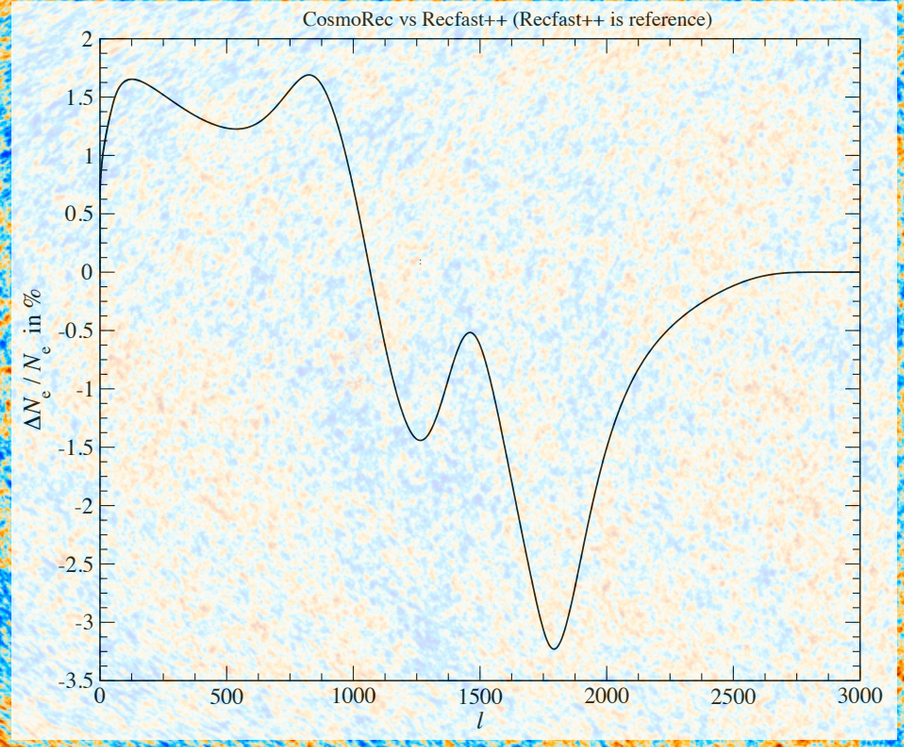
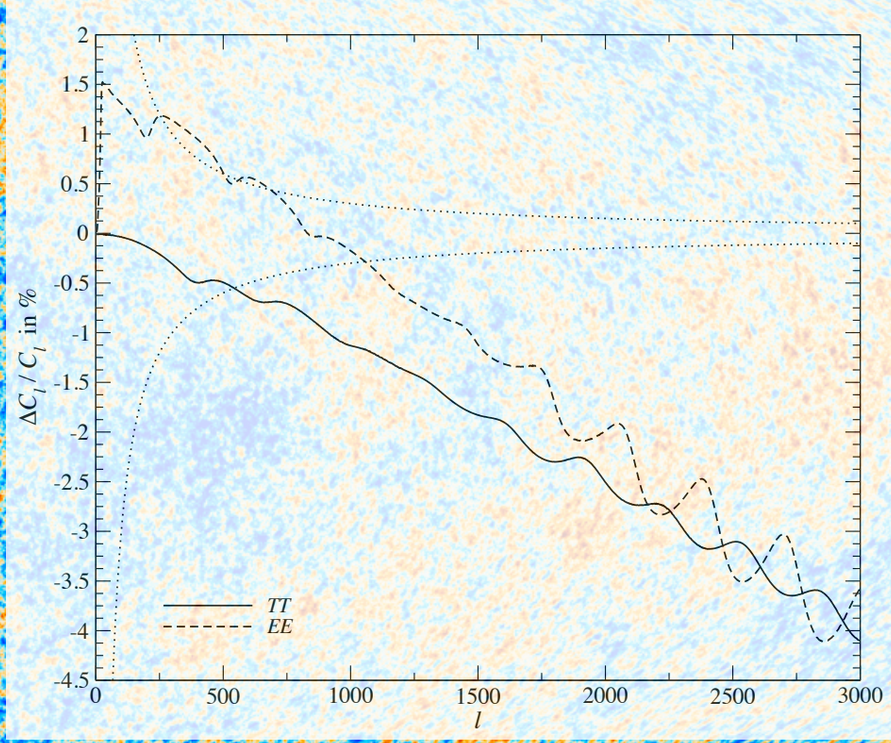
Introduction to Recombination Physics and Why it is Important for Cosmology and Early-Universe Physics

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++`

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

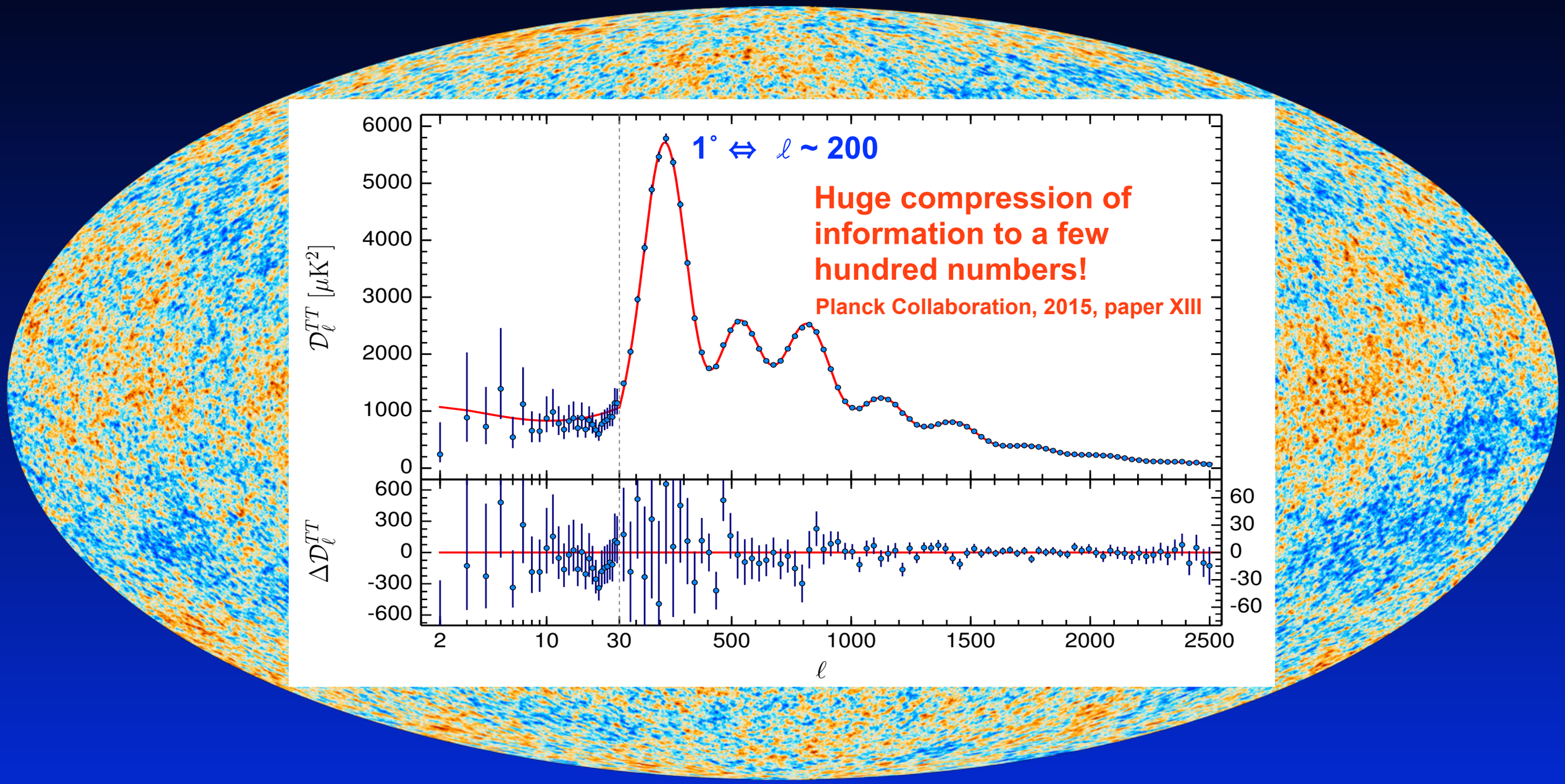
Today

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?*

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

Cosmic Microwave Background Anisotropies

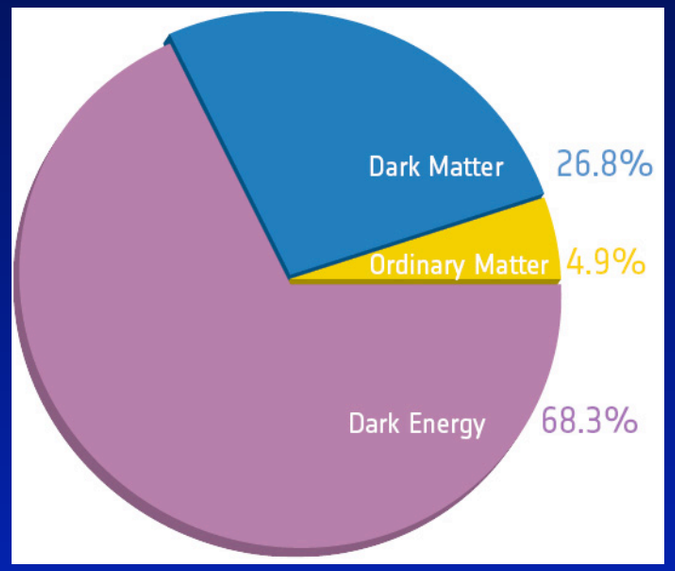


Planck all-sky temperature map

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

Planck Collaboration, 2015, paper XIII

Big Bang
0

Cosmic inflation
Origin of fluctuations
10^{-32} seconds

Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
10^{-30} seconds
1 second
100 seconds

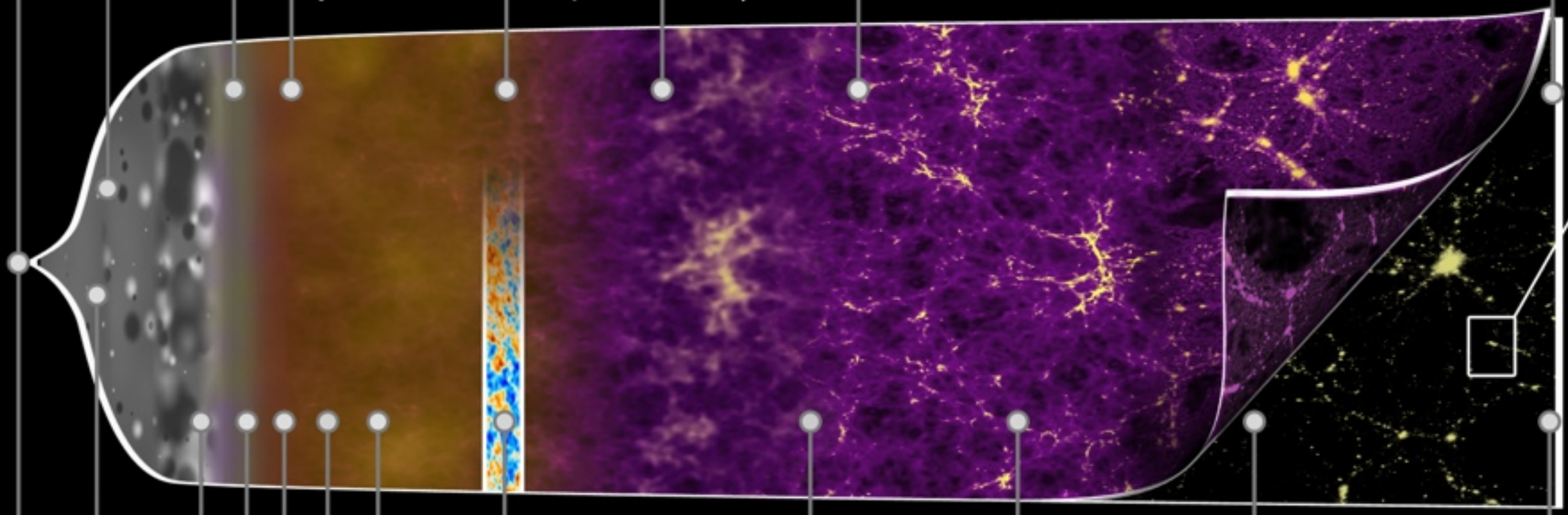
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
1 year

Dark ages
Ordinary matter particles fall into the structures created by dark matter
100 years
380 000 years

First stars & galaxies
200 million years

Galaxy evolution
Clusters of galaxies and superclusters form
1 billion years
10 billion years

Today
13.82 billion years



Big Bang

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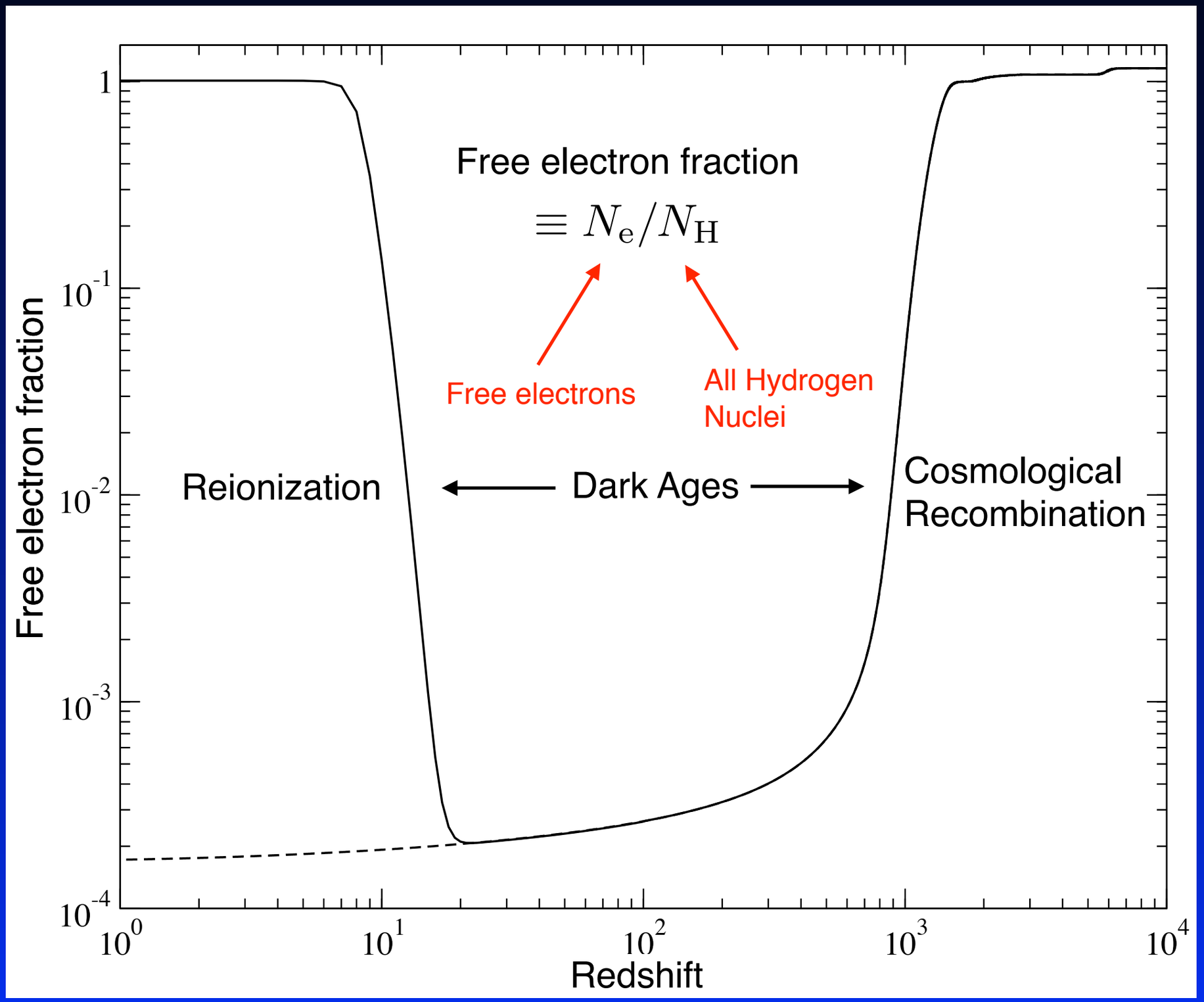
Initial conditions

CMB anisotropies

Large-scale E & B-modes
CMB Lensing
SZ effect

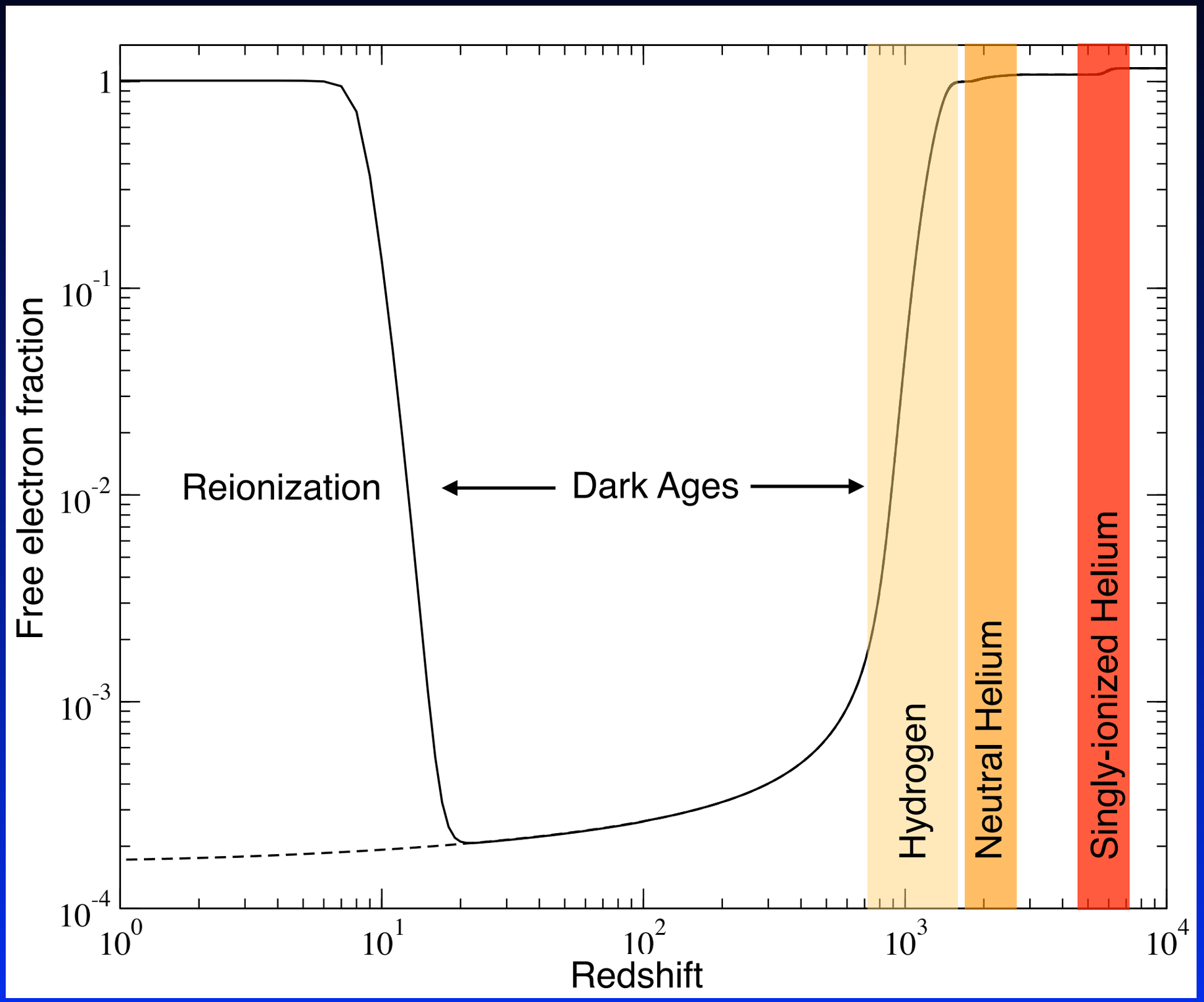
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13.82 billion years

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

Sketch of the Cosmic Ionization History

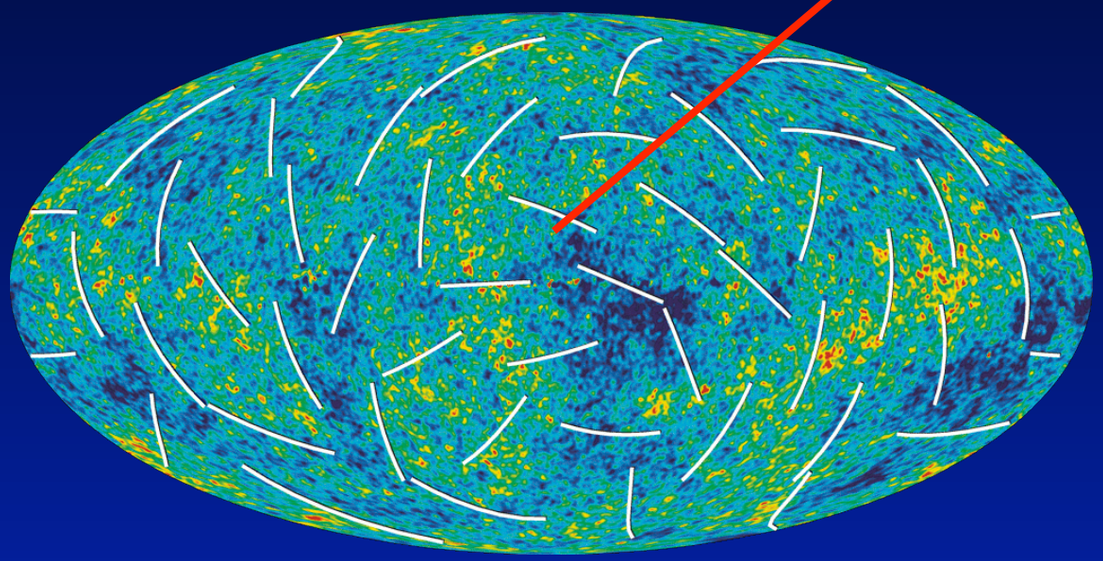


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- Neutral Helium recombination around z~2000
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CMB Sky → Cosmology

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

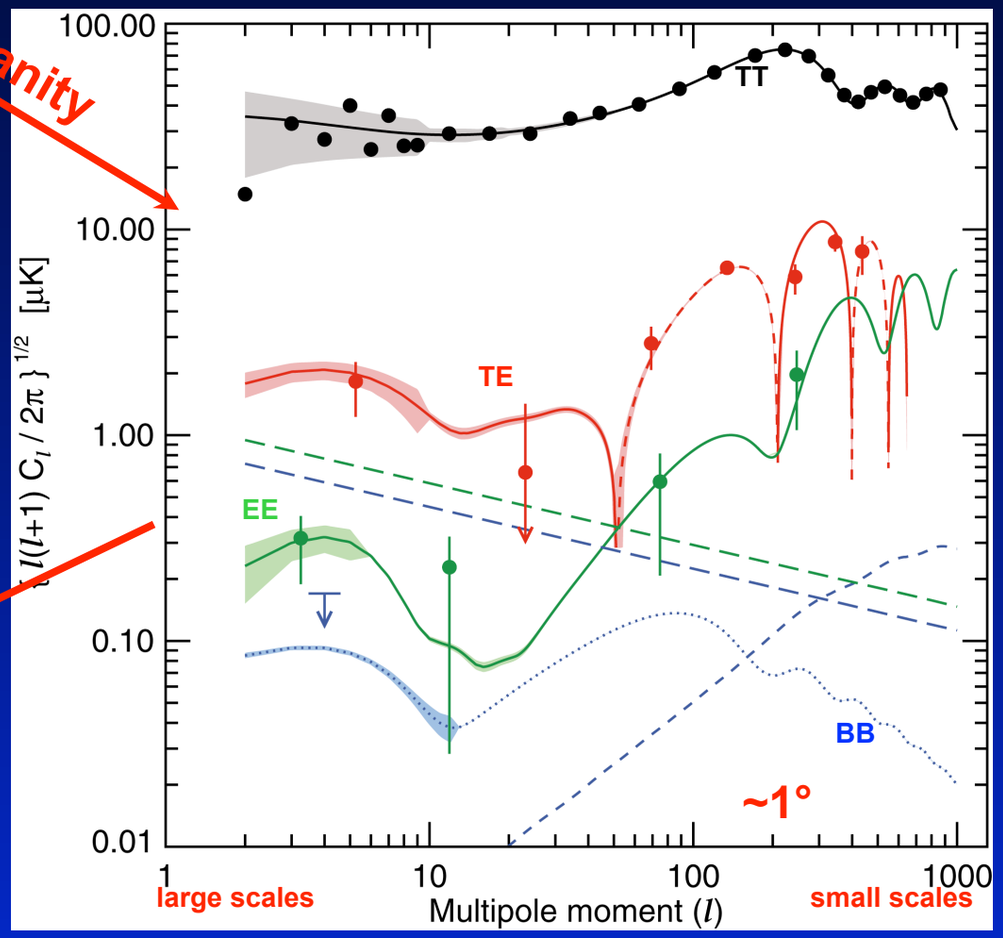
CMB Sky
(temperature & polarization)



a_{lm}

Gaussianity

Power spectra



(Joint) analysis

Cosmological Parameters

Ω_{tot}, Ω_m, Ω_b, Ω_Λ,
h, τ, n_s,...

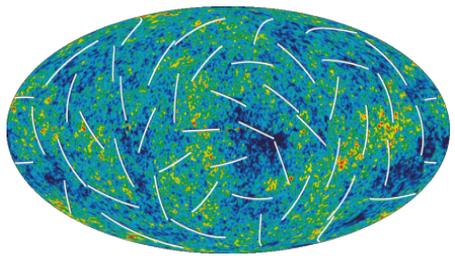
Other cosmological Datasets:

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

Cosmological Time in Years

790,000 370,000 260,000 130,000 18,000

CMB-Anisotropies



Why does the ionization history matter so much?

Free Electron Fraction

$N_e/[N_p+N_H]$

Plasma fully ionized

Plasma neutral

Visibility Function

- Free electron fraction determines *Thomson visibility function* (maximum at z~1100 where N_e / N_H ~ 16%)

$$\frac{\partial\tau}{\partial\eta} = \sigma_T N_e a$$

$$\mathcal{V}(\eta) = \frac{\partial\tau}{\partial\eta}\, e^{-\tau(\eta)} \qquad \eta = \int \frac{c\,dt}{a}$$

- Defines how photons and baryons *decouple* $\Longrightarrow$ *Last Scattering Surface*
- *Free streaming* of photons after recombination

0 0.2 0.4 0.6 0.8 1 1.2 1.4

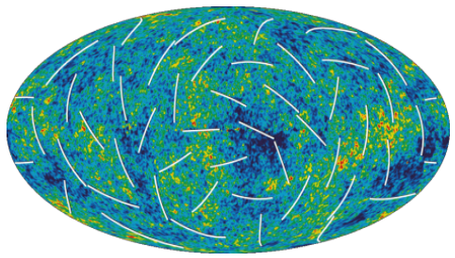
700 1100 2000 3000 4000 6000 8000

Redshift z

Cosmological Time in Years

790,000 370,000 260,000 130,000 18,000

CMB-Anisotropies



Why does the ionization history matter so much?

