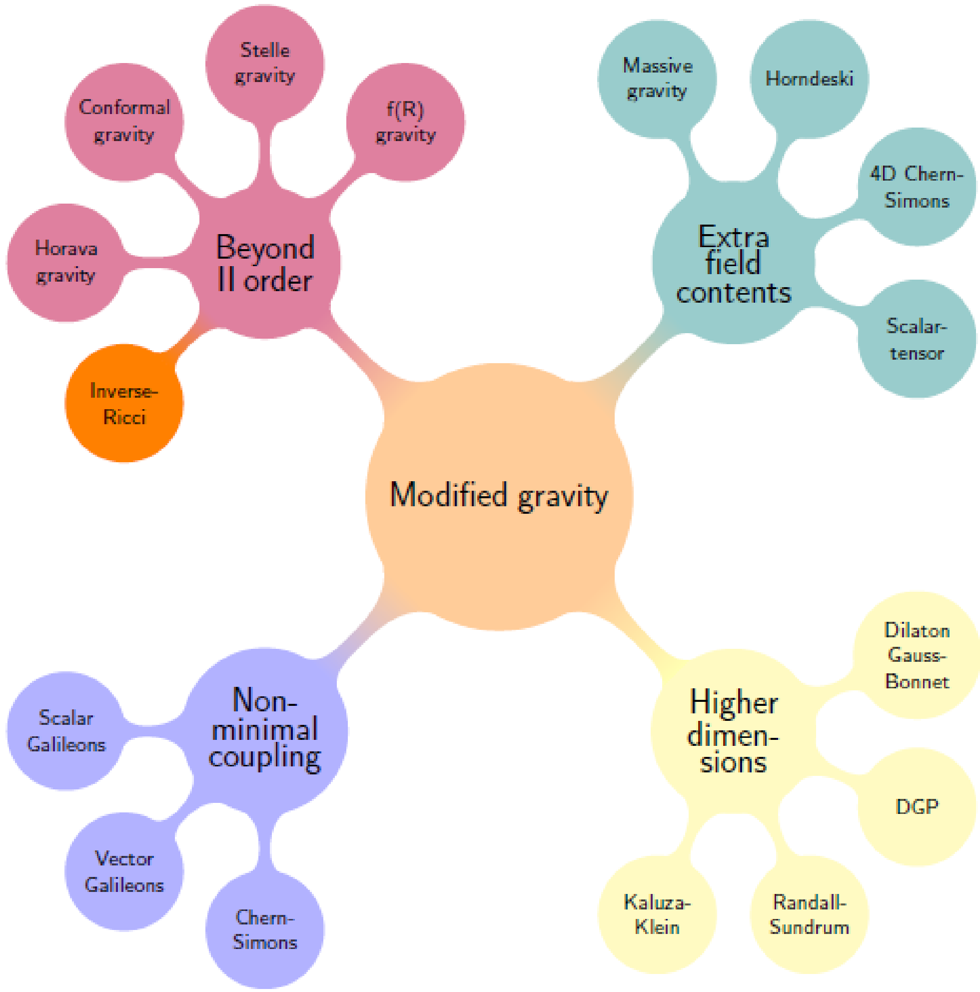
MGCLASS: modified gravity cosmological solver.

Heidelberg

Ziad Sakr - SKA SWG Meeting

Manchester : January 2023

Modified Gravity Landscape



See previous Gomes talk for more …

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

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

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

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

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

Parameterizing Modified Gravity Perturbations

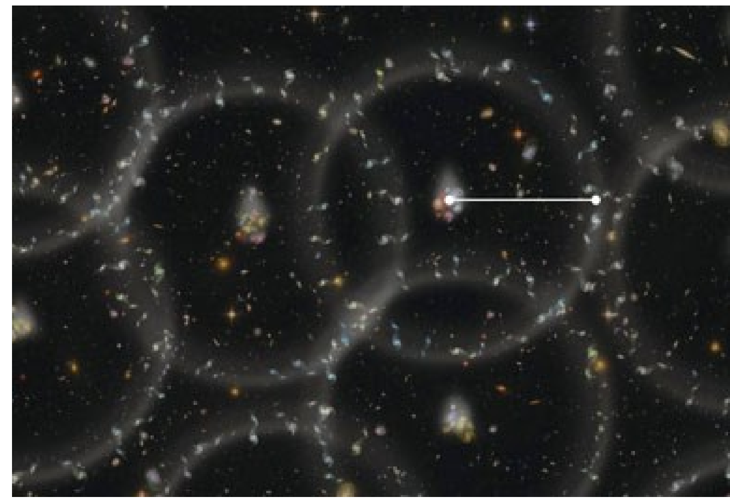
$$k^2\Psi = -\mu(a,k)4\pi G a^2\rho\Delta$$

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

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

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

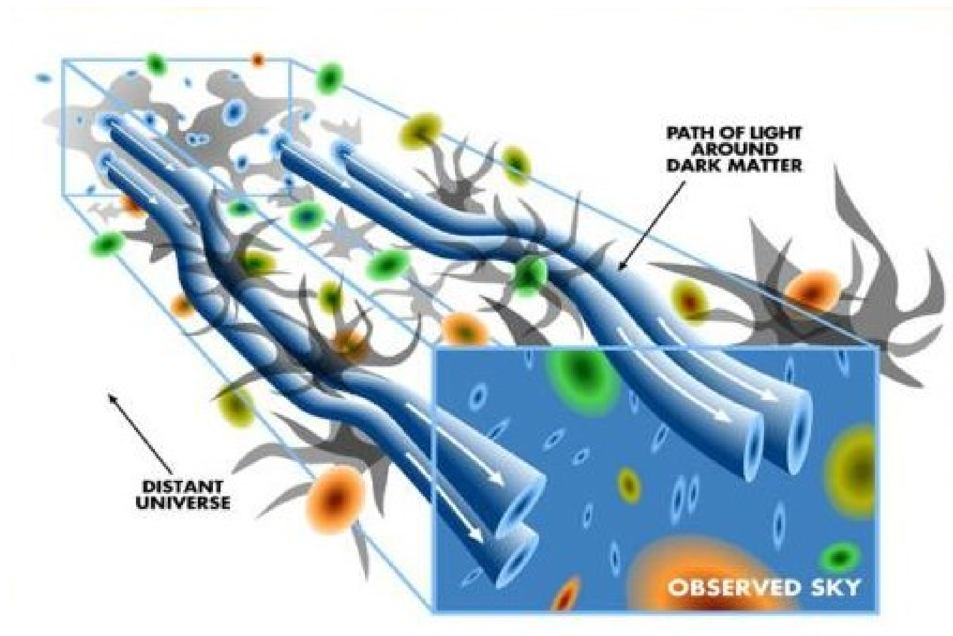
- *Medium-Deep Band 2 Survey* : SKA1-MID in Band 2 covering 5,000 $\deg^2$ and an integration time of approximately $t_{\rm tot} = 10,000$ hrs on sky. Main goals: a continuum weak lensing survey and an HI galaxy redshift survey out to $z \sim 0.4$
- *Wide Band 1 Survey* : SKA1-MID in Band 1 covering 20,000 $\deg^2$ and an integration time of approximately $t_{\rm tot} = 10,000$ hrs on sky. Main goals: a wide continuum galaxy survey and HI intensity mapping in the redshift range $z = 0.35 - 3$



