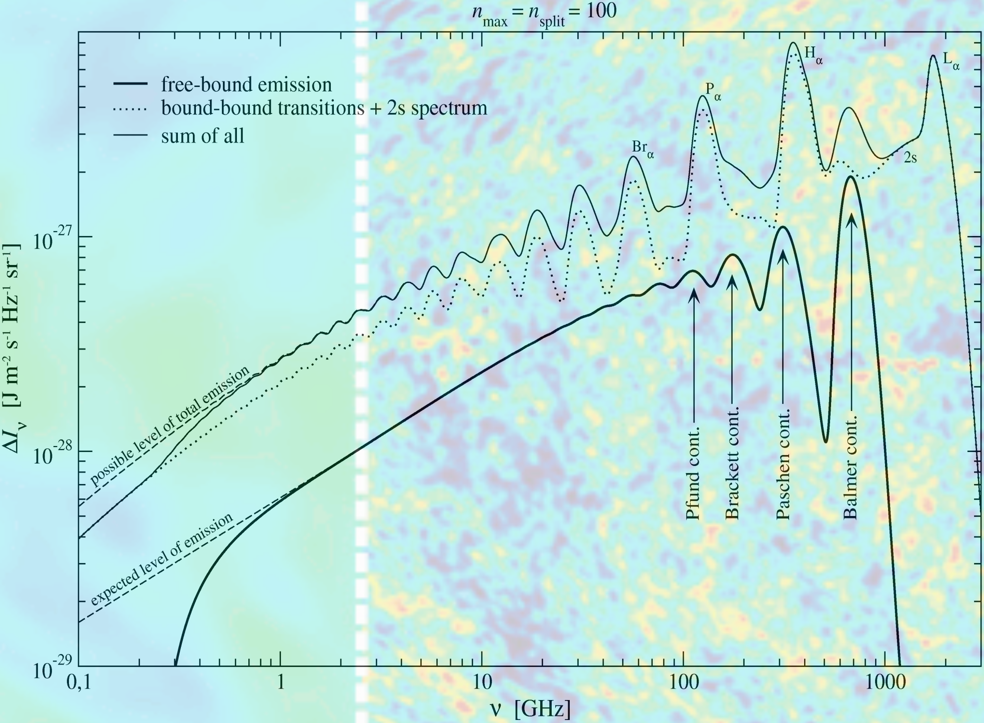
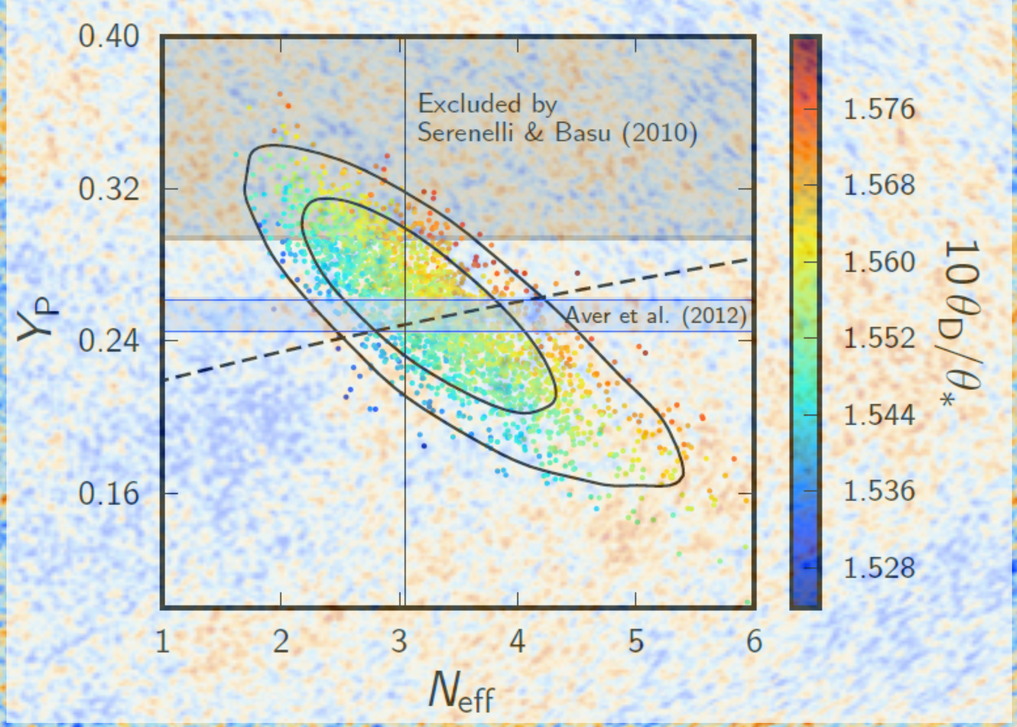
Recombination Physics and What this has to do with Cosmology and Particle Physics





JOHNS HOPKINS
UNIVERSITY

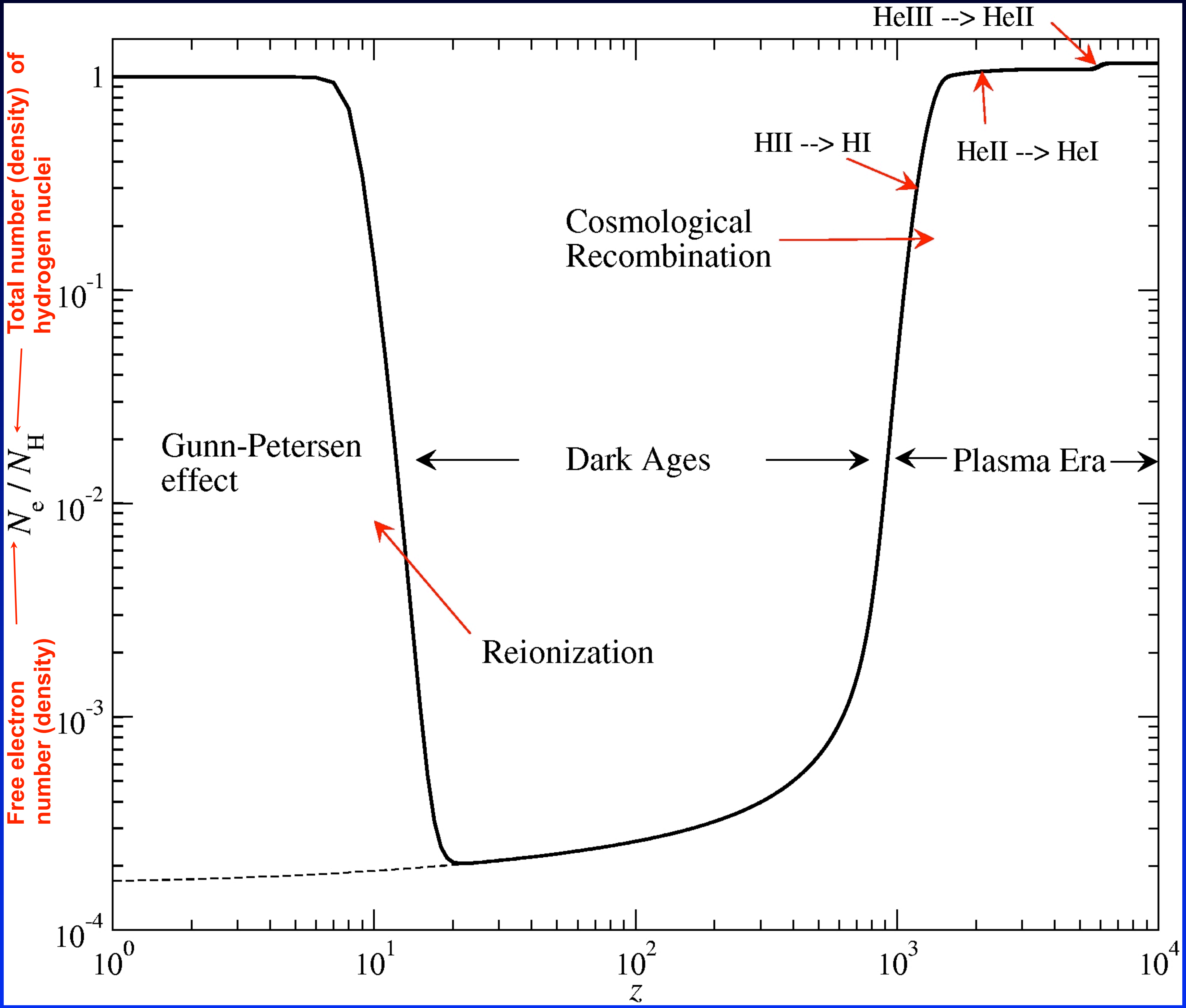
Jens Chluba

School on Cosmological Tools

Madrid, Spain, Nov 12th - 15th, 2013

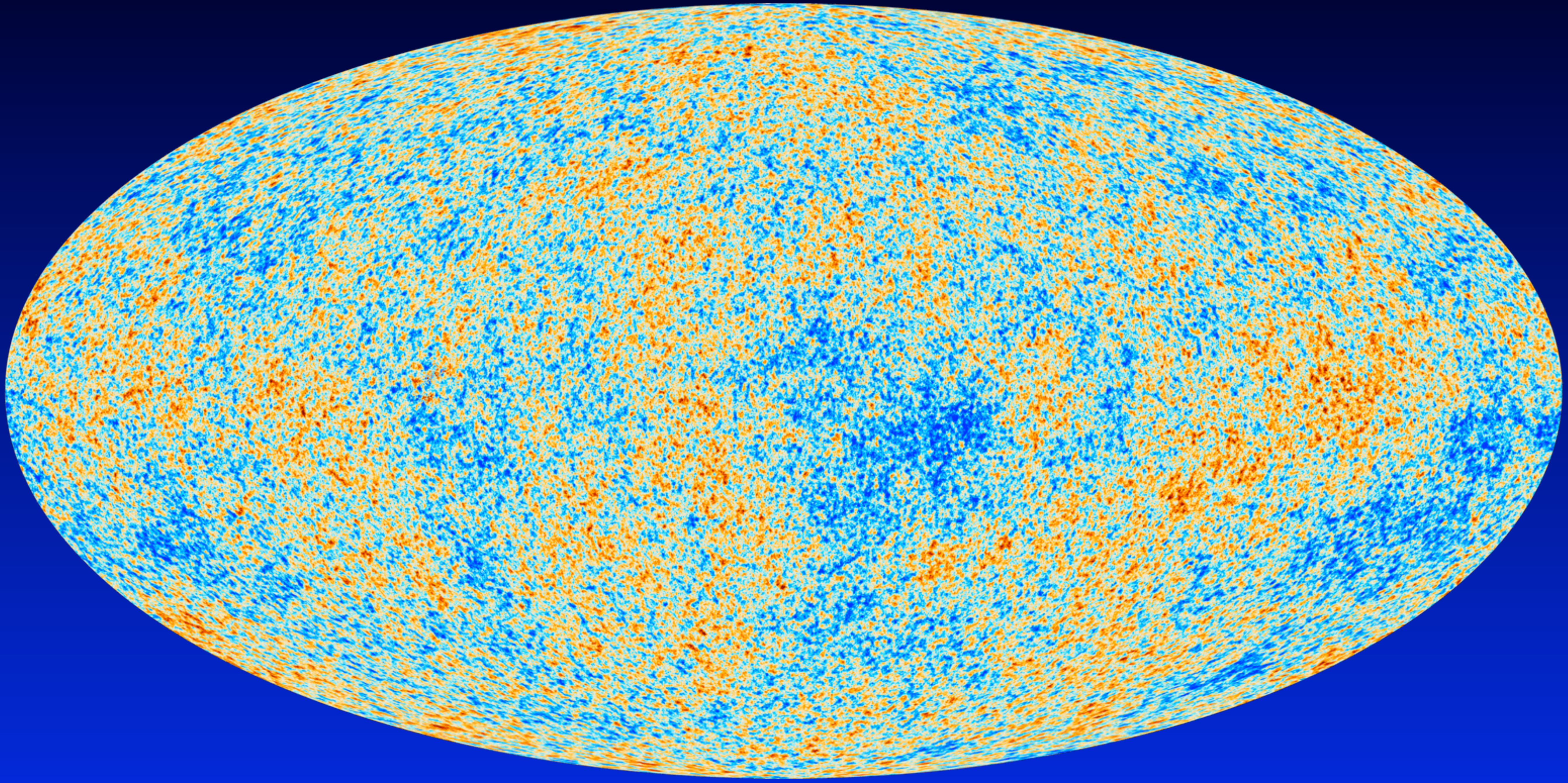
CITA ICAT
Canadian Institute for Theoretical Astrophysics
L'institut canadien d'astrophysique theorique

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**

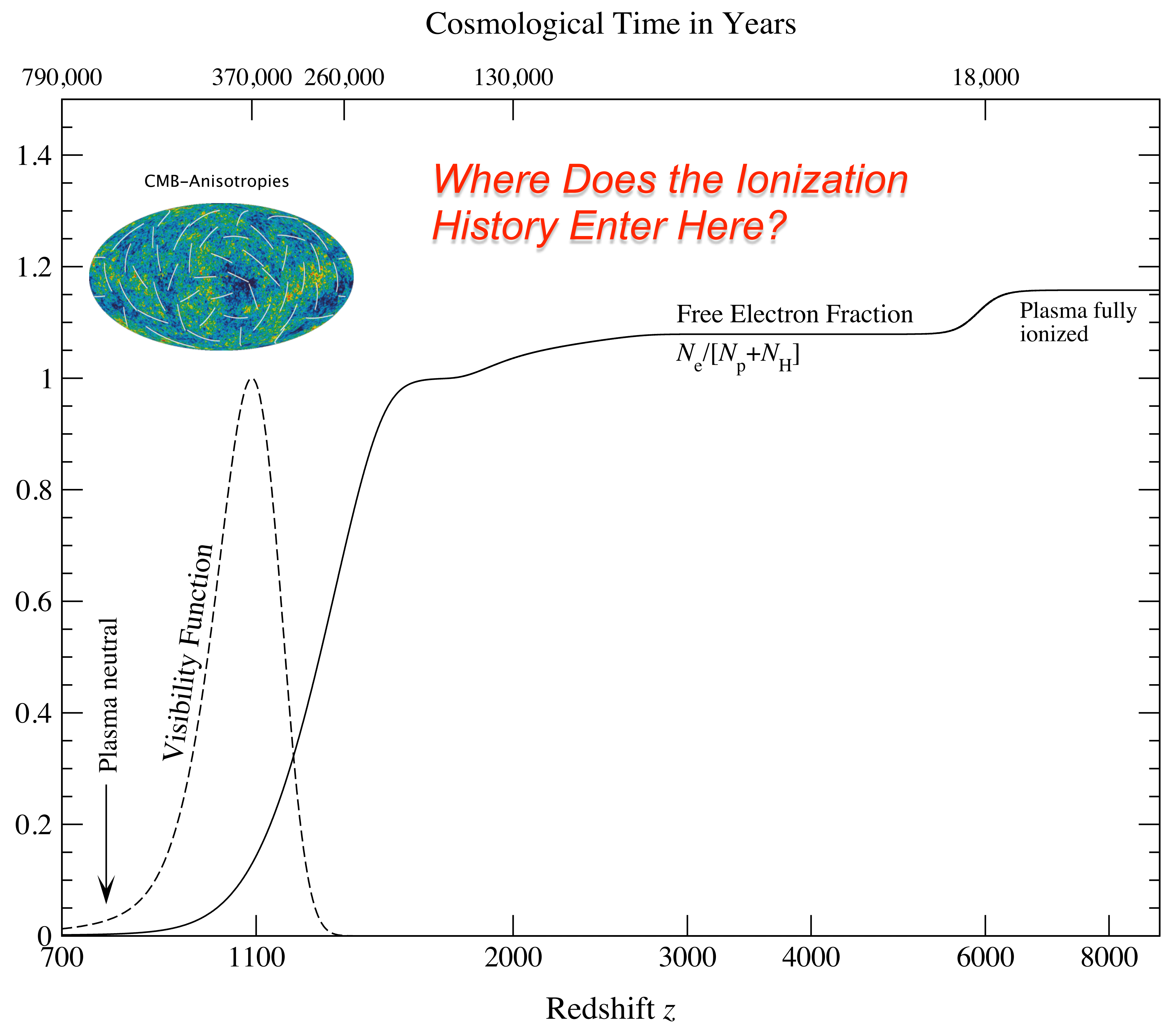
Cosmic Microwave Background Anisotropies



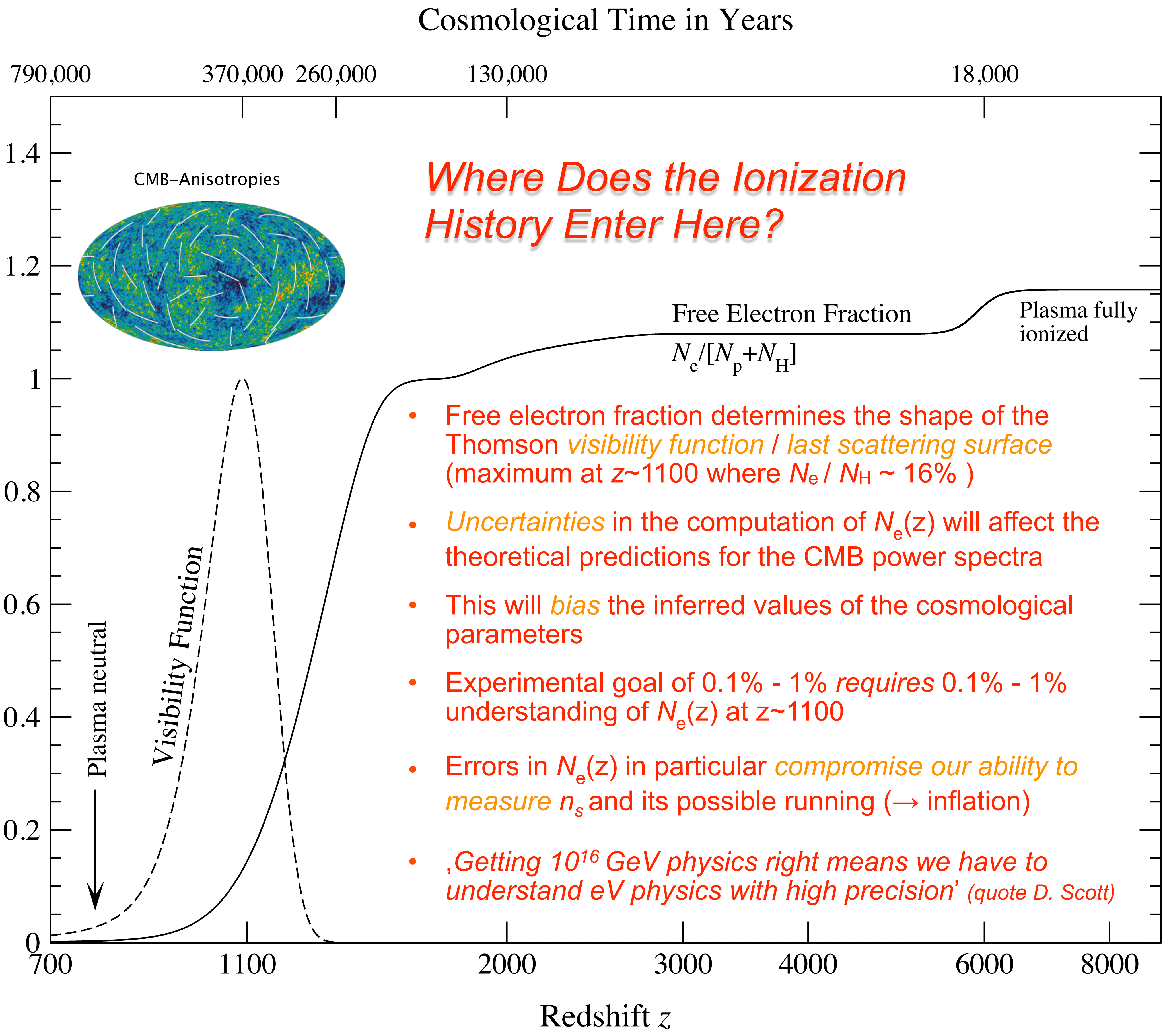
Planck all sky map

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

Where Does the Ionization History Enter Here?



Where Does the Ionization History Enter Here?

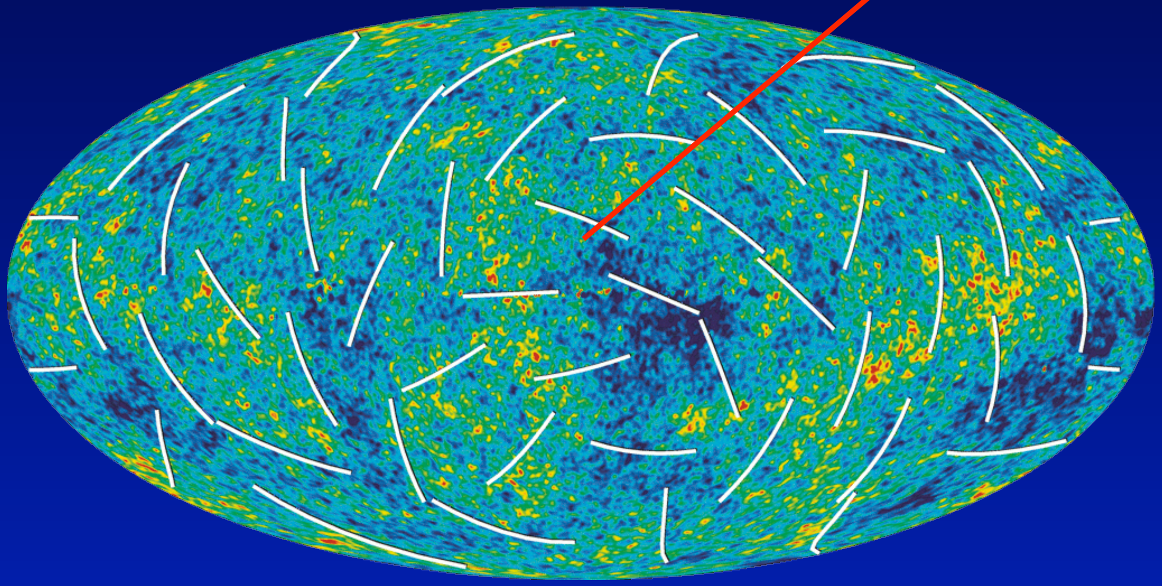


- Free electron fraction determines the shape of the Thomson *visibility function* / *last scattering surface* (maximum at z~1100 where N_e / N_H ~ 16%)
- *Uncertainties* in the computation of N_e(z) will affect the theoretical predictions for the CMB power spectra
- This will *bias* the inferred values 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)*

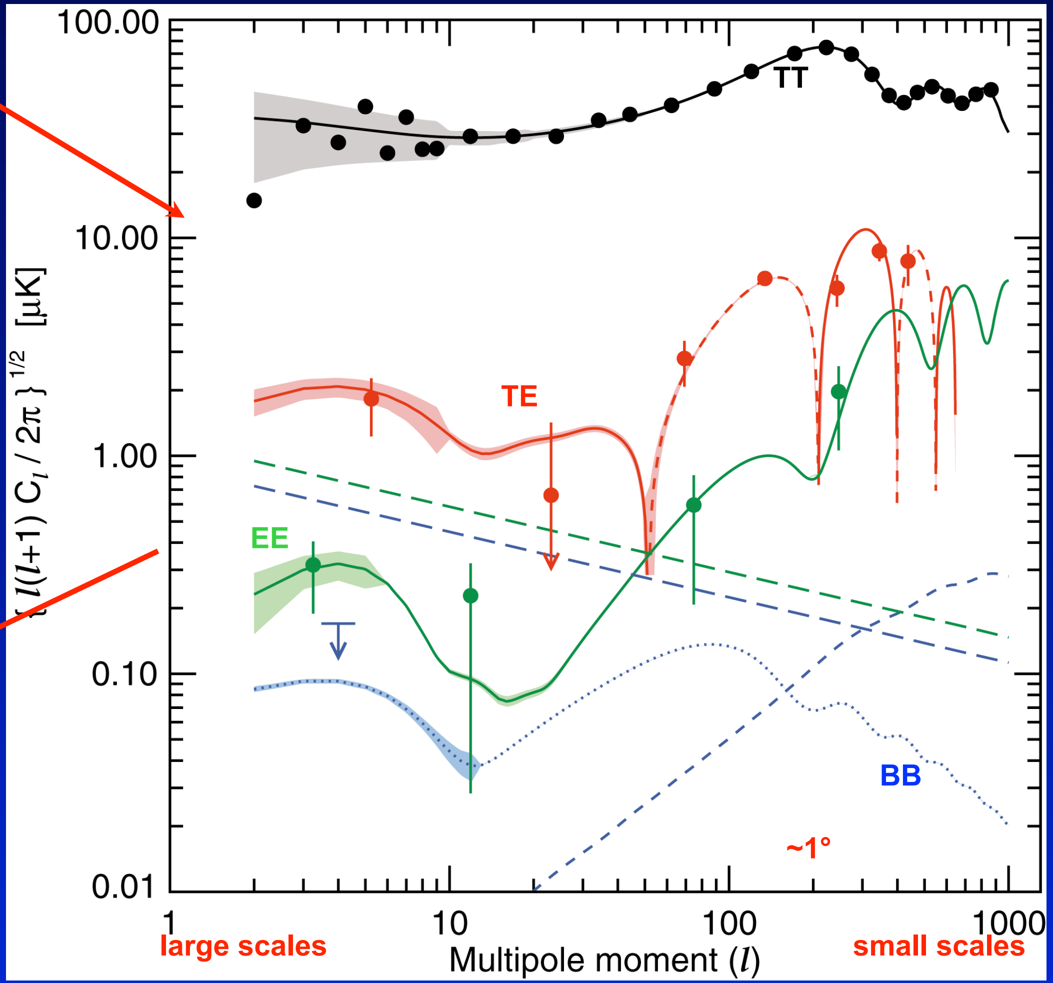
CMB Sky → Cosmology

a_{lm}

WMAP CMB Sky



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/ BAO, Lyman-α forest, lensing, ...

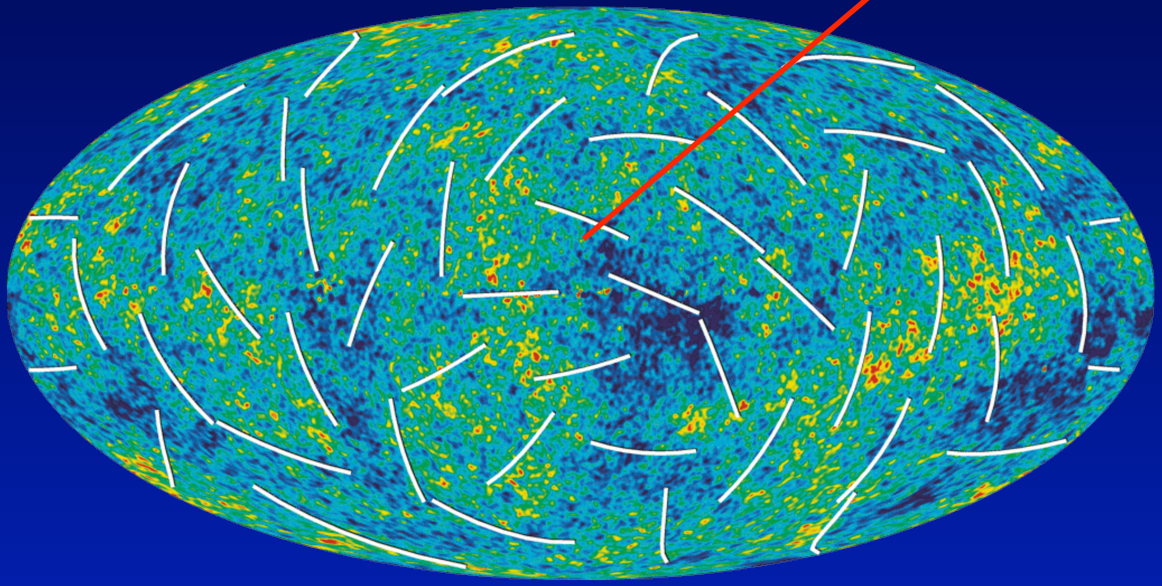
CMB Sky → Cosmology

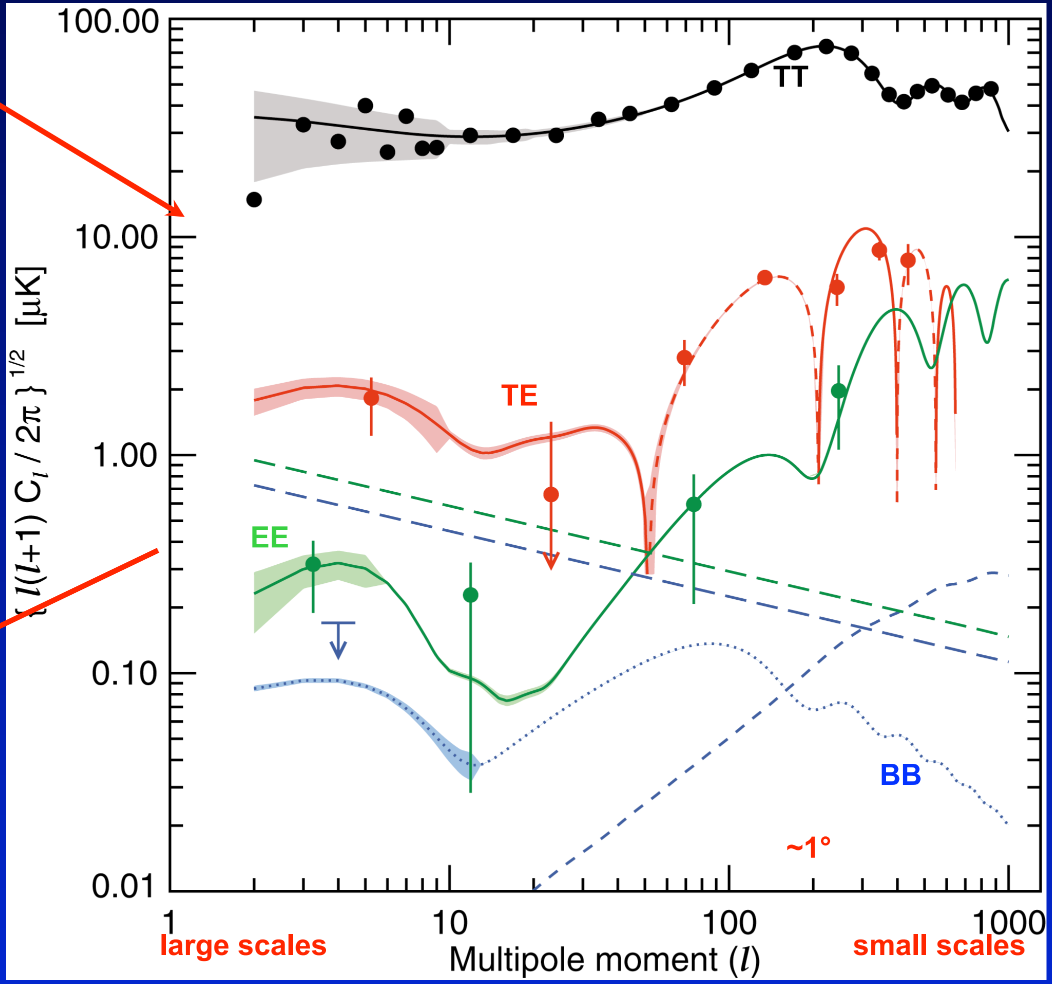
***$N_e(z)$* is a *crucial* input**

a_{lm}

Power spectra

WMAP CMB Sky





(Joint) analysis

Cosmological Parameters

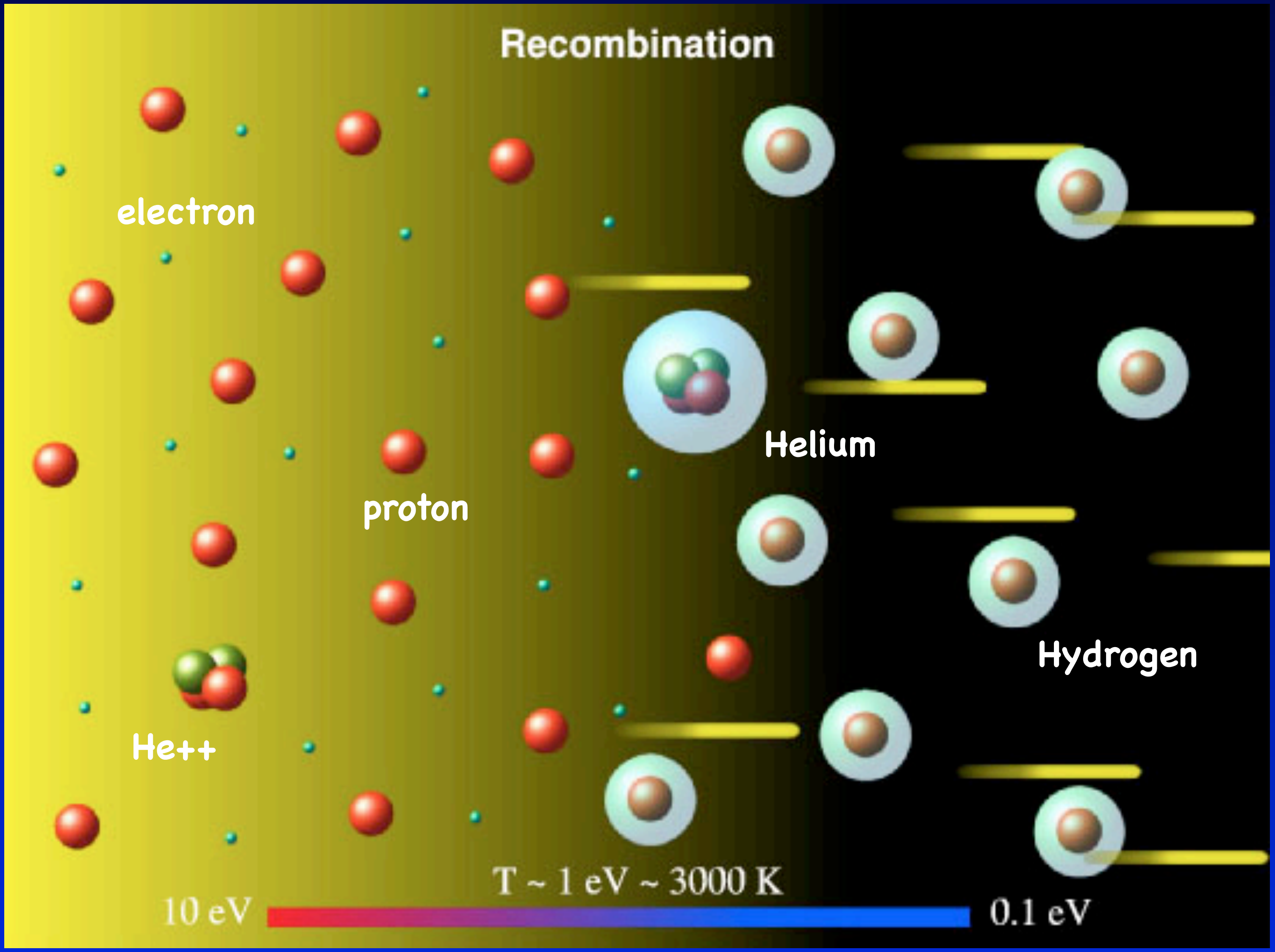
Ω_{tot}, Ω_m, Ω_b, Ω_Λ, h, τ, n_s,...

Other cosmological Dataset:

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

How does cosmological recombination work?

What is the recombination problem about?

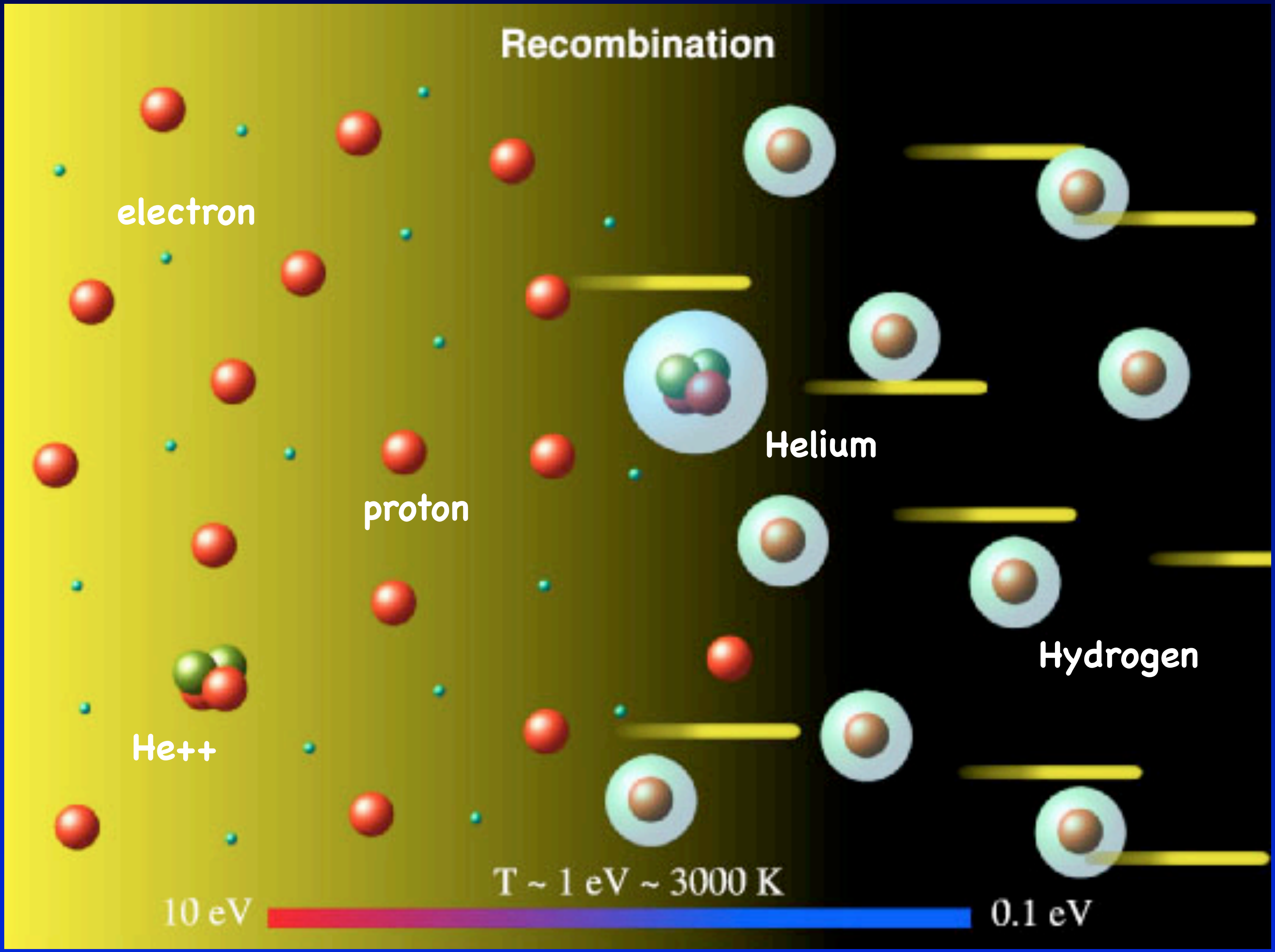


- coupled system describing the interaction of *matter* with the ambient CMB *photon* field
- atoms can be in different excitation states

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

  $\Longrightarrow$ *radiative transfer problem*

What is the recombination problem about?



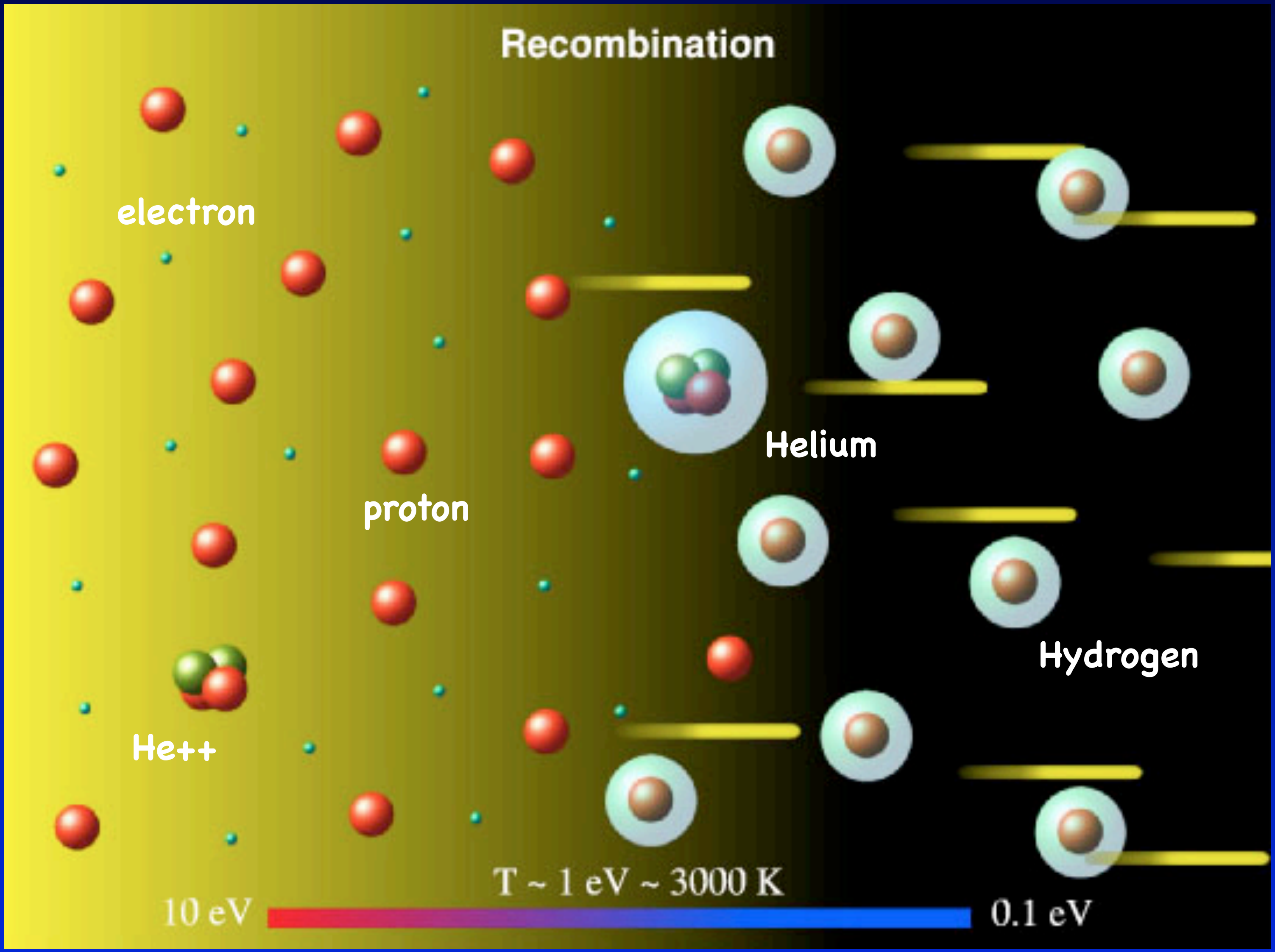
- coupled system describing the interaction of *matter* with the ambient CMB *photon* field
- atoms can be in different excitation states

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

  $\Longrightarrow$ *radiative transfer problem*

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

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

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

  $\Longrightarrow$ *radiative transfer problem*

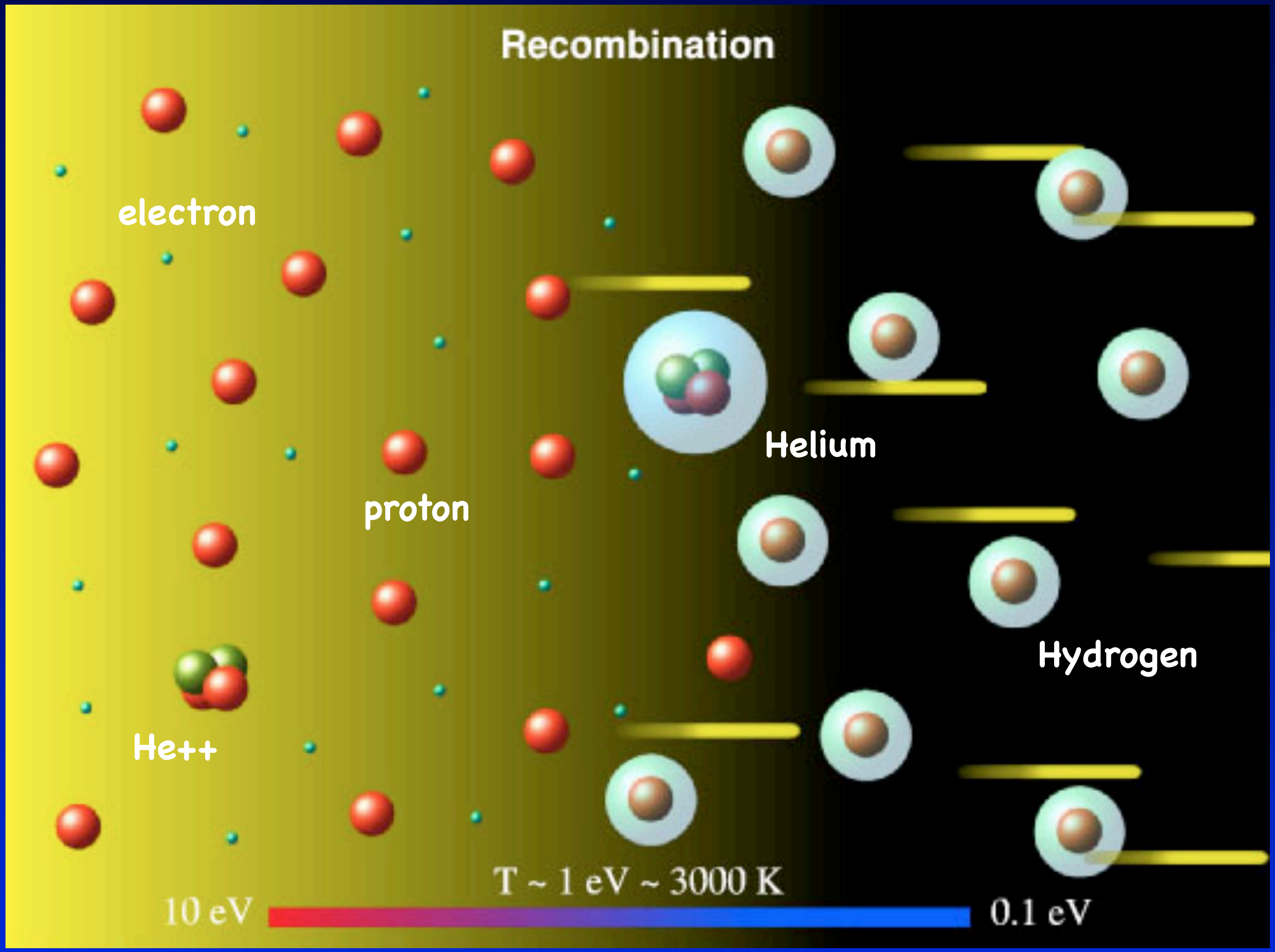
electron temperature

Have to follow evolution of: $N_\mathrm{e}, T_\mathrm{e}, N_\mathrm{p}, N_i \text{ and } \Delta I_\nu$

number densities

non-thermal photons

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

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

  $\Longrightarrow$ *radiative transfer problem*

electron temperature

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

number densities

non-thermal photons

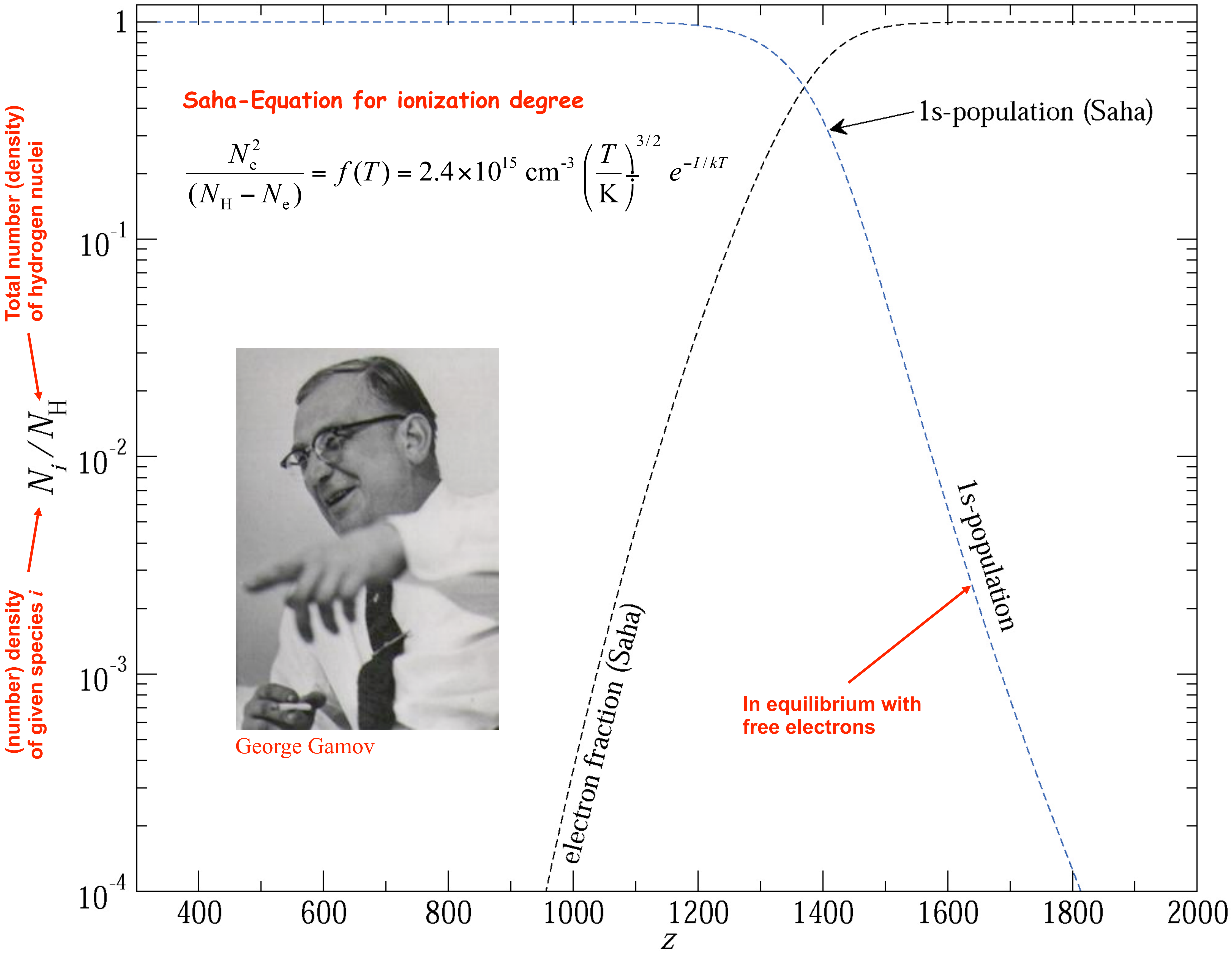
Only problem in time!