Free Electron Fraction

$N_e/[N_p+N_H]$

Plasma fully ionized

Plasma neutral

Visibility Function

- *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)*

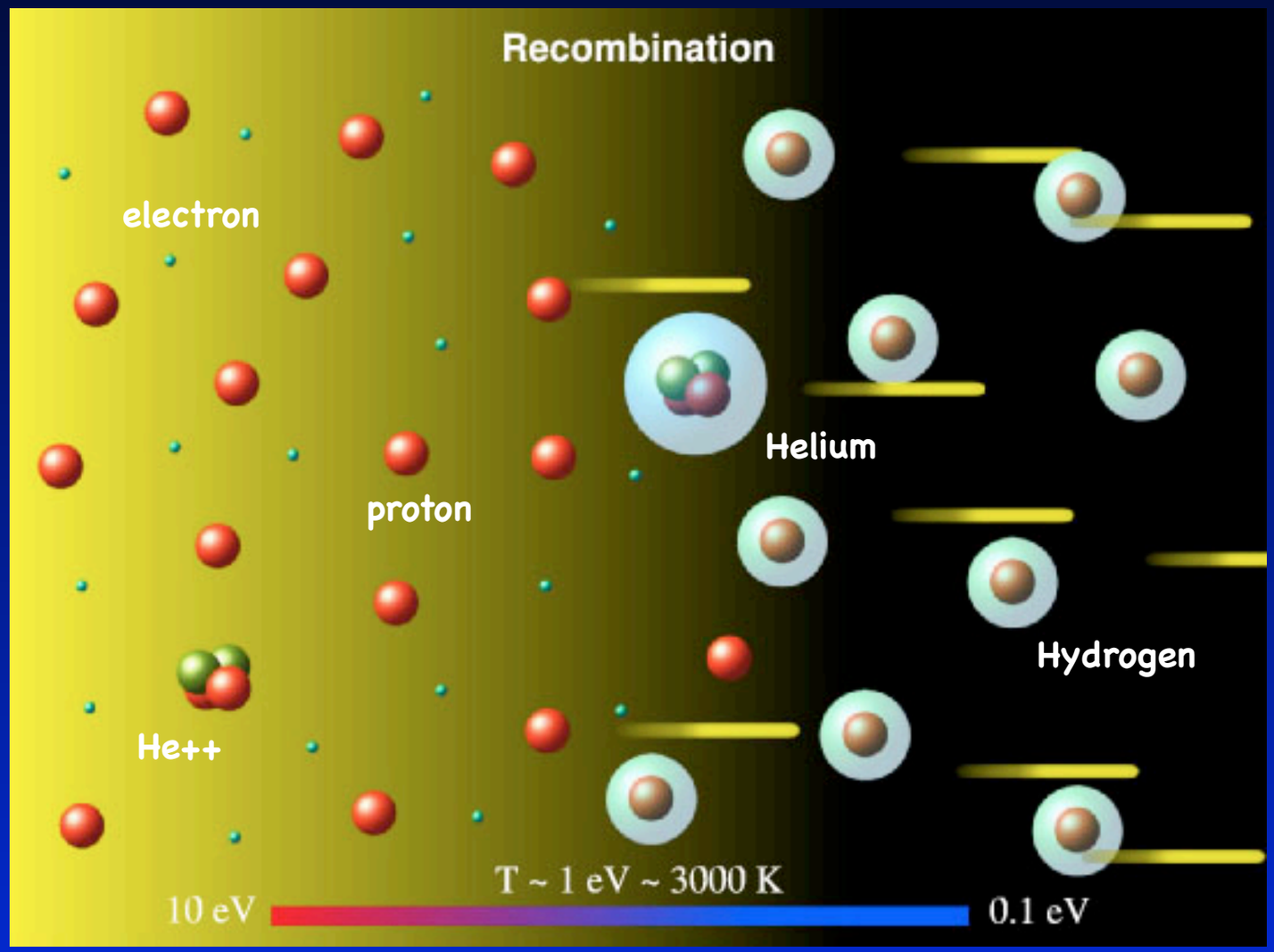
1.4 1.2 1 0.8 0.6 0.4 0.2 0

700 1100 2000 3000 4000 6000 8000

Redshift z

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*

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

electron temperature

number densities

non-thermal photons

Only problem in time!

Physical Conditions during Recombination

- Anisotropies negligible for recombination problem
- CMB temperature T_γ ~ 2.725 (1+z) K ~ 3000 K
- Baryon number density N_b ~ 2.5x10^{-7}cm^{-3} (1+z)^3 ~ 330 cm^{-3}
- Photon number density N_γ ~ 410 cm^{-3} (1+z)^3 ~ 2×10^9 N_b

  ⇒ photons in very distant Wien tail of blackbody spectrum can keep hydrogen ionized until $h\nu_\alpha$ ~ 40 kT_γ ⇔ T_γ ~ 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 ~ 200 ⇒ T_γ ~ T_e ~ T_m

Saha-Equation for ionization degree

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

Total number (density) of hydrogen nuclei

(number) density of given species *i*

N_i / N_H

1s-population (Saha)

ionized-population

electron fraction (Saha)

In equilibrium with free electrons



Meghnad Saha



George Gamov

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}

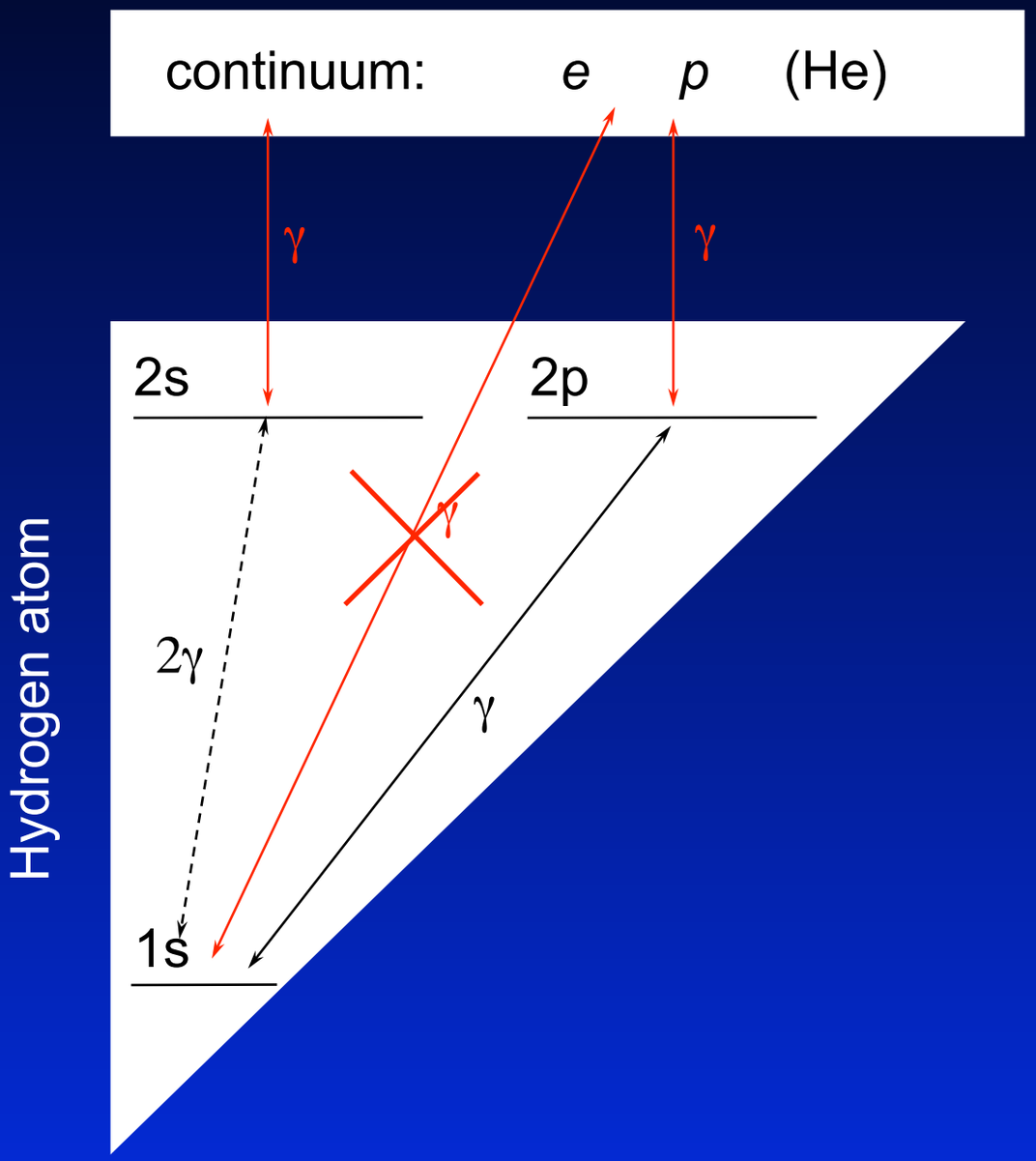
10^{-3}

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 $\sim 10^8$ 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!



Yakov Zeldovich

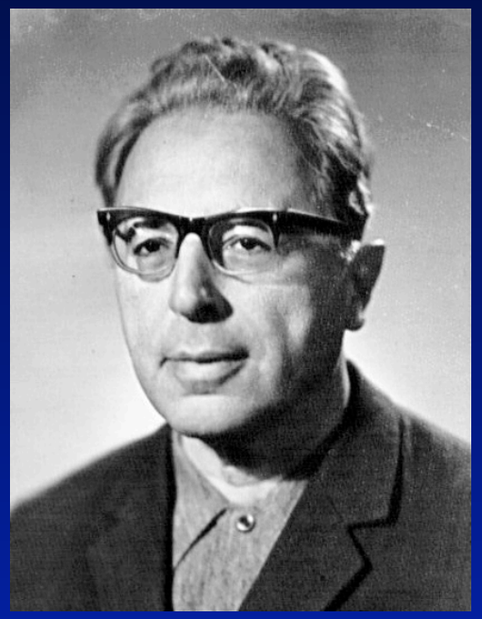
Moscow



Vladimir Kurt
(UV astronomer)

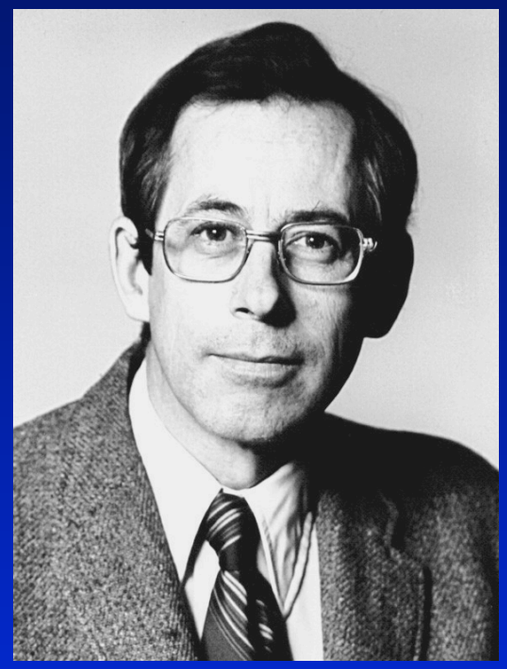


Rashid Sunyaev



Iosif Shklovsky
(radio astronomer)

Princeton

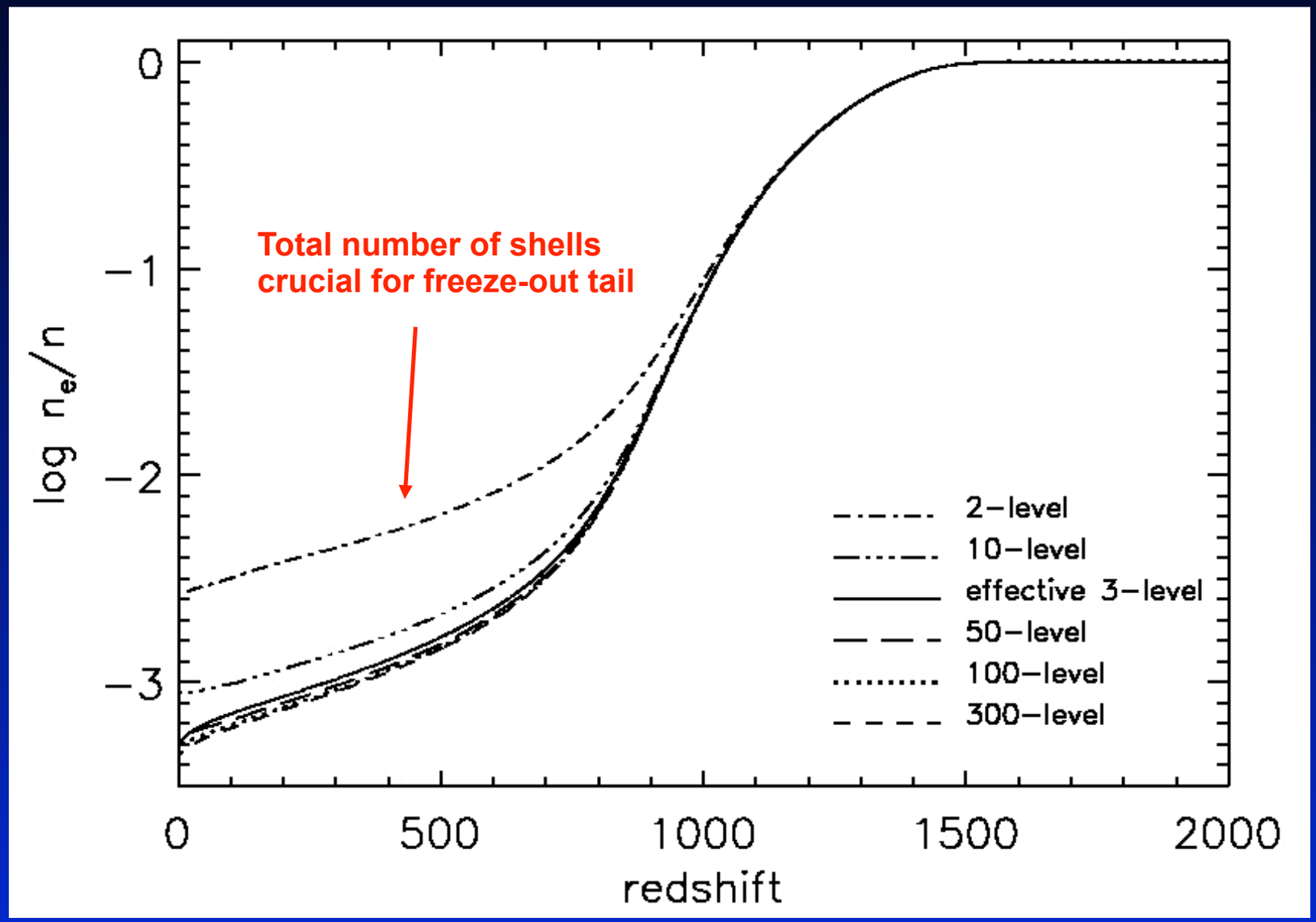


Jim Peebles

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

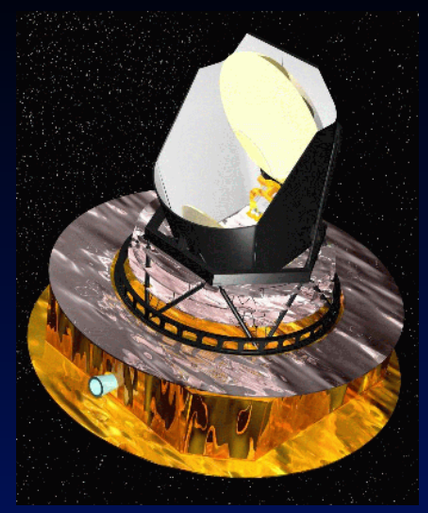
Low Redshifts:

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

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

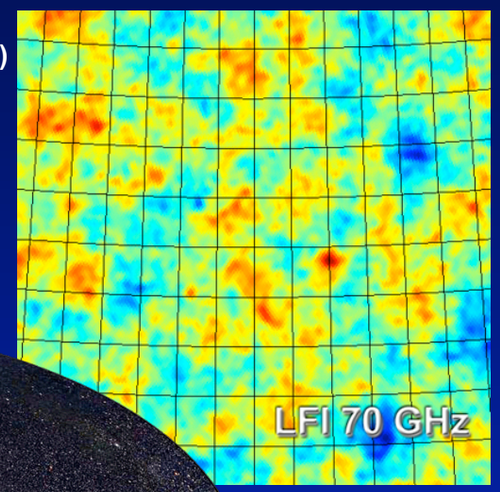
$\Delta N_e / N_e \sim 1\% - 3\%$

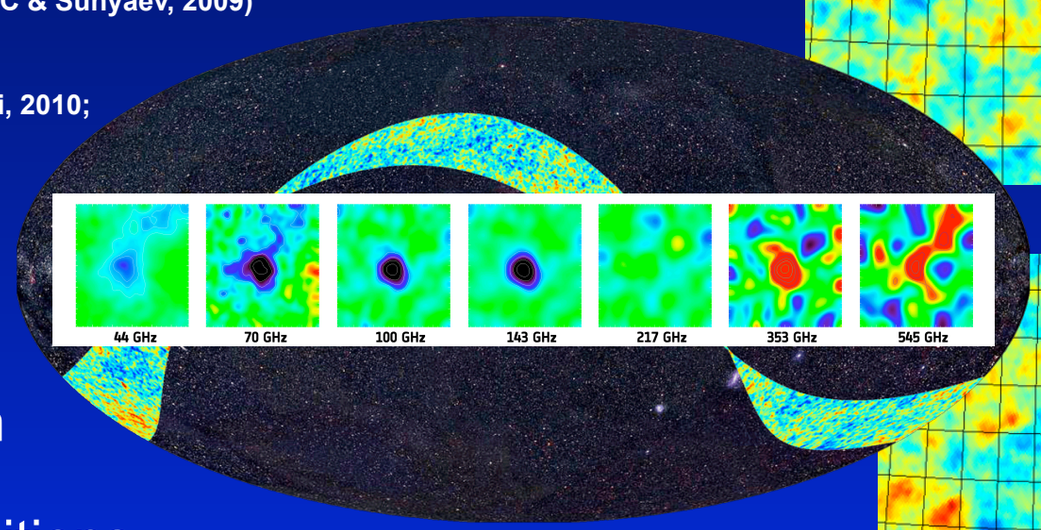
Getting the job done for *Planck*

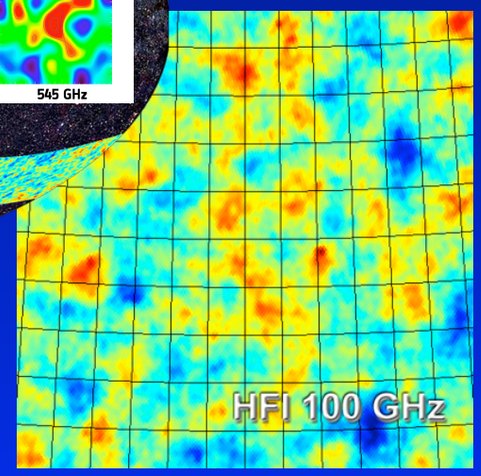


Hydrogen recombination

- 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

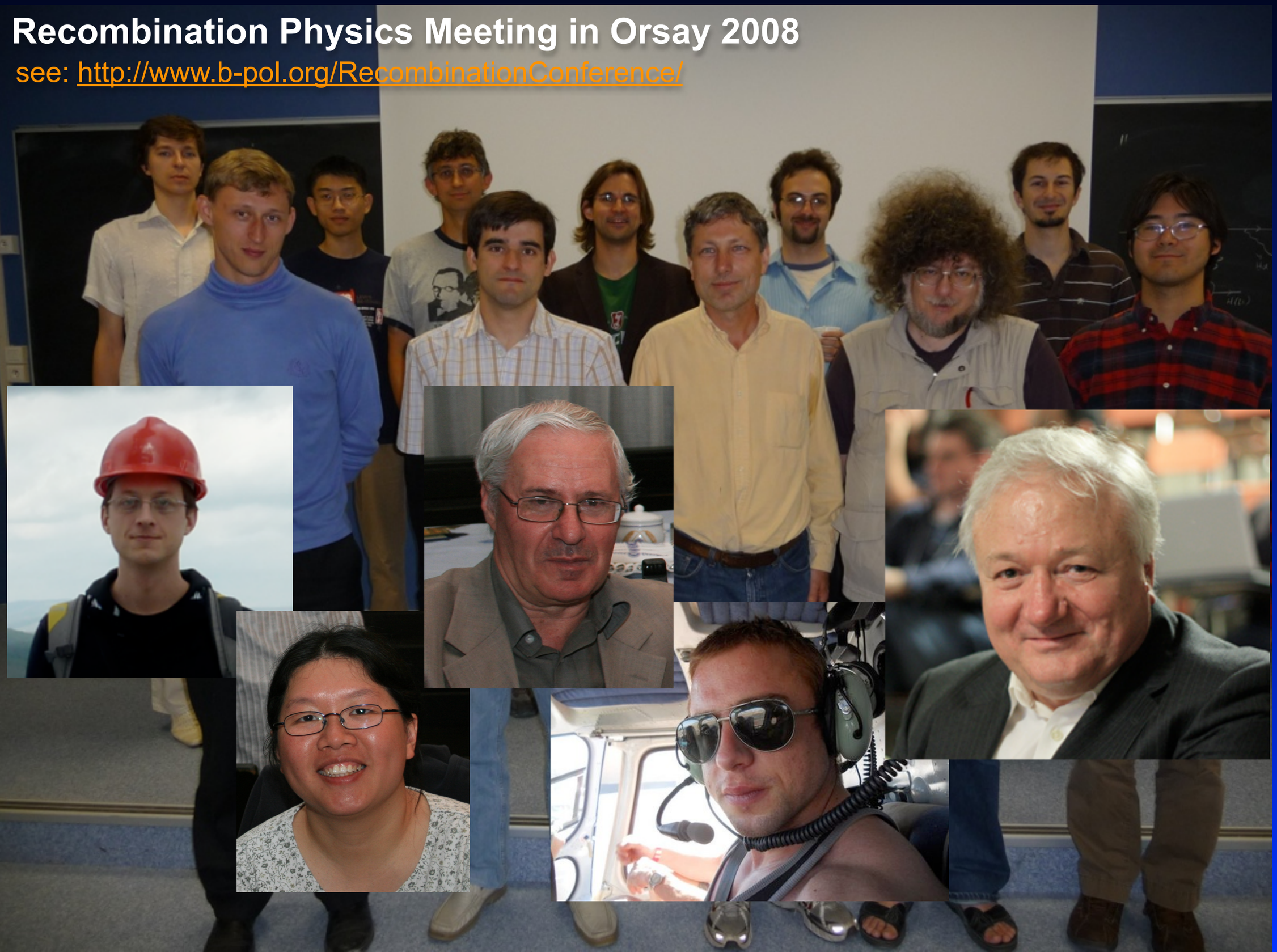
- Similar list of processes as for hydrogen
  (Switzer & Hirata, 2007a&b; Hirata & Switzer, 2007)
- Spin forbidden 2p-1s triplet-singlet transitions
  (Dubrovich & Grachev, 2005, Astr. Lett.; Wong & Scott, 2007; Switzer & Hirata, 2007; Kholupenko, Ivanchik&Varshalovich, 2007)
- Hydrogen continuum opacity 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

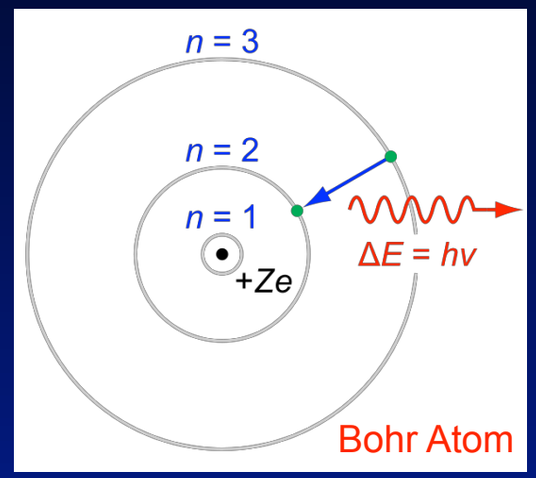
see: http://www.b-pol.org/RecombinationConference/



Atomic Physics Challenges

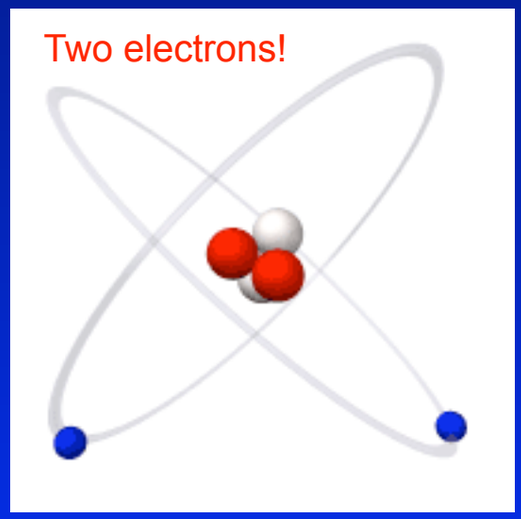
Hydrogen Atom & Hydrogenic Helium

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

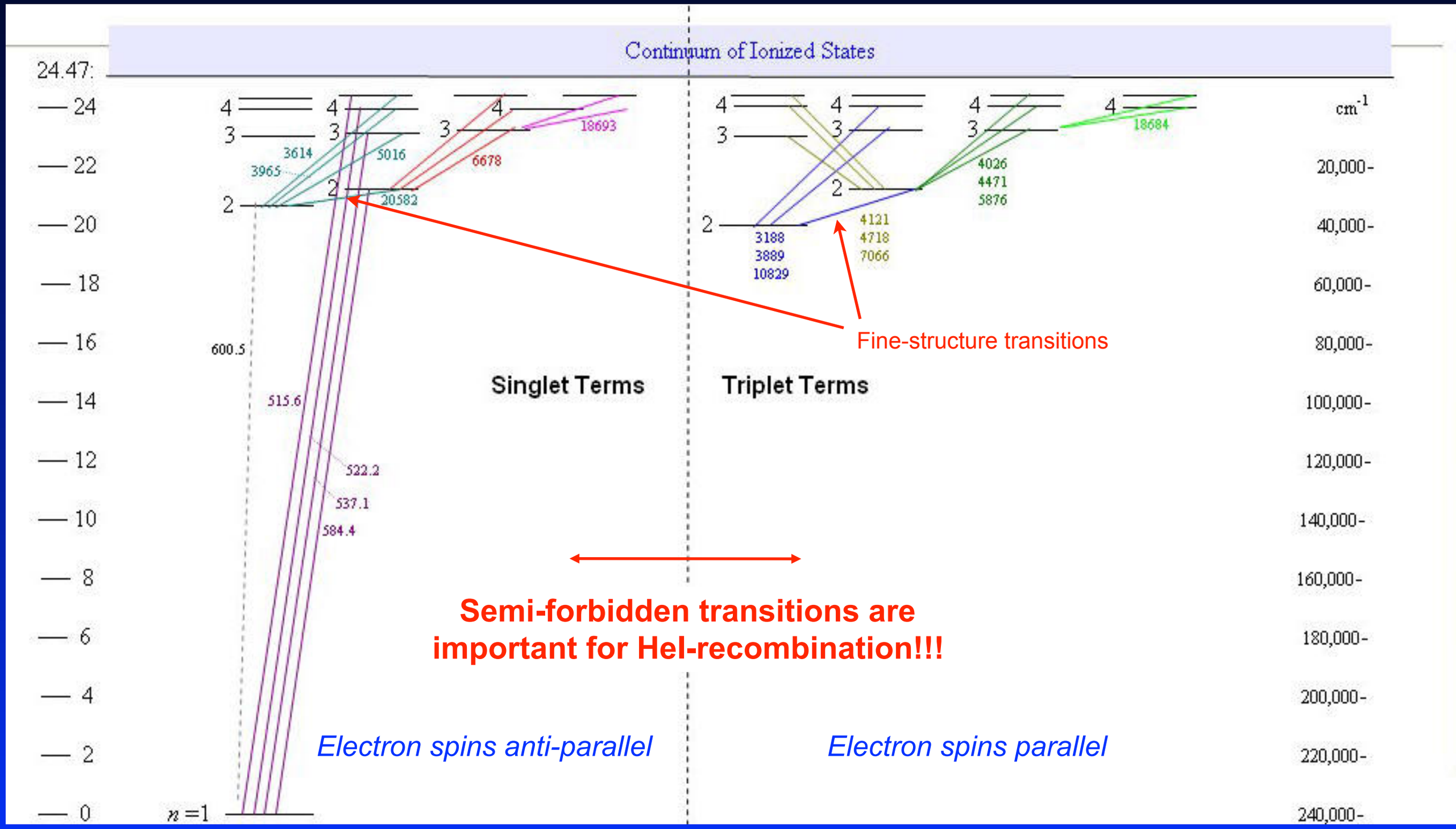


Neutral Helium

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



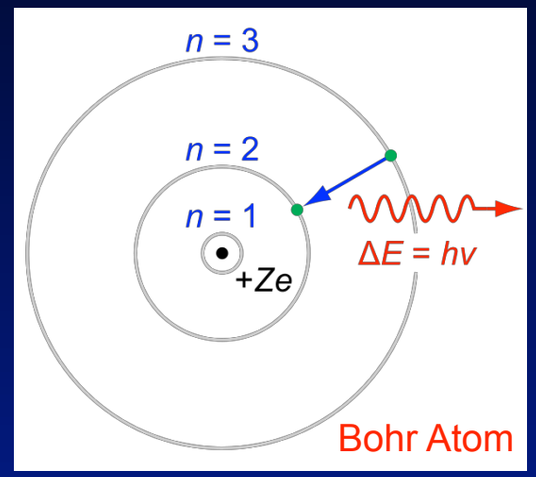
Grotrian diagram for neutral helium



Atomic Physics Challenges

Hydrogen Atom & Hydrogenic Helium

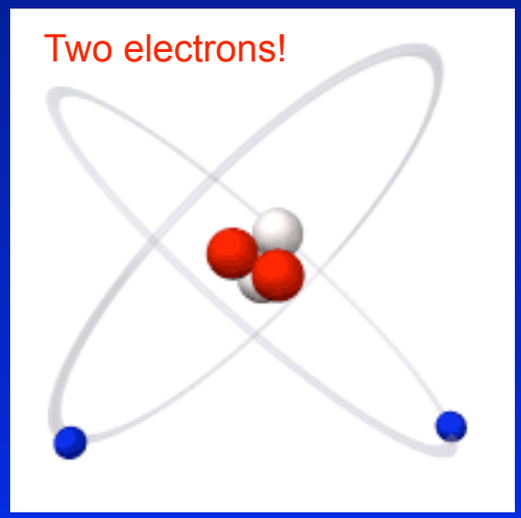
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- Collisional rates less robust, but effect small (new rates became available!)
- Biggest computational challenge is the number of levels (~ n^2)



