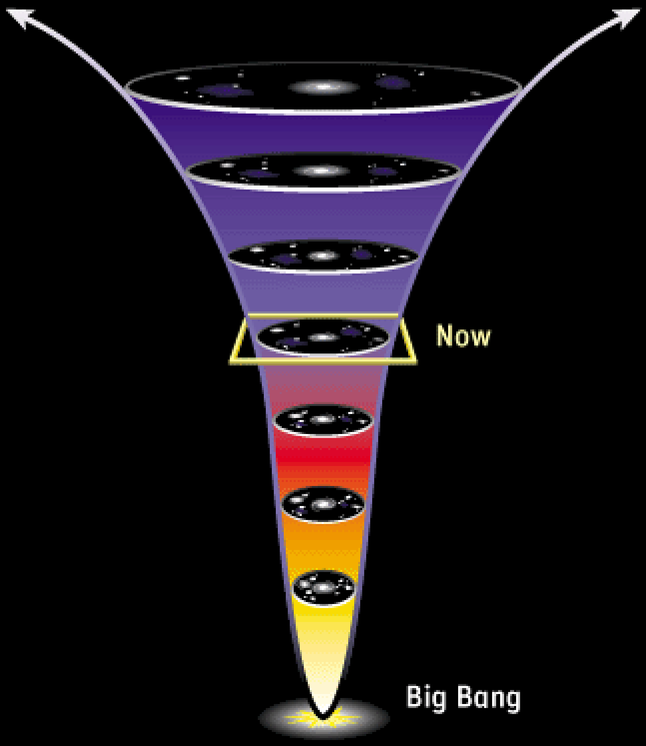
Dark Energy, or Worse?

Sean Carroll

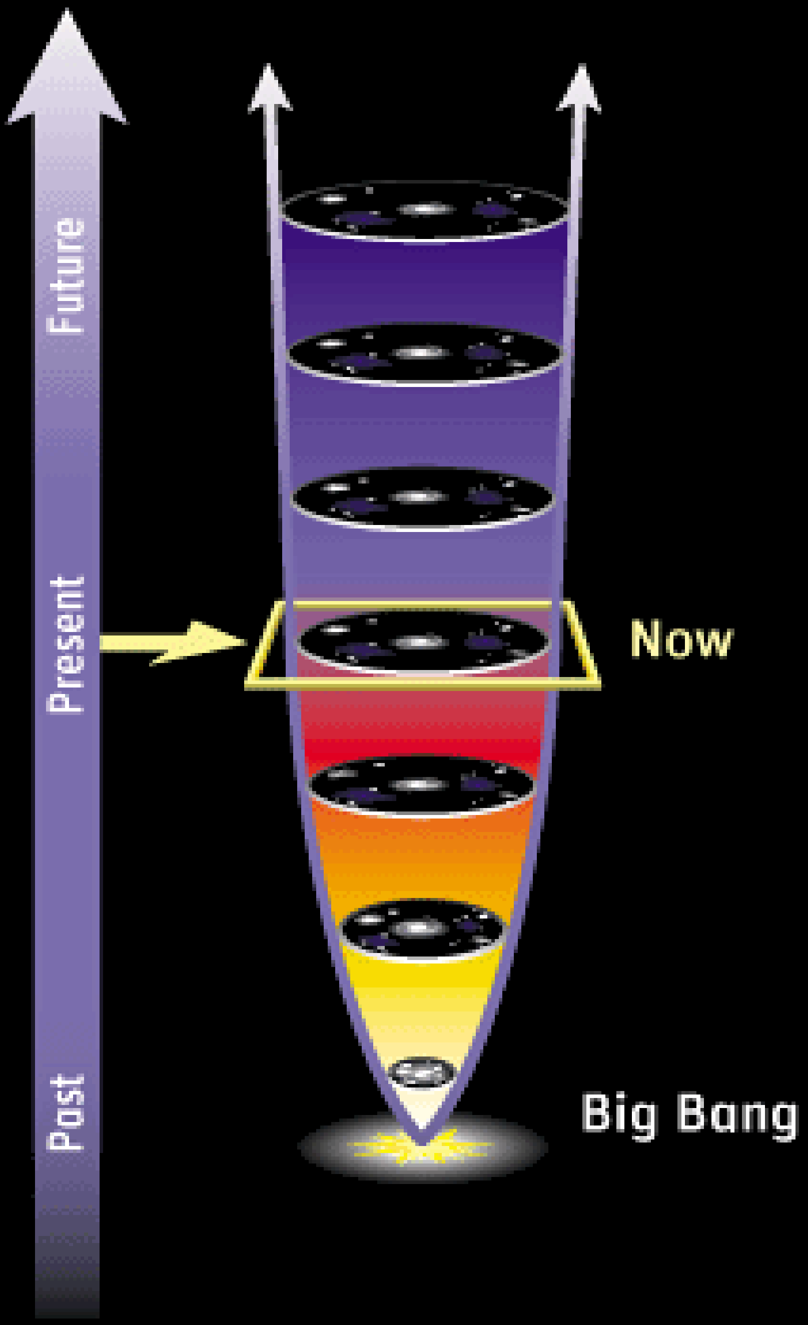
`http://pancake.uchicago.edu/~carroll/`



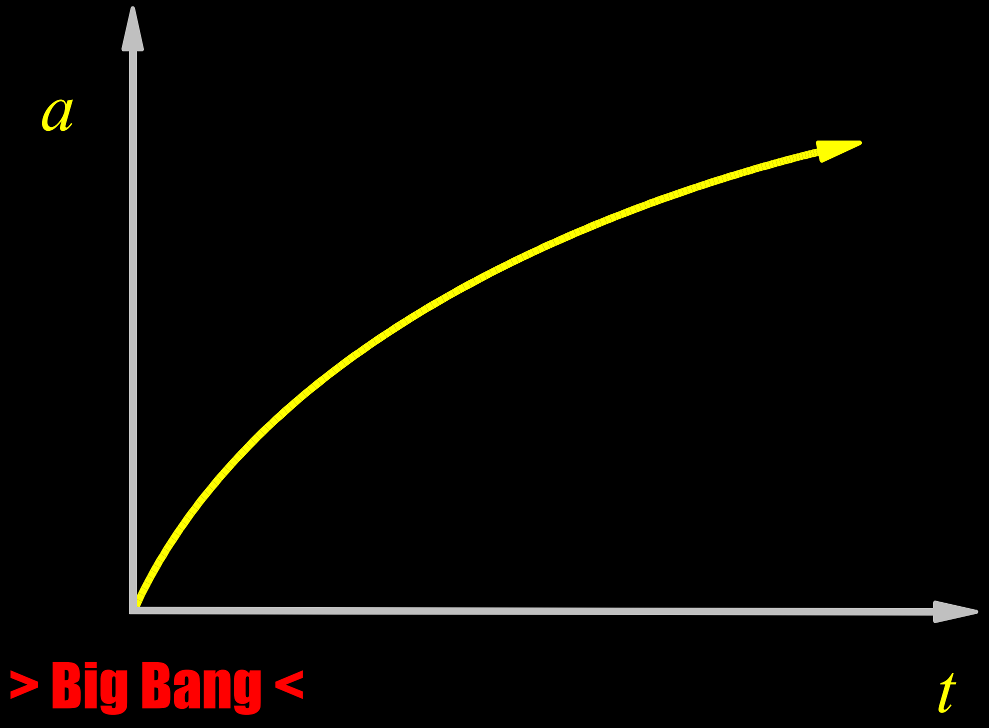
The universe is accelerating.

Time to get serious.

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



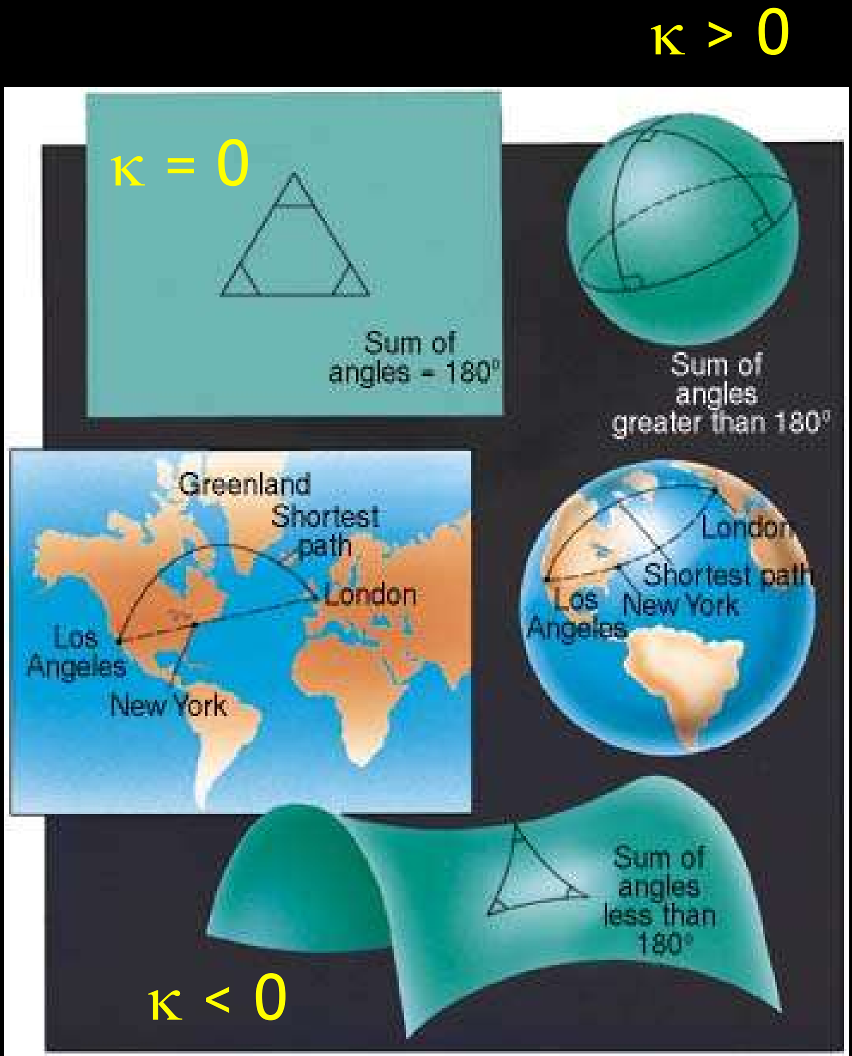
[Sky & Telescope]



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

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

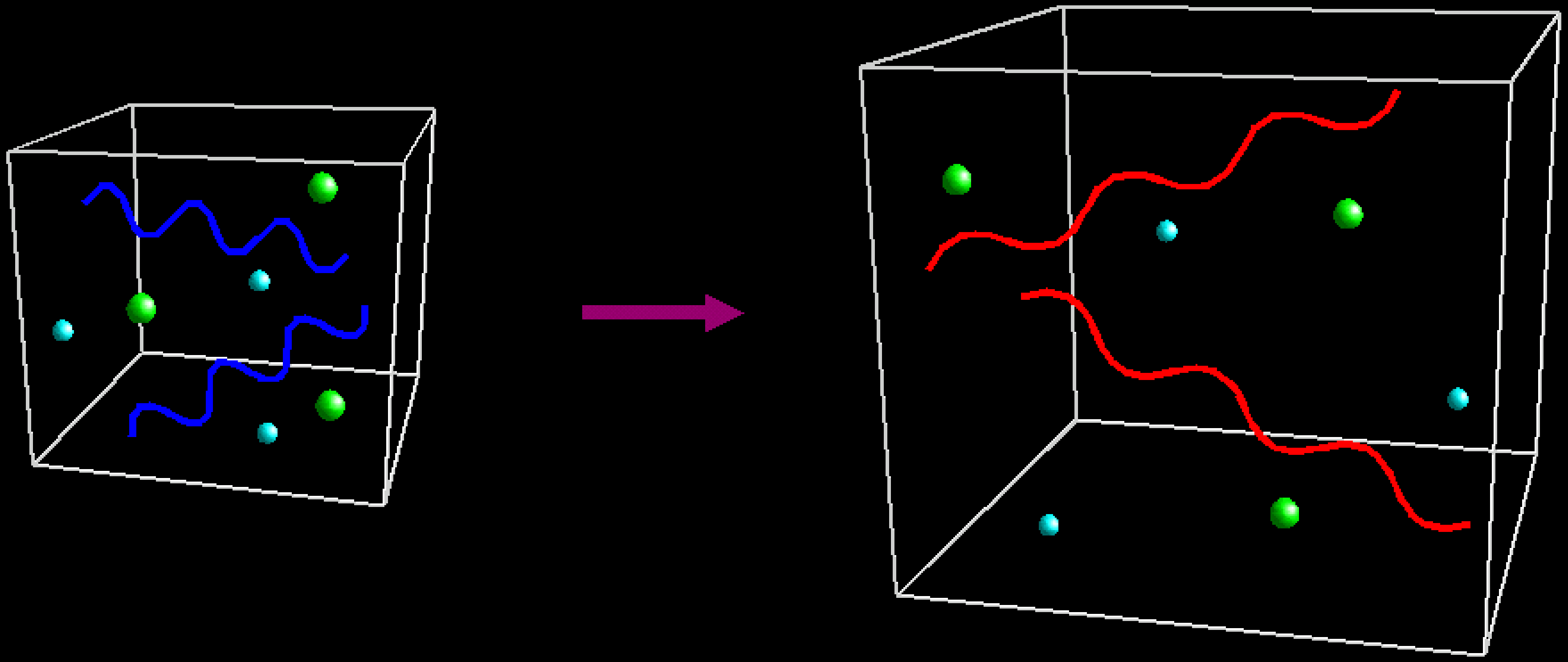
$$H^2 = \frac{8\pi G}{3}\rho - \frac{\kappa}{a^2}$$



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.

