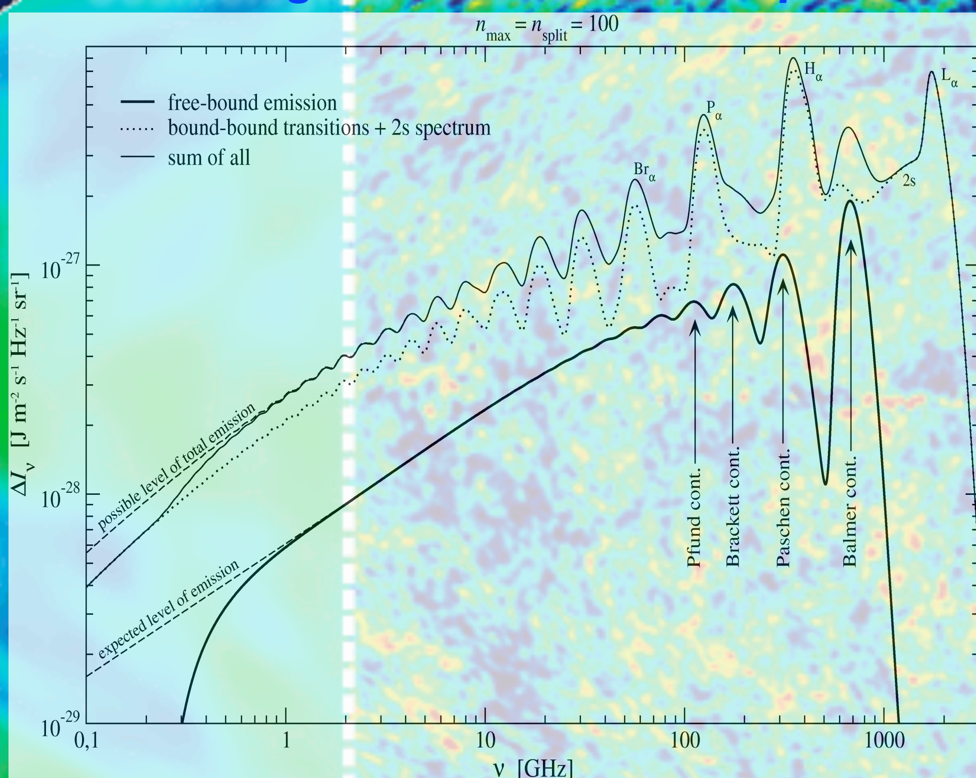
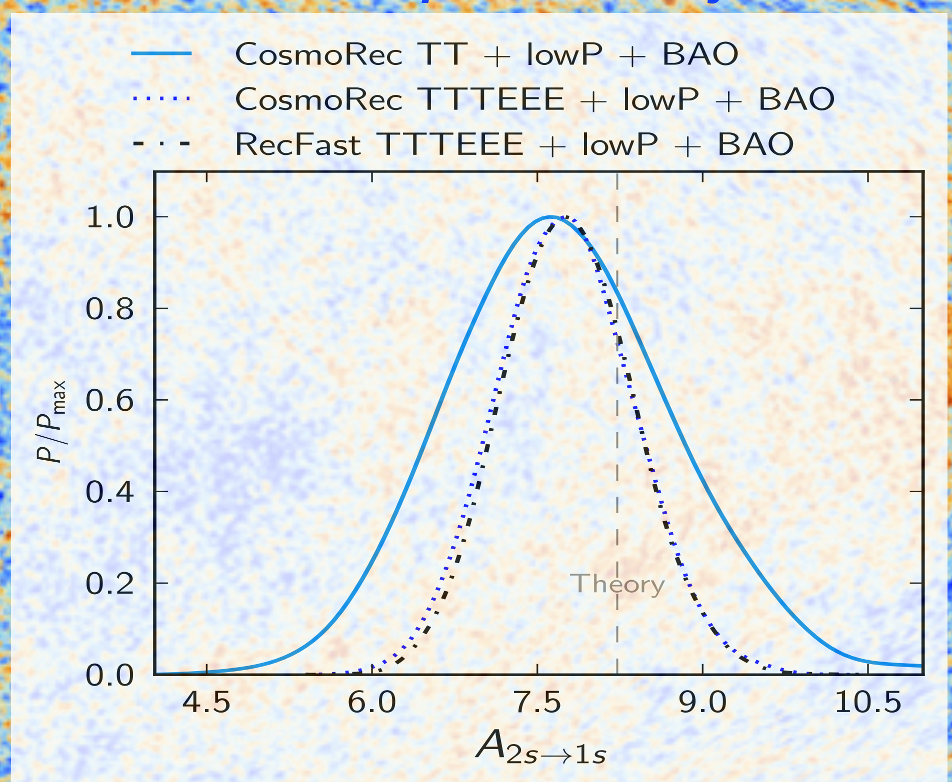
Introduction to Recombination Radiation, Non-Standard Recombination Models and Recombination Codes

Cosmological recombination spectrum



HI 2s-1s two-photon decay rate



MANCHESTER 1824
The University of Manchester

Jens Chluba

Cosmology - The Next Decade

ICTS, Bangalore, January 3th - 19th, 2019

erc
THE ROYAL SOCIETY

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 → $\Delta\varepsilon/\varepsilon \sim 13.6\,\mathrm{eV}\, N_b \,/\, (N_\gamma\, 2.7 k T_r) \sim 10^{-9} - 10^{-8}$

Viktor Dubrovich

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

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

→ There should be some *noticeable* 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!

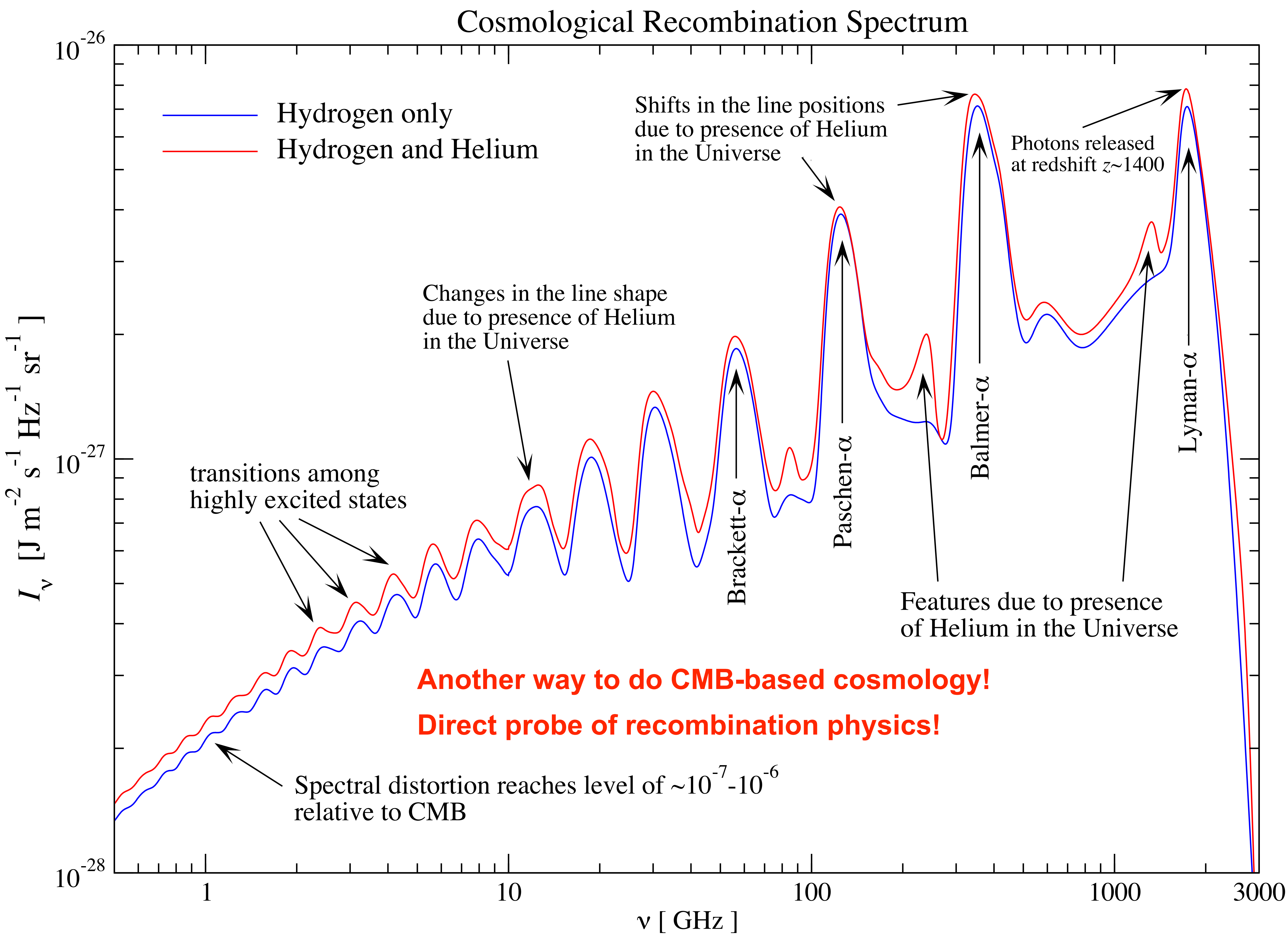
Hydrogen recombination lines of cosmological origin

V. K. Dubrovich

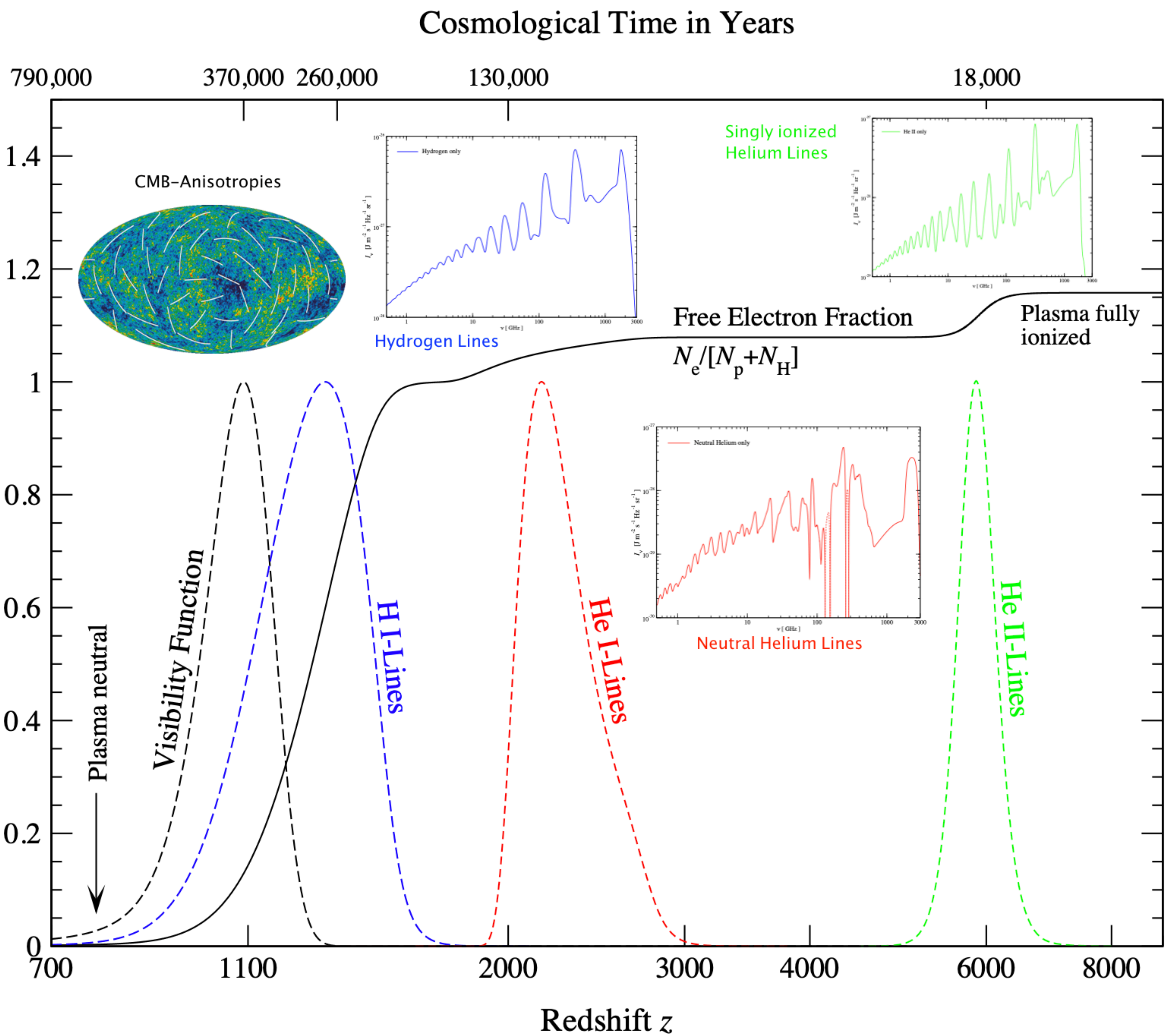
Special Astrophysical Observatory, USSR Academy of Sciences

(Submitted June 20, 1975)

Pis'ma Astron. Zh. **1**, No. 10, 3–4 (October 1975)

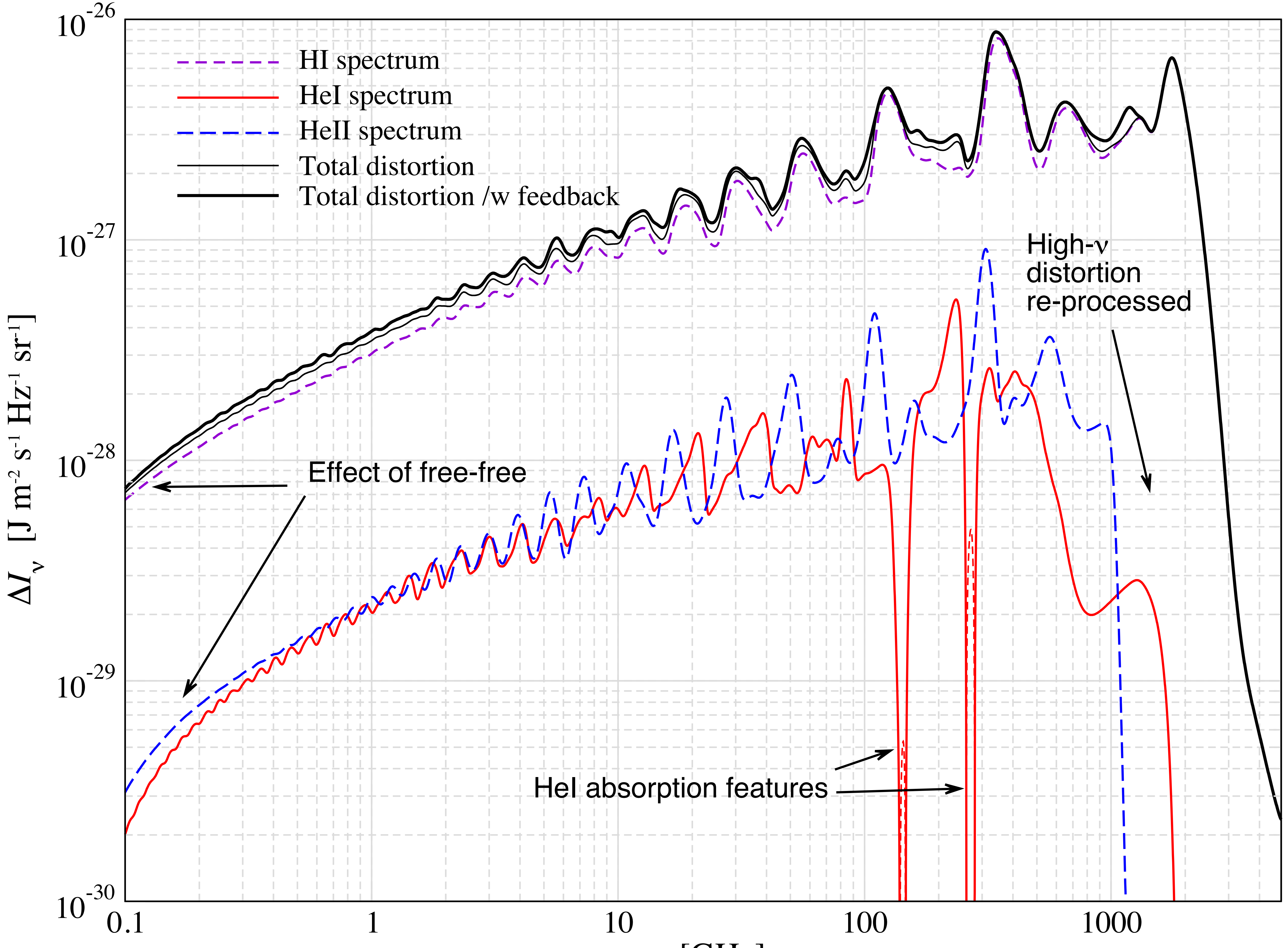


Rubino-Martin et al. 2006, 2008; Sunyaev & JC, 2009



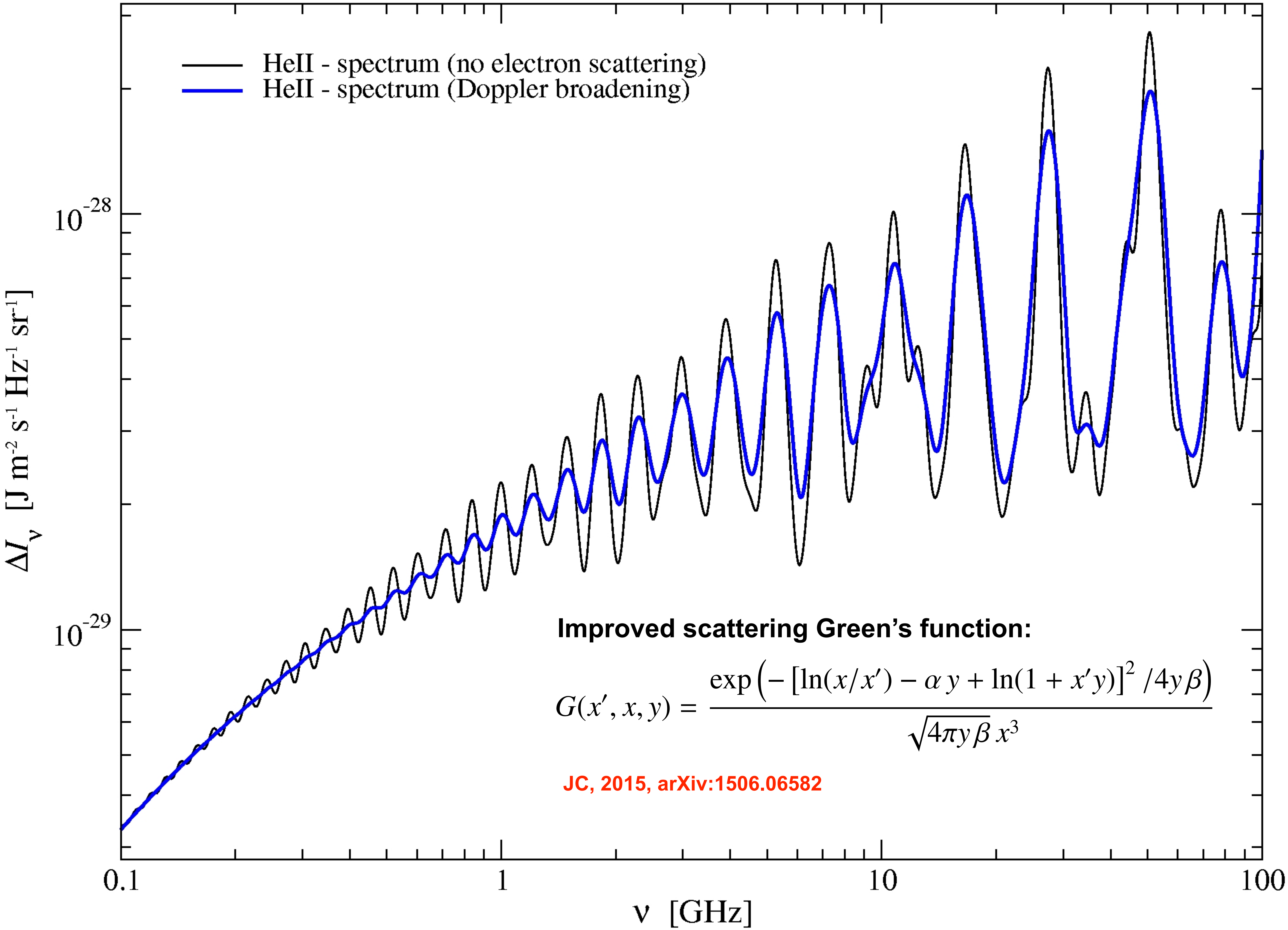
Cosmological Time in Years
790,000
370,000
260,000
130,000
18,000
CMB-Anisotropies
Hydrogen only
Hydrogen Lines
Singly ionized
Helium Lines
He II only
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully
ionized
Neutral Helium only
Neutral Helium Lines
Plasma neutral
Visibility Function
H I-Lines
He I-Lines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

