phenomenological aspects of dark energy / mod. gravity

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MK & Domenico Sapone, PRL **98**, 121301 (2007)

MK, astro-ph/0702615 (2007)

Luca Amendola, MK & Domenico Sapone, JCAP **04**, 013 (2008)

J. Larena, J.M. Alimi, T. Buchert, MK and P.S. Corasaniti, arXiv:0808.1161

"what can we measure?" (and how?)

- GR in cosmology
- the FLRW (background) case
- some complications (and opportunities)
- perturbation equations
- observational remarks
- outlook

(glossary: GR = General Relativity, MG = modified gravity (models), DM = dark matter, DE = dark energy, BAO = baryon acoustic oscillations, WL = weak lensing, ...)

GR in cosmology

- specific form of metric
- two kinds of equations:

$$\boxed{G_{\mu\nu} = -8\pi G T_{\mu\nu} \quad T^{\nu}_{\mu;\nu} = 0}$$

- "stuff": two kinds
  - visible components (baryons, light)
  - dark components (dark matter, dark energy, ...), *only* interacting through gravity
  - we use fluid description

(the dark components can always be re-arranged, but we assume that one is dark matter)

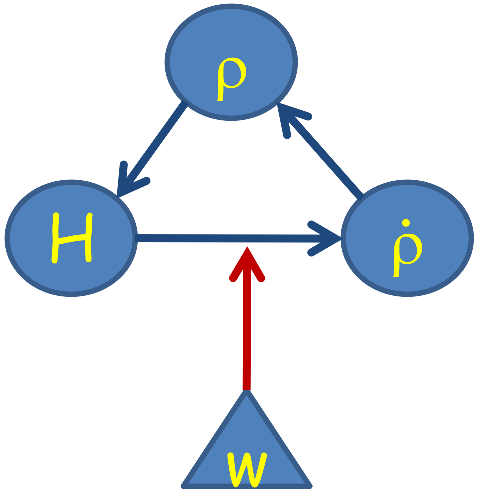
the background case

$$ds^2 = -dt^2 + a(t)^2 dx^2$$ metric "template"

Einstein eq'n $$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}(\rho_1 + \rho_2 + \ldots + \rho_n)$$

conservation $$\dot{\rho}_i = -3H(\rho_i + p_i) = -3H(1 + w_i)\rho_i \qquad i = 1, \ldots, n$$

- w_i describe the fluids
- normally all but one known
- H|a describe observables (distances, ages, etc)



MG at the background level

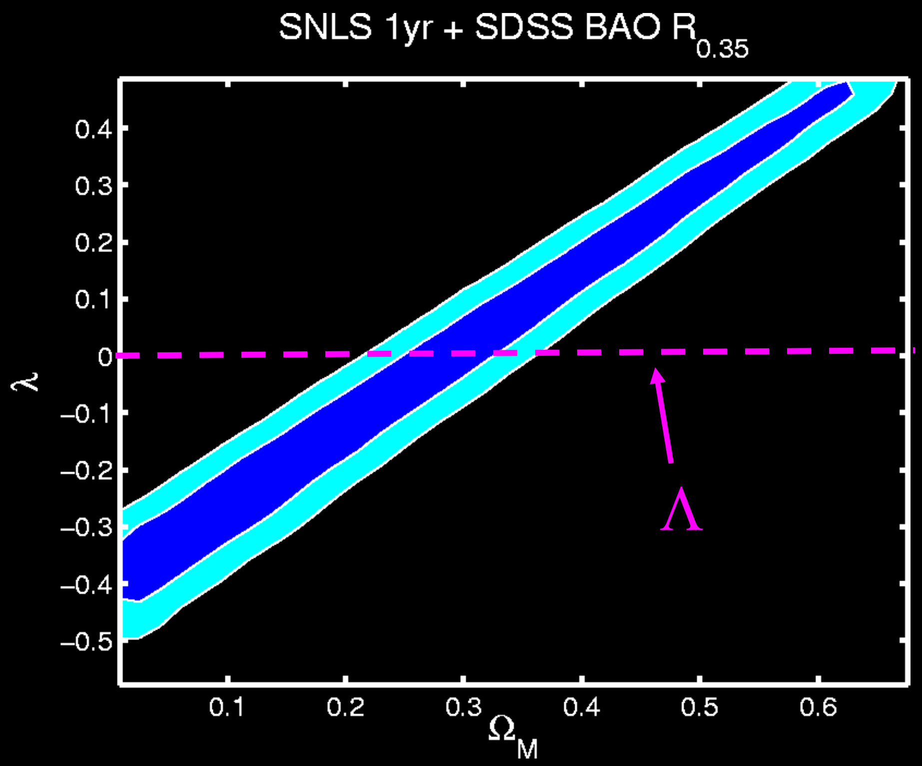
- modified gravity can change Friedmann eq'n:

$$H^2 - \frac{H}{r_c} = \frac{8\pi G}{3}\rho_m \qquad H^2 = \frac{8\pi G}{3}\rho_m\left(1+\frac{\rho_m}{2\lambda}\right)$$

- no DE, but DM still conserved
- since a DE model with free w(z) can give any H(z), we can construct a w(z) that gives the same expansion history (and observations):

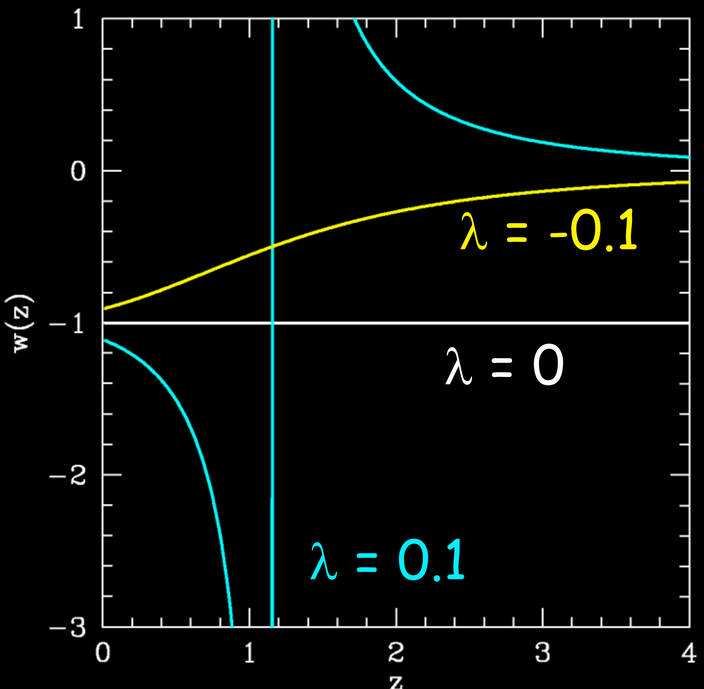
$$w(z) = \frac{H(z)^2 - \frac{2}{3}H(z)H'(z)(1+z)}{H_0^2\Omega_m(1+z)^3 - H(z)^2}$$

oops, wait a sec!



from Friedmann eqs:

$$w(z) = \frac{H(z)^2 - \frac{2}{3}H(z)H'(z)(1+z)}{\Omega_m H_0^2 (1+z)^3 - H(z)^2}$$



$$w(z) = \frac{-1}{1-\lambda(1+z)^3}$$

also curvature **cannot** be constrained together with free w(z)!

and how about curvature?

Is it possible to test the geometry directly?

Yes! Clarkson et al, Uzan et al -> in FLRW (integrate along ds=0):

$$H_0 D(z) = \frac{1}{\sqrt{-\Omega_k}} \sin\left(\sqrt{-\Omega_k}\int_0^z \frac{H_0}{H(u)}du\right)$$

$$\Rightarrow H_0 D'(z) = \frac{H_0}{H(z)} \cos\left(\sqrt{-\Omega_k}\int_0^z \frac{H_0}{H(u)}du\right)$$

$$\rightarrow (HD')^2 - 1 = \sin^2(\cdots) = -\Omega_k (H_0 D)^2$$

It is possible to reconstruct the curvature by comparing a distance measurement (which depends on the geometry) with a radial measurement of H(z) without dependence on the geometry.