Expansion dilutes matter (cold particles) and redshifts radiation.



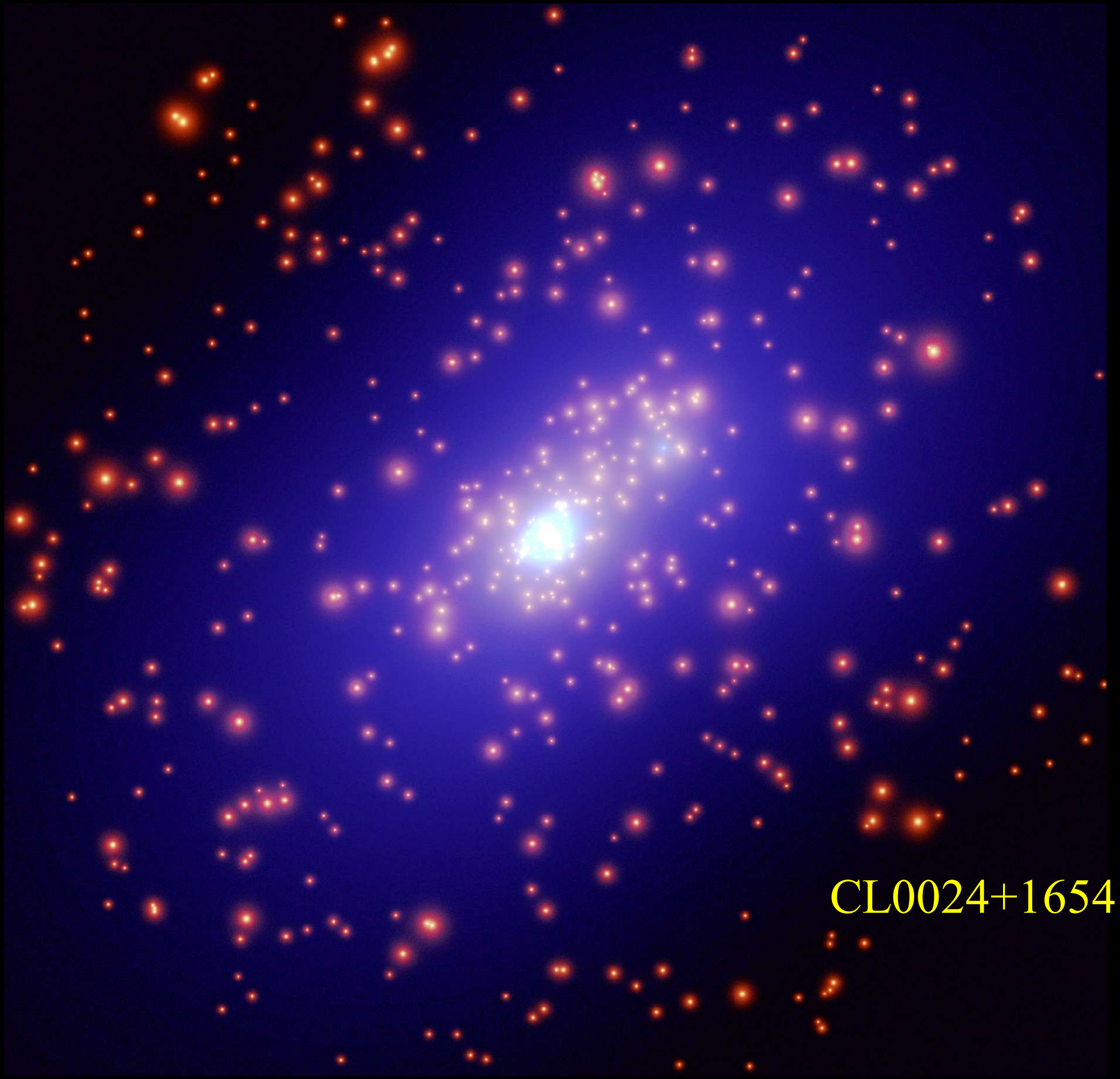
So the energy density in matter simply goes down inversely with the increase in volume: $\rho_M \propto a^{-3}$

And the energy density in radiation diminishes more quickly as each photon loses energy: $\rho_R \propto a^{-4}$

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.



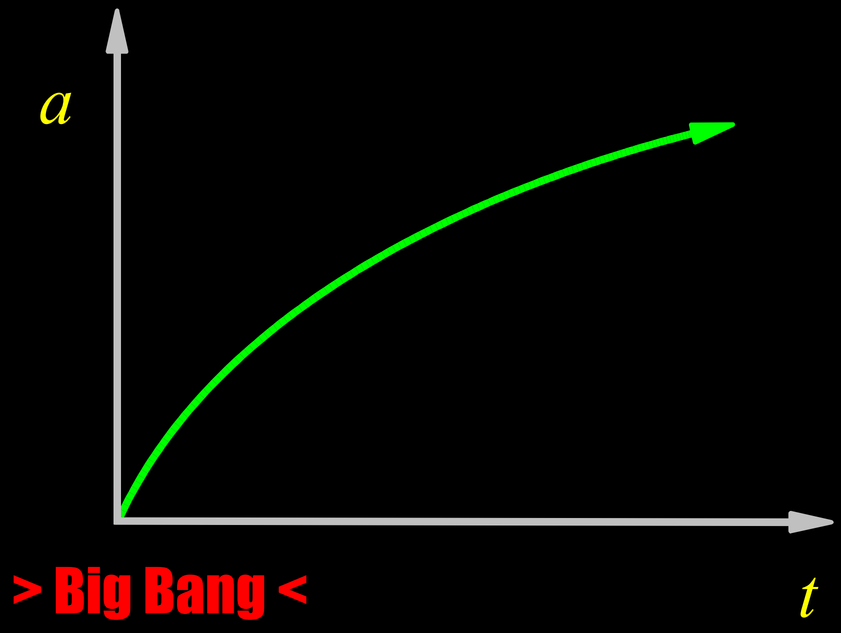
[Kneib et al.]

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 decelerating ($\dot{a}$ decreasing).

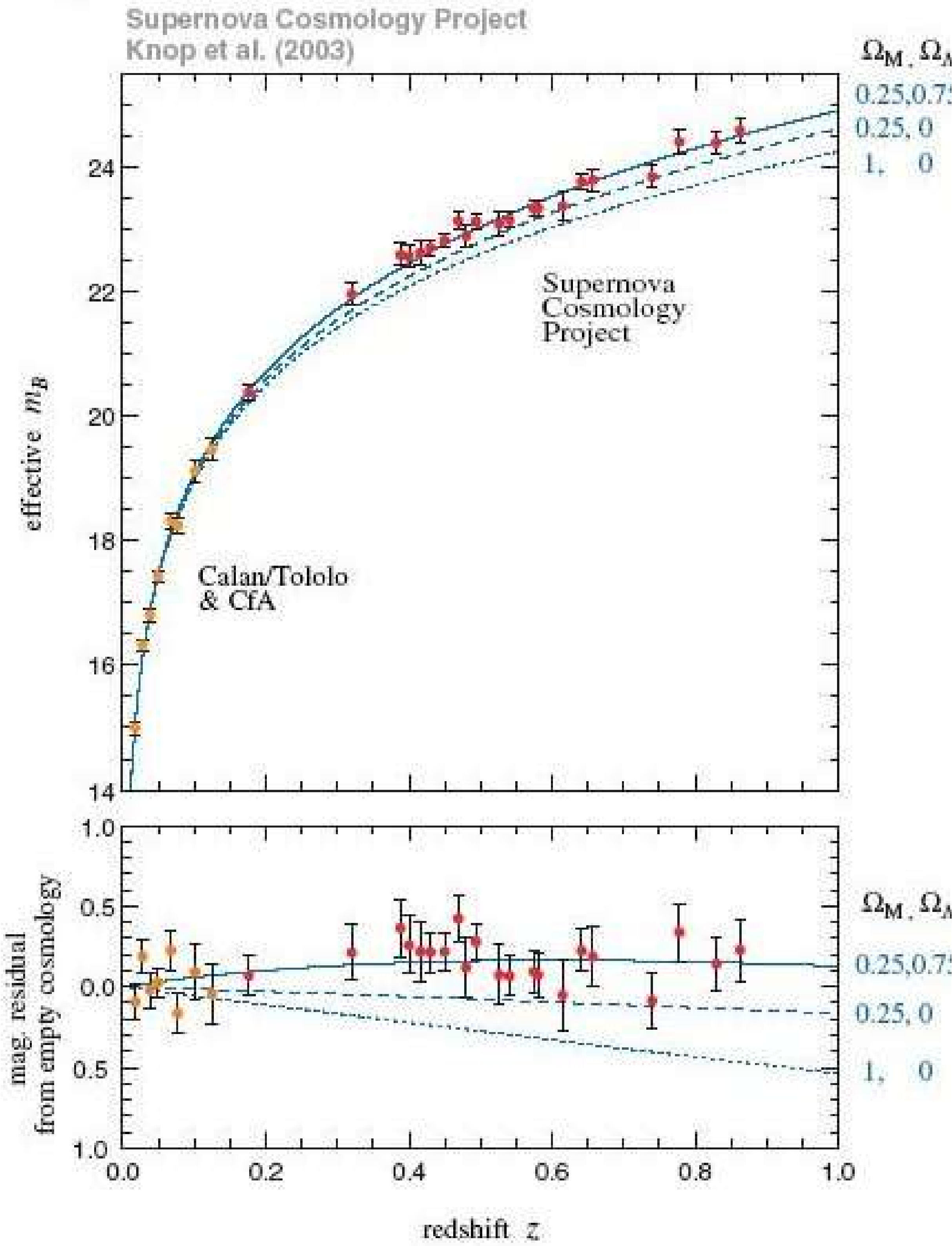


But it isn't.

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

Result: the universe is <u>accelerating</u>!

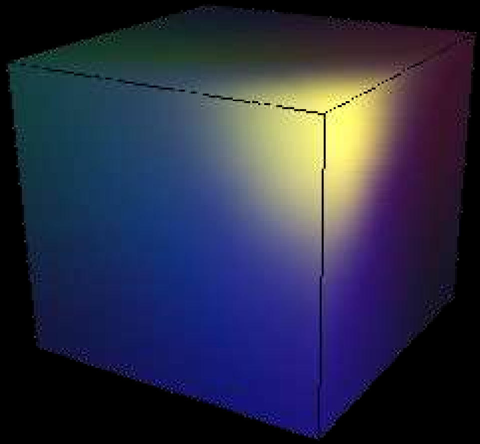
There seems to be a sort of energy density which <u>doesn't</u> decay away: “dark energy.”



