K-mouflage

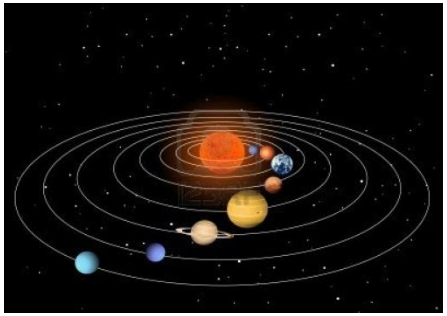
Philippe Brax

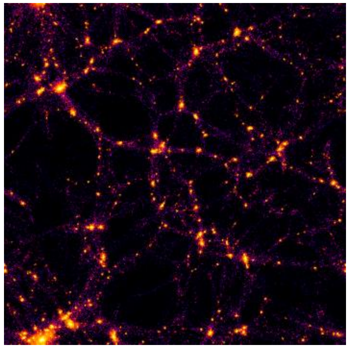
IPhT Saclay

Collaboration with P. Valageas, A. Barreira, S. Clesse and B. Li

Sao Paulo
December 2014

GRAVITY ACTS ON ALL SCALES





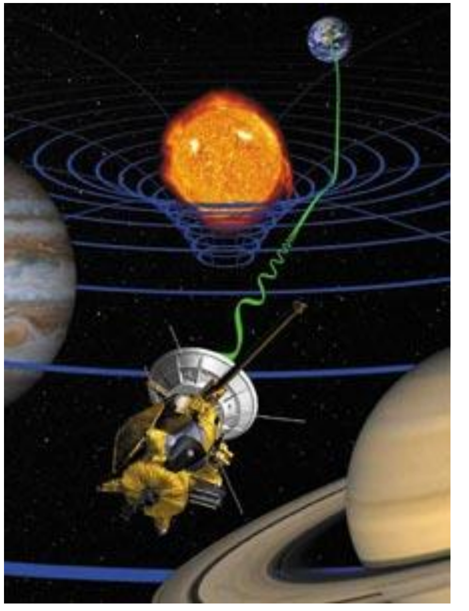
Nothing guarantees that a modification of gravity on large scales is consistent with the gravity tests in the solar system.

Deviations from Newton's law are parametrised by:

$$\phi_N = -\frac{G_N}{r}(1 + 2\beta^2 e^{-r/\lambda})$$

For large range forces with large λ, the tightest constraint on the coupling β comes from the Cassini probe measuring the Shapiro effect (time delay):

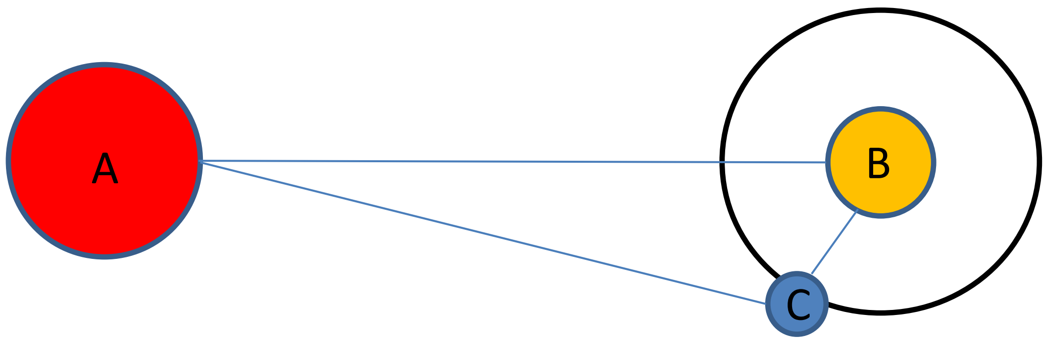
$$\beta^2 \leq 4 \cdot 10^{-5}$$



Bertotti et al. (2004)

Due to the scalar interaction, within the Compton wavelength of the scalar field, the inertial and gravitational masses differ for screened objects:

VIOLATION OF THE STRONG EQUIVALENCE PRINCIPLE



$$\eta_{BC} \equiv \left|\frac{a_C - a_B}{a_C + a_B}\right|$$

$$\eta_{\mathrm{moon-earth}} \leq 10^{-13}$$

SCREENING

Mechanisms whereby nearly massless scalars evade local gravitational tests

In fact, around a background configuration and in the presence of matter, the Lagrangian can be linearised and the main screening mechanisms can be schematically distinguished :

$$\mathcal{L} \supset \boxed{-\frac{Z(\phi_0)}{2}}(\partial\delta\phi)^2 - \frac{m^2(\phi_0)}{2}\delta\phi^2 + \frac{\beta(\phi_0)}{M_P}\delta\phi\delta T \ ,$$

The K-mouflage mechanism reduces the coupling by increasing Z

The K-mouflage mechanism can be nicely understood:

Effective Newtonian potential:

$$\Psi = (1 + \frac{2\beta^2(\phi)}{Z(\phi)})\Phi_N$$

For theories with second order eom:

$$Z(\phi) = 1 + \underbrace{a(\phi) L^2 \frac{D^\mu D_\mu \phi}{m_{\rm Pl}}}_{\text{Vainshtein}} + \underbrace{b(\phi) \frac{(\partial\phi)^2}{M^4}}_{\text{K-mouflage}} + \dots$$

$$M^4 \sim 3H_0^2 m_{\rm Pl}^2, \quad L \sim H_0^{-1}$$

K-mouflage

Newtonian gravity retrieved when the gravitational acceleration is large enough:

$$|\nabla\Phi_N| \geq \frac{M^2}{2\beta m_{\rm Pl}}$$

On large cosmological scales, this tells us that overdensities such as galaxy clusters are not screened :

$$\frac{k}{H_0} \leq \beta\delta$$

On small scales (solar system, galaxies) screening only occurs within the K-mouflage radius:

$$R_K = \left(\frac{\beta m}{4\pi m_{\rm Pl} M^2}\right)^{1/2}$$

Dwarf galaxies are not screened.

