# Dynamical Dark Energy: Theory and Data

#### Ruth Durrer

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Dark Energy, Munich, October 8, 2008

Image: Image:

### Introduction

2 Requirements on a effective physical theory

3 Scalar field dark energy

4 Dark gravity

5 Inhomogeneities (back-reaction)

6 Conclusions

Supernova observations, CMB data, measurements of the Hubble parameter, BAO are in good agreement with a flat  $\Lambda$ CDM Universe with cosmological constant,  $\Omega_{\Lambda} \simeq 0.74$ .



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Komatsu et al. 2008

$$H_0 d_L(z) = \frac{1+z}{\sqrt{-\Omega_k}} \sin\left(\sqrt{-\Omega_k} \int_0^z dz' \frac{H_0}{H(z')}\right) = (1+z)D(z)$$
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 $W(Z) = \frac{2(1+z)(1+\Omega_k D^2)D'' - [(1+z)^2\Omega_k D'^2 + 2(1+z)\Omega_k DD' - 3(1+\Omega_k D^2)]D'}{3((1+z)^2[\Omega_k + (1+z)\Omega_m]D'^2 - (1+\Omega_k D^2))D'}$ 

Fitting w(z) from luminosity distances strongly depends on a precise measurement of  $\Omega_m$  and  $\Omega_k$ .

Consistency test for flat ACDM

(Zunckel & Clarkson, 2008)

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- Fine tuning: What determines this small value? A cosmological constant is not protected from quantum corrections. So for a cutoff scale  $E_c$  we would naturally expect a cosmological constant of the order  $\rho_{\Lambda} \simeq E_c^4$ . Certainly,  $E_c \ge 1$ TeV.
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#### What are the possibilities?

- Changing the matter Lagrangian, but not the gravitational sector. The graviton is a massless spin 2 particle. (Quintessence, k-essence, *f*(*R*), Brans-Dicke)
- Changing gravity, 'dark gravity': braneworlds, massive gravity, de-gravitation, non-locality, emergent gravity...
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# possibilities for dark energy



Ruth Durrer (Université de Genève)

- Dark energy is an infrared phenomenon. If we want to change physics to accommodate it, we have to change physics in the infrared.
- We can interpret the low energy theory as some 'effective theory' which may therefore not be as restricted as the underlying high energy theory. What are the basic requirements which we nevertheless want to demand?
- A mathematical description
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Tracking solution  $\Rightarrow P = \phi^{-2} p(X)$ .

Such models have a radiation fix-point,  $w_k = 1/3$ ,  $\Omega_k \ll 1$  and a k-essence fix-point,  $w_k < -1/3$ ,  $\Omega_k \simeq 1$ .

In certain cases (for certain parameters of the Lagrangian) k-essence automatically goes from the radiation to the k-essence fix-point when the Universe becomes matter dominated.

One can show that in order to do this k-essence has to pass through a phase with  $c_s^2 > 1$ .

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- If the energy density of a scalar field is dominated by the potential,  $w_q = \frac{\frac{1}{2}\dot{\phi}^2 - V}{\frac{1}{2}\dot{\phi}^2 + V}$  becomes negative.
- If  $V(\phi) \propto \phi^{-\alpha}$ , or  $V(\phi) \propto e^{-\phi/m}$ , the scalar field has scaling attractor (Peebles &Ratra, 1988; Wetterich, 1988) solutions with  $w_q = (\alpha w_m 2)/(\alpha + 2)$ .
- If α ≫ 2 the scalar field 'tracks' the matter behavior, but decays somewhat slower, so that it comes to dominate eventually.
- Note also that if α ≥ 4, quintessence domination does not mean acceleration.
- The transition to an accelerating solution with  $w_q \simeq -1$  needs one or several additional ingredients often involving fine tuning.

