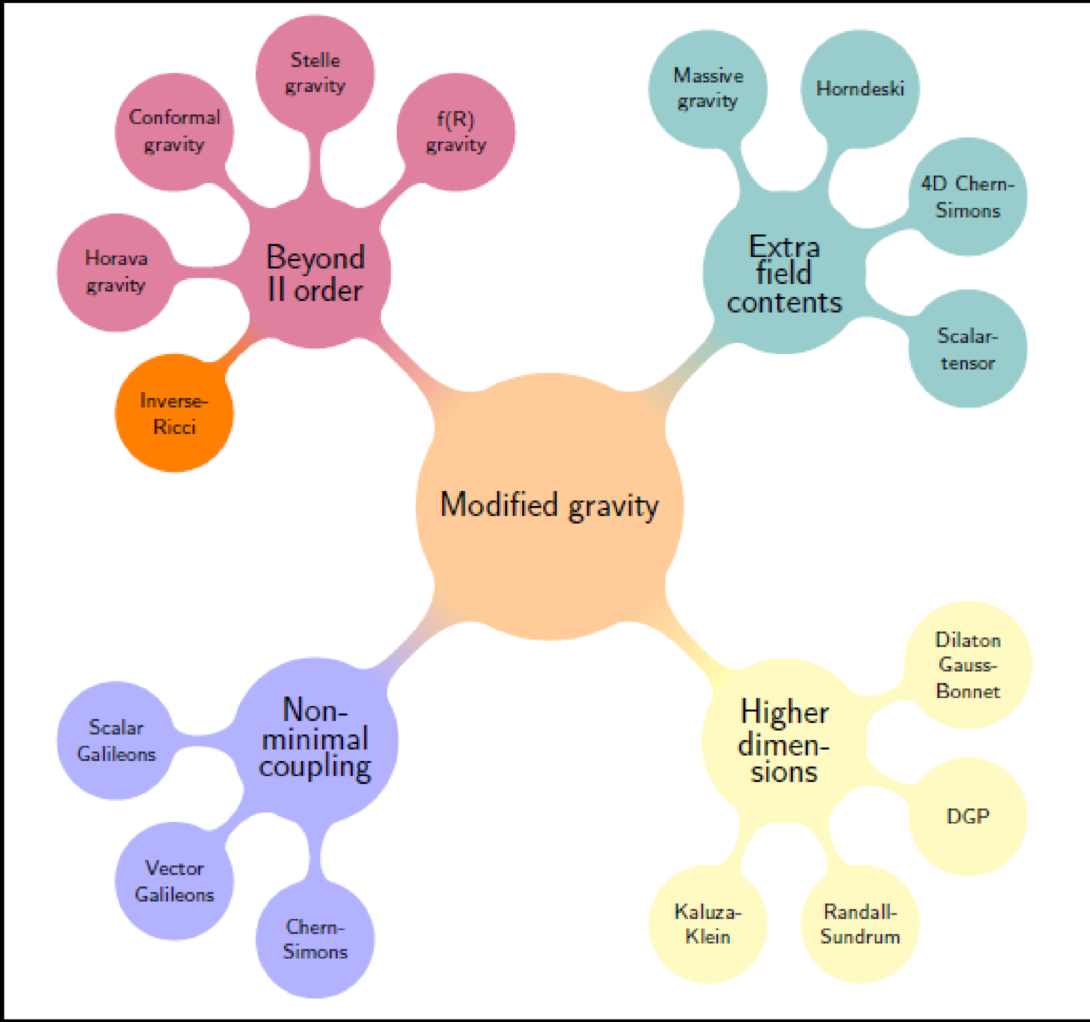
Cosmology at Intermediate Redshifts & the tensions.

Ziad Sakr - Corfu 2022

Modified Gravity Landscape



from Shankaranarayanan & Johnson 2022

Modifying Gravity in a more general phenomenological oriented way

- *Cosmo Background driven … ?*

- *Formation of structures ?*

- *Or a mix from both …*

- Cosmo Background driven … ?

Background Metric resulting in Friedman equations …

Essentially we modify the energy tensor

$$ds^2 = -c^2 dt^2 + a(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 (d\theta^2 + \sin^2\theta d\phi^2) \right)$$

$$R_{\mu\nu} - \frac{1}{2} R \, g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$H^2 = \left(\frac{\dot{a}}{a} \right)^2 = \frac{8\pi G}{3} \rho - \frac{kc^2}{a^2} \quad + f\,(H, H', H'')$$

$$\dot{H} + H^2 = \frac{\ddot{a}}{a} = -\frac{4\pi G}{3} \left(\rho + \frac{3p}{c^2} \right) \quad + f\,(H, H')$$

Parameterizing Modified Gravity Perturbations

$$ds^2 = a^2\left[-(1+2\Psi)d\tau^2 + (1-2\Phi)d\vec{x}^2\right]$$

$$k^2\Psi = -\mu(a,k)4\pi G a^2 \rho\Delta$$

$$\eta(a,k) = \frac{\Phi}{\Psi}$$

$$k^2\left[\Phi+\Psi\right] = -\Sigma(a,k)8\pi G a^2 \rho\Delta$$

MGCLASS MG Cosmo Solver

Sakr & Martinelli 2021 arxiv 2112.14175

https://gitlab.com/zizgitlab/mgclass--ii

USJ 1875 Université Saint-Joseph de Beyrouth

$$k^2\Psi = -\mu(a,k)4\pi G a^2 \rho \Delta$$

$$\eta(a,k) = \frac{\Phi}{\Psi}$$

$$\delta' + \frac{k}{aH} v - 3\Phi' \ = \ 0,$$

$$v' + v - \frac{k}{aH}\Psi \ = \ 0 \ ,$$

$$p \equiv \frac{k}{aH} \qquad u \equiv pv \qquad E_m = \frac{\Omega_M}{a^3} \qquad E = \frac{H^2}{H_0^2}$$

$$\Delta' = \frac{-\frac{9E_m}{2E}\eta\mu\left[\frac{1-\eta}{\eta} + \frac{(\eta\mu)'}{\eta\mu}\right]\Delta + \left[3\frac{H'}{H} - p^2\right]u}{p^2 + \frac{9E_m}{2E}\eta\mu}$$

$$u' = -\left[2 + \frac{H'}{H}\right]u - \frac{3}{2}\frac{E_m}{E}\mu\Delta\,.$$

Sub Horizon Scales

$$\Delta' = -u$$

$$u' = -\left[2 + \frac{H'}{H}\right] u - \frac{3}{2}\frac{E_m}{E}\mu\Delta \, .$$

$$\Delta'' + \left[2 + \frac{H'}{H}\right]\Delta' - \frac{3}{2}\Omega_m(a)\mu\Delta = 0,$$

Super Horizon Scales

$$\Delta' = -\Delta\left[\frac{1-\eta}{\eta} + \frac{(\eta\mu)'}{\eta\mu}\right] + \frac{2}{3}\frac{H'H}{\eta\mu E_m}u$$

$$u' = -\left[2 + \frac{H'}{H}\right]u - \frac{3}{2}\frac{E_m}{E}\mu\Delta\ .$$

$$\Psi'' + \left(2\frac{\eta'}{\eta} - \frac{H''}{H'} + \frac{1}{\eta}\right)\Psi' + \left[\frac{\eta''}{\eta} - \frac{H''}{H'}\frac{\eta'}{\eta} + \left(\frac{H'}{H} - \frac{H''}{H'}\right)\frac{1}{\eta}\right]\Psi = \mathcal{O}\left(\frac{p^2}{\mu\eta}\right)$$

Practically …

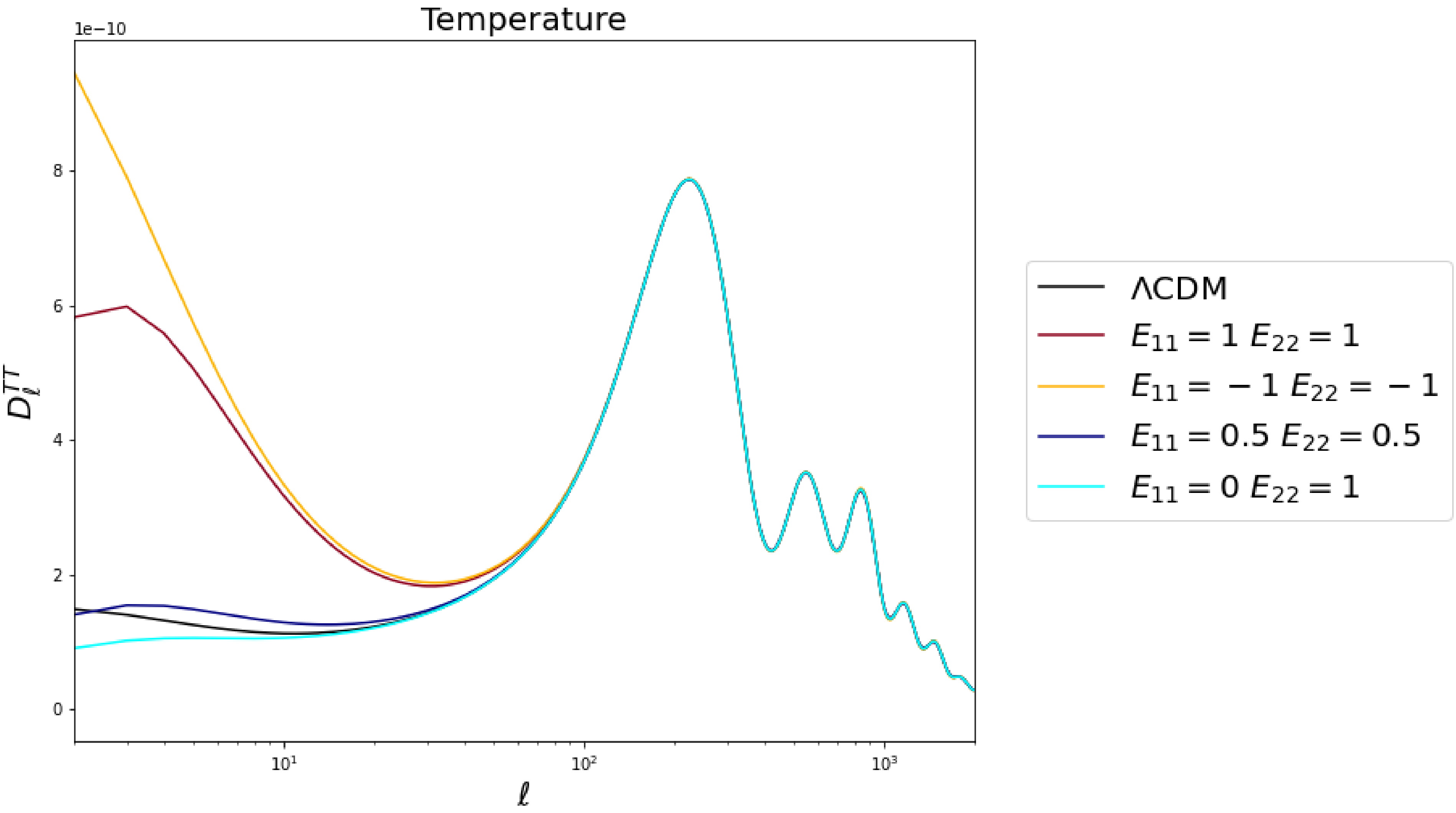
Planck : MG mu,eta parameterization

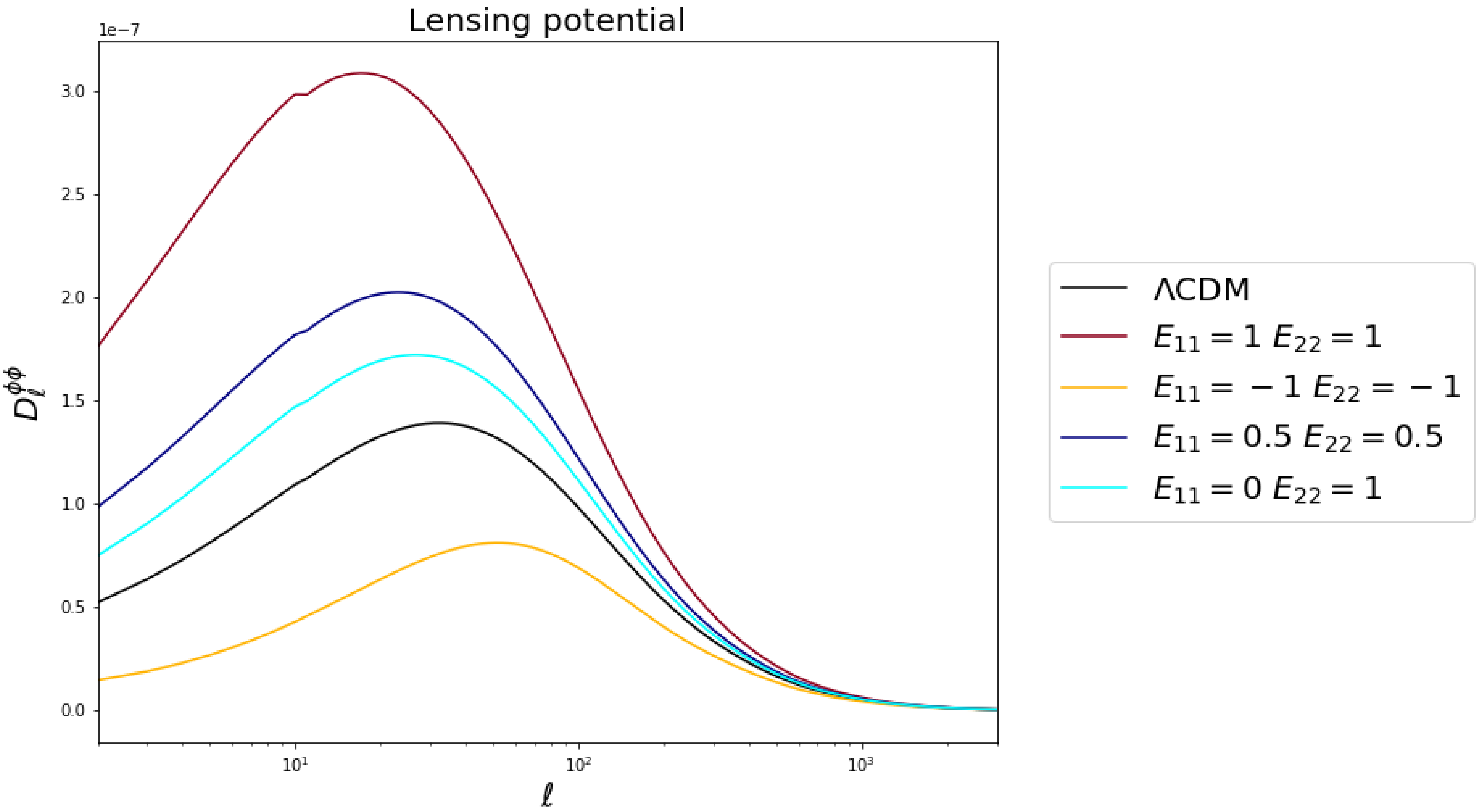
$$\mu(k,z) = 1 + f_1(z)\frac{1 + c_1\left(\frac{\mathcal{H}}{k^2}\right)}{1 + \left(\frac{\mathcal{H}}{k^2}\right)},$$

