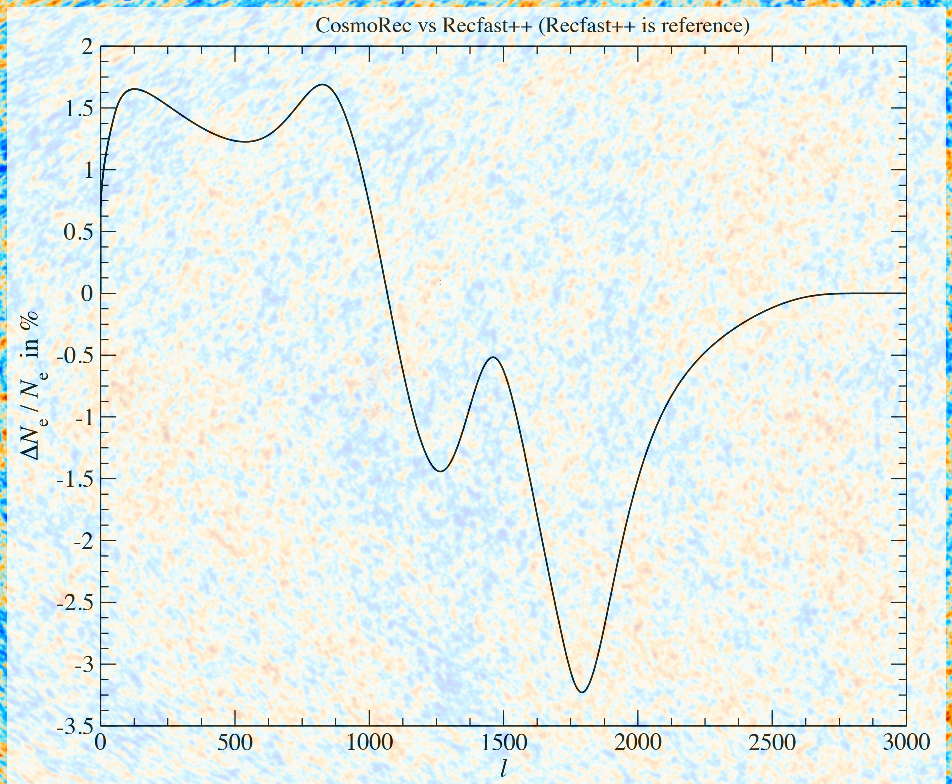
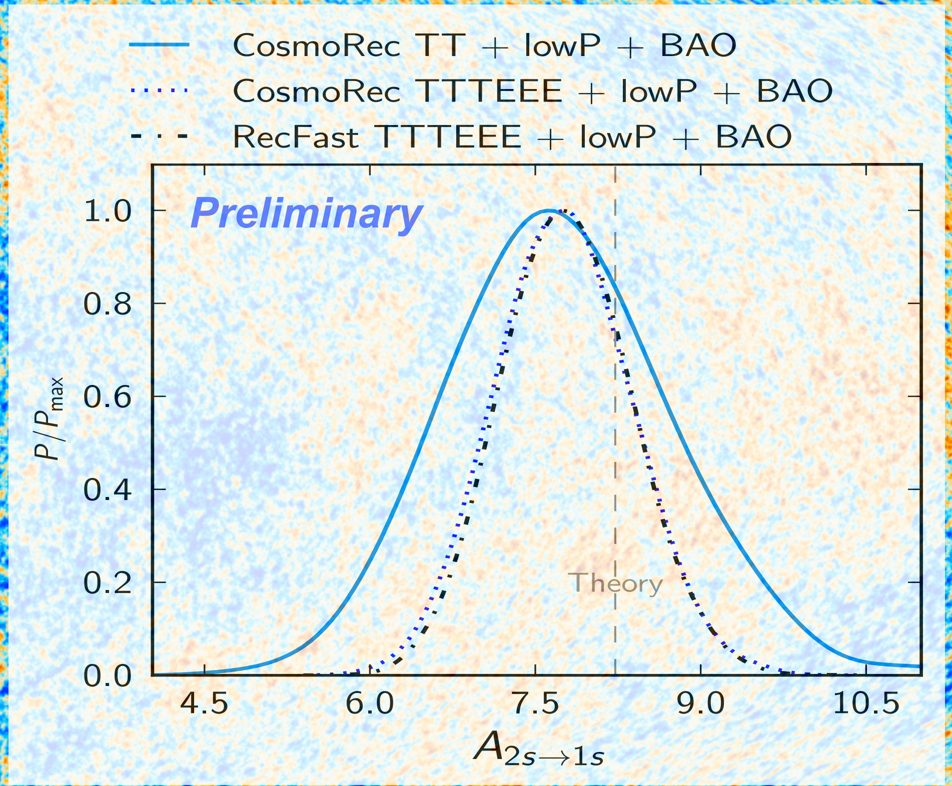
Why recombination is so important for the interpretation of *Planck* data