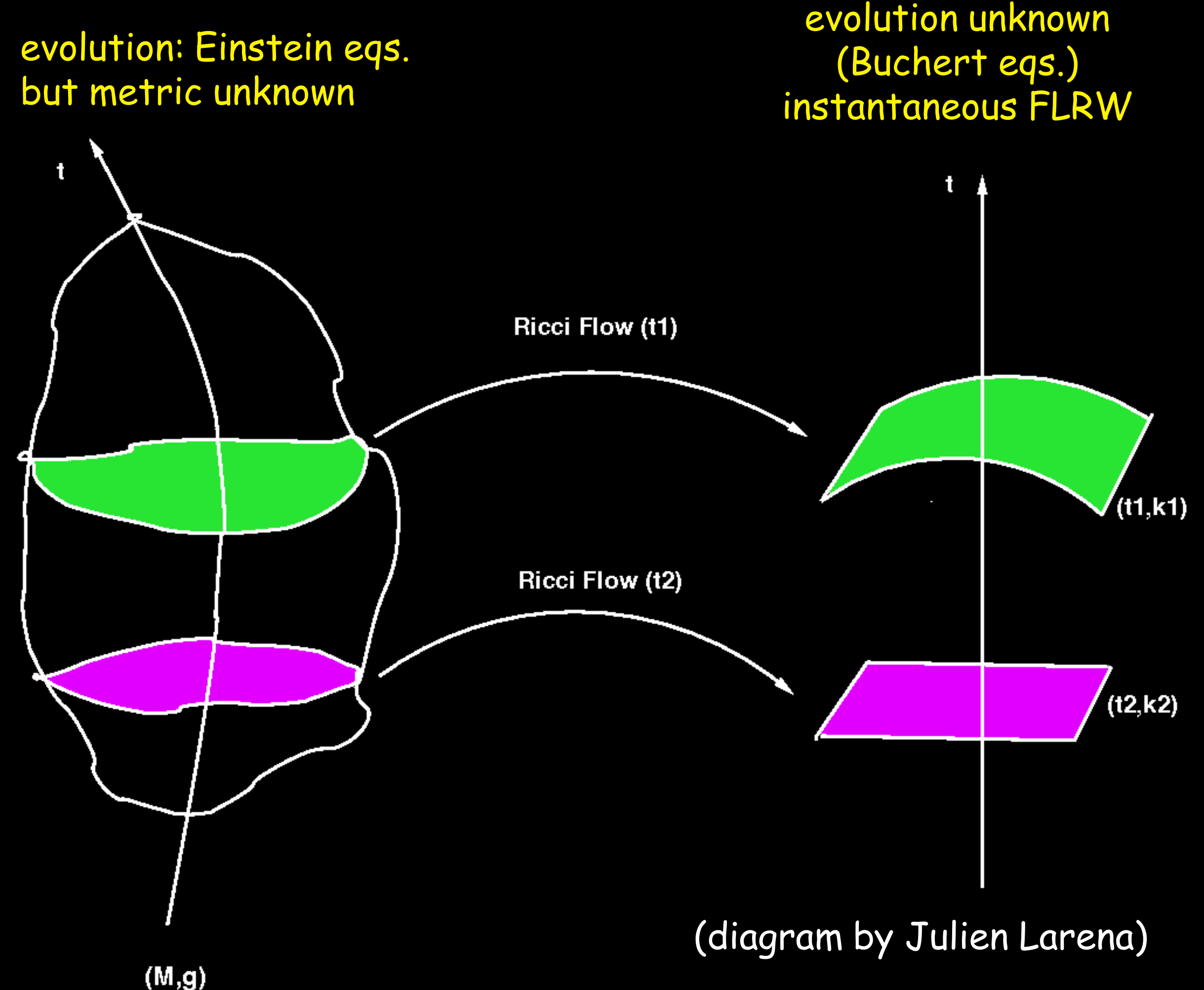
Baryon Acoustic Oscillations may be able to do that
(or supernova dipole, Bonvin, Durrer, MK, PRL **96**, 191302, 2006).

evolution of the curvature?

