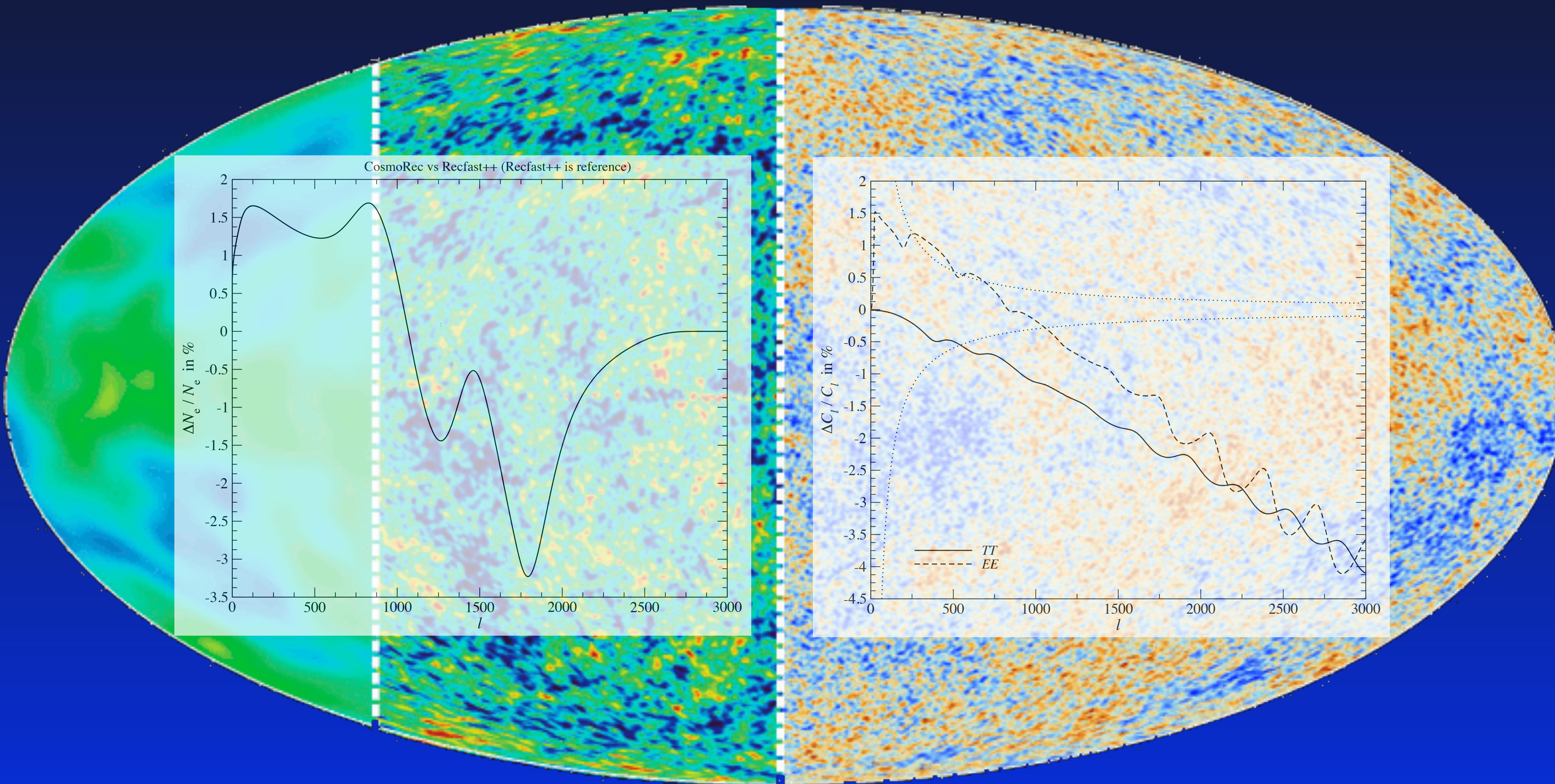
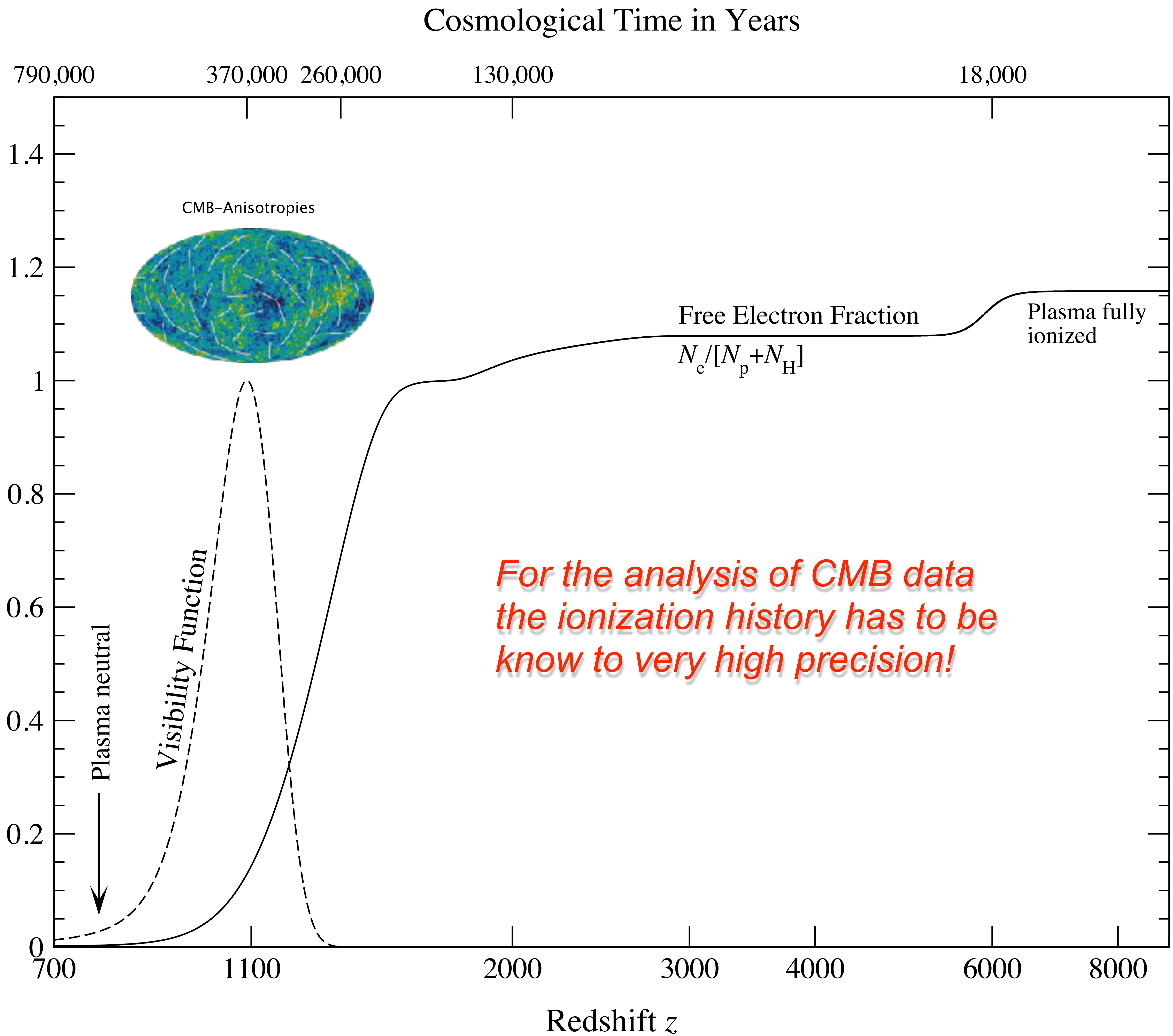
Overview of different recombination codes



