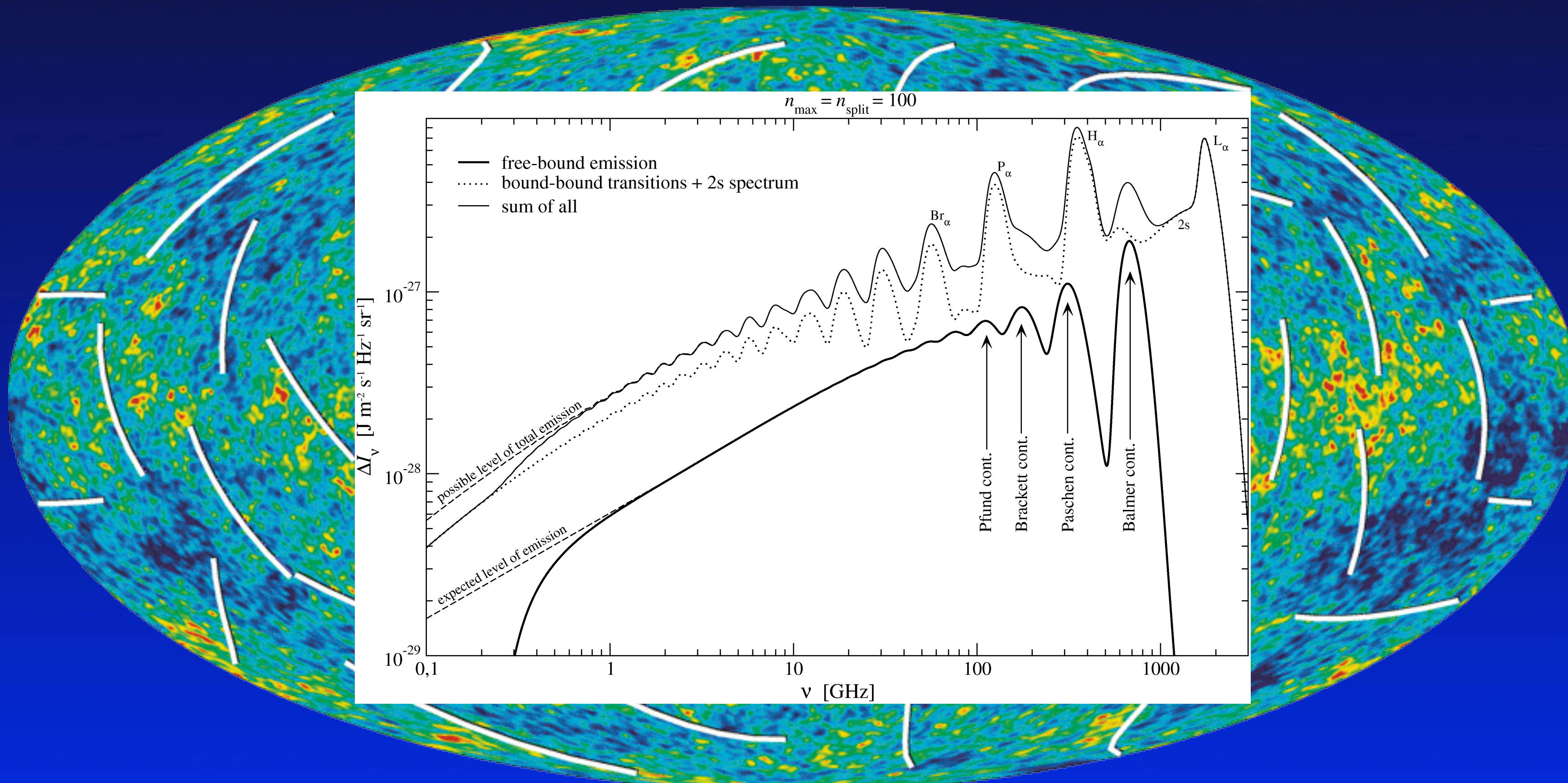
Atomic Lines from the Recombination Era, Compton *y*-Parameter, and Chemical Potential (μ)



J. Chluba

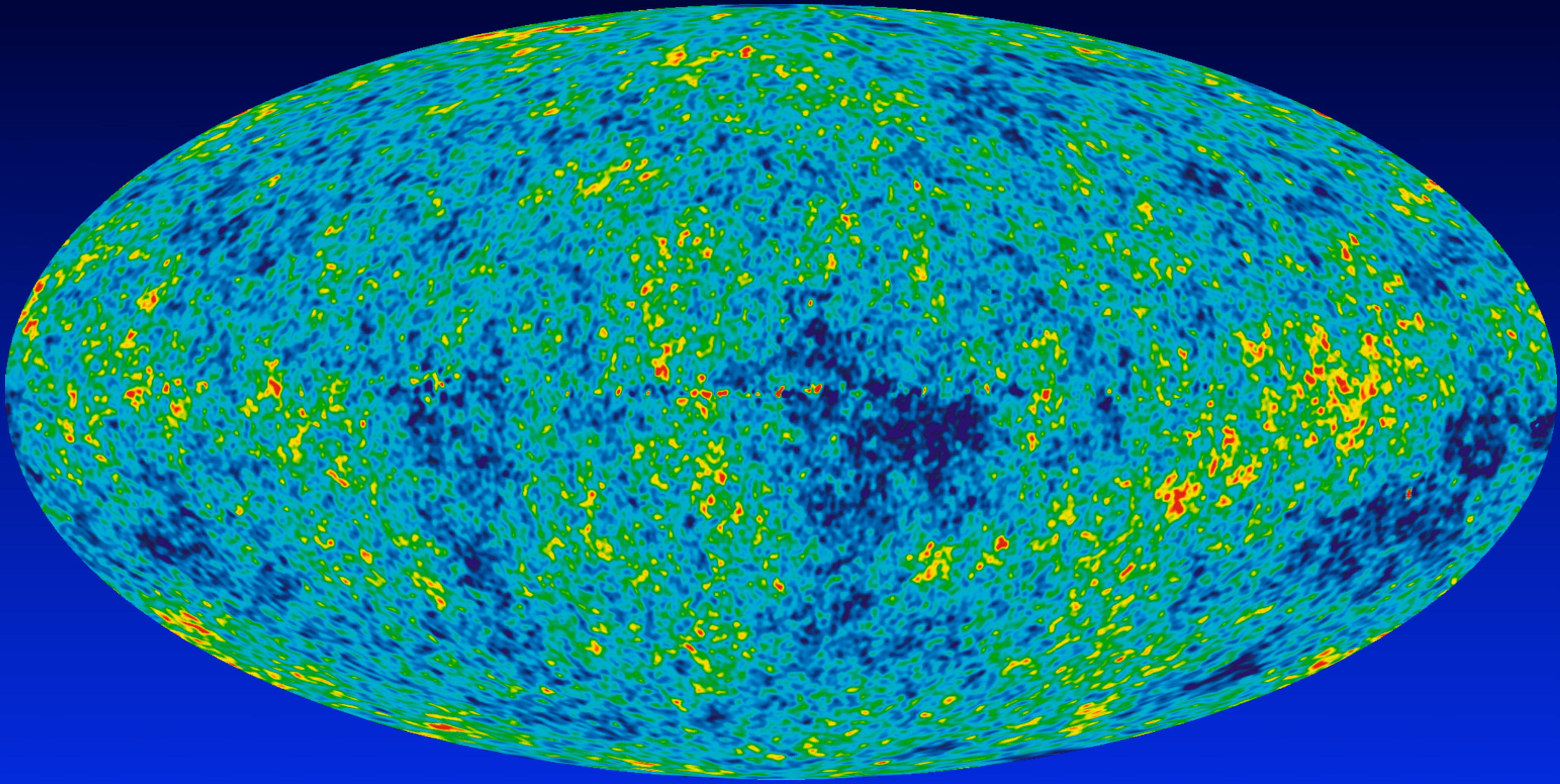
Workshop on "The First Billion Years"

August 16, 2010, Pasadena

Collaborators: R.A. Sunyaev (MPA) and J.A. Rubiño-Martín (IAC)

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

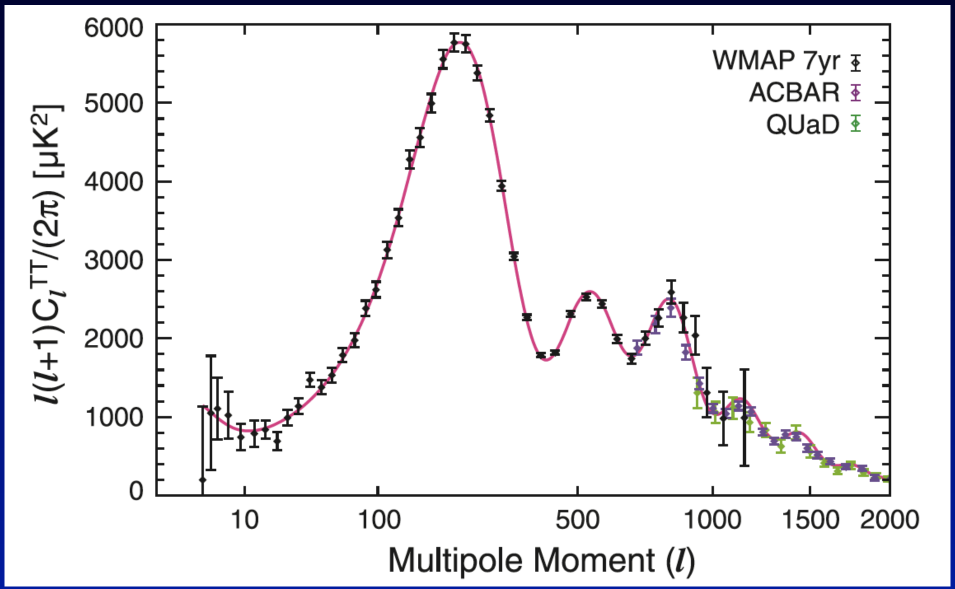
Cosmic Microwave Background Anisotropies



Example: WMAP-7

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

CMB anisotropies clearly have helped us a lot to learn details about the Universe we live in!



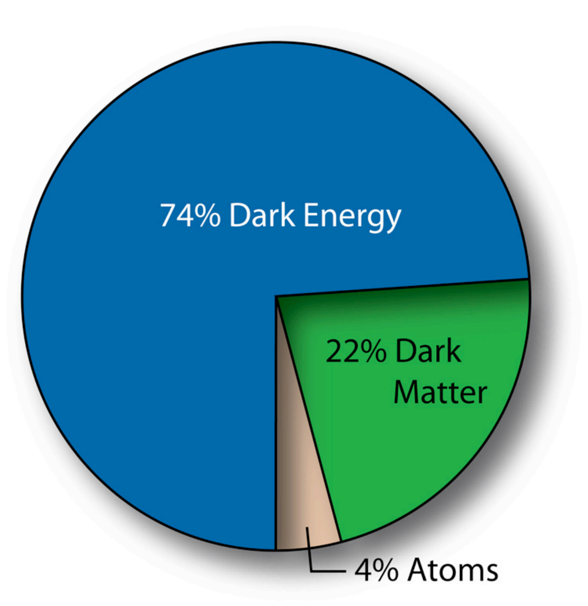
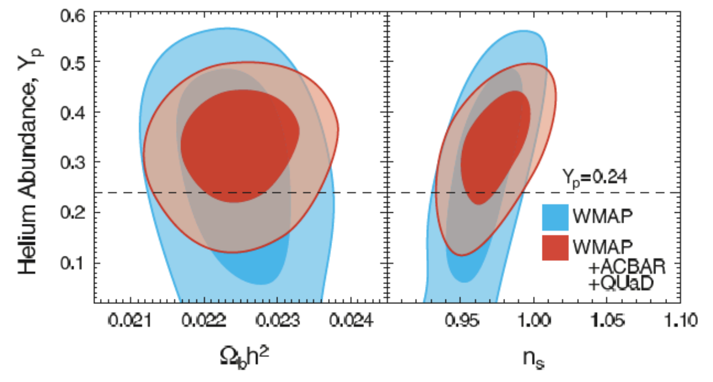


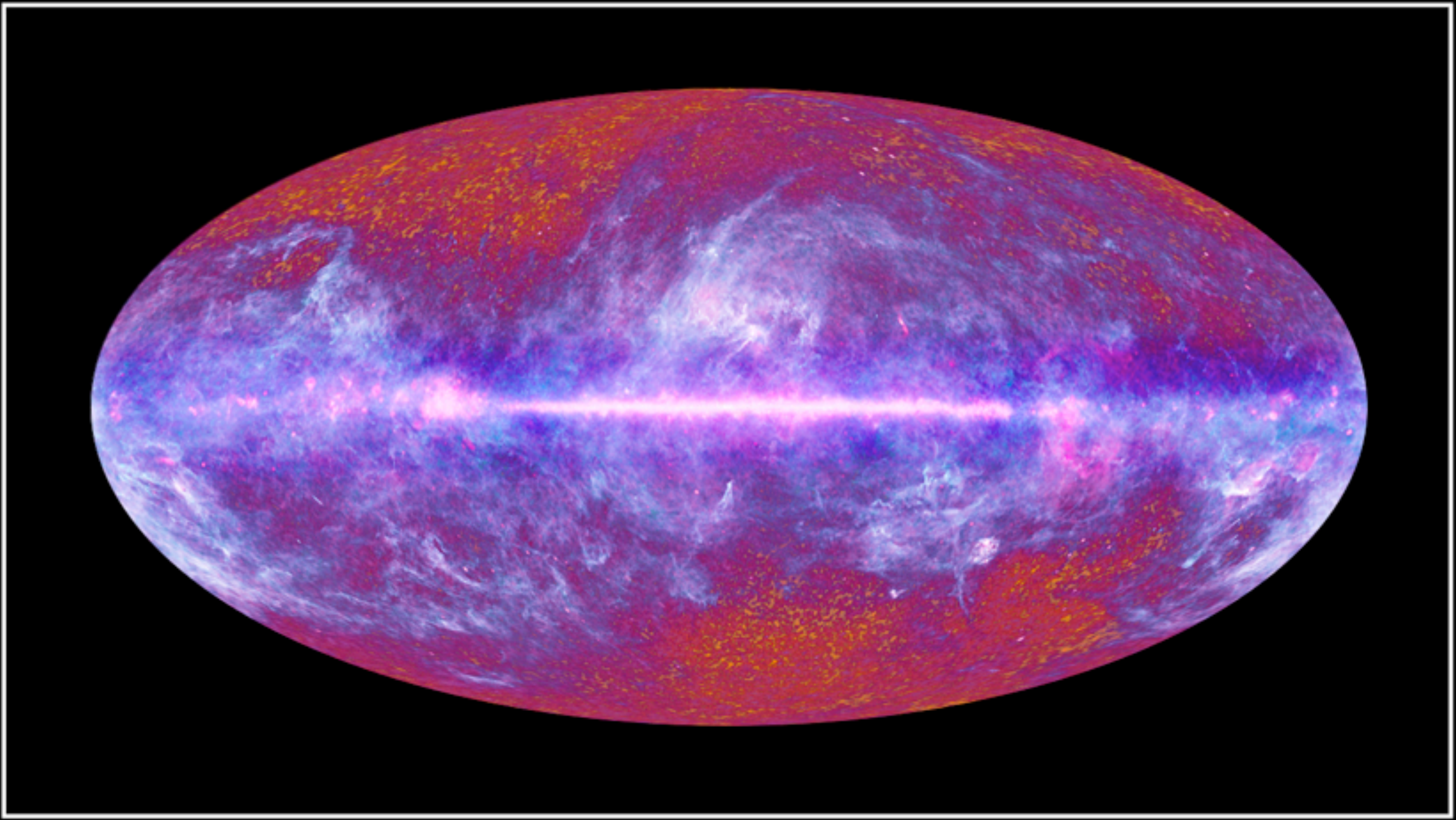
TABLE 1
Summary of the cosmological parameters of ΛCDM model

Class	Parameter	*WMAP* 7-year ML[a]	*WMAP*+BAO+H_0 ML	*WMAP* 7-year Mean[b]	*WMAP*+BAO+H_0 Mean
Primary	$100\Omega_b h^2$	2.270	2.246	$2.258^{+0.057}_{-0.056}$	2.260 ± 0.053
	$\Omega_c h^2$	0.1107	0.1120	0.1109 ± 0.0056	0.1123 ± 0.0035
	Ω_Λ	0.738	0.728	0.734 ± 0.029	$0.728^{+0.015}_{-0.016}$
	n_s	0.969	0.961	0.963 ± 0.014	0.963 ± 0.012
	τ	0.086	0.087	0.088 ± 0.015	0.087 ± 0.014
	$\Delta^2_{\mathcal{R}}(k_0)$[c]	2.38×10^{-9}	2.45×10^{-9}	$(2.43 \pm 0.11) \times 10^{-9}$	$(2.441^{+0.088}_{-0.092}) \times 10^{-9}$
Derived	σ_8	0.803	0.807	0.801 ± 0.030	0.809 ± 0.024
	H_0	71.4 km/s/Mpc	70.2 km/s/Mpc	71.0 ± 2.5 km/s/Mpc	$70.4^{+1.3}_{-1.4}$ km/s/Mpc
	Ω_b	0.0445	0.0455	0.0449 ± 0.0028	0.0456 ± 0.0016
	Ω_c	0.217	0.227	0.222 ± 0.026	0.227 ± 0.014
	$\Omega_m h^2$	0.1334	0.1344	$0.1334^{+0.0056}_{-0.0055}$	0.1349 ± 0.0036
	$z_{\rm reion}$[d]	10.3	10.5	10.5 ± 1.2	10.4 ± 1.2
	t_0[e]	13.71 Gyr	13.78 Gyr	13.75 ± 0.13 Gyr	13.75 ± 0.11 Gyr

[a] Larson et al. (2010). "ML" refers to the Maximum Likelihood parameters.
[b] Larson et al. (2010). "Mean" refers to the mean of the posterior distribution of each parameter. The quoted errors show the 68% confidence levels (CL).
[c] $\Delta^2_{\mathcal{R}}(k) = k^3 P_{\mathcal{R}}(k)/(2\pi^2)$ and $k_0 = 0.002$ Mpc^{-1}.
[d] "Redshift of reionization," if the universe was reionized instantaneously from the neutral state to the fully ionized state at $z_{\rm reion}$. Note that these values are somewhat different from those in Table 1 of Komatsu et al. (2009b), largely because of the changes in the treatment of reionization history in the Boltzmann code CAMB (Lewis 2008).
[e] The present-day age of the universe.

