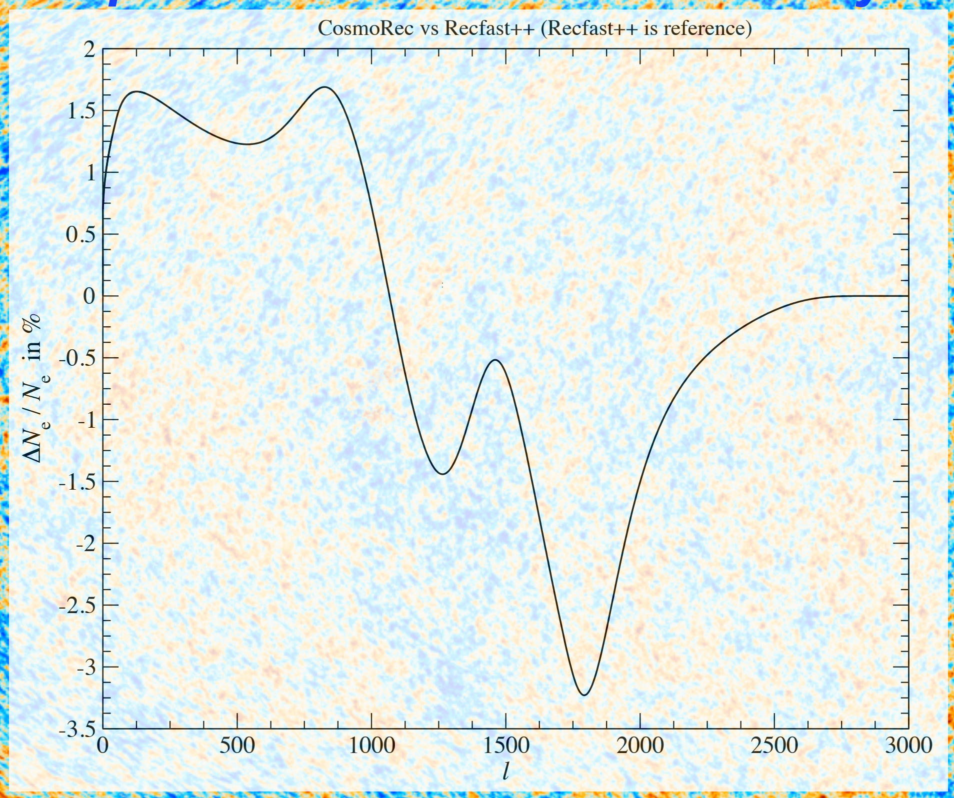
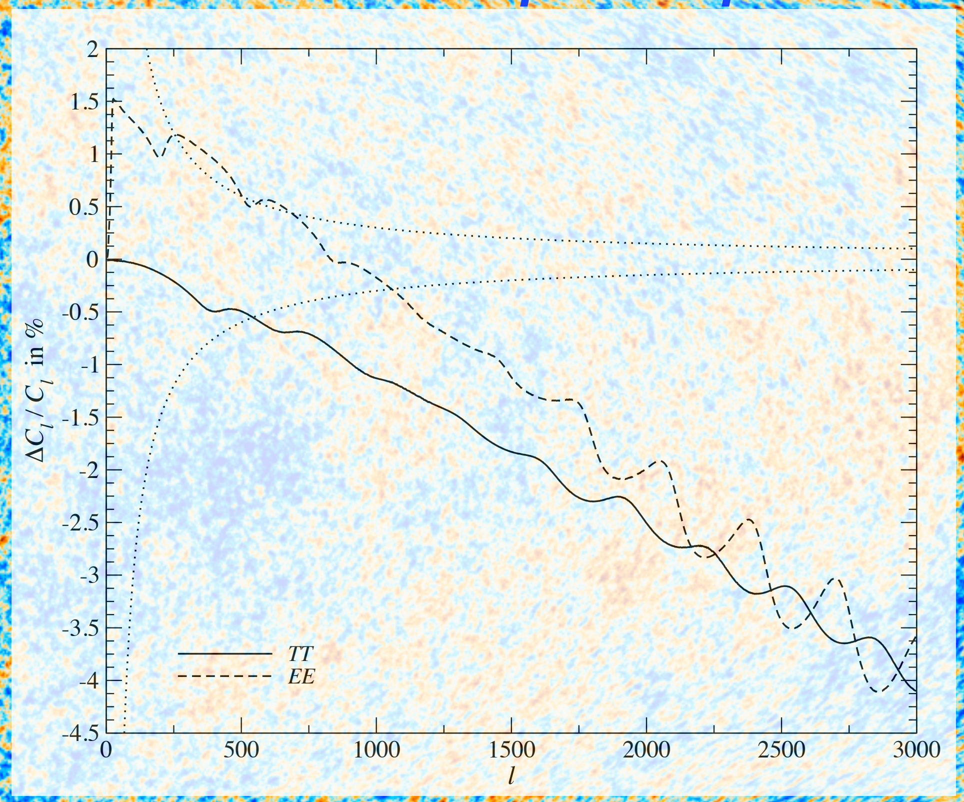
# Introduction to Recombination Physics and Why it is Important for Cosmology and Early-Universe Physics

*Improved Recombination History*




*Correction to the power spectra*





MANCHESTER 1824
The University of Manchester

**Jens Chluba**


**Cosmology - The Next Decade**

**ICTS, Bangalore, January 3th - 19th, 2019**


erc
THE ROYAL SOCIETY

# Plan for the Lectures (in theory)

## Lecture I:

- Introduction to the cosmological recombination problem
- Overview of standard recombination physics
- Relevance to the analysis of CMB data

## Lecture II:

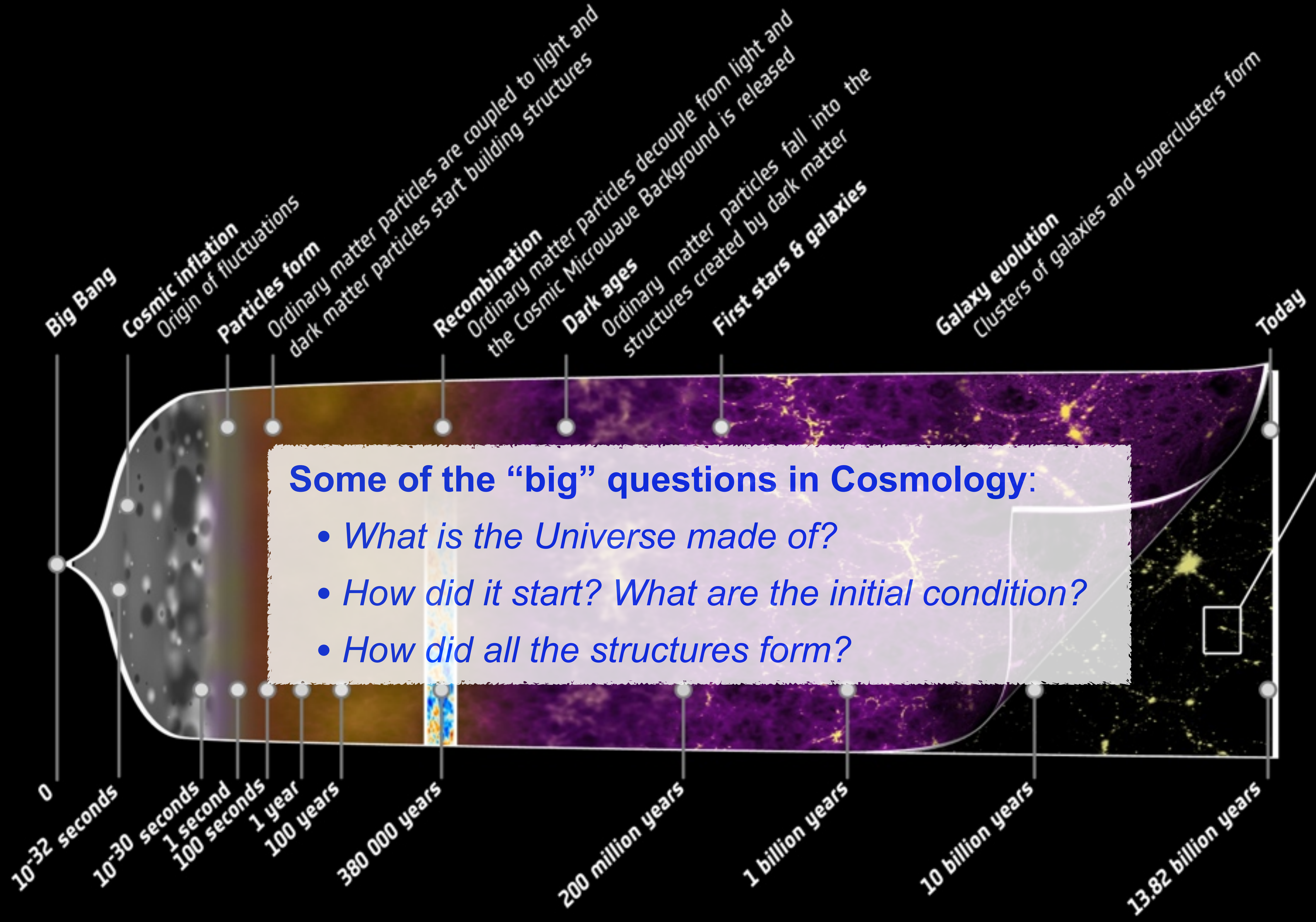
- Cosmological recombination radiation
- Non-standard recombination models
- Overview of cosmological recombination codes

## Lecture III / Tutorial:

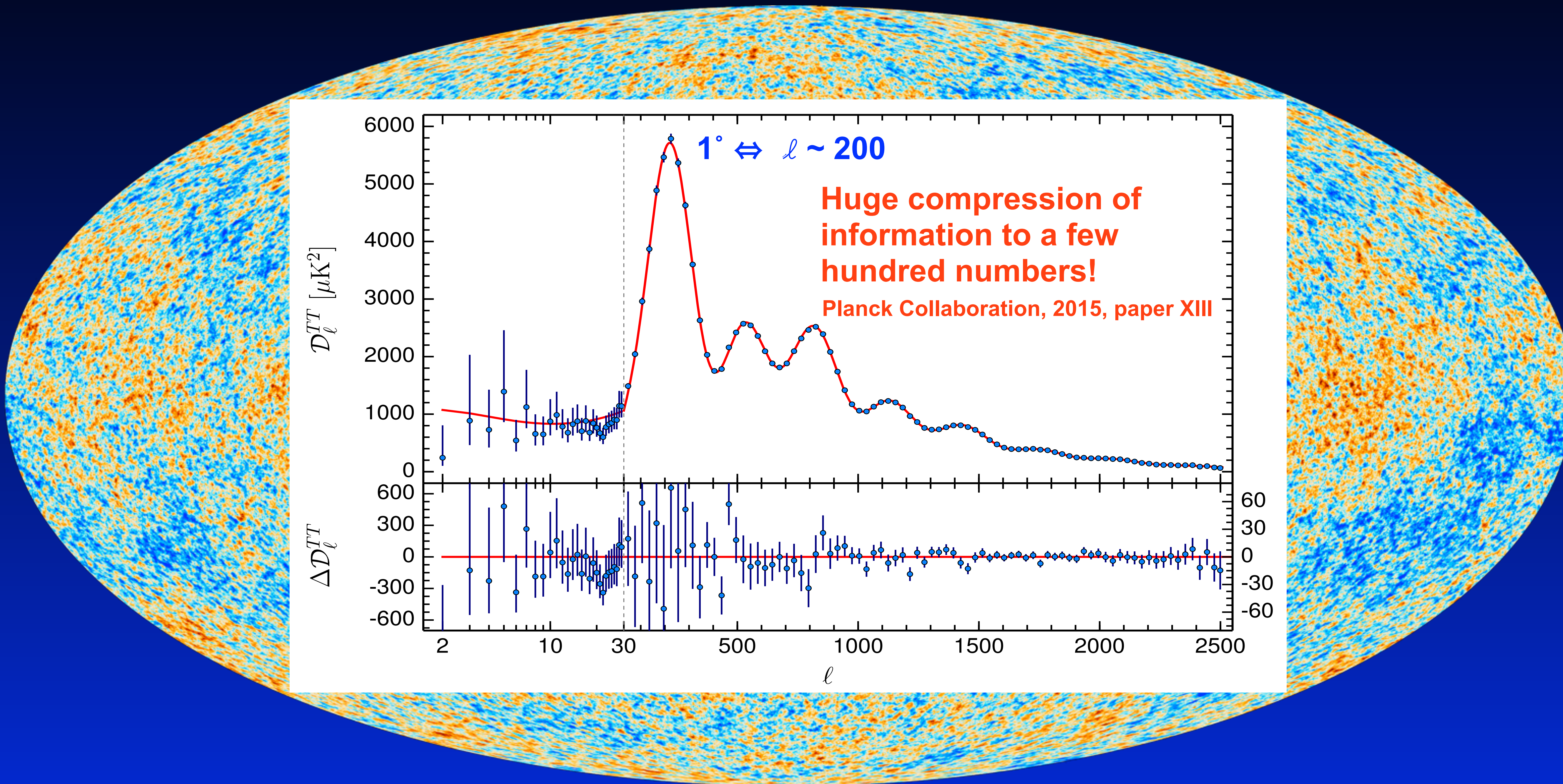
- Brief walk-through of `CosmoRec`
- Some examples with `Recfast++`

## 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

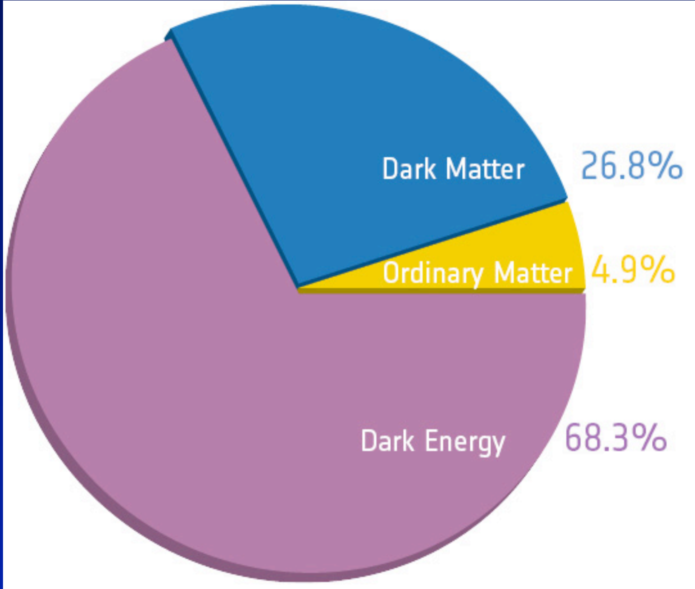



Planck all-sky temperature map

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

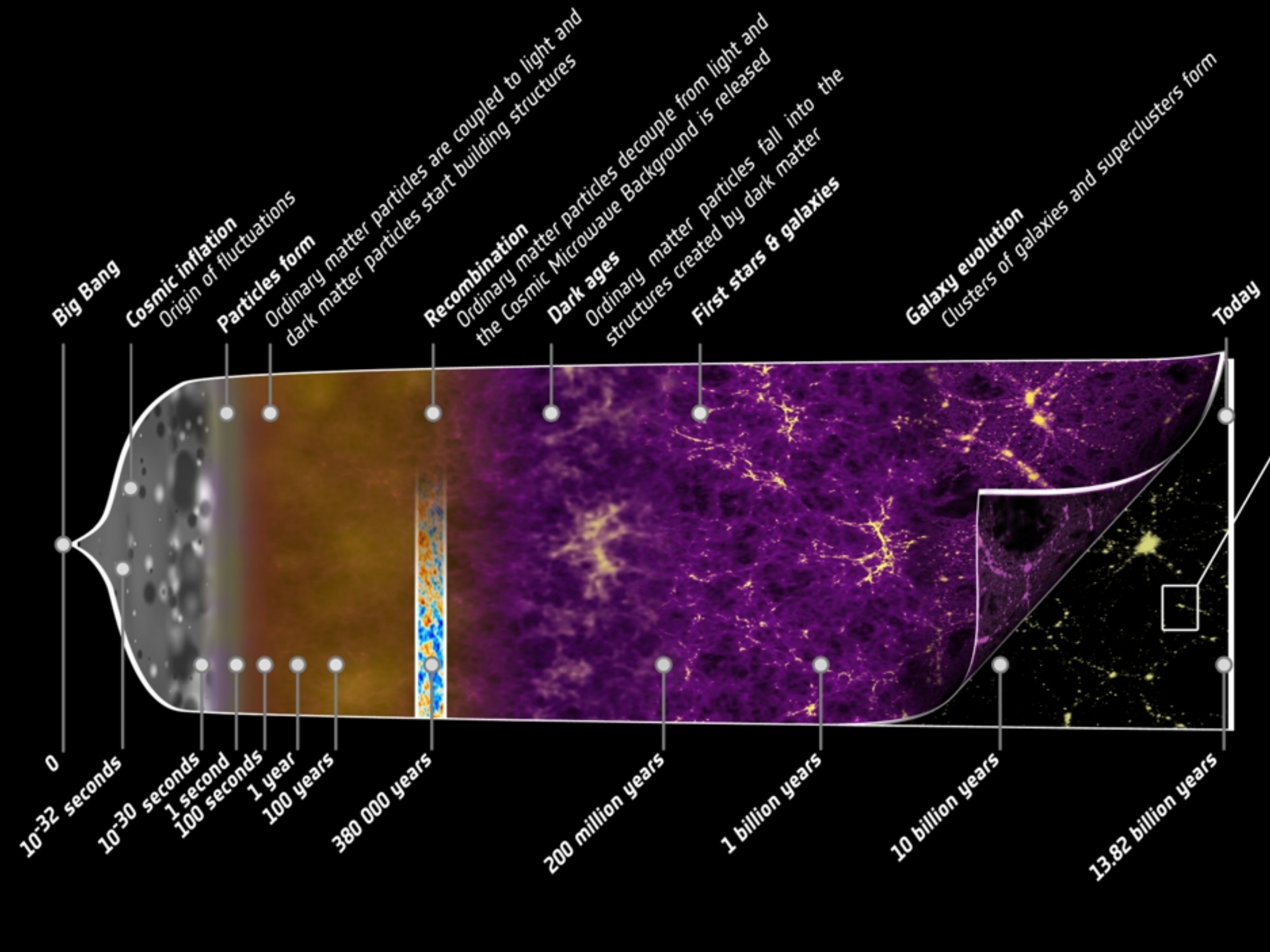
# *CMB anisotropies (with SN, LSS, etc...) clearly taught us a lot about the Universe we live in!*

- Standard 6 parameter concordance cosmology with values known to percent level precision (+ $T_0$ from COBE/FIRAS)
- Gaussian-distributed adiabatic fluctuations with nearly scale-invariant power spectrum tested 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 → $N_{\rm e}(z)$

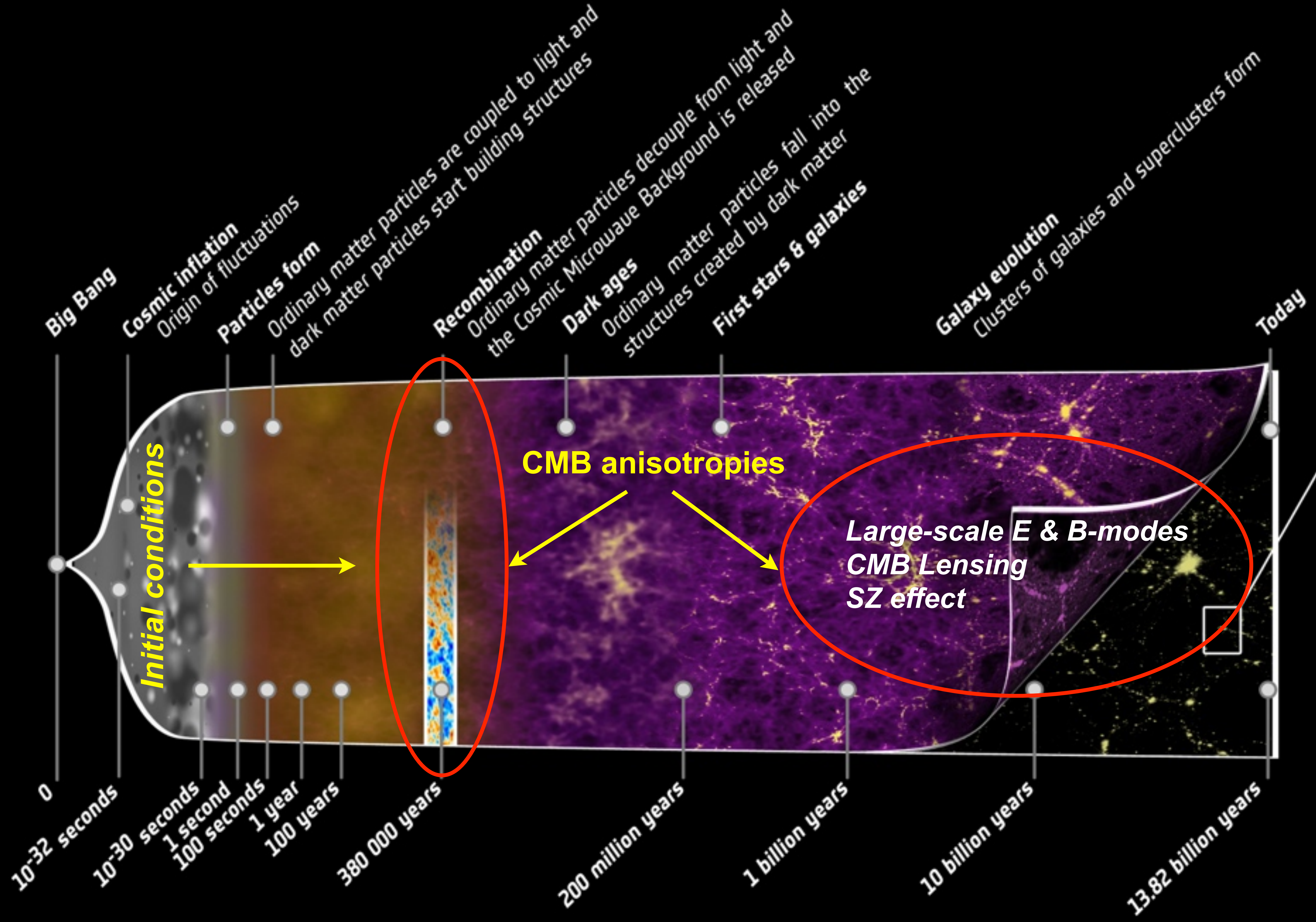



| Parameter | TT+lowP 68 % limits | TT+lowP+lensing 68 % limits | TT+lowP+lensing+ext 68 % limits | TT,TE,EE+lowP 68 % limits | TT,TE,EE+lowP+lensing 68 % limits | TT,TE,EE+lowP+lensing+ext 68 % limits |
|---|---|---|---|---|---|---|
| $\Omega_{\rm b}h^2$ . . . . . . . . . . . | $0.02222 \pm 0.00023$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

**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
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


Big Bang
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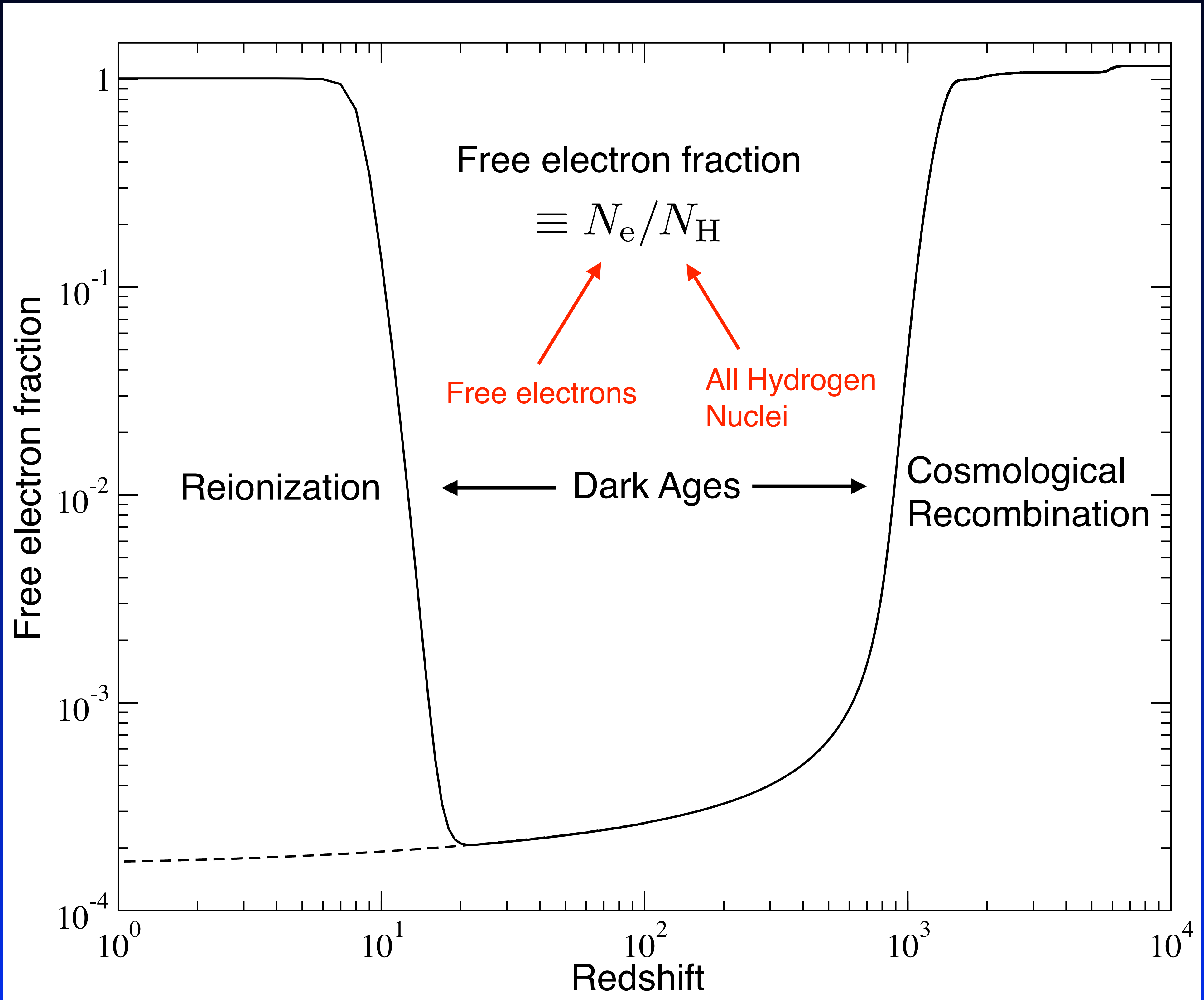
Clusters of galaxies and superclusters form
Today
Initial conditions
CMB anisotropies
Large-scale E & B-modes
CMB Lensing
SZ effect
0
$10^{-32}$ seconds
$10^{-30}$ seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

# Sketch of the Cosmic Ionization History




- at redshifts higher than ~$10^4$ Universe → *fully ionized*
- at $z \geq 10^4$ → $N_e/N_H$ **~ 1.16** (Helium has 2 electrons and abundance ~ 8%)
- Singly-ionized Helium recombination around $z$~6000
- Neutral Helium recombination around z~2000
- Hydrogen recombination around $z$~1000

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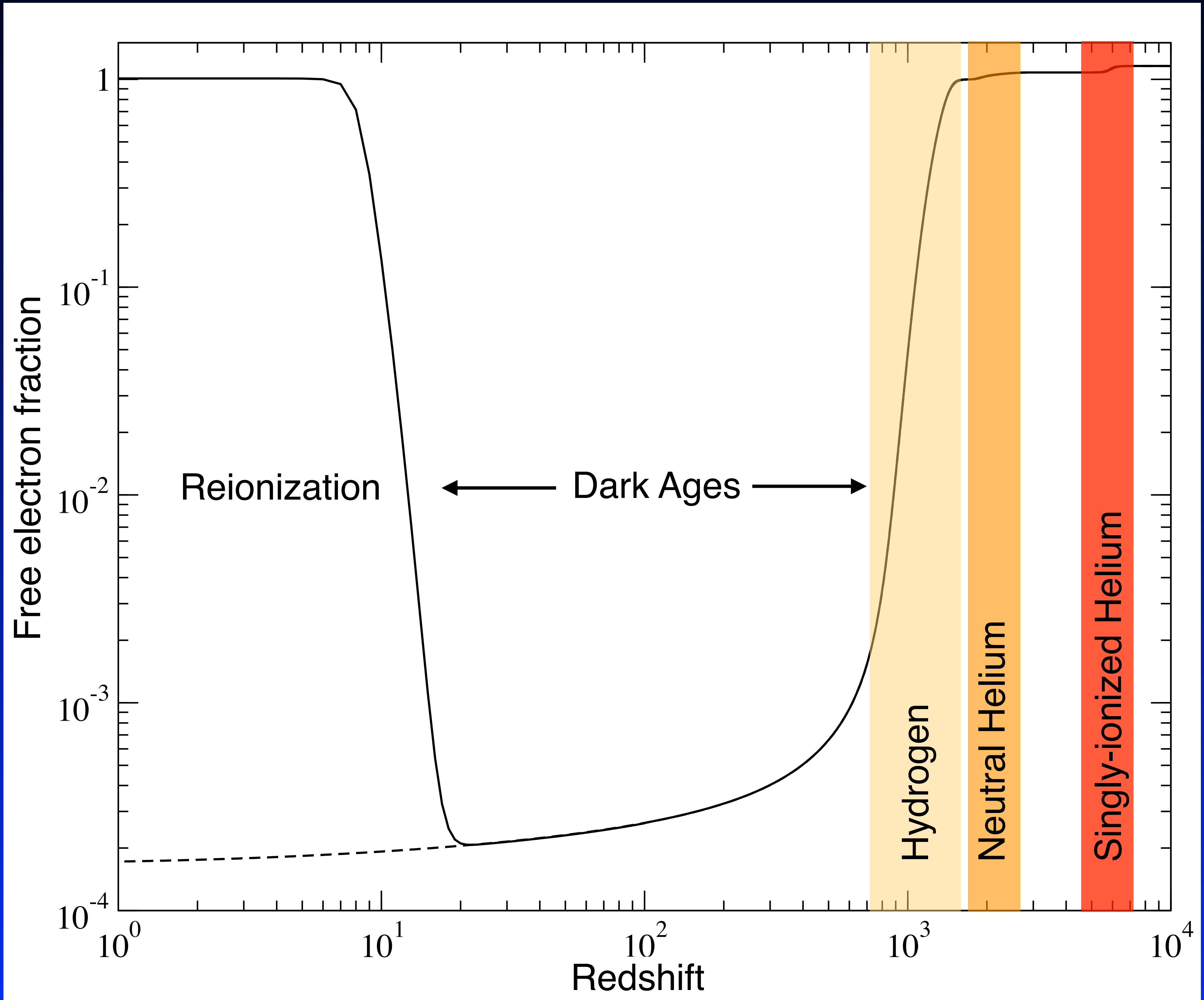


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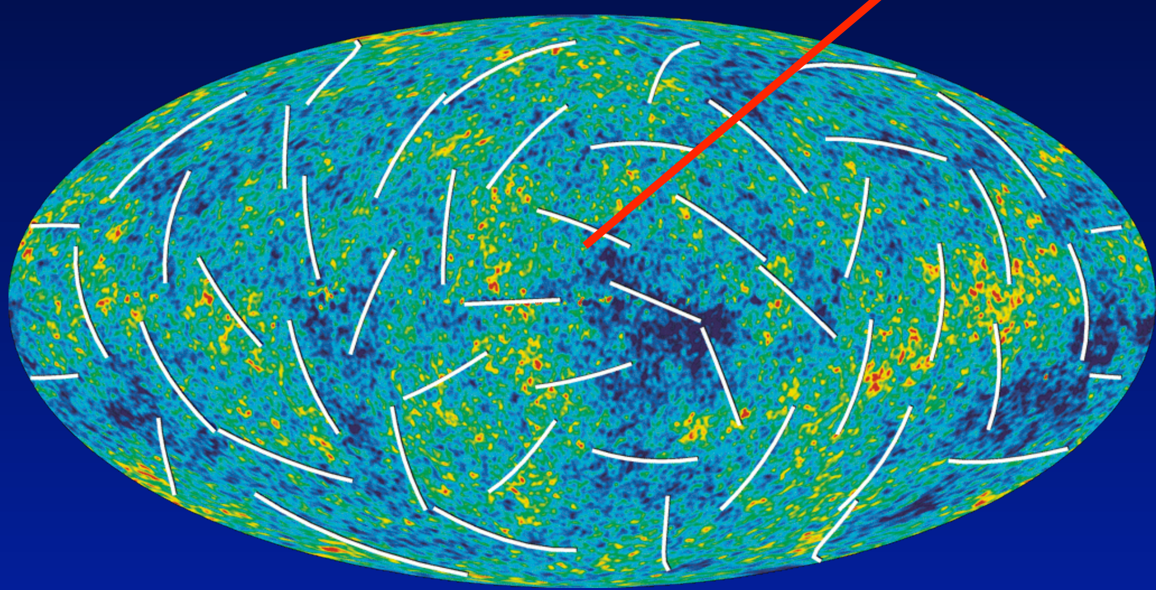
# CMB Sky → Cosmology

