Introduction to CAMB

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Outline

- Compile/run CAMB (Reqs: make, gfortran)
- The various files (.f90, .ini etc)
- The equations (in synchronous gauge)
- Effects of the parameters
- Various tests (change Omega_m, n_s etc) and plots

Download CAMB

1) Get CAMB from :
www.camb.info/CAMB.tar.gz
https://github.com/cmbant/CAMB

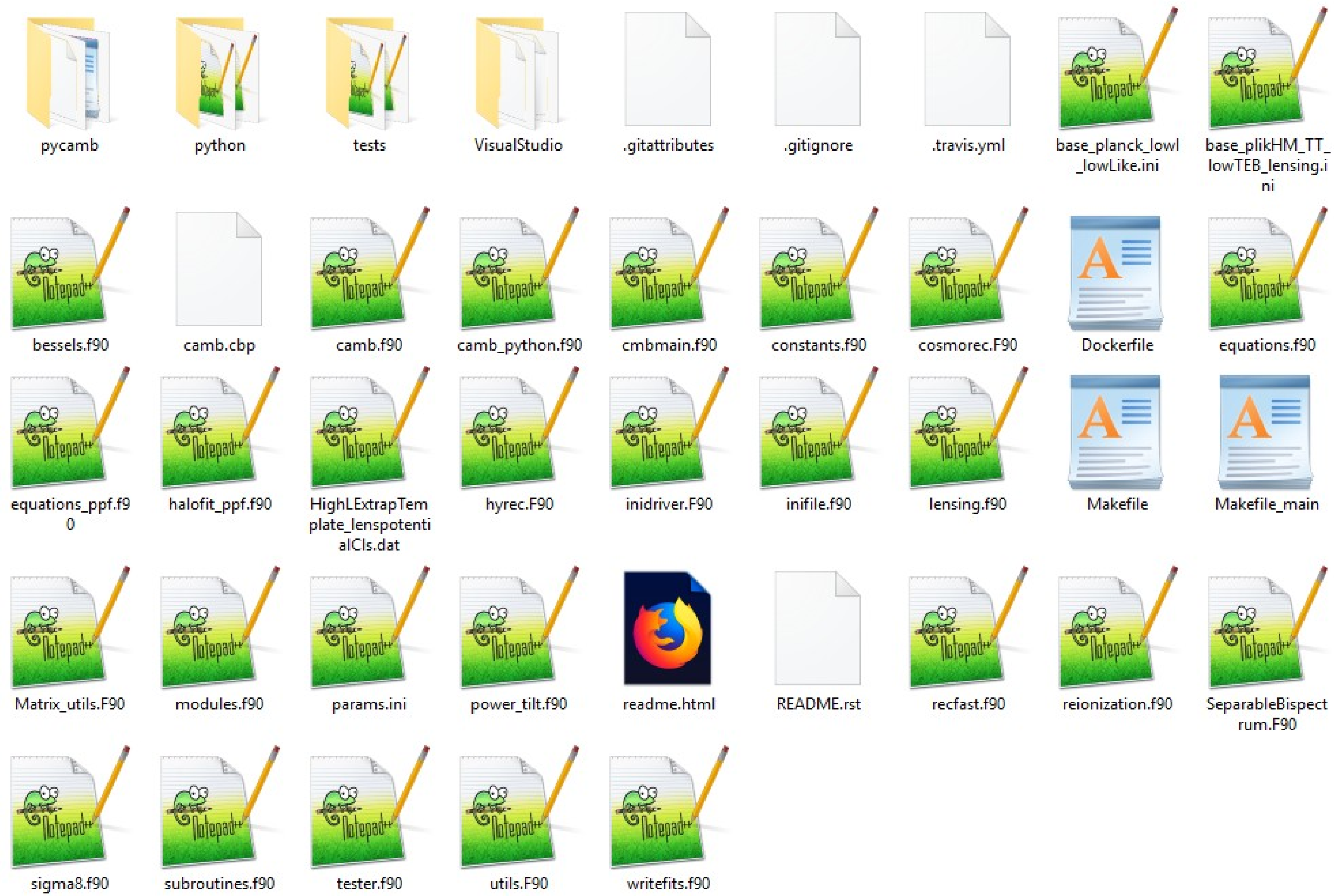
2) Unzip with a tool (WinZip, 7 Zip etc) or on Macs, Linux:
tar xfv CAMB.tar.gz

