Dark Energy, or Worse?

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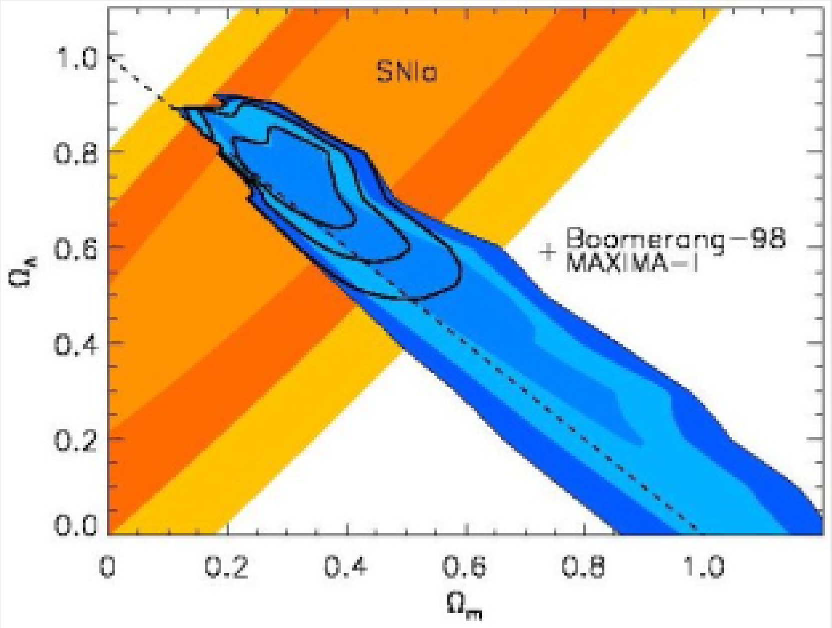
Observation tells us: the universe is spatially flat (CMB) and accelerating (SNe).



[Jaffe et al.]

There is a straightforward interpretation: The universe is dominated by "dark energy", essentially smooth and slowly−varying, comprising 70% of the total energy density.

Simplest candidate: vacuum energy,

$$\rho_{vac}(t, \vec{x}) = const.$$

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

This raises (at least) two big problems:

- Why is $\rho_{vac} \approx 10^{-120} M^4_{planck}$?
- Why is $\rho_{vac} \sim \rho_{Matter}$?

What might be going on?

Possibilities include:

1. The vacuum energy ("true" or "false") is small, but nonzero.
2. A slowly−varying dynamical component is mimicking a vacuum energy.
3. Einstein was wrong.

1) Might the true vacuum energy be nonzero?

Some numerology:

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

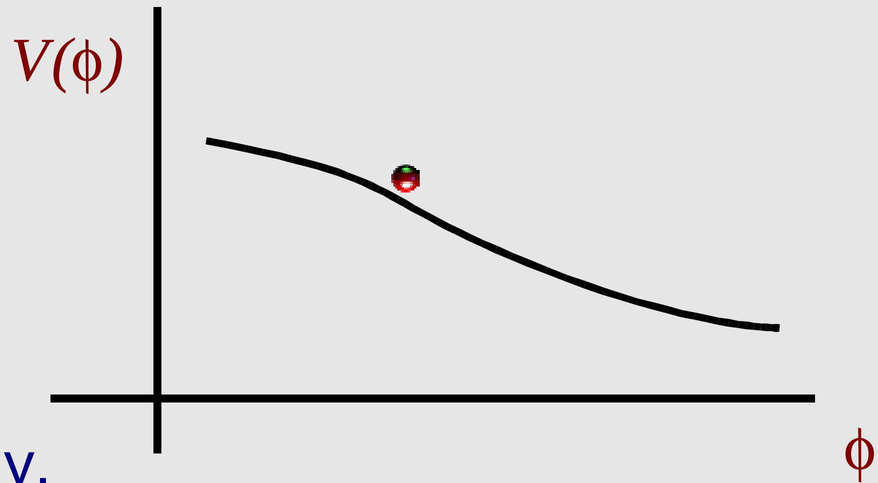
$$M_{vac}^4 = e^{-2/\alpha} M_{Planck}^4$$

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

Perfectly reasonable people are driven to invoke the anthropic principle.

