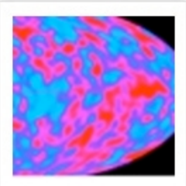

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DE from non-local effective gravity modifications

Stefano Foffa

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Département de physique théorique

Center for Astroparticle Physics
GENEVA

with: YVES DIRIAN, MAUD JACCARD, ALEX KEHAGIAS, NIMA KHOSARVI, MARTIN KUNZ, MICHELE MAGGIORE, MICHELE MANCARELLA, ERMIS MITSOU

Outline

Part I: theory

- Motivations and context: the DE problem
- Local and non-local GR modifications

Part II: phenomenology

- Spherical solutions (no vDVZ discontinuity)
- Cosmology: background & perturbations

Modify GR in the infrared to get a DE model with same # of parameters as ΛCDM:

$$m \longleftrightarrow \Lambda$$

Local modifications: massive gravity

Fierz-Pauli: ghost-free at the linear level

dRGT: ghost-free at the nonlinear level

no flat FRW, instabilities
need for a reference, nondynamical metric

bigravity: extra massive spin2,
general covariant and still ghost-free

good background
perturbations under investigations

Non-local modifications: general covariance without extra degrees of freedom

degravitation:

$$\left(1 - \frac{m^2}{\Box}\right) G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

(Arkani-Hamed, Dimopoulos, Dvali and Gabadadze 2002)

$$\Box_{\mathrm{r}}^{-1} f(x) \equiv \int \mathrm{d}^4 y \; G_r(x, y) \; f(y)$$

↓

retarded Green function to ensure causality

Cannot be obtained from a variational principle:

$$\frac{\delta}{\delta\phi(x)}\int dx'\phi(x')(\Box_{\rm r}^{-1}\phi)(x') = \frac{\delta}{\delta\phi(x)}\int dx'dx''\phi(x')G_{\rm r}(x',x'')\phi(x'')$$

$$= \int dx'[G_{\rm r}(x,x') + G_{\rm r}(x',x)]\phi(x')$$

↓

no fundamental lagrangian: effective theory

(ghost problem cannot be addressed)

Still, non-local terms arise naturally in several contexts:

- when integrating out extra degrees of freedom (other fields or short-wavelength modes)
- in QFT, computing effective equations for in-in matrix elements (associated to classical observables)

possible implementations:

first try:

$$G_{\mu\nu} - m^2(\Box_{\mathrm{r}}^{-1} G_{\mu\nu})^T = 8\pi G T_{\mu\nu}$$

$$\Big(S_{\mu\nu} = S^T_{\mu\nu} + (\nabla_\mu V_\nu + \nabla_\nu V_\mu) \qquad \nabla^\mu S^T_{\mu\nu} = 0 \Big)$$

does not work:

in general, taking the transverse part of tensors brings instabilities:

$$S^T_{\mu\nu} \leftarrow S^0_0 \,, S^i_i \,, V_0$$

two ways out :

I: $$G_{\mu\nu} - m^2 (g_{\mu\nu} \Box_{\mathrm{r}}^{-1} R)^T = 8\pi G T_{\mu\nu}$$

$$(g_{\mu\nu} S)^T \leftarrow S$$

II: $$G_{\mu\nu} - m^2 K_{\mu\nu}^{NL} = 8\pi G T_{\mu\nu}$$

with

$$\nabla^\mu K_{\mu\nu}^{NL} \equiv 0$$

trick: "derive" it from an "action", e.g.:

$$S_{\mathrm{NL}} = \frac{1}{16\pi G} \int d^4 x \sqrt{-g} \left[R - m^2 R \frac{1}{\Box_{\mathrm{r}}^2} R \right]$$

$$\Box \rightarrow \Box_r$$

I and II are equivalent at linear level

Part II

Spherical solutions

Absence of vDVZ discontinuity and of a strong coupling regime

- write the eqs of motion of the non-local theory in spherical symmetry

$$ds^2 = -A(r)dt^2 + B(r)dr^2 + r^2(d\theta^2 + \sin^2\theta\, d\phi^2)$$

- for $mr \ll 1$: low-mass expansion

- for $r \gg r_S$: Newtonian limit (perturbation over Minowski)

- match the solutions for $r_S \ll r \ll m^{-1}$ (this fixes all coefficients)

For both models I and II one finds:

for $r_s \ll r \ll m^{-1}$: $$A(r) \simeq 1 - \frac{r_S}{r}\left(1 + \frac{m^2 r^2}{6}\right)$$

the limit $m \to 0$ is smooth !