3) Navigate to the camb directory and have a look at the files

i) cd CAMB

ii) on Windows just navigate to the folder

Download CAMB



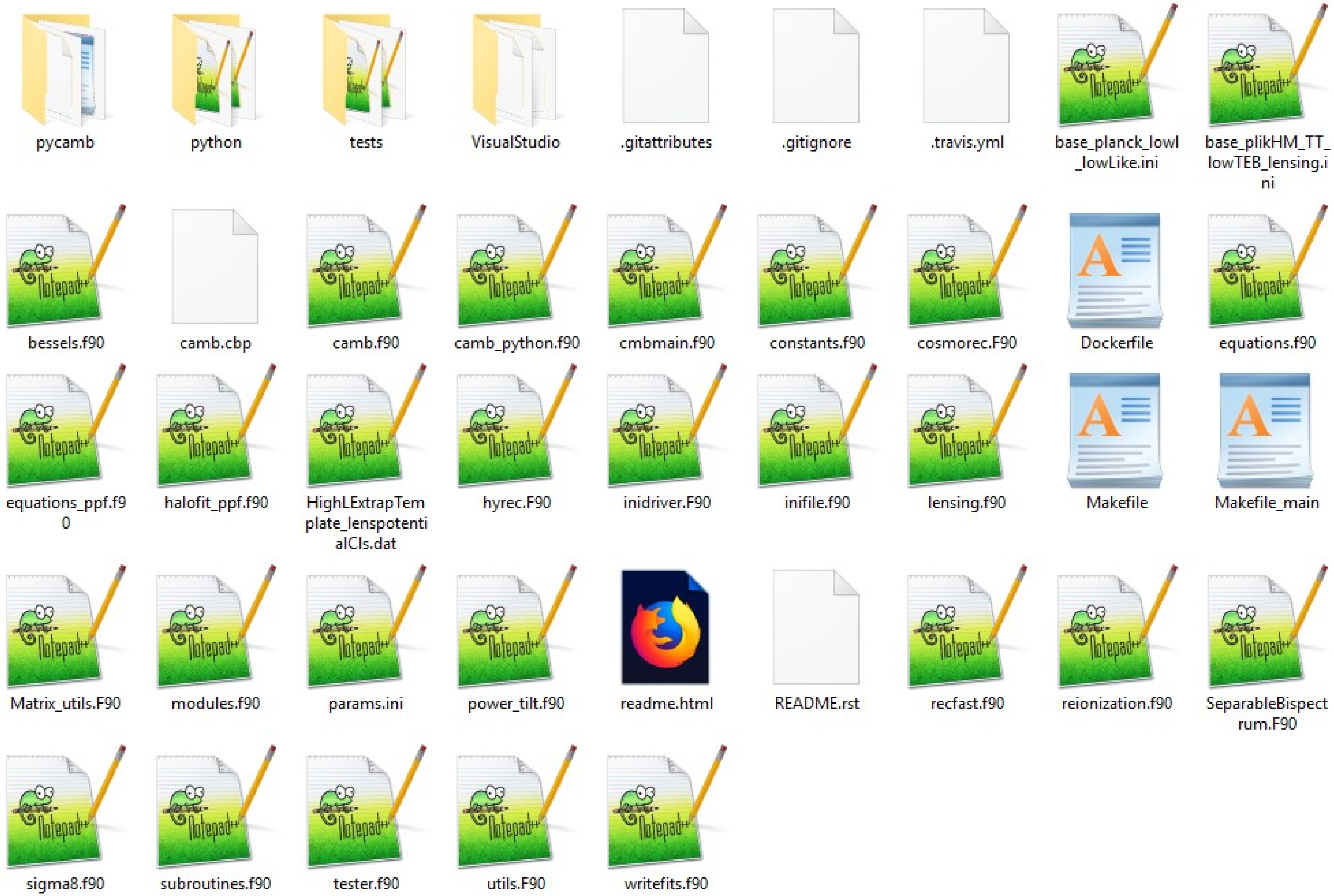
F90: Files with equations

params.ini: File with cosmological parameters

Readme.html: A file you **SHOULD read!!! DISCUSS**

.m, /python, /VisualStudio, .git*: Crap we don't care about

Download CAMB



Makefile: File the contains compiler options

Makefile_main: Other compilation options

Compile CAMB

Run: make

```
/cygdrive/c/Users/ragnar/Desktop/CAMB-master
ragnar@DESKTOP-OLS6DQK /cygdrive/c/Users/ragnar/Desktop/CAMB-master
$ make
gfortran -O3 -fopenmp -ffast-math -fmax-errors=4 -march=native -JRelease -IRelea
se/ -c constants.f90 -o Release/constants.o
gfortran -O3 -fopenmp -ffast-math -fmax-errors=4 -march=native -JRelease -IRelea
se/ -c utils.F90 -o Release/utils.o
gfortran -O3 -fopenmp -ffast-math -fmax-errors=4 -march=native -JRelease -IRelea
se/ -c subroutines.f90 -o Release/subroutines.o
gfortran -O3 -fopenmp -ffast-math -fmax-errors=4 -march=native -JRelease -IRelea
se/ -c inifile.f90 -o Release/inifile.o
gfortran -O3 -fopenmp -ffast-math -fmax-errors=4 -march=native -JRelease -IRelea
se/ -c power_tilt.f90 -o Release/power_tilt.o
gfortran -O3 -fopenmp -ffast-math -fmax-errors=4 -march=native -JRelease -IRelea
se/ -c recfast.f90 -o Release/recfast.o
gfortran -O3 -fopenmp -ffast-math -fmax-errors=4 -march=native -JRelease -IRelea
se/ -c reionization.f90 -o Release/reionization.o
gfortran -O3 -fopenmp -ffast-math -fmax-errors=4 -march=native -JRelease -IRelea
se/ -c modules.f90 -o Release/modules.o
gfortran -O3 -fopenmp -ffast-math -fmax-errors=4 -march=native -JRelease -IRelea
se/ -c bessels.f90 -o Release/bessels.o
gfortran -O3 -fopenmp -ffast-math -fmax-errors=4 -march=native -JRelease -IRelea
se/ -c equations.f90 -o Release/equations.o
gfortran -O3 -fopenmp -ffast-math -fmax-errors=4 -march=native -JRelease -IRelea
se/ -c halofit_ppf.f90 -o Release/halofit_ppf.o
gfortran -O3 -fopenmp -ffast-math -fmax-errors=4 -march=native -JRelease -IRelea
se/ -c lensing.f90 -o Release/lensing.o
gfortran -O3 -fopenmp -ffast-math -fmax-errors=4 -march=native -JRelease -IRelea
se/ -c SeparableBispectrum.F90 -o Release/SeparableBispectrum.o
gfortran -O3 -fopenmp -ffast-math -fmax-errors=4 -march=native -JRelease -IRelea
se/ -c cmbmain.f90 -o Release/cmbmain.o
gfortran -O3 -fopenmp -ffast-math -fmax-errors=4 -march=native -JRelease -IRelea
se/ -c camb.f90 -o Release/camb.o
gfortran -O3 -fopenmp -ffast-math -fmax-errors=4 -march=native -JRelease -IRelea
se/ Release/constants.o  Release/utils.o   Release/subroutines.o Release/inifile
.o  Release/power_tilt.o  Release/recfast.o Release/reionization.o Release/modul
es.o Release/bessels.o Release/equations.o Release/halofit_ppf.o Release/lensing
```