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* $h\nu_\alpha \sim 40\,kT_\gamma \iff T_\gamma \sim 0.26$ 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

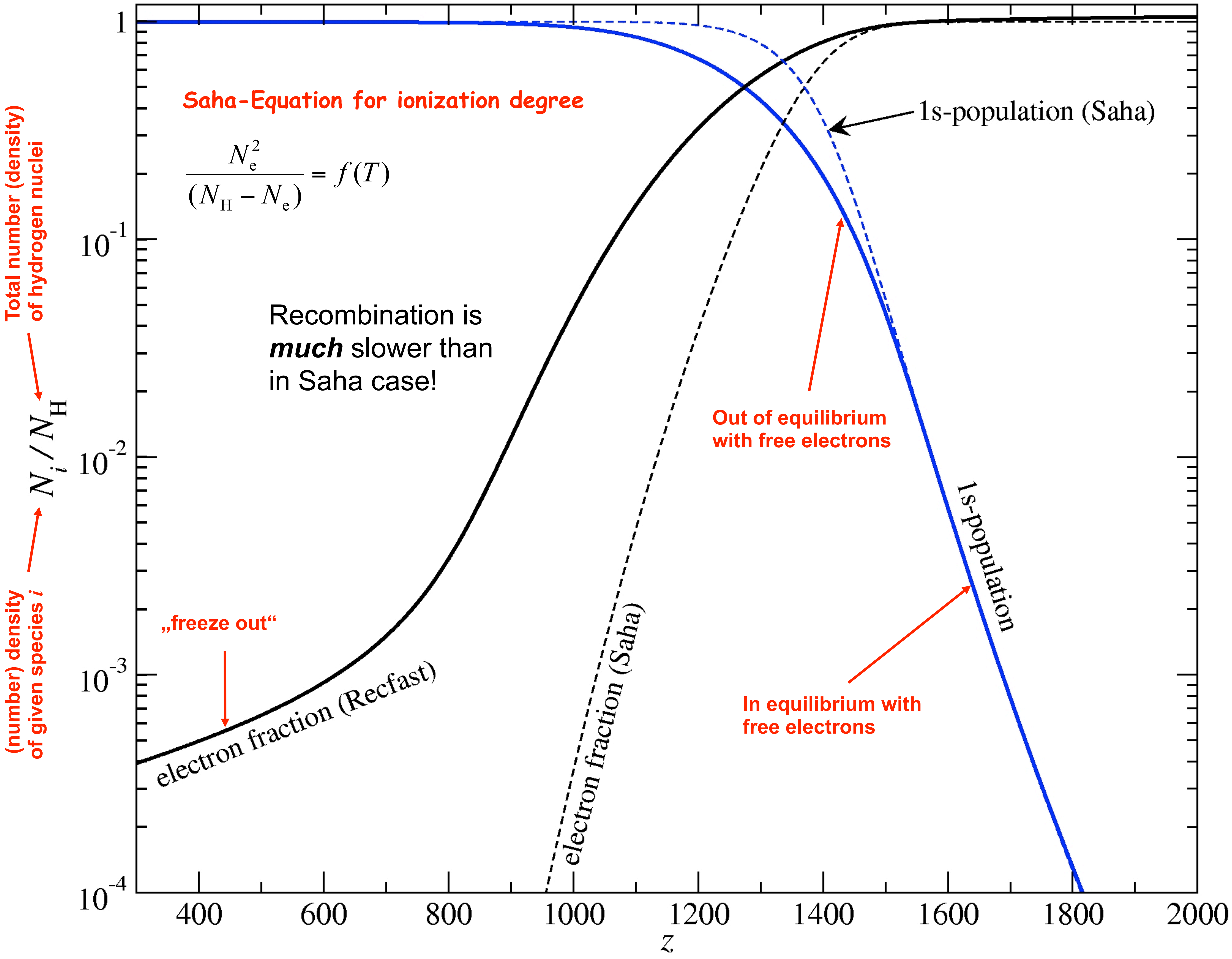
$$\frac{N_e^2}{(N_H - N_e)} = f(T) = 2.4\times10^{15}\ \mathrm{cm}^{-3}\left(\frac{T}{\mathrm{K}}\right)^{3/2} e^{-I/kT}$$

George Gamov

In equilibrium with free electrons

Total number (density) of hydrogen nuclei

(number) density of given species *i*



Saha-Equation for ionization degree

$$\frac{N_\mathrm{e}^2}{(N_\mathrm{H} - N_\mathrm{e})} = f(T)$$

Recombination is ***much*** slower than in Saha case!

„freeze out“

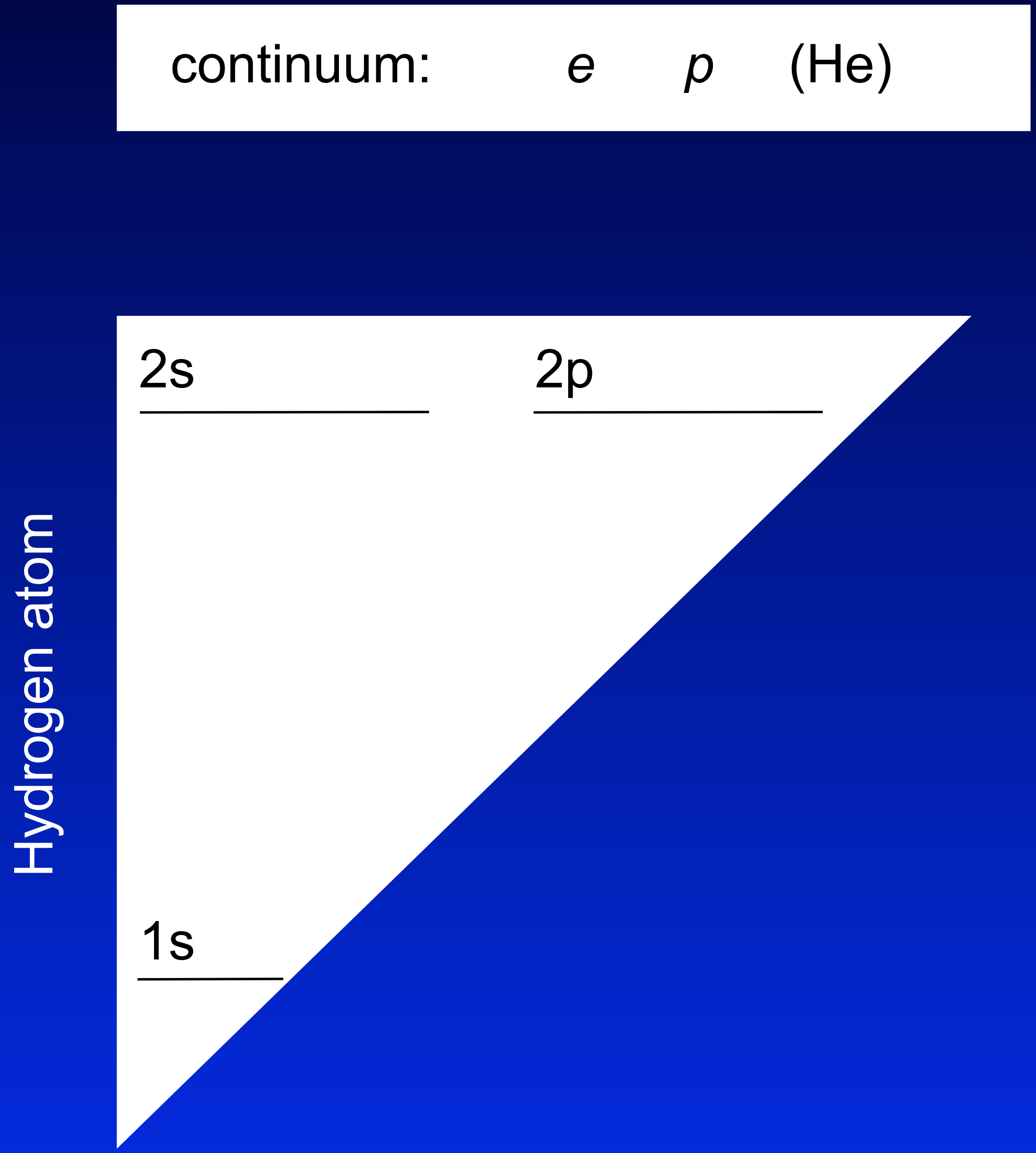
Out of equilibrium with free electrons

In equilibrium with free electrons

Total number (density) of hydrogen nuclei

(number) density of given species *i*

3-level Hydrogen Atom and Continuum



continuum: *e* *p* (He)

2s

2p

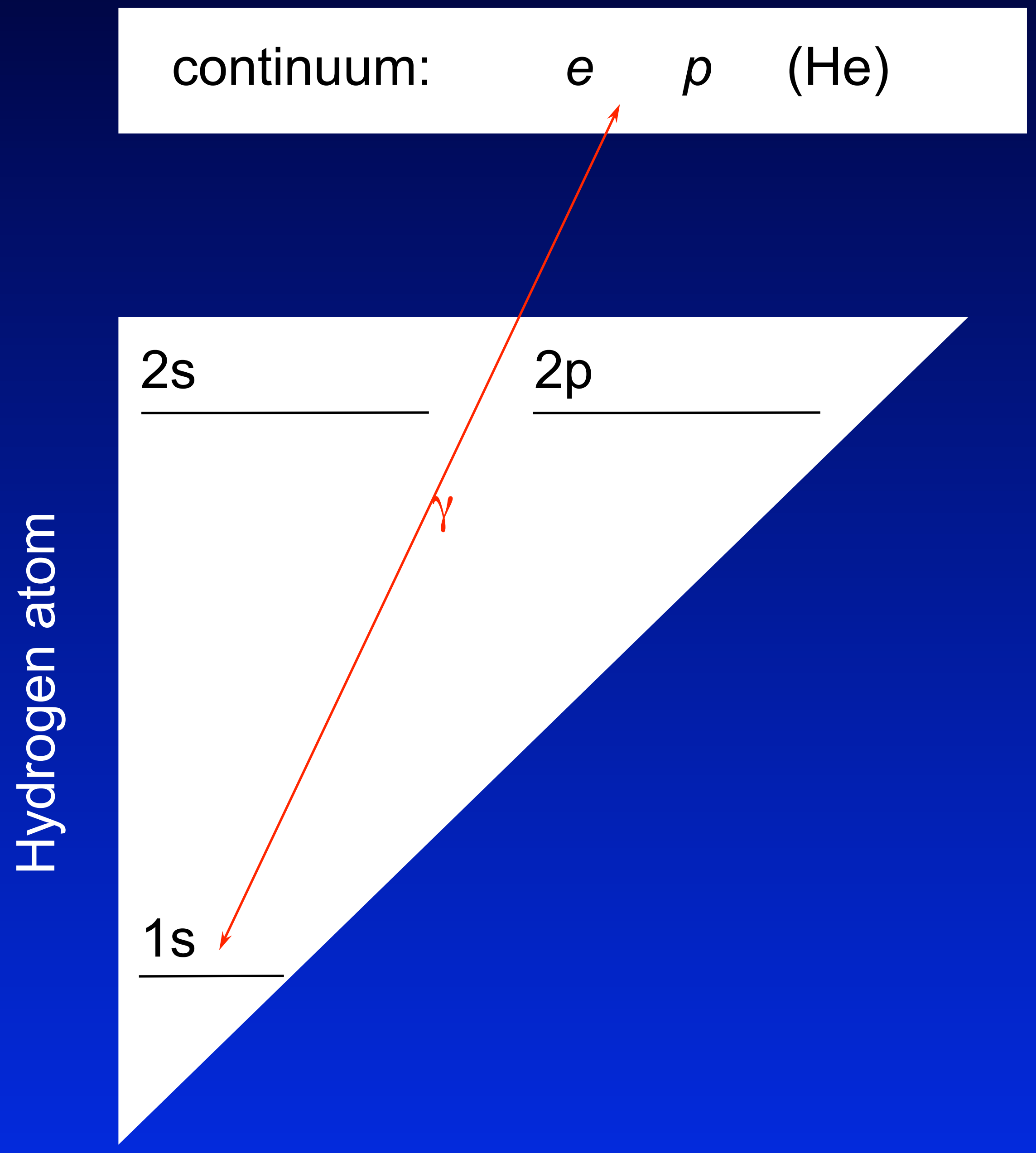
1s

Hydrogen atom

Routes to the ground state ?

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

3-level Hydrogen Atom and Continuum

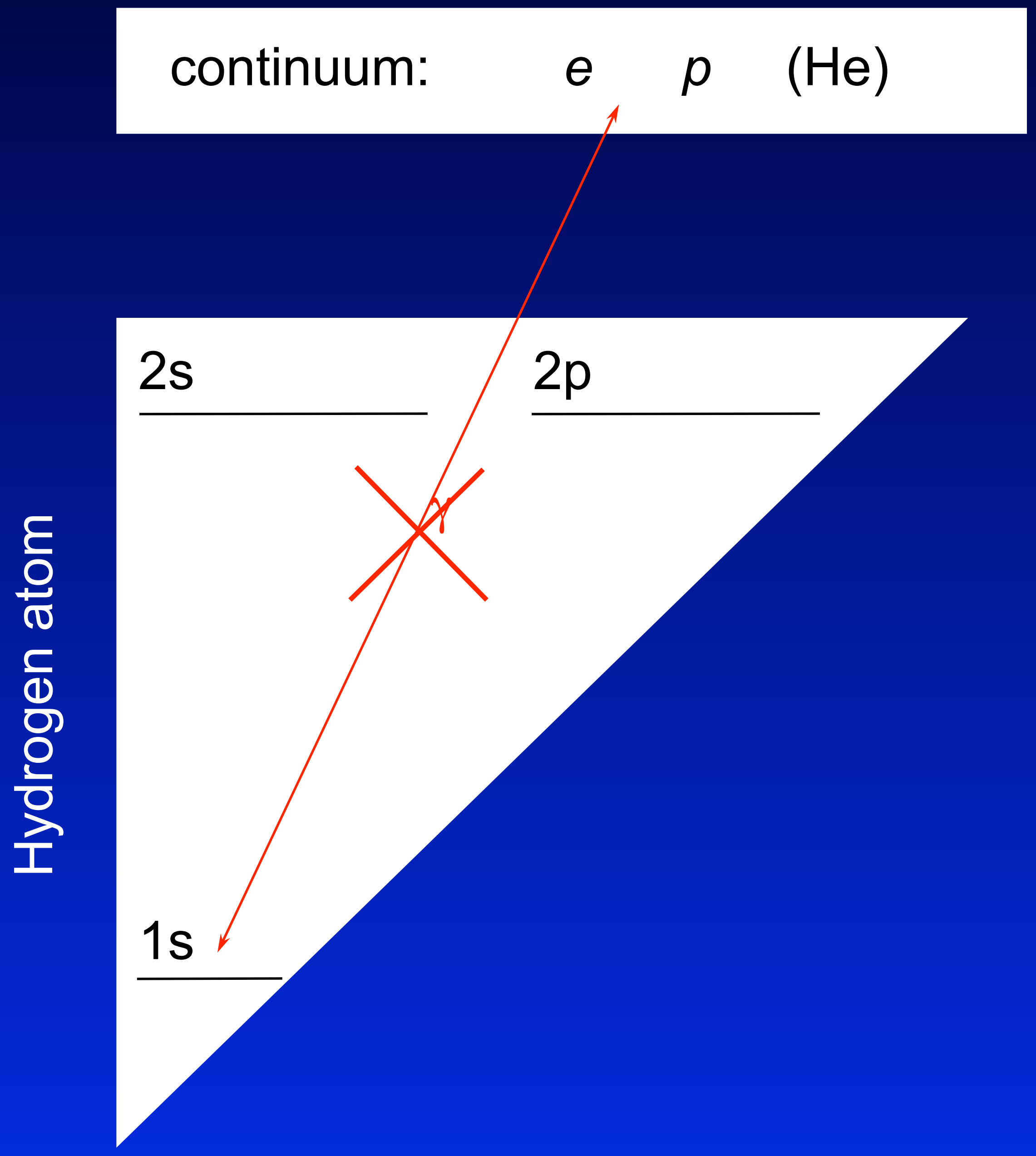


Routes to the ground state ?

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

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

3-level Hydrogen Atom and Continuum



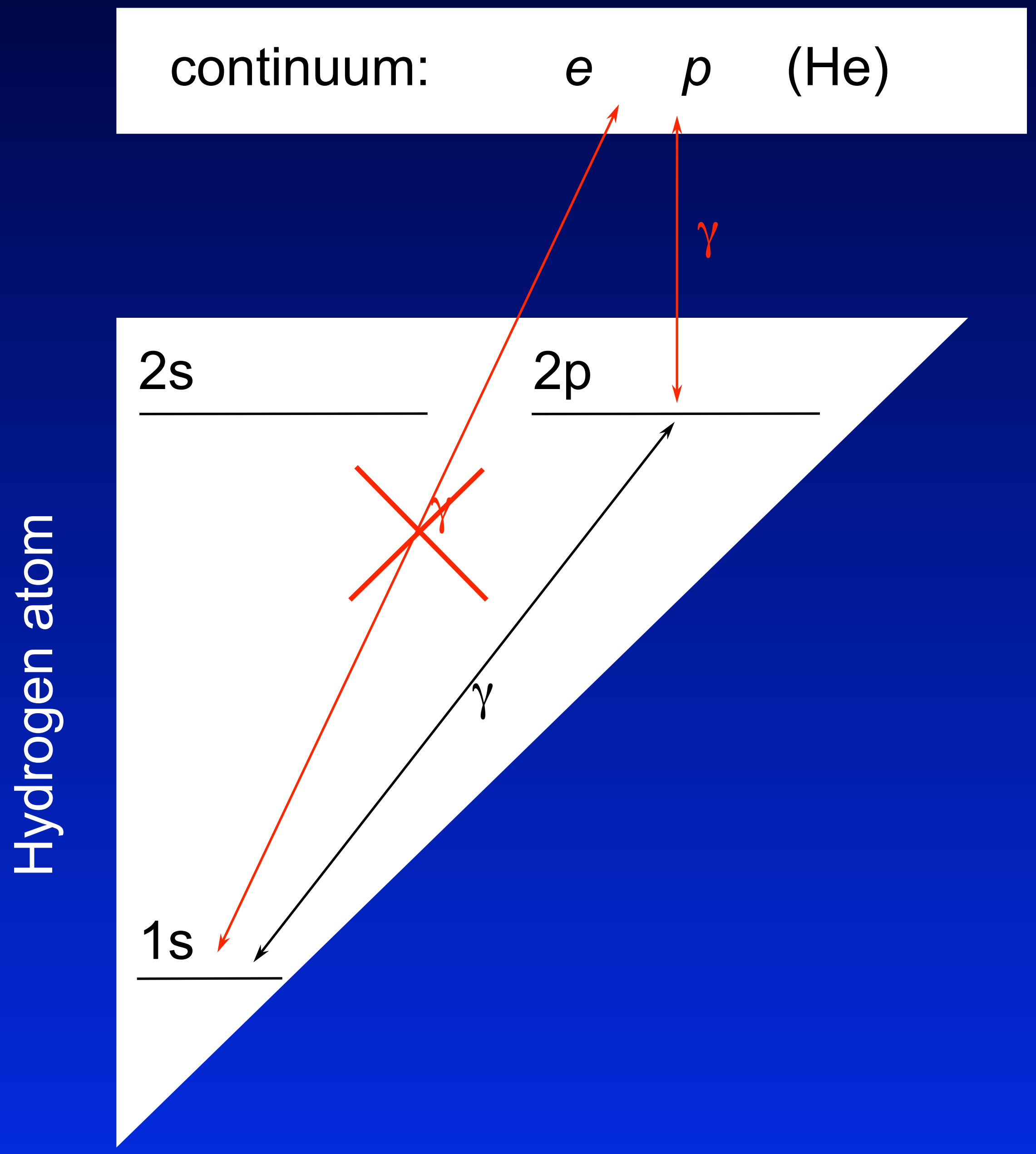
Routes to the ground state ?

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

No

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

3-level Hydrogen Atom and Continuum



Routes to the ground state ?

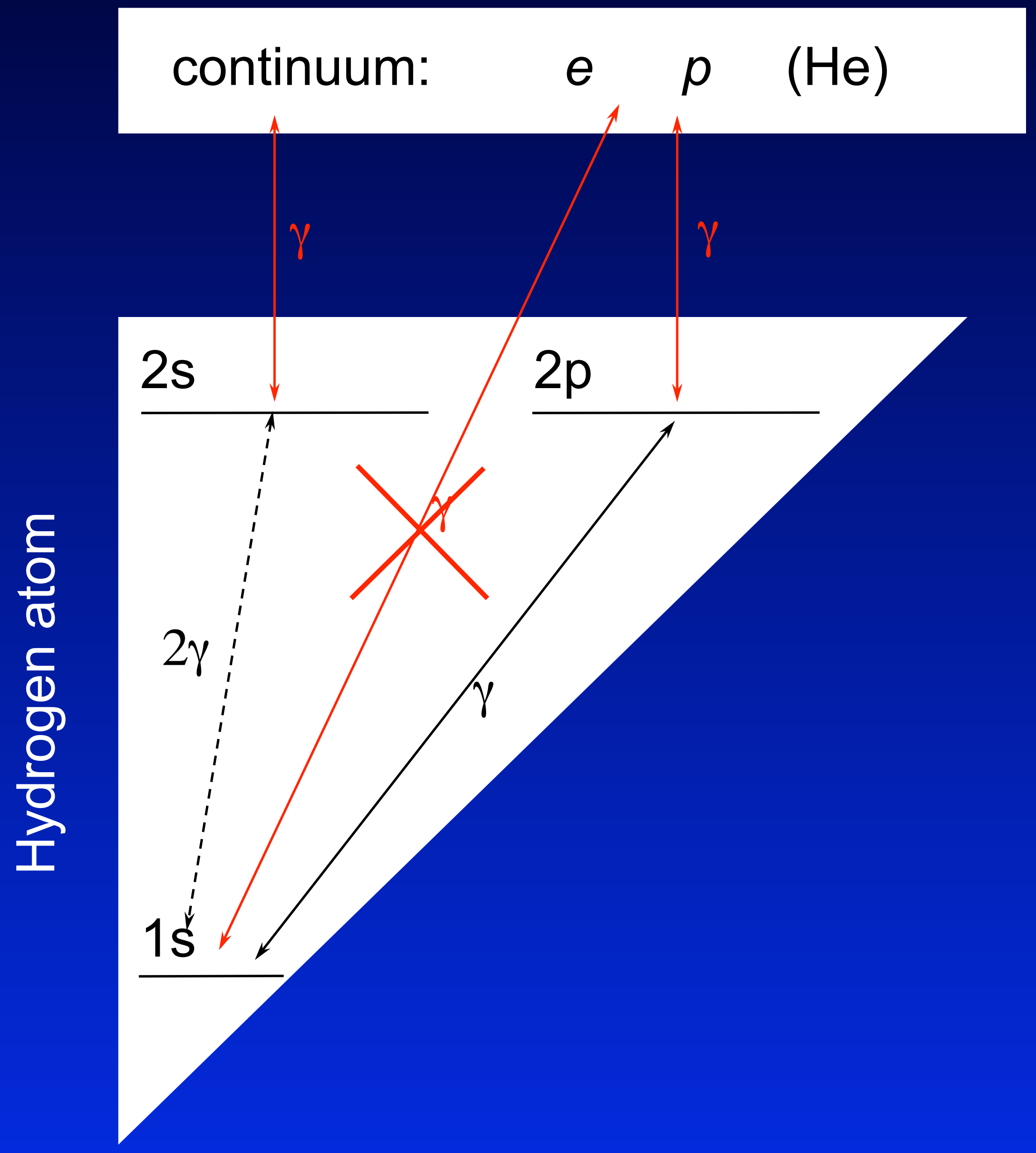
- **direct recombination to 1s**
  - **Emission of photon is followed by immediate re-absorption**

No

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

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

3-level Hydrogen Atom and Continuum



Routes to the ground state ?

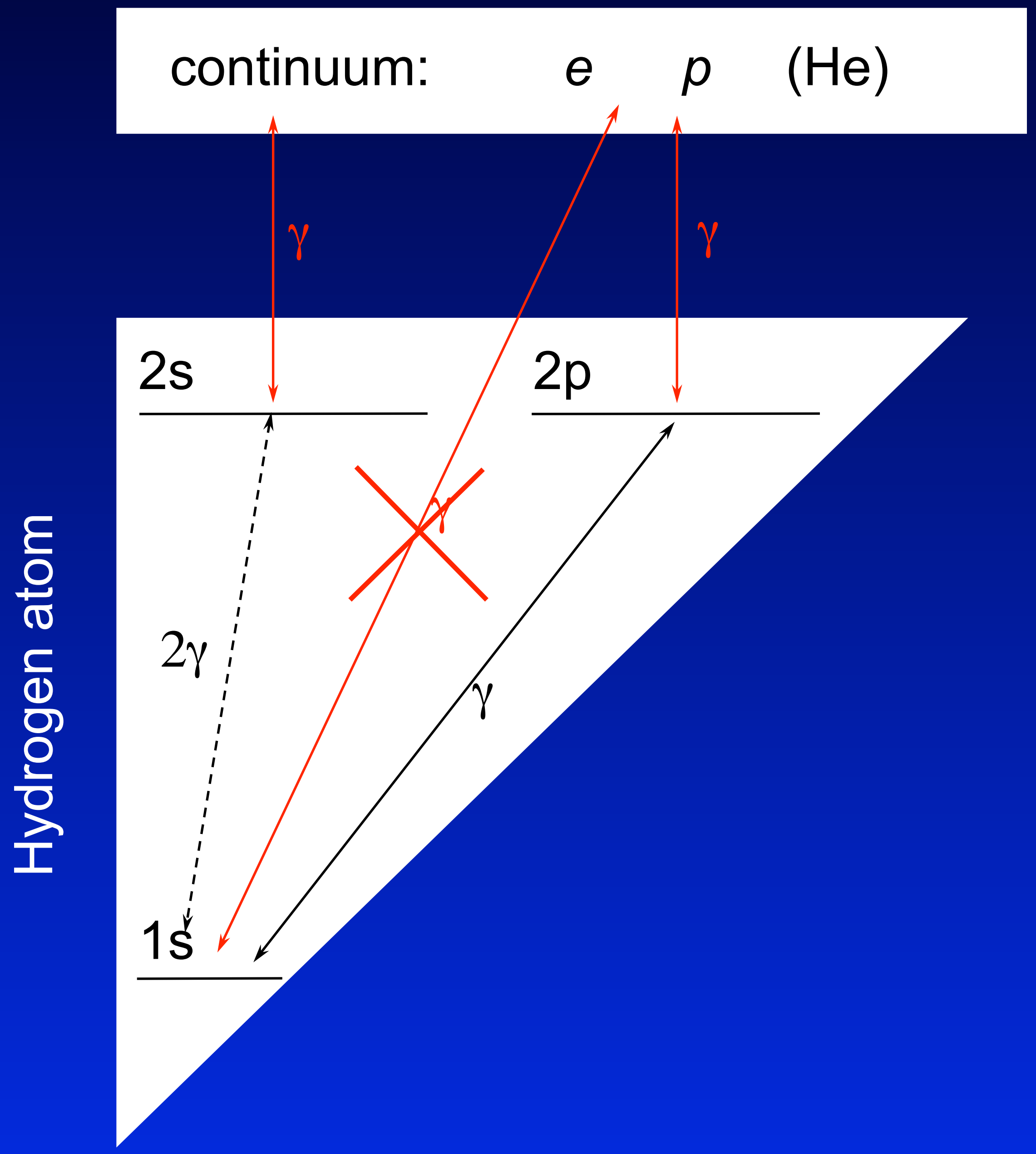
- **direct recombination to 1s**
  - **Emission of photon is followed by immediate re-absorption**

No

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

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

3-level Hydrogen Atom and Continuum



Routes to the ground state ?

- **direct recombination to 1s**
  - **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 ($p \sim 10^{-9}$ @ $z \sim 1100$)**

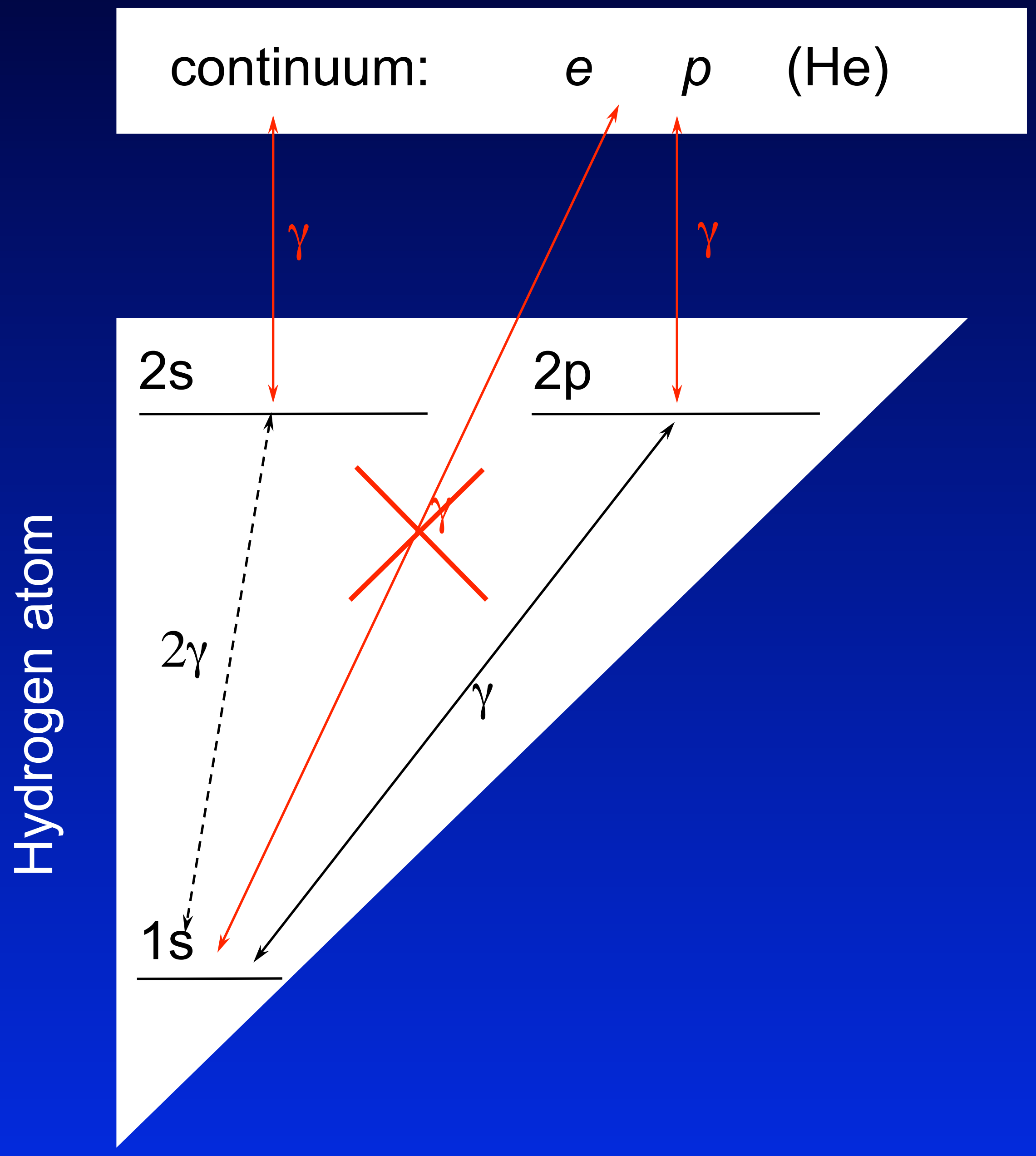
~ 43%

- **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

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%

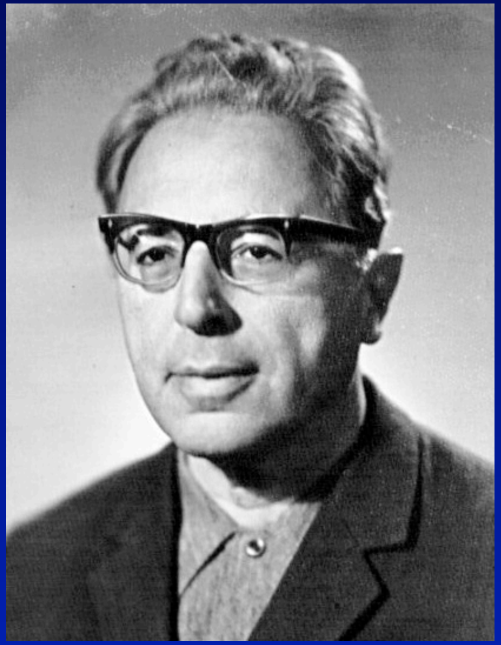
Zeldovich, Kurt & Sunyaev, 1968, ZhETF, 55, 278
Peebles, 1968, ApJ, 153, 1

$$\boxed{\Delta N_e\ /\ N_e \sim 10\% - 20\%}$$

These first computations were completed in 1968!

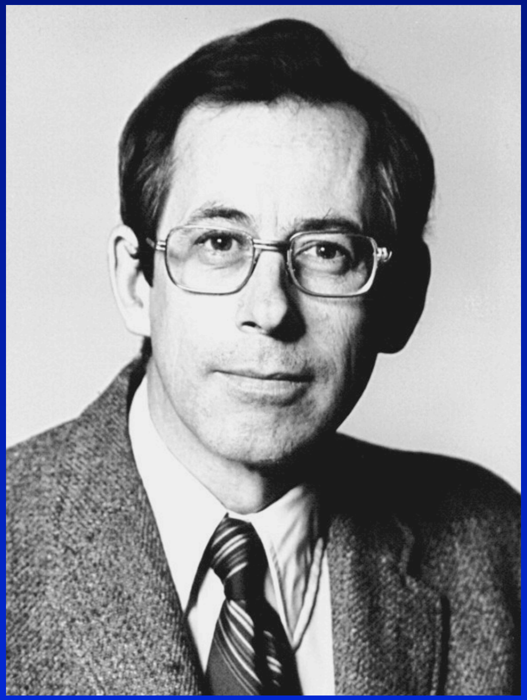
Moscow

Yakov Zeldovich



Iosif Shklovskii

Princeton

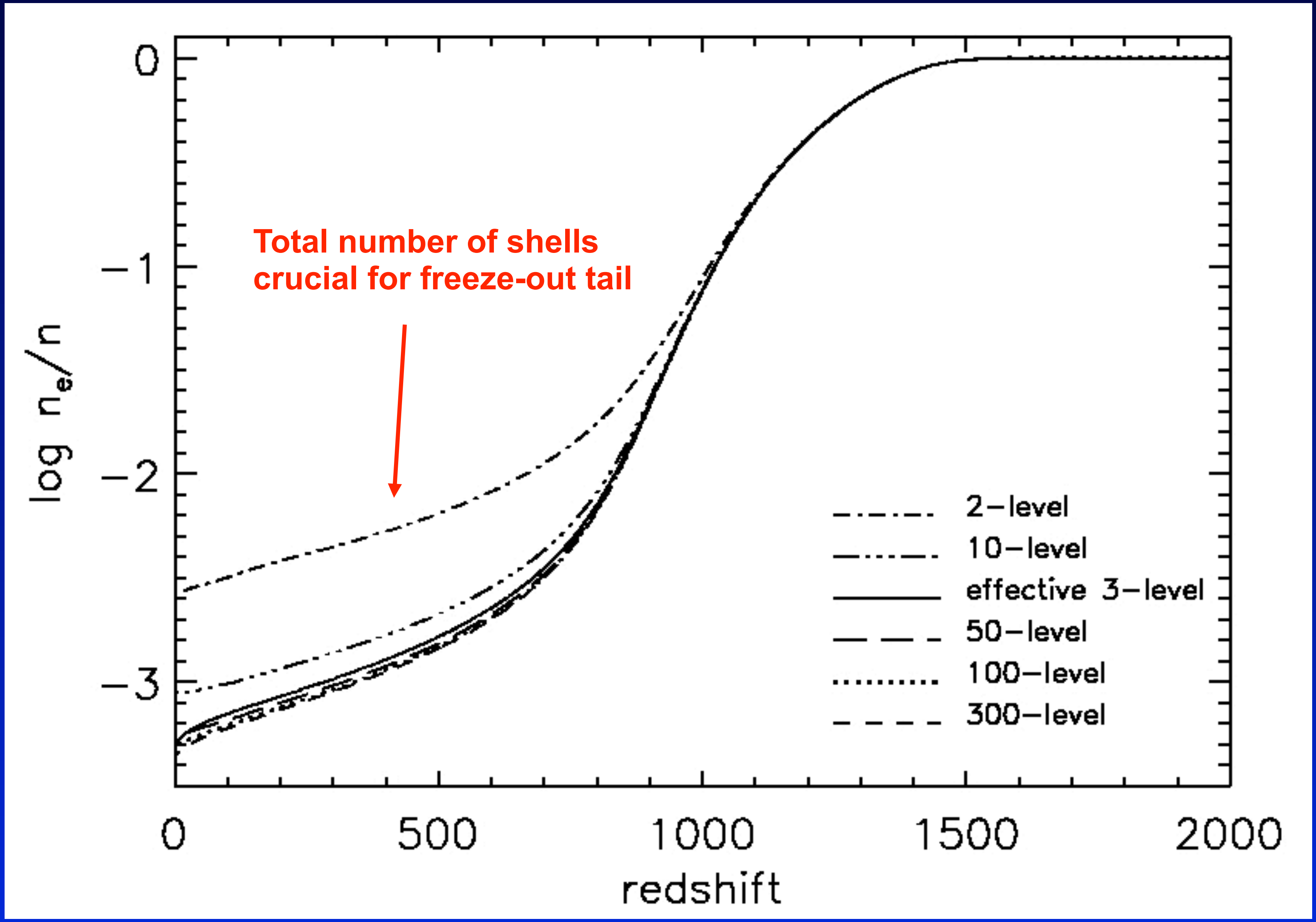


Jim Peebles

Vladimir Kurt
(UV astronomer)

Rashid Sunyaev

Multi-level Atom ⟺ Recfast-Code



Total number of shells crucial for freeze-out tail

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

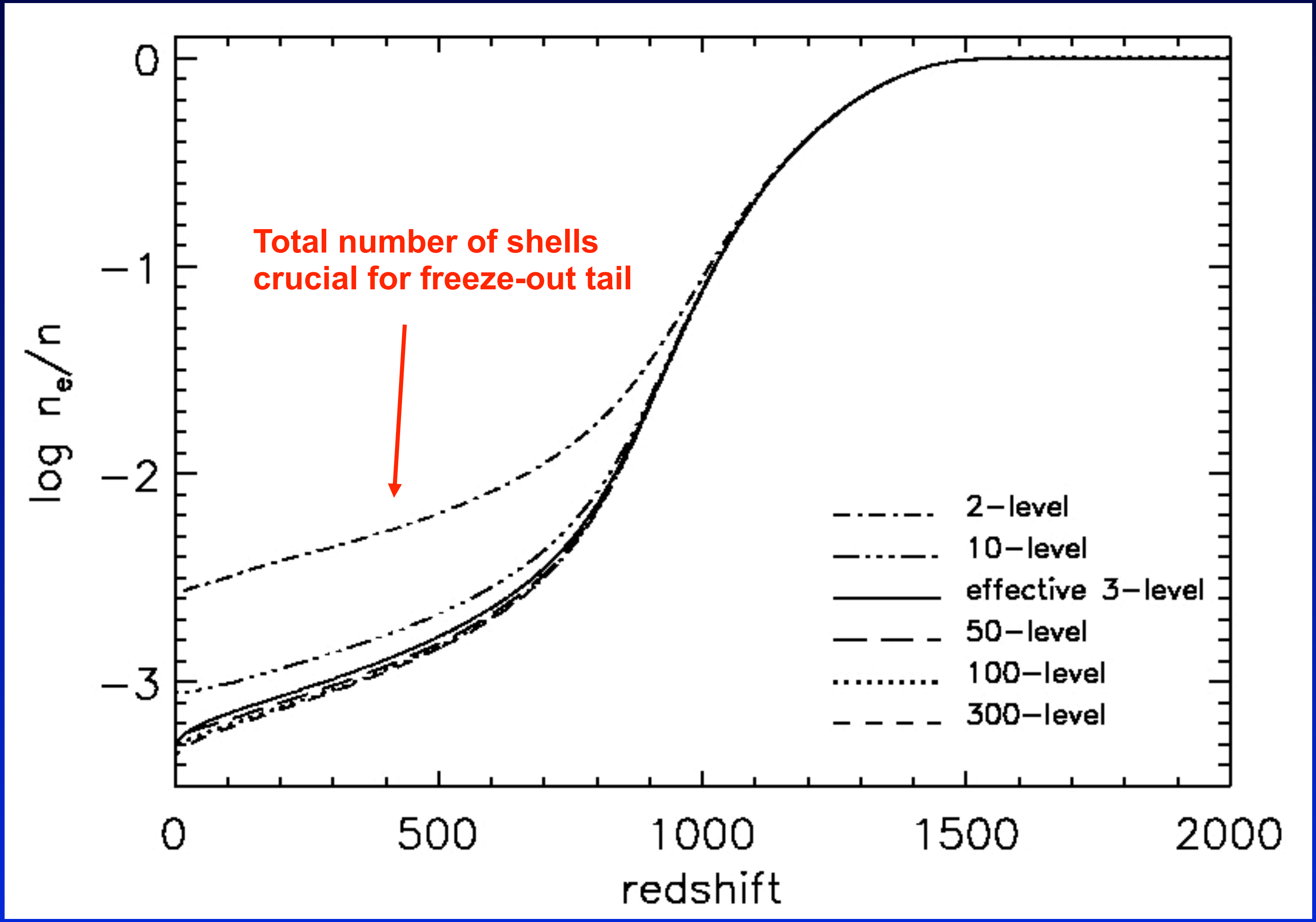
Helium:

- 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)

Multi-level Atom ⟺ Recfast-Code



Total number of shells crucial for freeze-out tail

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)
- $n \geq 2 \rightarrow$ full SE for l-sub-states

Helium:

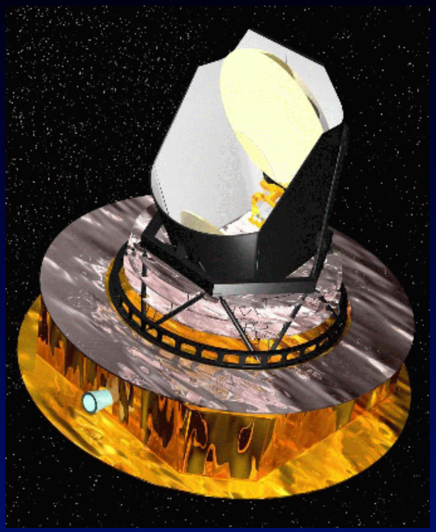
- HeI 200-levels (*z* ~ 1400-1500)
- HeII 100-levels (*z* ~ 6000-6500)
- HeIII 1 equation

Low Redshifts:

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

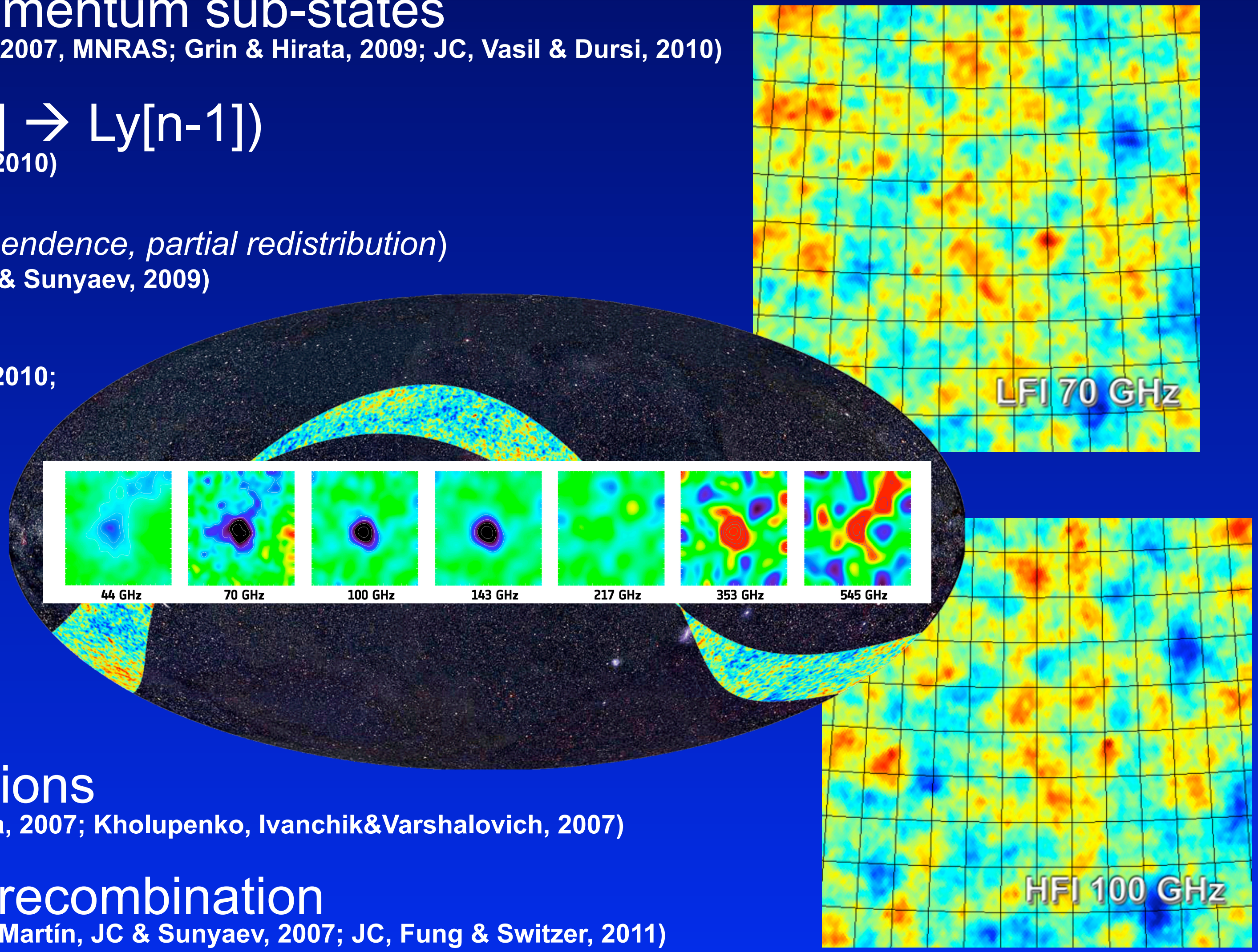
$\Delta N_e \, / \, N_e \sim 1\% - 3\%$

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/

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

Recombination Physics Meeting in Orsay 2008

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

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

Recombination Physics Meeting in Orsay 2008

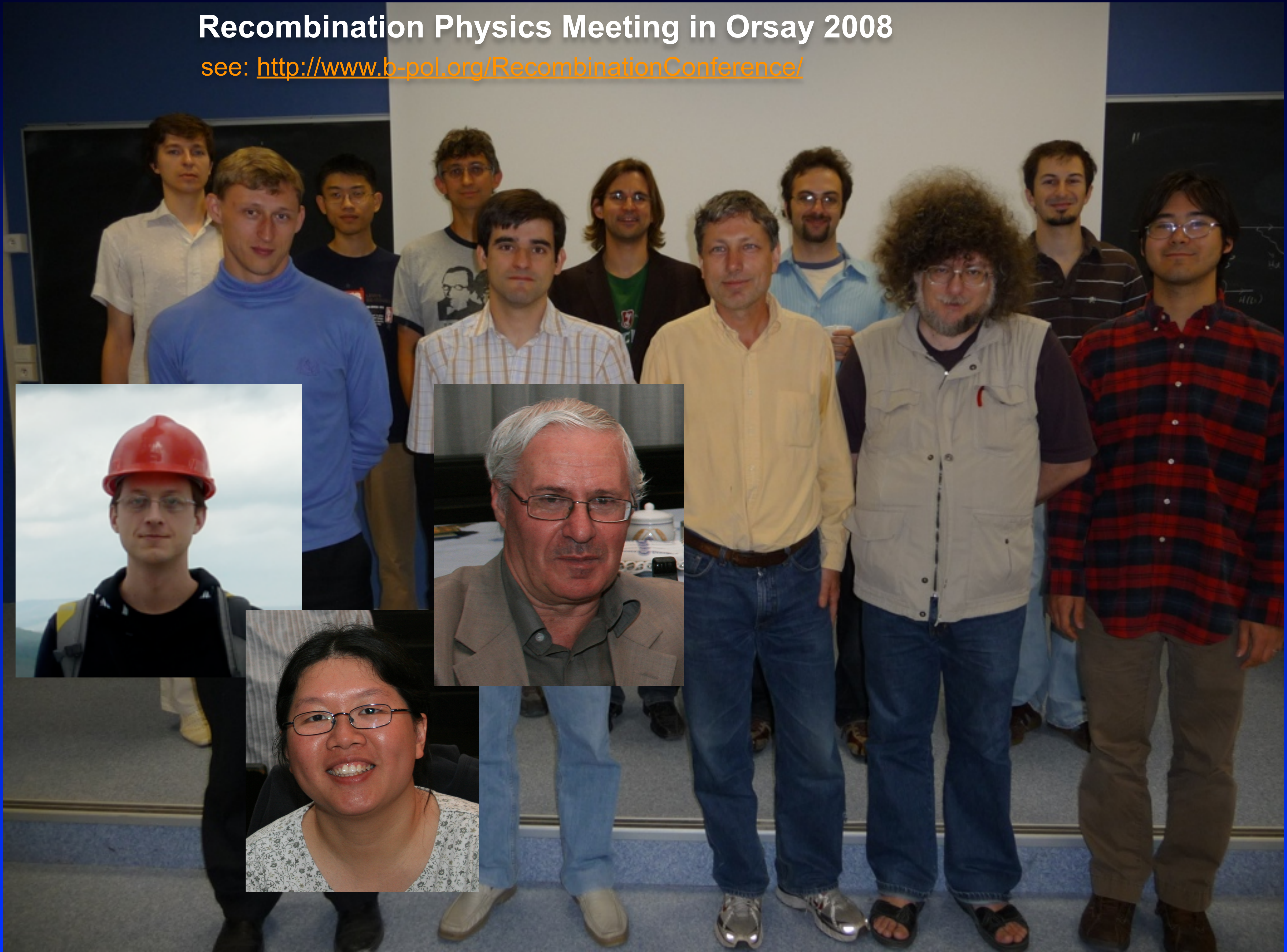
see: http://www.b-pol.org/RecombinationConference/

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

Recombination Physics Meeting in Orsay 2008

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

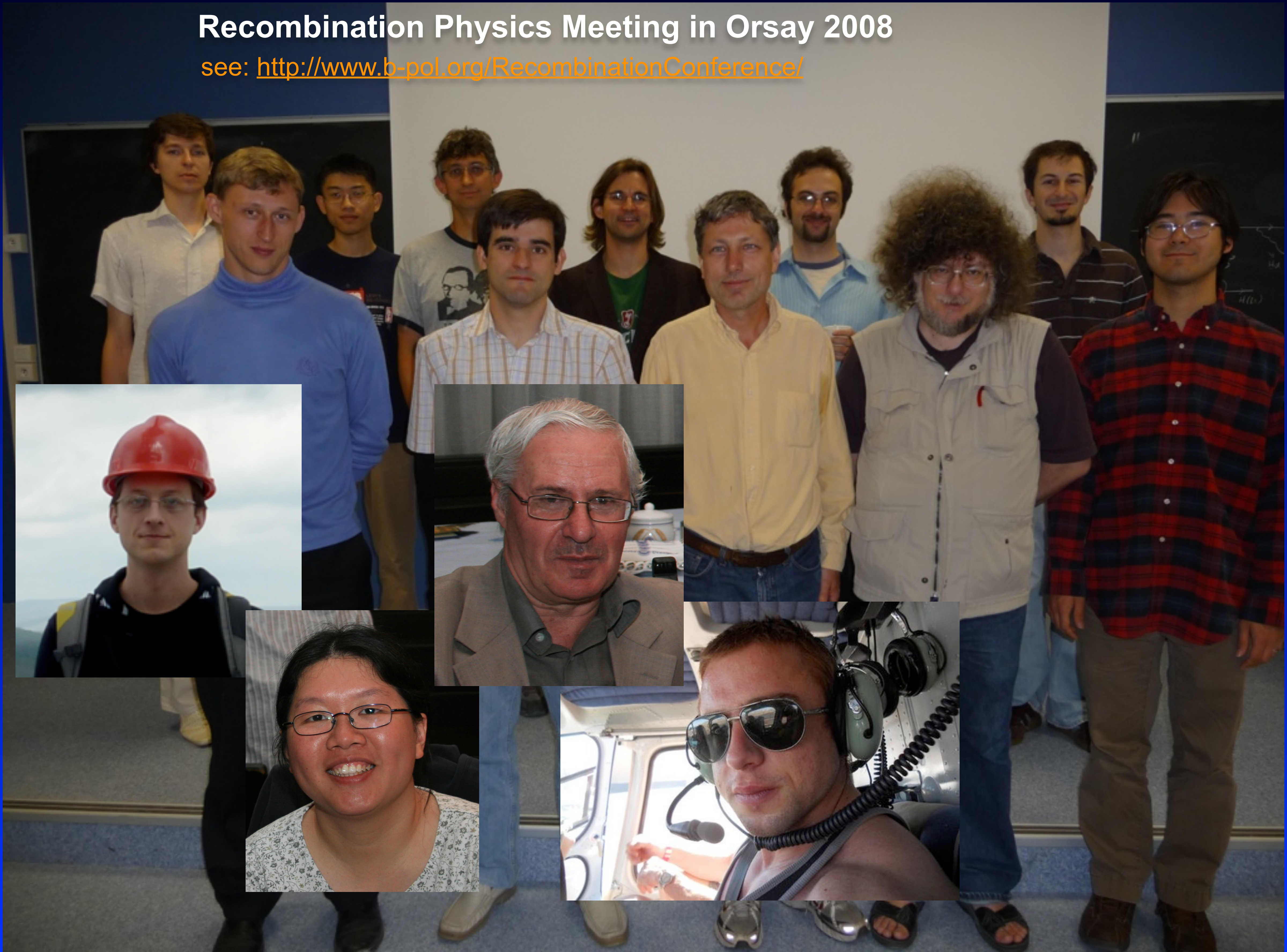
Solving the problem for the Planck Collaboration was a common effort!



Recombination Physics Meeting in Orsay 2008

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

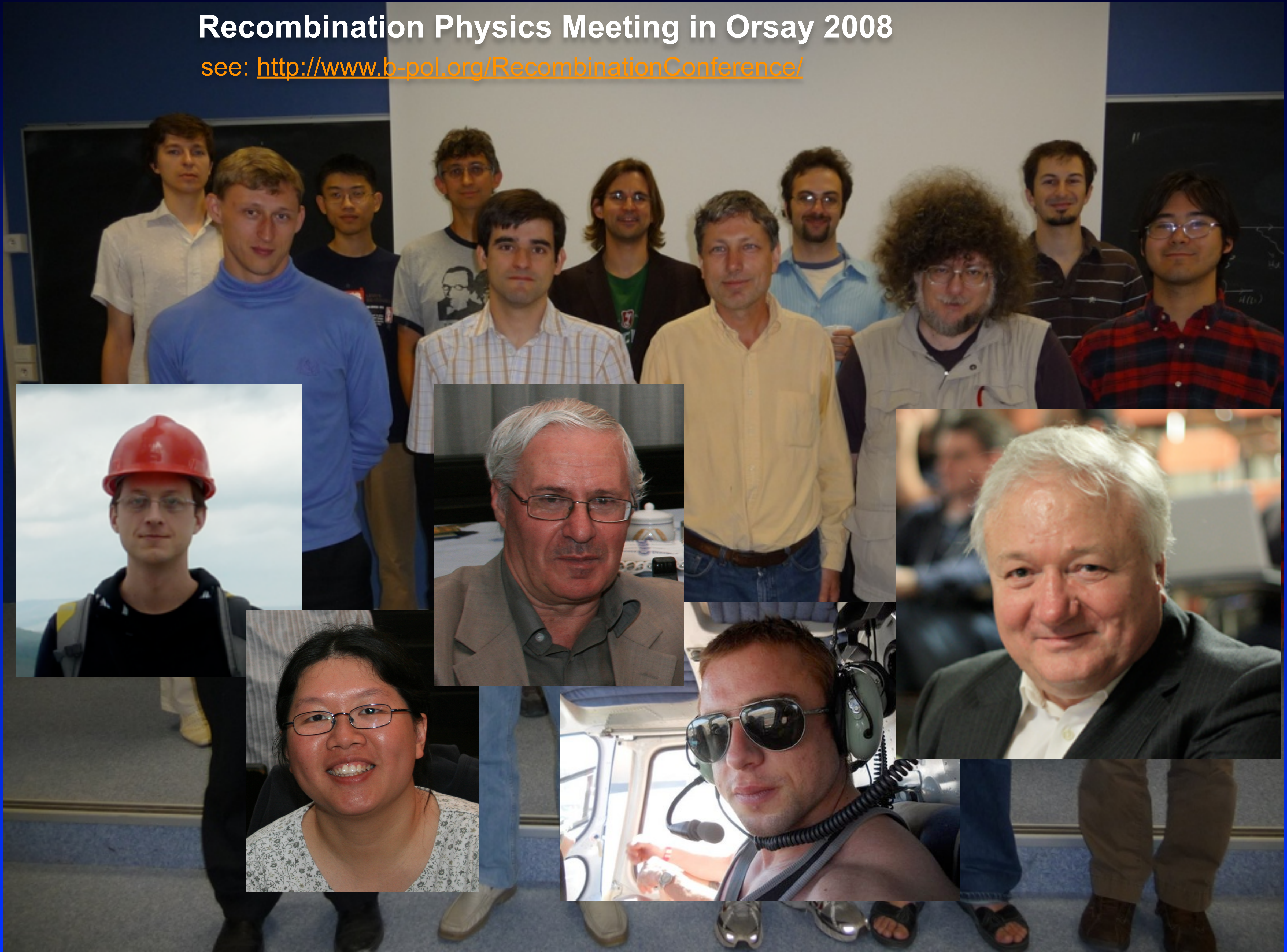
Solving the problem for the Planck Collaboration was a common effort!



Recombination Physics Meeting in Orsay 2008

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

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



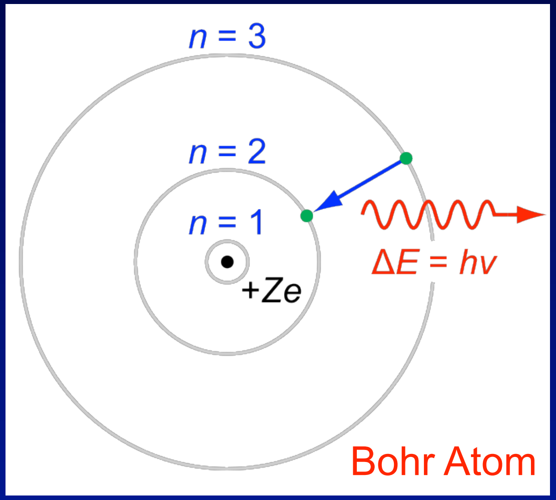
Recombination Physics Meeting in Orsay 2008

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

Atomic Physics Challenges

Hydrogen Atom & Hydrogenic Helium

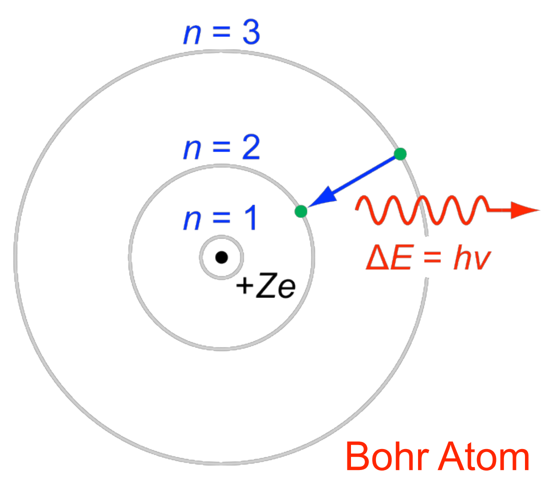
- Rather simple and basically analytic (e.g., Karzas & Latter, 1961)
- Even 2γ rates can be computed precisely (e.g., Goeppert-Mayer, 1931)
- Collision rates less robust, but effect small (new rates became available!)
- Biggest computational challenge is the number of levels (~ n^2)



Atomic Physics Challenges

Hydrogen Atom & Hydrogenic Helium

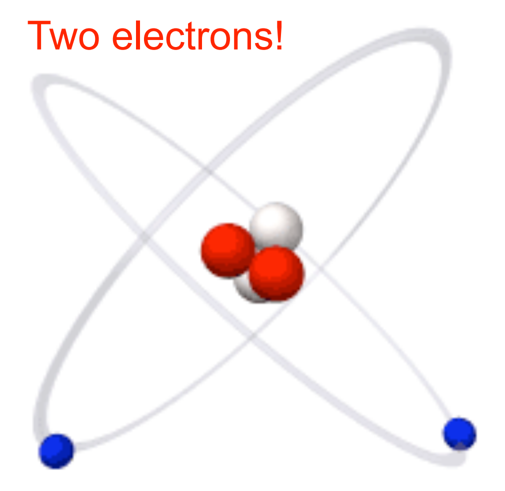
- Rather simple and basically analytic (e.g., Karzas & Latter, 1961)
- Even 2γ rates can be computed precisely (e.g., Goeppert-Mayer, 1931)
- Collision rates less robust, but effect small (new rates became available!)
- Biggest computational challenge is the number of levels (~ n^2)



Bohr Atom

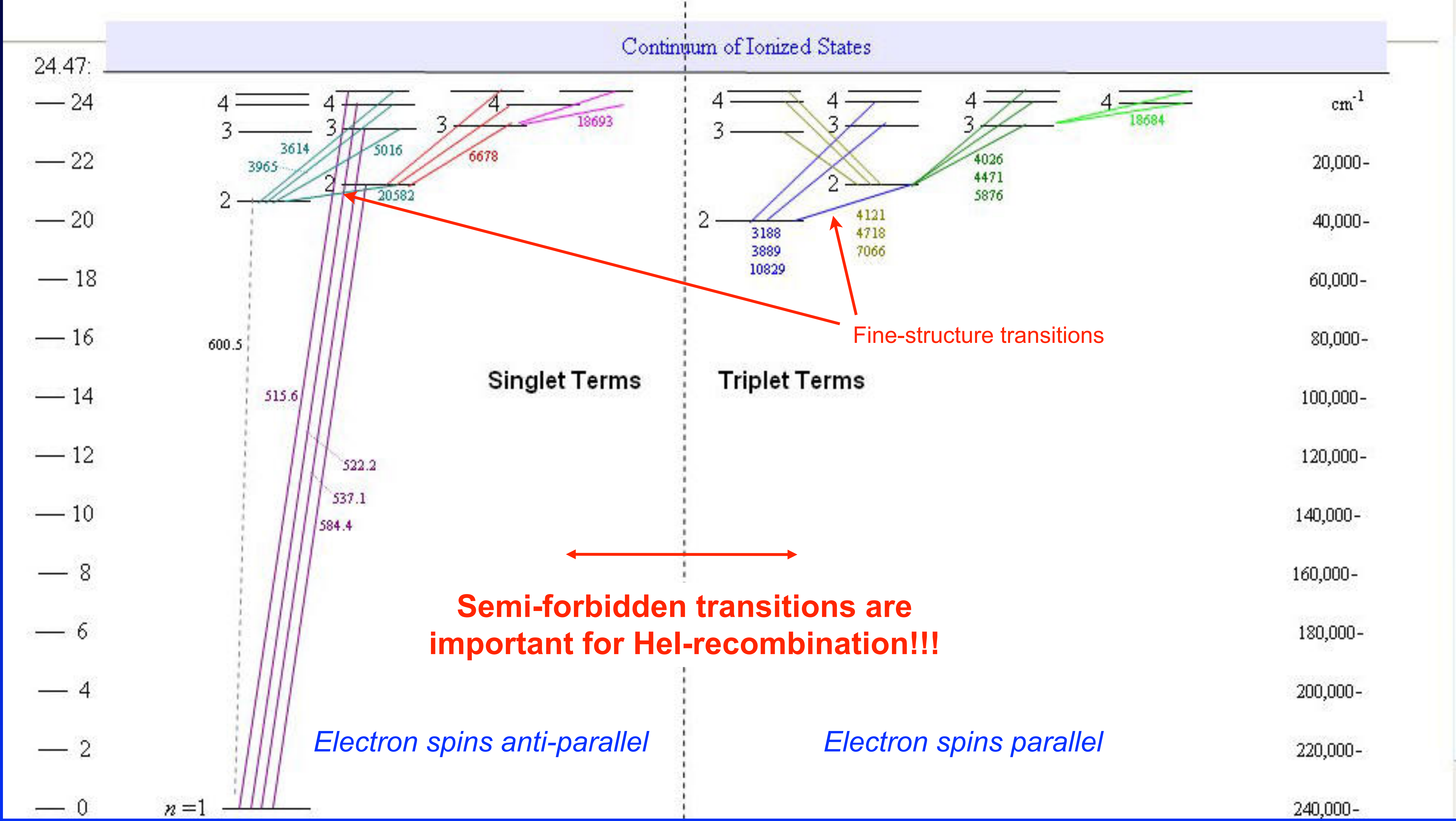
Neutral Helium

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



Two electrons!

Grotrian diagram for neutral helium



Fine-structure transitions

Semi-forbidden transitions are important for HeI-recombination!!!

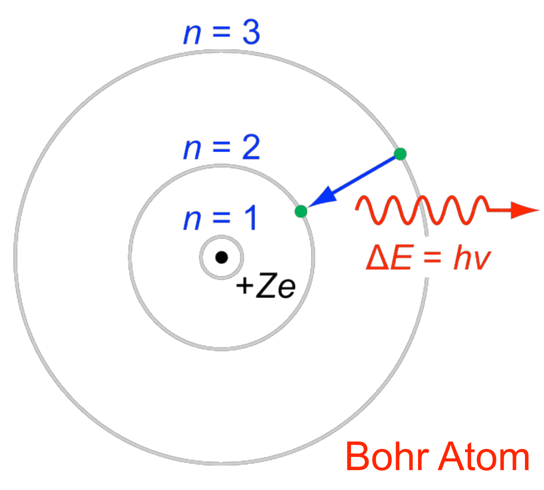
Electron spins anti-parallel

Electron spins parallel

Atomic Physics Challenges

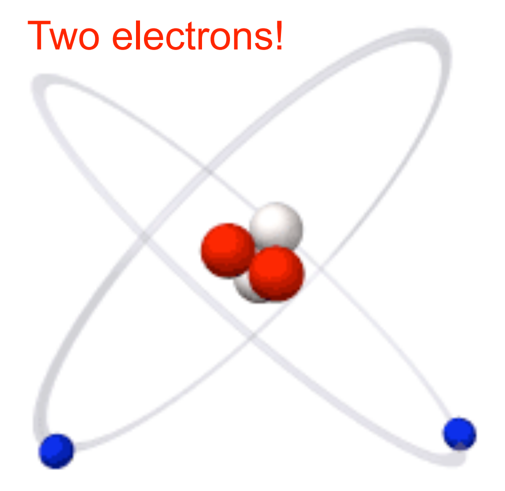
Hydrogen Atom & Hydrogenic Helium

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

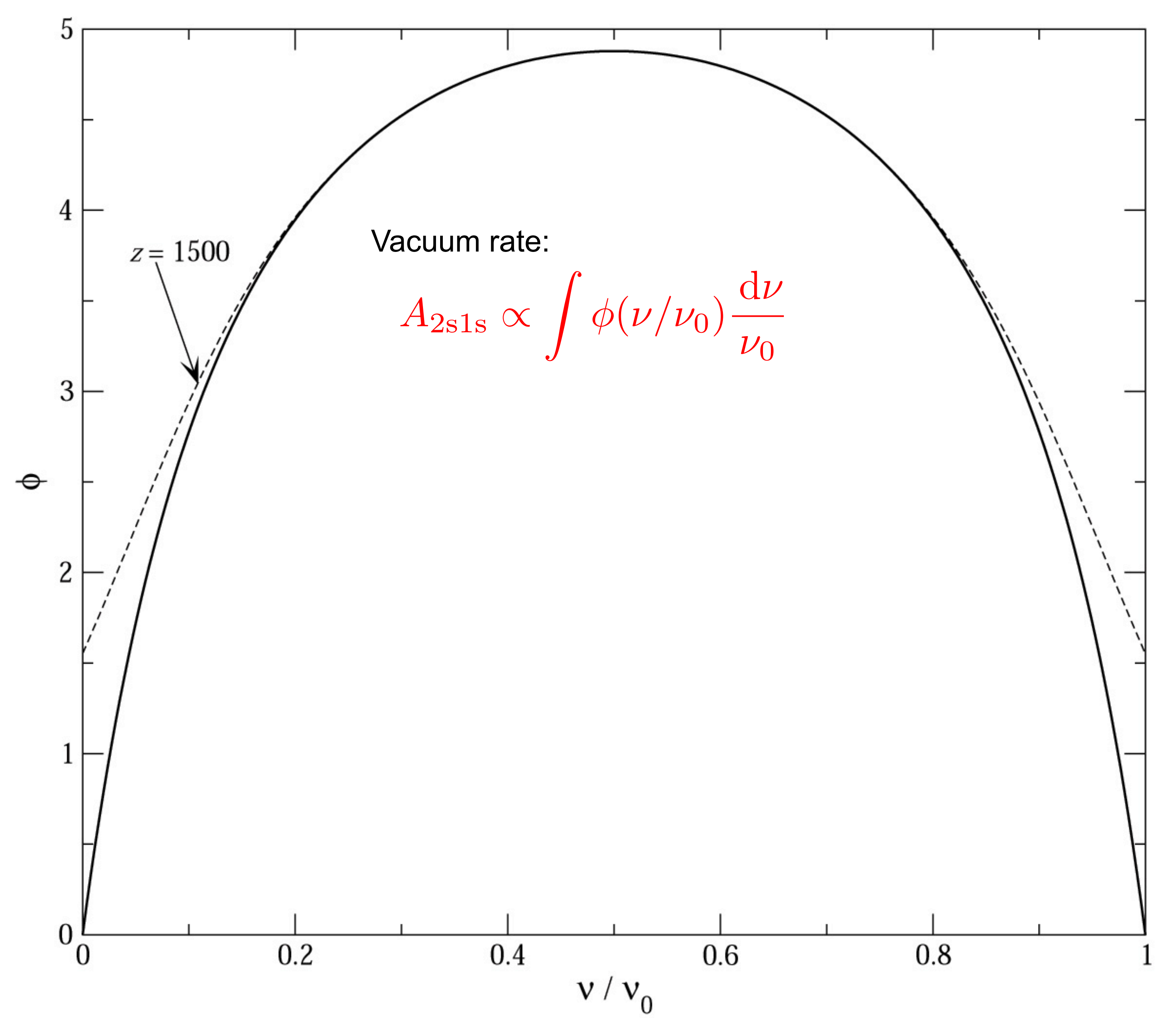


Neutral Helium

- Lower levels non-hydrogenic (perturbative approach needed)
- Spectrum complicated and data (was) rather incomplete
(e.g., Drake & Morton, 2007)
- Collision rates pretty rough (important for distortions...)
- Computational challenge because of levels not as severe



Stimulated 2s →1s decay



Vacuum rate:

$$A_{2s1s} \propto \int \phi(\nu/\nu_0)\,\frac{d\nu}{\nu_0}$$

2s-1s emission profile

Transition rate in vacuum

→ A_{2s1s}~ 8.22 sec^{-1}

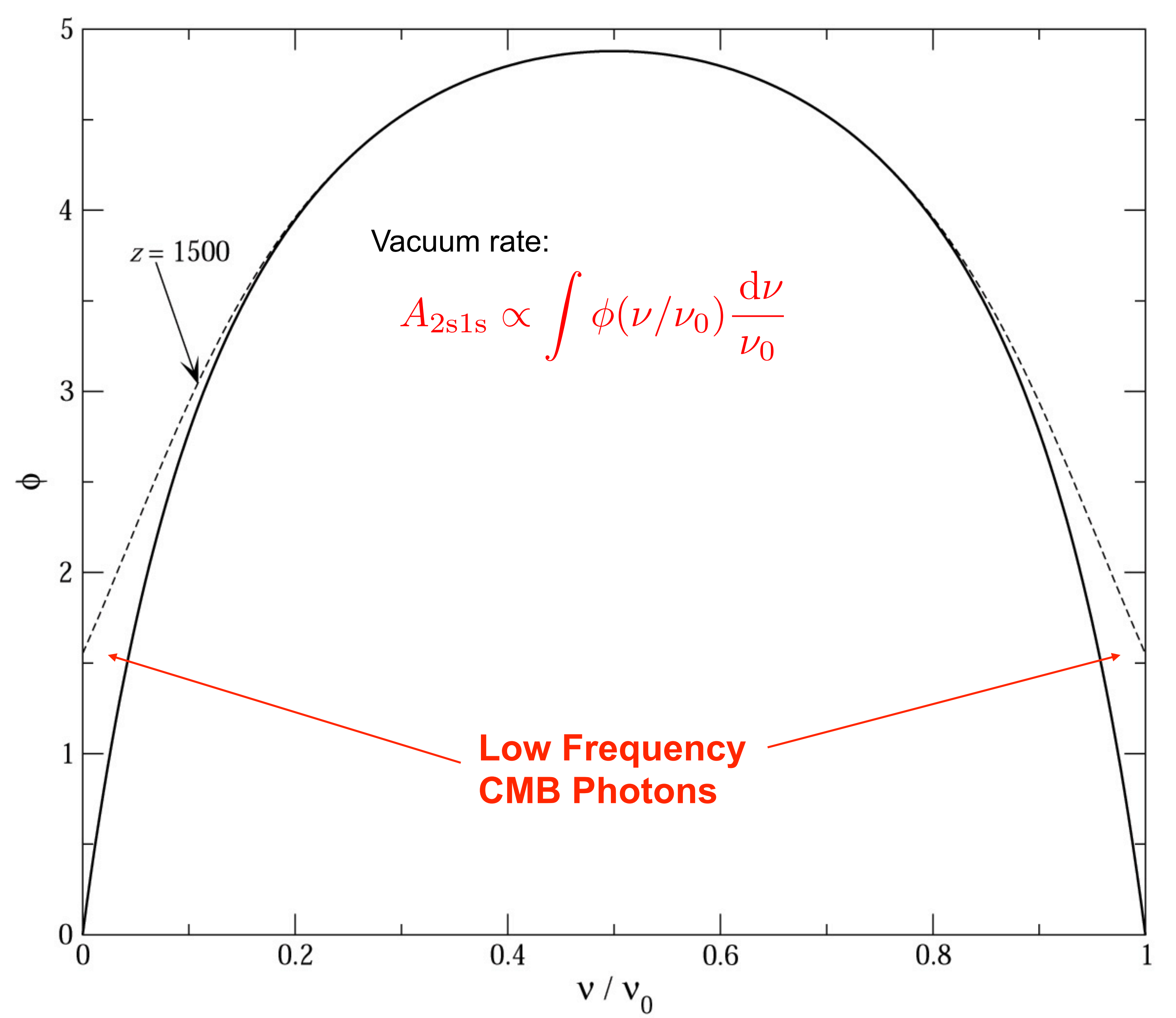
CMB ambient photons field

→ A_{2s1s} increased by ~1%-2%

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

JC & Sunyaev, 2006, A&A

Stimulated 2s → 1s decay



2s-1s emission profile

Transition rate in vacuum

→ A_{2s1s}~ 8.22 sec^{-1}

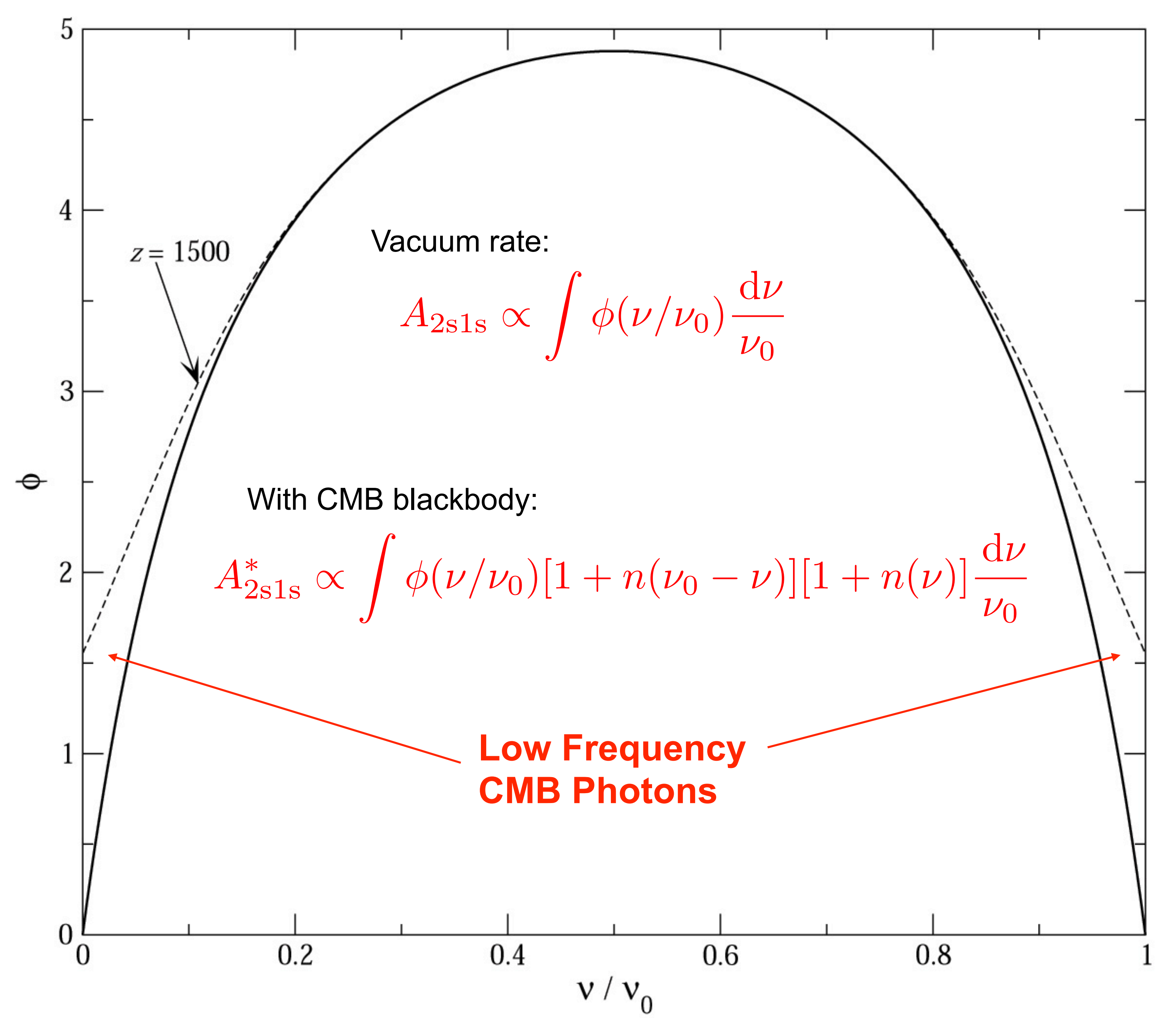
CMB ambient photons field

→ A_{2s1s} increased by ~1%-2%

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

JC & Sunyaev, 2006, A&A

Stimulated 2s →1s decay



Vacuum rate:

$$A_{2s1s} \propto \int \phi(\nu/\nu_0)\,\frac{d\nu}{\nu_0}$$

With CMB blackbody:

$$A^*_{2s1s} \propto \int \phi(\nu/\nu_0)[1+n(\nu_0-\nu)][1+n(\nu)]\,\frac{d\nu}{\nu_0}$$

Low Frequency CMB Photons

2s-1s emission profile

Transition rate in vacuum

→ A_{2s1s}~ 8.22 sec^{-1}

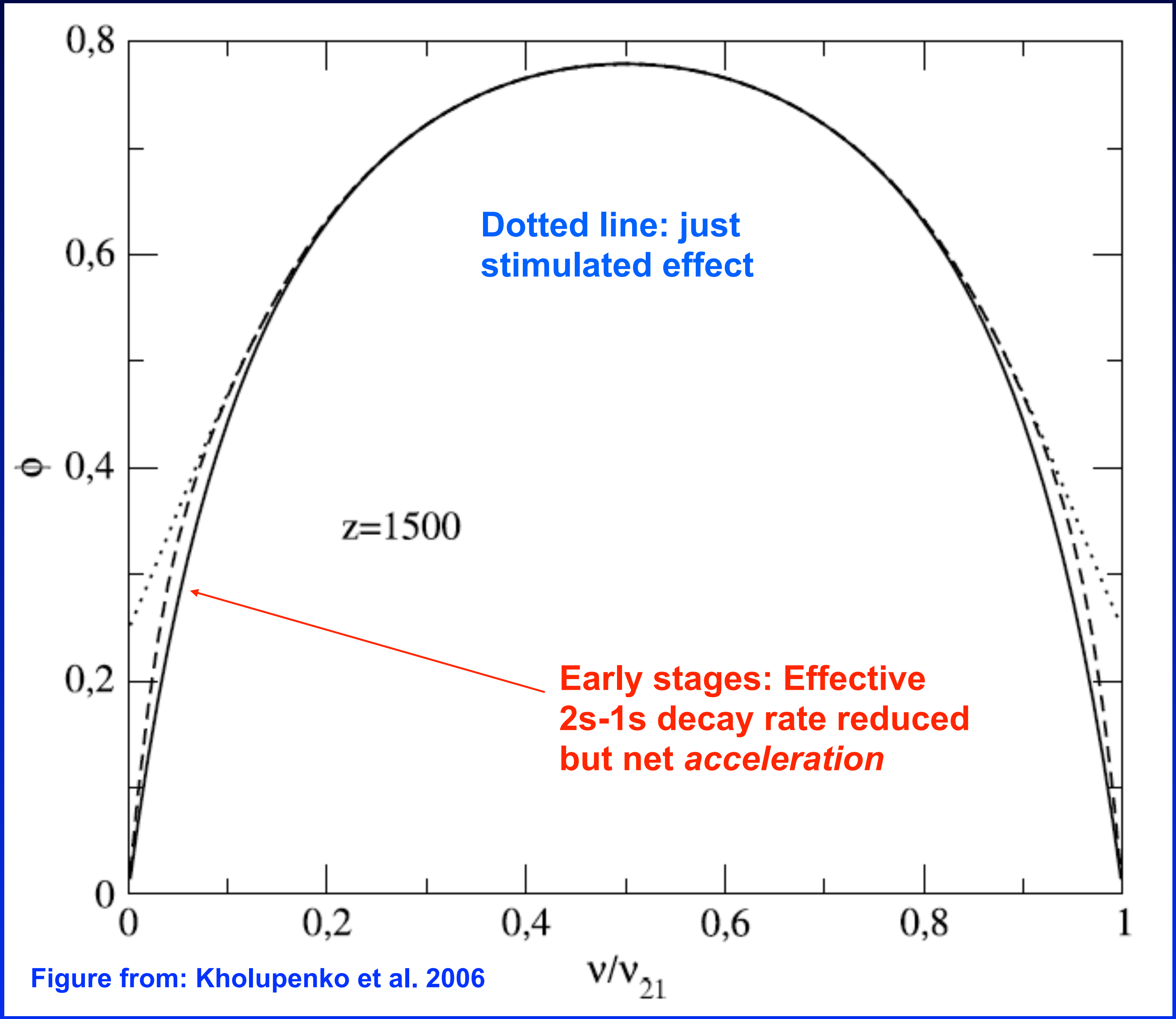
CMB ambient photons field

→ 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 1s →2s transition



Dotted line: just stimulated effect

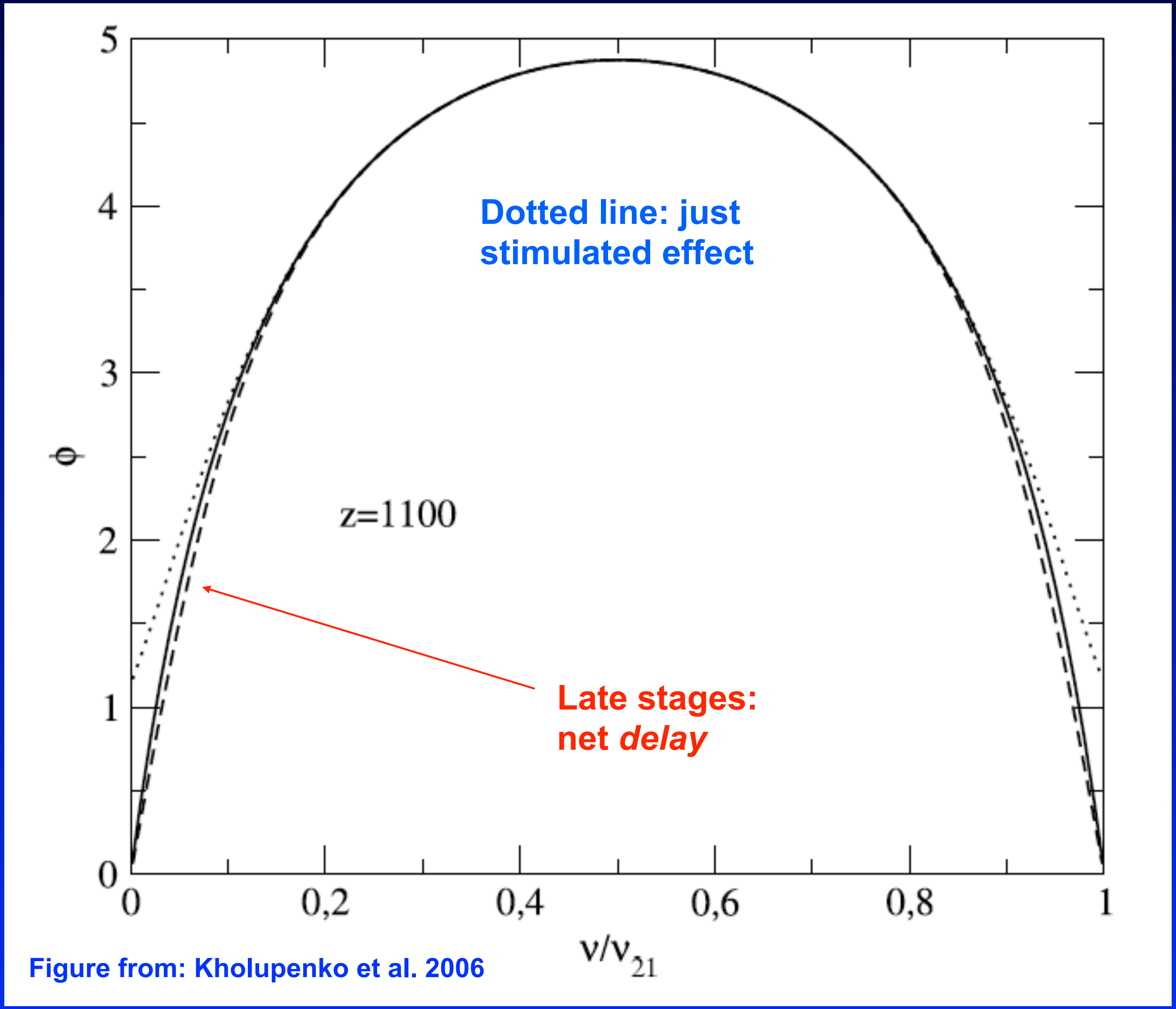
Early stages: Effective 2s-1s decay rate reduced but net *acceleration*

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

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



Dotted line: just stimulated effect

Late stages: net *delay*

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

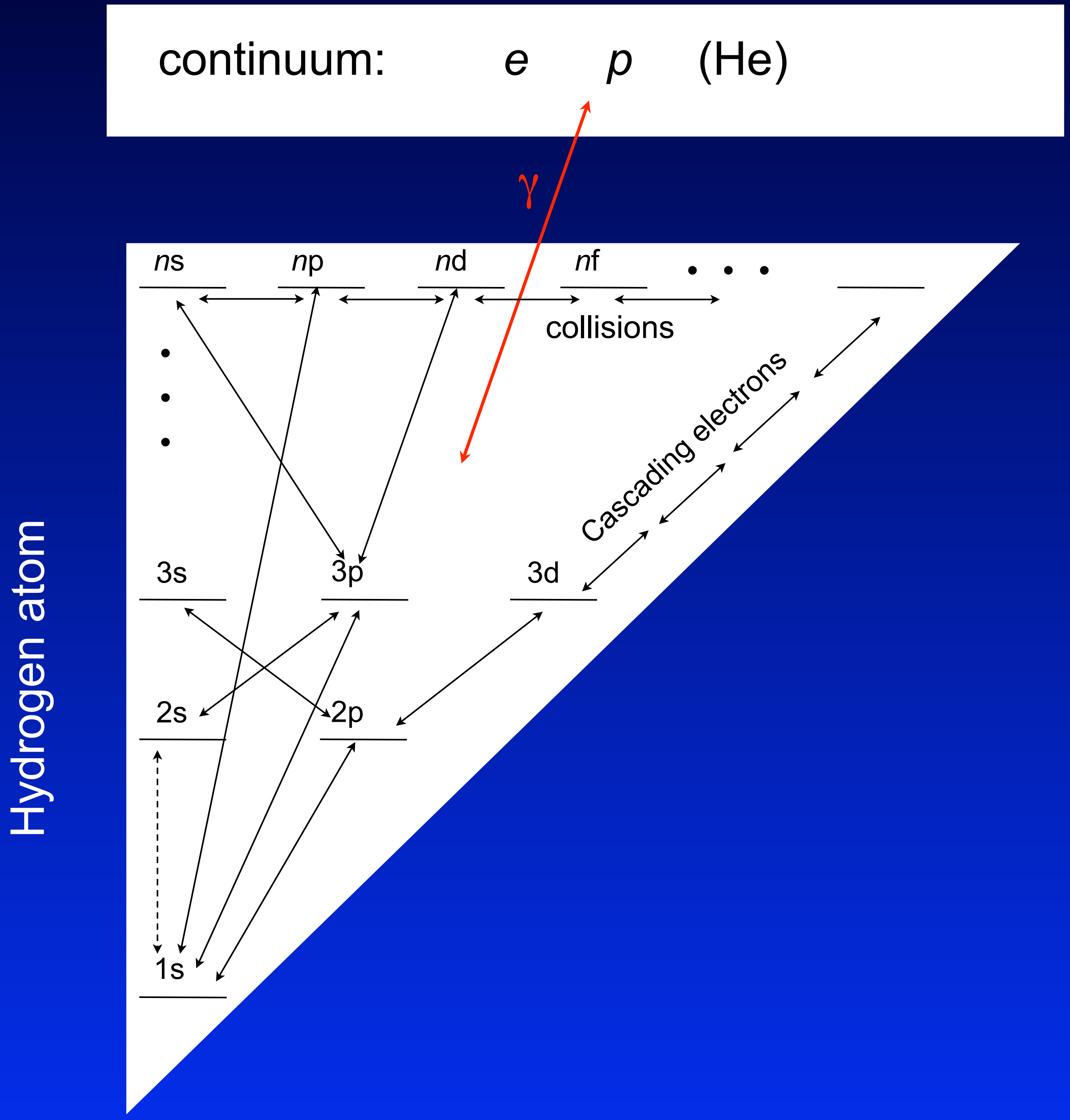
Deviations from Statistical Equilibrium in the upper levels