$$\eta(k,z) = 1 + f_2(z)\frac{1 + c_2\left(\frac{\mathcal{H}}{k^2}\right)}{1 + \left(\frac{\mathcal{H}}{k^2}\right)}.$$

$$f_i(z) = E_{i1} + E_{i2}\frac{z}{1+z}.$$

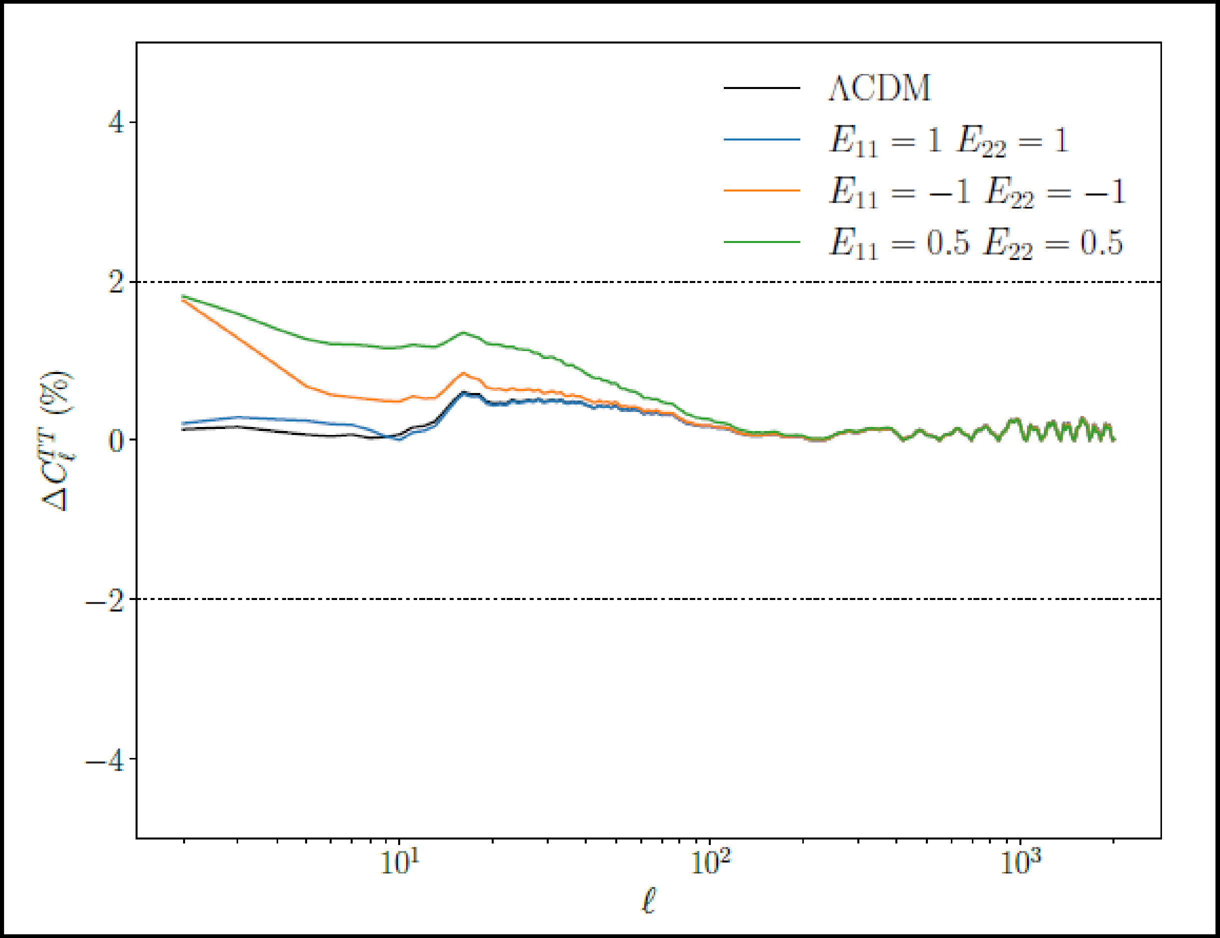
Reproduce fig. 1 of Planck 2015 results. XIV



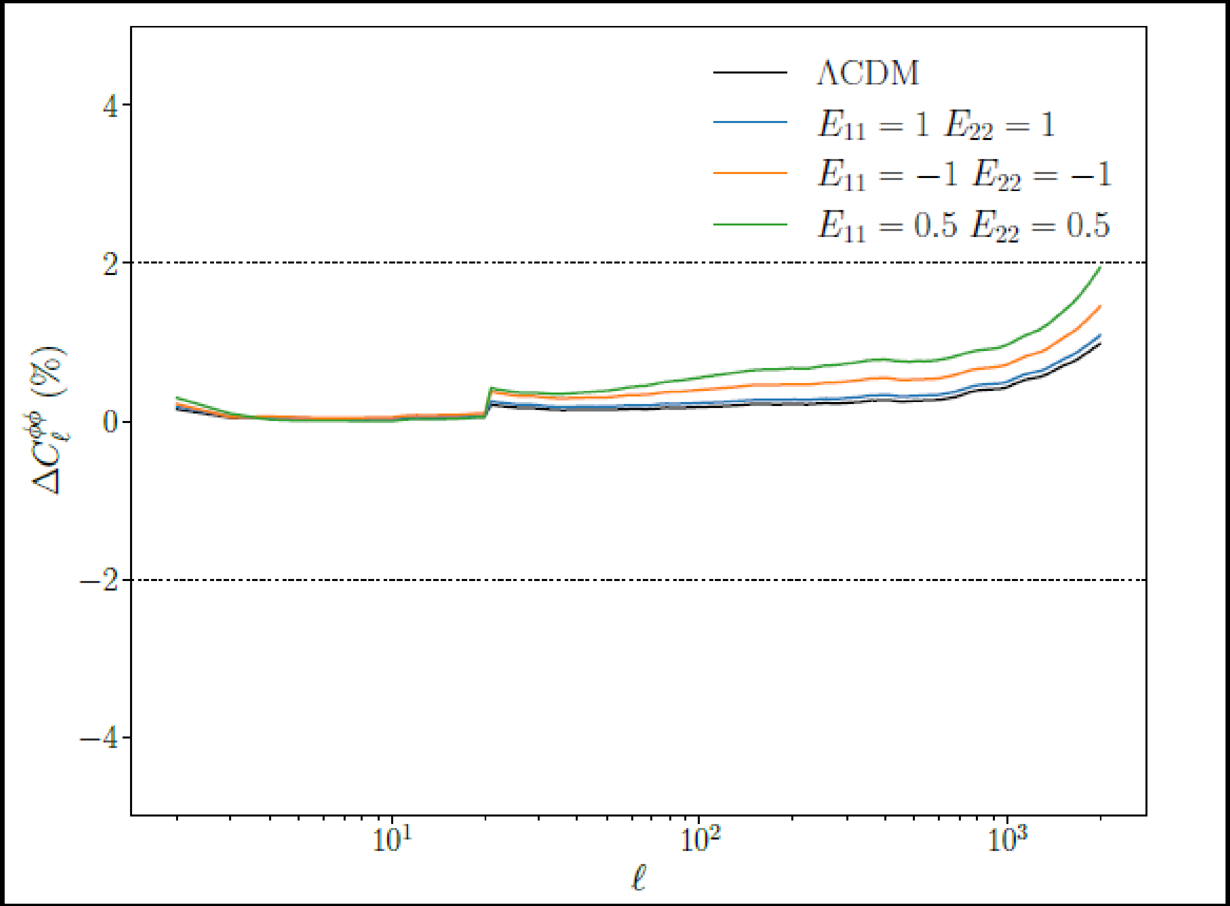


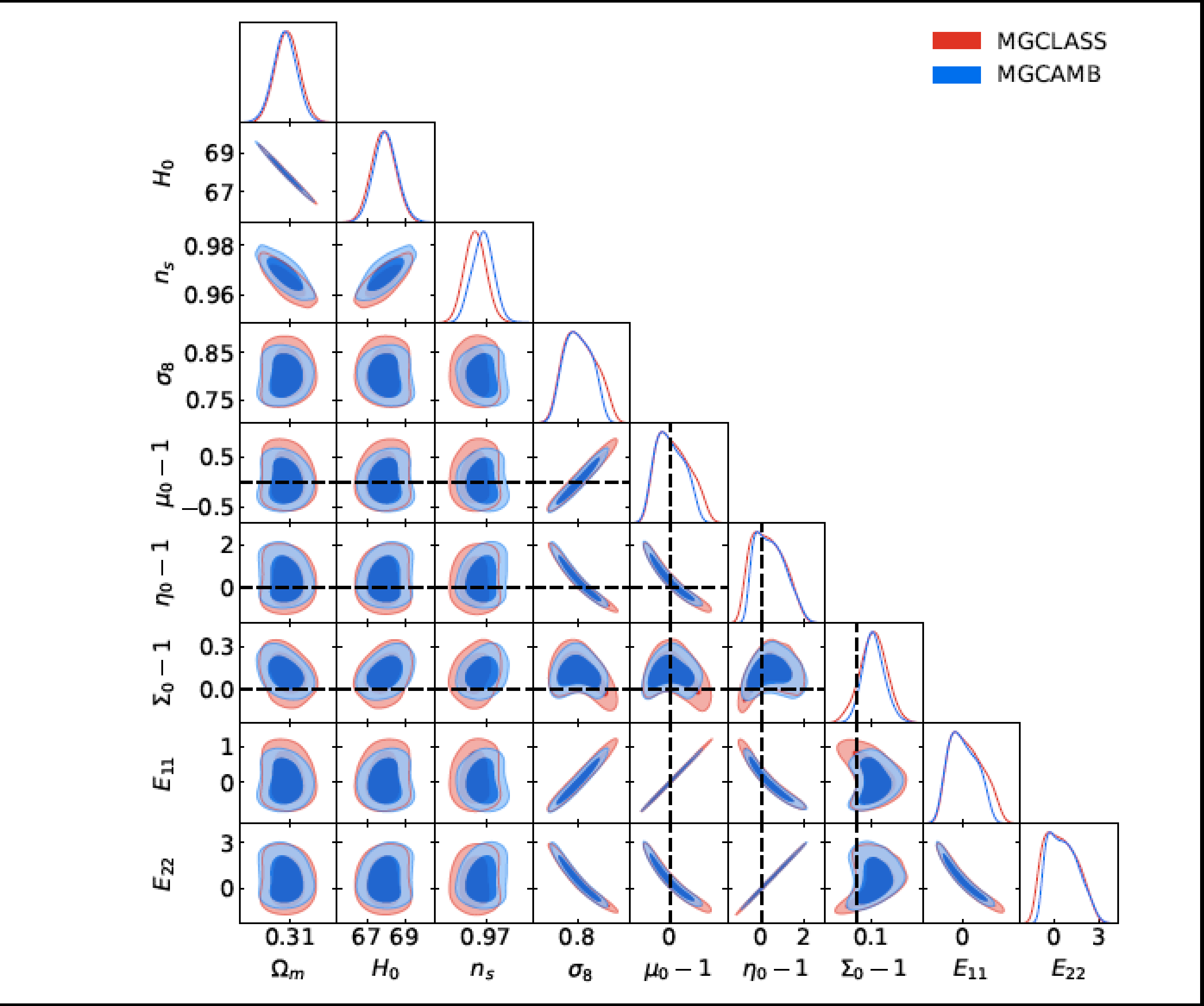
Lensing potential
1e−7
3.0
2.5
2.0
1.5
1.0
0.5
0.0
$D_\ell^{\phi\phi}$
10^1
10^2
10^3
ℓ
ΛCDM
$E_{11} = 1$ $E_{22} = 1$
$E_{11} = -1$ $E_{22} = -1$
$E_{11} = 0.5$ $E_{22} = 0.5$
$E_{11} = 0$ $E_{22} = 1$

MGCLASS vs MGCAMB …



MGCLASS vs MGCAMB …





MGCLASS
MGCAMB
H_0
69
67
n_s
0.98
0.96
σ_8
0.85
0.75
$\mu_0 - 1$
0.5
−0.5
$\eta_0 - 1$
2
0
$\Sigma_0 - 1$
0.3
0.0
E_{11}
1
0
E_{22}
3
0
0.31
67 69
0.97
0.8
0
0 2
0.1
0
0 3
Ω_m
H_0
n_s
σ_8
$\mu_0 - 1$
$\eta_0 - 1$
$\Sigma_0 - 1$
E_{11}
E_{22}