Compilation

Linking

-O3: Optimization O, O2, O3

-fopenmp: parallelization (export OMP_NUM_THREADS=4)

-ffast-math: do fast math optimizations!

Finally, run CAMB!

Run: ./camb ./params.ini

/cygdrive/c/Users/savvas/Desktop/camb_lecture/camb

```
savvas@Surtur /cygdrive/c/Users/savvas/Desktop/camb_lecture/camb
$ ./camb.exe ./params.ini
Reion redshift           =  10.713
Om_b h^2                 =  0.022600
Om_c h^2                 =  0.112000
Om_nu h^2                =  0.000640
Om_Lambda                =  0.724000
Om_K                     =  0.000000
Om_m (1-Om_K-Om_L)       =  0.276000
100 theta (CosmoMC)      =  1.039532
N_eff (total)            =  3.046000
 1 nu, g= 1.0153 m_nu*c^2/k_B/T_nu0=    353.71 (m_nu=  0.060 eV)
Reion opt depth          =  0.0900
Age of universe/GYr      =  13.777
zstar                    =  1088.72
r_s(zstar)/Mpc           =  146.38
100*theta                =  1.039841
zdrag                    =  1059.70
r_s(zdrag)/Mpc           =  149.01
k_D(zstar) Mpc           =  0.1392
100*theta_D              =  0.160271
z_EQ (if v_nu=1)         =  3216.47
100*theta_EQ             =  0.847737
tau_recomb/Mpc           =  284.95  tau_now/Mpc =  14362.3

savvas@Surtur /cygdrive/c/Users/savvas/Desktop/camb_lecture/camb
$ _
```

params.ini File containing the cosmological parameters etc

Discuss the file!

Various results

Result:

Nombre

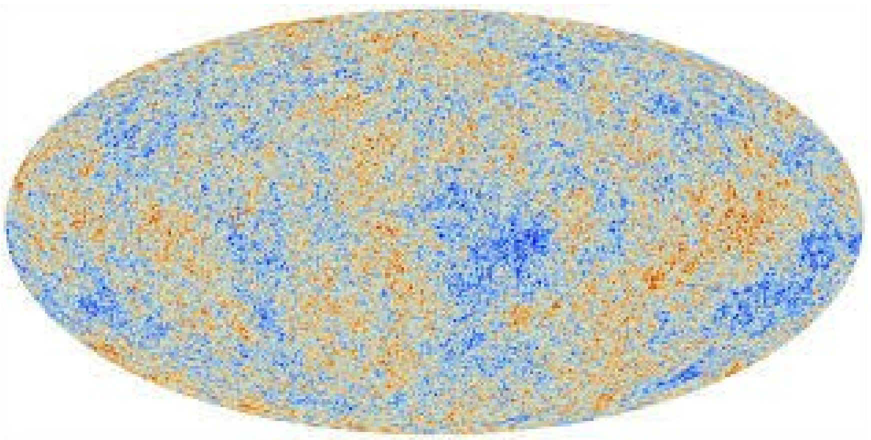
- test_lensedCls.dat
- test_lenspotentialCls.dat
- test_scalCls.dat
- test_scalCovCls.dat
- test_params.ini

test_scalCls.dat - WordPad

l	Cl^TT	Cl^EE	Cl^TE	Cl^φ	Cl^φT
2	0.11298E+04	0.54881E-01	0.33937E+01	0.10135E+07	0.32065E+05
3	0.10516E+04	0.88313E-01	0.42454E+01	0.15600E+07	0.38033E+05
4	0.97912E+03	0.97755E-01	0.43547E+01	0.20438E+07	0.40775E+05
5	0.92326E+03	0.85339E-01	0.40251E+01	0.24702E+07	0.41813E+05
6	0.88264E+03	0.62030E-01	0.34908E+01	0.28459E+07	0.41909E+05
7	0.85435E+03	0.38882E-01	0.29006E+01	0.31785E+07	0.41490E+05
8	0.83517E+03	0.22214E-01	0.23449E+01	0.34740E+07	0.40741E+05
9	0.82297E+03	0.13102E-01	0.18701E+01	0.37377E+07	0.39759E+05
10	0.81618E+03	0.94193E-02	0.15010E+01	0.39734E+07	0.38644E+05
11	0.81323E+03	0.82926E-02	0.12455E+01	0.41855E+07	0.37517E+05
12	0.81423E+03	0.77399E-02	0.11011E+01	0.43757E+07	0.36441E+05
13	0.81741E+03	0.69109E-02	0.10435E+01	0.45464E+07	0.35419E+05
14	0.82183E+03	0.60053E-02	0.10438E+01	0.47003E+07	0.34444E+05
15	0.82774E+03	0.53140E-02	0.10830E+01	0.48390E+07	0.33483E+05
16	0.83551E+03	0.50432E-02	0.11454E+01	0.49638E+07	0.32514E+05
17	0.84507E+03	0.51886E-02	0.12159E+01	0.50764E+07	0.31563E+05
18	0.85545E+03	0.55084E-02	0.12829E+01	0.51780E+07	0.30660E+05
19	0.86747E+03	0.58697E-02	0.13410E+01	0.52694E+07	0.29797E+05
20	0.87947E+03	0.62505E-02	0.13852E+01	0.53511E+07	0.28960E+05

