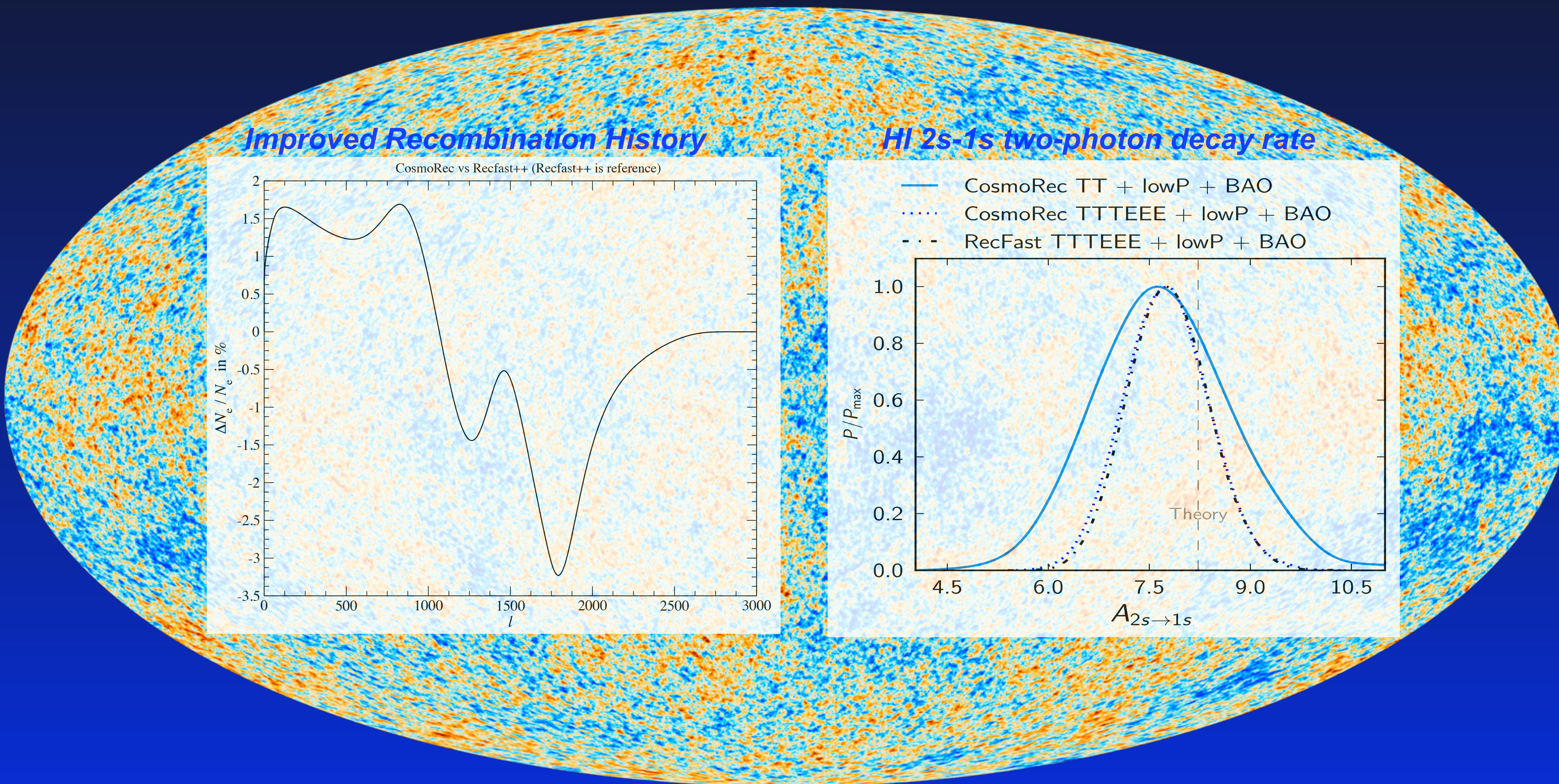
Recombination Physics and Why it is Important for Cosmology and Early-Universe Physics



Jens Chluba

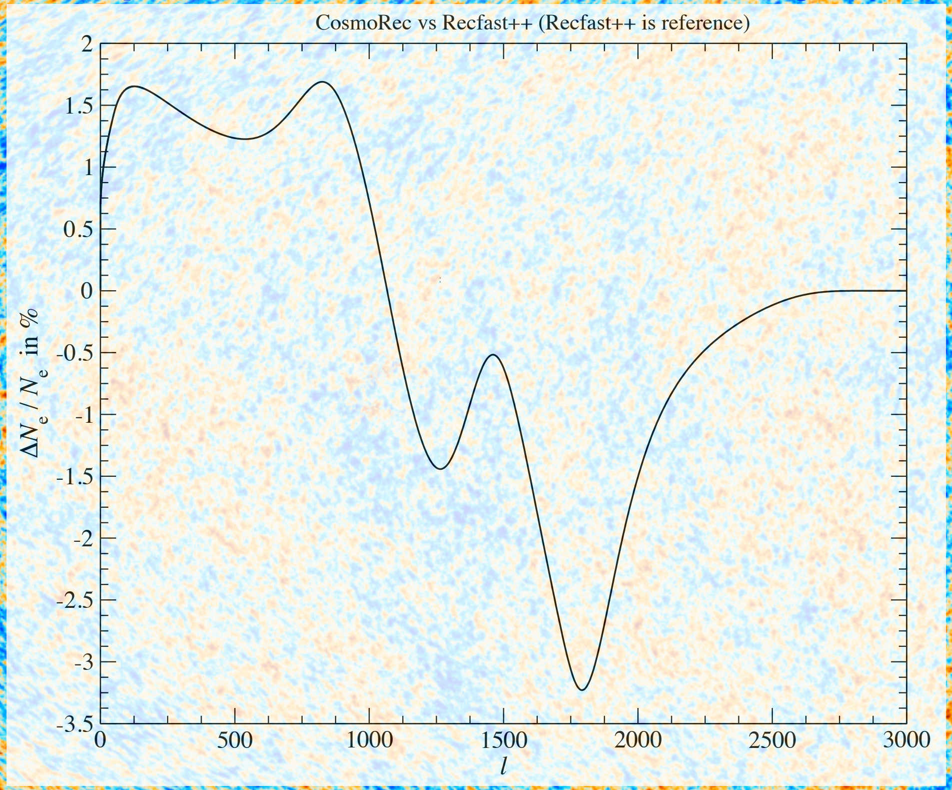
The University of Manchester

2nd IFT School on Cosmological Tools

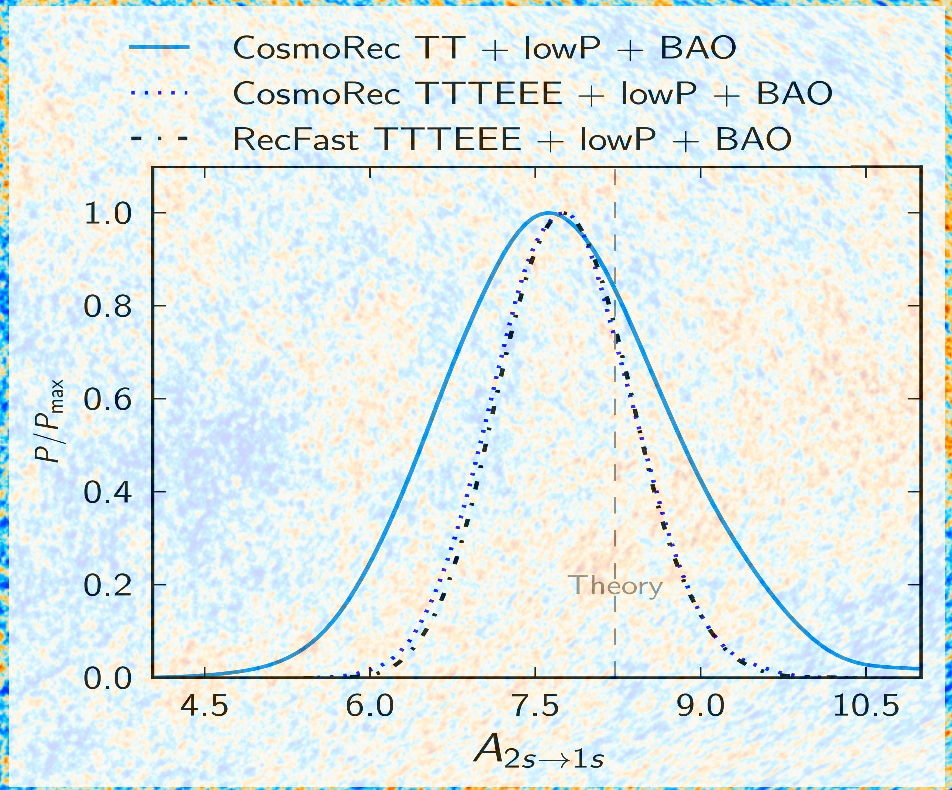
Madrid, Spain, March 13th - 17th, 2017

Everything you always wanted to know about recombination but never dared to ask

Improved Recombination History



HI 2s-1s two-photon decay rate



MANCHESTER 1824
The University of Manchester

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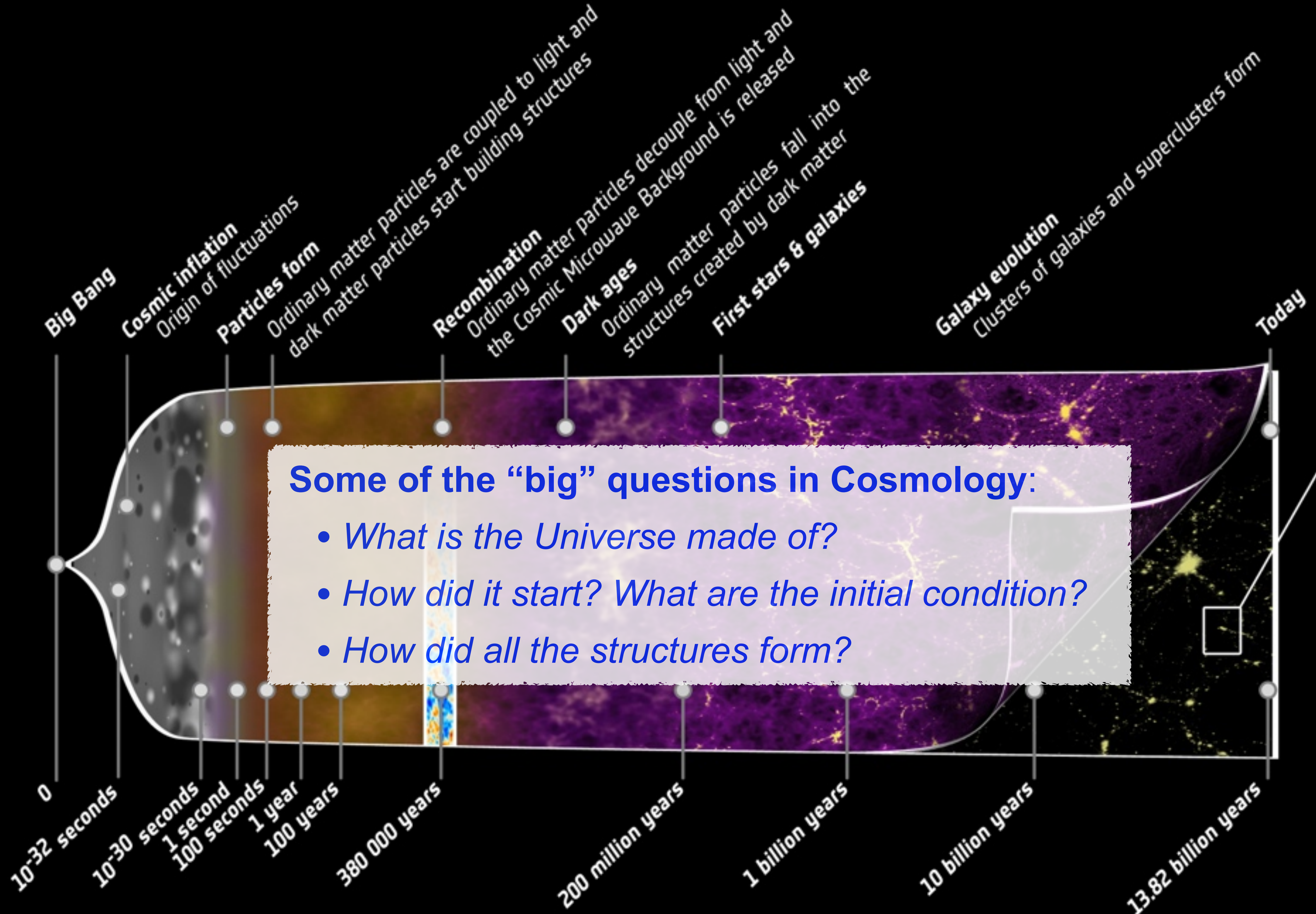
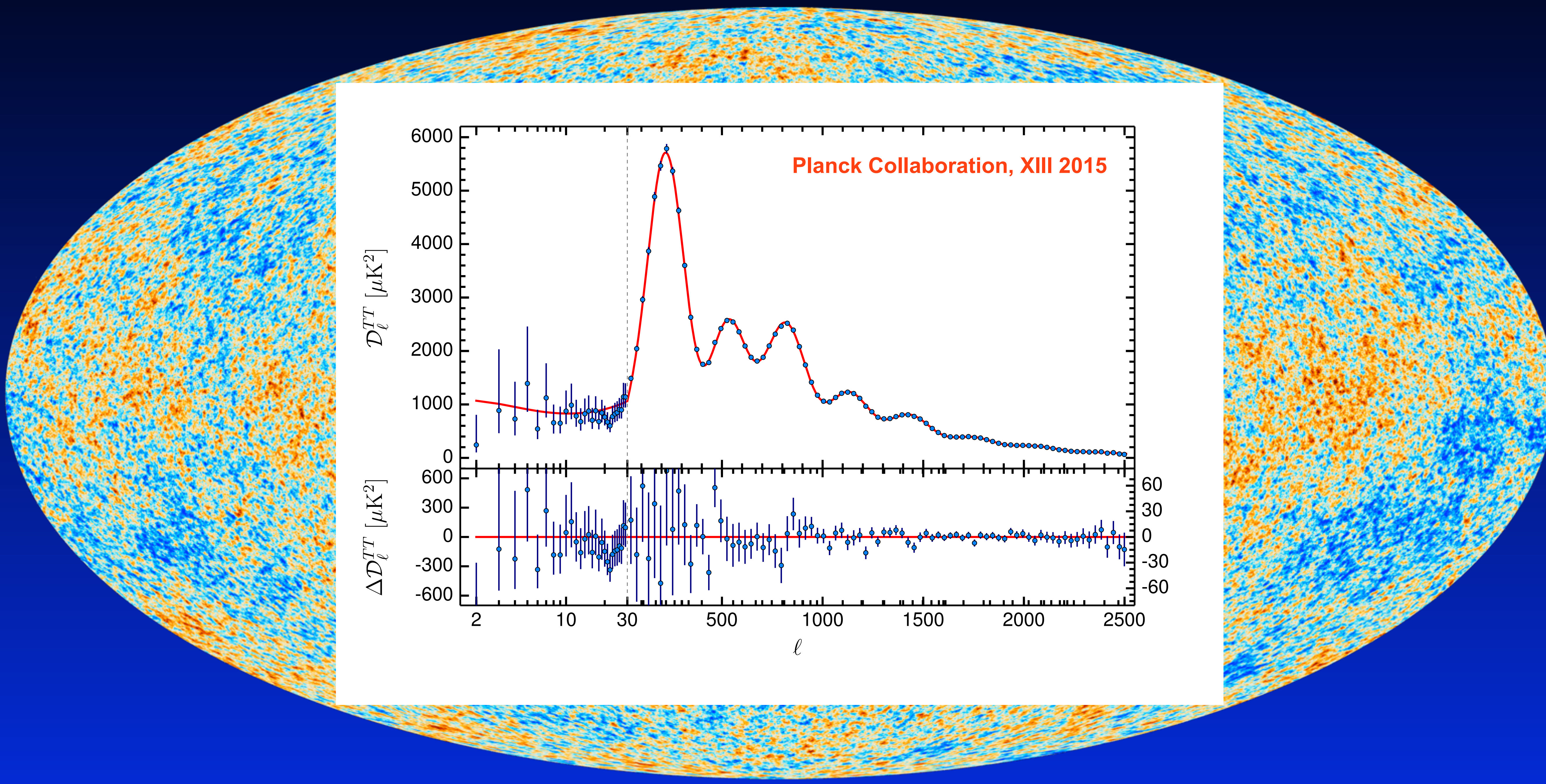
erc THE ROYAL SOCIETY



Some of the "big" questions in Cosmology:

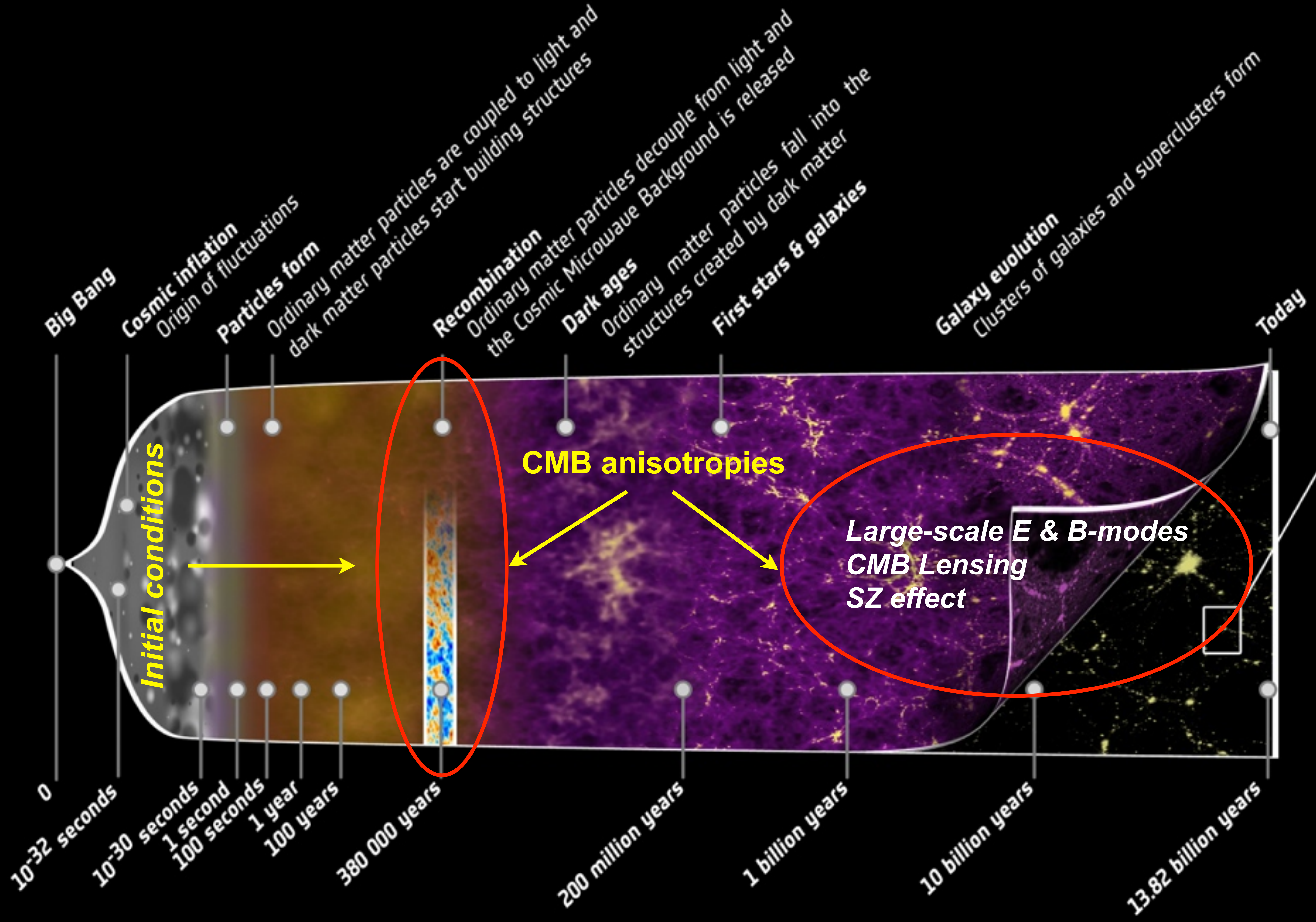
- *What is the Universe made of?*
- *How did it start? What are the initial condition?*
- *How did all the structures form?*

Cosmic Microwave Background Anisotropies

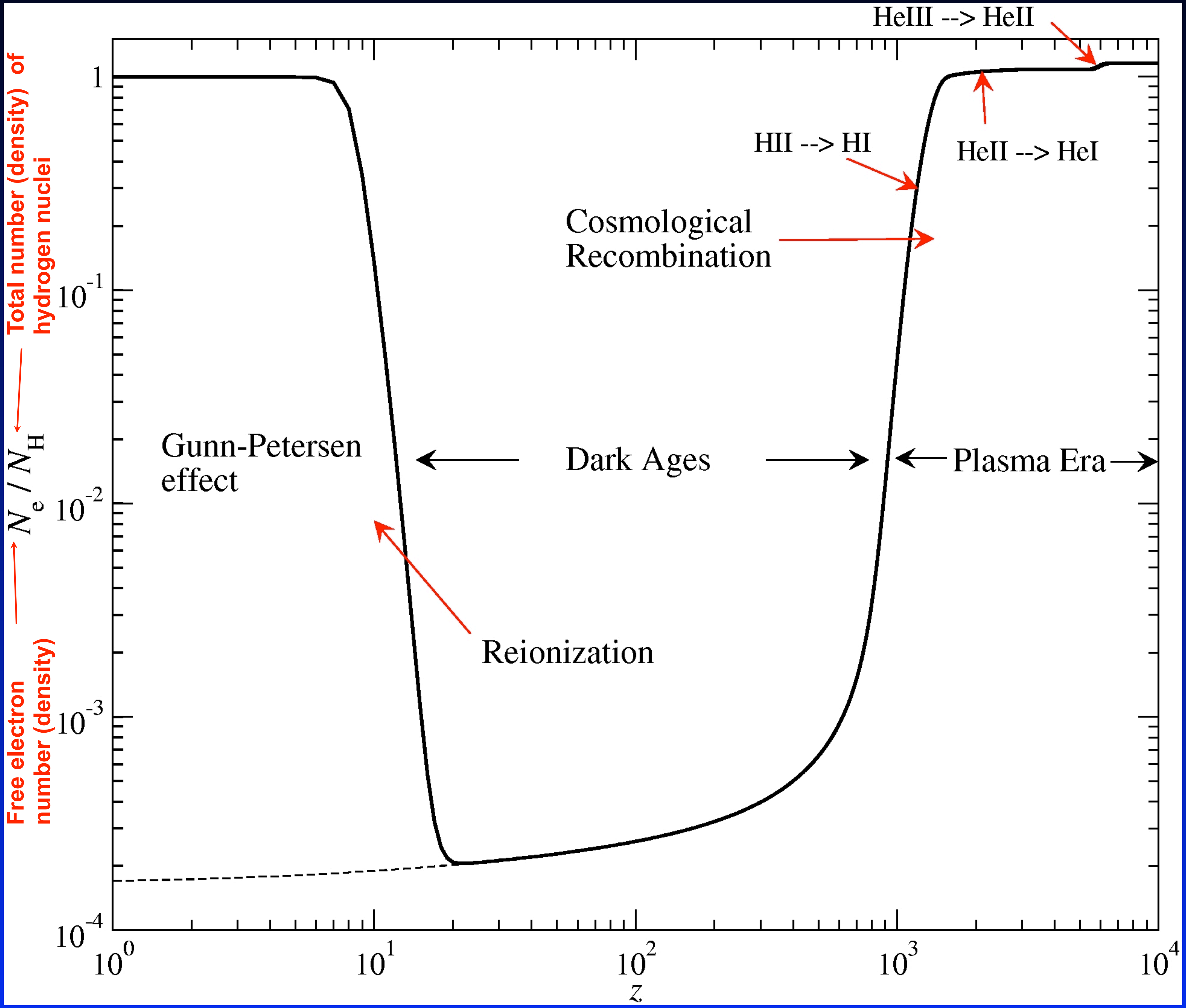


Planck all sky map

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


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

Sketch of the Cosmic Ionization History



- at redshifts higher than ~10^4 Universe → *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

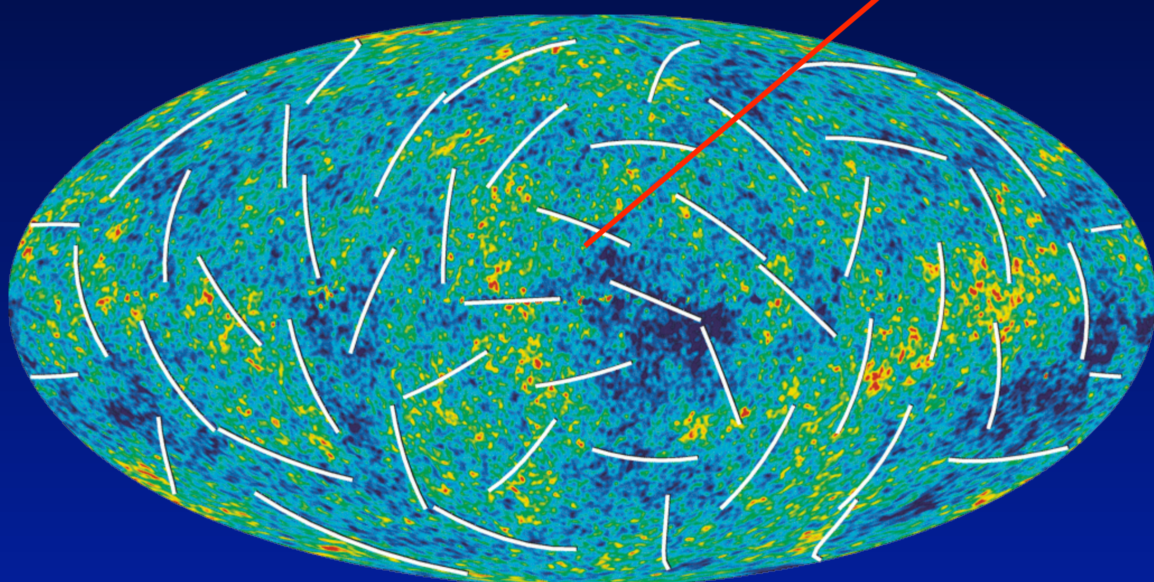
CMB Sky → Cosmology

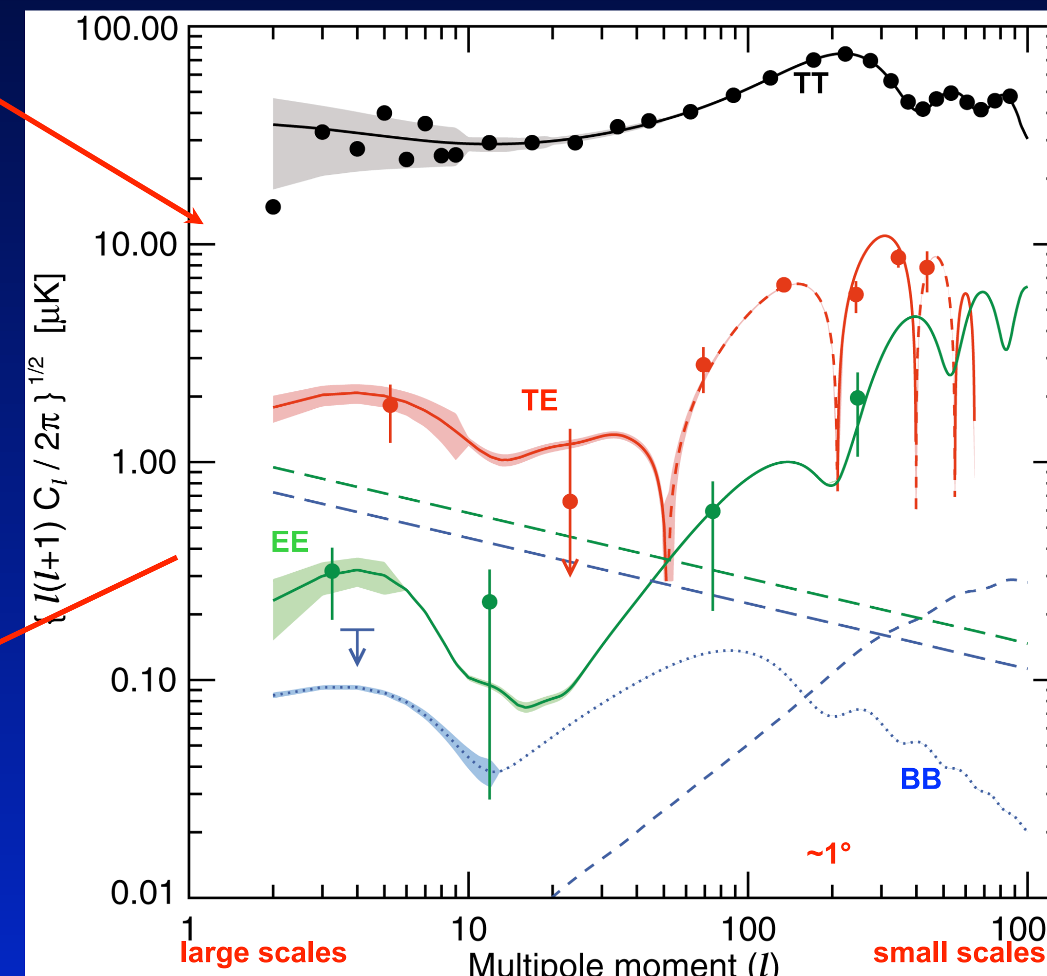
$N_e(z)$ is a *crucial* input

a_{lm}

Power spectra

WMAP CMB Sky





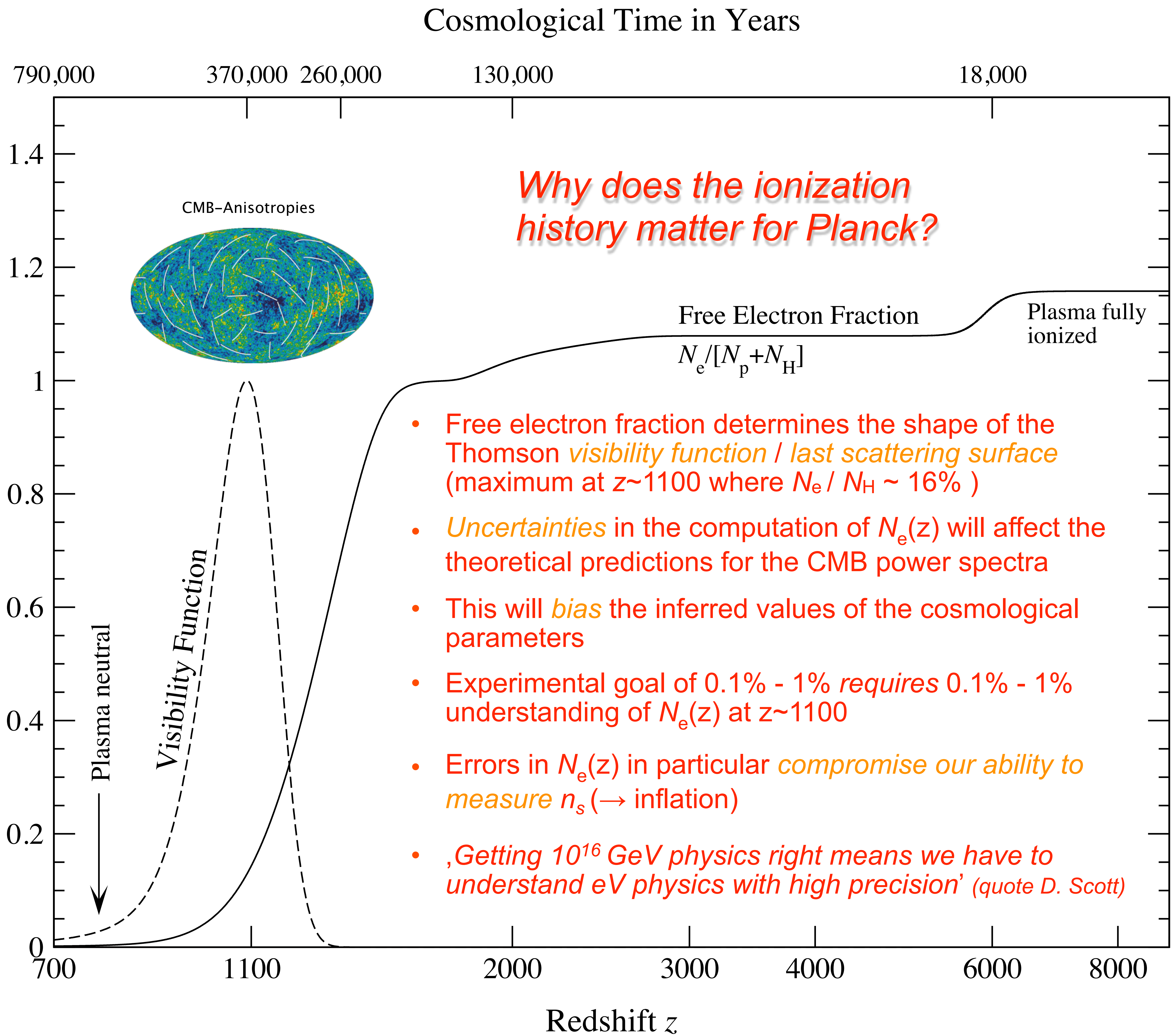
(Joint) analysis

Cosmological Parameters

Ω_{tot}, Ω_m, Ω_b, Ω_Λ,
h, τ, n_s,...

