The dark side of gravity

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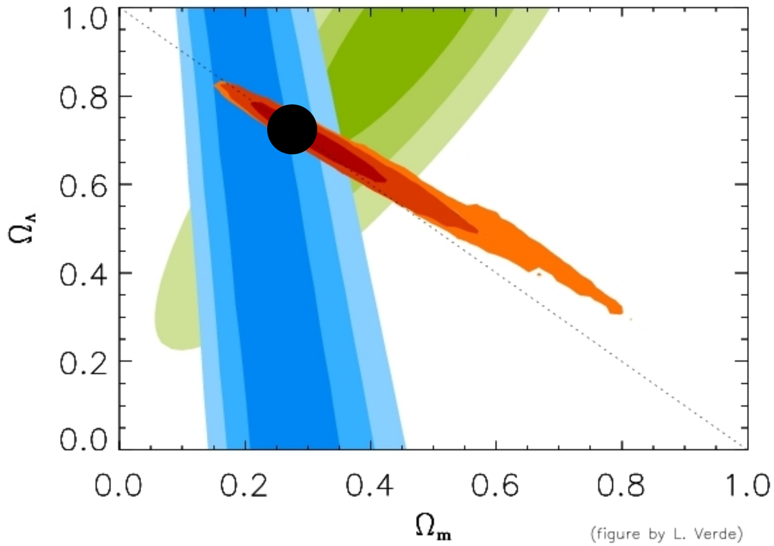
Observations are converging…



…to an unexpected universe

The dark energy problem

$$F(g_{\mu\nu}) + R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu} + 8\pi G T_{\mu\nu}(\phi)$$

gravity matter

$$\Omega_{tot} \approx 1$$

$$\Omega_{cluster} \approx 0.3$$

Solution: modify either the Matter sector → DE

or the Gravity sector → MG

...in such a way that : $$\frac{p_X}{\rho_X} = w_X \approx -1$$

Modified matter

Problem:

All the matter particles we know possess an effective interaction range that is much smaller than the cosmological scales

→ **the effective pressure is always positive !**

Solution:

add new forms of matter with strong interaction/self-interaction

→ **the effective pressure can be large and negative**

Dark Energy=scalar fields, generalized perfect fluids etc

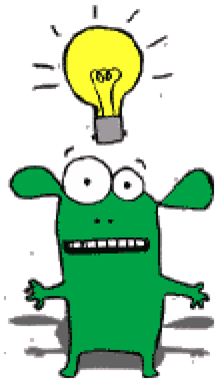
Modified gravity

Can we detect traces of modified gravity at $\left\{ \begin{array}{c} \text{background} \\ \text{linear} \\ \text{non-linear} \end{array} \right\}$ level ?

What is modified gravity ?

What is gravity ?

A universal force in 4D mediated by a massless tensor field



What is modified gravity ?

A non-universal force in nD mediated by (possibly massive) tensor, vector and scalar fields

Cosmology and modified gravity

in laboratory

in the solar system

} very limited time/space/energy scales; only baryons

at astrophysical scales

complicated by non-linear/non-gravitational effects

at cosmological scales

unlimited scales; mostly linear processes; baryons, dark matter, dark energy !

Simplest MG (I): DGP

(Dvali, Gabadadze, Porrati 2000)

$$S = \int d^5x\sqrt{-g^{(5)}}\; R^{(5)} \;+\; L\int d^4x\sqrt{-g}\,R$$

$$H^2 - \frac{H}{L} = \frac{8\pi G}{3}\rho$$

L = crossover scale:

$$r << L \Rightarrow V \propto \frac{1}{r}$$

$$r >> L \Rightarrow V \propto \frac{1}{r^2}$$

- **5D gravity dominates at low energy/late times/large scales**
- **4D gravity recovered at high energy/early times/small scales**

Simplest MG (II): f(R)

Let's start with one of the simplest MG model: f(R)

$$\int dx^4 \sqrt{g}\left[f(R) + L_{matter}\right]$$

eg higher order corrections $\int dx^4 \sqrt{g}\left(R + R^2 + R^3 + \ldots\right)$

✓ f(R) models are simple and self-contained (no need of potentials)
✓ easy to produce acceleration (first inflationary model)
✓ high-energy corrections to gravity likely to introduce higher-order terms
✓ particular case of scalar-tensor and extra-dimensional theory

Is this already ruled out by local gravity?

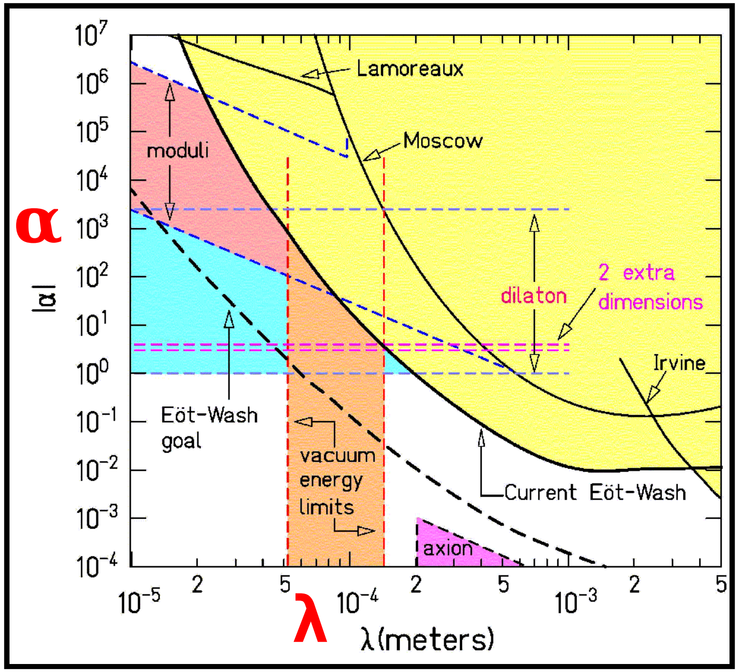
$$\int dx^4 \sqrt{g}\,(f(R) + L_{matter})$$

is a scalar-tensor theory with Brans-Dicke parameter ω=0 or a coupled dark energy model with coupling β=1/2

$$G^* = G(1 + \frac{4}{3}\beta^2 e^{-m_\phi r}) = G(1 + \alpha e^{-r/\lambda})$$

$$m^2{}_\phi = \frac{1}{f''} + \frac{Rf' - 4f}{f'^2} \rightarrow \frac{1}{f''}$$

(on a local minimum)