By comparison, in massive gravity the same computation gives

$$A(r) = 1 - \frac{4}{3}\frac{r_S}{r}\left(1 - \frac{r_S}{12 m^4 r^5}\right)$$

vDVZ discontinuity

breakdown of linearity below $r_V = (r_s/m^4)^{1/5}$

Both I and II are ok with solar system constraints

Cosmology: background

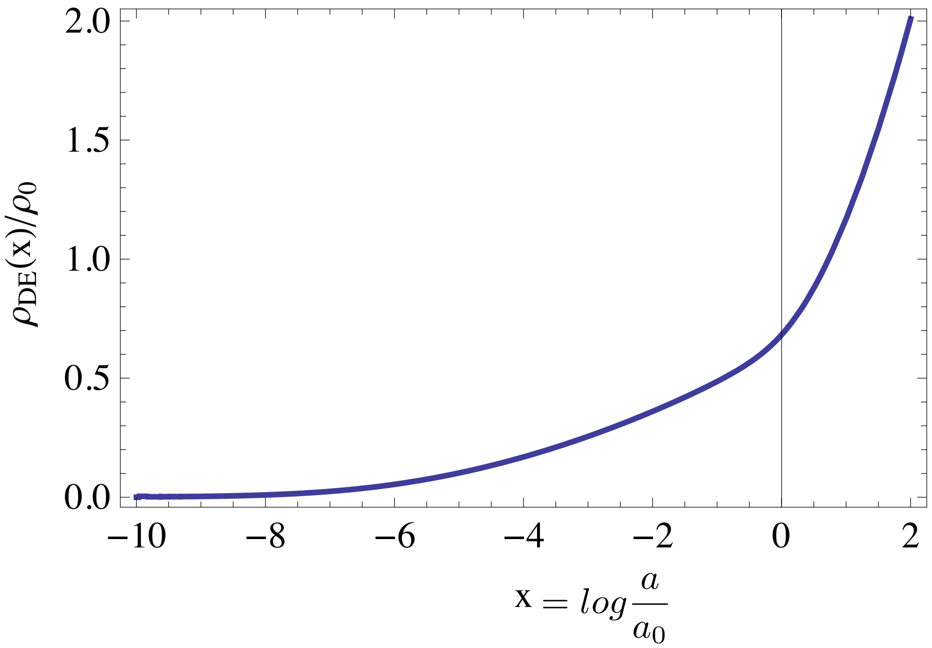
trade nonlocal for local terms

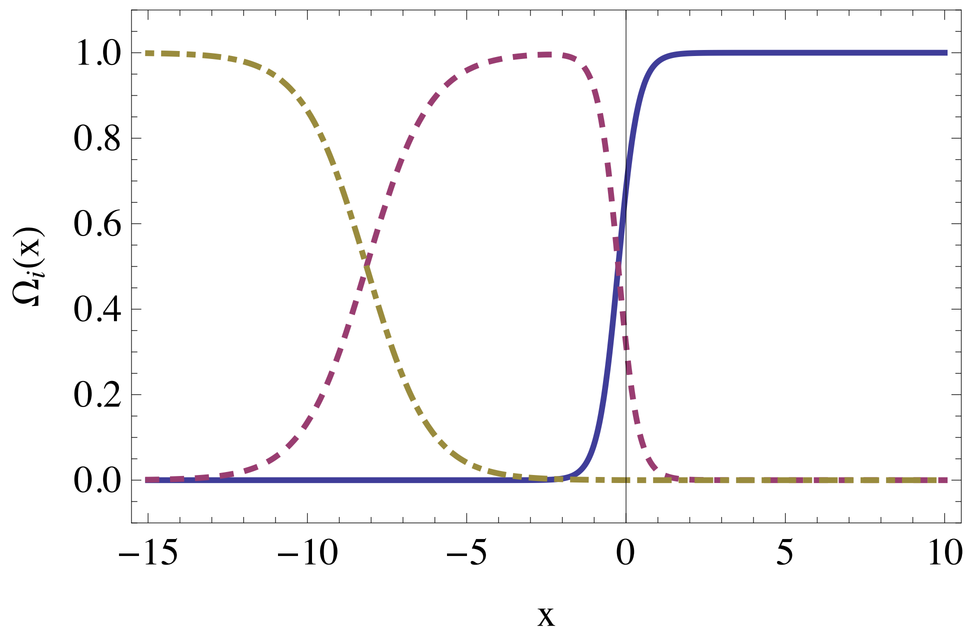
$$\Box_r^{-1} R \to U : \Box_r U = R \, , R = 0 \Rightarrow U = 0$$

