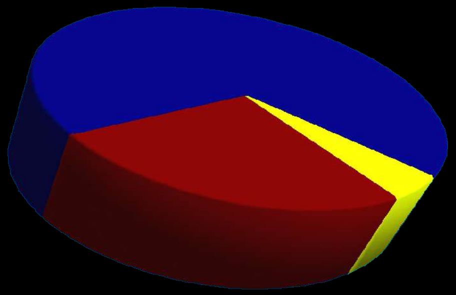
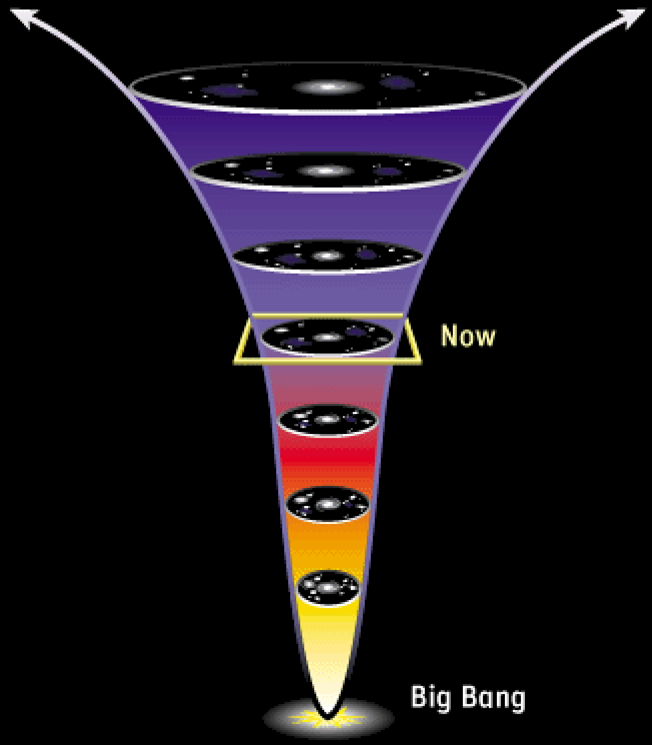


Dark Energy, or Worse?

Sean Carroll

http://pancake.uchicago.edu/~carroll/



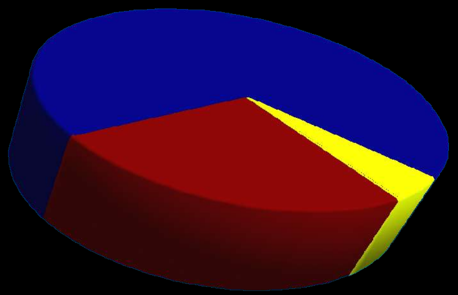
The universe is accelerating.

Time to get serious.

What we think we know:

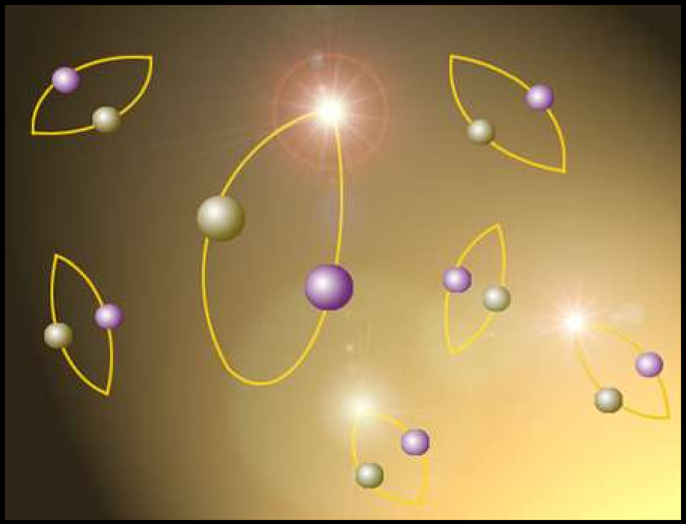
- Most "matter" is non-baryonic and dark.
- Total amount of matter is sub-critical: $\Omega_M \sim 0.3$.
- But spatial curvature is negligible.
- The universe is accelerating.
- A good fit:

5% ordinary matter
25% non-baryonic cold dark matter
70% smooth, persistent dark energy



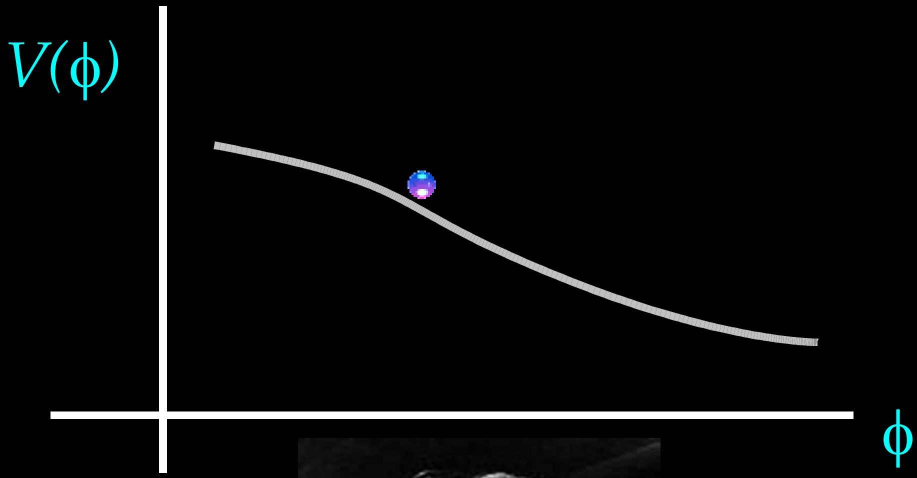
Leading ideas

- Vacuum energy
  (cosmological constant)



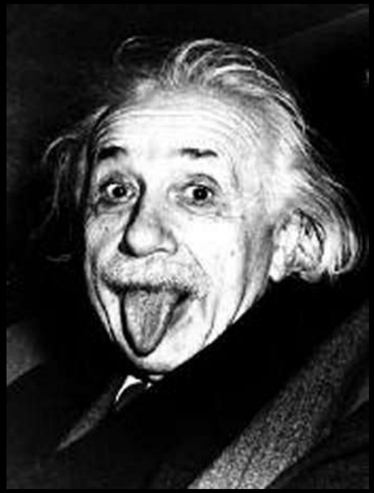
- Dynamical dark energy
  (e.g. quintessence)

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



- Modified gravity

$$H^2 = f(\rho)$$



Vacuum Energy (Cosmological Constant)

For $\rho_{vac} = E_{vac}{}^4$, we expect $E_{vac} = E_{pl}$, but find $E_{vac} = 10^{-30} E_{pl}$.

Nobody knows why.

Possibilities:

- Dilution: $E_{vac} = \gamma * E_{pl}$, with $\gamma = 10^{-30}$.
- Elimination and correction: $E_{vac} = 0 * E_{pl} + E_{vac}$
- Cancellation: $E_{vac} = (E_{pl} + E_{vac}) - E_{pl}$

The (hypothetical) supersymmetry scale is the geometric mean of the vacuum scale and the Planck scale. Coincidence?