The simplest case

$$\int dx^4 \sqrt{g}\left(R - \frac{\mu^4}{R} + L_{matter}\right)$$

Turner, Carroll, Capozziello etc. 2003

In Einstein Frame

$$\hat{g}_{\mu\nu} = (f')^2 g_{\mu\nu}$$

$$\ddot{\phi} + 3H\dot{\phi} + V(\phi)' = \frac{\sqrt{3}}{2}\beta\rho_m$$

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

$$\dot{\rho}_m + 3H\rho_m = 0$$

$$\dot{\rho}_m + 3H\rho_m = -\frac{\sqrt{3}}{2}\beta\dot{\phi}\rho_m$$

$$V(\phi)' = \frac{fR - f'}{f'^2}$$

$$\phi = \log f'$$

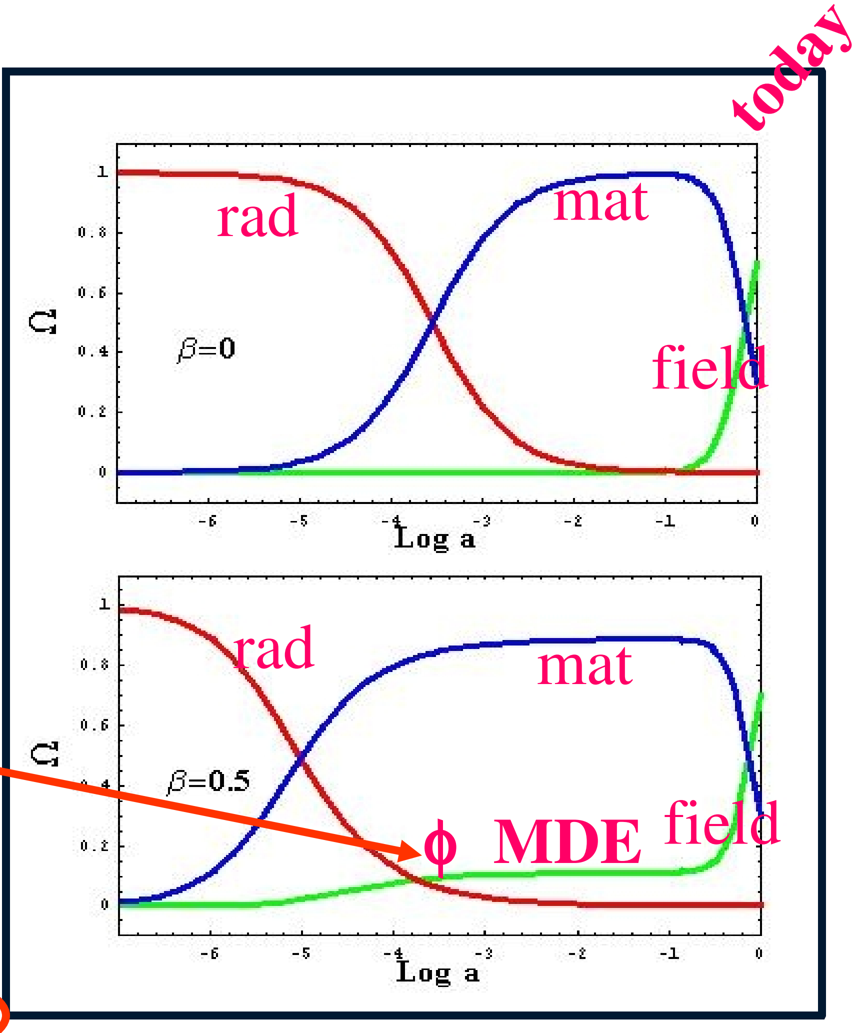
$$\beta = 1/2$$

R-1/R model : the φMDE

$$\ddot{\phi} + 3H\dot{\phi} + V(\phi)' = \frac{\sqrt{3}}{2}\beta\,\rho_m$$

$$\dot{\rho}_m + 3H\rho_m = -\frac{\sqrt{3}}{2}\beta\dot{\phi}\rho_m$$

$$H^2 = \frac{8\pi}{3}(\rho_m + \rho_\phi)$$



$$\beta = 1/2$$

$$\Omega_\varphi = 1/9$$

In Jordan frame: $a = t^{1/2}$

instead of $a = t^{2/3}$!!

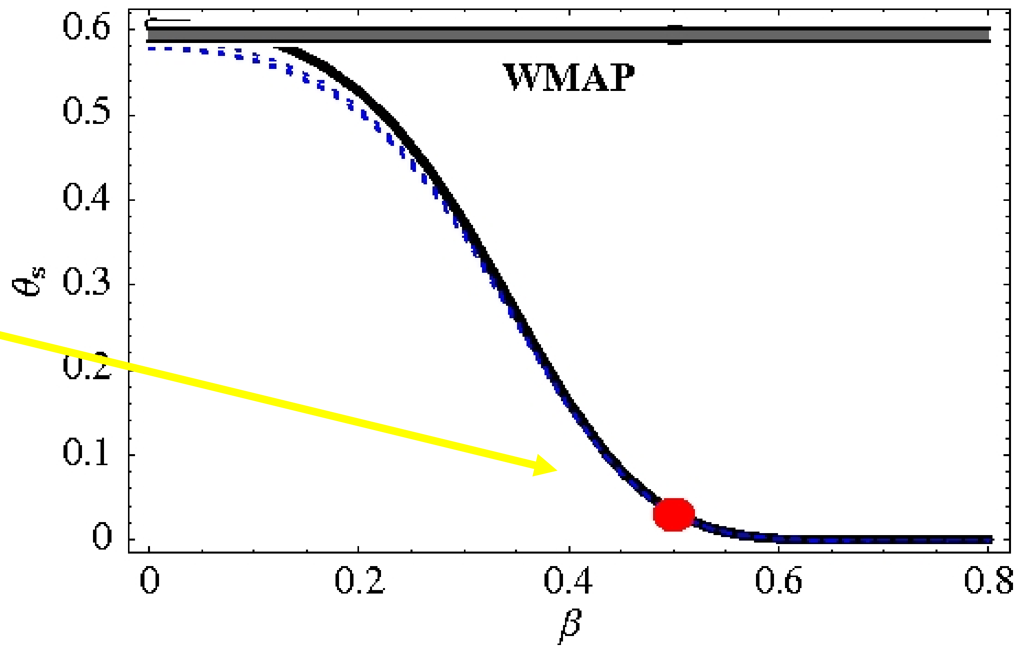
Caution:
Plots in the
Einstein frame!

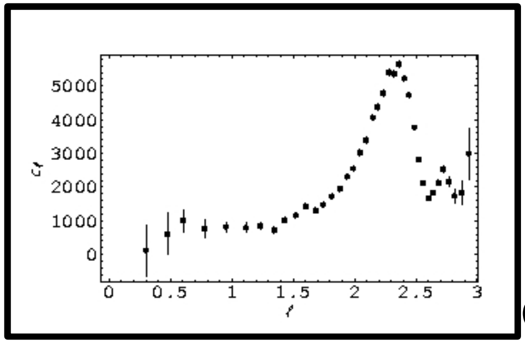
Sound horizon in R+R^n model

$$a = t^{1/2}$$

$$w_{eff} = 1/3$$

$$\theta = \int_{z_{dec}}^{\infty} \frac{c_s dz}{H(z)} \Big/ \int_{0}^{z_{dec}} \frac{dz}{H(z)}$$





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L.A., D. Polarski, S. Tsujikawa, PRL 98, 131302, astro-ph/0603173

