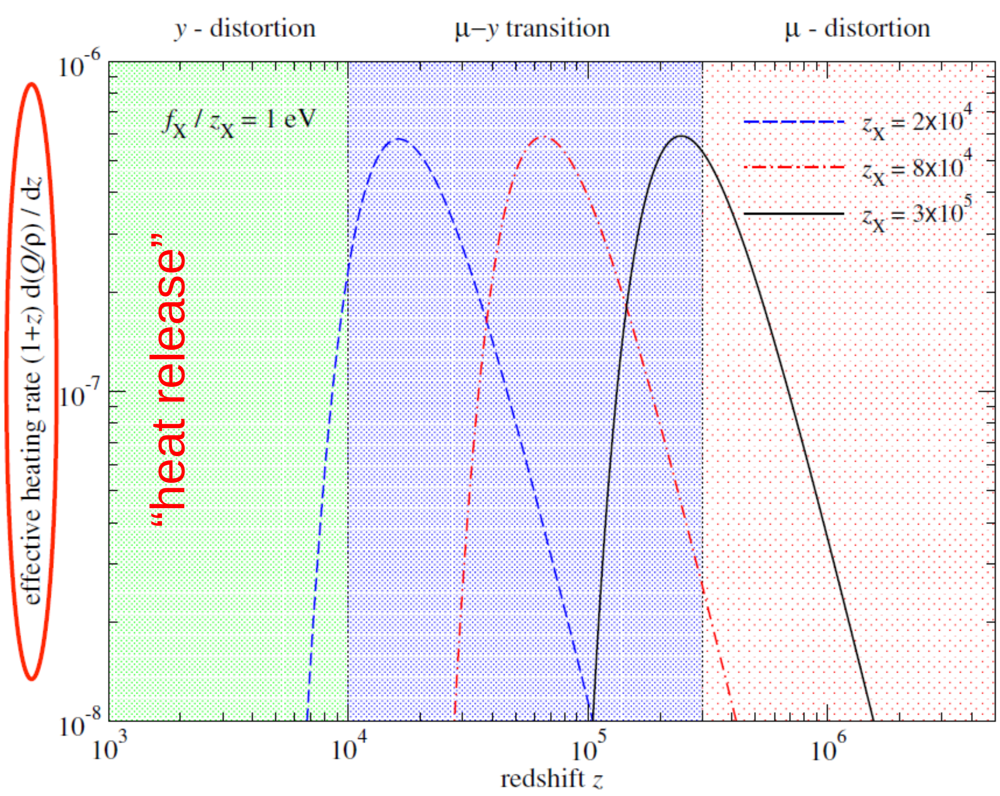
- Energy release rate $$\frac{\mathrm{d}(Q/\rho_\gamma)}{\mathrm{d}z} \approx \frac{f^* M_X c^2}{H(z)(1+z)} \frac{N_X(z)}{\rho_\gamma(z)} \Gamma_X \mathrm{e}^{-\Gamma_X t}$$
- *For computations*: $f_X = f^* M_X c^2 N_X / N_H$ and $\varepsilon_X = \dfrac{f_X}{z_X}$
- Efficiency factor f^* contains all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

  $\Rightarrow$ *branching ratios into heat, ionizations, and atomic e*

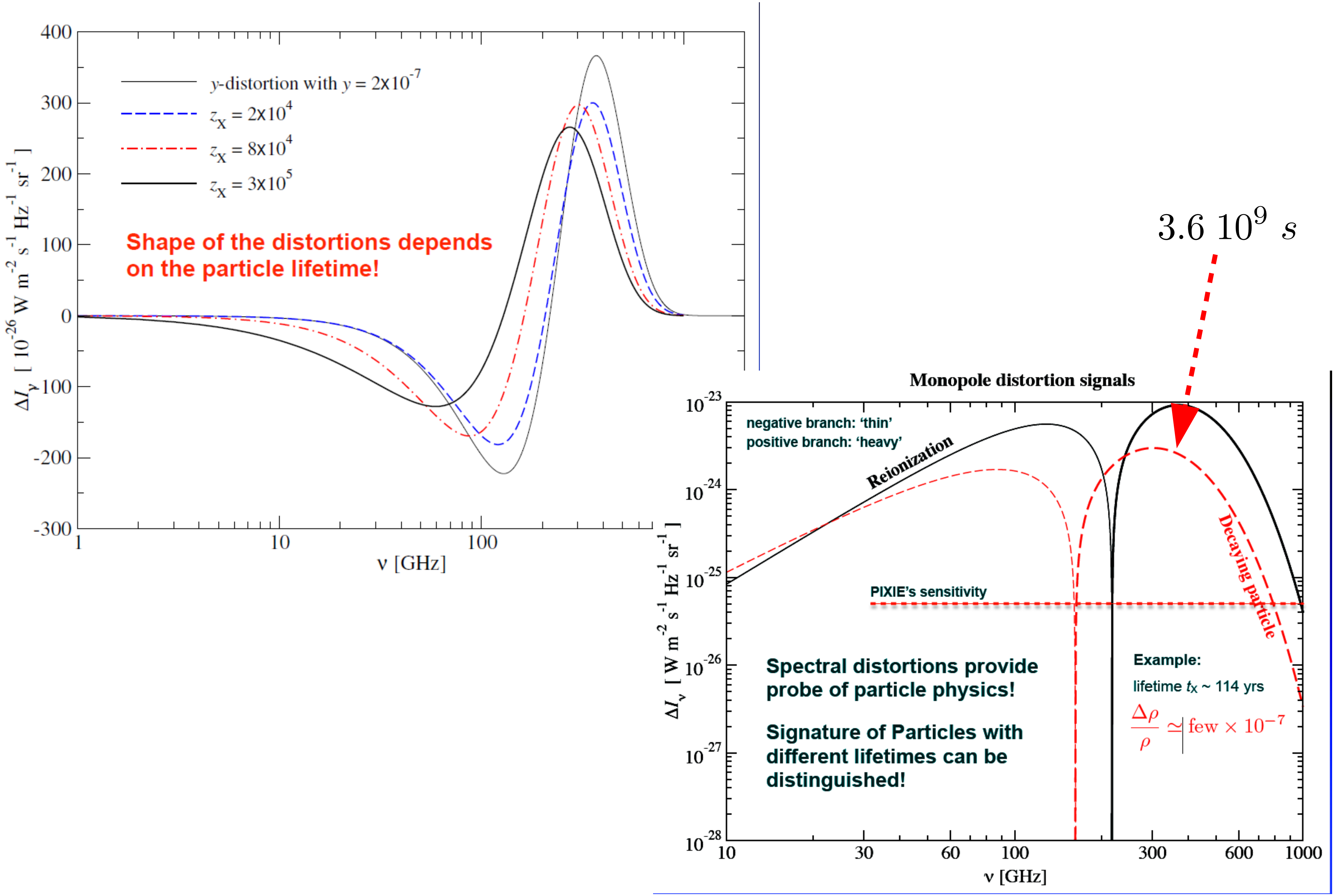
$$large\ \tau_X \;\rightarrow\; smaller\ z_X \;\rightarrow\; y - like$$

