



Dark Energy and Cosmology

74% Dark Energy

22% Dark
Matter

4% Atoms

Mark Trodden
Center for Particle Cosmology
University of Pennsylvania

Melbourne, Australia
11 July 2012



Overview

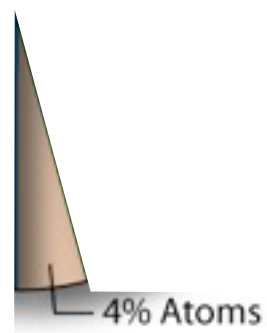
- Motivations - background, and the problems of modern cosmology.
- The meaning of cosmic acceleration
- A tasting menu of theoretical approaches
 - The cosmological constant
 - Dynamical dark energy
 - Modified gravity
- Theoretical progress has been slow - reflected here. But there are some very recent nontrivial possibilities.
- How do we distinguish between models?



Modern Cosmology

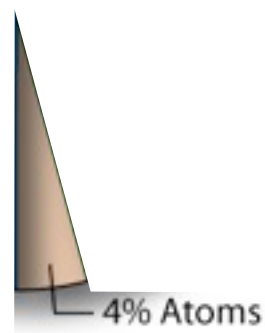


Modern Cosmology





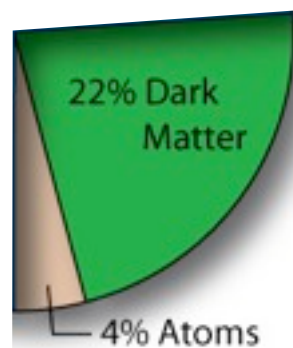
Modern Cosmology



Why is there more
matter than antimatter?
(See Petraki, Von Harling, Parallels)



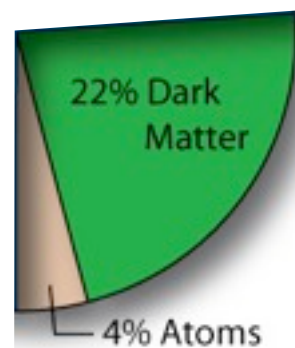
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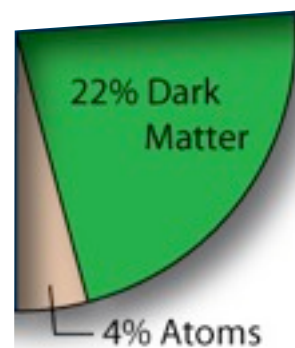


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(See Weiner, Hsu
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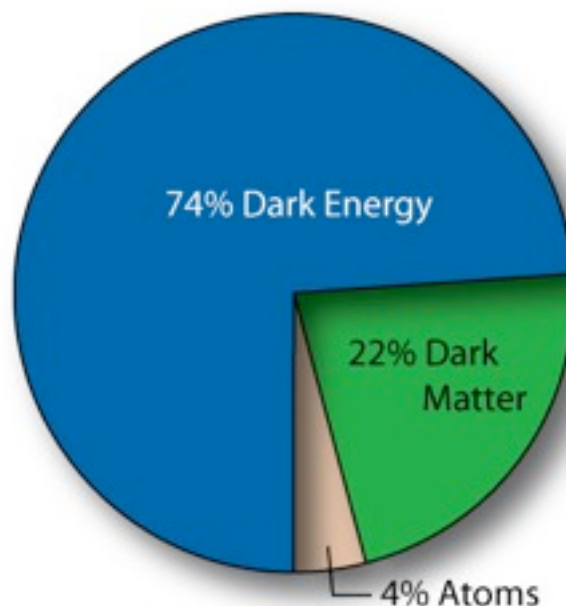
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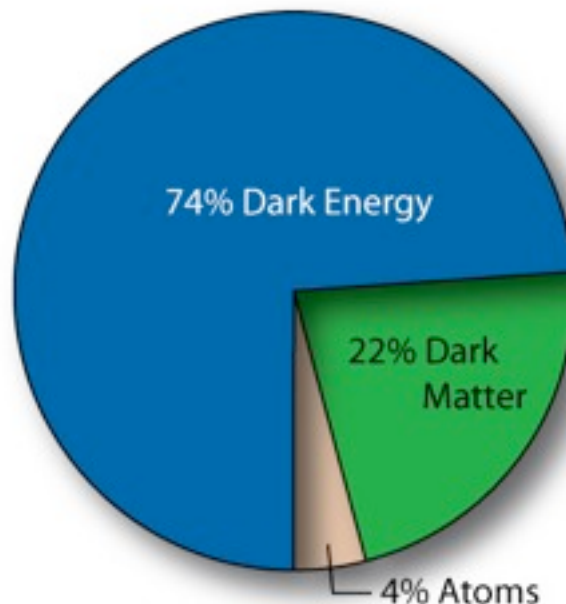
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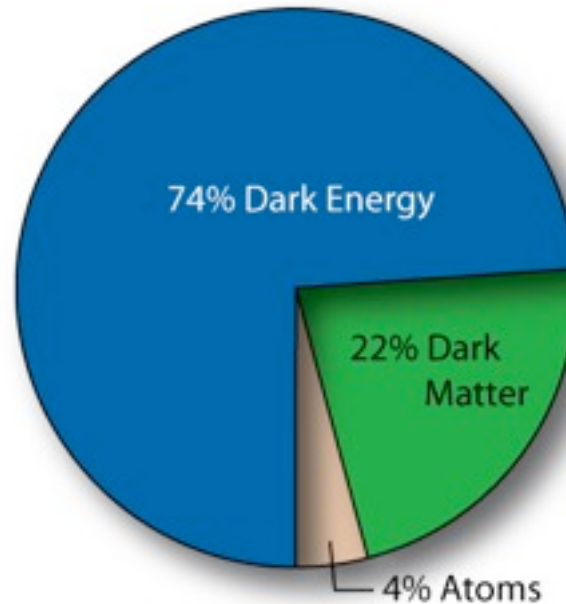
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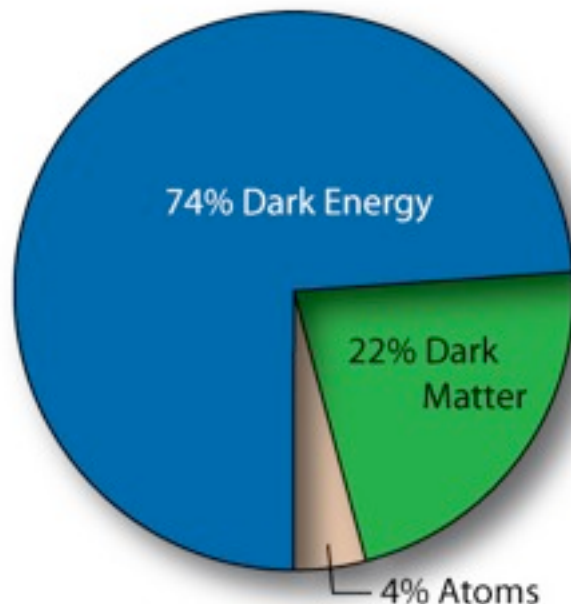


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Is cosmic acceleration a
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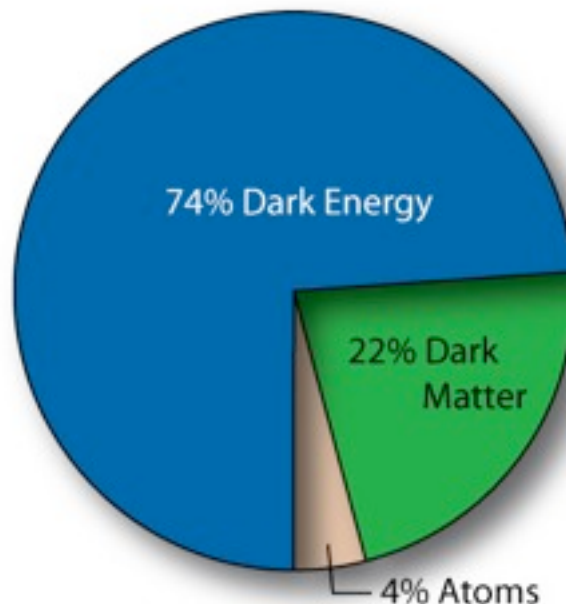
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Genesis:

- Why is the universe so flat?
- Why is the universe so homogeneous?
- Why did the universe begin from a low entropy state?
- What resolves the big bang singularity?