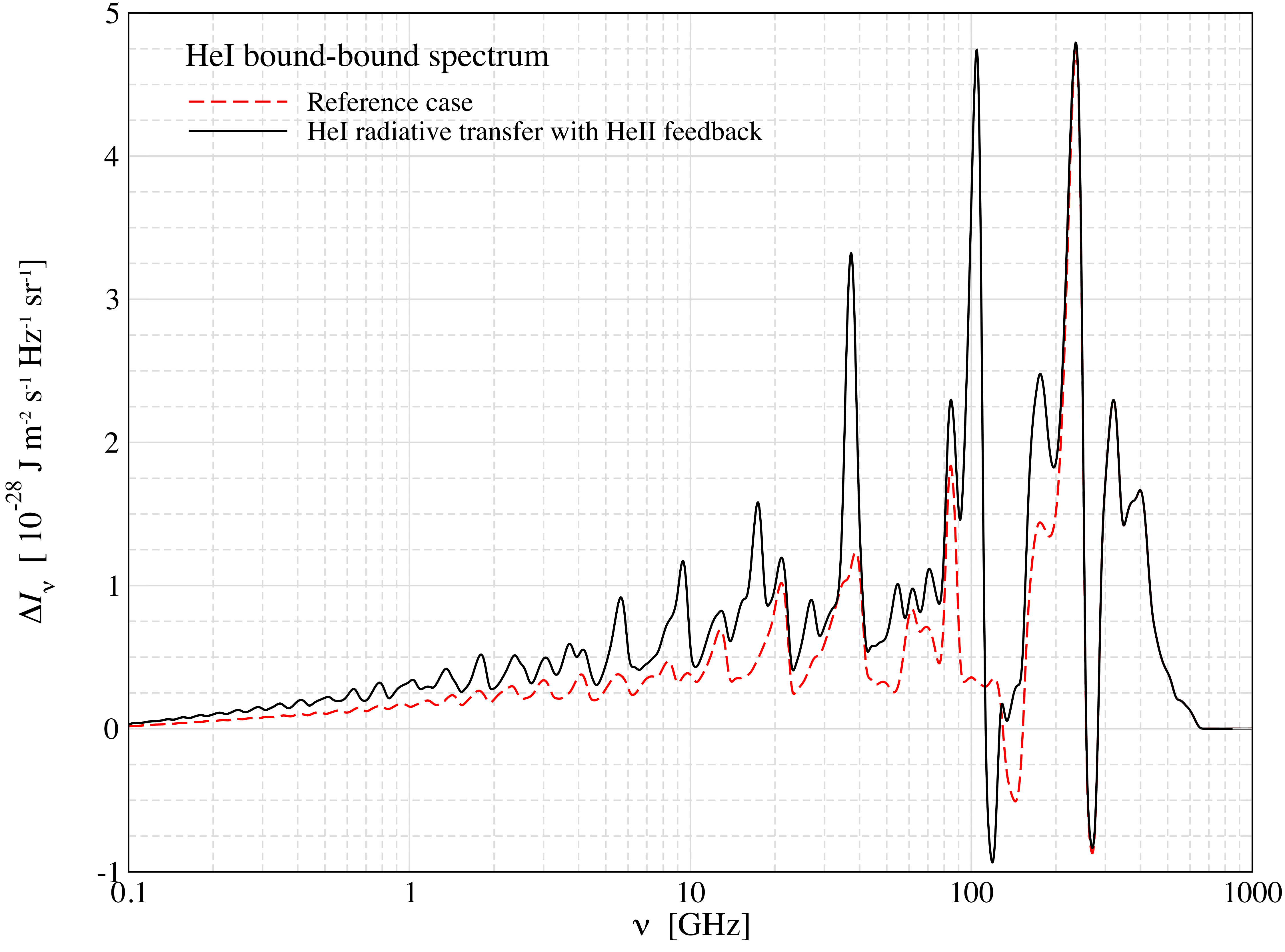


JC & Ali-Haimoud, arXiv:1510.03877

Line broadening due to the Doppler-term



Importance of feedback processes



JC & Ali-Haimoud, arXiv:1510.03877

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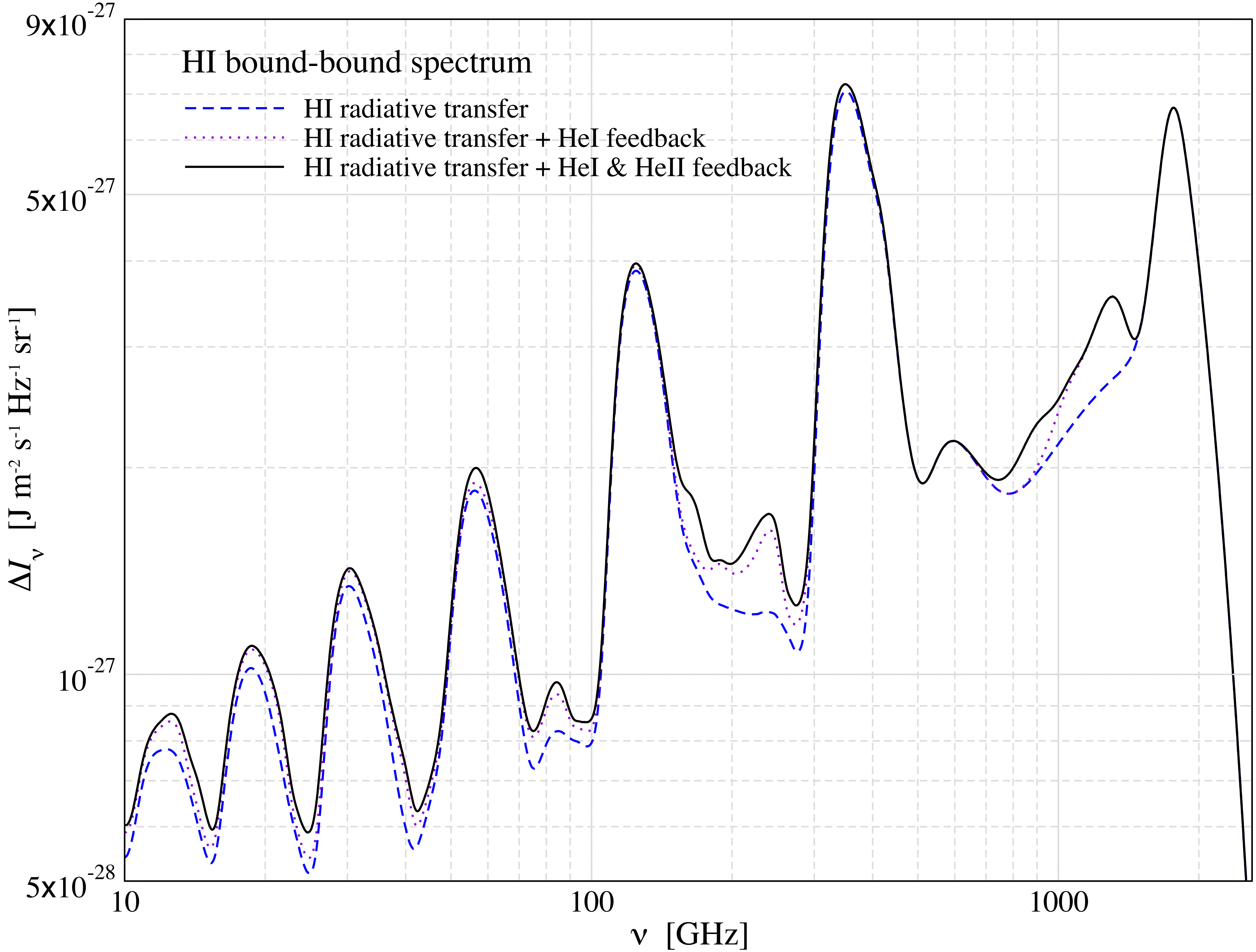
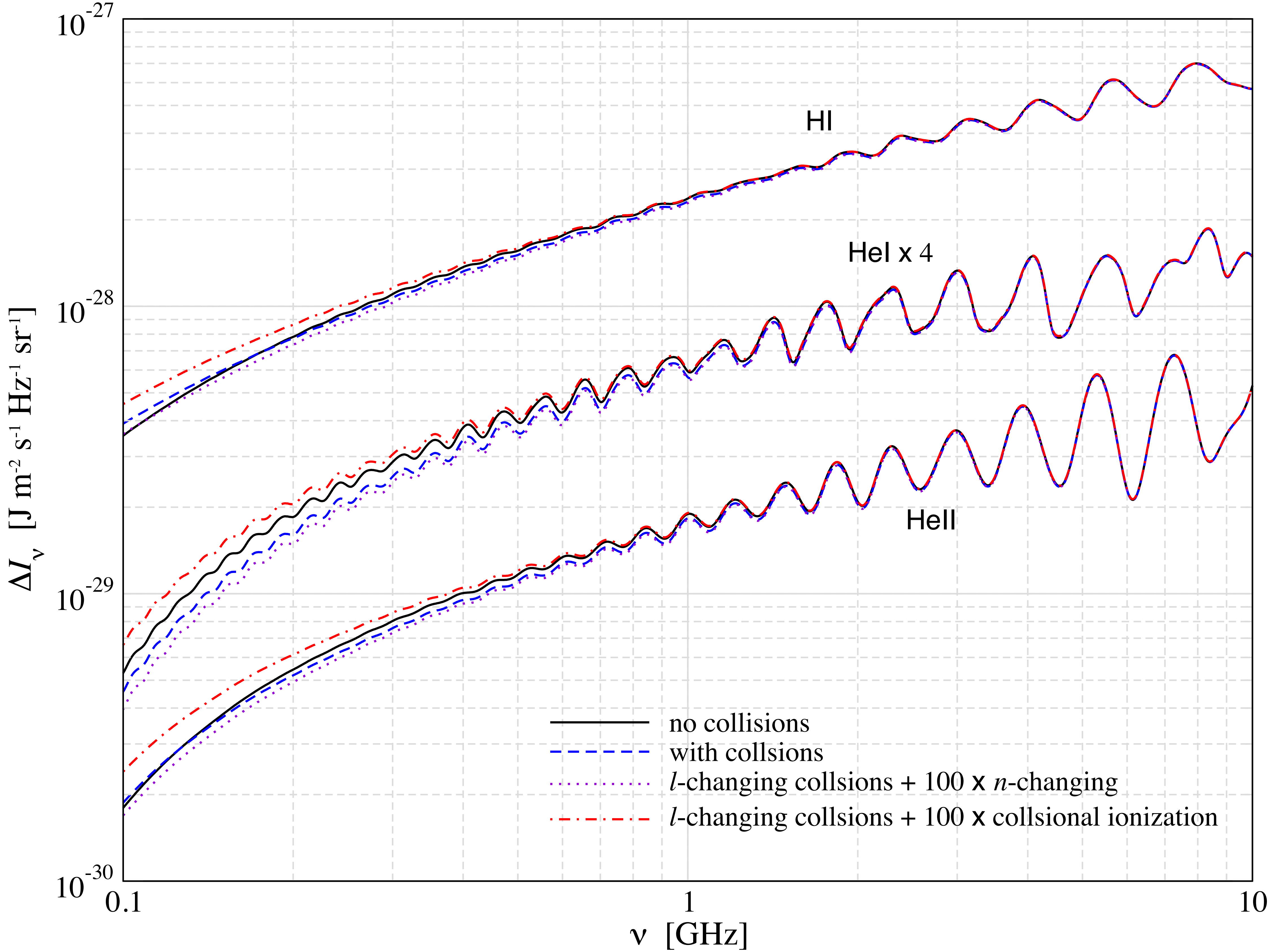


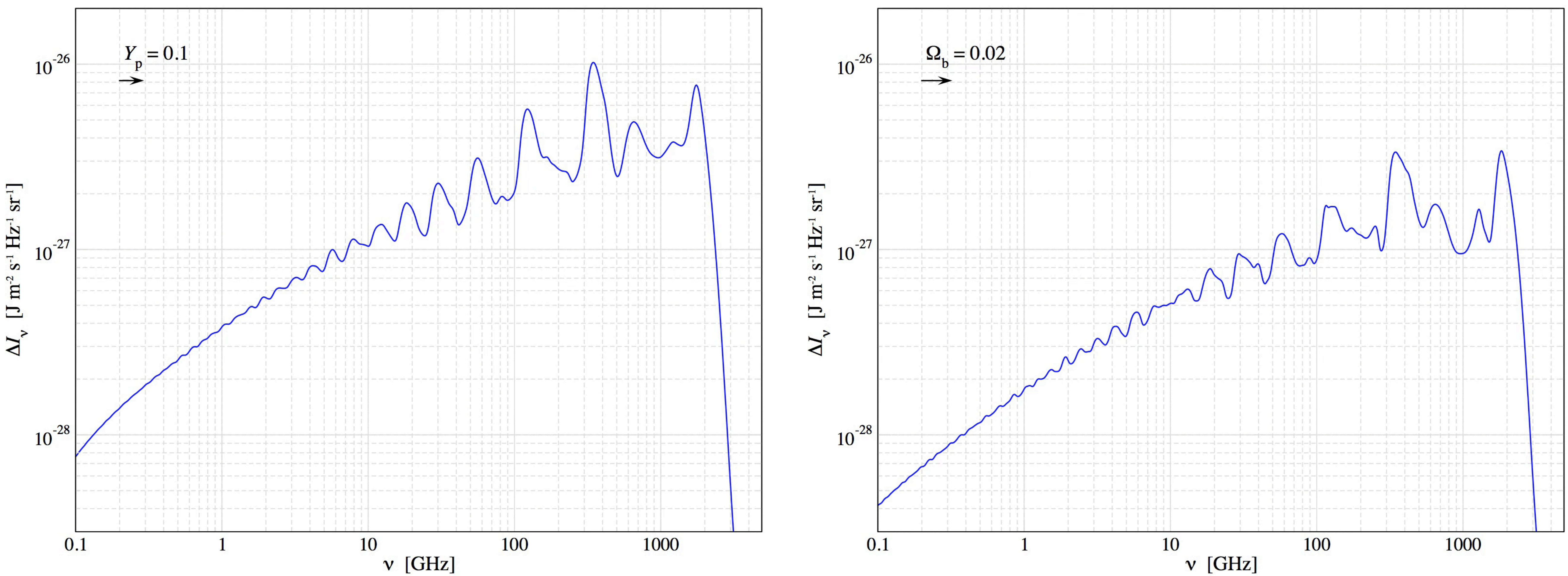
JC & Ali-Haimoud, arXiv:1510.03877

Importance of collisions



JC & Ali-Haimoud, arXiv:1510.03877

CosmoSpec: fast and accurate computation of the CRR



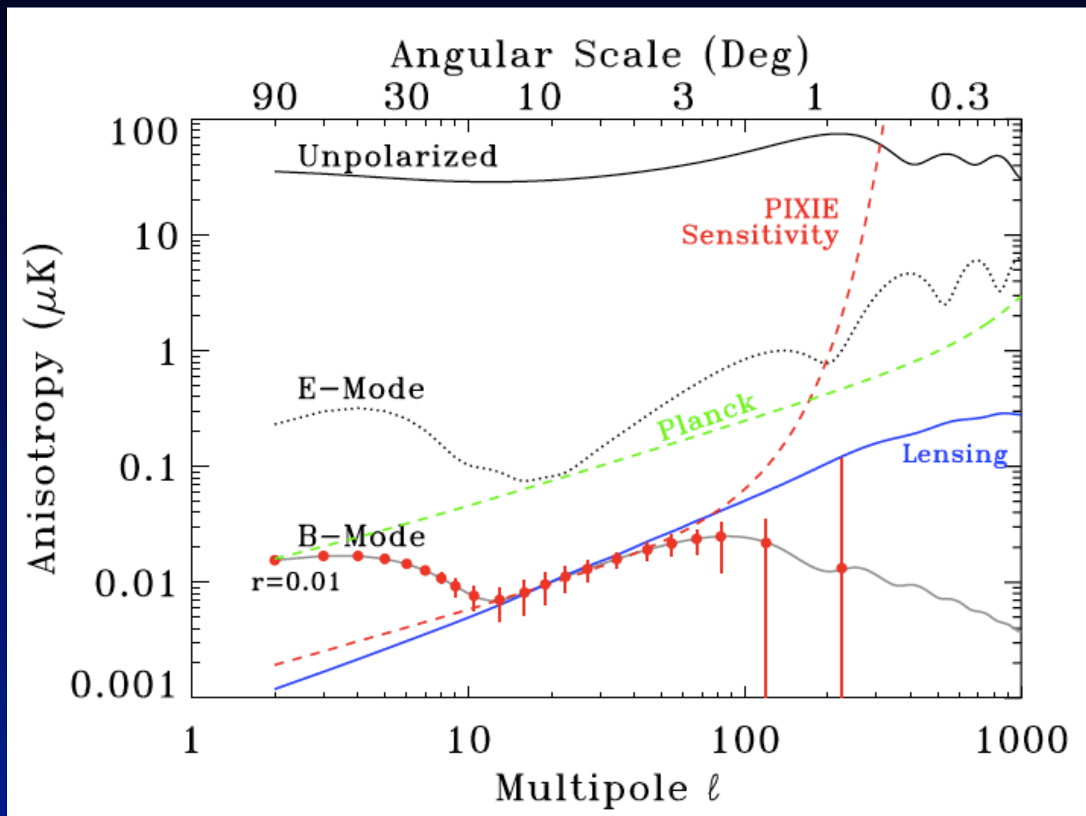
- Like in old days of CMB anisotropies!
- detailed forecasts and feasibility studies
- non-standard physics (variation of α, energy injection etc.)

CosmoSpec will be available here:

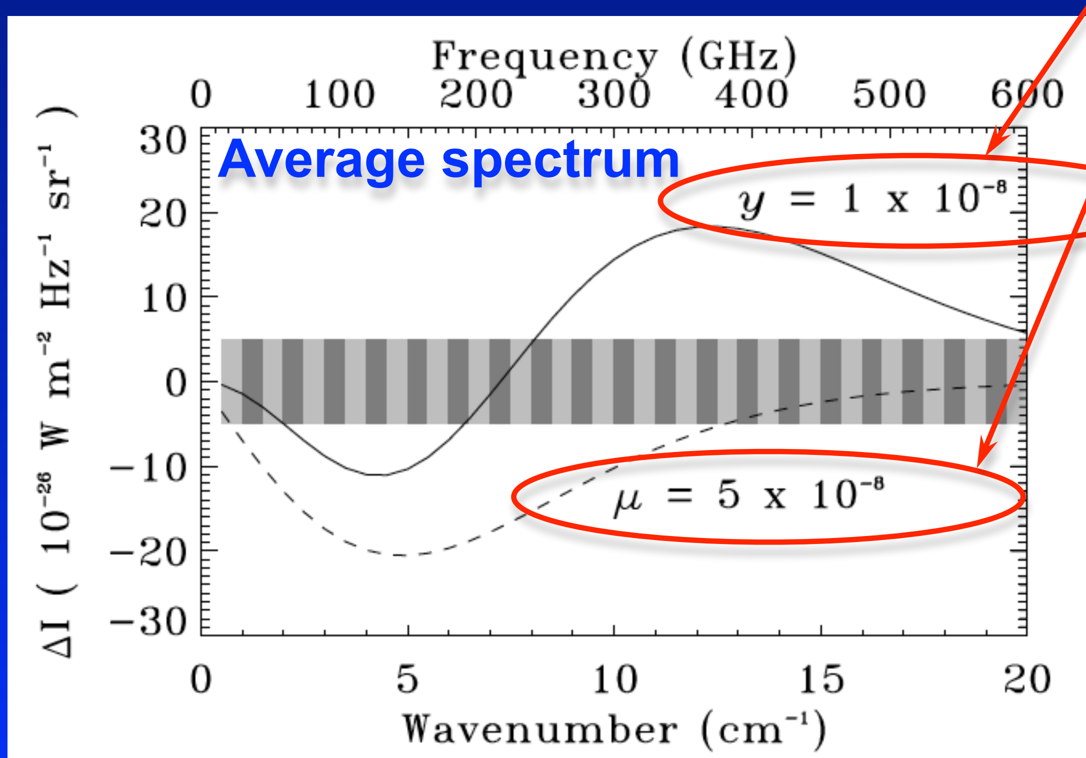
www.Chluba.de/CosmoSpec

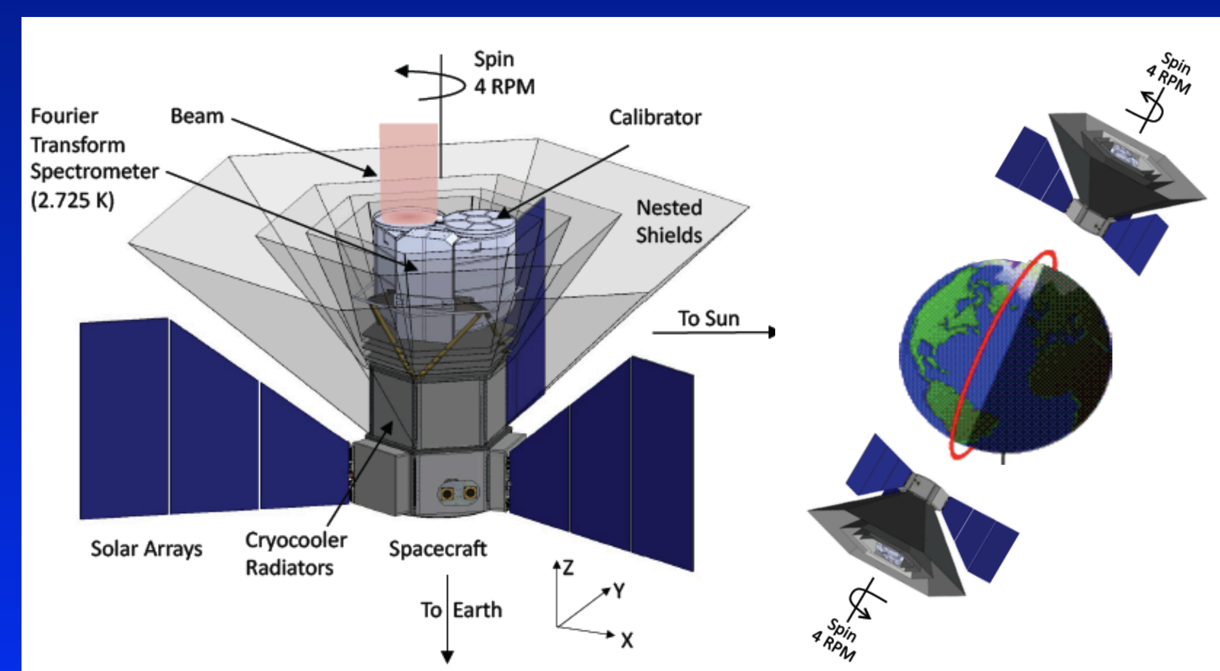
JC & Ali-Haimoud, arXiv:1510.03877

PIXIE: Primordial Inflation Explorer



- 400 spectral channel in the frequency range 30 GHz and 6THz (Δv ~ 15GHz)
- about 1000 (!!!) times more sensitive than COBE/FIRAS
- B-mode polarization from inflation ($r \approx 10^{-3}$)
- improved limits on μ and y
- was proposed 2011 & 2016 as NASA EX mission (i.e. cost ~ 200-250 M$)

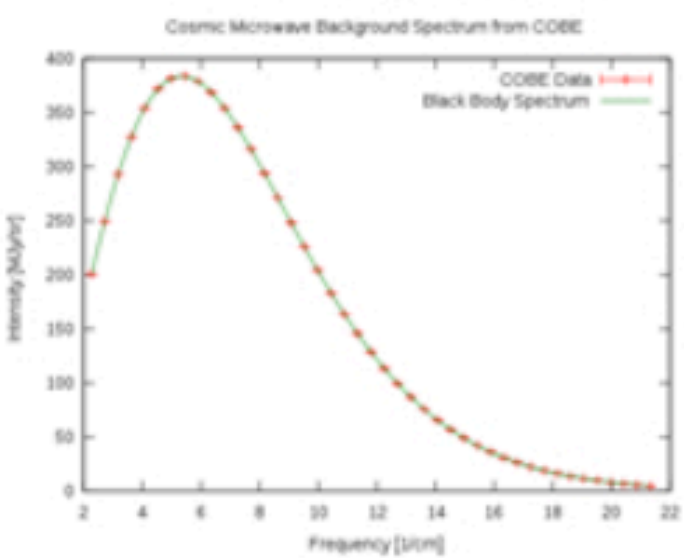




Kogut et al, JCAP, 2011, arXiv:1105.2044

Array of Precision Spectrometers for detecting spectral ripples from the Epoch of RecombinAtion

HOME PEOPLE



About APSERa

The Array of Precision Spectrometers for the Epoch of RecombinAtion - APSERa - is a venture to detect recombination lines from the Epoch of Cosmological Recombination. These are predicted to manifest as 'ripples' in wideband spectra of the cosmic radio background (CRB) since recombination of the primeval plasma in the early Universe adds broad spectral lines to the relic Cosmic Radiation. The lines are extremely wide because recombination is stalled and extended over redshift space. The spectral features are expected to be isotropic over the whole sky.