Jens Chluba

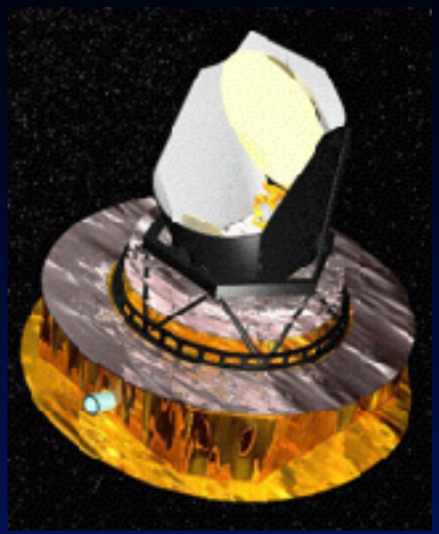
2nd IFT School on Cosmological Tools

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



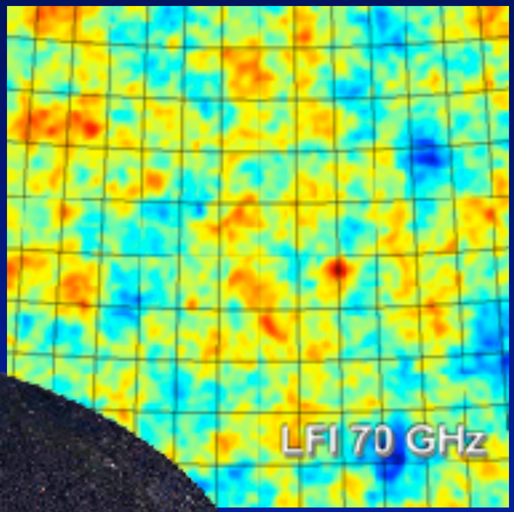
For the analysis of CMB data the ionization history has to be know to very high precision!

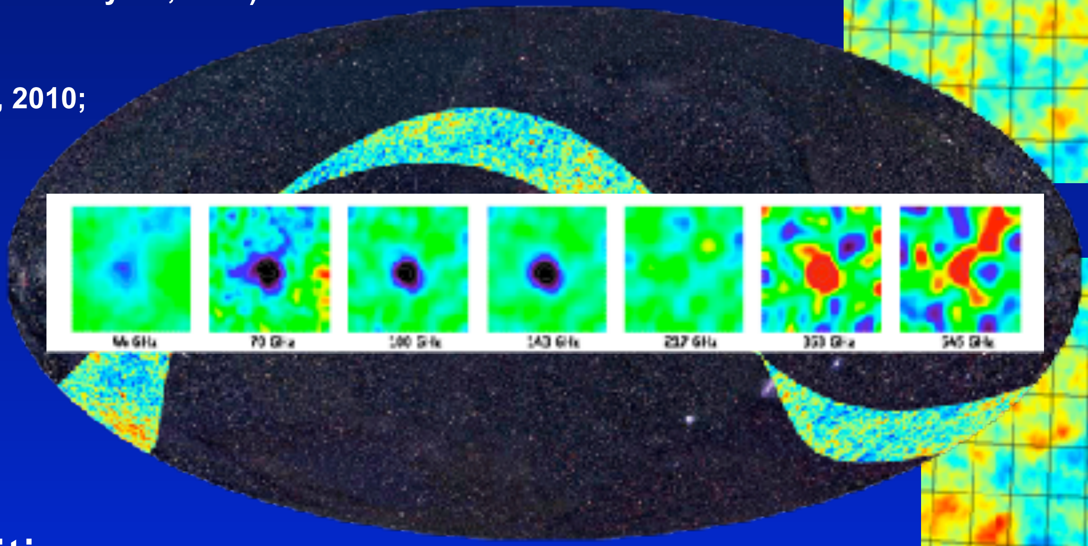
Getting the job done for *Planck*

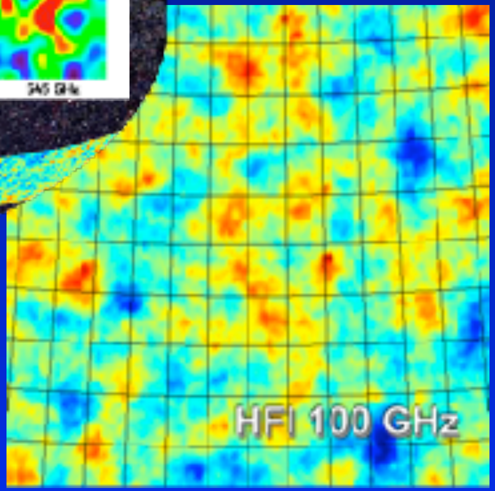


Hydrogen recombination

- 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)





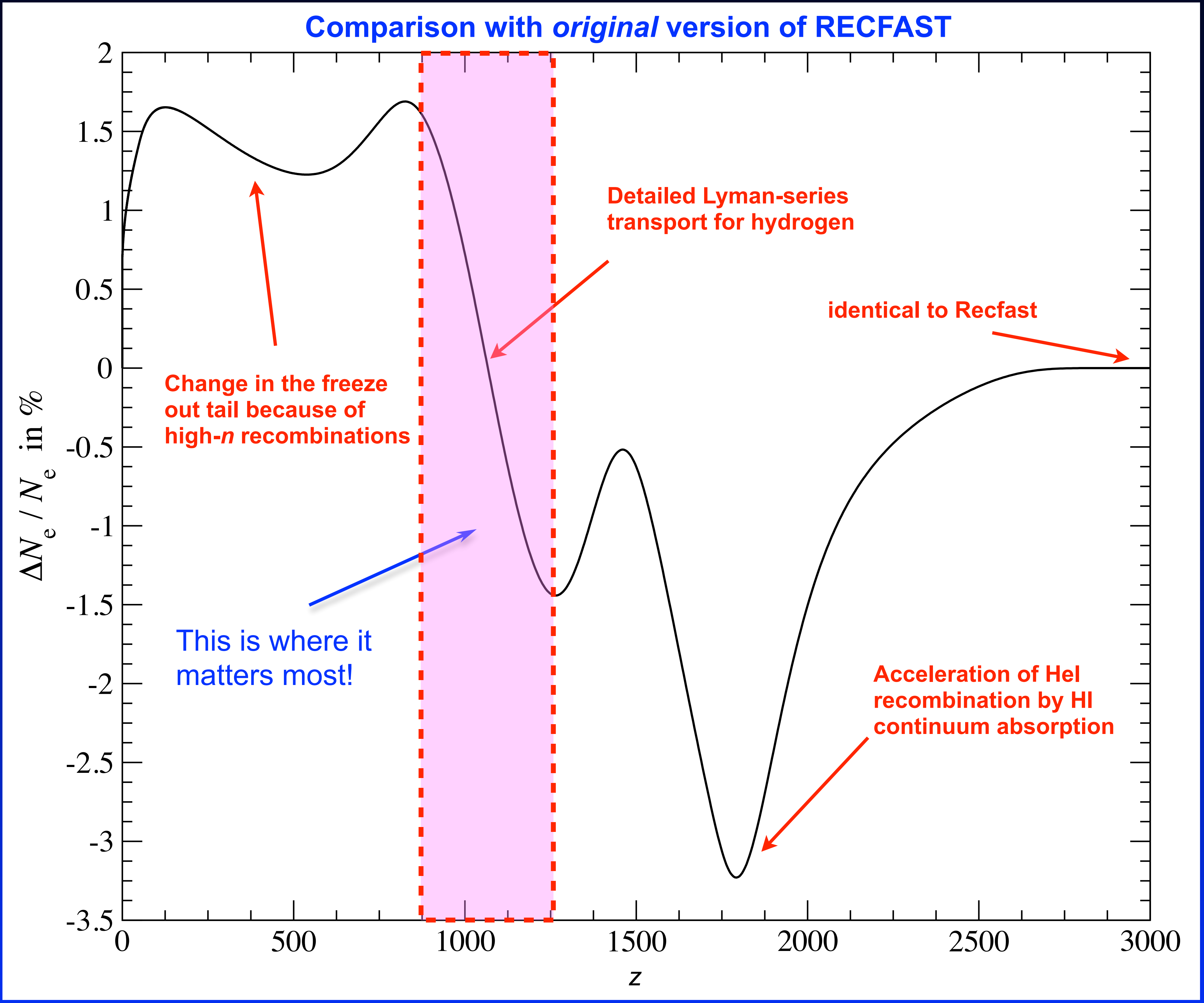


Helium recombination

- 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)