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

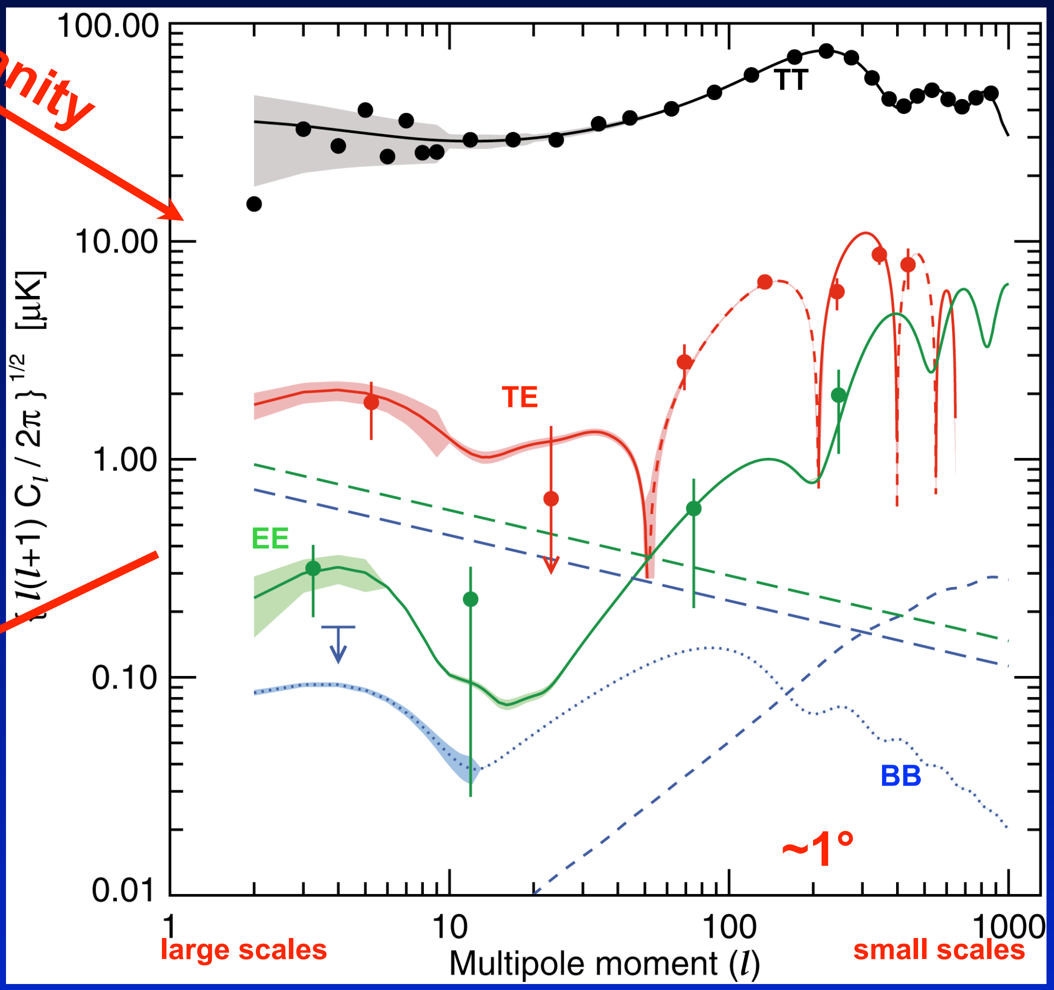
**CMB Sky**
**(temperature & polarization)**



$a_{lm}$

**Gaussianity**

**Power spectra**



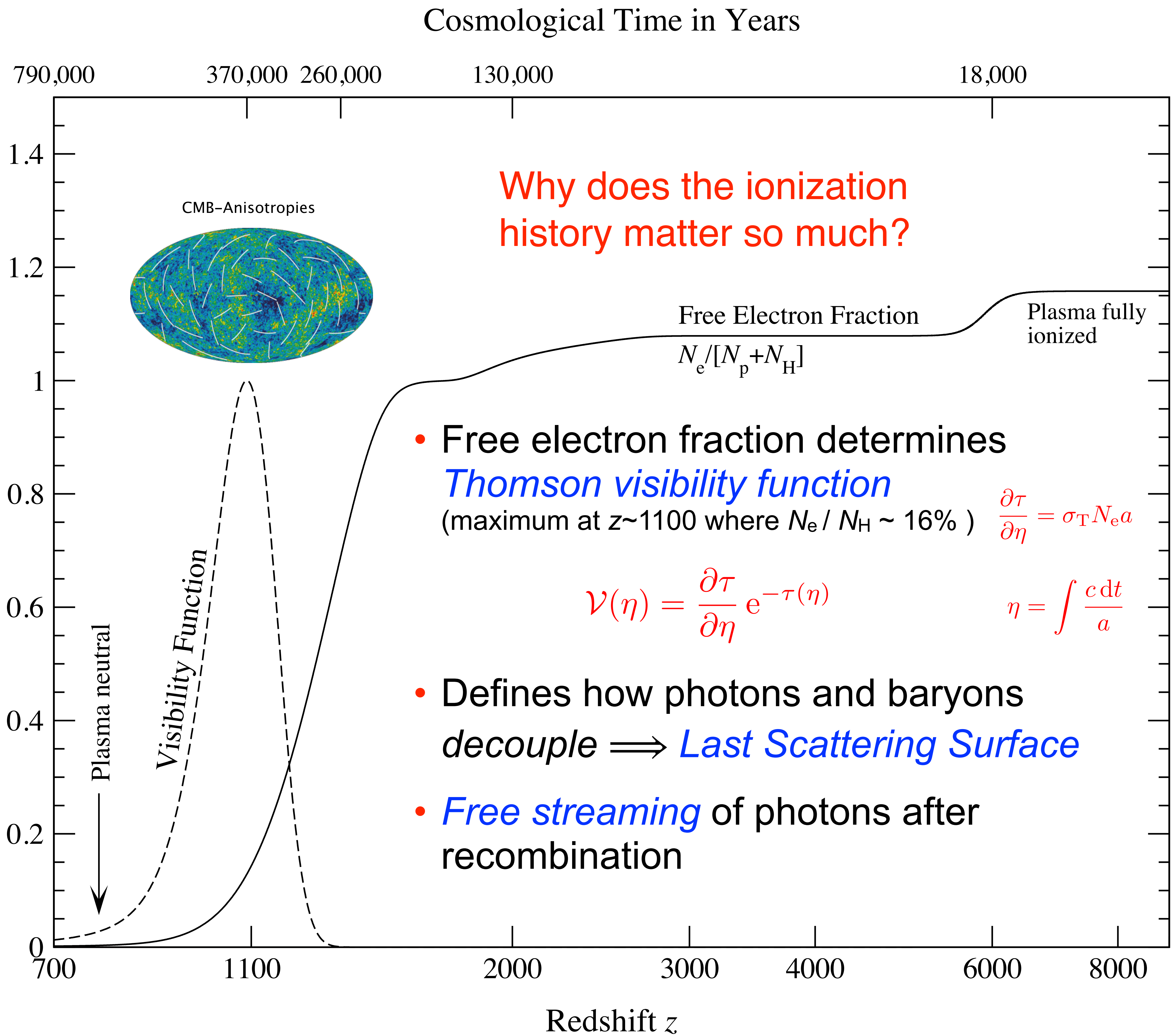

**(Joint) analysis**

**Cosmological Parameters**

$\Omega_{tot}$, $\Omega_m$, $\Omega_b$, $\Omega_\Lambda$,
$h$, $\tau$, $n_s$,...

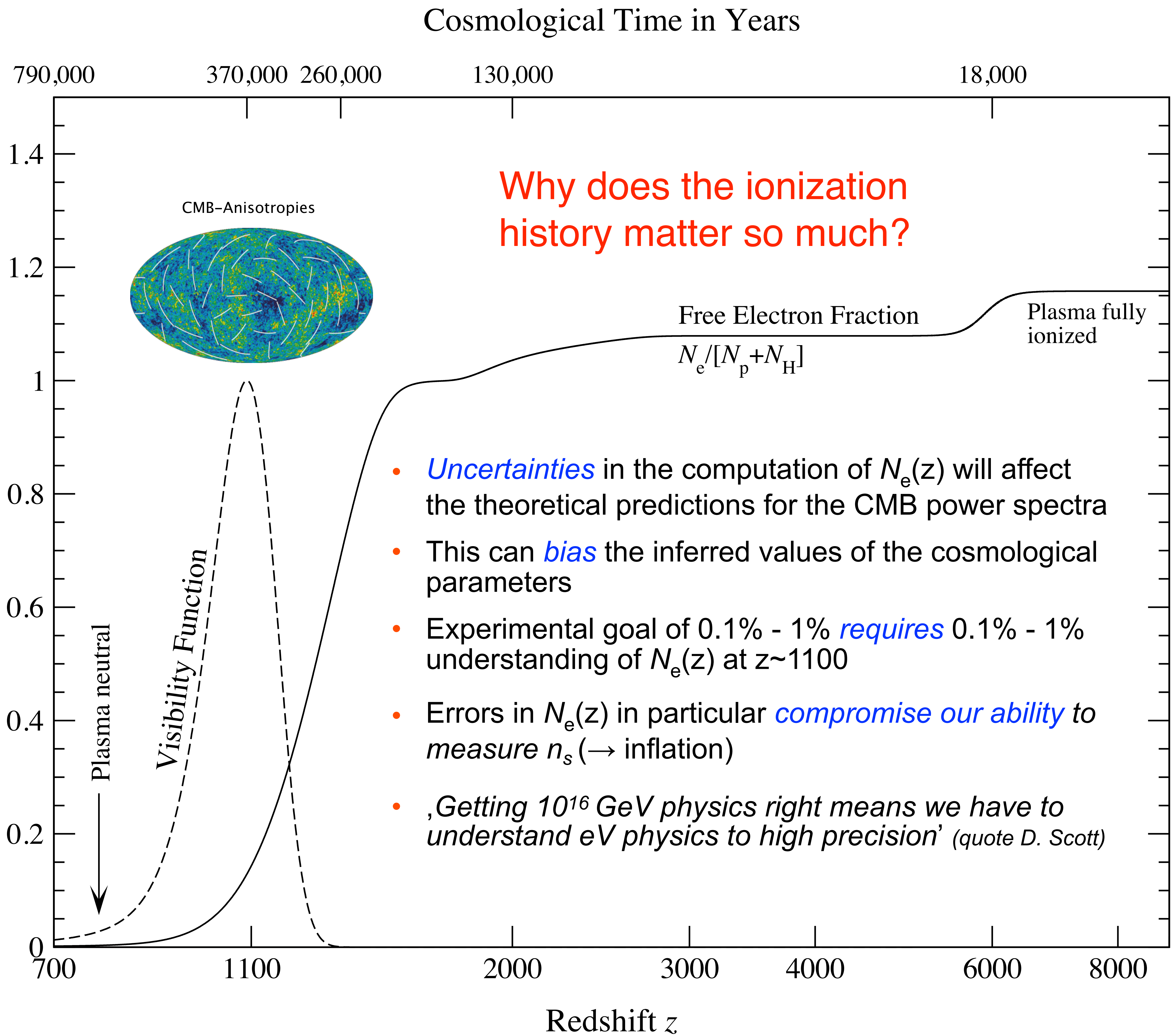
**Other cosmological Datasets:**

**Supernovae, large-scale structure/BAO, Lyman-α forest, weak lensing, ...**


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
Why does the ionization history matter so much?
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully ionized
• Free electron fraction determines *Thomson visibility function*
(maximum at $z$~1100 where $N_e$ / $N_H$ ~ 16% )
$\frac{\partial\tau}{\partial\eta} = \sigma_T N_e a$
$\mathcal{V}(\eta) = \frac{\partial\tau}{\partial\eta}\,e^{-\tau(\eta)}$
$\eta = \int \frac{c\,dt}{a}$
• Defines how photons and baryons *decouple* $\Longrightarrow$ *Last Scattering Surface*
• *Free streaming* of photons after recombination
Visibility Function
Plasma neutral
700
1100
2000
3000
4000
6000
8000
Redshift $z$

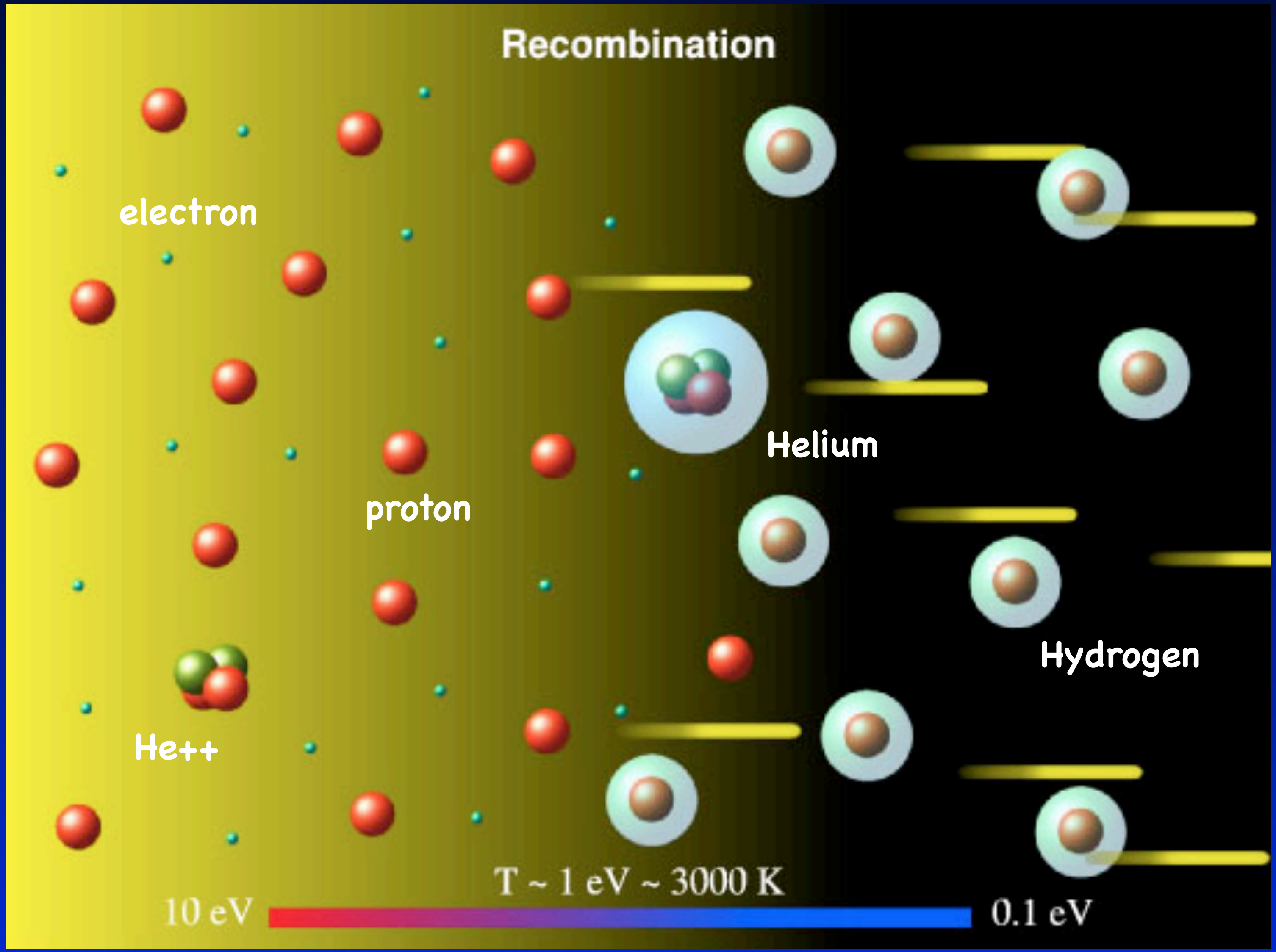
## Why does the ionization history matter so much?

- *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 to 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 $\Delta I_\nu$

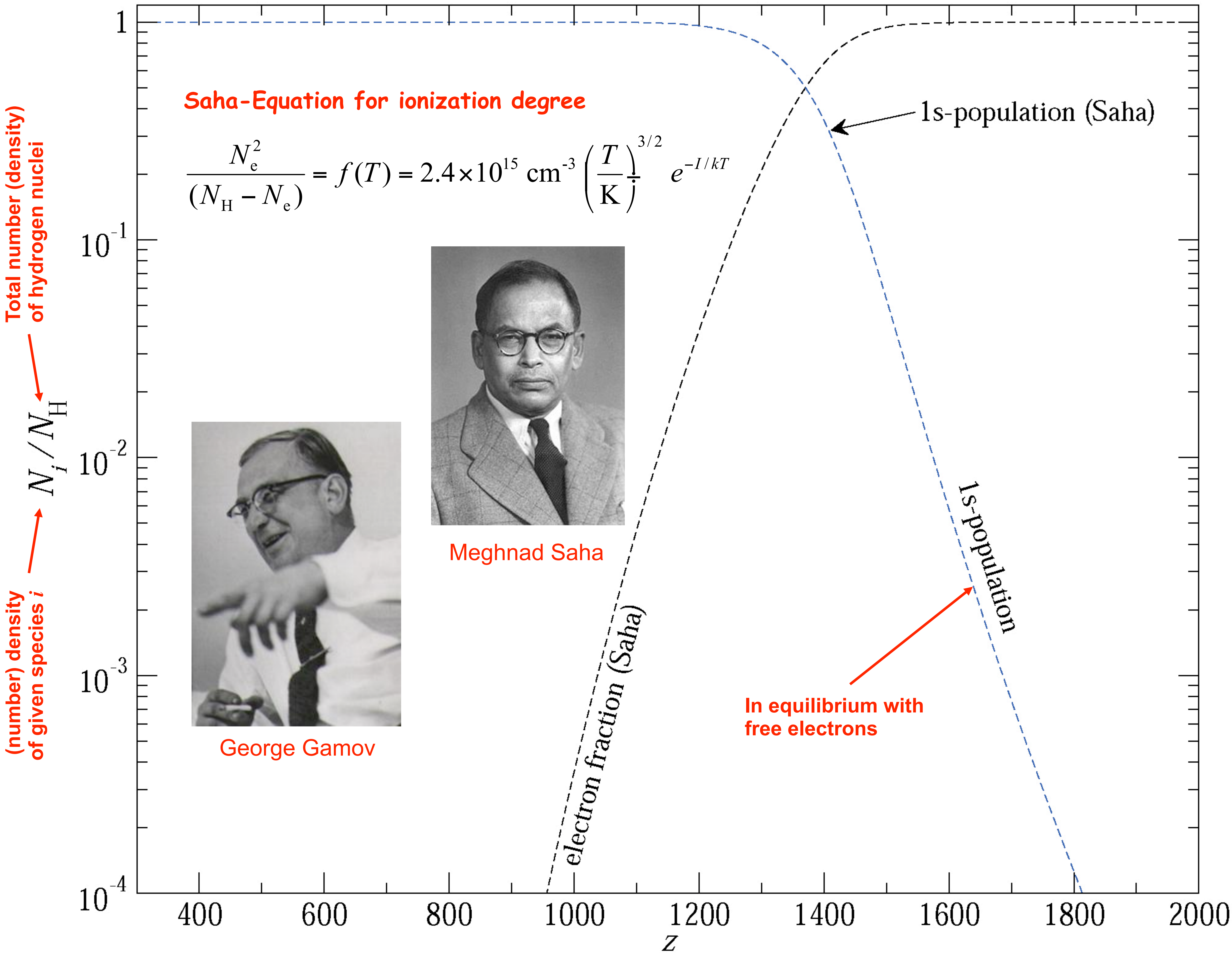
number densities

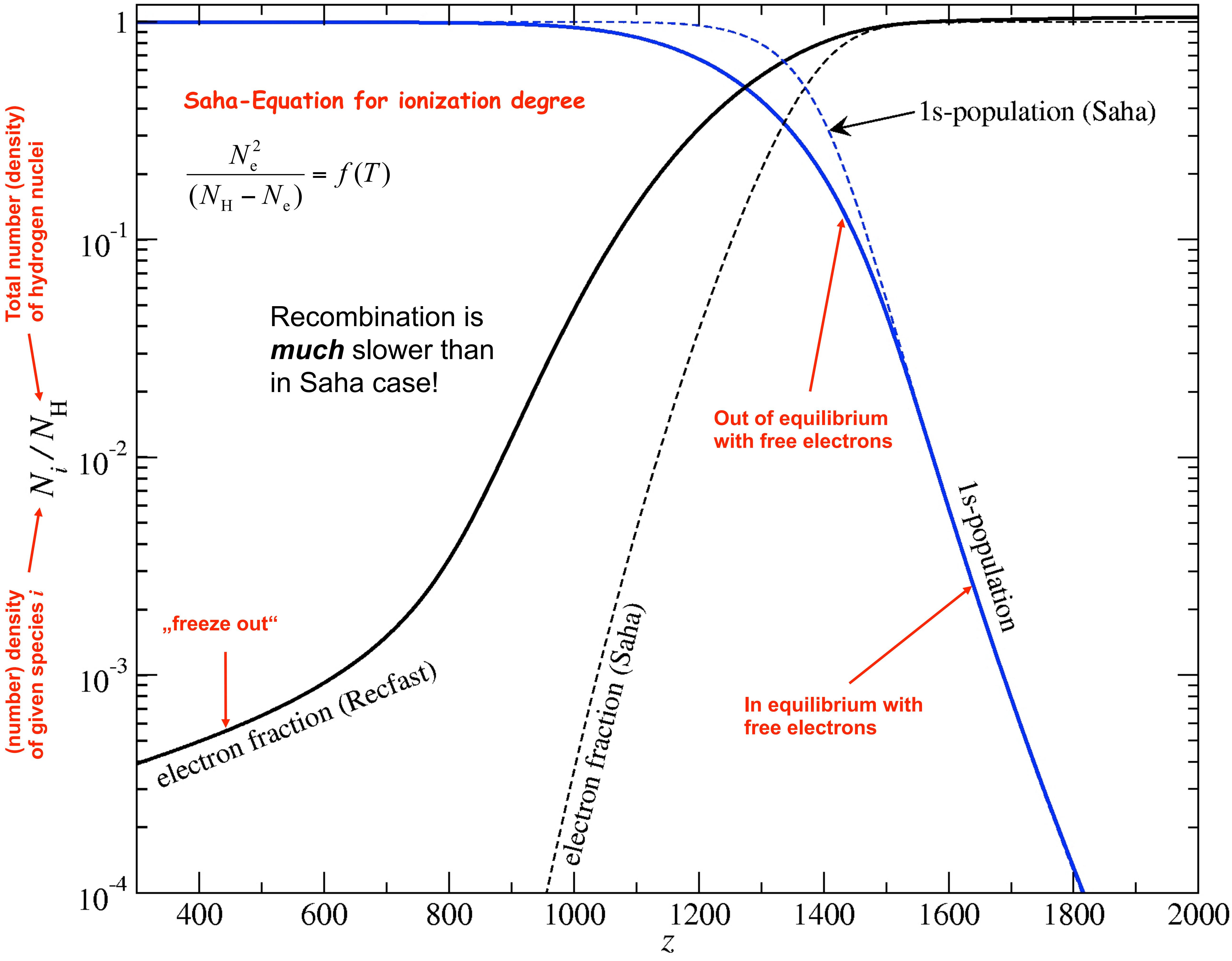
non-thermal photons

# Physical Conditions during Recombination

- Anisotropies negligible for recombination problem
- CMB 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 $N_\gamma \sim 410\ \text{cm}^{-3}\,(1+z)^3 \sim 2\times10^9\,N_b$

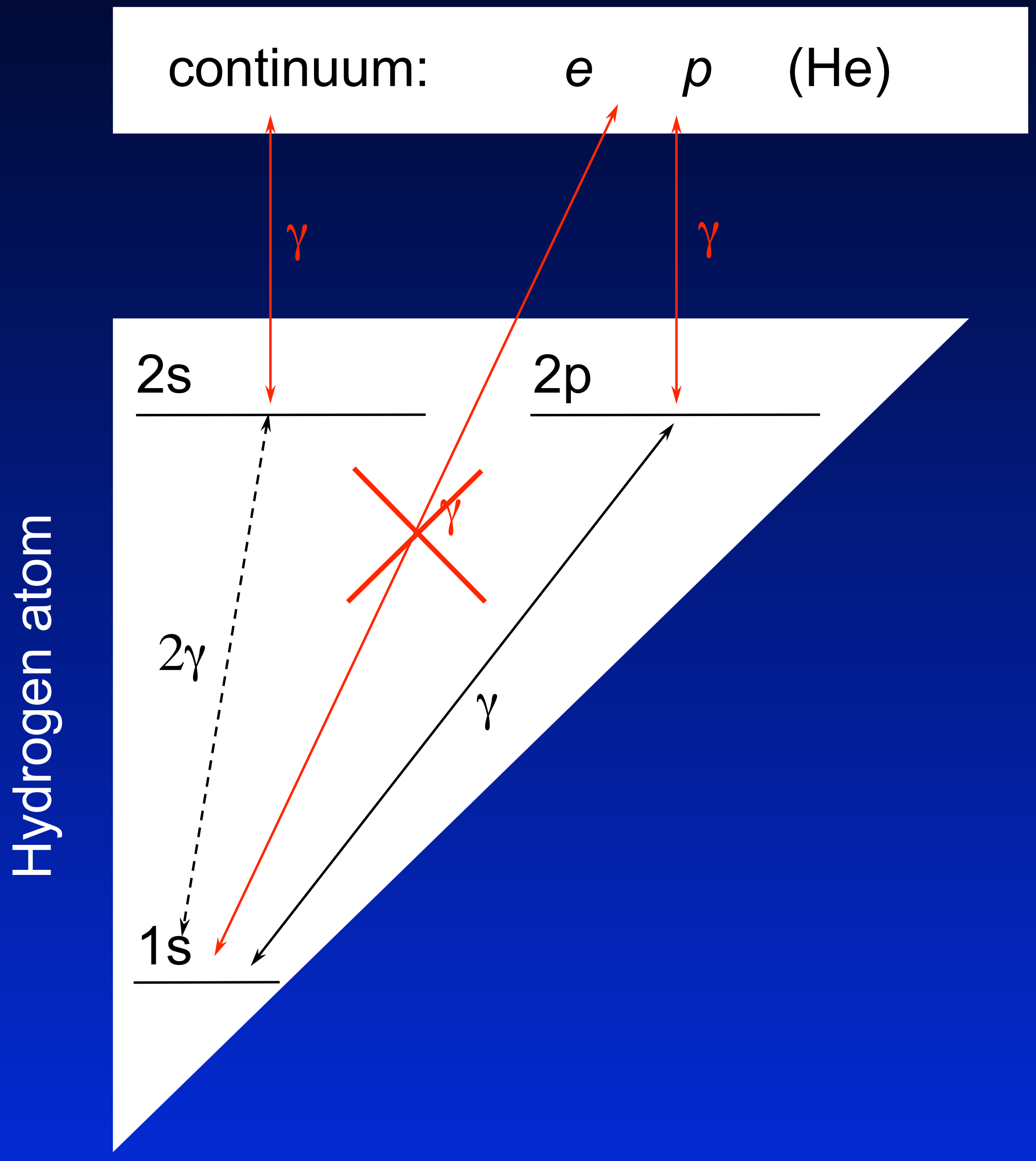
  ⇒ *photons in very distant Wien tail of blackbody spectrum can keep hydrogen ionized until* $h\nu_\alpha \sim 40\,kT_\gamma \Leftrightarrow T_\gamma \sim 0.26$ eV *(Ly-c 13.6 eV!)*
- Collisional processes negligible (*completely different in stars!!!*)
- Rates dominated by radiative processes
  (*e.g. 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)
Meghnad Saha
George Gamov
electron fraction (Saha)
1s-population
In equilibrium with
free electrons
Total number (density)
of hydrogen nuclei
$N_i / N_H$
(number) density
of given species $i$
1
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
400
600
800
1000
1200
1400
1600
1800
2000
$z$



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
$N_i / N_H$
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 ?**

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

**No**

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

**~ 43%**

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

**~ 57%**

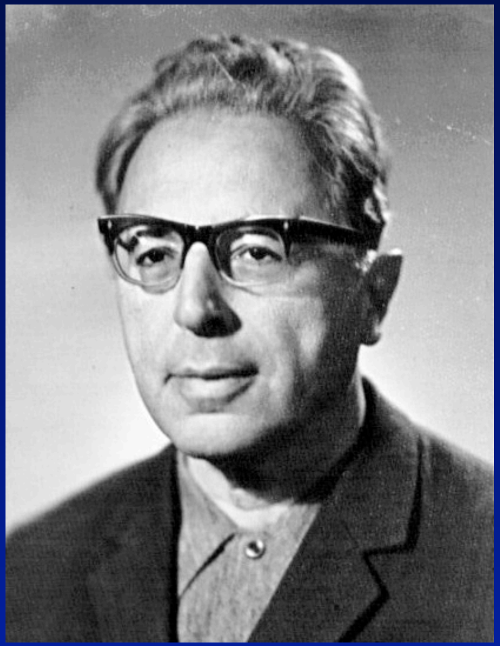
**Zeldovich, Kurt & Sunyaev, 1968, ZhETF, 55, 278**
**Peebles, 1968, ApJ, 153, 1**

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

# These first computations were completed in 1968!

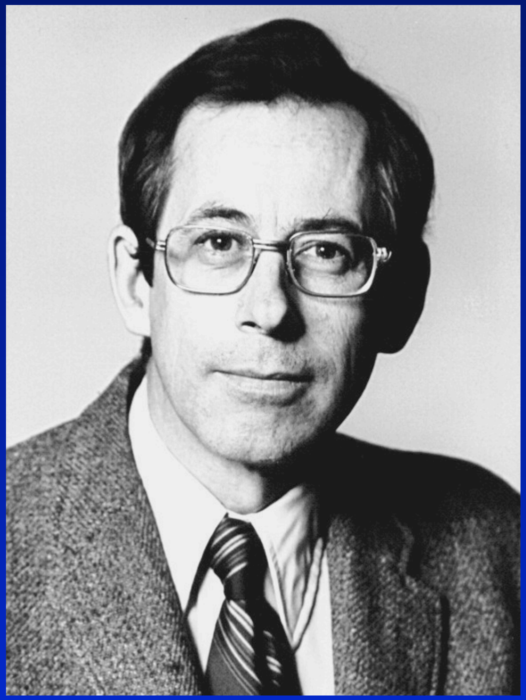
**Moscow**

Yakov Zeldovich



Iosif Shklovsky
(radio astronomer)