The Cls and the correlation function

Result is txt files with the Cls...



$$T(\vec{x},\hat{p},\eta) = T(\eta)\,[1+\Theta(\vec{x},\hat{p},\eta)]$$

$$\Theta(\vec{x},\hat{p},\eta) = \sum_{l=1}^{\infty}\sum_{m=-l}^{l} a_{lm}(\vec{x},\eta)Y_{lm}(\hat{p})$$

$$\langle a_{lm}\rangle = 0 \qquad ; \qquad \langle a_{lm}a^*_{l'm'}\rangle = \delta_{ll'}\delta_{mm'}C_l$$

… and the matter power spectrum P(k)

$$\delta(\vec{x}) \equiv \frac{\rho(\vec{x})-\langle\rho\rangle}{\langle\rho\rangle} \qquad P(k) \equiv \langle|\delta_k|^2\rangle$$

$$\xi(\vec{r}) \equiv \langle\delta(\vec{x})\delta(\vec{x}+\vec{r})\rangle$$

$$\xi(r) = \frac{1}{(2\pi)^3}\int P(k)\frac{\sin(kr)}{kr}\,4\pi k^2 dk$$

Correlation function:
Denotes probability to find
galaxy at position r

The variables and the equations

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G a^2 \bar{\rho} - \kappa \,,$$

$$\frac{d}{d\tau}\left(\frac{\dot{a}}{a}\right) = -\frac{4\pi}{3} G a^2 (\bar{\rho} + 3\bar{P})$$

Conformal Newtonian gauge

$$\begin{aligned}
k^2\phi + 3\frac{\dot{a}}{a}\left(\dot{\phi} + \frac{\dot{a}}{a}\psi\right) &= 4\pi G a^2 \delta T^0{}_0(\mathrm{Con})\,, \\
k^2\left(\dot{\phi} + \frac{\dot{a}}{a}\psi\right) &= 4\pi G a^2 (\bar{\rho} + \bar{P})\theta(\mathrm{Con})\,, \\
\ddot{\phi} + \frac{\dot{a}}{a}(\dot{\psi} + 2\dot{\phi}) + \left(2\frac{\ddot{a}}{a} - \frac{\dot{a}^2}{a^2}\right)\psi + \frac{k^2}{3}(\phi - \psi) &= \frac{4\pi}{3} G a^2 \delta T^i{}_i(\mathrm{Con})\,, \\
k^2(\phi - \psi) &= 12\pi G a^2 (\bar{\rho} + \bar{P})\sigma(\mathrm{Con})\,,
\end{aligned}$$

The variables and the equations

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G a^2 \bar{\rho} - \kappa ,$$

$$\frac{d}{d\tau}\left(\frac{\dot{a}}{a}\right) = -\frac{4\pi}{3} G a^2 (\bar{\rho} + 3\bar{P})$$

Synchronous gauge —

$$k^2\eta - \frac{1}{2}\frac{\dot{a}}{a}\dot{h} = 4\pi G a^2 \, \delta T^0{}_0(\mathrm{Syn}) ,$$

$$k^2\dot{\eta} = 4\pi G a^2 (\bar{\rho} + \bar{P})\theta(\mathrm{Syn}) ,$$

$$\ddot{h} + 2\frac{\dot{a}}{a}\dot{h} - 2k^2\eta = -8\pi G a^2 \, \delta T^i{}_i(\mathrm{Syn}) ,$$

$$\ddot{h} + 6\ddot{\eta} + 2\frac{\dot{a}}{a}(\dot{h} + 6\dot{\eta}) - 2k^2\eta = -24\pi G a^2 (\bar{\rho} + \bar{P})\sigma(\mathrm{Syn}) .$$

The variables and the equations

CAMB language A,B,C

Background: grho$=8\pi G\rho a^2$, adotoa$=\dfrac{a'}{a}=\dfrac{\mathrm{d}a/\mathrm{d}\tau}{a}$, tau=conformal time

$\delta T^{\mu\nu}$: dgrho$=8\pi G a^2\sum_i \rho_i\delta_i$, dgq$=8\pi G a^2\sum_i(\rho_i+p_i)v_i$

clxc$=\delta_{\mathrm{c}}$, clxb$=\delta_{\mathrm{b}}$, clxq$=\delta_{\mathrm{DE}}$

