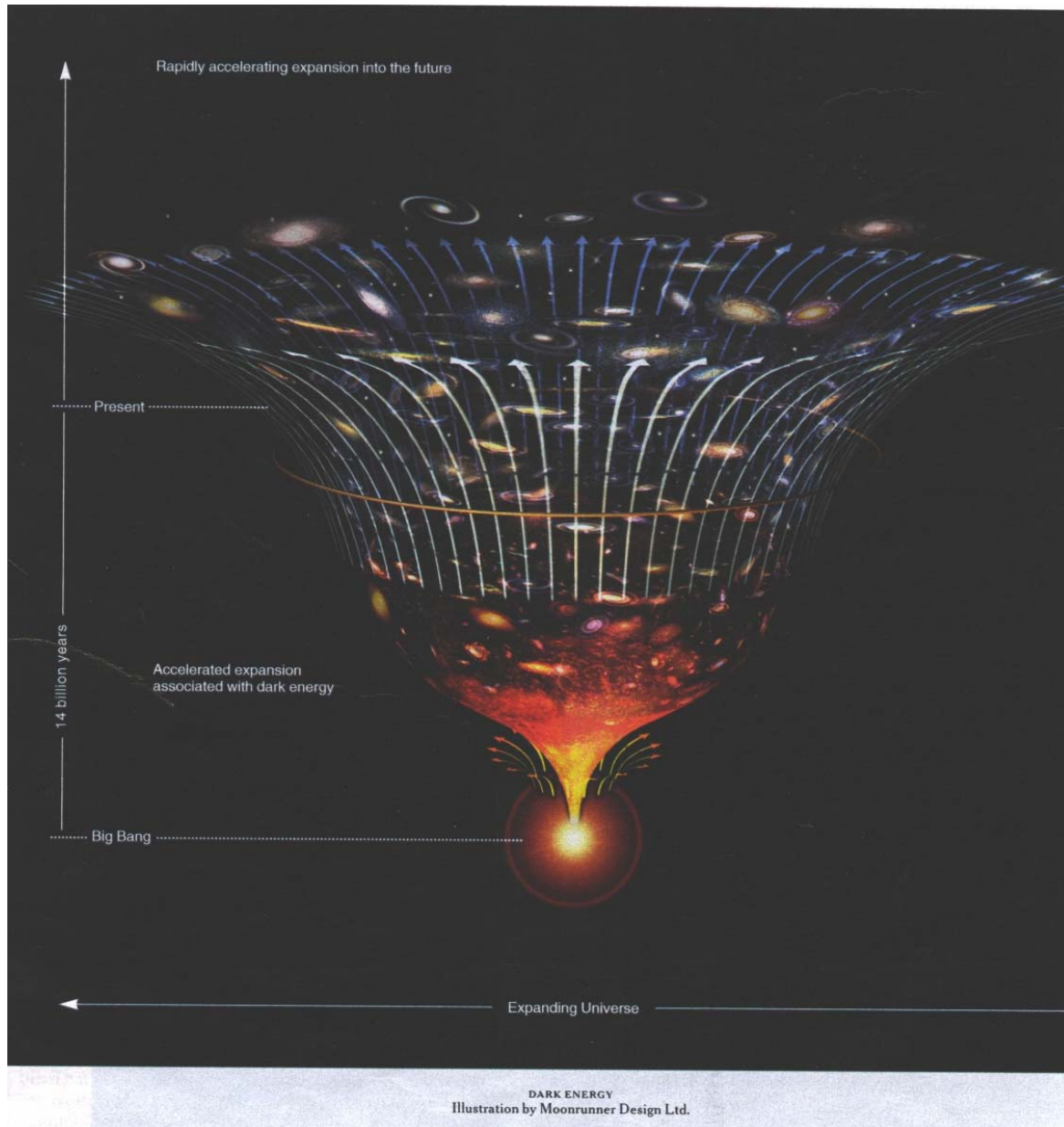


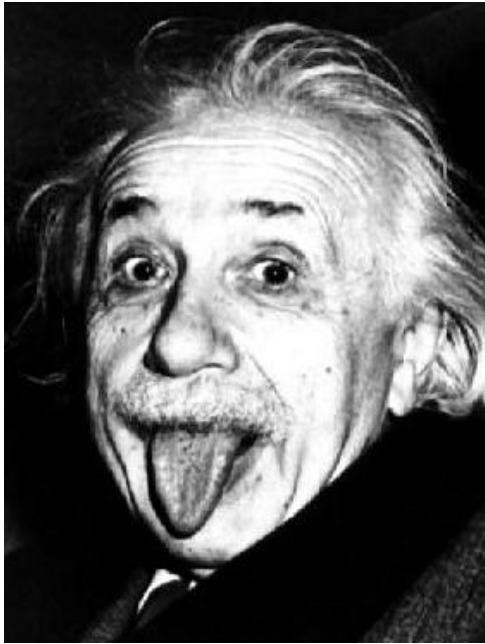
MISC

1. HW 5 is due today after class.
2. HW 6 is distributed – due next Friday.
(Also available as PDF on the class website)



The greatest blunder or the greatest guess?

$$G_{\mu\nu} - \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$



Einstein originally introduced *cosmological constant* as an *ad hoc* term in his equations to create homogeneous, finite and static Universe. The constant provides a repulsive force which counteracts gravity due to matter on large scales.