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



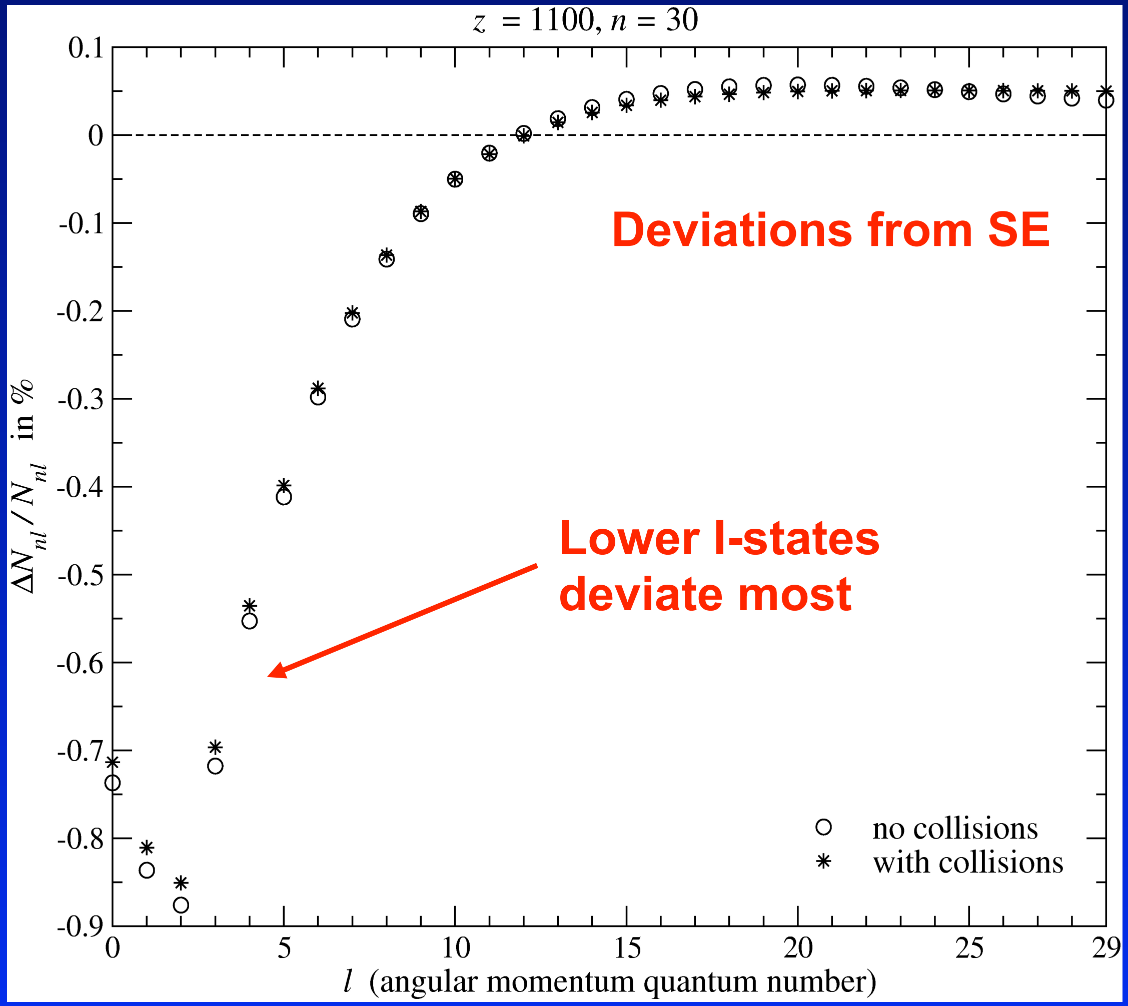
- **recombination & photoionization**
  - **n small → l-dependence not drastic**
  - **high shells → more likely to l<<n**
  - **large n → *induced* recombination**
- **many radiative dipole transitions**
  - **Lyman-series optically thick**
  - **$\Delta l = \pm 1$ restriction (electron cascade)**
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

Basis for Recfast computation (Seager et al. 2000)

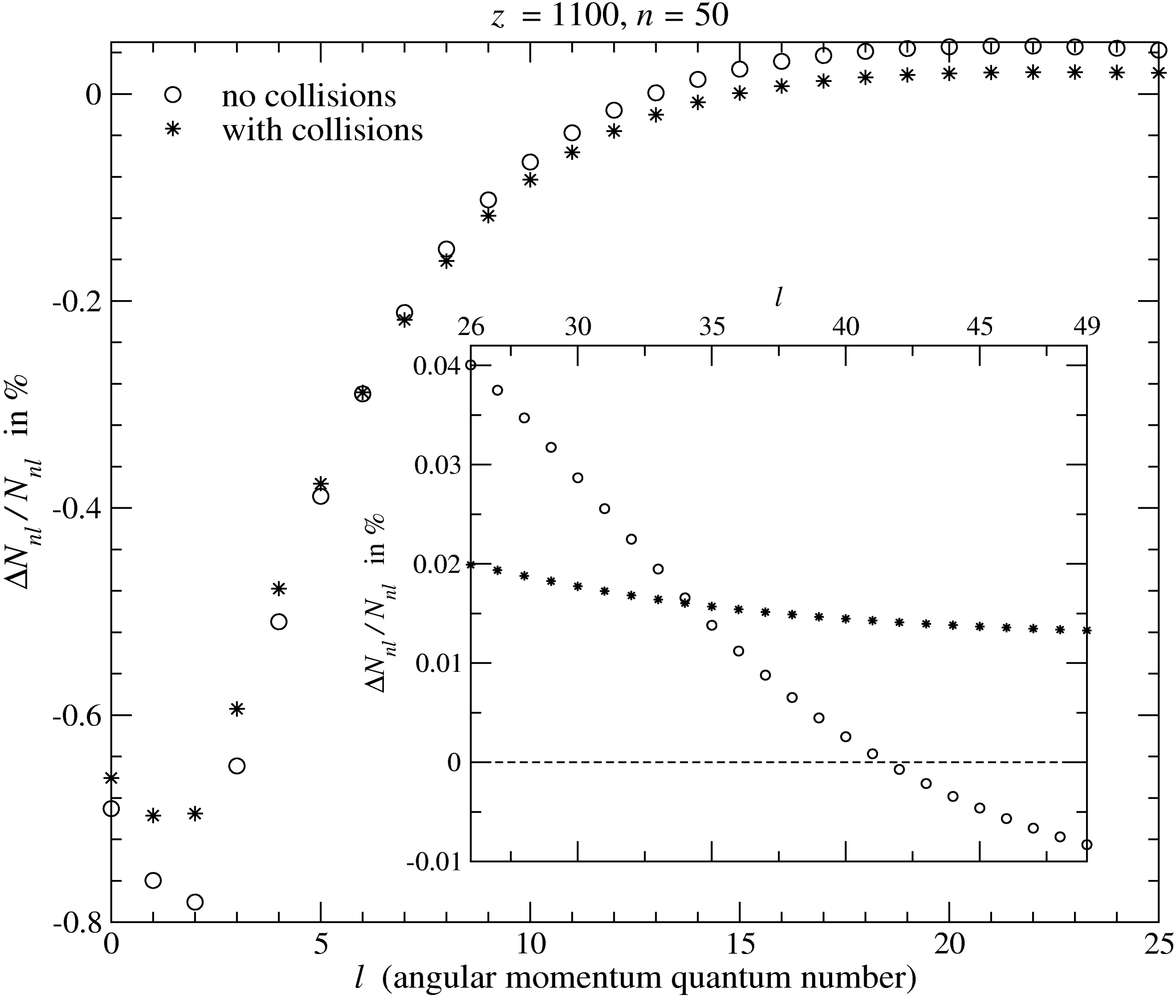
$$N_{nl} = \frac{2l+1}{n^2} N_{\mathrm{tot},n}$$

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



Deviations from SE

Lower l-states deviate most



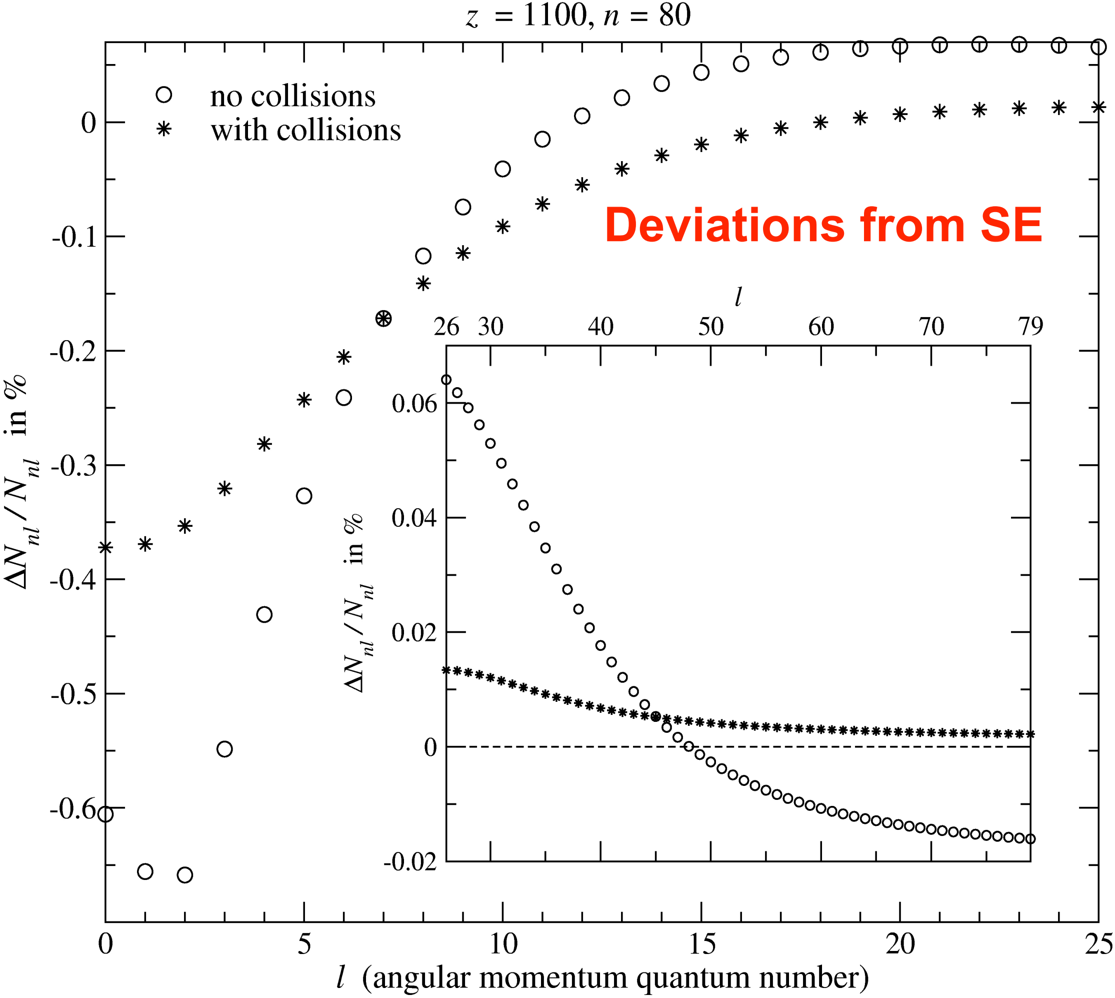
JC, Rubino-Martin & Sunyaev, MNRAS, 2007

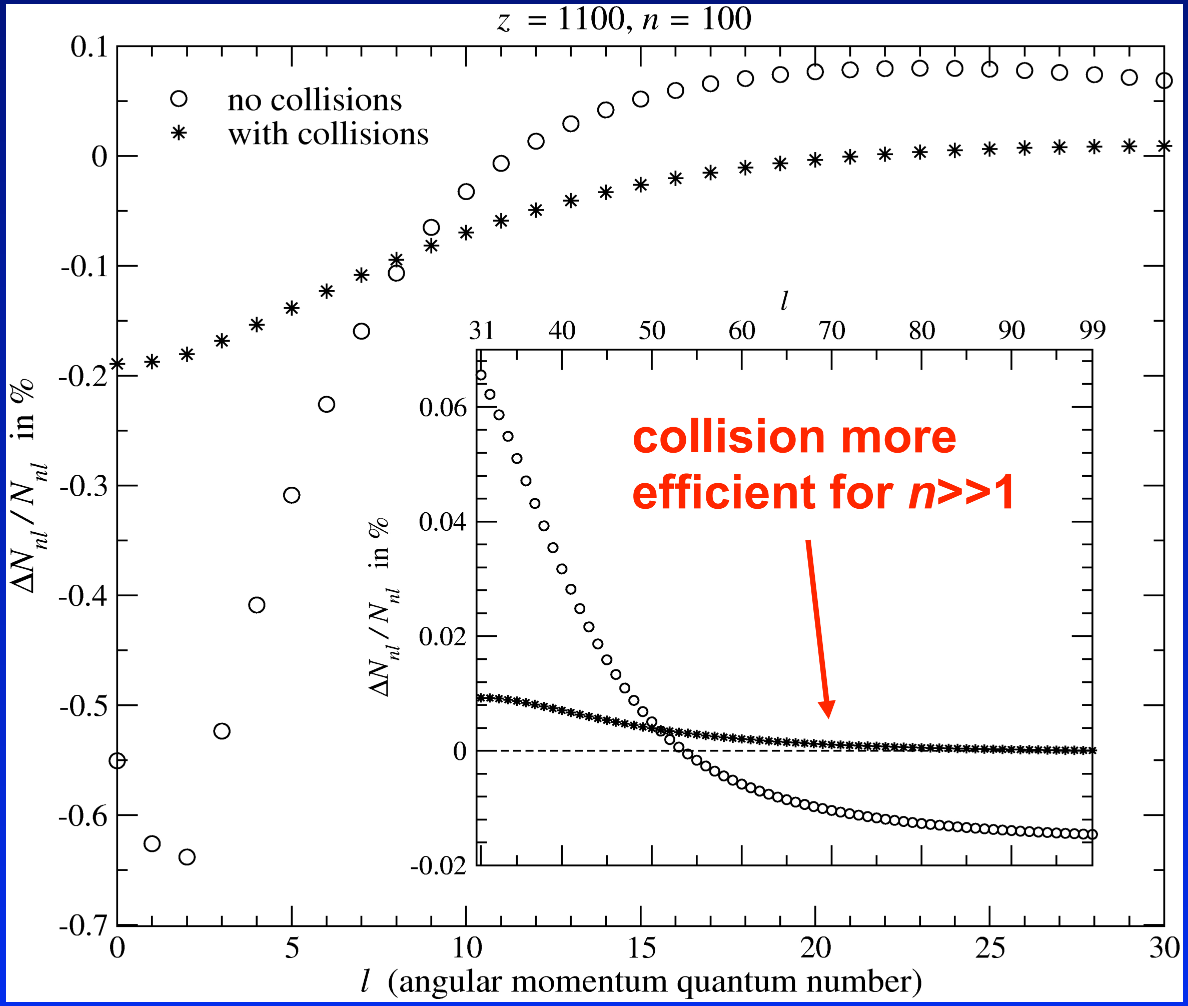
Deviations from Statistical Equilibrium in the upper levels

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 ~ $n_{\max}$





collision more efficient for n>>1

JC, Rubino-Martin & Sunyaev, MNRAS, 2007

Deviations from Statistical Equilibrium in the upper levels

Basis for Recfast computation (Seager et al. 2000)

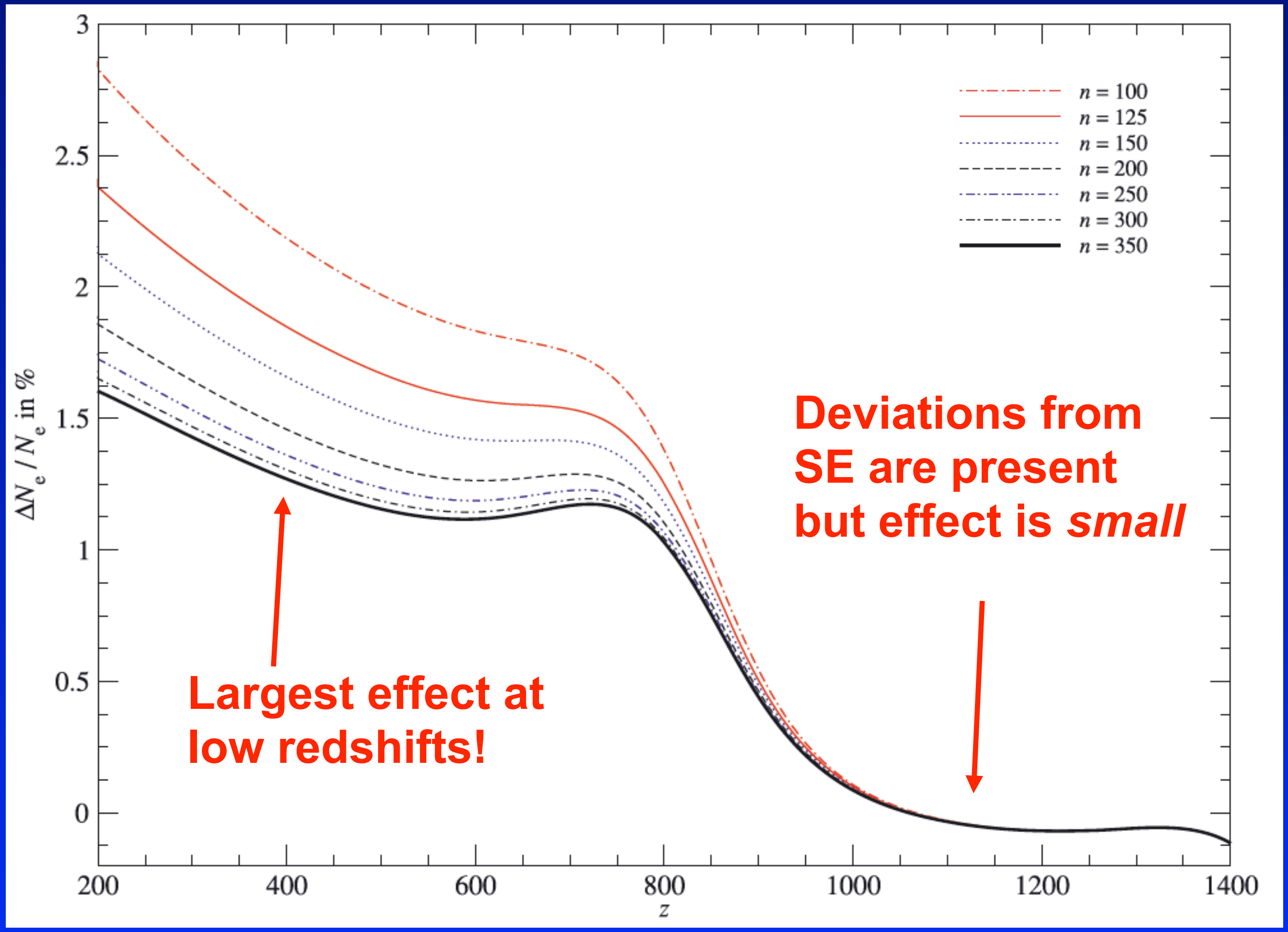
$$N_{nl} = \frac{2l+1}{n^2} N_{\mathrm{tot},n}$$

- 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 things are to SE
- Complexity of problem scales like ~ n^2_{max}
- But problem very *sparse* (Grin & Hirata, 2010; JC, Vasil & Dursi, 2010)



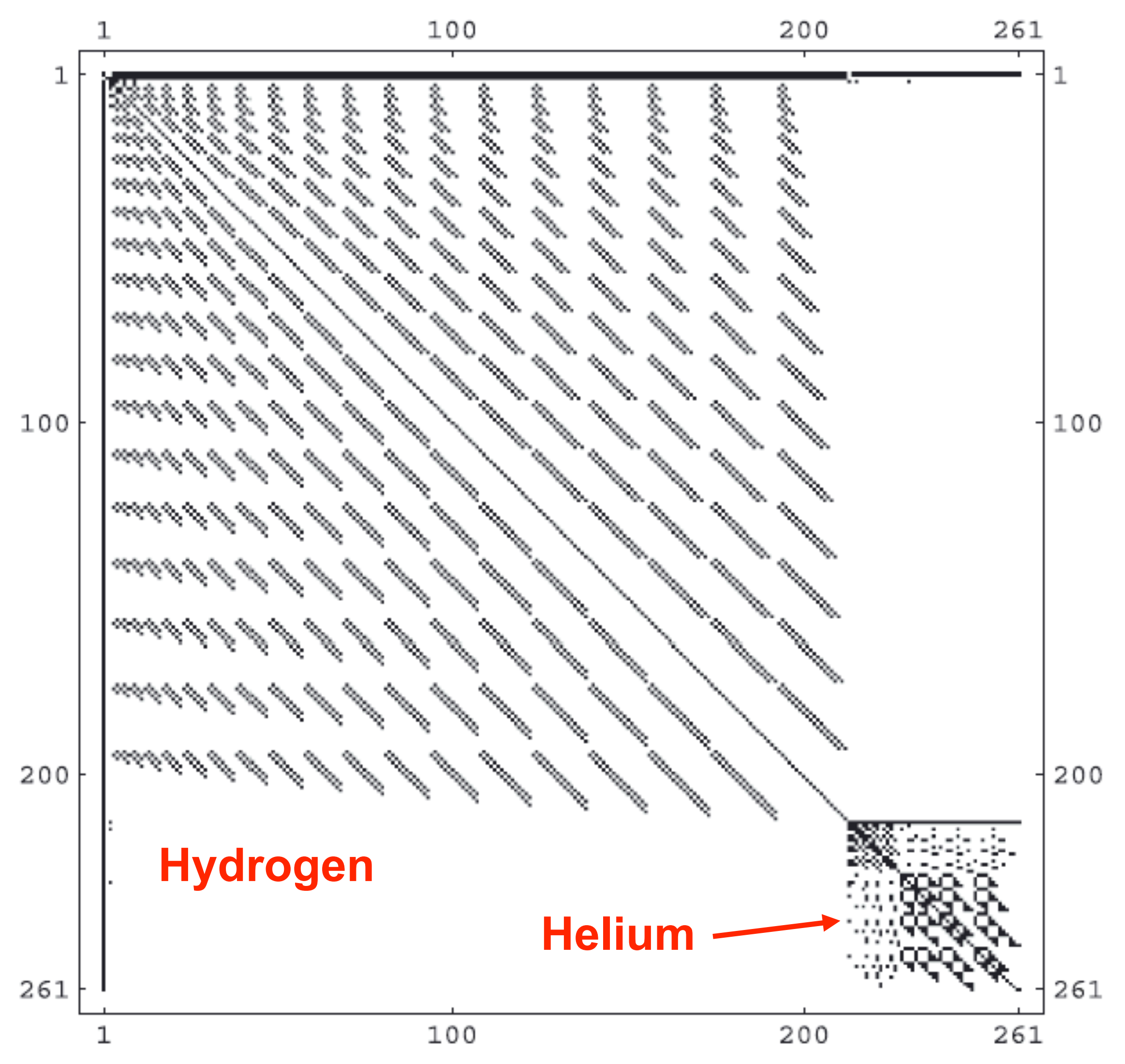
Largest effect at low redshifts!

Deviations from SE are present but effect is *small*

JC, Vasil & Dursi, MNRAS, 2010

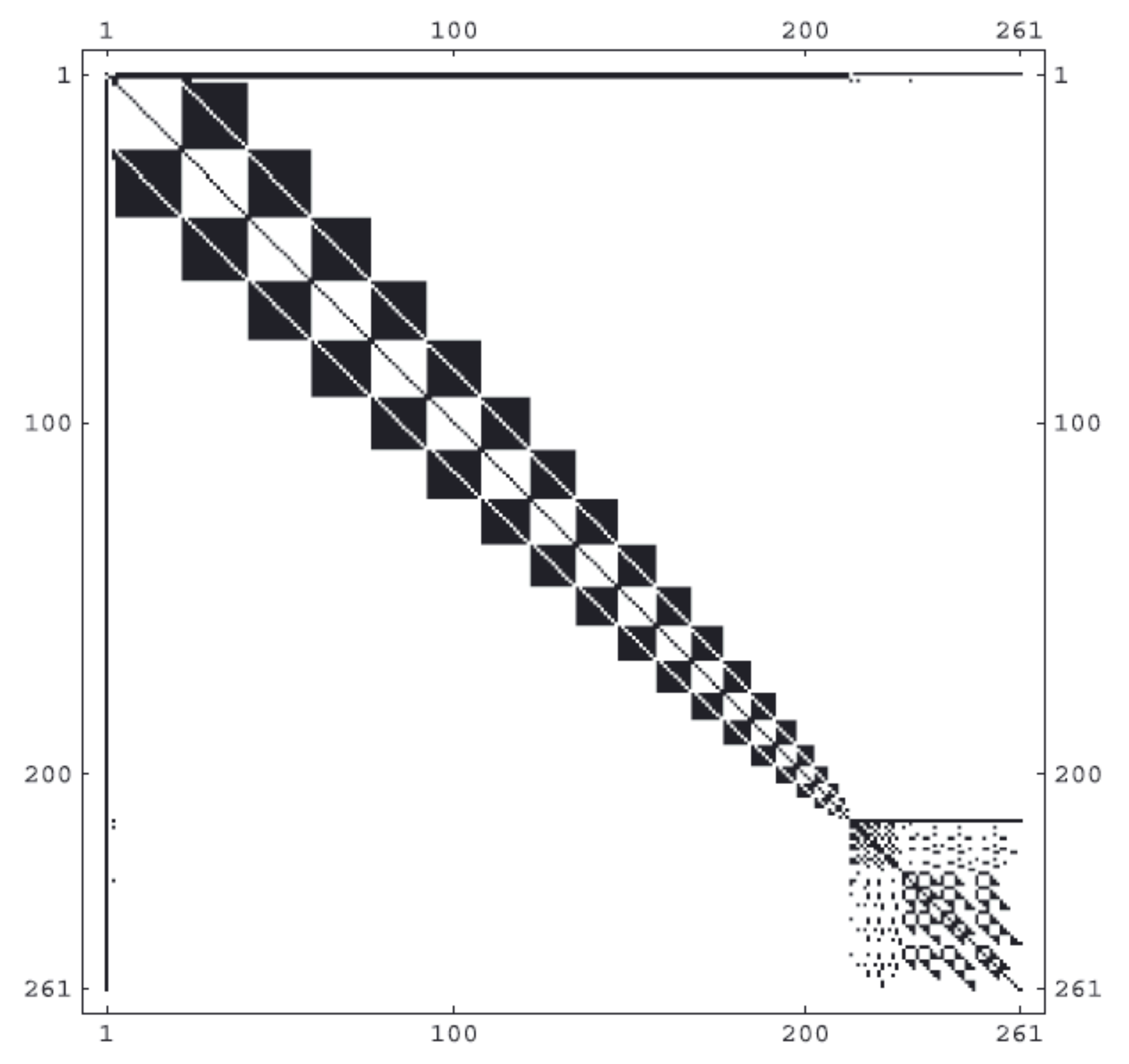
Sparsity of the problem and effect of ordering

20 shell Hydrogen + 5 shell Helium model



Shell-by-Shell ordering

$$1s, 2s, 2p, 3s, 3p, 3d, \ldots$$

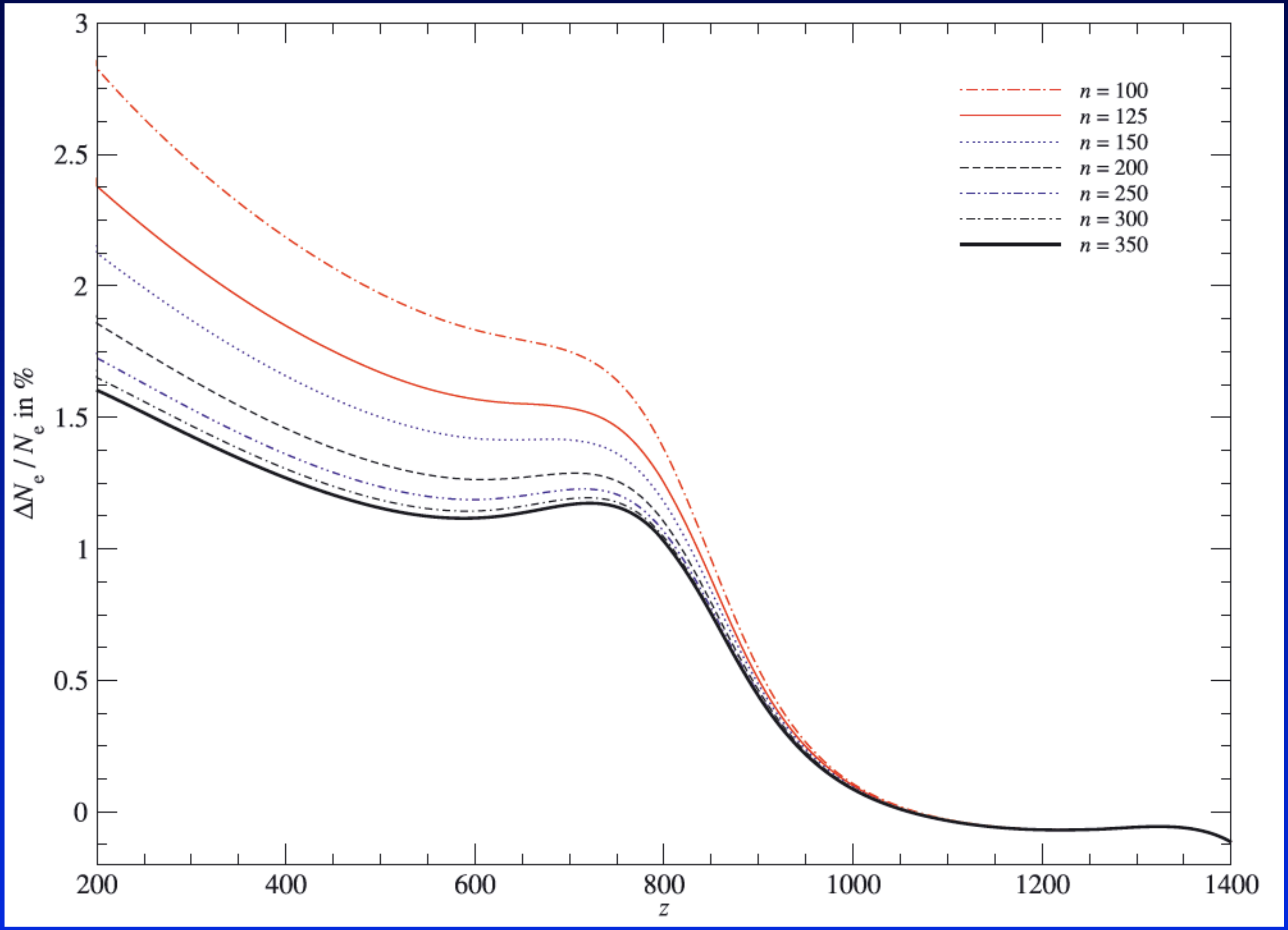


Angular momentum ordering

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

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

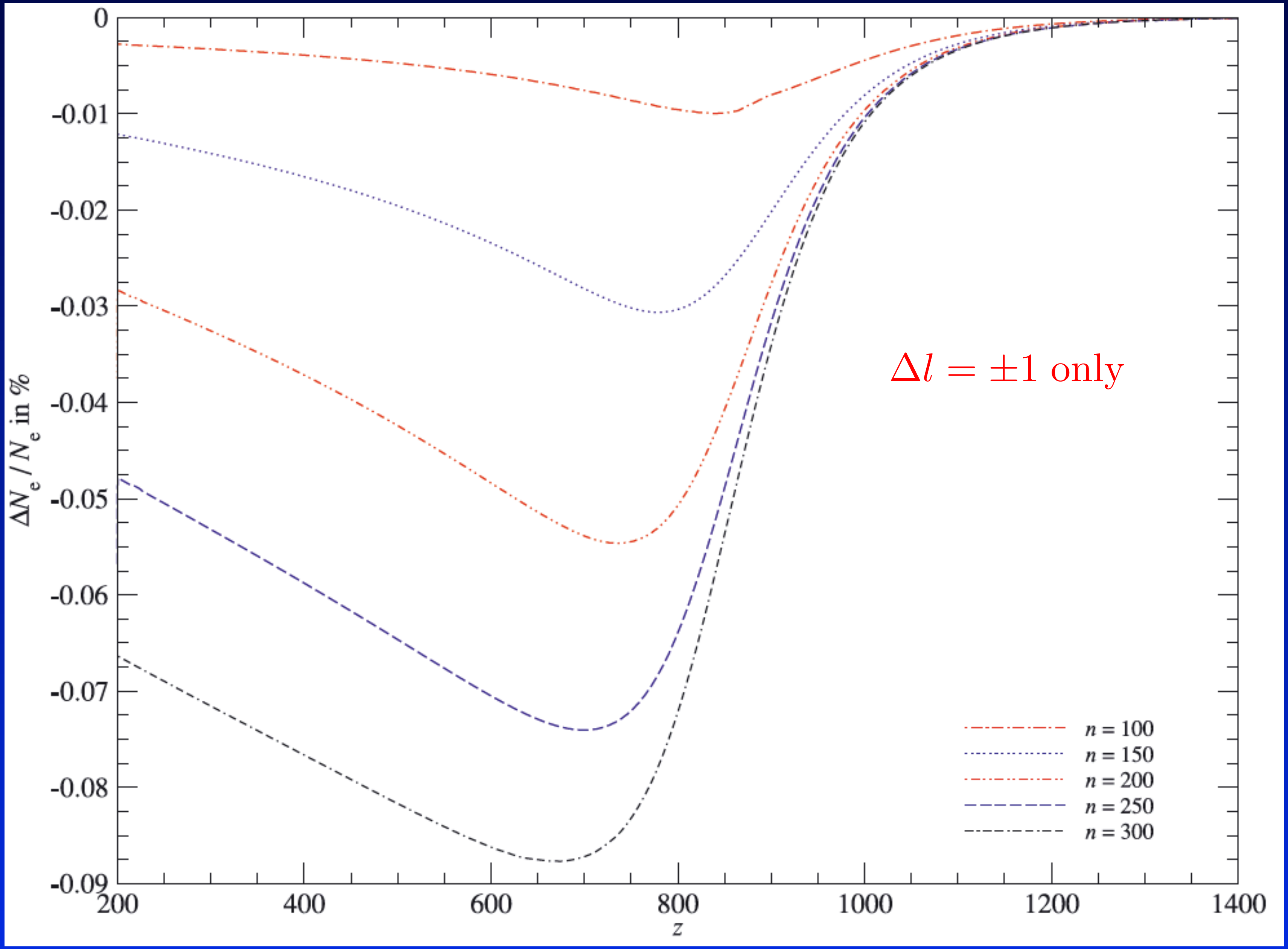
Collisions during hydrogen recombination



- **effective recombination cross section of the atom matters most at low *z***

JC, Vasil & Dursi, MNRAS, 2010

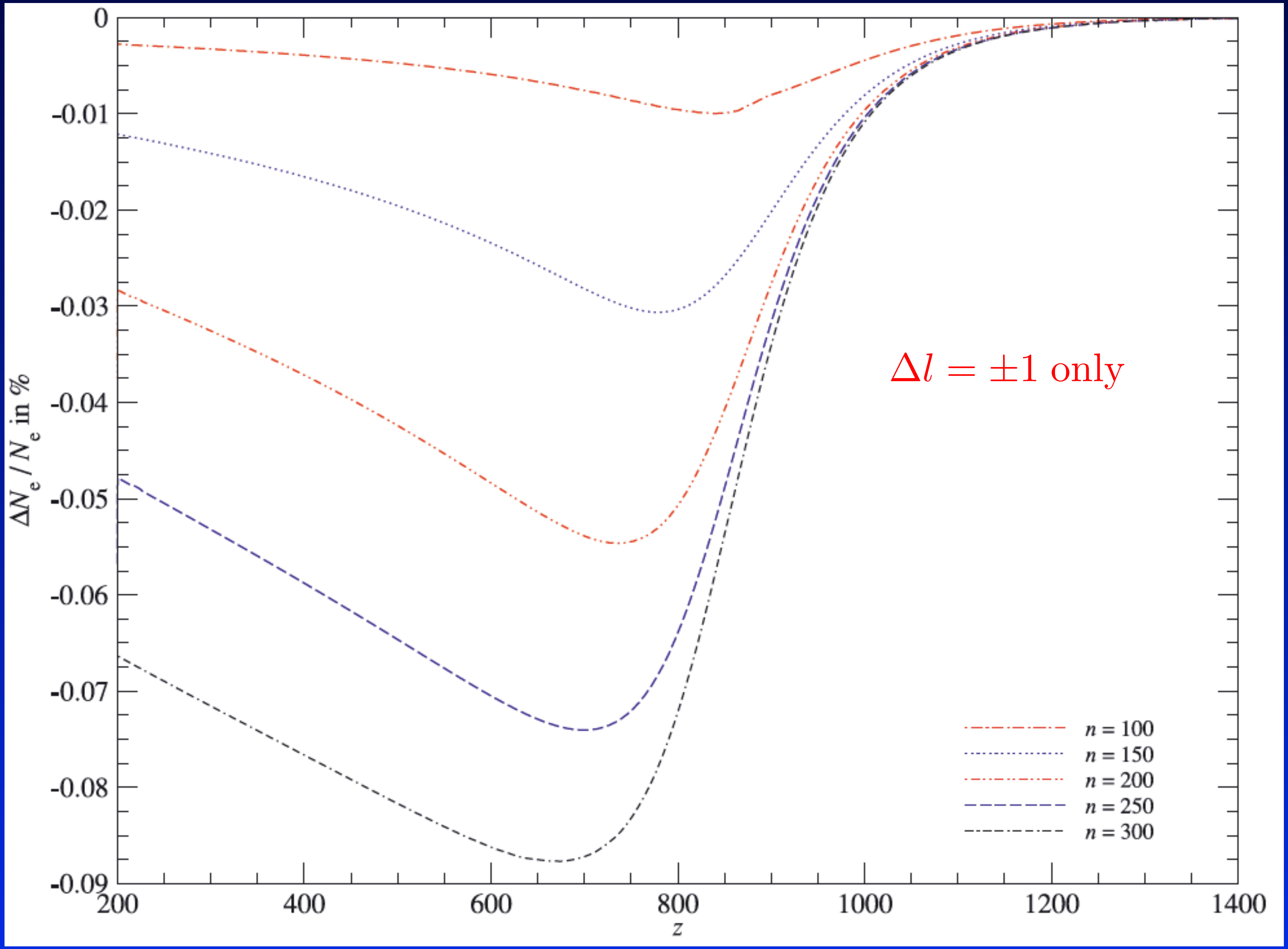
Collisions during hydrogen recombination



- **effective recombination cross section of the atom matters most at low *z***
- **collisions increase recombination rate**

JC, Vasil & Dursi, MNRAS, 2010

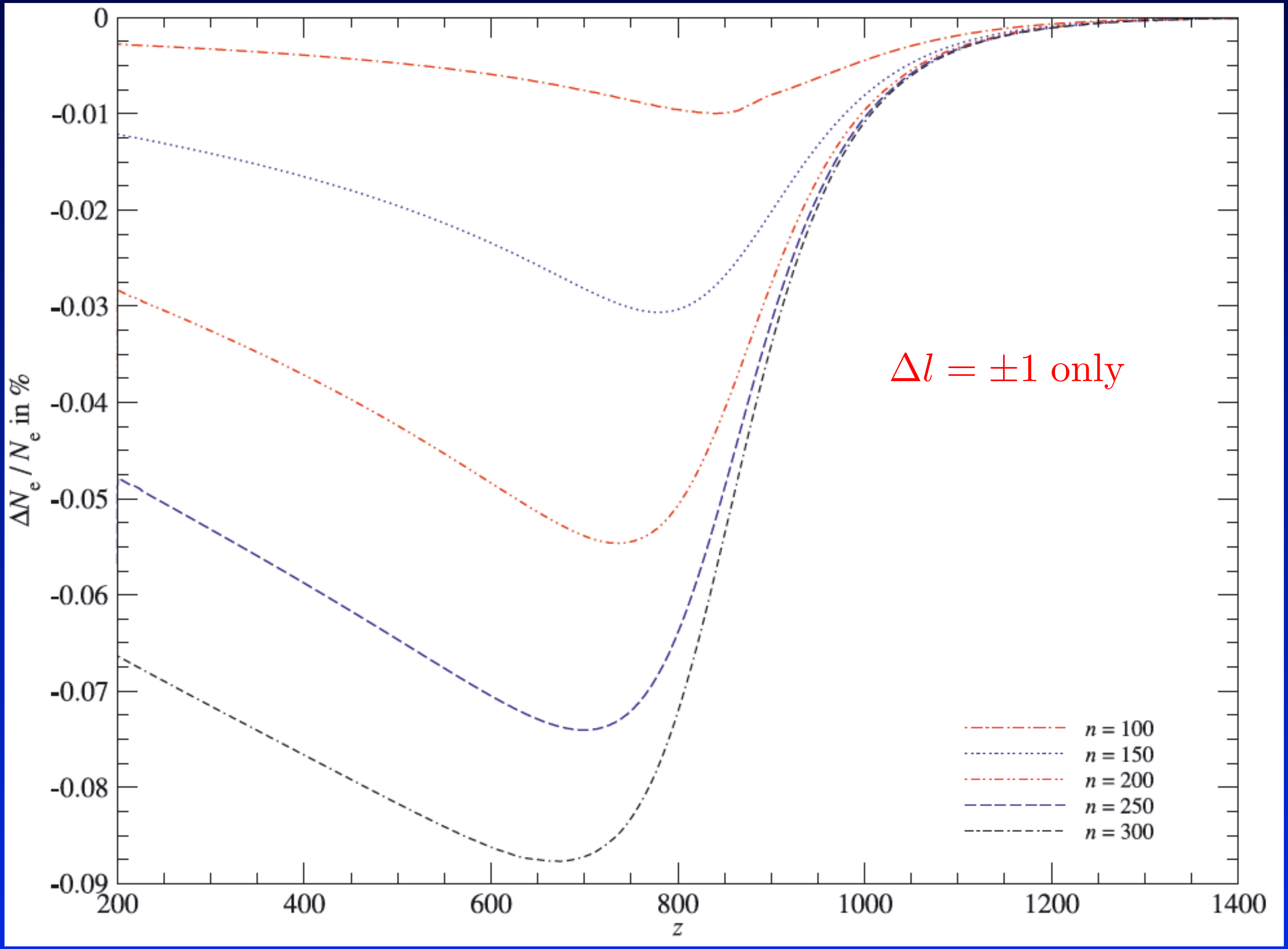
Collisions during hydrogen recombination



- **effective recombination cross section of the atom matters most at low *z***
- **collisions increase recombination rate**
- **effect on ionization history remains small**

JC, Vasil & Dursi, MNRAS, 2010

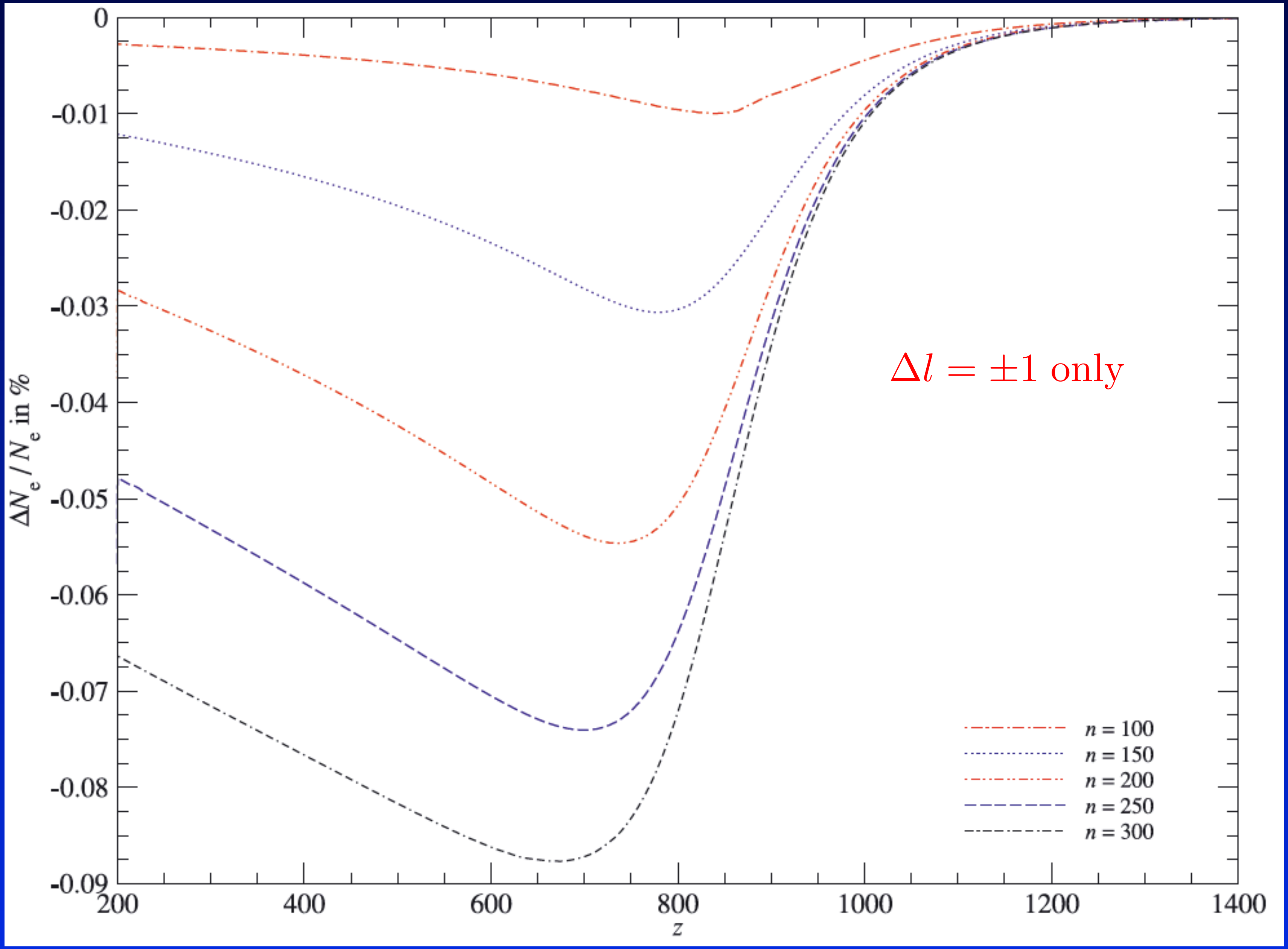
Collisions during hydrogen recombination



- 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

JC, Vasil & Dursi, MNRAS, 2010

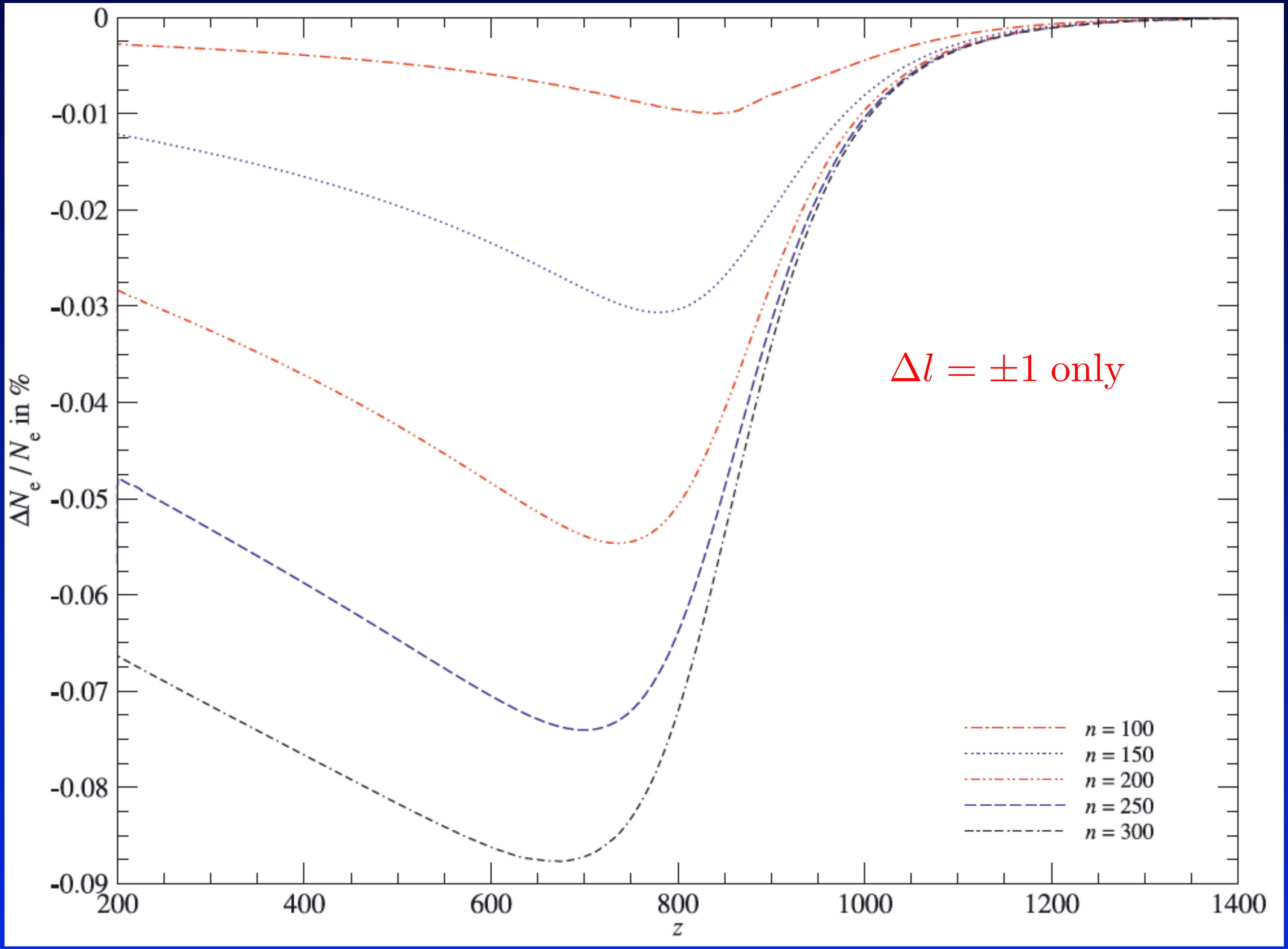
Collisions during hydrogen recombination



- 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
- this should be checked, even if the final result may not dramatically change things

JC, Vasil & Dursi, MNRAS, 2010

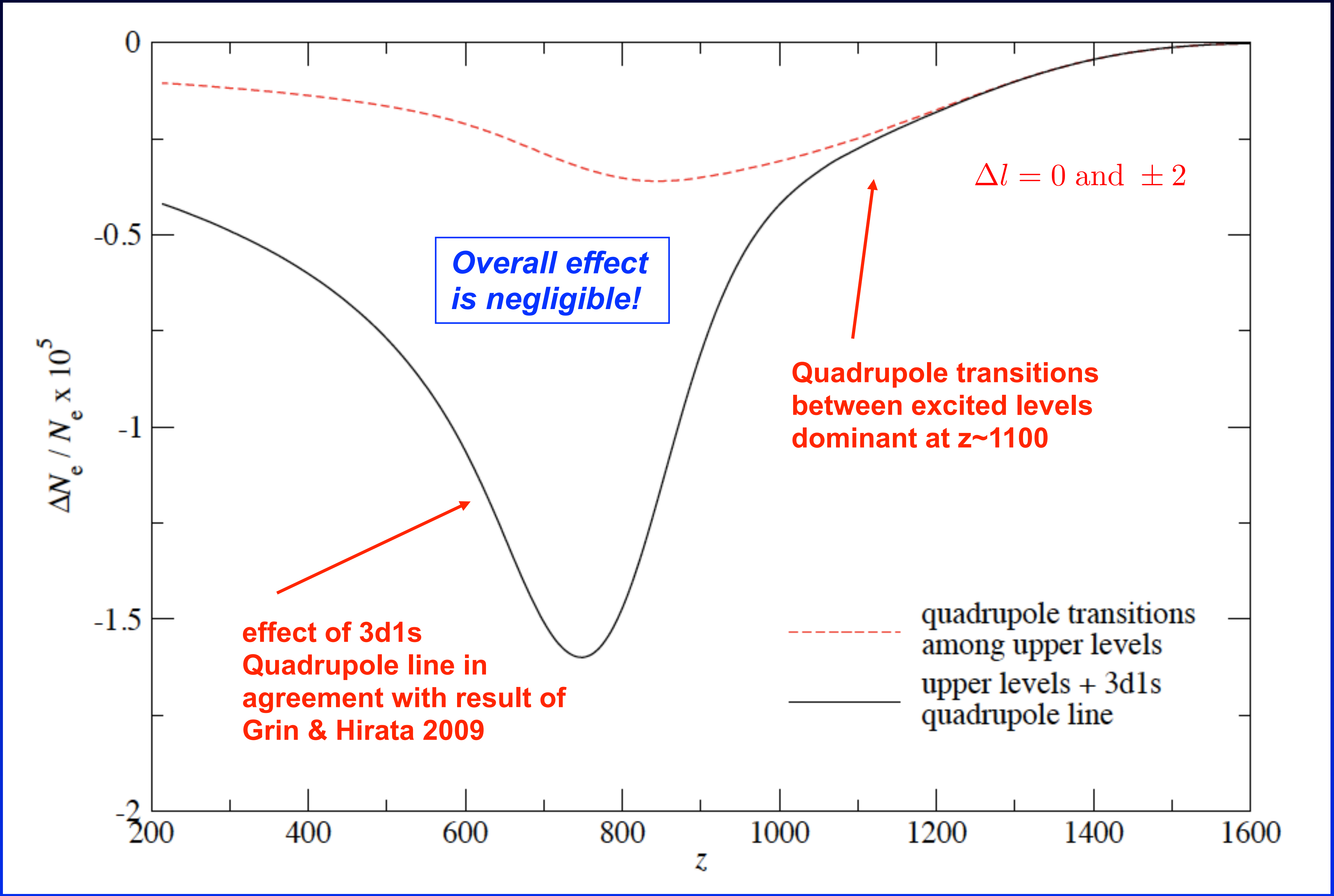
Collisions during hydrogen recombination



- **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**
- **this should be checked, even if the final result may not dramatically change things**
- *updated rates (with large Δl) available!*

JC, Vasil & Dursi, MNRAS, 2010

Quadrupole lines during hydrogen recombination



Overall effect is negligible!