(See Antusch, MT Parallels)



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Simple Cosmology - a Reminder



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Evolution of the universe governed by Einstein eqns

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Metric

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When evolution dominated by type i , obtain

$$a(t) \propto t^{2/3(1+w_i)} \quad \rho(a) \propto a^{-3(1+w_i)} \quad (w_i \neq -1)$$



The Cosmic Expansion History



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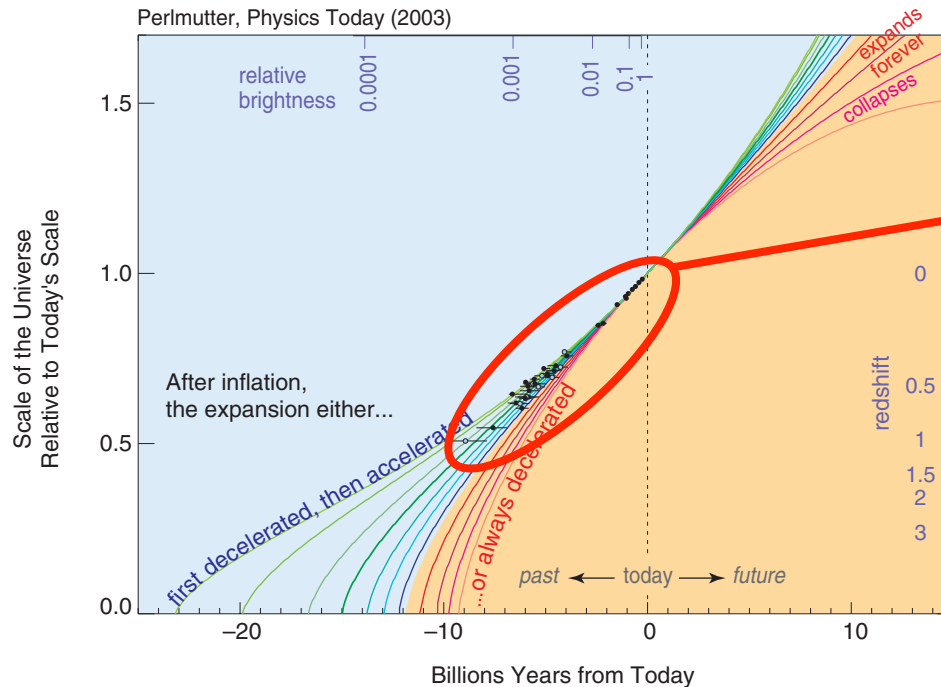


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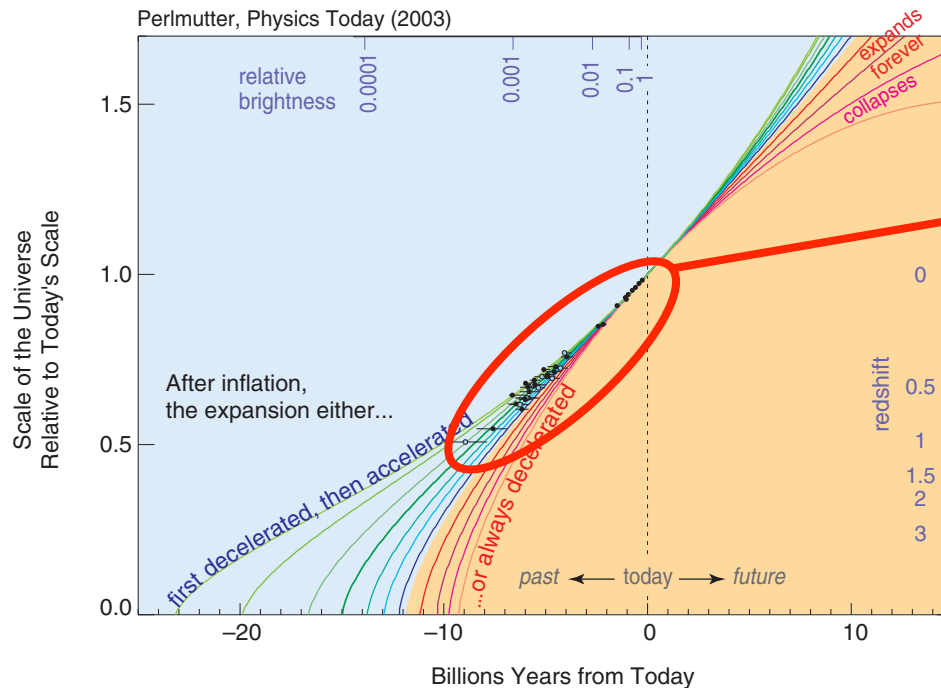


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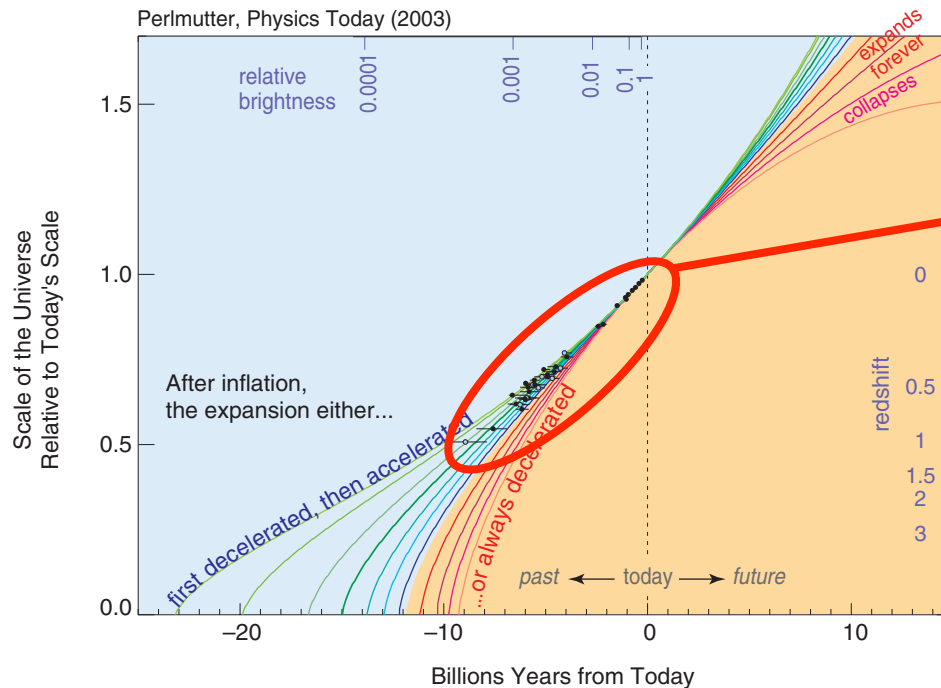


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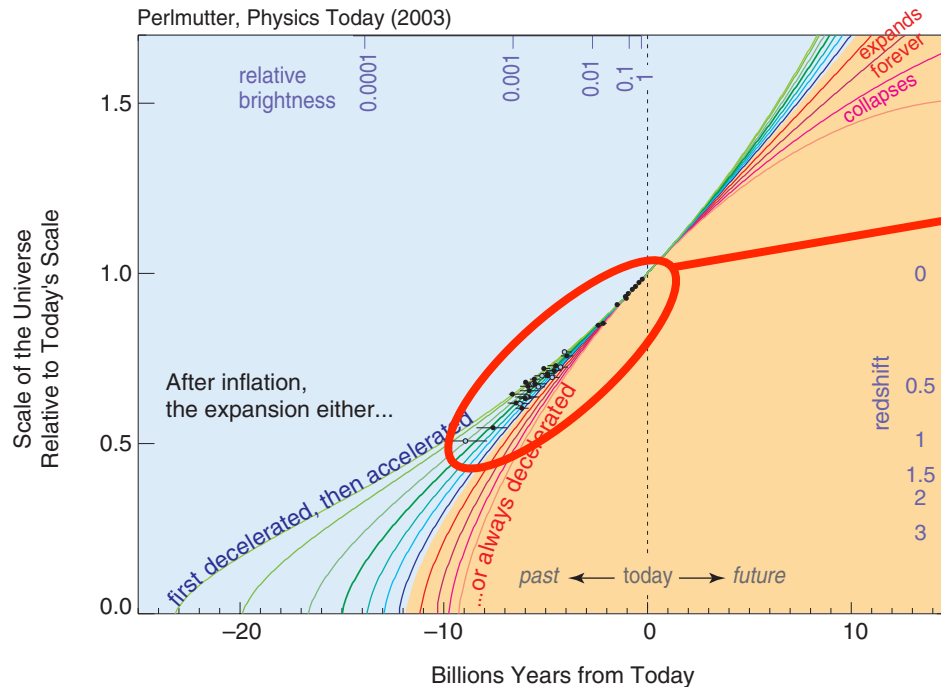


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Then we infer that the universe must be dominated by some strange stuff with $p < -\rho/3$. We call this **dark energy**!



Cosmic Acceleration

So, accelerating expansion means

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

$$p < -\rho/3 \text{ or}$$

$$w < -1/3$$

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	$-1 < w < -1/3$	$w = -1$	$w < -1$
Evolution of Energy Density	Dilutes slower than any matter	Stays absolutely constant (Λ)	Increases with the expansion!!
Evolution of Scale Factor	Power-law quintessence	Exponential expansion	Infinite value in a finite time!!



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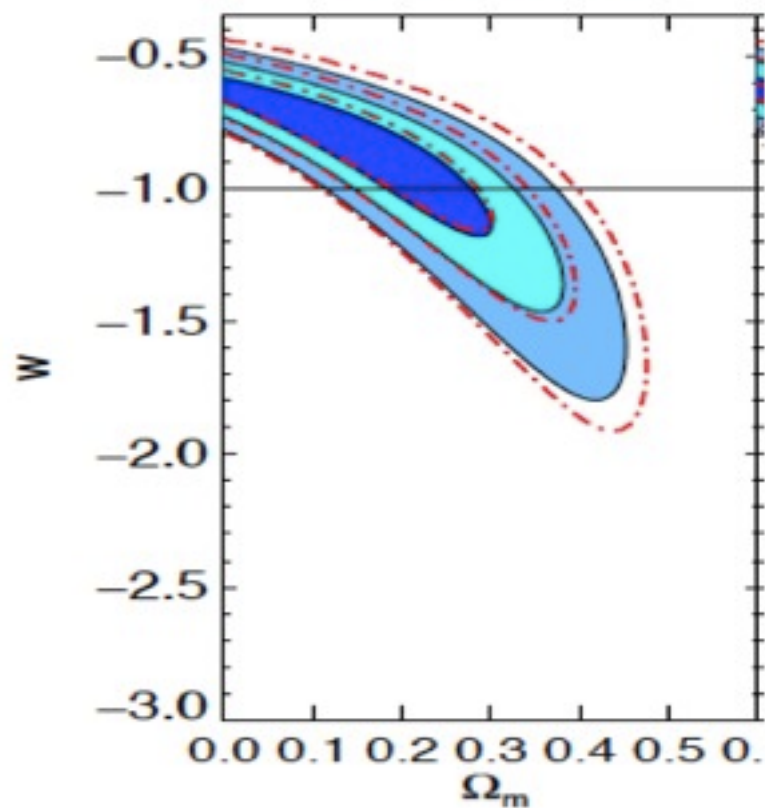
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Conley et al. 2011





