Modified Gravity and the CMB

Philippe Brax, IphT Saclay, France

arXiv:1109.5862 PhB, A.C. Davis
Work in progress PhB, ACD, B. Li

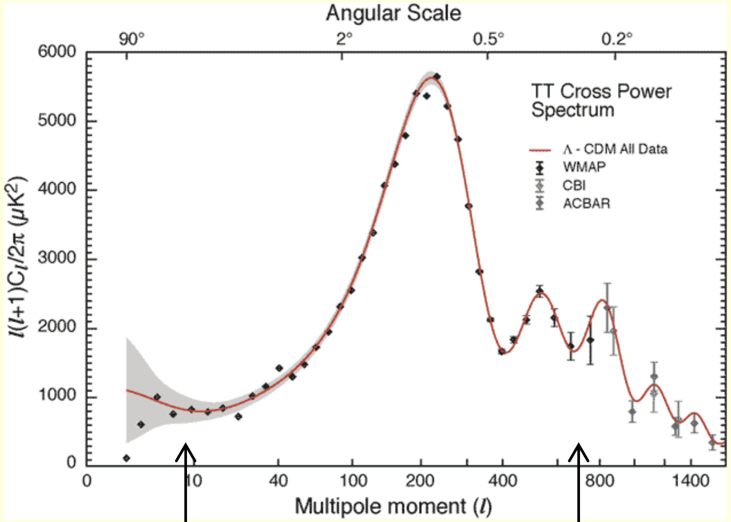
Minneapolis October 2011

PLANCK will give us very precise information on inflationary physics.

What would happen if gravity were modified ?

In general, Newton's potential would not be constant since last scattering: ISW effect.

Effects on the peak structures for modes entering the horizon early enough if gravity is modified.



ISW

Early modification of gravity

Phenomenologically, modified gravity can be parameterised in many different ways:

The growth of structures can be modified:

$$\frac{d \ln \delta}{d \ln a} = \Omega_m^{\gamma}, \quad \gamma_{\mathrm{GR}} \sim 0.55$$

The Poisson equation and the null geodesics can be altered:

$$\Delta \Phi = 4\pi G_N \mu(k,a) \rho \delta$$

$$\Delta(\Phi + \Psi) = 8\pi G_N \Sigma(a,k) \rho \delta$$

Need to embed these approaches in field theory to analyse modification of gravity from cosmological scales to the laboratory and solar system

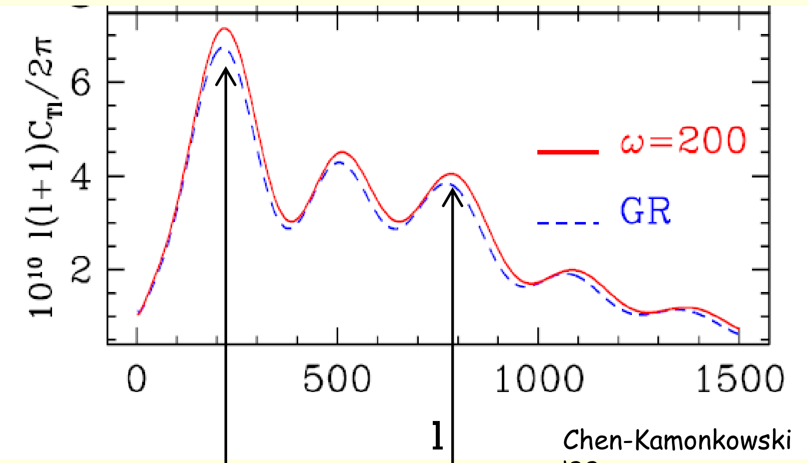
A simple modification of gravity : Brans-Dicke theory

$$S = \frac{1}{16\pi G_N}\int d^4x\sqrt{-g}(\phi R - \frac{\omega}{\phi}(\partial\phi)^2 + L_m(\psi))$$