Quadrupole transitions between excited levels dominant at z~1100

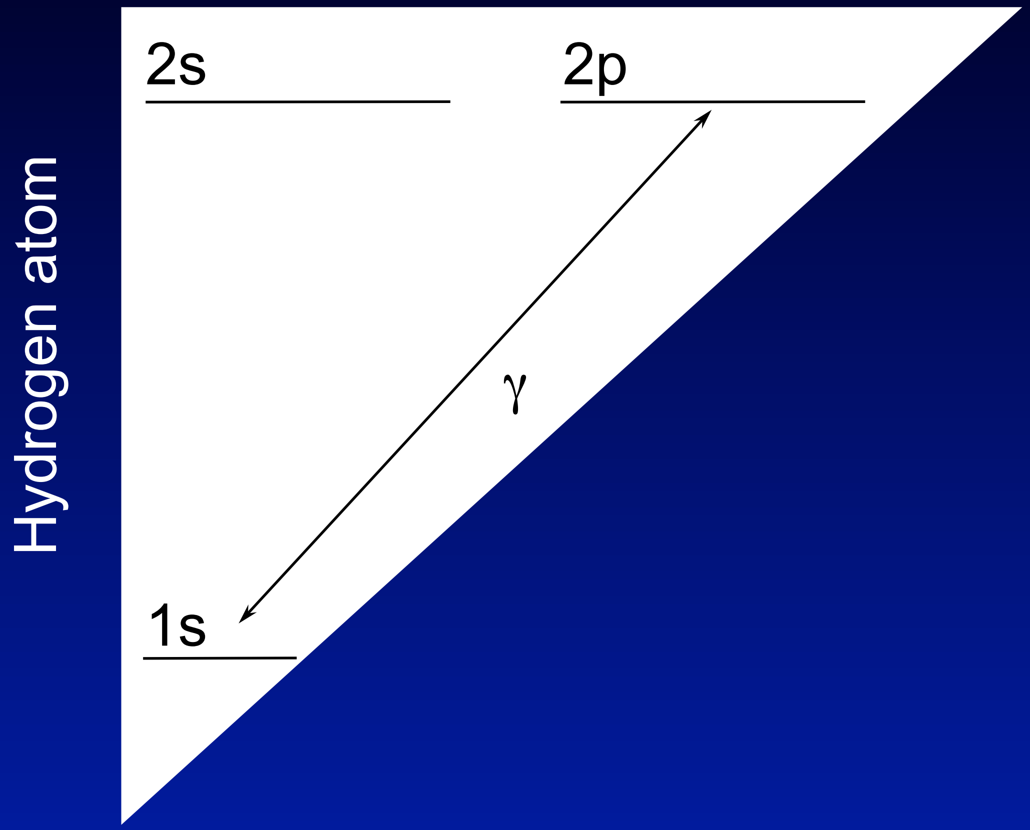
effect of 3d1s Quadrupole line in agreement with result of Grin & Hirata 2009

JC, Fung & Switzer, 2011

Two-photon transitions from the upper levels and the Lyman-α escape problem

Sobolev approximation

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



- To solve the coupled system of rate-equations

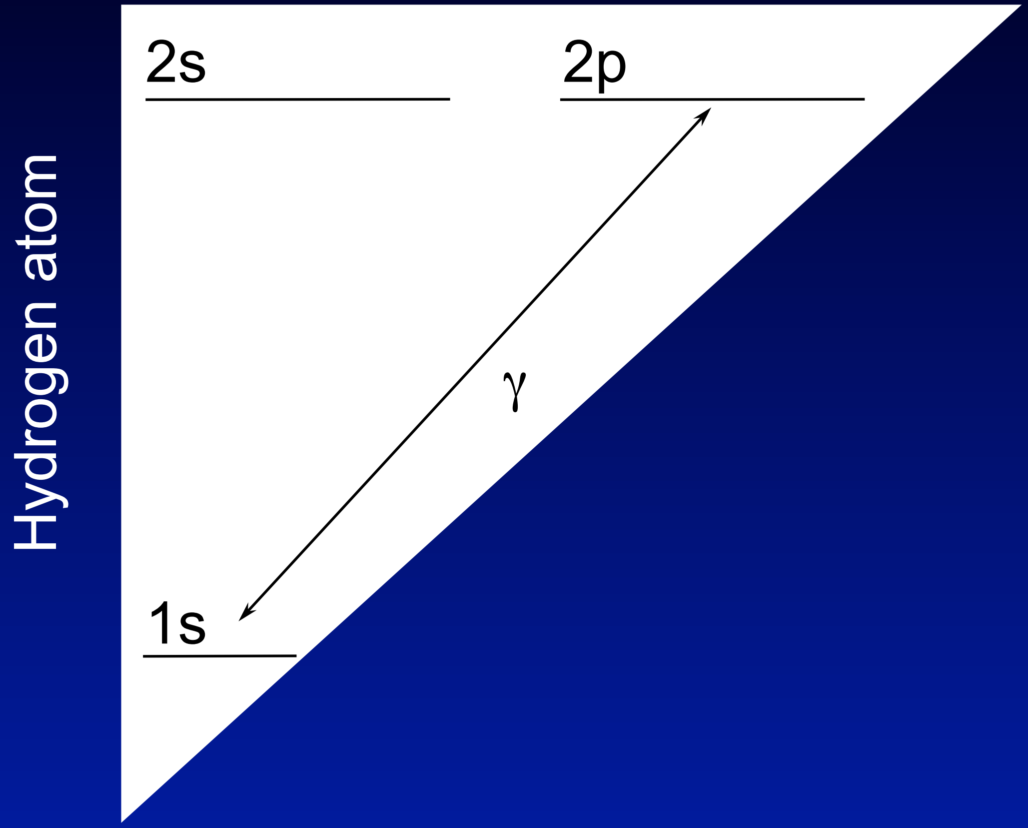
→ need to know mean intensity across the Ly-α (& Ly-n) resonance at different times

→ solution by introducing the *escape probability*

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

Sobolev approximation

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



- To solve the coupled system of rate-equations

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

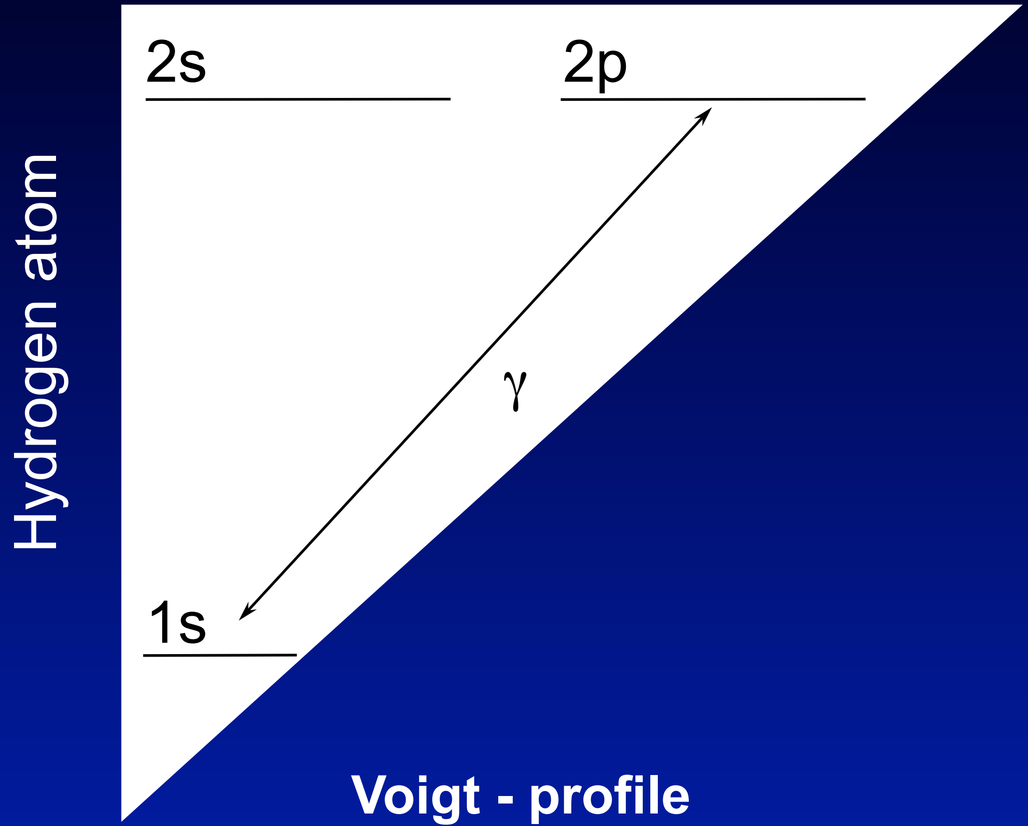
  → solution by introducing the *escape probability*

  → *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*

Sobolev approximation

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



- To solve the coupled system of rate-equations

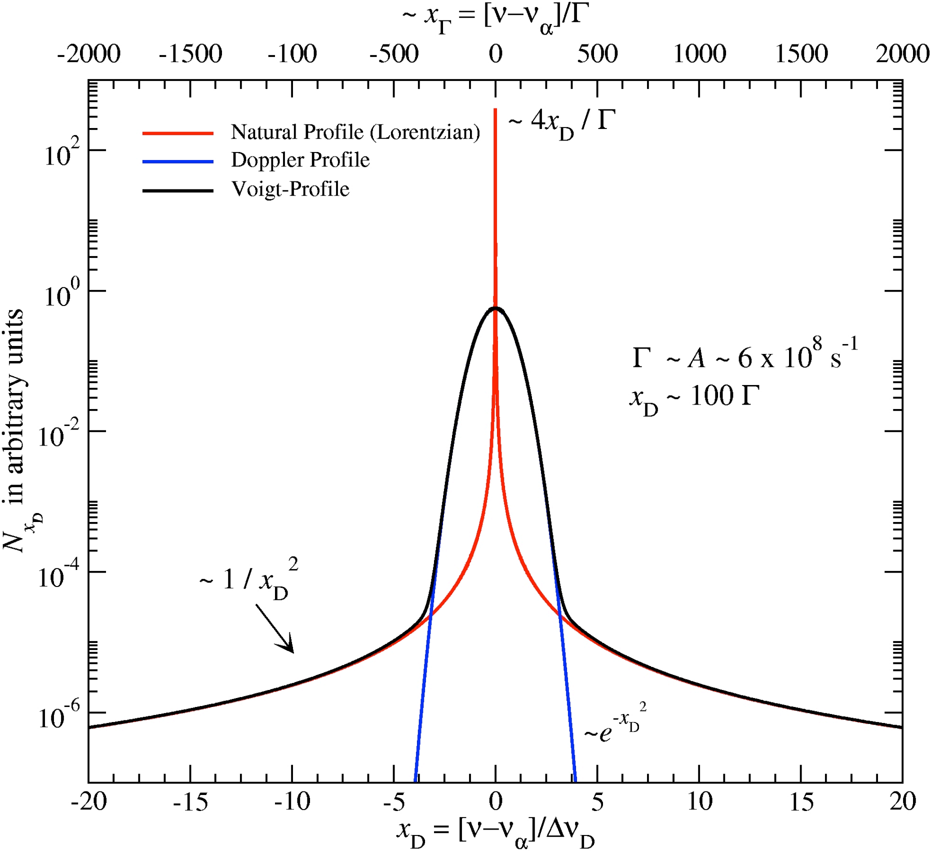
  → need to know mean intensity across the Ly-α (& Ly-n) resonance at different times

  → solution by introducing the *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*

Voigt - profile

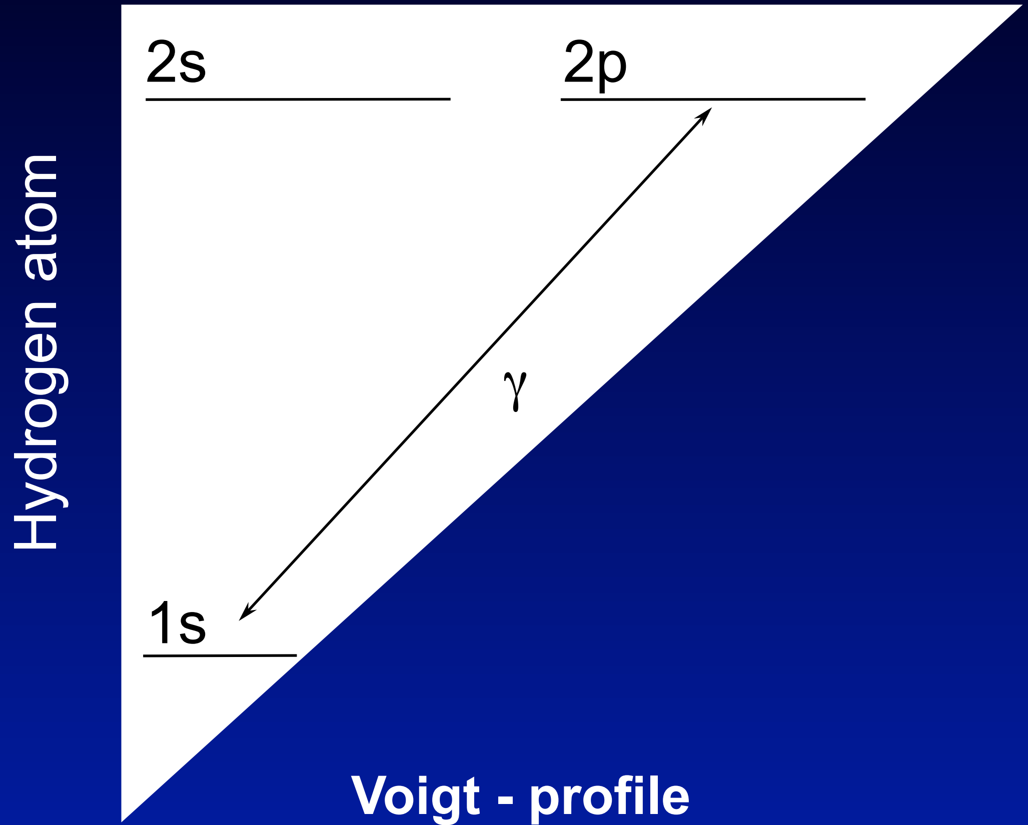


Doppler width

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

Sobolev approximation

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



- To solve the coupled system of rate-equations

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

  → solution by introducing the *escape probability*

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

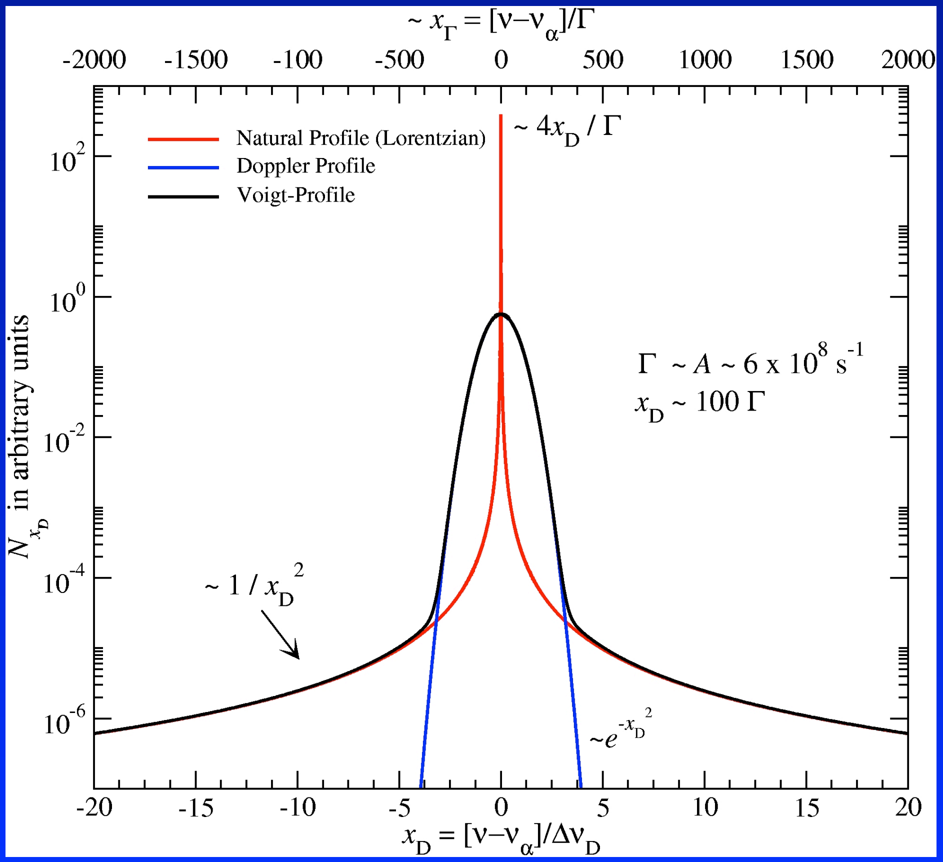
- Main assumptions of Sobolev approximation
  - populations of level + radiation field *quasi-stationary*
  - every ‘scattering’ leads to *complete redistribution*
  - emission & absorption profiles have the *same shape*

- Sobolev escape probability & optical depth

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

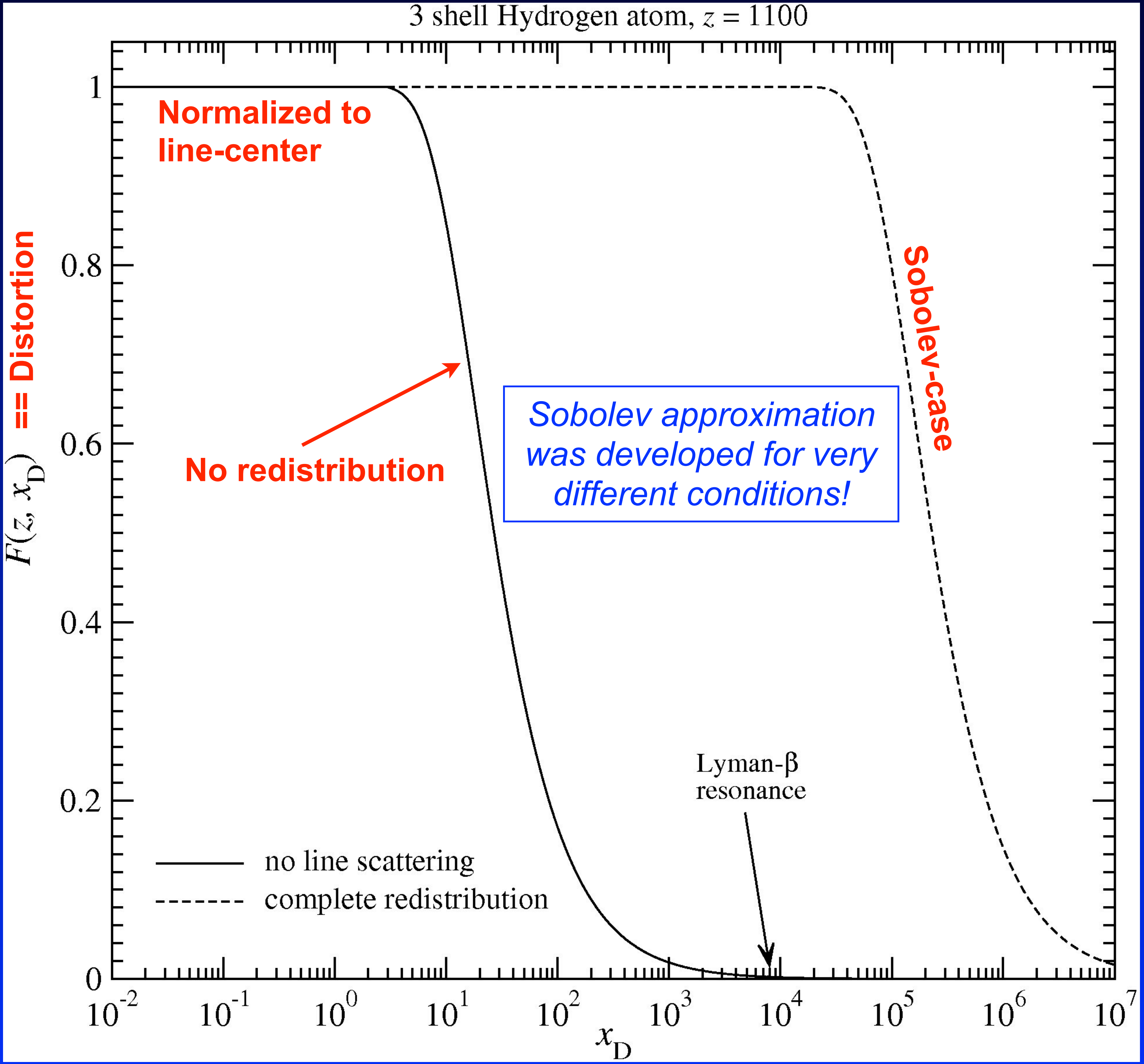
$$\tau_{\rm S} = \frac{c\,\sigma_{\rm r} N_{\rm 1s}}{H} \frac{\Delta\nu_{\rm D}}{\nu} = \frac{g_{\rm 2p}}{g_{\rm 1s}} \frac{A_{21}\lambda_{21}^3}{8\pi H} N_{\rm 1s}$$

Voigt - profile



Problems with Sobolev approximation:

Complete redistribution ⟺ partial redistribution



Normalized to line-center

No redistribution

Sobolev approximation was developed for very different conditions!

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})

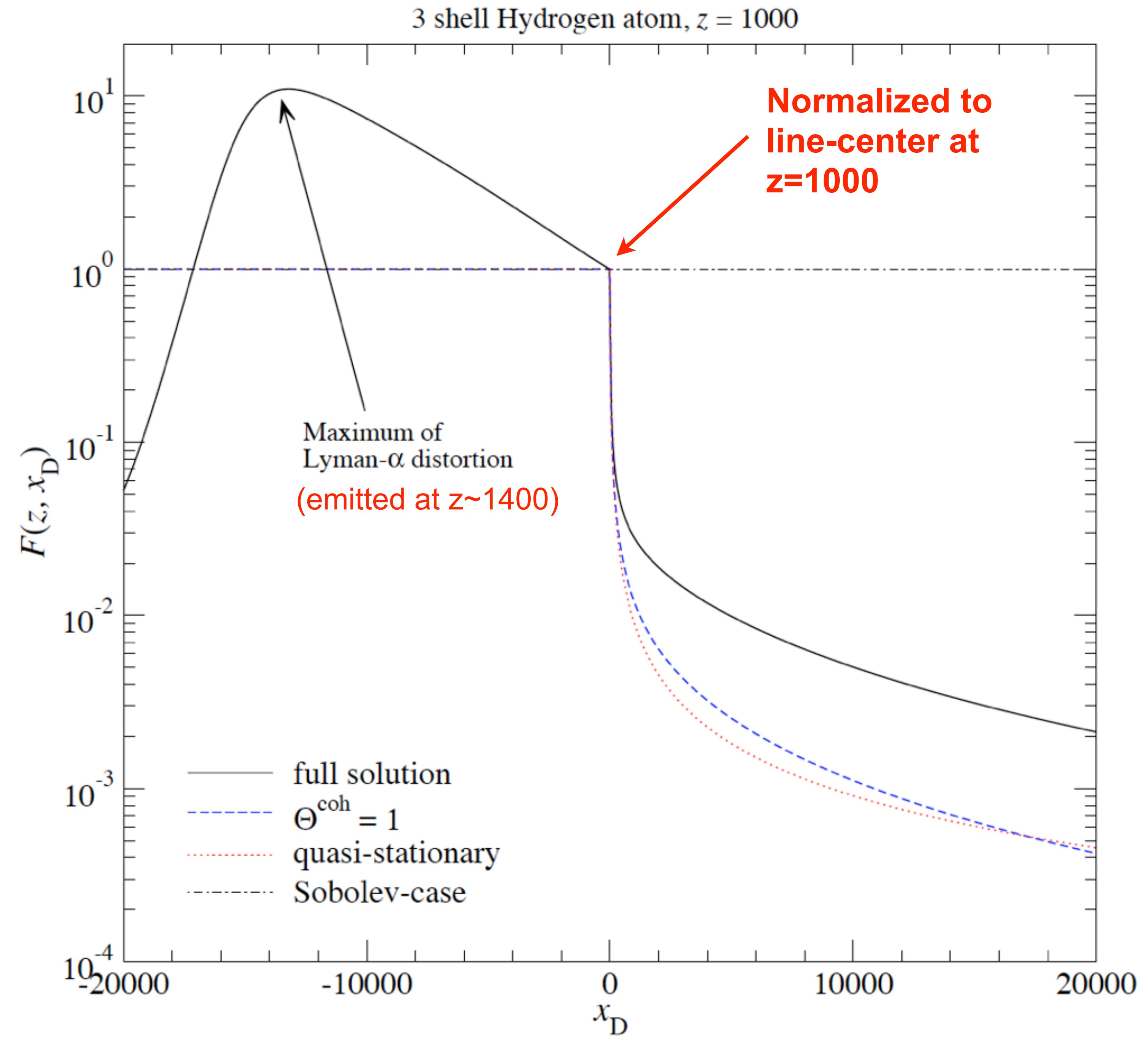
No redistribution case:

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

JC & Sunyaev, 2009

Problems with Sobolev approximation:

Time dependence of radiation field



Normalized to line-center at z=1000

(emitted at z~1400)

- Evolution close to line center is indeed quasi-stationary
- non-stationarity important in the wings

  $\Longrightarrow$ *information* takes time to travel from line center to the wings
- For support of 2p level even spectrum up to $|x_D| \sim 10^4$ is important

  $\Longrightarrow$ *time dependence* has to be included

JC & Sunyaev, 2009

Problems with Sobolev approximation:

Difference between emission and absorption profile

- Standard textbook:

Normalized Ly-α profile

$$\int \phi(\nu)\,\mathrm{d}\nu\,\mathrm{d}\Omega = 1$$

$$\frac{1}{c}\,\frac{\mathrm{d}N_\nu}{\mathrm{d}t}\bigg|_{\mathrm{Ly}-\alpha} = A_{21}\phi(\nu)\left[N_{2\mathrm{p}}(1+n_\nu) - \frac{g_{2\mathrm{p}}}{g_{1\mathrm{s}}}N_{1\mathrm{s}}n_\nu\right]$$

photon occupation number

Problems with Sobolev approximation:

Difference between emission and absorption profile

- Standard textbook:

Normalized Ly-α profile $\int \phi(\nu)\,\mathrm{d}\nu\,\mathrm{d}\Omega = 1$

$$\frac{1}{c}\frac{\mathrm{d}N_\nu}{\mathrm{d}t}\bigg|_{\mathrm{Ly}-\alpha} = A_{21}\phi(\nu)\left[N_{2\mathrm{p}}(1+n_\nu) - \frac{g_{2\mathrm{p}}}{g_{1\mathrm{s}}}N_{1\mathrm{s}}n_\nu\right]$$

photon occupation number

$$\Leftrightarrow\ \frac{1}{c}\frac{\mathrm{d}N_\nu}{\mathrm{d}t}\bigg|_{\mathrm{Ly}-\alpha} = A_{21}\frac{g_{2\mathrm{p}}}{g_{1\mathrm{s}}}N_{1\mathrm{s}}\,\phi(\nu)(1+n_\nu)\left[\frac{g_{1\mathrm{s}}N_{2\mathrm{p}}}{g_{2\mathrm{p}}N_{1\mathrm{s}}} - \frac{n_\nu}{1+n_\nu}\right]$$

Problems with Sobolev approximation:

Difference between emission and absorption profile

- Standard textbook:

Normalized Ly-α profile $\int \phi(\nu)\,\mathrm{d}\nu\,\mathrm{d}\Omega = 1$

$$\left.\frac{1}{c}\frac{\mathrm{d}N_\nu}{\mathrm{d}t}\right|_{\mathrm{Ly}-\alpha} = A_{21}\phi(\nu)\left[N_{\mathrm{2p}}(1+n_\nu) - \frac{g_{\mathrm{2p}}}{g_{\mathrm{1s}}}N_{\mathrm{1s}}n_\nu\right]$$

photon occupation number

$$\Leftrightarrow \left.\frac{1}{c}\frac{\mathrm{d}N_\nu}{\mathrm{d}t}\right|_{\mathrm{Ly}-\alpha} = A_{21}\frac{g_{\mathrm{2p}}}{g_{\mathrm{1s}}}N_{\mathrm{1s}}\,\phi(\nu)(1+n_\nu)\left[\frac{g_{\mathrm{1s}}N_{\mathrm{2p}}}{g_{\mathrm{2p}}N_{\mathrm{1s}}} - \frac{n_\nu}{1+n_\nu}\right]$$

In equilibrium: $\frac{n_\nu}{1+n_\nu} = \mathrm{e}^{-\frac{h\nu}{kT_\gamma}}$ and $\frac{g_{\mathrm{1s}}N_{\mathrm{2p}}}{g_{\mathrm{2p}}N_{\mathrm{1s}}} = \mathrm{e}^{-\frac{h\nu_{21}}{kT_{\mathrm{m}}}} \Longrightarrow T_\gamma \equiv T_{\mathrm{m}}$ and $\nu \equiv \nu_{21}$

Problems with Sobolev approximation:

Difference between emission and absorption profile

- Standard textbook:

Normalized Ly-α profile $\int \phi(\nu)\,\mathrm{d}\nu\,\mathrm{d}\Omega = 1$

$$\frac{1}{c}\frac{\mathrm{d}N_\nu}{\mathrm{d}t}\bigg|_{\mathrm{Ly-}\alpha} = A_{21}\phi(\nu)\left[N_{\mathrm{2p}}(1+n_\nu) - \frac{g_{\mathrm{2p}}}{g_{\mathrm{1s}}}N_{\mathrm{1s}}n_\nu\right]$$

photon occupation number

$$\Leftrightarrow \frac{1}{c}\frac{\mathrm{d}N_\nu}{\mathrm{d}t}\bigg|_{\mathrm{Ly-}\alpha} = A_{21}\frac{g_{\mathrm{2p}}}{g_{\mathrm{1s}}}N_{\mathrm{1s}}\,\phi(\nu)(1+n_\nu)\left[\frac{g_{\mathrm{1s}}N_{\mathrm{2p}}}{g_{\mathrm{2p}}N_{\mathrm{1s}}} - \frac{n_\nu}{1+n_\nu}\right]$$

In equilibrium: $\frac{n_\nu}{1+n_\nu} = \mathrm{e}^{-\frac{h\nu}{kT_\gamma}}$ and $\frac{g_{\mathrm{1s}}N_{\mathrm{2p}}}{g_{\mathrm{2p}}N_{\mathrm{1s}}} = \mathrm{e}^{-\frac{h\nu_{21}}{kT_{\mathrm{m}}}} \implies T_\gamma \equiv T_{\mathrm{m}}$ and $\nu \equiv \nu_{21}$

Only fulfilled at line center!

Detailed balance not guaranteed in the line wings!

Problems with Sobolev approximation:

Difference between emission and absorption profile

- Standard textbook:

Normalized Ly-α profile

$$\int \phi(\nu)\,\mathrm{d}\nu\,\mathrm{d}\Omega = 1$$

$$\frac{1}{c}\frac{\mathrm{d}N_\nu}{\mathrm{d}t}\bigg|_{\mathrm{Ly}-\alpha} = A_{21}\phi(\nu)\left[N_{2\mathrm{p}}(1+n_\nu) - \frac{g_{2\mathrm{p}}}{g_{1\mathrm{s}}}N_{1\mathrm{s}}n_\nu\right]$$

photon occupation number

$$\Leftrightarrow \frac{1}{c}\frac{\mathrm{d}N_\nu}{\mathrm{d}t}\bigg|_{\mathrm{Ly}-\alpha} = A_{21}\frac{g_{2\mathrm{p}}}{g_{1\mathrm{s}}}N_{1\mathrm{s}}\,\phi(\nu)(1+n_\nu)\left[\frac{g_{1\mathrm{s}}N_{2\mathrm{p}}}{g_{2\mathrm{p}}N_{1\mathrm{s}}} - \frac{n_\nu}{1+n_\nu}\right]$$

In equilibrium: $\frac{n_\nu}{1+n_\nu} = \mathrm{e}^{-\frac{h\nu}{kT_\gamma}}$ and $\frac{g_{1\mathrm{s}}N_{2\mathrm{p}}}{g_{2\mathrm{p}}N_{1\mathrm{s}}} = \mathrm{e}^{-\frac{h\nu_{21}}{kT_\mathrm{m}}} \implies T_\gamma \equiv T_\mathrm{m}$ and $\nu \equiv \nu_{21}$

Only fulfilled at line center!

Detailed balance not guaranteed in the line wings!

- Effective 1γ expression

$$\Rightarrow \frac{1}{c}\frac{\mathrm{d}N_\nu}{\mathrm{d}t}\bigg|_{\mathrm{Ly}-\alpha} = A_{21}\frac{g_{2\mathrm{p}}}{g_{1\mathrm{s}}}N_{1\mathrm{s}}\,\phi(\nu)(1+n_\nu)\left[\frac{g_{1\mathrm{s}}N_{2\mathrm{p}}}{g_{2\mathrm{p}}N_{1\mathrm{s}}} - \mathrm{e}^{\frac{h(\nu-\nu_{21})}{kT_\gamma}}\frac{n_\nu}{1+n_\nu}\right]$$

Problems with Sobolev approximation:

Difference between emission and absorption profile

- Standard textbook:

Normalized Ly-α profile $\int \phi(\nu)\,\mathrm{d}\nu\,\mathrm{d}\Omega = 1$

$$\frac{1}{c}\frac{\mathrm{d}N_\nu}{\mathrm{d}t}\bigg|_{\mathrm{Ly}-\alpha} = A_{21}\phi(\nu)\left[N_{2\mathrm{p}}(1+n_\nu) - \frac{g_{2\mathrm{p}}}{g_{1\mathrm{s}}}N_{1\mathrm{s}}n_\nu\right]$$

photon occupation number

$$\Leftrightarrow \frac{1}{c}\frac{\mathrm{d}N_\nu}{\mathrm{d}t}\bigg|_{\mathrm{Ly}-\alpha} = A_{21}\frac{g_{2\mathrm{p}}}{g_{1\mathrm{s}}}N_{1\mathrm{s}}\,\phi(\nu)(1+n_\nu)\left[\frac{g_{1\mathrm{s}}N_{2\mathrm{p}}}{g_{2\mathrm{p}}N_{1\mathrm{s}}} - \frac{n_\nu}{1+n_\nu}\right]$$

In equilibrium: $$\frac{n_\nu}{1+n_\nu} = \mathrm{e}^{-\frac{h\nu}{kT_\gamma}} \text{ and } \frac{g_{1\mathrm{s}}N_{2\mathrm{p}}}{g_{2\mathrm{p}}N_{1\mathrm{s}}} = \mathrm{e}^{-\frac{h\nu_{21}}{kT_\mathrm{m}}} \implies T_\gamma \equiv T_\mathrm{m} \text{ and } \nu \equiv \nu_{21}$$

Only fulfilled at line center!

Detailed balance not guaranteed in the line wings!

- Effective 1γ expression

$$\Rightarrow \frac{1}{c}\frac{\mathrm{d}N_\nu}{\mathrm{d}t}\bigg|_{\mathrm{Ly}-\alpha} = A_{21}\frac{g_{2\mathrm{p}}}{g_{1\mathrm{s}}}N_{1\mathrm{s}}\,\phi(\nu)(1+n_\nu)\left[\frac{g_{1\mathrm{s}}N_{2\mathrm{p}}}{g_{2\mathrm{p}}N_{1\mathrm{s}}} - \mathrm{e}^{\frac{h(\nu-\nu_{21})}{kT_\gamma}}\frac{n_\nu}{1+n_\nu}\right]$$

Asymmetry of emission and absorption profile

Problems with Sobolev approximation:

Difference between emission and absorption profile

- Standard textbook:

Normalized Ly-α profile

$$\int \phi(\nu)\,\mathrm{d}\nu\,\mathrm{d}\Omega = 1$$

$$\left.\frac{1}{c}\frac{\mathrm{d}N_\nu}{\mathrm{d}t}\right|_{\mathrm{Ly}-\alpha} = A_{21}\phi(\nu)\left[N_{2\mathrm{p}}(1+n_\nu) - \frac{g_{2\mathrm{p}}}{g_{1\mathrm{s}}}N_{1\mathrm{s}}n_\nu\right]$$

photon occupation number

$$\Leftrightarrow \left.\frac{1}{c}\frac{\mathrm{d}N_\nu}{\mathrm{d}t}\right|_{\mathrm{Ly}-\alpha} = A_{21}\frac{g_{2\mathrm{p}}}{g_{1\mathrm{s}}}N_{1\mathrm{s}}\,\phi(\nu)(1+n_\nu)\left[\frac{g_{1\mathrm{s}}N_{2\mathrm{p}}}{g_{2\mathrm{p}}N_{1\mathrm{s}}} - \frac{n_\nu}{1+n_\nu}\right]$$

In equilibrium: $$\frac{n_\nu}{1+n_\nu} = \mathrm{e}^{-\frac{h\nu}{kT_\gamma}} \text{ and } \frac{g_{1\mathrm{s}}N_{2\mathrm{p}}}{g_{2\mathrm{p}}N_{1\mathrm{s}}} = \mathrm{e}^{-\frac{h\nu_{21}}{kT_\mathrm{m}}} \implies T_\gamma \equiv T_\mathrm{m} \text{ and } \nu \equiv \nu_{21}$$

Only fulfilled at line center!

Detailed balance not guaranteed in the line wings!

