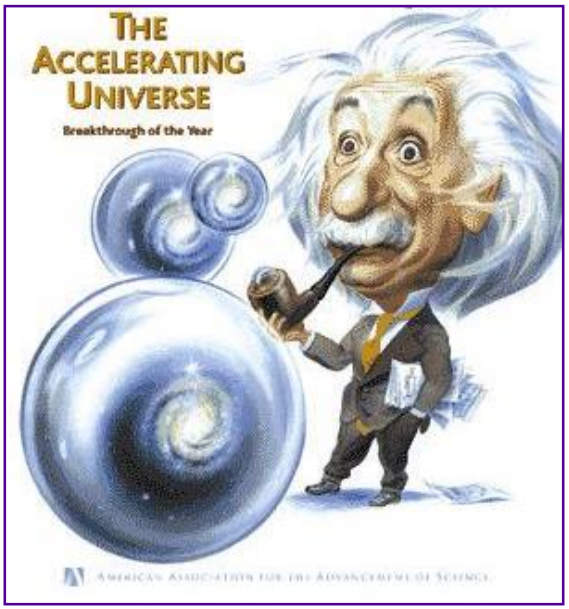
Dark Energy
Rules the Universe!
(and why the dinosaurs don't)

Eric Linder

Berkeley Lab
UC Berkeley

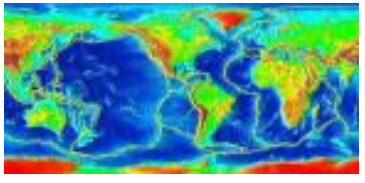


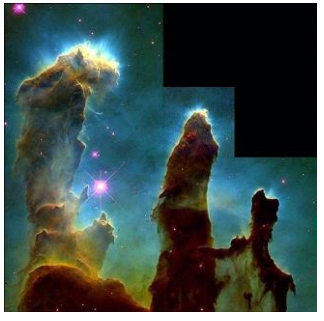
Did You Ever Wonder…?

Steep hills:

Building up -

Eroding away -

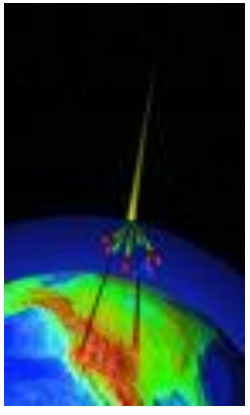




with thanks to Timothy Ferris

Up to the Universe

There is no division between the human world and the universe.

...





...

Everything is dynamic, all the way to the expansion of the universe.

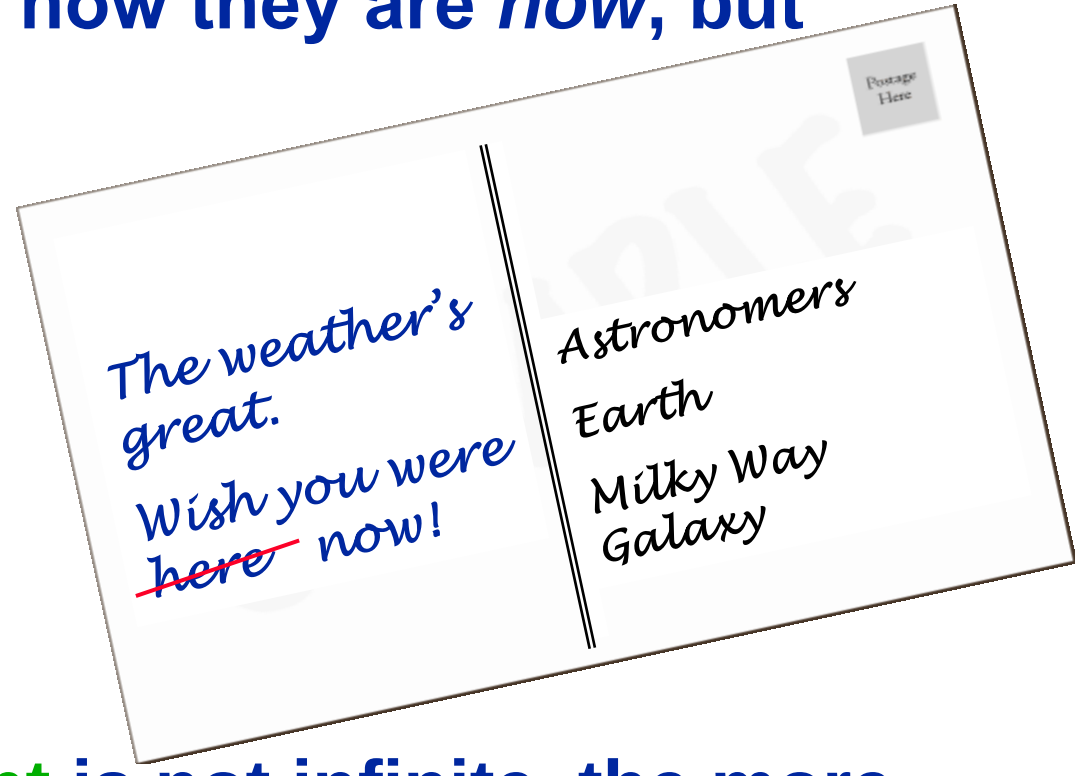
Our Expanding Universe

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Astronomy is a Time Machine

Looking out in space is looking back in time.

Imagine you get postcards from a traveling friend. You don't know how they are *now*, but how they *were*.



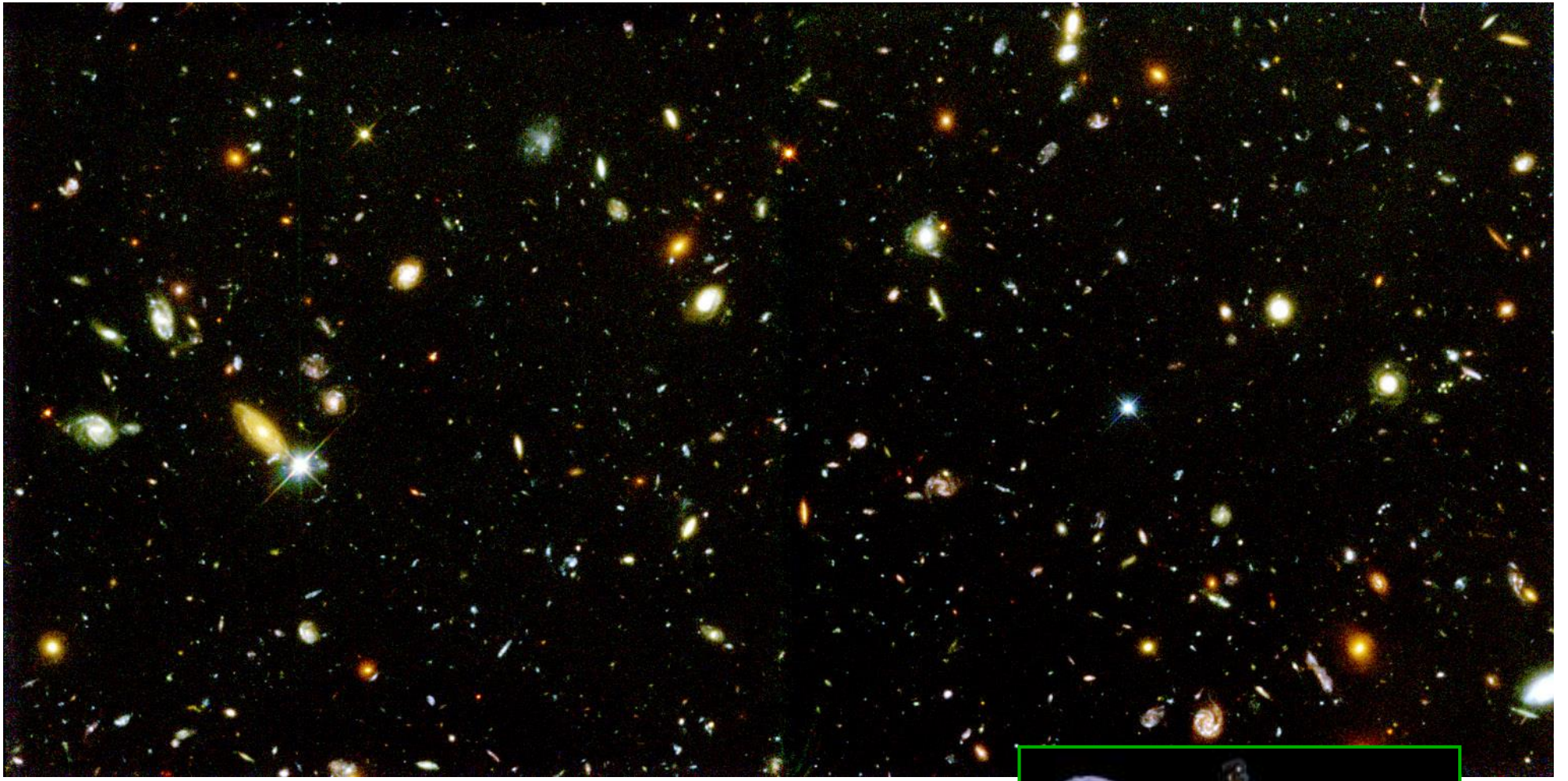
Since the speed of light is not infinite, the more distant an object, the more we see the universe as it was long ago. Looking out is looking back.