**Princeton**



Jim Peebles

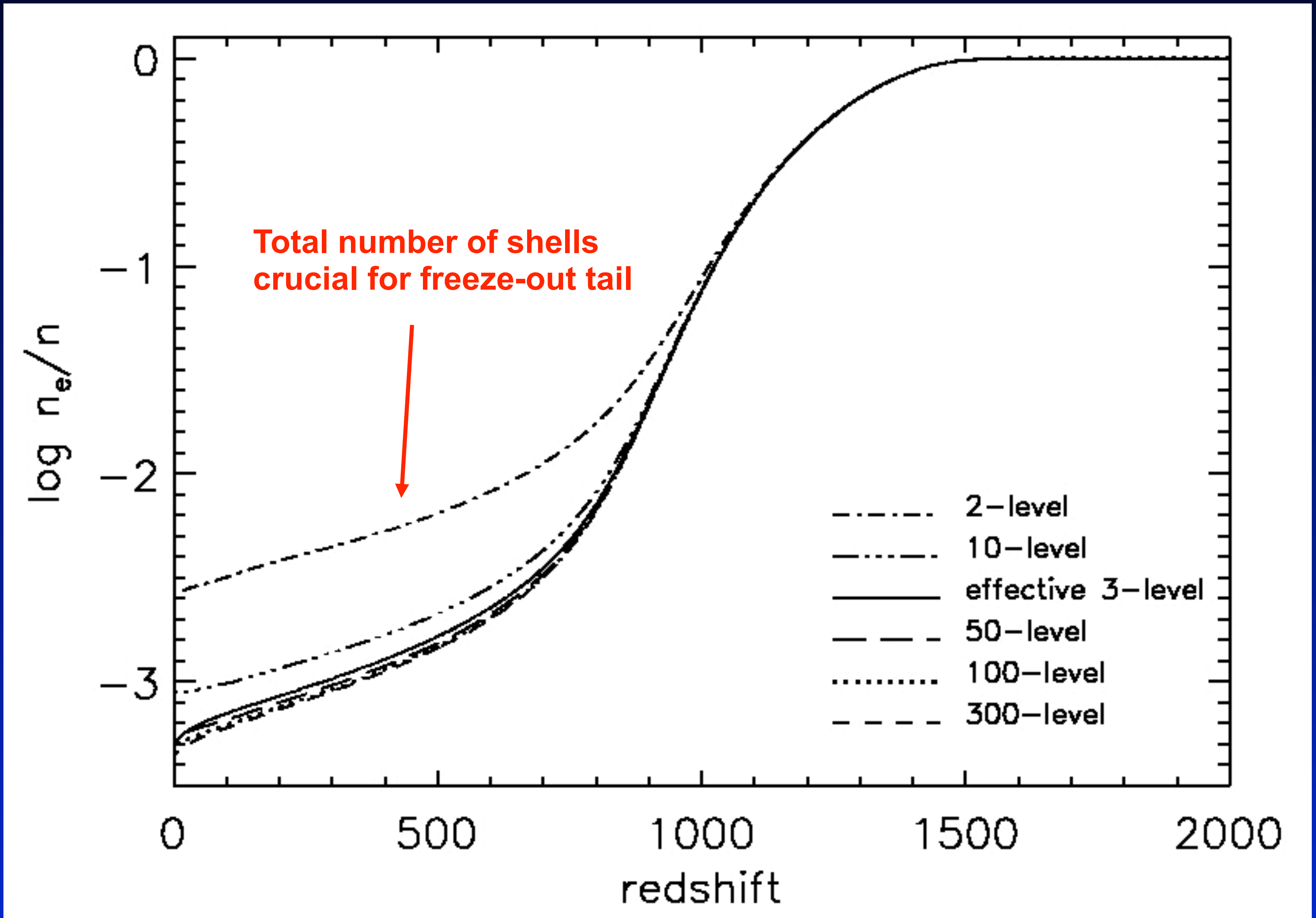
Vladimir Kurt
(UV astronomer)

Rashid Sunyaev

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

*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**

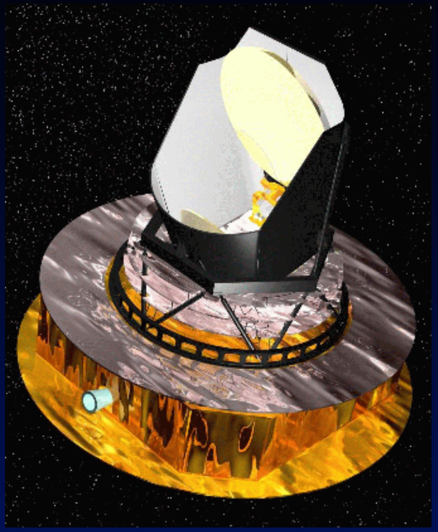
**Low Redshifts:**

- **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*

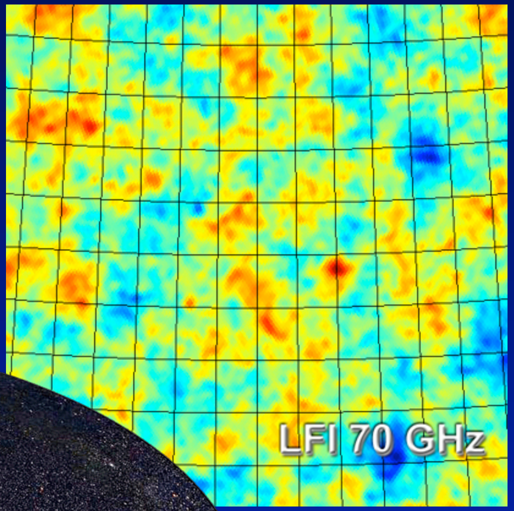
$\Delta N_e \;/\; N_e$ ~ 1% - 3%

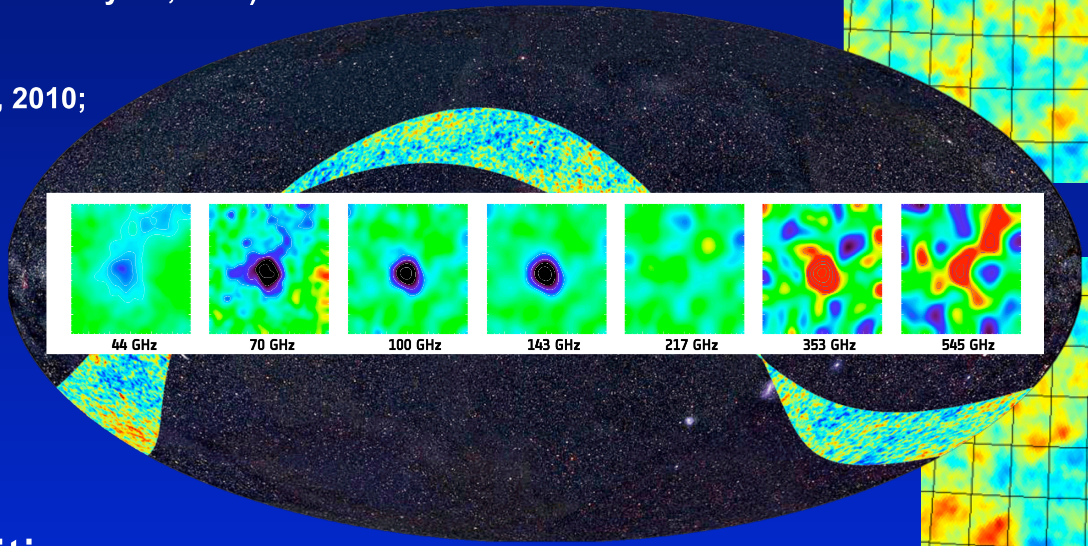
# Getting the job done for *Planck*



## Hydrogen recombination

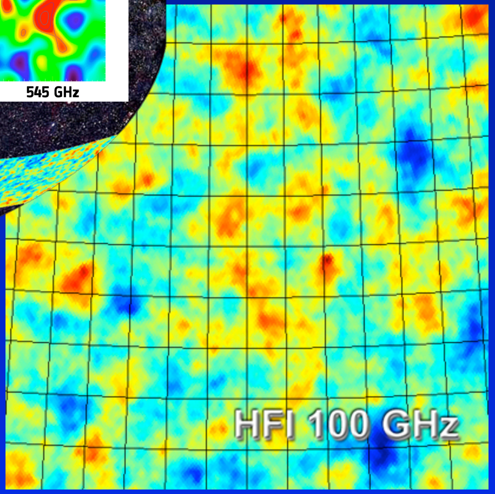
- Two-photon decays from higher levels
  (Dubrovich & Grachev, 2005, Astr. Lett., 31, 359; Wong & Scott, 2007; JC & Sunyaev, 2007; Hirata, 2008; JC & Sunyaev 2009)
- Induced 2s two-photon decay for hydrogen
  (JC & Sunyaev, 2006, A&A, 446, 39; Hirata 2008)
- Feedback of the Lyman-$\alpha$ distortion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



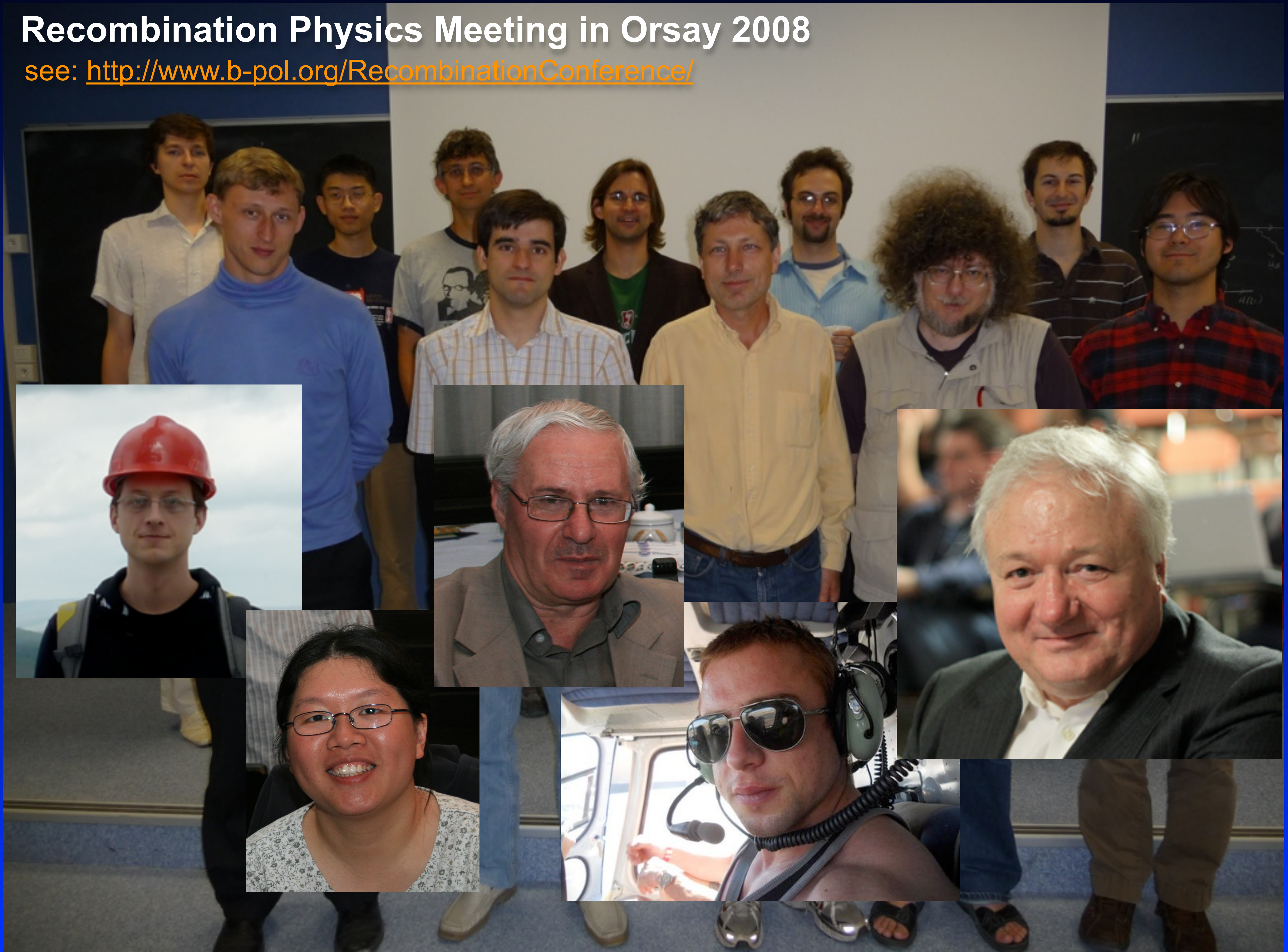

## Helium recombination

- 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)




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

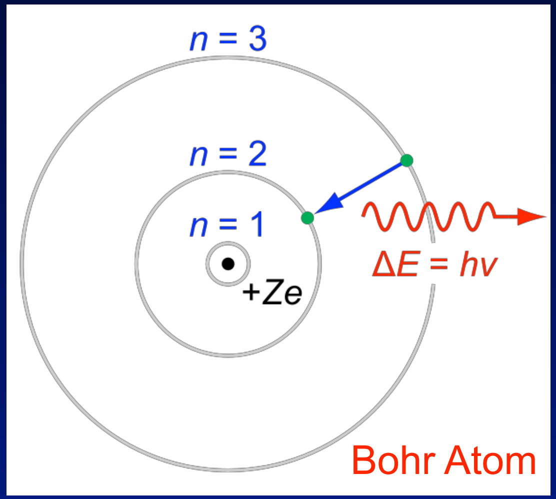
# Solving the problem for the *Planck* Collaboration was a common effort!



# Atomic Physics Challenges

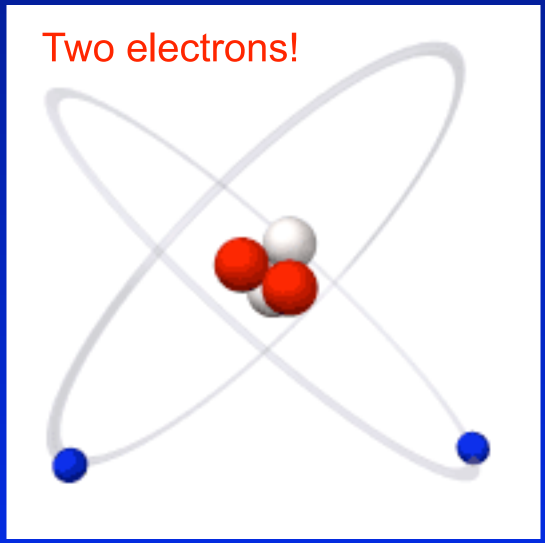
## Hydrogen Atom & Hydrogenic Helium

- Rather simple and basically analytic (e.g., Karzas & Latter, 1961)
- Even 2$\gamma$ 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 (~ $n^2$)

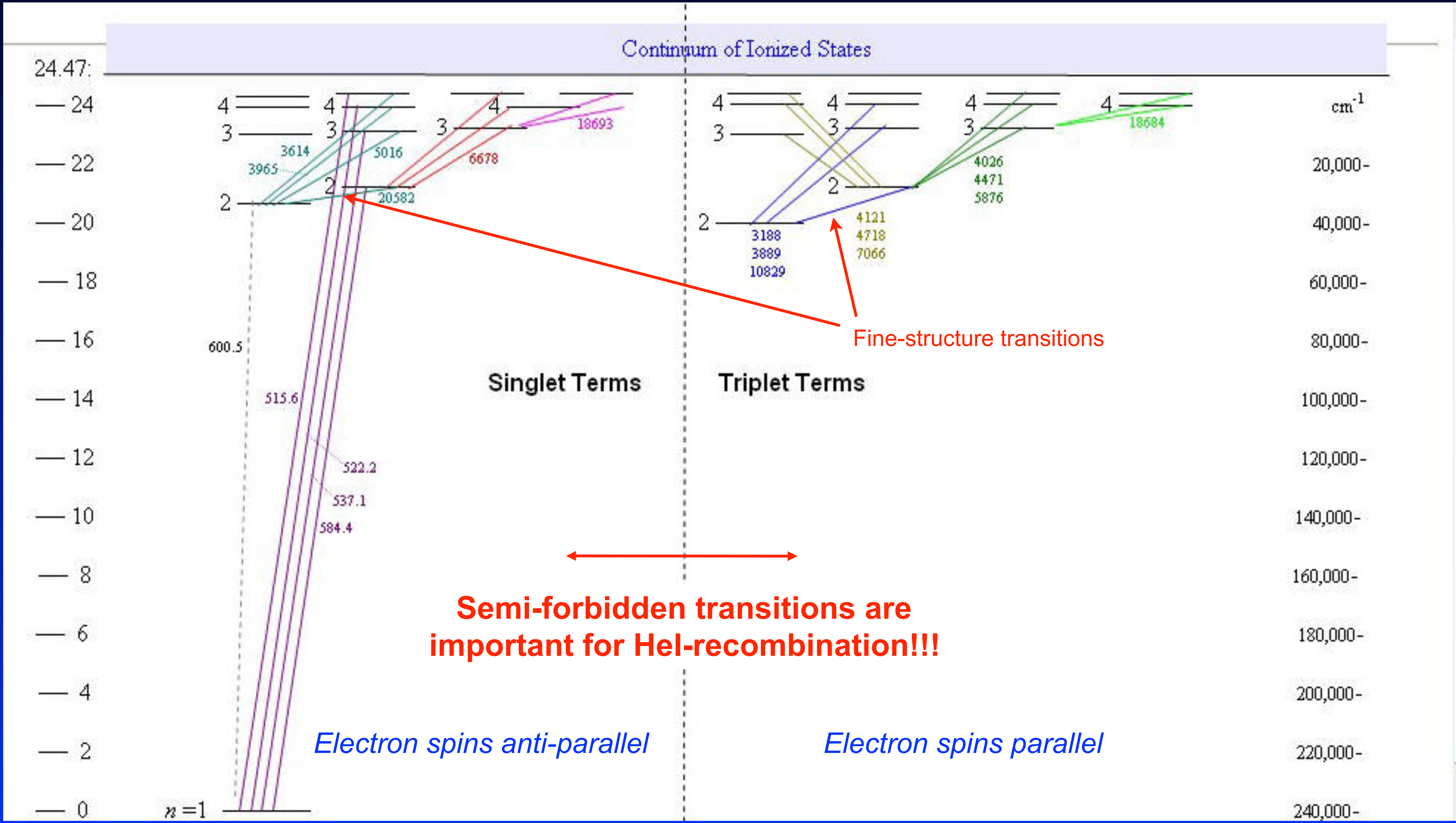



## Neutral Helium

- 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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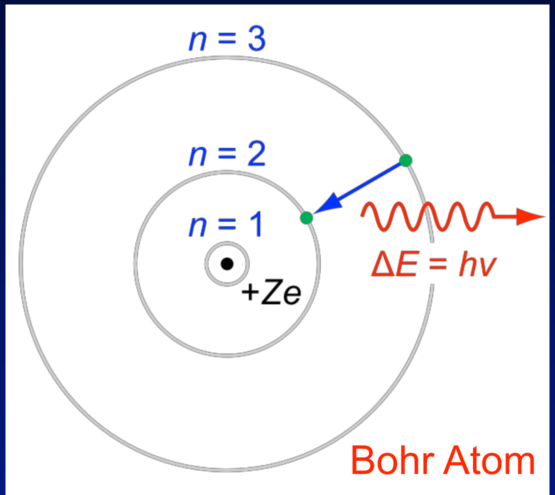
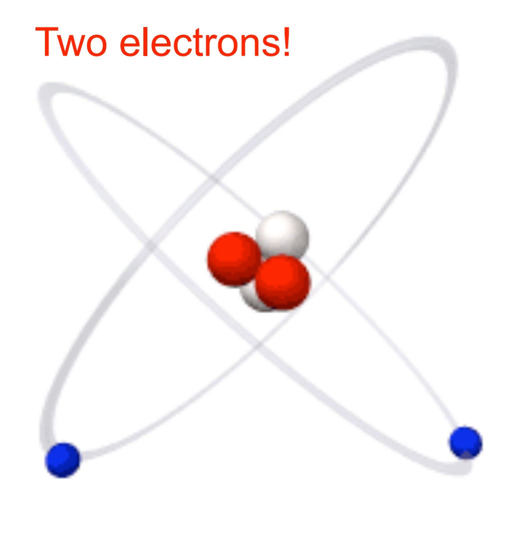


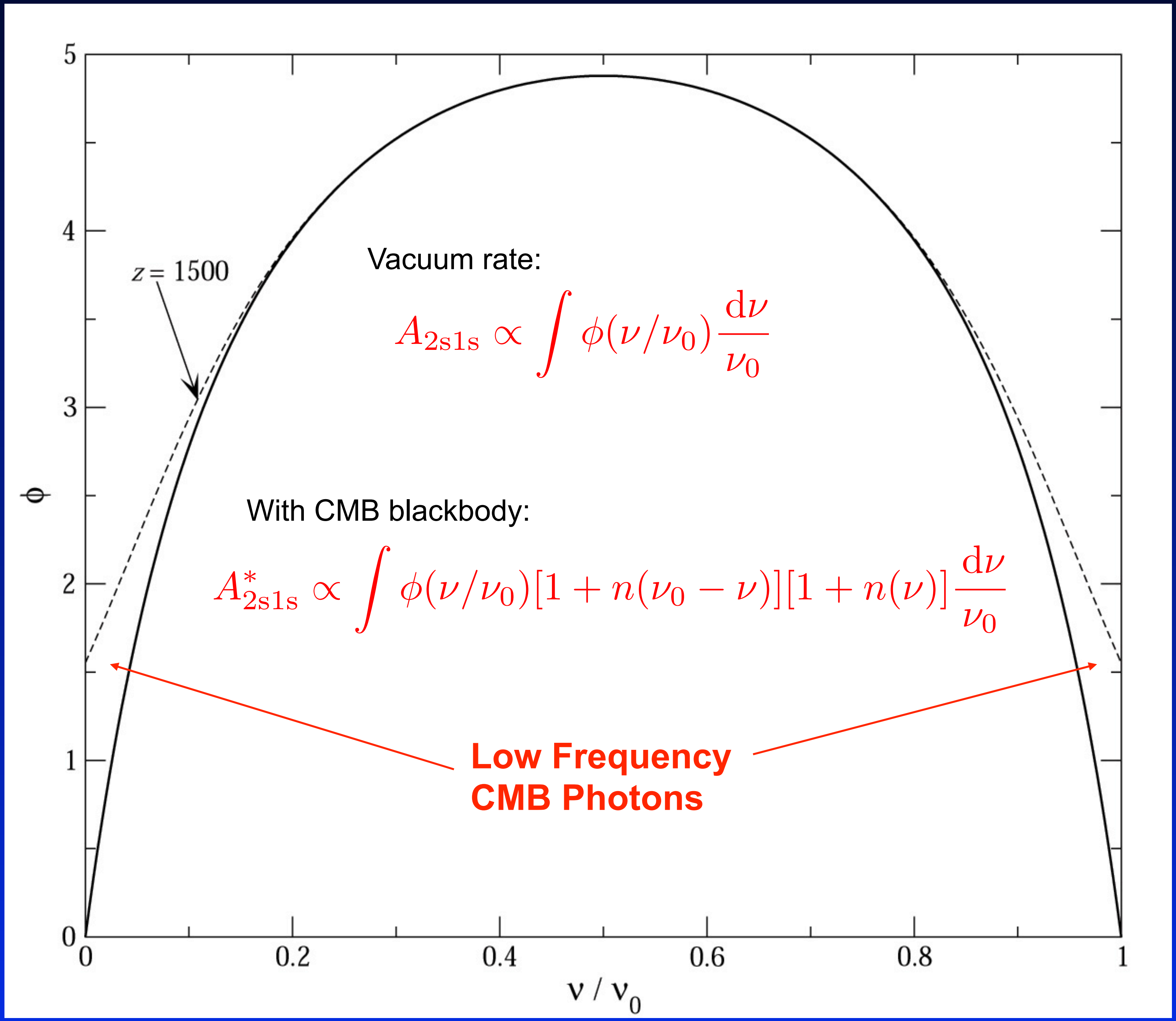

## Neutral Helium

- 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 recombination radiation…)



# Stimulated HI 2s →1s decay




**2s-1s emission profile**

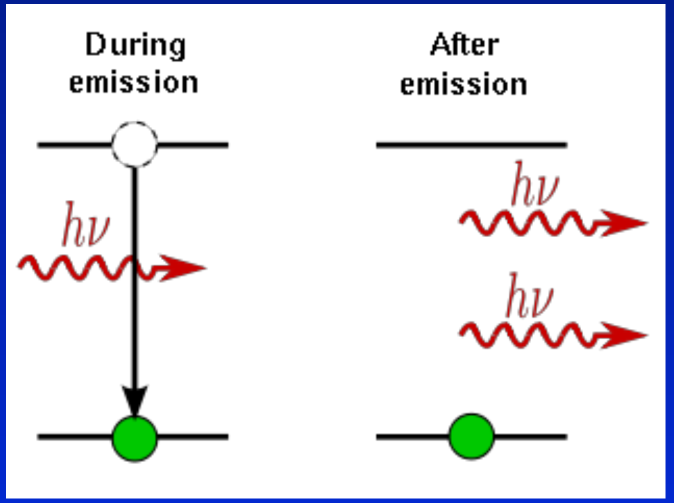
Transition rate in vacuum

→ $A_{2s1s}$ ~ 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

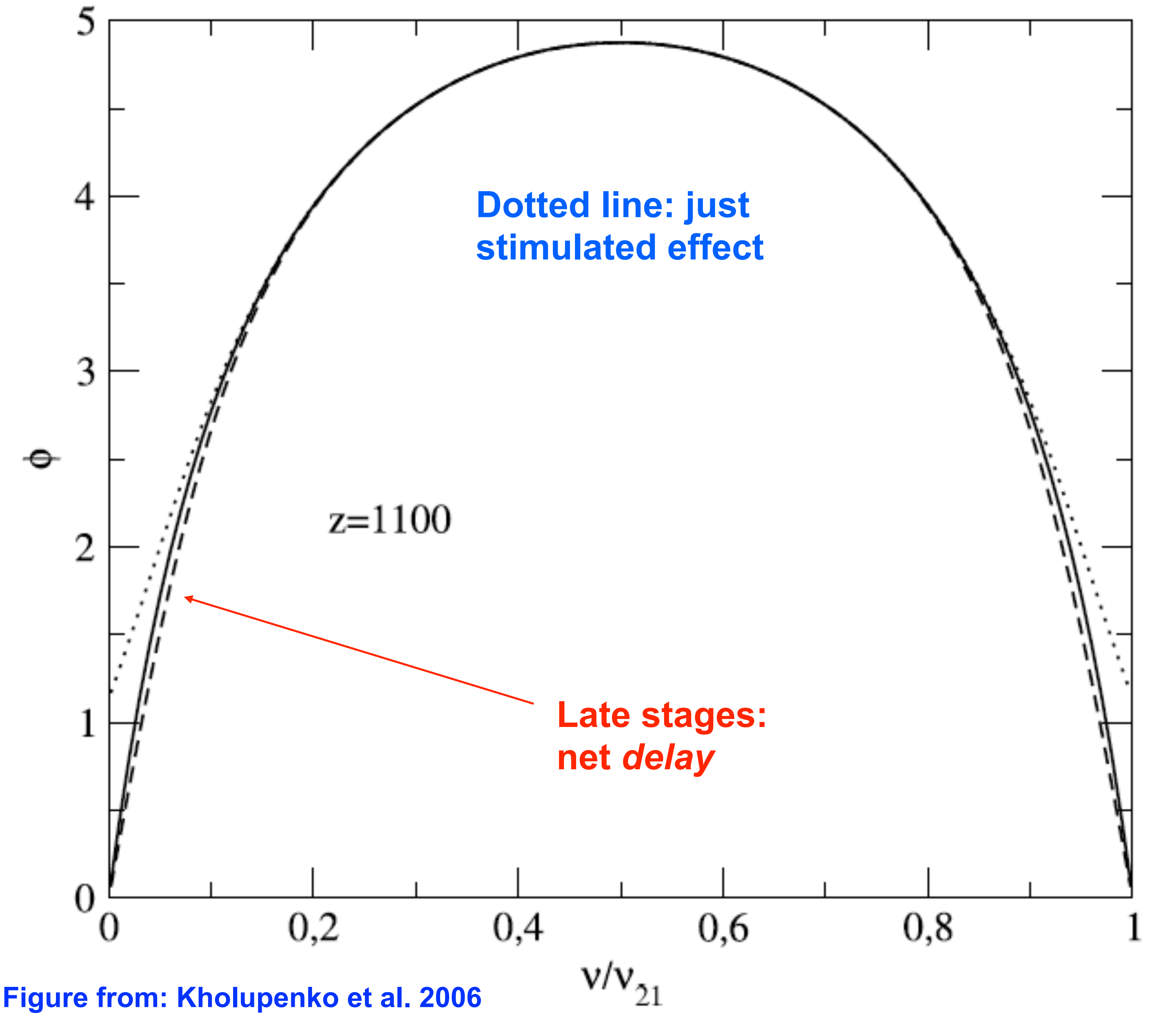


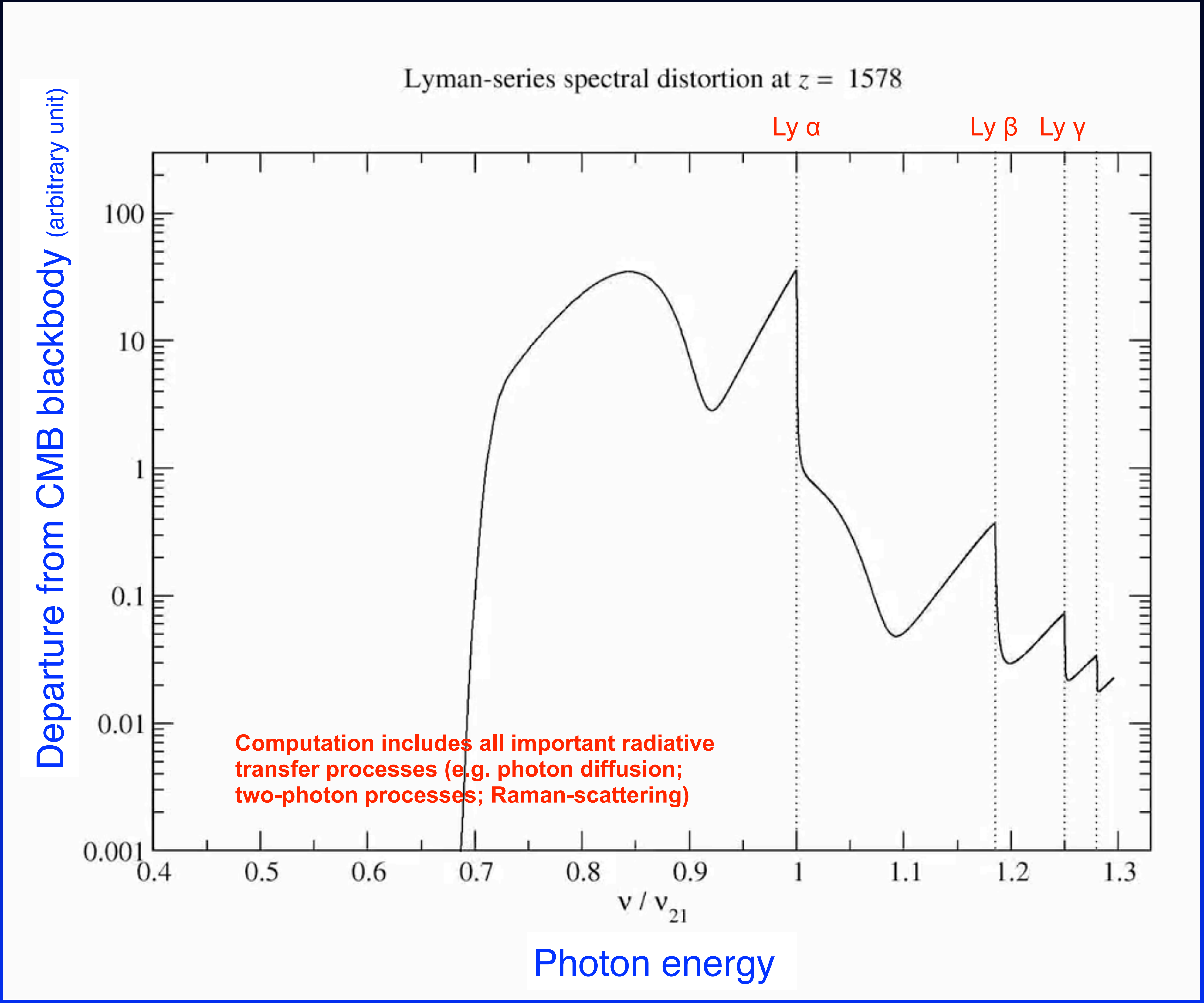

Figure from: Kholupenko et al. 2006

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

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

*The Lyman-series radiative transfer problem*

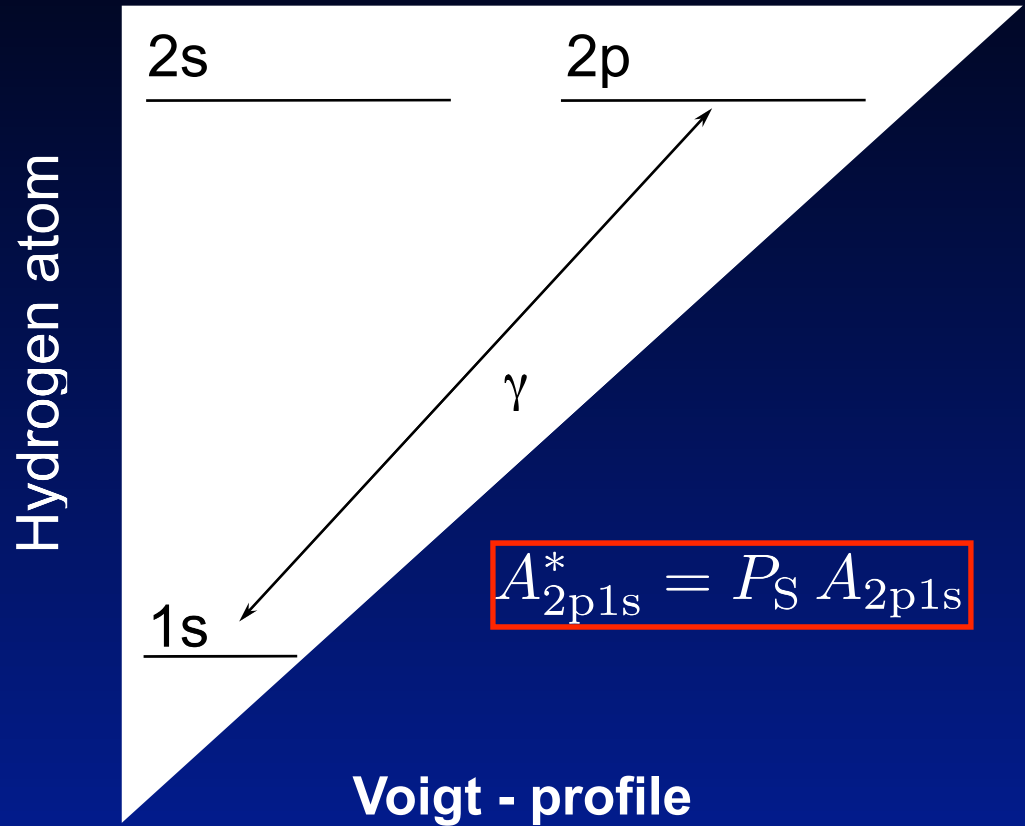
# Evolution of the HI Lyman-series distortion