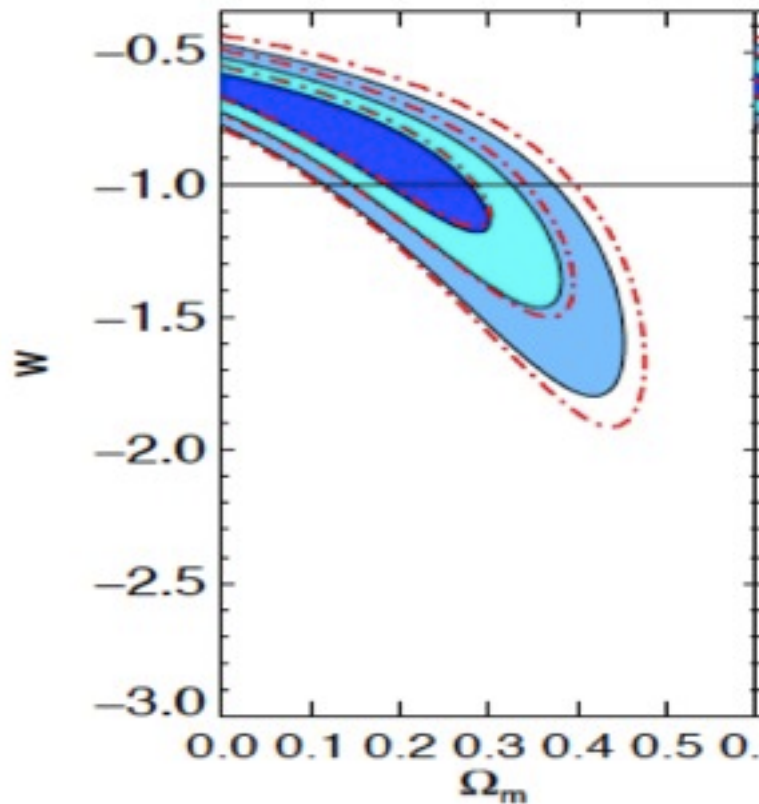
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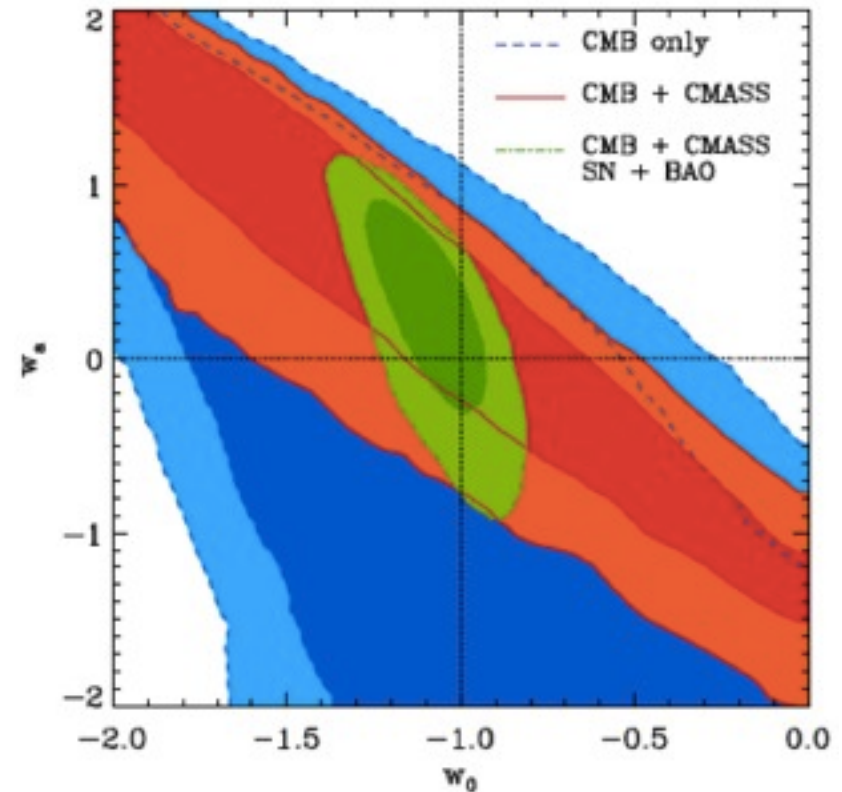
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Sanchez et al. 2012





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This describes a *cosmological constant*. Acceleration could be due to this; but if so, how to understand its absurd value?



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



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

If DE is time or space dependent, would be hard to explain this way.



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



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[Ratra, Peebles; Wetterich; Caldwell, Dave, Steinhardt; Freiman, Hill, Stebbins, Waga; Armendariz-Picon, Mukhanov;
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Use scalar fields to source Einstein's equation - *Quintessence*.

Difference: no minimum or reheating

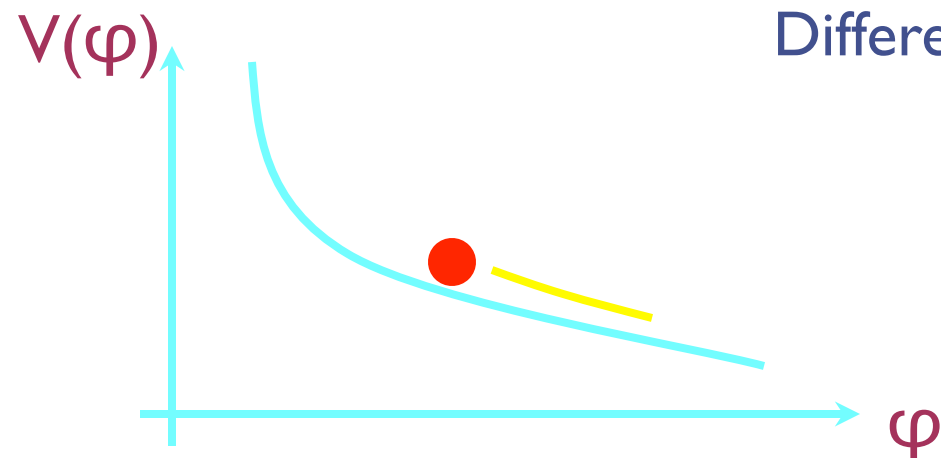


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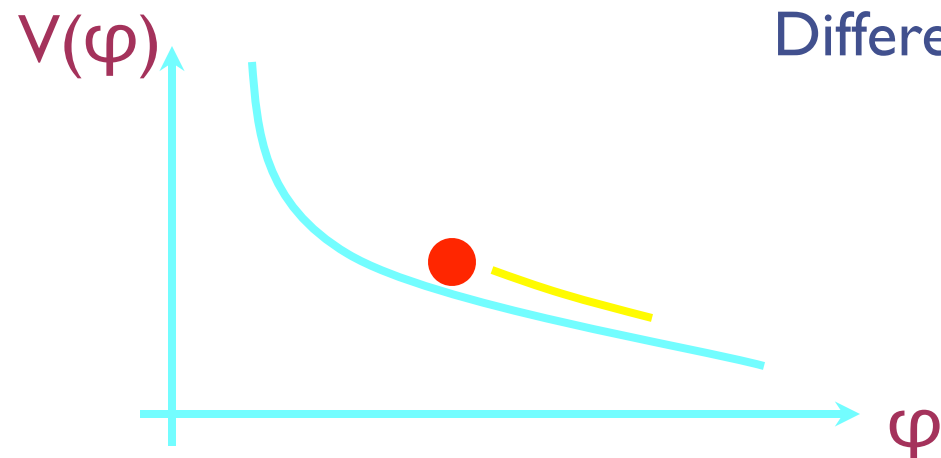


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Small slope

$$\rho_\phi \approx V(\phi) \approx \text{constant}$$

$$w = - \left[\frac{2V(\phi) - \dot{\phi}^2}{2V(\phi) + \dot{\phi}^2} \right]$$



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- On the other hand, some models, including those with exotic kinetic structure (k-essence), have the possibility of addressing the coincidence problem, and so there are advantages. [Armendariz-Picon, Mukhanov, Steinhardt; Caldwell. ...]
- At present there are no compelling models, although some success in embedding some of the above ideas within string theory.



Are we Being Fooled by Gravity?

(Carroll, De Felice & M.T., *Phys.Rev. D71*: 023525 (2005) [astro-ph/0408081])

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One example - Brans-Dicke theories

$$S_{BD} = \int d^4x \sqrt{-g} \left[\phi R - \frac{\omega}{\phi} (\partial_\mu \phi) \partial^\mu \phi - 2V(\phi) \right] + \int d^4x \sqrt{-g} L_m(\psi_i, g)$$

$\omega > 40000$ (Signal timing measurements from Cassini)

We showed that (with difficulty) can measure $w < -1$, even though no energy conditions are violated.



