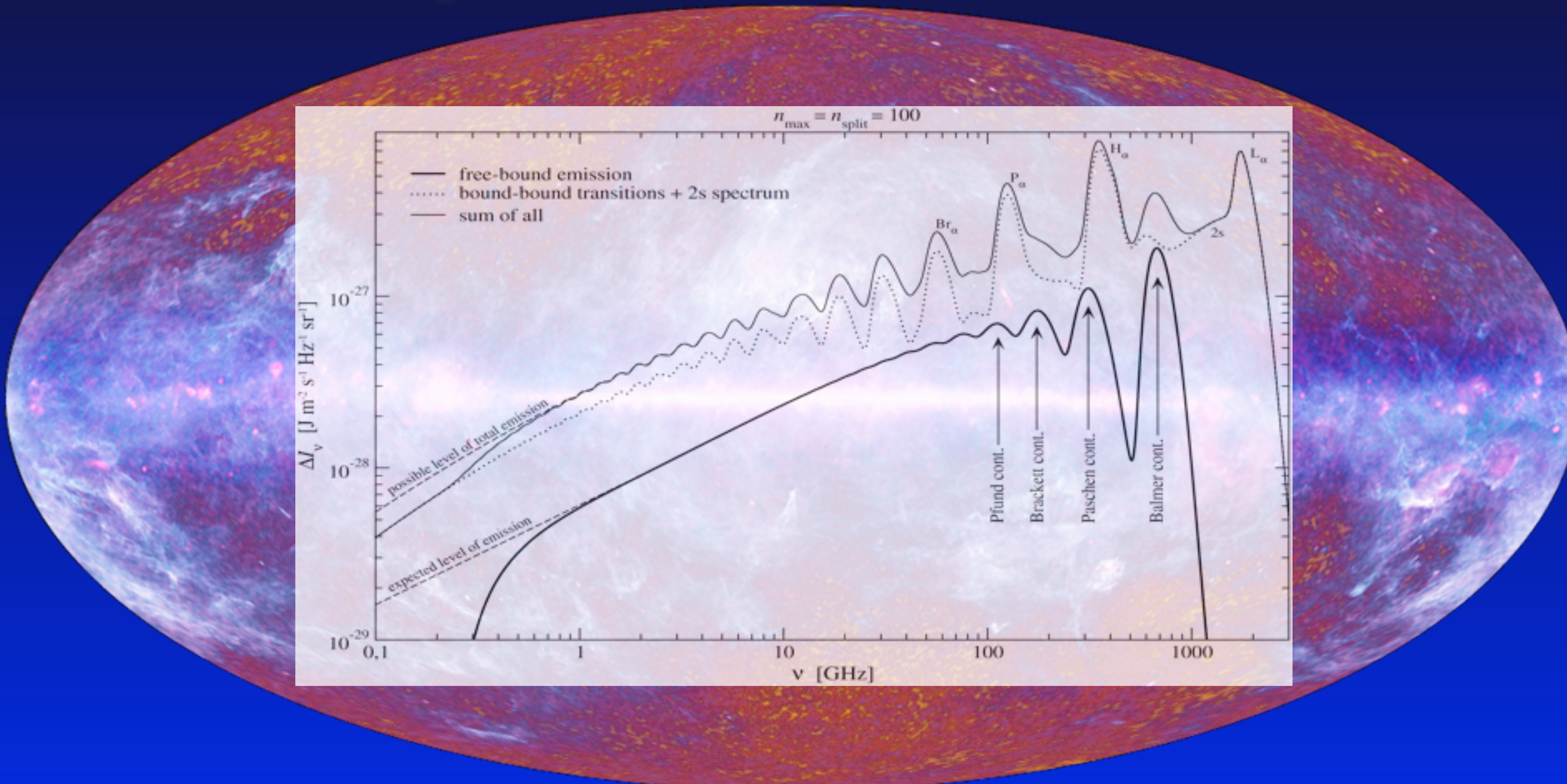
Signals from the Cosmological Recombination Era and Spectral Distortions of the CMB



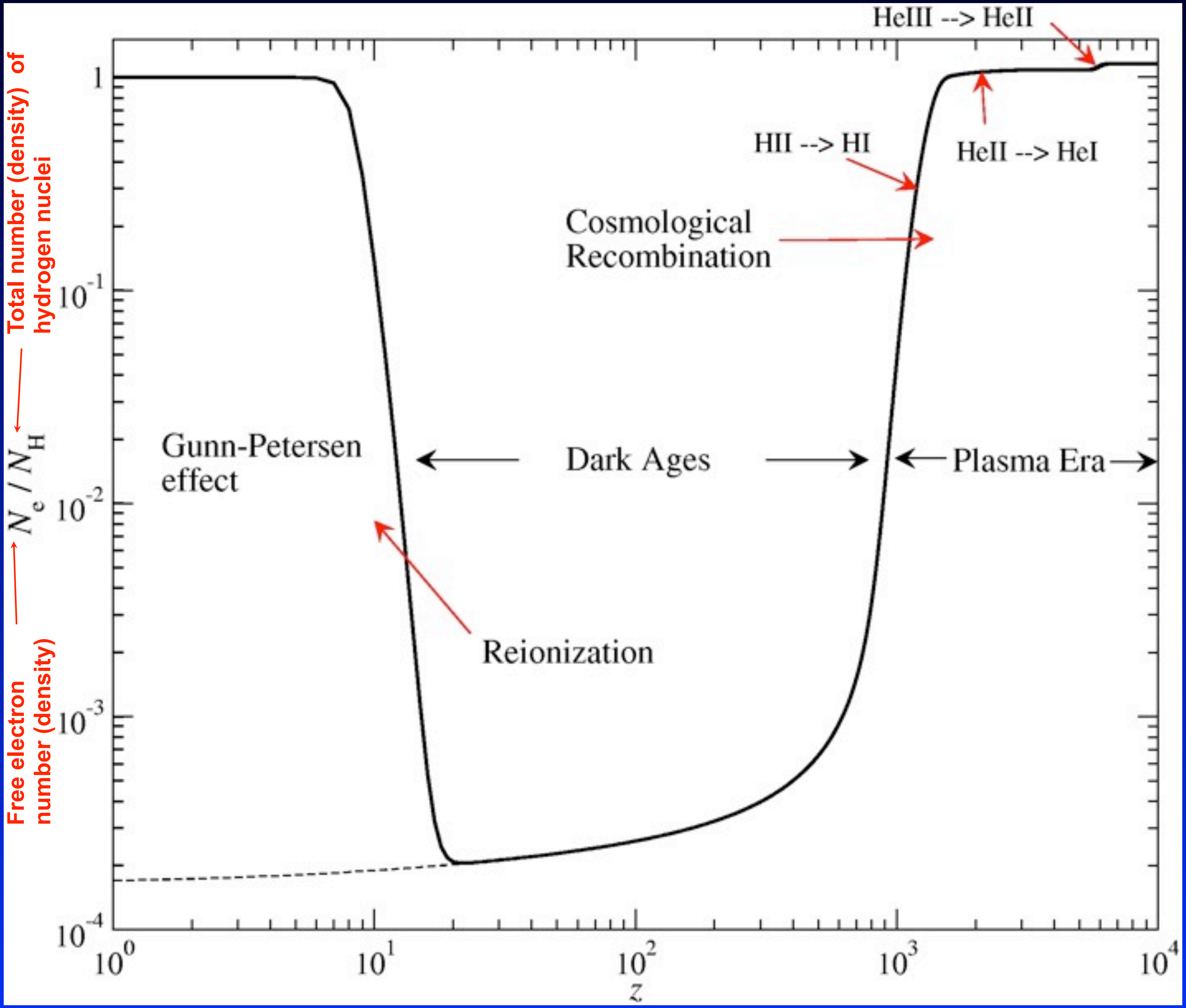
Jens Chluba

IPMU ACP Seminar

November 17, 2011, IPMU Tokyo

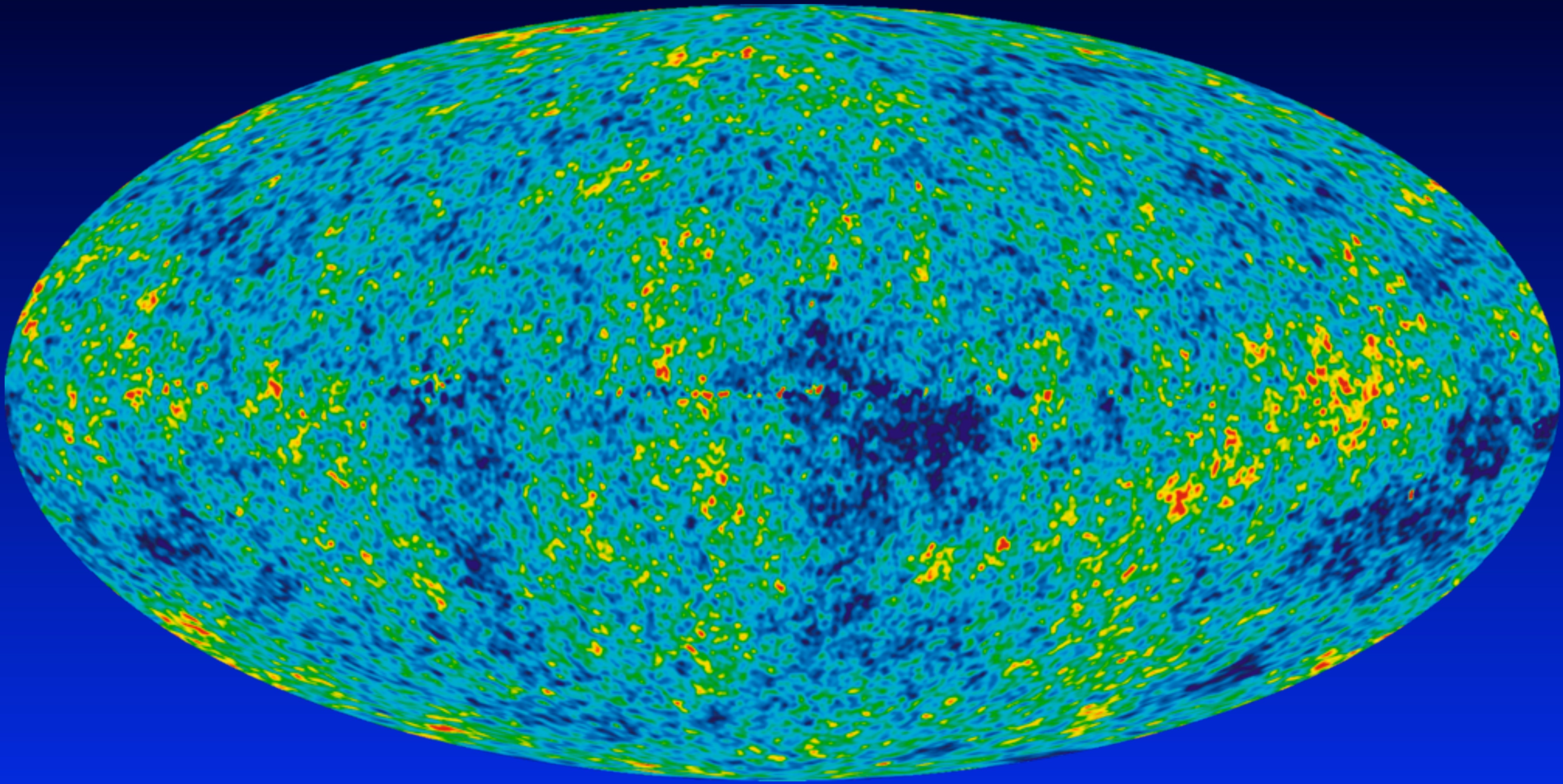
Collaborators: R.A. Sunyaev (MPA), J.A. Rubiño-Martín (IAC), Dick Bond (CITA), Ben Wandelt, Richard Shaw, Marzieh Farhang, Rajat Thomas, Geoff Vasil

Sketch of the Cosmic Ionization History



- **at redshifts higher than ~10^4 Universe** → *fully ionized*
- **z ≥ 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



Example: WMAP-7

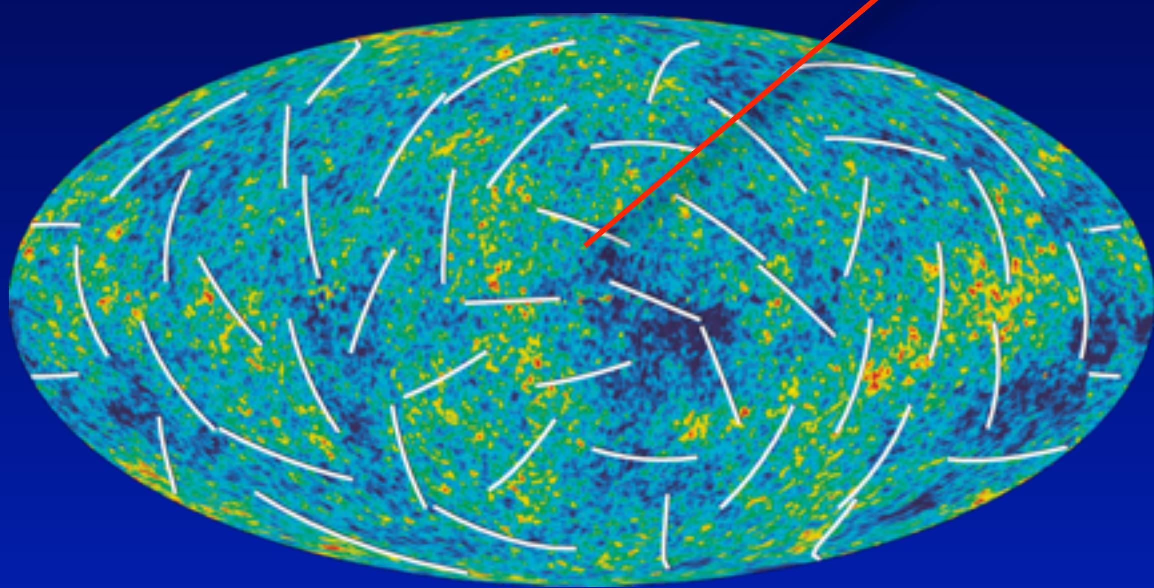
- CMB has blackbody spectrum in every direction
- Variations of the CMB temperature $\Delta T/T \sim 10^{-5}$

CMB Anisotropies → Cosmology

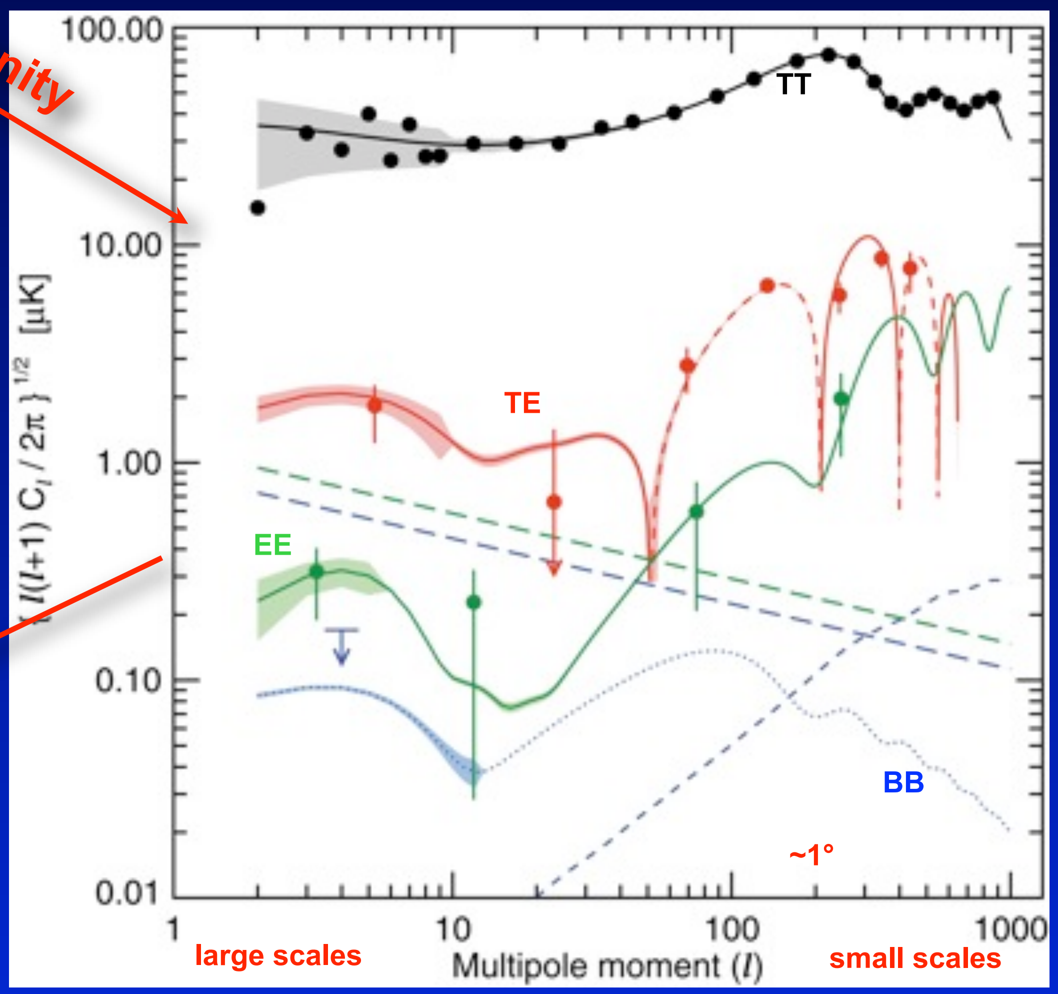
a_{lm}

Gaussianity

WMAP CMB Sky



CMB Power spectra



(Joint) analysis

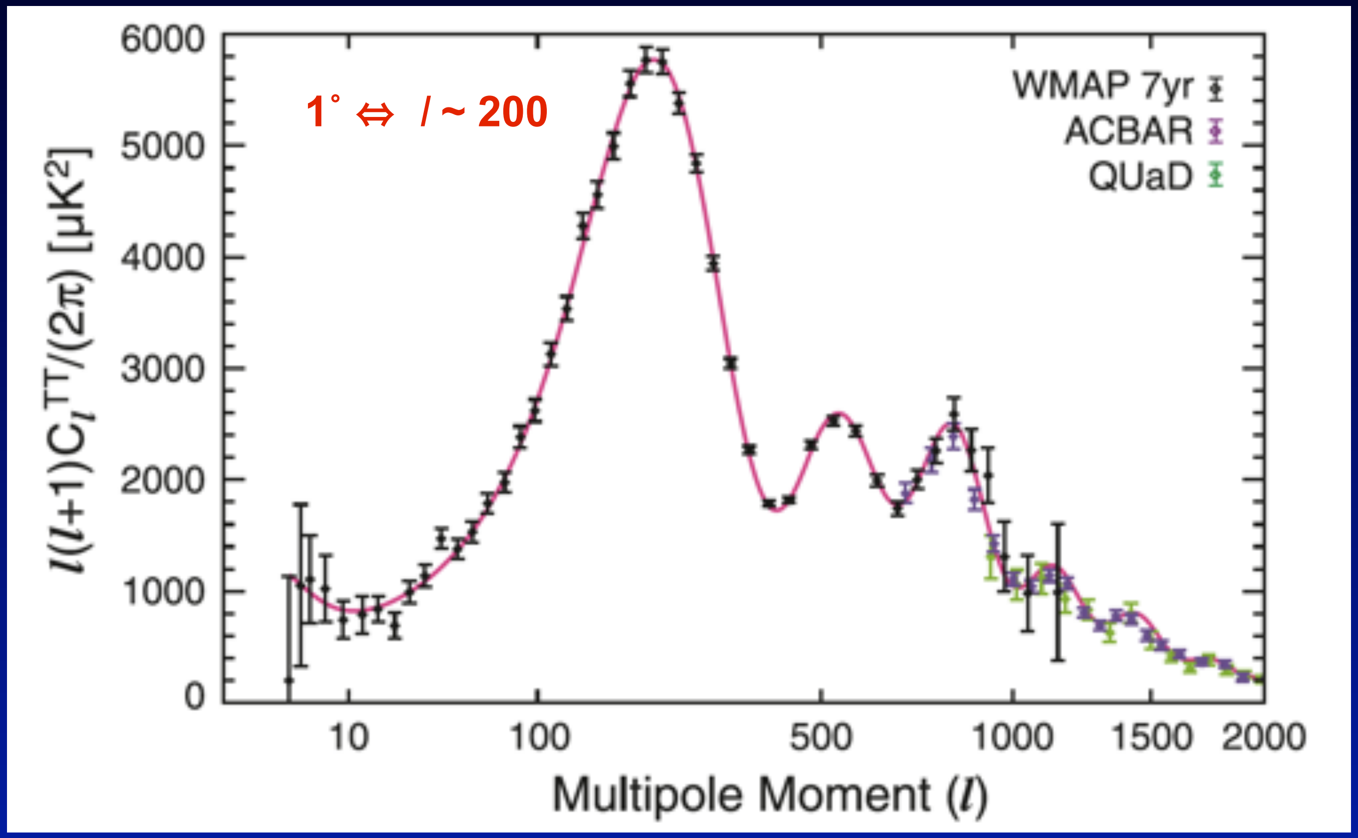
Cosmological Parameters

Ω_{tot}, Ω_m, Ω_b, Ω_Λ, h, τ, n_s,...

Other cosmological Dataset:

small-scale CMB, supernovae, large-scale structure, Lyman-α forest, weak lensing, ...

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



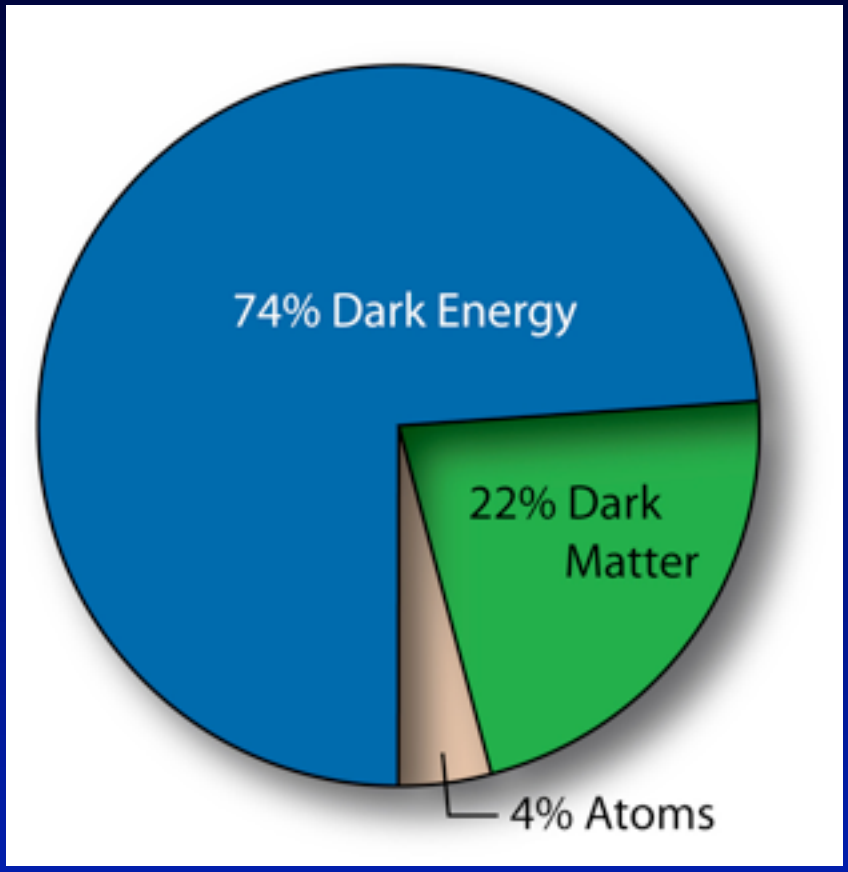
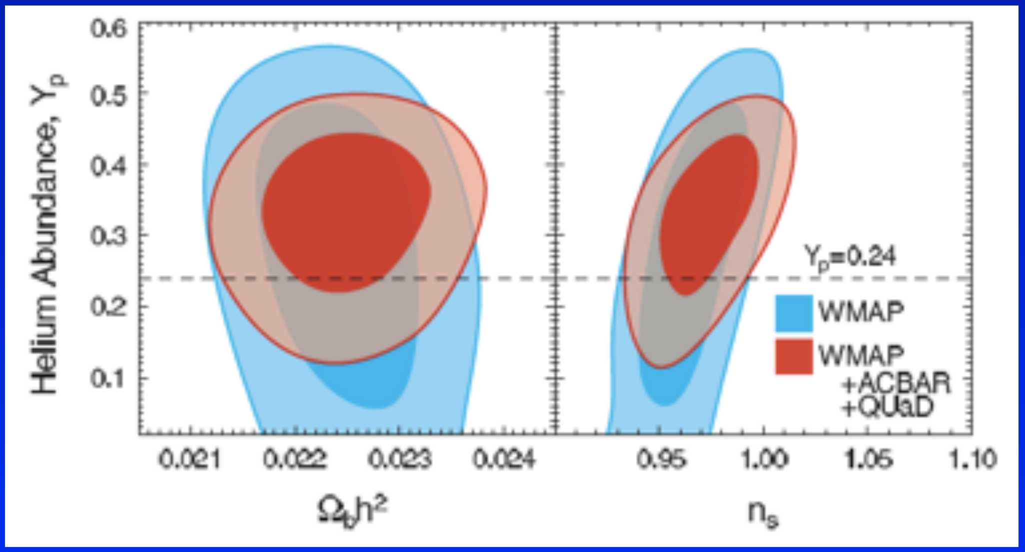


TABLE 1
SUMMARY OF THE COSMOLOGICAL PARAMETERS OF ΛCDM MODEL

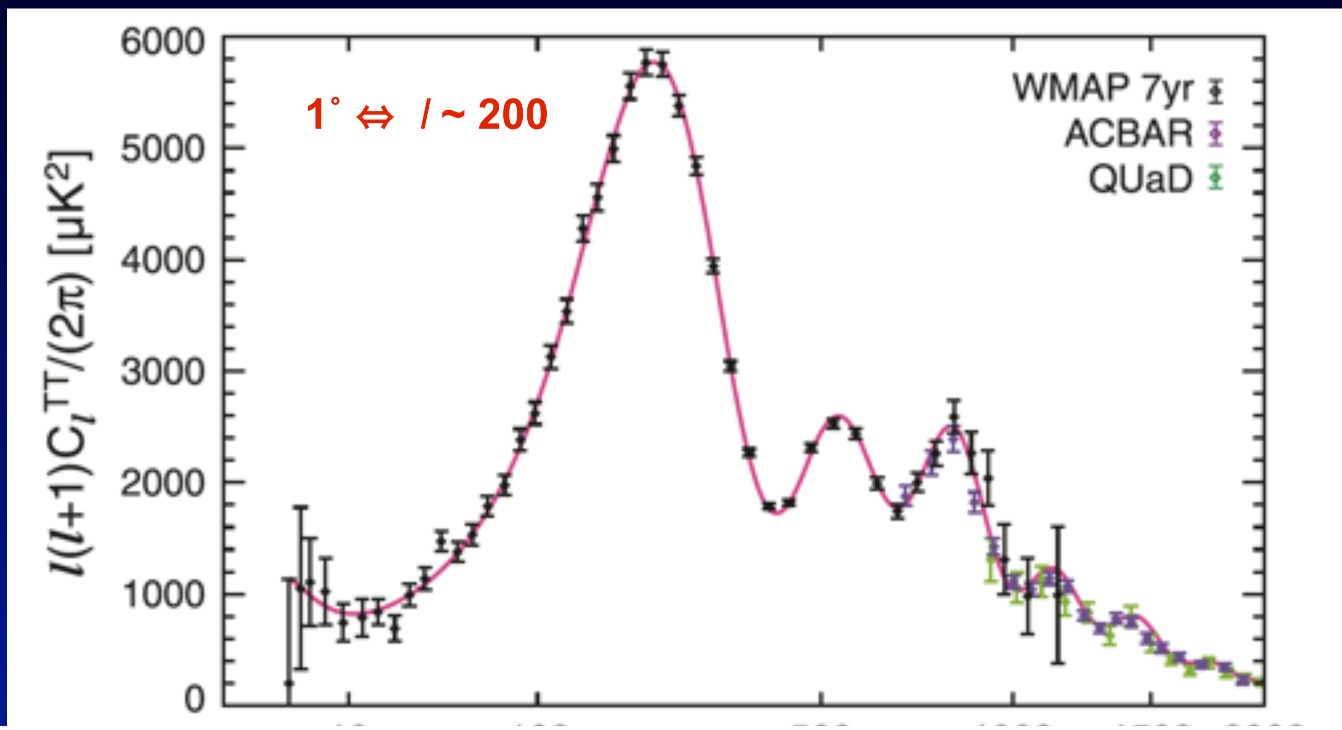
Class	Parameter	*WMAP* 7-year ML[a]	*WMAP*+BAO+H_0 ML	*WMAP* 7-year Mean[b]	*WMAP*+BAO+H_0 Mean
Primary	$100\Omega_b h^2$	2.270	2.246	$2.258^{+0.057}_{-0.056}$	2.260 ± 0.053
	$\Omega_c h^2$	0.1107	0.1120	0.1109 ± 0.0056	0.1123 ± 0.0035
	Ω_Λ	0.738	0.728	0.734 ± 0.029	$0.728^{+0.015}_{-0.016}$
	n_s	0.969	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

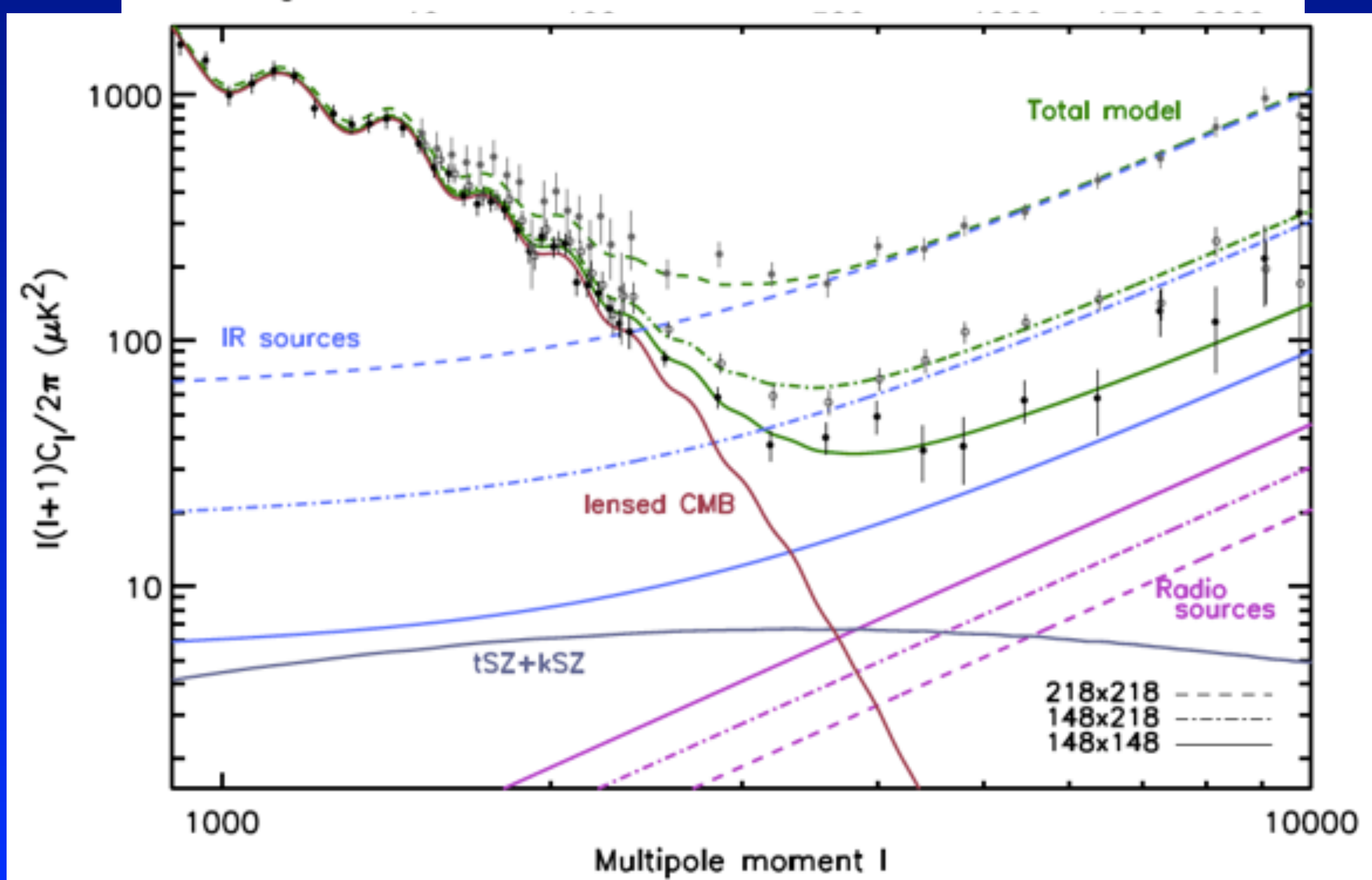
[a] Larson et al. (2010). "ML" refers to the Maximum Likelihood parameters.
[b] Larson et al. (2010). "Mean" refers to the mean of the posterior distribution of each parameter. The quoted errors show the 68% confidence levels (CL).
[c] $\Delta^2_{\mathcal{R}}(k) = k^3 P_{\mathcal{R}}(k)/(2\pi^2)$ and $k_0 = 0.002$ 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.