Other cosmological Dataset:

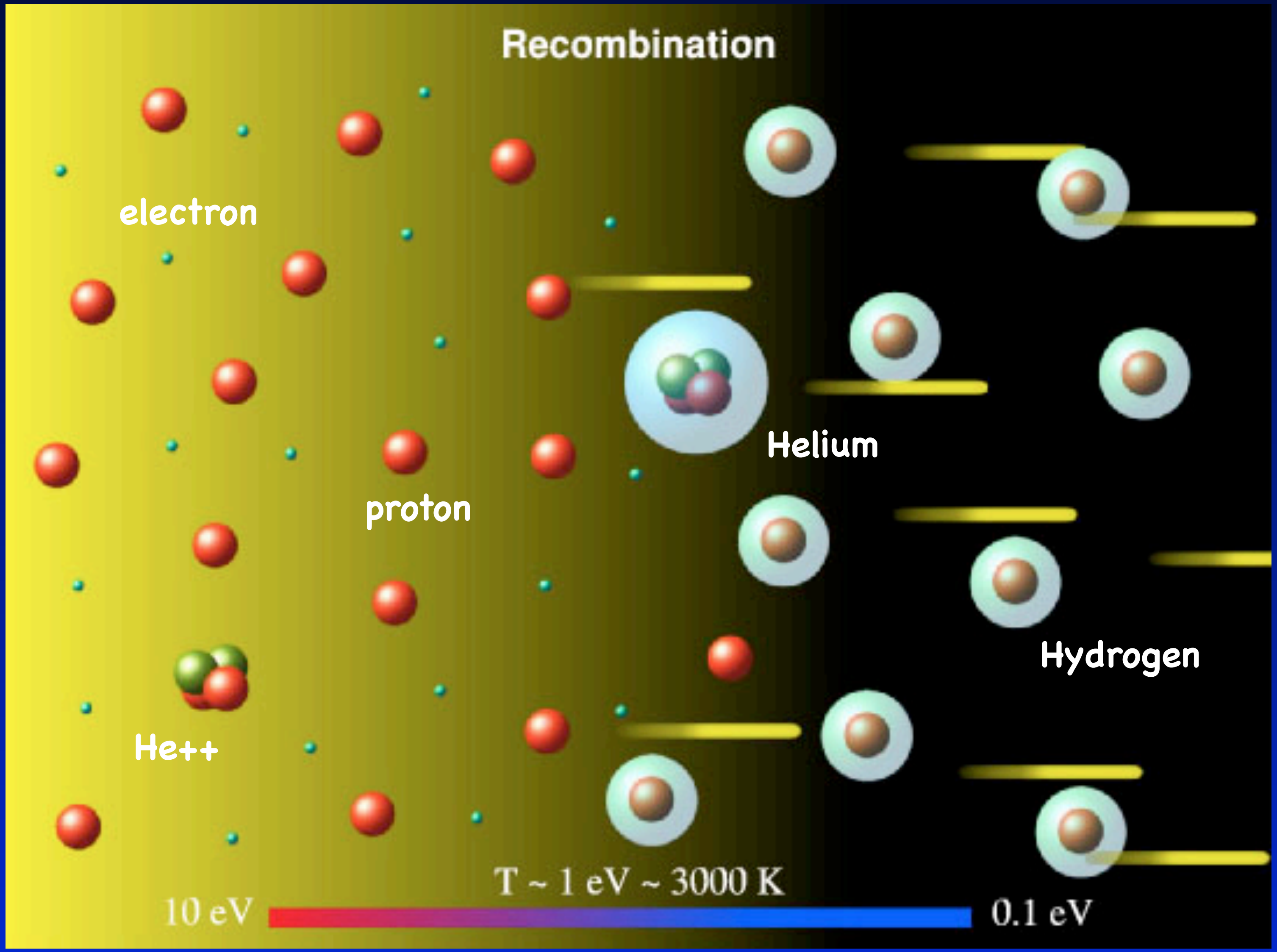
small-scale CMB, Supernovae, large-scale structure/ BAO, Lyman-α forest, lensing, ...



Cosmological Time in Years
790,000
370,000
260,000
130,000
18,000
1.4
1.2
1
0.8
0.6
0.4
0.2
0
CMB-Anisotropies
Why does the ionization history matter for Planck?
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully ionized
Plasma neutral
Visibility Function
• Free electron fraction determines the shape of the Thomson *visibility function / last scattering surface* (maximum at $z \sim 1100$ where $N_e / N_H \sim 16\%$)
• *Uncertainties* in the computation of $N_e(z)$ will affect the theoretical predictions for the CMB power spectra
• This will *bias* the inferred values of the cosmological parameters
• Experimental goal of 0.1% - 1% *requires* 0.1% - 1% understanding of $N_e(z)$ at z~1100
• Errors in $N_e(z)$ in particular *compromise our ability to measure* n_s (→ inflation)
• *‚Getting 10^{16} GeV physics right means we have to understand eV physics with high precision'* *(quote D. Scott)*
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*

Only problem in time!

electron temperature

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

number densities

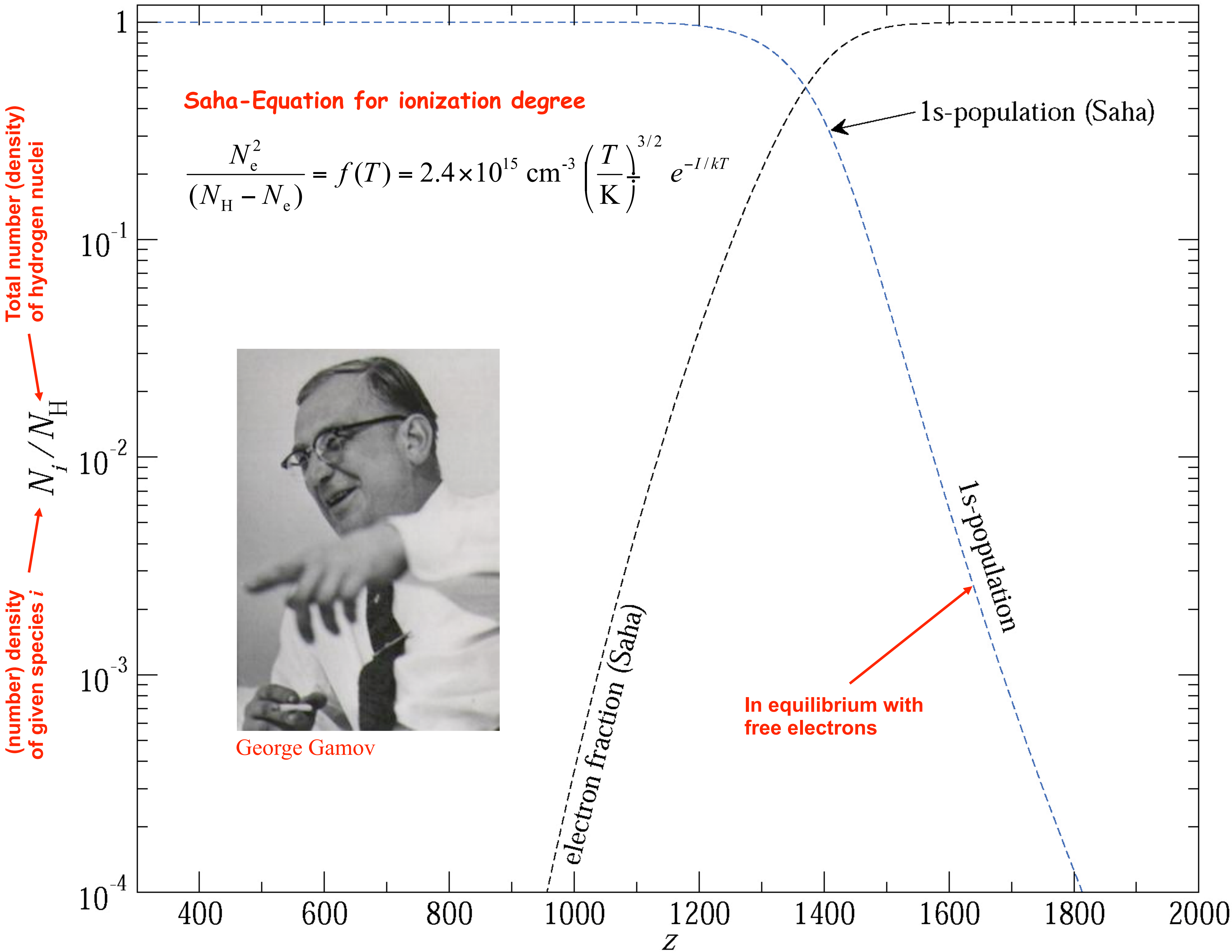
non-thermal photons

Physical Conditions during Recombination

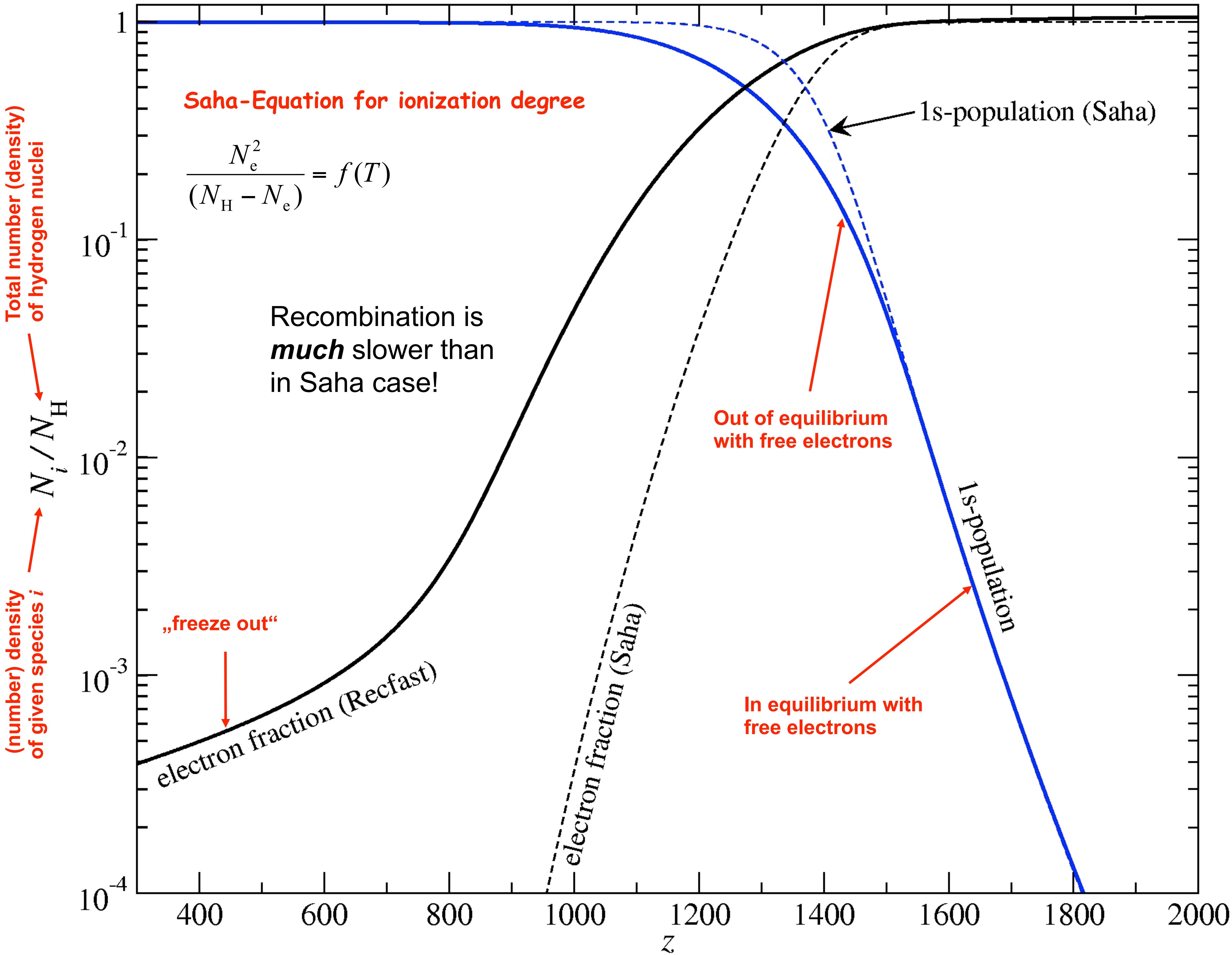
- Temperature T_γ ~ 2.725 (1+z) K ~ 3000 K
- Baryon number density N_b ~ 2.5×10^{-7} cm^{-3} $(1+z)^3$ ~ 330 cm^{-3}
- Photon number density N_γ ~ 410 cm^{-3} $(1+z)^3$ ~ 2×10^9 N_b

  ⇒ *photons in very distant Wien tail of blackbody spectrum can keep hydrogen ionized until* $h\nu_\alpha \sim 40\ kT_\gamma \Leftrightarrow T_\gamma \sim 0.26$ 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 ~ 200 ⇒ $T_\gamma \sim T_e \sim T_m$

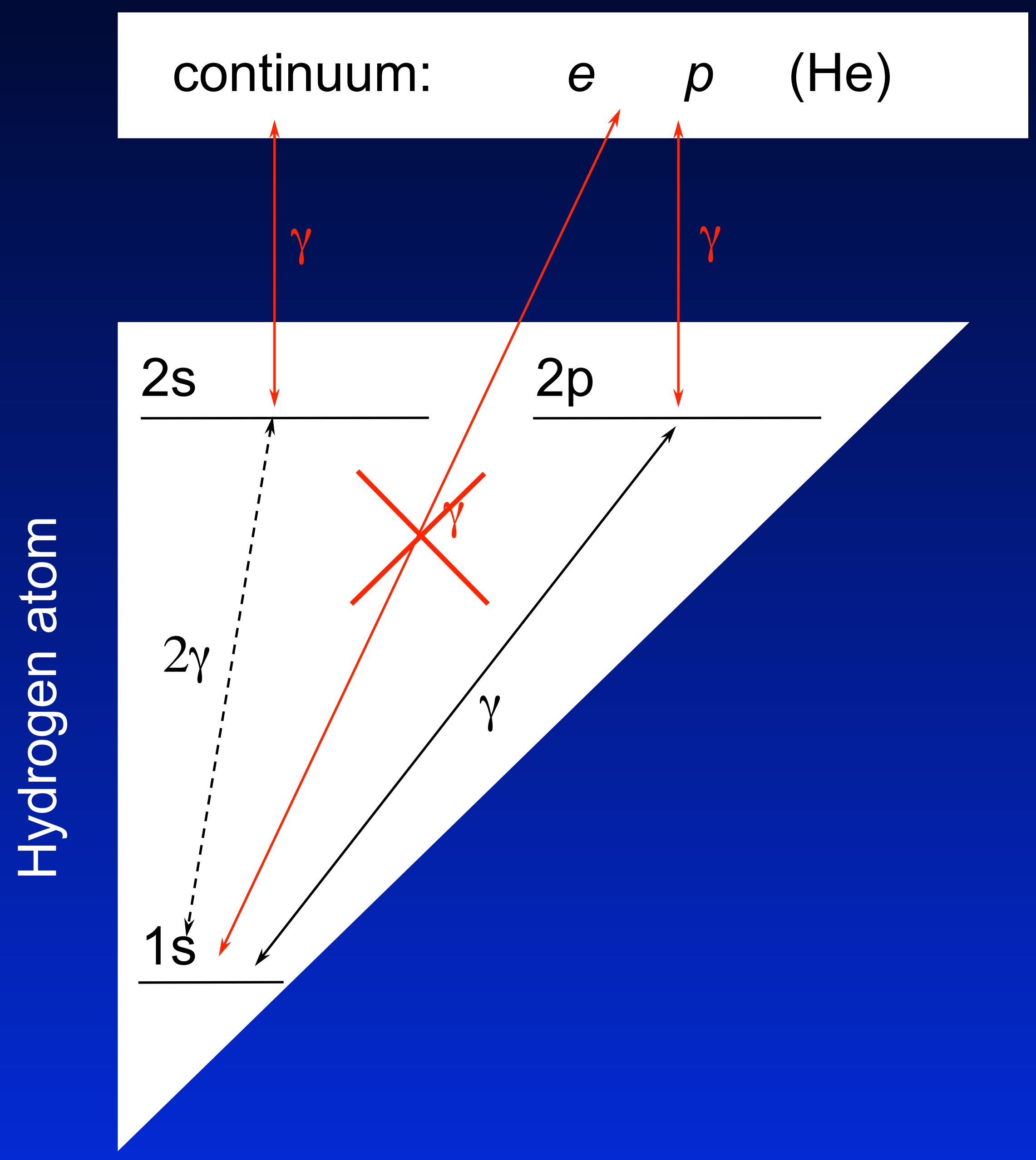


Saha-Equation for ionization degree
$$\frac{N_e^2}{(N_H - N_e)} = f(T) = 2.4\times10^{15}\ \mathrm{cm}^{-3}\left(\frac{T}{\mathrm{K}}\right)^{3/2} e^{-I/kT}$$
1s-population (Saha)
electron fraction (Saha)
1s-population
In equilibrium with free electrons
George Gamov
Total number (density) of hydrogen nuclei
(number) density of given species i
N_i / N_H
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
400
600
800
1000
1200
1400
1600
1800
2000
z



Saha-Equation for ionization degree
$\frac{N_e^2}{(N_H - N_e)} = f(T)$
Recombination is *much* slower than in Saha case!
1s-population (Saha)
Out of equilibrium with free electrons
In equilibrium with free electrons
1s-population
„freeze out“
electron fraction (Recfast)
electron fraction (Saha)
Total number (density) of hydrogen nuclei
(number) density of given species i
N_i / N_H
z
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
400
600
800
1000
1200
1400
1600
1800
2000

3-level Hydrogen Atom and Continuum



Routes to the ground state ?

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

No

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

~ 43%

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

~ 57%

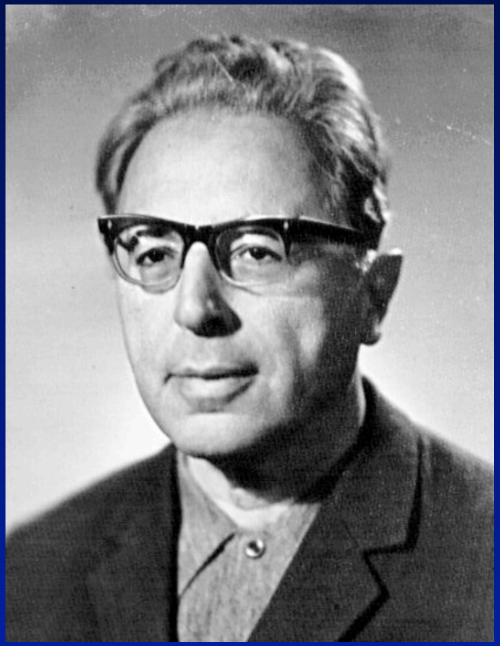
Zeldovich, Kurt & Sunyaev, 1968, ZhETF, 55, 278
Peebles, 1968, ApJ, 153, 1

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

These first computations were completed in 1968!

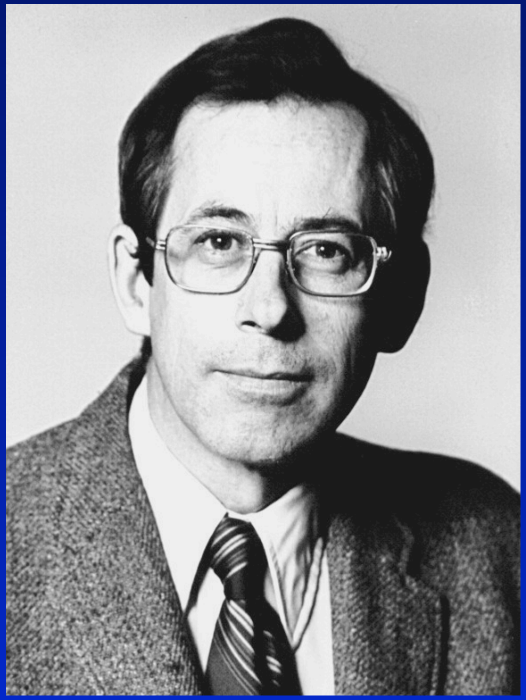
Moscow

Yakov Zeldovich



Iosif Shklovskii

Princeton

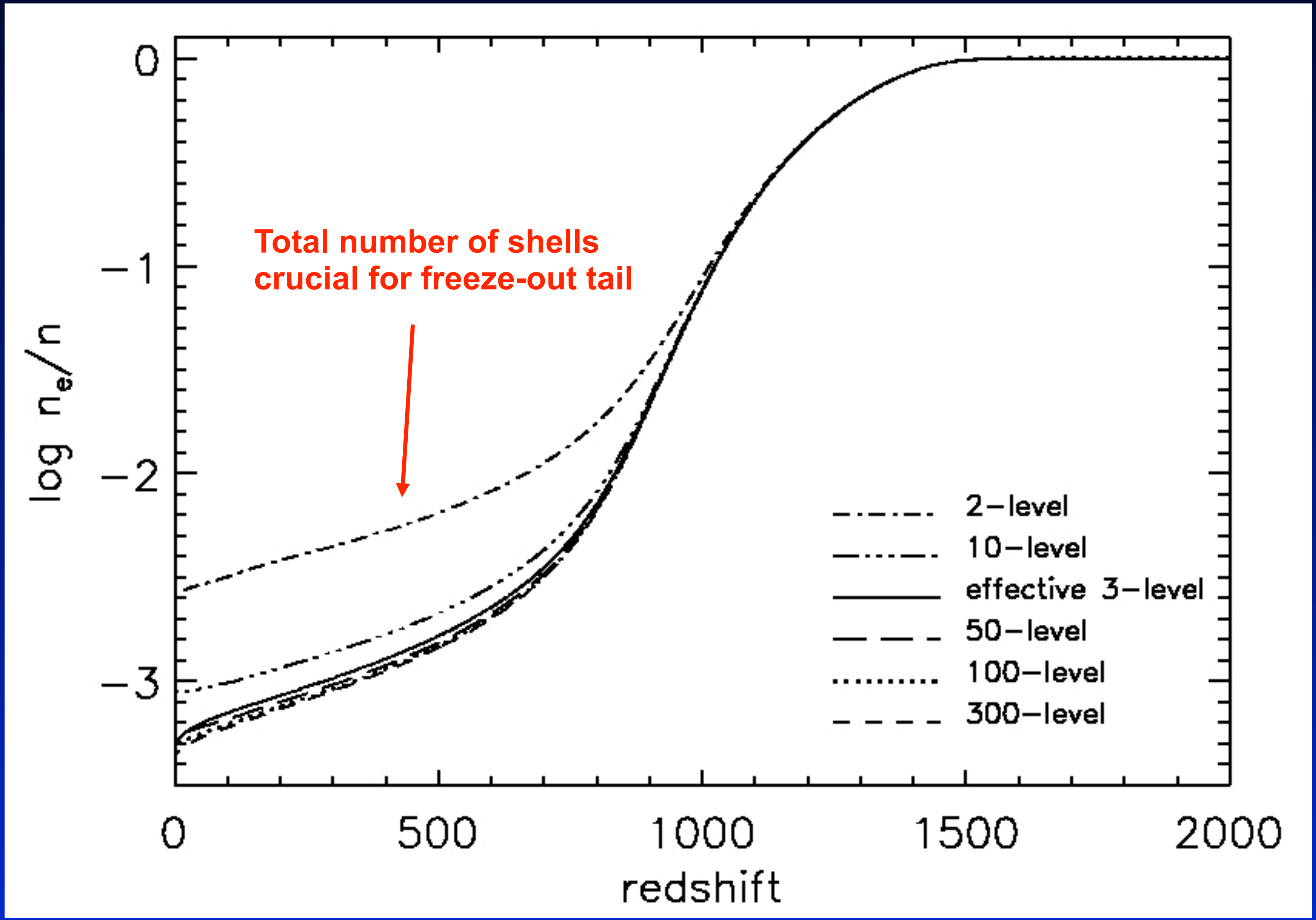


Jim Peebles

Vladimir Kurt
(UV astronomer)

Rashid Sunyaev

Multi-level Atom ⟺ Recfast-Code



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:

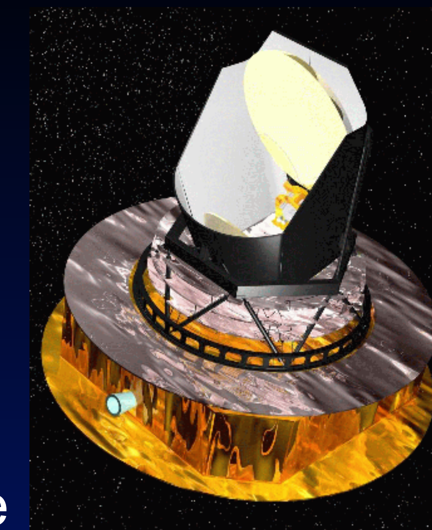
- H chemistry (only at low z)
- cooling of matter (Bremsstrahlung, collisional cooling, line cooling)

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

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

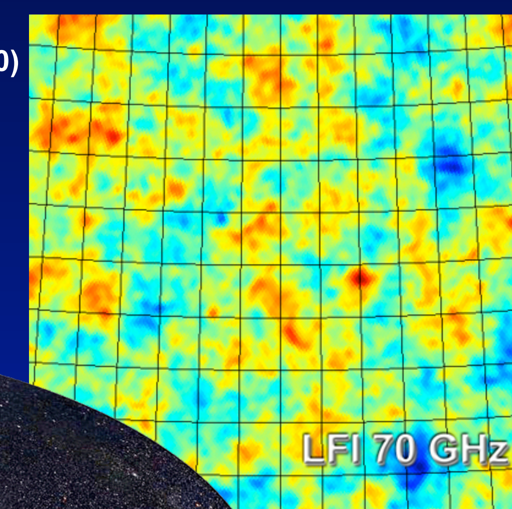
$\Delta N_e \,/\, N_e$ ~ 1% - 3%

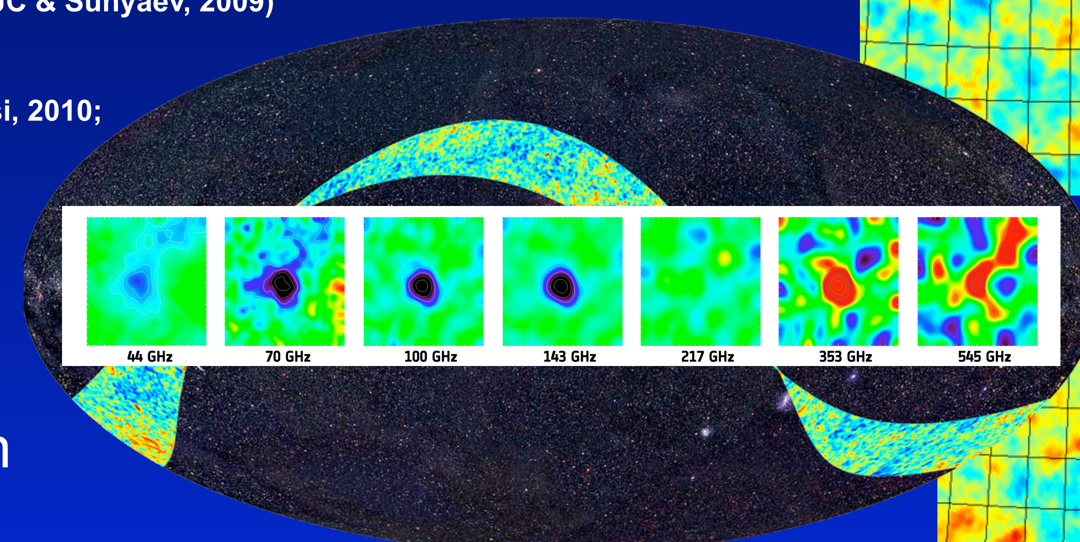
Getting the job done for *Planck*



Hydrogen recombination

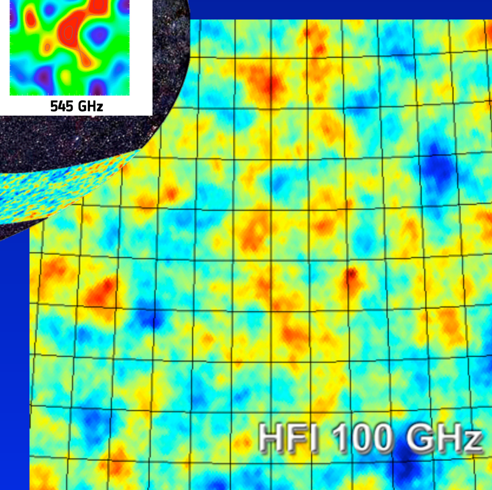
- Two-photon decays from higher levels
  (Dubrovich & Grachev, 2005, Astr. Lett., 31, 359; Wong & Scott, 2007; JC & Sunyaev, 2007; Hirata, 2008; JC & Sunyaev 2009)
- Induced 2s two-photon decay for hydrogen
  (JC & Sunyaev, 2006, A&A, 446, 39; Hirata 2008)
- Feedback of the Lyman-α distortion on the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





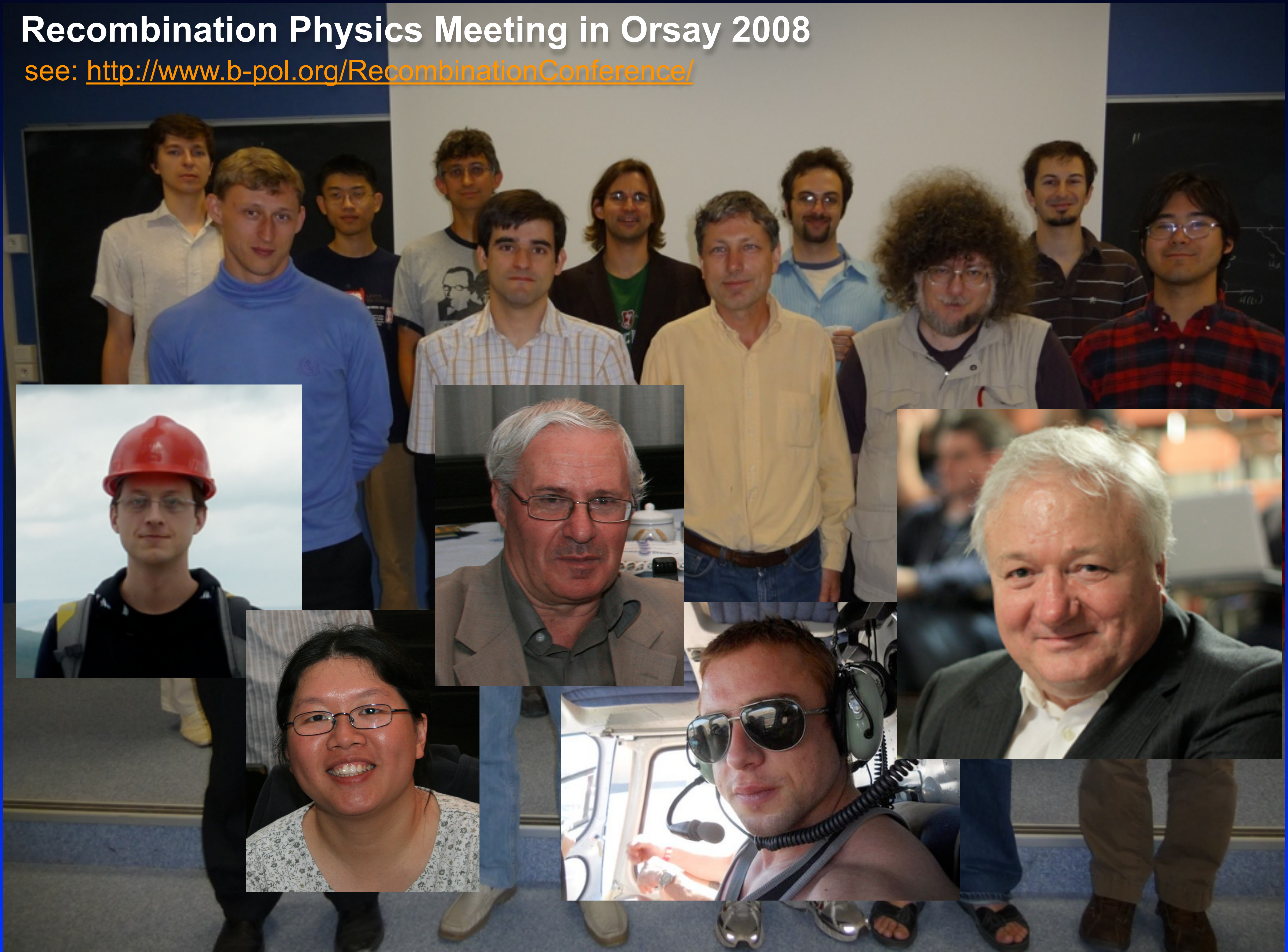
Helium recombination

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



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

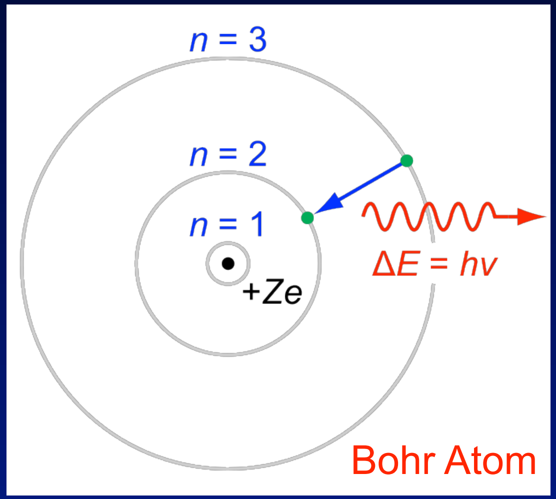
Solving the problem for the *Planck* Collaboration was a common effort!