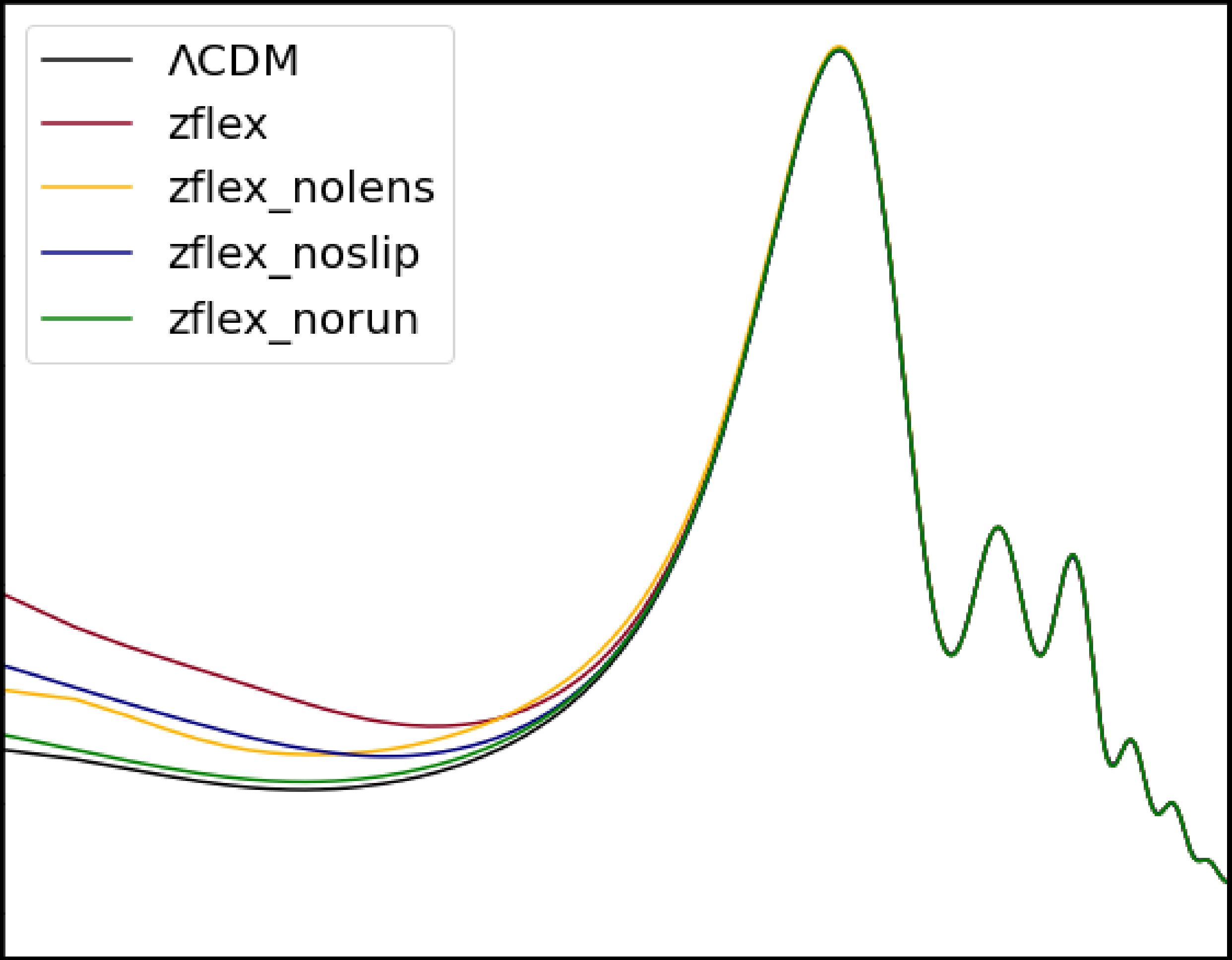
Cosmo Solver MGCLASS II

- `no run`: setting the Newtonian potential modified function to its GR value ($\mu(z,k) = 1$));
- `no slip`: setting the ratio between the two potentials to be one, thus effectively enforcing $\eta(z,k) = 1$;
- `no lens`: forces the code to work with a GR-like gravitational lensing ($\Sigma(z,k) = 1$), thus imposing a condition $\eta(k,z) = -1 + 2/\mu(k,z)$ that introduces a relation between otherwise free functions.

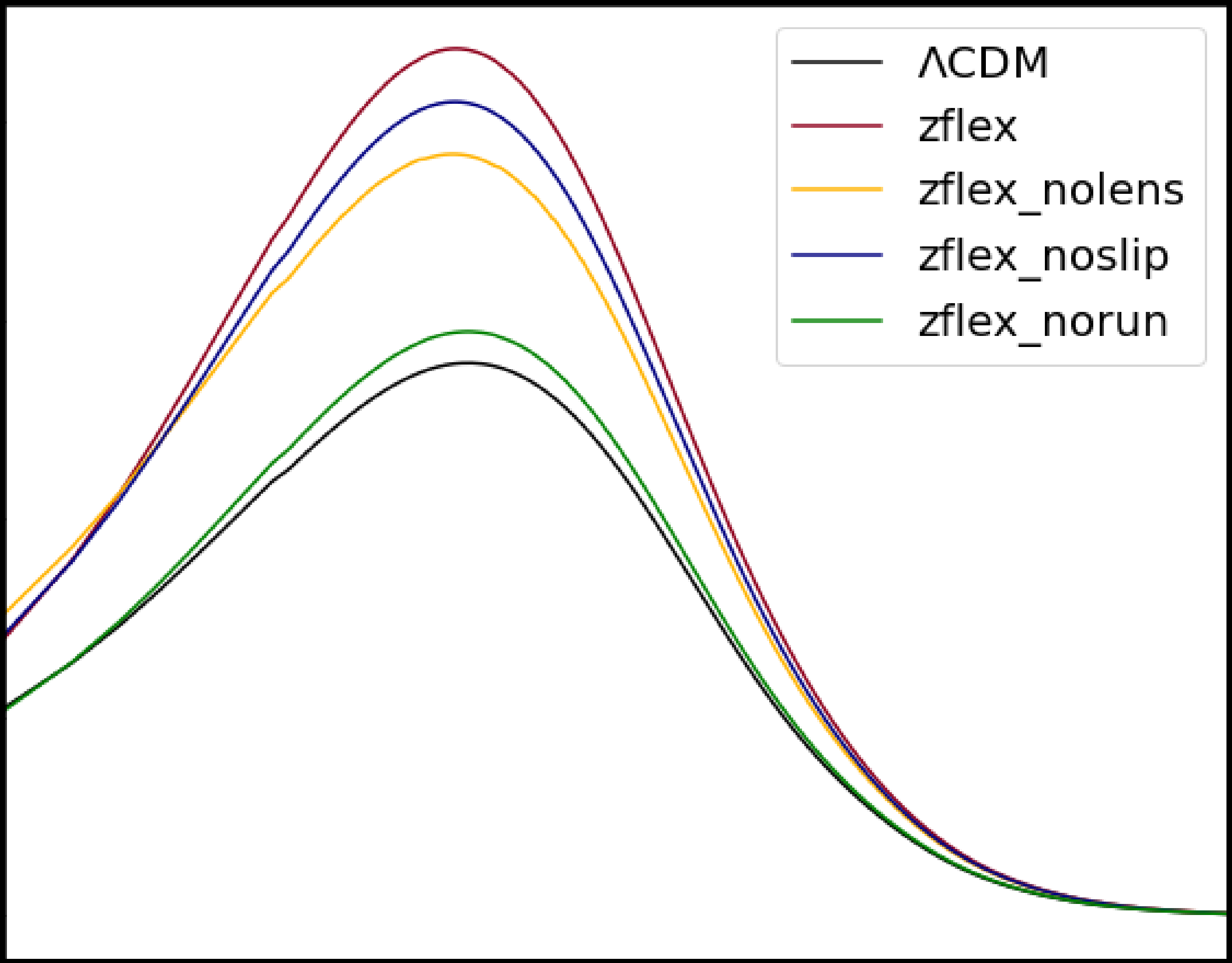
$$\mu(a) = 1 + g_\mu(1-a)^n - g_\mu(1-a)^{2n}\,,$$
$$\eta(a) = 1 + g_\eta(1-a)^n - g_\eta(1-a)^{2n}\,,$$