The project will comprise of an array of 128 small telescopes that are purpose built to detect a set of adjacent lines from cosmological recombination in the spectrum of the radio sky in the 2-6 GHz range. The radio receivers are being designed and built at the Raman Research Institute, tested in nearby radio-quiet locations and relocated to a remote site for long duration exposures to detect the subtle features in the cosmic radio background arising from recombination. The observing site would be appropriately chosen to minimize RFI from geostationary satellites and to be able to observe towards sky regions relatively low in foreground brightness.

Details in Rao et al., ArXiv:1501.07191

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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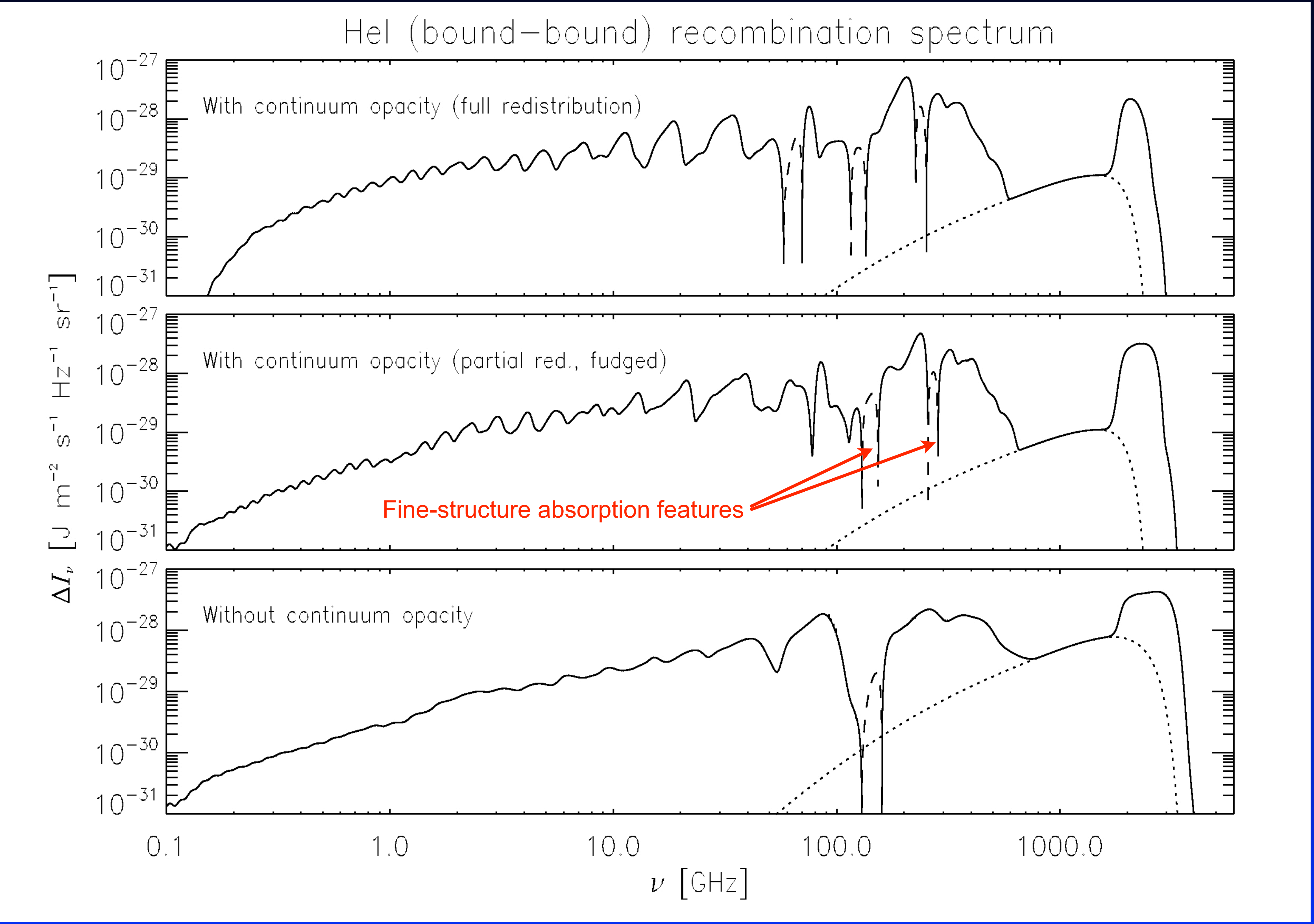
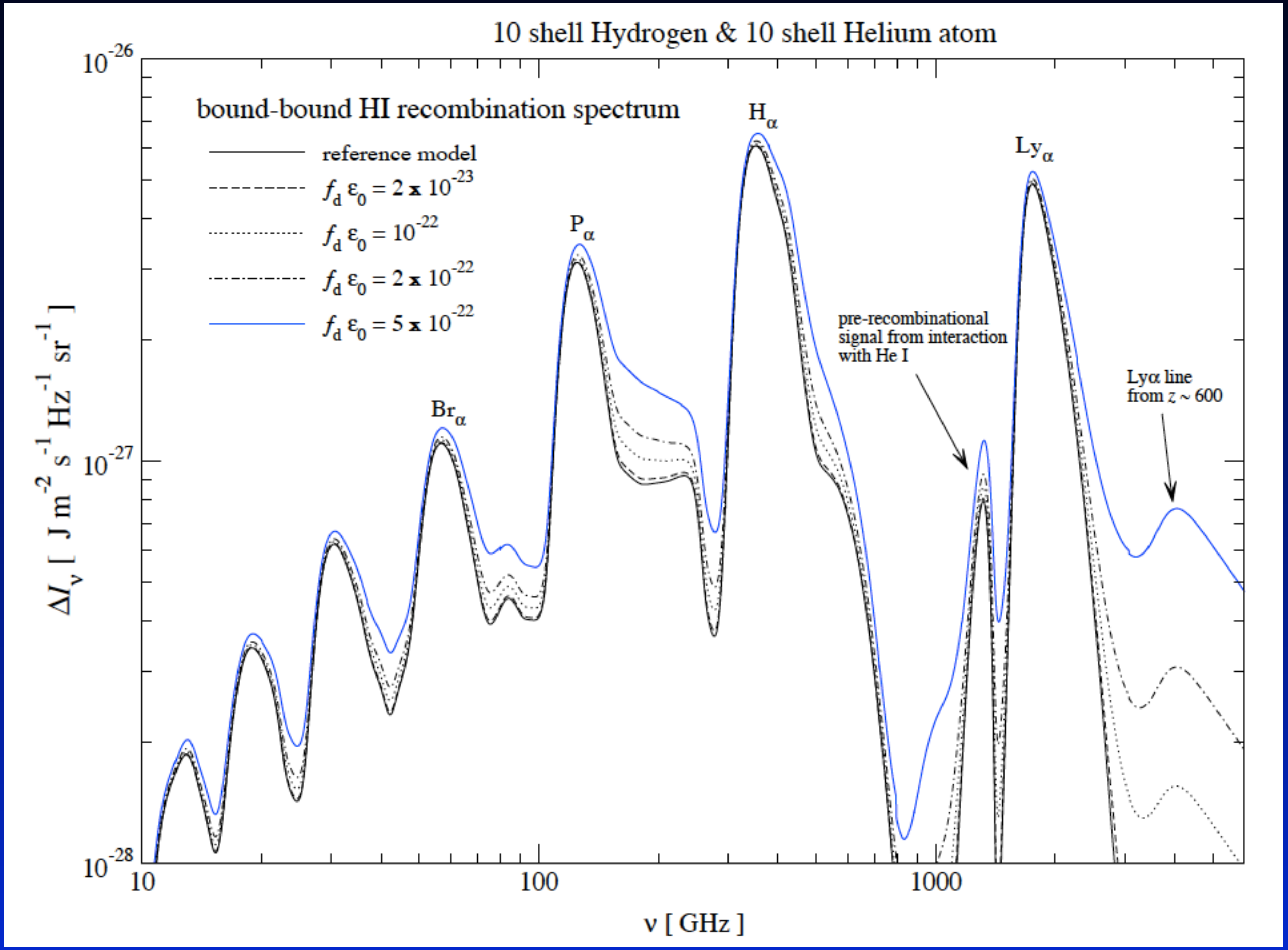
The importance of HI continuum absorption



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

→ More in later….

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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**

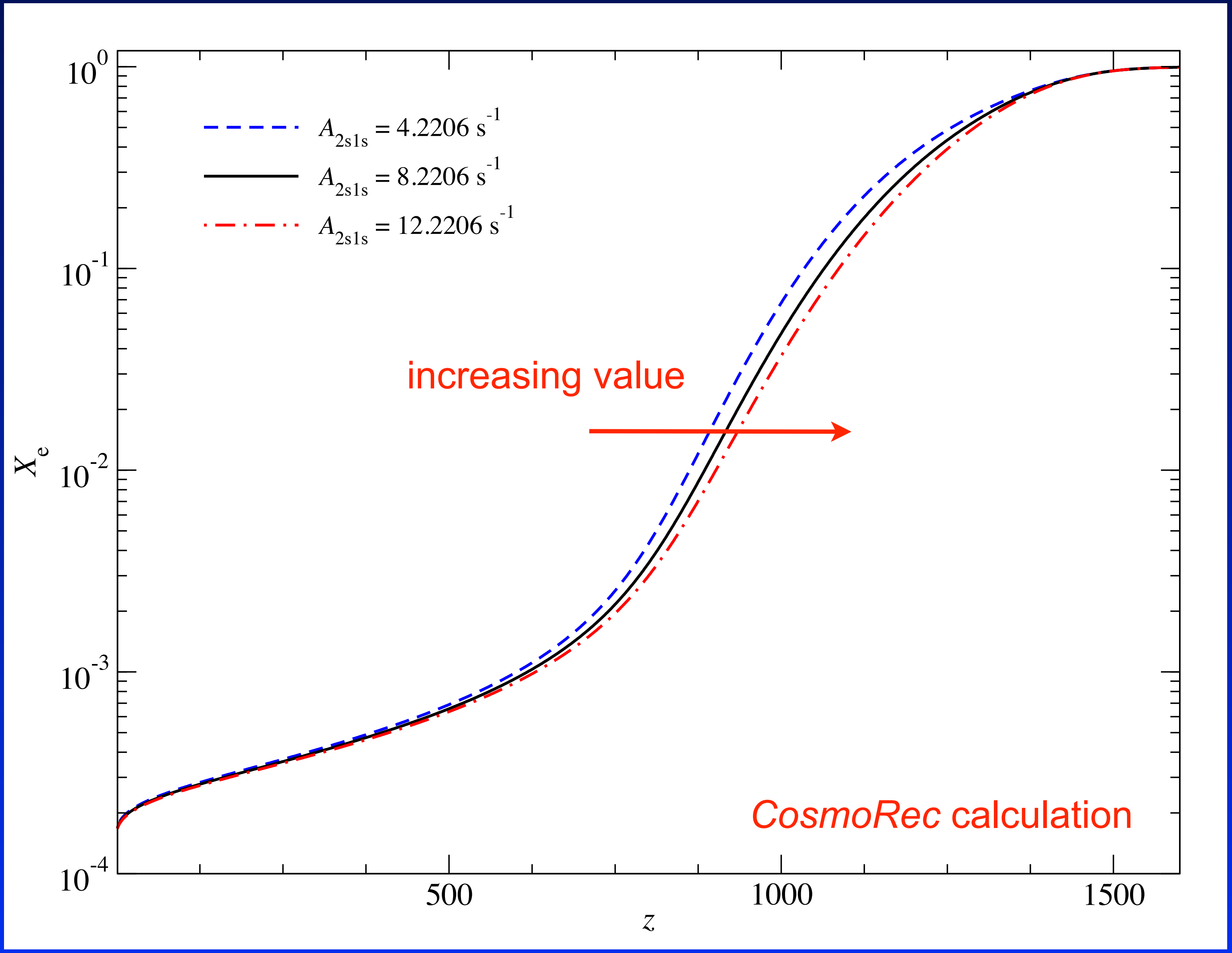
→ ***sensitive to energy release during recombination***

→ **variation of fundamental constants**

Non-standard recombination models that **`Recfast++`** *and* **`CosmoRec`** *can treat*

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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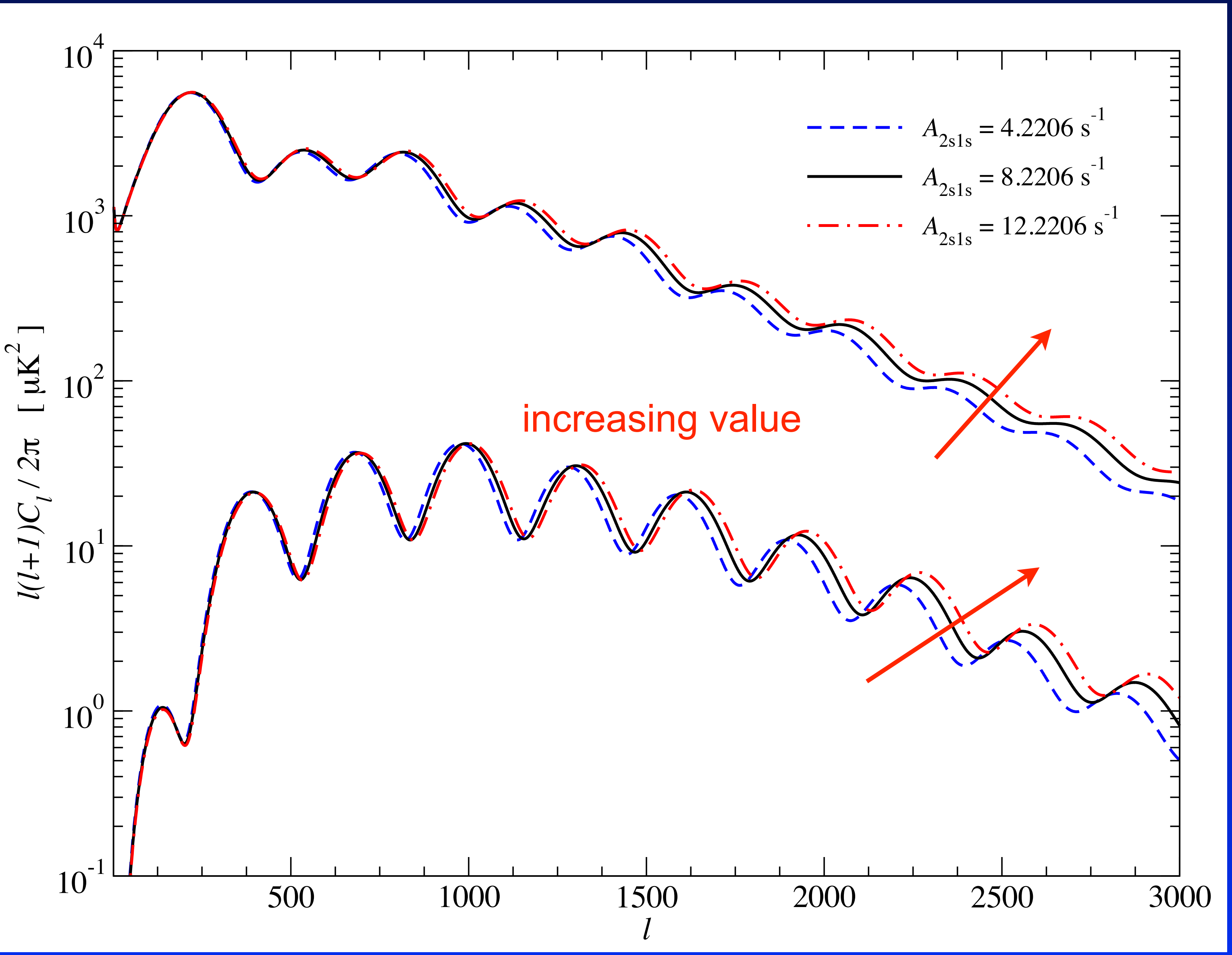

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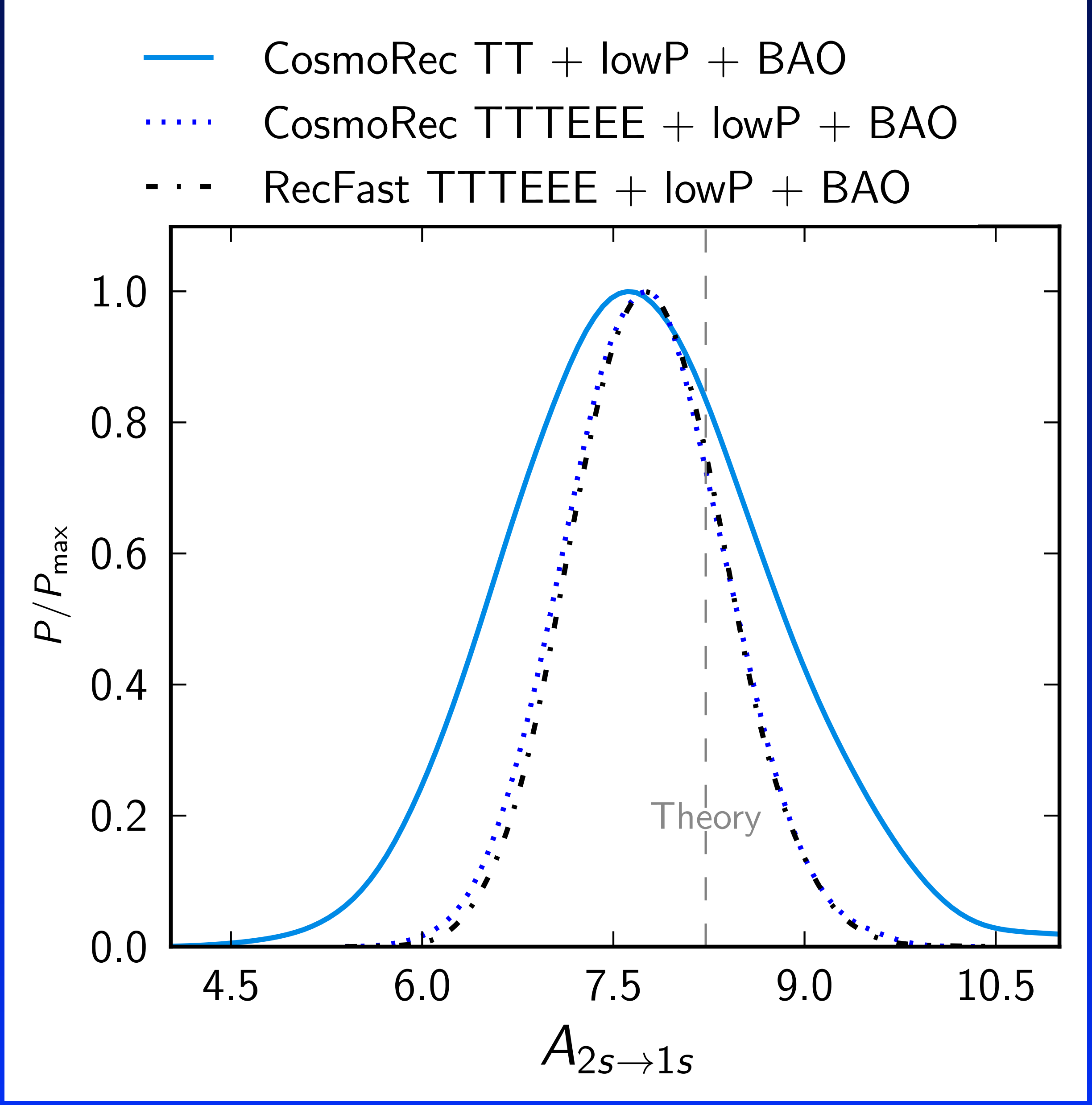


$$A_{2s\to 1s}^{\rm theory} = 8.2206\,{\rm s}^{-1} (\text{Labzowsky et al. 2005})$$