K-mouflage models

$$S = \int d^4x\sqrt{-g}\left(\frac{R}{16\pi G_N} + M^4 K(\chi)\right) + S_m(\psi, A^2(\phi)g_{\mu\nu}) \qquad \chi = -\frac{(\partial\phi)^2}{2M^4}$$

M is the dark energy scale for cosmologically interesting models. Examples that one may consider:

$$K(\chi) = -1 + \chi + K_0\chi^m$$ Higher order interaction

$$K(\chi) = -\sqrt{1-2\chi}$$ DBI model

$$K(\chi) = \sqrt{1+2\chi} - 2$$ DBIon

The couplage to matter is chosen to be linear:

$$A(\phi) = 1 + \frac{\beta\phi}{m_{\rm Pl}}$$

The background evolution follows from:

$$\dot{\phi}K' = -\frac{\beta\rho}{m_{\rm Pl}}t$$

The LHS is unbounded when t becomes very small (early Universe). There is a unique solution when the potential:

$$W_+(y) = yK'(\frac{y^2}{2}), \quad y = \frac{\dot{\phi}^2}{M^4}$$

is monotonic and unbounded. This rules out the DBIon model in the early Universe.

Perturbing around the background, the lowest order term is the Lagrangian becomes:

$$\mathcal{L}_2 = \frac{K' + 2\chi K''}{2}(\delta\dot{\phi})^2 - \frac{K'}{2}(\nabla\phi)^2$$

The absence of ghosts, negative kinetic energy states implying that the background is unstable with the creation ex-nihilo of a gamma ray background, requires that:

$$\frac{dW_+}{dy} > 0$$

The hyperbolicity of the propagation requires that K'>0 too. This selects models such as:

DBI

Polynomials with K0>0

For all these models, perturbations propagate with a speed which is subluminal.

The energy density of the scalar fluid is given by:

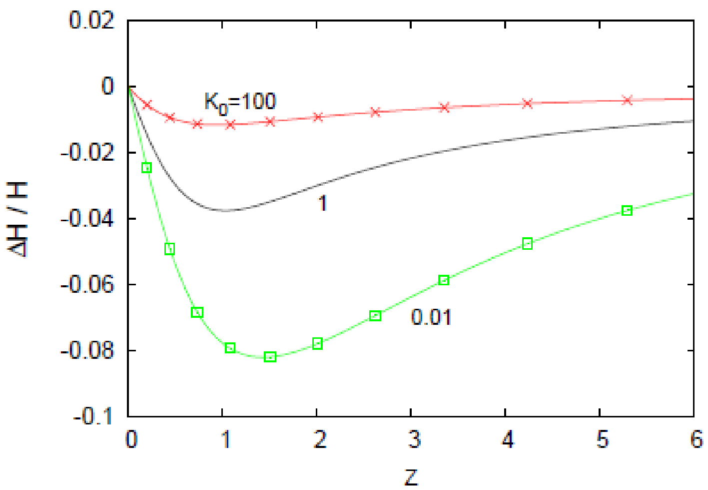
$$\rho_\phi = -M^4 K + \dot{\phi}^2 K' + (A-1)\rho$$

The pressure and the equation of state are given by:

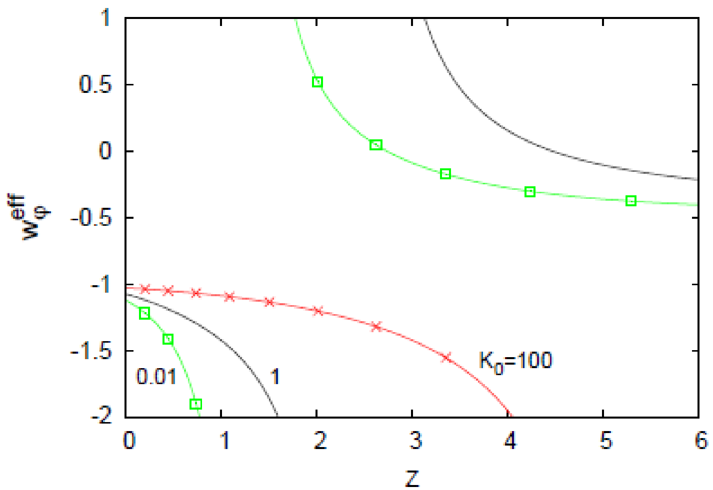
$$p_\phi = M^4 K, \quad w_\phi = \frac{p_\phi}{\rho_\phi}$$

For the ghost free models, it turns out that the scalar energy density becomes negative in the past implying a lower Hubble rate than for LCDM. But the total energy density of matter + scalar is still positive!

The equation of state also crosses the "phantom divide" and becomes less than -1 in the past.



