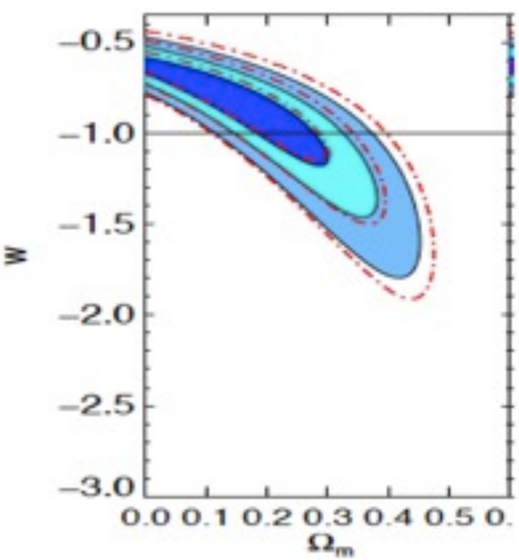
Cosmic Acceleration

$$\frac{\ddot{a}}{a} \propto -(\rho + 3p)$$

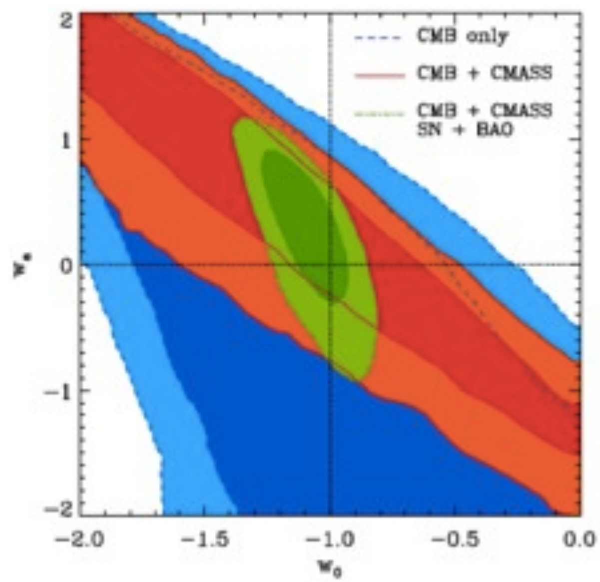
So, writing p=wρ, accelerating expansion means p<-ρ/3 or

$$\boxed{w<-1/3}$$

Conley et al. 2011



Sanchez et al. 2012



Data tantalizingly close to w=-1

Cosmological constant? Dark Energy? Modified Gravity? New physics at Hubble scales? New physics at millimeter scales? Cosmic Coincidence Problem? Cosmological Constant Problem

Lambda, the Landscape & the Multiverse

No known mechanism, and a no-go theorem (Weinberg) to be overcome.

Anthropics provide a logical possibility to explain this, and the string landscape, with eternal inflation, may provide a way to realize it.

Important step - understanding how to compute probabilities in such a spacetime - No currently accepted answer, but much serious work going on.

If a dynamical understanding of a small CC is found, it would be hard to accept this.

If DE is time or space dependent, may be a challenge to explain this way.

[Image: SLIM FILMS. Looking for Life in the Multiverse, A. Jenkins & G. Perez, Scientific American, December 2009]

Leading 'relevant operator' in action for gravity - but most UV sensitive!

Why doesn't Lambda get large contribution from Phase Transitions?

Potential energy of Higgs field $V \sim (100 GeV)^4$

QCD condensate energy in chiral symmetry breaking) $V \sim (100 MeV)^4$

Dark Energy vs. Modified Gravity?

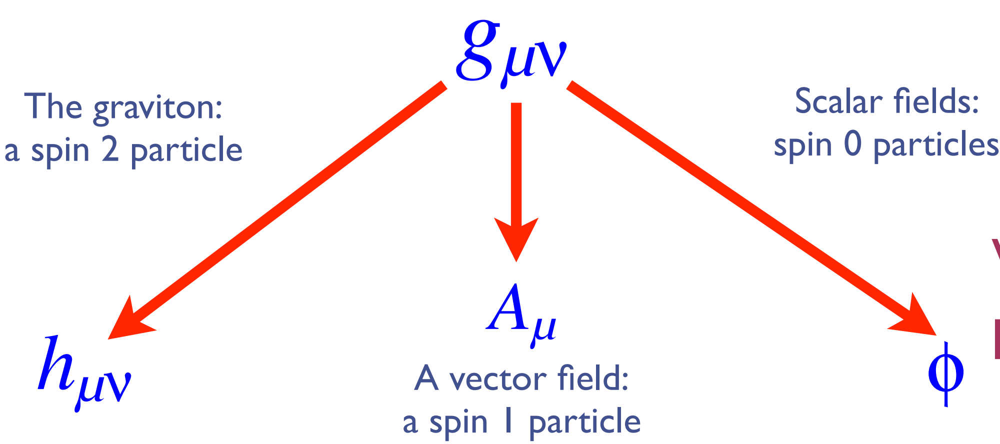
Once we allow dark energy to be dynamical, we are imagining that is is some kind of honest-to-goodness mass-energy component of the universe.

