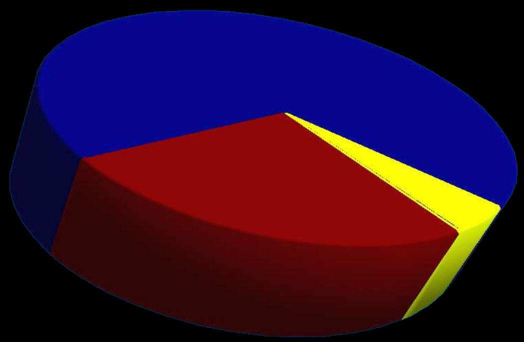
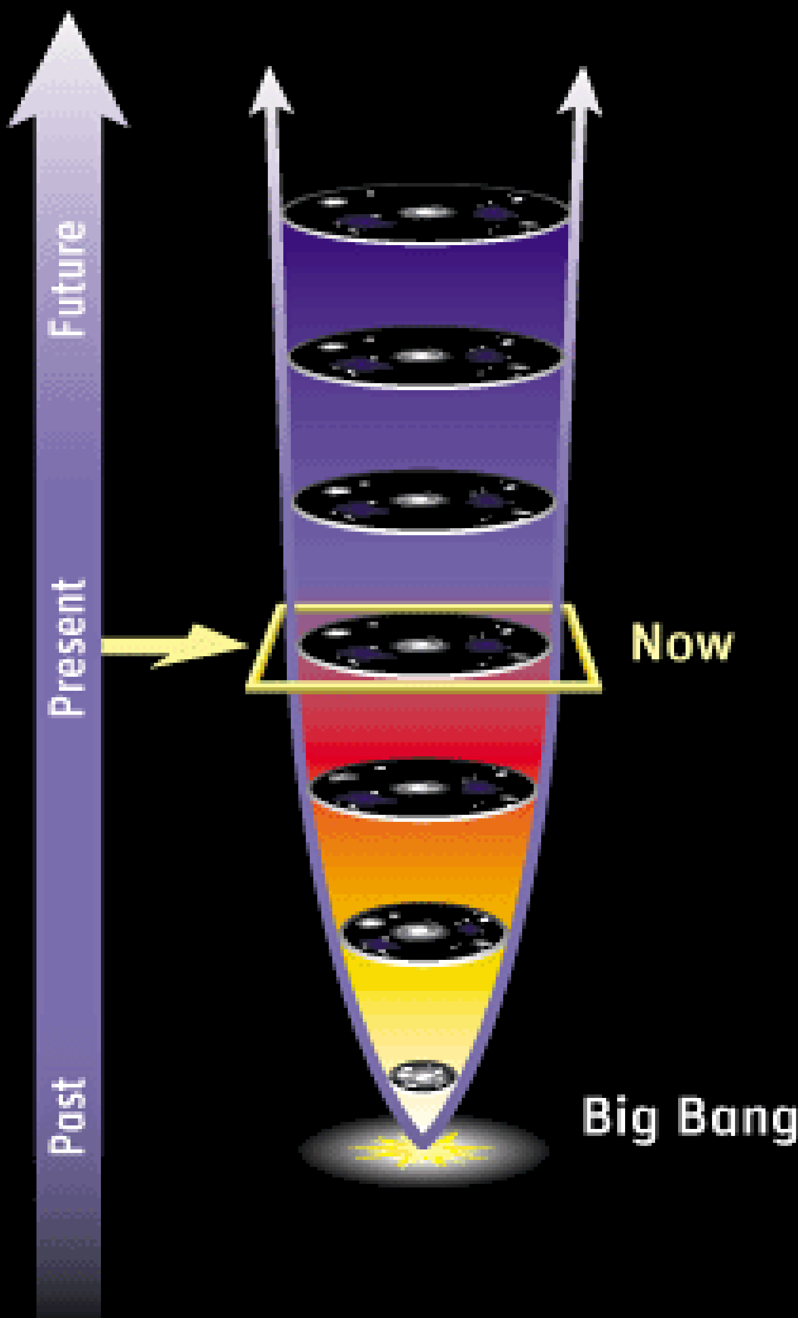
Dark Energy, or Worse?

Sean Carroll, University of Chicago

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

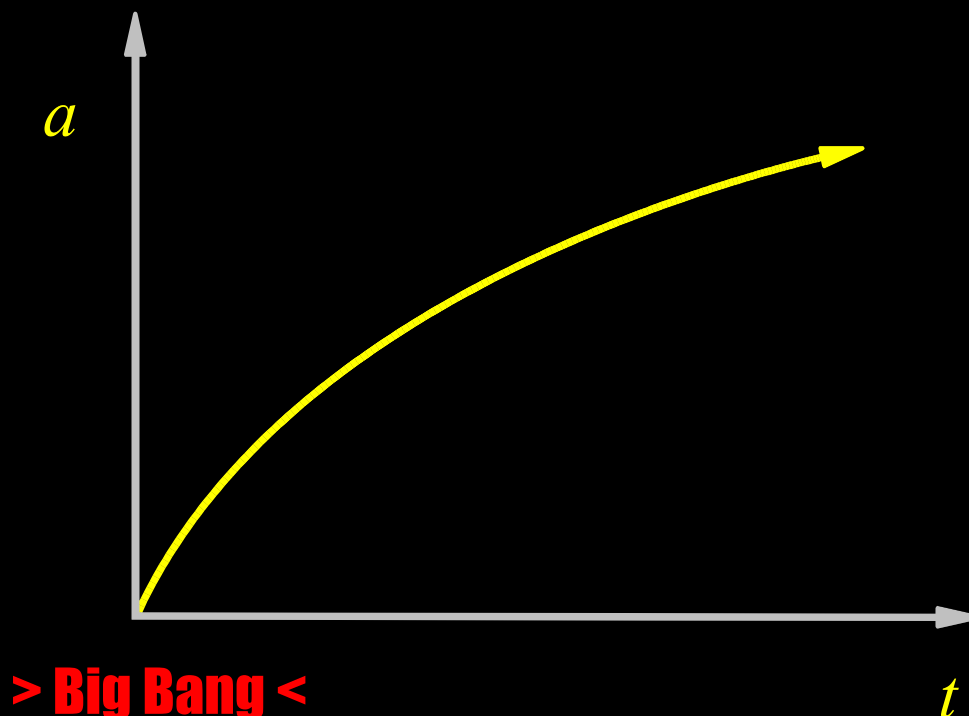


We have a model of the universe that fits the data, but makes no sense. What now?



[Sky & Telescope]

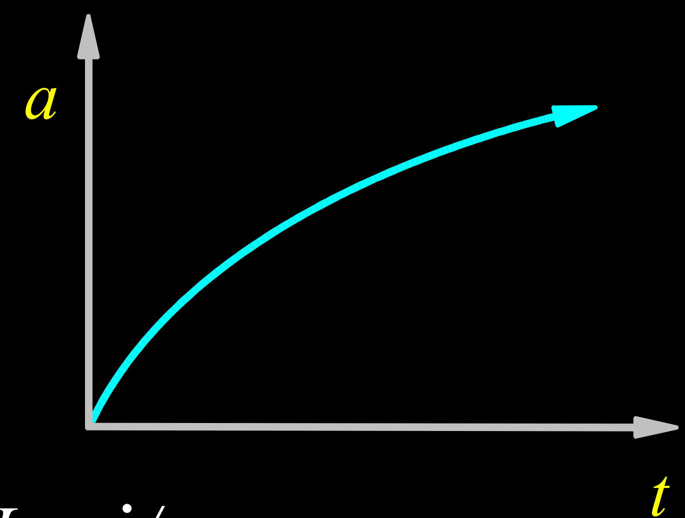
The universe: uniform (homogeneous and isotropic) space expanding with time.



Relative size at different times is measured by the scale factor $a(t)$.

General Relativity relates the expansion rate H (the "Hubble constant") to the energy density ρ (ergs/cm^3) and the spatial curvature κ:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{\kappa}{a^2}$$



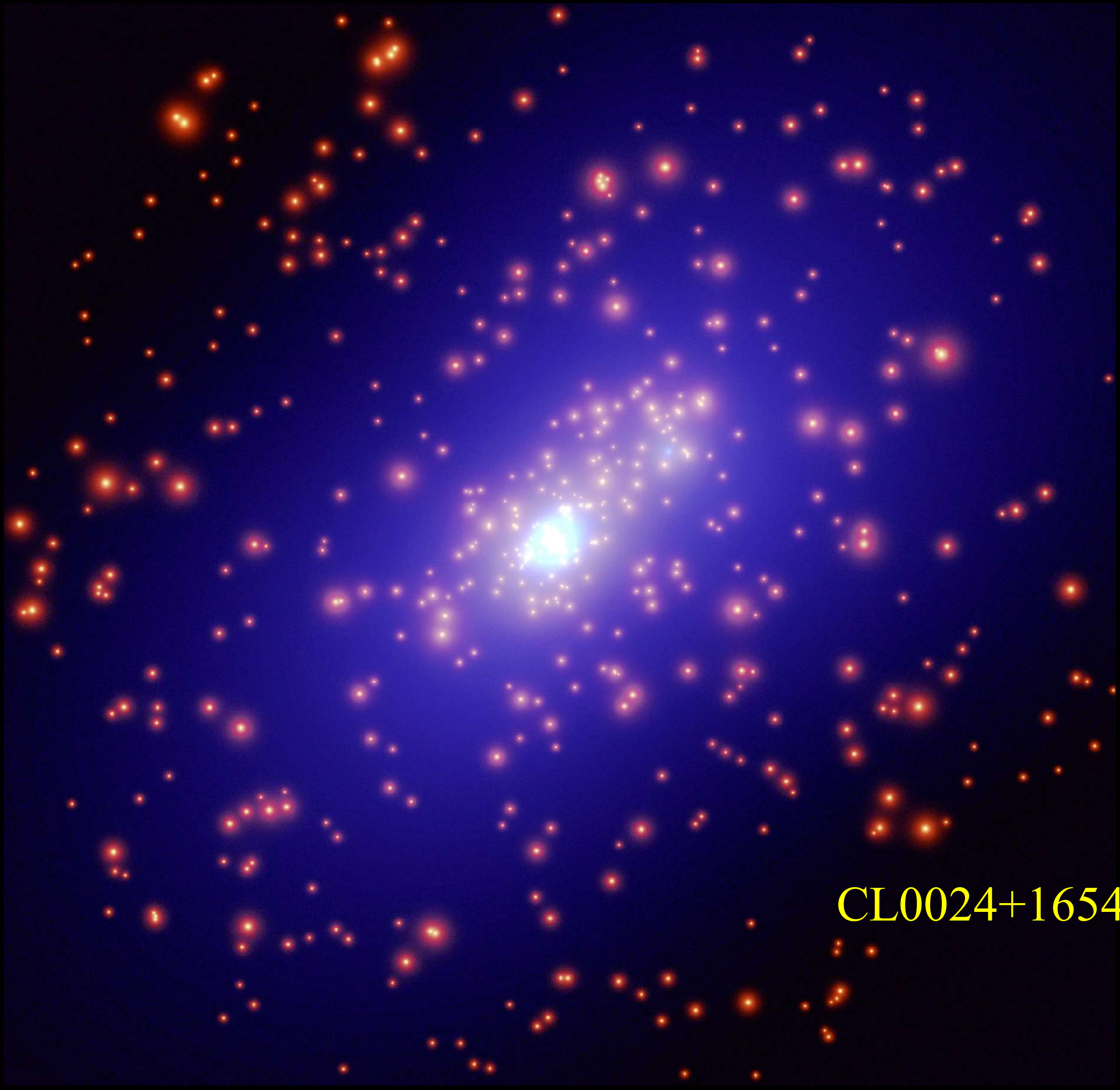
H is related to the scale factor by $H = \dot{a}/a$.
You can figure out the history of the universe if you know how ρ scales as a function of a.

So cosmologists want to know: what kind of stuff makes up the universe, and how does it evolve with a?

Some matter is “ordinary” -- protons, neutrons, electrons, for that matter any of the particles of the Standard Model. But much of it is dark.

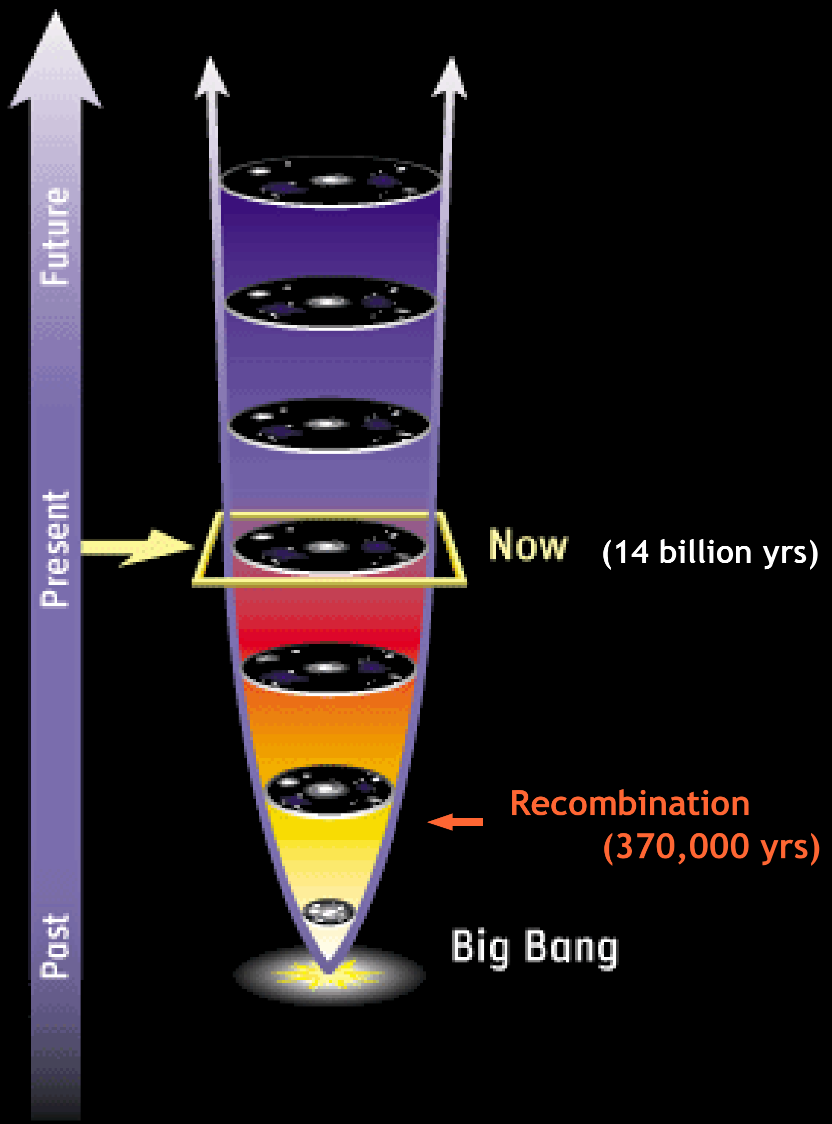
We can detect dark matter through its gravitational field – e.g. through gravitational lensing of background galaxies by clusters.