The Gravitational Physics Data Book:

Newton's constant:

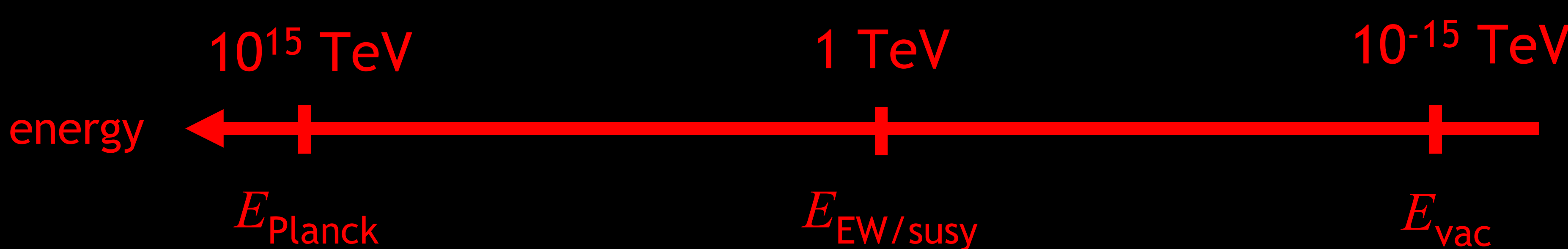
G = (6.67 $\pm$ 0.01) x 10^{-8} cm^3 g^{-1} sec^{-2}

Cosmological constant:

Λ = (1.2 $\pm$ 0.2) x 10^{-55} cm^{-2}

Equivalently ($\hbar = c = 1$),

$E_{Planck} = 10^{18}$ GeV , $E_{vac} = 10^{-12}$ GeV .



The multiverse and environmental selection

Imagine that:

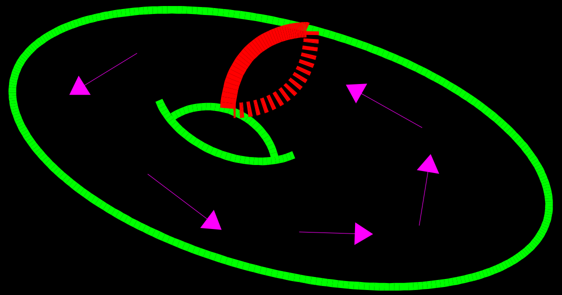
- There are many disconnected "universes."
- They each have a different vacuum energy.

Then we could never observe regions where the vacuum energy is large enough to rip us to shreds – the ultimate selection effect.

In other words, the cosmological constant may be an environmental variable, like the temperature of our atmosphere, rather than a fundamental parameter.

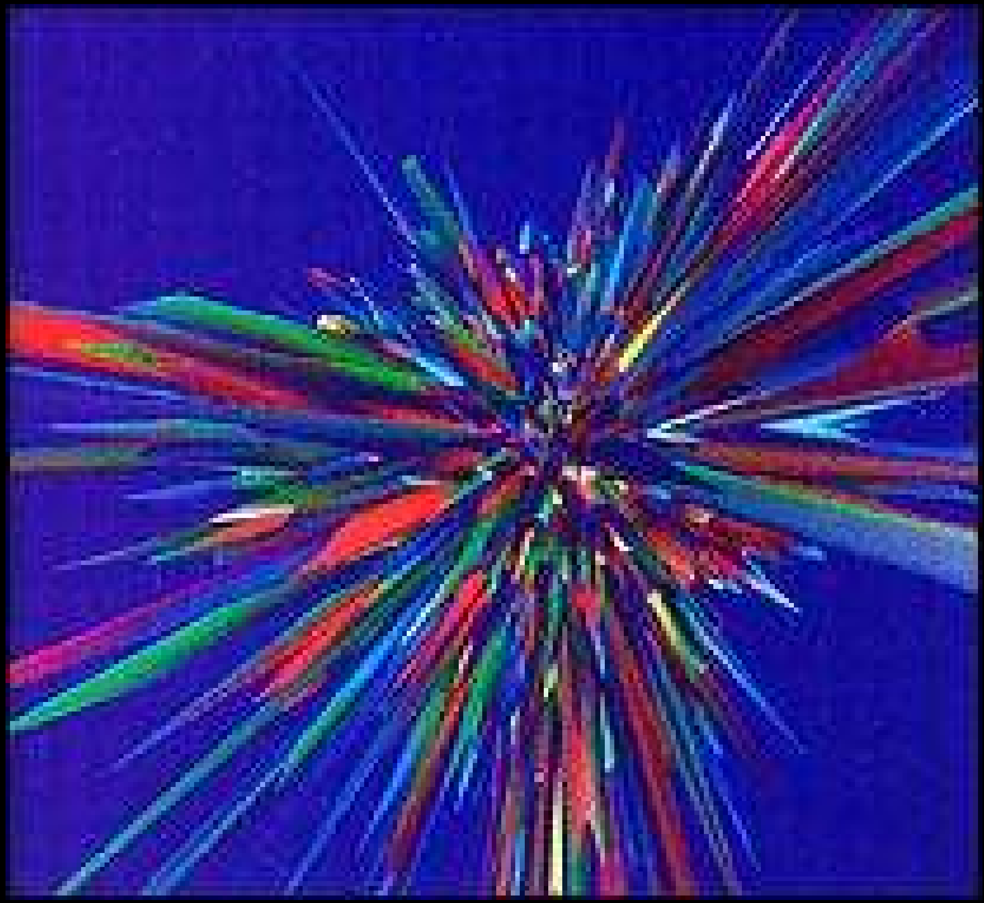
So <u>are</u> there really many domains with different properties?

String theory can have a landscape of many(10^{500}?) compactifications with branes and fluxes, each giving rise to different effective 4-dimensional physics.



$$E_{vac} = (E_{pl} + E_{vac}) - E_{pl}$$

[Feng et al.; Bousso & Polchinski; Kachru et al.; Douglas et al. but: Banks et al., Robbins & Sethi]



Eternal inflation can take small patches in different vacua and expand them to universe-sized regions. Our observable "universe" is just an infinitesimal piece of the big picture.

[Vilenkin; Linde]

Widely-held but untrue beliefs:

- Appealing to the multiverse to explain the value of the vacuum energy is unscientific, or religious, or a betrayal of the Enlightenment project of understanding nature using evidence and reason.
- S.N.A.P.: “environmental selection of coupling constants within a multiverse can't be responsible for anything, because I don't like it.”
- The multiverse already provides a compelling explanation for the value of the vacuum energy. Just like Weinberg predicted.

If you want to make predictions, counting the number of vacua with certain properties is not enough!

The multiversal Drake equation:

$$\begin{matrix}\text{Number of}\\ \text{observers}\\ \text{measuring } X\end{matrix} = \sum_{\text{vacua } n} \begin{pmatrix}\text{Does vacuum}\\ n \text{ have}\\ \text{property } X?\end{pmatrix} \begin{pmatrix}\text{Volume of}\\ \text{space in}\\ \text{vacuum } n\end{pmatrix} \begin{pmatrix}\text{Density of}\\ \text{observers in}\\ \text{vacuum } n\end{pmatrix}$$

String theory counts this | Cosmology determines this! | (this is just hopeless)

Even if there is only 1 vacuum with property X and 10^{500} without, if the rate of inflation that leads to that vacuum is just a little bit higher, its volume will quickly dominate.

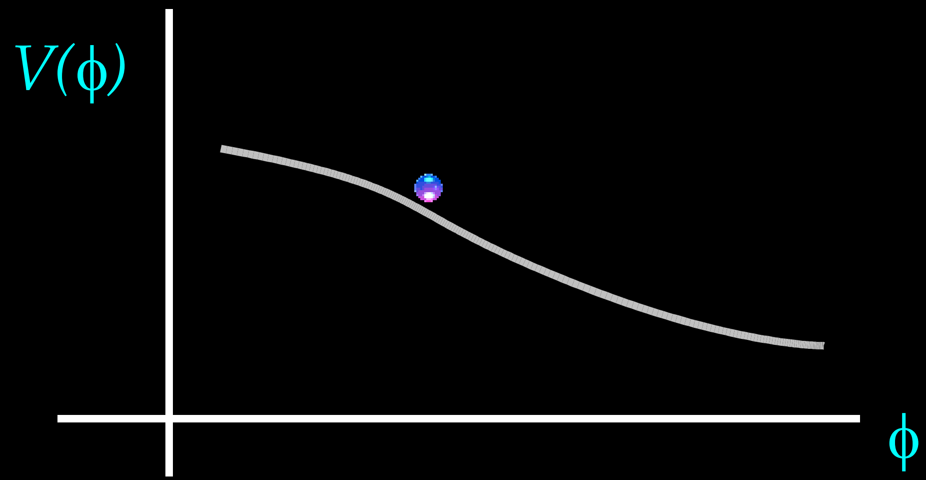
As of right now: environmental selection has not explained the observed value of the cosmological constant.