$\delta G^{\mu\nu}$: etak$=\eta k$, z$=h'/(2k)$, sigma$=\dfrac{h'+6\eta'}{2k}$

See dtauda and derivs in equations.f90

The variables and the equations

CAMB code	M+B ' 96 astro-ph/9506072
$\eta' k = \mathrm{dgq}/2$	$\eta' k^2 = 4\pi G a^2 (\bar{\rho} + \bar{P})\theta$
$\mathrm{clxcdot} = -kz$	$\delta'_c = -\frac{1}{2} h'$
$z = (0.5\mathrm{dgrho}/k + \eta k)/\mathrm{adotoa}$	$k^2 \eta - \frac{1}{2}\frac{a'}{a} h' = 4\pi G a^2 \delta T_0^0$
$\mathrm{sigma} = z + 1.5\mathrm{dgq}/k^2$	$\sigma = \frac{h' + 6\eta'}{2k}$

Differential equations to evolve in CAMB

Constraint equations (algebraic)

Slide from talk by G.B. Zhao at the “School for Cosmology Tools„

The variables and the equations

Baryons

$$\dot{\delta}_b = -\theta_b - \frac{1}{2}\dot{h}\,,$$

```
! Baryon equation of motion.
  clxbdot=-k*(z+vb)
  ayprime(4)=clxbdot
```

$$\dot{\theta}_b = -\frac{\dot{a}}{a}\theta_b + c_s^2 k^2 \delta_b + \frac{4\bar{\rho}_\gamma}{3\bar{\rho}_b} a n_e \sigma_T (\theta_\gamma - \theta_b)\,,$$

```
vbdot=-adotoa*vb+cs2*k*clxb-photbar*opacity*(4._dl/3*vb-qg)
```

The variables and the equations

Photons

$$\dot{\delta}_\gamma = -\frac{4}{3}\theta_\gamma - \frac{2}{3}\dot{h} ,$$

```
! Photon equation of motion
  clxgdot=-k*(4._dl/3._dl*z+qg)
```

$$\dot{\theta}_\gamma = k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) + an_e\sigma_T(\theta_b - \theta_\gamma) ,$$

```
!Once know slip, recompute qgdot, pig, pigdot
        qgdot = k*(clxg/4._dl-pig/2._dl) +opacity*slip
```

The variables and the equations

Higher moments, compare to CAMB equations in derivs

$$\dot{\delta}_\gamma = -\frac{4}{3}\theta_\gamma - \frac{2}{3}\dot{h} ,$$

$$\dot{\theta}_\gamma = k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) + an_e\sigma_T(\theta_b - \theta_\gamma) ,$$

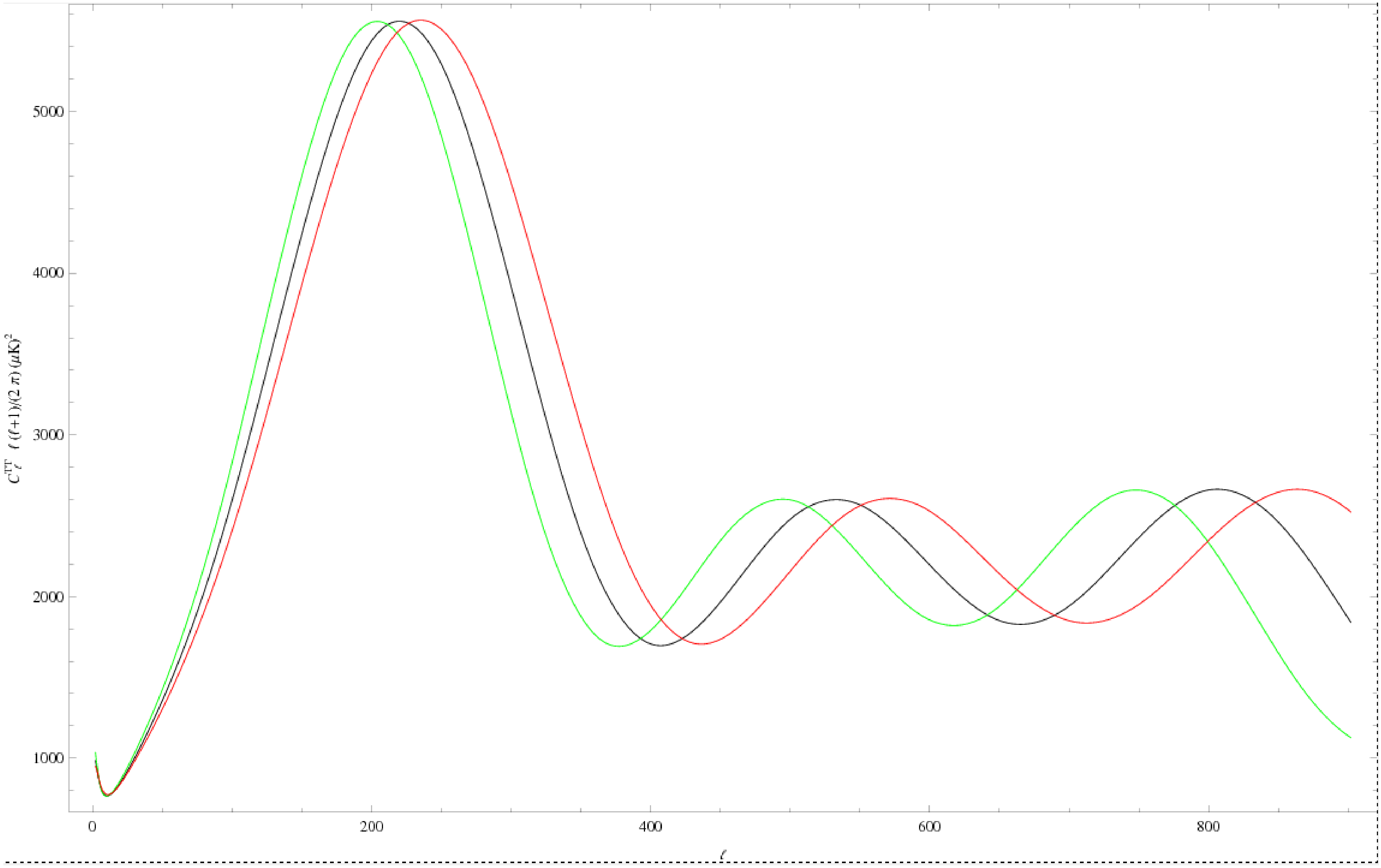
$$\dot{F}_{\gamma 2} = 2\dot{\sigma}_\gamma = \frac{8}{15}\theta_\gamma - \frac{3}{5}kF_{\gamma 3} + \frac{4}{15}\dot{h} + \frac{8}{5}\dot{\eta} - \frac{9}{5}an_e\sigma_T\sigma_\gamma + \frac{1}{10}an_e\sigma_T(G_{\gamma 0} + G_{\gamma 2}) ,$$