z_flex : g_mu, g_eta, znn

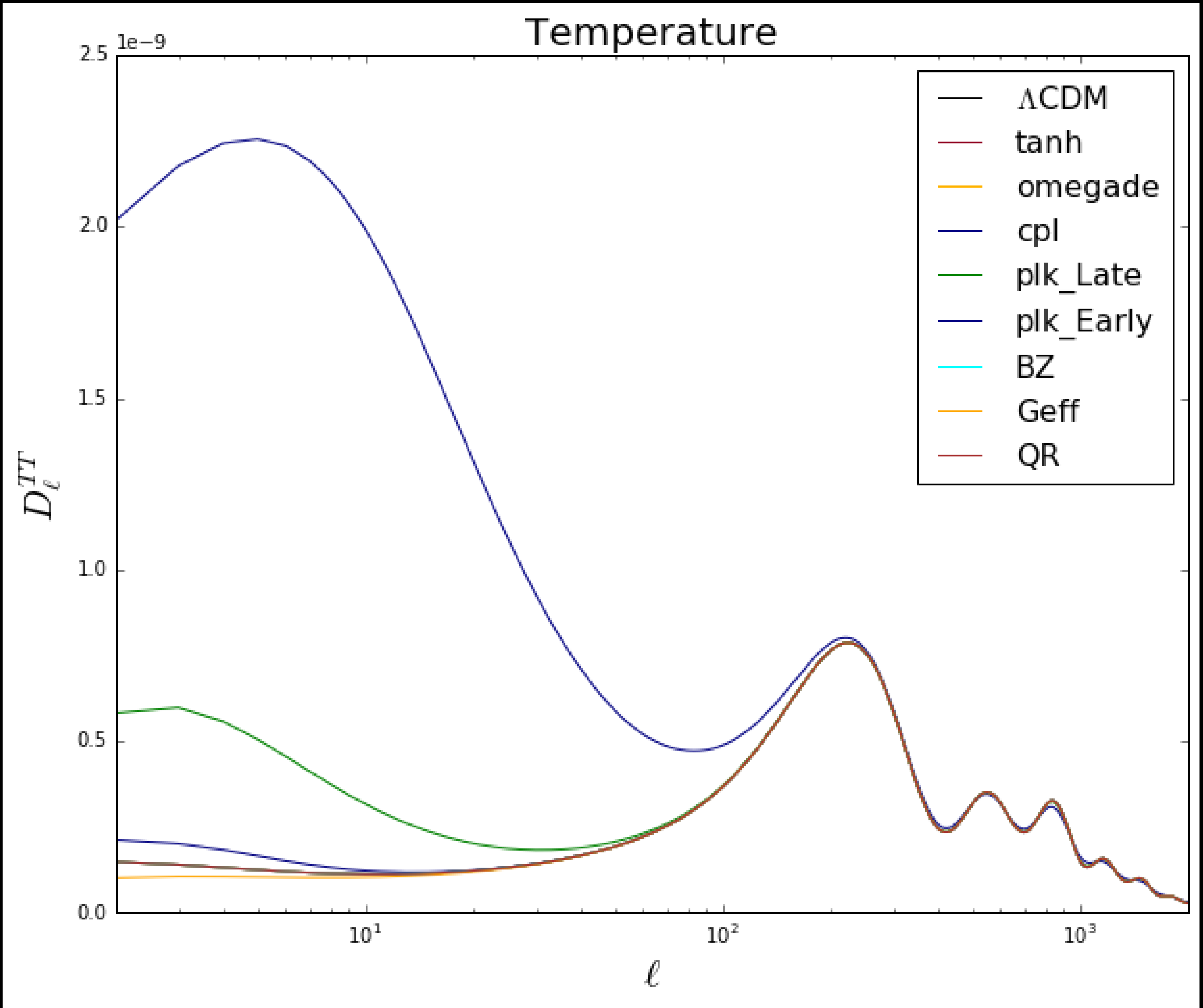
Cosmo Solver MGCLASS II



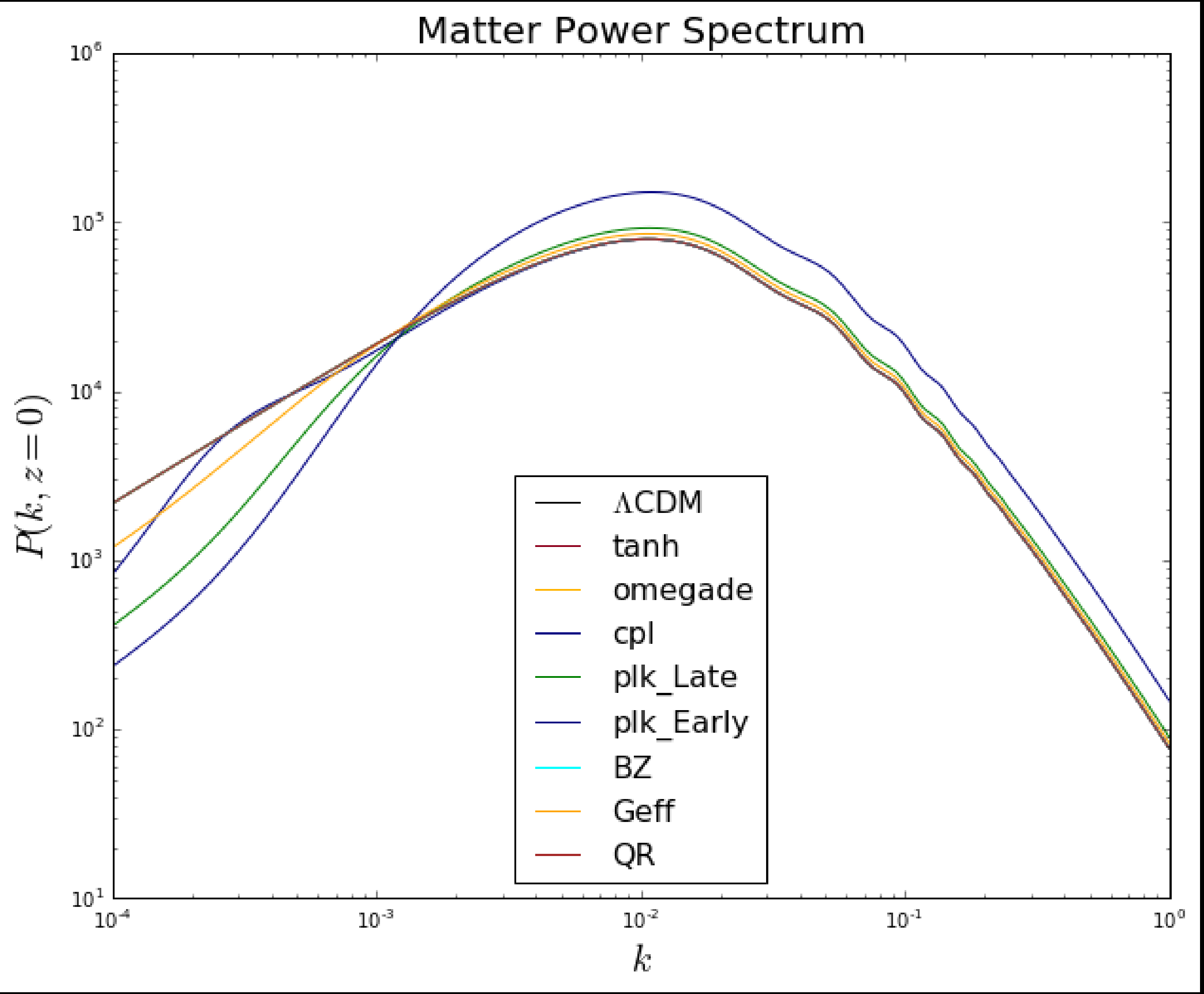
Cosmo Solver MGCLASS II

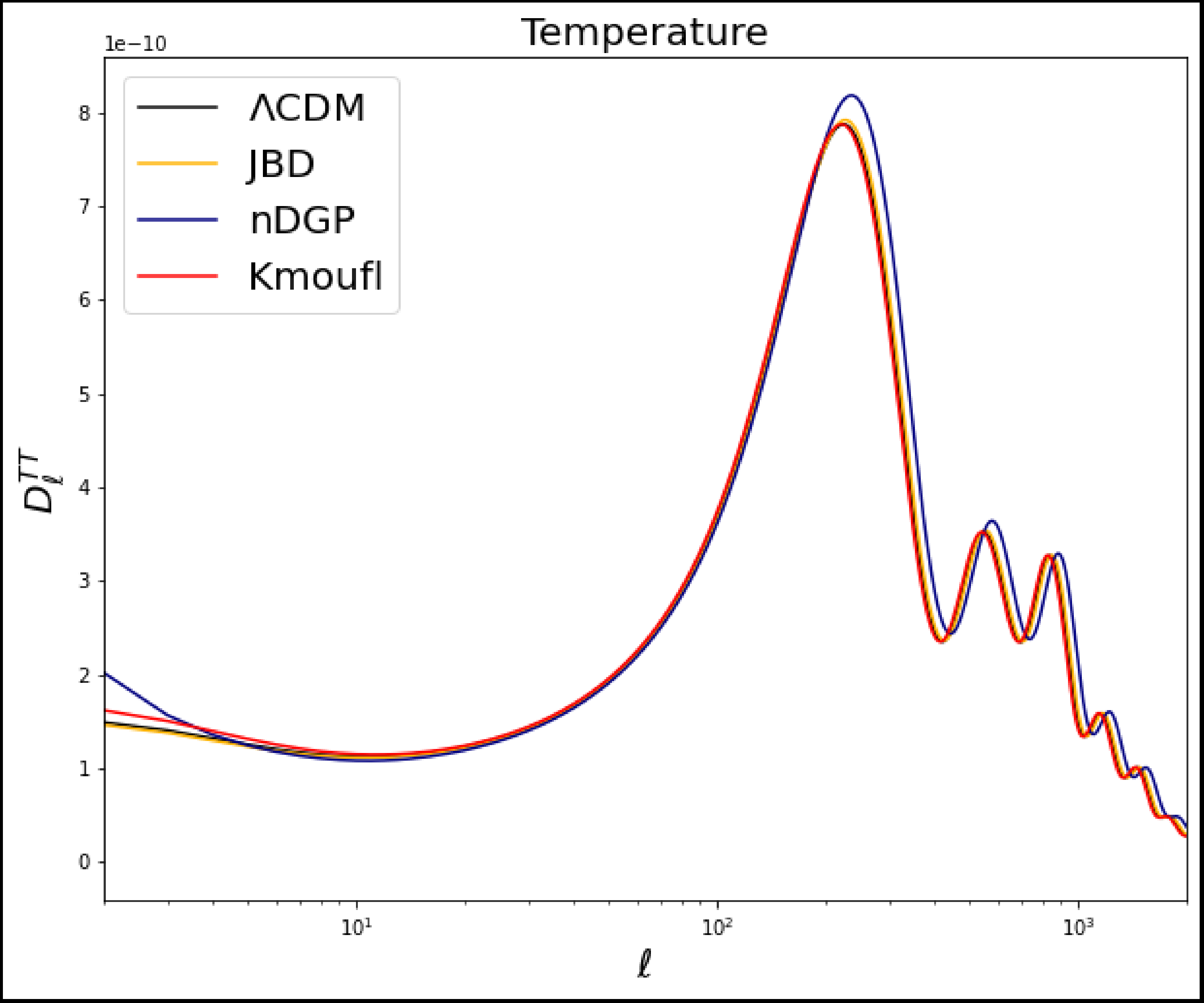


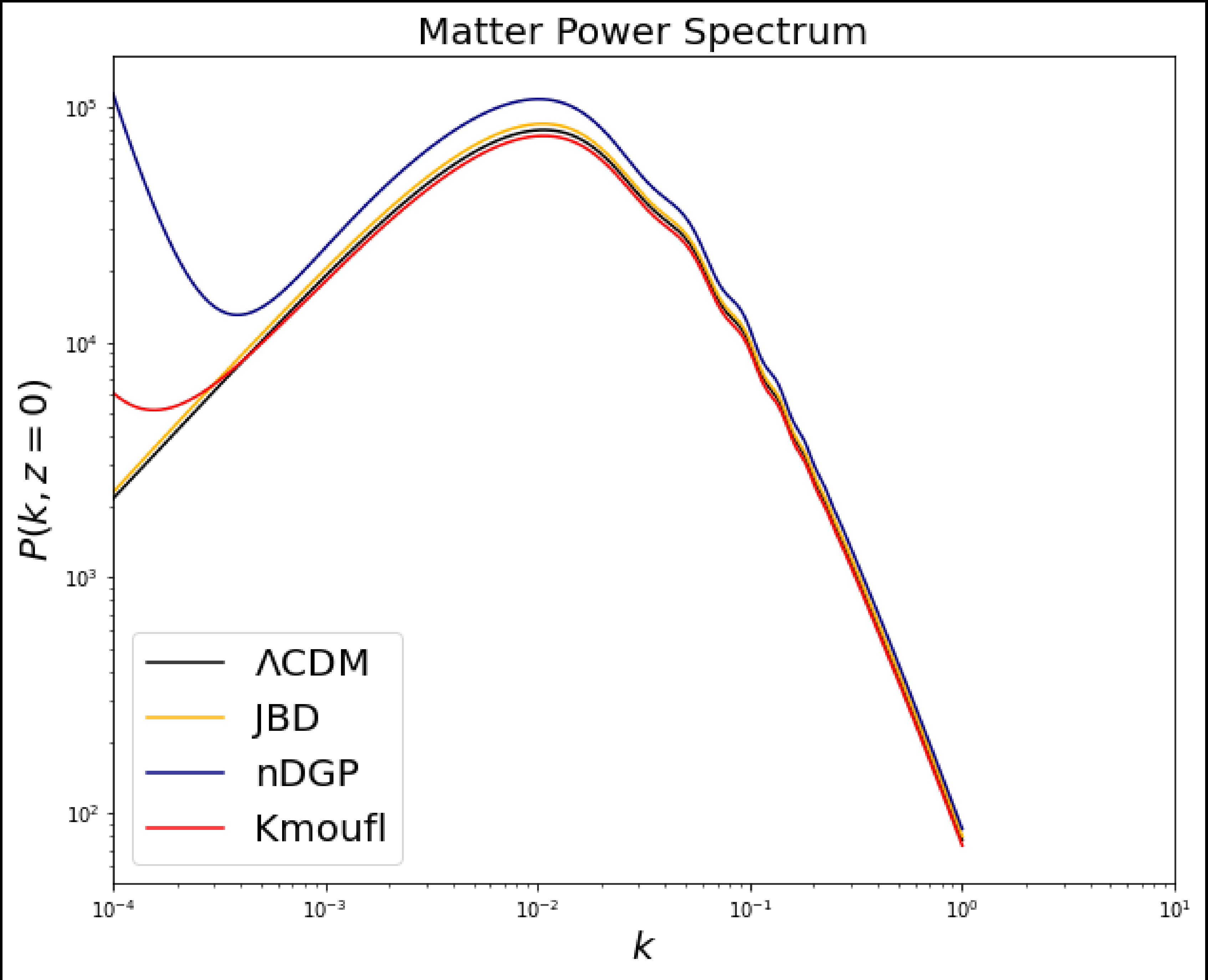
Cosmo Solver MGCLASS II



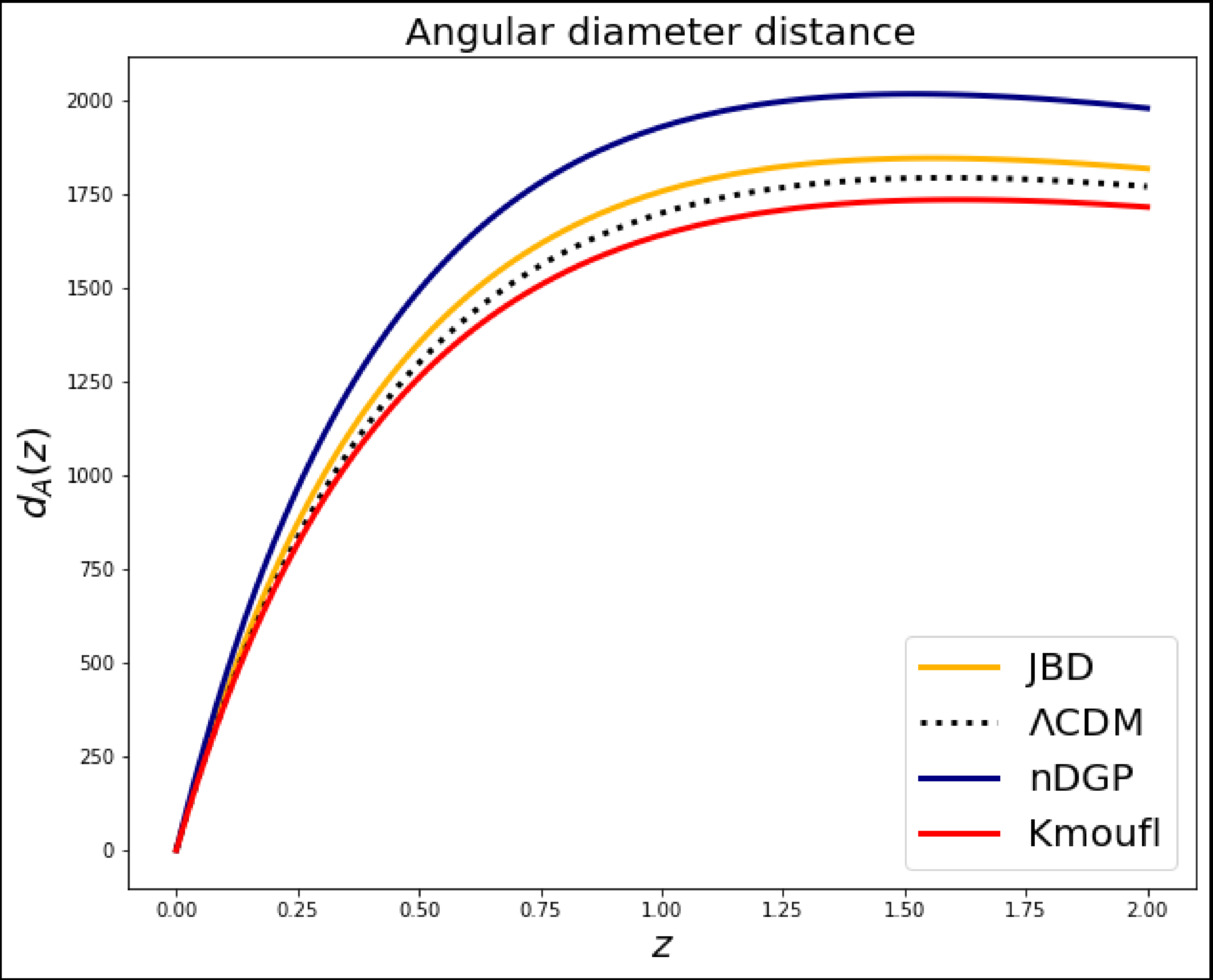
Cosmo Solver MGCLASS II




Temperature
1e−10
ΛCDM
JBD
nDGP
Kmoufl
8
7
6
5
4
3
2
1
0
D_ℓ^{TT}
10^1
10^2
10^3
ℓ



Matter Power Spectrum
$P(k, z=0)$
k
10^5
10^4
10^3
10^2
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
ΛCDM
JBD
nDGP
Kmoufl



