CLASS

the Cosmological Linear Anisotropy Solving System[1]

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[1] code developed by Julien Lesgourgues & Thomas Tram plus many others

Running class from python

class as a Python module

- based on wrapper located in python/classy.pyx (developed initially by B. Audren and extended by many others)
- the compilation produces a python module classy.py and installs it on your computer (can be called from anywhere)
- wrapper written in Cython, encapsulates most useful class variables/functions, contains extra functions (e.g. MontePython-motivated)
- (project: get most of the wrapper generated automatically from C code at compilation)
- goal: obtain, manipulate and plot the results directly within (i)python scripts or notebooks (recommended)

- we will now discuss several examples of scrips/notebooks which are available since v2.7.0 in the folders scripts/ and notebooks/
- with jupyter installed, open the notebooks with e.g.

```
> jupyter notebook notebooks/warmup.ipnyb
```

- if you can't make it with jupyter, you'll get the same results with

```
> python scripts/warmup.py
```

Python wrapper

First basic example (notebooks/warmup.ipynb or scripts/warmup.py)

```
# import classy module
from classy import Class
```

```
# create instance of the class "Class"
LambdaCDM = Class()
# pass input parameters
LambdaCDM.set({’omega_b’:0.022032,’omega_cdm’:0.12038,’h’:0.67556,’A_s’:2.215e
     -9,’n_s’:0.9619,’tau_reio’:0.0925})
LambdaCDM.set({’output’:’tCl,pCl,lCl,mPk’,’lensing’:’yes’,’P_k_max_1/Mpc’:3.0})
# run class
LambdaCDM.compute()
```

```
# get all C_l output
cls = LambdaCDM.lensed_cl(2500)
# To check the format of cls
cls.viewkeys()
```

```
dict_keys([’pp’, ’ell’, ’bb’, ’ee’, ’tt’, ’tp’, ’te’])
```

```
ll = cls[’ell’][2:]
clTT = cls[’tt’][2:]
clEE = cls[’ee’][2:]
clPP = cls[’pp’][2:]
```

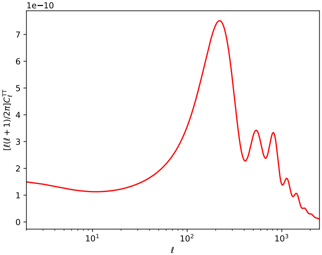
Python wrapper

First basic example (notebooks/warmup.ipynb or scripts/warmup.py)

```
# uncomment to get plots displayed in notebook
#%matplotlib inline
import matplotlib.pyplot as plt
from math import pi
```

(some systems prefer %matplotlib notebook to %matplotlib inline)

```
# plot C_l^TT
plt.figure(1)
plt.xscale('log');plt.yscale('linear');plt.xlim(2,2500)
plt.xlabel(r'$\ell$')
plt.ylabel(r'$[\ell(\ell+1)/2\pi]  C_\ell^\mathrm{TT}$')
plt.plot(ll,clTT*ll*(ll+1)/2./pi,'r-')
```



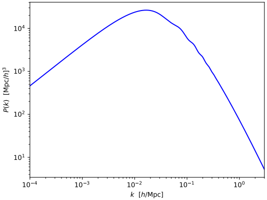
```
plt.savefig('warmup_cltt.pdf')
```

Python wrapper

First basic example (`notebooks/warmup.ipynb` or `scripts/warmup.py`)

```
# get P(k) at redhsift z=0
import numpy as np
kk = np.logspace(-4,np.log10(3),1000) # k in h/Mpc
Pk = [] # P(k) in (Mpc/h)**3
h = LambdaCDM.h() # get reduced Hubble for conversions to 1/Mpc
for k in kk:
    Pk.append(LambdaCDM.pk(k*h,0.)*h**3) # function .pk(k,z)
```

```
# plot P(k)
plt.figure(2)
plt.xscale(’log’);plt.yscale(’log’);plt.xlim(kk[0],kk[-1])
plt.xlabel(r’$k \,\,\,\, [h/\mathrm{Mpc}]$’)
plt.ylabel(r’$P(k) \,\,\,\, [\mathrm{Mpc}/h]^3$’)
plt.plot(kk,Pk,’b-’)
```



```
plt.savefig(’warmup_pk.pdf’)
```