Our only known way of describing such things, at a fundamental level is through quantum field theory, with a Lagrangian. e.g.

$$S_m = \int d^4x \, L_m[\phi, g_{\mu\nu}] \qquad T_{\mu\nu} \equiv -\frac{2}{\sqrt{-g}} \frac{\delta S_m}{\delta g^{\mu\nu}} \qquad R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

If we want to modify gravity itself, it will turn out we are either faced with similar considerations, or analogous ones.

A crucial question is: what degrees of freedom does the metric $g_{\mu\nu}$ contain.



Which degrees of freedom propagate depends on the action.

A Common Language - EFT

In fact, whether dark energy or modified gravity, ultimately, around a background, consists of a set of interacting fields in a Lagrangian. The Lagrangian contains 3 types of terms:

- Kinetic Terms: e.g.

$$\partial_\mu\phi\partial^\mu\phi \quad F_{\mu\nu}F^{\mu\nu} \quad i\bar{\psi}\gamma^\mu\partial_\mu\psi \quad h_{\mu\nu}\mathcal{E}^{\mu\nu;\alpha\beta}h_{\alpha\beta} \quad K(\partial_\mu\phi\partial^\mu\phi)$$

- Self Interactions (mass terms and potentials)

$$V(\phi) \quad m^2\phi^2 \quad \lambda\phi^4 \quad m\bar{\psi}\psi \quad m^2h_{\mu\nu}h^{\mu\nu} \quad m^2{h^\mu}_\mu{h^\nu}_\nu$$

- Interactions with other fields (such as matter, baryonic or dark)

$$\Phi\bar{\psi}\psi \quad A^\mu A_\mu\Phi^\dagger\Phi \quad e^{-\beta\phi/M_p}g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi \quad ({h^\mu}_\mu)^2\phi^2 \quad \frac{1}{M_p}\pi{T^\mu}_\mu$$

Depending on the background, such terms might have functions in front of them that depend on time and/or space.

We'd like to understand allowed forms of these Lagrangians, their predictions, and whether are theoretically consistent.

Consistency Issues I

When we write down a classical theory, described by one of our Lagrangians, we are usually implicitly assuming that the effects of higher order operators are small, and therefore mostly ignorable. This needs us to work below the strong coupling scale of the theory, so that quantum corrections, computed in perturbation theory, are small. We therefore need.

• The dimensionless quantities determining how higher order operators, with dimensionful couplings (irrelevant operators) affect the lower order physics be <<1 (or at least <1)

$$\frac{E}{\Lambda} << 1 \qquad \text{(Energy << cutoff)}$$

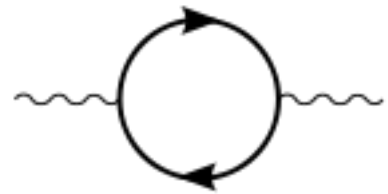
But be careful - this is tricky! Remember that our kinetic terms, couplings and potentials all can have background-dependent functions in front of them, and even if the original parameters are small, these may make them large - the ***strong coupling problem***! You can no longer trust the theory!

Consistency Issues II

Even if can trust your theory, especially small couplings might be a problem.

Unless theory has a special extra symmetry, quantum corrections may drive these up to the cutoff of your theory.

$$m_{\mathrm{eff}}^2 \sim m^2 + \Lambda^2$$



- Without this, requires extreme fine tuning to keep the potential flat and mass scale ridiculously low - ***challenge of technical naturalness.***

The Kinetic terms in the Lagrangian, around a given background, tell us, in a sense, whether the particles associated with the theory carry positive energy or not.

- Remember the Kinetic Terms: e.g.

$$-\frac{f(\chi)}{2}K(\partial_\mu\partial^\mu\phi) \to F(t,x)\frac{1}{2}\dot{\phi}^2 - G(t,x)(\nabla\phi)^2$$

This sets the sign of the KE

- If the KE is negative then the theory has ***ghosts***! This can be catastrophic!

Screening

So a general theme here, in both quintessence and modified gravity is the need for new degrees of freedom, coupled to matter with gravitational strength, and hence extremely dangerous in the light of local tests of gravity.

- Successful models exhibit "screening mechanisms". Dynamics of new degrees of freedom rendered irrelevant at short distances and only become free at large distances (or in regions of low density).
- There exist several versions, depending on parts of the Lagrangian used
    - Vainshtein: Kinetic terms make coupling to matter weaker than gravity around massive sources.
    - Chameleon: Matter coupling gives scalar large mass in high-density regions
    - Symmetron: Uses coupling to give scalar small VEV in regions of low density, lowering coupling to matter
- In each case should "resum" theory about the relevant background, and EFT of excitations around a nontrivial background is not the naive one.
- Around the new background, theory can be safe from local tests of gravity.

General tests of couplings and complexity in the dark sector!