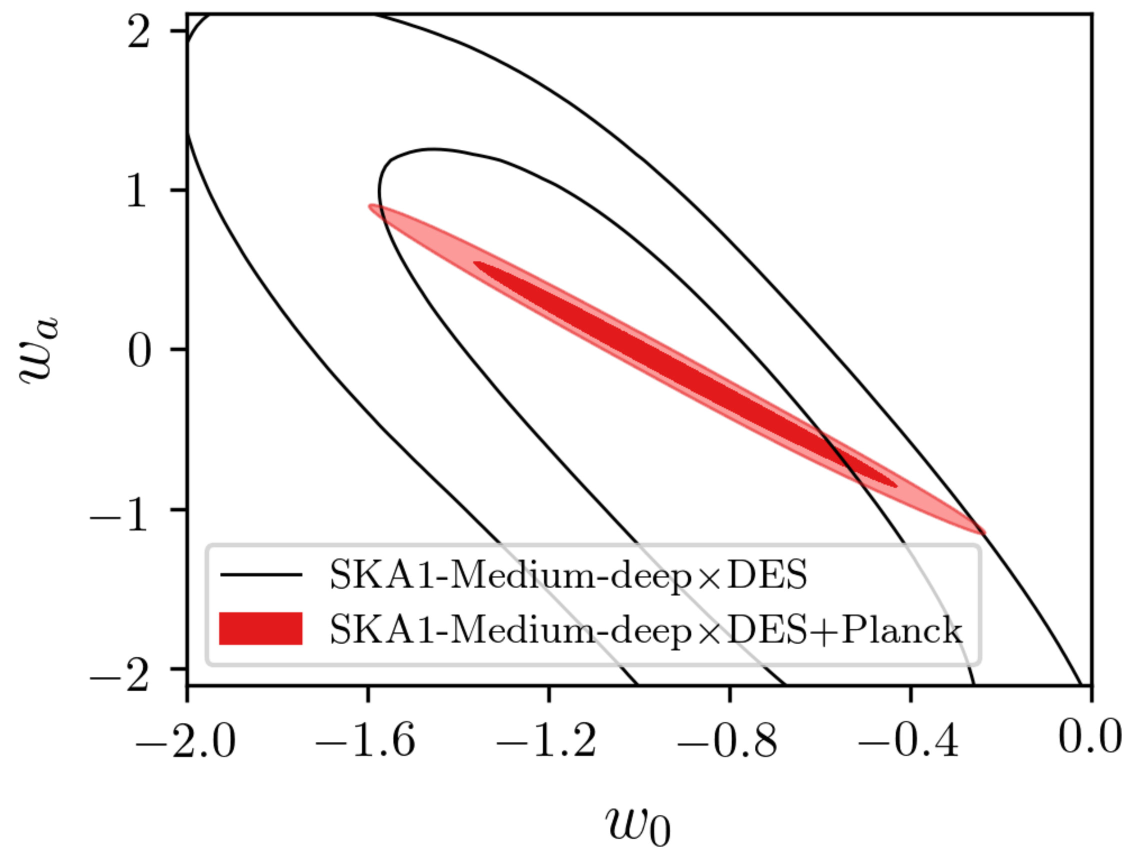
$$D_{\rm V}(z) = \left[(1+z)^2 D_{\rm A}^2(z) \frac{cz}{H(z)}\right]^{1/3}$$

$$d_z = \frac{r_{\rm s}(z_{\rm drag})}{D_{\rm V}(z)}$$

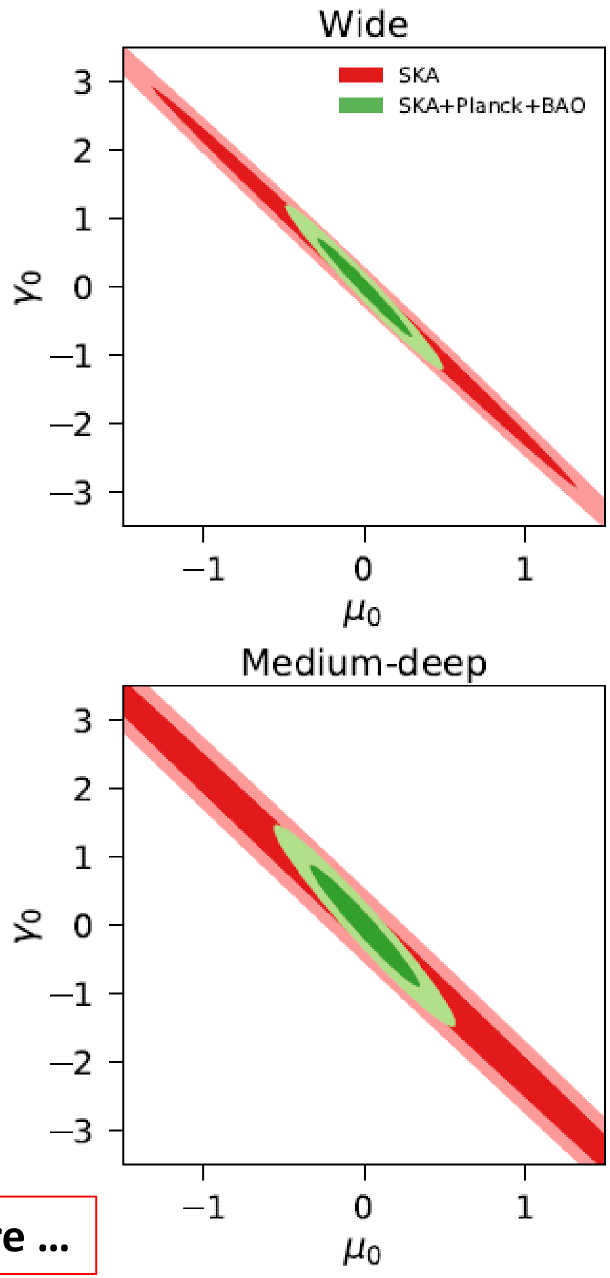
$$C_{ij}^{XY}(\ell) = c \int_{z_{\rm min}}^{z_{\rm max}} {\rm d}z \, \frac{W_i^X(z) W_j^Y(z)}{H(z) r^2(z)} P_{\delta\delta}(k_\ell, z)$$



$$W_i^{\rm L}(k, z) = \frac{3}{2} \Omega_{\rm m,0} \frac{H_0^2}{c^2} (1 + z) \, r(z) \, \Sigma(z) \int_z^{z_{\rm max}} {\rm d}z' \, \frac{n_i(z')}{\bar{n}_i} \frac{r(z' - z)}{r(z')}$$



SKA Red Book 2018



See next Casas' Talk for more …

SKA Red Book 2018

MGCLASS MG Cosmo Solver

Baker & Bull 2015 ver. I

Sakr & Martinelli 2022 ver. II

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

MGCLASS MG Cosmo Solver

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

- New extended fast MG patch solver to CLASS.
- Easy to Modify and Use. Works with *Cobaya* and *Montepython*.
- Suitable for SKA and Synergies with Surveys linear, sub horizon scales