JC & Thomas, MNRAS, 2010

# Sobolev approximation

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




$$A^*_{2p1s} = P_S\, A_{2p1s}$$

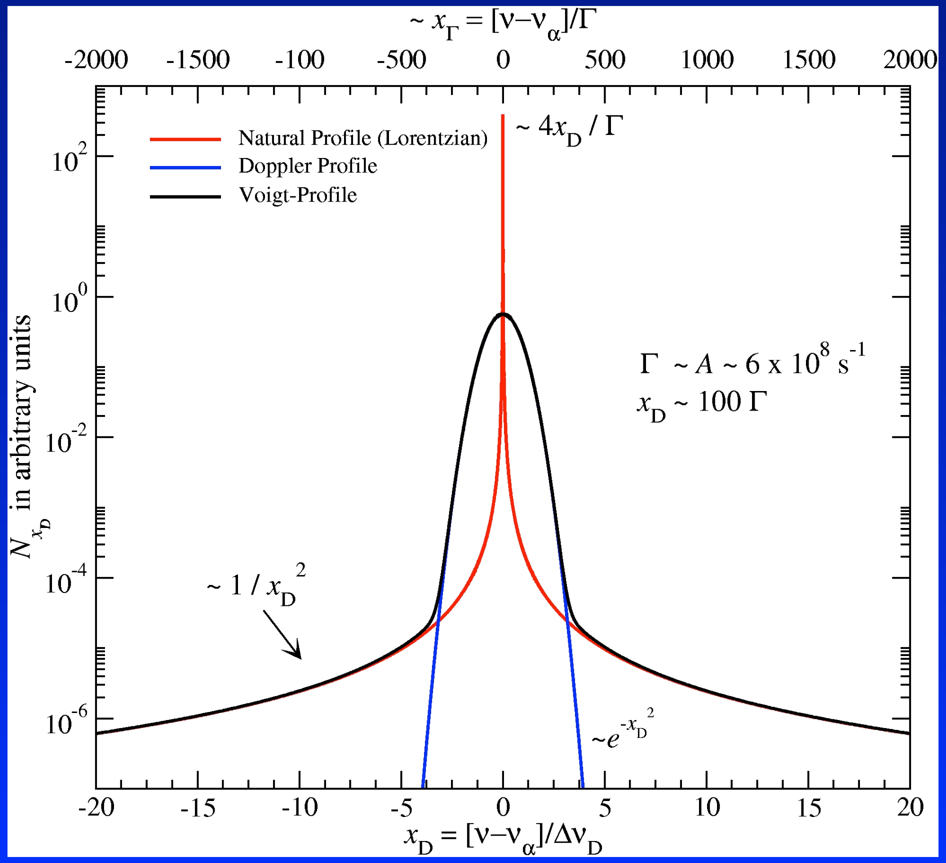
- To solve the coupled system of rate-equations

  → 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*

**Voigt - profile**




- 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*

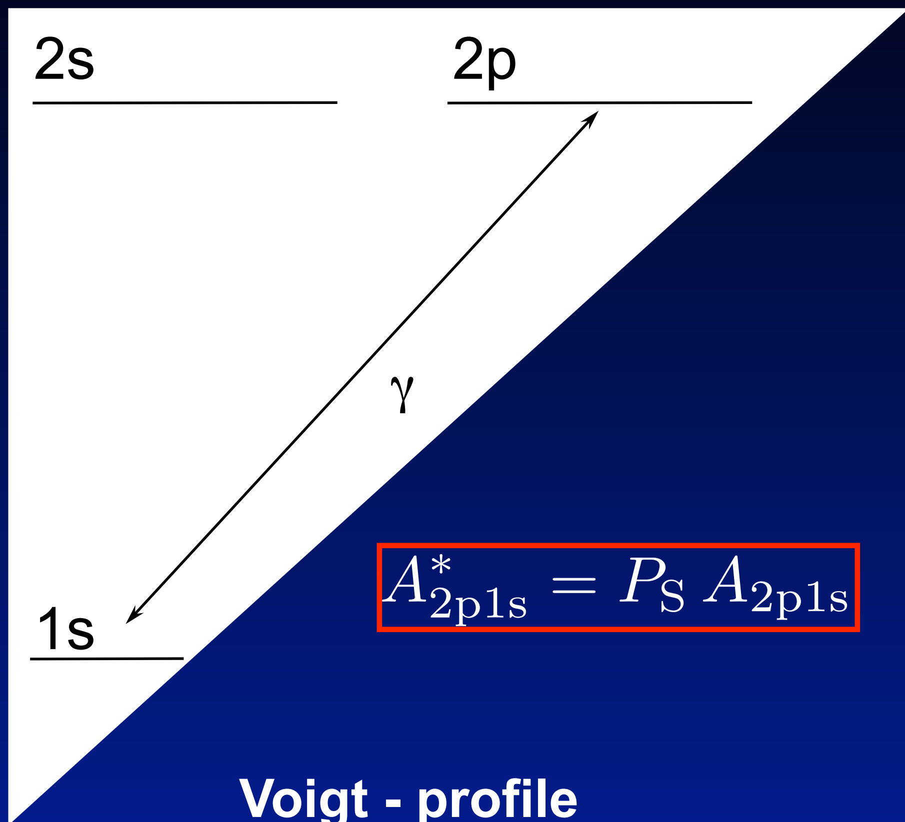
***Doppler width*** *(due to atomic motions)*

$$\frac{\Delta\nu_D}{\nu} = \sqrt{\frac{2kT}{m_H c^2}} \simeq \text{few} \times 10^{-5}$$

# Sobolev approximation

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

Hydrogen atom




$$A^*_{\rm 2p1s} = P_{\rm S}\, A_{\rm 2p1s}$$

- 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*

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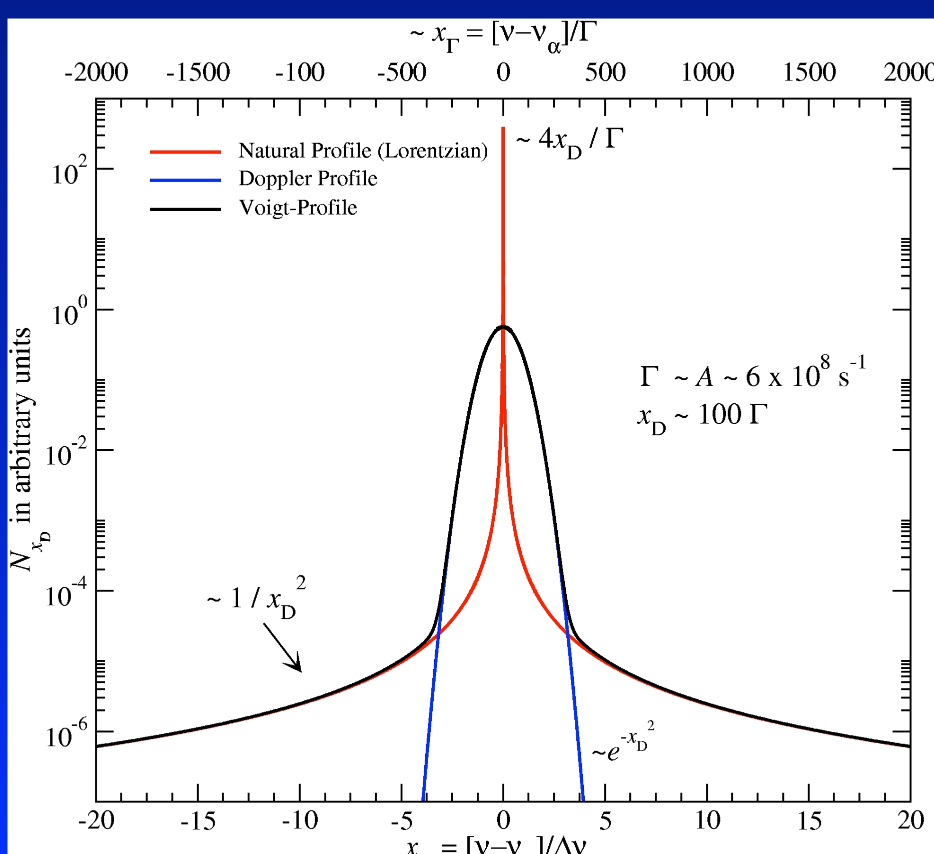
- Main assumptions of Sobolev approximation
  - populations of level + radiation field *quasi-stationary*
  - every 'scattering' leads to *complete redistribution*
  - emission & absorption profiles have the *same shape*

- Sobolev escape probability & optical depth

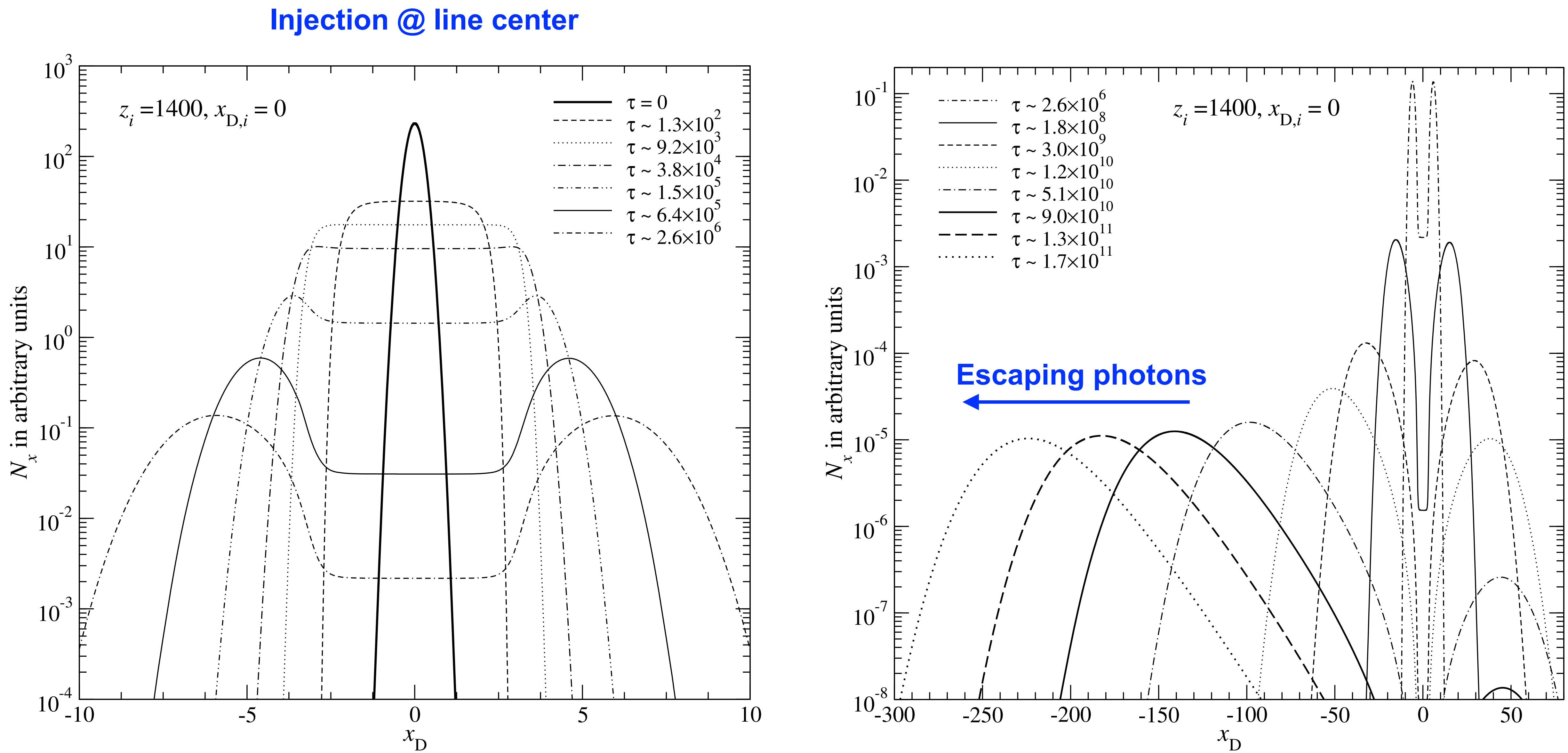
$$P_{\rm S} = \frac{1 - {\rm e}^{-\tau_{\rm S}}}{\tau_{\rm S}} \simeq 10^{-8}$$

$$\tau_{\rm S} = \frac{c\,\sigma_{\rm r} N_{\rm 1s}}{H}\,\frac{\Delta\nu_{\rm D}}{\nu} = \frac{g_{\rm 2p}}{g_{\rm 1s}}\,\frac{A_{21}\lambda_{21}^3}{8\pi H}\,N_{\rm 1s}$$

**Voigt - profile**



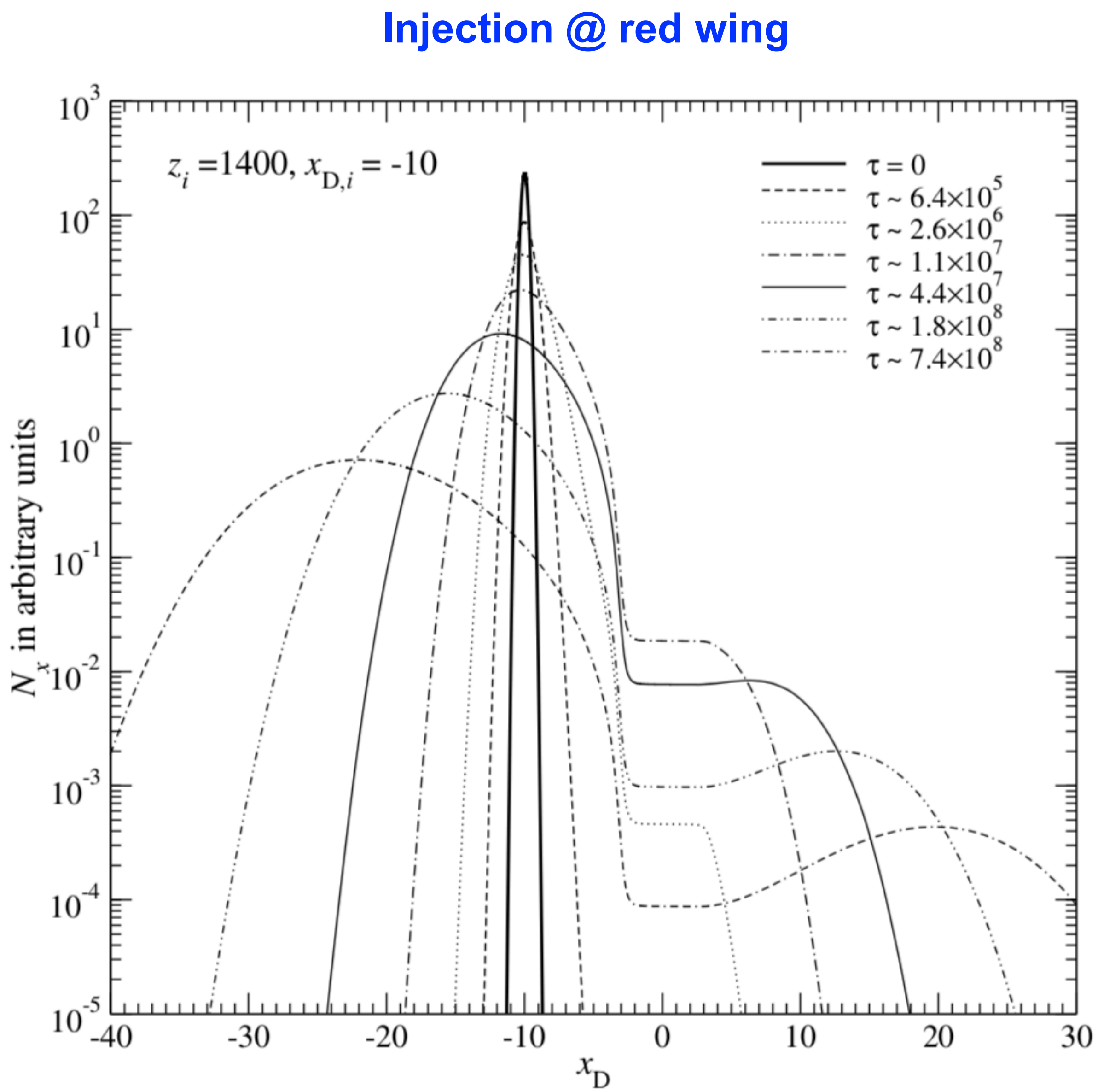
# Escape from resonance in expanding medium

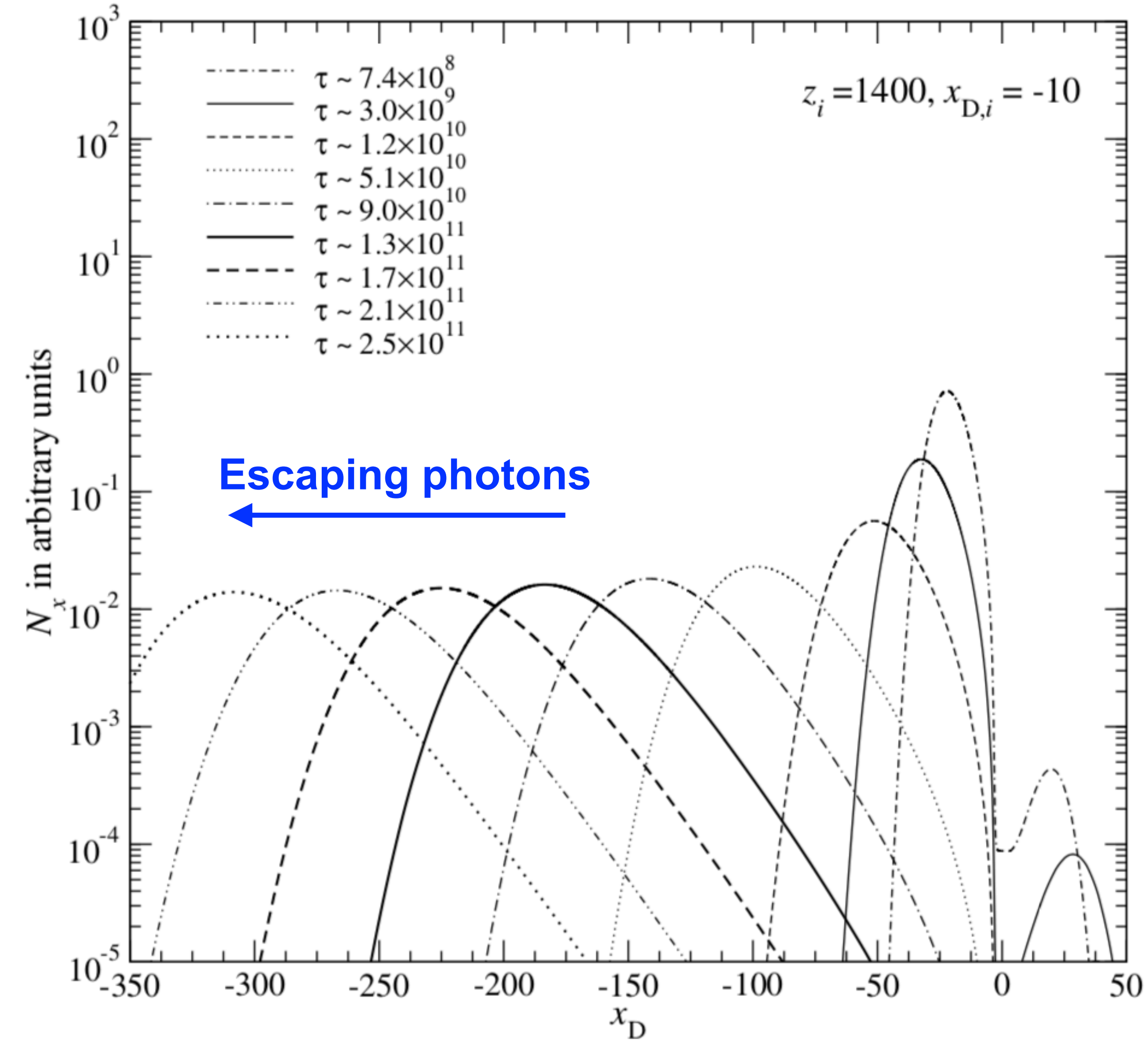



- Initial evolution dominated by broadening (atomic recoil smaller)
- Redshift takes over later (much longer time-scale than scattering and real absorption)
- Only a very small fraction of photons escape from line-center

JC & Sunyaev, 2009, A&A, 503

# Escape from resonance in expanding medium



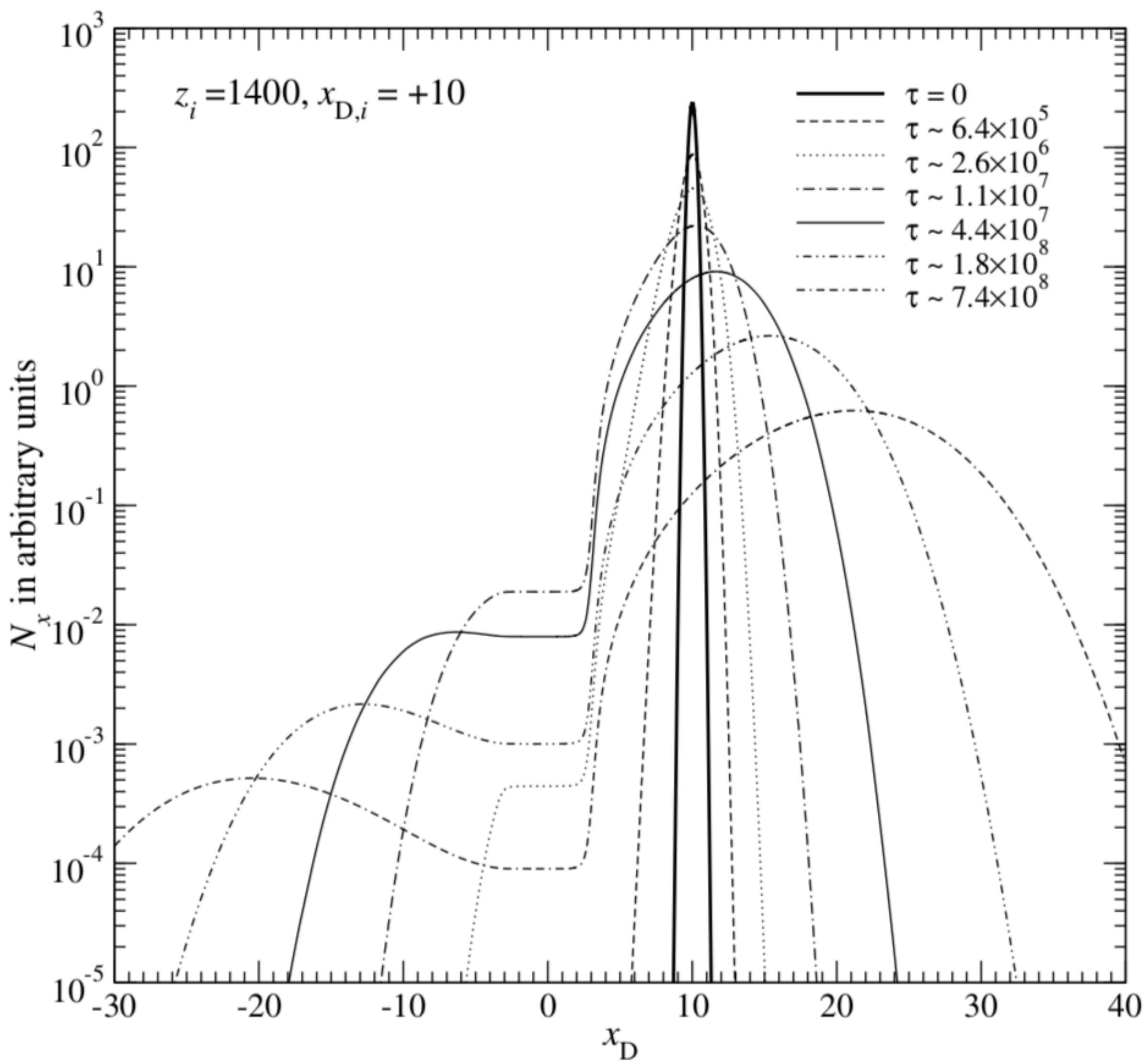



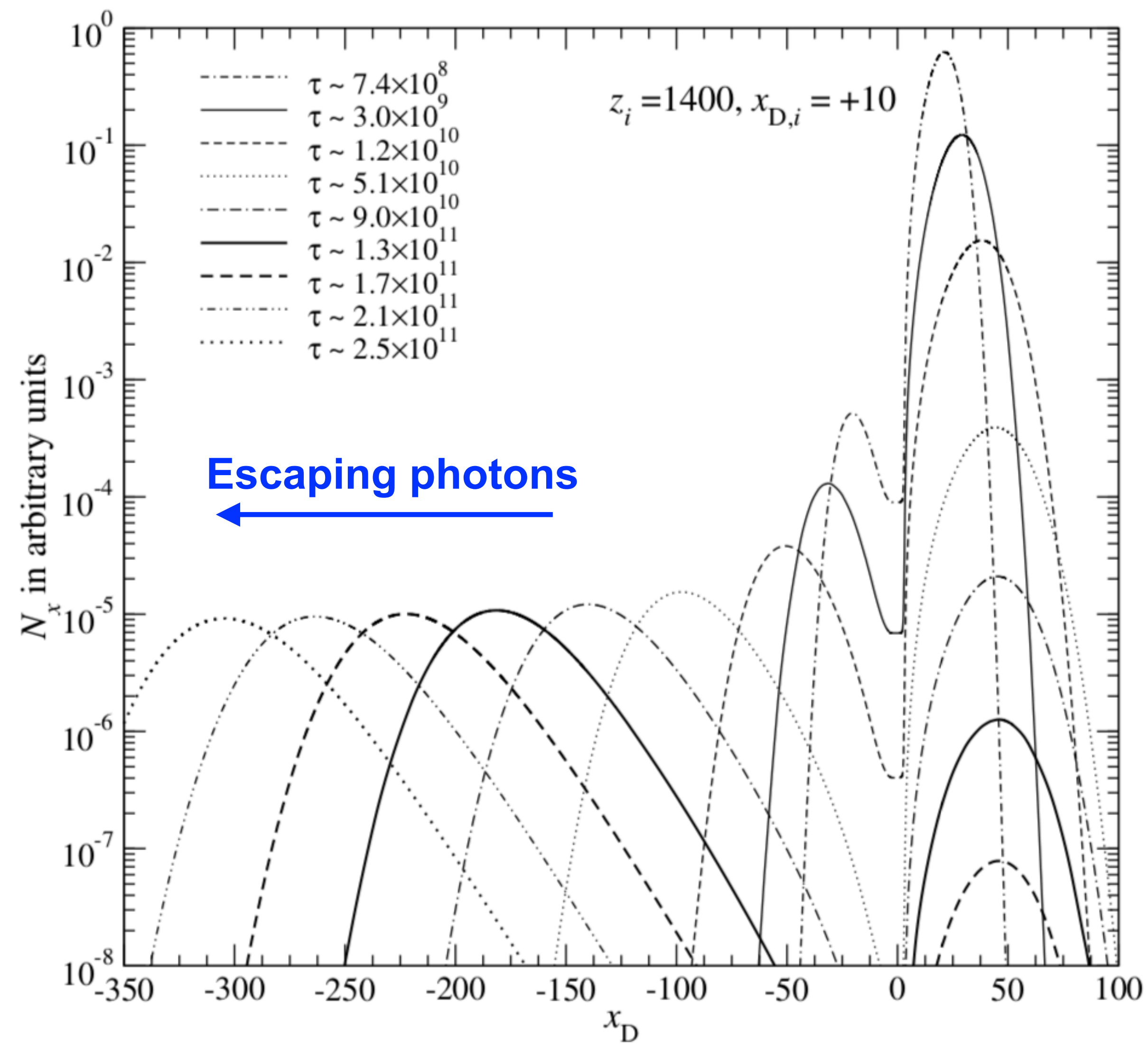

- Initial evolution dominated by broadening (atomic recoil smaller)
- Redshift takes over later (much longer time-scale than scattering and real absorption)
- Only a very small fraction of photons escape from line-center
- Escape from red wing easier (more photons survive)

JC & Sunyaev, 2009, A&A, 503

# Escape from resonance in expanding medium

**Injection @ blue wing**



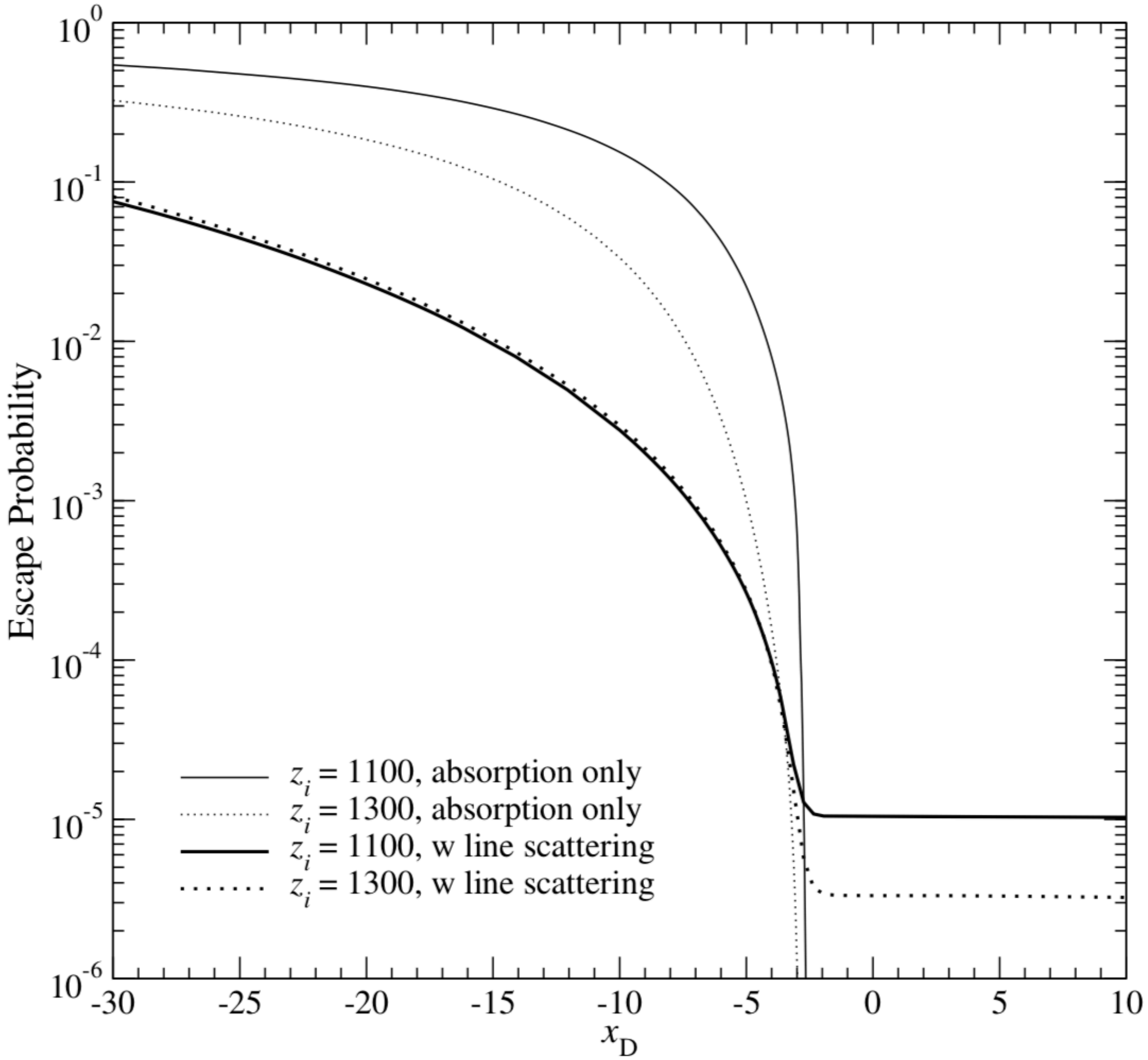




- Initial evolution dominated by broadening (atomic recoil smaller)
- Redshift takes over later (much longer time-scale than scattering and real absorption)
- Only a very small fraction of photons escape from line-center
- Escape from red wing easier (more photons survive)
- Non-vanishing probability to ‘survive’ even from blue wing