$$small\ \tau_X \;\rightarrow\; larger\ z_X \;\rightarrow\; \mu - like$$

$$in\ practice: \quad 10^9\ s \;<\; \tau_X \;<\; 10^{11}\ s$$



Energy release by decaying particles



Shape of the distortions depends on the particle lifetime!

$3.6\ 10^9\ s$

Spectral distortions provide probe of particle physics!

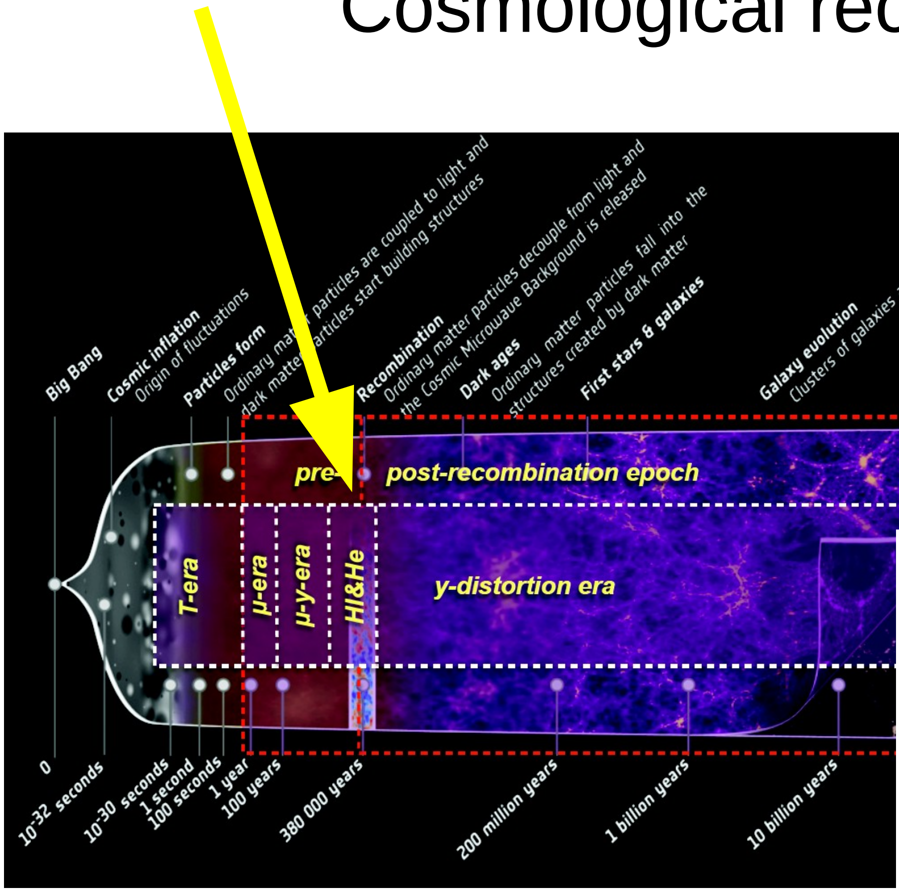
Signature of Particles with different lifetimes can be distinguished!

Example:

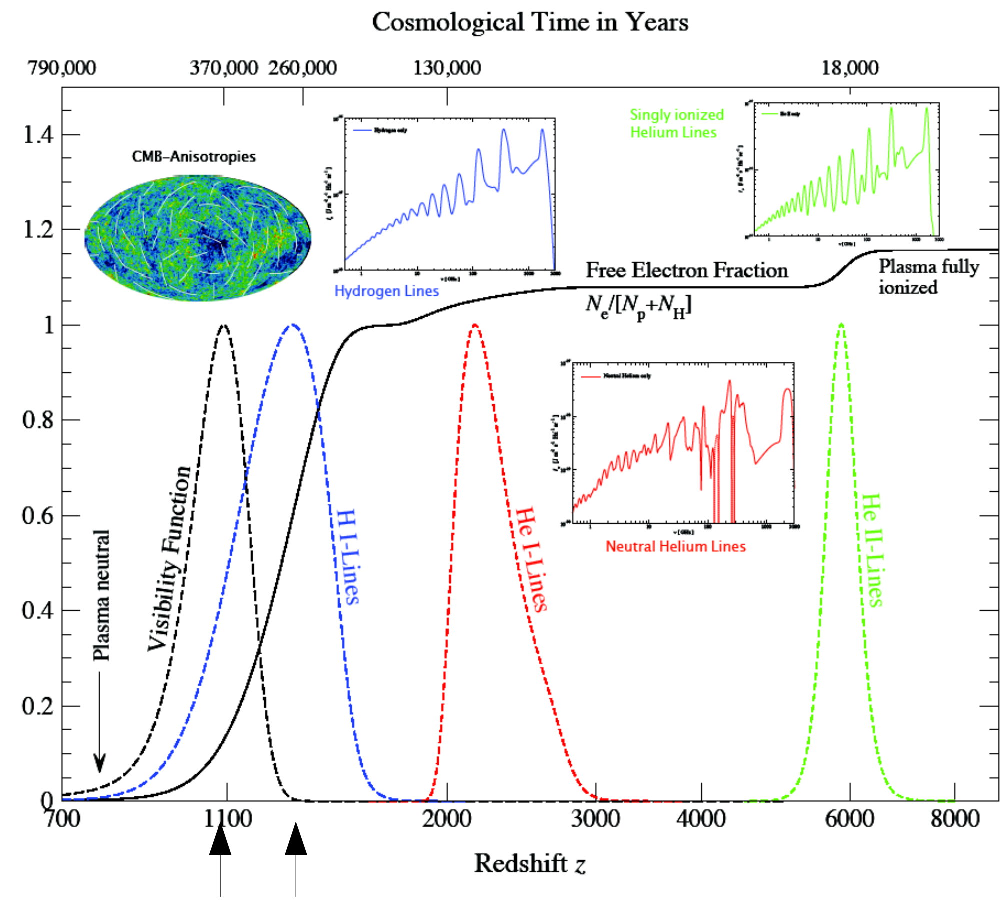
lifetime t_X ~ 114 yrs

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

Cosmological recombination radiation



~ 5 photons / hydrogen atom



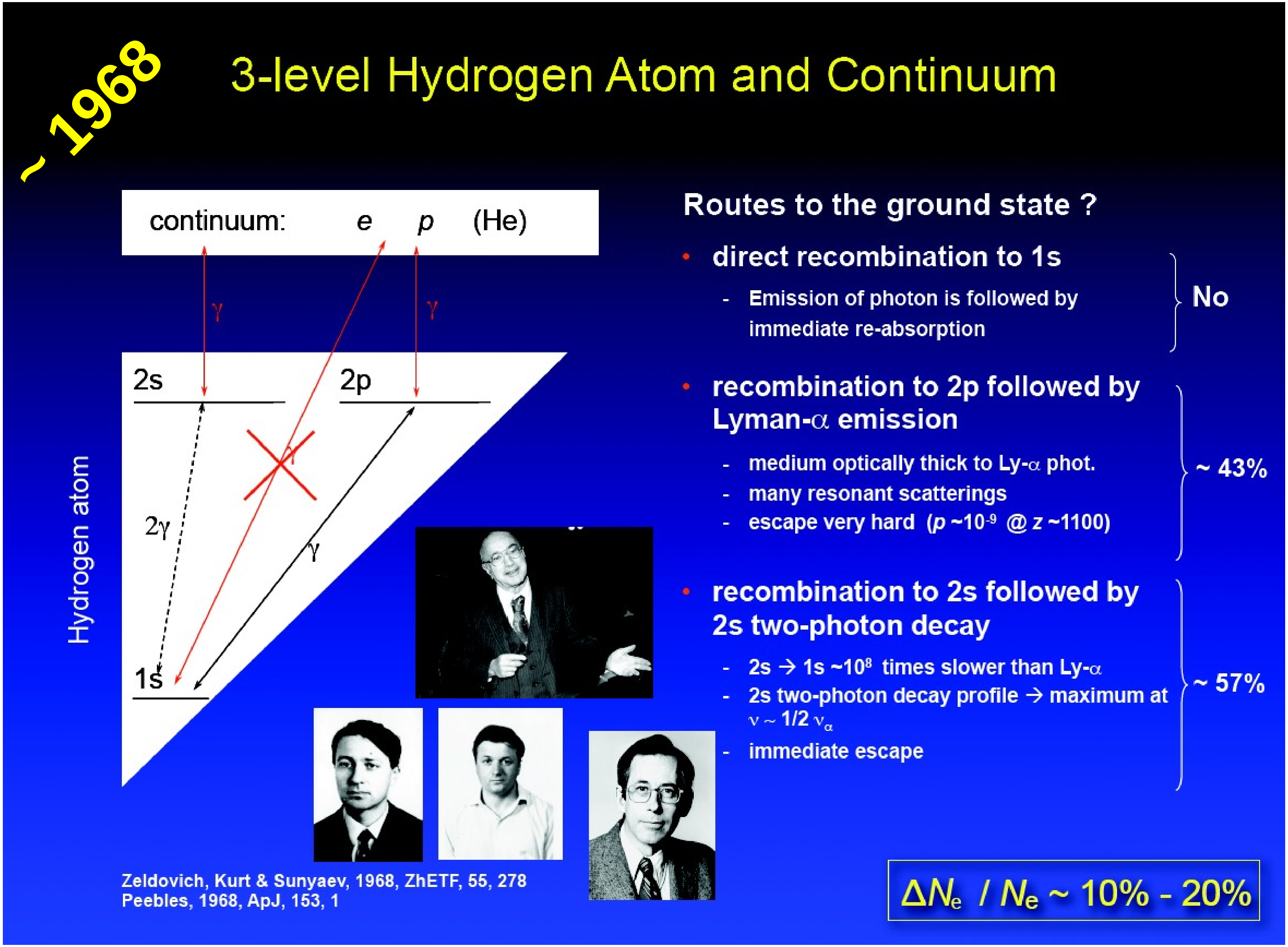
Line recombination:

$$HII \rightarrow HI \ : \ z \sim 1300$$

$$H_eII \rightarrow H_eI \ : \ z \sim 2000$$

$$H_eIII \rightarrow H_eII \ : \ z \sim 5900$$

1968 : Kurt, Zeldovich, Sunyaev & Peebles



3-level Hydrogen Atom and Continuum

Routes to the ground state ?