Angular diameter distance
2000
1750
1500
1250
1000
750
500
250
0
$d_A(z)$
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
z
JBD
ΛCDM
nDGP
Kmoufl

Two files in principle :

input.c

modgrav.c

```
}else if (pba->mg_ansatz == z_flex_late) {

   // Set default values (GR limit by default)
   pba->mg_muz  = 0.0; // ~ 0 force to GR
   pba->mg_gamz = 0.0; // ~ 0 focce to GR
   pba->mg_zzn  = 0.0; // ~ 0 closest to GR

   // Load values from parameter file, if specified

   class_call(parser_read_double(pfc, "mg_muz", &param1, &flag1, errmsg),
              errmsg, errmsg);
   if (flag1 == _TRUE_){ pba->mg_muz = param1; }

   class_call(parser_read_double(pfc, "mg_zzn", &param1, &flag1, errmsg),
              errmsg, errmsg);
   if (flag1 == _TRUE_){ pba->mg_zzn = param1; }

   class_call(parser_read_double(pfc, "mg_gamz", &param1, &flag2, errmsg),
              errmsg, errmsg);
   if (flag2 == _TRUE_){ pba->mg_gamz = param1; }
```

$$\mu(a) = 1 + g_\mu \Omega_\Lambda^n - g_\mu \Omega_\Lambda^{2n}$$

$$\eta(a) = 1 + g_\eta \Omega_\Lambda^n - g_\eta \Omega_\Lambda^{2n}$$

https://gitlab.com/zizgitlab/mgclass--ii https://gitlab.com/zizgitlab/mgclass--ii

$$\mu(a) = 1 + g_\mu \Omega_\Lambda^n - g_\mu \Omega_\Lambda^{2n}$$

$$\eta(a) = 1 + g_\eta \Omega_\Lambda^n - g_\eta \Omega_\Lambda^{2n}$$

$$\dot{\mu}(a) = n.\dot{\Omega}_\Lambda.g_\mu \Omega_\Lambda^{n-1} - 2n.\dot{\Omega}_\Lambda.g_\mu \Omega_\Lambda^{2n-1}$$

$$\dot{\eta}(a) = n.\dot{\Omega}_\Lambda.g_\eta \Omega_\Lambda^{n-1} - 2n.\dot{\Omega}_\Lambda.g_\eta \Omega_\Lambda^{2n-1}$$

```
   }
else if (pba->mg_ansatz == z_flex_late) {
if (pba->mg_bckg == _TRUE_)

        pmg->mu = 1.0 + pba->mg_muz*pow(omegaDE*pba->Omega0_lambda,pba->mg_zzn)-pba->mg_muz*pow(omegaDE*pba->Omega0_lambda,2.0*pba->mg_zzn);

        pmg->mu_dot = pba->mg_muz*omegaDEdot*pba->Omega0_lambda*pba->mg_zzn*pow(omegaDE*pba->Omega0_lambda,pba->mg_zzn-1.0) -pba-
>mg_muz*omegaDEdot*pba->Omega0_lambda*2.0*pba->mg_zzn*pow(omegaDE*pba->Omega0_lambda,2.0*pba->mg_zzn-1.0);

        pmg->gamma = 1.0 + pba->mg_gamz*pow(omegaDE*pba->Omega0_lambda,pba->mg_zzn)-pba->mg_gamz*pow(omegaDE*pba->Omega0_lambda,2.0*pba-
>mg_zzn);

        pmg->gamma_dot = pba->mg_gamz*omegaDEdot*pba->Omega0_lambda*pba->mg_zzn*pow(omegaDE*pba->Omega0_lambda,pba->mg_zzn-1.0) -pba-
>mg_gamz*omegaDEdot*pba->Omega0_lambda*2.0*pba->mg_zzn*pow(omegaDE*pba->Omega0_lambda,2.0*pba->mg_zzn-1.0);

   }
```

Playing with μ and η, with a "back reacting" on/from the background

Cosmo Solver MGCLASS II

$$S = \int d^4x \sqrt{-g} \left(\frac{1}{2} f(R, \phi, X) + \mathcal{L}_m \right)$$

$$\mathcal{L} = \frac{F(\phi)}{2} R + X - U(\phi)$$

$$\mu(a, k) = \frac{1}{F(\phi)} \frac{F(\phi) + 2F_{,\phi}^2}{F(\phi) + \frac{3}{2} F_{,\phi}^2}$$

$$\eta(a, k) = \frac{F_{,\phi}^2}{F(\phi) + 2F_{,\phi}^2} ,$$

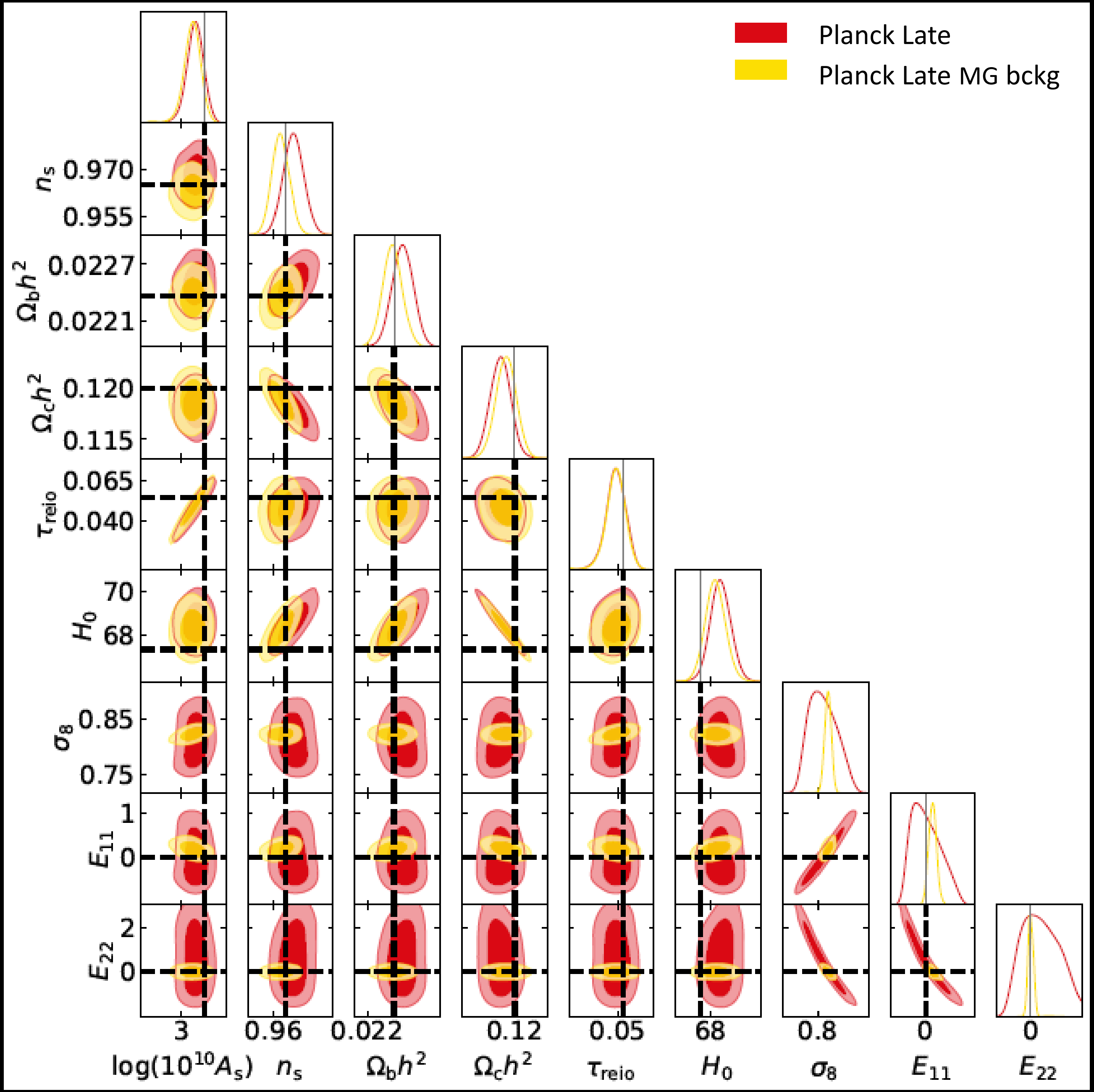
Cosmo Solver MGCLASS II

$$F = \frac{2}{\mu + \mu\eta}\,,$$

$$\dot{F} = -\frac{2(\dot{\mu}(1+\eta) + \mu\dot{\eta})}{(\mu + \mu\eta)^2}\,.$$

$$3FH^2 = \rho_m + \frac{1}{2}\dot{\phi}^2 - 3H\dot{F} + U$$

$$-2F\dot{H} = (\rho_\Lambda + p_\Lambda) + \ddot{F} - H.\dot{F} + \rho_{tot}$$



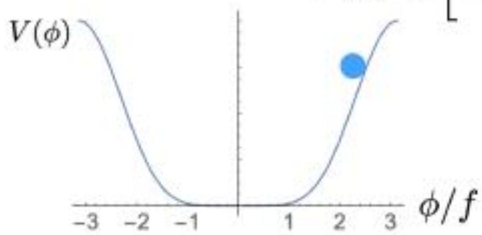
Planck Late
Planck Late MG bckg
n_s
0.970
0.955
$\Omega_b h^2$
0.0227
0.0221
$\Omega_c h^2$
0.120
0.115
τ_{reio}
0.065
0.040
H_0
70
68
σ_8
0.85
0.75
E_{11}
1
0
E_{22}
2
0
3
0.96
0.022
0.12
0.05
68
0.8
0
0
$\log(10^{10}A_s)$
n_s
$\Omega_b h^2$
$\Omega_c h^2$
τ_{reio}
H_0
σ_8
E_{11}
E_{22}

Recent work

Tensions reliefs

Early Dark Energy

$$V(\phi) \propto \left[1 - \cos\left(\frac{\phi}{f}\right)\right]^n$$



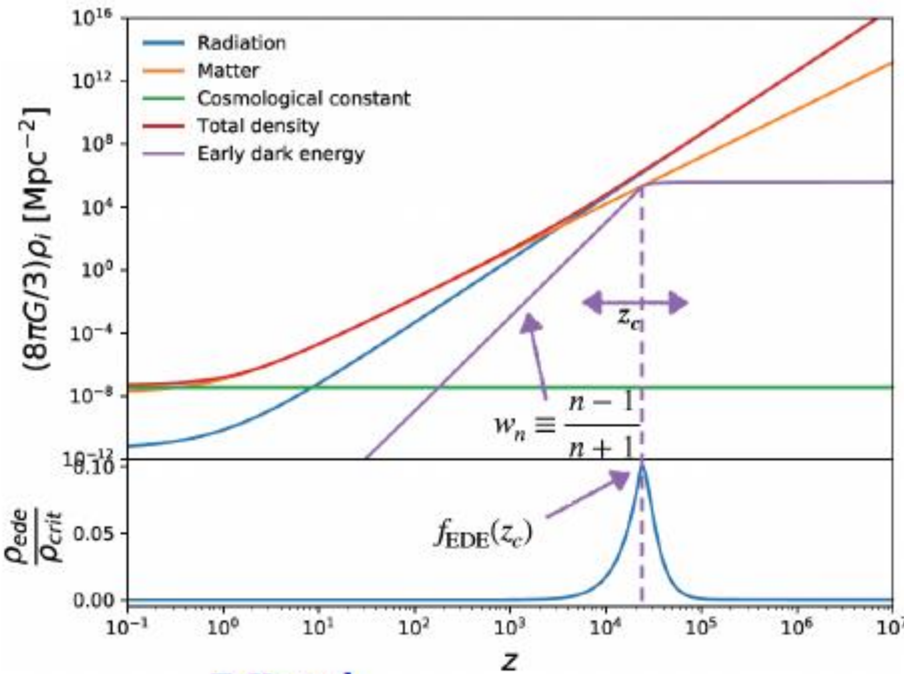
Scalar field initially frozen, then dilutes away equal or faster than radiation

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

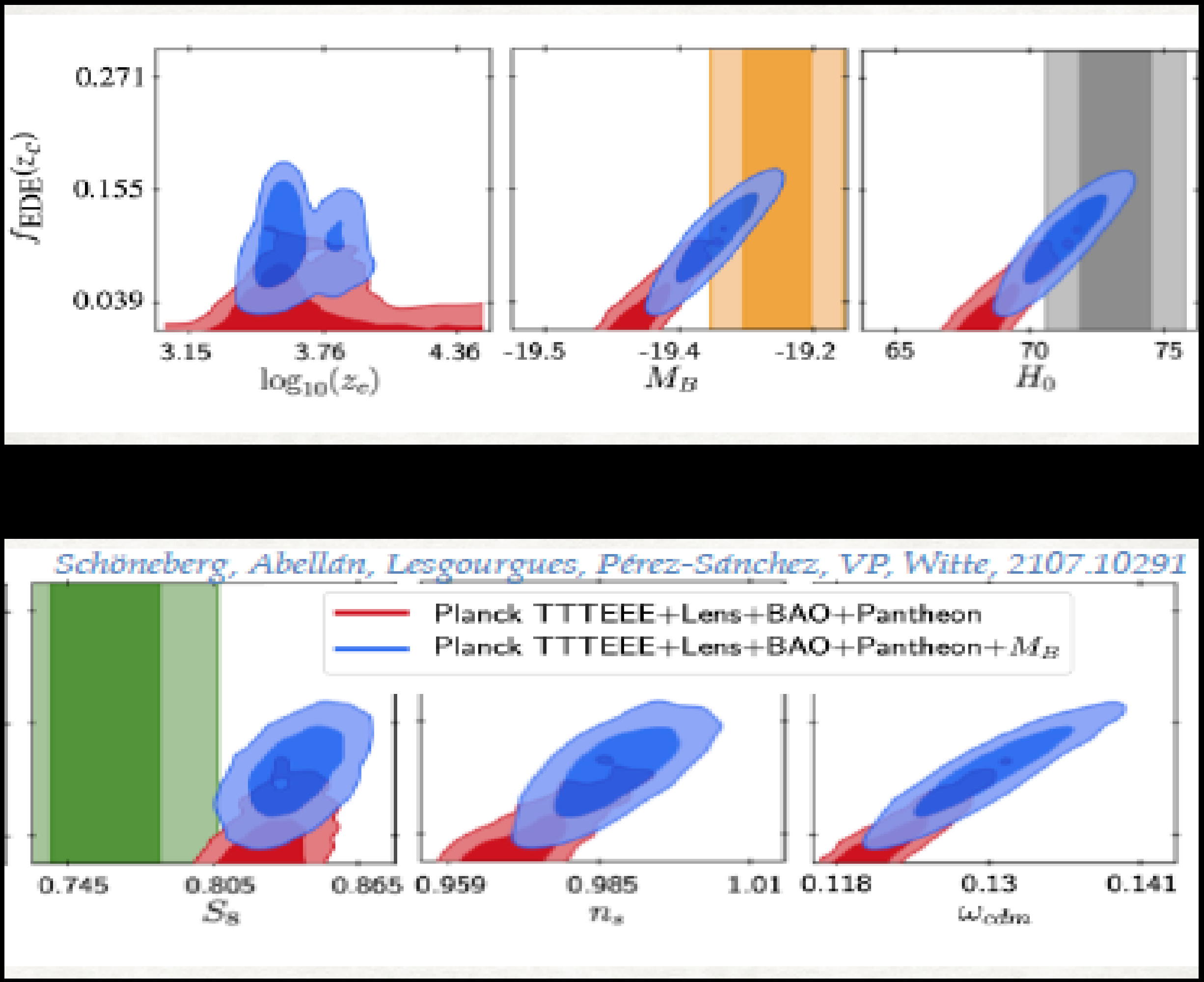
+ perturbed linear eqs.