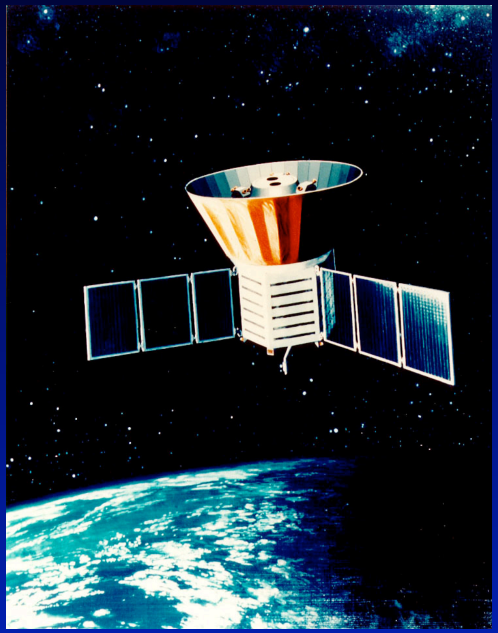


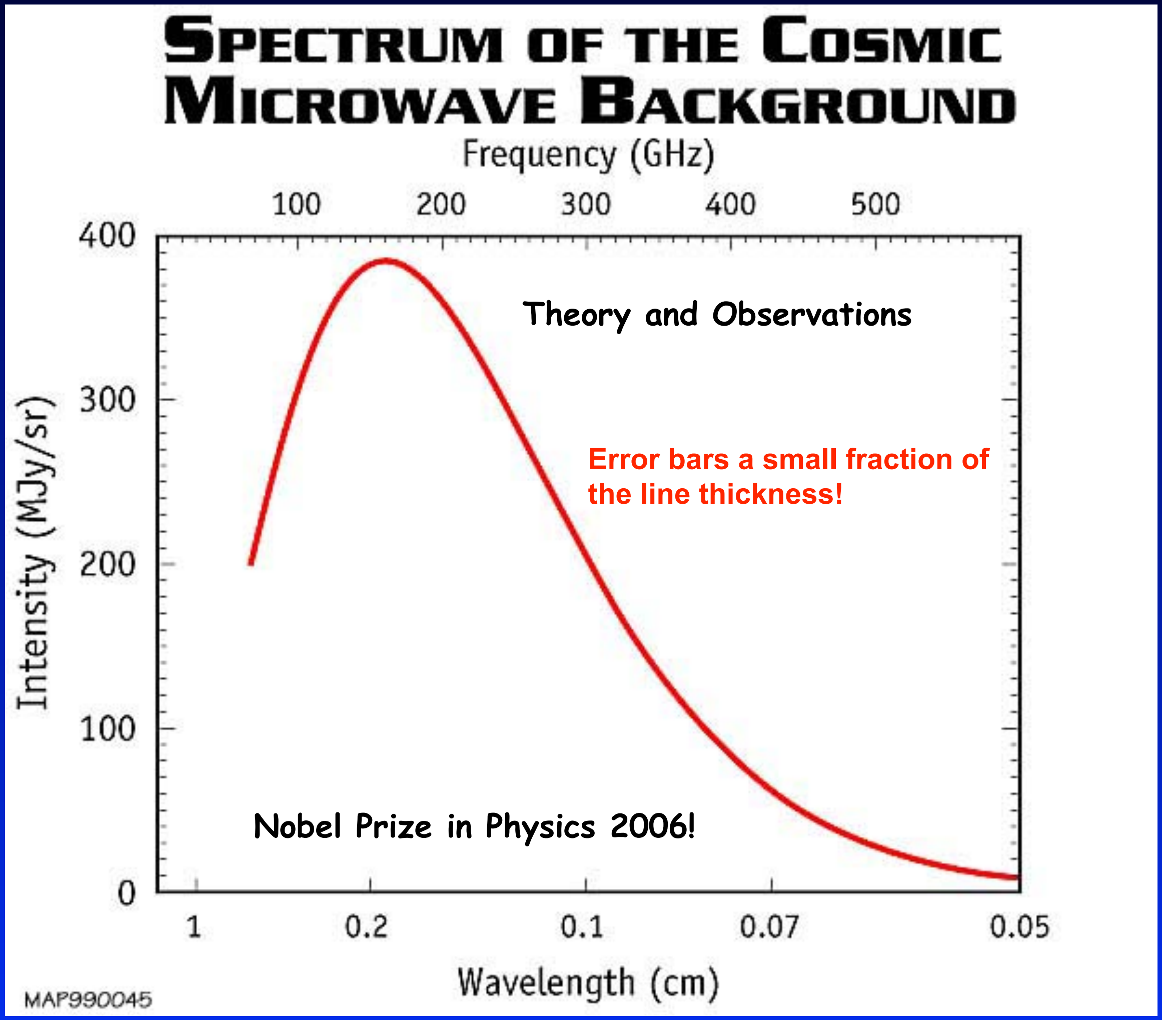
e.g. Komatsu et al., 2010, arXiv:1001.4538v1



The Planck one-year all-sky survey

COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)





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

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

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

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

Only very small distortions of CMB spectrum are still allowed!

Why should one expect some spectral distortions?

Full thermodynamic equilibrium (certainly valid at very high redshift)

- CMB has a blackbody spectrum at every time (not affected by expansion...)
- Photon number density and energy density determined by temperature T_γ
  - $T_\gamma \sim 2.725\,(1+z)$ K
  - $N_\gamma \sim 410\ \mathrm{cm}^{-3}\,(1+z)^3 \sim 2\times10^9\,N_\mathrm{b}$
  - $\rho_\gamma \sim 5.1\times10^{-7}\,m_\mathrm{e}c^2\ \mathrm{cm}^{-3}\,(1+z)^4 \sim \rho_\mathrm{b} \times (1+z)/900$

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Perturbing full equilibrium for example by

- Energy injection (*matter* ←→ *photons*)
- Production of energetic photons and/or particles (i.e. change of entropy)

→ CMB spectrum deviates from a pure blackbody

→ distortions partially erased by thermalization process

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Which mechanisms could lead to release of energy and what determines how the residual spectral distortion looks today?

Physical mechanisms that lead to release of energy

- Very simple example: $T_\gamma \sim (1+z) \Leftrightarrow T_m \sim (1+z)^2$
  - continuous *cooling* of photons down to z~150
  - due to huge heat capacity of photon field very small effect ($\Delta\rho/\rho \sim 10^{-10}$-$10^{-9}$)
- another simple example: *electron-positron annihilation* ($z \sim 10^8$-10^9)
  - too early to leave some important traces (completely thermalized)
- Heating by *decaying* or *annihilating* relic particles
  - How is energy transferred to the medium?
  - lifetimes, decay channels, (at low redshifts: environments), ...
- *Evaporation* of *primordial black holes* and *phase transitions*
  (Carr et al. 2010; Ostriker & Thompson, 1987)
  - rather fast, quasi-instantaneous energy release
- Dissipation of primordial acoustic waves
  (Zeldovich et al., 1972; Daly 1991; Hu et al. 1994)

„high" redshifts

„low" redshifts

- Signatures due to first supernovae and their remnants
  (Oh, Cooray & Kamionkowski, 2003)
- Shock waves arising due to large scale structure formation
  (Sunyaev & Zeldovich, 1972; Cen & Ostriker, 1999)
- SZ-effect from clusters; Effects of Reionization (Heating of medium by X-Rays, Cosmic Rays, etc)

How does the thermalization process work? (I)

- Plasma fully ionized before recombination
  - → free electrons, protons and helium nuclei
- Coulomb scattering $e + p \leftrightarrow e' + p$
  - → electrons in thermal equilibrium with baryons
  - → electrons follow thermal Maxwell Boltzmann distribution
  - → efficient down to very low redshifts ($z \sim 10$)
- Hubble expansion
  - → adiabatic cooling of photons ($T_\gamma \sim (1+z)$)
  - → redshifting of photons

How does the thermalization process work? (II)

- Compton scattering $e + \gamma \leftrightarrow e' + \gamma'$

→ *redistribution* of photons in frequency

  - up-scattering due to the ***Doppler*** effect for

    $$h\nu < 4kT_e$$

  - down-scattering due to ***recoil*** for

    $$h\nu > 4kT_e$$

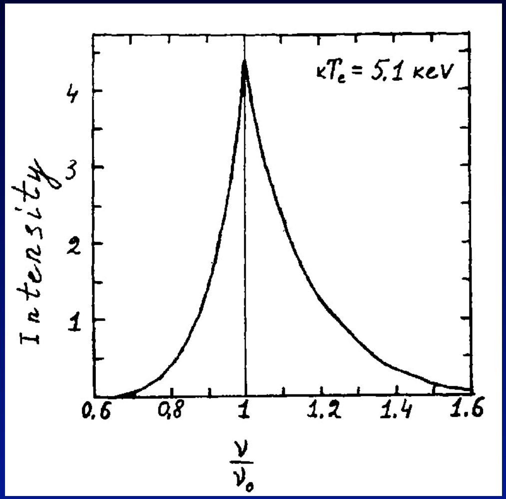
→ strongly couples (free) electrons to the CMB down to redshifts z~150

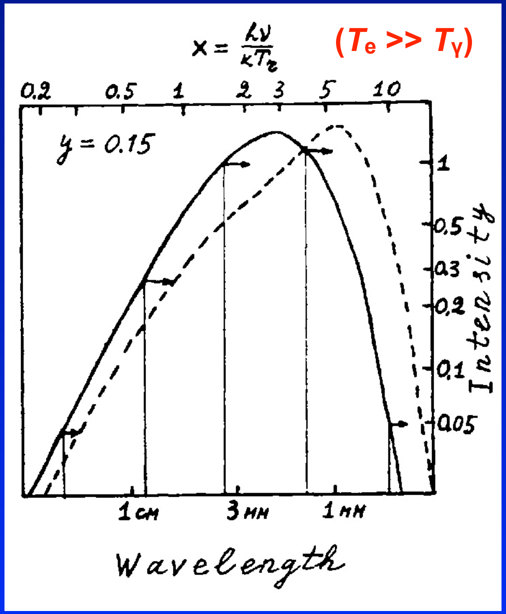
Kompaneets-Equation → 'pure' ***y*-distortion**

$$\frac{\Delta I_\nu}{B_\nu} = y \times \frac{x\, e^x}{e^x - 1}\left[x \frac{e^x + 1}{e^x - 1} - 4 \right]$$

where $x = \frac{h\nu}{kT_\gamma}$ and $y = \int \frac{k(T_e - T_\gamma)}{m_e c^2} \sigma_T n_e \mathrm{d}l << 1$

Temperature difference





Sunyaev& Zeldovich, 1980, Ann. Rev. Astr. Astrophy., 18, pp.537

How does the thermalization process work? (III)

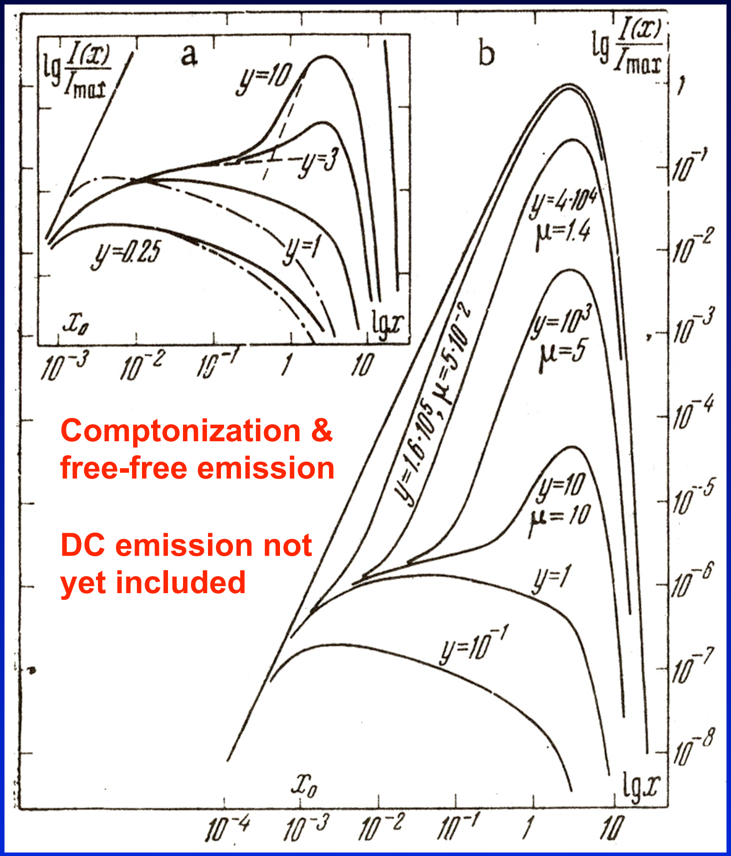
- Bremsstrahlung $e + p \leftrightarrow e' + p + \gamma$
  - → 1. order α correction to Coulomb scattering
  - → production of low frequency photons
  - → $\tau_{ff} \sim 10^{-8}\,(1+z)^{1/2}\;[kT\,/\,h\nu]^2$

    free-free process is *unable* to restore blackbody spectrum up to very high *z*!!!

- Double Compton scattering (Lightman 1981; Thorne, 1981)

  $$e + \gamma \leftrightarrow e' + \gamma' + \gamma_2$$

  - → 1. order α correction to Compton scattering
  - → production of low frequency photons
  - → very important at high redshifts ($z > 2 \times 10^5$)

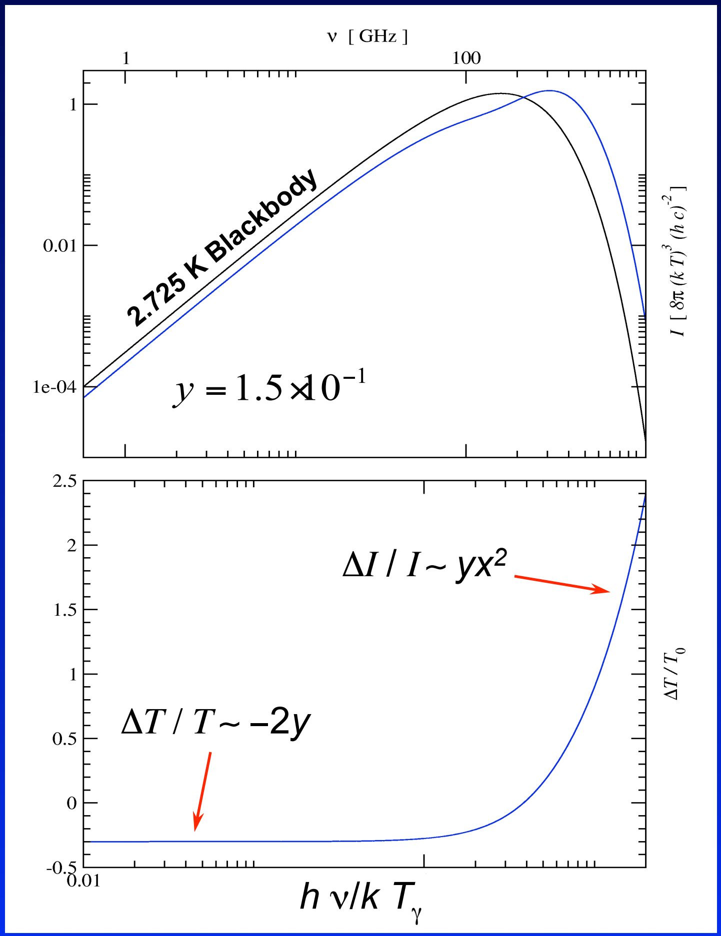


Illarionov & Sunyaev, 1975, Sov. Astr, 18, pp.413

Compton *y* and chemical potential distortions

„Late“ Energy Release ($z \lesssim 50000$)

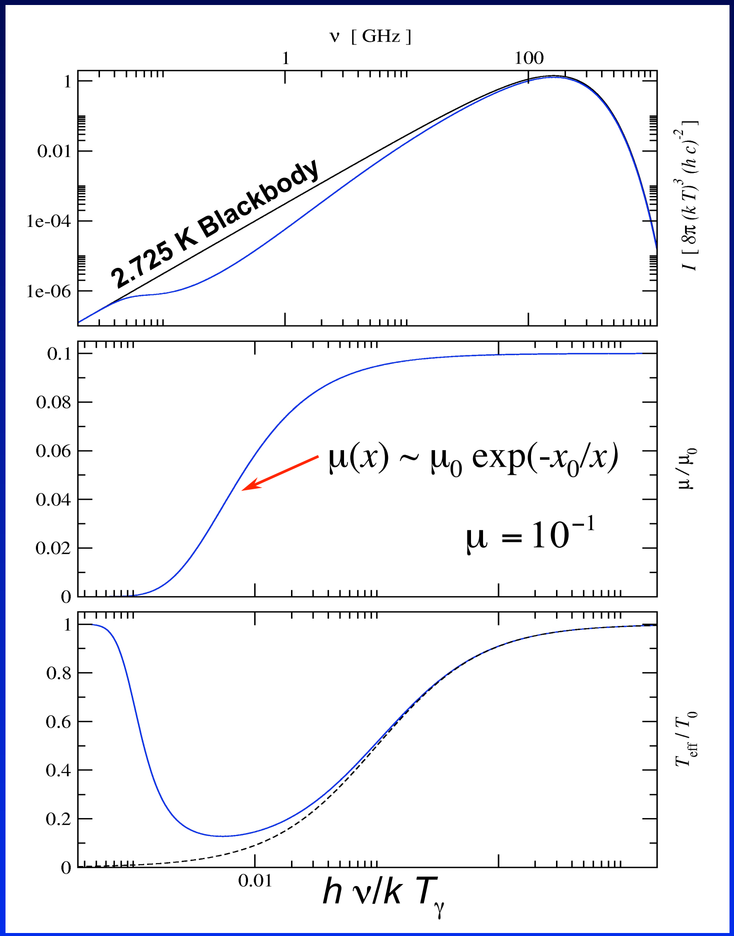
→ y-type spectral distortion



Zeldovich & Sunyaev, 1969, Ap&SS, 4, pp. 301

„Early“ Energy Release ($z \gtrsim 50000$)

→ μ-type spectral distortion



Sunyaev & Zeldovich, 1970, Ap&SS, 7, pp.20-30
Illarionov & Sunyaev, 1975, Sov.Astr., 18, pp. 413
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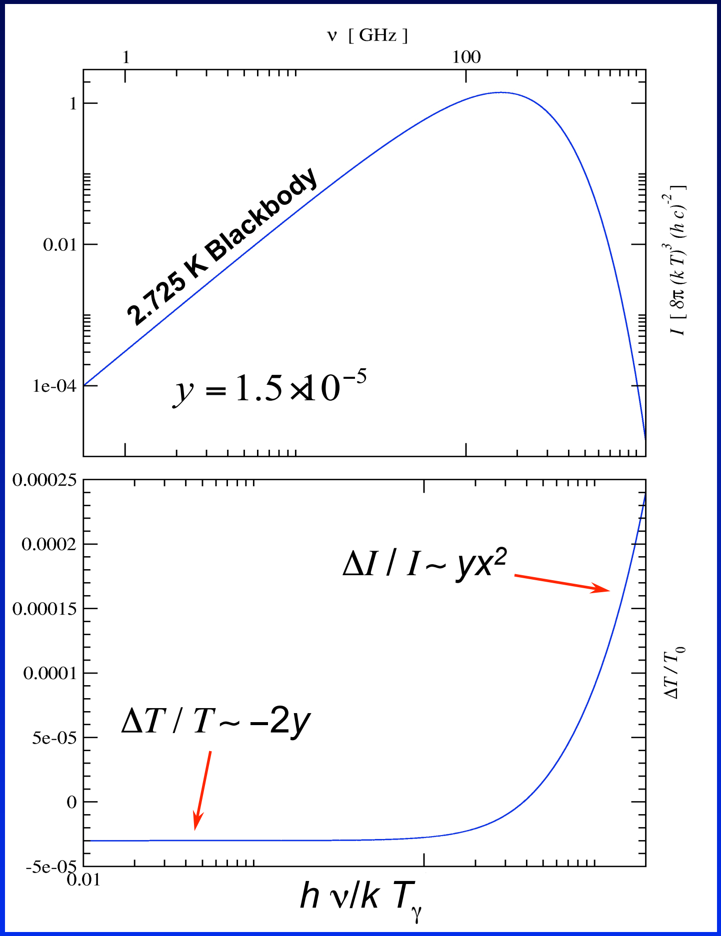