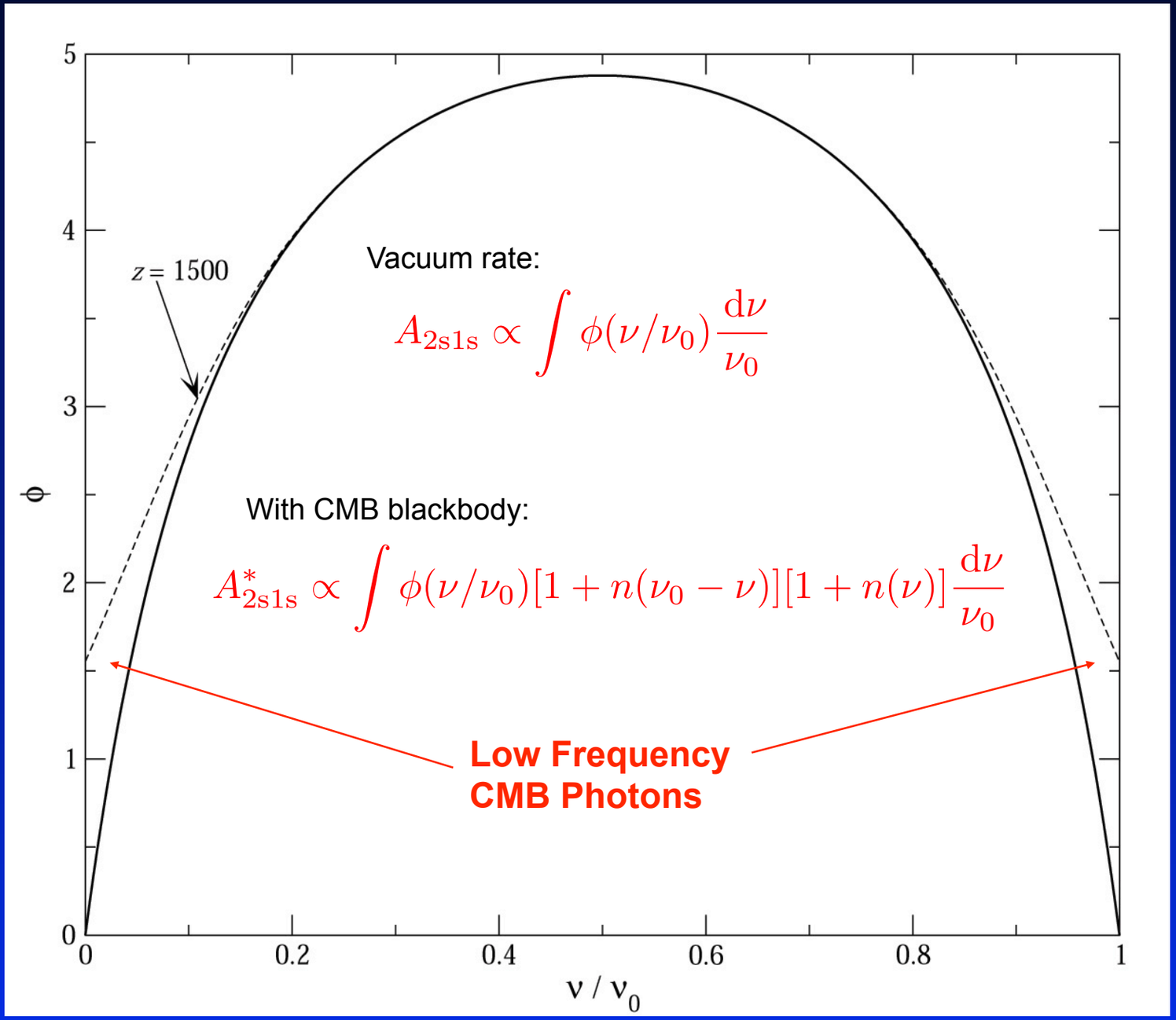
Neutral Helium

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



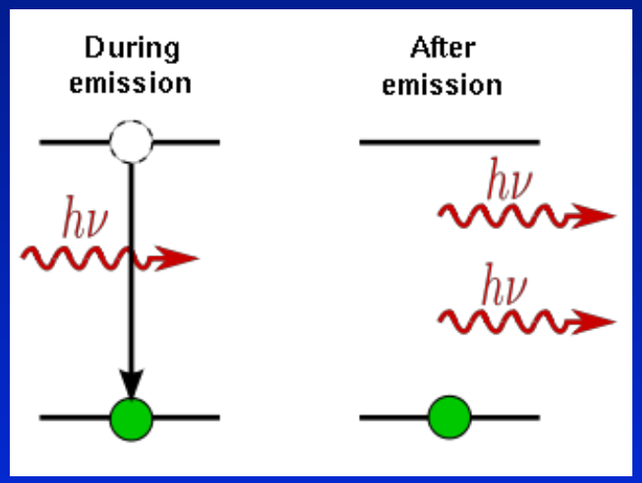
2s-1s emission profile

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

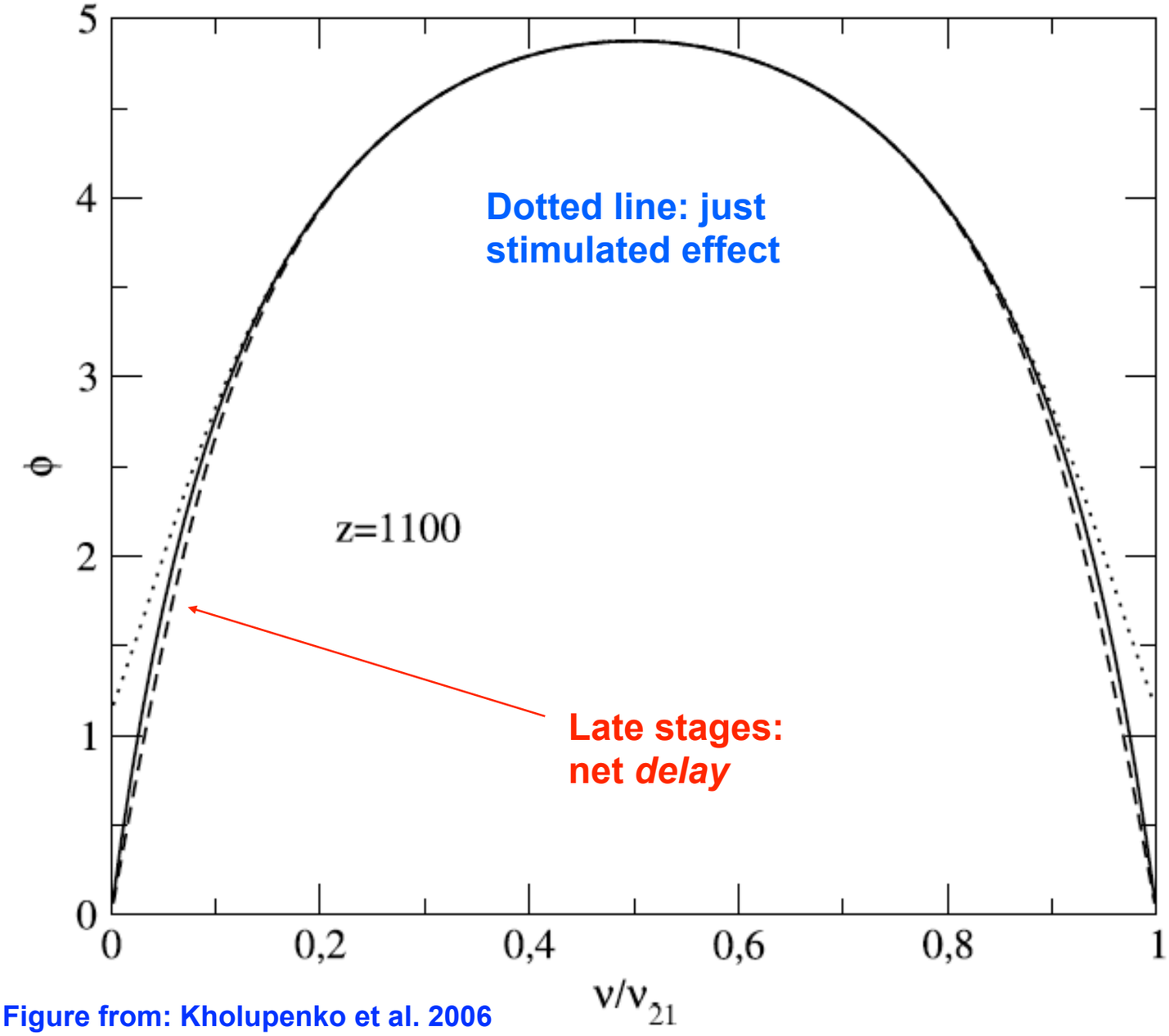


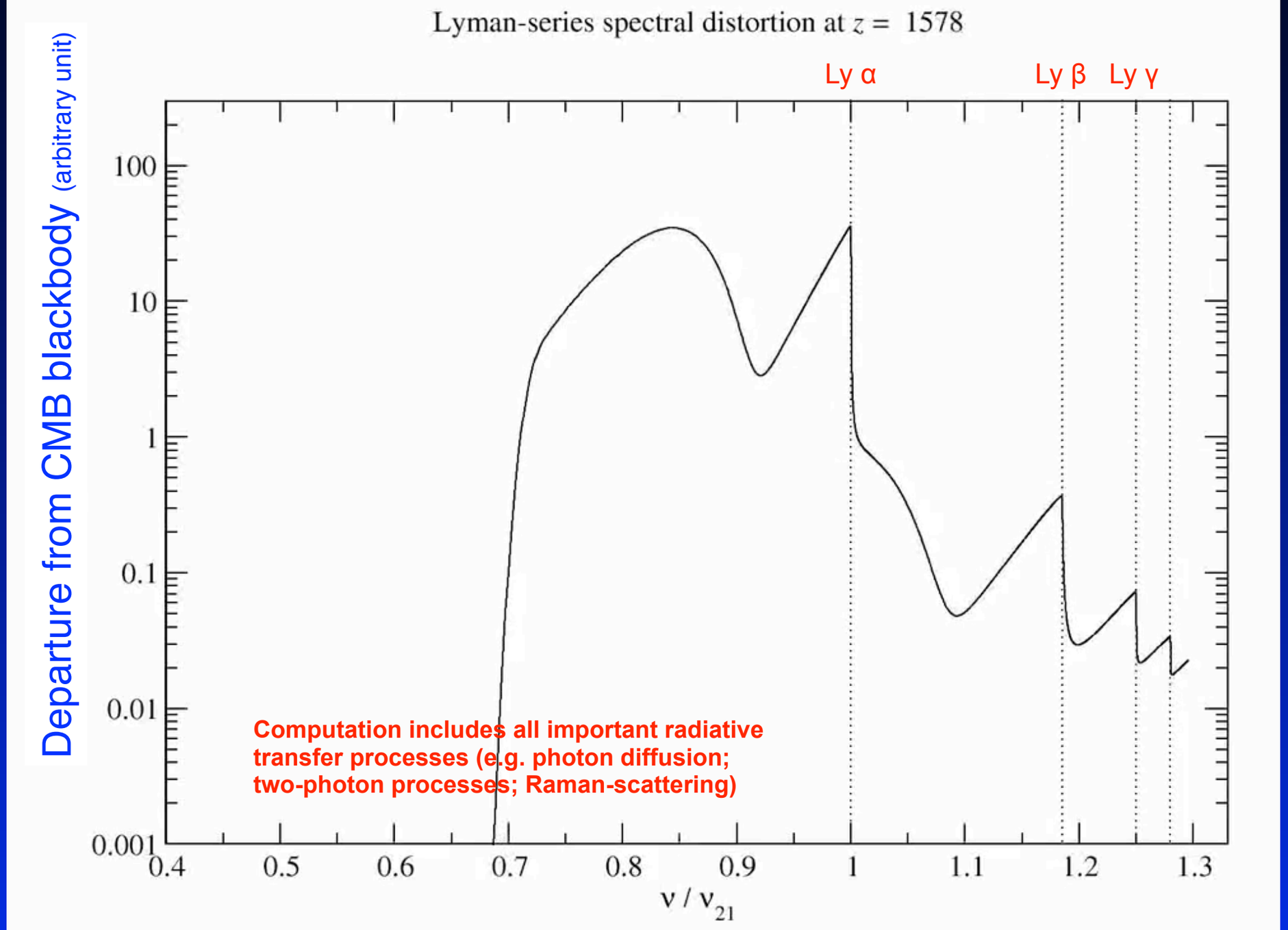
Figure from: Kholupenko et al. 2006

- 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

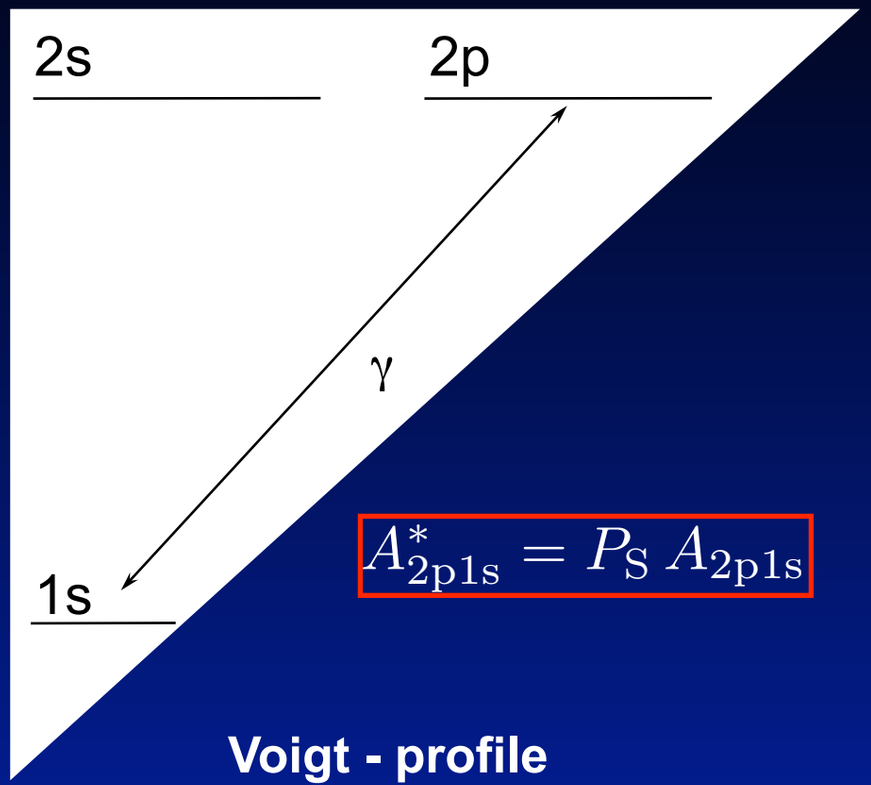
Evolution of the HI Lyman-series distortion



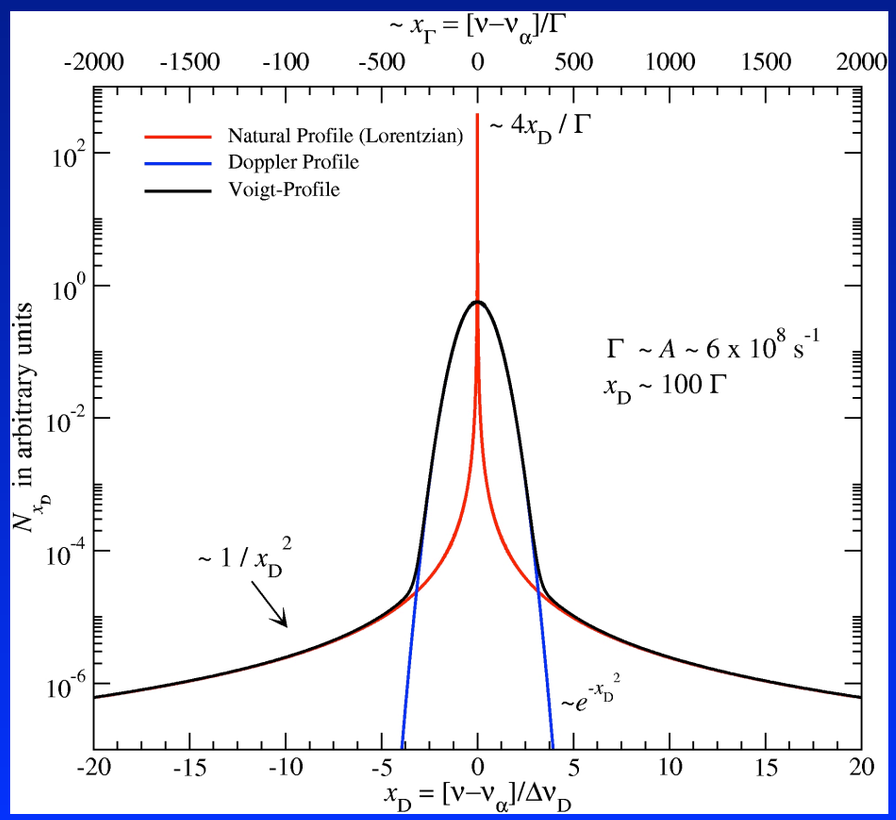
JC & Thomas, MNRAS, 2010

Sobolev approximation

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



Voigt - profile



- To solve the coupled system of rate-equations

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

  → approximate solution using *escape probability*

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

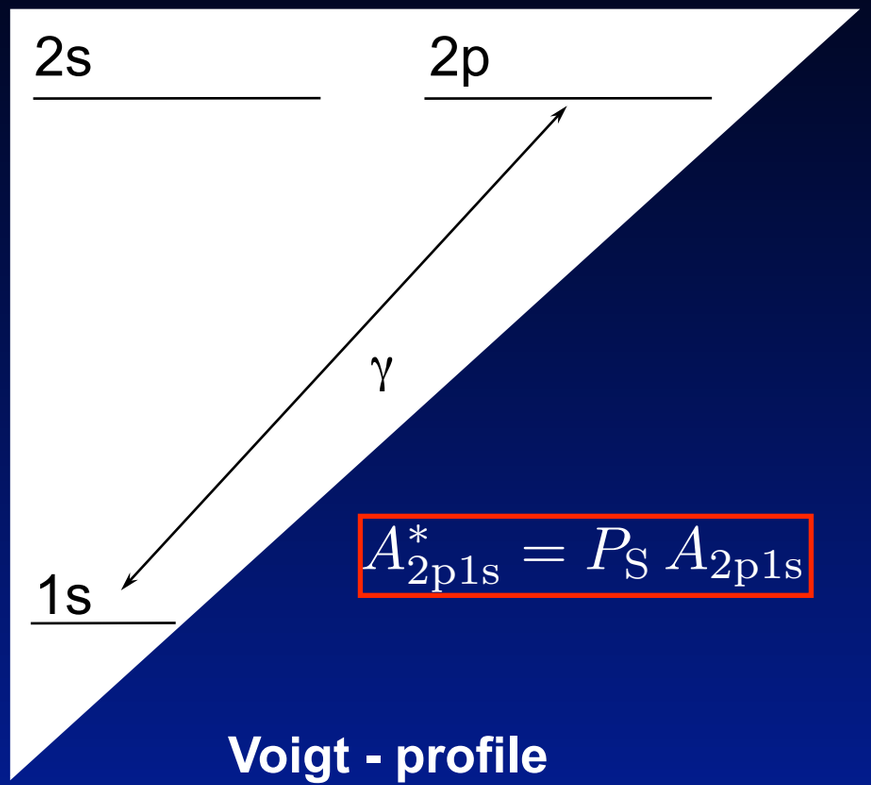
- Main assumptions of Sobolev approximation
  - populations of level + radiation field *quasi-stationary*
  - every ‘scattering’ leads to *complete redistribution*
  - emission & absorption profiles have the *same shape*

Doppler width *(due to atomic motions)*

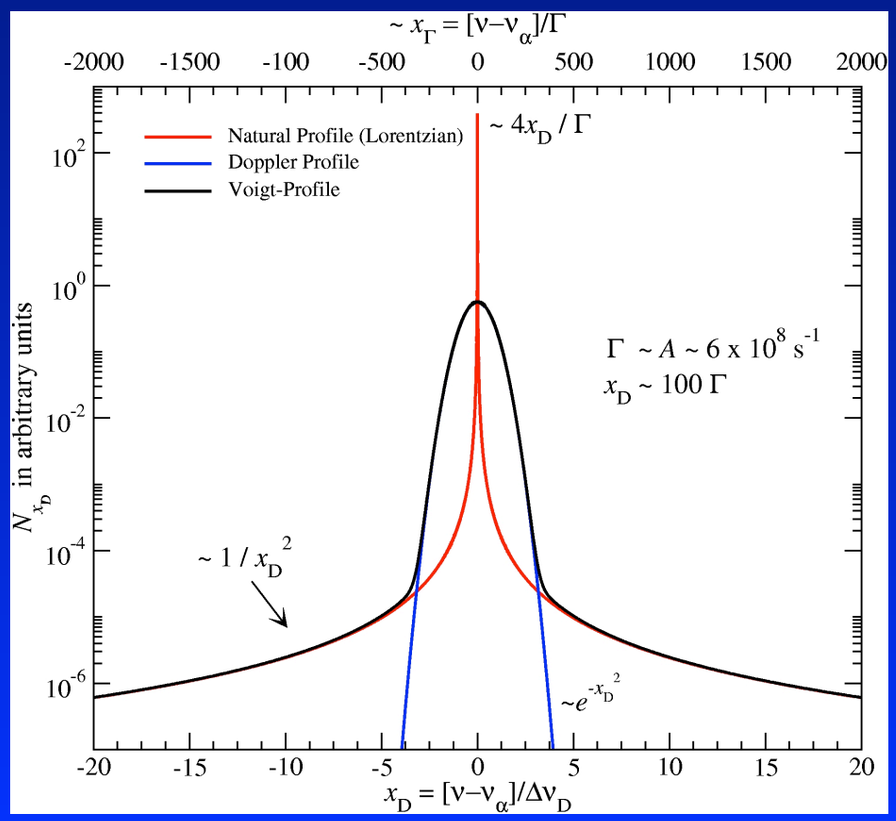
$$\frac{\Delta\nu_{\rm D}}{\nu} = \sqrt{\frac{2kT}{m_{\rm H}c^2}} \simeq \text{few} \times 10^{-5}$$

Sobolev approximation

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



Voigt - profile



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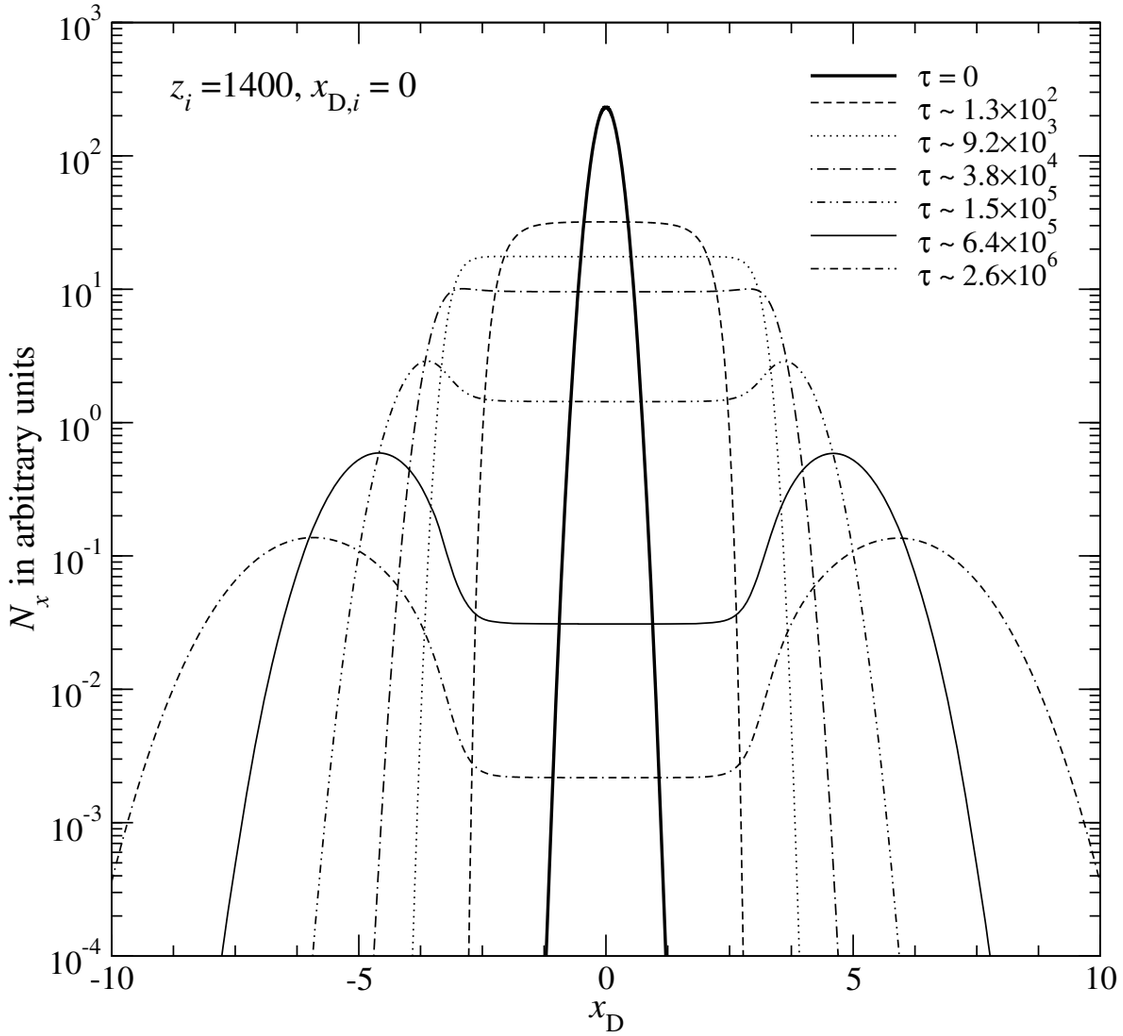
- Sobolev escape probability & optical depth