Atomic Physics Challenges

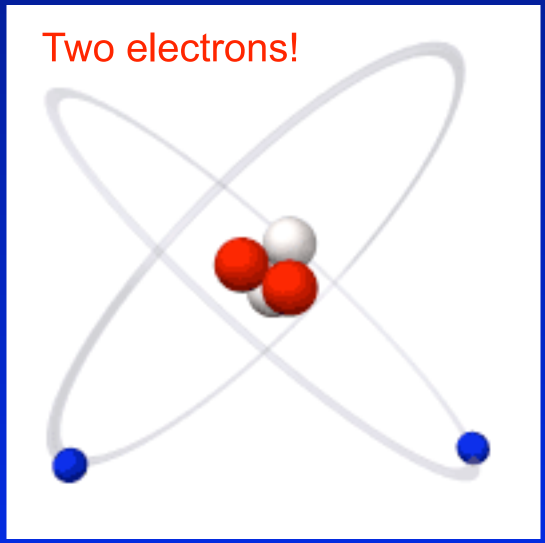
Hydrogen Atom & Hydrogenic Helium

- 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 ($\sim n^2$)

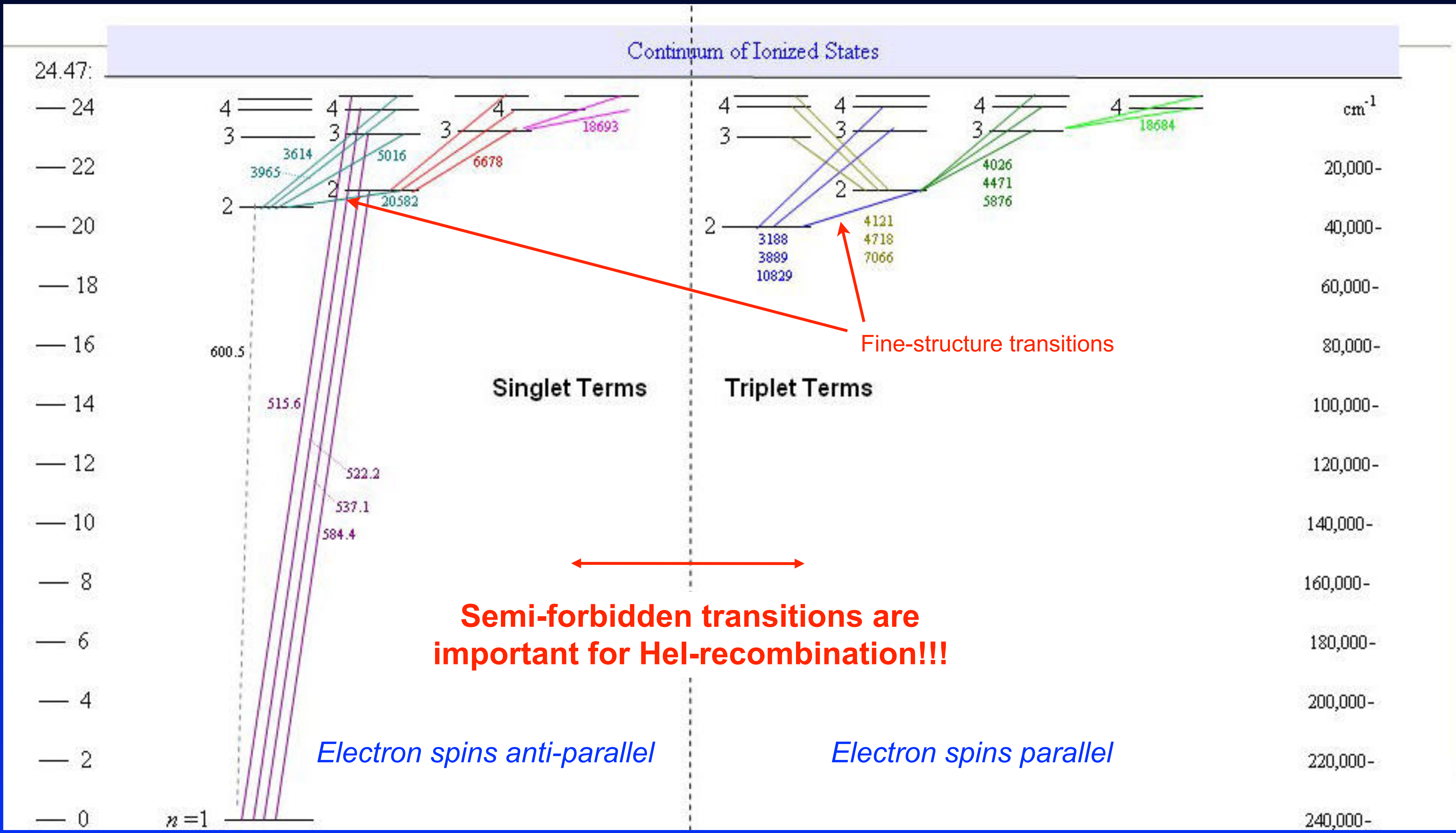


Neutral Helium

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



Grotrian diagram for neutral helium



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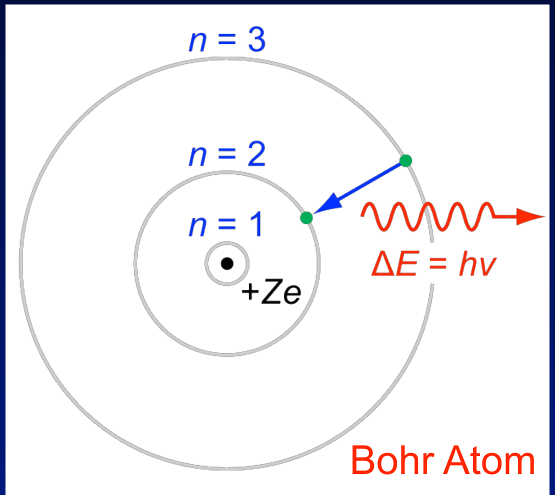
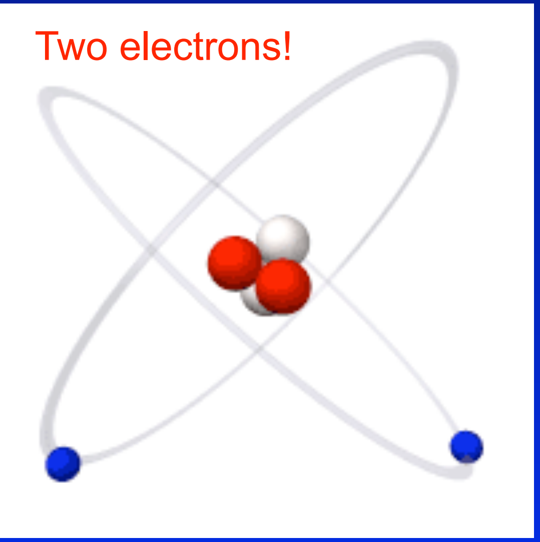
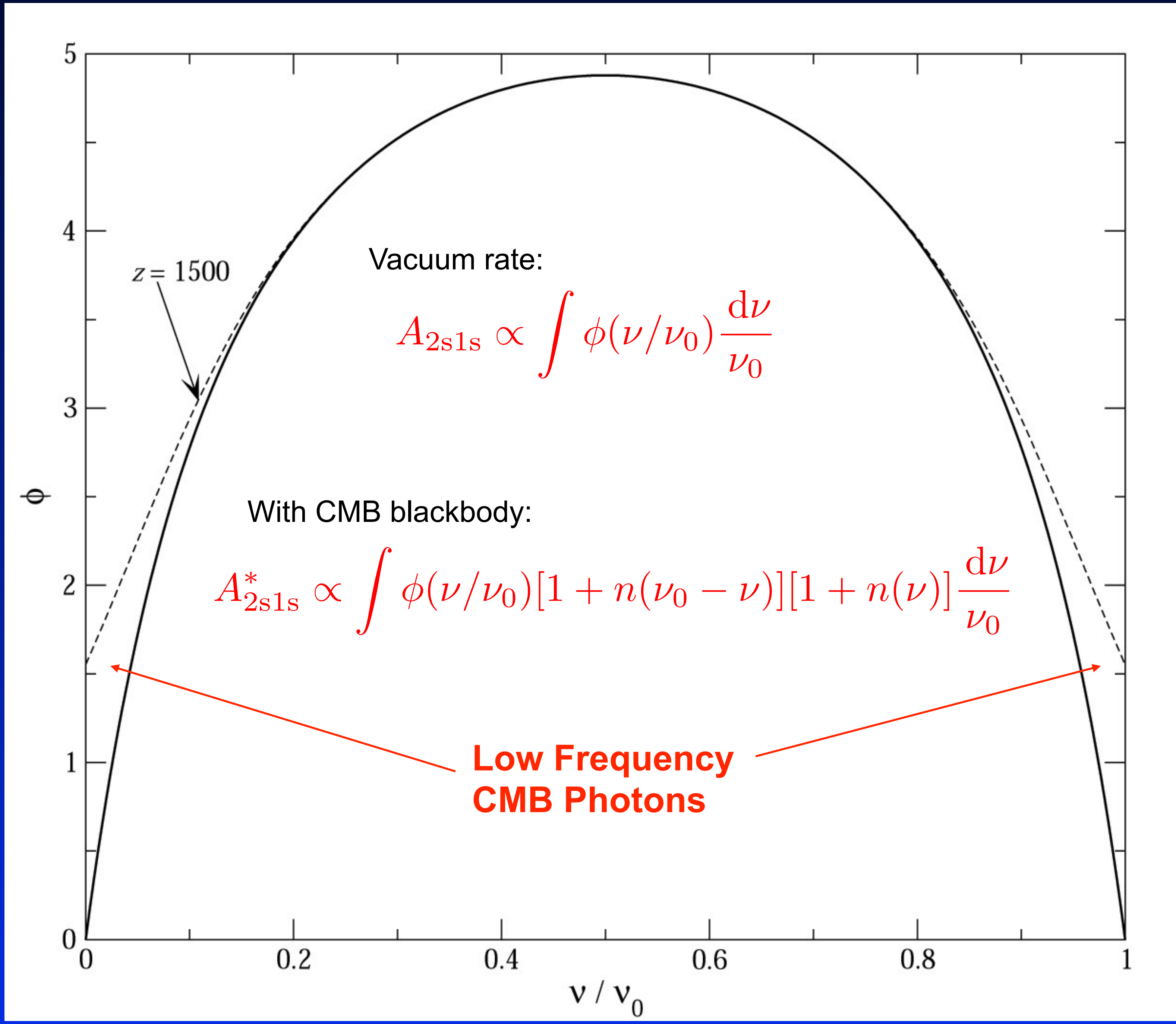


Neutral Helium

- Lower levels non-hydrogenic (perturbative approach needed)
- Spectrum complicated and data (was) rather sparse (e.g., Drake & Morton, 2007)
- Collision rates pretty rough (important for distortions...)
- Computational challenge because of levels not as demanding to get free electron fraction right (not true for spectrum…)



Stimulated 2s →1s decay



2s-1s emission profile

Transition rate in vacuum

→ A_{2s1s}~ 8.22 sec^{-1}

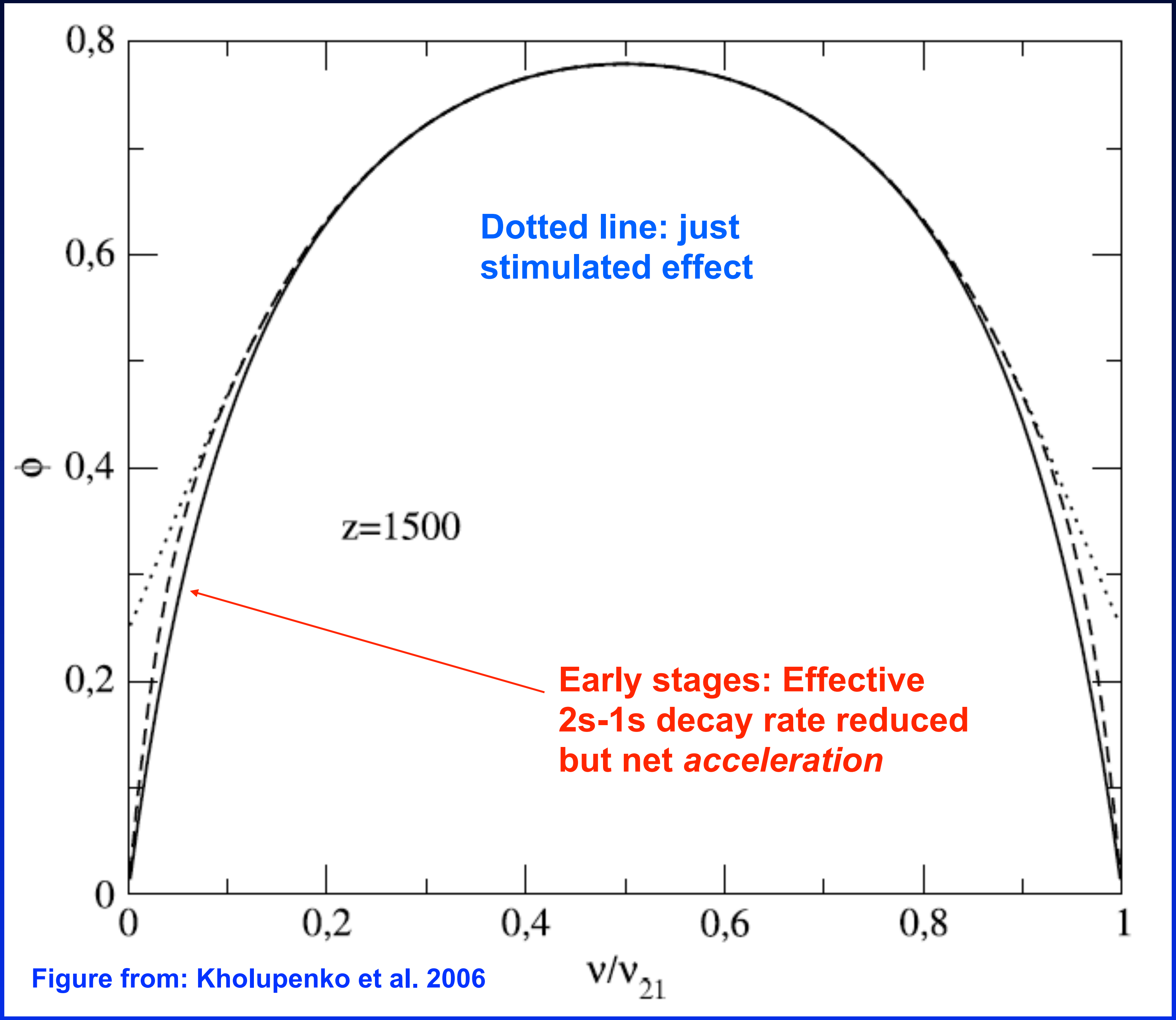
CMB ambient photons field

→ A_{2s1s} increased by ~1%-2%

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

JC & Sunyaev, 2006, A&A

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



- 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

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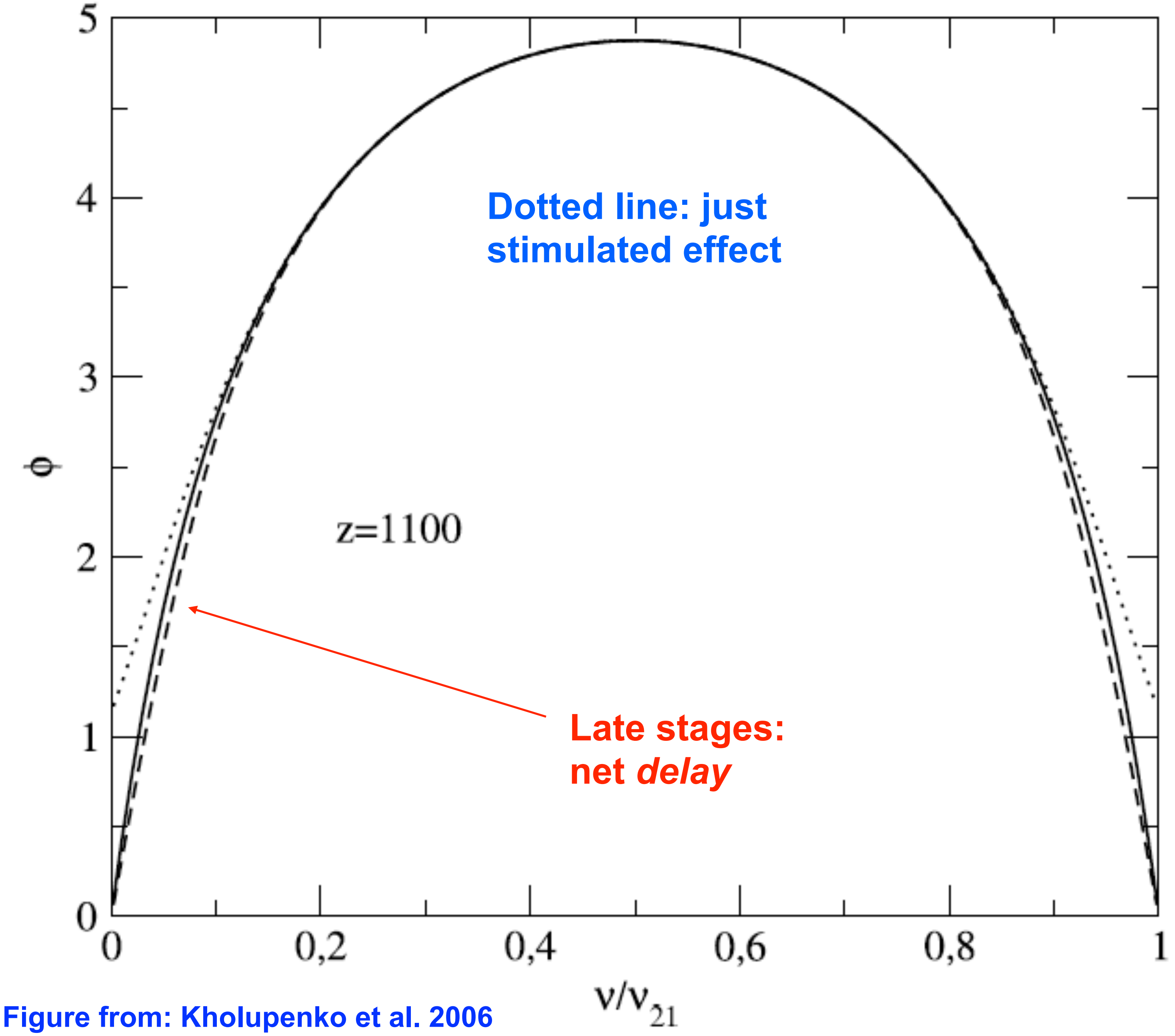

Figure from: Kholupenko et al. 2006

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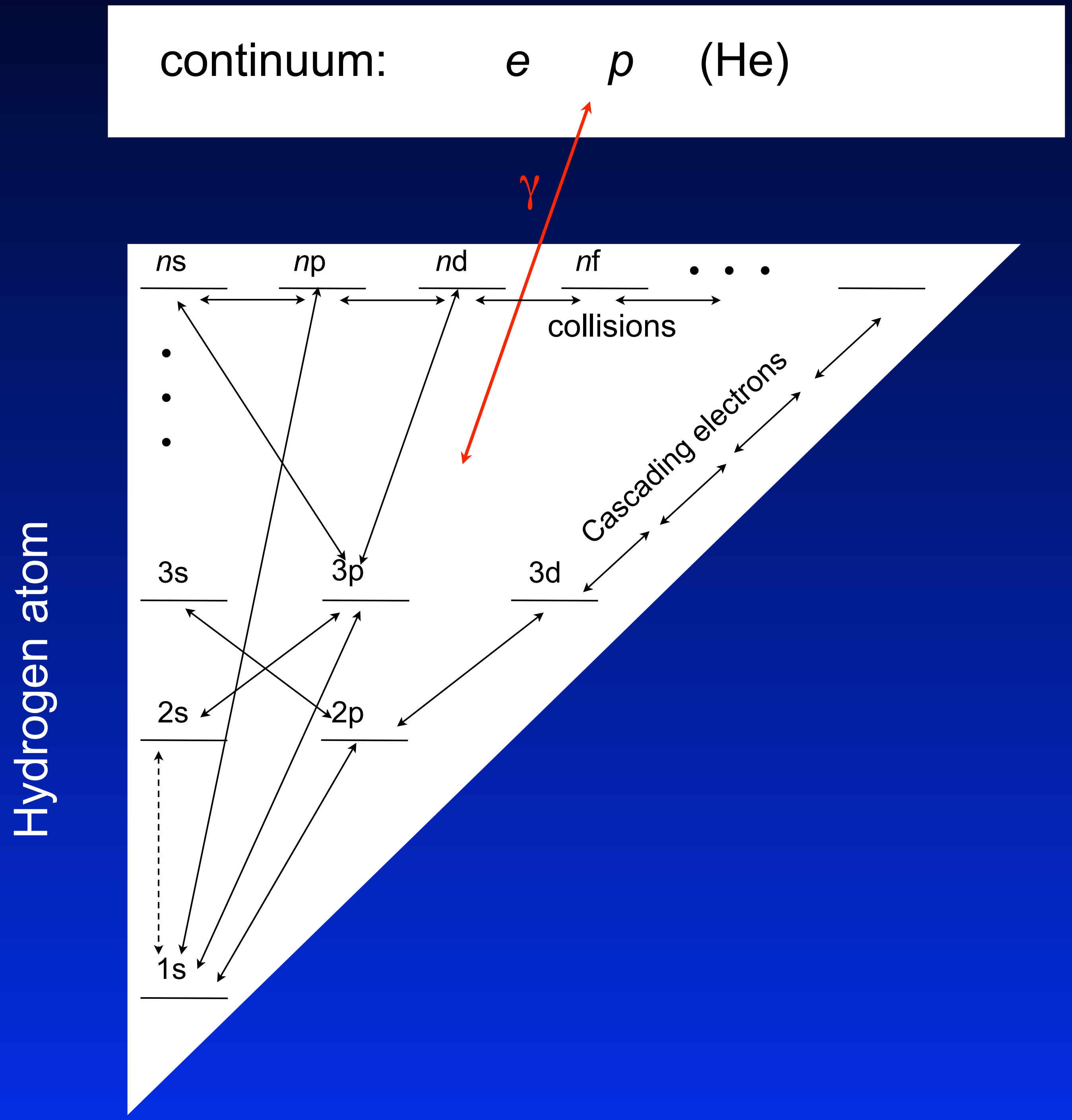
Deviations from Statistical Equilibrium in the upper levels

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

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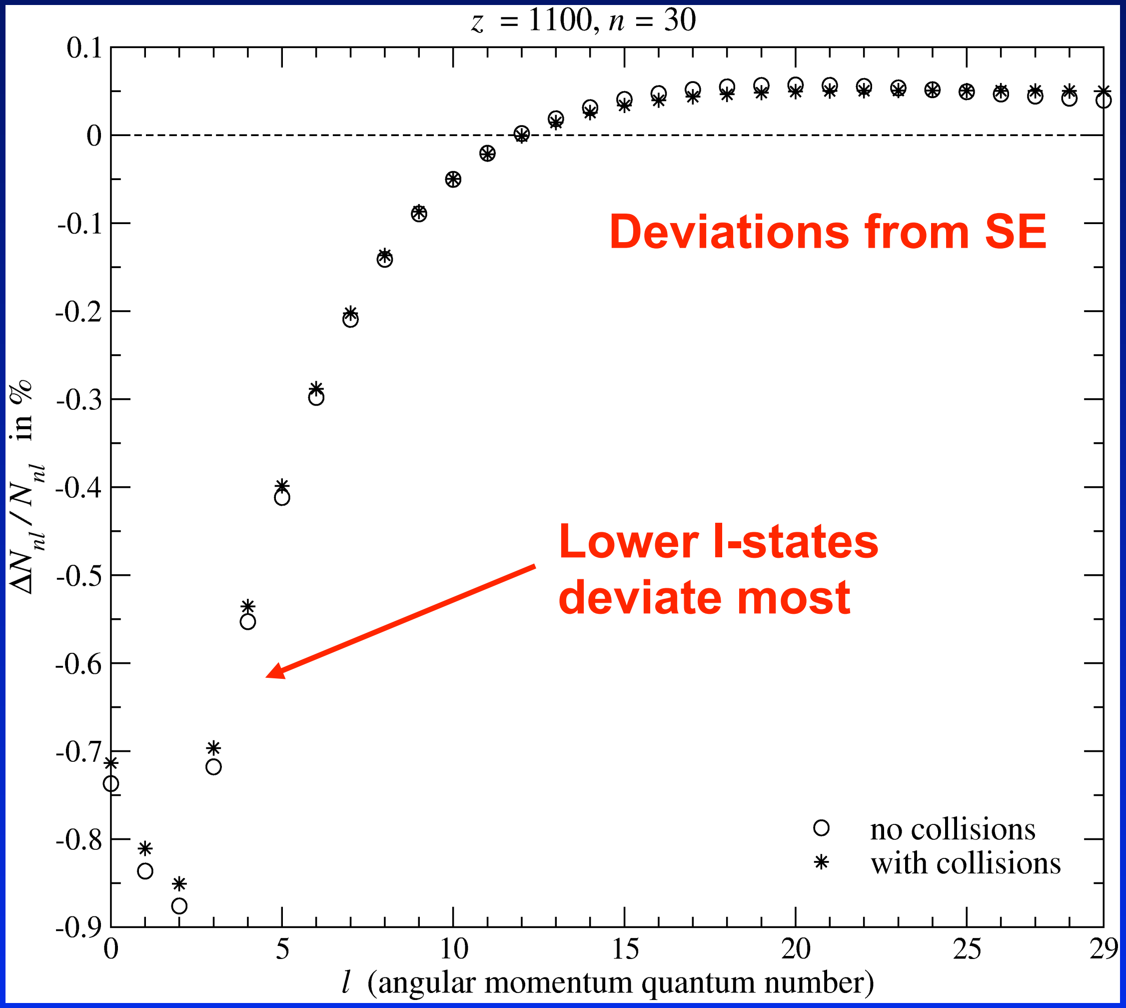

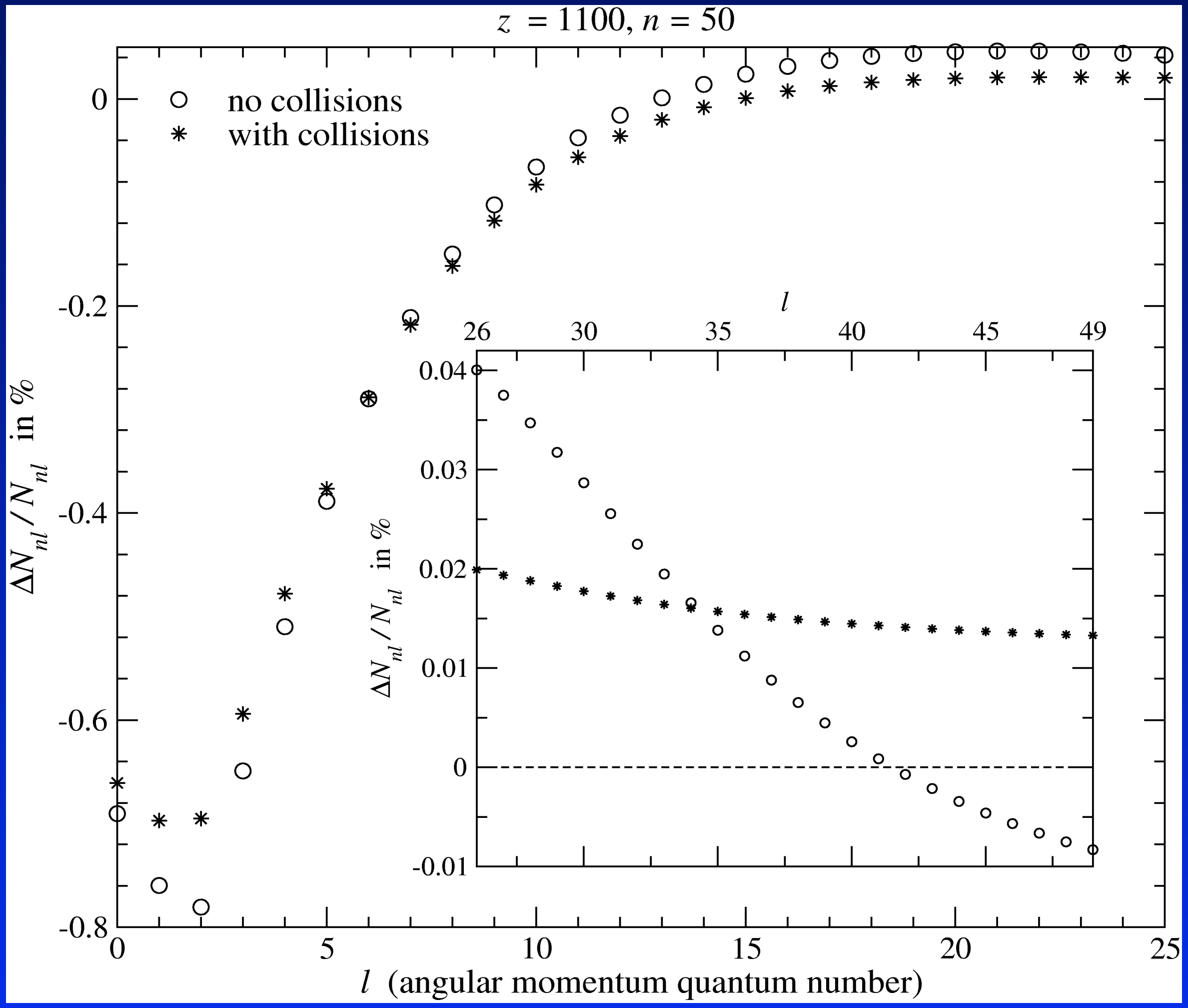

JC, Rubino-Martin & Sunyaev, MNRAS, 2007

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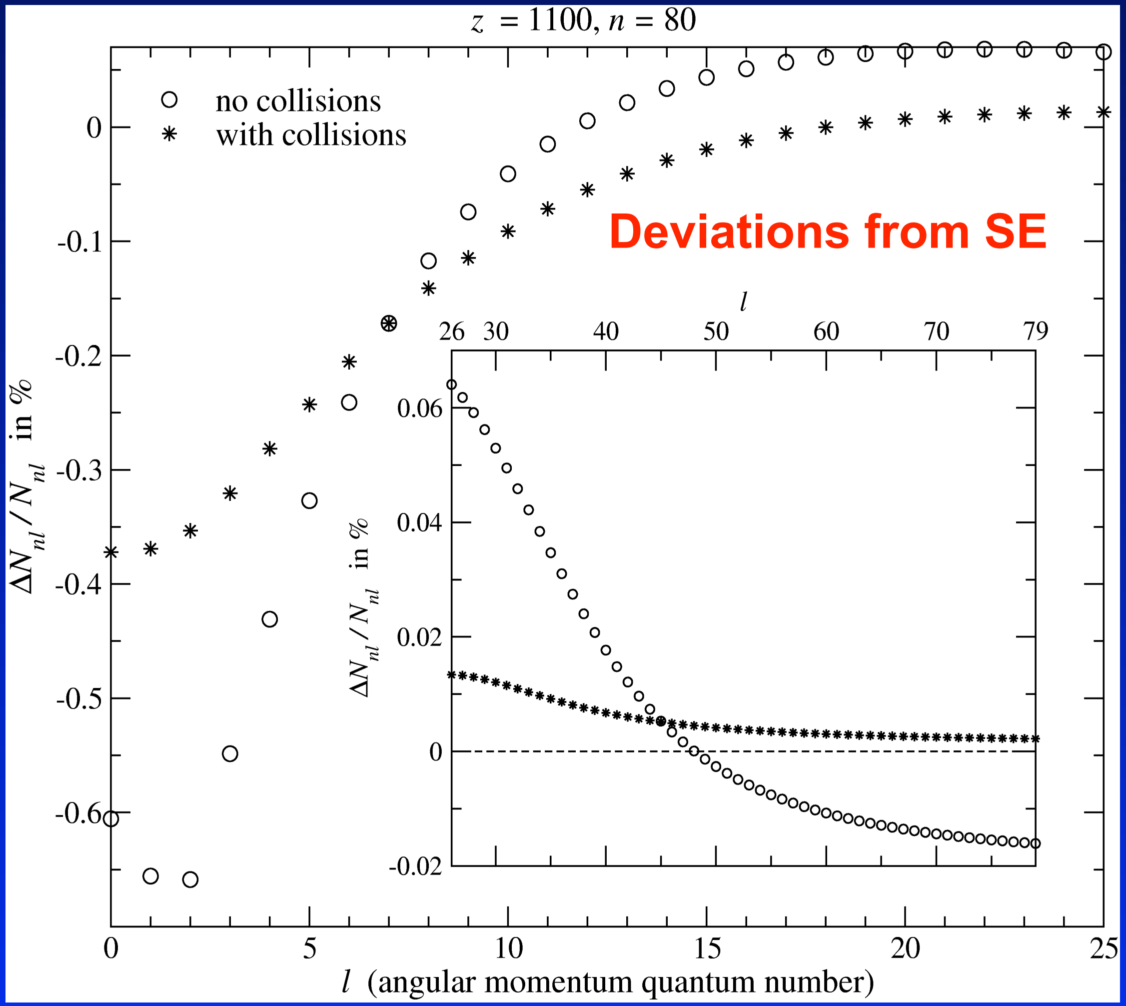