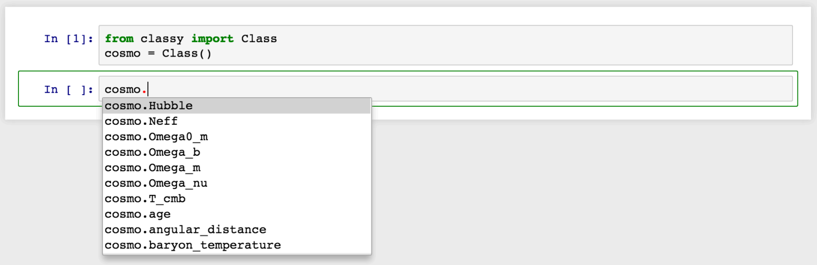
Python wrapper

First basic example (notebooks/warmup.ipynb or scripts/warmup.py)

```
# optional: clear content of LambdaCDM (to reuse it for another model)
LambdaCDM.struct_cleanup()
# optional: reset parameters to default
LambdaCDM.empty()
```

Python wrapper: IPython notebooks

The TAB key after the dot gives you the list of available classy methods (= available functions and quantities) in a scrolling menu:

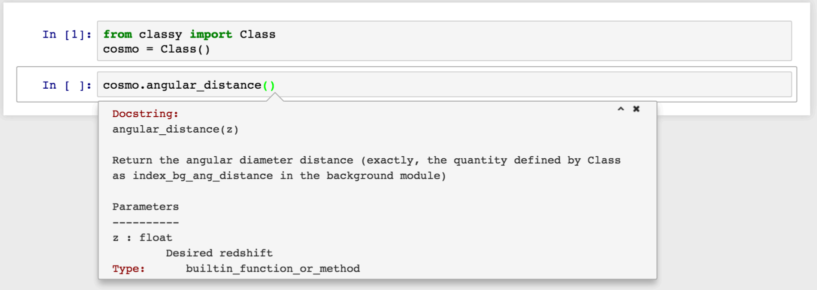


```
In [1]: from classy import Class
        cosmo = Class()

In [ ]: cosmo.
```

Python wrapper: IPython notebooks

The TAB+SHIFT keys after the () gives you a short doc on each method (expand it by clicking +):



```
In [1]: from classy import Class
        cosmo = Class()

In [ ]: cosmo.angular_distance()
```

```
Docstring:
angular_distance(z)

Return the angular diameter distance (exactly, the quantity defined by Class
as index_bg_ang_distance in the background module)

Parameters
----------
z : float
        Desired redshift
Type:      builtin_function_or_method
```

Species in public class

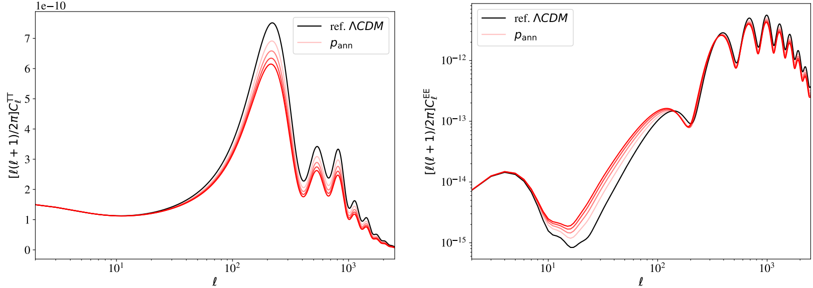
- compulsory: photons: T_cmb or Omega_g or omega_g
- compulsory: baryons: Omega_b or omega_b
- ultra-relativistic species (massless neutrinos): N_ur or Omega_ur or omega_ur
- cold dark matter: Omega_cdm or omega_cdm (possibly annihilating: annihilation, etc.)
- N_ncdm distinct non-cold dark matter species (massive neutrinos, warm dark matter...): m_ncdm or Omega_ncdm or omega_ncdm plus lots of options
- cold dark matter decaying into dark radiation: Omega_dcdmdr or omega_dcdmdr plus Gamma_dcdm
- spatial curvature Omega_k
- cosmological constant Omega_Lambda
- fluid Omega_fld plus w0_fld, wa_fld, cs2_fld, etc.
- scalar field (quintessence) Omega_scf plus specifications