Mapping Our History

The subtle slowing down and speeding up of the expansion, of distances with time: a(t), maps out cosmic history like tree rings map out the Earth's climate history.

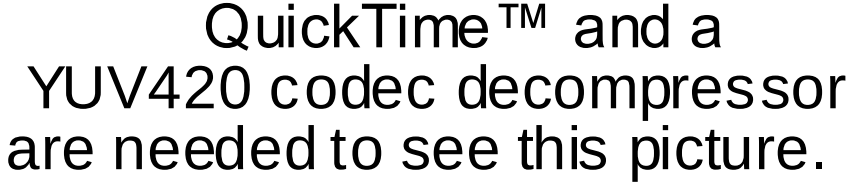
STScI

Looking Back 10 Billion Years



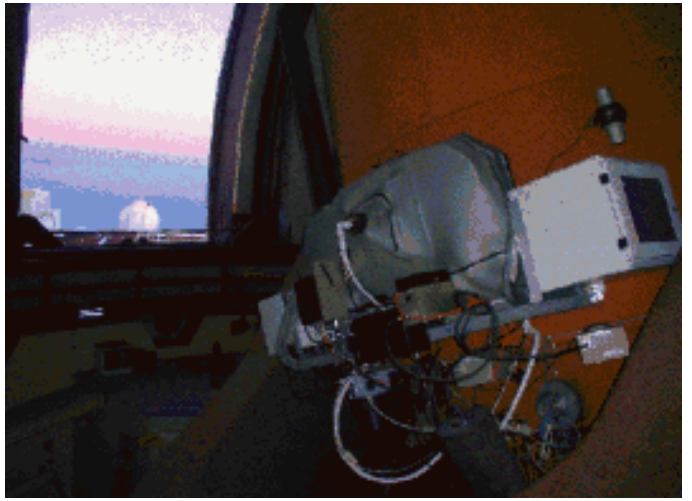
STScI

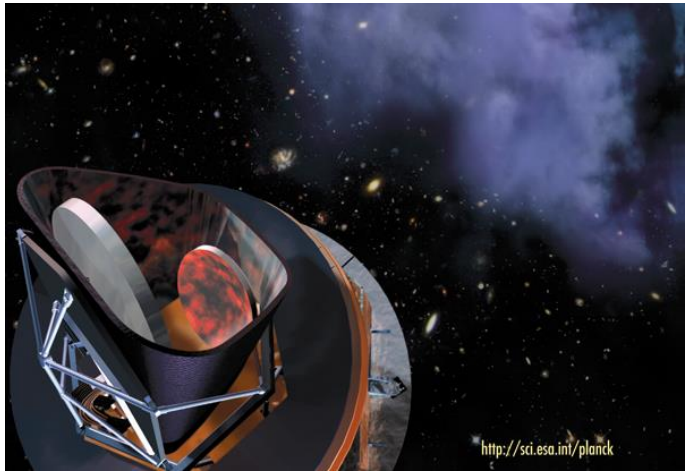
Looking Back 10 Billion Years



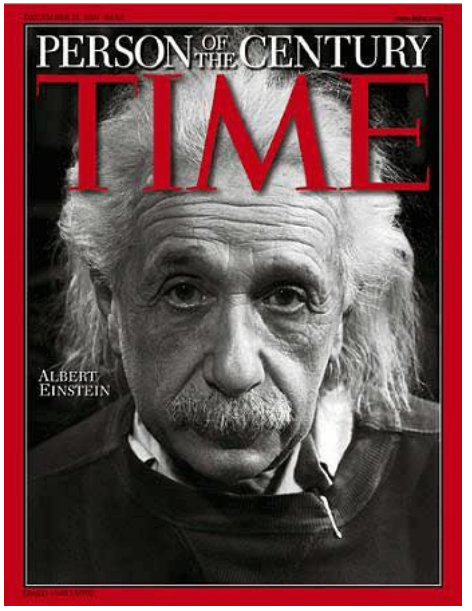
How Do We Learn about the Universe?

Observation

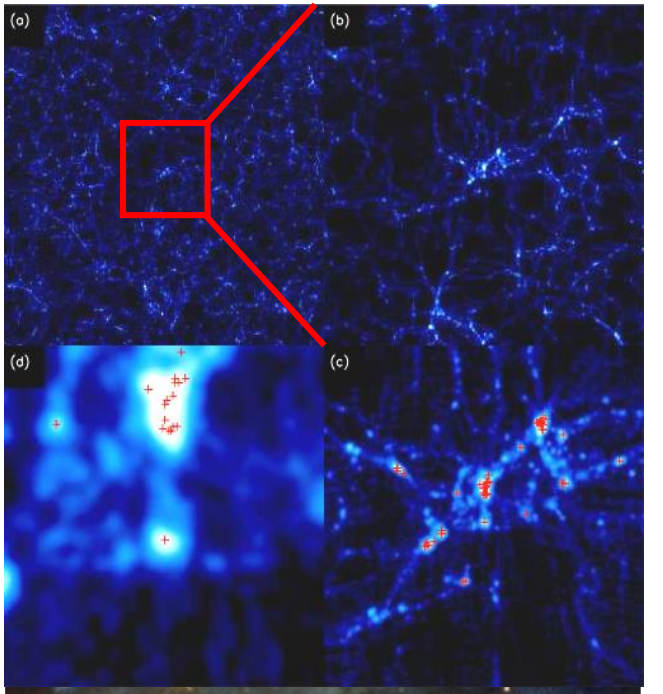




Theory

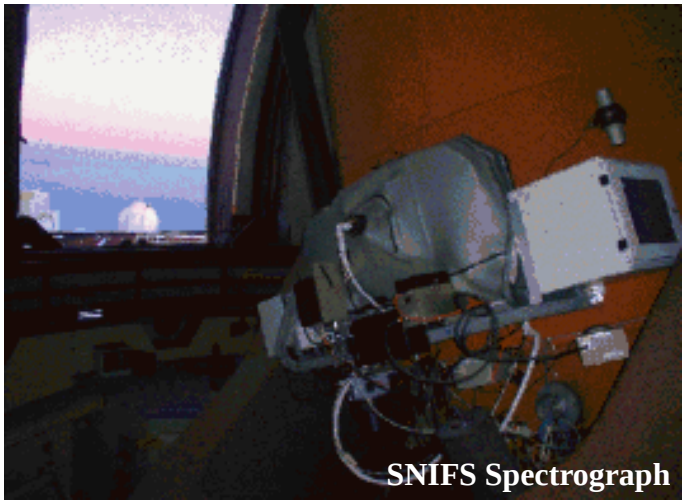


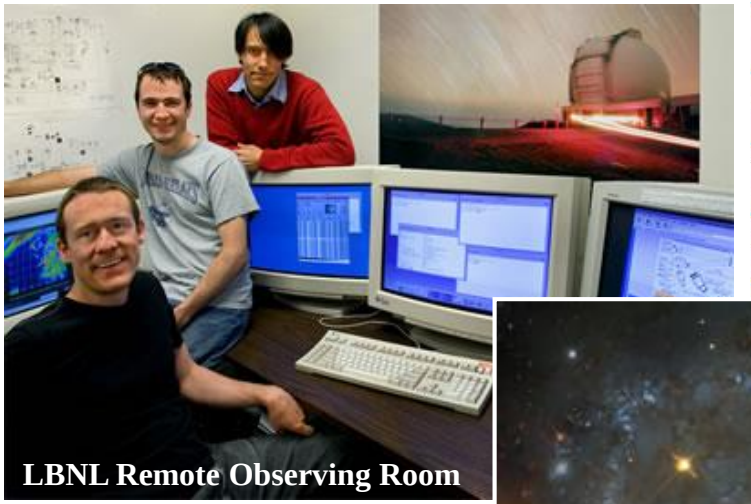
Computation

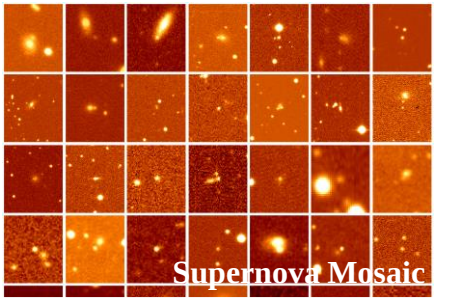


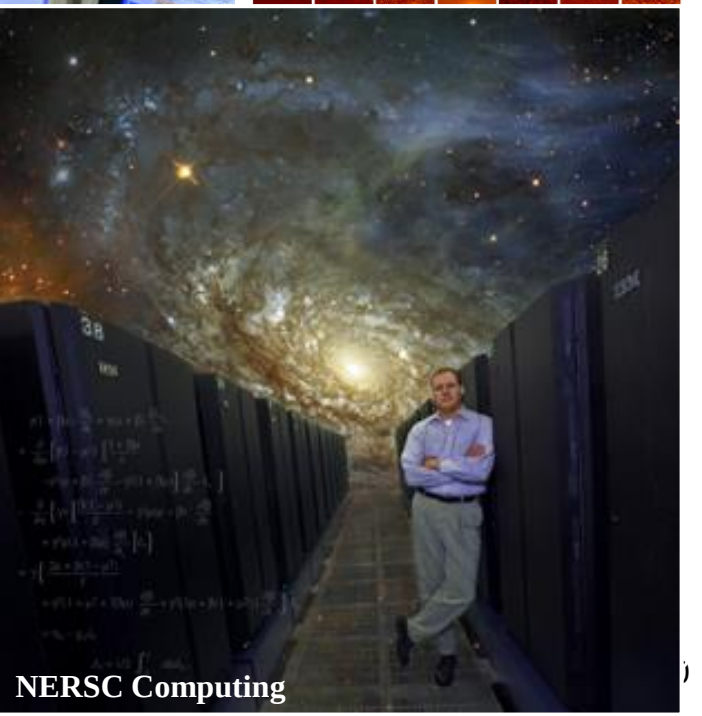
Hunting Supernovae

Hunting supernovae takes a blend of technology, effort, high performance computing, and understanding.