Is the dark energy a slowly-varying dynamical component?

e.g. a slowly-rolling scalar field: "quintessence"

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

kinetic energy   potential energy



[Wetterich; Peebles & Ratra; Zlatev, Wang & Steinhardt; etc.]

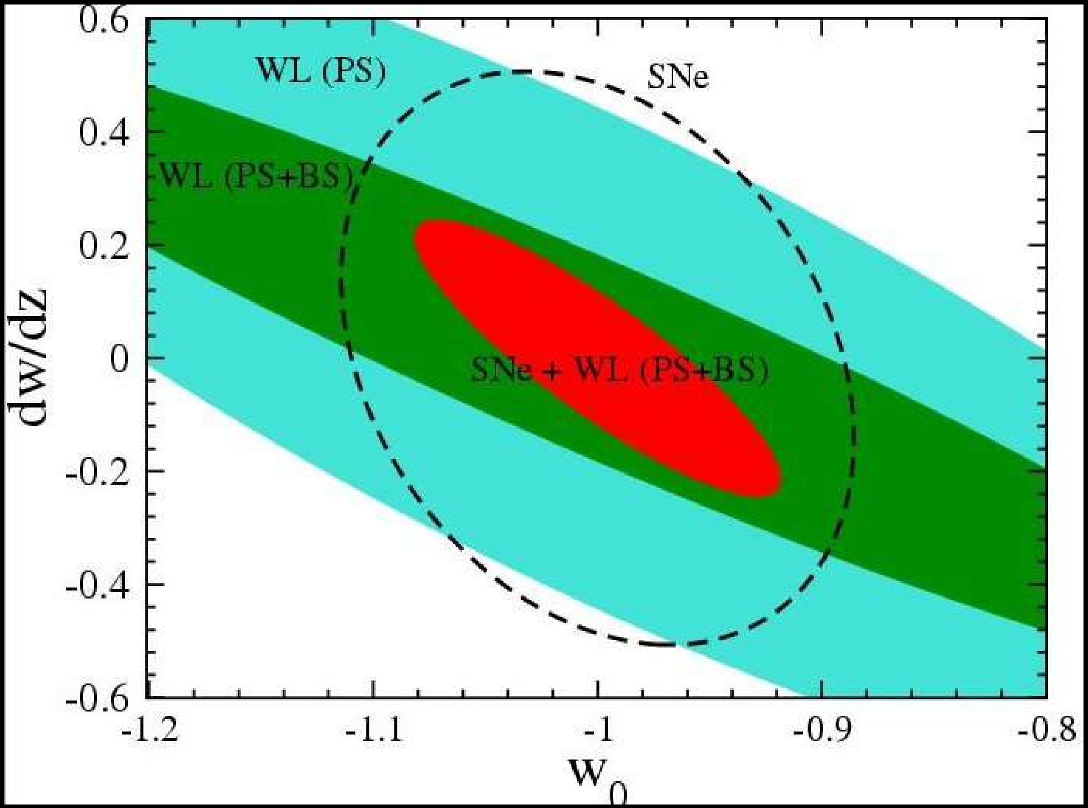
- This is an observationally interesting possibility, and at least holds the possibility of a dynamical explanation of the coincidence scandal.

- But it is inevitably finely-tuned: requires a scalar-field mass of $m_\phi < 10^{-33}$ eV, and very small couplings to matter.

Testing models of dynamical dark energy

Characterize using an effective equation of state relating pressure to energy density:

$$p = w\rho \longrightarrow \rho \propto a^{-3(1+w)}$$



For matter, $w = 0$; for actual vacuum energy, $w = -1$.

More than anything else, we need to know whether $w = -1$ (and $w' = 0$) or not.

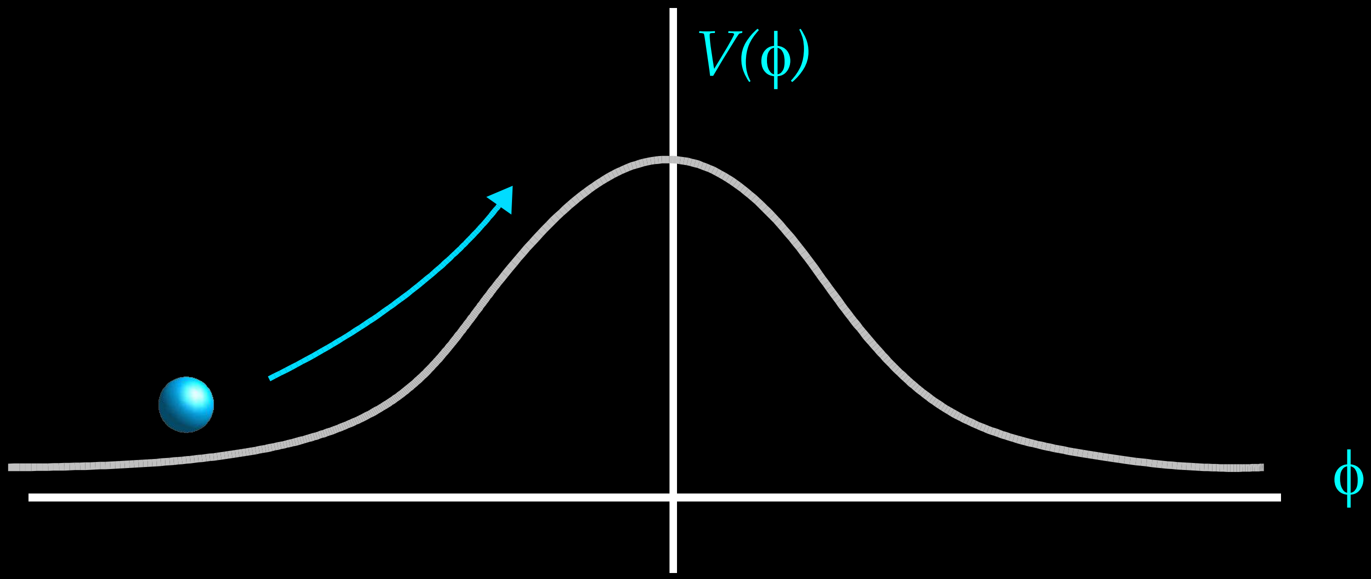
projections for SNAP

[Huterer]

If $w = p/\rho$ is less than -1, it means that the dark energy density is increasing with time – seemingly crazy.

But: we can invent a field theory with $w < -1$: a negative-kinetic-energy, or “phantom,” field. The energy density is

$$\rho_\phi = -\frac{1}{2}\dot{\phi}^2 + V(\phi)$$



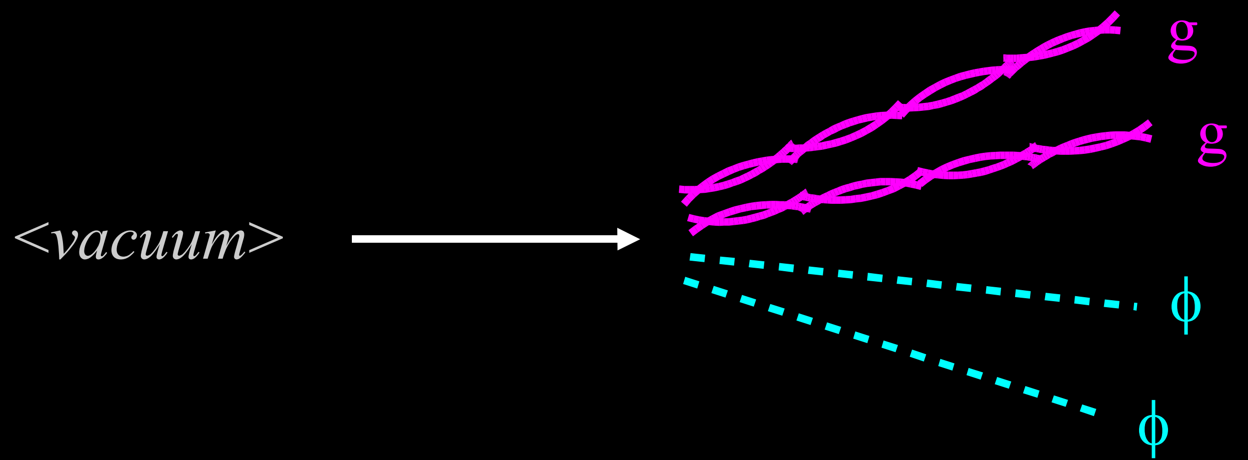
[Caldwell]

Phantom fields roll up the potential, increasing energy.

