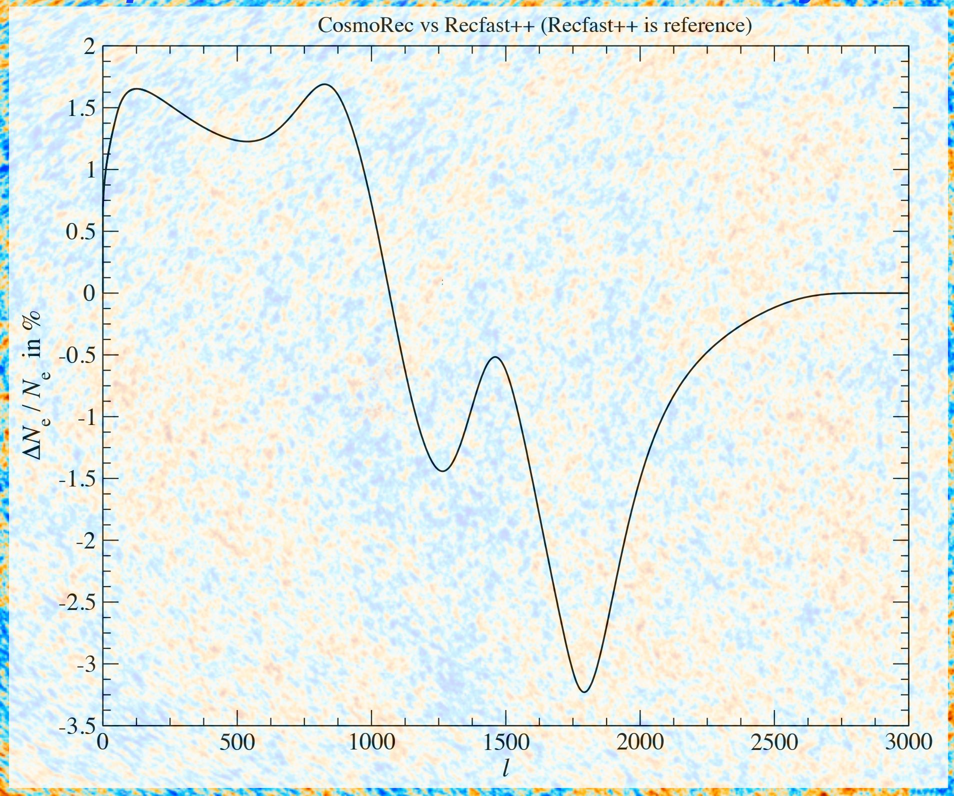
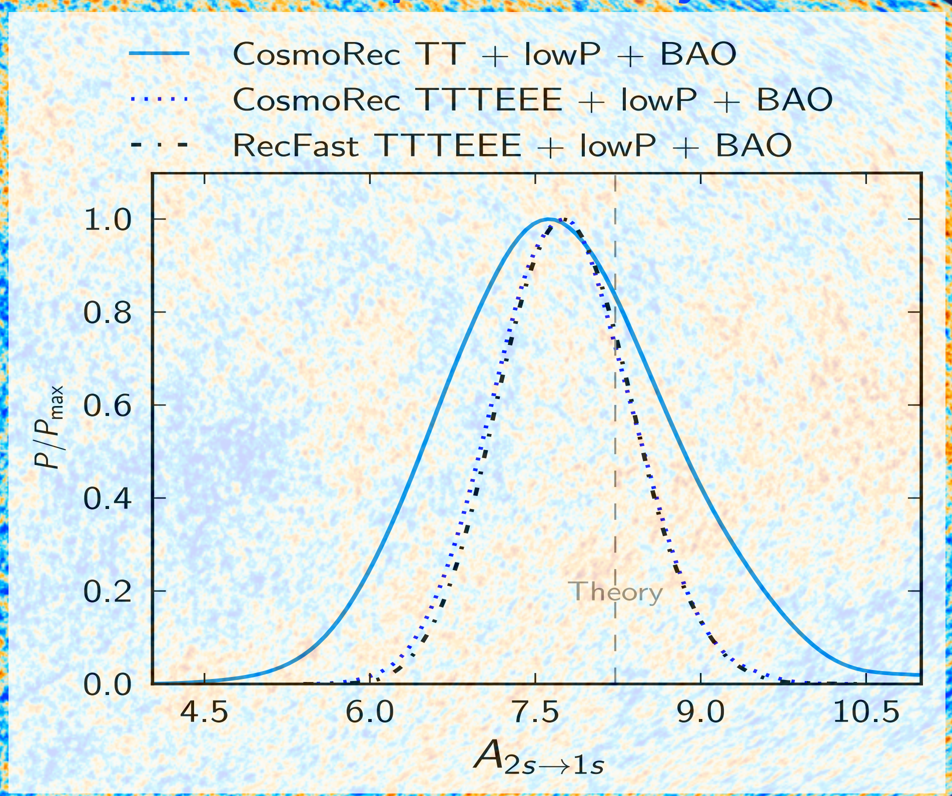
Introduction to Recombination Physics and Why it is Important for Cosmology and Early-Universe Physics





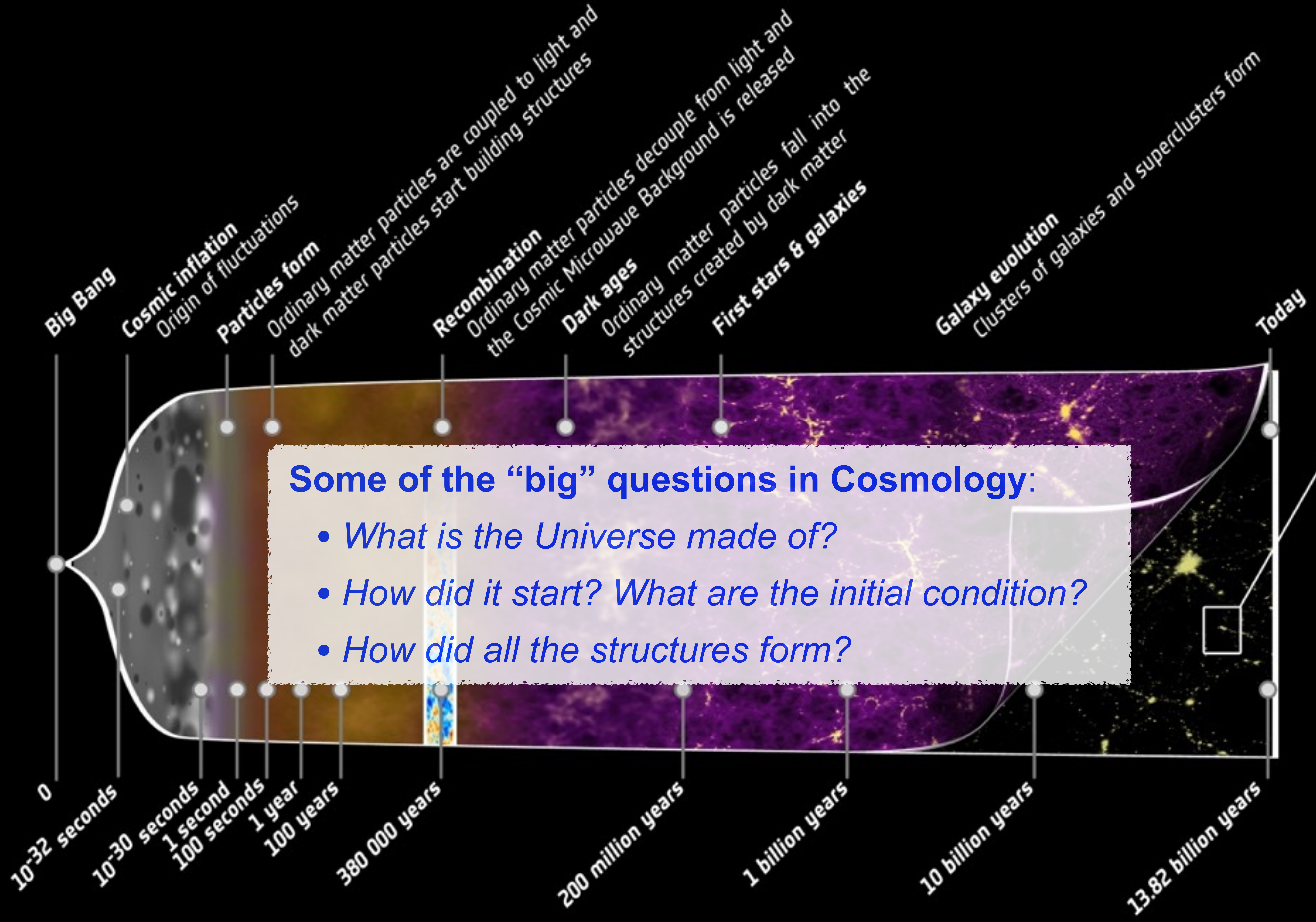
MANCHESTER 1824
The University of Manchester

Jens Chluba

CosmoTools 2018

Aachen, Germany, April 23th - 27th, 2018

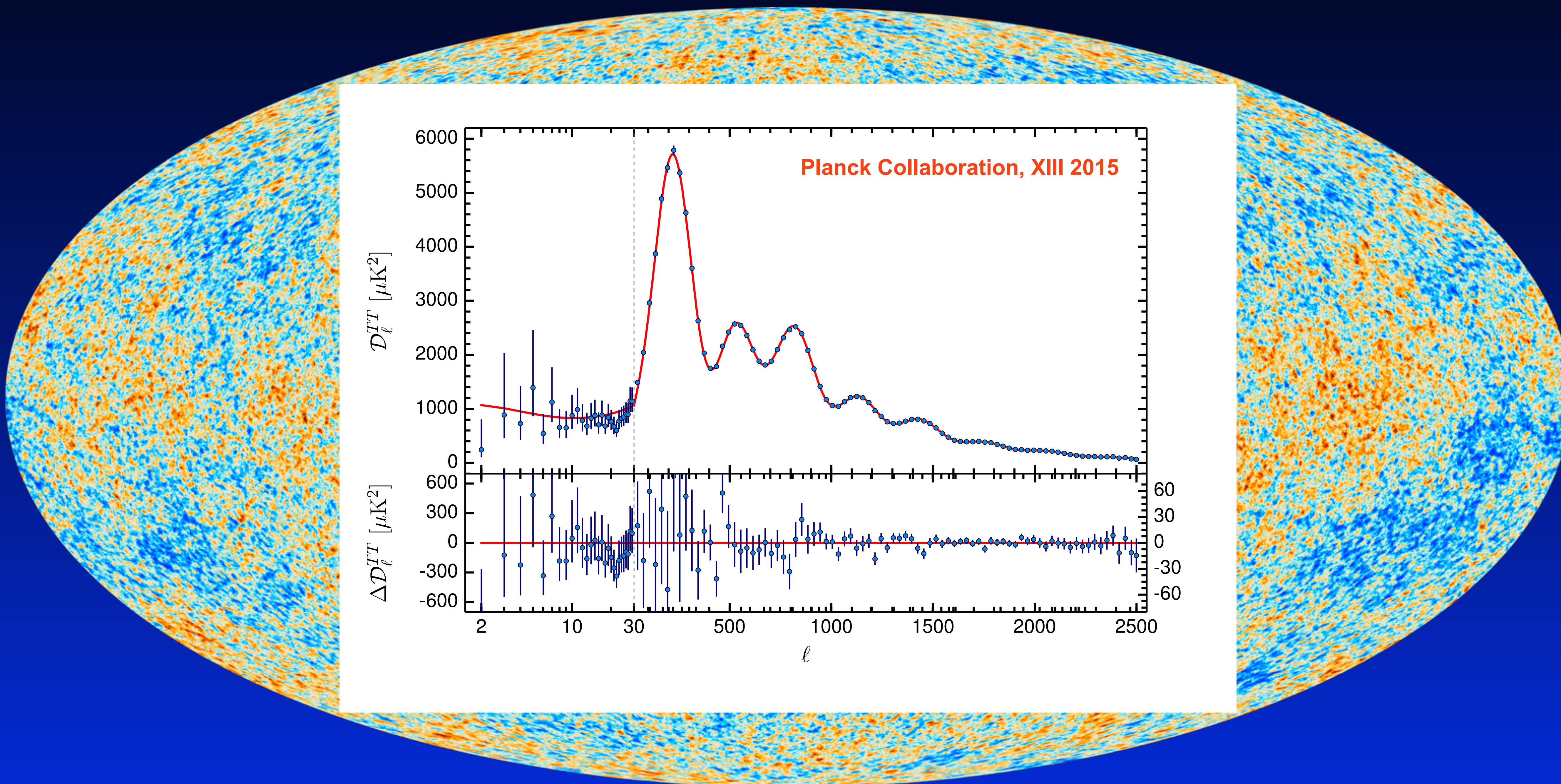
erc
THE ROYAL SOCIETY



Some of the "big" questions in Cosmology:

- *What is the Universe made of?*
- *How did it start? What are the initial condition?*
- *How did all the structures form?*

Cosmic Microwave Background Anisotropies

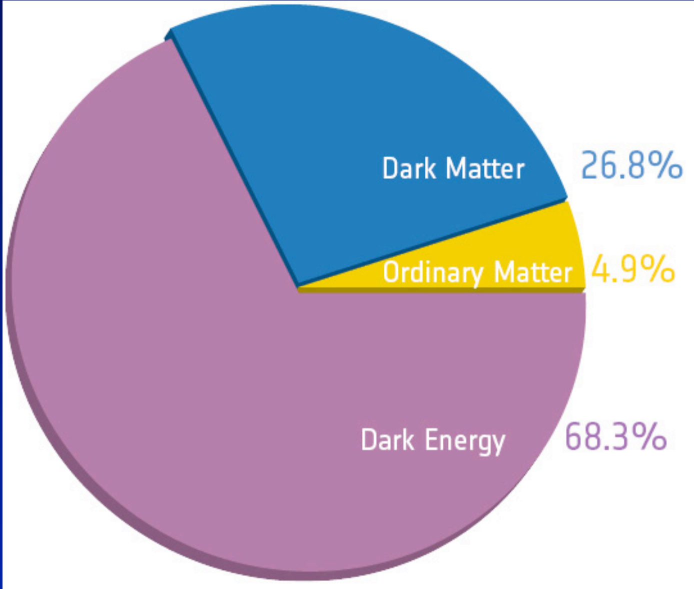


Planck all sky map

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

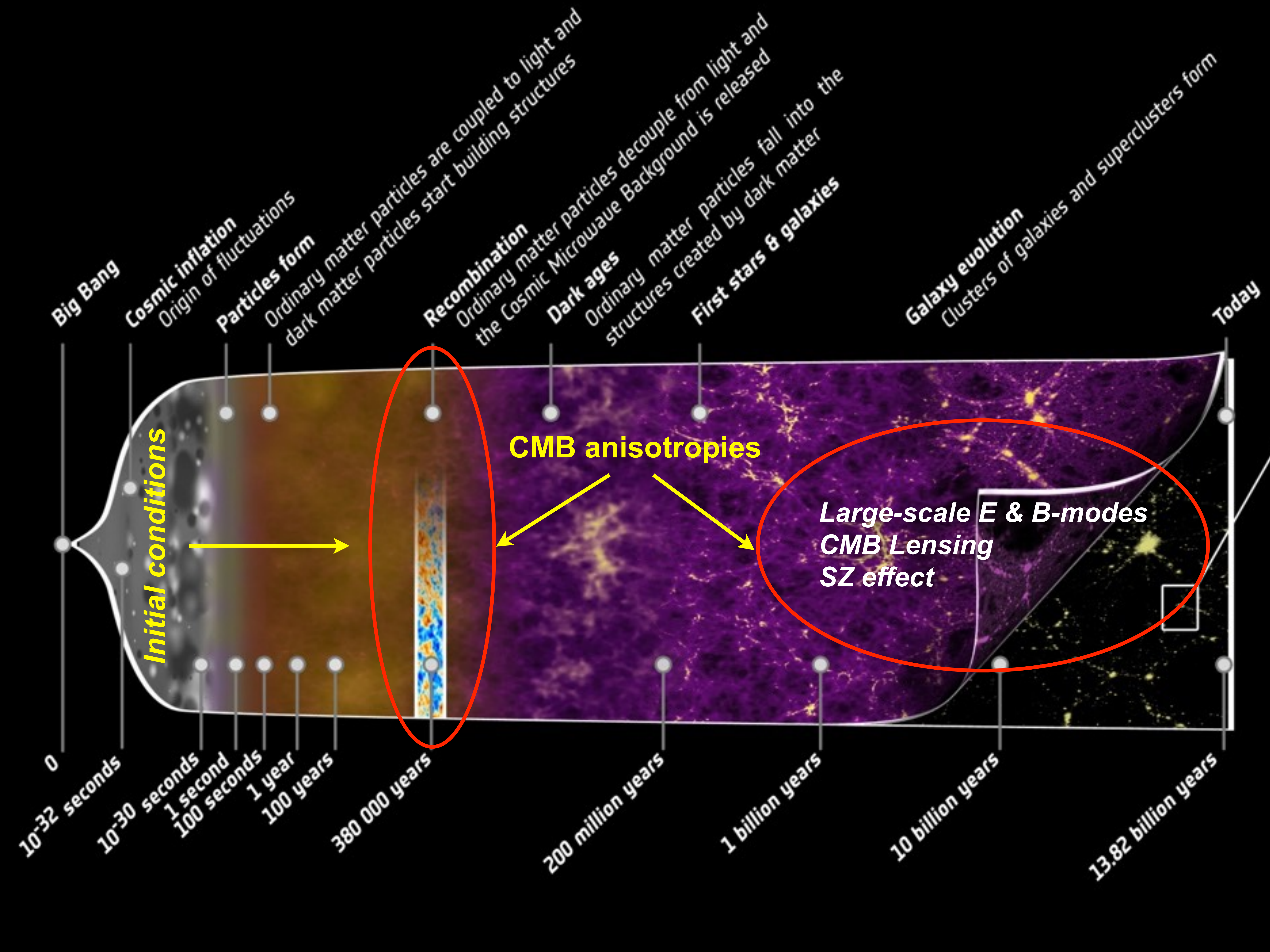
CMB anisotropies (with SN, LSS, etc...) clearly taught us a lot about the Universe we live in!

- Standard 6 parameter concordance cosmology with parameters known to percent level precision
- Gaussian-distributed adiabatic fluctuations with nearly scale-invariant power spectrum over a wide range of scales
- cold dark matter ("CDM")
- accelerated expansion today ("Λ")
- Standard BBN scenario → $N_{\rm eff}$ and $Y_{\rm p}$
- Standard ionization history → $N_{\rm e}(z)$



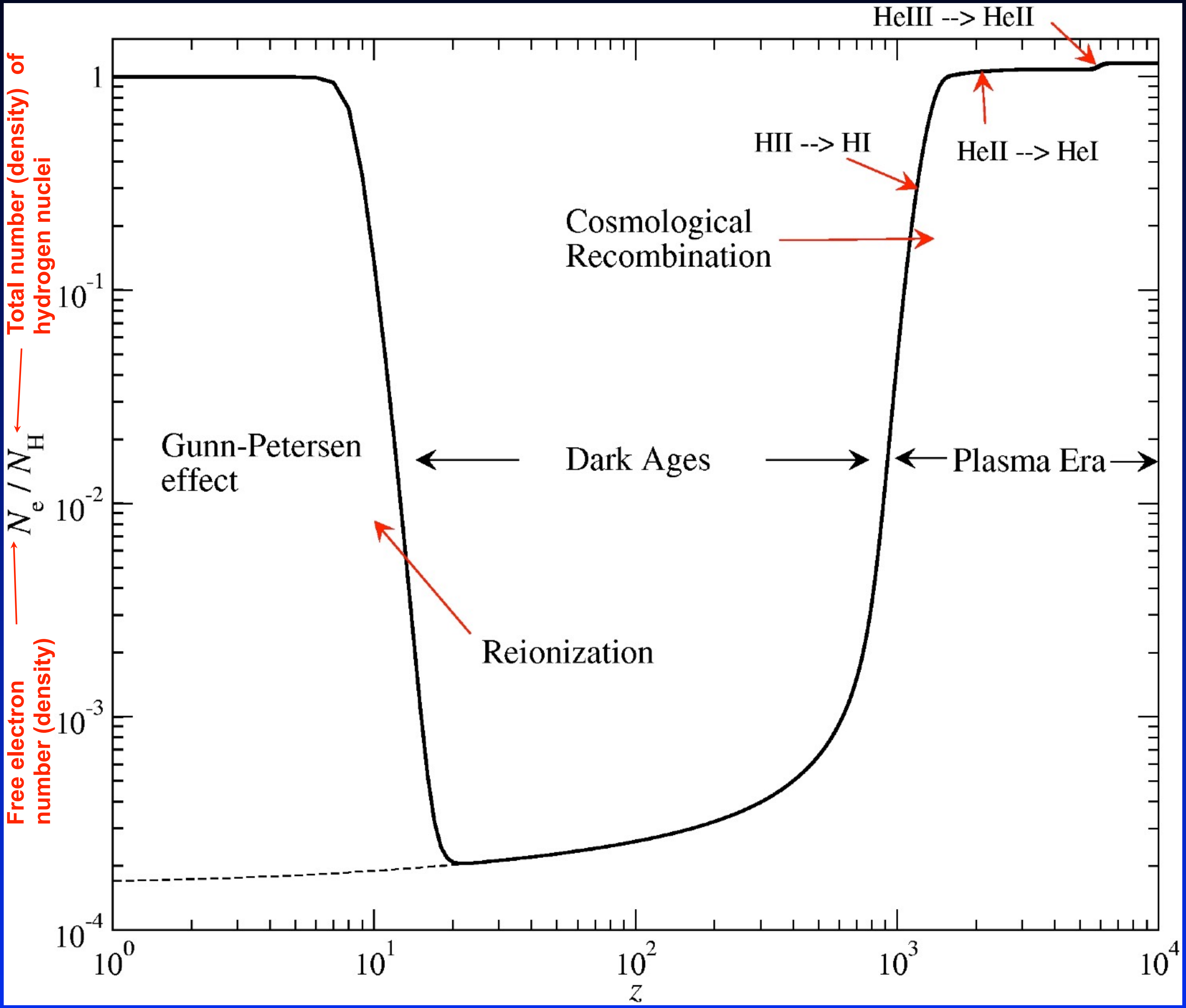
Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_{\rm b}h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_{\rm c}h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010
$100\theta_{\rm MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041	1.04077 ± 0.00032	1.04087 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.066 ± 0.016	0.067 ± 0.013	0.079 ± 0.017	0.063 ± 0.014	0.066 ± 0.012
$\ln(10^{10}A_{\rm s})$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
$n_{\rm s}$	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9681 ± 0.0044	0.9645 ± 0.0049	0.9653 ± 0.0048	0.9667 ± 0.0040

Planck Collaboration, 2015, paper XIII



Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
Initial conditions
CMB anisotropies
Large-scale E & B-modes
CMB Lensing
SZ effect
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

