Alternatives to the cosmological constant

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Plan of Talk

- Alternatives to Dark Energy
  - New Fields
  - Modified Gravity
- Sources of Observational Evidence
  - Cosmological
  - Astrophysical
  - Detectors

Quintessence

- Dynamic scalar field ***φ*** evolving in a potential ***V(φ)***
- Its equation of state ***w*** varies with time:

$$w = \frac{\dot{\phi}^2/2 - V(\phi)}{\dot{\phi}^2/2 + V(\phi)}$$

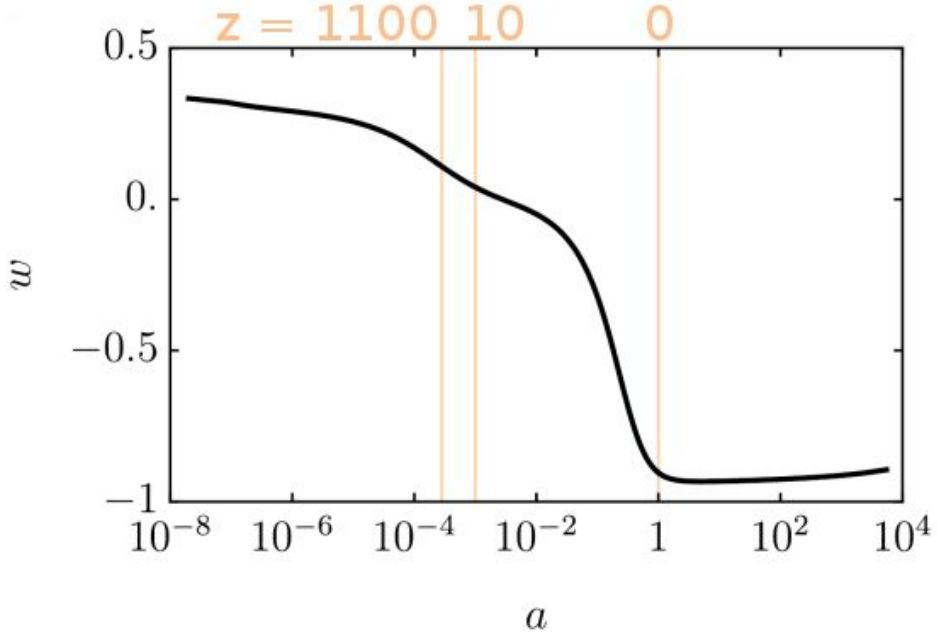
- Can be generalized to a gauge field with isotropic configuration:

$$S = \int d^4x\sqrt{-g}\left(\frac{M_P^2}{2}R - \frac{1}{4}F_{a\mu\nu}F^{a\mu\nu} - \frac{\lambda}{M_P^4}(F_{a\mu\nu}\tilde{F}^{a\mu\nu})^2 + \mathcal{L}_m\right)$$