- direct recombination to 1s
  - Emission of photon is followed by immediate re-absorption

  } No

- recombination to 2p followed by Lyman-α emission
  - medium optically thick to Ly-α phot.
  - many resonant scatterings
  - escape very hard ($p \sim 10^{-9}$ @ $z \sim 1100$)

  } ~ 43%

- recombination to 2s followed by 2s two-photon decay
  - 2s → 1s ~10^8 times slower than Ly-α
  - 2s two-photon decay profile → maximum at $\nu \sim 1/2\ \nu_\alpha$
  - immediate escape

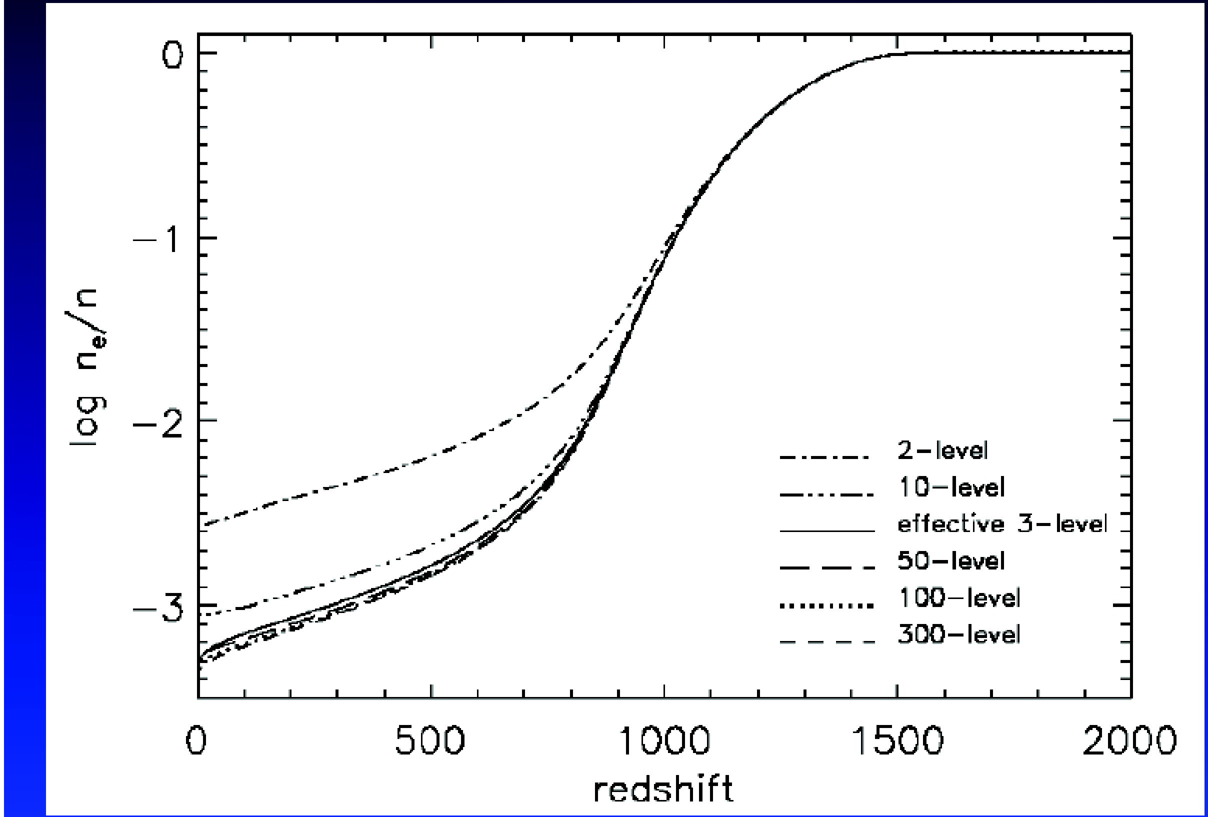
  } ~ 57%

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

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

1975 (Dubrovitch) → importance of (n,n-1) transitions
2006 – 2008 → full recombination spectrum

Multi-level Atom ⇒ The 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 ($z \sim$ 1400-1500)
- HeII 100-levels ($z \sim$ 6000-6500)
- HeII 1 equation

Low Redshifts:

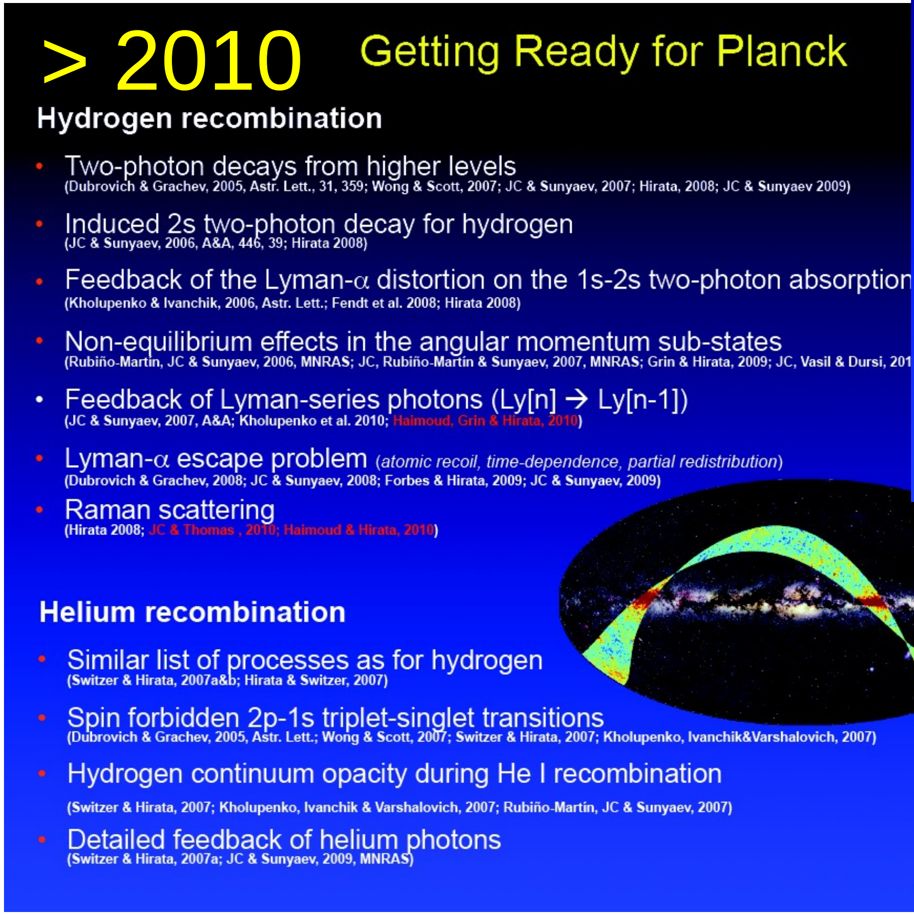
- H chemistry (only at low z)
- cooling of matter (Bremsstrahlung, collisional cooling, line cooling)

2006 - 2008

$\Delta N_e \,/\, N_e \sim 1\% - 3\%$

Requested accuracy for Planck

Add detailed effects



> 2010 Getting Ready for Planck

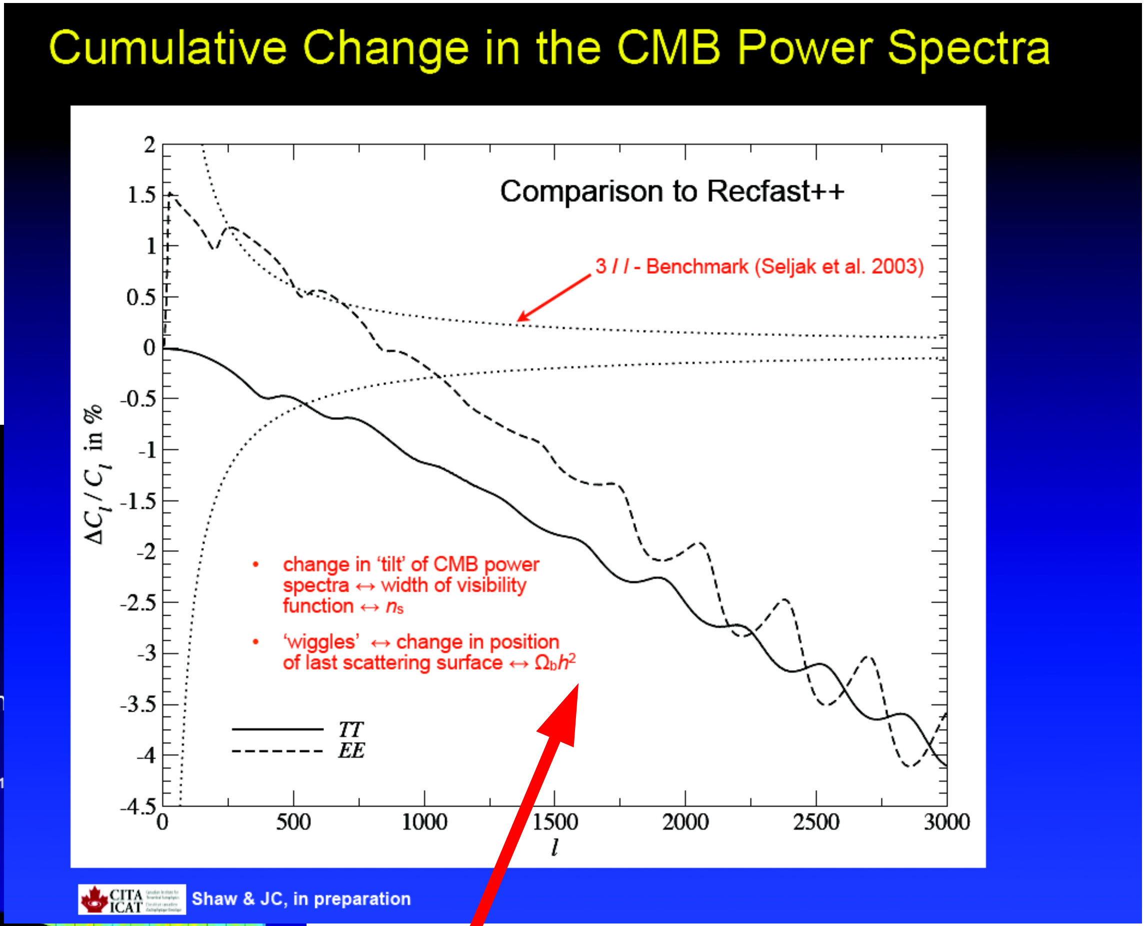
Hydrogen recombination

- 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
  (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, 201
- 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)
- 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)
- Hydrogen continuum opacity during He I recombination
  (Switzer & Hirata, 2007; Kholupenko, Ivanchik & Varshalovich, 2007; Rubiño-Martín, JC & Sunyaev, 2007)
- Detailed feedback of helium photons
  (Switzer & Hirata, 2007a; JC & Sunyaev, 2009, MNRAS)