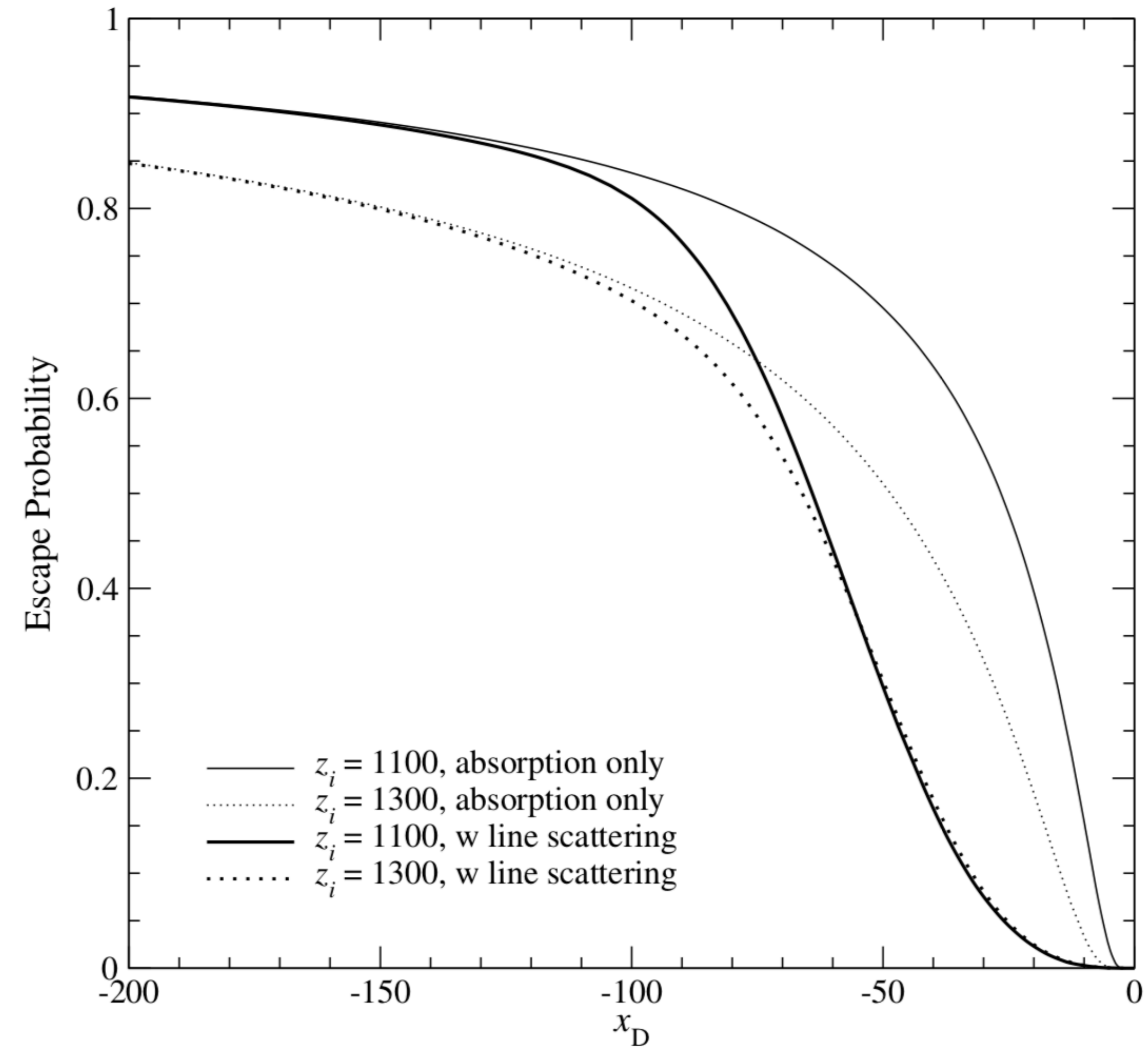
**JC & Sunyaev, 2009, A&A, 503**

# Differential Escape Probability

**Close to line center**




**Distant red wing**

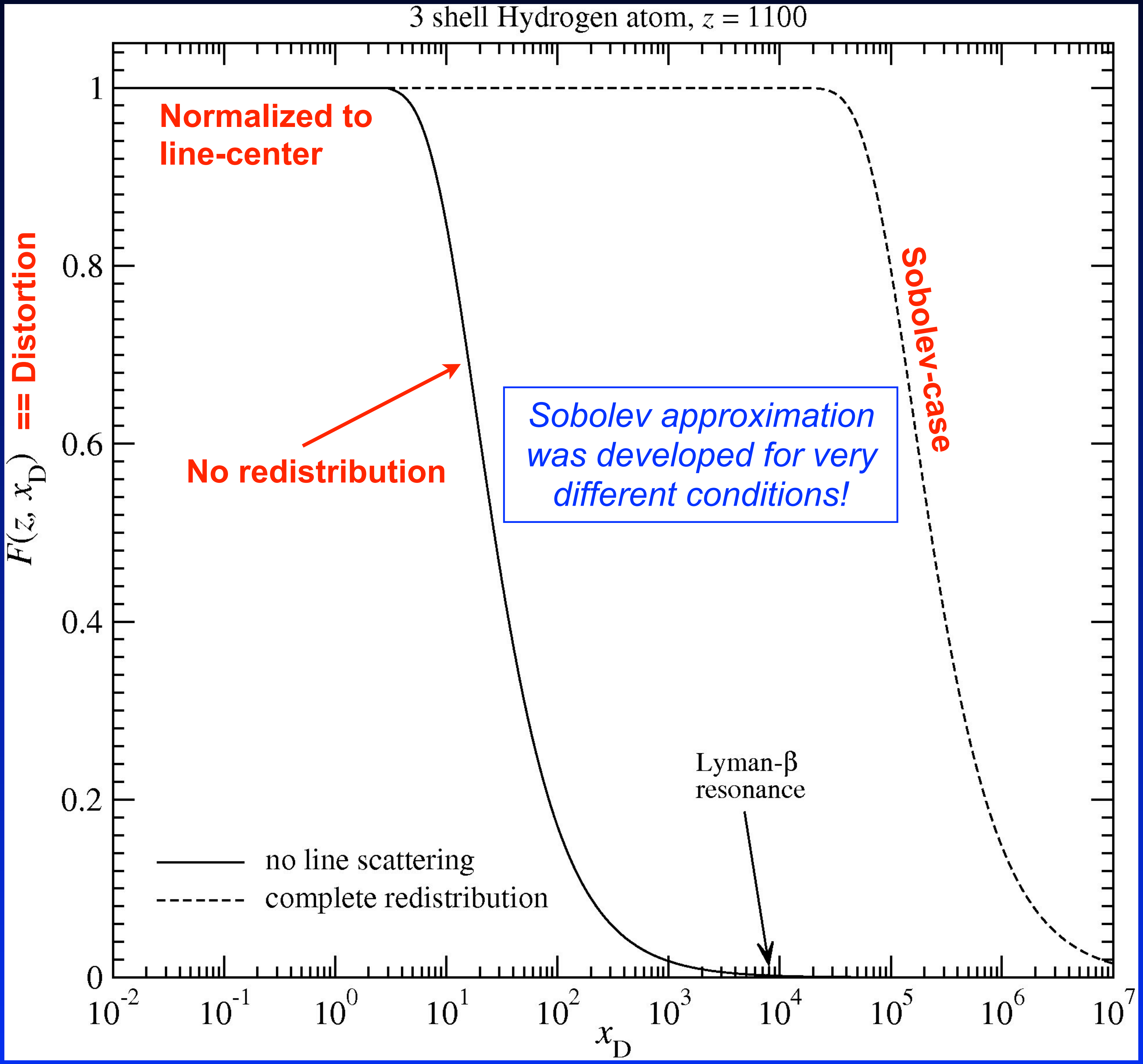



- Escape depends on physical assumptions (e.g., scattering and absorption)
- Escape probability is a strong function of frequency and redshift
- Escape from Doppler core very similar to escape from blue wing
- Ly-α resonance becomes optically thin only in very distant red wing

JC & Sunyaev, 2009, A&A, 503

# Problems with Sobolev approximation:

*Complete redistribution ⟺ partial redistribution*




JC & Sunyaev, 2009, A&A, 496

**Sobolev-approximation:**

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

**No redistribution case:**

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

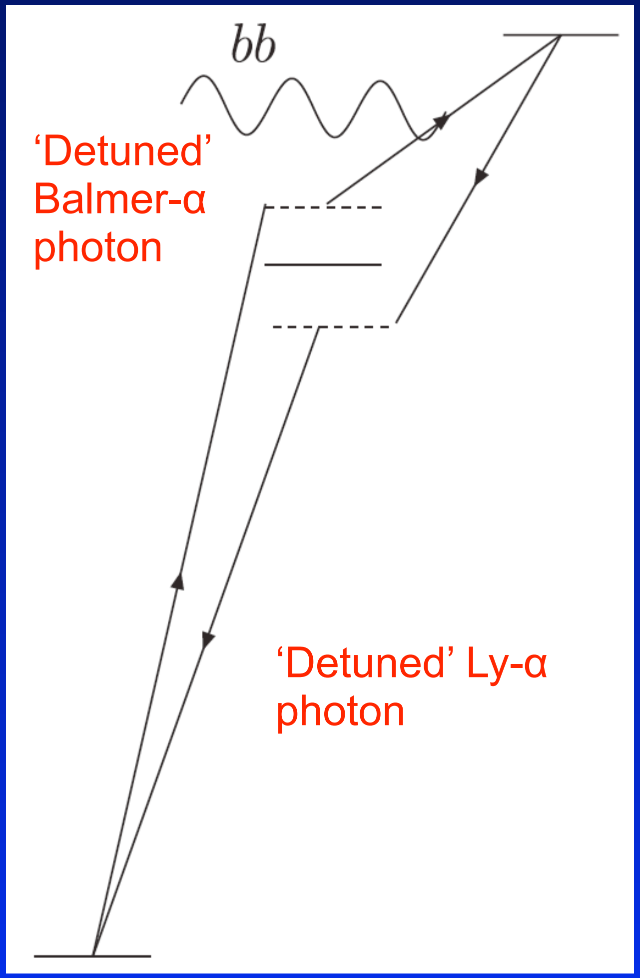
# Other Problems with Sobolev approximation

## 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 $\nu \sim \nu_0$
- Very *inaccurate* in distant damping wings
- Detailed balance off → blackbody not conserved!
- Formulation that includes profile asymmetries required

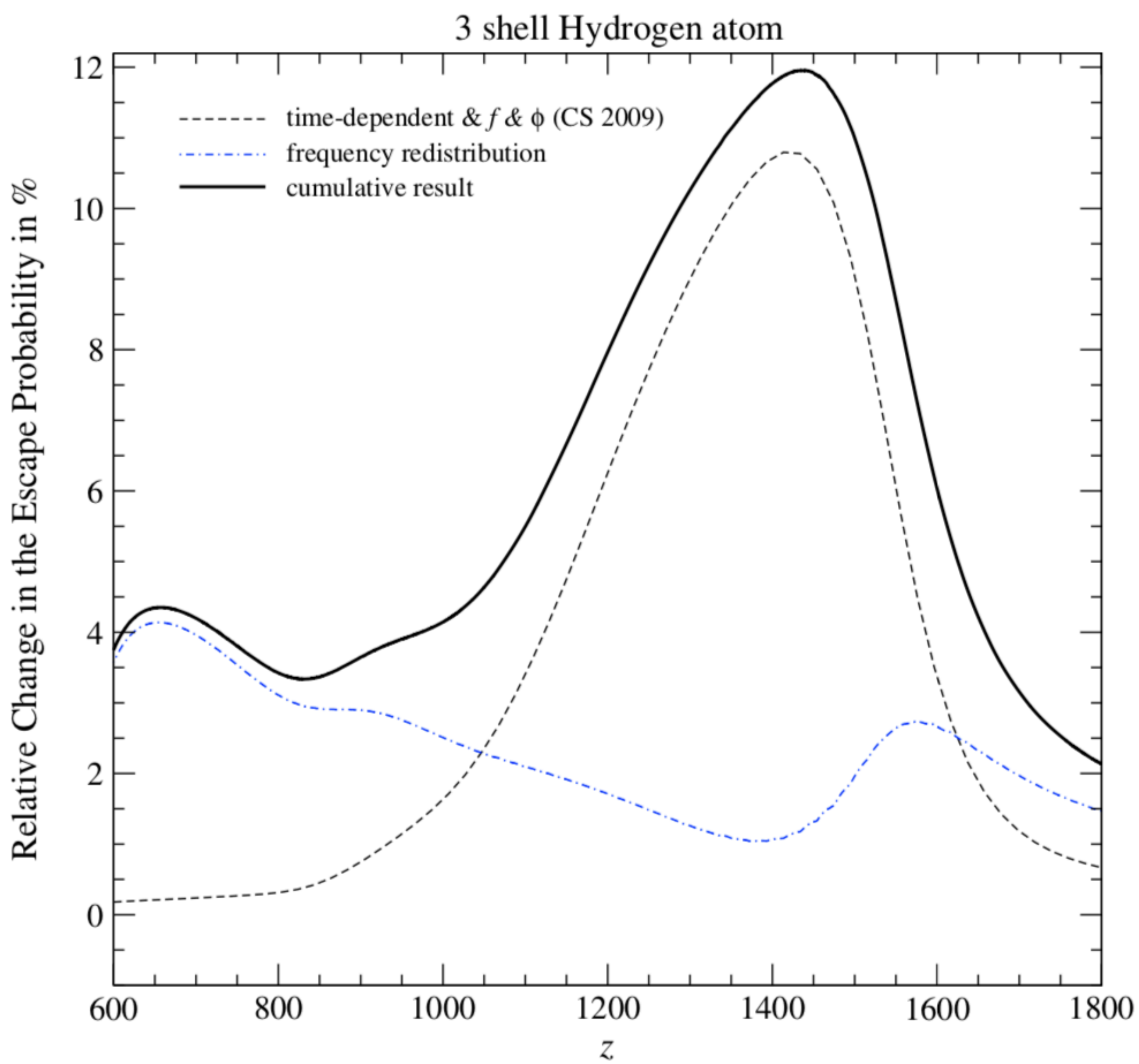



See JC & Sunyaev, 2009, A&A, 496 for more details

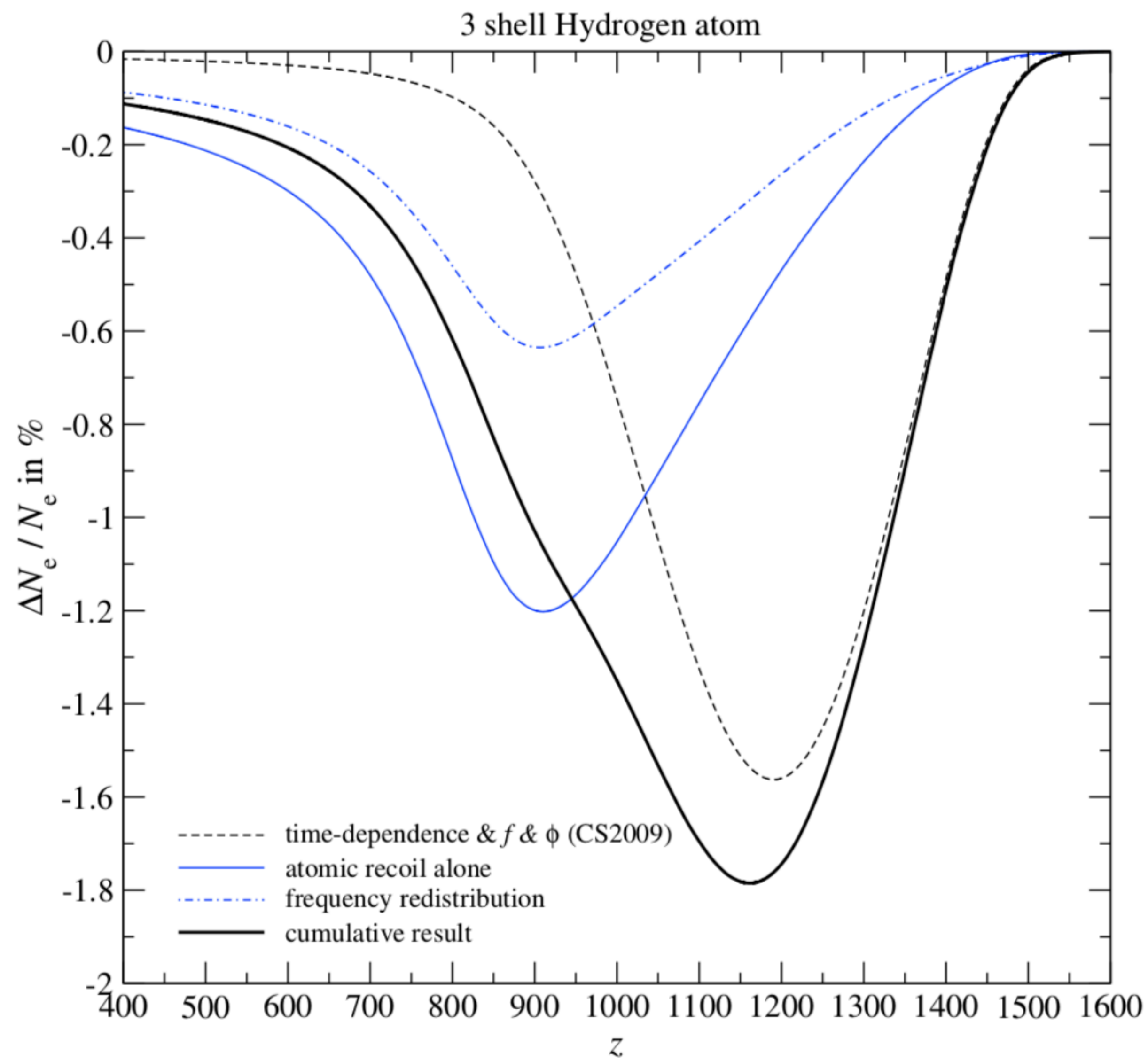
Illustration from Switzer & Hirata 2007 (meant for Helium)

# Sobolev approximation is still pretty good (sadly…)

**Total escape probability correction**



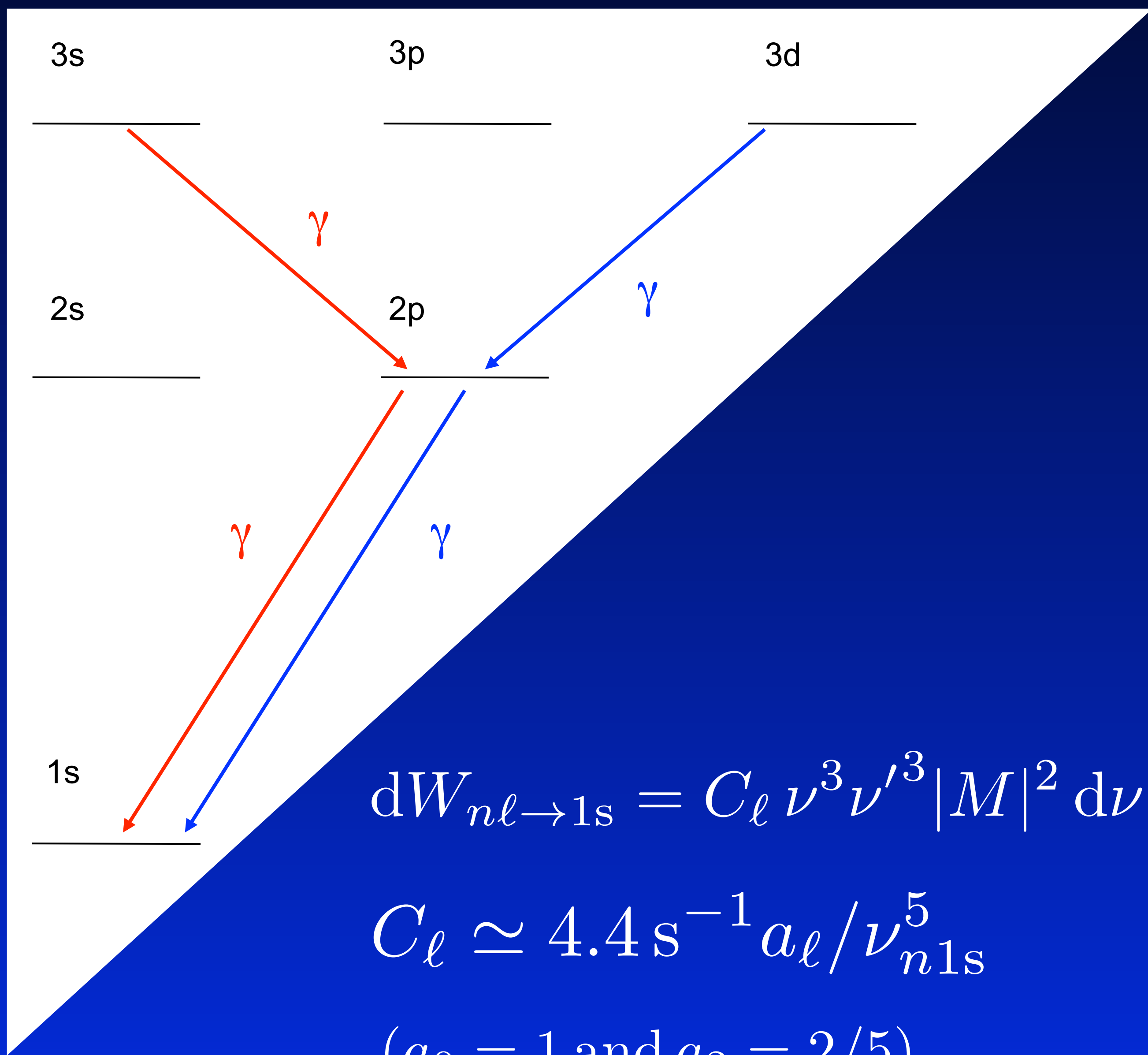

**Change in ionization history**




- In spite of being developed for totally different purpose and issues with the physical formulation….
- Time-dependence largest correction to the Ly-α escape problem
- Total correction $\Delta N_e/N_e$ ~ -1.8% @ $z$~1150

JC & Sunyaev, 2009, A&A, 503

# Two-photon emission process from upper levels




$$\mathrm{d}W_{n\ell\to 1\mathrm{s}} = C_\ell\, \nu^3 \nu'^3 |M|^2\, \mathrm{d}\nu$$

$$C_\ell \simeq 4.4\,\mathrm{s}^{-1} a_\ell / \nu_{n1\mathrm{s}}^5$$

$$(a_0 = 1 \;\mathrm{and}\; a_2 = 2/5)$$

*Seaton* cascade (1+1 photon)

*No collisions* → two photons (mainly H-$\alpha$ and Ly-$\alpha$) are emitted

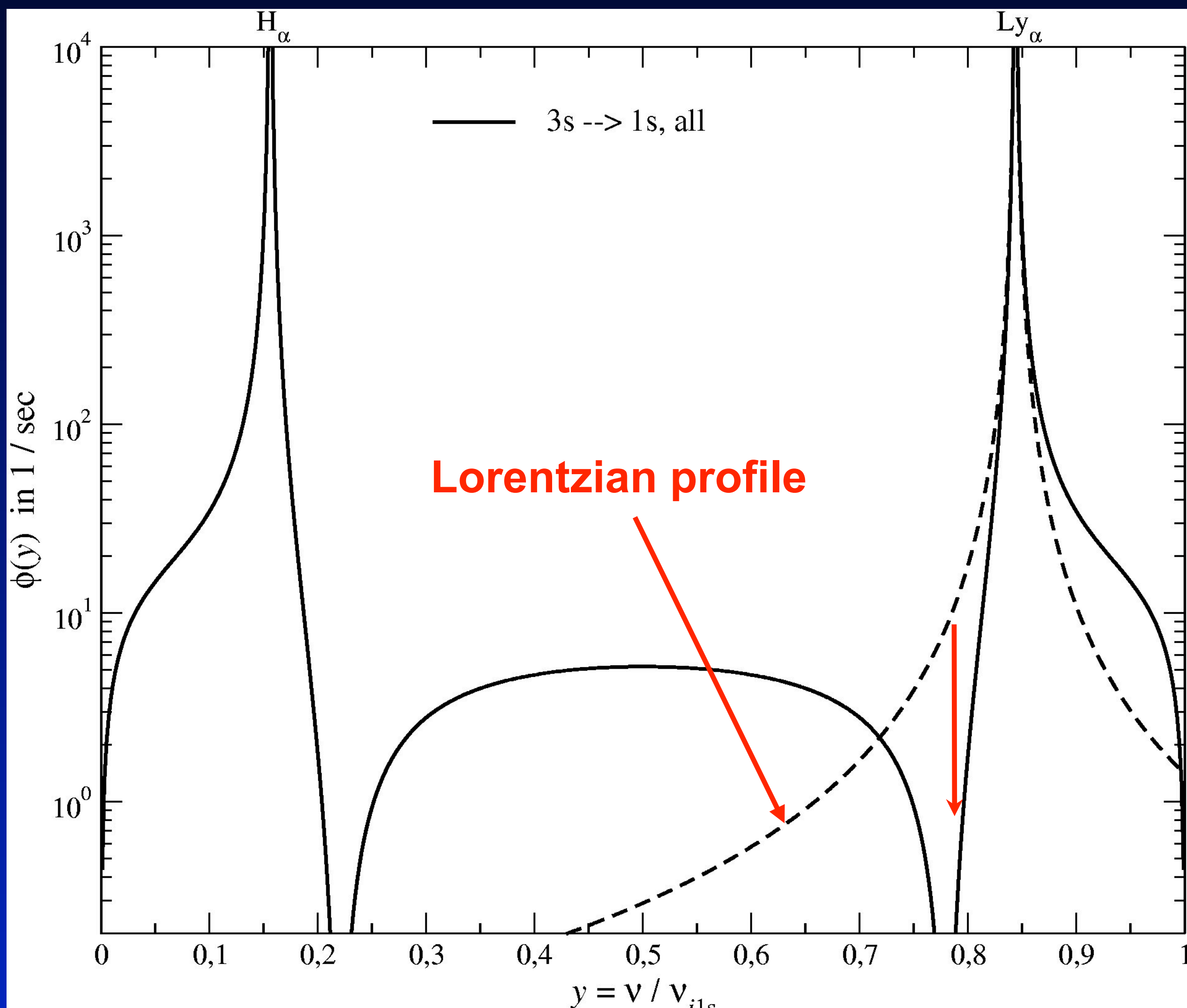
***Maria-Göppert-Mayer*** (1931): description of two-photon emission as *single quantum act*

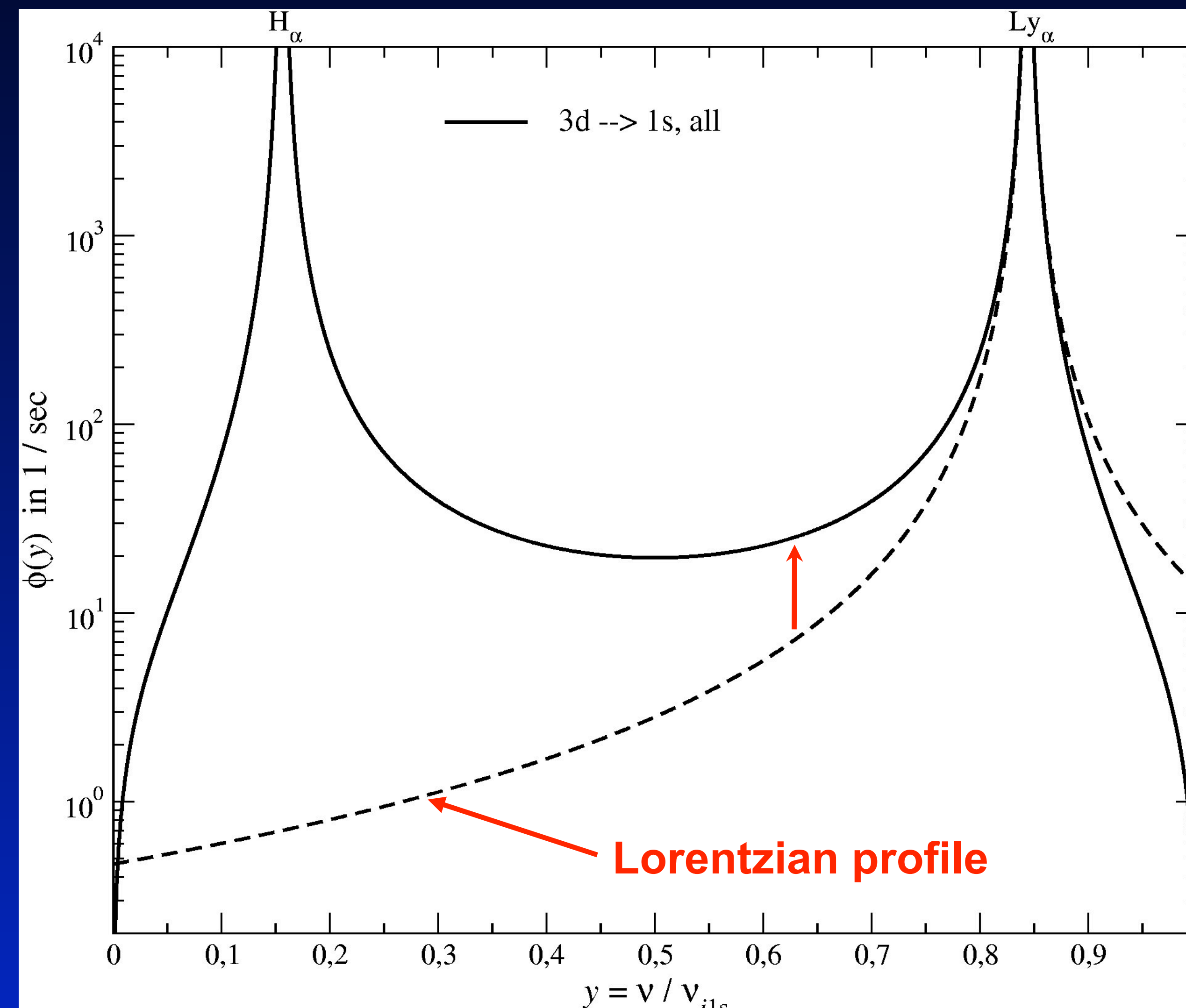
→Deviations of the *two-photon line profile* from the Lorentzian in the damping wings

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

$$M = \sum_{n'=2} \langle R_{1\mathrm{s}} | r | R_{n'\mathrm{p}} \rangle \langle R_{n'\mathrm{p}} | r | R_{n\ell} \rangle \; g_{n,n'}(\nu) \qquad g_{n,n'}(\nu) = \frac{1}{h\nu_{nn'} - h\nu} + \frac{1}{h\nu_{nn'} - h\nu'}$$

