

Dark Energy and the Preposterous Universe

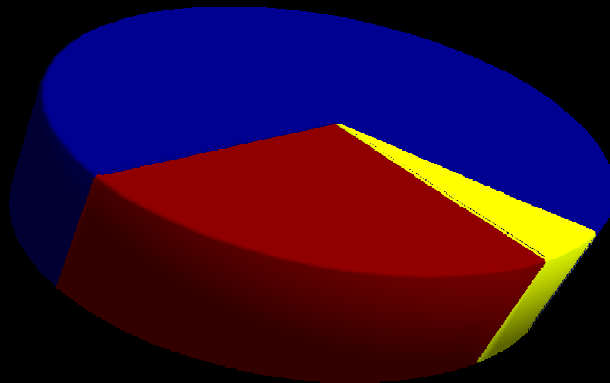
Sean Carroll, University of Chicago

Our universe, as
inventoried over
the last ten years:

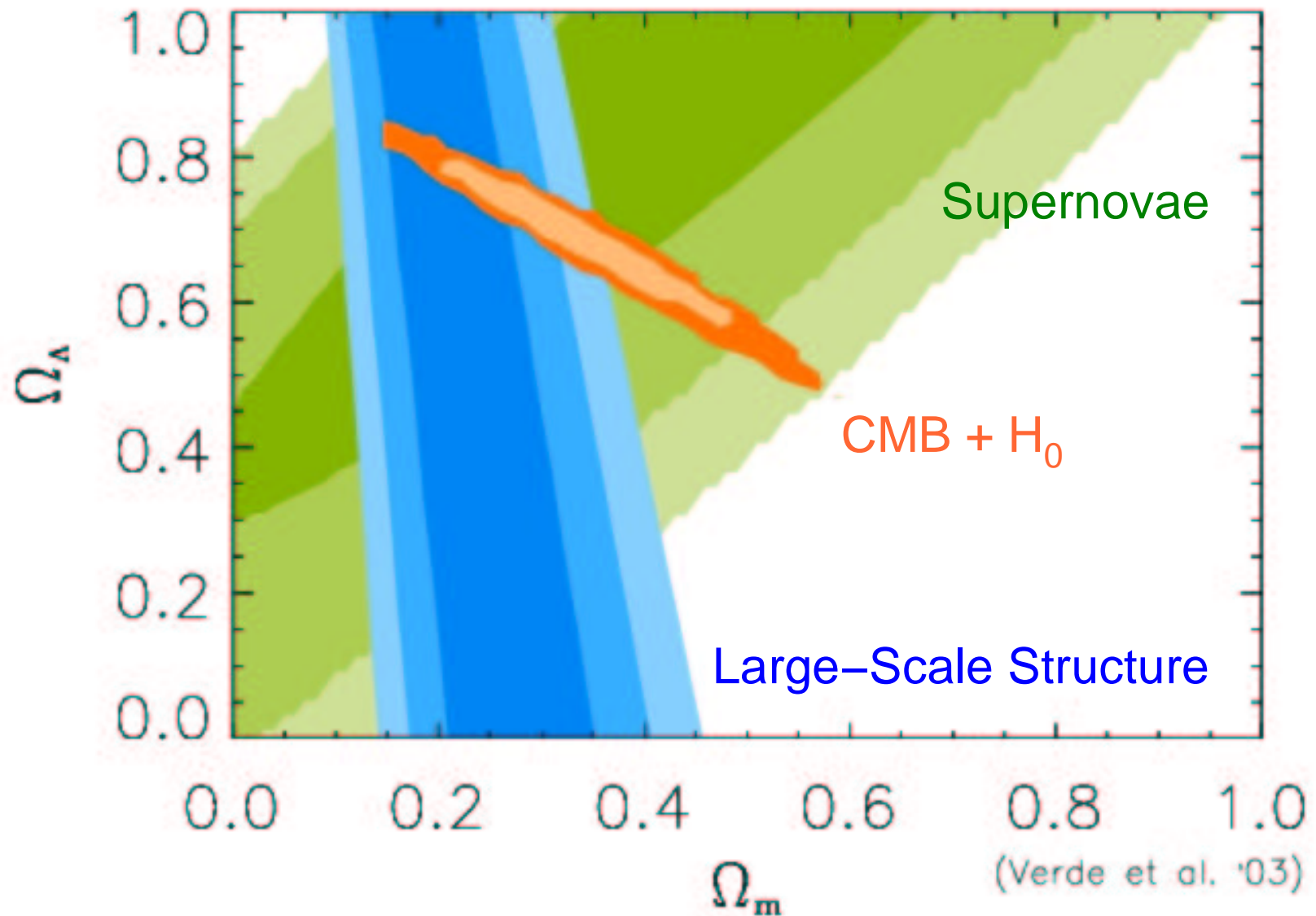
5% Ordinary Matter

25% Dark Matter

70% Dark Energy



Concordance: $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$.



This is a preposterous universe.

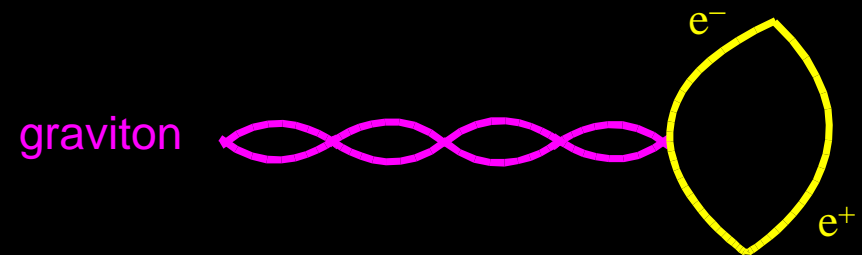
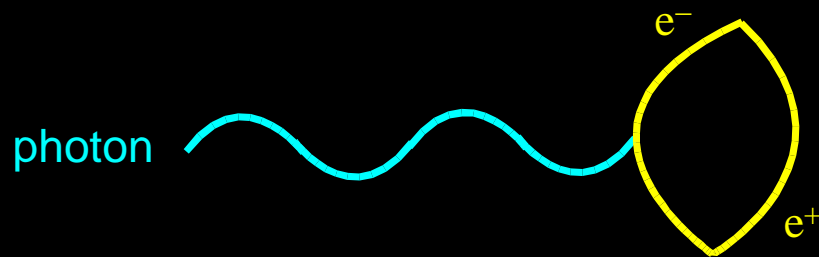
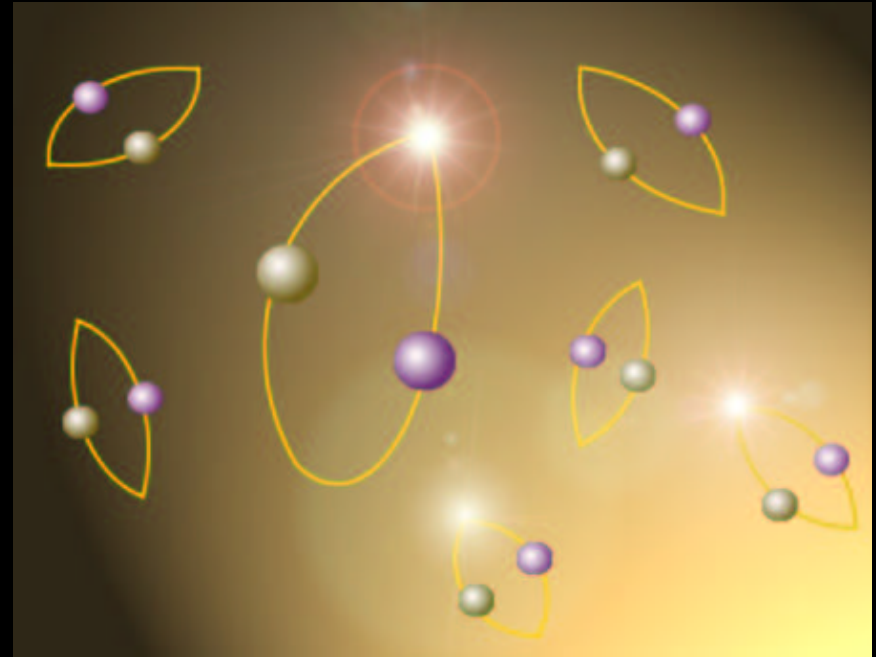
- Why is the vacuum energy density so much smaller than it should be? Naive expectation:

$$\rho_{\text{DE}}^{(\text{theory})} = 10^{120} \rho_{\text{DE}}^{(\text{obs})}$$

- What is the nonzero dark energy? A tiny vacuum energy, a dynamical field, or something even more dramatic?
- Why now? Remember $\rho_{\text{DE}}/\rho_{\text{M}} \sim a^3$. So why are they approximately equal today?