BBN bound: $\omega \geq 32$ Damour-Pichon '99

CMB bound: $\omega \geq 1000$ Ali-Gannouji-Sami '10, Acquaviva et al '04

Planck sensitivity: $\omega \leq 3000$ Chen-Kamonkowski '99



Chen-Kamonkowski '99

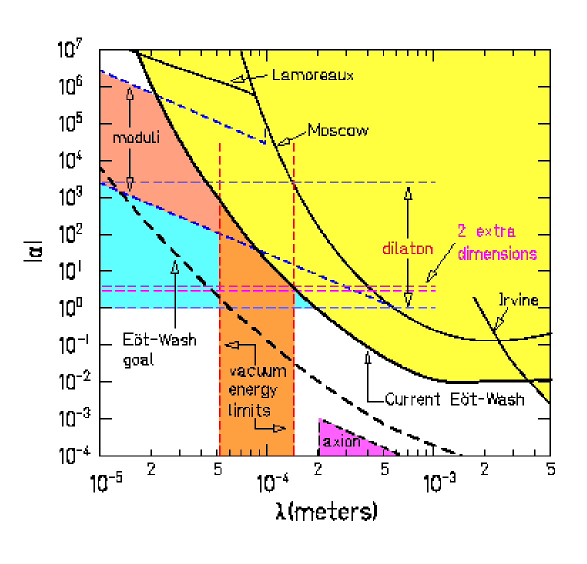
Increase of the amplitude

Shift of the peaks

- Locally, deviations from Newton's law are parametrised by:

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

$$\beta_\phi^2 = \frac{1}{2\omega + 3}$$



The tightest constraint on β comes from the Cassini probe measuring the Shapiro effect (time delay):

$$\beta_\phi^2 \leq 1.2\,10^{-5}$$

In the Brans-Dicke case, this translates to

$$\omega \geq 40000$$

CMB constraints are not competitive. If local constraints relaxed somehow (screening), one could expect to see effects of modified gravity on the CMB with Planck.

So far, known models of modified gravity involve scalar fields :

- DGP, Galileon
- Dilaton (runaway)
- Symmetron
- Chameleon, f(R)

Scalars couple to matter with potential fifth force in the solar system and the laboratory. Need to invoke a screening mechanism locally in order to preserve the possibility of modifying gravity on large scales (CMB, LSS).

Effective action

Effective field theories with gravity and scalars:

$$S = \int d^4x\sqrt{-g}\left(\frac{1}{16\pi G_N}R - F(\phi,\partial\phi) - V(\phi) + \mathcal{L}_m(\psi_m, A^2(\phi)g_{\mu\nu})\right)$$

Effective action

Effective field theories with gravity and scalars:

$$S=\int d^4x\sqrt{-g}\left(\frac{1}{16\pi G_N}R-\boxed{F(\phi,\partial\phi)}-V(\phi)+\mathcal{L}_m(\psi_m,A^2(\phi)g_{\mu\nu})\right)$$

$$\Big\downarrow \text{DGP}$$

$$\nabla^2\phi+\frac{r_c^2}{3}[(\nabla^2\phi)^2-\nabla_i\nabla_j\phi\nabla^i\nabla^j\phi]=\frac{8\pi G_N}{3}\delta\rho$$

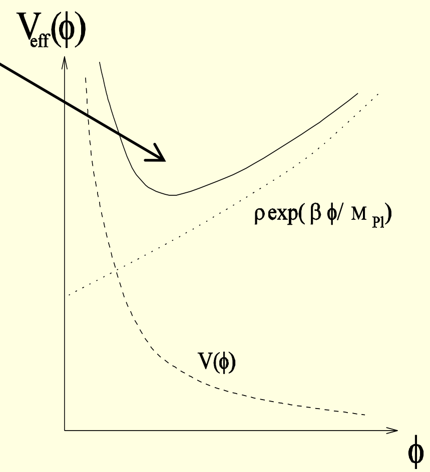
Large non-linearities in the kinetic terms imply a suppression of the coupling to matter (Vainshtein's mechanism)

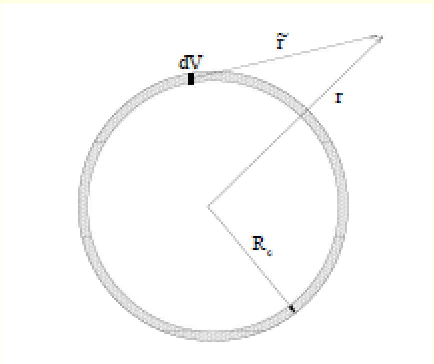
Canonical scalar fields have a matter dependent effective potential

$$\boxed{V_{eff}(\phi) = V(\phi) + \rho_m A(\phi)}$$

Khoury-Weltman

Environment dependent minimum. Chameleon mechanism





F(R) models

$$\beta = \frac{1}{\sqrt{6}}$$

The field generated from deep inside is Yukawa suppressed. Only a thin shell radiates outside the body. Hence suppressed scalar contribution to the fifth force.