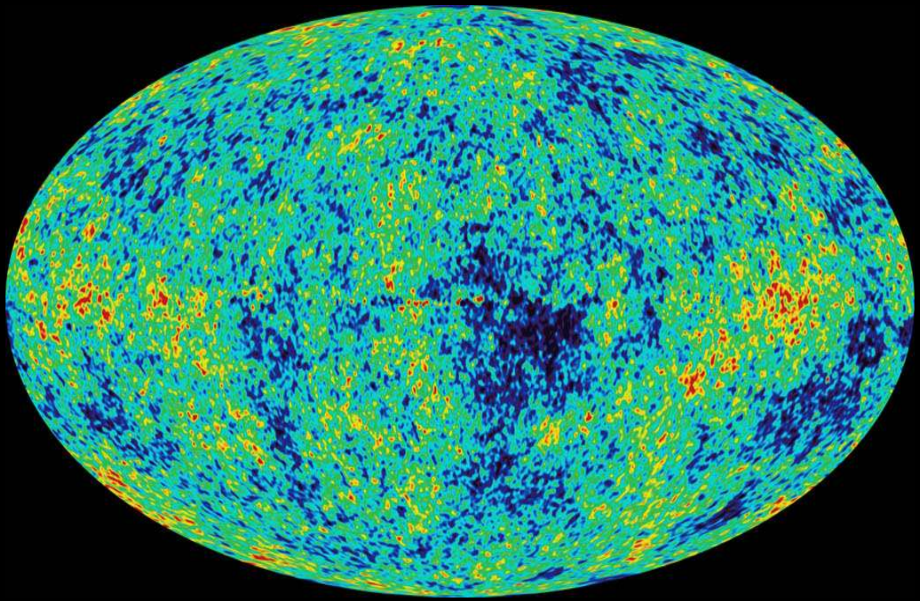
[Riess et al.; Perlmutter et al.; Knop et al.]

Dark Energy must have these properties:

- smoothly distributed through space
- varies slowly (if at all) with time
- negative pressure, $p \approx -\rho$.



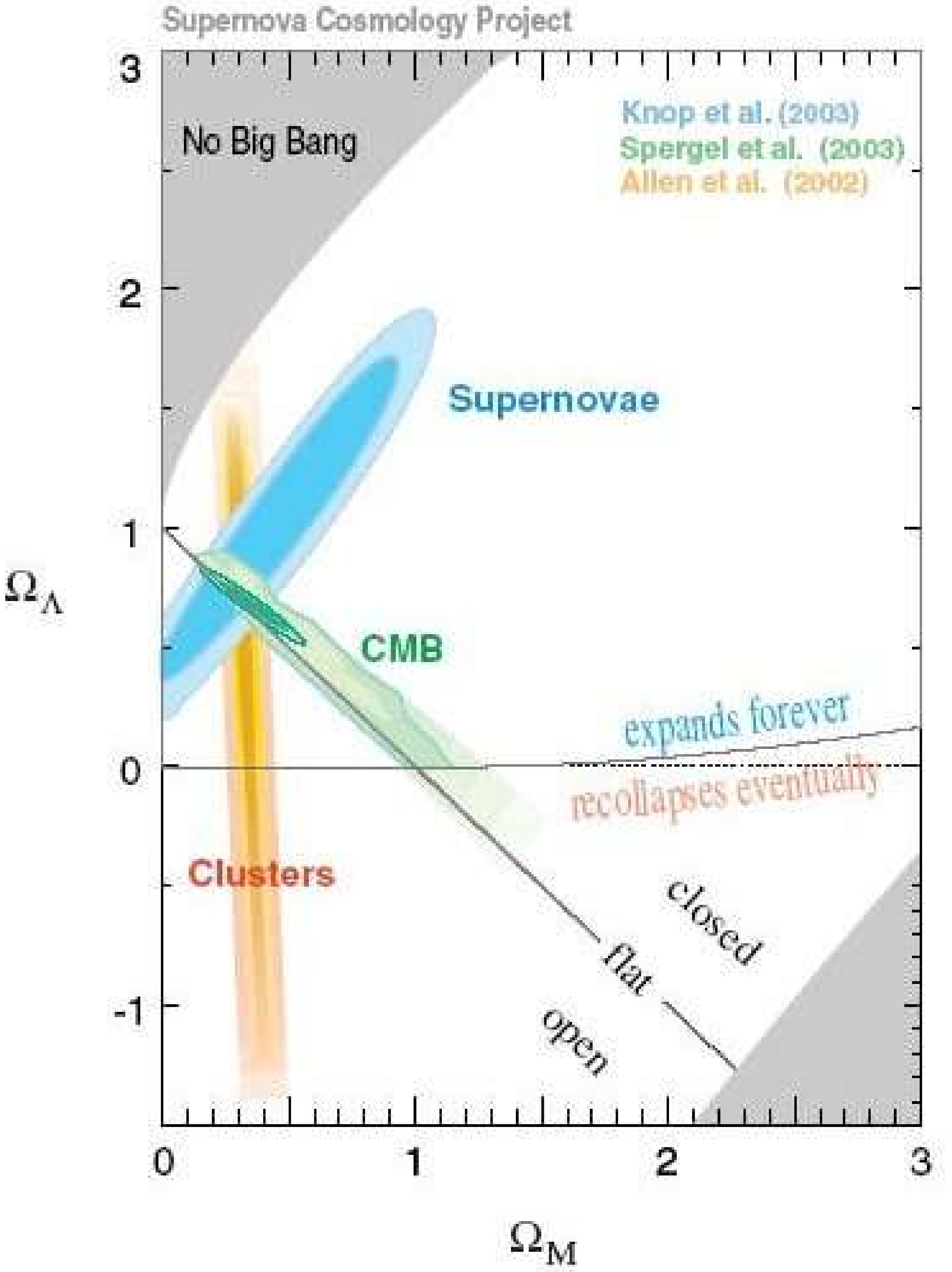
(artist's impression of dark energy)



[WMAP]

Check: fluctuations in the Cosmic Microwave Background indicate that the universe is spatially flat ($\kappa = 0$), even though matter only comprises 30% of the critical density.

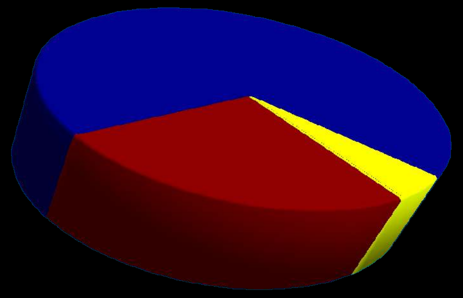
Something must be the other 70%: that something is dark energy.



Express density in terms of density parameter, the fraction of critical density needed for a flat universe,

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

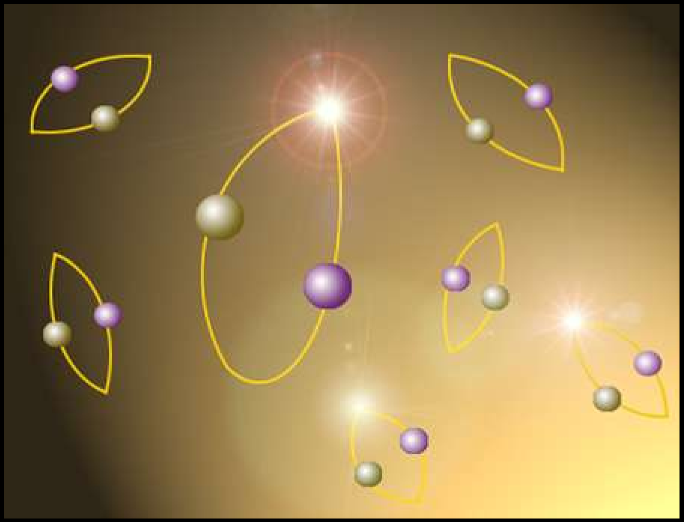
Concordance:



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

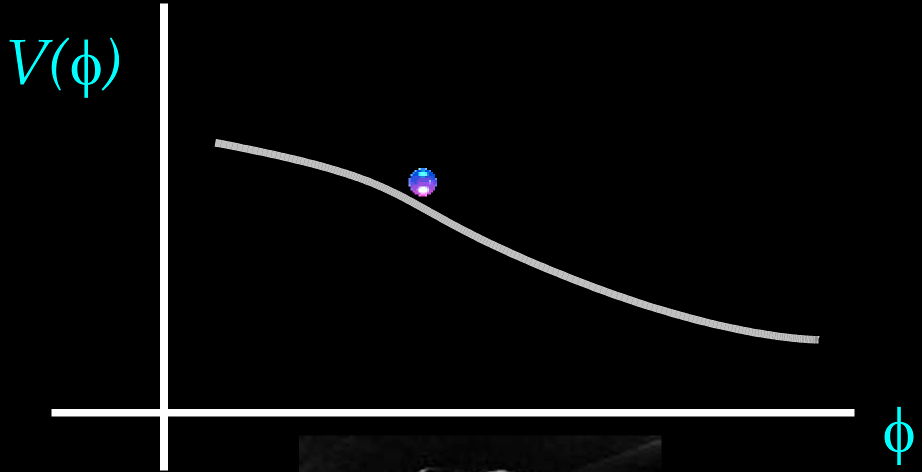
Leading ideas

- Vacuum energy
  (cosmological constant)



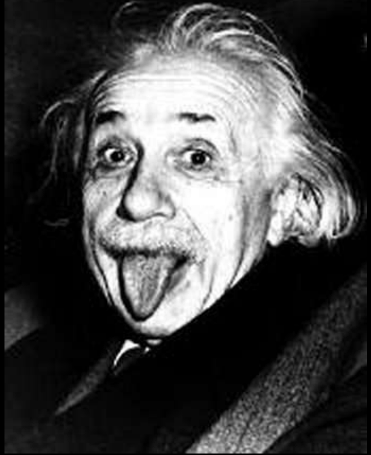
- Dynamical dark energy
  (e.g. quintessence)

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

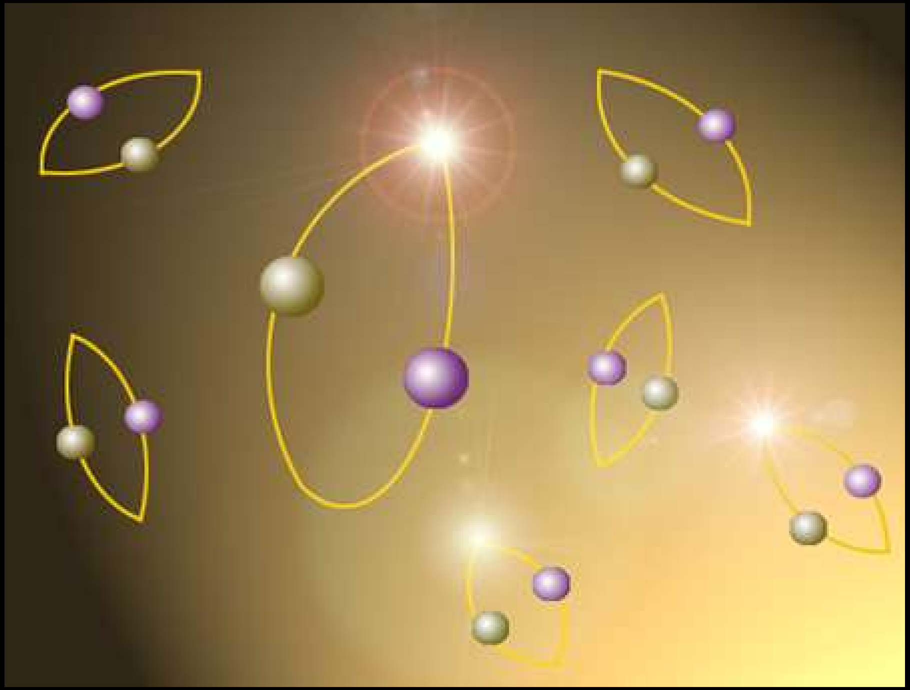


- Modified gravity

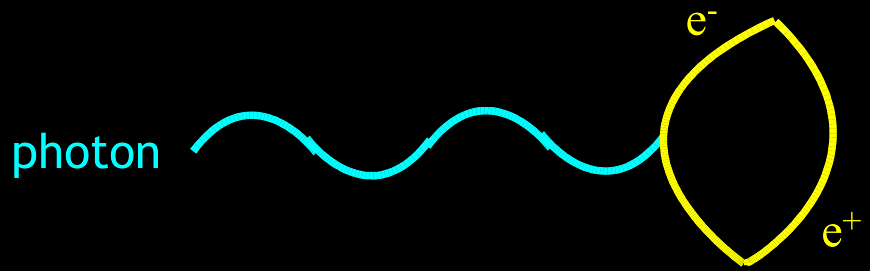
$$H^2 = f(\rho)$$

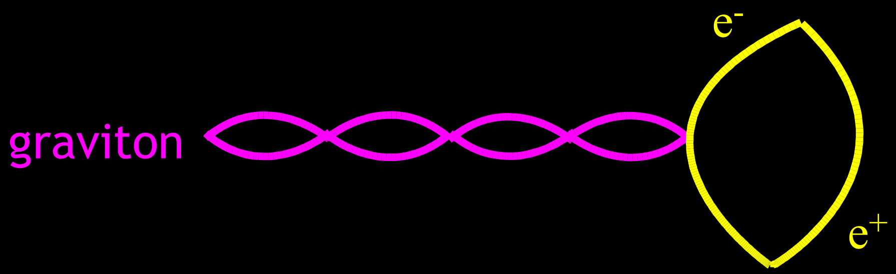


Vacuum Energy (Cosmological Constant)



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





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

The (hypothetical) supersymmetry scale, 1 TeV, is the geometric mean of the vacuum scale and the Planck scale. Coincidence?