Lower expansion rate than LCDM



Equation of state less than -1

K-mouflage must also screen in local environments. To simplify the analysis, the spherical case:

$$(\nabla\phi)K' = \frac{\beta m(r)}{m_{\rm Pl} 4\pi r^2}, \quad m(r) = 4\pi \int_0^r dr' r'^2 \rho(r')$$

Requiring that K'=1 at infinity (free behaviour), one must have:

$$K'(\chi) > 0, \quad \chi < 0$$

We must also have an increasing and unbounded potential:

$$W_-(y) = yK'(-\frac{y^2}{2}), \qquad \frac{dW_-}{dy} > 0$$

This rules out DBI models and selects polynomials with m odd and K0>0.

Particles have modified trajectories compared to Newton's law in this background:

$$\frac{d^2r}{dt^2} = -\frac{G_N m}{r^2}\left(1 + \frac{2\beta^2}{K'}\right)$$

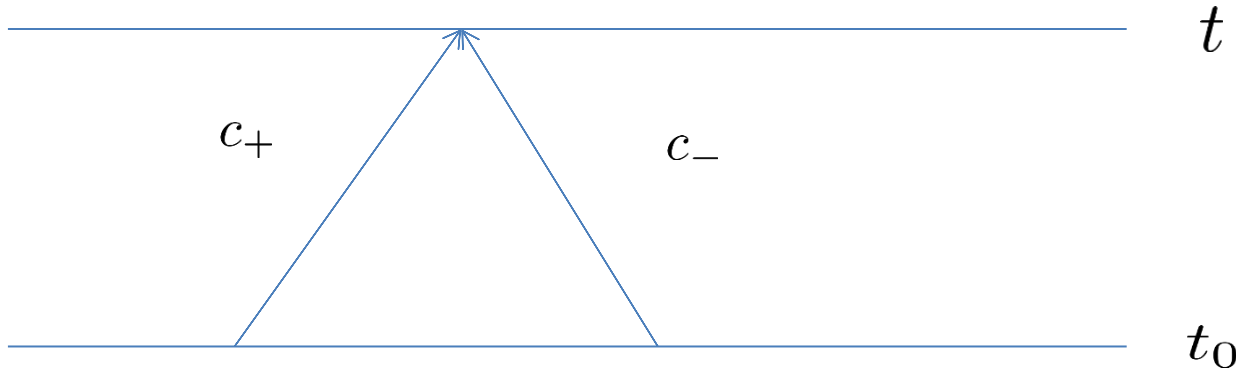
Screening happens inside the K-mouflage radius where K'>>1.

Spherical waves in this background satisfy:

$$K'(\delta\dot{\phi})^2 - \frac{1}{r^2}\nabla(r^2(K' + 2\chi K'')\nabla\delta\phi)) = 0$$

The propagation is always superluminal when screening (otherwise K''>0 and K' grows from 0 to 1 on the negative axis) .

It is instructive to study the non-linear time evolution of the scalar profile when an overdensity appears (Gaussian here with an amplitude linearly growing with time until it reaches the static distribution of matter).



The time evolution from initial data happens on characteristic curves determined by characteristic speeds. The system has a well defined Cauchy problem when the characteristic curves exist, i.e. the light cones do not close. This is guaranteed when:

$$K' > 0, \quad K' + 2\chi K'' > 0$$

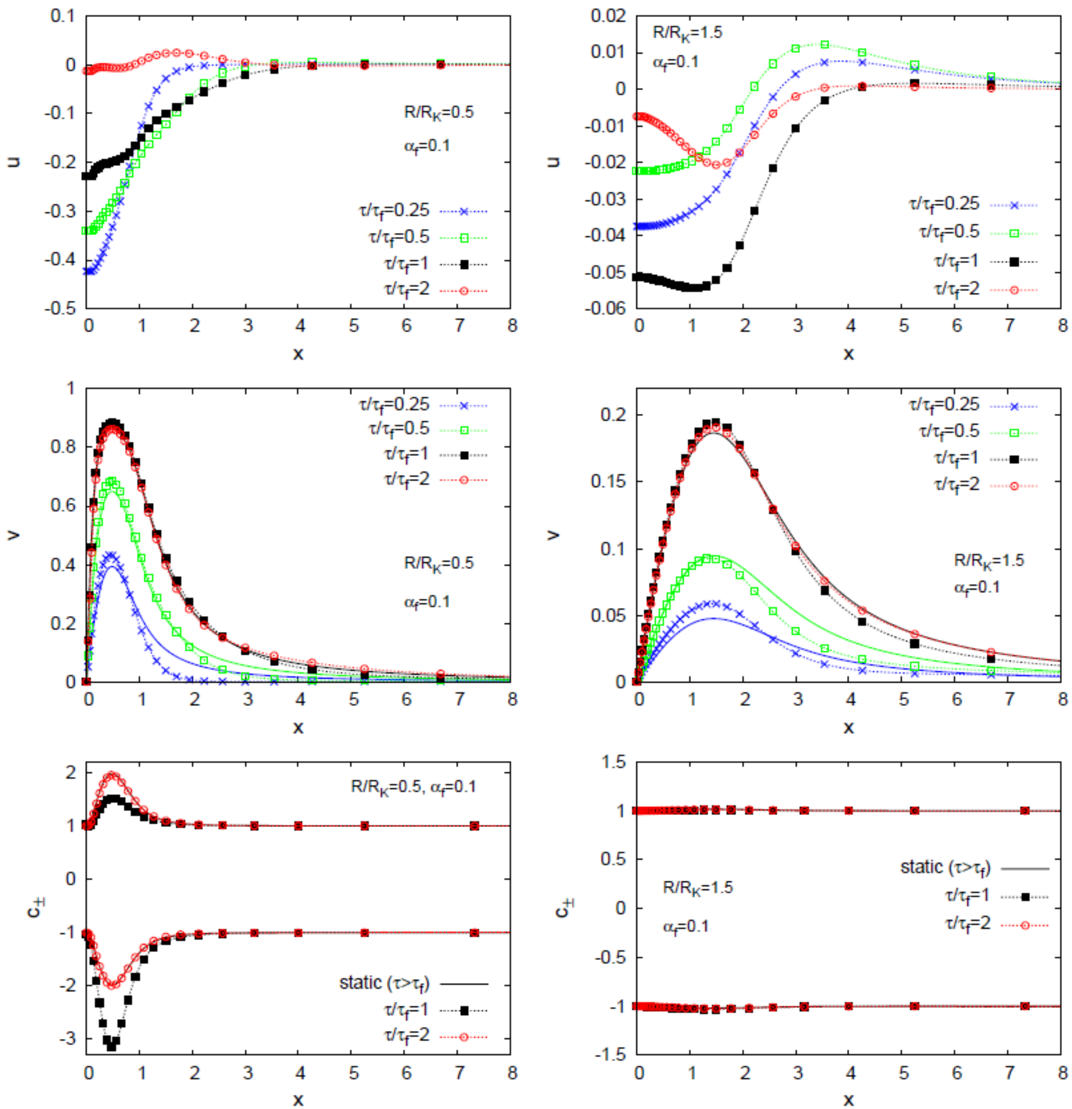
There can also be shocks when characteristic curves cross.