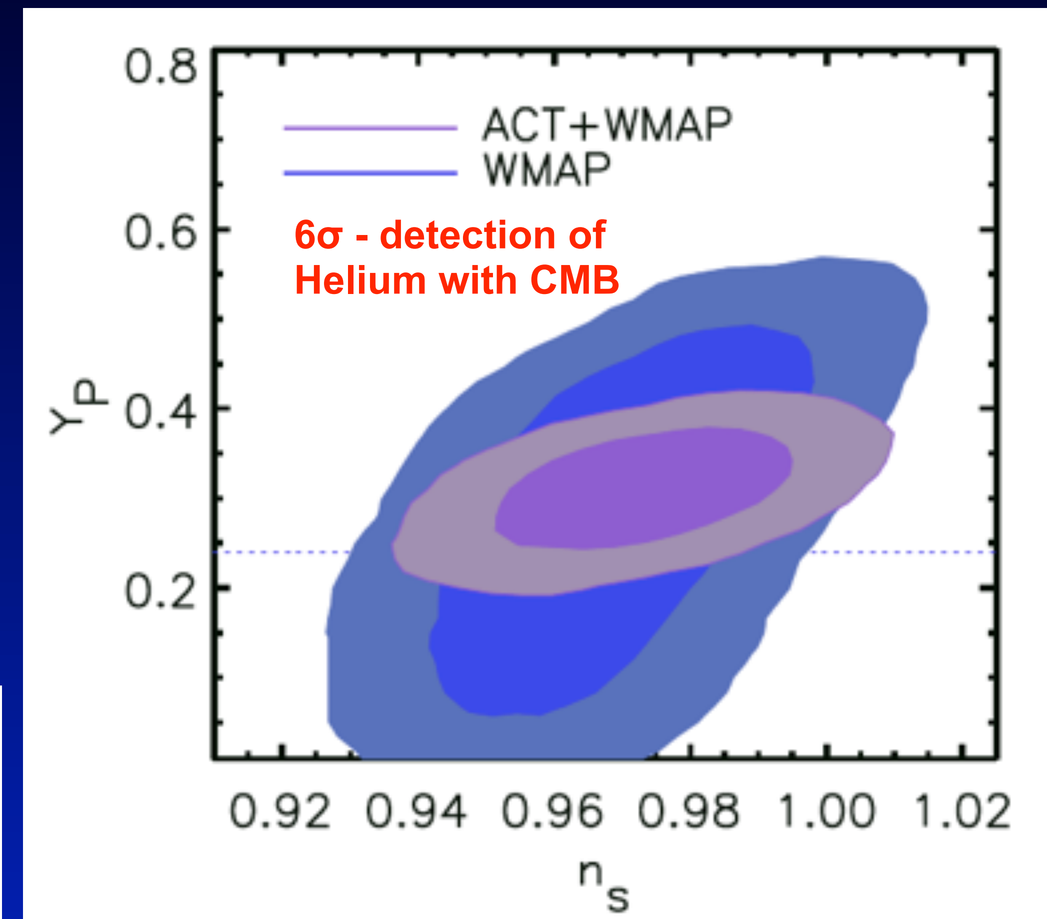


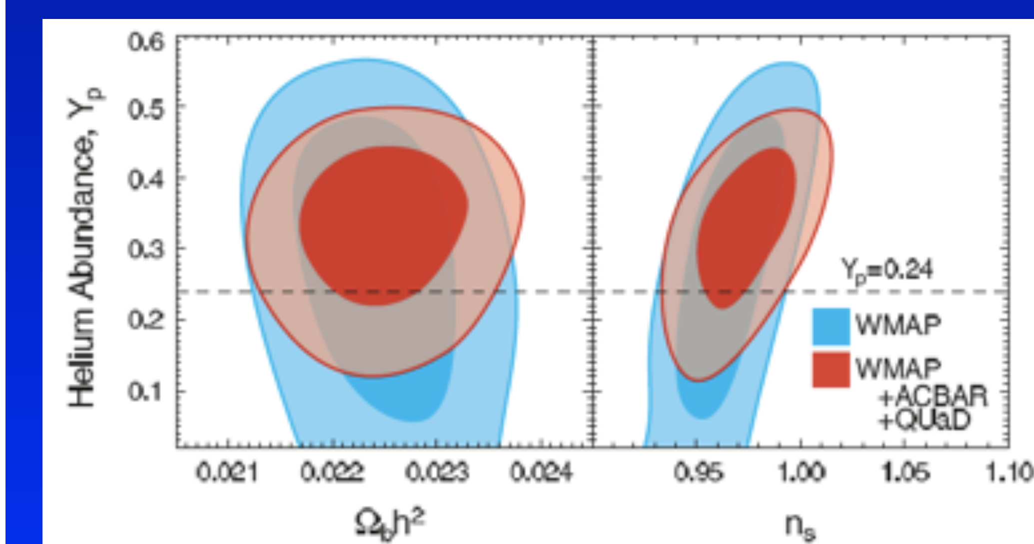
e.g. Komatsu et al., 2010, arXiv:1001.4538v1
Dunkley et al., 2010, arXiv:1009.0866v1
Das et al., 2011, arXiv:1103.2124v1

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









e.g. Komatsu et al., 2010, arXiv:1001.4538v1
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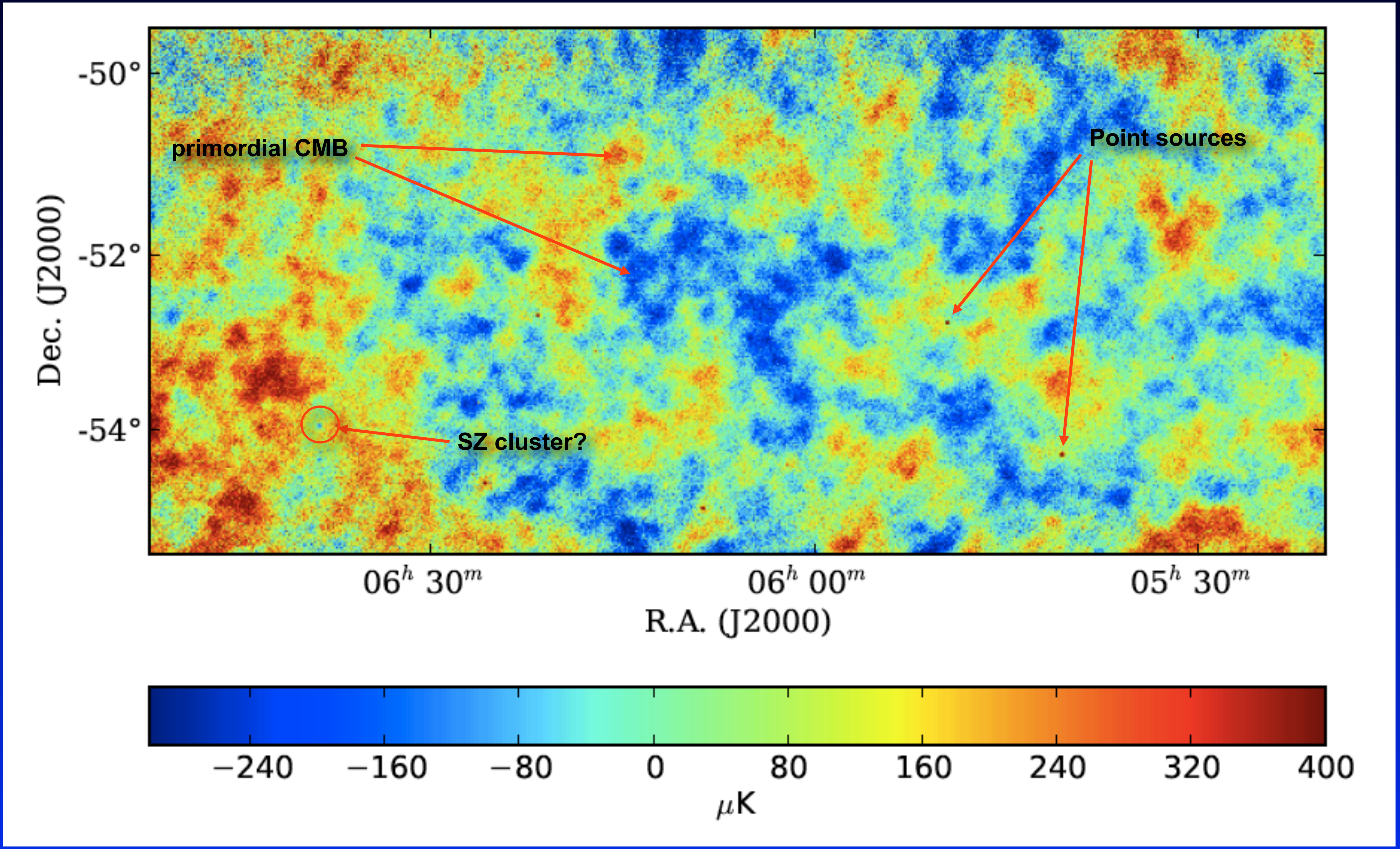
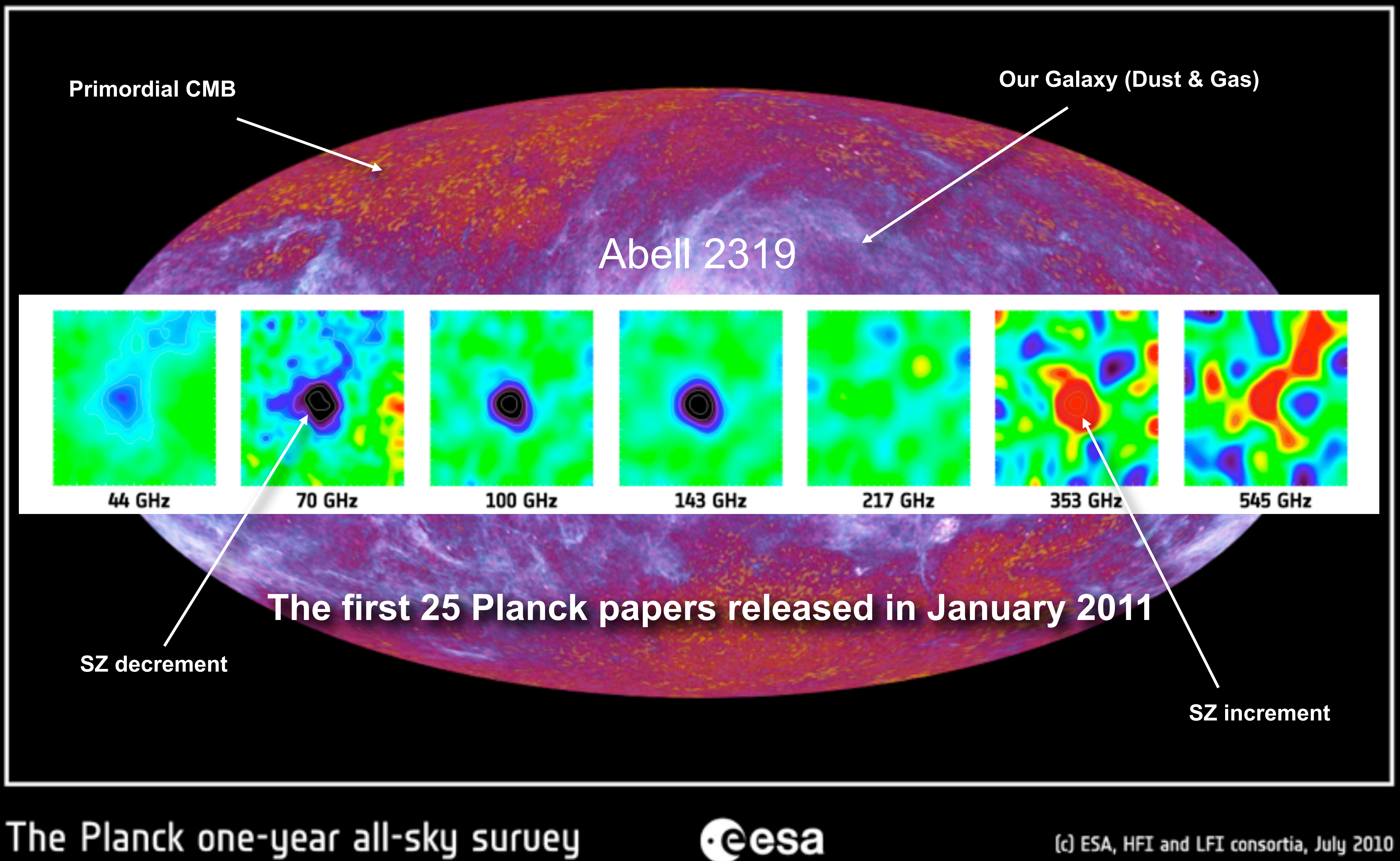
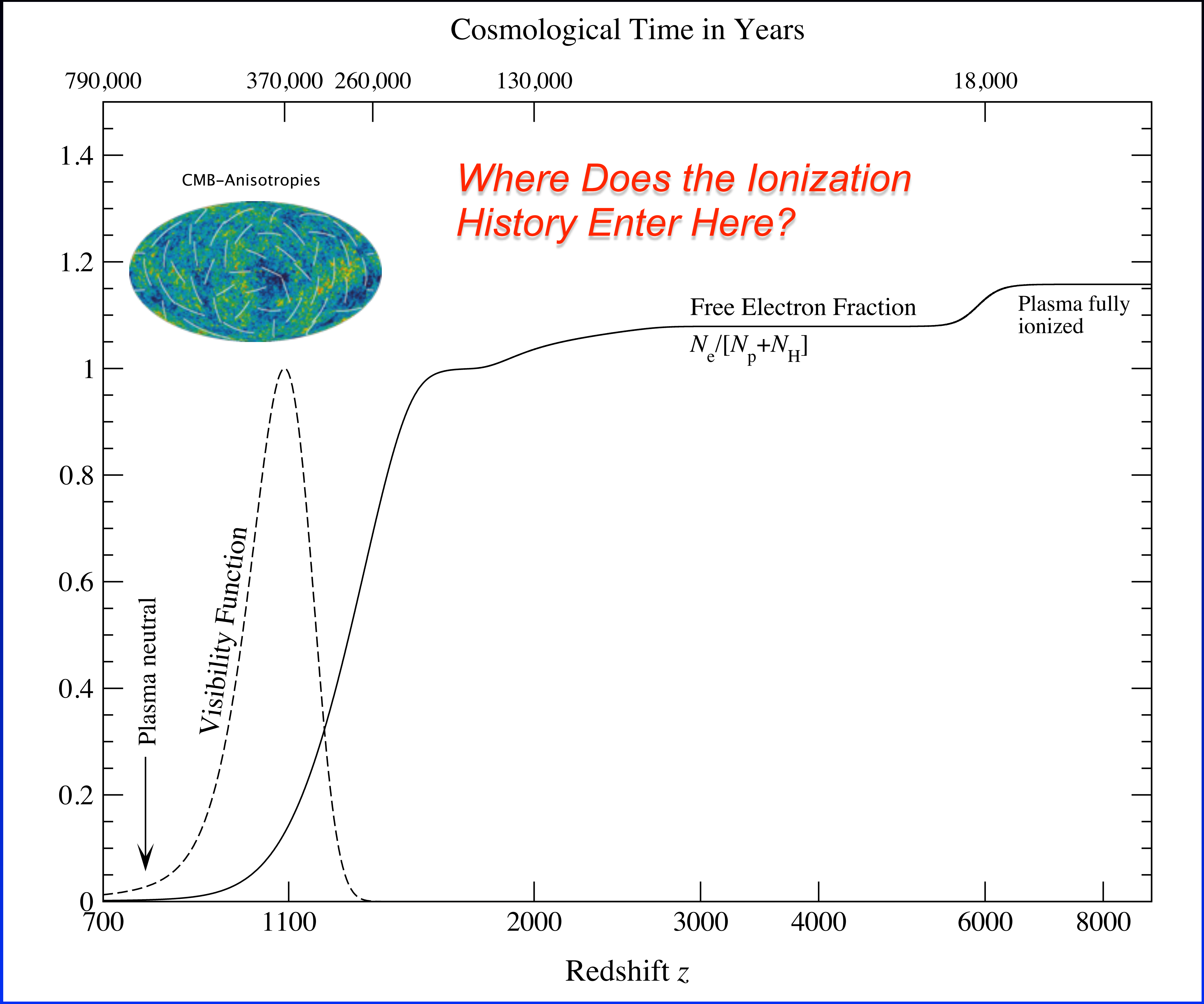
Cosmic Microwave Background Anisotropies from ACT

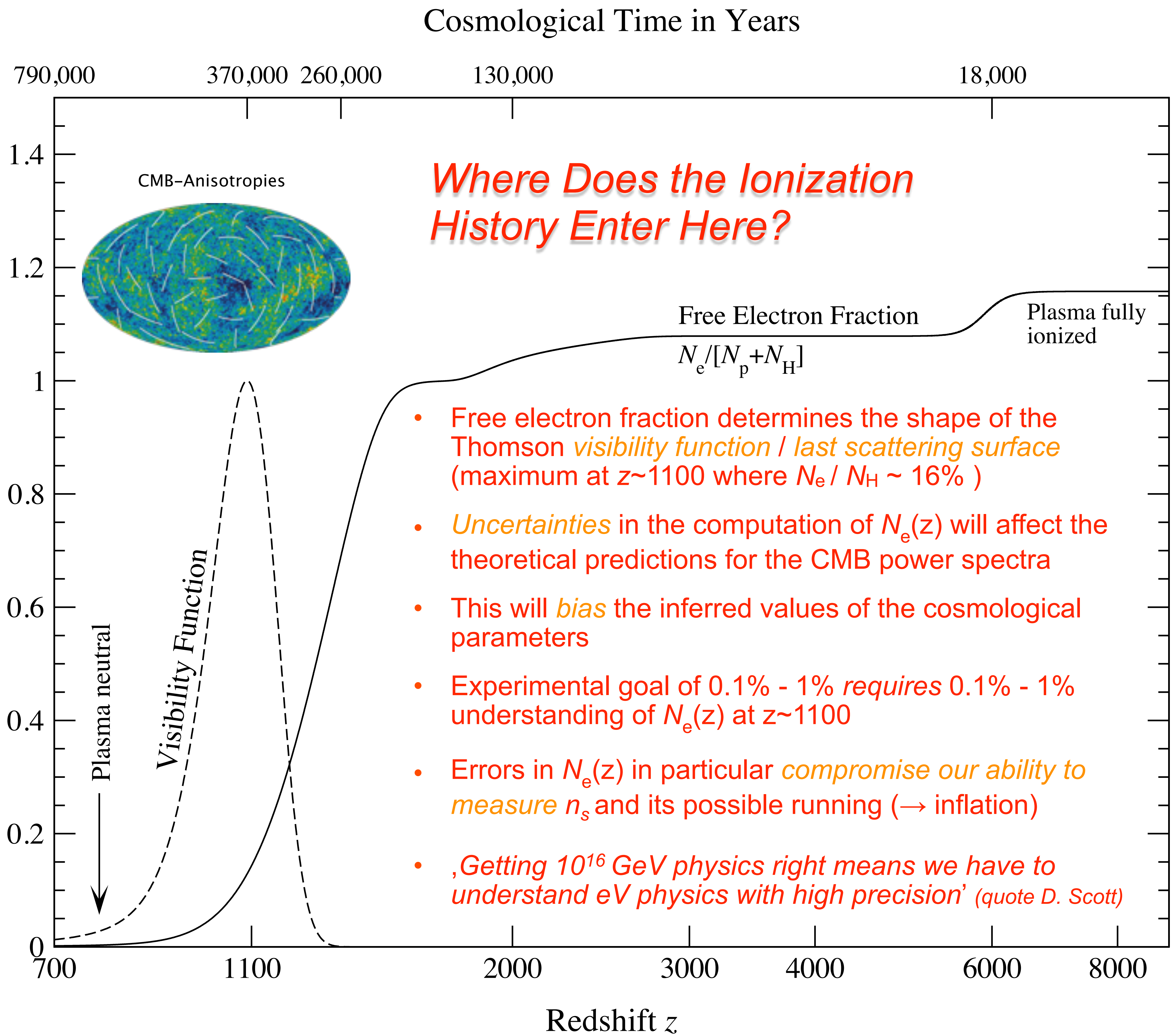


ACT - collaboration, 148 GHz Map, Hajian et al. 2010


Primordial CMB
Our Galaxy (Dust & Gas)
Abell 2319
44 GHz
70 GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
The first 25 Planck papers released in January 2011
SZ decrement
SZ increment
The Planck one-year all-sky survey
esa
(c) ESA, HFI and LFI consortia, July 2010


Cosmological Time in Years
790,000
370,000
260,000
130,000
18,000
Where Does the Ionization History Enter Here?
CMB-Anisotropies
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully ionized
Visibility Function
Plasma neutral
1.4
1.2
1
0.8
0.6
0.4
0.2
0
700
1100
2000
3000
4000
6000
8000
Redshift z

Where Does the Ionization History Enter Here?



- Free electron fraction determines the shape of the Thomson *visibility function* / *last scattering surface* (maximum at $z \sim 1100$ 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~1100
- 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)

How does cosmological recombination work?

Physical Conditions during Recombination

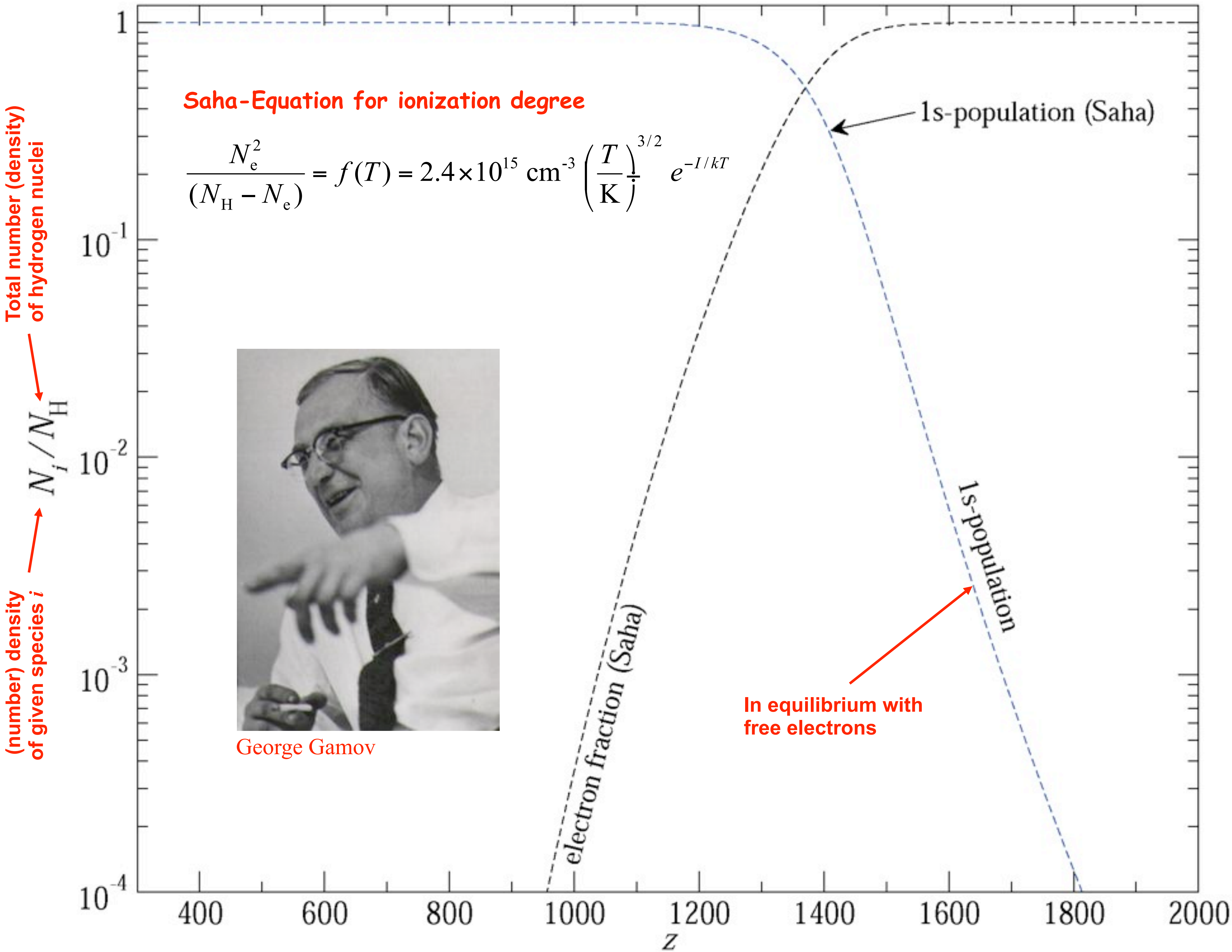
- Temperature $T_\gamma \sim 2.725\,(1+z)$ K ~ 3000 K
- Baryon number density $N_b \sim 2.5\text{x}10^{-7}\text{cm}^{-3}\,(1+z)^3 \sim 330\ \text{cm}^{-3}$
- Photon number density $N_\gamma \sim 410\ \text{cm}^{-3}\,(1+z)^3 \sim 2\times10^9\,N_b$

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

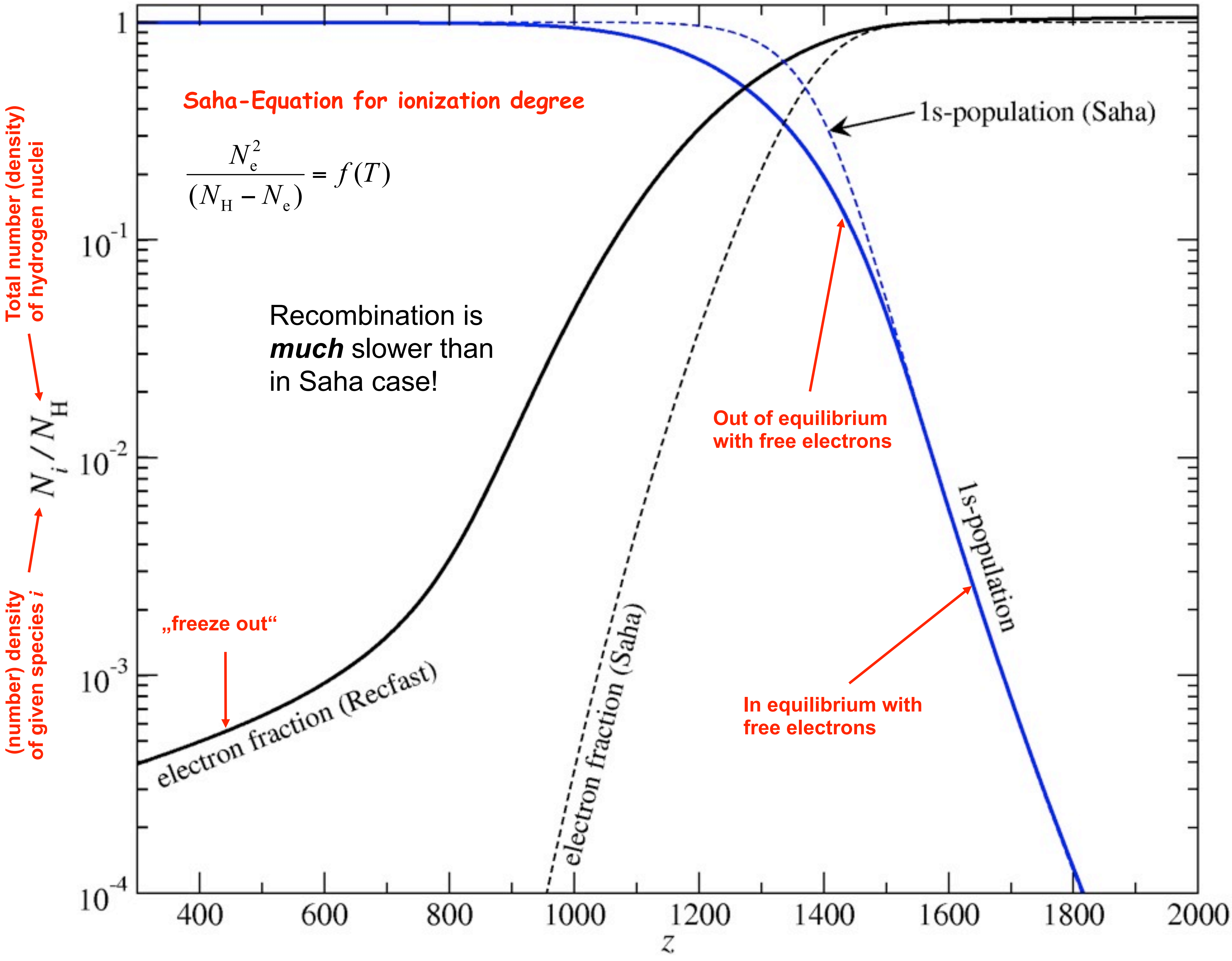
  (e.g. stimulated emission & stimulated recombination)
- Compton interaction couples electrons very tightly to photons until $z \sim 200 \Rightarrow T_\gamma \sim T_e \sim T_m$

Saha-Equation for ionization degree

$$\frac{N_e^2}{(N_H - N_e)} = f(T) = 2.4\times10^{15}\ \mathrm{cm}^{-3}\left(\frac{T}{\mathrm{K}}\right)^{3/2} e^{-I/kT}$$



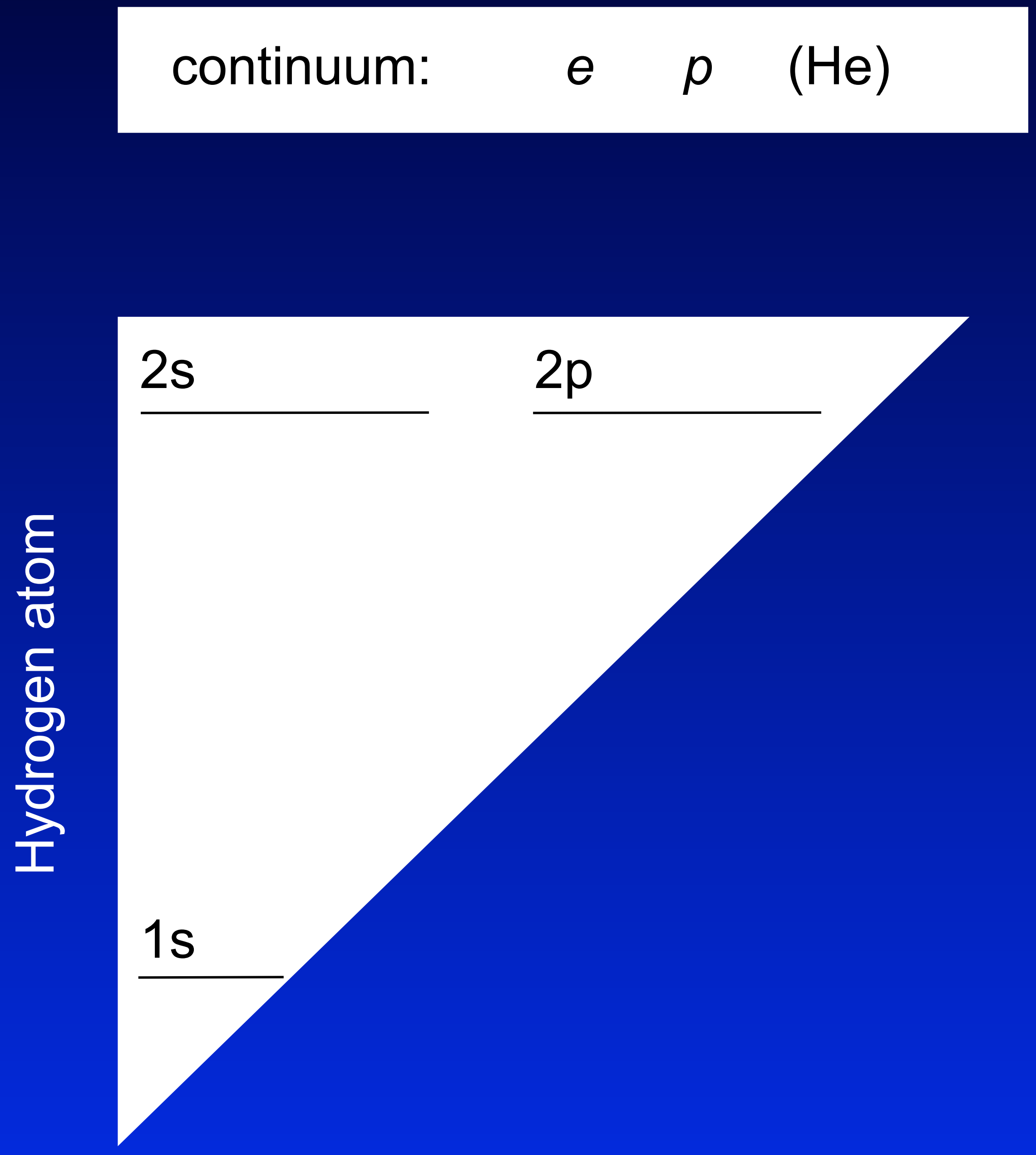
George Gamov



Saha-Equation for ionization degree
$$\frac{N_e^2}{(N_H - N_e)} = f(T)$$
Recombination is
much slower than
in Saha case!
1s-population (Saha)
Out of equilibrium
with free electrons
1s-population
In equilibrium with
free electrons
„freeze out“
electron fraction (Recfast)
electron fraction (Saha)
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

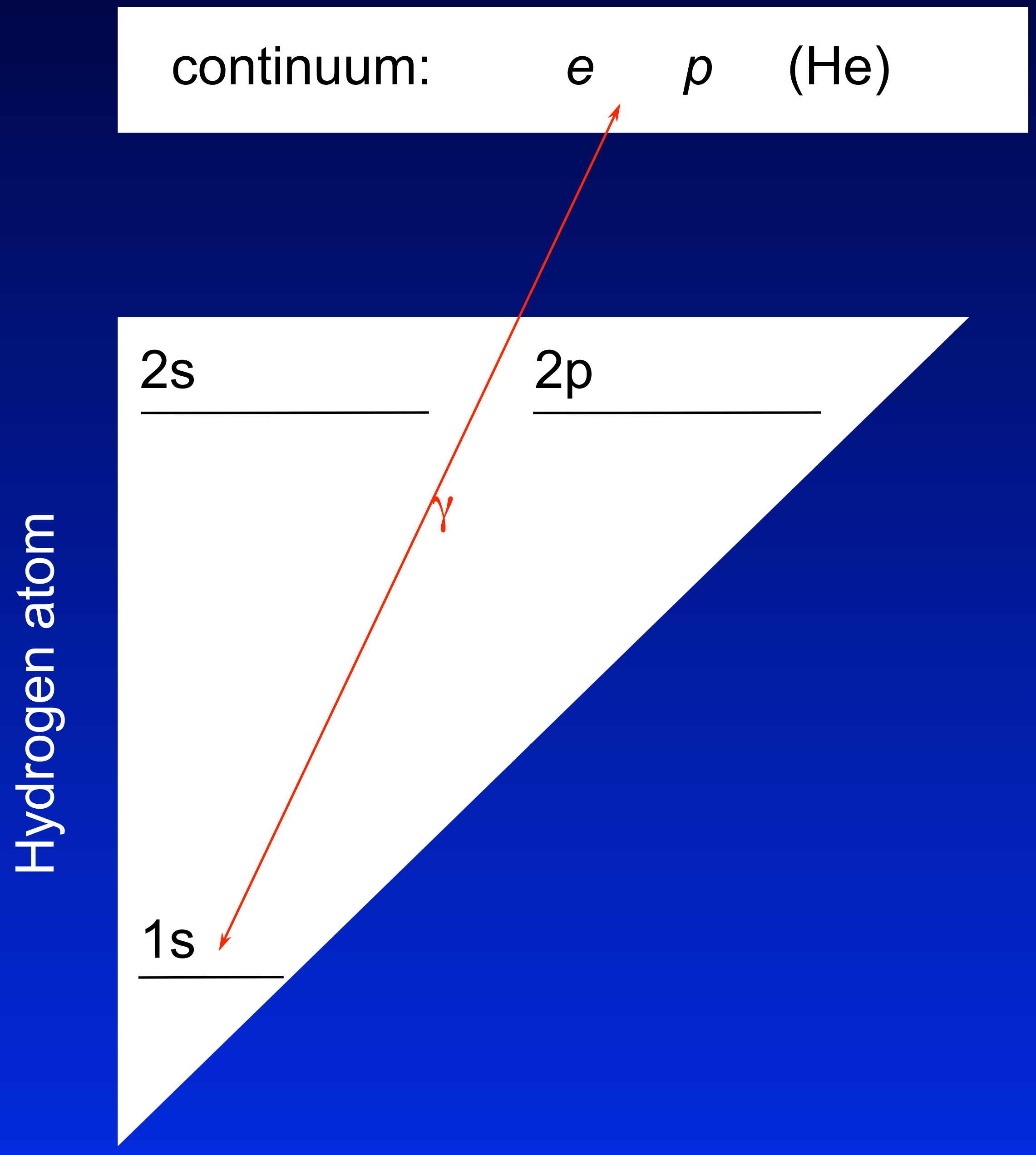
3-level Hydrogen Atom and Continuum

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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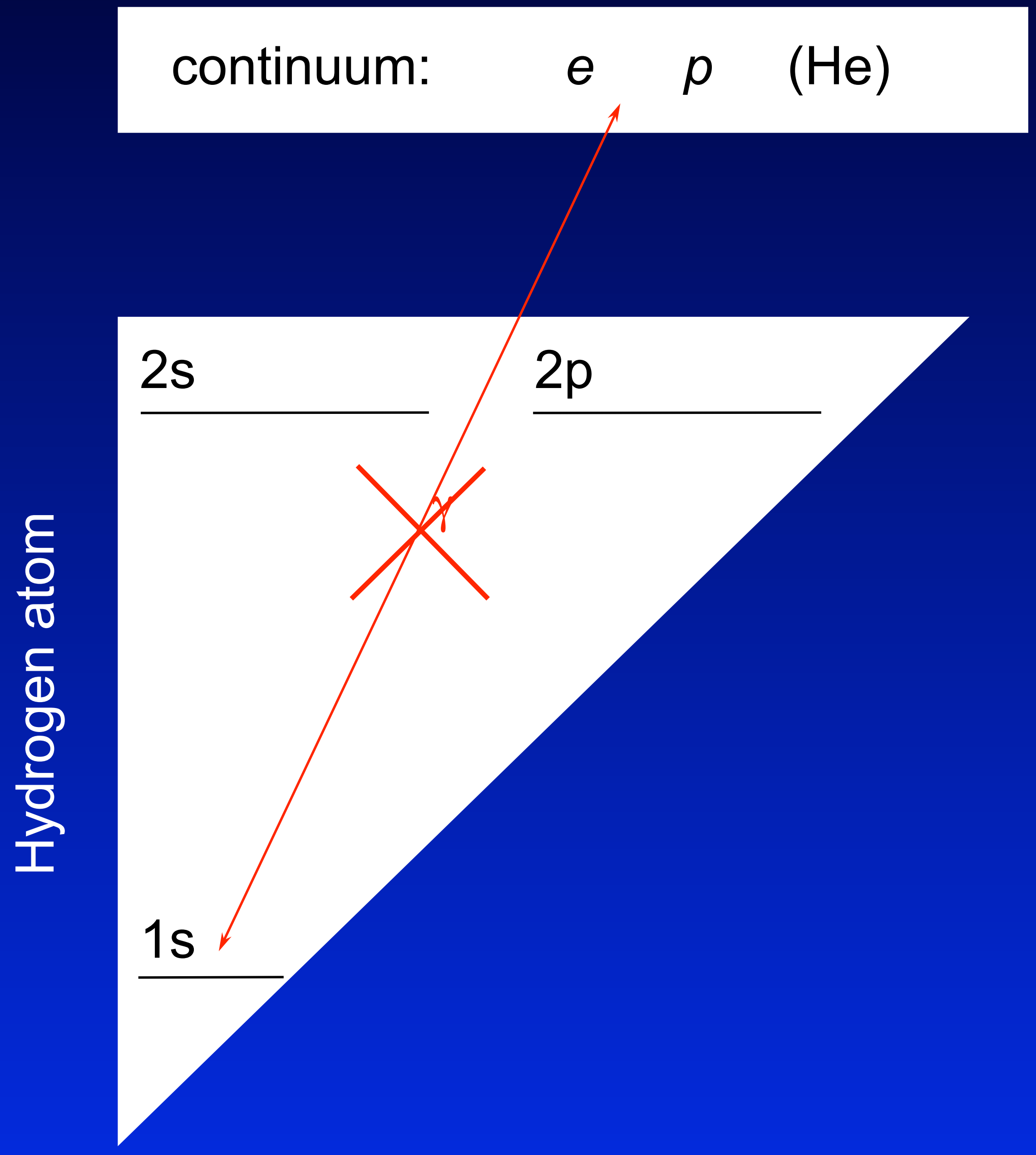

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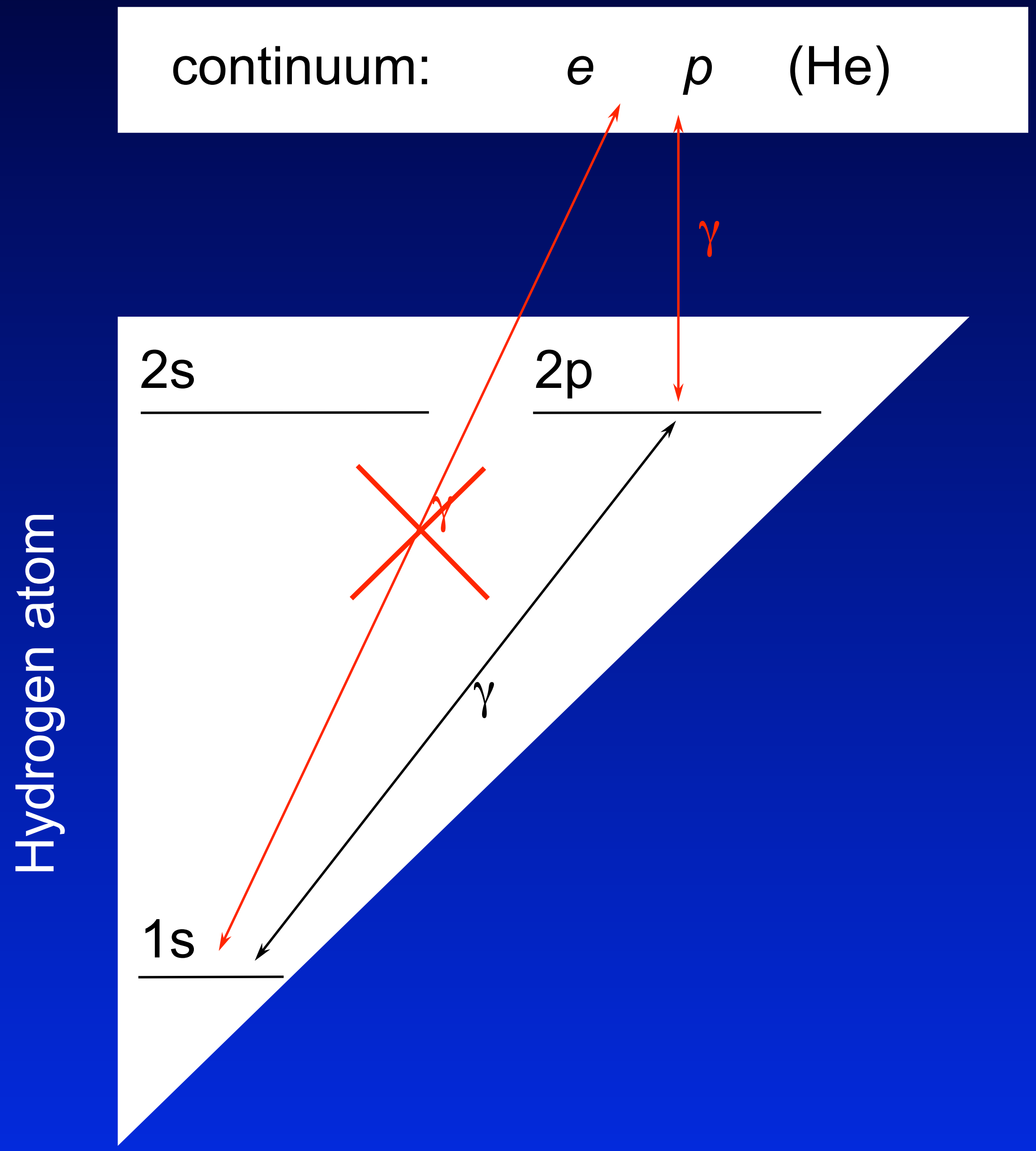