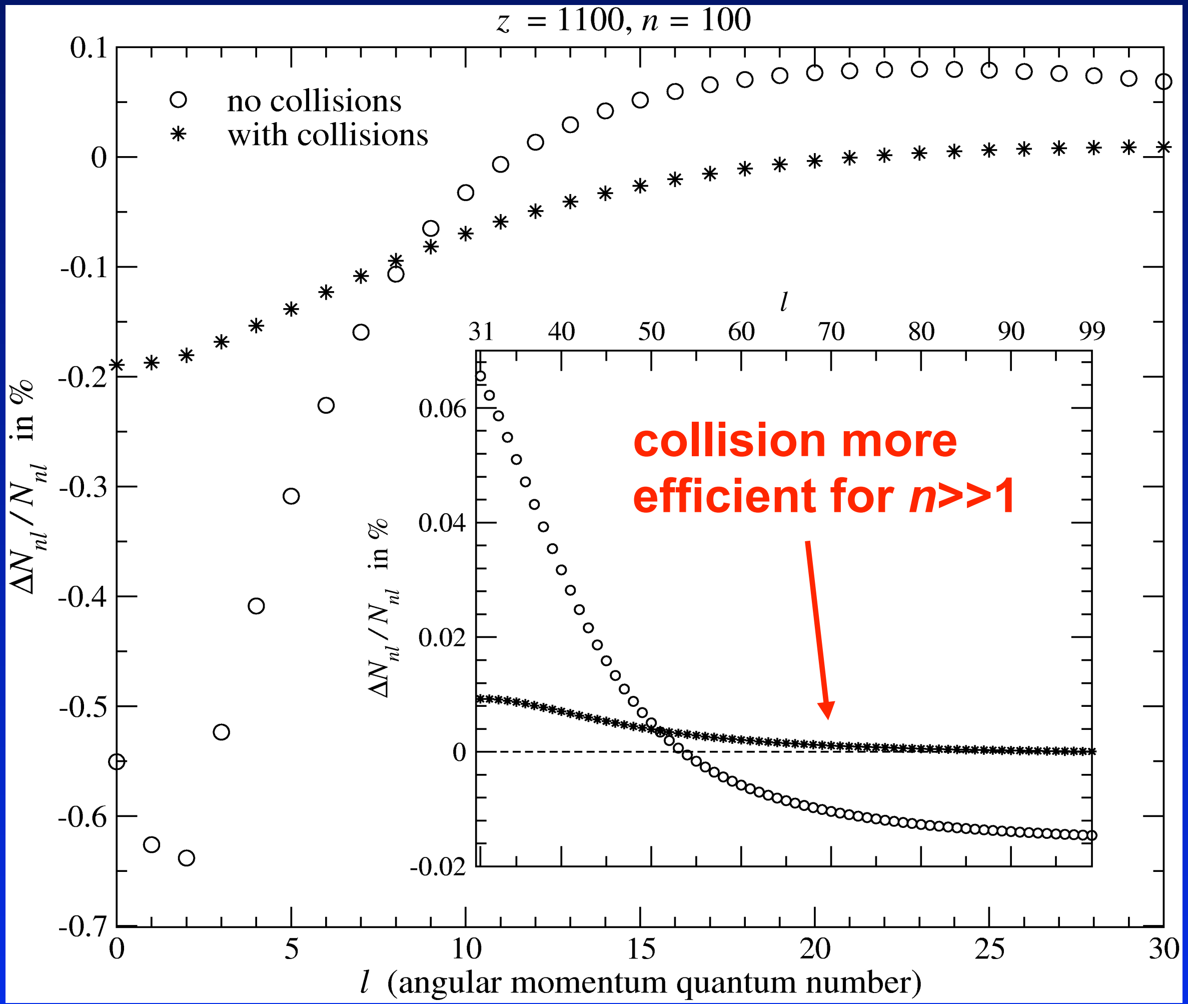

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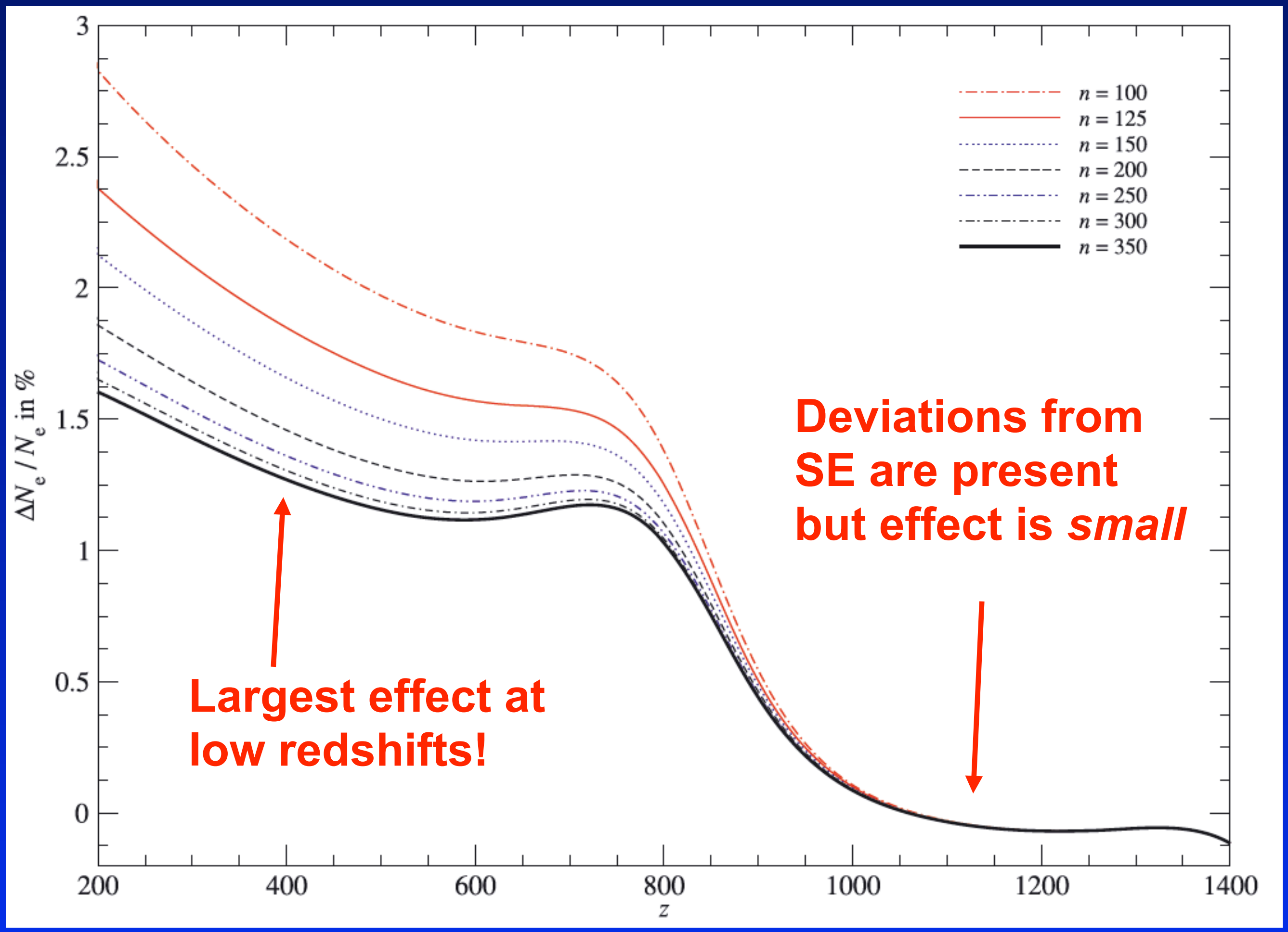
Refined computation

(JC, Rubino-Martin & Sunyaev, 2007)

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

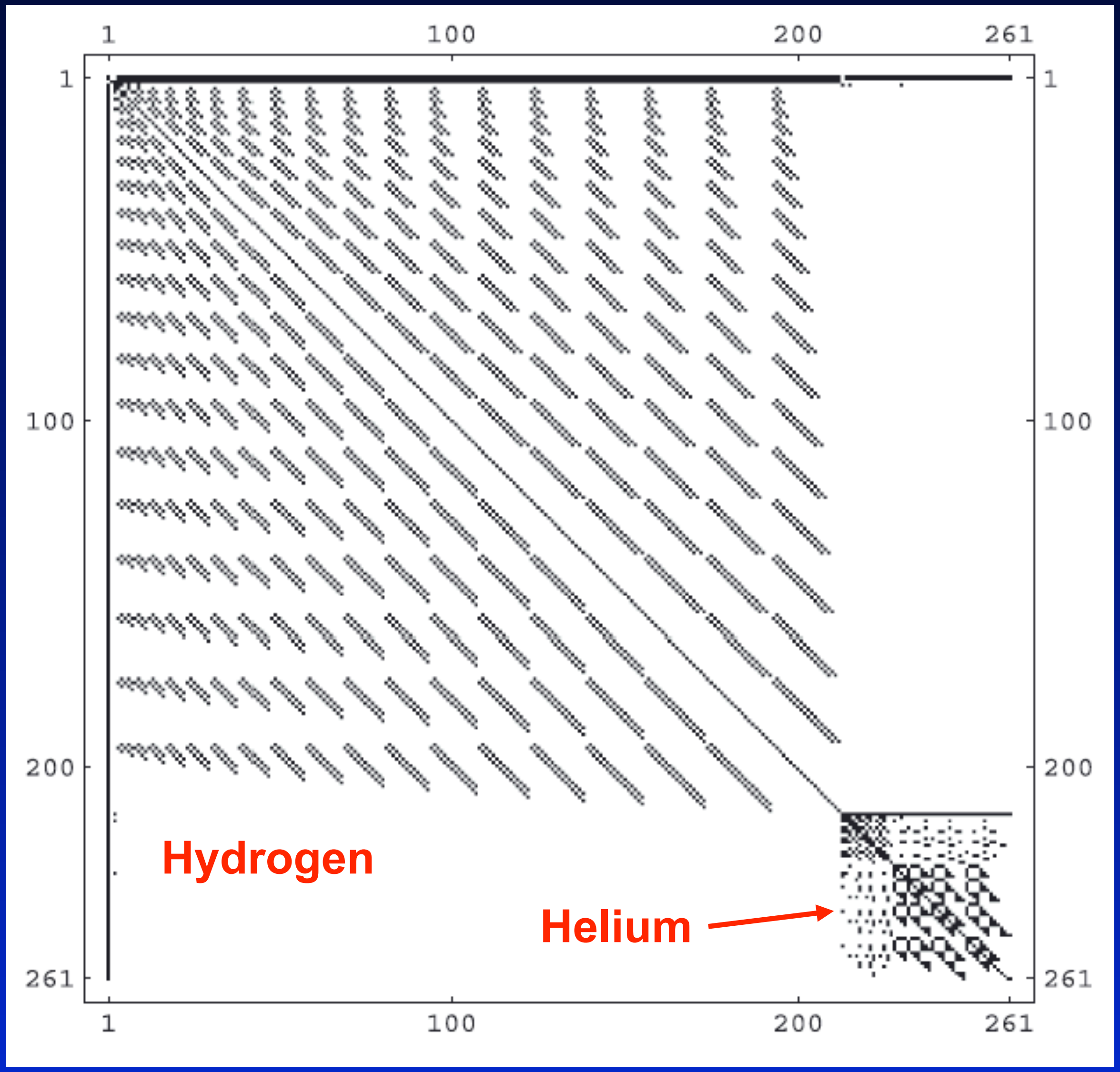
(Grin & Hirata, 2010; JC, Vasil & Dursi, 2010)

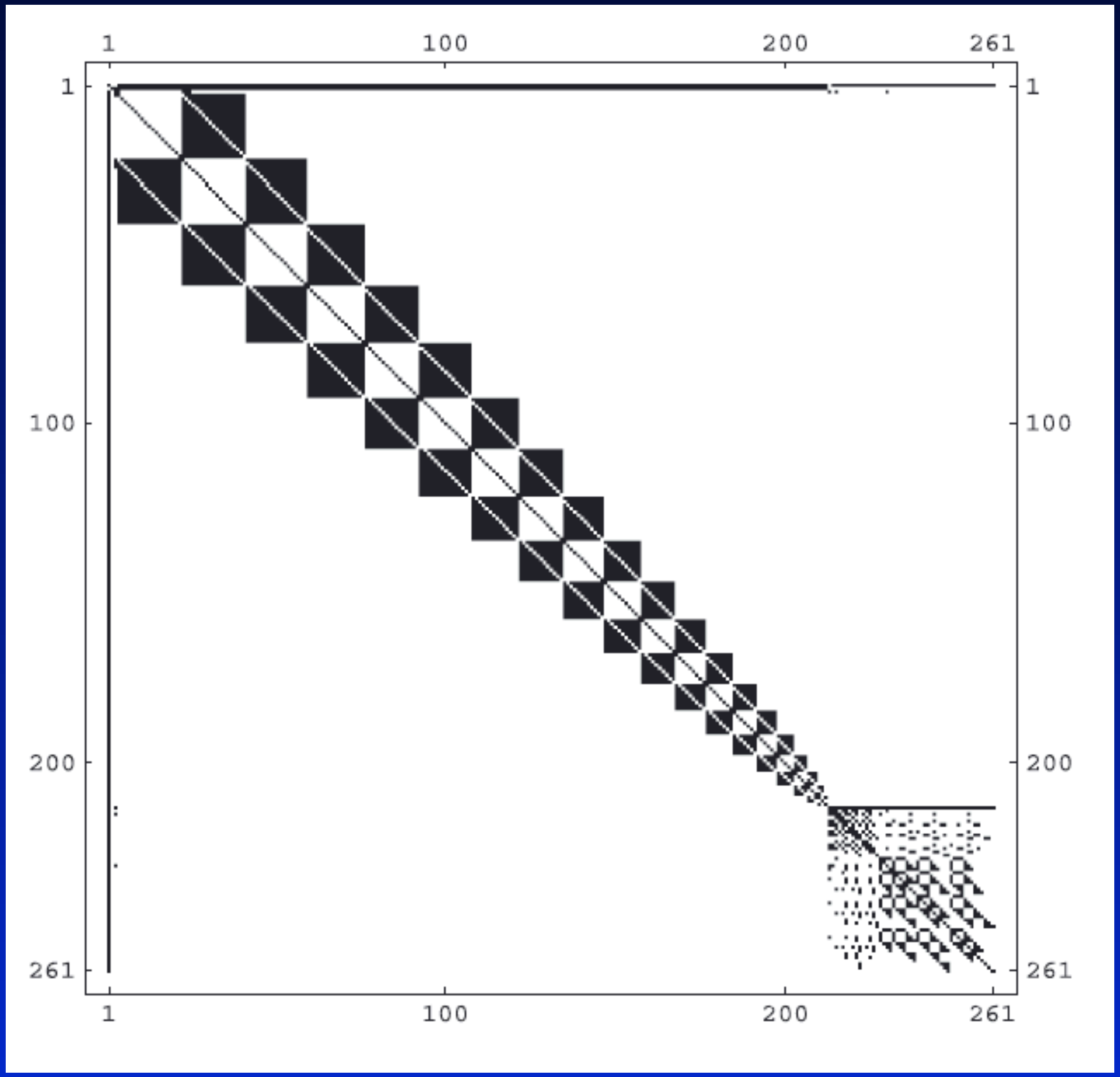


JC, Vasil & Dursi, MNRAS, 2010

Sparsity of the problem and effect of ordering

20 shell Hydrogen + 5 shell Helium model





Shell-by-Shell ordering

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

Angular momentum ordering

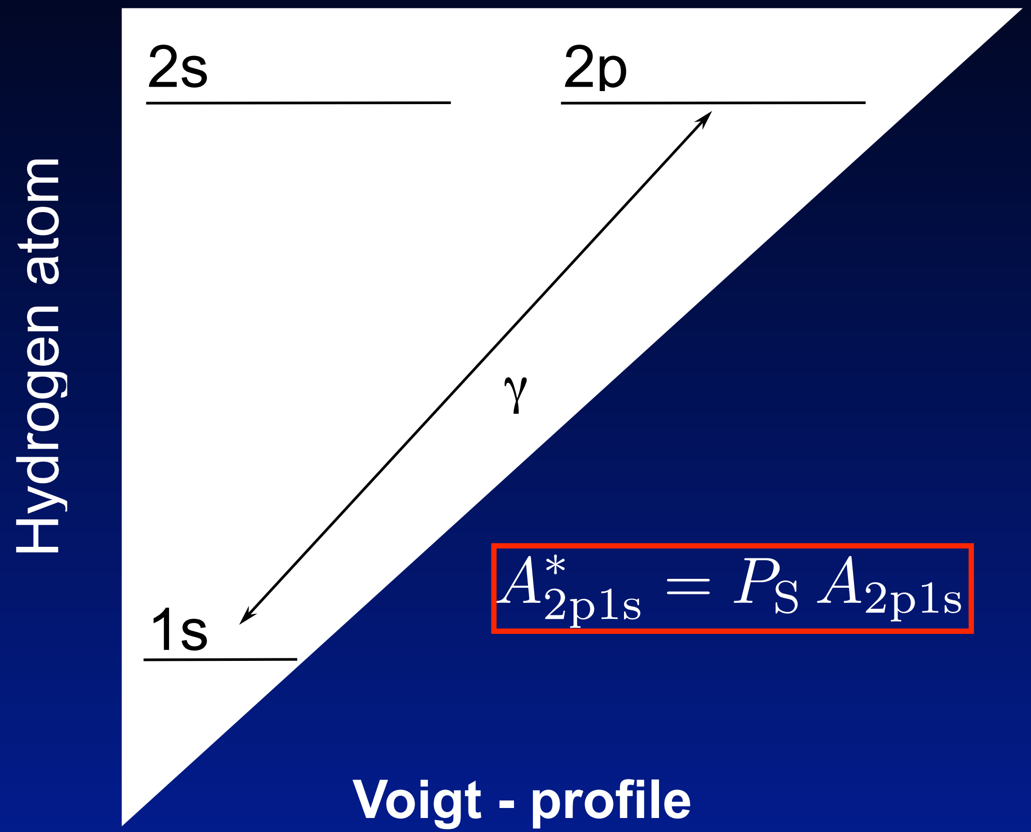
$$1s, 2s, 3s, \ldots, ns, 2s, 3p, \ldots, np, 3d, 4d, ...$$

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

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)



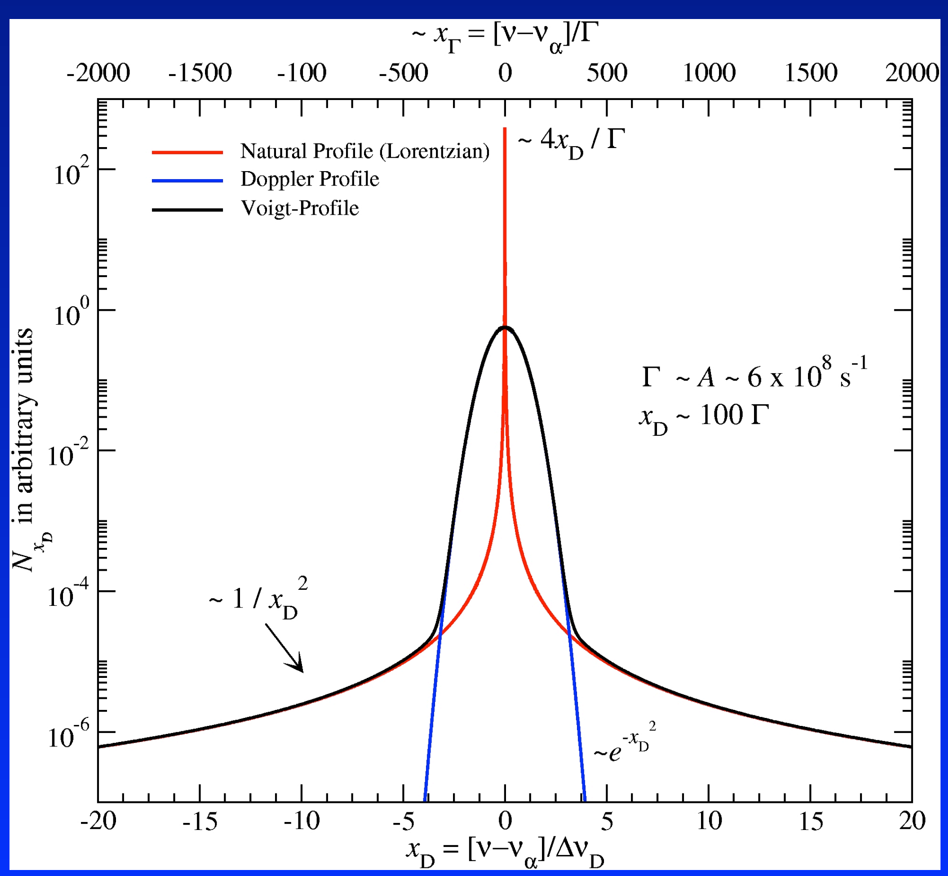
- To solve the coupled system of rate-equations

  → 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*

Voigt - profile



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

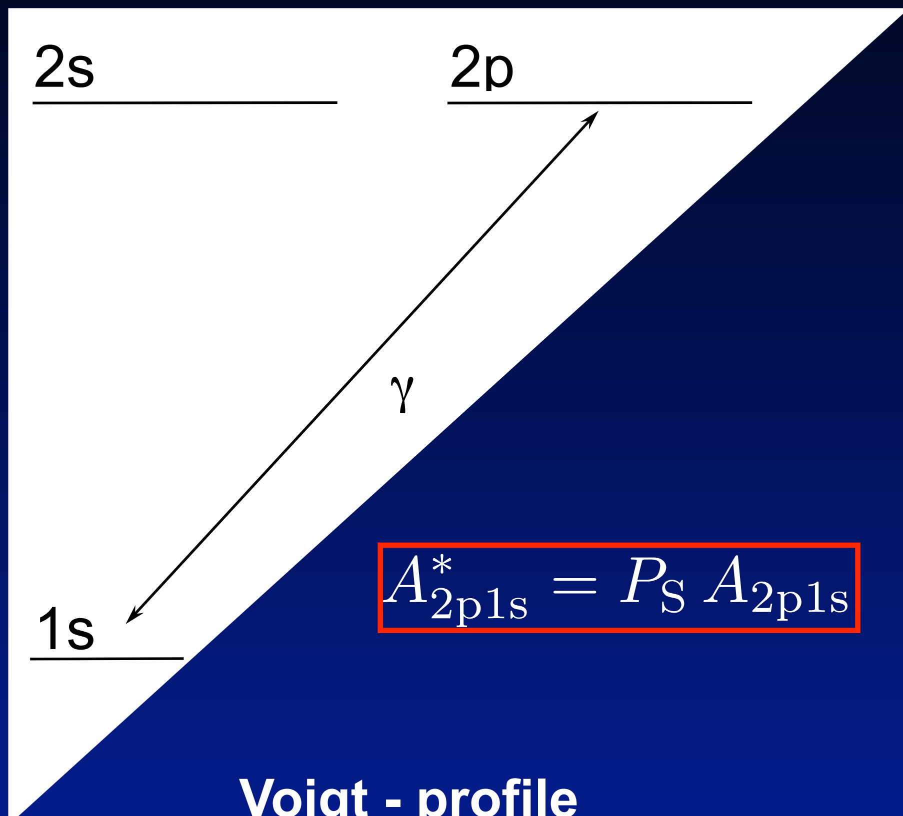
Doppler width

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

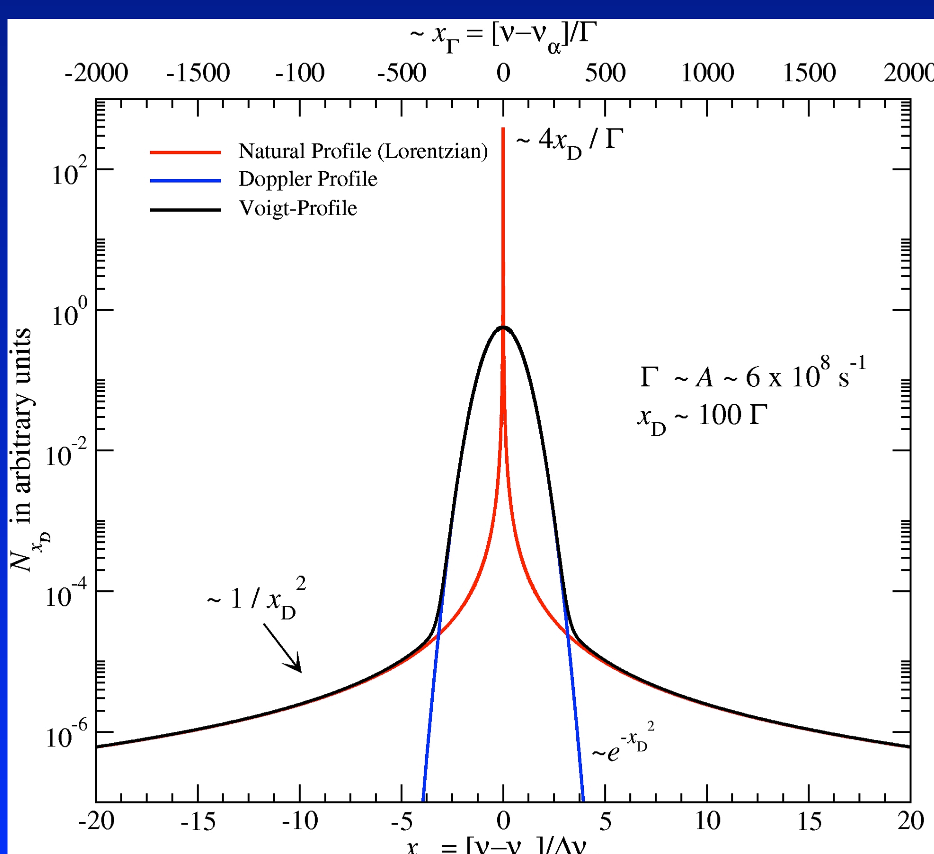
Sobolev approximation

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

Hydrogen atom



Voigt - profile



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

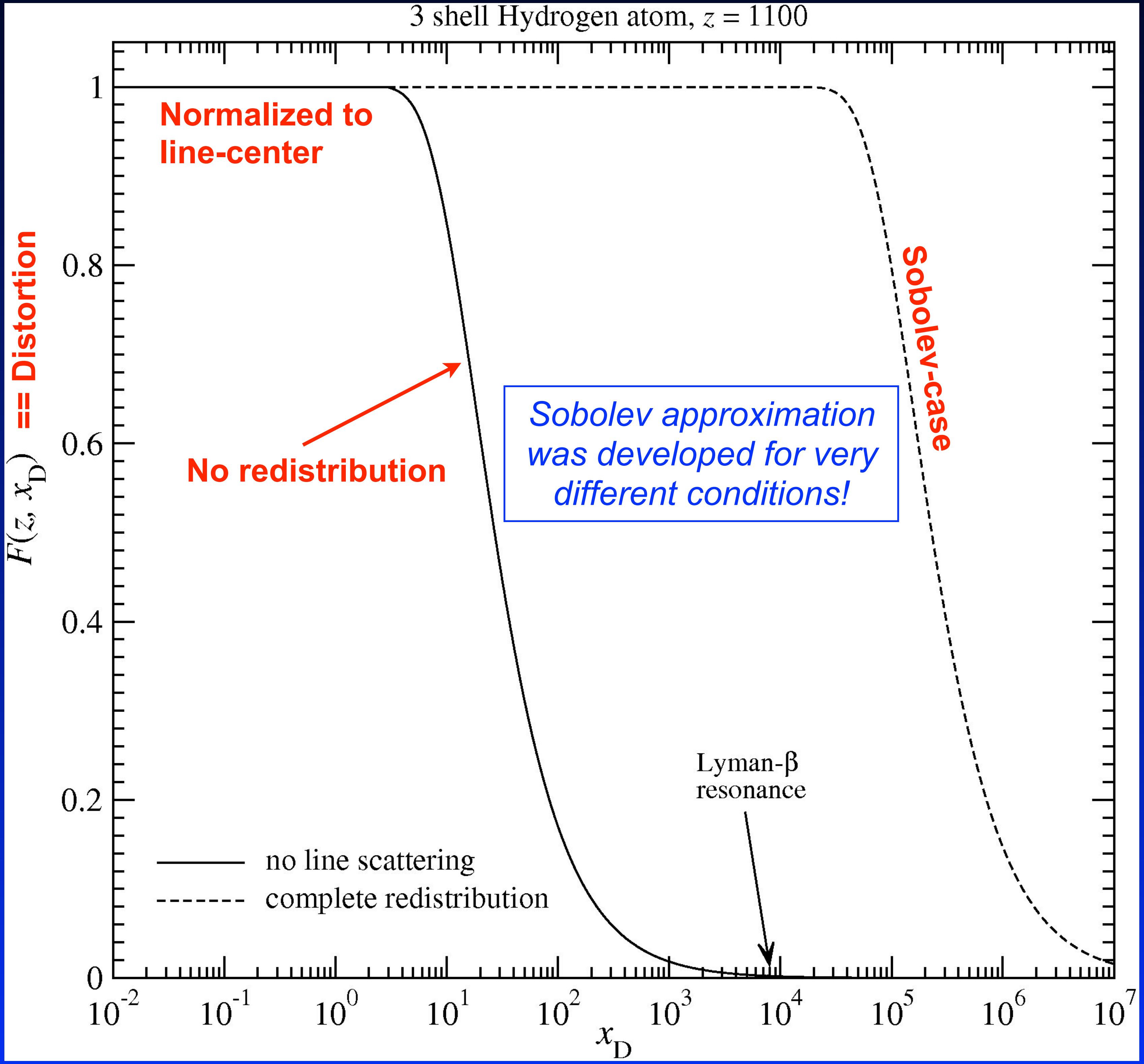
- Sobolev escape probability & optical depth