The Gravitational Physics Data Book:

Newton's constant:

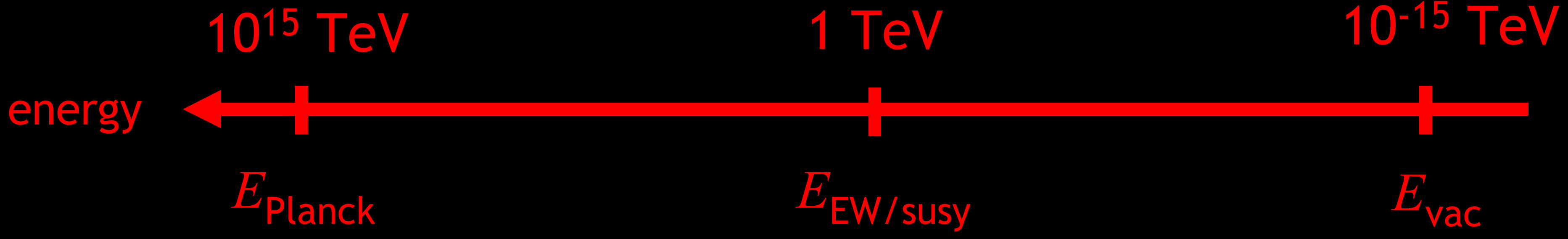
$G = (6.67 \pm 0.01)\ \mathrm{x}\ 10^{-8}\ \mathrm{cm}^3\ \mathrm{g}^{-1}\ \mathrm{sec}^{-2}$

Cosmological constant:

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

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

$E_{\mathrm{Planck}} = 10^{27}$ eV , $E_{\mathrm{vac}} = 10^{-3}$ eV .



10^{15} TeV

1 TeV

10^{-15} TeV

energy

E_{Planck}

$E_{\mathrm{EW/susy}}$

E_{vac}

The multiverse and environmental selection

Imagine that:

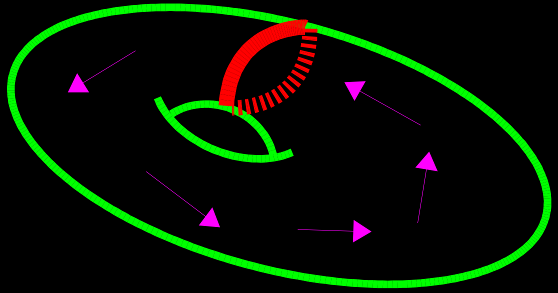
- There are many disconnected "universes."
- They each have a different vacuum energy.

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.

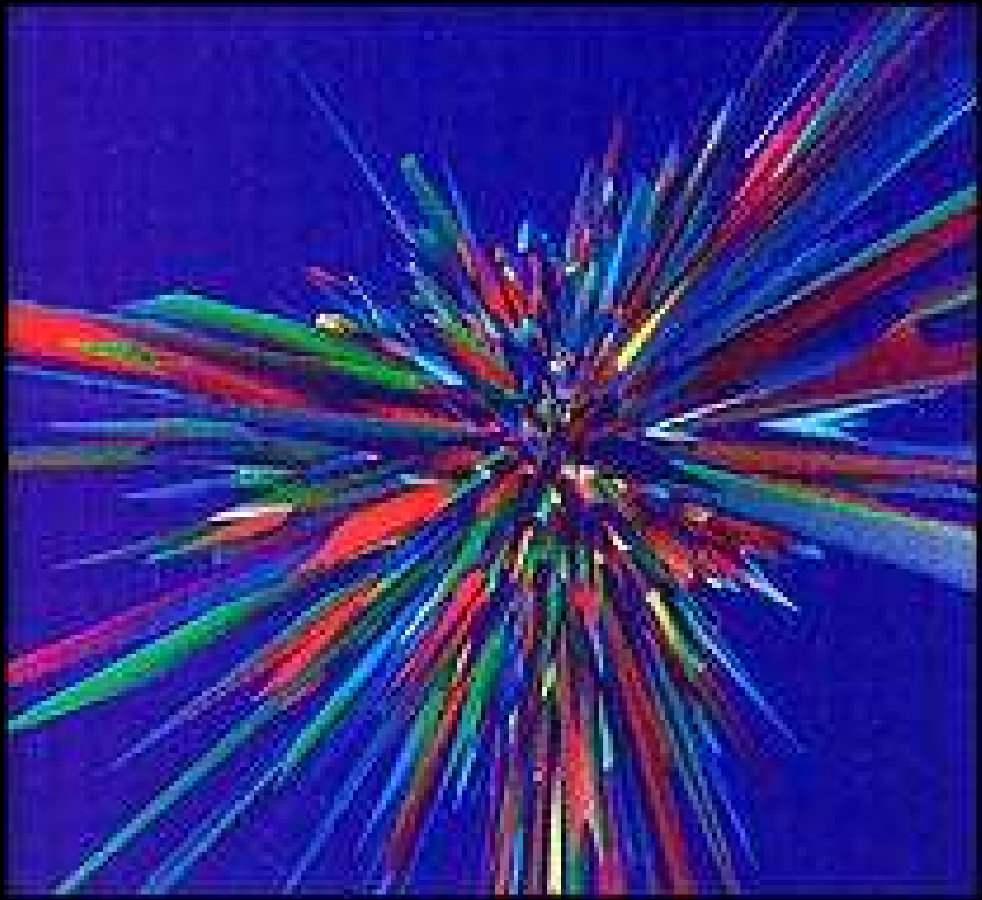
So are there really many domains with different properties?

String theory 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]

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

The multiversal Drake equation:

$$\text{Number of observers measuring } X = \sum_{\text{vacua } n} \underbrace{\left(\text{Does vacuum } n \text{ have property } X?\right)}_{\text{String theory counts this}} \underbrace{\left(\text{Volume of space in vacuum } n\right)}_{\text{Cosmology determines this!}} \underbrace{\left(\text{Density of observers in vacuum } n\right)}_{\text{(this is just hopeless)}}$$

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.

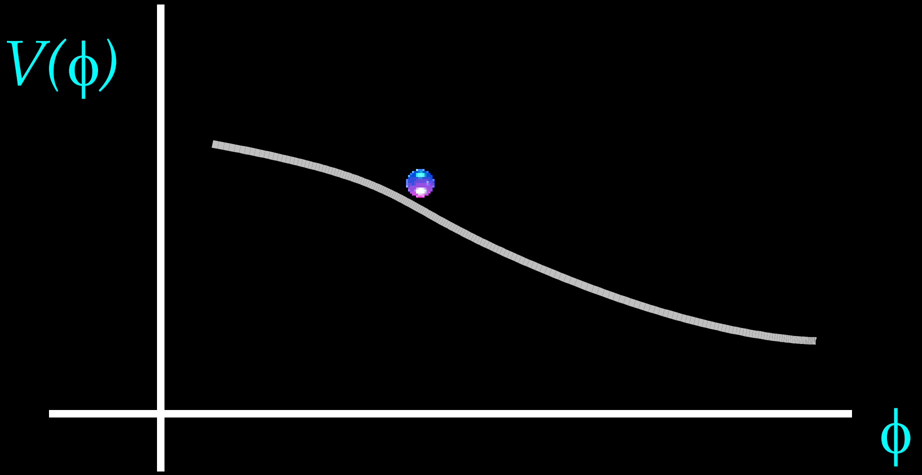
Is the dark energy a slowly-varying dynamical component?

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.]

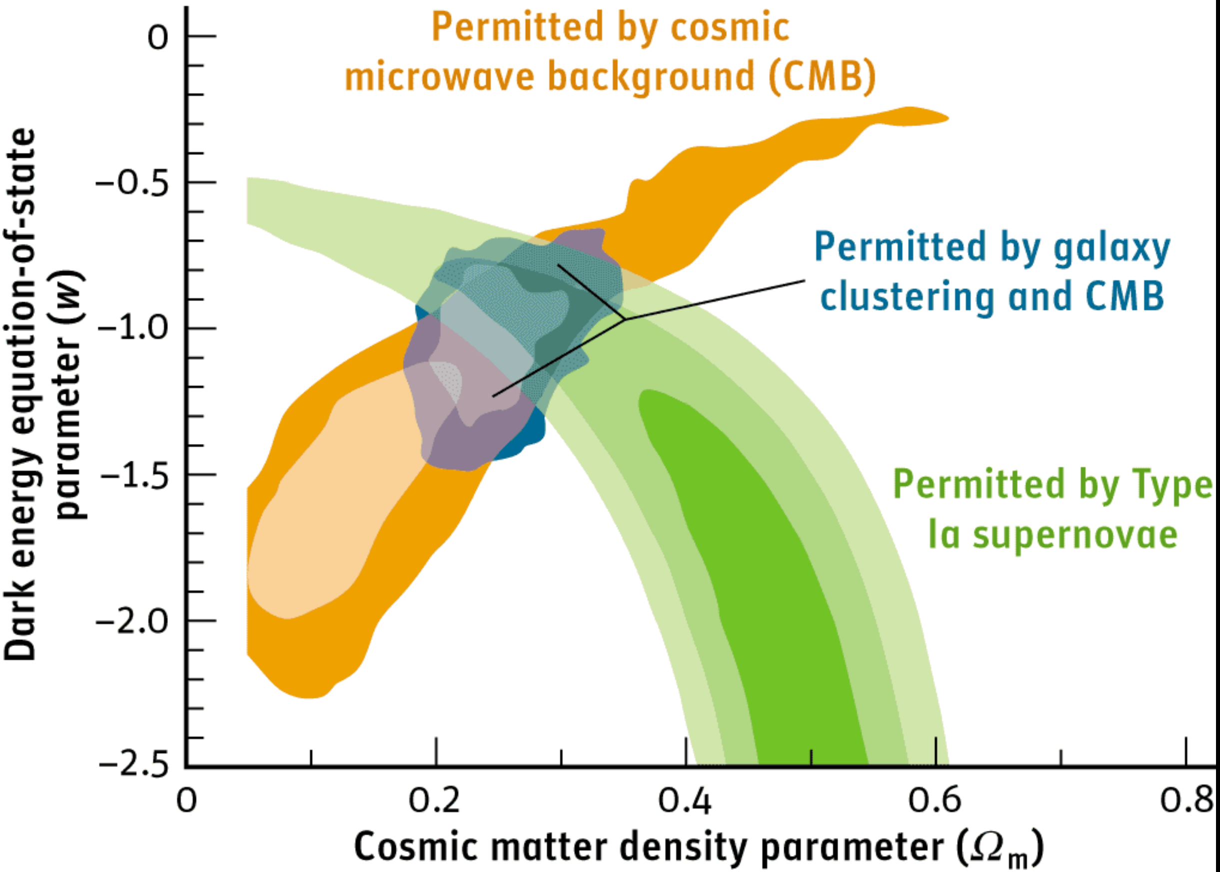
- This is an observationally interesting possibility, and at least holds the possibility of a dynamical explanation of the coincidence scandal.