2) 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.
- Solve the coincidence problem?

Bad:

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

Characterize using an effective equation of state:

$$p = w\,\rho\ .$$

For actual vacuum energy, $w = -1$ (forever).

The more negative pressure (negative w), the more acceleration you get:

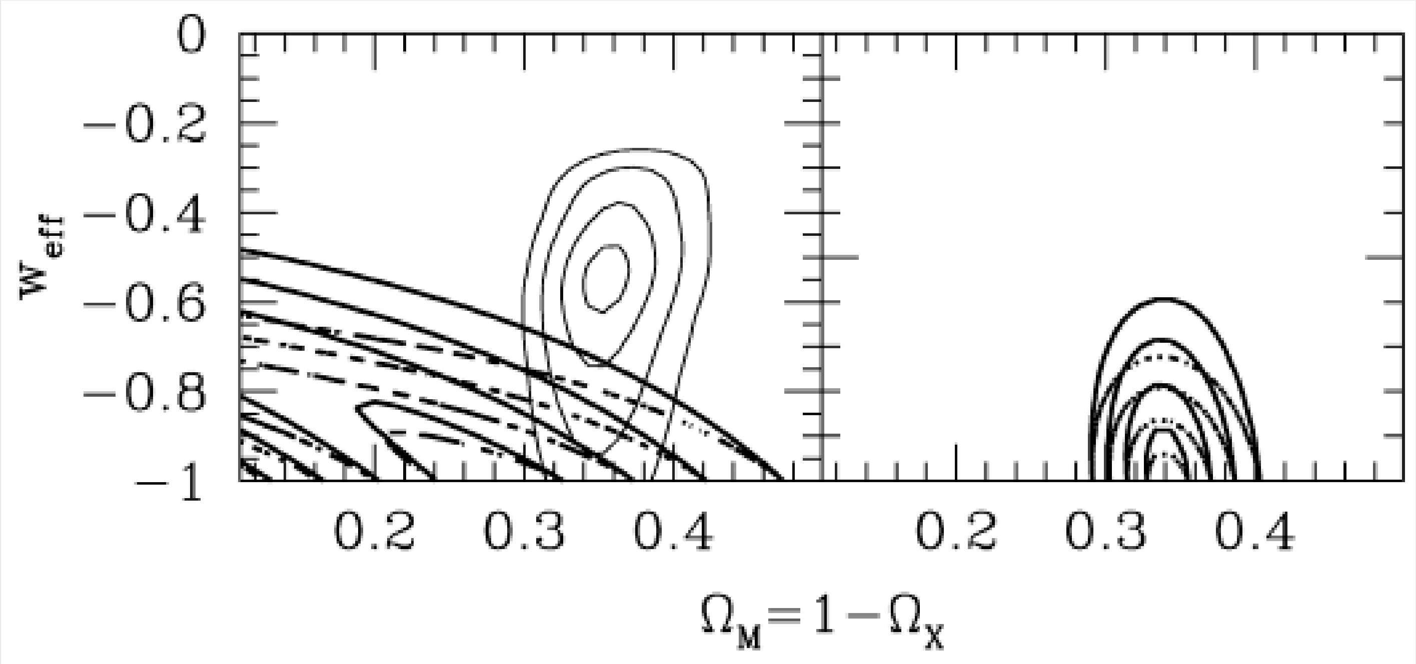
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p).$$

w

First thing to ask: is the dark energy dynamical?

$$(\,w \neq -1 \quad \text{or} \quad w' \neq 0\,)$$

Limits from SNe and LSS are already pretty good:



[Perlmutter, Turner & White]

Should we consider $w < -1$?

Against: Violates "null dominant energy condition" ($\rho + p > 0$, $|\rho| > |p|$); might allow faster−than−light transmission of energy.

For: We are clueless about dark energy, and should be correspondingly humble.