The model is fully specified by

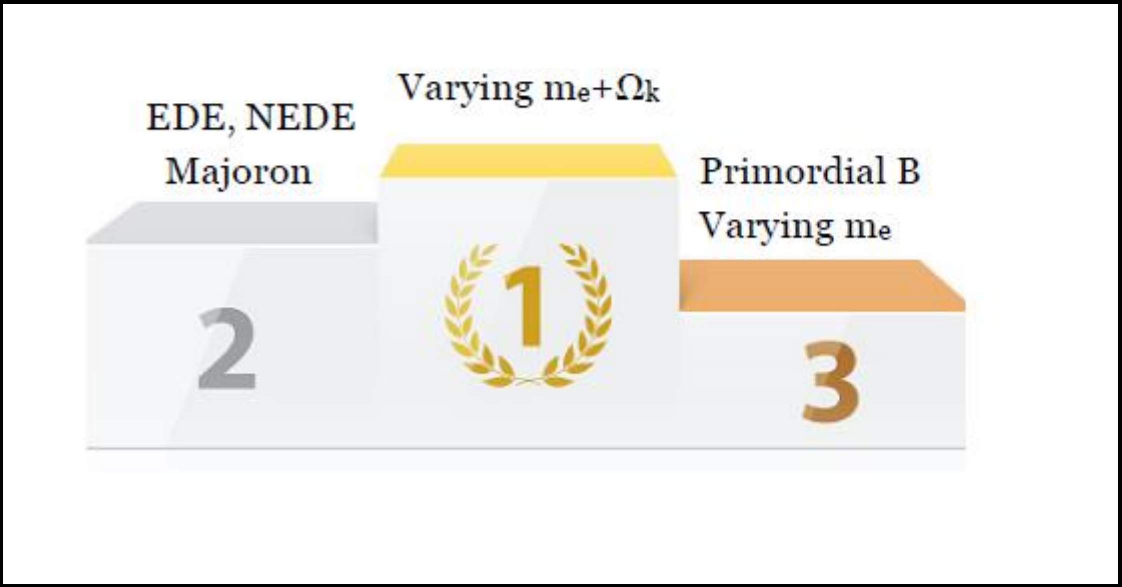
$$\{f_{\mathrm{EDE}}(z_c),\, z_c,\, n,\, \phi_i\}$$



T. Karwal



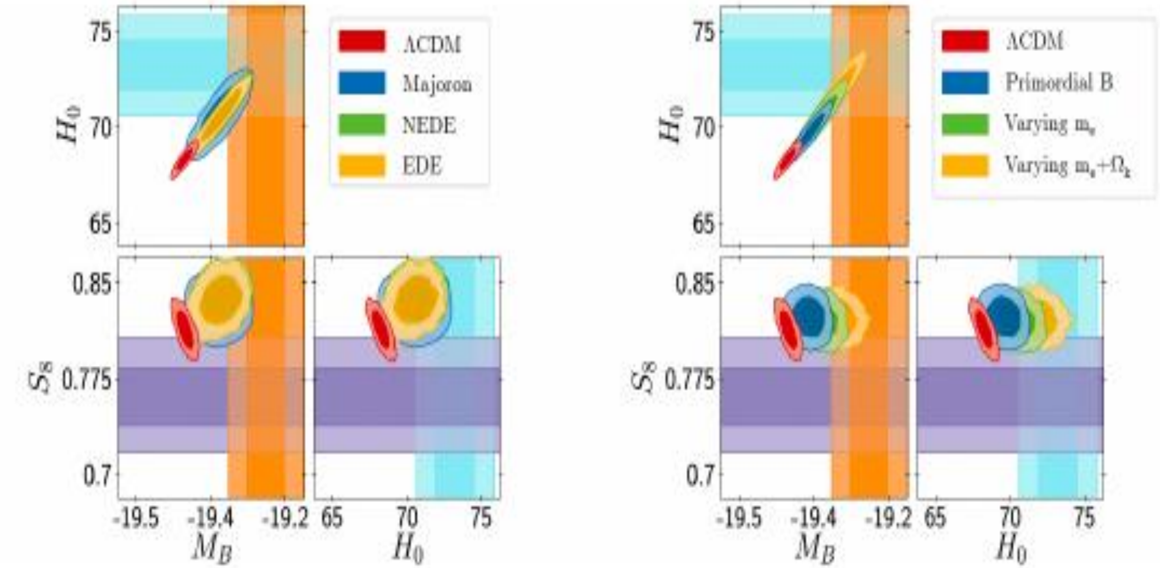
$f_{\rm EDE}(z_c)$
0.271
0.155
0.039
3.15
3.76
4.36
$\log_{10}(z_c)$
-19.5
-19.4
-19.2
M_B
65
70
75
H_0
Schöneberg, Abellán, Lesgourgues, Pérez-Sánchez, VP, Witte, 2107.10291
Planck TTTEEE+Lens+BAO+Pantheon
Planck TTTEEE+Lens+BAO+Pantheon+M_B
0.745
0.805
0.865
S_8
0.959
0.985
1.01
n_s
0.118
0.13
0.141
ω_{cdm}



Schöneberg, GFA, Pérez, Witte, Poulin, Lesgourgues 2107.10291

Results of the contest

Unfortunately, the most successful models are unable to explain the S_8 tension



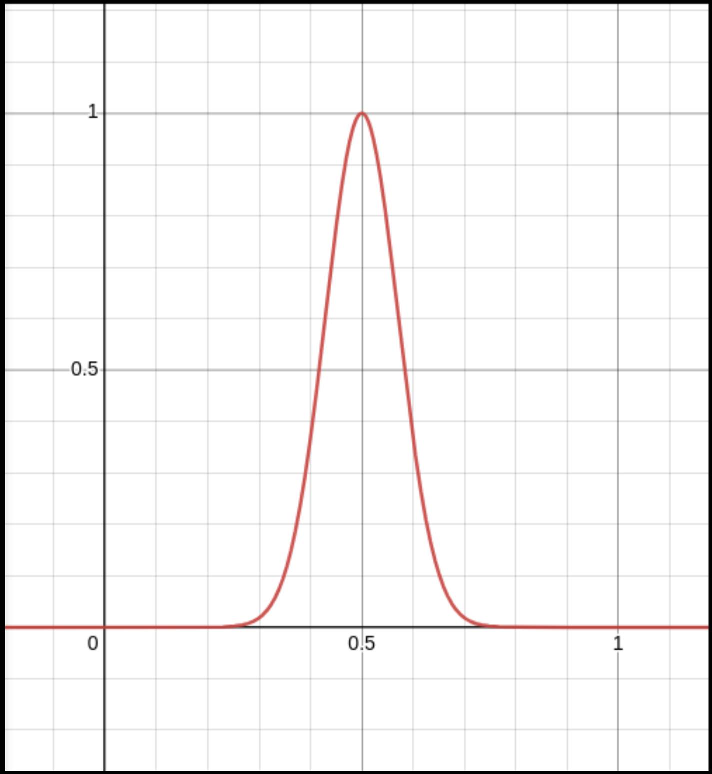
Schöneberg, GFA, Pérez, Witte, Poulin, Lesgourgues 2107.10291

Late and early has problems why not trying modifications at intermediate times

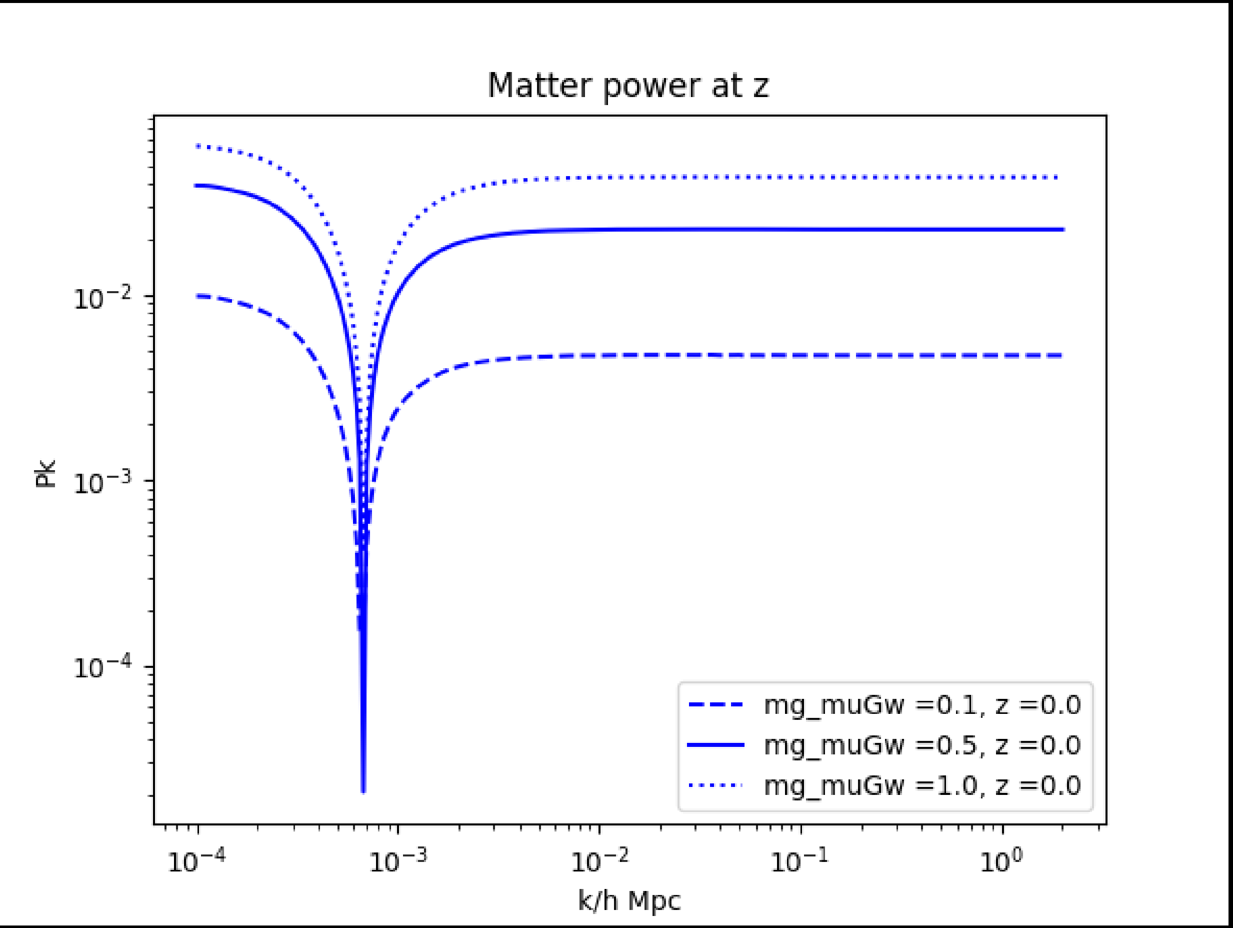
$$1 + \mu e^{-\left(\frac{(x-bin)}{\Delta_{bin}}\right)^2}$$