- 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:

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



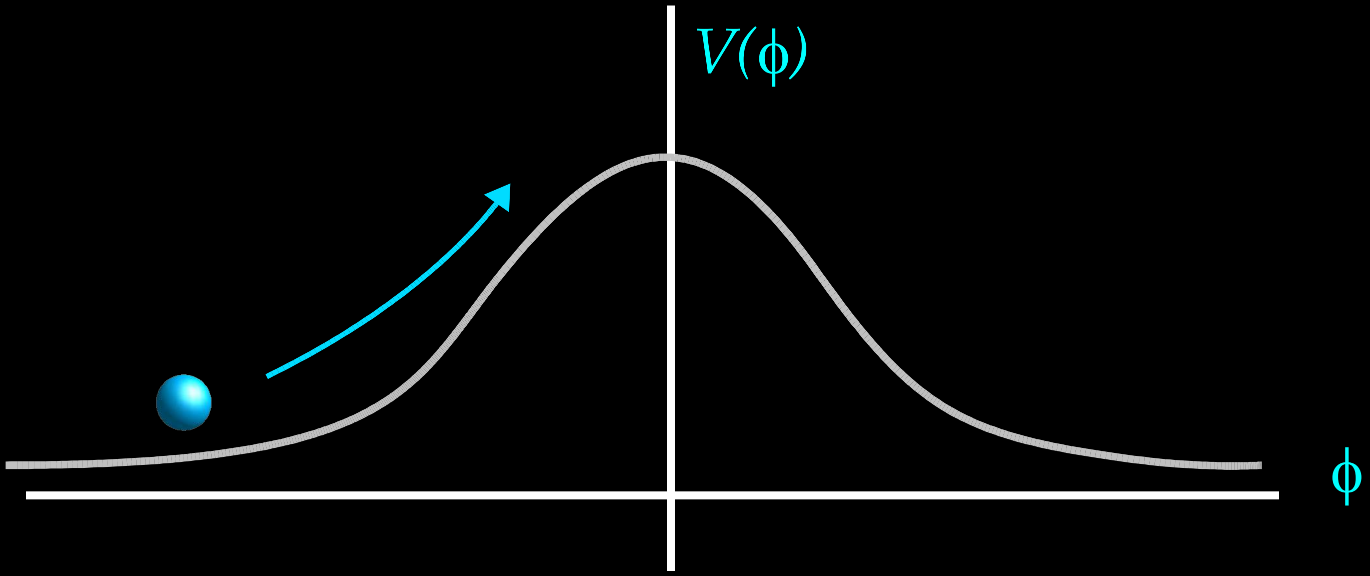
For matter, $w = 0$; for actual vacuum energy, $w = -1$.

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

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

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

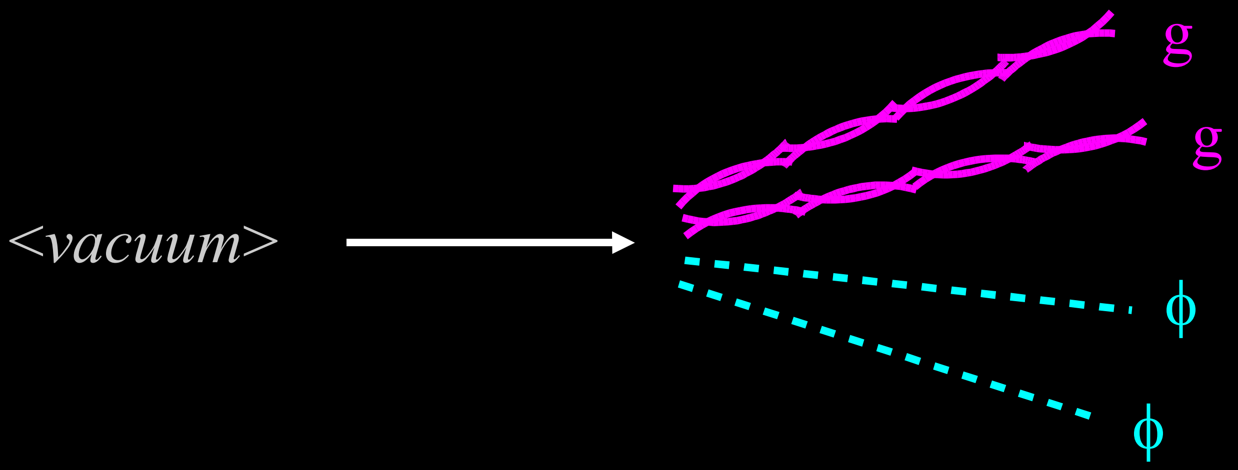


[Caldwell]

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.



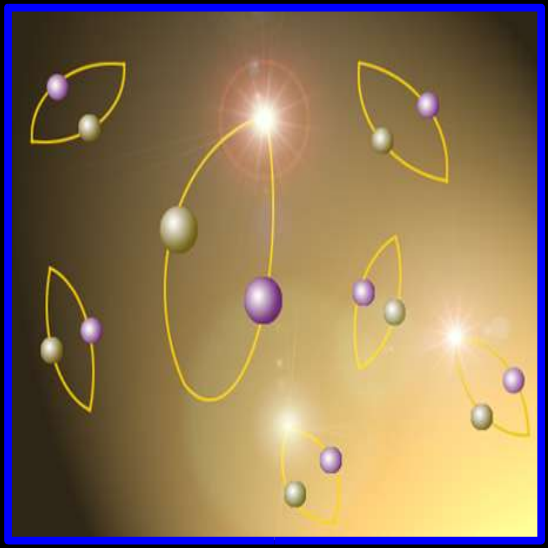
[Carroll, Hoffman & Trodden; Cline, Jeon, & Moore; Carroll, De Felice & Trodden]

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

[Arkani-Hamed, Cheng, Luty & Mukohyama]

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

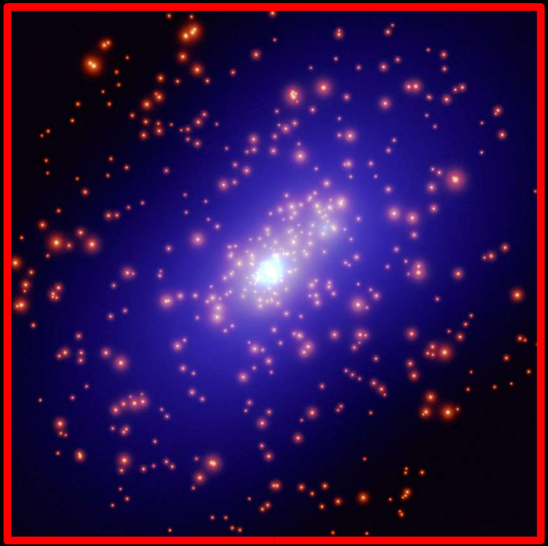
An introverted dark sector?



dark energy

ordinary matter

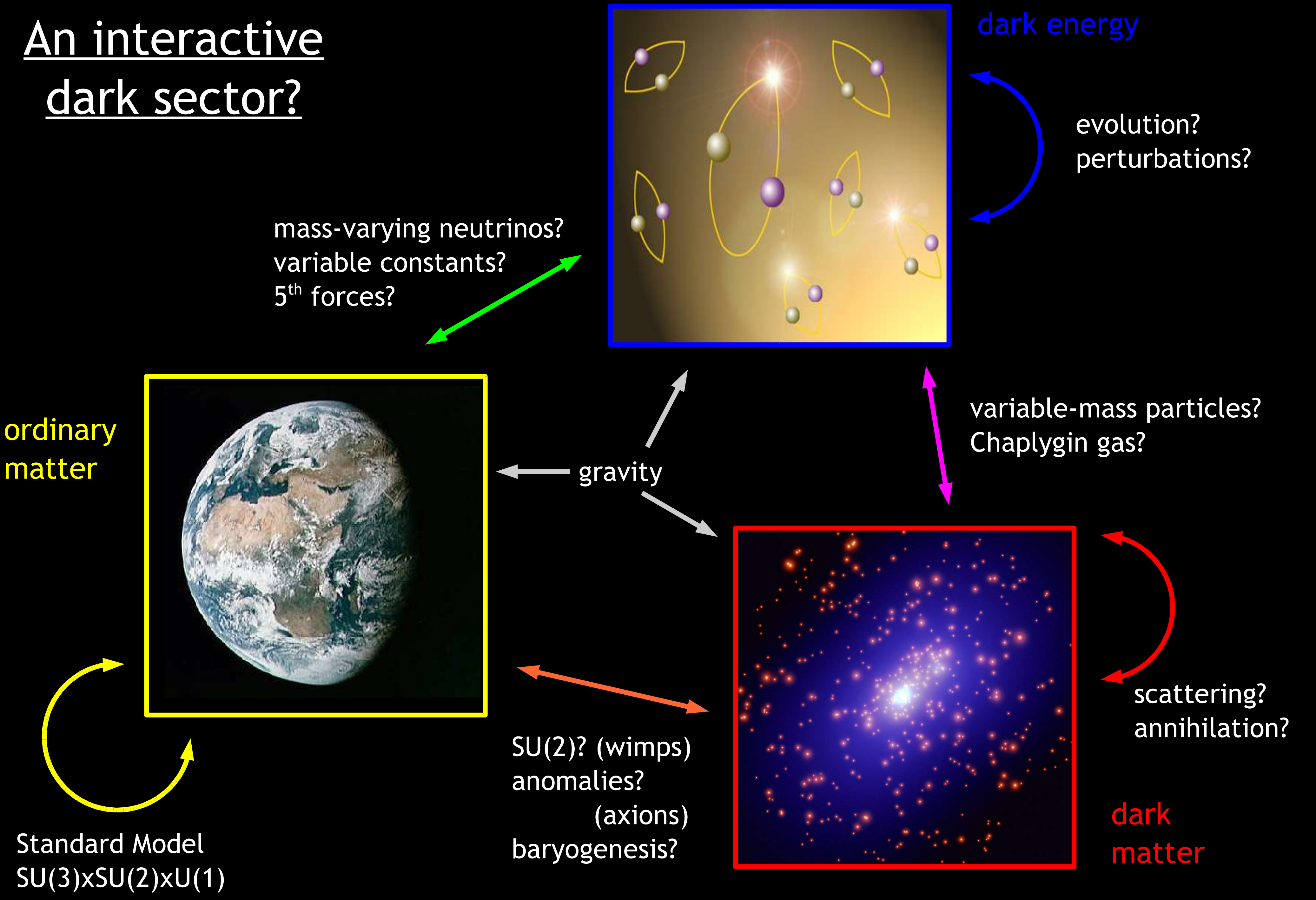
gravity



dark matter

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

An interactive dark sector?



dark energy

evolution?
perturbations?

mass-varying neutrinos?
variable constants?
5th forces?

ordinary
matter

gravity

variable-mass particles?
Chaplygin gas?

scattering?
annihilation?

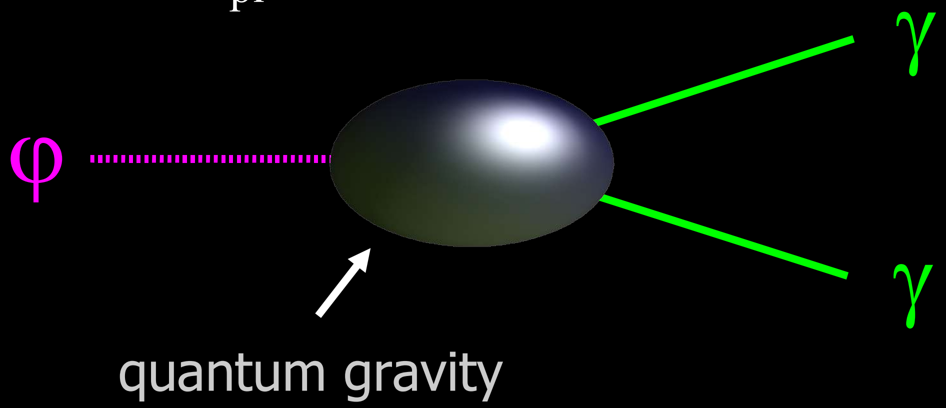
SU(2)? (wimps)
anomalies?
(axions)
baryogenesis?

dark
matter

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

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 $1/M_{\mathrm{pl}}$.



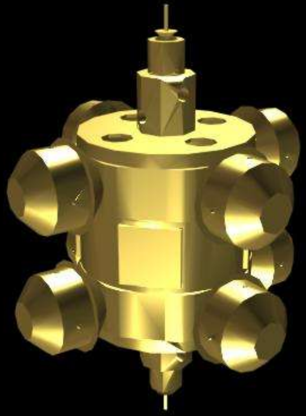
These interactions are constrained by 5th-force and time-dependent-constant measurements.