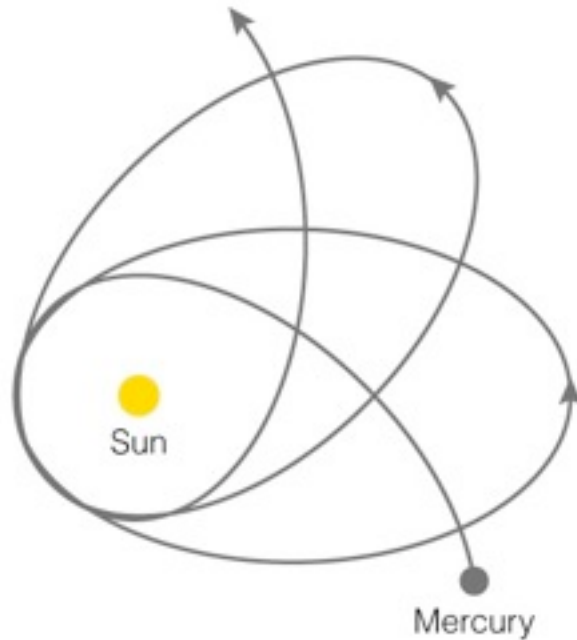
A Cautionary Tale

A related tale played out over 50 years over a century ago



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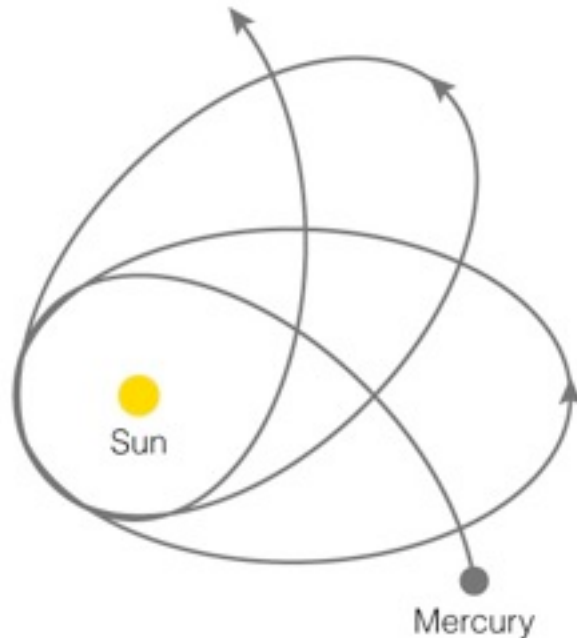
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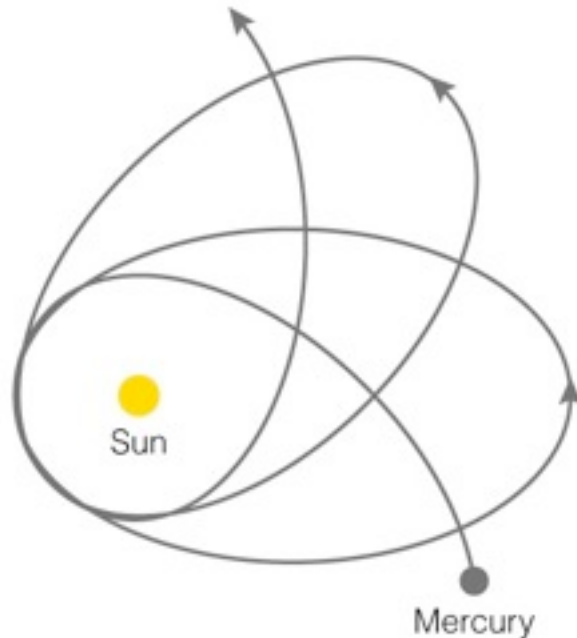
Annales de l'Observatoire Impérial de Paris. Publiées par U. J. Leverrier, Directeur de l'Observatoire, tom. v. 4to, Paris, 1859.

This volume contains the theory and tables of *Mercury* by M. Leverrier; the discrepancy as regards the secular motion of the perihelion which is found to exist between theory and observation, led, as is well known, to the suggestion by M. Leverrier of the existence of a planet or group of small planets interior to *Mercury*. The volume contains also a memoir by M. Foucault, on the "Construction of Telescopes with Silvered



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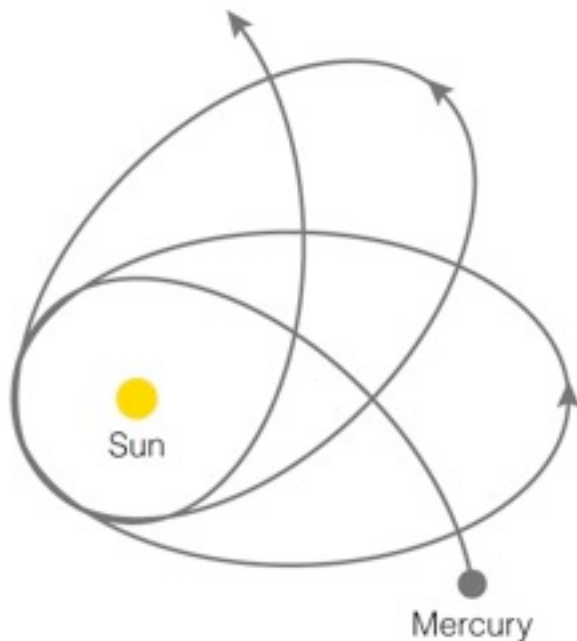
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A Cautionary Tale

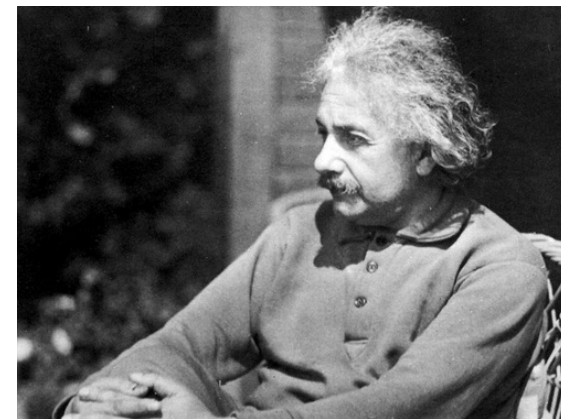
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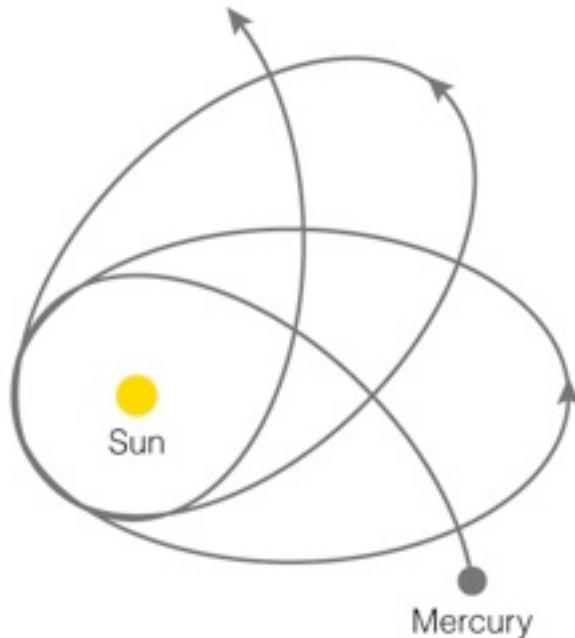
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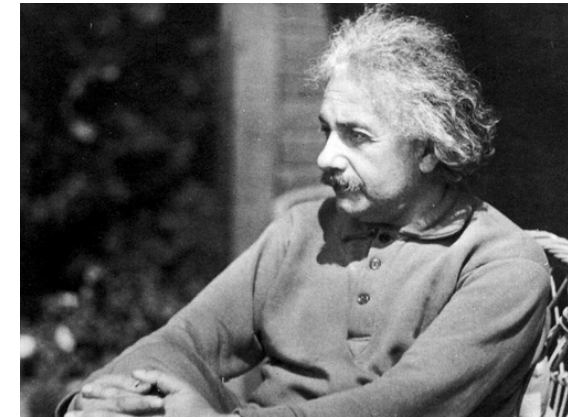
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Could a similar story be unfolding today, with cosmic acceleration the canary in the mine, warning of the breakdown of gravity?



Modifying Gravity



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A crucial first question (for particle theorists) is: what degrees of freedom does the metric $g_{\mu\nu}$ contain in general?