This original motivation is obsolete given that the observed Universe is expanding and Einstein abandoned it after discovery of expansion of the Universe, calling it his “greatest blunder.”

Given that the acceleration of the Universe expansion is measured, cosmological constant may not be zero after all...

***some interesting
reading about history
and meaning of Λ***

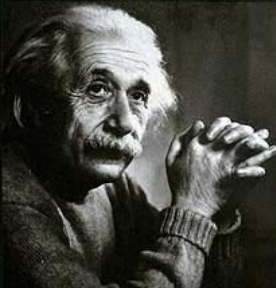
→ <http://xxx.lanl.gov/abs/0712.2196>

EINSTEIN'S REPULSIVE IDEA

He invented antigravity in desperation and abandoned it first chance he got—but it may be the most powerful force in the universe

By MICHAEL D. LEMONICK

ALBERT EINSTEIN NEVER DID LIKE THE idea of antigravity. It wasn't that he had a problem with farfetched notions. After all, his special and general relativity theories made the astonishing assertion that time, space and matter could be squeezed and stretched like so much India rubber. The trouble was that some sort of antigravity force—Einstein called it the "cosmological term"—was required to make the predictions of general relativity



NOT SO DUMB What he called a blunder may have been a Nobel-caliber discovery

match what astronomers believed the actual universe looked like. And that extra term marred the mathematical elegance of his beloved equations. The great physicist was hugely relieved when the discovery of the expanding universe in the 1920s let him cross out what he declared was "my greatest blunder."

But he might have been a bit too hasty. Last week scientists made a powerful case that Einstein's blunder may actually have been another Nobel-worthy prediction. Using the Hubble Space Telescope to find

1 GRAVITY

● **WHAT IT IS:** An attractive force that pulls matter together like a rubber band

● **HOW IT OPERATES:** Gravity weakens over distance; when the distance between two galaxies doubles, the force between them is one-fourth as strong

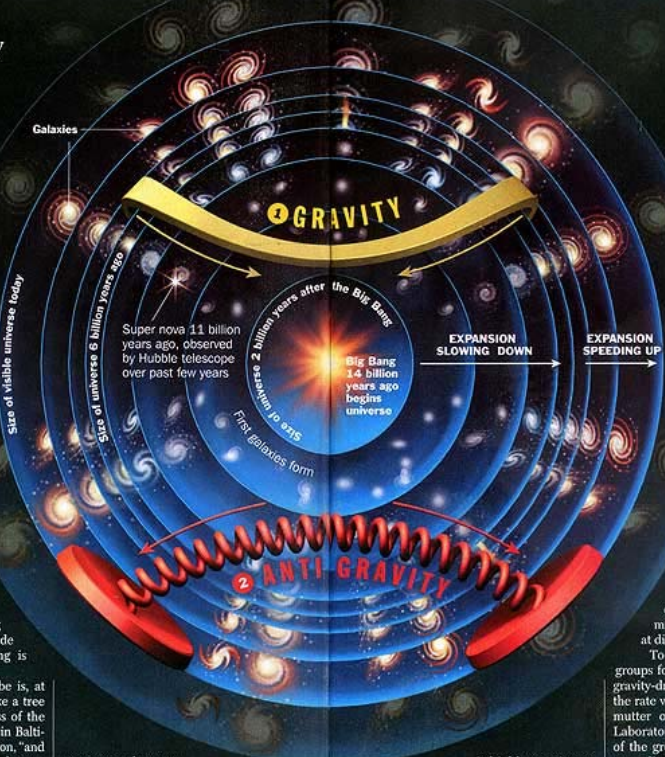
● **WHAT THAT MEANS:** As the universe expands, gravity is less and less effective at slowing the expansion

TIME Diagrams by Joe Lenora

and study a distant supernova—an exploding star—astronomers from two rival research teams have jointly gathered the strongest evidence yet that the expansion of the universe is actually speeding up, like a rocket with its throttle wide open. And that means something is pushing it.

What that something might be is, at this point, anybody's guess. "Shake a tree full of theorists," says Adam Riess of the Space Telescope Science Institute in Baltimore, Md., leader of the collaboration, "and 30 ideas will fall out." For now, the unknown force is simply being called "dark energy," to emphasize its mysterious nature.

But its existence is becoming hard to dispute. The first hint came a couple of



years ago, when two independent teams of astronomers tried to calibrate the cosmic expansion using Type Ia supernovas, a kind of exploding star whose intrinsic brightness

is highly consistent. Comparing the known brightness of such a supernova with how bright it appears in the sky gives a good measure of how far away it is—and thus how long ago

2 ANTIGRAVITY (Dark Energy)

● **WHAT IT IS:** A property of empty space that exerts an outward force like a compressed spring at every point in space

● **HOW IT OPERATES:** A given volume of space always has the same amount of dark energy, so when the distance between two galaxies doubles, the force pushing them away from each other is twice as strong

● **WHAT THAT MEANS:** As the universe expands the volume of space increases, which means more dark energy. By now, 14 billion years after the Big Bang, antigravity has overwhelmed gravity, so the expansion will get faster and faster

in cosmic history its light was emitted. Then, by measuring how fast each supernova is moving away from Earth in the overall ballooning of the universe, it can be determined what the expansion rate was at different times in the past.

