Dark Energy and the Preposterous Universe

Sean Carroll, University of Chicago

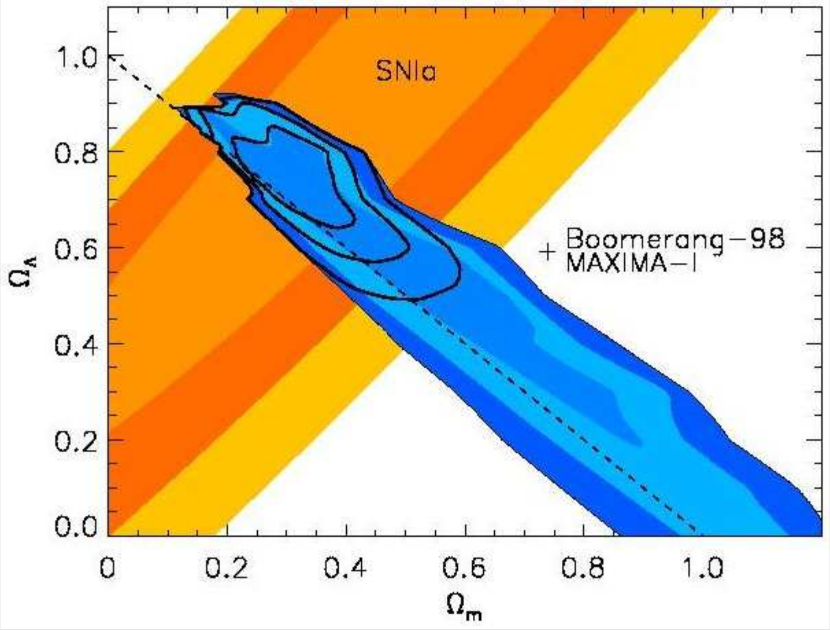
Observation tells us: there is a dark, smooth, slowly–varying energy component comprising 70% of the energy in the universe.

- $\Omega_{clustered} = 0.3$; a flat universe

  implies ρ_{Dark} is smooth

- $\dot{a}^2 = \frac{8\pi G}{3} a^2 \rho - k$; acceleration

  implies ρ_{Dark} is slowly–varying



[Jaffe et al.]

Simplest candidate: vacuum energy, $\rho_{vac}(t, \vec{x}) = const.$

In fact, we have: $\rho_{vac} \approx 10^{-8}\, ergs/cm^3 \approx (10^{-3}\, eV)^4$.

This raises (at least) two big problems:

- Why is $\rho_{vac} \ll (10^{18}\, GeV)^4$?
- Why is $\rho_{vac} \sim \rho_{Matter}$?

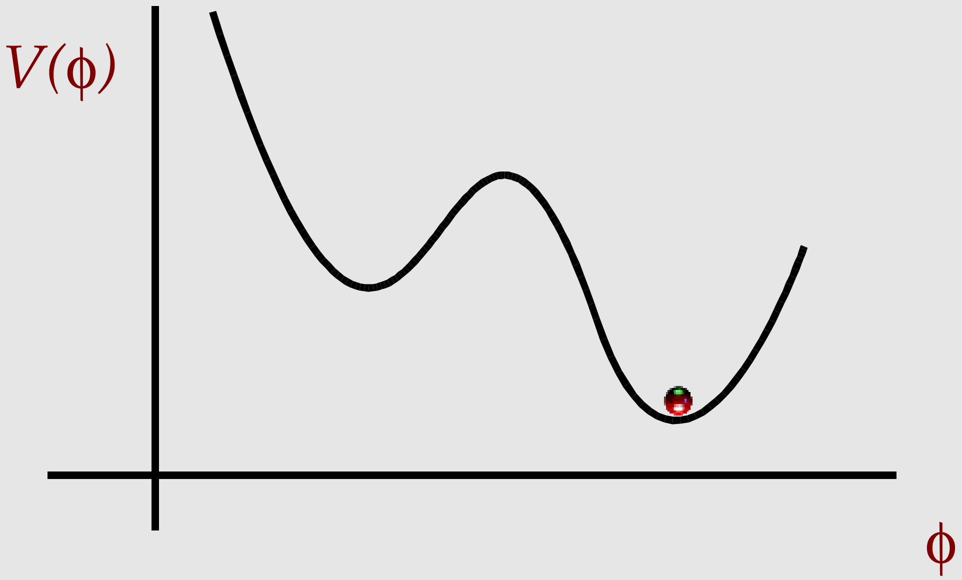
Problem One: Why is the vacuum energy so small?

Vacuum energy is the most natural thing in the world.

Consider a single scalar field: $\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}(\nabla\phi)^2 + V(\phi)$

$$\phi = const \longrightarrow \rho_\phi = V(\phi) = const.$$

Crucial point:
no known (unbroken)
symmetry would
prefer $V(\phi) = 0$.