Baker & Bull 2015 ver. I

Sakr & Martinelli 2022 ver. II

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

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

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

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

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

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

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

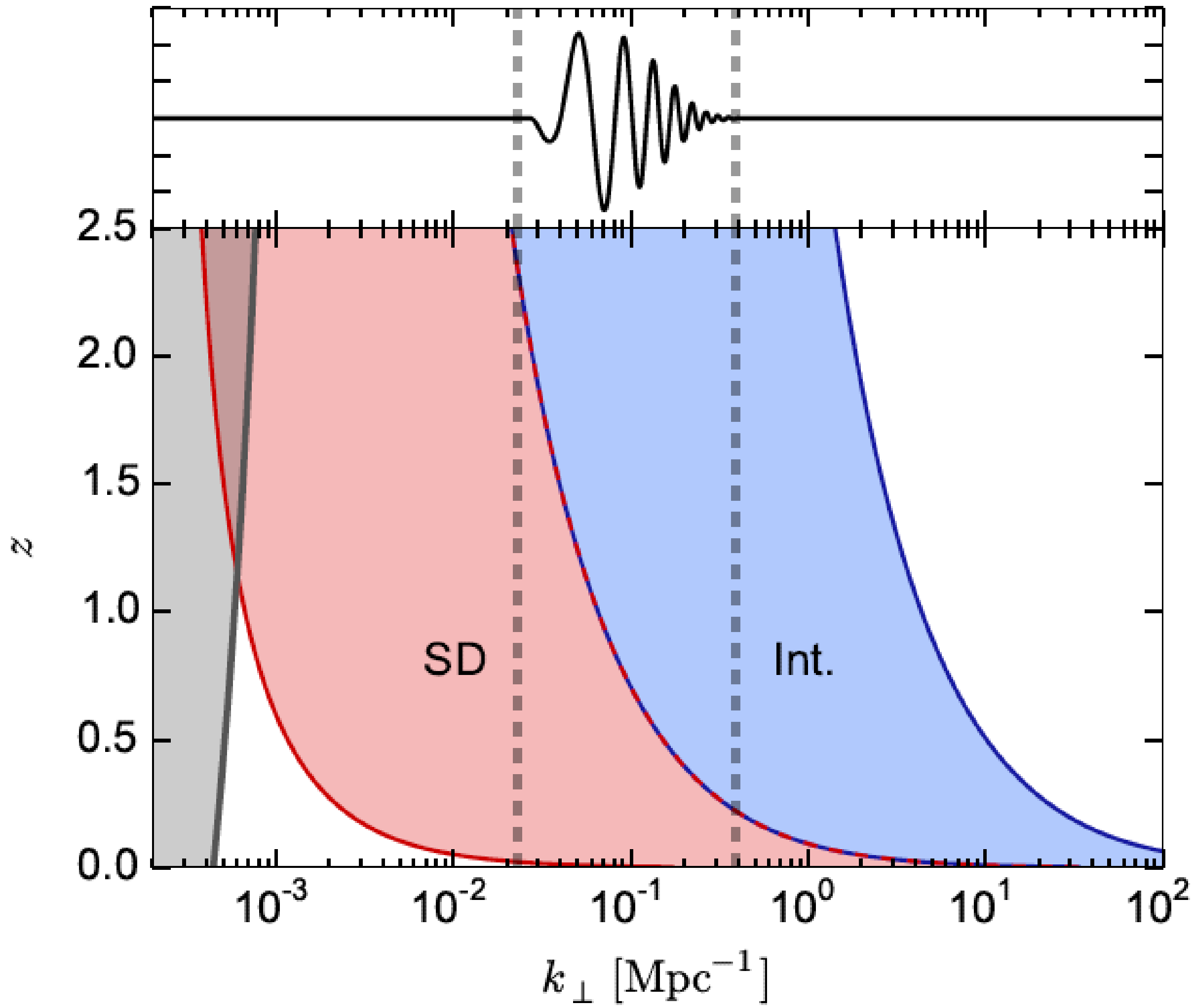
$$u' = -\left[2 + \frac{H'}{H}\right]u - \frac{3}{2}\frac{E_m}{E}\mu\Delta\,.$$

Sub Horizon Scales

$$\Delta' = -u$$

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

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



k < a.h

k > a.h

k >> a.h

Bull et al. 2015

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 …

$$ds^2 = a^2(\eta)\Big\{ -(1+2A)d\eta^2 - 2B_i dx^i d\eta + [(1+2H_L)\delta_{ij} + 2H_{T\,ij}]\, dx^i dx^j \Big\},$$

In the Newtonian Gauge

$$\Psi = A - \frac{\mathcal{H}}{k}\left(\frac{\dot{H}_T}{k} - B\right) - \frac{1}{k}\left(\frac{\ddot{H}_T}{k} - \dot{B}\right),$$

$$\Phi = -H_L - \frac{1}{3}H_T + \frac{\mathcal{H}}{k}\left(\frac{\dot{H}_T}{k} - B\right),$$

$$-2k^2\dot{\Psi} = 3\mathcal{H}^2\Omega_\mathrm{M}\frac{\left(Y_\mathrm{M} - 3\frac{\mathcal{H}}{k^2}\dot{Y}_\mathrm{M}\right)}{\left(1 + \frac{9}{2}\frac{\mathcal{H}^2}{k^2}\Omega_\mathrm{M}\eta\right)}.$$

$$\dot{\Phi} = \left(1 + \frac{9}{2}\frac{aH^2}{k^2}\Omega_\mathrm{M}\eta\right)^{-1}\left[\Phi\left(\frac{\dot{\eta}}{\eta} + \frac{\dot{\tilde{\mu}}}{\tilde{\mu}} - aH\right) + \frac{9}{2}\frac{aH^2}{k^2}\Omega_\mathrm{M}\eta V\left(\frac{k}{3} + \frac{aH^2 - a\dot{H}}{k}\right) - \frac{9}{2}\frac{aH^2}{k^2}\Omega_\mathrm{M}\eta\Psi\, aH\right]$$

Two files in principle :