SNIFS Spectrograph


LBNL Remote Observing Room


Supernova Mosaic


NERSC Computing

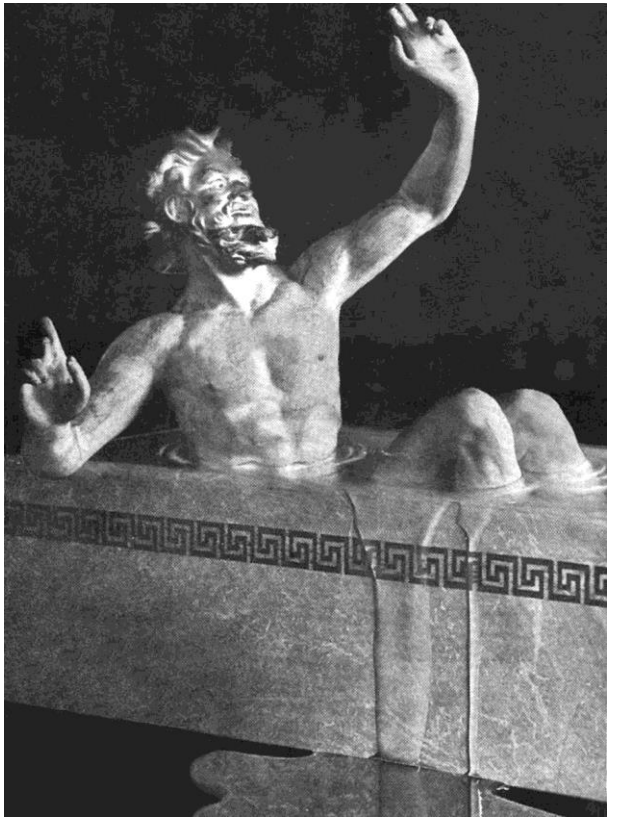

KAIT Telescope


Mauna Kea Observatory

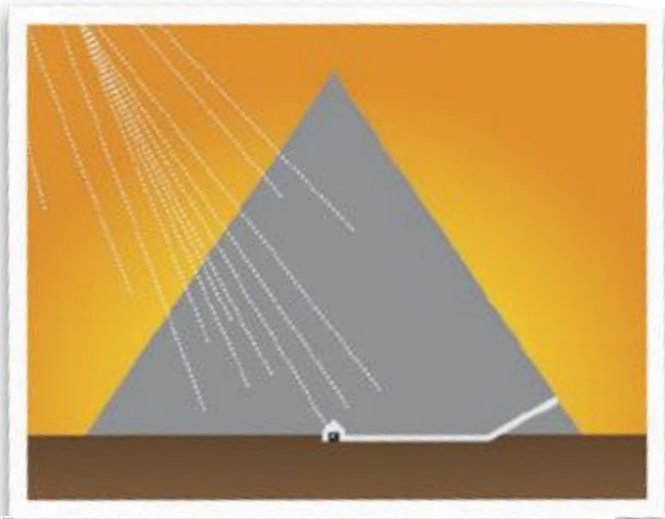
Eureka!

1835: "We shall never be able to know the composition of stars" -- Comte

1849: Kirchhoff discovers that the spectrum of electromagnetic radiation encodes the composition



Eureka!



1968: Nobel Prize in Physics to Luis Alvarez

Dinosaurs to Dark Energy

In 1980, Luis Alvarez received a paperweight rock from his son, geologist Walter Alvarez.

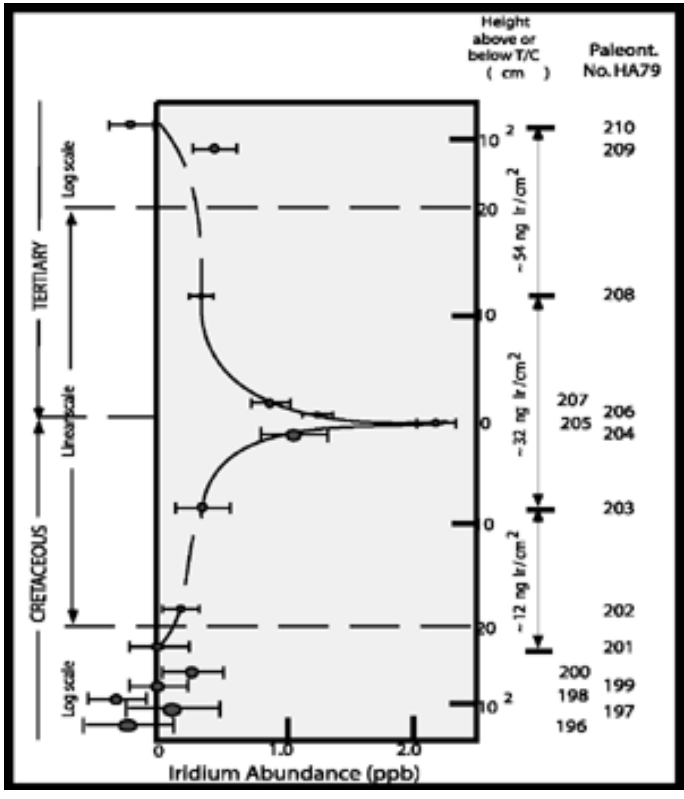
The rock had a well-defined mineral layer high in iridiu
The layer dated to 65 milli
years ago.

Iridium is "left over" from when the solar system formed and is much more common in asteroids than on Earth.

65 My ago is interesting: this is the "KT" boundary between the Cretaceous and Tertiary periods of species on Earth -- the death of the dinosaurs.

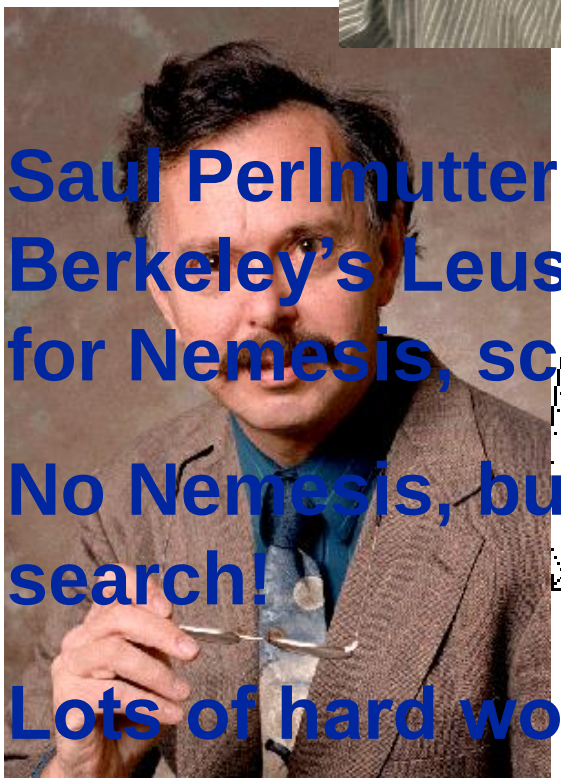
Dinosaurs to Dark Energy

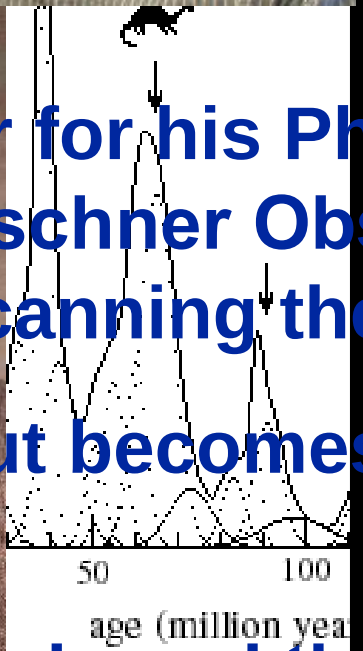
The team followed up the connection.