Problem: the vacuum is unstable to decay.

If a scalar field has negative kinetic energy, its particle excitations have negative energy. So empty space can decay into positive-energy gravitons and negative-energy ϕ particles.

[Carroll, Hoffman & Trodden; Carroll, De Felice & Trodden]

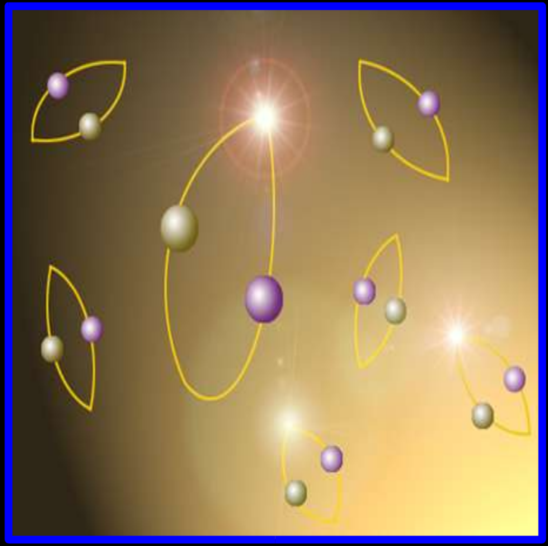


Can be avoided if we put a cutoff on the theory.

[Arkani-Hamed, Cheng, Luty & Mukohyama]

Theorists need to be careful, but <u>observers should keep an open mind</u>. Nobody ever measures w, really. We only measure the behavior of the scale factor.

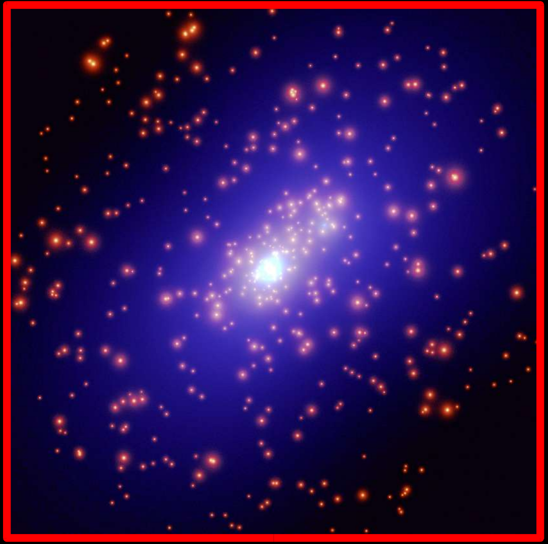
An introverted dark sector?



dark energy

ordinary matter

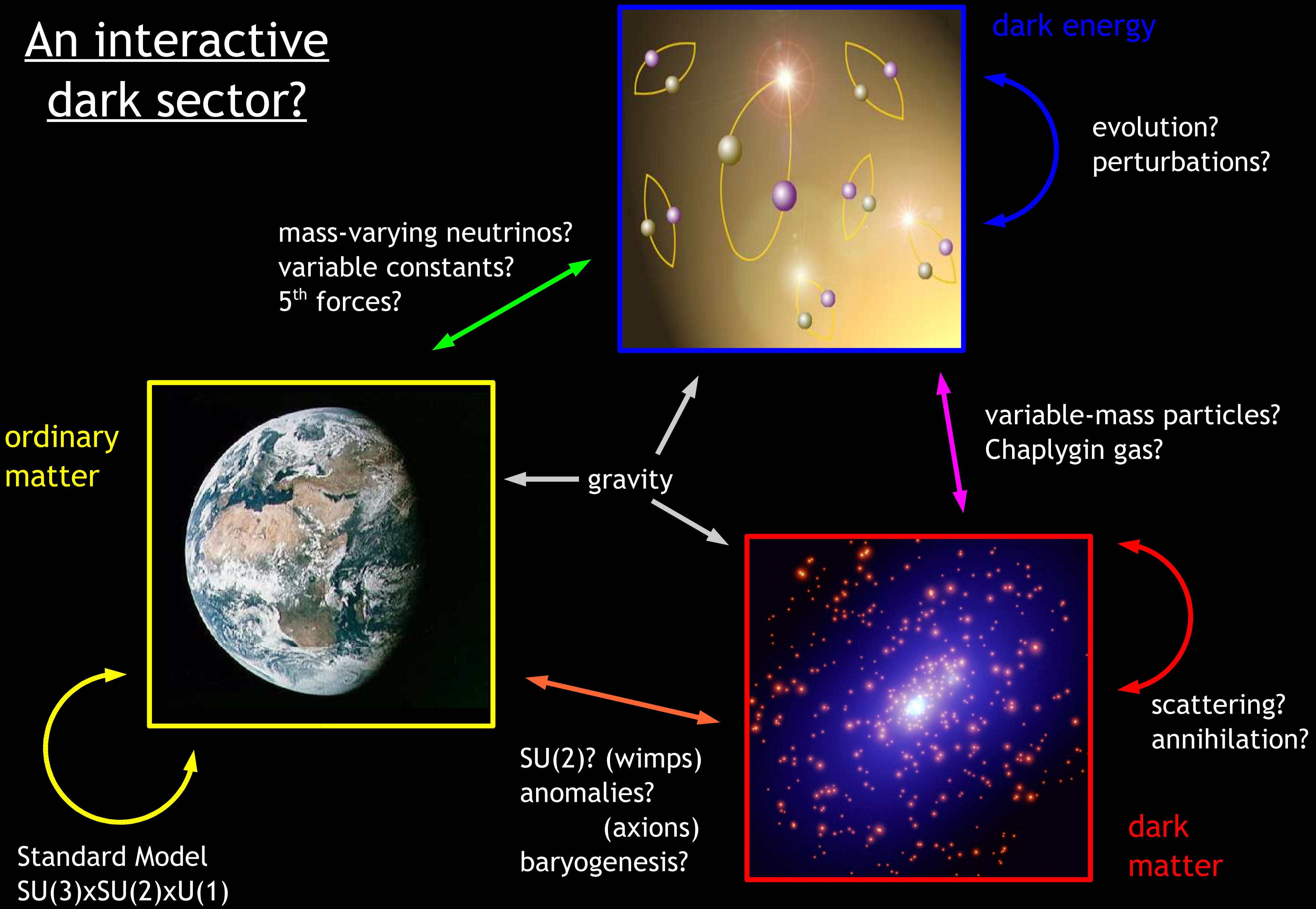
gravity



dark matter

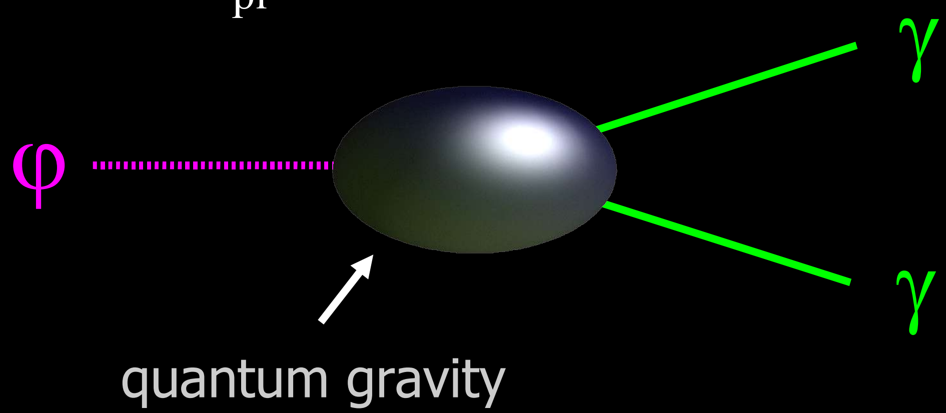
Standard Model
SU(3)xSU(2)xU(1)

An interactive dark sector?