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

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

Problems with Sobolev approximation:

Complete redistribution ⟺ partial redistribution



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})

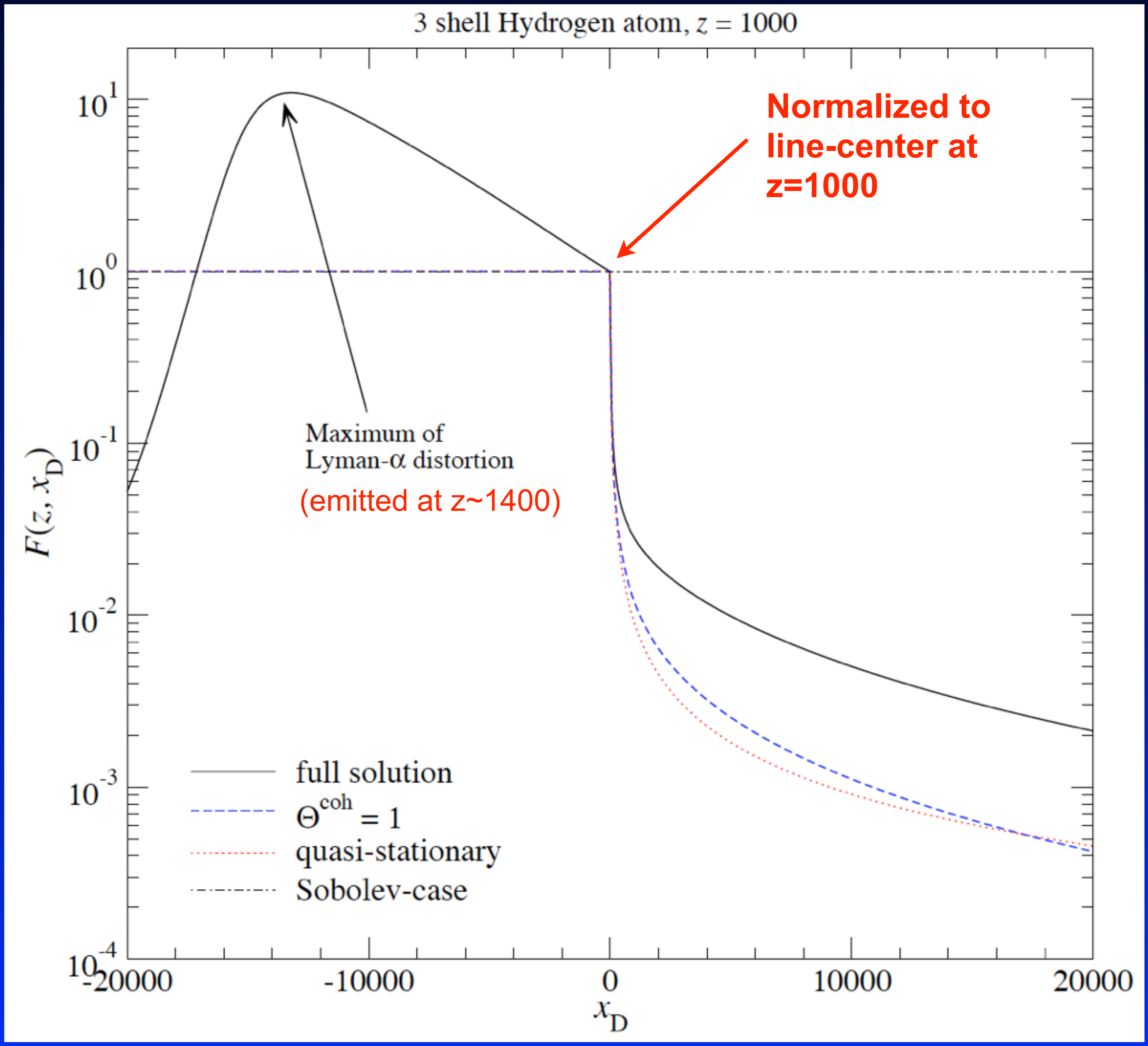
No redistribution case:

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

JC & Sunyaev, 2009

Problems with Sobolev approximation:

Time dependence of radiation field



- 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

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

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

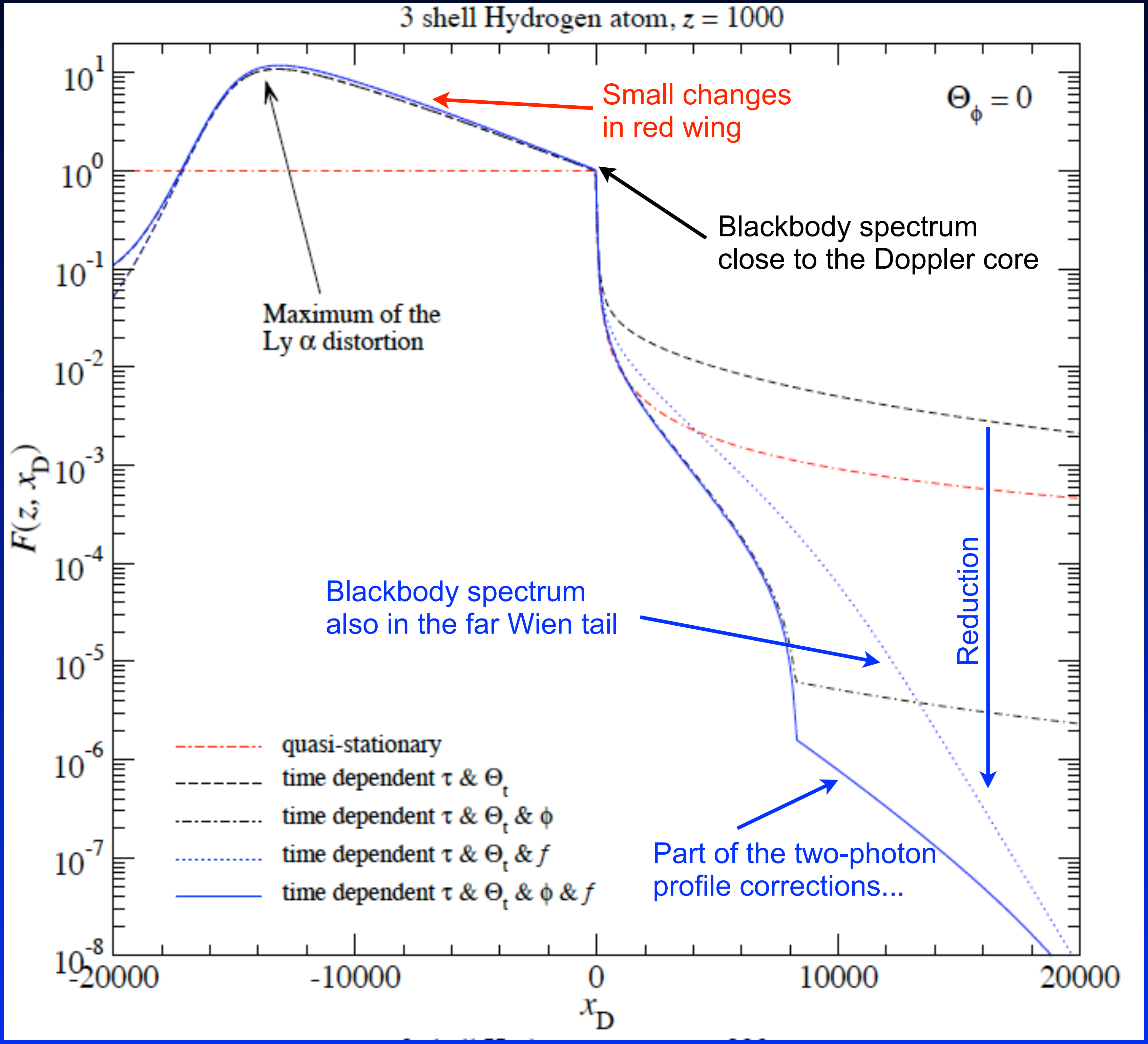
$$\Rightarrow \frac{1}{c}\frac{\mathrm{d}N_\nu}{\mathrm{d}t}\bigg|_{\mathrm{Ly}-\alpha} = A_{21}\frac{g_{2\mathrm{p}}}{g_{1\mathrm{s}}}N_{1\mathrm{s}}\,\phi(\nu)(1+n_\nu)\left[\frac{g_{1\mathrm{s}}N_{2\mathrm{p}}}{g_{2\mathrm{p}}N_{1\mathrm{s}}} - \mathrm{e}^{\frac{h(\nu-\nu_{21})}{kT_\gamma}}\frac{n_\nu}{1+n_\nu}\right]$$

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



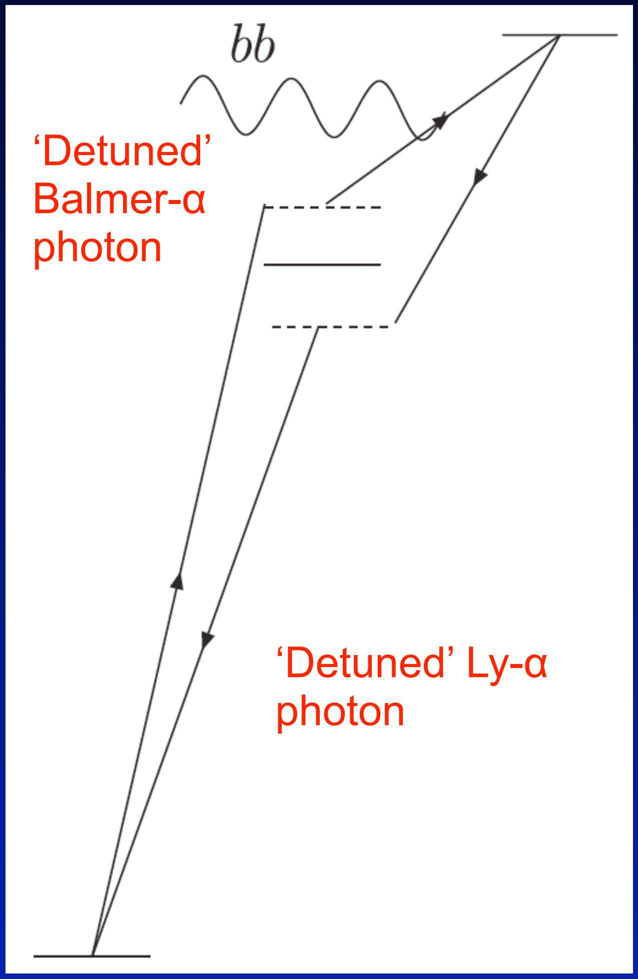
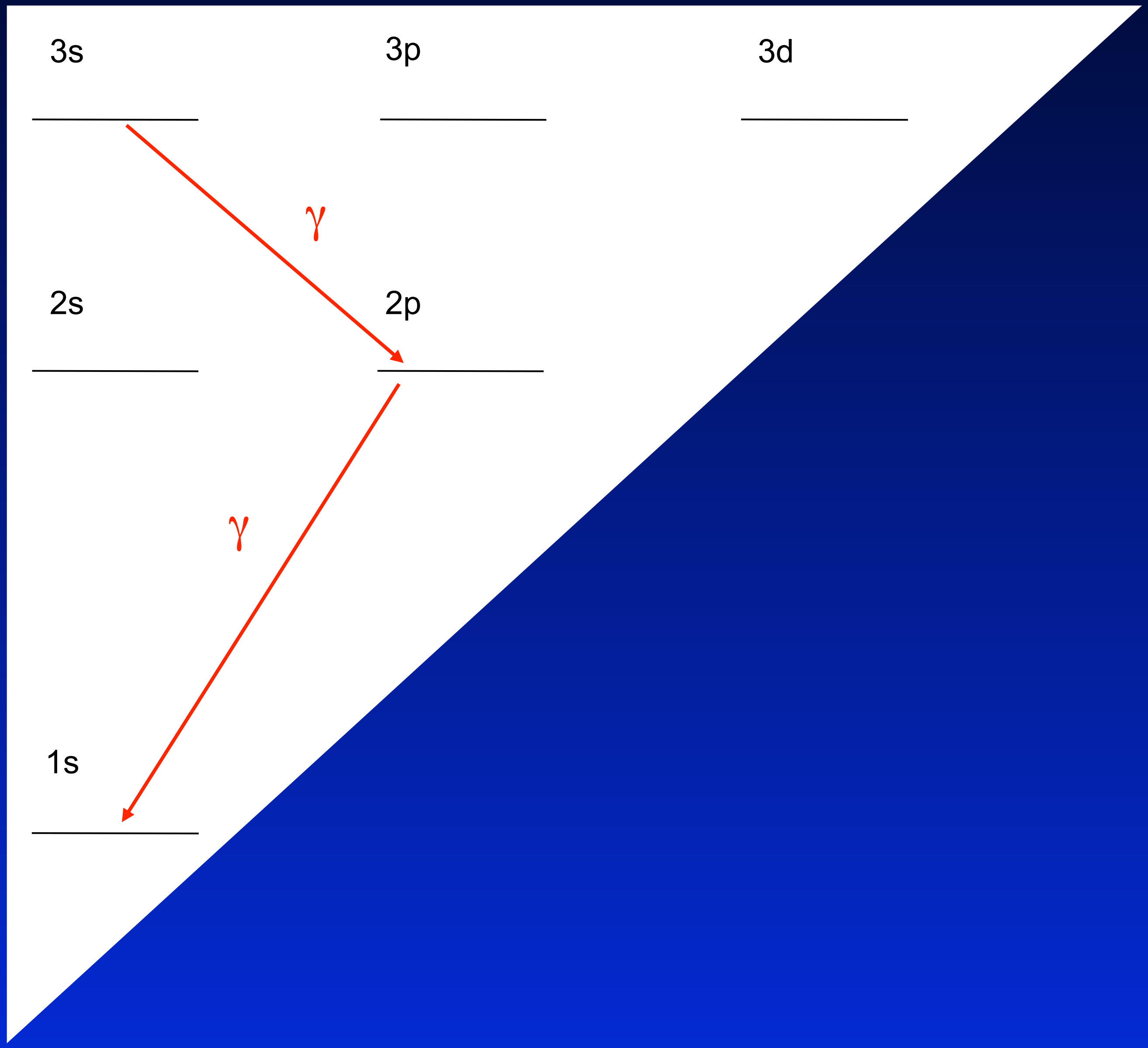


Illustration from Switzer & Hirata 2007 (meant for Helium)

- Real absorption & emission requires a second photon!

JC & Sunyaev, 2009

Two-photon emission profile



Seaton cascade (1+1 photon)

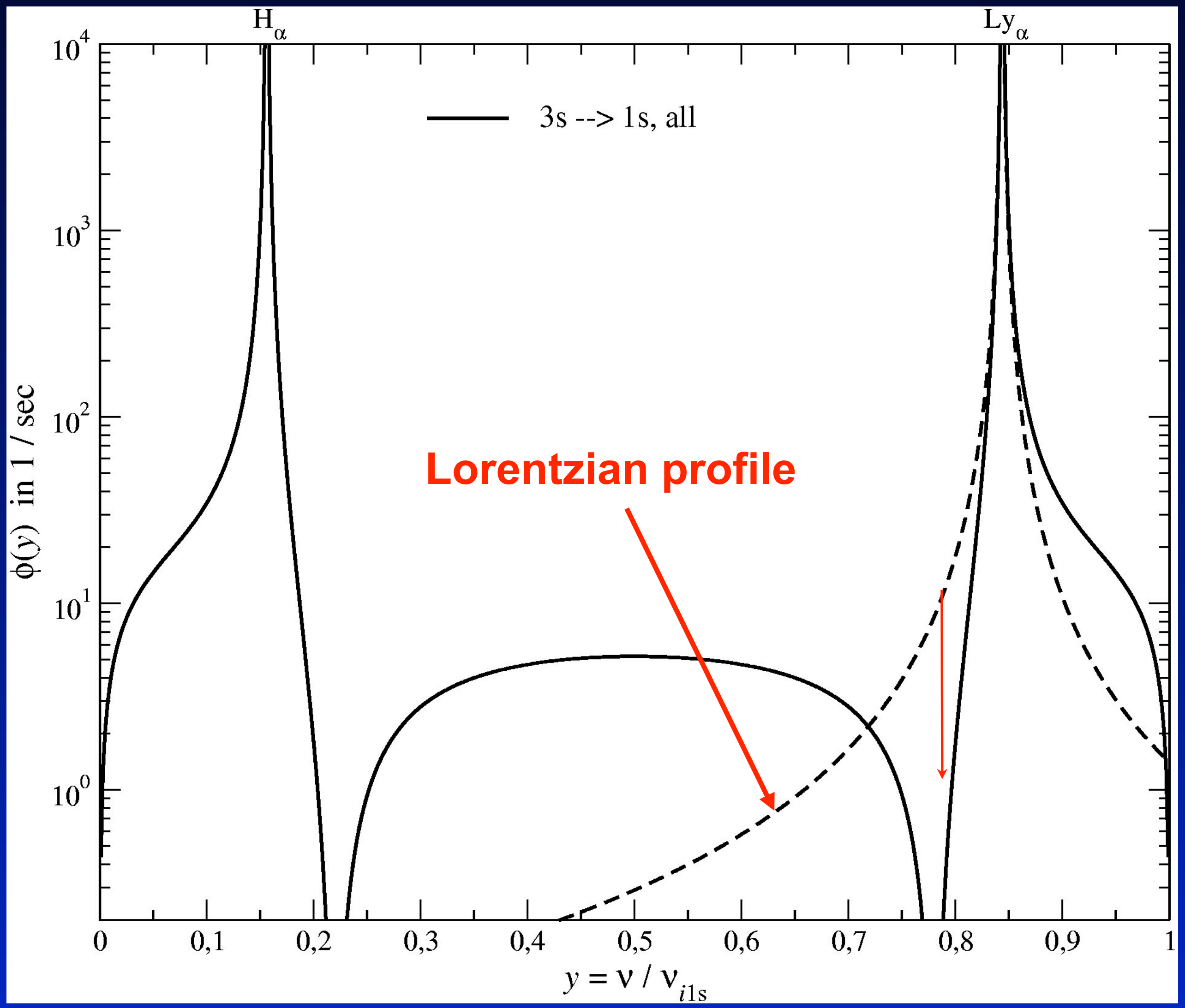
No collisions → two photons (mainly H-α and Ly-α) are emitted!

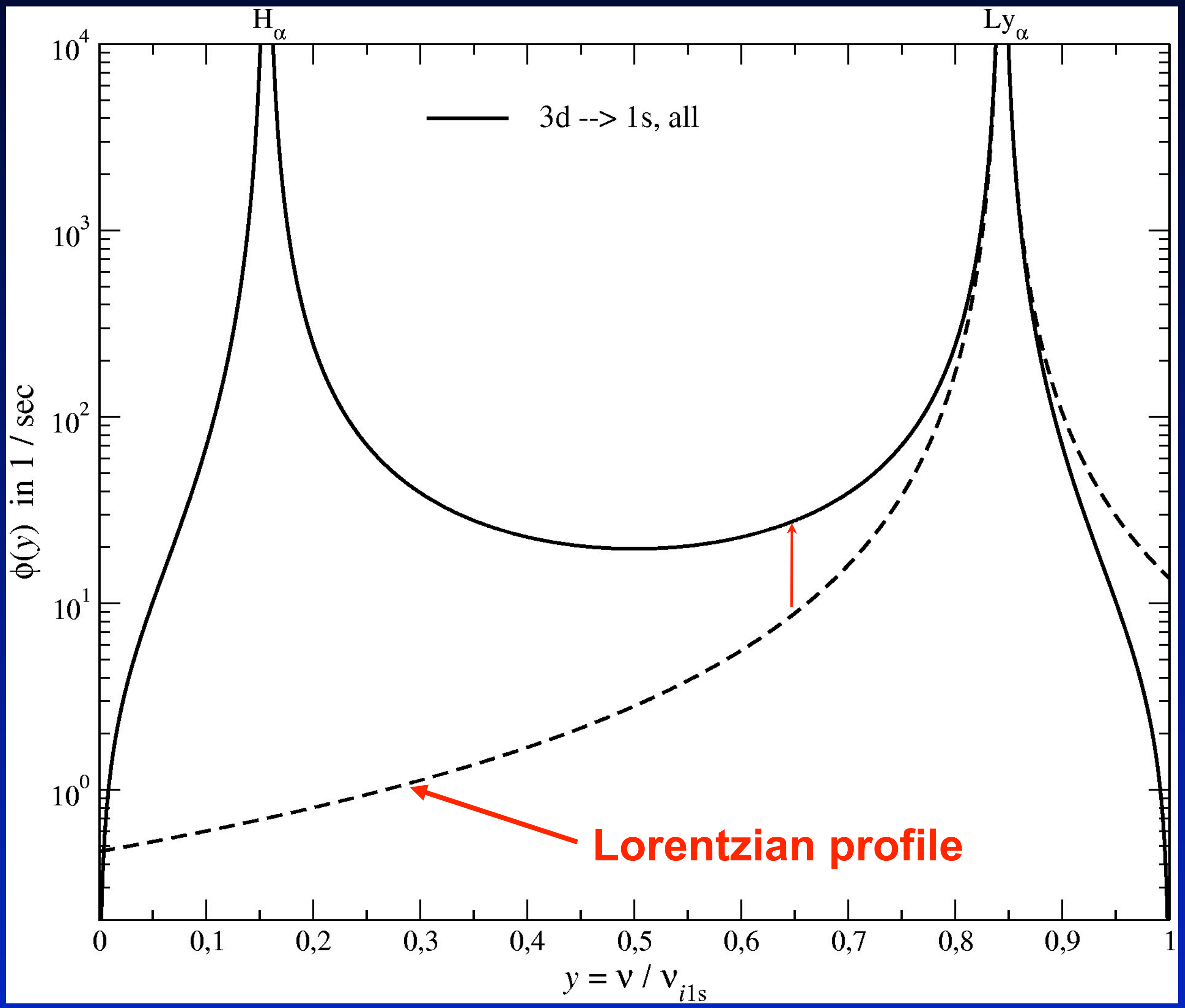
Maria-Göppert-Mayer (1931): description of two-photon emission as single process in Quantum Mechanics

→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





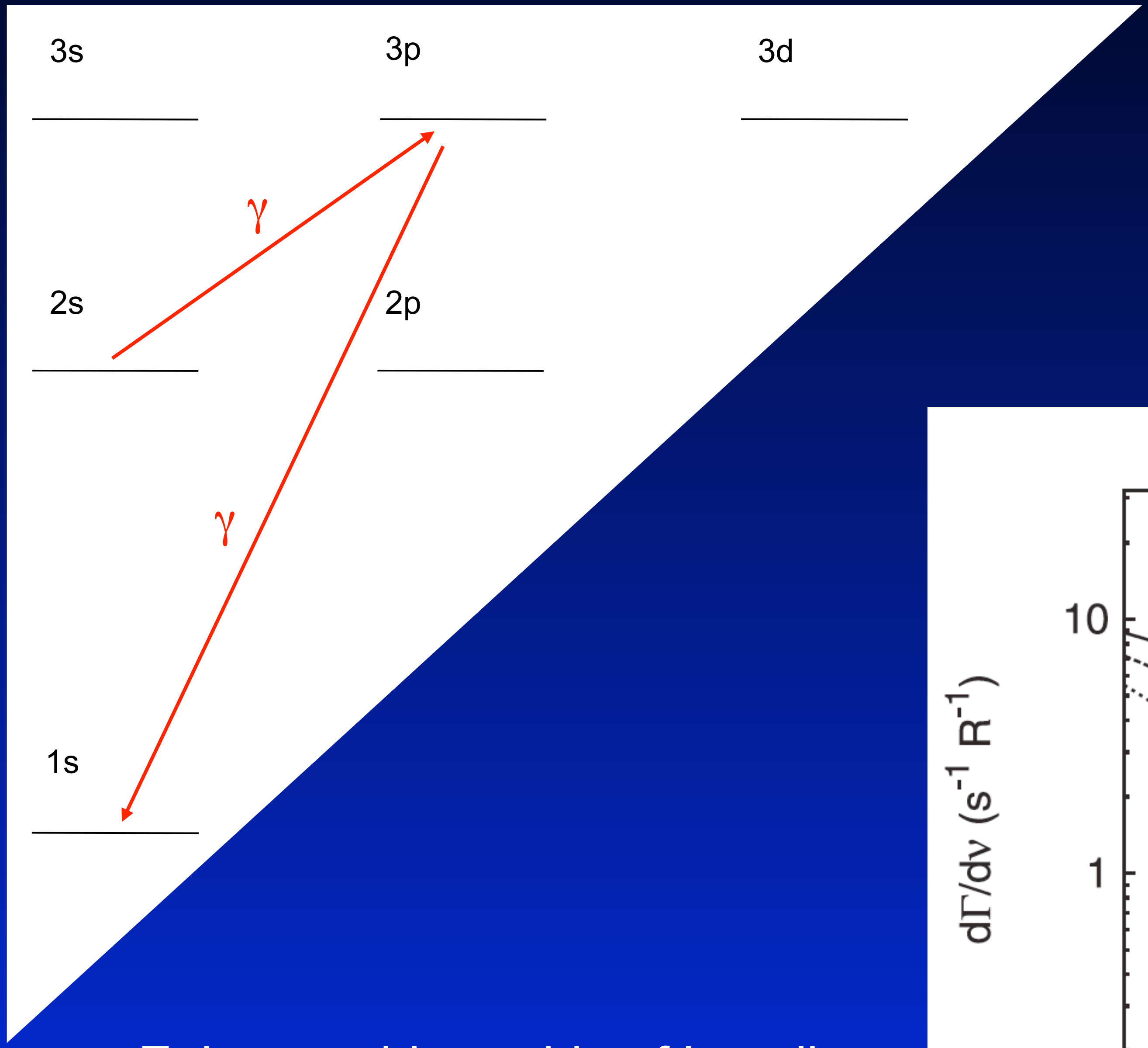
Direct Escape in optically thin regions:

→ 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



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

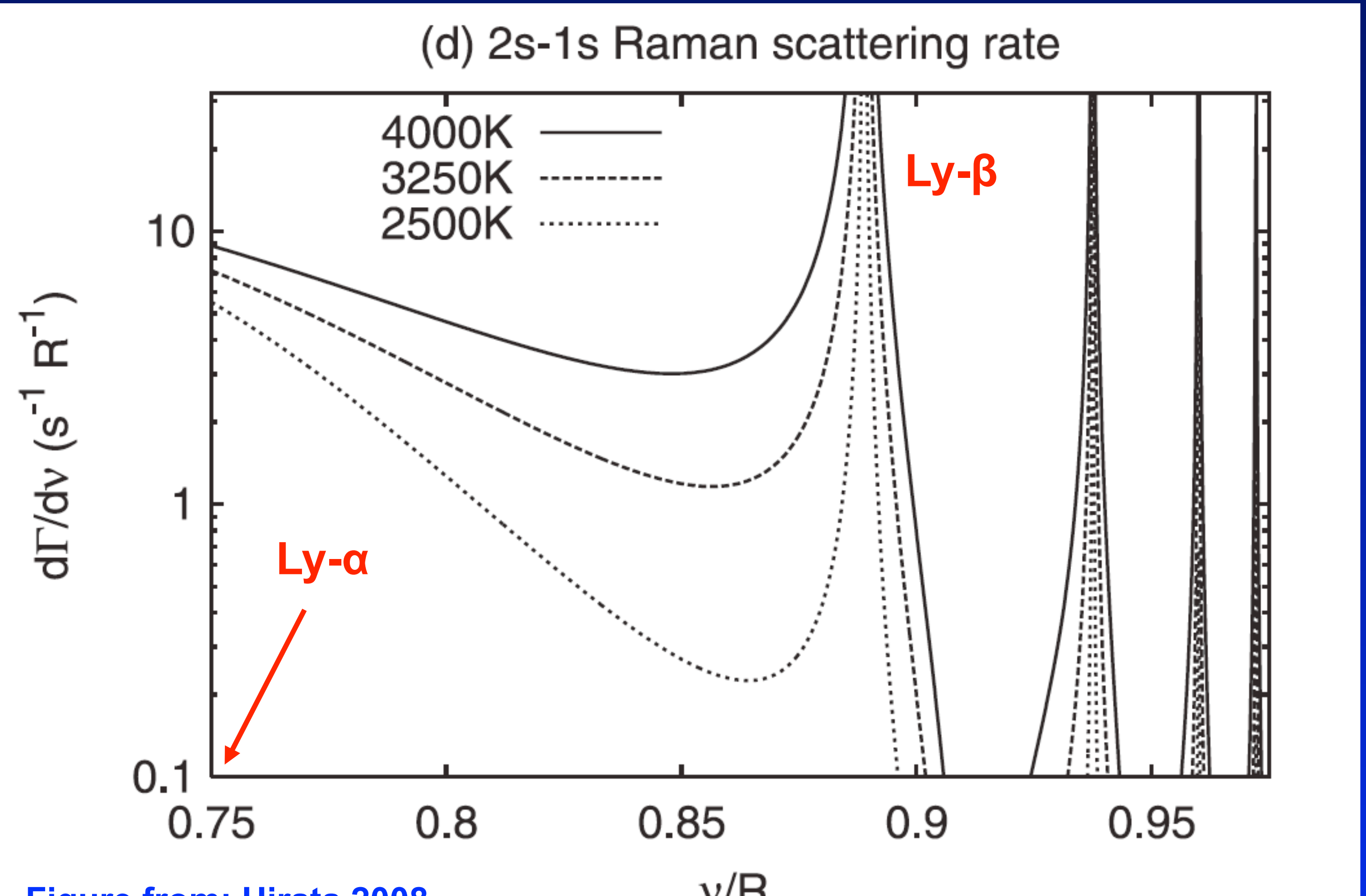
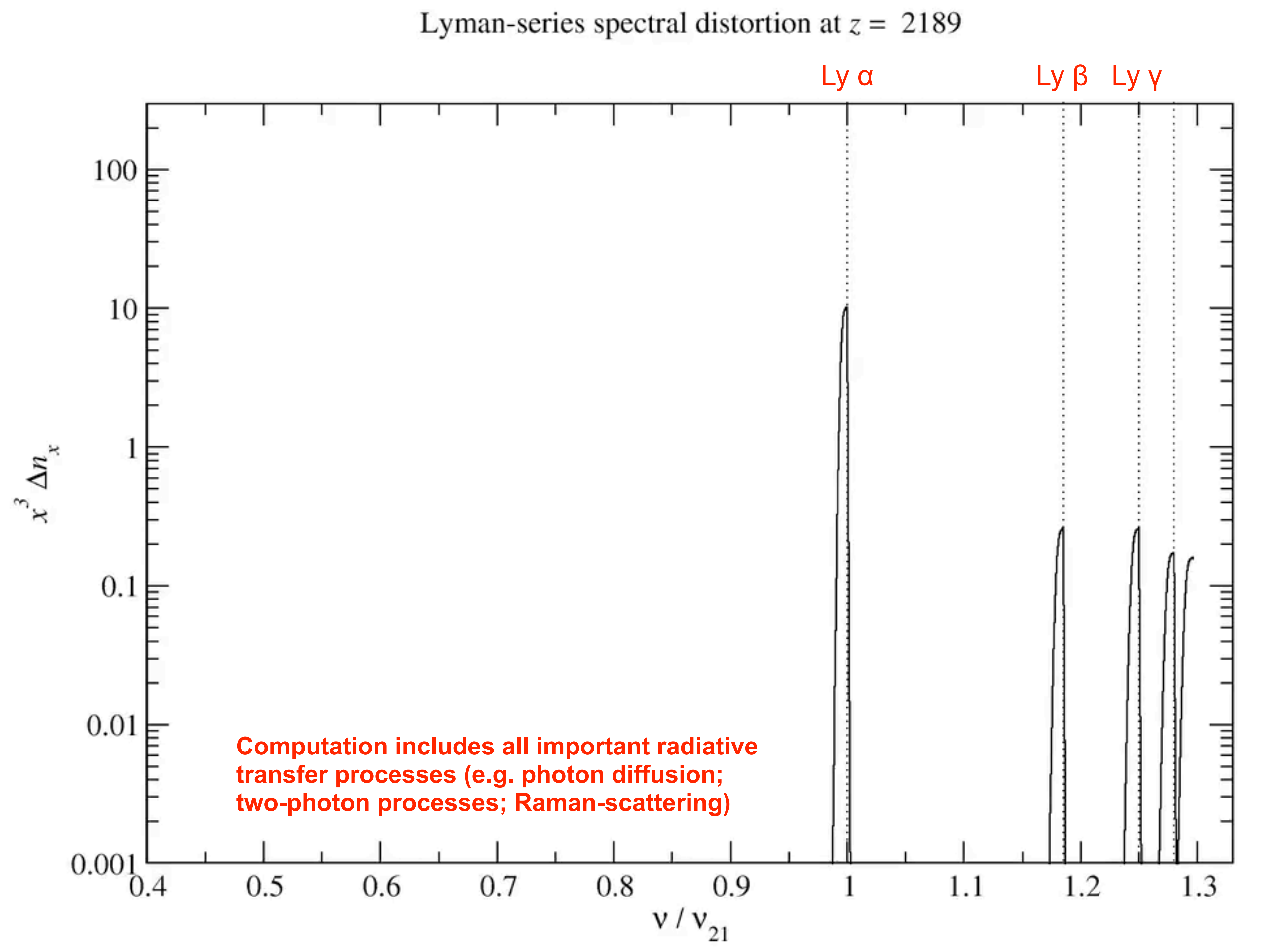