Sketch of the Cosmic Ionization History



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

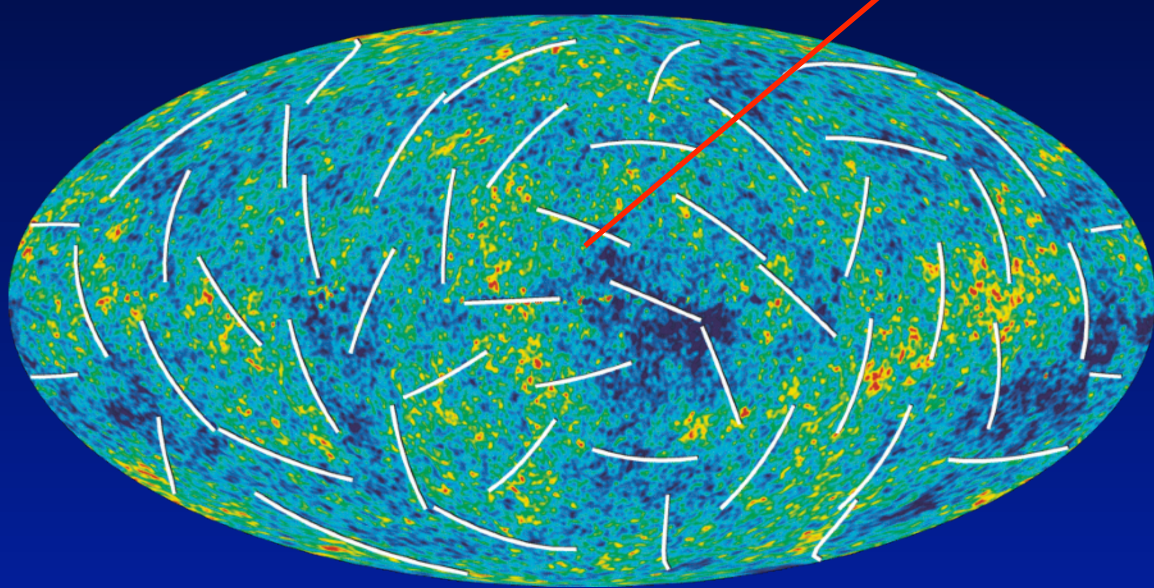
CMB Sky → Cosmology

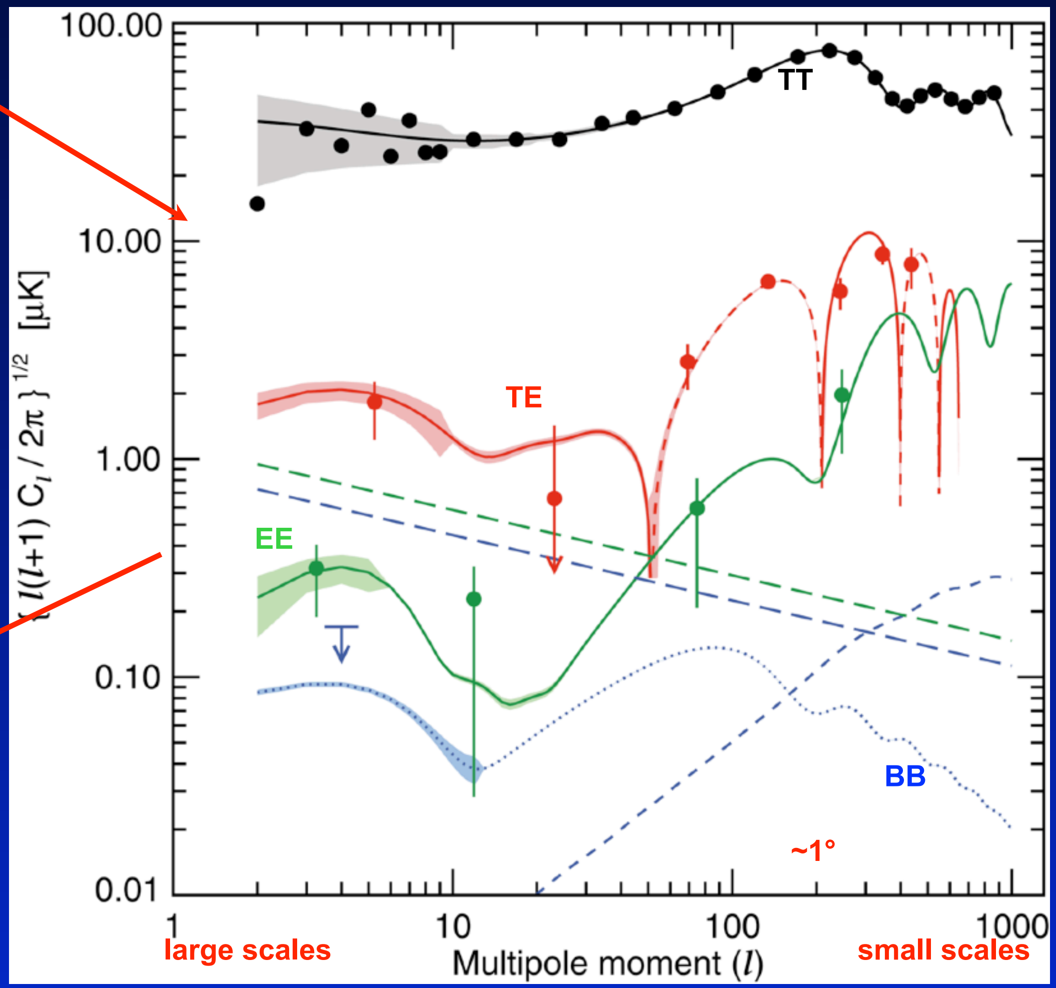
$N_e\,(z)$ is a *crucial* input

a_{lm}

Power spectra

WMAP CMB Sky





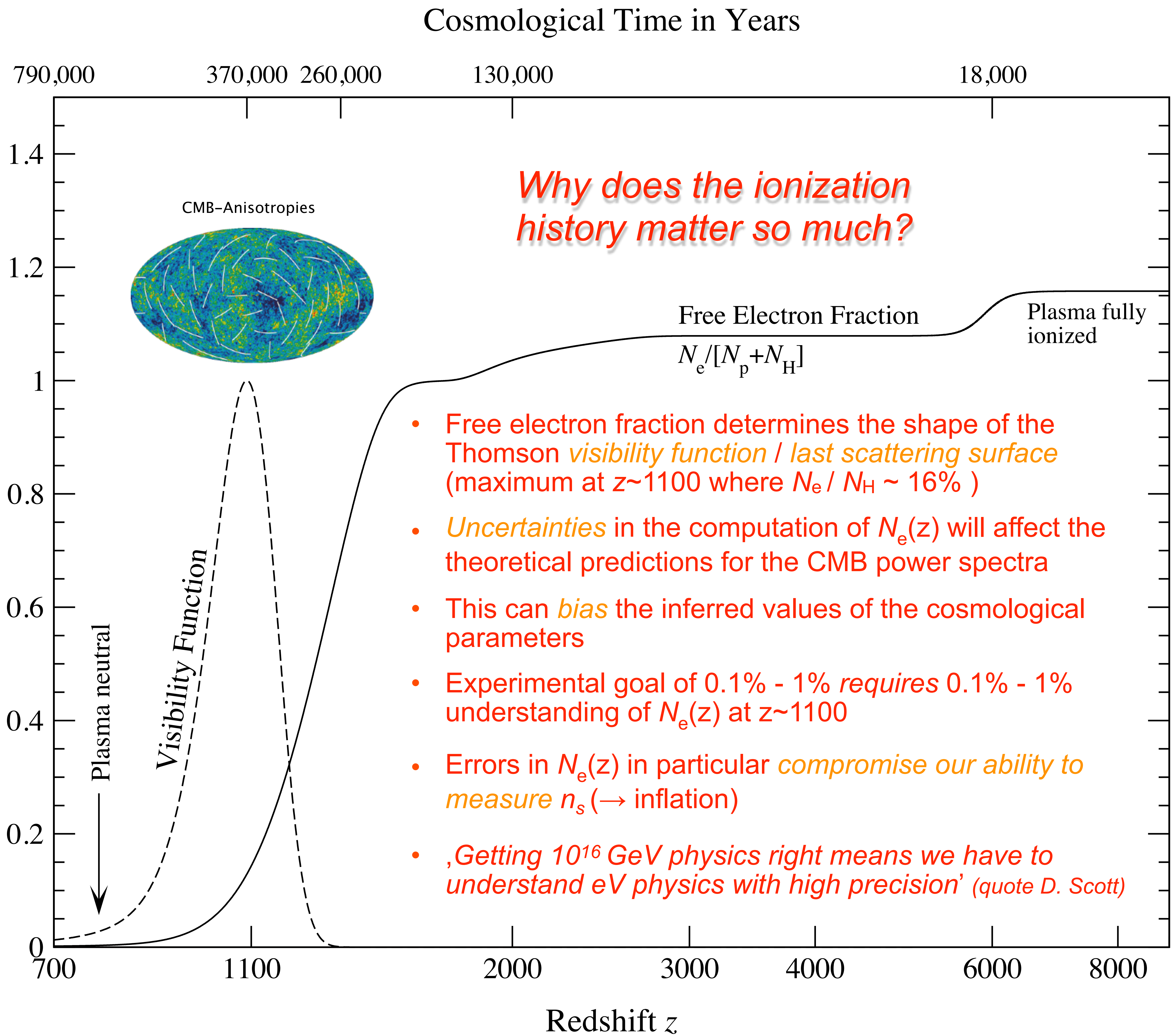
(Joint) analysis

Cosmological Parameters

Ω_{tot}, Ω_m, Ω_b, Ω_Λ,
h, τ, n_s,...

Other cosmological Dataset:

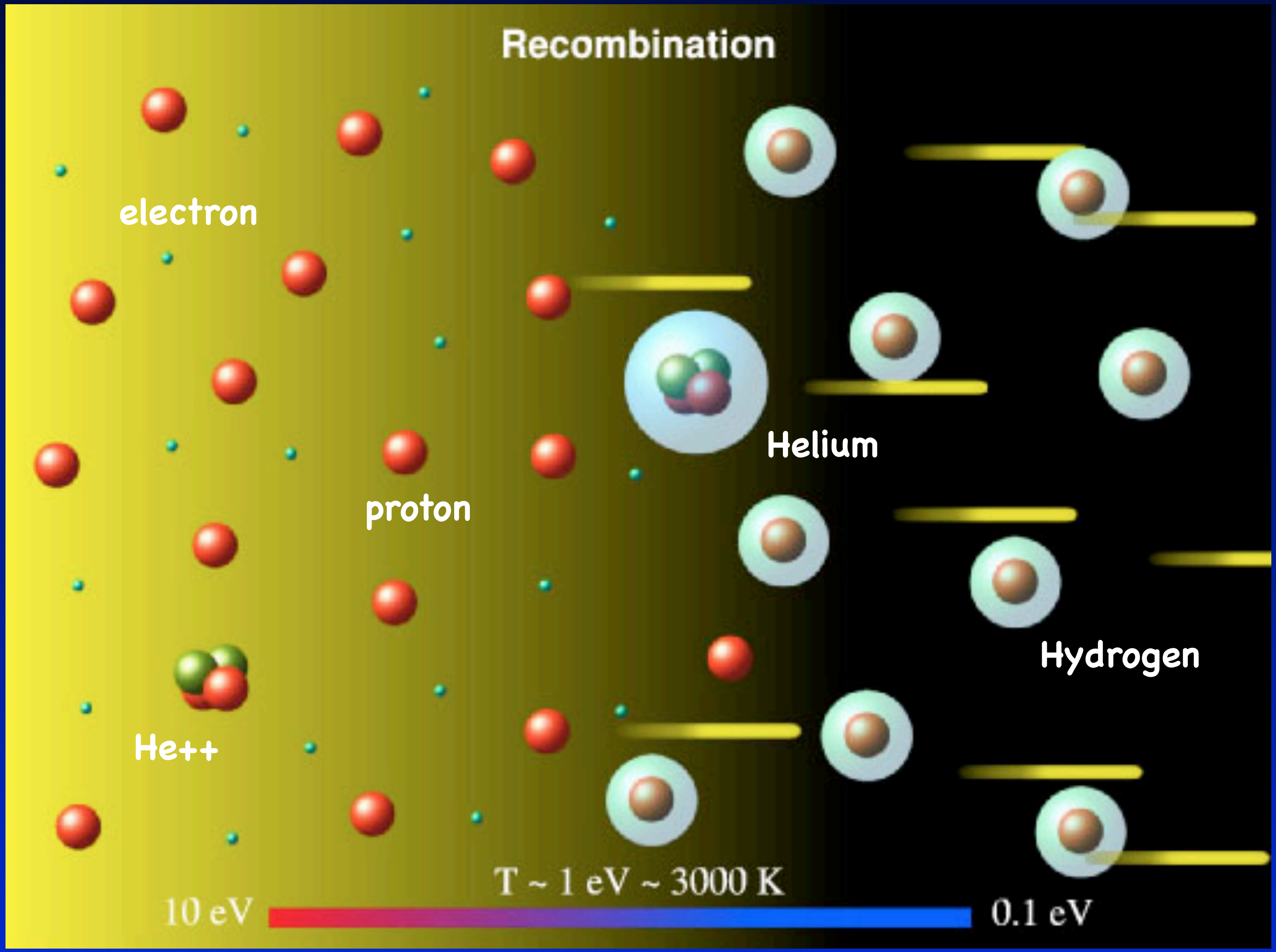
small-scale CMB, Supernovae, large-scale structure/ BAO, Lyman-α forest, lensing, ...



Cosmological Time in Years
790,000
370,000
260,000
130,000
18,000
CMB-Anisotropies
Why does the ionization history matter so much?
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully ionized
Plasma neutral
Visibility Function
1.4
1.2
1
0.8
0.6
0.4
0.2
0
700
1100
2000
3000
4000
6000
8000
Redshift z
• Free electron fraction determines the shape of the Thomson *visibility function / last scattering surface* (maximum at z~1100 where N_e / N_H ~ 16%)
• *Uncertainties* in the computation of $N_e(z)$ will affect the theoretical predictions for the CMB power spectra
• This can *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* (→ 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?

What is the recombination problem about?



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

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

  $\Longrightarrow$ *radiative transfer problem*

Only problem in time!

electron temperature

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

number densities

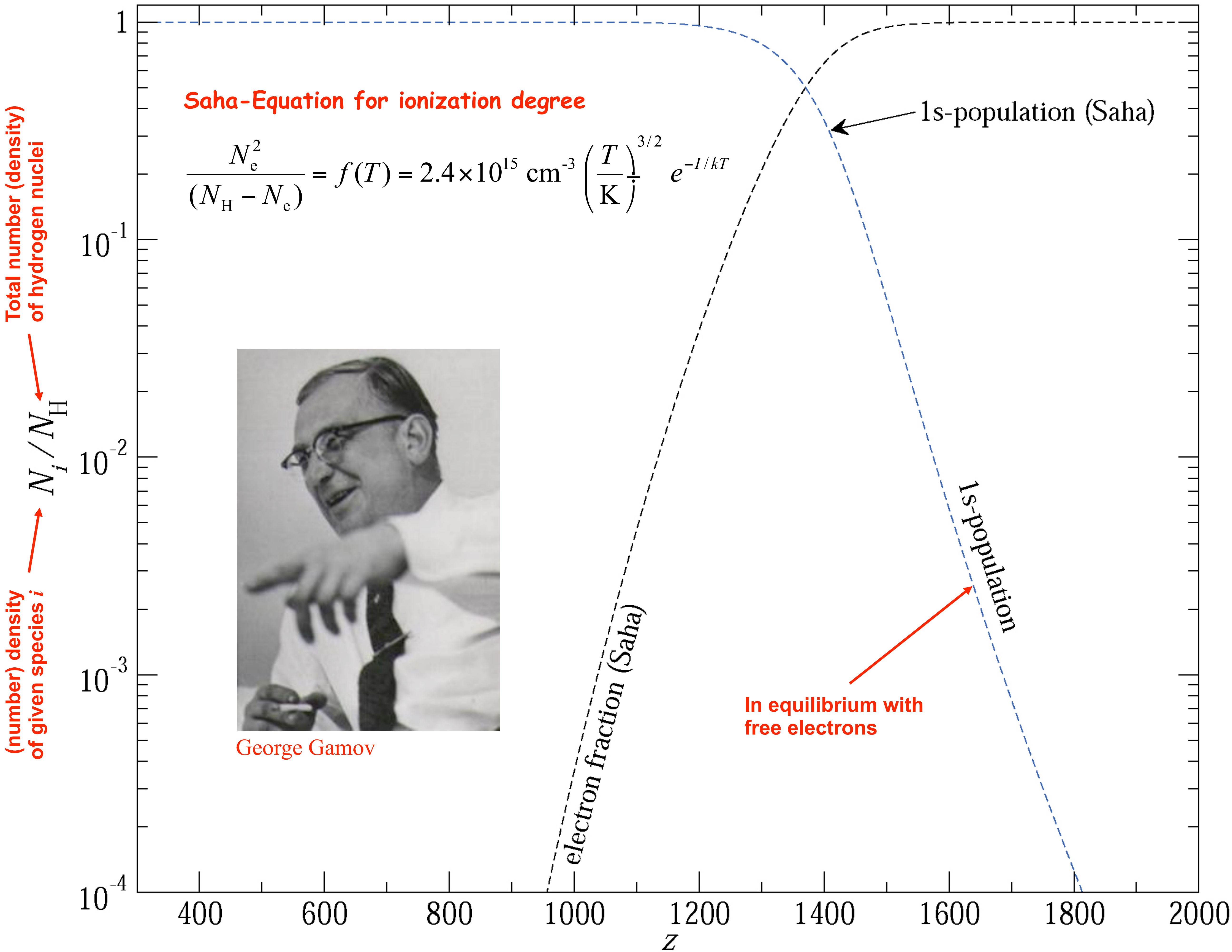
non-thermal photons

Physical Conditions during Recombination

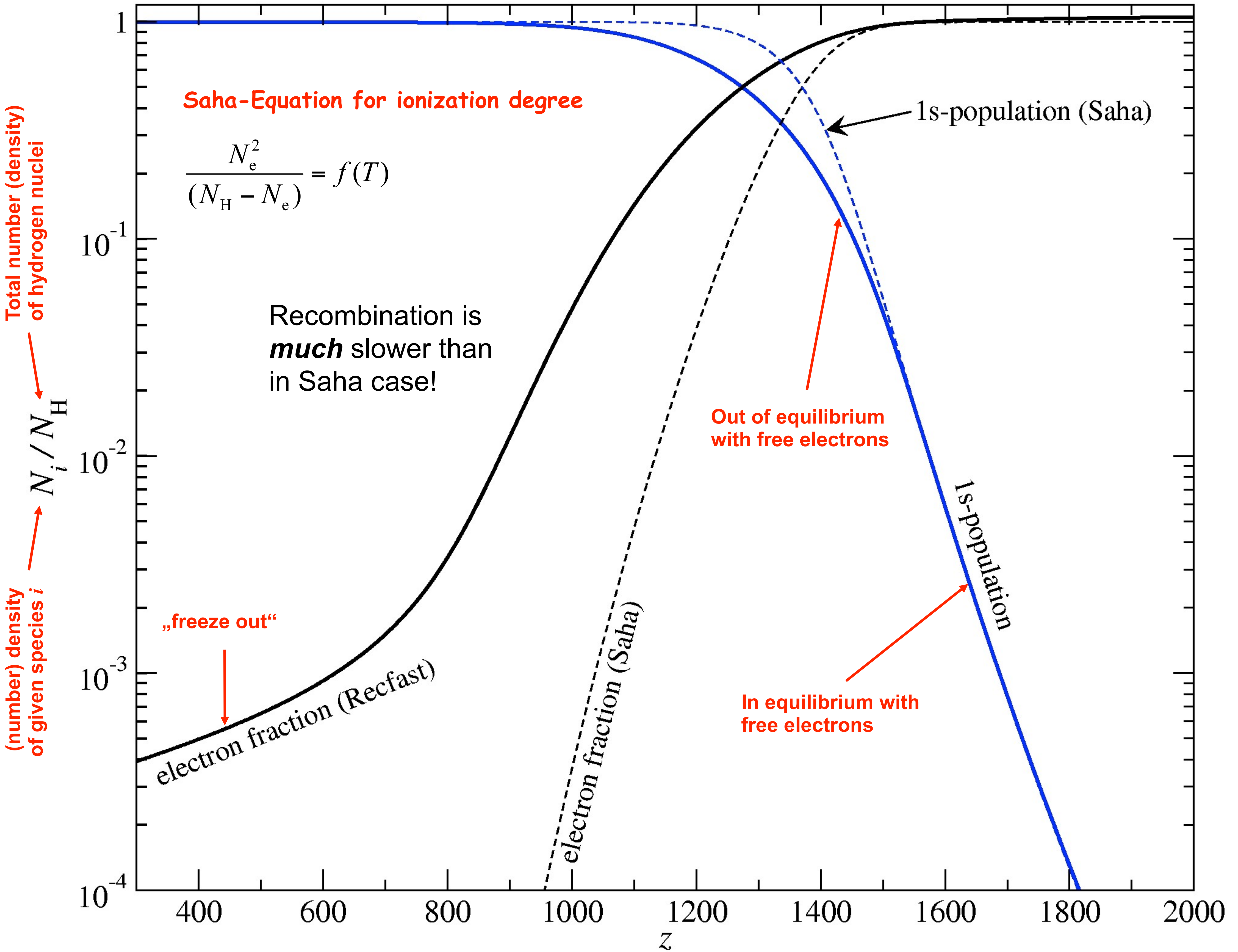
- Anisotropies negligible for recombination problem
- Temperature T_γ ~ 2.725 (1+z) K ~ 3000 K
- Baryon number density $N_b \sim 2.5\text{x}10^{-7}\text{cm}^{-3}\,(1+z)^3 \sim 330\ \text{cm}^{-3}$
- Photon number density $N_\gamma \sim 410\ \text{cm}^{-3}\,(1+z)^3 \sim 2\times10^9\,N_b$

  ⇒ photons in very distant Wien tail of blackbody spectrum can keep hydrogen ionized until $h\nu_\alpha \sim 40\,kT_\gamma \Leftrightarrow T_\gamma \sim 0.26$ eV *(Ly-c 13.6 eV!)*
- Collisional processes negligible (*completely different in stars!!!*)
- Rates dominated by radiative processes

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

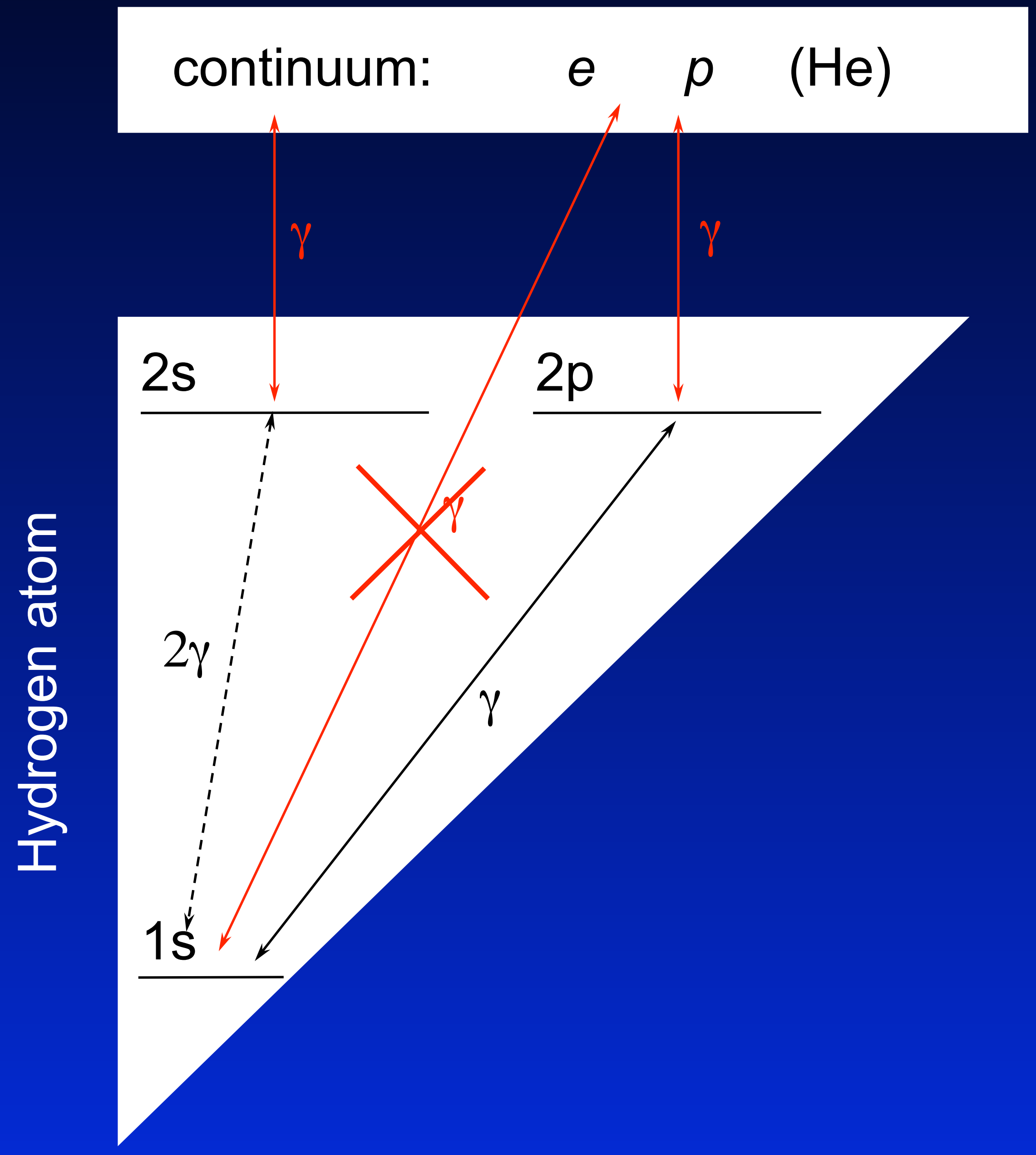


Saha-Equation for ionization degree
$$\frac{N_e^2}{(N_H - N_e)} = f(T) = 2.4\times10^{15}\ \mathrm{cm}^{-3}\left(\frac{T}{\mathrm{K}}\right)^{3/2} e^{-I/kT}$$
1s-population (Saha)
electron fraction (Saha)
1s-population
In equilibrium with free electrons
George Gamov
Total number (density) of hydrogen 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



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
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 ?

- **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)**

  ~ 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%

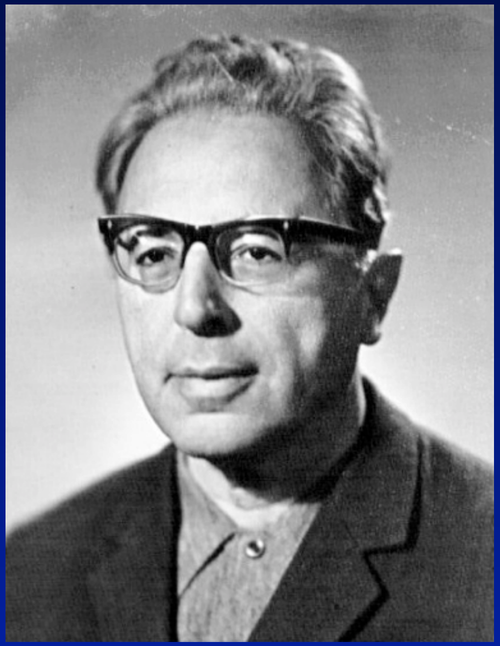
Zeldovich, Kurt & Sunyaev, 1968, ZhETF, 55, 278
Peebles, 1968, ApJ, 153, 1

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

These first computations were completed in 1968!