and run numerical evolution
starting from deep in radiation era $(R = 0)$

adjust the only parameter m in order to have $\rho + \rho_{DE} = \rho_0$ today,
if possible

(as is done in ΛCDM, after all)





$$\gamma \equiv \frac{m^2}{9H_0^2} = \begin{array}{ll} 0.0504 & (\mathrm{I}) \\ 0.0891 & (\mathrm{II}) \end{array}$$

The effective DE is sourced by R and starts growing only during MD

DE equation of state

$$\dot{\rho}_{\rm DE} + 3(1 + w_{\rm DE}) H \rho_{\rm DE} = 0$$

$w^0_{DE} =$ -1.04 (I)

-1.14 (II)

phantom

a general feature of DE models sourced by R:

one unavoidably has $\dot{\rho}_{DE} > 0$ and $\rho_{DE} > 0$ at some point

Stability:

strictly speaking, one never has $R = 0$

so one should check that small deviations from the natural initial conditions for the auxiliary local fields $U_{in} = 0$

do not spoil the good behaviour.

Indeed one always finds:

$$\delta U \simeq \mathrm{e}^{\alpha x} \, , \alpha < 0$$

Perturbations

are a much more stringent test

e.g.: Deser-Woodward model $Rf(\Box^{-1}R)$

ruled out by structure formation at 8σ level.

Perturbations equations for models I and II have been studied in the fluid approximation:

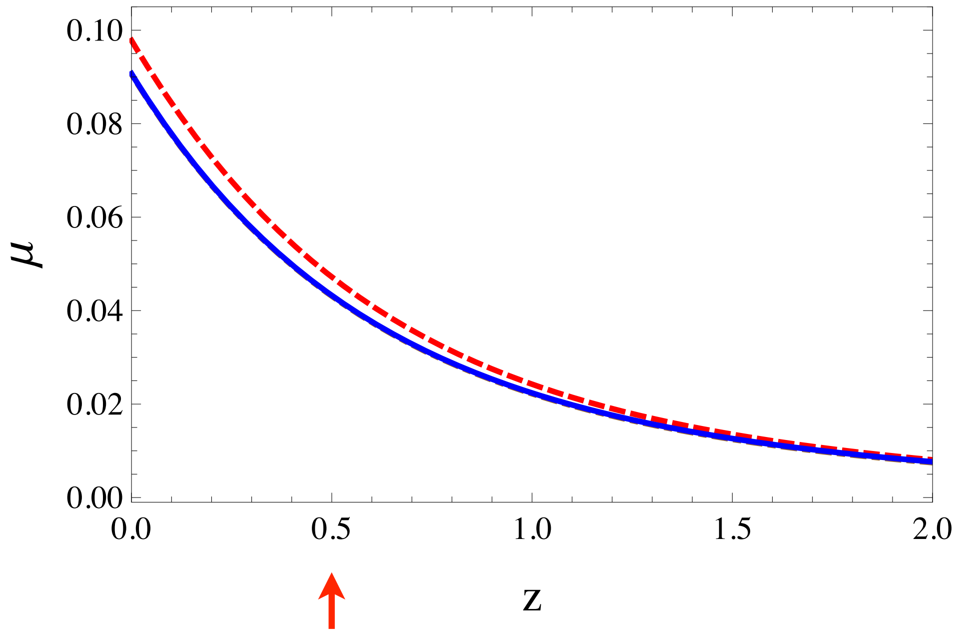
both are well compatible with observations,
and differ from ΛCDM at a few % level