Improved Recombination History



HI 2s-1s two-photon decay rate

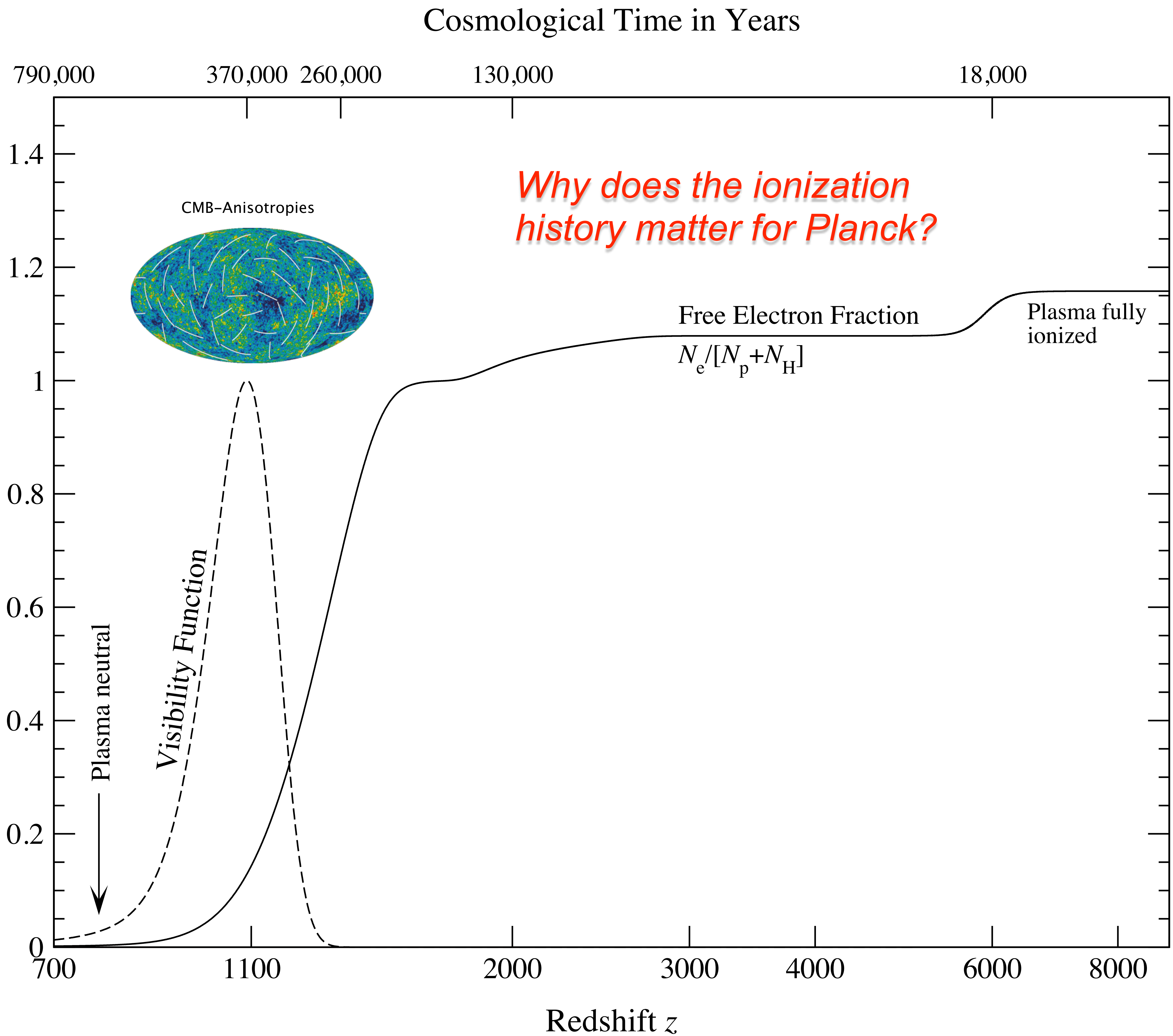


Jens Chluba

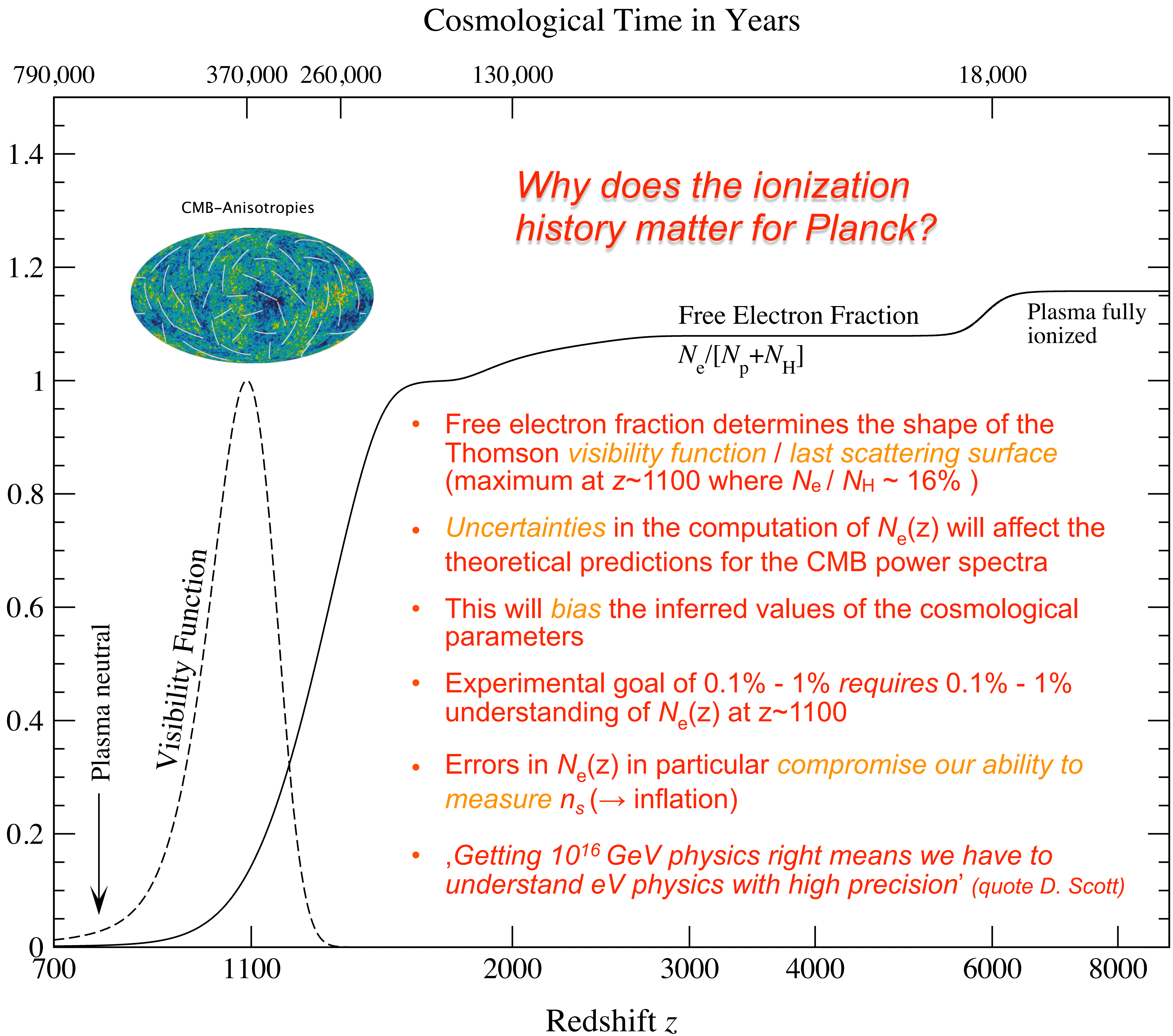
on behalf of the Planck Collaboration

Planck 2014 - The microwave sky in temperature and polarization

Ferrara, Italy, Dec 1st - 5th, 2014



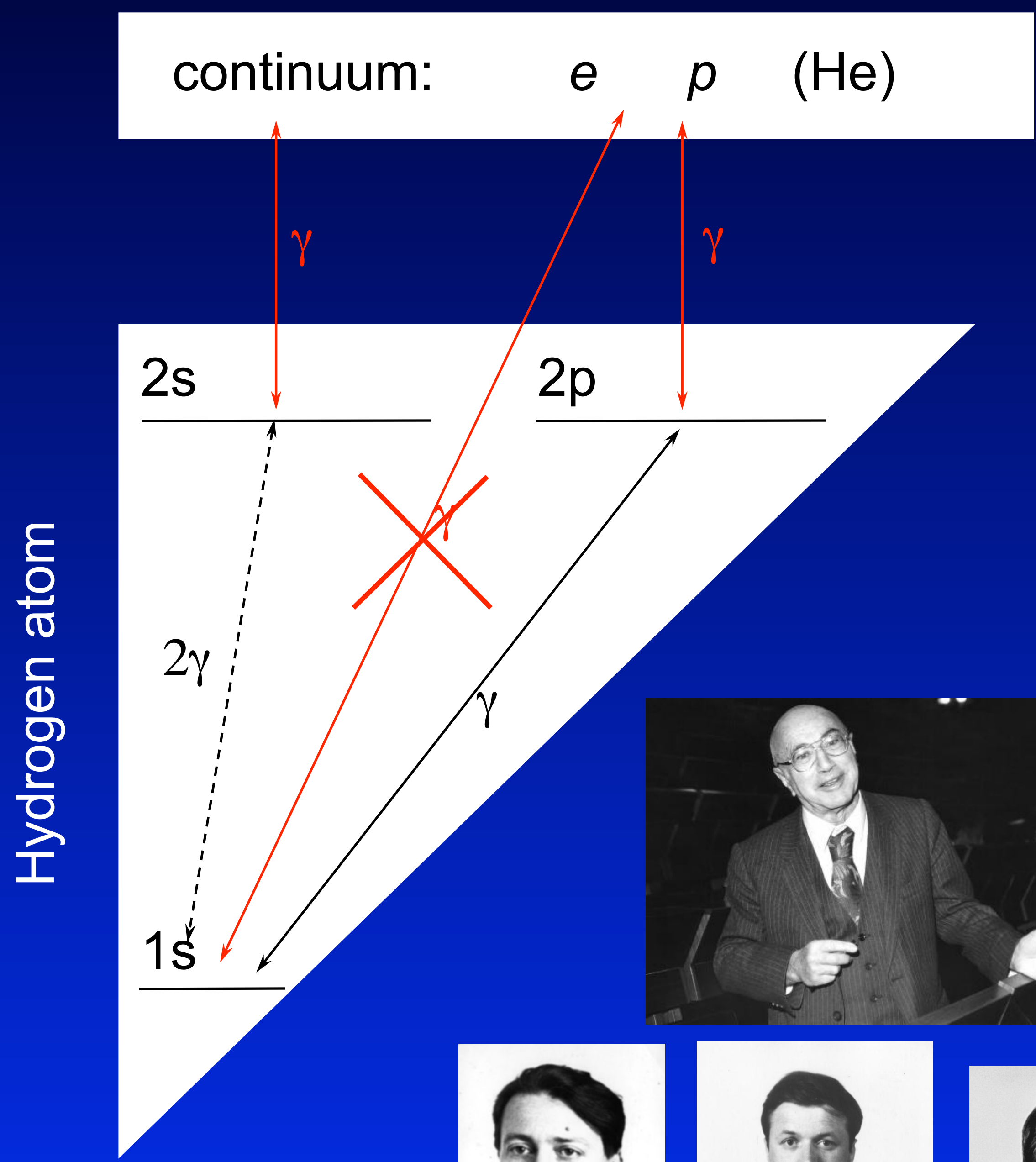
Cosmological Time in Years
790,000
370,000
260,000
130,000
18,000
Why does the ionization history matter for Planck?
CMB-Anisotropies
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully ionized
Visibility Function
Plasma neutral
1.4
1.2
1
0.8
0.6
0.4
0.2
0
700
1100
2000
3000
4000
6000
8000
Redshift z

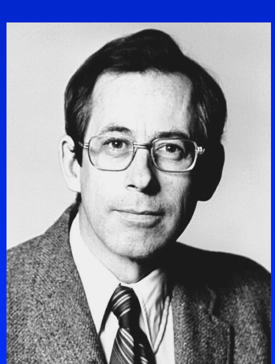


Why does the ionization history matter for Planck?

- 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)*

3-level Hydrogen Atom and Continuum





Routes to the ground state ?

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

No

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

~ 43%

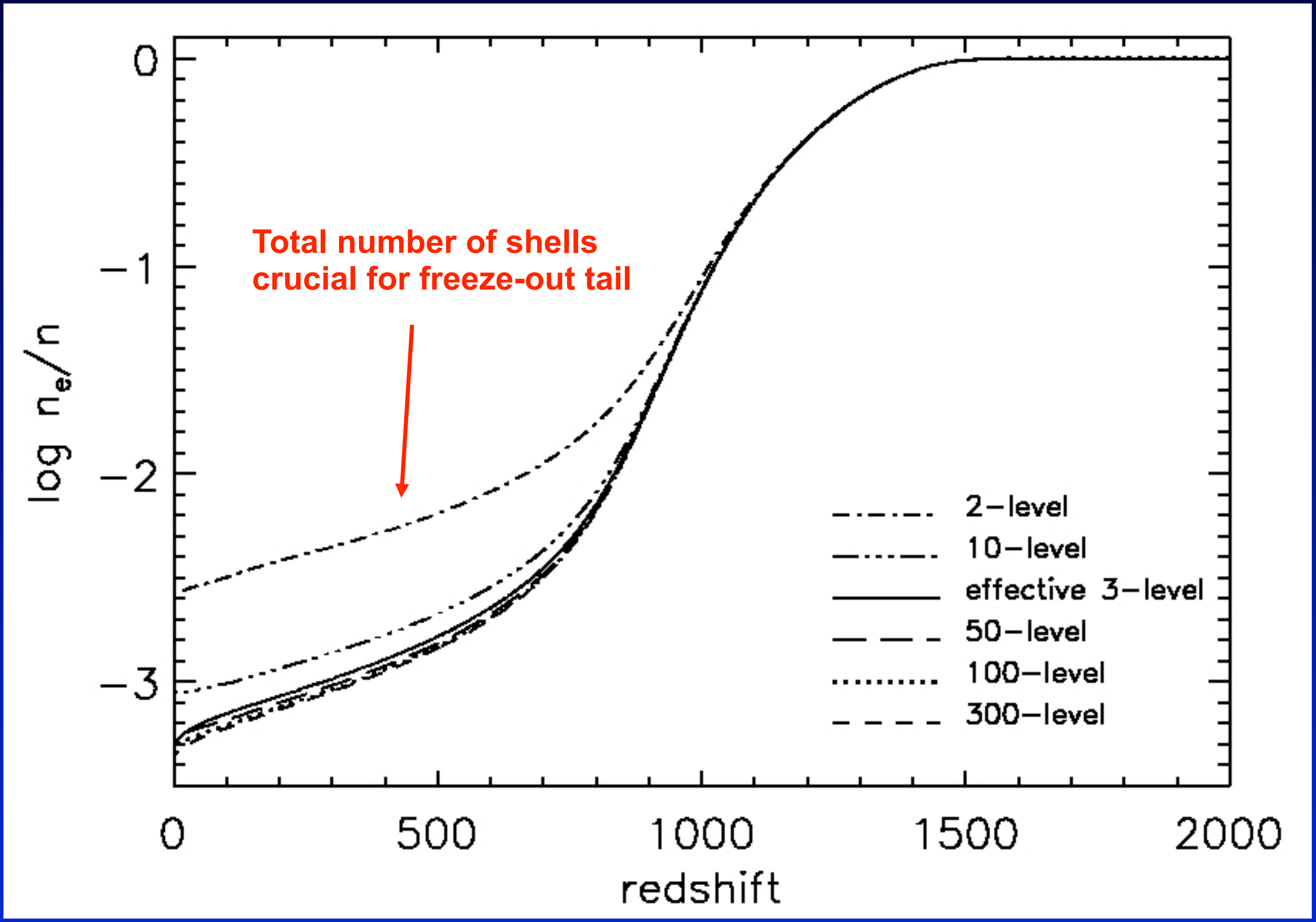
- **recombination to 2s followed by 2s two-photon decay**
  - **2s → 1s ~10^8 times slower than Ly-α**
  - **2s two-photon decay profile → maximum at $\nu \sim 1/2\ \nu_\alpha$**
  - **immediate escape**

~ 57%

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

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

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

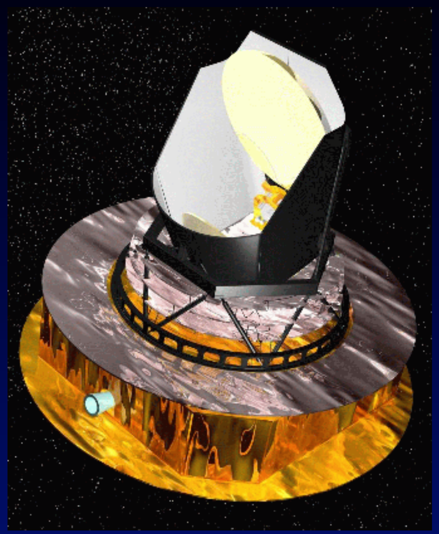
Low Redshifts:

- 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

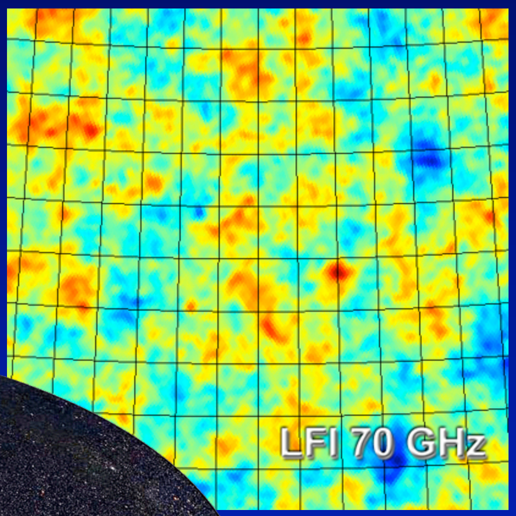
$\Delta N_e \,/\, N_e \sim 1\% - 3\%$

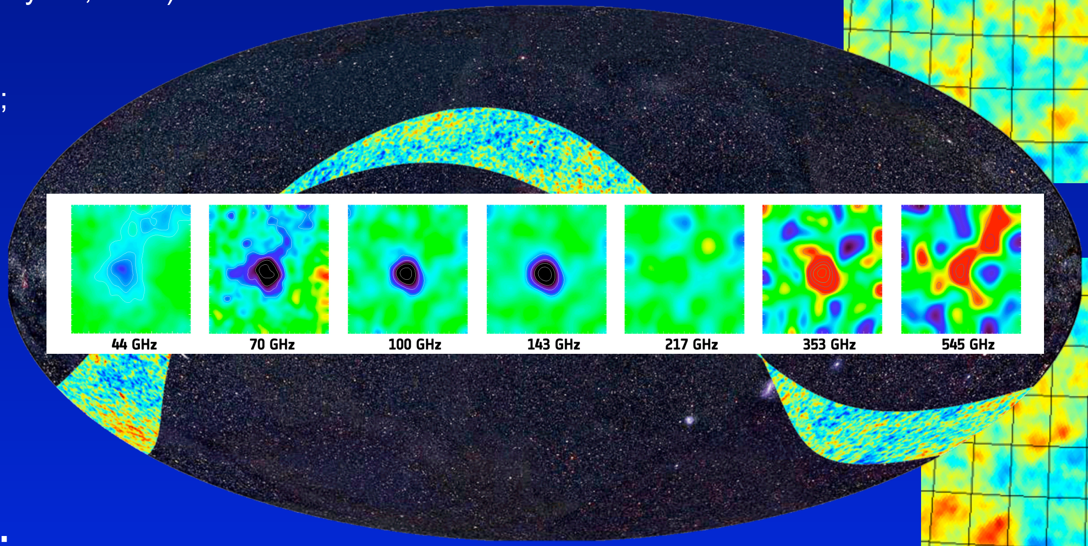
Getting the job done for *Planck*



Hydrogen recombination

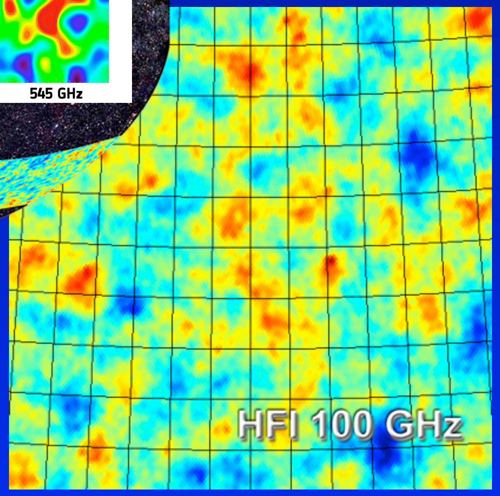
- Two-photon decays from higher levels
  (Dubrovich & Grachev, 2005, Astr. Lett., 31, 359; Wong & Scott, 2007; JC & Sunyaev, 2007; Hirata, 2008; JC & Sunyaev 2009)
- Induced 2s two-photon decay for hydrogen
  (JC & Sunyaev, 2006, A&A, 446, 39; Hirata 2008)
- Feedback of the Lyman-α distortion on the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





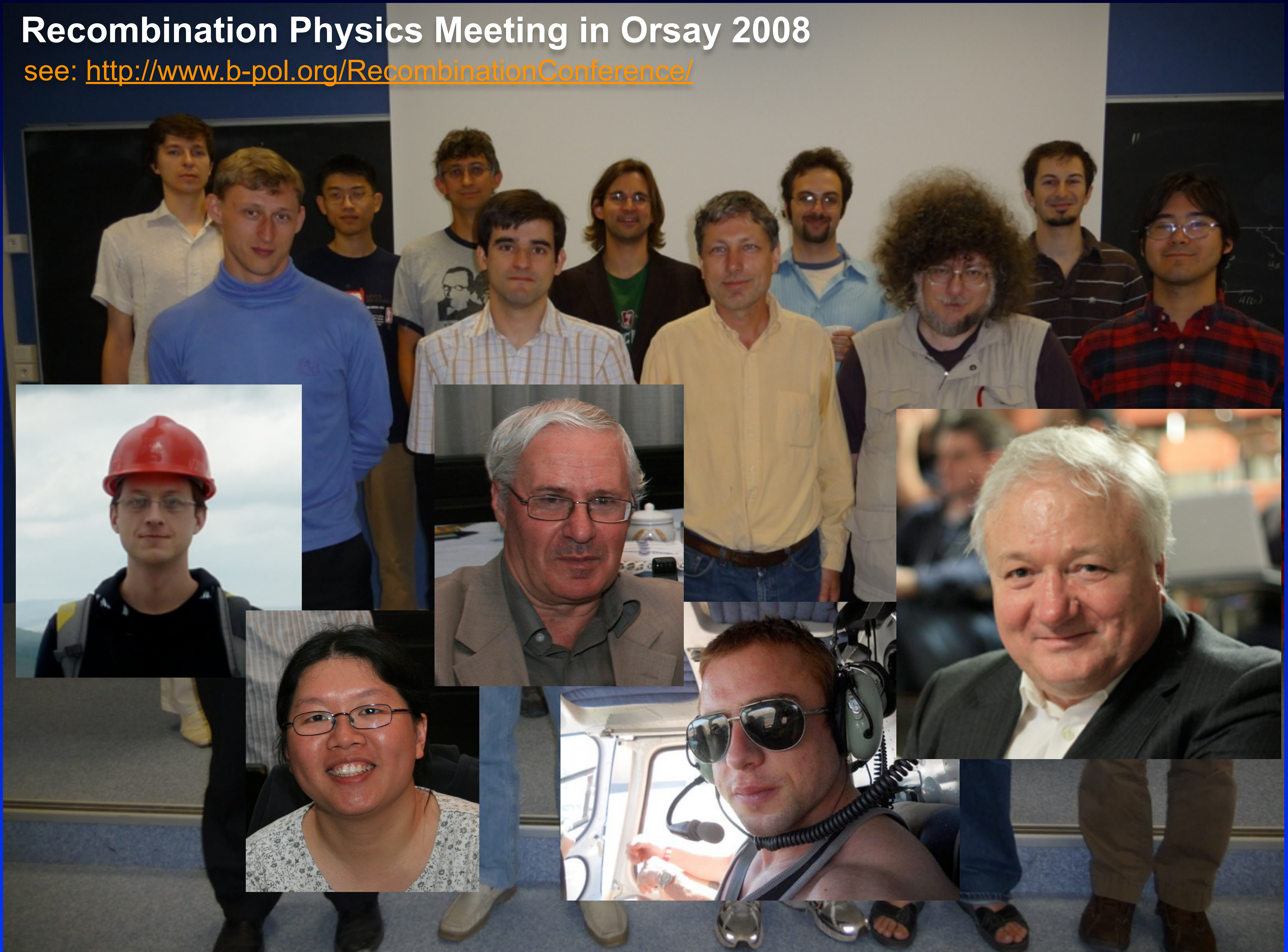
Helium recombination

- 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)