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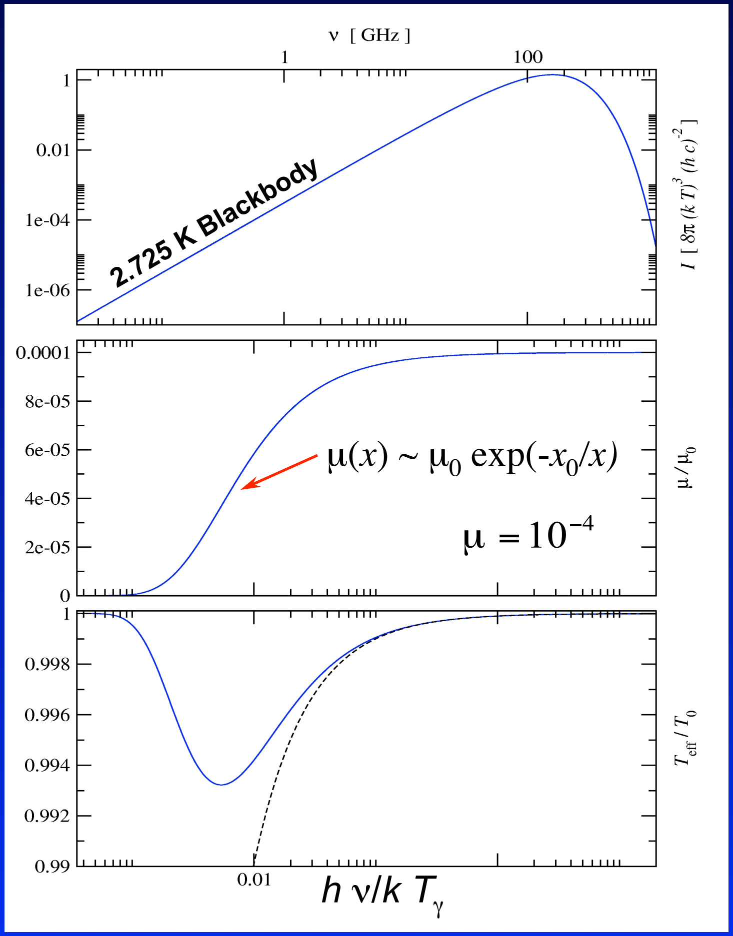
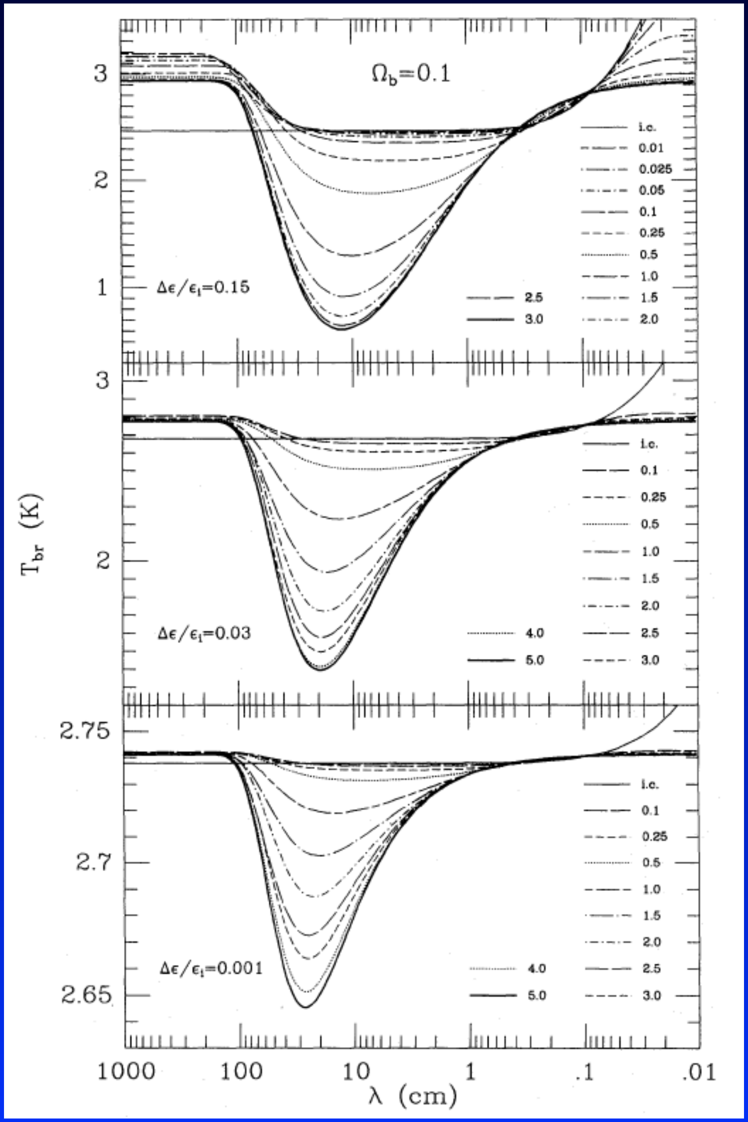
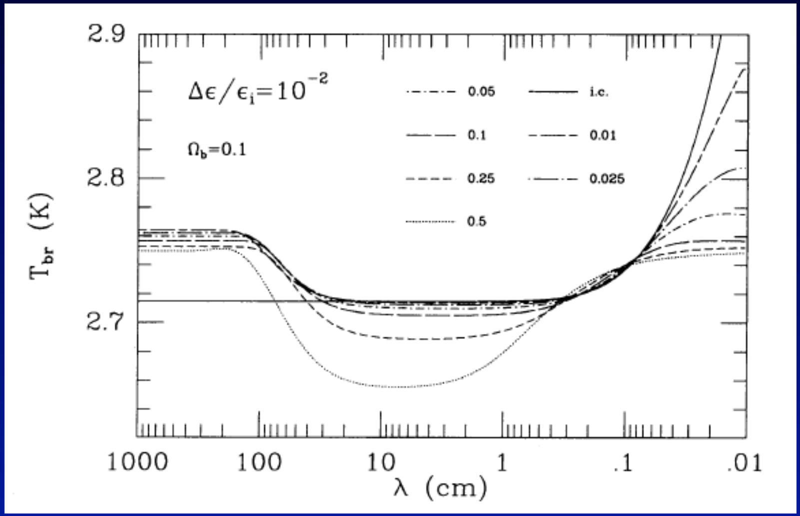


Sunyaev & Zeldovich, 1970, Ap&SS, 7, pp.20-30
Illarionov & Sunyaev, 1975, Sov.Astr., 18, pp. 413
Danese & de Zotti, 1982, A&A, 107, 39-42

Thermalization from y → μ





- amount of energy

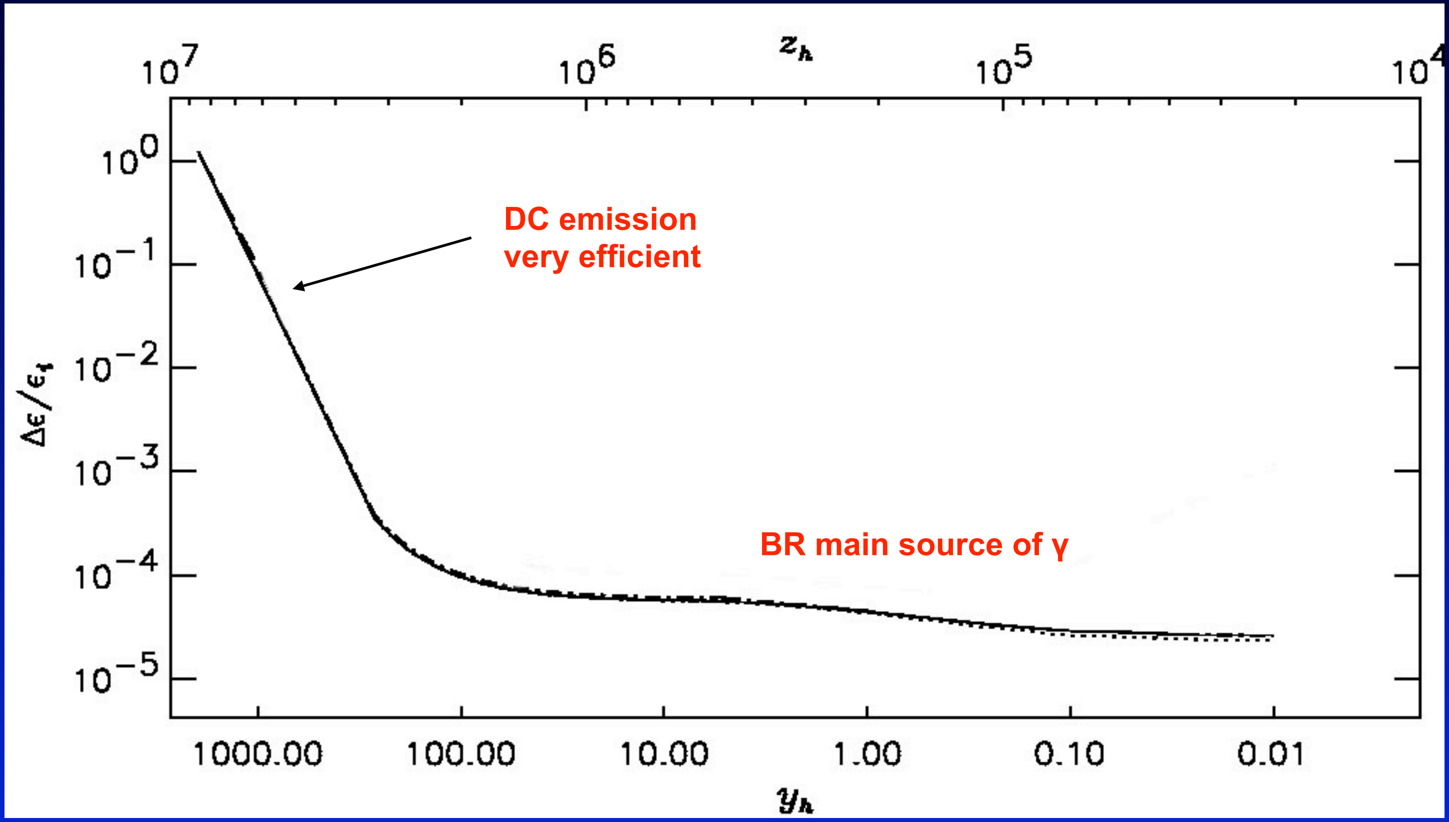
  ↔ amplitude of distortion

  ↔ position of 'dip'
- Intermediate case ($3\text{x}10^5 \geq z \geq 6000$)

  ⇒ mixture between μ & y
- only details at low frequencies change!

Burigana, De Zotti & Danese, 1991, ApJ
Burigana, Danese & De Zotti, 1991, A&A

Constraint on the amount of injected energy

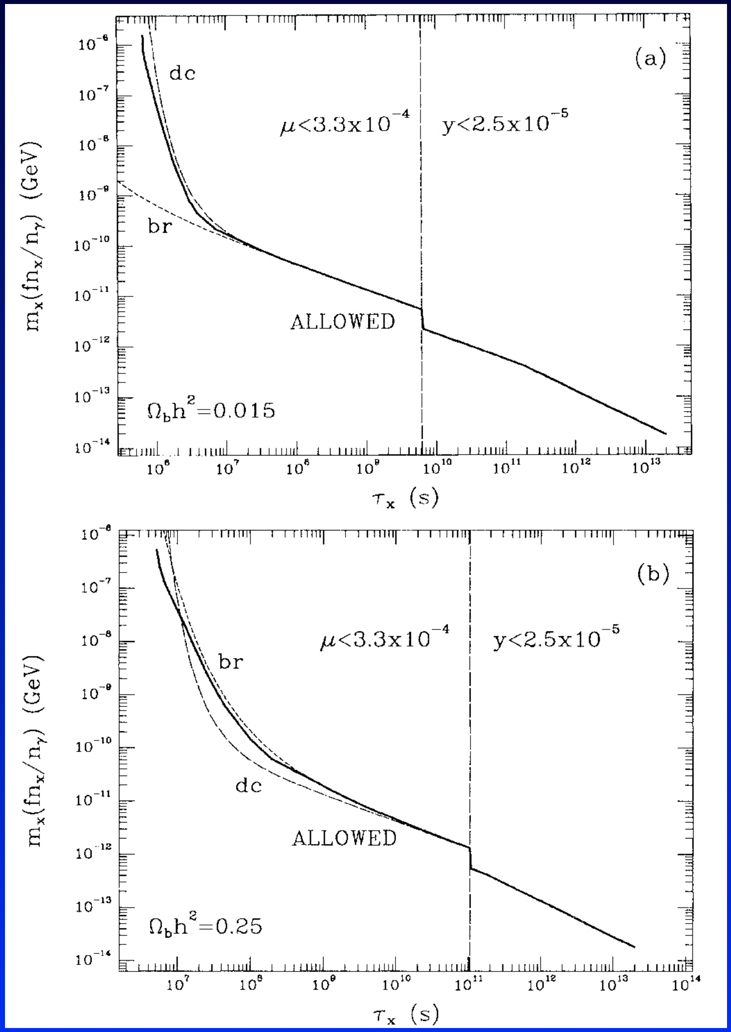


Salvaterra & Burigana, 2002, MNRAS, 336, pp. 592

- Arbitrary amounts of energy can be thermalized before redshift $z \sim 10^6$-10^7
- Limits depend slightly on choice of scenario (single - double injection)

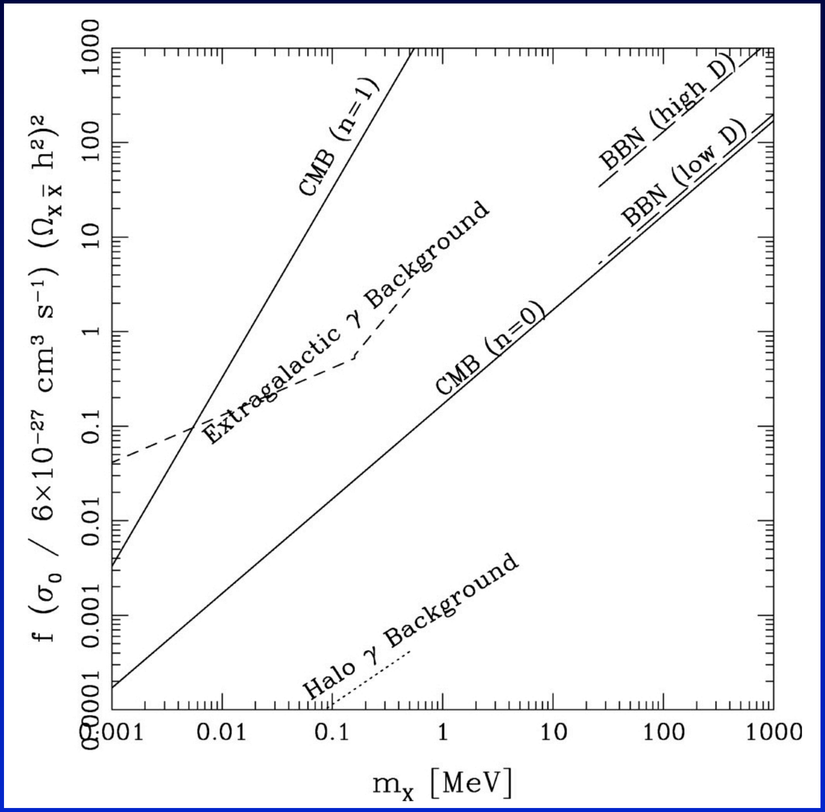
Constraint on mass, lifetime and annihilation cross section

Decaying relict particle



Hu & Silk, 1993, Phys. Rev. Letters, 70, pp. 2661

Particle annihilation



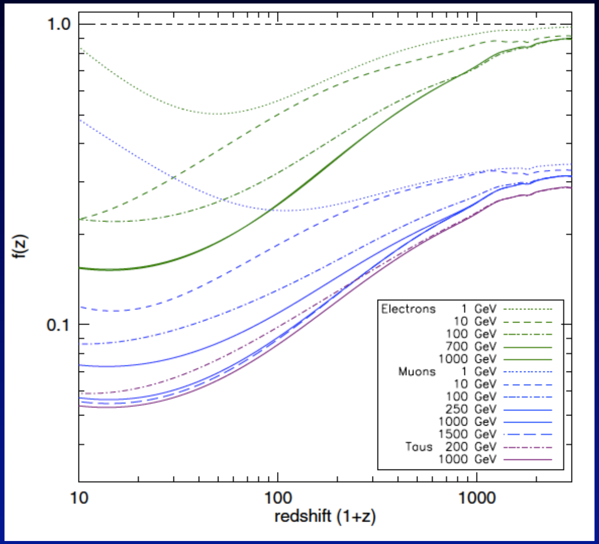
McDonald et al., 2002, Phys. Rev. D, 63, id 023001

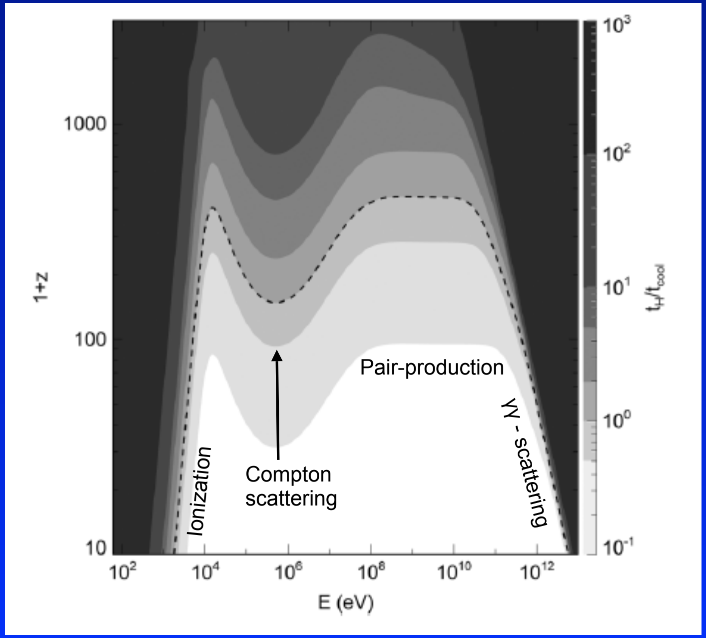
$$y \sim \tfrac{1}{4}\ \delta\rho / \rho$$

$$\mu \sim 1.4\ \delta\rho / \rho$$

What are the parameters that determine the distortion?