Maybe we can detect dark energy directly?

Dynamical dark energy has no right to be completely "dark"; even if it only directly couples to gravity, there will be indirect couplings to all standard-model fields, proportional to $1/M_{\rm pl}$.



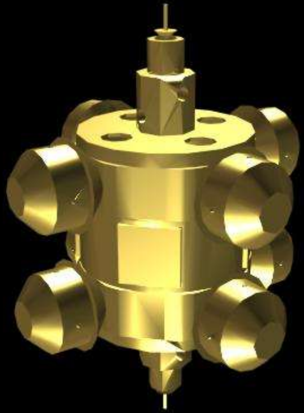
These interactions are constrained by 5th-force and time-dependent-constant measurements.

Even if the couplings are as small as naturalness allows, they are still ruled out! Need suppression by an extra 10^5. Perhaps a new symmetry?

[Carroll; Dvali & Zaldarriaga]

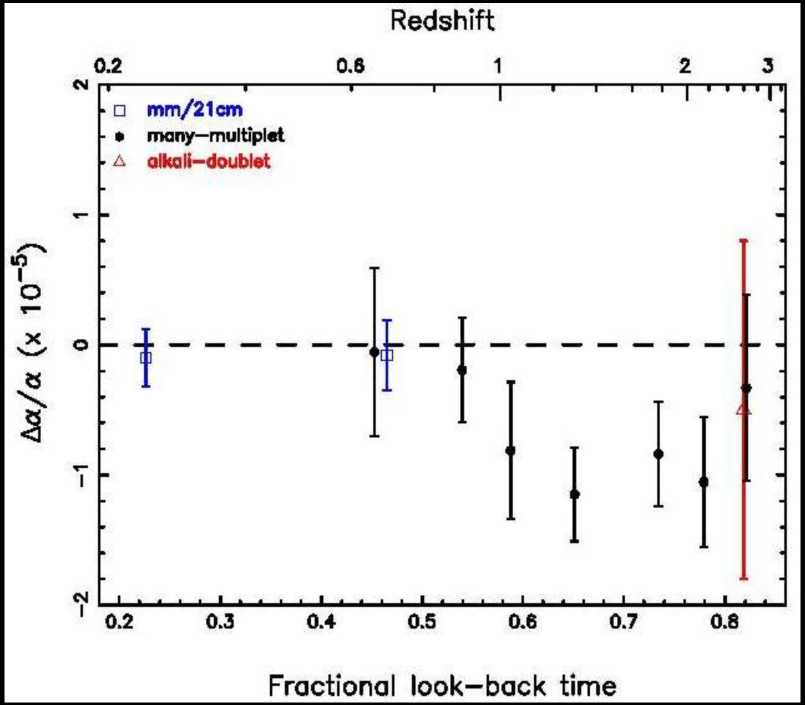
Direct dark energy detection search strategies:

- 5^{th} forces.



[Adelberger et al.]

- Time-dependent "constants of nature" (e.g., α).



[Webb et al.]

- Neutrino experiments (MaVaNs).

[Fardon, Nelson & Weiner]

[MiniBooNE]

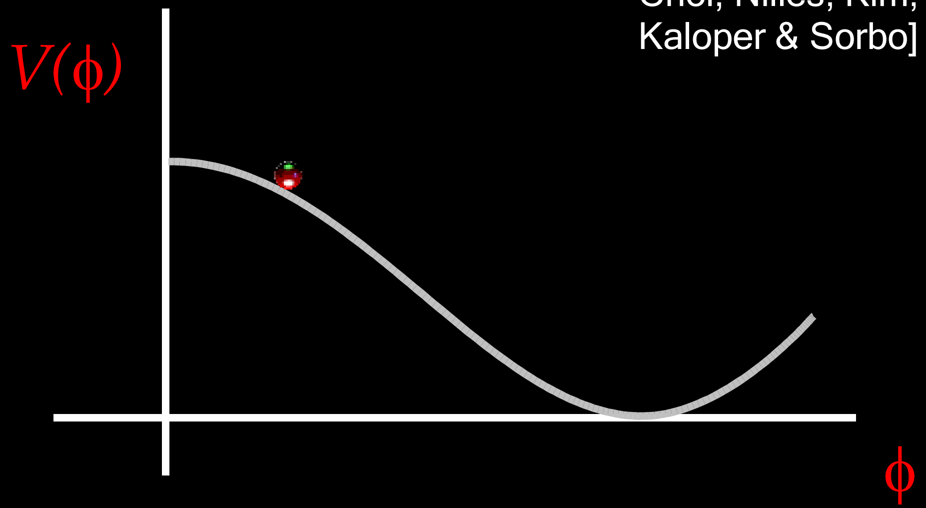
Sensible particle physics models?

Pseudo-Goldstone bosons: approx symmetry $\phi \rightarrow \phi + const.$

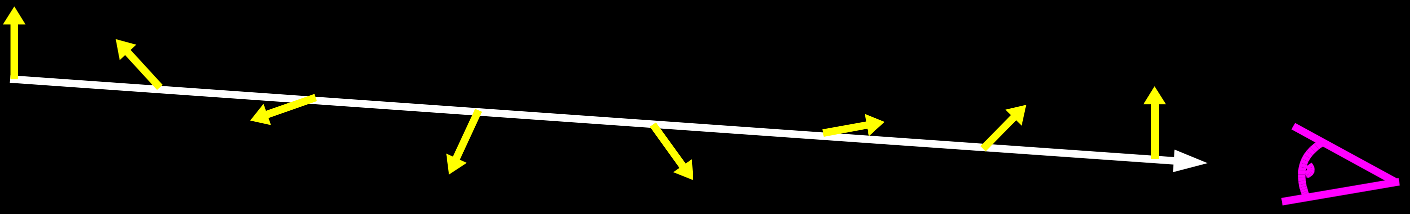
Naturally small masses; naturally small couplings.

[Hill, Freiman, et al; Choi; Nilles; Kim; Kaloper & Sorbo]

$$V(\phi) = \mu^4[1+\cos(\phi)]$$



Possible signature: cosmological birefringence.