Gauge - Quintessence

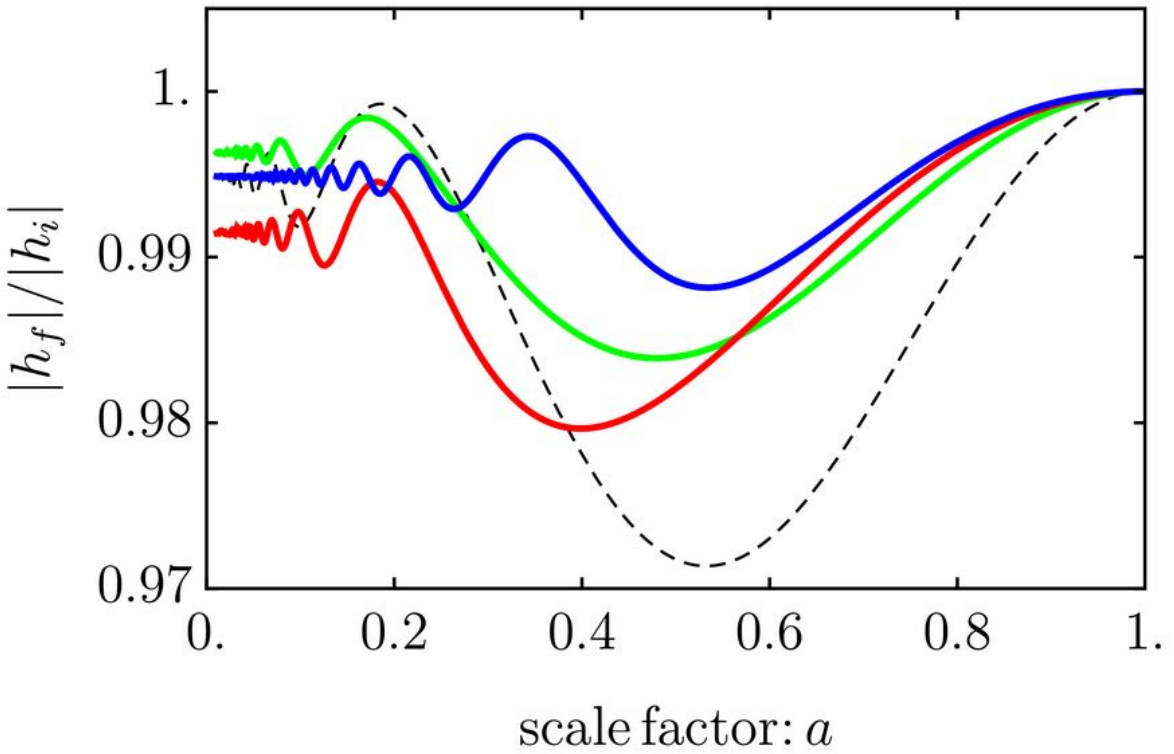
$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu$$

$$A^a_\mu = \begin{cases} \phi(t)\delta^a_\mu & \mu = 1,2,3 \\ 0 & \mu = 0 \end{cases}$$



Gauge - Quintessence

- Gravitational Wave - Gauge Field Interactions



$\hat{g}$	Ω_{EDE}
1	0.0023
5	0.0013
10	0.00083
10	0.0019

f(R) Gravity

Instead of adding new fields just change Lagrangian

$$\mathcal{L} = \sqrt{-g}\,\kappa R \rightarrow \sqrt{-g}\,\kappa f(R)$$

Conformally Equivalent to Scalar Quintessence ⟶ Same kind of dynamics

Coupling to Matter is VERY DIFFERENT

DGP Model

Higher Dimensional Model

$$S = -\kappa_5 \int d^5x \sqrt{-\tilde{g}}\, \tilde{R} - \kappa \int d^4x \sqrt{-g} R + S_{Matter}$$

Crossover between 4D and 5D Gravity allows DE to turn on at late times

No free function → Easier to constrain

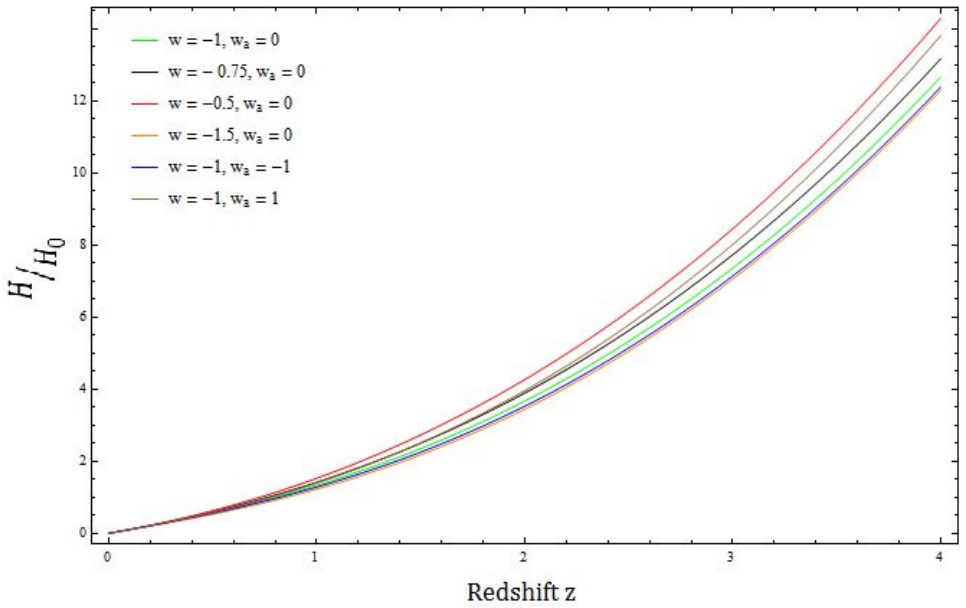
Geometric Observables

Different models have different geometries

Some models can produce any H(z) (Quintessence, f(R) etc)