A recipe to modify gravity

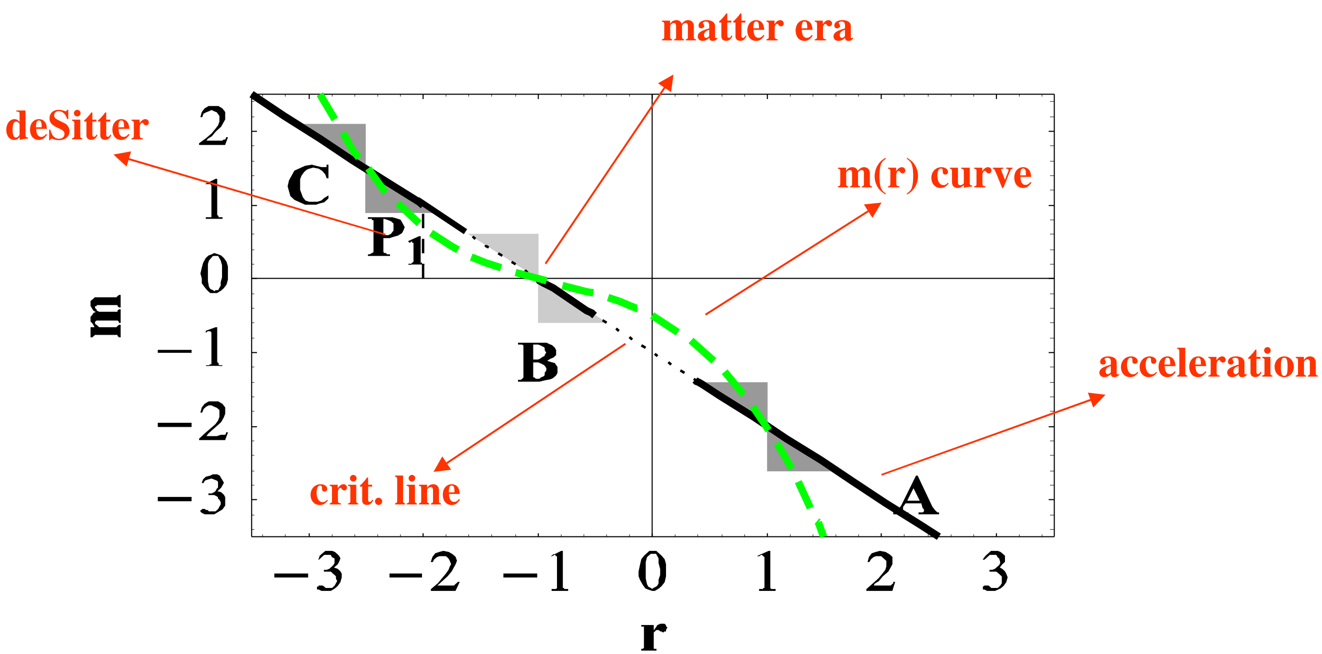
Can we find f(R) models that work?

The m,r plane

The qualitative behavior of any f(R) model can be understood by looking at the geometrical properties of the m,r plot

$$m(r) = \frac{Rf''}{f'}$$

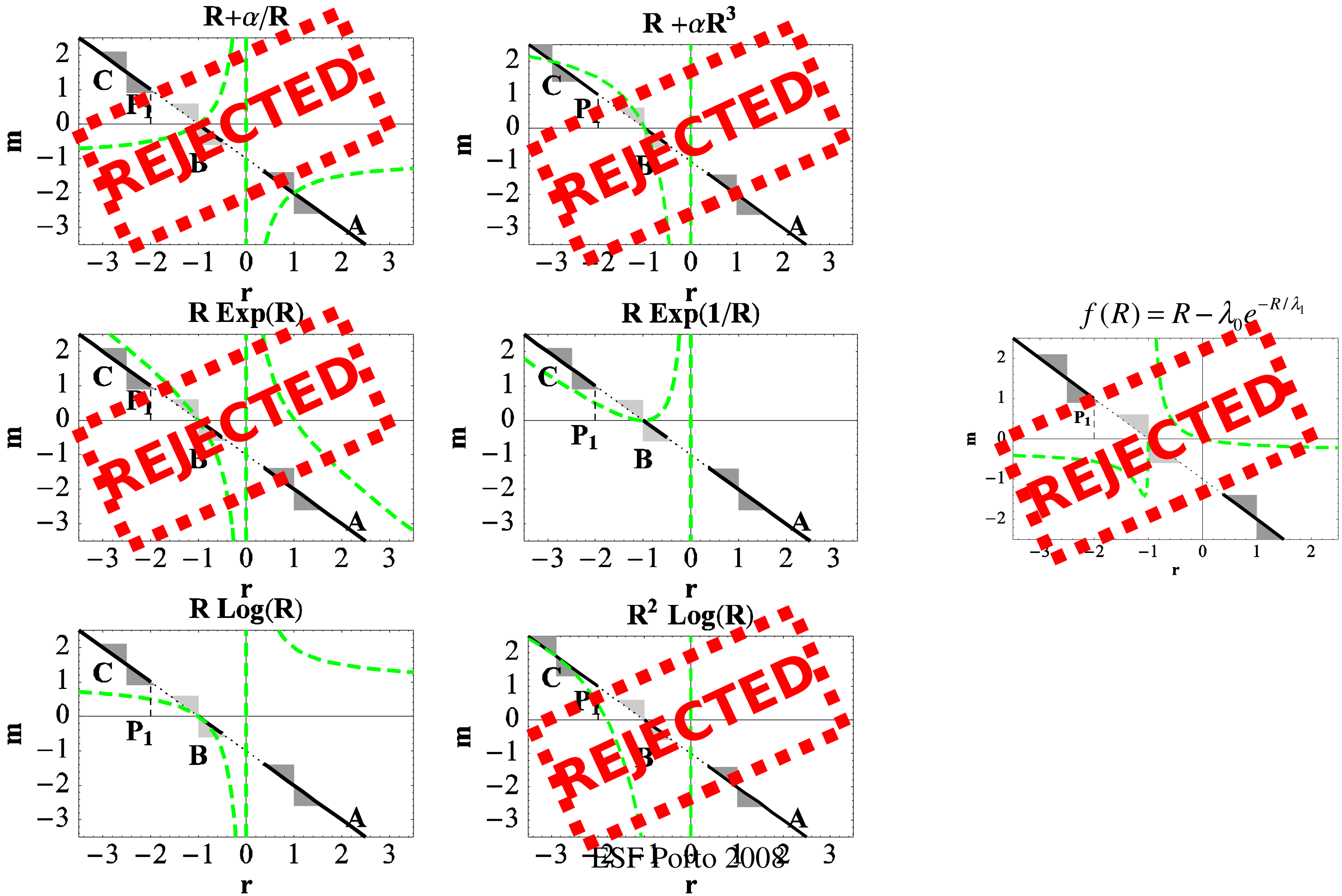
$$r = -\frac{Rf'}{f}$$



The dynamics becomes 1-dimensional !