- Effective 1γ expression

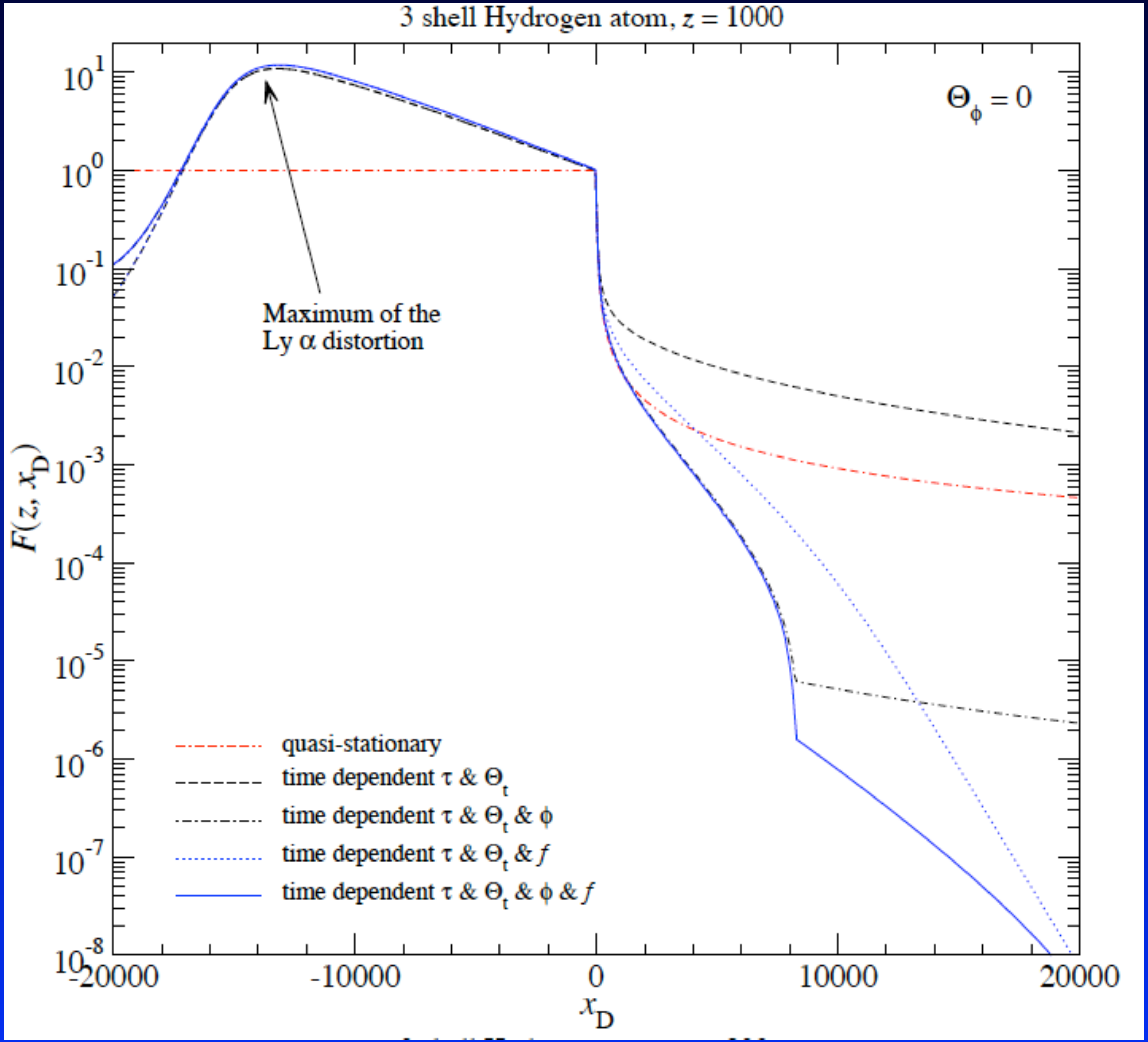
$$\Rightarrow \left.\frac{1}{c}\frac{\mathrm{d}N_\nu}{\mathrm{d}t}\right|_{\mathrm{Ly}-\alpha} = A_{21}\frac{g_{2\mathrm{p}}}{g_{1\mathrm{s}}}N_{1\mathrm{s}}\,\phi(\nu)(1+n_\nu)\left[\frac{g_{1\mathrm{s}}N_{2\mathrm{p}}}{g_{2\mathrm{p}}N_{1\mathrm{s}}} - \mathrm{e}^{\frac{h(\nu-\nu_{21})}{kT_\gamma}}\frac{n_\nu}{1+n_\nu}\right]$$

Asymmetry of emission and absorption profile

- Naturally comes out of 2γ treatment (JC & Sunyaev 2009)

Problems with Sobolev approximation:

Difference between emission and absorption profile



JC & Sunyaev, 2009

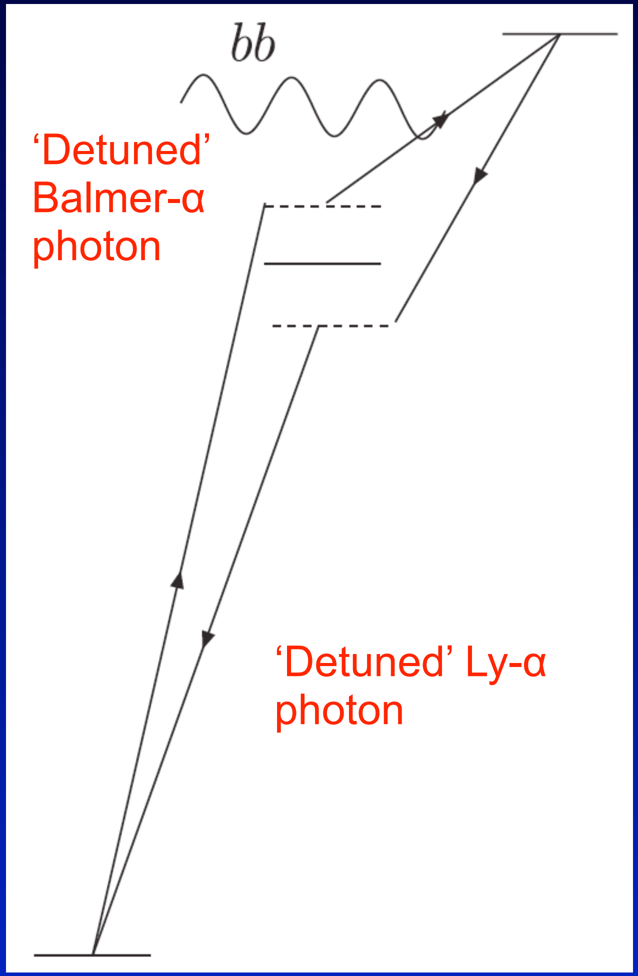
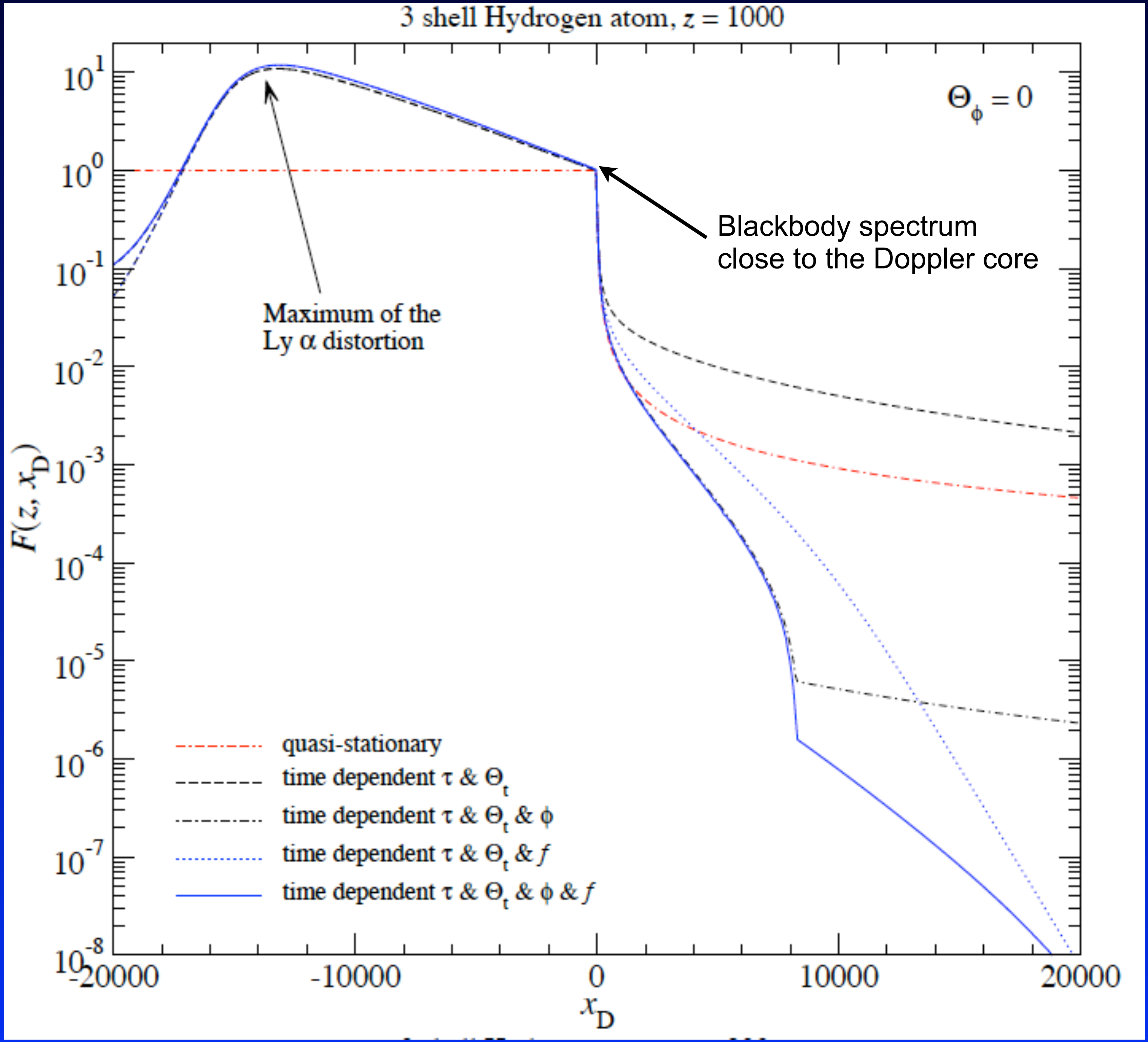


Illustration from Switzer & Hirata 2007 (meant for Helium)

- Real absorption & emission requires a second photon!

Problems with Sobolev approximation:

Difference between emission and absorption profile



Blackbody spectrum close to the Doppler core

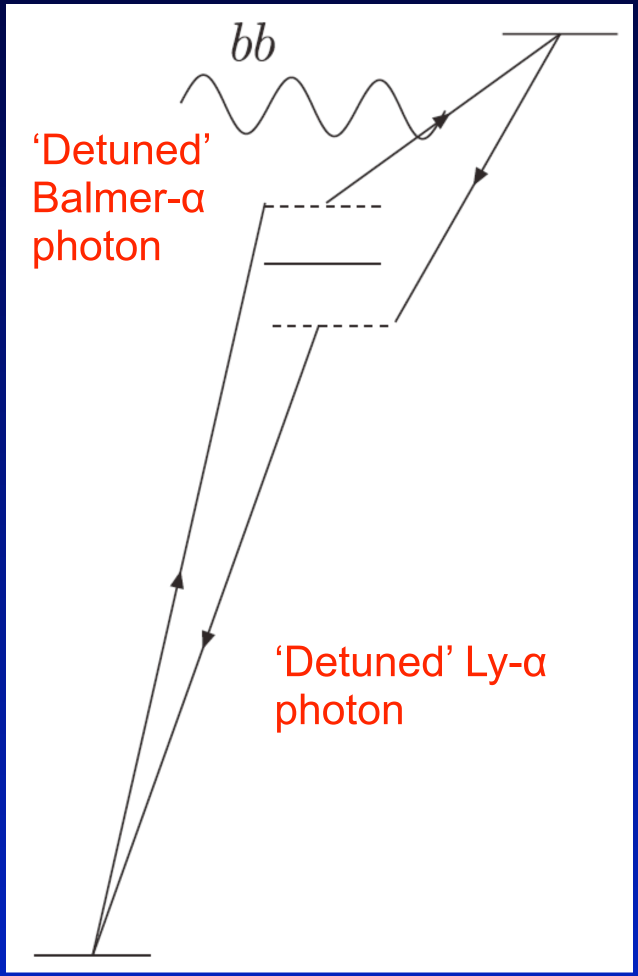


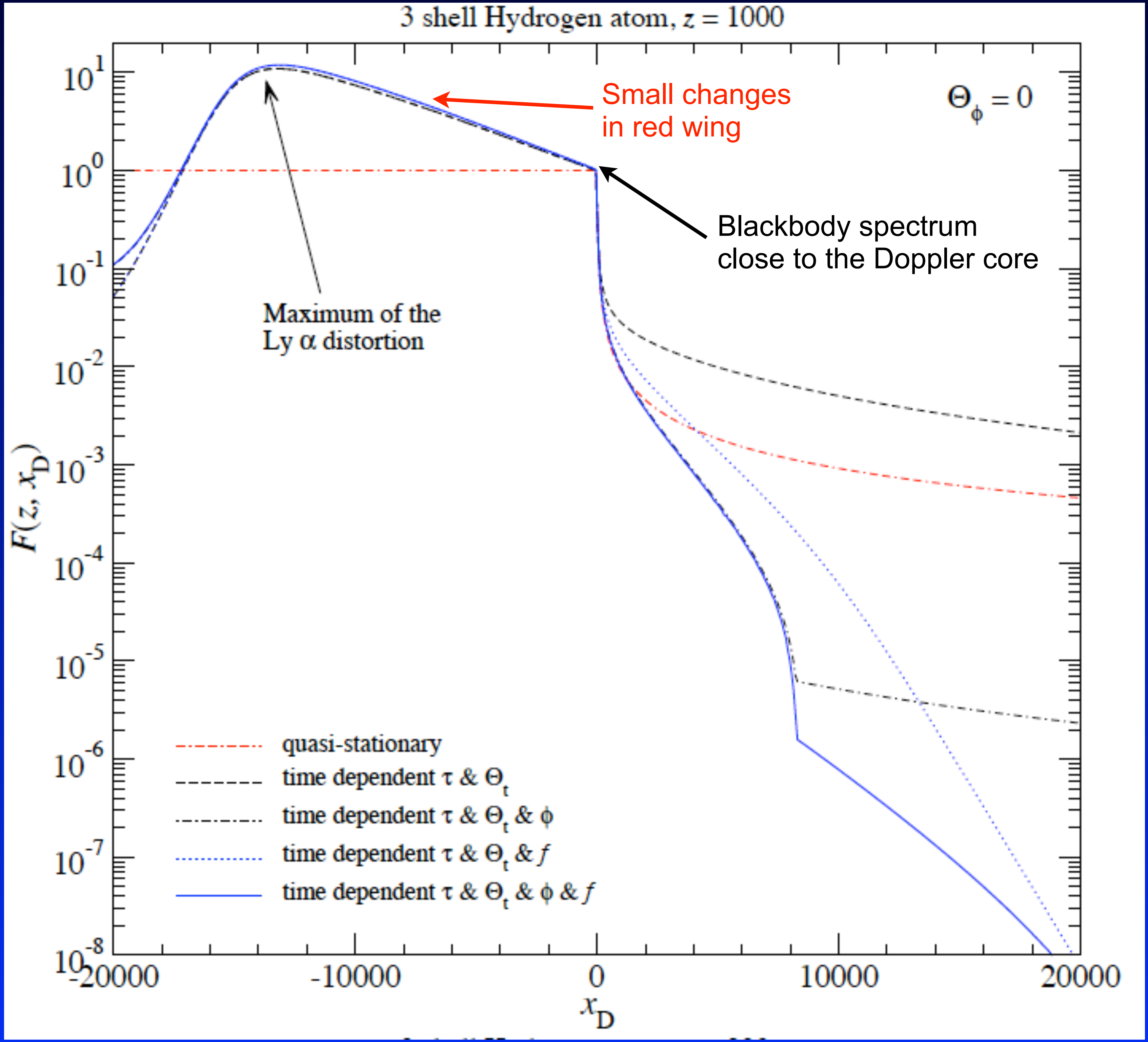
Illustration from Switzer & Hirata 2007 (meant for Helium)

- Real absorption & emission requires a second photon!

JC & Sunyaev, 2009

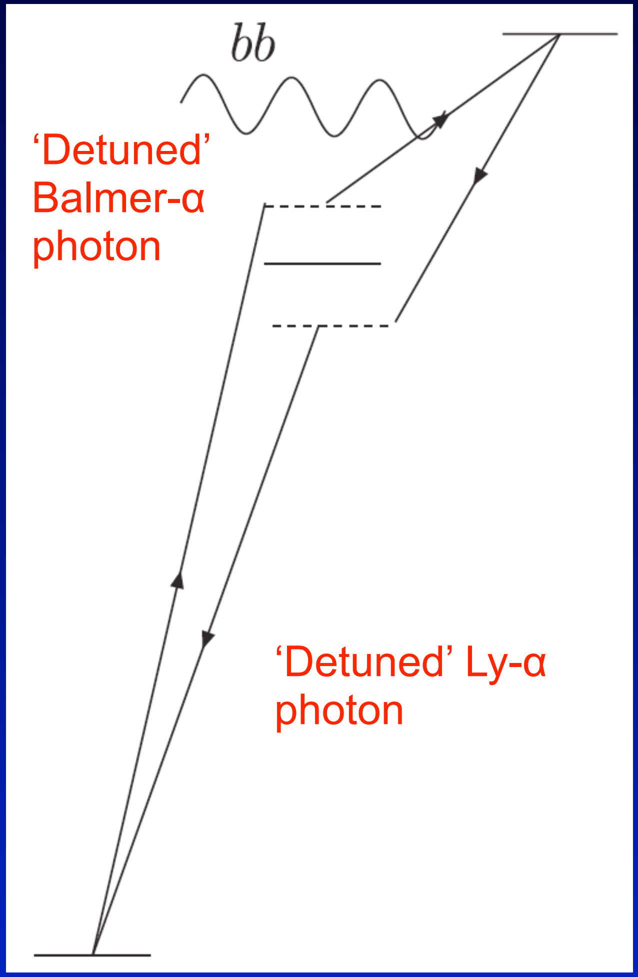
Problems with Sobolev approximation:

Difference between emission and absorption profile



Small changes in red wing

Blackbody spectrum close to the Doppler core



'Detuned' Balmer-α photon

'Detuned' Ly-α photon

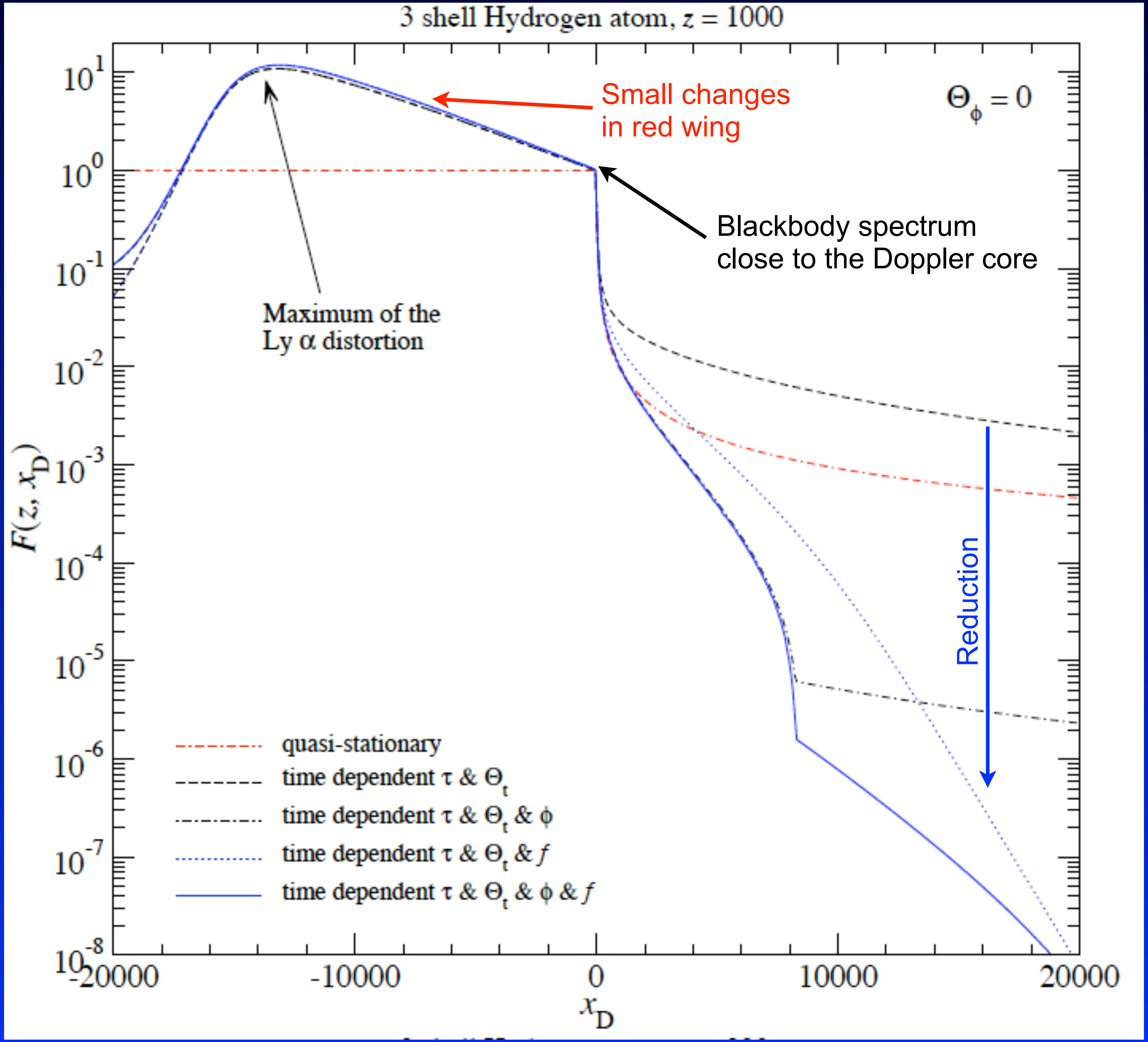
Illustration from Switzer & Hirata 2007 (meant for Helium)

- Real absorption & emission requires a second photon!

JC & Sunyaev, 2009

Problems with Sobolev approximation:

Difference between emission and absorption profile

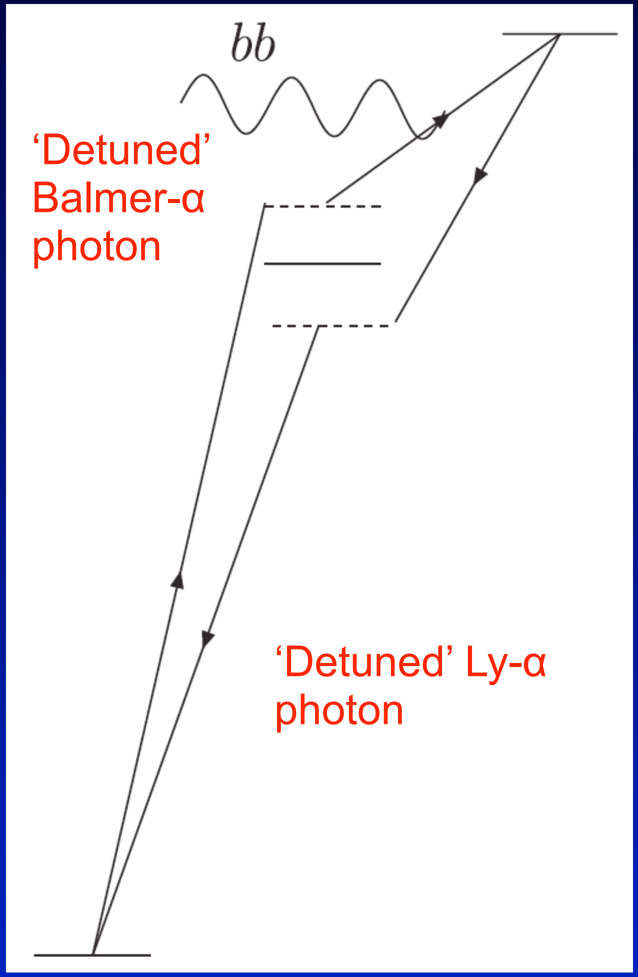


Small changes in red wing

Blackbody spectrum close to the Doppler core

Maximum of the Ly α distortion

Reduction



'Detuned' Balmer-α photon

'Detuned' Ly-α photon

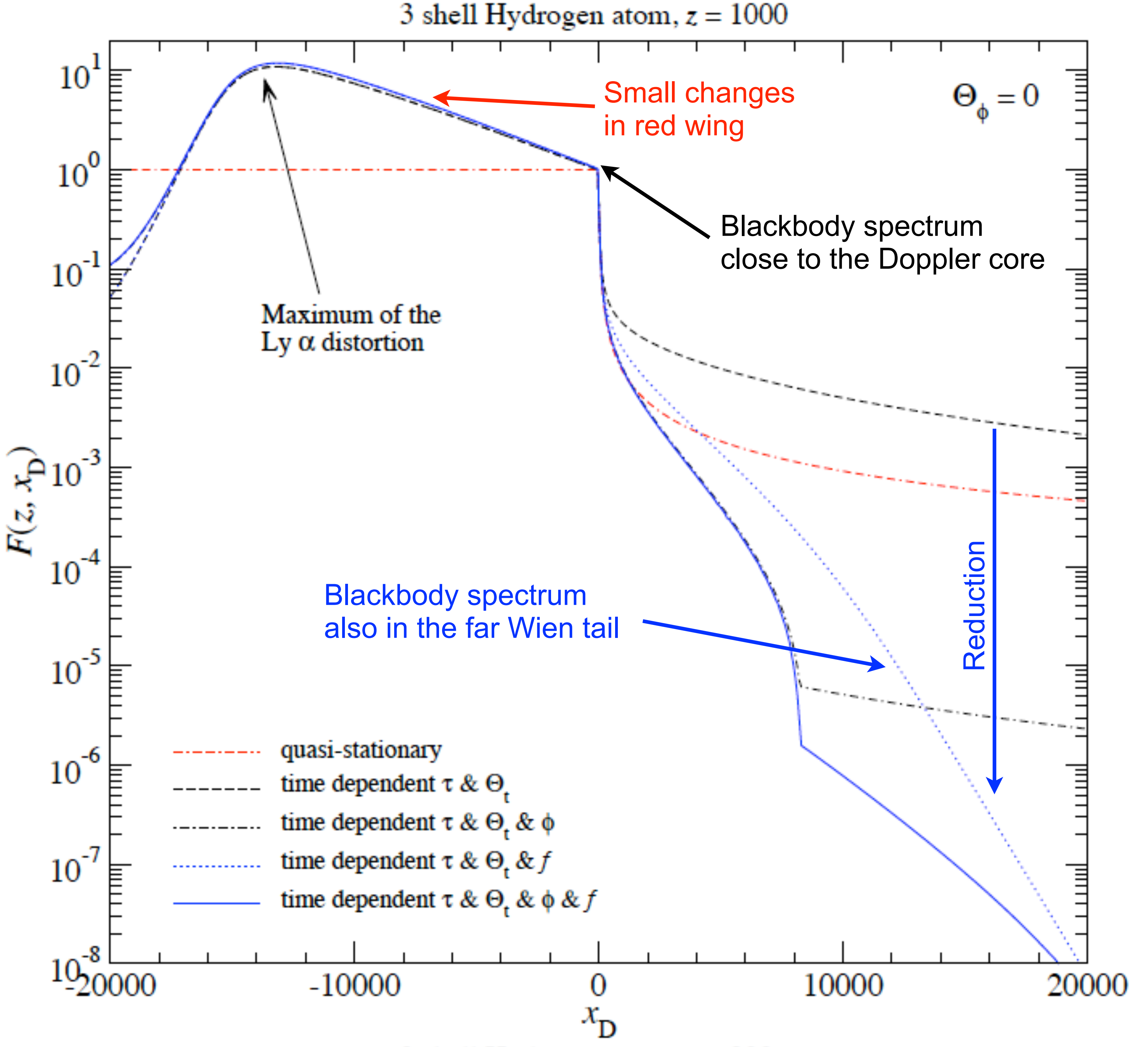
Illustration from Switzer & Hirata 2007 (meant for Helium)

- Real absorption & emission requires a second photon!

JC & Sunyaev, 2009

Problems with Sobolev approximation:

Difference between emission and absorption profile



Small changes in red wing

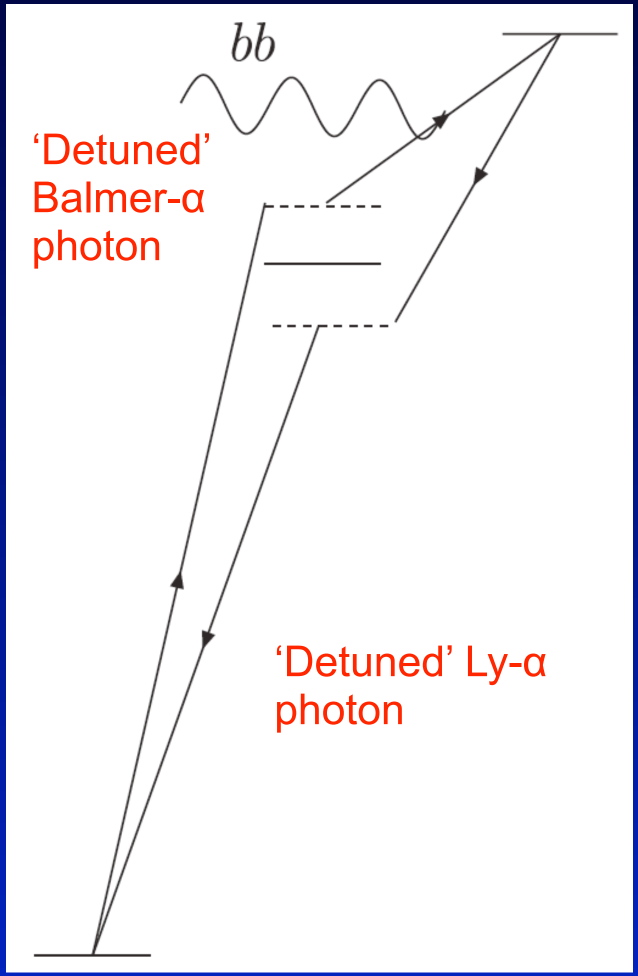
Maximum of the Ly α distortion

Blackbody spectrum close to the Doppler core

Blackbody spectrum also in the far Wien tail

Reduction

JC & Sunyaev, 2009



'Detuned' Balmer-α photon

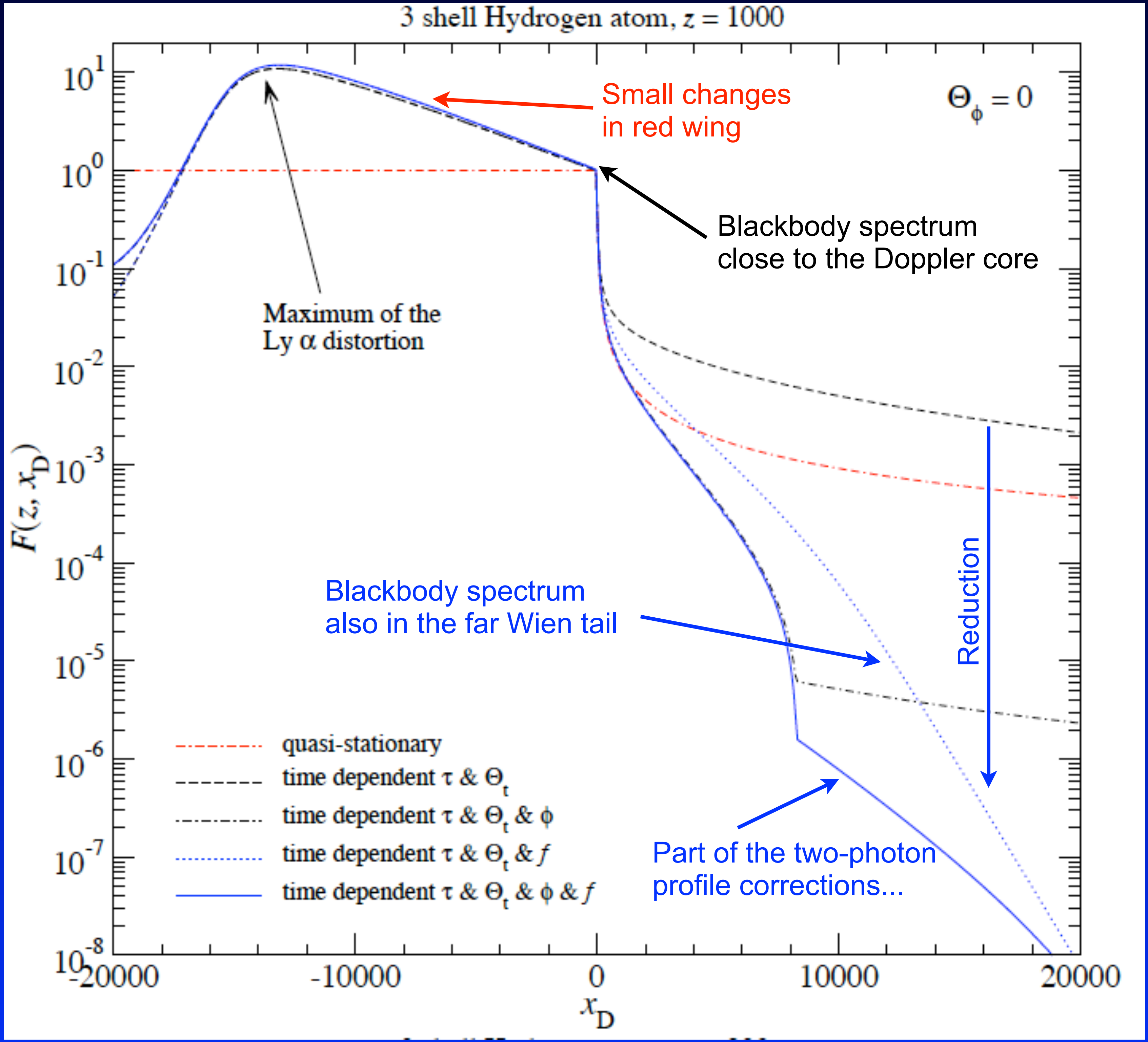
'Detuned' Ly-α photon

Illustration from Switzer & Hirata 2007 (meant for Helium)

- Real absorption & emission requires a second photon!

Problems with Sobolev approximation:

Difference between emission and absorption profile

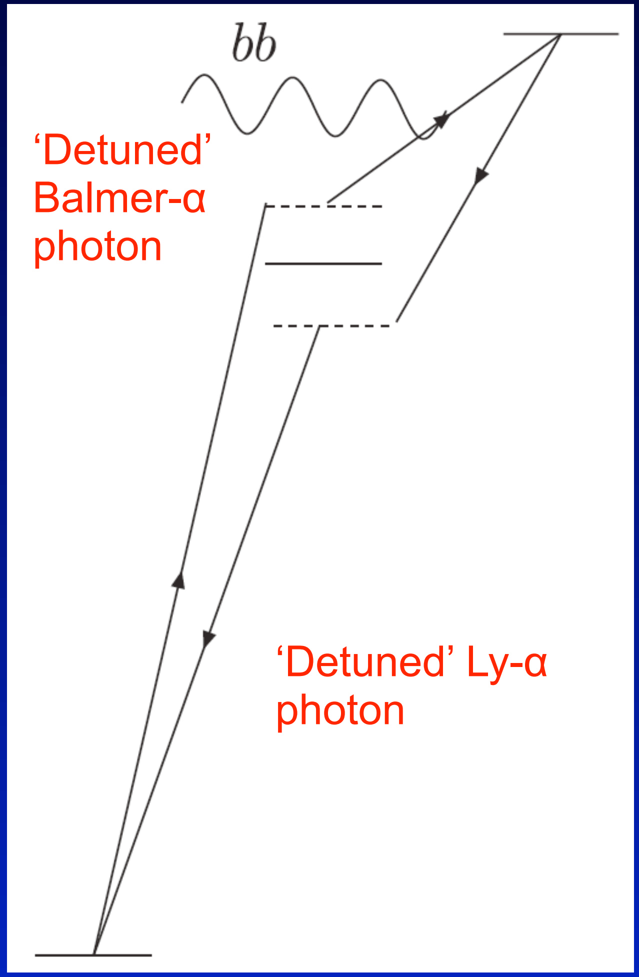


Small changes in red wing

Blackbody spectrum close to the Doppler core

Blackbody spectrum also in the far Wien tail

Part of the two-photon profile corrections...



‘Detuned’ Balmer-α photon

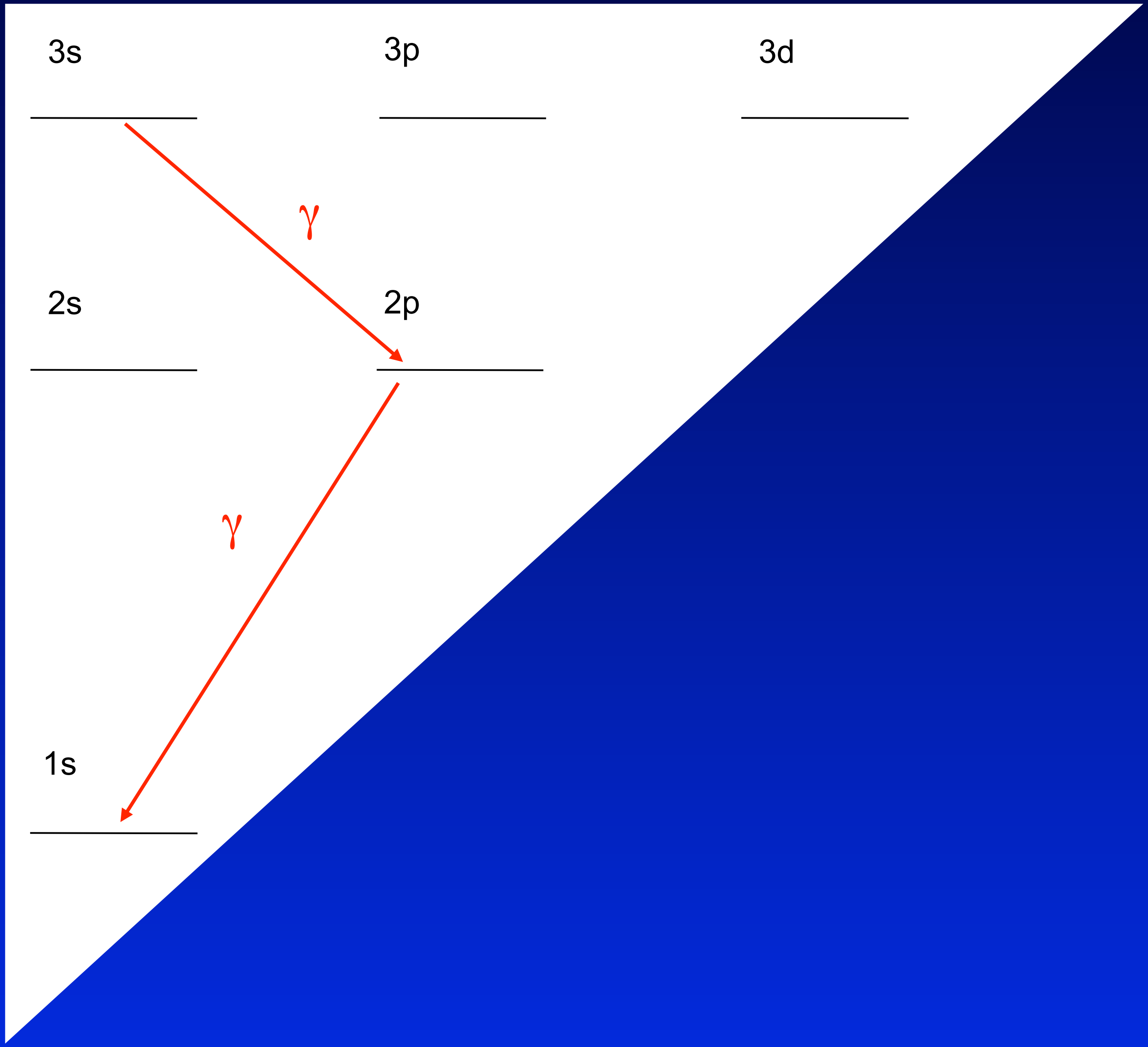
‘Detuned’ Ly-α photon

Illustration from Switzer & Hirata 2007 (meant for Helium)

- Real absorption & emission requires a second photon!

JC & Sunyaev, 2009

Two-photon emission profile



Seaton cascade (1+1 photon)

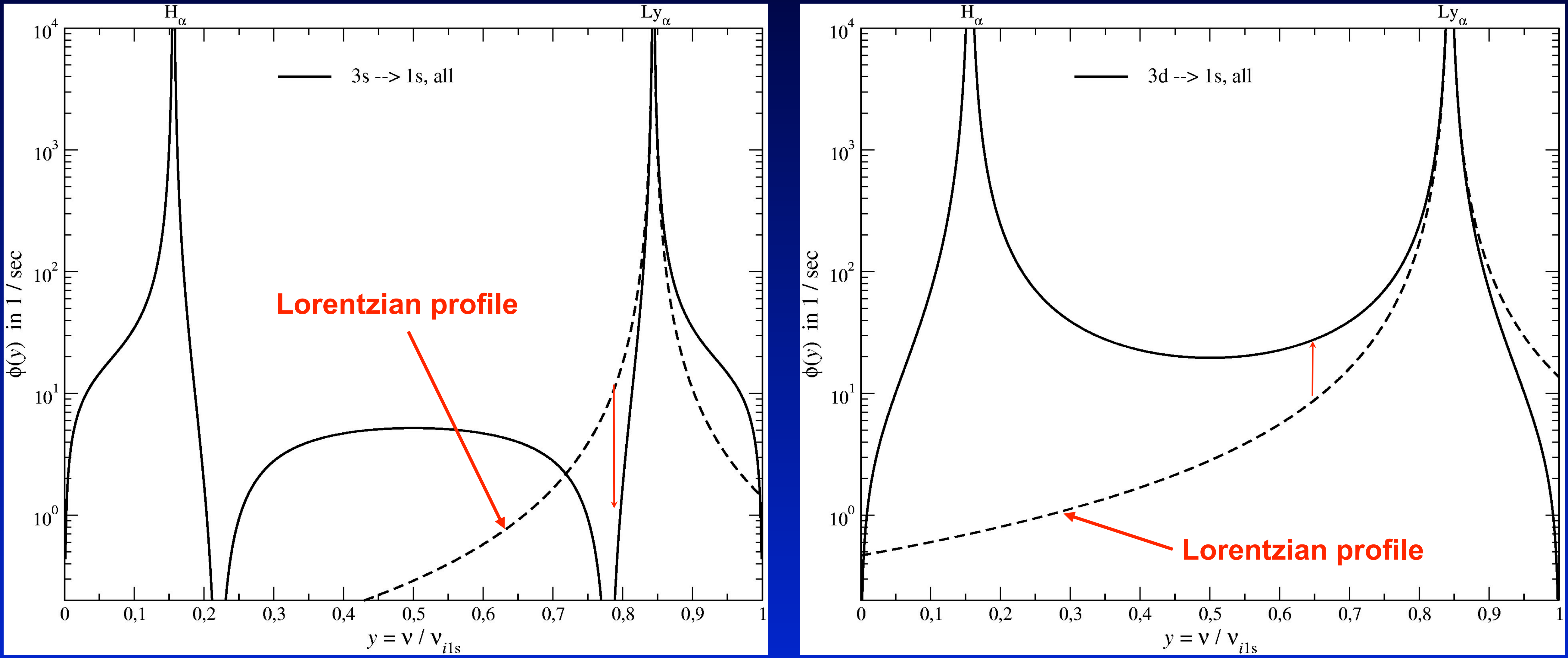
No collisions → two photons (mainly H-α and Ly-α) are emitted!