Effective action

Effective field theories with gravity and scalars:

$$S=\int d^4x\sqrt{-g}\left(\frac{1}{16\pi G_N}R-\frac{1}{2}(\partial\phi)^2-V(\phi)+\mathcal{L}_m(\psi_m,\boxed{A^2(\phi)}g_{\mu\nu})\right)$$

$$\beta_\phi=m_{\mathrm{Pl}}\frac{d\ln A}{d\phi}$$

$$A(\phi)=1+\frac{A_2}{2}(\phi-\phi_0)^2+\ldots$$

Coupling to matter driven to vanish dynamically.

Damour-Polyakov mechanism

Effective action

Effective field theories with gravity and scalars:

$$S = \int d^4x\sqrt{-g}(\frac{1}{16\pi G_N}R - \frac{1}{2}(\partial\phi)^2 - V(\phi) + \mathcal{L}_m(\psi_m, \boxed{A^2(\phi)}g_{\mu\nu}))$$

$$V = V_0 + b(\phi - \phi_1)^2$$

Olive-Pospelov model

$$A(\phi) = 1 + \frac{A_2}{2}(\phi - \phi_0)^2 + \ldots$$

Damour-Polyakov mechanism

Effective action

Effective field theories with gravity and scalars:

$$S = \int d^4x\sqrt{-g}(\frac{1}{16\pi G_N}R - \frac{1}{2}(\partial\phi)^2 - V(\phi) + \mathcal{L}_m(\psi_m, \boxed{A^2(\phi)}g_{\mu\nu}))$$

$$V = V_0 e^{-\phi}$$

$$A(\phi) = 1 + \frac{A_2}{2}(\phi - \phi_0)^2 + \dots$$

Runaway dilaton

Damour-Polyakov mechanism

Damour, Piazza, Veneziano
Brax, van de Bruck, Davis, Shaw

Effective action

Effective field theories with gravity and scalars:

$$S = \int d^4x\sqrt{-g}\left(\frac{1}{16\pi G_N}R - \frac{1}{2}(\partial\phi)^2 - V(\phi) + \mathcal{L}_m(\psi_m, \boxed{A^2(\phi)}g_{\mu\nu})\right)$$

$$V = V_0 - \mu\phi^2 + \lambda\phi^4$$

$$A(\phi) = 1 + A_2\phi^2$$

Symmetron

Khoury, Hinterbichler

The Einstein equations are not modified, Klein-Gordon is:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = T^m_{\mu\nu} + T^\phi_{\mu\nu}$$

$$\nabla^\mu \nabla_\mu \phi = \partial_\phi V - \beta T^m$$

The dynamics of pressureless matter are modified

$$T^m_{\mu\nu} = \rho^E u_\mu u_\nu$$

Source in the Poisson equation

Matter is still conserved:

$$\dot{\rho} + 3h\rho = 0, \quad \rho^E = A(\phi)\rho$$

The geodesics are bent (modified Euler equation):

$$\dot{u}^\mu + \cancel{\beta \dot{\phi}} u^\mu = -\beta \partial^\mu \phi$$

At the background level, non-self accelerating models behave like pure cosmological constant models (chameleon, dilaton, symmetron…).

Fortunately, this is not the case at the perturbation level where the CDM density contrast evolves like:

$$\delta_c'' + \mathcal{H}\delta_c' - \frac{3}{2}\mathcal{H}^2 \frac{\rho_c}{\rho_c + \rho_b + \rho_\gamma + \rho_\phi}\left(1 + \frac{2\beta_c^2}{1 + \frac{m^2 a^2}{k^2}}\right)\delta = 0$$

The new factor in the brackets is due to a modification of gravity depending on the comoving scale k.

This is equivalent to a scale dependent Newton constant.

The growth of structures depends on the comoving Compton length:

$$\lambda_c = \frac{1}{ma}$$

Gravity acts in an usual way for scales larger than the Compton length (matter era)

$$\delta \sim a$$

Gravity is modified inside the Compton length with a growth (matter era):

$$\boxed{\delta \sim a^{\frac{\nu}{2}}}, \quad \nu = \frac{-1 + \sqrt{1 + 24(1 + 2\beta_c^2)}}{2}$$

For a given scale k, if am(a) decreases, the CDM density contrast first grows logarithmically in the radiation era, then like in GR before entering the Compton radius and the modified gravity regime resulting in an anomalous growth.