Figure from: Hirata 2008

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

Hirata 2008
JC & Thomas, 2010

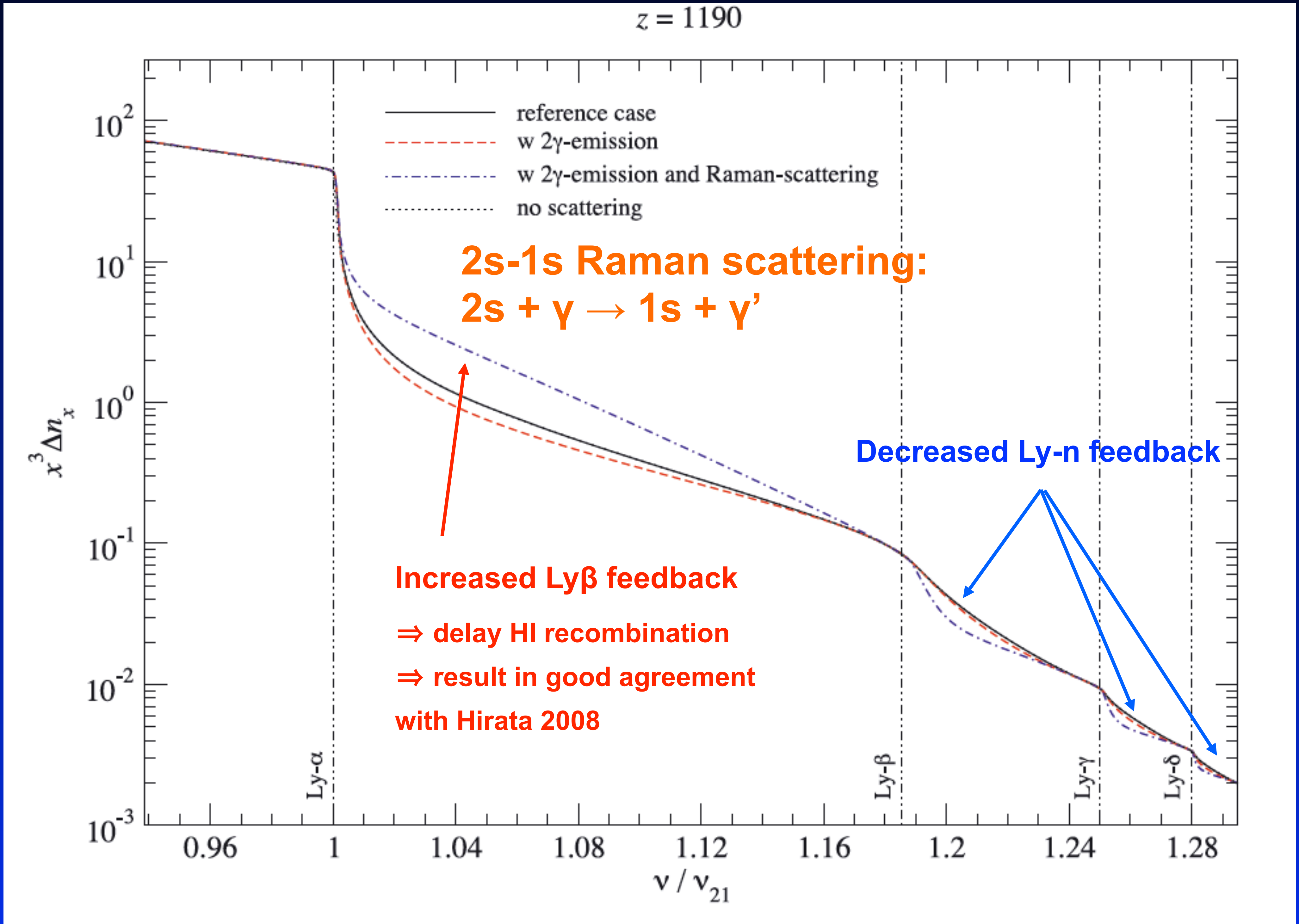
Evolution of the HI Lyman-series distortion



CITA ICAT

JC & Thomas, MNRAS, 2010

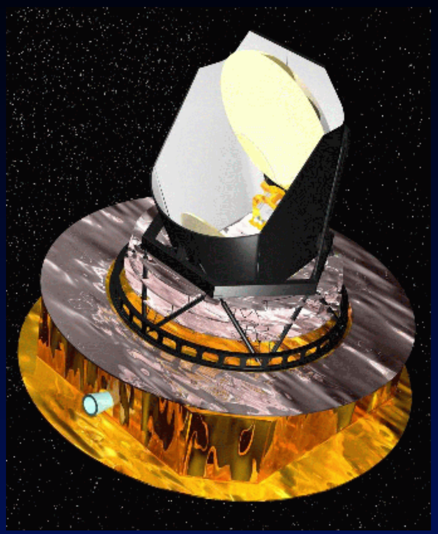
Effect of Raman scattering and 2γ decays



CITA ICAT

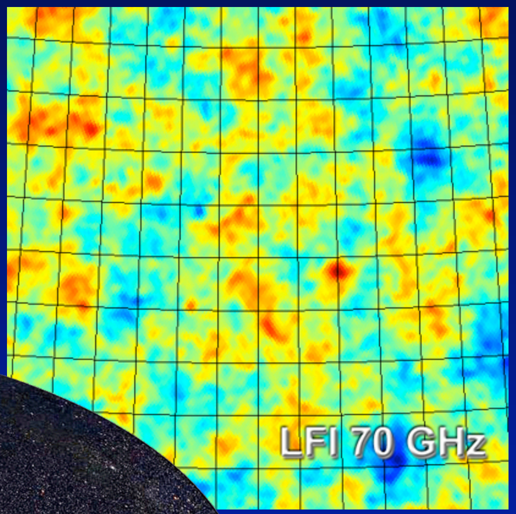
JC & Thomas, MNRAS, 2010

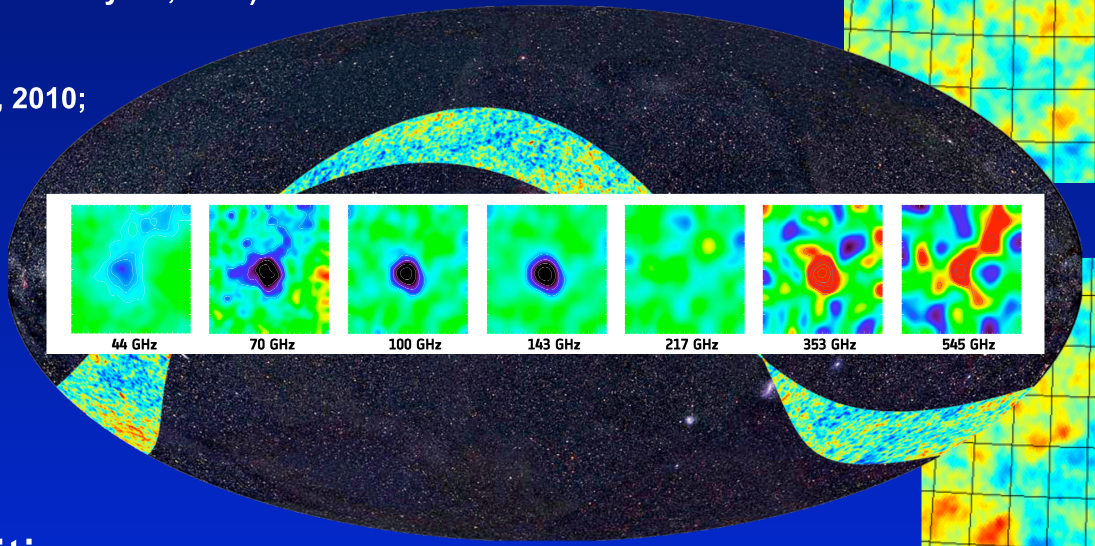
Getting the job done for *Planck*

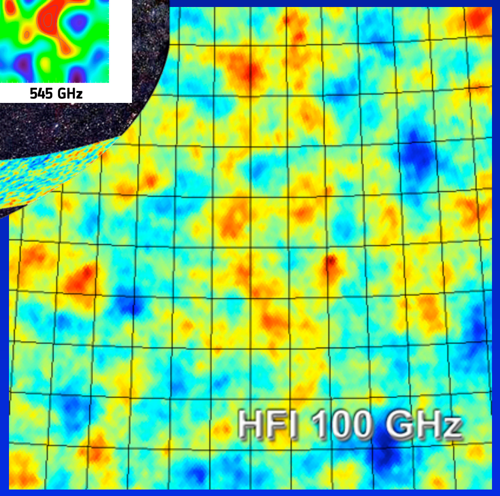


Hydrogen recombination

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







Helium recombination

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

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

Main corrections during HeI Recombination

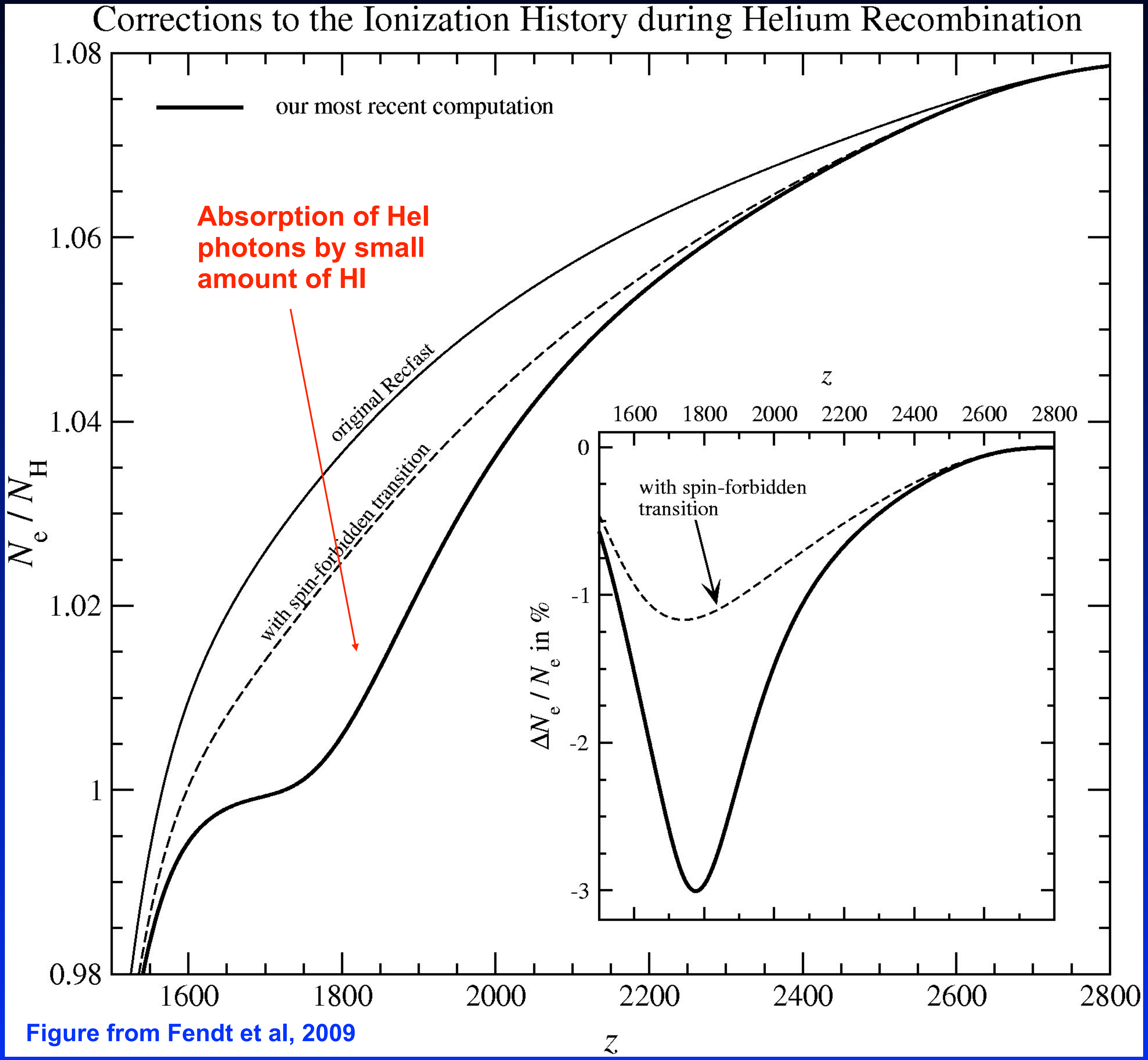
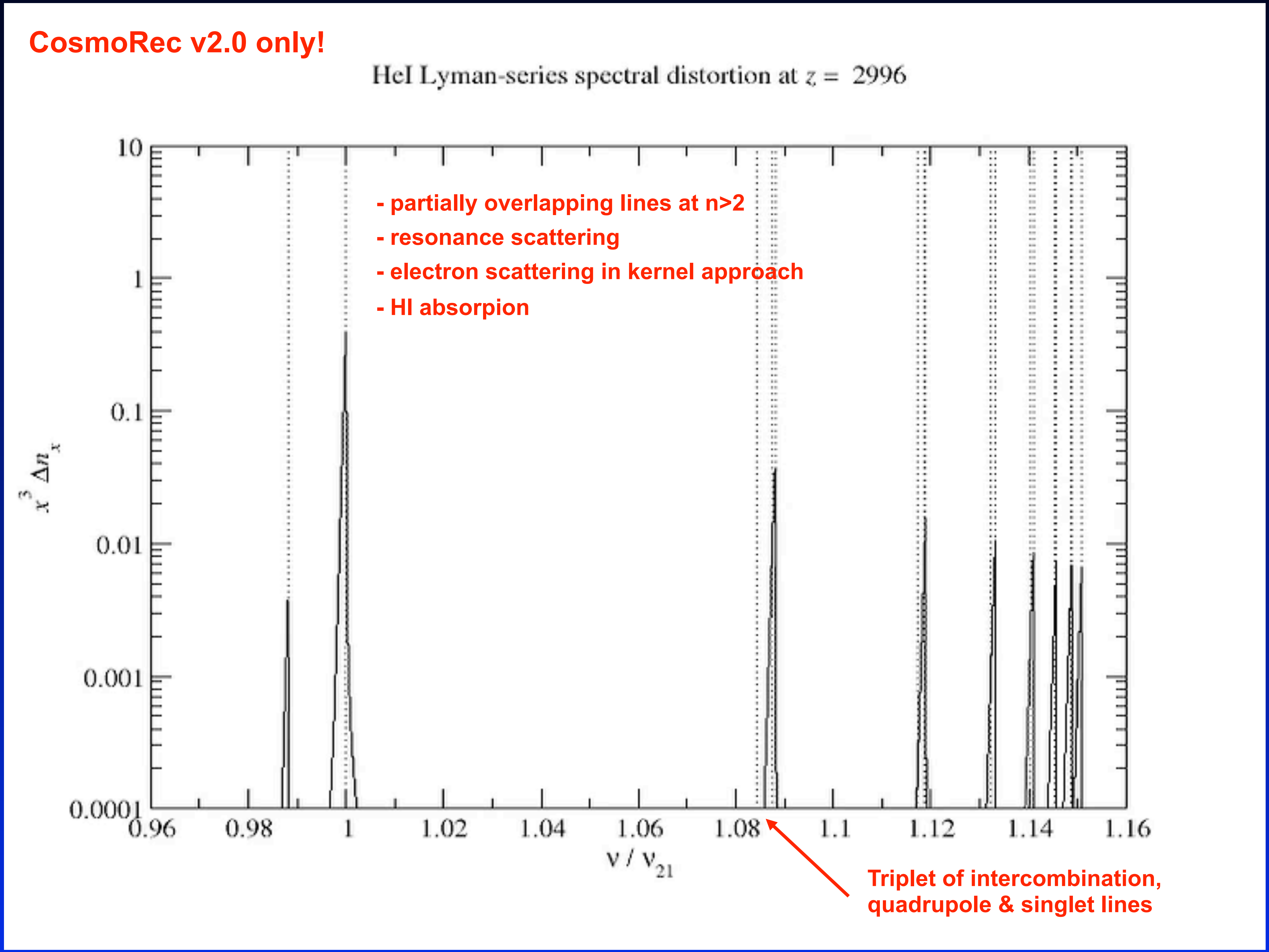


Figure from Fendt et al, 2009

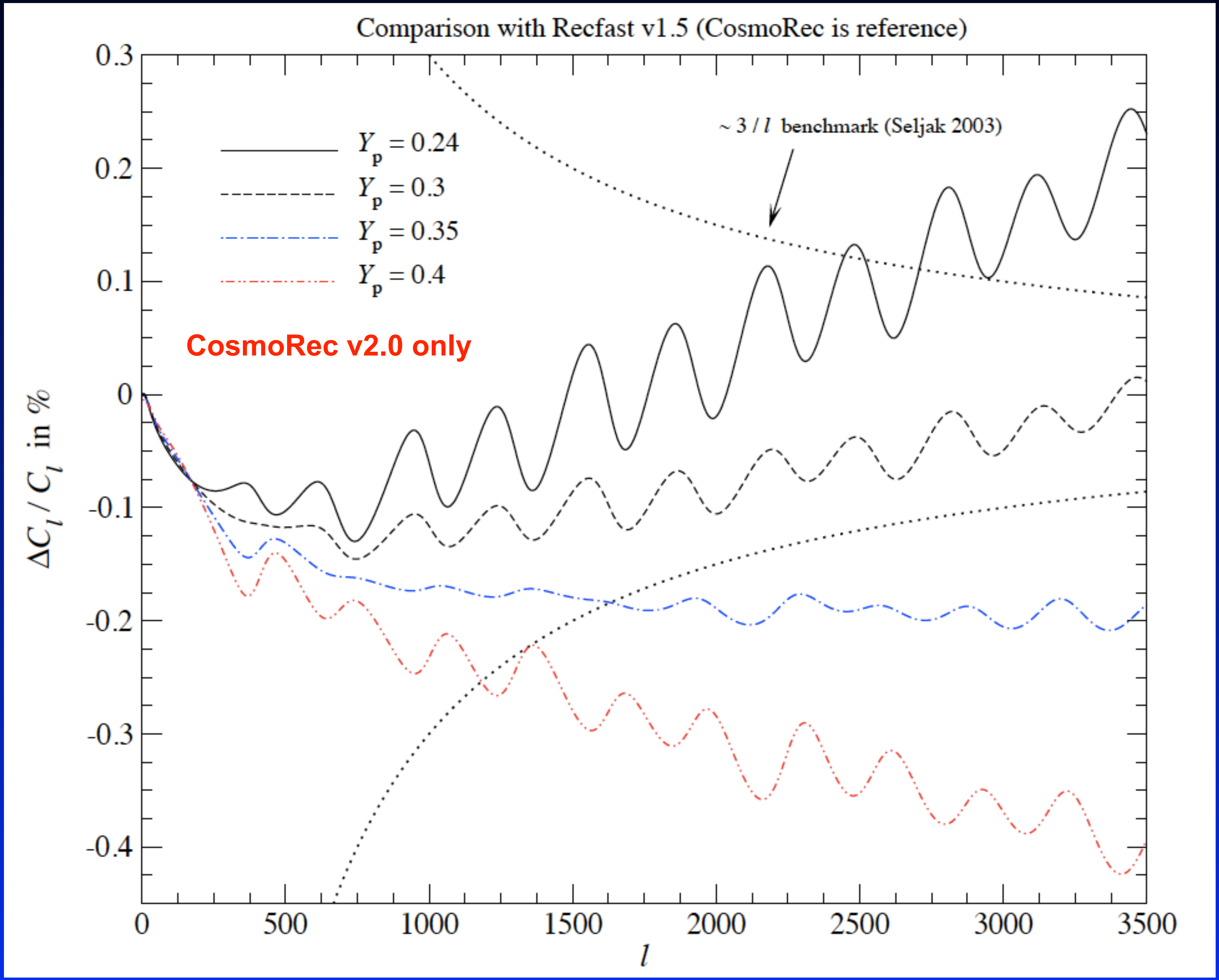
Kholupenko et al, 2007
Switzer & Hirata, 2007

Evolution of the HeI high frequency distortion



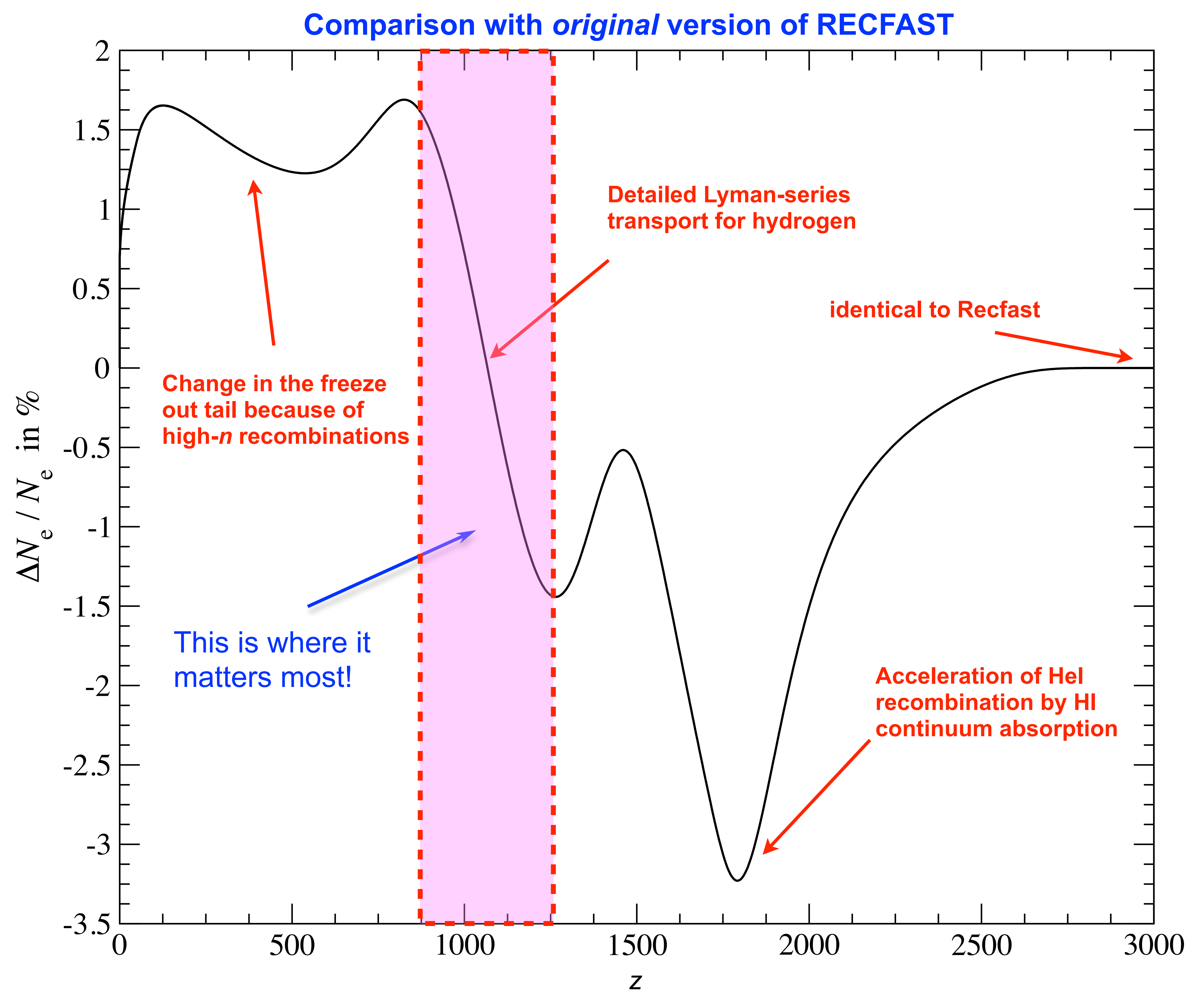
CITA ICAT JC, Fung & Switzer, 2011

Overall effect of detailed HeI radiative transfer



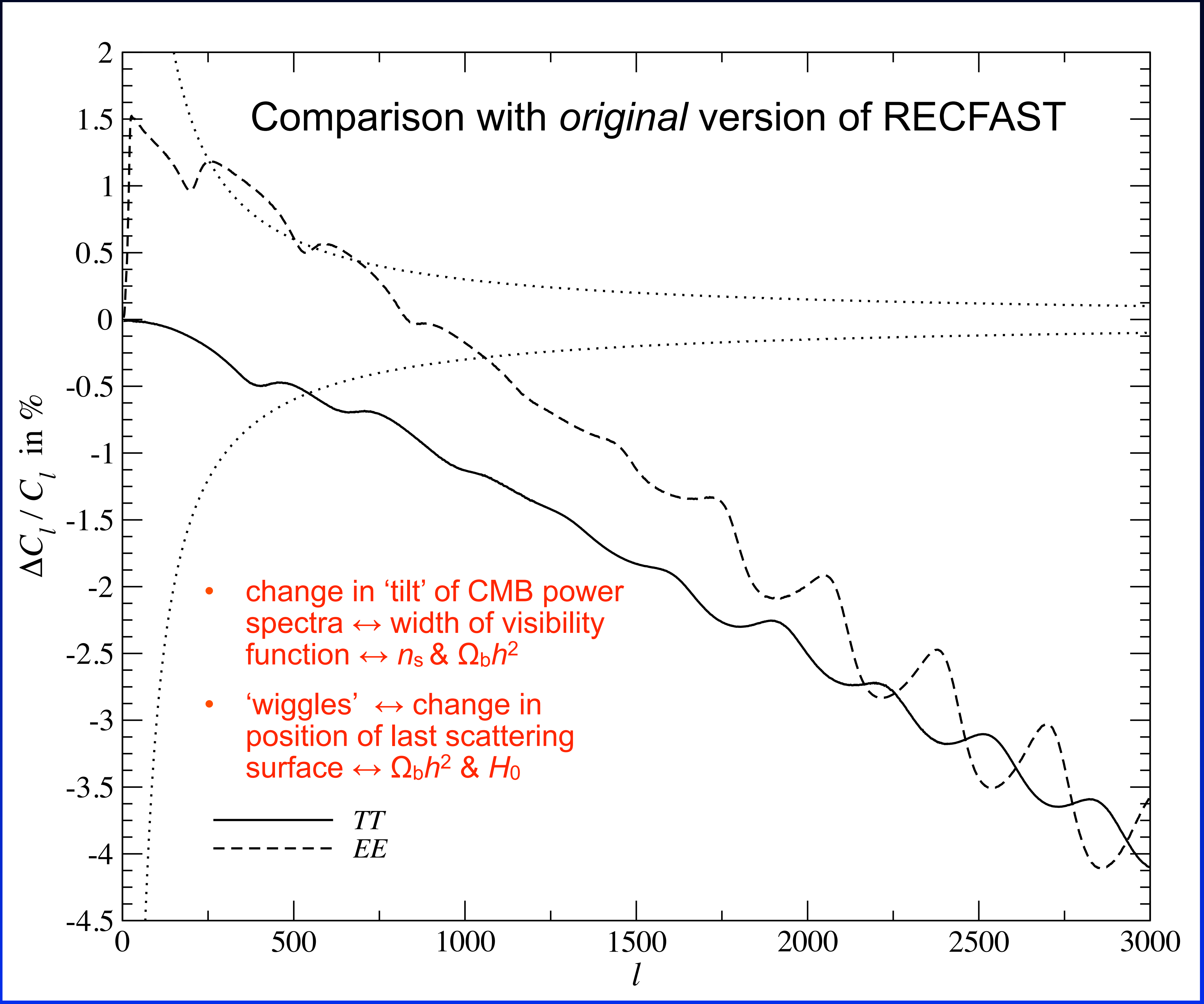
JC, Fung & Switzer, 2011

Cumulative Changes to the Ionization History



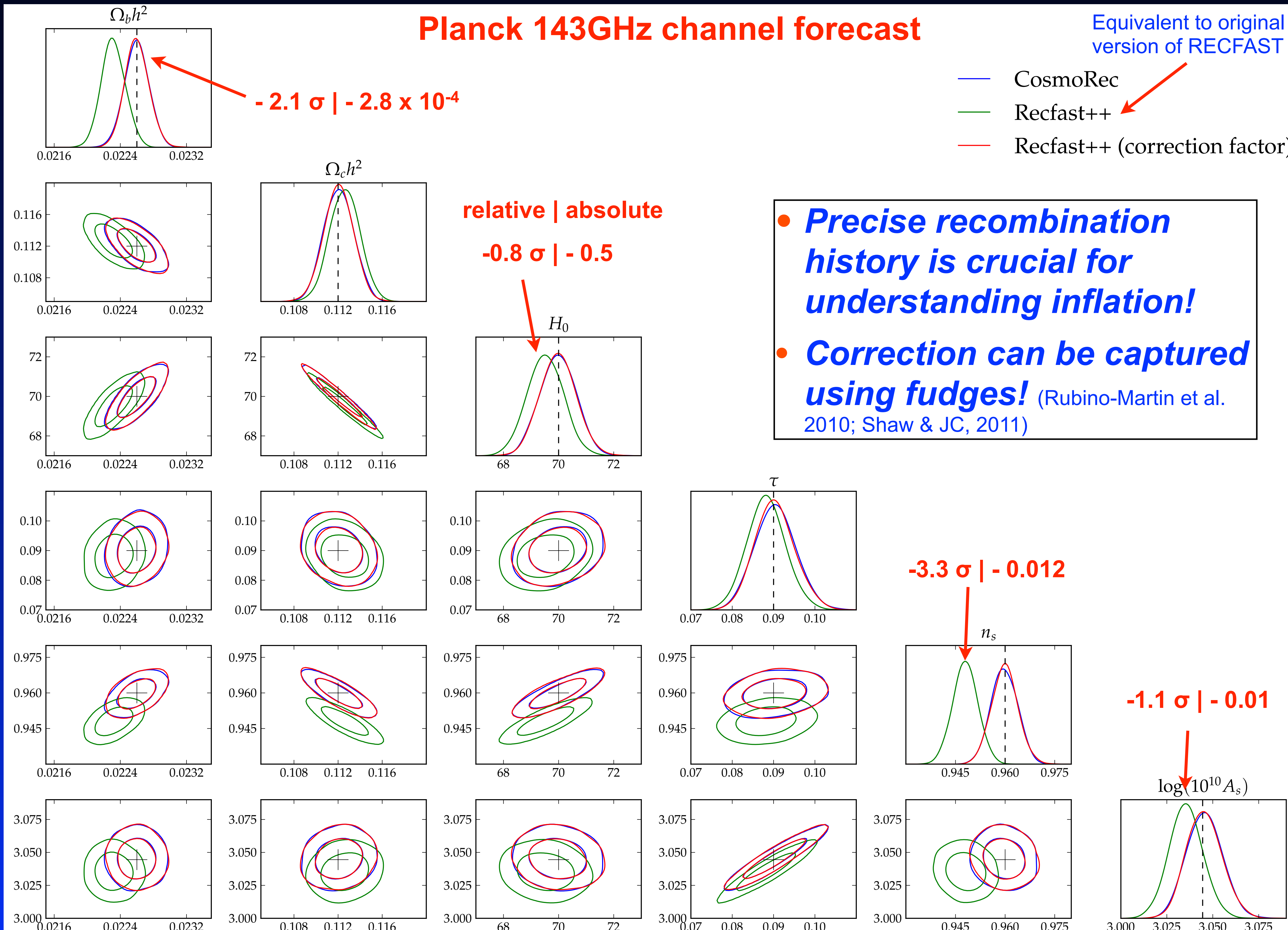
JC & Thomas, MNRAS, 2010; Shaw & JC, MNRAS, 2011