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



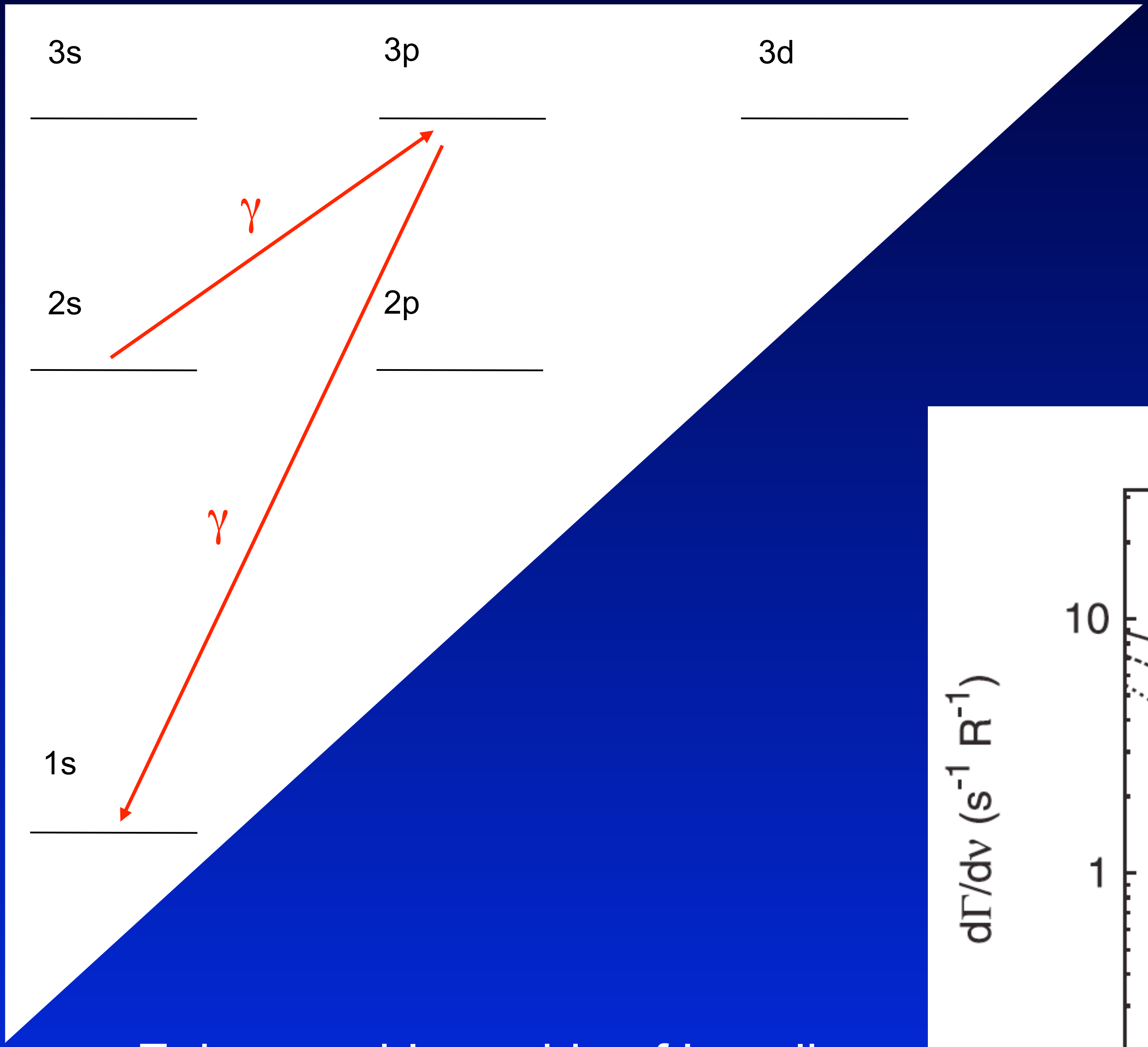
Direct Escape in optically thin regions:

→ 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



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

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

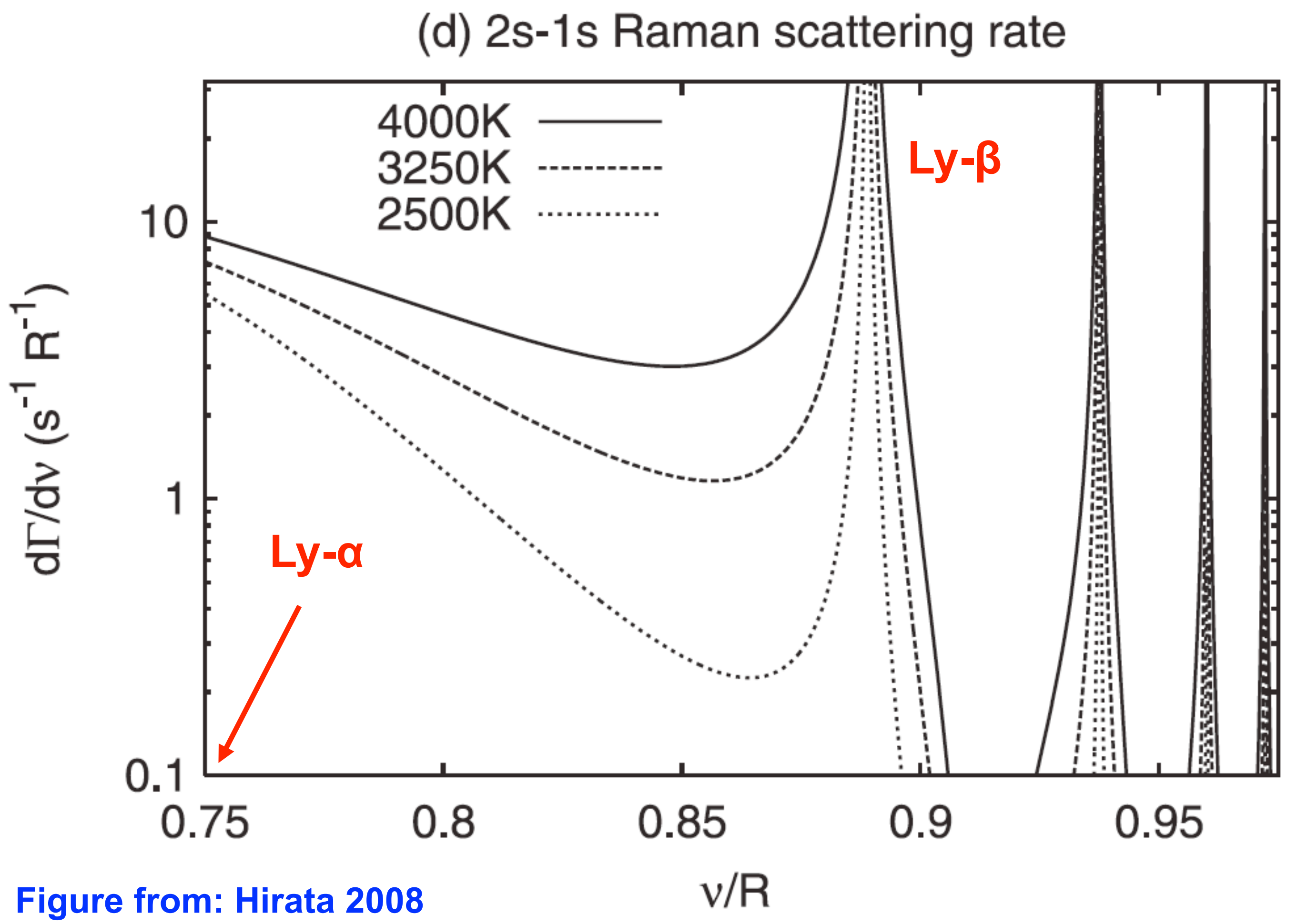
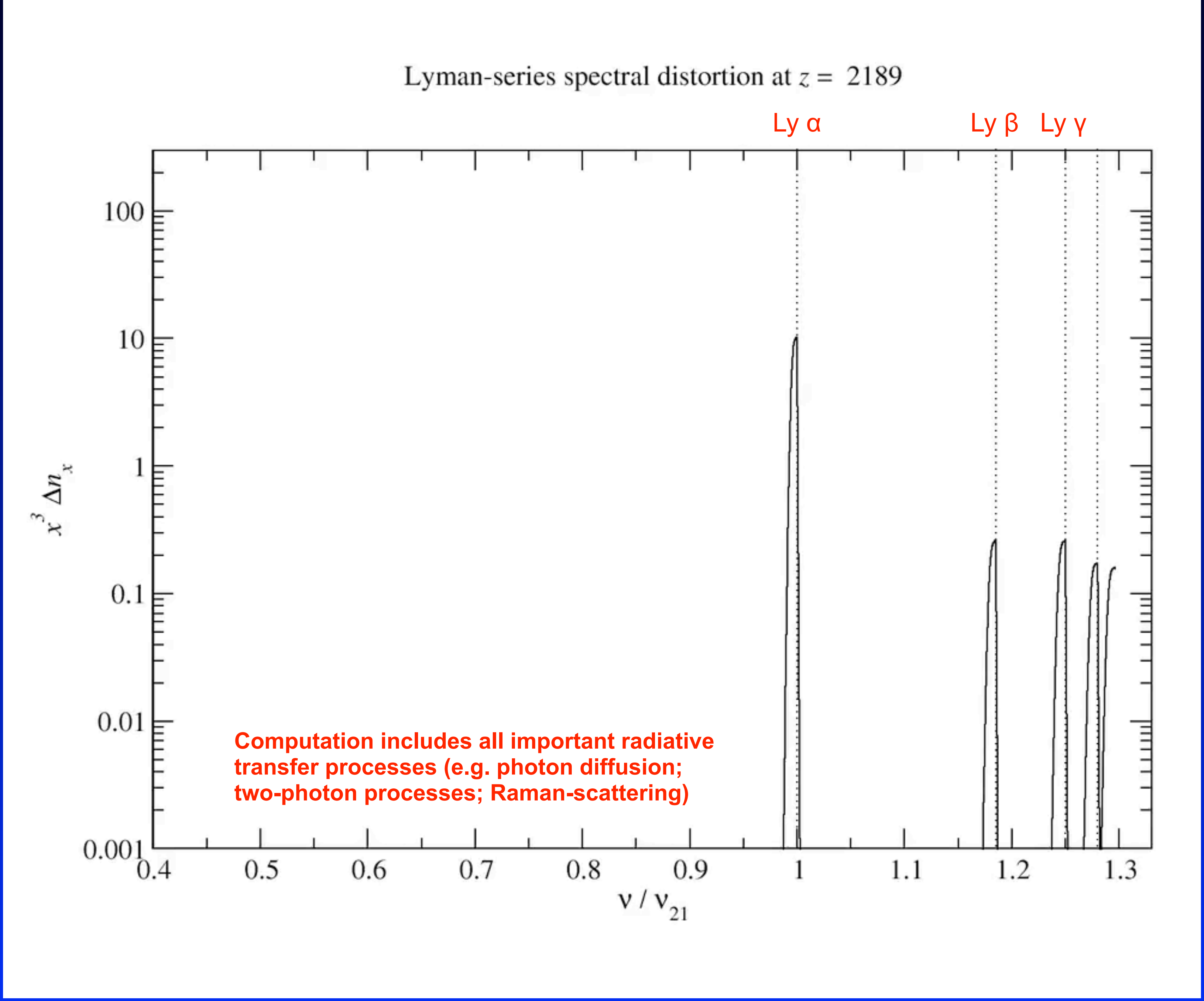


Figure from: Hirata 2008

Hirata 2008
JC & Thomas, 2010

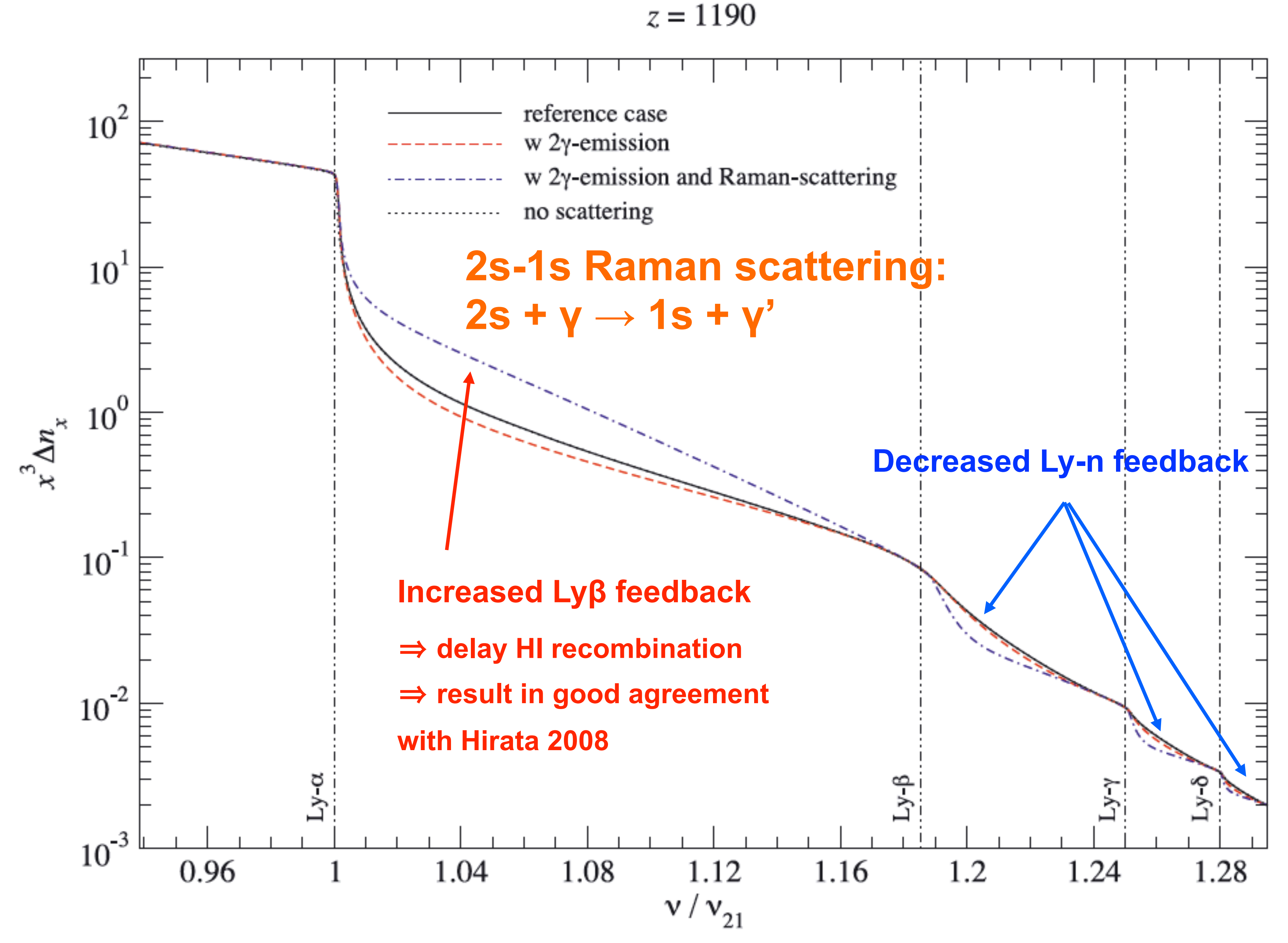
Evolution of the HI Lyman-series distortion



Computation includes all important radiative transfer processes (e.g. photon diffusion; two-photon processes; Raman-scattering)

JC & Thomas, MNRAS, 2010

Effect of Raman scattering and 2γ decays



2s-1s Raman scattering:
2s + γ → 1s + γ'

Decreased Ly-n feedback

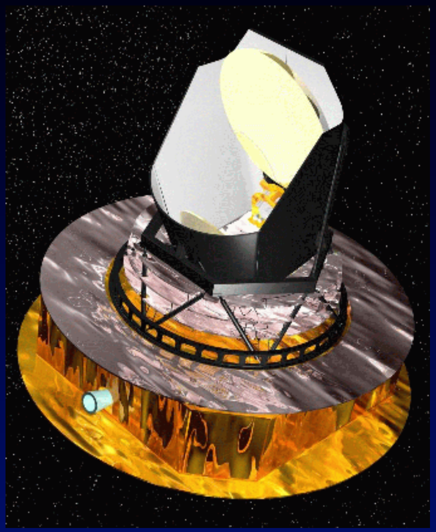
Increased Lyβ feedback

⇒ delay HI recombination

⇒ result in good agreement with Hirata 2008

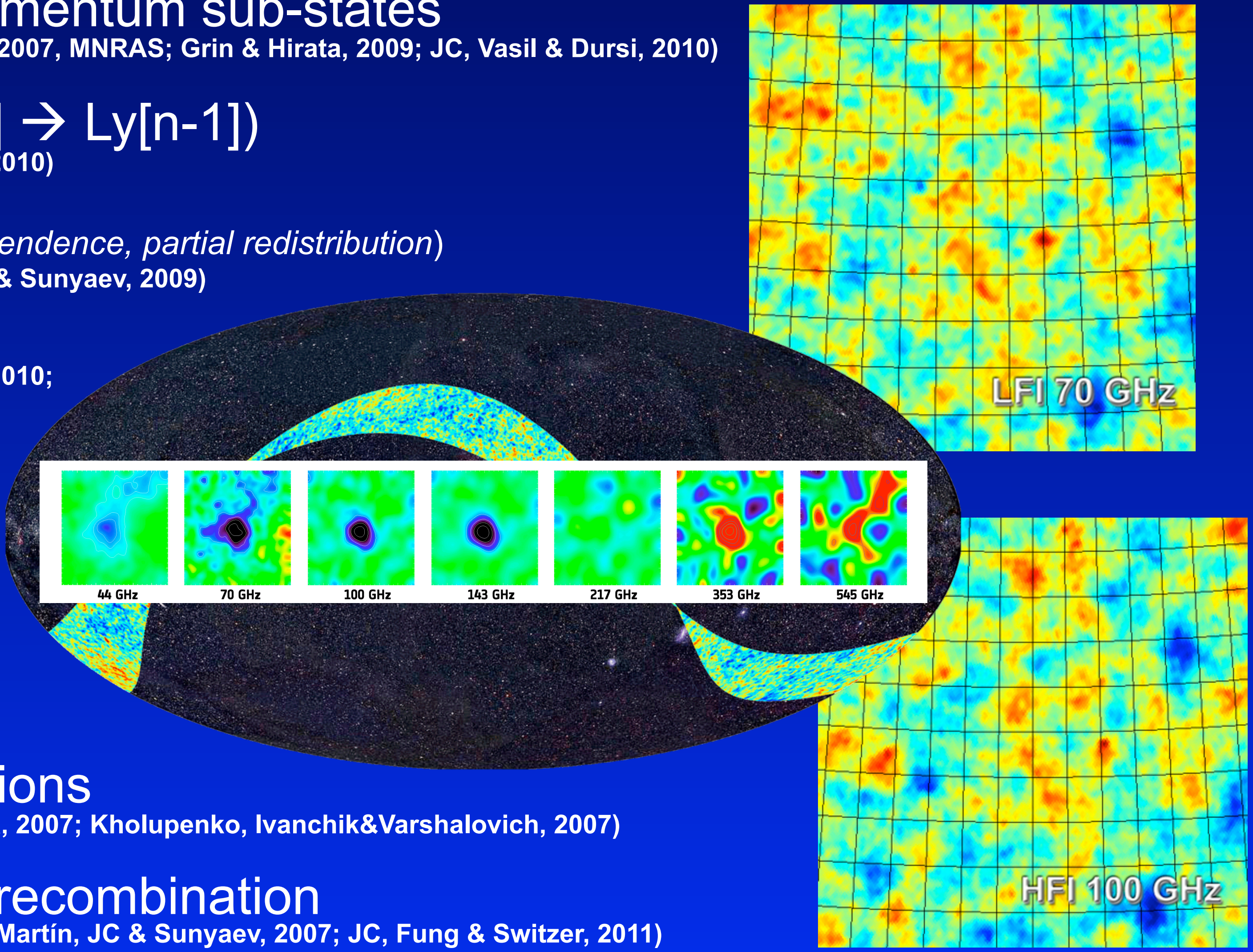
JC & Thomas, MNRAS, 2010

Getting Ready for Planck



Hydrogen recombination

- Two-photon decays from higher levels
  (Dubrovich & Grachev, 2005, Astr. Lett., 31, 359; Wong & Scott, 2007; JC & Sunyaev, 2007; Hirata, 2008; JC & Sunyaev 2009)
- Induced 2s two-photon decay for hydrogen
  (JC & Sunyaev, 2006, A&A, 446, 39; Hirata 2008)
- Feedback of the Lyman-α distortion on the 1s-2s two-photon absorption 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)

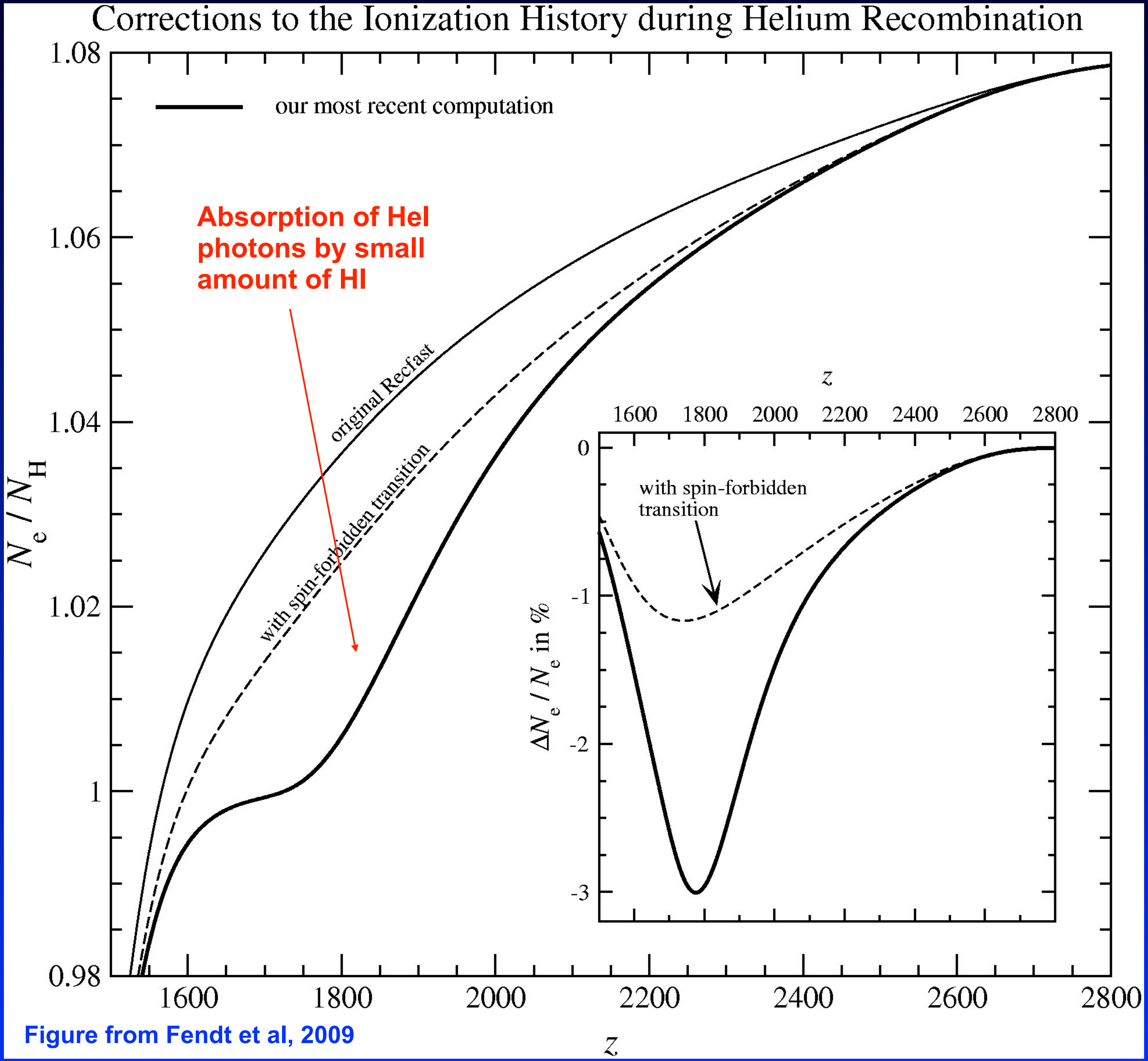


Helium recombination

- 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)

$$\boxed{\Delta N_e \;/\; N_e \sim 0.1\ \%}$$

Main corrections during HeI Recombination



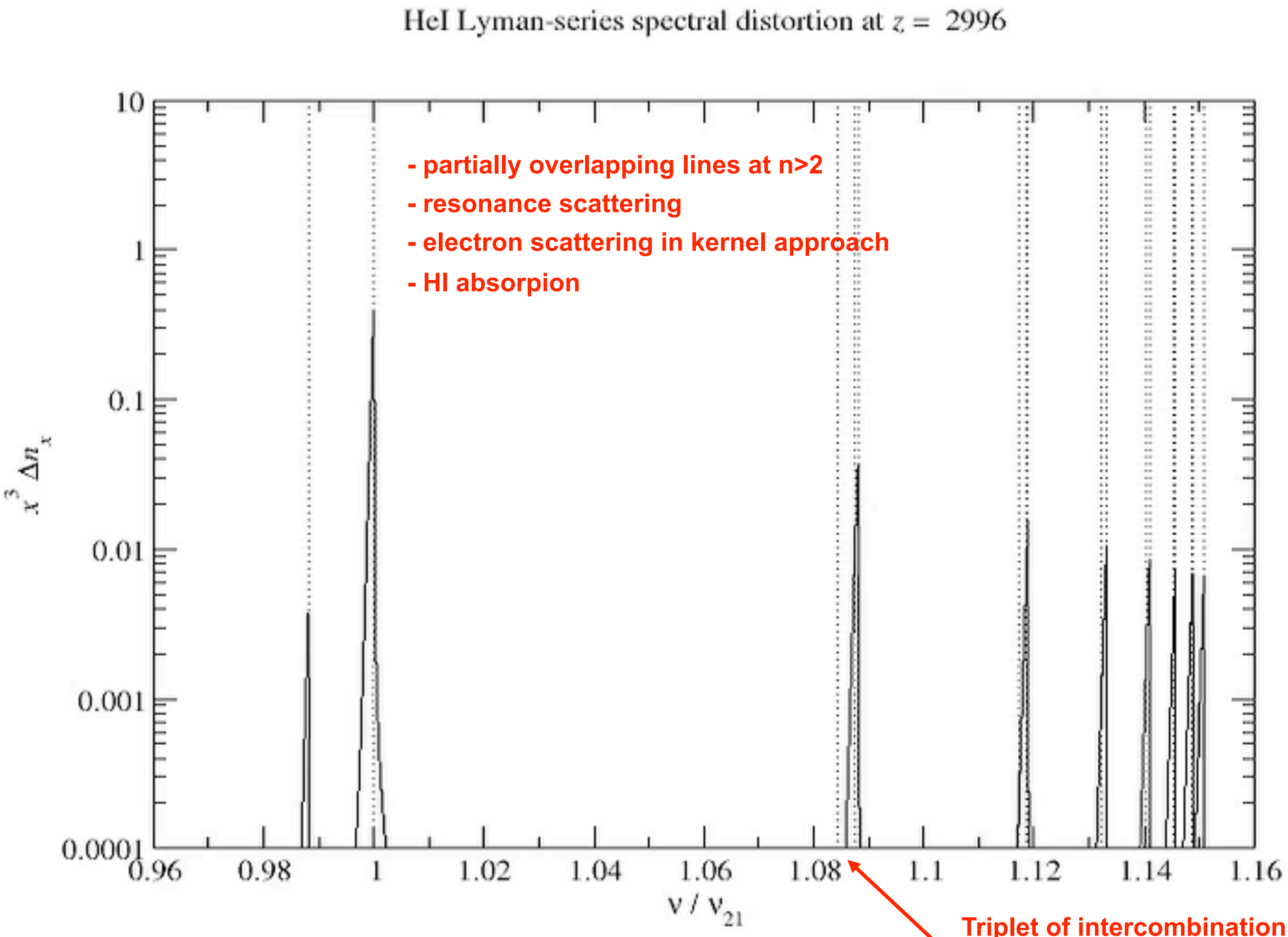
Absorption of HeI photons by small amount of HI

Figure from Fendt et al, 2009

Kholupenko et al, 2007
Switzer & Hirata, 2007

Evolution of the HeI high frequency distortion

CosmoRec v2.0 only!

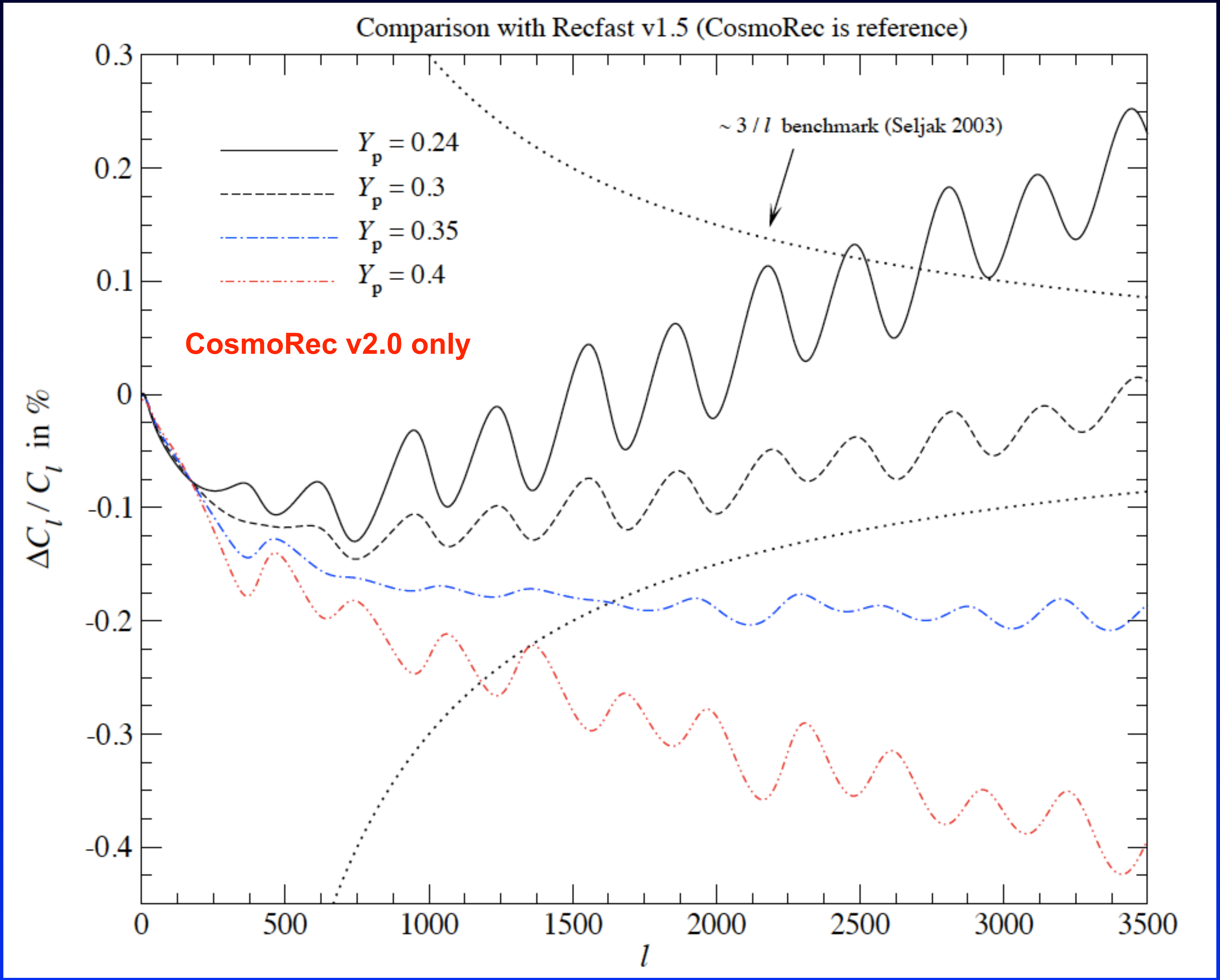

HeI Lyman-series spectral distortion at $z = 2996$

- partially overlapping lines at n>2
- resonance scattering
- electron scattering in kernel approach
- HI absorption

Triplet of intercombination, quadrupole & singlet lines

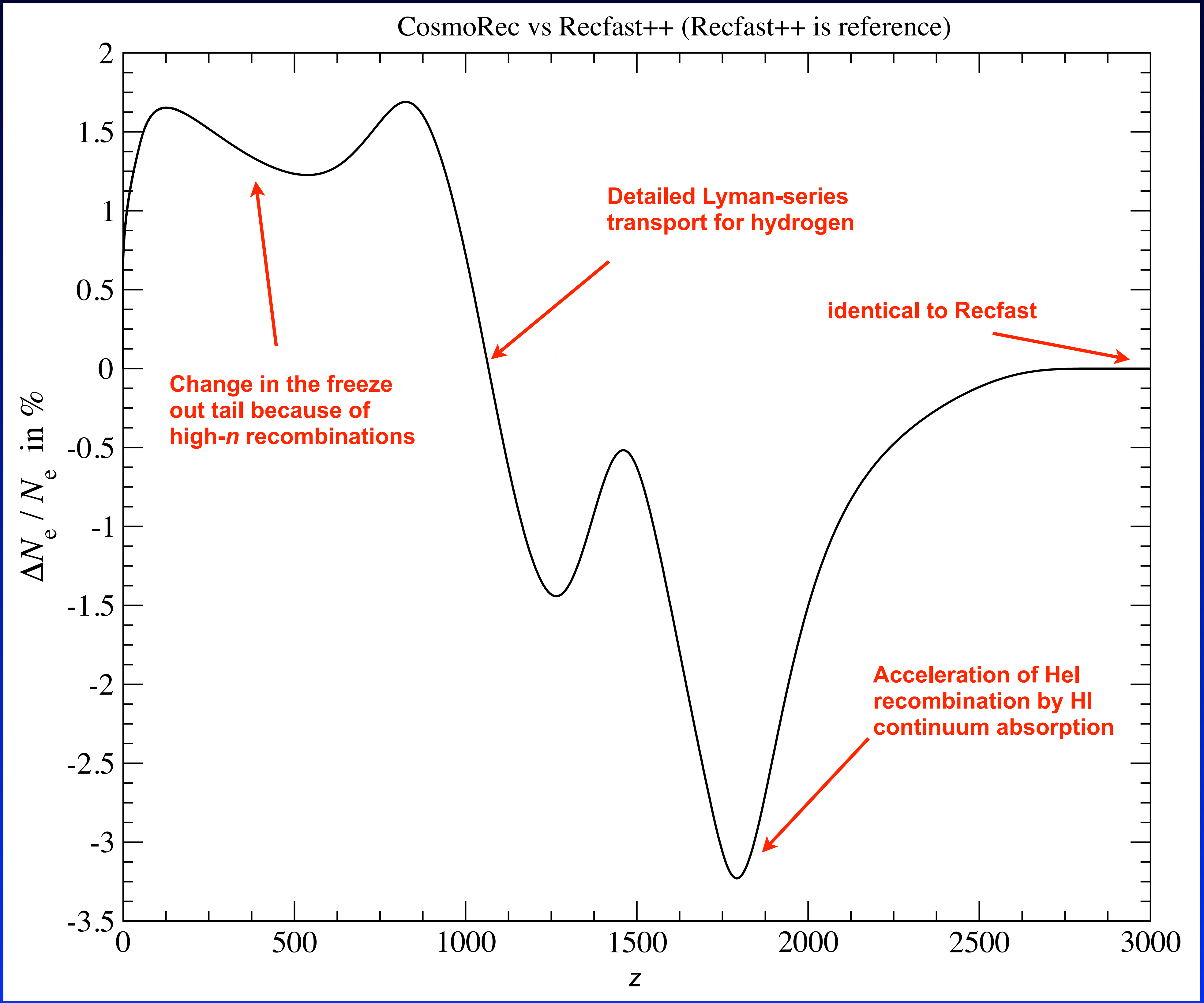
JC, Fung & Switzer, 2011

Overall effect of detailed HeI radiative transfer



JC, Fung & Switzer, 2011

Cumulative Changes to the Ionization History



Change in the freeze out tail because of high-*n* recombinations

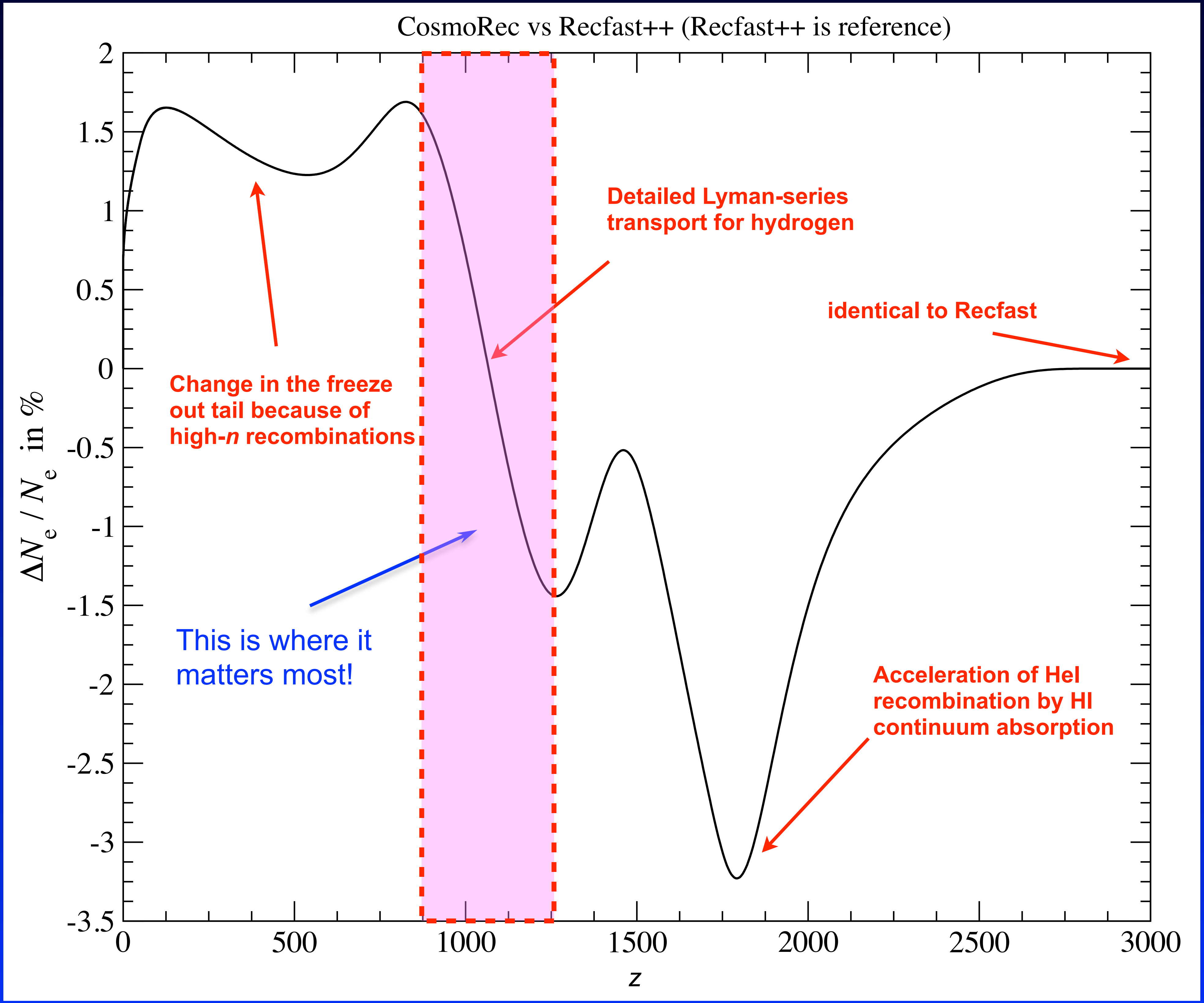
Detailed Lyman-series transport for hydrogen

identical to Recfast

Acceleration of HeI recombination by HI continuum absorption

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

Cumulative Changes to the Ionization History



Change in the freeze out tail because of high-*n* recombinations

Detailed Lyman-series transport for hydrogen

identical to Recfast

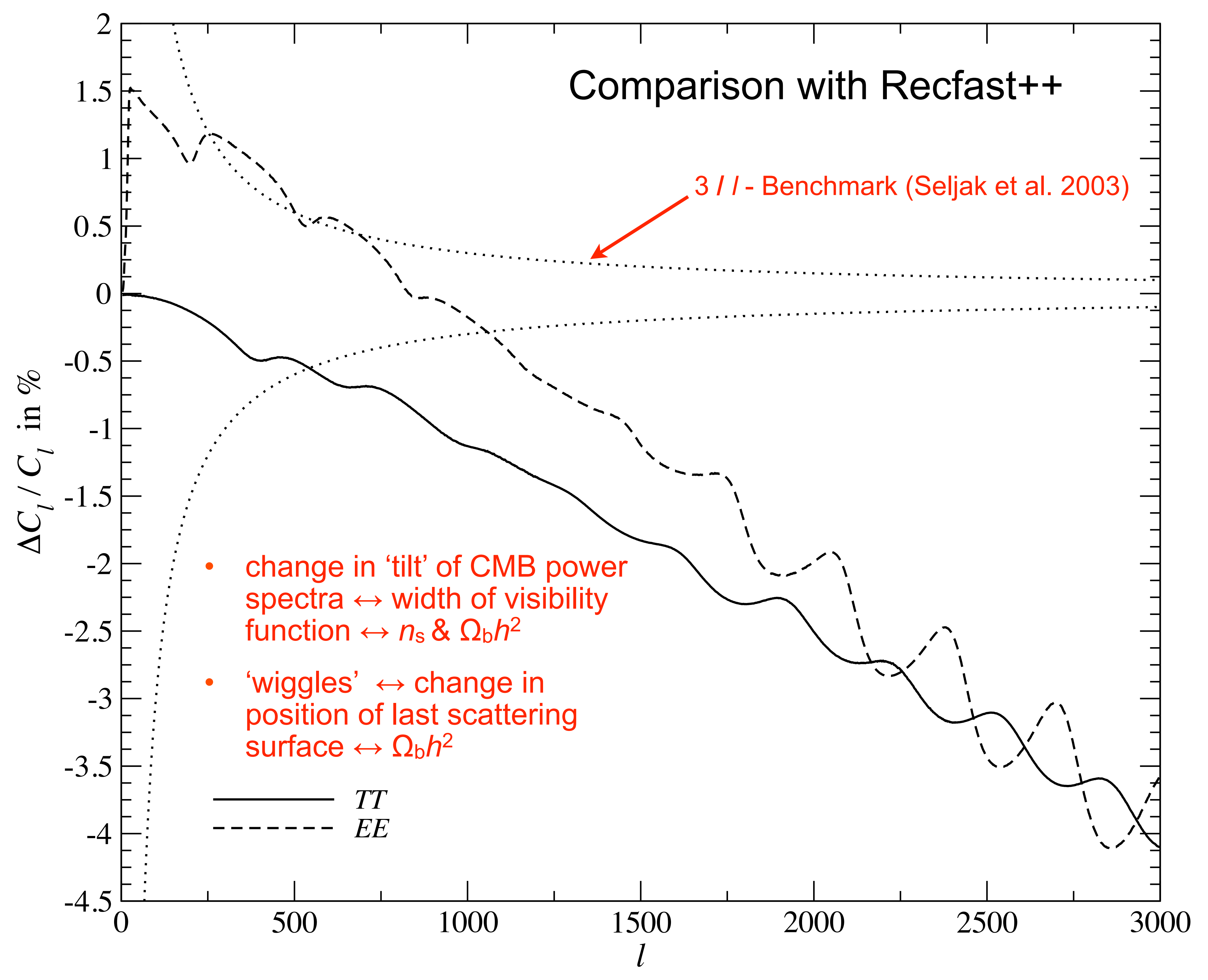
This is where it matters most!

Acceleration of HeI recombination by HI continuum absorption

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

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

Cumulative Change in the CMB Power Spectra



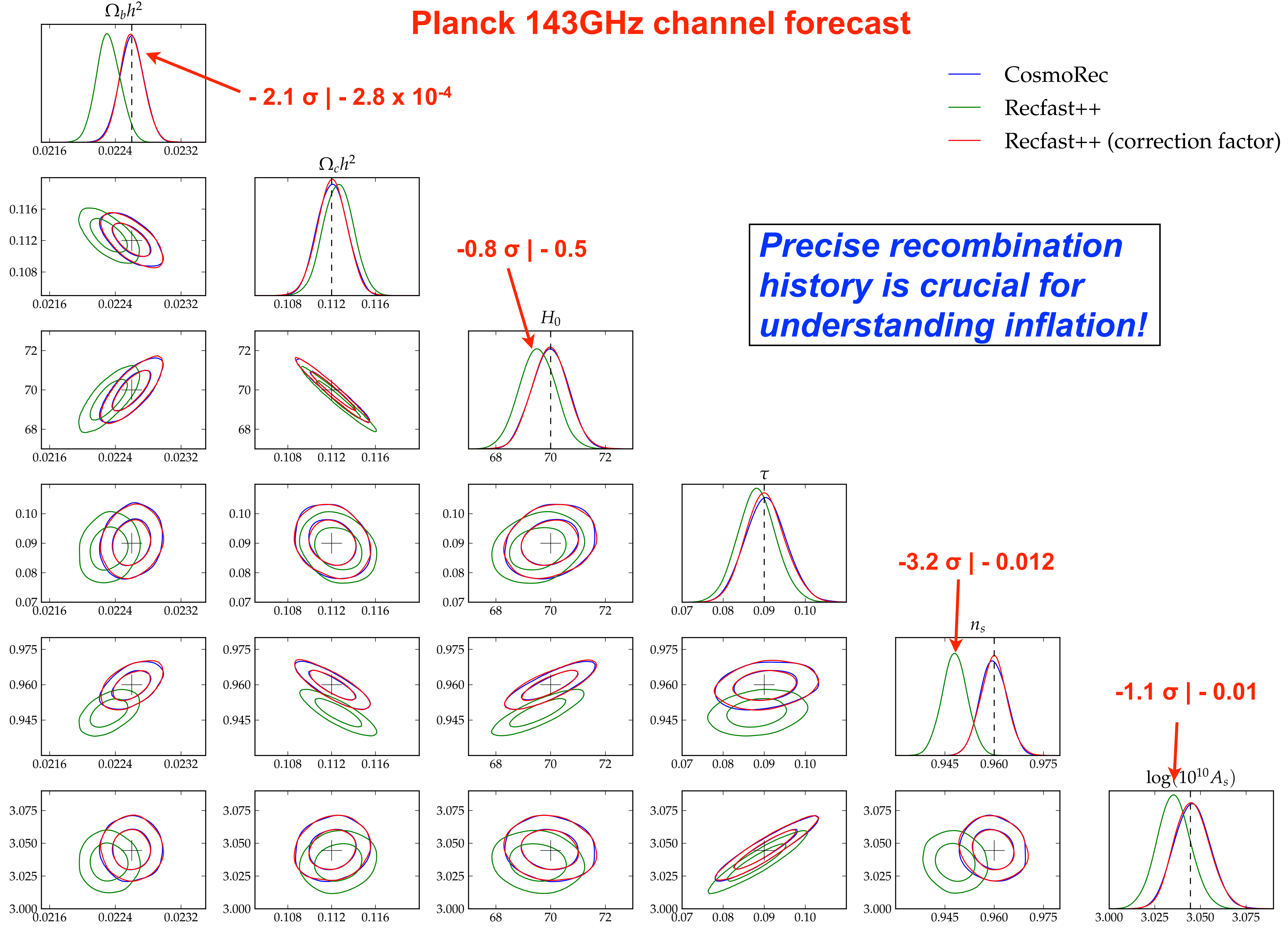
Comparison with Recfast++

$3 / l$ - Benchmark (Seljak et al. 2003)

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

Shaw & JC, MNRAS, 2011

Importance of recombination for inflation



Planck 143GHz channel forecast

- 2.1 σ | - 2.8 x 10^{-4}

-0.8 σ | - 0.5

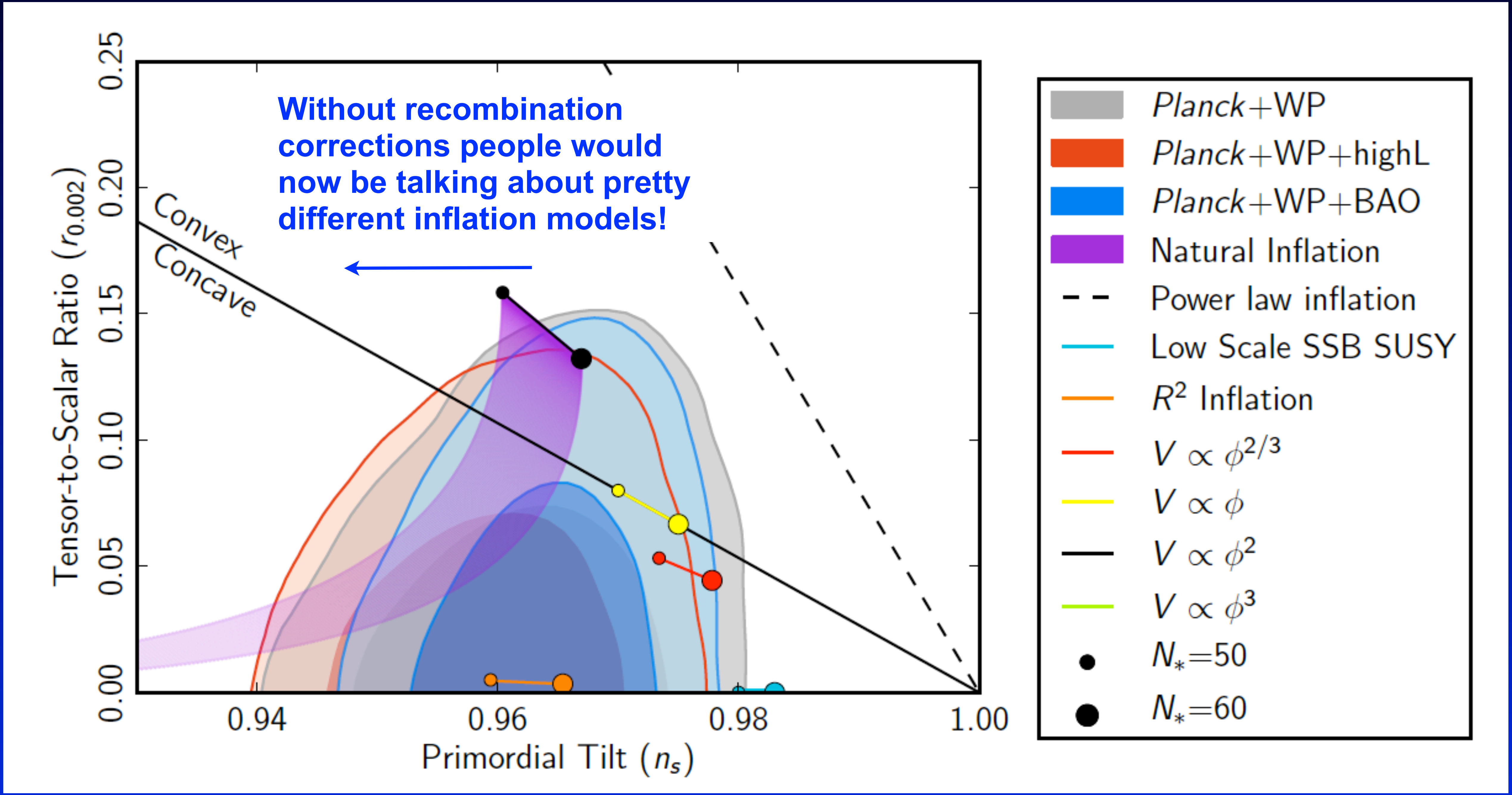
-3.2 σ | - 0.012

-1.1 σ | - 0.01

Precise recombination history is crucial for understanding inflation!

Shaw & JC, 2011, and references therein

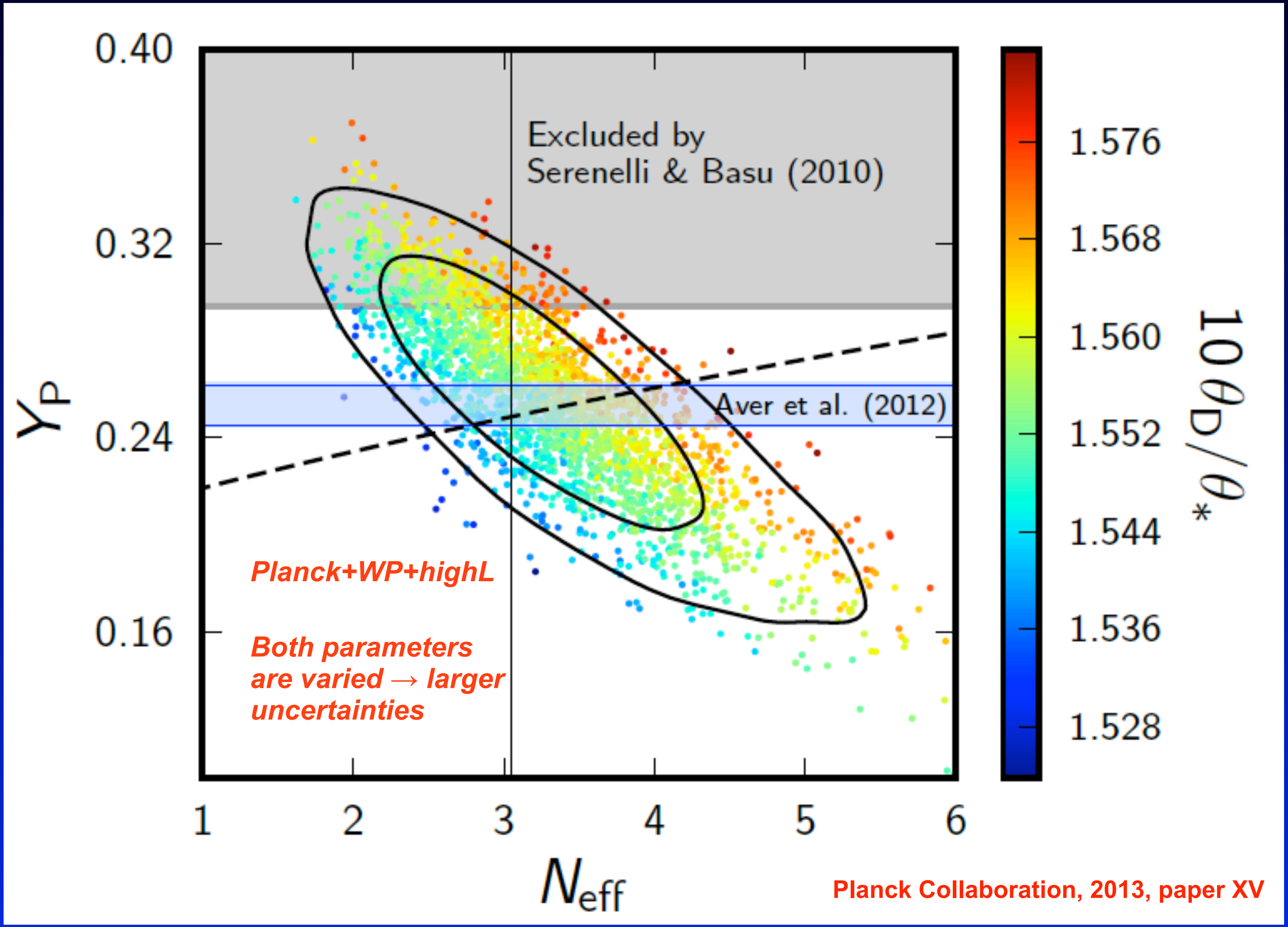
Importance of recombination for inflation



Without recombination corrections people would now be talking about pretty different inflation models!