How big a problem is the cosmological constant problem?

$$\begin{array}{ccccccccccc} \rho_{vac} & = & \rho_{Higgs} & + & \rho_{QCD} & + & \rho_{0-point} & + & \rho_{\Lambda_0} & + & \ldots \\ & & (10^2 GeV)^4 & & (10^{-1} GeV)^4 & & \infty & & (10^{18} GeV)^4 & & \end{array}$$

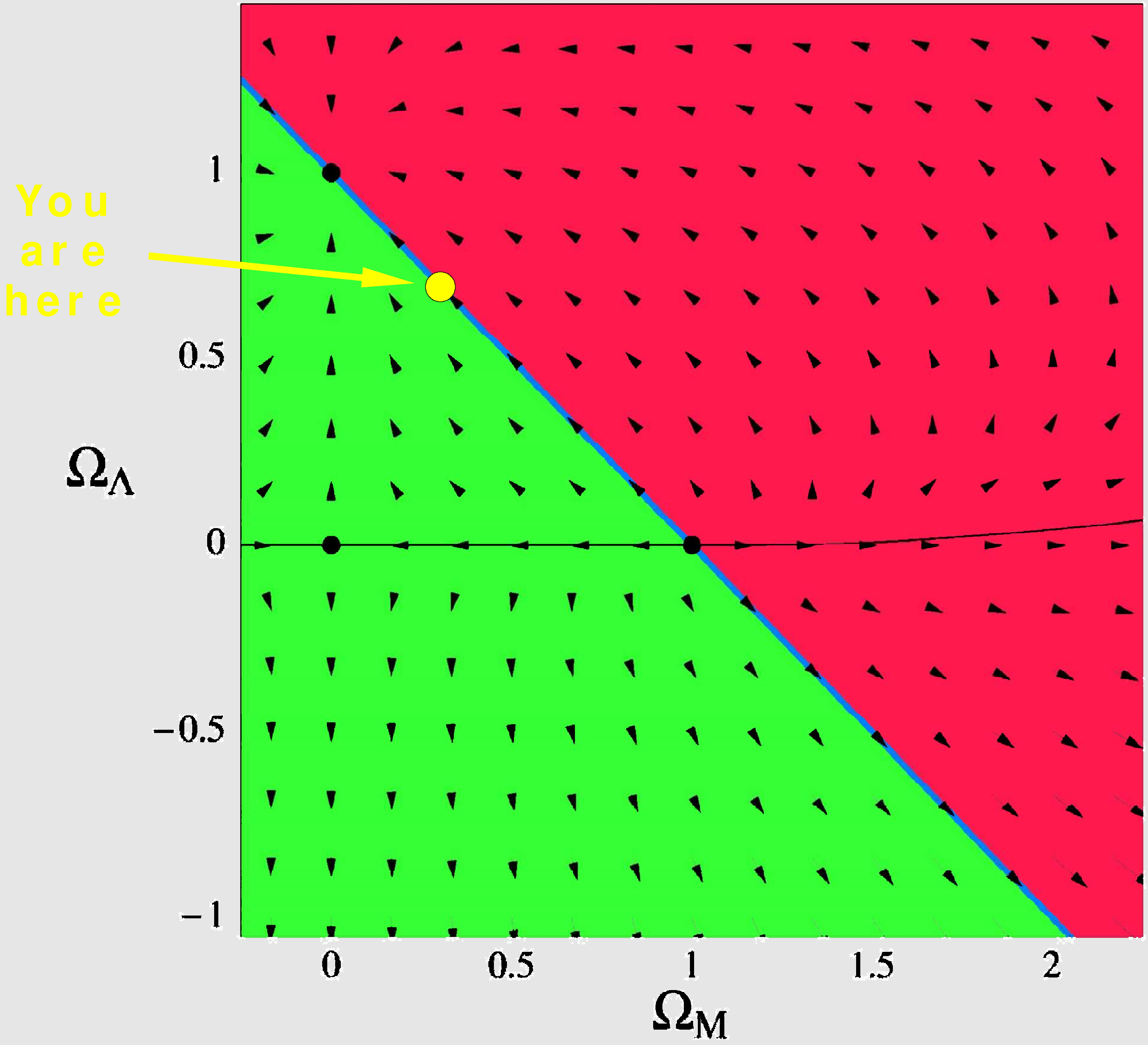
So we predict: $\boxed{\rho_{vac}^{(theory)} \approx (10^{18} GeV)^4 = 10^{120} \rho_{vac}^{(obs)}}$

That’s a cheat; really $\rho_{vac} = M_{vac}^4 ;$ $\boxed{M_{vac}^{(theory)} = 10^{30} M_{vac}^{(obs)}}$

In fact, in supersymmetry, $M_{vac} \approx M_{\cancel{SUSY}} \approx 10^3 GeV = 10^{12} eV ,$