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

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

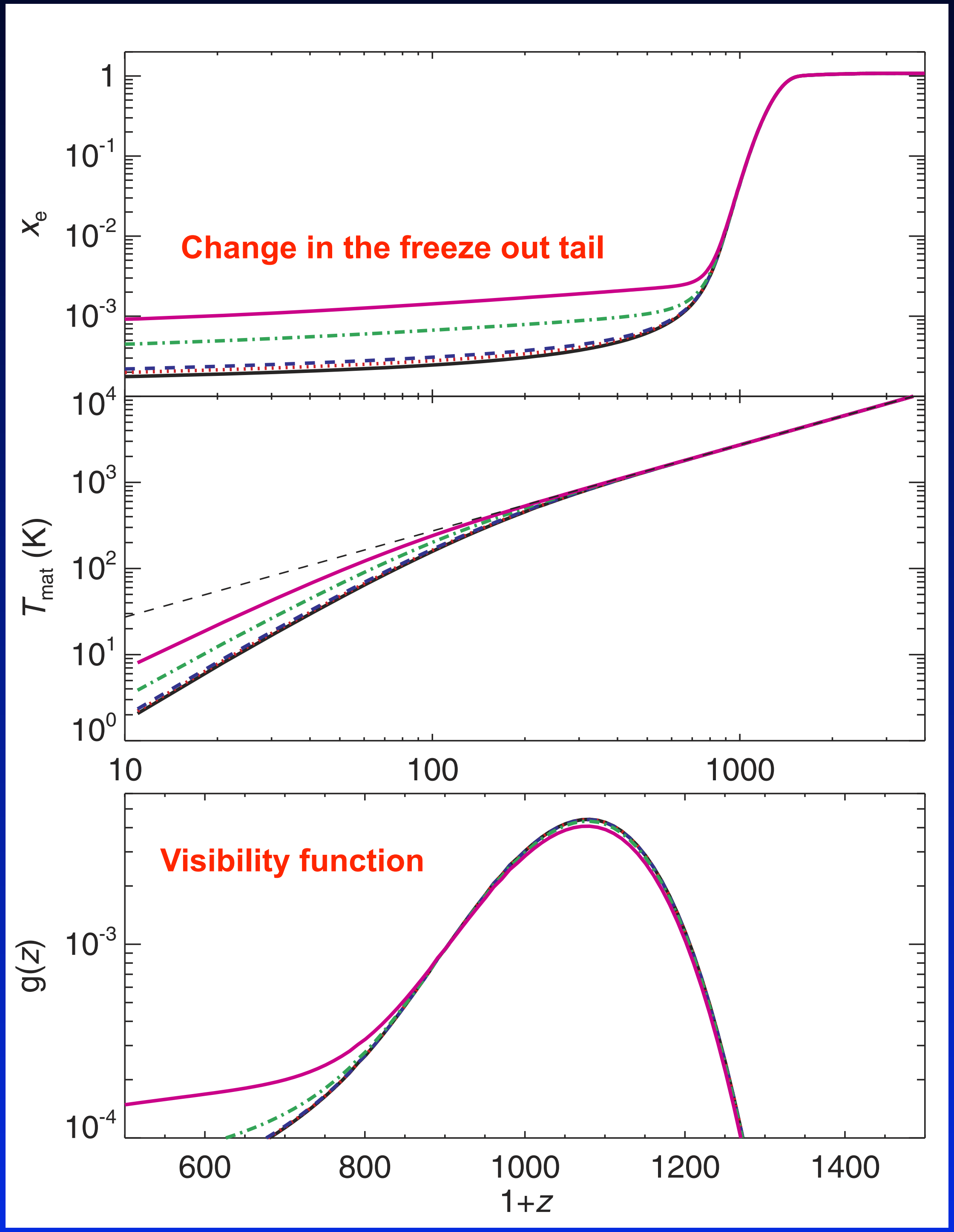
- *Planck* measurement in excellent agreement with theoretical value
- *Planck* only values very similar
- *CosmoRec* and *Recfast* agree...

Planck Collaboration, XIII 2015

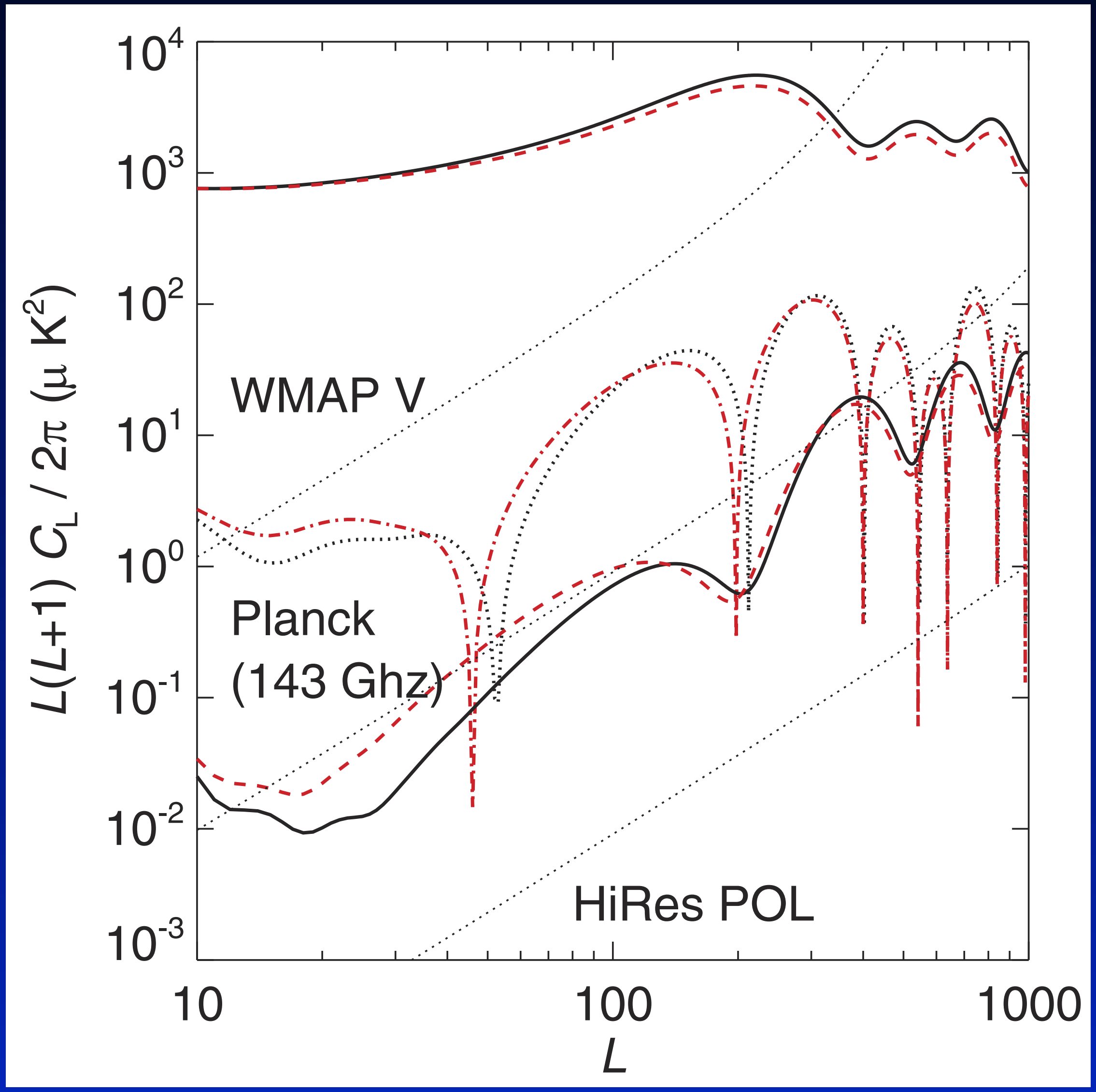
Annihilating / Decaying (dark matter) particles

Changes of CMB anisotropies by annihilating particles

95% c.l.

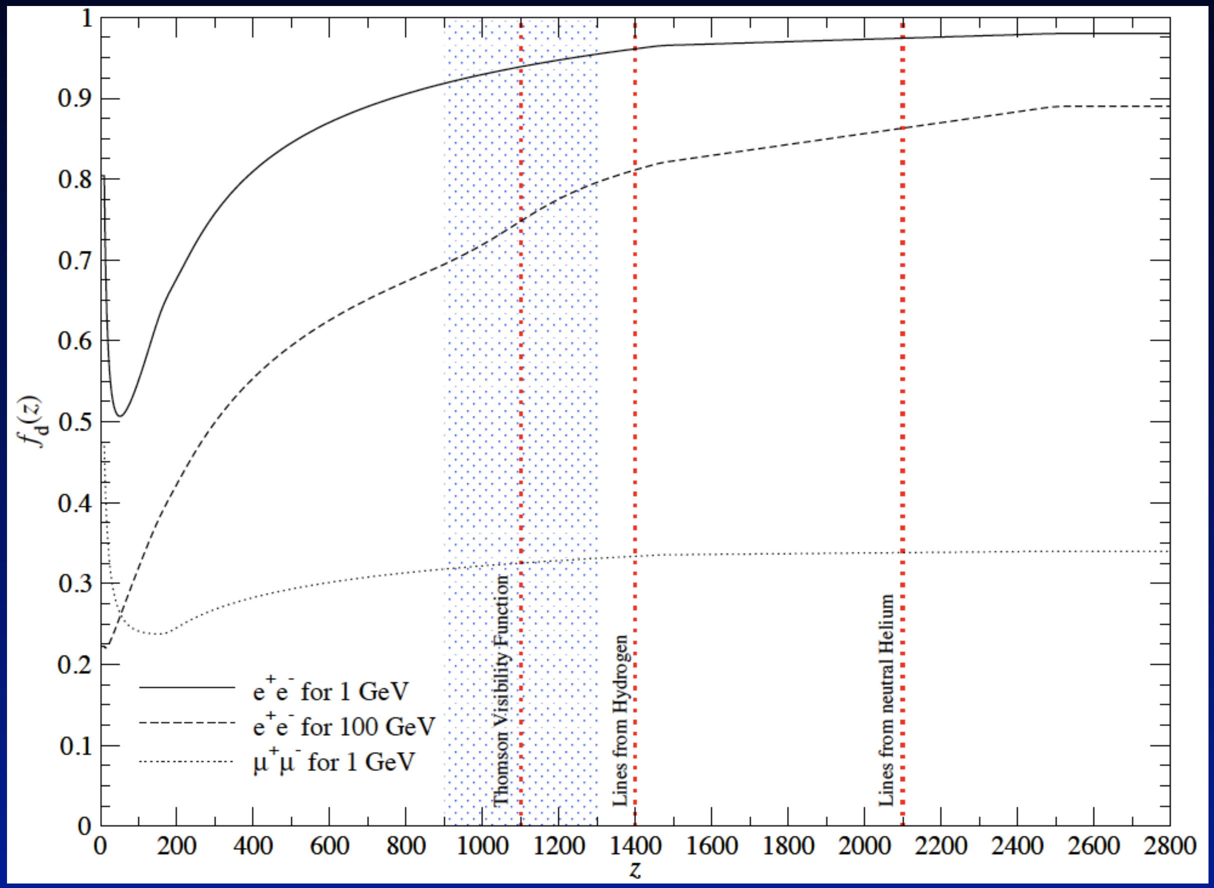


Chen & Kamionikowski, 2004
Padmanabhan & Finkbeiner, 2005

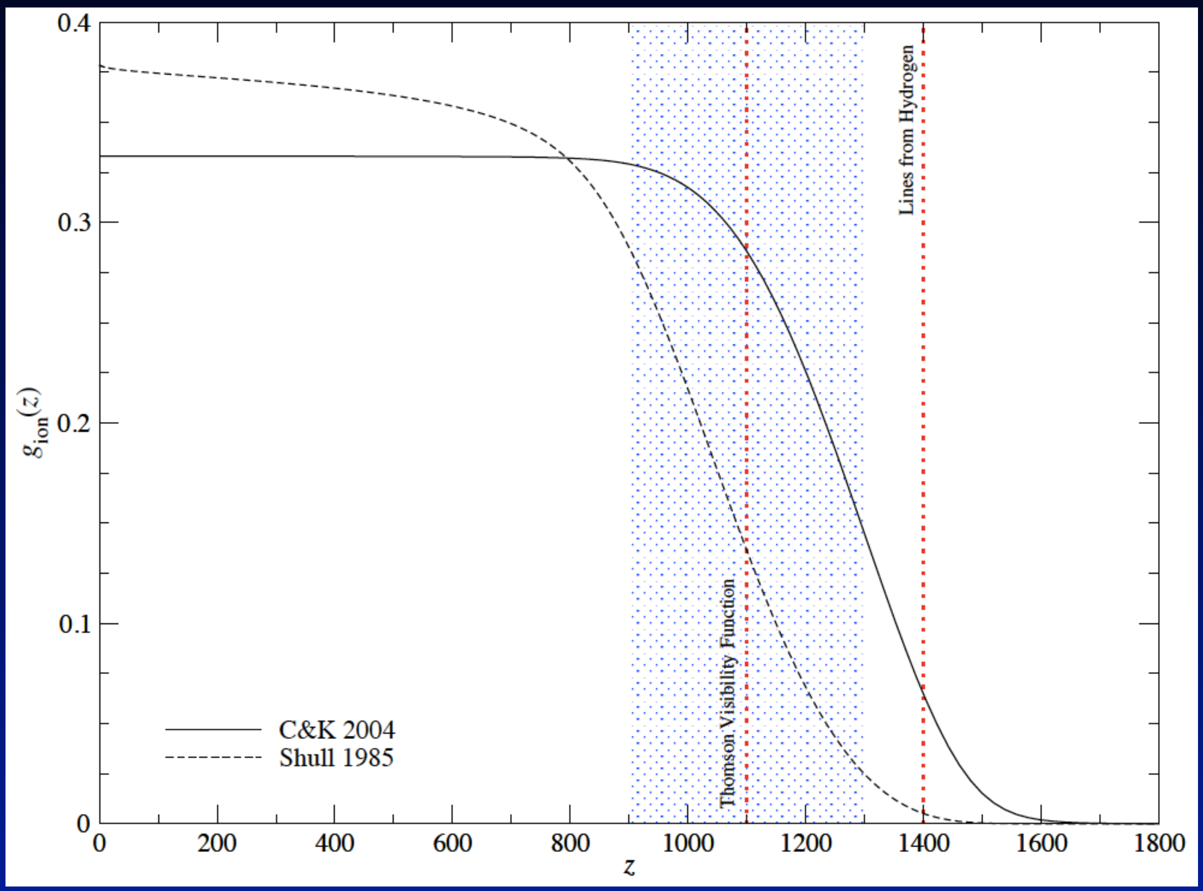


- more damping because τ increases
- change close to visibility maximum → shift in peak positions

Dark Matter Annihilation: Energy Branching Ratios



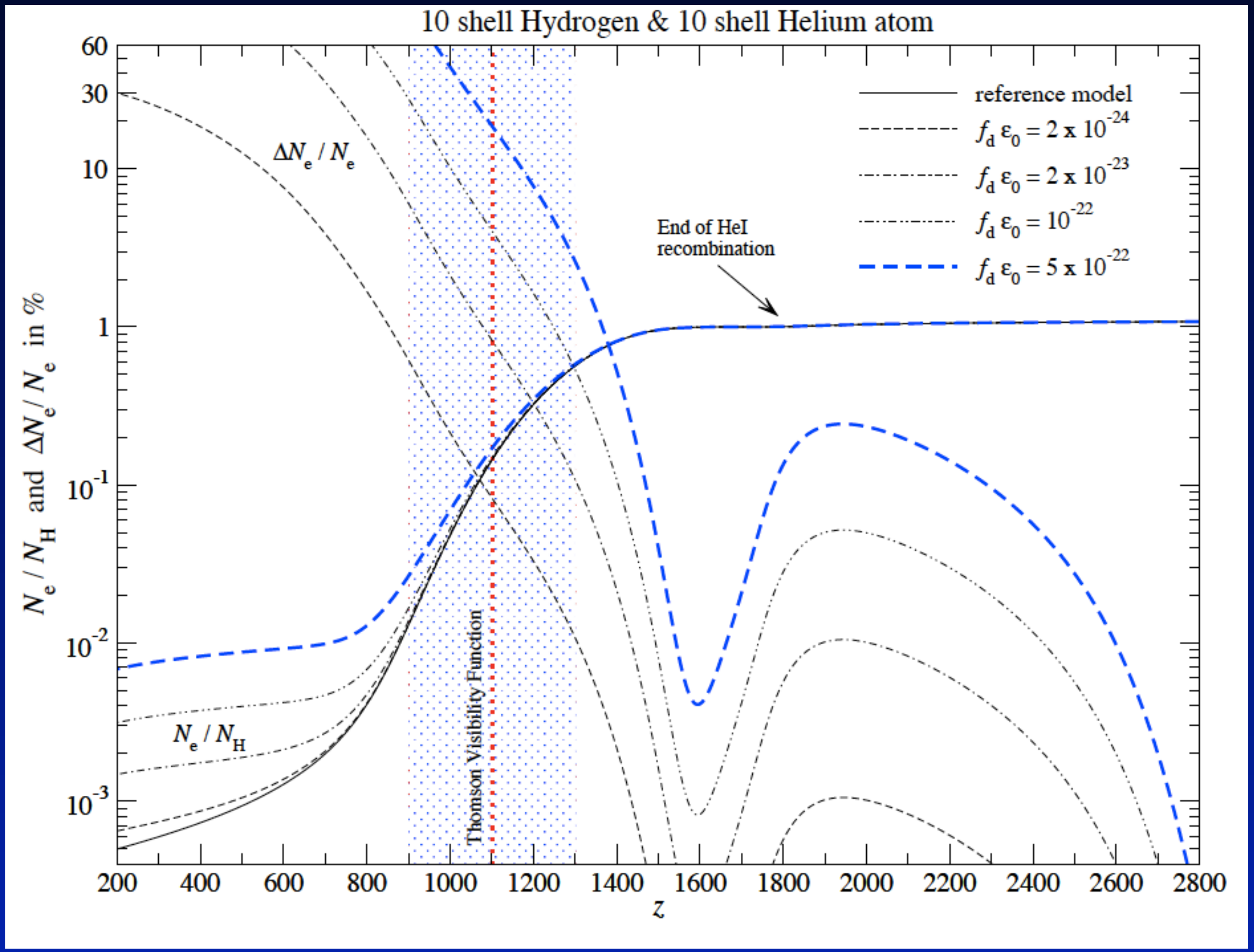
curves from Slatyer et al. 2009

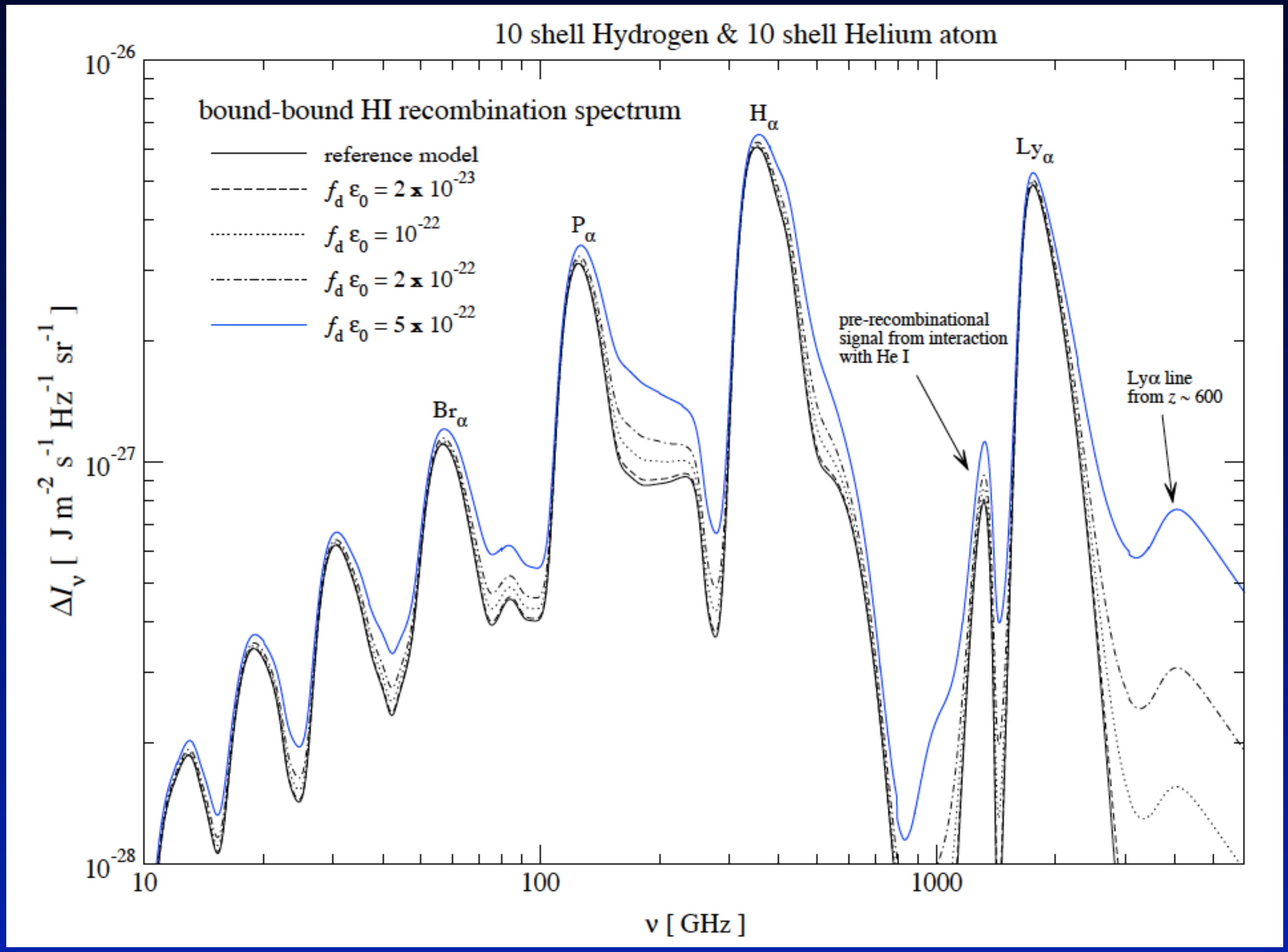


Efficiencies according to Chen & Kamionkowski, 2004 & Shull & van Steenberg 1985

- N^2 - dependence $\Rightarrow$ dE/dt $\propto (1+z)^6$ and dE/dz $\propto (1+z)^{3\ldots3.5}$
- only part of the energy is really deposited ($f_d \sim 0.1$)
- Branching into *heating* (effective at high z), *ionizations* and *excitations* (mainly during recombination)
- Branching depends on considered DM model