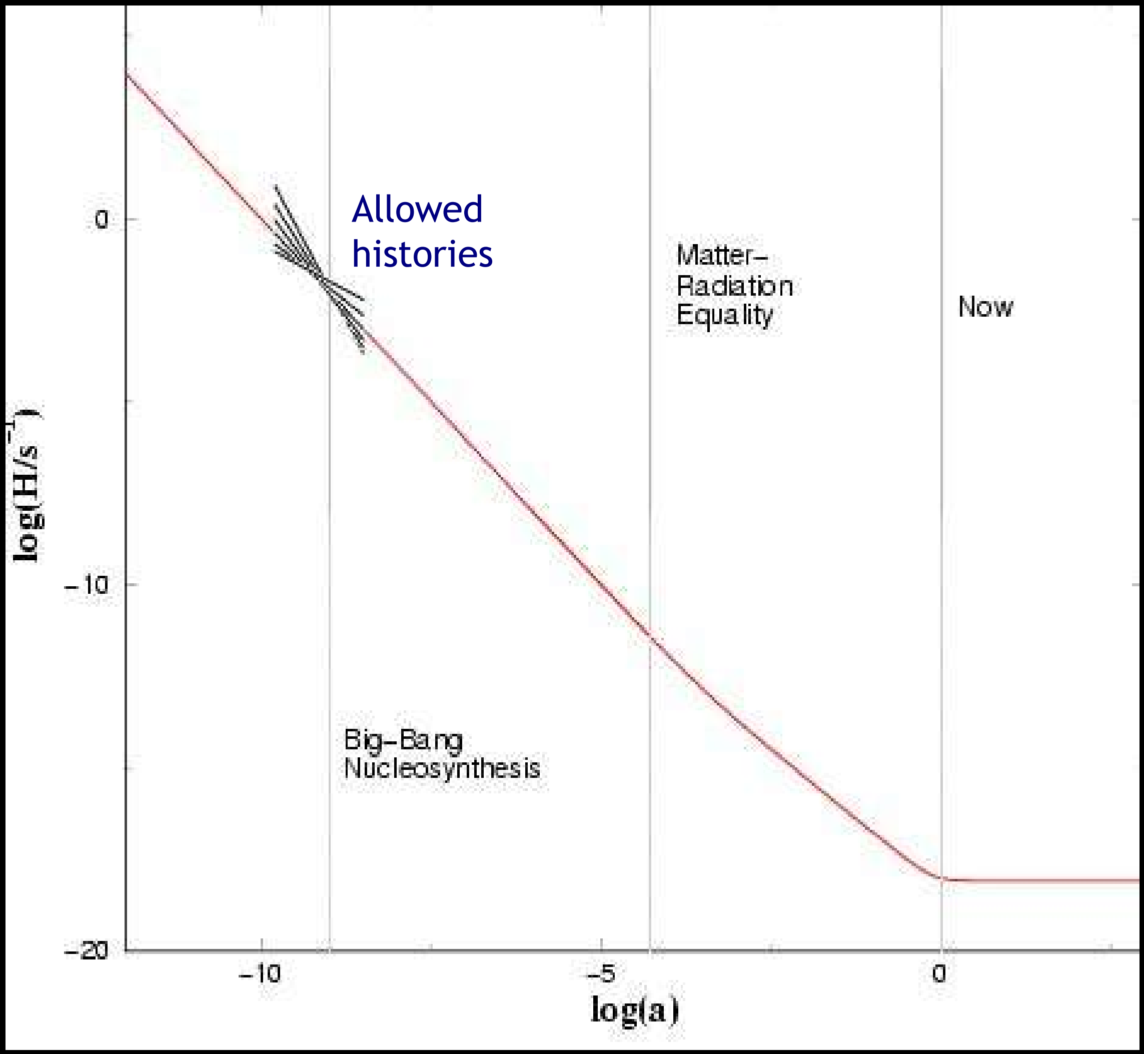
[Carroll; Lue, Wang & Kamionkowski]

Was Einstein wrong?

Can we change the Friedmann equation from $H^2 = 8\pi G\rho/3$ to $H^2 = f(\rho)$ to make the universe accelerate?

Big-Bang Nucleosynthesis tests the Friedmann equation as well as the values of G, Ω_b, N_n.

If the Friedmann equation is wrong, it's wrong only at late times/on large length scales; still a coincidence problem!



[Carroll & Kaplinghat]

Aside: Can we do away with dark energy <u>without</u> modifying gravity?

Idea: take the perturbed Einstein equation

$$\bar{G}_{00} + \delta G_{00} = 8\pi G \left(T_{00} + \delta T_{00} \right)$$

and treat the averaged 00 component of the Einstein tensor as an effective energy density:

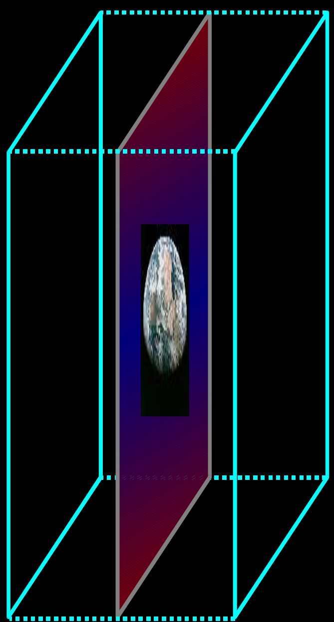
$$H^2 = \frac{8\pi G}{3} \left(\rho + \delta\rho \right) + \frac{1}{3} \left\langle \delta G_{00} \right\rangle$$

Calculate to second order and hope that it acts like dark energy (both in magnitude and evolution). Perhaps a bit optimistic.

[Kolb, Matarrese & Riotto]

Can branes make the universe accelerate?

Dvali, Gabadadze, & Porrati (DGP): a flat infinite extra dimension, with gravity weaker on the brane; 5-d kicks in at large distances.



$$S = M^2 \int R_4 d^4x + \frac{M^2}{r_c} \int R_5 d^5x$$

4-d gravity term with conventional Planck scale

5-d gravity term suppressed by $r_c \sim H_0^{-1}$

Difficult to analyze, but potentially observable new phenomena, both in cosmology and in the Solar System. (E.g., via lunar radar ranging.)

[Dvali, Gabadadze & Porrati 2000; Deffayet 2000]

Self-acceleration in DGP cosmology

Imagine that somehow the cosmological constant is set to zero in both brane and bulk. The DGP version of the Friedmann equation is then

$$H^2 - \frac{H}{r_c} = \frac{8\pi G}{3}\rho$$

This exhibits self-acceleration: for $\rho = 0$, there is a de Sitter solution with $H = 1/r_c$ = constant.

Under investigation: perturbation evolution on large scales. Issues include strong coupling, ghost modes, treatment of off-brane fluctuations.

[Deffayet; Lue & Starkman; Song; Ishak, Upadhye & Spergel; Sawicki & Carroll; Koyama & Maartens]

Can we modify gravity purely in four dimensions?