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- **direct recombination to 1s**
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  } **No**

- **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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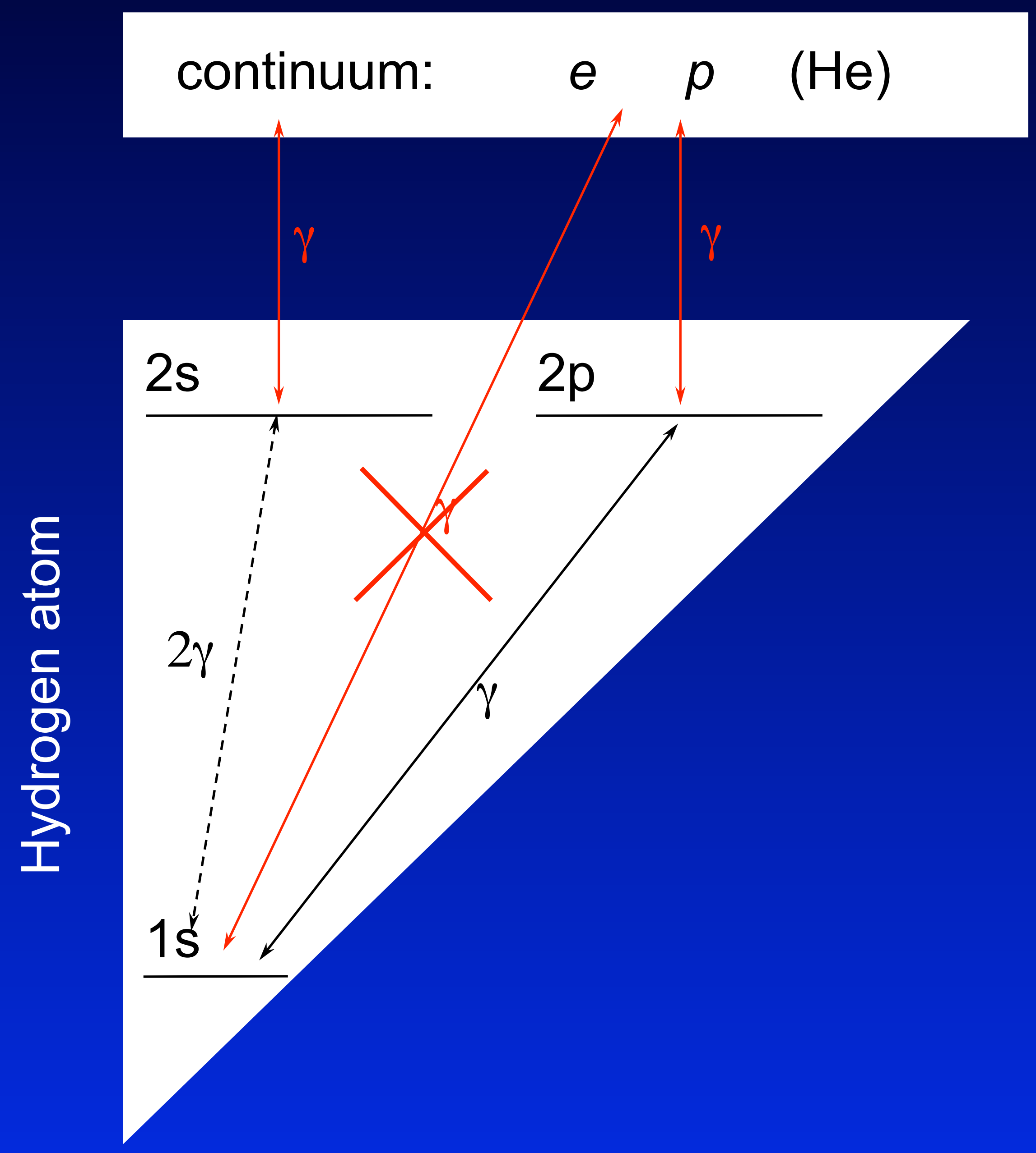
3-level Hydrogen Atom and Continuum



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- **recombination to 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
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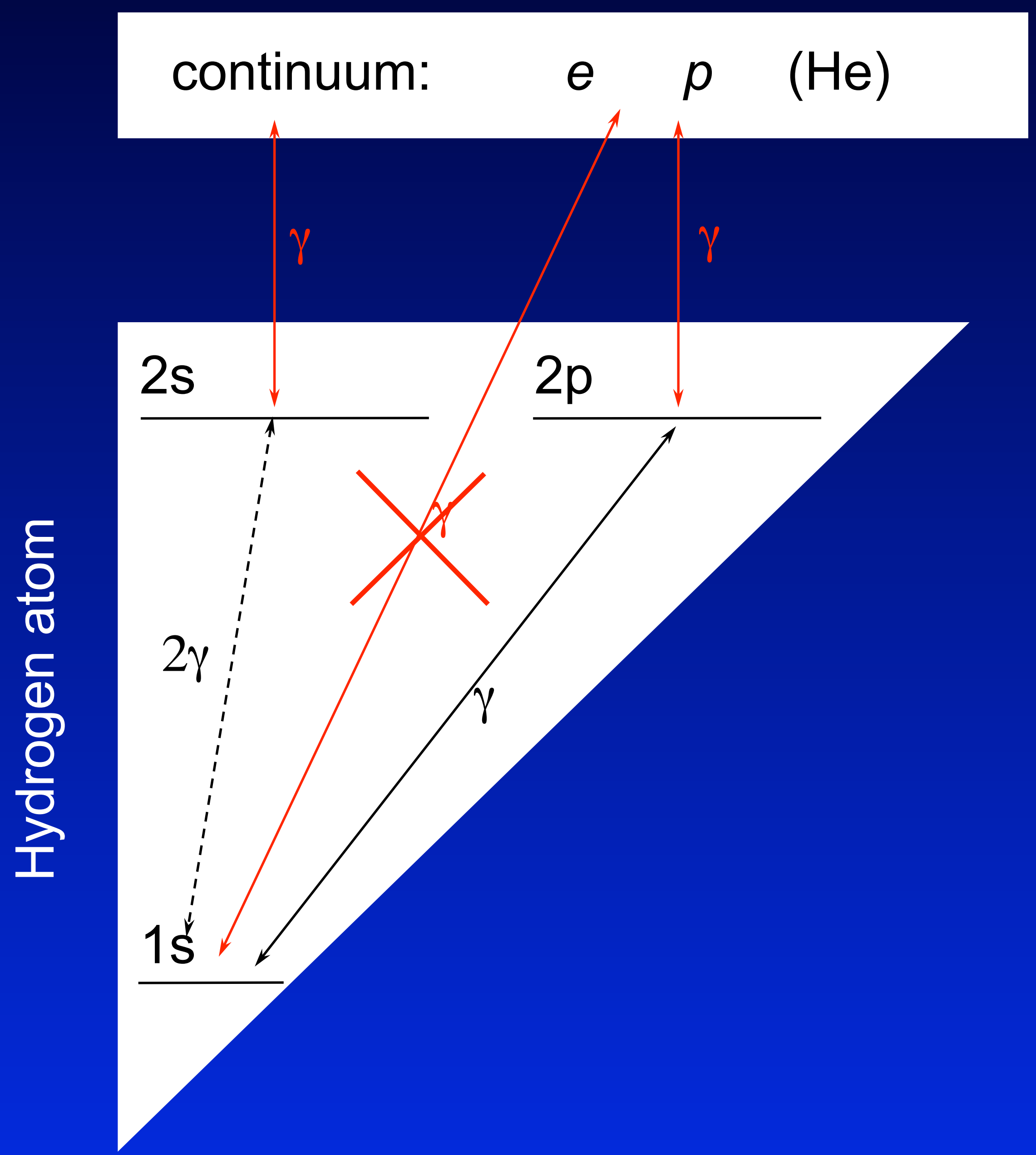
3-level Hydrogen Atom and Continuum



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 ($p \sim 10^{-9}$ @ $z \sim 1100$)**
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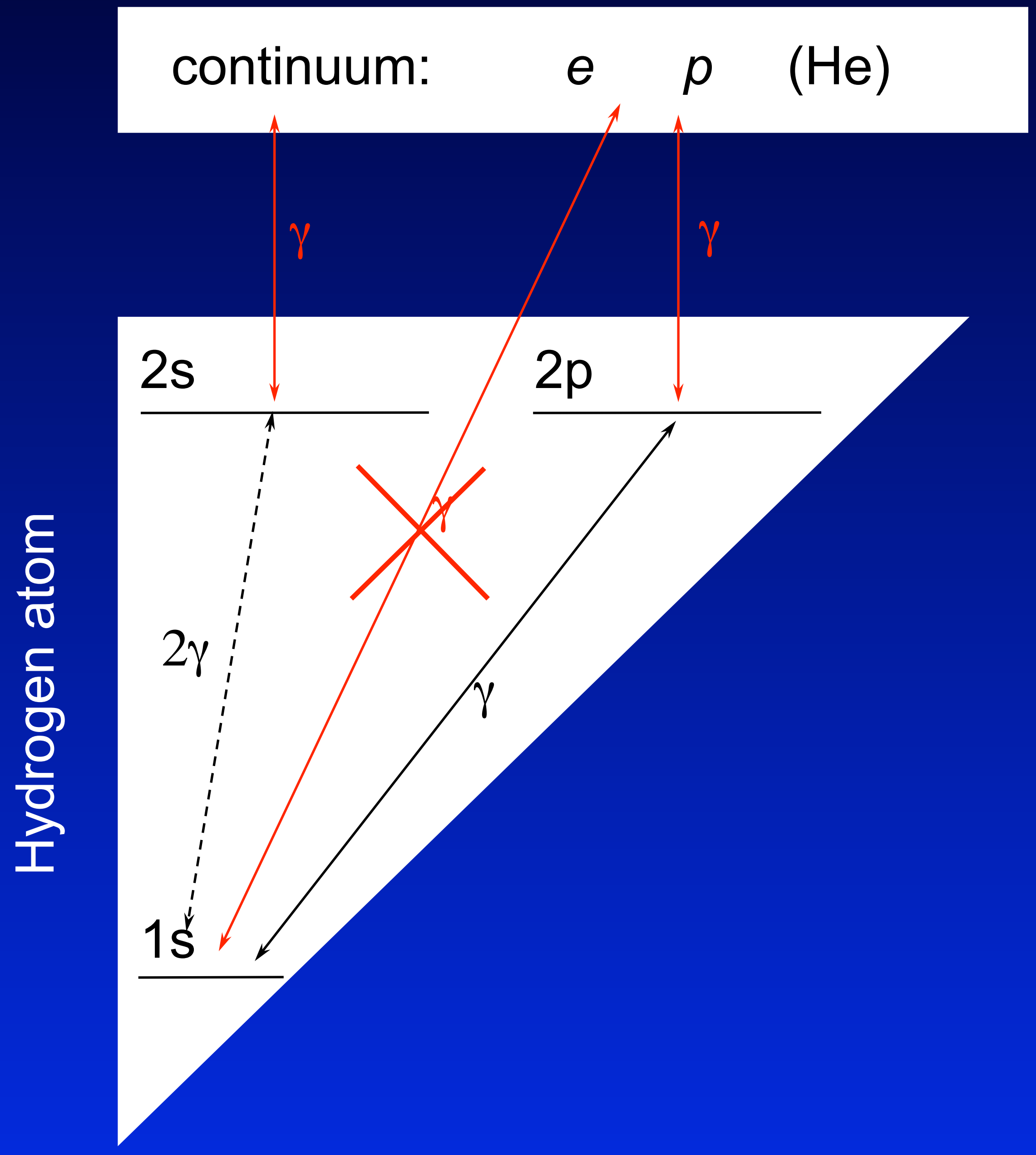

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  ~ 57%

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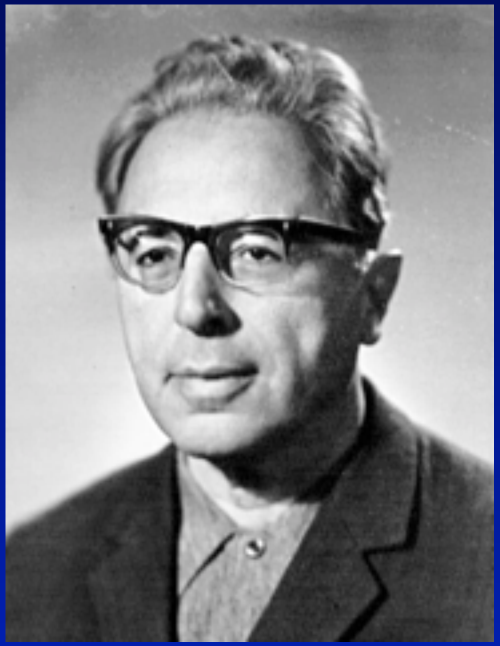
Peebles, 1968, ApJ, 153, 1

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

These first computations were completed in 1968!

Moscow

Yakov Zeldovich

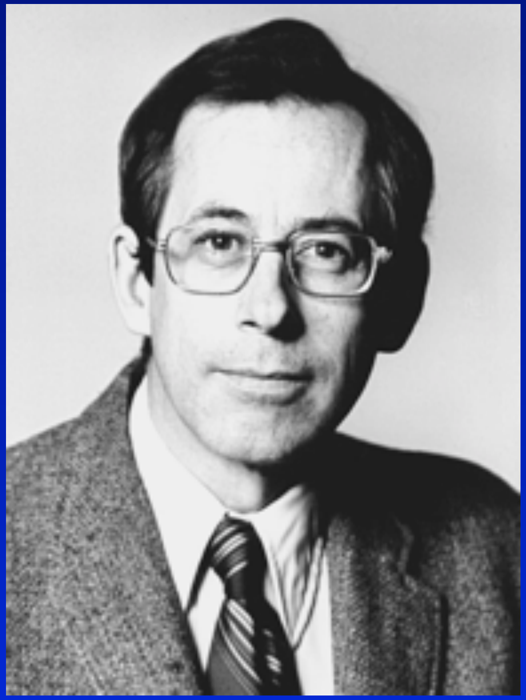


Iosif Shklovskii

Vladimir Kurt
(UV astronomer)

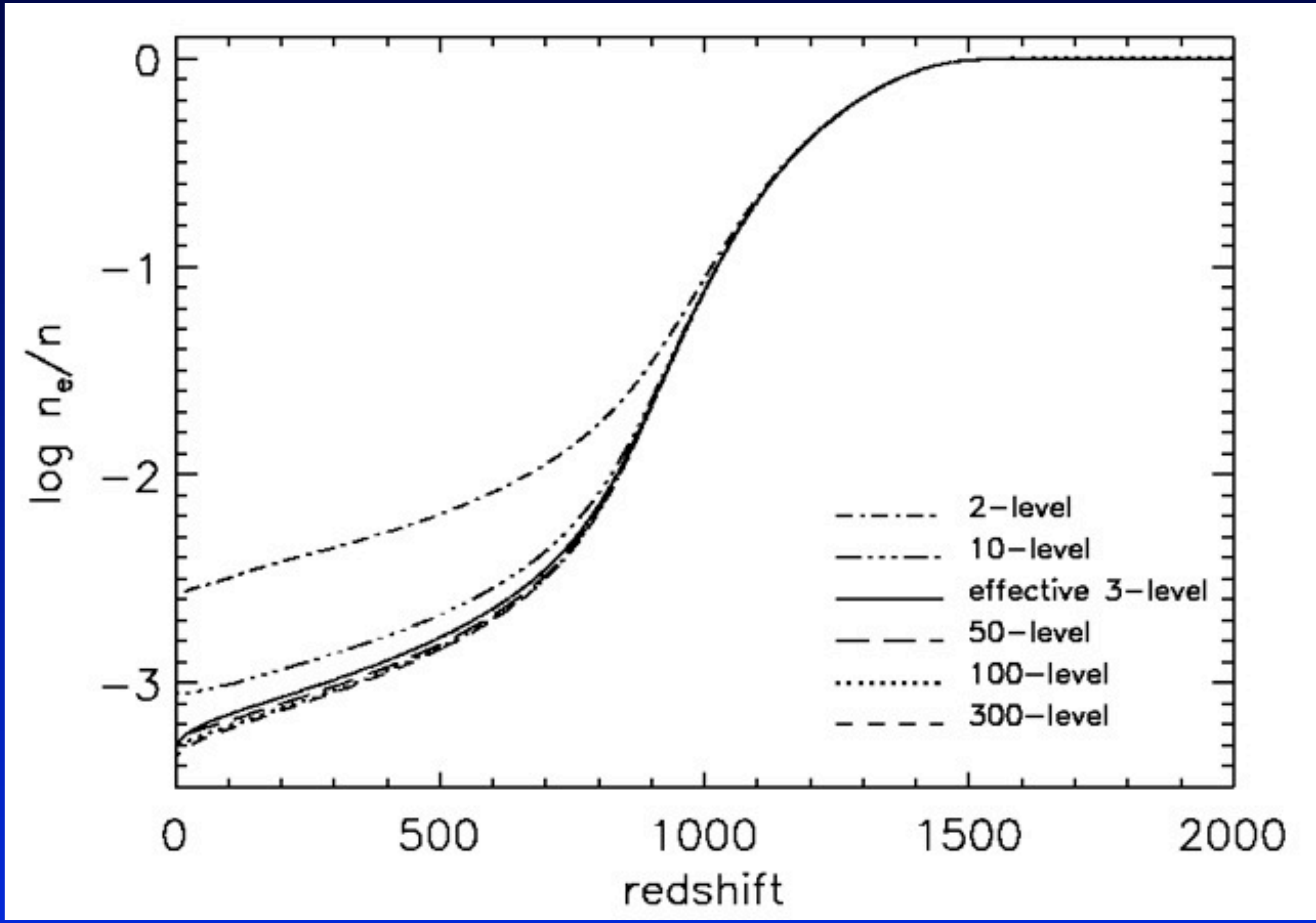
Rashid Sunyaev

Princeton



Jim Peebles

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

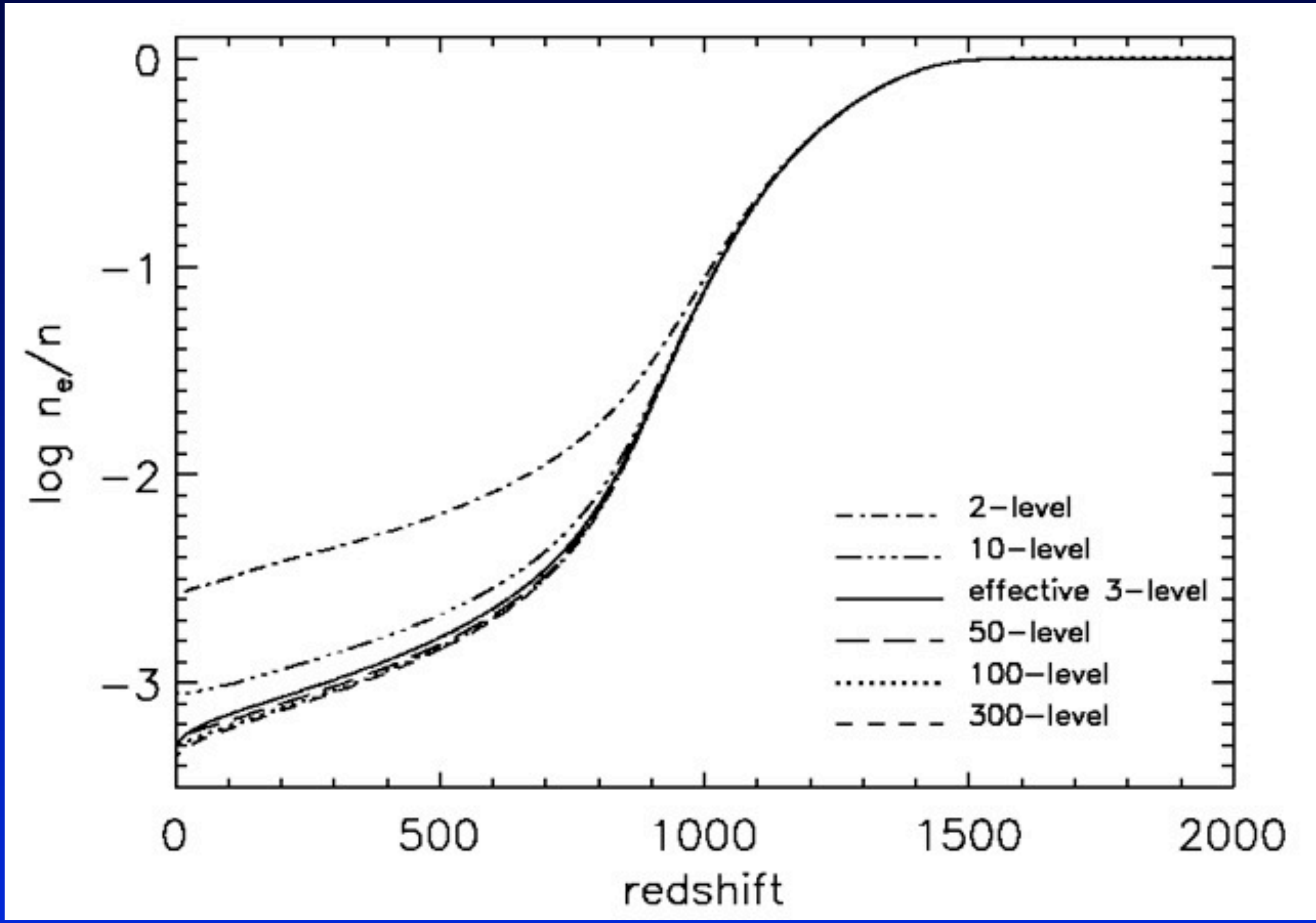
Helium:

- HeI 200-levels ($z \sim$ 1400-1500)
- HeII 100-levels ($z \sim$ 6000-6500)
- HeIII 1 equation

Low Redshifts:

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

Multi-level Atom ⇒ The Recfast-Code



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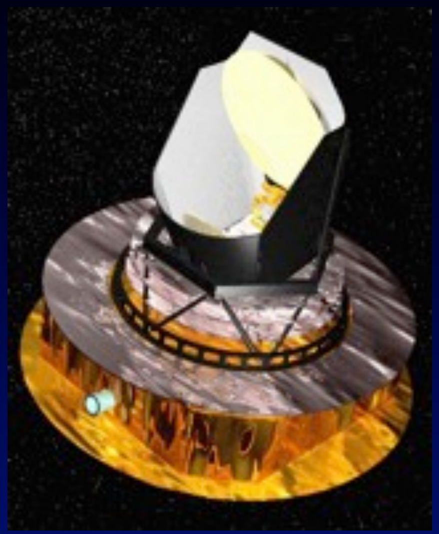
Low Redshifts:

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

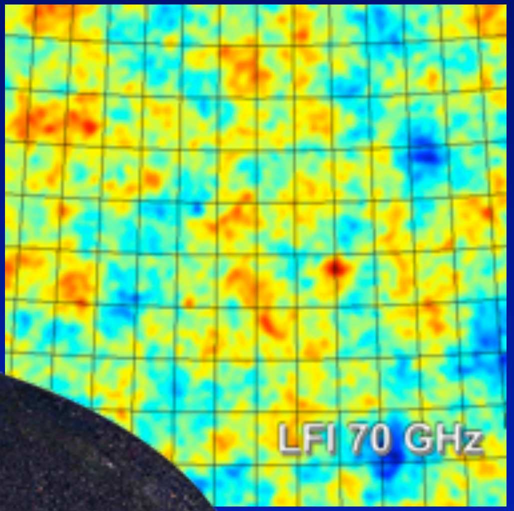
$\Delta N_e \, / \, N_e \sim 1\% - 3\%$

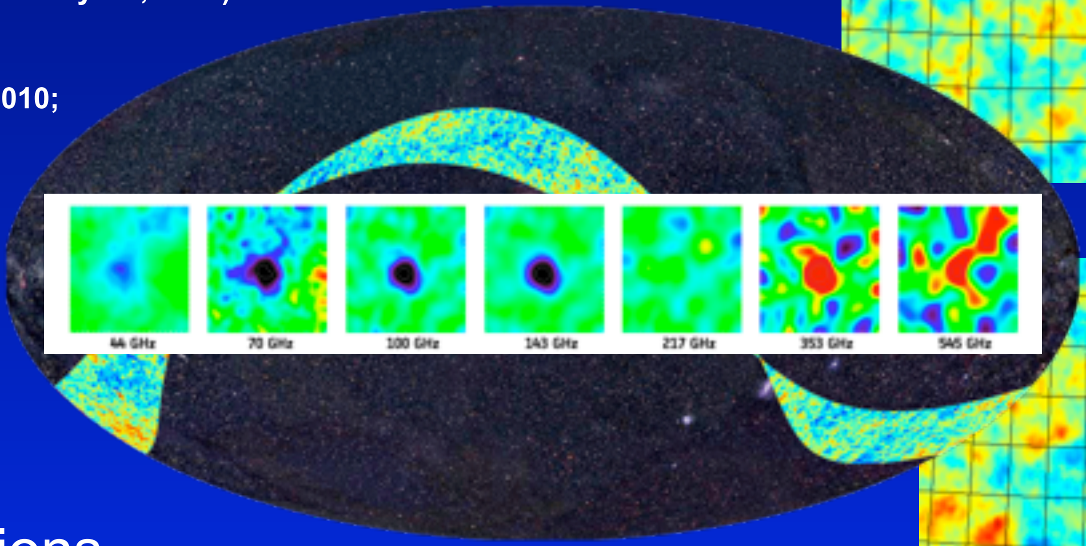
Getting Ready for Planck



Hydrogen recombination

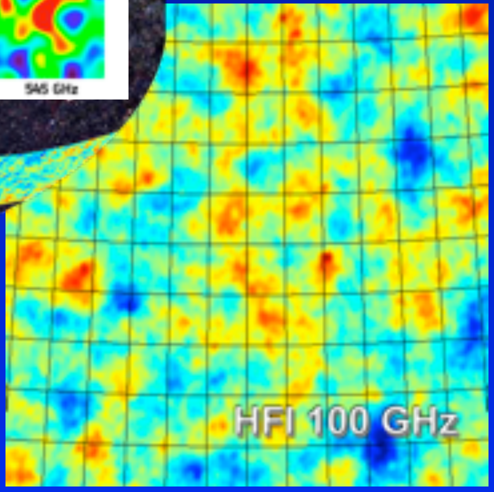
- Two-photon decays from higher levels
  (Dubrovich & Grachev, 2005, Astr. Lett., 31, 359; Wong & Scott, 2007; JC & Sunyaev, 2007; Hirata, 2008; JC & Sunyaev 2009)
- Induced 2s two-photon decay for hydrogen
  (JC & Sunyaev, 2006, A&A, 446, 39; Hirata 2008)
- Feedback of the Lyman-α distortion on the 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)





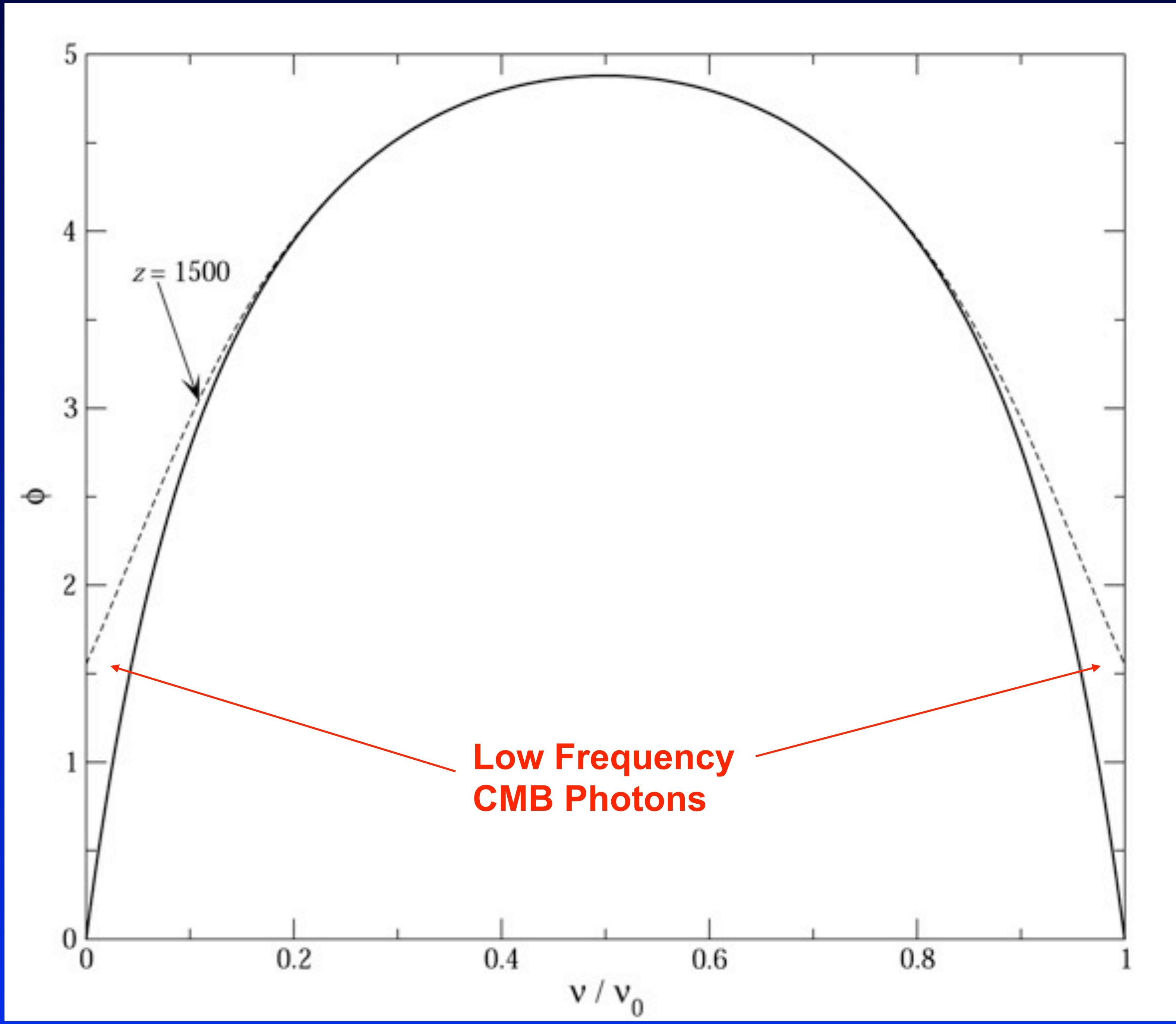
Helium recombination

- Similar list of processes as for hydrogen
  (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)



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

Stimulated 2s →1s decay



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 slightly faster

JC & Sunyaev, 2006, A&A

Main corrections during HeI Recombination

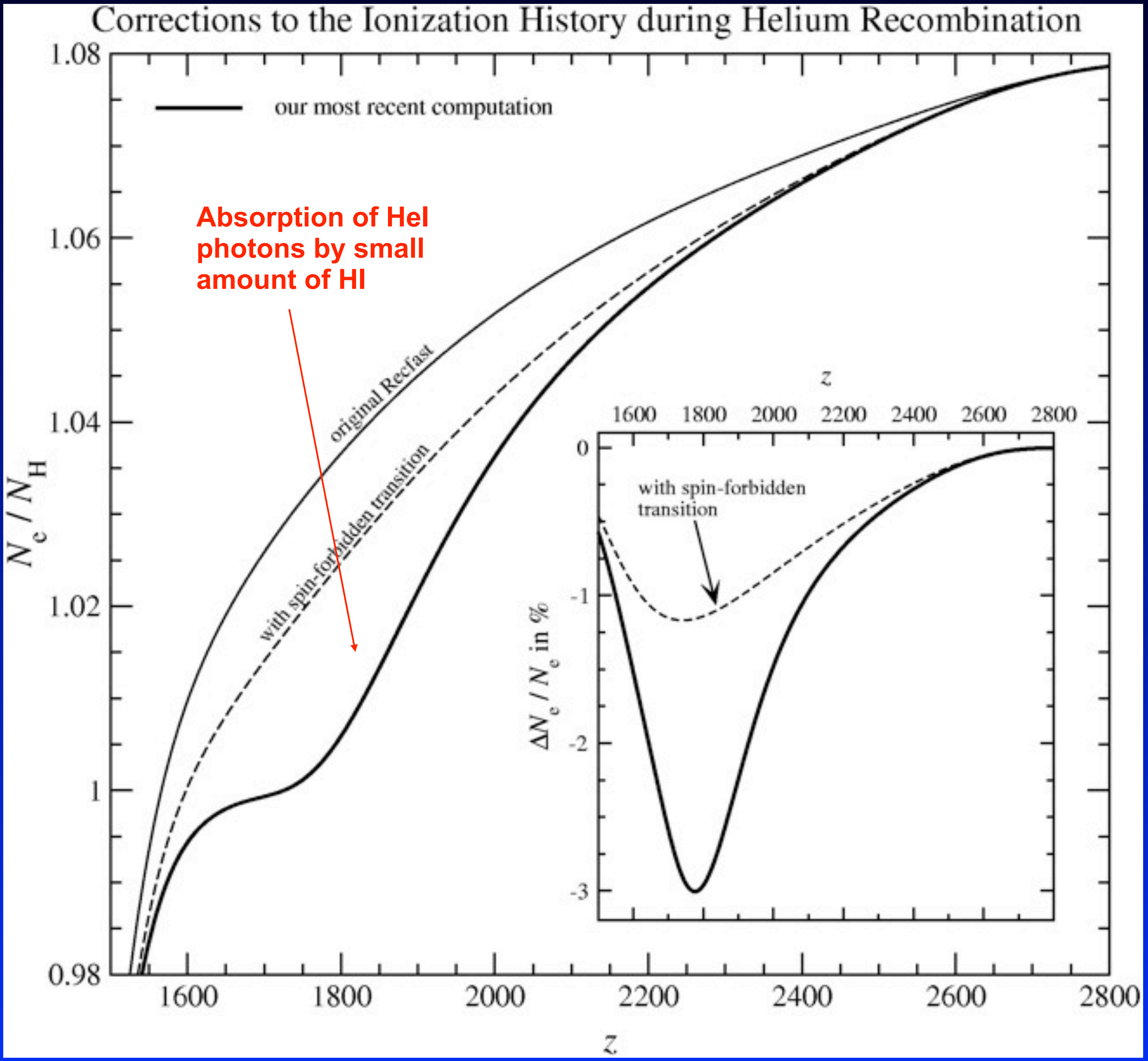
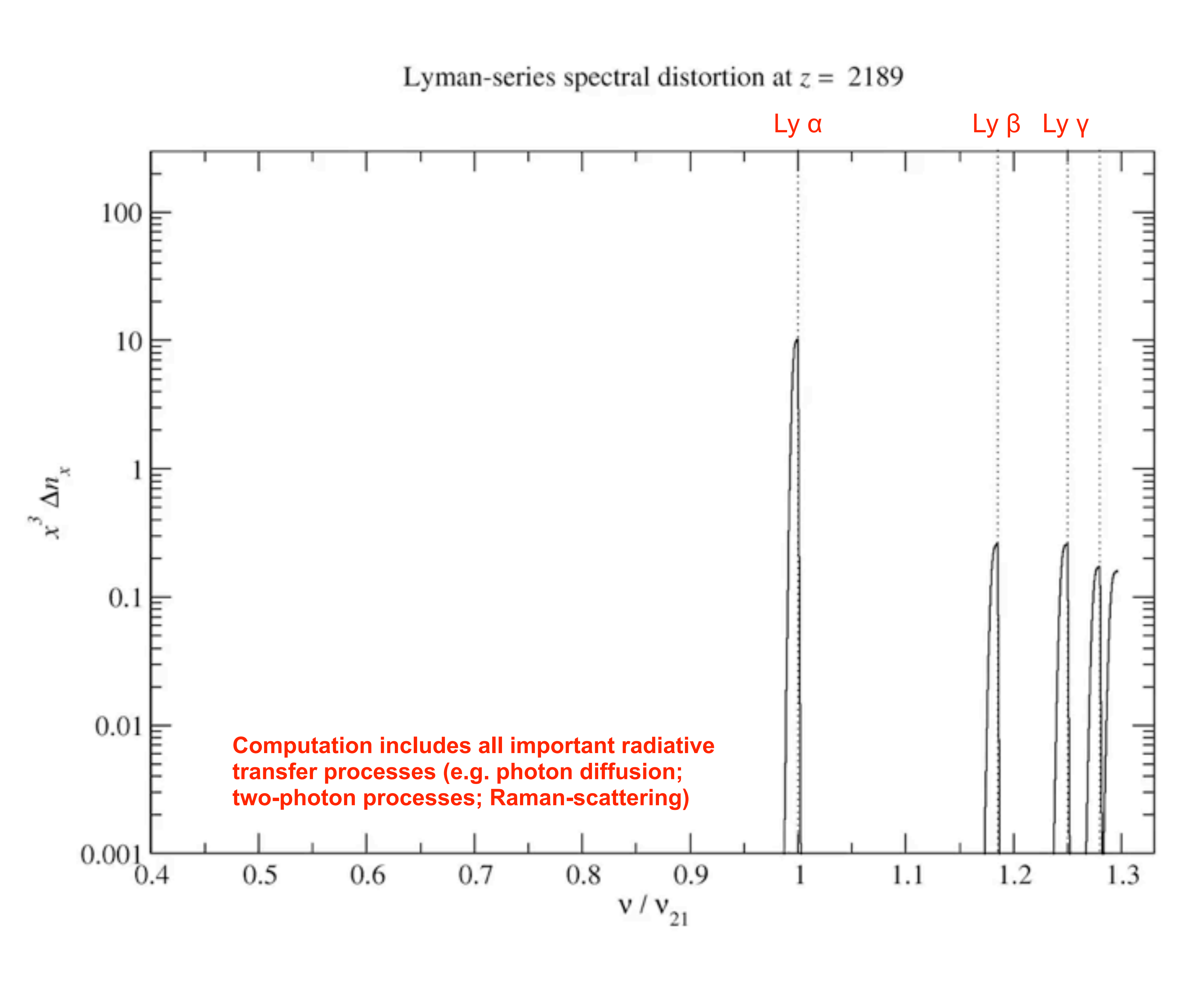