To everyone's astonishment, both groups found that instead of the gradual, gravity-driven slowdown they expected, the rate was getting faster. Says Saul Perlmutter of Lawrence Berkeley National Laboratory in California, who heads one of the groups: "We spent at least a year struggling to understand what we were seeing." In the end, both groups decided that dark energy, functioning as a kind of antigravity, was their best guess. Critics argued that there might be a

more conventional explanation, such as intergalactic dust, which could contaminate the brightness measurements. But the new observations seem to have closed that loophole. The newly identified supernova went off about 11 billion years ago—about 50% further back in time than the previous record holder. "If the dust were there," says Lawrence Berkeley astrophysicist Peter Nugent, a member of Perlmutter's team and Riess's collaborator on the new research, "the supernova would have been much dimmer than it was."

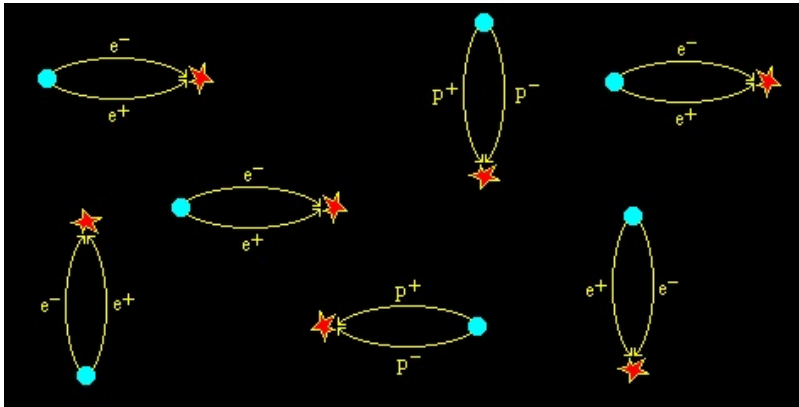
The new supernova's remoteness was even more important for another reason. "If dark energy is really the explanation for what we see," says Riess, a member of the rival team, "then its effect should have been weaker in the early universe." That's because while the force of gravity between galaxies falls as they move farther apart, dark energy is a property of space and gets stronger as the universe expands. Shortly after the Big Bang, when the universe took up relatively little space, there wasn't much dark energy. Now much bigger, the modern universe has more space and thus more energy to shove galaxies apart. Sure enough, this distant supernova shows that the expansion was slower long ago.

While the new observations go a long way toward confirming that dark energy is real, astronomers would love to see a few more distant supernovas, just to be sure. Unfortunately, that won't be happening soon. The Hubble pictures that Riess and Nugent analyzed were all taken purely by chance, while the telescope was looking for other things. Aiming at distant galaxies in hopes a supernova will go off is an inefficient use of the telescope's valuable time. The best bet would be a satellite devoted to such a project—and indeed, Perlmutter and others are working on that idea, although it will take years to get off the ground.

If space really does seethe with dark energy, the fate of the universe, a matter of longstanding debate, will be clear. With more dark energy today than yesterday, and more of the stuff tomorrow than today, the cosmos should fly apart faster and faster as time goes by. There will be no Big Crunch, as some have predicted, with billions of galaxies falling in on one another in a fiery apocalypse. Tens of billions of years from now, our Milky Way galaxy will find itself alone in empty space, with its nearest neighbors too far away to see. In the end, the stars will simply wink out—and the universe will end not with a bang but with the meekest of whimpers. ■

$$\ddot{r} = -\frac{GM}{r^2} + \frac{\Lambda}{3}r$$

What is cosmological constant?



- ❑ We have ***no clue*** yet.
- ❑ cosmological constant can be the quantum energy of vacuum, in principle...
- ❑ Such energy is predicted by quantum field theory and its effects are observed and measured in the laboratory (Kasimir effect).
- ❑ However, straightforward calculations predict cosmological constant some ~ 60 - 120 orders (10^{120} times!) larger than what's observed.

Generalizing Λ : dark energy



Michael Turner
(U.Chicago)

Cosmologists now discuss a general dark energy as a possible driving force behind acceleration of the Universe (U.Chicago's Michael Turner coined the term *the dark energy*).

The dark energy is due to some field, the quintessence, associated with a yet unknown interaction or particle (new physics)

1	2	3	4
E Earth	W Water	A Air	F Fire
			5 Et Ether

What is Dark Energy?