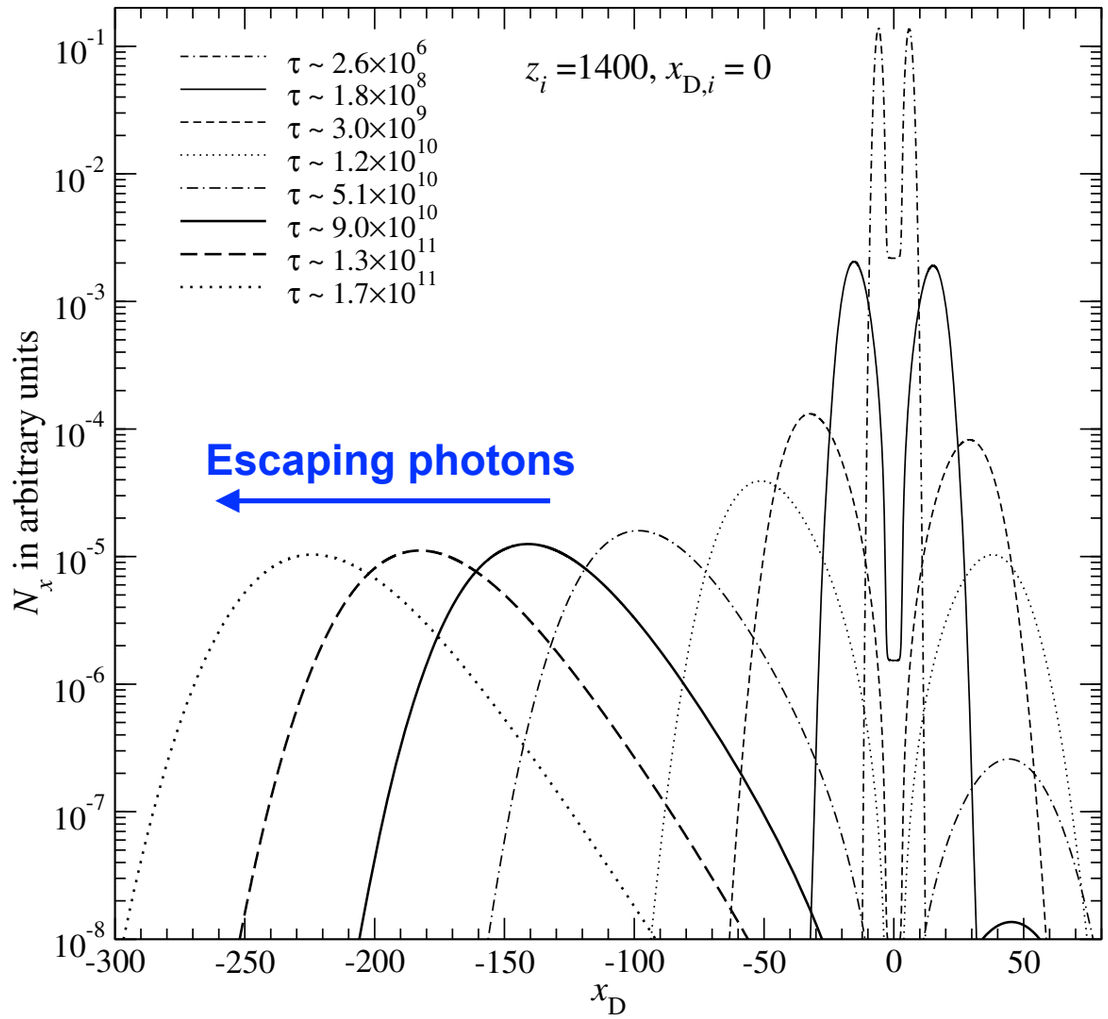
$$P_S = \frac{1 - e^{-\tau_S}}{\tau_S} \simeq 10^{-8}$$

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

Escape from resonance in expanding medium

Injection @ line center



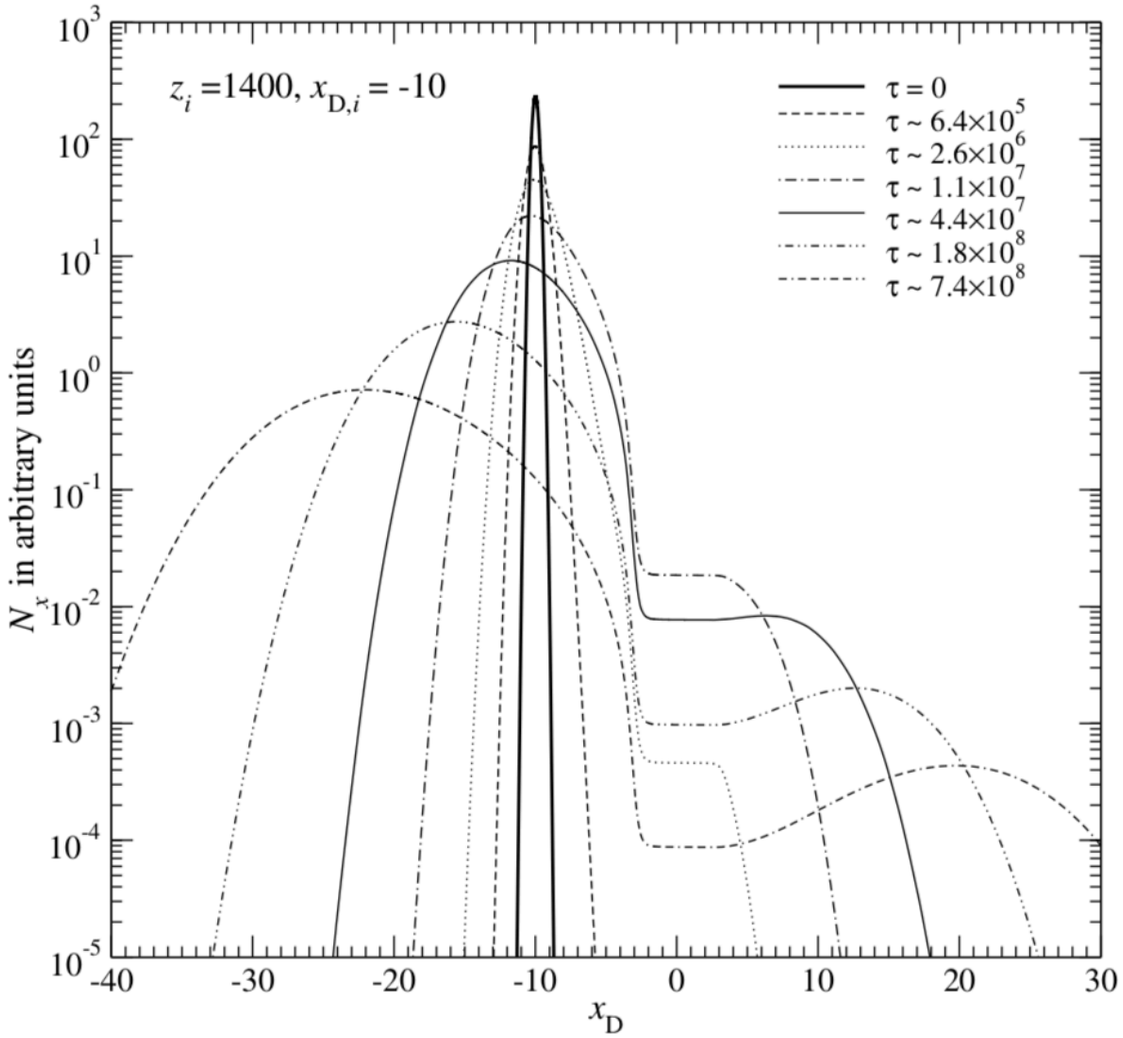


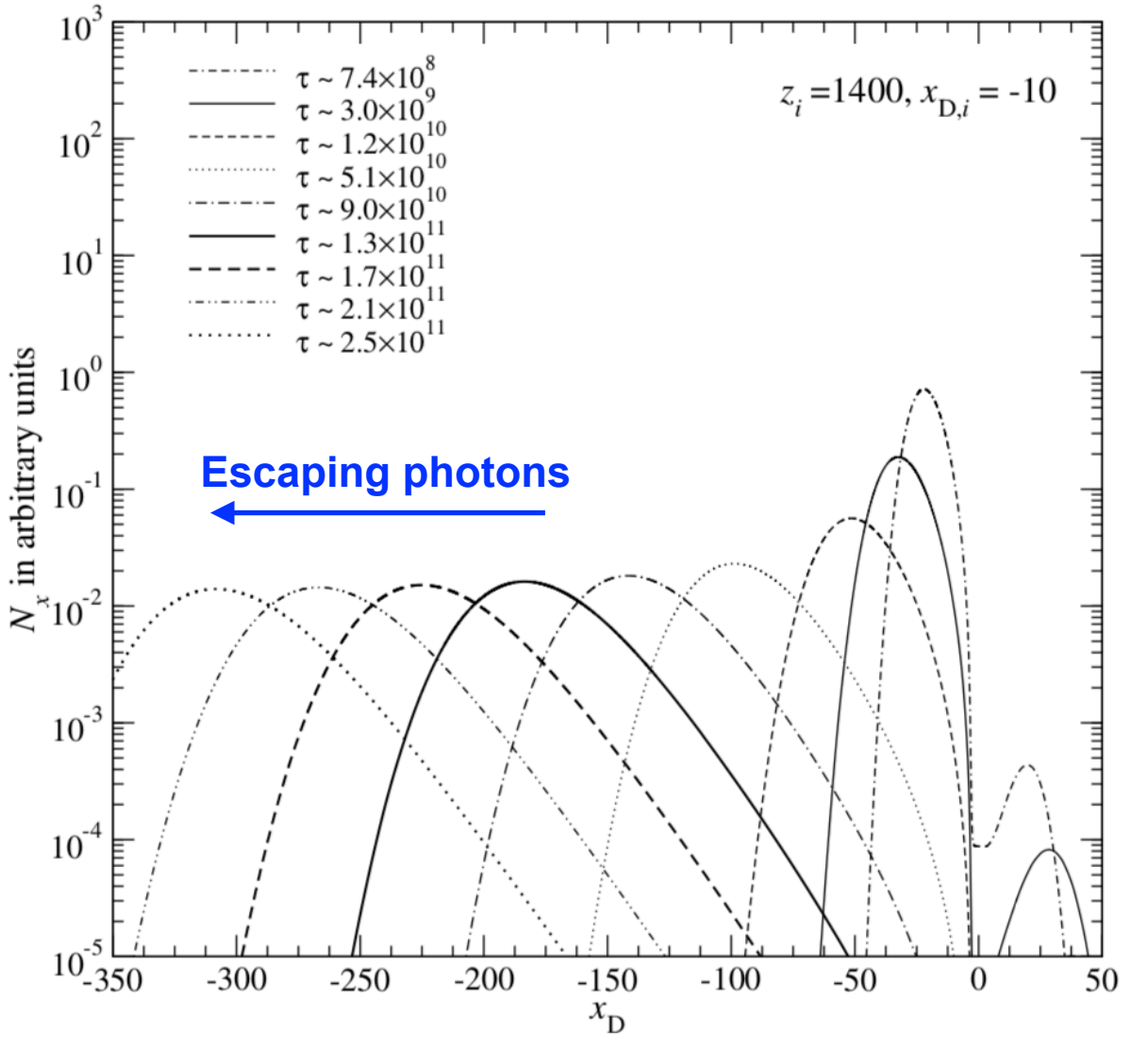
- Initial evolution dominated by broadening (atomic recoil smaller)
- Redshift takes over later (much longer time-scale than scattering and real absorption)
- Only a very small fraction of photons escape from line-center

JC & Sunyaev, 2009, A&A, 503

Escape from resonance in expanding medium

Injection @ red wing



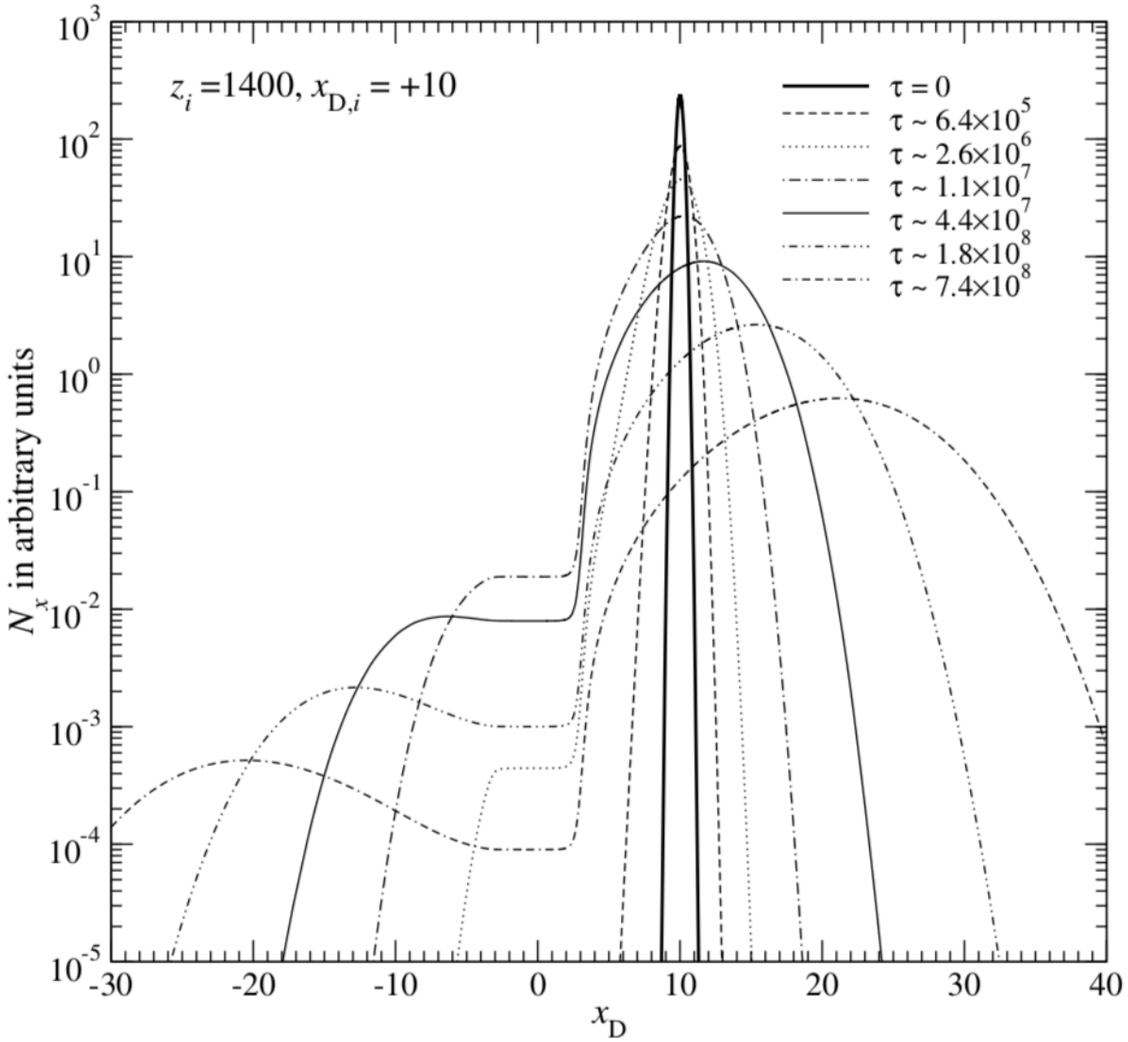


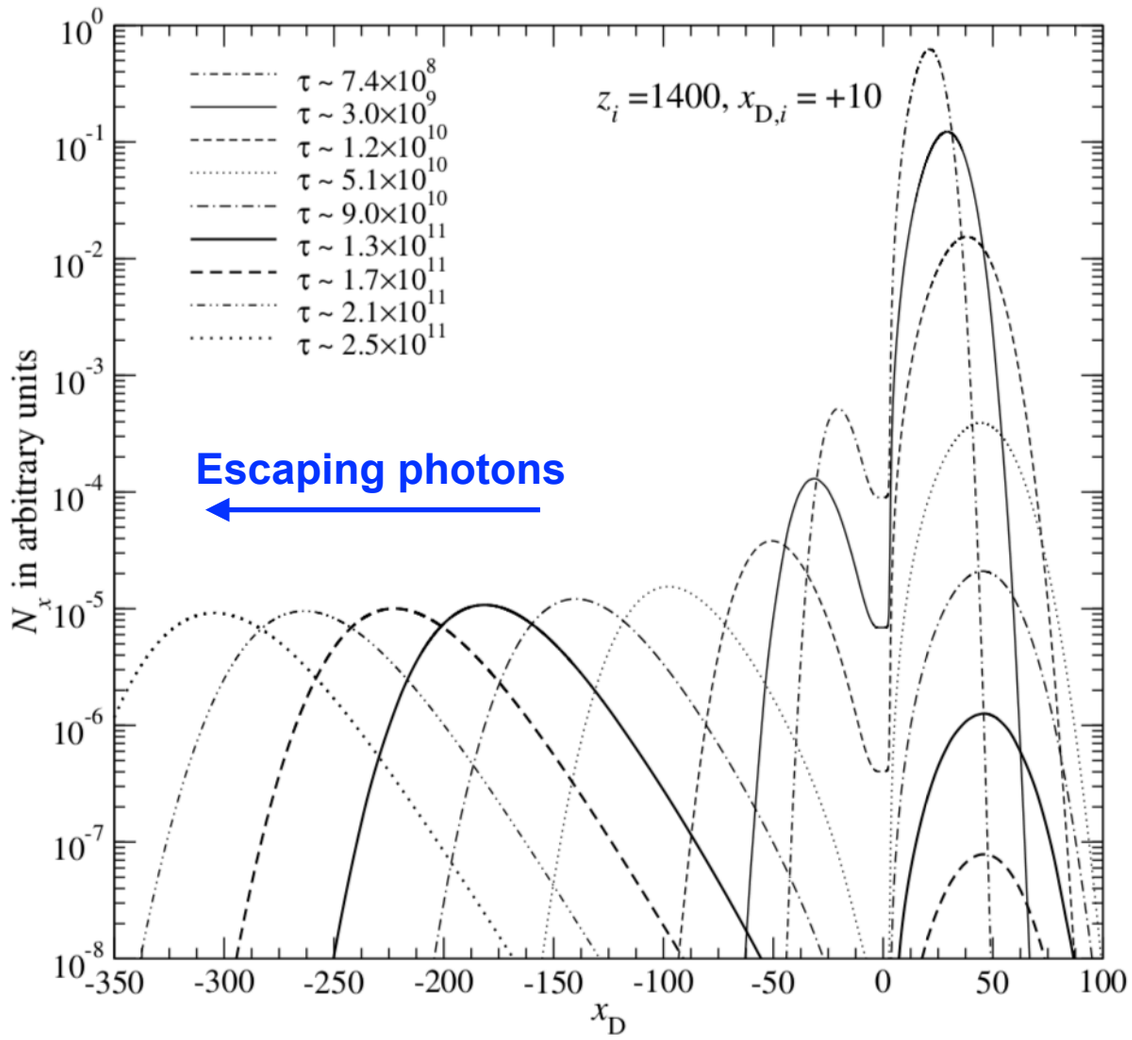
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- Only a very small fraction of photons escape from line-center
- Escape from red wing easier (more photons survive)

JC & Sunyaev, 2009, A&A, 503

Escape from resonance in expanding medium

Injection @ blue wing



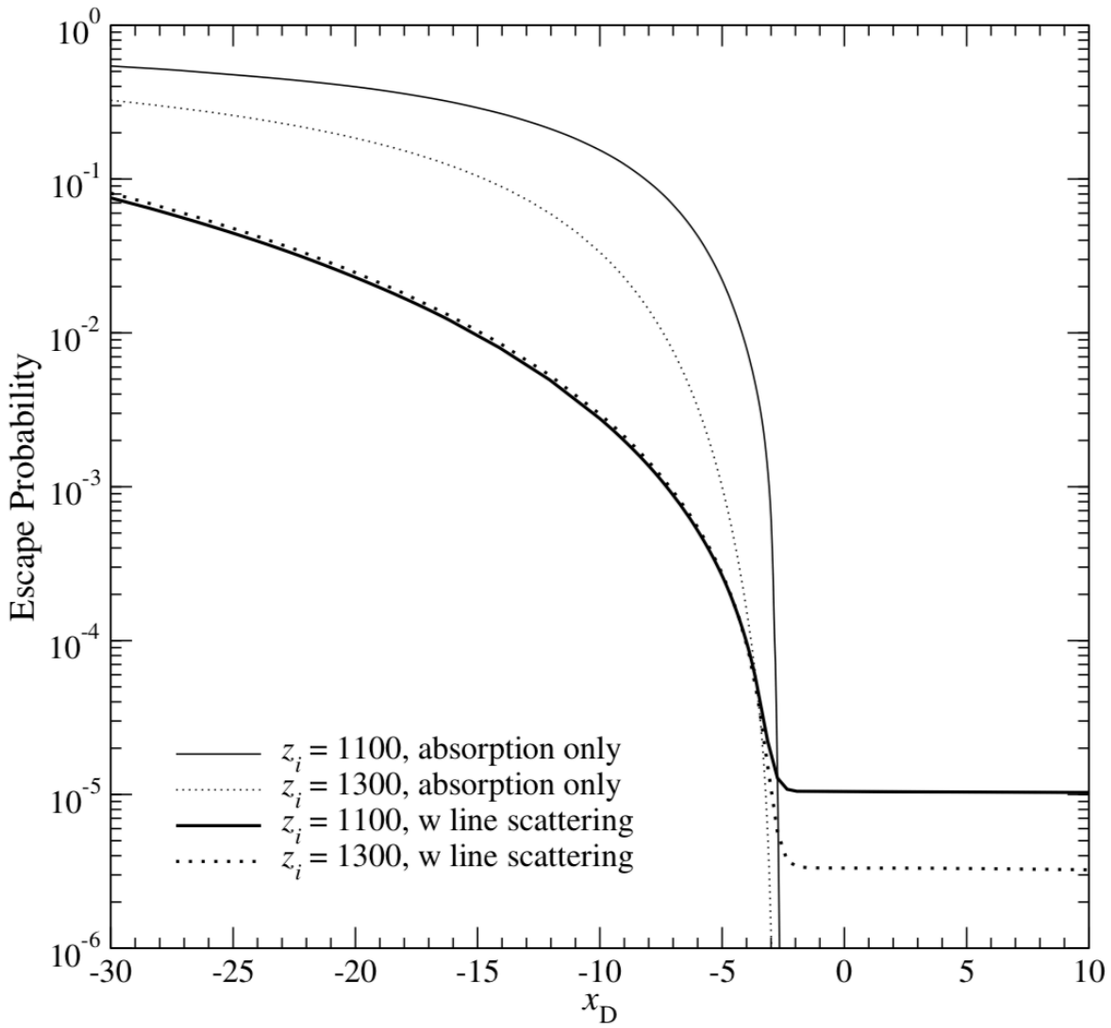


- Initial evolution dominated by broadening (atomic recoil smaller)
- Redshift takes over later (much longer time-scale than scattering and real absorption)
- Only a very small fraction of photons escape from line-center
- Escape from red wing easier (more photons survive)
- Non-vanishing probability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

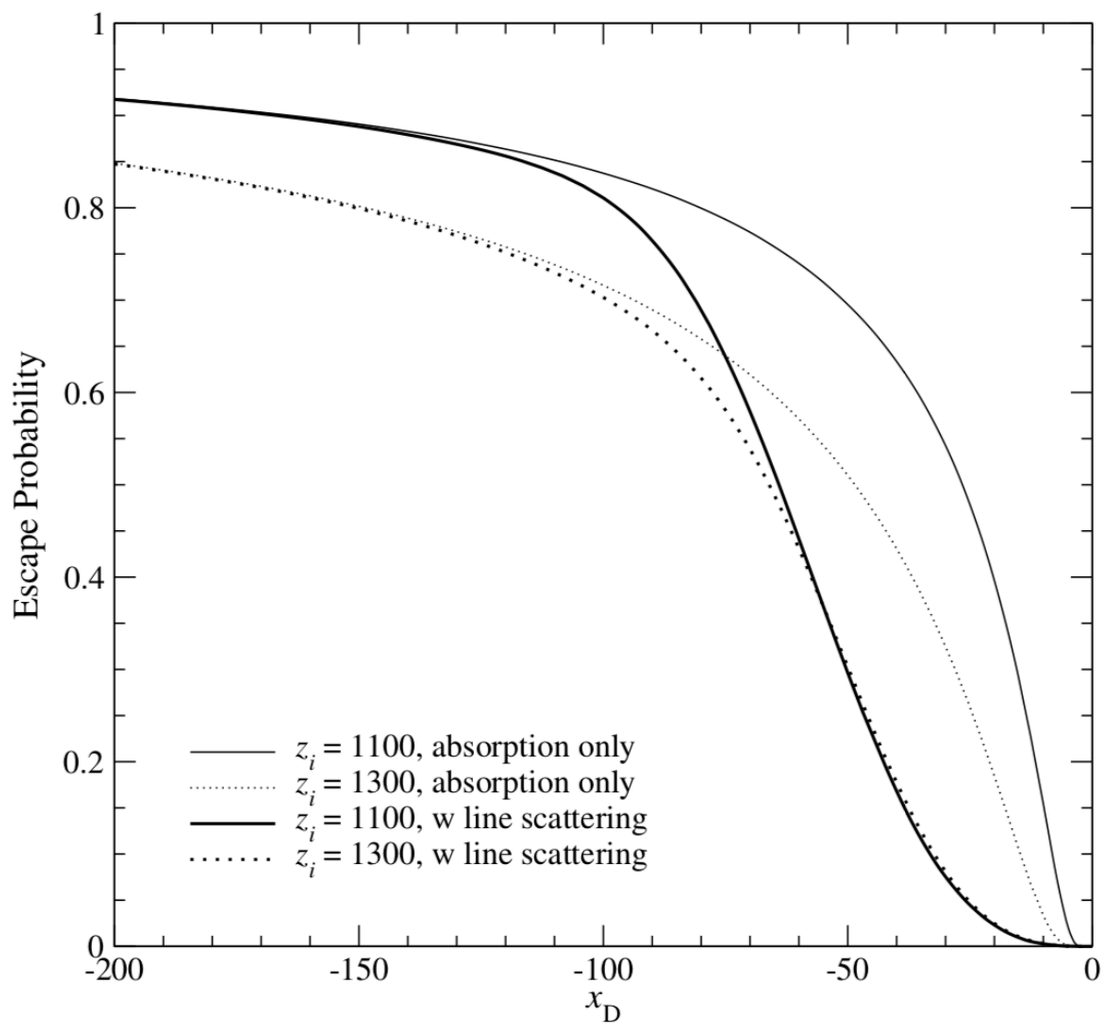
JC & Sunyaev, 2009, A&A, 503

Differential Escape Probability

Close to line center



Distant red wing

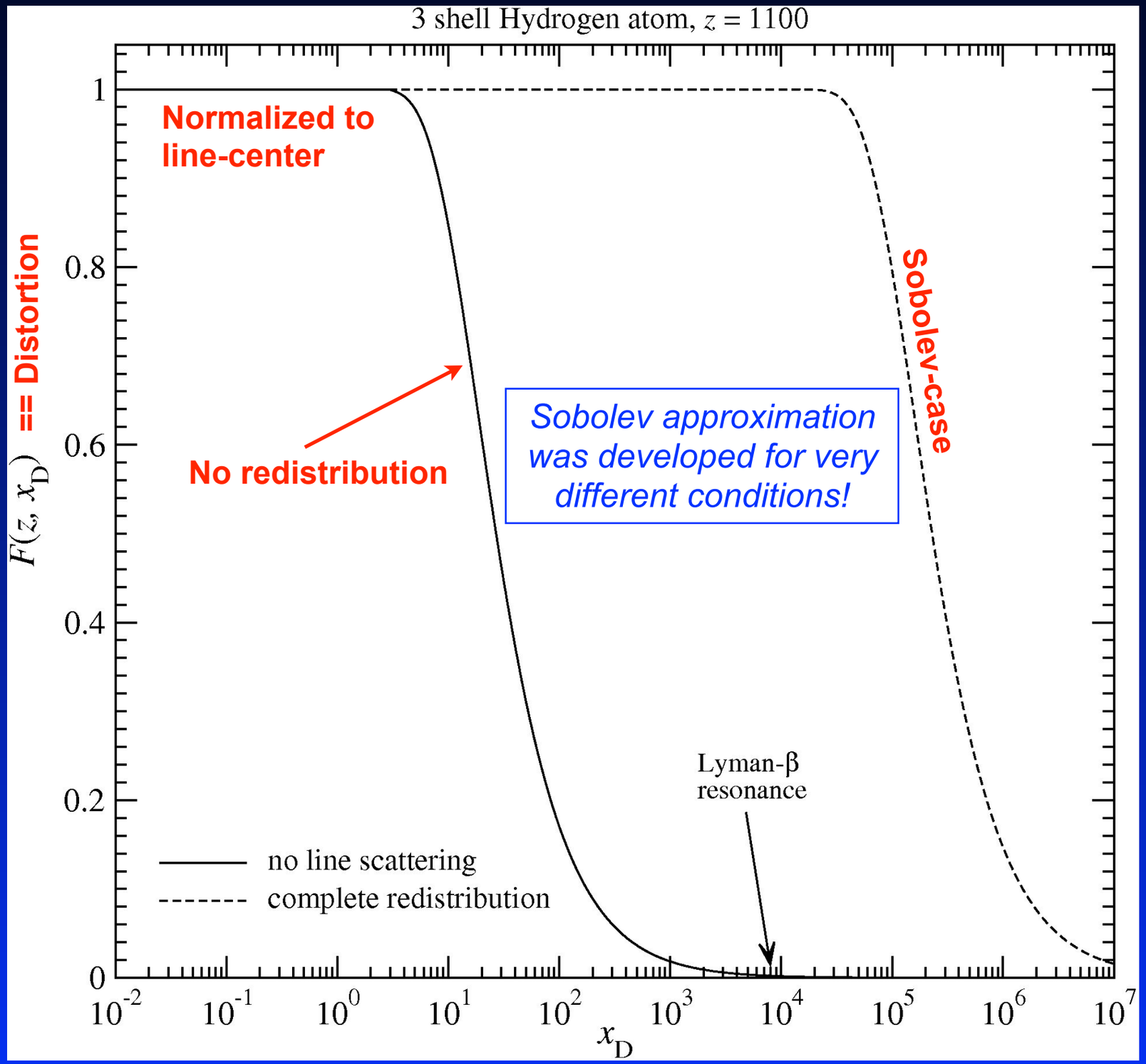


- Escape depends on physical assumptions (e.g., scattering and absorption)
- Escape probability is a strong function of frequency and redshift
- Escape from Doppler core very similar to escape from blue wing
- Ly-α resonance becomes optically thin only in very distant red wing