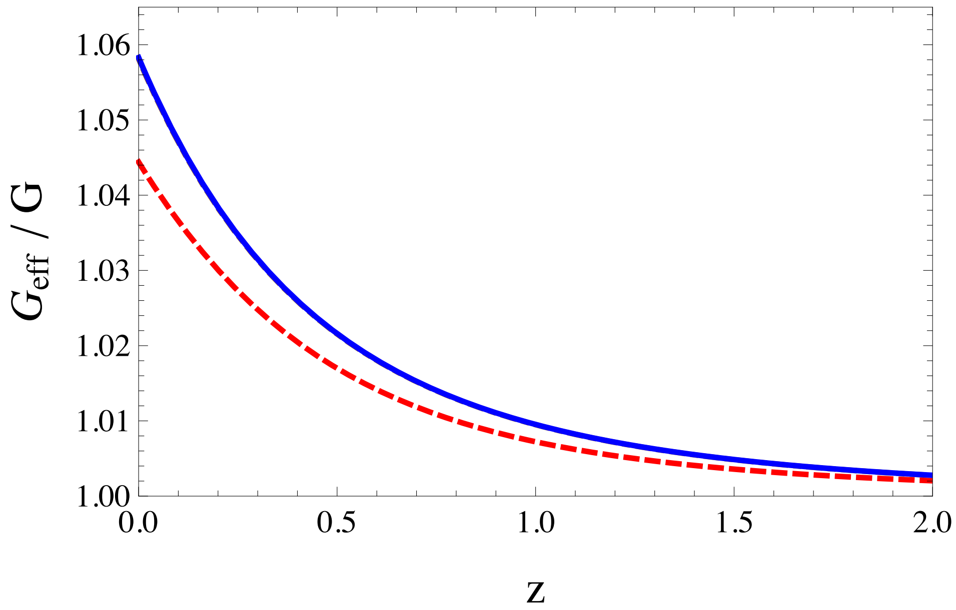
see also: NESSERIS, TSUJIKAWA: 1402.4613

BARREIRA, LI, HELLWING, BAUGH, PASCOLI, in preparation

$$\Psi = [1+\mu(a;k)]\Psi_{\rm GR}$$
$$\Psi - \Phi = [1+\Sigma(a;k)](\Psi-\Phi)_{\rm GR}$$