- Amount of released energy in comparison with CMB energy density
  - huge number of photons to fight with!
- When is the energy released?
  - full erasure, μ-type, y-type and mixture
- Time-dependence of the energy release
  - annihilation ($N^2 \sim (1+z)^6$)
  - decaying particles ($N \sim (1+z)^3 \exp(-t/t_X)$)
- Strength / efficiency of coupling to CMB
  - decay channels
  - transparency of the Universe
- Global ⇔ local energy injection
  - spectral-angular CMB distortions
  - e.g. SZ effect from clusters
  - clumping factor for DM annihilation





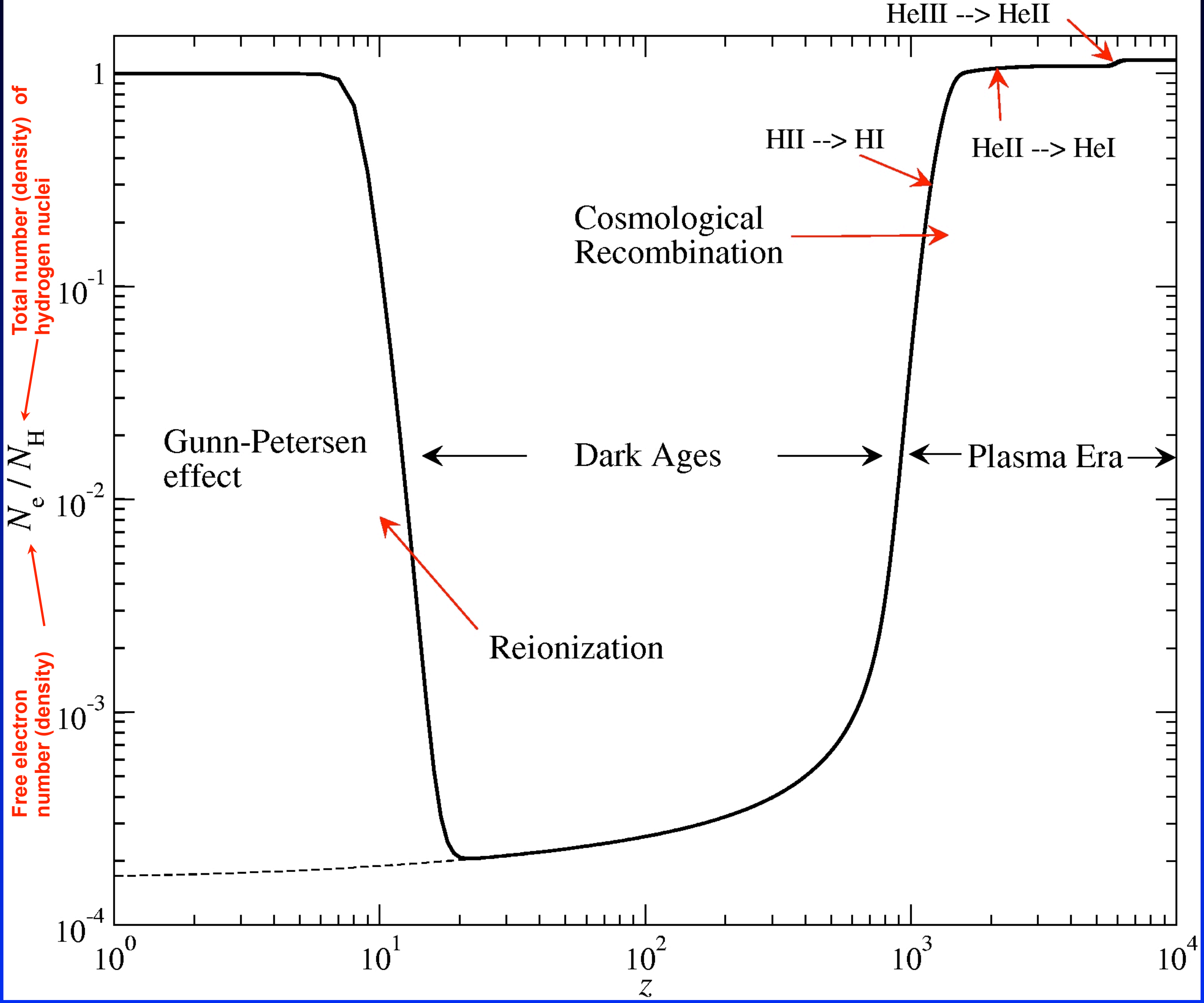
Chen & Kamionkowski 2004
Slatyer, Padmanabhan, Finkbeiner 2009

Summary and future work (part I)

- Type / shape of the distortions depend on parameters of the injection process
  - allows us to put constraints on different scenarios
  - COBE/FIRAS constraints rule out large energy injections at $z < 10^6$
- However, different scenarios lead to *very* similar distortions!
  - distortions very broad and rather featureless → 'dating' is very hard
  - distortions have to be measured accurately and over many frequencies to distinguish different scenarios
  - distortions show strongest differences at low frequencies ($\nu \sim 1$ GHz and below)
- Numerical computations should to be improved
  - full time-dependence (only single injection scenarios were treated numerically...)
  - heating efficiencies have to be recomputed
  - non-thermal particles / hard photons should be followed more precisely
- Question: what are the lower limits on distortions prior to recombination?

What about cosmological recombination?

Sketch of the Cosmic Ionization History



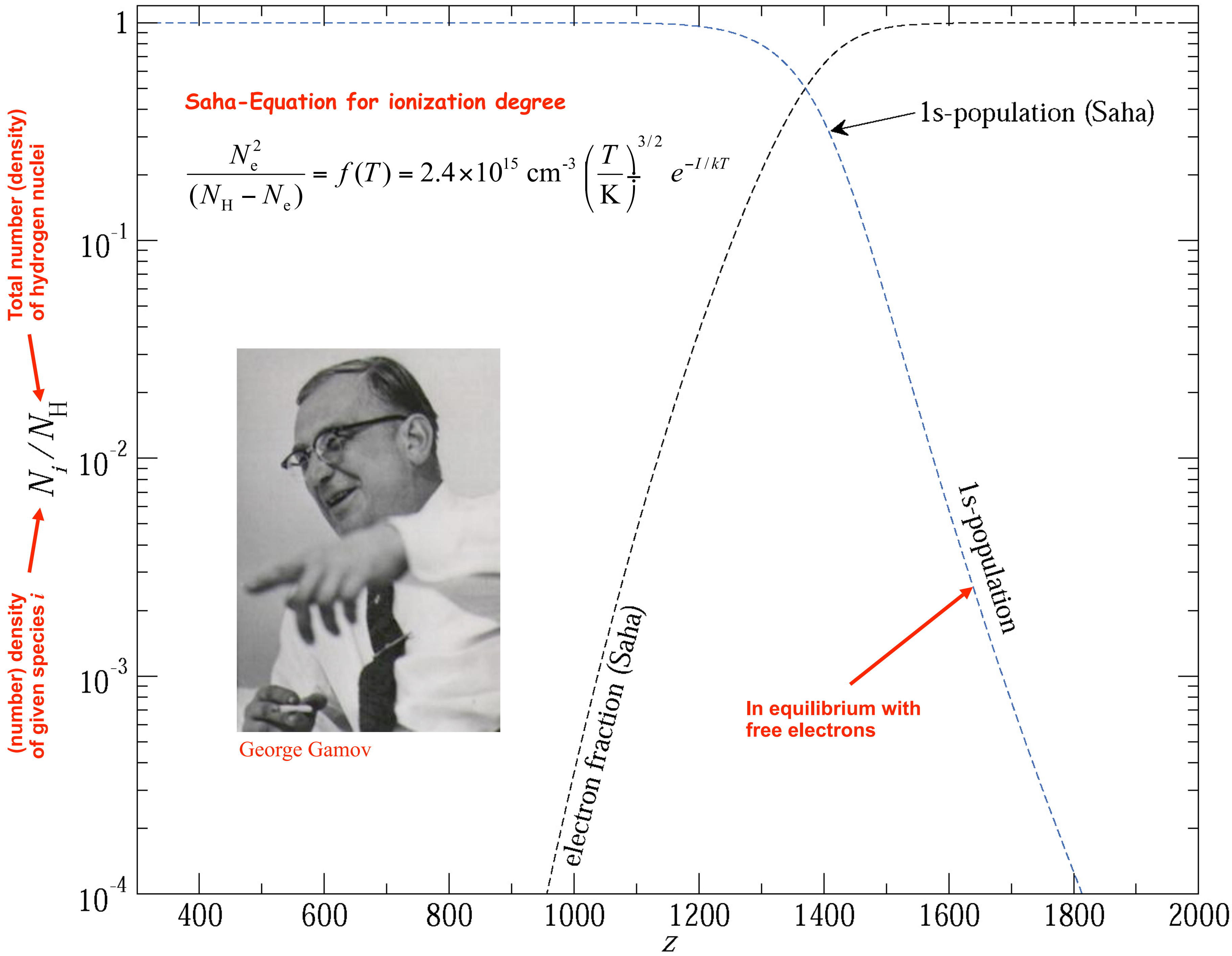
- at redshifts larger than ~10^4 Universe → *fully ionized*
- $z \geq 10^4$ → *free electron fraction N_e/N_H* ~ 1.16 because Helium has 2 electrons and abundance ~ 8%
- HeIII → HeII recombination at z~6000
- HeII → HeI recombination at z~2000
- HII → HI recombination at z~1000

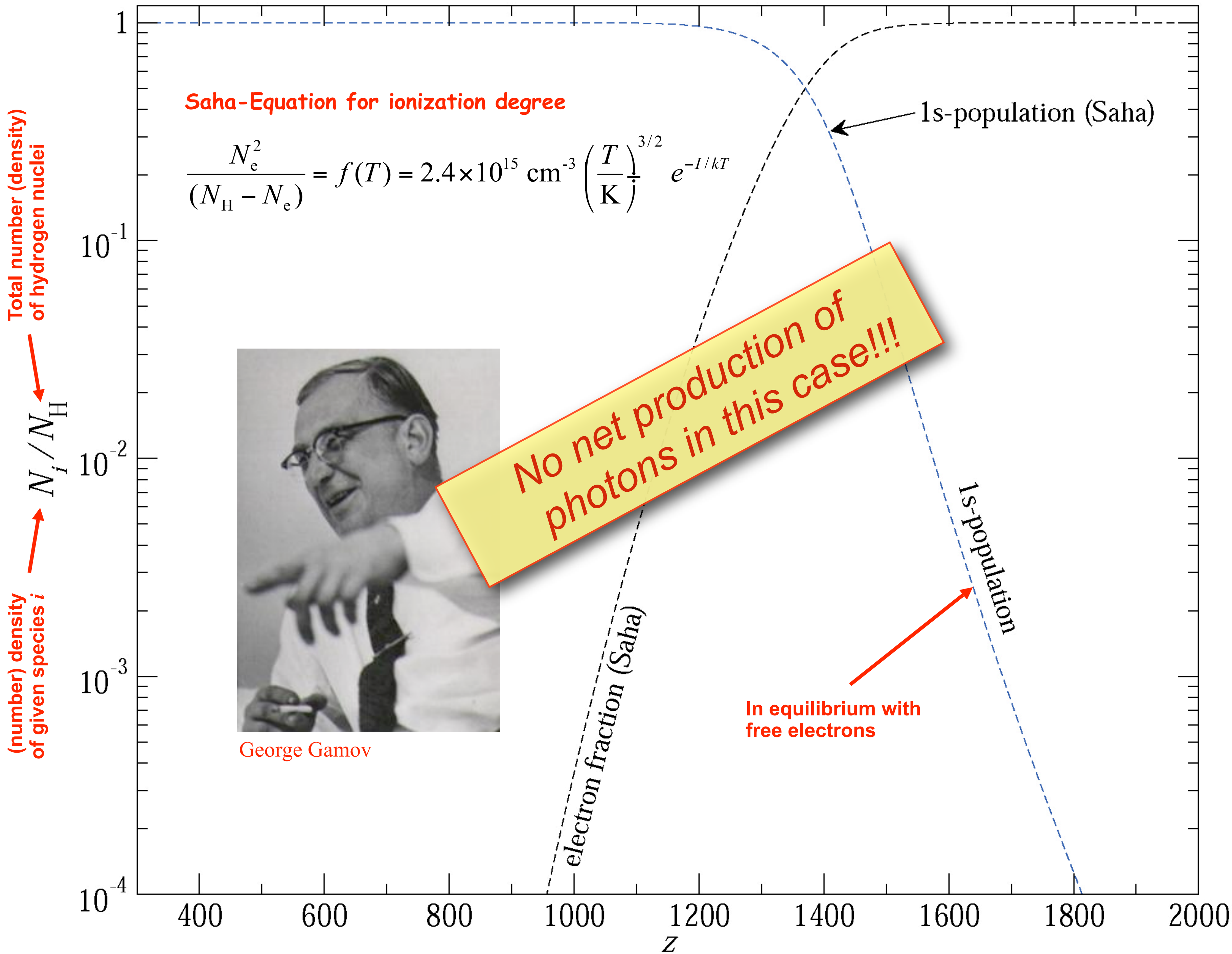
Physical Conditions during Recombination

- Temperature T_γ ~ 2.725 (1+z) K ~ 3000 K
- Baryon number density N_b ~ $2.5\times10^{-7}\,\mathrm{cm}^{-3}\,(1+z)^3$ ~ $330\,\mathrm{cm}^{-3}$
- Photon number density N_γ ~ $410\,\mathrm{cm}^{-3}\,(1+z)^3$ ~ $2\times10^9\,N_b$

  ⇒ photons in very distant Wien tail of blackbody spectrum can keep hydrogen ionized until $h\nu_\alpha$ ~ 40 kT_γ
- Collisional processes negligible (completely different from stars!!!)
- Rates dominated by radiative processes

  (e.g. stimulated emission & stimulated recombination)
- Compton interaction couples electrons very tightly to photons until z ~ 200 ⇒ T_γ ~ T_e ~ T_m


Saha-Equation for ionization degree
$$\frac{N_e^2}{(N_H - N_e)} = f(T) = 2.4\times10^{15}\ \mathrm{cm}^{-3} \left(\frac{T}{\mathrm{K}}\right)^{3/2} e^{-I/kT}$$
1s-population (Saha)
electron fraction (Saha)
1s-population
In equilibrium with free electrons
George Gamov
Total number (density) of hydrogen nuclei
(number) density of given species i
N_i / N_H
z
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
400
600
800
1000
1200
1400
1600
1800
2000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1s-population (Saha)
No net production of photons in this case!!!
electron fraction (Saha)
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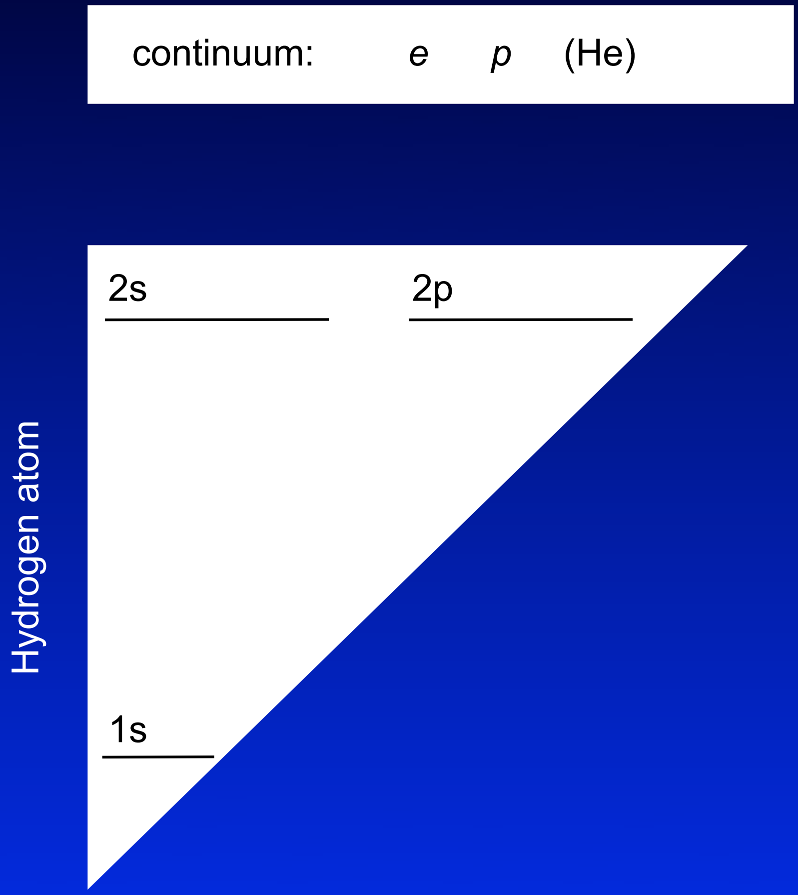
In equilibrium with free electrons
George Gamov
Total number (density) of hydrogen nuclei
(number) density of given species i
N_i / N_H
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
400
600
800
1000
1200
1400
1600
1800
2000
z

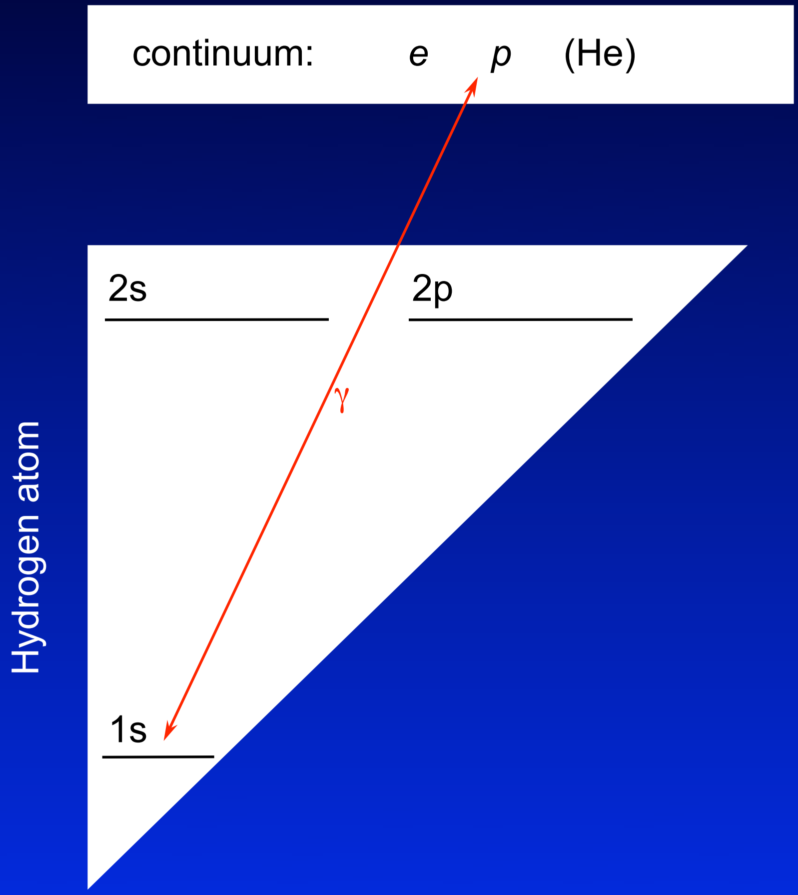
3-level Hydrogen Atom and Continuum



Routes to the ground state ?