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

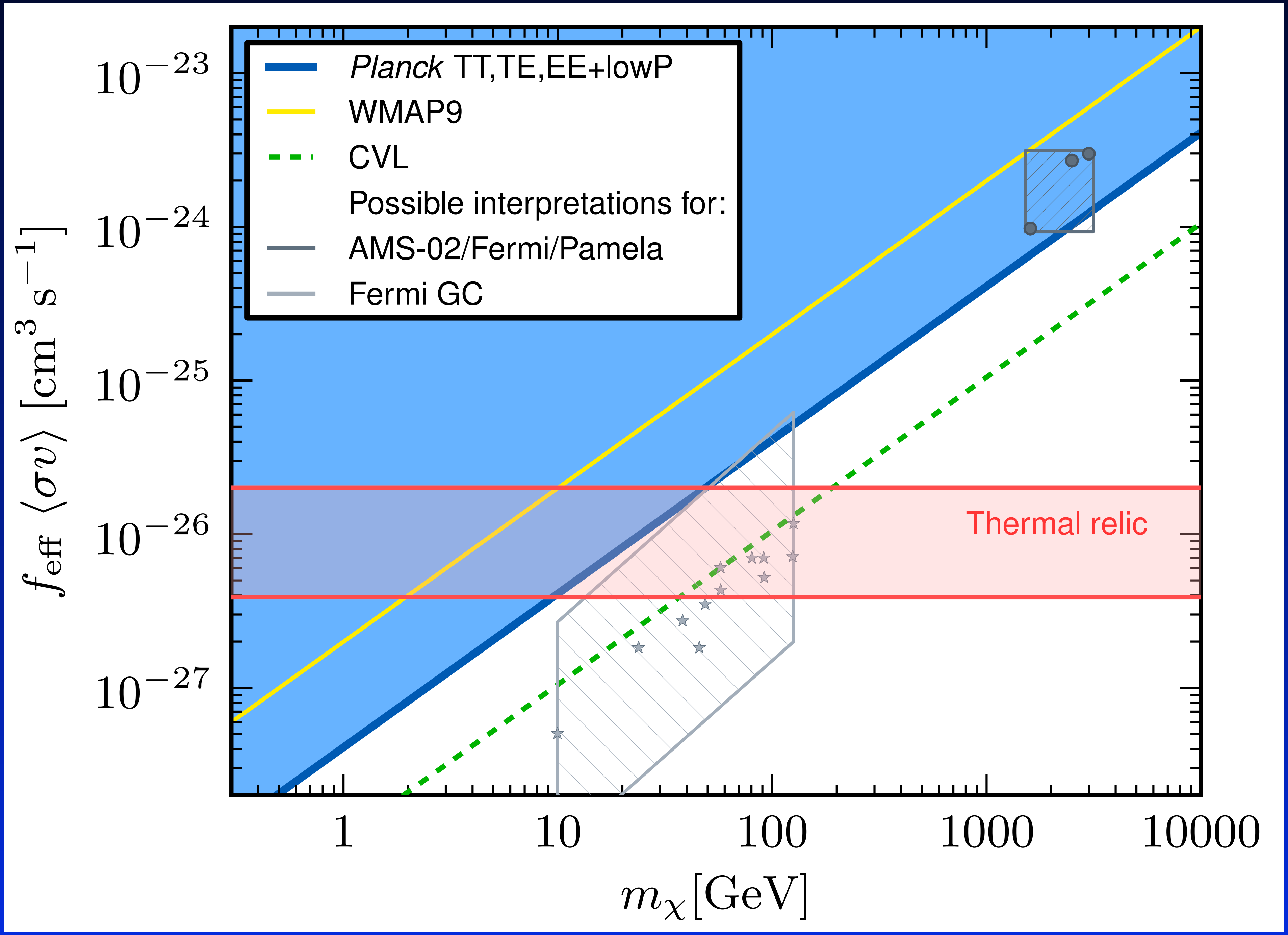
- Additional photons at all frequencies
- Broadening of spectral features
- Shifts in the positions

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

JC, 2009, arXiv:0910.3663

Latest Planck limits on annihilation cross section

95% c.l.

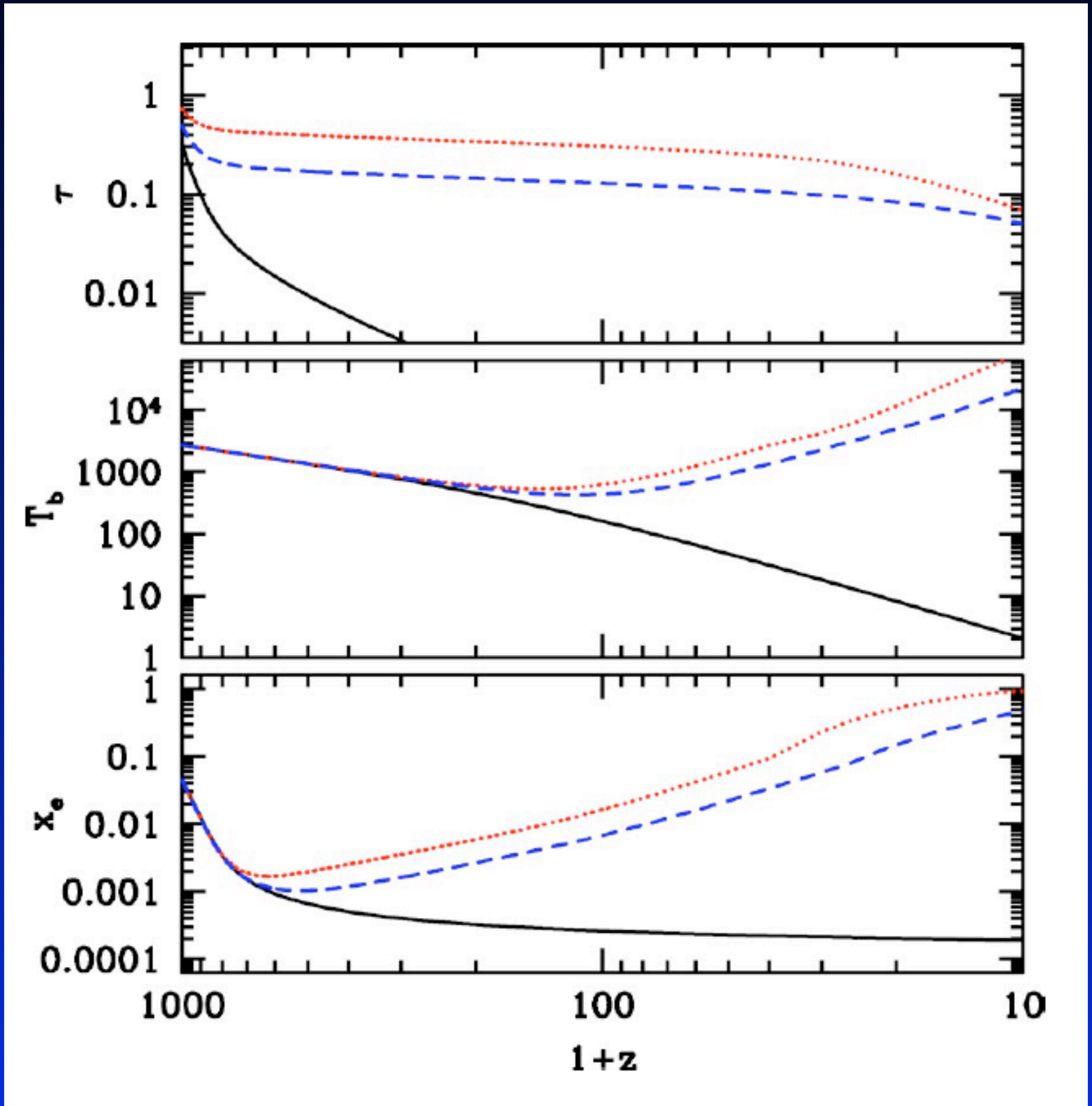


Planck Collaboration, paper XIII, 2015

- 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

Decaying particle during & after recombination

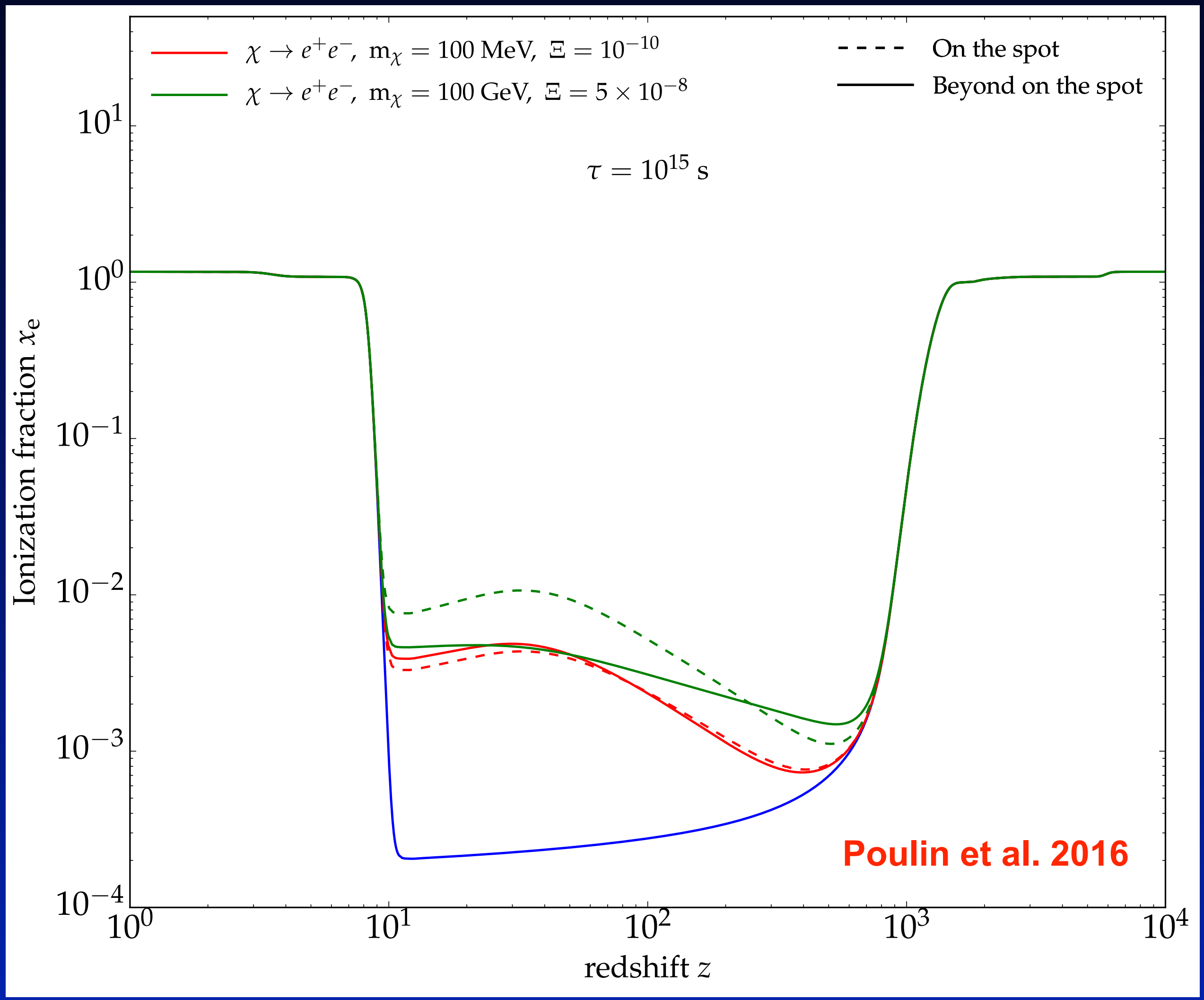


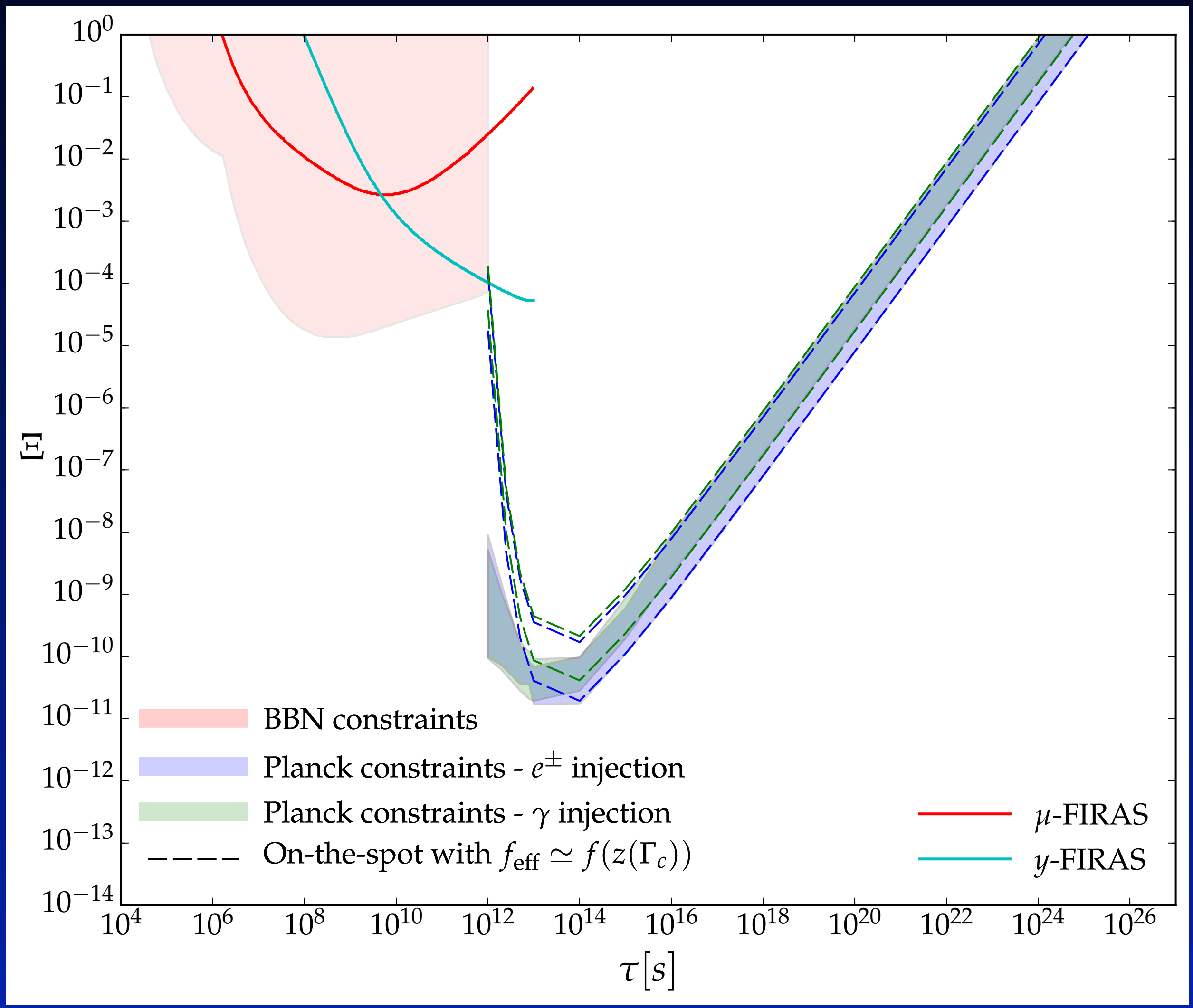
Chen & Kamionkowski, 2004

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

  probing particles with lifetimes $\gtrsim 10^{12}$ sec
- CMB spectral distortions provide complementary probe!

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

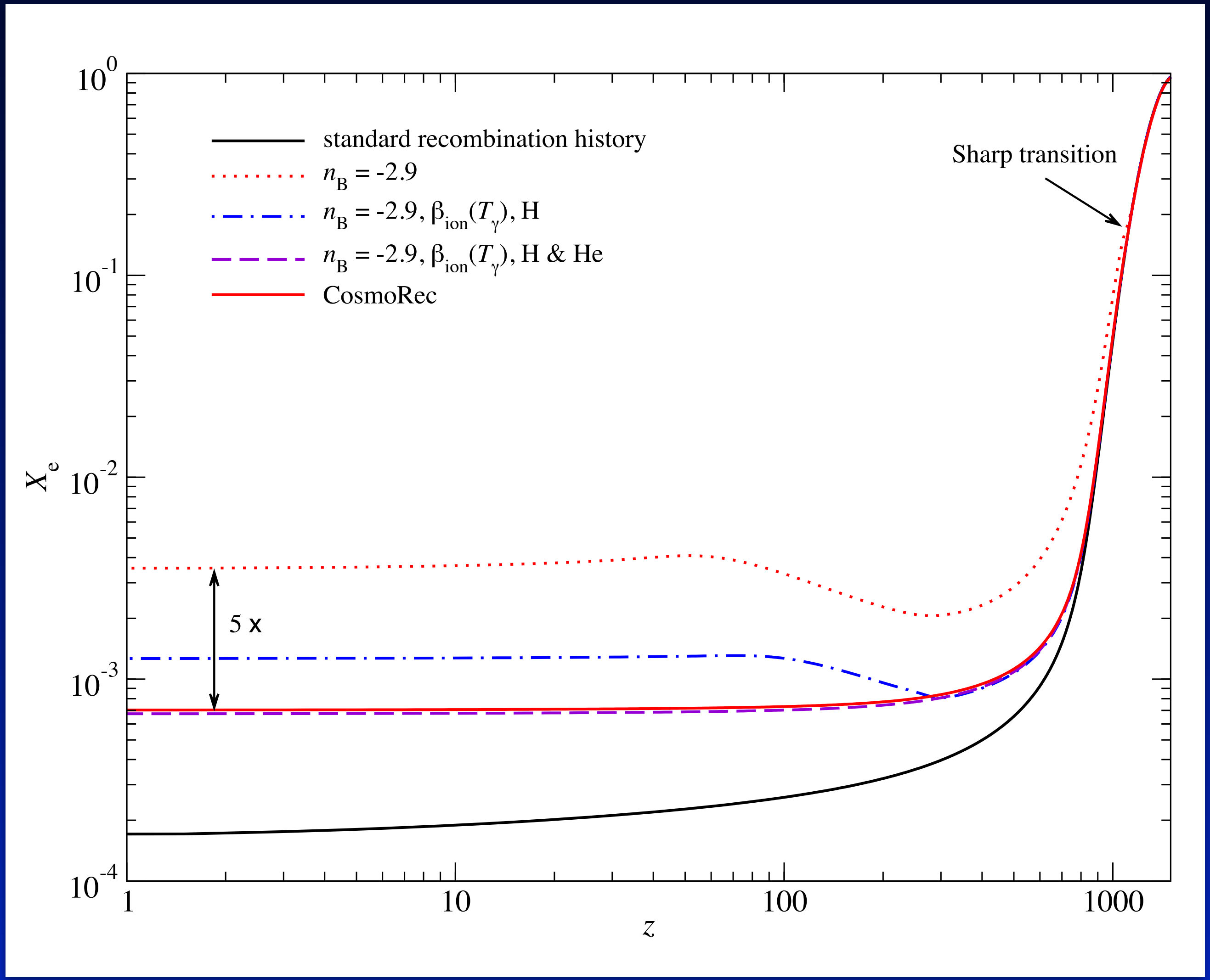
Ξ Relative amount of energy per decay and per DM