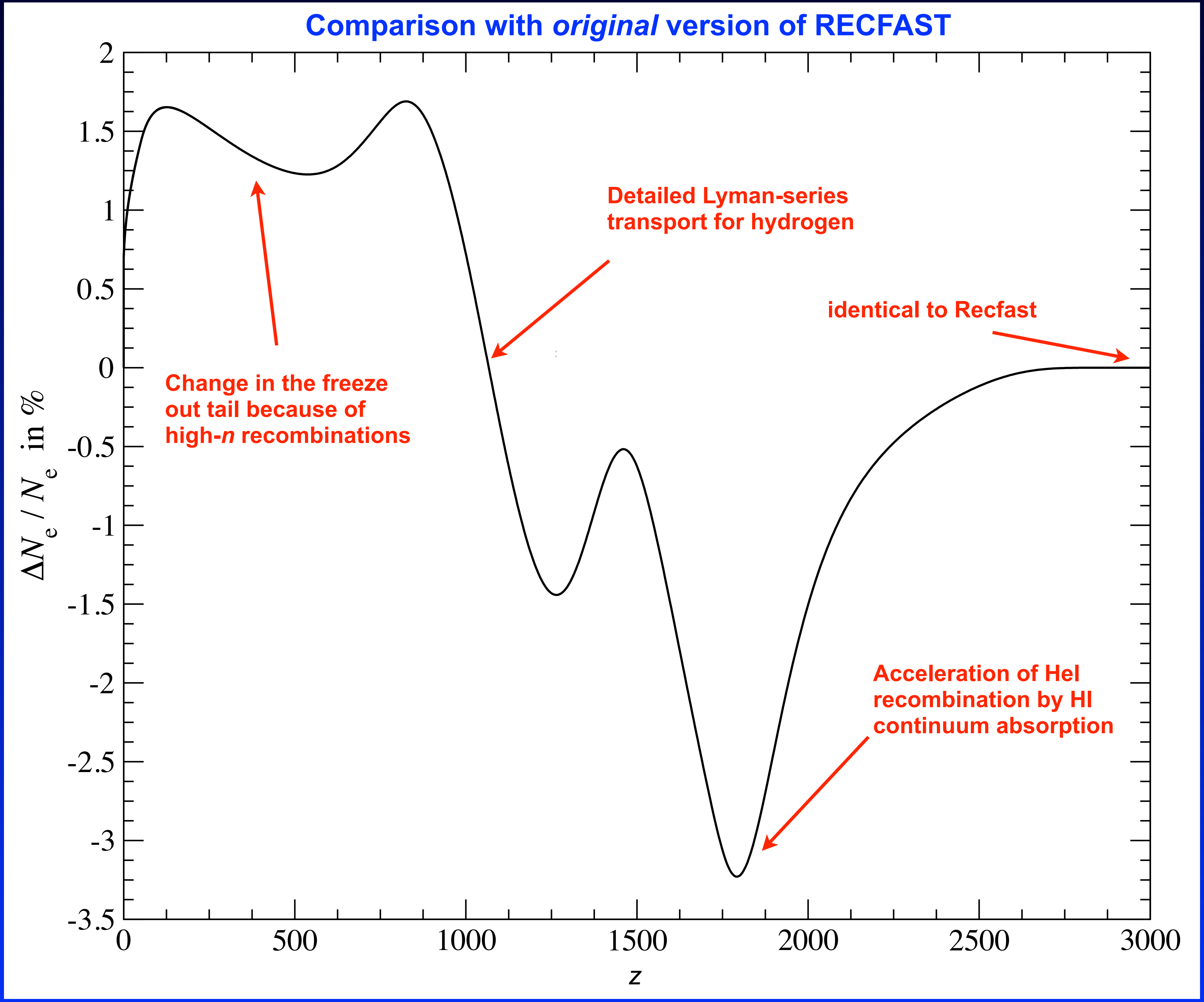


$\boxed{\Delta N_e \,/\, N_e \sim 0.1\ \%}$

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



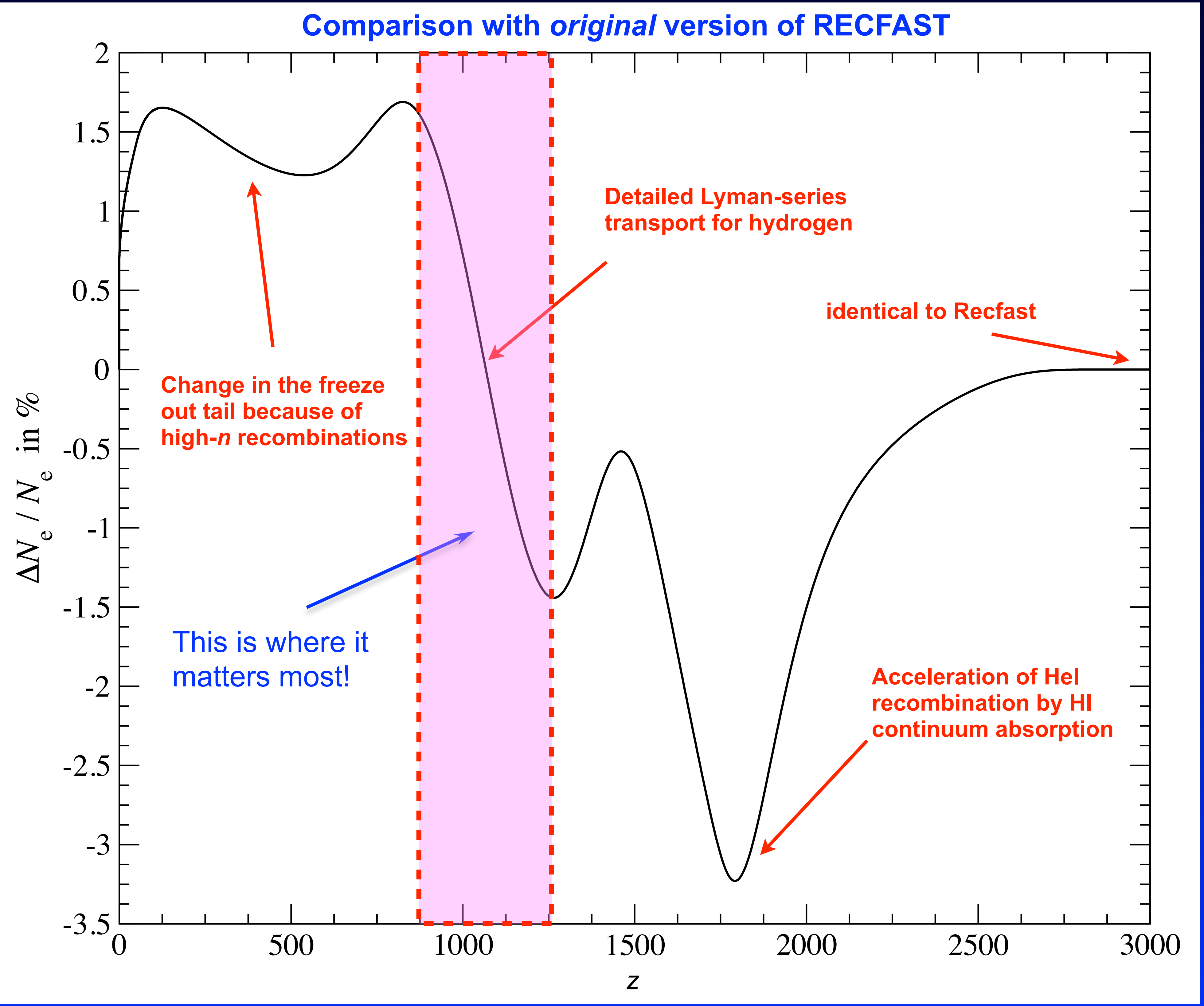
Cumulative Changes to the Ionization History



CITA ICAT

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

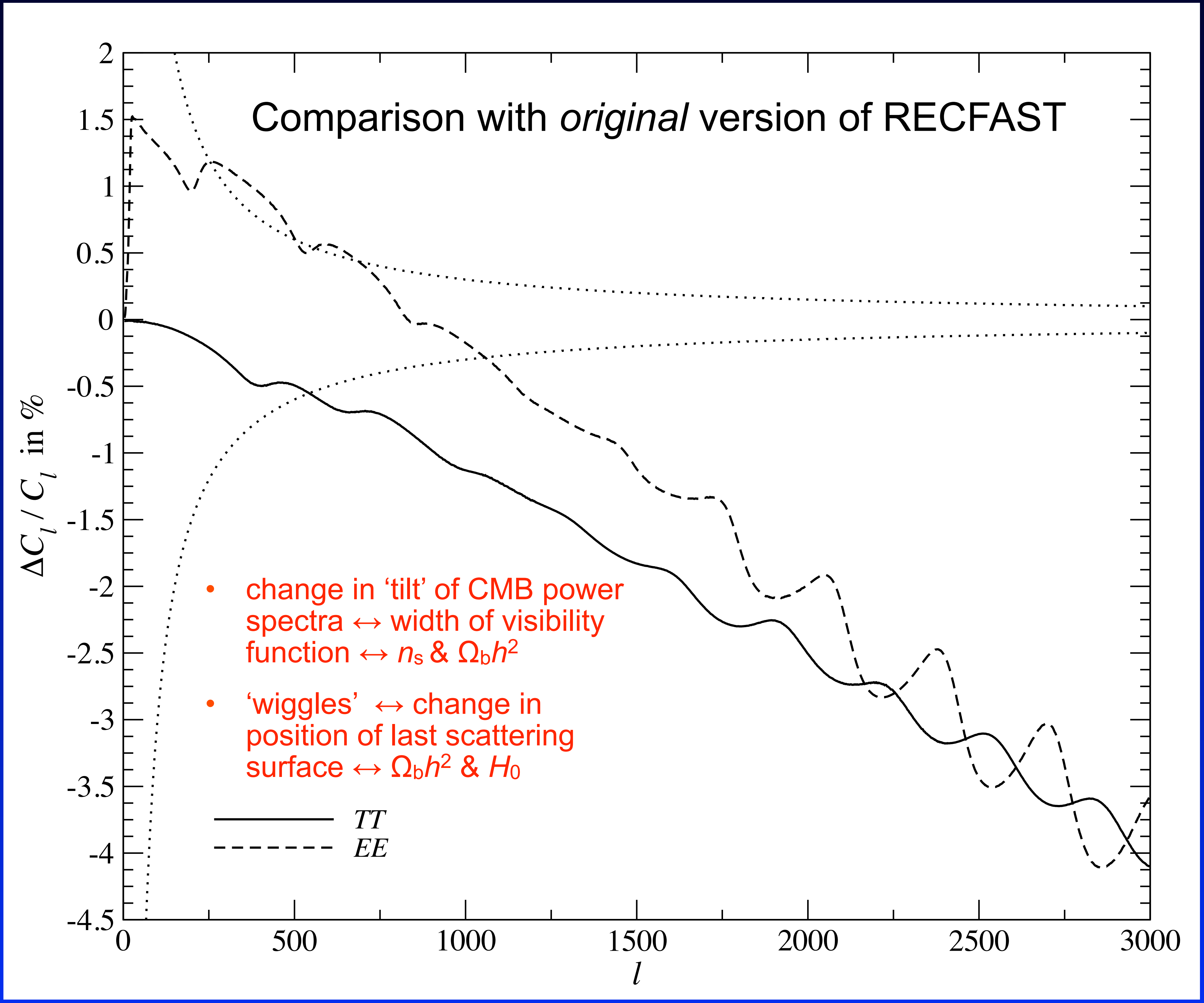
Cumulative Changes to the Ionization History



CITA ICAT

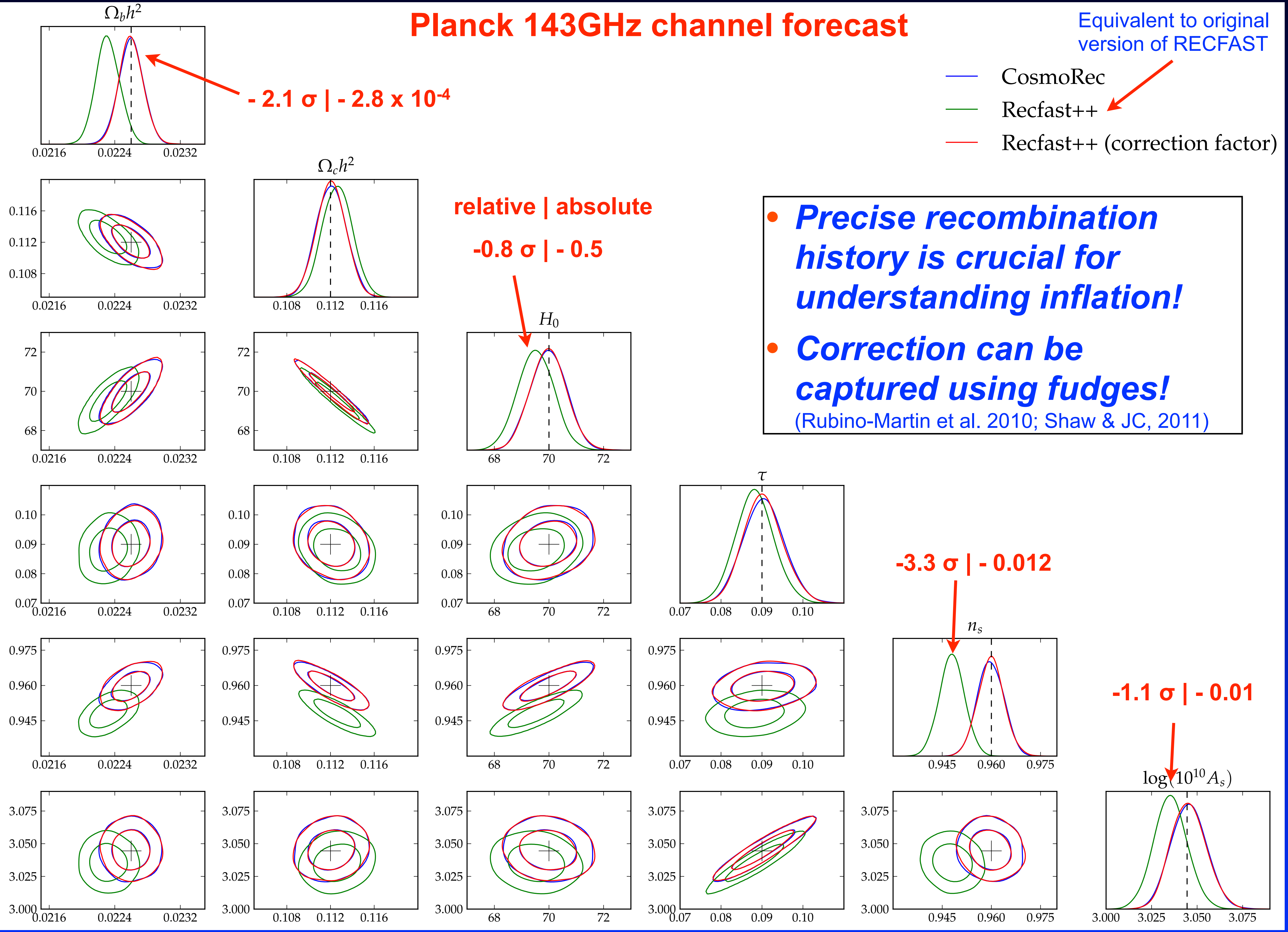
JC & Thomas, MNRAS, 2010; Shaw & JC, MNRAS, 2011