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



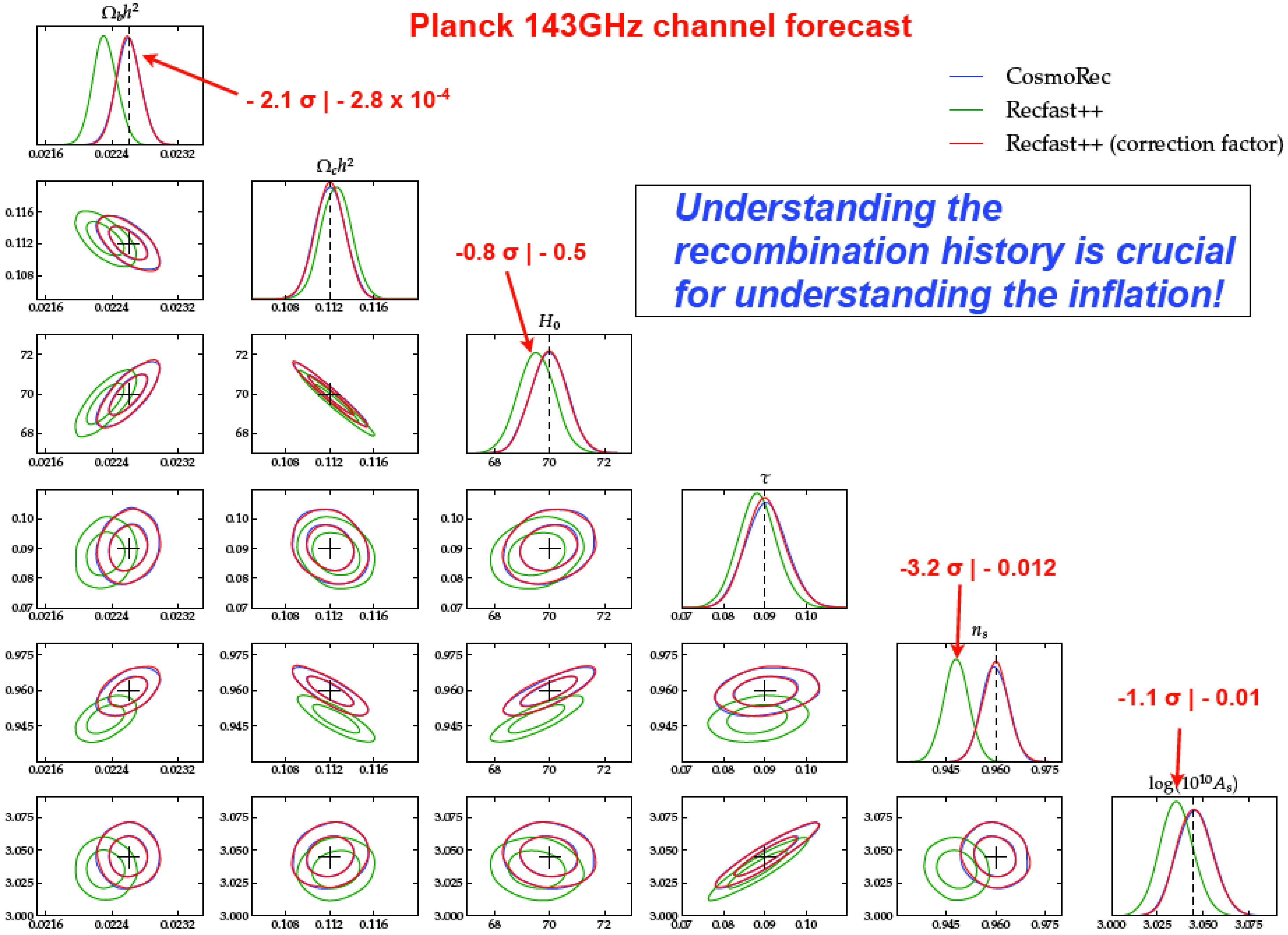
Cumulative Change in the CMB Power Spectra