input.c
modgrav.c

```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

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

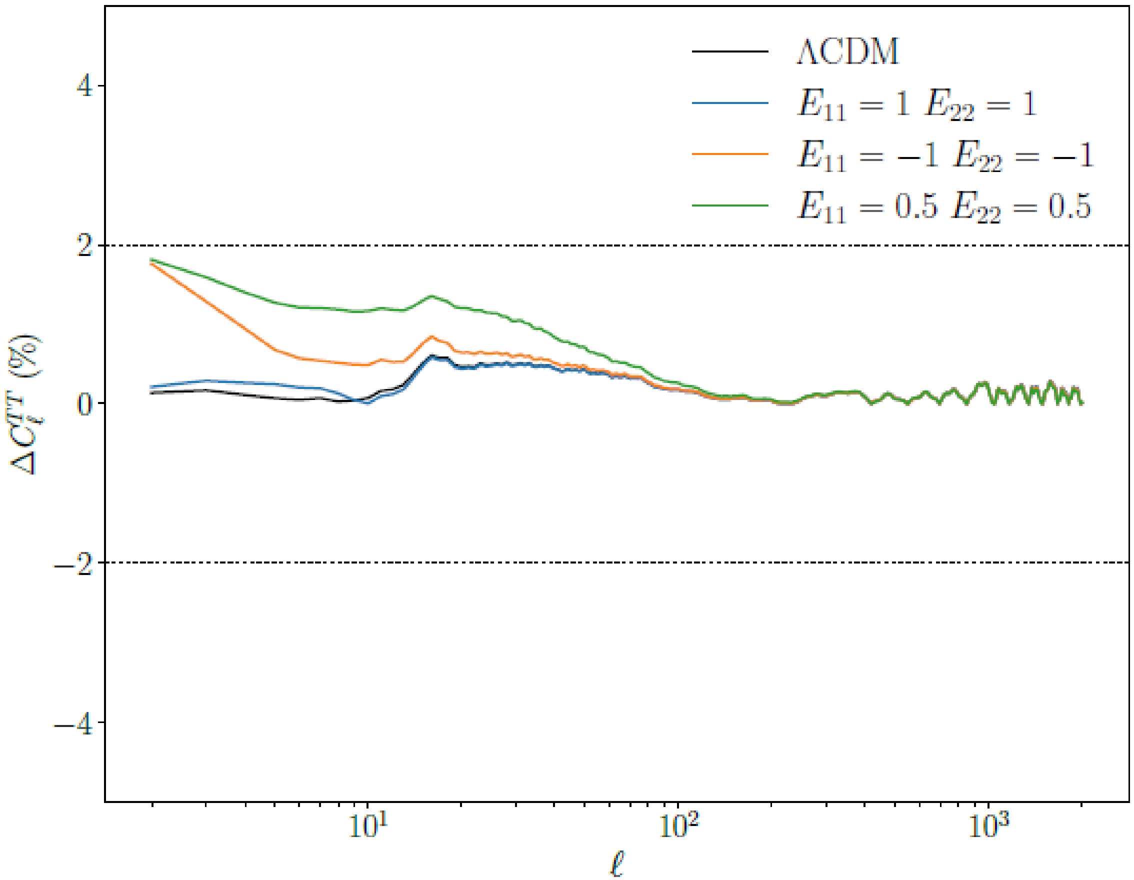
$$\eta(a) = 1 + g_\eta \Omega_\Lambda^n - g_\eta \Omega_\Lambda^{2n}$$

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

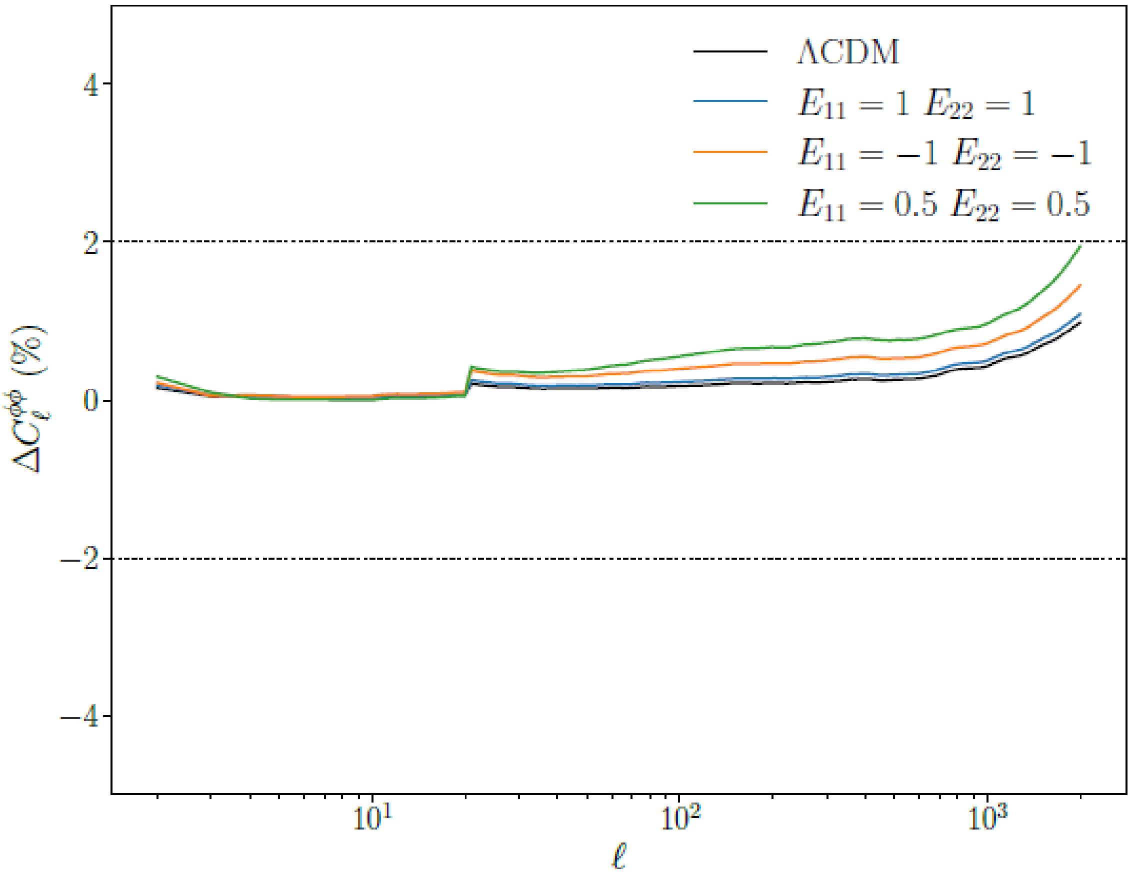
$$\dot{\eta}(a) = n.\dot{\Omega}_\Lambda.g_\eta \Omega_\Lambda^{n-1} - 2n.\dot{\Omega}_\Lambda.g_\eta \Omega_\Lambda^{2n-1}$$

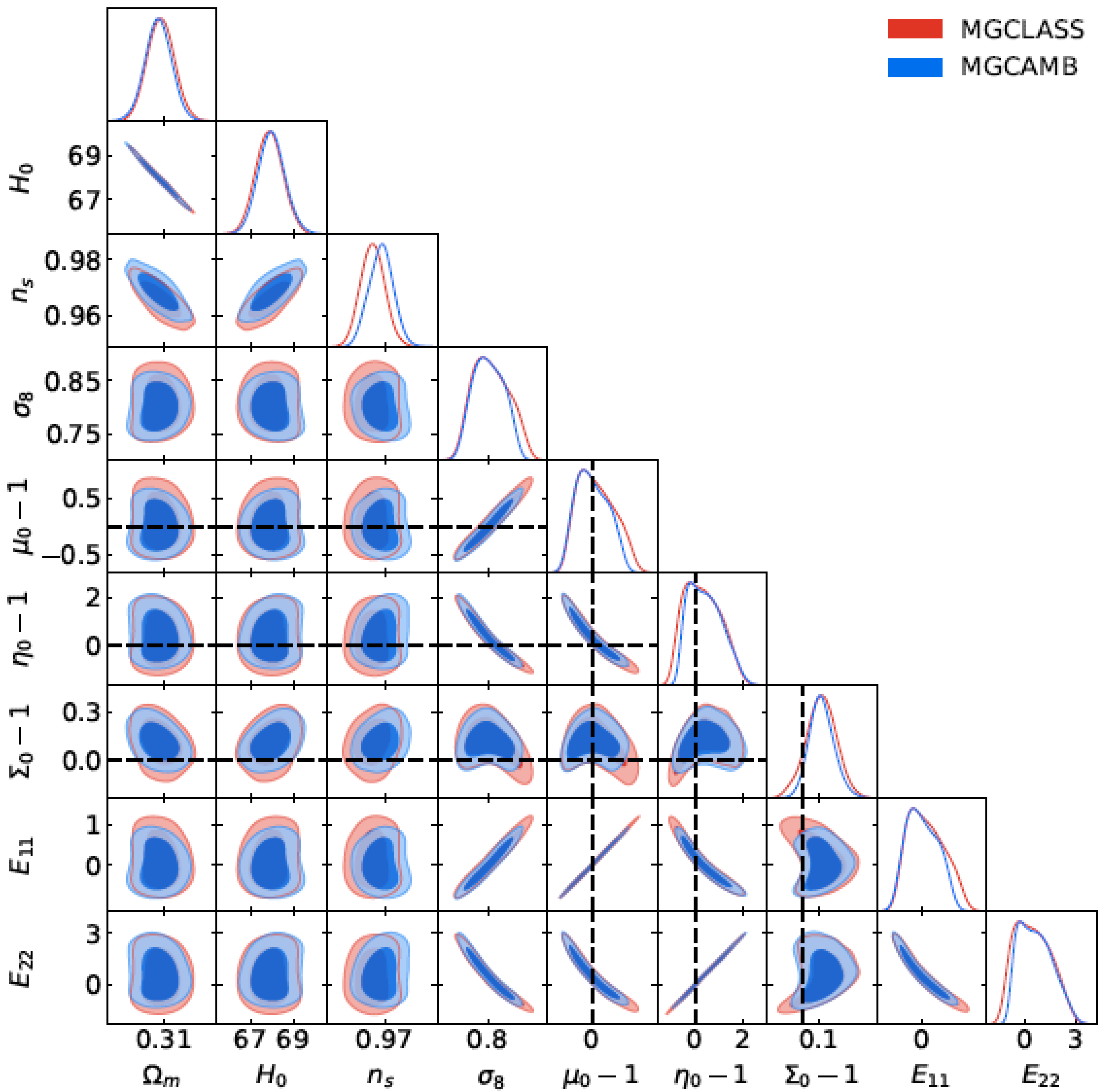
```
   }
else if (pba->mg_ansatz == z_flex_late) {
if (pba->mg_bckg == _TRUE_)


        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);