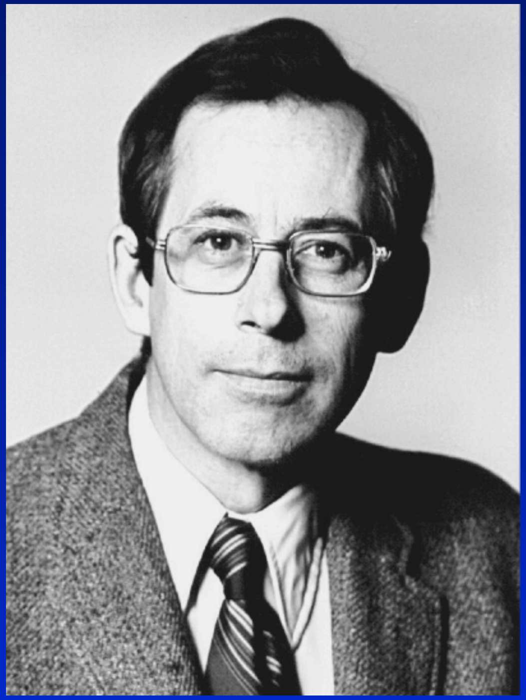
Moscow

Yakov Zeldovich



Iosif Shklovskii

Princeton



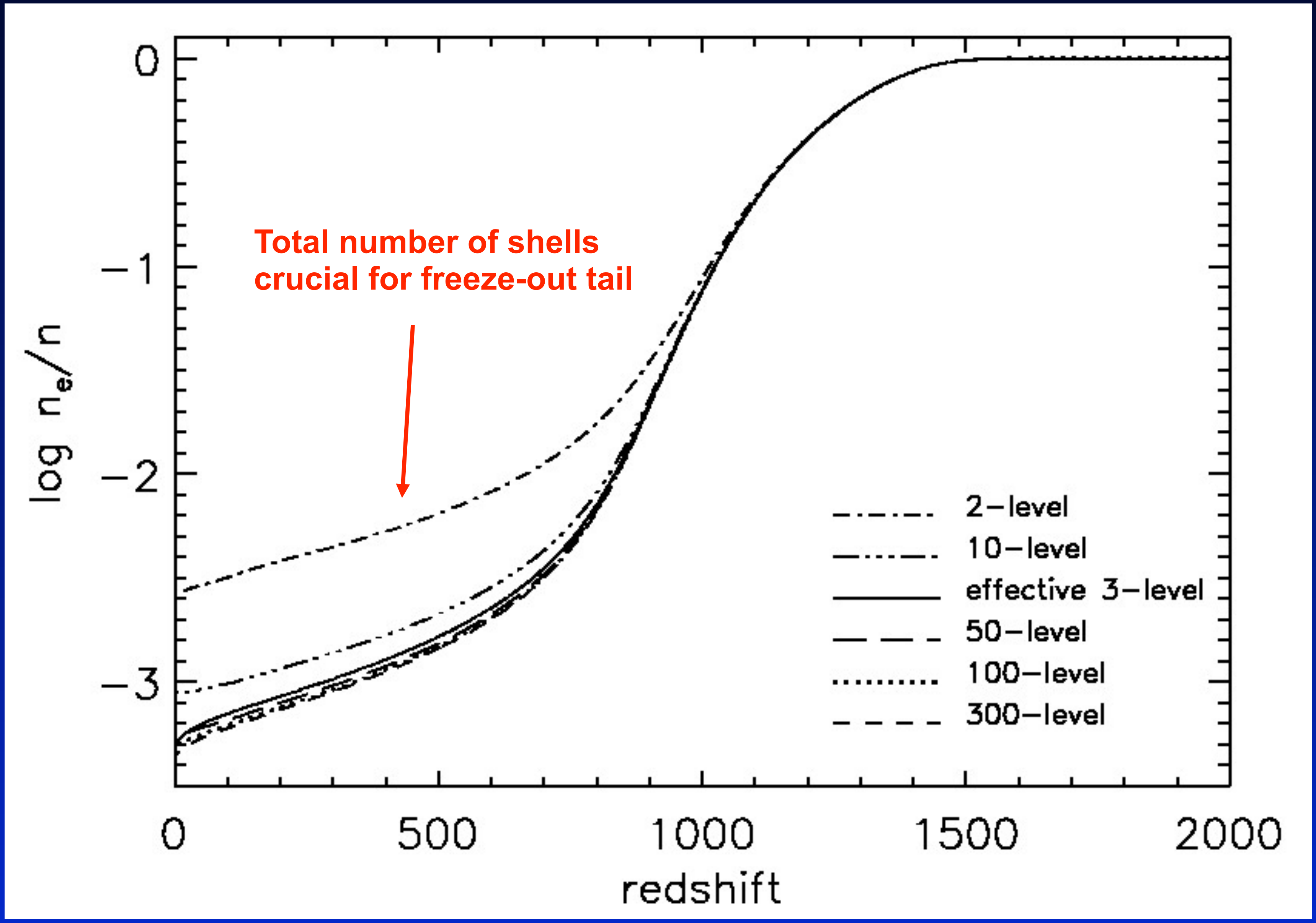
Jim Peebles

Vladimir Kurt
(UV astronomer)

Rashid Sunyaev

Let’s do the simple 3-level atom derivation?

Multi-level Atom ⇔ Recfast-Code



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

Output of N_e/N_H

Hydrogen:

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

Helium:

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

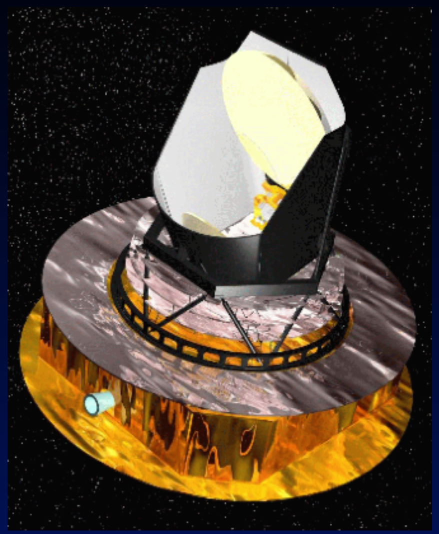
Low Redshifts:

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

RECFAST reproduces the result of detailed recombination calculation using fudge-functions

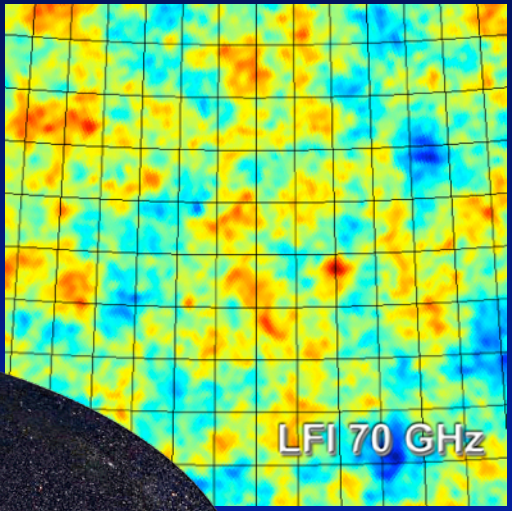
$\Delta N_e \,/\, N_e$ ~ 1% - 3%

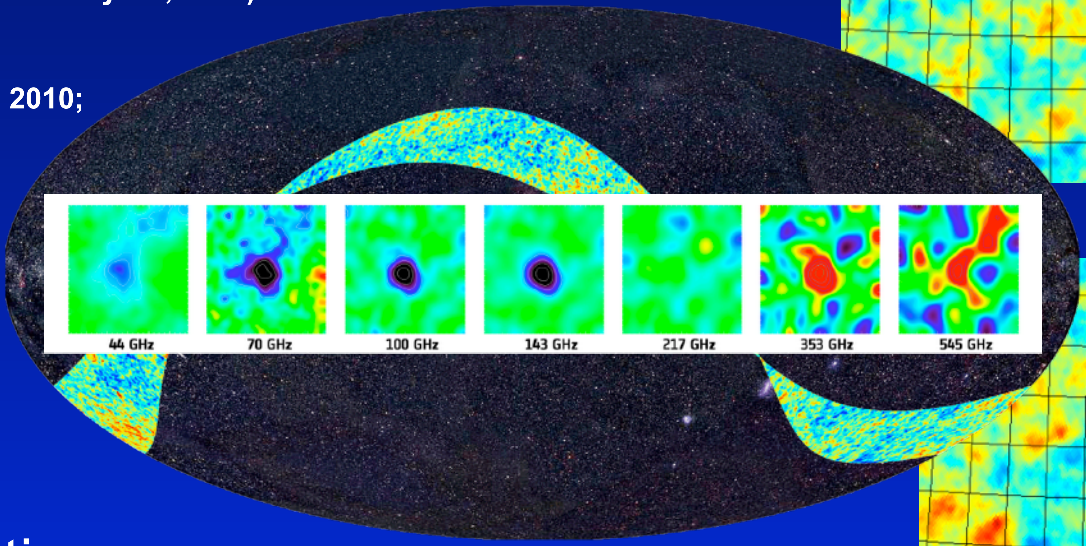
Getting the job done for *Planck*



Hydrogen recombination

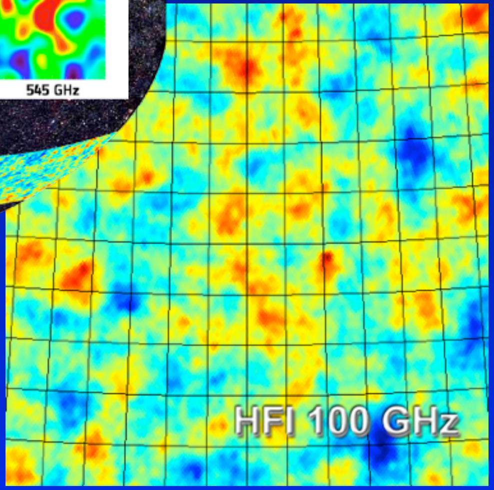
- Two-photon decays from higher levels
  (Dubrovich & Grachev, 2005, Astr. Lett., 31, 359; Wong & Scott, 2007; JC & Sunyaev, 2007; Hirata, 2008; JC & Sunyaev 2009)
- Induced 2s two-photon decay for hydrogen
  (JC & Sunyaev, 2006, A&A, 446, 39; Hirata 2008)
- Feedback of the Lyman-α distortion on the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





Helium recombination

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

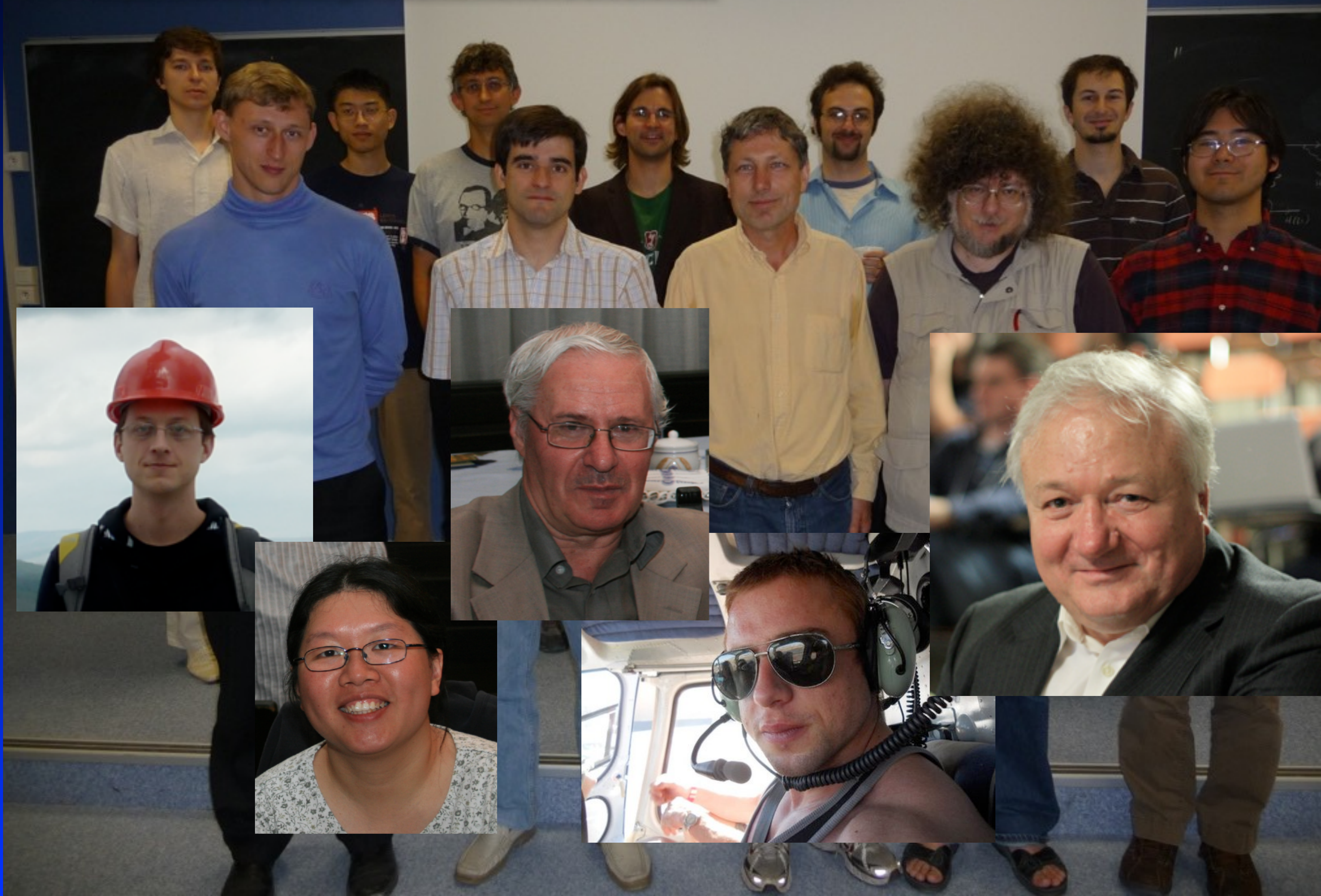


$\Delta N_e \;/\; N_e \sim 0.1$ %

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

Recombination Physics Meeting in Orsay 2008

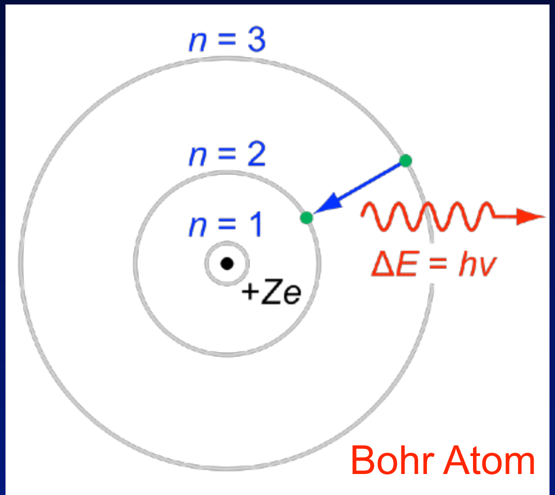
see: http://www.b-pol.org/RecombinationConference/



Atomic Physics Challenges

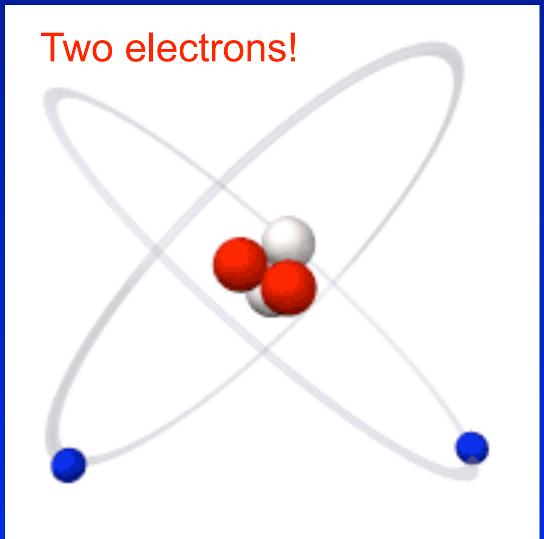
Hydrogen Atom & Hydrogenic Helium

- Rather simple and basically analytic (e.g., Karzas & Latter, 1961)
- Even 2γ rates can be computed precisely (e.g., Goeppert-Mayer, 1931)
- Collisional rates less robust, but effect small (new rates became available!)
- Biggest computational challenge is the number of levels ($\sim n^2$)

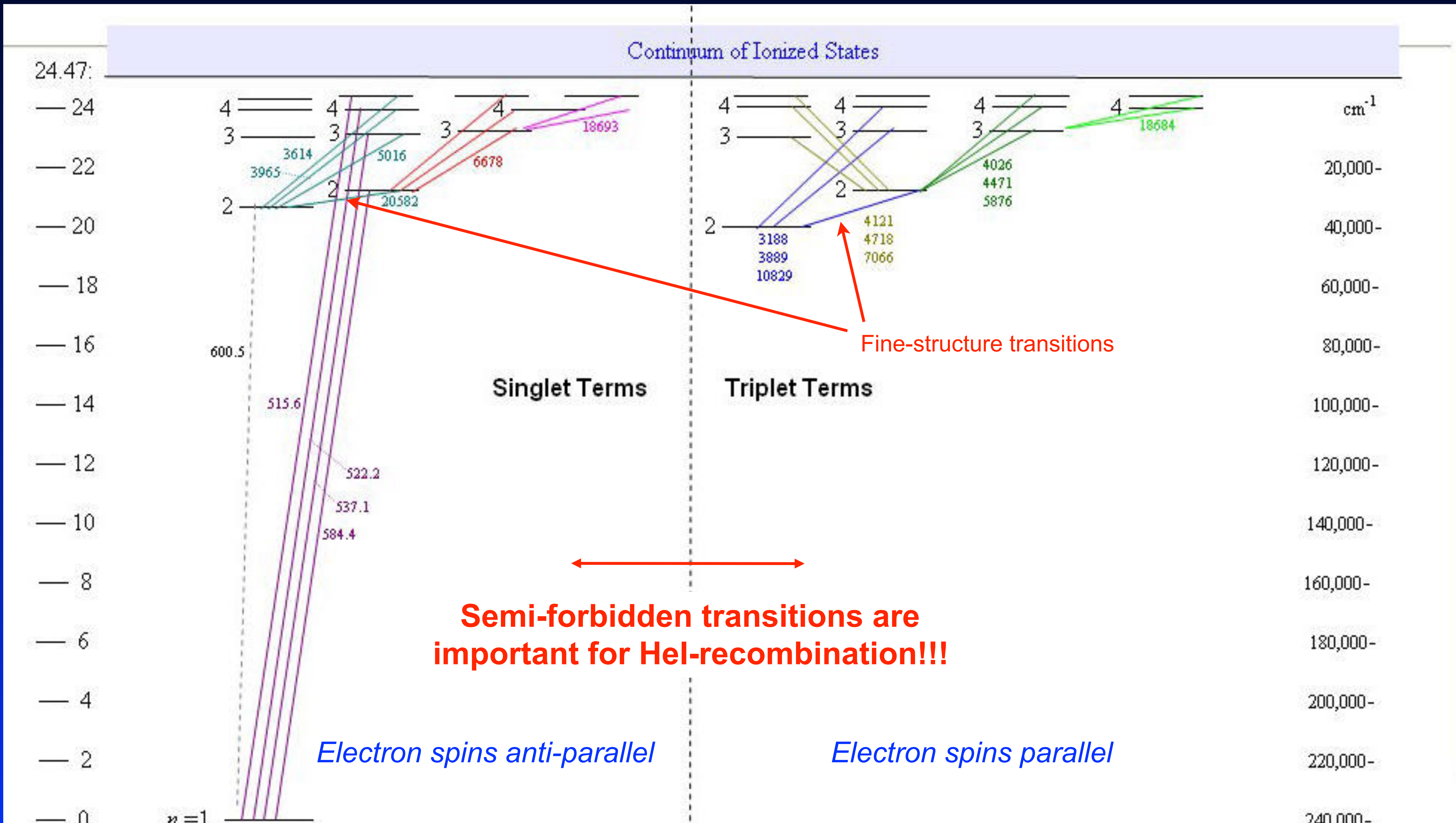


Neutral Helium

- Lower levels non-hydrogenic (perturbative approach needed)
- Spectrum complicated and data (was) rather sparse (e.g., Drake & Morton, 2007)



Grotrian diagram for neutral helium



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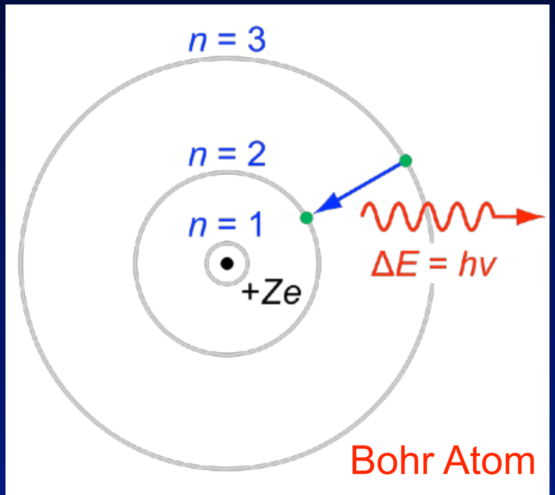
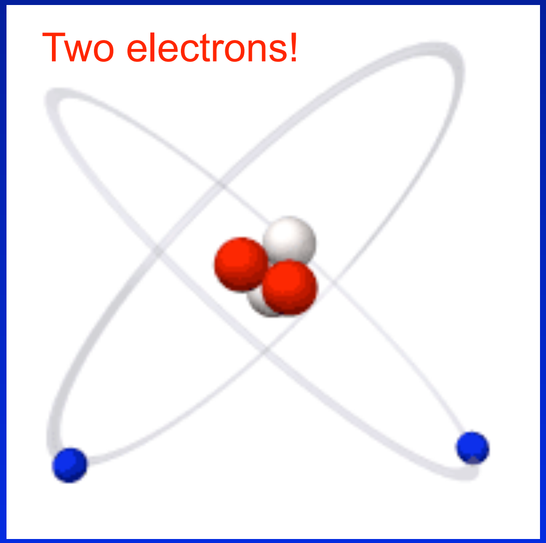


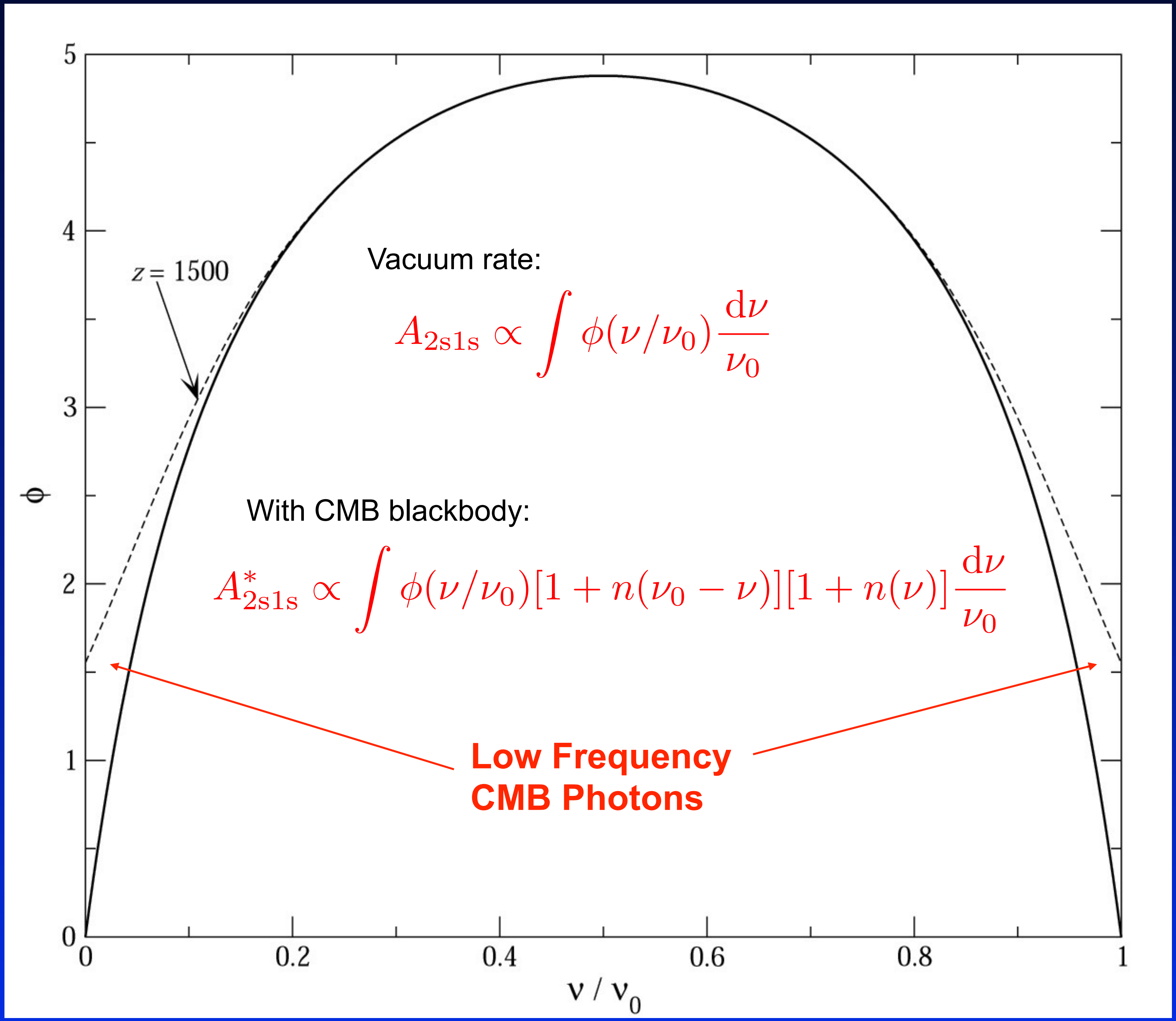
Neutral Helium

- Lower levels non-hydrogenic (perturbative approach needed)
- Spectrum complicated and data (was) rather sparse
  (e.g., Drake & Morton, 2007)
- Collisional rate estimates pretty rough (important for distortions...)
- Computational challenge because of levels not as demanding if you only want to get the free electron fraction right

  (not true for spectrum…)