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

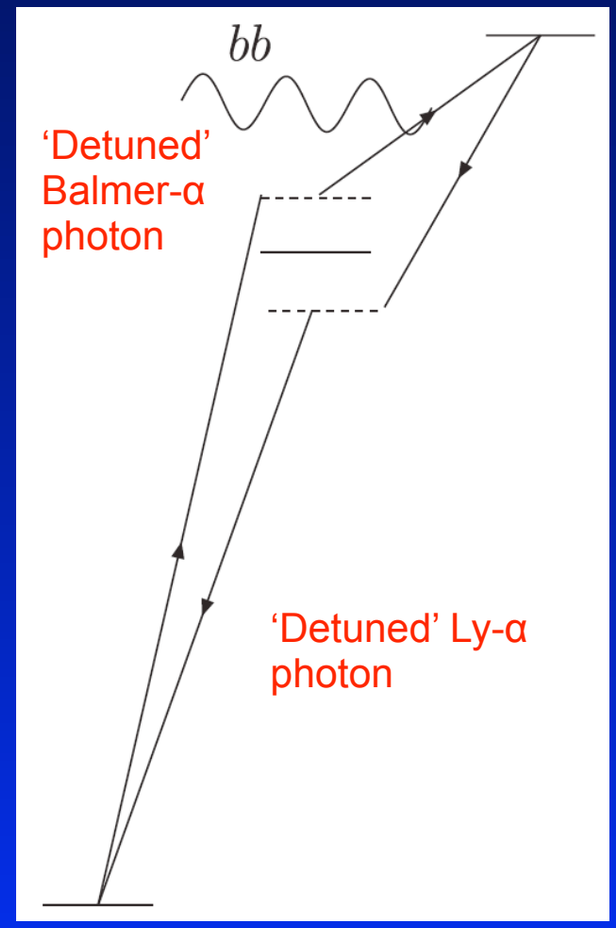
Other Problems with Sobolev approximation

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

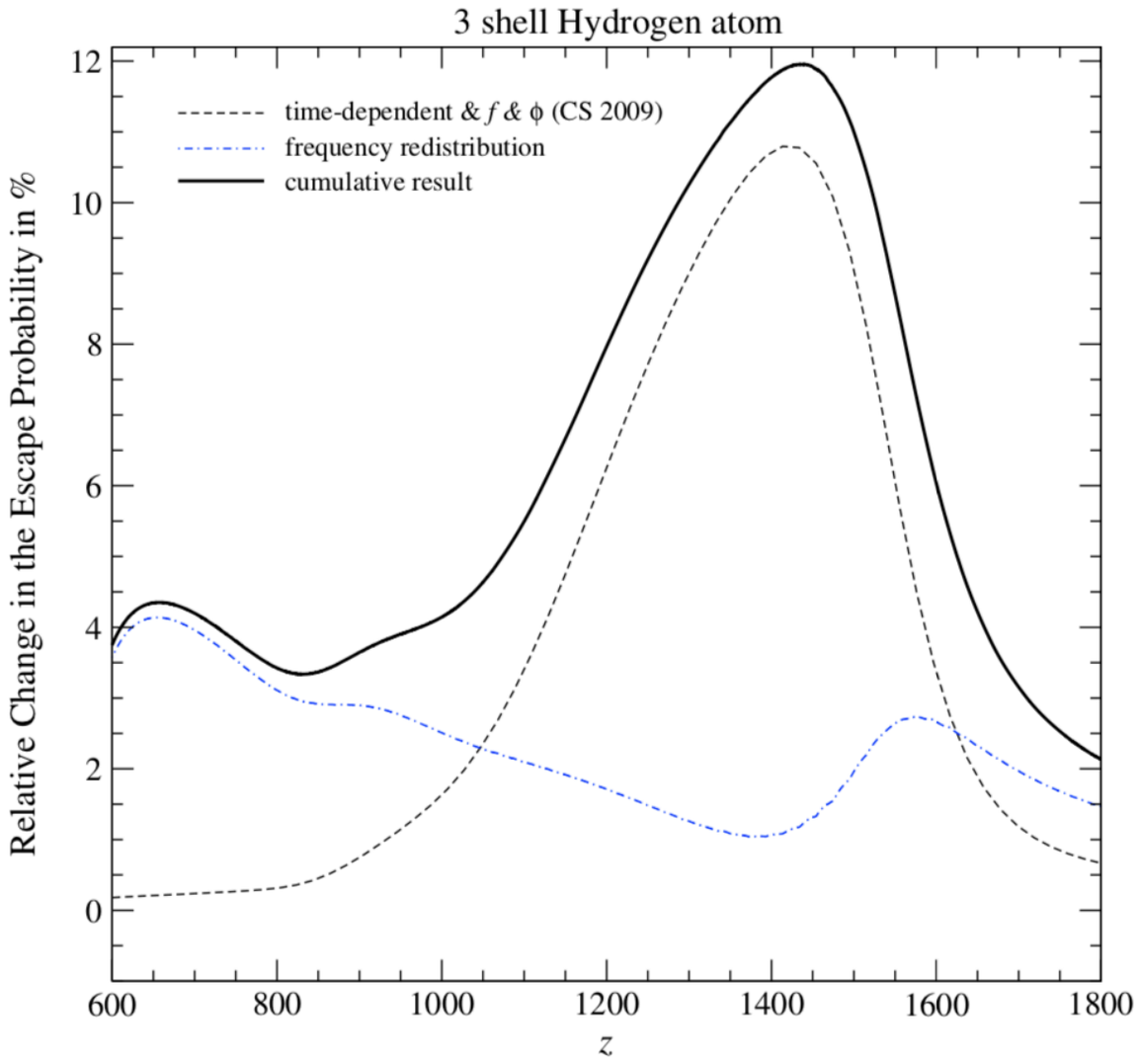


See JC & Sunyaev, 2009, A&A, 496 for more details

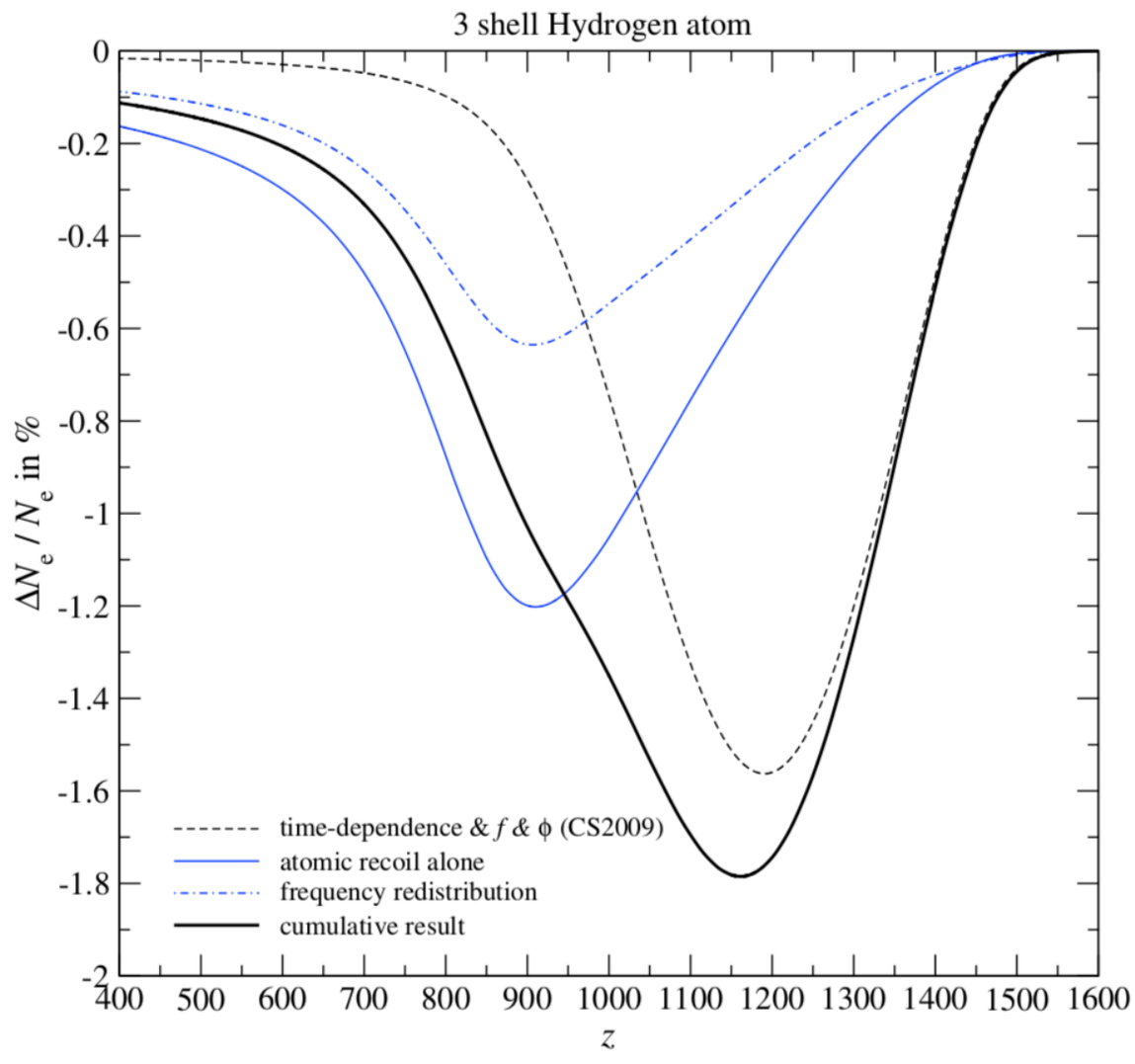
Illustration from Switzer & Hirata 2007 (meant for Helium)

Sobolev approximation is still pretty good (sadly…)

Total escape probability correction



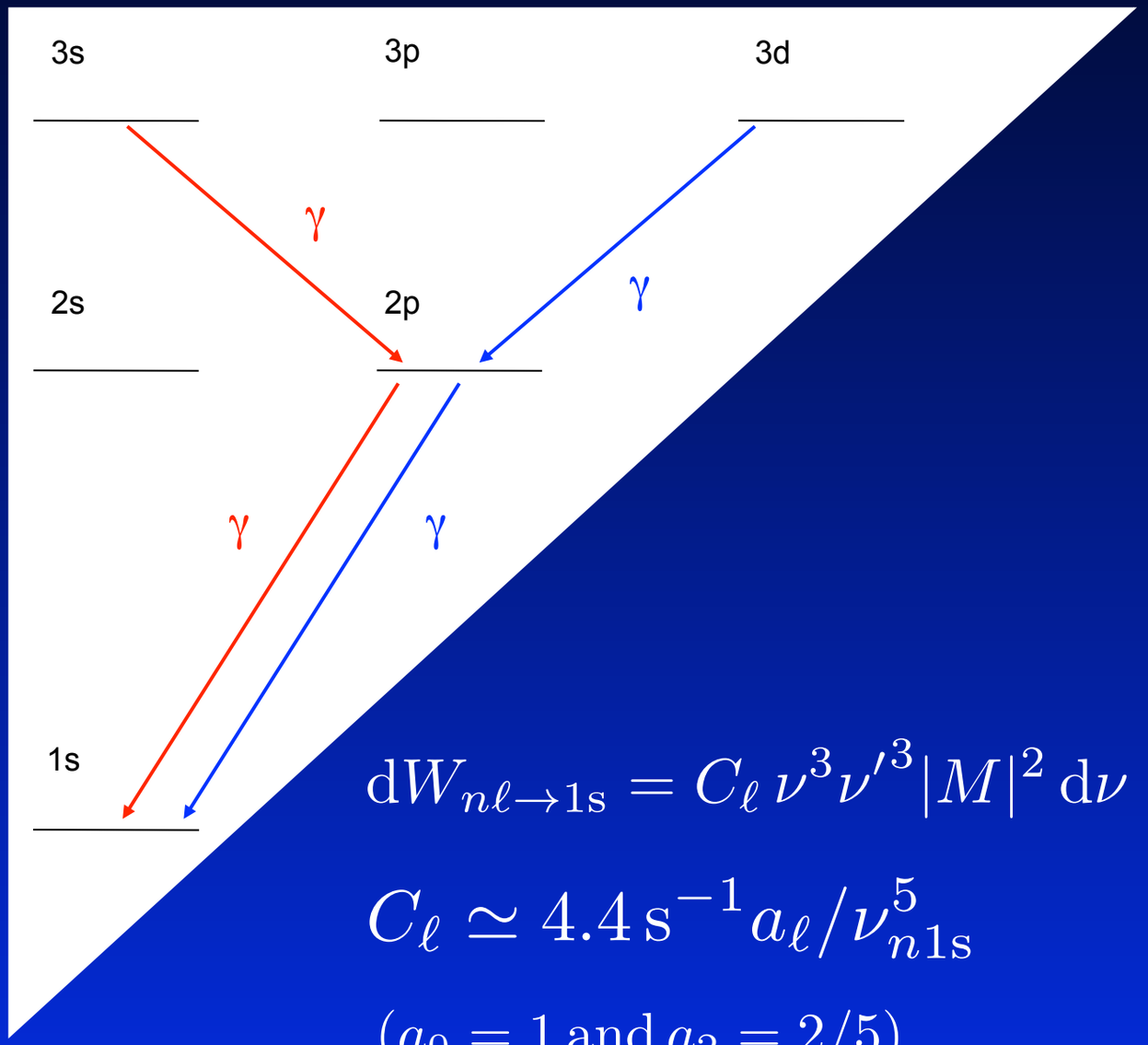
Change in ionization history



- 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



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 quantum act*

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

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

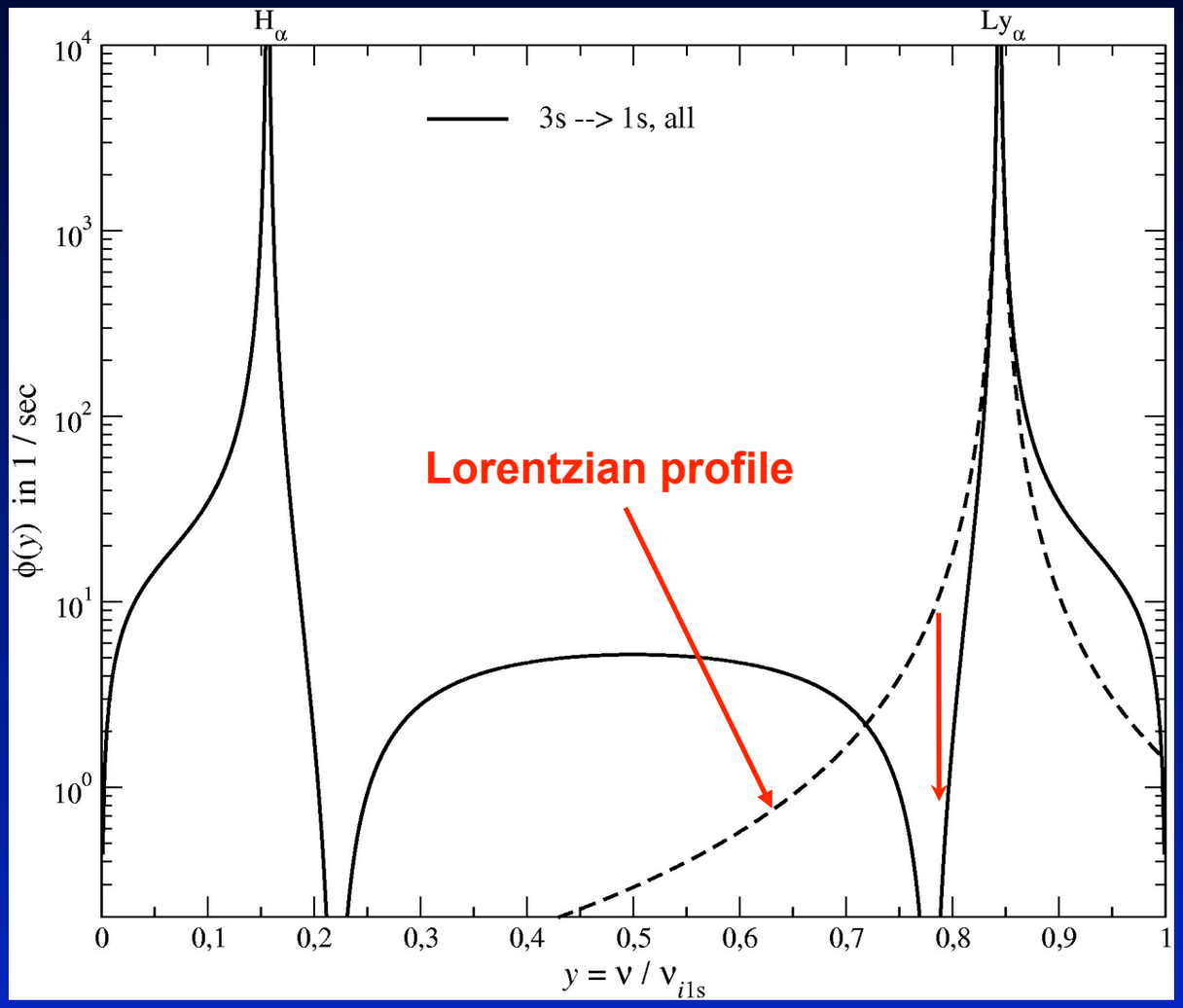
$$(a_0 = 1 \,\mathrm{and}\, a_2 = 2/5)$$

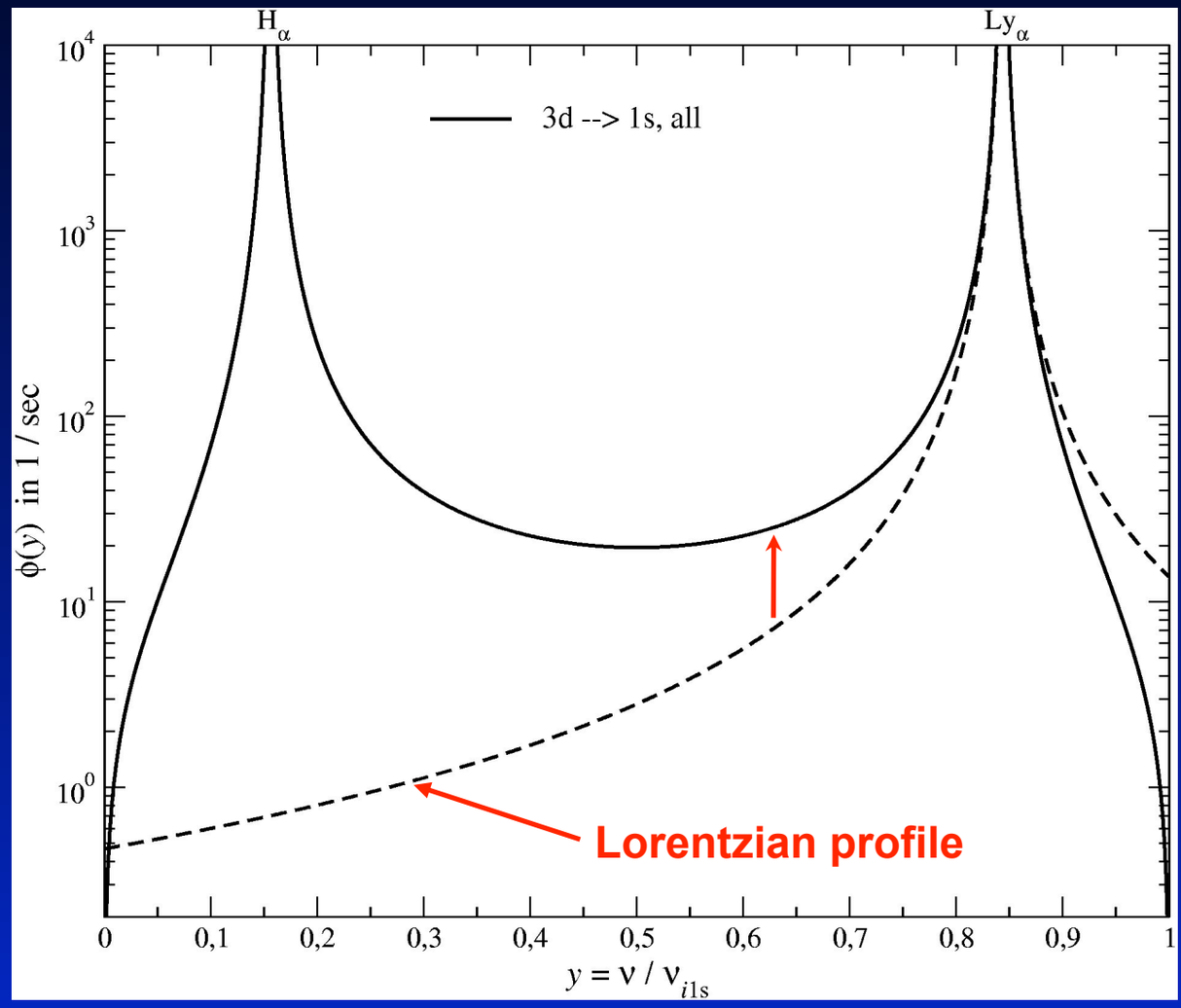
→Deviations of the *two-photon line profile* from the Lorentzian in the damping wings

→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





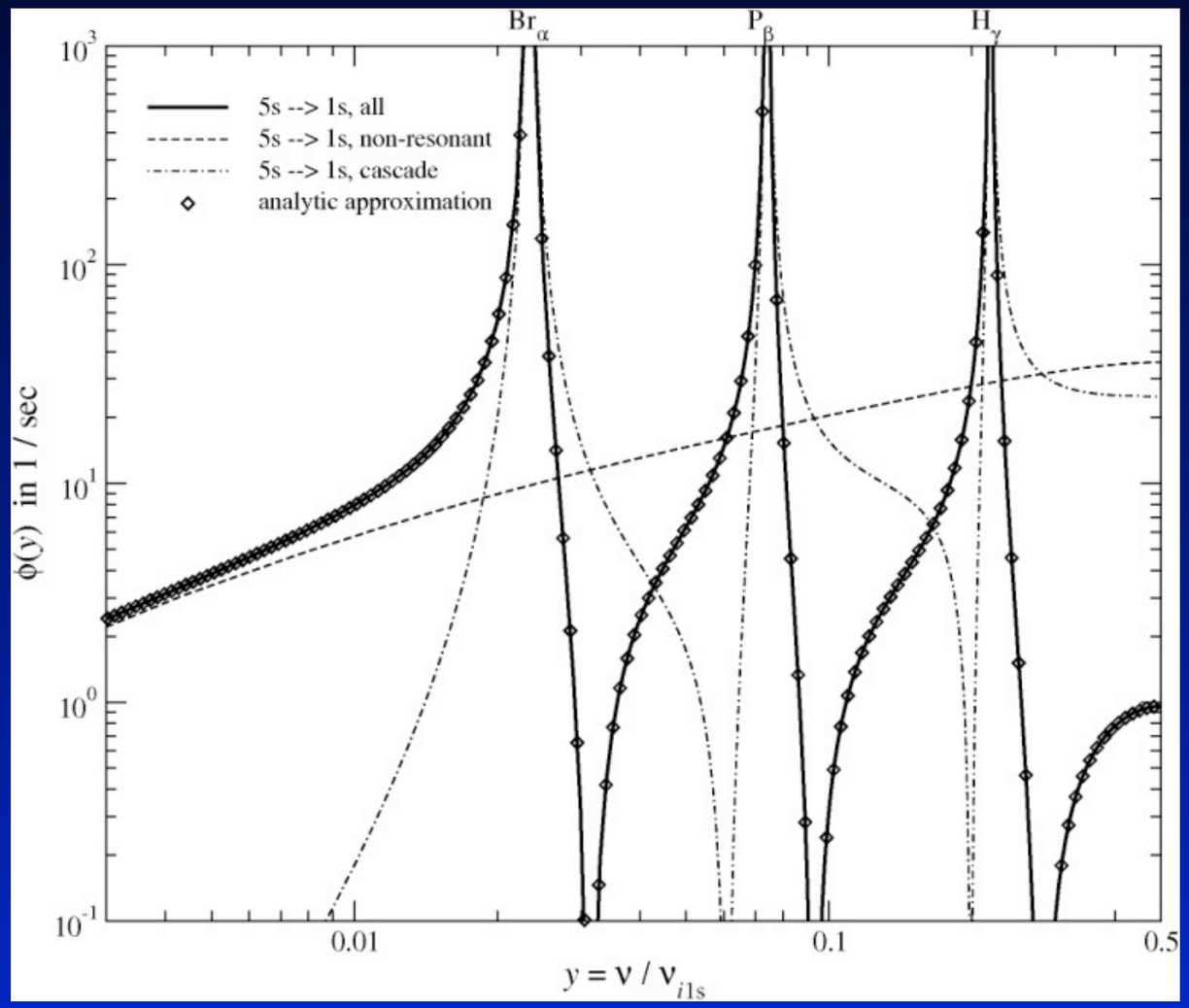
Direct Escape from optically thin regions:

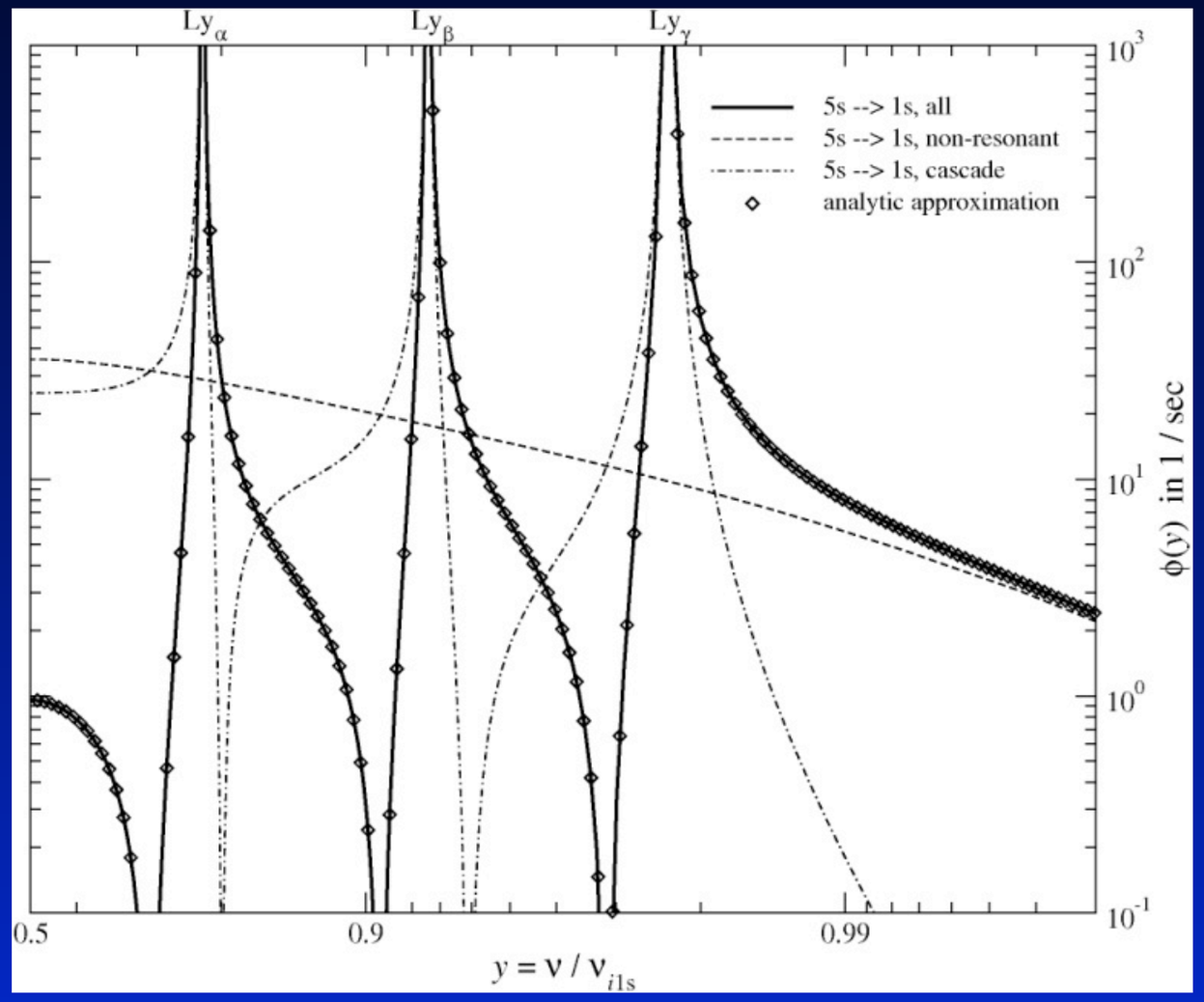
→ HI -recombination is a bit *slower* due to 2γ-transitions from s-states