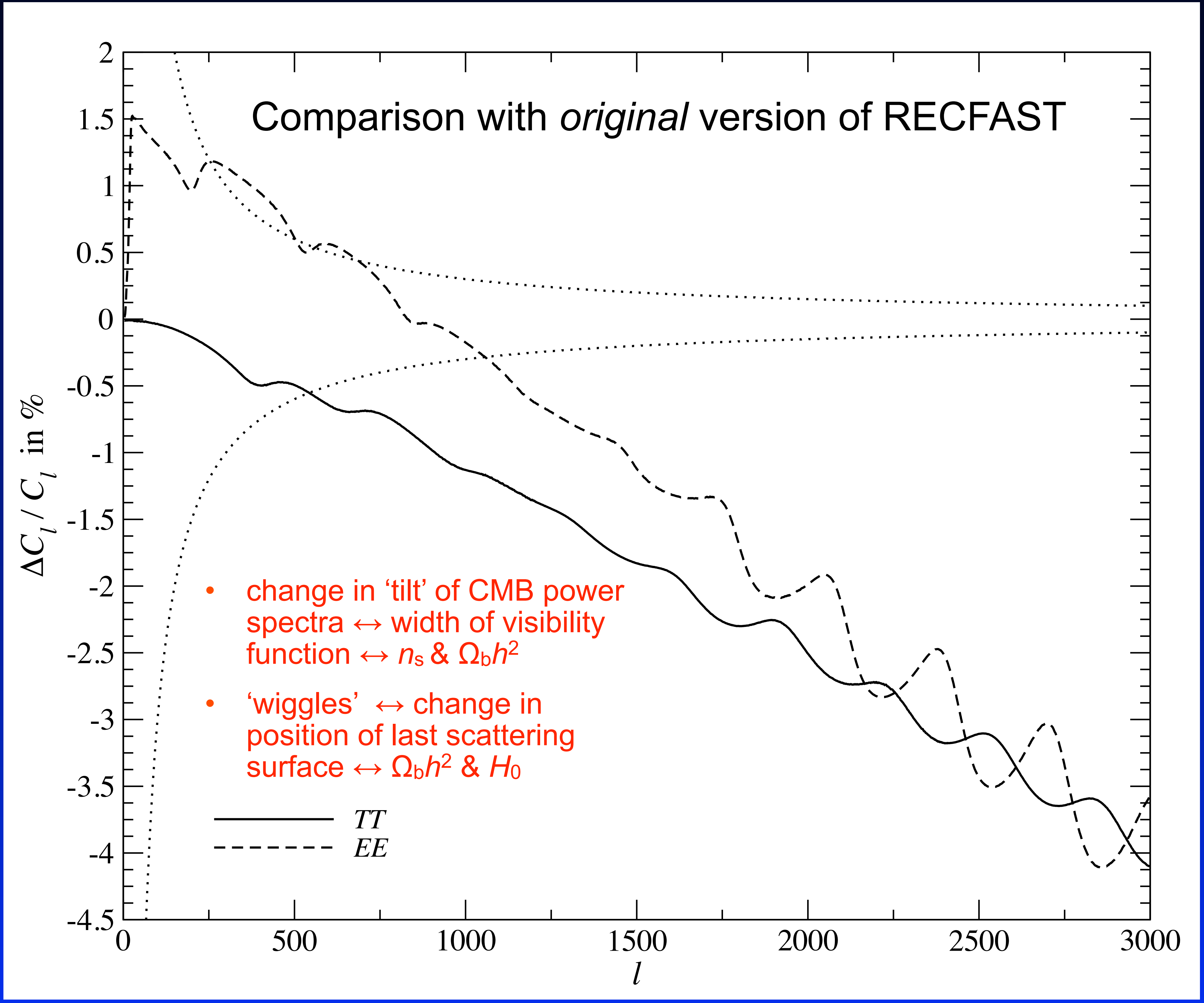
$\boxed{\Delta N_e \,/\, N_e \sim 0.1\ \%}$

Cumulative Changes to the Ionization History



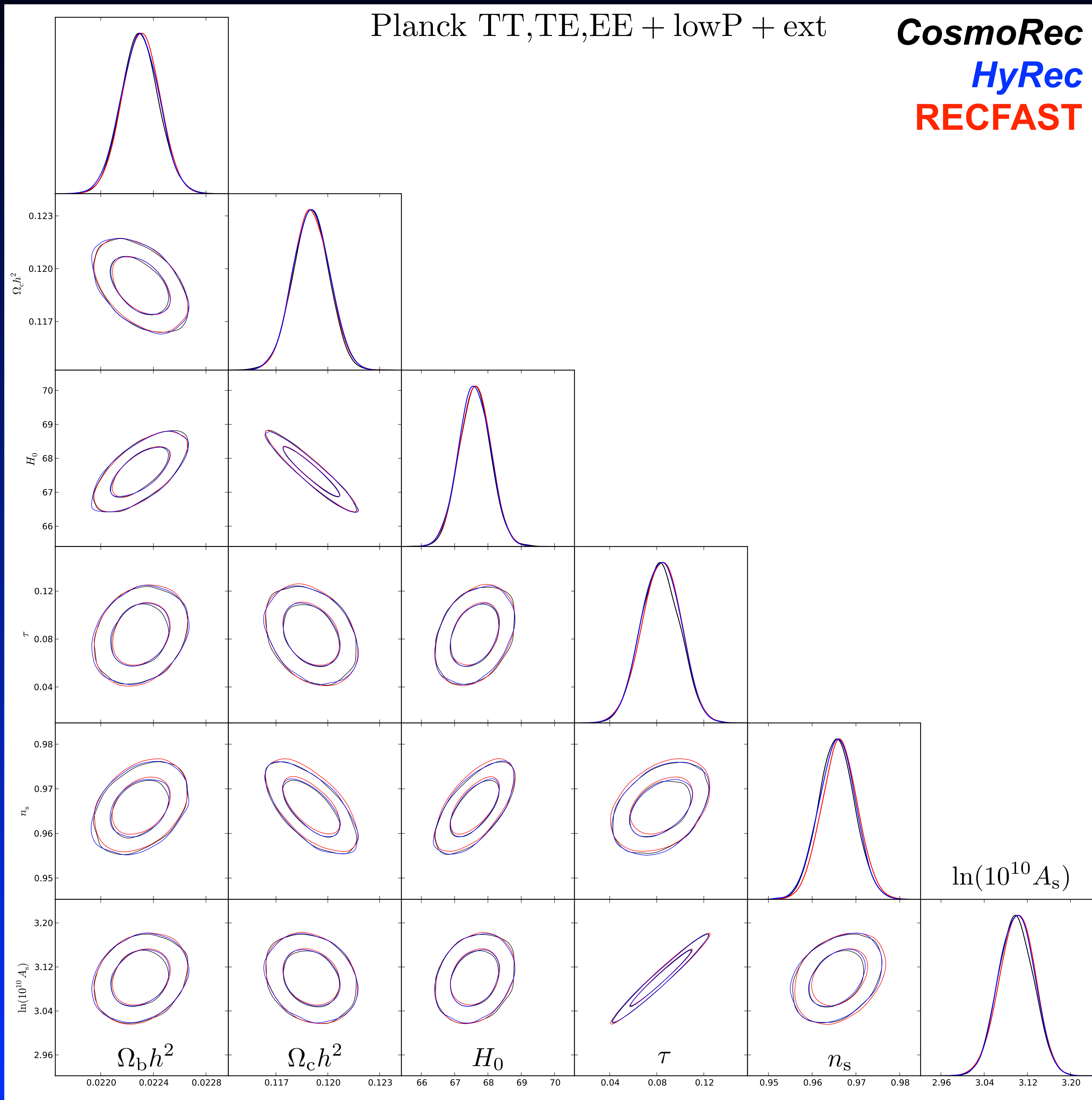
JC & Thomas, MNRAS, 2010; Shaw & JC, MNRAS, 2011