$$1 + \eta e^{-\left(\frac{(x-bin)}{\Delta_{bin}}\right)^2}$$

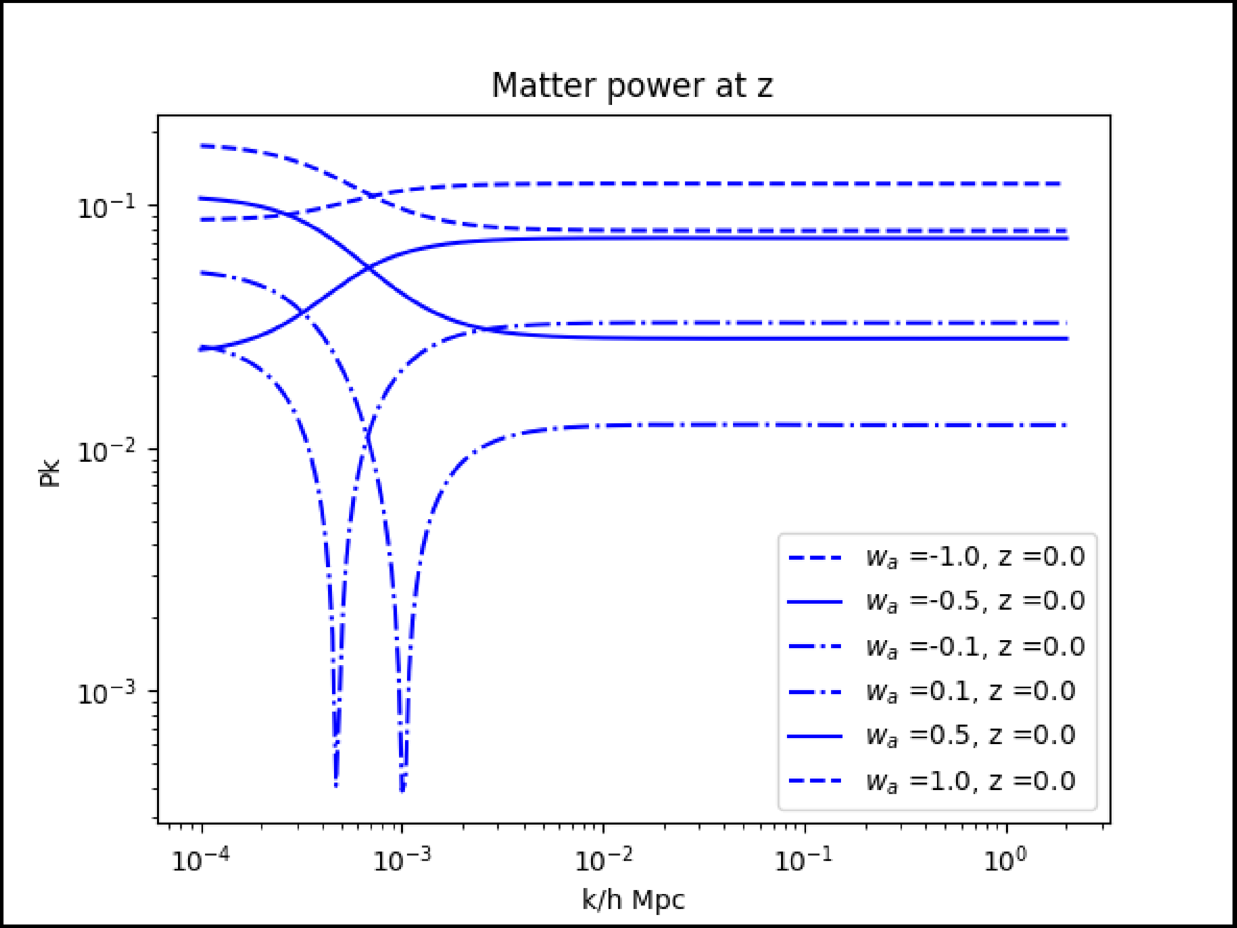
$$w_0 + w_a e^{-\left(\frac{(x-bin)}{\Delta_{bin}}\right)^2}$$



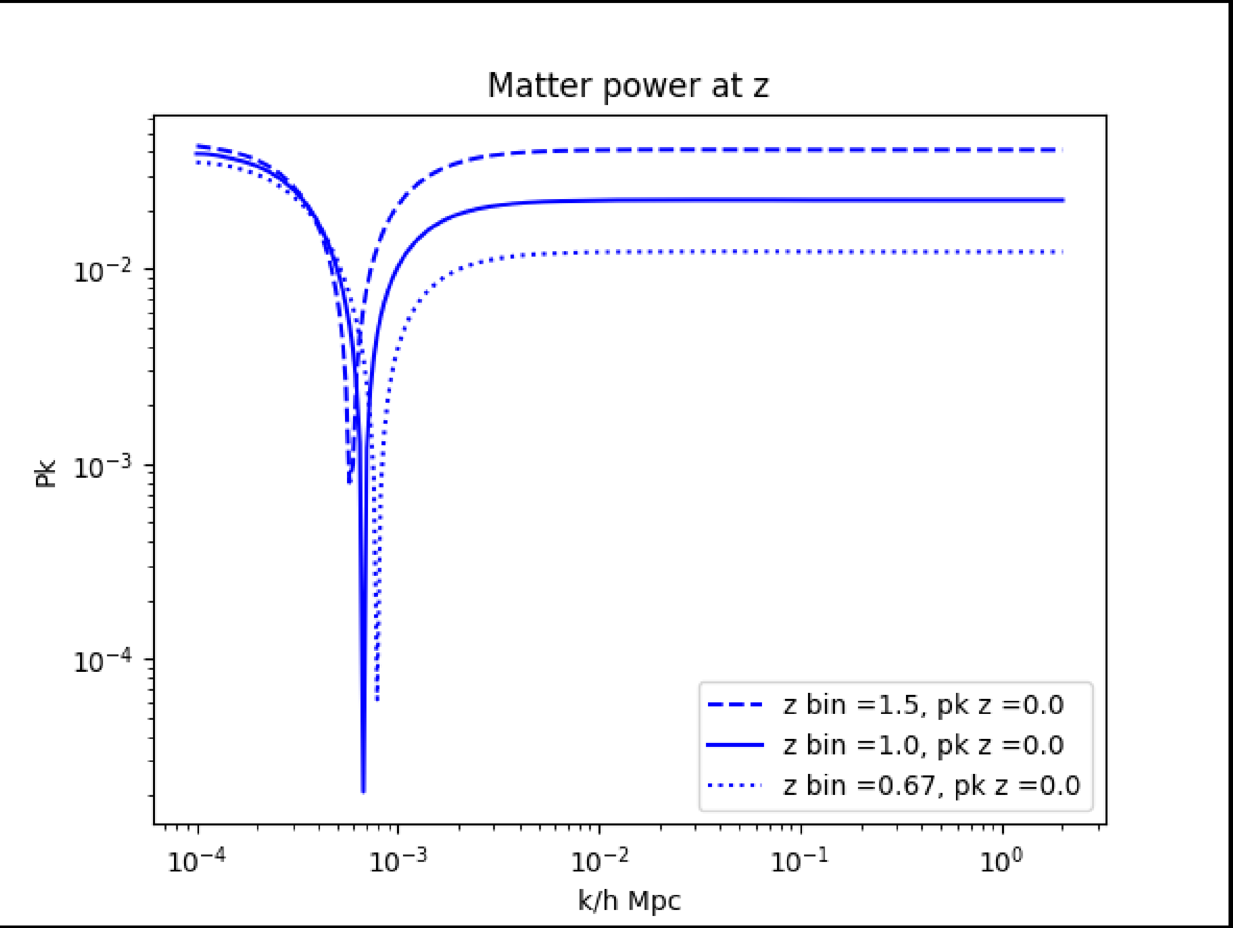
$$e^{-\left(\frac{(x-0.5)}{0.1}\right)^2}$$

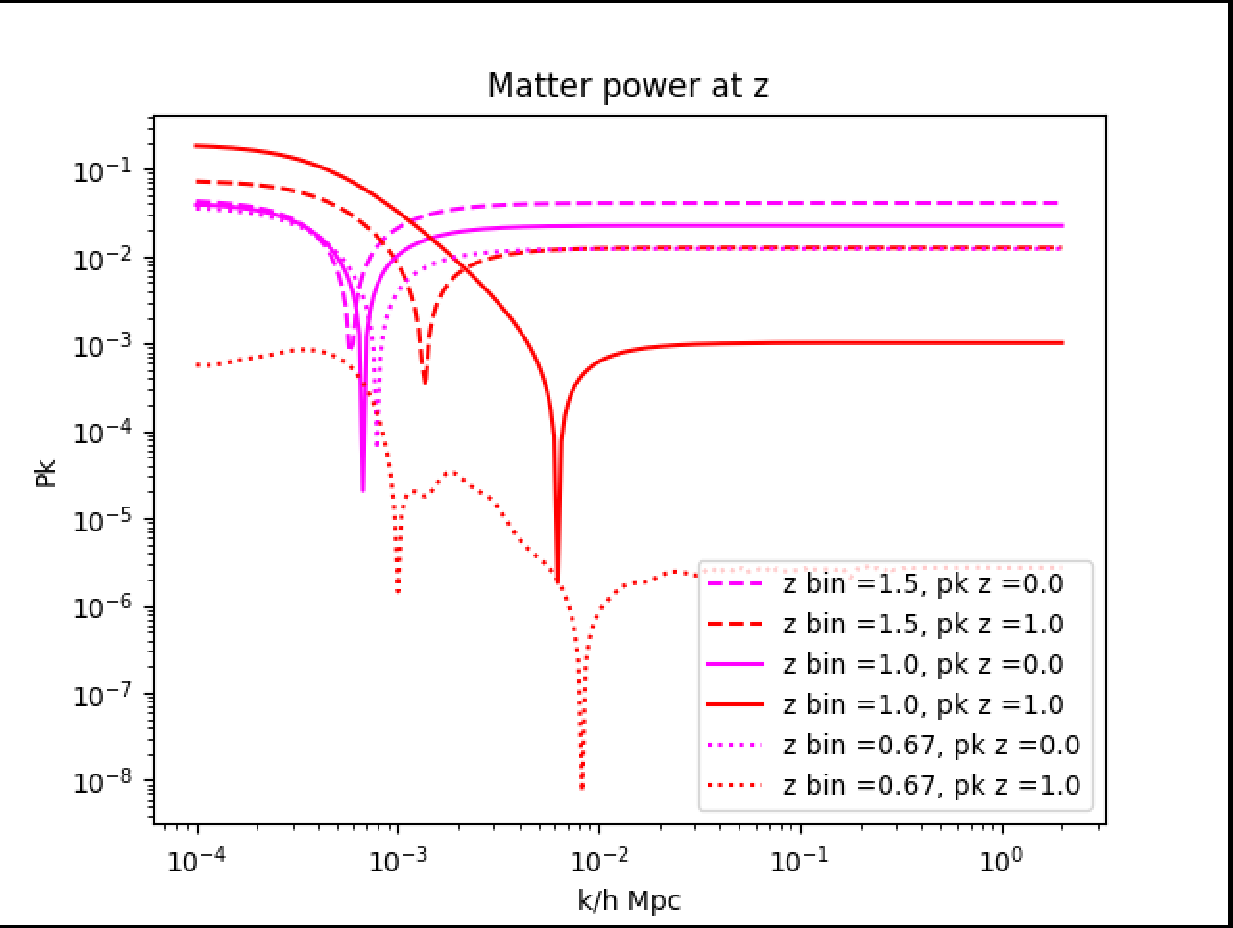


Matter power at z
Pk
10^{-2}
10^{-3}
10^{-4}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
k/h Mpc
mg_muGw =0.1, z =0.0
mg_muGw =0.5, z =0.0
mg_muGw =1.0, z =0.0