Why is the vacuum energy so small?

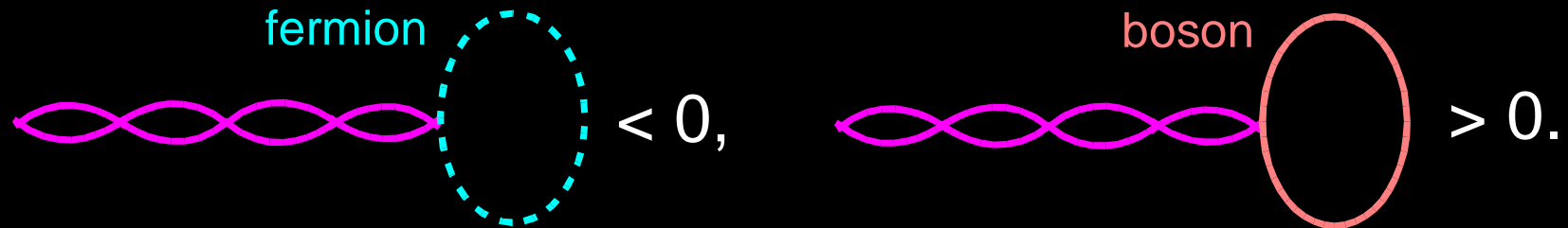
We know that virtual particles couple to photons (e.g. Lamb shift); why not to gravity?



Naively: $\rho_{\text{vac}} = \infty$, or at least $\rho_{\text{vac}} = M_{\text{Pl}}^4 = 10^{120} \rho_{\text{vac}}^{(\text{obs})}$.

On the other hand, maybe an infinite answer is just wrong. **Supersymmetry** does better. (In a manner of speaking.)

- **Good news:** In a perfectly supersymmetric state, bosonic and fermionic contributions to ρ_{vac} exactly cancel.



- **Bad news:** We don't live in a perfectly supersymmetric universe; SUSY is (at least) broken around $M_{SUSY} = 10^{12}$ eV.
- **Good news:** This makes the cosmological constant problem not so bad: $\rho_{\text{vac}}^{(\text{theory})} = M_{SUSY}^4 = 10^{60} \rho_{\text{vac}}^{(\text{obs})}$.
- **Bad news:** This is a much more reliable calculation!

What is the small nonzero dark energy?

The Gravitational Physics Data Book:

Newton's constant:

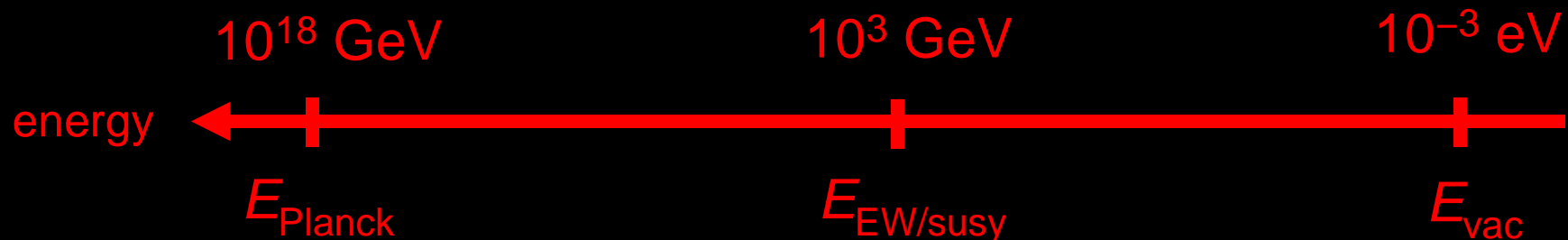
$$G = (6.67 \pm 0.01) \times 10^{-8} \text{ cm}^3 \text{ g}^{-1} \text{ sec}^{-2}$$

Cosmological constant:

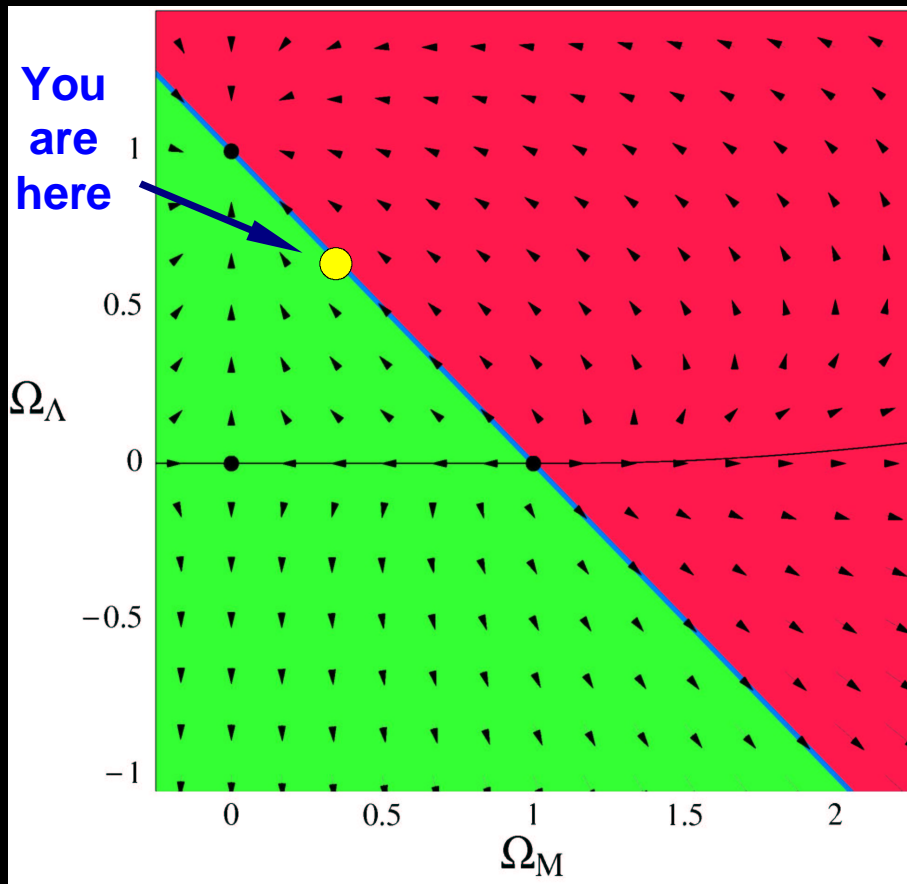
$$\Lambda = (1.2 \pm 0.2) \times 10^{-55} \text{ cm}^{-2}$$