For a model with 1 free function, fixing geometry fixes the model

$$w(z) = w_0 + \frac{w_a z}{(1+z)}$$



How to Get Any Geometry From Quintessence

$$3H^2 = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

$$-2\dot{H} - 3H^2 = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

$$\phi_0(t) = \phi_i + \int_{t_i}^{t} dt' \sqrt{\frac{-\dot{H}(t')}{16\pi G}}$$

$$V(\phi) = \frac{1}{8\pi G}\left[\dot{H}(t) + 3H^2(t)\right]_{t=t(\phi)}$$

We have to use multiple probes!

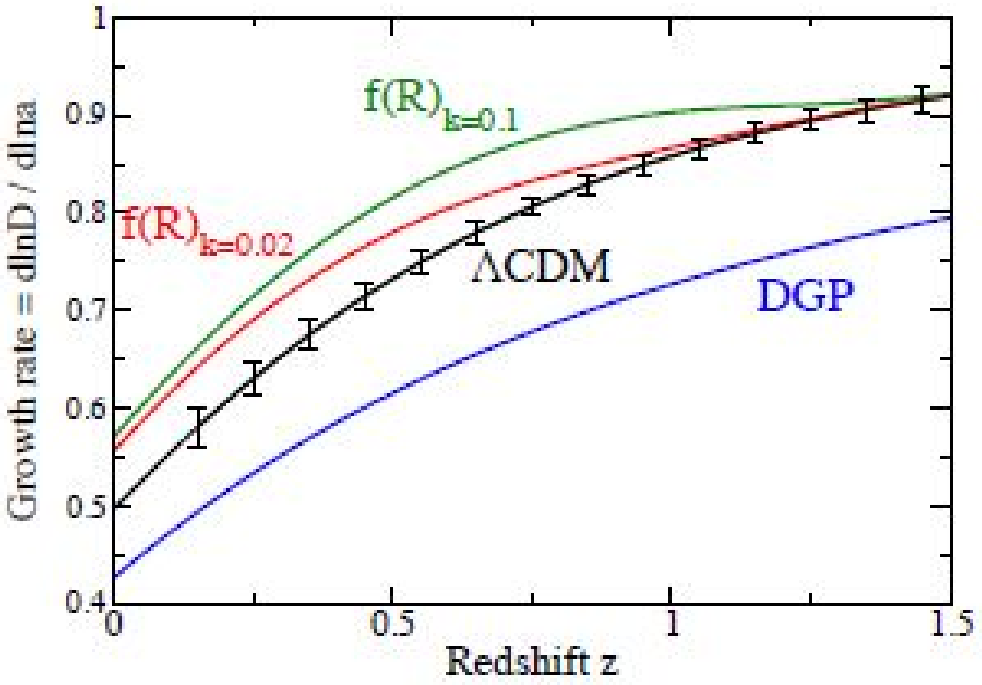
Growth Rate of Structure

More power to discriminate than just the geometric observables

$$f(a) = \frac{d \ln D}{d \ln a}$$

We measure:

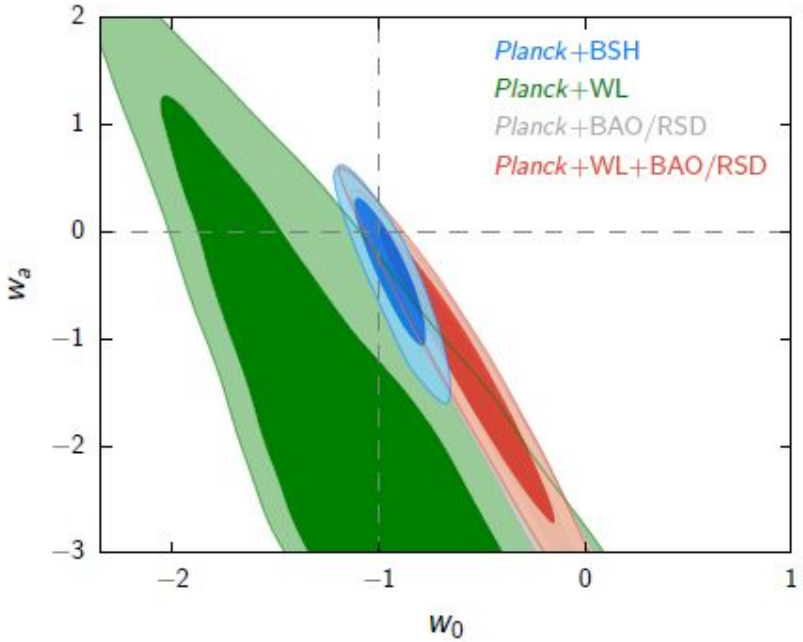
$$f(z)\sigma_8(z)$$



CMB and Weak Lensing

Why does D.E. influence CMB data?

- Changes Lensing Potentials
- Gravitational Potentials Decay
- Change in Structure Growth causes mismatch with late time probes



Solar System Tests

Great Arena for testing Gravity

Some mechanisms exist for hiding your theory (See Mark's Talk)

Some Constraints:

Lunar Ranging - $\frac{\dot{G}}{G} < 4 \pm 9 \times 10^{-13}$

Shapiro Delay - $\frac{1+\gamma}{2} < 10^{-5}$

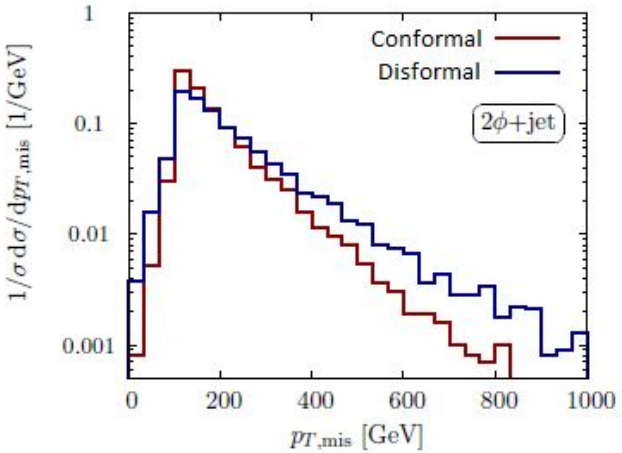
Scalar Tensor Theories, f(R), DGP all constrained in Solar System

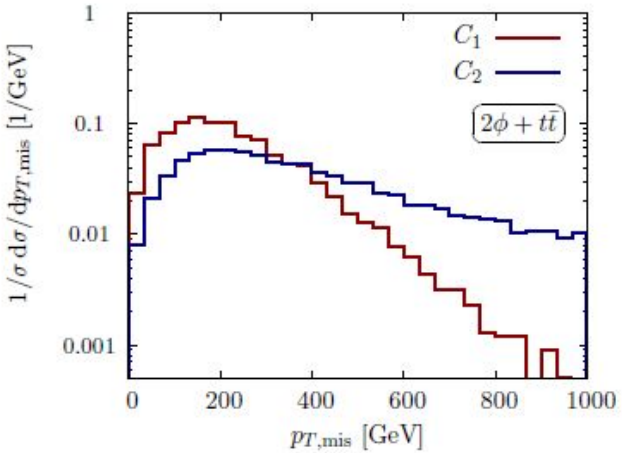
Detector Signatures

Need couplings to matter to be detectable

Bottom up approach. Expand In : $\mathcal{L}_{Con} = \frac{\partial_\mu \phi \partial^\mu \phi}{M^4} T^\nu_\nu$; $\mathcal{L}_{Dis} = \frac{\partial_\mu \phi \partial_\nu \phi}{M^4} T^{\mu\nu}$

Different terms have different signals in Jets + MET





Conclusions

Failure of Lambda CDM would be a source of crisis/opportunity

As always, true difficulty will be in reconciling old data with new paradigm

“No amount of experimentation can prove me right; a single experiment can prove me wrong” - Albert Einstein

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Gauge - Quintessence

- Observational constraints. ***g*** = 1, 2, 10