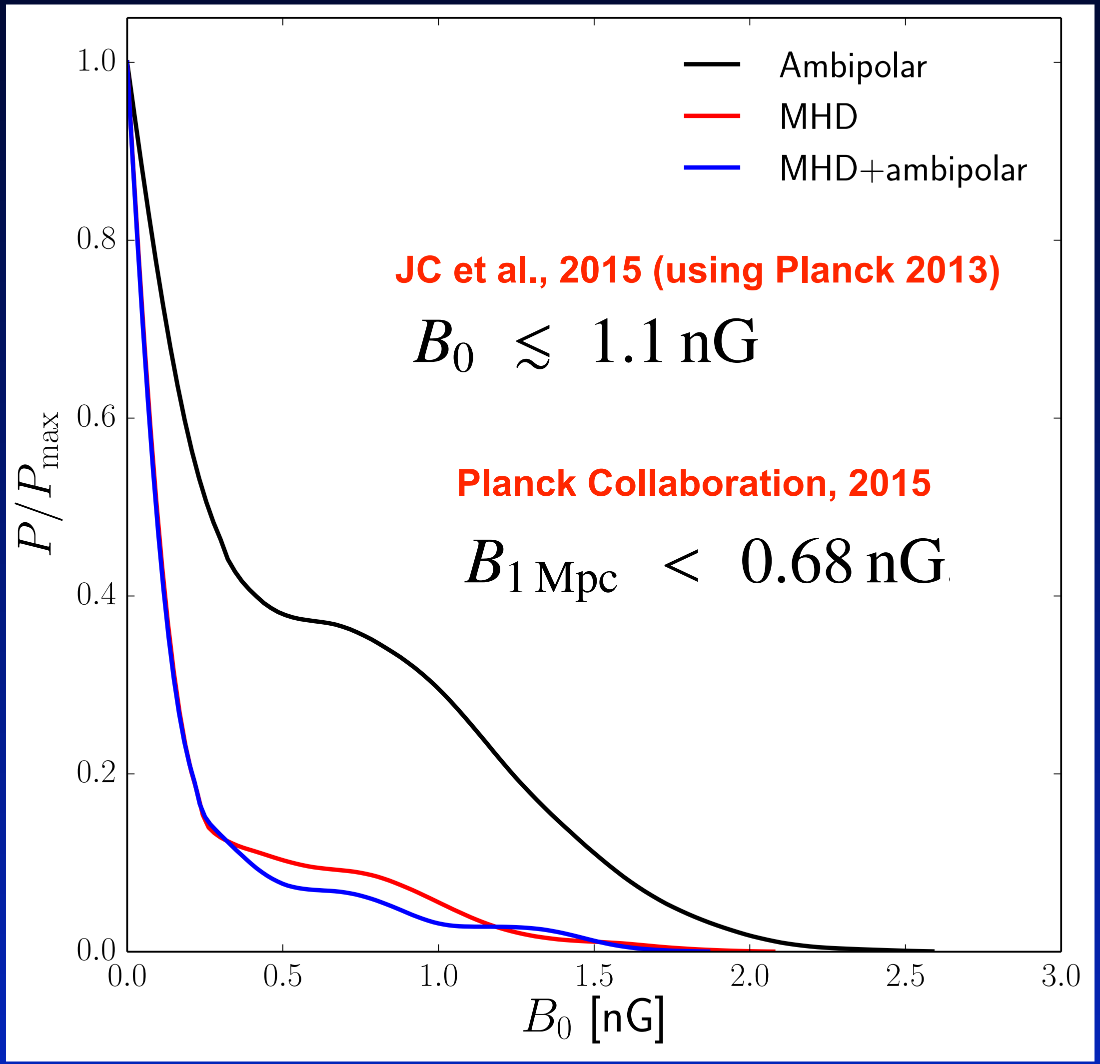
Recfast++ can do this now

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

Primordial magnetic fields

Changes to recombination from PMFs

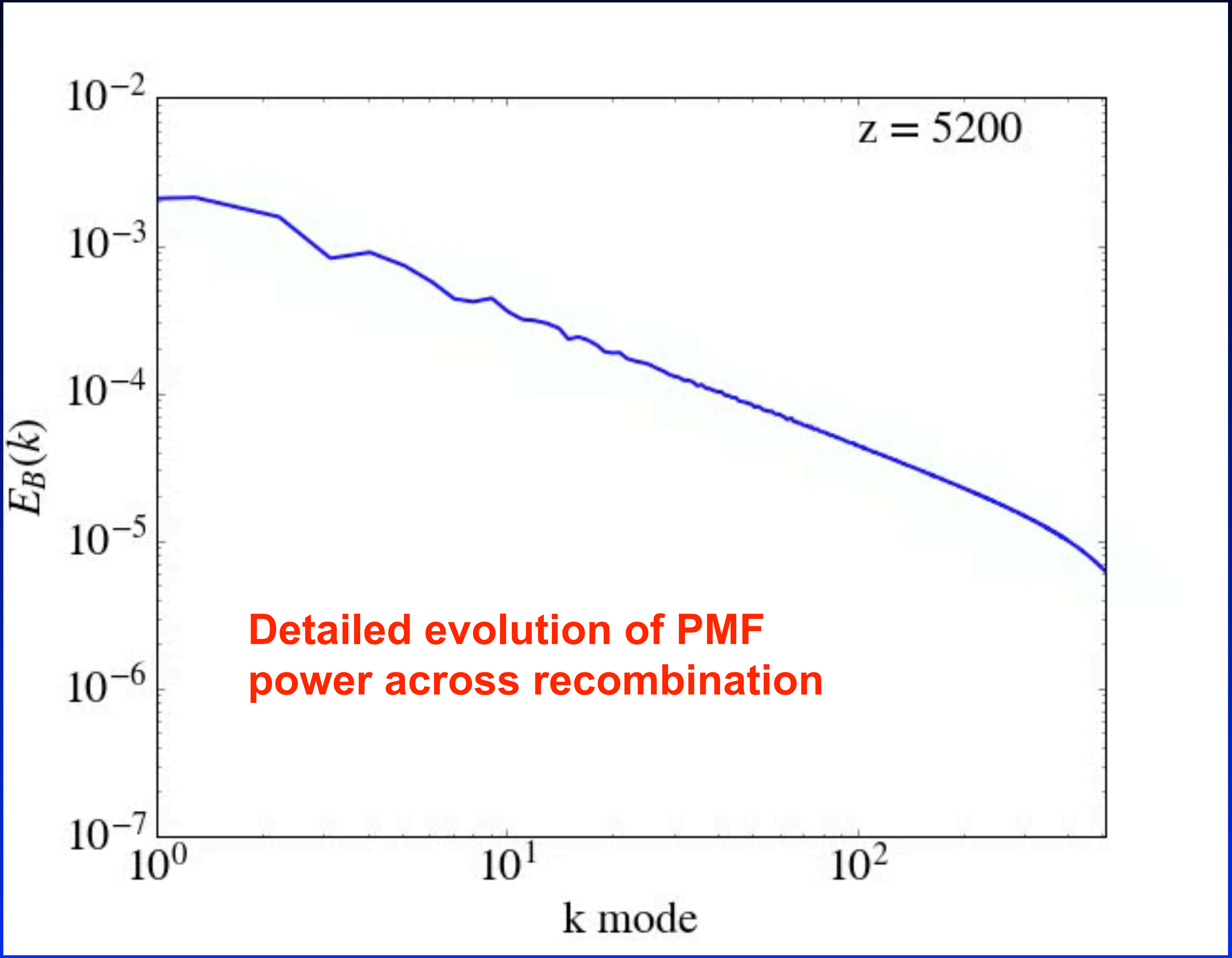




- One has to be careful how to compute the effect…
- Large uncertainties in the heating rates → *first improvements done*
- Constraints from this effect better than other CMB effects

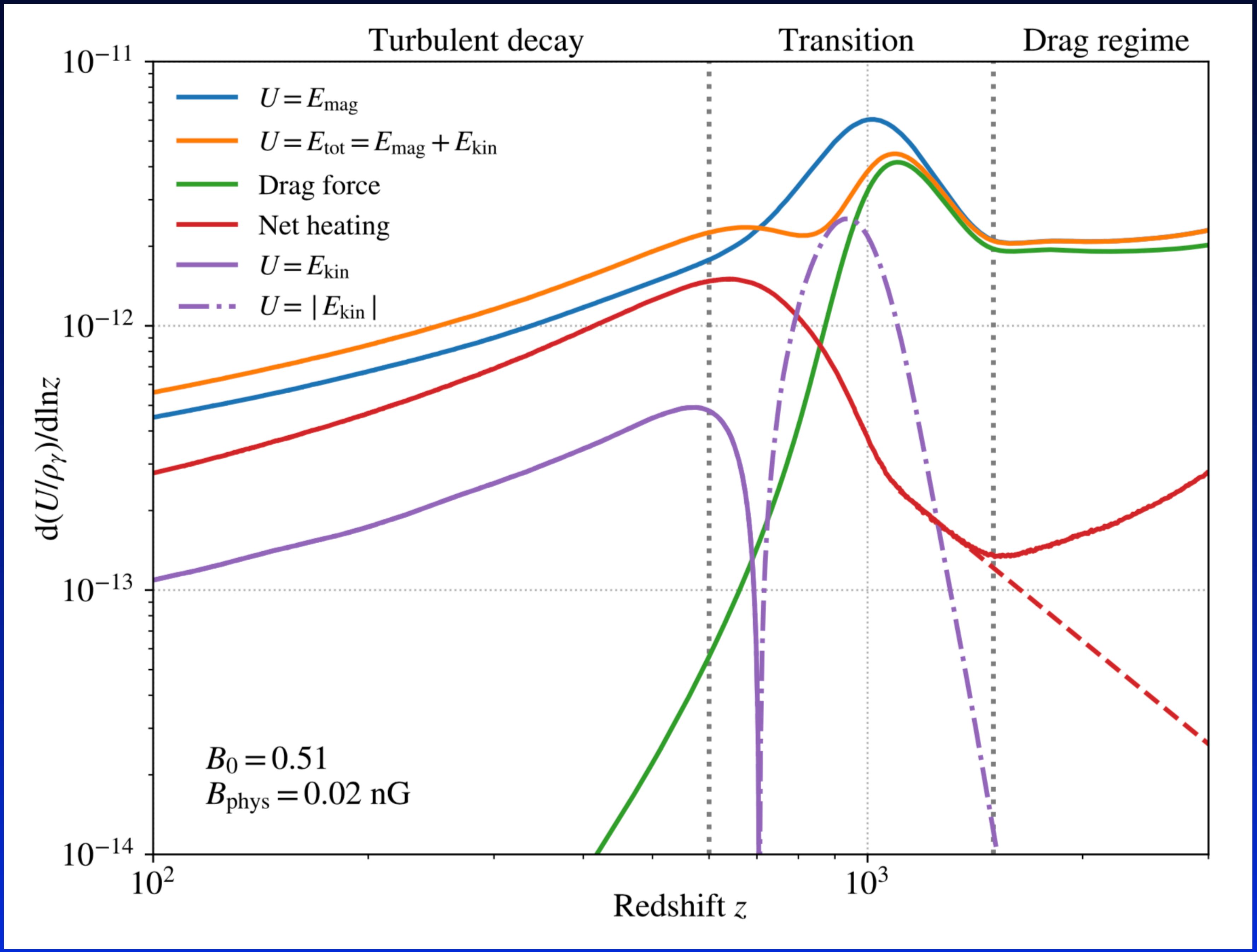
Sethi et al. 2005, Kunze et al, 2014/2015, JC et al. 2015

Improved estimates for PMF heating rates



Trivedi, JC, Reppin and Banerjee, 2018

Improved estimates for PMF heating rates



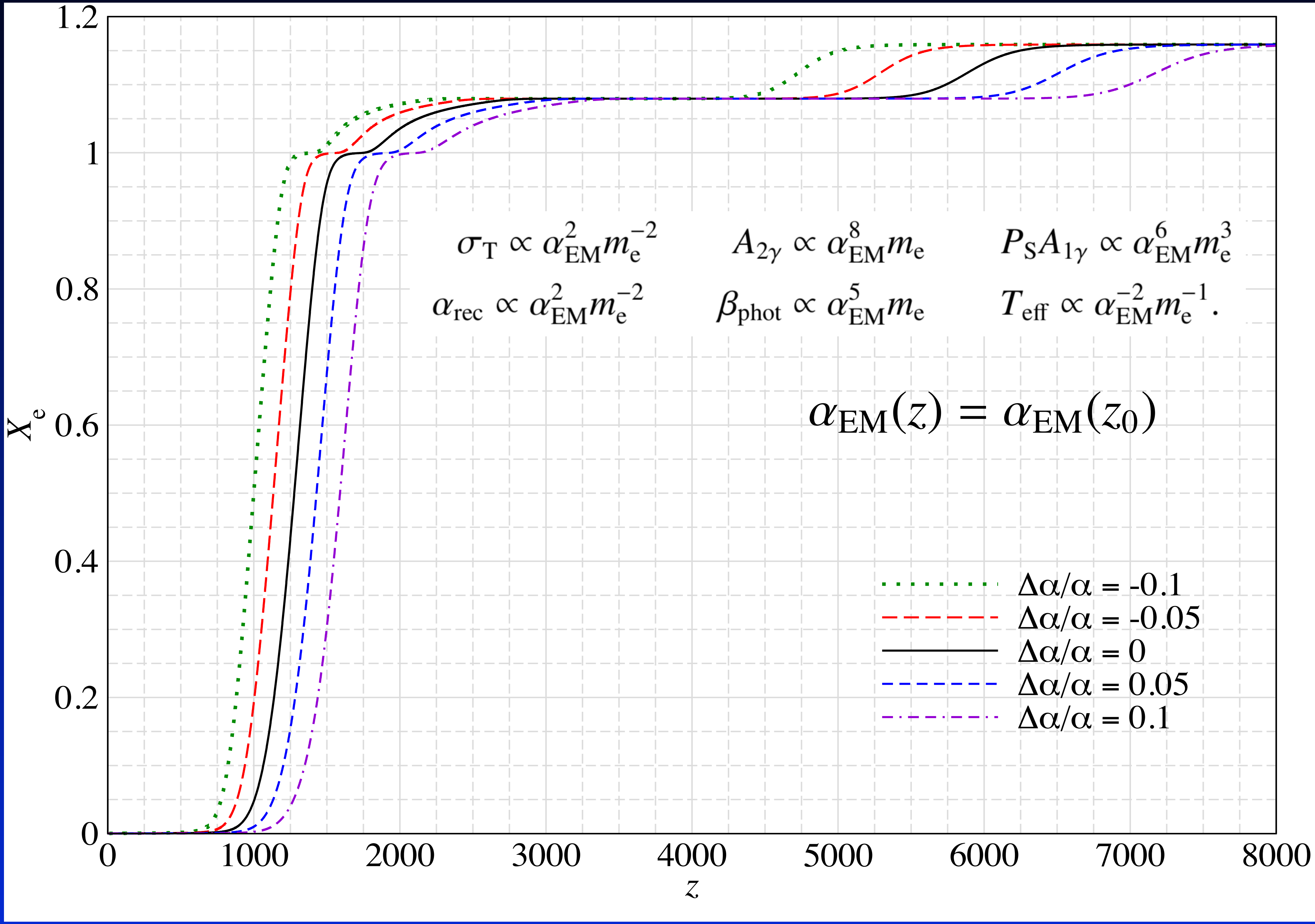
- Model the transition from pre- to post-recombination evolution
- Latent phase
- Heating rate scaling with PMF amplitude and spectral index
- Important improvement for CMB constraints

Trivedi, JC, Reppin and Banerjee, 2018

Constraints will be updated soon!

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)

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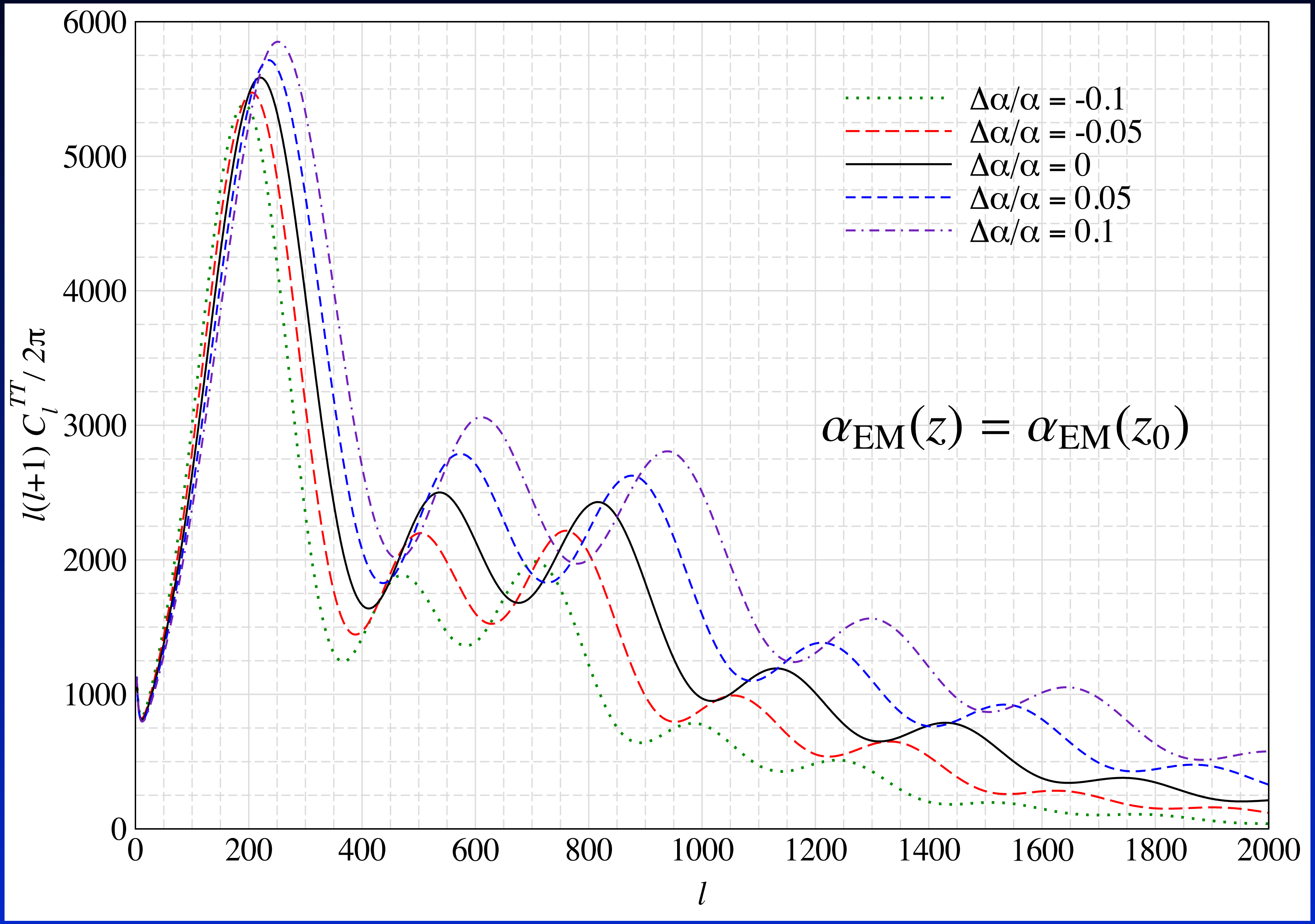

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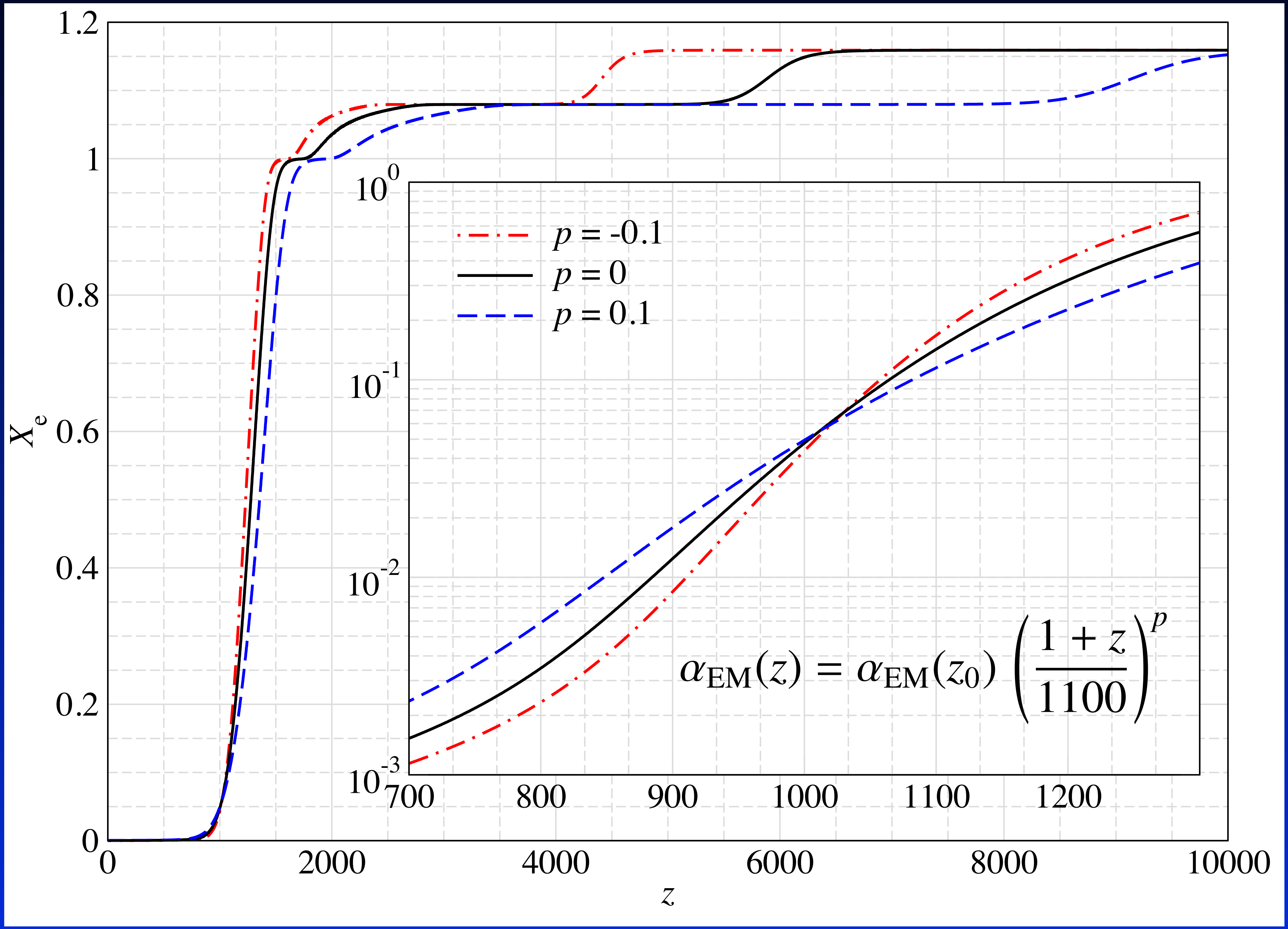