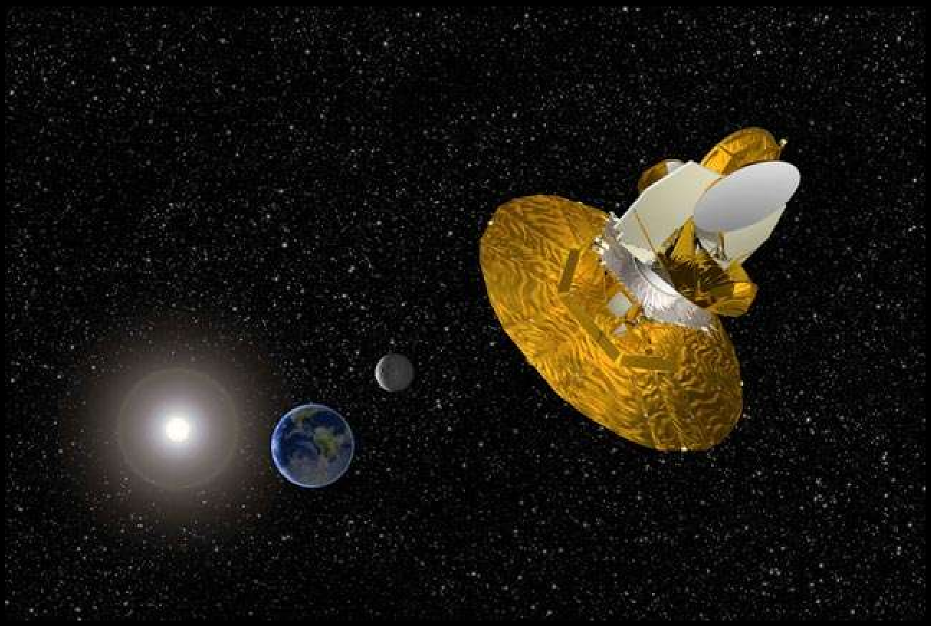
Whatever the dark matter is, it's not a particle we've discovered – it's something new.



[Kneib et al.]

Most of the photons in our universe are in the Cosmic Microwave Background (CMB) – the leftover blackbody radiation from the Big Bang.





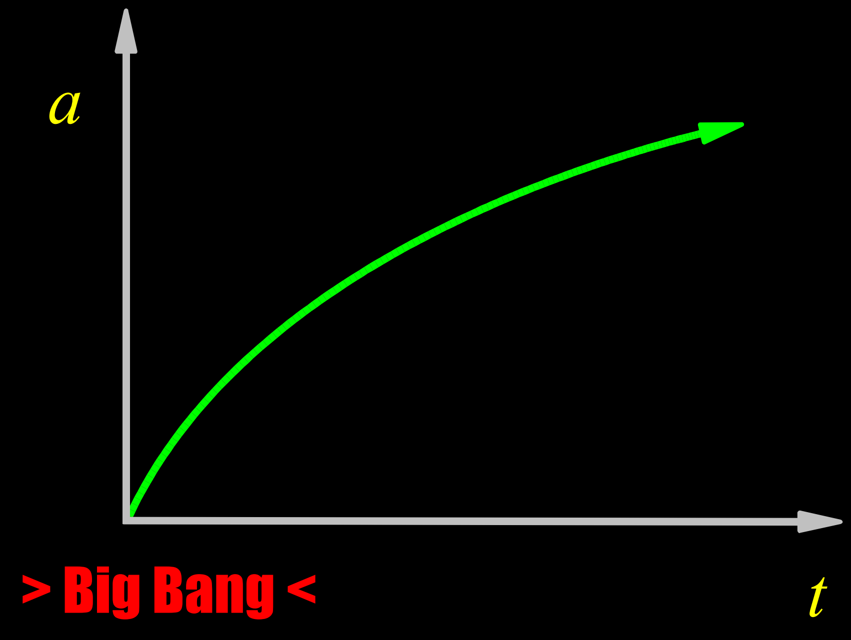
Experiments like the Wilkinson Microwave Anisotropy Probe (WMAP) satellite allow us to observe tiny fluctuations in the 2.7K CMB radiation.

The Friedmann equation with matter and radiation:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\left(\frac{\rho_{M0}}{a^3} + \frac{\rho_{R0}}{a^4}\right) - \frac{\kappa}{a^2}$$

Multiply by a^2 to get: $$\dot{a}^2 \propto \frac{\rho_{M0}}{a} + \frac{\rho_{R0}}{a^2} + const$$

If *a* is *increasing*, each term on the right is *decreasing*; we therefore predict the universe should be <u>decelerating</u> ($\dot{a}$ decreasing).



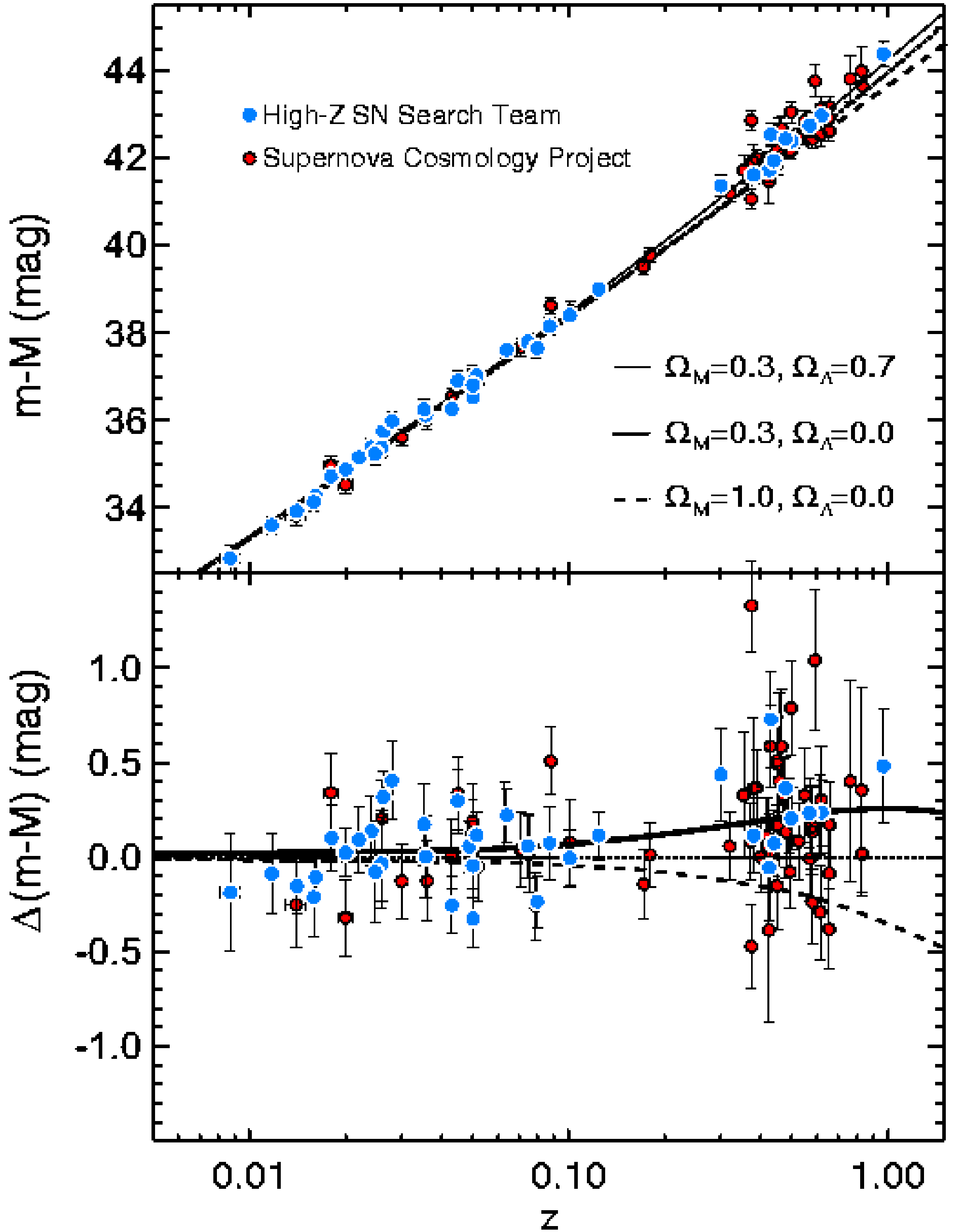
But it isn't.

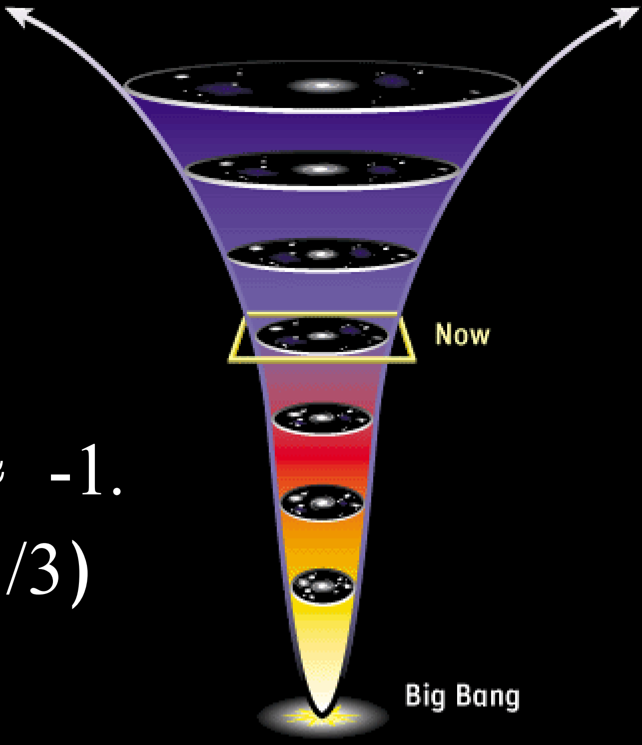
Type Ia supernovae are standardizable candles; observations of many at high redshift test the time evolution of the expansion rate.

Result: the universe is accelerating!

There seems to be a sort of energy density which doesn't decay away: "dark energy."

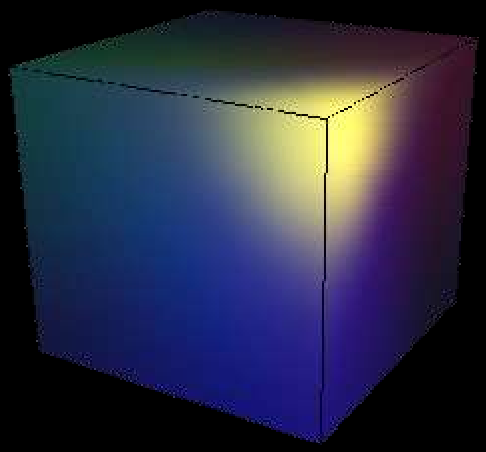
[Riess et al.; Perlmutter et al.]





Dark Energy is characterized by:

- smoothly distributed through space
- varies slowly (if at all) with time
- --> has negative pressure, $w = p/\rho \approx -1$.
  (causes acceleration when $w < -1/3$)

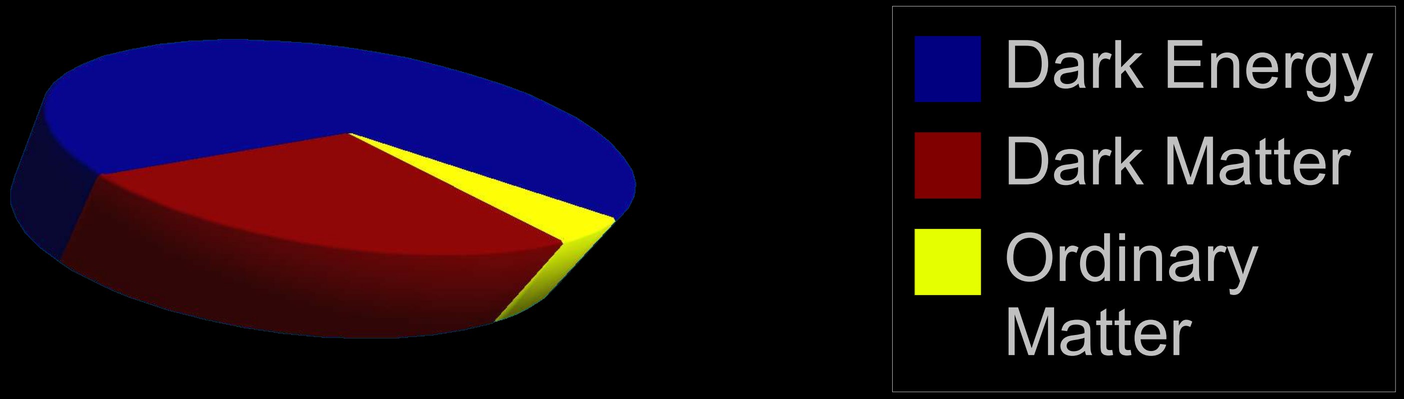


(artist's impression of vacuum energy)

Paradigmatic candidate:
vacuum energy (a/k/a the cosmological constant, Λ).
An immutable energy inherent in every cubic centimeter of space.

