Tutorial and Exercise Session

Installation

Recfast++

`> make` (unless you do not have `g++`)

CosmoRec

- Need GSL (GNU Scientific Library)
- Optionally add GRACE Lib (for movie generation)

Steps:

- Set path to GSL lib properly in `Makefile.in`
- Set path to GRACE and activate in `Makefile.in`

`> make`

```
#=============================================
# GSL lib
#=============================================
GSL          = gsl
#GSL_INC_PATH = /usr/local/include/
#GSL_LIB_PATH = /usr/local/lib/
GSL_INC_PATH = /opt/local/include/
GSL_LIB_PATH = /opt/local/lib/
LIBSGSL = -L$(GSL_LIB_PATH) -l$(GSL) -lgslcblas
```

```
#=============================================
# grace lib (for outputs with xmgrace from th
#=============================================
# If grace support should be used, uncomment
# and set them accordingly. This is not recom
#=============================================
#USE_GRACE    = -D GRACE_DEFINED
#GR           = grace_np
#GR_INC_PATH = /opt/local/include/
#GR_LIB_PATH = /opt/local/lib/
#LIBSGR   = -L$(GR_LIB_PATH)  -l$(GR)
```

Some useful commands

Making and cleaning

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

Execute CosmoRec like

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

Execute Recfast++ like using CosmoRec

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

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

Execute Recfast++ itself

`./Recfact++ runfiles/parameters.ini` **(with detailed settings explained)**

Exercise 0: Checking **Recfast++** out

```
#--------------------------------------------------------------------------------------
#
# 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
```

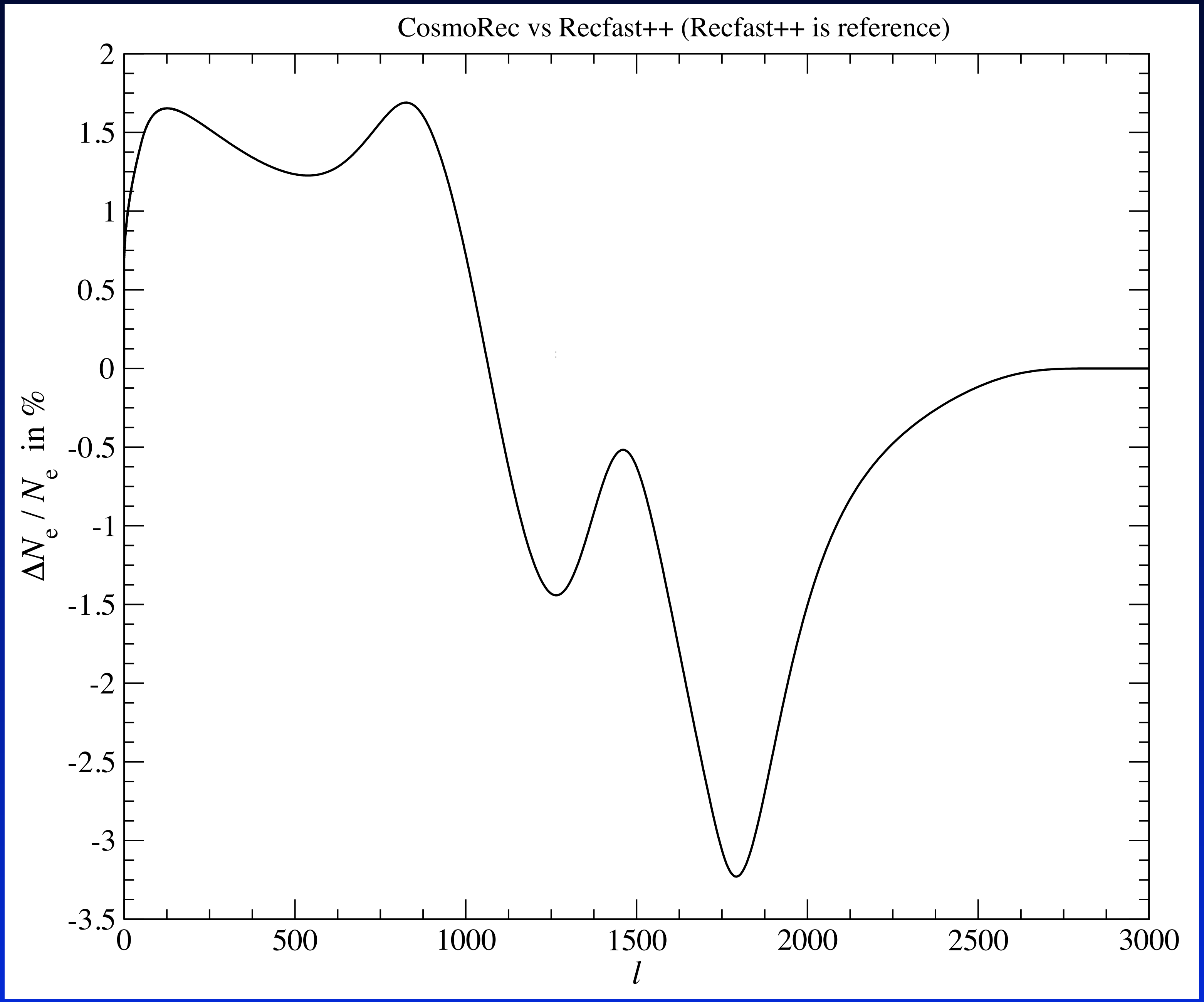
```
#--------------------------------------------------------------------------------------
# annihilating particles        (Chluba, 2010, MNRAS, 402, 1195-1207)
#--------------------------------------------------------------------------------------

f_ann = 0.0e-24       # in eV s^-1. Should be >=0.
                      # values < 1.0e-25 - 1.0e-24 is compatible with Planck 2015.
```