Polynomial model m=3

$R < R_K$ $R > R_K$

$$u = \frac{\partial \phi}{\partial t}$$

$$v = \frac{\partial \phi}{\partial r}$$

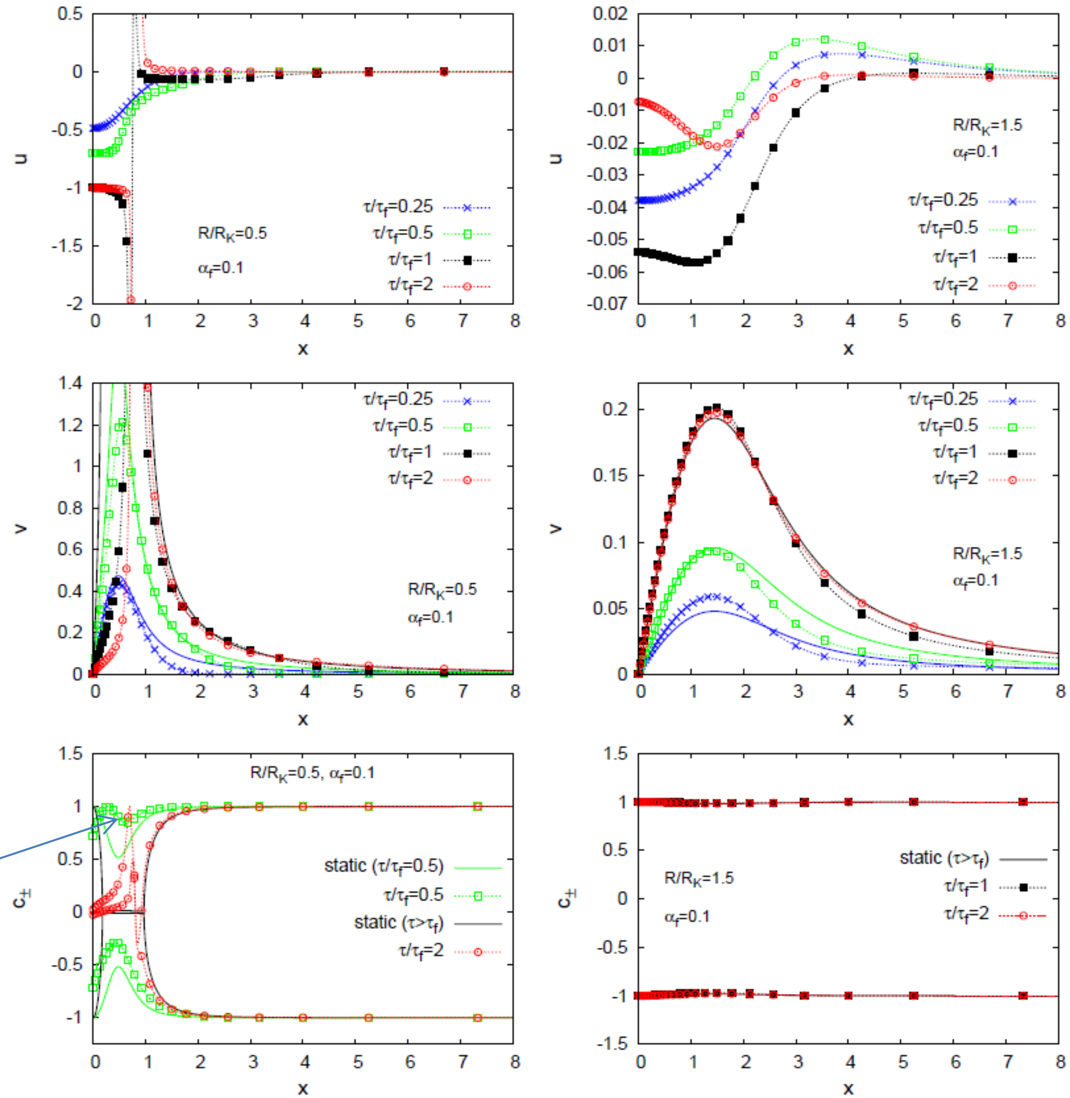


Screened Unscreened

DBI

$R < R_K$ $R > R_K$

No static solution at high enough density



Shocks

Screened

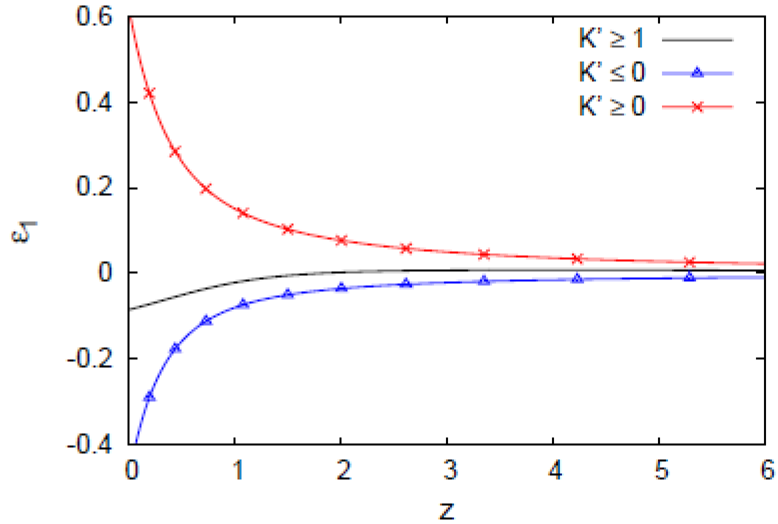
Unscreened

For healthy K-mouflage models, e.g polynomial with m=3 and K0>0, we can be interested in structure formation. We have seen that clusters are not screened so expect large effects on linear scales in the growth of density fluctuations.

