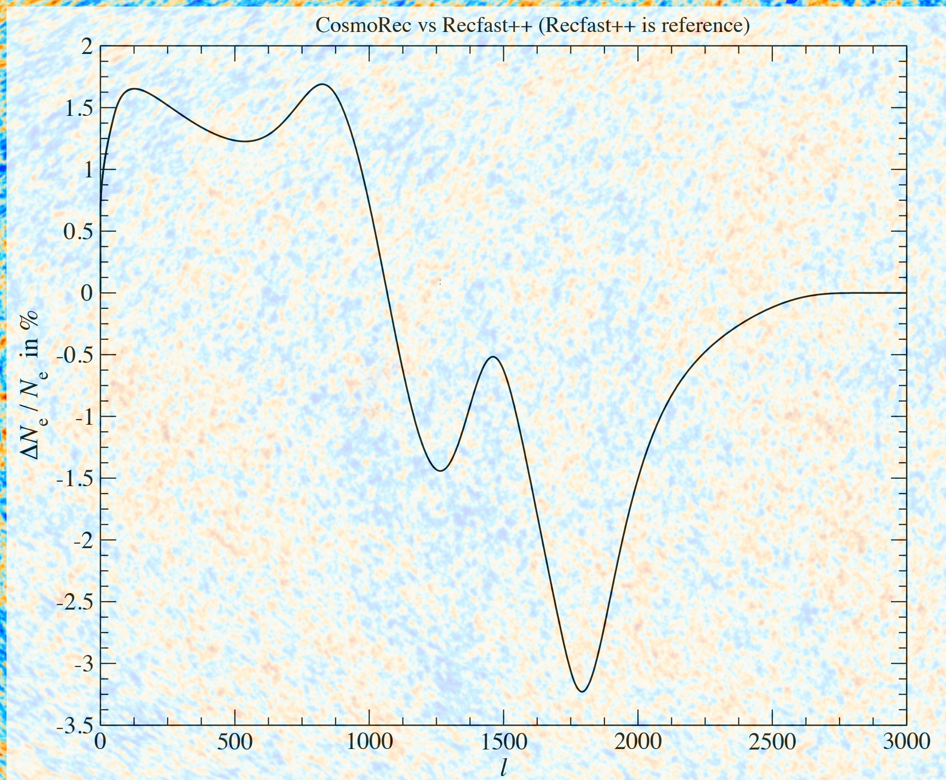
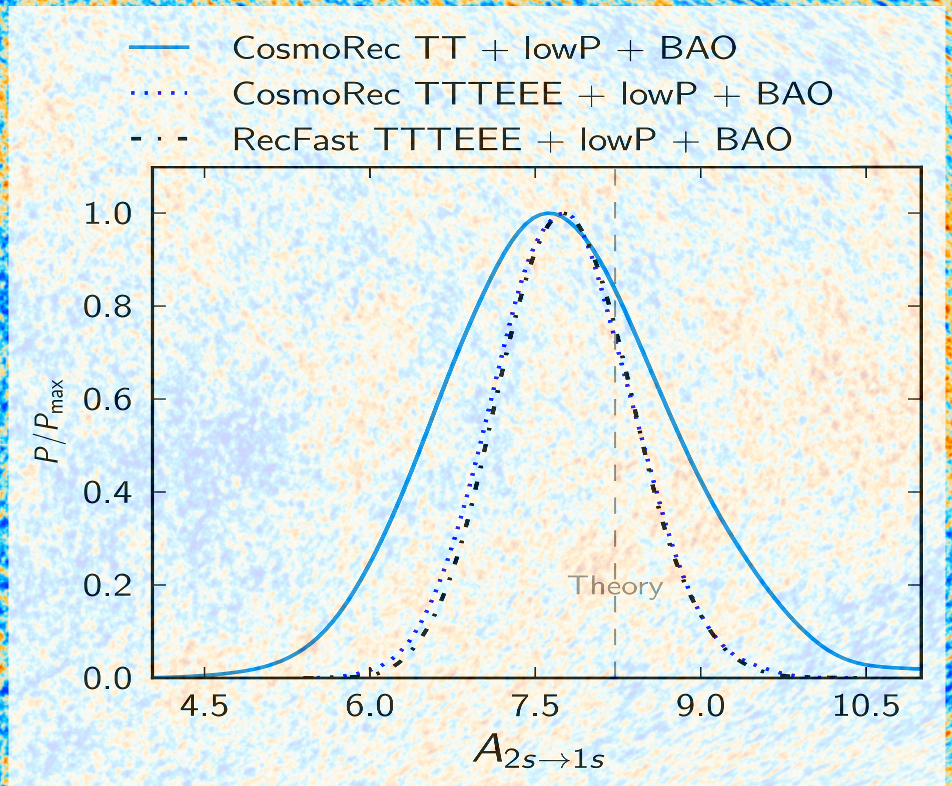
Understanding the Cosmological Recombination Problem to ~0.1% Precision

Accurate Recombination History



HI 2s-1s two-photon decay rate



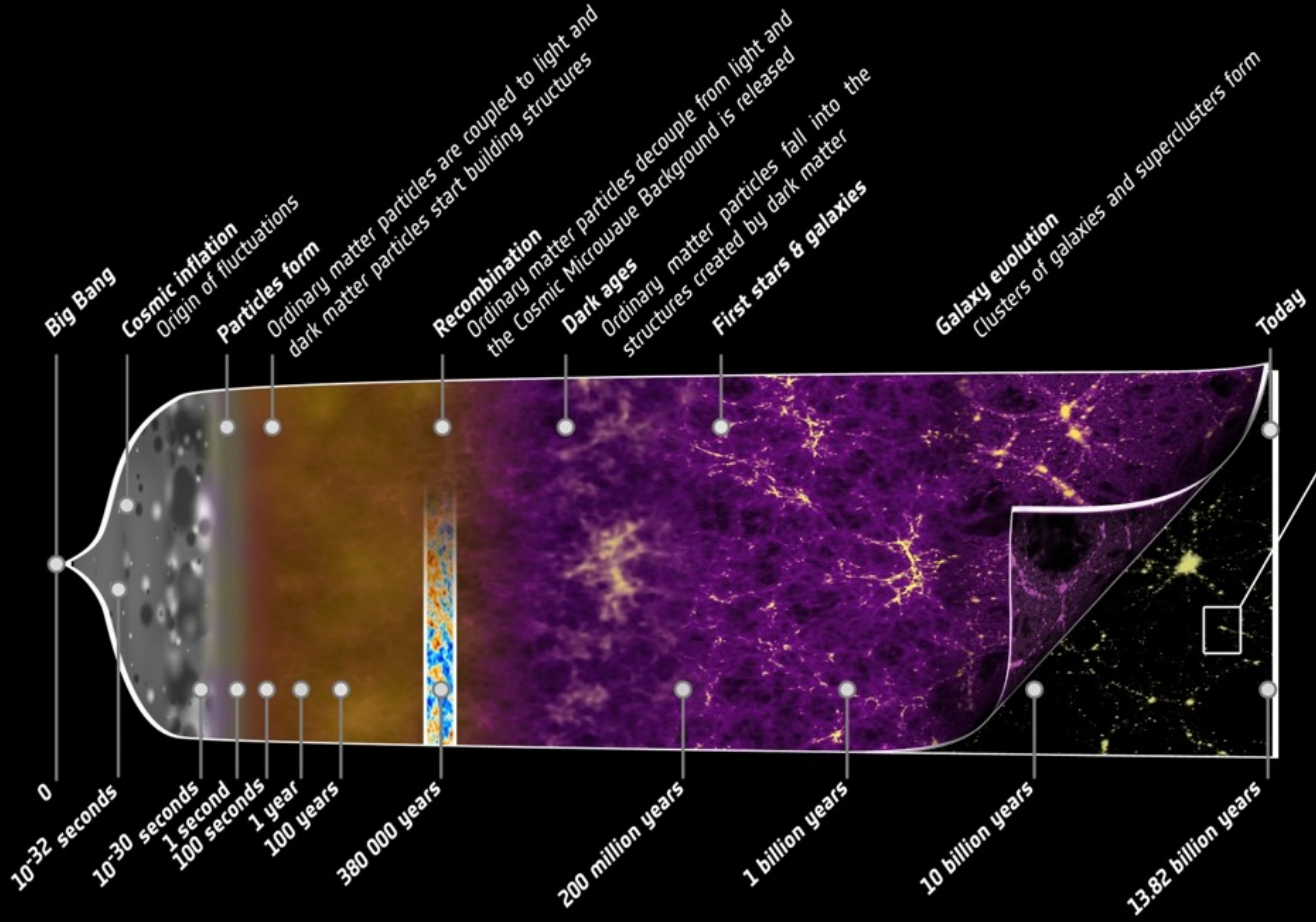
Jens Chluba

The Reionization History of the Universe

Bielefeld, Germany, March 8th - 9th, 2018

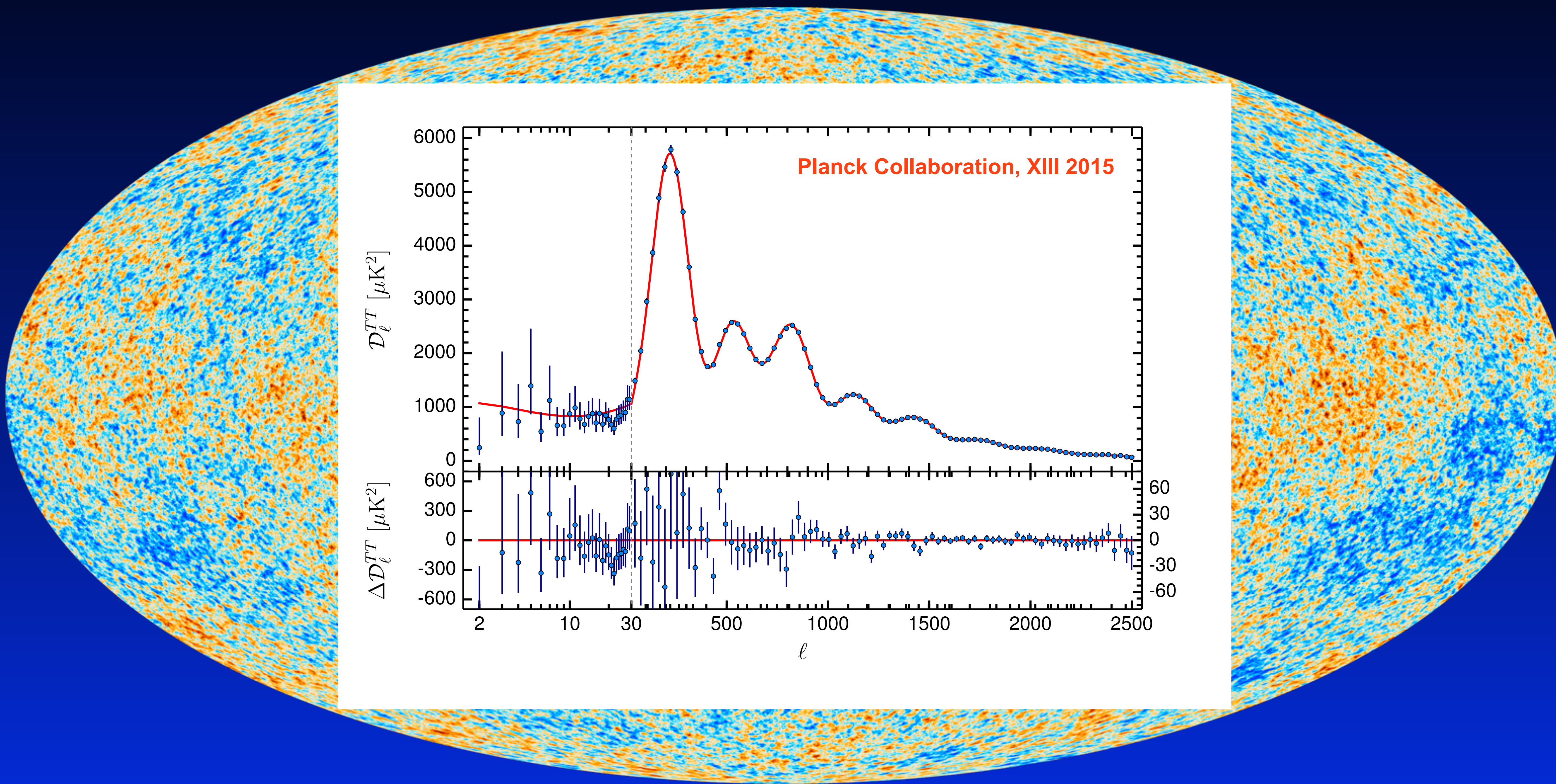
MANCHESTER 1824
The University of Manchester

erc THE ROYAL SOCIETY



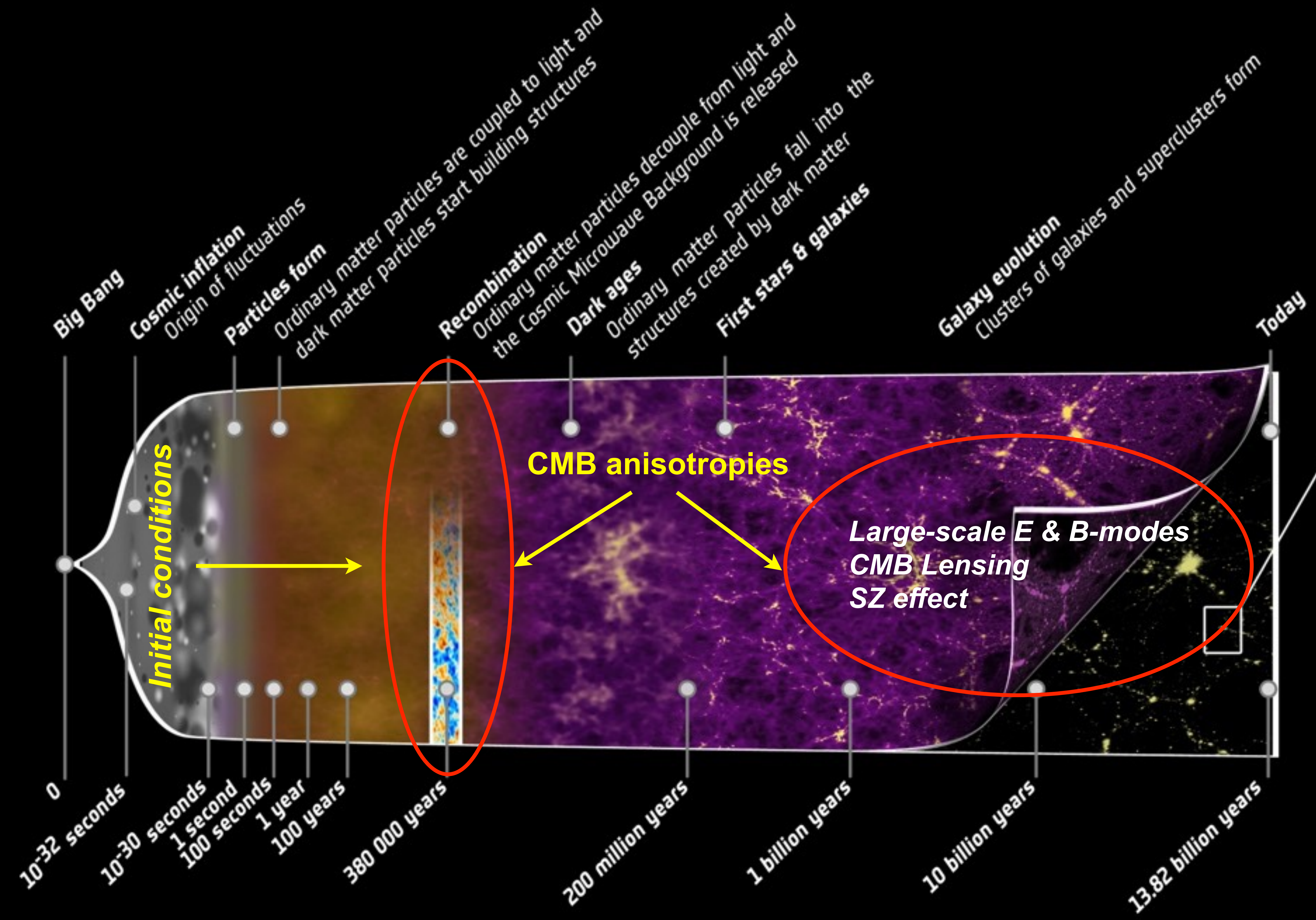
Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and
dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and
the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles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

Cosmic Microwave Background Anisotropies



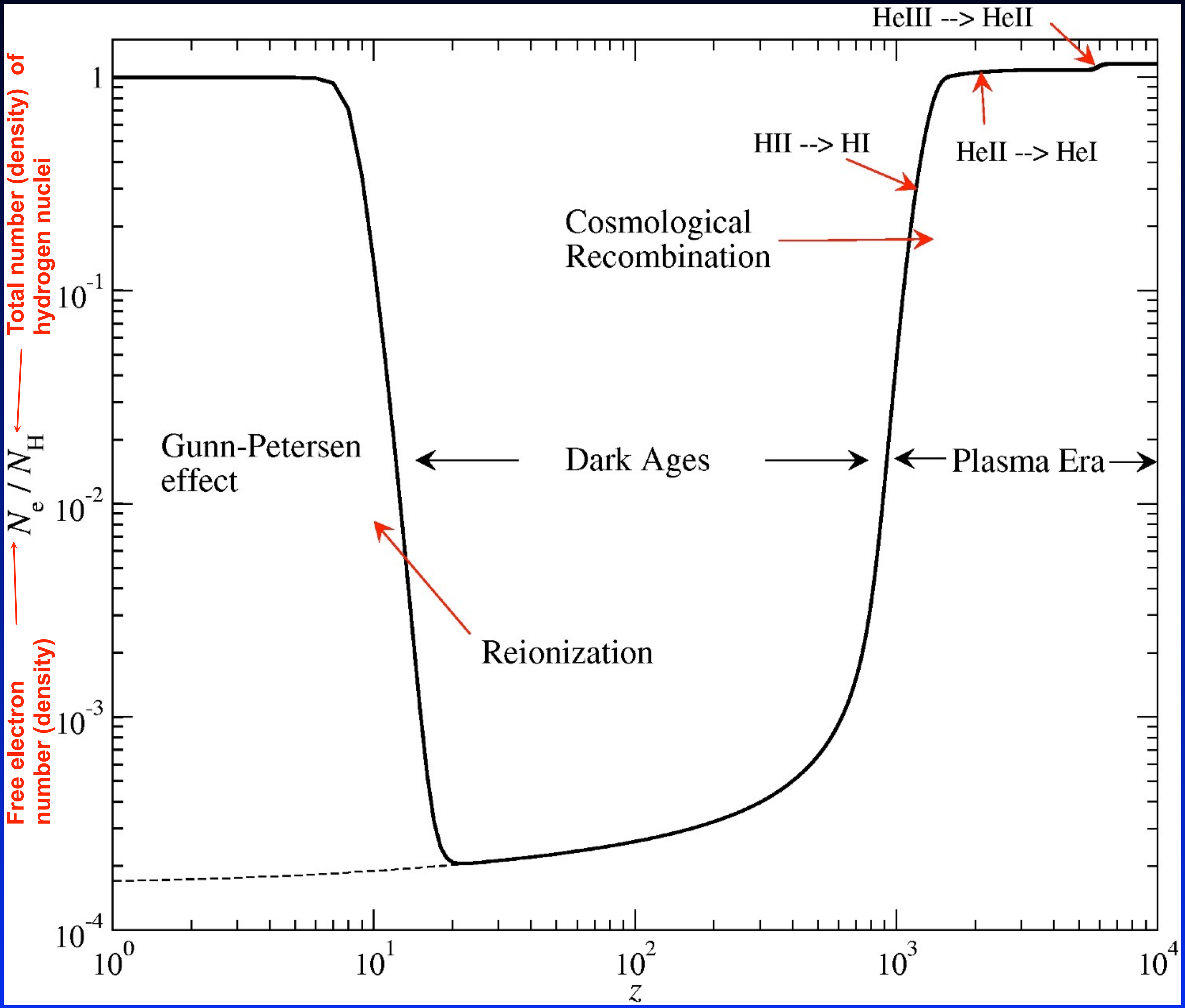
Planck all sky map

- 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**

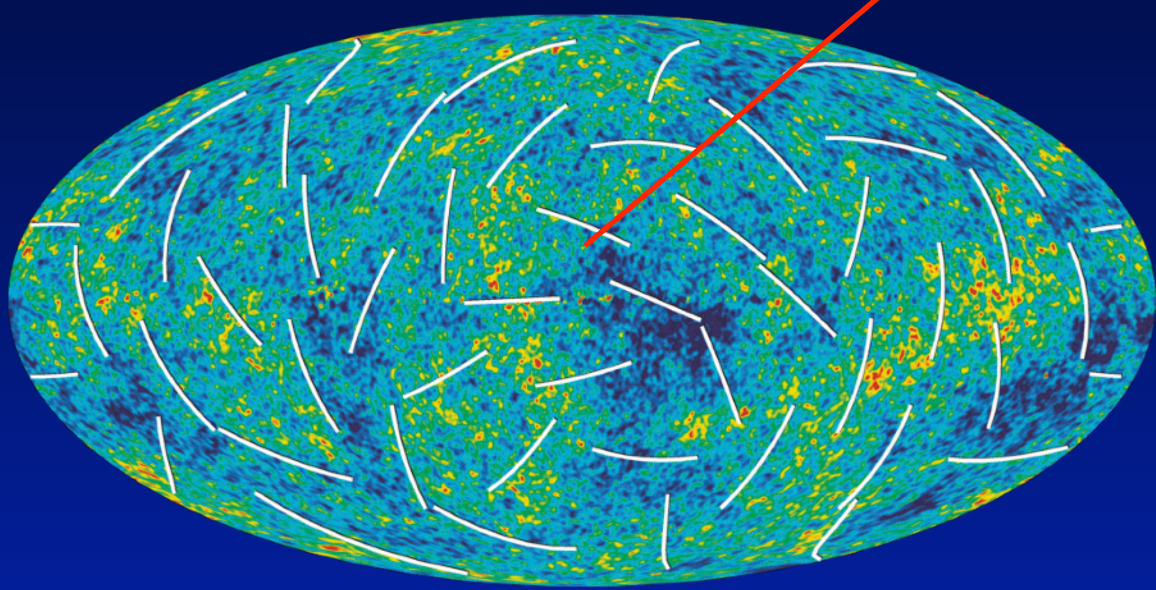
CMB Sky → Cosmology

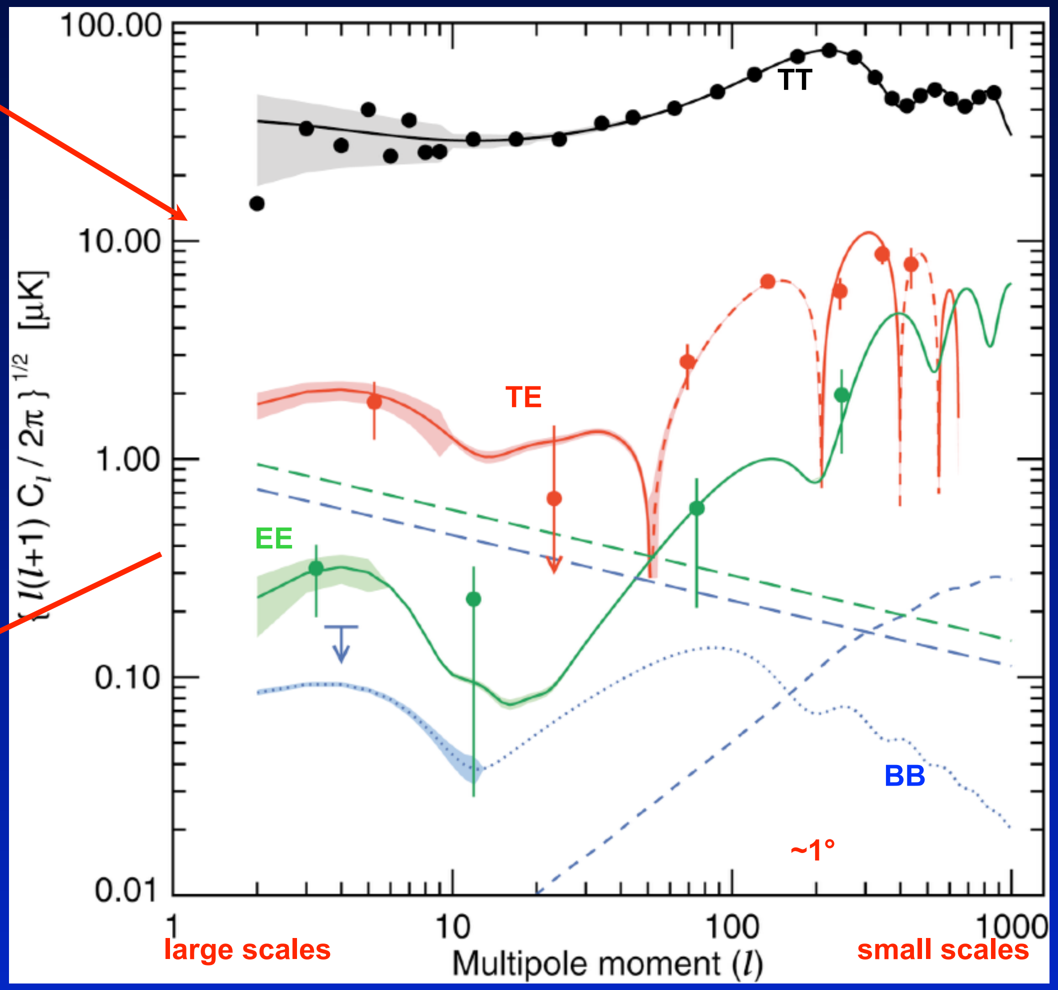
$N_e(z)$ is a *crucial* input

a_{lm}

Power spectra

WMAP CMB Sky





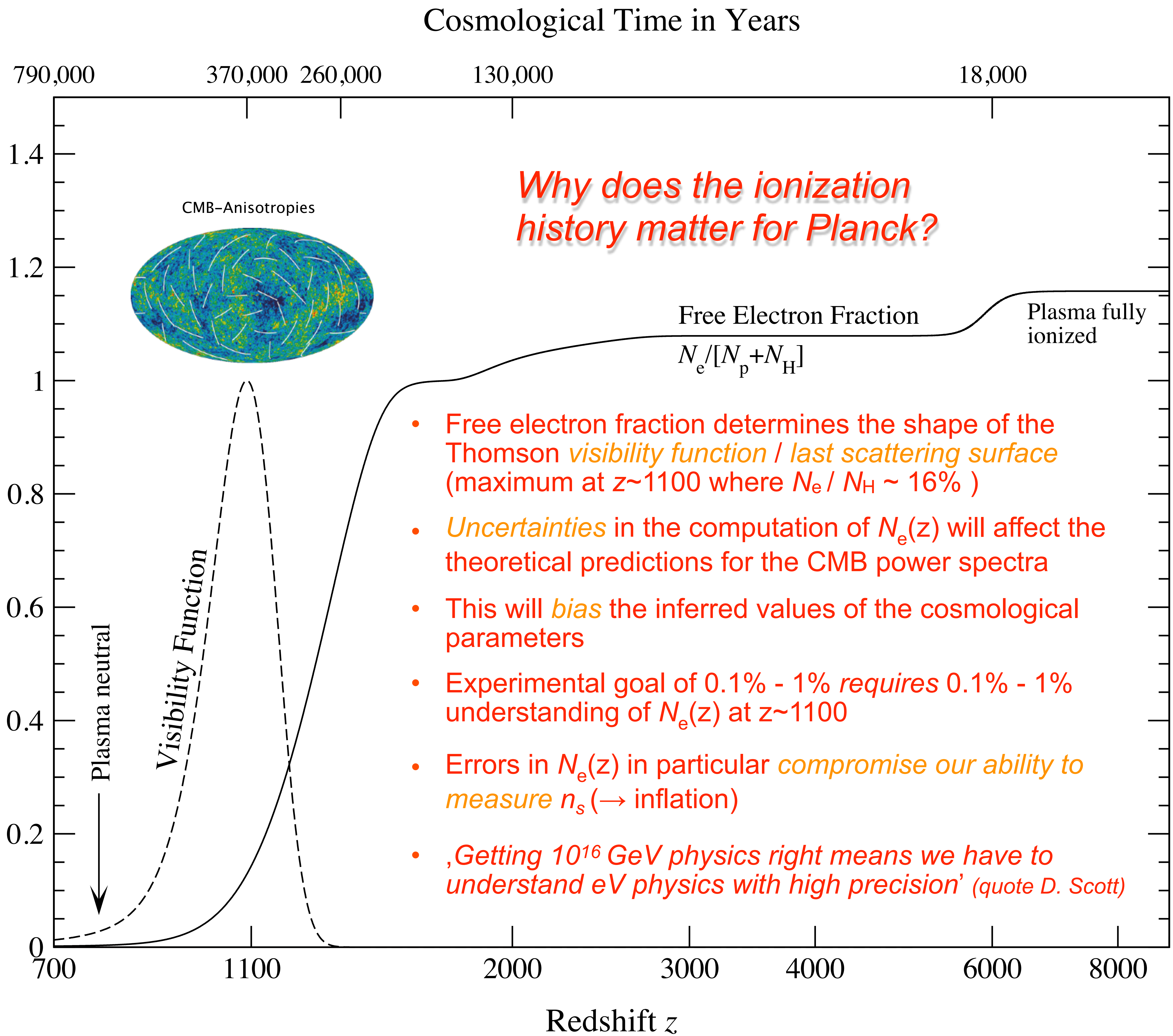
(Joint) analysis

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
Why does the ionization history matter for Planck?
CMB-Anisotropies
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~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 (→ inflation)
• *‚Getting 10^{16} GeV physics right means we have to understand eV physics with 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?