- Data also sensitive to explicit time-dependence around recombination (Luke Hart & JC, 2017)

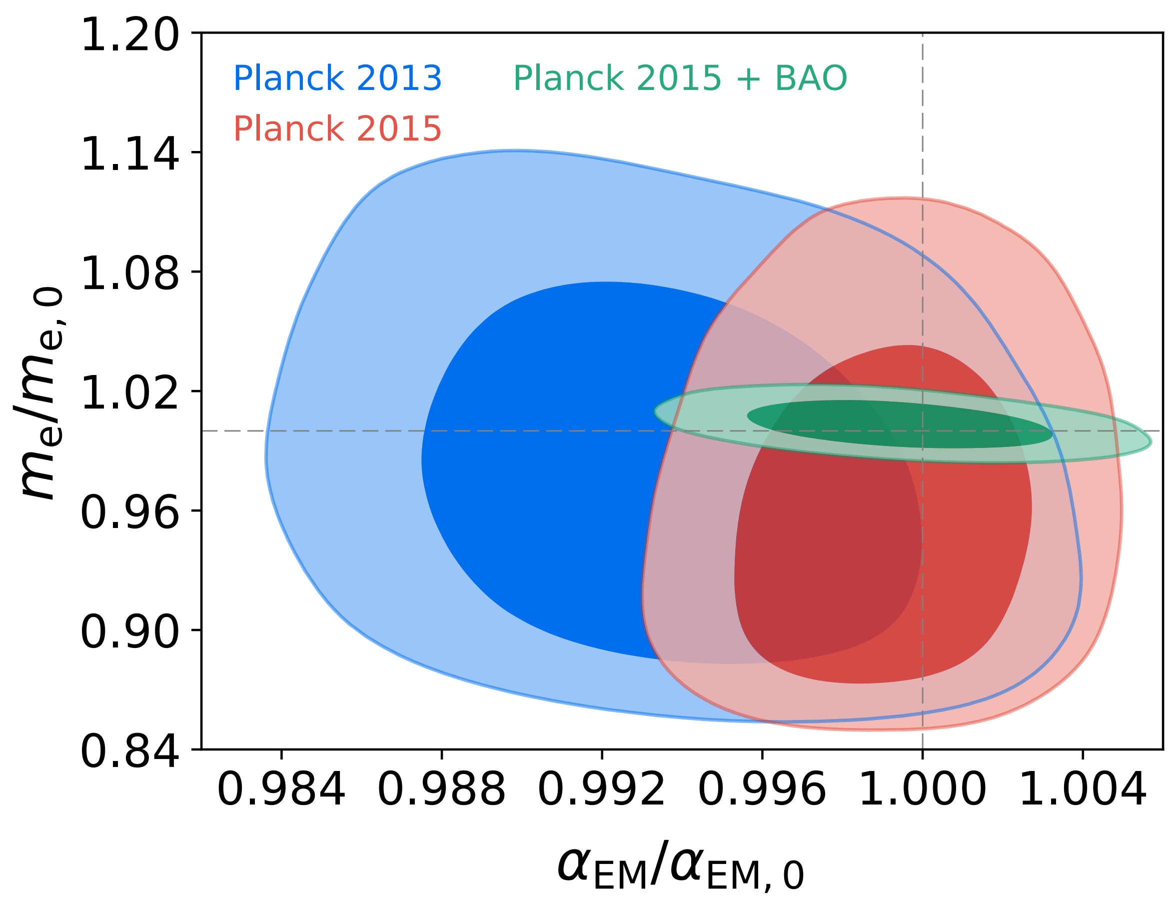
Current constraints using Planck 2015

Parameter	*Planck* 2015	+ varying $\alpha_{\rm EM}/\alpha_{\rm EM,0}$	+ varying p	+ varying $\alpha_{\rm EM}/\alpha_{\rm EM,0}$ 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
$100\theta_{\rm MC}$	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
$\alpha_{\rm EM}/\alpha_{\rm EM,0}$	–	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



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

Luke Hart & JC, 2017

Model-independent constraints

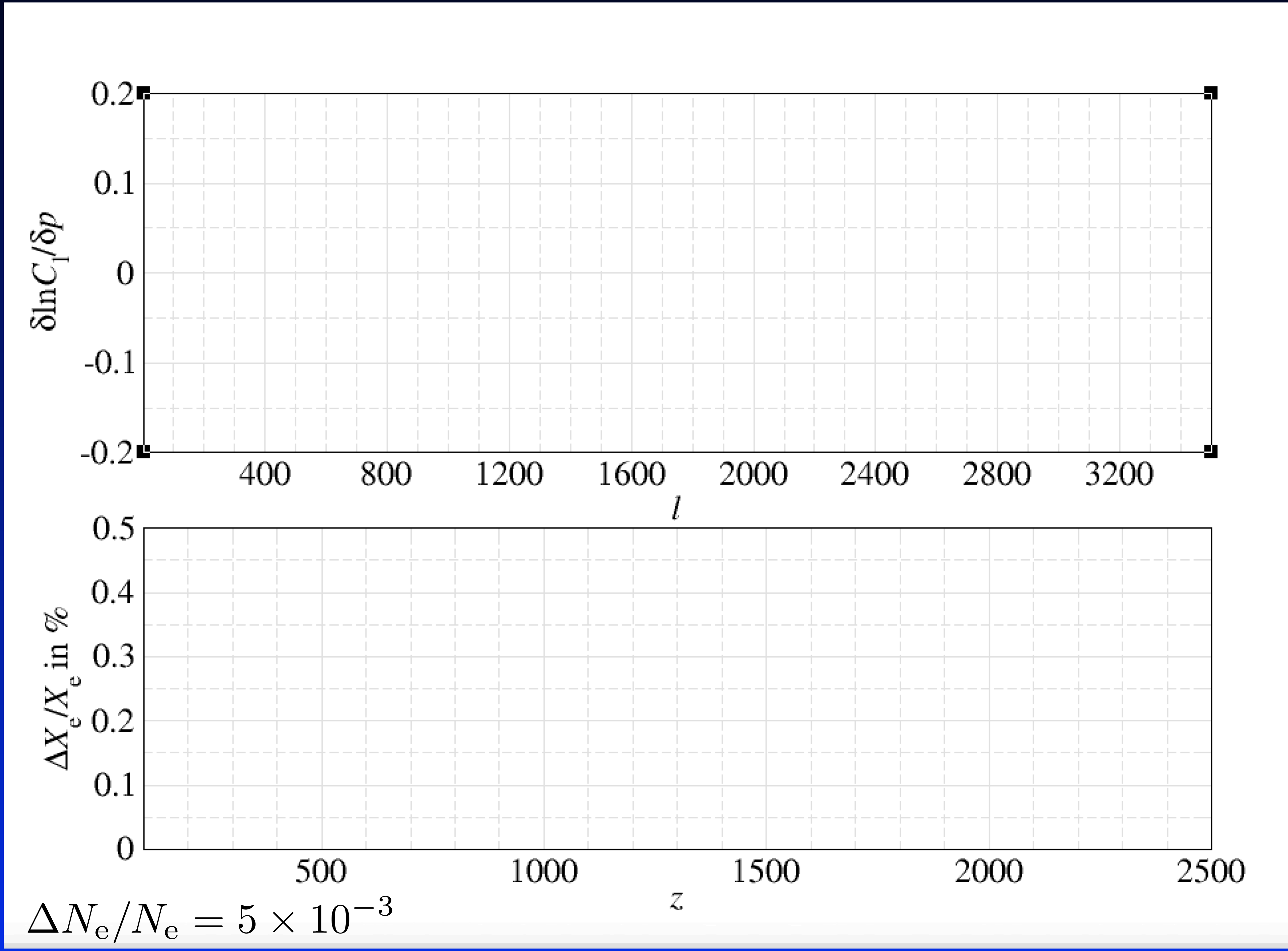
Principle component analysis for recombination

- **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)**

CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut canadien d'astrophysique théorique

Farhang, Bond & JC, 2012

Power spectrum response at different redshifts



Movie courtesy Luke Hart

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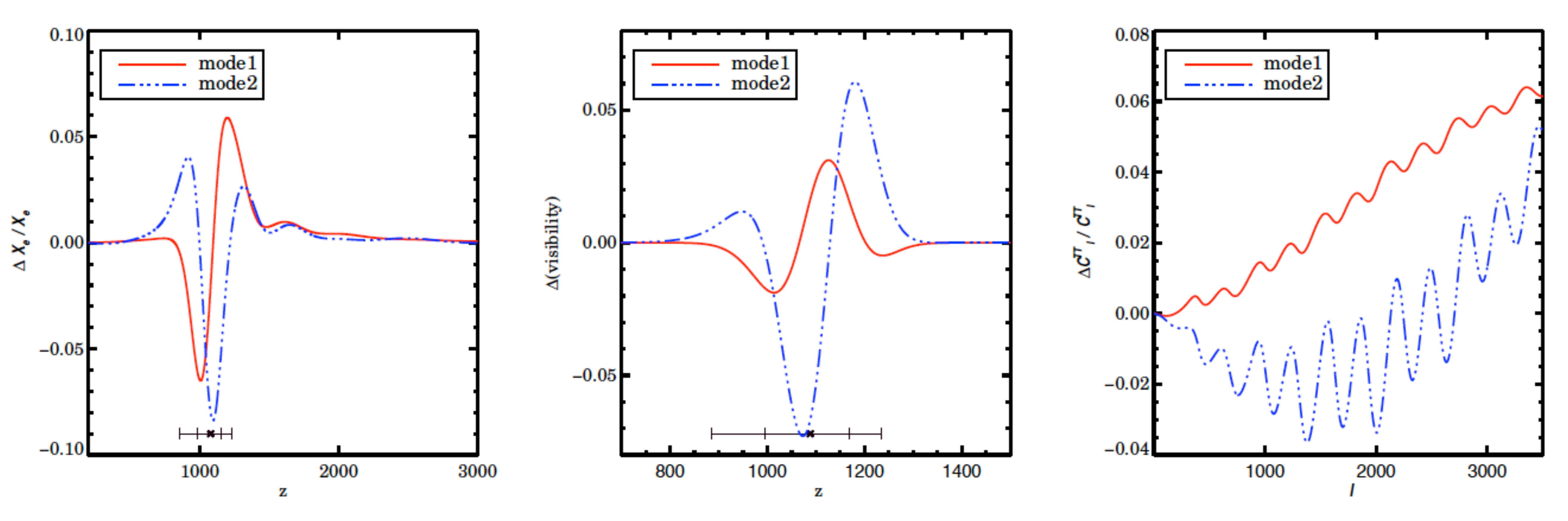
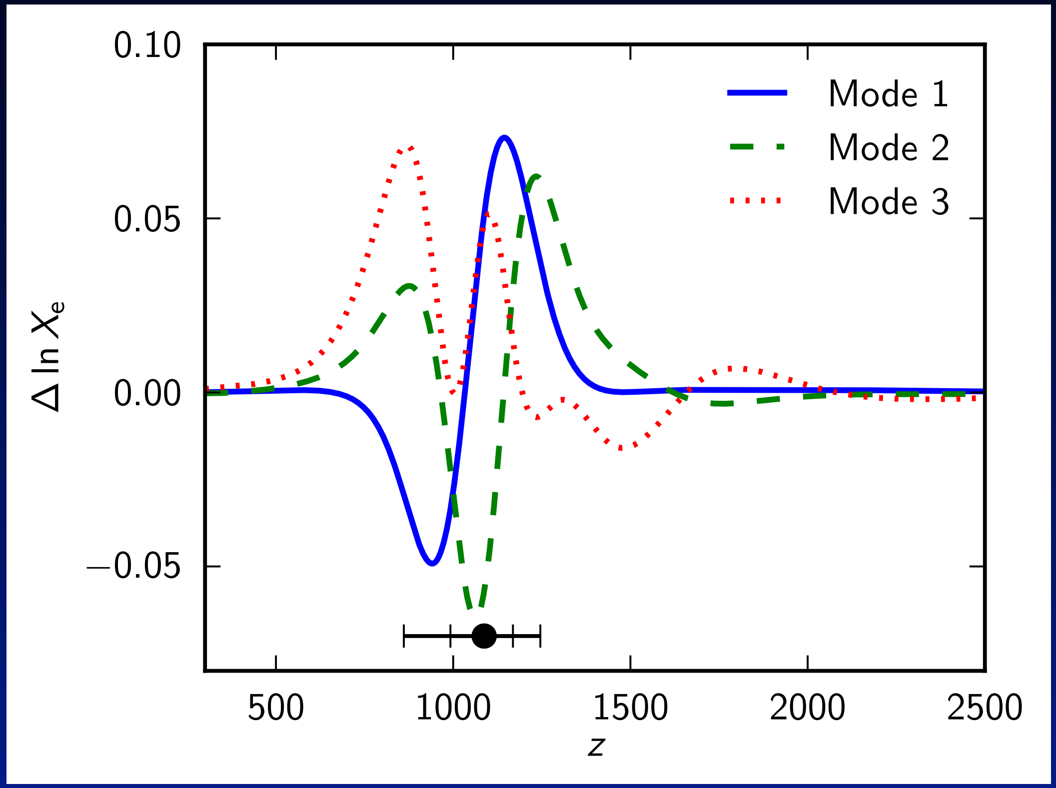
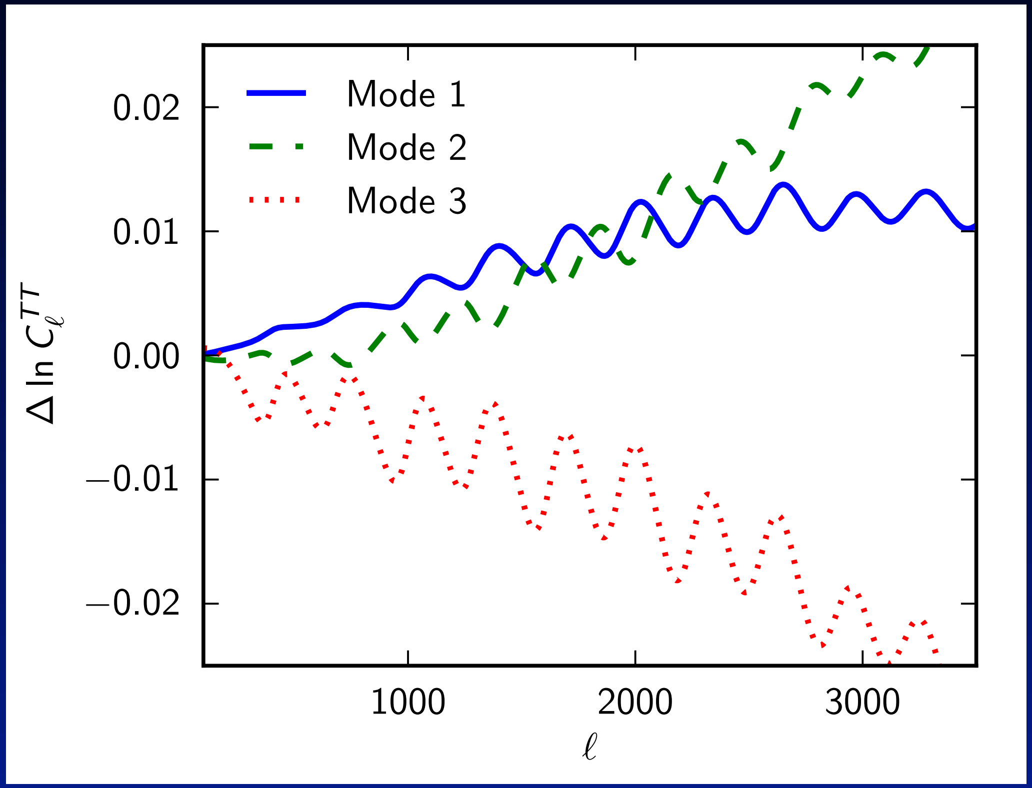


Farhang, Bond & JC, 2012

PCA analysis with Planck 2015



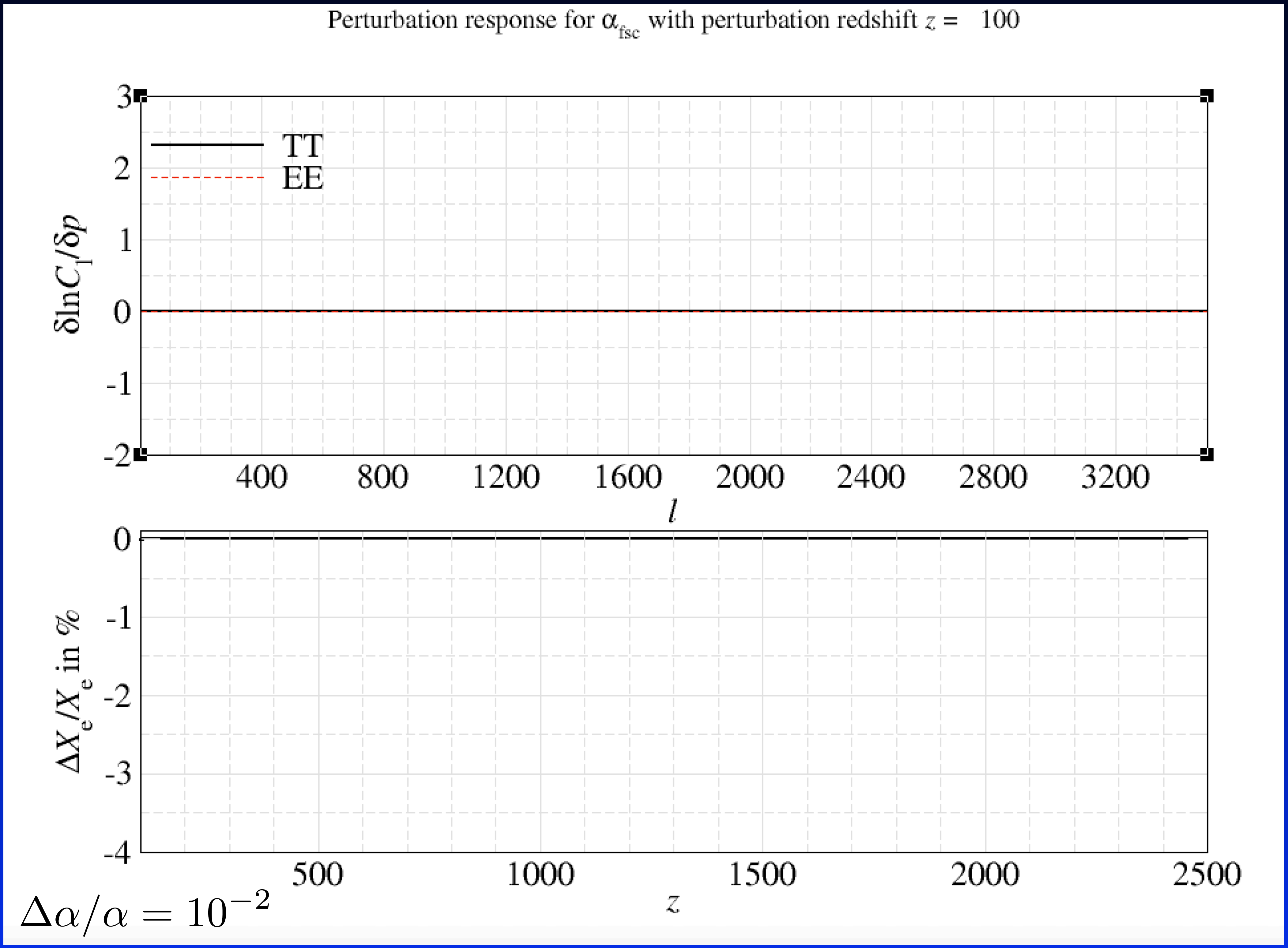


- Planck data is *consistent* with standard recombination
- Non-trivial statement, even if it is expected!
- Small improvement with Planck 2018 data (3rd mode)

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

Framework will be added to Recfast++ and CosmoRec

Overview of Recombination codes

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…)

Updates for **CosmoRec** & **Recfast++** also include effects of *primordial magnetic fields, variation of fundamental constants & decaying particles*