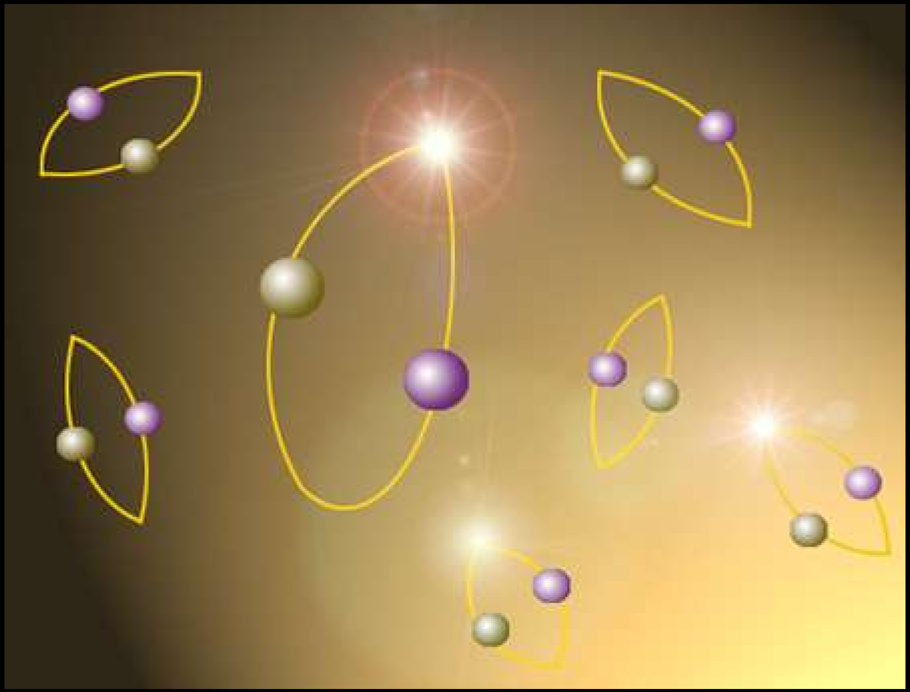
The final accounting seems to be:

5% Ordinary Matter
25% Dark Matter
70% Dark Energy

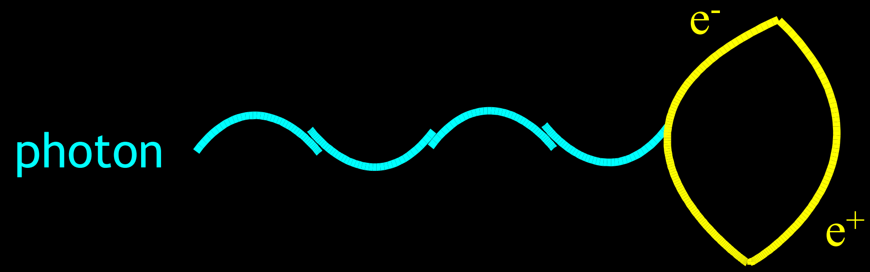


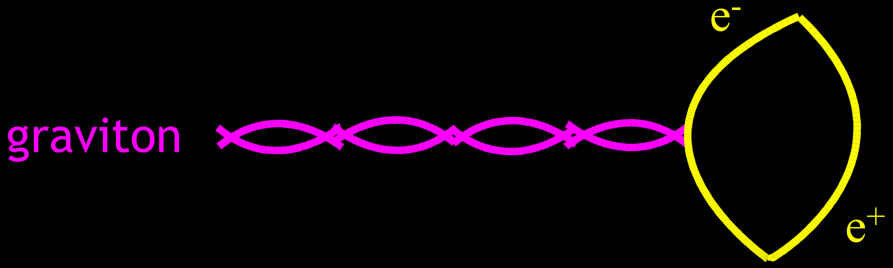
This is a preposterous universe.
Are we sure that we're on the right track?

Why is the vacuum energy so small?



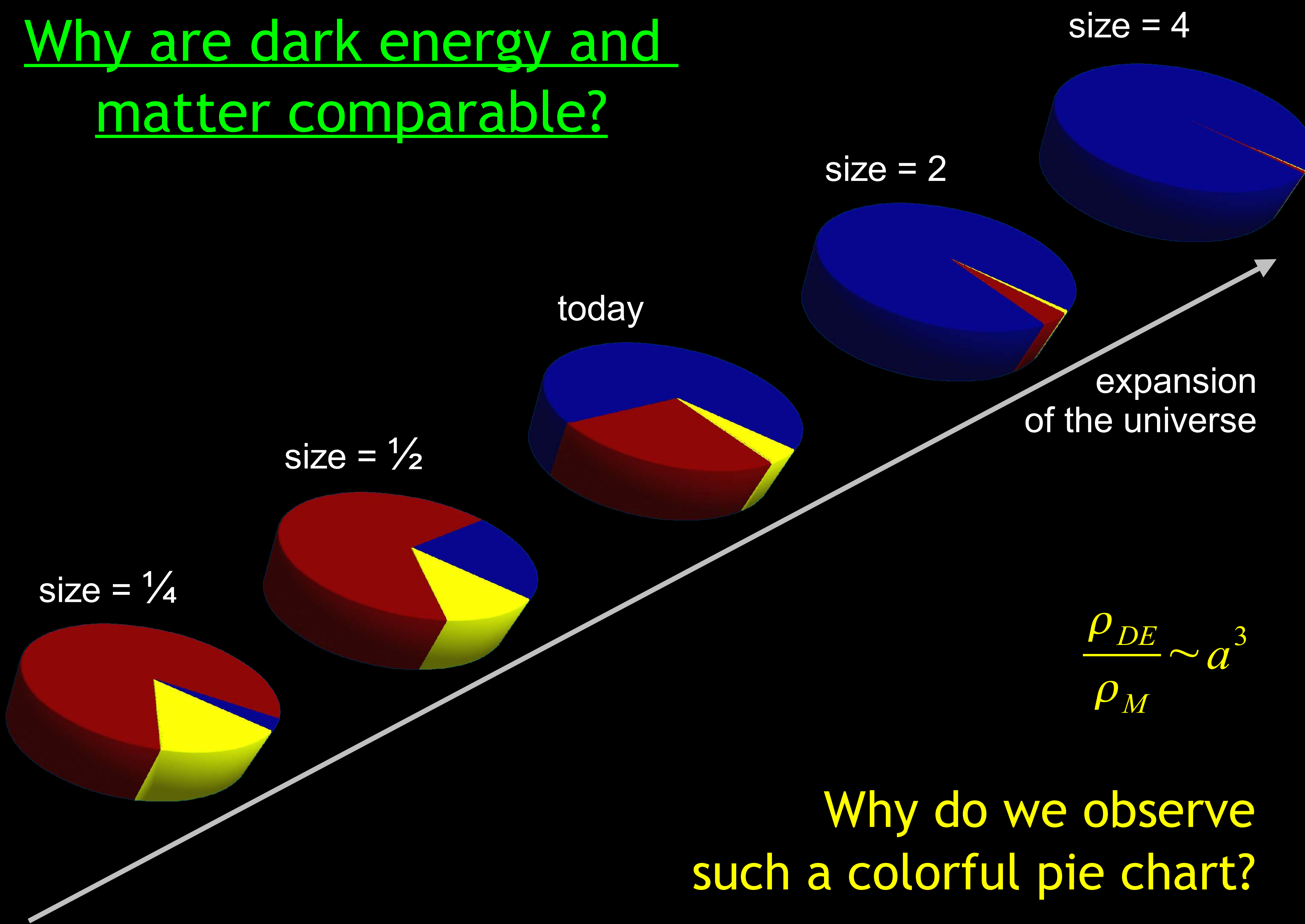
We know that virtual particles couple to photons (e.g. Lamb shift); why not to gravity?





Naively: $\rho_{vac} = \infty$, or at least $\rho_{vac} = E_{Pl}/L_{Pl}^3 = 10^{120}\,\rho_{vac}^{(obs)}$.

Why are dark energy and matter comparable?



$$\frac{\rho_{DE}}{\rho_M} \sim a^3$$

Why do we observe
such a colorful pie chart?

Why is the universe accelerating?

A flowchart of possibilities:

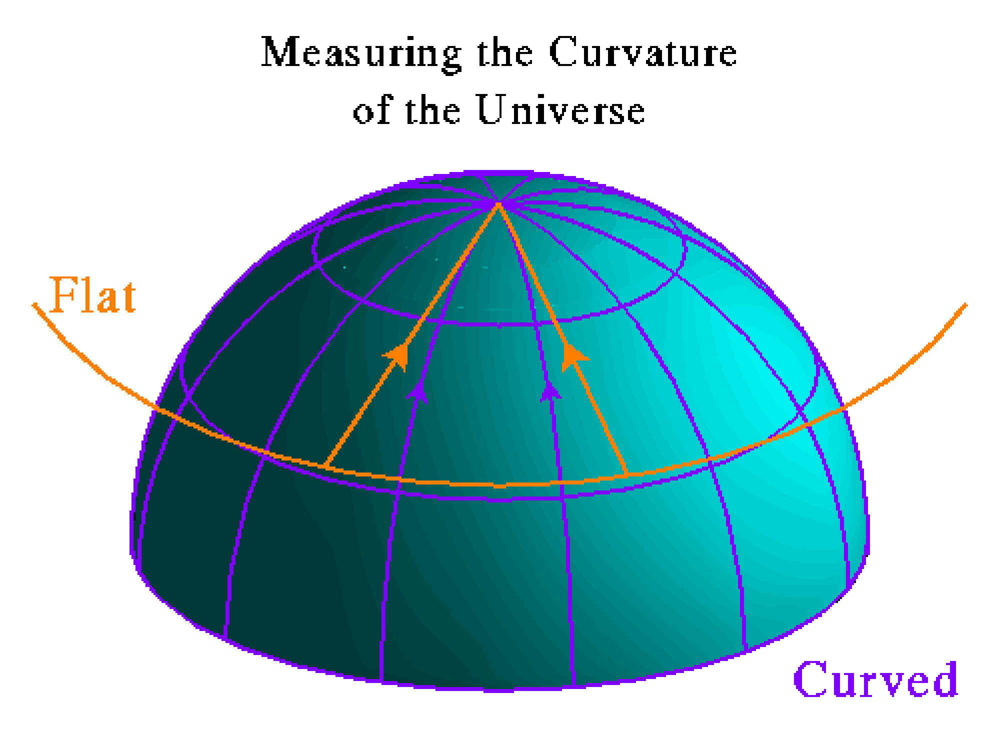
Is the universe actually accelerating?

↓ N

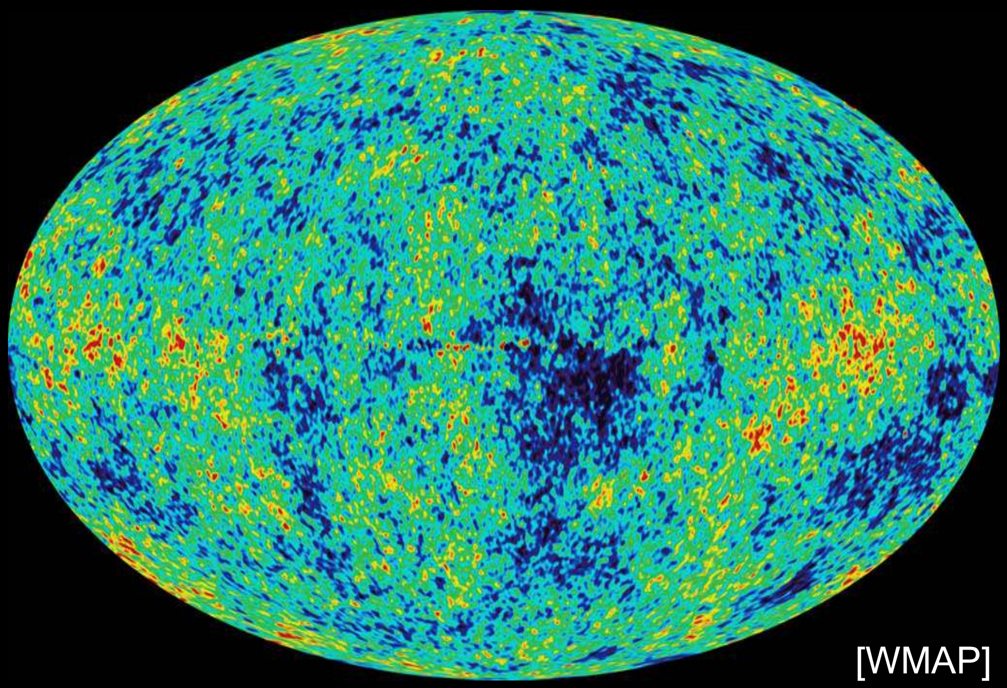
Misinterpreted data

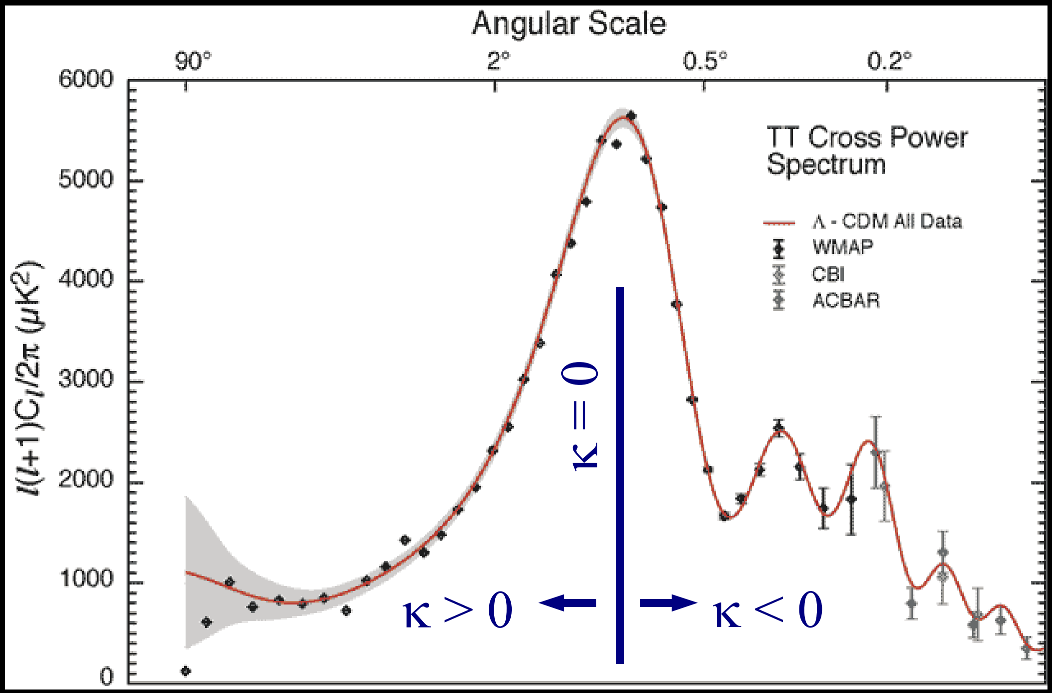
Could we simply be misinterpreting the data?

This preposterous universe has just enough energy to make the spatial curvature vanish: a flat universe (κ = 0). We can check this by using a standard triangle, happily provided by temperature fluctuations of the CMB.



Fluctuations in the Cosmic Microwave Background peak at a characteristic length scale of 370,000 light years; observing the corresponding angular scale measures the geometry of space.