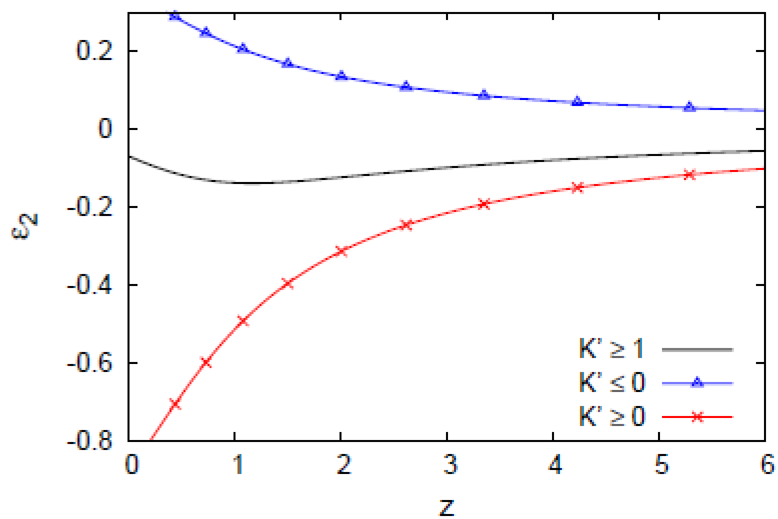
$$\delta'' + (H + \underbrace{\boxed{\frac{A'}{A}}}_{\epsilon_2})\delta' - \frac{3}{2}H^2(1 + \underbrace{\boxed{(A-1) + \frac{2\beta^2 A}{K'}}}_{\epsilon_1})\delta = 0$$

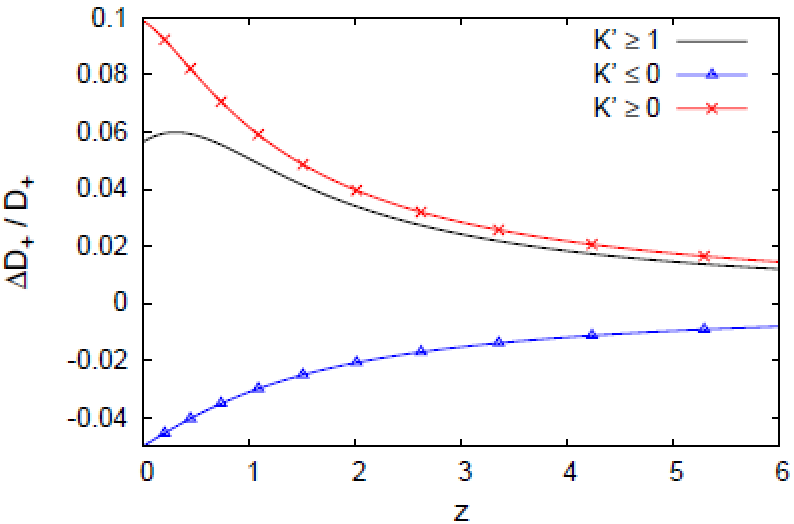
There is a new friction term and a correction to newton's constant which are scale independent but time dependent. This affects the growth factor and the growing mode and implies that on large scale, the power spectrum is enhanced by a scale independent factor.

Increase of Newton's constant.