All details are in explanatory.ini

To avoid over-constraining the input, one of the last three (Omega_Lambda, Omega_fld, Omega_scf) must be left unspecified and class will assign it using budget equation. Defaut: Omega_fld = Omega_scf = 0 so Omega_Lambda is automatically adjusted.

Plots with varying parameters

With `notebooks/varying_pann.ipynb` or `scripts/varying_pann.py`:



We called `class` within a loop with different values of the DM annihilation parameter $p_{\rm ann} = \frac{\langle \sigma v \rangle}{m}$.

Plots with varying parameters

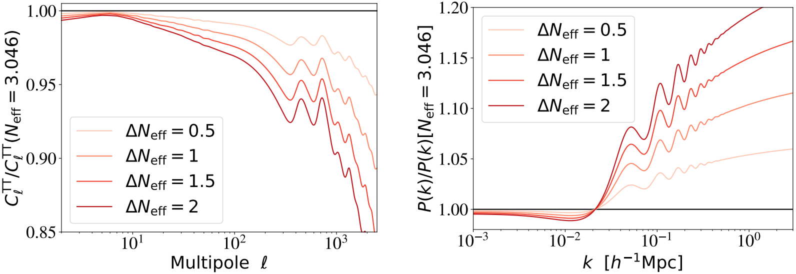
With `notebooks/varying_pann.ipynb` or `scripts/varying_pann.py`:

Main steps:

```
var_name = 'annihilation'
var_array = np.linspace(0,1.e-5,5)
common_settings = {'output':'tCl,pCl,lCl,mPk', ...}
# loop over varying parameter values
for i,var in enumerate(var_array):
  M = Class()
  M.set(common_settings)
  M.set({var_name:var})
  M.compute()
  clM = M.lensed_cl(2500)
  # ... plotting ...
  M.struct_cleanup() # clear all class output
  M.empty()          # clear input previously set by .set()
```

Plots with varying parameters

With `notebooks/varying_neff.ipynb` or `scripts/varying_neff.py`:



Slightly more elaborate: we had to call `class` with different values of $N_{\rm eff}$ for massless neutrinos (in fact `N_ur`) while keeping $z_{\rm eq}$ and z_Λ fixed, which implies to adjust `h` and `omega_cdm` in a non-trivial way. We also wanted a separate cell for calling `class` for each model, and then for plotting.

Plots with varying parameters

With notebooks/varying_neff.ipynb or scripts/varying_neff.py:
Main steps:

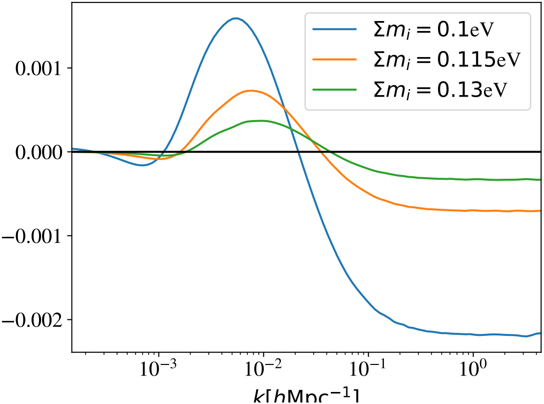
```
M = {}
for i, N_ur in enumerate(var_array):
    # The goal is to vary
    # - omega_cdm by a factor alpha = (1 + coeff*Neff)/(1 + coeff*3.046)
    # - h by a factor sqrt*(alpha)
    # in order to keep a fixed z_equality(R/M) and z_equality(M/Lambda)
    alpha = (1.+coeff*N_ur)/(1.+coeff*3.046)
    omega_cdm = (0.022032 + 0.12038)*alpha - 0.022032
    h = 0.67556*math.sqrt(alpha)
    M[i] = Class()
    M[i].set(common_settings)
    M[i].set({'N_ur':N_ur})
    M[i].set({'omega_cdm':omega_cdm})
    M[i].set({'h':h})
    M[i].compute()
```