# 3s and 3d two-photon decay spectrum



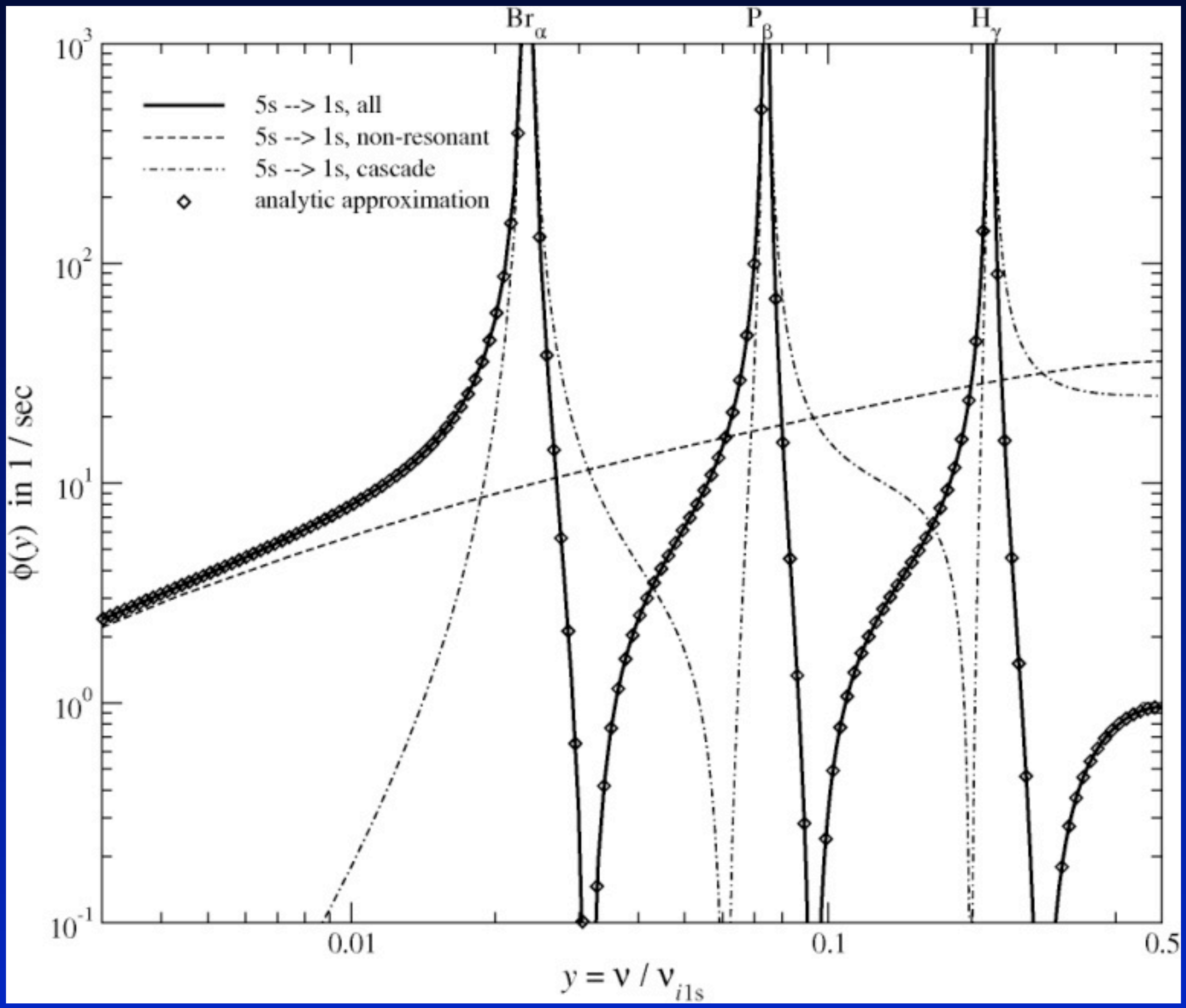

*Direct Escape from optically thin regions:*

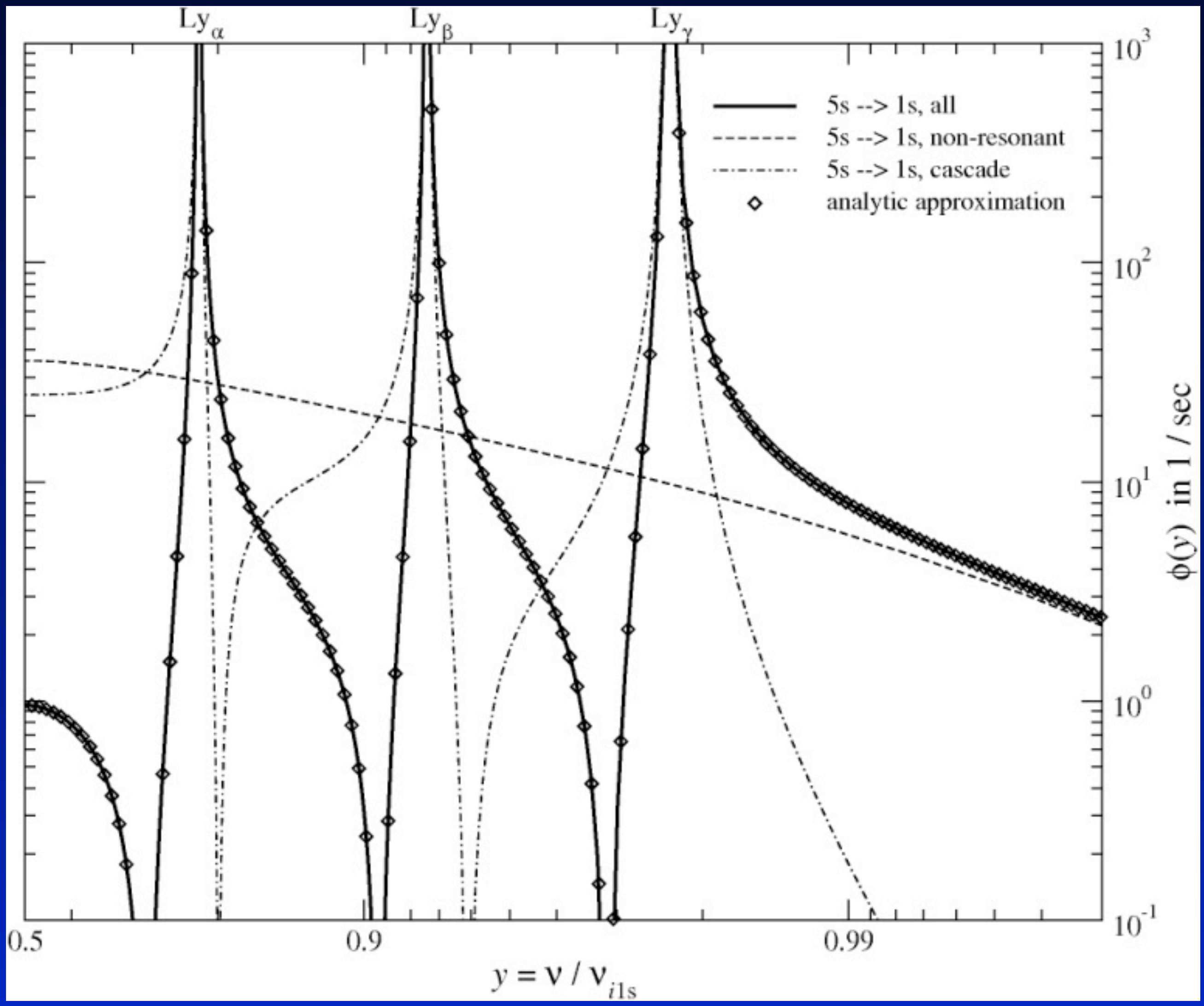
→ HI -recombination is a bit *slower* due to 2γ-transitions from s-states

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

**JC & Sunyaev, A&A, 2008**

# 5s two-photon decay spectrum



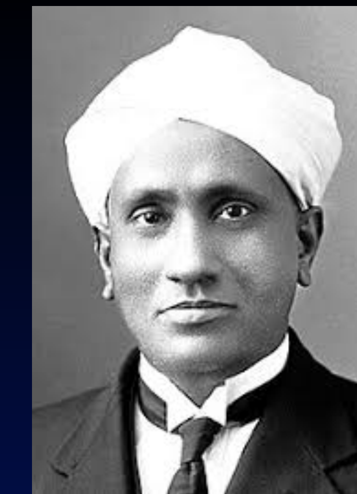

→ matters become more complicated quickly

→ splitting of resonance and non-resonant parts simplify the computation greatly

→ luckily including these effects up to *n* ~ 4-5 is enough

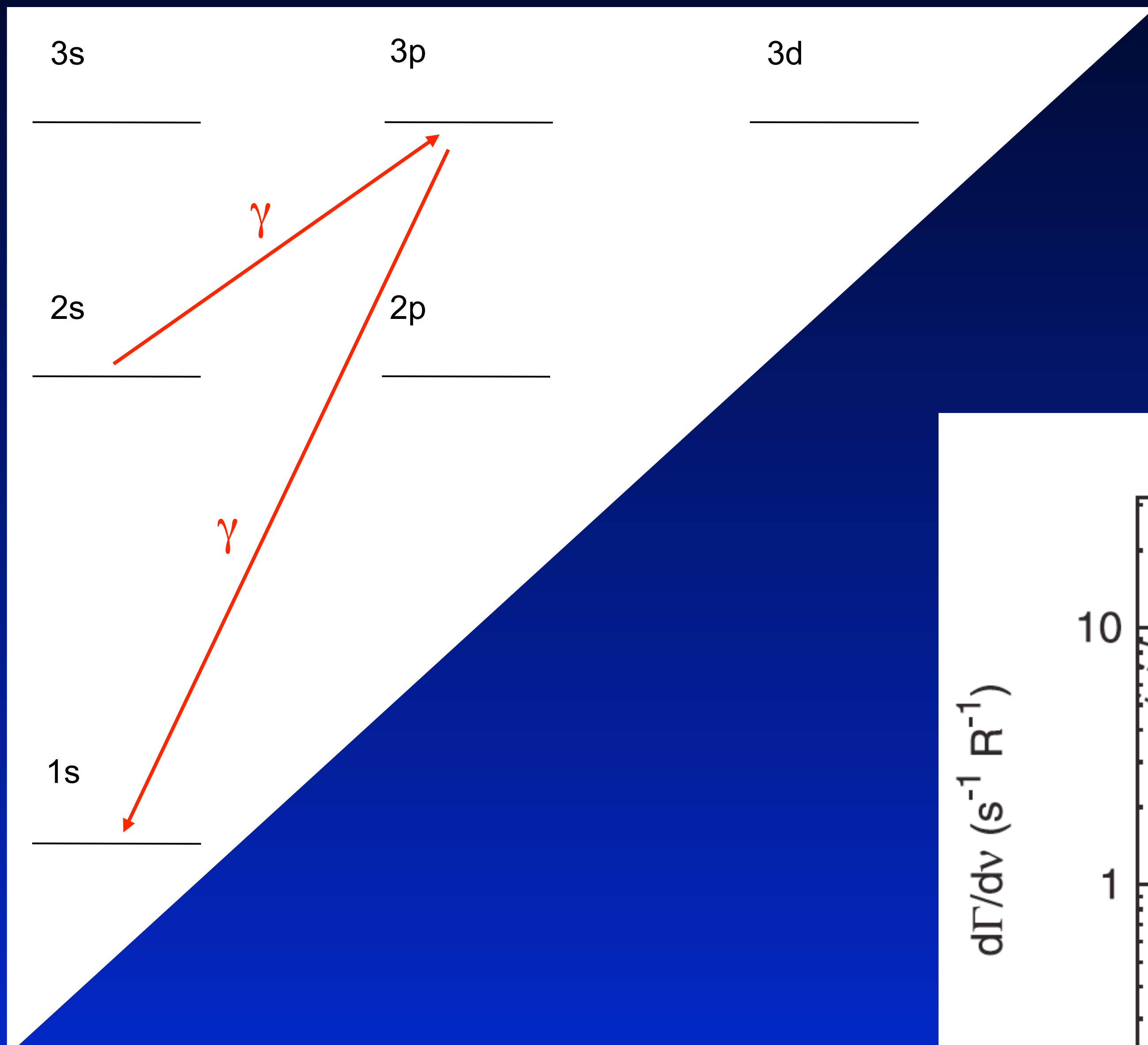
**JC & Sunyaev, 2008, A&A, 480**

# 2s-1s Raman scattering



C.V. Raman

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



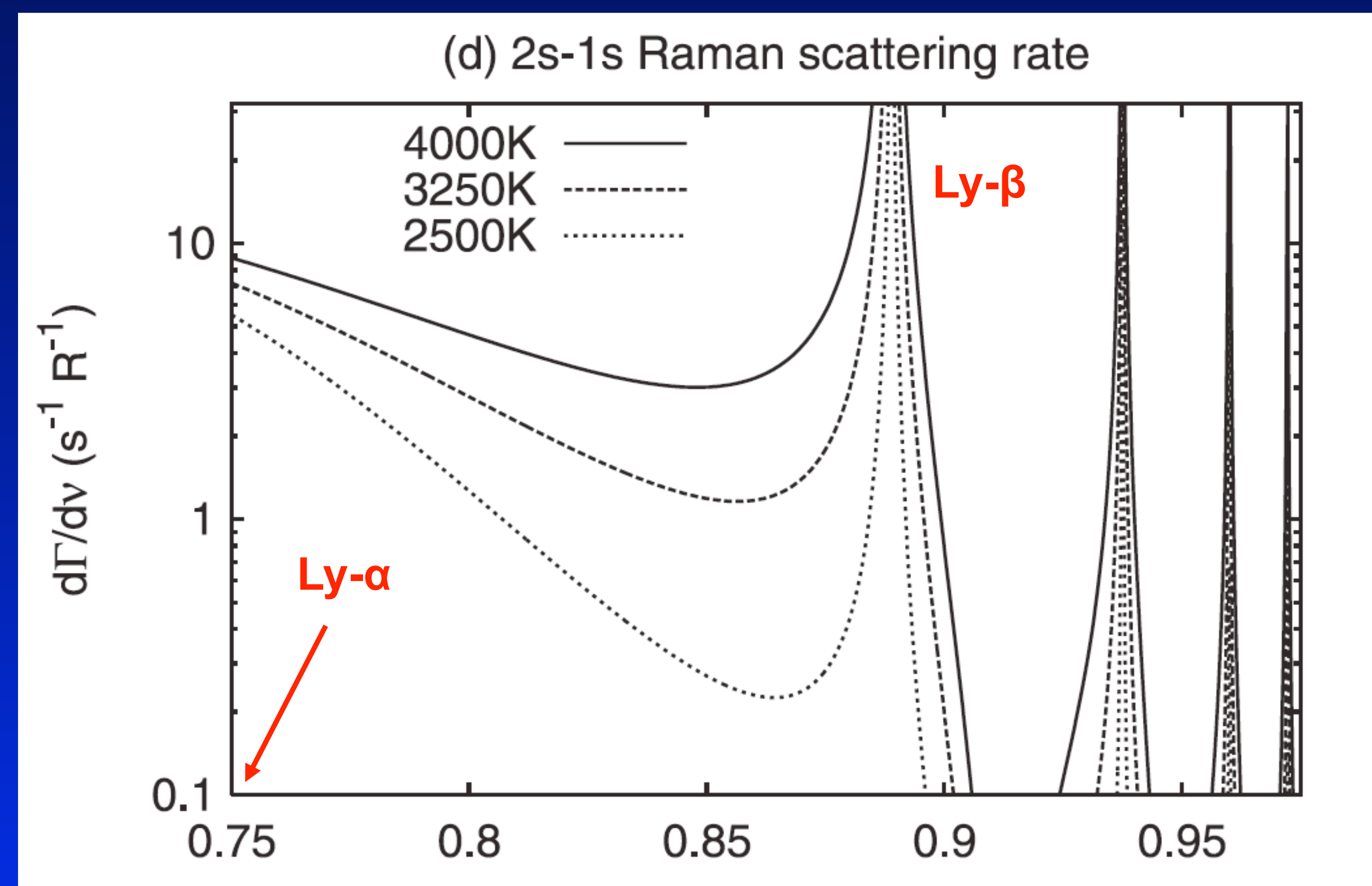
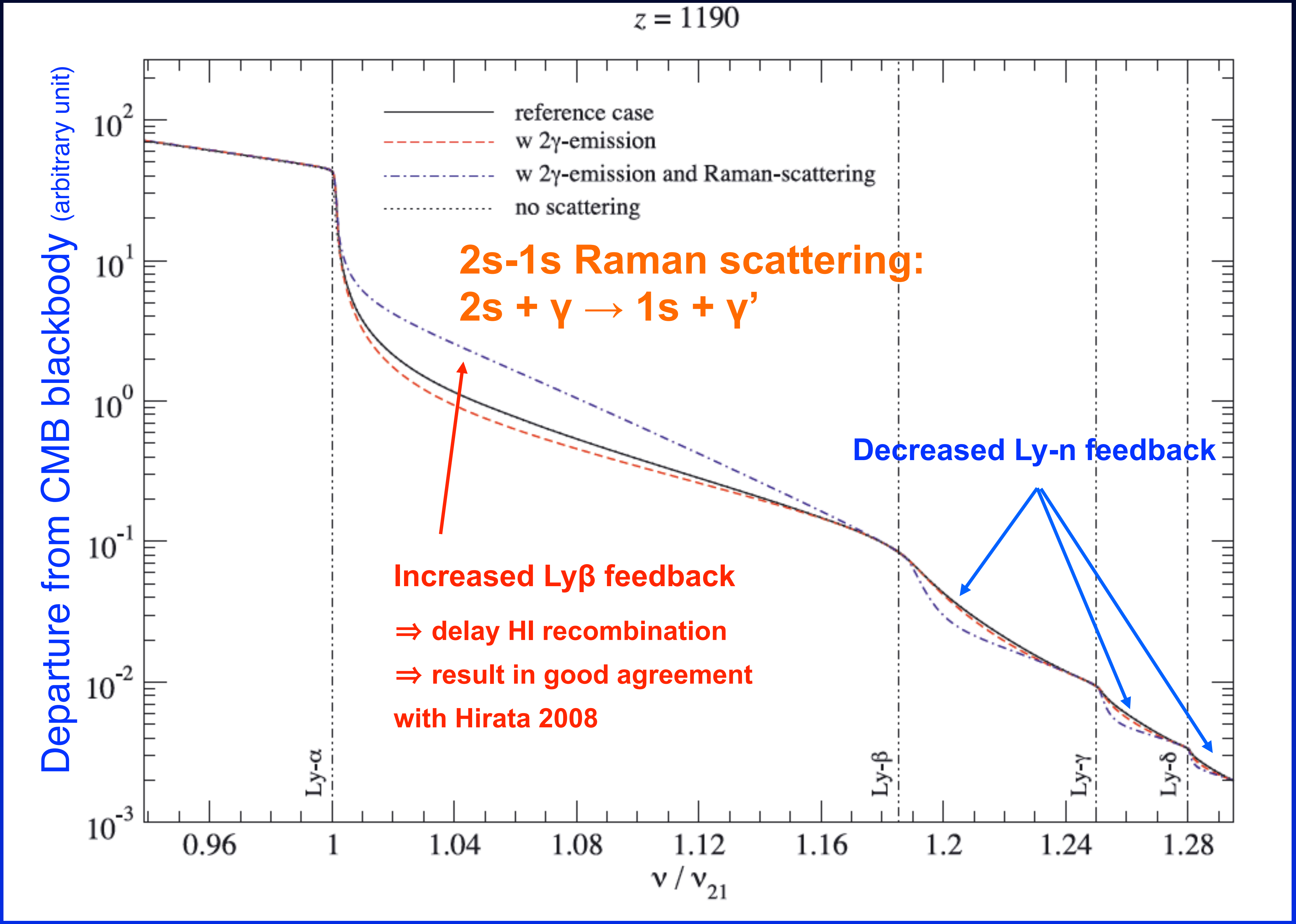




Figure from: Hirata 2008

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

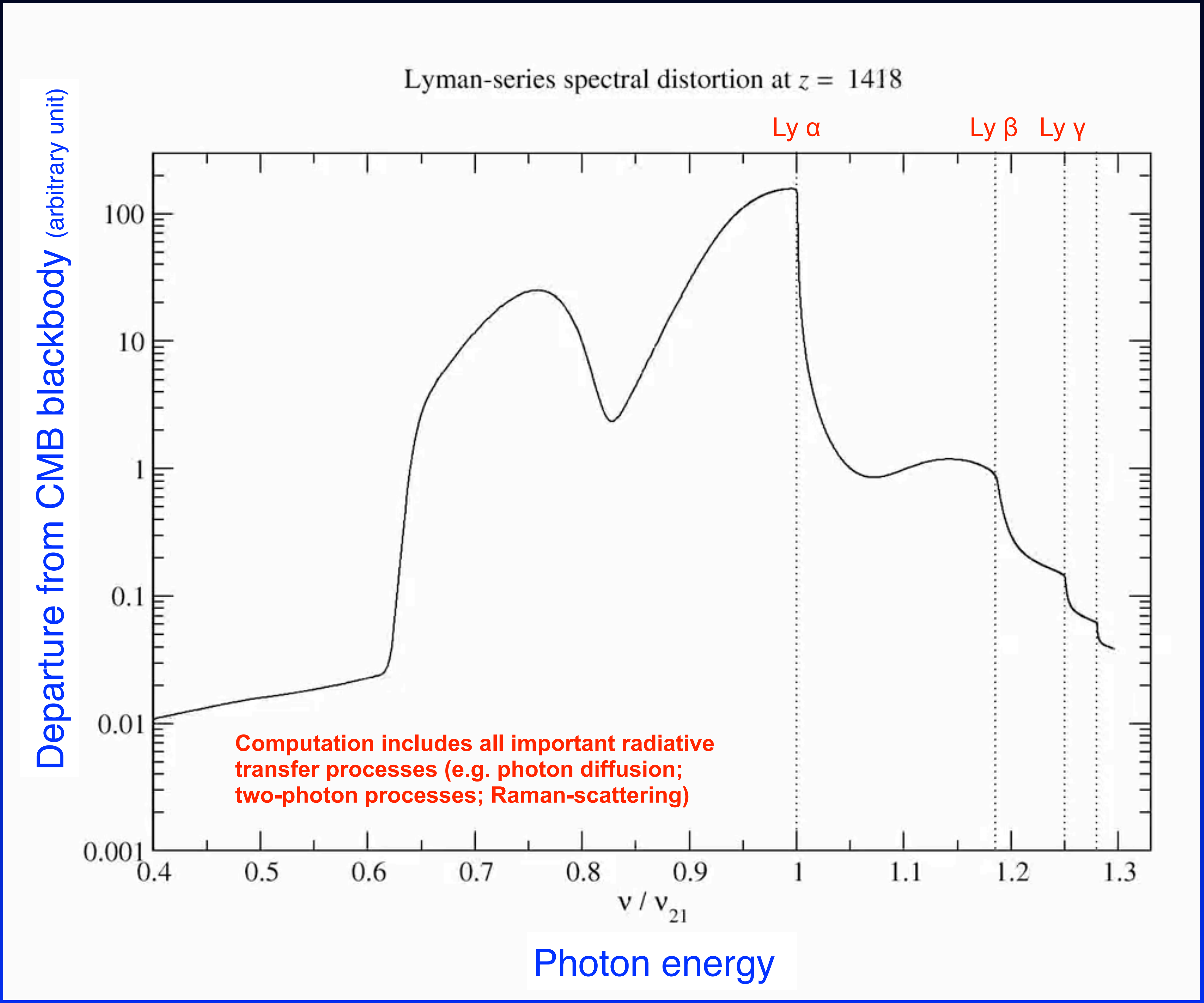
**Hirata 2008**
**JC & Thomas, 2010**

# Effect of Raman scattering and 2γ decays




JC & Thomas, MNRAS, 2010

# Evolution of the HI Lyman-series distortion




JC & Thomas, MNRAS, 2010

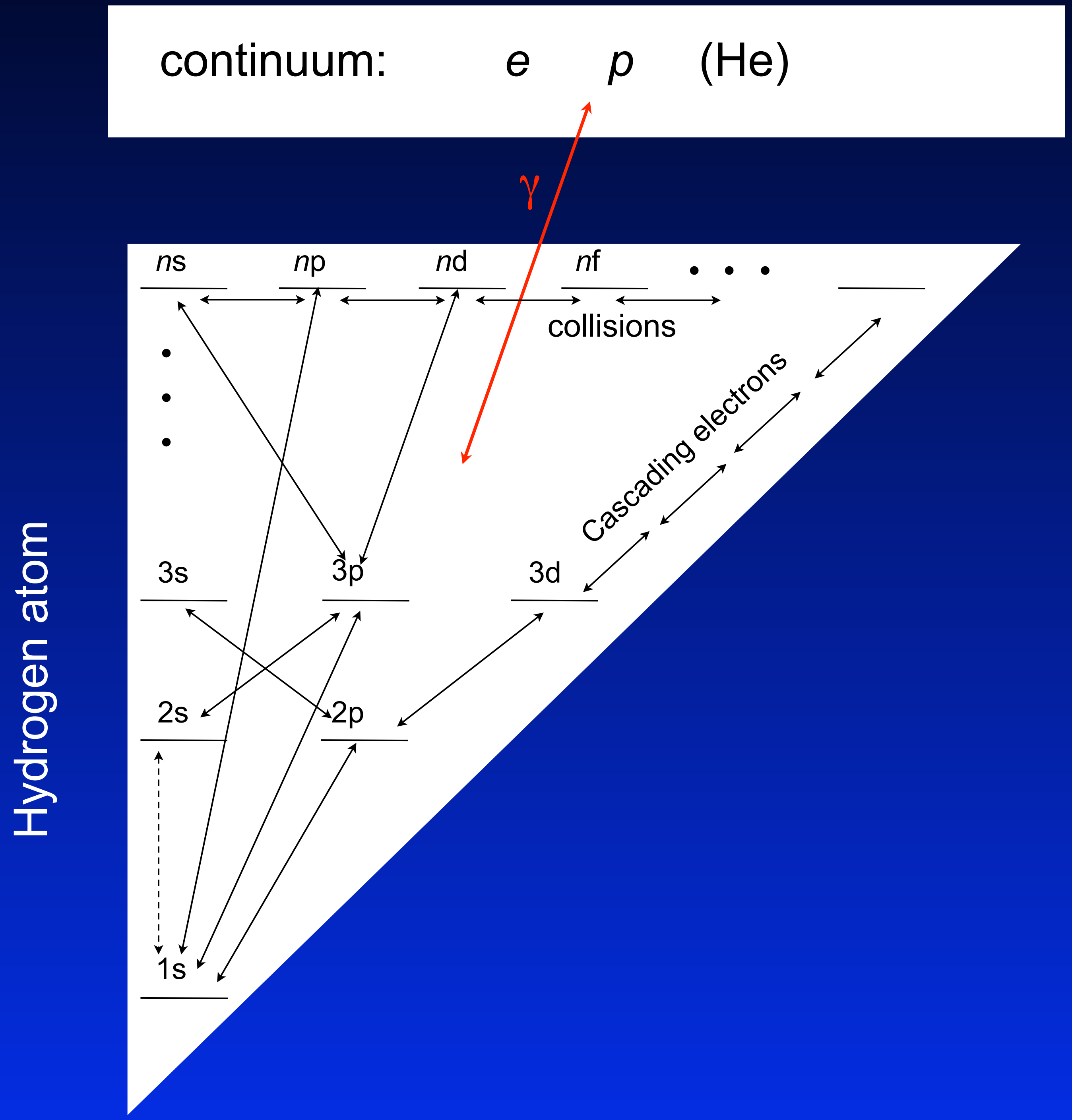
# Deviations from Statistical Equilibrium in the upper levels

**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 ~ $n_{\mathrm{max}}$

# Processes for the upper levels




- **recombination & photoionization**
  - ***n*** **small → $l$-dependence not drastic**
  - **high shells → more likely to $l$<<*n***
  - **large *n* → *induced* recombination**
- **many radiative dipole transitions**
  - **Lyman-series optically thick**
  - **$\Delta l = \pm 1$ restriction (electron cascade)**
  - **large *n* & small $\Delta n$ → *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

**Basis for Recfast computation** (Seager et al. 2000)

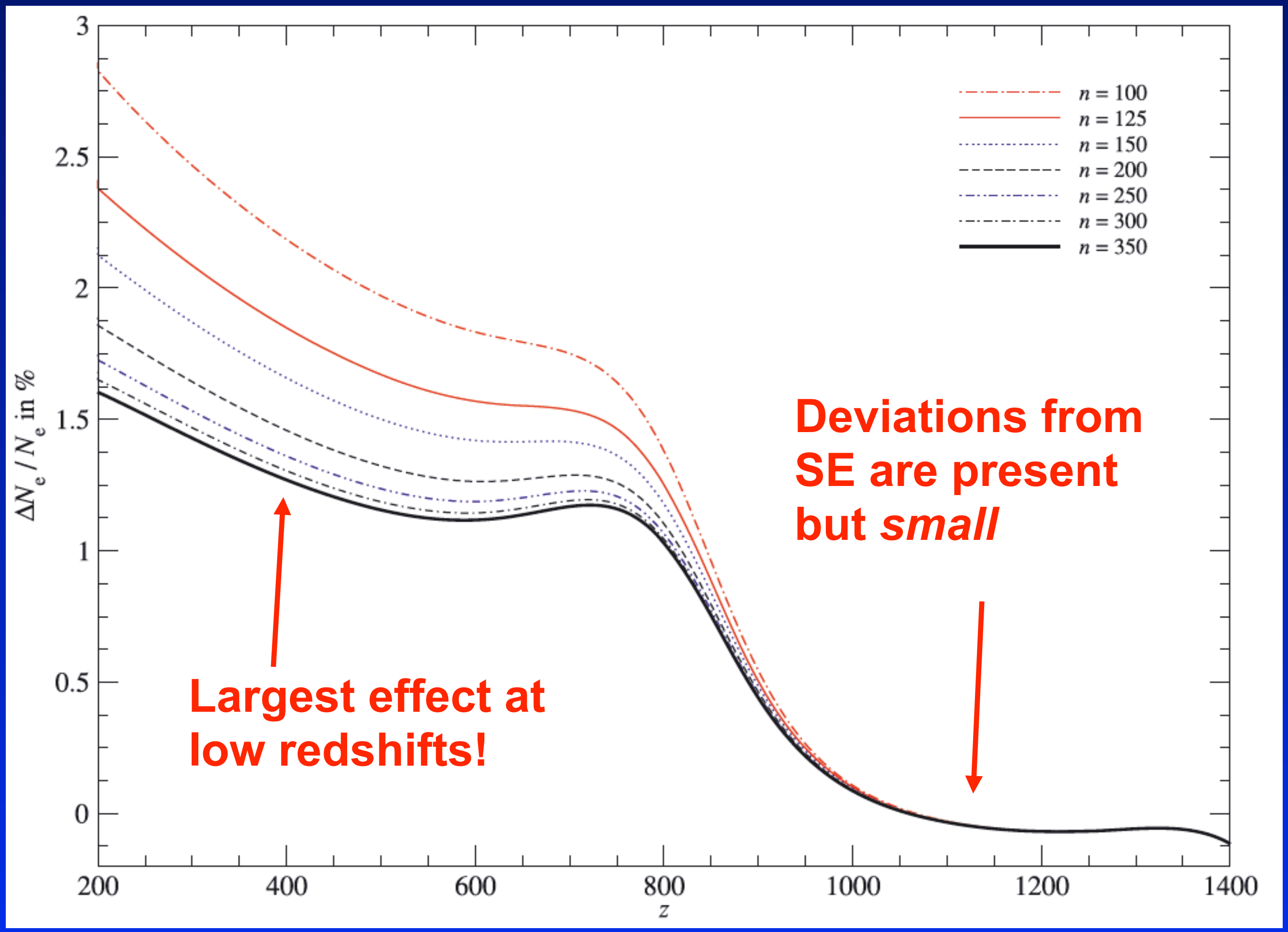
$$N_{nl} = \frac{2l+1}{n^2} N_{\mathrm{tot},n}$$