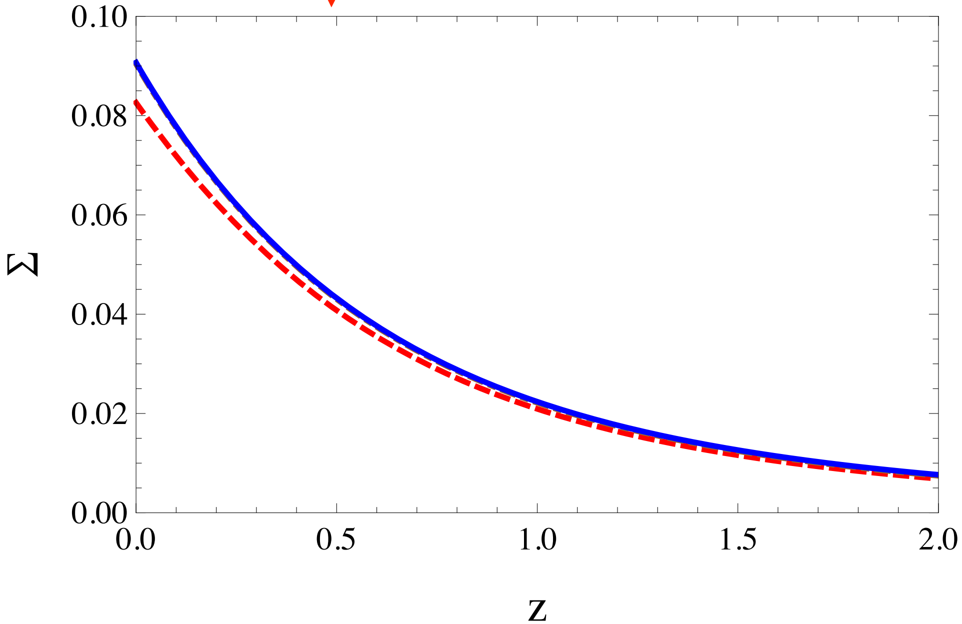
$$k^2\Phi = 4\pi G_{eff}\delta\rho$$

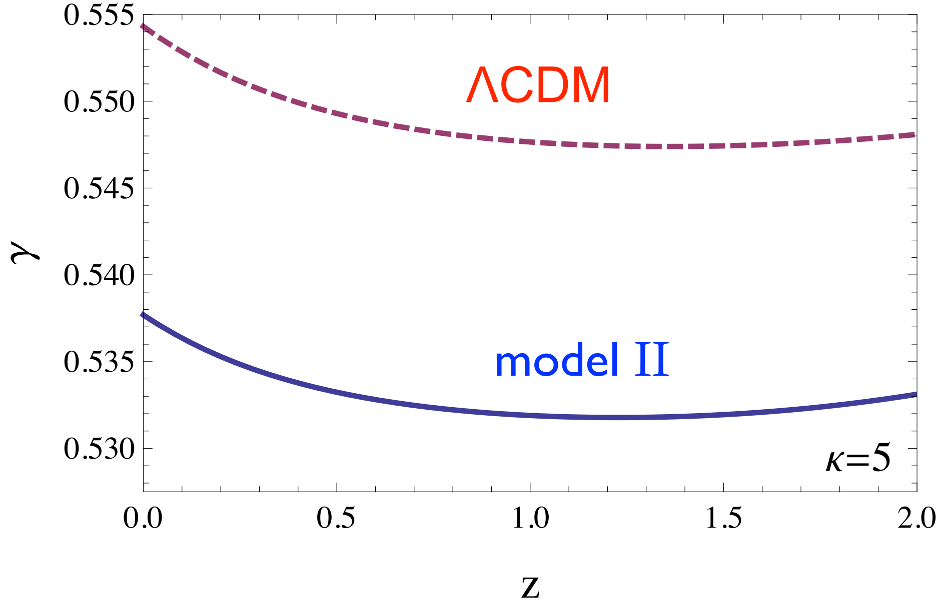




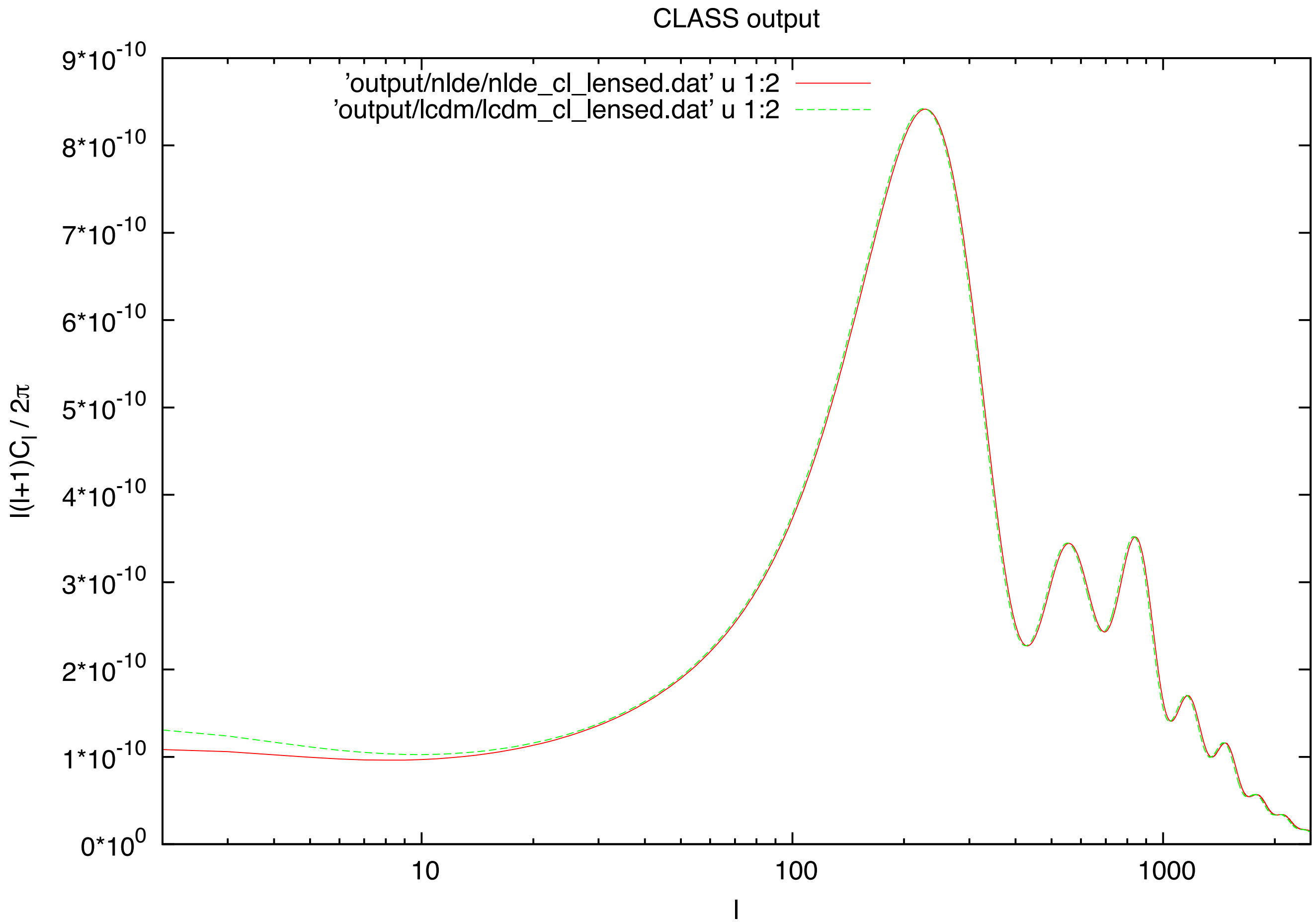