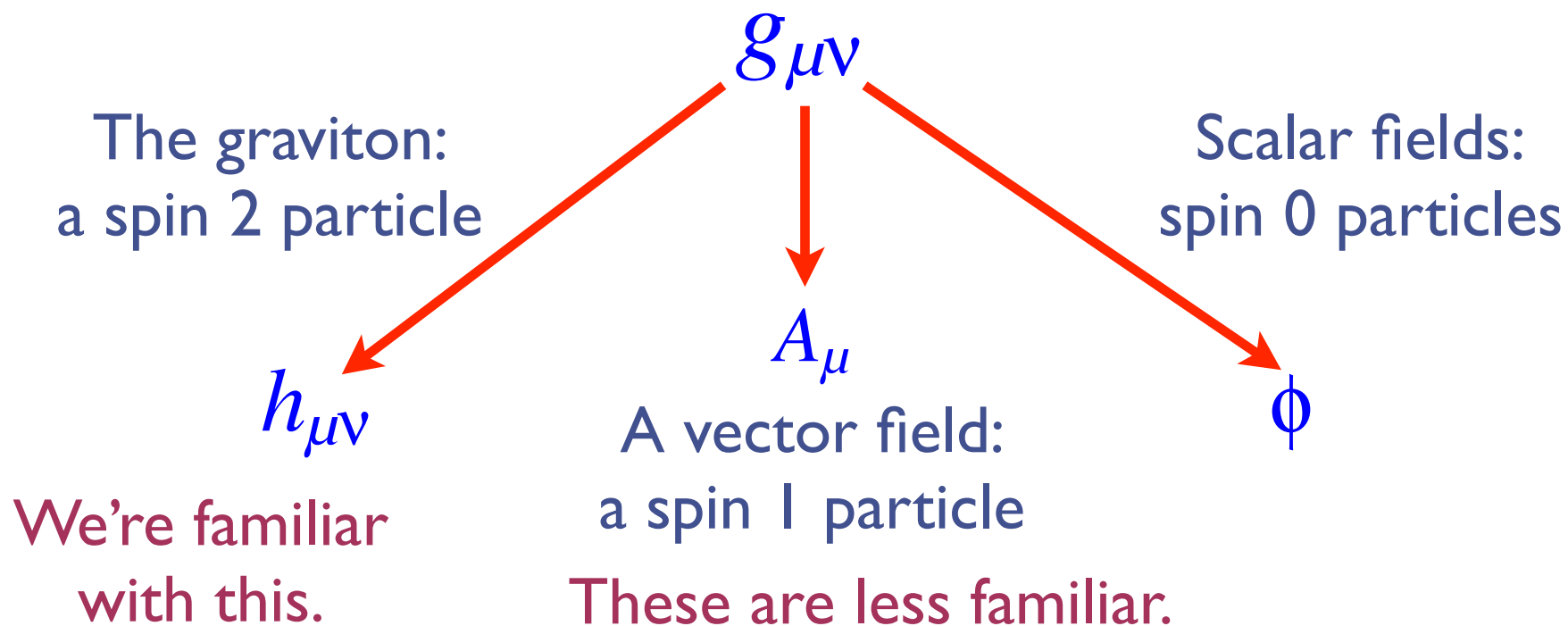
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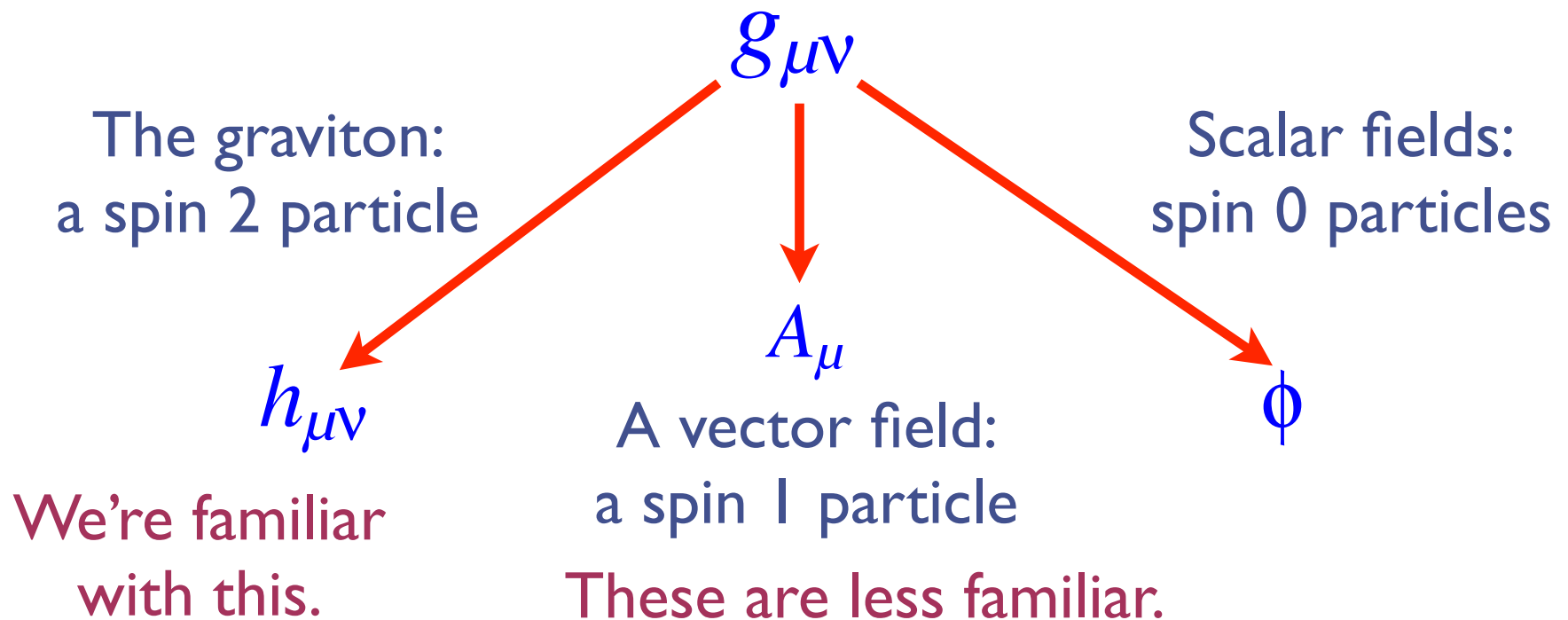
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Almost any other action will free some of them up



Issues with new d.o.f.



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- GR is very well tested in the solar system.
The new fields can change the paths of light.



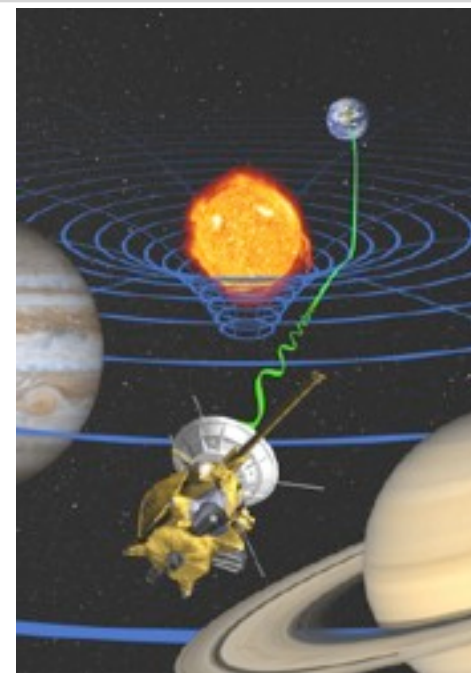
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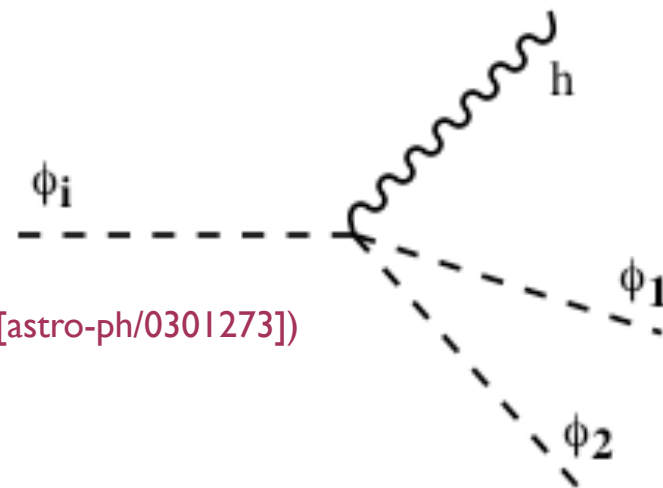
If we were to take these seriously, they'd have negative energy!!

- Ordinary particles could decay into heavier particles plus ghosts

(Carroll, Hoffman & M.T., *Phys.Rev.* **D68**: 023509 (2003) [astro-ph/0301273])

- Vacuum could fragment

(Cline, Jeon & Moore. (2004))





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- Also protects against local tests of gravity.



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So forces much smaller than gravitational strength within the Vainshtein radius - hence safe from 5th force tests.



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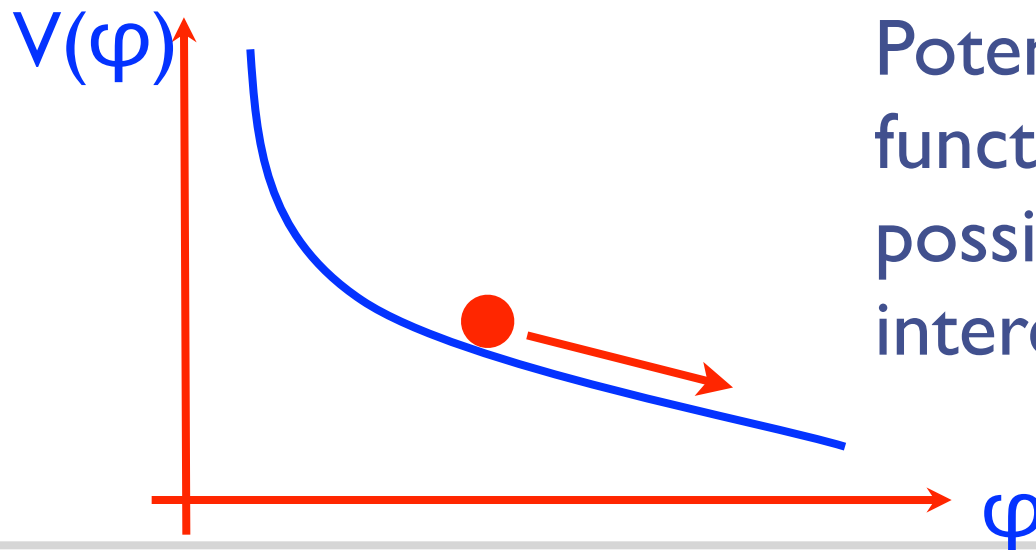
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Potential determined by the function $f(R)$. Opens up the possibility of cosmologically interesting evolution.



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BUT: Disastrous disagreement with solar system constraints unless chameleon mechanism works - strongly restricts models!



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- May exist new self-accelerating solution
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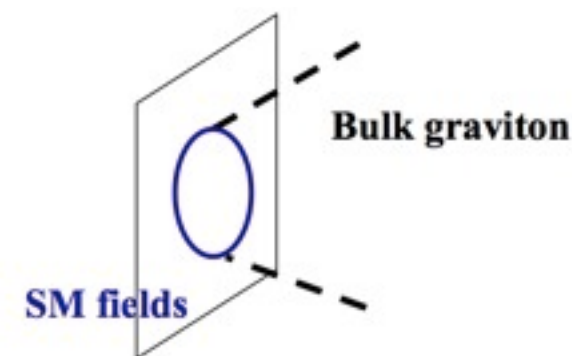
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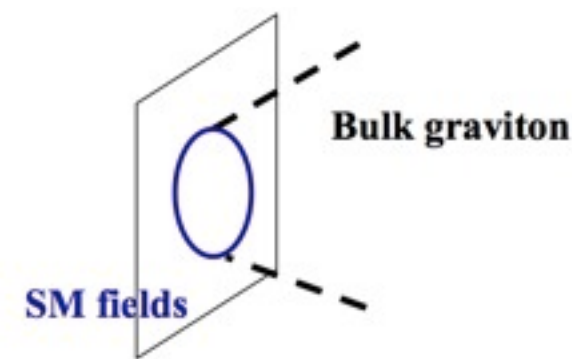
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Old example: DGP model. - Can get some degravitation, and some acceleration. But comes with some problems

[Dvali, Gabadadze & Porrati]

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Now proven to be ghost free, and investigations of the resulting cosmology - acceleration, degravitation, ... are underway, both as a gravity theory and as ...