$$\dot{F}_{\gamma l} = \frac{k}{2l+1}[lF_{\gamma(l-1)} - (l+1)F_{\gamma(l+1)}] - an_e\sigma_T F_{\gamma l} , \quad l \geq 3 ,$$

$$\dot{G}_{\gamma l} = \frac{k}{2l+1}[lG_{\gamma(l-1)} - (l+1)G_{\gamma(l+1)}] + an_e\sigma_T\left[-G_{\gamma l} + \frac{1}{2}(F_{\gamma 2} + G_{\gamma 0} + G_{\gamma 2})\left(\delta_{l0} + \frac{\delta_{l2}}{5}\right)\right] ,$$

The effect of the parameters

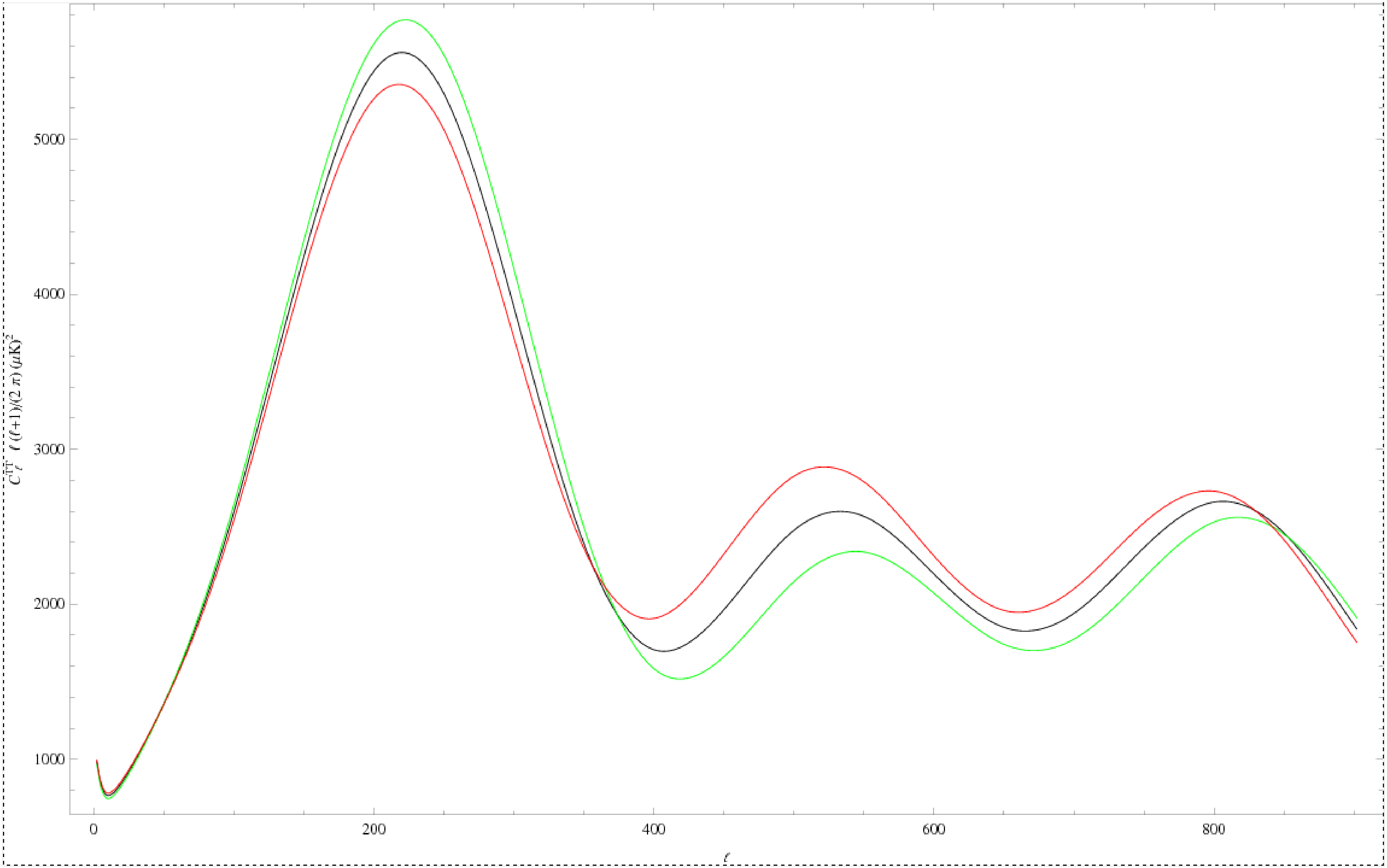
Ωk=[-0.05, 0, 0.05]