General Relativity $\Rightarrow$ Modified gravity

$$z = z_k$$

This type of modification of gravity on large scales can have an influence on the CMB as the baryonic density contrast and Newton's potential may be affected.

Newton's potential at the last scattering surface (LS) is modified for scales having grown anomalously after matter-radiation equality and before last scattering . For $k_1 < k < k_c$

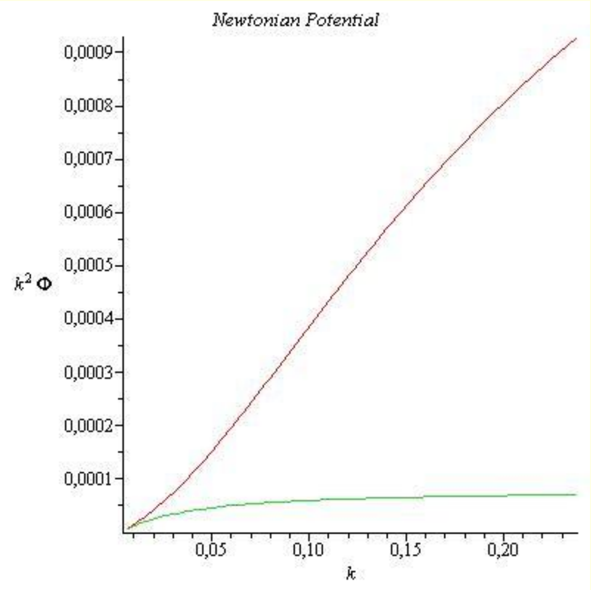
$$k^2\Phi \sim (\frac{k}{k_1})^{(1-\nu/2)/(1+r)}(1 + 2\ln\frac{a_{\rm eq}}{a_k})$$

$$k_1 = a_{LS}m(a_{LS})$$

For smaller and larger scales, the growth is only logarithmic.

We have illustrated this fact with:

$$m(a) = m(a_{LS})(\frac{a}{a_{LS}})^r$$



$$k_1 \sim 0.035h \cdot \mathrm{Mpc}^{-1}, \quad k_c \sim 0.1h \cdot \mathrm{Mpc}^{-1}$$

$$\beta_c = 100, \beta_b = 0$$

Baryons couple to the scalar field implying a modification of the speed of sound:

$$\tilde{c}_s^2 = c_s^2\left(1 - \frac{9\Omega_b \beta_b^2 A_b^2 R \mathcal{H}^2}{k^2 + m^2 a^2}\right)$$

The baryon density contrast at the last scattering surface oscillates with a modified sound horizon. In the tight binding approximation, the Sach-Wolfe temperature receives new contributions:

$$\Theta = \frac{\tilde{\delta}}{3(1+R)^{1/2}} + \frac{R}{R+1}\left(1 + \frac{9\Omega_b \mathcal{H}^2}{k^2}\tilde{\beta}_b^2 + 2\tilde{\beta}_b\tilde{\beta}_c\right)\frac{\Phi}{3\tilde{c}_s^2}$$

where:

$$\tilde{\delta} = \frac{3}{2}(1+R_k)^{1/4}(1+2R_k)\Phi(0)(1+R)^{1/4}\cos \tilde{r}_s k$$

New sound horizon

Effects on the CMB only when

$$\tilde{\beta} = \frac{\beta}{\sqrt{1 + \frac{m^2 a^2}{k^2}}}$$

is not too small. If m(a)a smaller or roughly of the order of $k_1 = a_{LS} m(a_{LS})$, this behaves essentially like a Brans-Dicke model at last scattering.