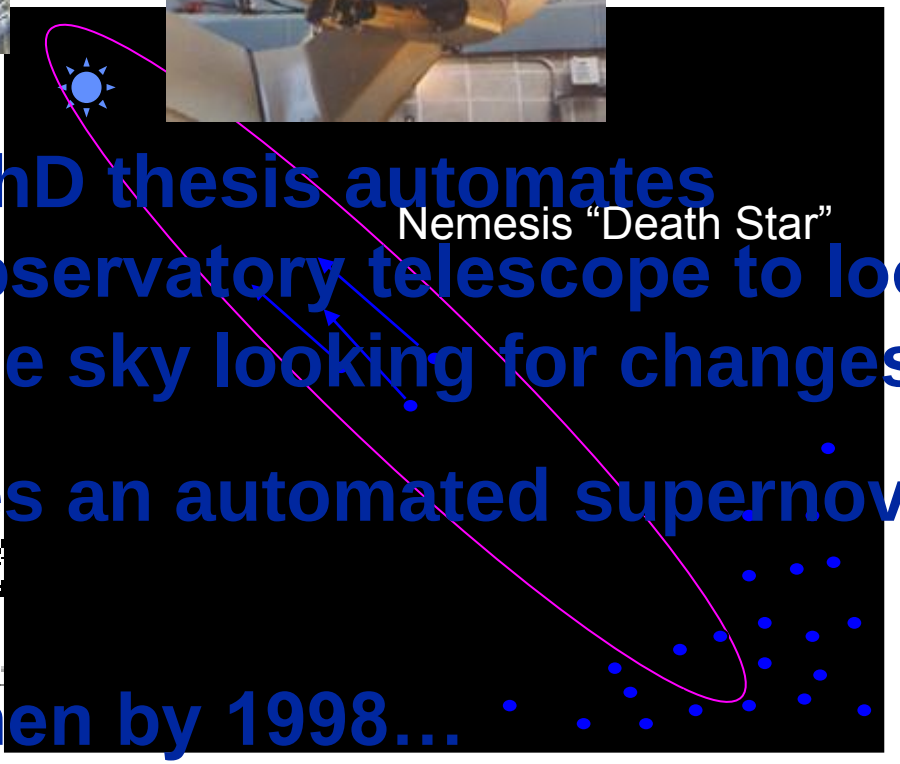


After much hard work, the idea that a large (10 km) meteorite impact caused the extinction of the dinosaurs was confirmed.

Dinosaurs to Dark Energy





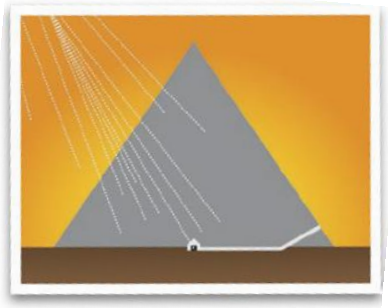


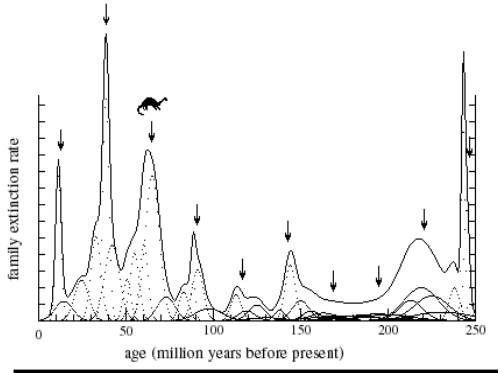
Saul Perlmutter for his PhD thesis automates Berkeley's Leuschner Observatory telescope to look for Nemesis, scanning the sky looking for changes.

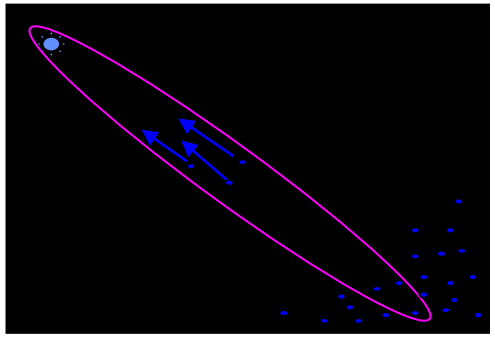
No Nemesis, but becomes an automated supernova search!