Stimulated HI 2s →1s decay



2s-1s emission profile

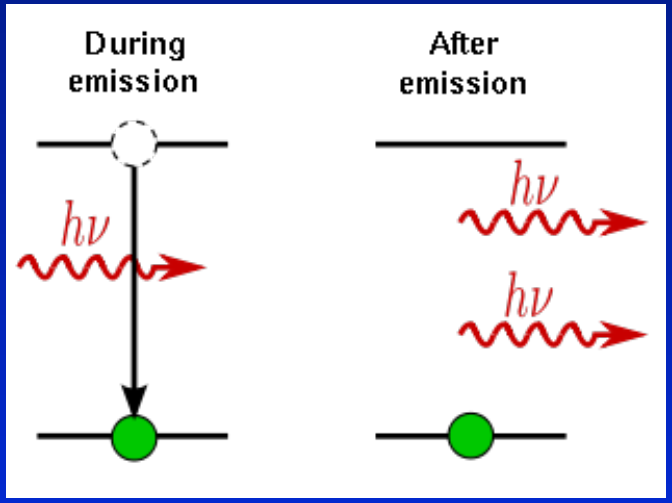
Transition rate in vacuum

→ A_{2s1s} ~ 8.22 sec^{-1}

CMB ambient photons field

→ A_{2s1s} increased by ~1%-2%

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



JC & Sunyaev, 2006, A&A

Feedback of Ly-α on the HI 1s → 2s transition

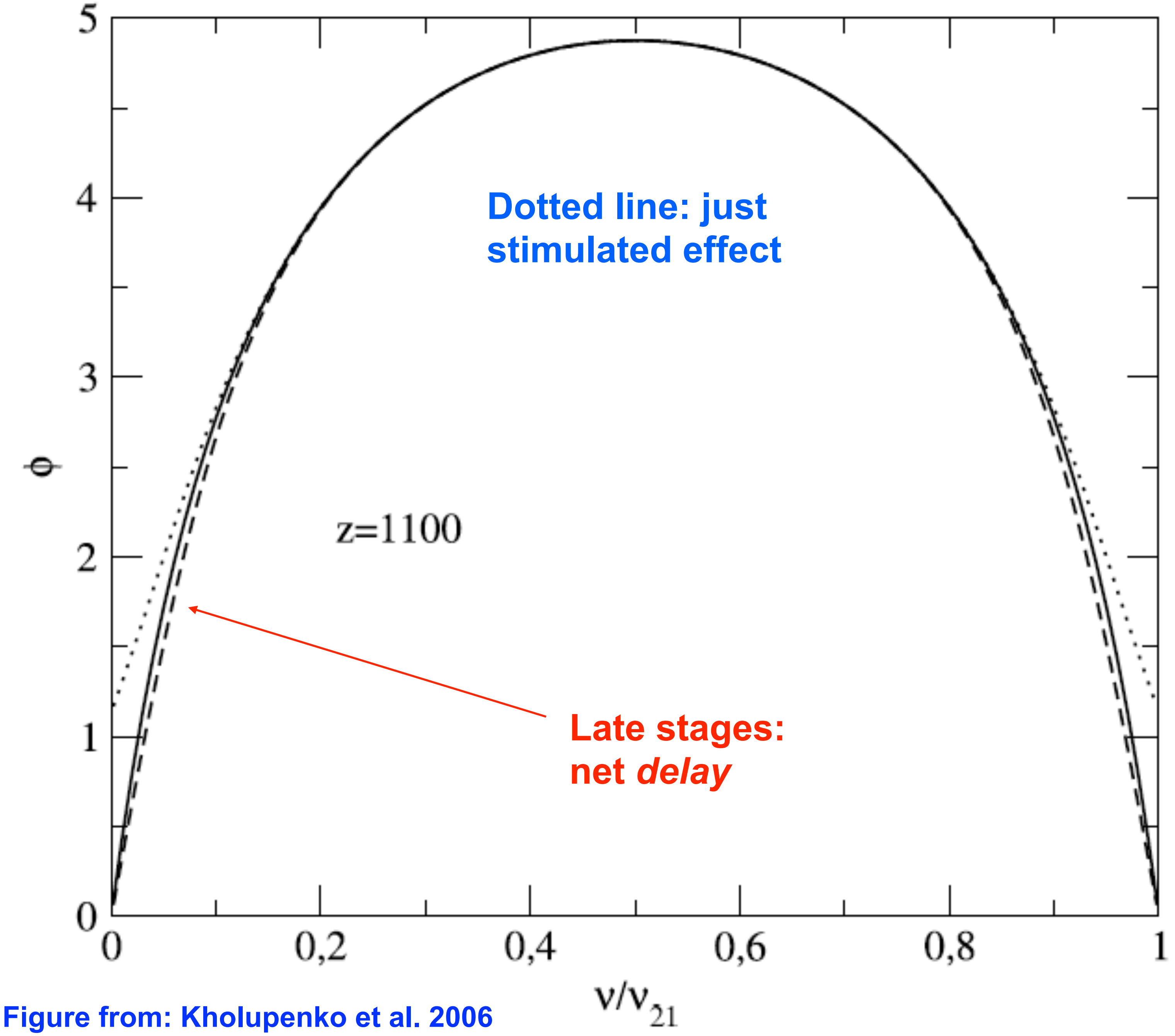
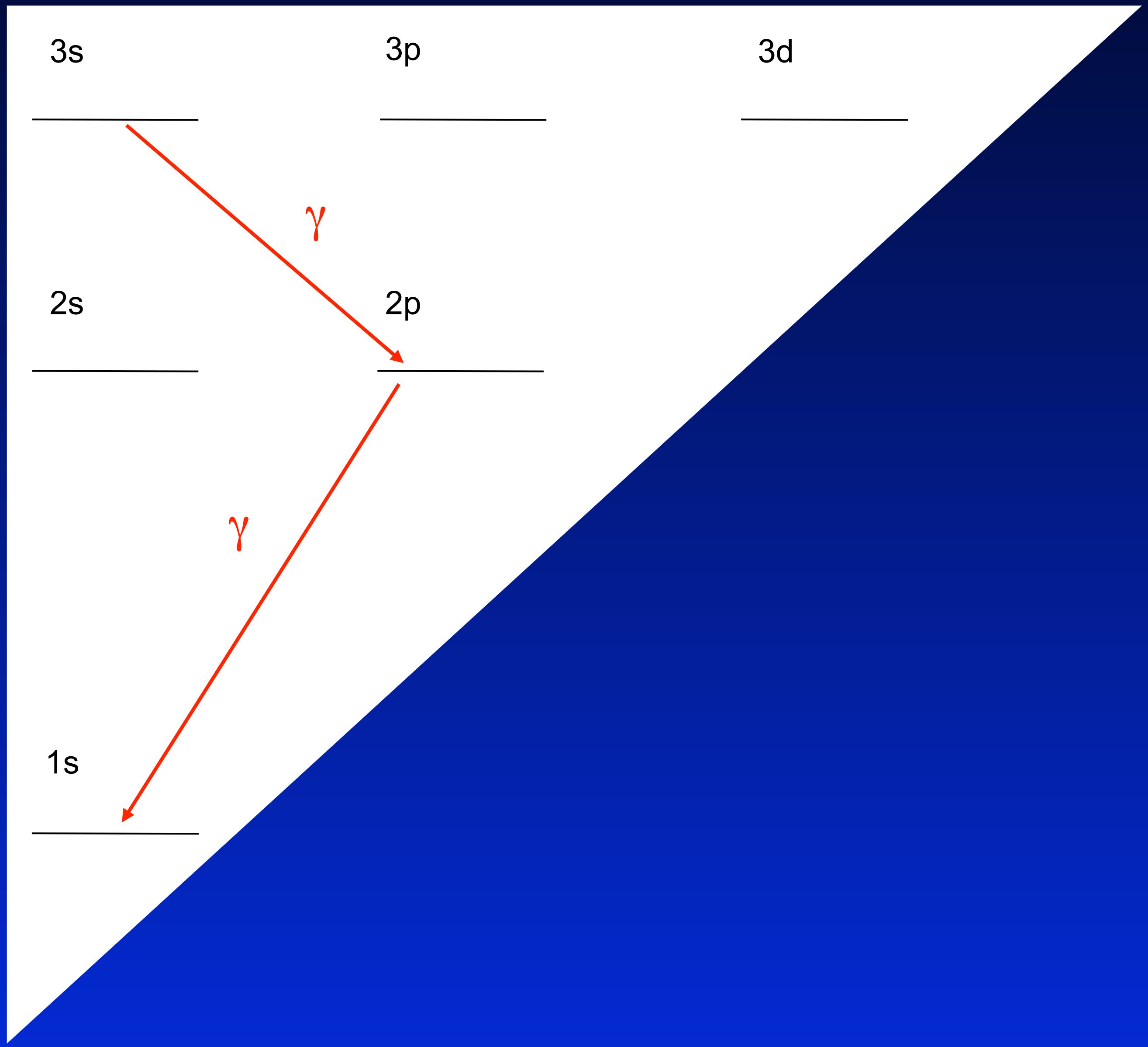


Figure from: Kholupenko et al. 2006

- Some Ly-α photon are re-absorbed in the 1s-2s channel
- delays recombination
- net effect on 2s-1s channel $\Delta N_e/N_e \sim 0.6\%$ around z~1100
- 2s-1s *self-feedback* $\Delta N_e/N_e \sim -0.08\%$ around z~1100 (JC & Thomas, 2010)

Kholupenko et al. 2006
Fendt, JC, Rubino-Martin & Wandelt, 2009

Two-photon emission process from upper levels



Seaton cascade (1+1 photon)

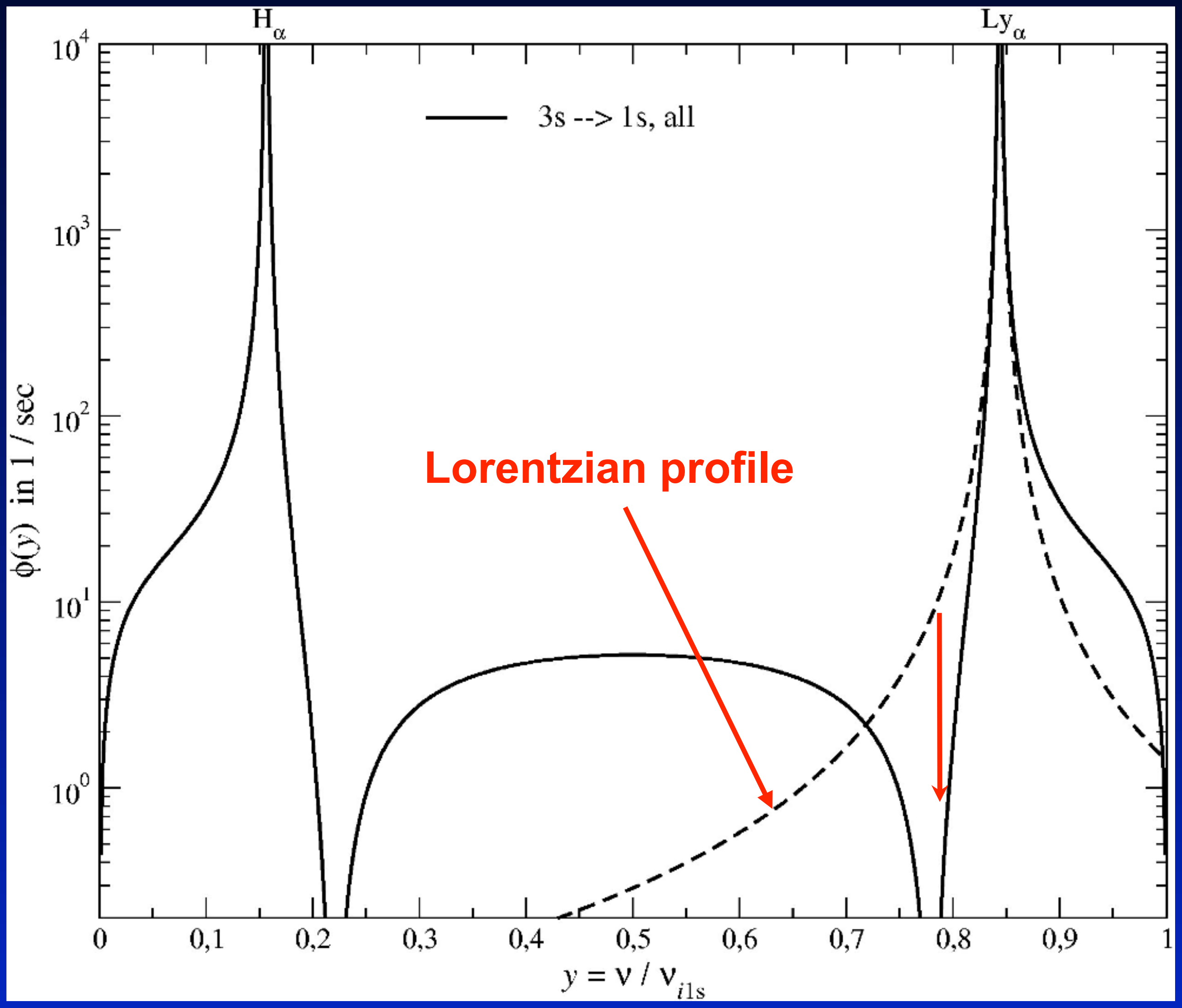
No collisions → two photons (mainly H-α and Ly-α) are emitted!

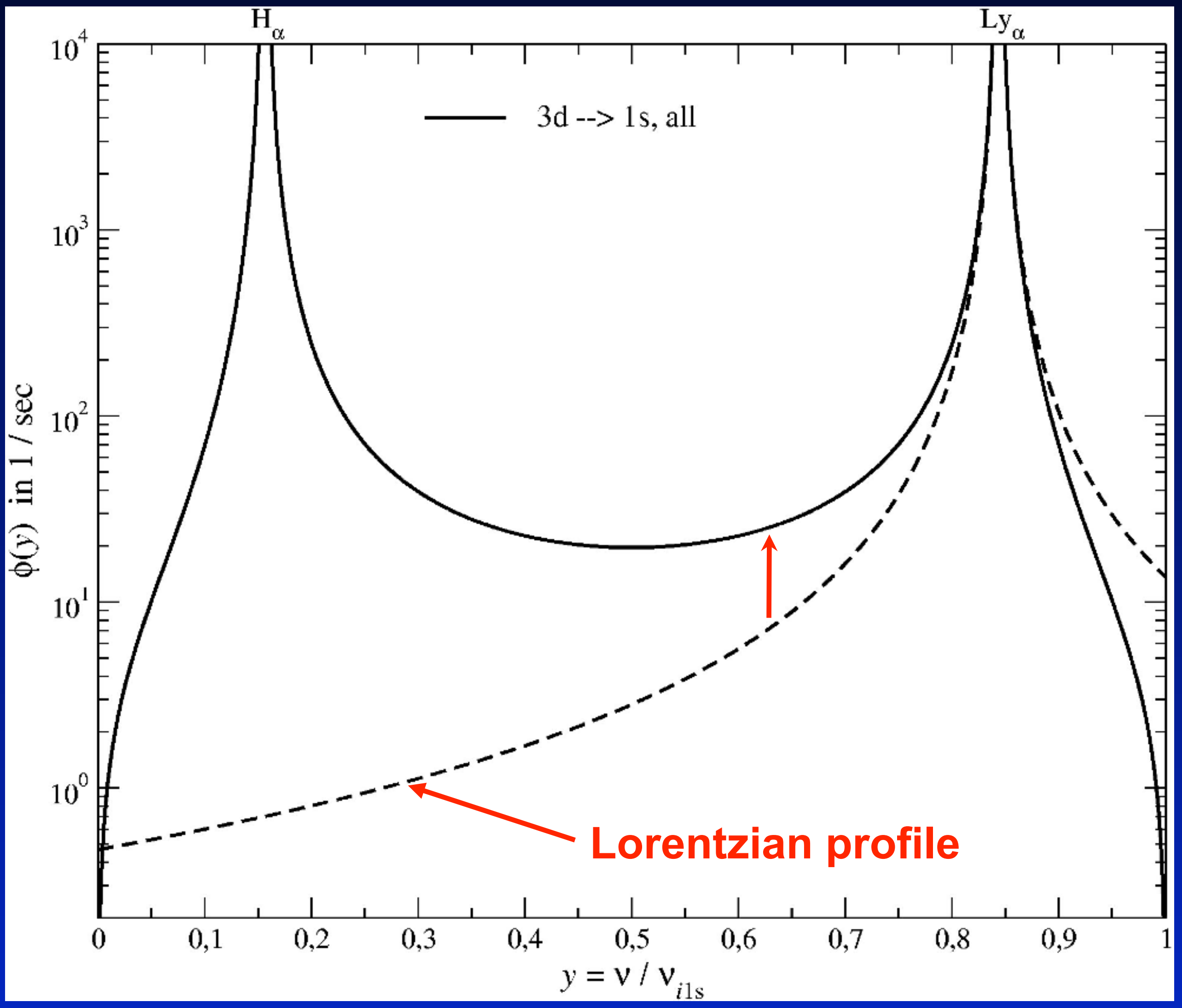
Maria-Göppert-Mayer (1931): description of two-photon emission as single process in Quantum Mechanics

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

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

3s and 3d two-photon decay spectrum





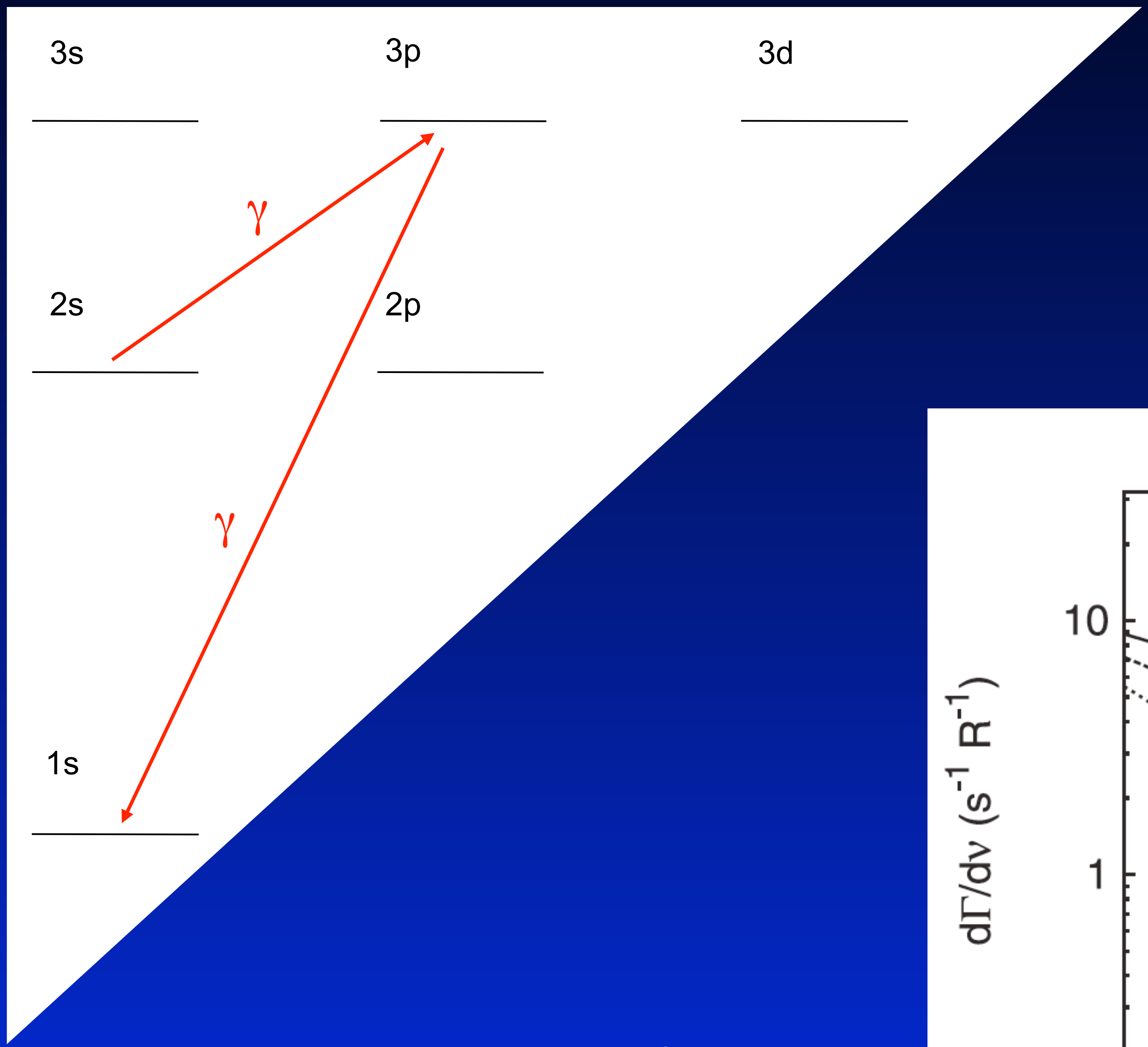
Direct Escape in optically thin regions:

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

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

JC & Sunyaev, A&A, 2008

2s-1s Raman scattering



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

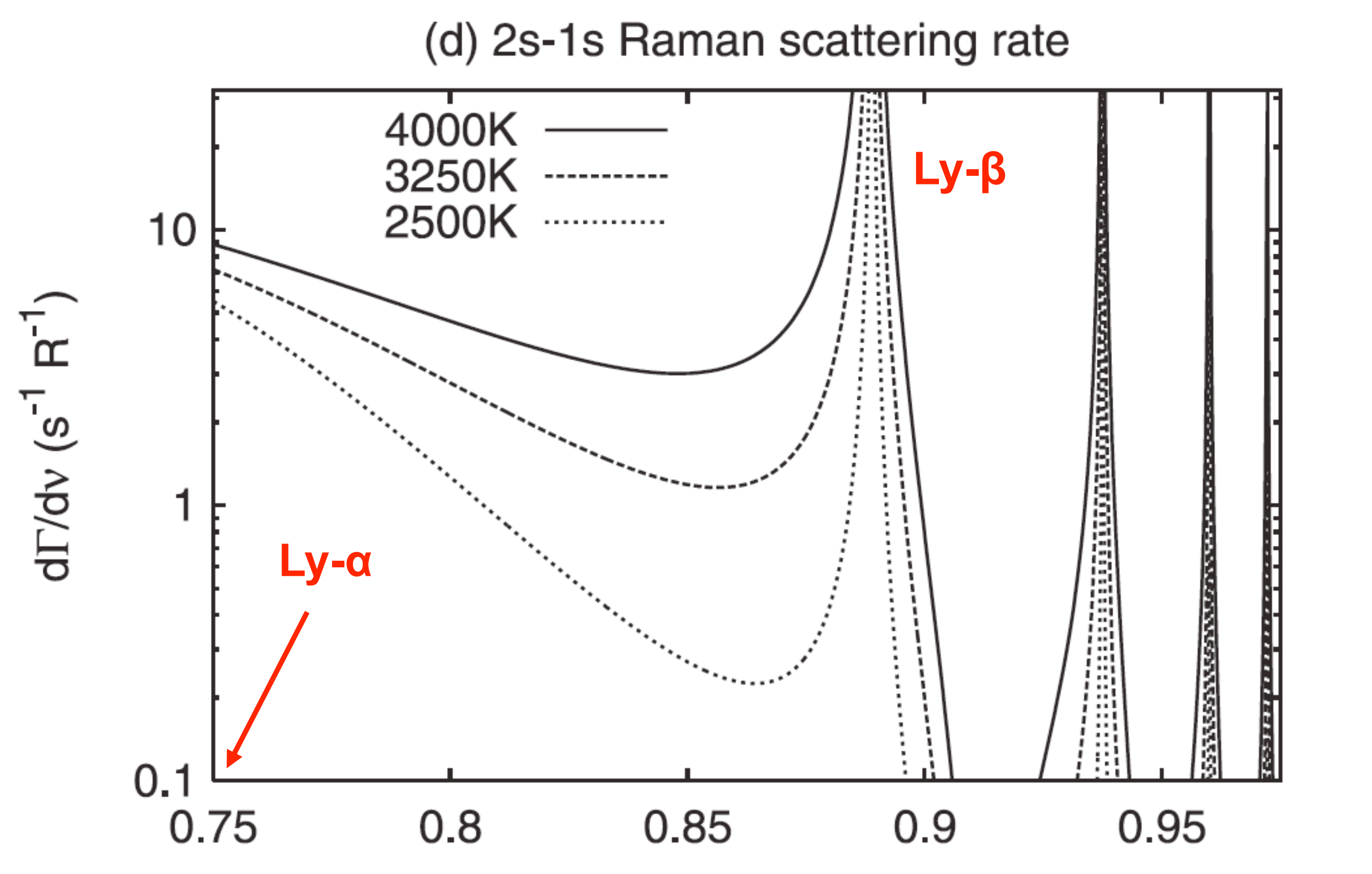


Figure from: Hirata 2008

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

Hirata 2008
JC & Thomas, 2010

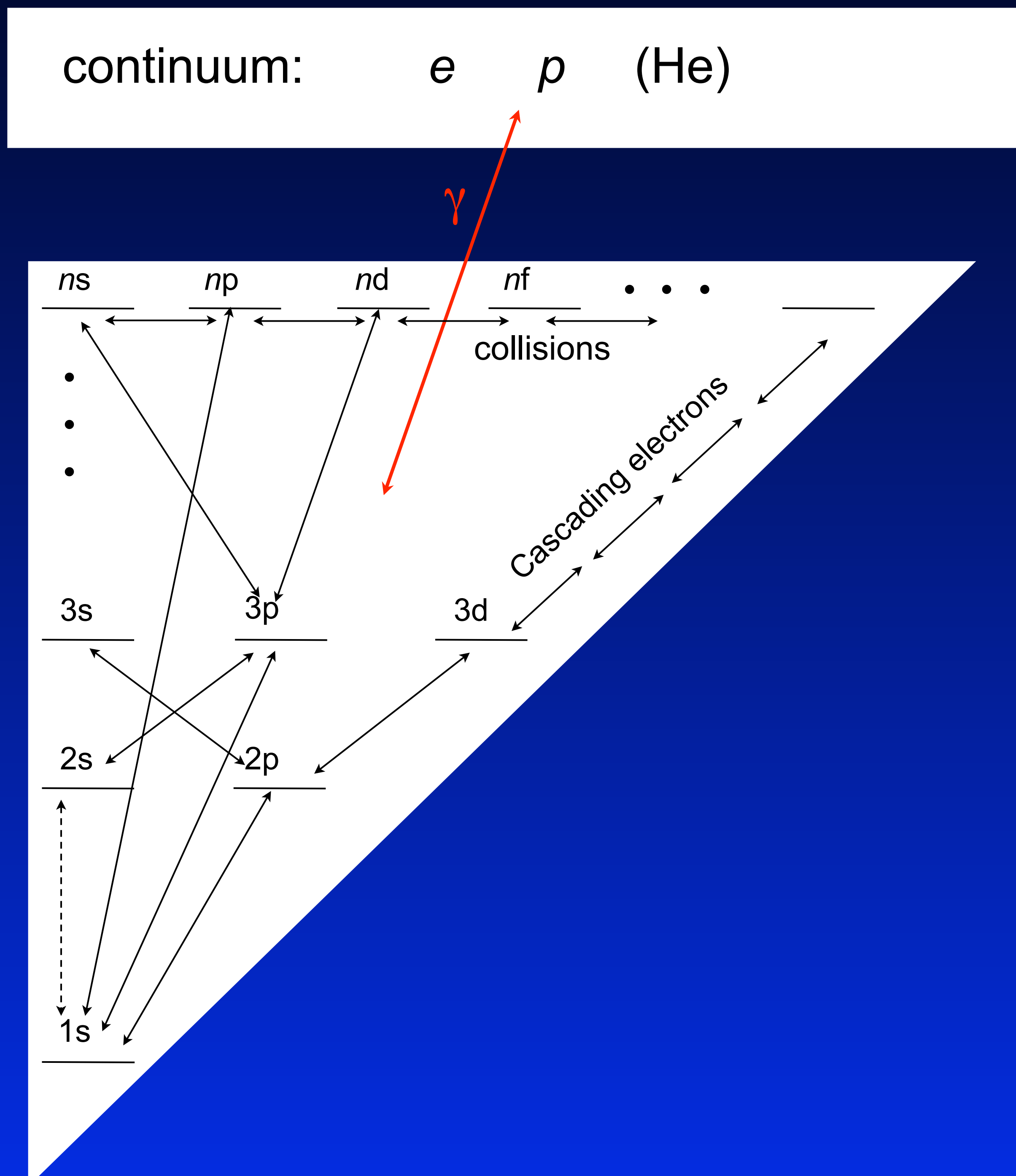
Deviations from Statistical Equilibrium in the upper levels