so $M_{vac}^{(SUSY)} = 10^{15} M_{vac}^{(obs)} .$

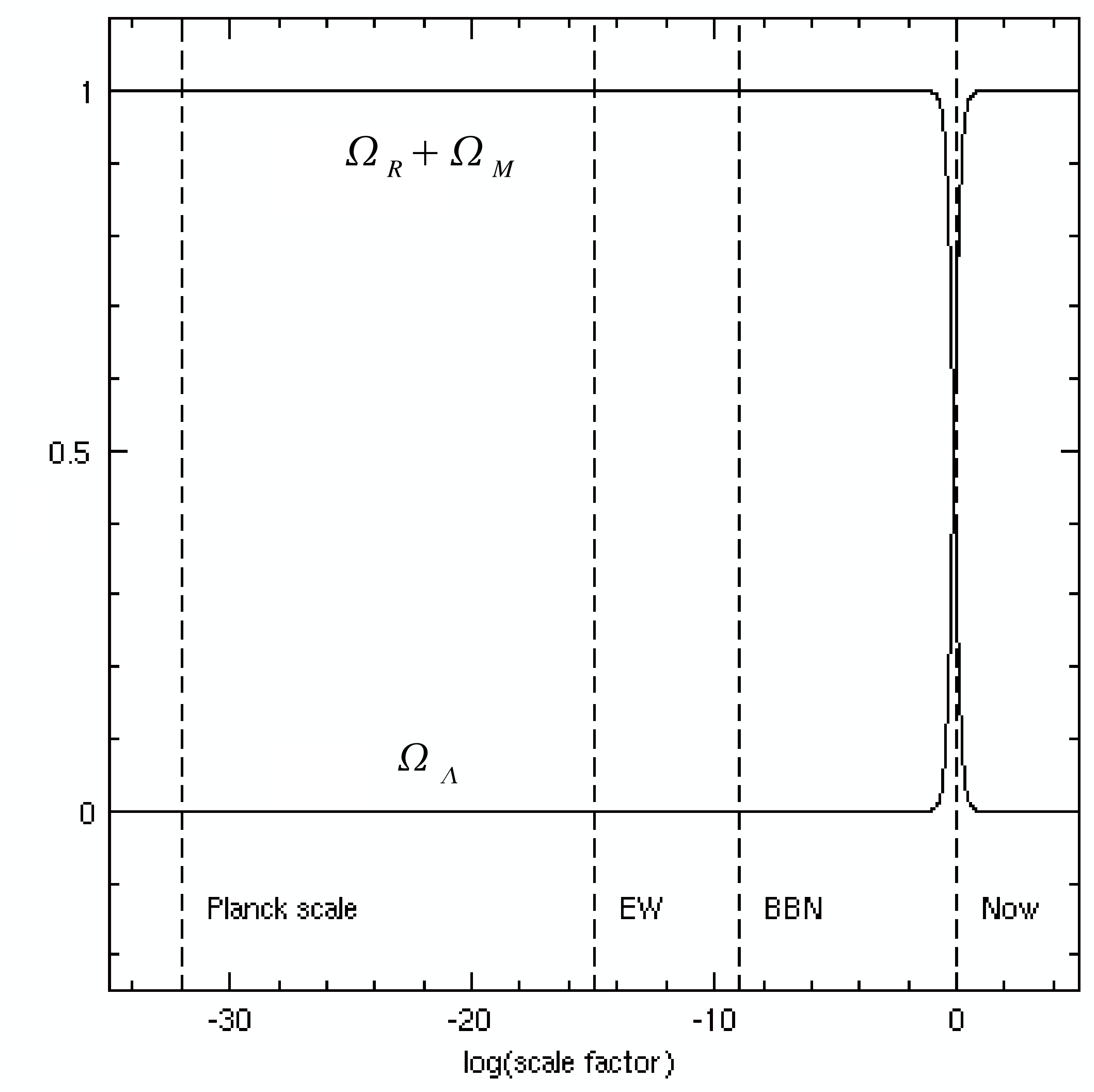
Problem Two: Why are vacuum and matter comparable?



The "best–fit universe" with $\Omega_M = 0.3,\ \ \Omega_\Lambda = 0.7$ is an unstable point, caught in the process of evolving from purely matter to purely vacuum.

And it's moving quickly:

$$\boxed{\frac{\Omega_{\Lambda}}{\Omega_{M}} \sim a^{3}}$$



What might be going on?

Possibilities include:

1) The true vacuum energy is small, but nonzero.
2) We live in a false vacuum; the true vacuum has zero energy.
3) A slowly–varying dynamical component is mimicking a vacuum energy.
4) Einstein was wrong.

Interlude: How should we deal with theorists?

Theorist: "X is possible, it might happen."
Response: Pay attention, go look for it.

Theorist: "X is just not possible."
Response: Nod politely, ignore them.

1) Might the true vacuum energy be nonzero?

Some numerology:

$$M_{SUSY} = \sqrt{M_{Planck} M_{vac}}$$

$$M_{vac}^{4} = e^{-2/\alpha} M_{Planck}^{4}$$

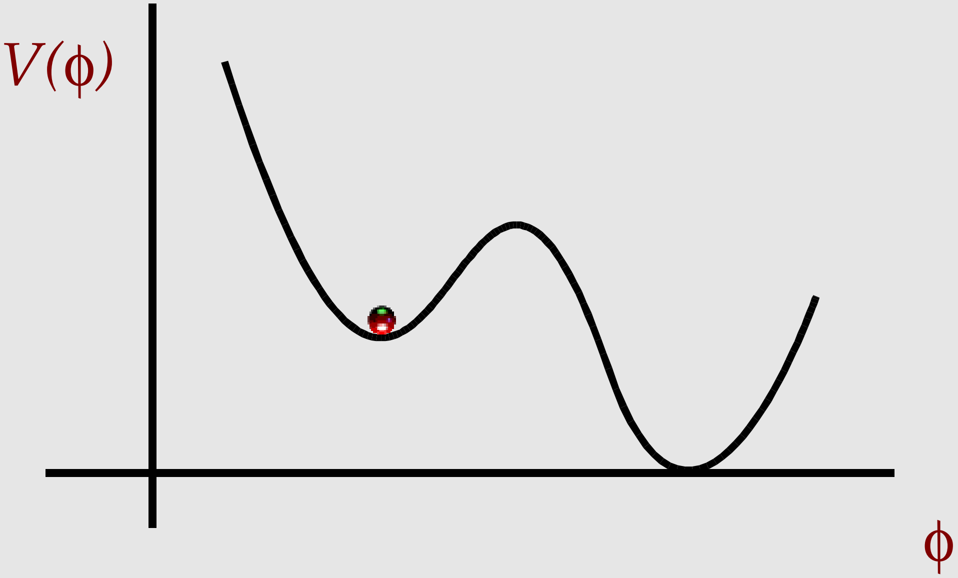
This is the state of the art. That should tell you something.