Equivalently,

$$E_{\text{Planck}} = 10^{18} \text{ GeV} , \quad \rho_{\text{vac}} = (10^{-3} \text{ eV})^4 .$$

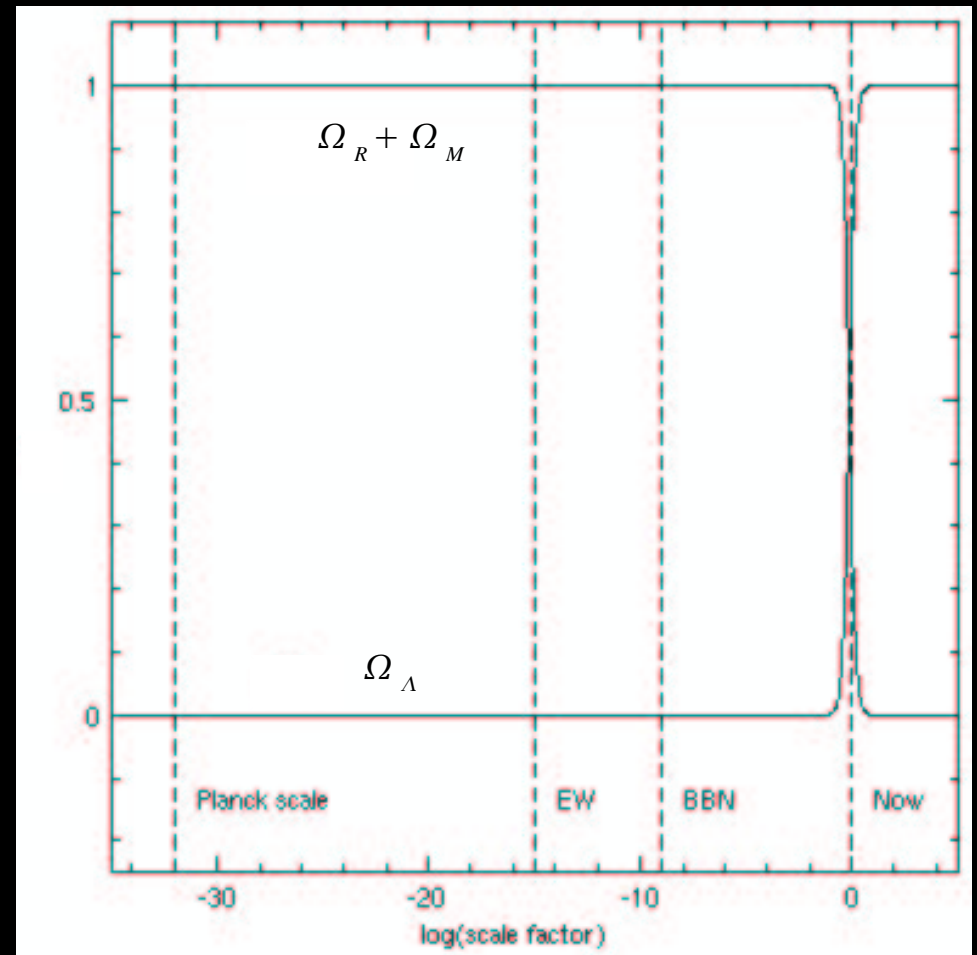


Why are vacuum and matter comparable?

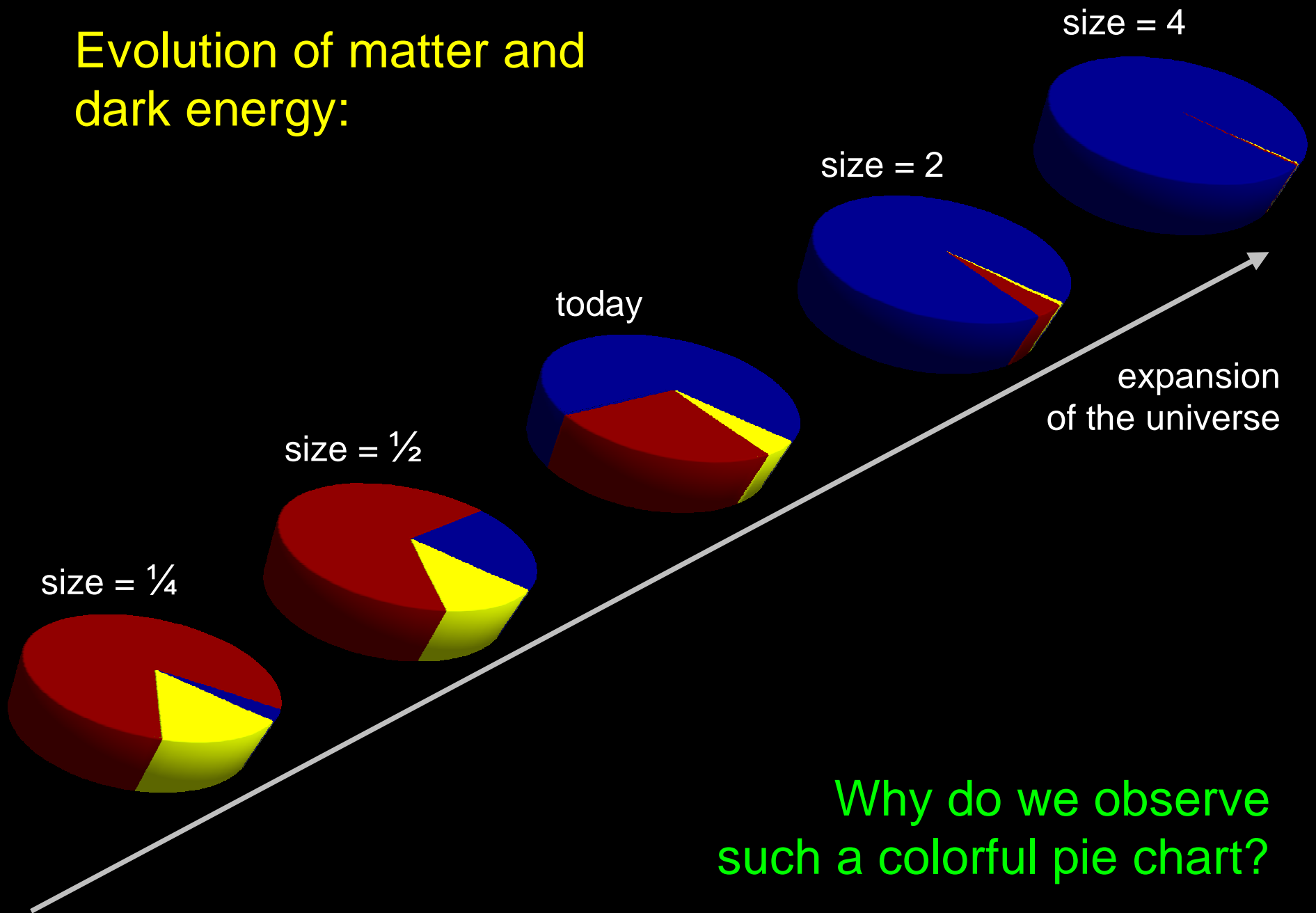


The "best-fit universe" with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ is an unstable point.

$$\frac{\Omega_\Lambda}{\Omega_M} \sim a^3$$



Evolution of matter and dark energy:



What might be going on?

Possibilities include:

- We just got lucky.
- The vacuum energy is very different in other parts of the universe.
- A slowly-varying dynamical component is mimicking a vacuum energy.
- Einstein was wrong.

1) Could we just be lucky?

Perhaps, when we can successfully calculate the vacuum energy, it will just happen to coincide with the present matter density.