Cumulative Change in the CMB Power Spectra



Shaw & JC, MNRAS, 2011

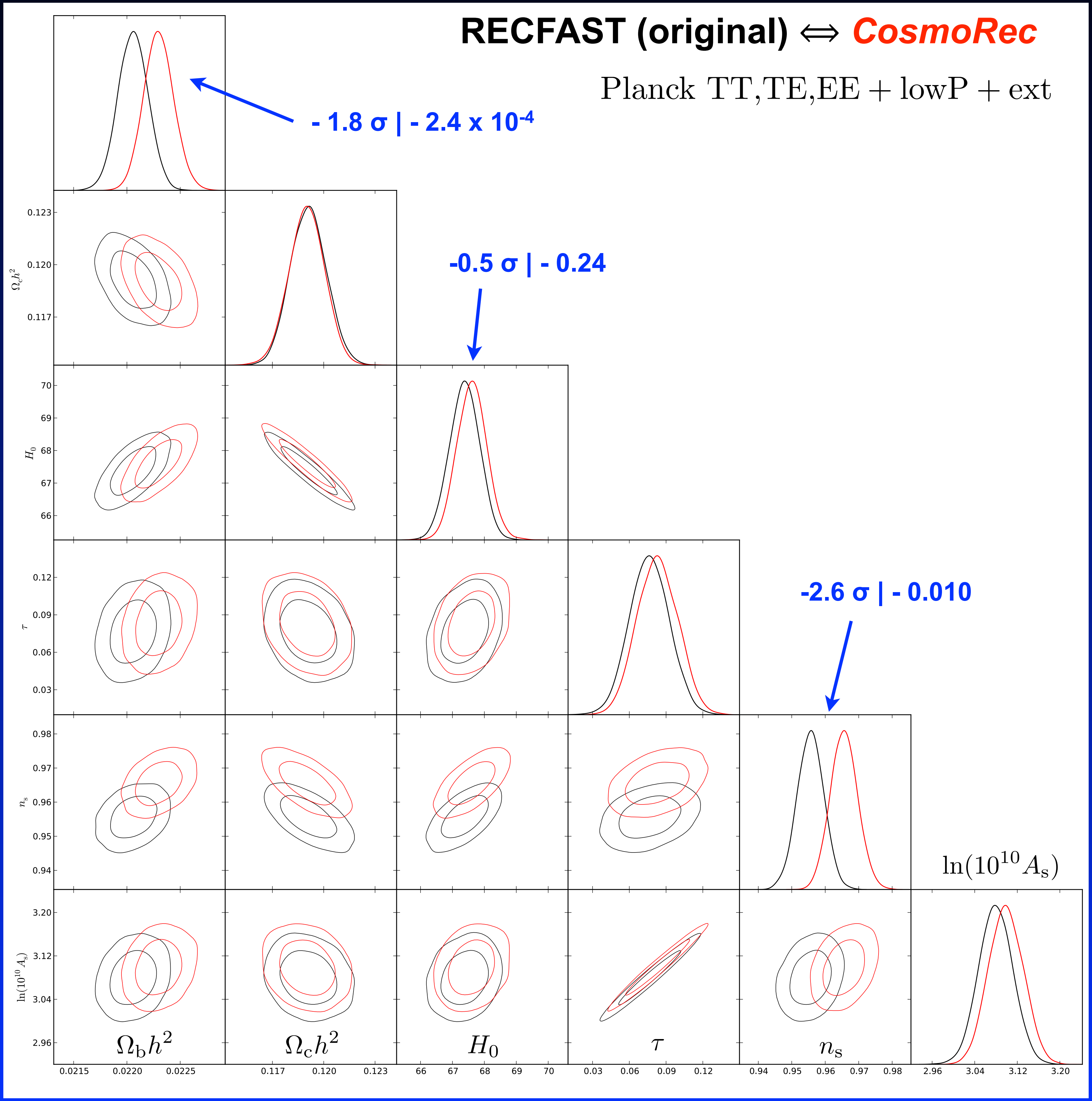
Importance of recombination for *Planck*



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

CITA ICAT Shaw & JC, 2011, and references therein

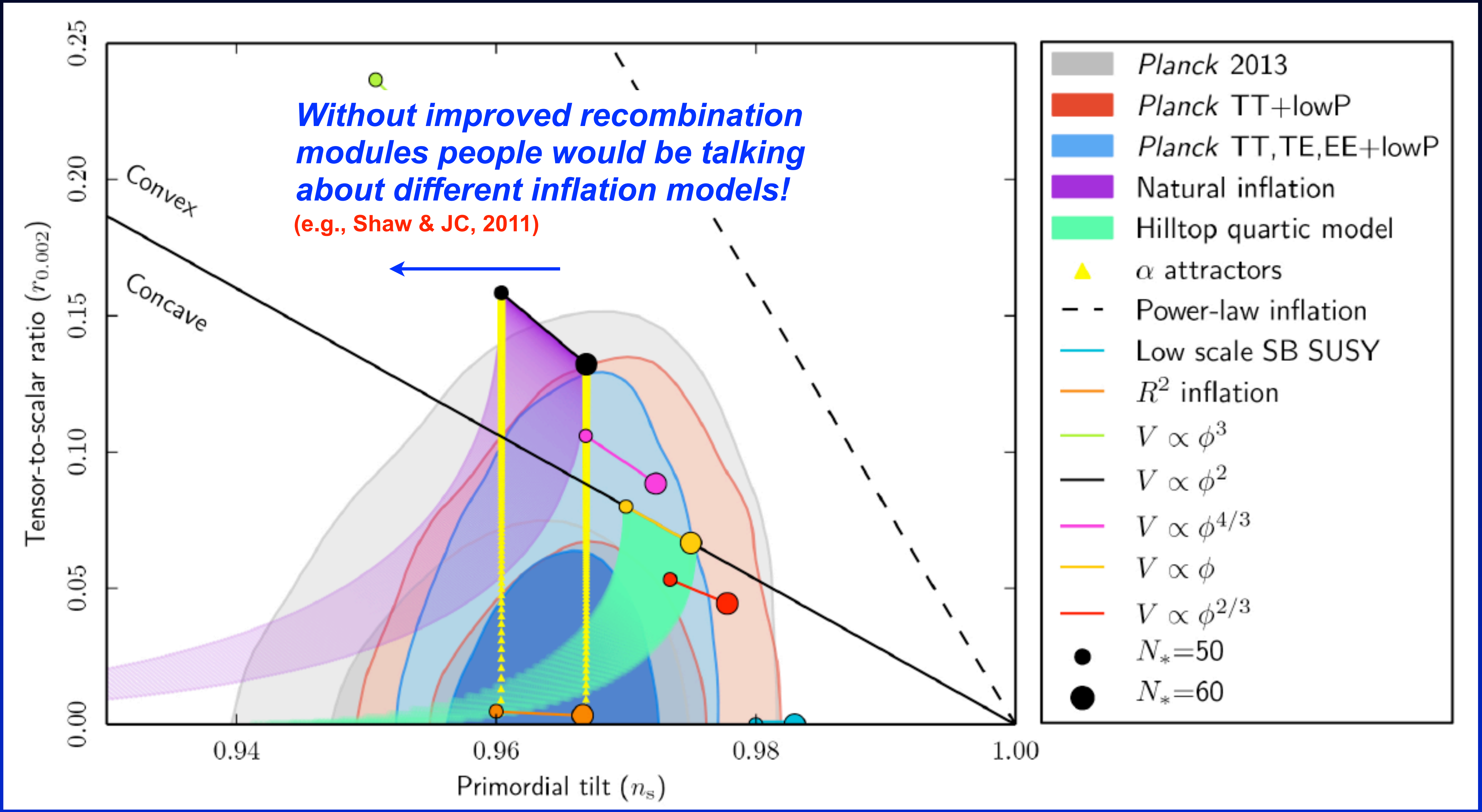
Biases as they *would* have been for *Planck*



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

Planck Collaboration, XIII 2015

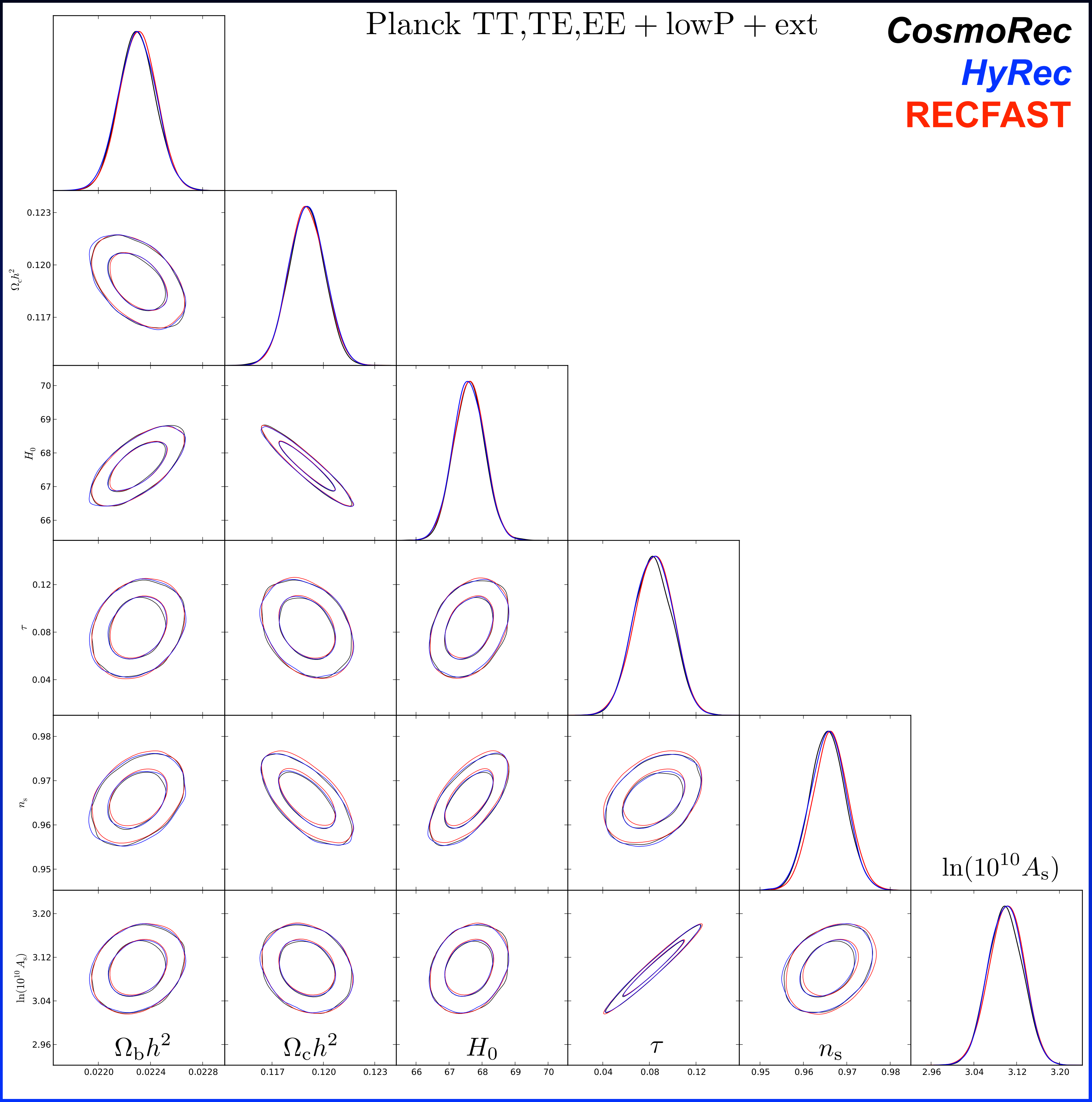
Importance of recombination for inflation constraints



Planck Collaboration, 2015, paper XX

- Analysis uses refined recombination model (CosmoRec/HyRec)

Differences for current recombination codes



- Different codes agree very well!
- largest biases

  $\Delta n_s \approx 0.15\sigma$

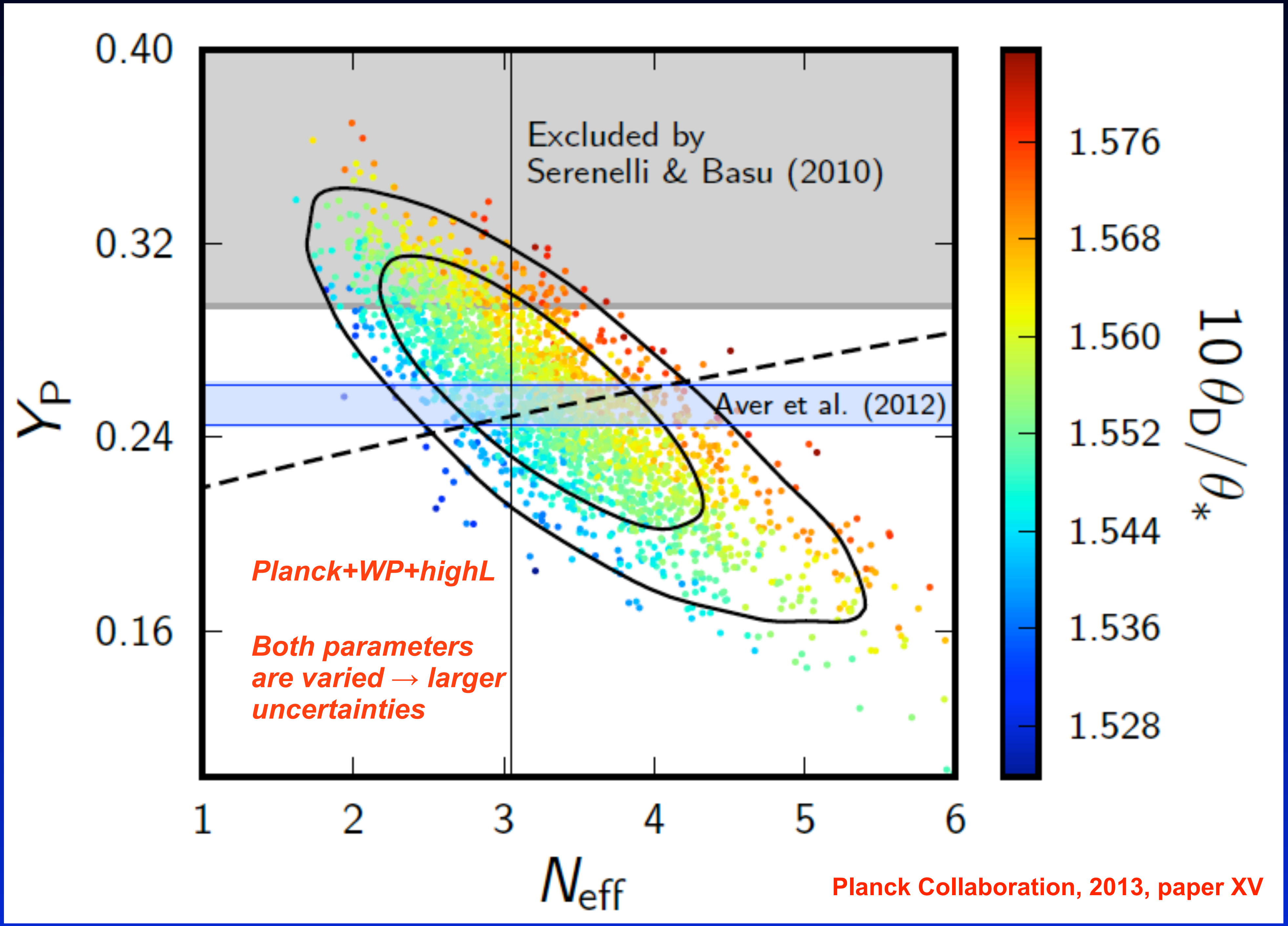
  (*CosmoRec* ⟺ RECFAST)

  $\Delta n_s \approx 0.03\sigma$

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

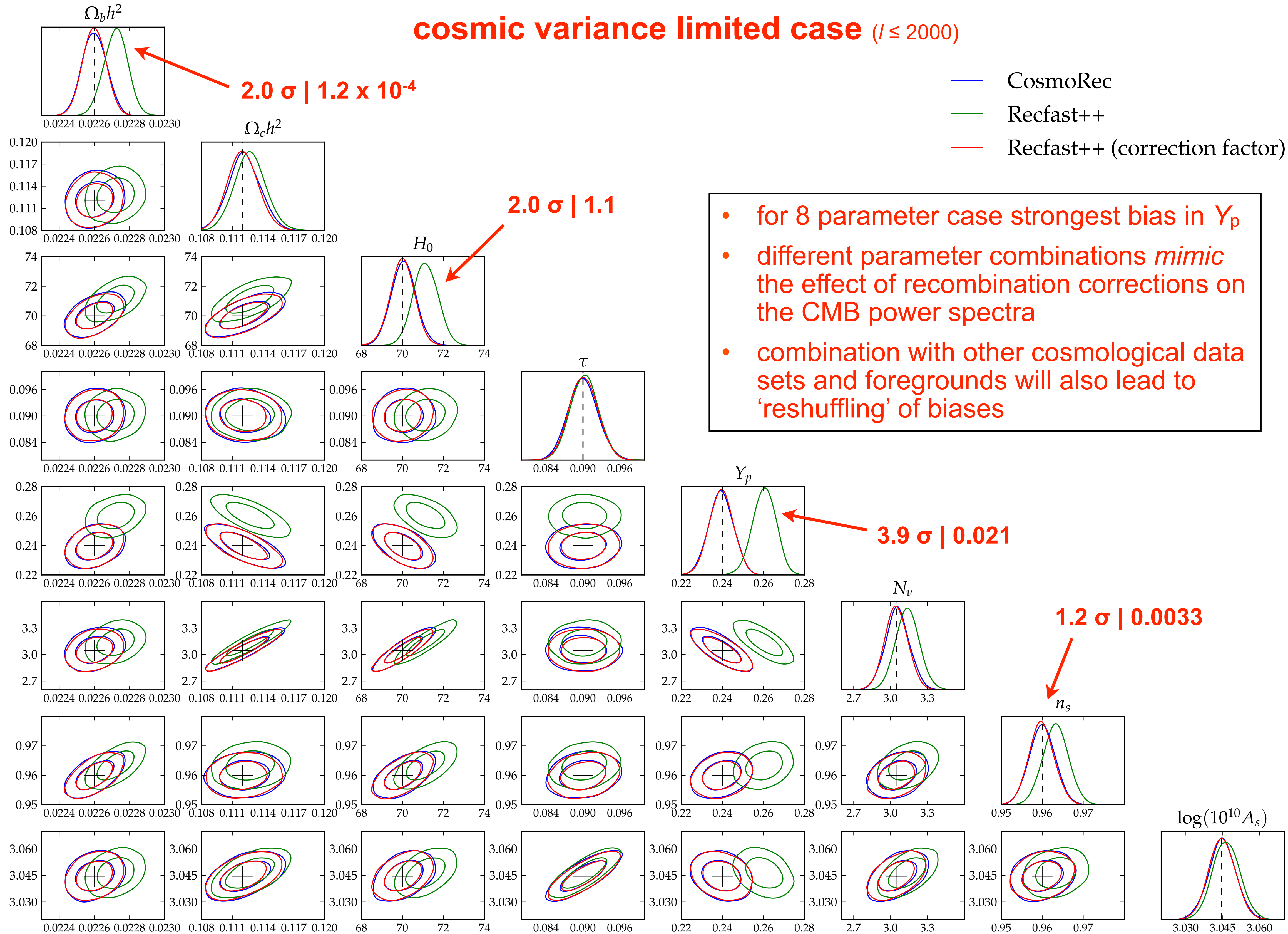
Planck Collaboration, XIII 2015

CMB constraints on N_{eff} and Y_p



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

Importance of recombination for measuring helium

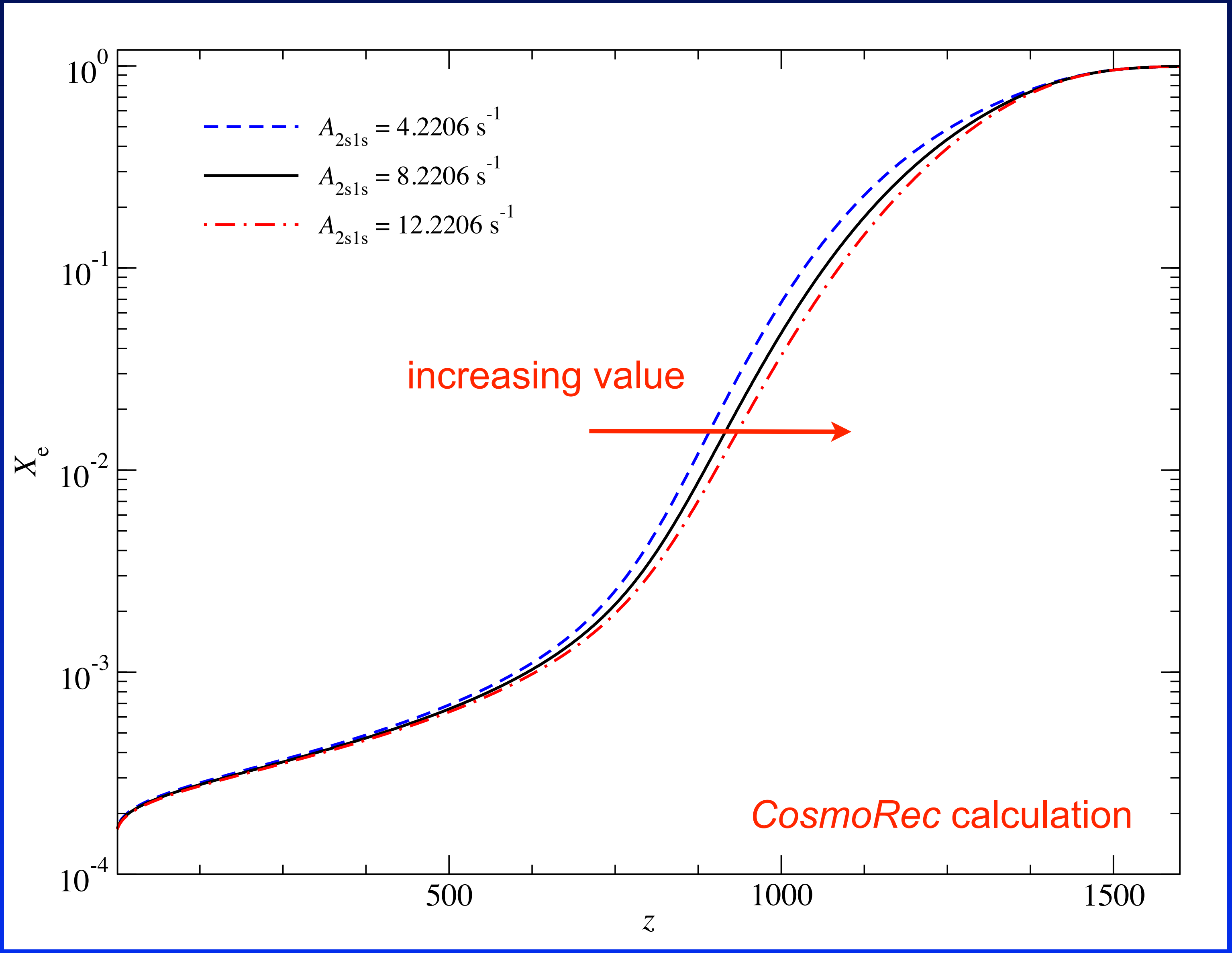


- for 8 parameter case strongest bias in Y_p
- different parameter combinations *mimic* the effect of recombination corrections on the CMB power spectra
- combination with other cosmological data sets and foregrounds will also lead to 'reshuffling' of biases

Shaw & JC, 2011, and references therein

Planck measurement of the HI 2s-1s two-photon rate

- HI 2s-1s two-photon rate crucial for recombination dynamics
- Value is not well measured in lab (best constraint ~ 43% error; Krueger & Oed 1975)
- *Planck* data can be used to directly constrain its value



Planck Collaboration, XIII 2015

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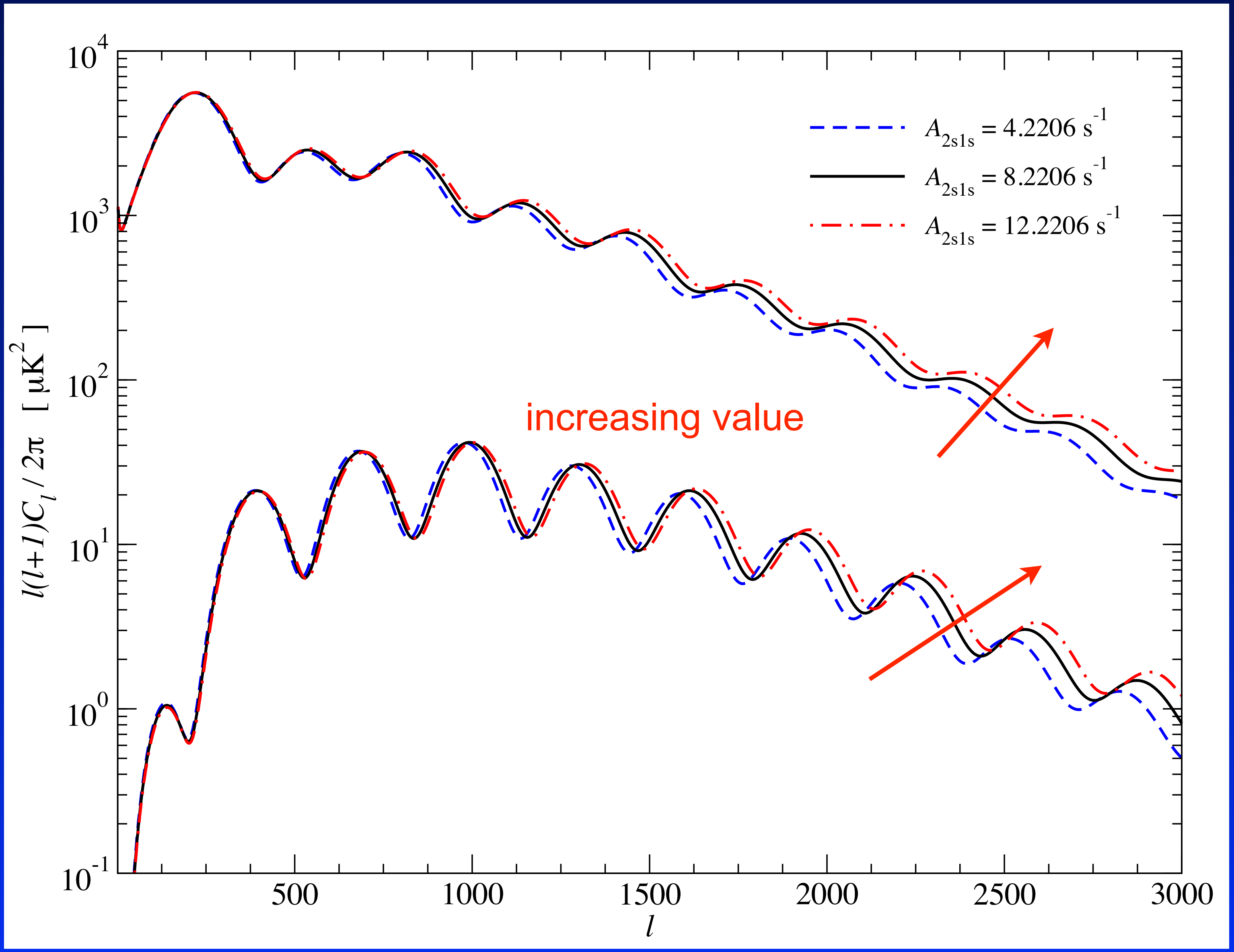

Planck Collaboration, XIII 2015

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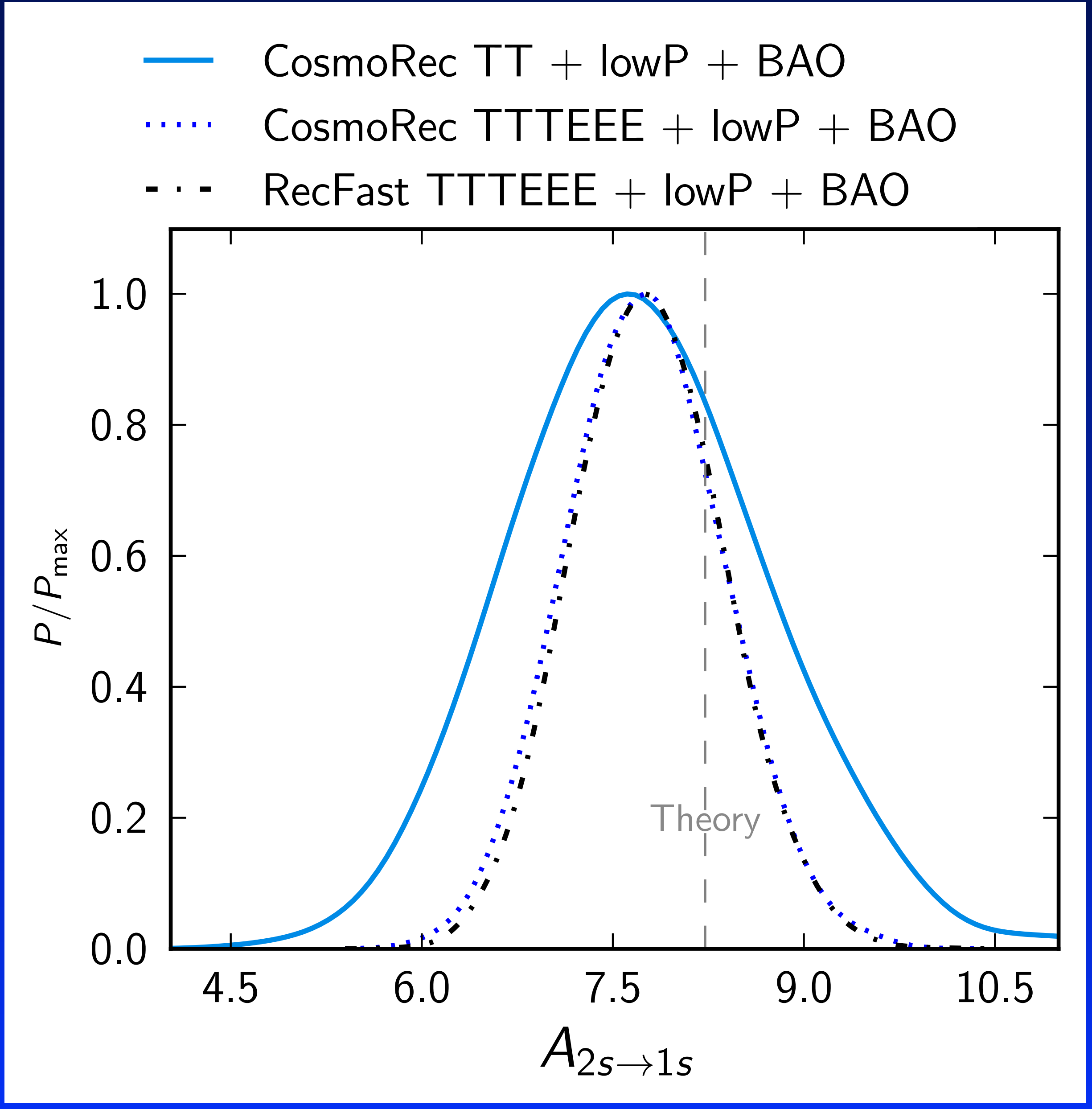


$$A^{\rm theory}_{2s\to 1s} = 8.2206\,{\rm s}^{-1} \text{(Labzowsky et al. 2005)}$$

$$A_{2s\to 1s} = 7.71 \pm 0.99\,{\rm s}^{-1}$$
(*Planck* TT+lowP+BAO)

$$A_{2s\to 1s} = 7.75 \pm 0.61\,{\rm s}^{-1}$$ **~ 8% error!**
(*Planck* TT,TE,EE+lowP+BAO)

- *Planck* measurement in excellent agreement with theoretical value
- *Planck* only values very similar
- *CosmoRec* and *Recfast* agree...