Perfectly reasonable people are driven to invoke the anthropic principle.

String theorists find it very hard to get $\rho_{vac} > 0$.

2) Do we live in a false vacuum?

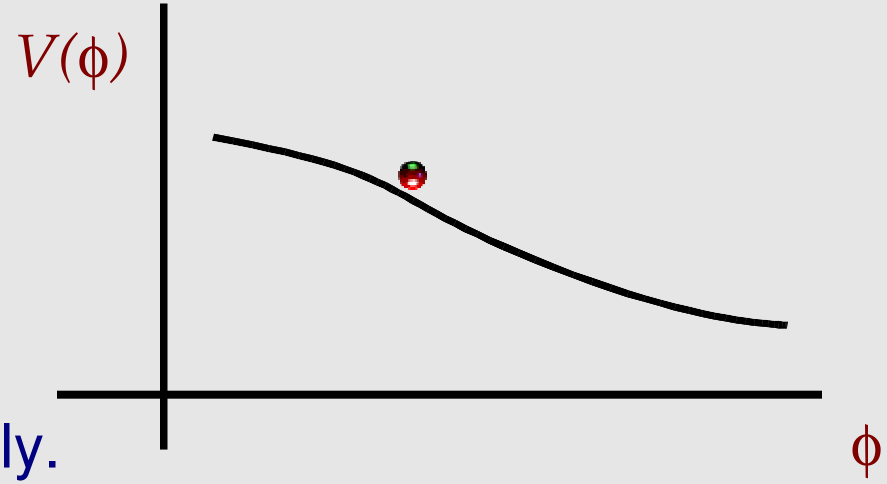
Good: compatible with $\rho_{vac} = 0$ ultimately.
Bad: why would the splitting be so tiny?



Keep in mind:

- *No* observational signature.
- Stability not really an issue.

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



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

Good:

- Consistent with $\rho_{vac} = 0$ ultimately.
- Observationally interesting.
- Consistent with string theory?
- Solve the coincidence problem?

Bad:

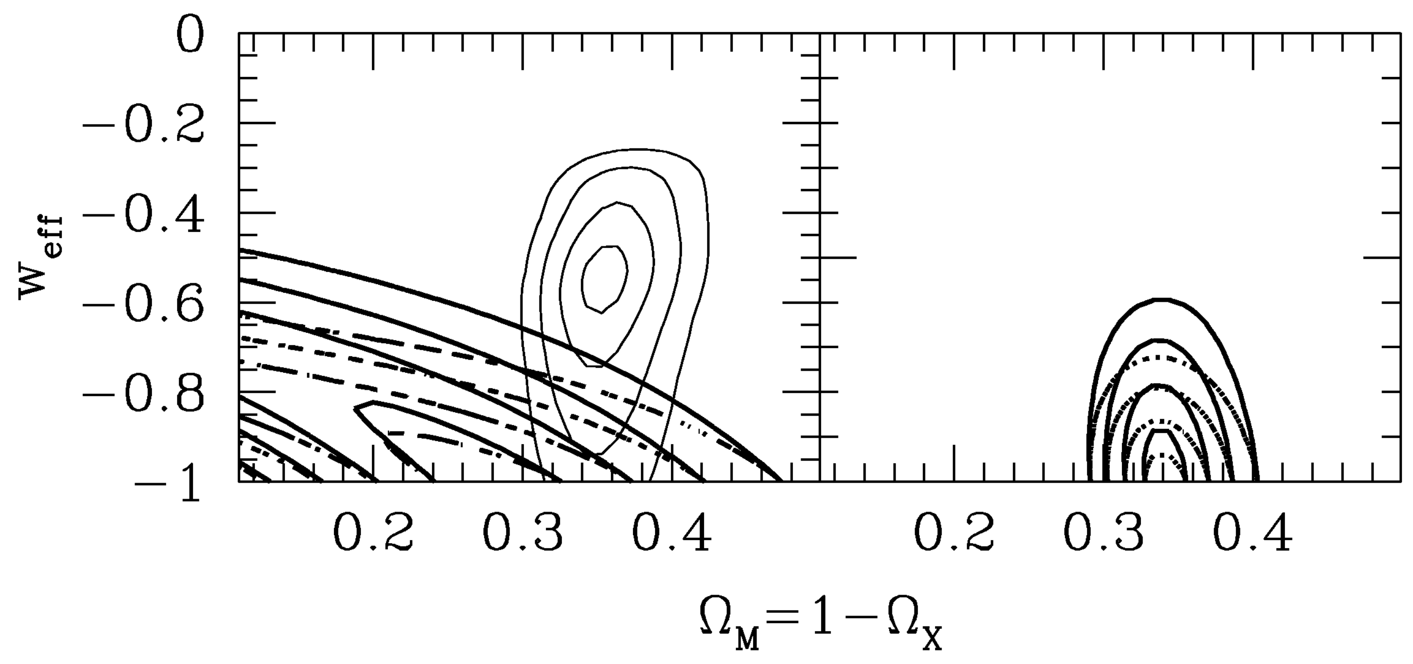
- Unnatural particle physics. $(m_\phi \approx 10^{-33} eV)$
- Should have been detected already.