   }
```

MGCLASS vs MGCAMB …



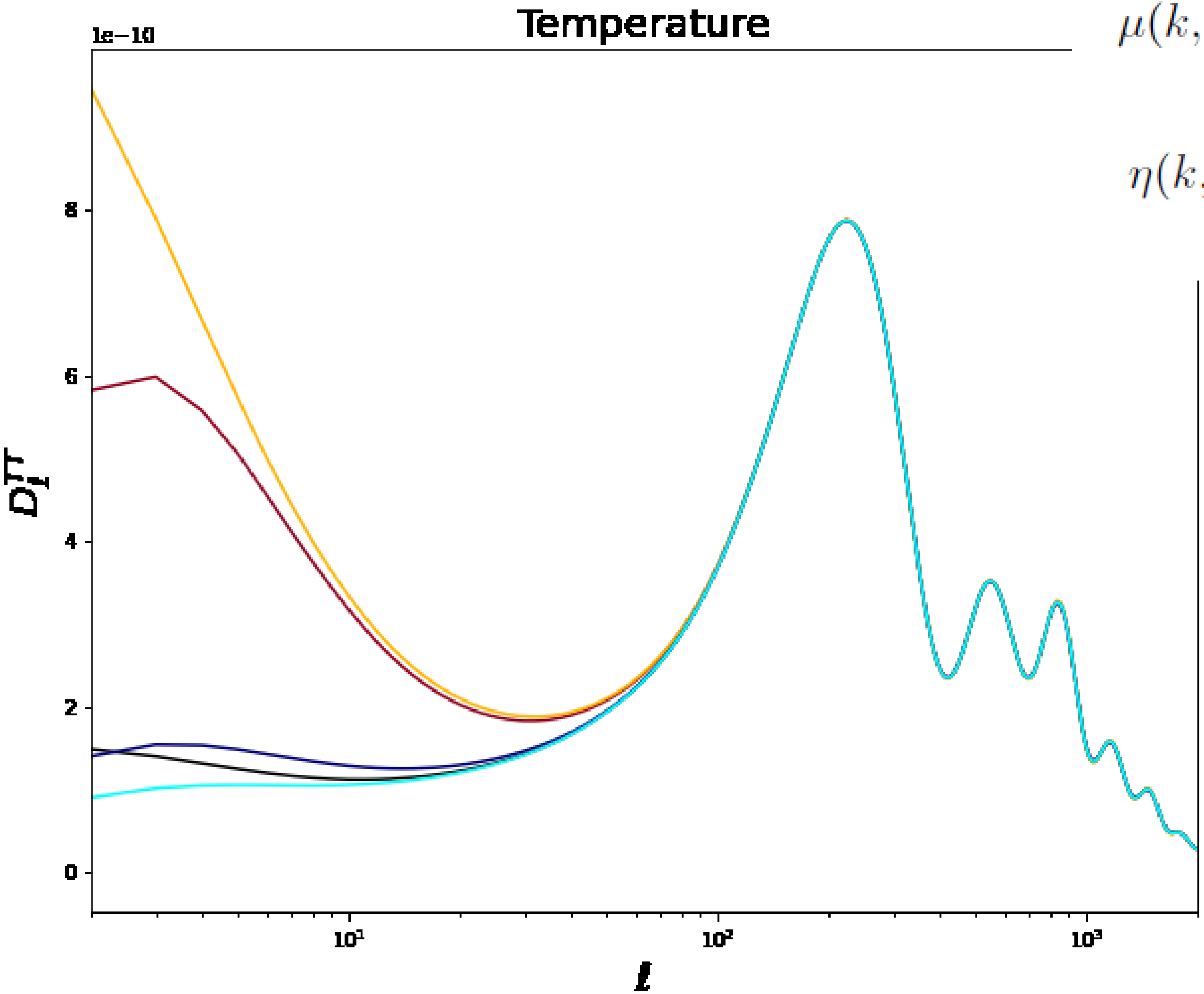
MGCLASS vs MGCAMB …





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}

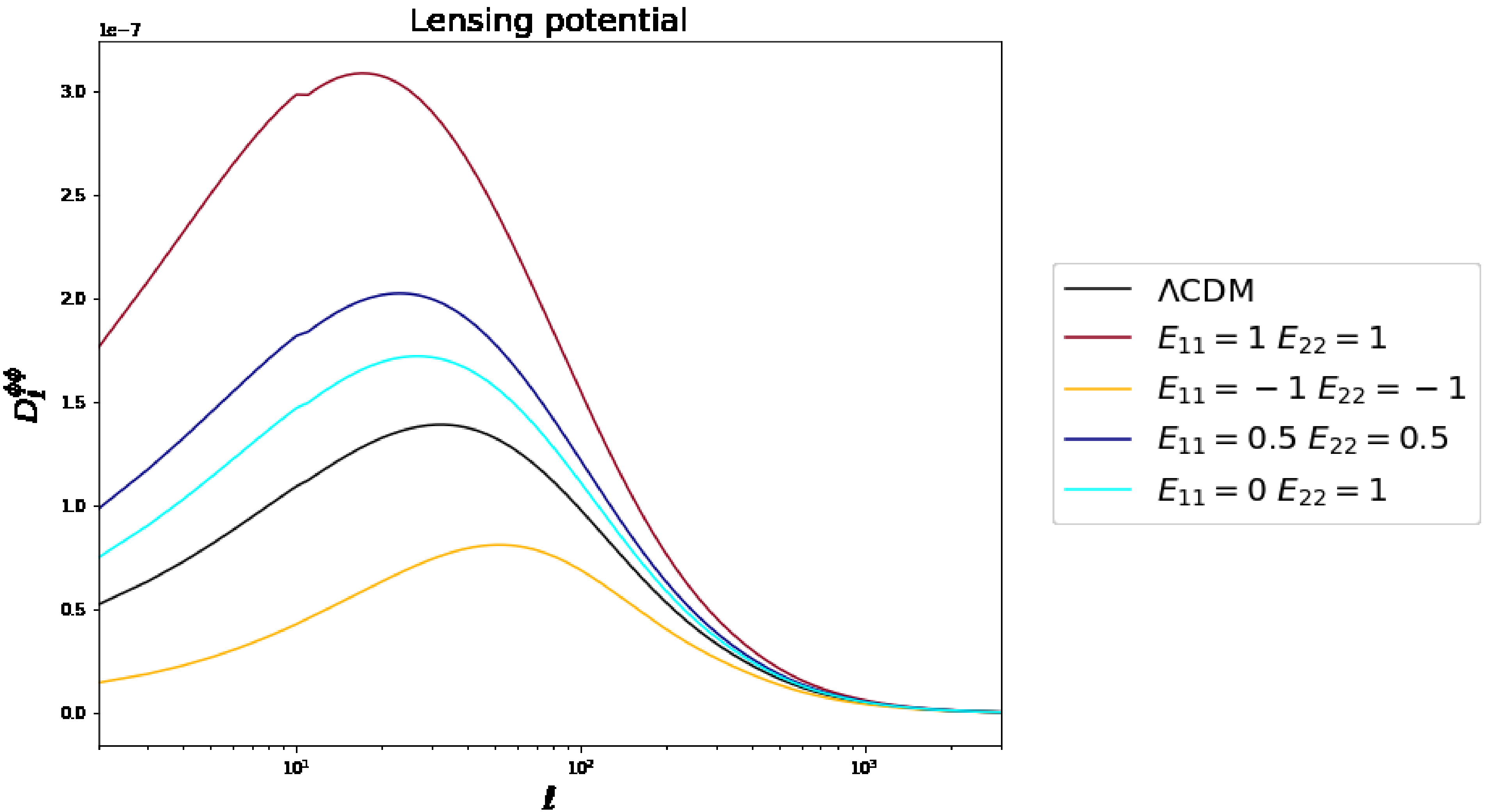
Reproduce fig. 1 of Planck 2015 results. XIV



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

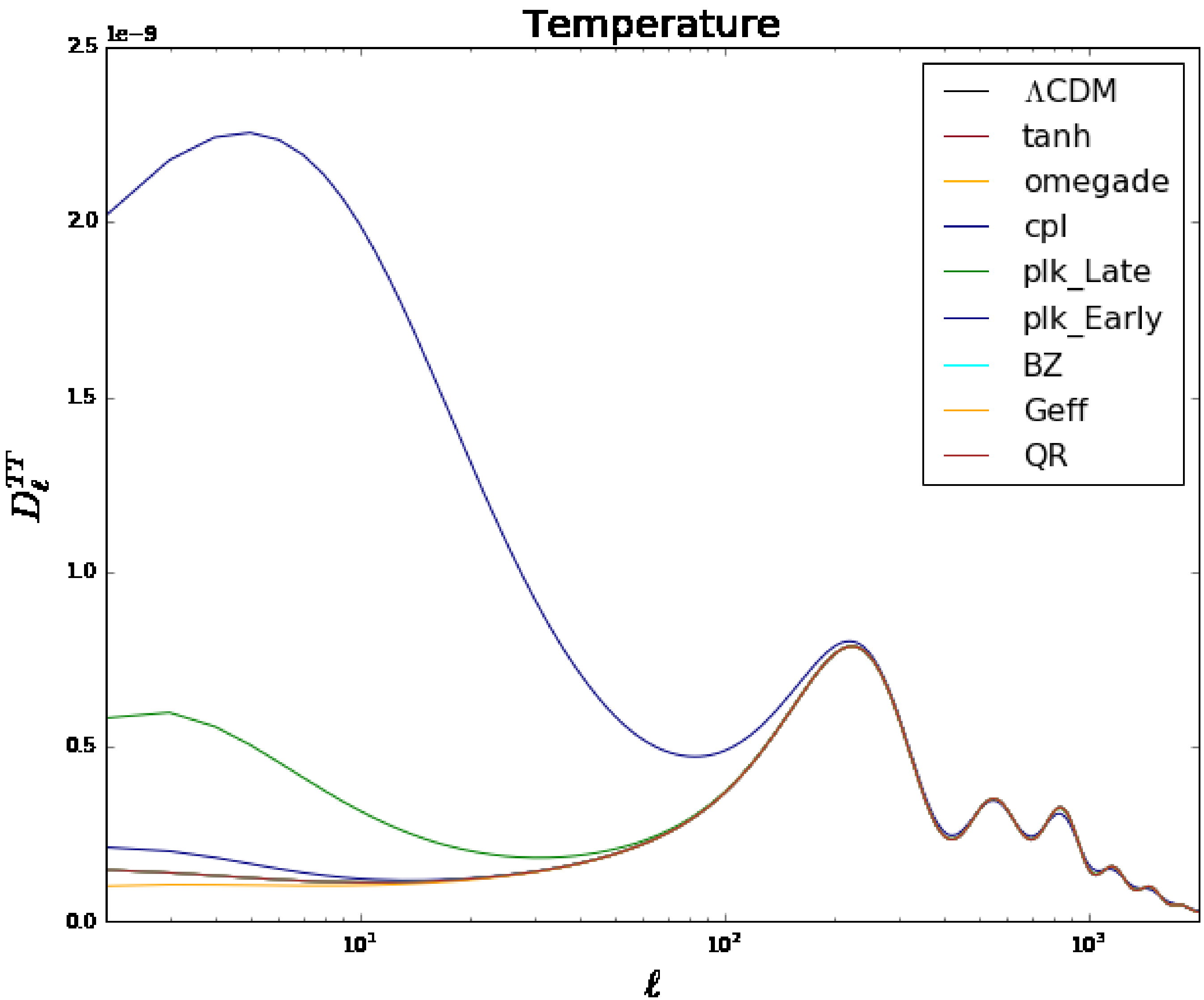
$$\eta(k,z) = 1 + f_2(z)\frac{1 + c_2\left(\frac{\mathcal{H}}{k^2}\right)}{1 + \left(\frac{\mathcal{H}}{k^2}\right)}.$$

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