In the next cell there is another loop for plotting the data from
clM[i] = M[i].lensed_cl(2500) and M[i].pk(k,0.)

Plots with varying parameters

With `notebooks/neutrinohierarchy.ipynb` or `scripts/neutrinohierarchy.py`:

The goal here is to plot the ratio of $P(k)$ with 3 massive neutrinos obeying to Normal Hierarchy over $P(k)$ with 3 massive neutrinos obeying to Inverted Hierarchy, both with the same total mass $\sum_i m_i$.



Plots with varying parameters

With notebooks/neutrinohierarchy.ipynb or scripts/neutrinohierarchy.py:

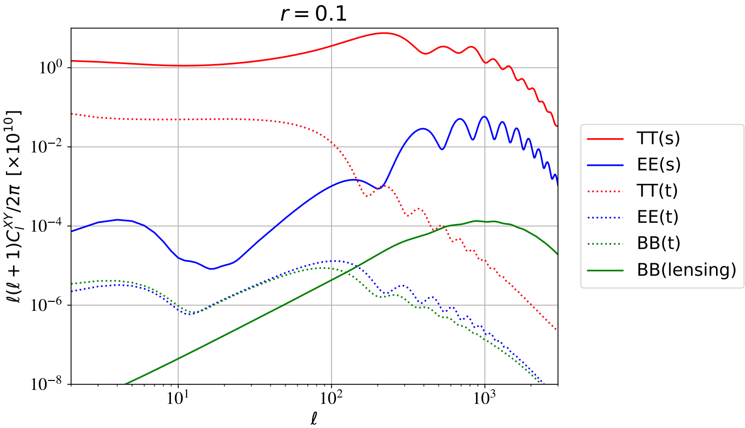
Main steps:

```
def get_masses(delta_m_squared_atm, delta_m_squared_sol,
    sum_masses, hierarchy):
    # function returning individual masses for given sum
```

```
# loop over total mass values
for sum_masses in [0.1, 0.115, 0.13]:
    # normal hierarchy
    [m1,m2,m3] = get_masses(2.45e-3,7.50e-5,sum_masses,’NH’)
    NH = Class()
    NH.set(commonsettings)
    NH.set({’m_ncdm’:str(m1)+’,’+str(m2)+’,’+str(m3)})
    NH.compute()
    # inverted hierarchy
    [m1,m2,m3] = get_masses(2.45e-3,7.50e-5,sum_masses,’IH’)
    IH = Class()
    IH.set(commonsettings)
    IH.set({’m_ncdm’:str(m1)+’,’+str(m2)+’,’+str(m3)})
    IH.compute()
    ...
```

Contributions to CMB C_l's

With `notebooks/cl_ST.ipynb` or `scripts/cl_ST.py`:



Contributions to CMB C_l's

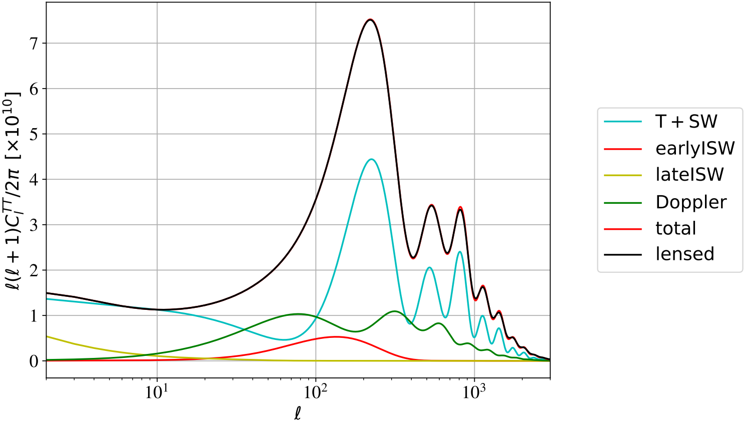
With notebooks/cl_ST.ipynb or scripts/cl_ST.py:

Main steps:

```
# scalars only
M = Class()
M.set({’output’:’tCl,pCl’,’modes’:’s’,’lensing’:’no’,’n_s’
    :0.9619,’l_max_scalars’:3000})
cls = M.raw_cl(3000)
...
# tensors only
M.set({’output’:’tCl,pCl’,’modes’:’t’,’lensing’:’no’,’r’
    :0.1,’n_t’:0,’l_max_tensors’:l_max_tensors})
clt = M.raw_cl(l_max_tensors)
...
# scalars + tensors (only in this case we can get the
    correct lensed ClBB)
M.set({’output’:’tCl,pCl,lCl’,’modes’:’s,t’,’lensing’:’yes’,
    ’r’:0.1,’n_s’:0.9619,’n_t’:0,’l_max_scalars’:3000,’
    l_max_tensors’:l_max_tensors})
M.compute()
cl_tot = M.raw_cl(3000)
cl_lensed = M.lensed_cl(3000)
...
```

Contributions to CMB C_l's

With `notebooks/cltt_terms.ipynb` or `scripts/cltt_terms.py`:



Contributions to CMB C_l's

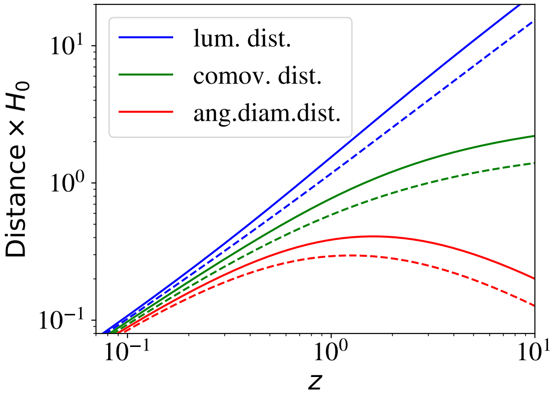
With `notebooks/cltt_terms.ipynb` or `scripts/cltt_terms.py`:

Main steps:

```
M = Class()
M.set(common_settings)
M.compute()
cl_tot = M.raw_cl(3000)
cl_lensed = M.lensed_cl(3000)
M.struct_cleanup()  # clean output
M.empty()           # clean input
...
M.set({'temperature contributions':'tsw'})
M.compute()
cl_tsw = M.raw_cl(3000)
...
M.set({'temperature contributions':'eisw'})
...
M.set({'temperature contributions':'lisw'})
...
M.set({'temperature contributions':'dop'})
```

Background quantities

With `notebooks/distances.ipynb` or `scripts/distances.py`:



Similar to plot in Scott Dodelson's *Modern Cosmology* book.
Solid $=$ ΛCDM, dashed $=$ Einstein-De-Sitter ($\Omega_m = 1$).

Background quantities

With notebooks/distances.ipynb or scripts/distances.py:

Main steps:

```
#Lambda CDM
LCDM = Class()
LCDM.set({'Omega_cdm':0.25,'Omega_b':0.05})
LCDM.compute()
#Einstein-de Sitter
CDM = Class()
CDM.set({'Omega_cdm':0.95,'Omega_b':0.05})
CDM.compute()
```

Remark: we did not pass anything to 'output' field. Seeing that no spectra need to be computed, class will only call its background and thermodynamics modules.

