

Dynamical Dark Energy: Theory and Data

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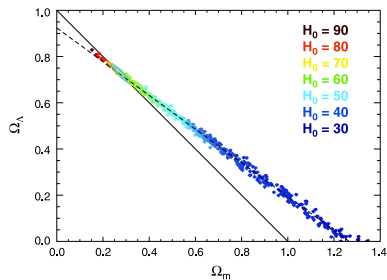


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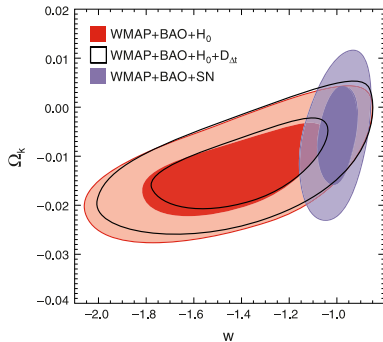
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- 2 Requirements on a effective physical theory
- 3 Scalar field dark energy
- 4 Dark gravity
- 5 Inhomogeneities (back-reaction)
- 6 Conclusions

The Dark Energy Problem

Supernova observations, CMB data, measurements of the Hubble parameter, BAO are in good agreement with a flat Λ CDM Universe with cosmological constant, $\Omega_\Lambda \simeq 0.75$.



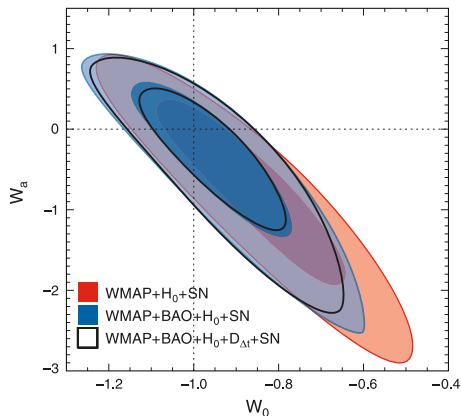
Larson et al. 2010



Komatsu et al. 2010

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The cosmological constant

- A cosmological constant $\Lambda \simeq 5 \times 10^{-66} \text{eV}^2$ or $\rho_\Lambda \simeq (2.3 \times 10^{-3} \text{eV})^4$ fits the data reasonably well.
- **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, $E_c \geq 1 \text{TeV}$.
- **Coincidence:** Why is the cosmological constant just **now** of the order of the critical density?

These problems have prompted researchers to look for other 'more natural' solutions...

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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...
- **Inhomogeneities** are strongly affecting $H(z)$ and $d_L(z)$, back-reaction, violation of the Copernican principle.

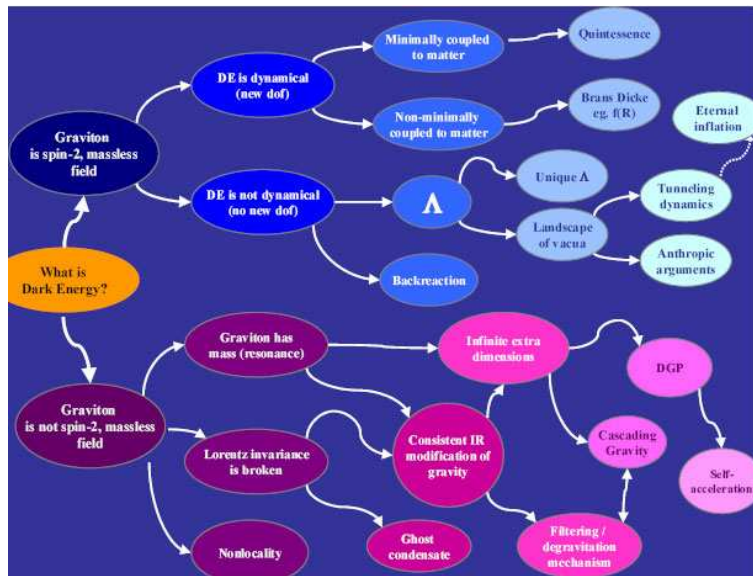
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possibilities for dark energy



de Rahm & Tolley, 2008

Requirements on a effective physical theory

- 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 **Lagrangian formulation** (every degree of freedom has a kinetic term).
- **Lorentz invariance** (not simply covariance, no 'absolute element').
- No **ghosts** (degrees of freedom with wrong sign of the kinetic term).
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The problem with k-essence

$$\mathcal{L} = \sqrt{-g}P(\phi, X), \quad X = \frac{1}{2}(\nabla\phi)^2$$

$$c_s^2 = \frac{P'}{2XP'' + P'}, \quad ' = \frac{d}{dX}.$$

Tracking solution $\Rightarrow P = \phi^{-2}p(X)$.

Such models have a radiation fix-point, $w_{ke} = 1/3$, $\Omega_{ke} \ll 1$ and a k-essence fix-point, $w_{ke} < -1/3$, $\Omega_{ke} \simeq 1$.

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 $c_s^2 > 1$.

If k-essence is to solve the coincidence problem, it has to exhibit super-luminal motion.