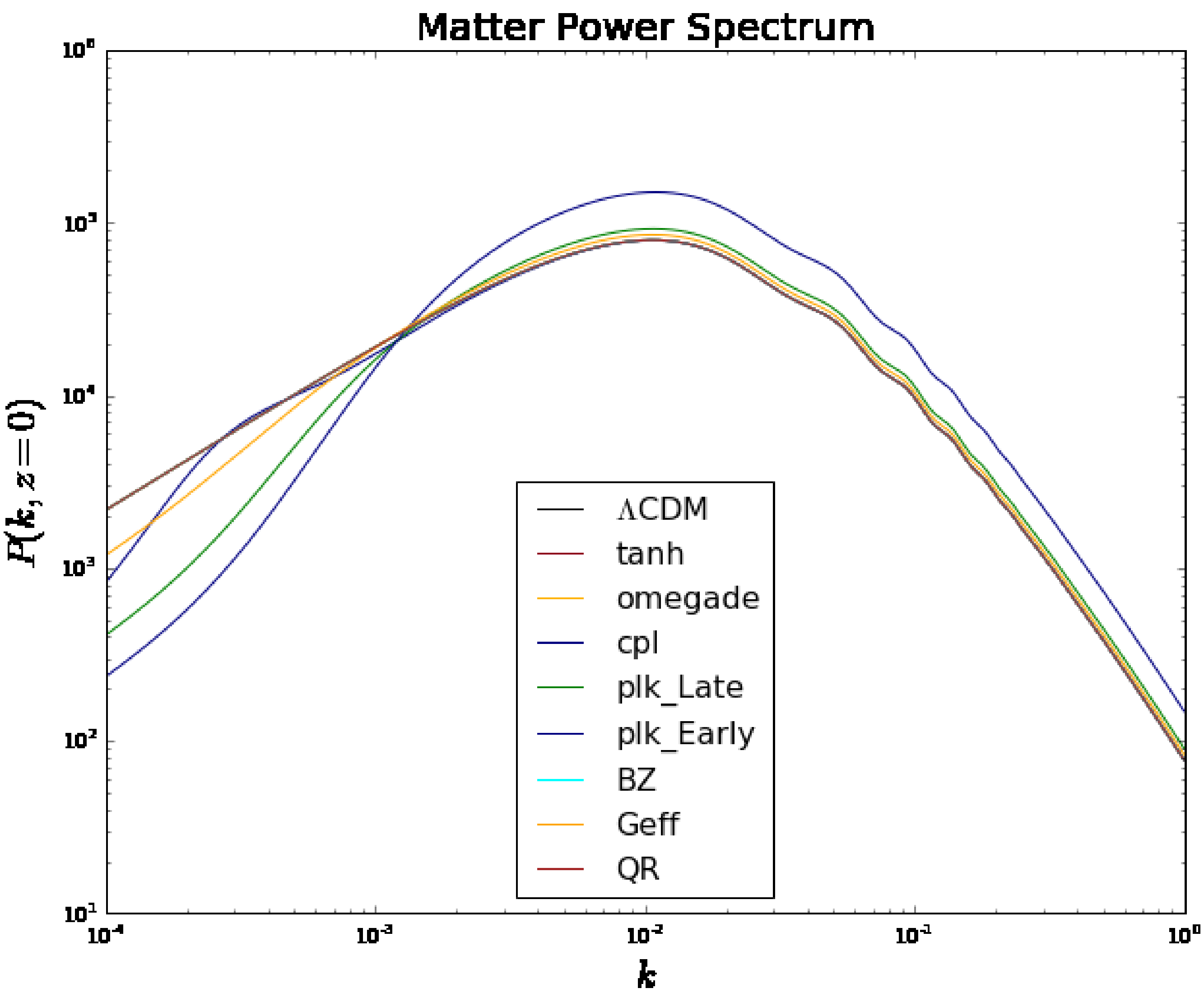


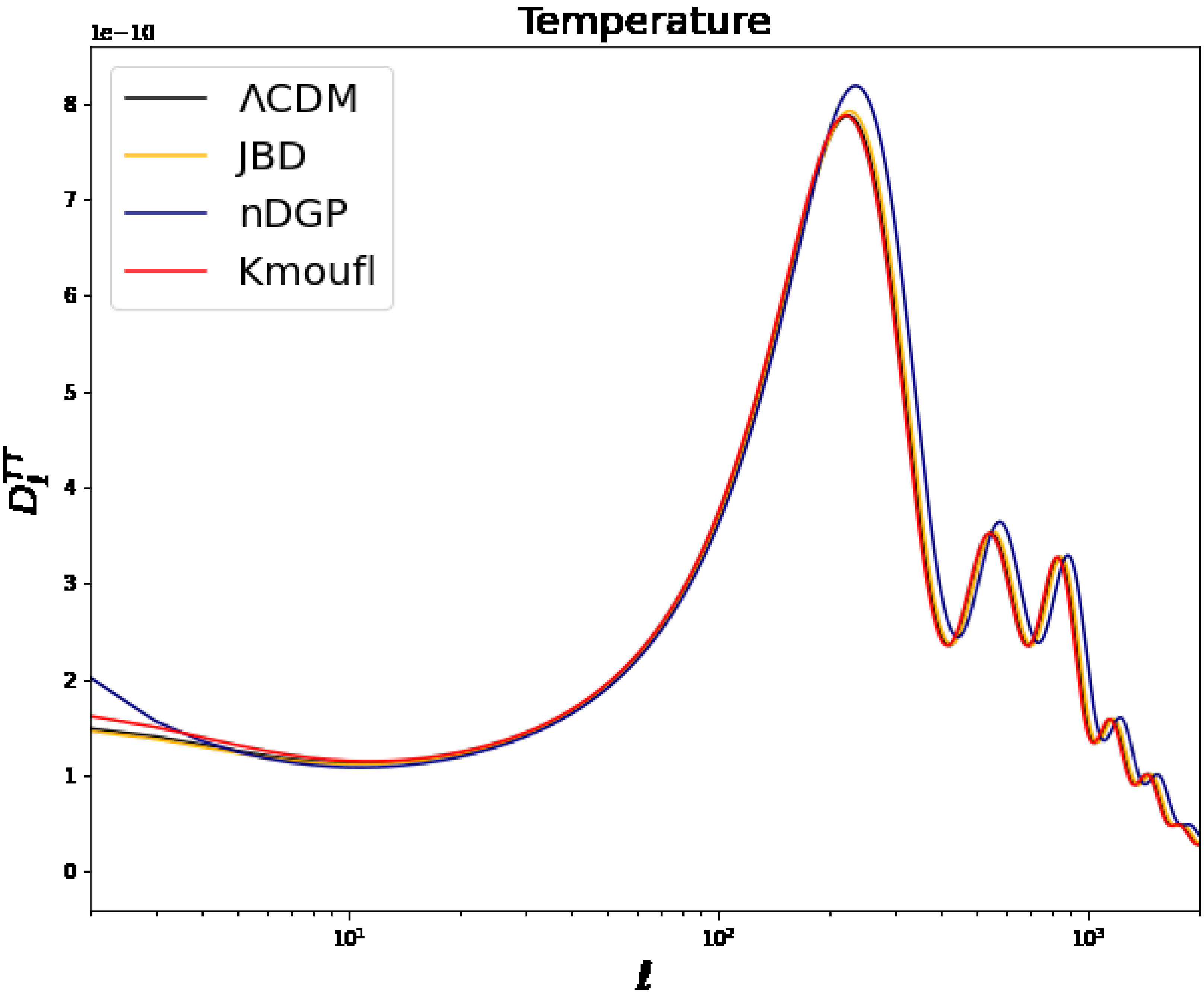
Lensing potential
1e−7
3.0
2.5
2.0
1.5
1.0
0.5
0.0
$D_l^{\phi\phi}$
10^1
10^2
10^3
ℓ
ΛCDM
$E_{11} = 1$ $E_{22} = 1$
$E_{11} = -1$ $E_{22} = -1$
$E_{11} = 0.5$ $E_{22} = 0.5$
$E_{11} = 0$ $E_{22} = 1$

Cosmo Solver MGCLASS II

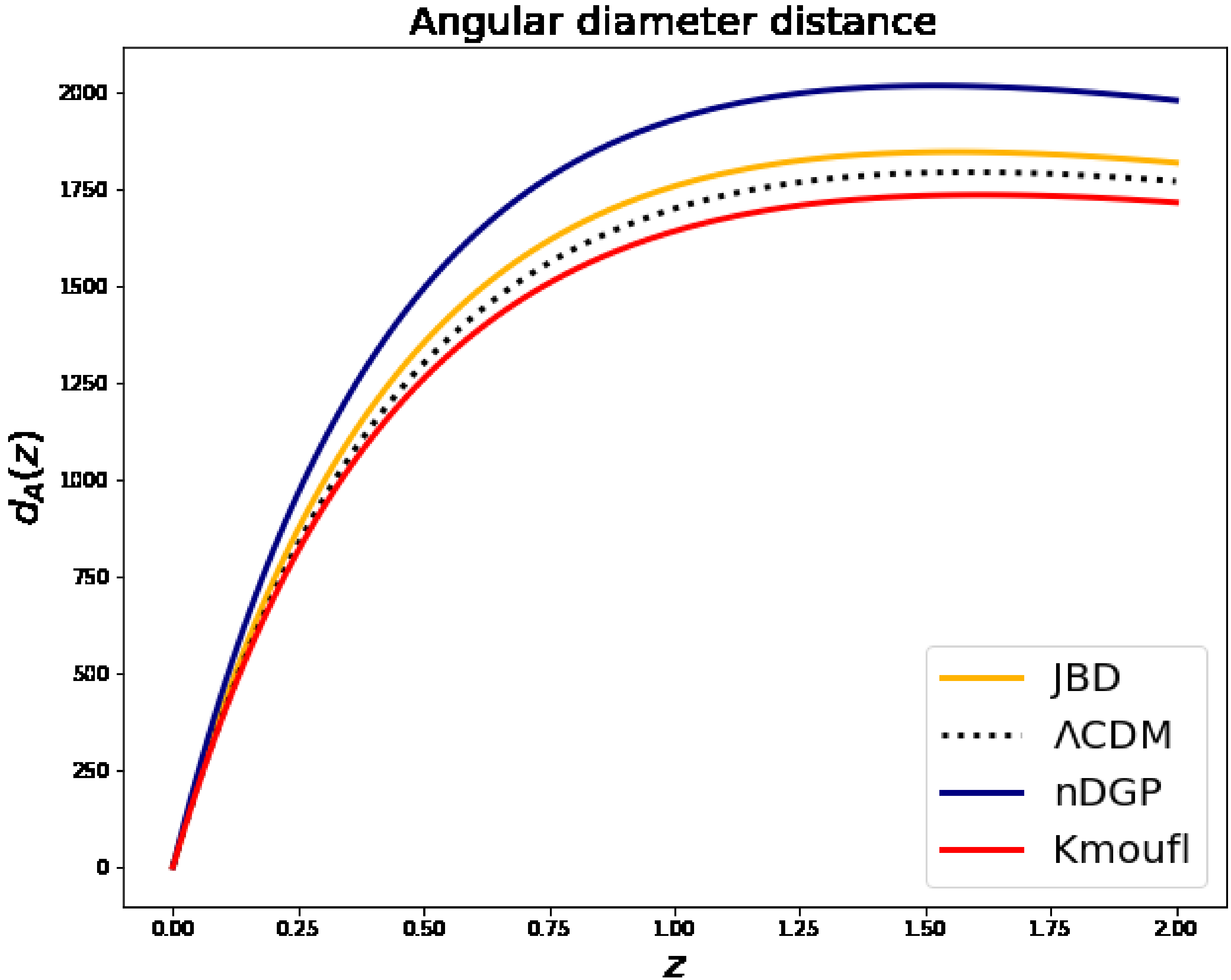


Cosmo Solver MGCLASS II





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



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

Cosmo Solver MGCLASS I