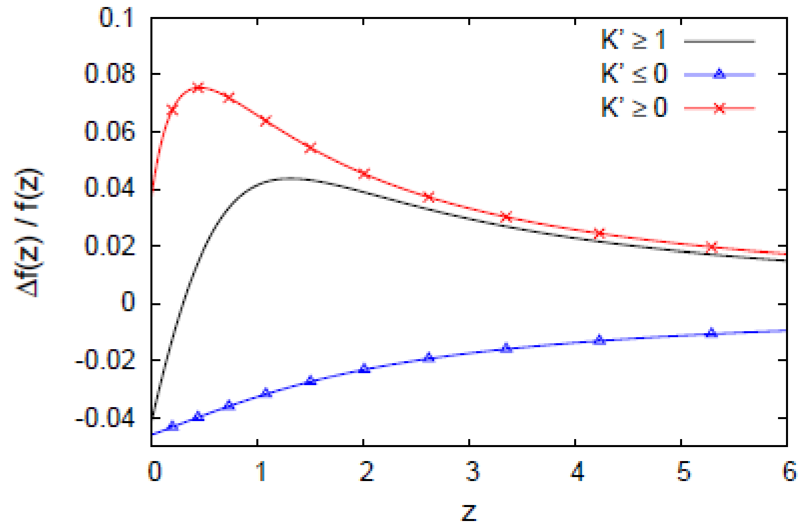


Friction term





Growing mode



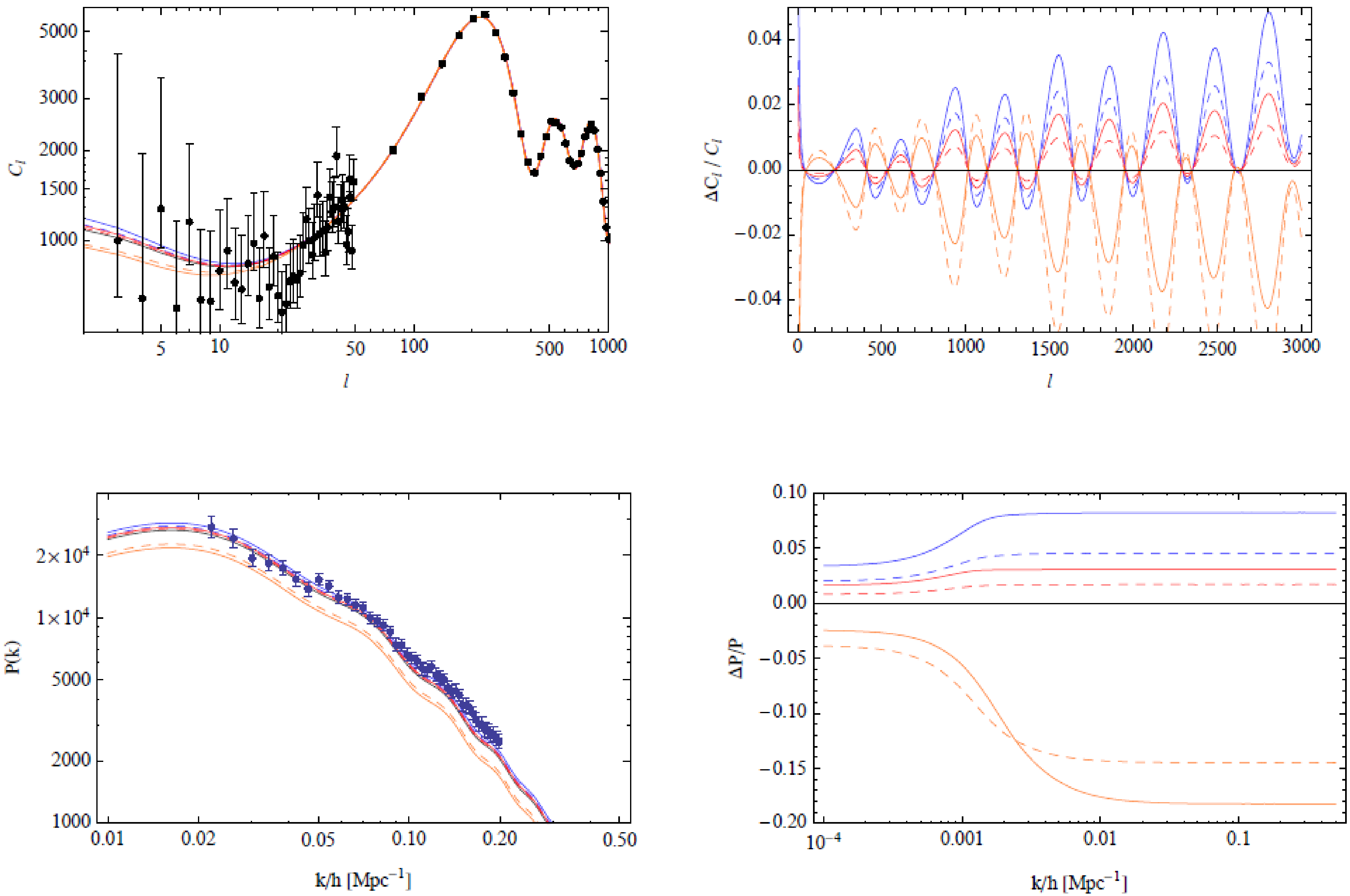
Growth factor

There is also an effect on the CMB spectrum. The fact that the Hubble rate is lower implies that the spectrum is shifted towards higher l. This would appear as a series of oscillations compared to the LCDM spectrum.