L.A., D. Polarski, S. Tsujikawa, PRD, astro-ph/0612180

The power of the m(r) method

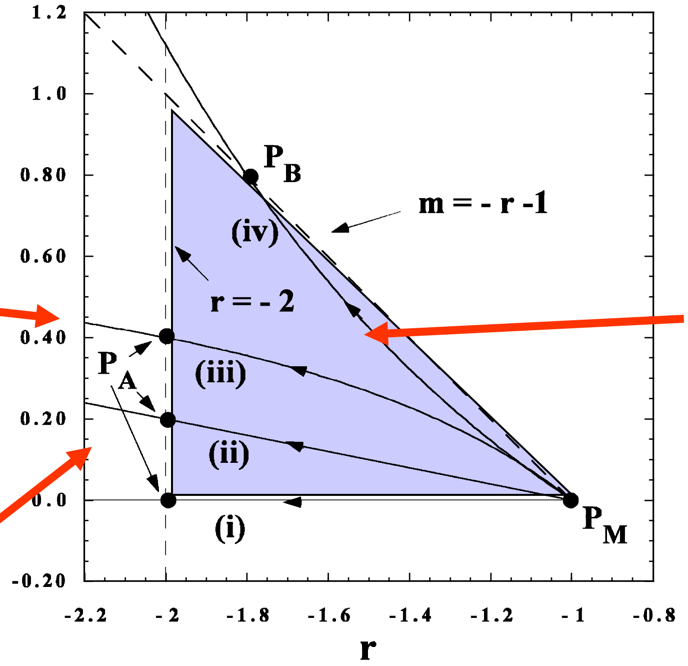


The triangle of viable trajectories

There exist only two kinds of cosmologically viable trajectories

$f(R) = R + aR^n$

$f(R) = (R^a - \Lambda)^b$



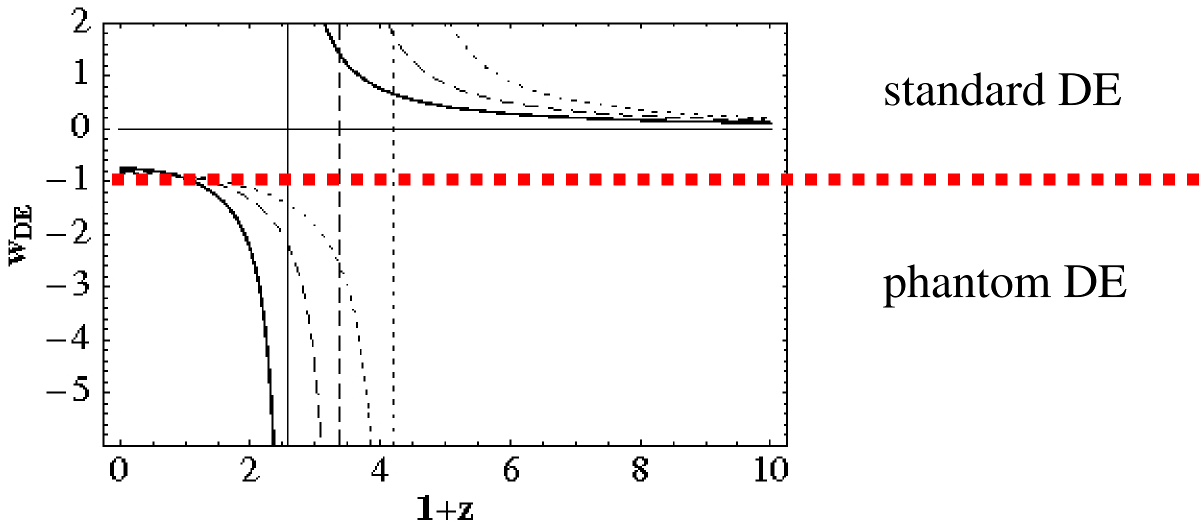
$f(R) = R^{\frac{p}{p-1}} (R - \Lambda)^{\frac{1}{1-p}}$

Notice that in the triangle m>0

A theorem on phantom crossing

Theorem: for all viable f(R) models

- there is a phantom crossing of w_{DE}
- there is a singularity of w_{DE}
- both occur typically at low z when $\Omega_m \to 1$



$$f(R) = (R^a - \Lambda)^b$$

L.A., S. Tsujikawa, 2007

Local Gravity Constraints are very tight

Depending on the local field configuration

$$m(R_s) = \frac{R_s f_s''}{f_s'} << 10^{-23} \div 10^{-6}$$

depending on the experiment: laboratory, solar system, galaxy

see eg. Nojiri & Odintsov 2003; Brookfield et al. 2006
Navarro & Van Acoyelen 2006; Faraoni 2006; Bean et al. 2006;
Chiba et al. 2006; Hu, Sawicky 2007;....

LGC+Cosmology

Take for instance the ΛCDM clone

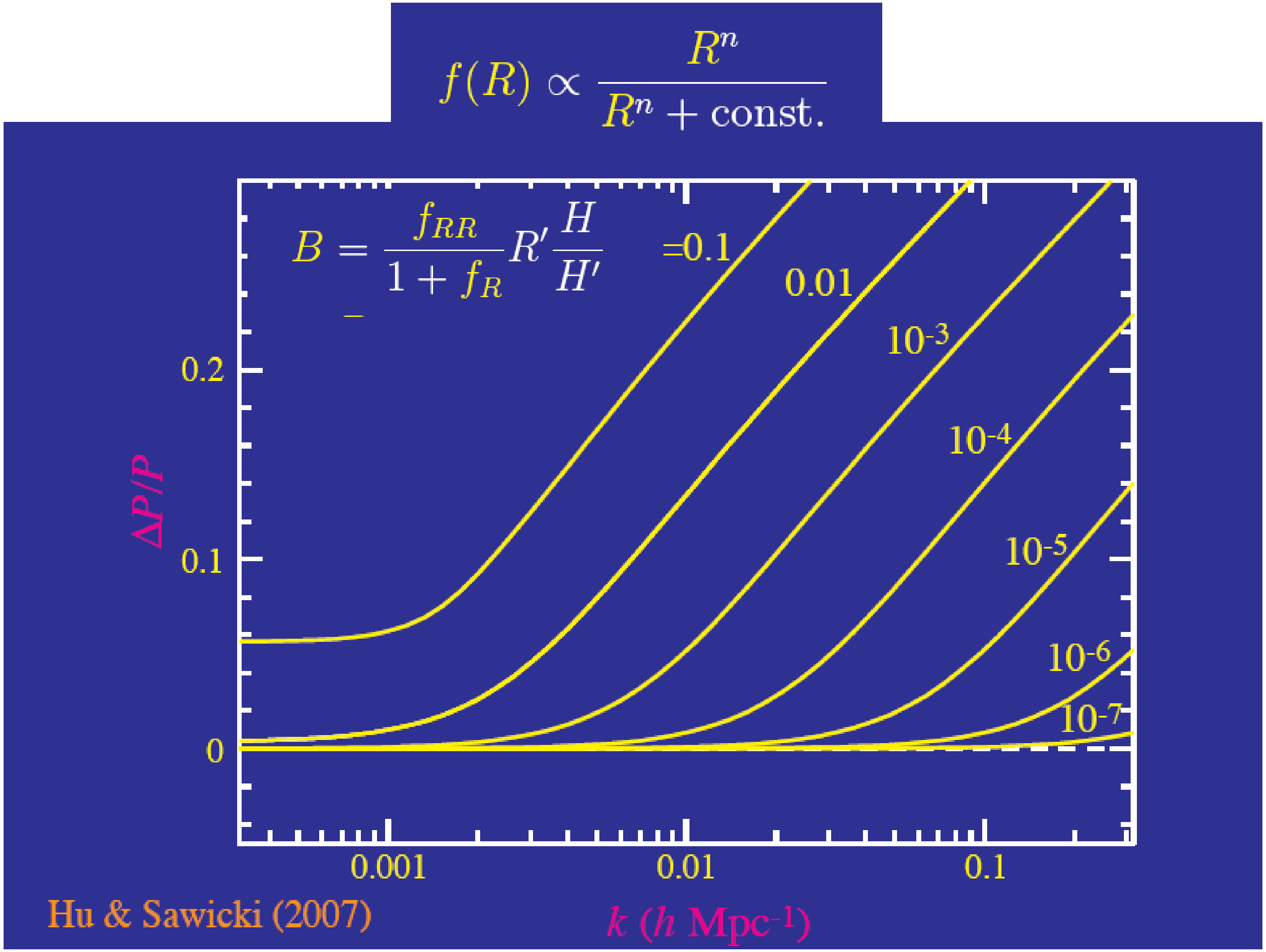
$$f(R) = (R^a - \Lambda)^b$$

Applying the criteria of
LGC and Cosmology

$$a \approx b \approx 1 \pm 10^{-23}$$

i.e. ΛCDM to an incredible precision

However. . . perturbations



MG at the linear level

$$ds^2 = a^2[(1+2\phi)dt^2 - (1-2\psi)(dx^2+dy^2+dz^2)]$$

At the linear perturbation level and sub-horizon scales, a modified gravity model will

- modify Poisson's equation $$k^2\phi = -4\pi G a^2 Q(k,a)\rho_m\delta_m$$
- induce an anisotropic stress $$\eta(k,a) = \frac{\phi-\psi}{\psi}$$
- modify the growth of perturbations $$\delta_k'' + \left(1+\frac{H'}{H}\right)\delta_k' - 4\pi G Q(k,a)\rho\,\delta_k = 0$$