Characterize using an effective equation of state:

$$w = p / \rho$$

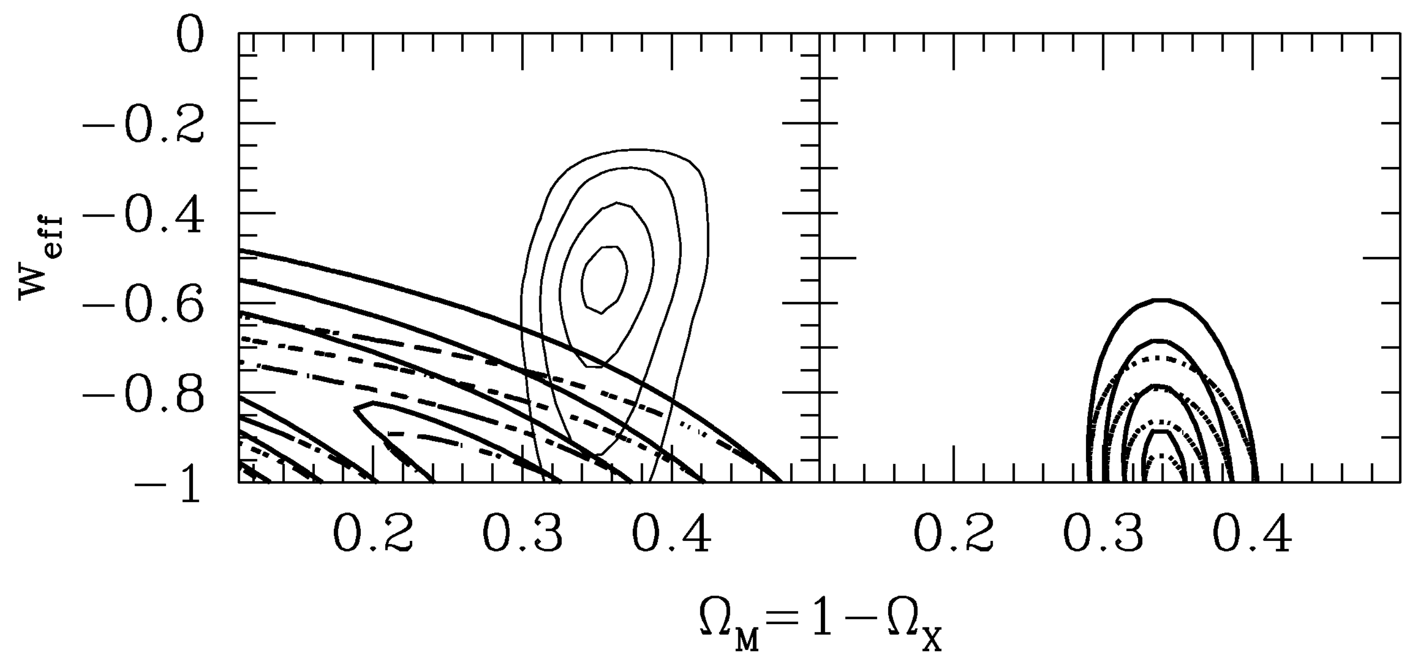
For actual vacuum energy, $w = -1$.

Limits from supernovae and large–scale structure are already pretty good:



[Perlmutter, Turner & White]

Should we consider $w < -1$?



Against: Violates "null dominant energy condition" ($\rho + p > 0$, $|\rho| > |p|$).

For: Remember "How should we deal with theorists?"

Could dark–energy dynamics solve the coincidence problem?

Potentials like $e^{-\phi}$ and $1/\phi$ are popular, but <u>don't</u> solve the coincidence problem!