If m(a)a is much larger, then ,unless the coupling is very large, there are no effects on the CMB.

$$\Theta = \frac{\tilde{\delta}}{3(1+R)^{1/2}} + \frac{R}{R+1}\left(1 + \cancel{\frac{9\Omega_b \mathcal{H}^2}{k^2}}\,\tilde{\beta}_b^2 + 2\tilde{\beta}_b\tilde{\beta}_c\right)\frac{\Phi}{3\tilde{c}_s^2}$$

$$\Theta = \frac{\tilde{\delta}}{3(1+R)^{1/2}} + \frac{R}{R+1}\left(1 + \cancel{\frac{9\Omega_b \mathcal{H}^2}{k^2}}\,\tilde{\beta}_b^2 + 2\tilde{\beta}_b\tilde{\beta}_c\right)\frac{\Phi}{3\tilde{c}_s^2}$$

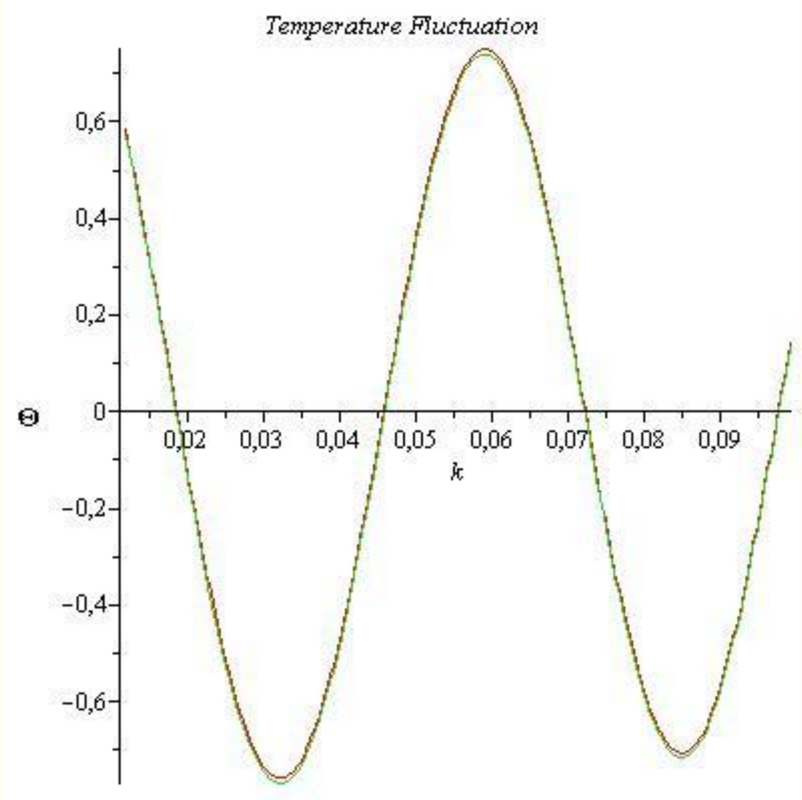
Modified speed of sound

$$\Theta = \frac{\tilde{\delta}}{3(1+R)^{1/2}} + \frac{R}{R+1}\left(1+\cancel{\frac{9\Omega_b\mathcal{H}^2}{k^2}}\tilde{\beta}_b^2 + 2\tilde{\beta}_b\tilde{\beta}_c\right)\frac{\Phi}{3\tilde{c}_s^2}$$

Modified growth of structures

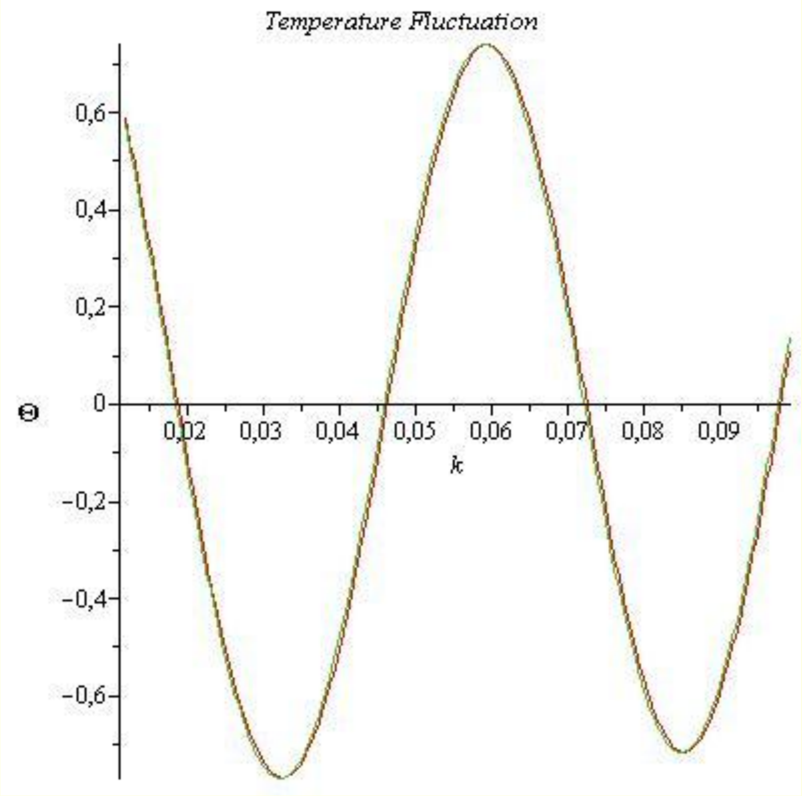
$$\Theta = \frac{\tilde{\delta}}{3(1+R)^{1/2}} + \frac{R}{R+1}\left(1+\cancel{\frac{9\Omega_b\mathcal{H}^2}{k^2}}\tilde{\beta}_b^2 + 2\tilde{\beta}_b\tilde{\beta}_c\right)\frac{\Phi}{3\tilde{c}_s^2}$$