Figure from Fendt, JC, Rubino-Martin, Wandelt, ApJS, 2009

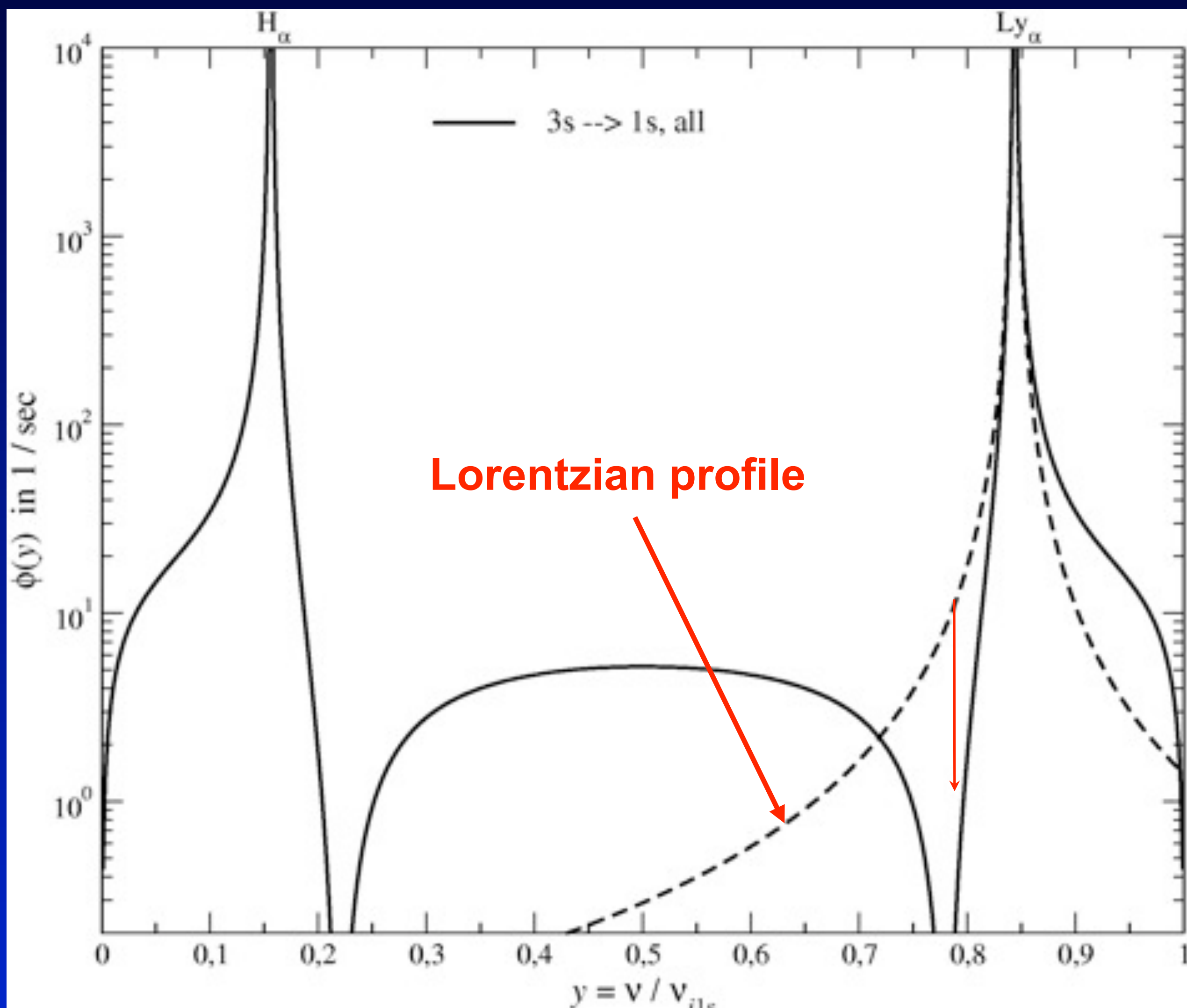
Evolution of the HI Lyman-series distortion

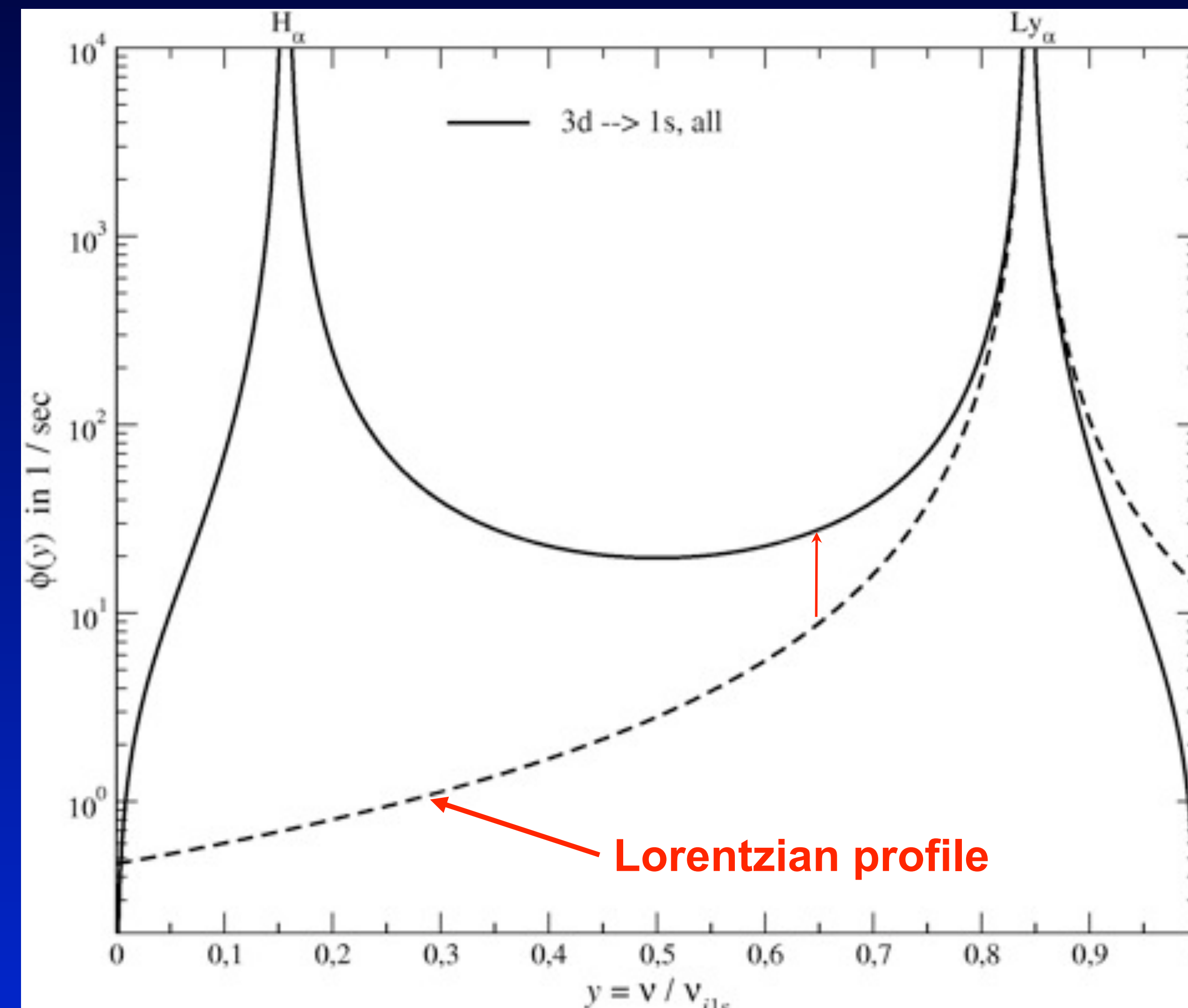


CITA ICAT

JC & Thomas, MNRAS, 2010

Example: 3s and 3d two-photon decay spectrum





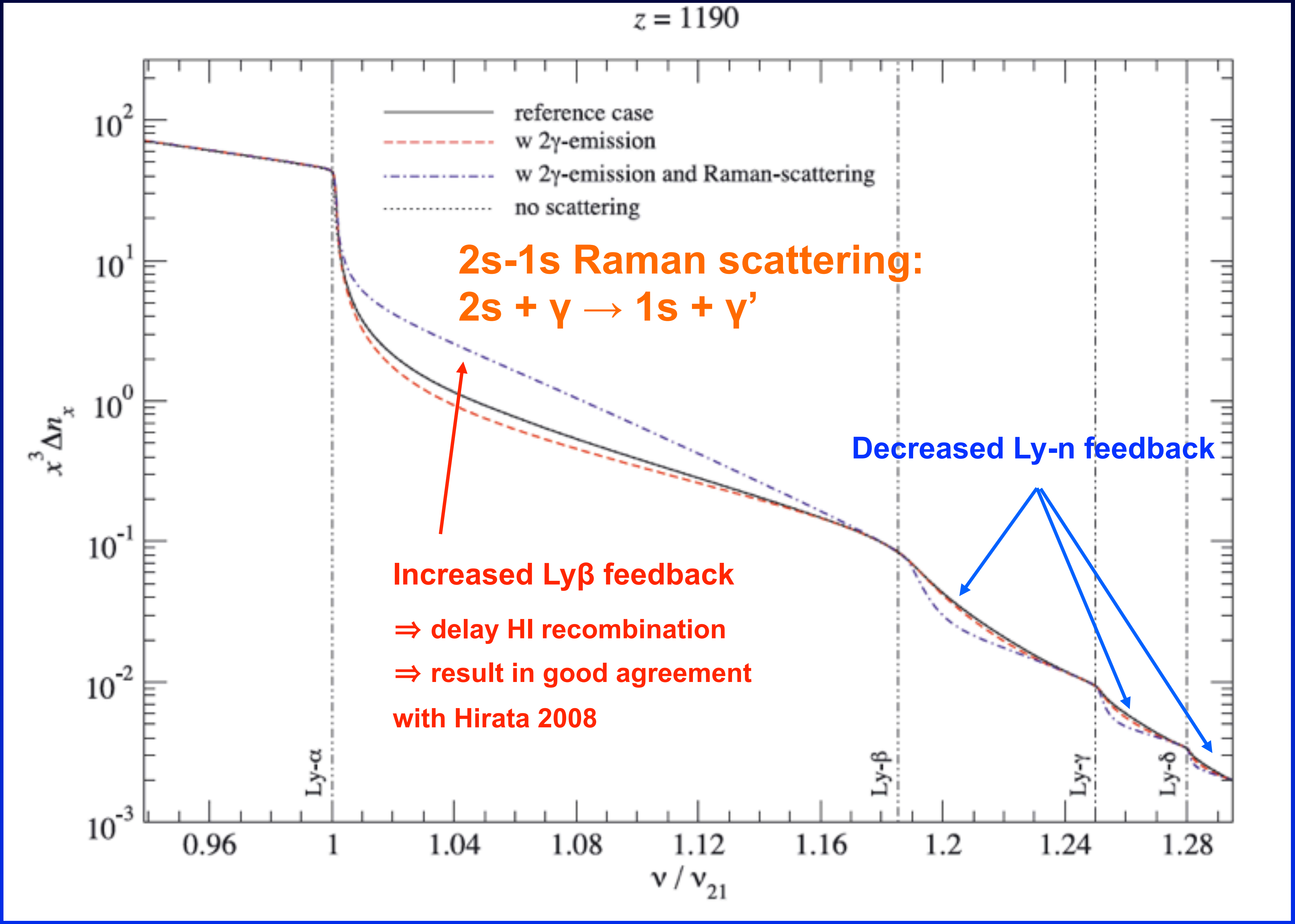
Direct Escape in optically thin regions:

→ 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

Effect of Raman scattering and 2γ decays

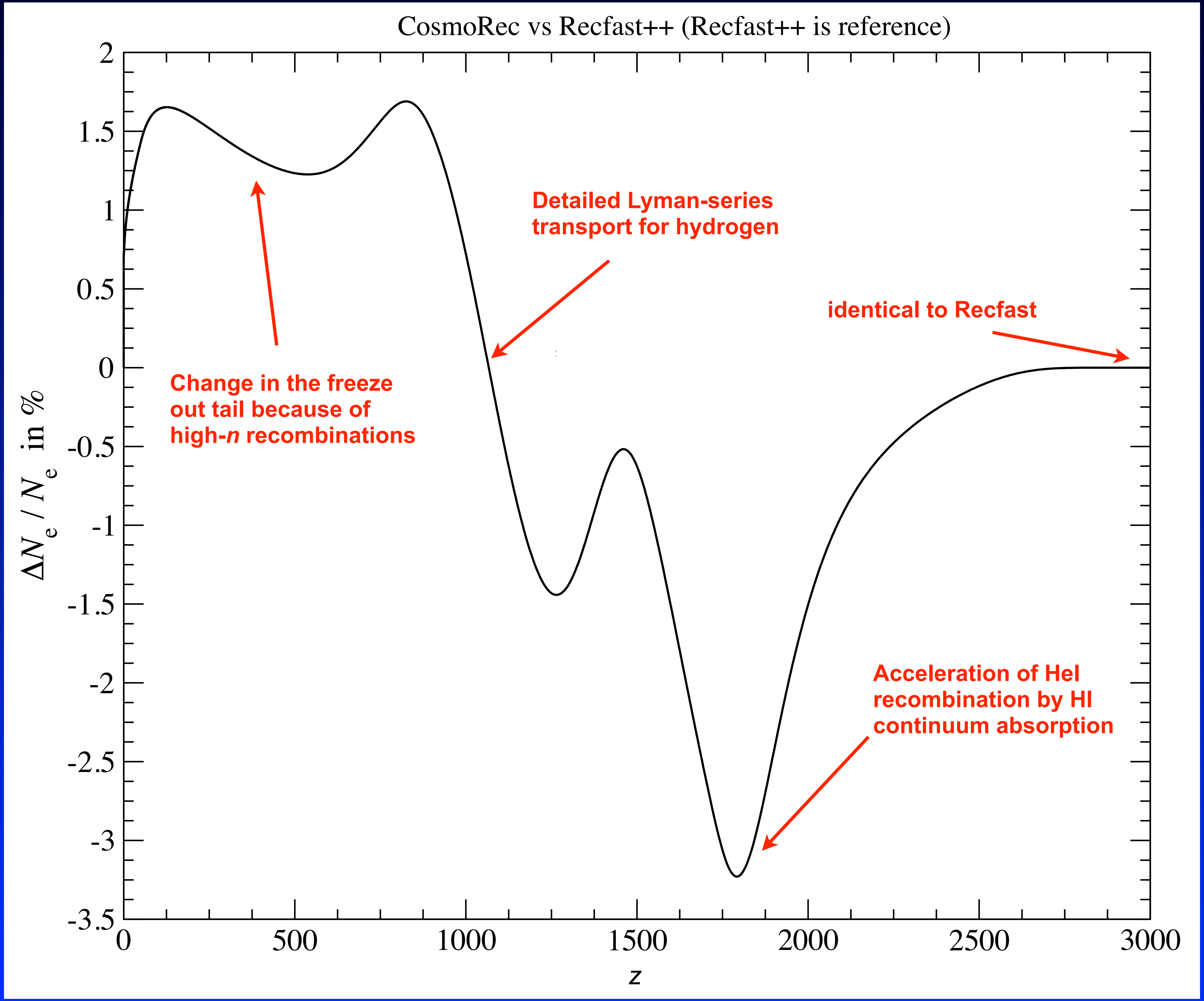


JC & Thomas, MNRAS, 2010

A New Cosmological Recombination Code: *CosmoRec*

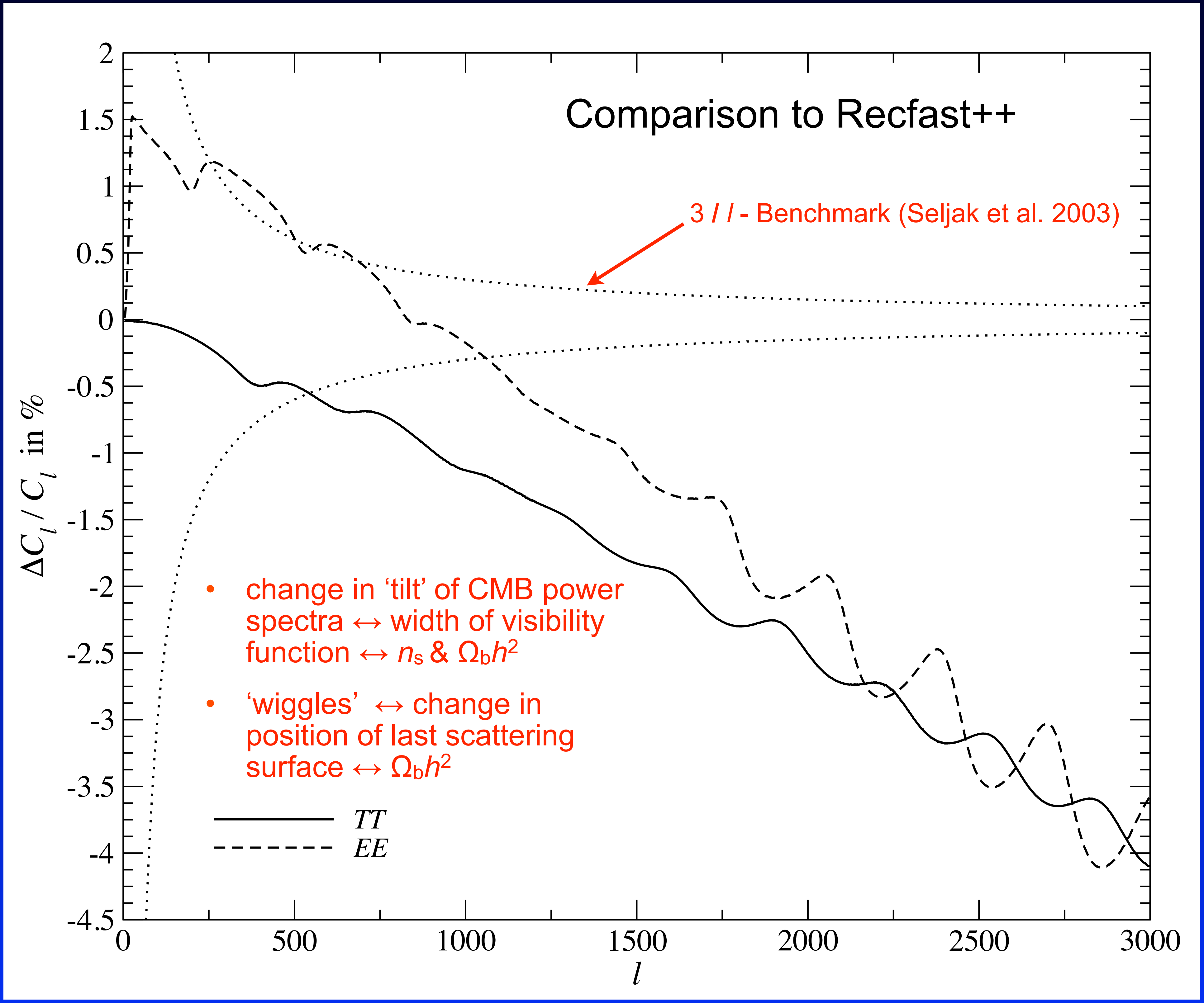
- uses an effective multi-level approach **(Haimoud & Hirata, 2010)**
- very *accurate* and *fast* (for ‘default’ setting ~1.3 sec per model!)
- solves the detailed radiative transfer problem for Ly-*n*
- no *fudging* *(Recfast)* or *multi-dimensional interpolation* *(RICO)*
- different *runmodes/accuracies* 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



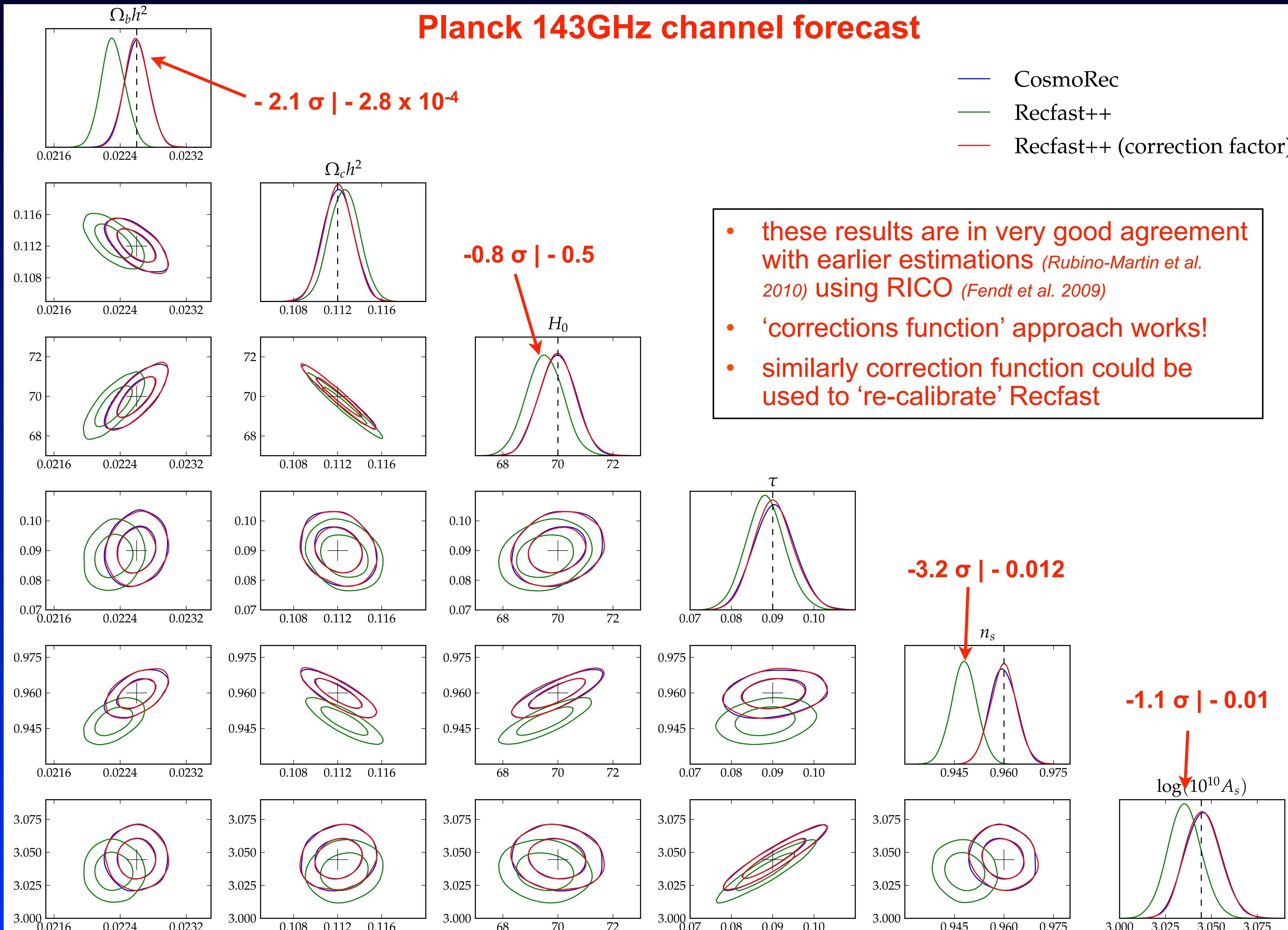
JC & Thomas, MNRAS, 2010; Shaw & JC, MNRAS, 2011

Cumulative Change in the CMB Power Spectra



CITA ICAT Shaw & JC, MNRAS, 2011

What are the biases in the cosmological parameters?



- these results are in very good agreement with earlier estimations *(Rubino-Martin et al. 2010)* using RICO *(Fendt et al. 2009)*
- 'corrections function' approach works!
- similarly correction function could be used to 're-calibrate' Recfast

CITA ICAT Shaw & JC, MNRAS, 2011

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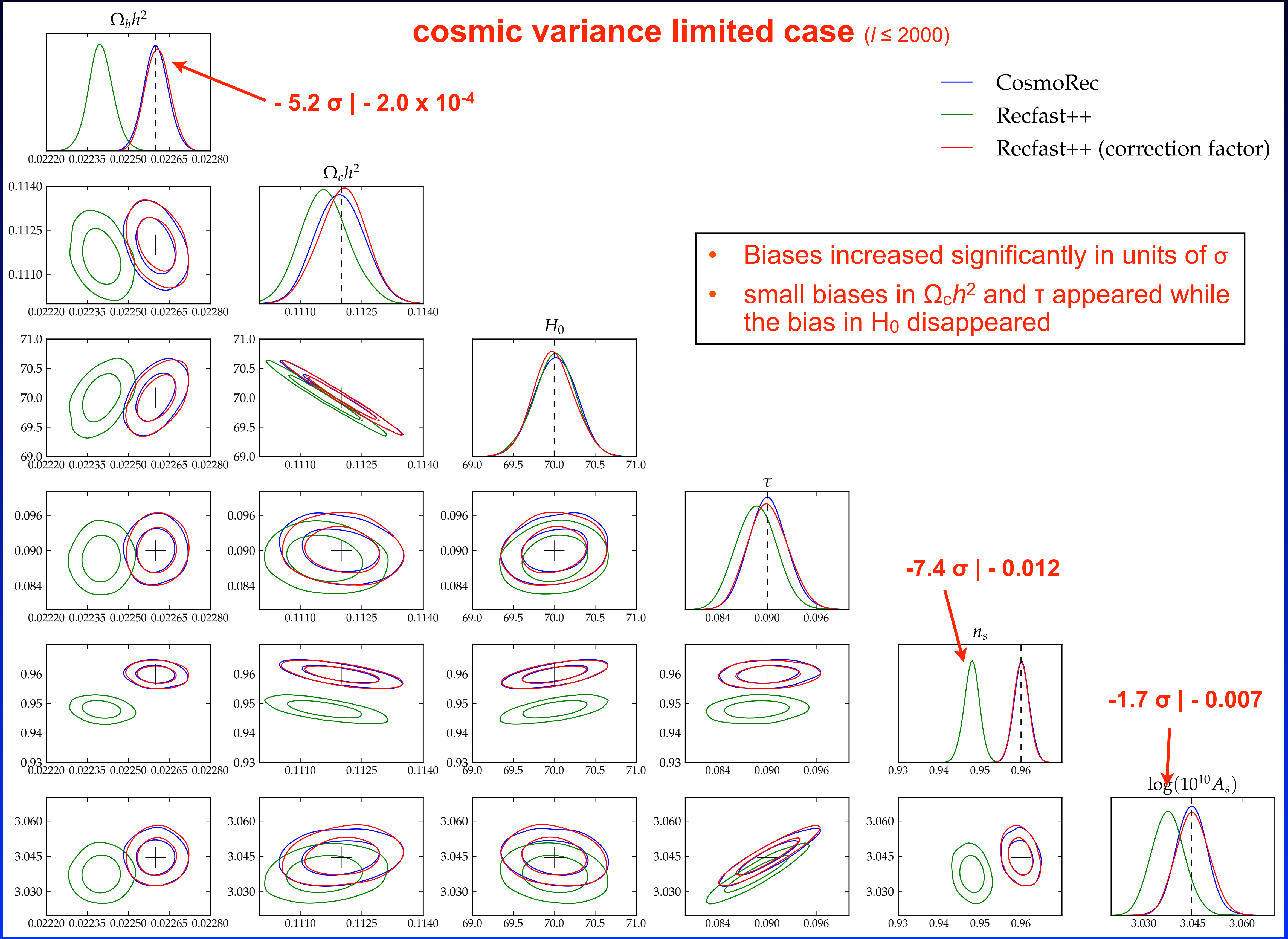

Shaw & JC, MNRAS, 2011

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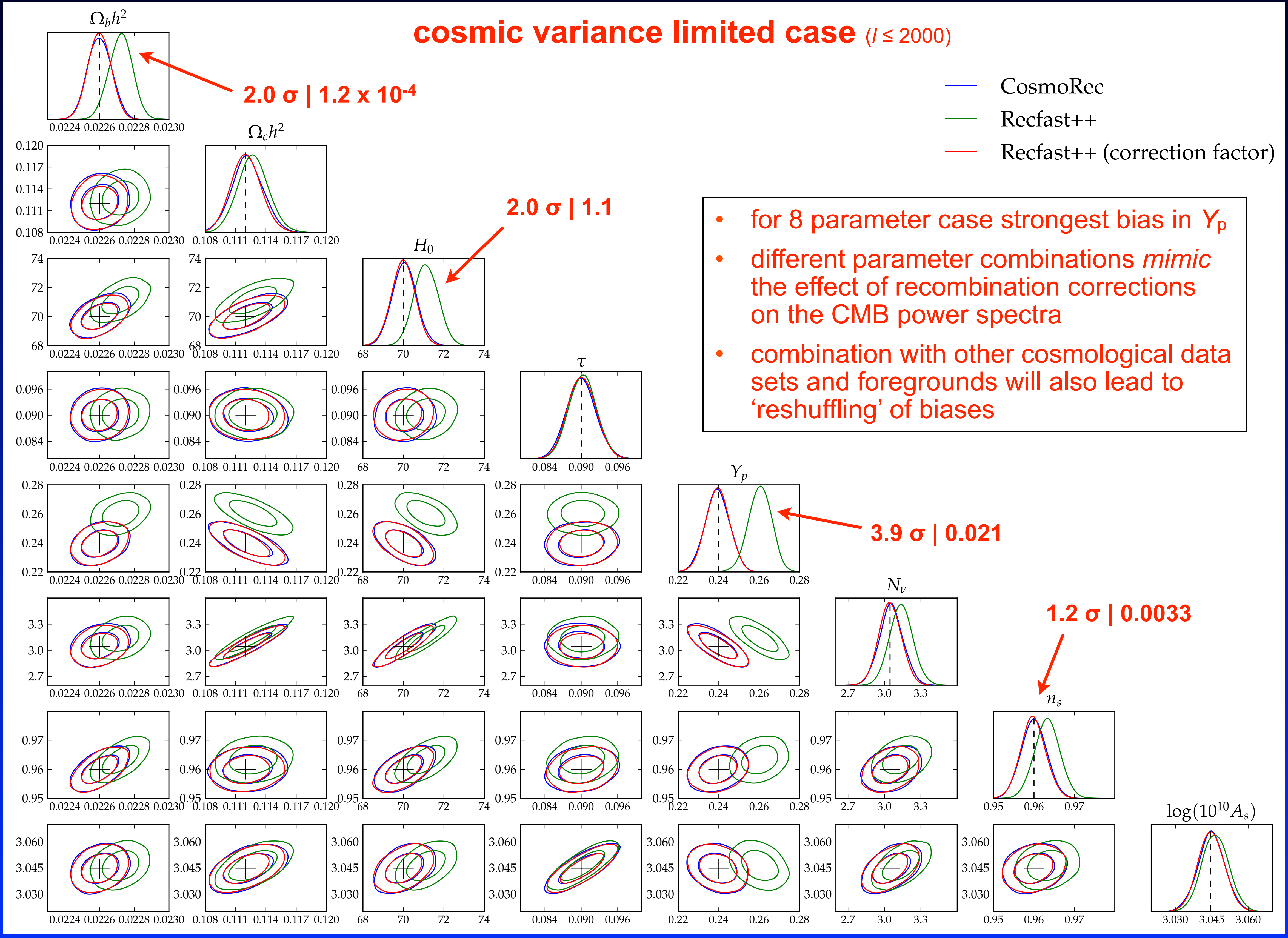
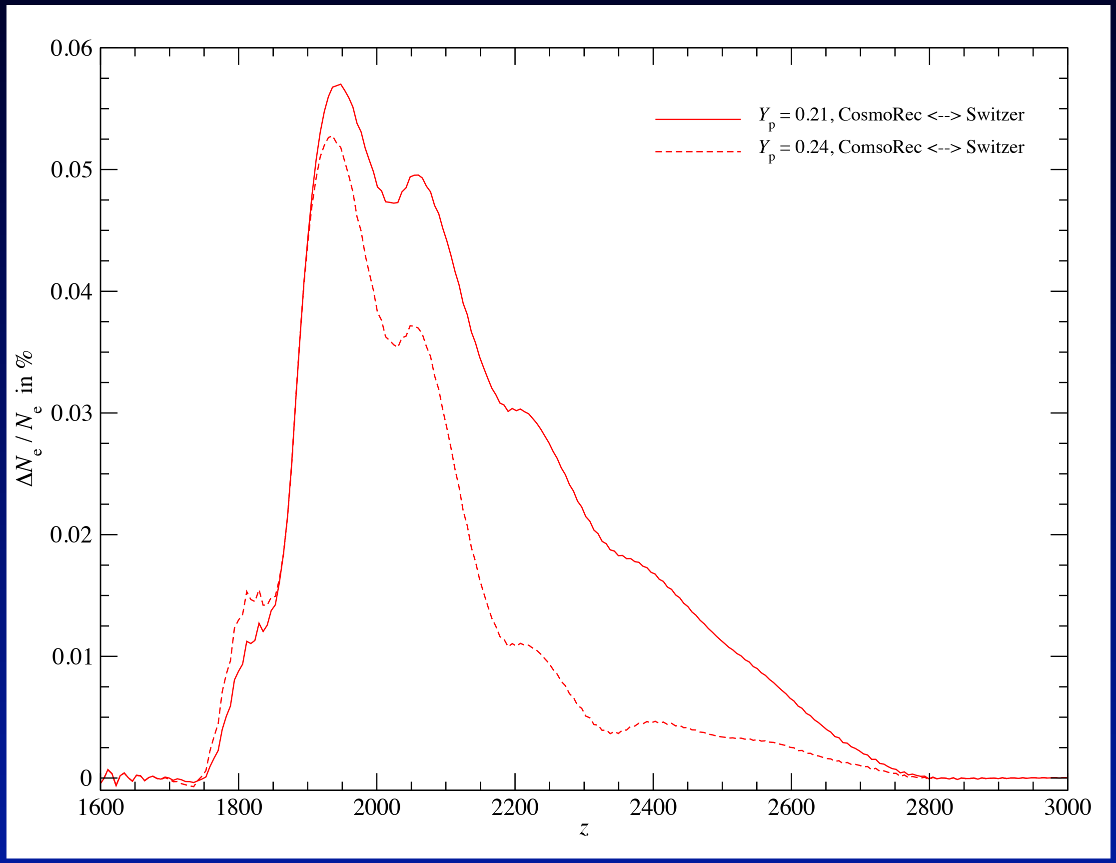


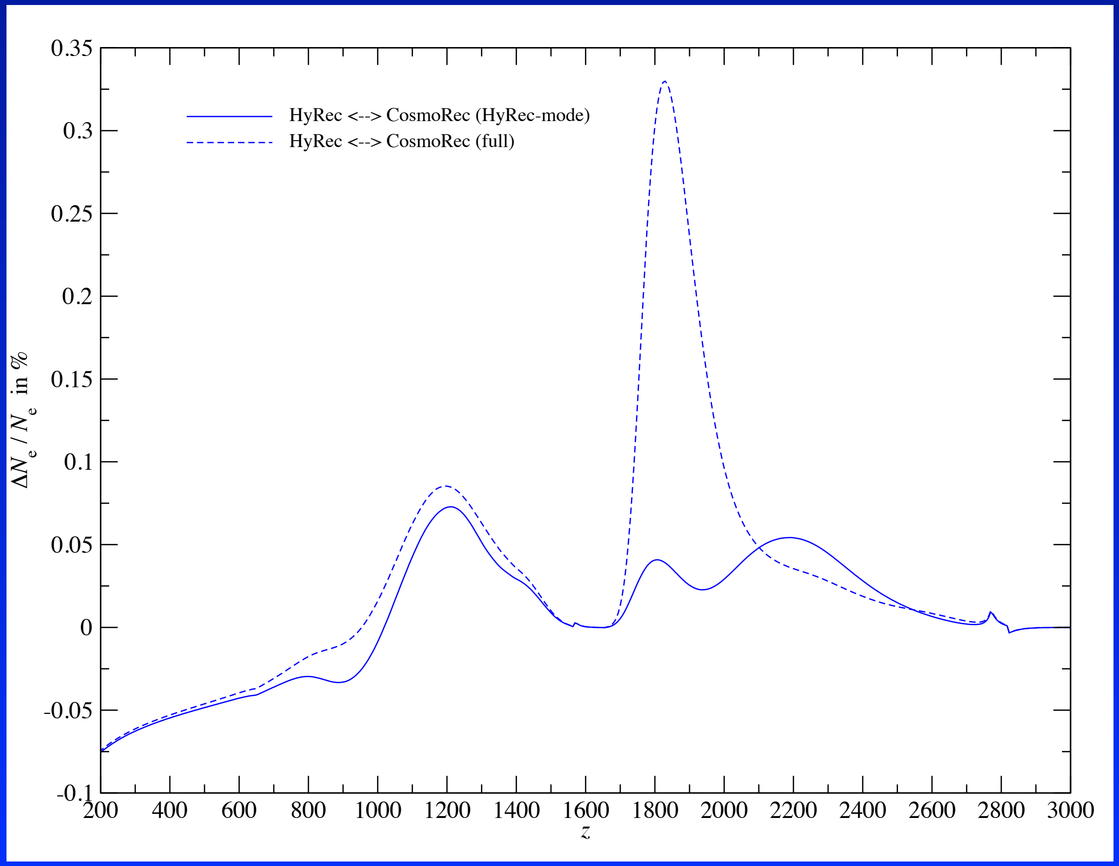
- for 8 parameter case strongest bias in Y_p
- different parameter combinations *mimic* the effect of recombination corrections on the CMB power spectra
- combination with other cosmological data sets and foregrounds will also lead to 'reshuffling' of biases

Shaw & JC, MNRAS, 2011

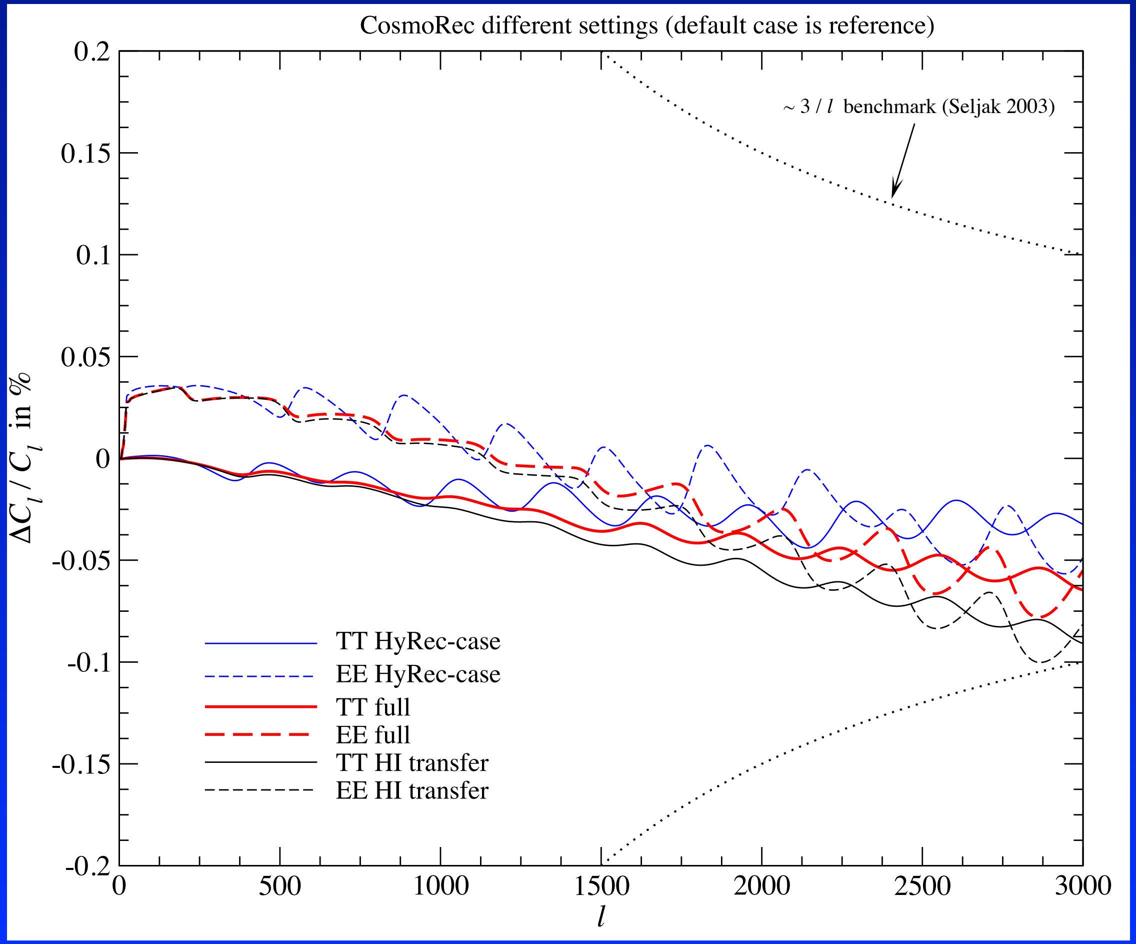
So, is the problem solved?