- `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.

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

$$\mu(a,k) = \frac{1}{8\pi F}\frac{f_{,X} + 4\left(f_{,X}\frac{k^2}{a^2}\frac{F_{,R}}{F} + \frac{F_{,\phi}^2}{F}\right)}{f_{,X} + 3\left(f_{,X}\frac{k^2}{a^2}\frac{F_{,R}}{F} + \frac{F_{,\phi}^2}{F}\right)},$$

$$\eta(a,k) = \frac{2f_{,X}\frac{k^2}{a^2}\frac{F_{,R}}{F} + \frac{2F_{,\phi}^2}{F}}{f_{,X}\left(1 + \frac{2k^2}{a^2}\frac{F_{,R}}{F}\right) + \frac{2F_{,\phi}^2}{F}}.$$

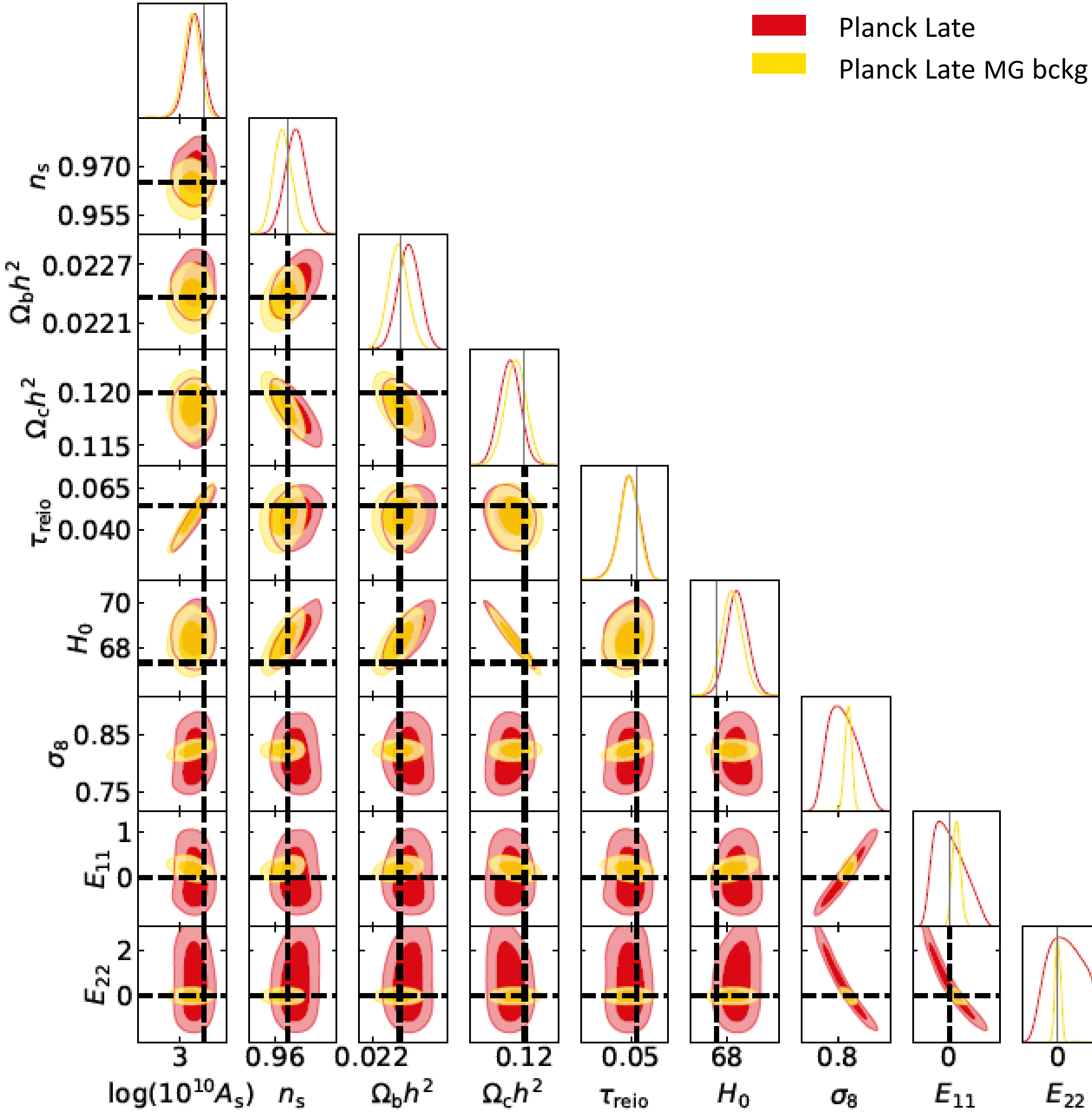
Cosmo Solver MGCLASS II