The effect of the parameters

Ωb=[0.0562, 0.0462, 0.0362] and H0=70

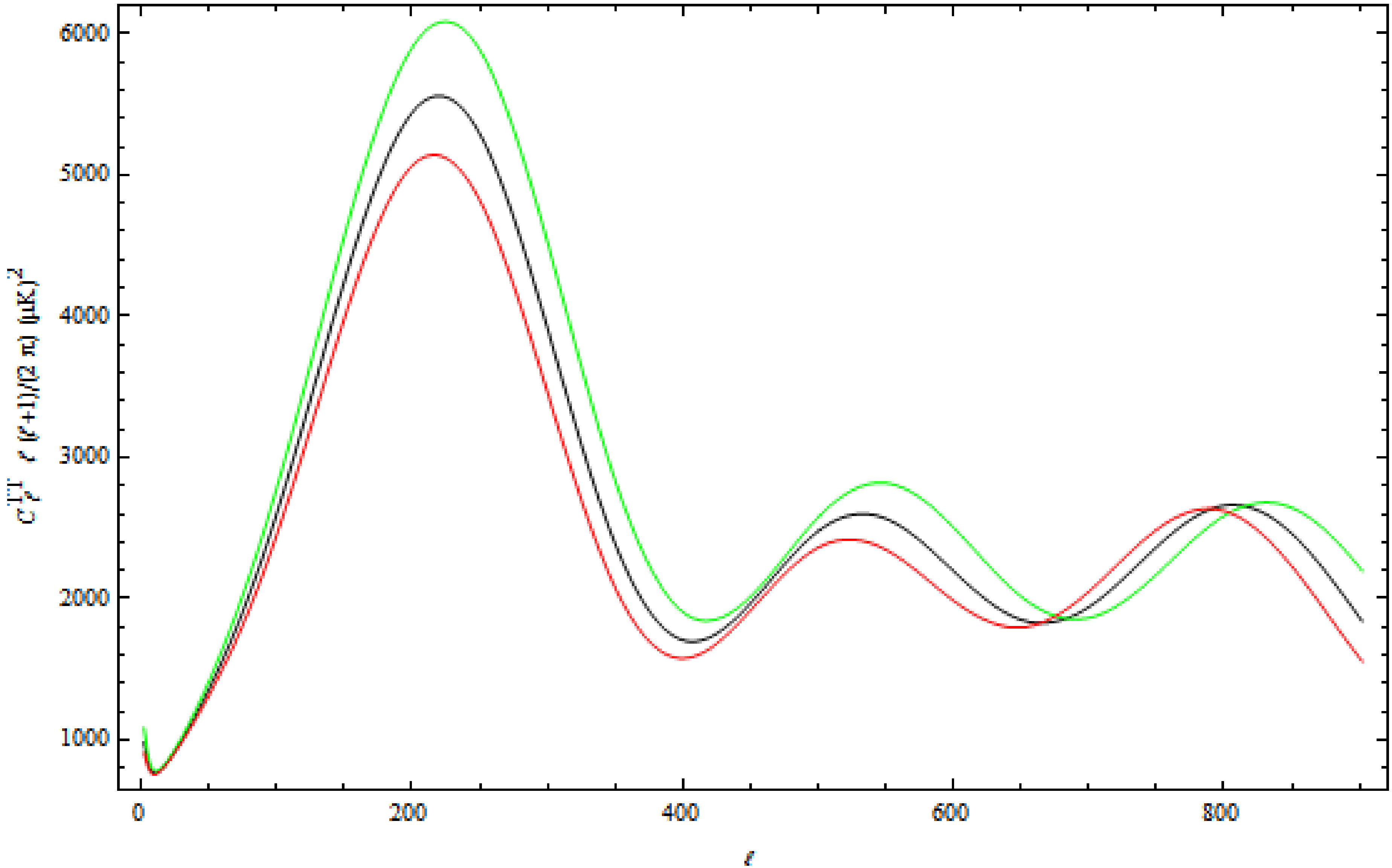
Ωbh^2=[0.027538, 0.022638, 0.017738]