For example: In supersymmetry, we expect

$$M_{vac} = M_{SUSY} ,$$

which is off by 10^{15} . But if instead we found

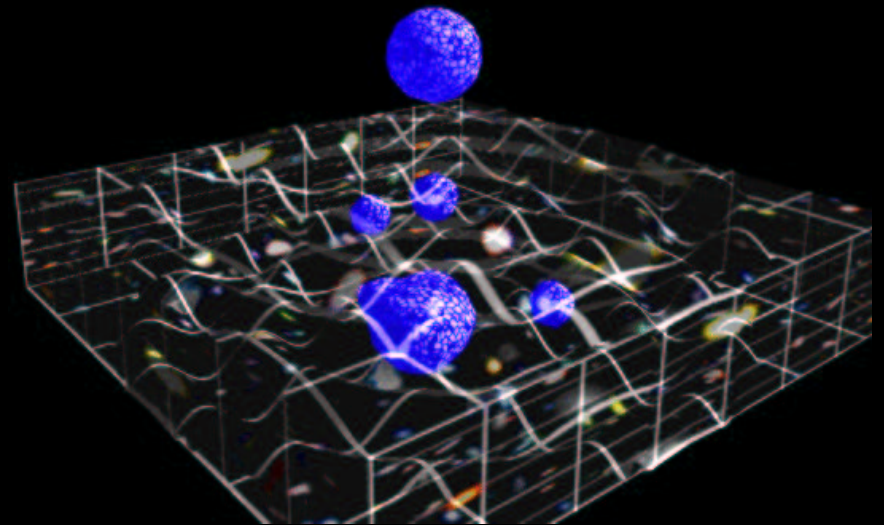
$$M_{vac} = \left(\frac{M_{SUSY}}{M_{Planck}} \right) M_{SUSY} ,$$

it would agree with experiment. (All we need is a theory that predicts this relation.)

Some profound possibilities lurking.

Holography: studying quantum gravity has taught us that the degrees of freedom giving us these vacuum fluctuations aren't really there. The degrees of freedom you see depend on how you look. This sounds like it should have something to do with the cosmological constant problem.

Extra dimensions: if there are large extra dimensions, we are measuring the induced geometry on a brane, not the intrinsic geometry of all spacetime. This changes the problem (although doesn't solve it in an obvious way).



2) Could the anthropic principle be responsible?

What if:

- The vacuum energy ρ_Λ takes on different values, with uniform probability, in different "parts of the universe" (in space, time, or branches of the wavefunction).
- Everything else remains the same from place to place: constants of nature, initial conditions, galaxy formation, etc.

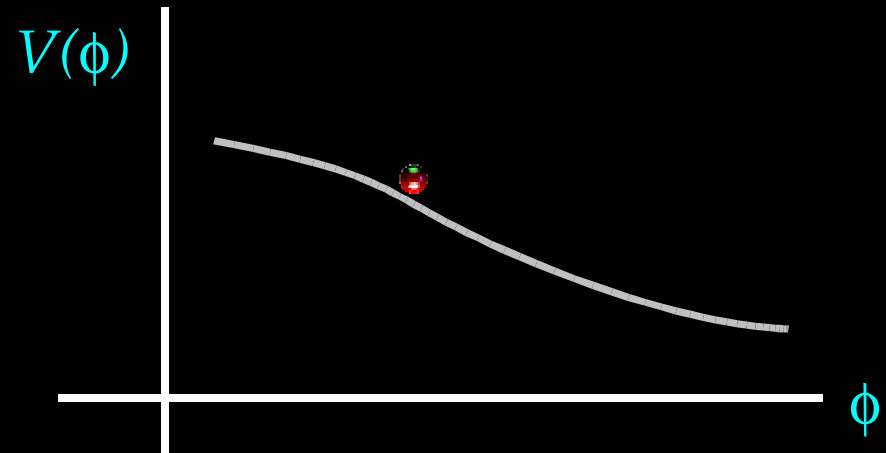
Then the most likely thing for observers in such an ensemble to find is that $|\rho_\Lambda| < 10 \rho_M$ (just as we do).

[Garriga & Vilenkin; Martel, Shapiro & Weinberg]

3) Is the dark energy a slowly-varying dynamical component?

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

$$\rho_\phi = \underbrace{\frac{1}{2} \dot{\phi}^2}_{\text{kinetic energy}} + \underbrace{\frac{1}{2} (\nabla \phi)^2}_{\text{gradient energy}} + \underbrace{V(\phi)}_{\text{potential energy}}$$



[Wetterich; Peebles & Ratra; 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.

Could dark-energy dynamics solve the coincidence problem?

Two possibilities:

- Today is not so far (on a log scale) from matter/radiation equality ($z_{\text{eq}} \sim 10^4$).

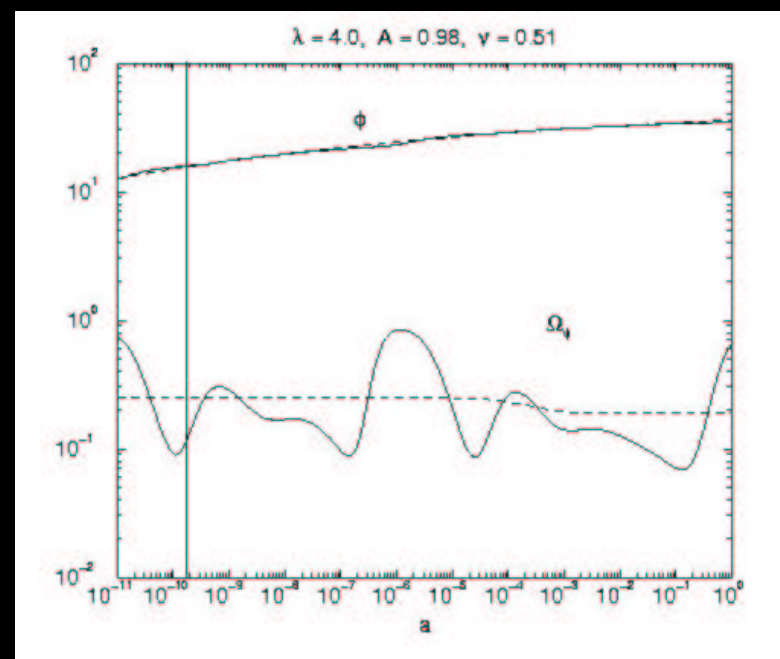
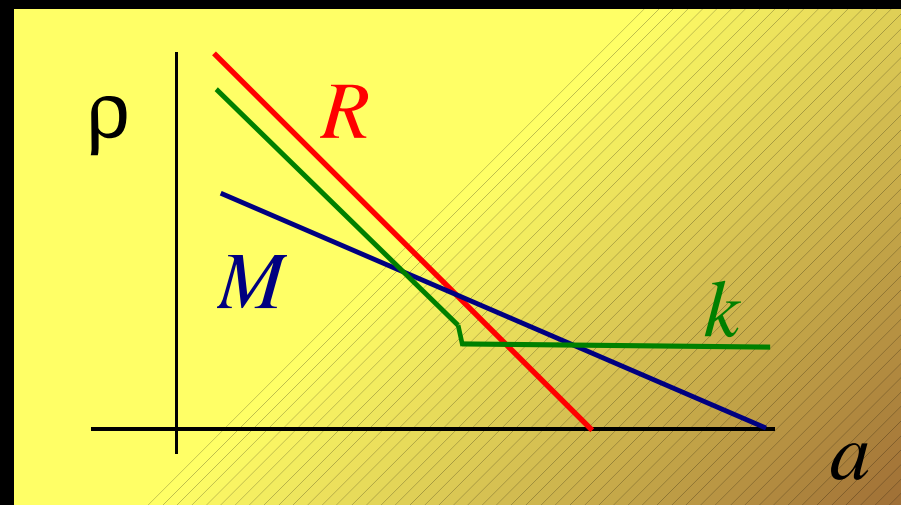
k-essence: Armendariz–Picon,
Mukhanov & Steinhardt

$$L = f(\phi) g[(\nabla \phi)^2]$$

- Perhaps acceleration is something that just happens from time to time.