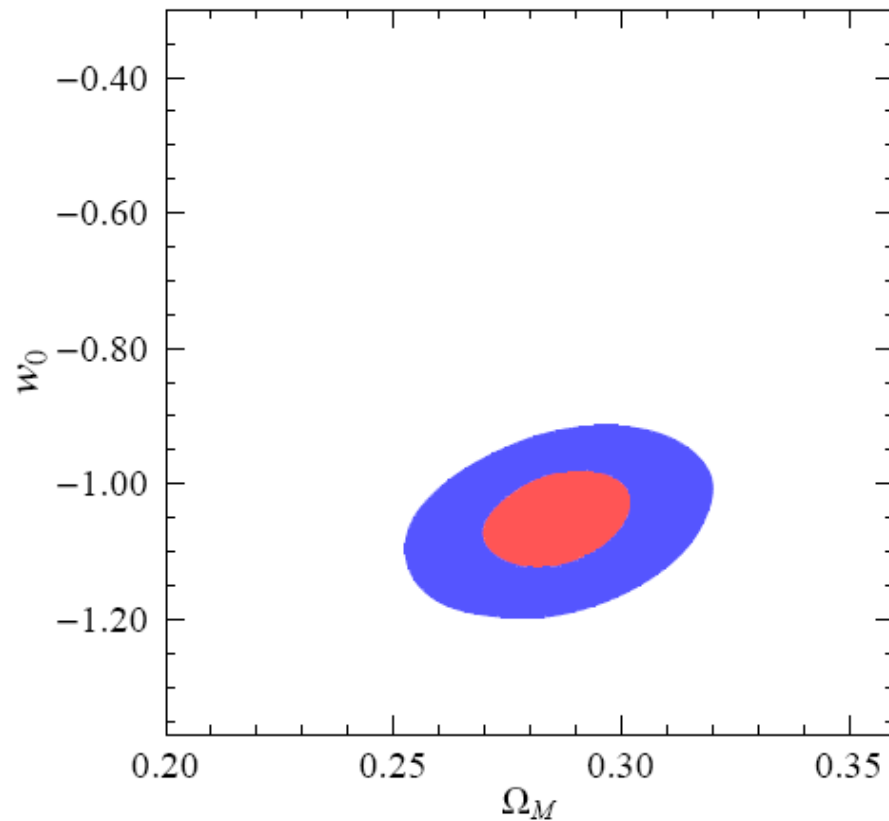
***cosmological constant
would correspond to
 $w=-1$***

- If it is a field, rather than cosmological constant, it stands to reason that its energy density does not have to be constant
- In general, acceleration can be caused by anything that provides negative energy which can act as anti-gravity in Einstein's equations
- cosmologists parameterize their current ignorance by adopting a simple form of equation of state for dark energy:

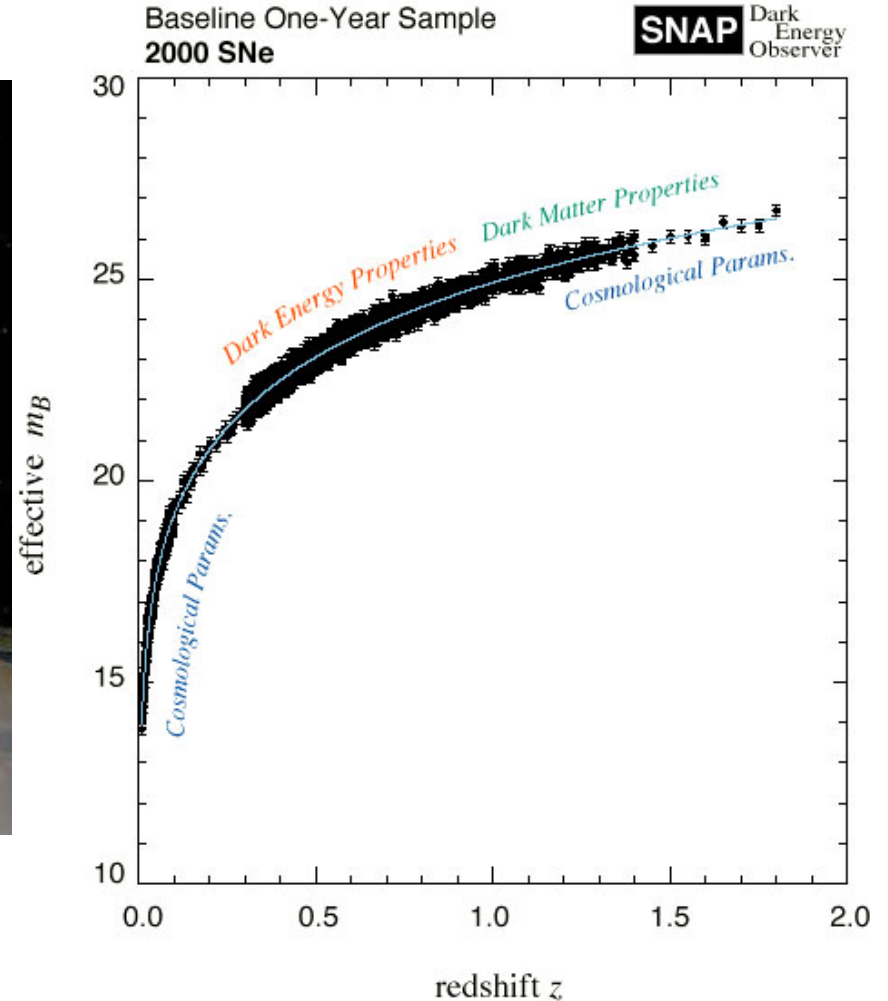
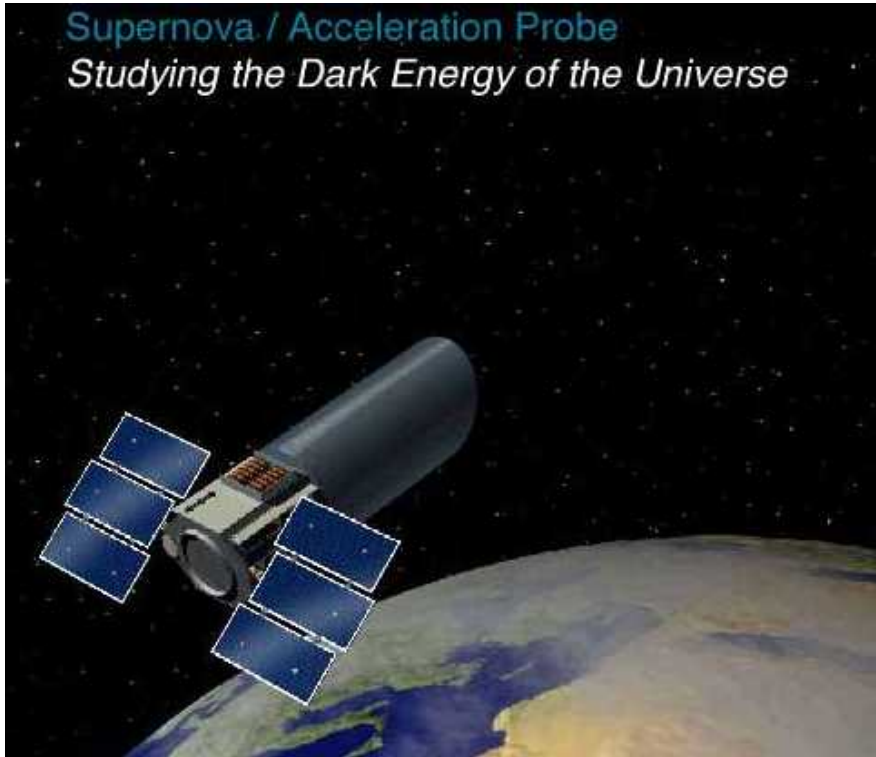
$$P = w \rho$$