Physical Conditions during Recombination

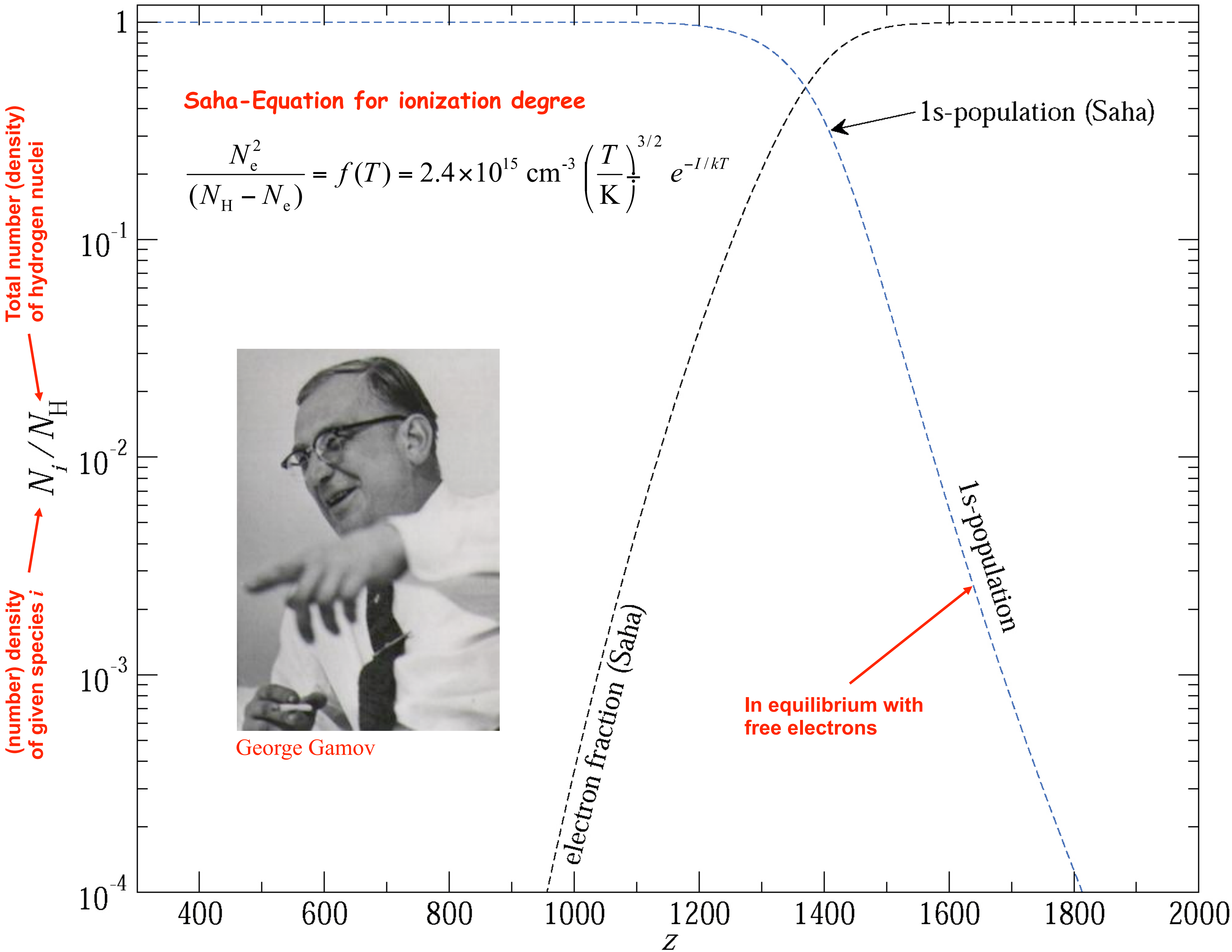
- Temperature T_γ ~ 2.725 (1+z) K ~ 3000 K
- Baryon number density N_b ~ 2.5×10^{-7}cm^{-3} $(1+z)^3$ ~ 330 cm^{-3}
- Photon number density N_γ ~ 410 cm^{-3} $(1+z)^3$ ~ 2×10^9 N_b

  ⇒ *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

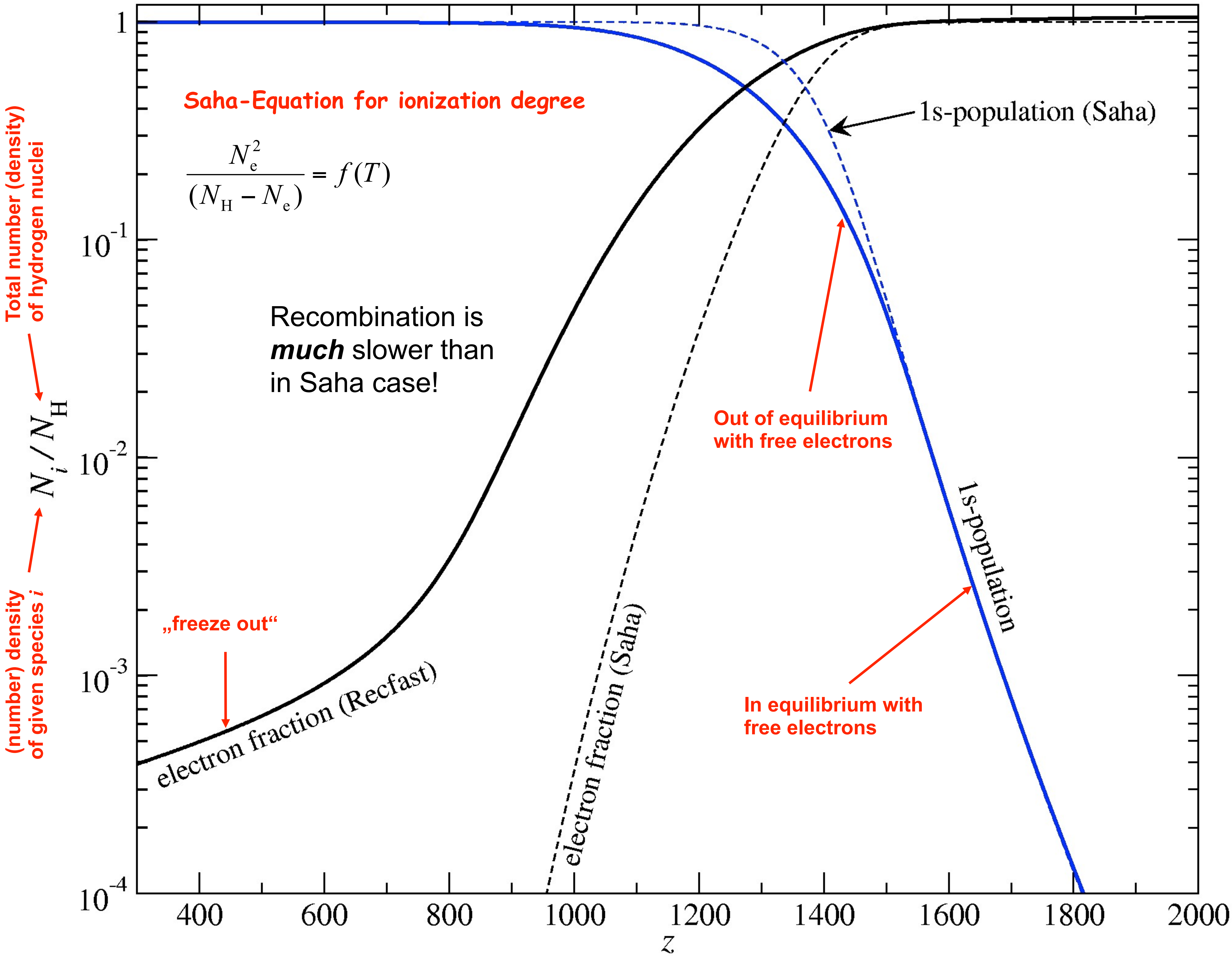
- Collisional processes negligible (*completely different in stars!!!*)
- Rates dominated by radiative processes

  (*e.g. stimulated emission & stimulated recombination*)

- Compton interaction couples electrons very tightly to photons until z ~ 200 ⇒ $T_\gamma \sim T_e \sim T_m$

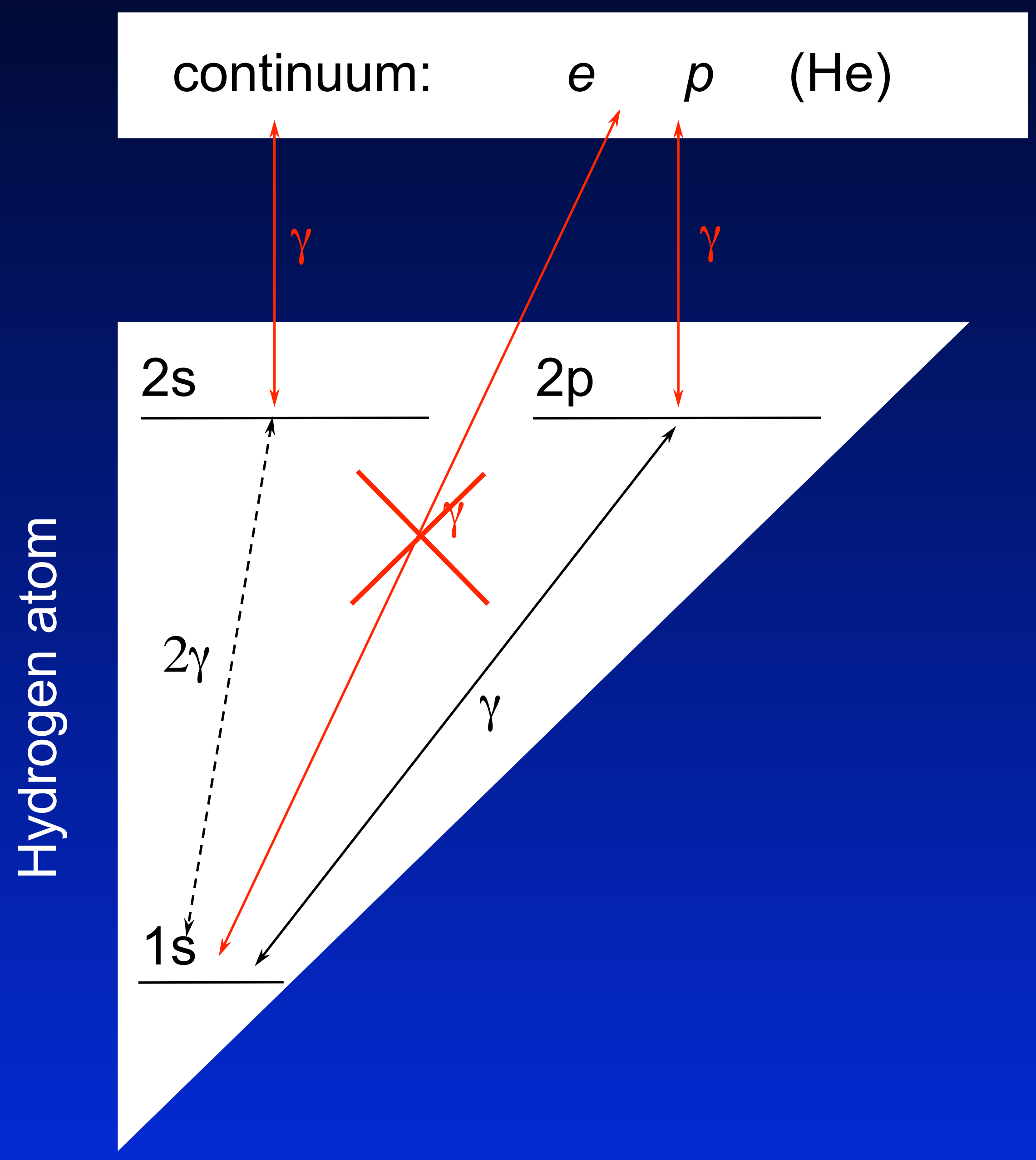


Saha-Equation for ionization degree
$$\frac{N_e^2}{(N_H - N_e)} = f(T) = 2.4\times10^{15}\ \mathrm{cm}^{-3}\left(\frac{T}{\mathrm{K}}\right)^{3/2} e^{-I/kT}$$
1s-population (Saha)
electron fraction (Saha)
1s-population
In equilibrium with free electrons
George Gamov
Total number (density) of hydrogen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



Saha-Equation for ionization degree
$$\frac{N_e^2}{(N_H - N_e)} = f(T)$$
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
N_i / N_H
(number) density of given species i
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
400
600
800
1000
1200
1400
1600
1800
2000
z

3-level Hydrogen Atom and Continuum



Routes to the ground state ?

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

  No

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

  ~ 43%

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

  ~ 57%

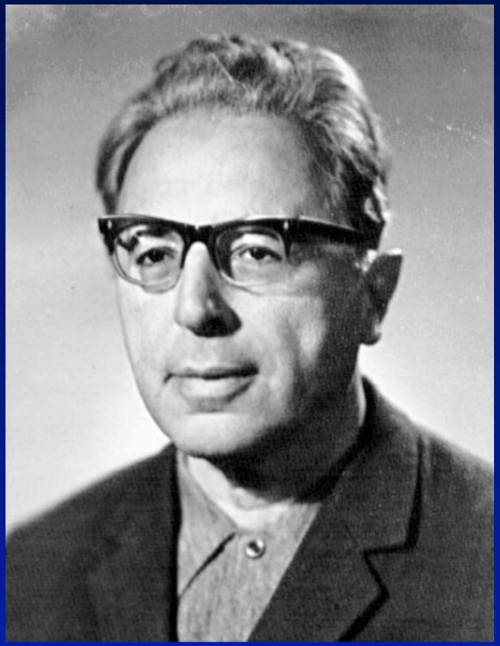
Zeldovich, Kurt & Sunyaev, 1968, ZhETF, 55, 278
Peebles, 1968, ApJ, 153, 1

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

These first computations were completed in 1968!

Moscow

Yakov Zeldovich

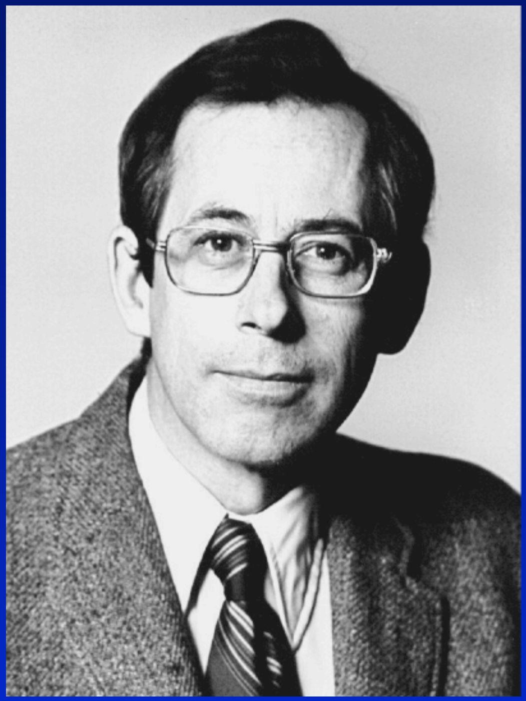


Iosif Shklovskii

Vladimir Kurt
(UV astronomer)

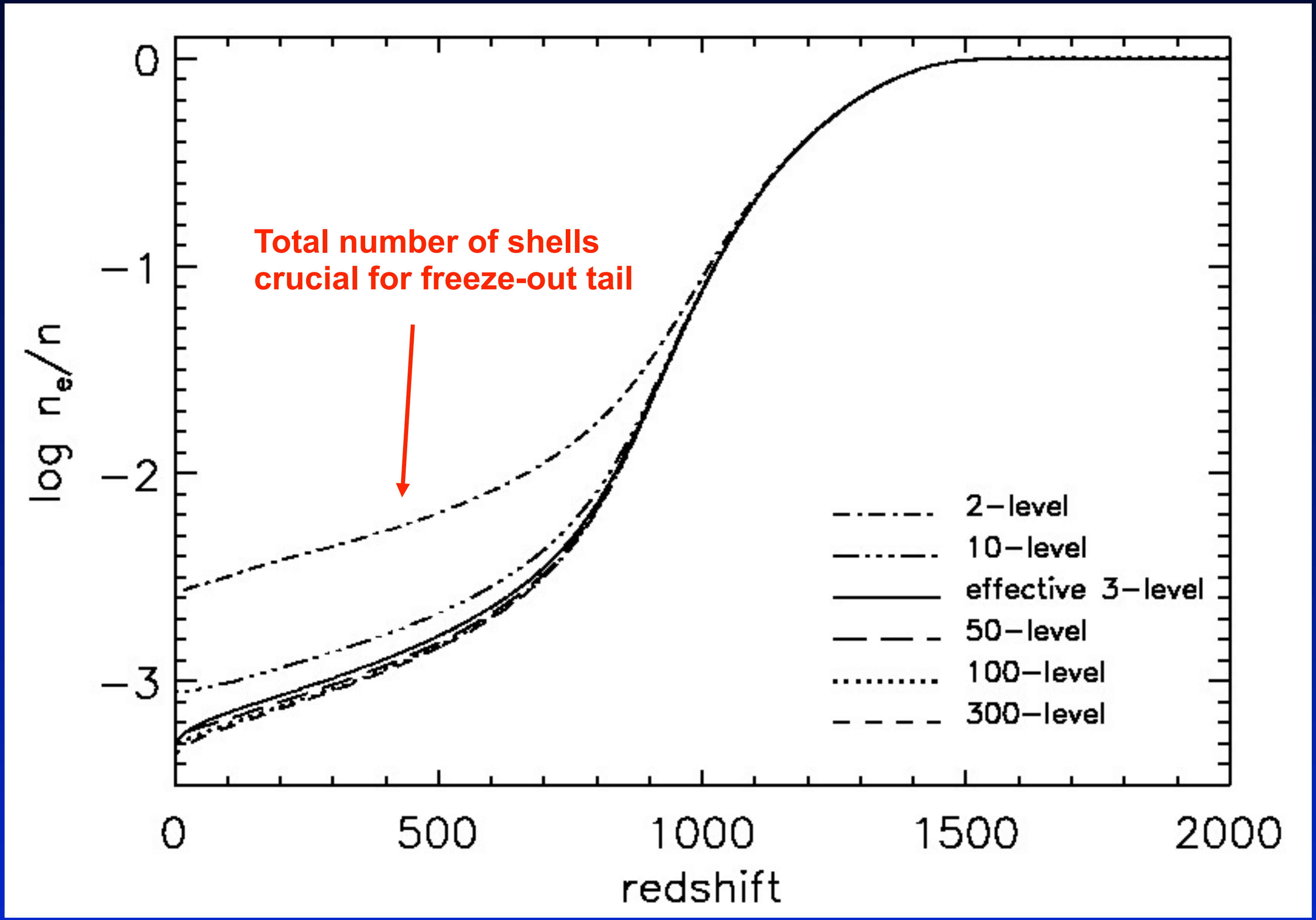
Rashid Sunyaev

Princeton



Jim Peebles

Multi-level Atom ⇔ Recfast-Code



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

Output of N_e/N_H

Hydrogen:

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

Helium:

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

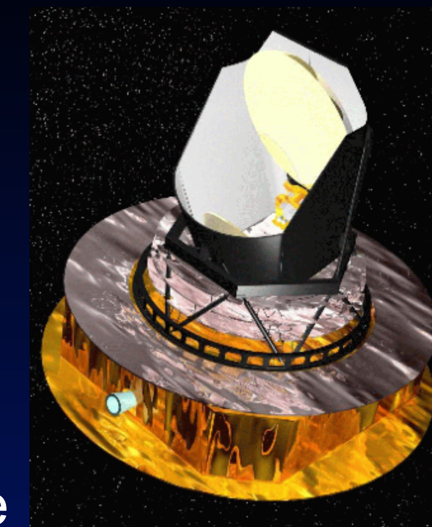
Low Redshifts:

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

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

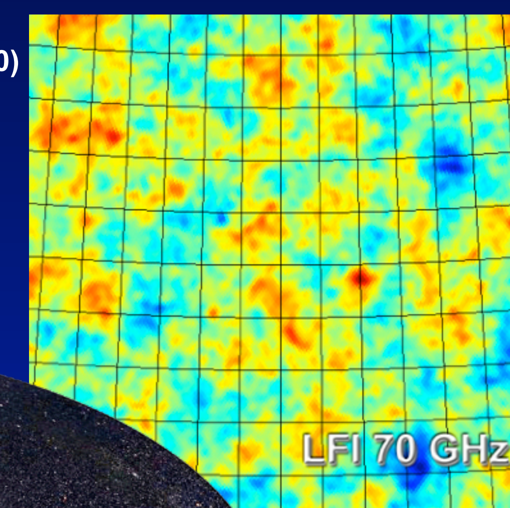
$\Delta N_e \,/\, N_e \sim 1\% - 3\%$

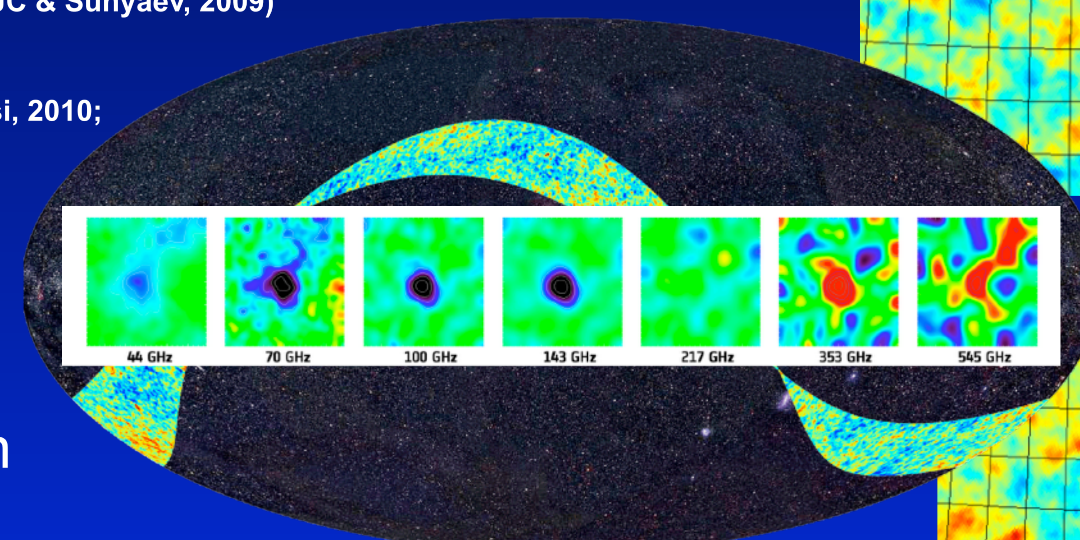
Getting the job done for *Planck*

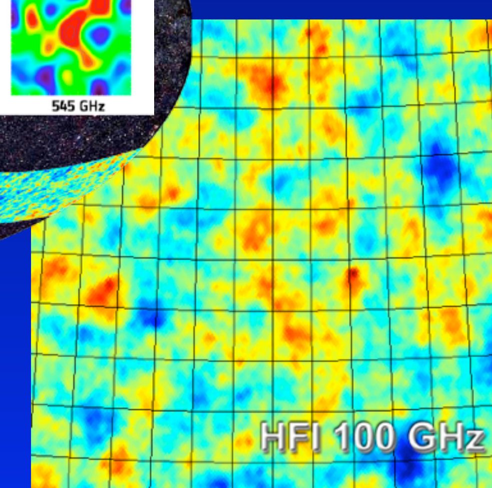


Hydrogen recombination

- 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)





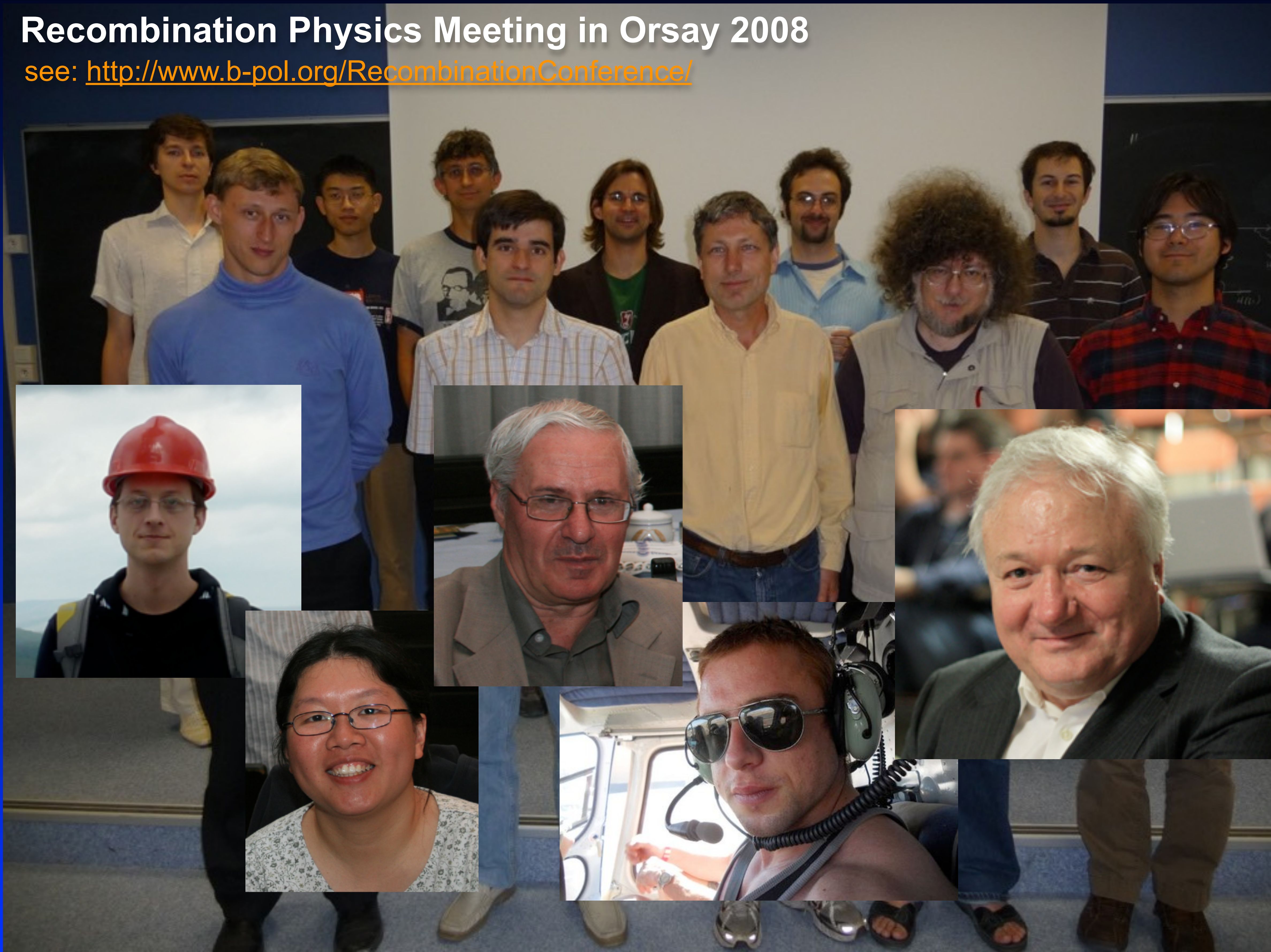


Helium recombination

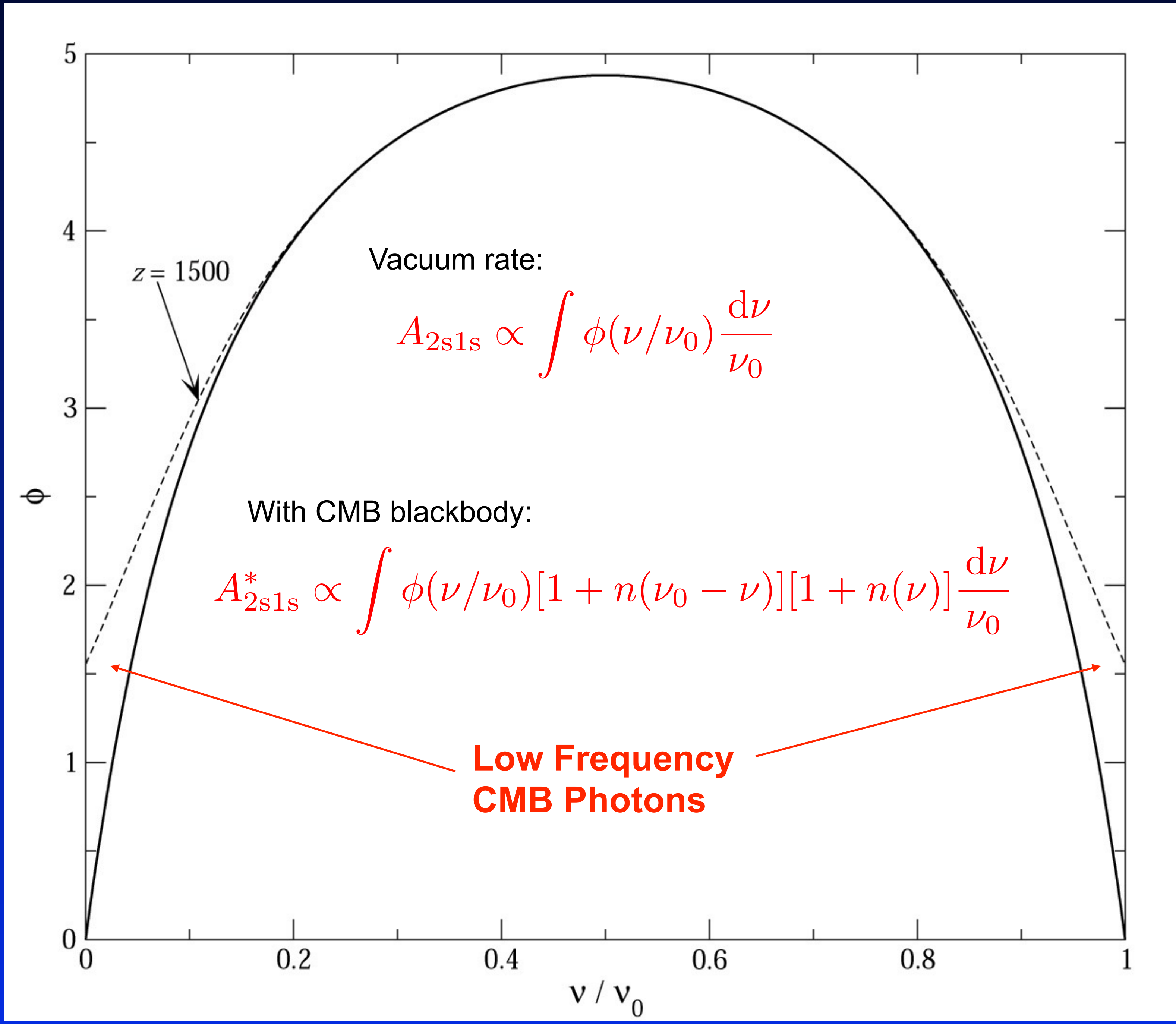
- Similar list of processes as for hydrogen
  (Switzer & Hirata, 2007a&b; Hirata & Switzer, 2007)
- Spin forbidden 2p-1s triplet-singlet transitions
  (Dubrovich & Grachev, 2005, Astr. Lett.; Wong & Scott, 2007; Switzer & Hirata, 2007; Kholupenko, Ivanchik&Varshalovich, 2007)
- Hydrogen continuum opacity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