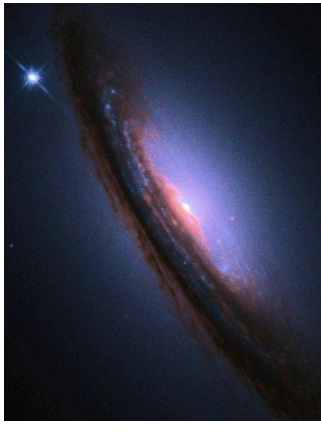
Lots of hard work, and then by 1998…

Dinosaurs to Dark Energy



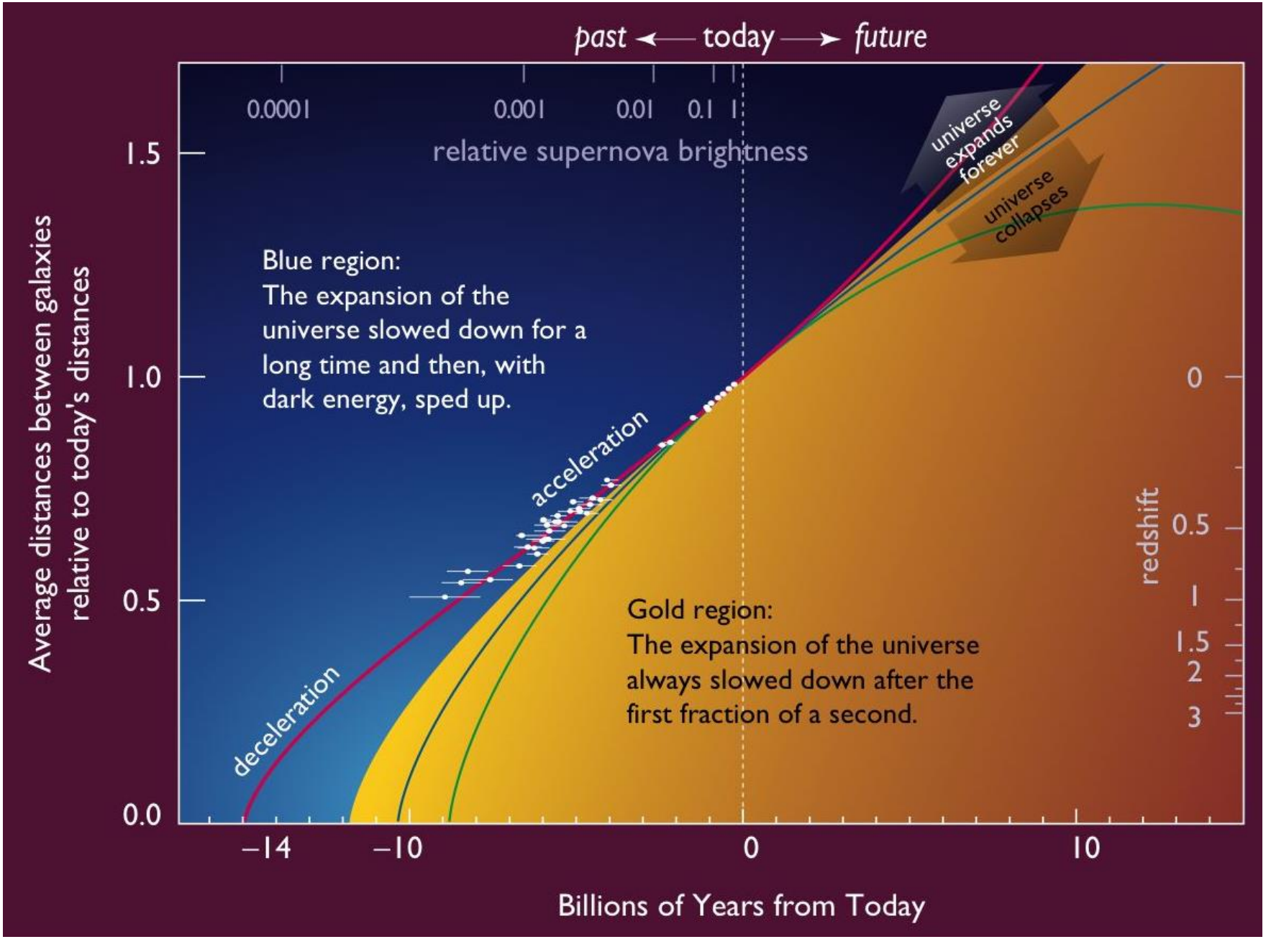






Lots of hard work, and then by 1998…

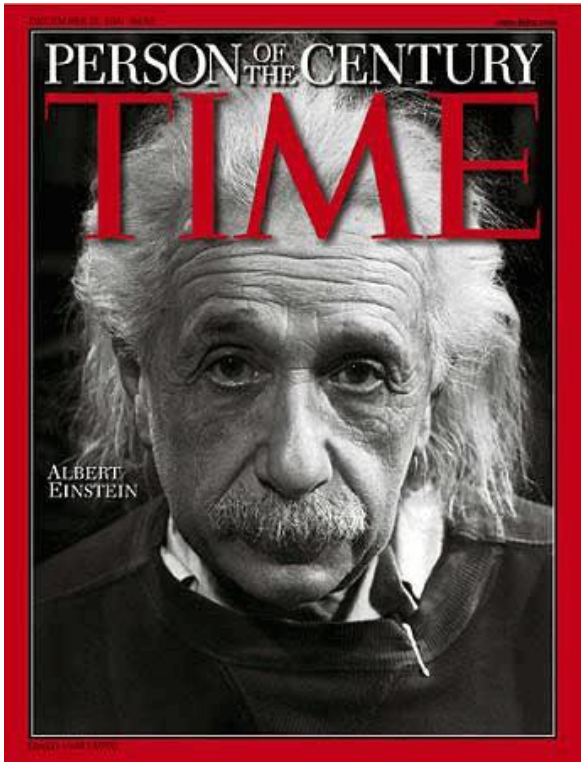
Discovery! Acceleration

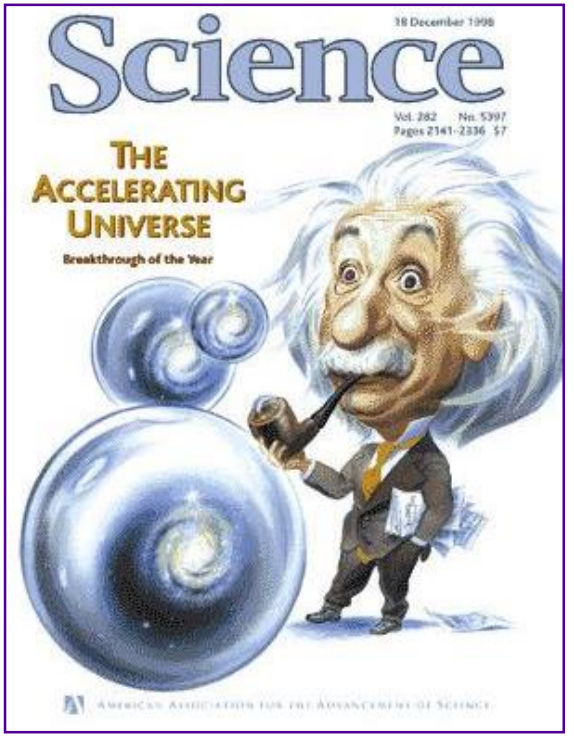


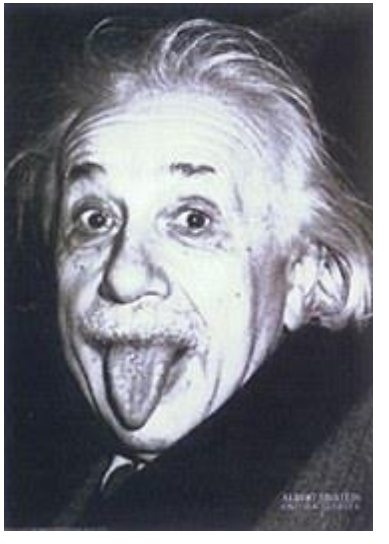
Discovery! Acceleration

In 1998, the Supernova Cosmology Project and Hi-Z Team discovered the expansion was *speeding up*

– but gravity pulls things together and should *slow* the expansion. What is counteracting gravity?







Gravity and Anti-Gravity

Einstein said that energy contributes to mass:

$$E=mc^2$$

Gravity arises from all energy, not just the usual mass.

One form of energy is pressure *P*. But doesn't this just add to the gravity?

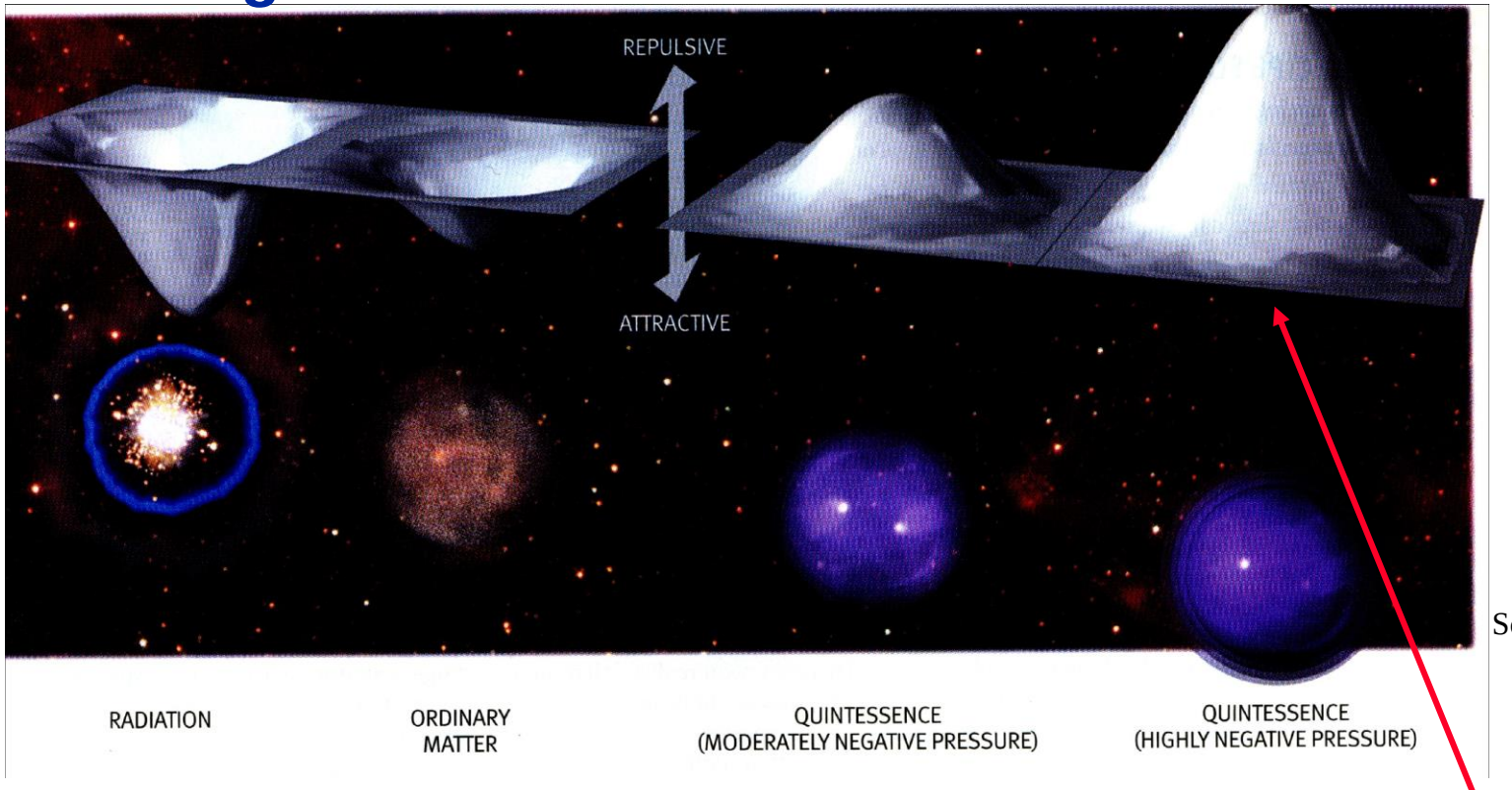
– *Unless the pressure is negative* –

Negative pressure gives negative mass.

When something expands, it usually cools (loses energy). But if you expand (stretch) a spring, it gains energy. (Usually, the pressure is so tiny that it affects the mass by less than a part in a trillion.)

New Frontiers

Beyond Einstein: What happens when gravity is no longer an attractive force?