→ 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

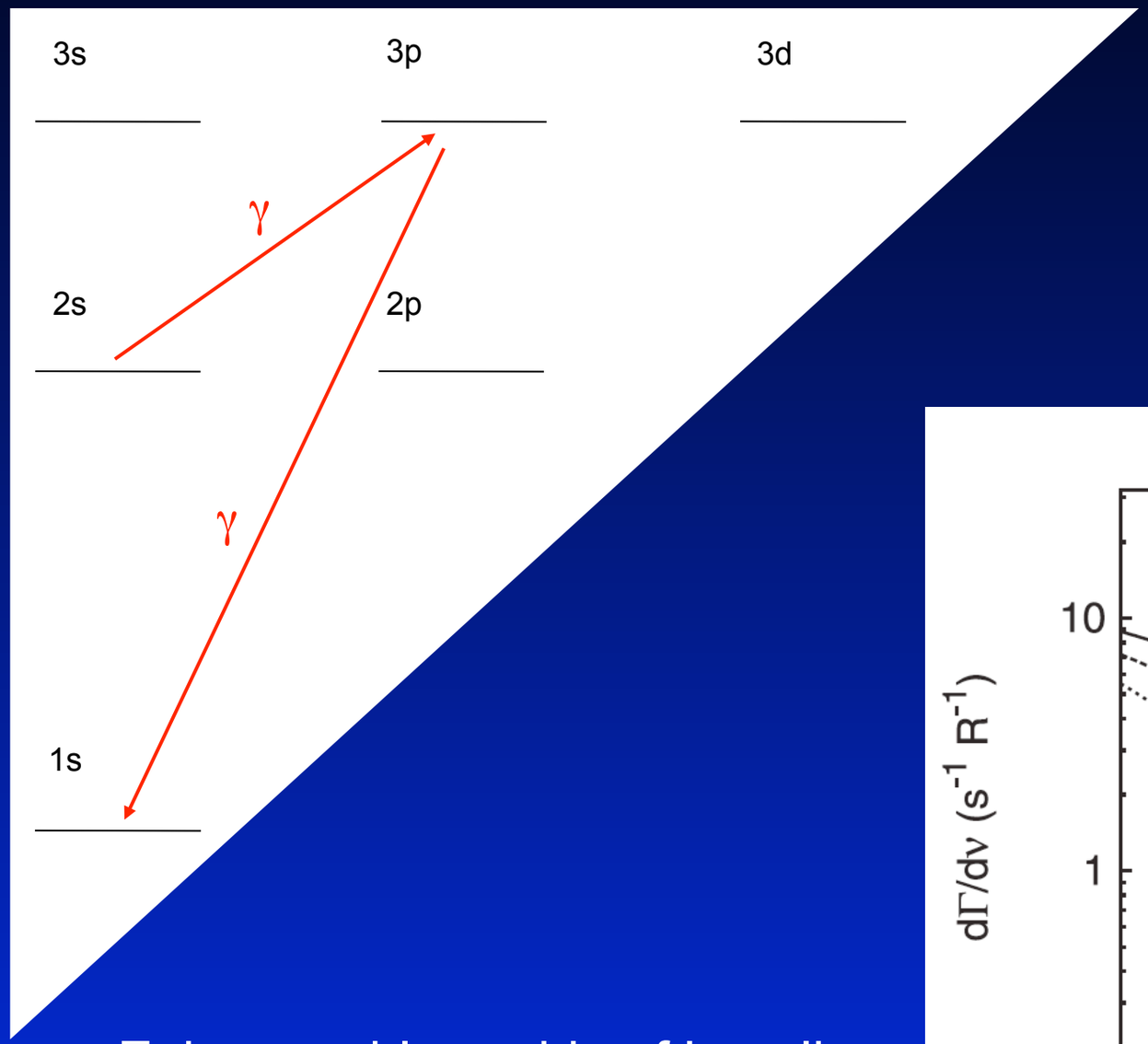
→ luckily including these effects up to n ~ 4-5 is enough

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*

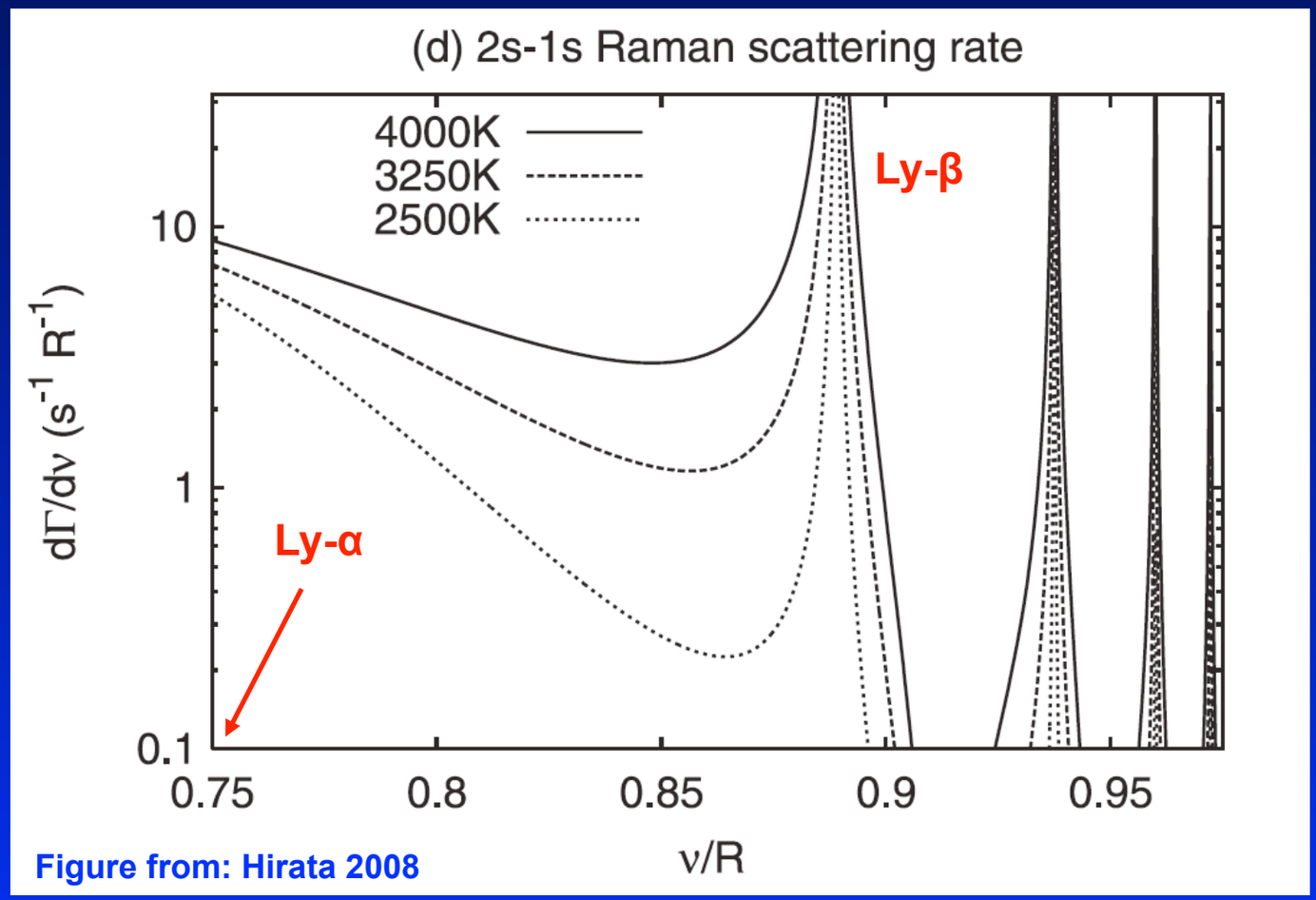
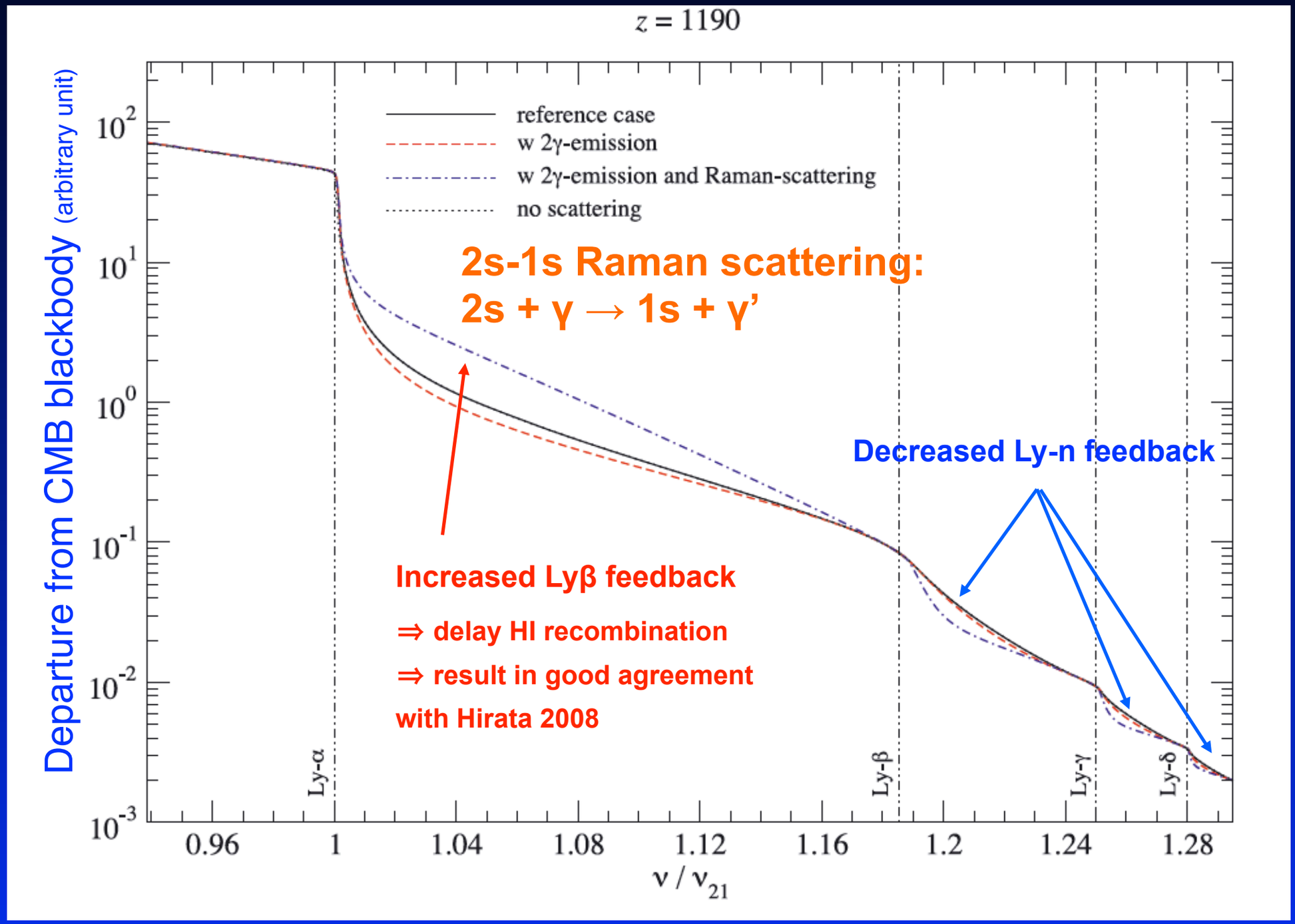


Figure from: Hirata 2008

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

Hirata 2008
JC & Thomas, 2010

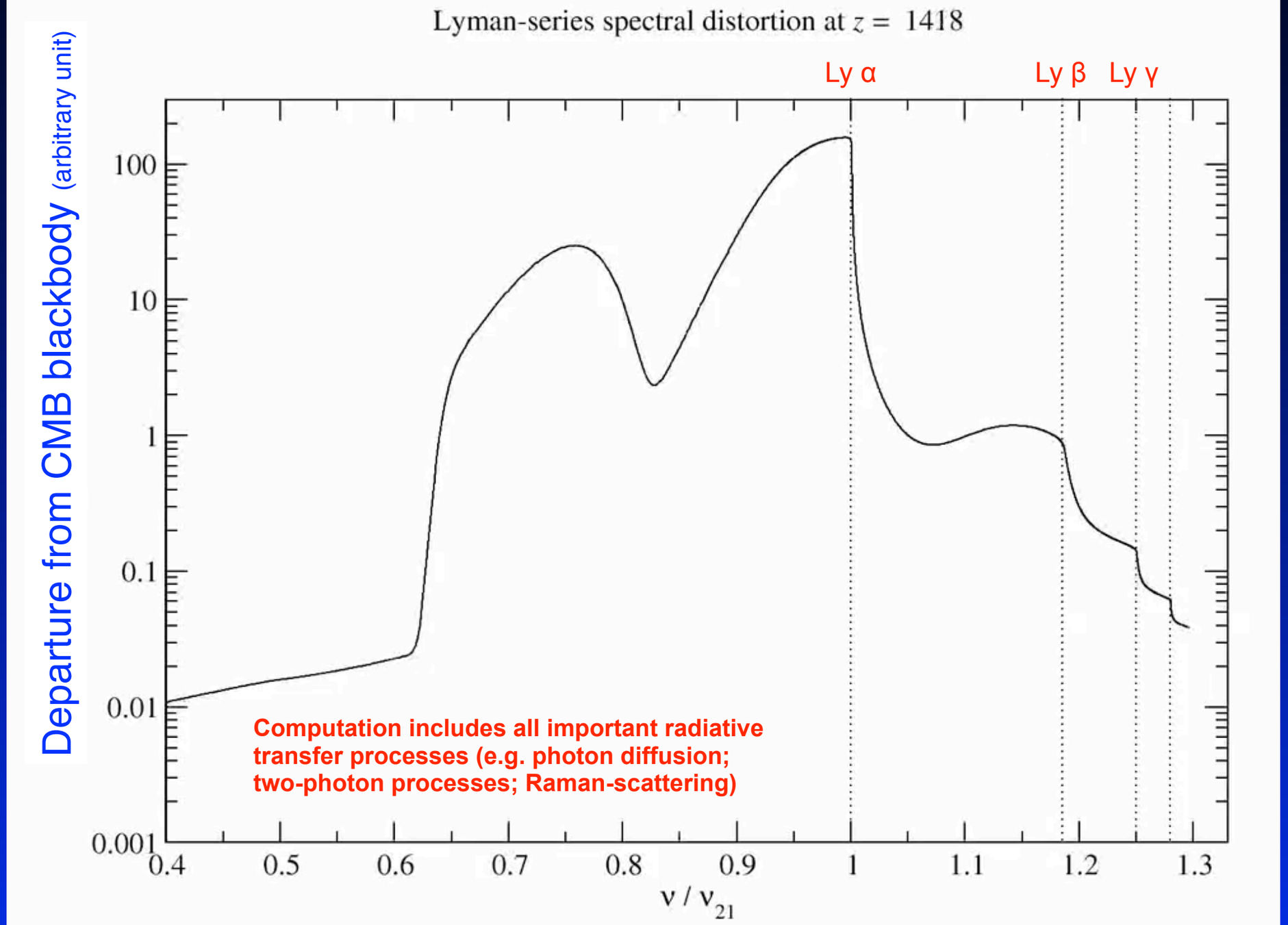
Effect of Raman scattering and 2γ decays



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JC & Thomas, MNRAS, 2010

Evolution of the HI Lyman-series distortion



JC & Thomas, MNRAS, 2010

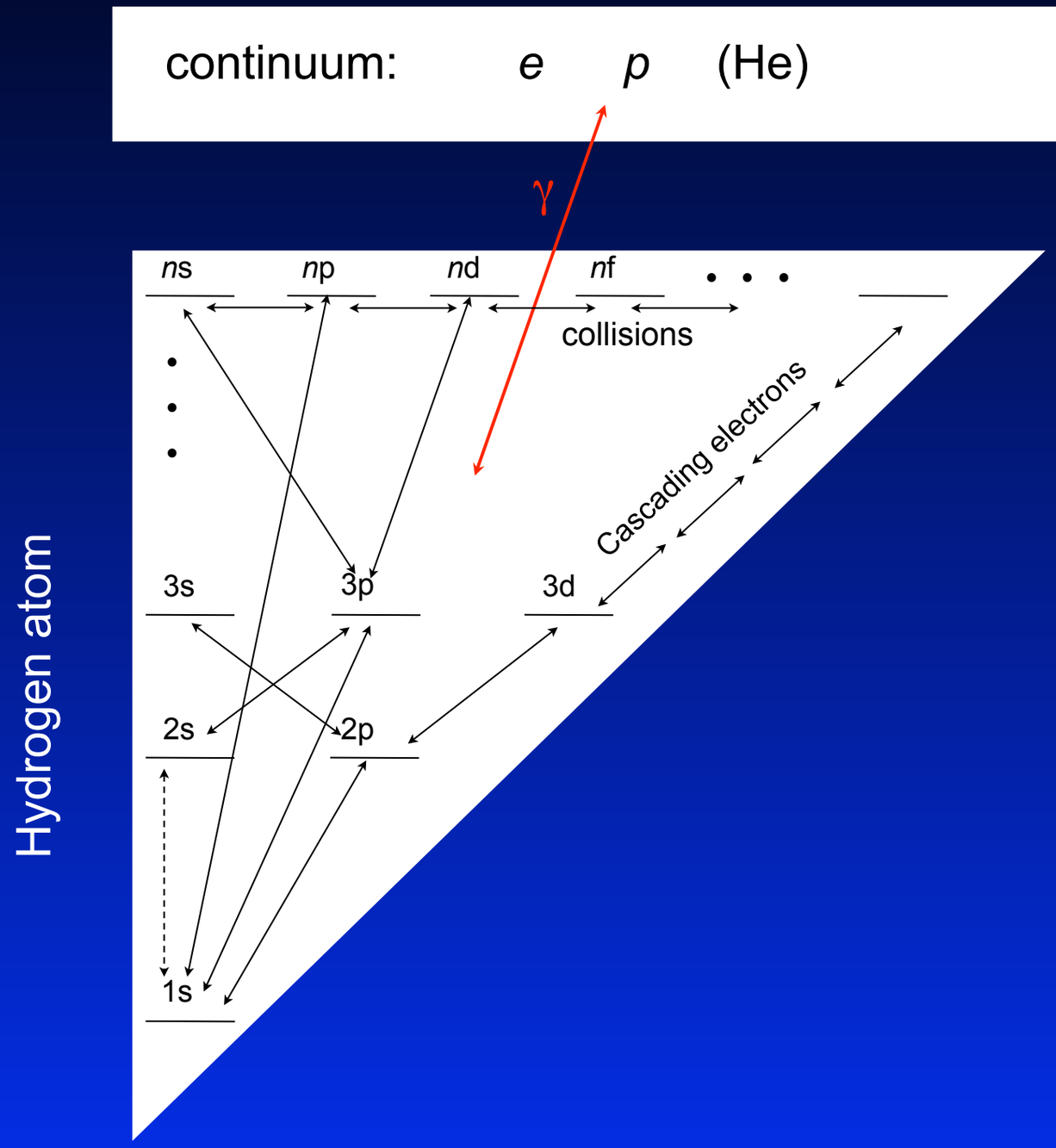
Deviations from Statistical Equilibrium in the upper levels

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_{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**
  - **Δl = ±1 restriction (electron cascade)**
  - **large *n* & small Δn → *induced* emission**
- **l-changing collisions**
  - **help to establish full SE within the shell**
  - **only effective for *n* > 25-30**
- **n-changing collisions**
- **Collisional photoionization**
- **Three-body-recombination**

Deviations from Statistical Equilibrium in the upper levels

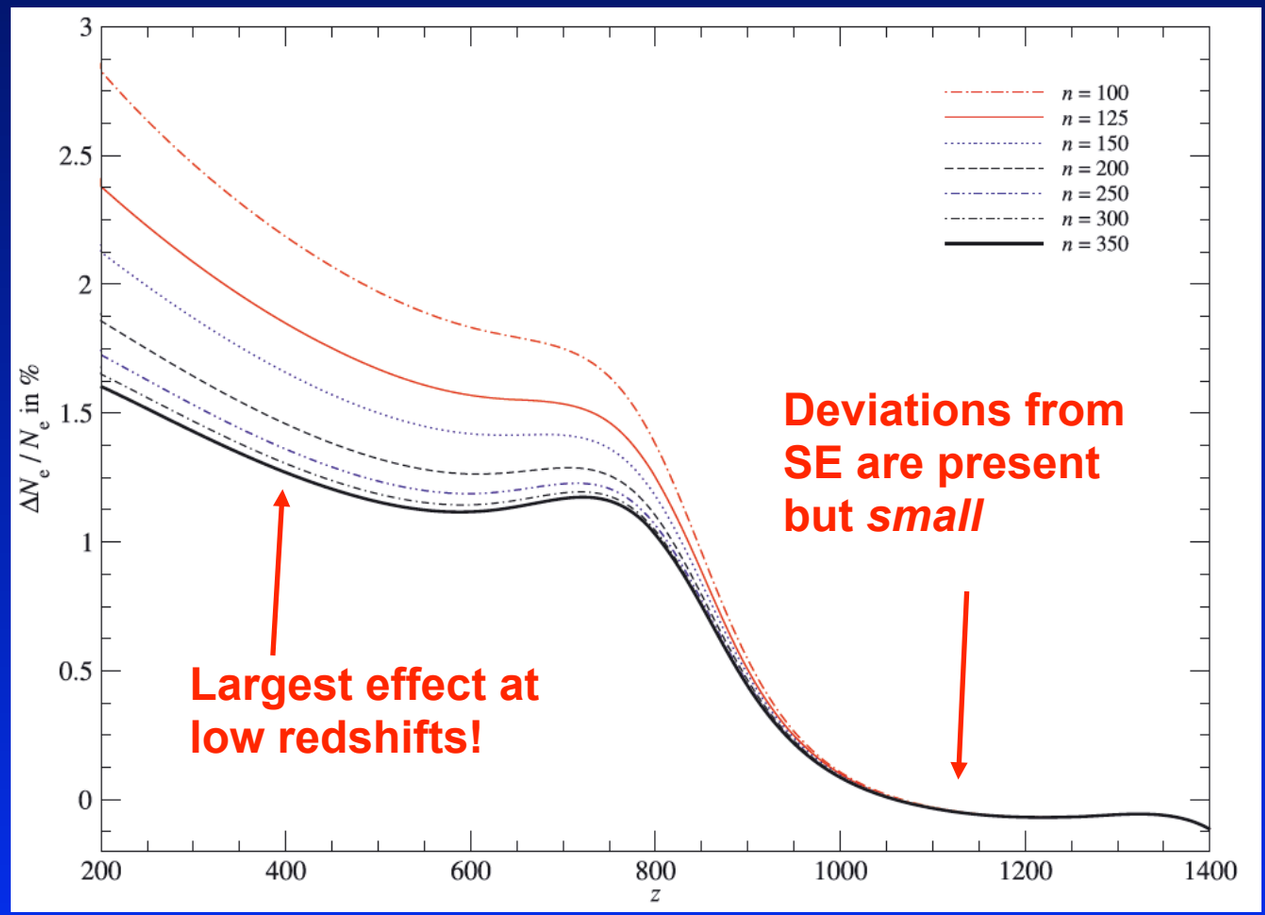
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Refined computation
(JC, Rubino-Martin & Sunyaev, 2007)

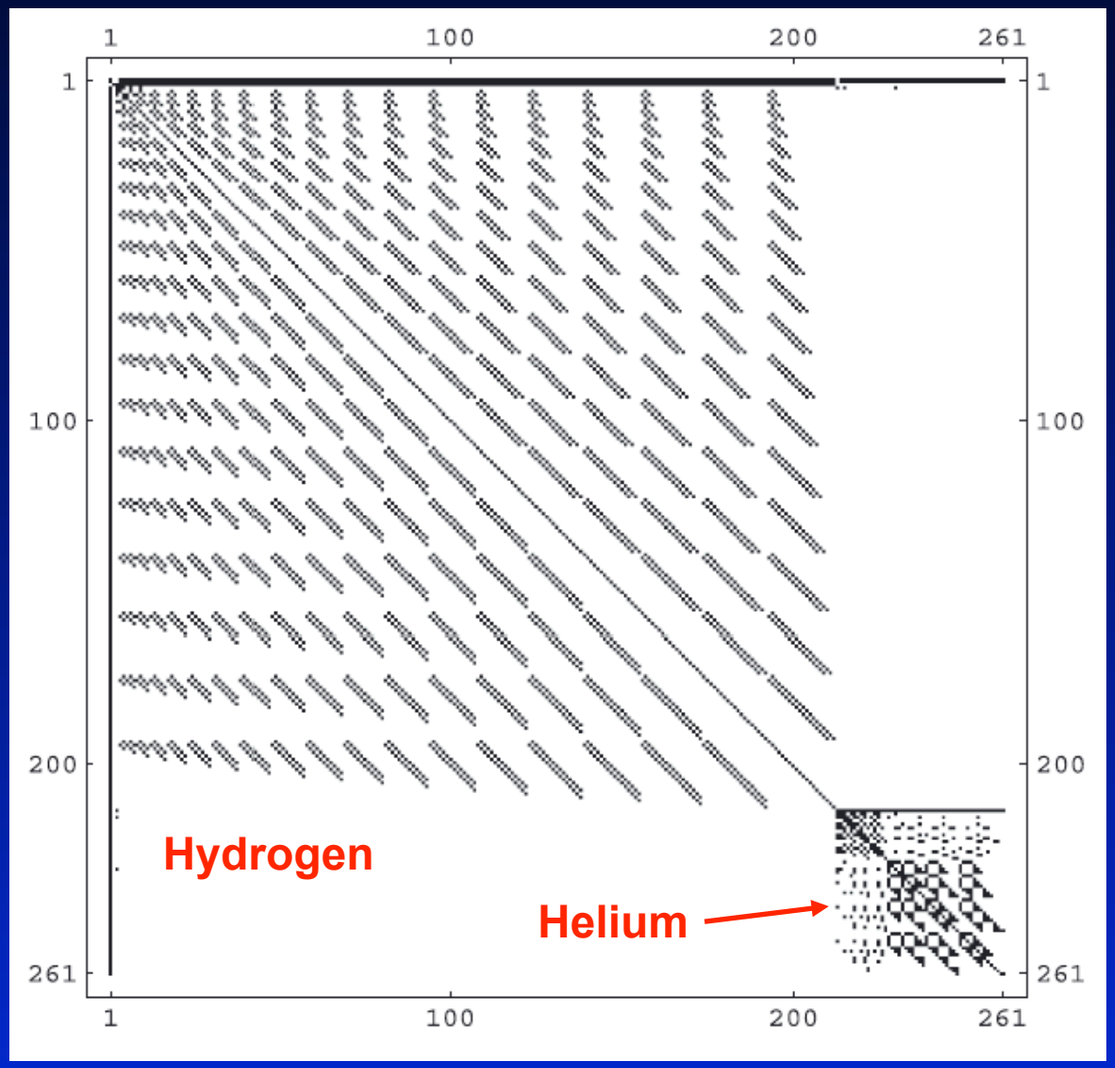
- need to treat angular momentum sub-levels separately!
- include collision to understand how close populations are to SE
- Complexity of problem scales like ~ n^2_{max}
- But problem very *sparse*
  (Grin & Hirata, 2010; JC, Vasil & Dursi, 2010)