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

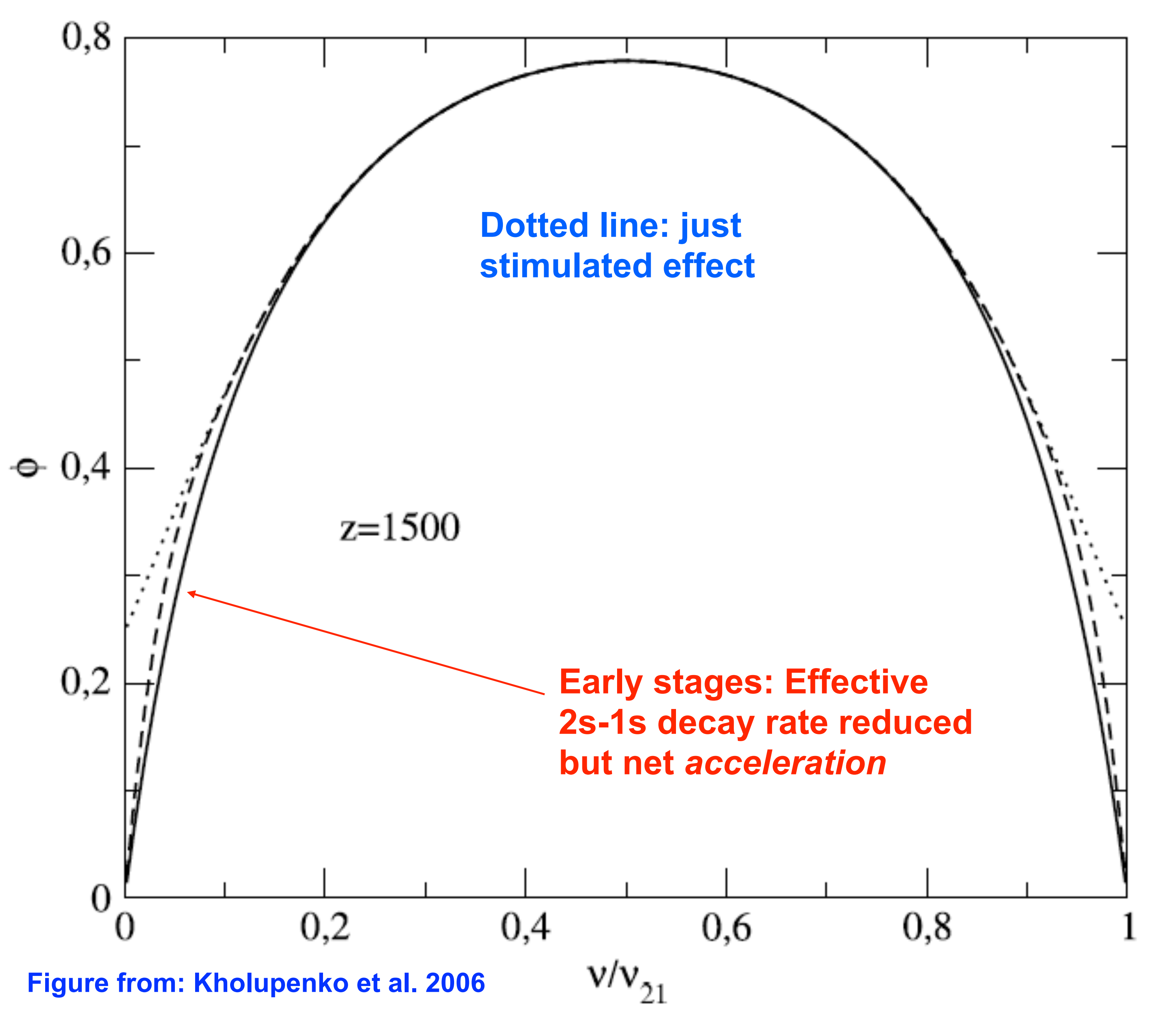


Figure from: Kholupenko et al. 2006

- 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

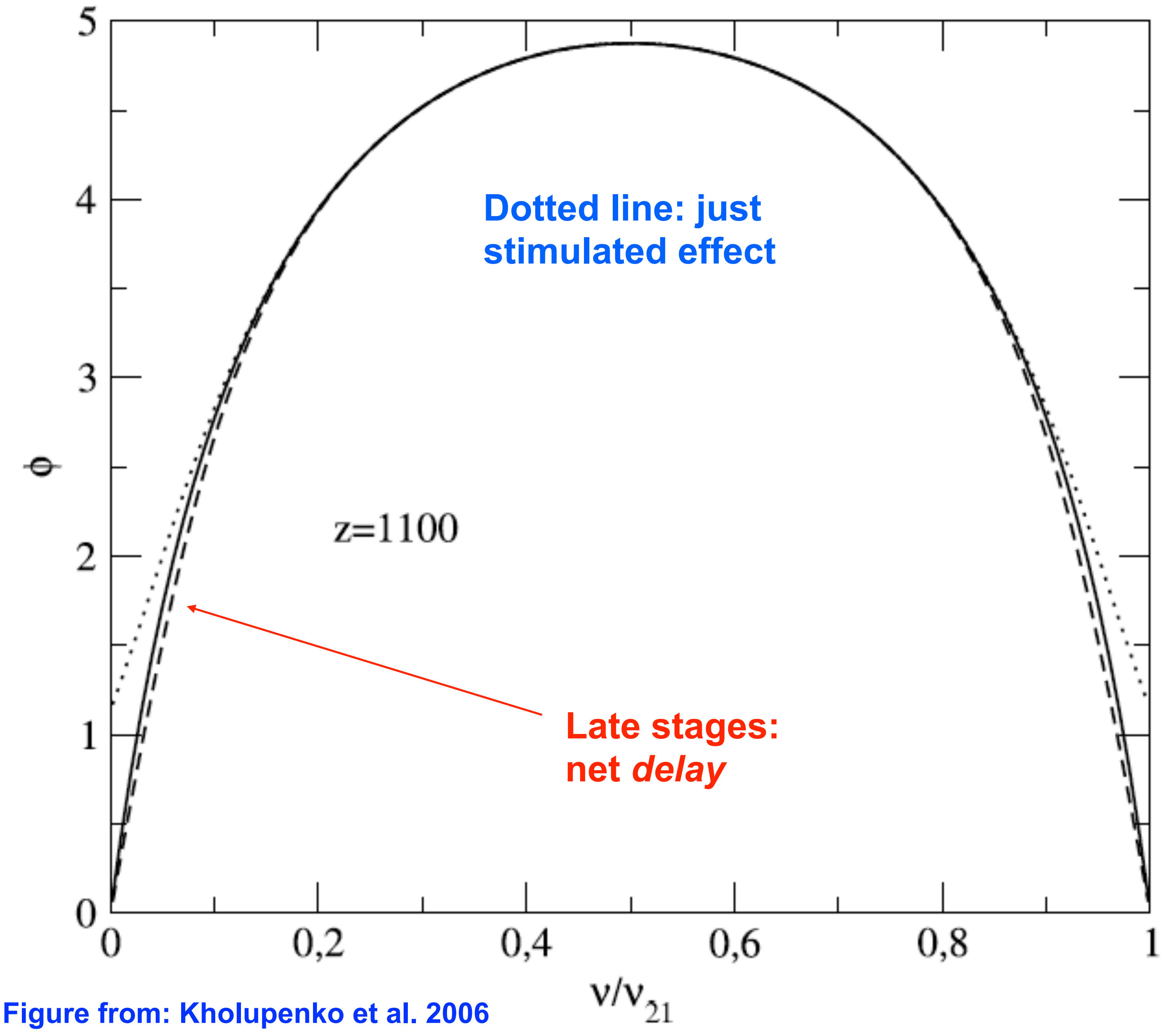
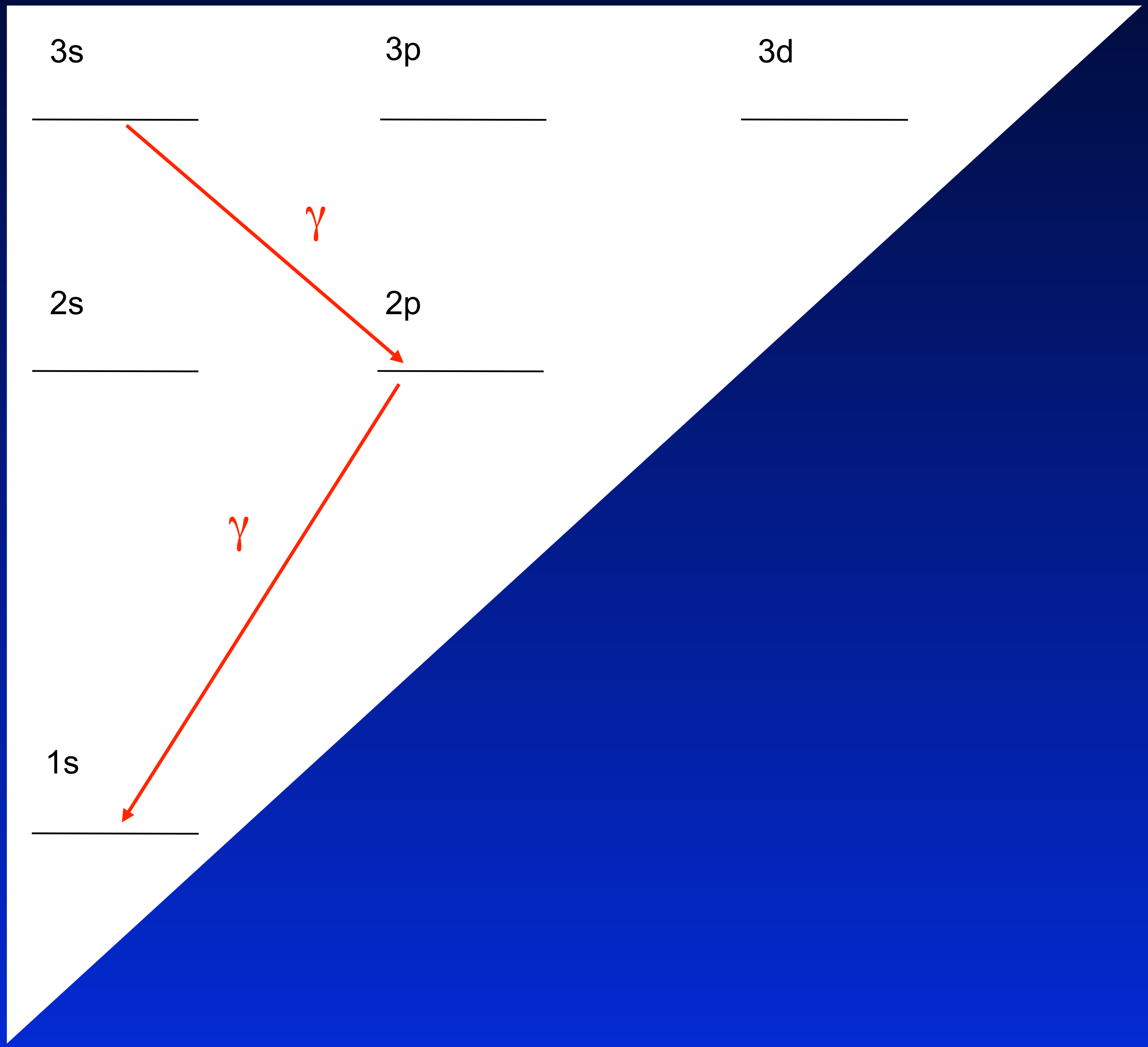


Figure from: Kholupenko et al. 2006

- 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

Two-photon emission process from upper levels



Seaton cascade (1+1 photon)

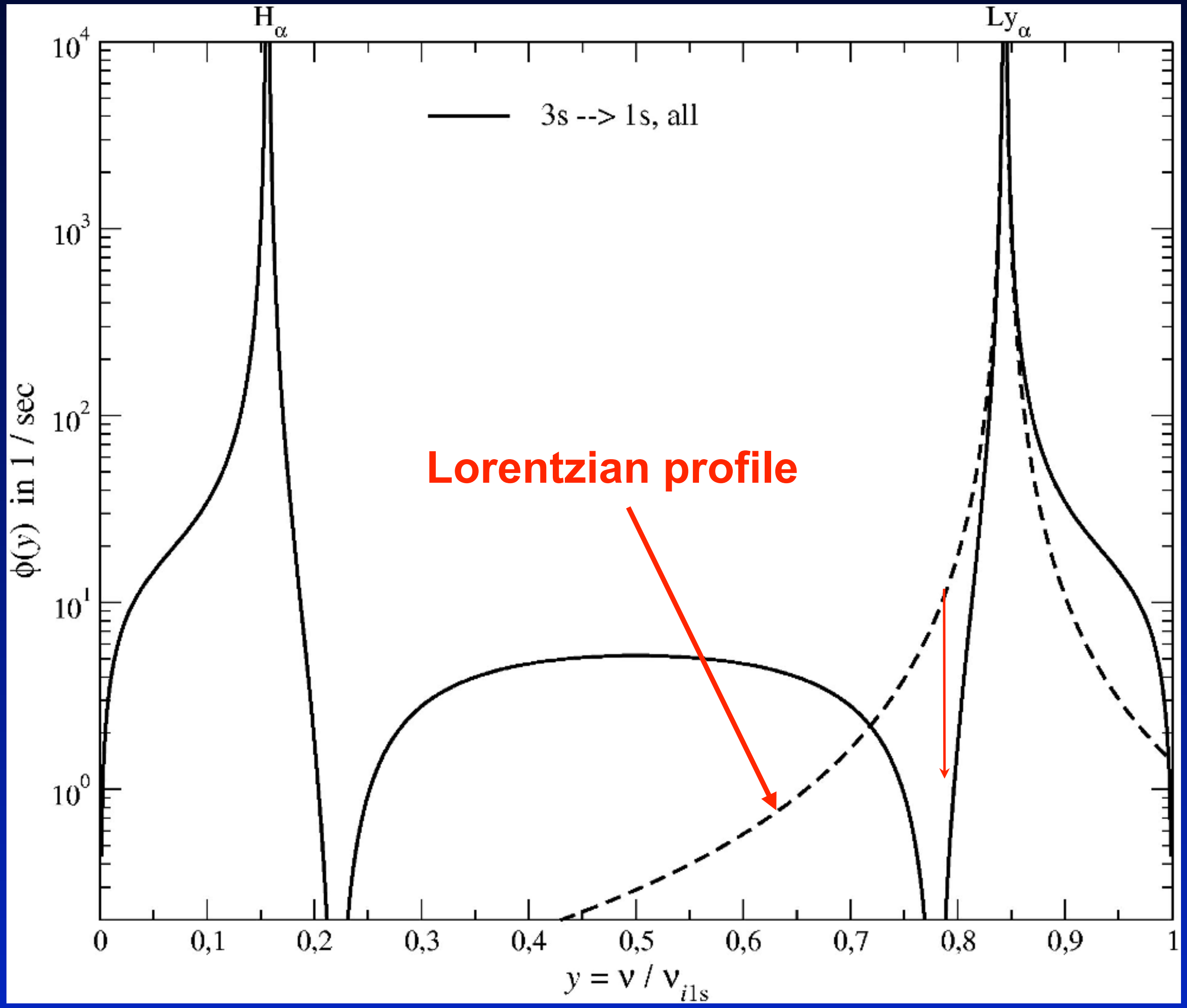
No collisions → two photons (mainly H-α and Ly-α) are emitted!

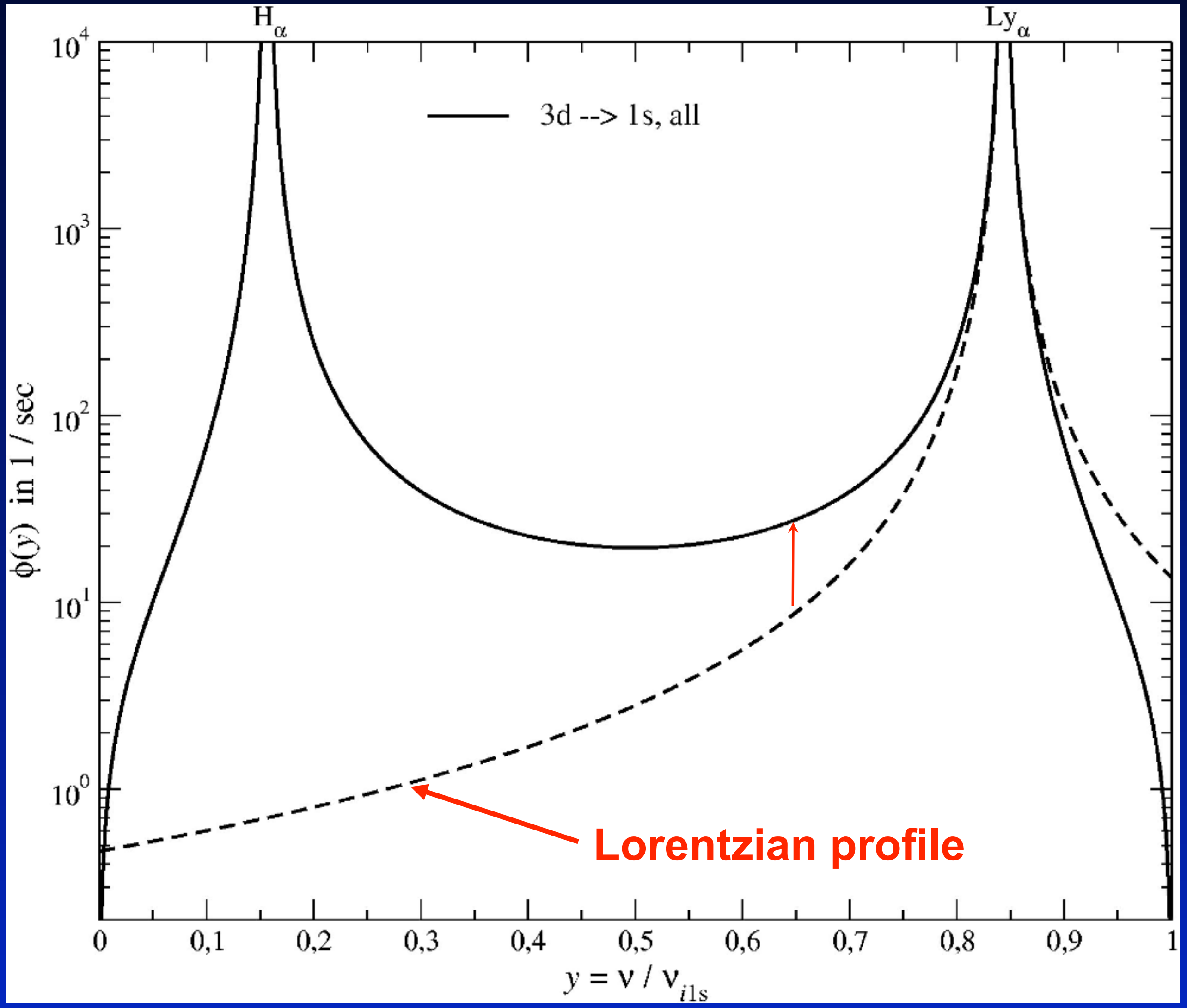
Maria-Göppert-Mayer (1931): description of two-photon emission as single process in Quantum Mechanics

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

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

3s and 3d two-photon decay spectrum





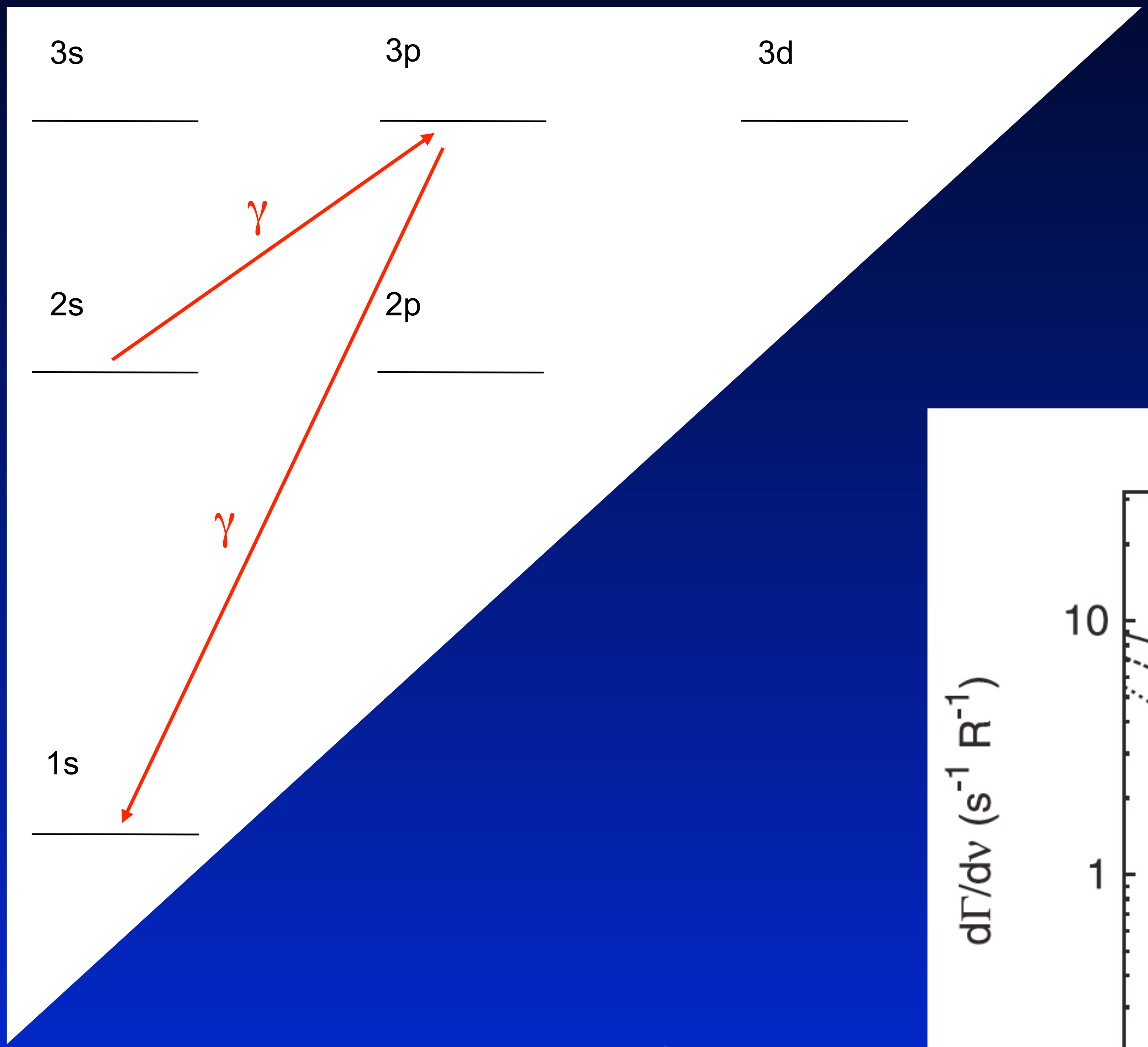
Direct Escape in optically thin regions:

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

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

JC & Sunyaev, A&A, 2008

2s-1s Raman scattering



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

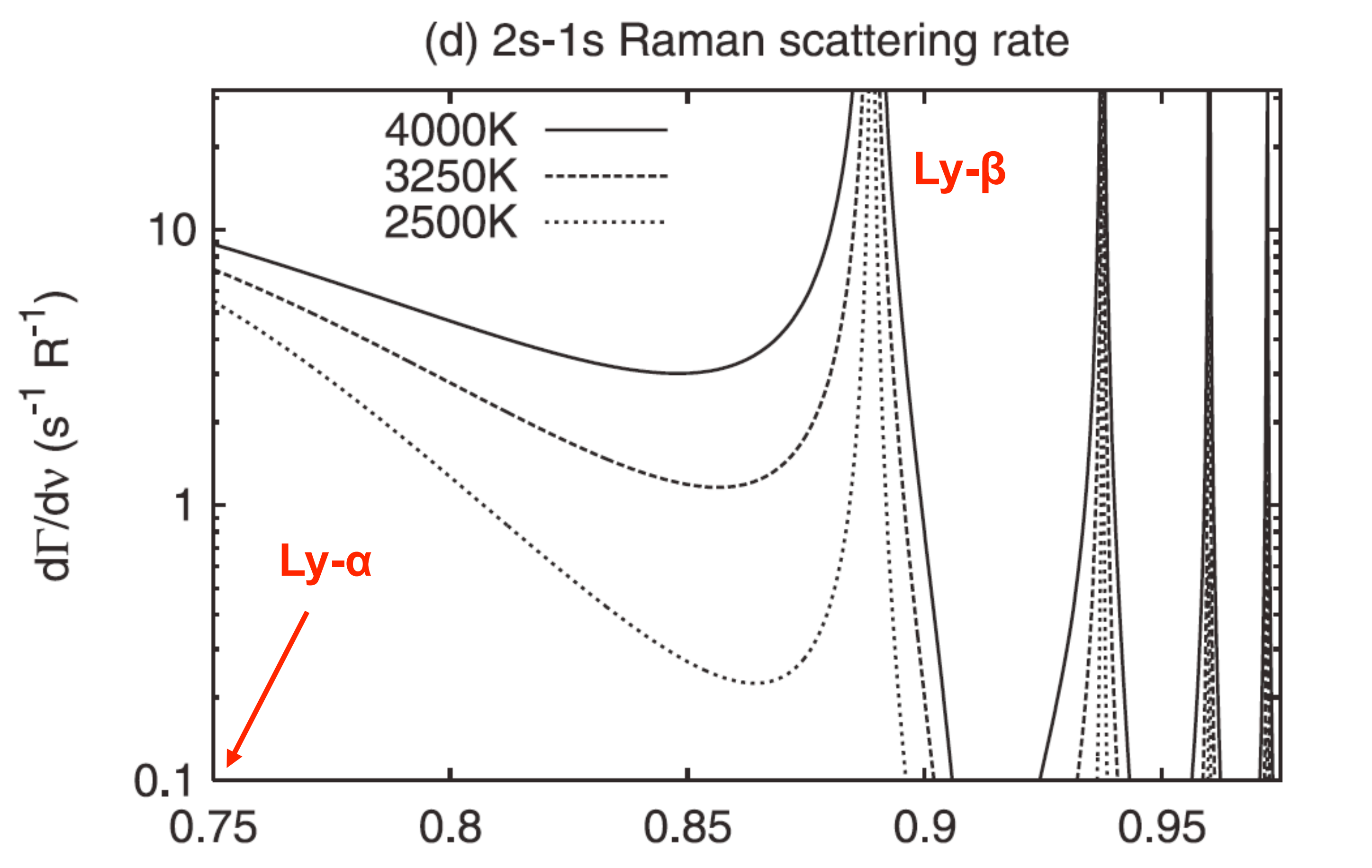
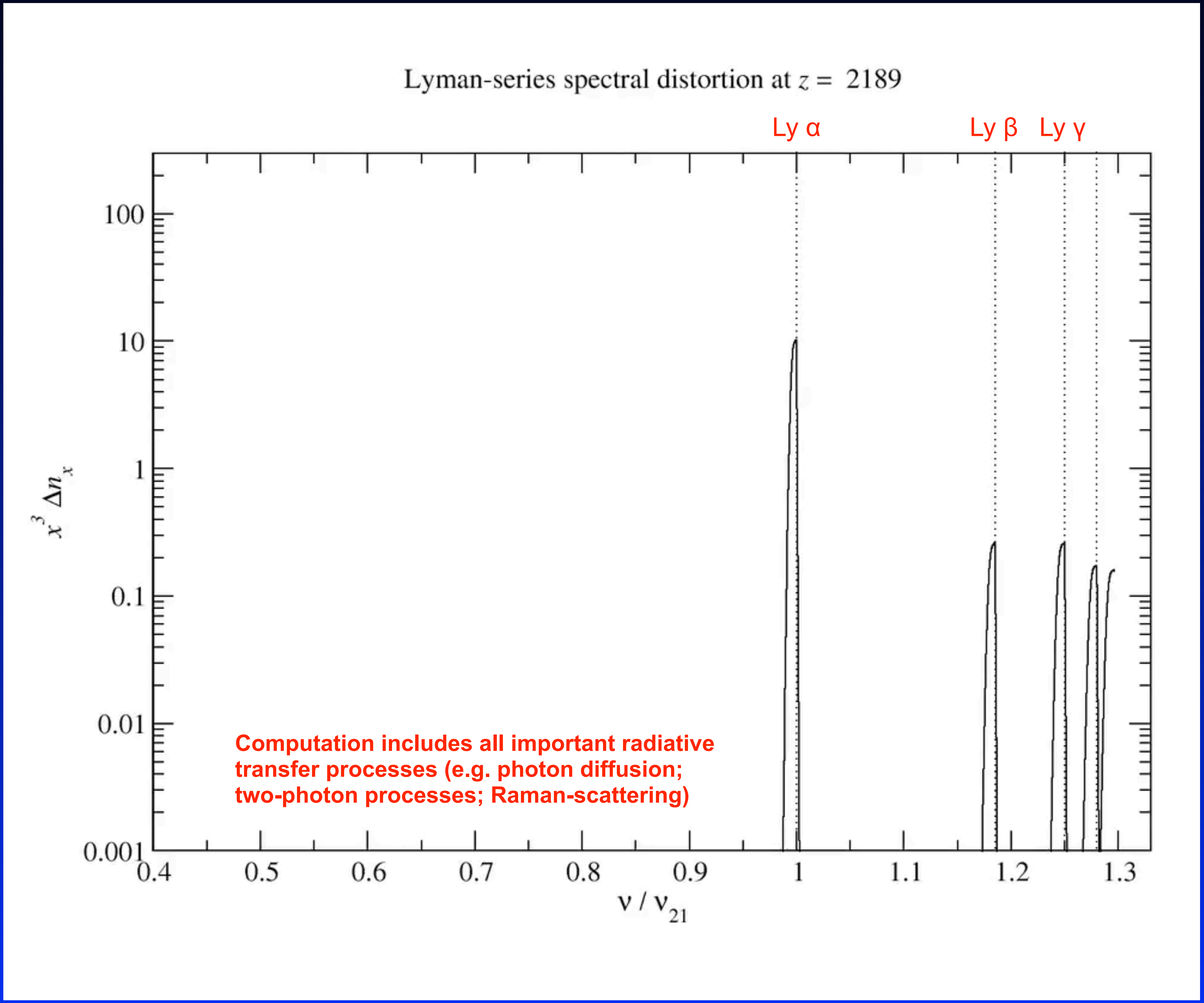