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

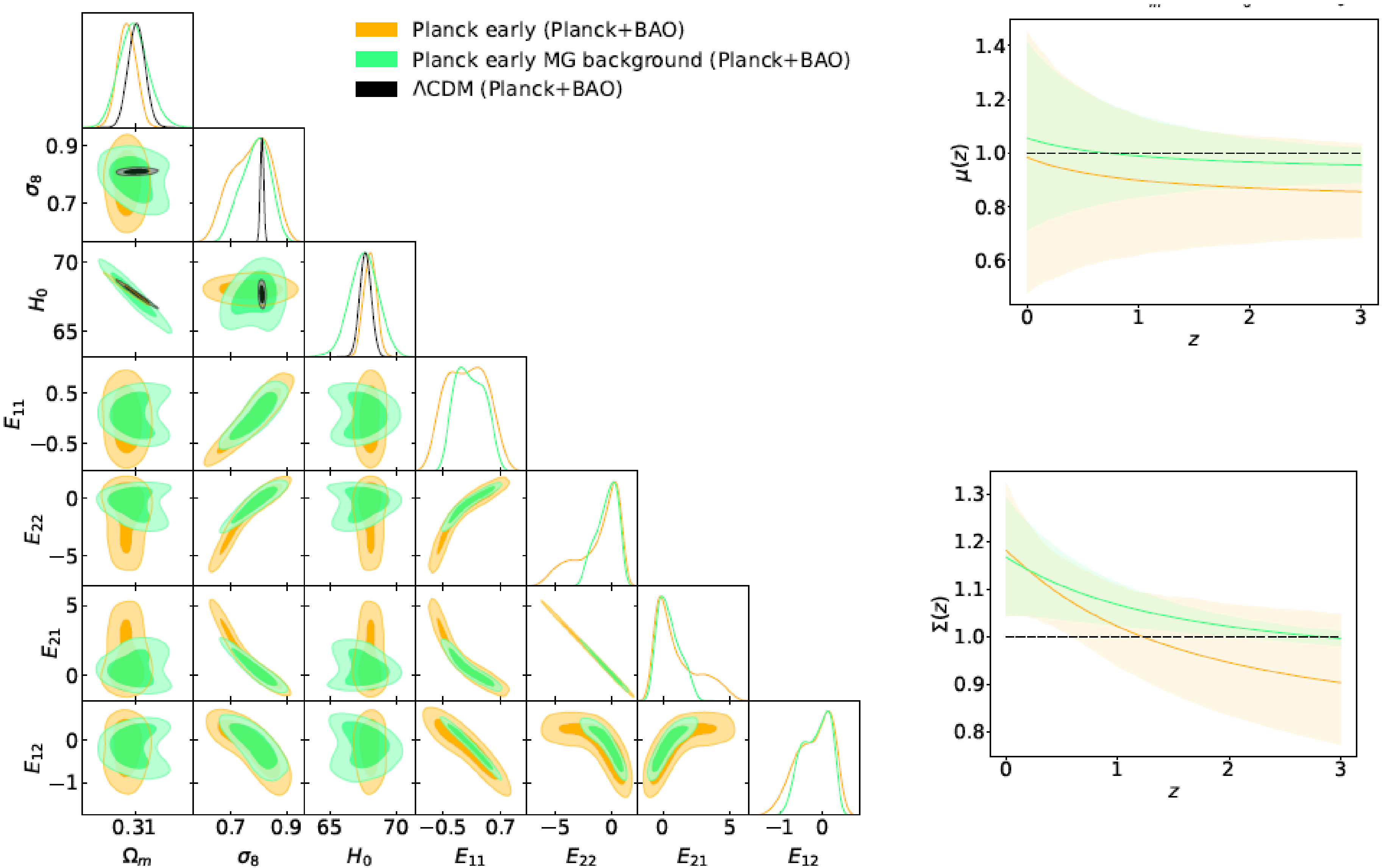
$$\dot{F} = -\frac{2(\dot{\mu}(1+\eta) + \mu\dot{\eta})}{(\mu + \mu\eta)^2}\,.$$

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

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



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}



Planck early (Planck+BAO)
Planck early MG background (Planck+BAO)
ΛCDM (Planck+BAO)
0.31
0.7
0.9
65
70
−0.5
0.7
−5
0
0
5
−1
0
Ωm
σ8
H0
E11
E22
E21
E12
μ(z)
Σ(z)
z
z

Recent work ….