Cumulative Change in the CMB Power Spectra



CITA ICAT Shaw & JC, MNRAS, 2011

Importance of recombination for *Planck*

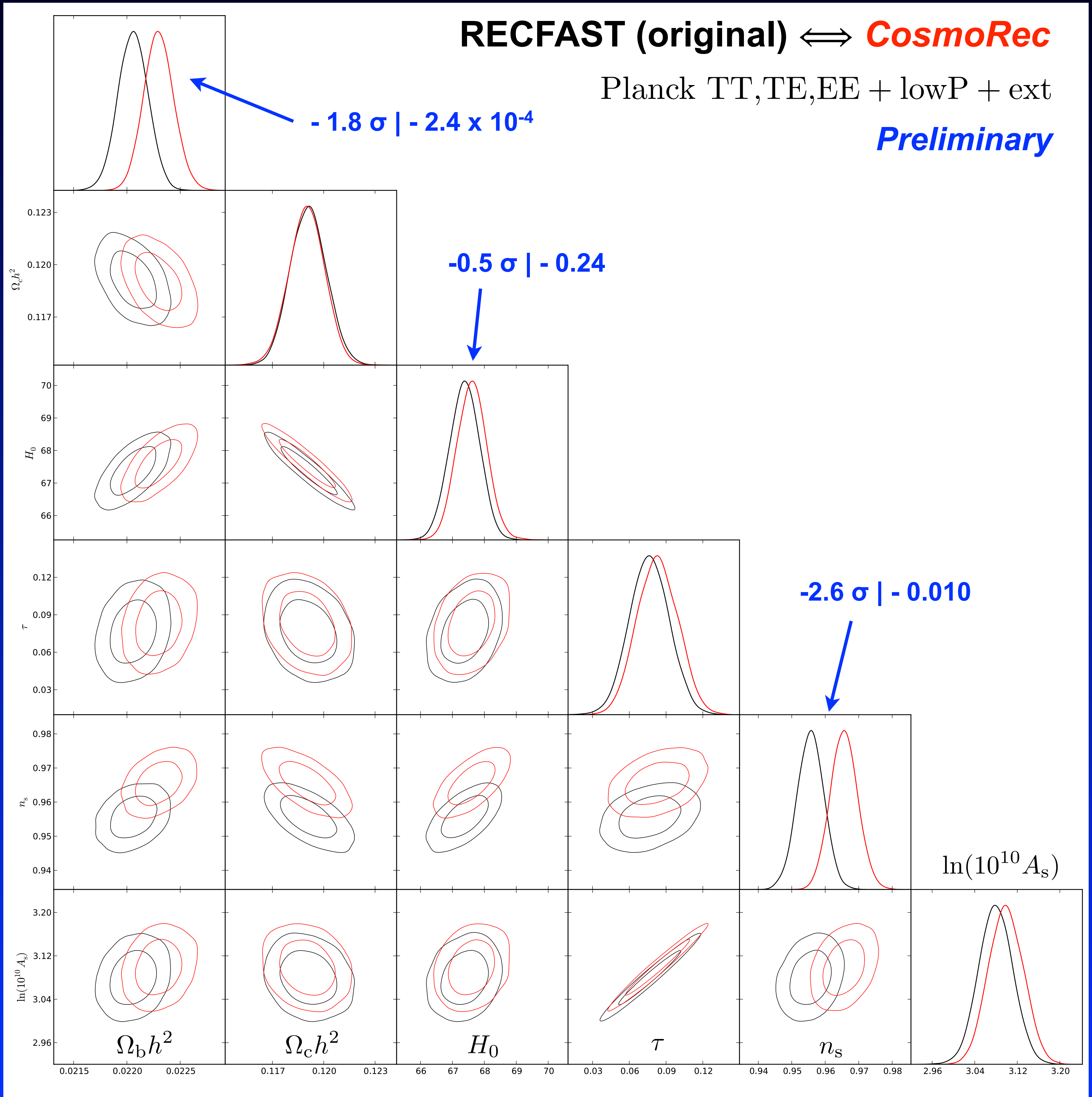


- ***Precise recombination history is crucial for understanding inflation!***
- ***Correction can be captured using fudges!***

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

Shaw & JC, 2011, and references therein

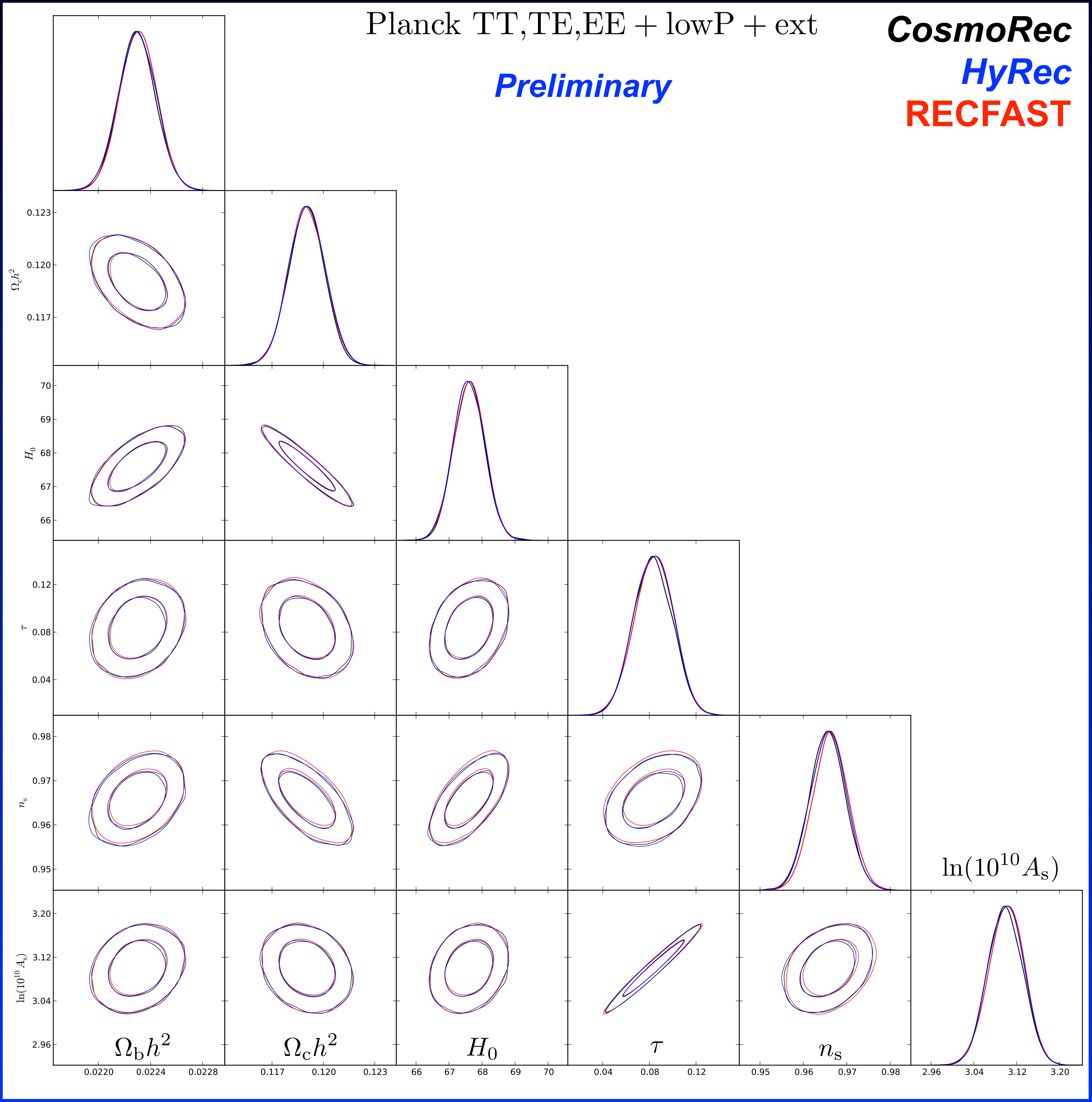
Biases as they *would* have been for *Planck*



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

Planck Collaboration, 2014

Differences for current recombination codes



- Different codes agree very well!
- largest biases

$\Delta n_s \approx 0.15\sigma$

(*CosmoRec* $\Longleftrightarrow$ RECFAST)

$\Delta n_s \approx 0.03\sigma$

(*CosmoRec* $\Longleftrightarrow$ *HyRec*)

- Nothing to worry about at this point!

Planck Collaboration, 2014

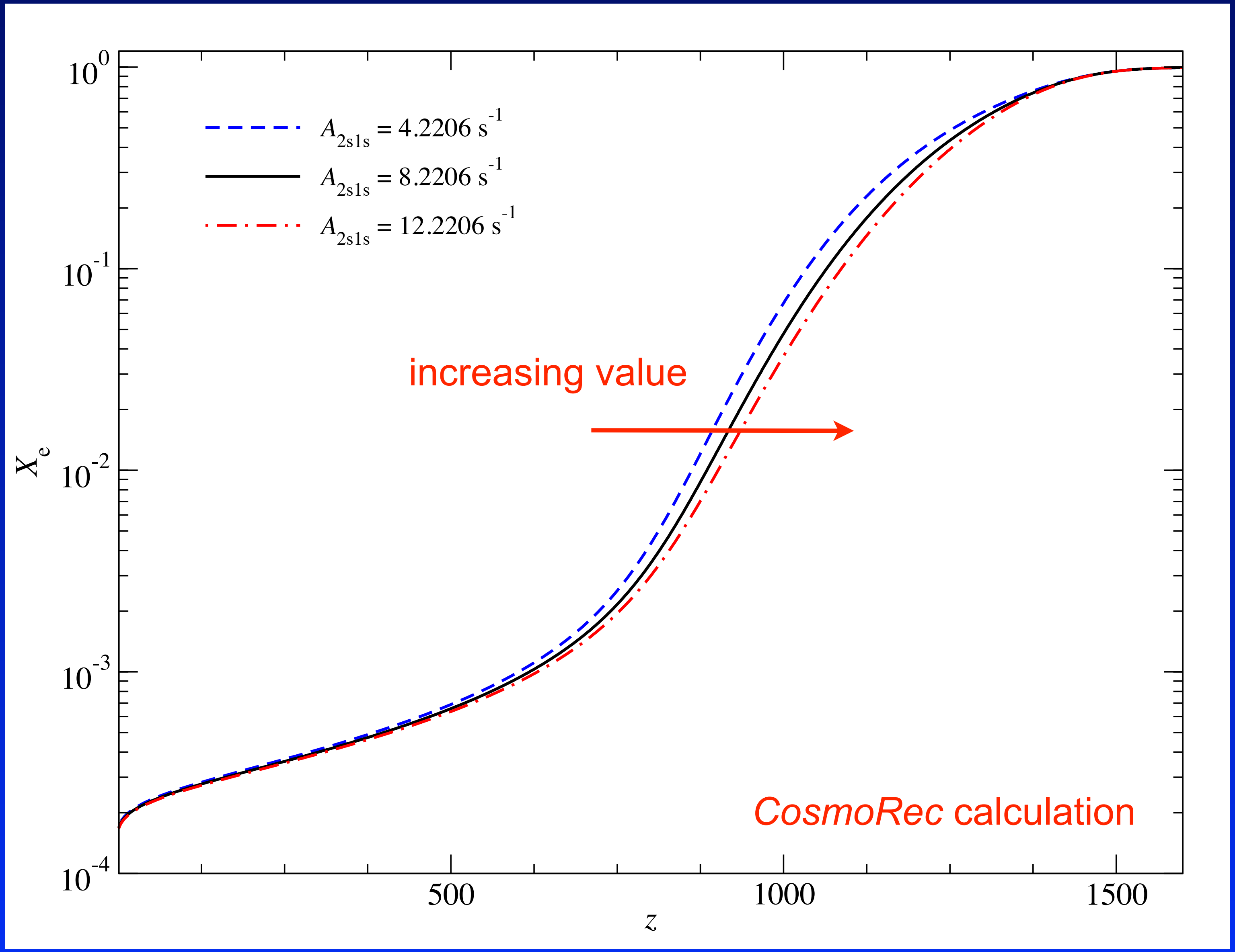
Planck measurement of the HI 2s-1s two-photon rate