Cumulative Change in the CMB Power Spectra



CITA ICAT Shaw & JC, MNRAS, 2011

Differences for current recombination codes



- Different codes agree very well!
- largest biases

  $\Delta n_\mathrm{s} \approx 0.15\sigma$

  (*CosmoRec* ⟺ RECFAST)

  $\Delta n_\mathrm{s} \approx 0.03\sigma$

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

Planck Collaboration, XIII 2015

Recombination code overview

Code	**Recfast**	**Recfast++**	**CosmoRec**
Language	Fortran 77/90 & C	C++	C++
Requirements	-	-	GNU Scientific Lib (GSL)
Solves for	$X_{\rm p}$, $X_{\rm HeI}$, $T_{\rm e}$	$X_{\rm p}$, $X_{\rm HeI}$, $T_{\rm e}$	$X_{\rm 1s}$, $X_{\rm ns}$, $X_{\rm np}$, $X_{\rm nd}$, $T_{\rm e}$
ODE-Solver	explicit	implicit (Gears method)	implicit (Gears method)
PDE-Solver	-	-	semi-implicit (Crank-Nicolson)
Approach	derivative fudge	correction function	full physics
Simplicity	rather simple	simpler	pretty big code
Flexibility	limited	quite flexible	very flexible
Validity	around standard cosmology	around standard cosmology	wide range of cosmologies
Tools	-	ODE Solver	*HI & He Atom, Solvers, Quadrature routines*
Extras	-	DM annihilation, $A_{\rm 2s1s}$	*DM annihilation, high-ν distortion,* $A_{\rm 2s1s}$
Runtime	0.01 sec	0.08 sec	1.5 - 2 sec (faster now…)

Update for **CosmoRec** & **Recfast++** soon to include effects of *primordial magnetic fields, variation of fundamental constants & decaying particles*

Recfast

Some **`Recfast`** facts

- Standalone Fortran and C versions
- C version not up to date (and buggy)
- Many personal versions in the community
- Part of CAMB and CLASS
- Recombination corrections included by fudging derivatives
- Today fudge function calibrated using **`CosmoRec`**
- Derivatives done analytically (cumbersome…)
- Download **http://www.astro.ubc.ca/people/scott/recfast.html**

$\texttt{Recfast}$ Equations

$$\frac{dx_p}{dz} = \frac{[x_e x_p n_{\rm H}\alpha_{\rm H} - \beta_{\rm H}(1-x_p)e^{-h\nu_{\rm H\,2s}/kT_M}][1+K_{\rm H}\Lambda_{\rm H}n_{\rm H}(1-x_p)]}{H(z)(1+z)[1+K_{\rm H}(\Lambda_{\rm H}+\beta_{\rm H})n_{\rm H}(1-x_p)]}, \tag{1}$$

$$\begin{aligned}\frac{dx_{\rm He\,II}}{dz} = &\{[x_{\rm He\,II}x_e n_{\rm H}\alpha_{\rm He\,I} - \beta_{\rm He\,I}(f_{\rm He}-x_{\rm He\,II})e^{-h\nu_{\rm He\,I\,2^1s}/kT_M}]\\ &\times [1+K_{\rm He\,I}\Lambda_{\rm He}n_{\rm H}(f_{\rm He}-x_{\rm He\,II})e^{-h\nu_{\rm He\,I\,2^1p2^1s}/kT_M}]\}\Big/\\ &\{H(z)(1+z)[1+K_{\rm He\,I}(\Lambda_{\rm He}+\beta_{\rm He\,I})n_{\rm H}\\ &\times (f_{\rm He}-x_{\rm He\,II})e^{-h\nu_{\rm He\,I\,2^1p2^1s}/kT_M}]\},\end{aligned} \tag{2}$$

$$\frac{dT_M}{dz} = \frac{8\sigma_{\rm T}a_R T_R^4}{3H(z)(1+z)m_e c}\frac{x_e}{1+f_{\rm He}+x_e}(T_M - T_R) + \frac{2T_M}{(1+z)}$$

Seager et al, 1999

- Old expressions from Peebles 1969
- second shell quasi-stationary
- recombination rates and escape probabilities fudged
- spin-forbidden transition added to helium equation (Wong, Moss & Scott, 2009)

recfast.readme

```
The input interface was designed to look familiar to users of Seljak &
Zaldarriaga's code CMBFAST.  A convenient way to run the program is by using
a file recfast.run of the form:

output.file
Omega_B, Omega_DM, Omega_vac
H_0, T_0, Y_p
Hswitch
Heswitch

For example:
junk.out
0.04 0.20 0.76
70 2.725 0.25
1
6
```