- If the energy density of a scalar field is dominated by the potential,  $w_q = \frac{\frac{1}{2}\dot{\phi}^2 - V}{\frac{1}{2}\dot{\phi}^2 + V}$  becomes negative.
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- Via φ = log(1 + f'(R)) and a conformal transformation of the metric (to the Einstein frame) they can be converted into scalar-tensor models (quintessence models).
- Via a conformal trafo (to the Einstein frame), Brans-Dicke theories can be converted into scalar-tensor models.
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- Simple f(R) = R + μ<sup>4</sup>/R theories do not work. They cannot satisfy the solar system constraints and play the rôle of dark energy. More complicated models can work (see talk by Wayne Hu).
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Ruth Durrer (Université de Genève)

Dynamical Dark Energy

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• Surprisingly, branes with infinite extra dimensions and

$$S = \frac{\kappa^{2}}{2} \left[ \int_{brane} d^{4}x \sqrt{-g_{4}}R_{4} + r_{c}^{-1} \int_{bulk} d^{5}x \sqrt{-g_{5}}R_{5} \right]$$

can exhibit infrared modifications of gravity, (DGP model, Dvali et al. 2000, see talk by R. Maartens)

$$H^2 - H/r_c = rac{\kappa^2}{3}\rho$$
, if  $ho \to 0$ ,  $H \to H_\infty = 1/r_c$ .

- This model is at the verge of being excluded observationally, and it has a ghost.
- The ghost can be avoided when embedding this construction in a 6d bulk with non-vanishing 3-brane tension. The gravitational law then cascades from 6d, at very large scales to 5d to 4d behavior (de Rahm et al. 2007).
- Gravity becomes weaker on larger scales.
- Higher dimensional theories contain a tower of KK gravitons.
- The graviton in higher dimensions transforms under SO(2 + d) with spin 2 ⇒ number of degrees of freedom. For d = 1 this are 2 ⋅ 2 + 1 = 5, the helicity 2 graviton, a massless gravi-vector and a massless gravi-scalar.

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- Instead of asking why is A so small we may ask why does vacuum gravitate so little.
- Promoting Newton's constant to an operator,  $M_P^2 f(L^2 \Box) G_{\mu\nu} = T_{\mu\nu}$  we can choose  $f(x) \rightarrow_{x \rightarrow 0} 1$  such that we recover Einstein gravity on small scales and  $f(x) \rightarrow_{x \rightarrow \infty} \infty$  such that very large scale / slowly varying energy distributions do no gravitate (degravitate, Dvali et al. 2005-08).
- It can be shown that such 'high pass filters' always correspond to a graviton mass or resonance... (see Dvali).
- Padmanabhan put forward the idea that the metric, space time curvature be an emergent phenomena, like entropy or temperature. From generalizations of the Bekenstein-Hawking entropy formula he then motivates to modify Einstein's eq. to  $M_P^2 G_{\mu\nu} n^{\mu} n^{\nu} = T_{\mu\nu} n^{\mu} n^{\nu} \quad \forall n^{\mu} \text{ lightlike.}$
- These are attempts to solve the maybe deeper problem why do we not observe a large cosmological constant, but do they also have a bearing on dark energy?

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Can it be that we 'live' in a large void and the local Hubble parameter is significantly larger than the mean Hubble parameter? And can this 'fool' us into an interpretation of 'acceleration'.

 $\chi^2 = 186$  d.o.f.= 181 Riess et al. Gold data set (2006) (ACDM has  $\chi^2 =$ 150).

Can also fit the WMAP data if we allow  $n_s \simeq 0.75$  and running (or a bump in the power spectrum and/or curvature).



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Can we distinguish observationally a LTB Universe from a Friedmann Lemaître universe with arbitrary matter content?

 $\Omega_k = \frac{-K}{H_0^2} = \frac{\frac{H(z)^2}{H_0^2}D'(z)^2 - 1}{D(z)^2}$ 

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- That the fact that most regions of the Universe are rather empty and matter has condensed into relatively thin 'shells', a weblike structure, severely affects the luminosity distance,  $d_L(z)$ ?
- Even though present calculations (using toy models) rather give effects of the order of 10% (Li et al, 2007; Räsänen, 2008), we are not sure that this is impossible. See talks by D. Wiltshire, S. Räsänen
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- A FL Universe with cosmological constant, ACDM can fit present cosmological data.
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