- 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, 2014

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

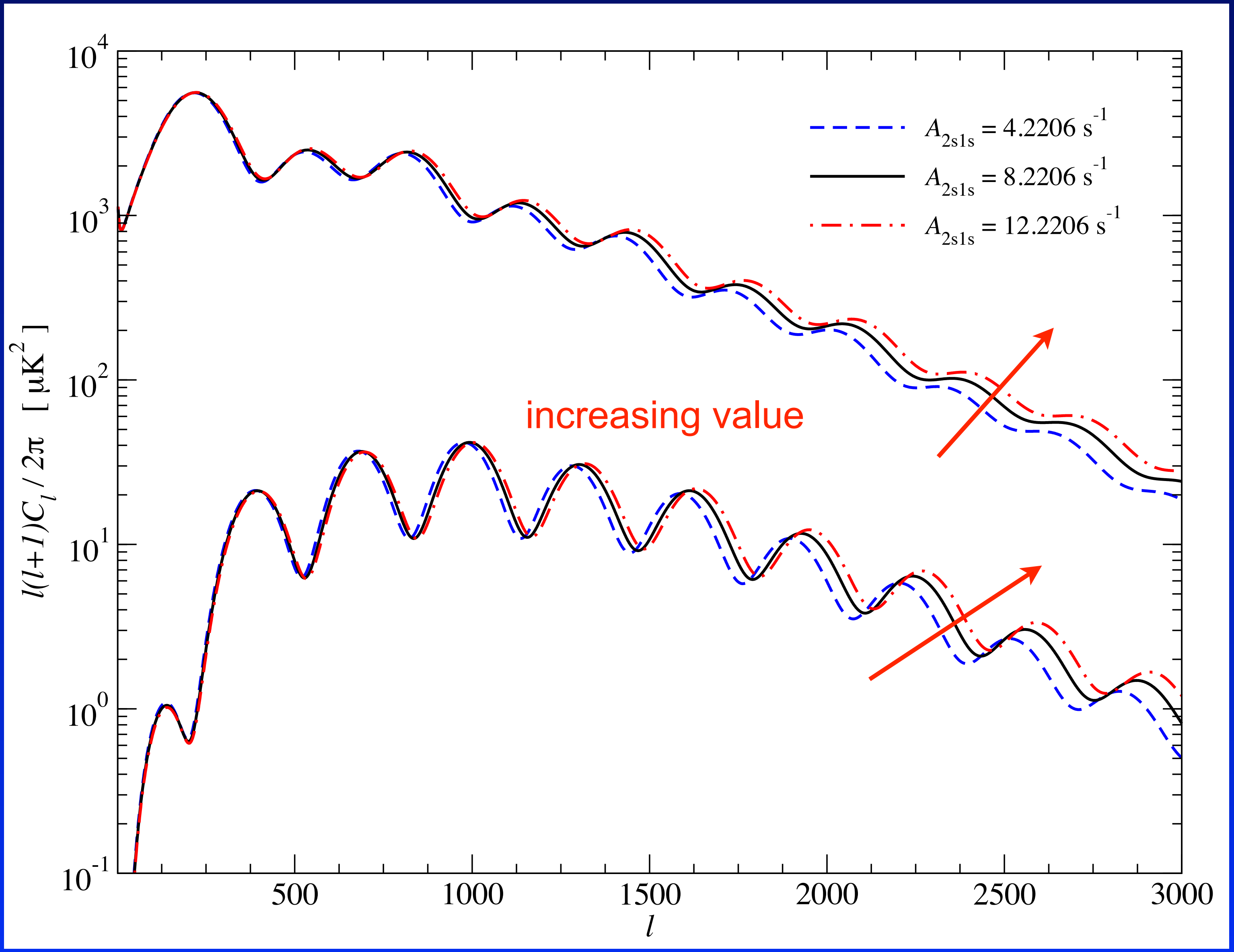
- HI 2s-1s two-photon rate crucial for recombination dynamics
- Value is not well measured in lab (best constraint ~ 43% error; Krueger & Oed 1975)
- *Planck* data can be used to directly constrain its value



Planck Collaboration, 2014

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

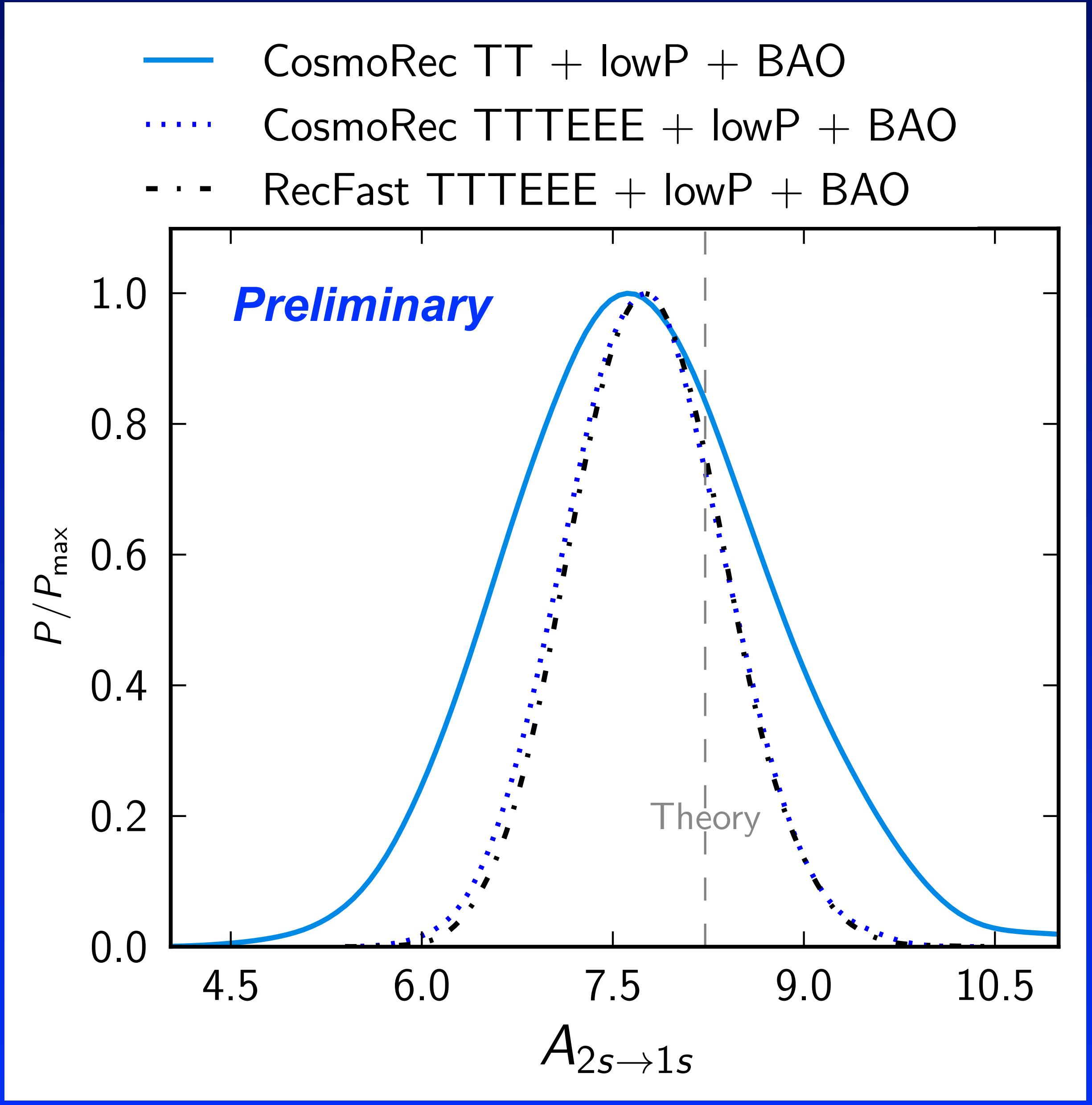
- HI 2s-1s two-photon rate crucial for recombination dynamics
- Value is not well measured in lab (best constraint ~ 43% error; Krueger & Oed 1975)
- *Planck* data can be used to directly constrain its value



Planck Collaboration, 2014

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



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

$$A_{2s\to1s} = 7.71 \pm 0.99\,{\rm s}^{-1}$$

(*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, 2014

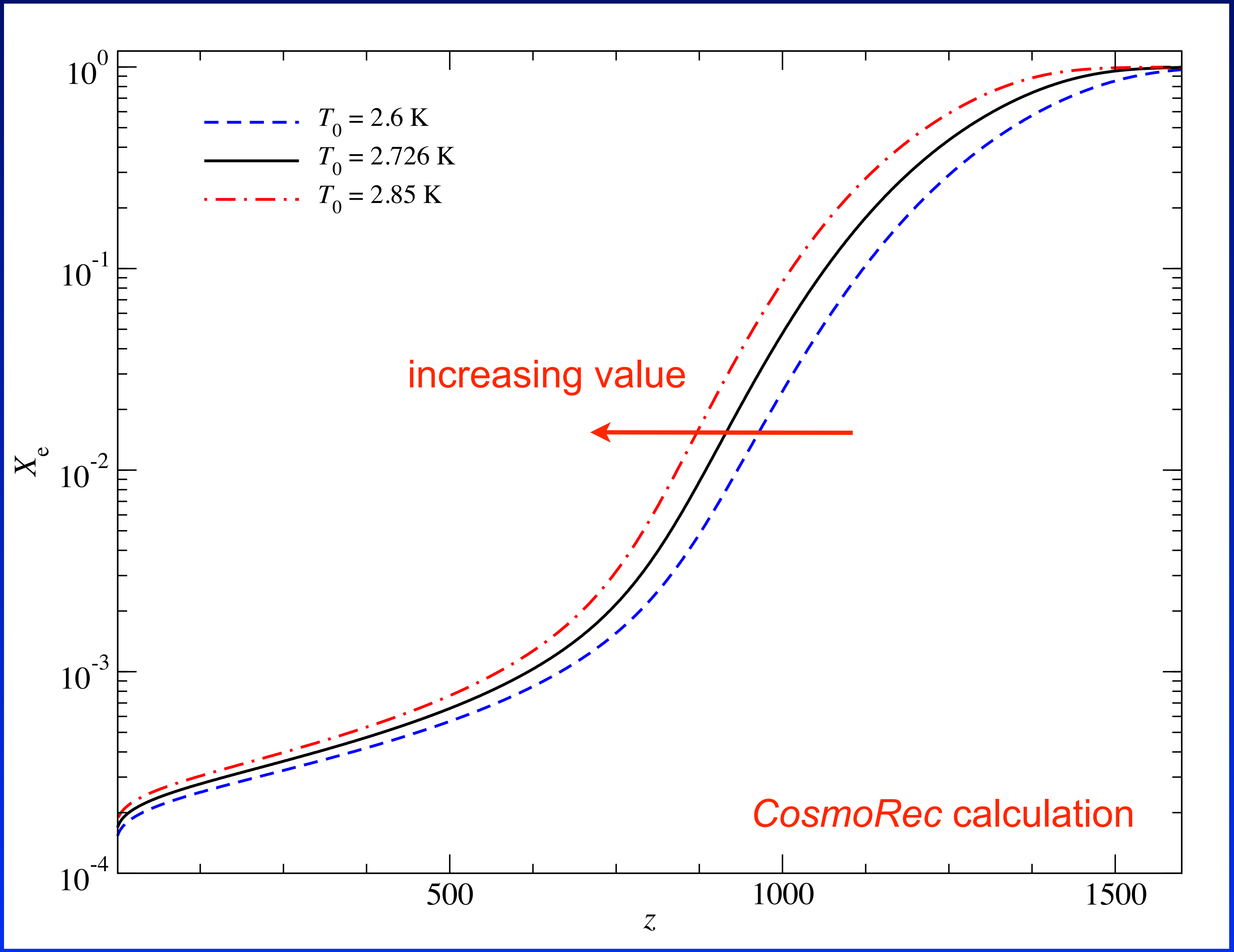
Planck measurement of T_0 at decoupling

- COBE/FIRAS measurement still the best we have
- *Planck* data gives another measurement of T_{CMB} at z~1000
- constraint on temperature redshift relation