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]

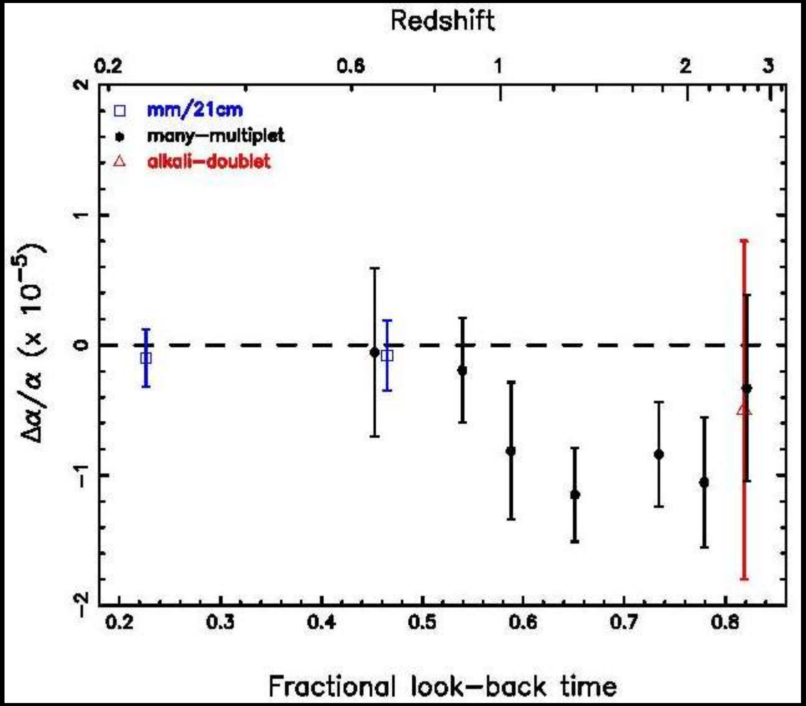
Direct dark energy detection search strategies:

- 5th forces.



[Adelberger et al.]

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



[Webb et al.]

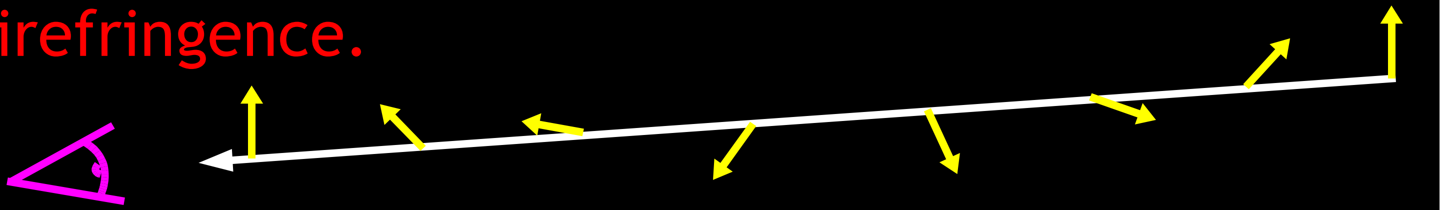
- Neutrino experiments (MaVaNs).

[Fardon, Nelson & Weiner]

[MiniBooNE]

- Cosmological birefringence.

[Carroll; Lue, Wang & Kamionkowski]

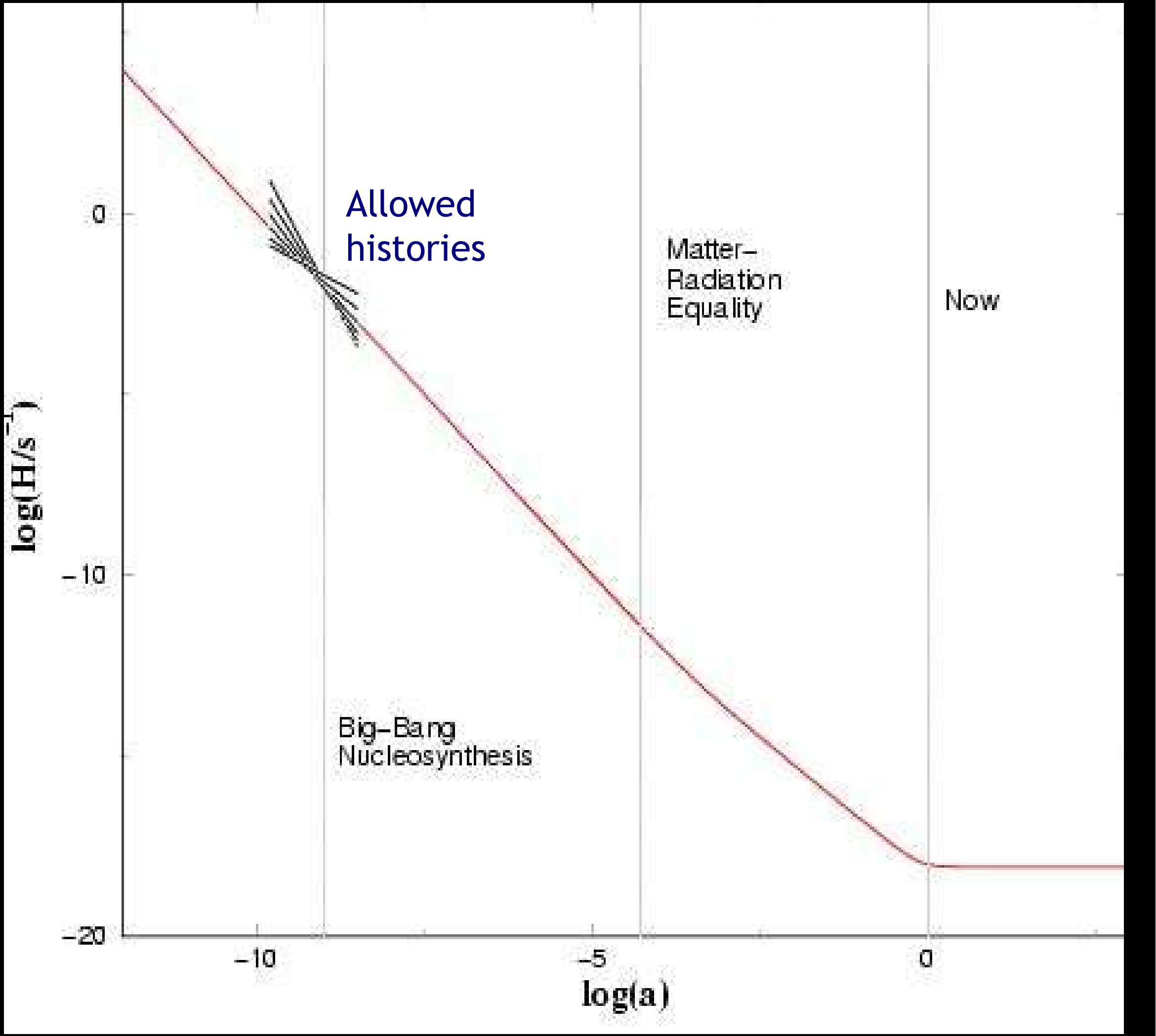


Was Einstein wrong?

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

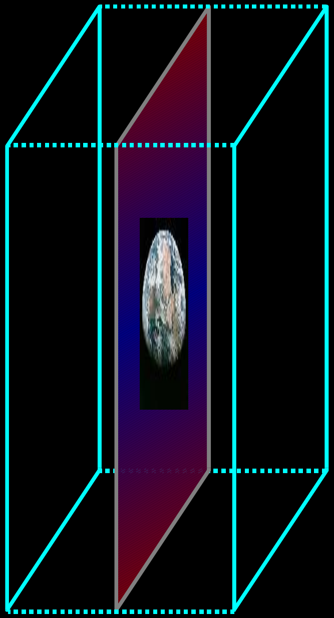
Big-Bang Nucleosynthesis tests the Friedmann equation as well as the values of G, Ω_b, N_ν.

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



[Carroll & Kaplinghat]

Can branes make the universe accelerate?

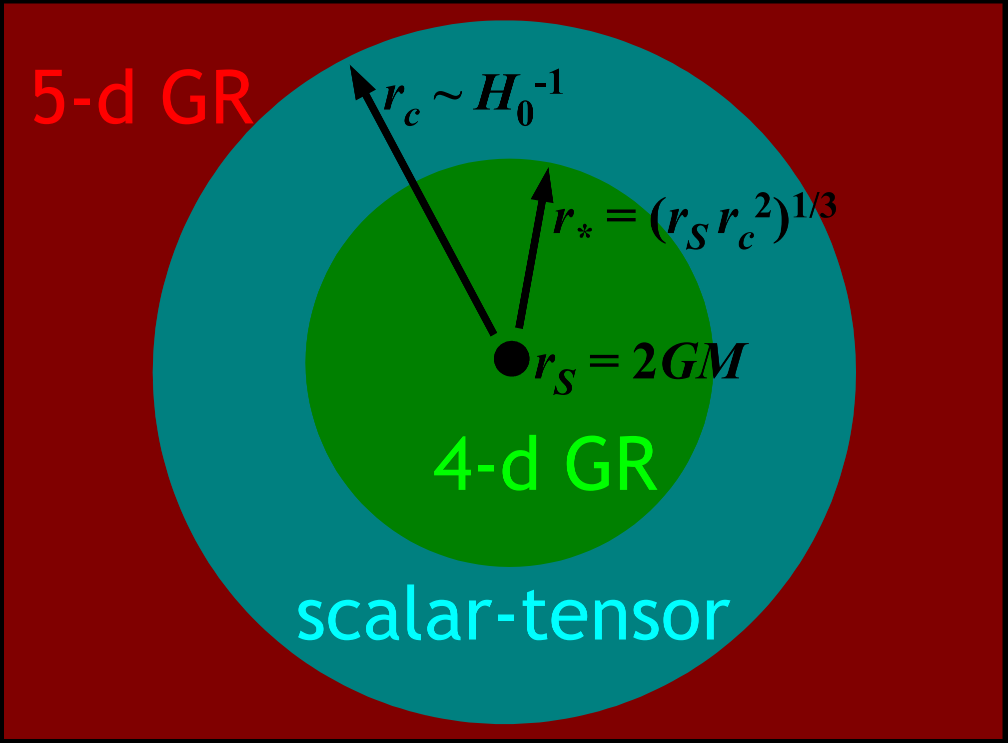


Dvali, Gabadadze, & Porrati (DGP) gravity:
an infinite extra dimension, with gravity weaker on the brane. Gravity is 4-d on small scales, 5-d kicks in at large distances.

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

4-d gravity term with conventional Planck scale

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



[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

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

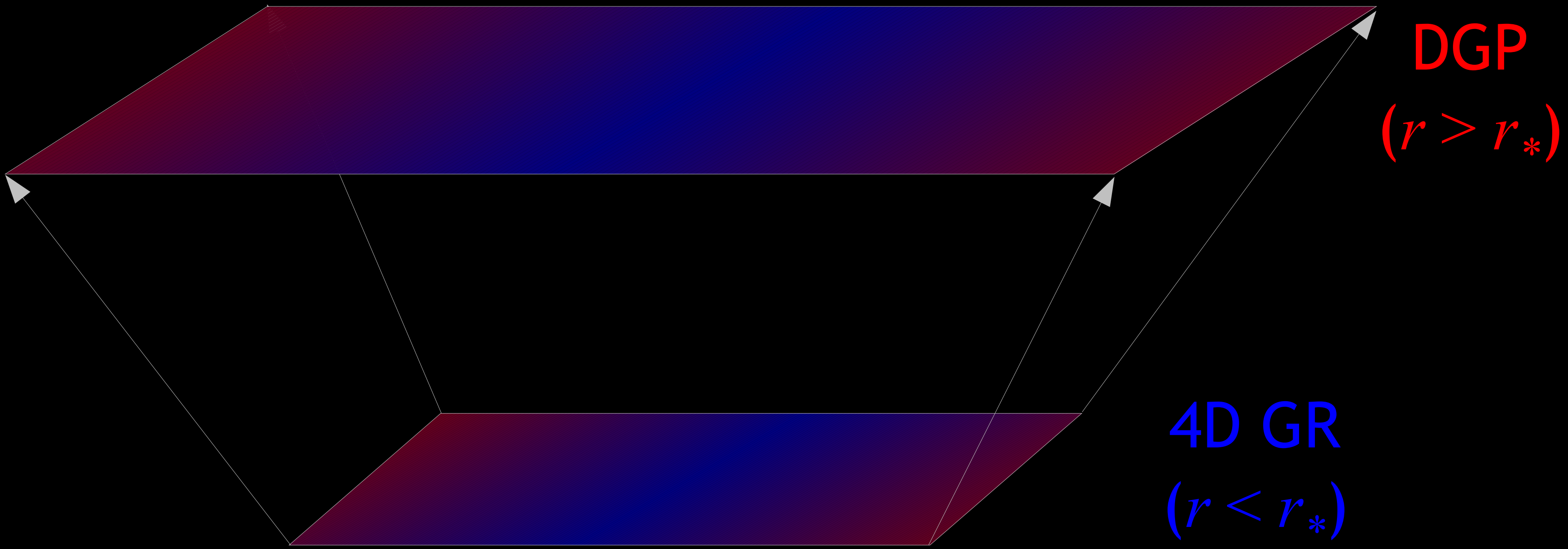
This exhibits self-acceleration: for $\rho = 0$, there is a de Sitter solution with $H = 1/r_c$ = constant.