The '*final*' step: a detailed code comparison

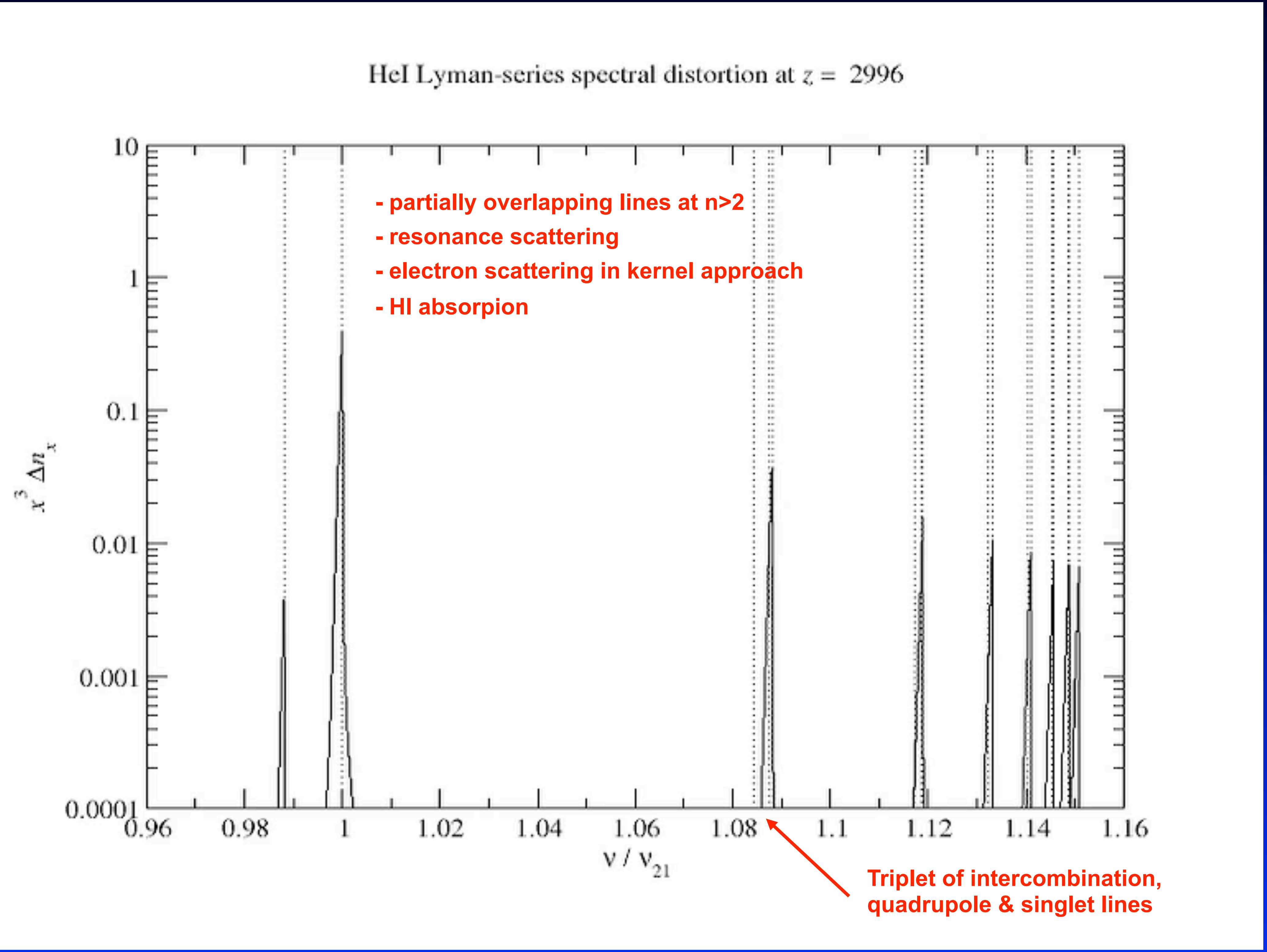




- **comparison of different *detailed* multi-level recombination codes (*slow*) to confirm precision of *fast* effective multi-level recombination codes *HyRec* (Haimoud & Hirata, 2010) and *CosmoRec***
- **First '*out of the box*' comparisons are extremely promising! (difference at z~1100 about 0.1%)**
- **code comparison will also allow to give an answer about which processes *really* need to be included**
- ***Collisions*? *HI Quadrupole* lines? *HeI physics* lines?**



Evolution of the HeI high frequency distortion



JC, Fung & Switzer, 2011

What if something unexpected happened?

- **e.g., something *standard* was missed, or something *non-standard* happened !?**
- **A *Non-parametric estimation* of possible *corrections* to the recombination history would be very useful → *Principle component analysis* (PCA)**
- **Determine how many *eigenmodes* can be constrained using future CMB data and use these modes to understand possible hidden effects**

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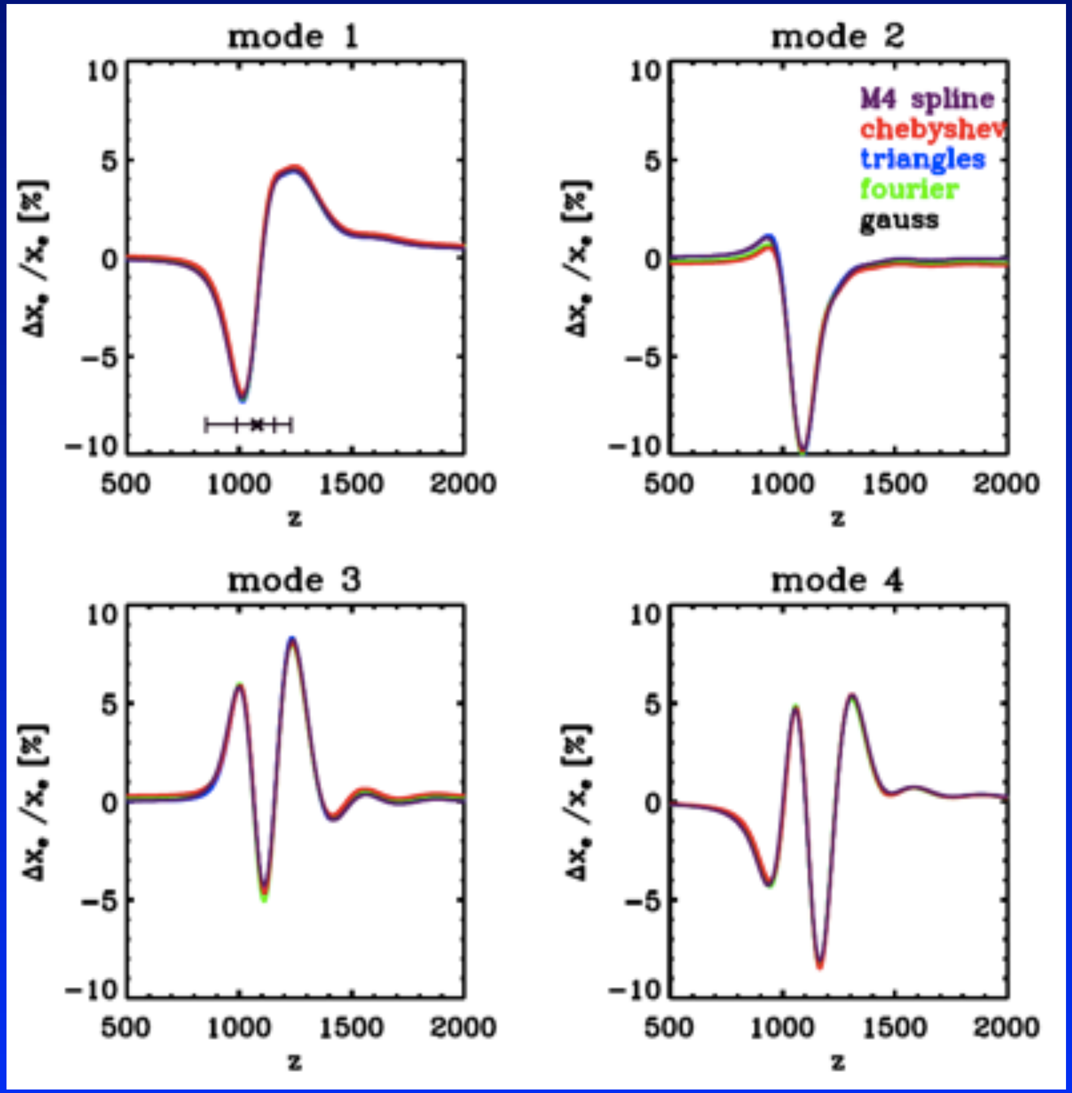
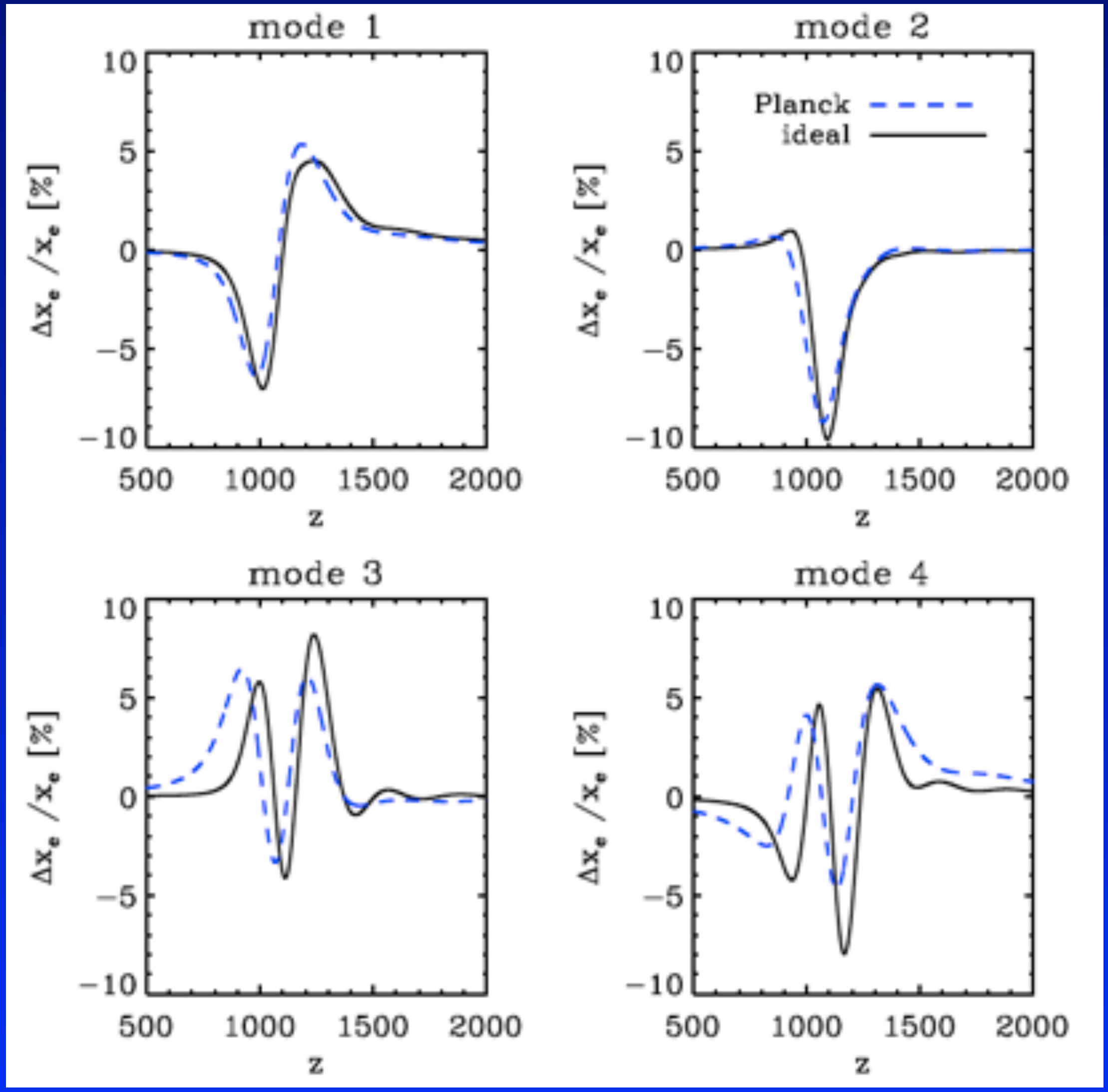
cosmic variance limited case ($l \leq 3000$)



Planck case ↔ CV limited case

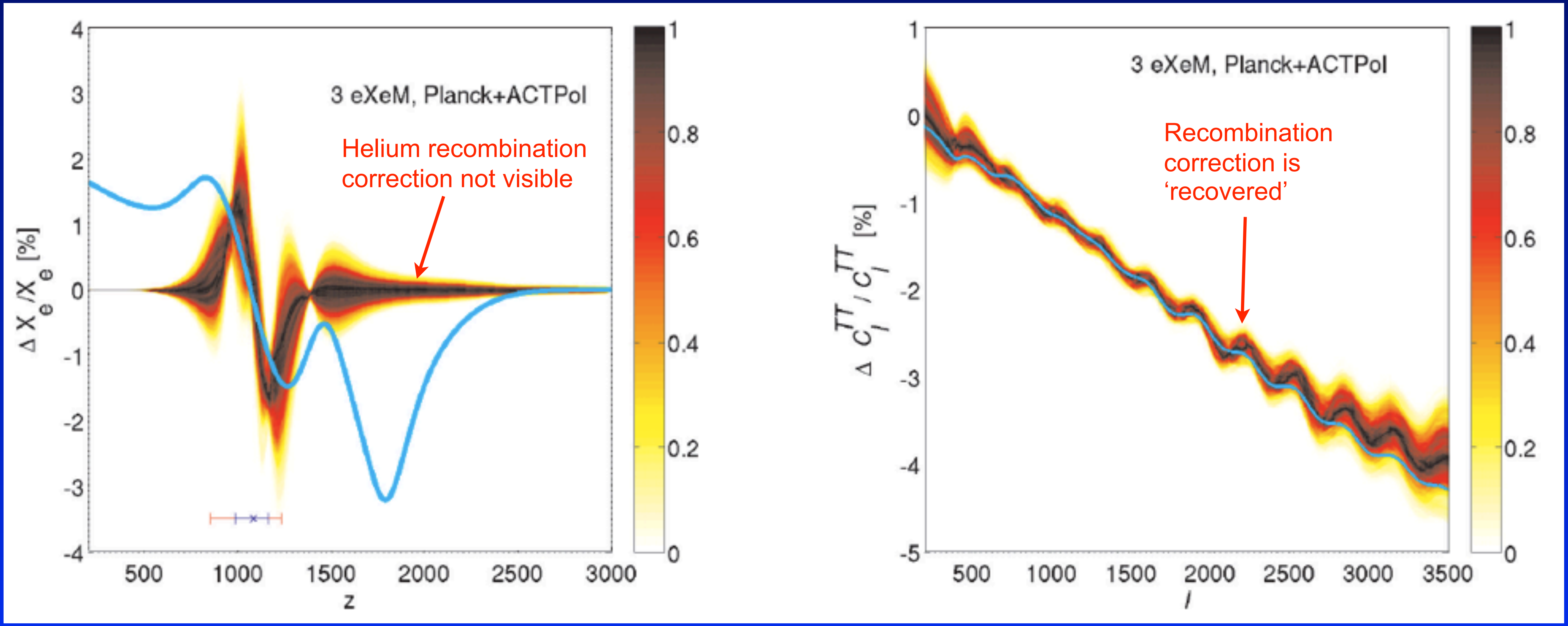


CITA ICAT **Farhang, Bond & JC, 2011**

Tests and first results of PCA

- **checked** ***convergence*** **of most constrained modes with spacial resolution**
- **checked** ***orthogonality*** **and** ***completeness***
- **tried different** ***parametrizations*** **and investigated** ***fiducial model dependence***

Parameter estimation 6std + first 3 modes (Planck+ACTPol for *l* ≤ 3500)



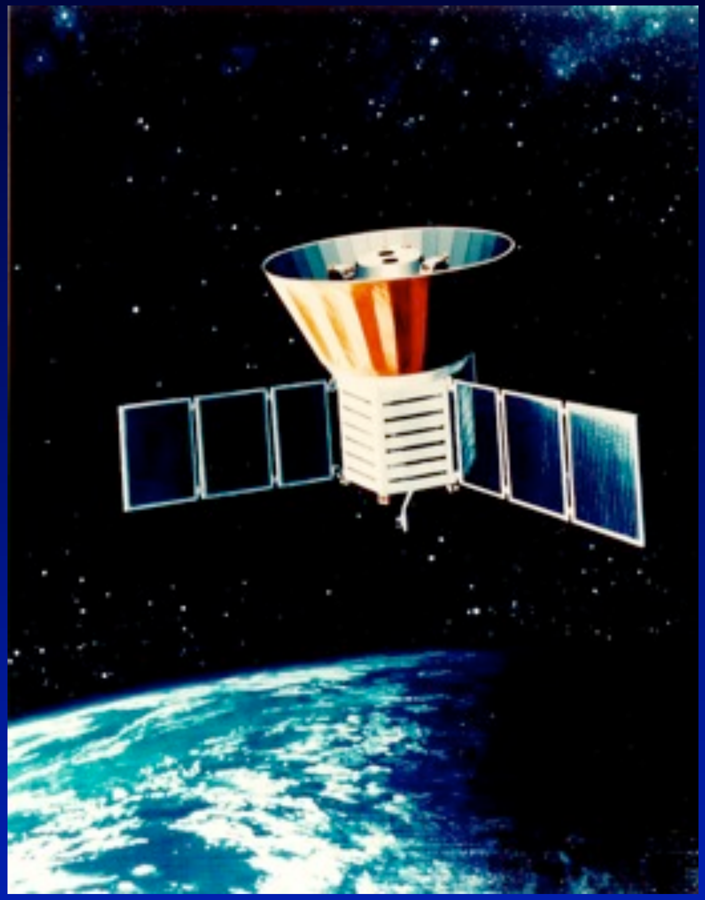
Farhang, Bond & JC, 2011

Summary (part I)

- It seems that the cosmological recombination problem is solved at a level of precision required for Planck!
- Neglecting HI & HeI corrections (6 parameter case):
  - → -3.2 σ bias in n_S and -2.1 σ in $\Omega_b h^2$ (Planck)
  - → -7.4 σ bias in n_S and -5.2 σ in $\Omega_b h^2$ (CV limited case for $l \leq 2000$)
- When varying helium abundance biases are 'reshuffled'
- Final code comparison will be important and has already started with very positive preliminary results
- Collisions could still be important at low-z **(JC, Vasil & Dursi, 2010)**
- improved helium recombination module **(JC, Fung & Switzer, 2011)**
- *Principle component analysis* for perturbed recombination histories could help shedding light on possible hidden effects **(Farhang, Bond & JC, 2011)**

The Cosmological Recombination Spectrum and what we could learn by observing it?

COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)

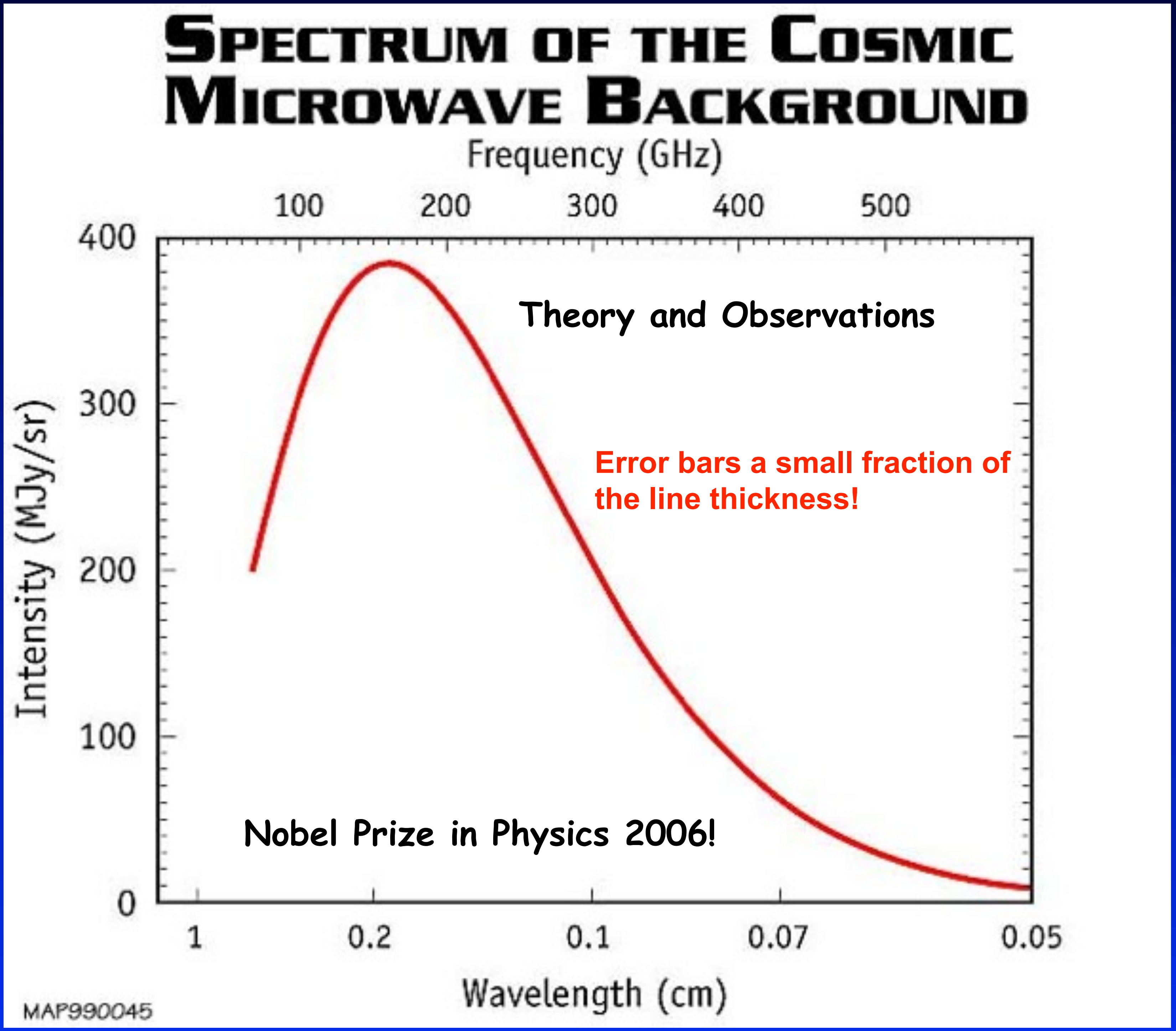


$$T_0 = 2.725 \pm 0.001\,\mathrm{K}$$

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

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

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!

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 → $\Delta\varepsilon/\varepsilon \sim 13.6\ \mathrm{eV}\ N_b\ /\ N_\gamma\ 2.7kT_r \sim 10^{-9} - 10^{-8}$

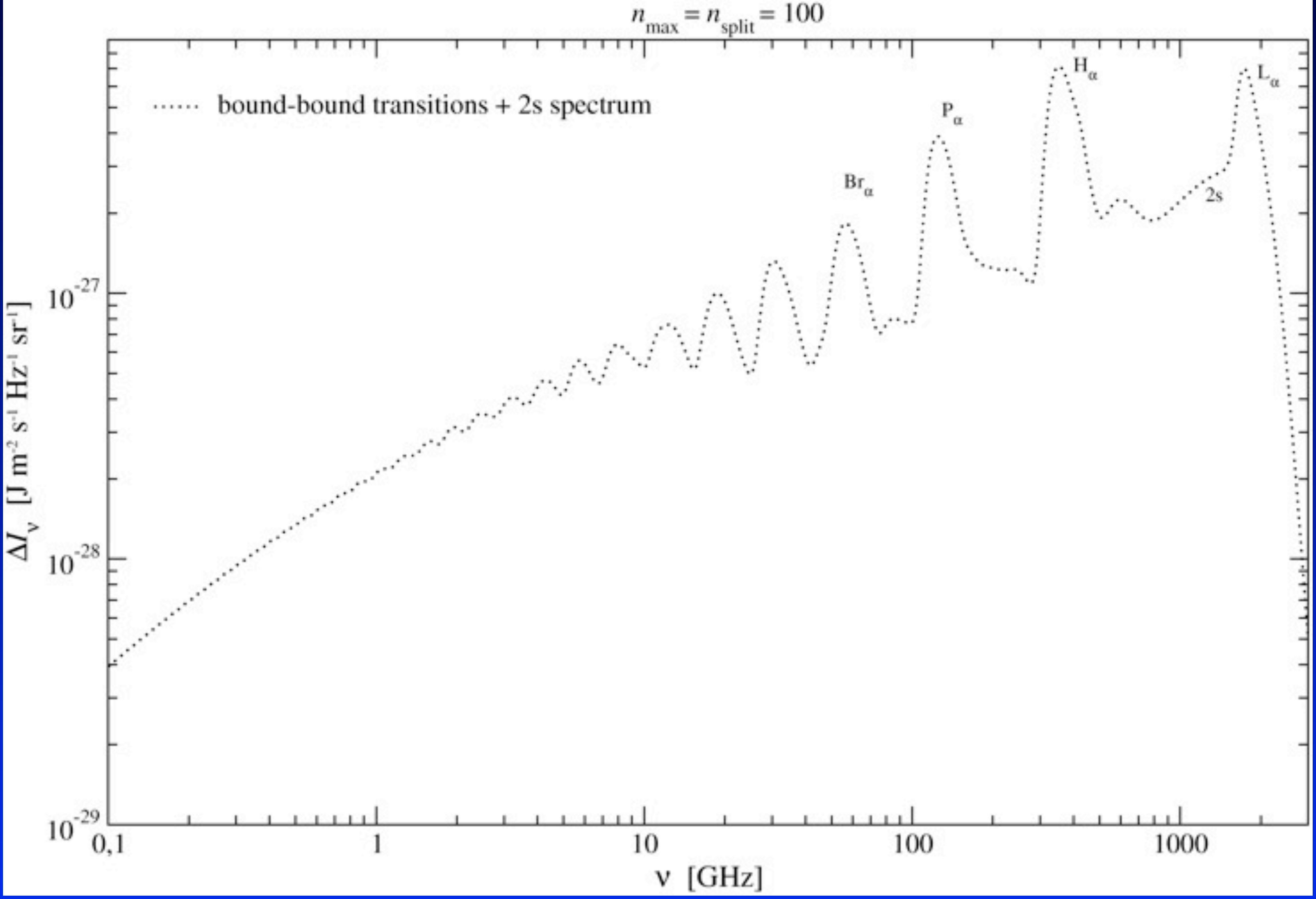
→ recombination occurs at redshifts $z < 10^4$

→ At that time the thermalization process 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 Δn<<n!

100-shell hydrogen atom and continuum *CMB spectral distortions*

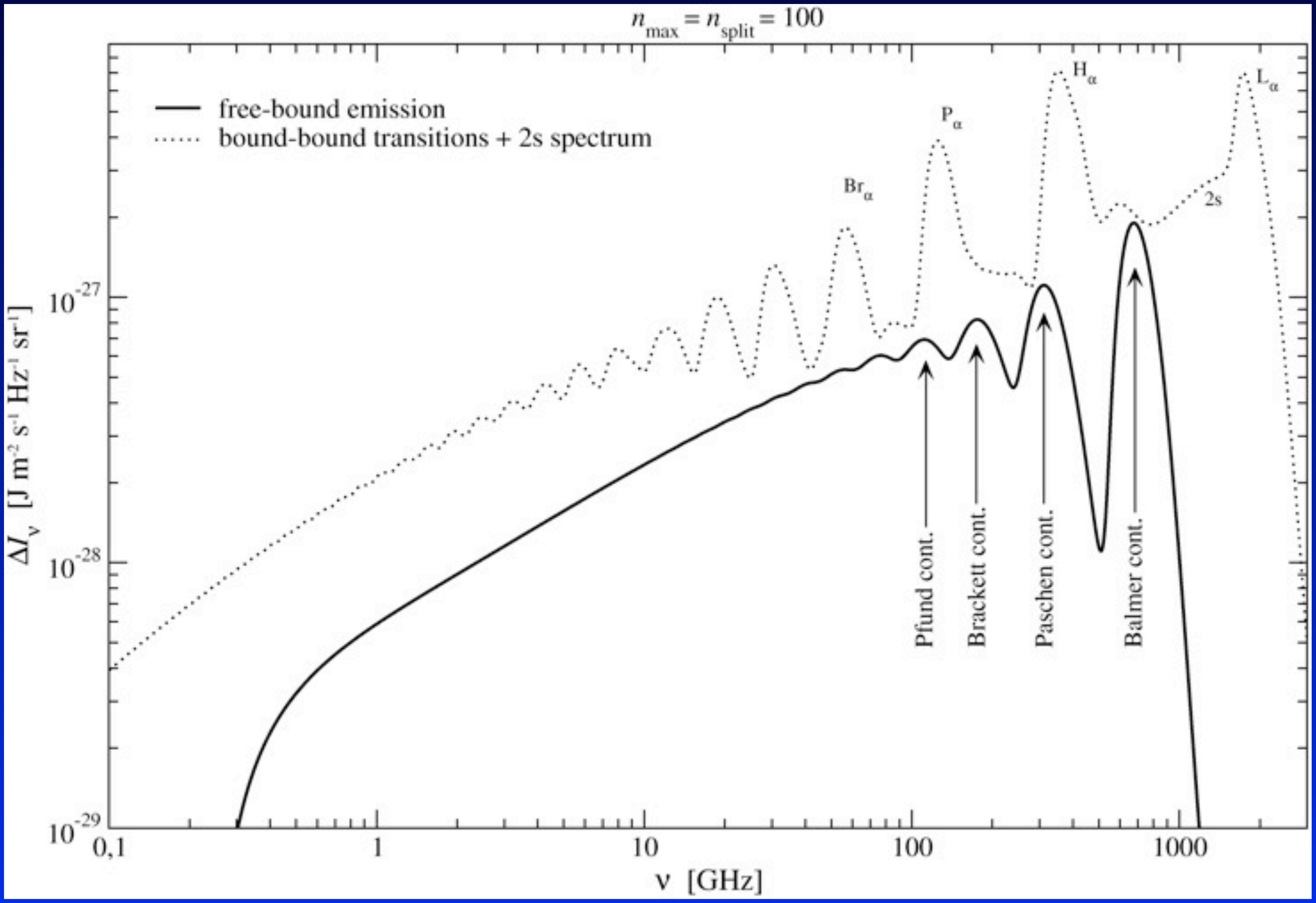


bound-bound & 2s:

- 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



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bound-bound & 2s:

- at ν>1GHz: distinct features
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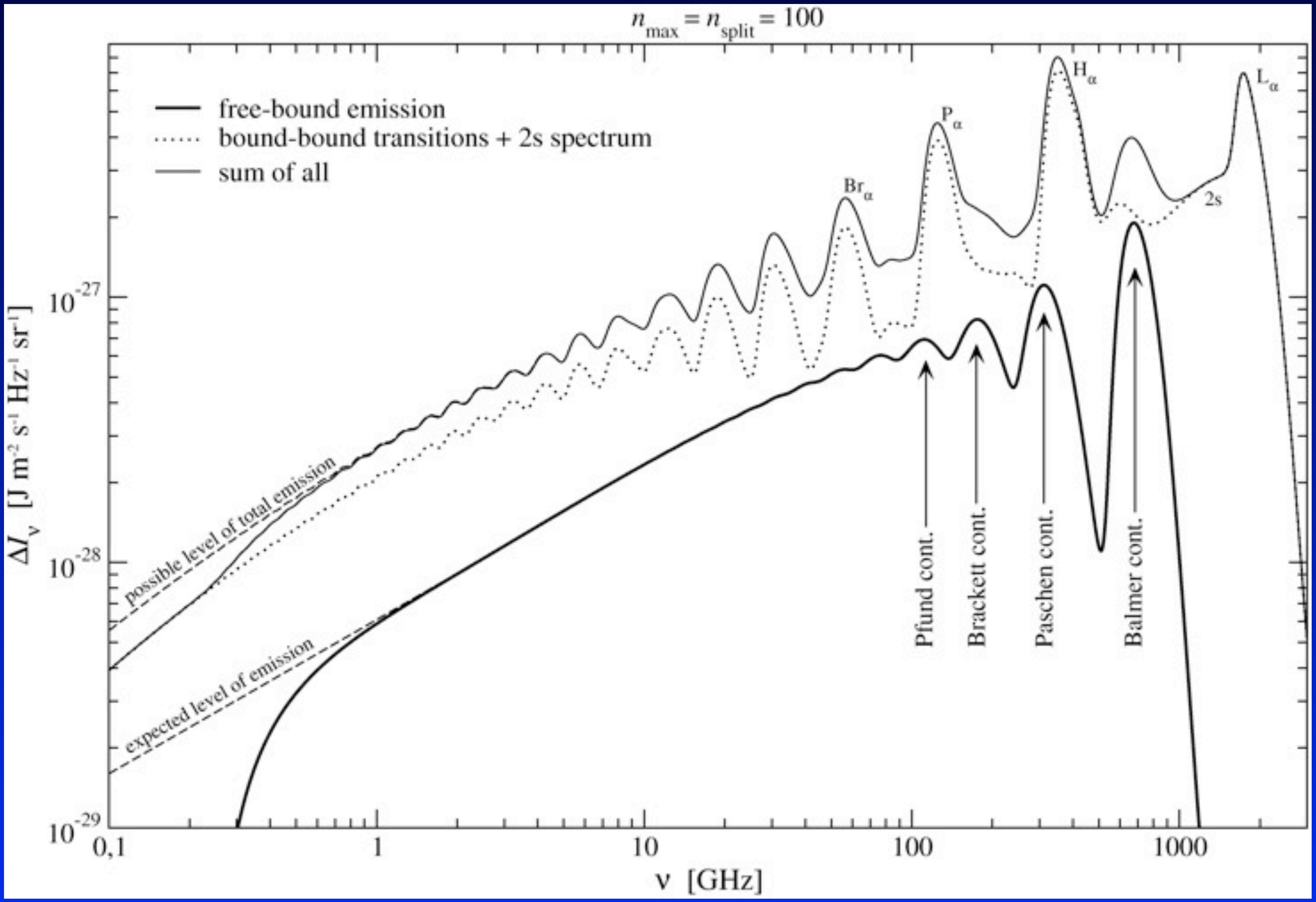
free-bound:

- only a few features distinguishable
- slope ~ 0.6

100-shell hydrogen atom and continuum
CMB spectral distortions



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bound-bound & 2s:

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

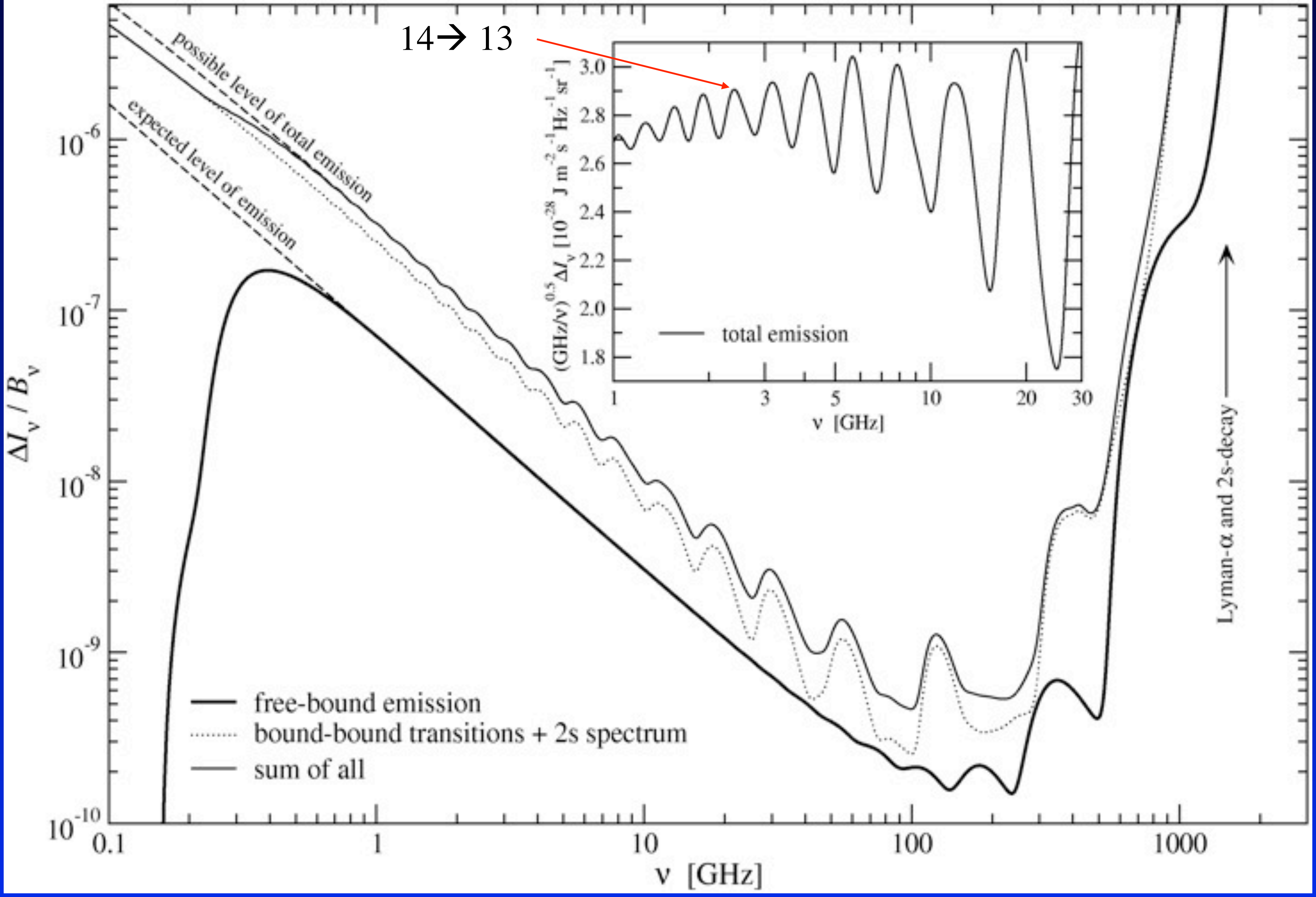
free-bound:

- 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



Wien-region:

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

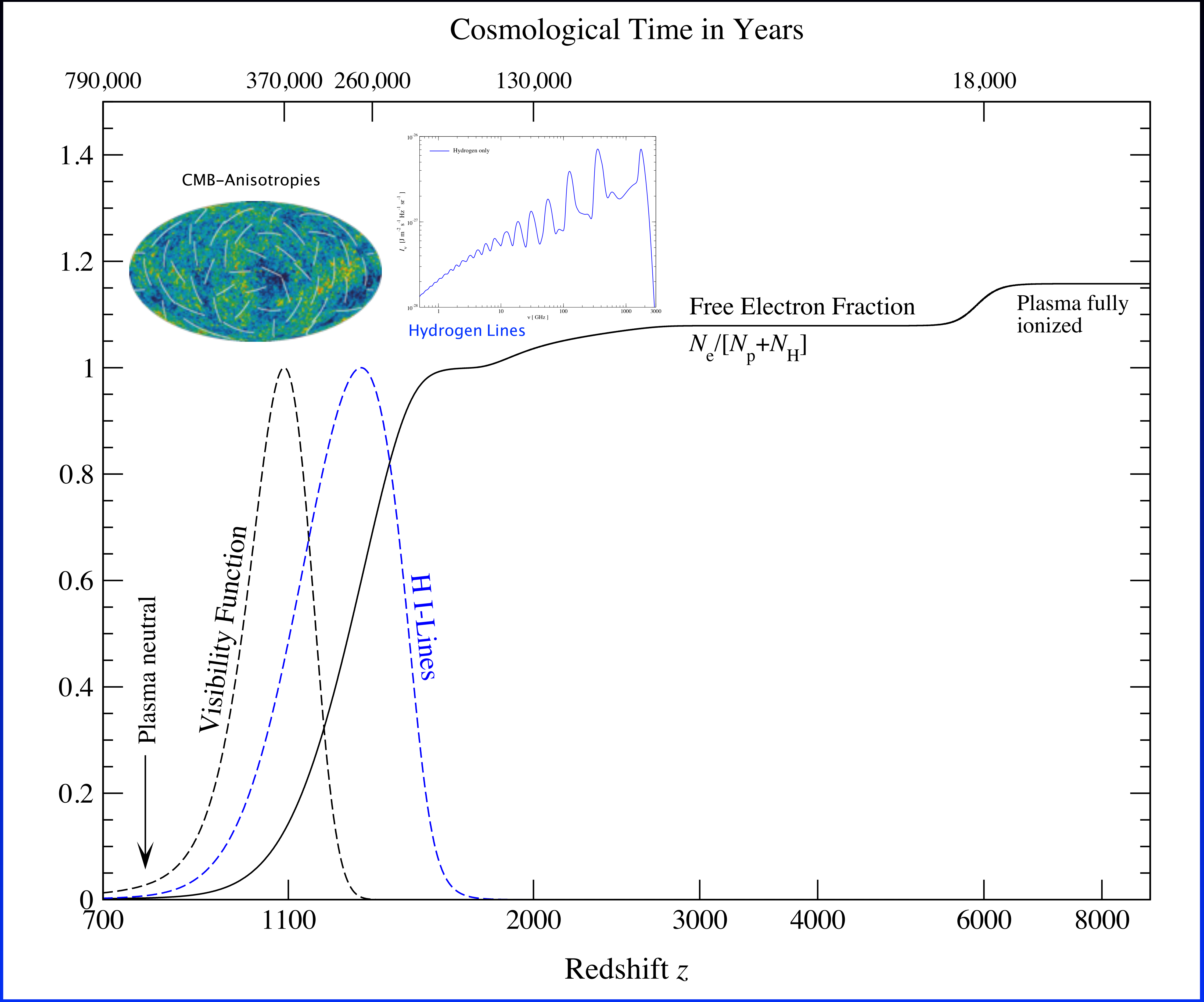
@ CMB maximum:

- 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*

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



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

What about the contributions from helium recombination?