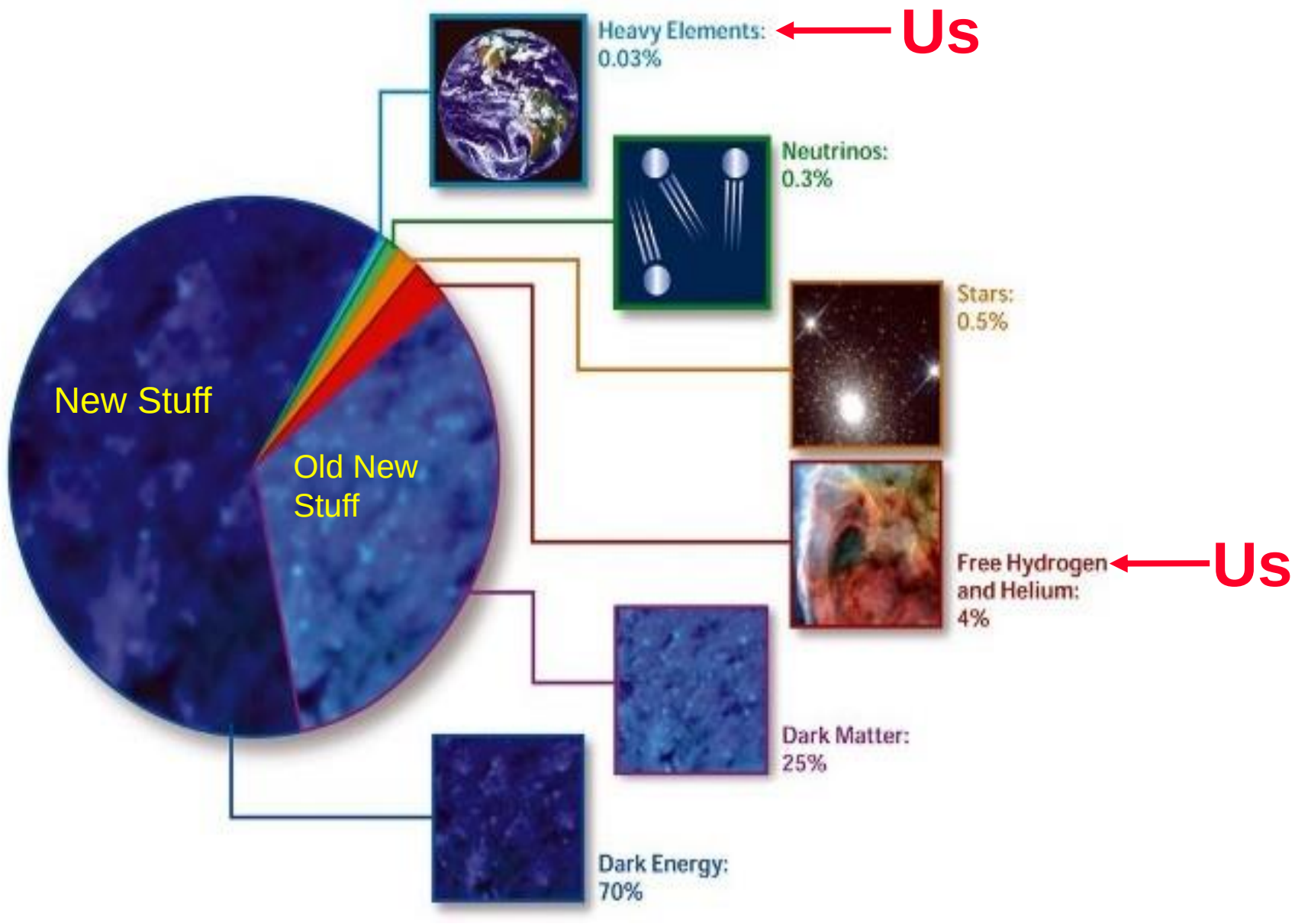


Scientific American

Discovery (SCP,HiZ 1998): 70% of the universe acts this way!

Fundamentally new physics. Cosmology is the key.

Describing Our Universe



STScI

95% of the universe is unknown!

Dark Energy Rules!!!

- 70-75% of the energy density of the universe
- Accelerating the expansion of the universe, like inflation at 10^{-35}s
- Determining the fate of the universe, like inflation at 10^{-35}s

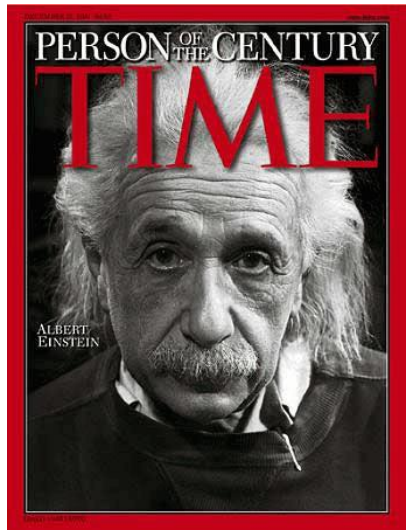
95% of the universe is unknown!

Repulsive gravity!

Fate of the universe!

"Most abundant and weirdest stuff in the universe"

Is this mysterious dark energy Einstein's original cosmological constant Λ?



What's the Matter with Energy?

Why not just bring back the cosmological constant (Λ)?

When physicists calculate how big Λ should be, they don't quite get it right.

They are off by a factor of

**1,000,000,000,000,
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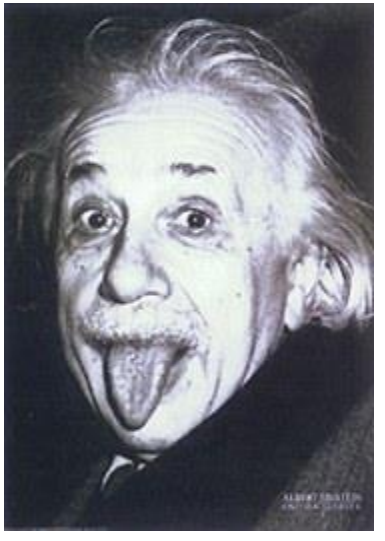
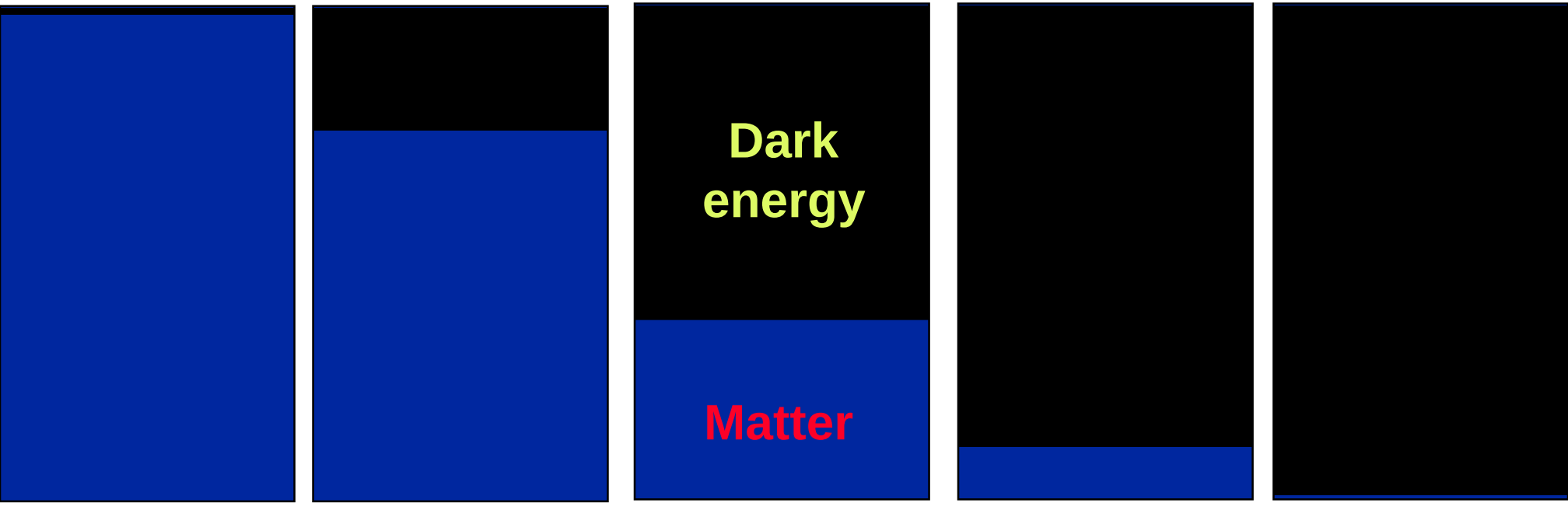


This is modestly called the fine tuning problem.

Cosmic Coincidence

We cannot calculate the vacuum energy to within 10^{120}. *But it gets worse:* Think of the energy in Λ as the level of the quantum "sea". At most times in history, matter is either drowned or dry.



On Beyond Λ!

We need to explore further frontiers **in high energy physics, gravitation, and cosmology.**

New quantum physics? **Does nothing weigh something?**

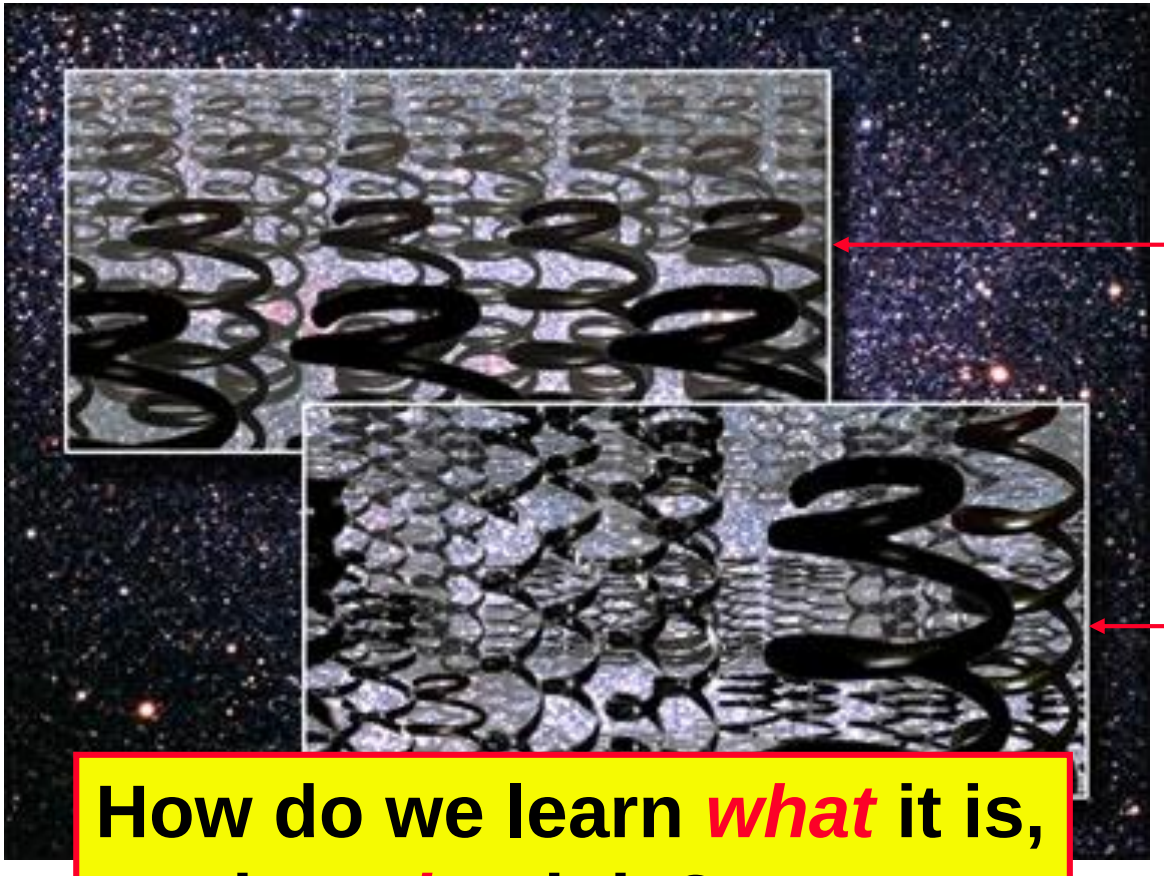
Einstein's cosmological constant, Quintessence, String theory

New gravitational physics? **Is nowhere somewhere?**

Quantum gravity, supergravity, extra dimensions?