Best current constraint on w
using all available data

***still consistent with cosmological constant
($w=-1$)!***



SNAP satellite proposal

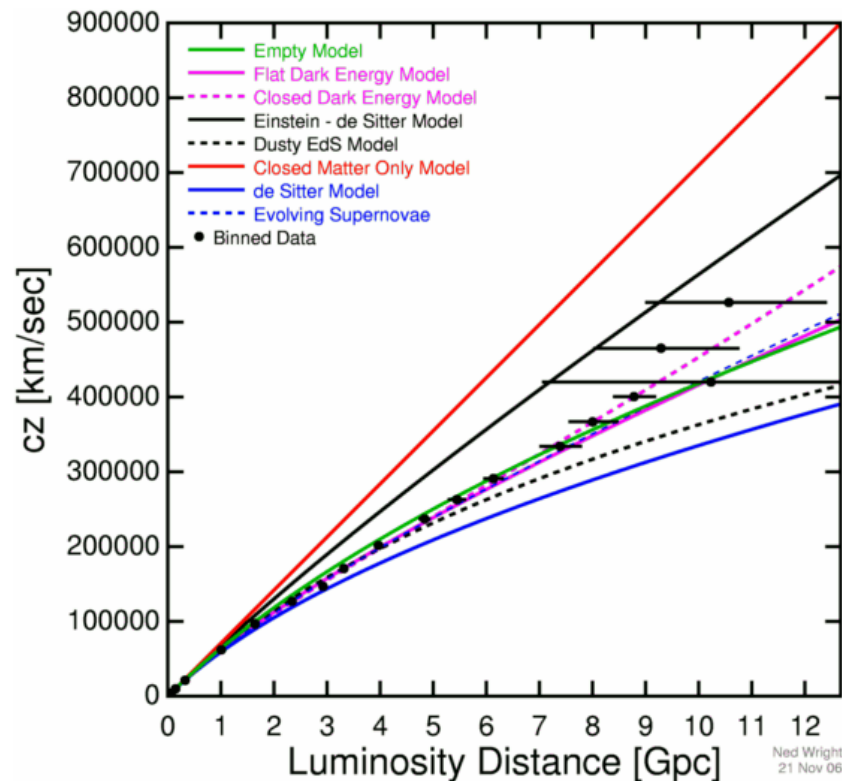


***future accurate experiments can
measure w and its change with time***

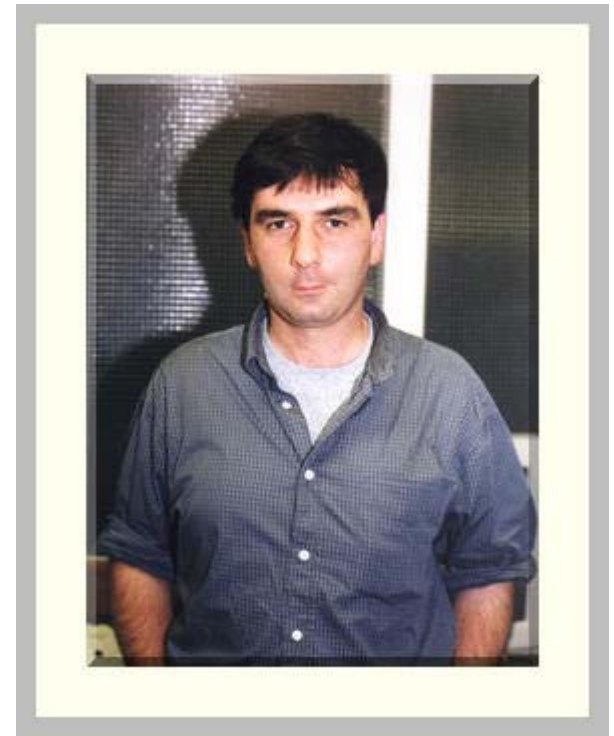
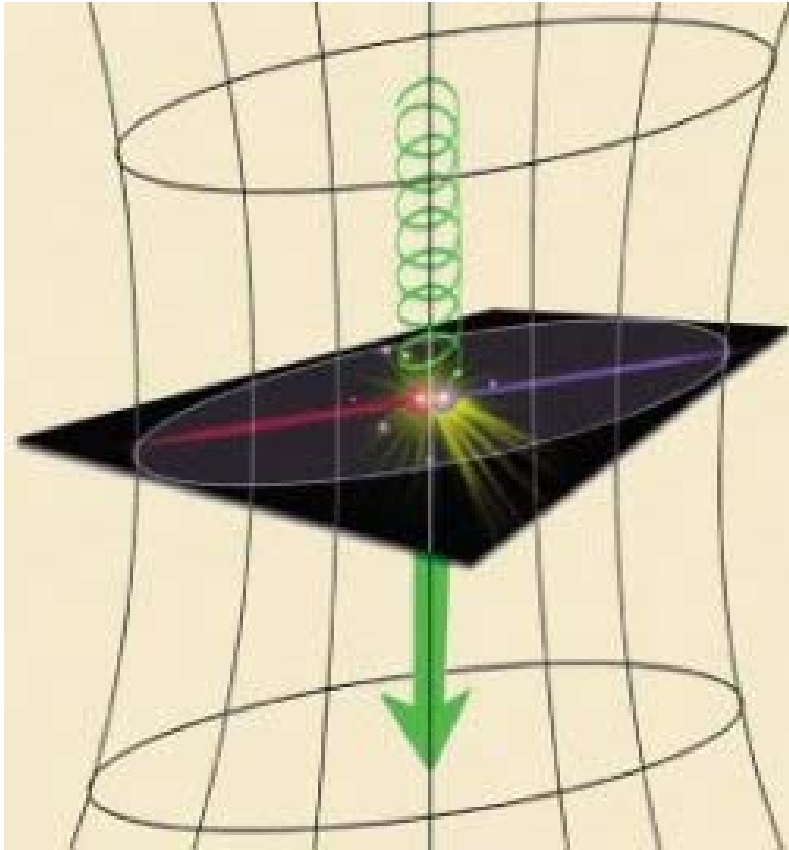
We should remember that the data show accelerated expansion

It can be interpreted as dark energy in the context of general relativity theory

OR as failure of the GR theory itself (i.e. signature that gravity is different from what GR predicts on large scales)