Figure from: Hirata 2008

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

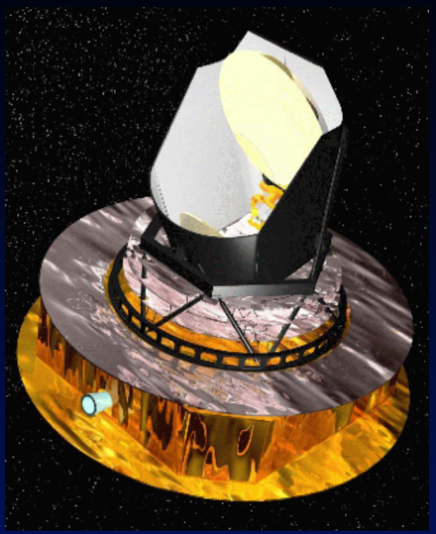
Hirata 2008
JC & Thomas, 2010

Evolution of the HI Lyman-series distortion



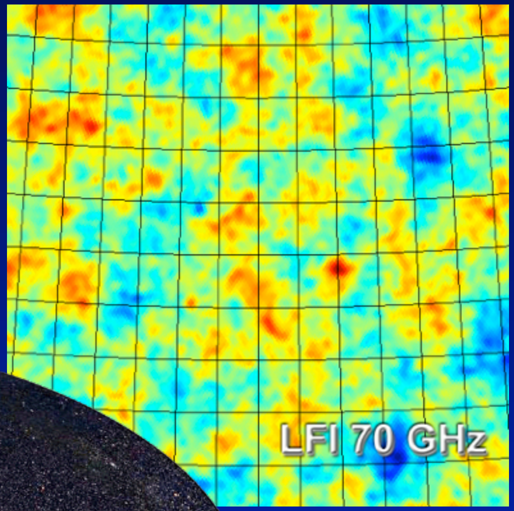
JC & Thomas, MNRAS, 2010

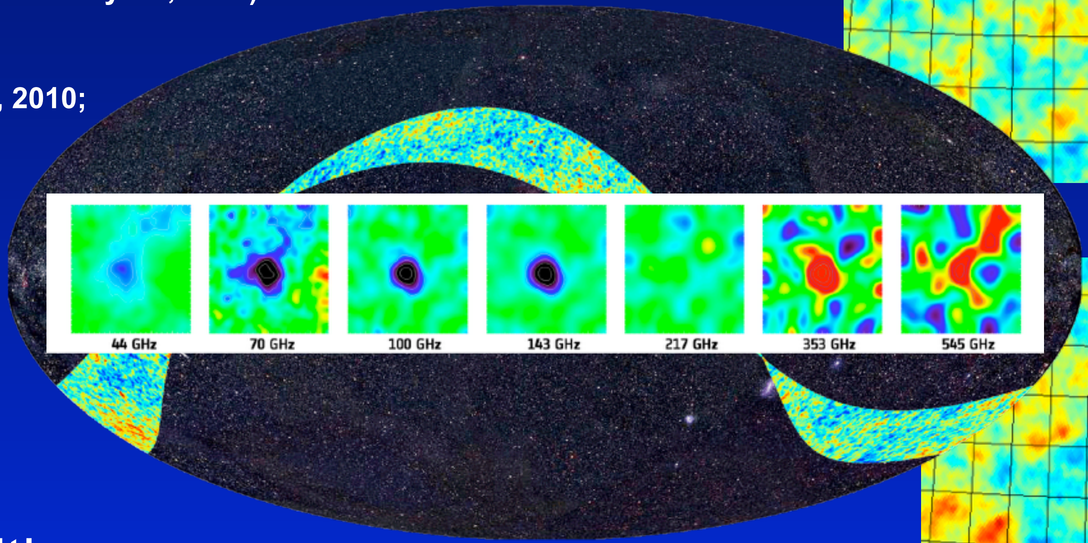
Getting the job done for *Planck*

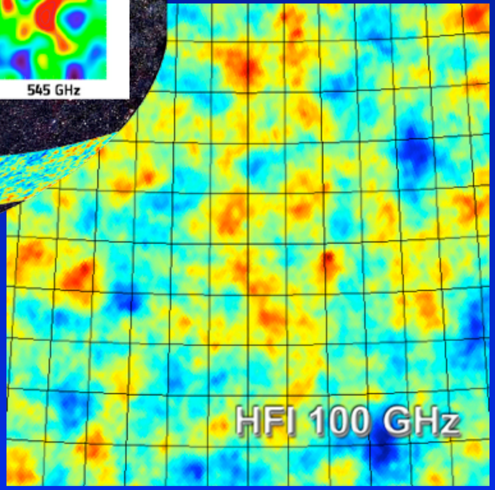


Hydrogen recombination

- 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)





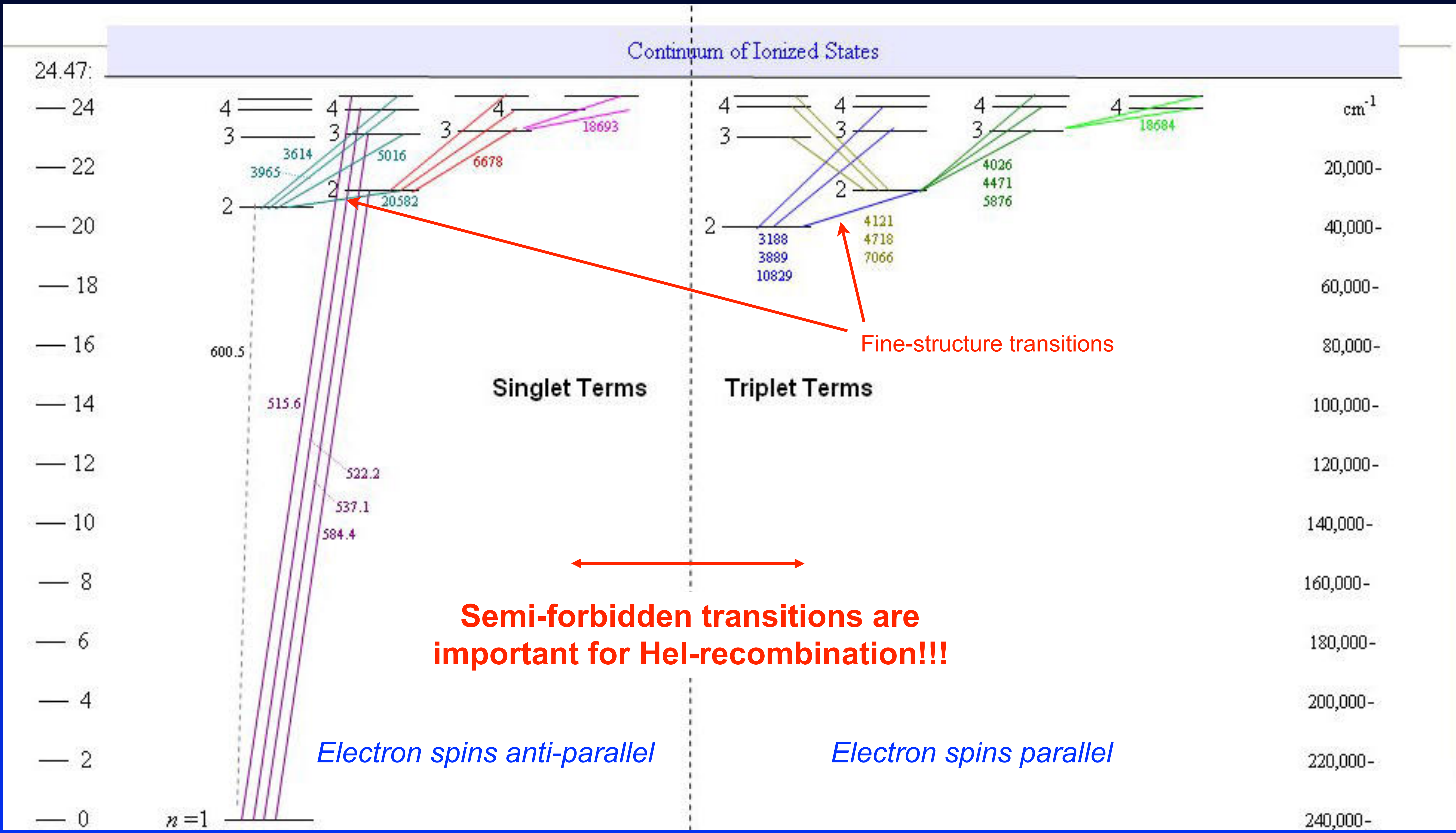


Helium recombination

- 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)

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

Grotrian diagram for neutral helium



Main corrections during HeI Recombination

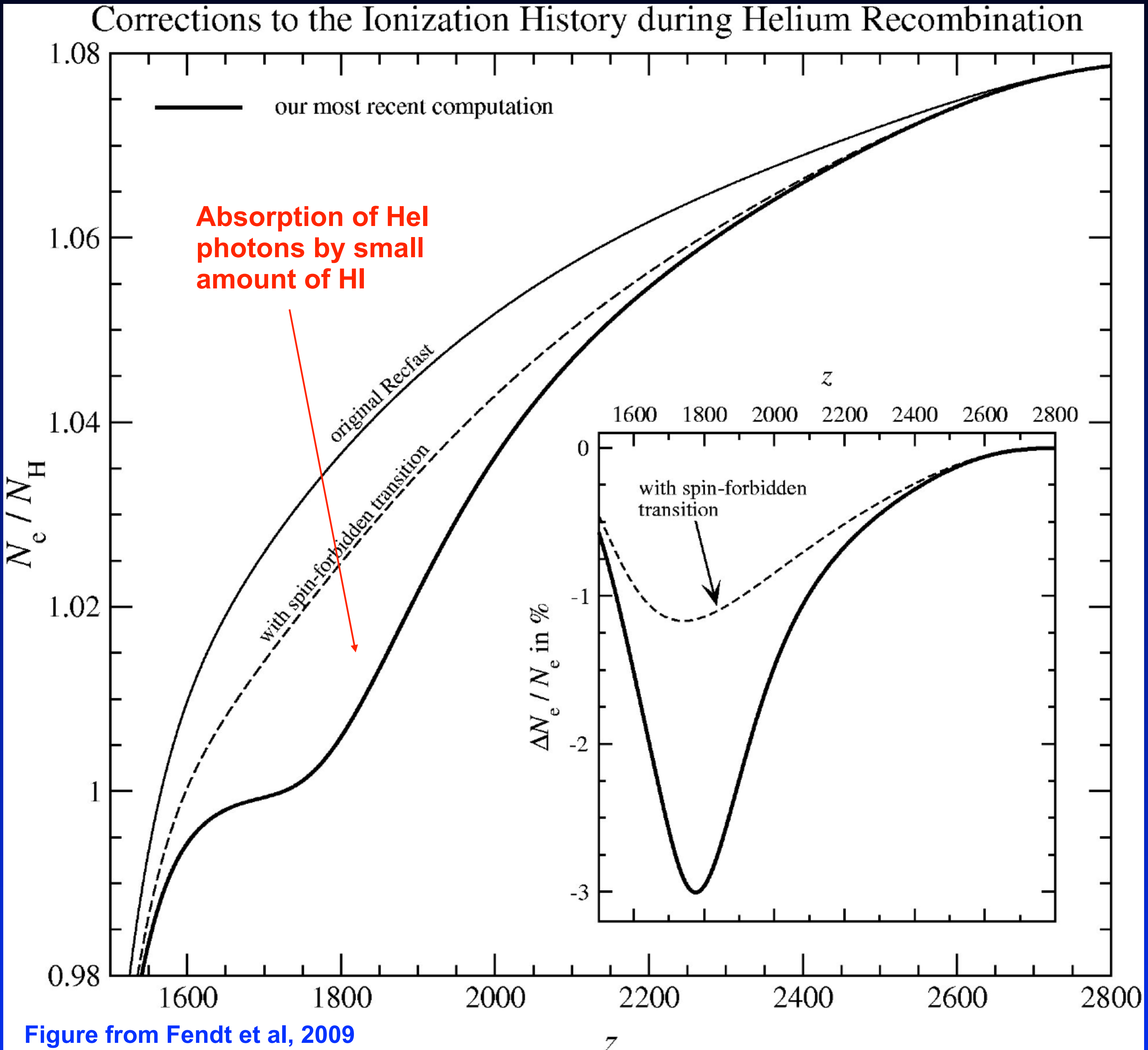
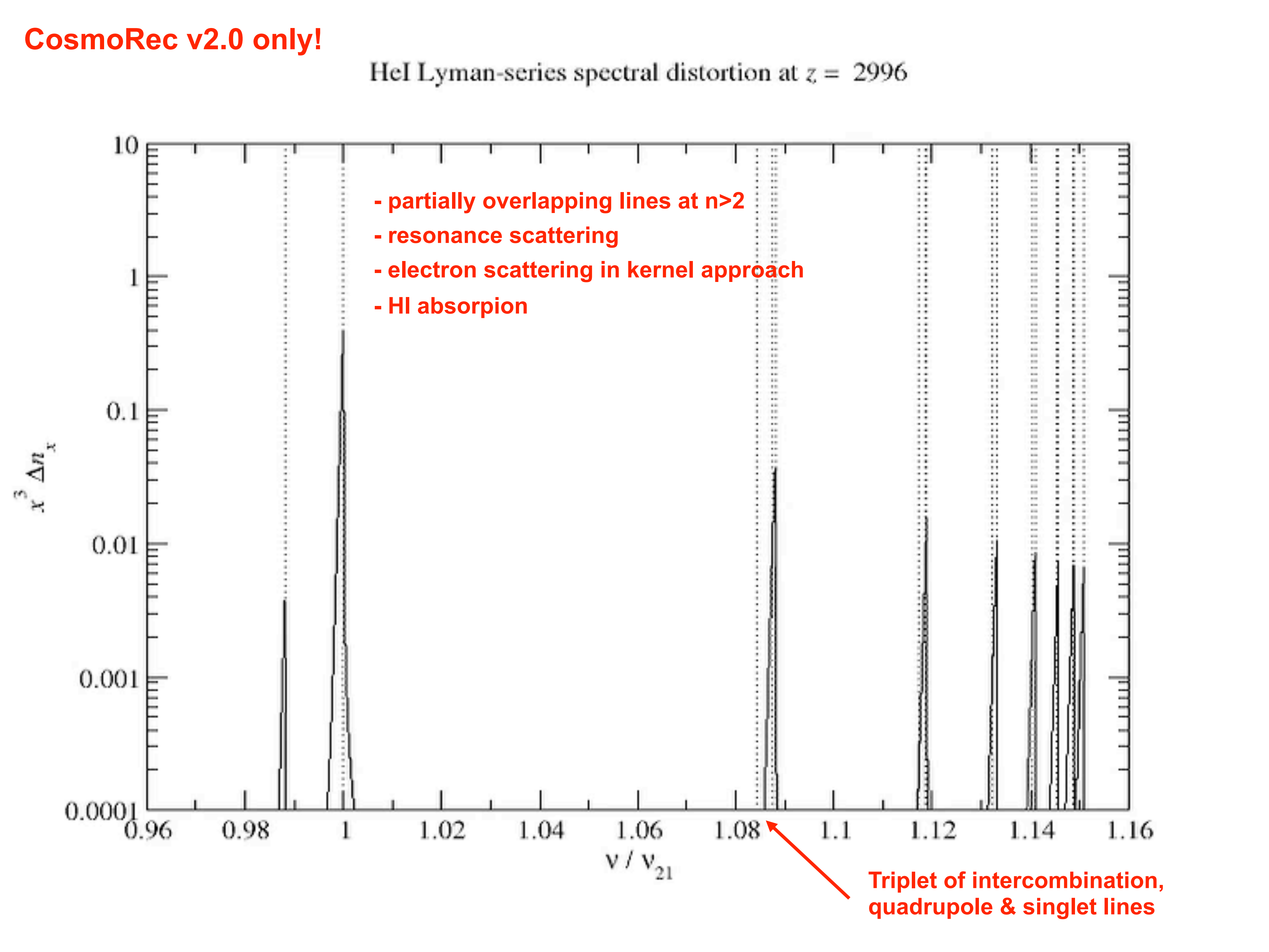


Figure from Fendt et al, 2009

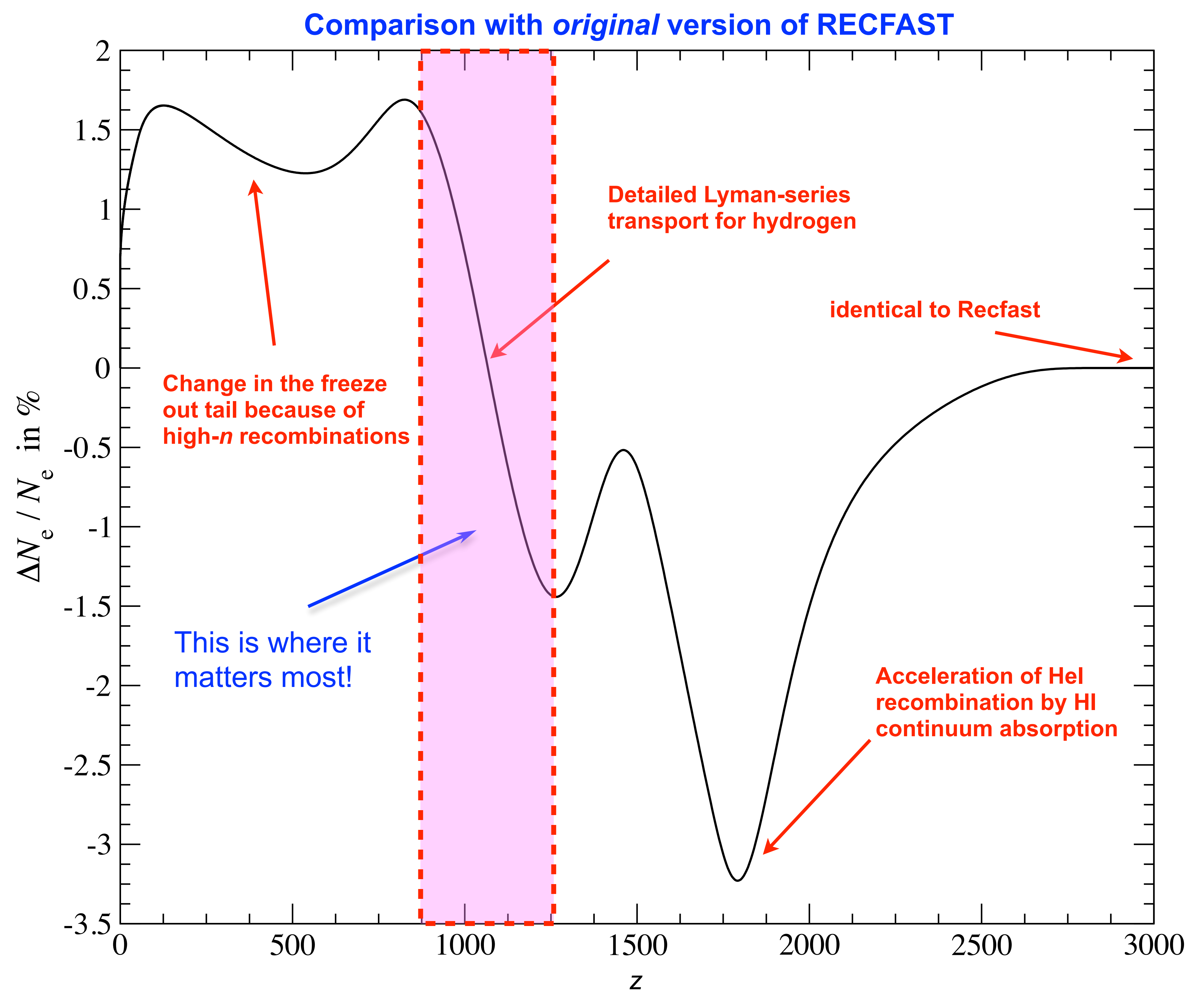
Kholupenko et al, 2007
Switzer & Hirata, 2007

Evolution of the HeI high frequency distortion



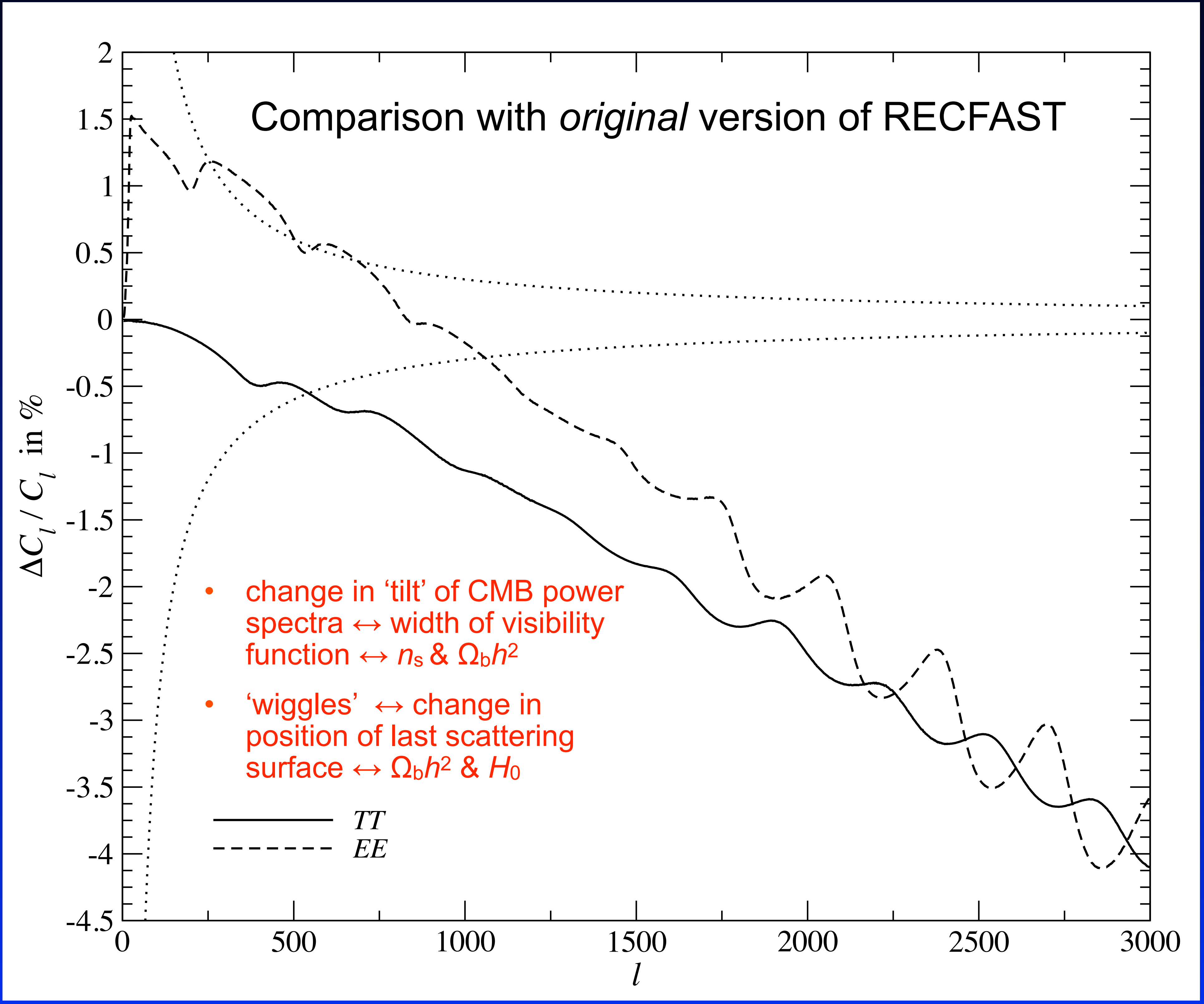
JC, Fung & Switzer, 2011

Cumulative Changes to the Ionization History



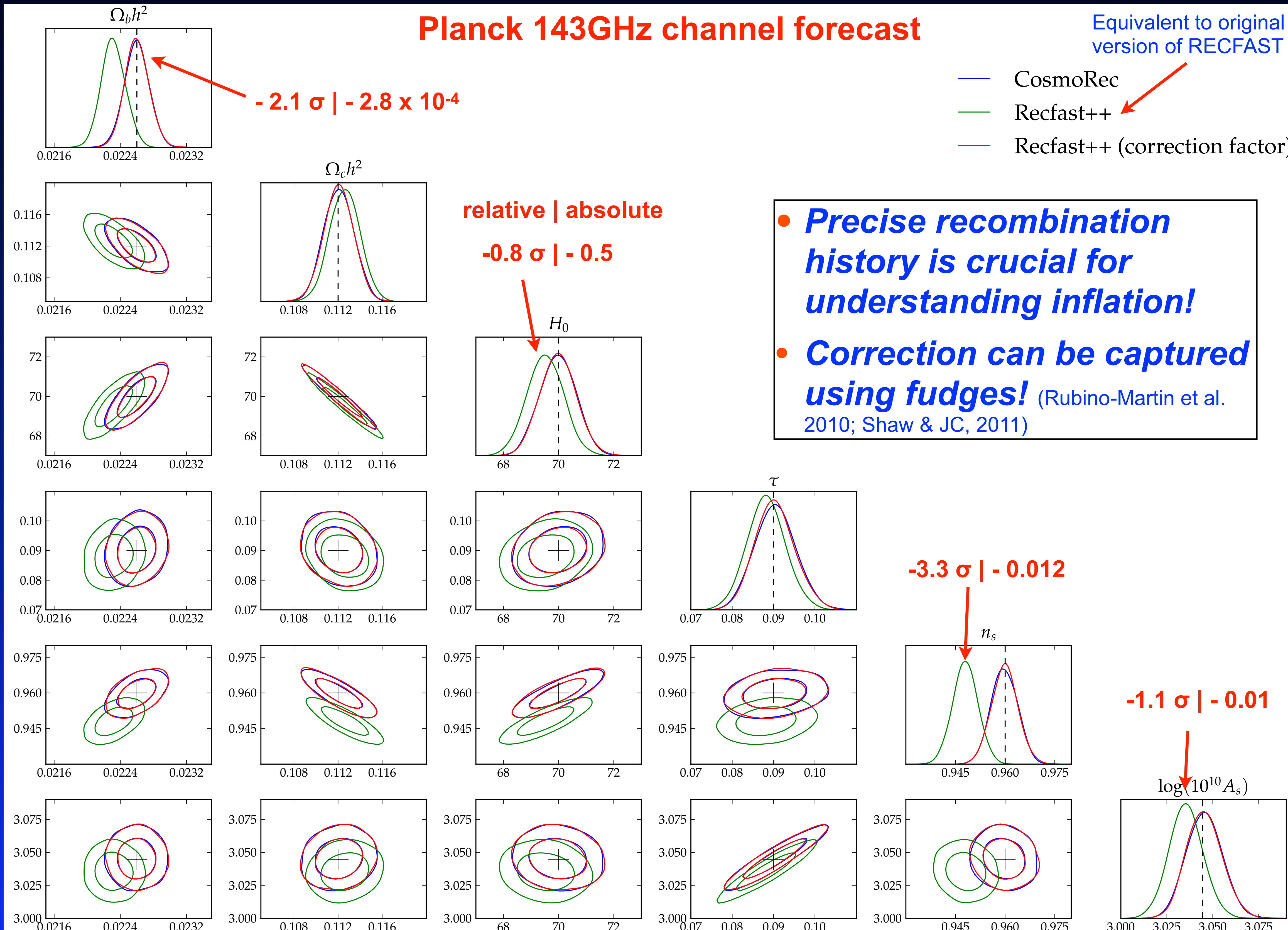
JC & Thomas, MNRAS, 2010; Shaw & JC, MNRAS, 2011