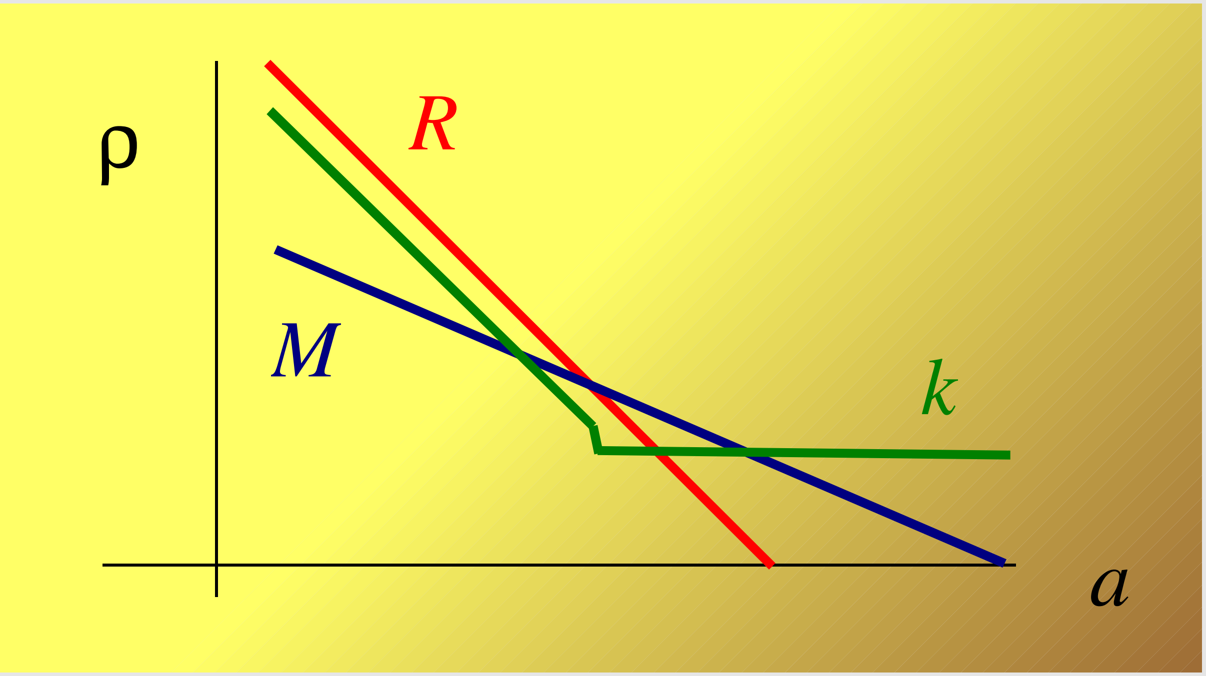
At issue: we need something special about today in order to make today special.

Two possibilities:

- Today is not so far (on a log scale) from matter/radiation equality ($z_{\mathrm{eq}} \sim 10^4$).
- Perhaps acceleration is something that just happens from time to time.

"k–essence": energy density evolves differently during matter– & radiation–dominated eras

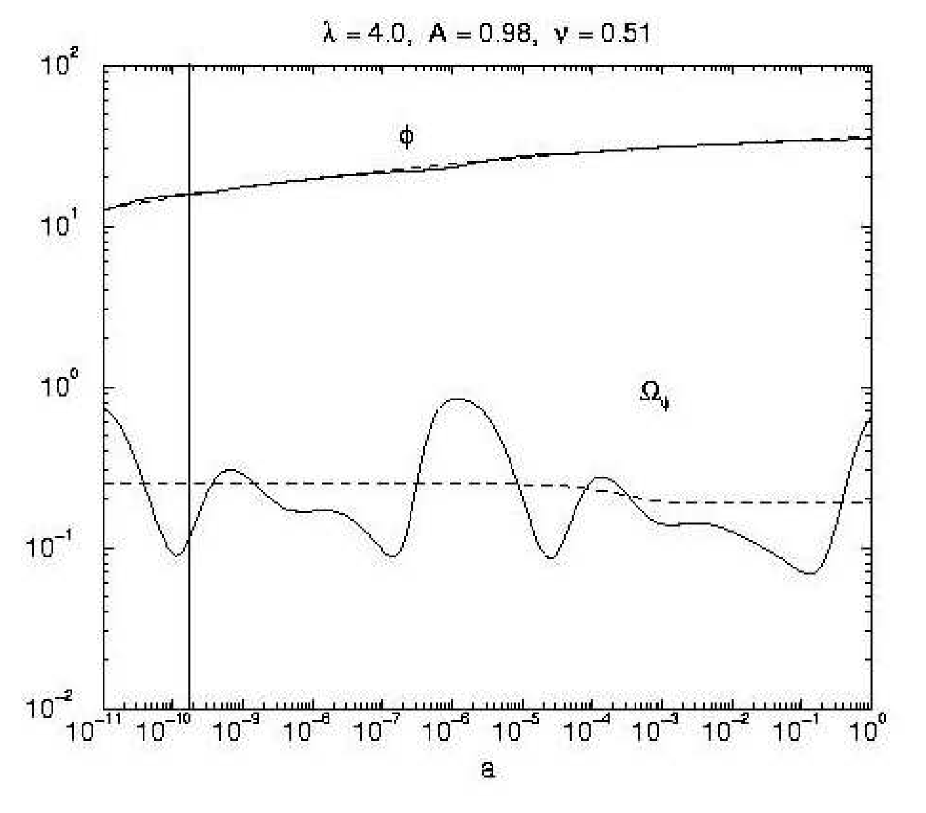
"Tracks" during radiation era, then "sticks" during matter era.



Mechanism: Novel kinetic energy: $L = f(\phi)\, g[(\nabla\phi)^2]$

[Armendariz–Picon,
Mukhanov & Steinhardt]

Oscillating dark energy: just something that happens from time to time.