oscillating dark energy:
Dodelson, Kaplinghat, and Stewart

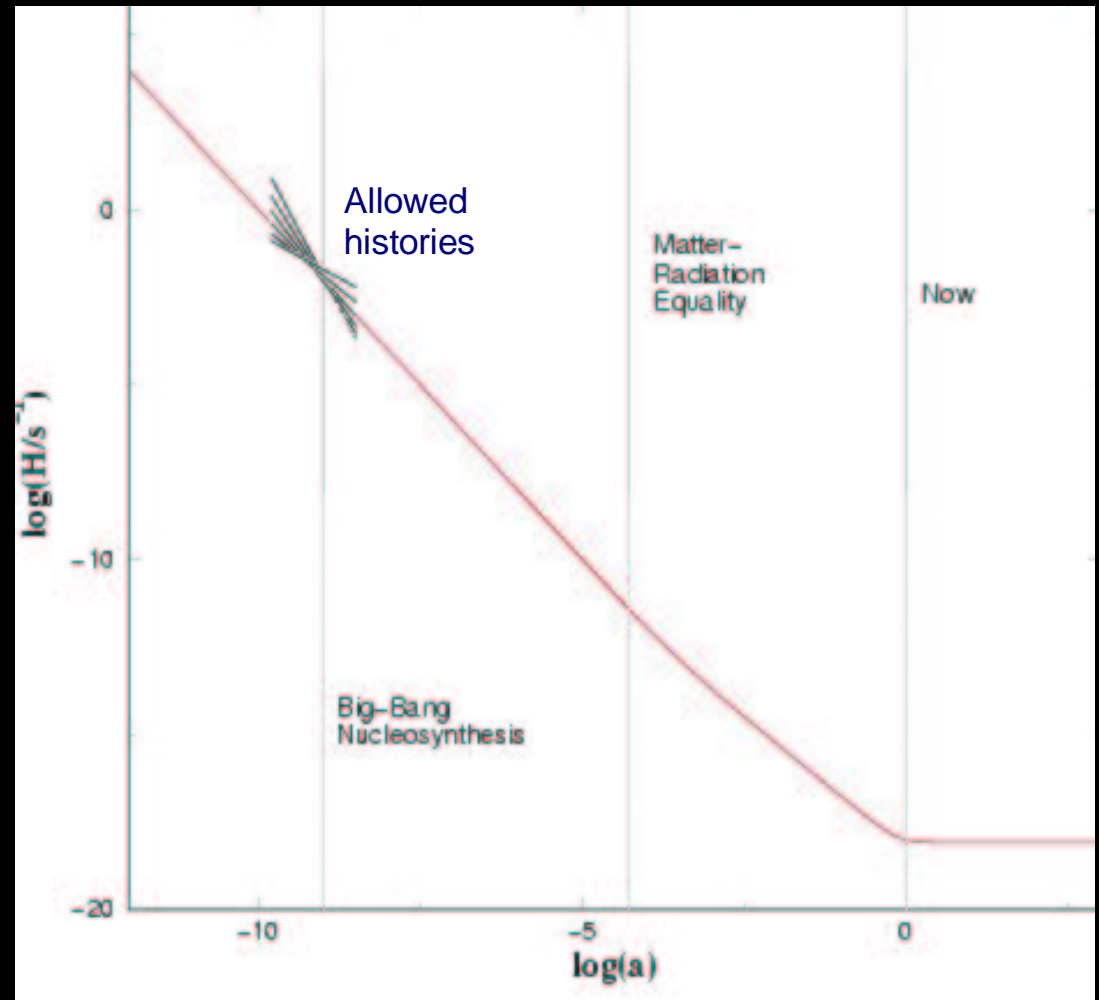
$$V(\phi) = e^{-\phi} [1 + \alpha \sin(\phi)]$$



Is acceleration purely a recent phenomenon?

Evidence for conventional expansion history:

- **Big-Bang Nucleosynthesis** ($z \sim 10^9$) is the most model-independent test; unconventional expansion possible, but constrained.
- **CMB anisotropies** ($z \sim 10^3$), e.g. location of acoustic peaks, are consistent with conventional expansion.
- **Structure growth** harder to quantify, but consistent with $a = t^{2/3}$ (MD) until quite recently.



[Carroll & Kaplinghat]

Notice: there is a coincidence problem!

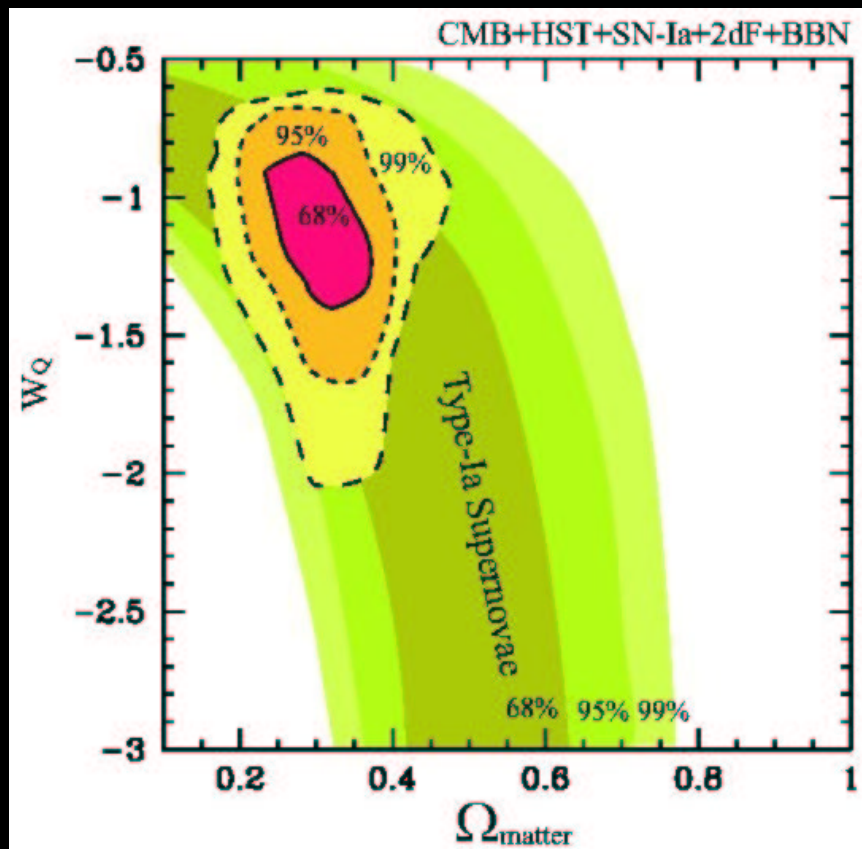
Testing models of dark energy

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

$$p = w \rho$$

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

More than anything else, we need to know whether $w = -1$ or not.