Background quantities

With `notebooks/distances.ipynb` or `scripts/distances.py`:

Main steps:

```
# Just to cross-check that Omega_Lambda is negligible
# (but not exactly zero because we neglected radiation)
der = CDM.get_current_derived_parameters(['Omega0_lambda'])
print der
print "Omega_Lambda =",der['Omega0_lambda']
```

```
{'Omega0_lambda':  -9.167135654530867e-05}
Omega_Lambda = -9.16713565453e-05
```

Background quantities

List of derived parameters that can be passed as arguments of `.get_current_derived_parameters([..,..,...])`:

```
# background:
’h’, ’H0’, ’Omega_Lambda’, ’Omega0_fld’,
’age’, ’conformal_age’,  ’m_ncdm_in_eV’,
’m_ncdm_tot’, ’Neff’, ’Omega_m’, ’omega_m’,
# thermodynamics:
’tau_reio’, ’z_reio’, ’100*theta_s’, ’YHe’, ’n_e’,
# quantities at recombination:
’z_rec’, ’tau_rec’, ’rs_rec’, ’rs_rec_h’, ’ds_rec’,
’ds_rec_h’, ’ra_rec’, ’ra_rec_h’, ’da_rec’, ’da_rec_h’,
# quantities at baryon drag:
’z_d’, ’tau_d’, ’ds_d’, ’ds_d_h’, ’rs_d’, ’rs_d_h’,
# primordial perturbations:
’A_s’, ’ln10^{10} A_s’, ’n_s’, ’sigma8’, ’exp_m_2_tau_As’,
’alpha_s’, ’beta_s’, ’r’, ’r_0002’, ’n_t’, ’alpha_t’,  ’
    exp_m_2_tau_As’,
+ others related to inflation/isocurvature
```

Background quantities

With notebooks/distances.ipynb or scripts/distances.py:

Main steps:

```
#Get background quantities and recover their names:
baLCDM = LCDM.get_background()
baCDM = CDM.get_background()
baCDM.viewkeys()
```

```
dict_keys(['(.)rho_crit', 'lum. dist.', '(.)rho_b', 'H [1/Mpc]', 'conf.
time [Mpc]', 'comov.snd.hrz.', '(.)rho_g', '(.)rho_lambda', 'comov. dist
.', '(.)rho_cdm', 'ang.diam.dist.', 'proper time [Gyr]', 'gr.fac. D', '
gr.fac. f', 'z', '(.)rho_ur'])
```

So this big array contains all background quantities for each value of 'z' (redshift) or 'proper time [Gyr]'.

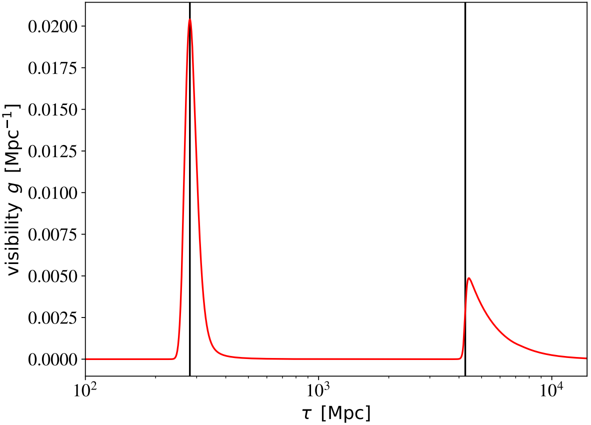
There are also many functions directly giving interpolated values of background quantities at a given redshift:

```
.Hubble(z), .angular_distance(z), .luminosity_distance(z),
.scale_independent_growth_factor(z),
.scale_independent_growth_factor_f(z),
.sigma(R,z),
```

(Also .z_of_r([z_1, z_n]) which returns r and dz/dr).

Thermodynamics quantities

With `notebooks/thermo.ipynb` or `scripts/thermo.py`:



Visibility function = probability of last interaction of a photon. Rescaled by factor 100 at late times to make reionisation peak visible on the same scale.