We need new, highly precise data

Nature of Acceleration



Is dark energy static? Einstein's cosmological constant Λ.

Is dark energy dynamic? A new, time- and space-varying field.

How do we learn *what* it is, not just *that* it is?

How much dark energy is there?

How springy/stretchy is it?

Theory of Fields

Scalar field:

At every point in a field of grass, you can measure the height of the grass: a single number or scalar h(x).

Vector fields:

At every point in a trampled field of grass, you can measure the length of the grass and the direction it is lying: a vector $\vec{g}(x)$.

Hidden Dimensions and Warped Gravity

A tuning fork radiates sound in all directions, but the waves are stronger if localized.

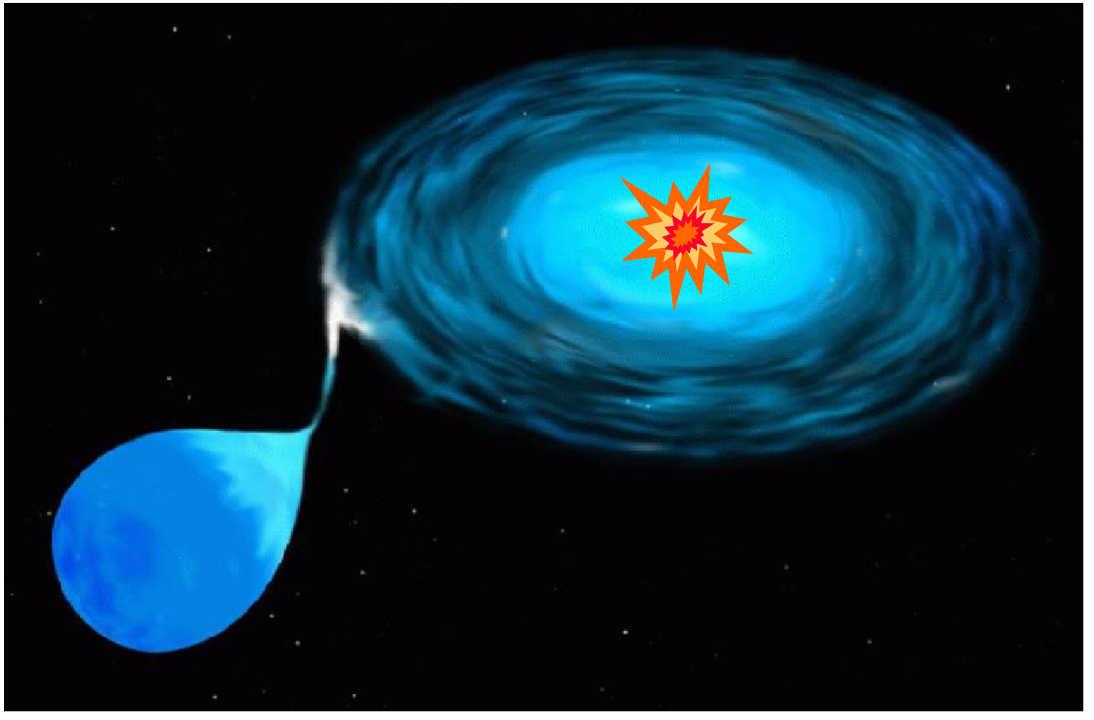
On large (cosmological distances) gravity may "leak" into extra dimensions. The cosmic expansion would appear slower over these distances, i.e. accelerating today!

Type Ia Supernovae

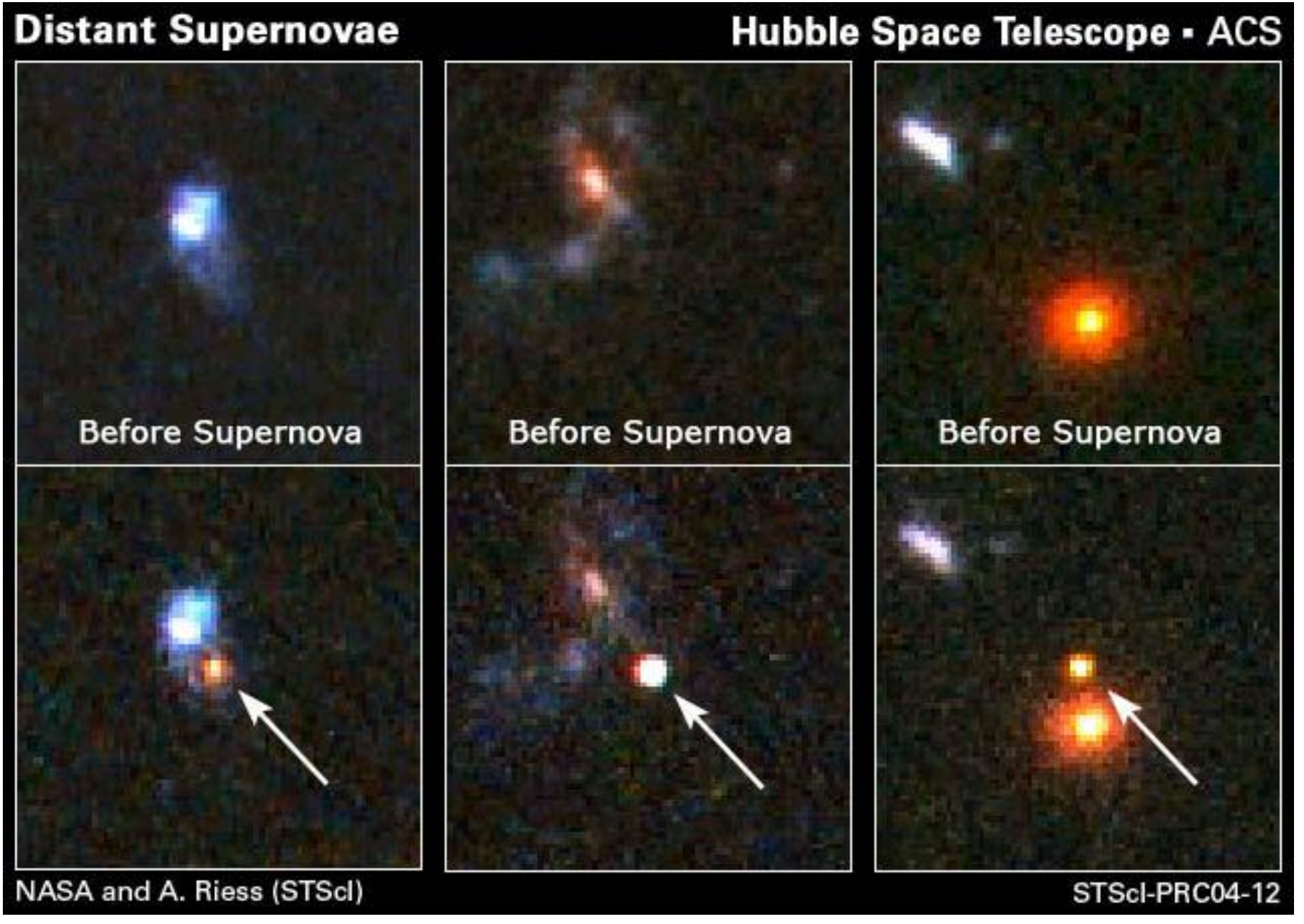
- Exploding star, briefly as bright as an entire galaxy
- Characterized by no Hydrogen, but with Silicon
- Gains mass from companion until undergoes thermonuclear runaway

Standard explosion from nuclear physics

Insensitive to initial conditions: "Stellar amnesia"



Discovering Supernovae



Standard Candles

Brightness tells us distance away (lookback time)

Redshift measured in spectrum tells us expansion factor (average distance between galaxies)

Supernovae are Rich

All the elements from carbon on up were created in supernovae. Later stars, planets, and we owe our existence to supernovae.

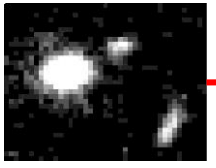
A Type Ia supernova produces ~0.6 of the mass of our Sun in Nickel in the explosion.