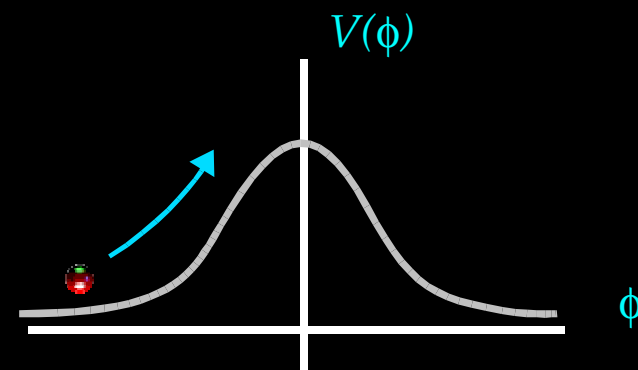
[Melchiorri, Mersini,
Odman & Trodden]

Should we consider $w < -1$?

[Caldwell;
Carroll, Hoffman & Trodden]

In GR, the **dominant energy condition** ensures that energy doesn't propagate faster than light; it says $|p| \leq |\rho|$, so $-1 \leq w \leq 1$.

But we can make a model with $w < -1$:
a **negative-kinetic-energy** (ghost) scalar field, $L = -\dot{\phi}^2 - \exp(-\phi^2)$.

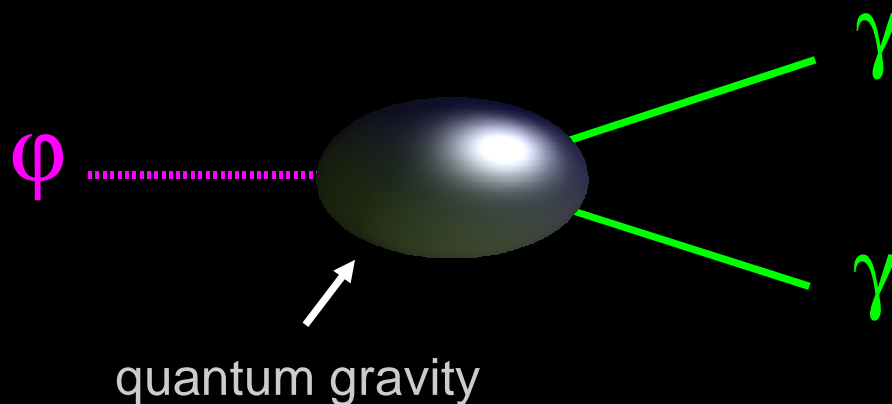


Problem: **instability to decay** (positive-energy gravitons, negative-energy ϕ bosons). Can be avoided if we put a cutoff on the theory: momenta less than 10^{-3} eV.

Remember: **nobody ever measures w , really**. We only measure the behavior of the scale factor.

Don't forget the possibility of direct detection of dark energy.

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.



Loophole: pseudo-Goldstone bosons. (Or an honest cosmological constant.)

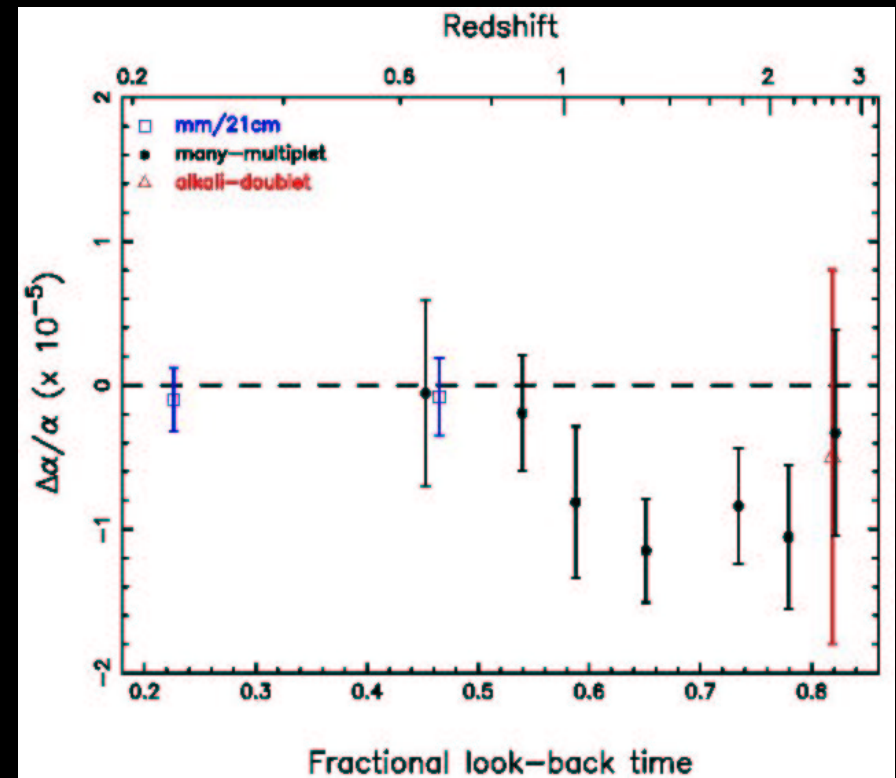
Direct dark energy detection search strategies:

- 5th forces.



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

Recent claim: observations of absorption lines in quasar spectra at redshifts $z \sim 1-3$ imply $\Delta\alpha/\alpha \sim 10^{-5}$.



[Webb et al.]

But there's a competing limit: the Oklo Natural Reactor.



1.8 billion years ago, a natural water-moderated fission reactor operated in Gabon, West Africa.

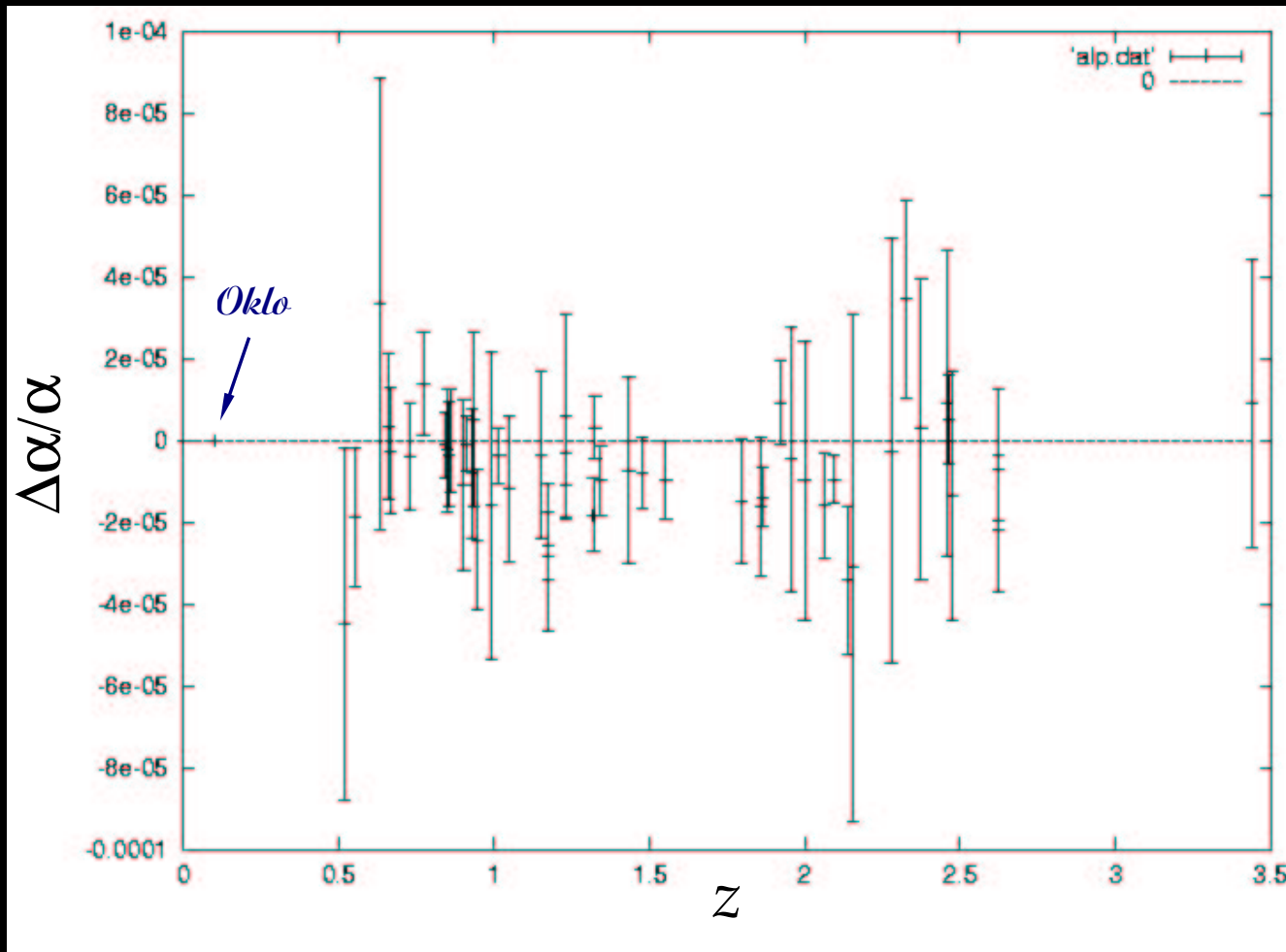
Isotopic abundances constrain the ^{149}Sm neutron-capture cross-section, and thus α .