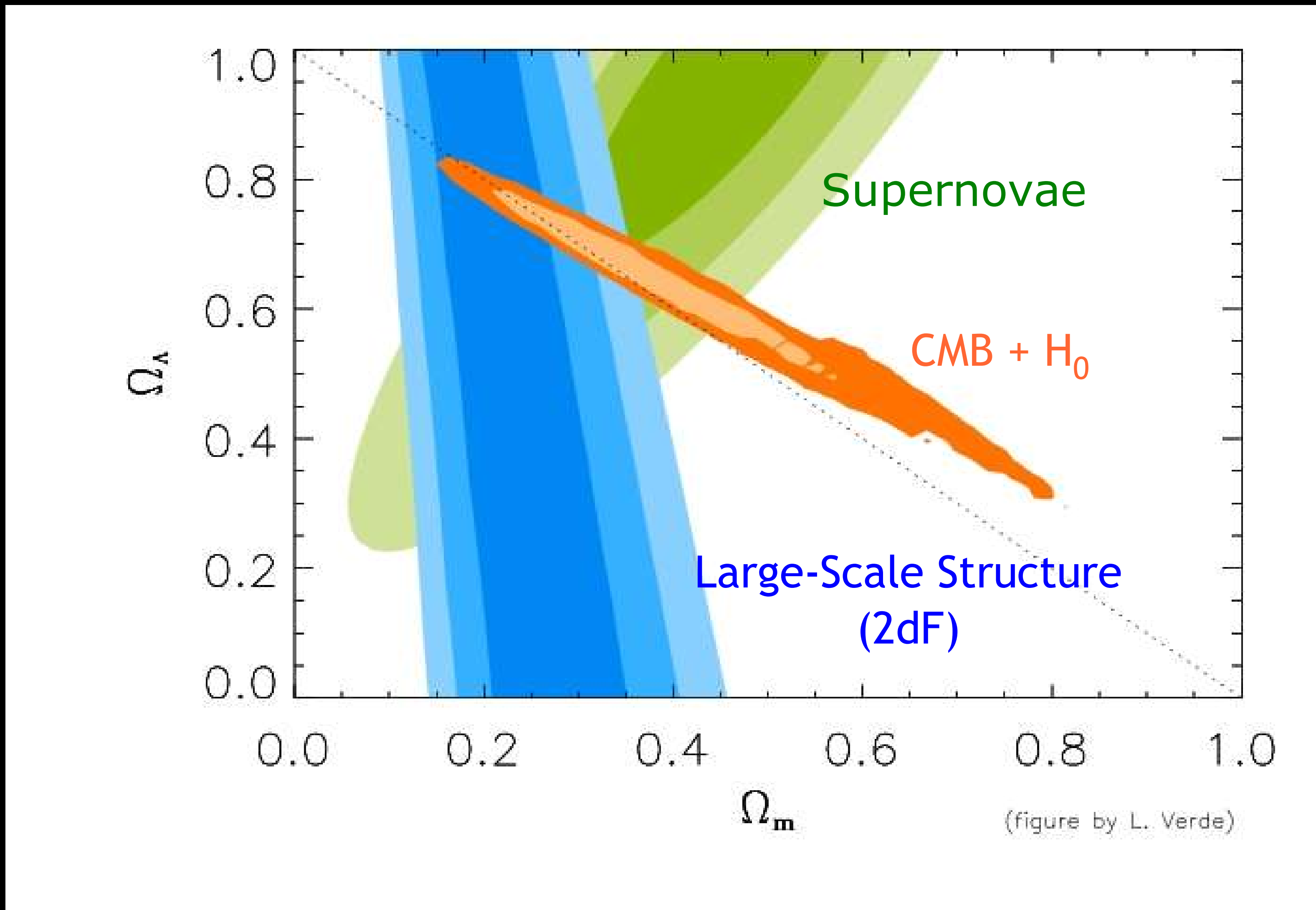


Take angular power spectrum of temperature fluctuations; the position of the peak is a curvature-meter.

Observation: $\theta_{peak} = 1^o$.

Consistent with a flat universe: $\kappa = 0$.

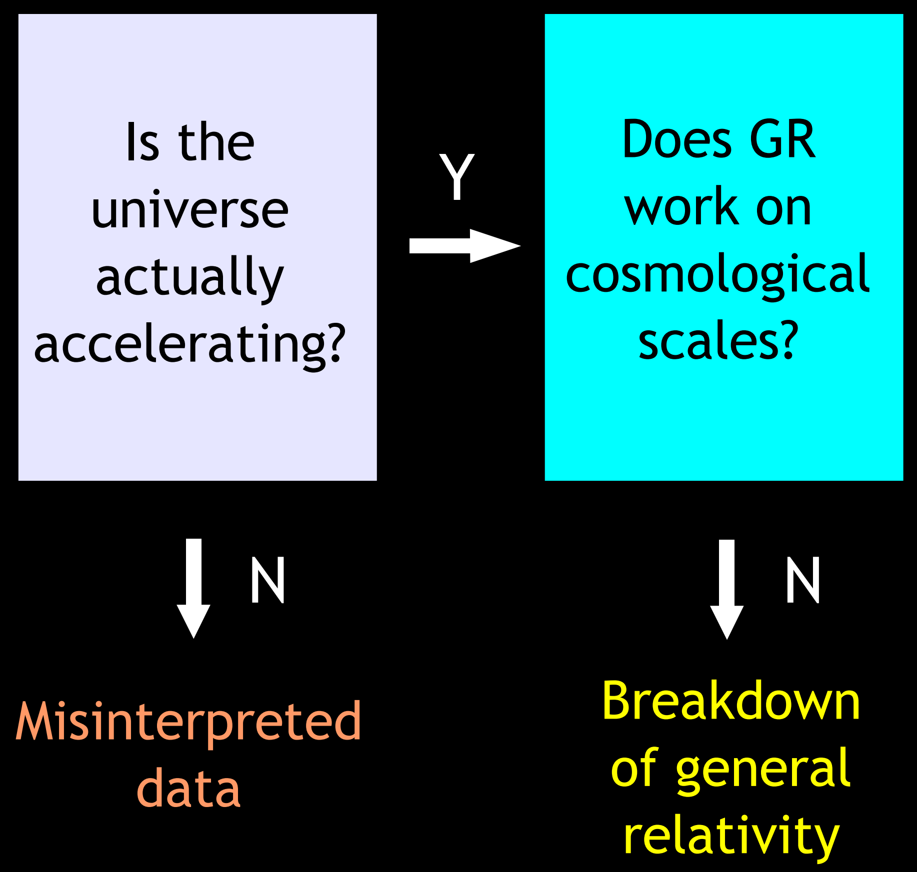
Express density in terms of density parameter, $\Omega = \dfrac{8\pi G}{3H^2}\rho$



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

Why is the universe accelerating?

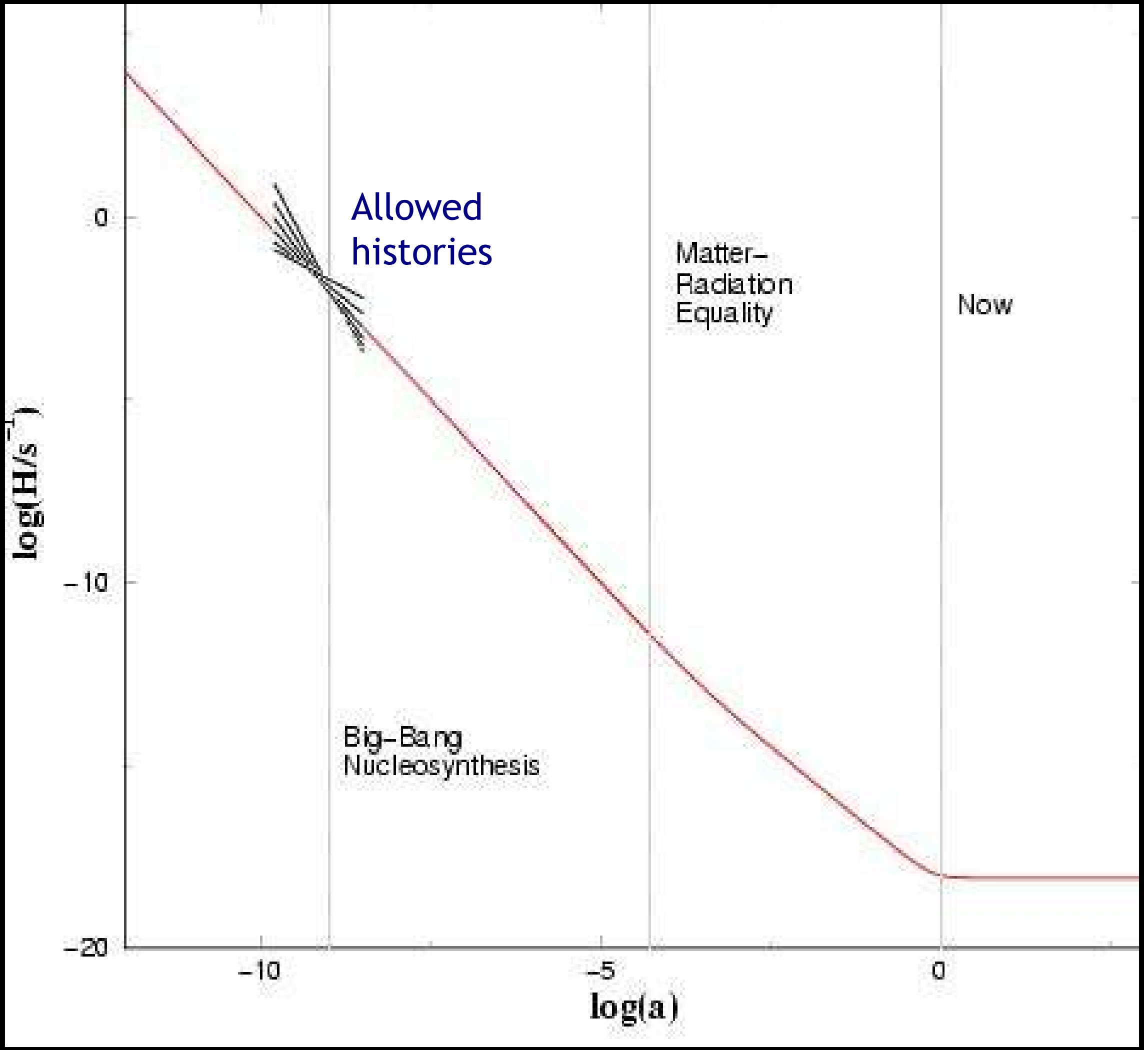
A flowchart of possibilities:



Was Einstein wrong?

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.

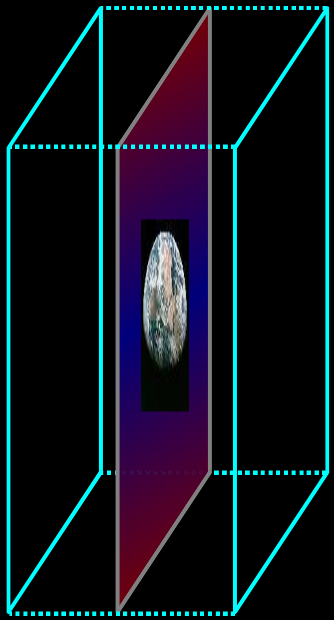


[Carroll & Kaplinghat]

Notice: there is a coincidence problem!

Can branes make the universe accelerate?

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



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

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

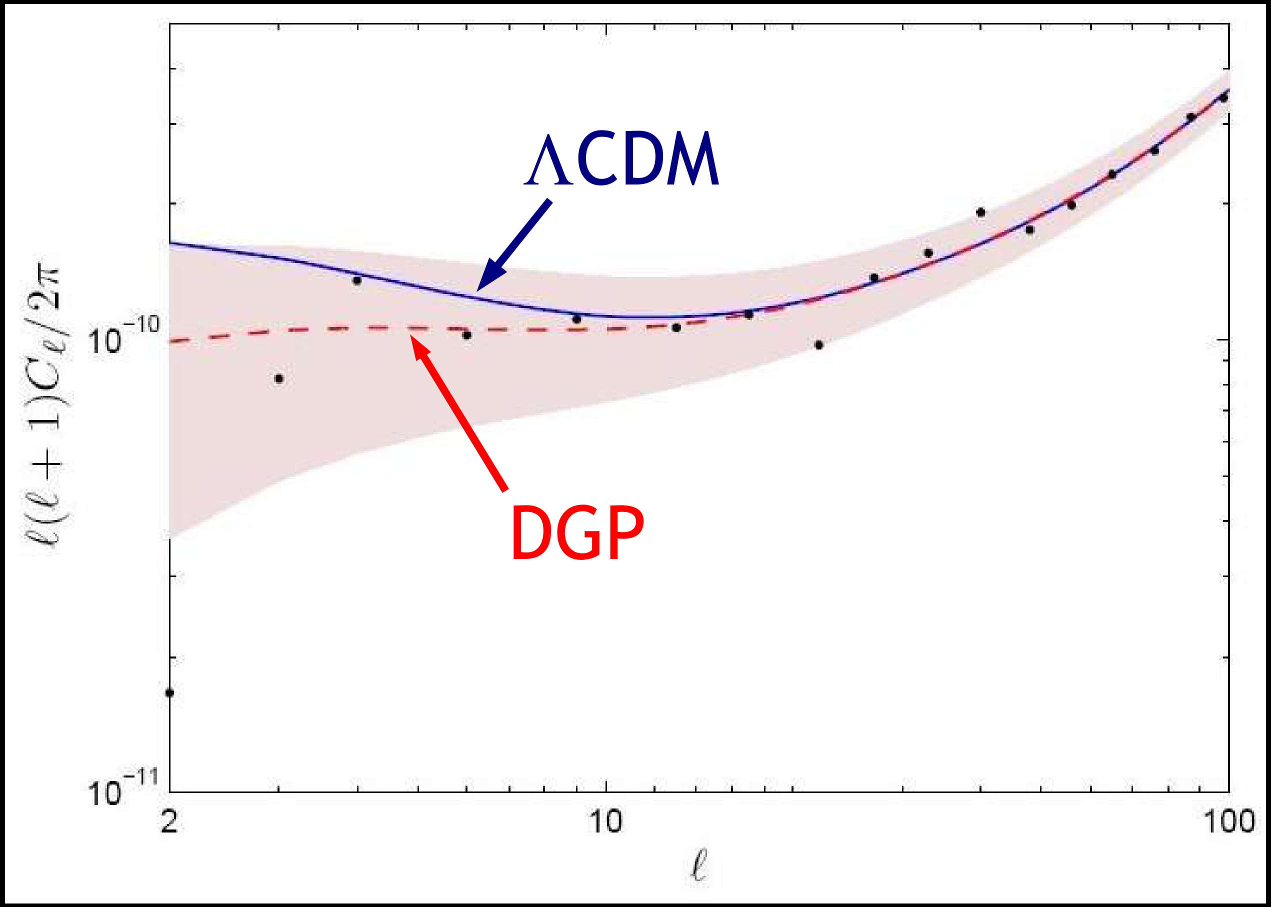
Imagine that somehow the cosmological constant is set to zero in both brane and bulk. The DGP version of the Friedmann equation is then

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

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

The acceleration is somewhat mild; equivalent to an equation-of-state parameter $w_{eff} \sim -0.7$ – on the verge of being inconsistent with present data.

We have studied <u>perturbation growth</u> in DGP. Interestingly, DGP fits WMAP better than ΛCDM does, since it predicts less "integrated Sachs-Wolfe"; small power on large scales.



[Sawicki & Carroll 2005]

But: it's a tiny improvement. And ΛCDM fits the Supernova data better, as well as the combined SNe+CMB sets.

Can we modify gravity purely in four dimensions, with an ordinary field theory?