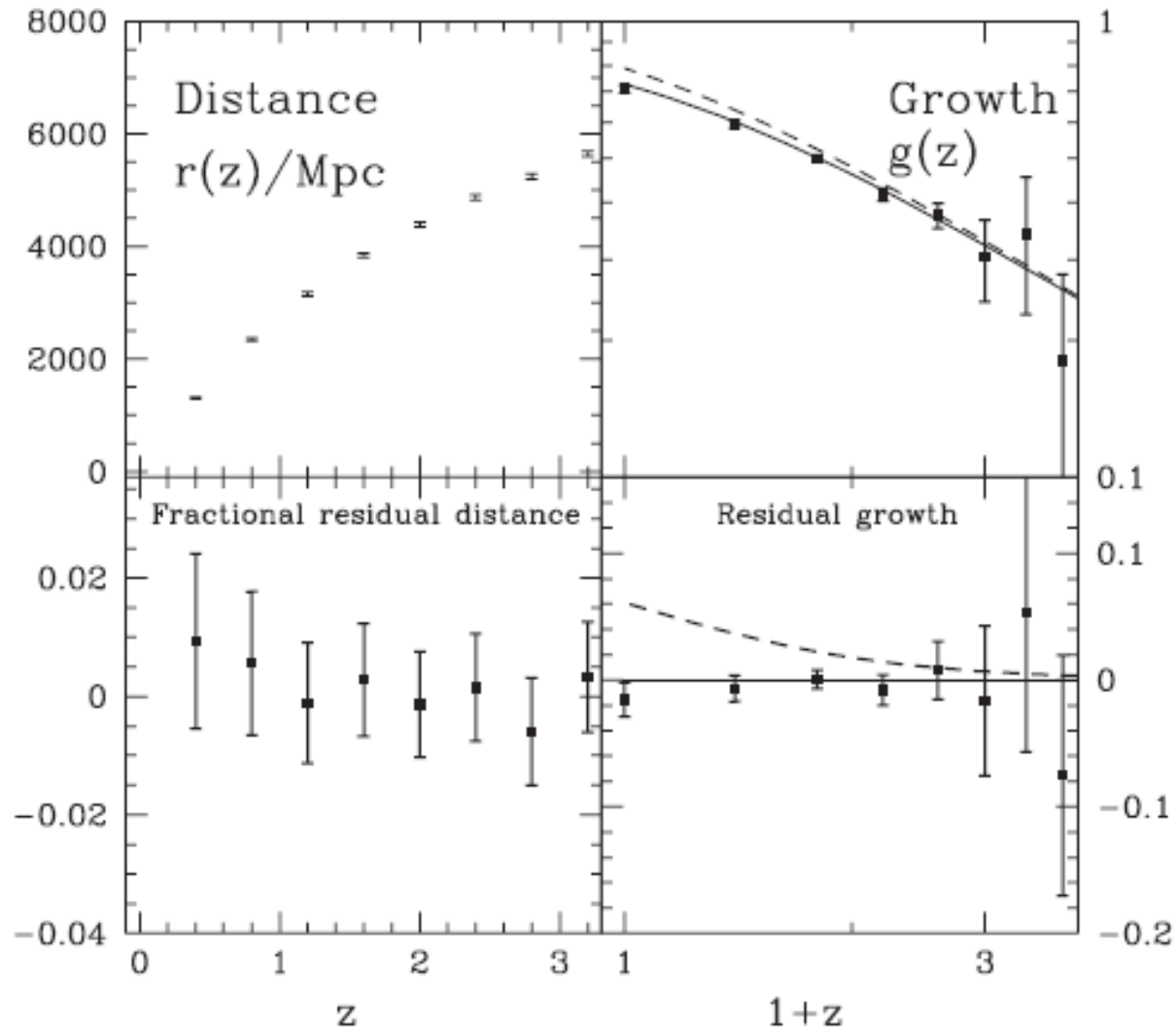
Modified gravity model of Dvali, Gababadze & Porrati



Gia Dvali
(NYU)

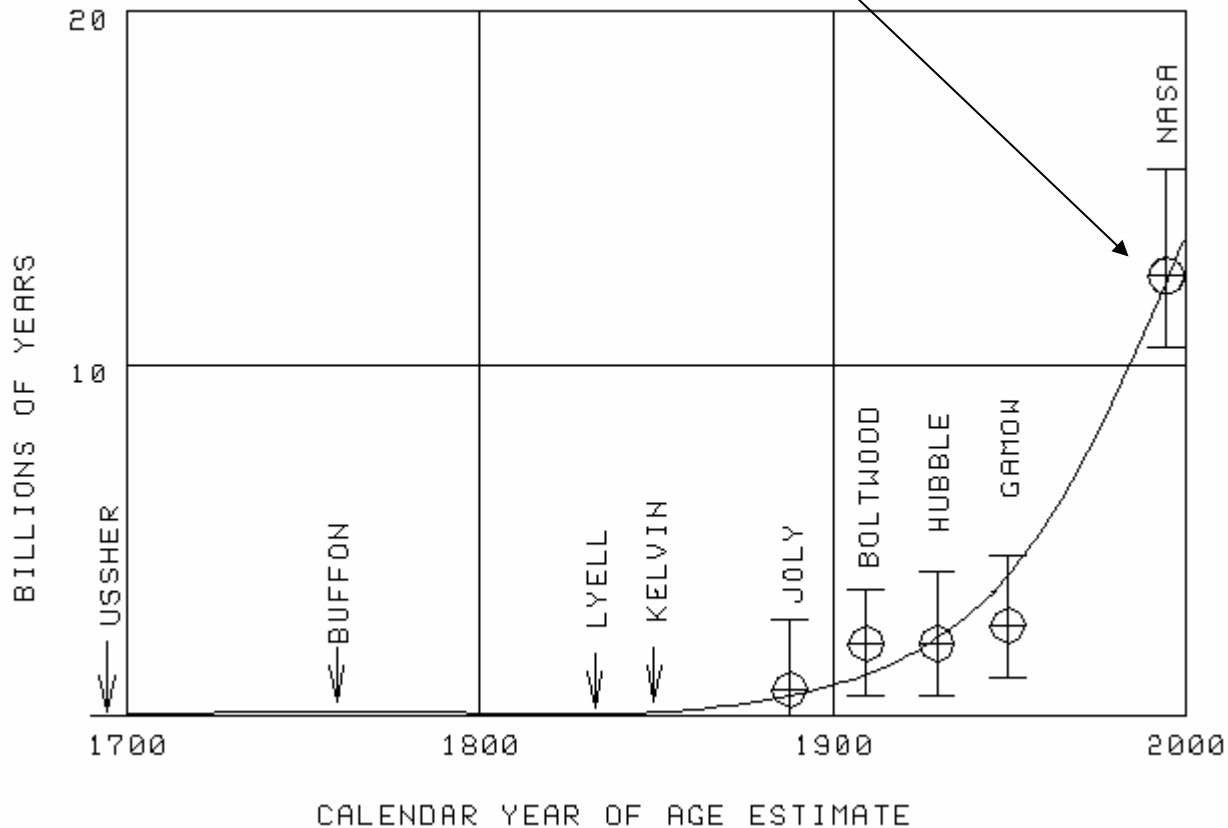
the model predicts that gravity gets weaker because some of the gravitons, force carriers of gravity leak into extra dimension(s)