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

CITA ICAT Shaw & JC, in preparation

New code
COSMOREC
By J.Chluba

Importance of recombination



Planck 143GHz channel forecast

- 2.1 σ | - 2.8 x 10^{-4}

-0.8 σ | - 0.5

-3.2 σ | - 0.012

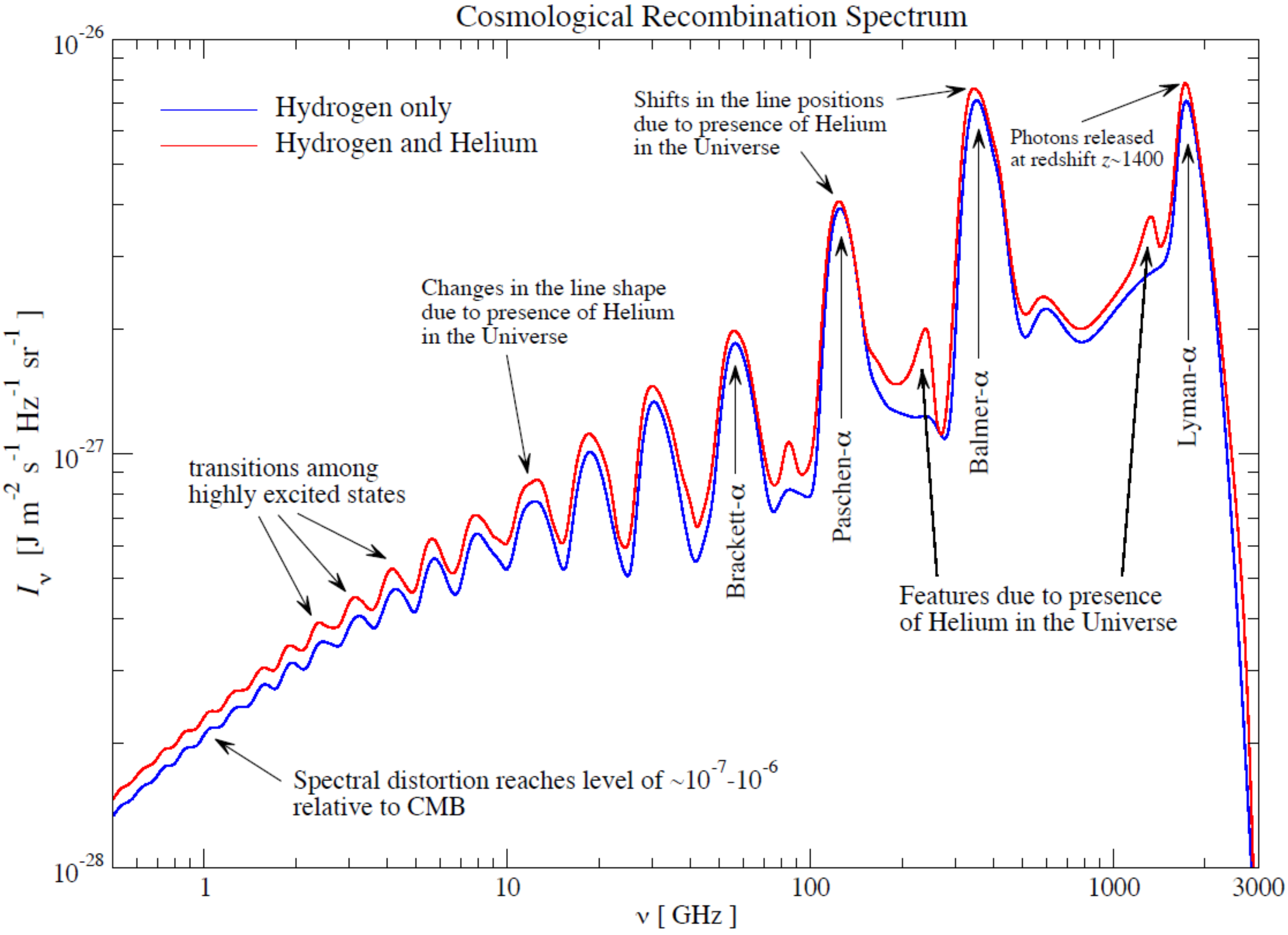
-1.1 σ | - 0.01

Understanding the recombination history is crucial for understanding the inflation!

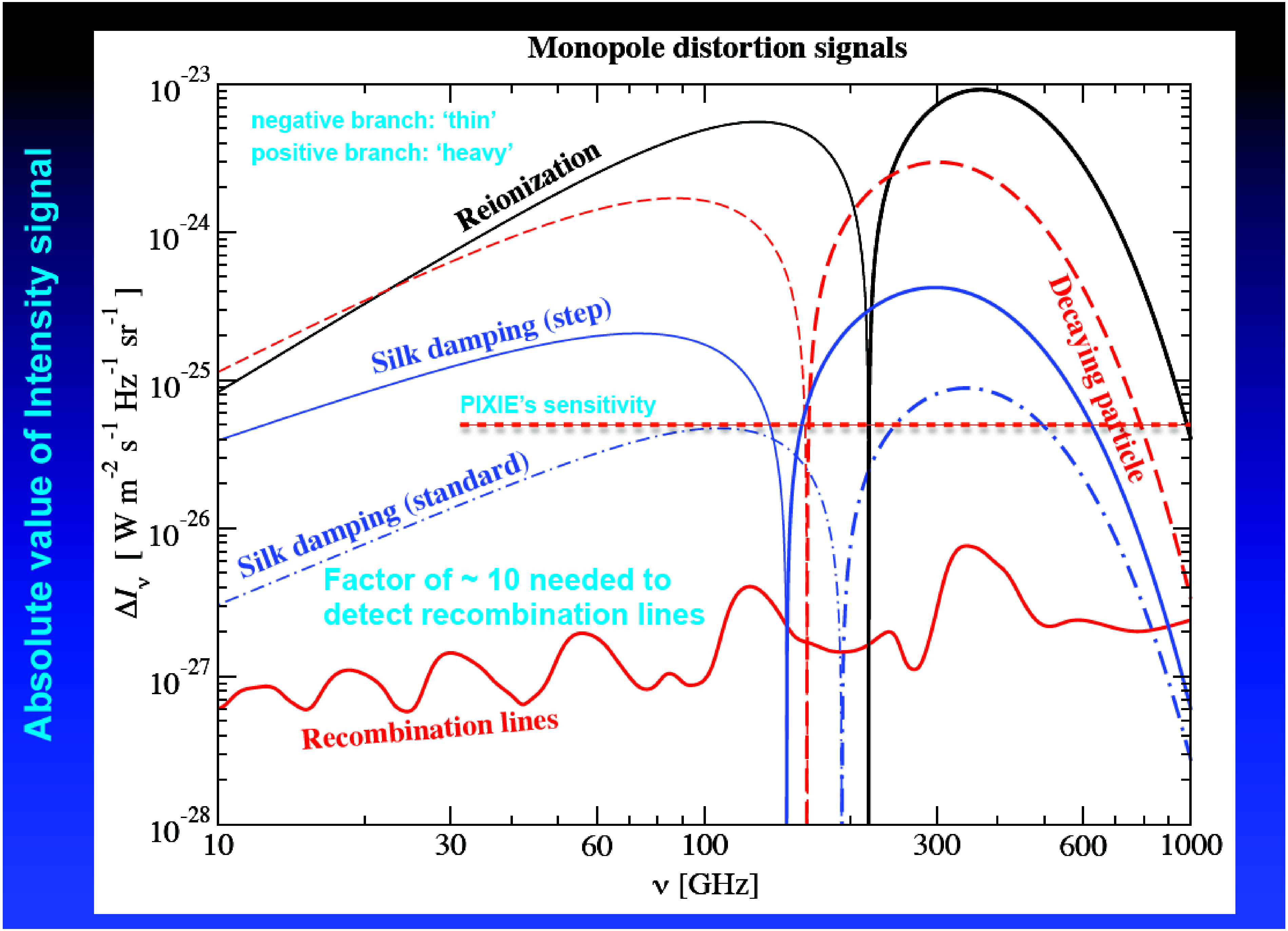
Predicted recombination spectral distortion