Basis for Recfast computation (Seager et al. 2000)

$$N_{nl} = \frac{2l+1}{n^2} N_{\mathrm{tot},n}$$

- l-dependence of populations neglected
- Levels in a given shell assumed to be in Statistical Equilibrium (SE)
- Complexity of problem scales like ~ n_{max}

Processes for the upper levels



Hydrogen atom

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

Deviations from Statistical Equilibrium in the upper levels

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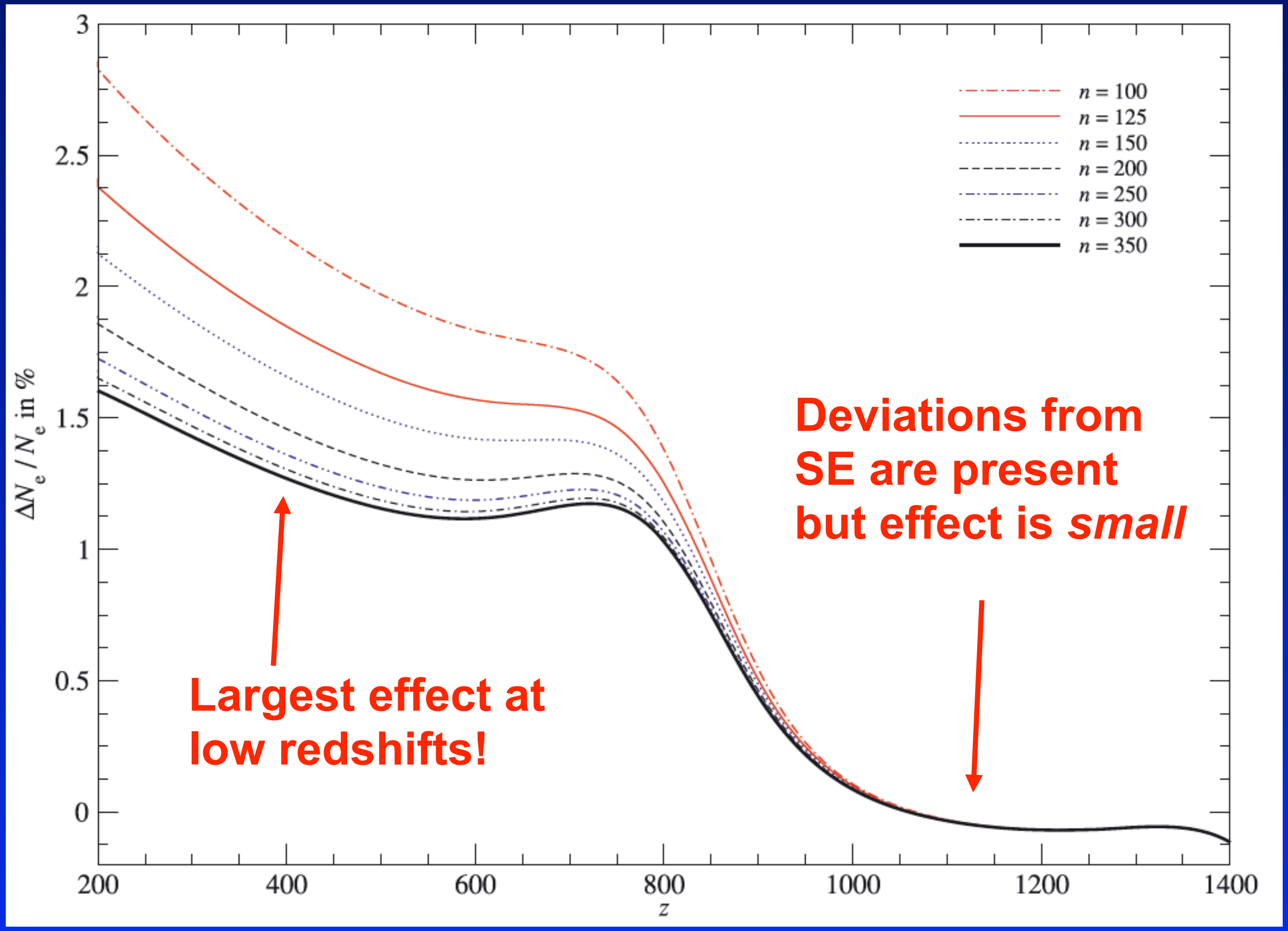
- l -dependence of populations neglected
- Levels in a given shell assumed to be in Statistical Equilibrium (SE)
- Complexity of problem scales like ~ n_{max}

Refined computation

(JC, Rubino-Martin & Sunyaev, 2007)

- need to treat angular momentum sub-levels separately!
- include collision to understand how close things are to SE
- Complexity of problem scales like ~ n^2_{max}
- But problem very *sparse*

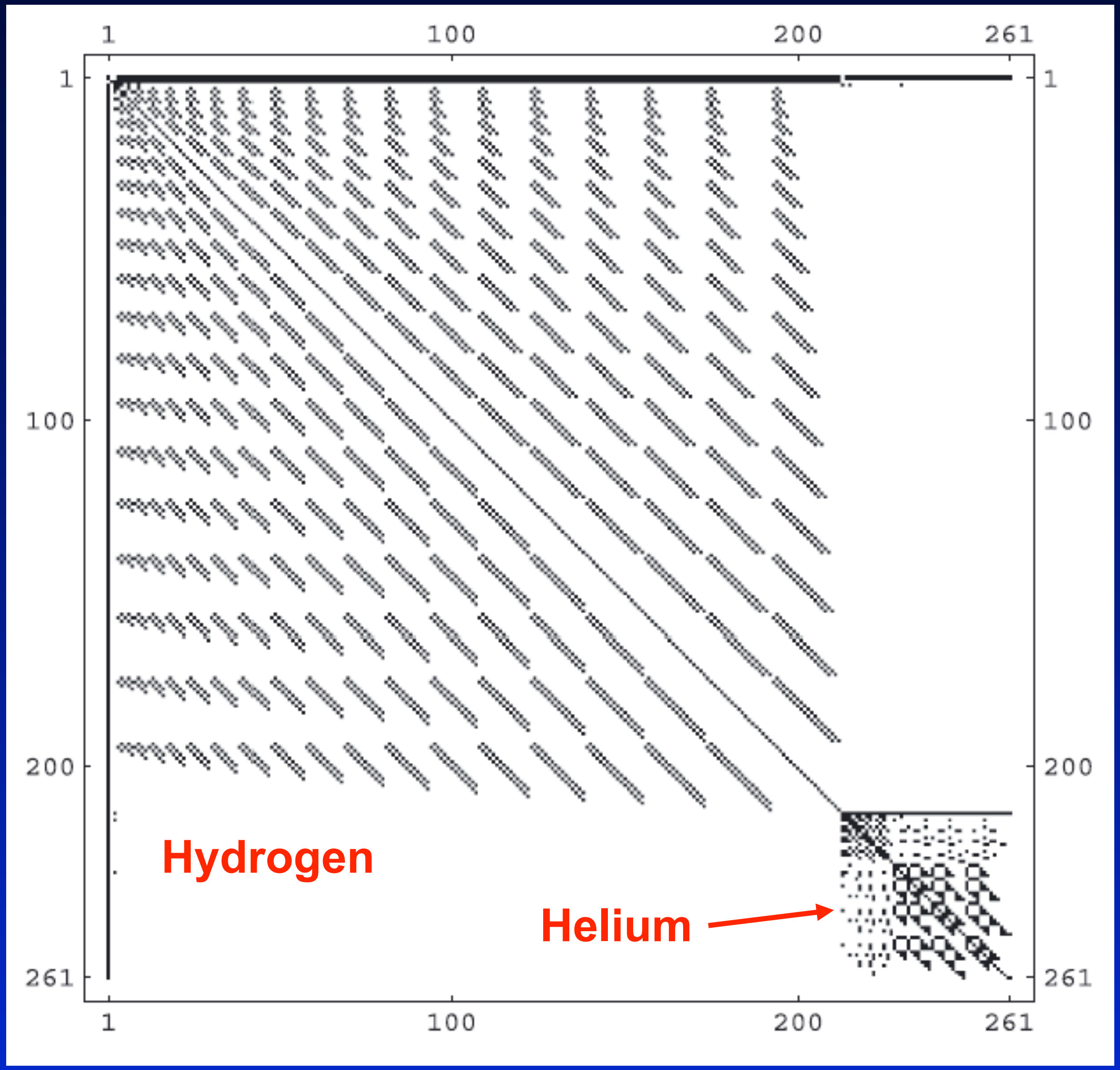
(Grin & Hirata, 2010; JC, Vasil & Dursi, 2010)



JC, Vasil & Dursi, MNRAS, 2010

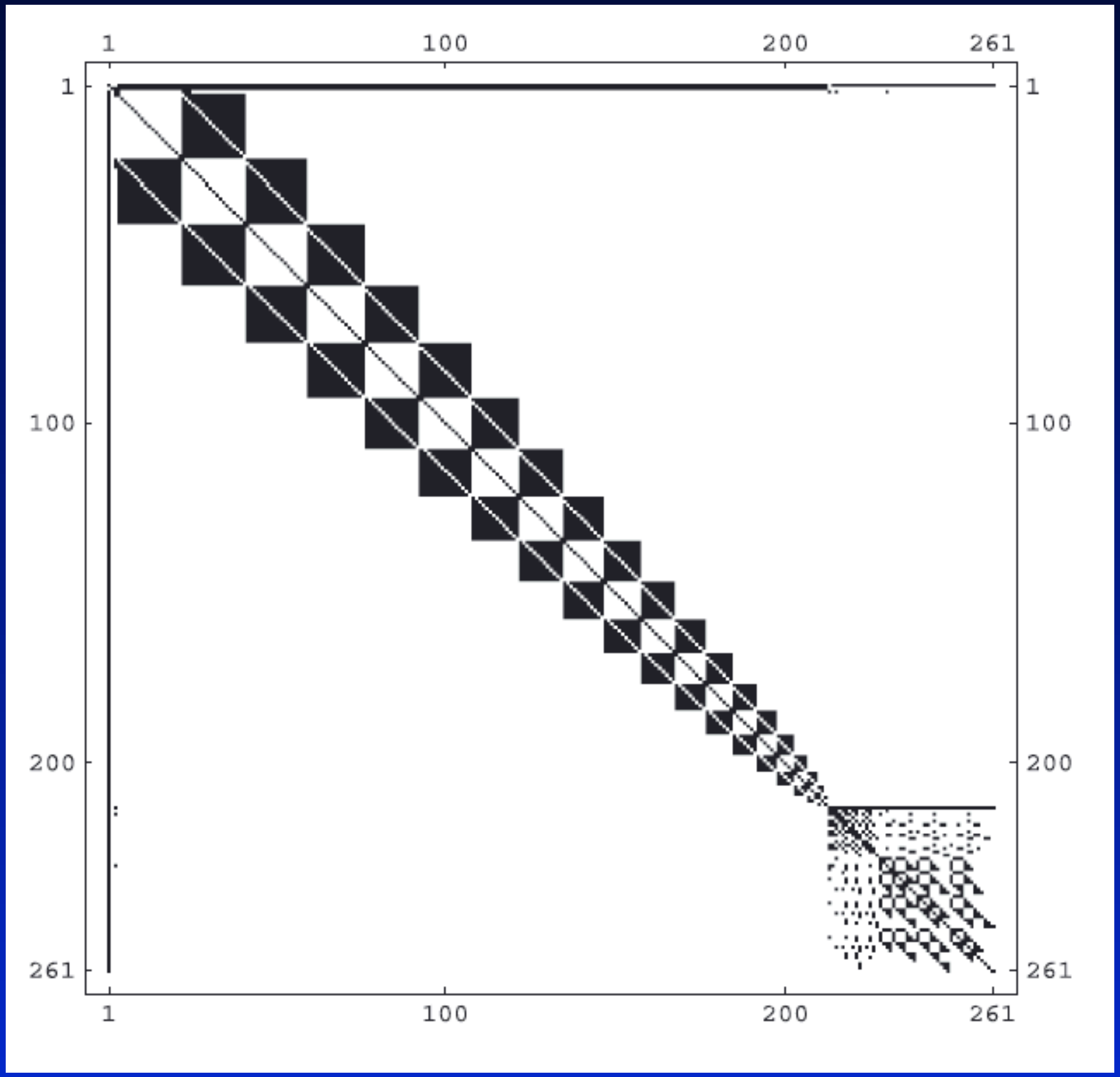
Sparsity of the problem and effect of ordering

20 shell Hydrogen + 5 shell Helium model



Shell-by-Shell ordering

$1s, 2s, 2p, 3s, 3p, 3d, ...$



Angular momentum ordering

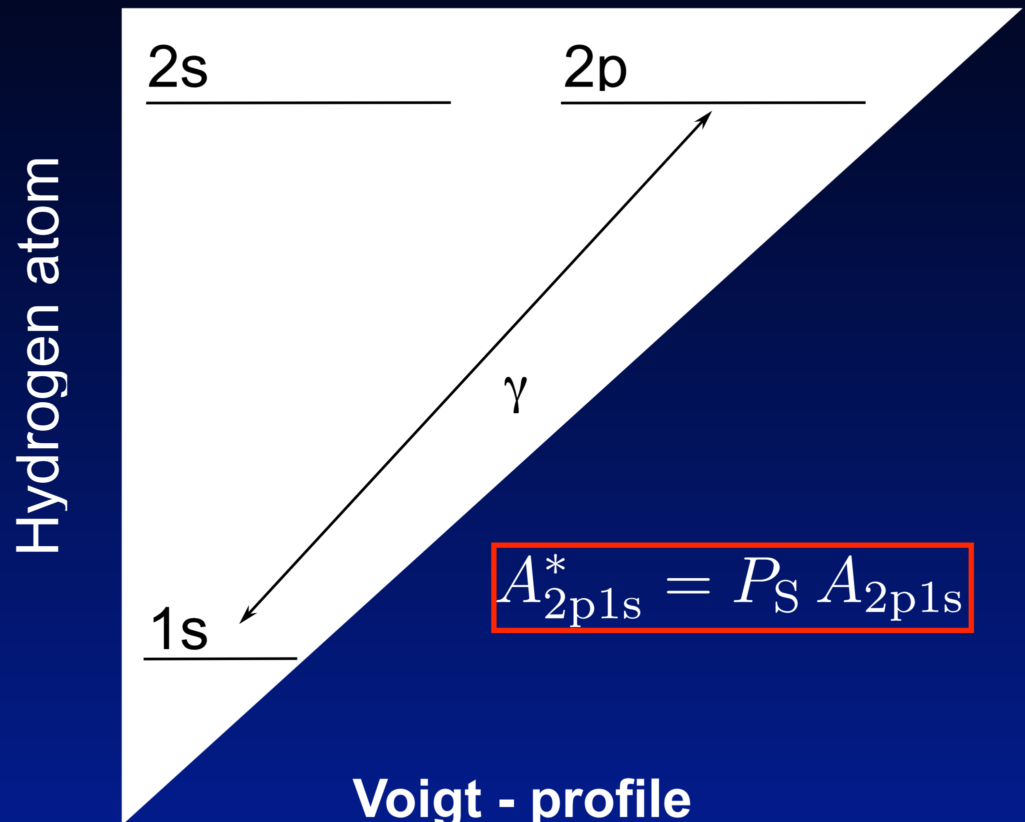
$1s, 2s, 3s, \ldots, ns, 2s, 3p, \ldots, np, 3d, 4d, ...$

Grin & Hirata, 2010
JC, Vasil & Dursi, MNRAS, 2010

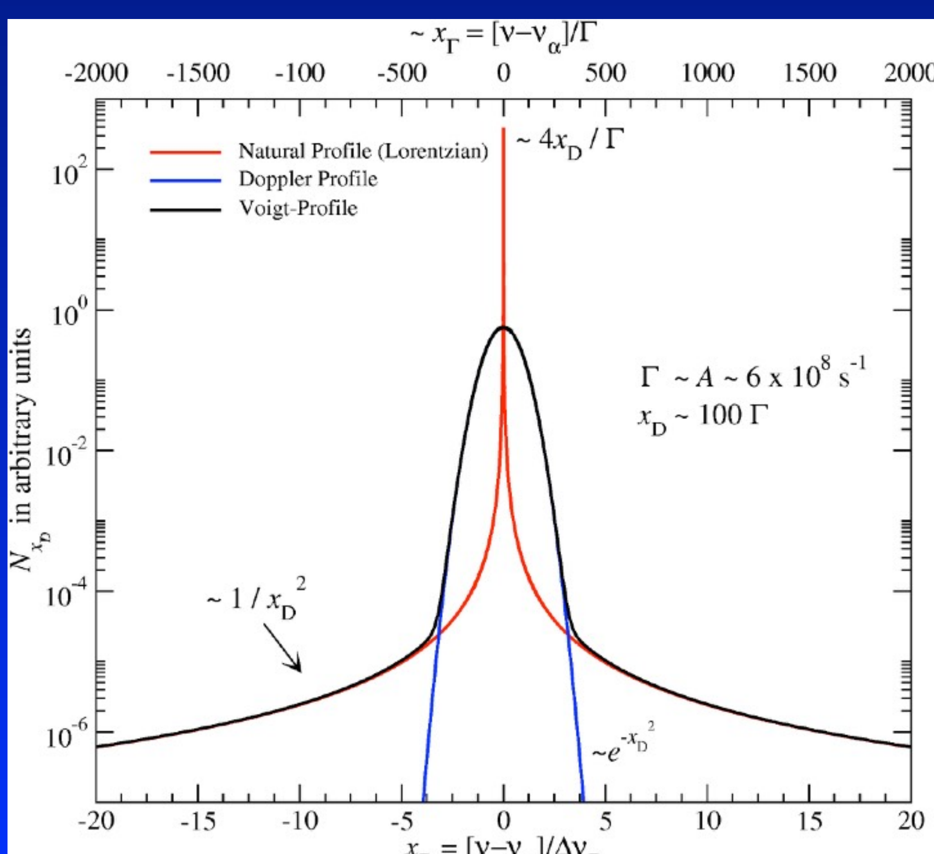
The Lyman-α radiative transfer problem

Sobolev approximation

(developed in late 50's to model moving envelopes of stars)



Voigt - profile



- To solve the coupled system of rate-equations

  → need to know mean intensity across the Ly-α (& Ly-*n*) resonance at different times

  → approximate solution using *escape probability*

  → *Escape == photons stop interacting with Ly-α resonance*
  == photons stop supporting the 2p-level
  == photons reach the very distant red wing

- Main assumptions of Sobolev approximation
  - populations of level + radiation field *quasi-stationary*
  - every 'scattering' leads to *complete redistribution*
  - emission & absorption profiles have the *same shape*

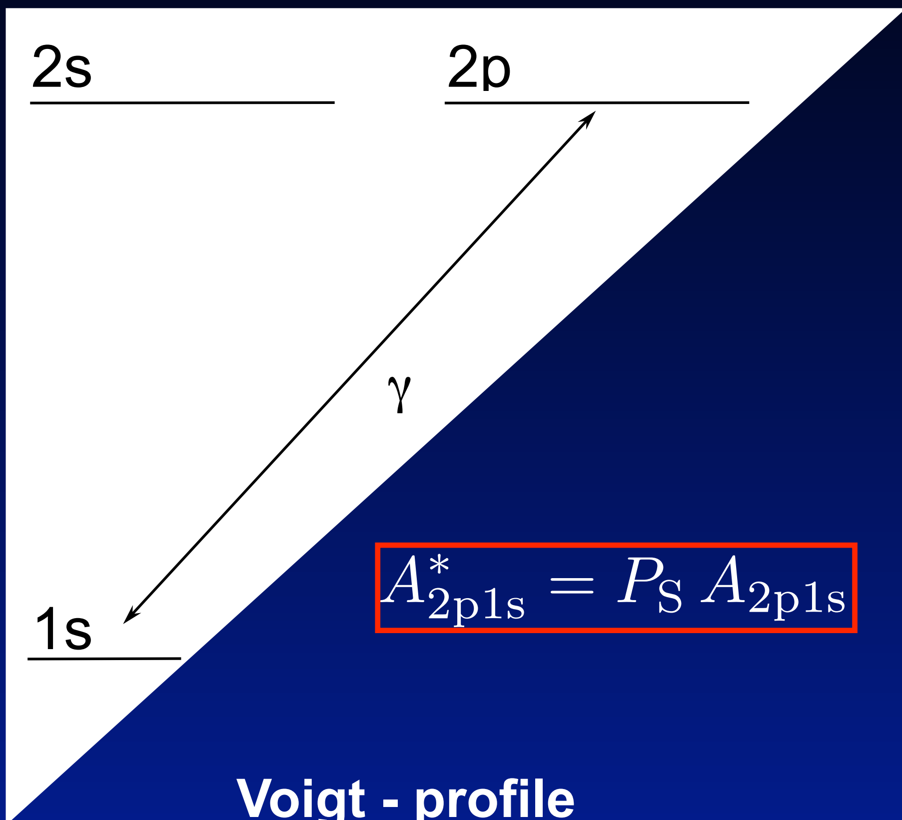
Doppler width

$$\frac{\Delta\nu_{\rm D}}{\nu} = \sqrt{\frac{2kT}{m_{\rm H}c^2}} \simeq {\rm few} \times 10^{-5}$$

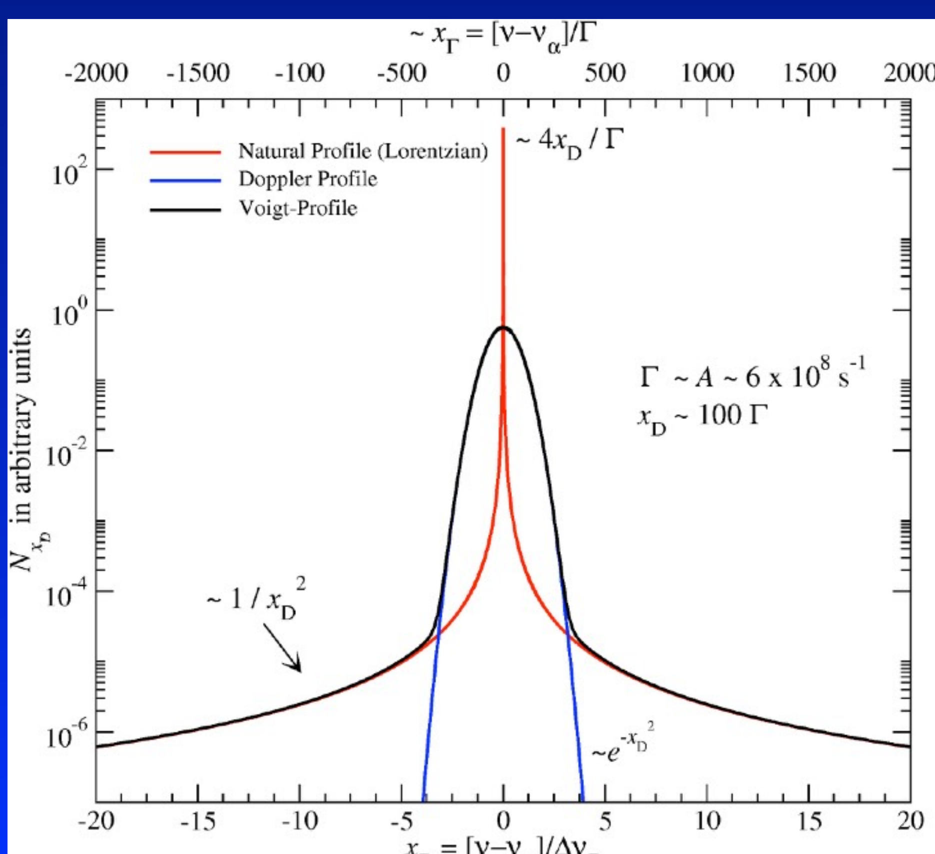
Sobolev approximation

(developed in late 50's to model moving envelopes of stars)