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

[Dodelson, Kaplinghat & Stewart]

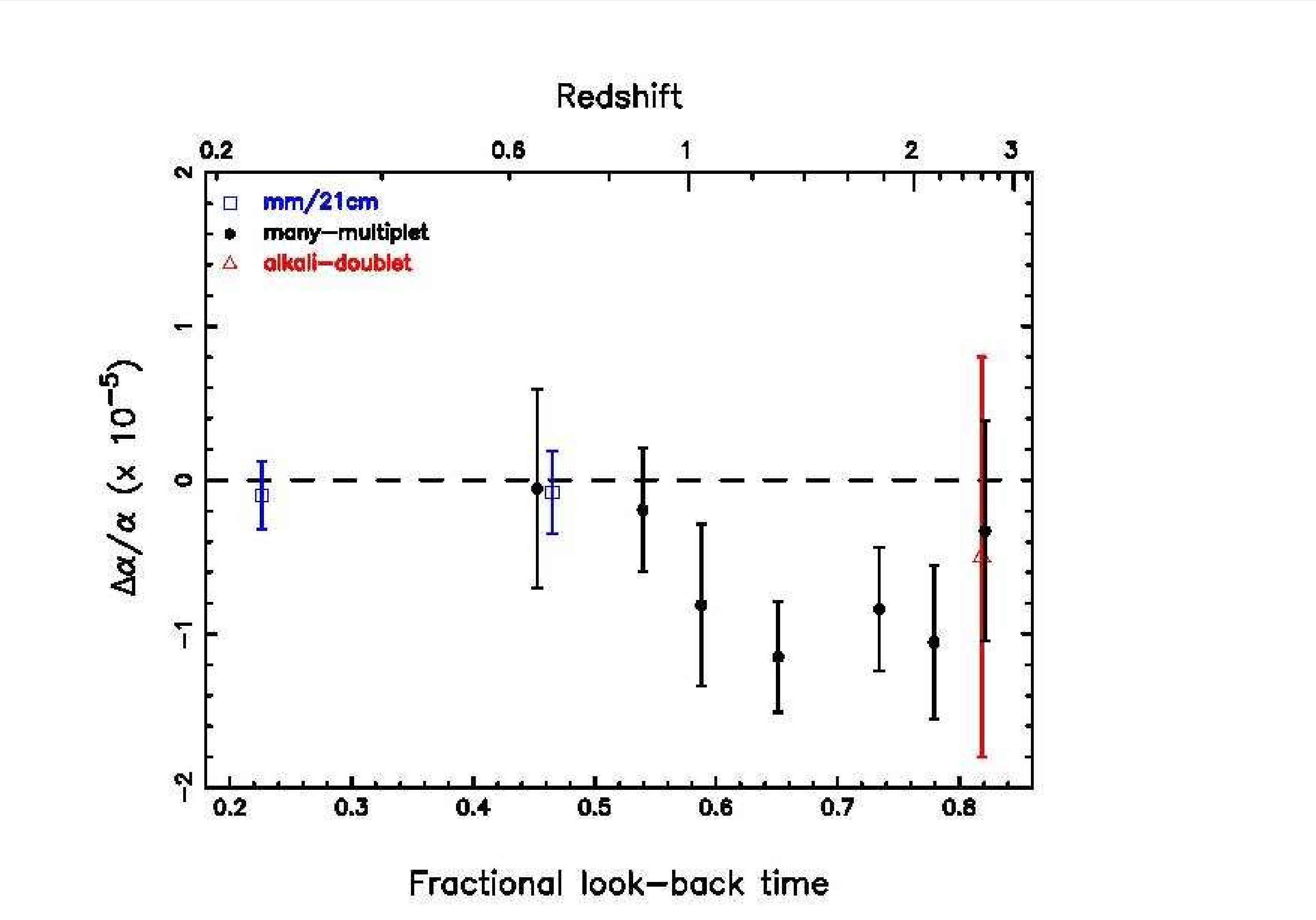
Dark energy has no right to be completely "dark";
it should couple weakly to standard–model fields.

Slowly–rolling, nearly–massless fields lead to long–range "5th forces", in addition to gradual evolution of the "constants" of nature.

To avoid detection in experiments to date, we need to introduce dimensionless couplings of order 10^{-4}–10^{-5} or less.

`on the other hand...`

... maybe α is changing slowly with time?



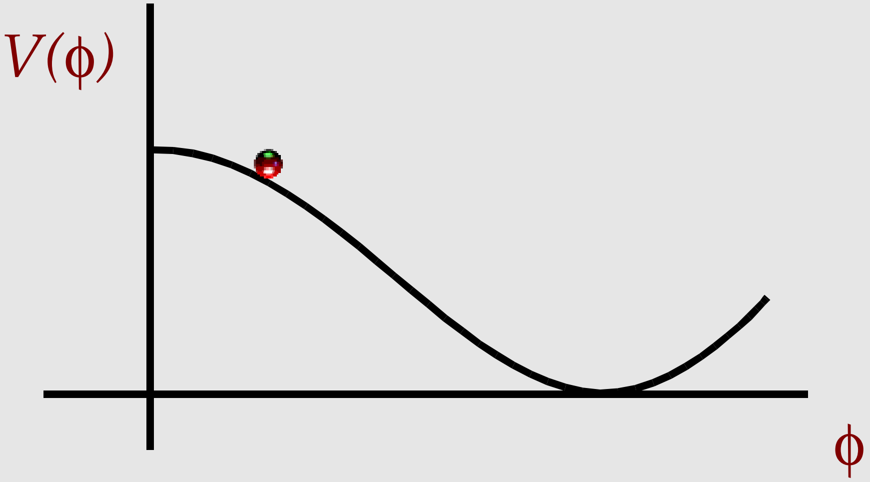
[Webb et al.]

Sensible particle physics models?