MG at the linear level

▪ standard gravity	$Q(k,a)=1$ $\eta(k,a)=0$	
▪ scalar-tensor models	$Q(a)=\frac{G^*}{FG_{cav,0}}\frac{2(F+F'^2)}{2F+3F'^2}$ $\eta(a)=\frac{F'^2}{F+F'^2}$	Boisseau et al. 2000 Acquaviva et al. 2004 Schimd et al. 2004 L.A., Kunz &Sapone 2007
▪ f(R)	$Q(a)=\frac{G^*}{FG_{cav,0}}\frac{1+4m\frac{k^2}{a^2R}}{1+3m\frac{k^2}{a^2R}},\quad \eta(a)=\frac{m\frac{k^2}{a^2R}}{1+2m\frac{k^2}{a^2R}}$	Bean et al. 2006 Hu et al. 2006 Tsujikawa 2007
▪ DGP	$Q(a)=1-\frac{1}{3\beta};\quad \beta=1+2Hr_c w_{DE}$ $\eta(a)=\frac{2}{3\beta-1}$	Lue et al. 2004; Koyama et al. 2006
▪ coupled Gauss-Bonnet	$Q(a)=\ldots$ $\eta(a)=\ldots$	see L. A., C. Charmousis, S. Davis 2006

Growth of fluctuations as a measure of modified gravity

$$\delta_k'' + \left(1+\frac{H'}{H}\right)\delta_k' - 4\pi G Q(k,a)\rho\,\delta_k = 0$$

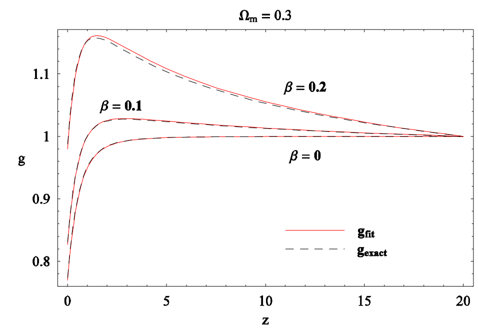
→ **good fit**

$$\frac{d\log\delta}{d\log a} = \Omega_m(a)^\gamma$$

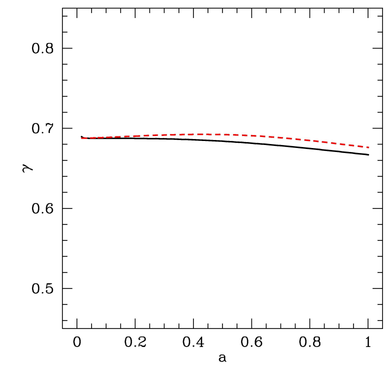
Peebles 1980
Lahav et al. 1991
Wang et al. 1999
Bernardeau 2002
L.A. 2004
Linder 2006

Instead of $Q(k,a)$ **we parametrize** $\gamma = const$

LCDM	$\gamma = 0.55$
DE	$\gamma = 0.55[1+0.05(w+1)]$
DGP	$\gamma = 0.67$
ST	$\Omega_m{}^\gamma(1+0.5\beta^2)$

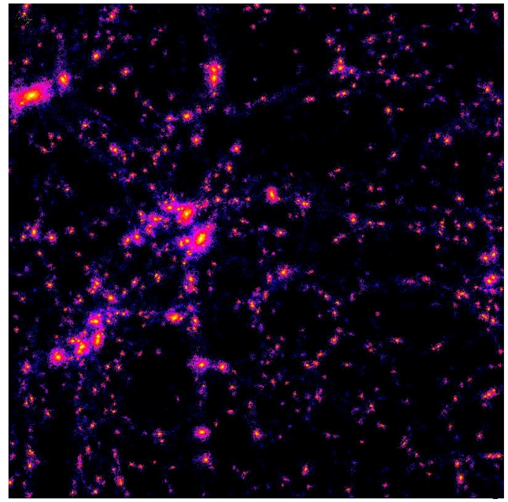


Di Porto & L.A. 2007



$\gamma \neq 0.55$ **is an indication of modified gravity**

Two MG observables



?

Correlation of galaxy positions:
galaxy clustering

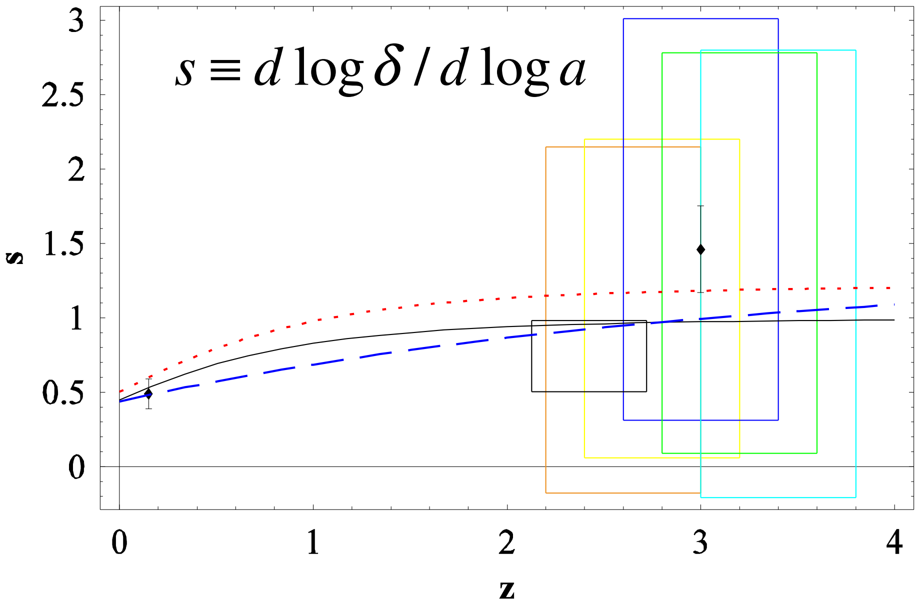
$$P_{gal}(k,z) = b^2 P_{matt}(k,z) \propto \Psi^2$$

Correlation of galaxy ellipticities:
galaxy weak lensing

$$P_{ellipt}(k,z) \propto (\Phi + \Psi)^2$$

Present constraints on gamma

z	s
ref. [23]	
2.125-2.72	0.74±0.24
ref. [25]	
2.2 - 3	0.99±1.16
2.4 - 3.2	1.13±1.07
2.6 - 3.4	1.66±1.35
2.8 - 3.6	1.43±1.34
3 - 3.8	1.30±1.50
ref. [24]	
3	1.46±0.29
ref. [27]	
0.15	0.49±0.10