In FLRW curvature is constant.

But in LTB / big void models, the light traverses regions of different curvature.

And when smoothing a true, perturbed model to FLRW, there is no reason why the curvature of the smoothed universe should remain constant.



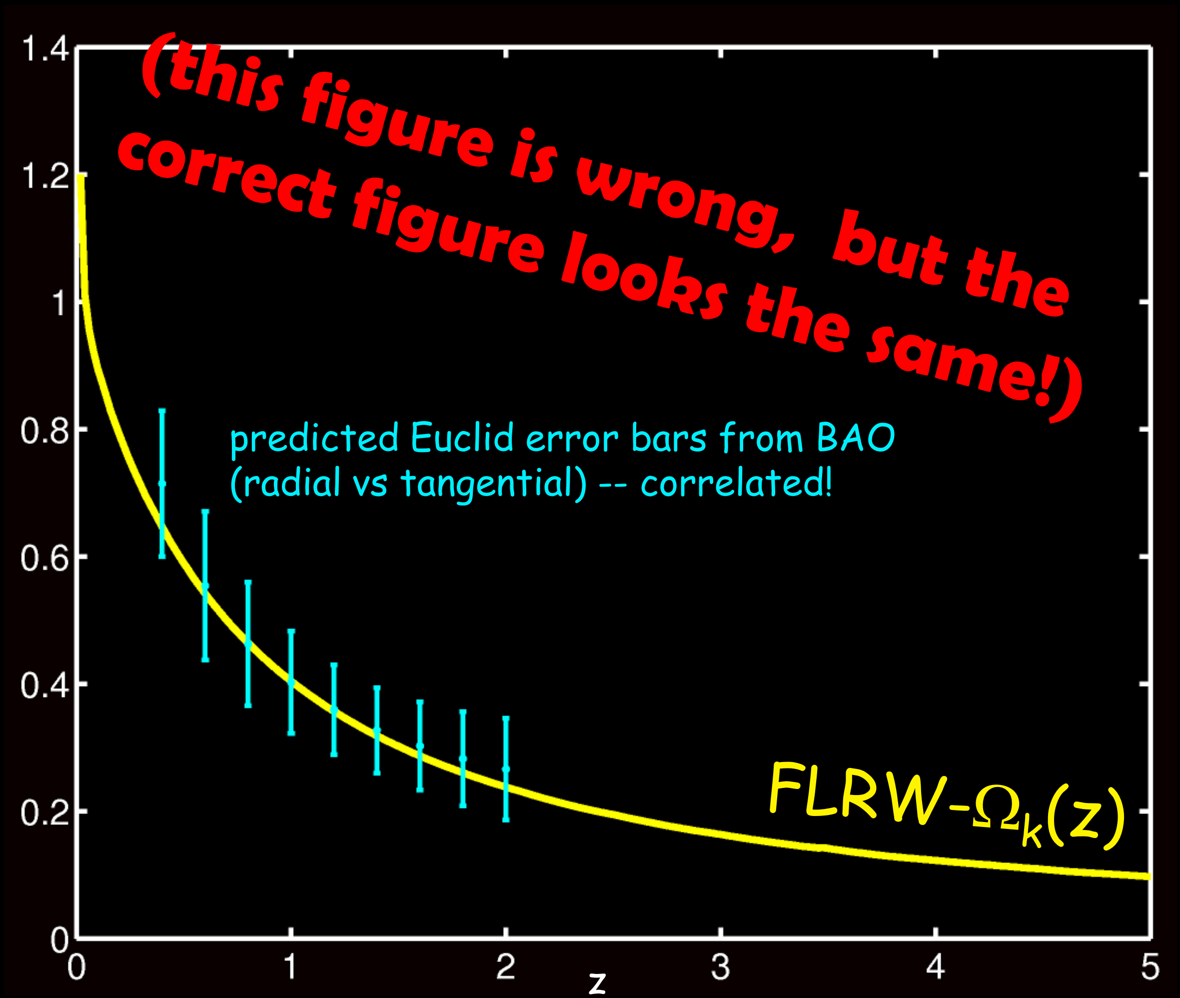
(diagram by Julien Larena)

this effect can also be constrained by measuring H(z) AND r(z)!

testing the geometry directly

if dynamic curvature is to explain the apparent acceleration of the universe then $\Omega_k(z)$ needs to deviate substantially from a constant at low z.