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

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

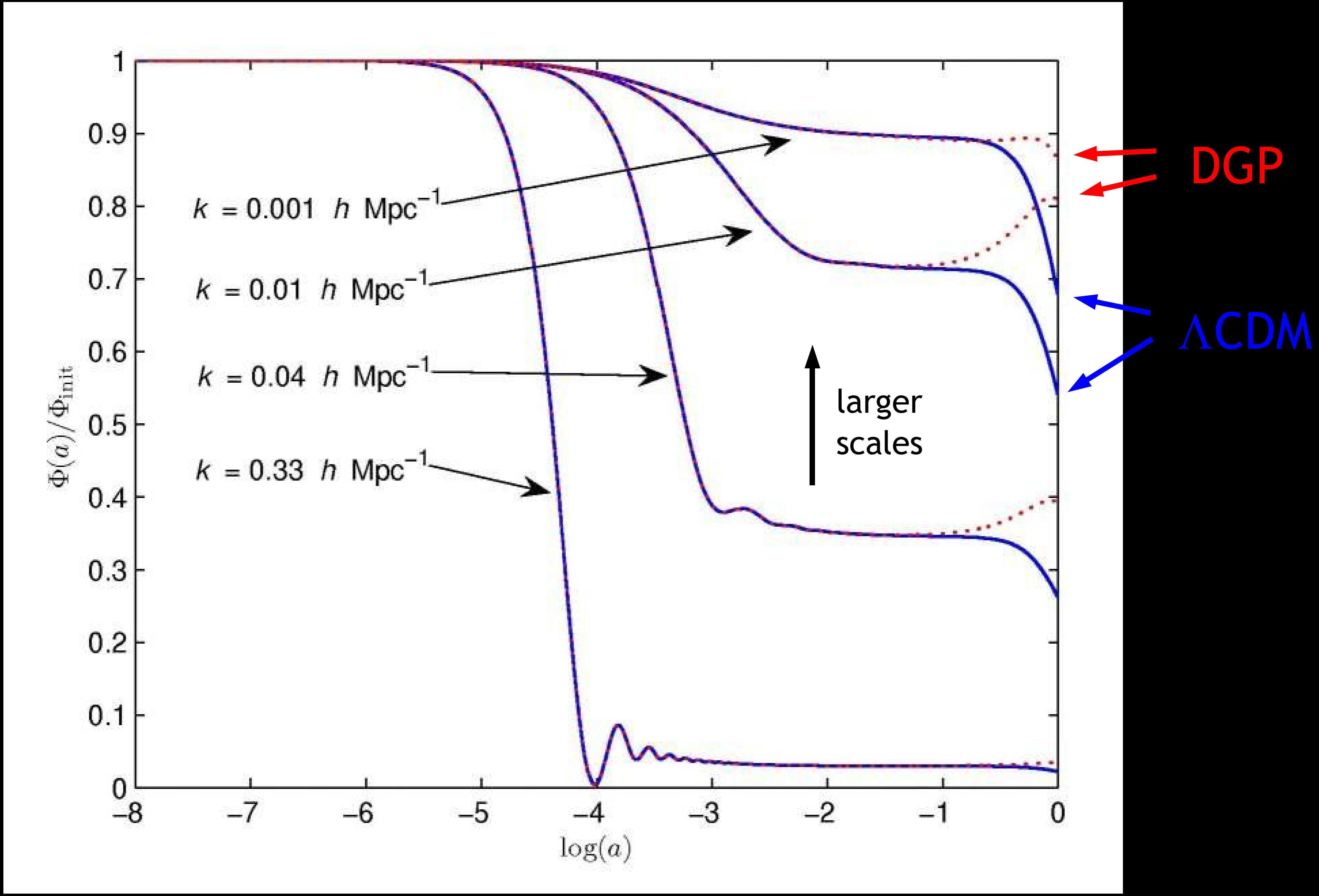
Perturbation evolution

As the universe expands, modes get stretched, and evolve from the 4-d GR regime into the scalar-tensor ("DGP") regime.



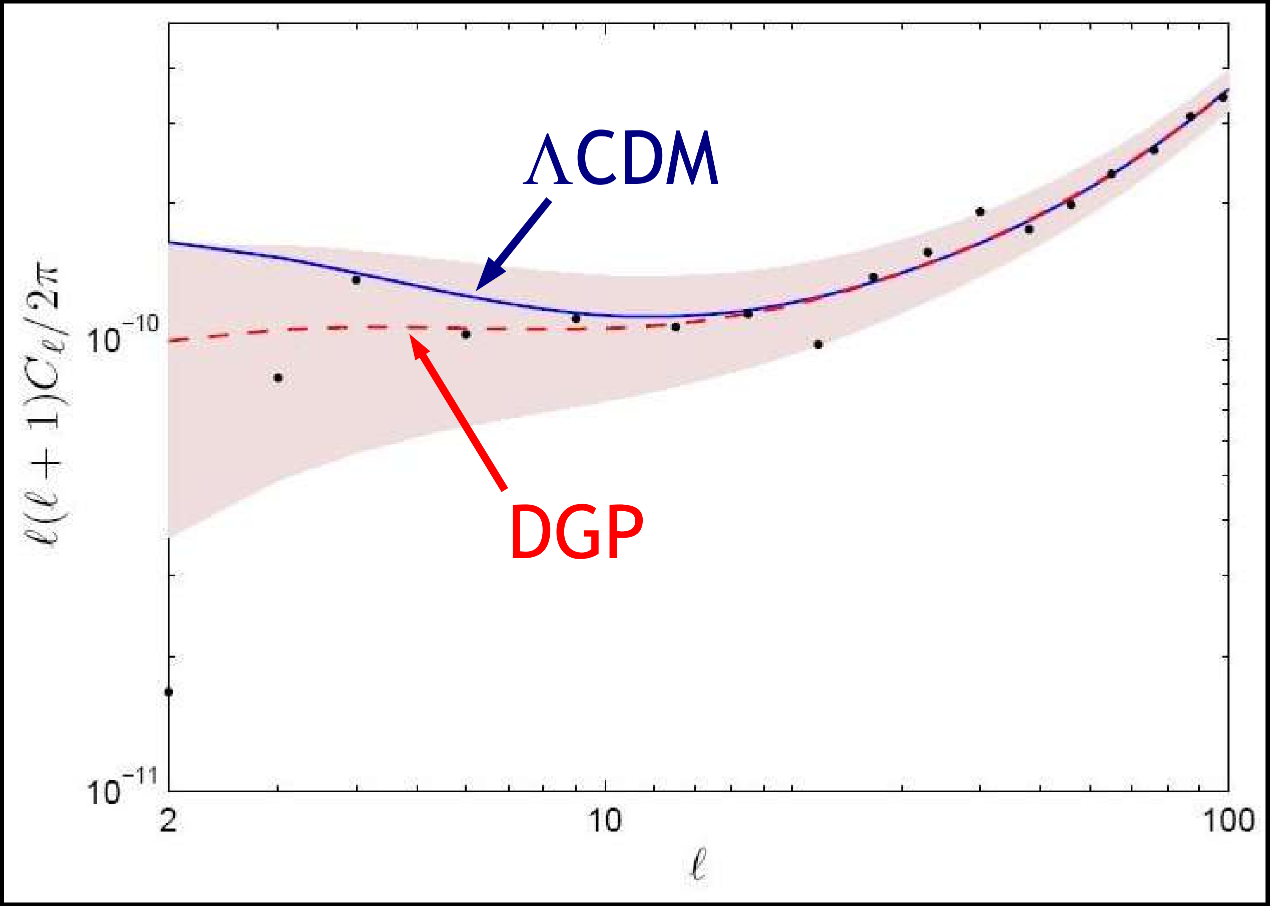
Scalar-tensor effects become important for long-wavelength modes at late times.

Evolution of Newtonian potentials in DGP vs. ΛCDM:



[Sawicki & Carroll 2005]

We have studied perturbation growth 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?

Simplest possibility: replace

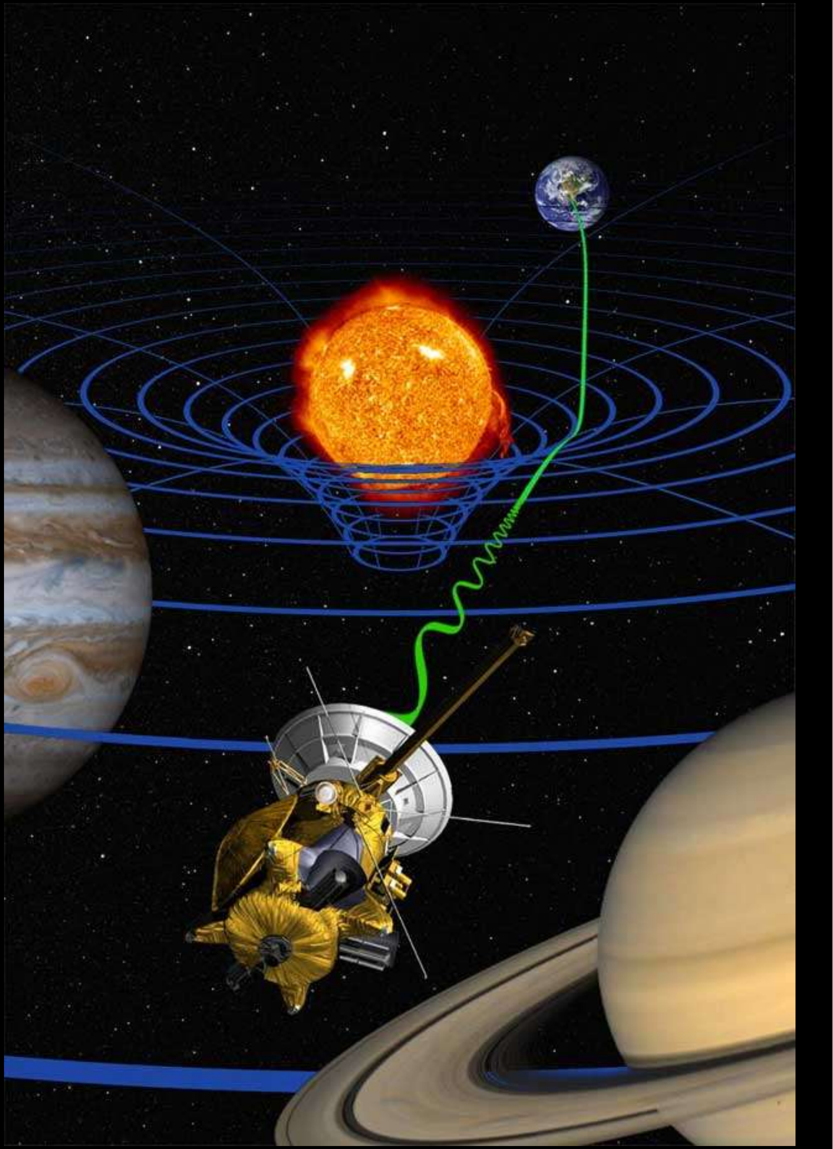
$$S = \int R \, d^4x$$

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 $T^{(matter)}$.