4% difference at z=.5

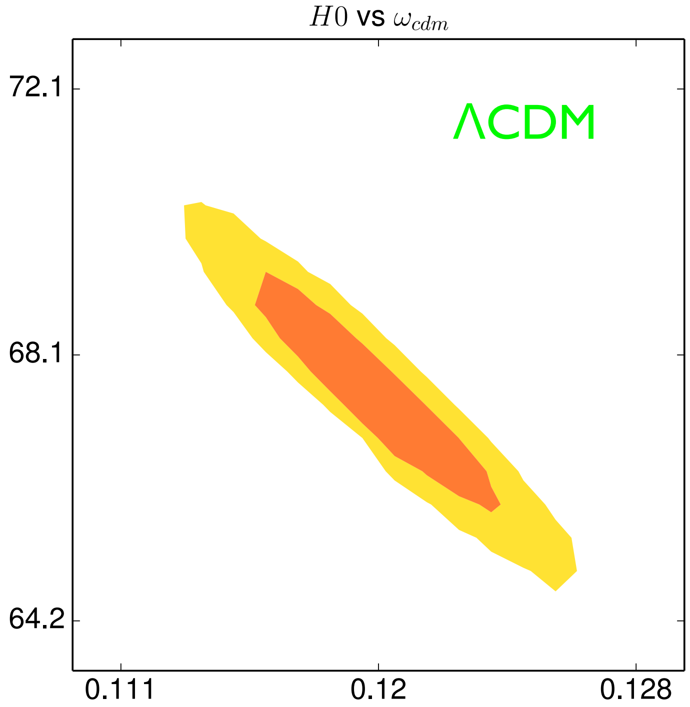
$$\frac{d\log\delta_M(a;k)}{d\ln a} = [\Omega_M]^{\gamma(z;k)}$$