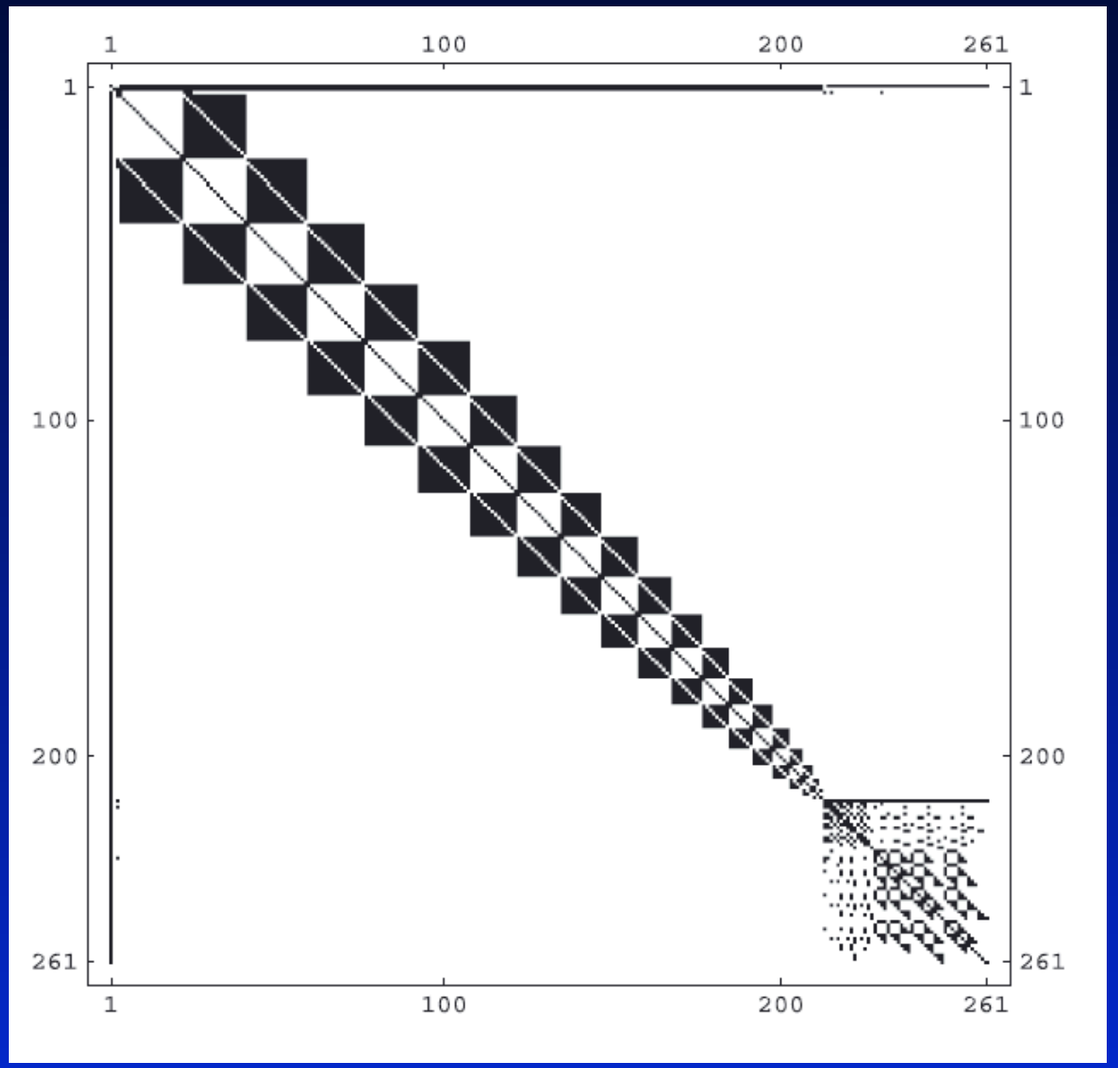


JC, Vasil & Dursi, MNRAS, 2010

Sparsity of the problem and effect of ordering

20 shell Hydrogen + 5 shell Helium model





Shell-by-Shell ordering

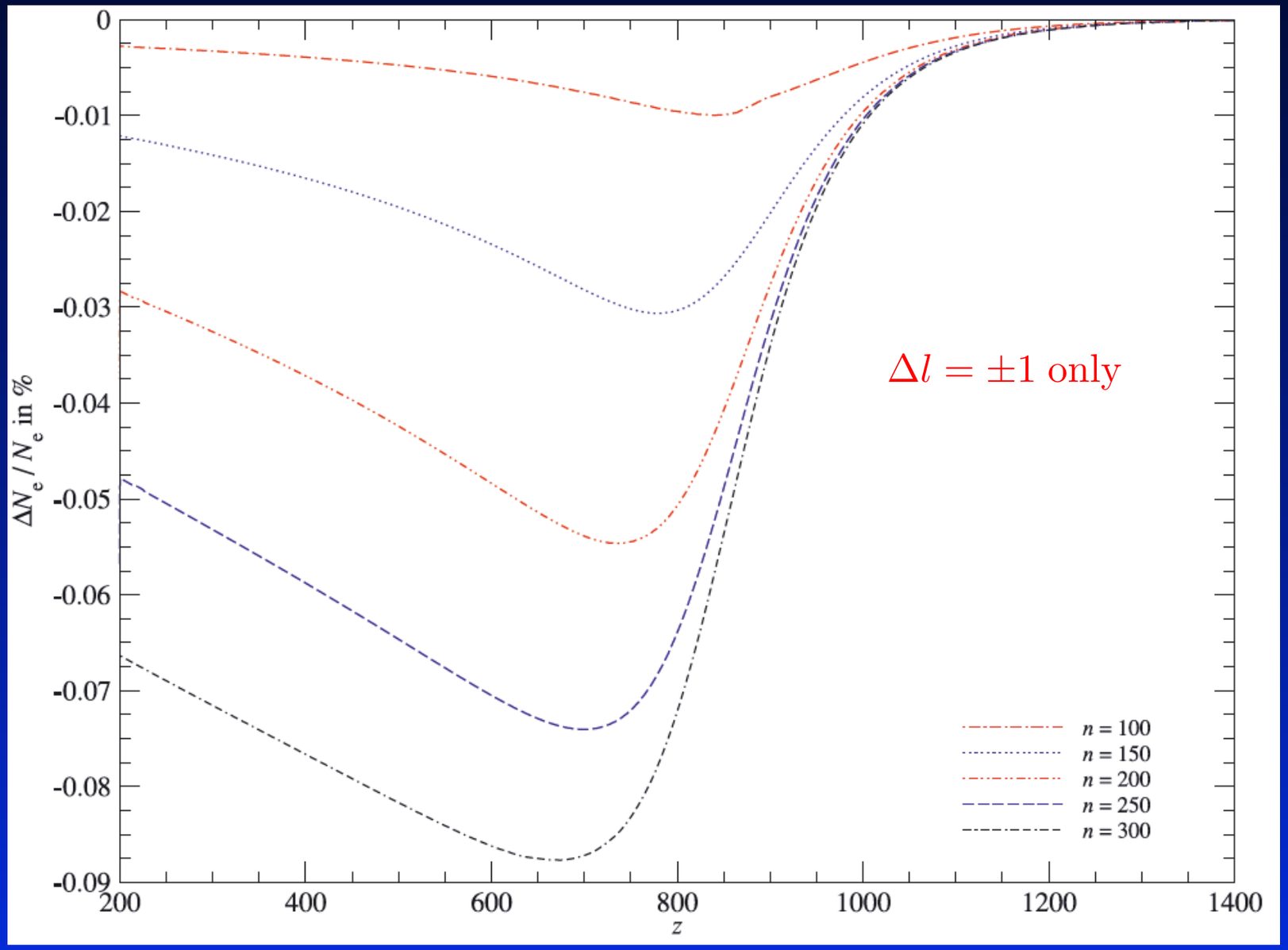
$$1s, 2s, 2p, 3s, 3p, 3d, \ldots$$

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

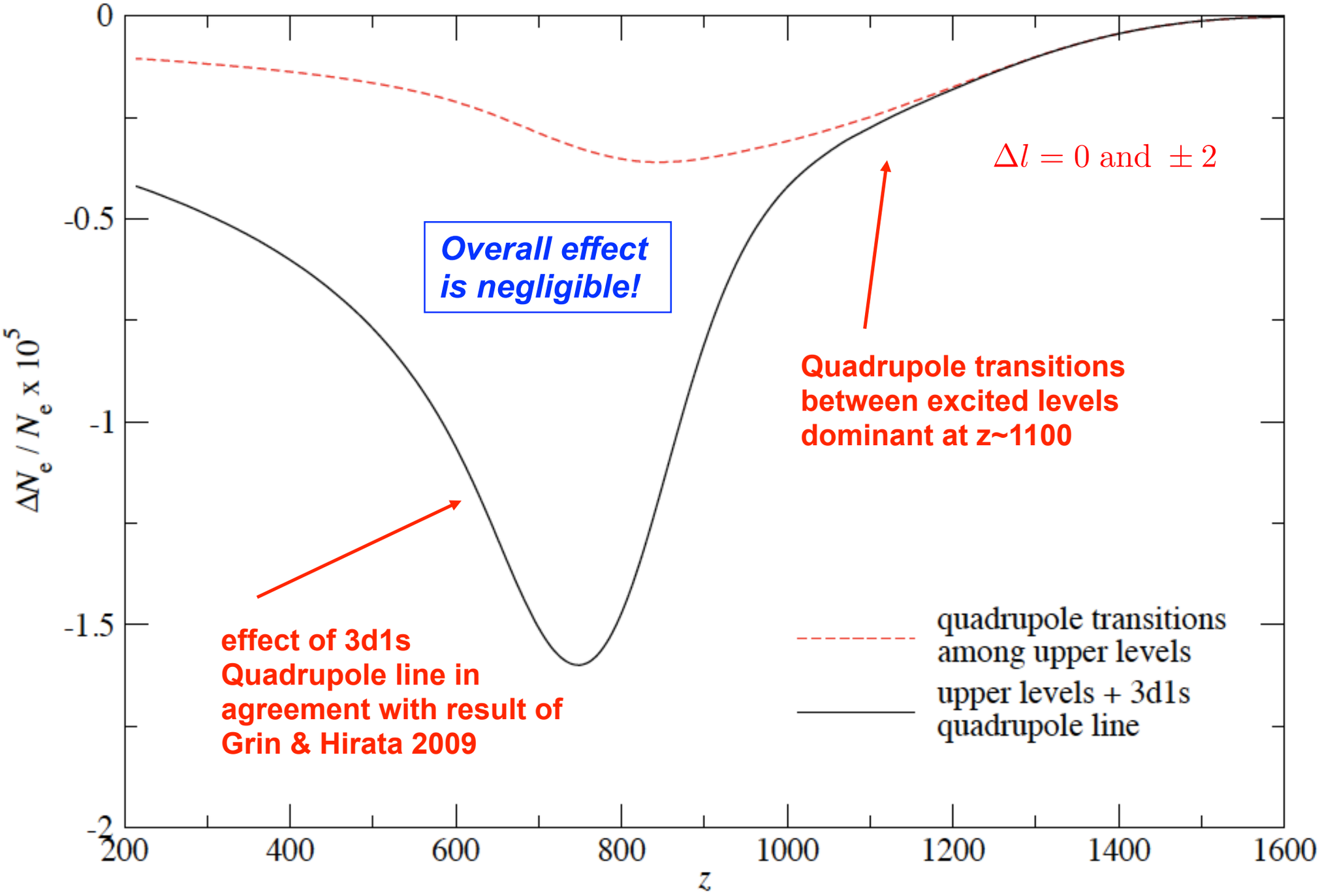


- **effective recombination cross section of the atom matters most at low *z***
- **collisions *increase* recombination rate**
- **effect on ionization history remains *small***
- ***uncertainties* in collision rates may change this by factors of a few**
- ***updated rates* (with large Δl) became available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

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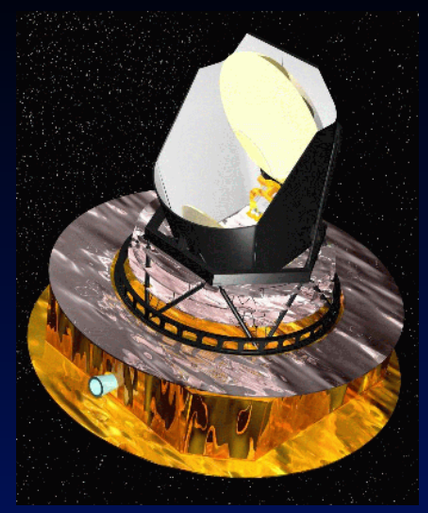
JC, Vasil & Dursi, MNRAS, 2010

Quadrupole lines during hydrogen recombination



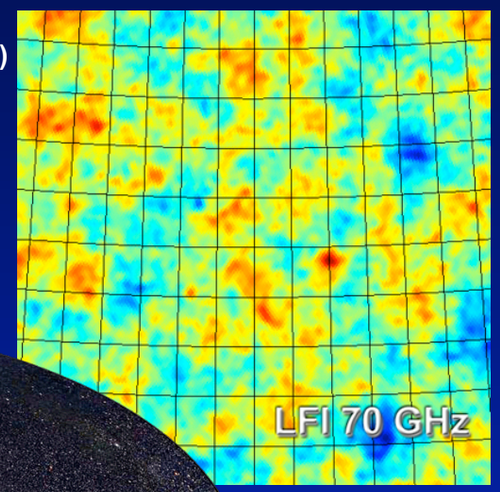
JC, Fung & Switzer, 2011

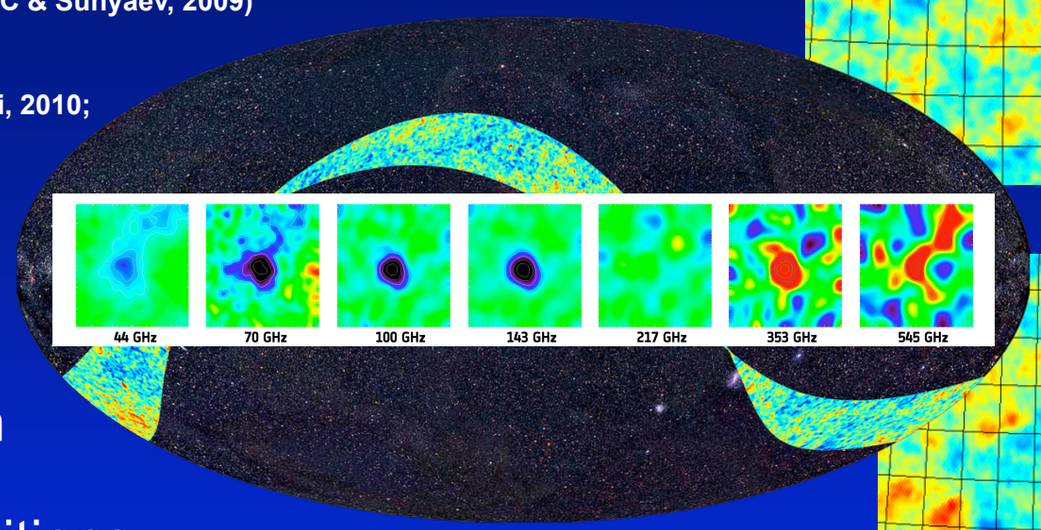
Getting the job done for *Planck*

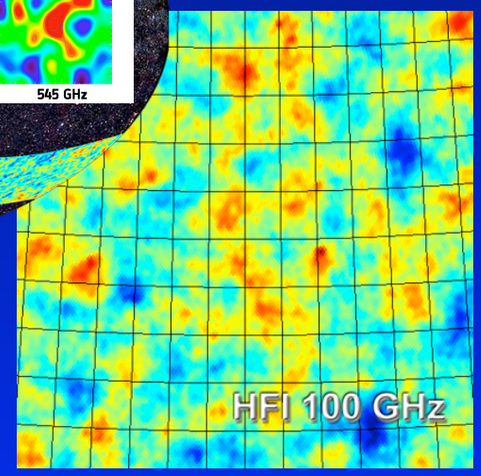


Hydrogen recombination

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







Helium recombination

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

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

Main corrections during HeI Recombination

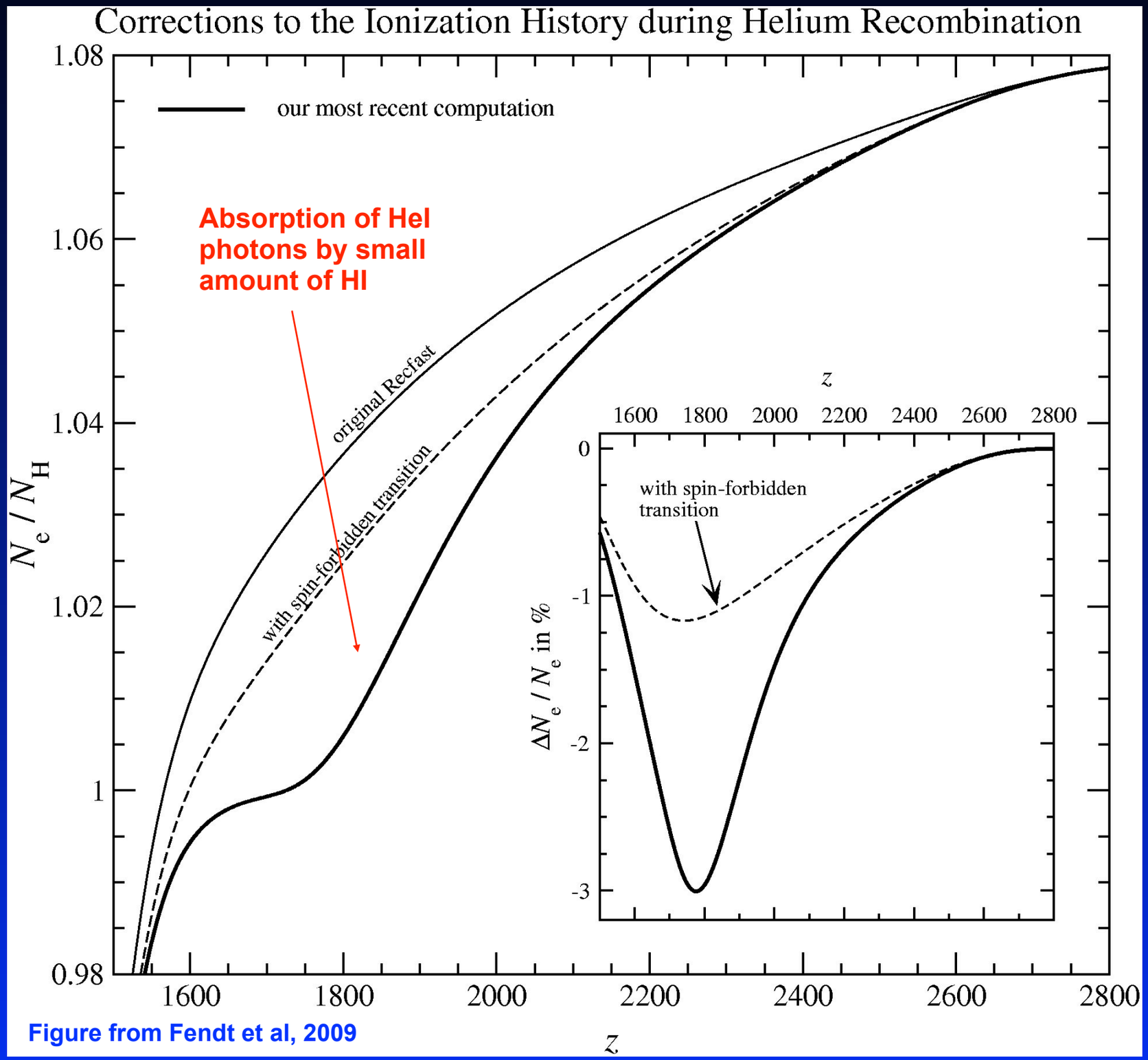


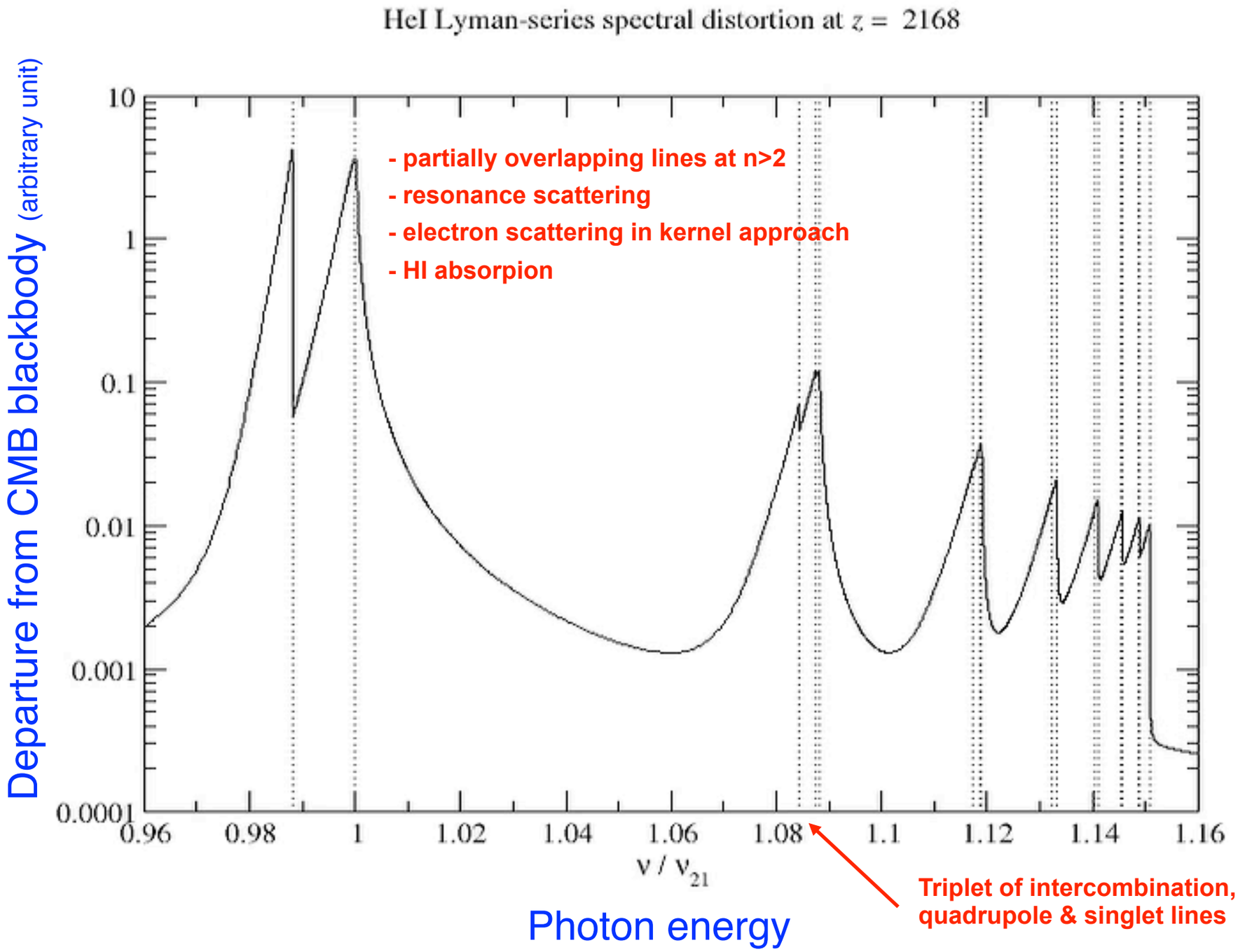
Figure from Fendt et al, 2009

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

Kholupenko et al, 2007
Switzer & Hirata, 2007

Evolution of the HeI high frequency distortion

CosmoRec v2.0 only!



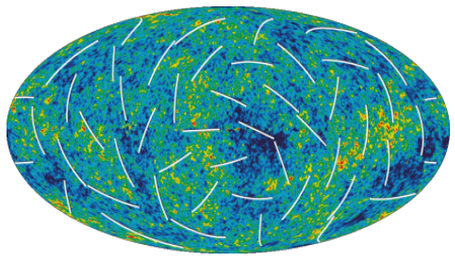
JC, Fung & Switzer, 2011

So why is all this so important?

Cosmological Time in Years

790,000 370,000 260,000 130,000 18,000

CMB-Anisotropies



Free Electron Fraction

$N_e/[N_p+N_H]$

Plasma fully ionized

Visibility Function

Plasma neutral

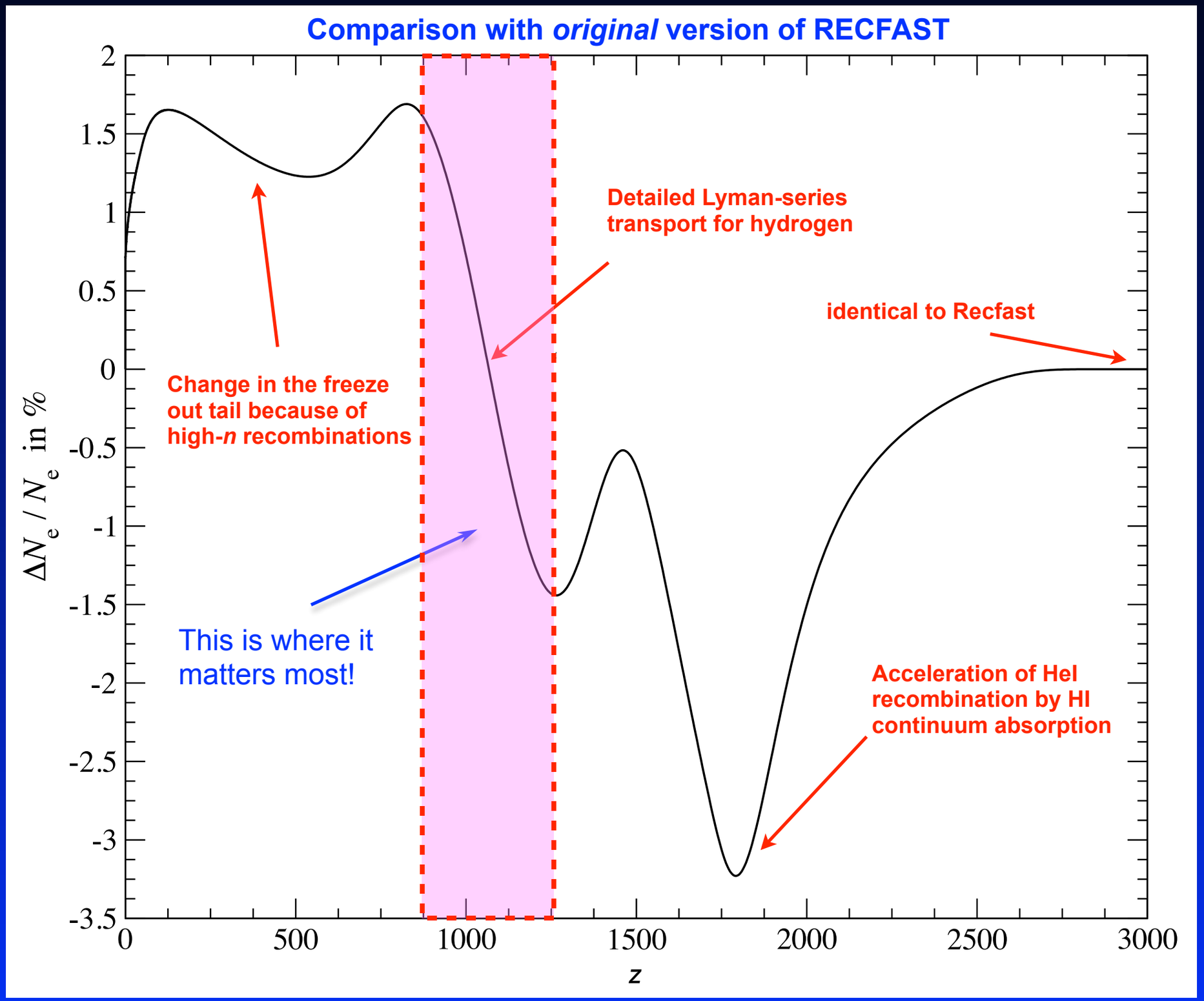
For computations of the CMB anisotropies the ionization history has to be known to high precision!