[Hassan & Rosen(2011)]



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In a limit yields novel and fascinating 4d EFT that many of us have been studying. Symmetry: $\pi(x) \rightarrow \pi(x) + c + b_\mu x^\mu$

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- So can study non-linear classical solutions.



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There is a separation of scales

- Allows for classical field configurations with order one nonlinearities, but quantum effects under control.
- So can study non-linear classical solutions.
- Some of these very important (Vainshtein screening)



... Galileons

In a limit yields novel and fascinating 4d EFT that many of us have been studying. Symmetry: $\pi(x) \rightarrow \pi(x) + c + b_\mu x^\mu$

Relevant field referred to as the *Galileon*

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Amazingly terms of galilean form are nonrenormalized.

Possibly useful for particle physics & cosmology. We'll see.

[Luty, Porrati, Rattazzi (2003); Nicolis, Rattazzi (2004); Hinterbichler, MT, Wesley (2012)]



Prospects



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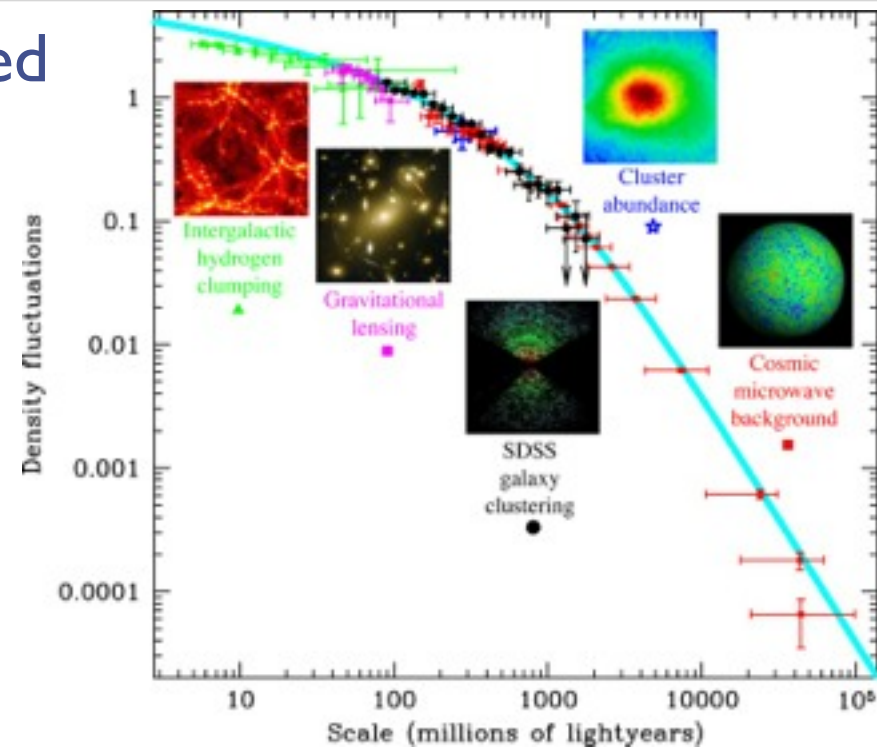
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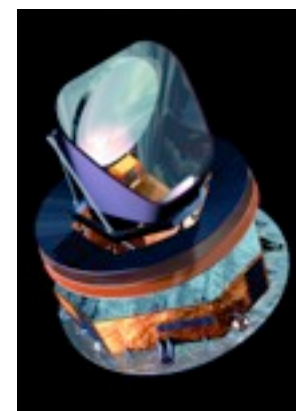
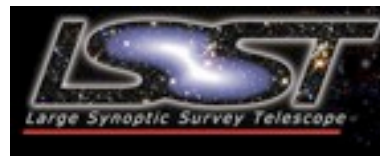
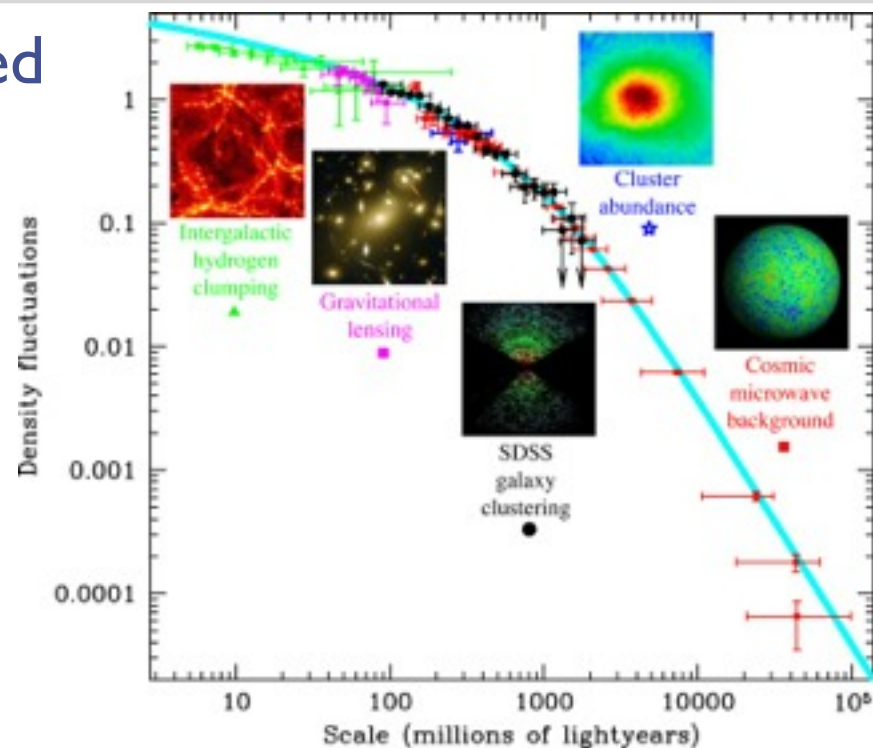




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[Lue, Scoccimarro & Starkman (2004); Bertschinger (2006); Bean, Bernat, Pogorian, Silvestri & MT (2006); Hu & Sawicki (2007); Jain & Zhang (2007); Zhang, Liguori, Bean, & Dodelson (2007,8); Reyes et al. (2010)]