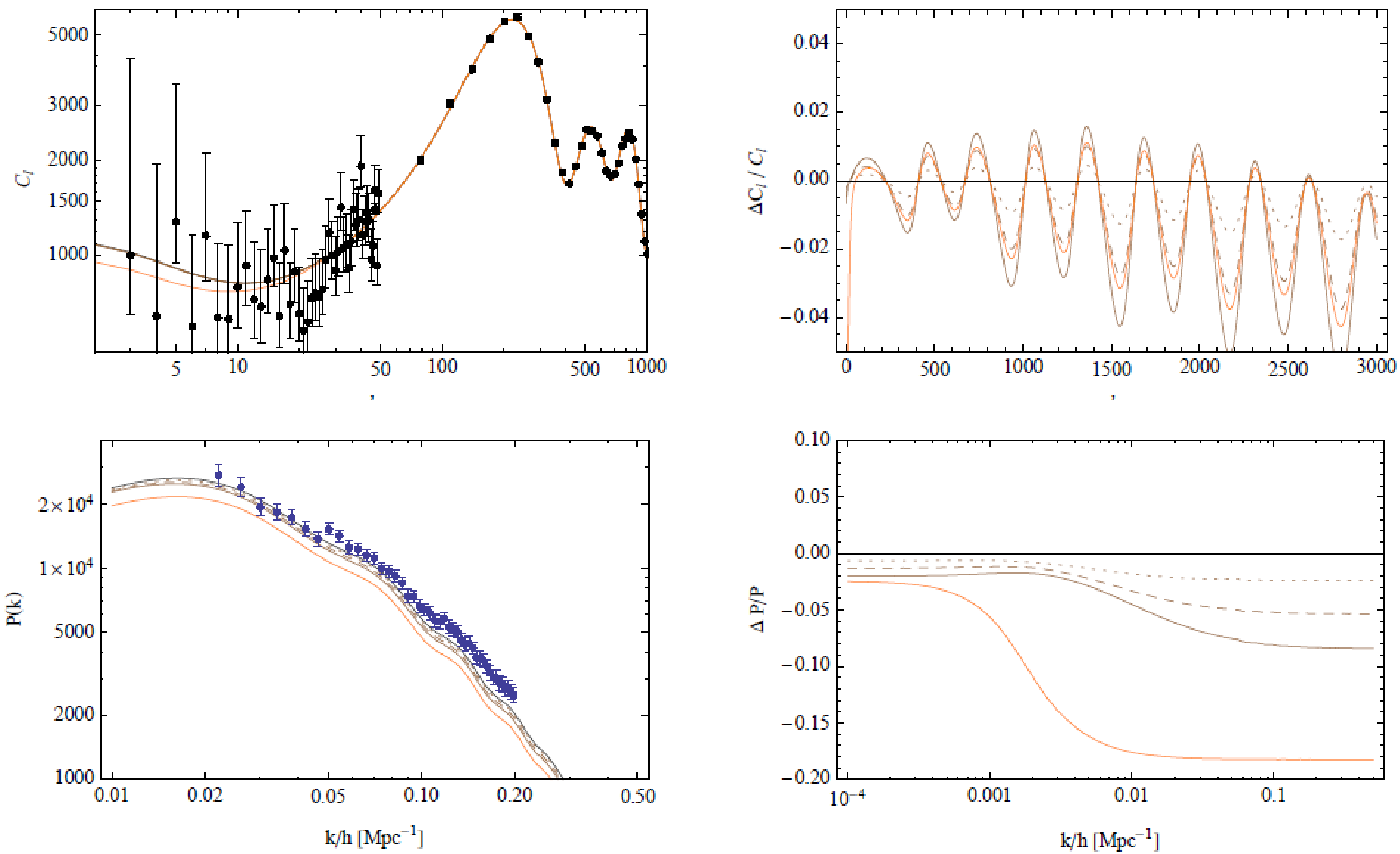
These oscillations are in phase opposition with the ones due to massive neutrinos, hence degeneracy (up to the damping induced by neutrinos)

Degeneracy!