Cumulative Change in the CMB Power Spectra



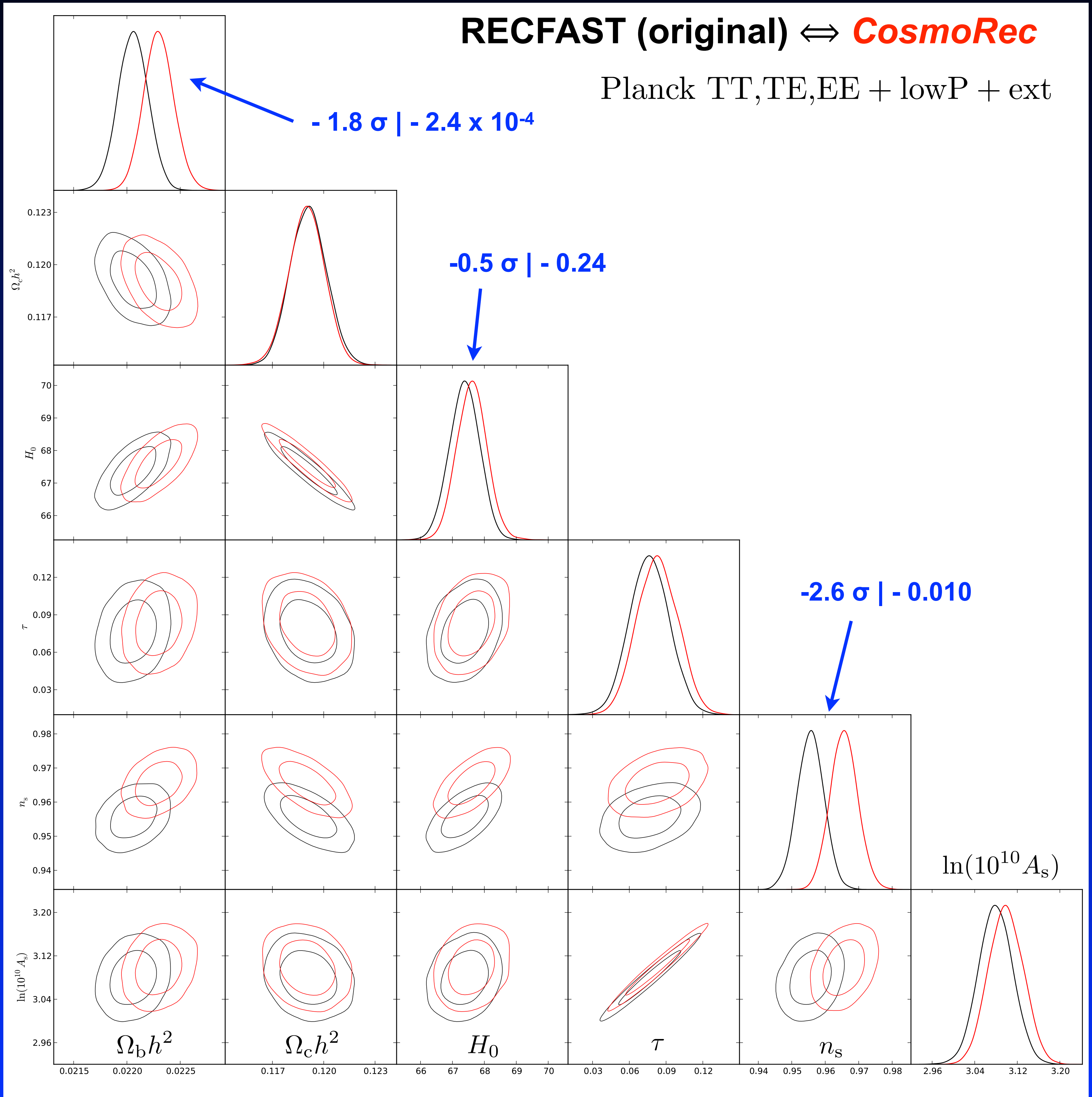
Shaw & JC, MNRAS, 2011

Importance of recombination for *Planck*



Shaw & JC, 2011, and references therein

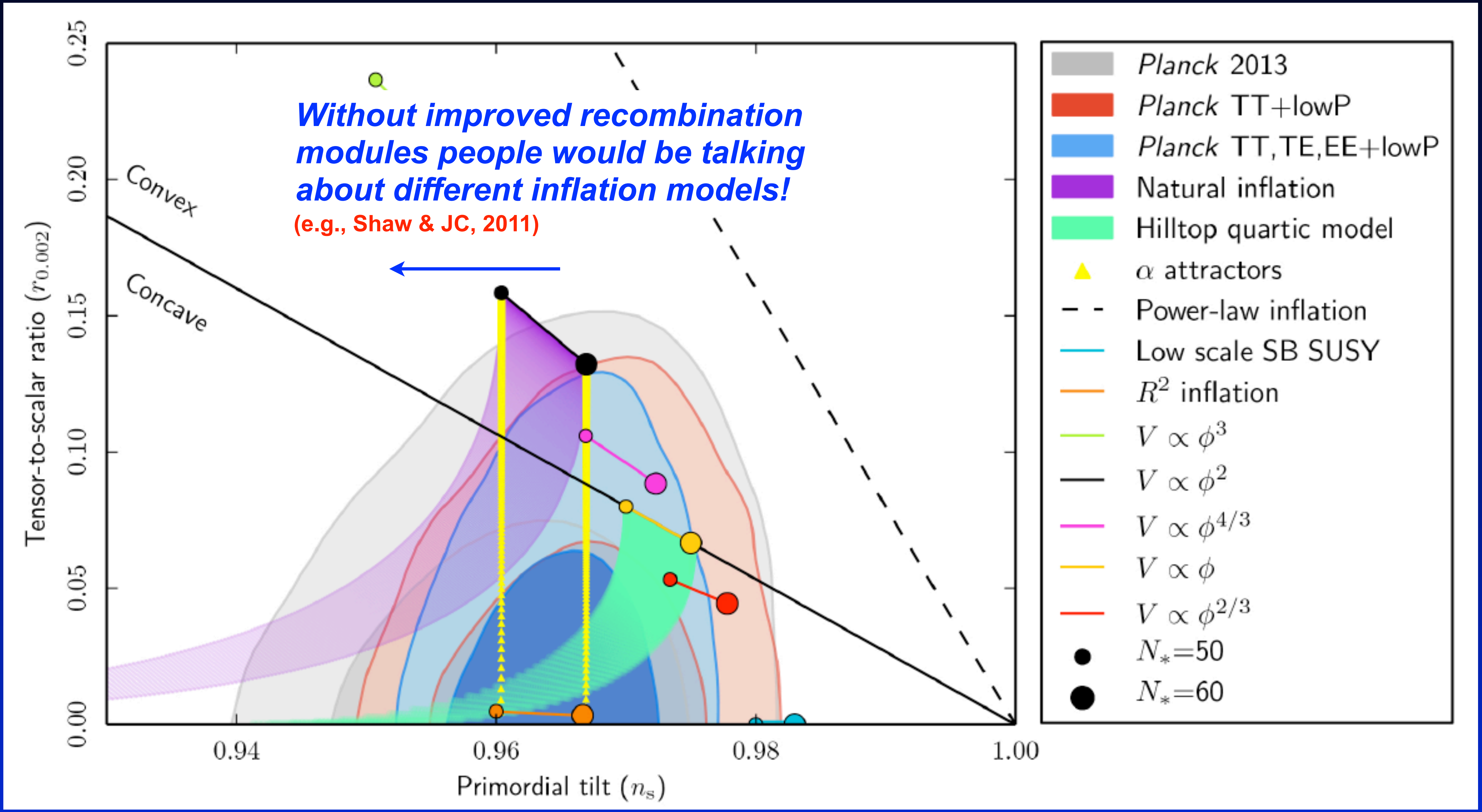
Biases as they *would* have been for *Planck*



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

Planck Collaboration, XIII 2015

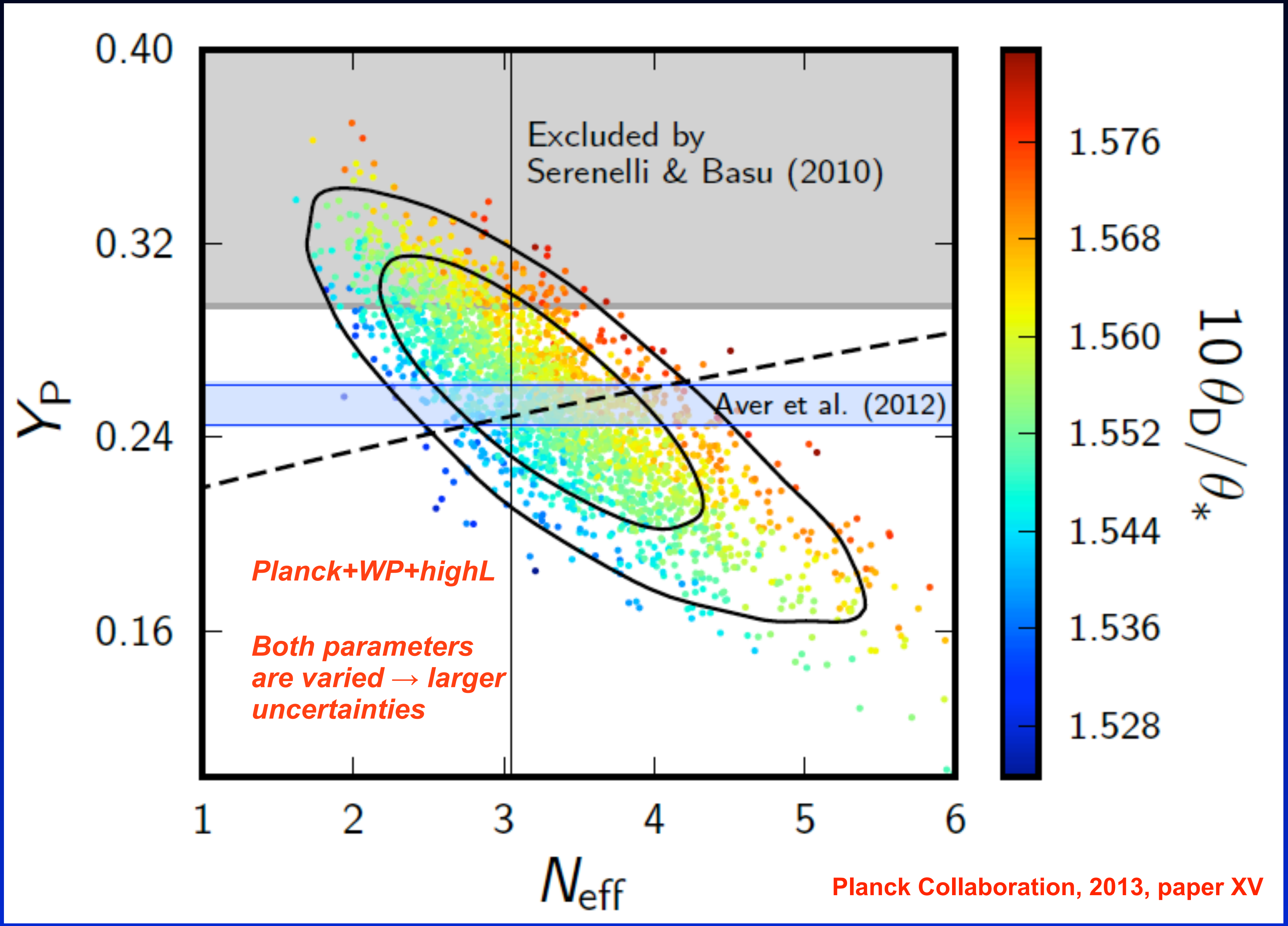
Importance of recombination for inflation constraints



Planck Collaboration, 2015, paper XX

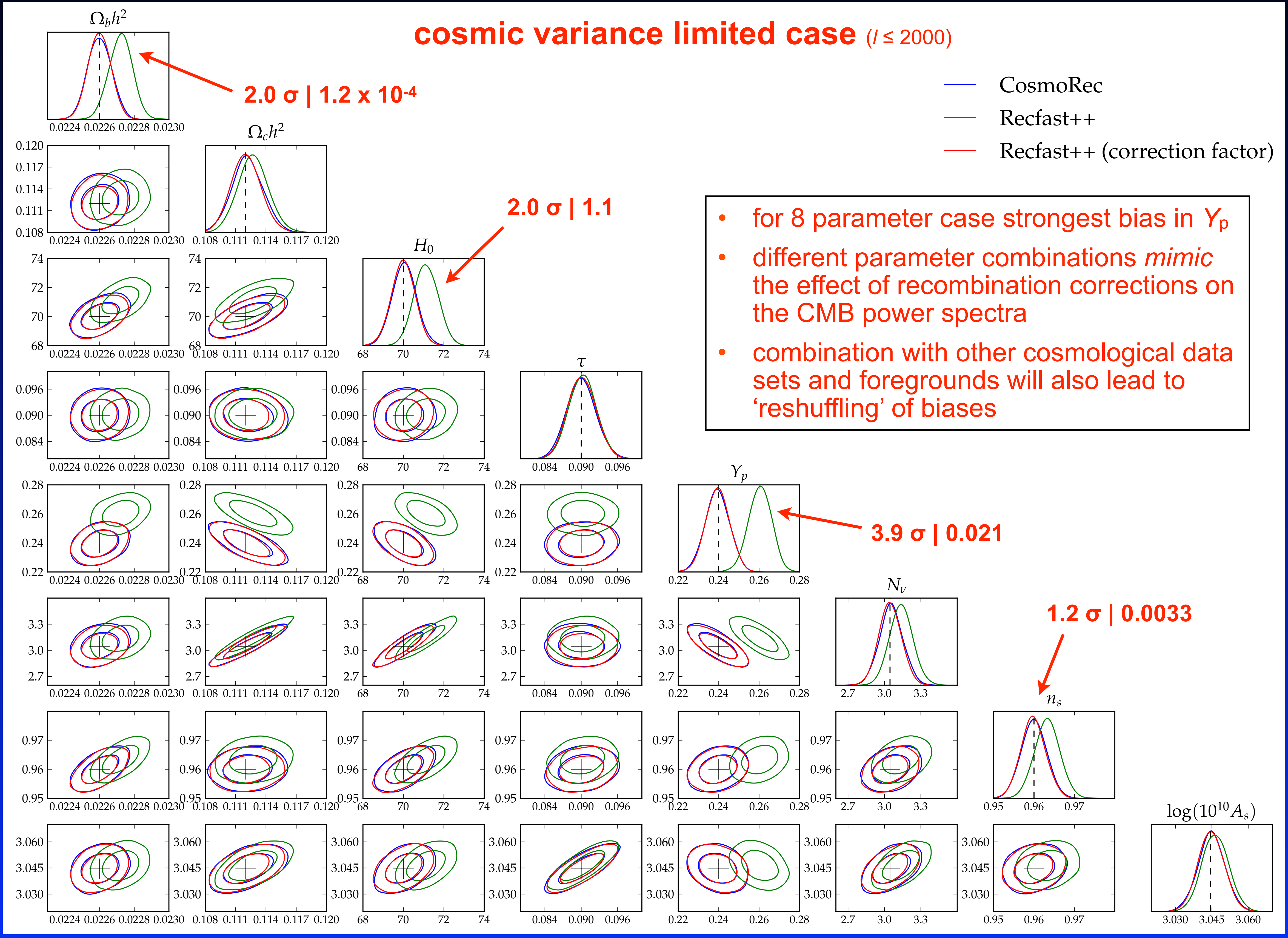
- Analysis uses refined recombination model (CosmoRec/HyRec)

CMB constraints on N_{eff} and Y_p



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

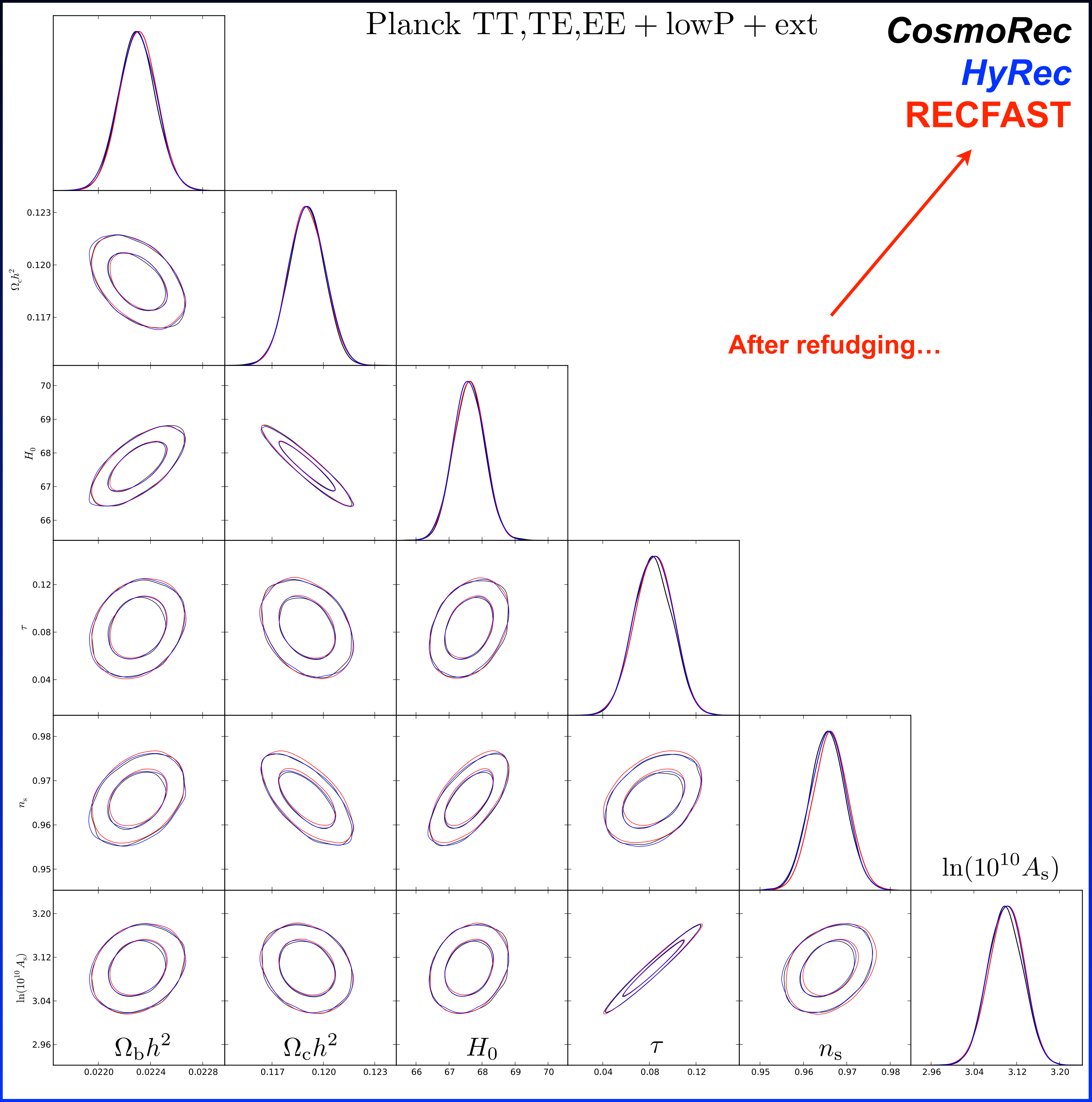
Importance of recombination for measuring helium



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

Shaw & JC, 2011, and references therein

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*)

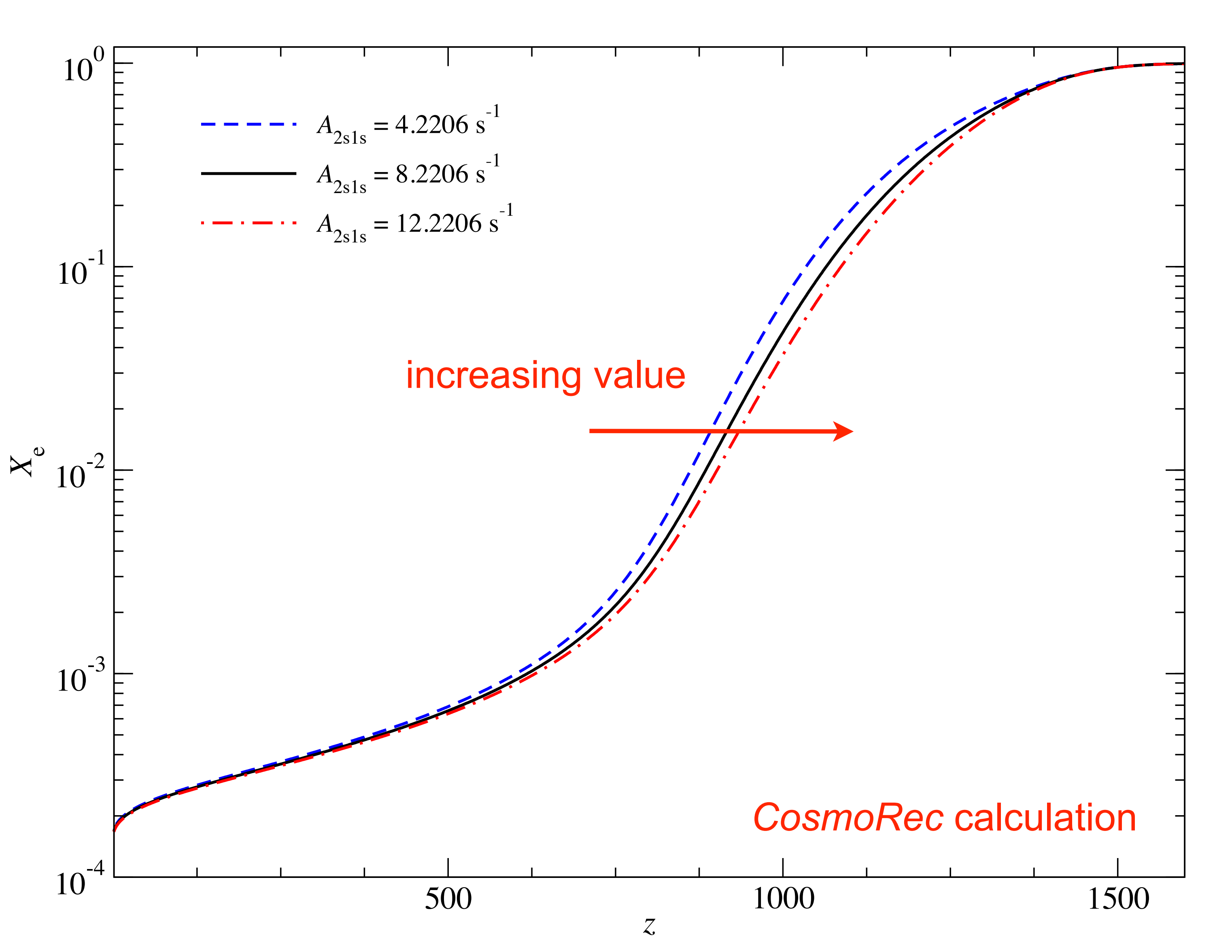
- Nothing to worry about at this point!

Planck Collaboration, XIII 2015

Constraints on possible departures from standard recombination history

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

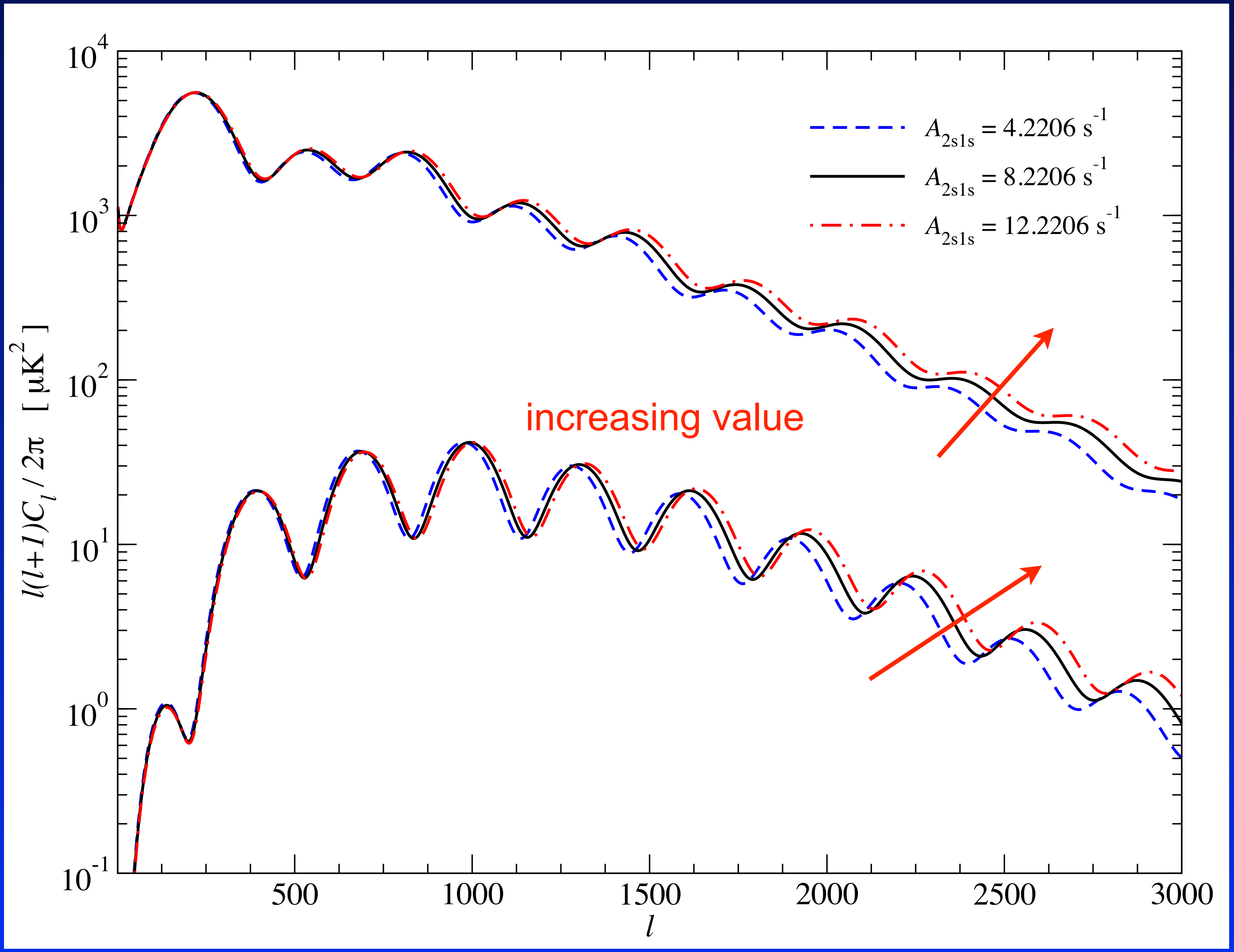
- HI 2s-1s two-photon rate crucial for recombination dynamics
- Value is not well measured in lab (best constraint ~ 43% error; Krueger & Oed 1975)
- *Planck* data can be used to directly constrain its value



Planck Collaboration, XIII 2015

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

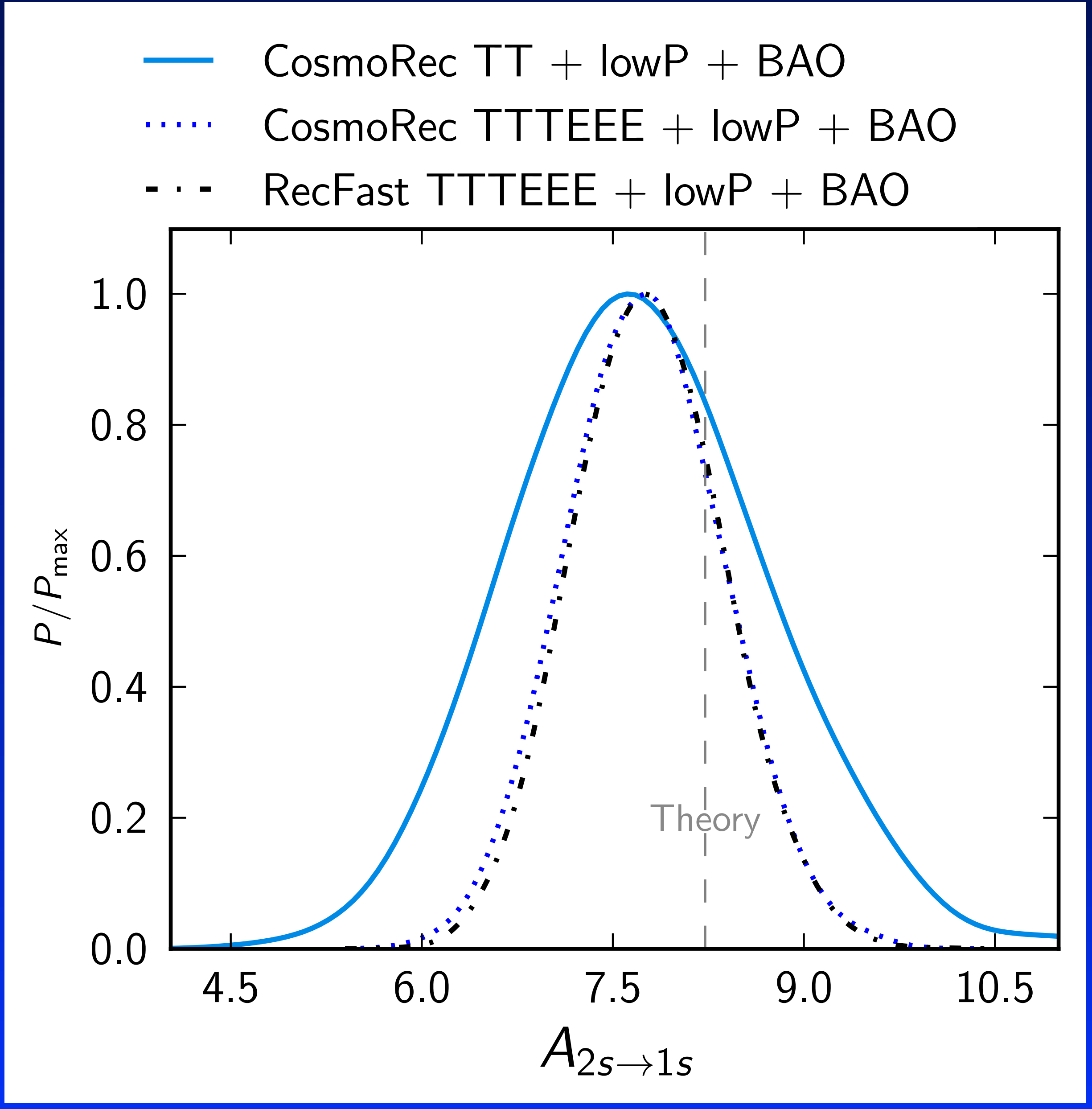
- HI 2s-1s two-photon rate crucial for recombination dynamics
- Value is not well measured in lab (best constraint ~ 43% error; Krueger & Oed 1975)
- *Planck* data can be used to directly constrain its value