We'd like something that matches Einstein in the early universe (large spacetime curvature R), but deviates when R gets small in the late universe. Simplest possibility: replace

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

with

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

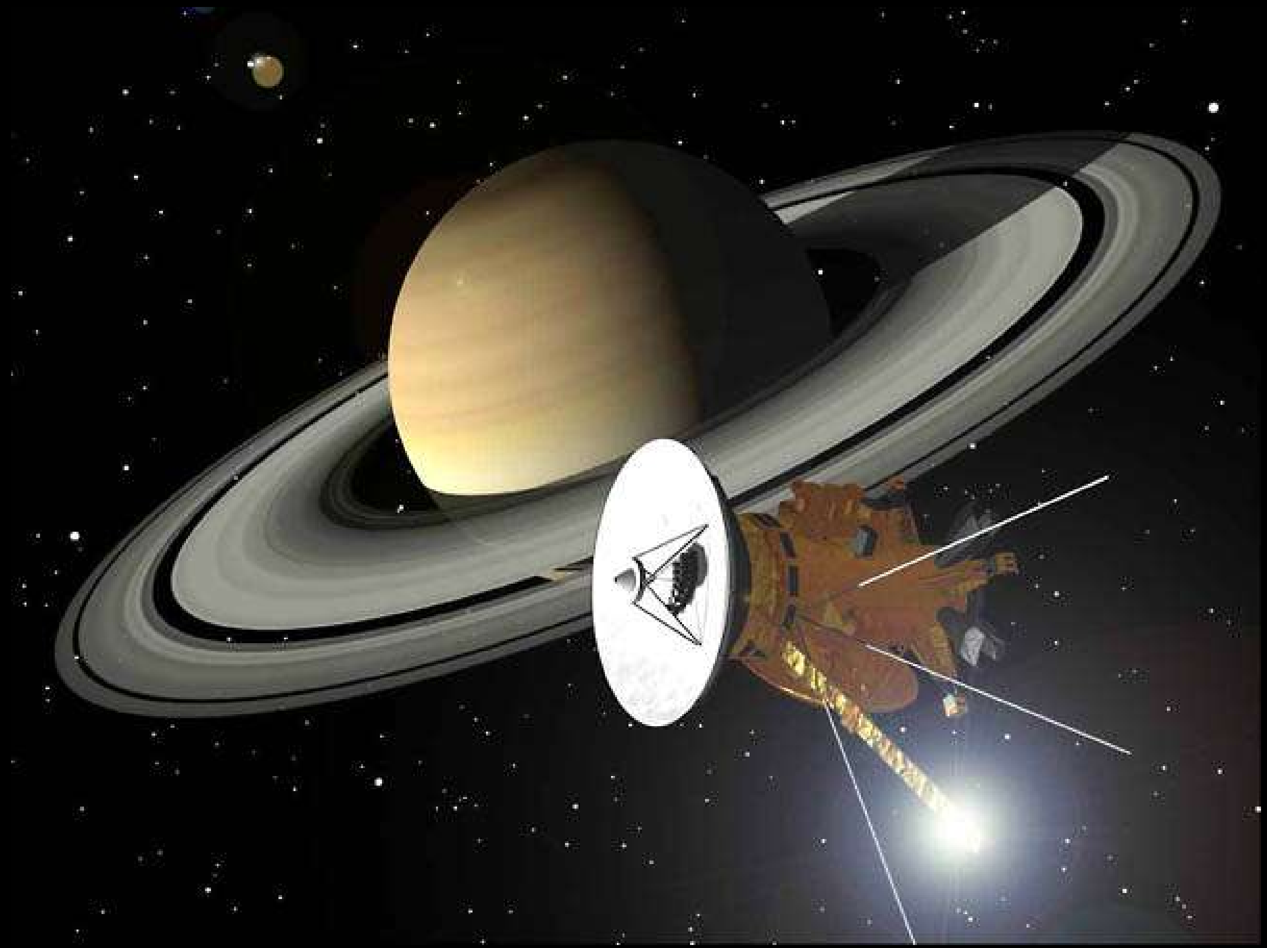
[Carroll, Duvvuri, Trodden & Turner 2003]

Not what you'd <u>expect</u>, but worth contemplating.

But: this theory $S = \int \left(R - \frac{1}{R} \right) d^4x$ is secretly just a scalar-tensor theory in disguise. The metric around the Sun is not precisely that of GR.

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

E.g., by tracking of the Cassini spacecraft.



[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

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

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.

In the modified-source-gravity equation of motion

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

the energy-momentum tensor for ψ looks like

$$T_{\mu\nu}^{(\psi)} = [(\nabla\psi)^2 + 2\nabla^2\psi - e^{-2\psi} U(\psi)] g_{\mu\nu}$$
$$-2\nabla_\mu\psi\nabla_\nu\psi + 2\nabla_\mu\nabla_\nu\psi$$

$U(\psi)$ is a "potential" defined in terms of ψ (T) via

$$U(\psi) = e^{4\psi}\int e^{-4\psi} T(\psi)\, d\psi$$

So the metric ultimately depends only on the matter energy-momentum – no new degrees of freedom.

[Carroll 2005]

Cosmology in modified-source gravity

The effective Friedmann equation for a matter-dominated universe is

$$\frac{\dot{a}^2}{a^2} = \frac{8\pi G}{3} e^{-2\psi} \underbrace{\left[1 - 3\rho\left(\frac{d\psi}{d\rho}\right)\right]^{-2}}_{\text{density-dependent correction to Newton's constant}} \left[\rho + U(\psi)\right]$$

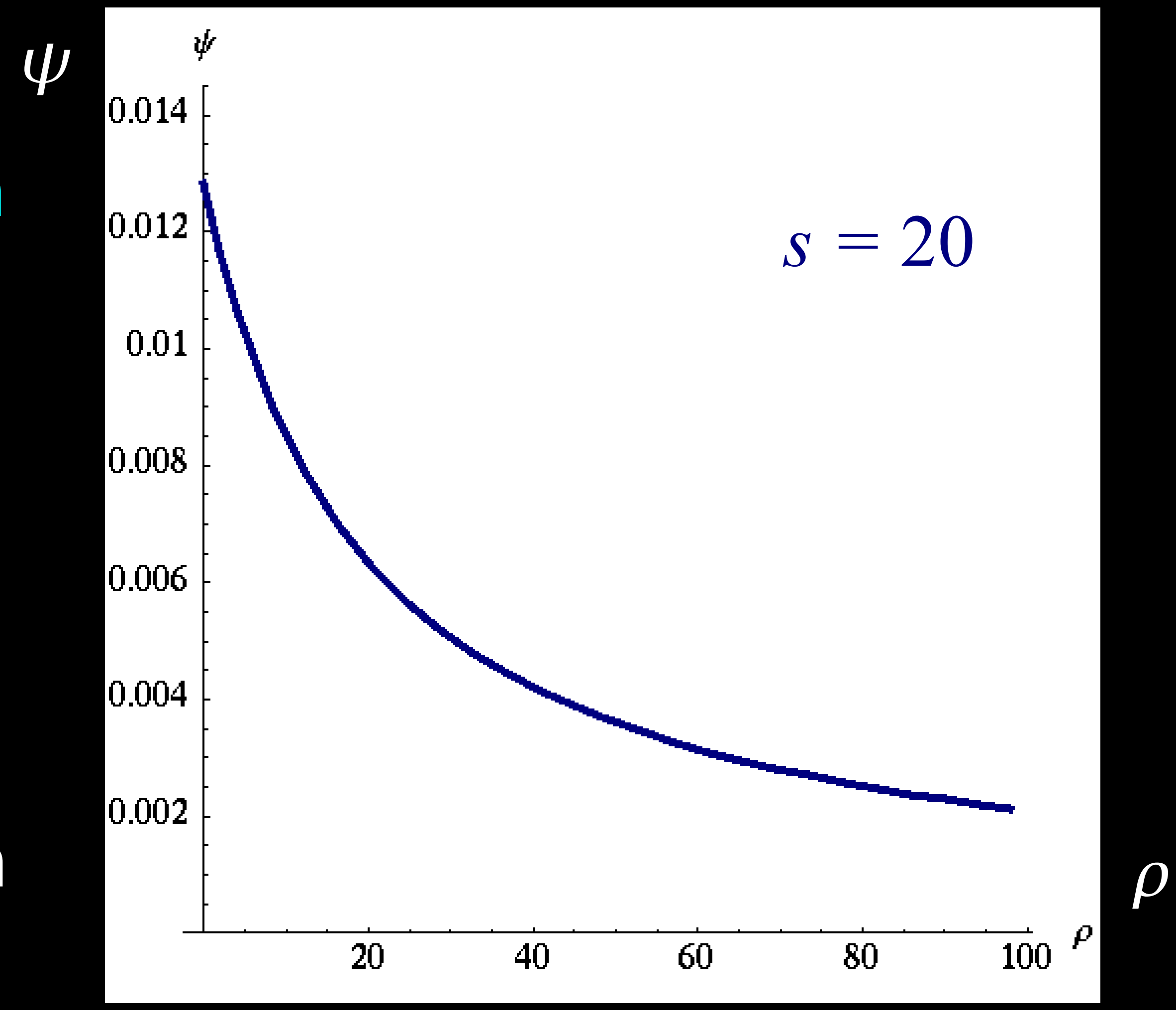
ordinary matter energy density

density-dependent vacuum energy

Early times are conventional if ψ -> 0 and $U(\psi) << \rho$ when ρ is large. (Remember ψ is a function of ρ.) Late-time behavior depends on your choice of $U(\psi)$.

A particular choice, such that ψ doesn't vary too much with ρ:

$$\rho(\psi) = \frac{1}{1-e^{-4\psi}} - s$$

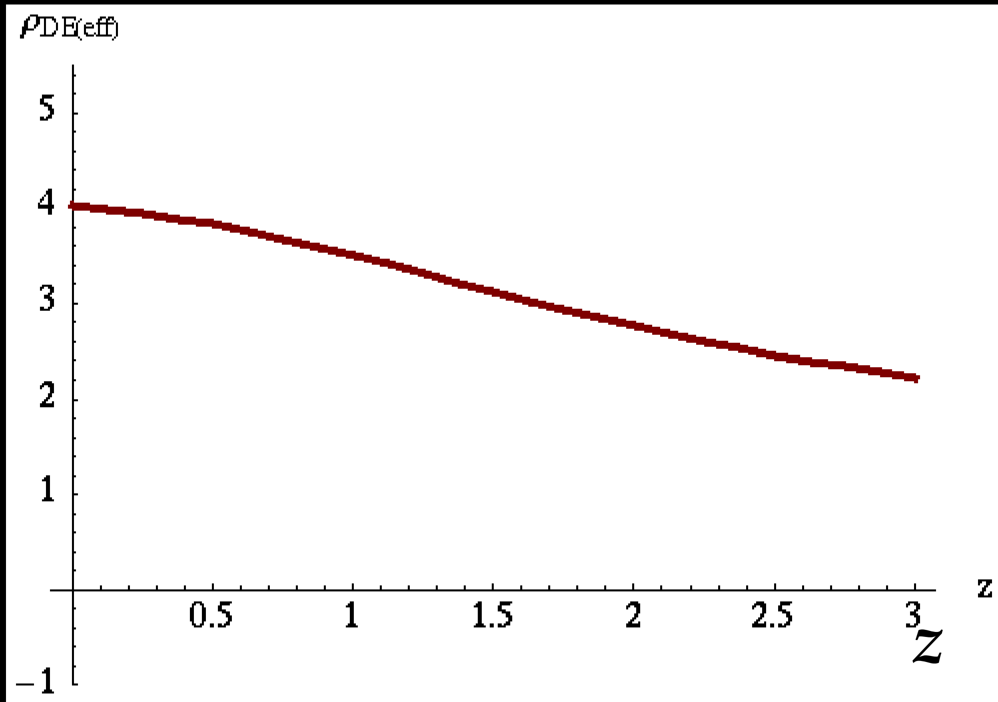


The effective Friedmann equation is obviously:

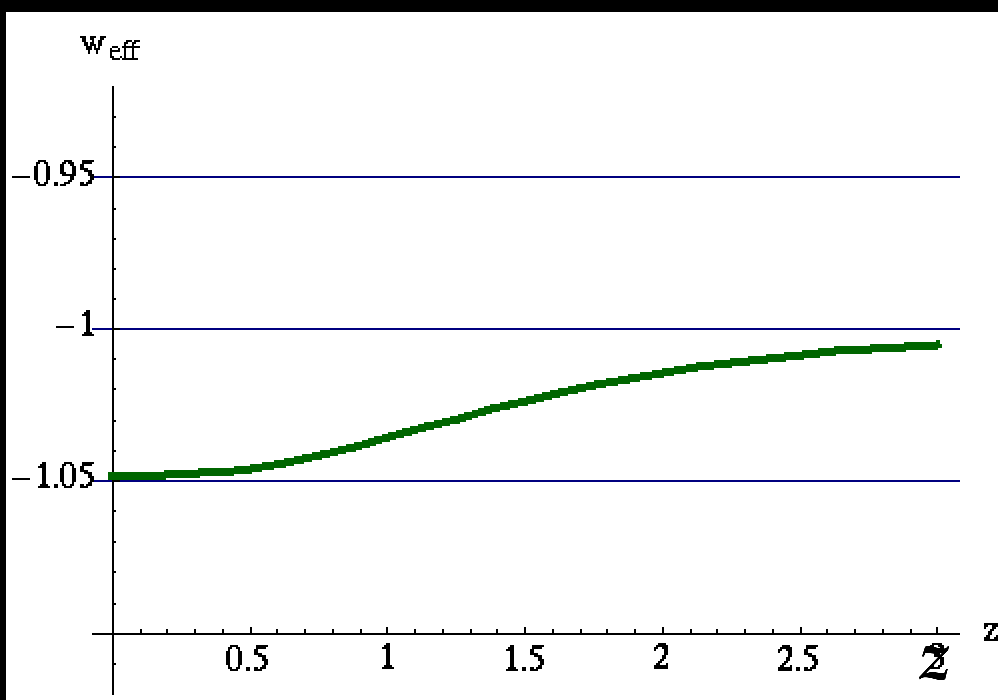
$$\frac{\dot{a}^2}{a^2} = \left(\frac{8\pi G}{3}\right) \frac{\left(\frac{\rho+s-1}{\rho+s}\right)^{1/2}\left[4\rho+s-\frac{(\rho+s)\ln(\rho+s)}{\rho+s-1}\right]}{\left[16+\frac{12\rho}{(\rho+s)(\rho+s-1)}\right]^2}$$

[Carroll 2005]

$\rho^{(DE)}_{eff}$



w_{eff}



Of course, observers might <u>think</u> they were measuring dark energy.

Here are the density and equation-of-state parameter $w = p/\rho$ you'd be tricked into thinking you had measured ($s = 20$).

The effective w can be less than minus one (or not), without causing trouble.

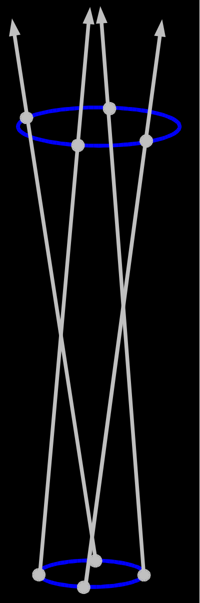
Aside: Can we get acceleration without dark energy <u>or</u> modified gravity? Just with GR?