meaning of parameters

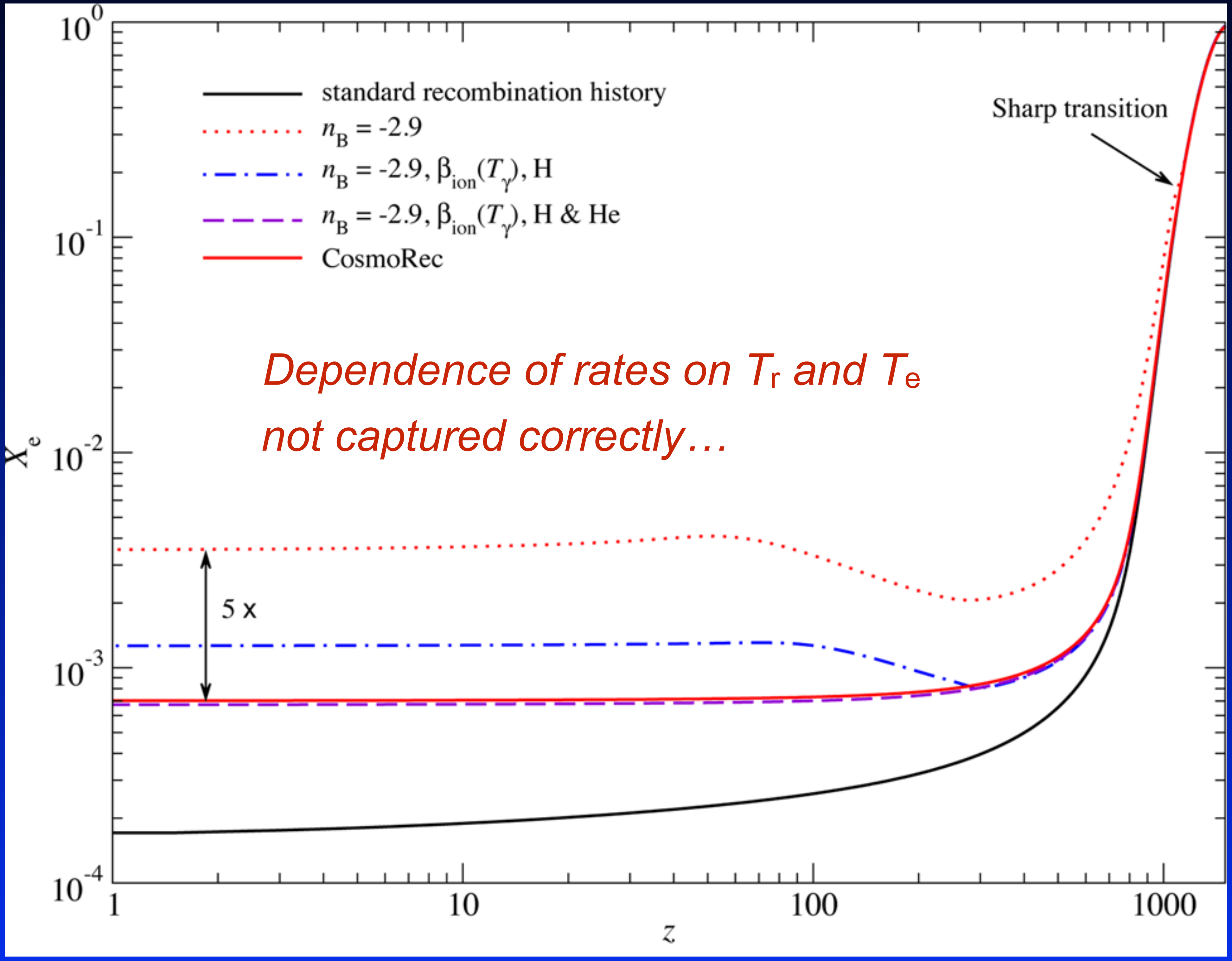
write into `recfast.ini`

Execute code like `./recfast < recfast.ini`

recfast.for

```
c       Modification for H correction (Hswitch):
        write(*,*) 'Modification for H recombination:'
        write(*,*)'0) no change from old Recfast'
    write(*,*)'1) include correction'
        write(*,*)'Enter the choice of modification for H (0-1):'
    read(*,*)Hswitch

C   Fudge factor to approximate the low z out of equilibrium effect
    if (Hswitch .eq. 0) then
      fu=1.14d0
    else
      fu=1.125d0
    end if

C   Modification for HeI recombination (Heswitch):
    write(*,*)'Modification for HeI recombination:'
    write(*,*)'0) no change from old Recfast'
    write(*,*)'1) full expression for escape probability for singlet'
    write(*,*)'   1P-1S transition'
    write(*,*)'2) also including effect of contiuum opacity of H on HeI'
    write(*,*)'   singlet (based in fitting formula suggested by'
    write(*,*)'   Kholupenko, Ivanchik & Varshalovich, 2007)'
    write(*,*)'3) only including recombination through the triplets'
    write(*,*)'4) including 3 and the effect of the contiuum '
    write(*,*)'   (although this is probably negligible)'
    write(*,*)'5) including only 1, 2 and 3'
    write(*,*)'6) including all of 1 to 4'
    write(*,*)'Enter the choice of modification for HeI (0-6):'
    read(*,*)Heswitch
```

Example of how things can go wrong with ***Recfast***…



JC et al., 2015, arXiv:1503.04827

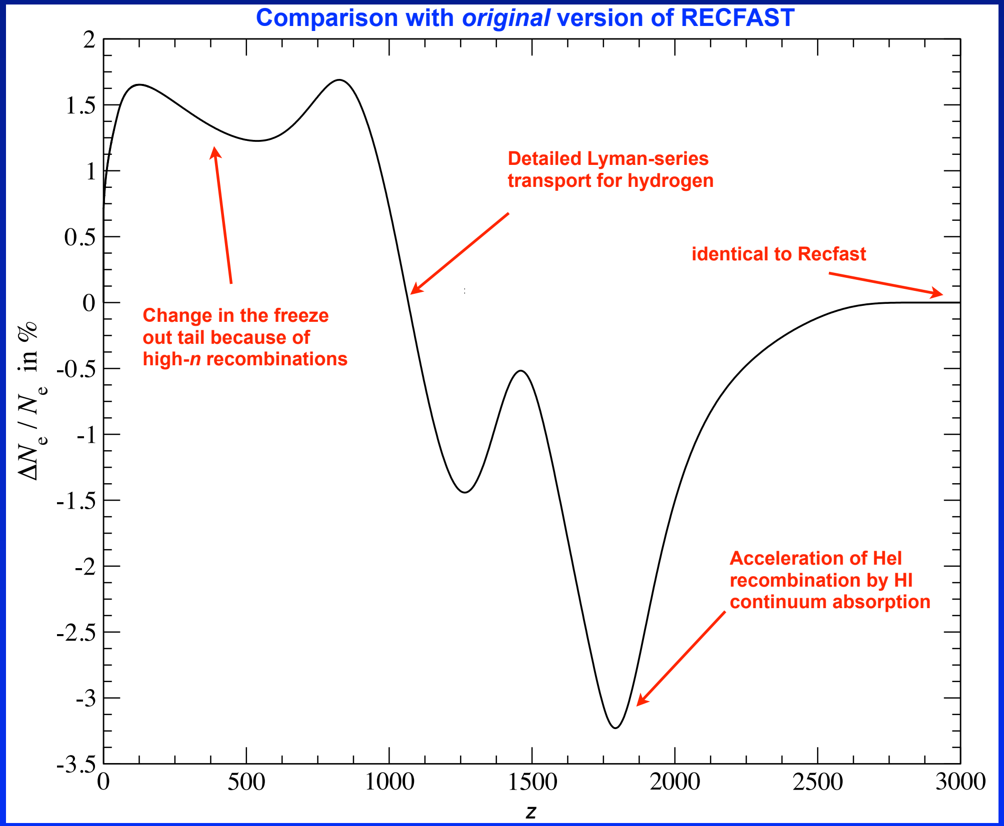
Recfast++

Some **`Recfast++`** facts

- Standalone C++ version
- Also part of cosmology object in **`CosmoRec`** (activated by runmode)
- High flexibility with non-standard cases implemented
- Uses correction function approach to represent the full calculation
  (introduced in Rubino-Martin et al, 2009)
- Correction function can be updated very easily
- Derivatives done numerically (super easy!!)
- Download **`www.Chluba.de/CosmoRec`**

$$X_{\rm e}^{\rm CR} \approx X_{\rm e}^{\rm RF}\left(1 + \frac{\Delta X_{\rm e}}{X_{\rm e}}\right)$$

Computed for reference cosmology



Initialization for Recfast++ uses same file as CosmoRec

```
//==========================================================================================
// the above parameters are (default values are given as examples)
//==========================================================================================

2000      == number of redshift points (for the range z= 50-3000 nz=500 is in principle sufficient)
3000      == starting redshift; above z=3400 the Recfast++ Solution should be used.
             This is automatically done in batch mode.
0         == ending redshift; below z=50 the Recfast++ system is solved with rescale dXe/dt

0.24      == Yp
2.725     == T0
0.2678    == Omega_m
0.0444    == Omega_b
0.7322    == Omega_L  (if <=0 it will be computed from the other variables)
0.0       == Omega_k
0.71      == h100
3.046     == N_nu
1.14      == Recfast++ fudge factor (usually leave unchanged)

3         == number of hydrogen shells for ODE problem (currently: 3, 4, 5 or 10; lite only 3)
500       == nS for effective HI rates (nS=10, 20, 50, 100, 128, 200, 300, 400 and 500; lite only 500)
             If the number of hydrogen shells is !=3, only effective rates for nS=500 are available.
1.0e-24   == dark matter annihilation efficiency in eV/sec (see Chluba 2009).
             Values <= 10^-23 eV/sec are recommended. For larger values the CosmoRec
             calculation breaks down. In Recfast-mode also larger values are possible.
8.2206    == A2s1s decay rate for hydrogen.
             If ==0 internal default is used.

3         == number of helium shells (currently: 2, 3, 5 or 10; lite only 2 & 3)
0         == HI absorption during HeI-recombination
             (0: off; 1: on; 2: on with Diffusion fudge; 3: radiative transfer code)
0         == spin forbidden transitions for HeI-recombination (0: off; 1: on)
0         == Feedback in Helium levels (positive: no HI abs between the lines
                                        negative: with HI abs between the lines)

1         == run PDE part (1) or not (0). In the latter case only ODE system will be solved.
             If this flag is set to 0 only the initial calculation without transfer corrections
             will be performed
2         == correction to 2s-1s channel; 0: no corr; 1: stim. 2s-1s; 2: full correction;
3         == nS for corrections because of two-photon decays.
             If set to <3 then only the diffusion correction is included.
2         == nS for corrections because of Raman-scattering
             If set to <2 then the 1+1 Raman rates are not corrected.

./outputs/ == path for output
.dat       == addition to name of files at the very end
```