Bonvin et al., 2006

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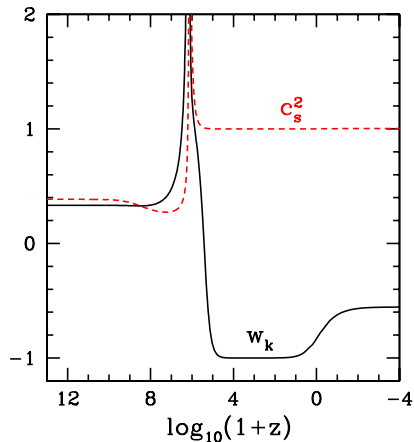
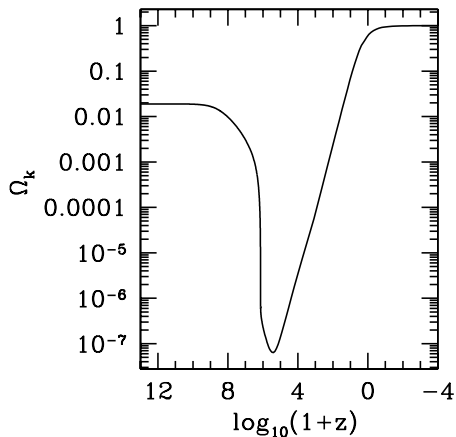
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- If the energy density of a scalar field is dominated by the potential, $w_q = \frac{\frac{1}{2}\dot{\phi}^2 - V}{\frac{1}{2}\dot{\phi}^2 + V}$ becomes negative.
- If $V(\phi) \propto \phi^{-\alpha}$, $\alpha > 0$ or $V(\phi) \propto e^{-\phi/m}$, the scalar field has scaling attractor (Peebles & Ratra, 1988; Wetterich, 1988) solutions with $w_q = (\alpha w_m - 2)/(\alpha + 2) < w_m$.
- If $\alpha \gg 2$ the scalar field 'tracks' the matter behavior, but decays somewhat slower, so that it comes to dominate eventually.
- Note also that if $\alpha \geq 4$, 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.

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$f(R)$ and Brans-Dicke theories

- The simplest modification of the gravitational Lagrangian which avoid the **Ostrogradski theorem (1850)** are $\mathcal{L} = \sqrt{-g}f(R)$.
- Via $\varphi = \log(1 + f'(R))$ 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.
- These models have, however a very particular **coupling to matter**.
- Simple $f(R) = R + \mu^4/R$ theories do not work. They cannot satisfy the solar system constraints **and** play the rôle of dark energy. More complicated models can work.
- Such models have no Minkowski vacuum solution (have no flat solutions).
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- Surprisingly, branes with infinite extra dimensions and

$$S = \frac{\kappa^2}{2} \left[\int_{brane} d^4x \sqrt{-g_4} R_4 + r_c^{-1} \int_{bulk} d^5x \sqrt{-g_5} R_5 \right]$$

can exhibit infrared modifications of gravity,
(DGP model, [Dvali et al. 2000](#))

$$H^2 - H/r_c = \frac{\kappa^2}{3} \rho, \text{ if } \rho \rightarrow 0, H \rightarrow H_\infty = 1/r_c.$$

- By now, this model is 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](#)).

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$$f(x) \xrightarrow{x \rightarrow 0} \infty, \quad f(x) \xrightarrow{x \rightarrow \infty} 1$$

such that we recover Einstein gravity on small scales and very large scale / slowly varying energy distributions do not gravitate (degravitate, [Dvali et al. 2005-08](#)).

- **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 $M_P^2 G_{\mu\nu} n^\mu n^\nu = T_{\mu\nu} n^\mu n^\nu \quad \forall n^\mu \text{ lightlike.}$
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such that we recover Einstein gravity on small scales and very large scale / slowly varying energy distributions do not gravitate (degravitate, [Dvali et al. 2005-08](#)).

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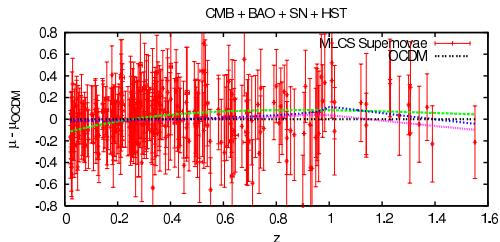
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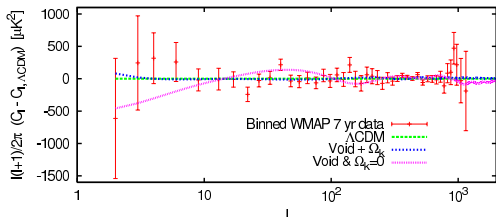
A large void

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'.

Can fit the SNIa data



and CMB,
(Biswang et al.
2010)



Violation of the Copernican principle

Spherically symmetric (Lemaître, Tolman Bondi, LTB) solutions can show "apparent acceleration" (i.e. a function $d_L(z)$ like a Λ CDM Universe) even if they contain only dust.

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

Yes (Clarkson et al. 2007)

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

This quantity is constant (indep. of z) in a Friedmann Universe but depends on z , curvature $K(r)$, in an LTB Universe.

But it is hard to measure...

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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, $d_L(z)$?
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Conclusions

- A FL Universe with cosmological constant, Λ CDM can fit present cosmological data.
- It is hard to motivate the 'observed value' of Λ .
- Acceleration can always be obtained from the potential energy of a scalar field. But even for scaling solutions the 'coincidence problem' remains an issue. (For a proposal see Wetterich, 2007.)
- Effective theories, like k-essence suffer often from problems like super-luminal motion, ghosts or unbounded Hamiltonians.
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