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

  → expected photon number rather small

- ***BUT:***

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

  (*ii*) Helium recombinations faster

  → more *narrow* features with *larger* amplitude

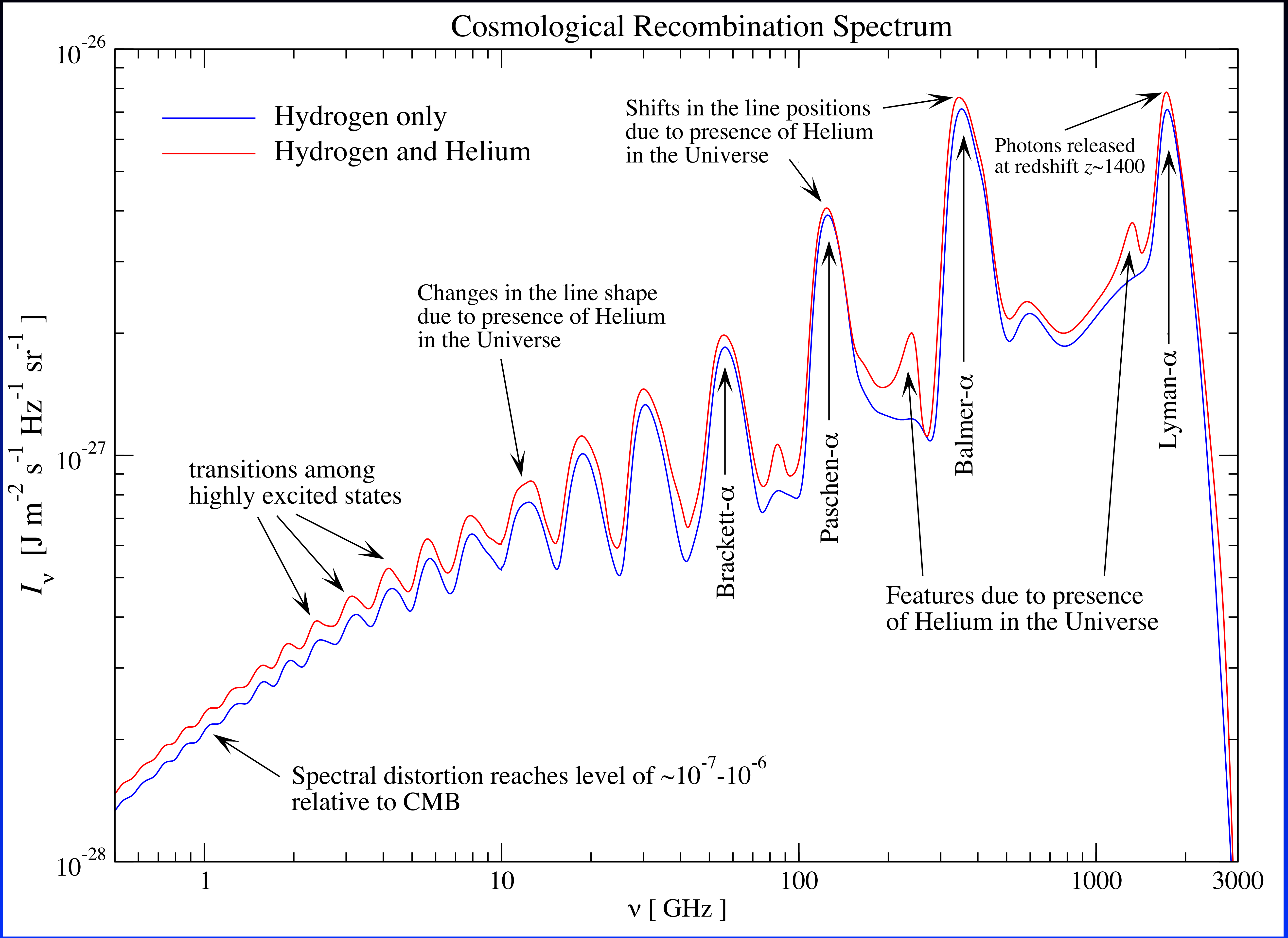
  (*iii*) non-trivial superposition

  → local amplification possible

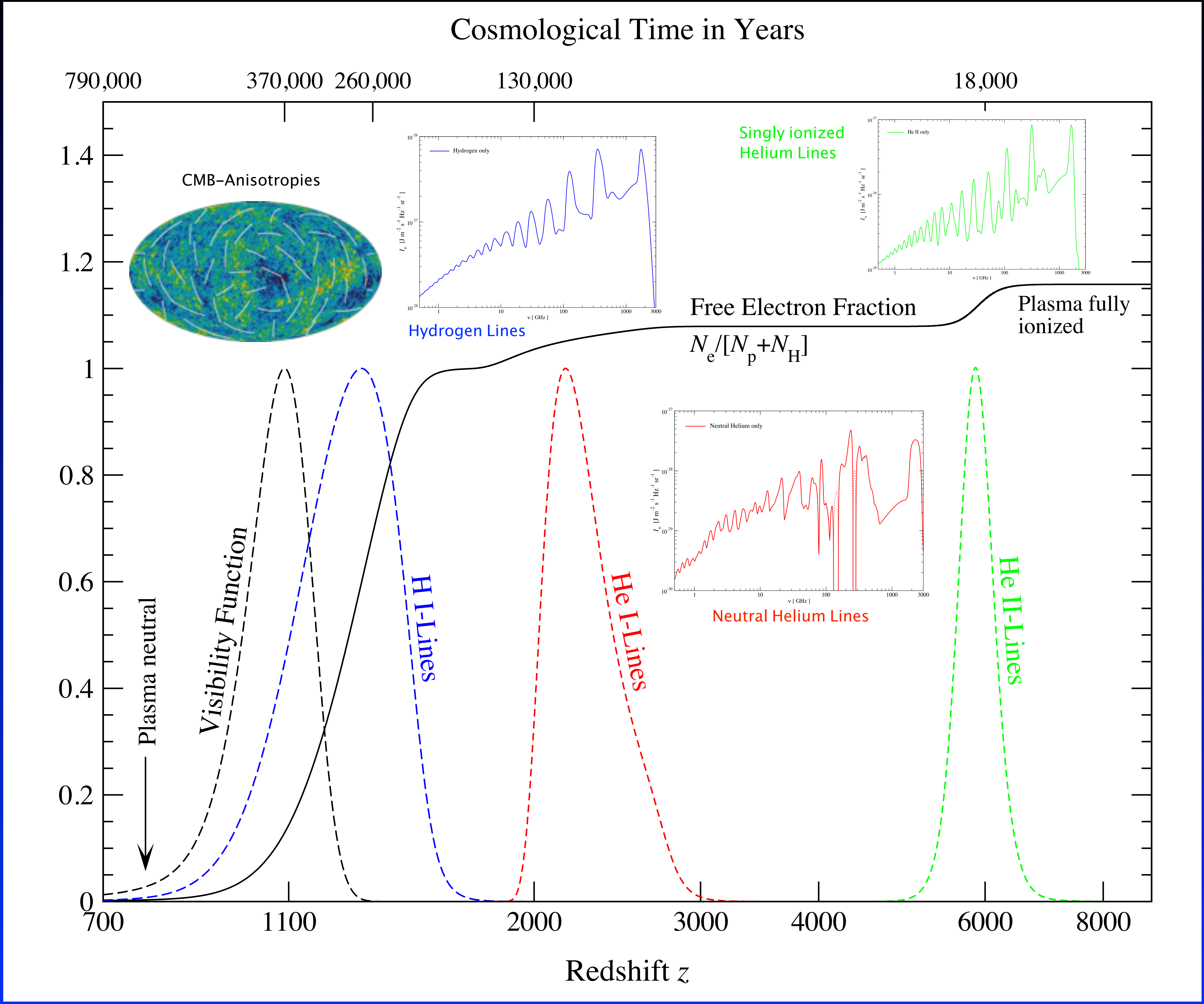
  (*iv*) reprocessing of HeII & HeI photons by HeI and HI

  → increases the number of helium-related photons

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



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
I_ν [J m^-2 s^-1 Hz^-1 sr^-1]
ν [GHz]
10^-26
10^-27
10^-28
1
10
100
1000
3000



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ionized
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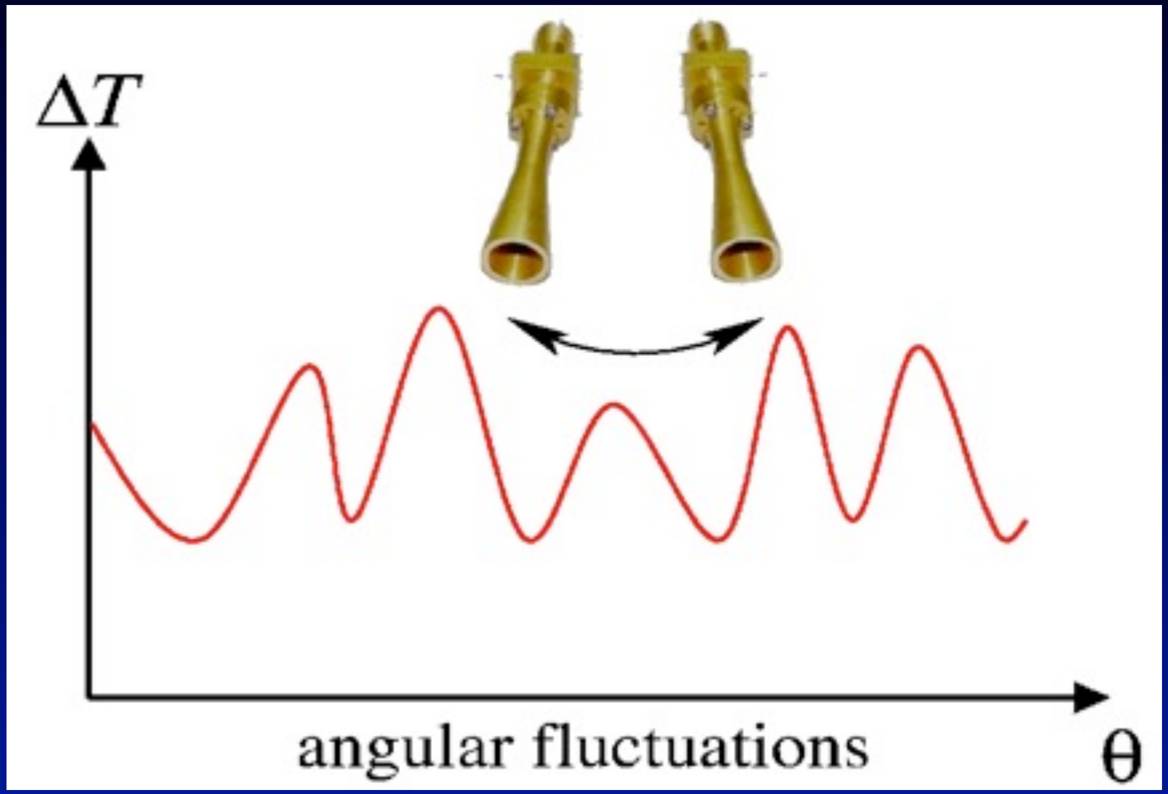
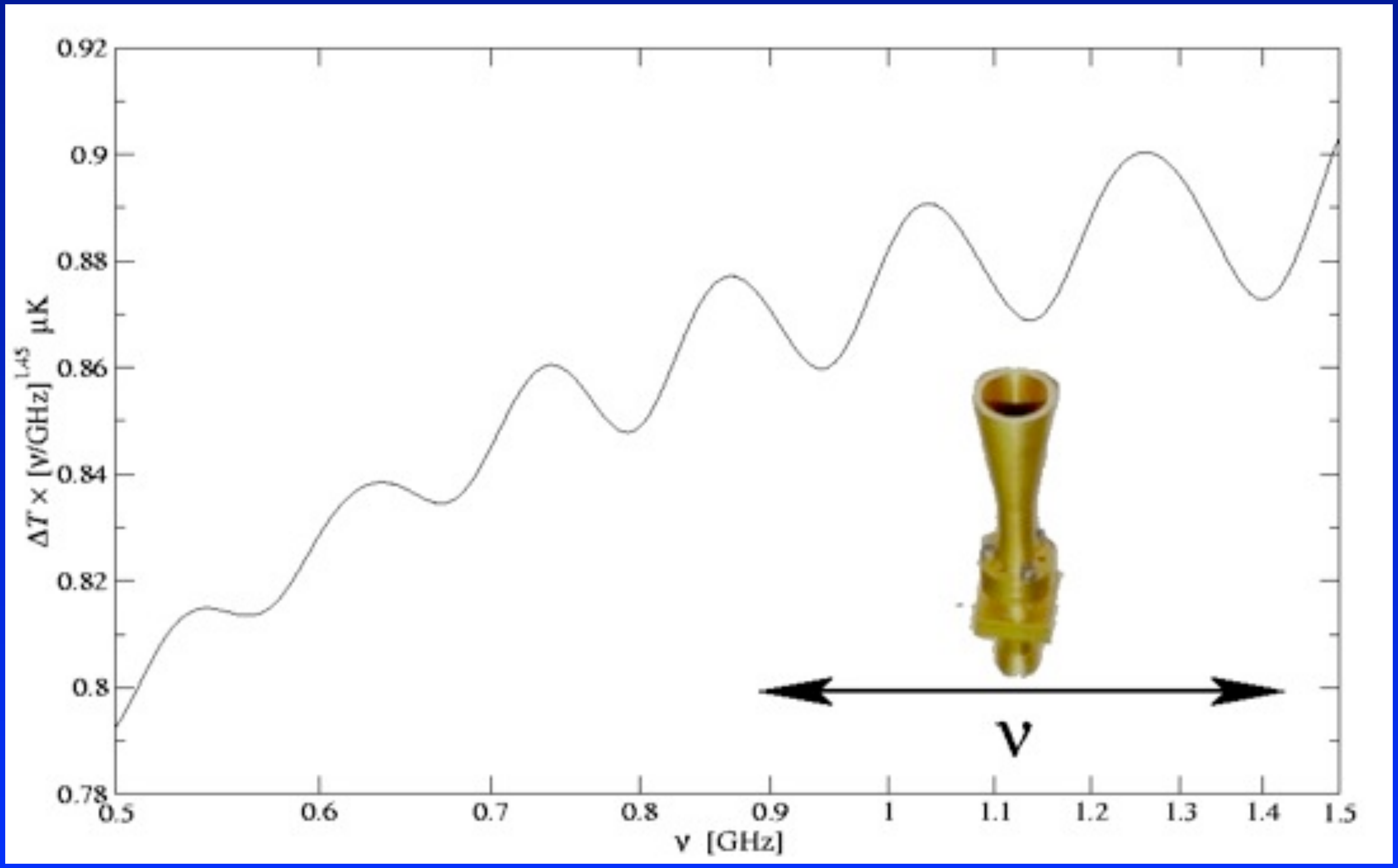
He I-Lines
He II-Lines
1.4
1.2
1
0.8
0.6
0.4
0.2
0
700
1100
2000
3000
4000
6000
8000
Redshift z

Sketch of proposed Observing Strategy



Scan over frequency instead of angular coordinate!!!



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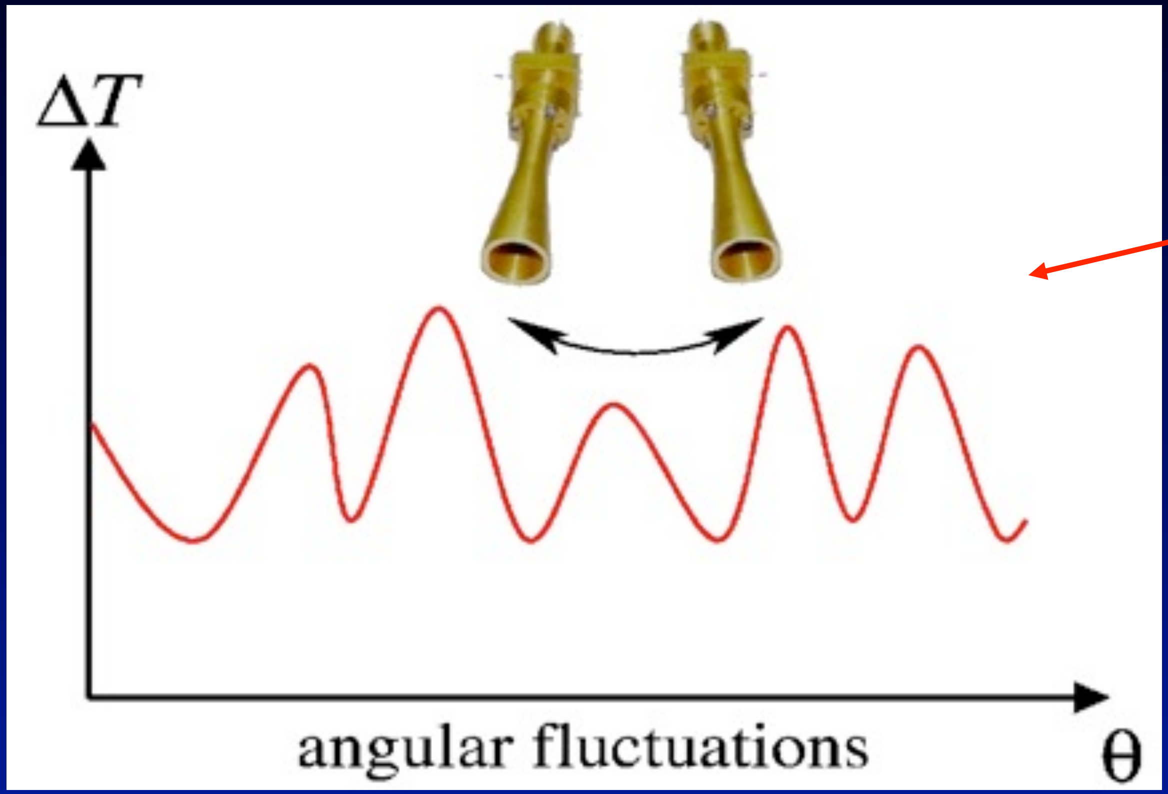
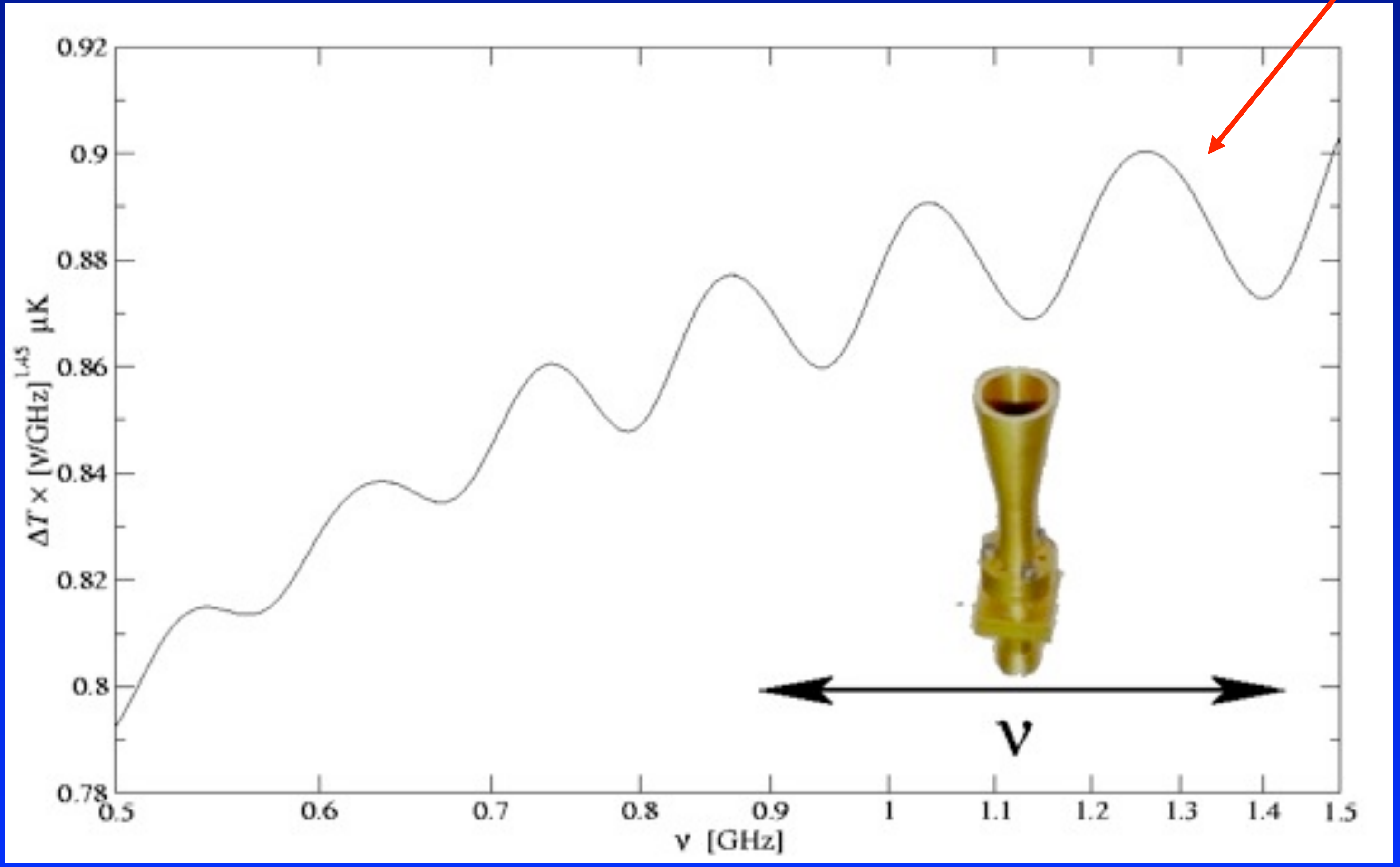


Experiments under construction are reaching the sensitivity on the level of 10 nK (A. Readhead, talk at NRAO Symposium in 2007)!

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 $\Omega_b h^2$)**

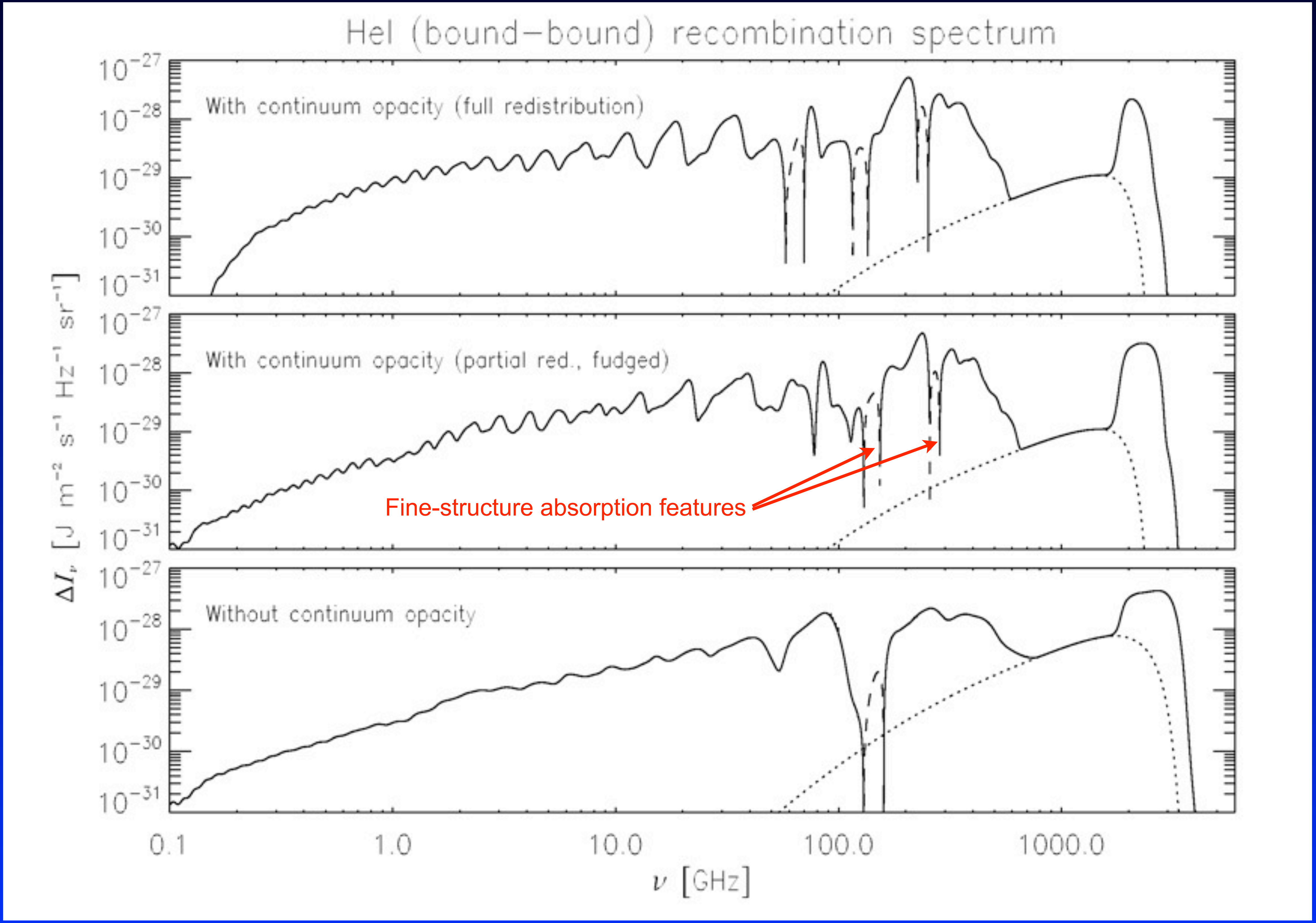
→ **the CMB *monopole* temperature T_0**

→ ***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!***

→ ***Allows us to directly check our understanding of the standard recombination physics → very important for conclusions on Inflation (n_S)***

The importance of HI continuum absorption



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

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→ **important limitation: (i) *HI & HeI collisional rates; (ii) HeI photo-ionization cross-sections and (iii) HeI bb-transition rates***

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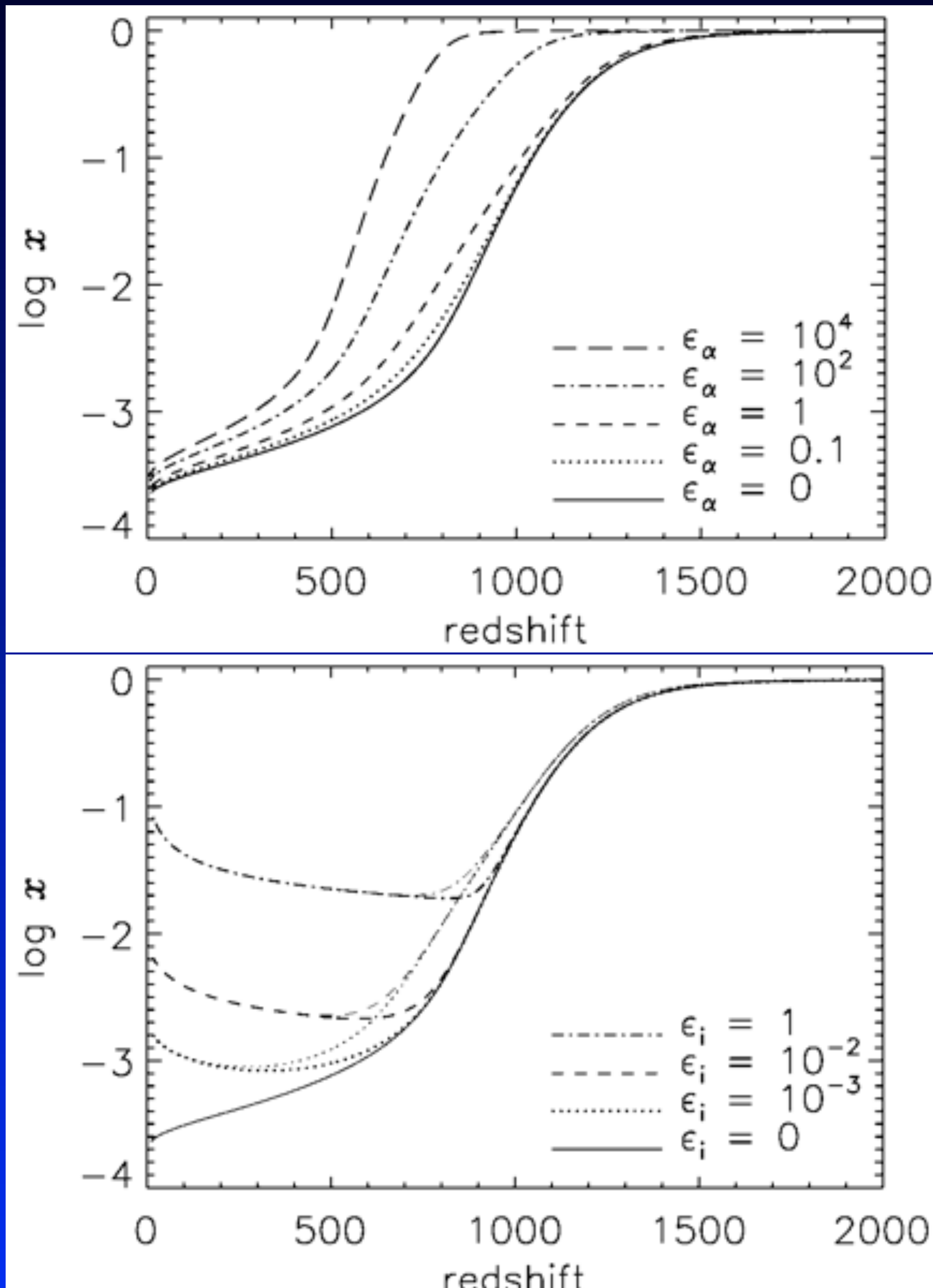
Is the *standard* cosmological recombination spectrum really interesting enough?

Extra Sources of Ionizations or Excitations

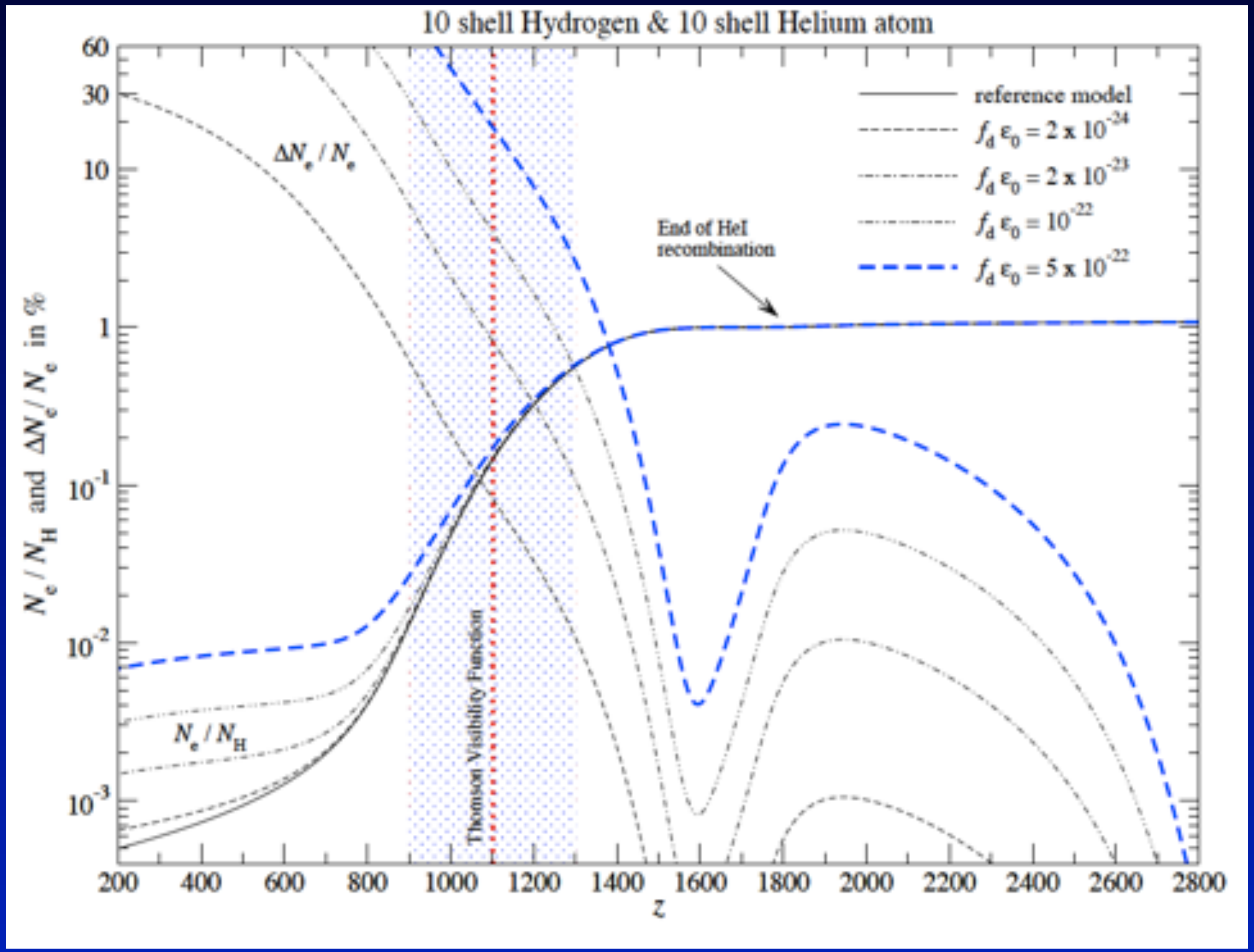


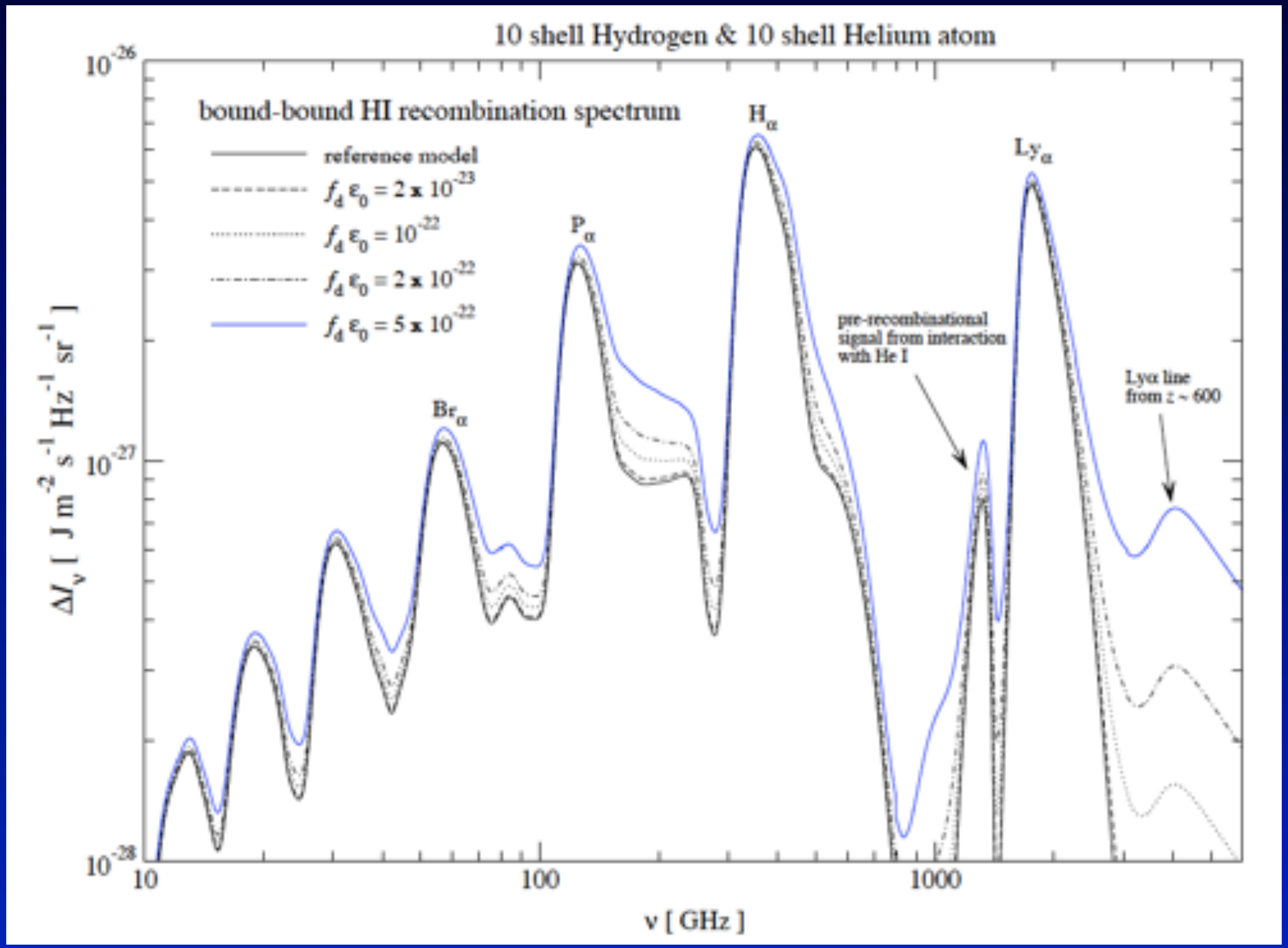
Peebles, Seager & Hu, ApJ, 2000

- ‚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

Example: Dark Matter Annihilations





- ‘Delay of recombination’
- Affects Thomson visibility function
- Possibility of Sommerfeld-enhancement

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

see also Padmanabhan & Finkbeiner, Phys. Rev. D, 2005

JC, 2009, arXiv:0910.3663

Example: Dark Matter Annihilations

- WMAP constraints on possible dark matter annihilation efficiencies already very tight (e.g. see Galli et al. 2009; Slatyer et al. 2009; Huetsi et al. 2009)
  - absolute changes to CMB power spectra have to be small (~ 1%-5%)
  - changes to cosmological recombination spectrum are also small

- So why bother anymore? What could the cosmological recombination spectrum teach us in addition?
(JC, 2009, arXiv:0910.3663)
  - spectrum is sensitive to cases for which the C_l's are not affected!
  - DM annihilation parameters are ‚degenerate' with n_S & $\Omega_b h^2$
  - CMB spectrum could help breaking this degeneracy
  - very direct way to check for sources of extra ionizations and excitations during *all three* recombination epochs

Another Example: Energy Release in the Early Universe

Full thermodynamic equilibrium (certainly valid at very high redshifts)

- CMB has a blackbody spectrum at every time (not affected by expansion!!!)
- Photon number density and energy density determined by temperature T_γ

Disturbance of full equilibrium for example by

- Energy injection
- Production of (energetic) photons and/or particles

→CMB spectrum would deviate from a pure blackbody today!