Planck Collaboration, 2013, paper XXII

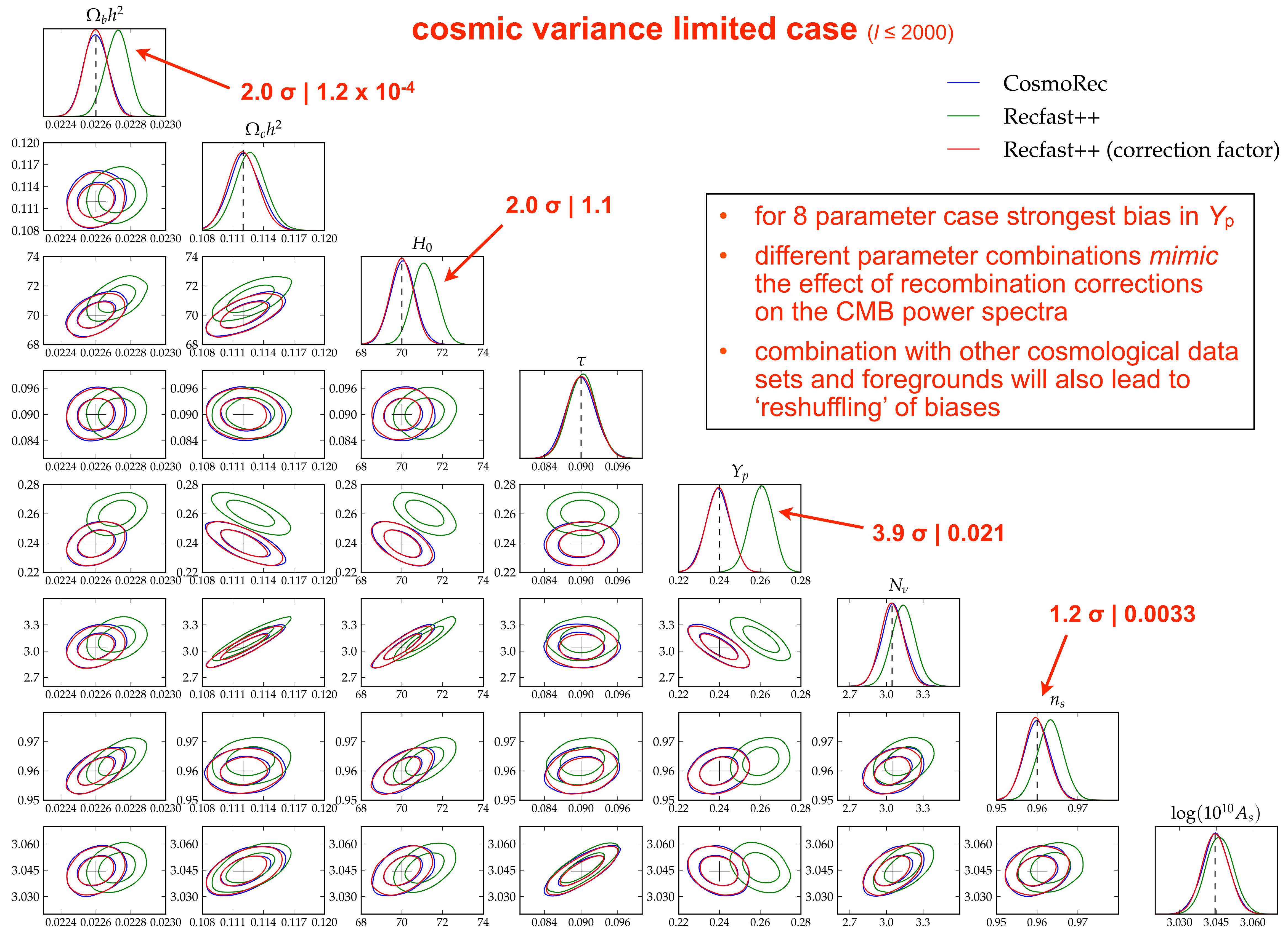
CMB constraints on N_{eff} and Y_{p}



Planck Collaboration, 2013, paper XV

- *Consistent with SBBN and standard value for* N_{eff}
- *Future CMB constraints (SPTPol & ACTPol) on* Y_{p} *will reach 1% level*

Importance of recombination for measuring helium



cosmic variance limited case ($l \leq 2000$)

2.0 σ | 1.2 x 10^{-4}

2.0 σ | 1.1

3.9 σ | 0.021

1.2 σ | 0.0033

- 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

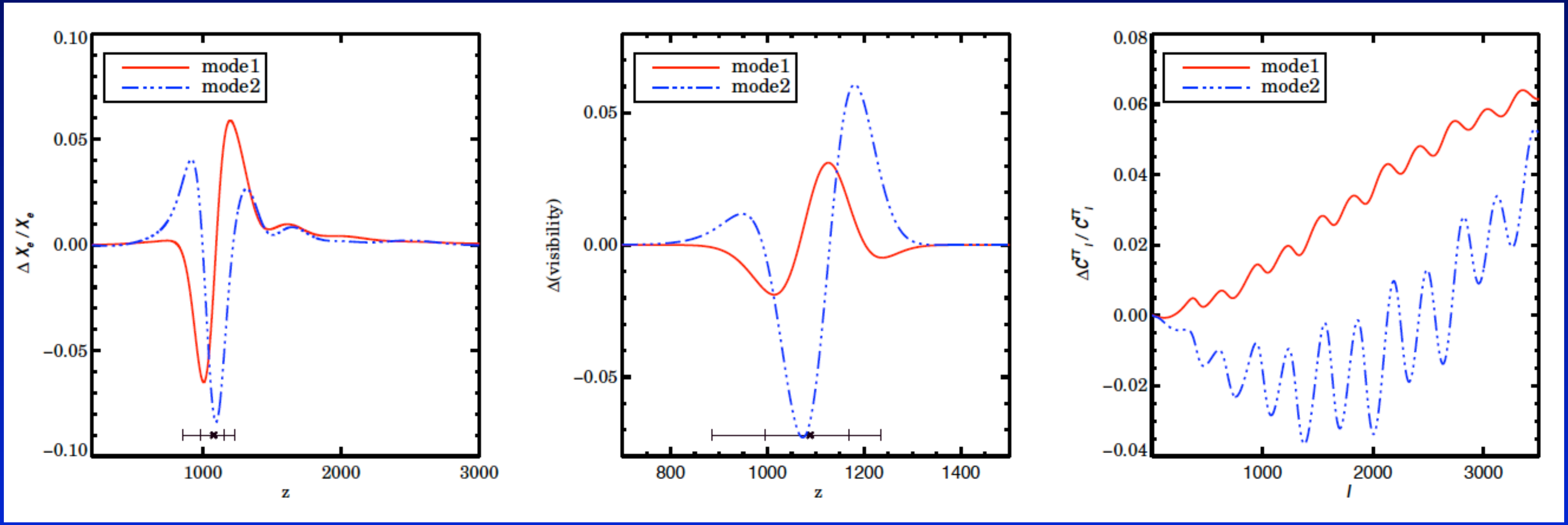
What if something unexpected happened?

- 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)

Farhang, Bond & JC, 2012

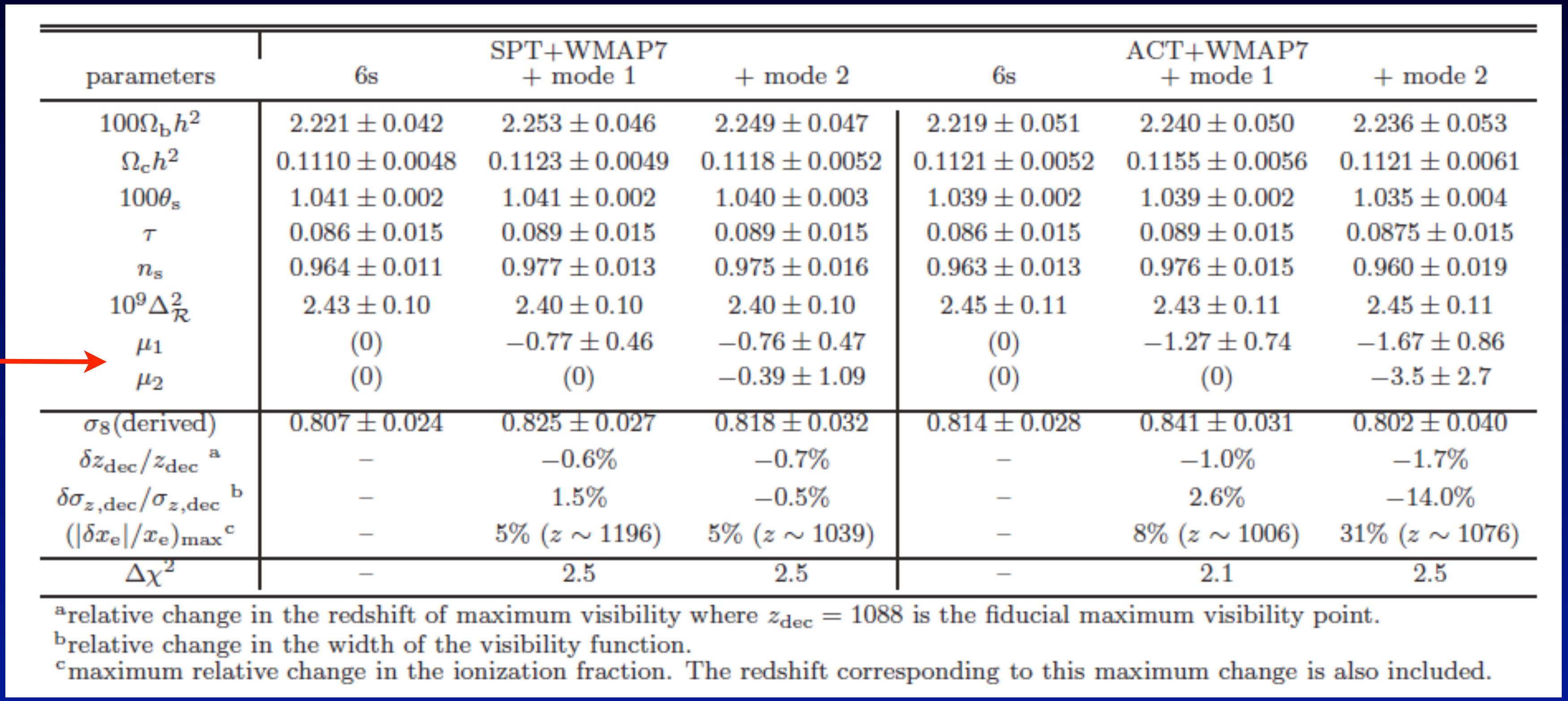
What if something unexpected happened?

- **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)**



Farhang, Bond & JC, 2012

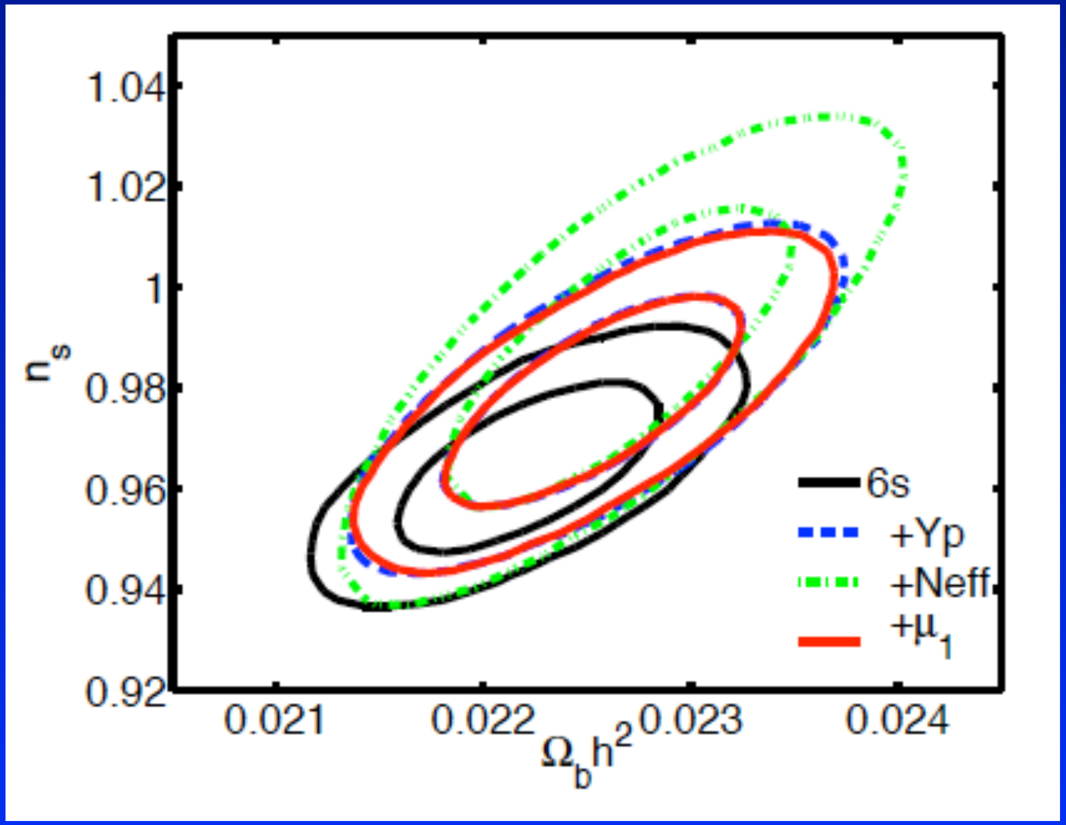
Measured mode amplitudes for ACT & SPT



parameters	SPT+WMAP7 6s	 + mode 1	 + mode 2	ACT+WMAP7 6s	 + mode 1	 + mode 2
$100\Omega_b h^2$	2.221 ± 0.042	2.253 ± 0.046	2.249 ± 0.047	2.219 ± 0.051	2.240 ± 0.050	2.236 ± 0.053
$\Omega_c h^2$	0.1110 ± 0.0048	0.1123 ± 0.0049	0.1118 ± 0.0052	0.1121 ± 0.0052	0.1155 ± 0.0056	0.1121 ± 0.0061
$100\theta_s$	1.041 ± 0.002	1.041 ± 0.002	1.040 ± 0.003	1.039 ± 0.002	1.039 ± 0.002	1.035 ± 0.004
τ	0.086 ± 0.015	0.089 ± 0.015	0.089 ± 0.015	0.086 ± 0.015	0.089 ± 0.015	0.0875 ± 0.015
n_s	0.964 ± 0.011	0.977 ± 0.013	0.975 ± 0.016	0.963 ± 0.013	0.976 ± 0.015	0.960 ± 0.019
$10^9 \Delta^2_{\mathcal{R}}$	2.43 ± 0.10	2.40 ± 0.10	2.40 ± 0.10	2.45 ± 0.11	2.43 ± 0.11	2.45 ± 0.11
μ_1	(0)	-0.77 ± 0.46	-0.76 ± 0.47	(0)	-1.27 ± 0.74	-1.67 ± 0.86
μ_2	(0)	(0)	-0.39 ± 1.09	(0)	(0)	-3.5 ± 2.7
σ_8(derived)	0.807 ± 0.024	0.825 ± 0.027	0.818 ± 0.032	0.814 ± 0.028	0.841 ± 0.031	0.802 ± 0.040
$\delta z_{\rm dec}/z_{\rm dec}$ [a]	–	−0.6%	−0.7%	–	−1.0%	−1.7%
$\delta\sigma_{z,\rm dec}/\sigma_{z,\rm dec}$ [b]	–	1.5%	−0.5%	–	2.6%	−14.0%
$(\lvert\delta x_e\rvert/x_e)_{\rm max}$ [c]	–	5% ($z \sim 1196$)	5% ($z \sim 1039$)	–	8% ($z \sim 1006$)	31% ($z \sim 1076$)
$\Delta\chi^2$	–	2.5	2.5	–	2.1	2.5

[a] relative change in the redshift of maximum visibility where $z_{\rm dec} = 1088$ is the fiducial maximum visibility point.
[b] relative change in the width of the visibility function.
[c] maximum relative change in the ionization fraction. The redshift corresponding to this maximum change is also included.

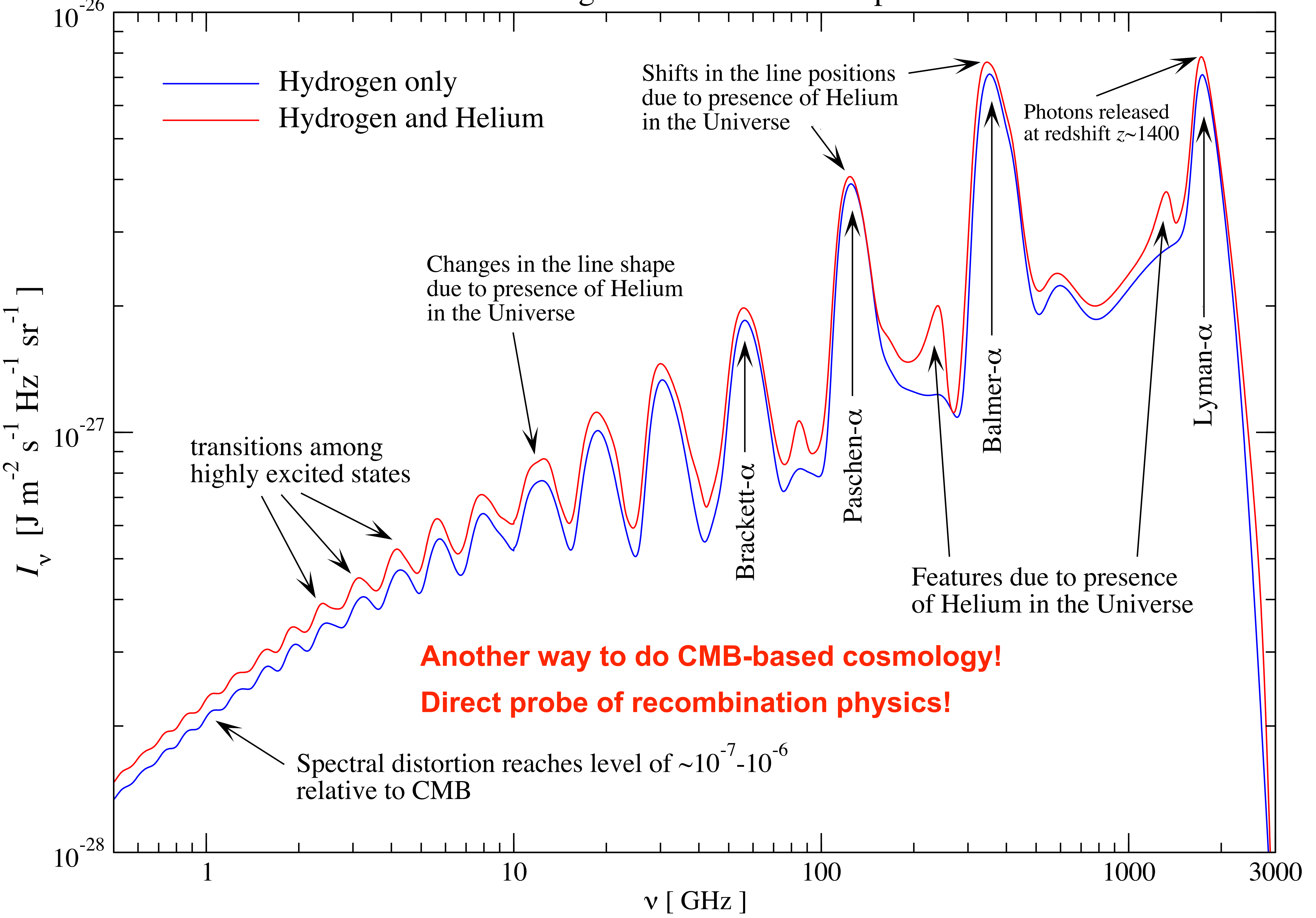
- *First mode detected at ~ 2σ*
- *Similar for current Planck data*
- *Effect very similar to the one of helium*
- *In the future 2-3 modes detectable*
- *Can we break the degeneracies???*



Farhang, Bond & JC, 2012

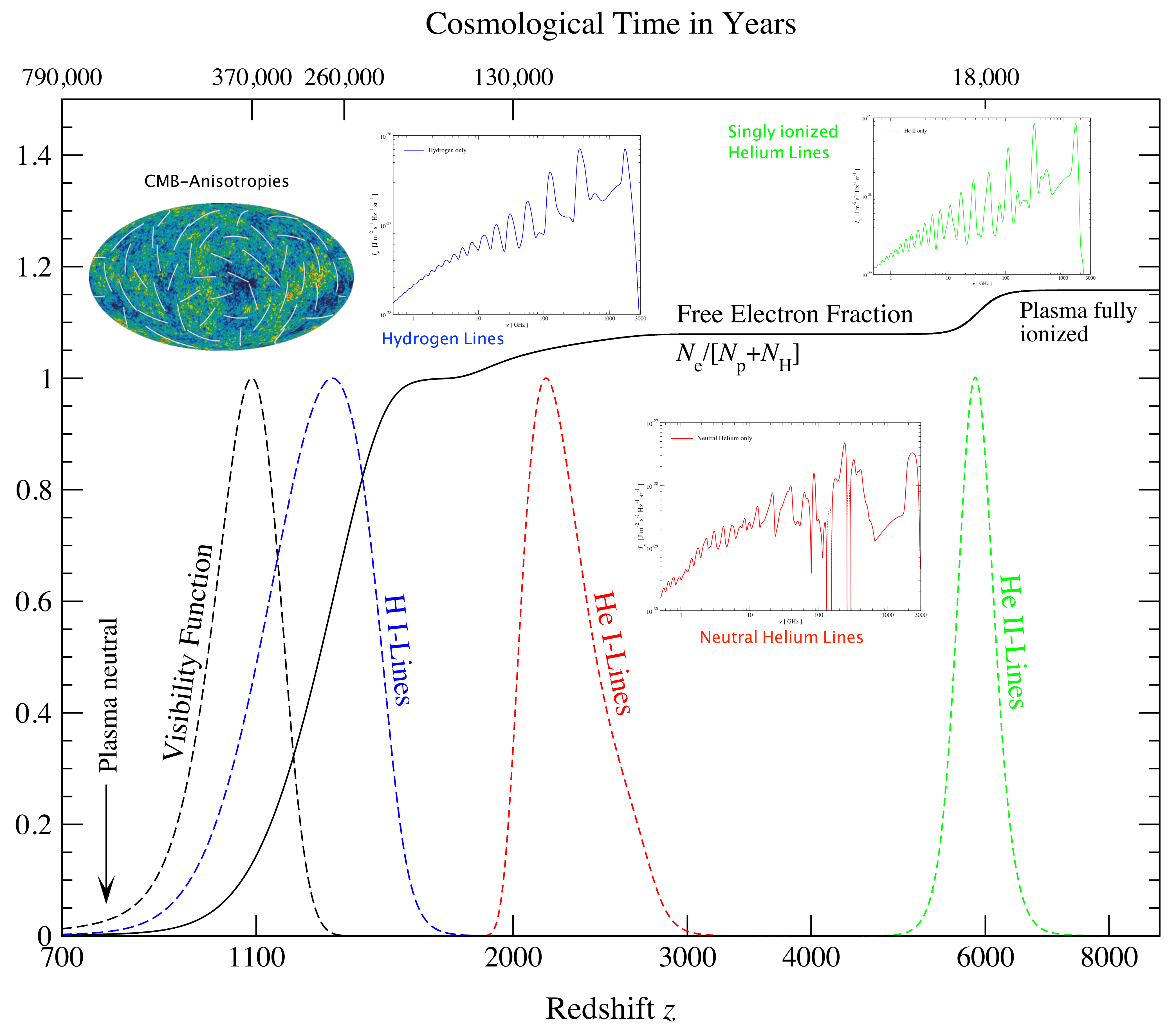
Can the Cosmological Recombination Radiation help us with this?

Cosmological Recombination Spectrum



Another way to do CMB-based cosmology!

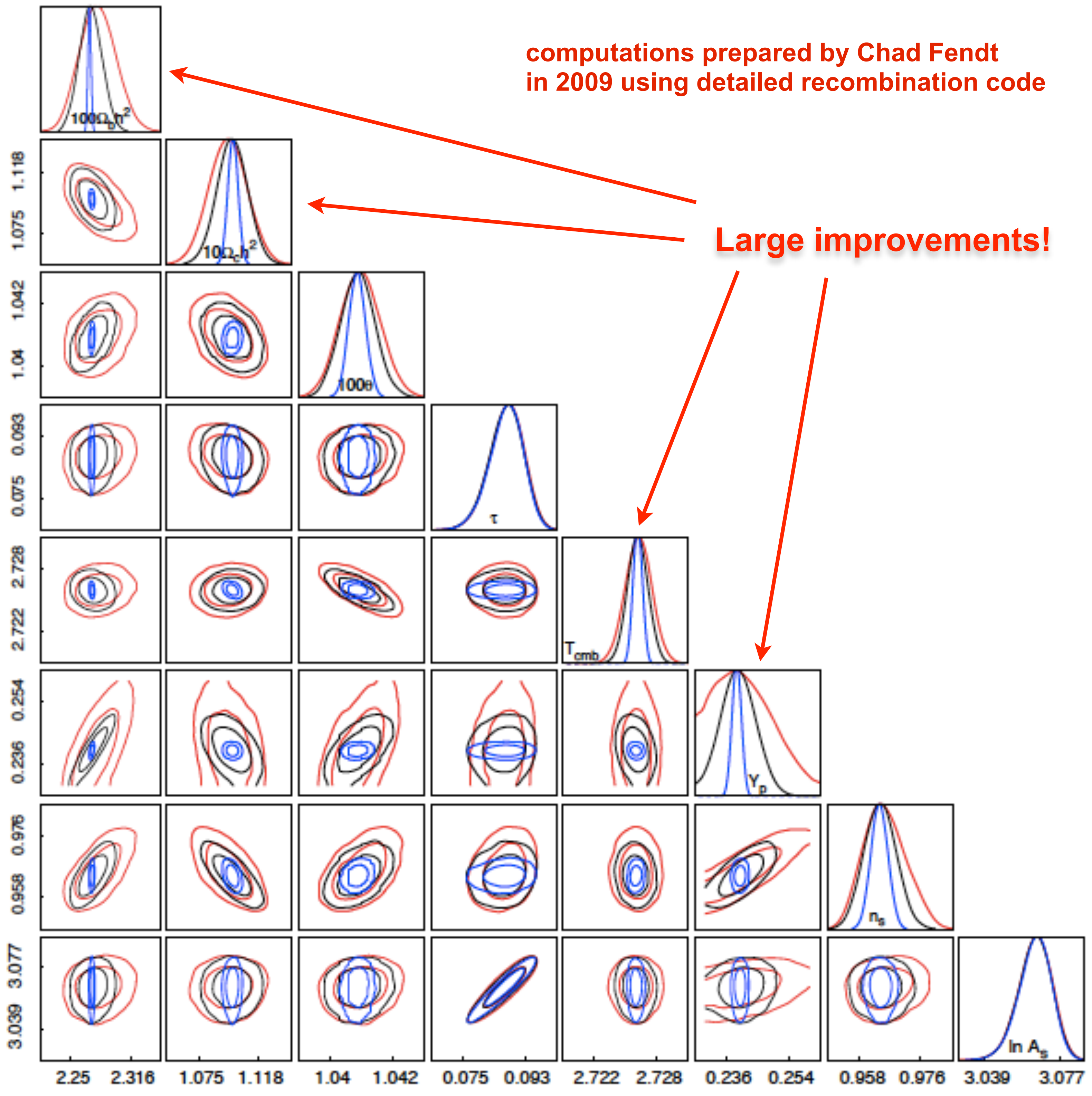
Direct probe of recombination physics!


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

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!***



computations prepared by Chad Fendt
in 2009 using detailed recombination code

Large improvements!

Figure 7.3: The 1 and 2 dimensional marginalized parameter posterior using the CMB spectral distortions. All three cases constrain the CMB power spectrum using a Gaussian likelihood based on Planck noise levels. The black line adds constraints due to a 10% measurement of the spectral distortions, while the blue line assumes a 1% measurement. The red line does not include the data from the spectral distortions.

- CMB based cosmology alone
- Spectrum helps to break some of the parameter degeneracies
- Planning to provide a module that computes the recombination spectrum in a fast way
- detailed forecasts: which lines to measure; how important is the absolute amplitude; how accurately one should measure; best frequency resolution;

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 $\Omega_b h^2$)**

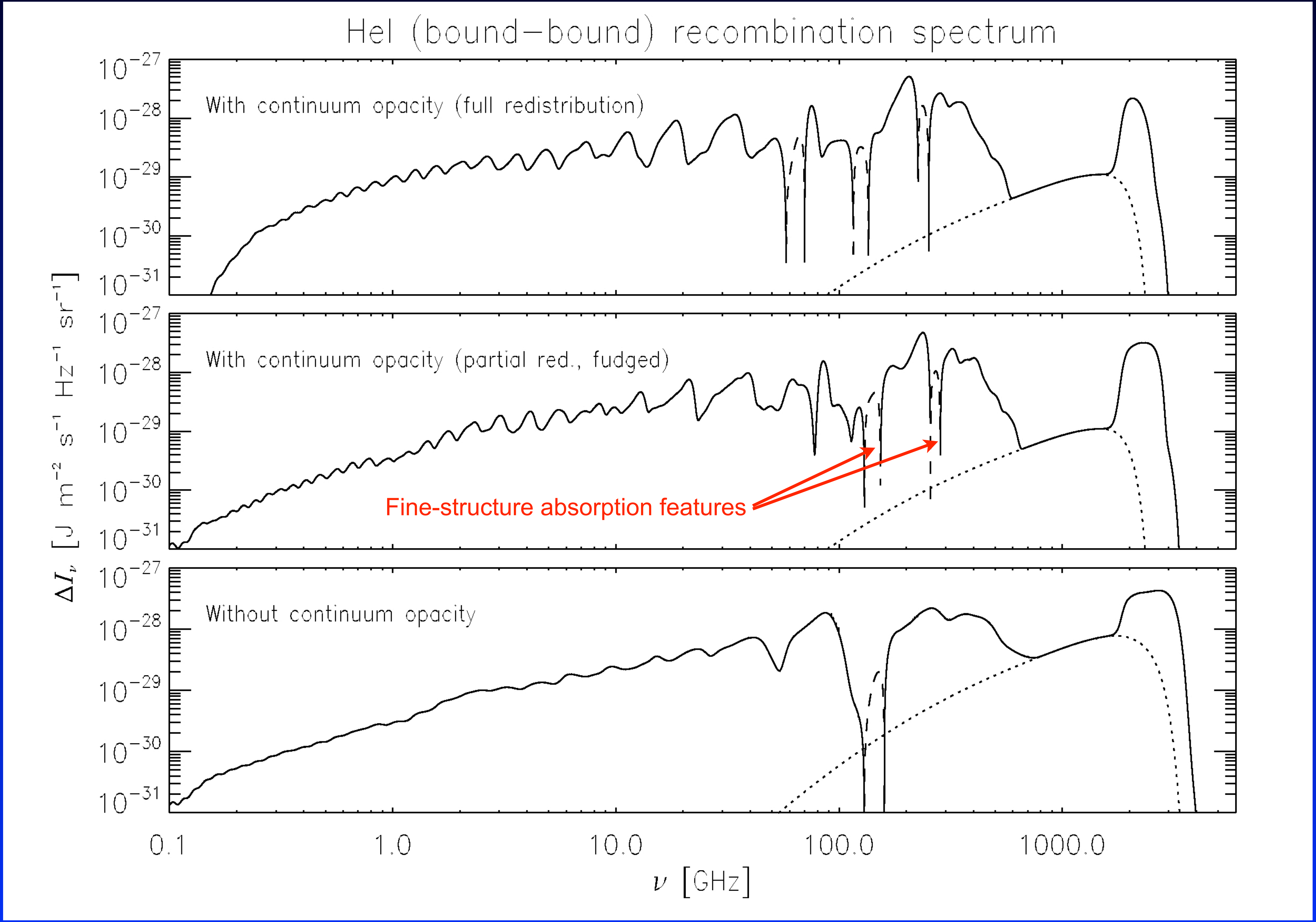
→ **the CMB *monopole* temperature T_0**

→ ***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!***

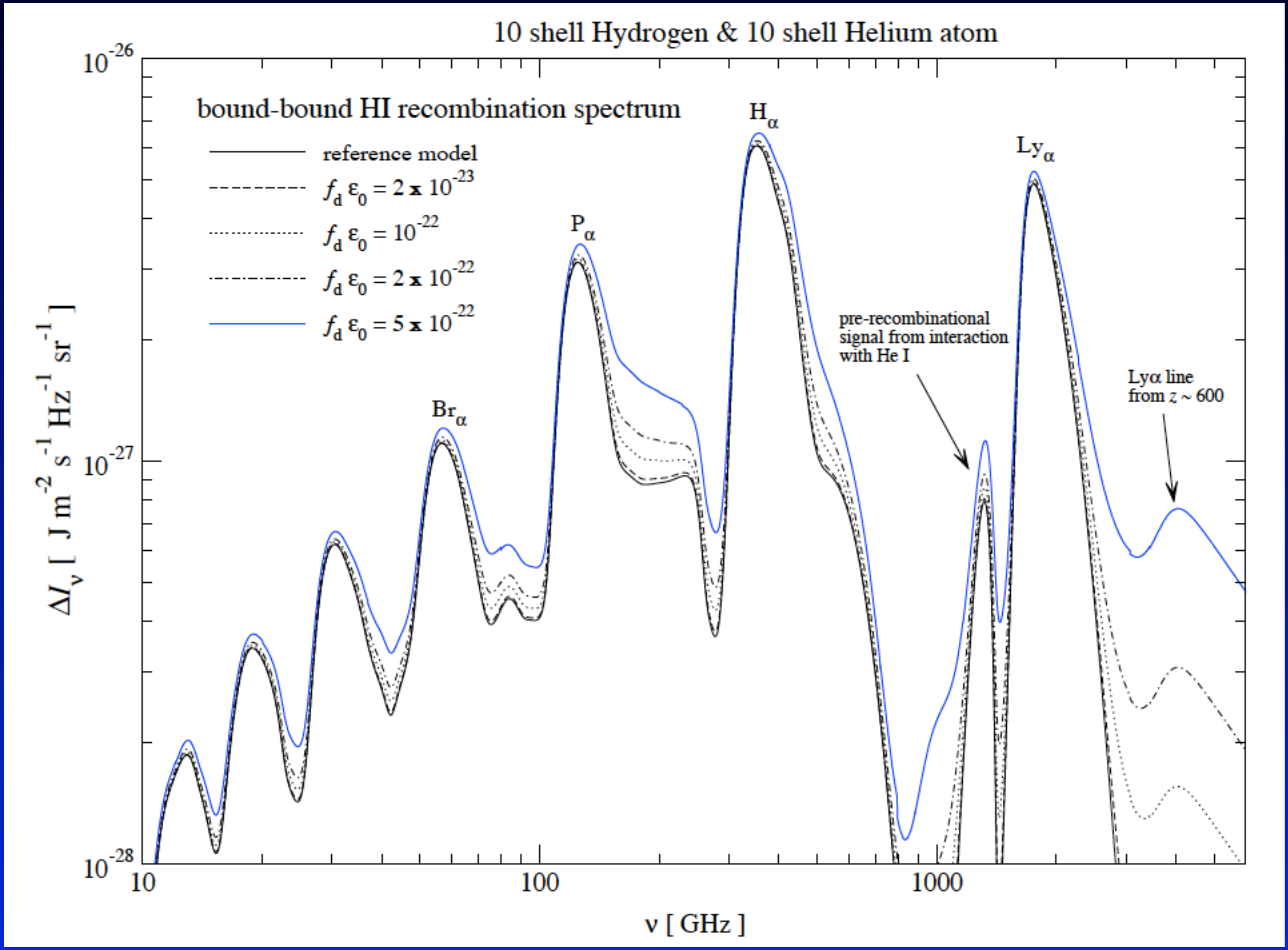
→ ***In principle allows us to directly check our understanding of the standard recombination physics***

The importance of HI continuum absorption



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

Dark matter annihilations / decays



JC, 2009, arXiv:0910.3663

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

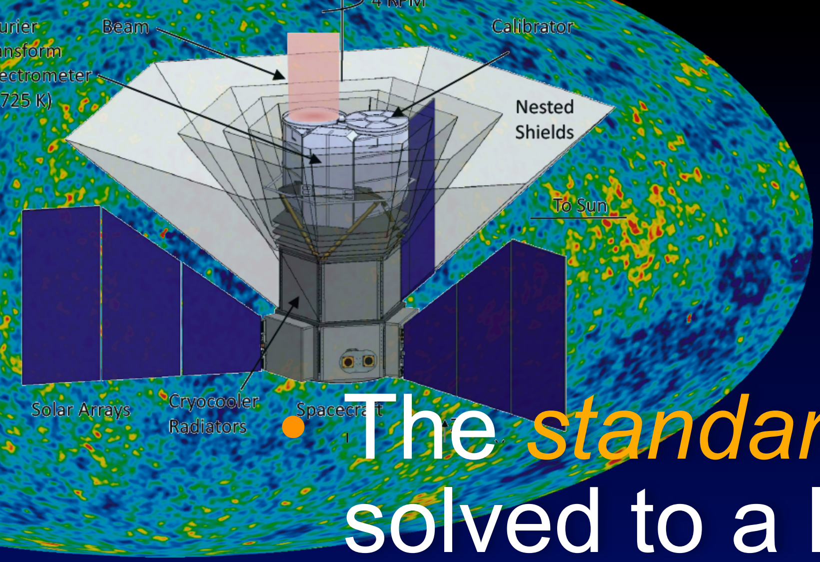
What would we actually learn by doing such hard job?

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***

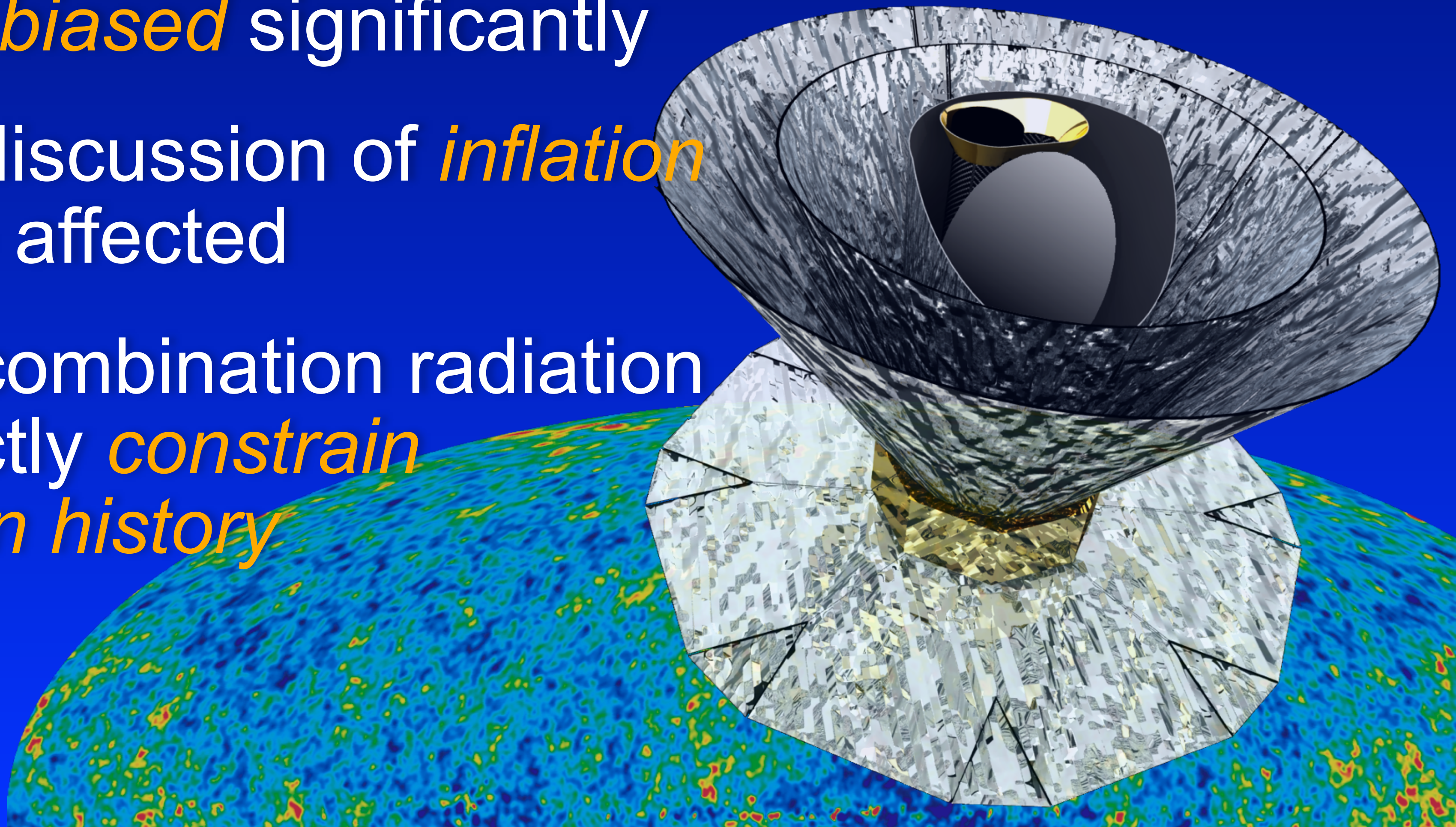
If something unexpected or non-standard happened:

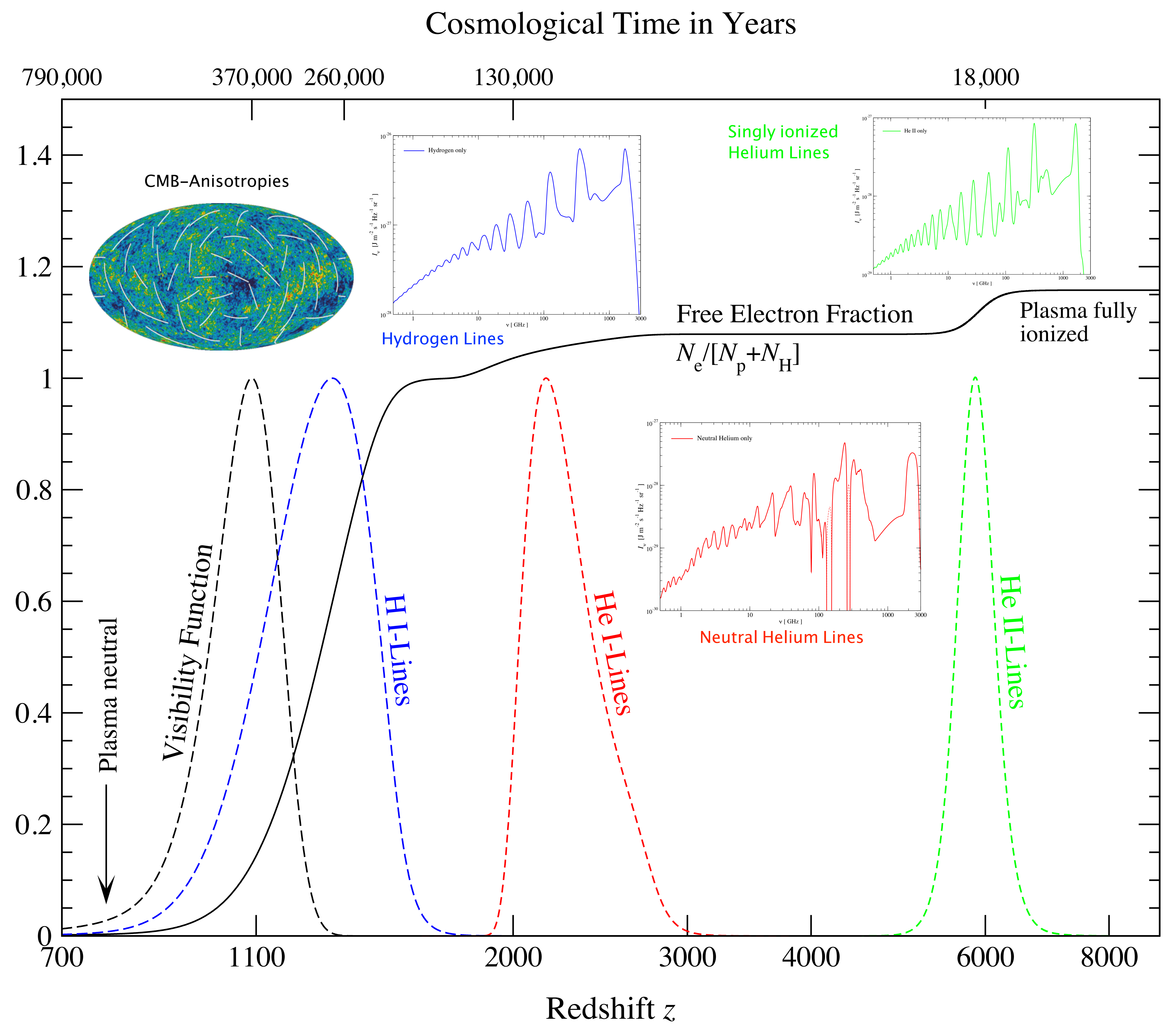
- → ***non-standard thermal histories should leave some measurable traces***
- → ***direct way to measure/reconstruct the recombination history!***
- → **possibility to distinguish *pre-* and *post-recombination y*-type distortions**
- → ***sensitive to energy release during recombination***
- → **variation of fundamental constants**



Conclusions

- 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 be affected
- Cosmological recombination radiation allows us to directly *constrain* the *recombination history*




Cosmological Time in Years
790,000
370,000
260,000
130,000
18,000
1.4
1.2
1
0.8
0.6
0.4
0.2
0
700
1100
2000
3000
4000
6000
8000
Redshift z
CMB-Anisotropies
Hydrogen only
Hydrogen Lines
Singly ionized Helium Lines
He II only
Neutral Helium only
Neutral Helium Lines
I_ν [J m^{-2} s^{-1} Hz^{-1} sr^{-1}]
ν [GHz]
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully ionized
Plasma neutral
Visibility Function
H I-Lines
He I-Lines
He II-Lines