Result: $|\Delta\alpha/\alpha| < 1.2 \times 10^{-7}$ (95% CL) at redshift $z \approx 0.13$.

[Damour and Dyson]

Issues: initial abundances, variation of other constants.

Can the Oklo and absorption–line results be reconciled?



If a scalar field ϕ is responsible, we need the evolution of ϕ to have slowed down significantly. This can happen in some models, but usually not by so much.

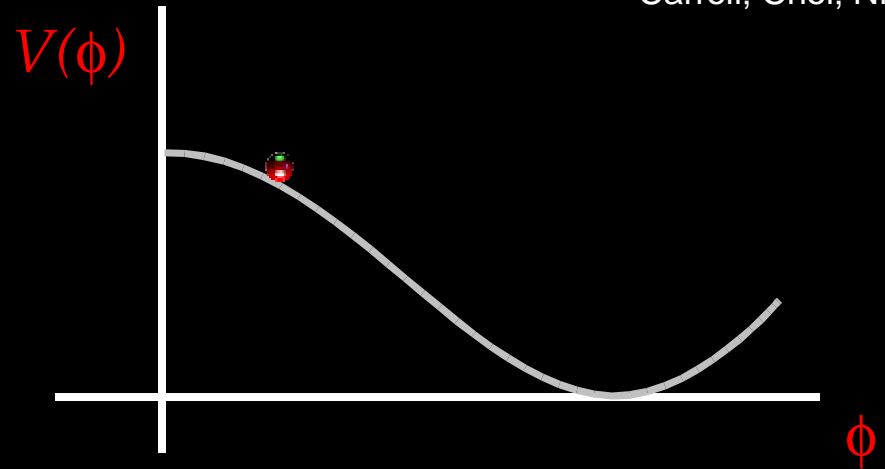
Sensible particle physics models?

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

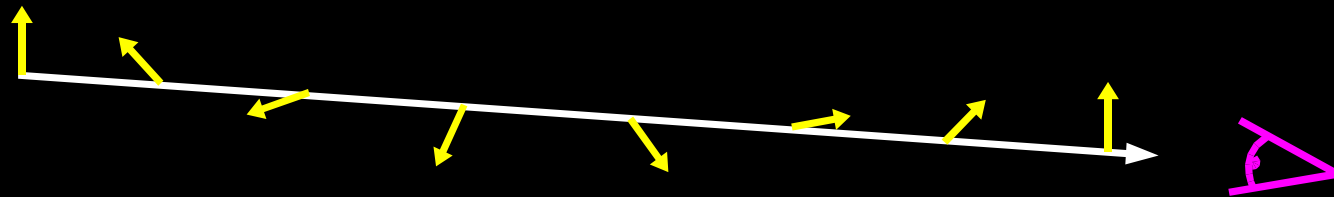
Naturally small masses; naturally small couplings.

[Hill, Freiman, et al;
Carroll; Choi; Nilles]

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



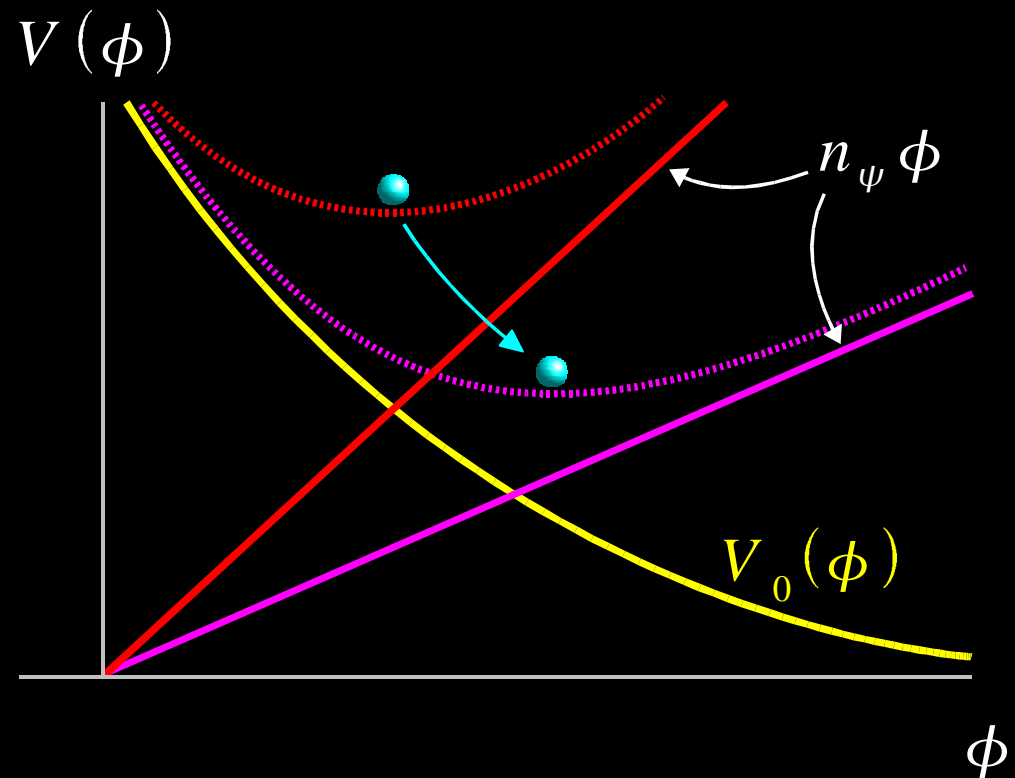
Possible signature: cosmological birefringence.



Keep in mind: the "dark sector" could be complicated.

Imagine a dark matter particle ψ which gets its mass from a rolling field ϕ , $m_\psi = \phi$. Effective potential for ϕ depends on the number density of ψ :

$$V_{eff}(\phi) = V_0(\phi) + n_\psi \phi$$



Because $n_\psi \propto a^{-3}$, the density gradually decreases, so the value of ϕ increases, so the mass of ψ increases: dark matter with time-dependent mass.

(Simple versions don't actually work.)

[Bekenstein; Garcia-Bellido;
Anderson & Carroll; Peebles]

4) Was Einstein wrong?