Decaying particles should be good fun…

```
#--------------------------------------------------------------------------------------
# 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


#--------------------------------------------------------------------------------------
```

- Have a look at the Recfast++ parameter file and play around a bit plotting cases (yes I am sure you can break Recfast++ ….)

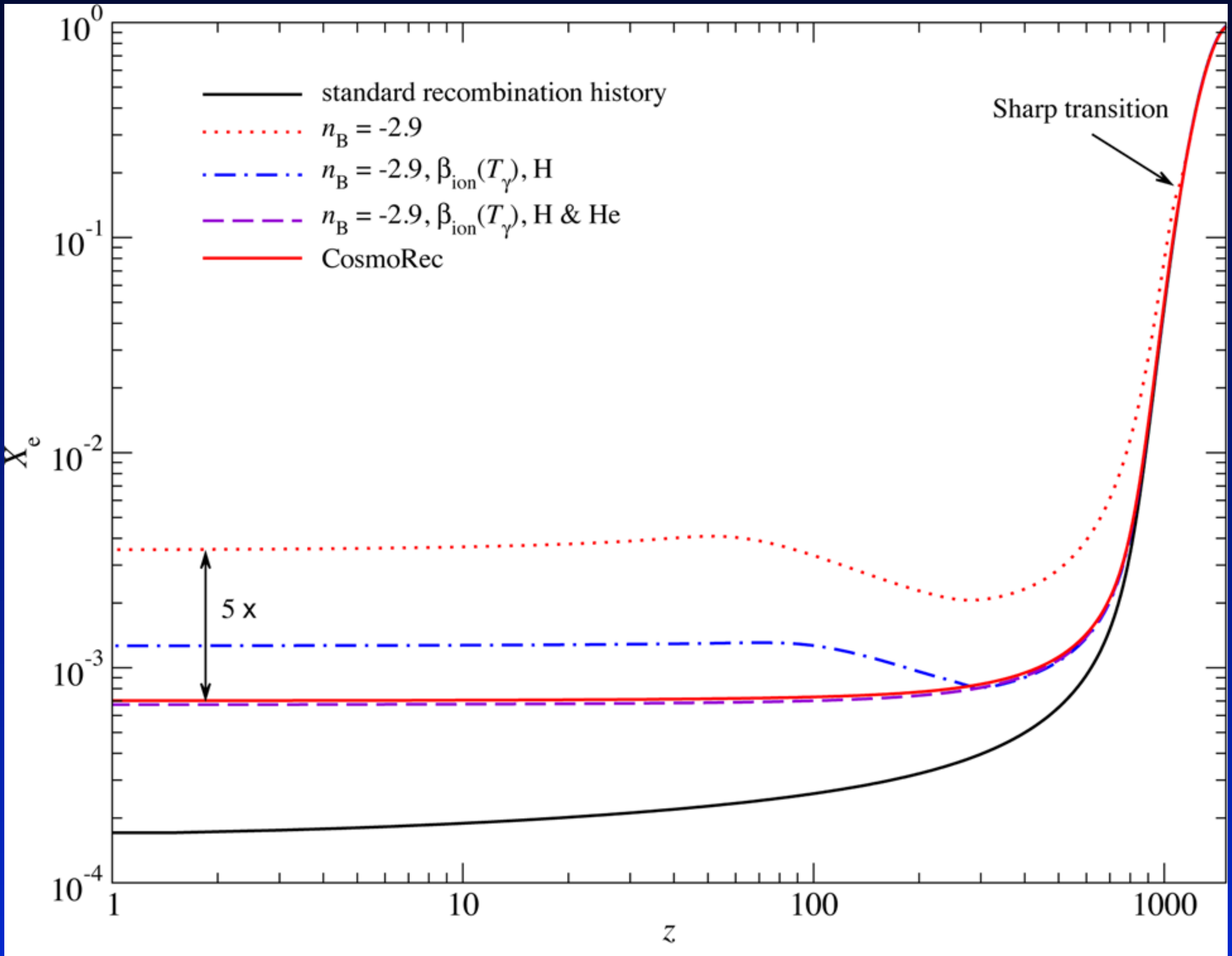
Exercise 1: Correction relative to `Recfast`



- Run Recfast++ in the original Recfast mode and with the correction function option
- Plot the free electron fraction as a function of redshift
- Can you explain why changes are so visible for helium but for HI you need a microscope?
- Compute the correction function with respect to Recfast (original version) [should look like figure to the left]

JC & Thomas, MNRAS, 2010;