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

**Refined computation**
(JC, Rubino-Martin & Sunyaev, 2007)

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

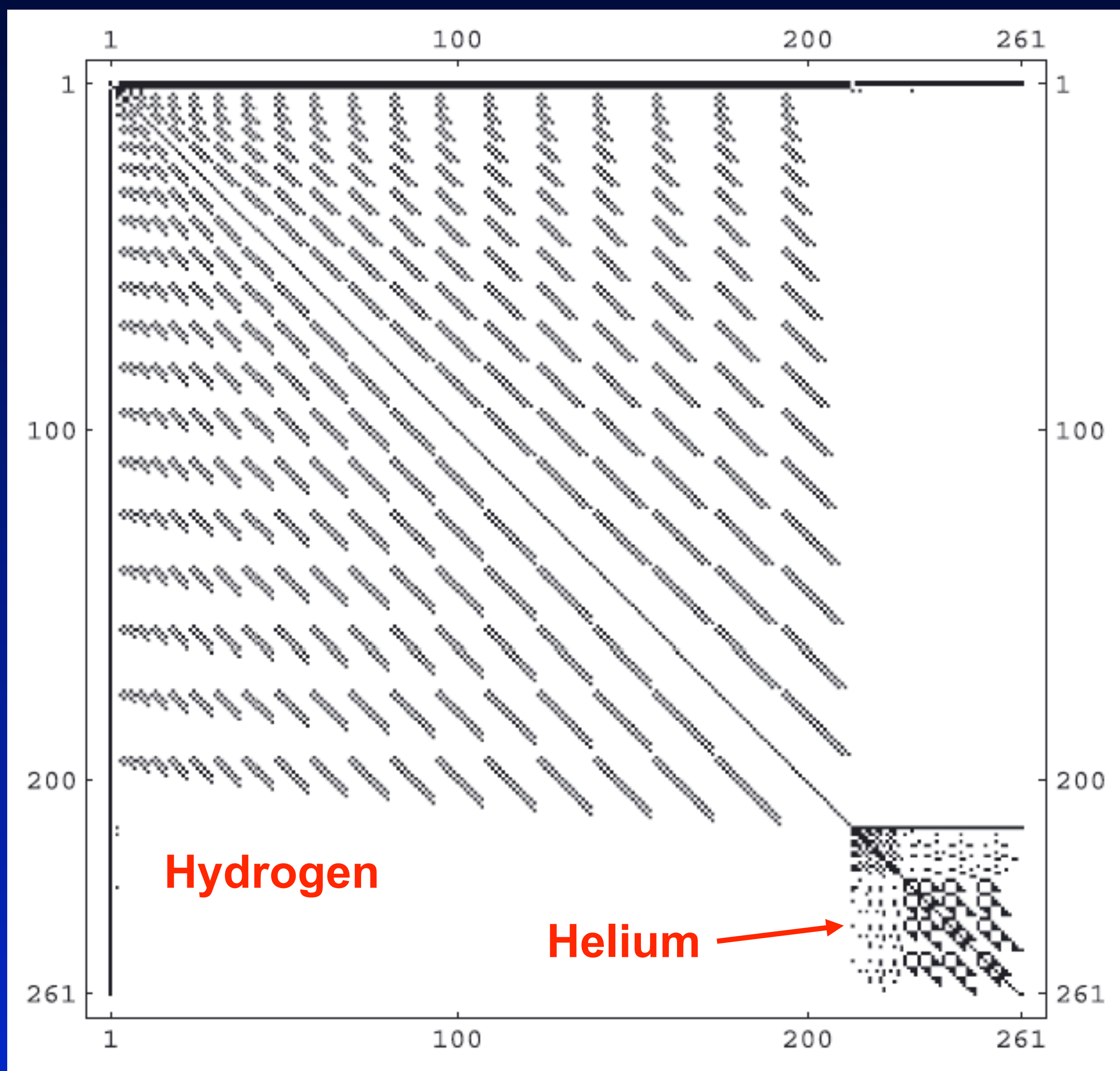
(Grin & Hirata, 2010; JC, Vasil & Dursi, 2010)




JC, Vasil & Dursi, MNRAS, 2010

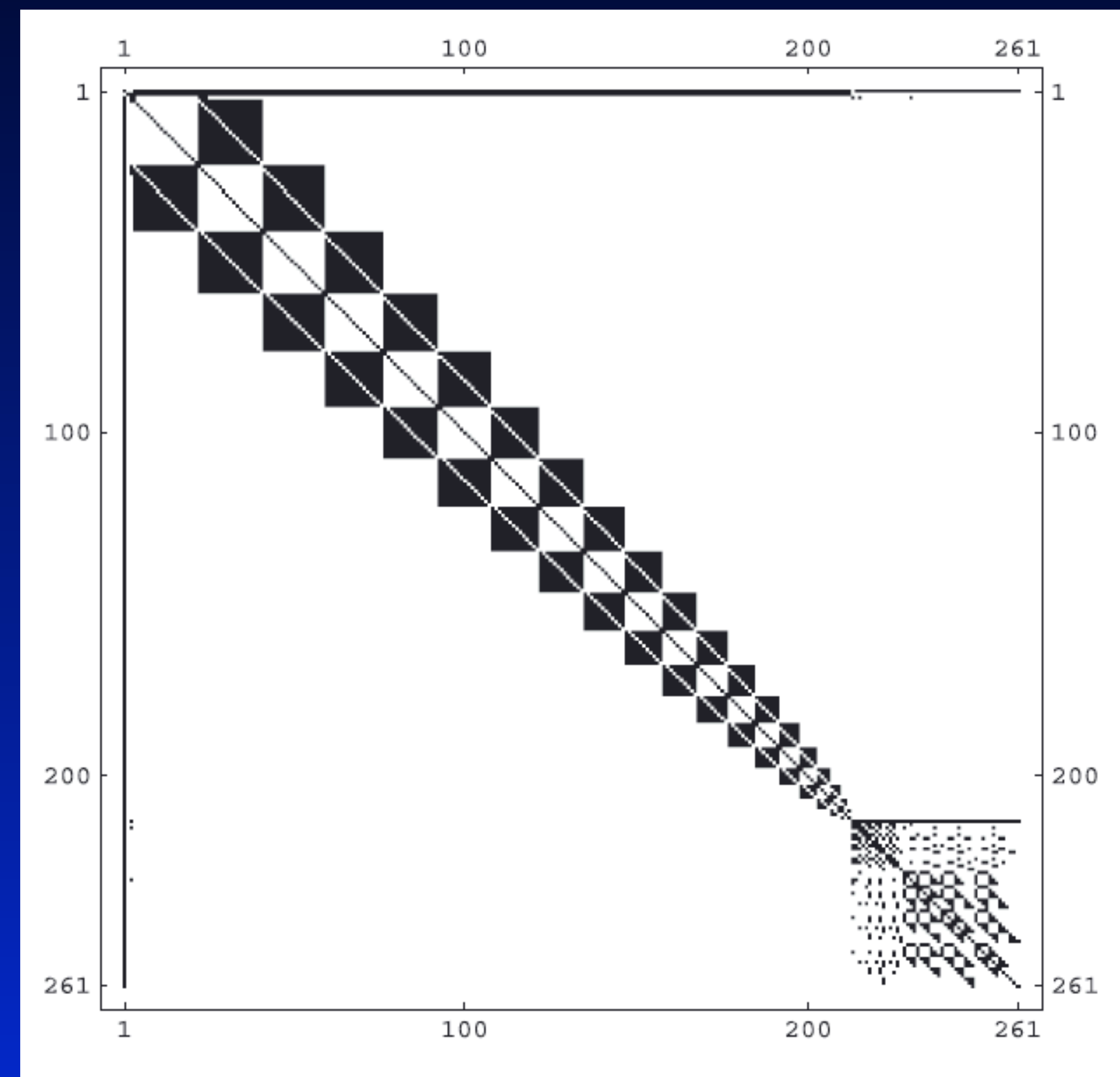
# Sparsity of the problem and effect of ordering

**20 shell Hydrogen + 5 shell Helium model**




**Shell-by-Shell ordering**

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

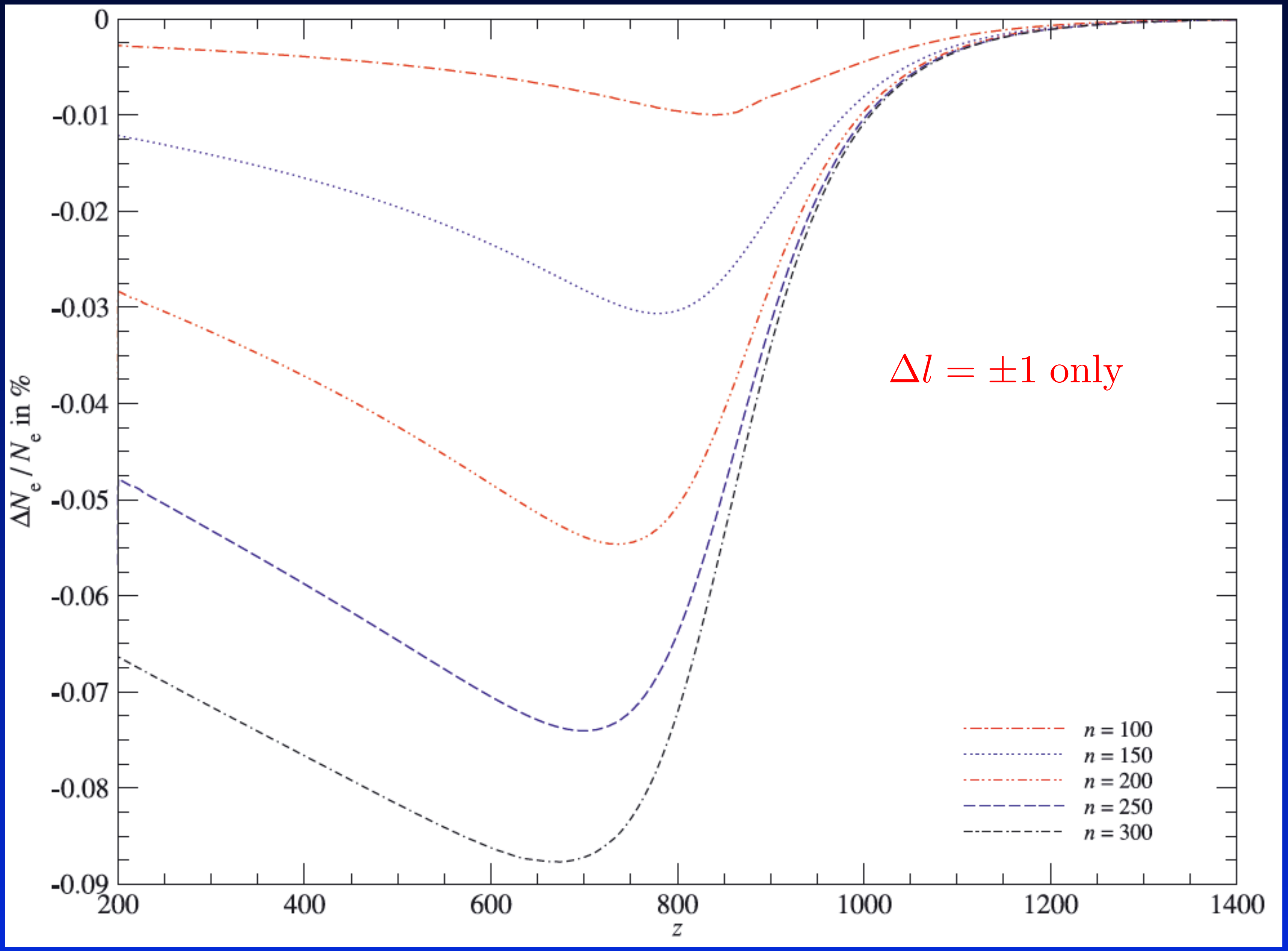



**Angular momentum ordering**

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

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

# Collisions during hydrogen recombination

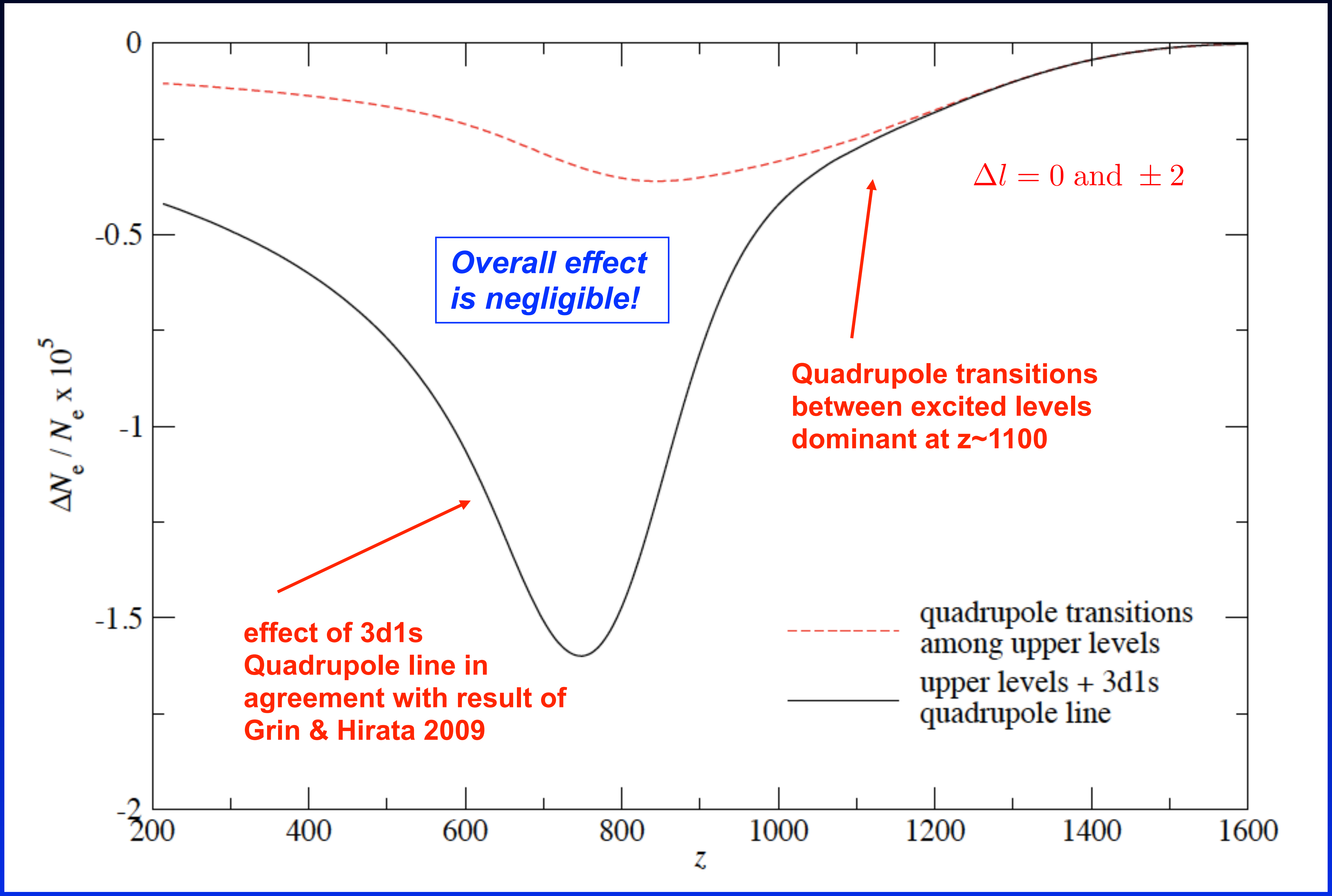



- **effective recombination cross section of the atom matters most at low *z***
- **collisions *increase* recombination rate**
- **effect on ionization history remains *small***
- ***uncertainties* in collision rates may change this by factors of a few**
- ***updated rates* (with large Δl) became available and effect remains negligible** (noticeable in recombination radiation though…)

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

**JC, Vasil & Dursi, MNRAS, 2010**

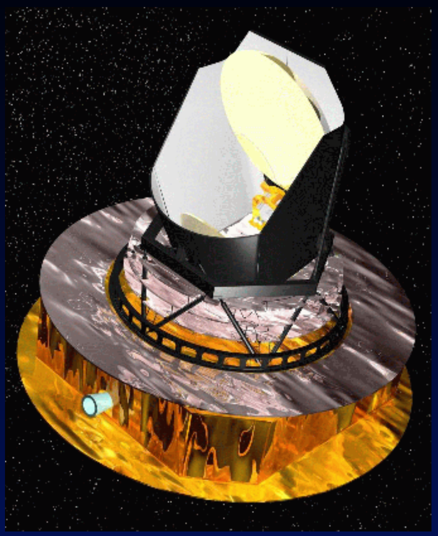
# Quadrupole lines during hydrogen recombination




CITA ICAT

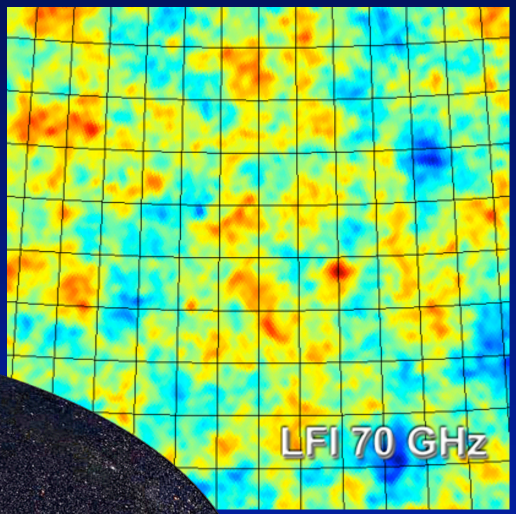
JC, Fung & Switzer, 2011

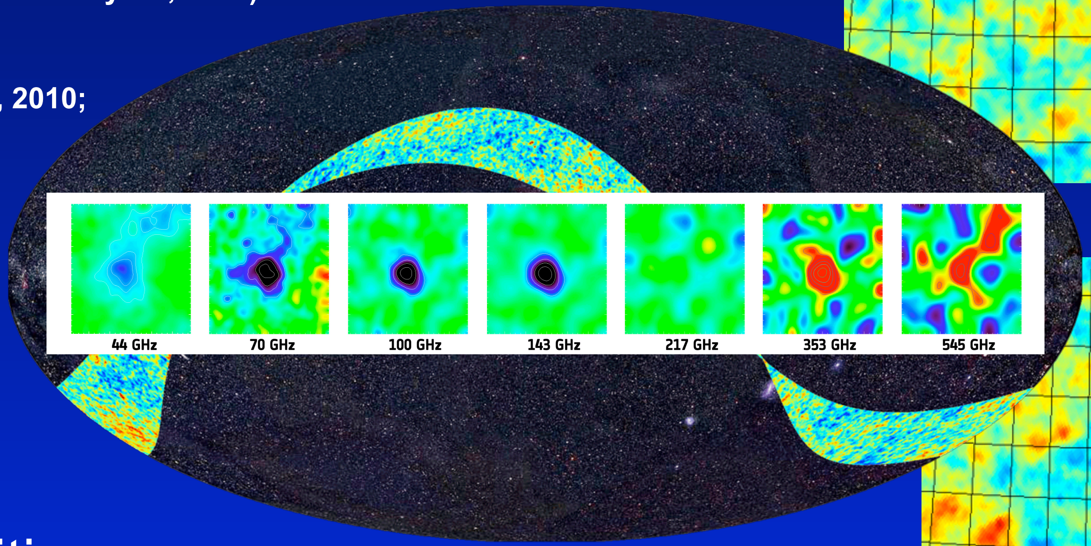
# Getting the job done for *Planck*



## Hydrogen recombination

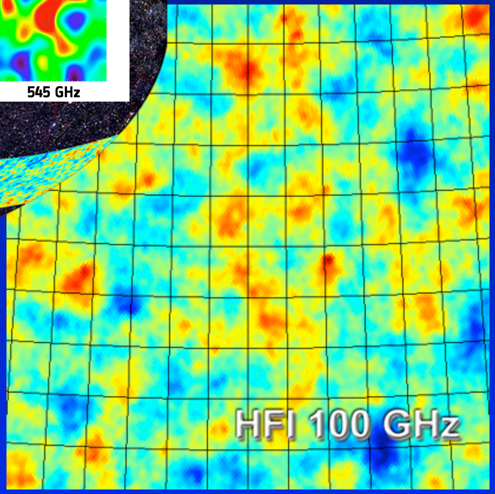
- Two-photon decays from higher levels
  **(Dubrovich & Grachev, 2005, Astr. Lett., 31, 359; Wong & Scott, 2007; JC & Sunyaev, 2007; Hirata, 2008; JC & Sunyaev 2009)**
- Induced 2s two-photon decay for hydrogen
  **(JC & Sunyaev, 2006, A&A, 446, 39; Hirata 2008)**
- Feedback of the Lyman-$\alpha$ distortion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



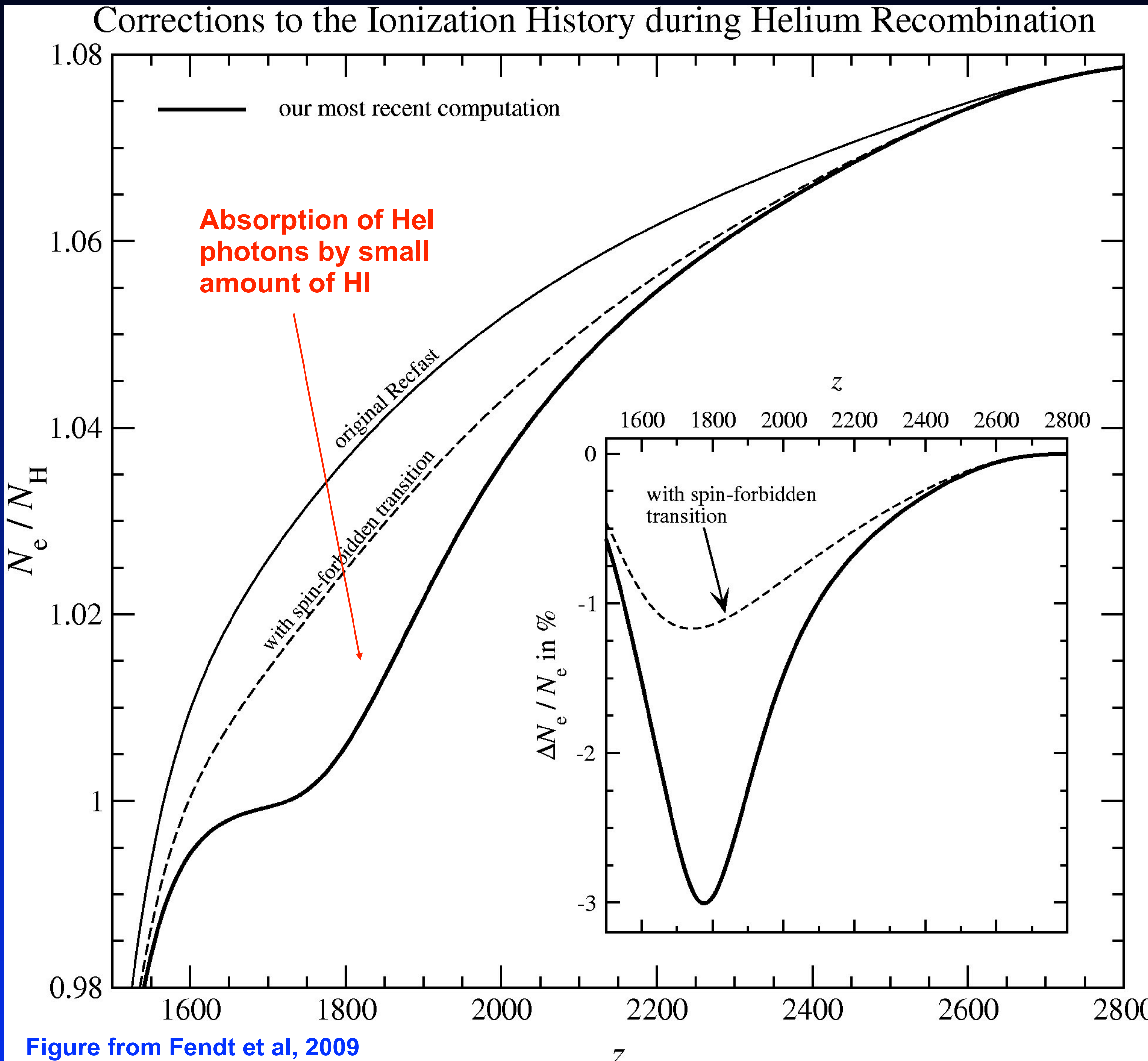

## Helium recombination

- 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)**




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

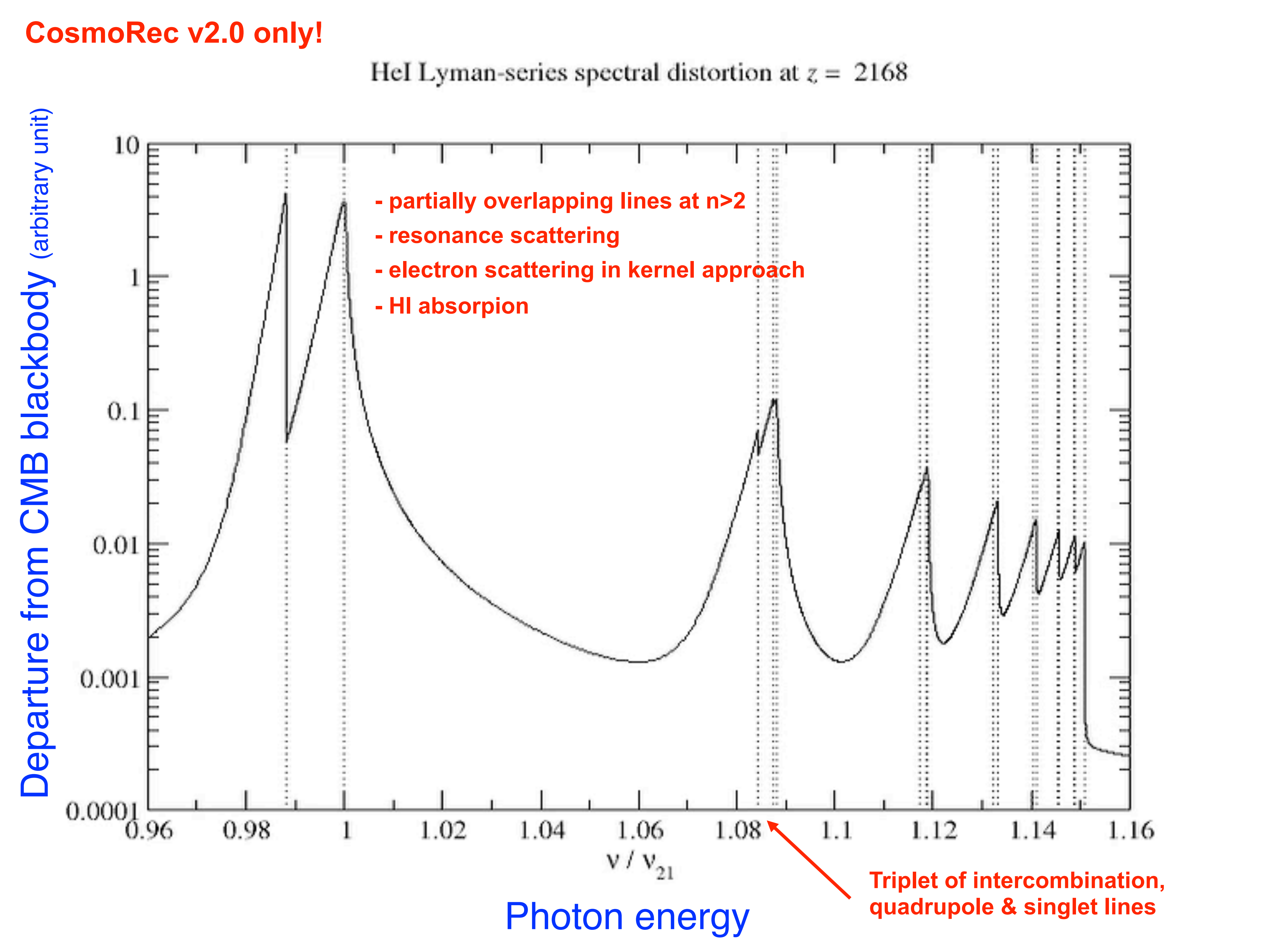
# Main corrections during HeI Recombination




Kholupenko et al, 2007
Switzer & Hirata, 2007

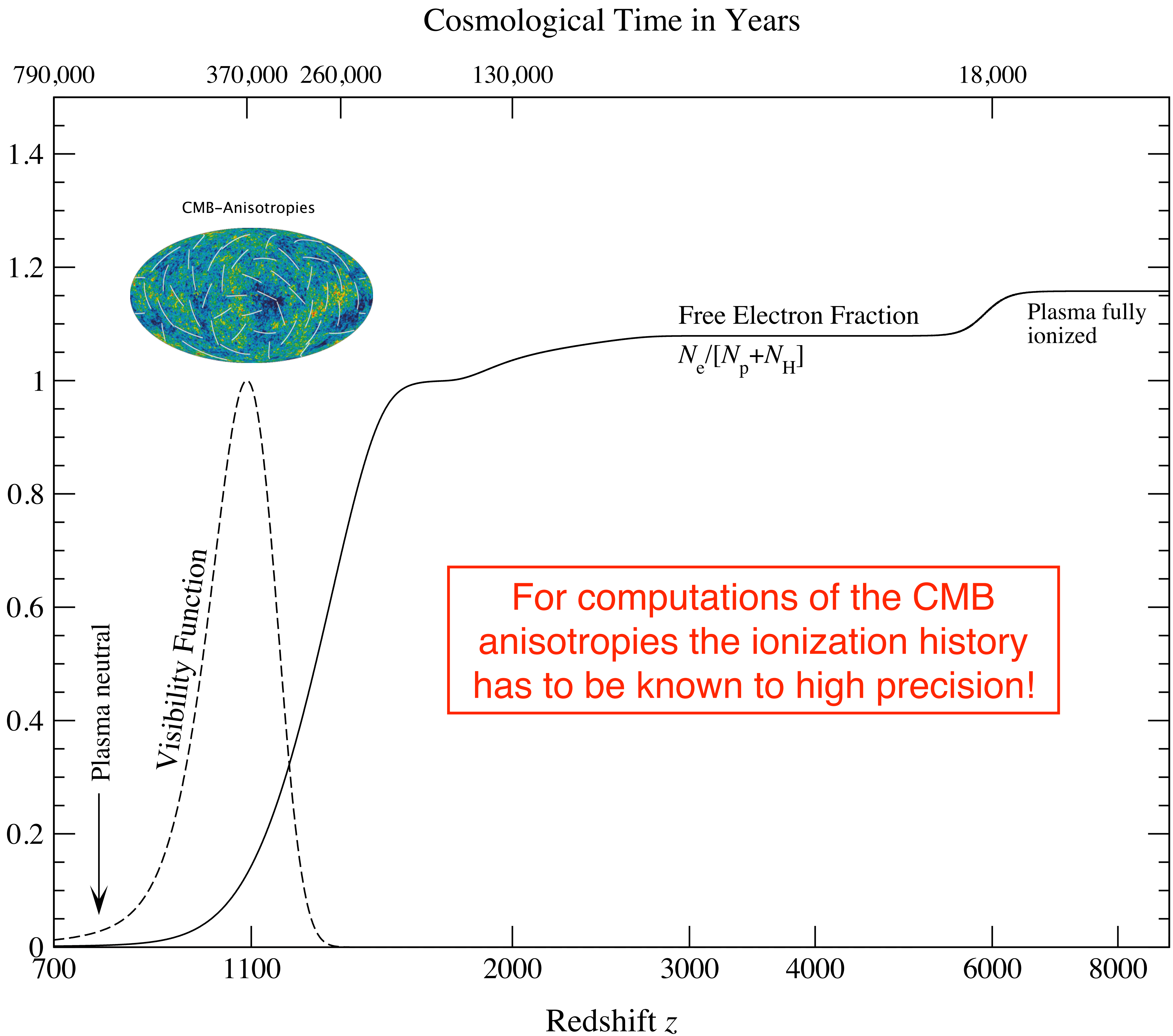
- Delayed neutral helium recombination was indeed one of the *Recfast* results
- Effect of HI absorption already mentioned in Hu et al. 1995 (priv. comm Peebles)
- Spin-forbidden HeI transition estimated in 1977 (Lin et al.)
- Luckily neutral helium recombination is not as crucial for Cl's…