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

3-level Hydrogen Atom and Continuum



Routes to the ground state ?

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

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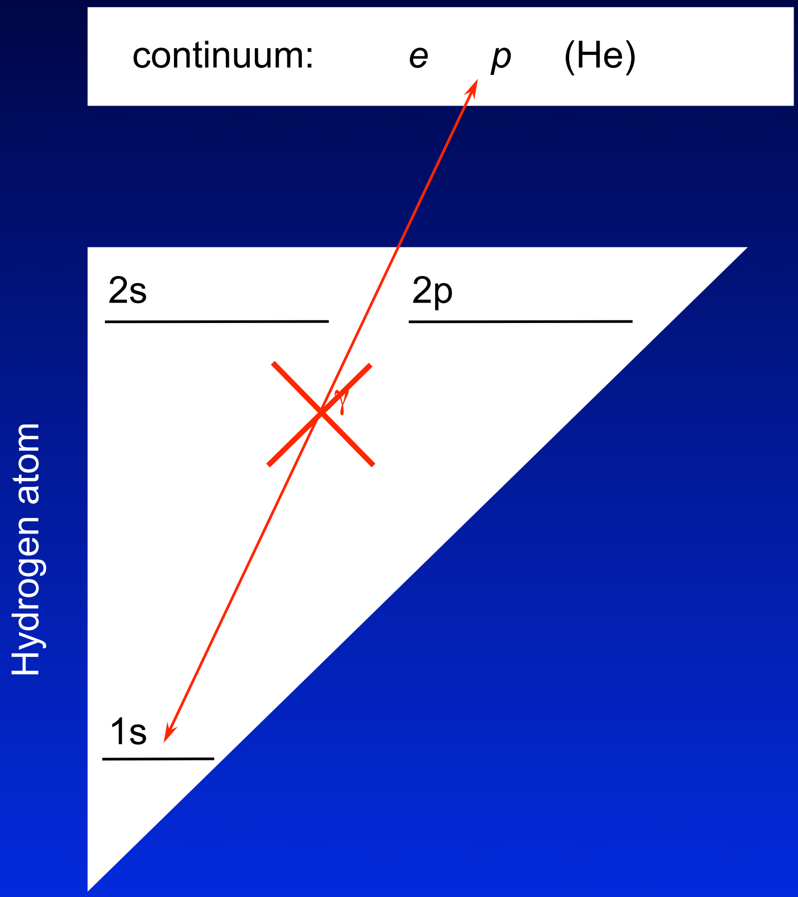

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Zeldovich, Kurt & Sunyaev, 1968, ZhETF, 55, 278
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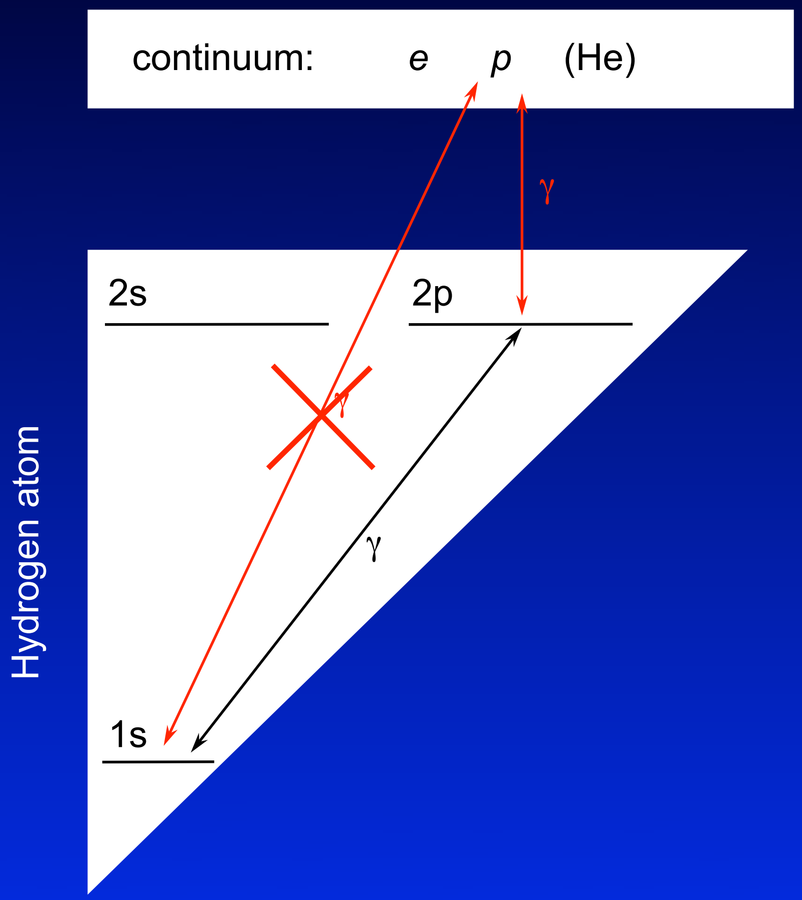

Routes to the ground state ?

- **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 ~10^{-9} @ z ~1100)**

Zeldovich, Kurt & Sunyaev, 1968, ZhETF, 55, 278
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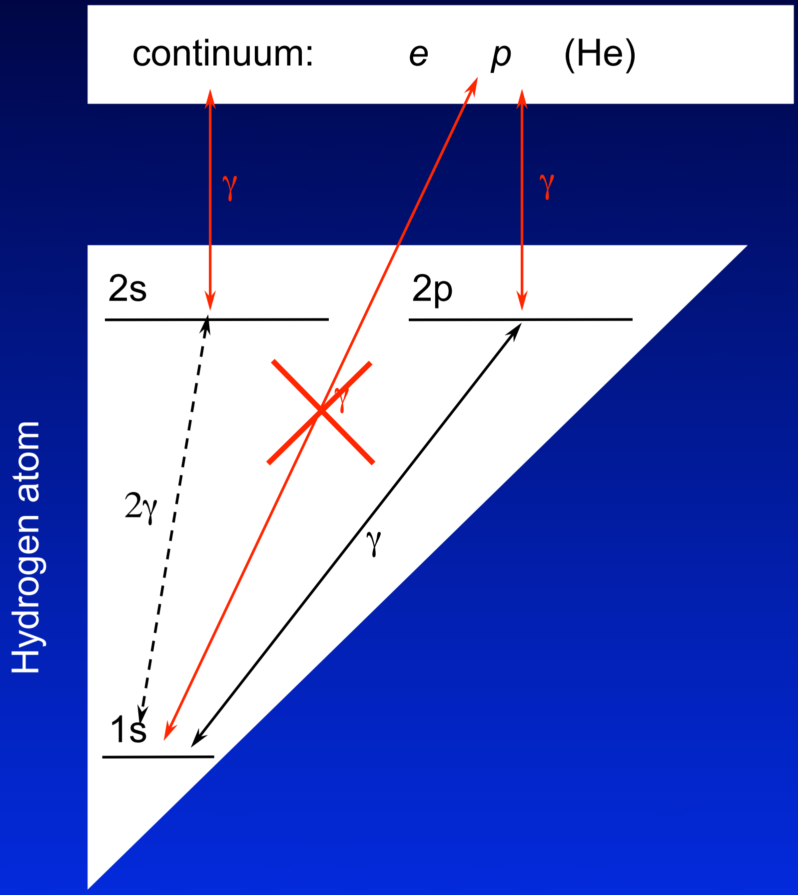
3-level Hydrogen Atom and Continuum



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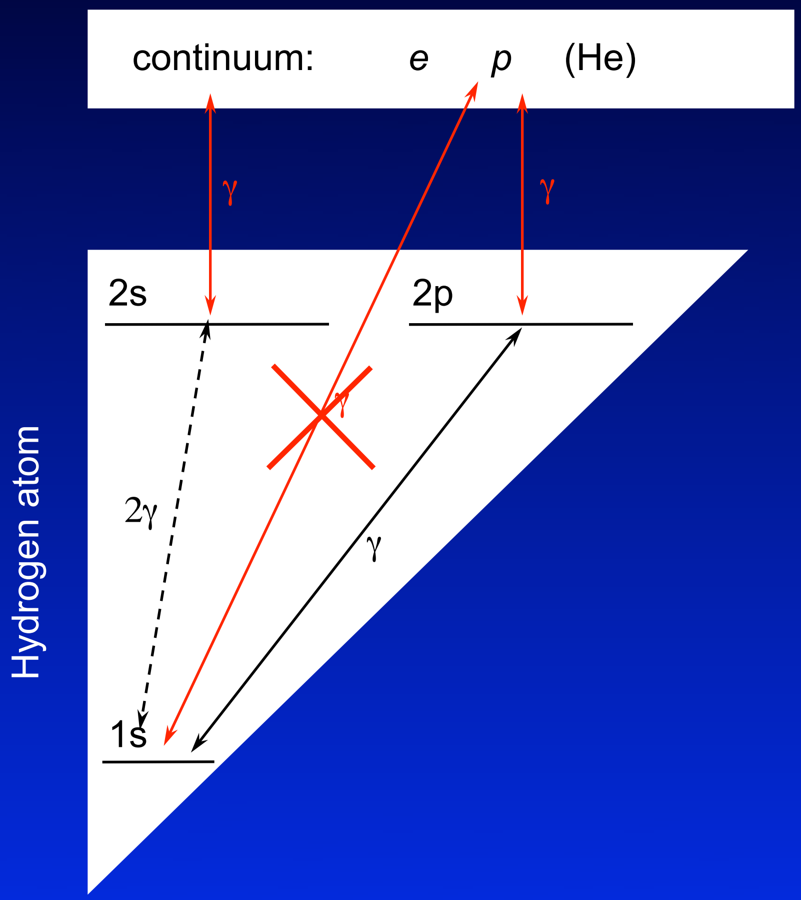
- **recombination to 2p followed by Lyman-α emission**
  - **medium optically thick to Ly-α phot.**
  - **many resonant scatterings**
  - **escape very hard ($p \sim 10^{-9}$ @ $z \sim 1100$)**
- **recombination to 2s followed by 2s two-photon decay**
  - **2s → 1s ~10^8 times slower than Ly-α**
  - **2s two-photon decay profile → maximum at $\nu \sim 1/2\ \nu_\alpha$**
  - **immediate escape**

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

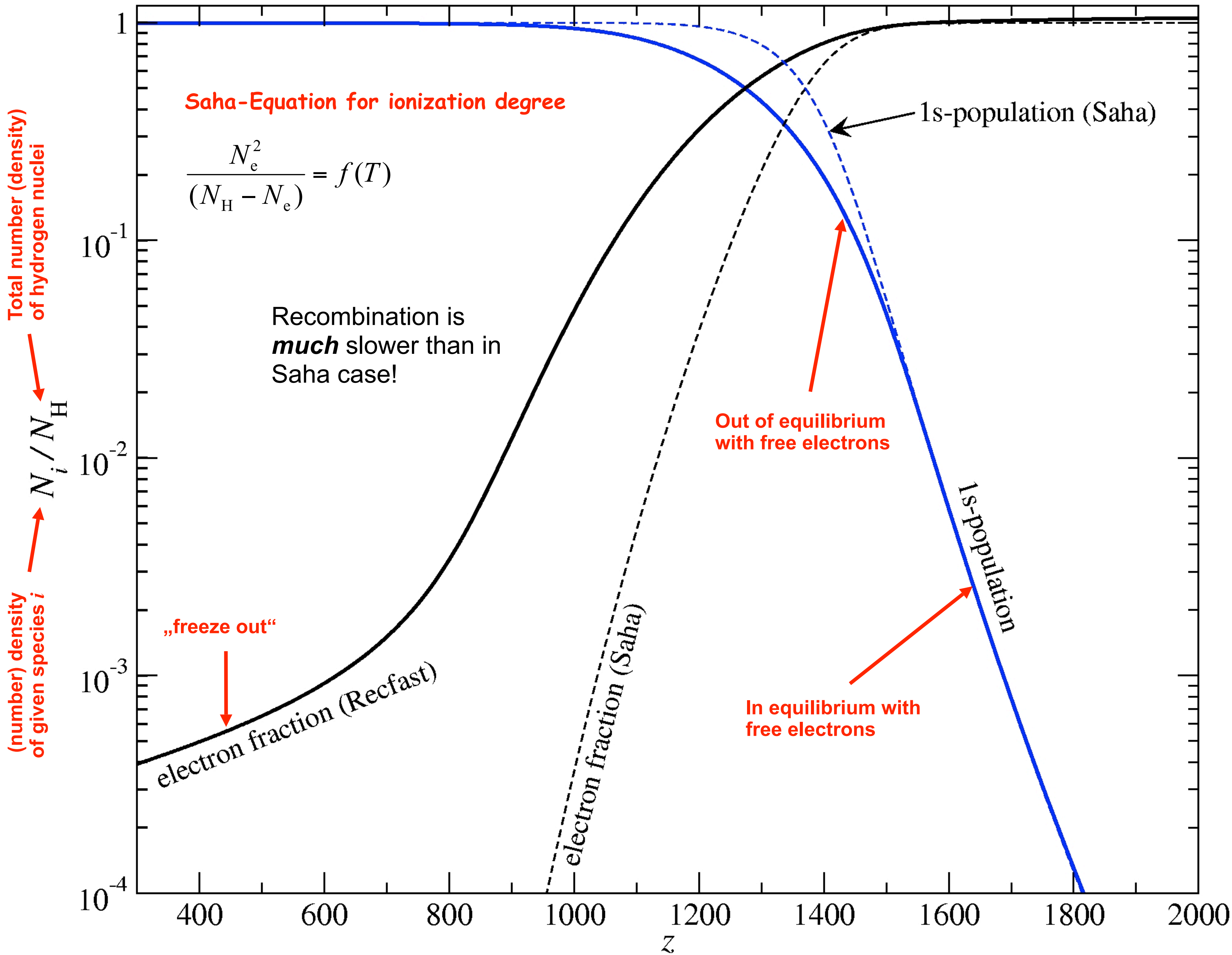
3-level Hydrogen Atom and Continuum



Routes to the ground state ?

- **direct recombination to 1s** — **No**
  - **Emission of photon is followed by immediate re-absorption**
- **recombination to 2p followed by Lyman-α emission** — **~ 43%**
  - **medium optically thick to Ly-α phot.**
  - **many resonant scatterings**
  - **escape very hard (p ~10^{-9} @ z ~1100)**
- **recombination to 2s followed by 2s two-photon decay** — **~ 57%**
  - **2s → 1s ~10^8 times slower than Ly-α**
  - **2s two-photon decay profile → maximum at $\nu \sim 1/2\ \nu_\alpha$**
  - **immediate escape**

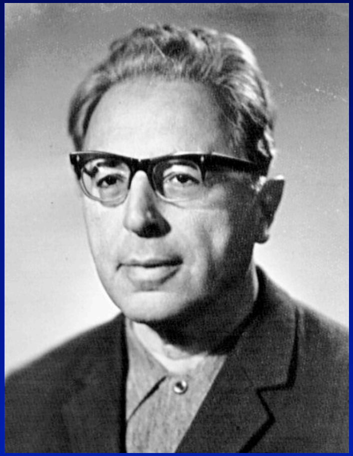
Zeldovich, Kurt & Sunyaev, 1968, ZhETF, 55, 278
Peebles, 1968, ApJ, 153, 1


Saha-Equation for ionization degree
$\frac{N_e^2}{(N_H - N_e)} = f(T)$
1s-population (Saha)
Recombination is
much slower than in
Saha case!
Out of equilibrium
with free electrons
In equilibrium with
free electrons
1s-population
„freeze out“
electron fraction (Recfast)
electron fraction (Saha)
Total number (density)
of hydrogen nuclei
(number) density
of given species i
N_i / N_H
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
400
600
800
1000
1200
1400
1600
1800
2000
z

These first computations were completed in 1968!