Perhaps a super-Hubble-radius perturbation with huge amplitude can lead to local acceleration?

[Kolb, Mattarese, Notari, Riotto]

Probably not.

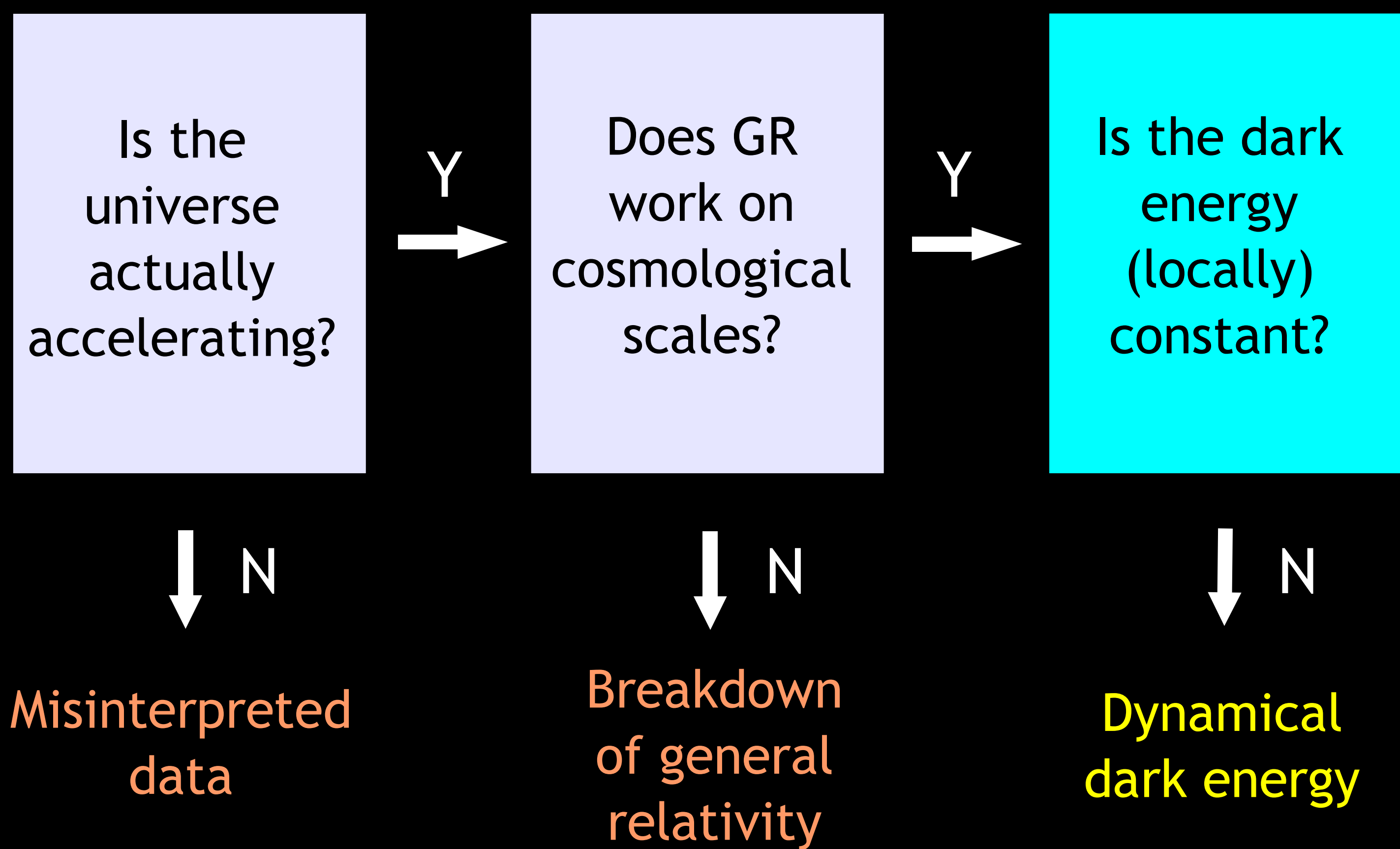
Rough idea: something like the Friedmann equation is true *locally*, but with some extra contributions from “shear” (stretching) and “vorticity” (twisting) of the cosmological fluid. Vorticity can indeed lead to local acceleration, but the amount you need would make the universe too anisotropic.



[Flanagan; Hirata & Seljak; Geshnizjani,Chung, and Afshordi]

Why is the universe accelerating?

A flowchart of possibilities:

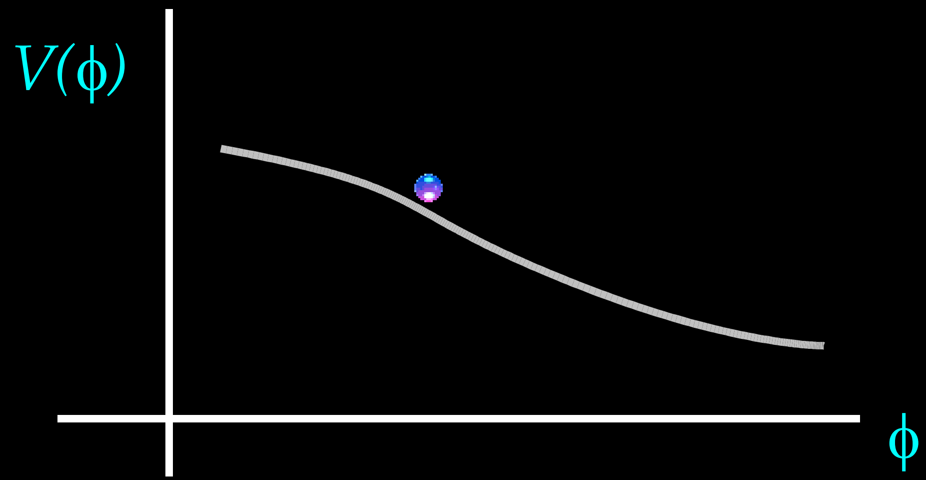


Is the dark energy a slowly-varying dynamical component?

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; etc.]

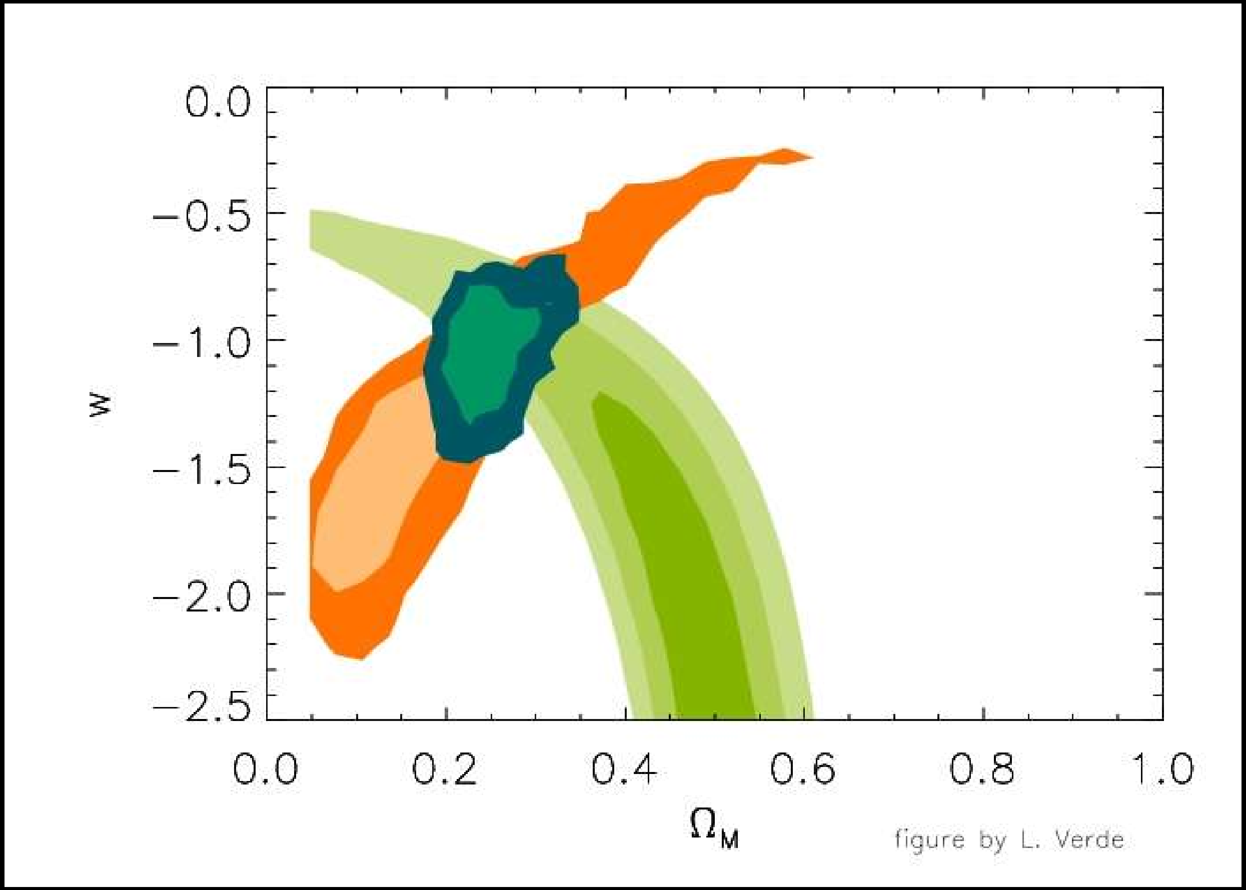
- This is an observationally interesting possibility, and at least holds the possibility of a dynamical explanation of the coincidence scandal.

- 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:

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

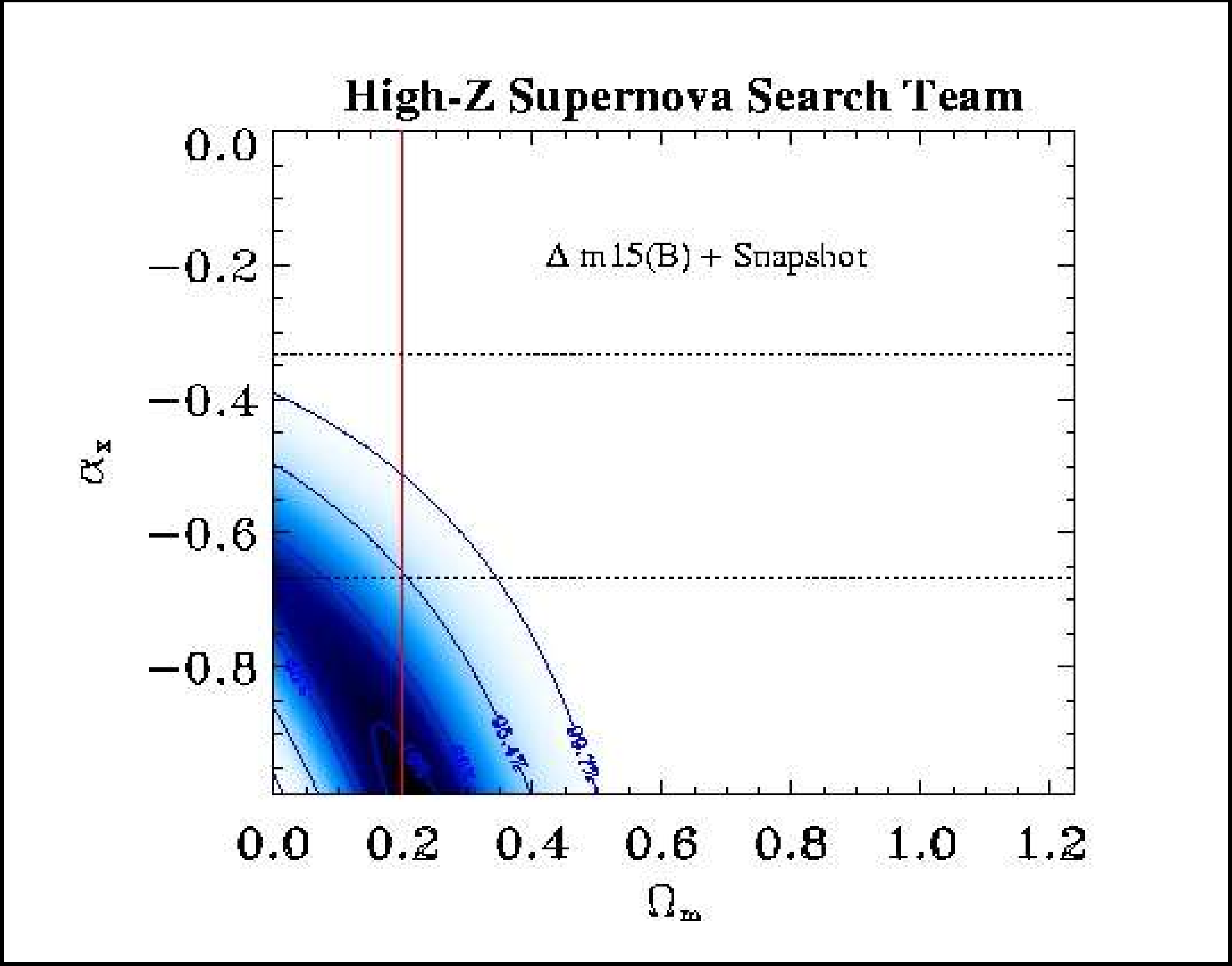


For matter, $w = 0$; for actual vacuum energy, $w = -1$.

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

Should we consider $w < -1$?