Planck Collaboration, XIII 2015

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



$$A^{\rm theory}_{2s\to1s} = 8.2206\,{\rm s}^{-1} \text{(Labzowsky et al. 2005)}$$

$$A_{2s\to1s} = 7.71 \pm 0.99\,{\rm s}^{-1}$$
(*Planck* TT+lowP+BAO)

$$A_{2s\to1s} = 7.75 \pm 0.61\,{\rm s}^{-1}$$ **~ 8% error!**
(*Planck* TT,TE,EE+lowP+BAO)

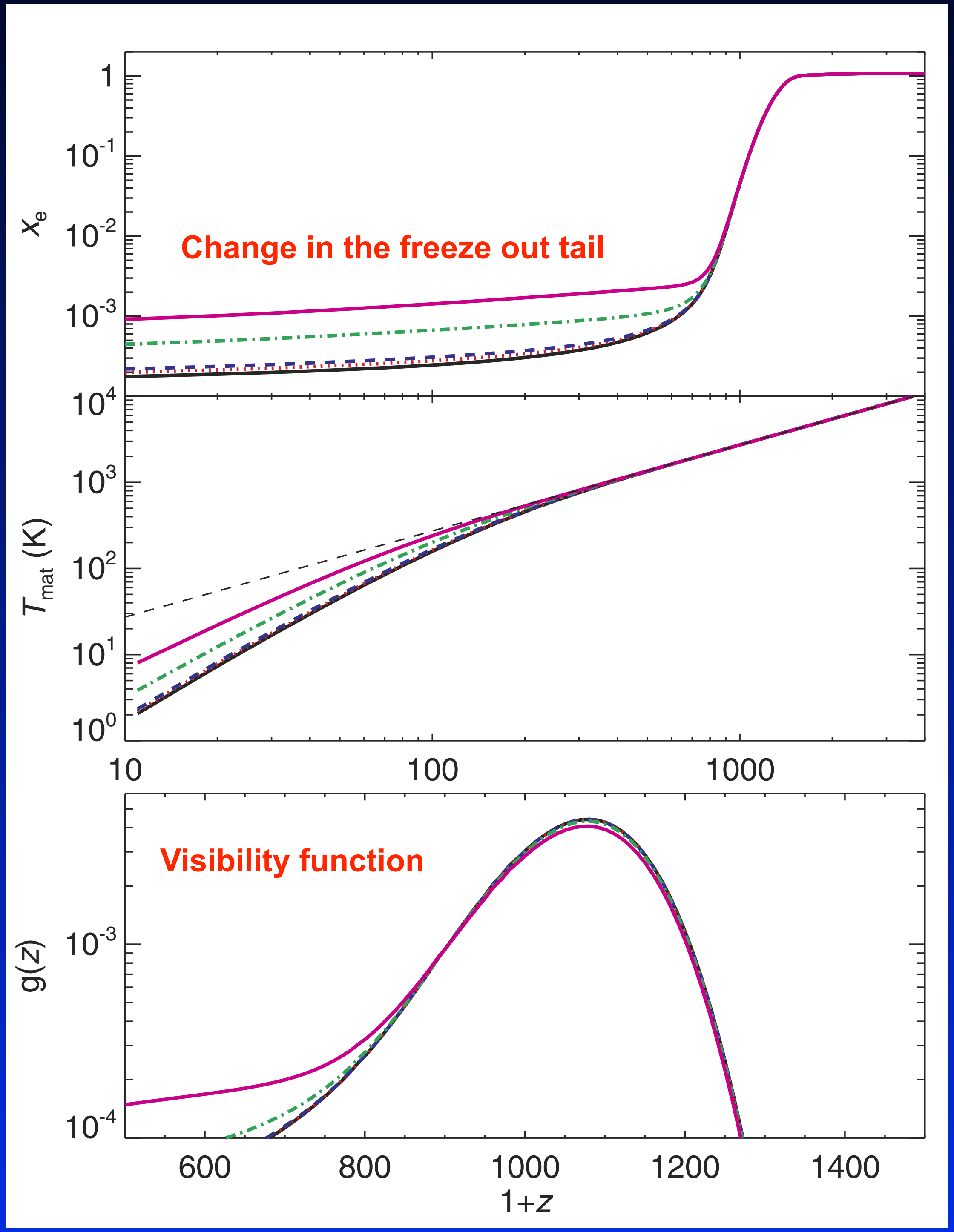
- *Planck* measurement in excellent agreement with theoretical value
- *Planck* only values very similar
- *CosmoRec* and *Recfast* agree...

Planck Collaboration, XIII 2015

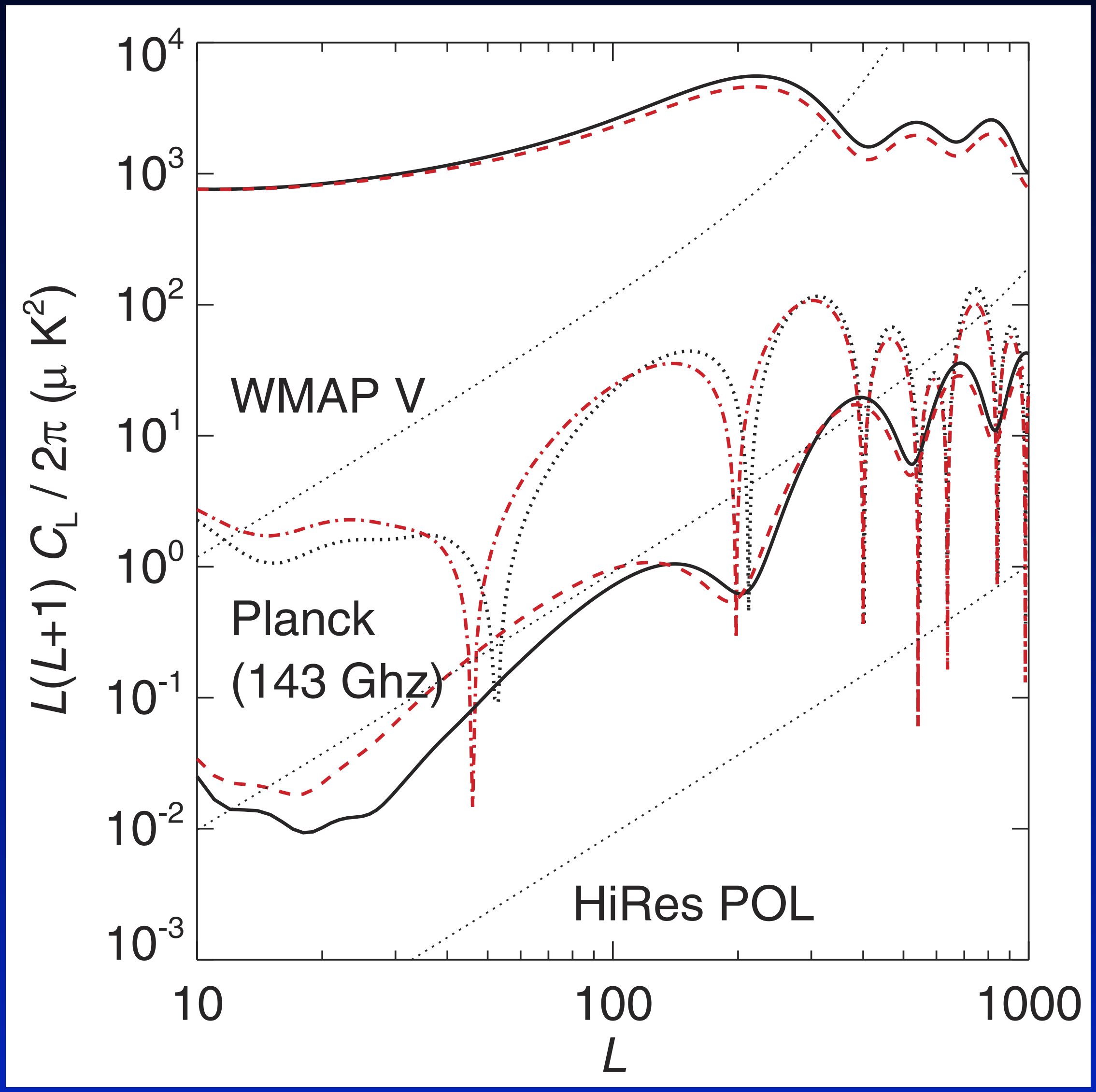
Annihilating / Decaying (dark matter) particles

Changes of CMB anisotropies by annihilating particles

95% c.l.



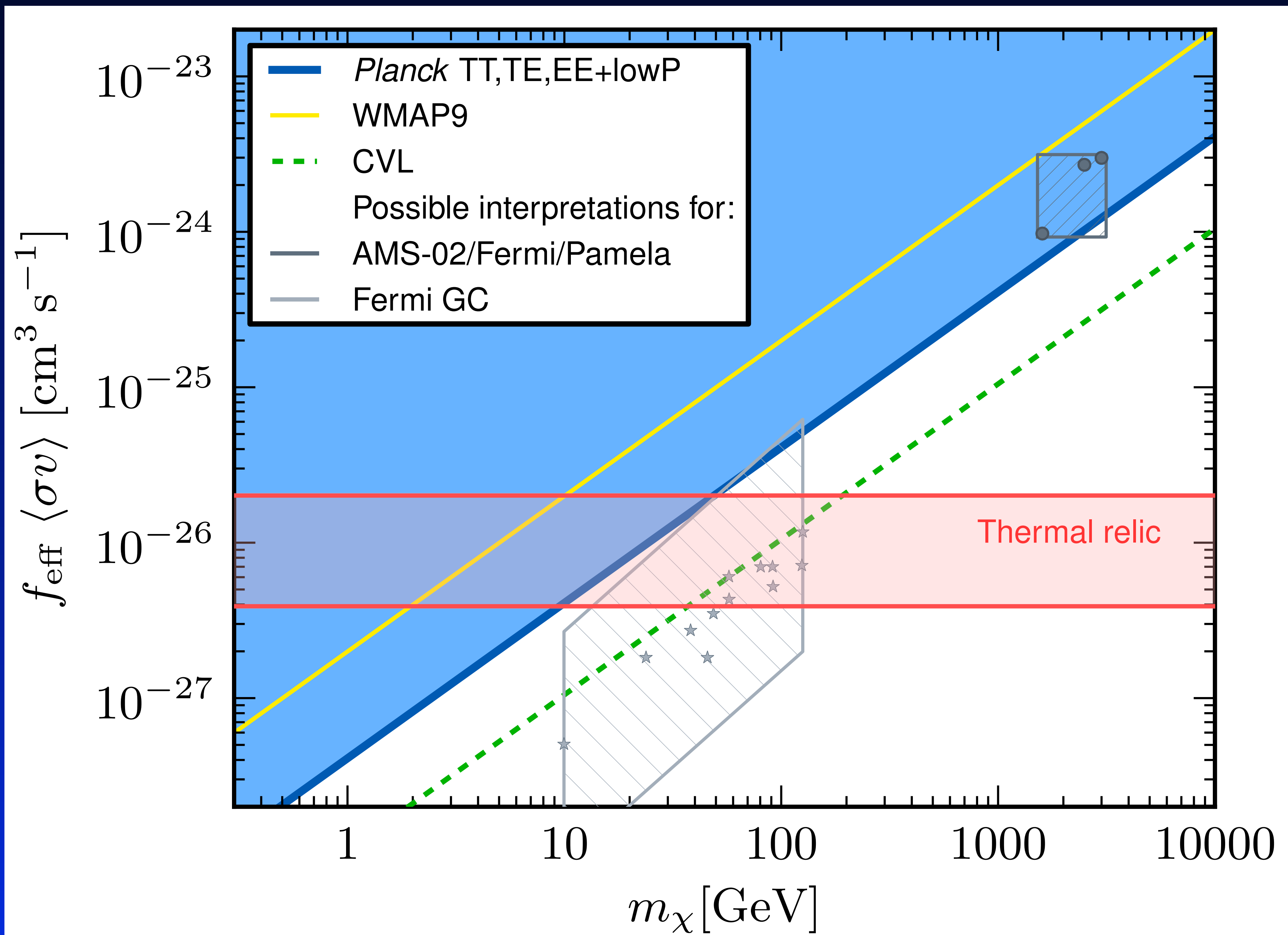
Chen & Kamionikowski, 2004
Padmanabhan & Finkbeiner, 2005



- more damping because τ increases
- change close to visibility maximum → shift in peak positions

Latest Planck limits on annihilation cross section

95% c.l.

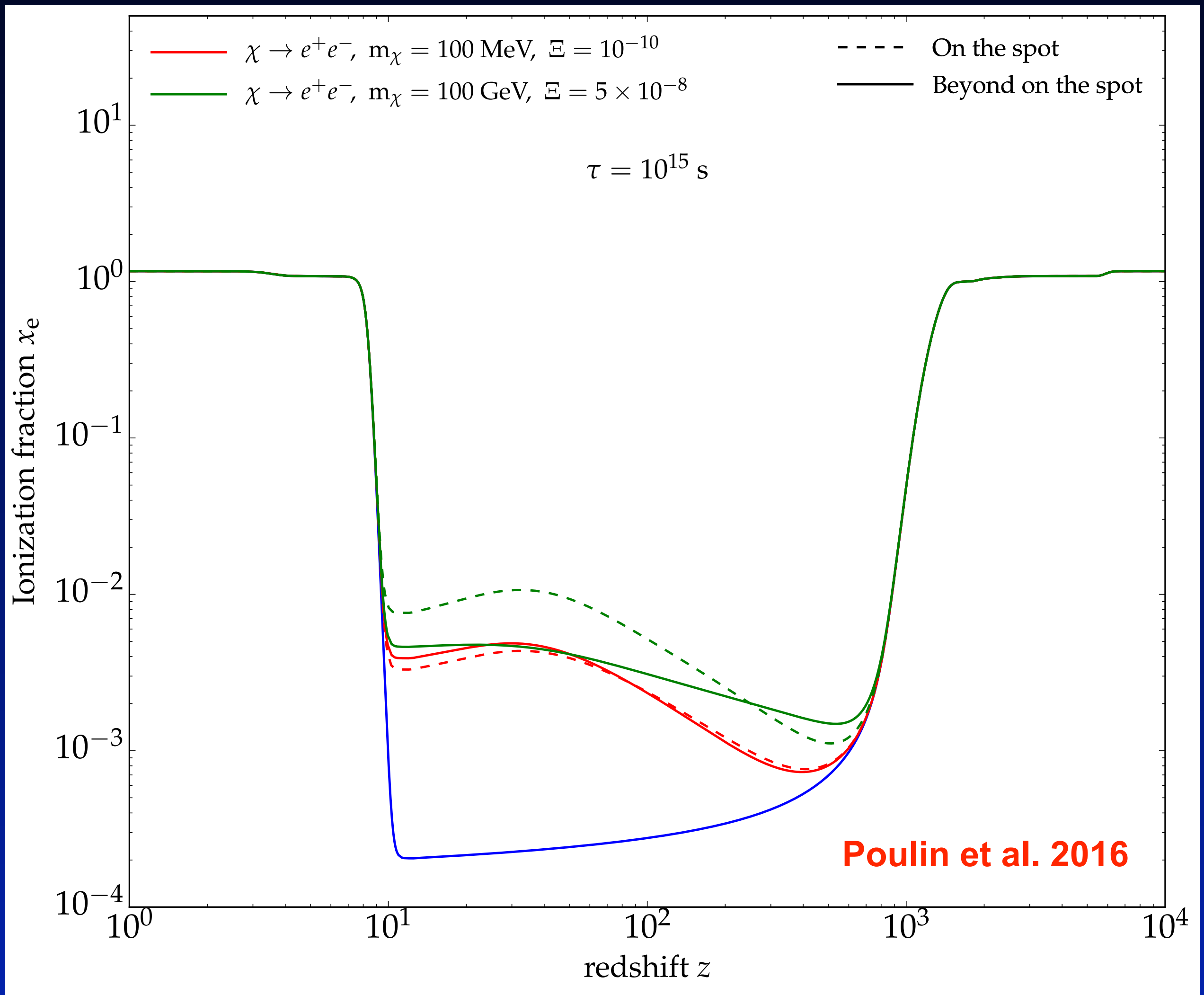


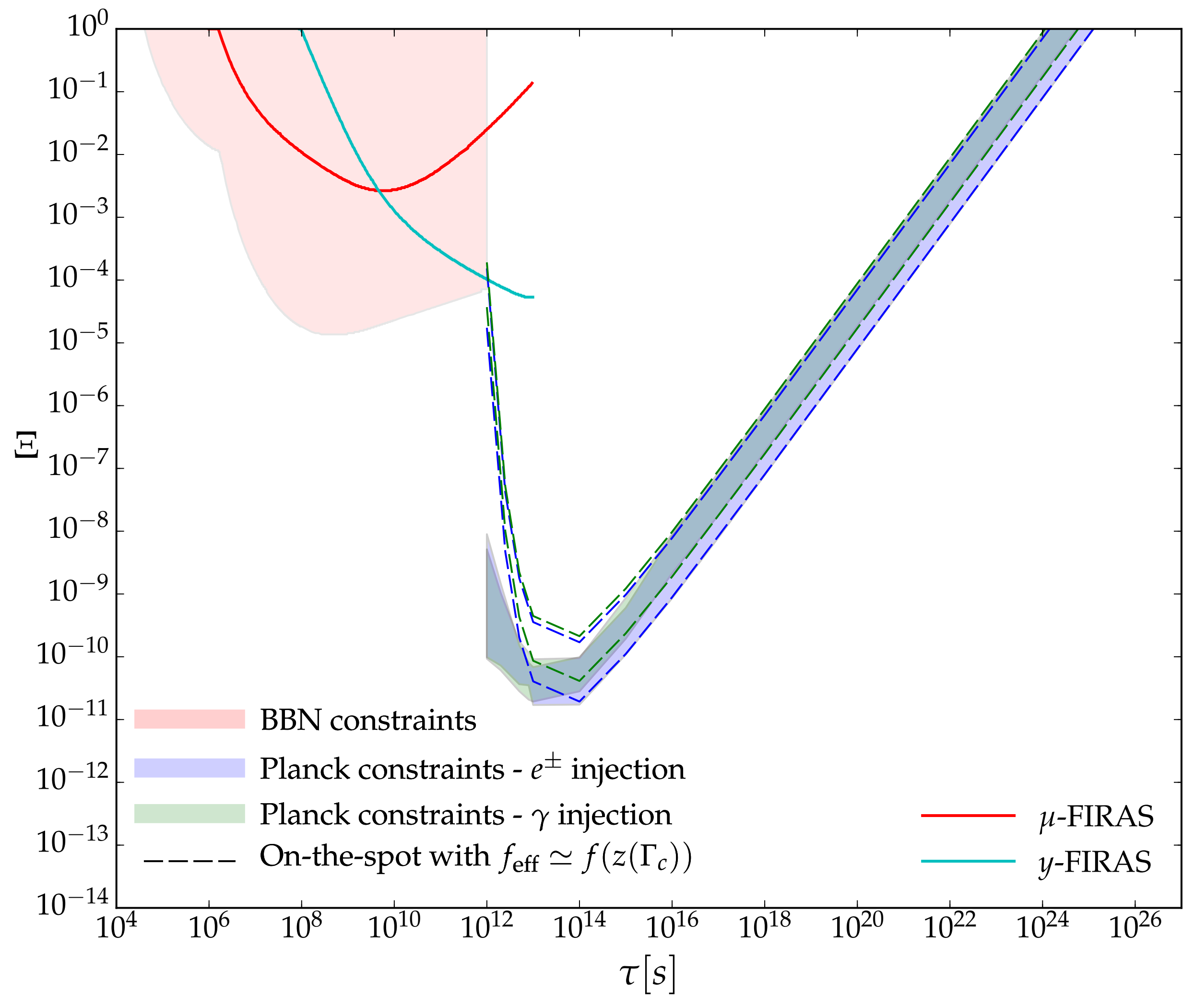
Planck Collaboration, paper XIII, 2015

- AMS/Pamela models in tension
- but interpretation model-dependent
- Sommerfeld enhancement?
- clumping factors?
- annihilation channels?

More references: Galli et al, 2009, Slatyer et al, 2009, Huetsi et al. 2009

Effect of decaying particles





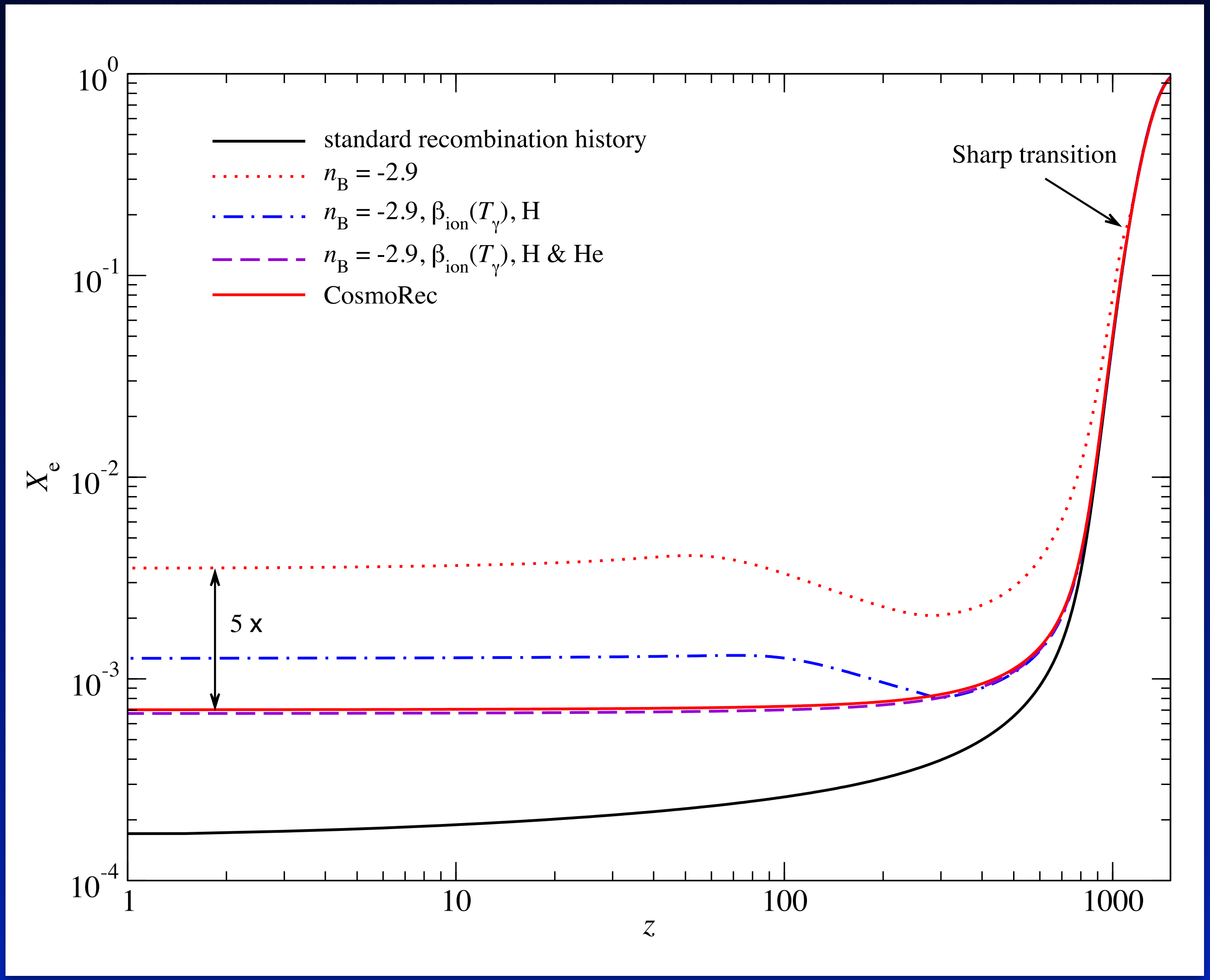
- Effect at different stages of the evolution
- CMB Anisotropies for long-lived particles
- CMB spectral distortions for short-lived particles
- PBHs are similar to decaying particles

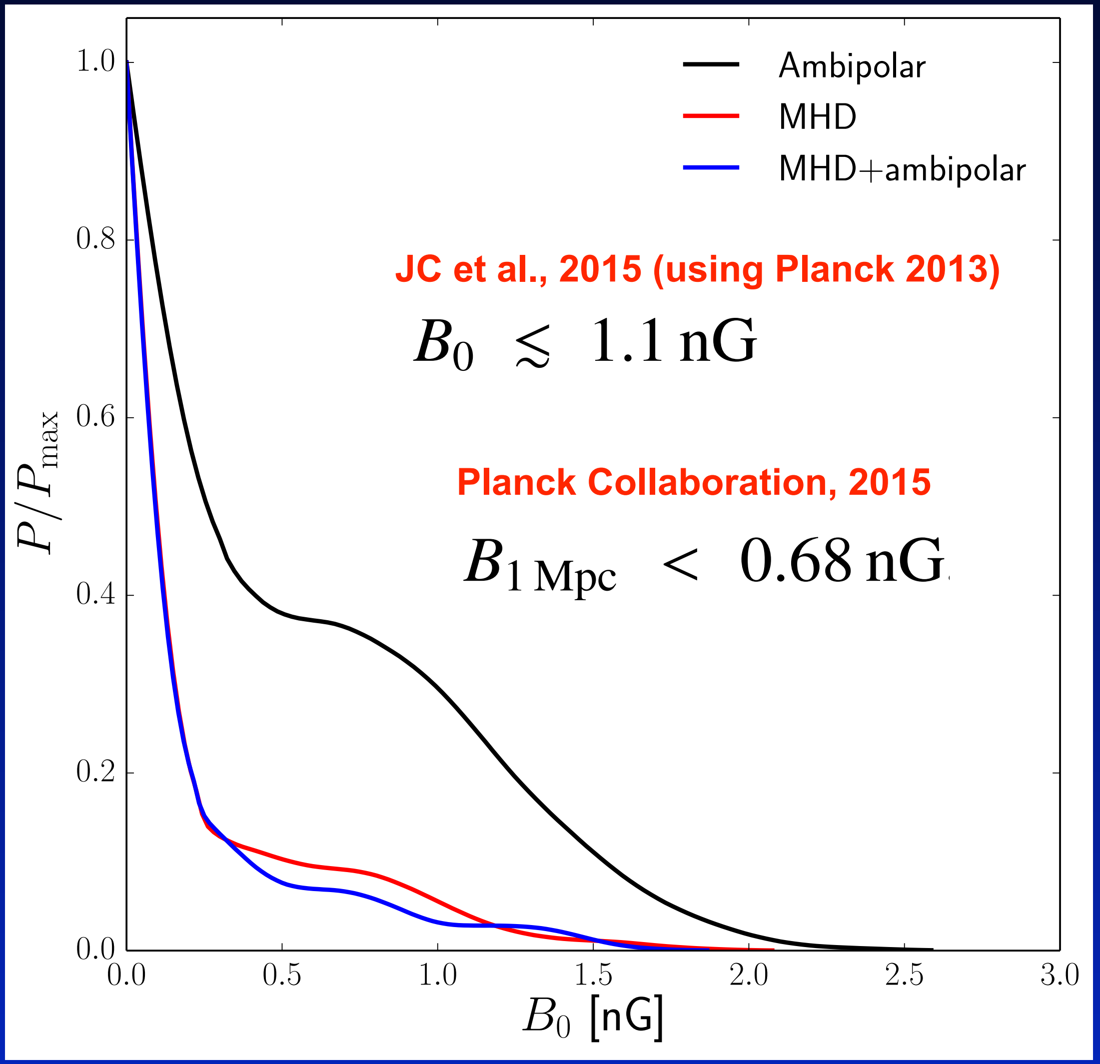
Ξ Relative amount of energy per decay and per DM