Planck Collaboration, 2014

Planck measurement of T_0 at decoupling

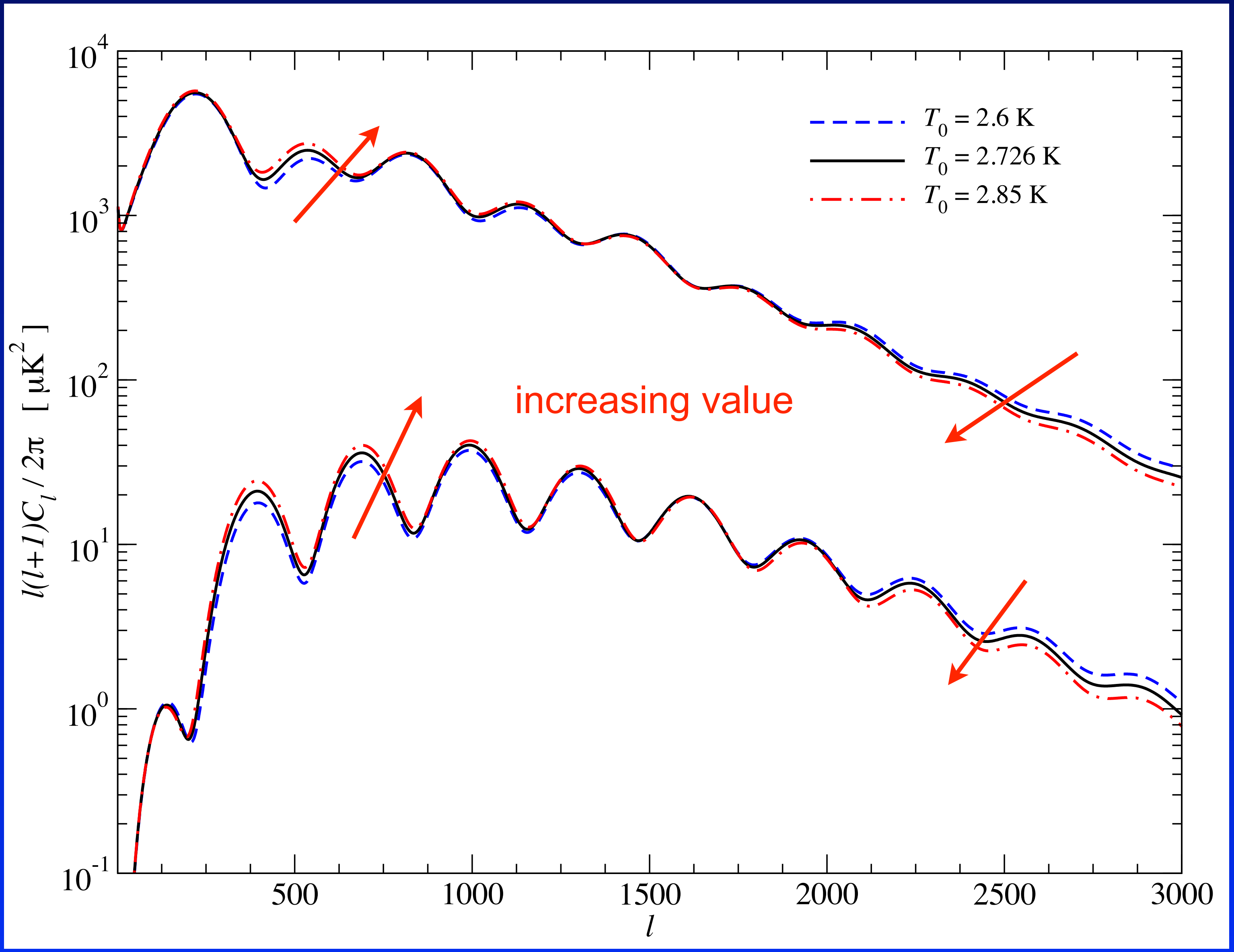
- COBE/FIRAS measurement still the best we have
- *Planck* data gives another measurement of T_{CMB} at z~1000
- constraint on temperature redshift relation



Planck Collaboration, 2014

Planck measurement of T_0 at decoupling

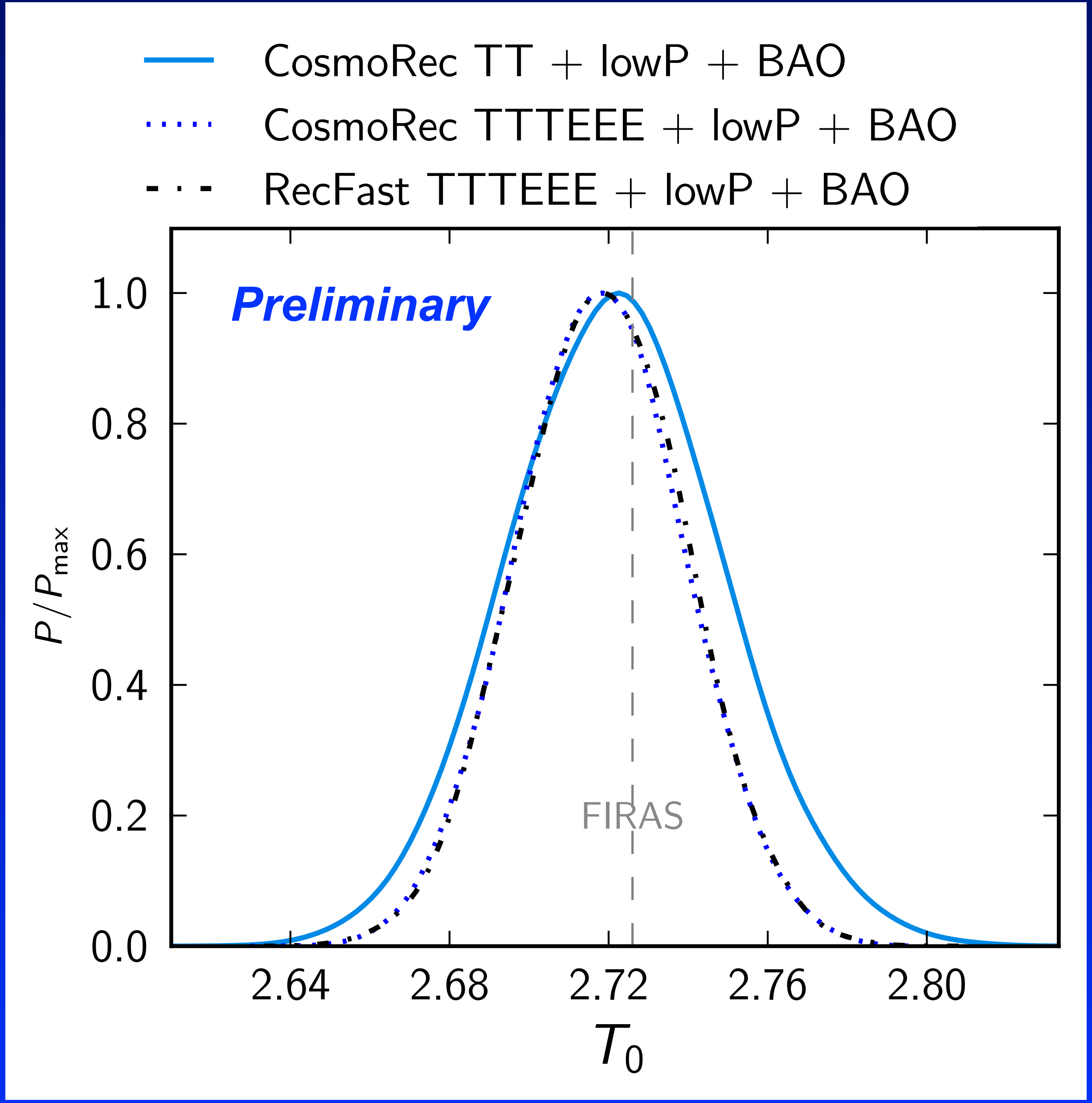
- COBE/FIRAS measurement still the best we have
- *Planck* data gives another measurement of T_{CMB} at z~1000
- constraint on temperature redshift relation



Planck Collaboration, 2014

Planck measurement of T_0 at decoupling

- COBE/FIRAS measurement still the best we have
- *Planck* data gives another measurement of T_{CMB} at z~1000
- constraint on temperature redshift relation



$$T_0 = 2.7255 \pm 0.0006\,\mathrm{K}(\mathrm{COBE/FIRAS})$$

$$T_0 = 2.722 \pm 0.027\,\mathrm{K}(\mathit{Planck}\ \mathrm{TT{+}lowP{+}BAO})$$
$$T_0 = 2.718 \pm 0.021\,\mathrm{K}(\mathit{Planck}\ \mathrm{TT,TE,EE{+}lowP{+}BAO})$$

- *Planck* measurement in excellent agreement with COBE/FIRAS
- external data needed to break degeneracies
- $T_{\mathrm{CMB}} = T_0(1+z)^{1-\beta}$

$$\beta = (0.2 \pm 1.4) \times 10^{-3}(\mathit{Planck}\ \mathrm{TT{+}lowP{+}BAO})$$
$$\beta = (0.4 \pm 1.1) \times 10^{-3}(\mathit{Planck}\ \mathrm{TT,TE,EE{+}lowP{+}BAO})$$

Planck Collaboration, 2014

Planck limits on perturbed recombination scenarios

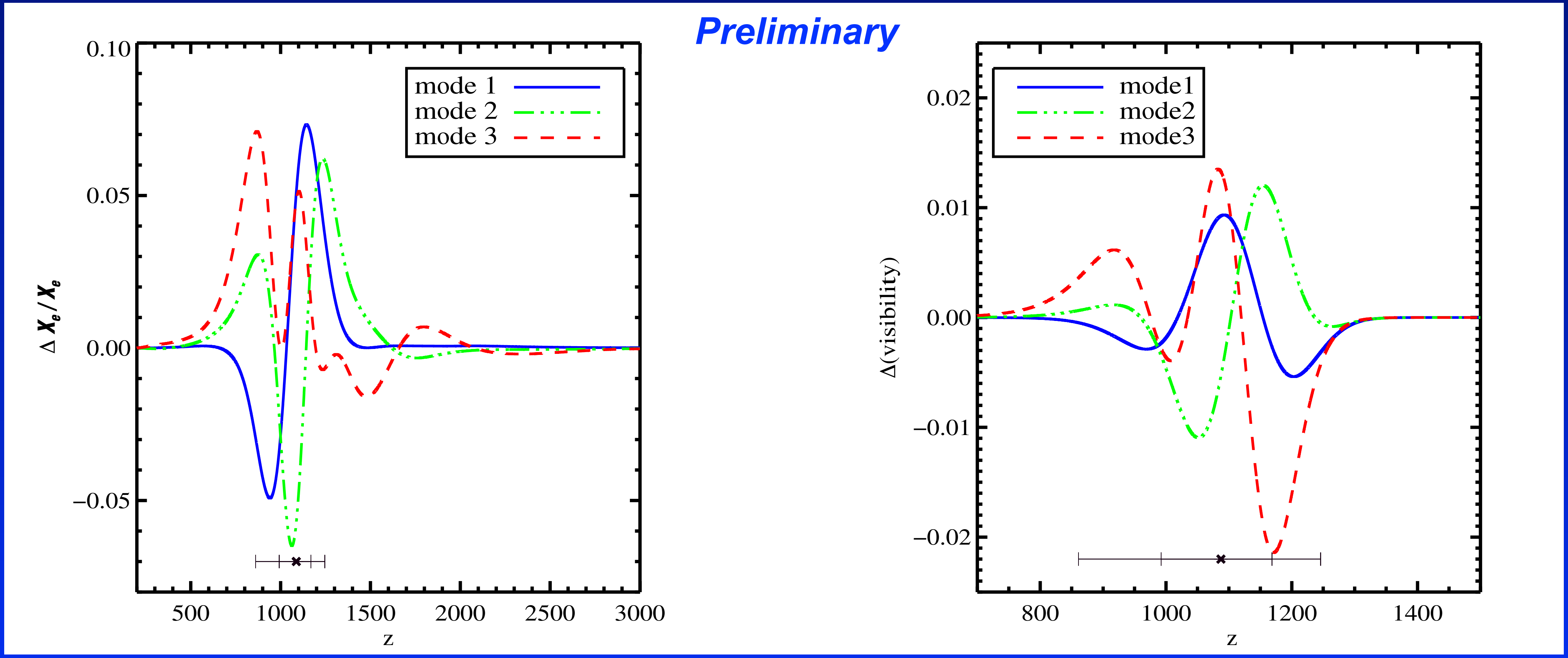
- Model-independent approach *(Farhang et al., 2012, 2013)*
- allows us to check the consistency of *Planck* data with the standard recombination scenarios
- pre-*Planck* data showed some small tensions (*Calabrese et al. 2013*)