Distinguishing modified gravity from dark energy

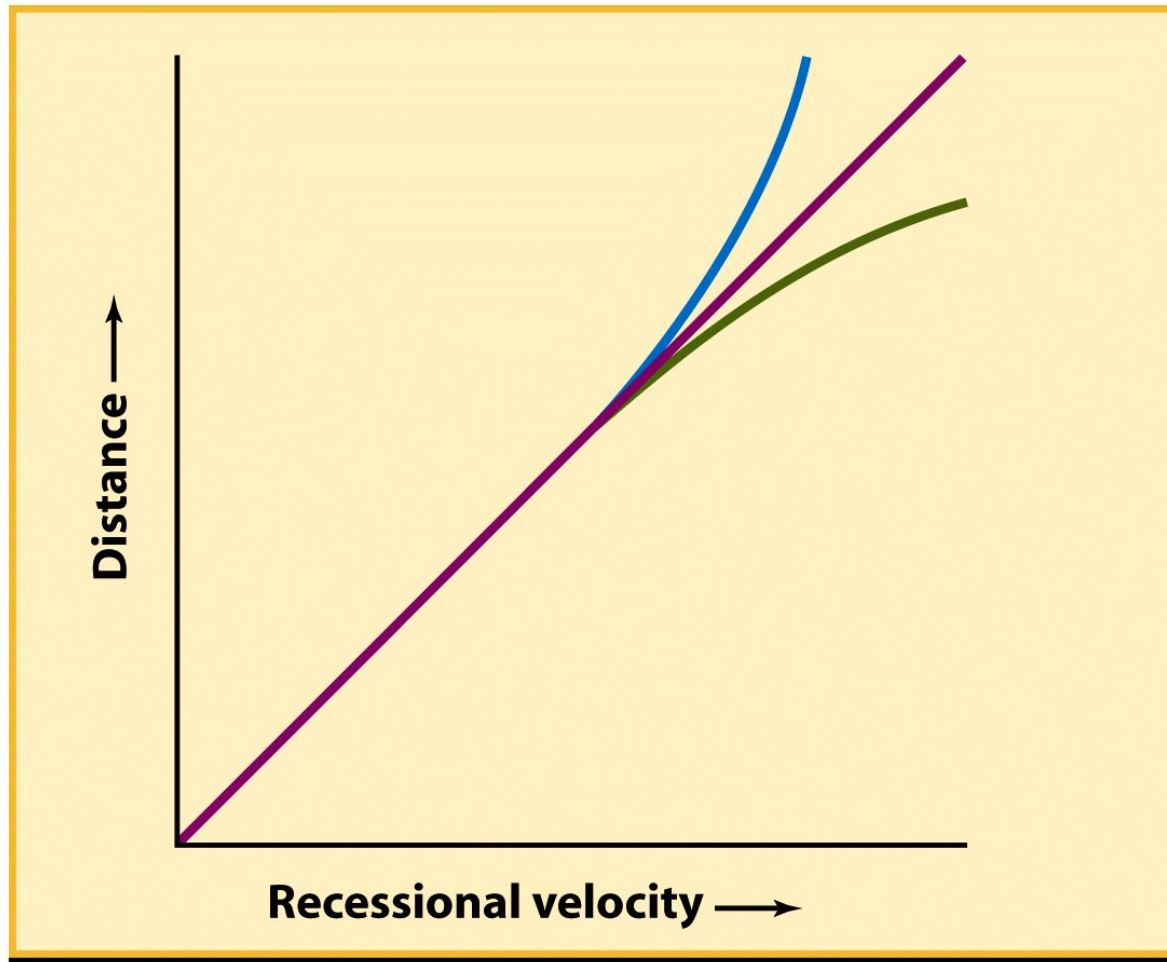


Cosmological parameters and the age of the universe

Modern age measurement: 13.7±0.3 billion years



Expansion history of the universe



Possible expansion histories of the universe

Figure 26-17b

Universe, Eighth Edition

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