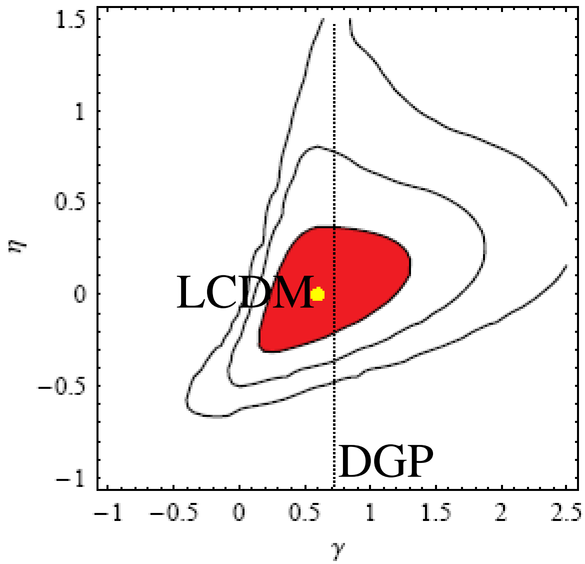


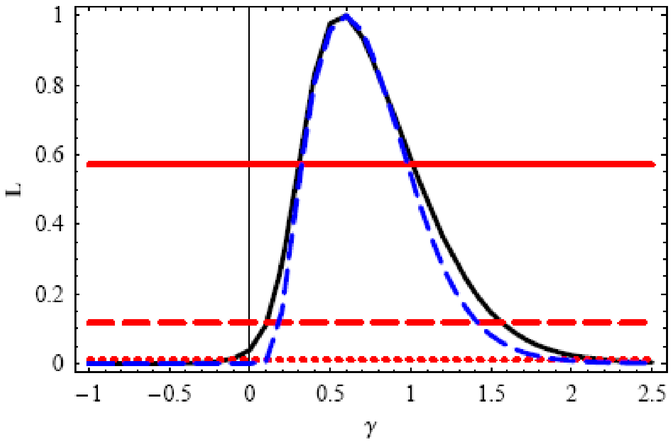
We consider the following data: *a*) Lyman-α power spectra at an average redshift $z = 2.125$, $z = 2.72$ [23], $z = 3$ [24]; *b*) the normalization σ_8 inferred from Lyman-α at z ranging between 2 and 3.8 [25]; *c*) galaxy power spectra at low z from SDSS [26] and 2dF [27]. From the three Lyman-α and the SDSS spectra we estimate the ratios

Viel et al. 2004,2006; McDonald et al. 2004; Tegmark et al. 2004

Present constraints on gamma

$$s_{fit} \equiv \Omega_m^{\gamma}(1+\eta)$$



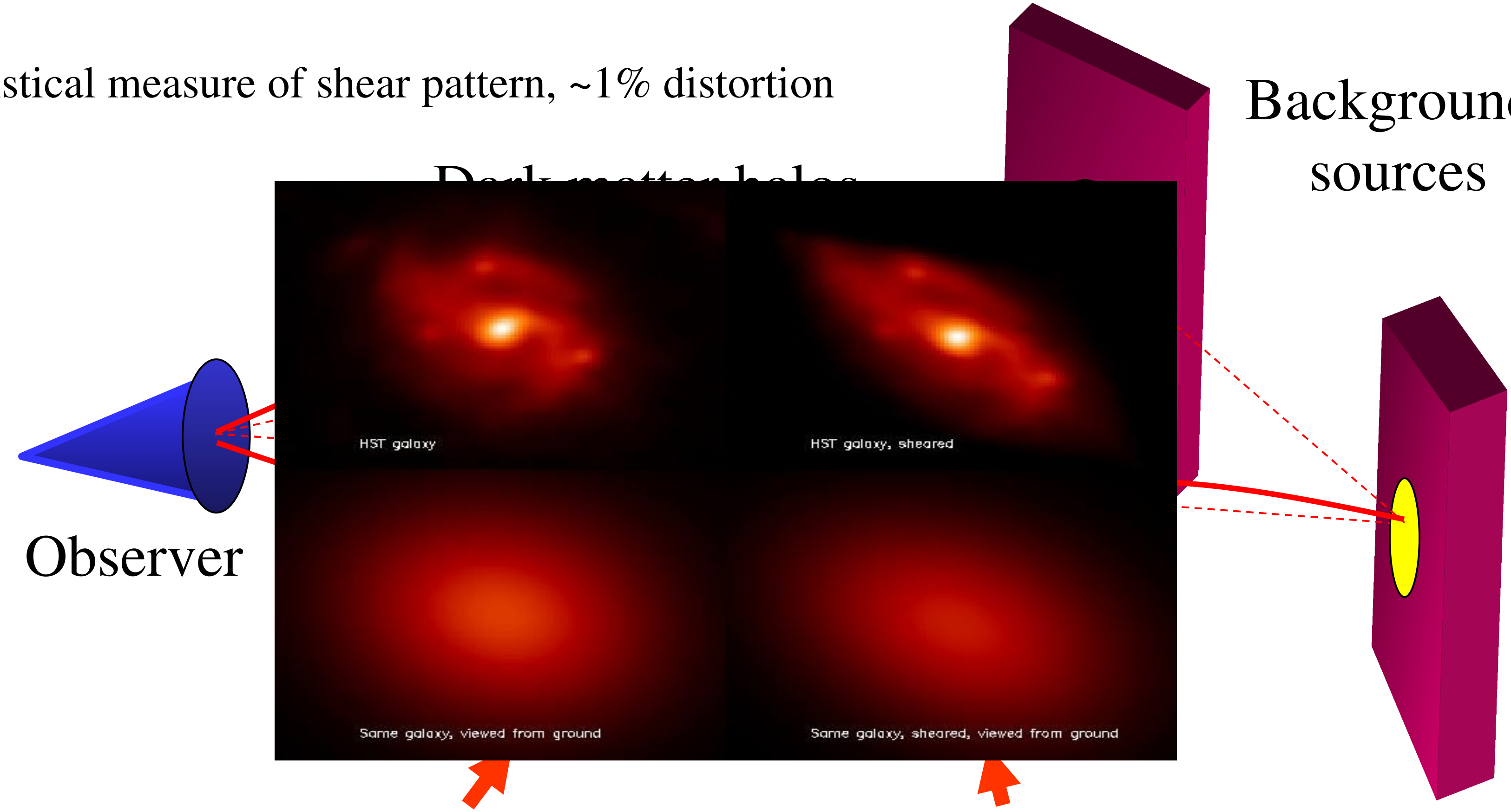


	1σ	2σ	3σ
η	$0.00^{+0.28}_{-0.18}$	$^{+0.58}_{-0.38}$	$^{+1.1}_{-0.58}$
γ	$0.60^{+0.41}_{-0.30}$	$^{+0.97}_{-0.49}$	$^{+1.6}_{-0.74}$
$\gamma_{standard}$	$0.60^{+0.34}_{-0.26}$	$^{+0.77}_{-0.40}$	$^{+1.4}_{-0.50}$

C. Di Porto & L.A. 2007

Probing gravity with weak lensing

Statistical measure of shear pattern, ~1% distortion



Radial distances depend on *geometry* of Universe

Foreground mass distribution depends on *growth/distribution* of structure

Probing gravity with weak lensing

In General Relativity, lensing is caused by the "lensing potential"

$$\Phi = \phi + \psi$$

and this is related to the matter perturbations via Poisson's equation.
Therefore the lensing signal depends on **two modified gravity functions**

$$\begin{cases} \Sigma = Q(1+\frac{\eta}{2}) \\ \eta(k,a) \end{cases}$$

in the WL power spectrum →

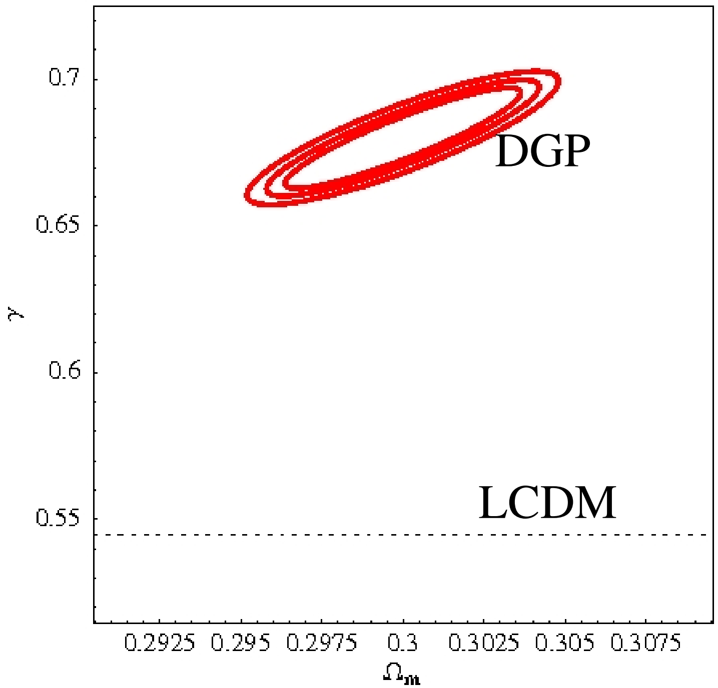
$$P_{ell}(\ell) = \int dz F(z;\Omega_{m,\Lambda,etc}) Q(1+\frac{\eta}{2}) P_m(z, k = \frac{H_0 \ell}{r(z)})$$