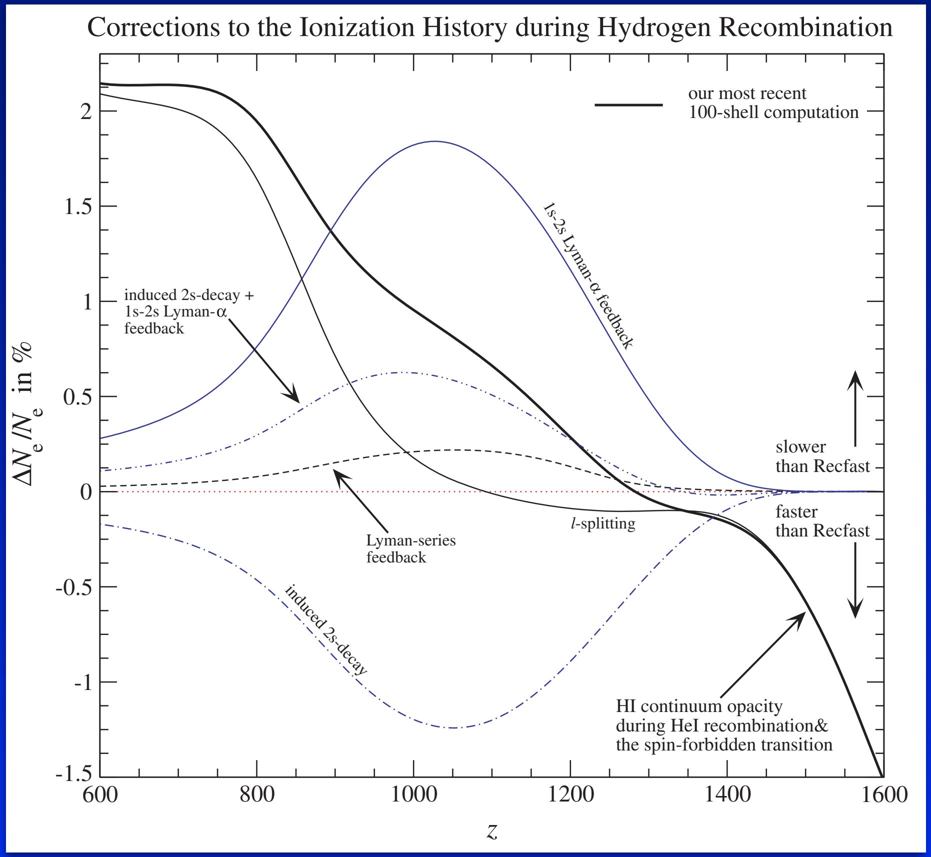
Other recombination codes / approaches

HyRec (Ali-Haimoud & Hirata, 2010)

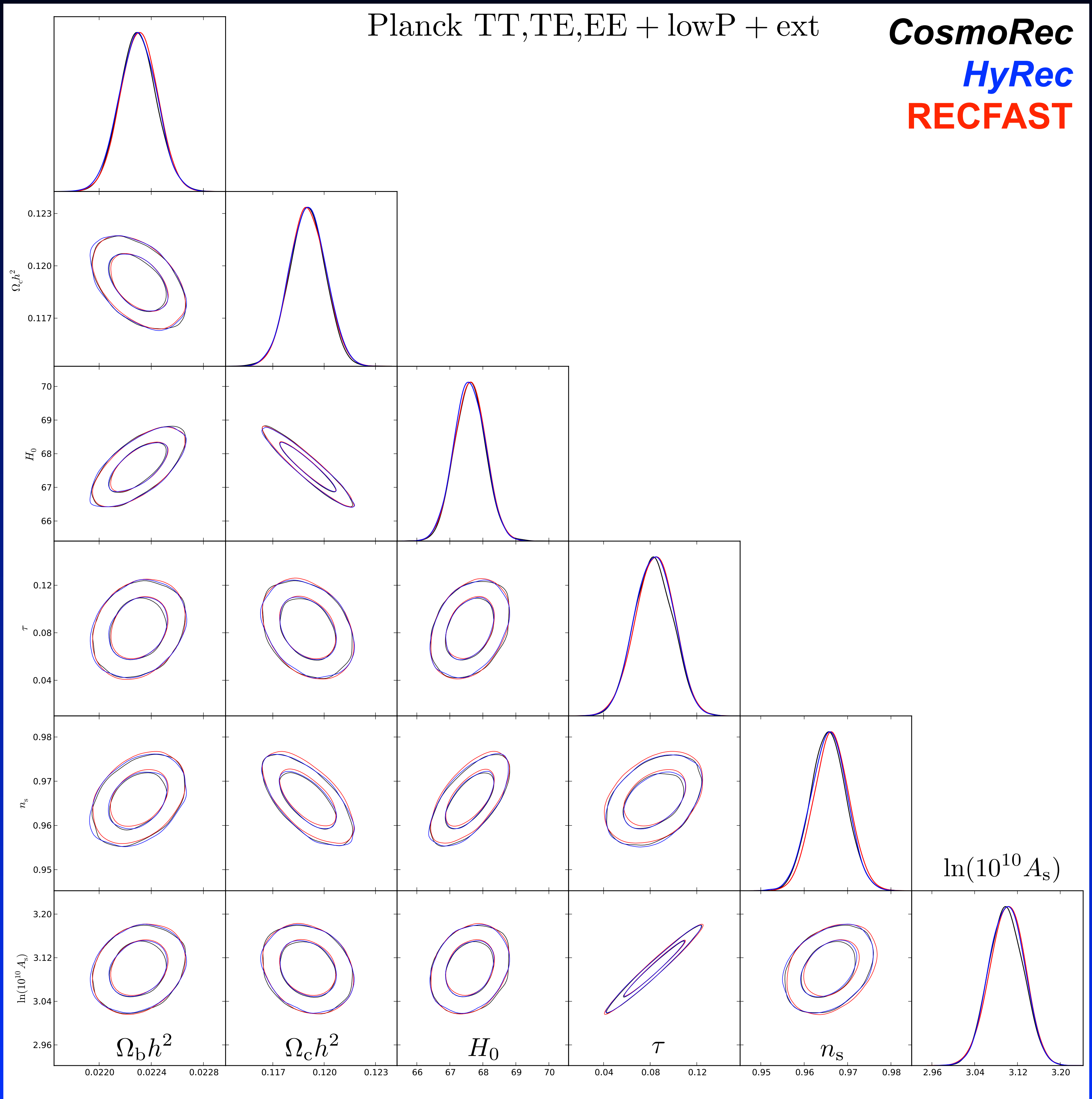
- Written in C
- Similar precision to **CosmoRec** **(but fewer features…)**
- Part of CAMB and CLASS
- Download **http://pages.jh.edu/~yalihai1/hyrec/hyrec.html**

RICO (Fendt, Chluba, Rubino-Martin and Wandelt, 2009)

- Interpolation scheme similar to **PICO**
- Done for older version of **CosmoRec**
- Allowed showing how large errors could be
- Download → *not really used anymore*



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

Recfast

Some `Recfast` facts

Fudging derivatives

$$\frac{\mathrm{d}N_\mathrm{e}}{\mathrm{d}t} \rightarrow f(z)\,\frac{\mathrm{d}N_\mathrm{e}}{\mathrm{d}t}$$

- Standalone Fortran and C versions
- C version not up to date (and buggy)
- *Many personal versions* in the community
- Part of CAMB and CLASS (still used by default… *Sigh*…)
- 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**

`Recfast` Equations

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

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

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

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)

From yesterday:

$$\frac{\mathrm{d}N_1}{\mathrm{d}t} \approx \frac{A_2}{A_2 + \beta_2} \left[N_{\mathrm{e}} N_{\mathrm{p}} \alpha_2 - N_1 \beta_2 \,\mathrm{e}^{-x_{21}} \right]$$

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`

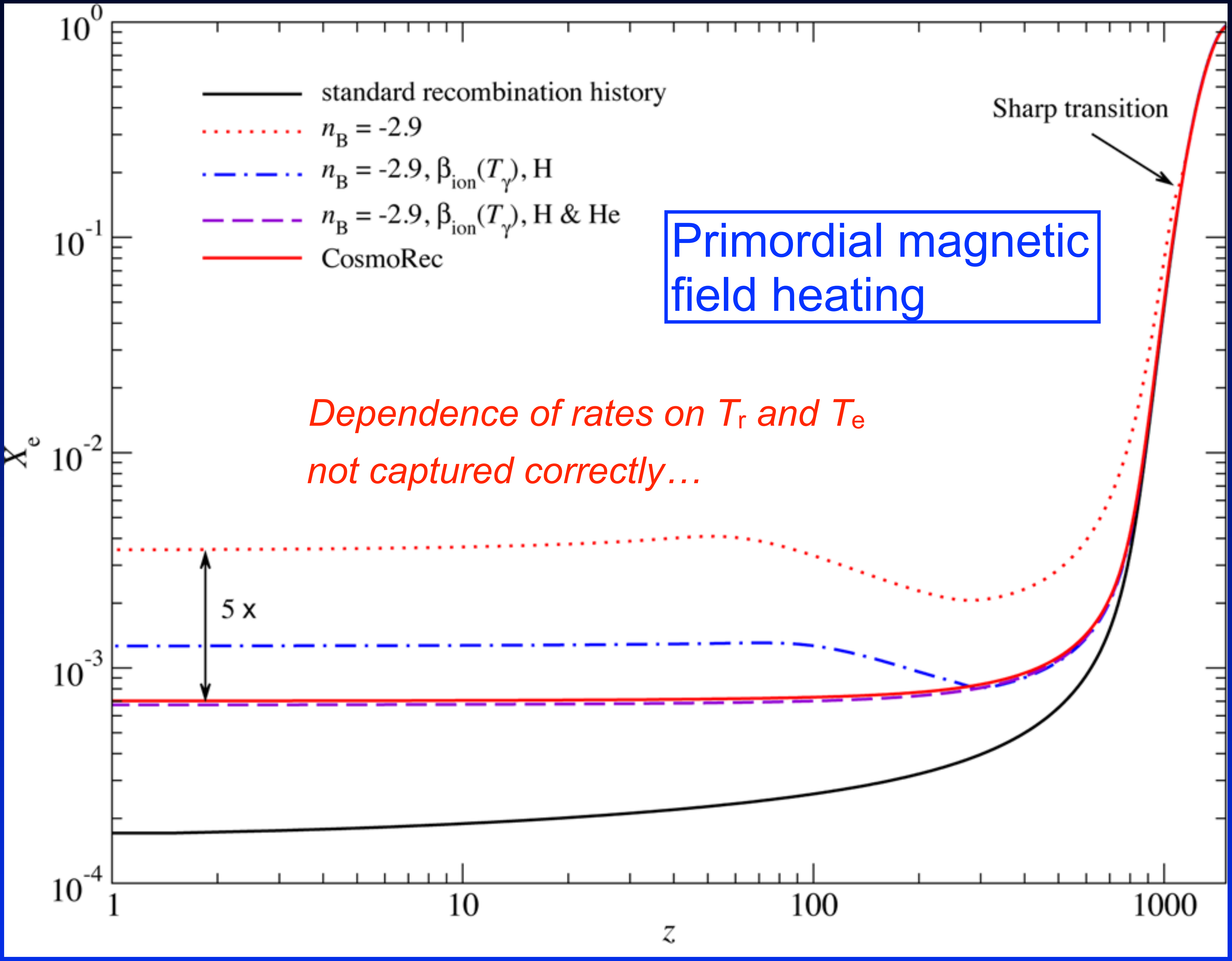
recfast.for

```
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` Equations

Should be photon temperature

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

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

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

Seager et al, 1999

- Old expressions from Peebles 1969
- second shell quasi-stationary
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From yesterday: $$\frac{\mathrm{d}N_1}{\mathrm{d}t} \approx \frac{A_2}{A_2+\beta_2}\left[N_{\rm e}N_{\rm p}\alpha_2 - N_1\beta_2\,{\rm e}^{-x_{21}}\right]$$

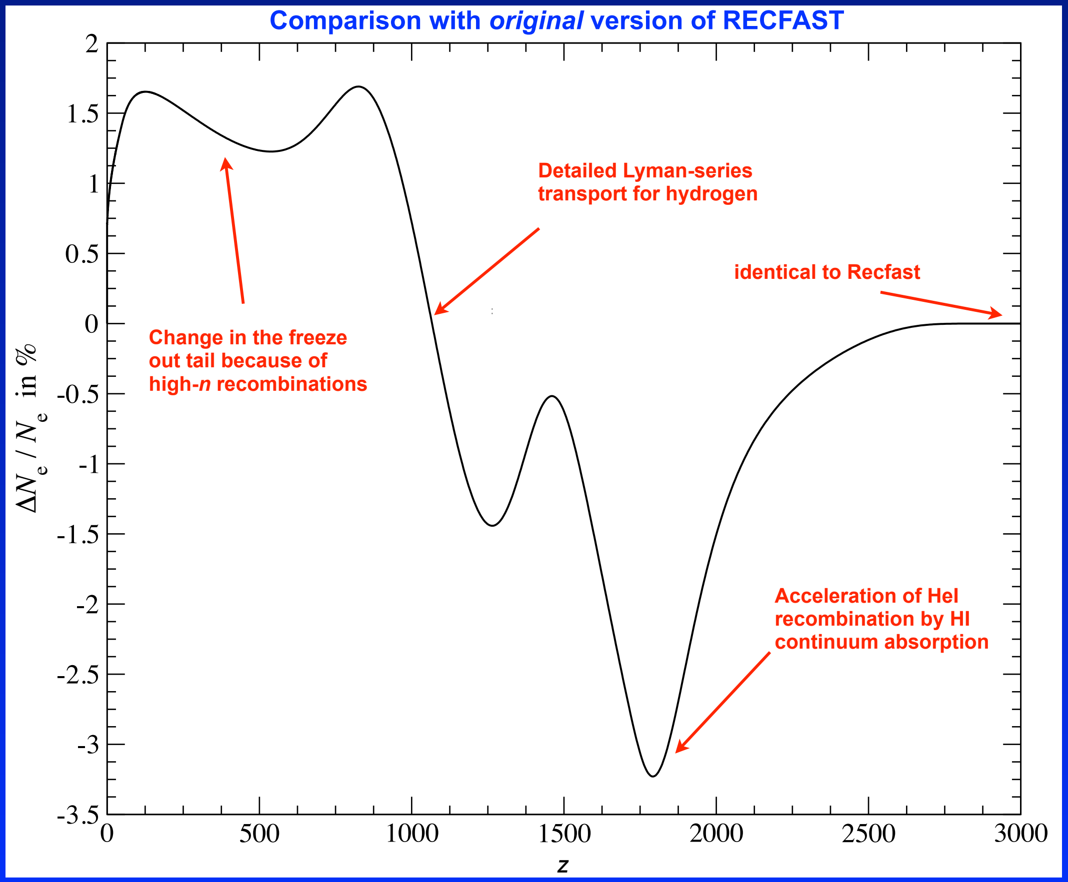
Recfast++

Some **Recfast++** facts

- Standalone C++ version of 3-level Atom
- Part of cosmology object in **CosmoRec** (activated by runmode)
- High flexibility with many 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



Running **Recfast++**

`./runfiles/parameters.ini`

```
#----------------------------------------------------------------------------------
#
# initial and final redshift for output
#
#----------------------------------------------------------------------------------

zstart = 2.5e+4     # starting redshift (zstart > 3500)
zend   = 0.0        # ending redshift   (zend >= 0)
npts   = 10000      # number of redshift points (linear grid used, npts > 10^3)


#----------------------------------------------------------------------------------
#
# cosmological parameters for Cosmos-object
#
#----------------------------------------------------------------------------------

T0    = 2.726       # Present CMB temperature in Kelvin
Yp    = 0.24        # Helium mass fraction
N_eff = 3.046       # Effective number of relativistic species

Omega_m = 0.26      # total matter density (Omega_cdm + Omega_b)
Omega_b = 0.044     # baryon density
Omega_L = 0.0       # (if <=0 it will be computed from the other variables)
Omega_k = 0.0       # curvature

h100 = 0.71         # reduced Hubble parameters H0 / 100


#----------------------------------------------------------------------------------
#
# recombination physics settings
#
#----------------------------------------------------------------------------------

Recfast fudge factor = 0         # mainly affects freeze-out tail
                                 # (F>=0, F==0 --> set to recfast default == 1.14)

include correction function = 1  # include Chluba & Thomas 2010 correction function
                                 # to mimic the full CosmoRec output

A2s1s = 0                        # A2s1s decay rate for hydrogen. If ==0 internal
                                 # default is used, which is A2s1s=8.22458 s^-1
```

- Added new parser
- Adding parameters becomes very simple
- Many non-standard cases already implemented and will be updated more soon

```
#--------------------------------------------------------------------------------------
# decaying particles
#--------------------------------------------------------------------------------------

f_dec     = 0      # fraction of dark matter that is decaying [ > 0 ]
Gamma_dec = 0      # decay rate in 1/sec

#--------------------------------------------------------------------------------------
# primordial magnetic fields    (Chluba et al., 2015, MNRAS, 451, 2244)
#--------------------------------------------------------------------------------------

B0                           =  0.0    # B0 is magnetic field amplitude in nG
                                       # if ==0 --> effects off
nB                           = -2.9    # nB == spectral index of PMF
                                       # (nB=-2.9 <--> scale-invariant case)

include turbulent decay      = 1       # one has to be !=0
include ambipolar diffusion  = 0       # one has to be !=0

#--------------------------------------------------------------------------------------
# variation of fundamental constants (Hart & Chluba, 2017, 474, 1850-1861)
#--------------------------------------------------------------------------------------

alp/alp_ref       = 1.0       # no rescaling for <=0; value ignored when mode==0
me/me_ref         = 1.0       # no rescaling for <=0; value ignored when mode==0
power for (1+z)^p = 0.0       # value ignored when mode==0

Variation mode    = 0         # 0 - no rescaling
                              # 1 - Rescaling of Boltzmann factor exponentials
                              #     (i.e., temperatures)
                              # 2 - Rescaling of Thomson scattering cross section
                              # 3 - Rescaling of 2s1s 2 photon rate
                              # 4 - Rescaling of alpha and beta co-efficients
                              # 5 - Rescaling of Ly-a channel
                              # 6 - Rescale everything
```

To execute simply type: > `./Recfast++ runfiles/parameters.ini`

Calling Recfast++ from 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)**

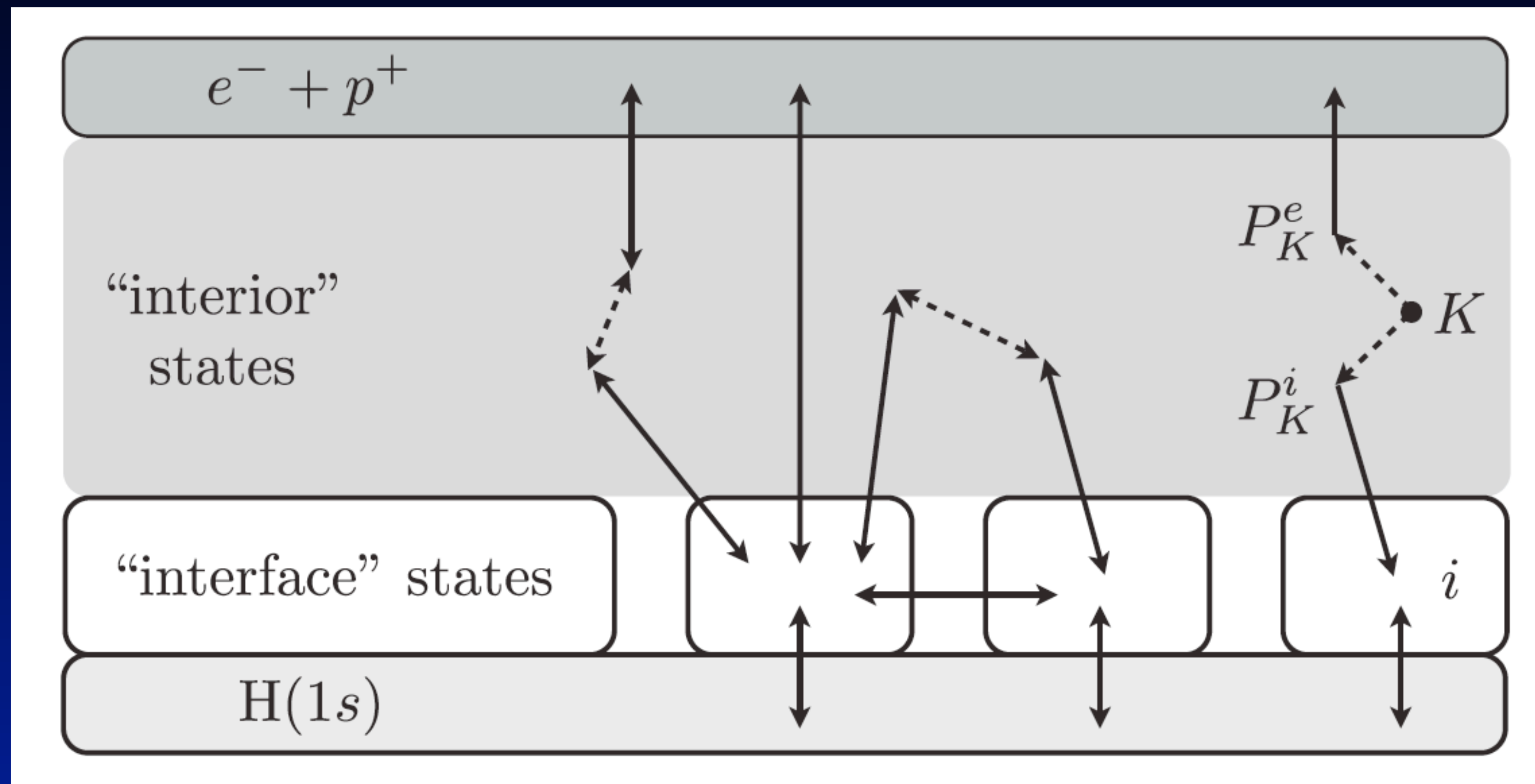
`./CosmoRec RECcf runfiles/parameters.dat` **(recfast + correction function)**

CosmoRec

New Cosmological Recombination Code: *CosmoRec*

- uses an effective multi-level approach **(Haimoud & Hirata, 2010)**
- very *accurate* and *fast* (for ‘default’ setting ~0.5 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`