Simplest possibility: replace

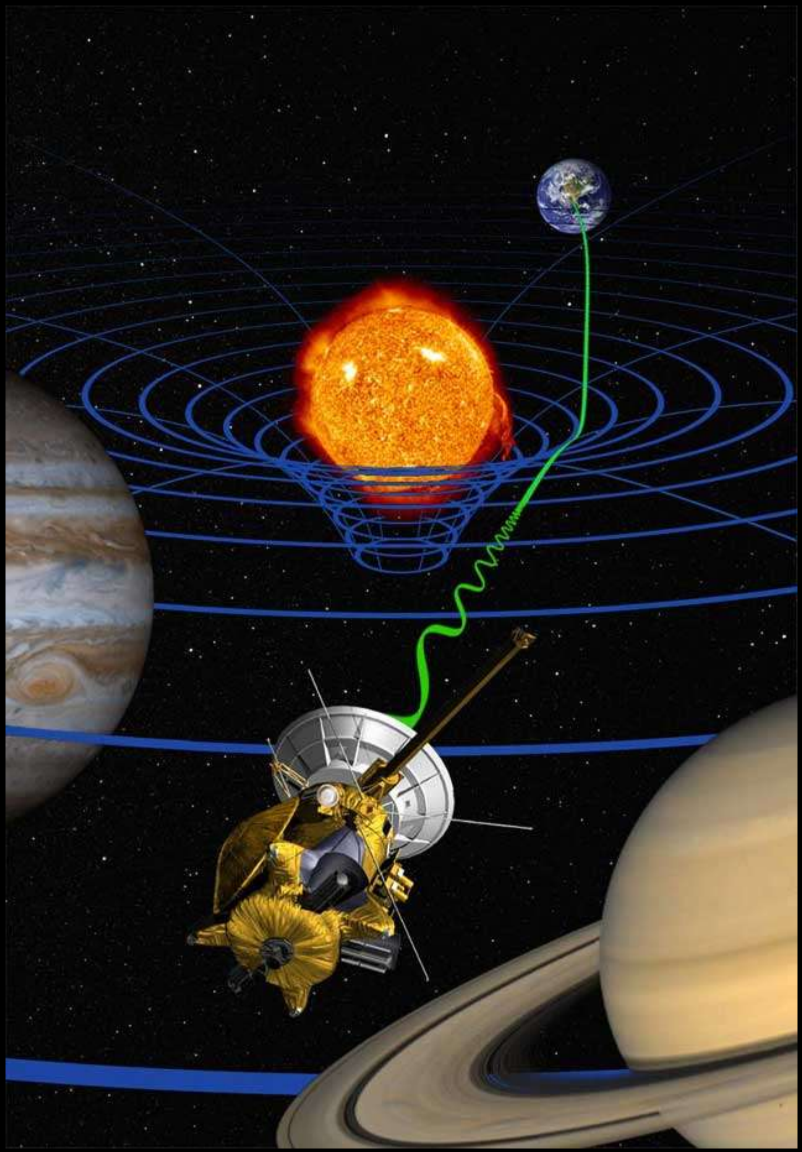
$$S = \int R\, d^4x$$

with

$$S = \int \left(R - \frac{1}{R} \right) d^4x$$

But this model is secretly a scalar-tensor theory in disguise. The metric around the Sun is not precisely that of GR.

Upshot: ruled out by solar-system tests of gravity.



[Carroll, Duvvuri, Trodden & Turner 2003; Chiba 2003]

This is a generic problem.

- Weak-field GR is a theory of spin-2 gravitons.
- Their dynamics is essentially unique; it's hard to modify that behavior without new degrees of freedom.
- Loophole: we want to modify the Friedmann equation, $H^2 = (8\pi G/3)\rho$. That has nothing to do with gravitons; it's a constraint, fixing the expansion rate in terms of ρ.
- In principle, we could change Einstein's equation from $G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$ to $G_{\mu\nu} = 8\pi G\, f_{\mu\nu}$, where $f_{\mu\nu}$ is some function of $T_{\mu\nu}$. Can we do it in practice?

Yes we can: "Modified-Source Gravity."

We specify a new function $\psi(T)$ that depends on the trace of the energy-momentum tensor, $T = -\rho + 3p$, where ρ is the energy density and p is the pressure.

The new field equations take the form

$$G_{\mu\nu} = 8\pi G\left(e^{-2\psi} T_{\mu\nu}^{(matter)} + T_{\mu\nu}^{(\psi)}\right)$$

density-dependent rescaling of Newton's constant

"ψ energy-momentum tensor"; determined in terms of $T^{(matter)}$.

Exactly like scalar-tensor theory, but with the scalar determined by the ordinary matter fields.

[Carroll 2005]

Cosmology in modified-source gravity

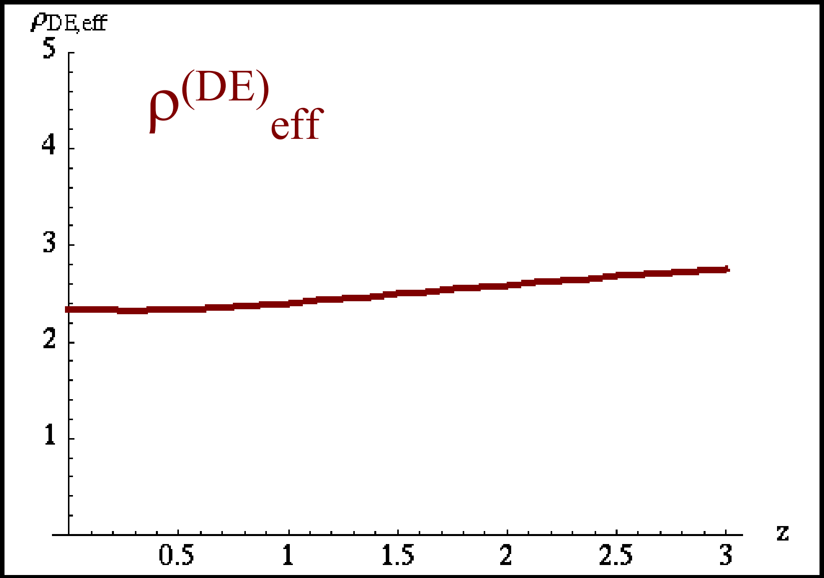
The effective Friedmann equation is

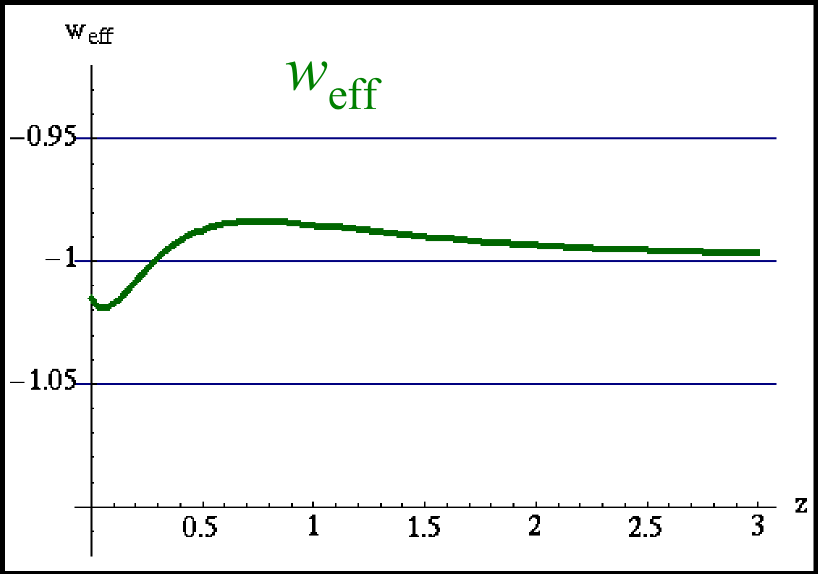
$$H^2 = \frac{8\pi G}{3} e^{-2\psi}\left[1 - 3\rho\left(\frac{d\psi}{d\rho}\right)\right]^{-2}\left[\rho + U(\psi)\right]$$