Thermodynamics quantities

With `notebooks/thermo.ipynb` or `scripts/thermo.py`:

Main steps:

```
M = Class()
M.set(common_settings)
M.compute()
derived = M.get_current_derived_parameters(['tau_rec','
    conformal_age'])
thermo = M.get_thermodynamics()
print thermo.viewkeys()
```

```
dict_keys(['x_e', 'g [Mpc^-1]', 'conf. time [Mpc]', "kappa' [Mpc^-1]", '
tau_d', 'Tb [K]', 'c_b^2', 'exp(-kappa)', 'z'])
```

So this big array contains all background quantities for each value of `'z'` (redshift). (Note: `x_e` is the ionisation fraction, `kappa` is the optical depth, `kappa'` is the scattering rate, `g` is the visibility function, `tau_d` is the baryon optical depth).

There are also two functions directly giving interpolated values of thermodynamical quantities at a given redshift:
`.ionisation_fraction(z)`, `.baryon_temperature(z)`

Primordial spectra

We don't have an example of notebook here, but there are lots of options for the primordial spectra, depending what `P_k_ini type` is set to (see `explanatory.ini` or https://lesgourg.github.io/class-tour/Tokyo2014/lecture12_primordial.pdf for more details):

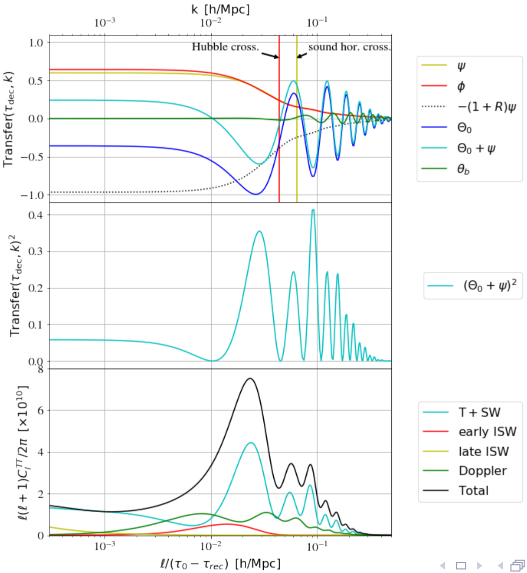
- `analytic_Pk`: traditional input (`A_s`, `n_s`, `alpha_s`, `k_pivot`, `r`, `n_t` plus many others, in particular for isocurvature modes)
- `two_scales`: an alternative used in Planck inflation papers for isocurvature modes
- `external_Pk`: primordial spectra read on-the-fly from external code
- `inflation_V`: full inflation simulator for given function $V(\phi - \phi_{\rm pivot})$
- `inflation_H`: full inflation simulator for given function $H(\phi - \phi_{\rm pivot})$
- `inflation_V_end`: full inflation simulator for given function $V(\phi)$ and N_*

In python notebook/script: the scalar and tensor primordial spectra $\mathcal{P}_\mathcal{R}(k)$, $\mathcal{P}_h(k)$ can be extracted with the function `.get_primordial()`

With the inflation simulator: the parameters `A_s`, `ln10^{10} A_s`, `n_s`, `alpha_s`, `beta_s`, `r`, `r_0002`, `n_t`, `alpha_t` are then *derived* parameter accessible with `.get_derived_parameters(...)`

Perturbations at given time

With `notebooks/one_time.ipynb` or `scripts/one_time.py`:



Perturbations at given time

With `notebooks/one_time.ipynb` or `scripts/one_time.py`:

Main steps:

```
M = Class()
M.set(common_settings)
common_settings = {'output':'tCl,mTk,vTk',...,
                   'gauge':'newtonian'}
M.set({'z_pk':z_rec}) # for transfer functions at z<z_rec
M.compute()
one_time = M.get_transfer(z_rec)
print one_time.viewkeys()
```