Hydrogen atom



Voigt - profile



- To solve the coupled system of rate-equations

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- Main assumptions of Sobolev approximation
  - populations of level + radiation field *quasi-stationary*
  - every 'scattering' leads to *complete redistribution*
  - emission & absorption profiles have the *same shape*

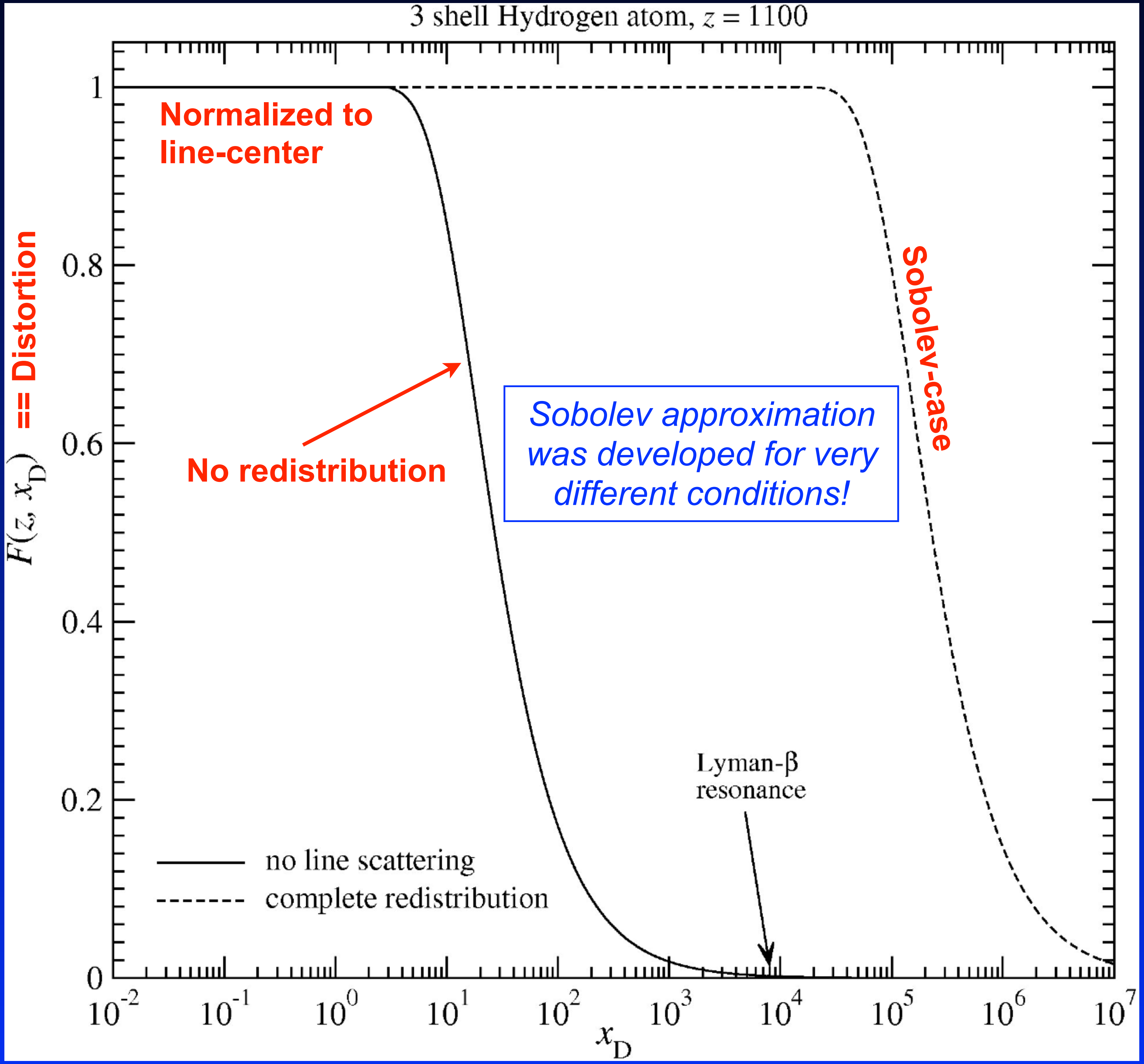
- Sobolev escape probability & optical depth

$$P_S = \frac{1 - e^{-\tau_S}}{\tau_S} \simeq 10^{-8}$$

$$\tau_S = \frac{c\,\sigma_r N_{1s}}{H}\,\frac{\Delta\nu_D}{\nu} = \frac{g_{2p}}{g_{1s}}\,\frac{A_{21}\lambda_{21}^3}{8\pi H}\,N_{1s}$$

Problems with Sobolev approximation:

Complete redistribution ⟺ partial redistribution



JC & Sunyaev, 2009

Sobolev-approximation:

- Important variation of the photon distribution at ~1.5 times the ionization energy!
- For 1% accuracy one has to integrate up to $\sim 10^7$ Doppler width!
- *Complete redistribution bad approximation and very unlikely* ($p \sim 10^{-4}$-10^{-3})

No redistribution case:

- Much closer to the correct solution (*partial redistribution*)
- Avoids some of the unphysical aspect

Other Problems with Sobolev approximation

Time-dependence of the emission process

- Quasi-stationarity ok close to line center
- Non-stationarity important in the distant wings
- Wings even at ~ 10^4 Doppler width ($\Delta\nu/\nu$ ~ 10%) required for <0.1% precision

Asymmetry of emission / absorption profiles

- *Standard textbook* equations always assume $\nu \sim \nu_0$
- Basically *wrong* in distant damping wings
- Detailed balance off → blackbody not conserved!
- Formulation that includes profile asymmetries required

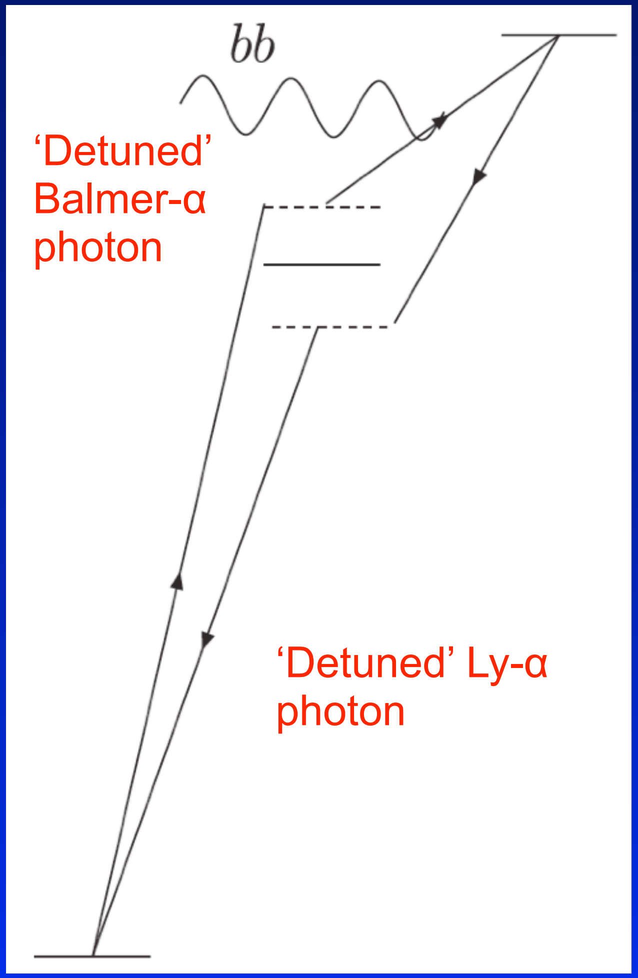
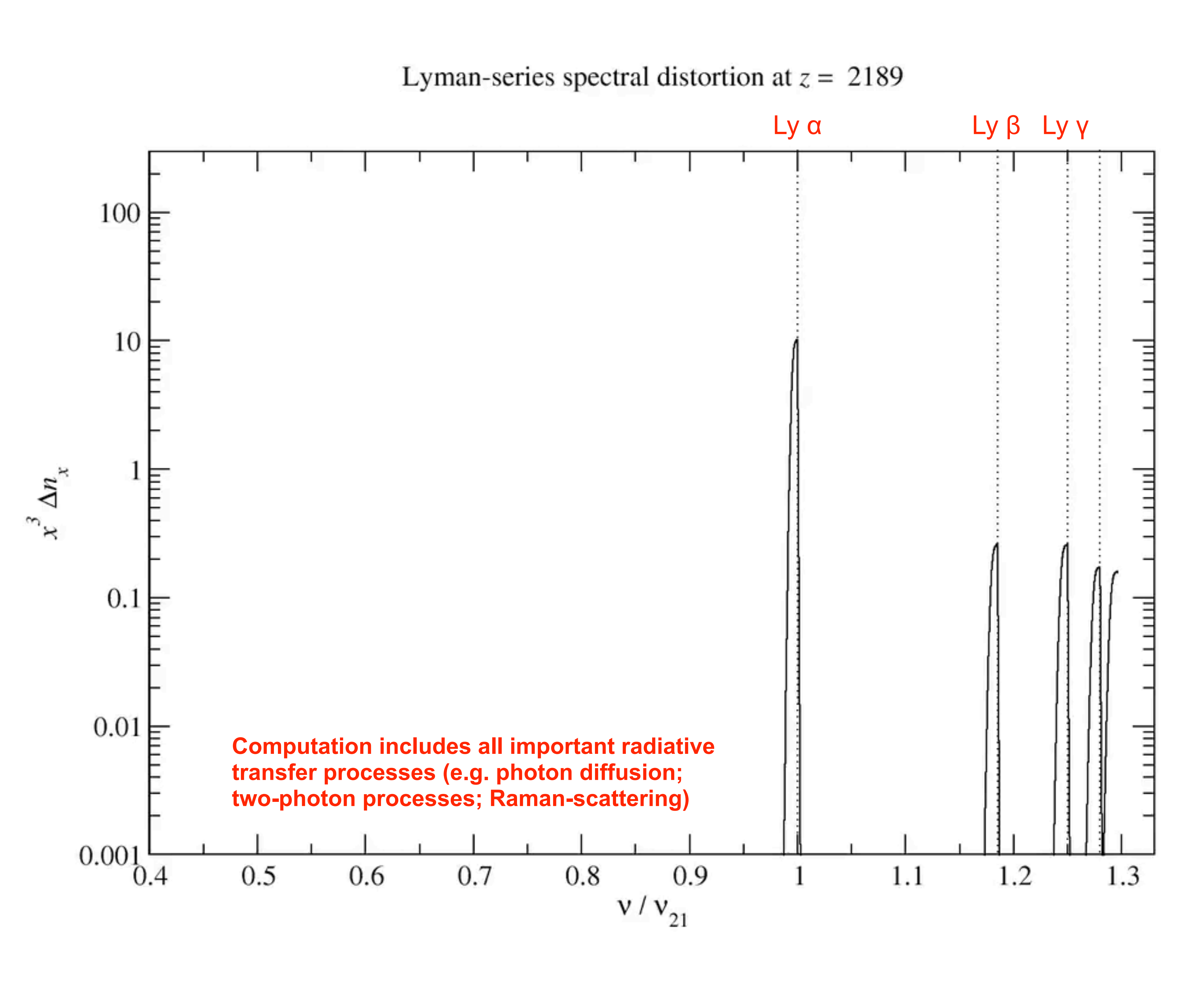


Illustration from Switzer & Hirata 2007 (meant for Helium)

See JC & Sunyaev, 2009 for detailed physics

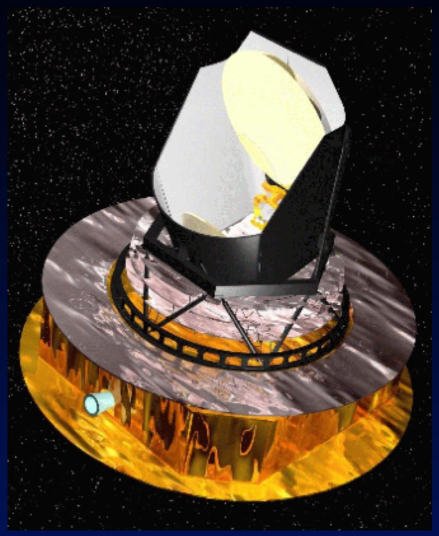
Evolution of the HI Lyman-series distortion



CITA ICAT

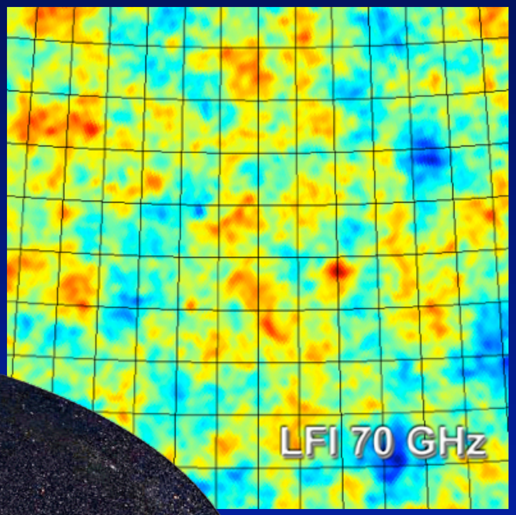
JC & Thomas, MNRAS, 2010

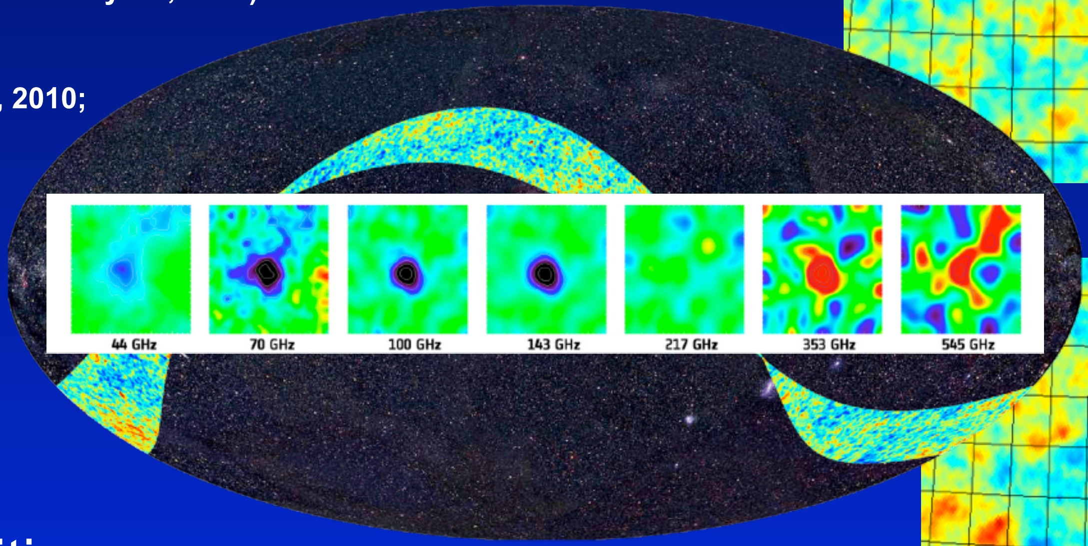
Getting the job done for *Planck*



Hydrogen recombination

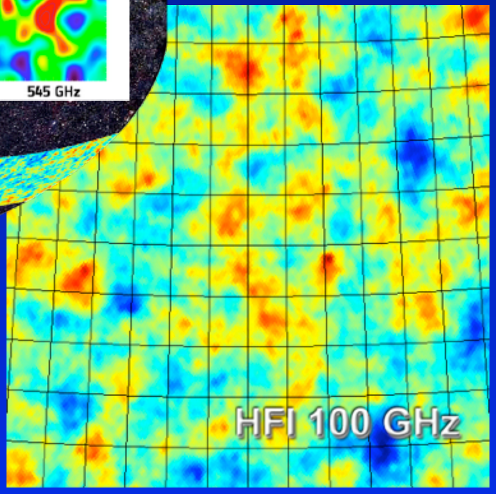
- Two-photon decays from higher levels
  (Dubrovich & Grachev, 2005, Astr. Lett., 31, 359; Wong & Scott, 2007; JC & Sunyaev, 2007; Hirata, 2008; JC & Sunyaev 2009)
- Induced 2s two-photon decay for hydrogen
  (JC & Sunyaev, 2006, A&A, 446, 39; Hirata 2008)
- Feedback of the Lyman-α distortion on the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





Helium recombination

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



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

Main corrections during HeI Recombination

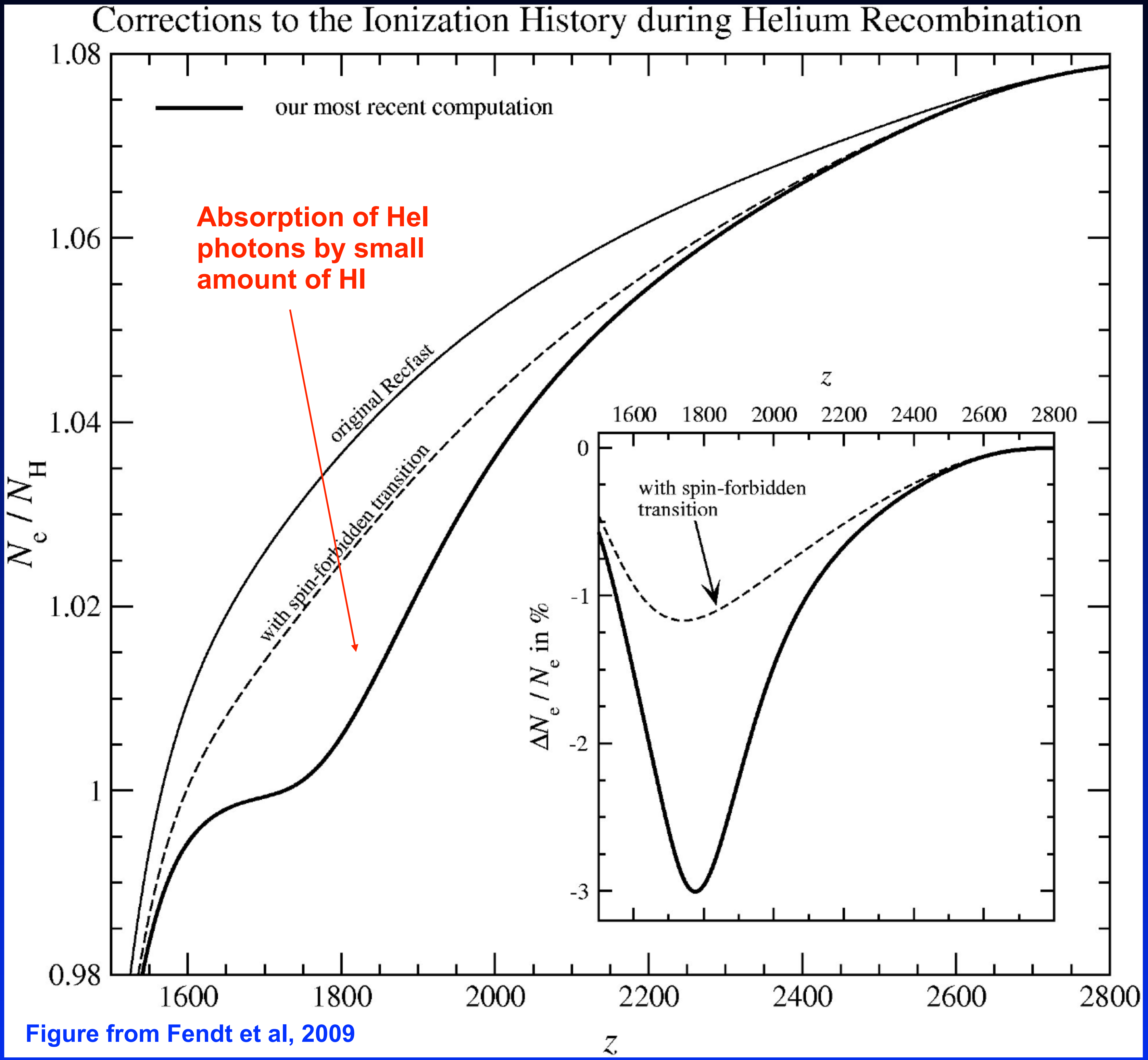
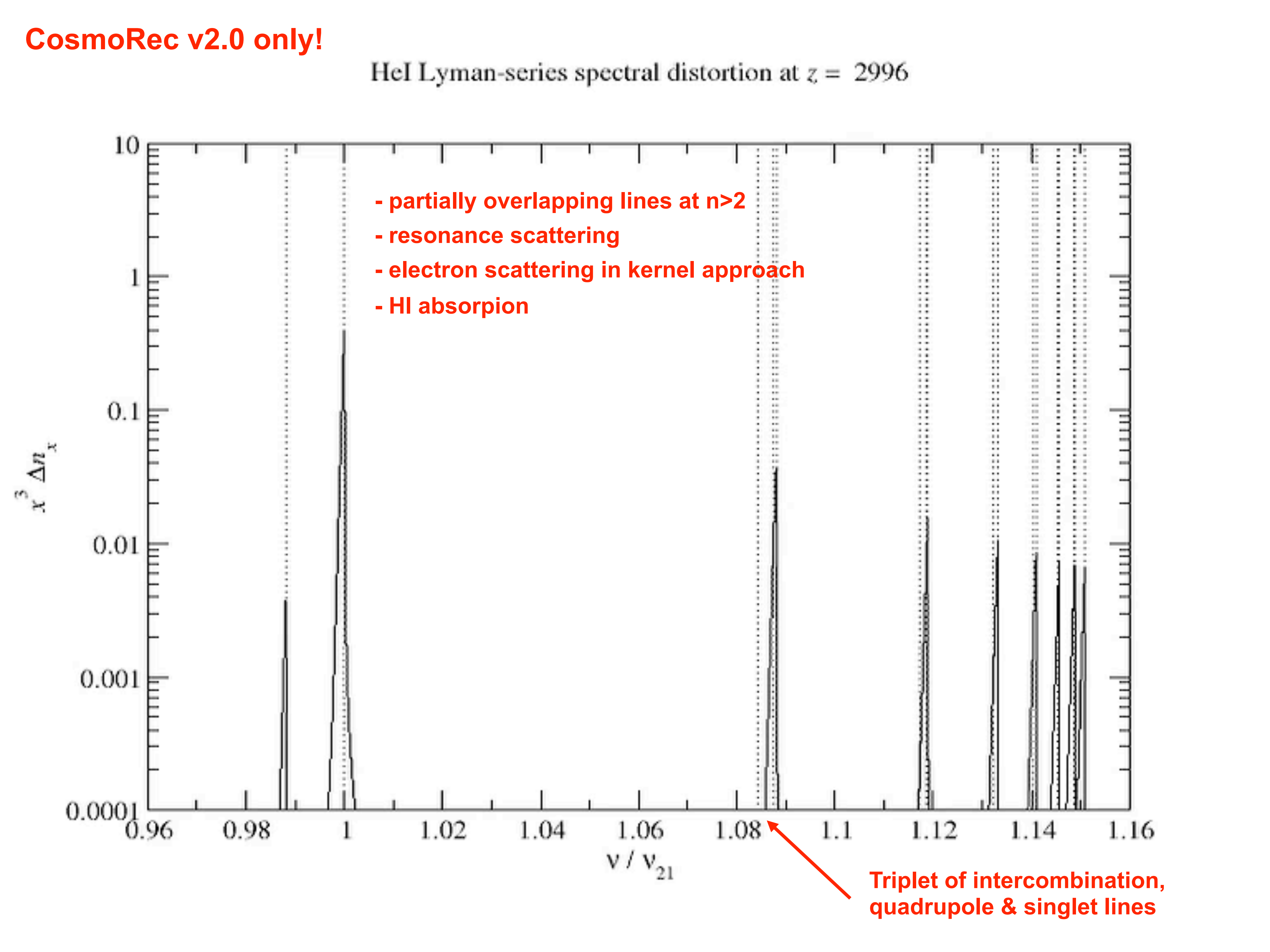


Figure from Fendt et al, 2009

- Delayed neutral helium recombination was indeed one of the *Recfast* results
- Effect of HI absorption already mentioned in Hu et al. 1995 (priv. comm Peebles)
- Spin-forbidden HeI transition estimated in 1977 (Lin et al.)
- But neutral helium recombination not as crucial for Cl's…