./runfiles/parameters.dat

parameters for both Recfast++ & CosmoRec

main CosmoRec parameters

Execute Recfast++ like

`./CosmoRec REC runfiles/parameters.dat` **(equivalent to old recfast)**

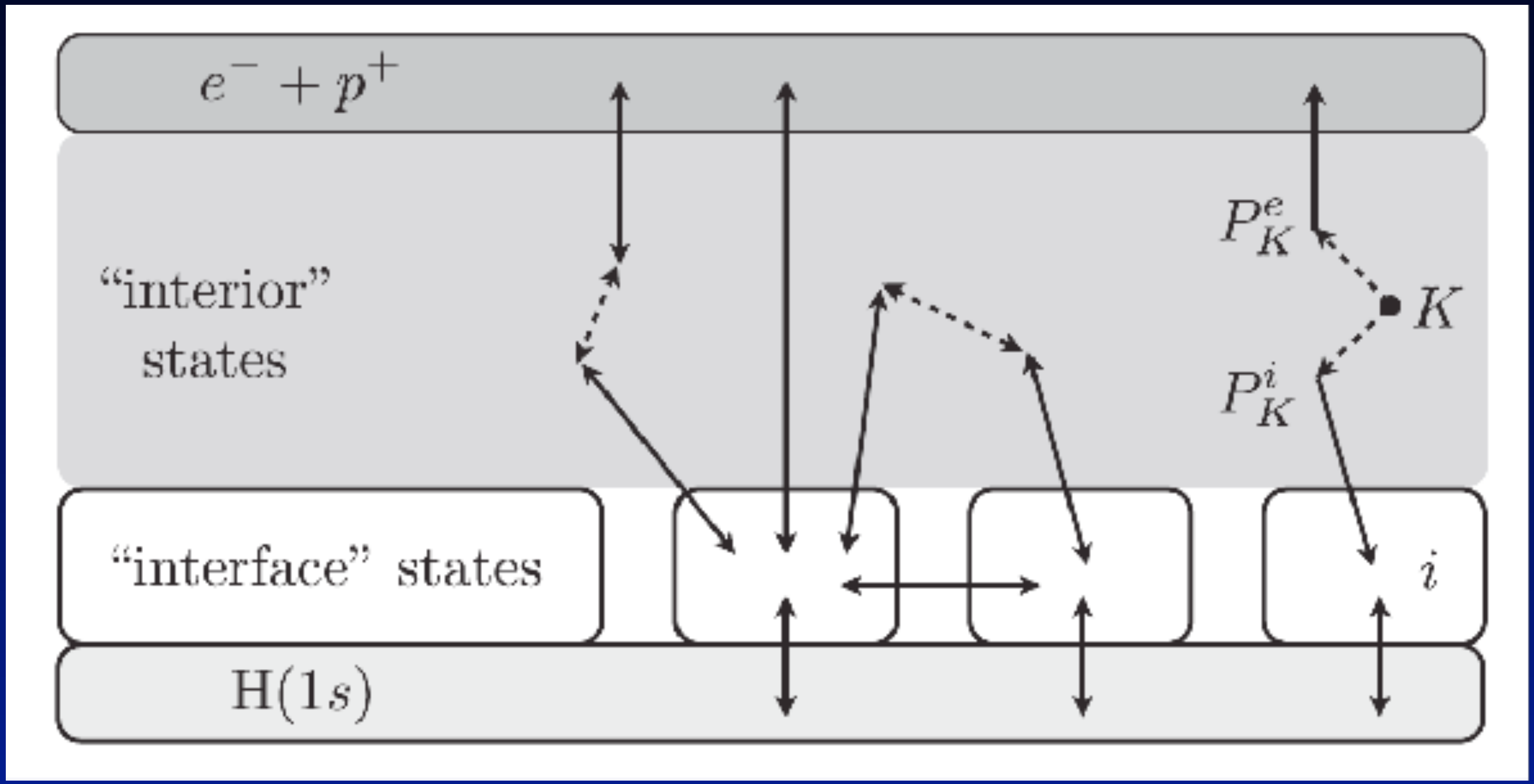
`./CosmoRec RECcf runfiles/parameters.dat` **(recfast + correction function)**

CosmoRec

New Cosmological Recombination Code: *CosmoRec*

- uses an effective multi-level approach **(Haimoud & Hirata, 2010)**
- very *accurate* and *fast* (for ‘default’ setting ~1 sec per model!)
- solves the detailed radiative transfer problem for Ly-*n*
- no *fudging* *(Recfast)* or *multi-dimensional interpolation* *(RICO)*
- different *runmodes/accuracies* implemented
- easily *extendable* (effect of dark matter annihilation already included)
- was already tested in a wide range of cosmologies
- runs smoothly with CAMB/CosmoMC **(Shaw & JC, 2011)**
- *CosmoRec* is available at: **`www.Chluba.de/CosmoRec`**

Extended Effective Multi-level Atom



CosmoRec & HyRec

- need to treat angular momentum sub-levels separately
- Complexity of problem scales like ~ n^2_{max}
- Full problem pretty demanding (500 shells ≃ 130000 equations!)

$\Longrightarrow$ *effective multi-level approach* (Ali-Haimoud & Hirata, 2010)

- This allowed fast computation of the recombination problem!

CosmoRec specific parameters

./runfiles/parameters.dat

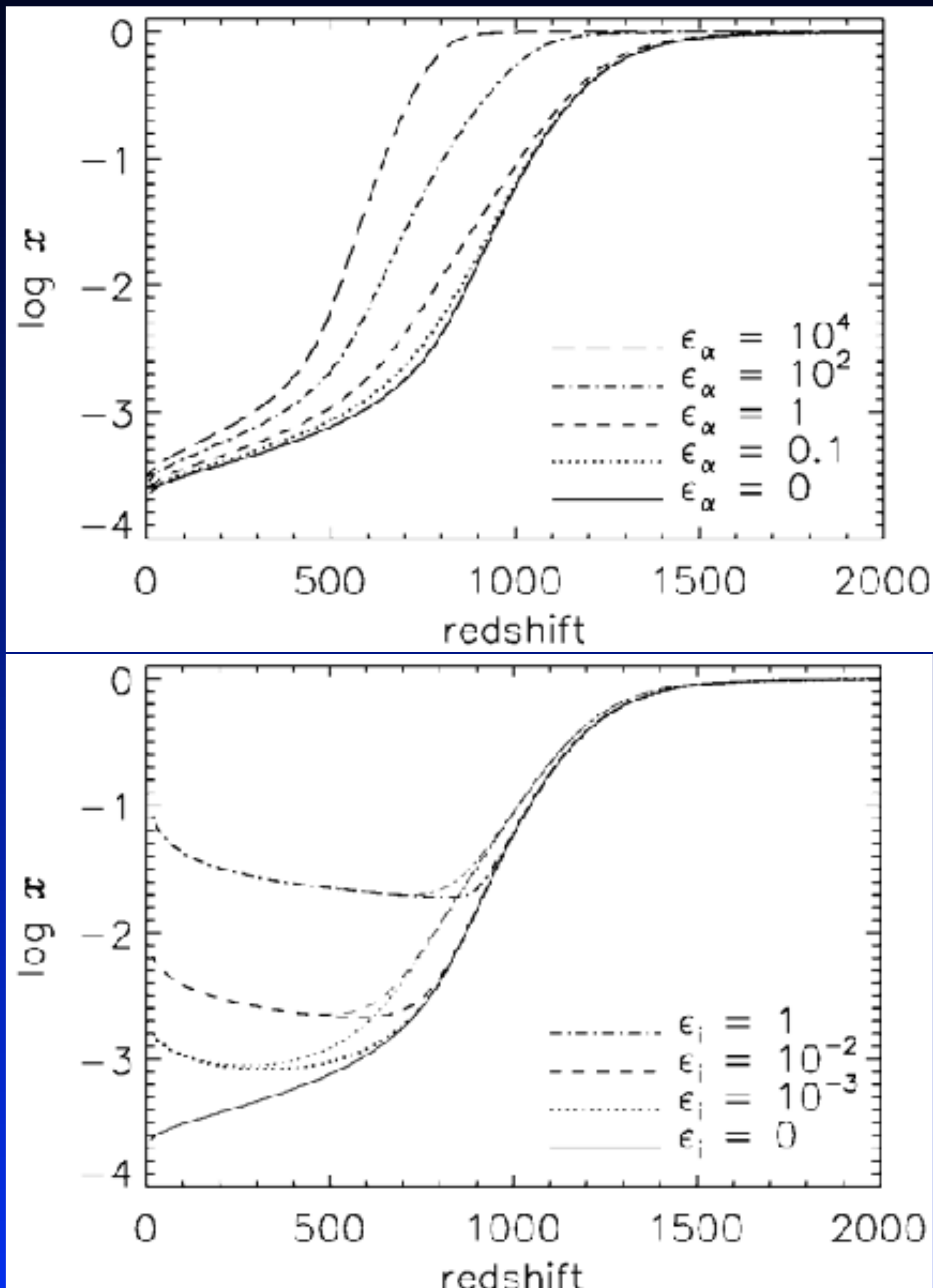
```
3          == number of hydrogen shells for ODE problem (currently: 3, 4, 5 or 10; lite only 3)
500        == nS for effective HI rates (nS=10, 20, 50, 100, 128, 200, 300, 400 and 500; lite only 500)
              If the number of hydrogen shells is !=3, only effective rates for nS=500 are available.
1.0e-24    == dark matter annihilation efficiency in eV/sec (see Chluba 2009).
              Values <= 10^-23 eV/sec are recommended. For larger values the CosmoRec
              calculation breaks down. In Recfast-mode also larger values are possible.
8.2206     == A2s1s decay rate for hydrogen.
              If ==0 internal default is used.

3          == number of helium shells (currently: 2, 3, 5 or 10; lite only 2 & 3)
0          == HI absorption during HeI-recombination
              (0: off; 1: on; 2: on with Diffusion fudge; 3: radiative transfer code)
0          == spin forbidden transitions for HeI-recombination (0: off; 1: on)
0          == Feedback in Helium levels (positive: no HI abs between the lines
                                         negative: with HI abs between the lines)

1          == run PDE part (1) or not (0). In the latter case only ODE system will be solved.
              If this flag is set to 0 only the initial calculation without transfer corrections
              will be performed
2          == correction to 2s-1s channel; 0: no corr; 1: stim. 2s-1s; 2: full correction;
3          == nS for corrections because of two-photon decays.
              If set to <3 then only the diffusion correction is included.
2          == nS for corrections because of Raman-scattering
              If set to <2 then the 1+1 Raman rates are not corrected.

./outputs/ == path for output
.dat        == addition to name of files at the very end
```