Planck Collaboration, XIII 2015

Cosmological Recombination Radiation

Simple estimates for hydrogen recombination

Hydrogen recombination:

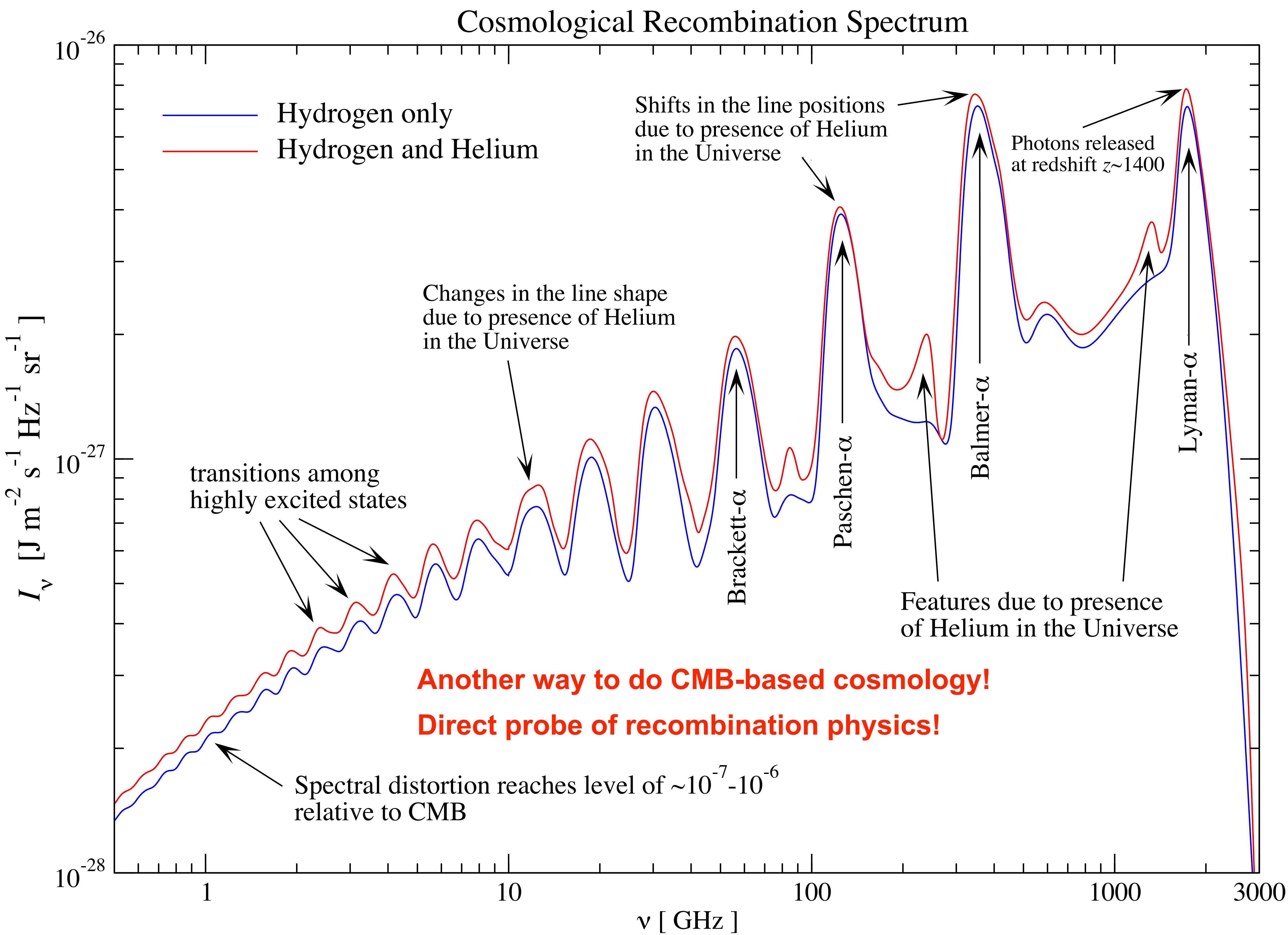
- per recombined hydrogen atom an energy of ~ 13.6 eV in form of photons is released
- at z ~ 1100 → $\Delta\varepsilon/\varepsilon$ ~ 13.6 eV N_b / (N_γ 2.7kT_r) ~ 10^{-9} -10^{-8}

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

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

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

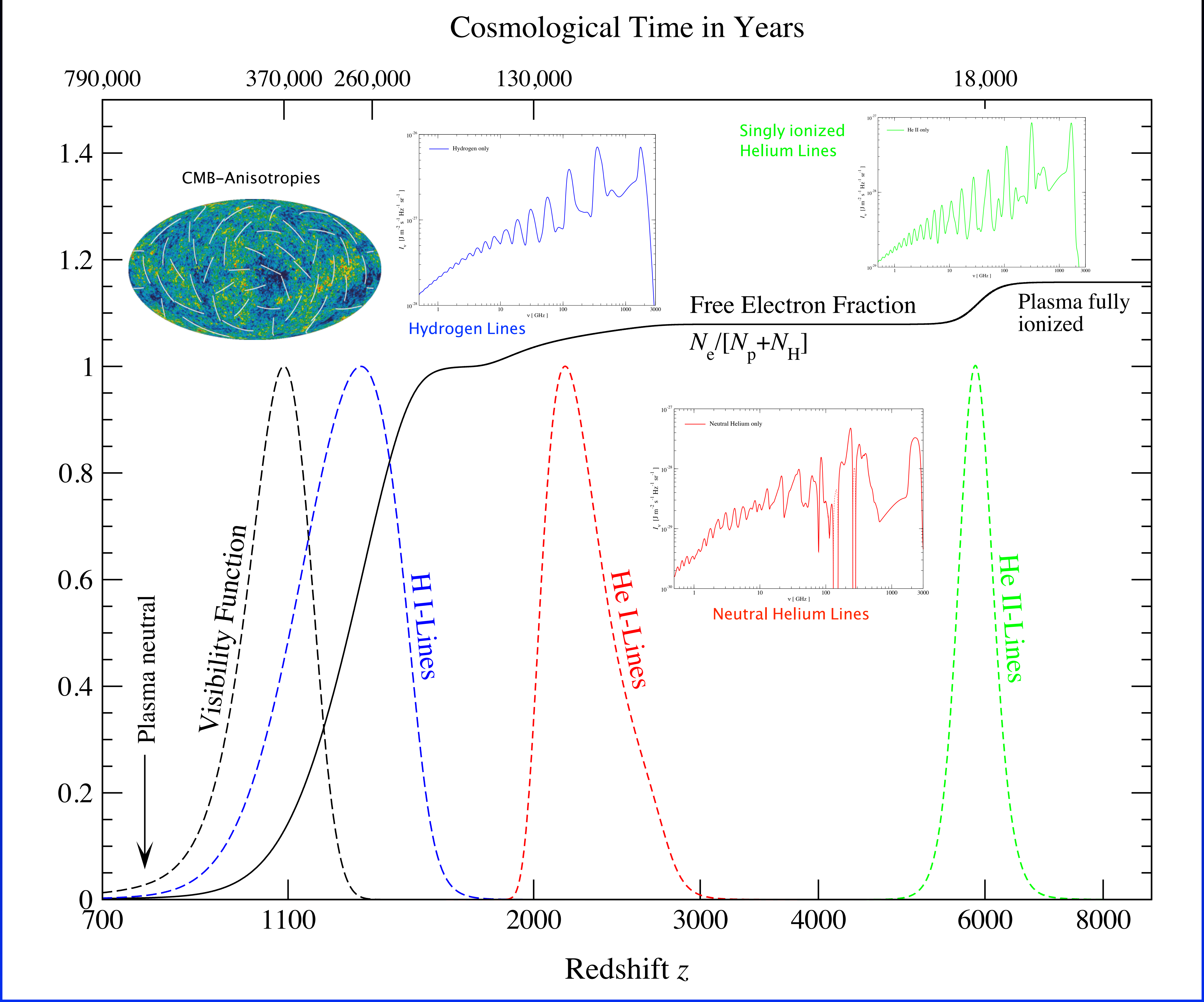
→ In 1975 ***Viktor Dubrovich*** emphasized the possibility to observe the recombinational lines from n > 3 and Δn << n!



Another way to do CMB-based cosmology!

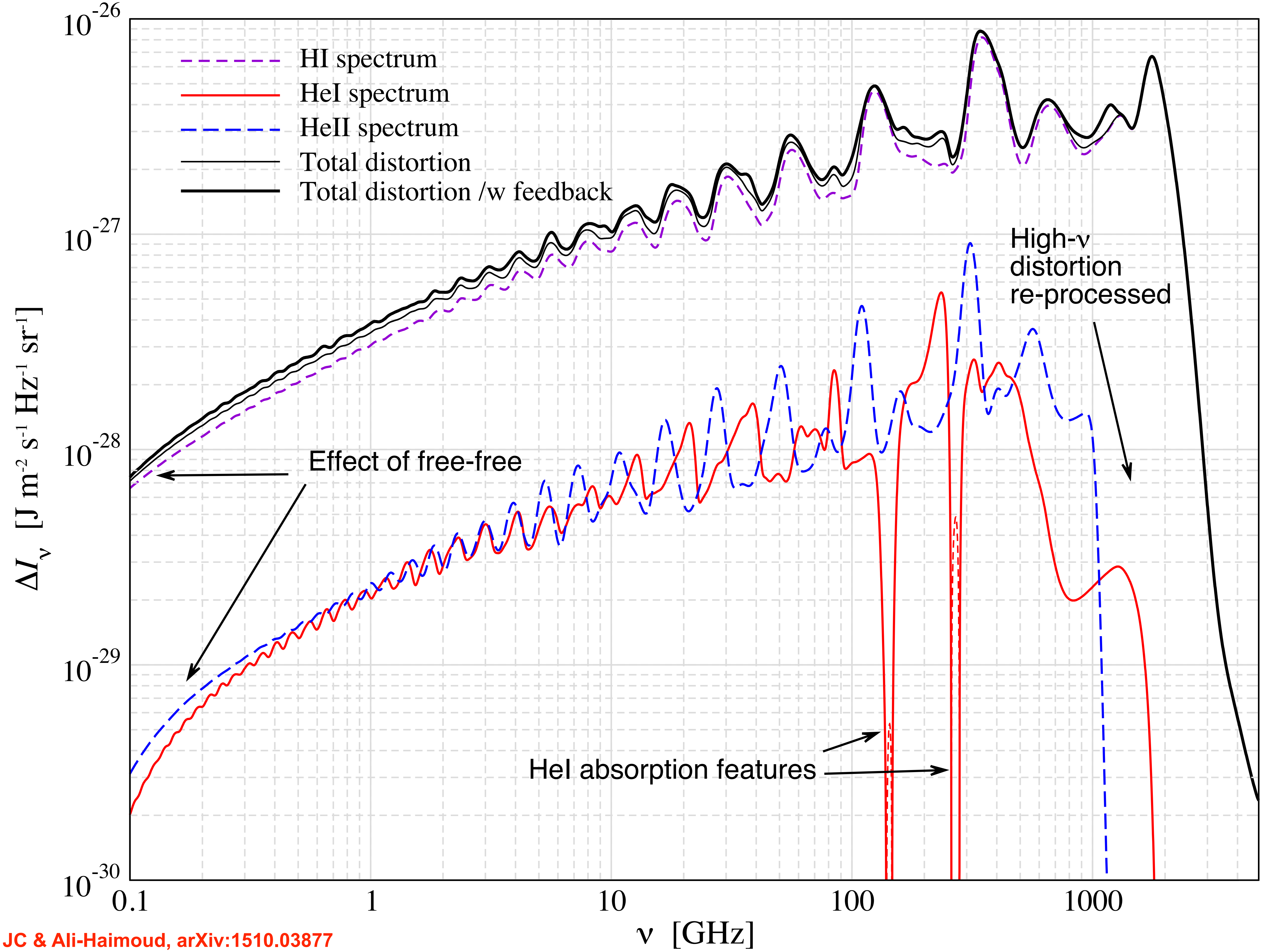
Direct probe of recombination physics!

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



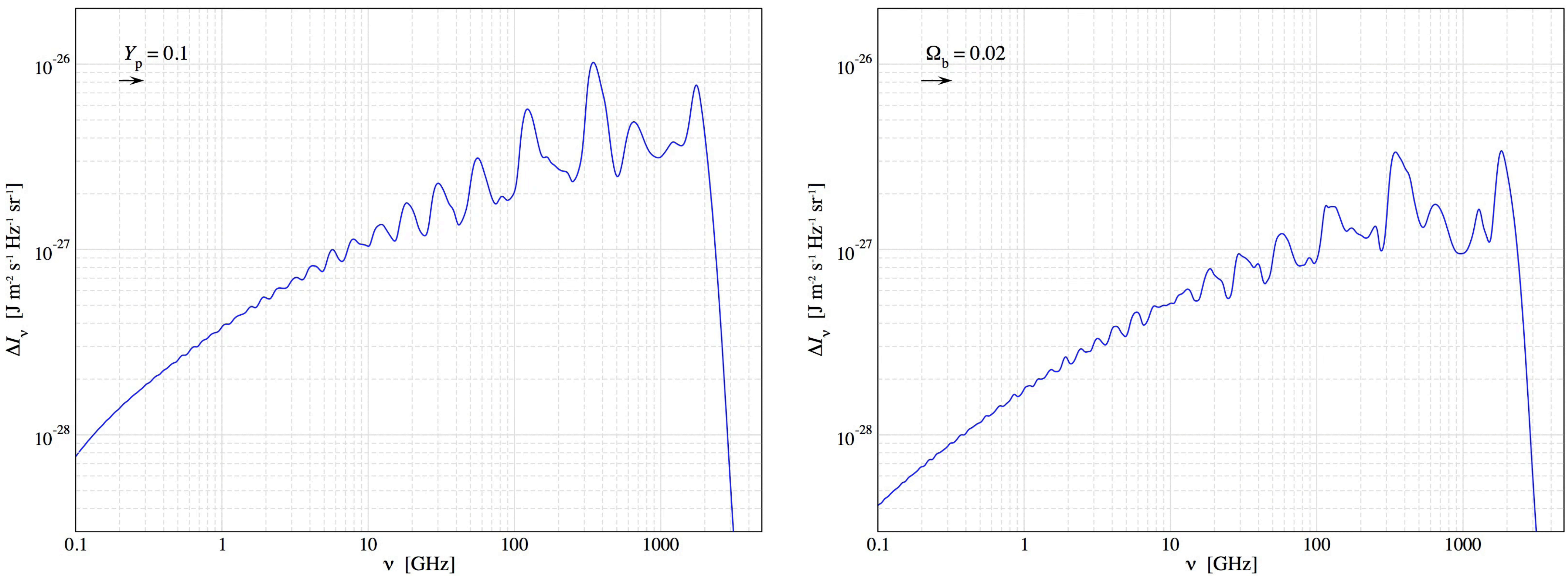
Cosmological Time in Years
790,000
370,000
260,000
130,000
18,000
CMB-Anisotropies
Hydrogen Lines
Singly ionized
Helium Lines
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully
ionized
Neutral Helium Lines
Plasma neutral
Visibility Function
H I-Lines
He I-Lines
He II-Lines
1.4
1.2
1
0.8
0.6
0.4
0.2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

New detailed and fast computation!



JC & Ali-Haimoud, arXiv:1510.03877

CosmoSpec: fast and accurate computation of the CRR



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

CosmoSpec will be available here:

www.Chluba.de/CosmoSpec

JC & Ali-Haimoud, arXiv:1510.03877

What would we actually learn by doing such hard job?

Cosmological Recombination Spectrum opens a way to measure:

→ **the specific *entropy* of our universe (related to $\Omega_b h^2$)**

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

→ ***the pre-stellar abundance of helium Y_p***

→ ***If recombination occurs as we think it does, then the lines can be predicted with very high accuracy!***

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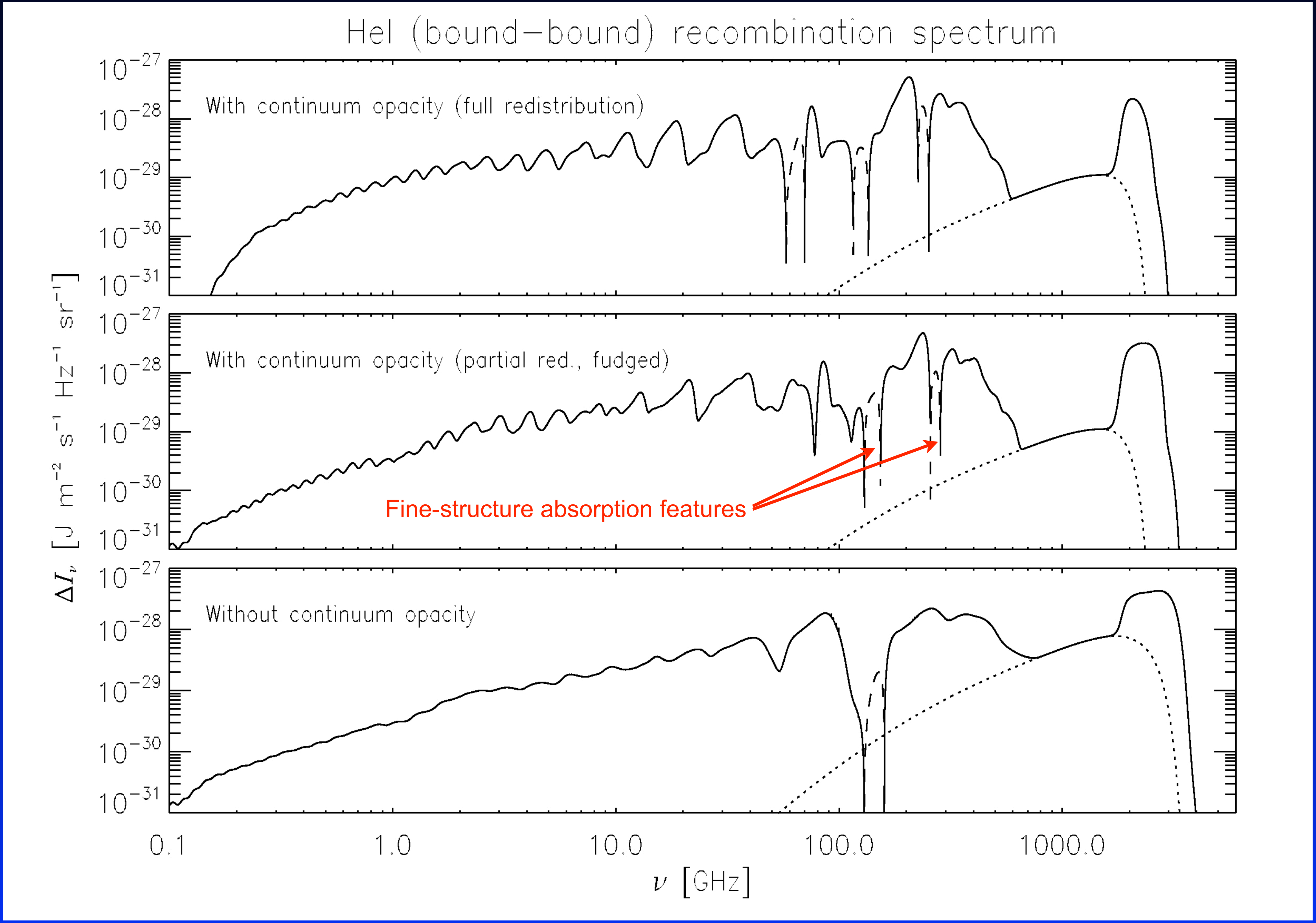
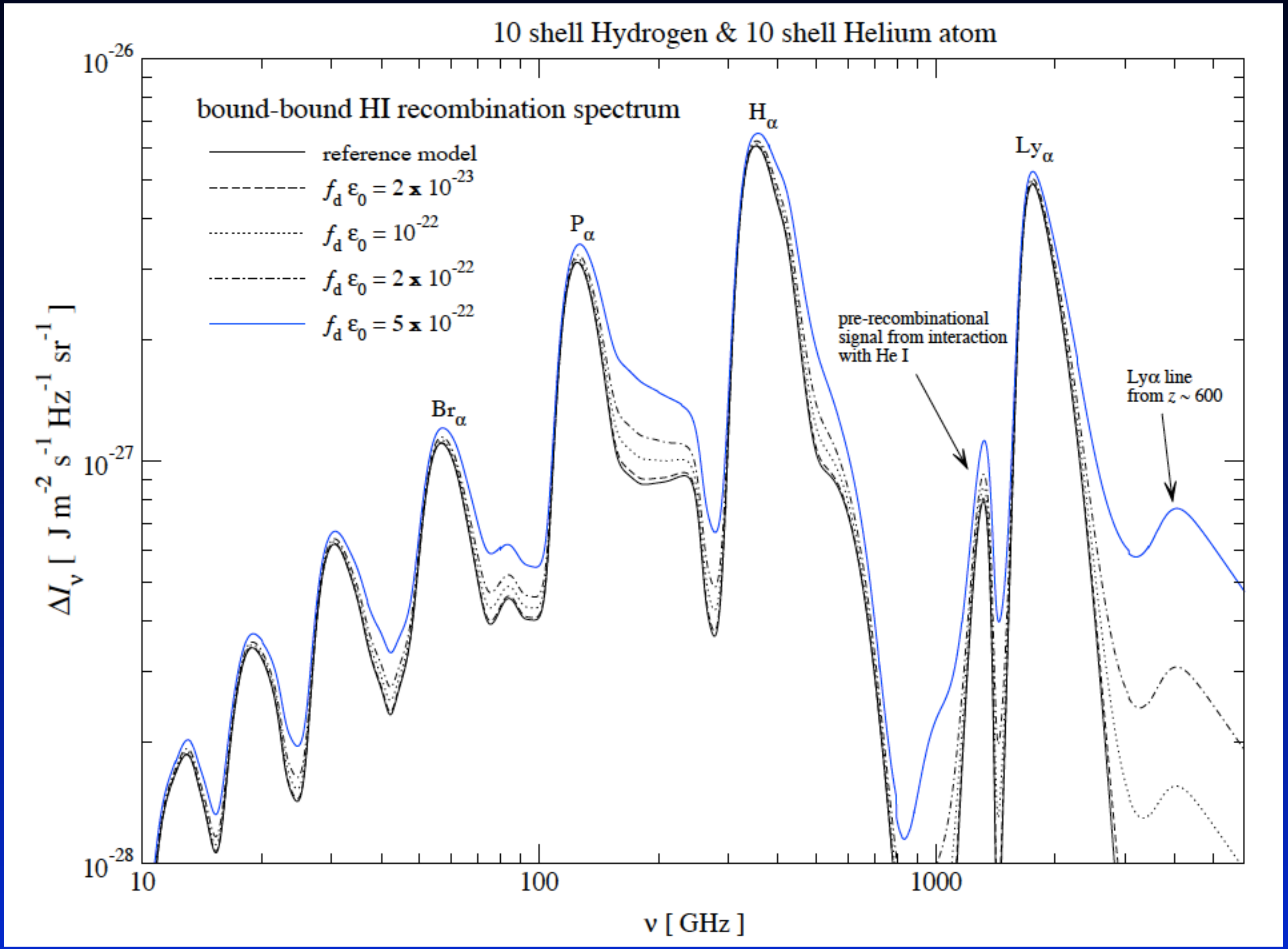
The importance of HI continuum absorption



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

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If something unexpected or non-standard happened:

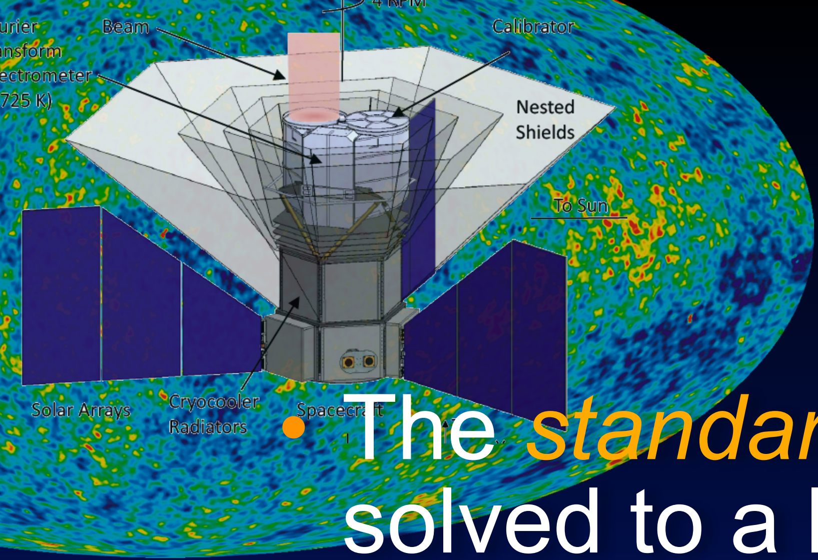
→ ***non-standard thermal histories should leave some measurable traces***

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

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

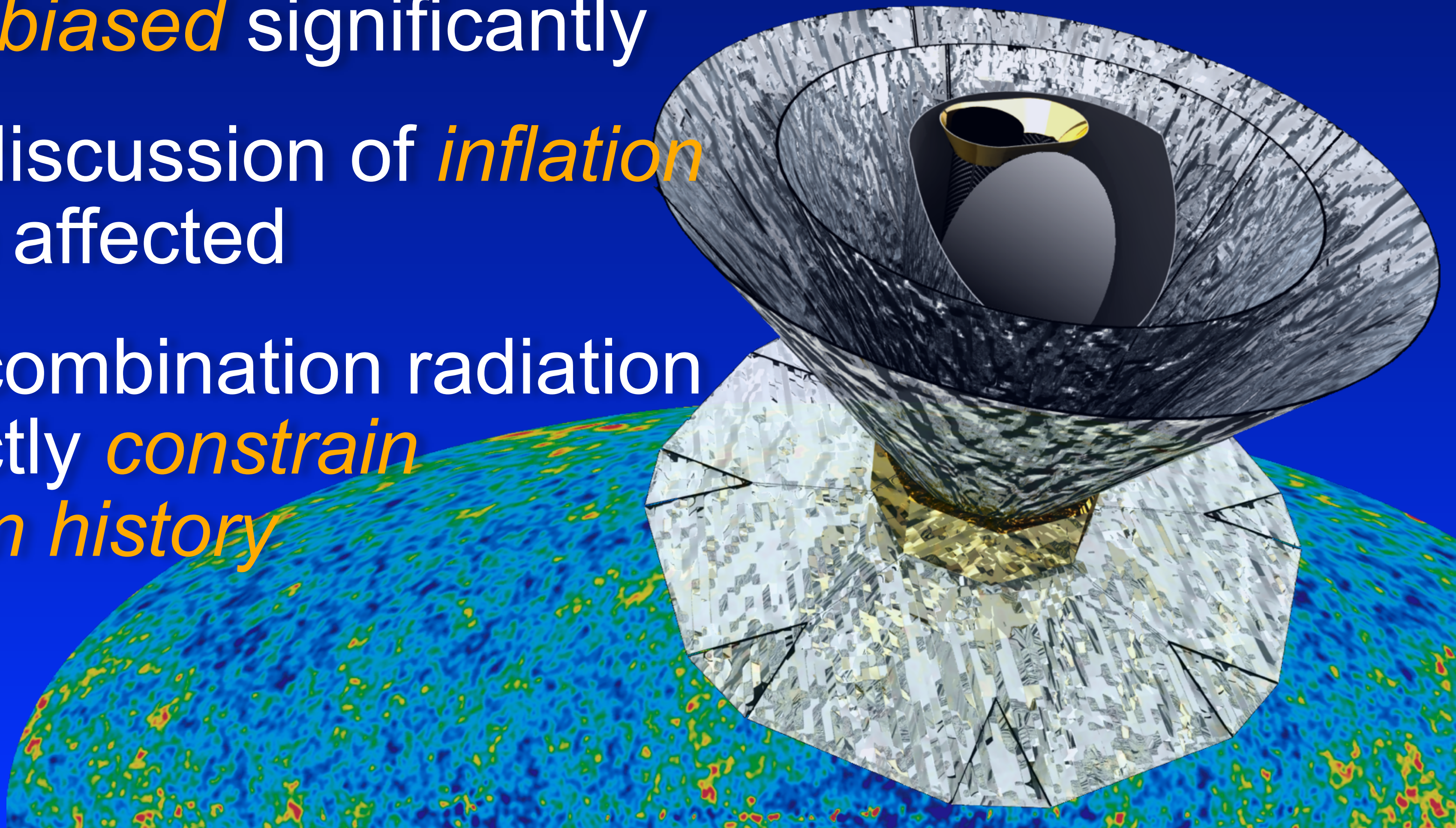
→ ***sensitive to energy release during recombination***

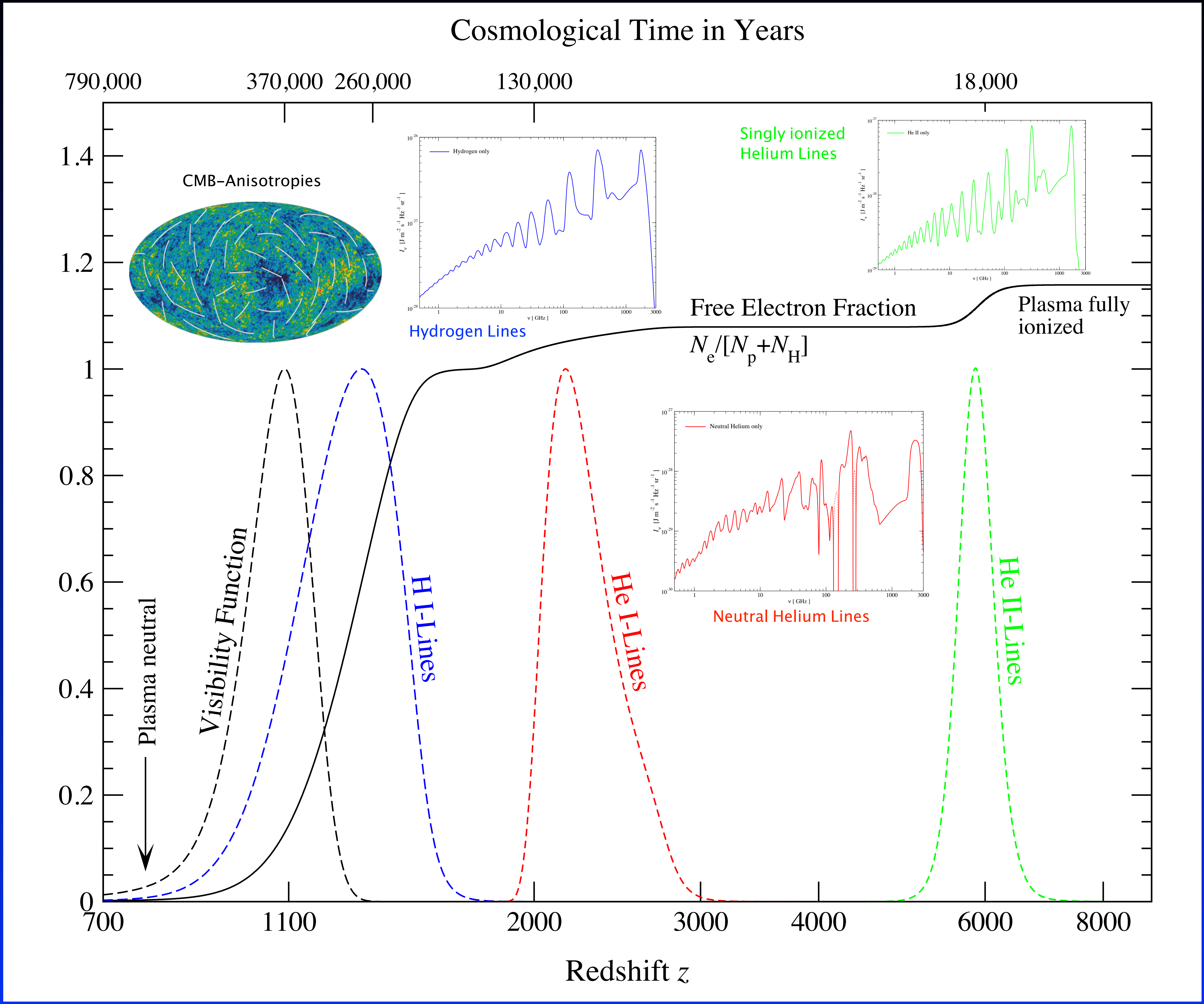
→ **variation of fundamental constants**



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
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully
ionized
Neutral Helium only
Neutral Helium Lines
Plasma neutral
Visibility Function
H I-Lines
He I-Lines
He II-Lines