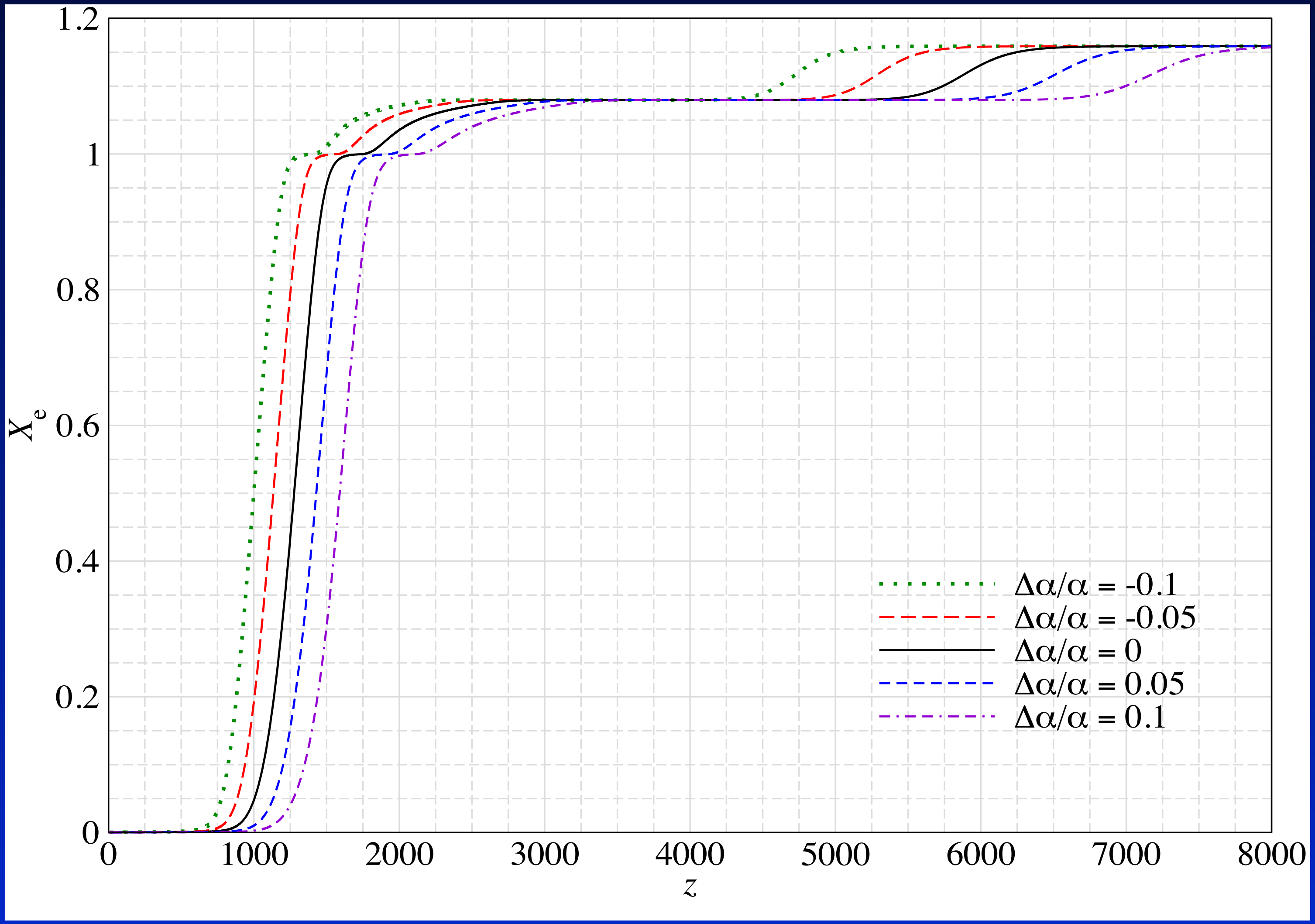
Exercise 2: PMF heating effects



- Switch on turbulent decay only and compute the result for B_0 = 3 nG and n_B = -2.9
- Compare X_e to the standard case
- Add ambipolar diffusion. Where is it most relevant?
- Can you switch T=Te and see what changes? [hint: either hack the ODE setup by hand or look at the setup in main_Recfast++.cpp]
- Prepare a plot of $T_e(z)$ for the considered cases. Are you surprised?
- Switch off collisional processes in evalode.Recfast++.cpp What happens to X_e and T_e?