Execute CosmoRec like

`./CosmoRec runfiles/parameters.dat`

Annihilation and extra energy release

Extra Sources of Ionizations or Excitations

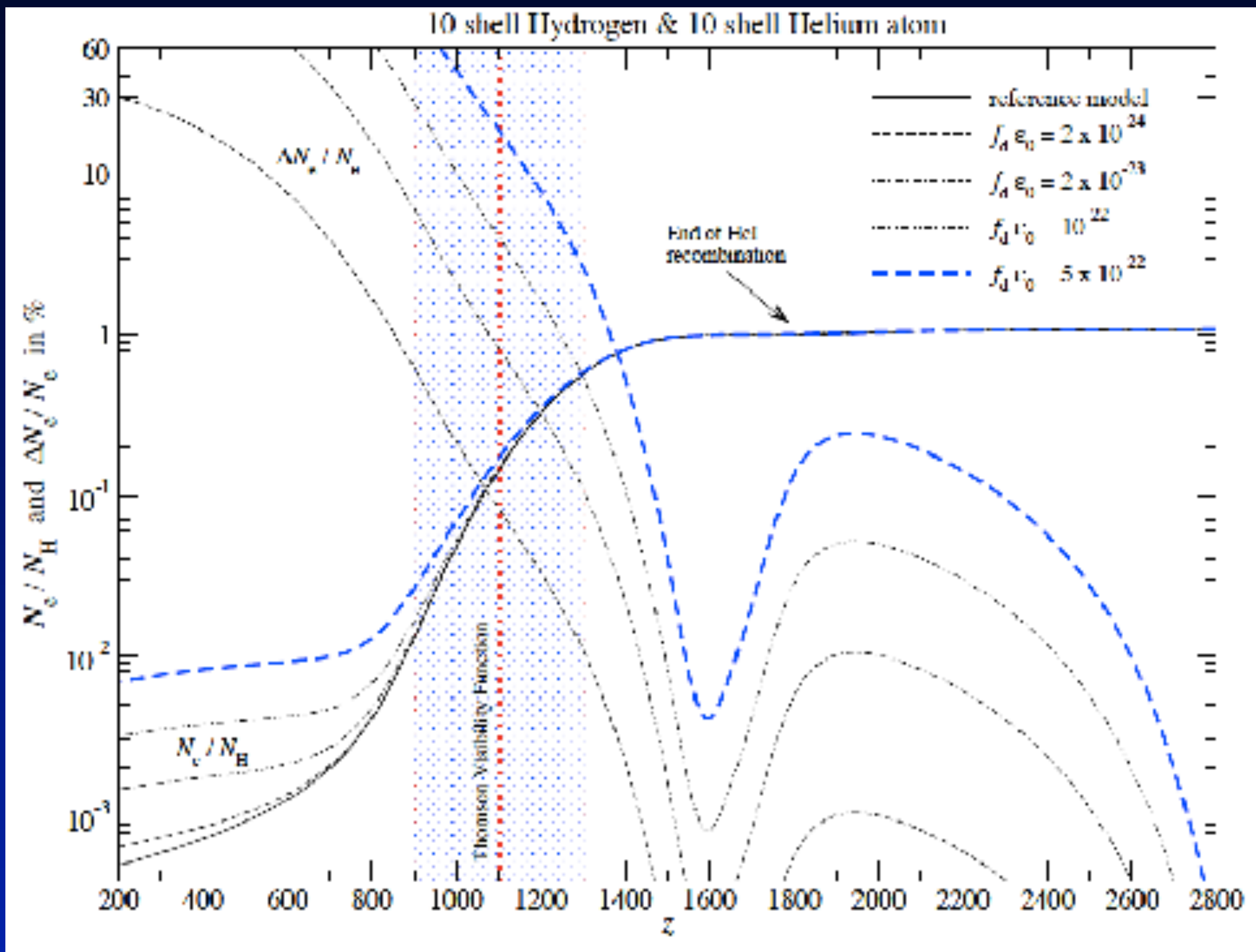


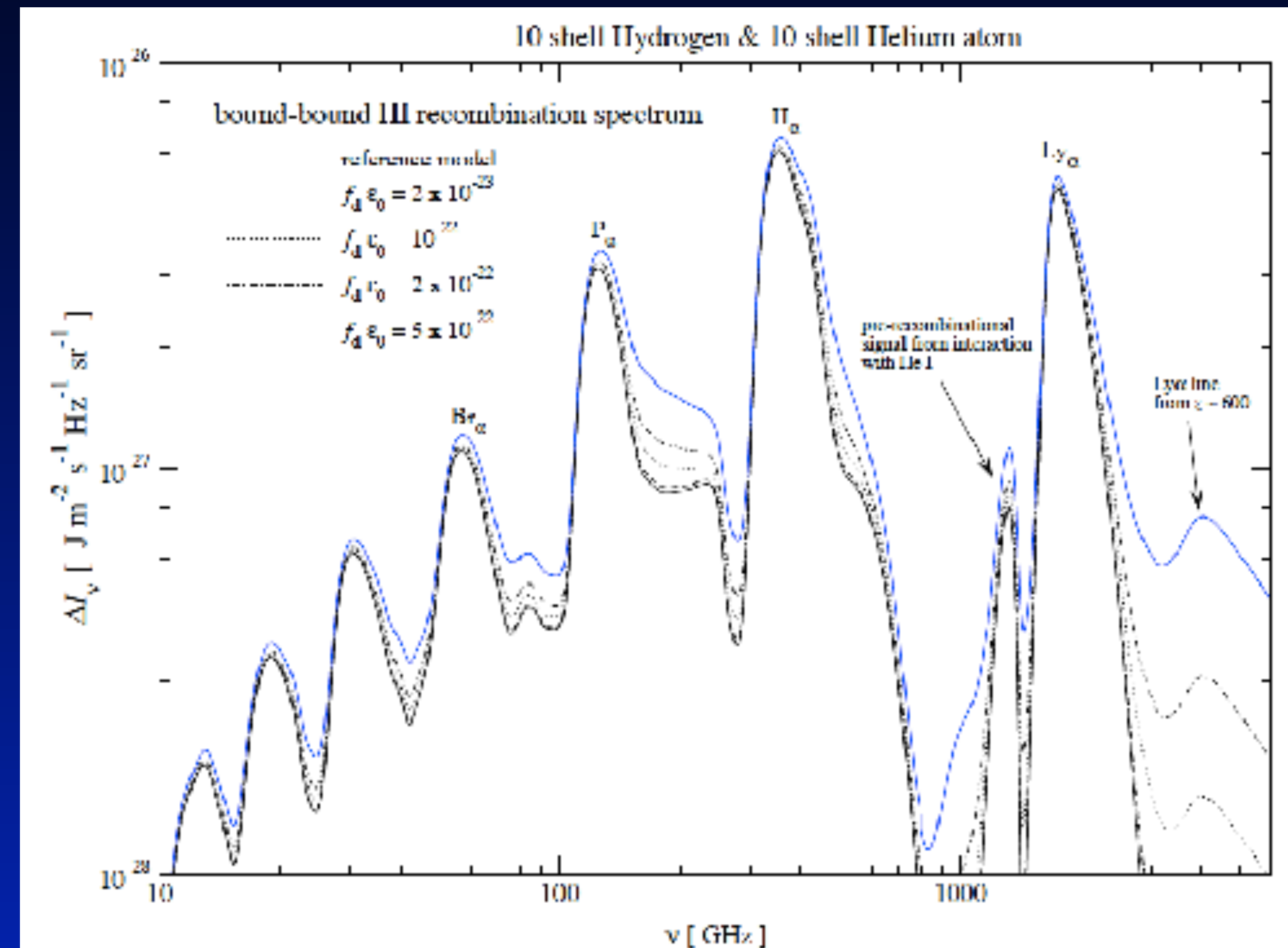
Peebles, Seager & Hu, ApJ, 2000

- ‚Hypothetical’ source of extra photons parametrized by ε_α & ε_i
- Extra excitations ⇒ delay of Recombination
- Extra ionizations ⇒ affect ‘freeze out’ tail
- This affects the Thomson visibility function
- From WMAP ⇒ $\varepsilon_\alpha < 0.39$ & $\varepsilon_i < 0.058$ at 95% confidence level (Galli et al. 2008)

- Extra ionizations & excitations should also lead to additional photons in the recombination radiation!!!
- This in principle should allow us to check for such sources at z~1000

Dark Matter Annihilation: Effect on Ionization History and the Recombination Spectrum





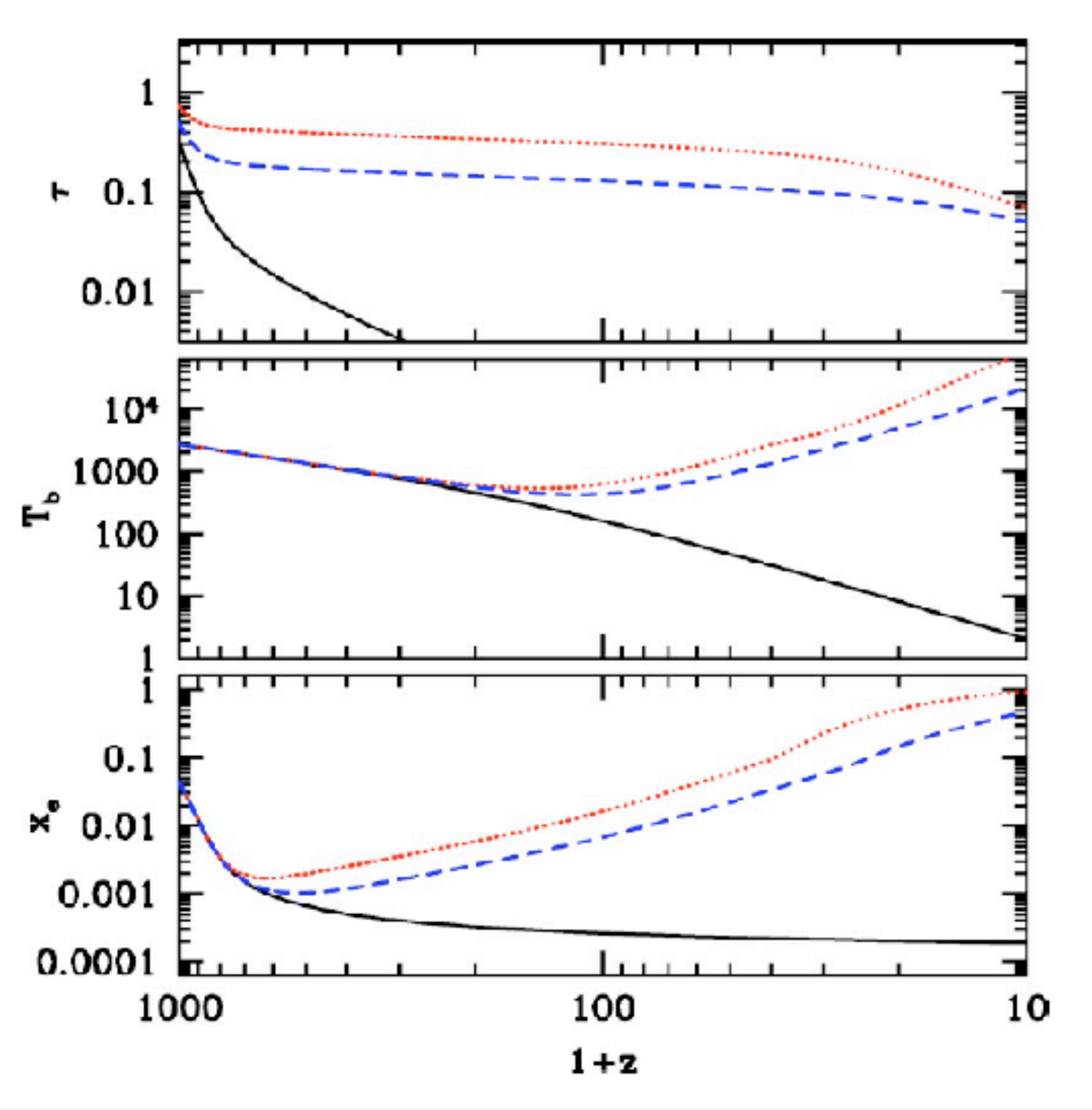
- ‘Delay of recombination’
- Affects Thomson visibility function
- Possibility of Sommerfeld-enhancement
- Clumpiness of matter at z<100

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

compare also Padmanabhan & Finkbeiner, Phys. Rev. D, 2005

JC, 2009, arXiv:0910.3663

Decaying particle during & after recombination



Chen & Kamionkowski, 2004

- Modify recombination history
- this changes Thomson visibility function and thus the CMB temperature and polarization power spectra
- ⇒ CMB anisotropies allow

  probing particles with lifetimes ≳ 10^{12} sec
- CMB spectral distortions provide complementary probe! (more tomorrow)

Some useful commands

Making and cleaning

```
> make
> make clean
> make tidy
```

Execute CosmoRec like

`./CosmoRec runfiles/parameters.dat` **(full computation)**

Execute Recfast++ like

`./CosmoRec REC runfiles/parameters.dat` **(equivalent to old recfast)**

`./CosmoRec RECcf runfiles/parameters.dat` **(recfast + correction function)**