Chen & Kamionikowski, 2004, Zhang et al. 2006, Poulin et al. 2016

Primordial magnetic fields

Changes to recombination from PMFs



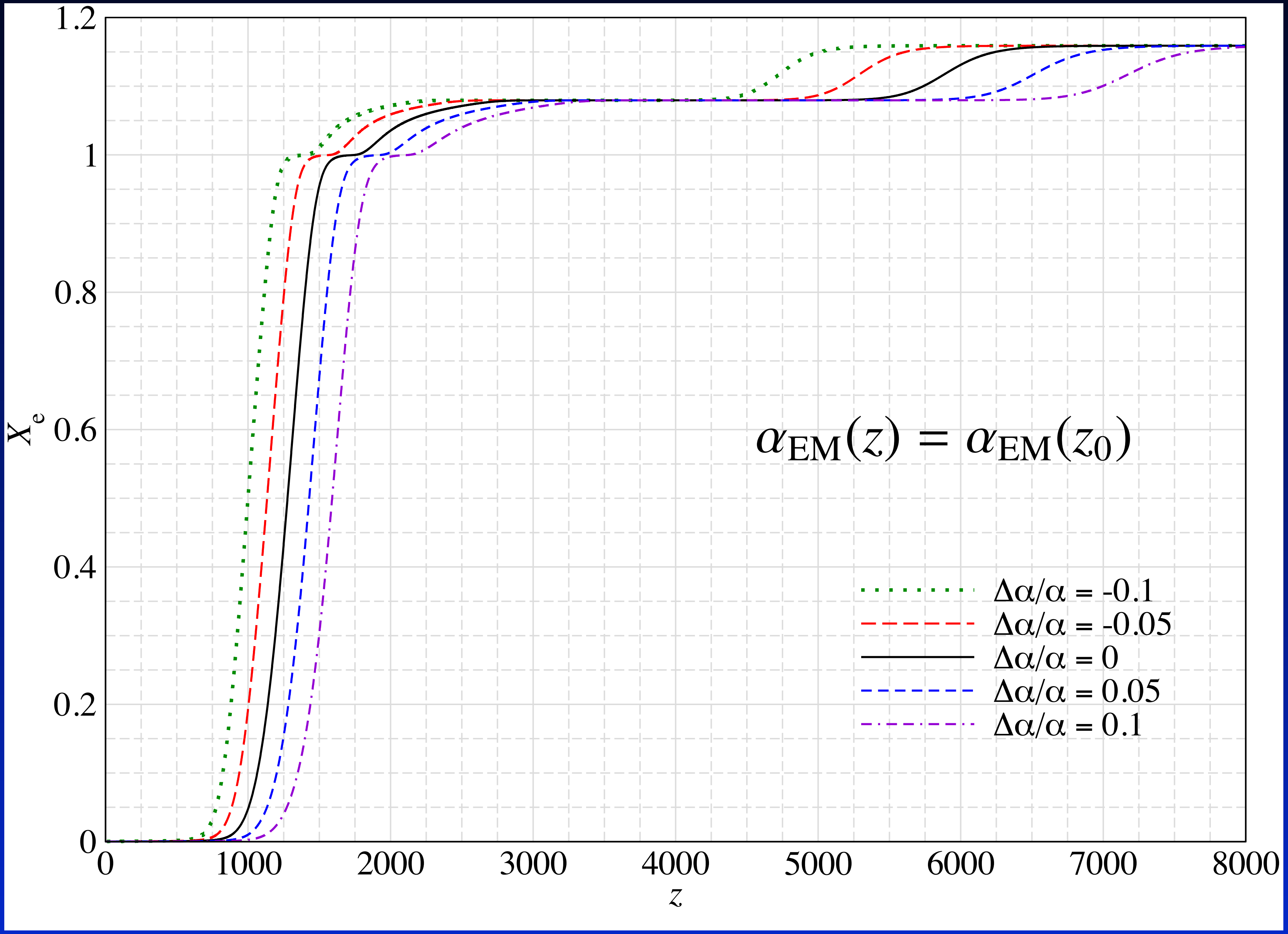


- One has to be careful how to compute the effect…
- Large uncertainties in the heating rates → *already working on it….*
- Constraints from this effect better than other CMB effects

Sethi et al. 2005, Kunze et al, 2014/2015, JC et al. 2015

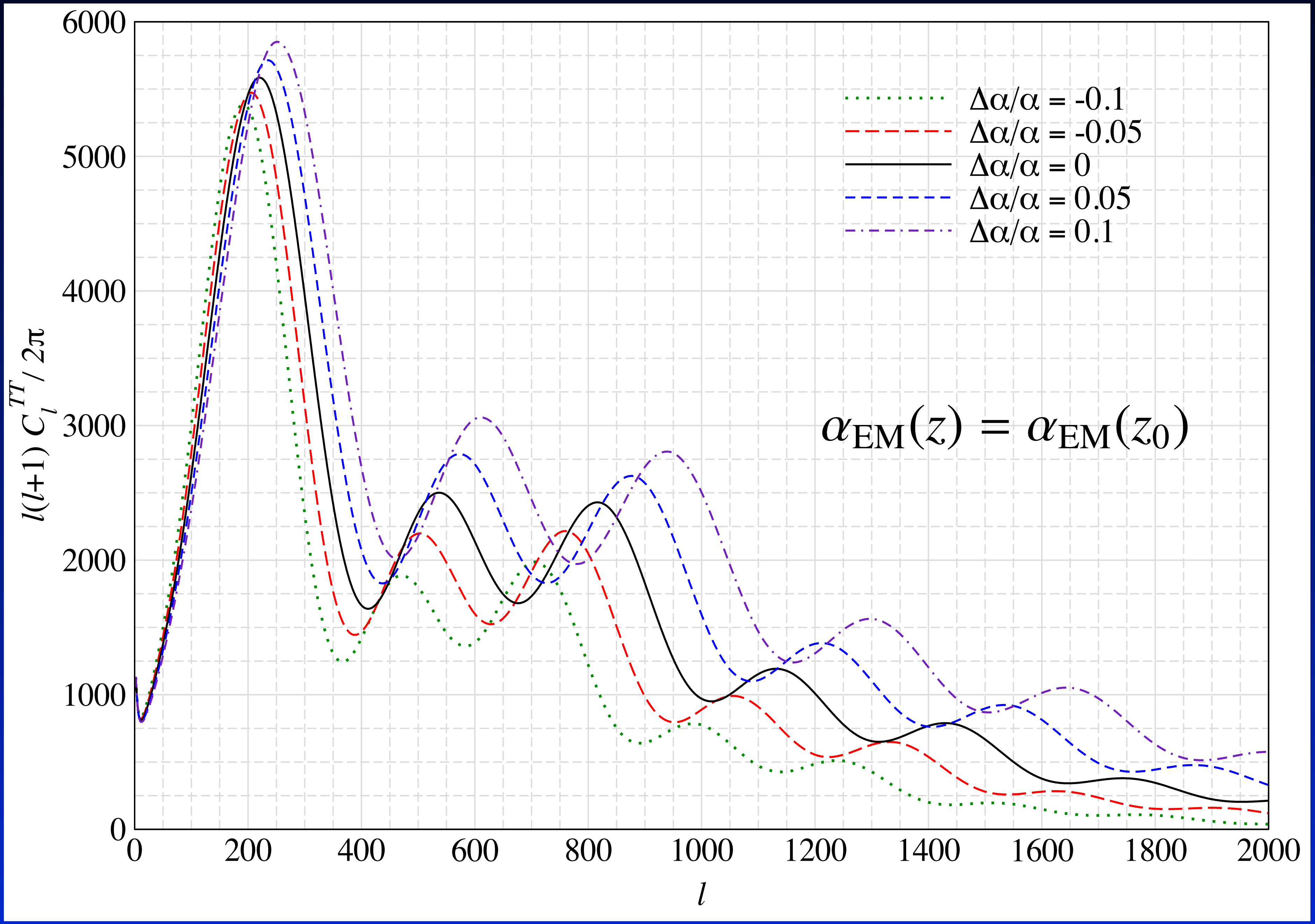
Variations of fundamental constants

Varying the fine-structure constants at recombination



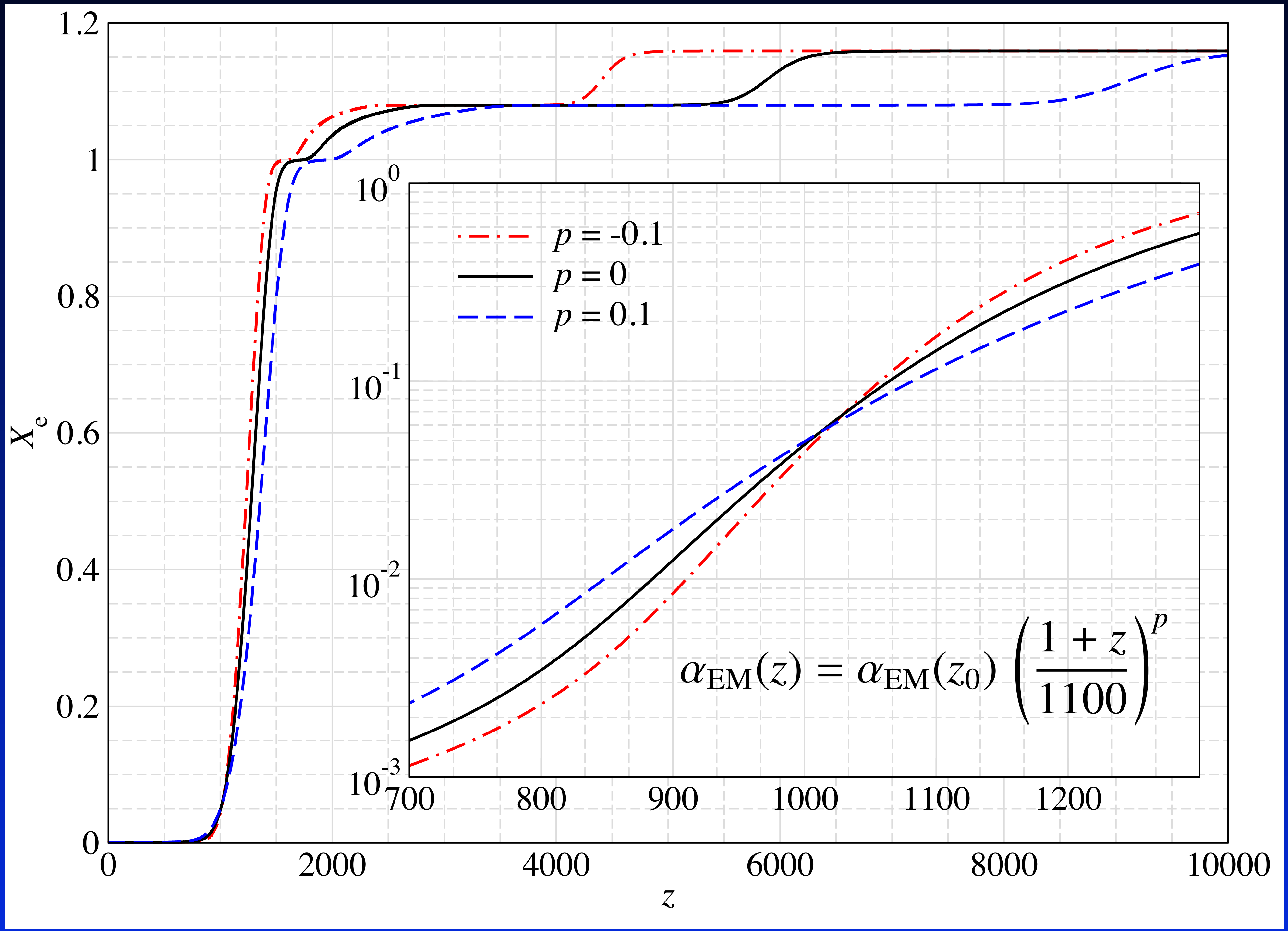
- Constant change of α and m_e were frequently considered
  (e.g., Kaplinghat et al., 1999; Battye et al., 2001; Planck Collaboration, 2015)

Varying the fine-structure constants at recombination



- Constant change of α and m_e were frequently considered
  (e.g., Kaplinghat et al., 1999; Battye et al., 2001; Planck Collaboration, 2015)

Varying the fine-structure constants at recombination



- Data also sensitive to explicit time-dependence around recombination (Luke Hart & JC, 2017)

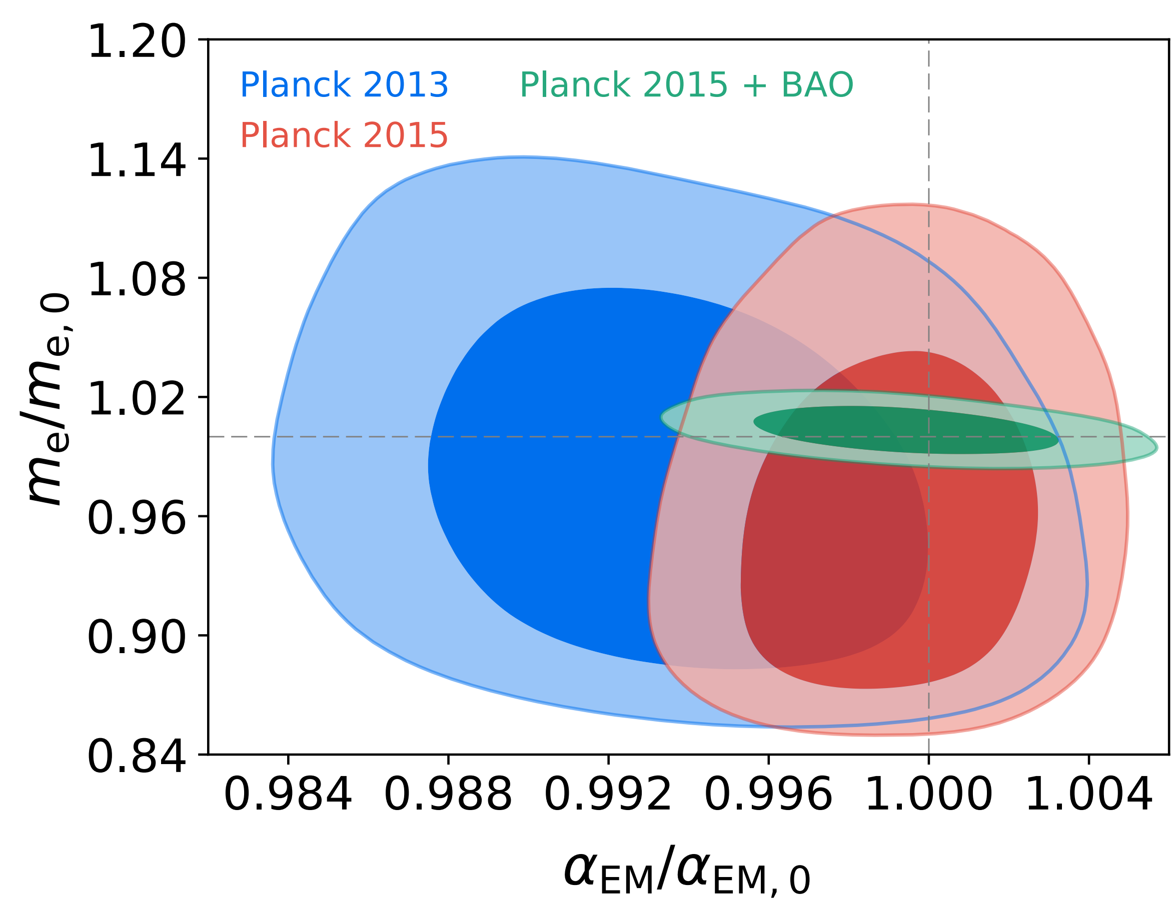
Current constraints using Planck 2015

Parameter	*Planck* 2015	+ varying $\alpha_{EM}/\alpha_{EM,0}$	+ varying p	+ varying $\alpha_{EM}/\alpha_{EM,0}$ and p
$\Omega_b h^2$	0.02224 ± 0.00016	0.02225 ± 0.00016	0.02226 ± 0.00018	0.02223 ± 0.00019
$\Omega_c h^2$	0.1193 ± 0.0014	0.1191 ± 0.0018	0.1194 ± 0.0014	0.1193 ± 0.0020
$100\theta_{MC}$	1.0408 ± 0.0003	1.0398 ± 0.0035	1.0408 ± 0.0003	1.0406 ± 0.0051
τ	0.062 ± 0.014	0.063 ± 0.014	0.062 ± 0.014	0.063 ± 0.015
$\ln(10^{10} A_s)$	3.057 ± 0.025	3.060 ± 0.027	3.058 ± 0.026	3.059 ± 0.027
n_s	0.9649 ± 0.0047	0.9668 ± 0.0081	0.9663 ± 0.0060	0.9666 ± 0.0081
$\alpha_{EM}/\alpha_{EM,0}$	–	0.9993 ± 0.0025	–	0.9998 ± 0.0036
p	–	–	0.0008 ± 0.0025	0.0007 ± 0.0036
H_0 [km s^{-1} Mpc^{-1}]	67.5 ± 0.6	67.2 ± 1.0	67.5 ± 0.6	67.3 ± 1.4

- For α, Planck 2015 gives slight improvement over Planck 2013 because of polarization (~30%)
- Constraint on m_e asymmetric

$$m_e/m_{e,0} = 0.961^{+0.046}_{-0.072}$$

- BAO improves m_e constraint and allows breaking degeneracies between α and m_e



Luke Hart & JC, 2017

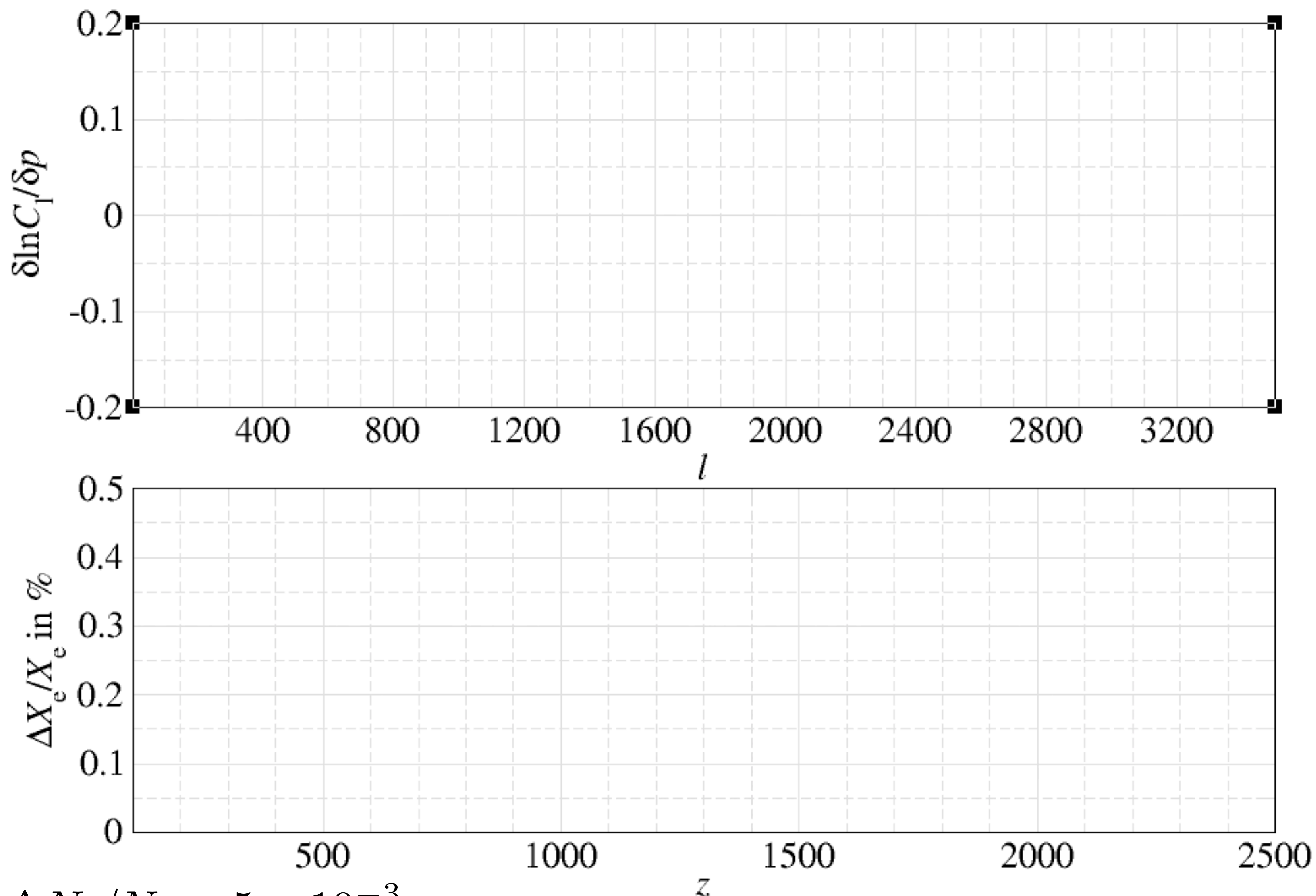
$$m_e/m_{e,0} = 1.0039 \pm 0.0074 \quad \text{with BAO}$$

Model-independent constraints

Principle component analysis for recombination

- **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)**

Power spectrum response at different redshifts

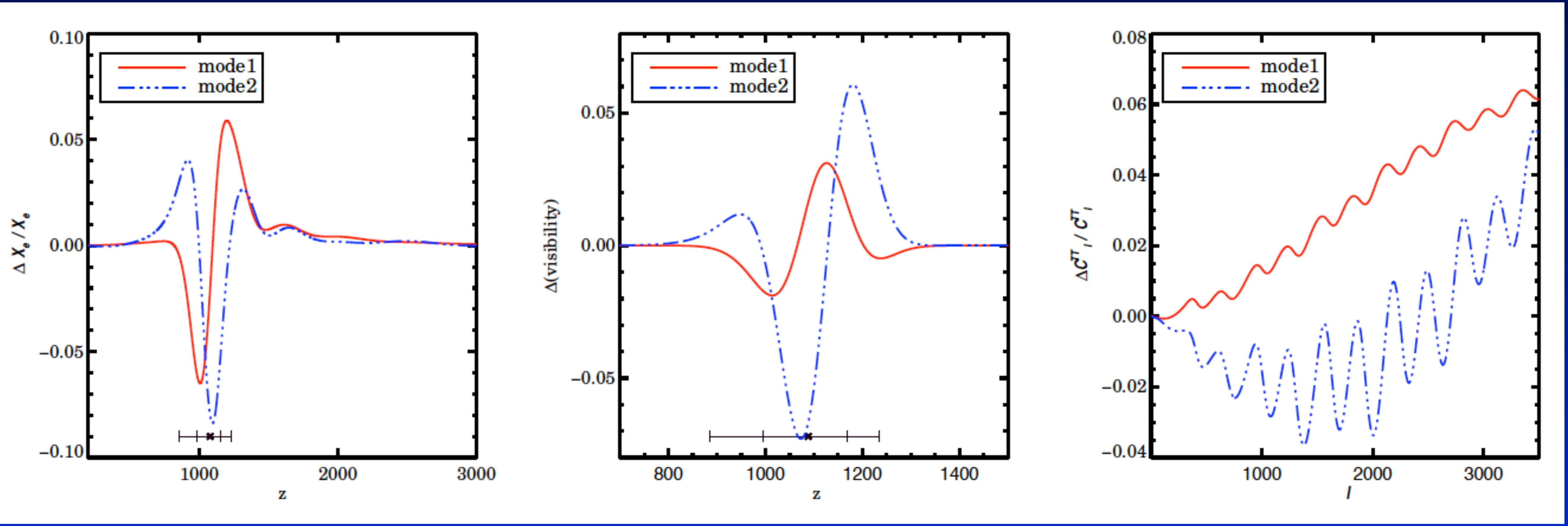


$\Delta N_{\rm e}/N_{\rm e} = 5 \times 10^{-3}$

Luke Hart & JC, in preparation

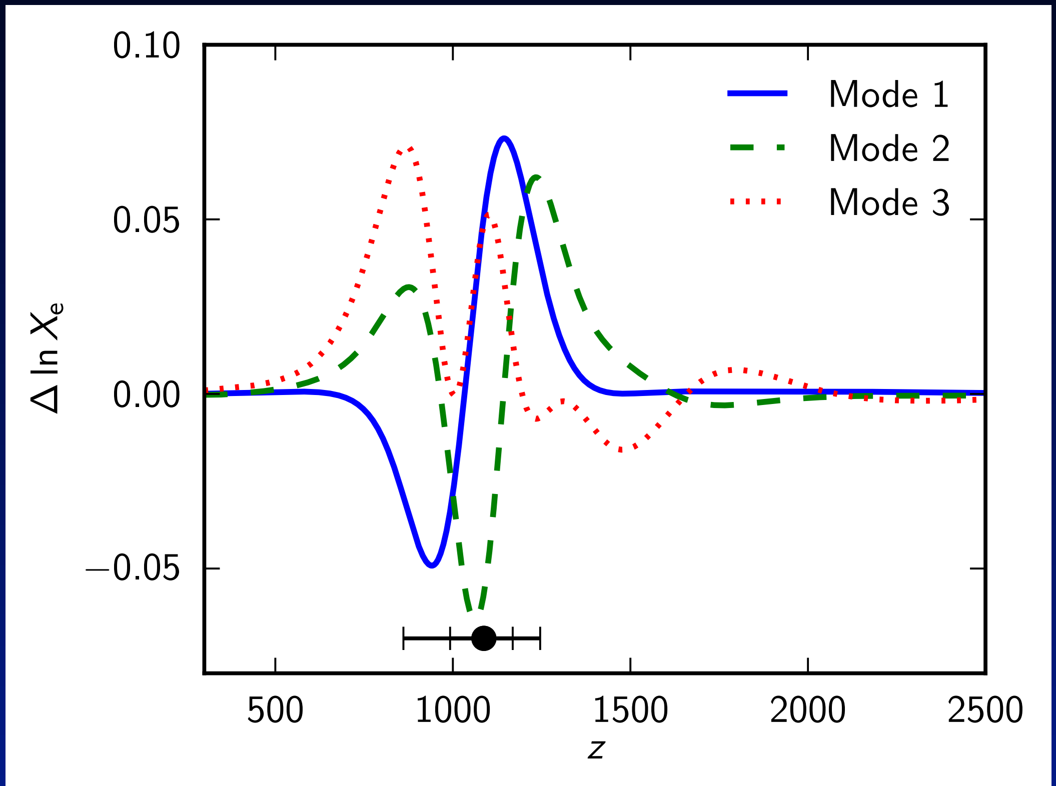
Principle component analysis for recombination

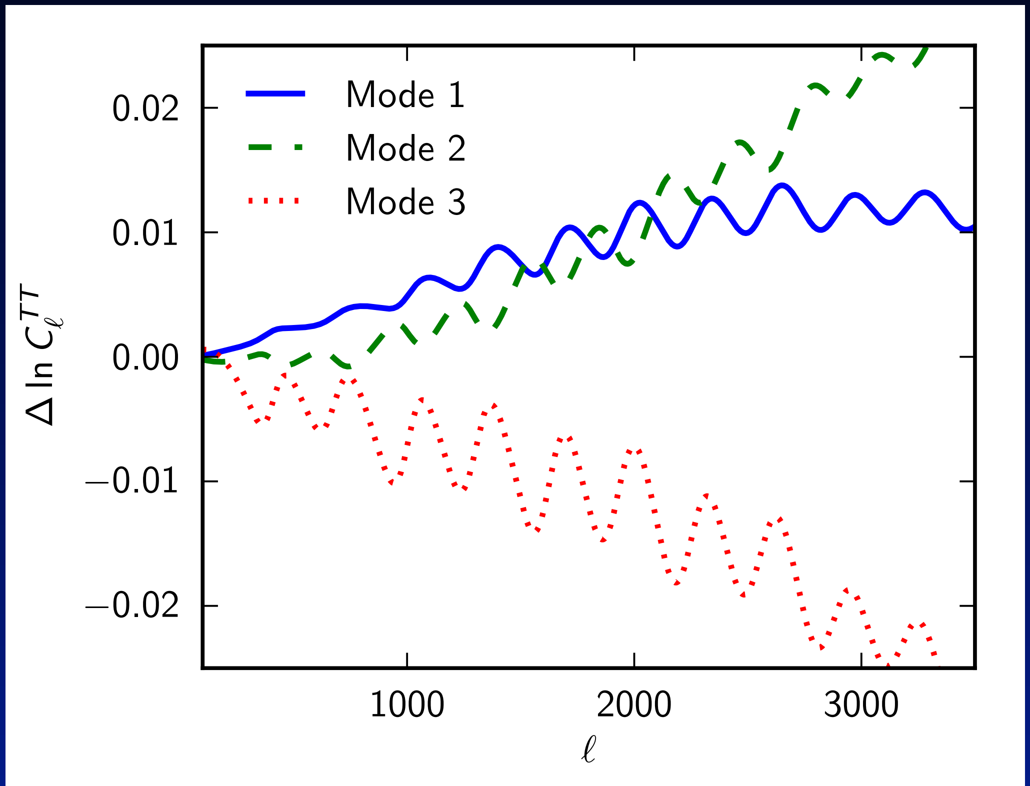
- E.g., something *standard* was missed, or something *non-standard* happened !?
- A *non-parametric estimation* of possible *corrections* to the recombination history would be very useful → *Principle component analysis* (PCA)