and in the growth function →

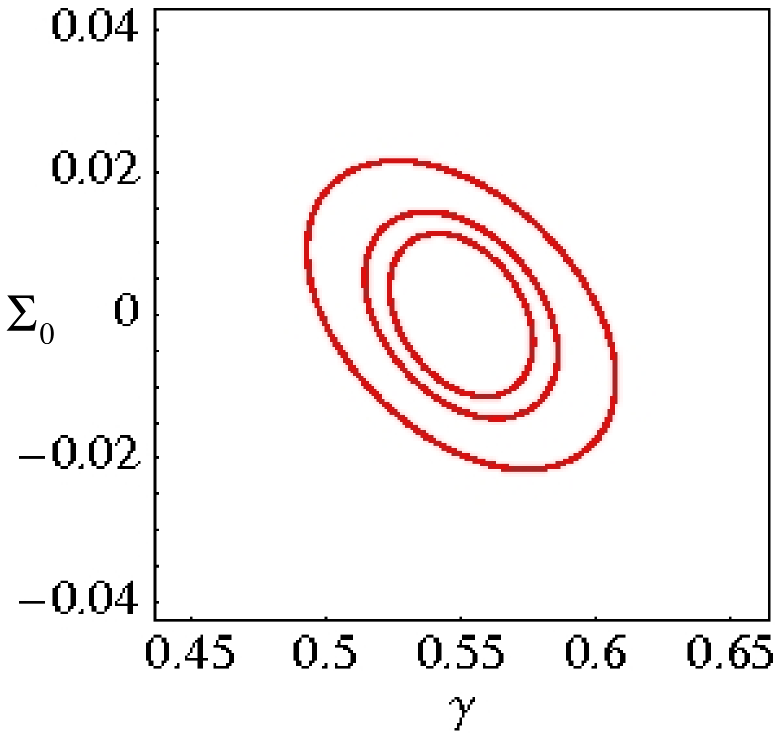
$$P_m(z,k) = D(z,Q)^2 P_m(z=0,k)$$

Weak lensing measures Dark Gravity

DGP $(\Sigma_0 = 0)$



Phenomenological DE

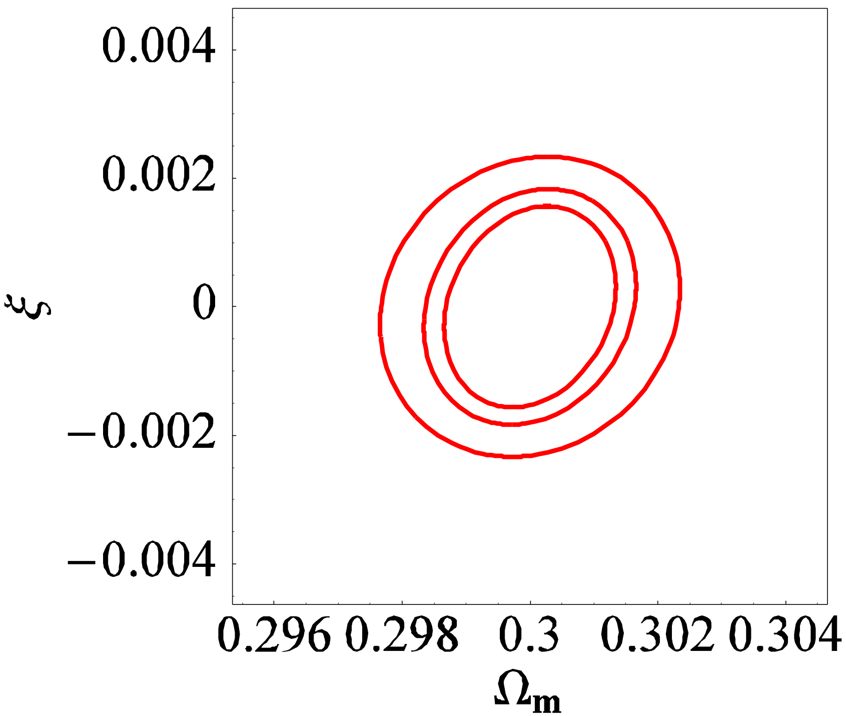


Weak lensing tomography over half sky

L.A., M. Kunz, D. Sapone
arXiv:0704.2421

Weak lensing measures Dark Gravity

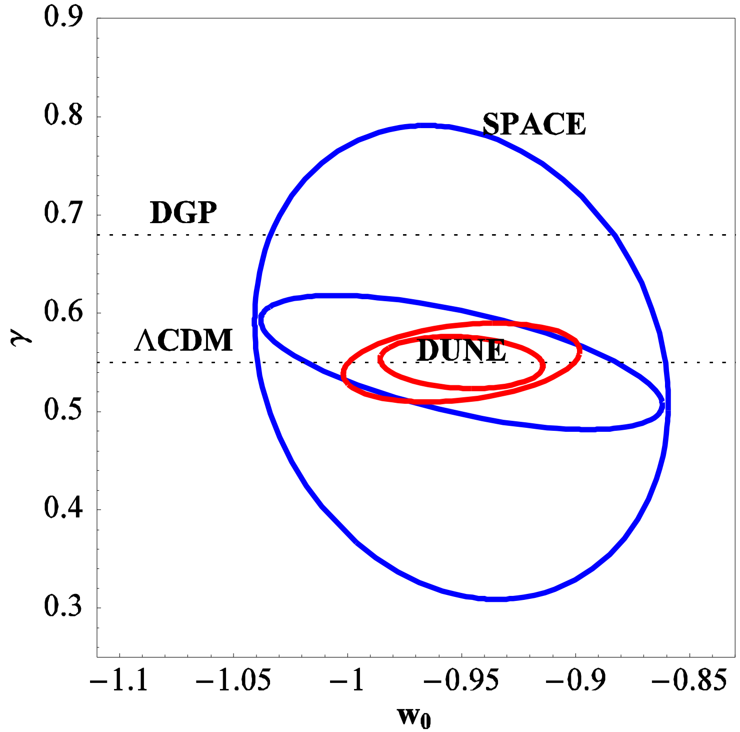
scalar-tensor model $(1+\frac{1}{2}\xi\phi^2)R$