Planck Collaboration, 2014

Planck limits on perturbed recombination scenarios

- Model-independent approach *(Farhang et al., 2012, 2013)*
- allows us to check the consistency of *Planck* data with the standard recombination scenarios
- pre-*Planck* data showed some small tensions (*Calabrese et al. 2013*)

Response in electron fraction and Thomson visibility

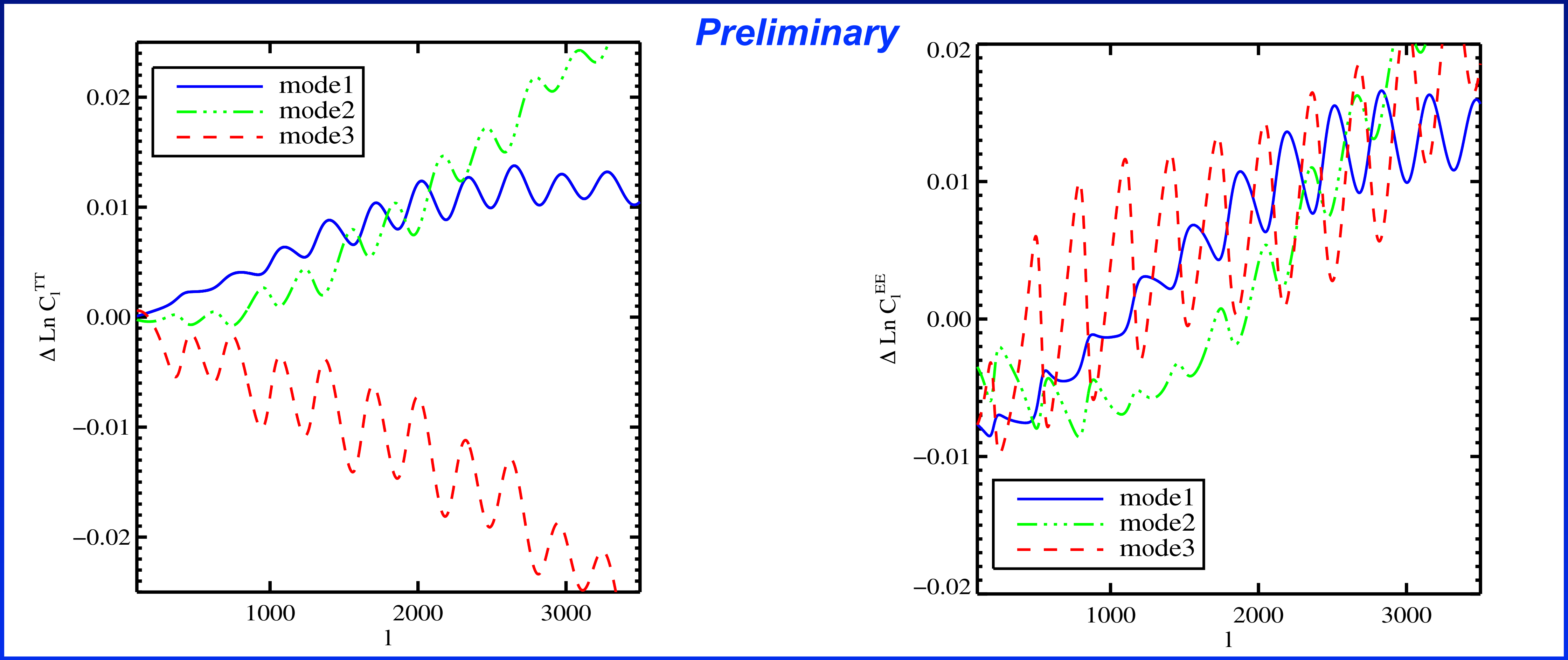


Planck Collaboration, 2014

Planck limits on perturbed recombination scenarios

- Model-independent approach *(Farhang et al., 2012, 2013)*
- allows us to check the consistency of *Planck* data with the standard recombination scenarios
- pre-*Planck* data showed some small tensions (*Calabrese et al. 2013*)

CMB power spectrum response



Planck Collaboration, 2014

Planck limits on perturbed recombination scenarios

- Model-independent approach *(Farhang et al., 2012, 2013)*
- allows us to check the consistency of *Planck* data with the standard recombination scenarios
- pre-*Planck* data showed some small tensions (*Calabrese et al. 2013*)

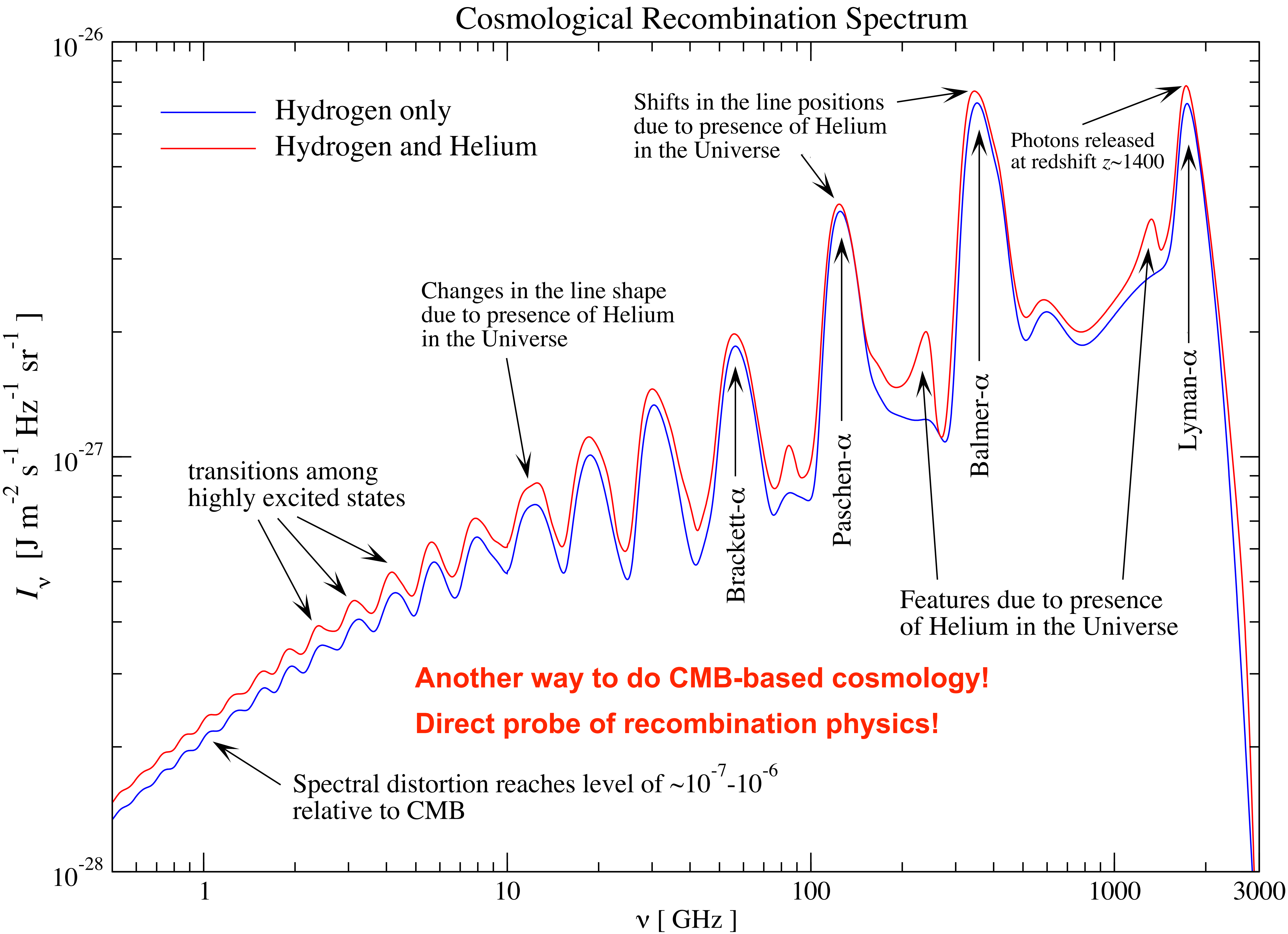
Table 8. Standard parameters and the first three X_e-modes as measured for *Planck* TT,TE,EE+lowP.

Preliminary

Parameter	+ 1mode	+ 2modes	+ 3modes
$\Omega_b h^2$	$0.0223^{+0.0002}_{-0.0002}$	$0.0224^{+0.0002}_{-0.0002}$	$0.0224^{+0.0002}_{-0.0002}$
$\Omega_c h^2$	$0.1199^{+0.0014}_{-0.0014}$	$0.1193^{+0.0015}_{-0.0015}$	$0.1194^{+0.0016}_{-0.0016}$
H_0	$67.28^{+0.65}_{-0.65}$	$67.55^{+0.71}_{-0.70}$	$67.20^{+0.87}_{-0.87}$
τ	$0.081^{+0.017}_{-0.017}$	$0.086^{+0.019}_{-0.019}$	$0.087^{+0.018}_{-0.018}$
n_s	$0.9657^{+0.0061}_{-0.0060}$	$0.9674^{+0.0064}_{-0.0063}$	$0.9698^{+0.0073}_{-0.0073}$
$\ln(10^{10}A_s)$	$3.098^{+0.034}_{-0.034}$	$3.106^{+0.036}_{-0.036}$	$3.112^{+0.037}_{-0.037}$
μ_1	$0.06^{+0.12}_{-0.12}$	$0.01^{+0.13}_{-0.14}$	$-0.03^{+0.15}_{-0.15}$
μ_2	-	$-0.15^{+0.18}_{-0.18}$	$-0.11^{+0.20}_{-0.20}$
μ_3	-	-	$-0.68^{+1.10}_{-0.98}$

- No significant tension with standard recombination scenario in *Planck*
- Without polarization data errors on mode amplitudes ~ 2-3 times larger

Planck Collaboration, 2014



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

Conclusions

- Improved recombination calculations crucial for the interpretation of precision data from *Planck*!
- Neglecting HI & HeI corrections would give (6 parameter case):

  → -2.6σ bias in n_S and -1.8σ in $\Omega_b h^2$

- First precise determination of the HI 2s-1s two-photon rate

$$A_{2s\to 1s} = 7.75 \pm 0.61\,\mathrm{s}^{-1} (\textit{Planck}\ \mathrm{TT,TE,EE{+}lowP{+}BAO})$$

- *Planck* measurement of the CMB monopole temperature in excellent agreement with *COBE/FIRAS* value today

$$T_0 = 2.718 \pm 0.021\,\mathrm{K} (\textit{Planck}\ \mathrm{TT,TE,EE{+}lowP{+}BAO})$$

- No indication for significant departures from the standard recombination scenario using eigenmode analysis

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.