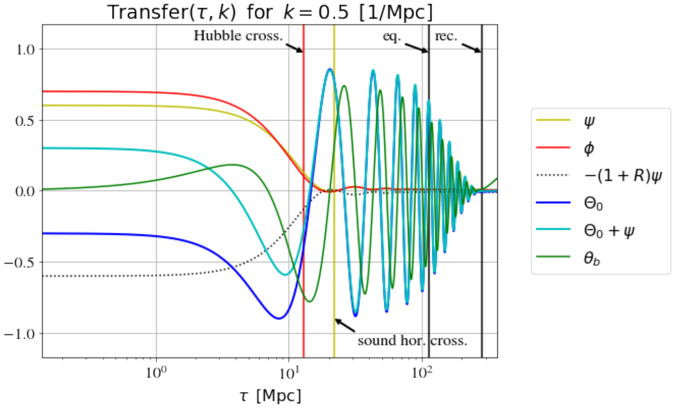
```
dict_keys(['phi', 'psi', 't_cdm', 't_b', 'd_tot', 't_g', 'd_ur', 'd_cdm'
, 'd_b', 't_tot', 't_ur', 'd_g', 'k (h/Mpc)'])
```

```
k = one_time['k (h/Mpc)']
Theta0 = 0.25*one_time['d_g']
phi = one_time['phi']
...
```

The key step was to include `'mTk'` in the output. Setting `'z_pk'` was also crucial to get transfer functions at high redshift (default: `'z_pk'`=0 and we would only be able to get the perturbations today).

Perturbations for a given wavenumber

With `notebooks/one_k.ipynb` or `scripts/one_k.py`:



Perturbations for a given wavenumber

With notebooks/one_k.ipynb or scripts/one_k.py:

Main steps:

```
k = 0.5   # 1/Mpc
common_settings = {'output':'mPk','k_output_values':k,...}
M = Class()
M.set(common_settings)
M.compute()
all_k = M.get_perturbations()
one_k = all_k['scalar'][0]
print one_k.viewkeys()
```

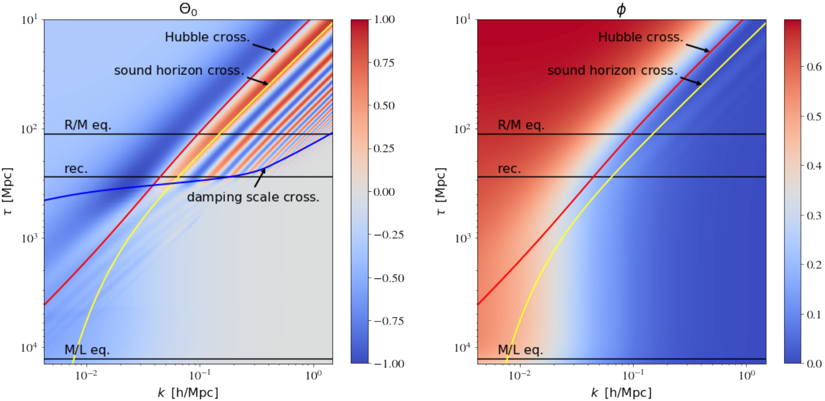
```
dict_keys(['a', 'theta_g', 'phi', 'pol0_g', 'theta_b', 'theta_ur', '
shear_ur', 'shear_g', 'tau [Mpc]', 'theta_cdm', 'delta_ur', 'psi', '
pol2_g', 'delta_g', 'delta_cdm', 'pol1_g', 'delta_b'])
```

```
tau = one_k['tau [Mpc]']
Theta0 = 0.25*one_k['delta_g']
phi = one_k['phi']
...
```

Remark: 'k_output_values' can be set to a list: 'k_output_values'='0.05,0.1,0.4'. Each is labelled by i starting from zero and the perturbations are in M.get_perturbations()['scalars'][i]['key']

Perturbations in (k, τ) space

With `notebooks/many_k.ipynb` or `scripts/many_k.py`:



Sophisticated script (and long to execute) but no new command with respect to previous cases.