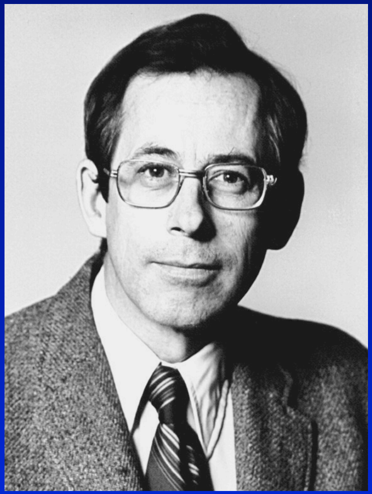
Moscow

Yakov Zeldovich



Iosif Shklovskii

Princeton

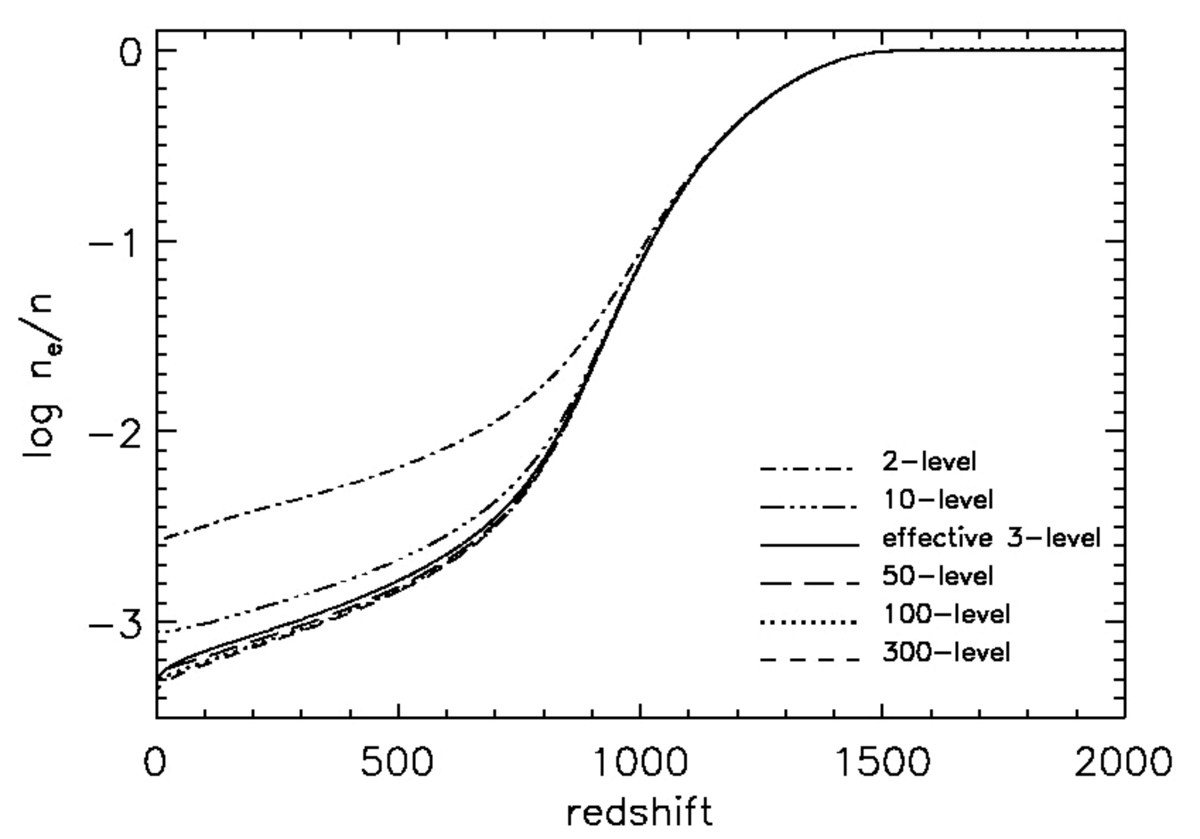


Jim Peebles

Vladimir Kurt
(UV astronomer)

Rashid Sunyaev

Multi-level Atom ⇒ The Recfast-Code



Output of N_e/N_H

Hydrogen:

- up to 300 levels
- only 2s & 2p separately
- *n*>2 → full SE for *l*-sub-states

Helium:

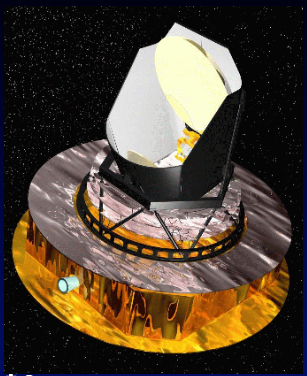
- HeI 200-levels (*z* ~ 1400-1500)
- HeII 100-levels (*z* ~ 6000-6500)
- HeIII 1 equation

Low Redshifts:

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

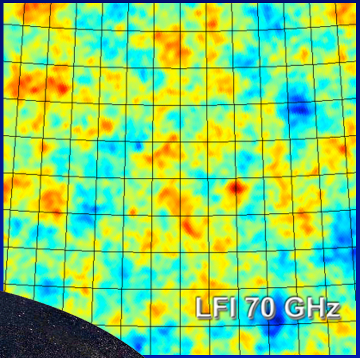
Seager, Sasselov & Scott, 1999, ApJL, 523, L1
Seager, Sasselov & Scott, 2000, ApJS, 128, 407

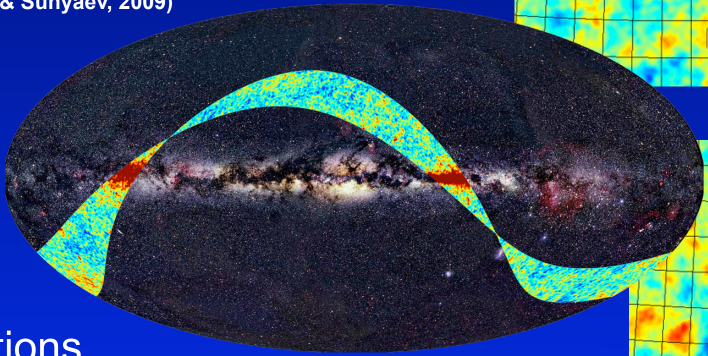
Getting Ready for Planck

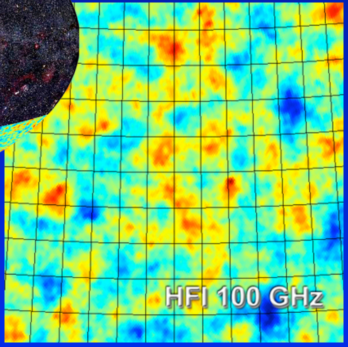


Hydrogen recombination

- 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)
- Feedback of Lyman-series photons (Ly[n] → Ly[n-1])
  (JC & Sunyaev, 2007, A&A; Kholupenko et al. 2010; Haimoud & Hirata in preparation)
- 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 in preparation)







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)

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

What About the Recombinational Photons?

Hydrogen recombination:

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

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

→ At that time the thermalization process does not work anymore!

→ There should be some *small* spectral distortion due to these additional 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 $\Delta n \ll n$!

List of groups around the world

Hydrogen recombination spectrum

- Zeldovich, Kurt & RS 1968; Peebles 1968
- Dubrovich 1975; Bernshtein et al. 1977; Beigman & Sunyaev 1978
- Rybicki and Dell´Antonio 1993; Dubrovich & Stolyarov 1995
- Burgin 2003; Dubrovich & Shakhvorostova 2004; Kholupenko et al. 2005; Wong, Seager & Scott, 2005; Rubino-Martin et al. 2006; JC & Sunyaev 2006; JC et al. 2007;

Helium recombination spectrum

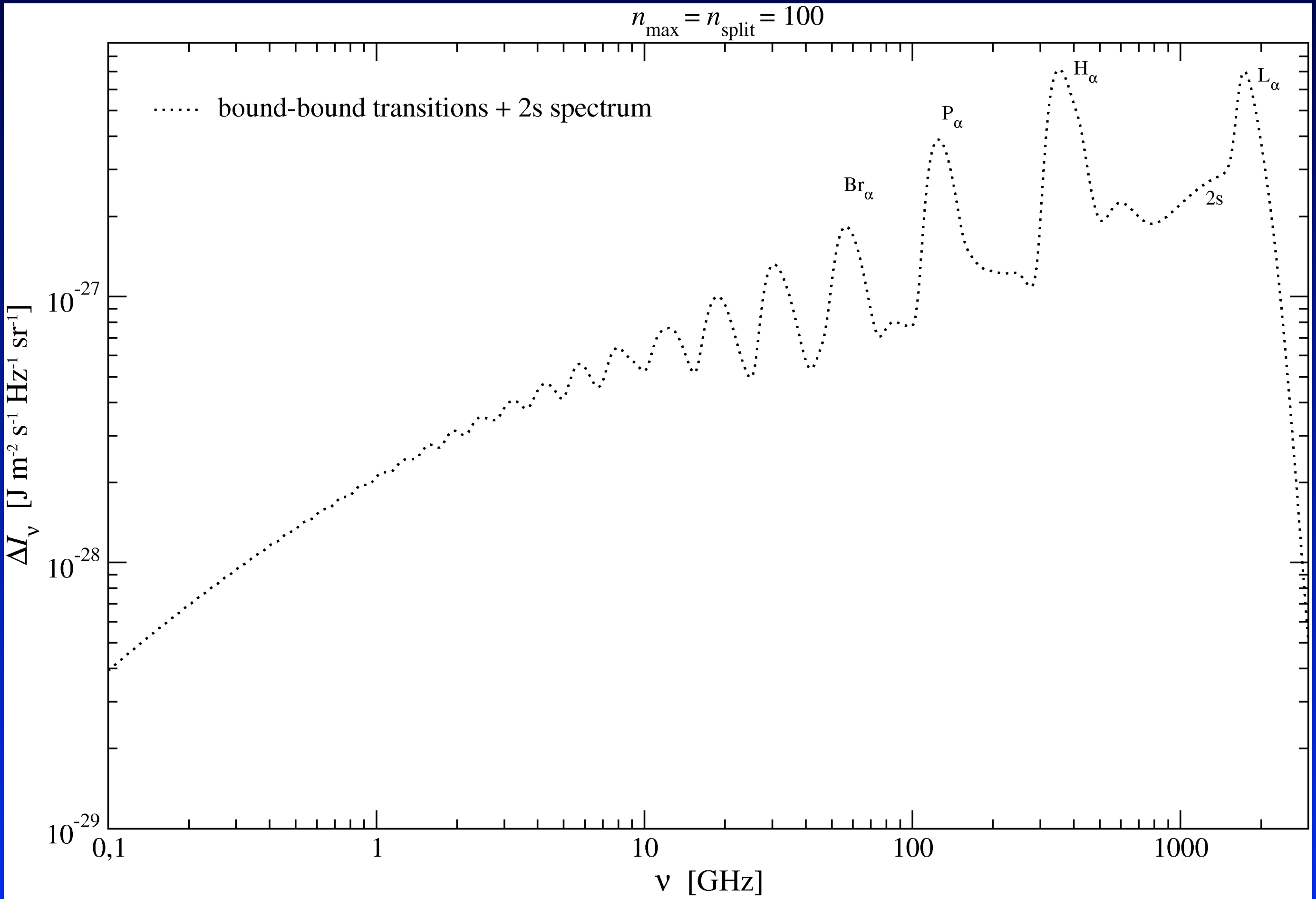
- Dubrovich and Stolyarov 1997; Rubino-Martin et al. 2007; JC & Sunyaev 2009

Main difficulties for accurate predictions

- Early works for pre-concordance cosmologies
- Computational limitations (hydrogen 100 l-resolved shells → ~5000 strongly coupled differential equations)
- *Accurate & sufficiently complete atomic data for neutral helium*

  (Drake & Morton 2007 and Beigman & Vainshtein)

100-shell hydrogen atom and continuum
CMB spectral distortions



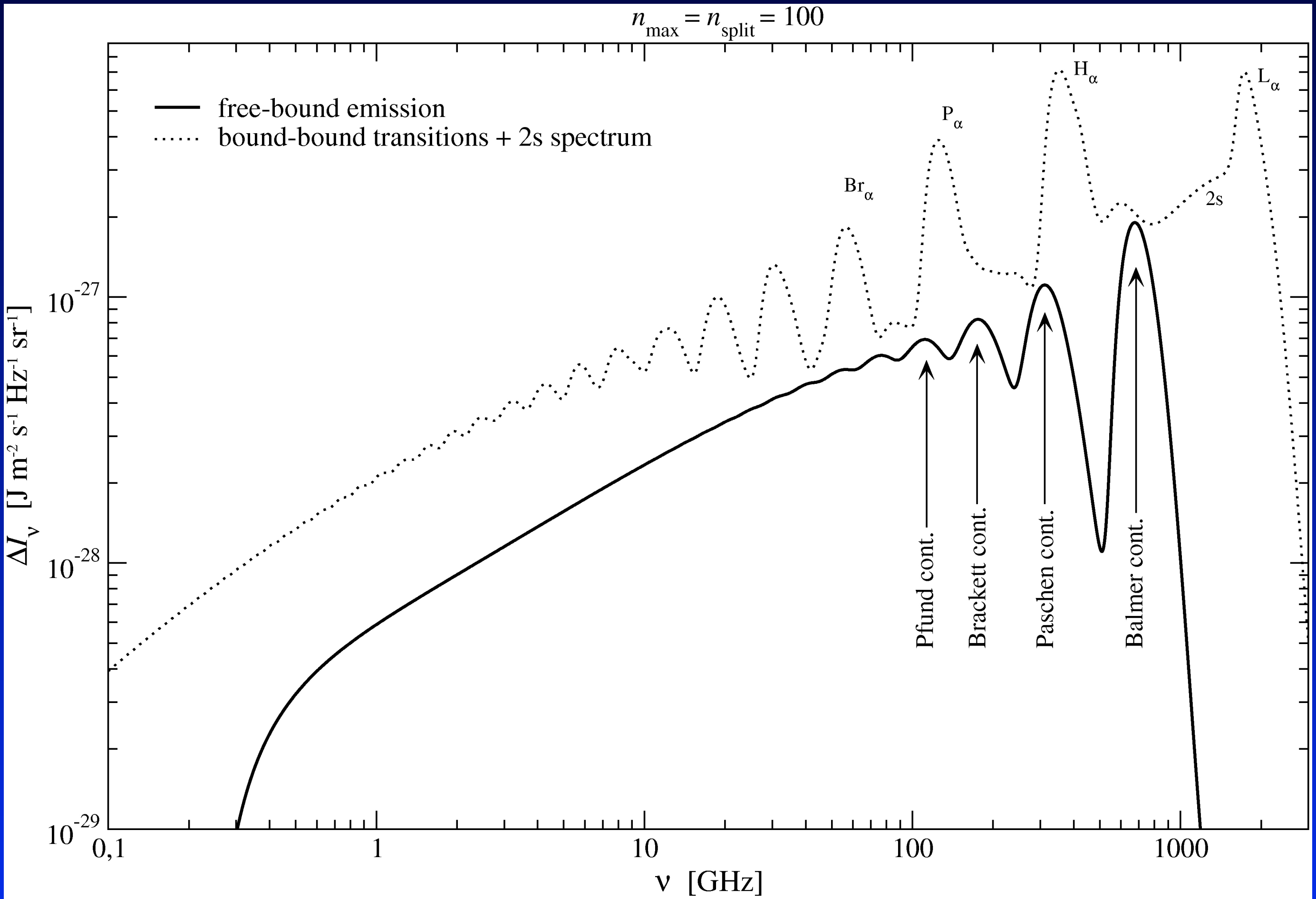
bound-bound & 2s:

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

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

100-shell hydrogen atom and continuum

CMB spectral distortions



bound-bound & 2s:

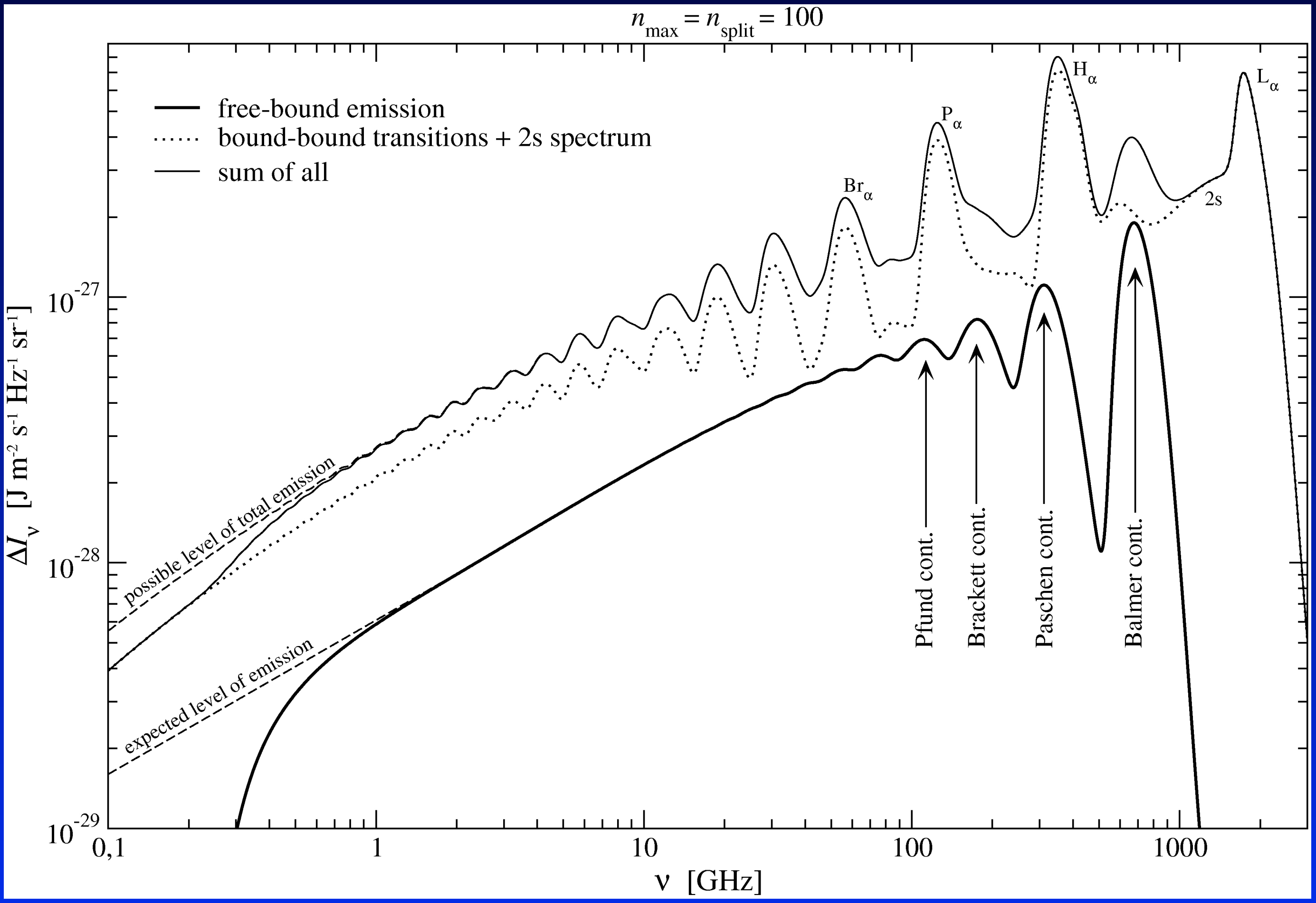
- at ν>1GHz: distinct features
- slope ~ 0.46

free-bound:

- only a few features distinguishable
- slope ~ 0.6

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

100-shell hydrogen atom and continuum
CMB spectral distortions



bound-bound & 2s:

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

free-bound:

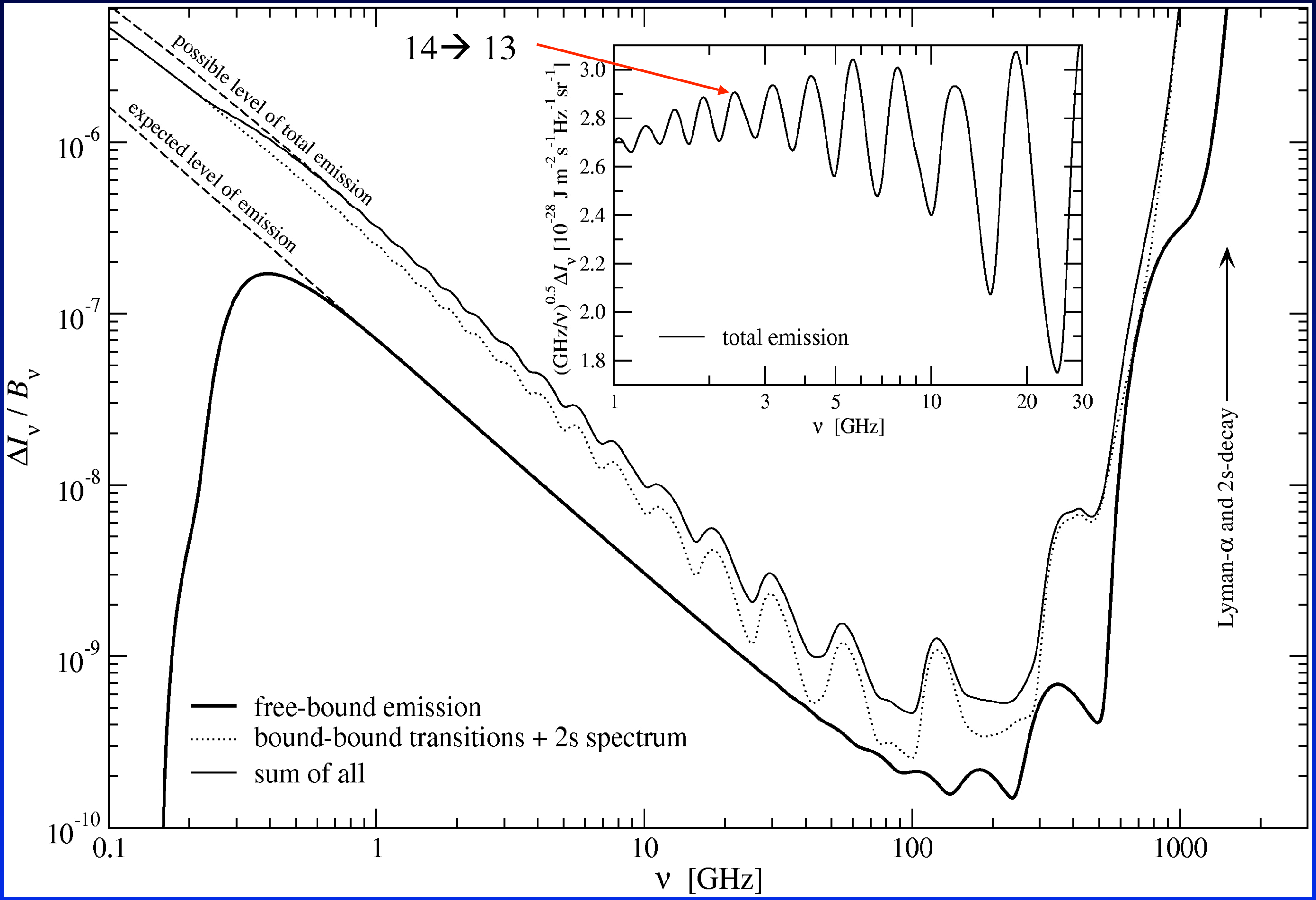
- only a few features distinguishable
- slope ~ 0.6

Total:

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

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

100-shell hydrogen atom and continuum
Relative distortions



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

Wien-region:

- L_α and 2s distortions are very strong
- but CIB more dominant

@ CMB maximum:

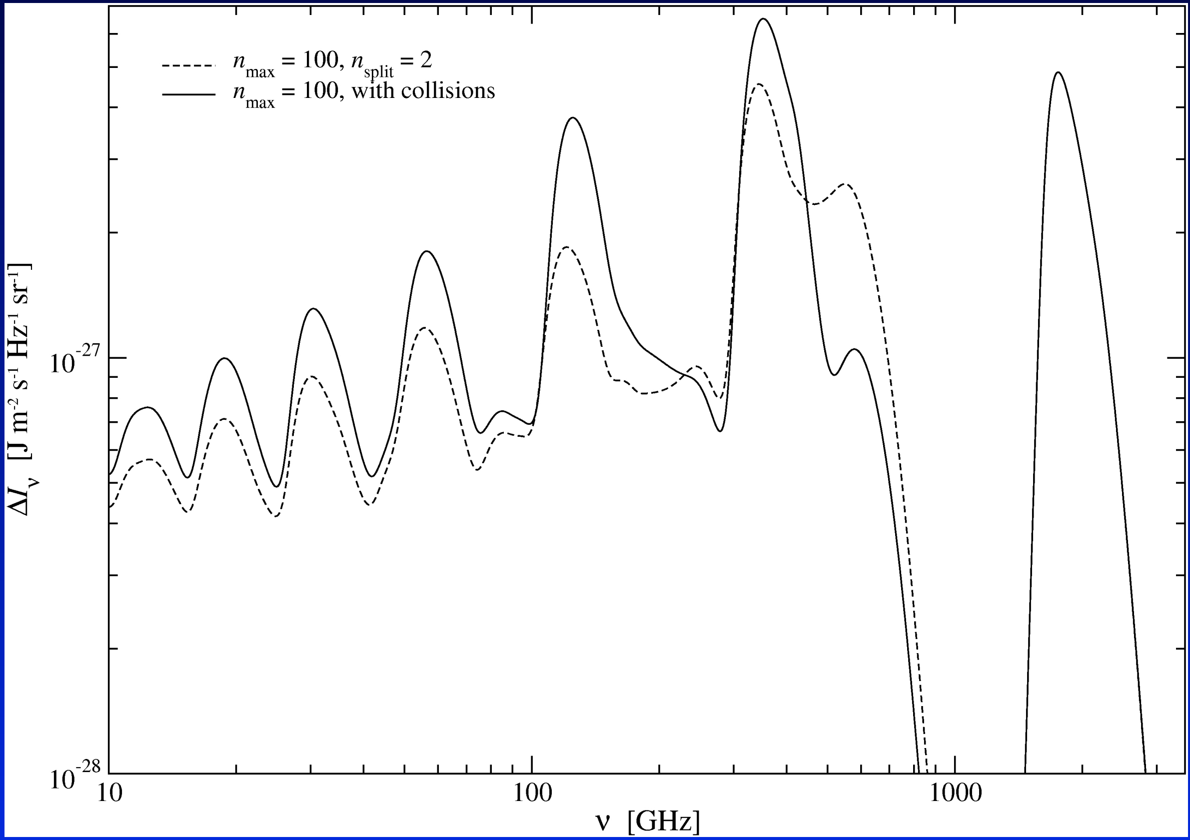
- relative distortions extremely small
- strong ν-dependence

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*

100-shell hydrogen atom and continuum

Non-equilibrium effects on the b-b-spectrum

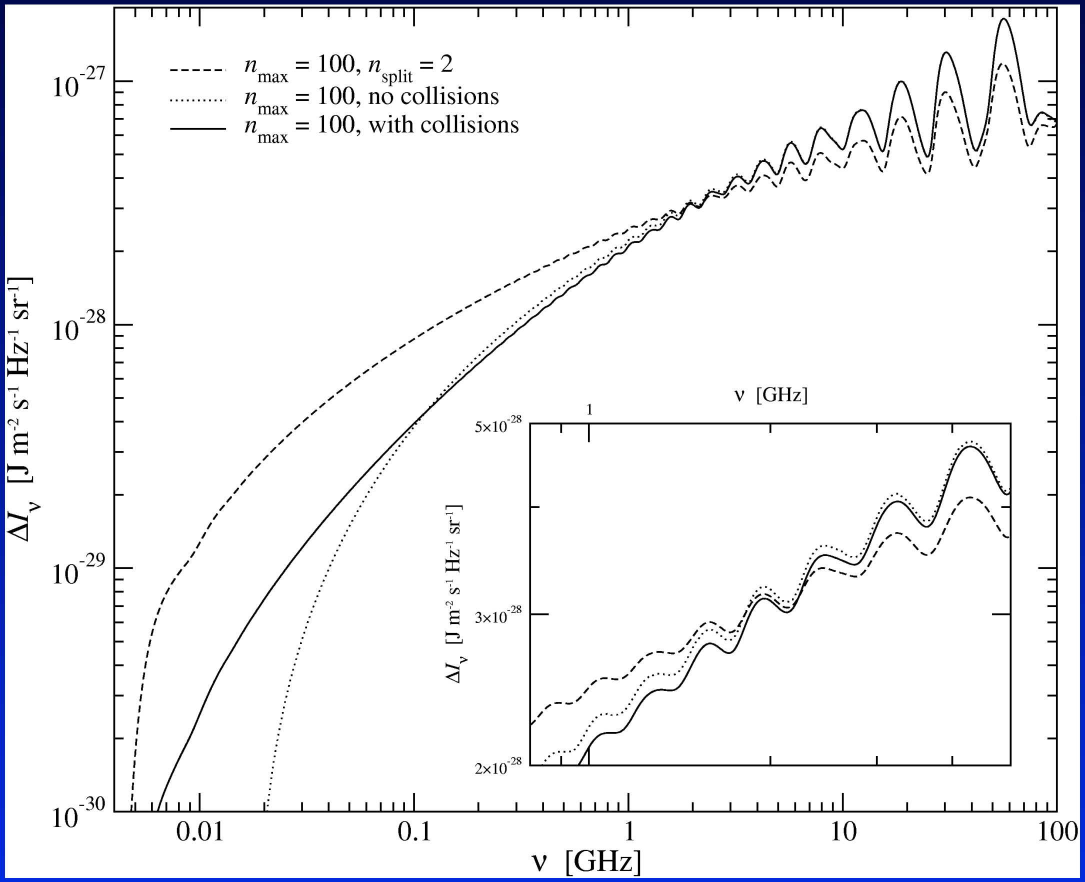


- Lyman- α unchanged
- Balmer-series:
  - B $_\alpha$ lower for n_{split}=2
  - for n_{split}=2 second peak more than 2 times higher
  - ratio first to second peak decreases from 6 → 2
- higher series:
  - n_{split}=2 → emission lower
- collision are negligible!

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

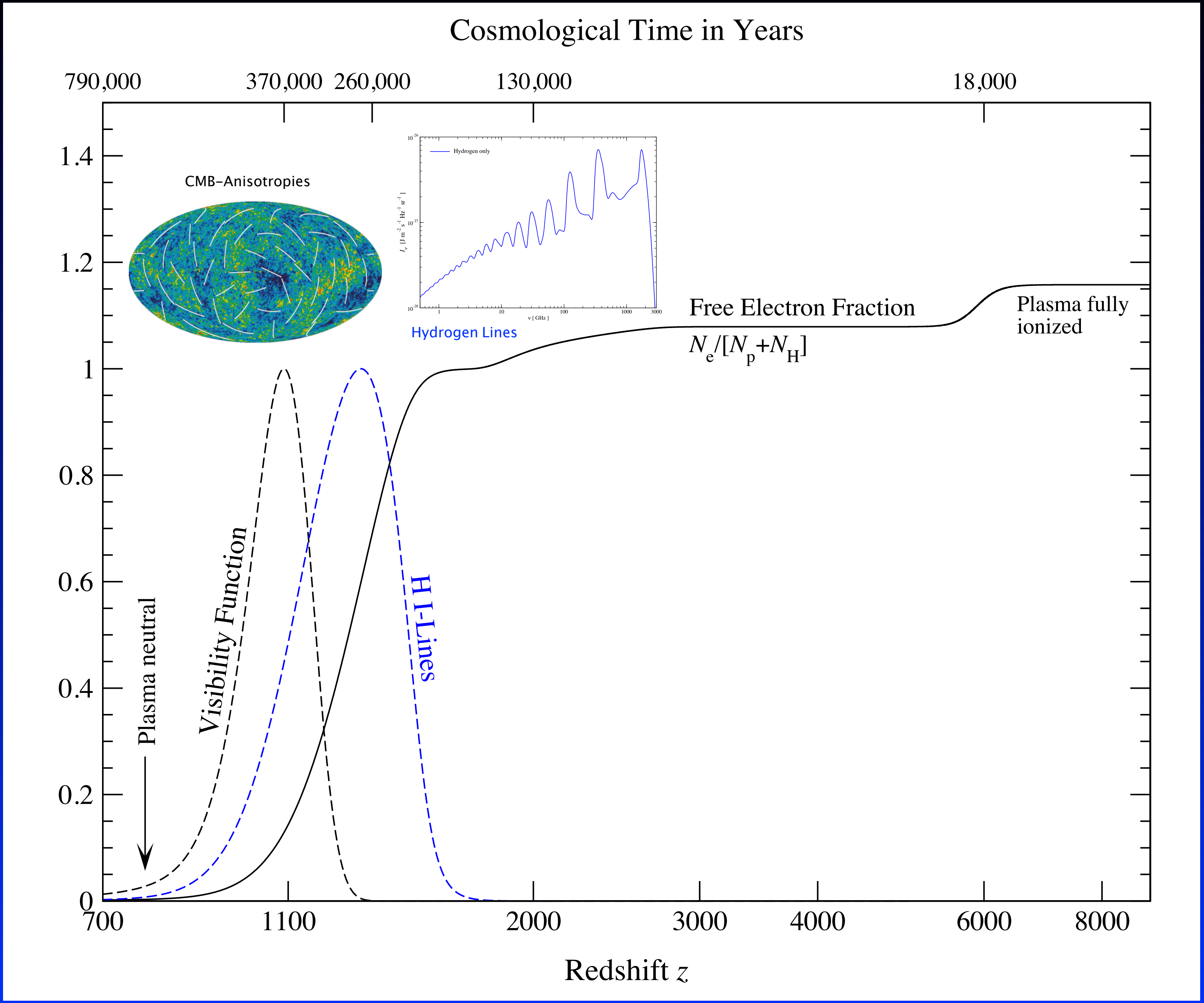
100-shell hydrogen atom and continuum

Effect of l-changing collisions on the b-b spectrum



- collisions start to be important for n above ~ 40
- at low frequencies solution for n_{split}=2 lies above those with n_{split}=100
- difference in the low frequency slope robust (0.35 ↔ 0.46)
- large n → transitions with Δn ~ n favoured for n_{split}=100

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



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
700
1100
2000
3000
4000
6000
8000
Redshift z
CMB–Anisotropies
Hydrogen only
Hydrogen Lines
Free Electron Fraction
N_e/[N_p+N_H]
Plasma fully
ionized
Visibility Function
H I-Lines
Plasma neutral

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

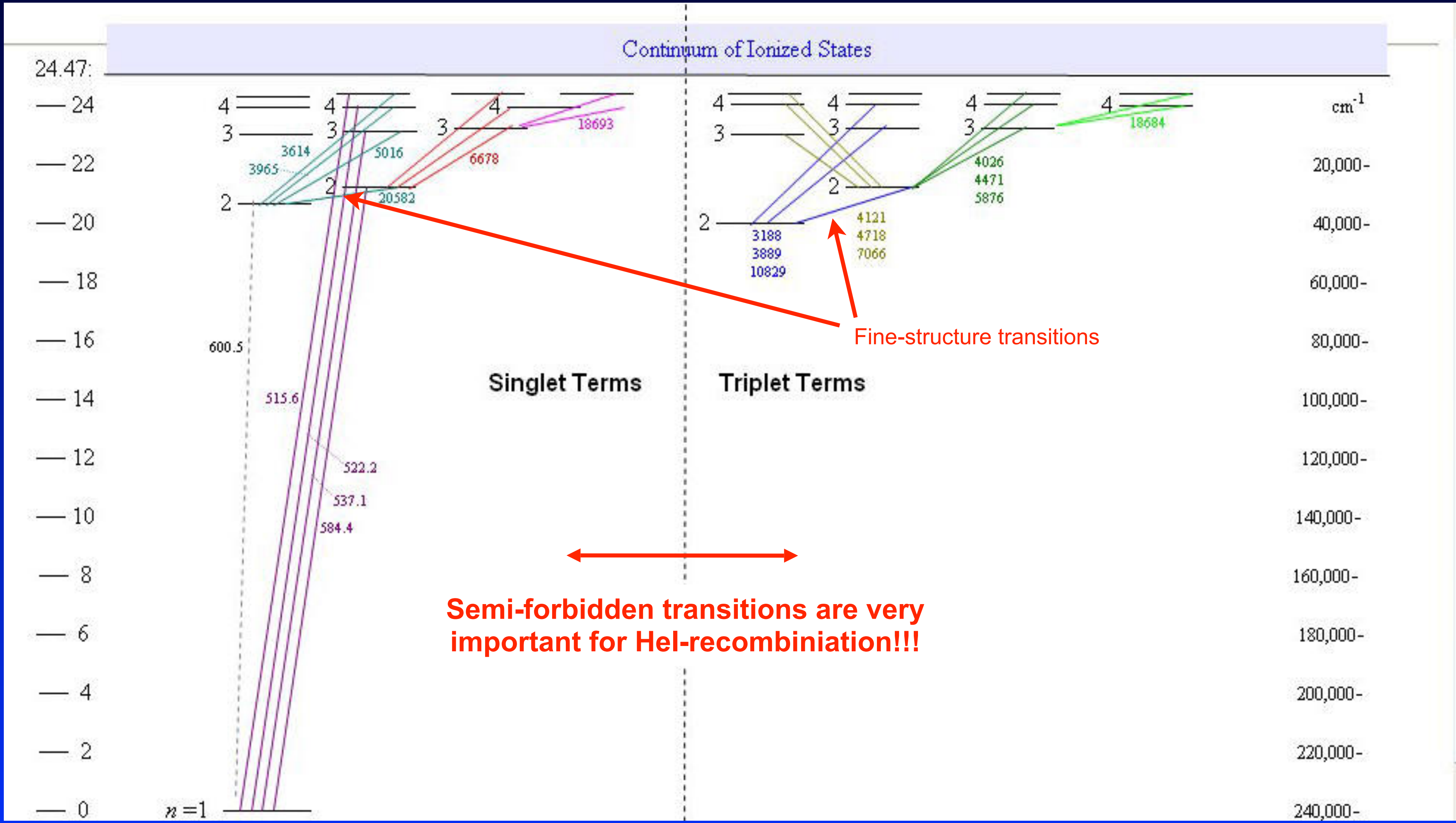
  (*ii*) Helium recombinations faster
  → more *narrow* features with *larger* amplitude