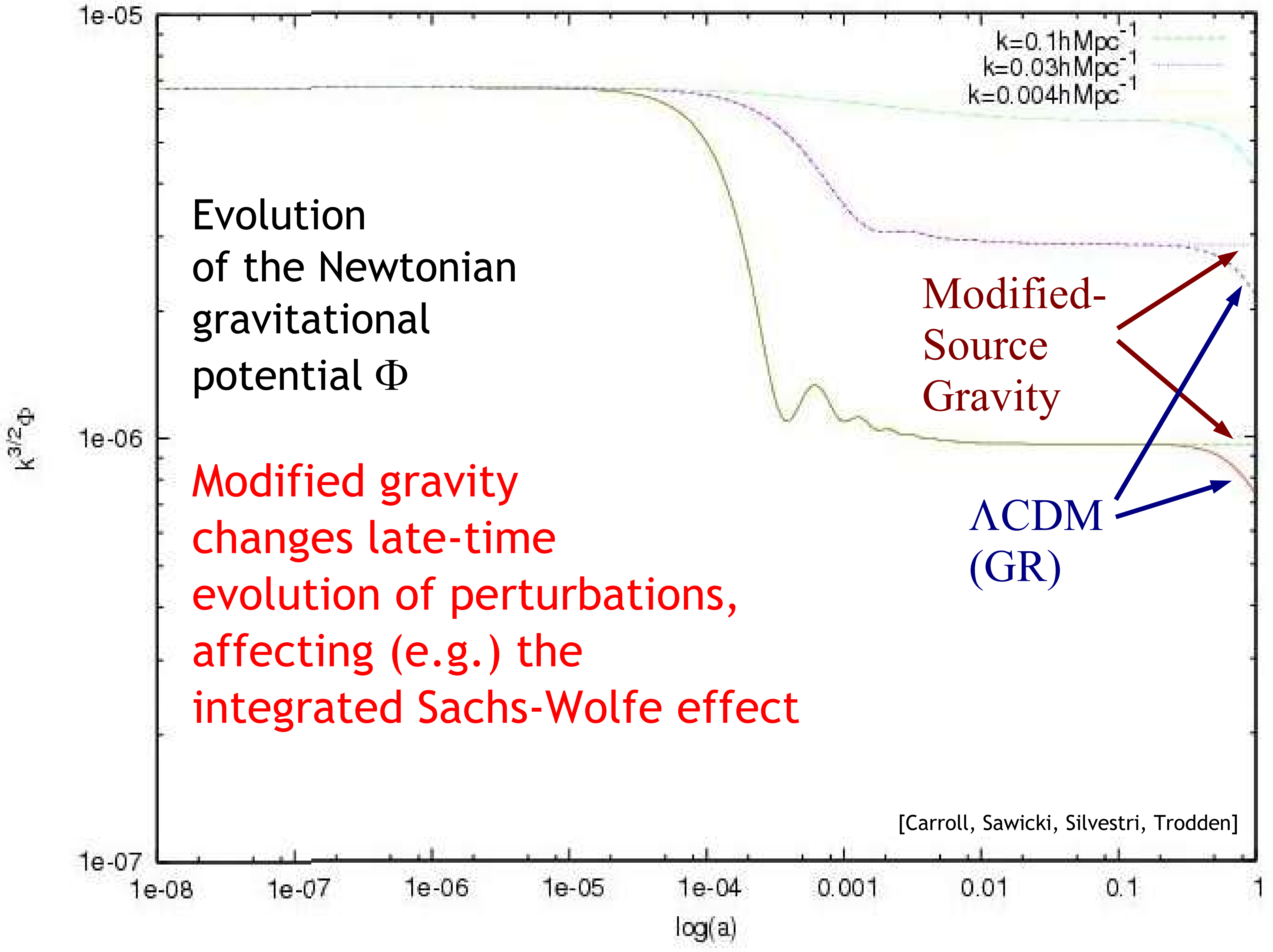
density-dependent correction to Newton's constant

ordinary matter energy density

density-dependent vacuum energy






Evolution
of the Newtonian
gravitational
potential Φ
Modified gravity
changes late-time
evolution of perturbations,
affecting (e.g.) the
integrated Sachs-Wolfe effect
Modified-
Source
Gravity
ΛCDM
(GR)
k=0.1hMpc-1
k=0.03hMpc-1
k=0.004hMpc-1
1e-05
1e-06
1e-07
k3/2Φ
1e-08
1e-07
1e-06
1e-05
1e-04
0.001
0.01
0.1
1
log(a)
[Carroll, Sawicki, Silvestri, Trodden]

This suggests a way to test GR on cosmological scales: compare kinematic probes of DE to dynamical ones, look for consistency. (Relevant to DGP, MSG, ...)

Kinematic probes [only sensitive to $a(t)$]:

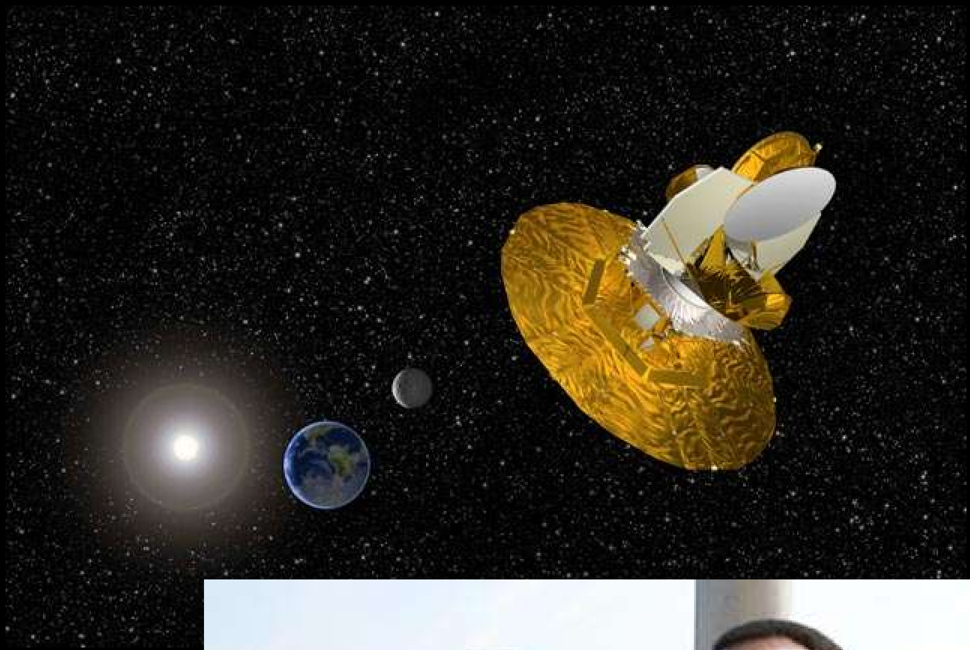
- Standard candles (luminosity distance vs. redshift)
- Baryon oscillations (angular diameter distance)

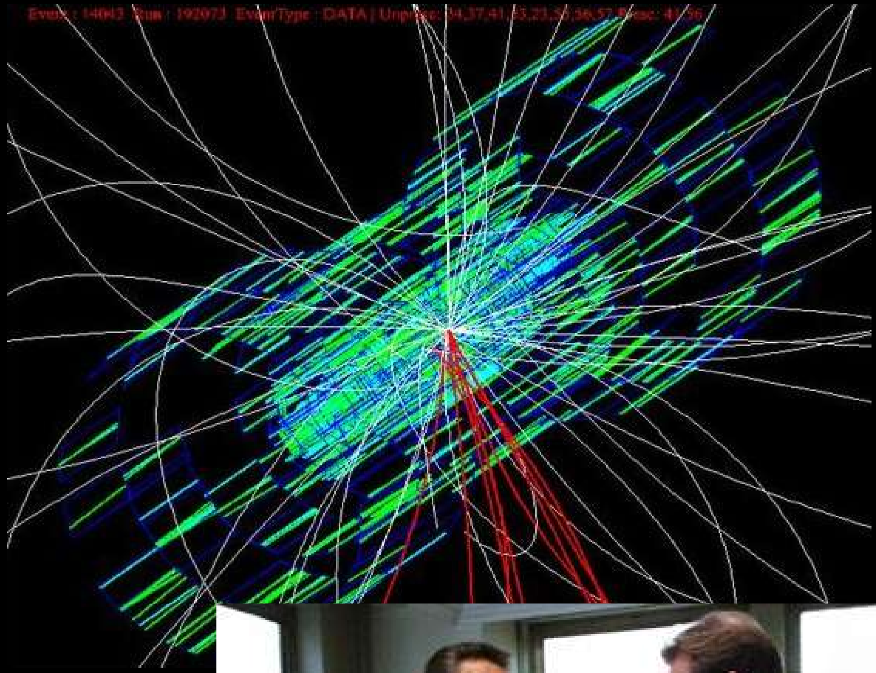
Dynamical probes [sensitive to $a(t)$ and growth factor]:

- Weak lensing
- Cluster counts (SZ effect)

[cf. Lue & Starkman; Ishak, Upadhye & Spergel; Linder]

The Universe and the Laboratory: complementary approaches





Surveillance

Interrogation

Conclusions

- The universe has handed us a clue about the fundamental architecture of reality. We don't yet understand what we've been given.
- Phenomenology is great, but don't forget that we're doing physics.
- It would be a shame if we couldn't calculate the vacuum energy from first principles. But the universe doesn't care.
- Nature fooled us once. We should be open to further surprises.