Experiments like WFMOS, Euclid or SKA may be able to test this directly!



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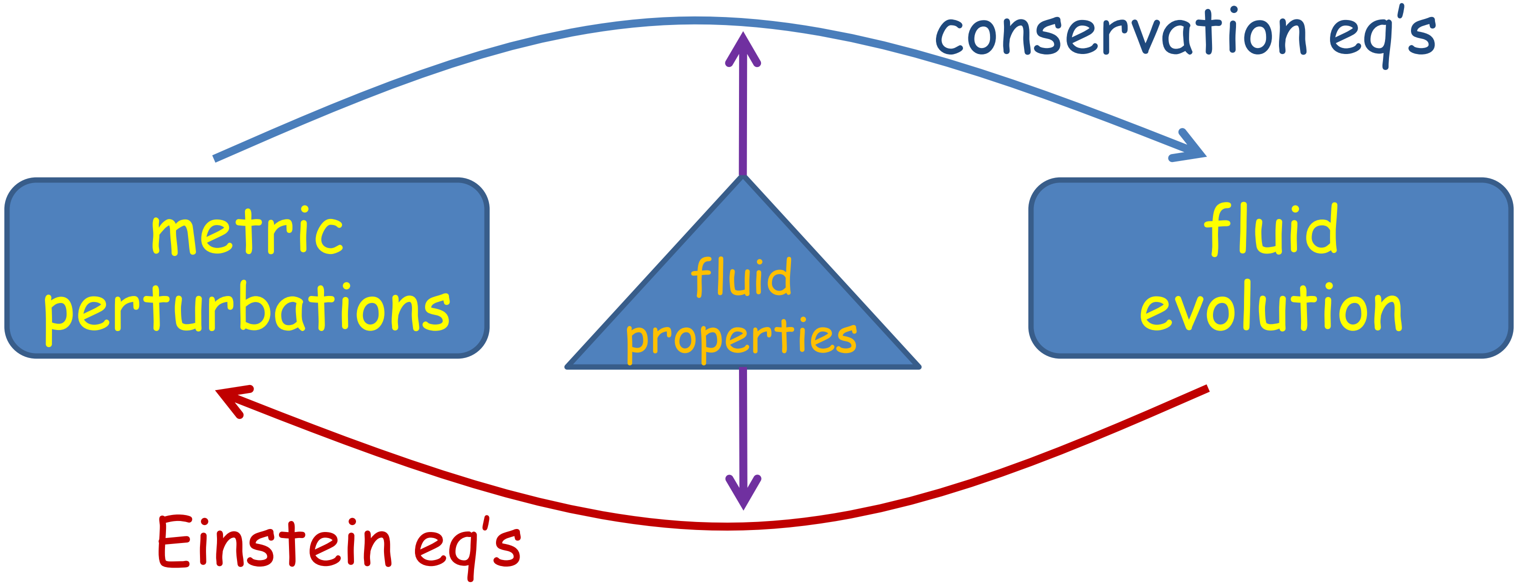
perturbations

$$ds^2 = -(1+2\psi)dt^2 + a^2(1-2\phi)dx^2$$ metric (gauge fixed, scalar dof)



$$k^2\phi = -4\pi G a^2 \sum_i \rho_i \left(\delta_i + 3Ha\frac{V_i}{k^2}\right), \quad k^2(\phi - \psi) = 12\pi G a^2 \sum_i (1+w_i)\rho_i \sigma_i$$

$$\delta_i' = 3(1+w_i)\phi' - \frac{V_i}{Ha^2} - \frac{3}{a}\left(\frac{\delta p_i}{\rho_i} - w_i\delta_i\right)$$

$$V_i' = -(1-3w_i)\frac{V_i}{a} + \frac{k^2}{Ha}\left(\frac{\delta p_i}{\rho_i} + (1+w_i)(\psi - \sigma_i)\right)$$