Confronting Data



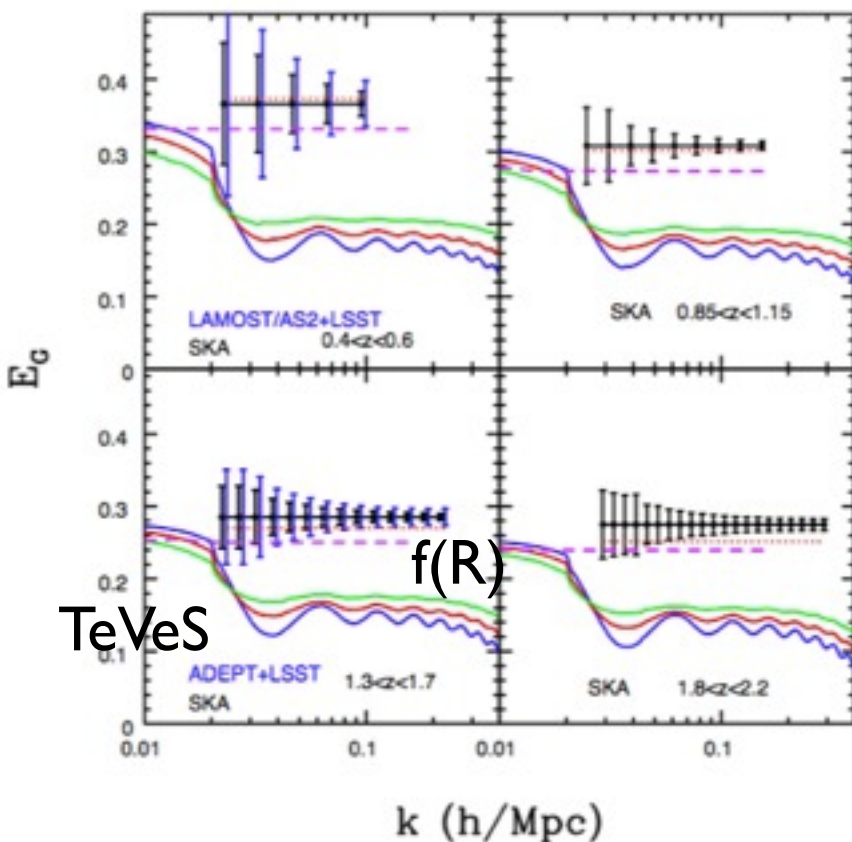
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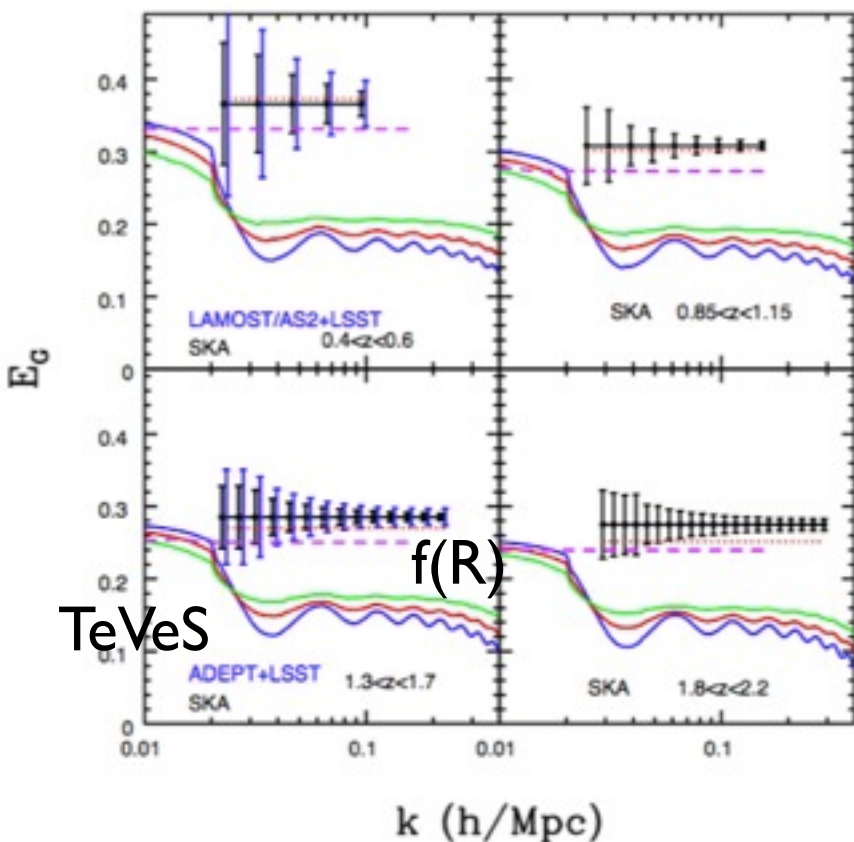
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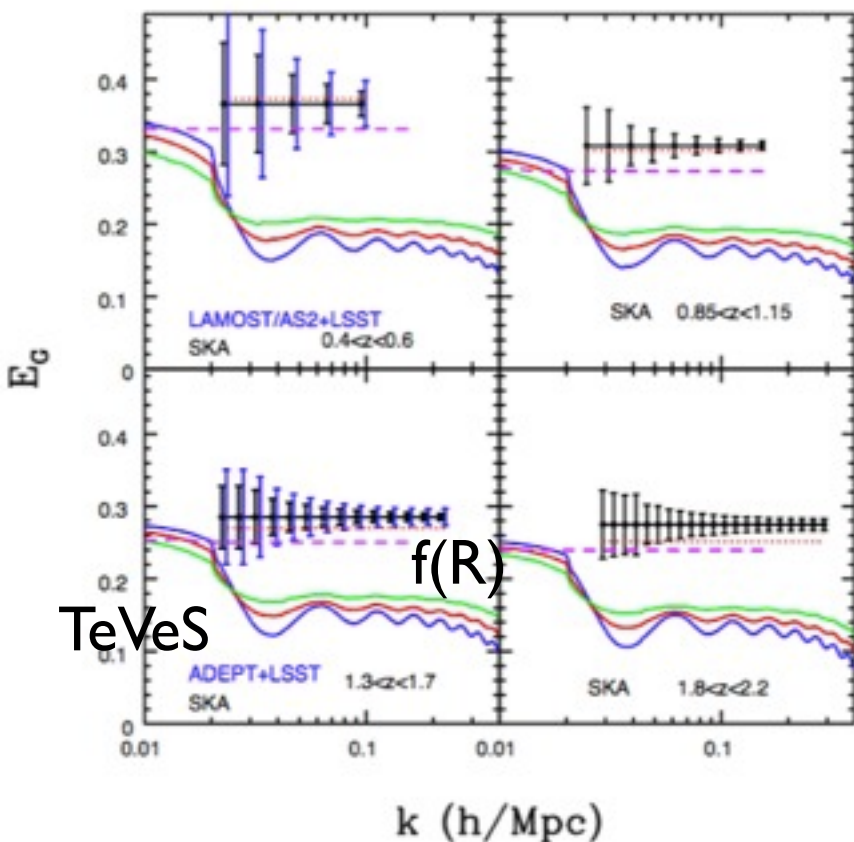


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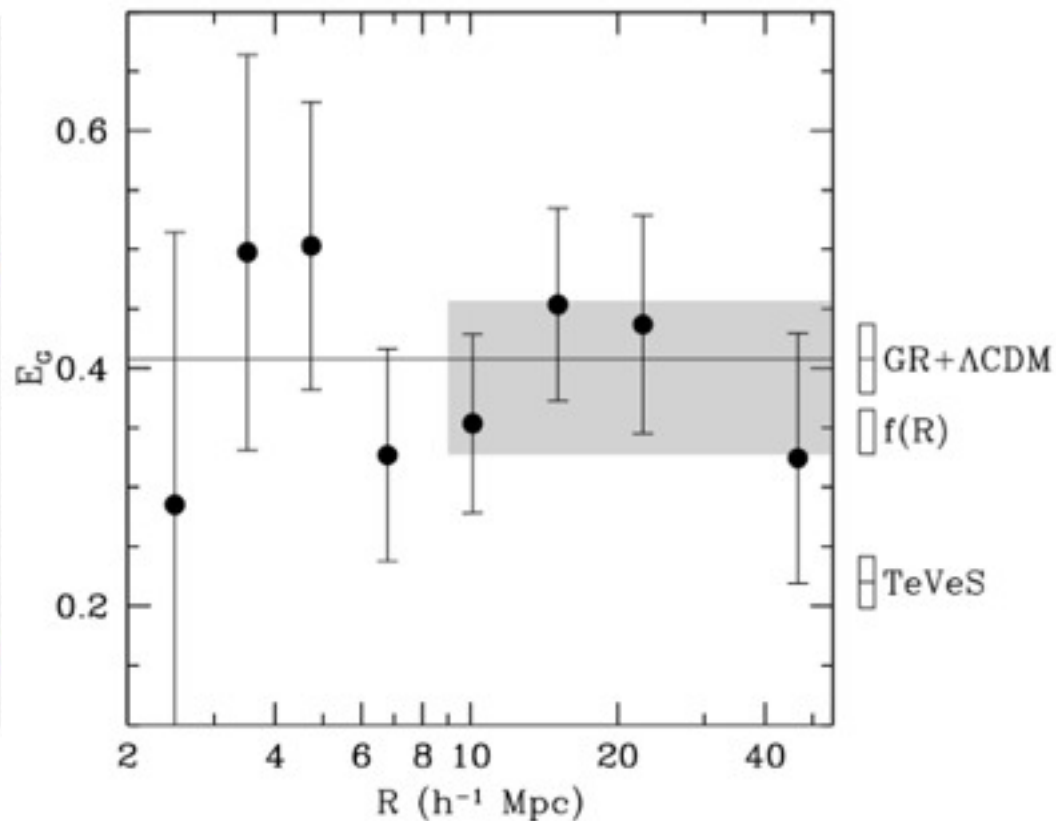
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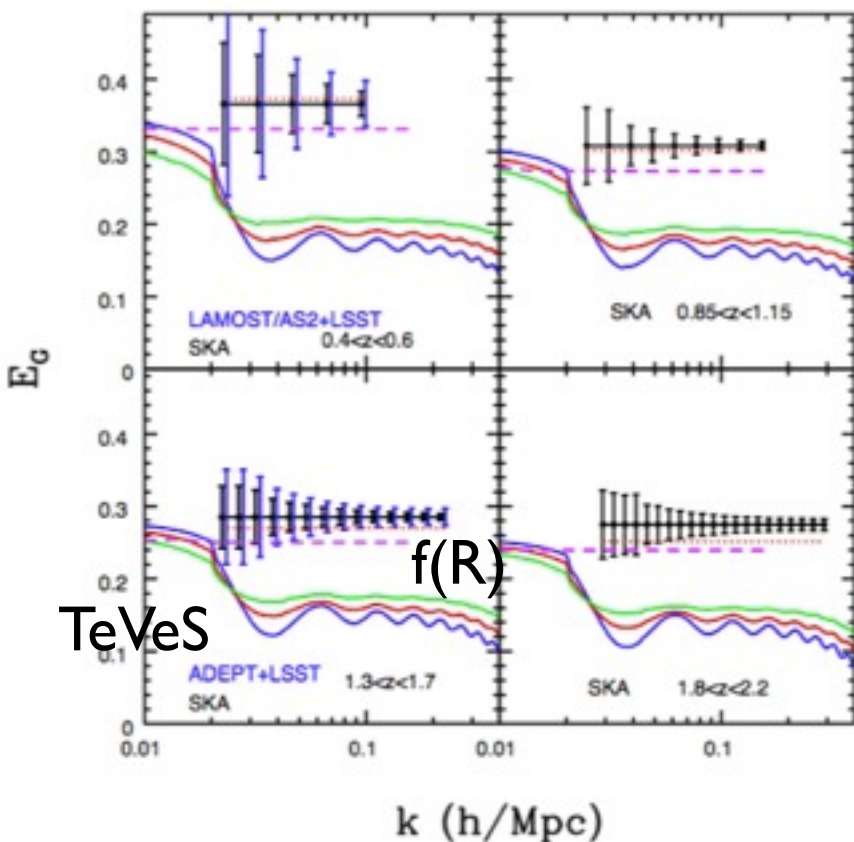