JC et al., 2015, arXiv:1503.04827

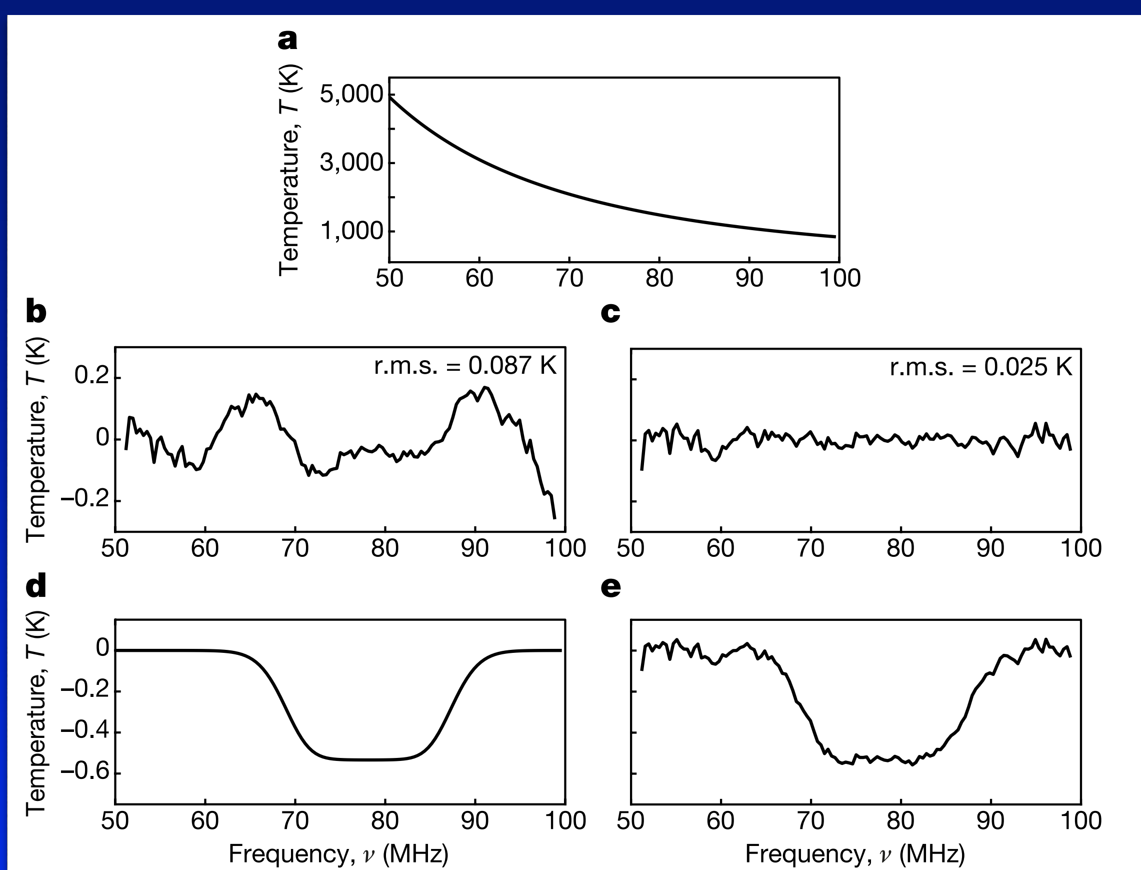
Exercise 3: Variation of fundamental constants



- Consider a variation $\Delta\alpha/\alpha \sim 5\%$ and switch on / off the different physical effects. What has the largest impact? Do you understand why?
- Prepare a figure like to the left but for m_e variation. What is different from the α-case? Ideas why?
- Also add time-dependent m_e using the implemented power-law option. Compare to a variation in α. Is this expected? [hint: make sure not to do the power-law scaling for α and m_e simultaneously…]

Luke Hart & JC, ArXiv:1705.03925

Exercise 4: EDGES result and recombination



Bowman et al., Nature, 2018

- Change the electron temperature equation to increase the Compton cooling term. This can be done by increasing the number of particles that couple to electrons. How much do you have to change to reduce the matter temperature at z~17 by a factor of 2?
- Physically, another way to achieve this is to decrease X_e at low redshifts. Play with the standard fudge factor to do this. How much do you have to modify things? Is this still ok with the CMB?

$$T_{21}(z) \approx 0.023\ \mathrm{K} \times x_{\mathrm{HI}}(z)\left[\left(\frac{0.15}{\Omega_{\mathrm{m}}}\right)\left(\frac{1+z}{10}\right)\right]^{\frac{1}{2}}\left(\frac{\Omega_{\mathrm{b}}h}{0.02}\right)\left[1-\frac{T_{\mathrm{R}}(z)}{T_{\mathrm{S}}(z)}\right]$$

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