Very sensitive to energy release during recombination
Check our understanding of recombination physics
Independent path to measure baryon density, Yp
Unexpected phenomena during recombination

$$!! \quad \frac{\Delta I_\nu}{I_\nu} \sim 10^{-9} \quad !!$$



CMB Spectral Distortions Summary



Absolute value of Intensity signal

negative branch: ‘thin’
positive branch: ‘heavy’

PIXIE’s sensitivity

Factor of ~ 10 needed to detect recombination lines

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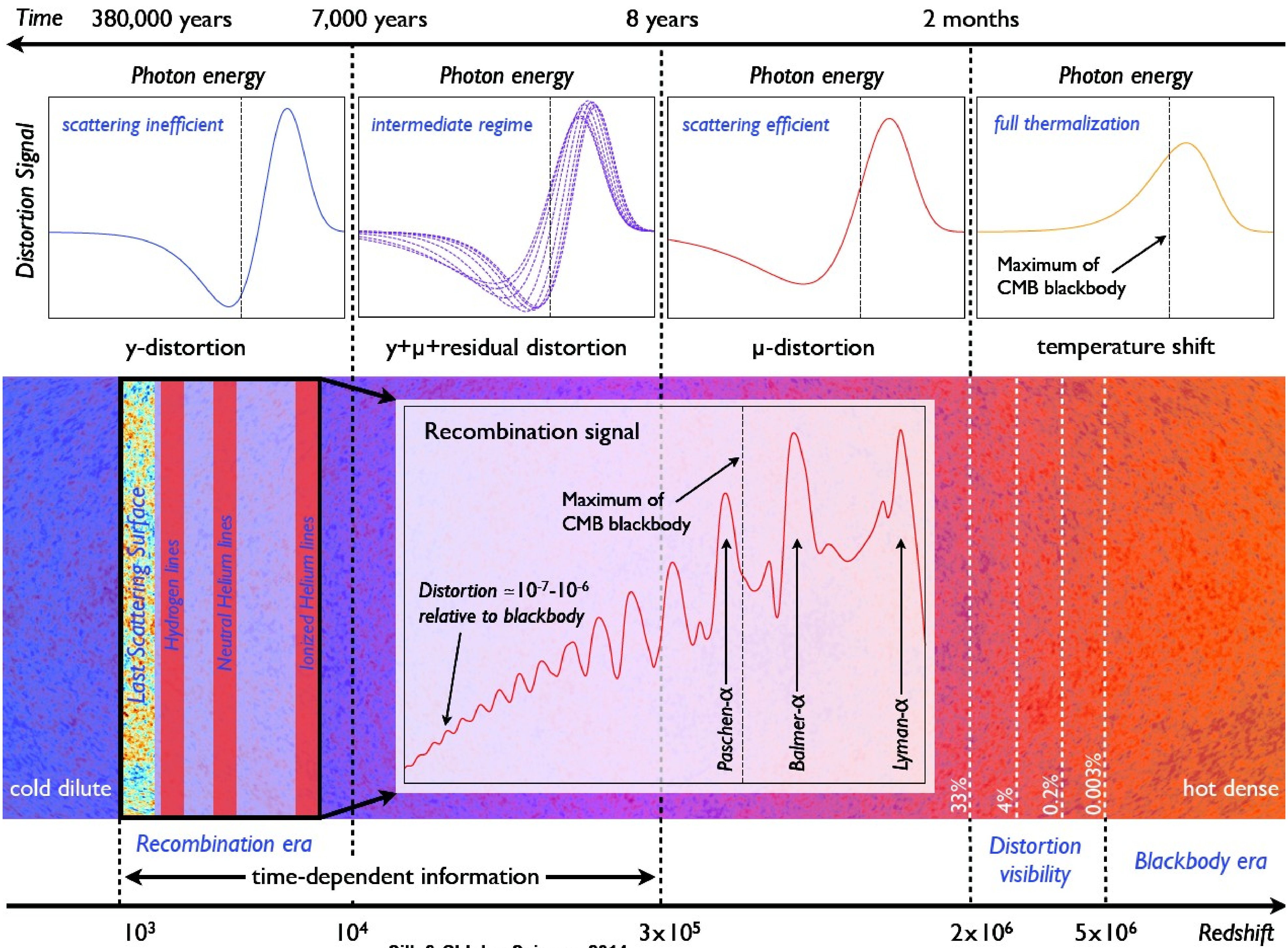

Silk & Chluba, Science, 2014