A modified Friedmann equation could help solve the cosmological constant problem. (E.g., "self-tuning" branes in extra dimensions):

$$H^2 \propto (\rho + p)$$

[Arkani-Hamed et al; Kachru et al;
Carroll & Mersini]

This would render the cosmological constant invisible, rather than small. Nobody yet has a feasible model.

But to account for dark energy, we need to alter the Friedmann equation at some fixed scale, of order the Hubble radius today. (BBN & CMB show us that early cosmology looks conventional.)

Phenomenological approaches to modifying the Friedmann equation

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

1) modified energy–density dependence

$$H^2 = \frac{8 \pi G}{3} \rho \left[1 + \left(\frac{\rho_x}{\rho} \right)^\alpha \right]$$

[Freese & Lewis]

2) modified Hubble–parameter dependence

$$H^2 \left[1 + \left(\frac{H_x}{H} \right)^\beta \right] = \frac{8 \pi G}{3} \rho$$

[Dvali & Turner]

It's hard to distinguish between these and dark energy.

What about an actual theory? Here is a simple toy model that departs from GR at long distances:

Replace the Einstein–Hilbert action

$$S = \frac{1}{16\pi G} \int R d^4x$$

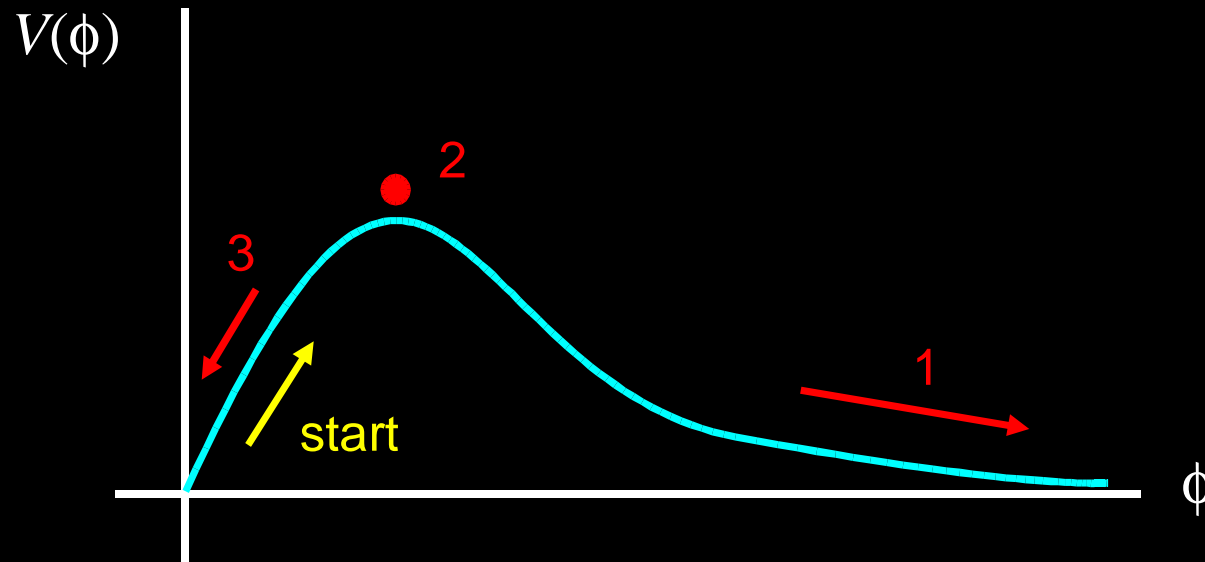
with the modified form

$$S = \frac{1}{16\pi G} \int \left(R - \frac{m^4}{R} \right) d^4x$$

This implies deviations from ordinary GR at **low curvatures**.
But does it make sense?

[Carroll, Duvvuri, Trodden & Turner;
see also Deffayet, Dvali, and
Gabadadze; etc.]

Theories with $L = f(R)$ are equivalent to scalar–tensor models, and have an Einstein–frame description with scalar field ϕ .



ϕ starts at zero and increases, with three possibilities:

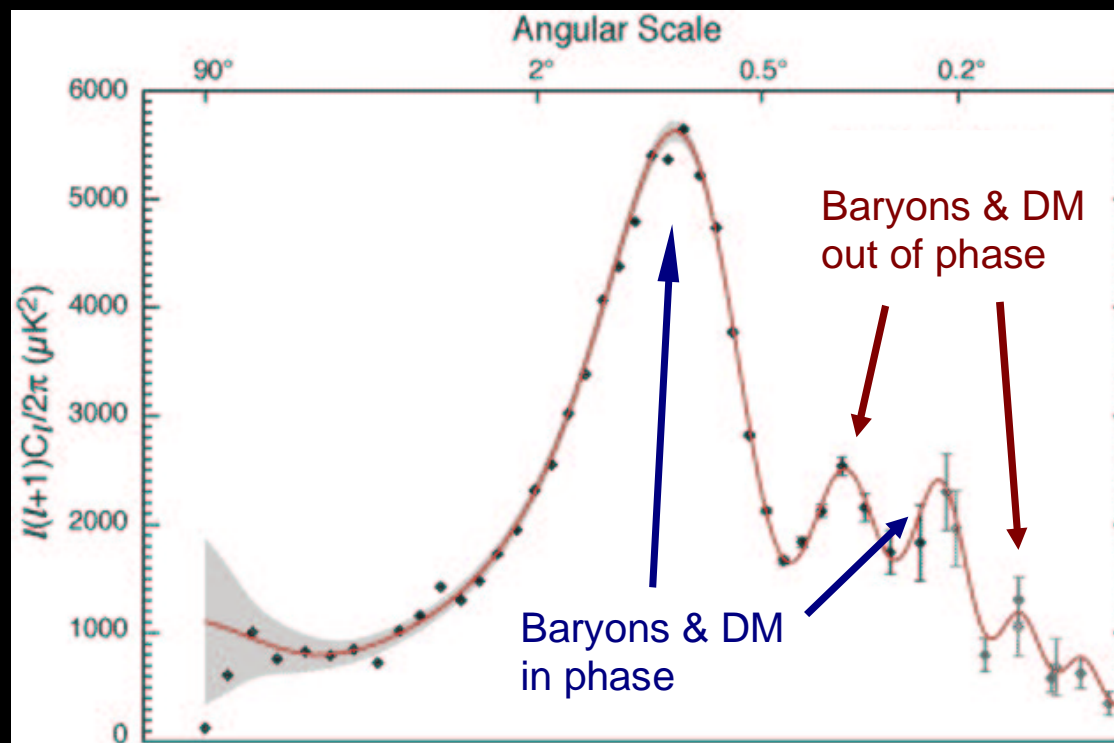
1. power–law acceleration ($a \sim t^2$ in original frame)
2. pure de Sitter expansion
3. super–exponential, but no "big rip" ($H \sim (t_0 - t)^{1/2}$)

No stable vacuum, but apparently no ghosts –not pretty, but not ruled out, either.

Could modified gravity replace dark matter?

That would be *great*, but I suspect it won't work. Reasons:

1. I don't know how to make a good theory. ("Bekenstein's Law")
2. There is some evidence that gravitational forces sometimes point in directions other than where the baryons are; e.g. dark matter boosts odd-numbered acoustic peaks in the CMB.



[WMAP]

Conclusions

- An ordinary cosmological constant is a perfect fit to the dark-energy data, even if we can't explain it.
- Dynamical mechanisms are interesting and testable; to date, they raise at least as many problems as they solve.
- Replacing dark components with modified gravity is interesting, but also difficult.
- My suspicion: we just got lucky.
Our task then is to figure out how to correctly calculate the vacuum energy. This will require a significant breakthrough.