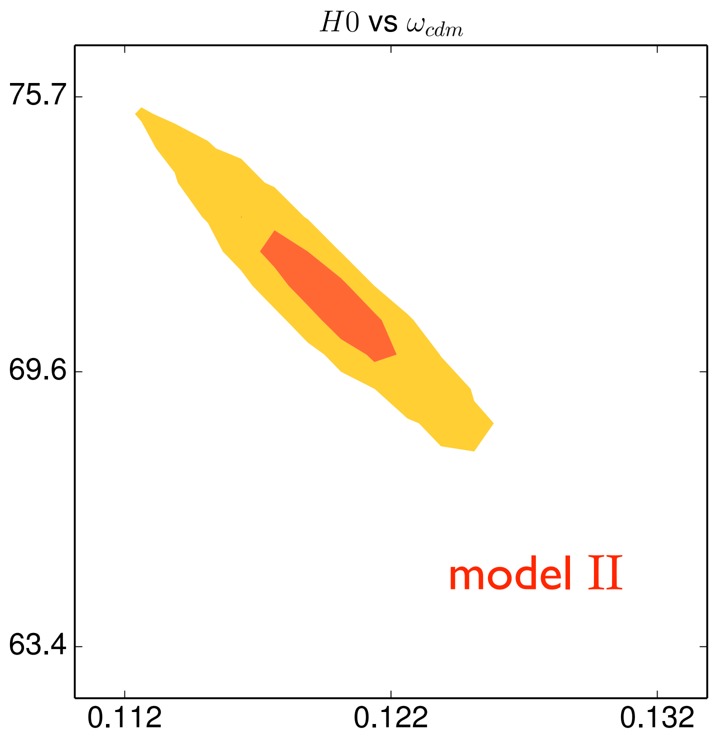




CMB (preliminary)







nonlocal models prefer high values for H_0

Conclusions

Nonlocal massive gravity is phenomenological approach providing:

- attenuation of coincidence problem
- phantom e.o.s. $w<-1$
- good structure formation,
  with % deviations form ΛCDM
- good agreement with CMB and high H_0

Can it be derived from a more fundamental theory?

...see for instance TSAMIS, WOODARD: 1405.4470
and CUSIN, FUMAGALLI, MAGGIORE: 1407.5580

A fake ghost in massless GR

$$S^{(2)}_{\rm EH} = \frac{1}{2}\int d^{d+1}x\, h_{\mu\nu}\mathcal{E}^{\mu\nu,\rho\sigma}h_{\rho\sigma}$$

$$h_{\mu\nu} = h^{\rm TT}_{\mu\nu} + \frac{1}{2}(\partial_\mu\epsilon_\nu + \partial_\nu\epsilon_\mu) + \frac{1}{d}\eta_{\mu\nu}s$$

$$S^{(2)}_{\rm EH} = \frac{1}{2}\int d^{d+1}x\,\left[h^{\rm TT}_{\mu\nu}\Box(h^{\mu\nu})^{\rm TT} - \frac{d-1}{d}\,s\Box s\right]$$

$$S_{\rm int} = \frac{\kappa}{2}\int d^{d+1}x\, h_{\mu\nu}T^{\mu\nu} = \frac{\kappa}{2}\int d^{d+1}x\,\left[h^{\rm TT}_{\mu\nu}(T^{\mu\nu})^{\rm TT} + \frac{1}{d}sT\right]$$

$$\Box h^{\rm TT}_{\mu\nu} = -\frac{\kappa}{2}T^{\rm TT}_{\mu\nu}\,, \qquad \Box s = \frac{\kappa}{2(d-1)}T$$

It looks as if there are many more propagating d.o.f

Furthermore s seems a ghost !

S. F. Hassan, R. A. Rosen, and A. Schmidt-May 2012