Why GR+DE is "good enough"

modified "Einstein" eq:
(projection to 3+1D)

$$X_{\mu\nu} = -8\pi G T_{\mu\nu}$$

$$\boxed{G_{\mu\nu} = -8\pi G T_{\mu\nu} - Y_{\mu\nu} \quad Y_{\mu\nu} \equiv X_{\mu\nu} - G_{\mu\nu}}$$

$Y_{\mu\nu}$ can be seen as an effective DE energy-momentum tensor.

Is it conserved?

Yes, since $T_{\mu\nu}$ is conserved, and since $G_{\mu\nu}$ obeys the Bianchi identities!

There is also no place "to hide", since $T_{\mu\nu}$ is also derived from a general symmetric tensor.

bug or feature?

- bug:
  - cannot directly test GR
- feature:
  - strong clues in result + need theory anyway
  - clear target for what should be measured
  - independent of whether MG or DE is realised

it's a feature!

observations

- what do we want to measure?
  - $w(z)$, $\Omega_k[z]$, $\phi(z,k)$, $\psi(z,k)$ [+ bias[k,z], δ_m, V_m]
- what can we measure?
  - CMB + ISW [-> $\partial_t(\phi+\psi)$], lensing [-> $(\phi+\psi)$]
  - weak lensing
  - $P(k,z,\mu)$ -> BAO, growth, shape, z-distortions
  - clusters
  - supernovae -> "monopole" + perturbations
  - peculiar velocity field -> feasible?
  - cross-correlations between the above

background

w(z) can be measured by:

- supernovae
- BAO wiggles
- in most other probes (but noise or signal?)
- "mature" subject (?)

curvature needs H(z), can be measured by:

- e.g. tangential + radial BAO scales
- redshift change of objects over time [ask PSC]
- supernova monopole + dipole [-> Durrer, Bonvin]
- certainly more, once we think about it

observational aspects

first measure background, then e.g.

- 5 quantities: ϕ, ψ, b, δ_m, V_m
- 2 conservation equations for δ_m, V_m
- 3 power spectra (lensing, galaxies, velocities)

-> should be possible!

in principle, we should not need dark matter:

- WL measures $\phi+\psi$ (not $\delta\rho_m$)
- pec. velocities measure ψ: $$V_m' = -\frac{V_m}{a} + \frac{k^2}{Ha}\psi$$
- only uses that galaxies flow like $p=c_s^2=0$ fluid

do galaxies trace dark matter?

how about the galaxies?

- $P_g = b^2 P_m$
- both galaxies and DM ~ pressureless fluids
- both move and pile up ($\delta' \sim V$) the same way
- but both trace ψ independently, no direct link between perturbations!
- (maybe there is no dark matter!)

more realistic version

(or what Luca and I would do if I still did any research)

- again assume background evolution known
- full power spectrum: $P = (1+\beta^2\mu^2)b^2\delta^2$

-> $P_0 = P(\mu=0) = b^2\delta^2$

$P_1 = P(\mu=1) = (1+\beta^2)b^2\delta^2$

- combine P_0 & P_1 -> $P_v = \beta = \delta'/(\delta b)$ (with $\delta' \sim V$ for cdm)
- slightly convoluted, but can now use growth rate information (P') to express δ and b separately using P_v and P_0
- then get ψ from cdm conservation equations
- and get ϕ from weak lensing

outlook

- at background level, we want to measure w(z)
- and the curvature
- measuring the perturbations gives important clues about physical nature of DE -> 2 functs -> is w(z) noise for this? Optimisation?
- requires several measurements combined, e.g. for background SN + BAO, for perturbations WL + galaxy P(k) + peculiar velocities / redshift space distortions
- now the observers just need to go and measure these things ☺