The effect of the parameters

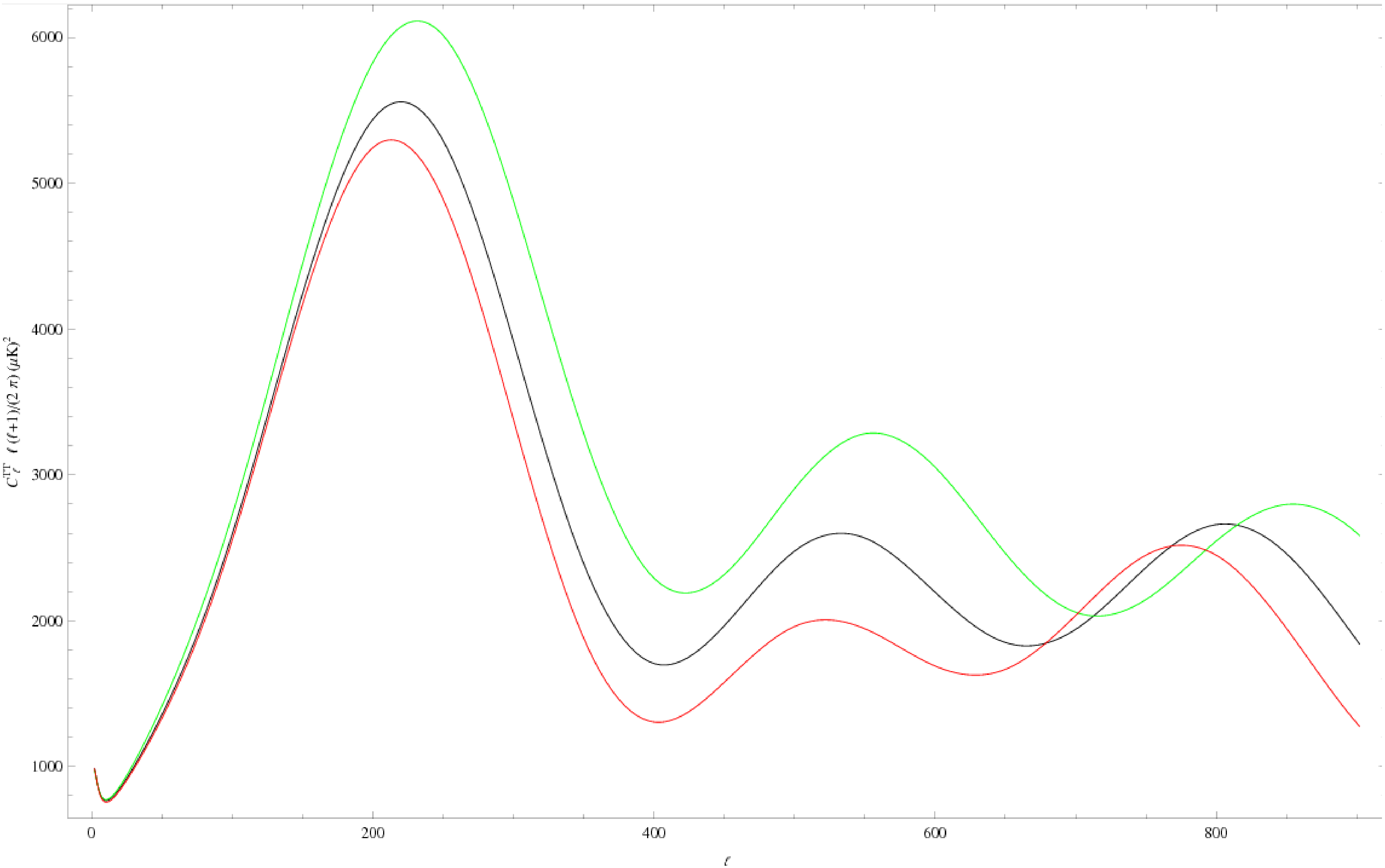
Ωm=[0.2038, 0.2538, 0.3038] and H0=70

Ωmh^2=[0.099862, 0.124362, 0.148862]



The effect of the parameters

H0=[60, 70, 80]



List of exercises

1) Compare the CMB power spectra while varying (only one each time):

i) ns (spectral_index)

ii) The running dns/dlnk (nrun)

iii) The amplitude (scalar_amp)

2) Try using the PPF module and compare LCDM with a w0wa model

3) Matter power spectrum stuff

i) Find the matter power spectrum P(k)

ii) Calculate the correlation function ξ(r)

iii) How does the BAO peak depend on H0? Why?

4) Plot the Planck power spectrum along with the theoretical (for the best-fit values). Is there a difference? Why?

Downloads

Savvas Nesseris

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In this part I will try to explain several key issues in data analysis and statistics with the use of explicit examples and numerical codes. Most of the following material is intended for master and fledgling PhD students who want to understand the basics of data analysis with a focus on cosmology and want to enter the world of research. However, some of the examples might be a bit more advanced...

Prerequisites:
1) Study Chapter 15 of Numerical Recipes regarding data-fitting, minimization, MCMC, statistics etc **[1]**, see also **[2]**.
2) Download the Mathematica codes found below and that illustrate several key issues, like minimization and basic statistical analysis, contours, MCMC, Fourier analysis, parallelization (CPU/GPU) etc.
3) Get CAMB from **here** and follow the instructions in the **Readme** to compile and install it. Gfortran 4.5+ is highly recommended.
4) Run the codes and try to understand what's going on and most importantly *why*.

Numerical codes: (right-click on "Download" and hit "Save as")
1) Statistical Significance and Sigmas. **Download**.
2) Stuff about covariance matrices. **Download**.
3) Data fitting, contours, error bars etc. **Download**.
4) Markov Chain Monte Carlo (MCMC). **Download**.
5) Bootstrap Monte Carlo. **Download**.
6) The Jack-knife **[3]**. **Download**.
7) Genetic Algorithms **[4]**. **Download**.
8) A Mathematica Interface for CosmoMC, go **here**.
9a) Fitting the SnIa data (standard) **[5]** **Download**.
9b) Fitting the SnIa data (**ultra-fast**) **[5]** **Download**.
10) Joint SnIa, CMB, BAO and growth-rate likelihood! (**ultra-fast**) **Download**.
11) Parallelization CPU/GPU (coming soon).
12) The CMB power spectrum and the cosmological parameters; the correlation function (no RSD) **Download**.

Available at:

http://members.ift.uam-csic.es/savvas.nesseris/

See also the "School for Cosmology Tools"

http://workshops.ift.uam-csic.es/iftw.php/inicio/congreso?id=150