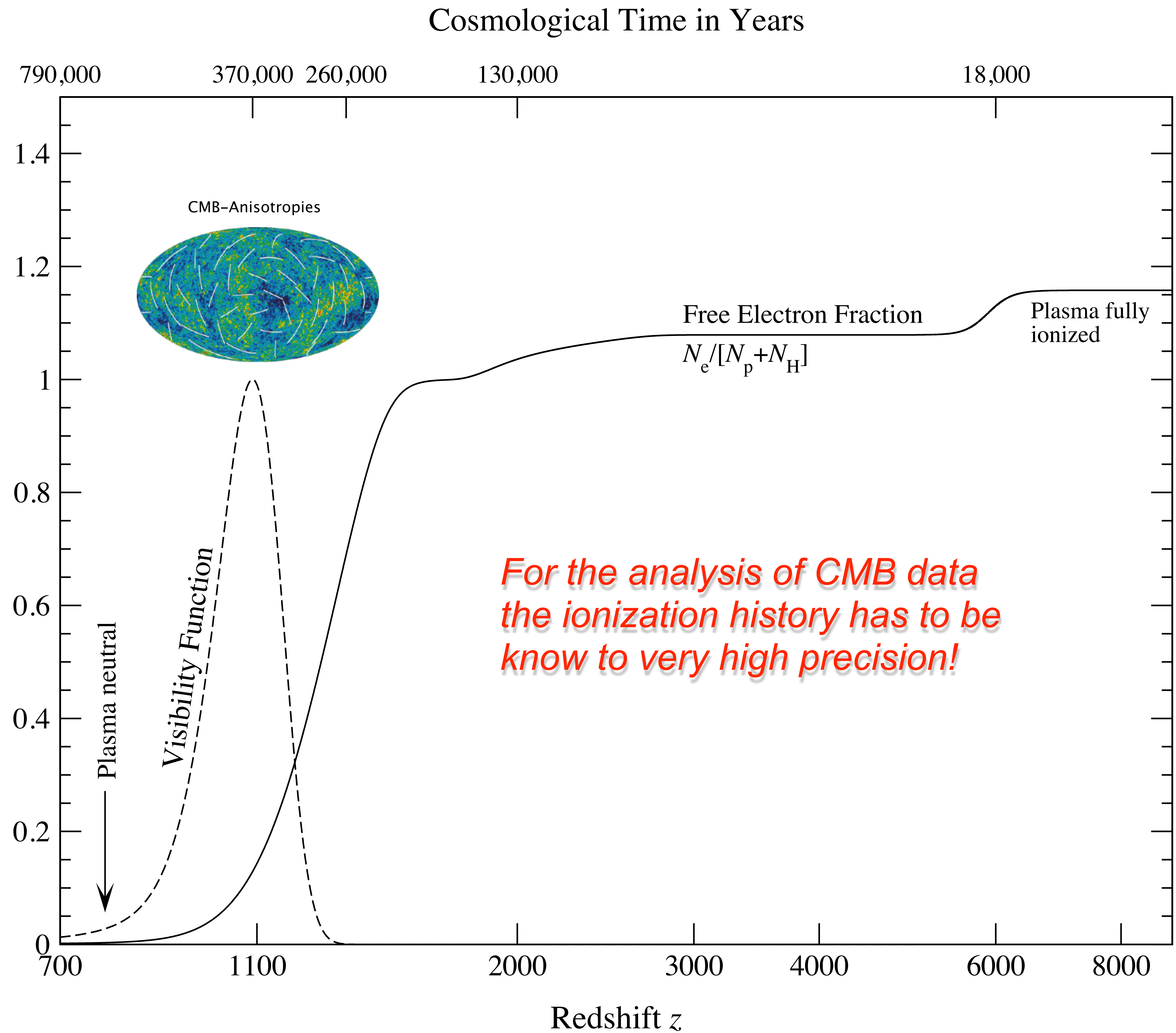
Kholupenko et al, 2007
Switzer & Hirata, 2007

Evolution of the HeI high frequency distortion

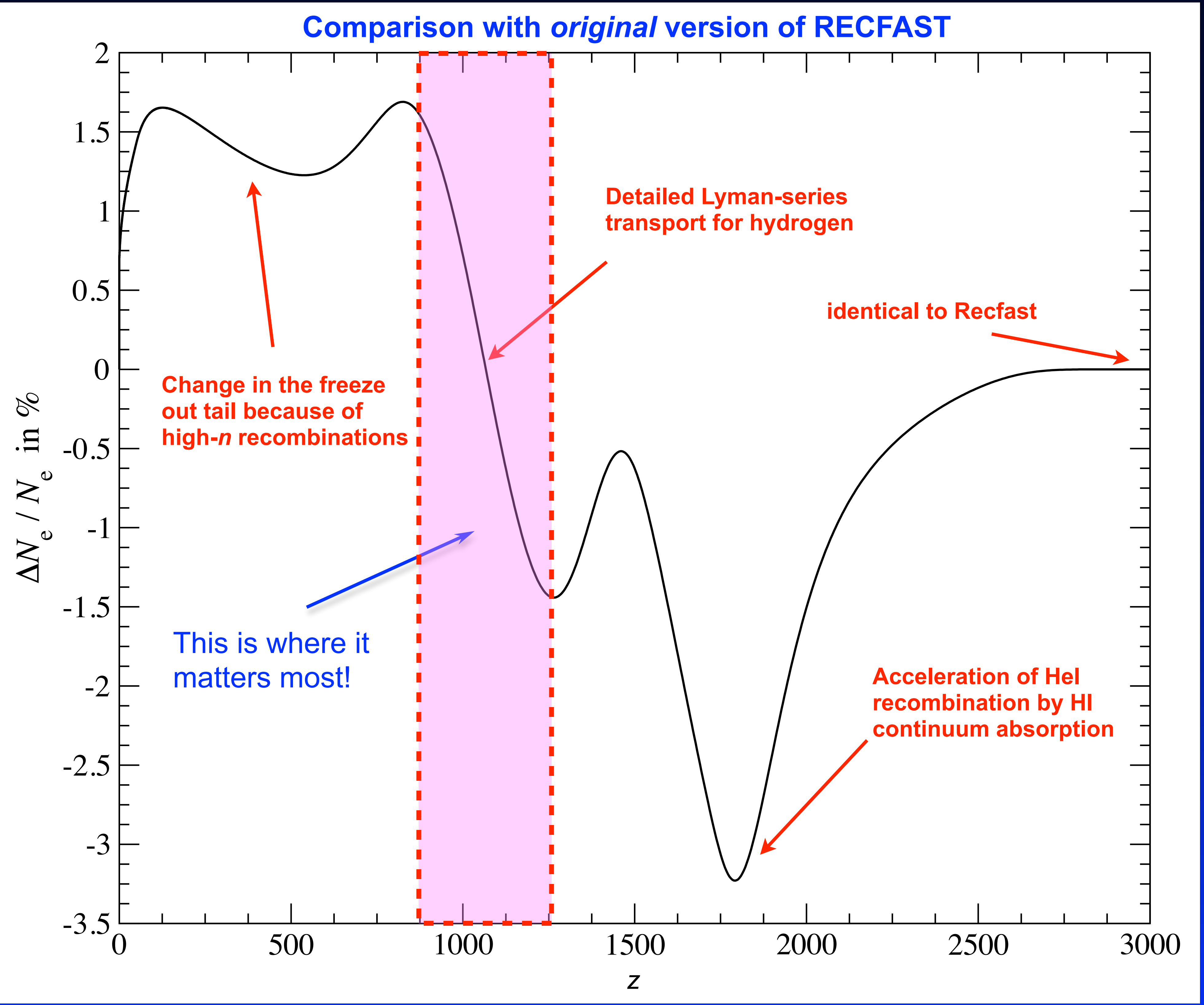


JC, Fung & Switzer, 2011

So why is all this so important?

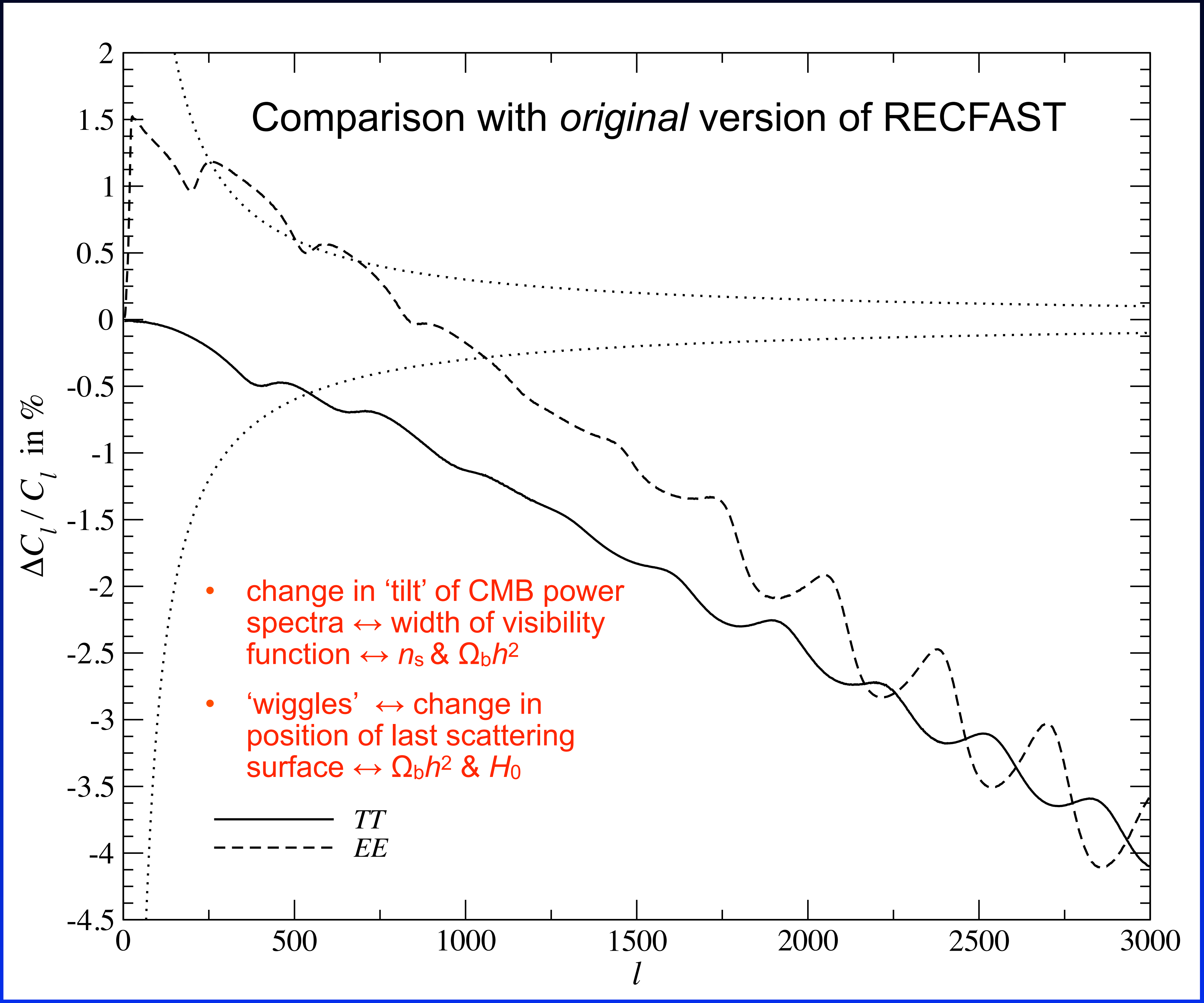

Cosmological Time in Years
790,000
370,000
260,000
130,000
18,000
1.4
1.2
1
0.8
0.6
0.4
0.2
0
CMB-Anisotropies
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully ionized
Visibility Function
Plasma neutral
For the analysis of CMB data the ionization history has to be know to very high precision!
700
1100
2000
3000
4000
6000
8000
Redshift z

Cumulative Changes to the Ionization History



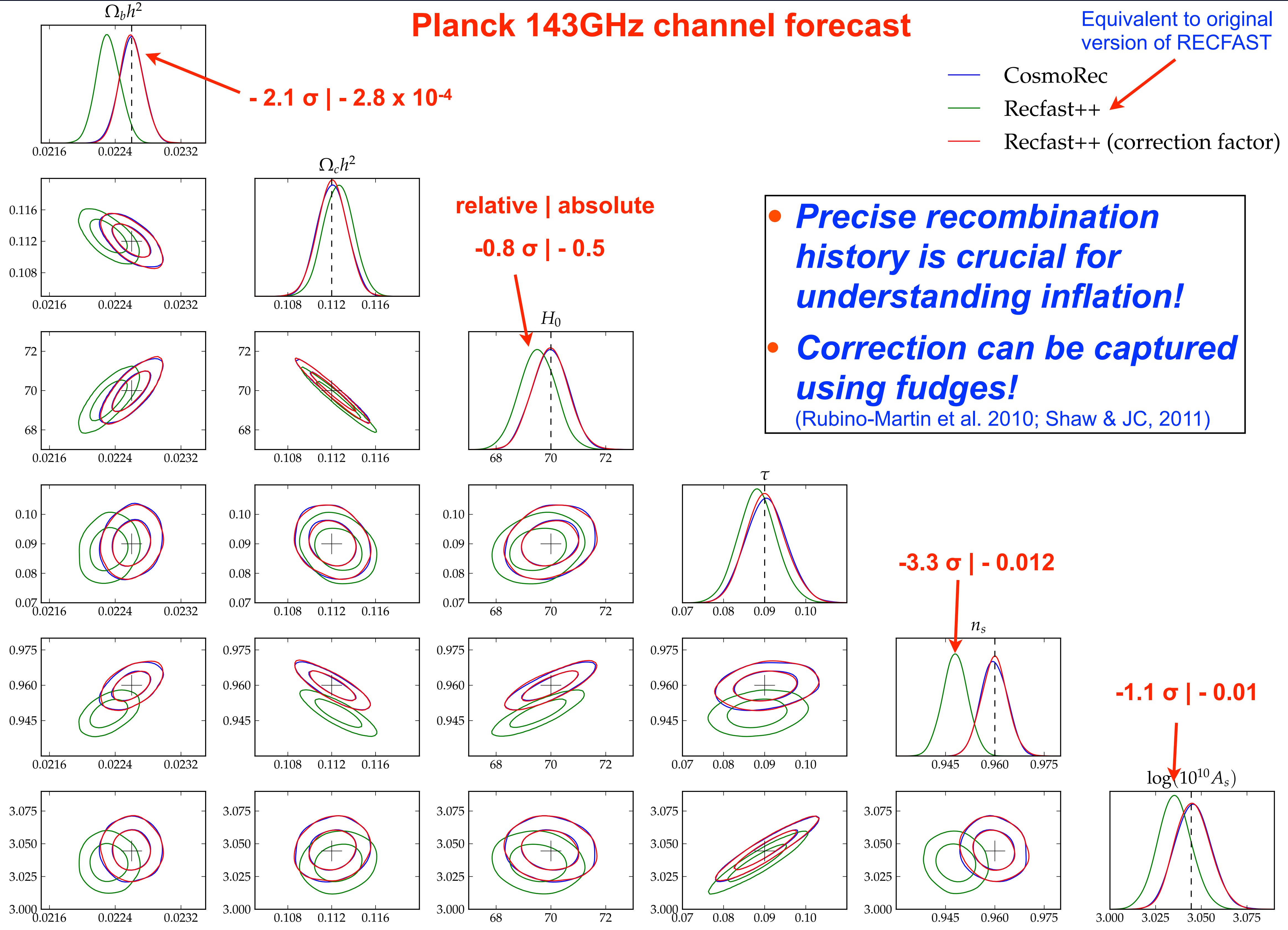
JC & Thomas, MNRAS, 2010; Shaw & JC, MNRAS, 2011

Cumulative Change in the CMB Power Spectra



Shaw & JC, MNRAS, 2011

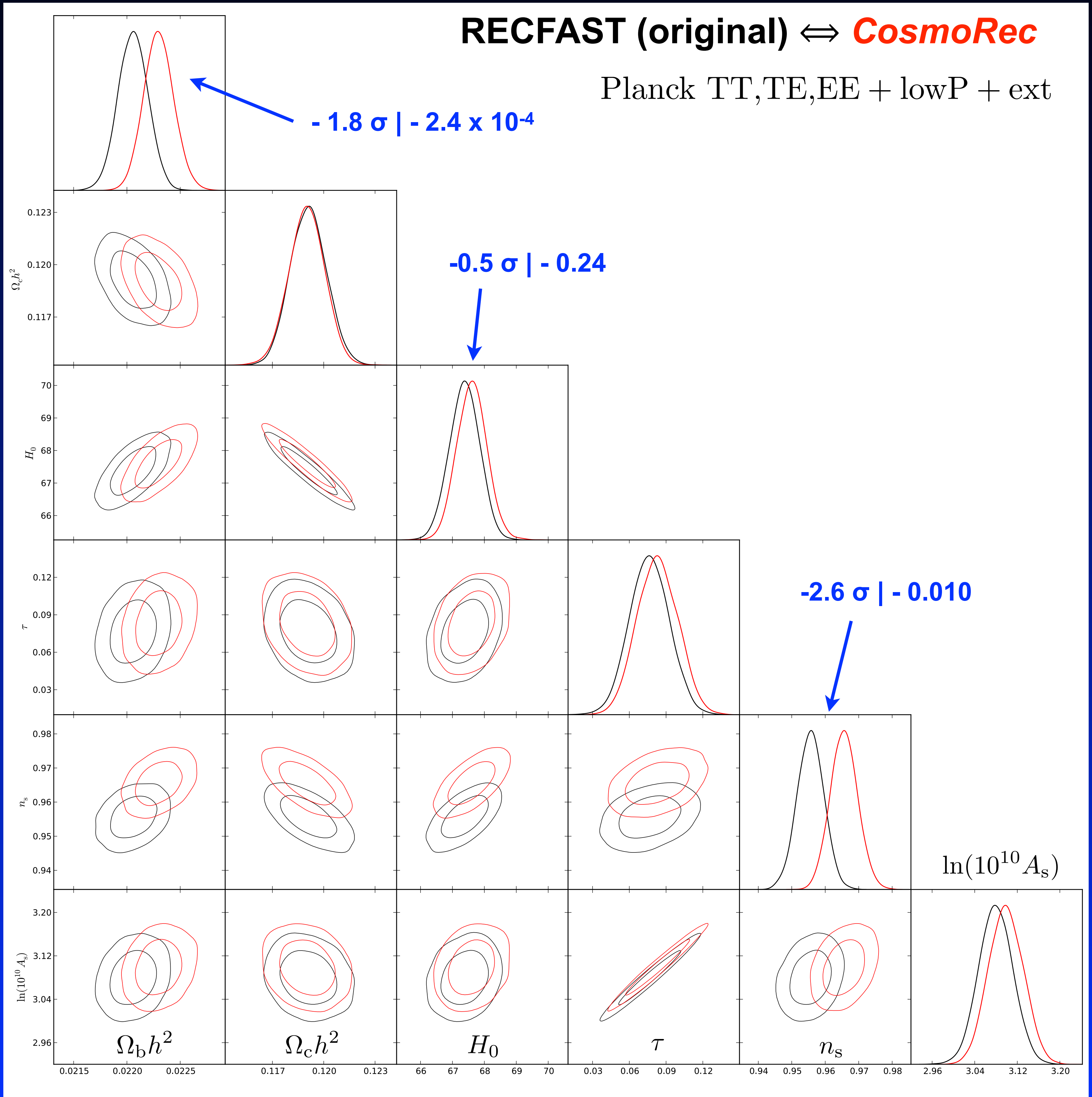
Importance of recombination for *Planck*



- ***Precise recombination history is crucial for understanding inflation!***
- ***Correction can be captured using fudges!***
  (Rubino-Martin et al. 2010; Shaw & JC, 2011)

Shaw & JC, 2011, and references therein

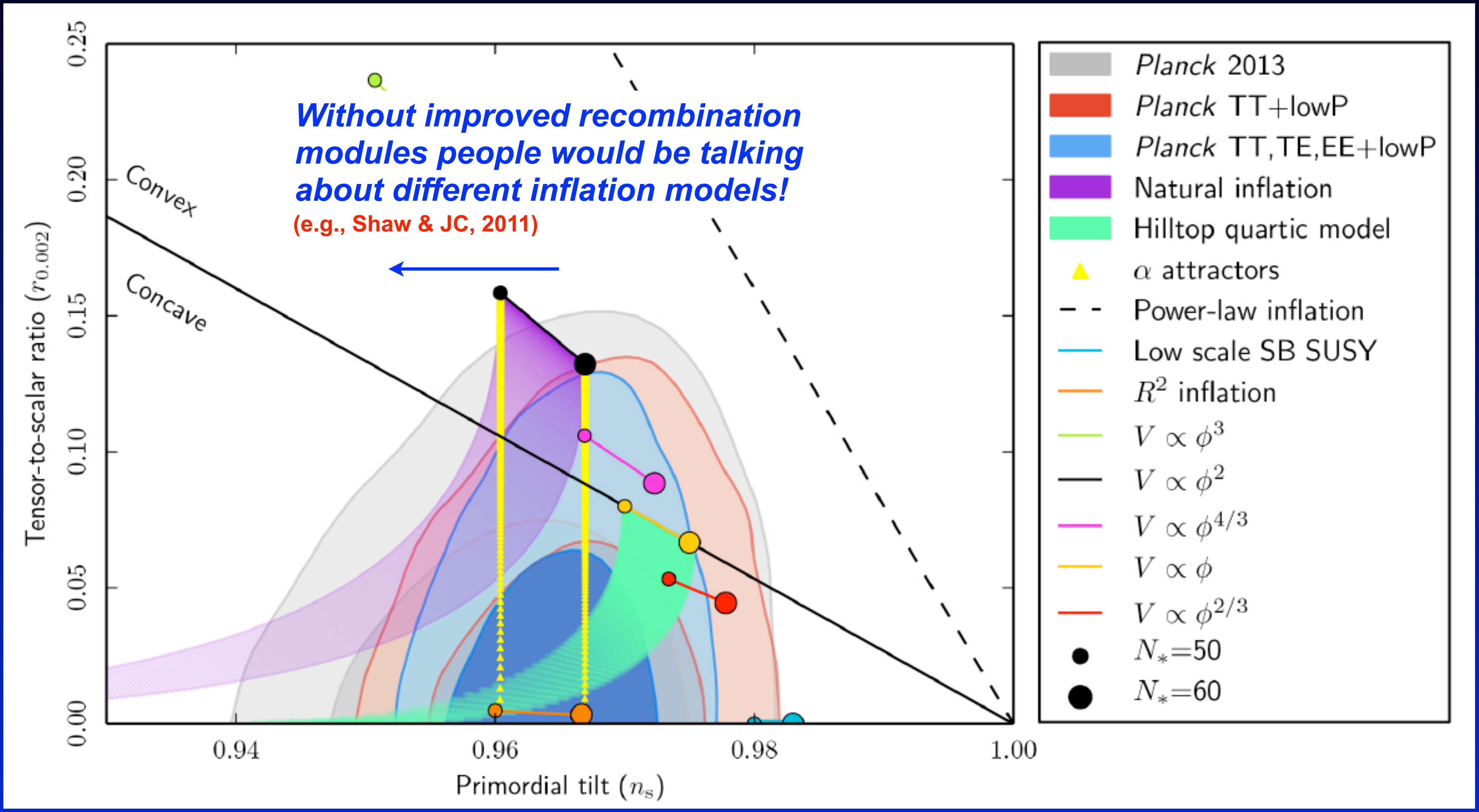
Biases as they *would* have been for *Planck*



- Biases a little less significant with real *Planck* data
- absolute biases very similar
- In particular n_s would be biased significantly

Planck Collaboration, XIII 2015

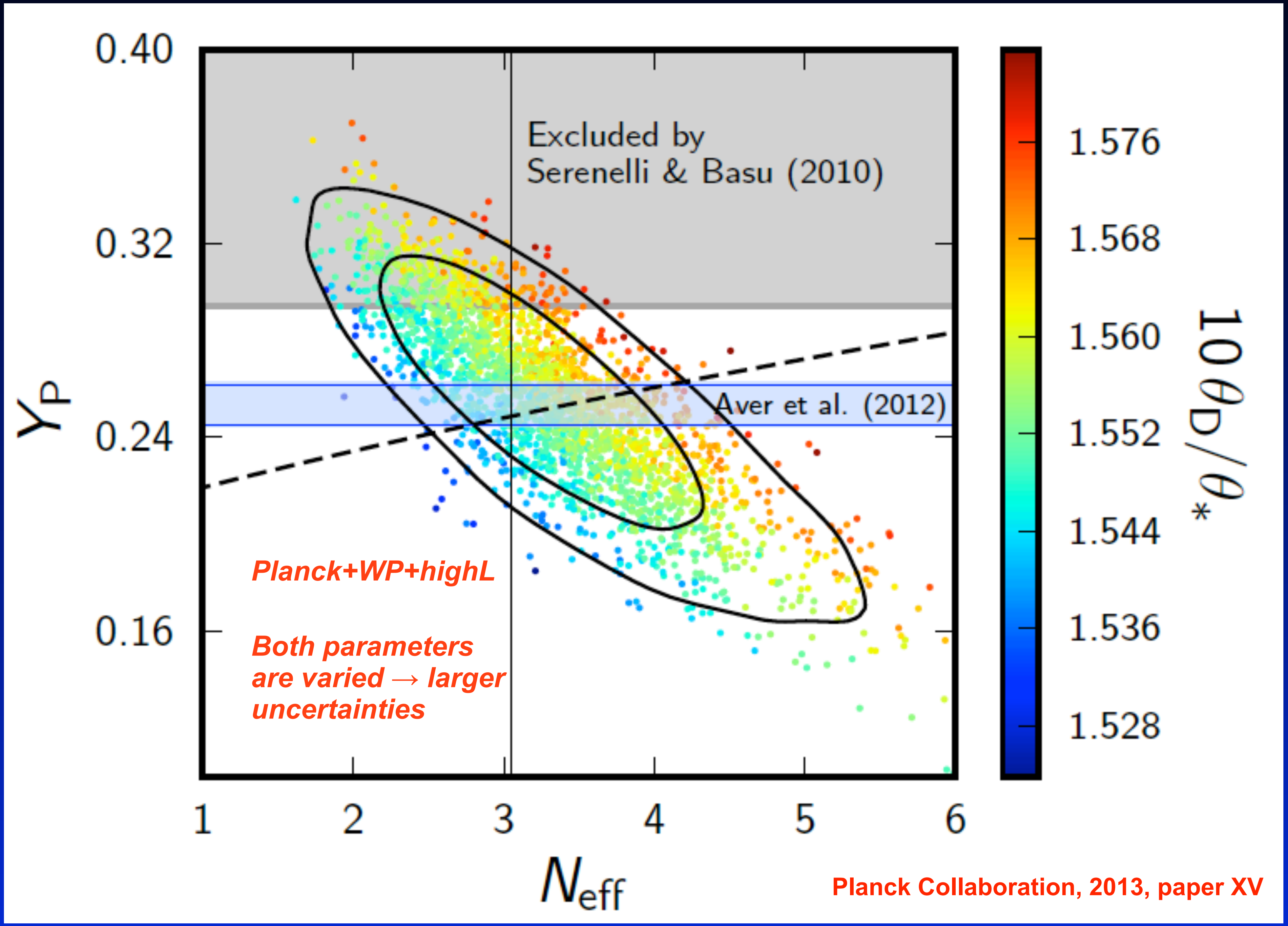
Importance of recombination for inflation constraints