Could dark−energy dynamics 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 ($z_{eq} \sim 10^4$).

[e.g. "k−essence": Armendariz−Picon, Mukhanov & Steinhardt]

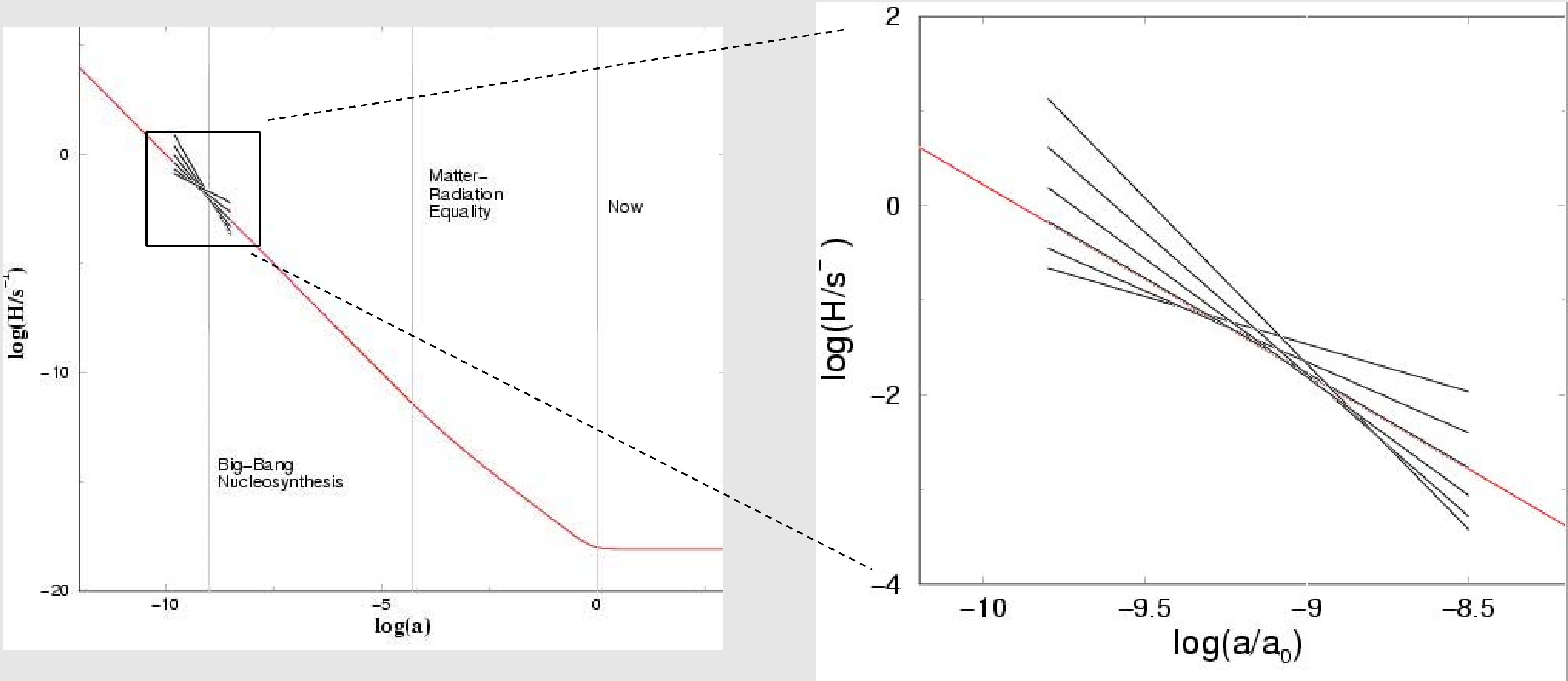
- Perhaps acceleration is something that just happens from time to time.

[e.g. "oscillating dark energy": Dodelson, Kaplinghat & Stewart]

4) Was Einstein wrong?

Issue: numerous observational constraints.

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



Notice: there is a coincidence problem!

[Carroll & Kaplinghat]

Conclusion:

We know much, we understand nothing.