1.4 1.2 1 0.8 0.6 0.4 0.2 0

700 1100 2000 3000 4000 6000 8000

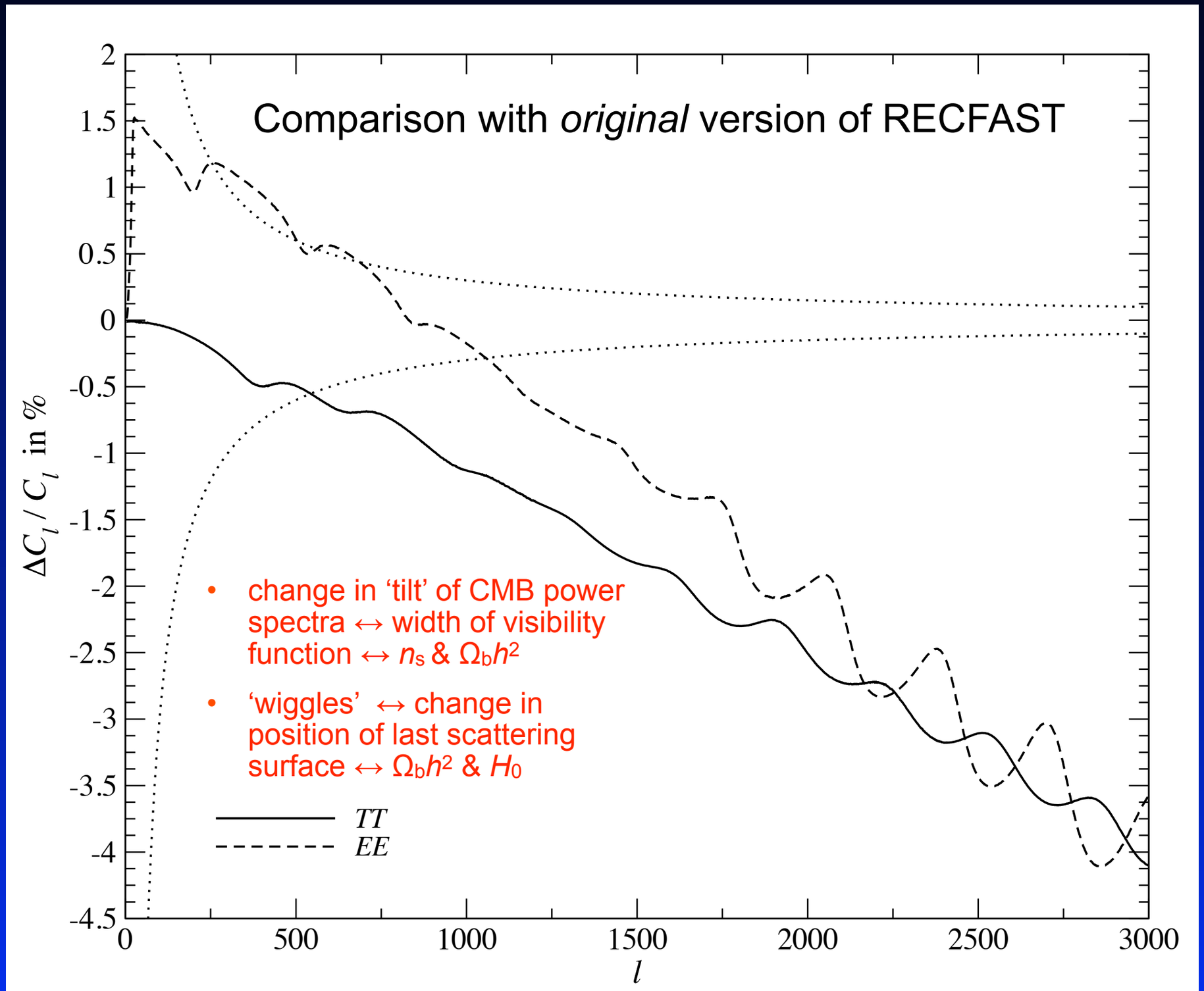
Redshift z

Cumulative Changes to the Ionization History



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

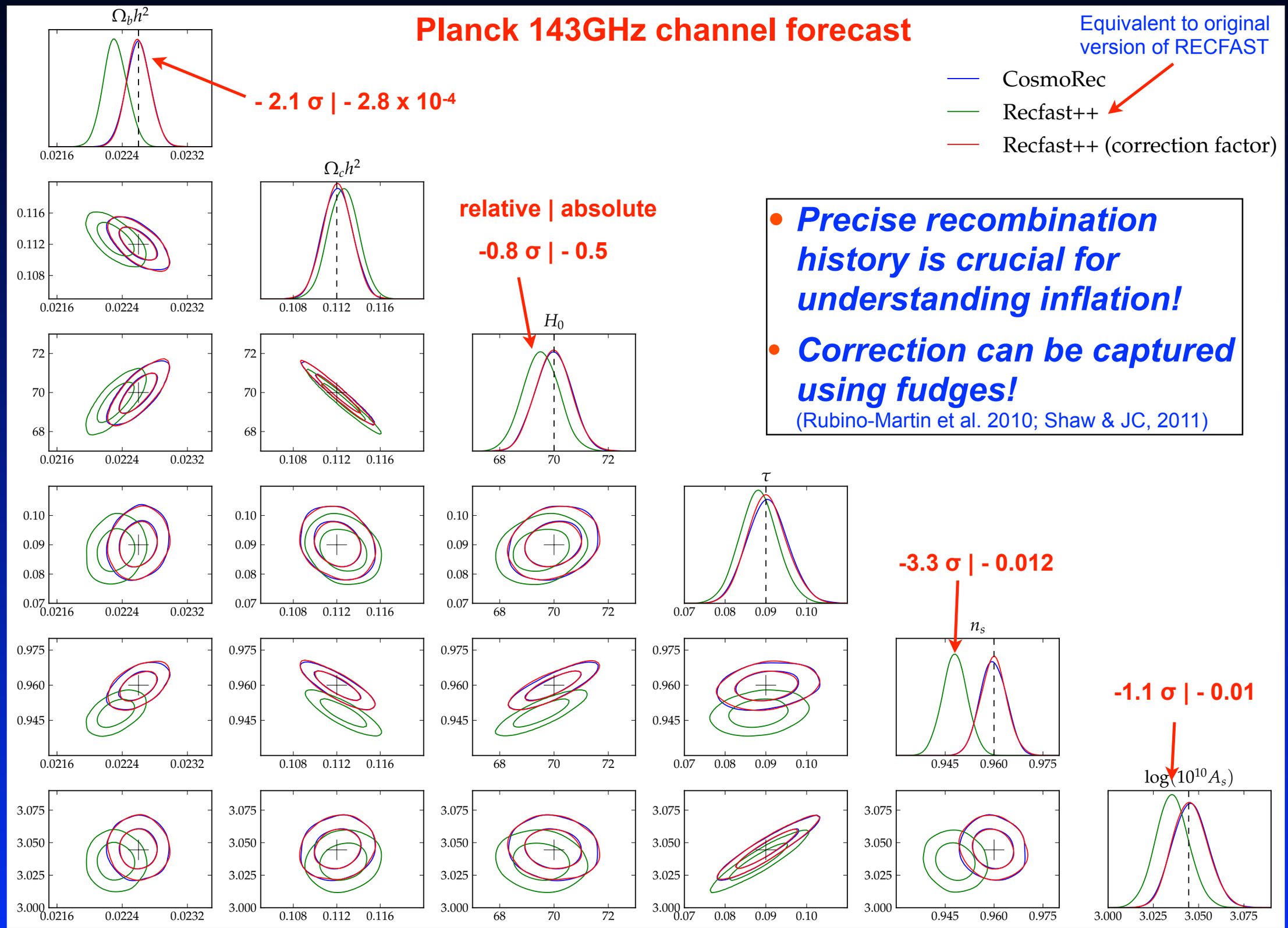
Cumulative Change in the CMB Power Spectra



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Shaw & JC, MNRAS, 2011

Importance of recombination for *Planck*

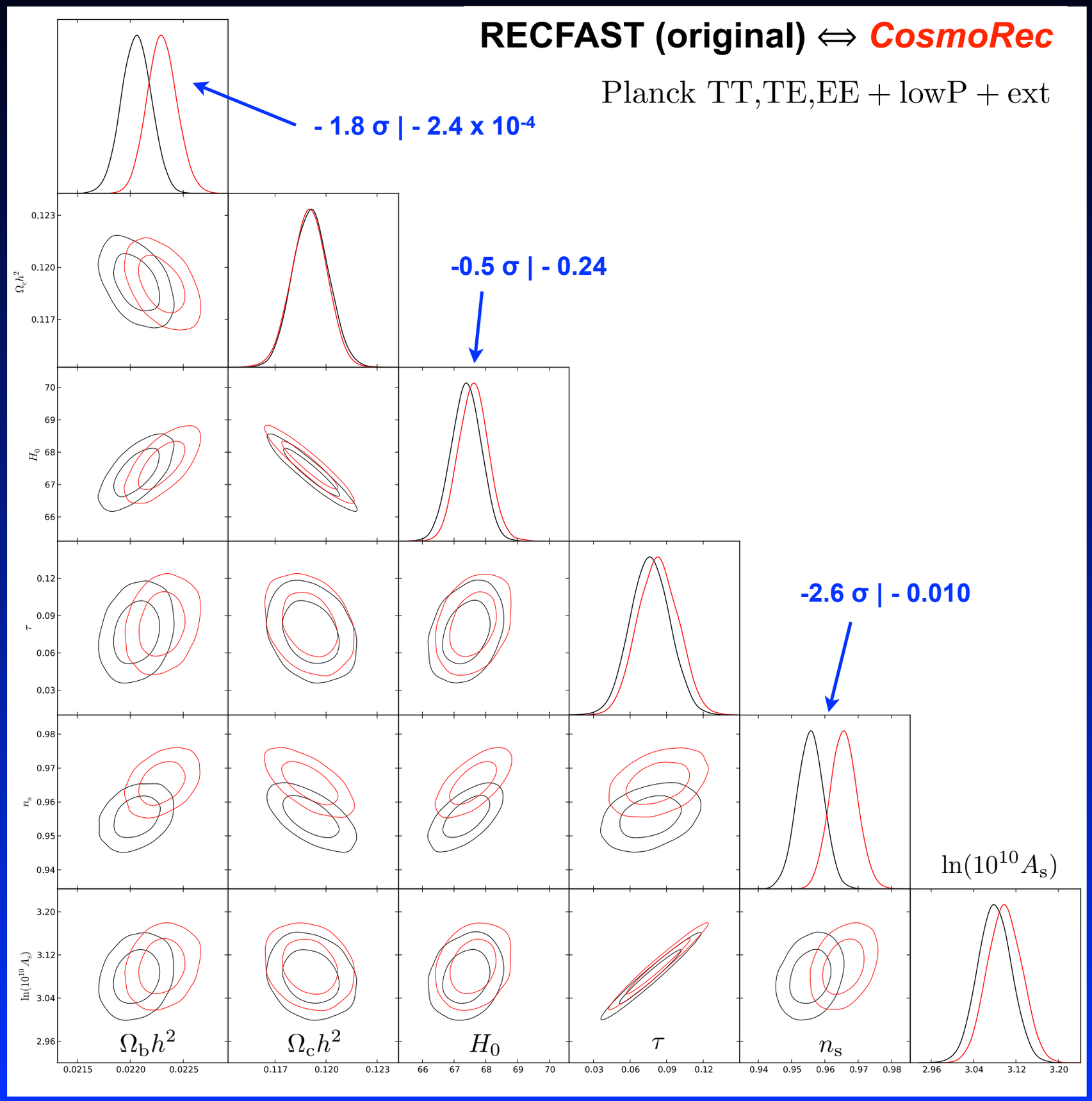


- ***Precise recombination history is crucial for understanding inflation!***
- ***Correction can be captured using fudges!***
  (Rubino-Martin et al. 2010; Shaw & JC, 2011)

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Shaw & JC, 2011, and references therein

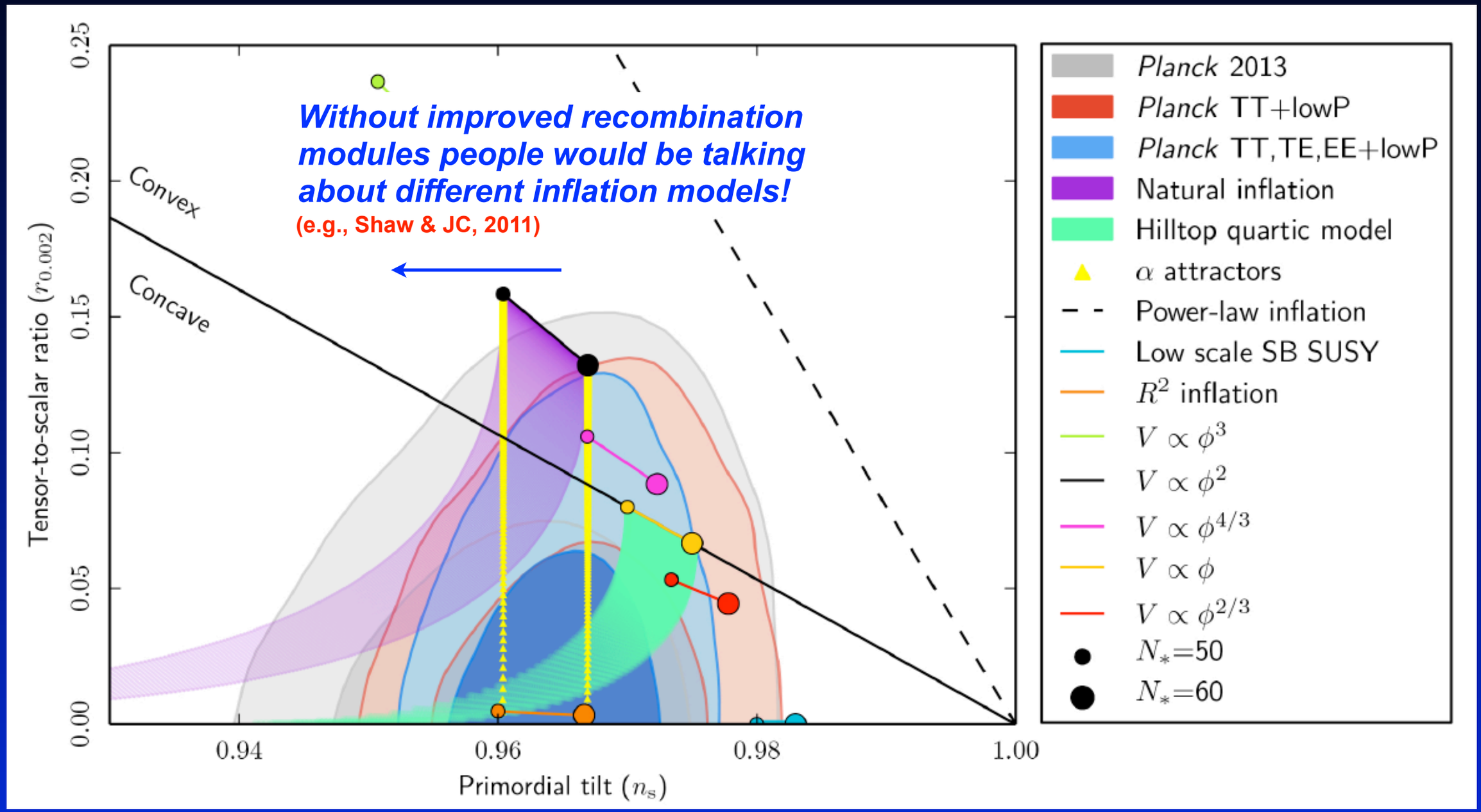
Biases as they *would* have been for *Planck* 15



- 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

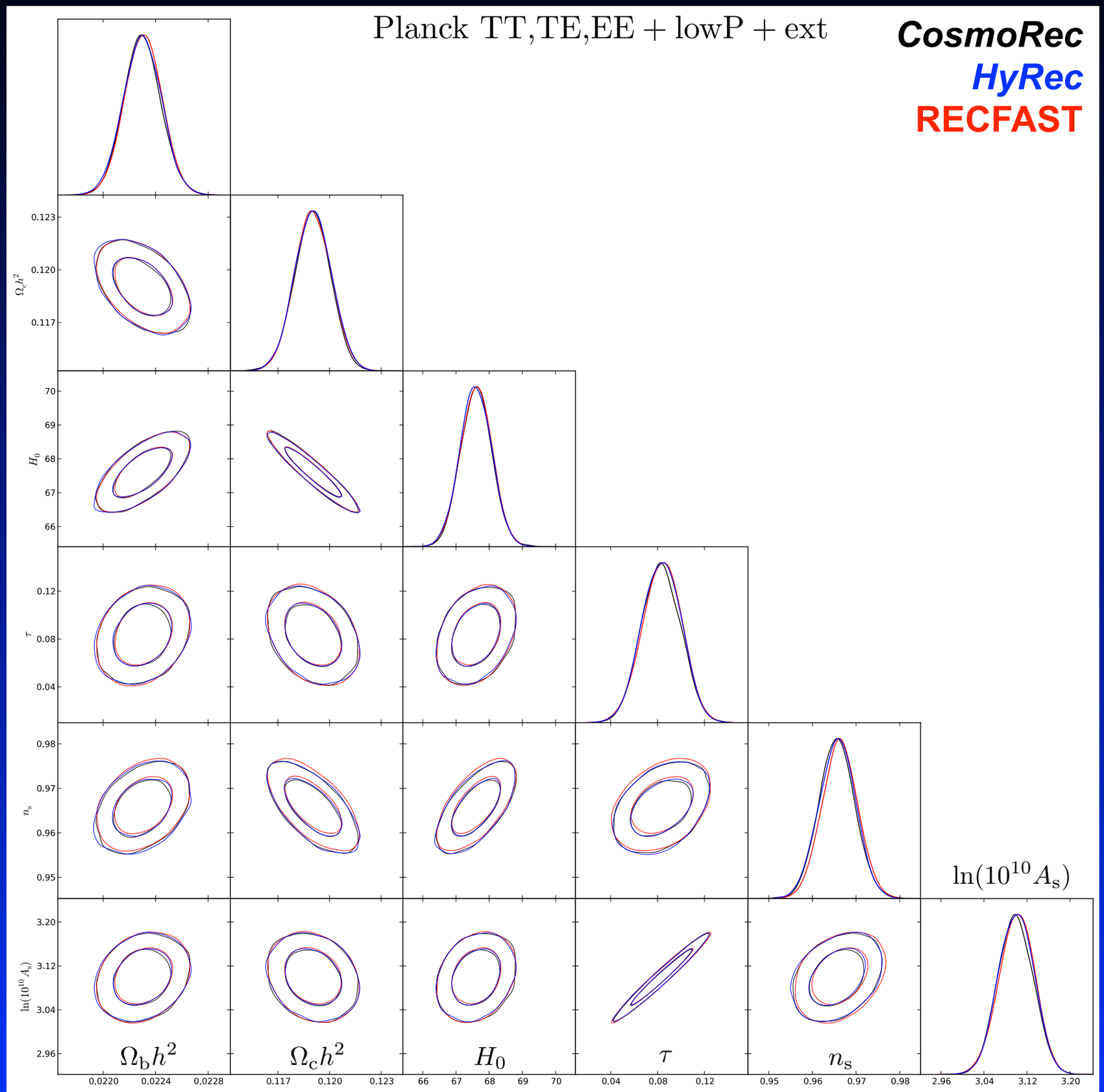
Importance of recombination for inflation constraints



Planck Collaboration, 2015, paper XX

- Analysis uses refined recombination model (CosmoRec/HyRec)

Differences for current recombination codes



- Different codes agree very well!
- largest biases

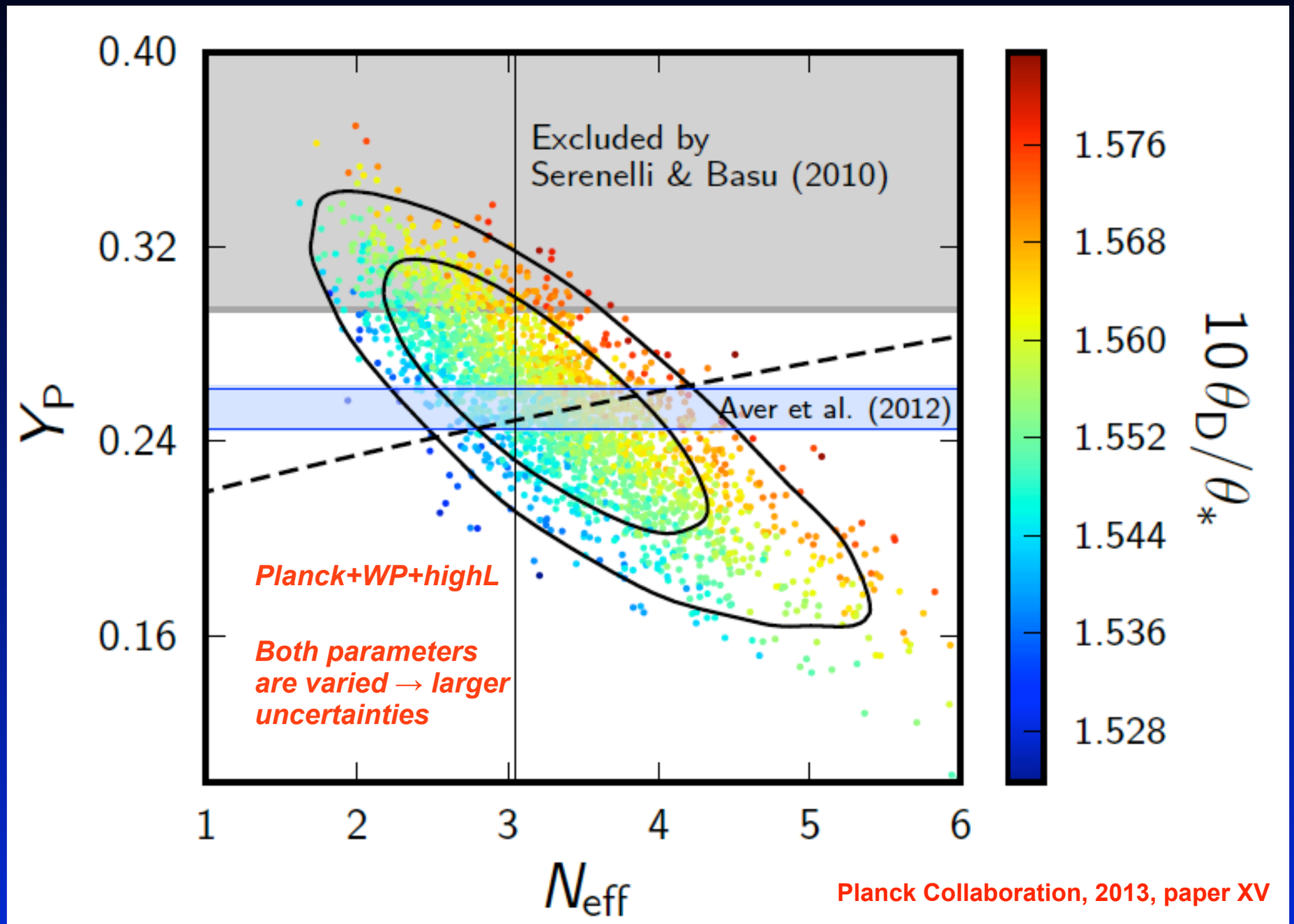
$\Delta n_s \approx 0.15\sigma$
(*CosmoRec* ⇔ RECFAST)

$\Delta n_s \approx 0.03\sigma$
(*CosmoRec* ⇔ *HyRec*)

- Nothing to worry about at this point!

Planck Collaboration, XIII 2015

CMB constraints on N_{eff} and Y_p

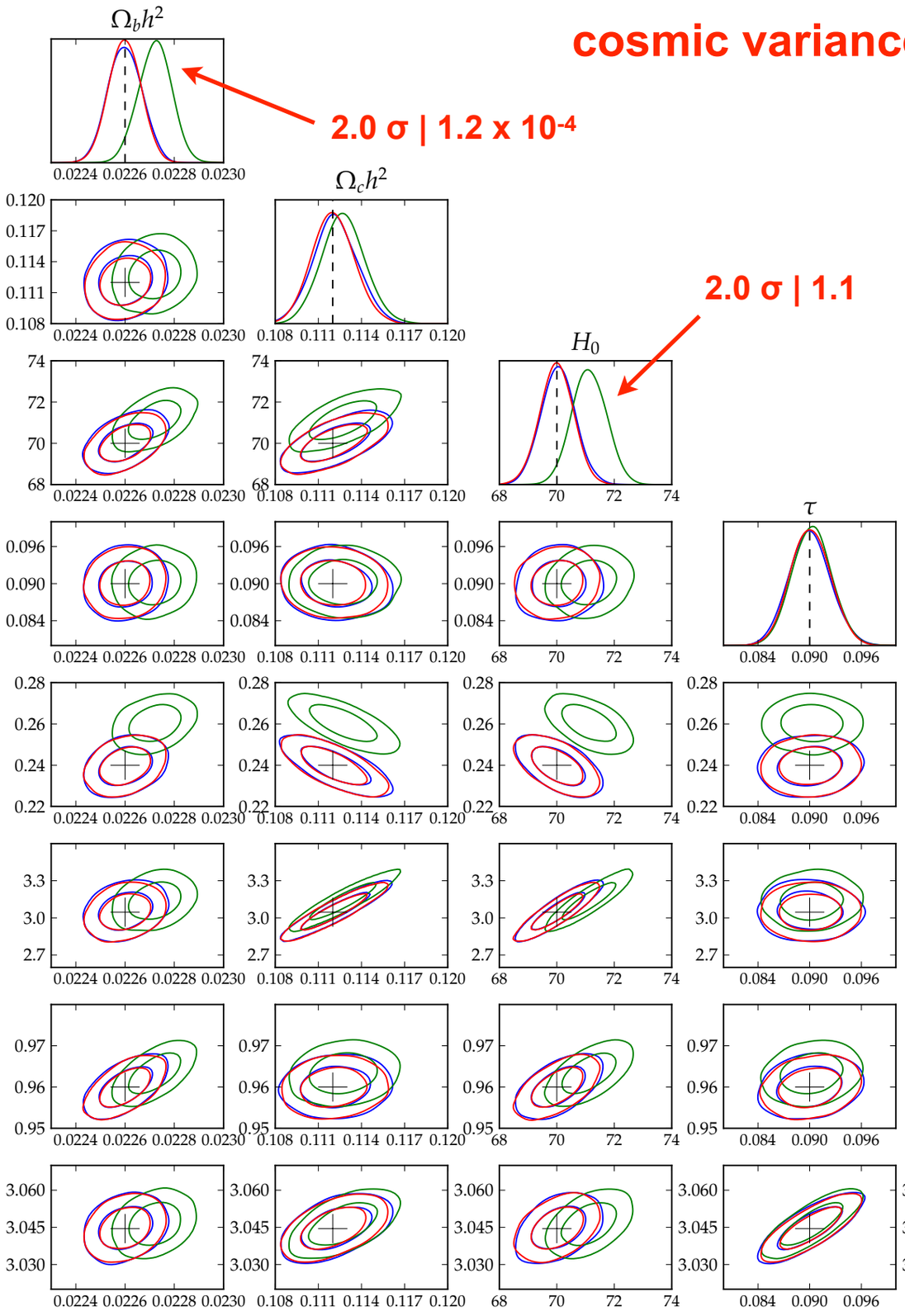


Planck Collaboration, 2013, paper XV

- *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

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



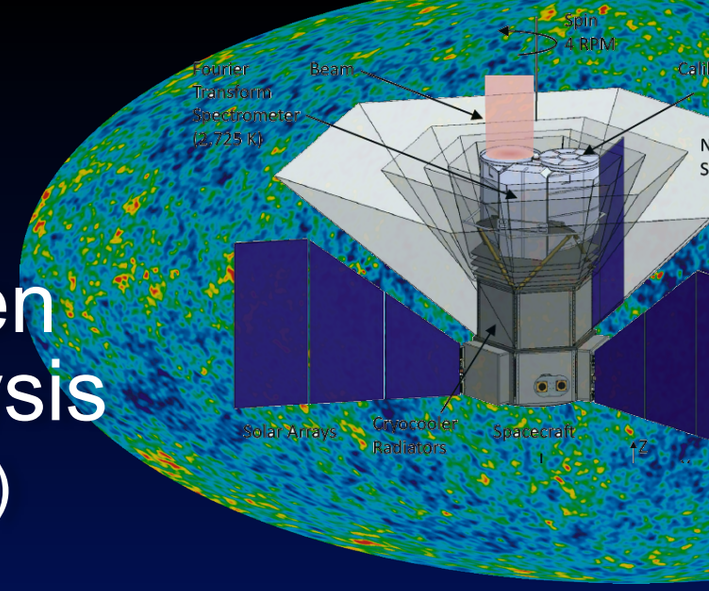
CosmoRec
Recfast++
Recfast++ (correction factor)

- 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

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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*…)