Planck Collaboration, 2015, paper XX

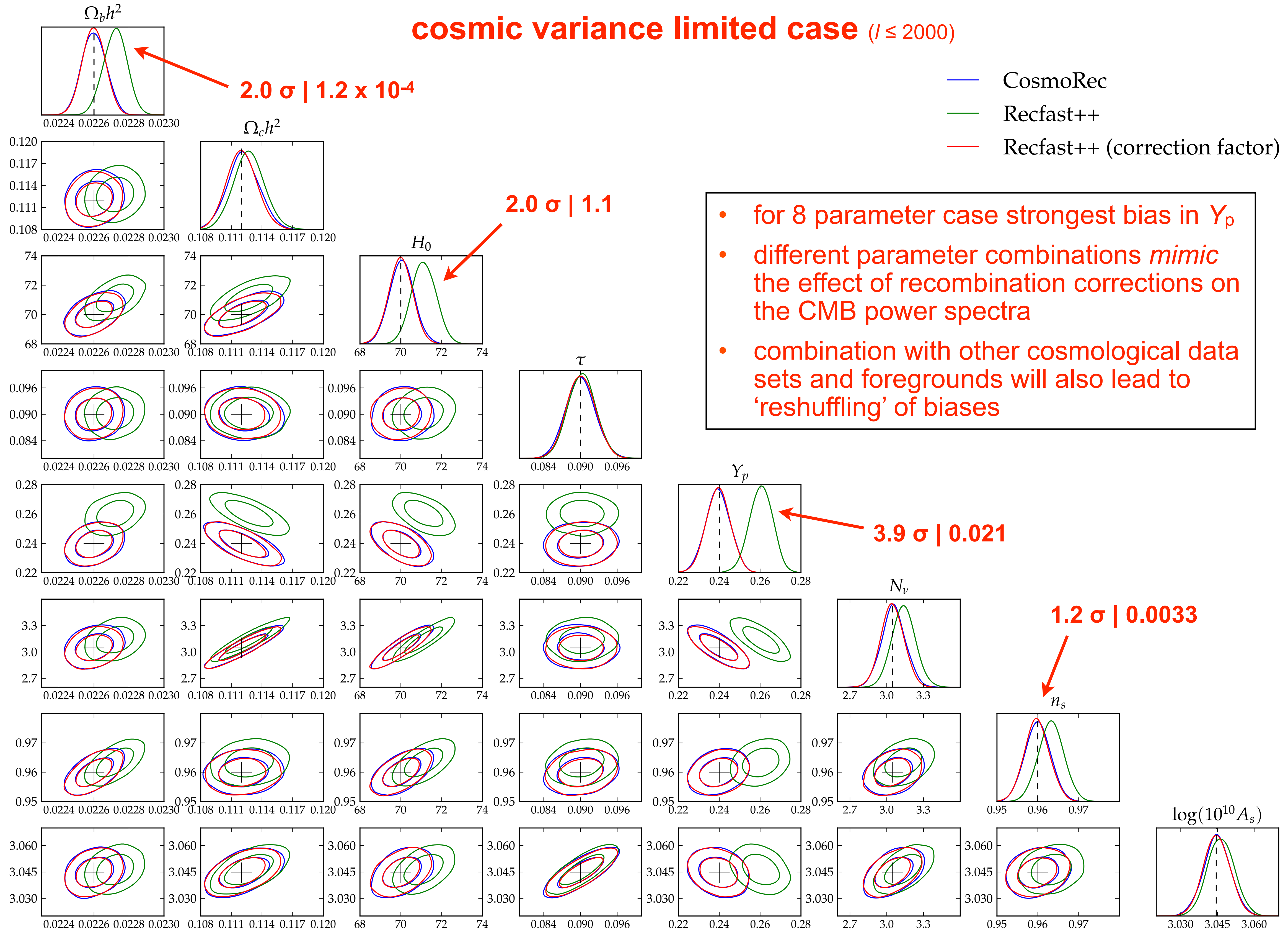
- Analysis uses refined recombination model (CosmoRec/HyRec)

CMB constraints on N_{eff} and Y_p



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

Importance of recombination for measuring helium



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

Shaw & JC, 2011, and references therein

Cosmological Recombination Radiation

Simple estimates for hydrogen recombination

Hydrogen recombination:

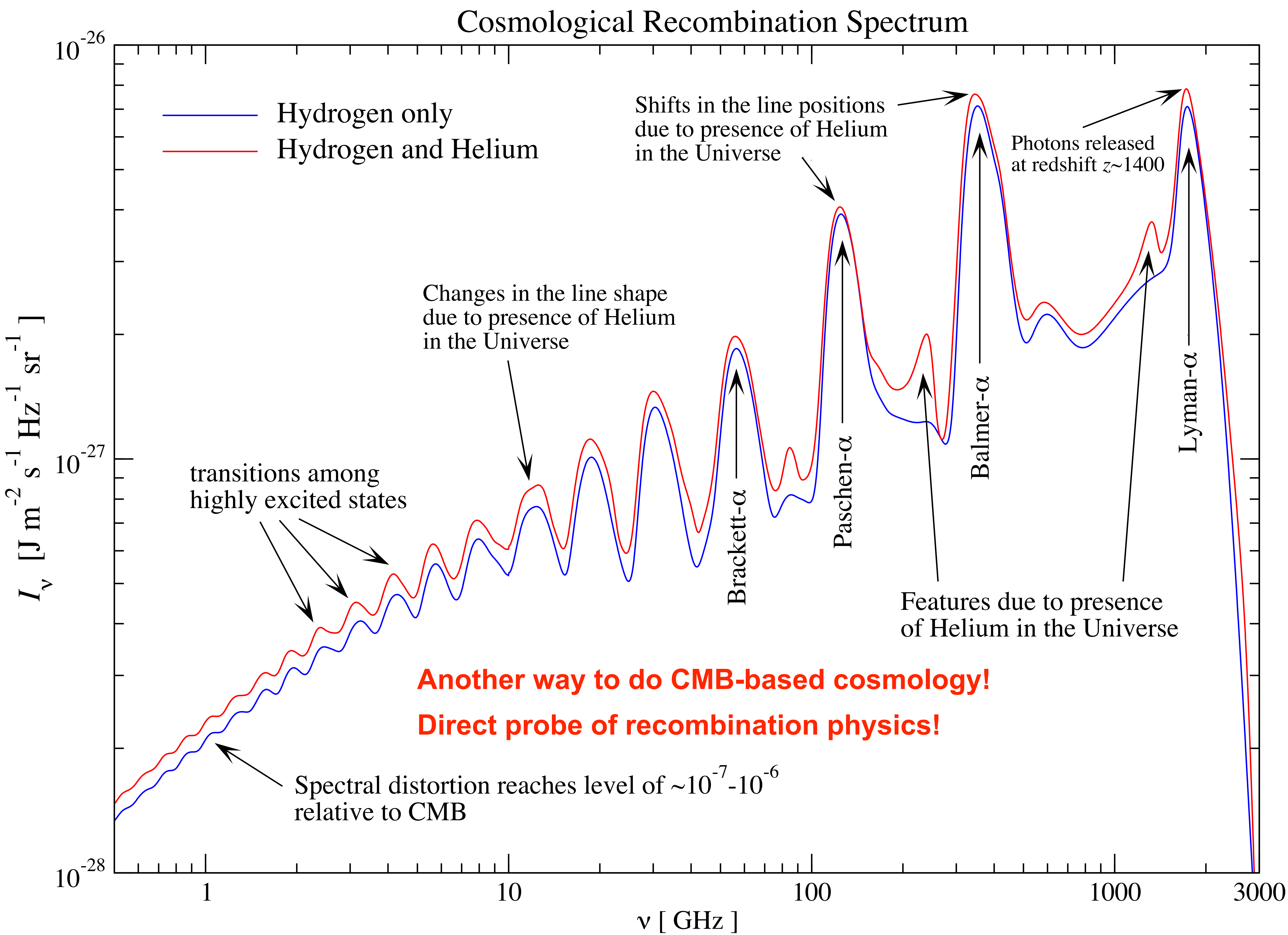
- per recombined hydrogen atom an energy of ~ 13.6 eV in form of photons is released
- at z ~ 1100 → $\Delta\varepsilon/\varepsilon \sim 13.6\ \mathrm{eV}\ N_b / (N_\gamma\, 2.7kT_r) \sim 10^{-9}$ - 10^{-8}

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

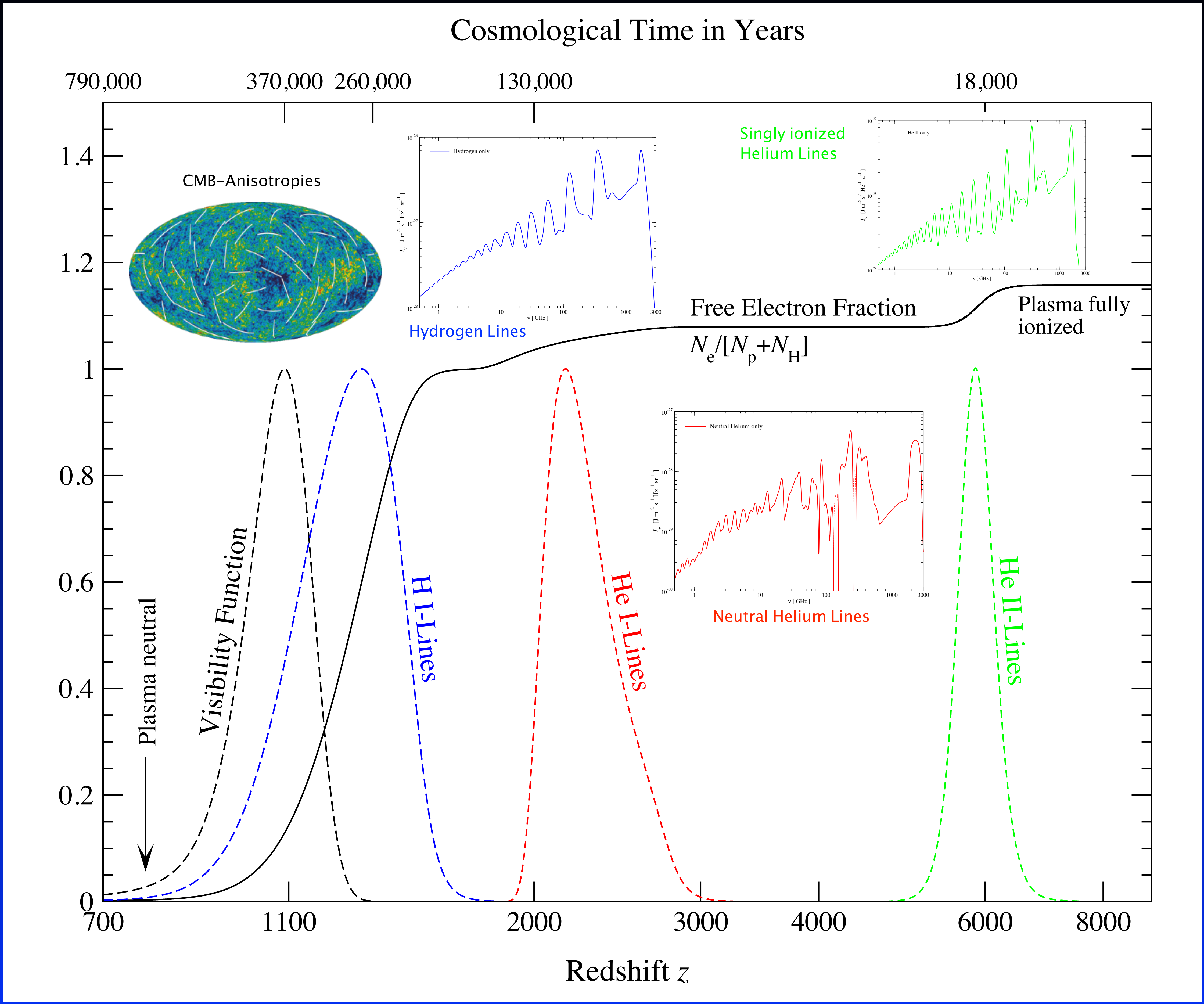
→ At that time the *thermalization* process doesn't work anymore!

→ There should be some *small* spectral distortion due to additional Ly-α and 2s-1s photons!
(Zeldovich, Kurt & Sunyaev, 1968, ZhETF, 55, 278; Peebles, 1968, ApJ, 153, 1)

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



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



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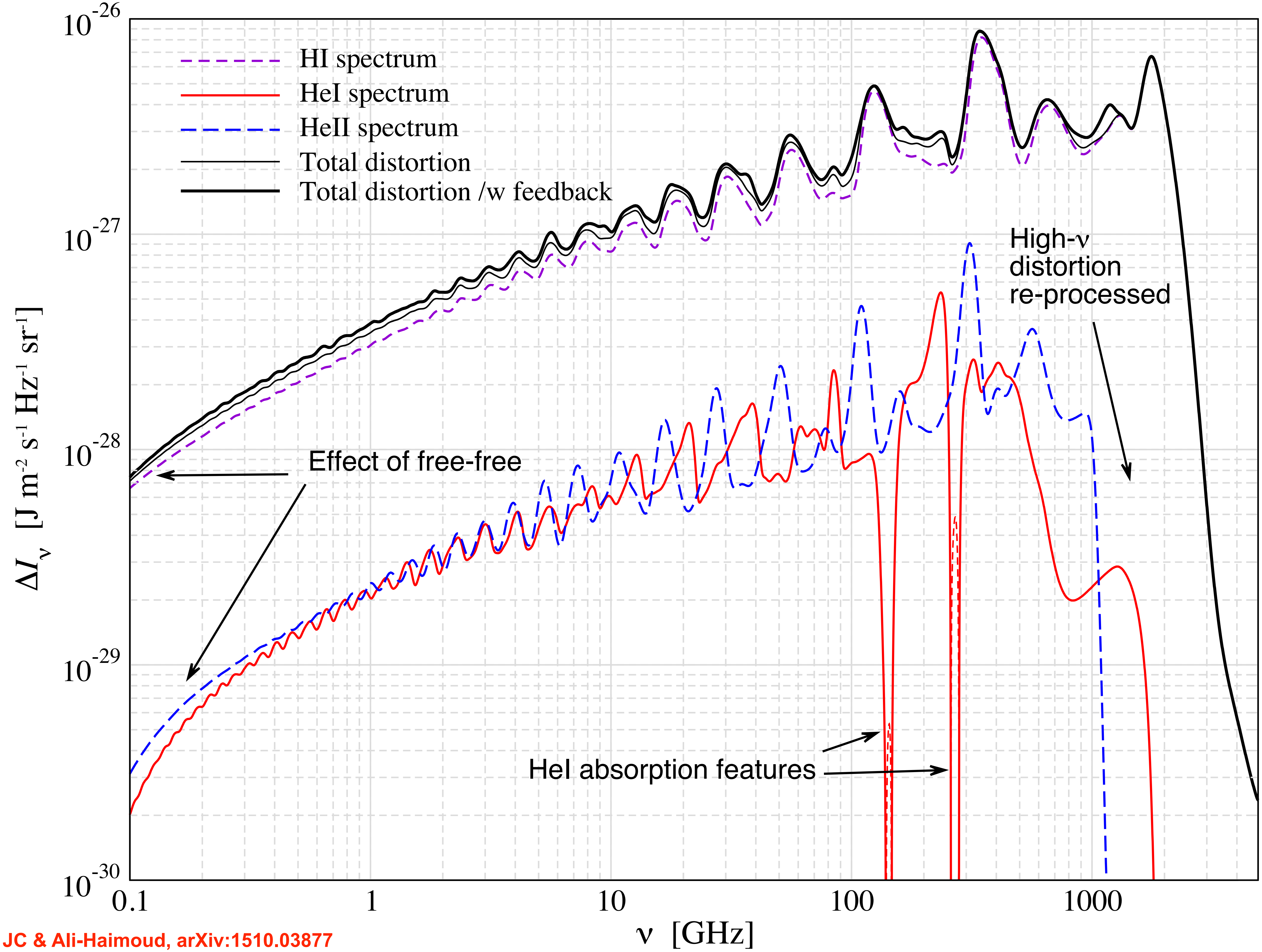
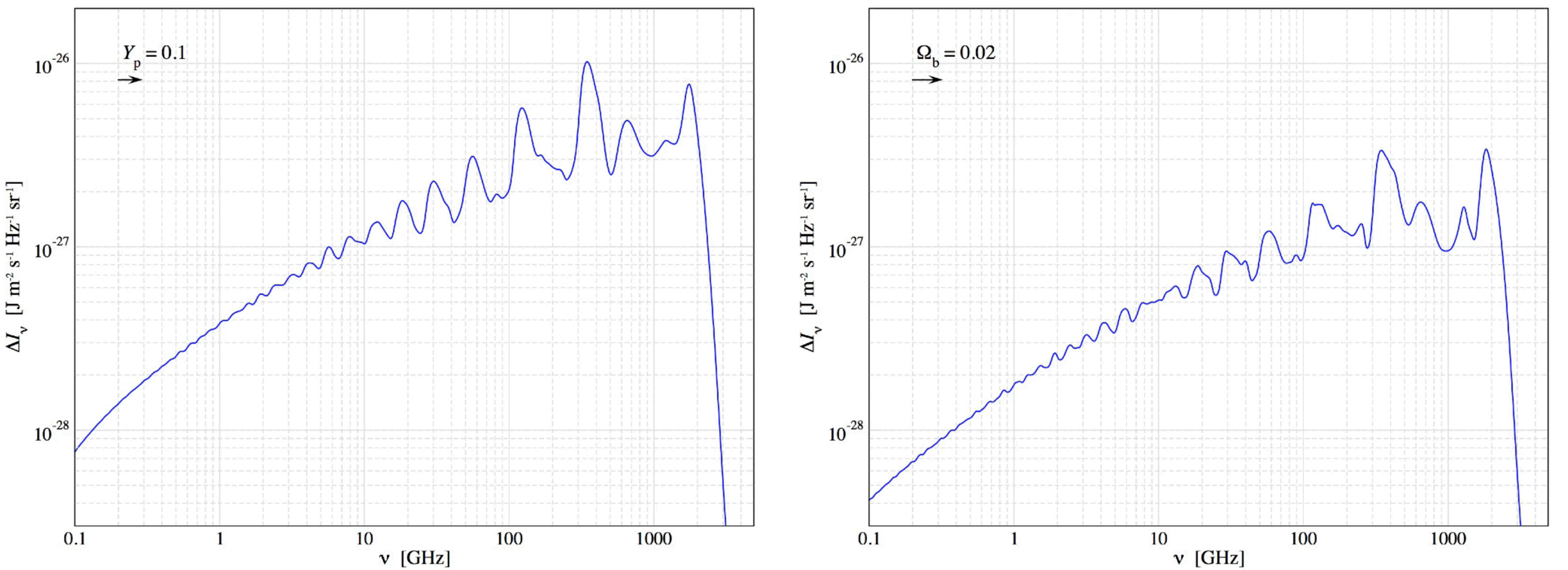
6000
8000
Redshift z
CMB–Anisotropies
Hydrogen only
Hydrogen Lines
Singly ionized
Helium Lines
He II only
Free Electron Fraction
Ne/[Np+NH]
Plasma fully
ionized
Neutral Helium only
Neutral Helium Lines
Plasma neutral
Visibility Function
H I-Lines
He I-Lines
He II-Lines

New detailed and fast computation!



JC & Ali-Haimoud, arXiv:1510.03877

CosmoSpec: fast and accurate computation of the CRR



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

CosmoSpec will be available here:

www.Chluba.de/CosmoSpec

JC & Ali-Haimoud, arXiv:1510.03877

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!***

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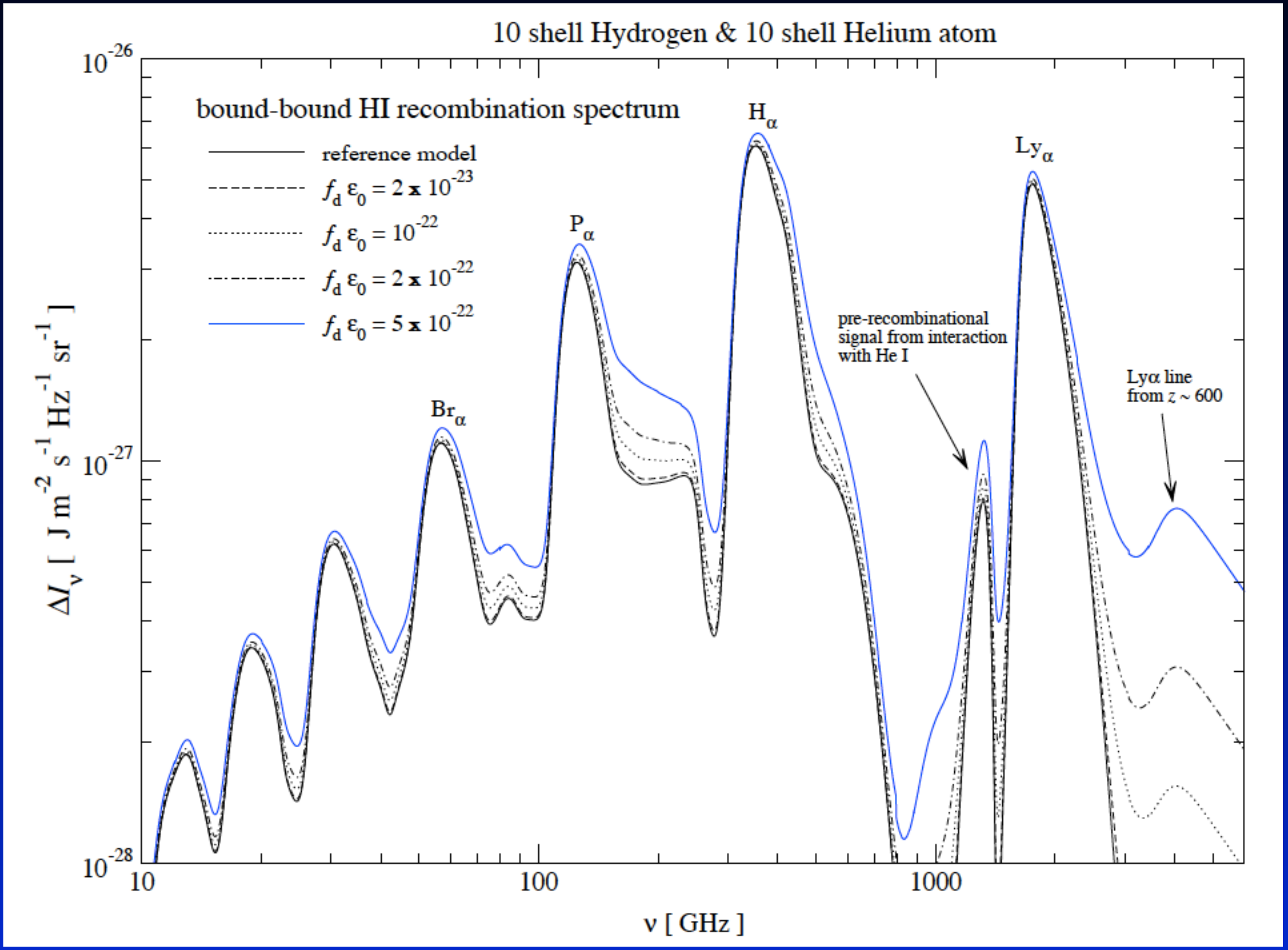
→ ***In principle allows us to directly check our understanding of the standard recombination physics***

Dark matter annihilations / decays



JC, 2009, arXiv:0910.3663

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

→ More tomorrow….

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→ ***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***

If something unexpected or non-standard happened:

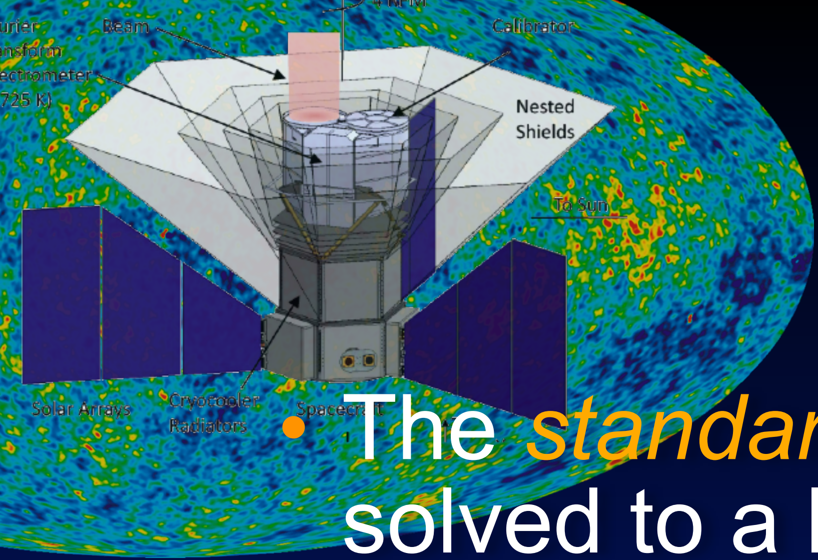
→ ***non-standard thermal histories should leave some measurable traces***

→ ***direct way to measure/reconstruct the recombination history!***

→ **possibility to distinguish *pre-* and *post-recombination y*-type distortions**

→ ***sensitive to energy release during recombination***

→ **variation of fundamental constants**



Summary

- The *standard recombination* problem has been solved to a level that is sufficient for the analysis of current and future CMB data (<0.1% precision!)
- Many people helped with this problem!
- Without the improvements over the original version of Recfast cosmological parameters derived from Planck would be *biased* significantly
- In particular the discussion of *inflation* models would have been affected
- Cosmological recombination radiation allows us to directly *constrain* the *recombination history*