Physical mechanisms that lead to release of energy

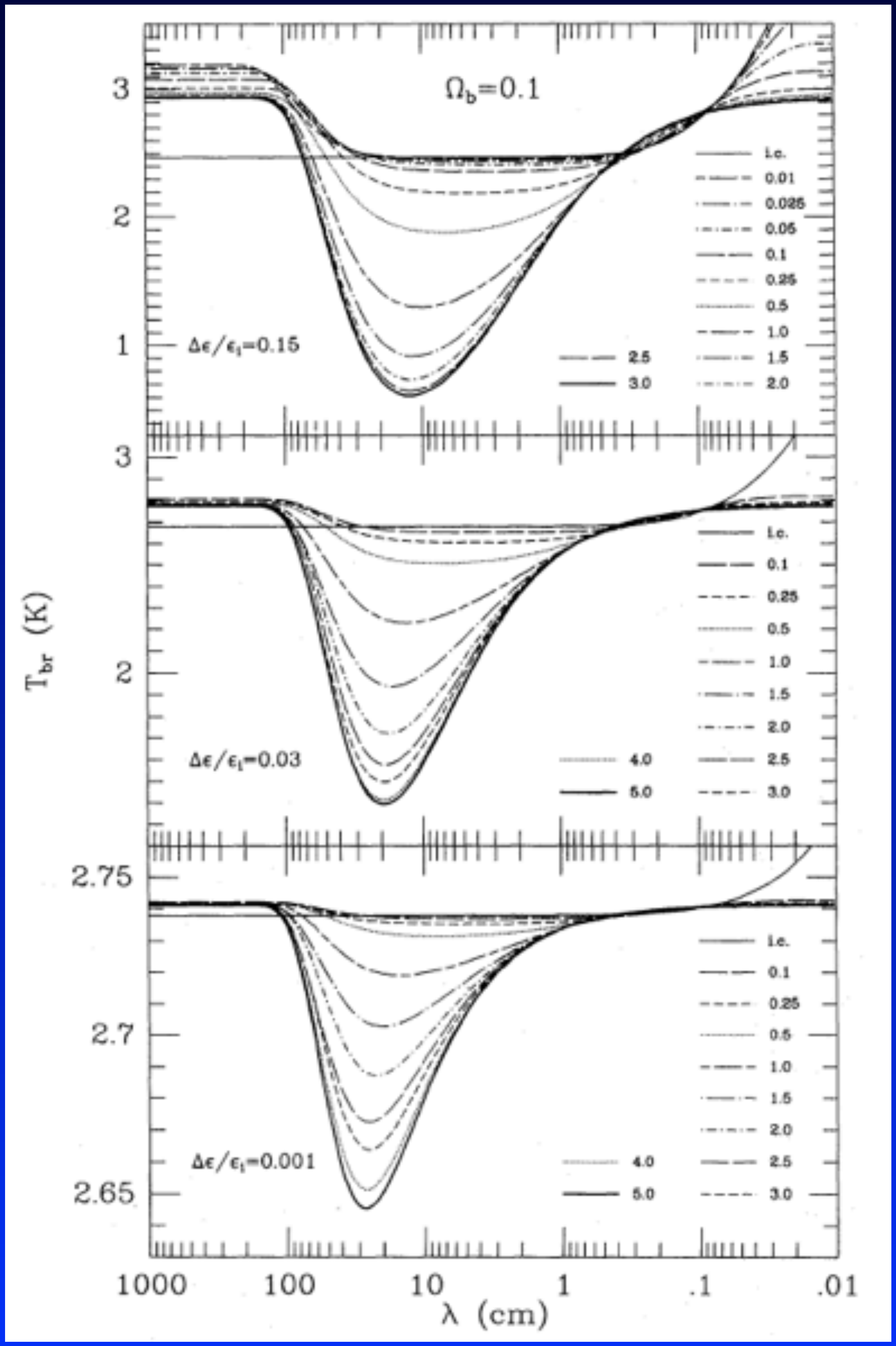
- Very simple example: $T_\gamma \sim (1+z) \Leftrightarrow T_m \sim (1+z)^2$
  - continuous *cooling* of photons down to $z\sim150$
  - due to huge heat capacity of photon field very small effect ($\Delta\rho/\rho \sim 10^{-10}$-$10^{-9}$)
- another simple example: *electron-positron annihilation* ($z\sim 10^8$-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)

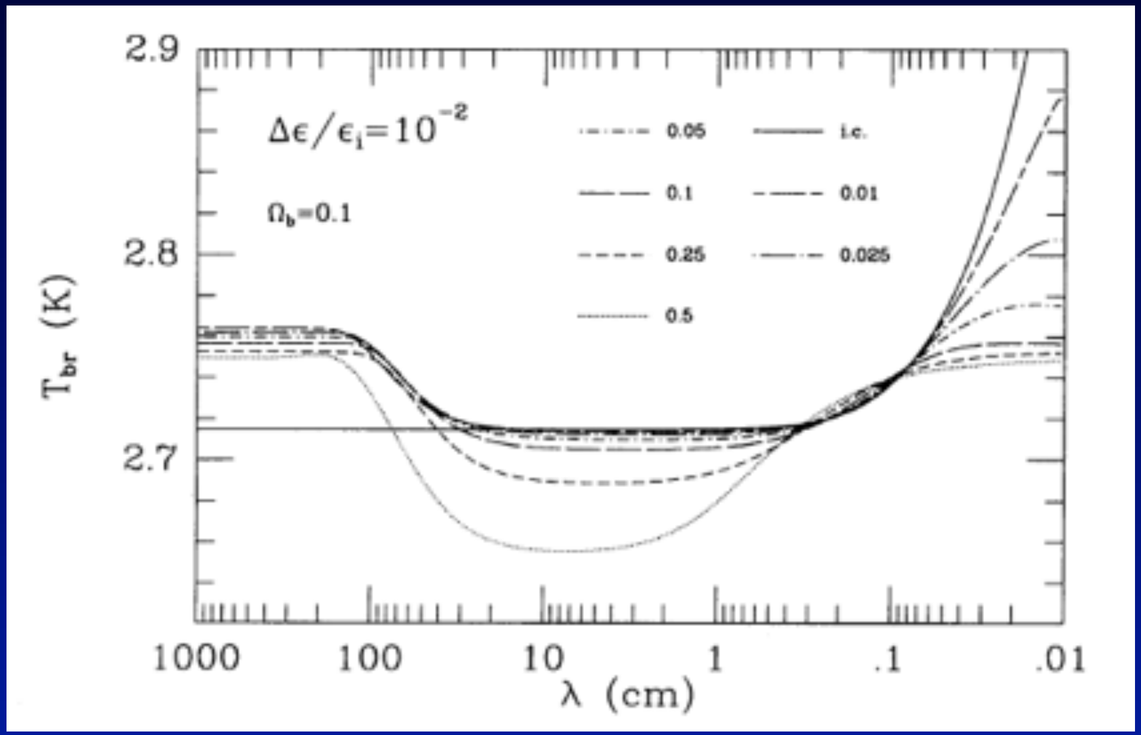
„high" redshifts

„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)

Thermalization from y → μ





- amount of energy

  ↔ amplitude of distortion

  ↔ position of 'dip'

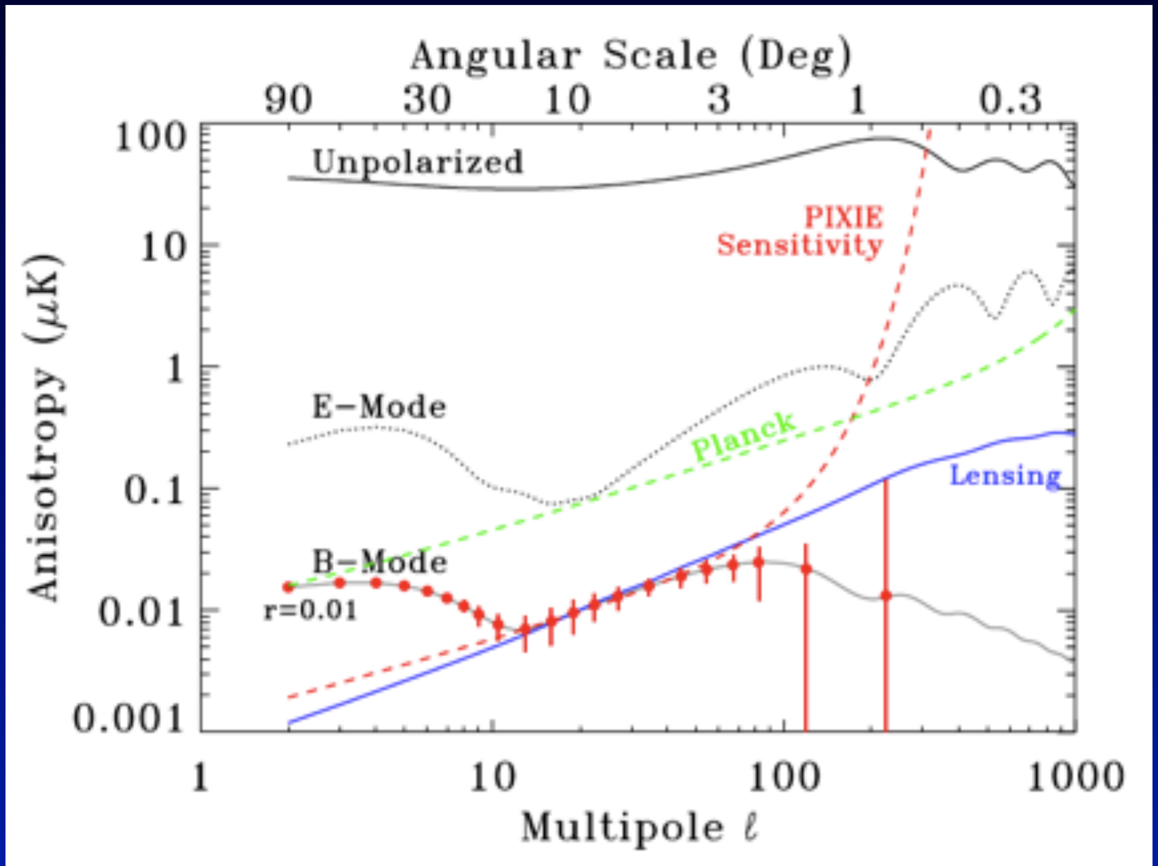
- Intermediate case ($3\text{x}10^5 \geq z \geq 6000$)

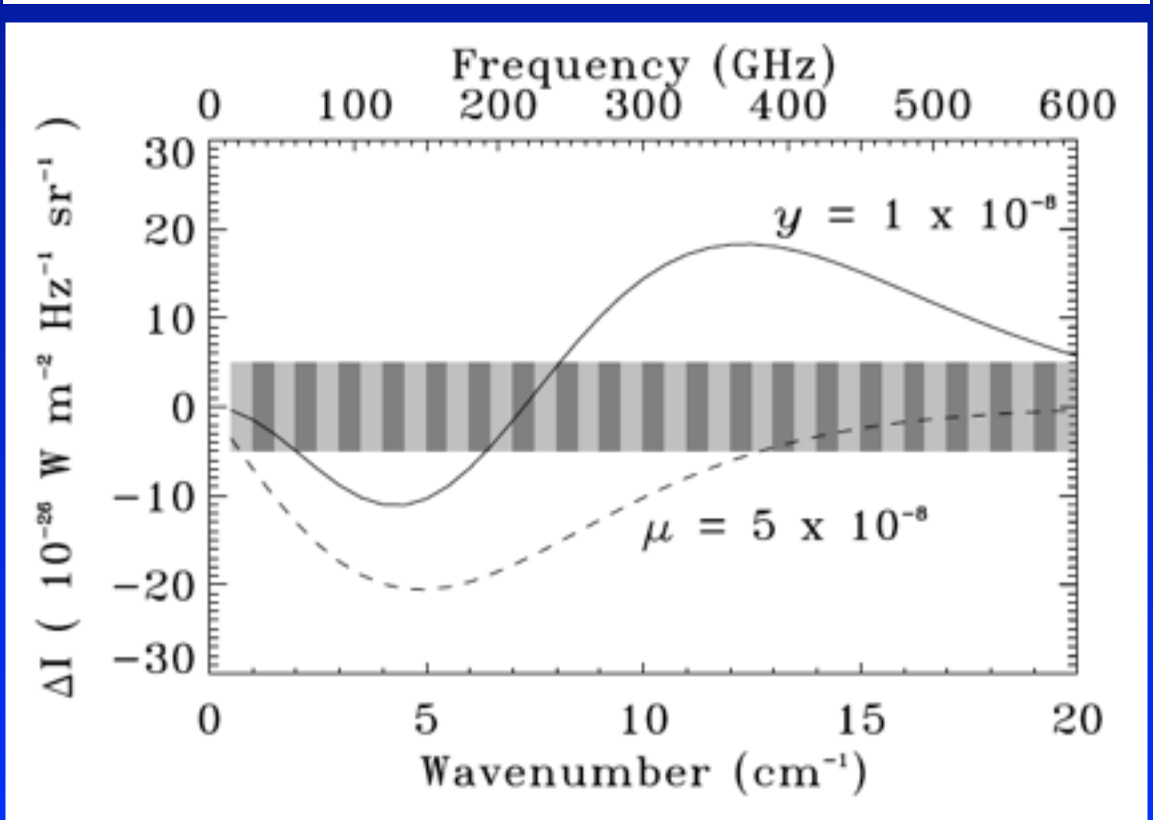
  ⇒ mixture between μ & y

- only details at low frequencies change!

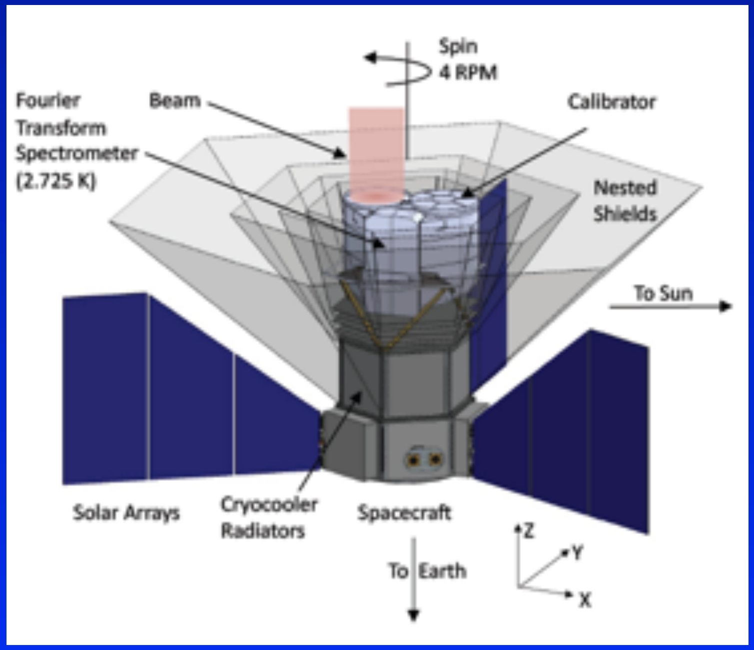
Burigana, De Zotti & Danese, 1991, ApJ
Burigana, Danese & De Zotti, 1991, A&A

PIXIE: Primordial Inflation Explorer



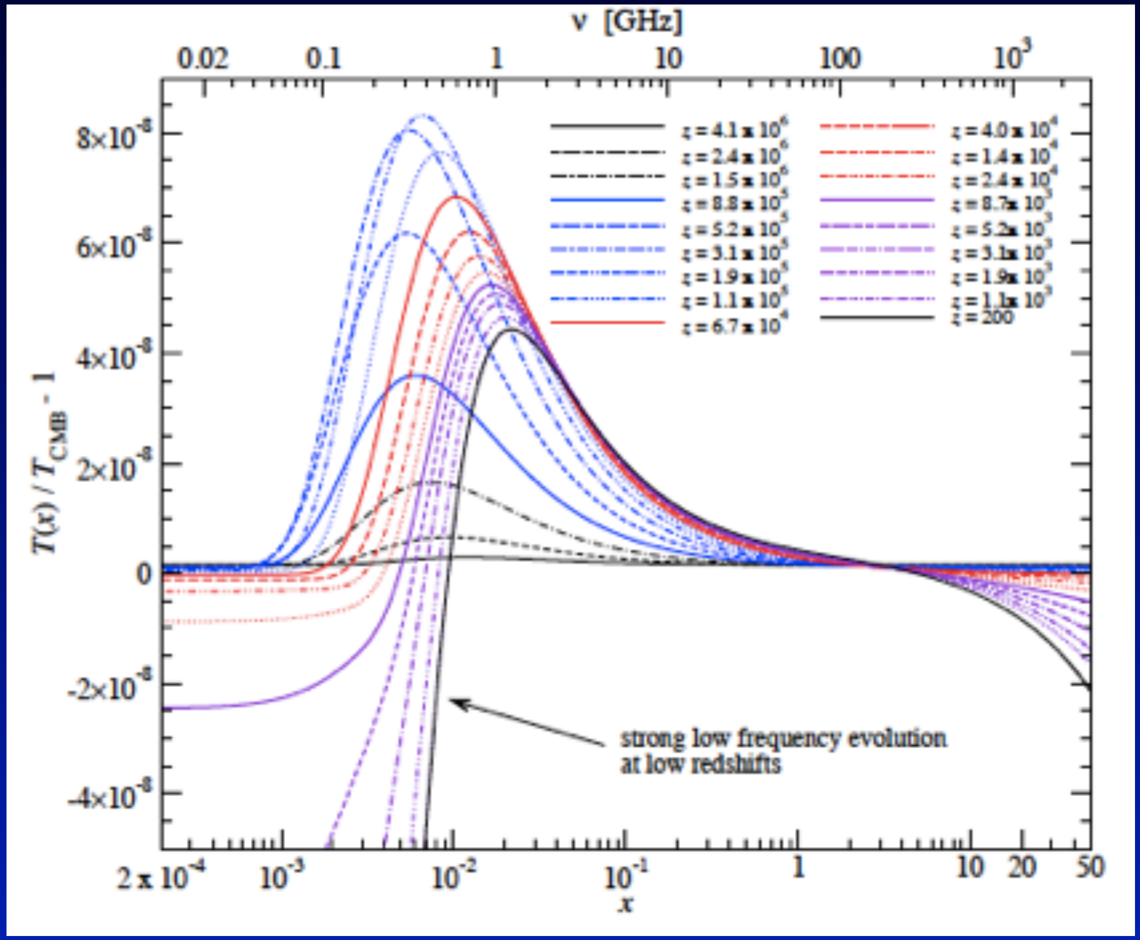


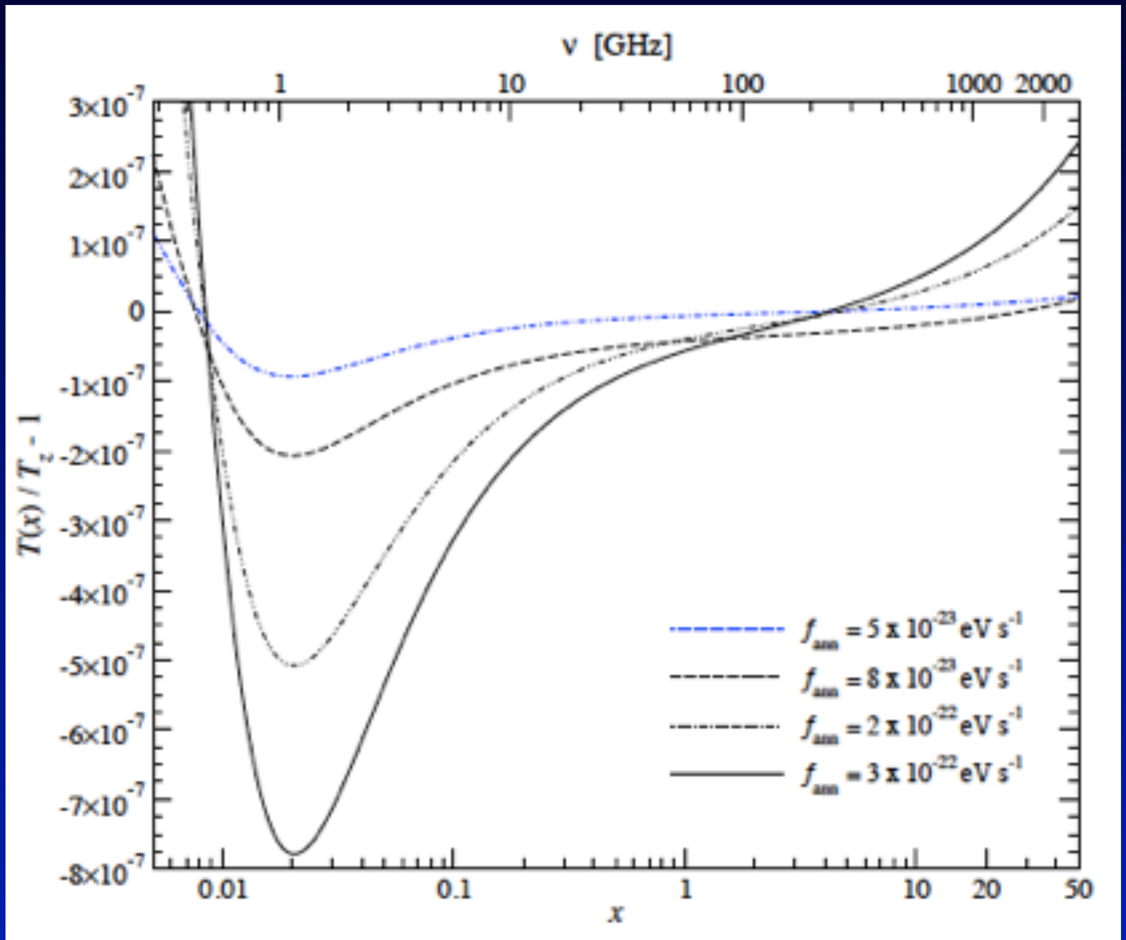
- 400 spectral channel in the frequency range 30 GHz and 6THz
- about 1000 times more sensitive than COBE/FIRAS
- B-mode polarization from inflation
- improved limits on μ and y
- y-signal from reionization
- recombination signal with 'template'



Kogut et al, 2011, arXiv:1105.2044

Improved Thermalization Calculations





- Solved for small distortions in agreement with COBE/FIRAS limits and PIXIE sensitivities
- Improved treatment of emission and absorption processes (double Compton/Bremsstrahlung)
- Took into account detailed time-dependence of the energy release process
- New thermalization code *CosmoTherm* should be useful for forecasts for PIXIE

JC & Sunyaev, 2011

Another Example: Energy Release in the Early Universe

Full thermodynamic equilibrium (certainly valid at very high redshifts)

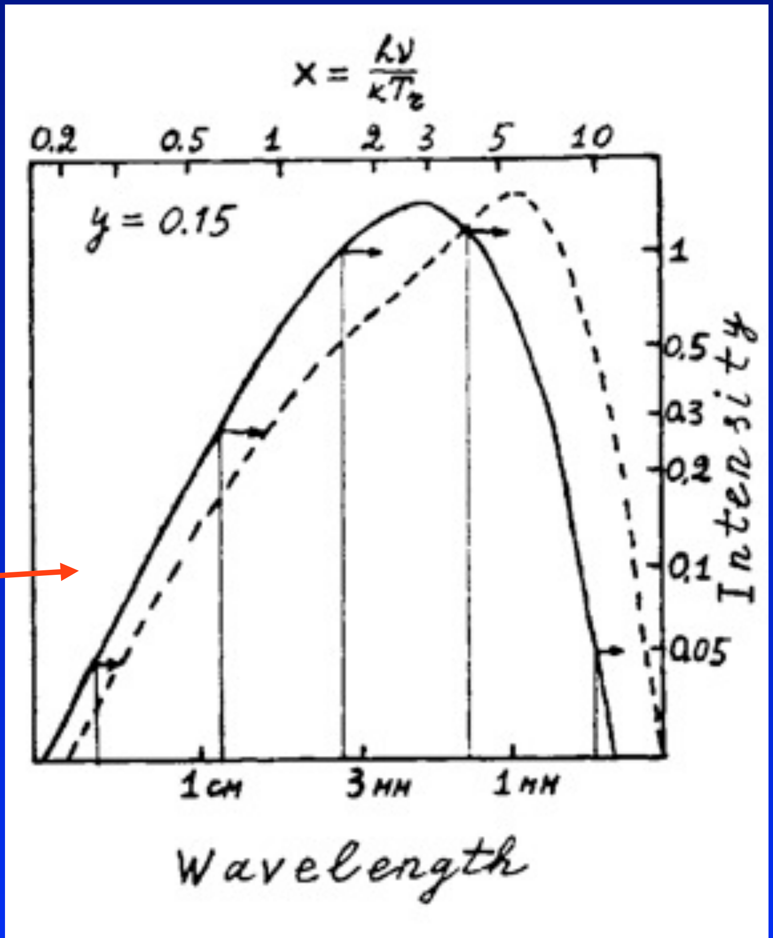
- CMB has a blackbody spectrum at every time (not affected by expansion!!!)
- Photon number density and energy density determined by temperature T_γ

Disturbance of full equilibrium for example by

- Energy injection (e.g. *decaying particles* or *phase transitions*)
- Production of (energetic) photons and/or particles

→CMB spectrum would deviate from a pure blackbody today!

- „Early“ energy release ($z \gtrsim 50000$)
  $\Rightarrow$ μ-type distortion
- „Late“ energy release ($z \lesssim 50000$)
  $\Rightarrow$ *y*-type distortion
- Cobe/Firas spectral measurements
  (Mather et al., 1996; Fixsen et al. 1996; Fixsen et al. 2002)
  → $|y| \leq 1.5 \times 10^{-5}$



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

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, JC & Sunyaev 2011)

  → Spectral distortions are *broad* and *featureless*

  → Absolute (COBE-type) measurements are required

- Different injection histories yield to rather 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.

  } ⇒ y-distortion

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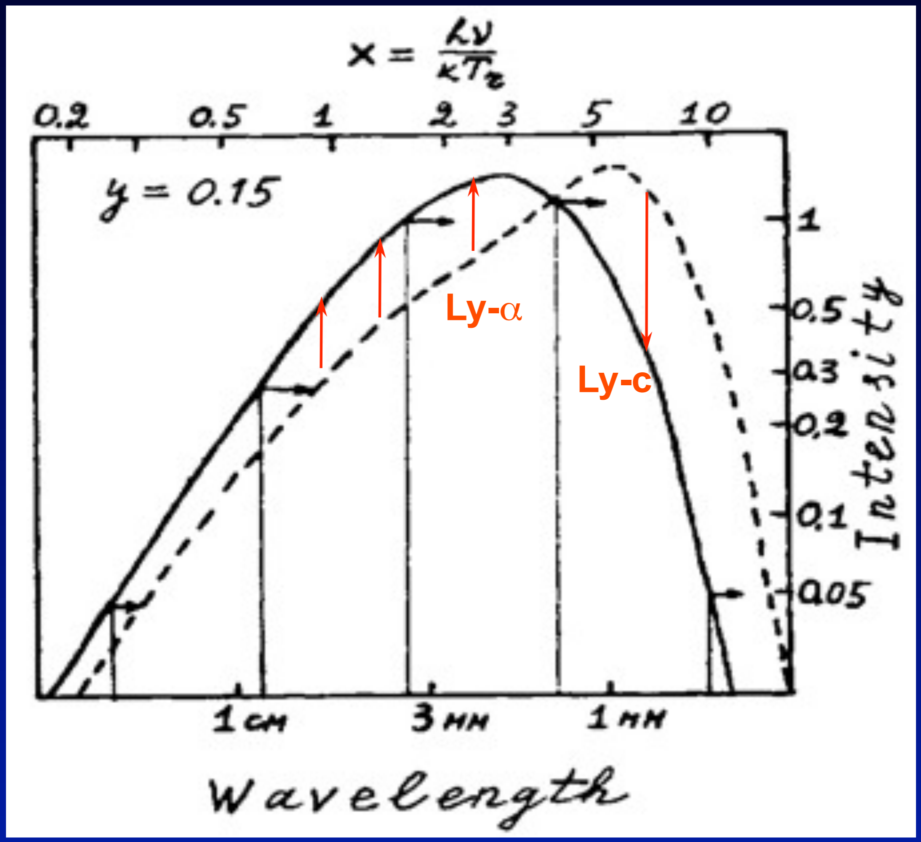
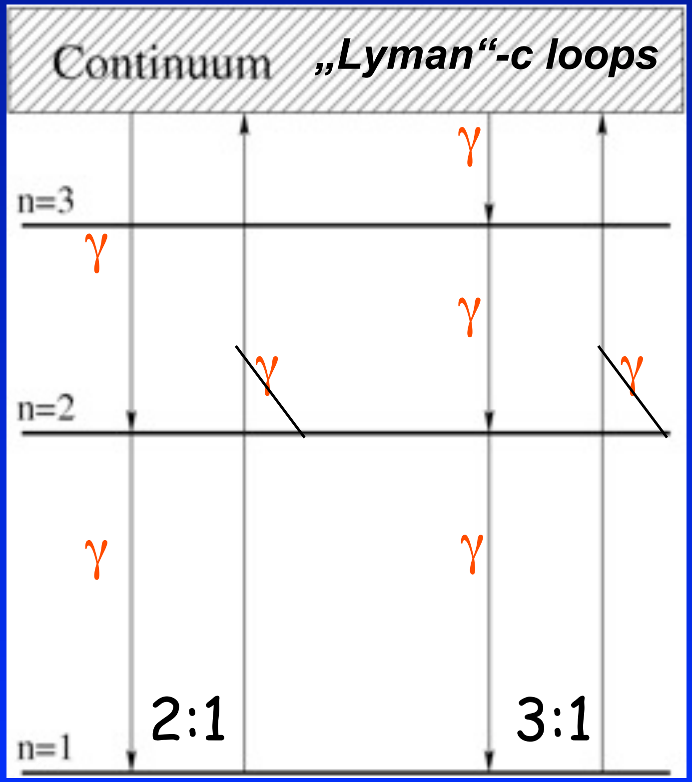
Absence of *narrow spectral features* makes it very hard to understand real details!!!