1 SN → $10 nonillion ($10^{31})!

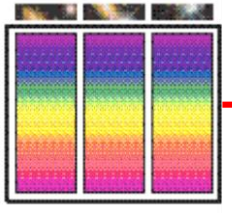
Supernovae are Rich

Each supernova is "sending" us a rich stream of information about itself.

Images



Spectra



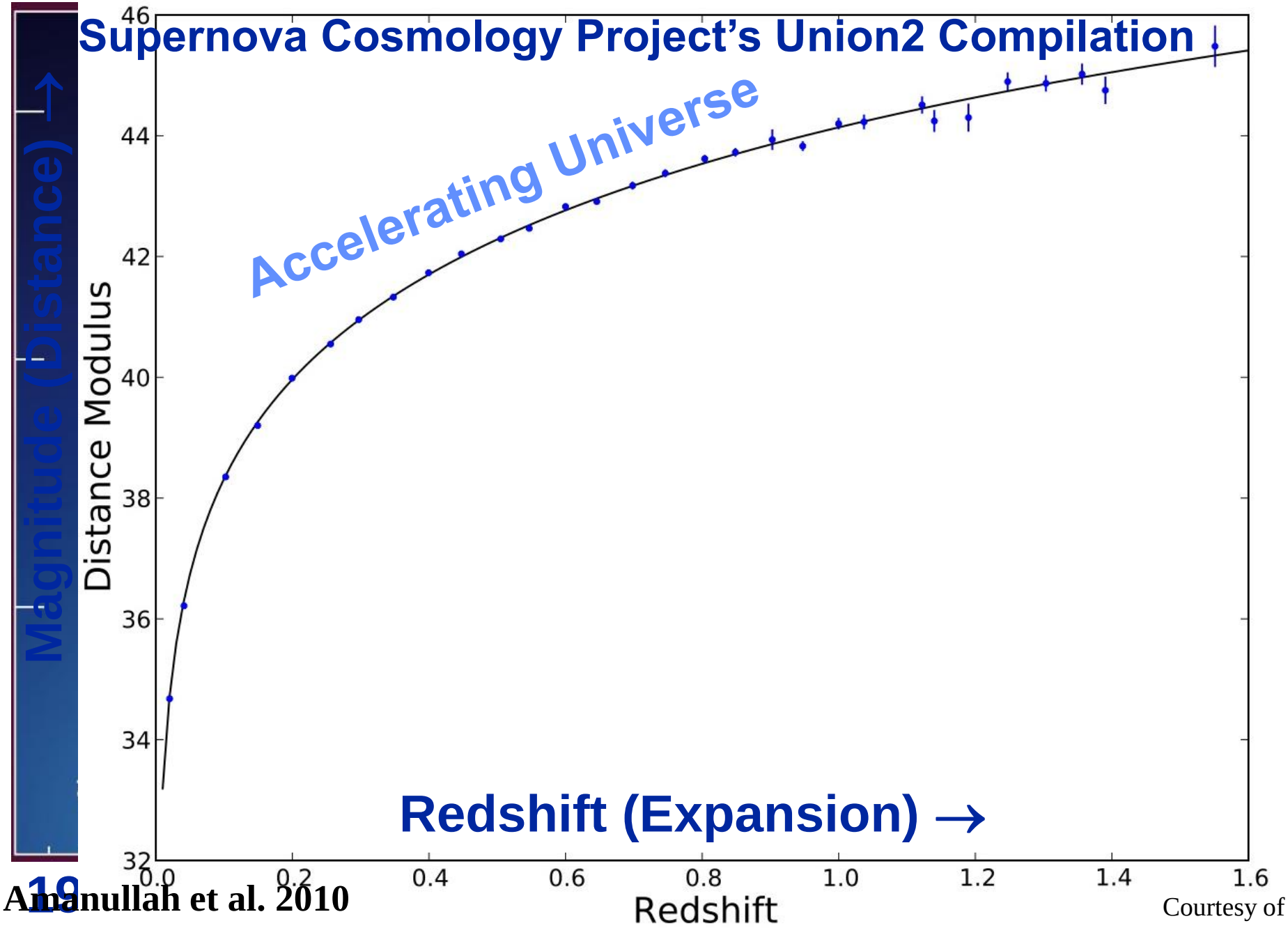
Redshift & SN Properties

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Nature of Dark Energy

data → **analysis** → **physics**

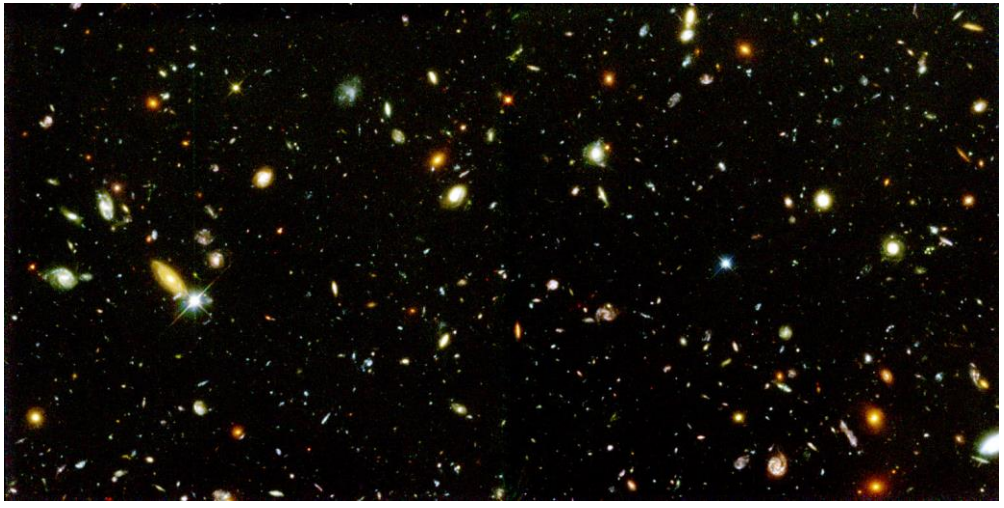
State of the Art



Amanullah et al. 2010

Courtesy of D.Rubin

Looking Back 10 Billion Years



STScI

To see the most distant supernovae, we must observe from space.

A Hubble Deep Field has scanned 1/25 millionth of the sky.

This is like meeting 12 people and trying to understand the complexity of all of the US!

Universe Fly-Through

SDSS DR4 movie

http://video.google.com/videoplay?docid=-8252705102362324792&q=sdss

Dark Energy – The Next Generation

wide 10000 × the Hubble Deep Field area (and deeper)
plus 10 million × HDF (almost as deep)

deep Mapping 10 billion years / 70% age of universe

colorful Optical + IR to see thru dust, to high redshift

NASA

Office of Science
U.S. Department of Energy

Frontiers of Science

What is dark energy?

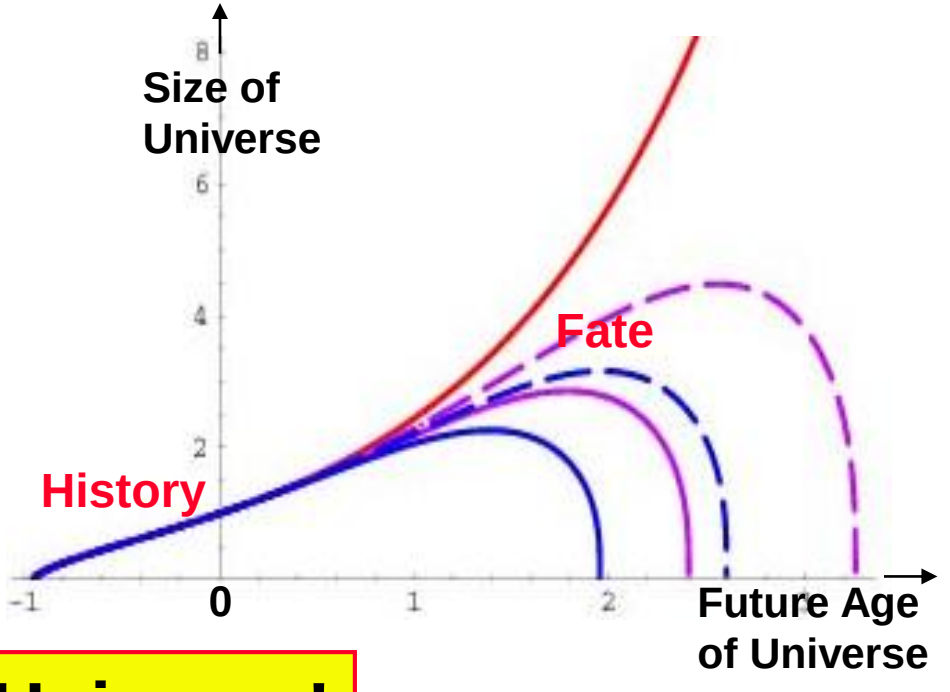
Do we know all the forces of nature?

How many dimensions are there?

Will the universe expansion accelerate forever?

How are quantum physics and gravity unified?

What is the fate of the universe?



thanks to Greg Aldering, Andy Howell, Peter Nugent, Saul Perlmutter, Greg Tarlé

Up to the Universe!