  (*iii*) non-trivial superposition
  → local amplification possible

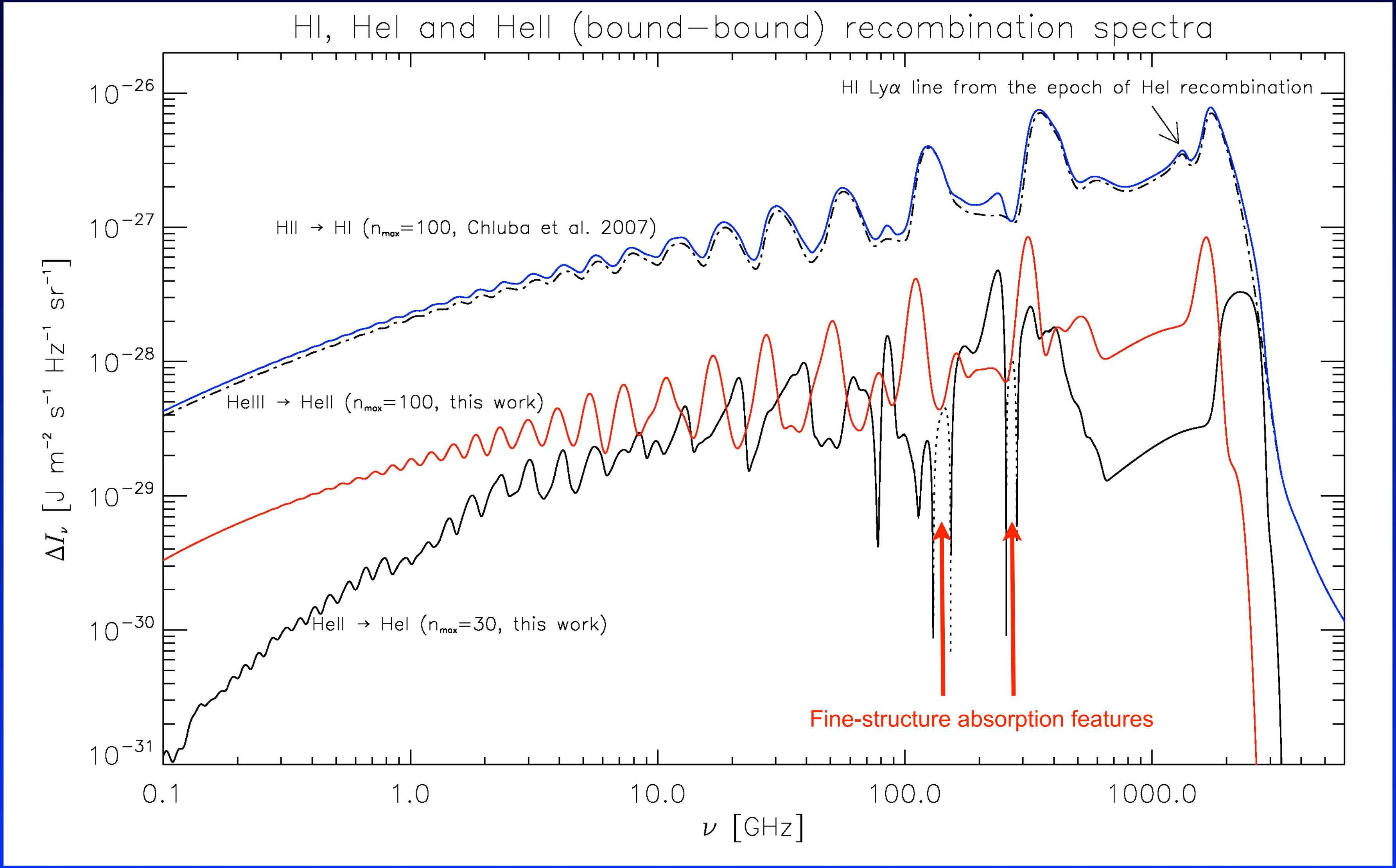
  (*iv*) reprocessing of HeII & HeI photons by HeI and HI
  → increases the number of helium-related photons

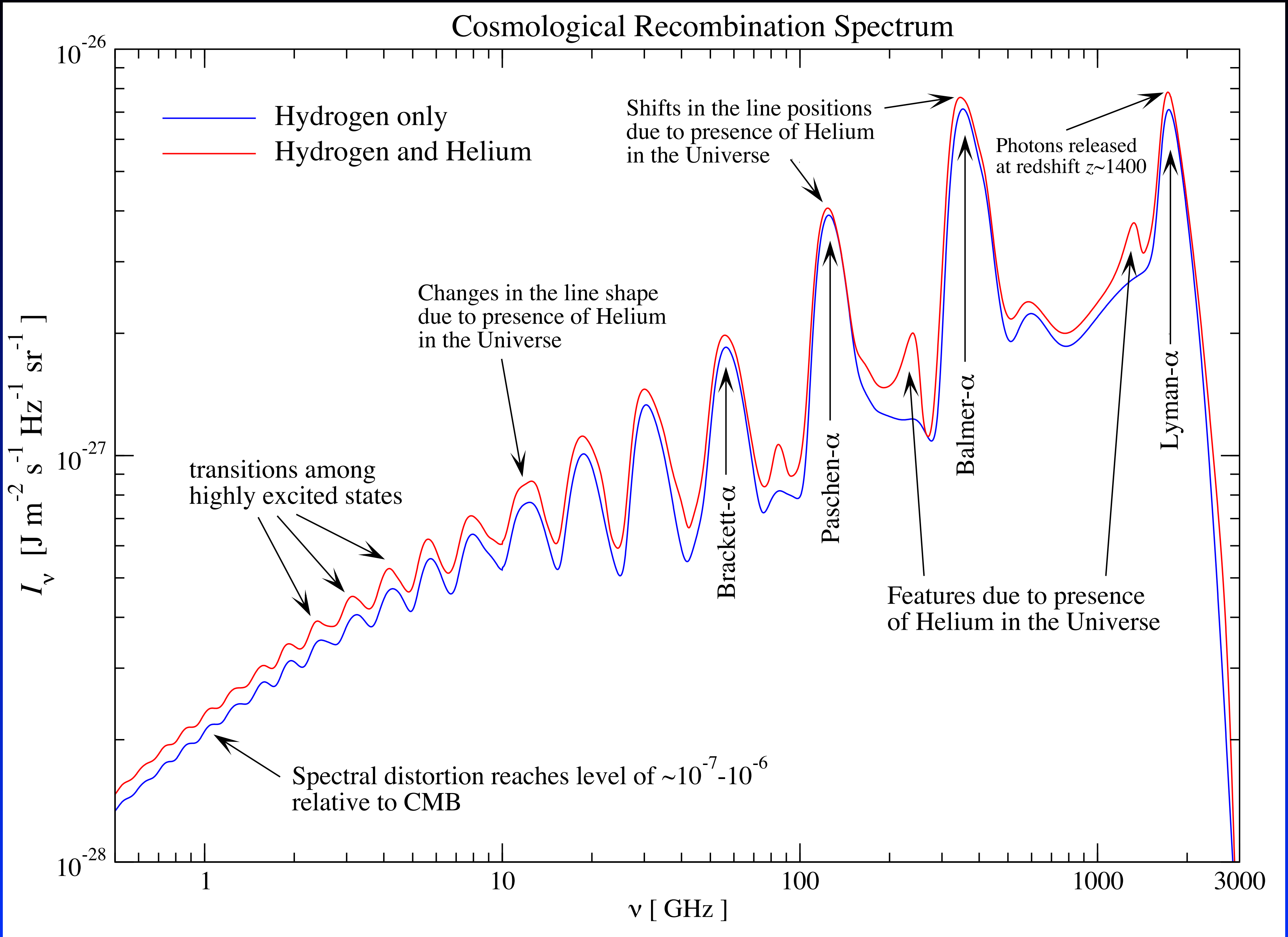
→ May opens a way to ***directly*** measure the primordial (pre-stellar!!!) helium abundance!

Grotrian diagram for neutral helium



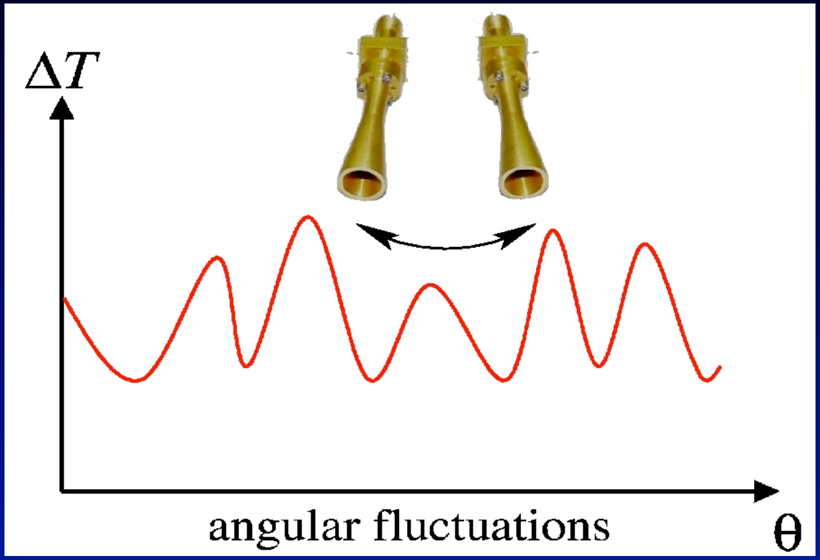
Helium contributions to the cosmological recombination spectrum

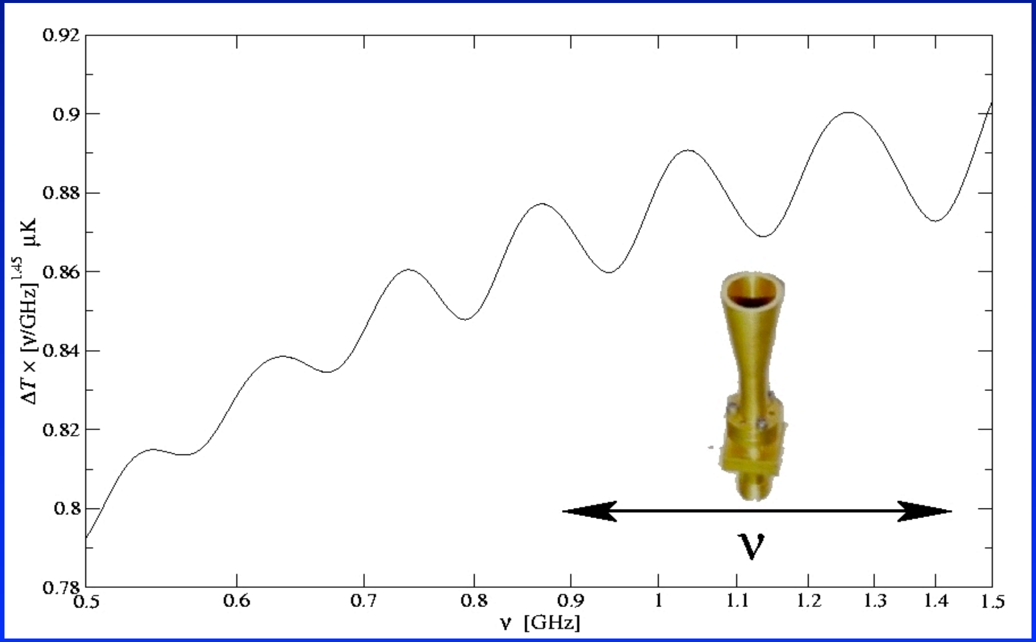




Cosmological Recombination Spectrum
Hydrogen only
Hydrogen and Helium
Shifts in the line positions due to presence of Helium in the Universe
Photons released at redshift z~1400
Changes in the line shape due to presence of Helium in the Universe
transitions among highly excited states
Brackett-α
Paschen-α
Balmer-α
Lyman-α
Features due to presence of Helium in the Universe
Spectral distortion reaches level of ~10^-7-10^-6 relative to CMB
10^-26
10^-27
10^-28
I_ν [J m^-2 s^-1 Hz^-1 sr^-1]
1
10
100
1000
3000
ν [GHz]

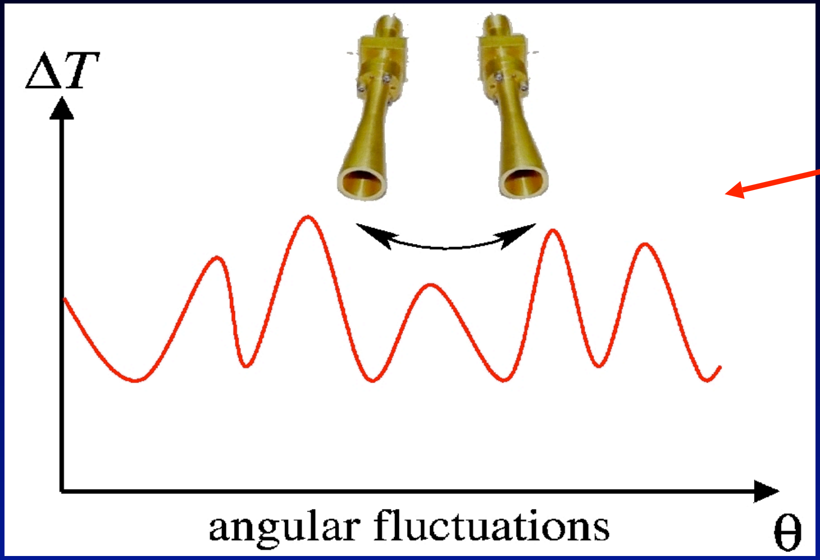
Sketch of proposed Observing Strategy





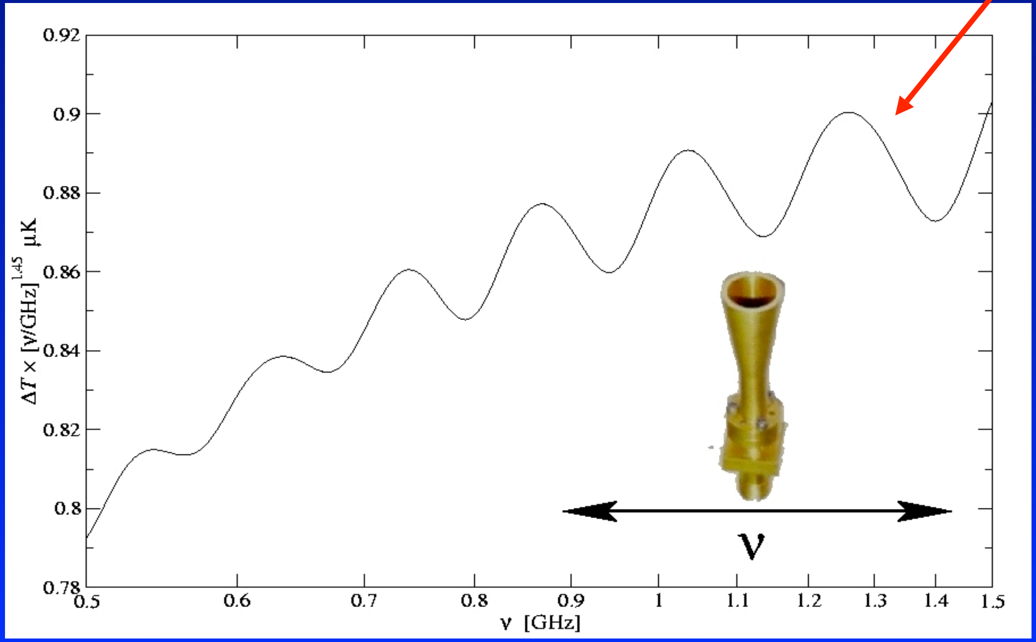
Scan over frequency instead of angular coordinate!!!

Sketch of proposed Observing Strategy



Experiments under construction are reaching the sensitivity on the level of 10 nK

Cosmological recombination Signal is close to ~1μK at ν~ 1GHz. The amplitude of the frequency modulated signal reaches ~30 nK



In both cases: No absolute measurement!

In the case of the recombinational lines one can compute a *„Template“* with frequencies and amplitude of all features

The lines in the CMB spectrum are the same on the whole sky

Lines are practically unpolarized

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***

→ ***If recombination occurs as we think it does, then the lines can be predicted with very high accuracy!***

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

→ **Current theoretical limitations: (i) *collisional rates; HeI (ii) photo-ionization cross-sections and (iii) bb-transition rates***

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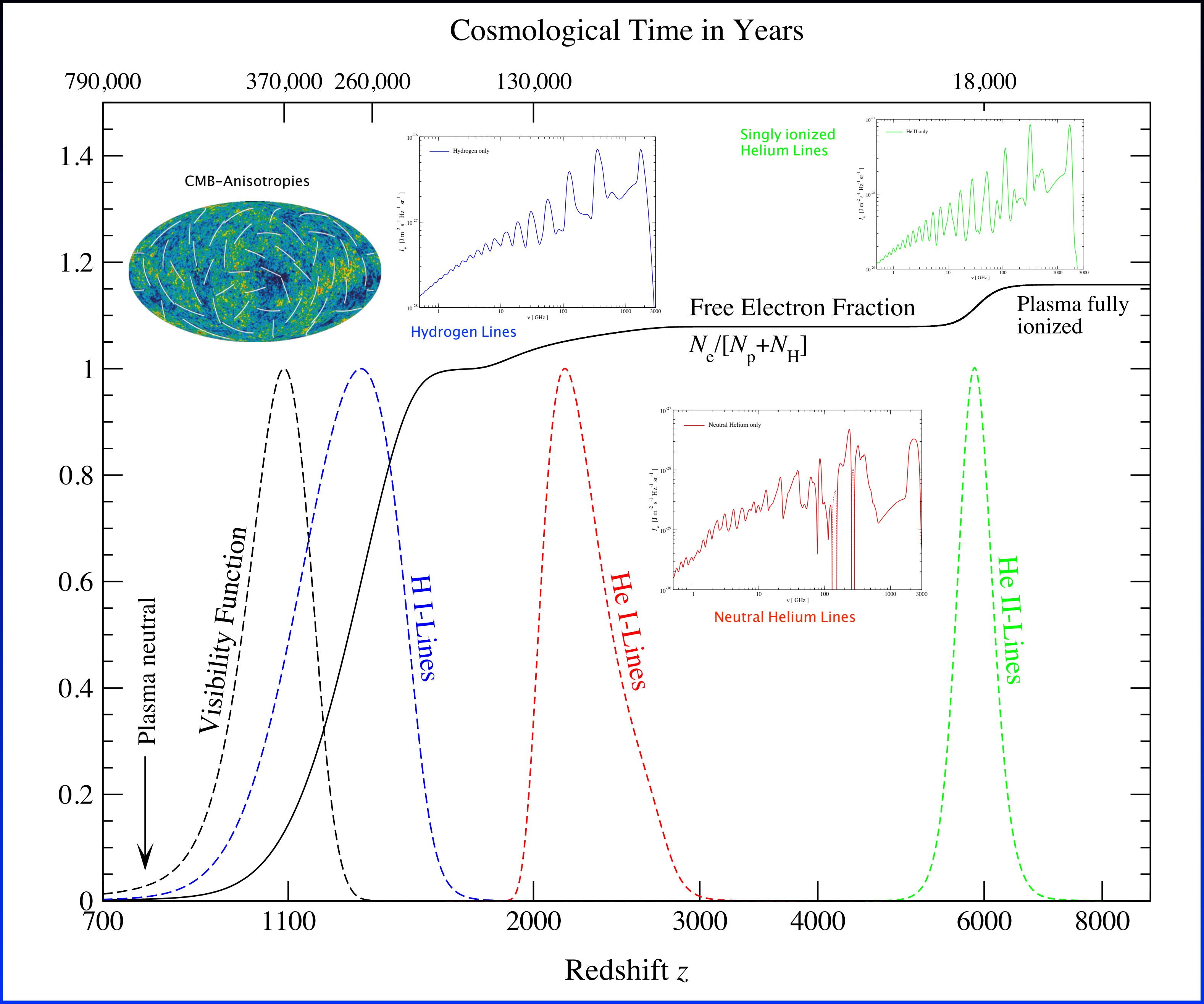
If something unexpected or non-standard happened:

→ ***non-standard thermal histories should leave some measurable traces***
→ ***direct way to measure/reconstruct the recombination history!***
→ **possibility to distinguish *pre-* and *post-recombinational y*-type distortions**
→ ***sensitive to dark matter annihilations during recombination***
→ **new way to constrain energy injection history**



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