# Evolution of the HeI high frequency distortion



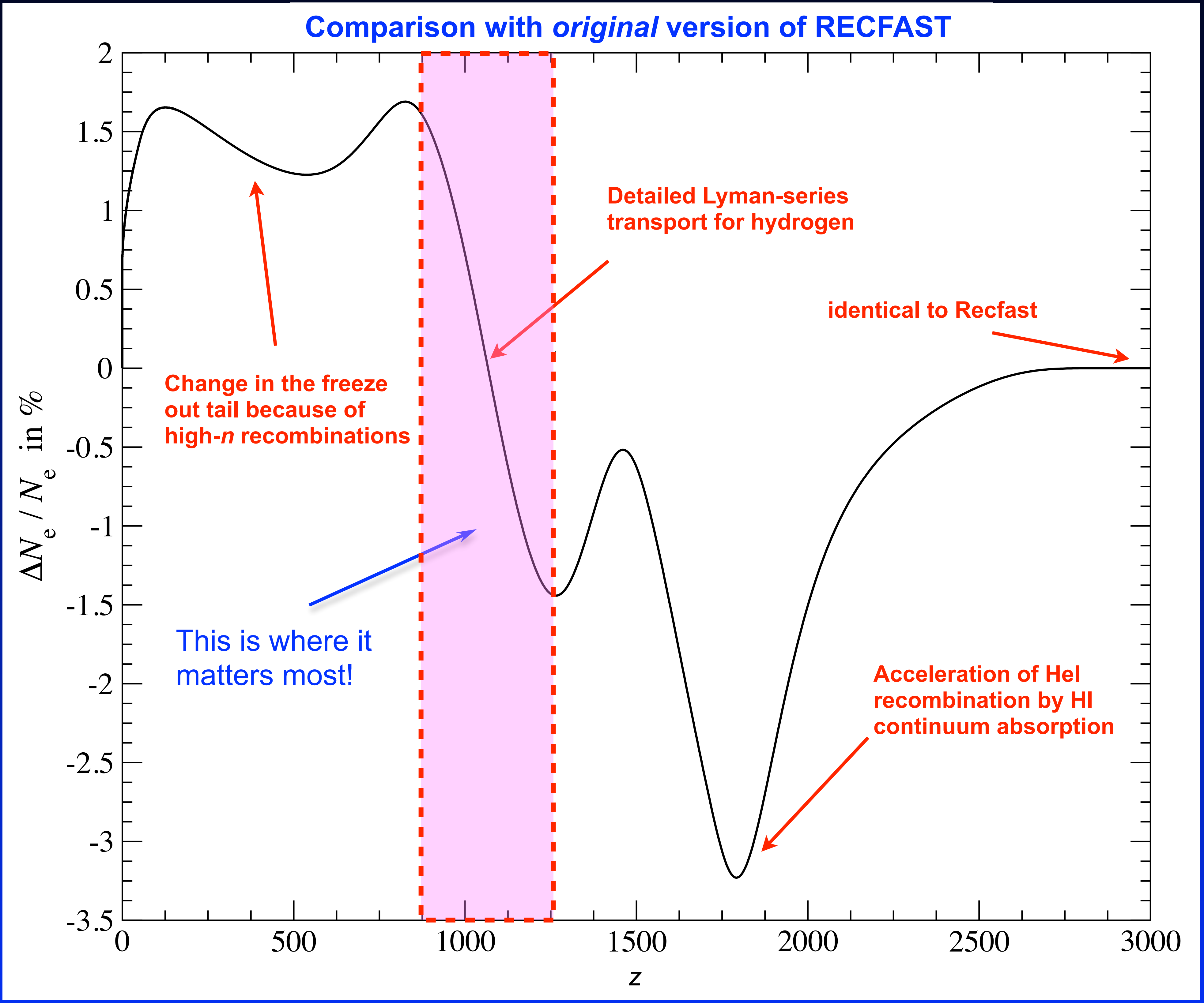

JC, Fung & Switzer, 2011

*So why is all this so important?*



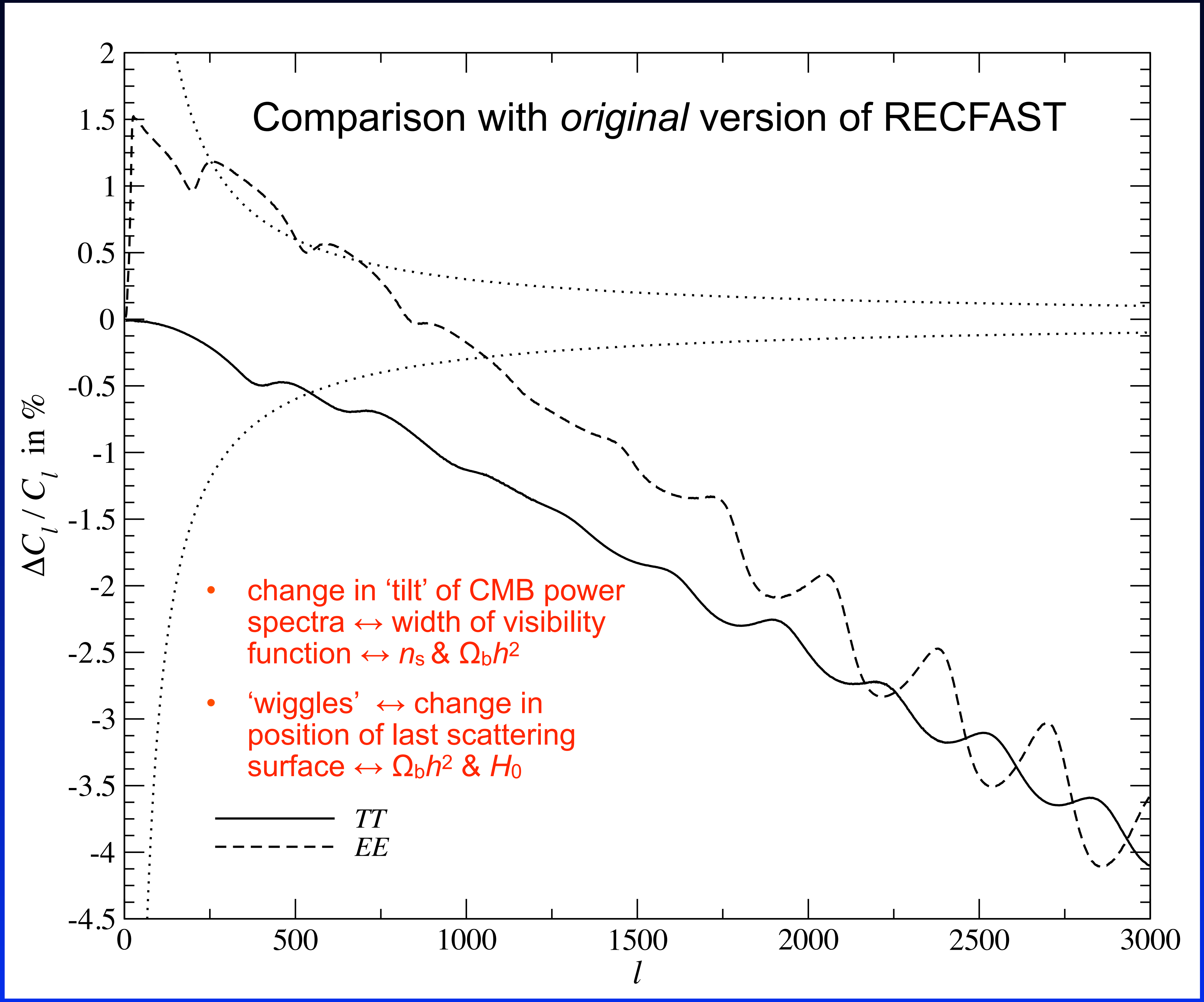
Cosmological Time in Years
790,000
370,000
260,000
130,000
18,000
1.4
1.2
1
0.8
0.6
0.4
0.2
0
CMB-Anisotropies
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully ionized
Visibility Function
Plasma neutral
For computations of the CMB anisotropies the ionization history has to be known to high precision!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

# Cumulative Changes to the Ionization History



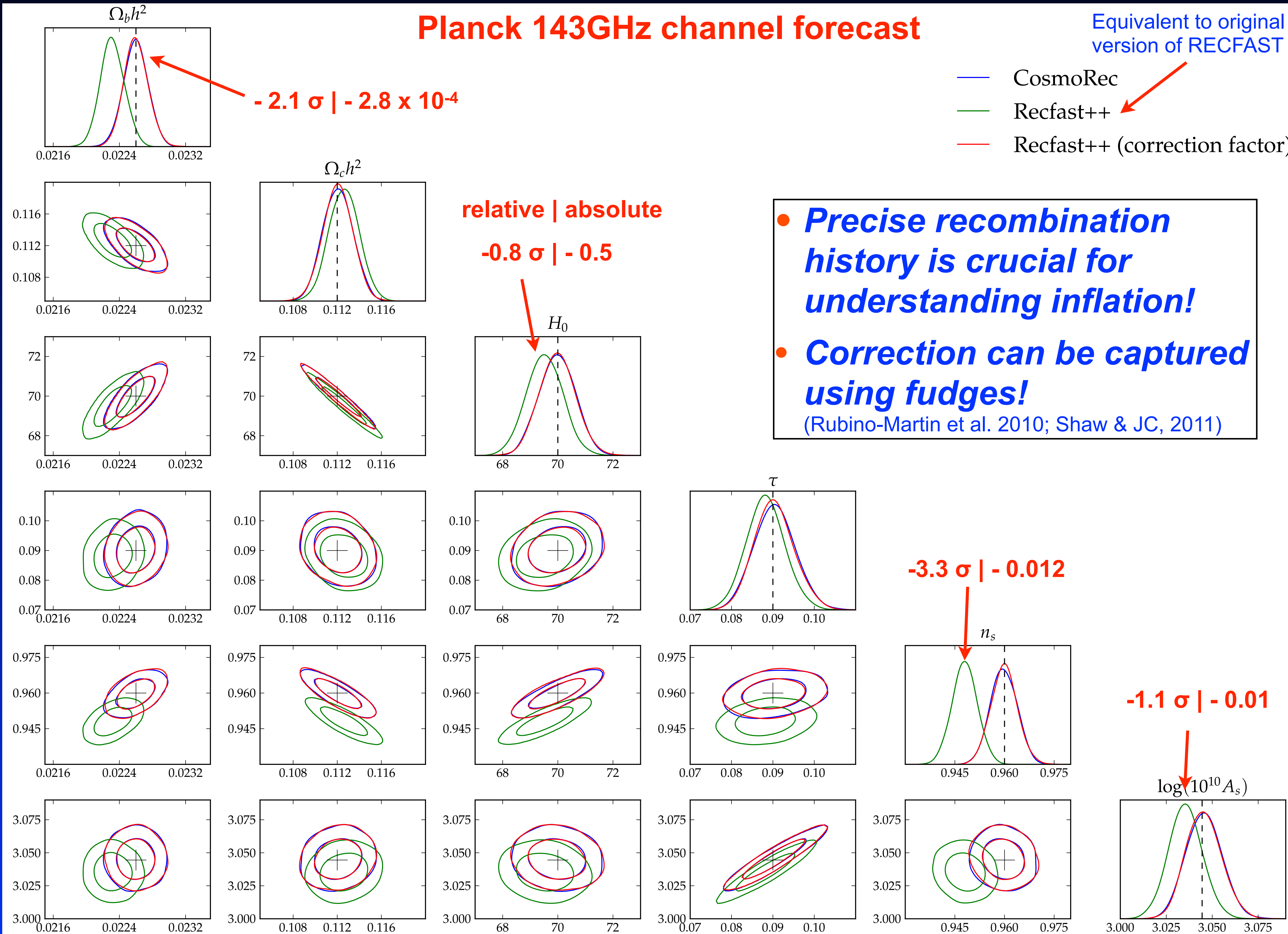

JC & Thomas, MNRAS, 2010; Shaw & JC, MNRAS, 2011

# Cumulative Change in the CMB Power Spectra




Shaw & JC, MNRAS, 2011

# Importance of recombination for *Planck*

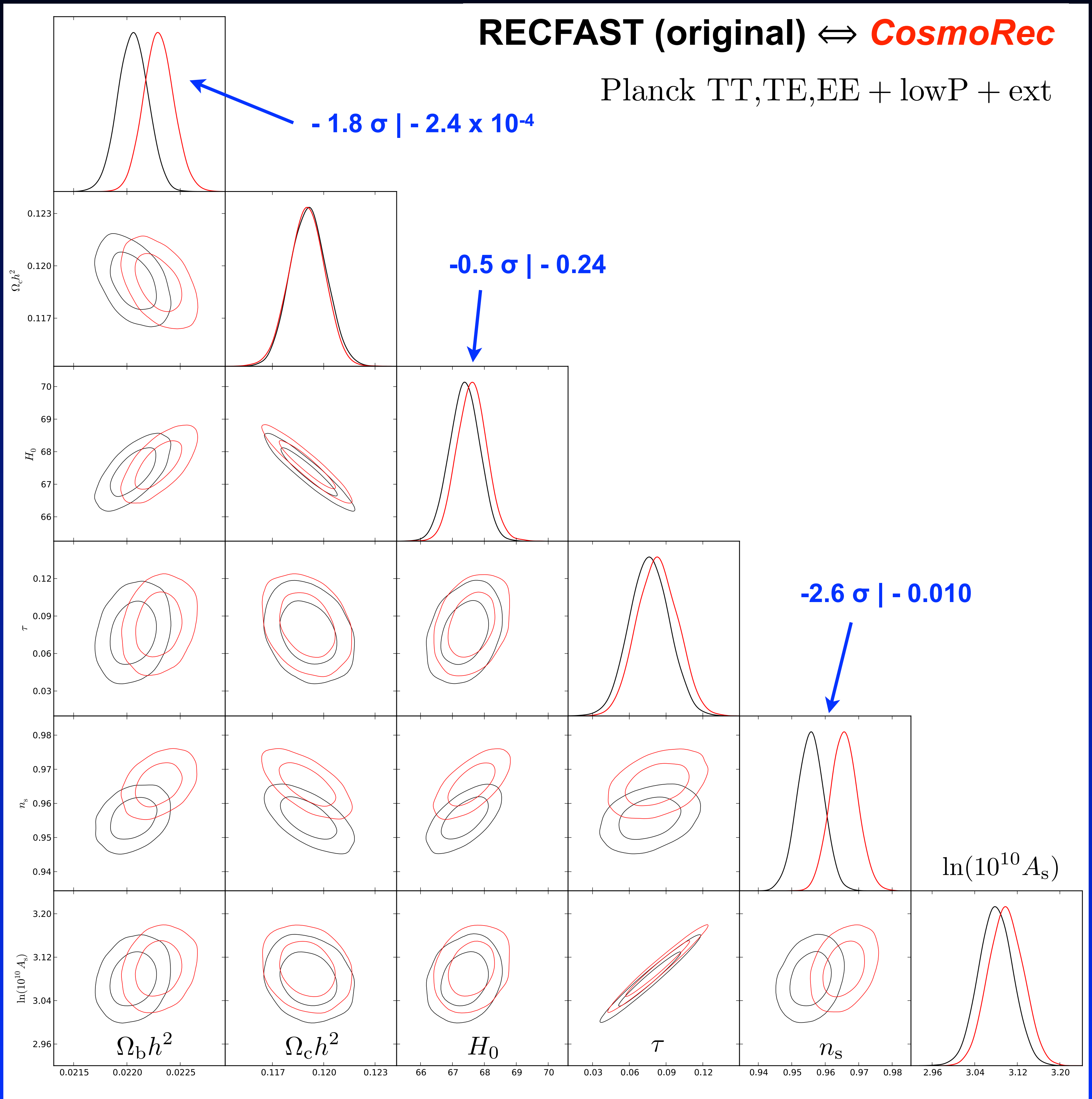



- ***Precise recombination history is crucial for understanding inflation!***
- ***Correction can be captured using fudges!***

(Rubino-Martin et al. 2010; Shaw & JC, 2011)

CITA ICAT Shaw & JC, 2011, and references therein

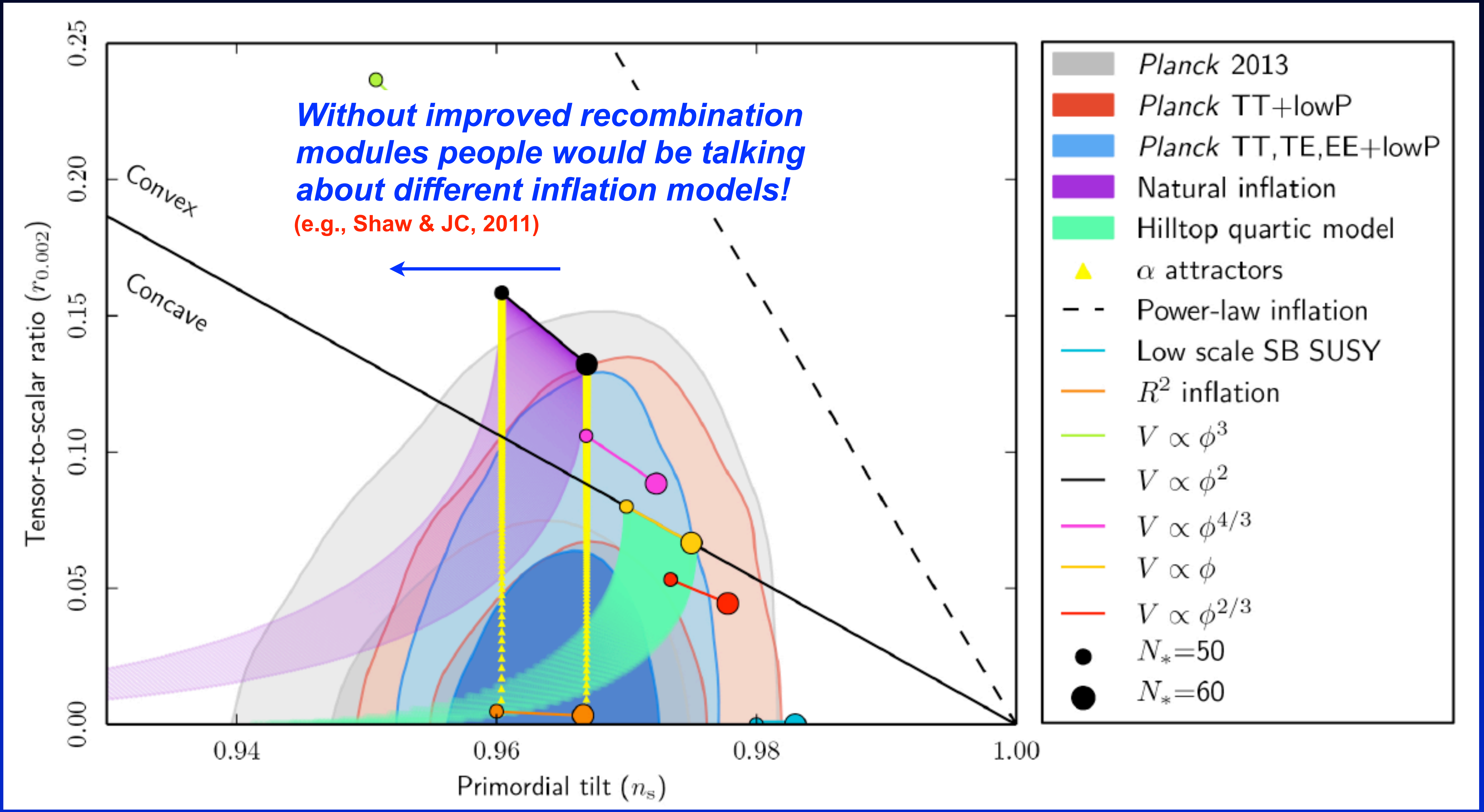
# Biases as they *would* have been for *Planck* 15




- Biases a little less significant with real *Planck* 2015 data
- absolute biases very similar to earlier estimates
- In particular $n_s$ would be biased significantly

Planck Collaboration, XIII 2015

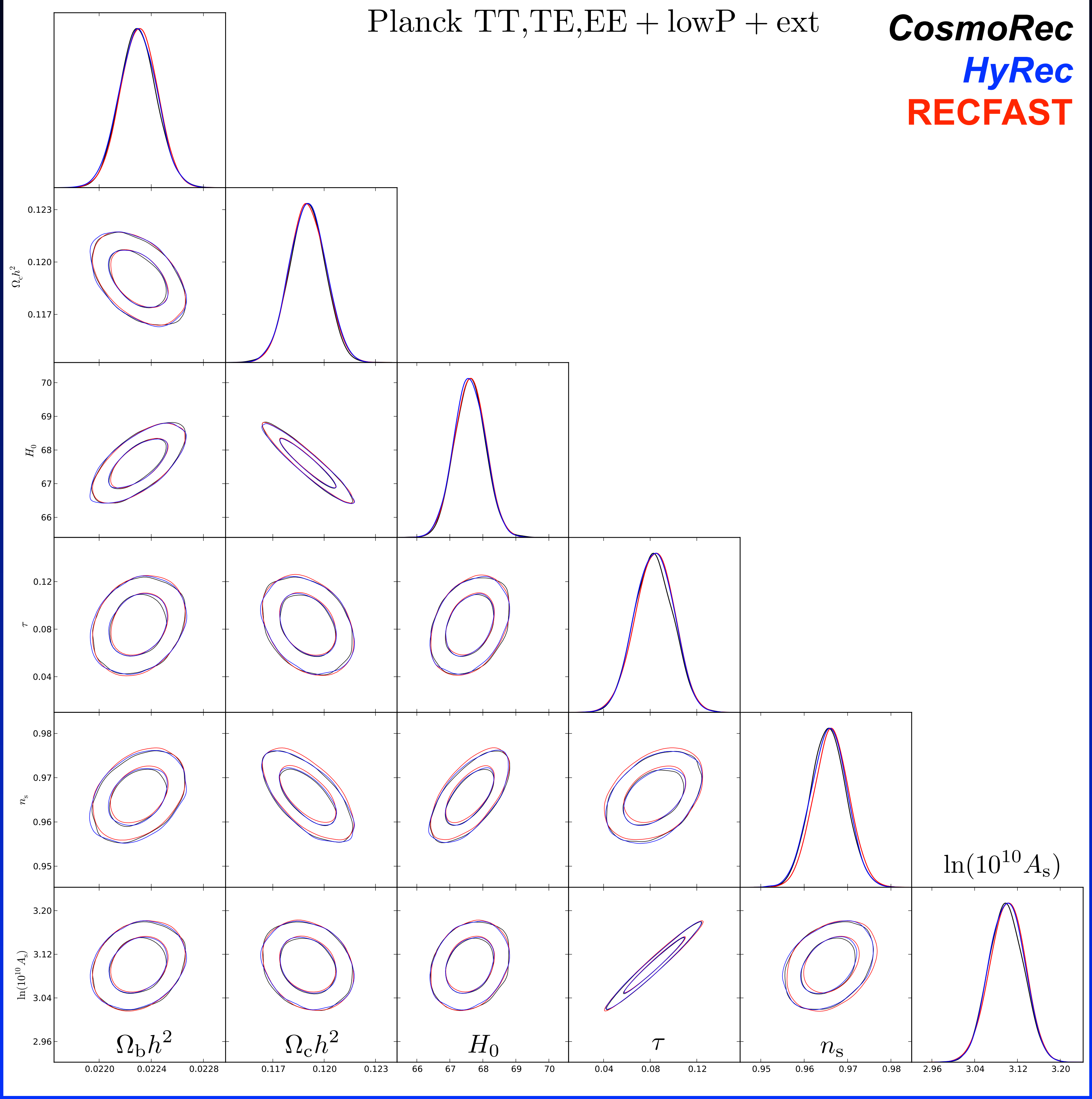
# Importance of recombination for inflation constraints




Planck Collaboration, 2015, paper XX

- Analysis uses refined recombination model (CosmoRec/HyRec)

# Differences for current recombination codes




- Different codes agree very well!
- largest biases

  $\Delta n_s \approx 0.15\sigma$

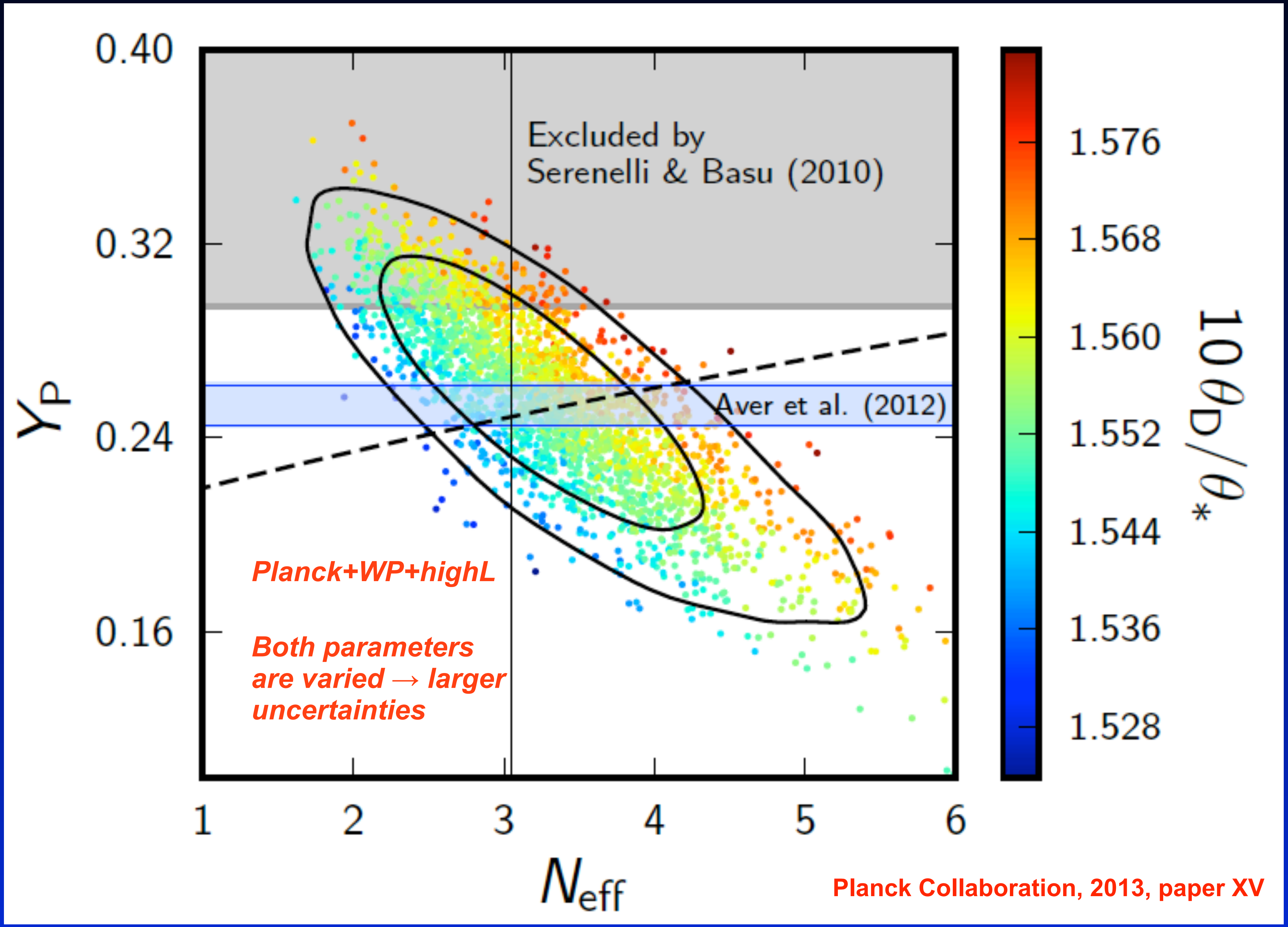
  (*CosmoRec* ⟺ RECFAST)

  $\Delta n_s \approx 0.03\sigma$

  (*CosmoRec* ⟺ *HyRec*)
- Nothing to worry about at this point!

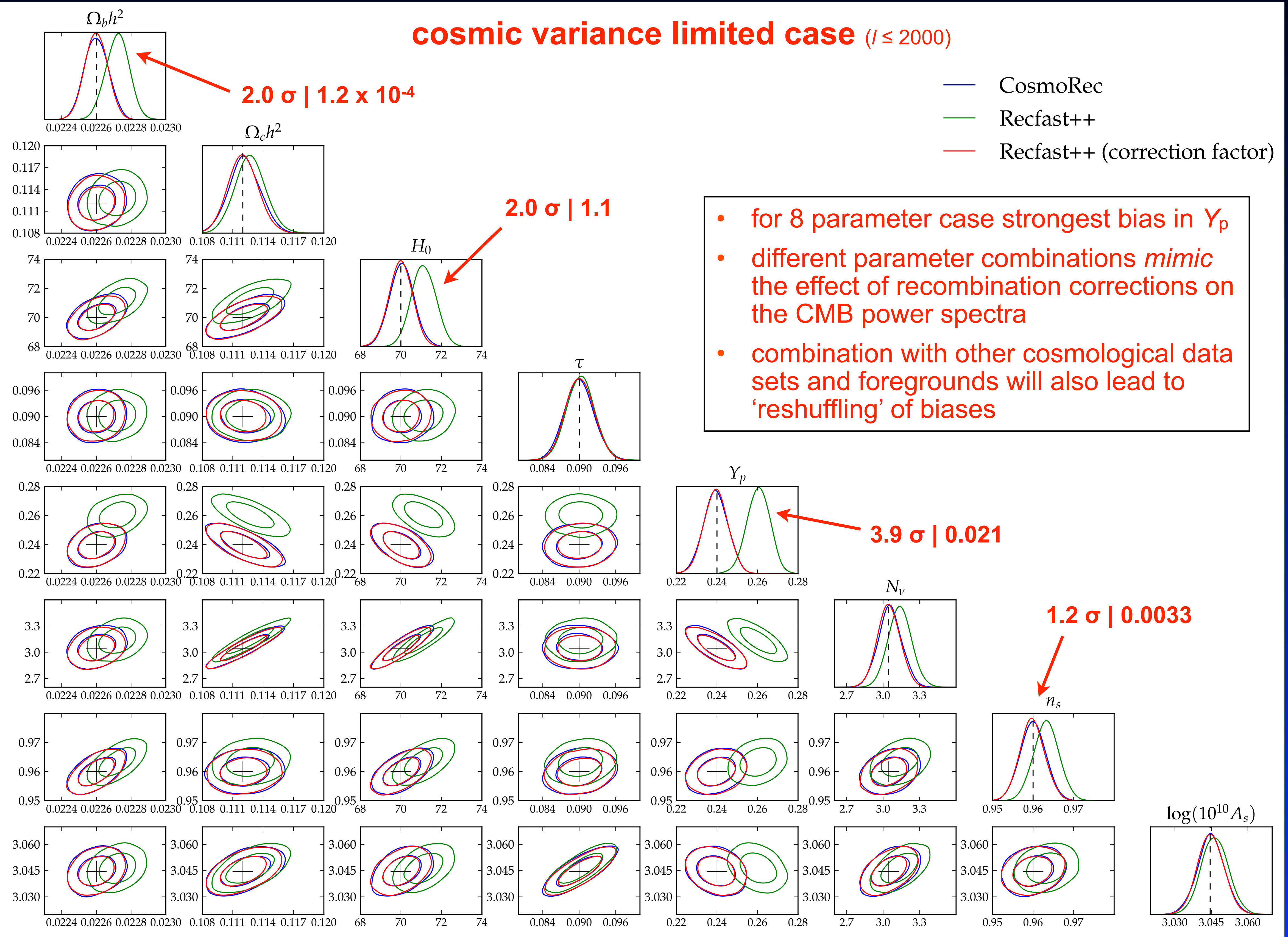
Planck Collaboration, XIII 2015

# 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*

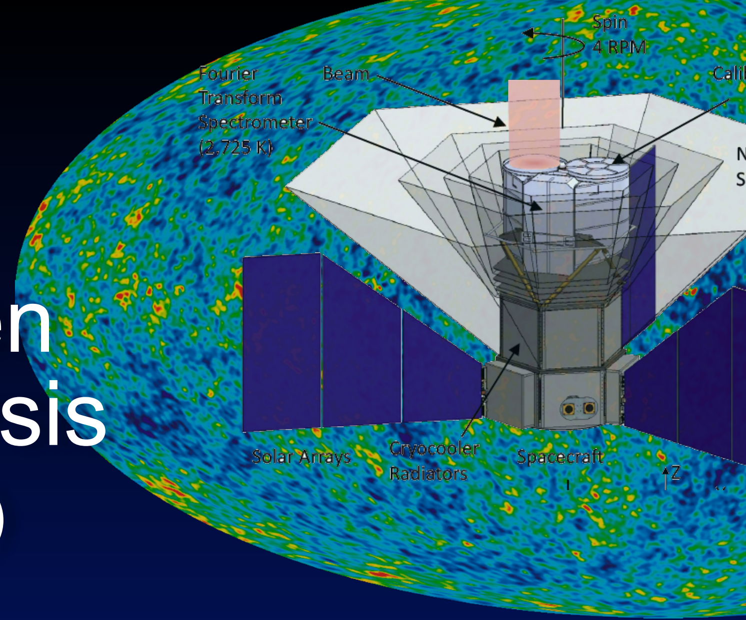
# Importance of recombination for measuring helium




- 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

CITA ICAT Shaw & JC, 2011, and references therein

# 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!
  (most of them were not in *Planck*…)
- Without the improvements over the original version of Recfast cosmological parameters derived from *Planck* would be *biased* significantly
- In particular the conclusions about *inflation* models would have been affected
- Cosmological recombination radiation allows us to directly *constrain* the *recombination history*
  (*more tomorrow…*)