Pseudo–Goldstone bosons: approx symmetry $\phi \to \phi + const.$

Naturally small masses; naturally small couplings.

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



No tracking behavior; any effective *w* possible.
Possible signature: cosmological birefringence.

[Hill, Freiman, et al; Carroll]

Dynamical dark energy doesn’t <u>have</u> to be a rolling scalar field.

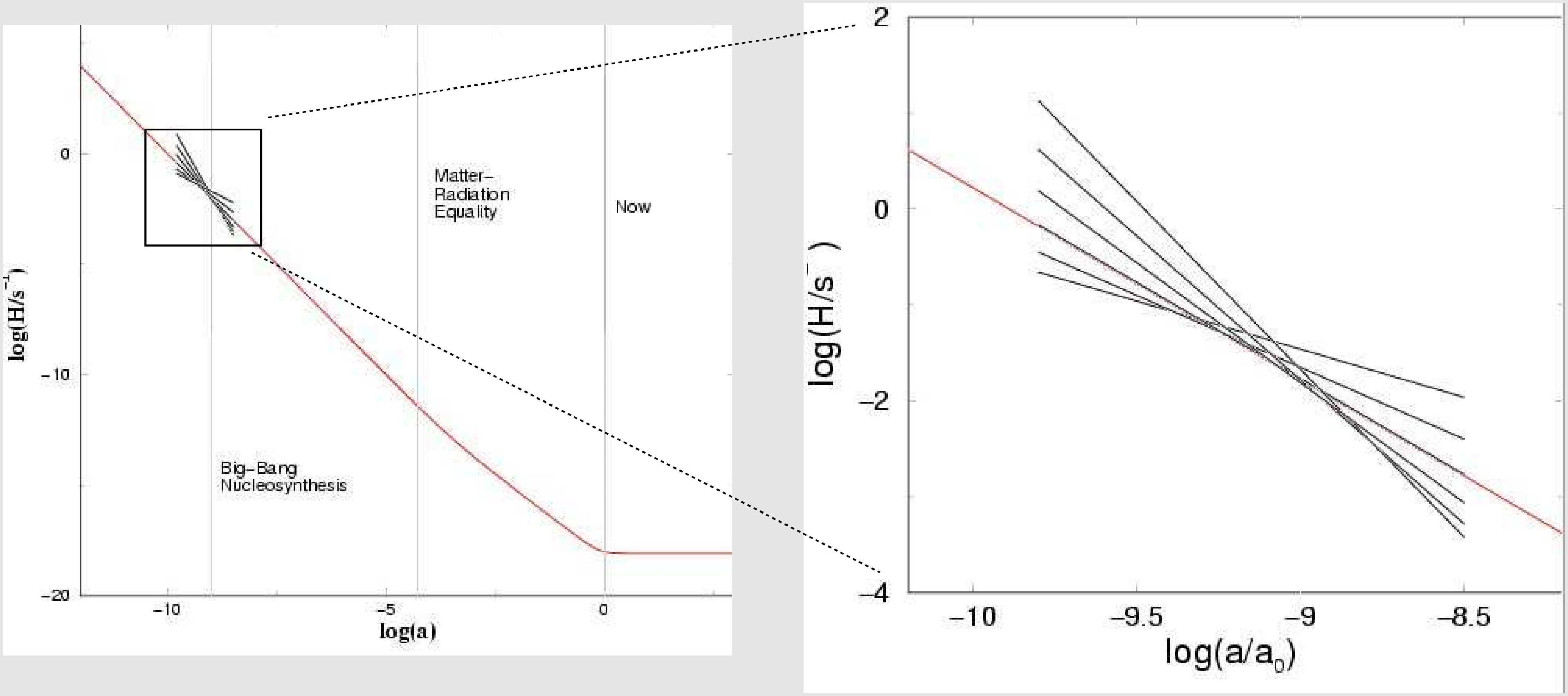
Some alternatives:

- A web of tangled topological defects (i.e. a "solid")
  [Vilenkin, Bucher, Pen, Spergel]
- Dark–matter particles with gradually increasing masses (so $\rho \sim nm$ diminishes more slowly than a^{-3})
  [Anderson & Carroll]
- Ultra–short wavelength (transplanckian) modes
  [Bastero–Gill, Mersini]
- Curved–spacetime renormalization effects
  [Parker & Raval]

4) Was Einstein wrong?

Extra dimensions, scalar fields, holography...
Issue: numerous observational constraints.

e.g., expansion history during Big Bang Nucleosynthesis:



[Carroll & Kaplinghat]

Notice: there is a coincidence problem!

It’s conceivable that GR breaks down at ultra–low curvatures. (But would be weird.)

Could a single modification of gravity explain both dark energy and dark matter?

Milgrom (infamously) points out: galactic dark matter is only required for accelerations

$$a/c < 10^{-18} s^{-1}$$

Meanwhile, the universe starts accelerating when the Hubble constant reaches

$$H_0 \approx 10^{-18} s^{-1}$$

Coincidence? Probably.

[see e.g. Kaplinghat & Turner]

Conclusions

- Something dark and mysterious is going on.
- An ordinary cosmological constant is a perfect fit, even if we can’t explain it.
- Dynamical mechanisms are interesting and testable; they also raise additional problems.
- Answering this question will tell us something extremely profound: either about particle physics or about gravity, and certainly about cosmology.