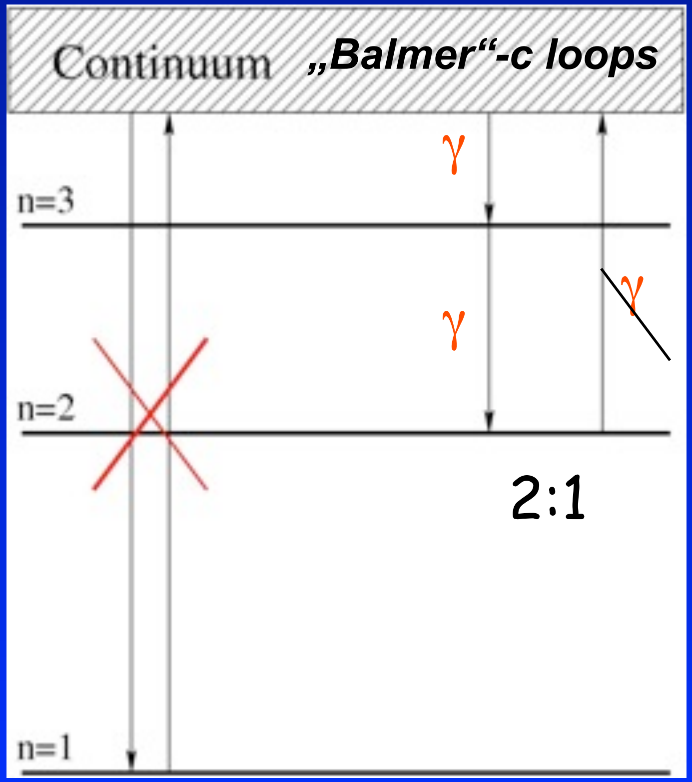
Pre-recombinational atomic transitions after possible early energy release

- 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
  → loops mainly end in Lyman-continuum
  → Balmer-cont. loops work just before recombination



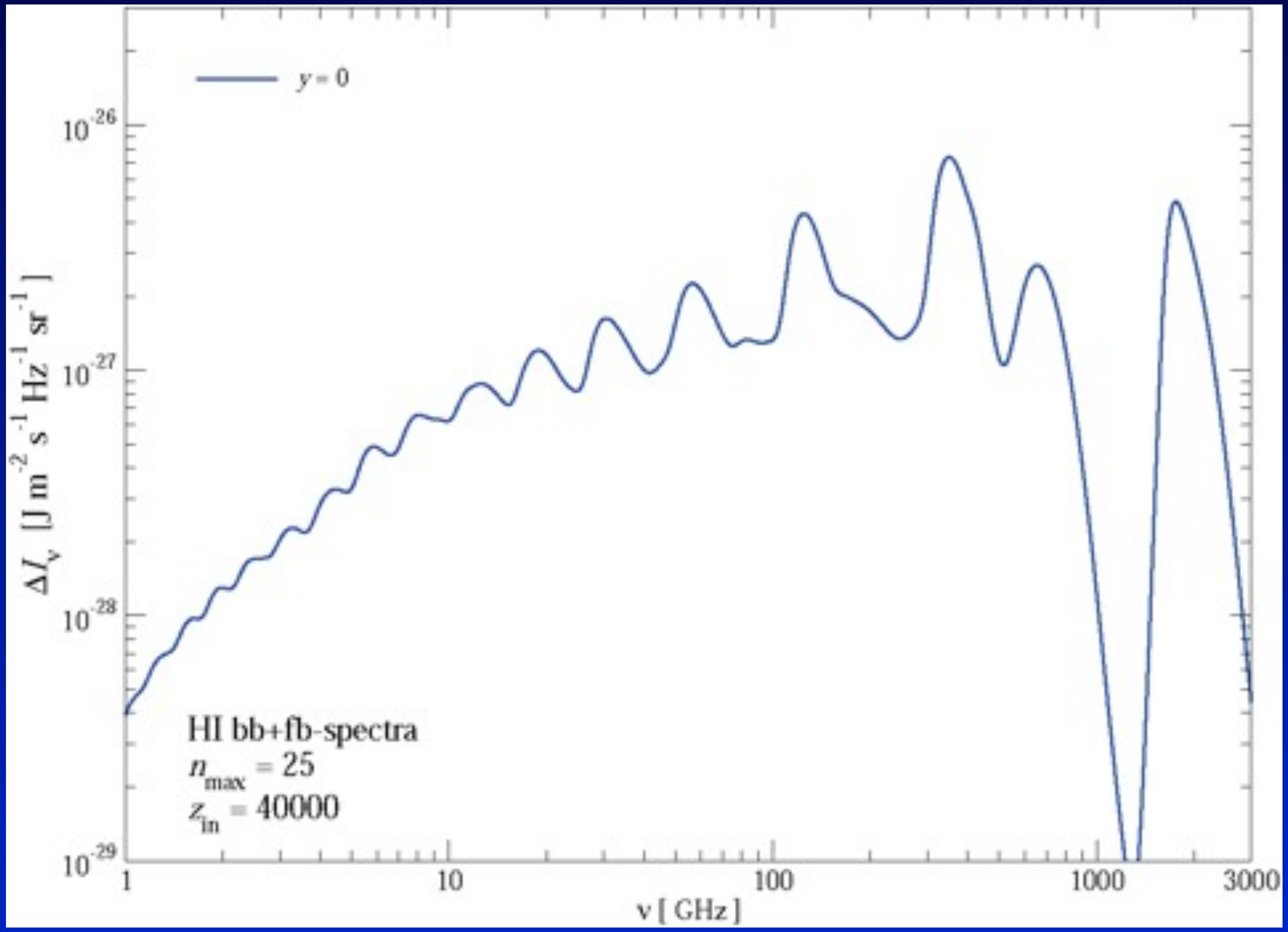




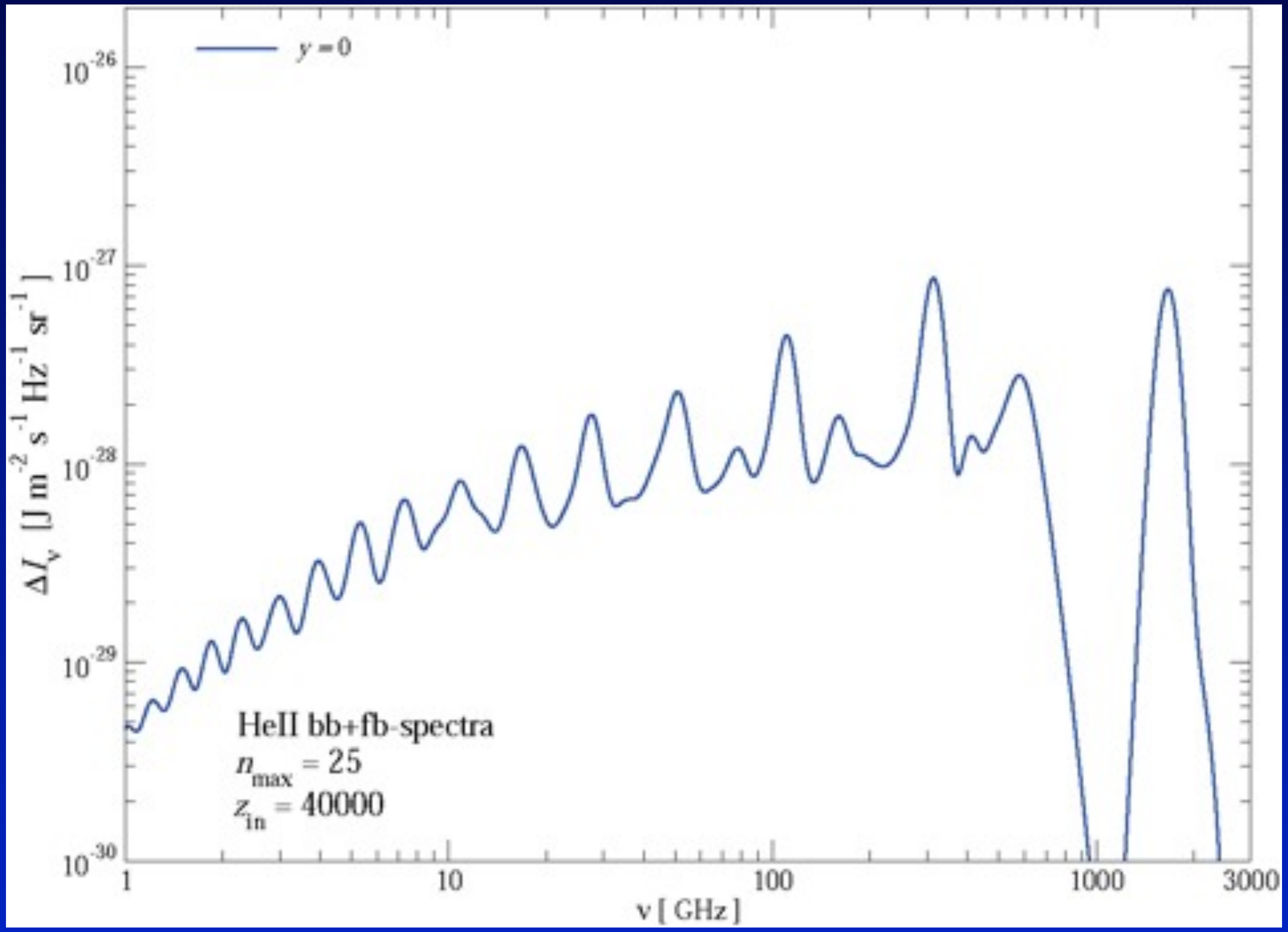
CMB spectral distortions after single energy release

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

Hydrogen



Helium +



JC & Sunyaev, 2008, astro-ph/0803.3584

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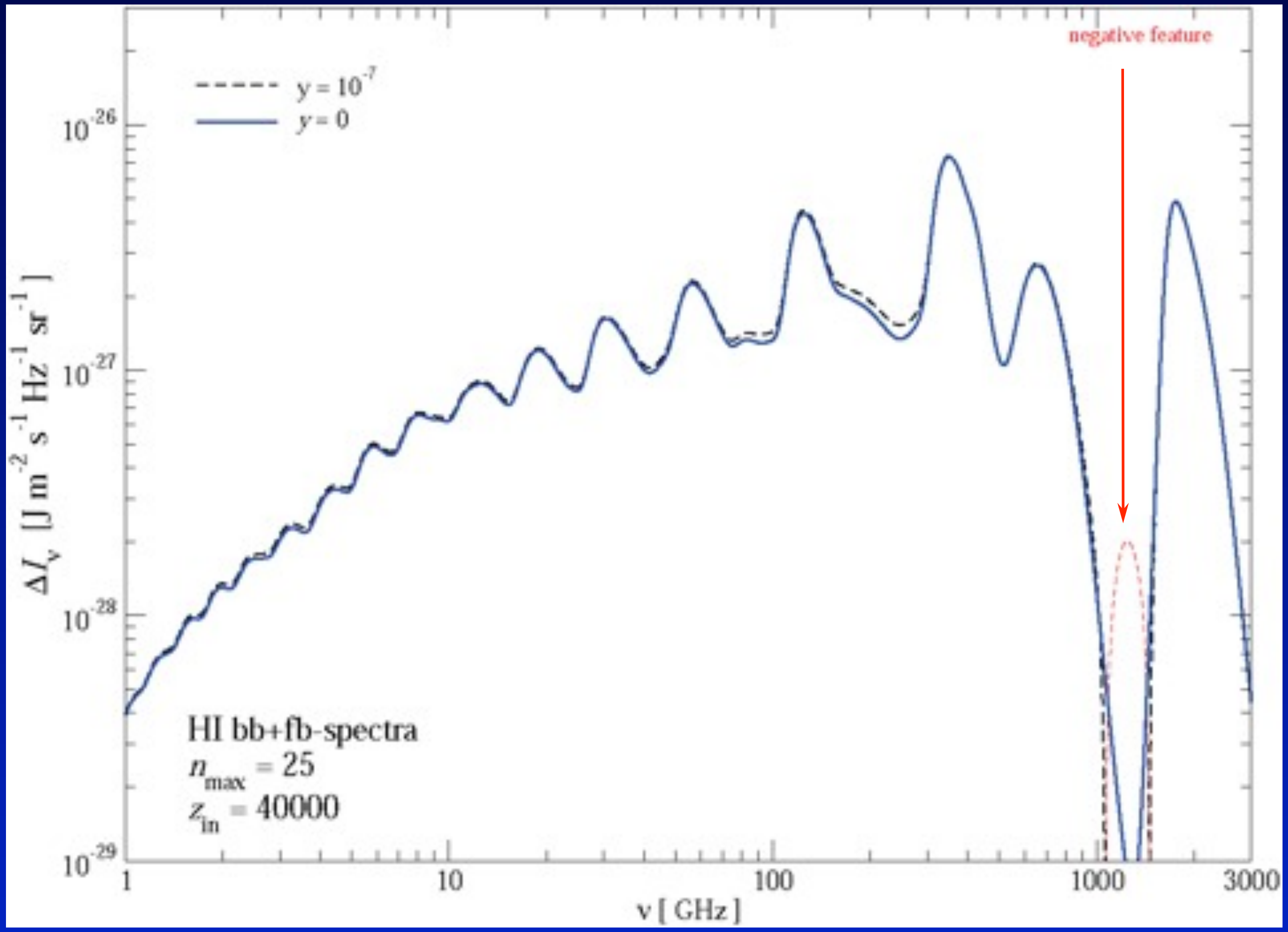
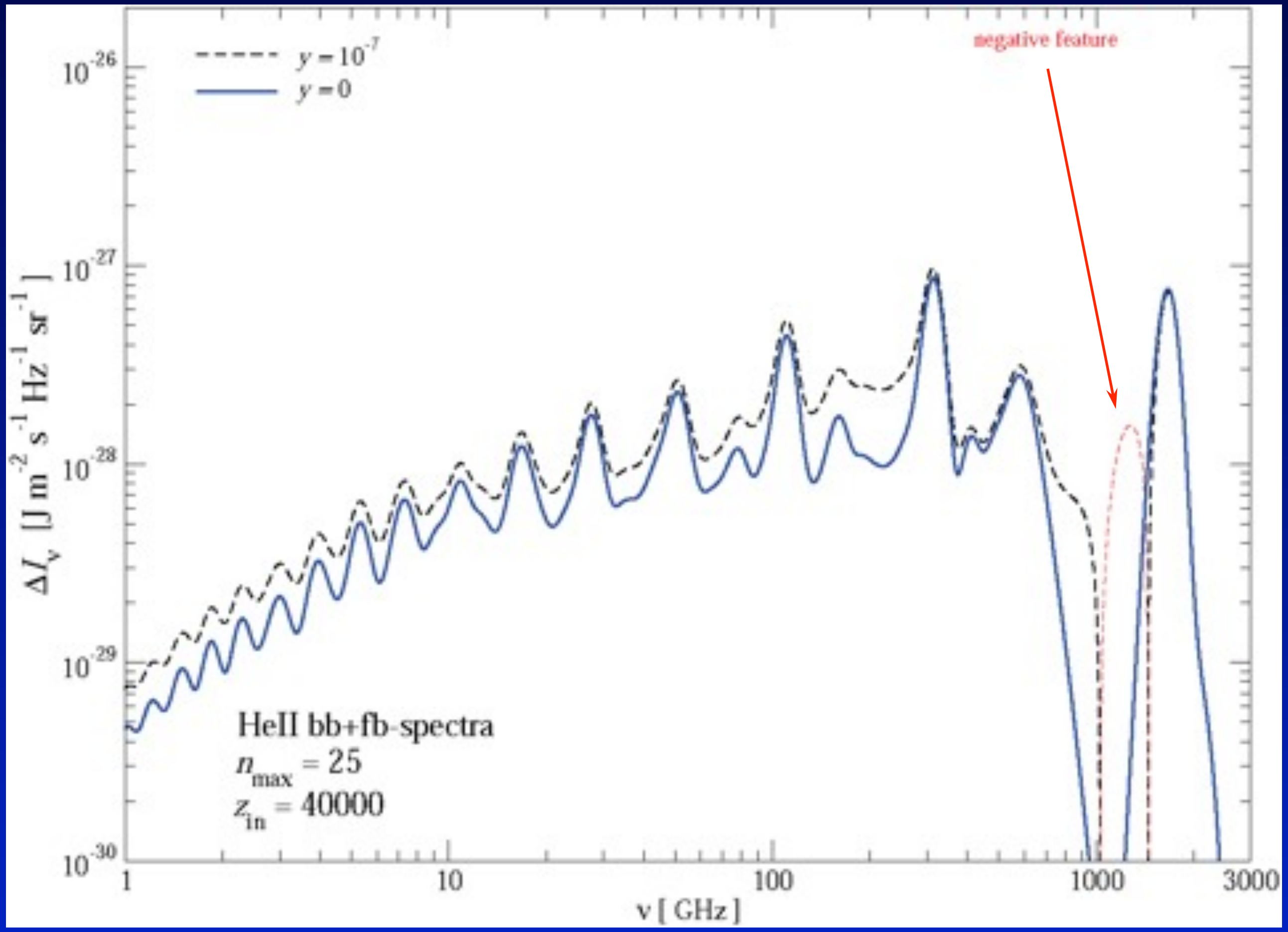


Helium +



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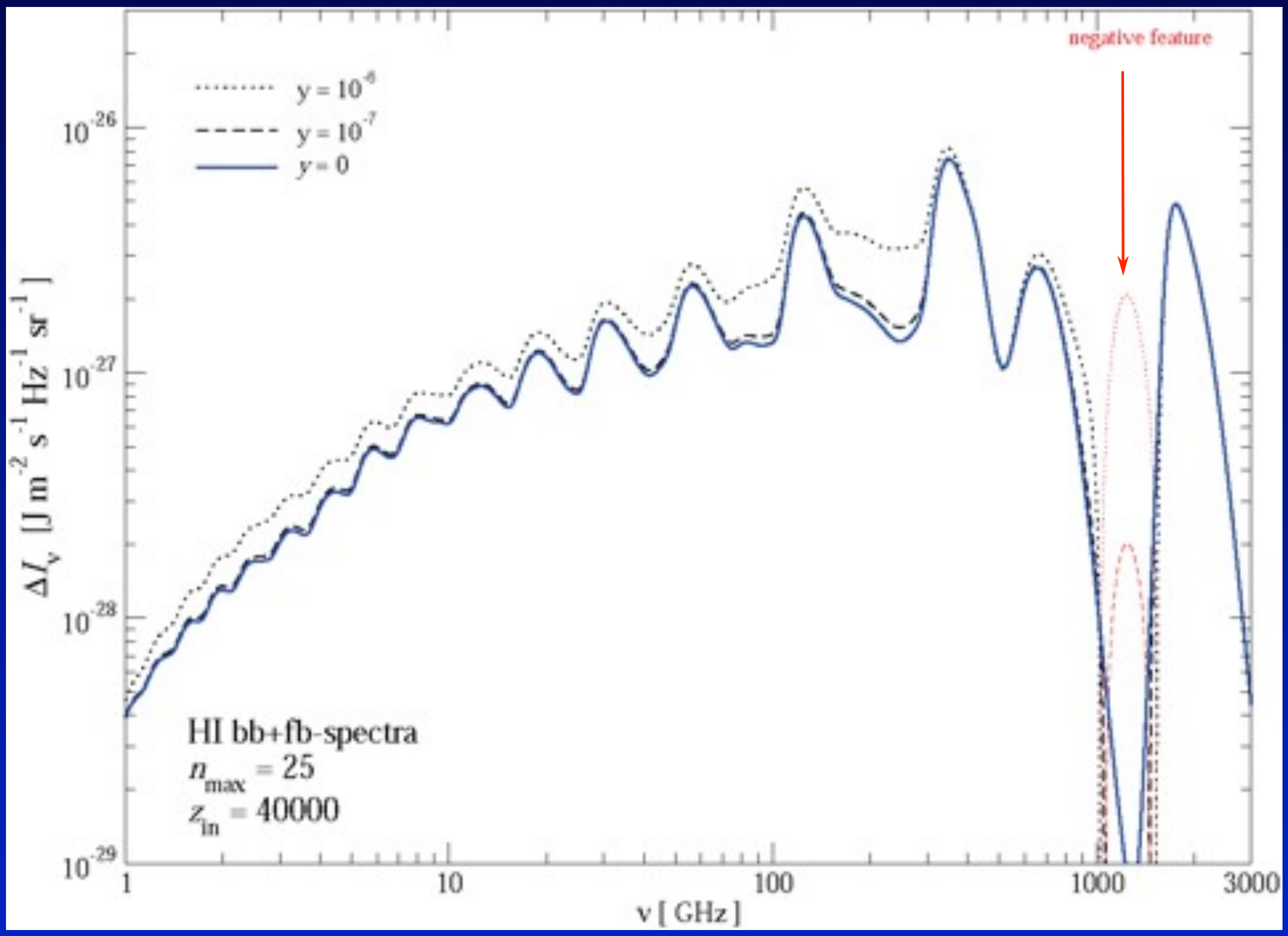
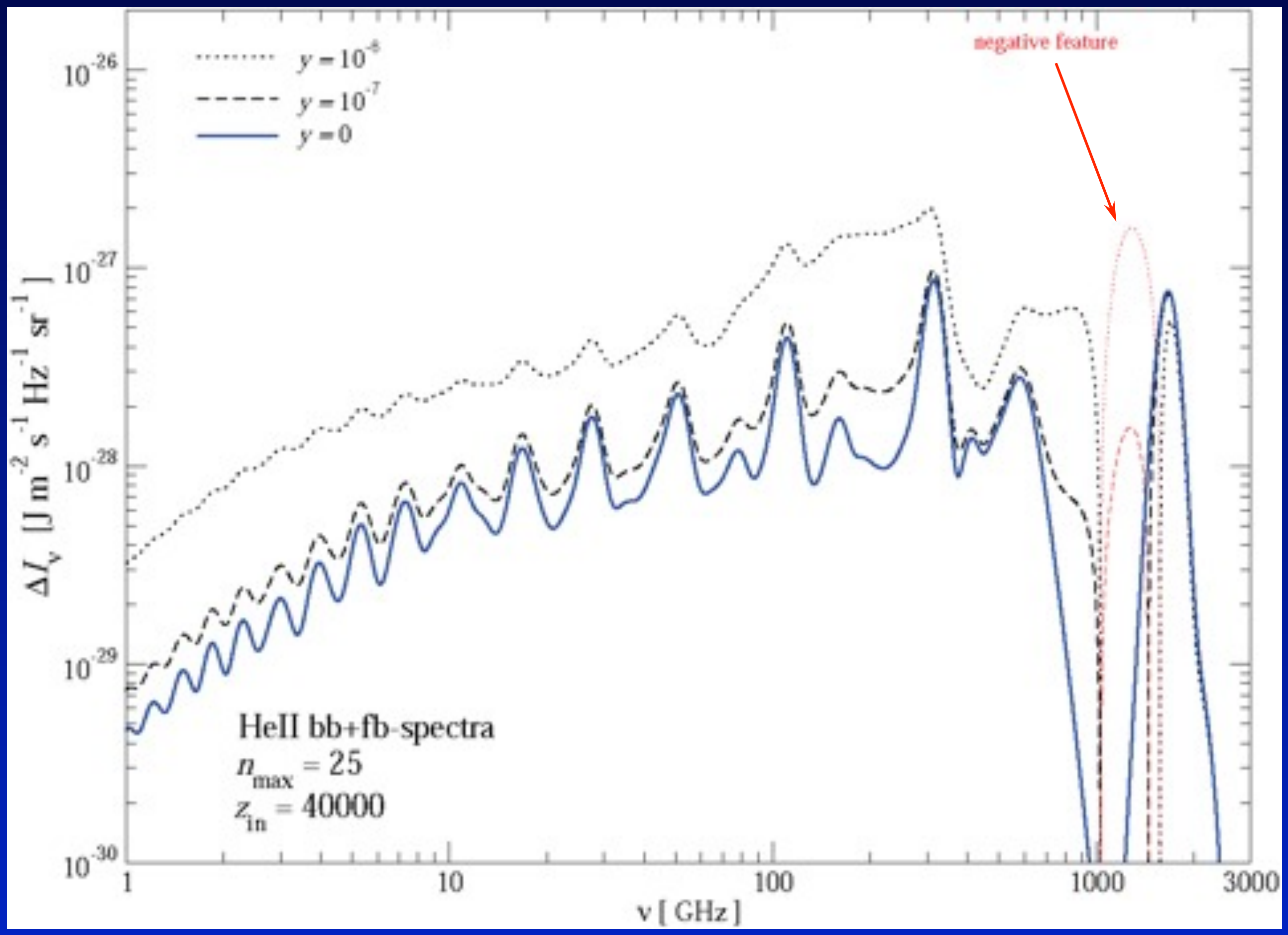


Helium +



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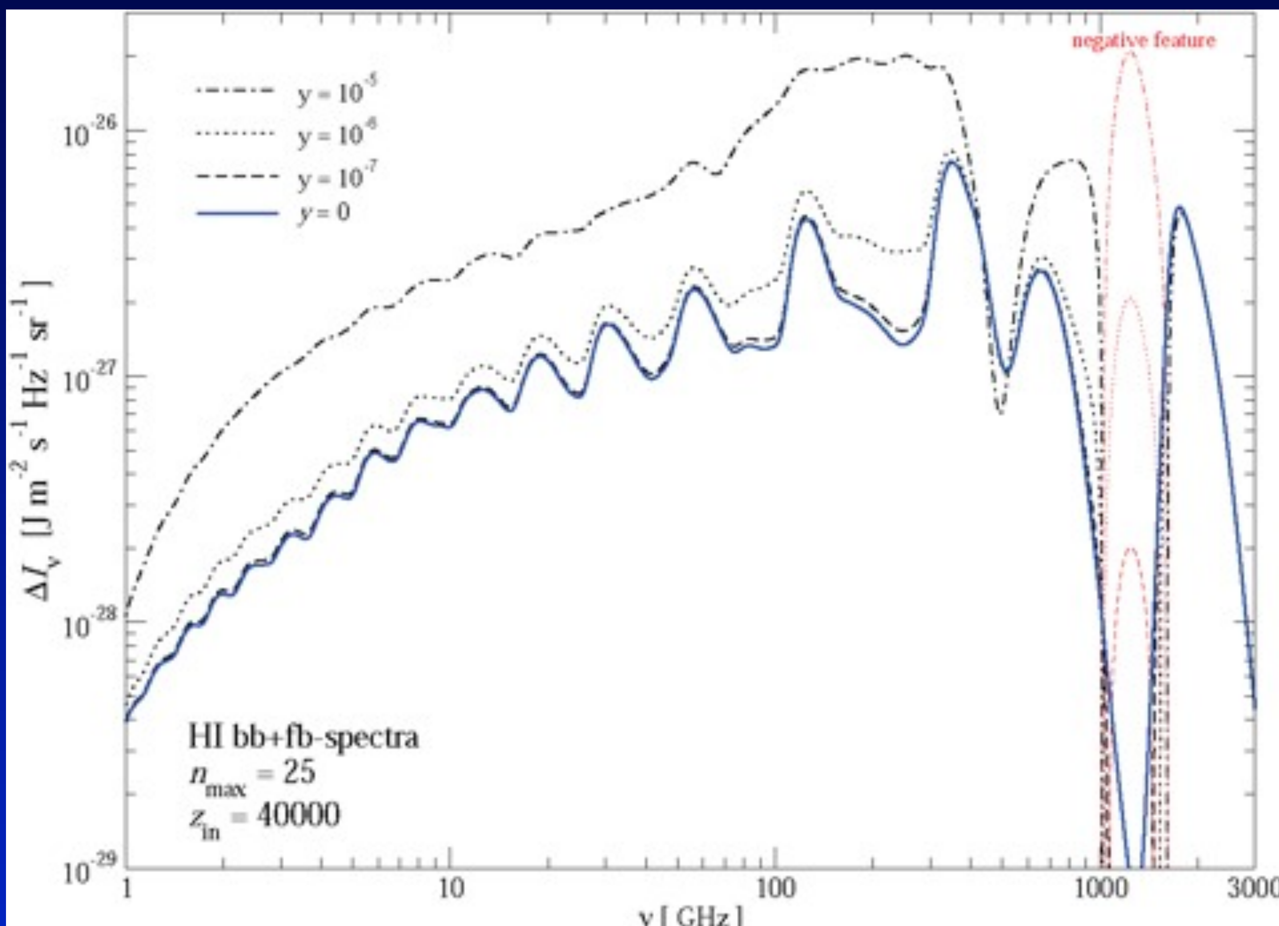
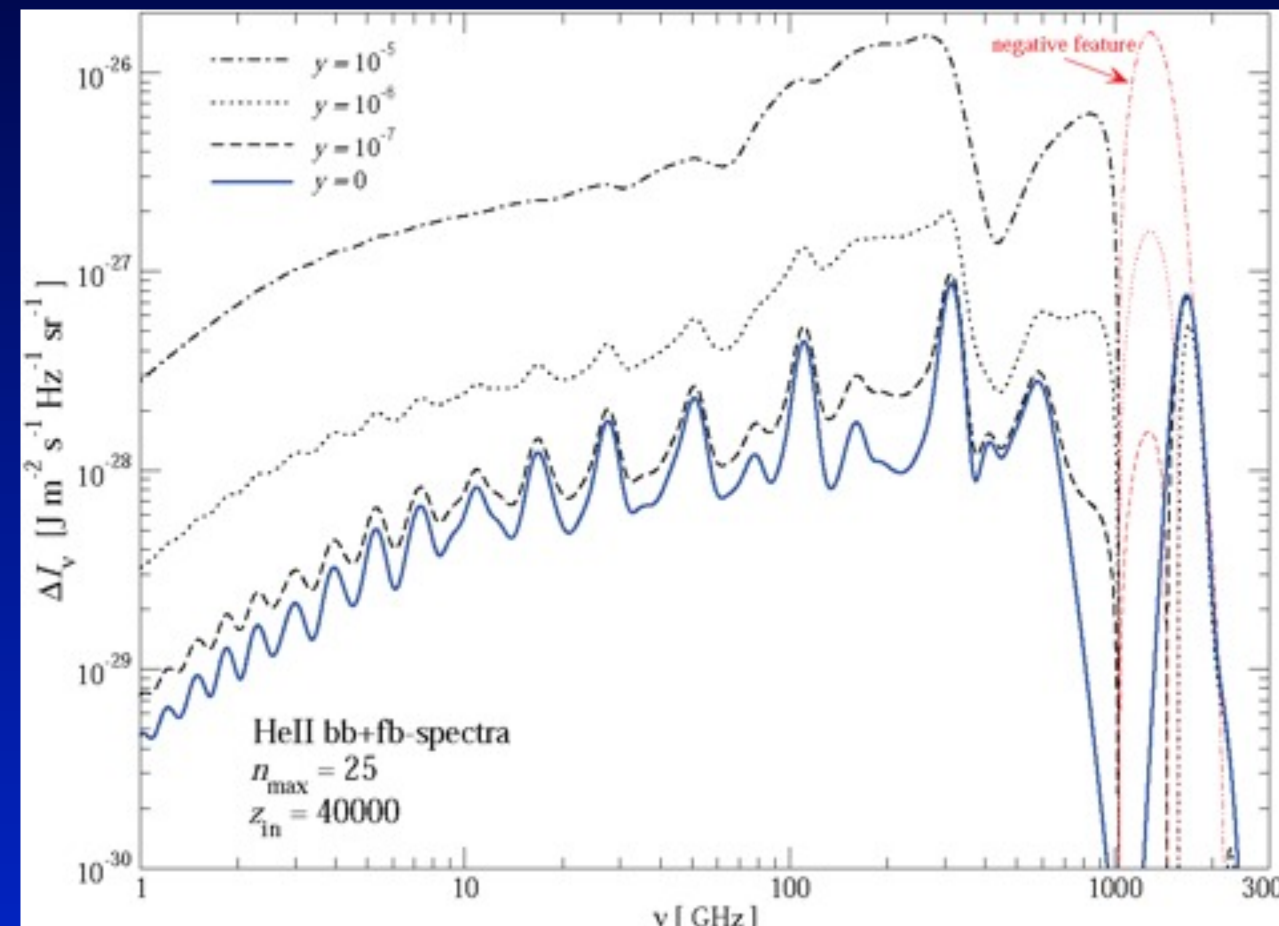


Helium +



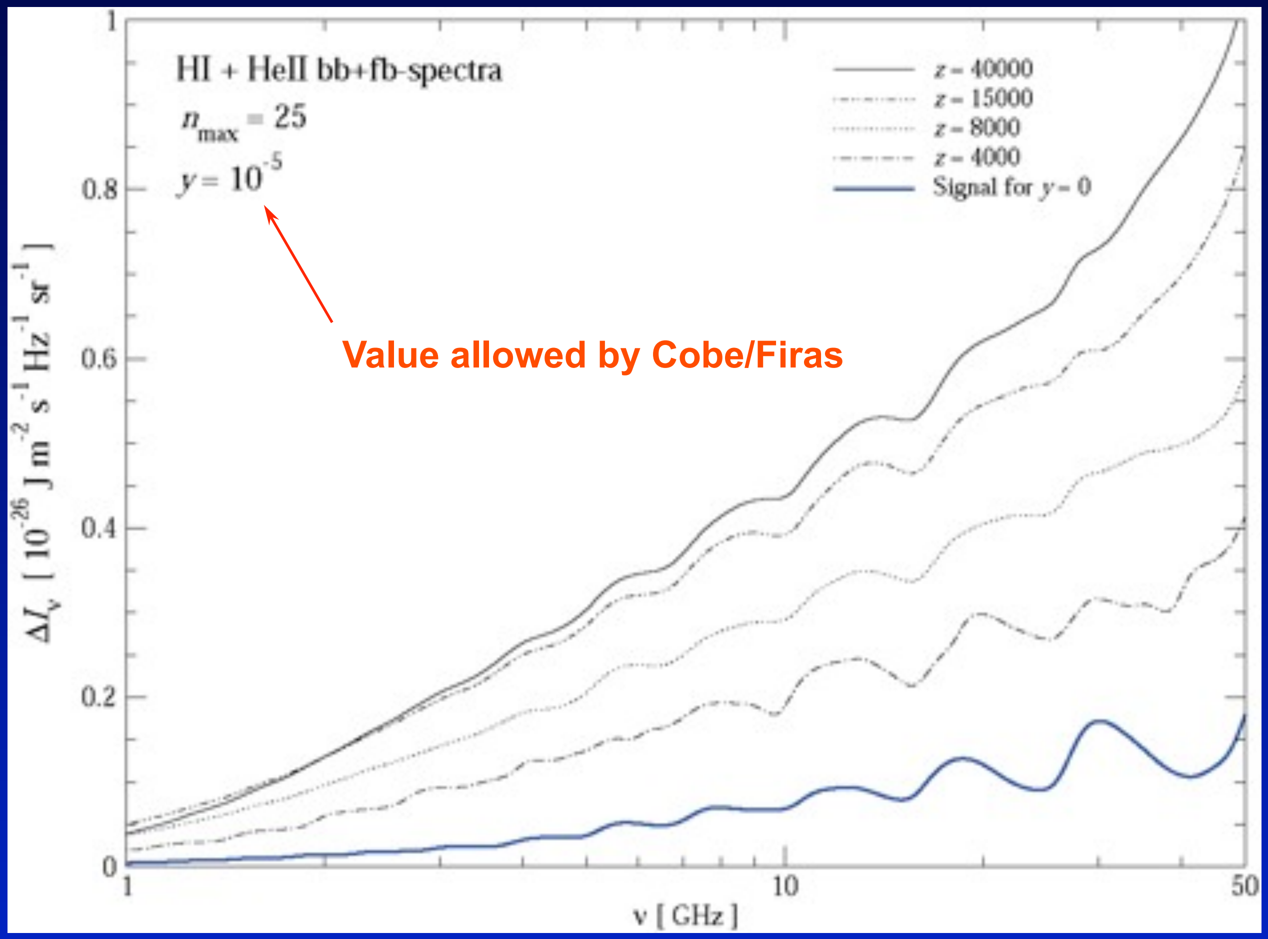
JC & Sunyaev, 2008, astro-ph/0803.3584

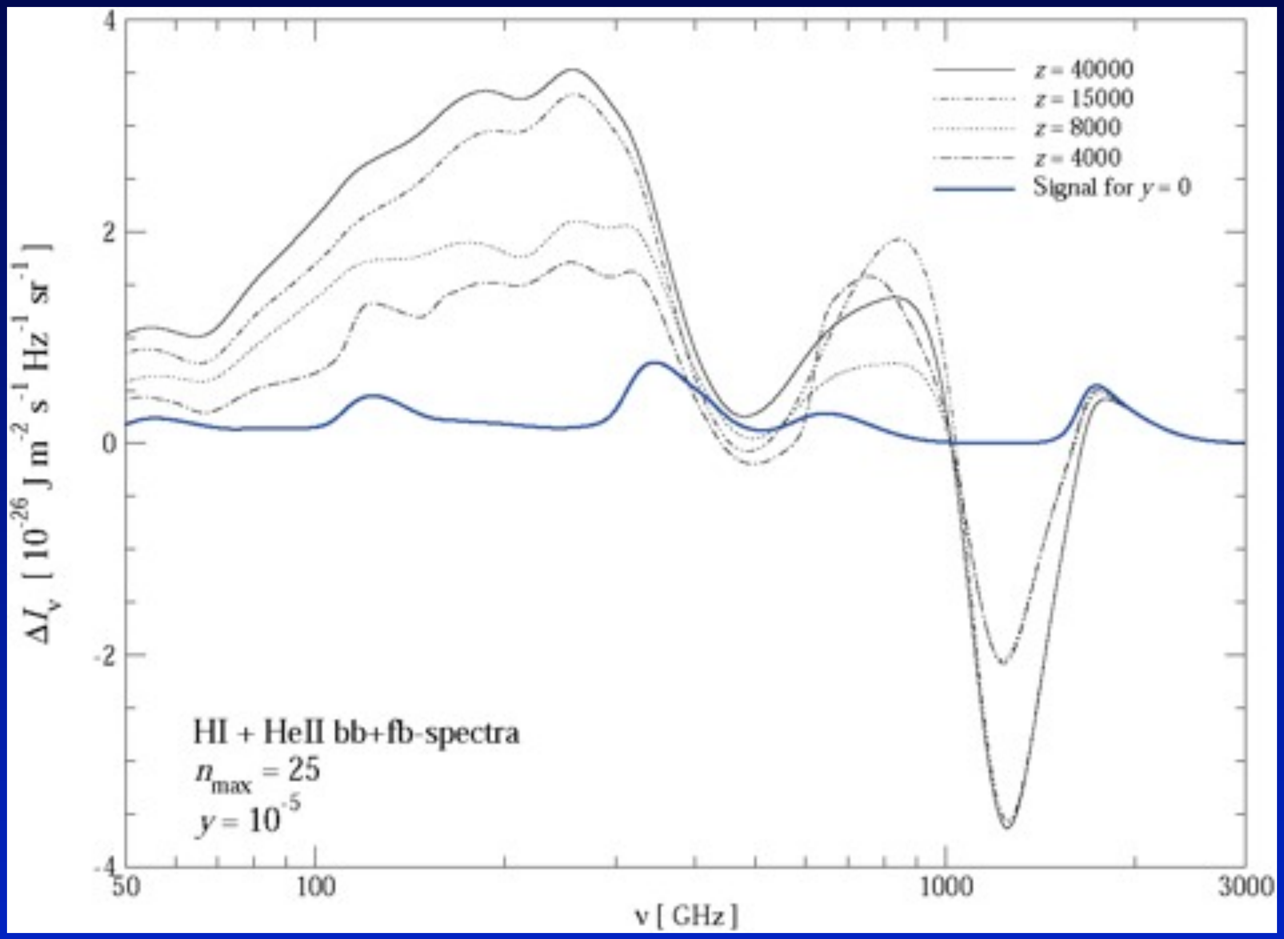
- Large increase in the total amplitude of the distortions with value of *y*!
- Strong emission-absorption feature in the Wien-part of CMB (absent for *y*=0!!!)
- HeII contribution to the pre-recombinational emission as strong as the one from Hydrogen alone !

CMB spectral distortions after single energy release

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

Hydrogen and Helium +





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?

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***

If something unexpected or non-standard happened:

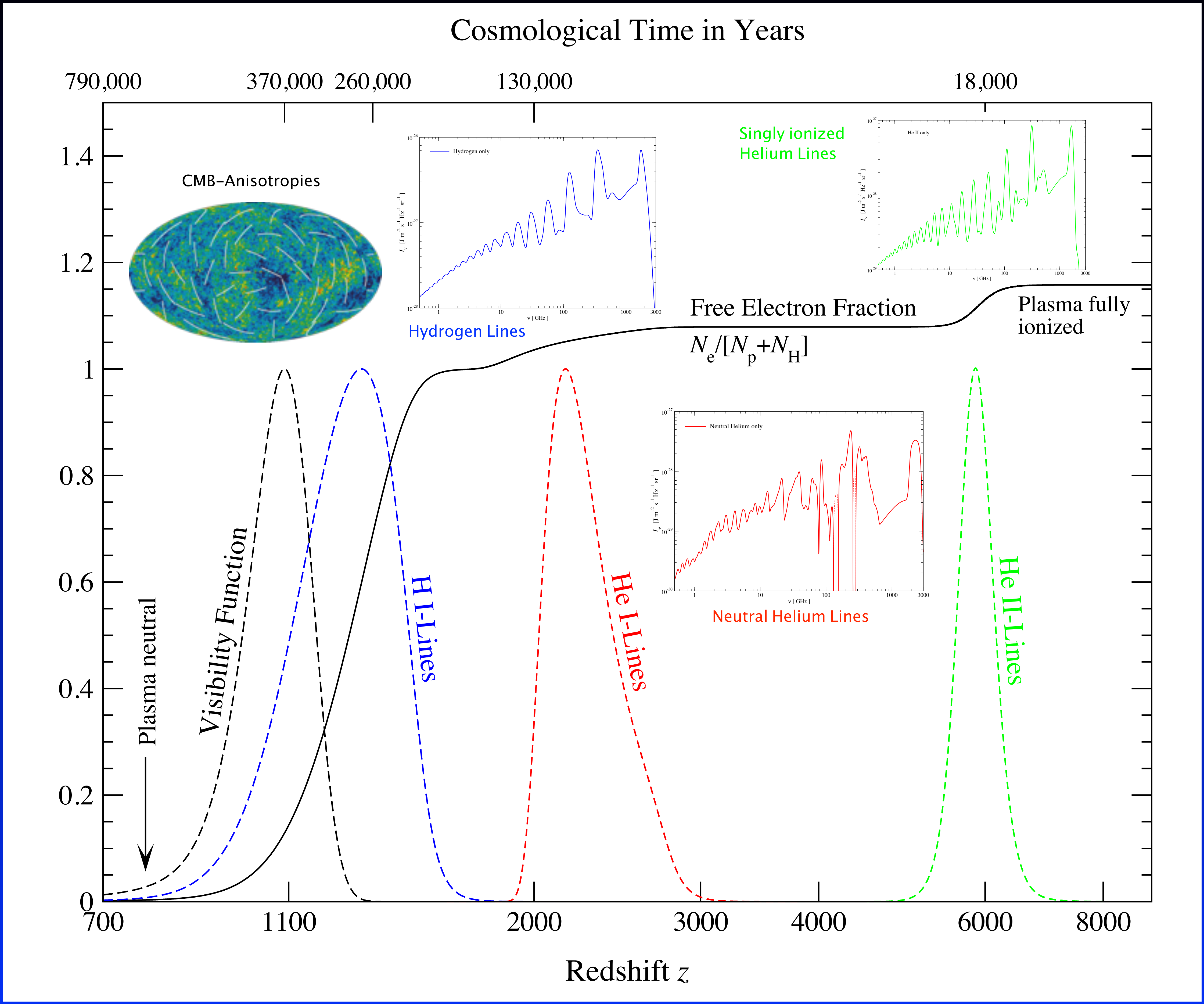
→ ***non-standard thermal histories should leave some measurable traces***

→ ***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**



Cosmological Time in Years
790,000
370,000
260,000
130,000
18,000
CMB–Anisotropies
Hydrogen Lines
Singly ionized Helium Lines
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully ionized
Neutral Helium Lines
Visibility Function
Plasma neutral
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