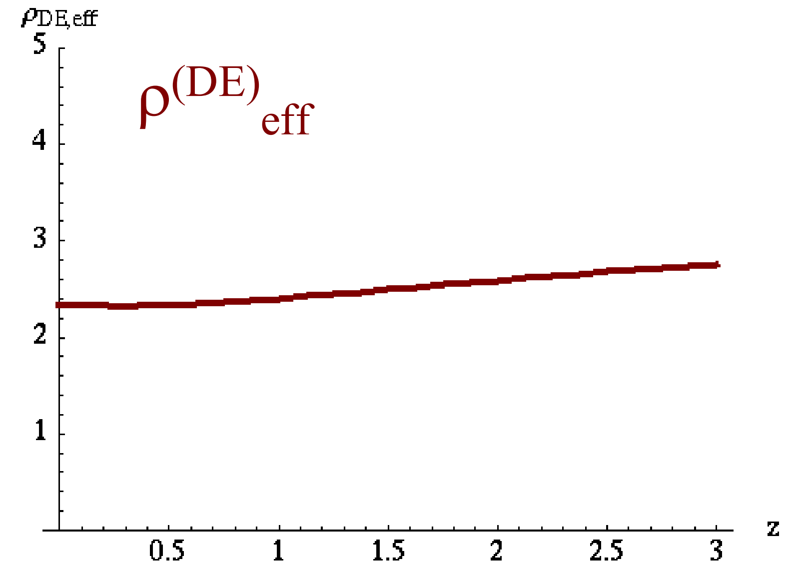
$$\frac{dU}{d\psi} - 4U(\psi) = -g^{\mu\nu}T_{\mu\nu}^{(matter)} = \rho - 3p$$

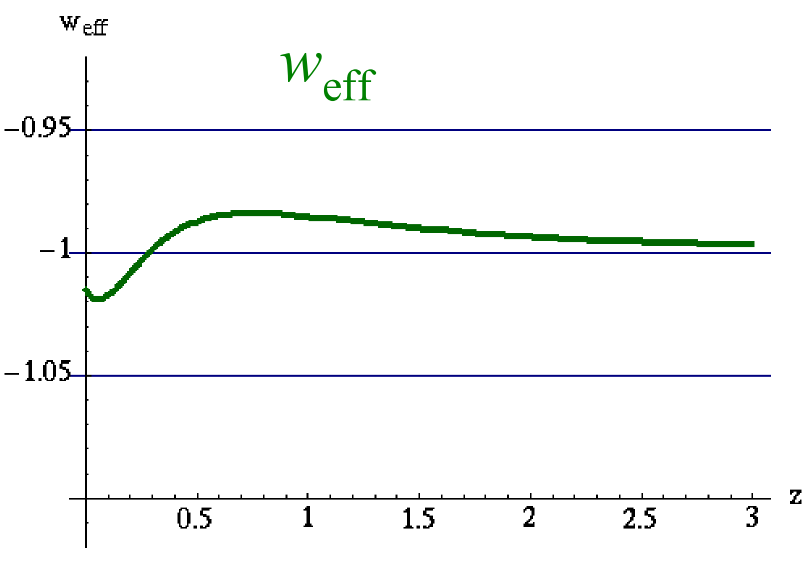
[Carroll 2006]

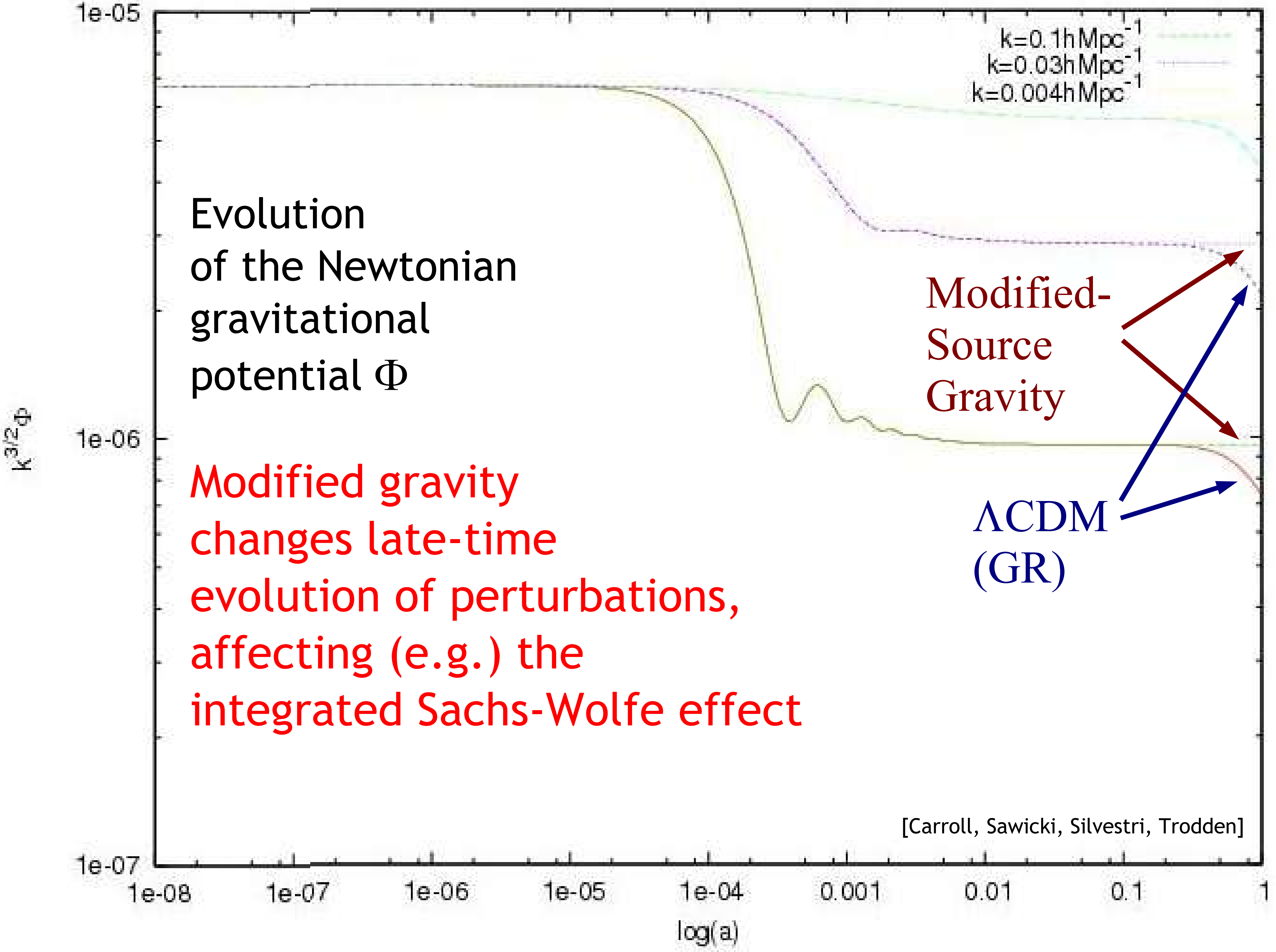
Cosmology in modified-source gravity

The effective Friedmann equation is

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







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)

[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 $a(t)$]:

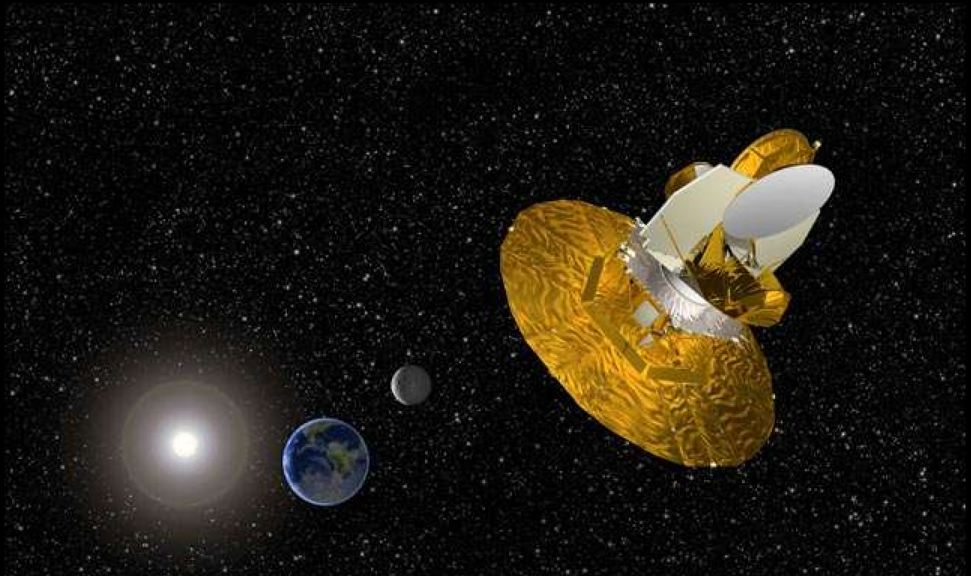
- Standard candles (luminosity distance vs. redshift)
- Baryon oscillations (angular diameter distance)

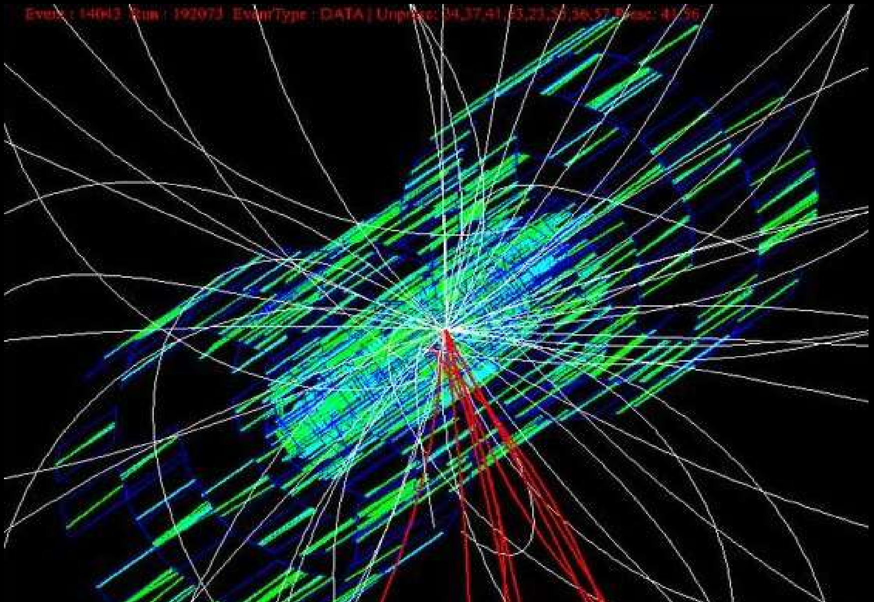
Dynamical probes [sensitive to $a(t)$ and growth factor]:

- Weak lensing
- Cluster counts (SZ effect)

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

The Universe and the Laboratory: complementary approaches



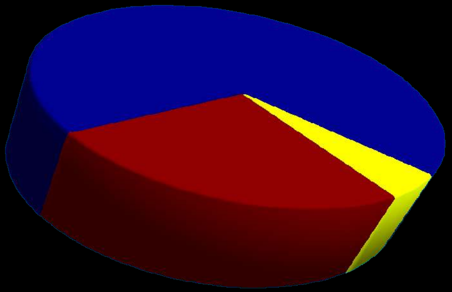


Surveillance

Interrogation

Conclusions

- 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 vacuum energy would be a surprise. But it would be an historic discovery, and a crucial clue; so it's worth making the effort.



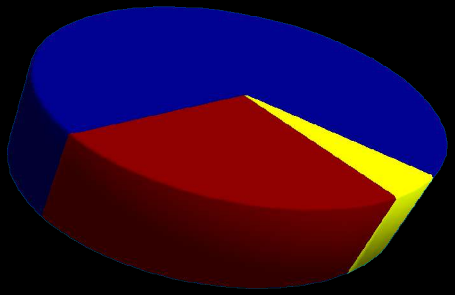
Conclusions

- 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.

What we think we know:

- Most “matter” is non-baryonic and dark.
- Total amount of matter is sub-critical: ~ 30%.
- But spatial curvature is negligible: < 10%.
- Even stranger, the universe is accelerating.

A good fit: 5% ordinary matter
25% cold dark matter
70% dark energy



- But: we should be open to dramatic possibilities.