Weak lensing tomography over half sky

V. Acquaviva, L.A., C. Baccigalupi, in prep.

Comparing BAO with WL



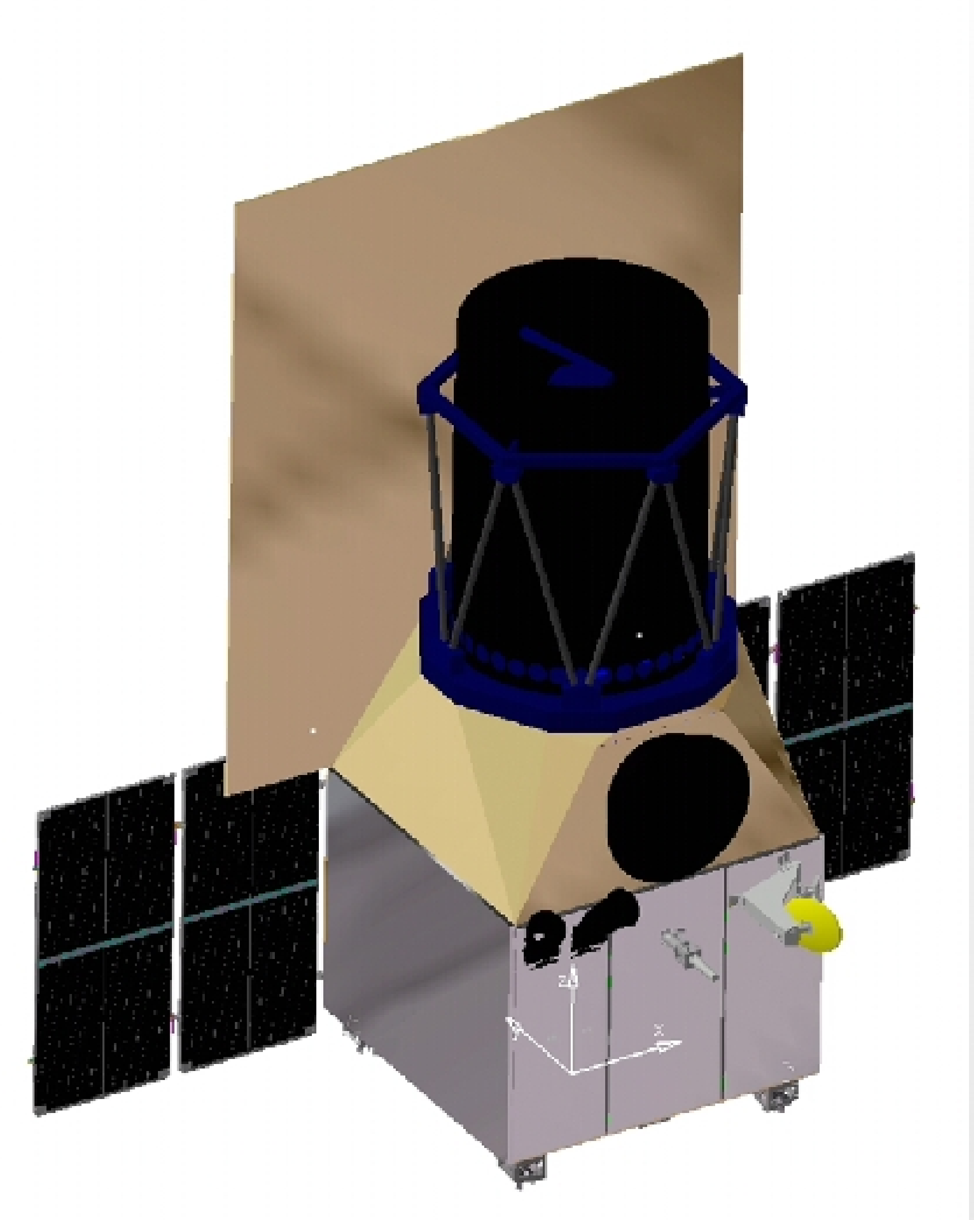
Weak lensing/ BAO over half sky

Dark Universe Explorer

- 1.2m telescope
- FOV 0.5 deg^2
- PSF FWHM 0.23"

- Weak Lensing Survey:
  - 20,000 deg^2
  - 1 Broad band
  - 35 Galaxies/$arcmin^2$
  - median z ~1
  - Ground based Photo-z

- Super Novae Survey:
  - 2x60 deg^2
  - Observed every 4 days for 9 months
  - 6 Bands
  - 10,000 SNe
  - Out to z~1



Conclusions: the teachings of DE

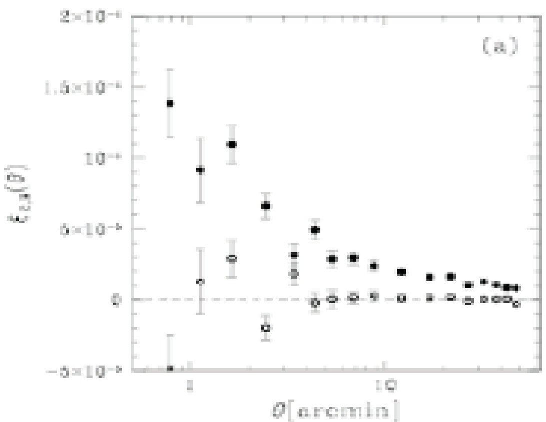
- **There is much more than meets the eyes in the Universe**
- **Two solutions to the DE mismatch: either add "dark energy" or "dark gravity"**
- **New MG parameters: γ,Σ**
- **The high precision data of present and near-future observations allow to test for dark energy/gravity**
- **It is crucial to combine background and perturbations**
- **Weak Lensing with DUNE is a good bet...**

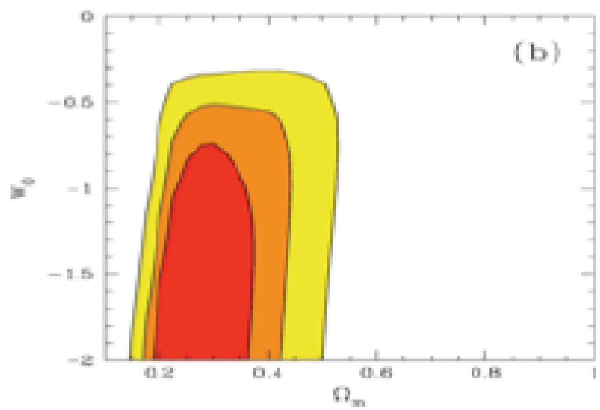
Current Observational Status: CFHTLS

Hoekstra et al. 2005
Semboloni et al. 2005

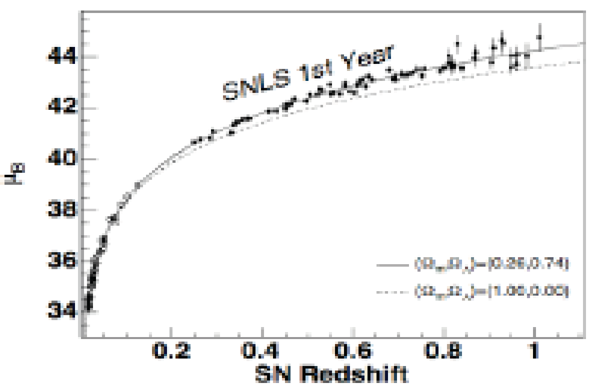
Weak Lensing

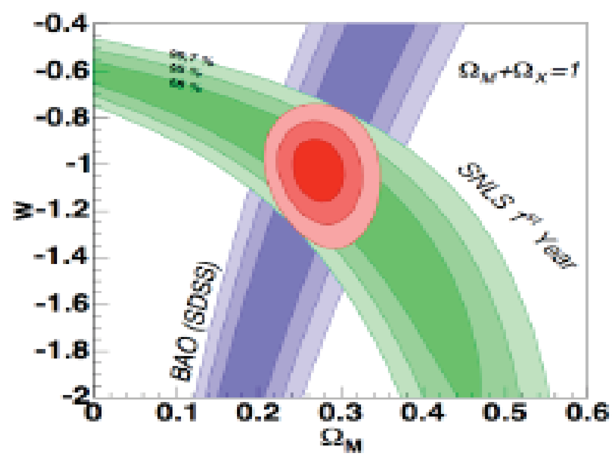
First results From CFHT Legacy Survey with Megacam





(w=constant and other priors assumed)





Type Ia Super-novae