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

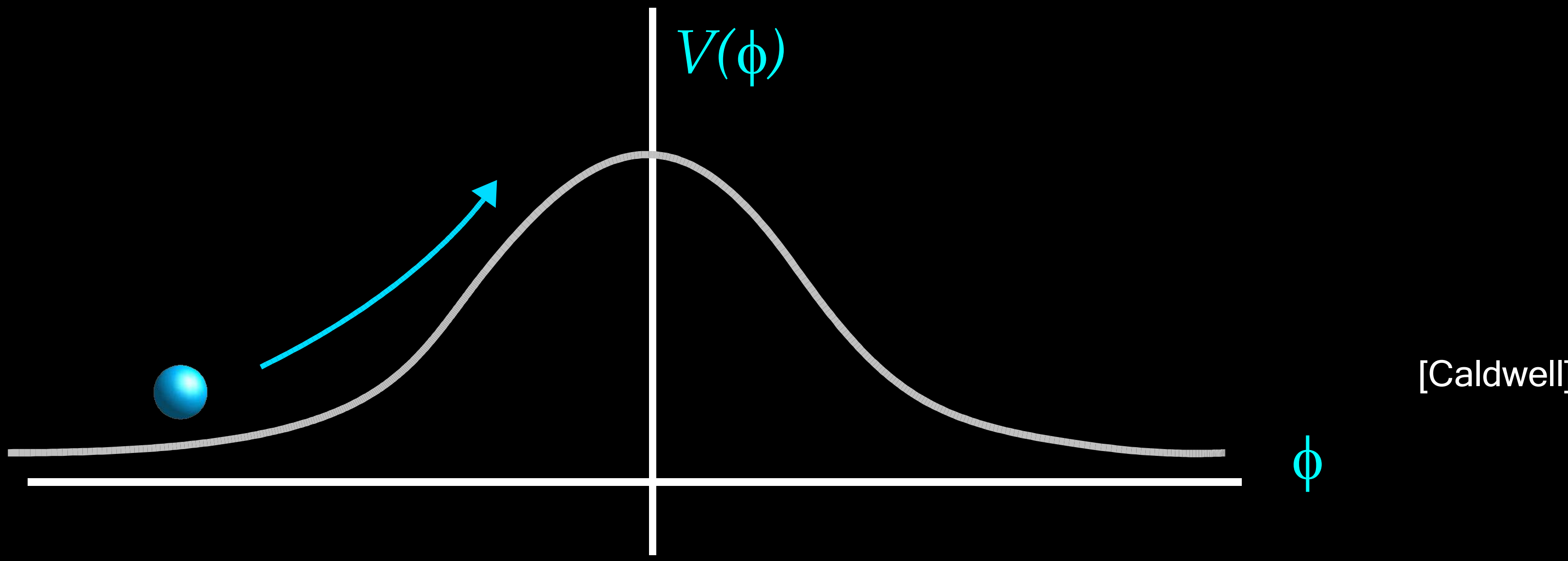


More specifically: it violates the Dominant Energy Condition of general relativity, which ensures that energy doesn't appear spontaneously.

[Garnavich et al.]

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

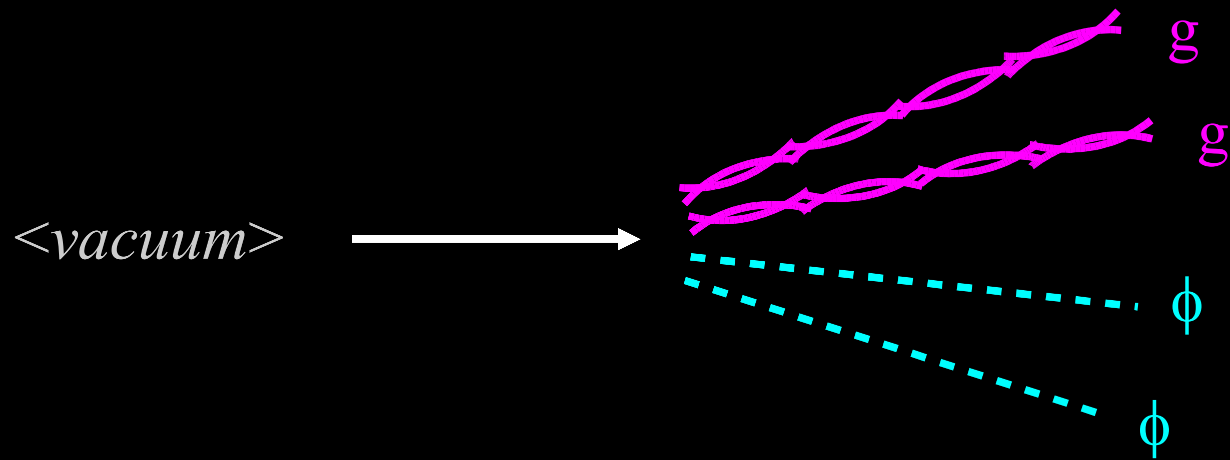
$$\rho_\phi = -\frac{1}{2}\dot{\phi}^2 + V(\phi)$$



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.



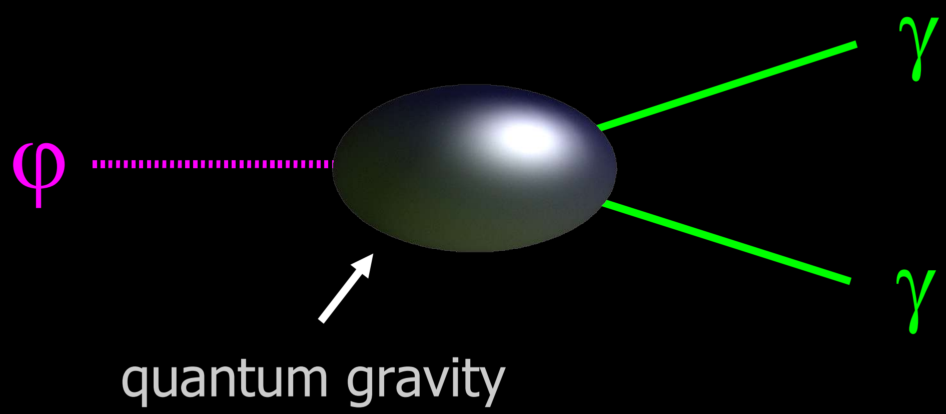
[Carroll, Hoffman & Trodden]

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

Theorists need to be careful, but observers should keep an open mind. 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.

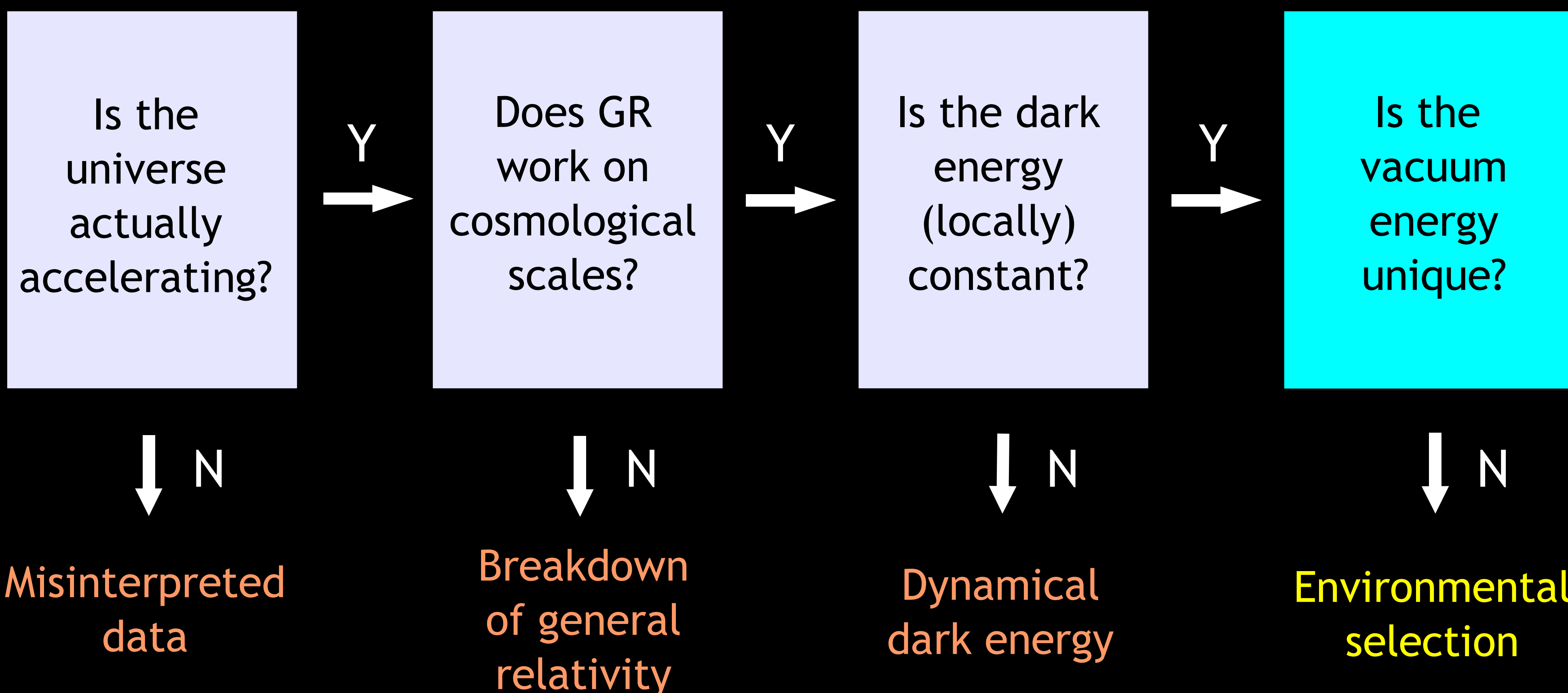


These interactions are constrained by 5th-force and time-dependent-constant measurements.
Even if the couplings are as small as naturalness allows, they are still ruled out! Need suppression by an extra 10^5. Perhaps a new symmetry?

[Carroll]

Why is the universe accelerating?

A flowchart of possibilities:



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.

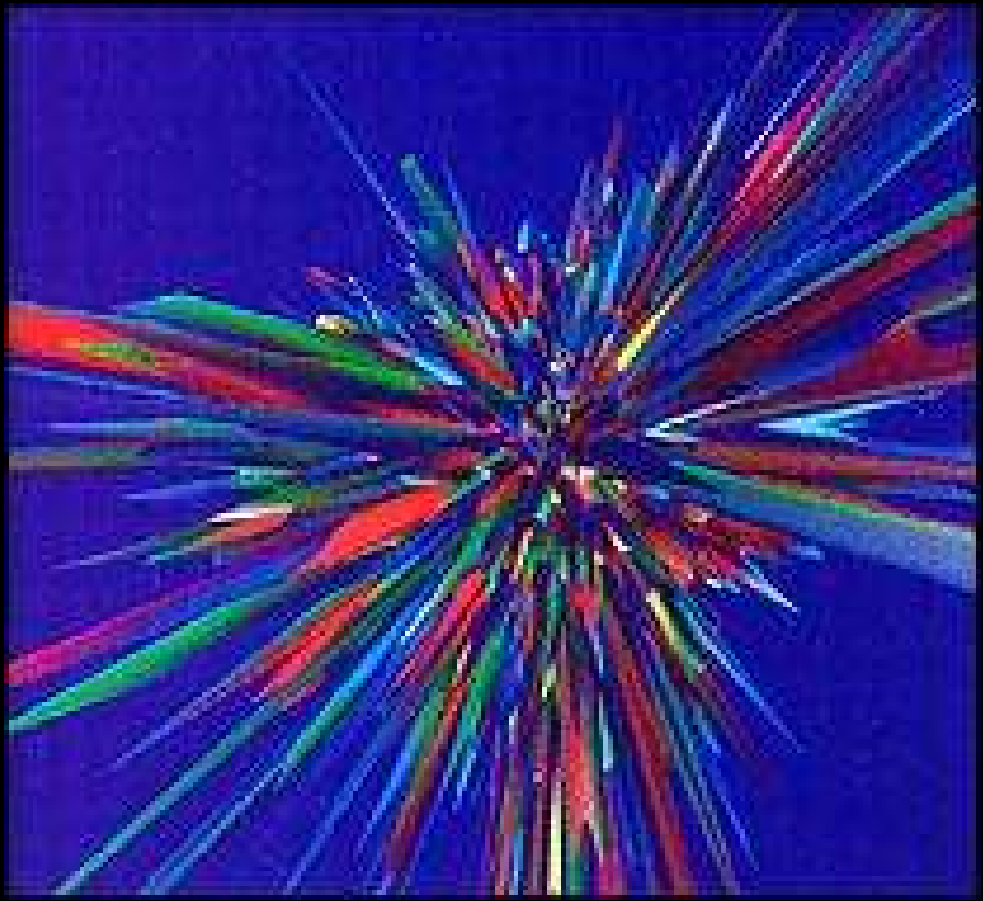
So are there really many domains with different properties?

String theory may very well predict that there can be regions of space with utterly different physical properties. Perhaps 10^{500} different vacuum states in the "landscape."

[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]



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

The multiversal Drake equation:

$$\begin{array}{c}\text{Number of}\\ \text{observers}\\ \text{measuring } X\end{array} = \sum_{\text{vacua } n} \left(\begin{array}{c}\text{Does vacuum}\\ n \text{ have}\\ \text{property } X?\end{array}\right)\left(\begin{array}{c}\text{Volume of}\\ \text{space in}\\ \text{vacuum } n\end{array}\right)\left(\begin{array}{c}\text{Density of}\\ \text{observers in}\\ \text{vacuum } n\end{array}\right)$$

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.

What you should think about the anthropic principle

Statement you certainly agree with:

Intelligent life only arises under conditions that allow for the existence of intelligent life.

Statement you really should agree with:

If there are different conditions in various parts of the universe, we will only ever observe those consistent with the existence of intelligent life.

Statements that may someday be true, but certainly not yet:

Current theories predict the existence and distribution of countless regions outside our observable universe, each with very different conditions.

We understand what "intelligent life" is, and when it can exist.

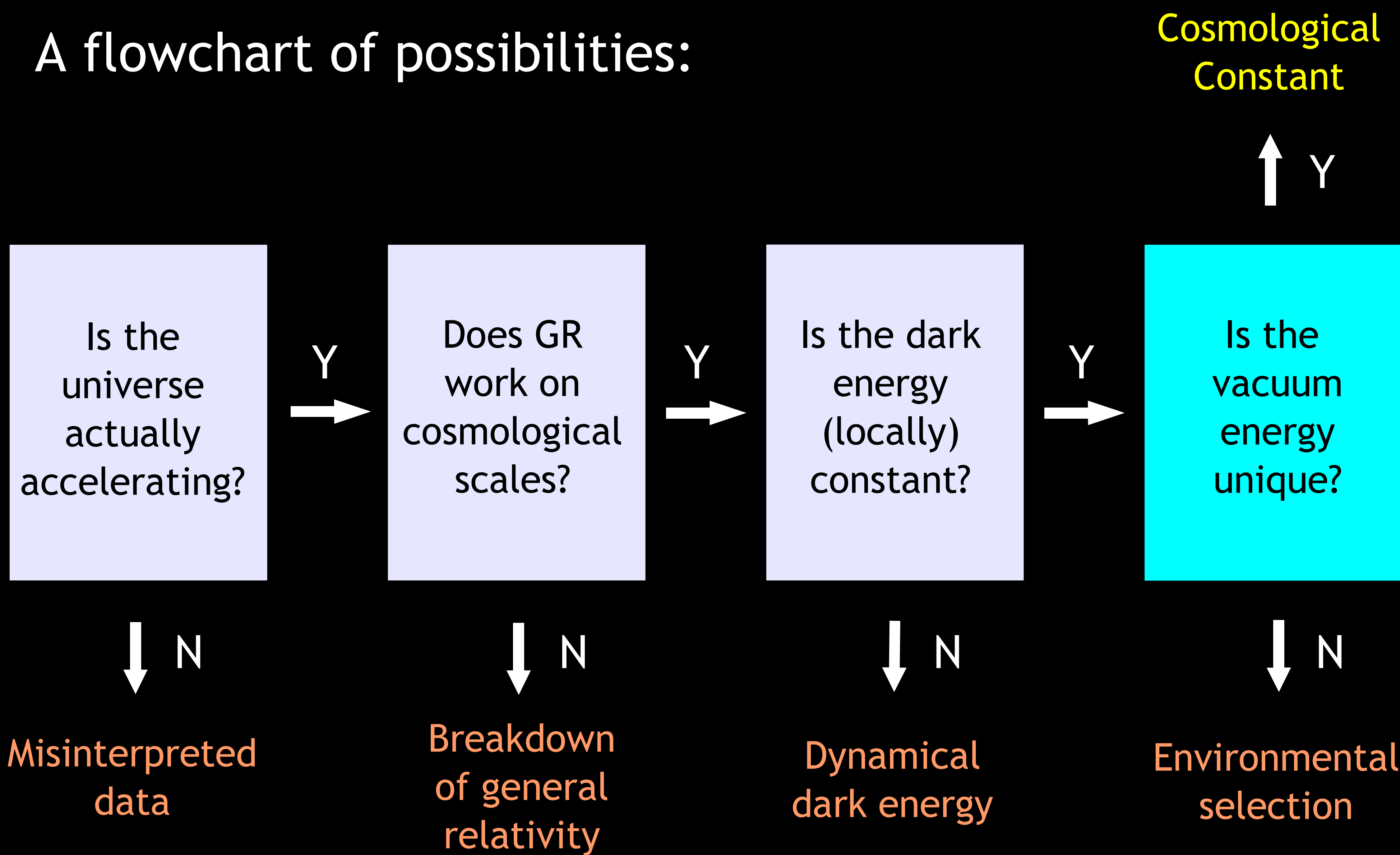
We can use the above information to predict likely values of observed quantities such as the cosmological constant.