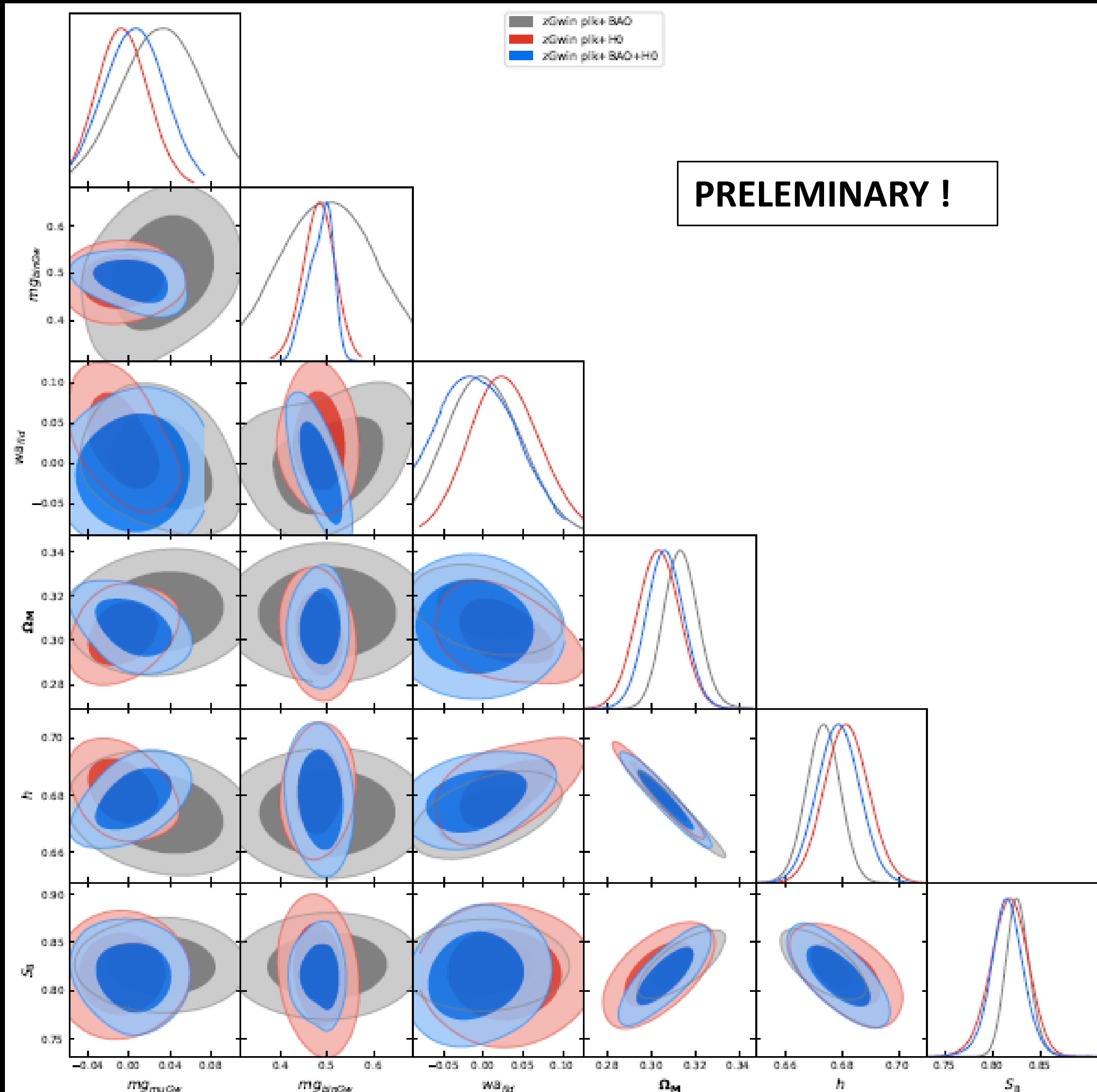


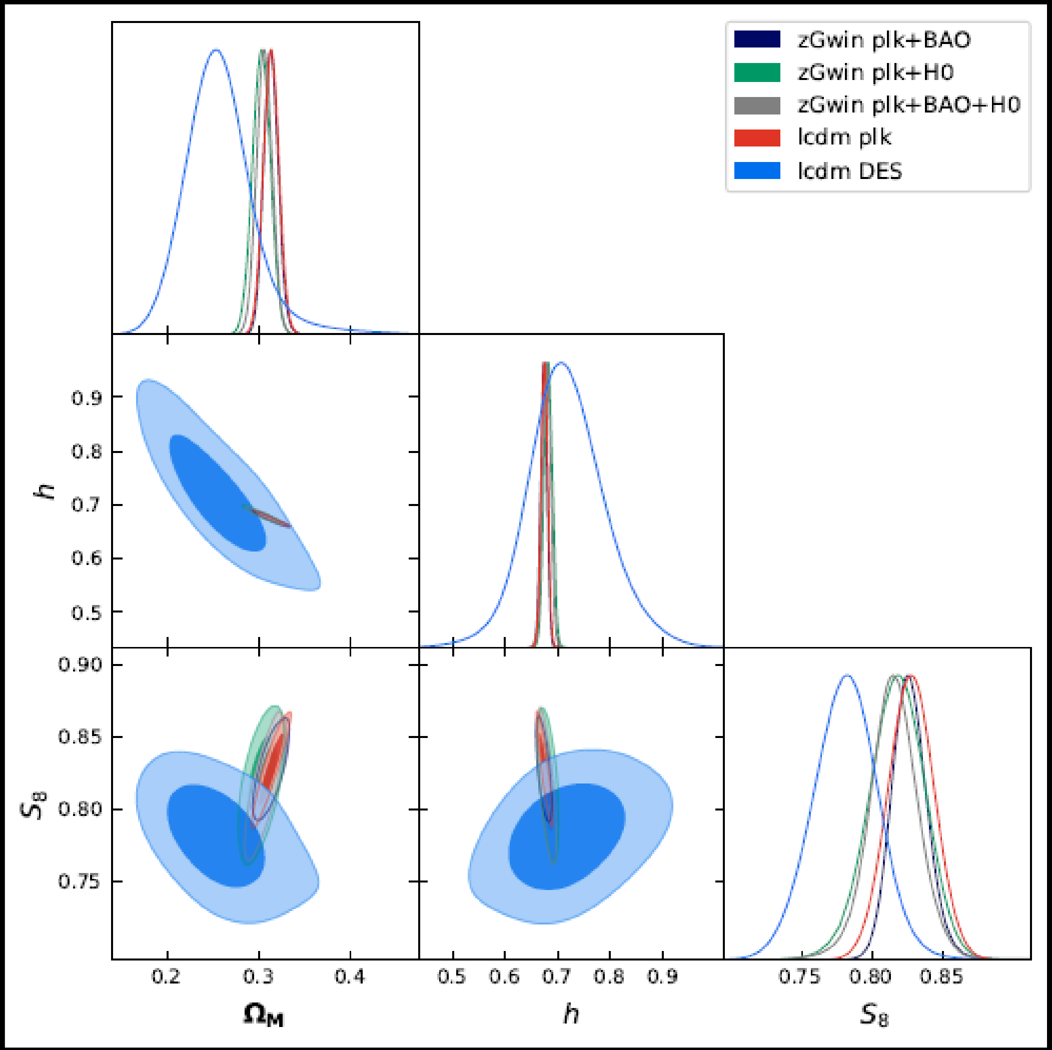
Matter power at z
Pk
k/h Mpc
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
w_a =-1.0, z =0.0
w_a =-0.5, z =0.0
w_a =-0.1, z =0.0
w_a =0.1, z =0.0
w_a =0.5, z =0.0
w_a =1.0, z =0.0


Matter power at z
Pk
10^{-2}
10^{-3}
10^{-4}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
k/h Mpc
z bin =1.5, pk z =0.0
z bin =1.0, pk z =0.0
z bin =0.67, pk z =0.0

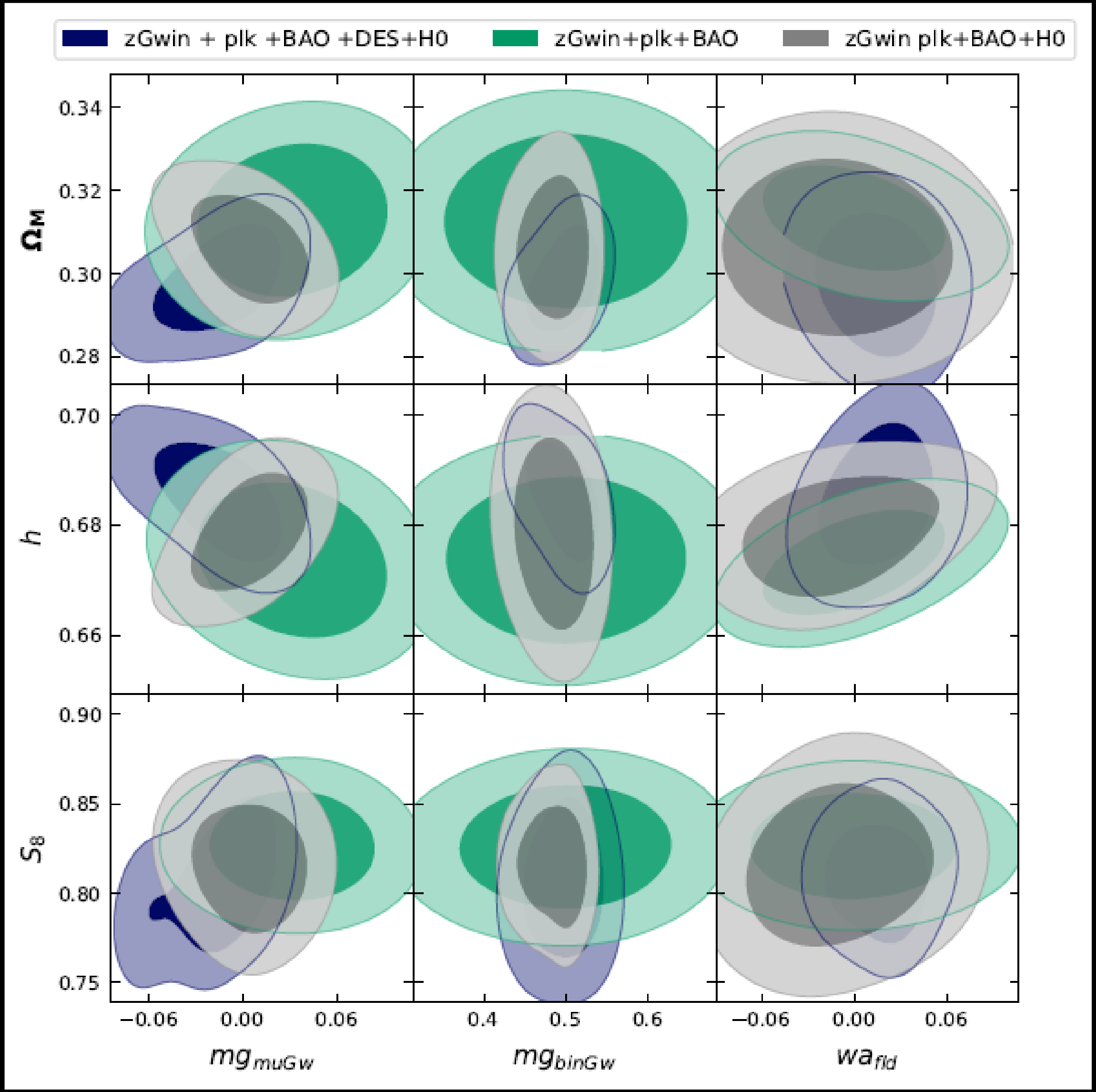

Matter power at z
Pk
k/h Mpc
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
z bin =1.5, pk z =0.0
z bin =1.5, pk z =1.0
z bin =1.0, pk z =0.0
z bin =1.0, pk z =1.0
z bin =0.67, pk z =0.0
z bin =0.67, pk z =1.0

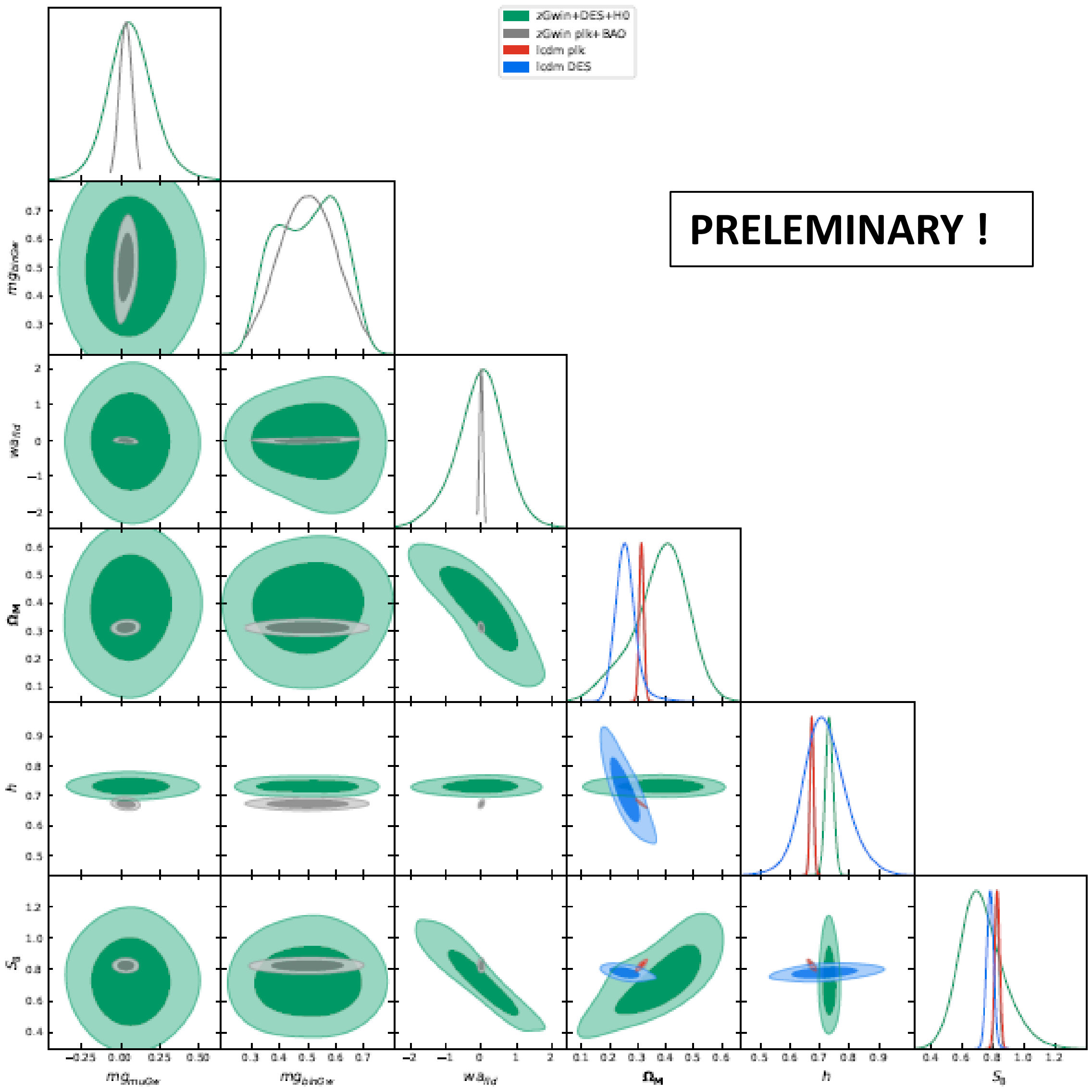
- *Plk 2018 TT,TE,EE high low ell + lens*
- *BAO low & high redshift measures*
- *H_0 Shoes*
- *DES 3x2 probe Y1 (linear scales cut)*


zGwin plk+ BAO
zGwin plk+ H0
zGwin plk+ BAO+H0
PRELEMINARY !
Ω_M
h
S_8



zGwin plk+BAO
zGwin plk+H0
zGwin plk+BAO+H0
lcdm plk
lcdm DES
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0.75
0.80
0.85
0.90
Ω_M
h
S_8


zGwin + plk +BAO +DES+H0
zGwin+plk+BAO
zGwin plk+BAO+H0
Ω_M
h
S_8
mg_{muGw}
mg_{binGw}
wa_{fld}


zGwin+DES+H0
zGwin plk+ BAO
lcdm plk
lcdm DES
PRELEMINARY !
Ω_M
h
S_8

Summary :

- Use https://gitlab.com/zizgitlab/mgclass--ii
- New phenomenology that emphasize on intermediate redshifts
- It does not solve the tensions especially H_0
- A preference though for $z = 1$

Thank you