Farhang, Bond & JC, 2012

PCA analysis with Planck 2015



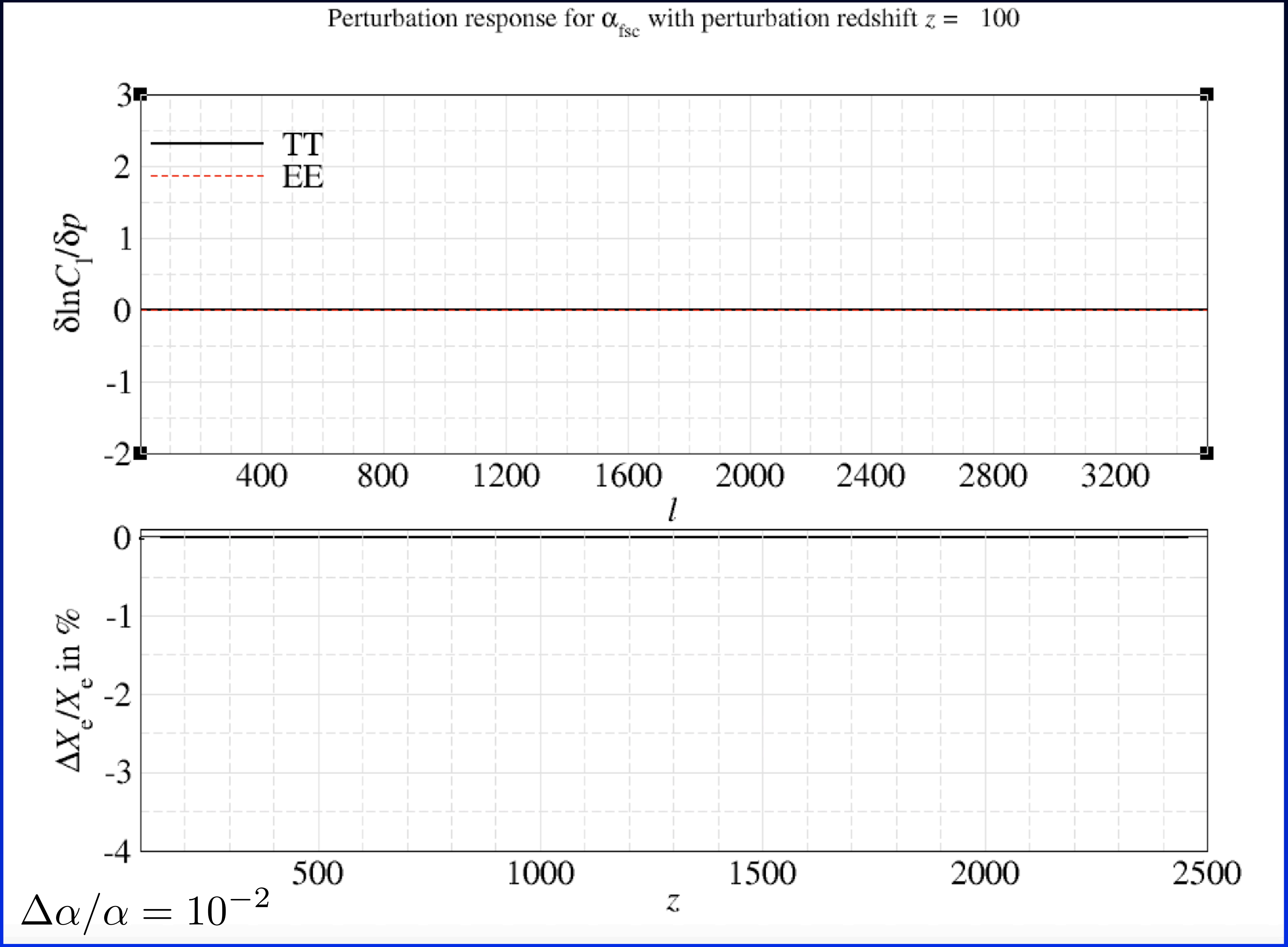


- Planck data is *consistent* with standard recombination
- Non-trivial statement, even if it is expected!
- Improvement in next release

Parameter	+ 1 mode	+ 2 modes	+ 3 modes
$\Omega_b h^2$	0.02229 ± 0.00017	0.02237 ± 0.00018	0.02237 ± 0.00019
$\Omega_c h^2$	0.1190 ± 0.0010	0.1186 ± 0.0011	0.1187 ± 0.0012
H_0	67.64 ± 0.48	67.80 ± 0.51	67.80 ± 0.56
τ	0.065 ± 0.012	0.068 ± 0.013	0.068 ± 0.013
n_s	0.9667 ± 0.0053	0.9677 ± 0.0055	0.9678 ± 0.0067
$\ln(10^{10} A_s)$	3.062 ± 0.023	3.066 ± 0.024	3.066 ± 0.024
μ_1	-0.03 ± 0.12	0.03 ± 0.14	0.02 ± 0.15
μ_2	. . .	-0.17 ± 0.18	-0.18 ± 0.19
μ_3	. . .	. . .	-0.02 ± 0.88

Planck Collaboration, XIII, 2015

We can do this for fundamental constants too…



Luke Hart & JC, in preparation

Cosmological Recombination Radiation

Simple estimates for hydrogen recombination

Hydrogen recombination:

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

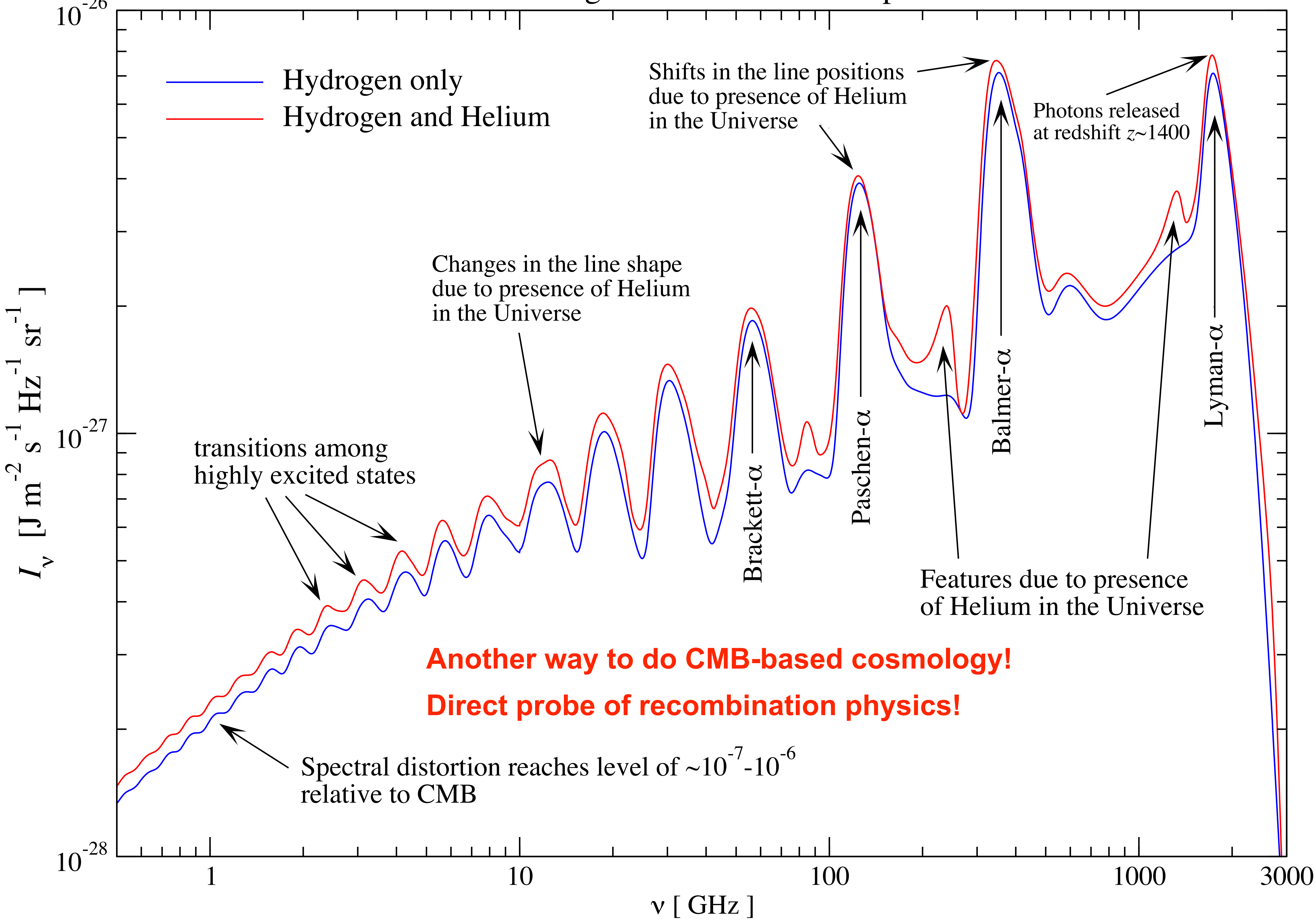
→ recombination occurs at redshifts $z < 10^4$

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

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

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

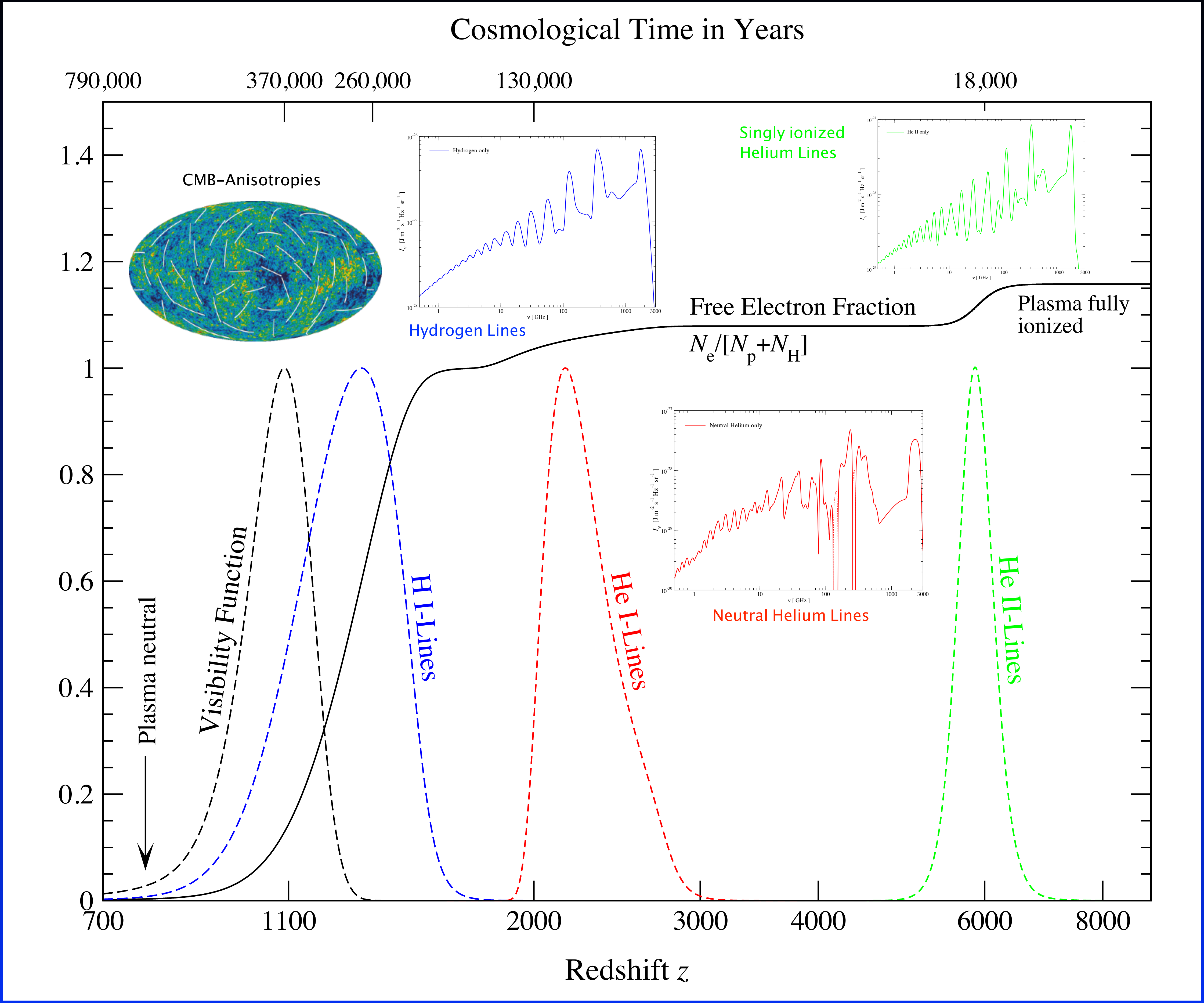
Cosmological Recombination Spectrum



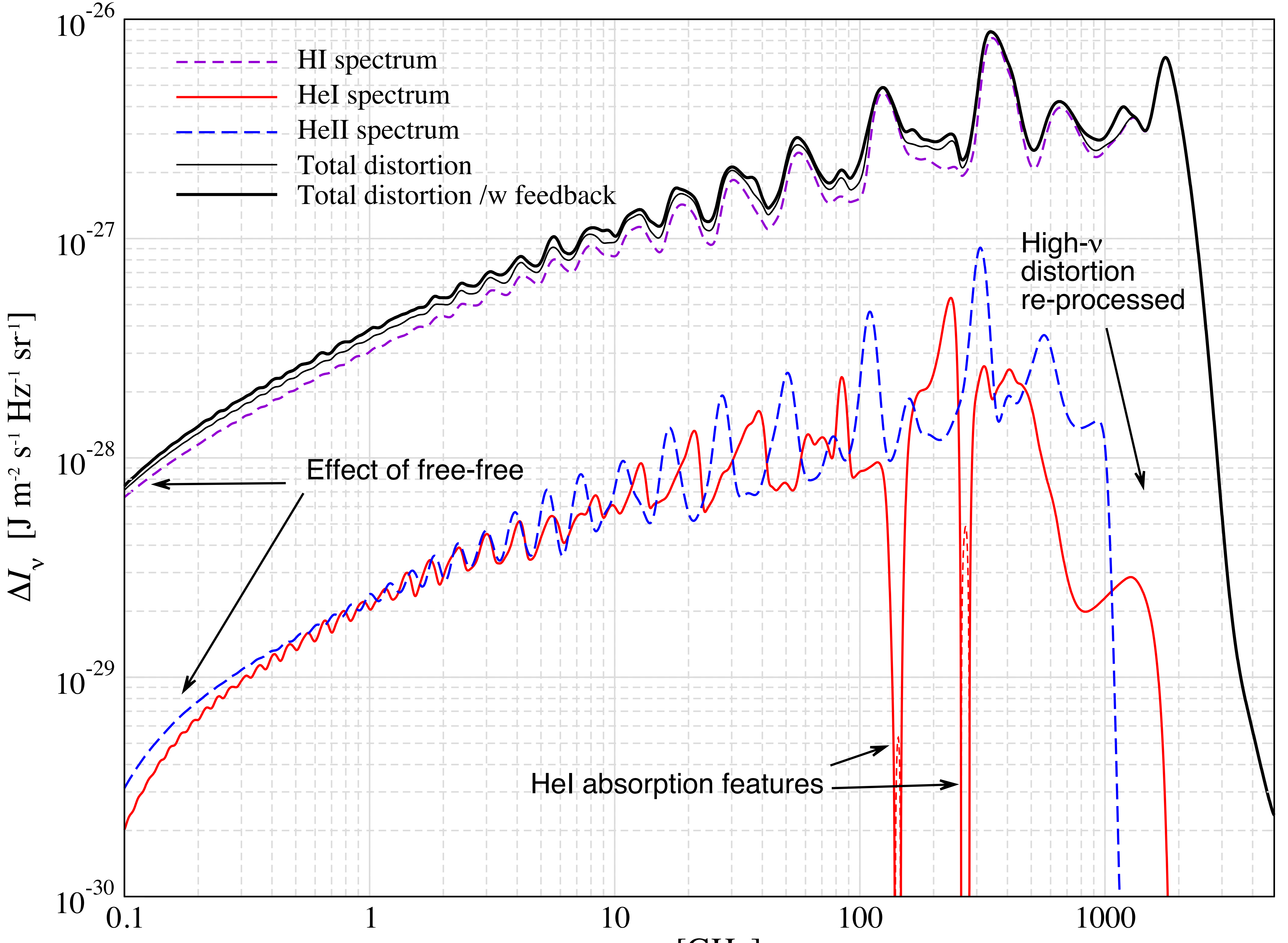
Another way to do CMB-based cosmology!

Direct probe of recombination physics!

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

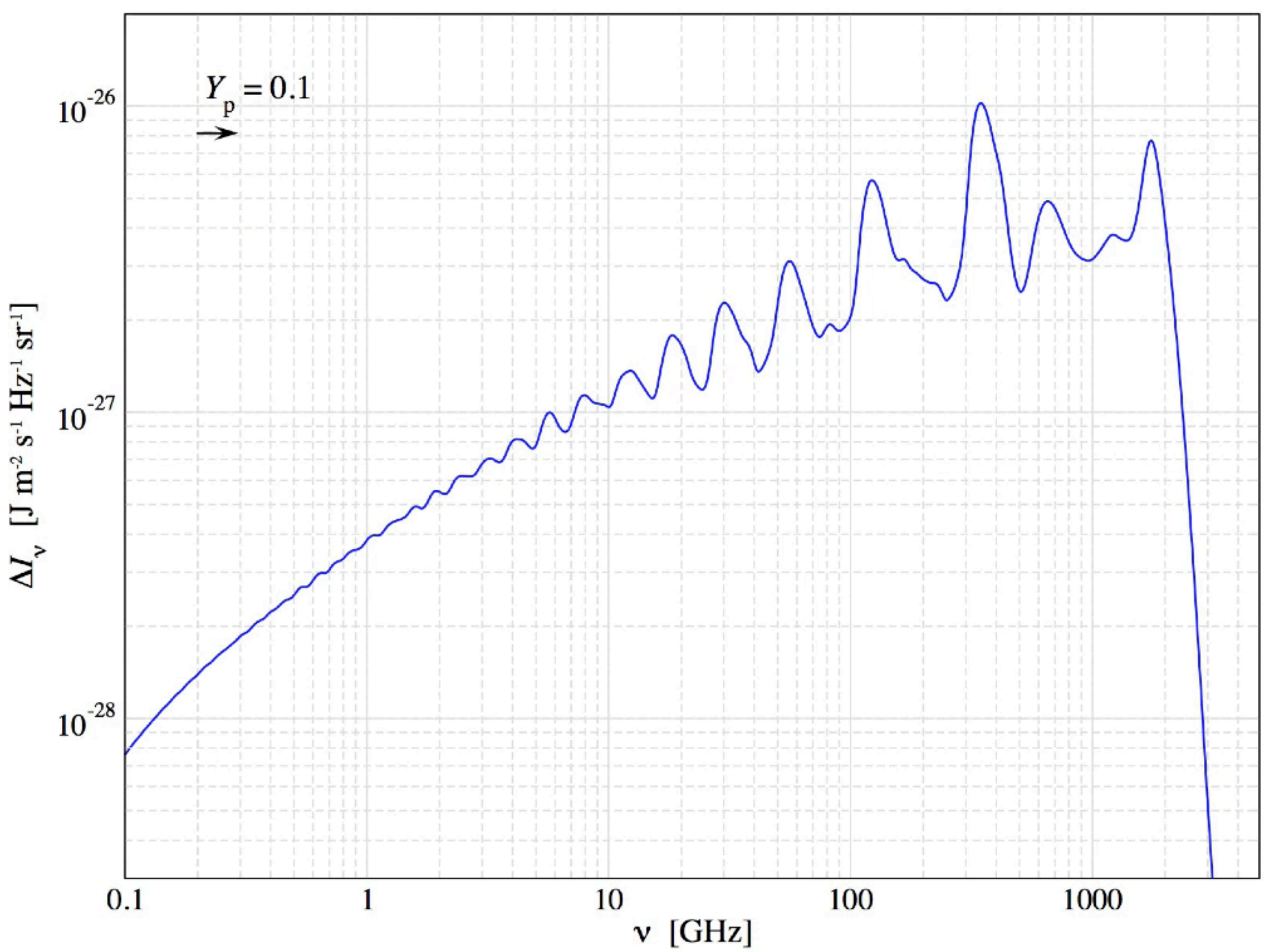

Cosmological Time in Years
790,000
370,000
260,000
130,000
18,000
CMB-Anisotropies
Hydrogen Lines
Singly ionized
Helium Lines
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully
ionized
Neutral Helium Lines
Visibility Function
Plasma neutral
H I-Lines
He I-Lines
He II-Lines
Redshift z

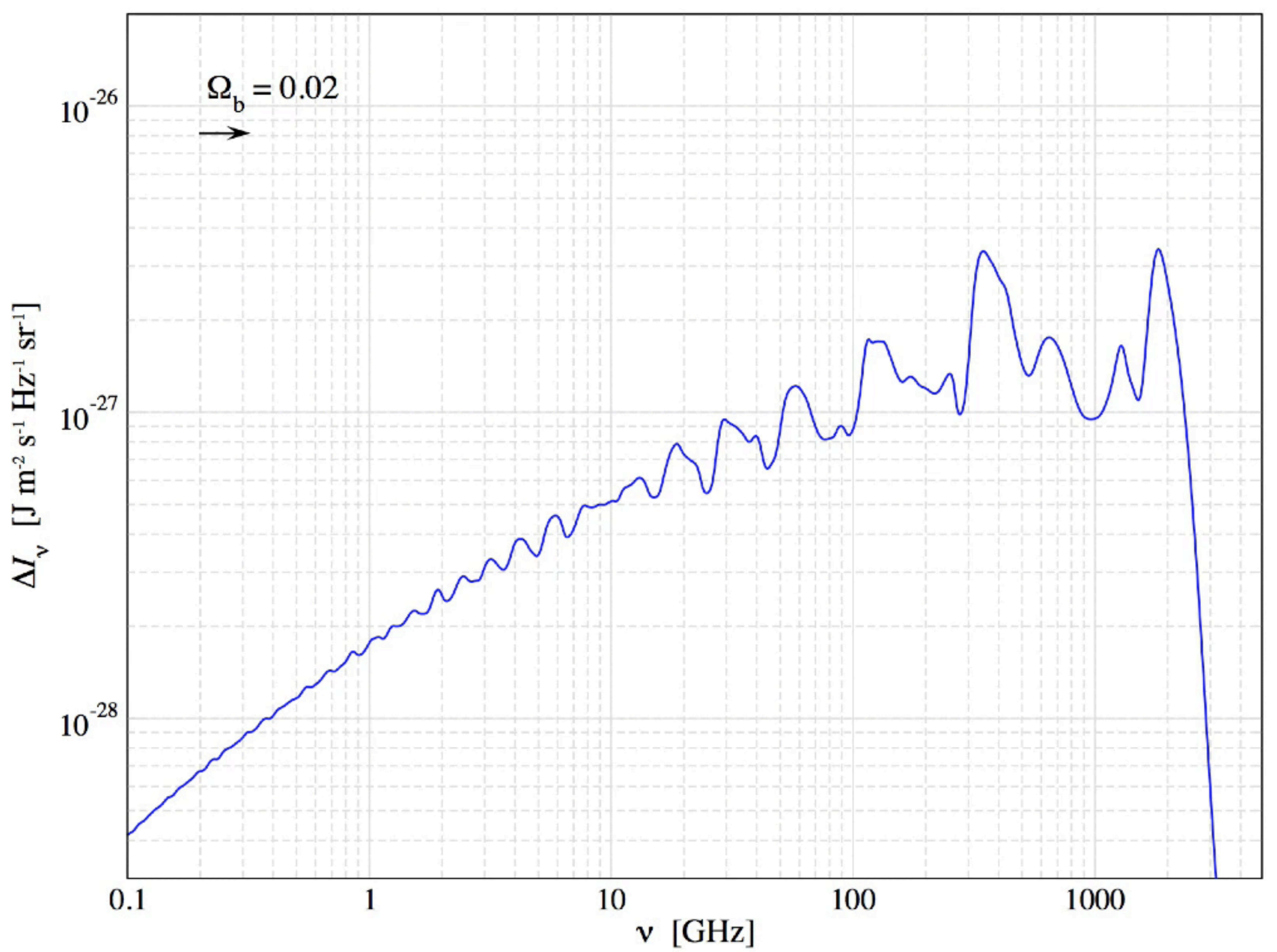
New detailed and fast computation!



JC & Ali-Haimoud, arXiv:1510.03877

CosmoSpec: fast and accurate computation of the CRR





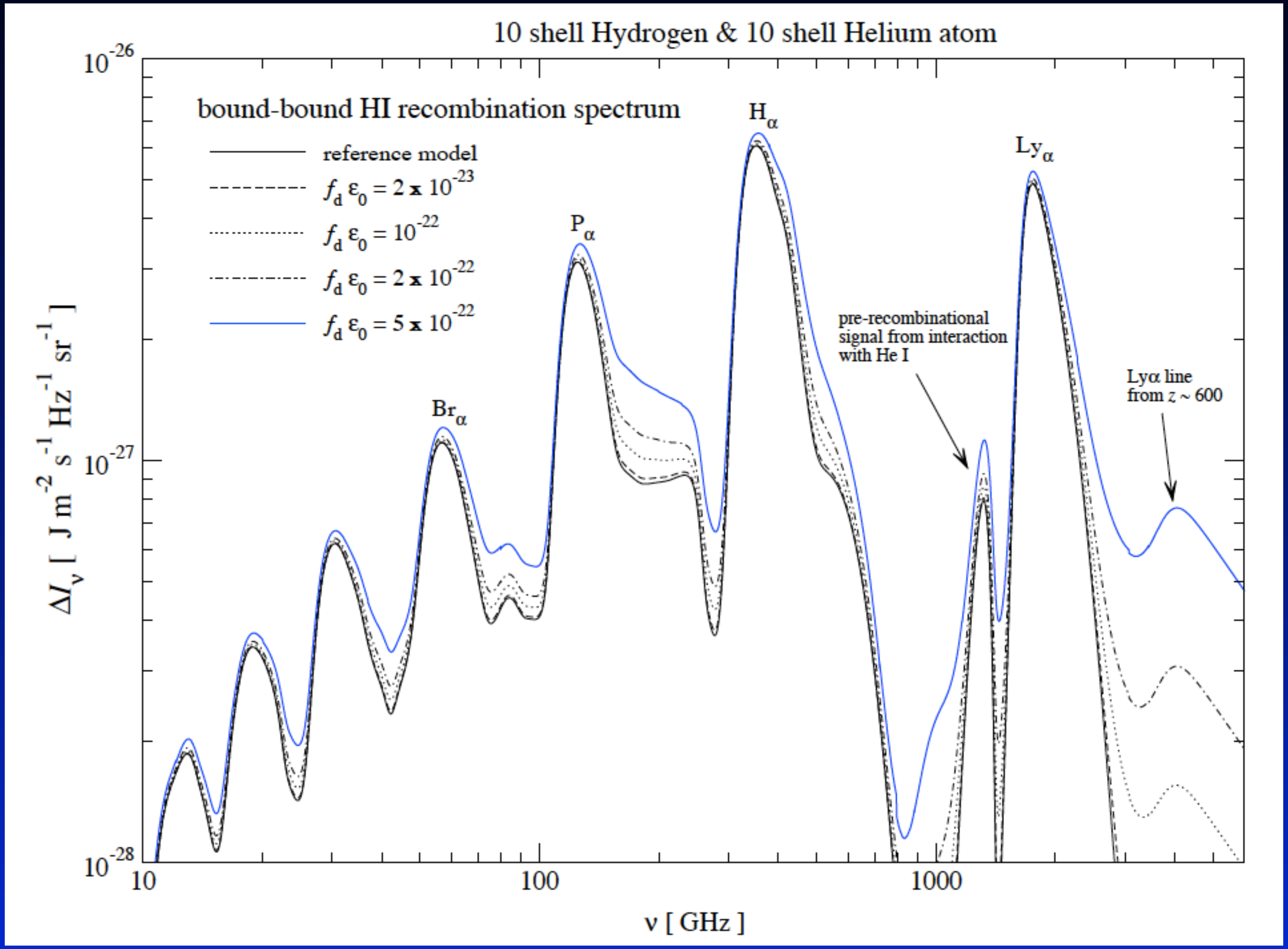
- Like in old days of CMB anisotropies!
- detailed forecasts and feasibility studies
- non-standard physics (variation of α, energy injection etc.)

CosmoSpec will be available here:

www.Chluba.de/CosmoSpec

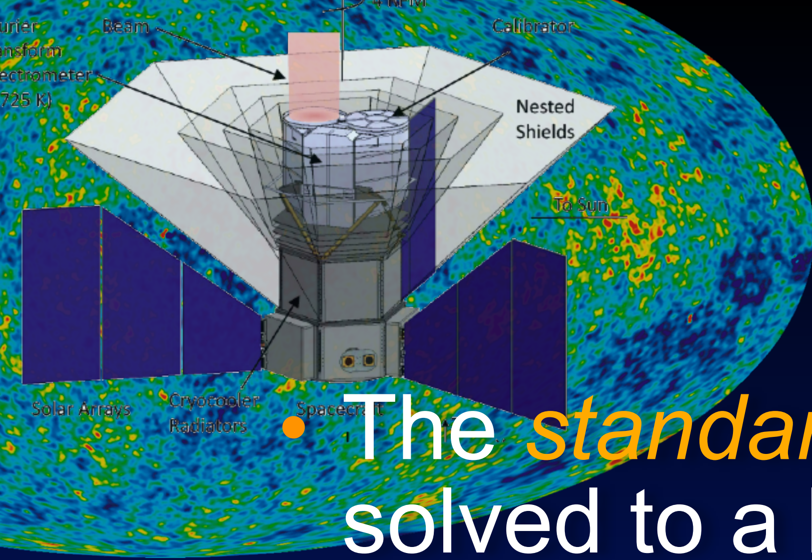
JC & Ali-Haimoud, arXiv:1510.03877

Dark matter annihilations / decays



JC, 2009, arXiv:0910.3663

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



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*