"It makes me sad to think that the vacuum energy might be a random variable whose observed value is determined by a selection effect. Isn't that a good argument against this idea?"

No.

Why is the universe accelerating?

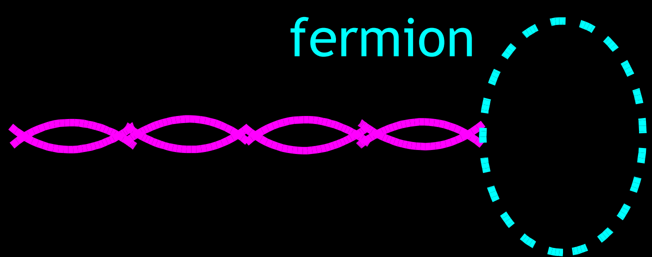
A flowchart of possibilities:



Do we live in the true vacuum?

Consider supersymmetry, a hypothetical symmetry that relates bosons (spin-0,1) to fermions (spin-1/2, etc).

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



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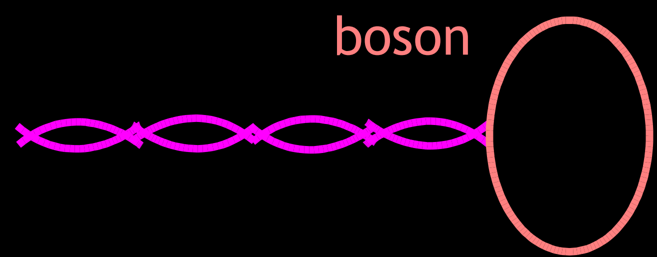

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- Bad news: We don't live in a perfectly supersymmetric universe; SUSY is (at least) broken at $M_{\text{susy}} = 10^{12}$ eV.
- Good news: This makes the cosmological constant problem not so bad: $\rho_{vac}^{(\text{theory})} = M_{\text{susy}}^{4}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

But the susy breaking scale is the geometric mean of the vacuum scale and the Planck scale. Coincidence?

The Gravitational Physics Data Book:

Newton's constant:

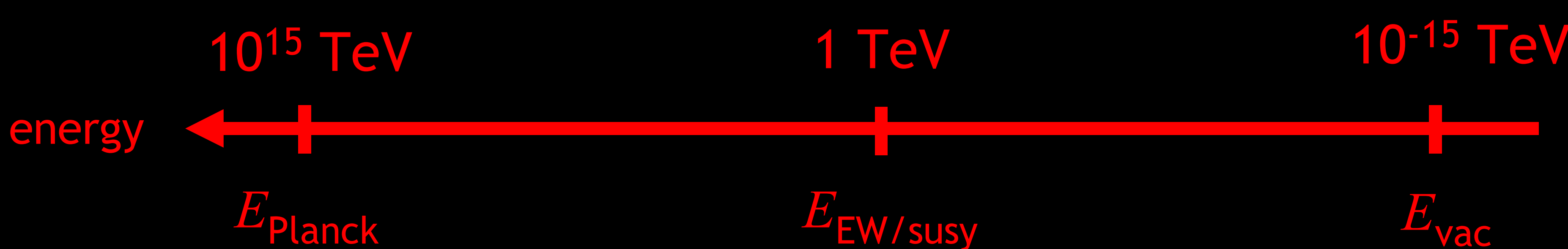
$$G = (6.67 \pm 0.01) \times 10^{-8}\ \text{cm}^3\ \text{g}^{-1}\ \text{sec}^{-2}$$

Cosmological constant:

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

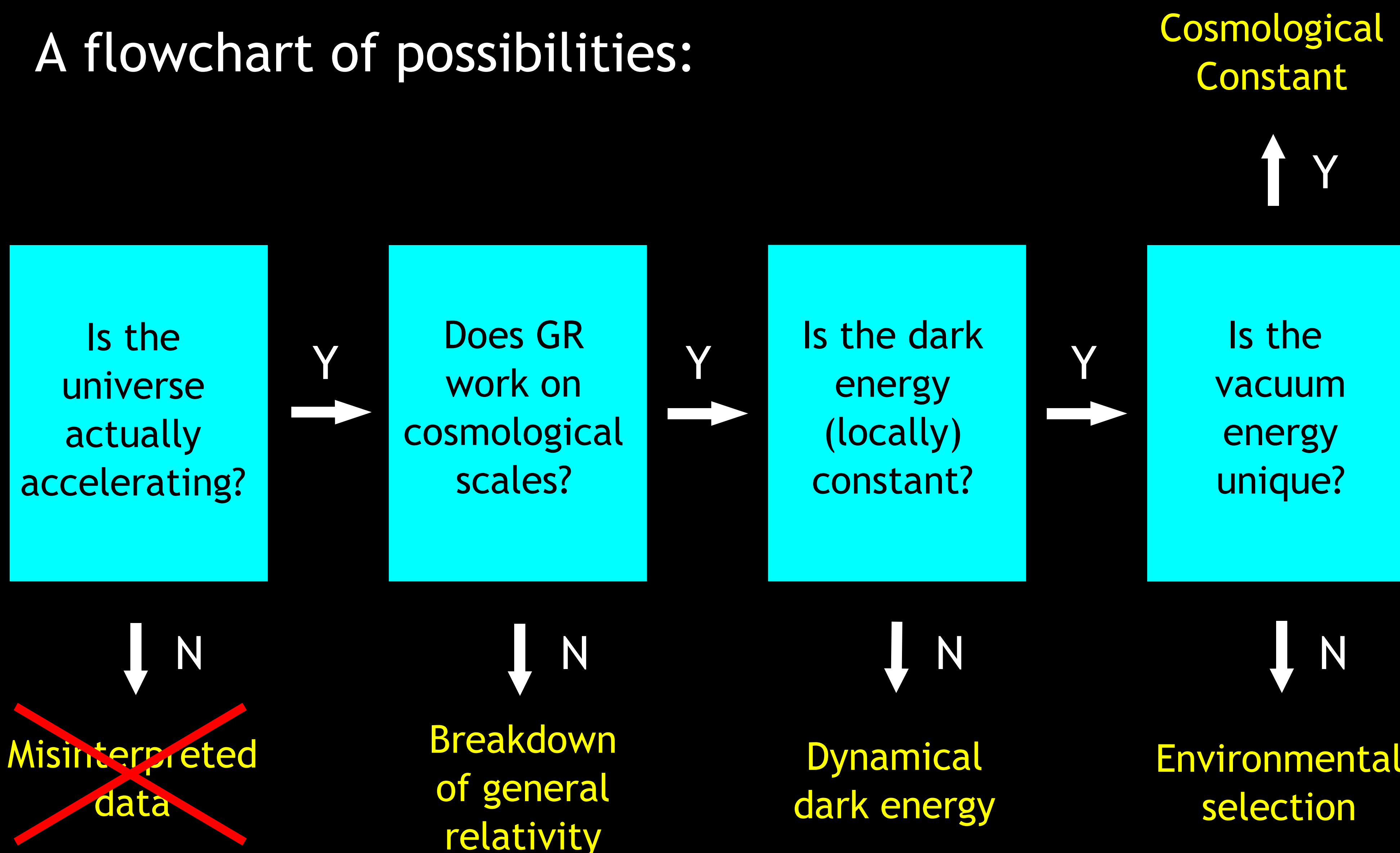
Equivalently ($\hbar = c = 1$),

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

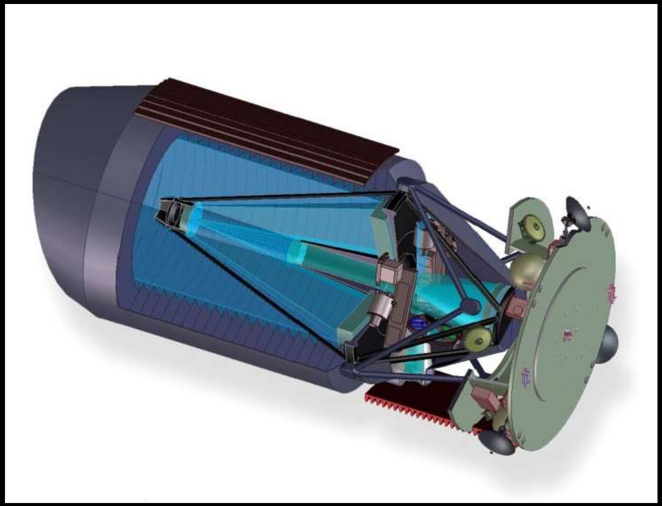


Why is the universe accelerating?

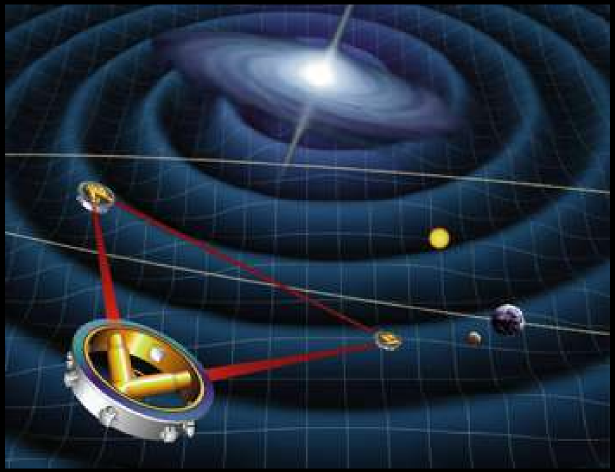
A flowchart of possibilities:



The future: A Comprehensive Attack on Dark Energy

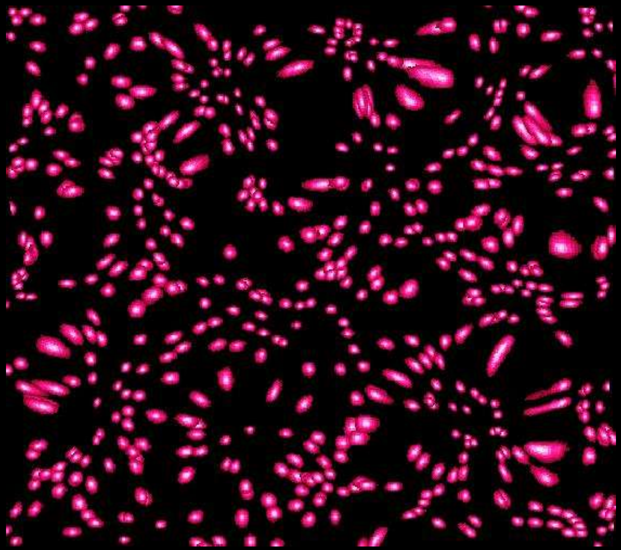


Supernovae

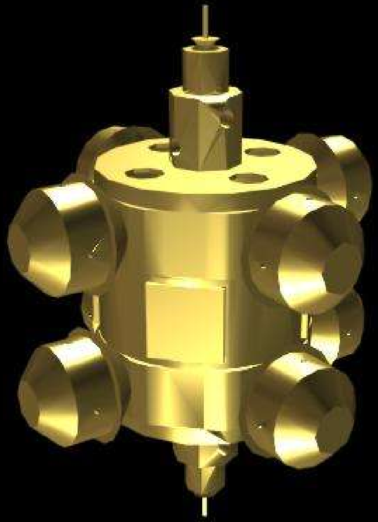


Gravitational Waves

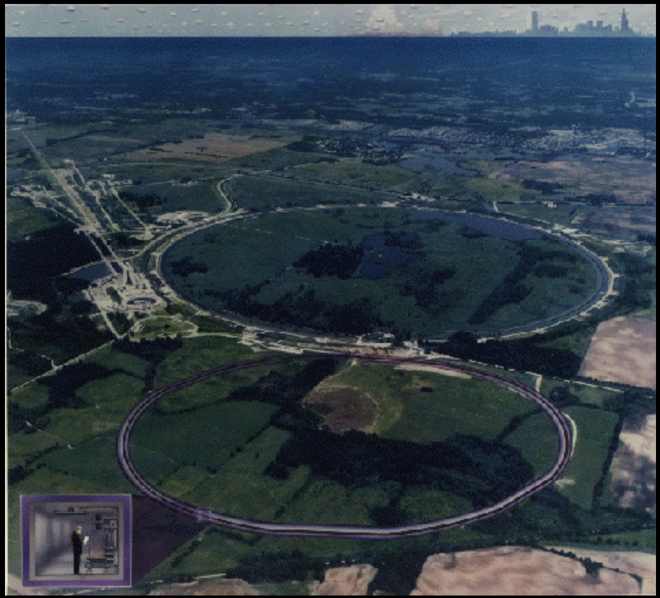
Galaxy Clusters



Weak Gravitational Lensing



5th-force experiments



Particle Accelerators

Conclusions

- An ordinary cosmological constant is a perfect fit to the dark-energy data, even if we can't explain it. Matter-domination is not a viable option.
- Dynamical mechanisms are interesting and testable; to date, they raise at least as many problems as they solve.
- Replacing dark energy with modified gravity is also interesting, but even more difficult.
- My suspicion: we just got lucky. Finding anything other than $w = -1$ would be a surprise. But it would be an historic discovery, and a crucial clue; so it's worth making the effort.