Baryon-CDM coupling



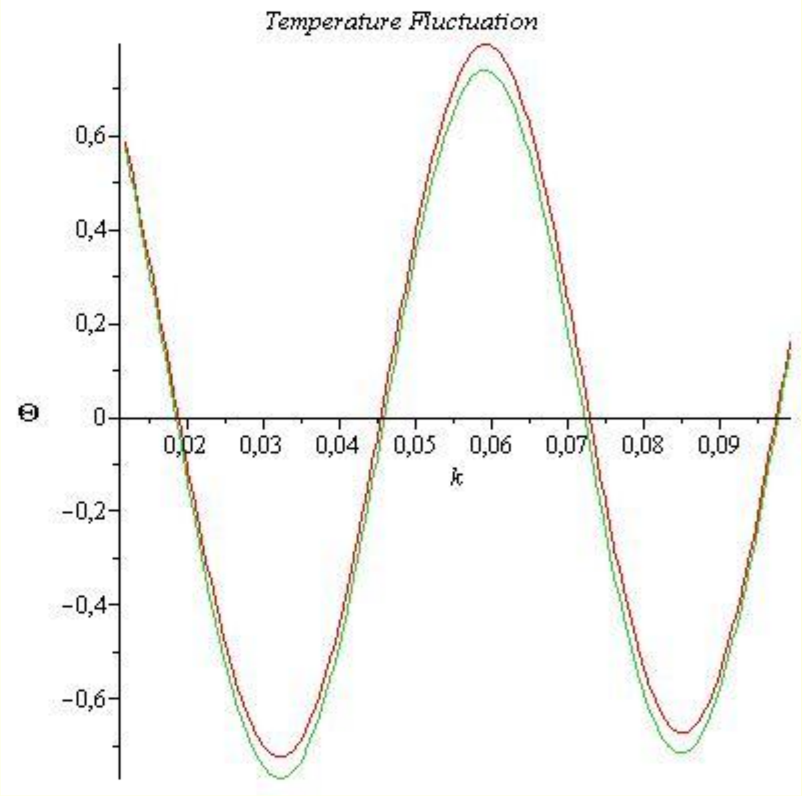
$\beta_c = 100, \beta_b = 0$

Increase of the amplitude due to the CDM coupling when k1 is equal to wave number of the first peak.



$\beta_c = 0, \beta_b = 3$

Shift of the peaks due to the baryon coupling only.



$$\beta_b = \beta_c = 2$$

Larger effect with both baryon and CDM couplings. Window for Planck?

Of course, effects at last scattering do not exist decoupled from other effects which must be taken into account:

Effects on BBN

Effects on large scale structures at small z

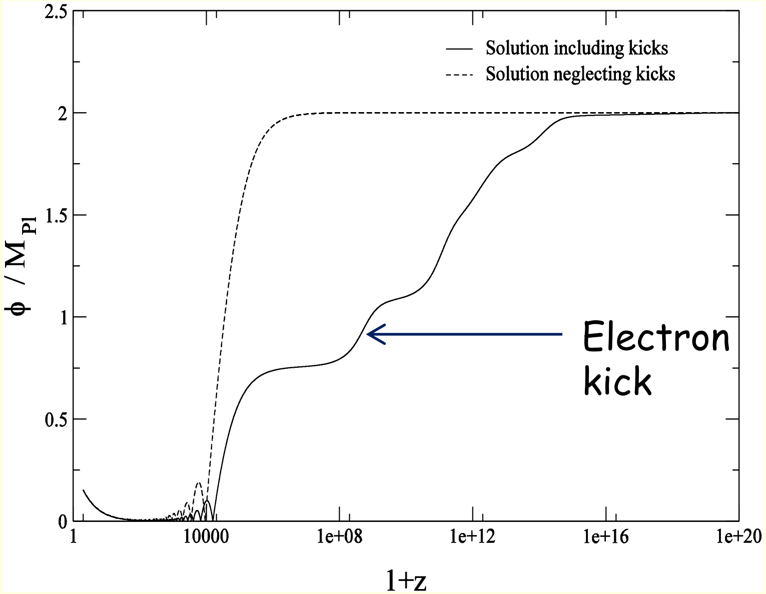
The compatibility with local tests of gravity

The variation of constants

...

Work in progress, PhB, A.C.Davis, B. Li.

In scalar-tensor theories, the scalar field must have converged towards the minimum of the effective potential before BBN otherwise large variation of particle masses due to the electron decoupling.



The scalar field follows the attractor (m>>H) from before BBN, where the matter density is similar to dense bodies now, to the present era with a tiny critical density.

$$10\ \mathrm{g}\cdot\mathrm{cm}^{-3} \rightarrow 10^{-29}\ \mathrm{g}\cdot\mathrm{cm}^{-3}$$

The dynamics of the scalar field can be reconstructed (for non-vanishing couplings in field space):

$$\phi(a) = \frac{3}{m_{\rm Pl}} \int_{a_{\rm ini}}^{a} \frac{\beta(a)}{a m^2(a)} \rho(a) da + \phi_c$$

The initial value before BBN corresponds to the field value inside a dense body.

The potential can also be inferred:

$$V = V_0 - 3 \int_{a_{\rm ini}}^{a} \frac{\beta(a)^2}{a m^2(a)} \frac{\rho^2}{m_{\rm Pl}^2} da.$$

By inversion, the coupling $\beta(\phi)$ can also be deduced.

Very stringent constraints from solar system physics. Can be avoided if thin shell mechanism.

$$\frac{|\phi_0 - \phi_c|}{m_{\rm Pl}} \ll 6\beta_c \Phi_G$$

Galactic Newton potential $\Phi_G \approx 10^{-6}$

where the ratio between the LHS and the RHS must be smaller than 10^{-5}

The thin shell condition is independent of the coupling . Putting

$$m(a) = m_0 f(a), \quad \beta(a) = \beta_0 g(a)$$

it becomes:

$$9\cancel{\beta_0}\frac{\Omega_{m0} H_0^2}{m_0^2}\int_{a_{\rm ini}}^1 da \frac{g(a)}{g(a_{\rm ini})}\frac{1}{a^4 f^2(a)} \ll 6\cancel{\beta_0}\Phi_G$$

$m_0 \geq 10^5 H_0$

Modified gravity on small scales.
Numerical simulations.

The integral must converge.
Constraint on the mass and coupling functions around BBN

Weak constraints from variation of constants, e.g. the electron to proton mass ratio μ:

$$\frac{\dot{\mu}}{\mu}|_0 = (-3.8 \pm 5.6)10^{-14}\mathrm{yr}^{-1}$$

Which gives a constraint on the coupling to matter now (essentially):

$$\frac{\dot{\mu}}{\mu} \approx 9\Omega_m \beta^2 \frac{H^2}{m^2}$$

The coupling is bounded by:

$$\beta_0 \leq 10^2$$

The connection between the present era and the last scattering (and even before BBN) requires to model the time evolution of the mass and coupling.

Moreover, need numerical simulations to ascertain the compatibility between structure formation and CMB, in particular to see how Planck could see effects of modified gravity.

Of course, there will be a certain level of degeneracy with other cosmological parameters, neutrinos etc…

21 cm physics probing the « dark ages » will also give new constraints.

Modified gravity tomography?

Work in progress

Conclusion

Scalar fields can modify gravity on large scales and preserve gravity locally.

Maybe a window for Planck to see a modified gravity effect.