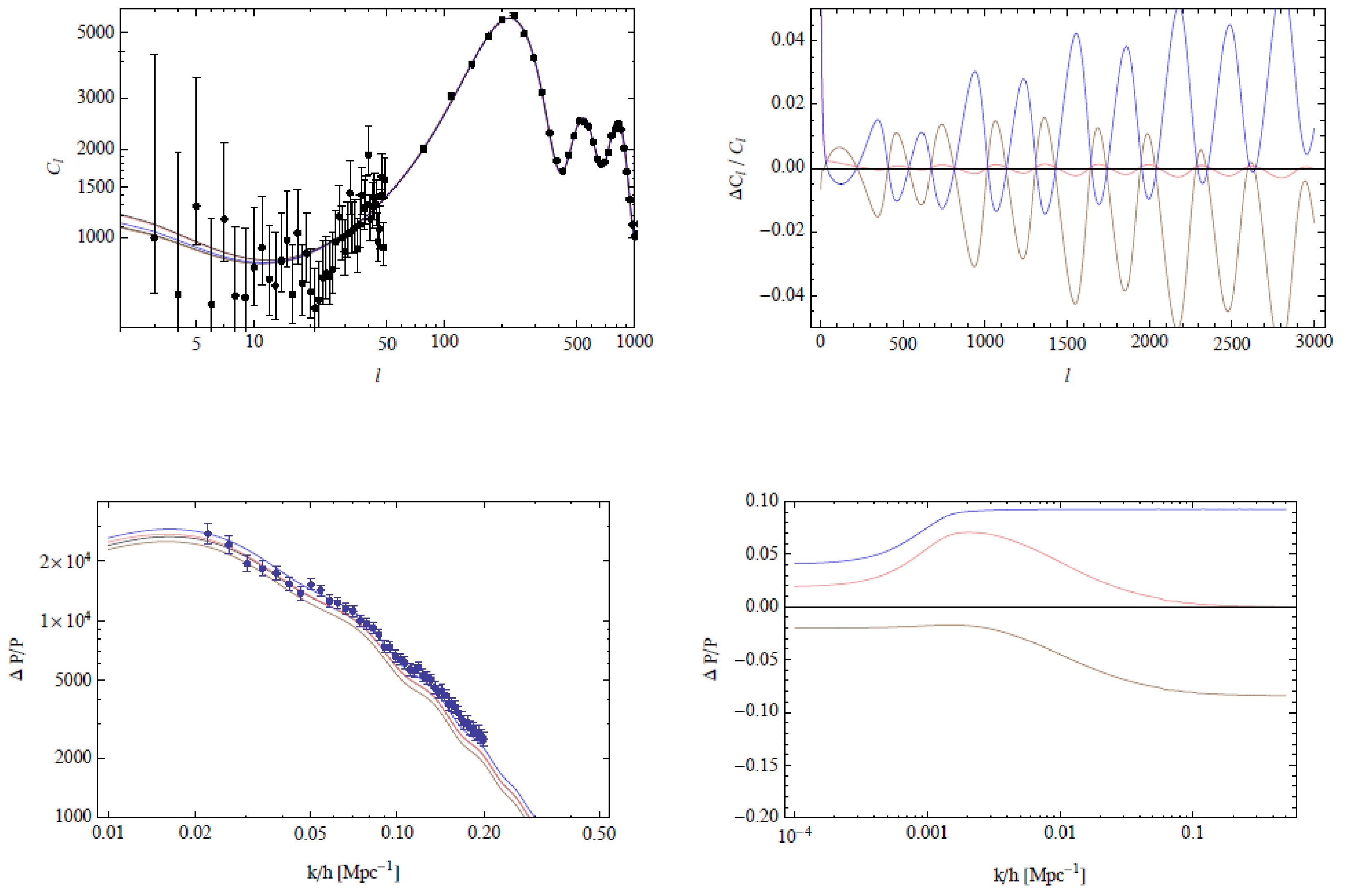
K-mouflage m=3 (blue,pink) K0>0



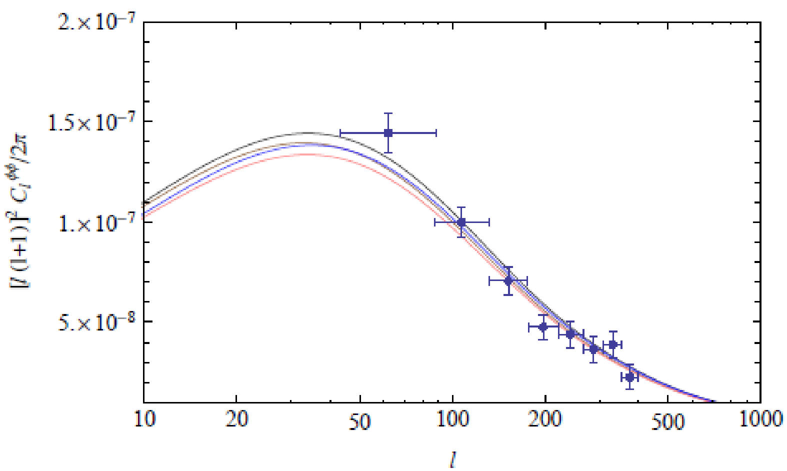
Neutrinos m=0.18 eV

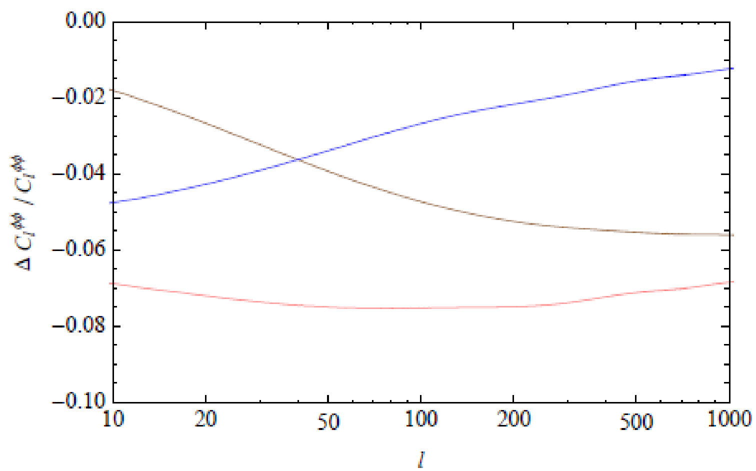


K-mouflage + neutrino



Lowering effect on the weak lensing spectrum more prominent at small l





Variation of the gravitational field due to the conformal factor A, same sign as massive neutrinos. Additive effect lifting the degeneracy.

Next steps: thorough study of the parameter space of polynomial models with MCMC, study of the degeneracy with neutrinos.

Effects on clusters (unscreened).