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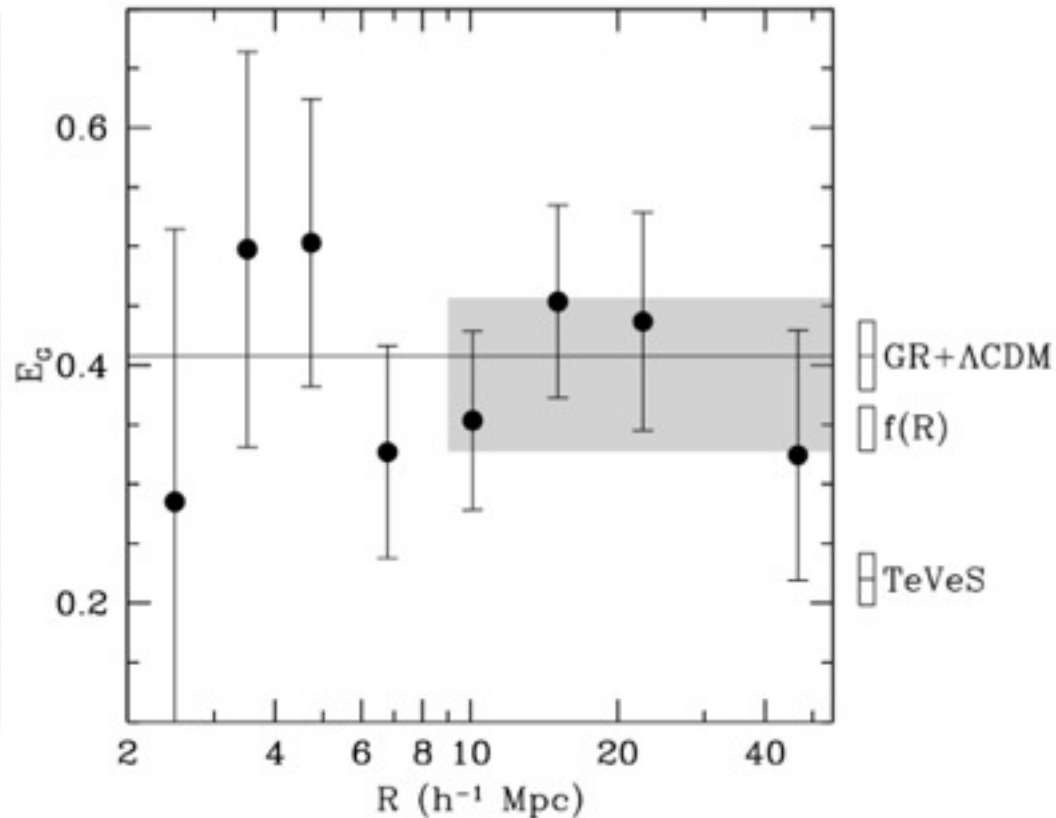
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(GR: $E_G = 0.4$. Data: $E_G = 0.39 \pm 0.96$). Expect a lot more of this from DES, LSST, ...



Things Could be More Complex



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J. Feng & M. Trodden, Scientific American, November 2010.



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Maybe dark matter and dark energy are part of a rich and complicated dark side of the universe, with its own interactions [e.g. see N.Weiner's plenary & R. Foot's parallel talk]



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This has been quite interesting recently. In some ways this can be tested through the structure formation measurements I just mentioned. But there are other ways.



J. Feng & M. Trodden, Scientific American, November 2010.



e.g. Equivalence Principle Tests ...

Can we test whether dark matter and regular matter feel the same long-range forces. Can we improve on Galileo?



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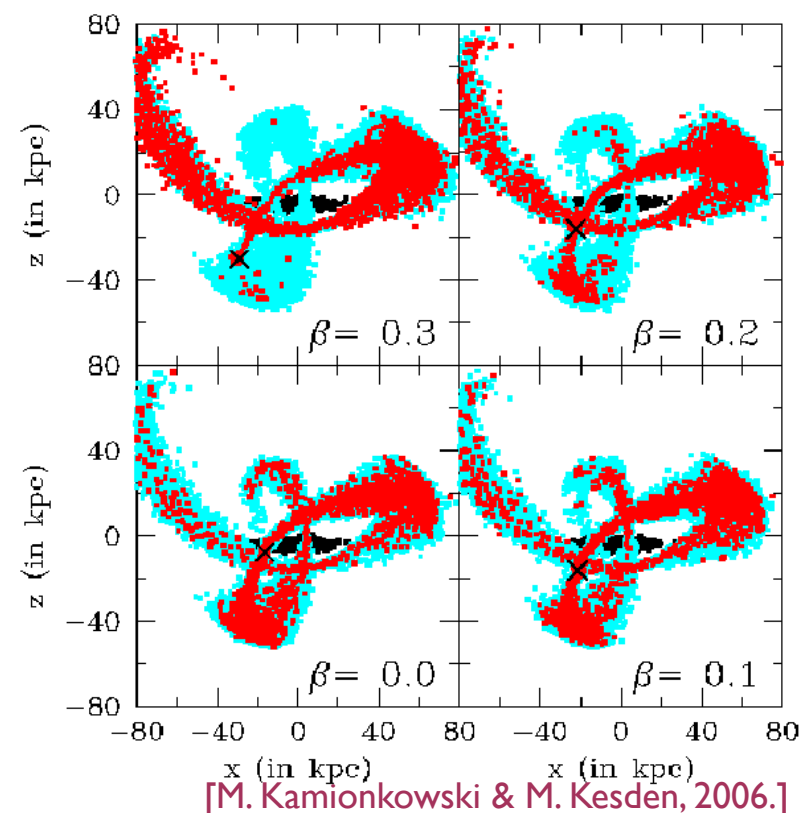
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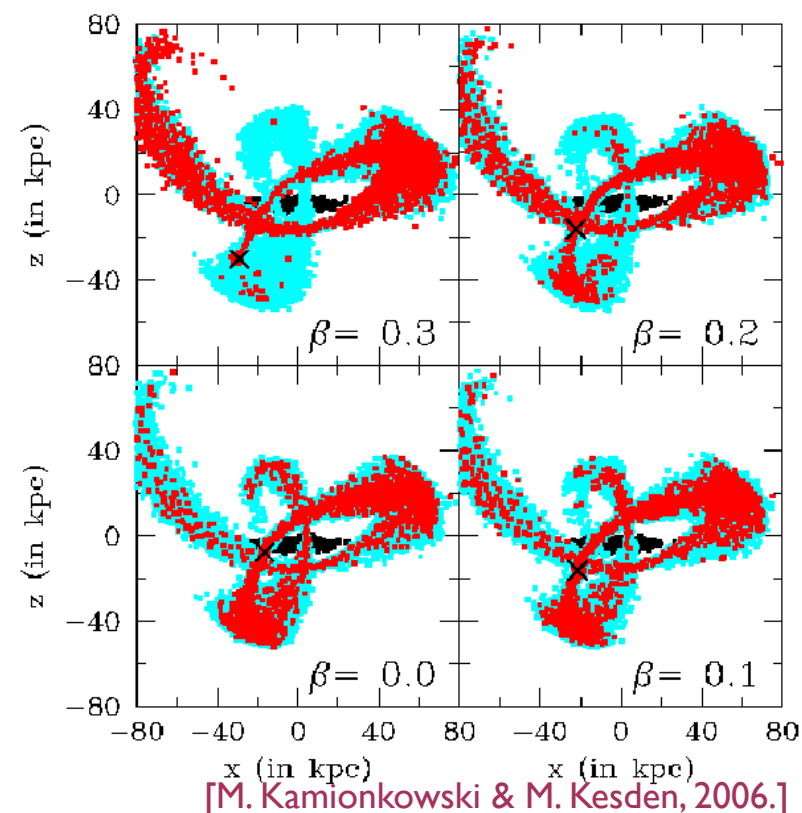


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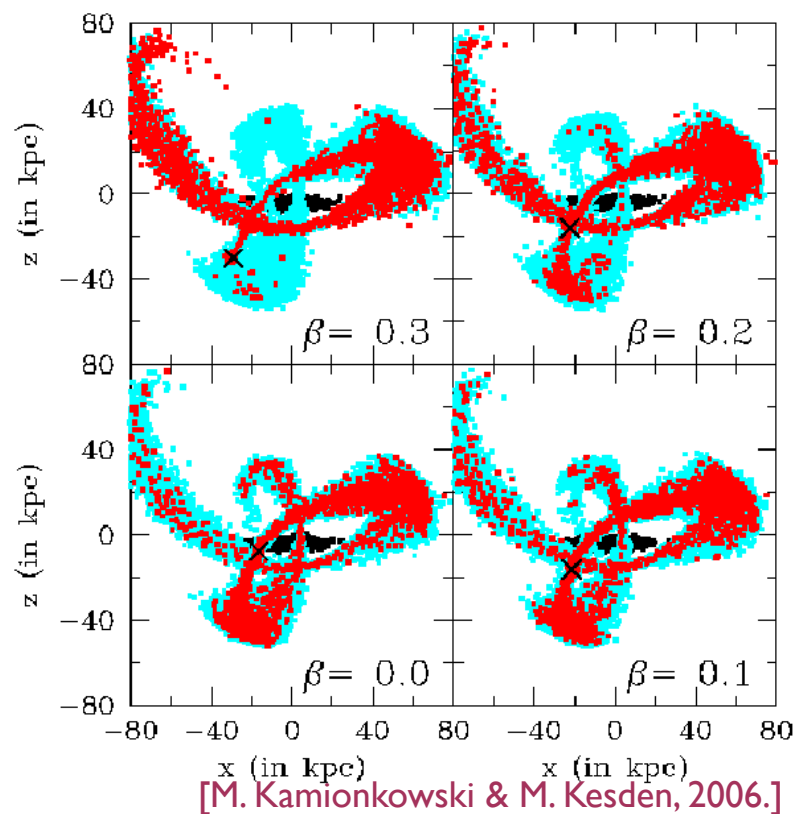
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Another example of using astrophysics to probe the fundamental laws of nature



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Clearly, there is room for contributions to this field from many different aspects of the experimental and observational program.



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Thank You!



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Thus, if we canonically normalize the kinetic term of the perturbations, we raise the effective strong coupling scale, and, more importantly, heavily suppress the coupling to matter!