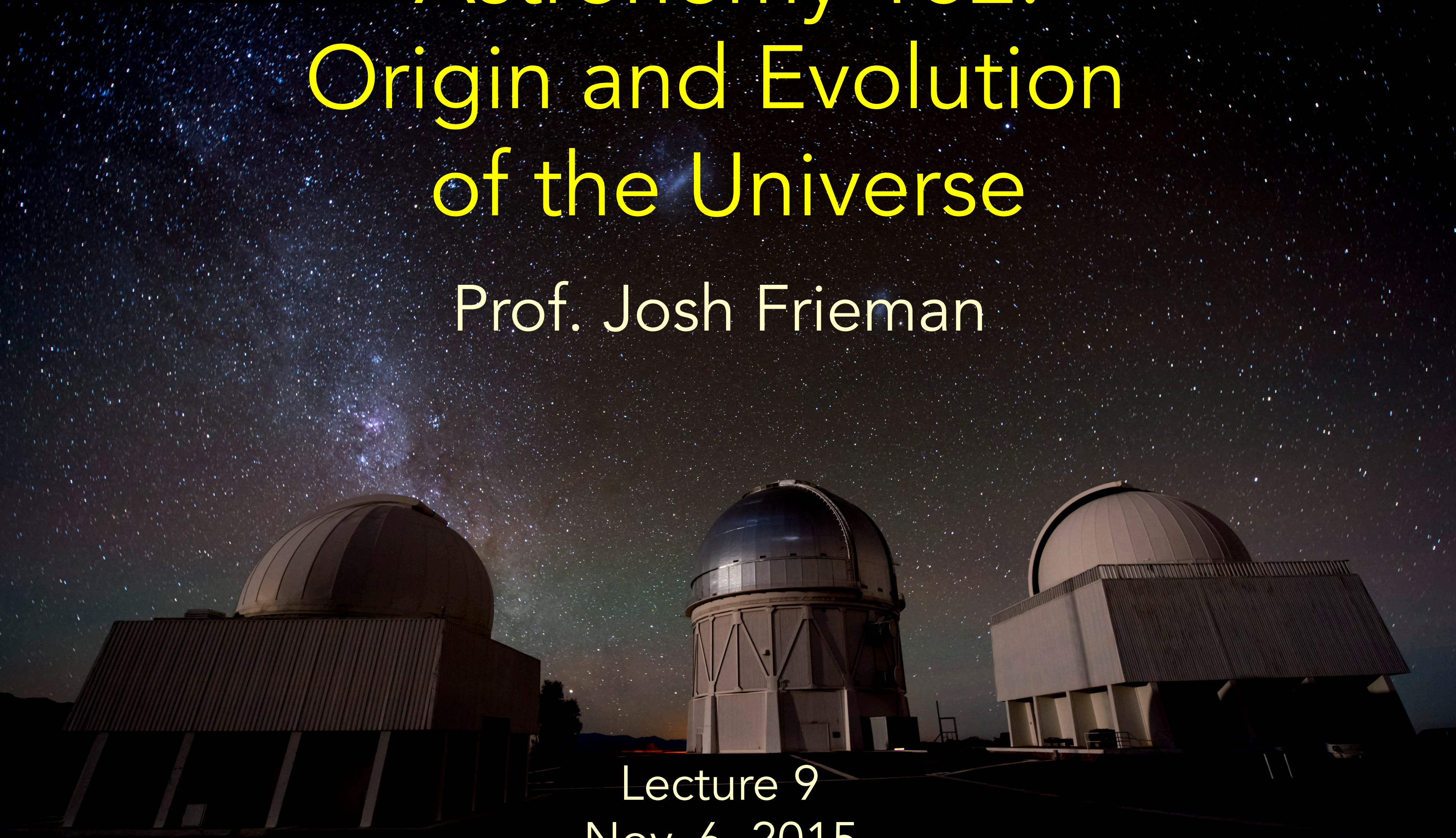
Astronomy 182: Origin and Evolution of the Universe

Prof. Josh Frieman



Lecture 9
Nov. 6, 2015

Today

- Dark Side of the Universe II: Dark Energy and the Accelerating Universe

Assignments

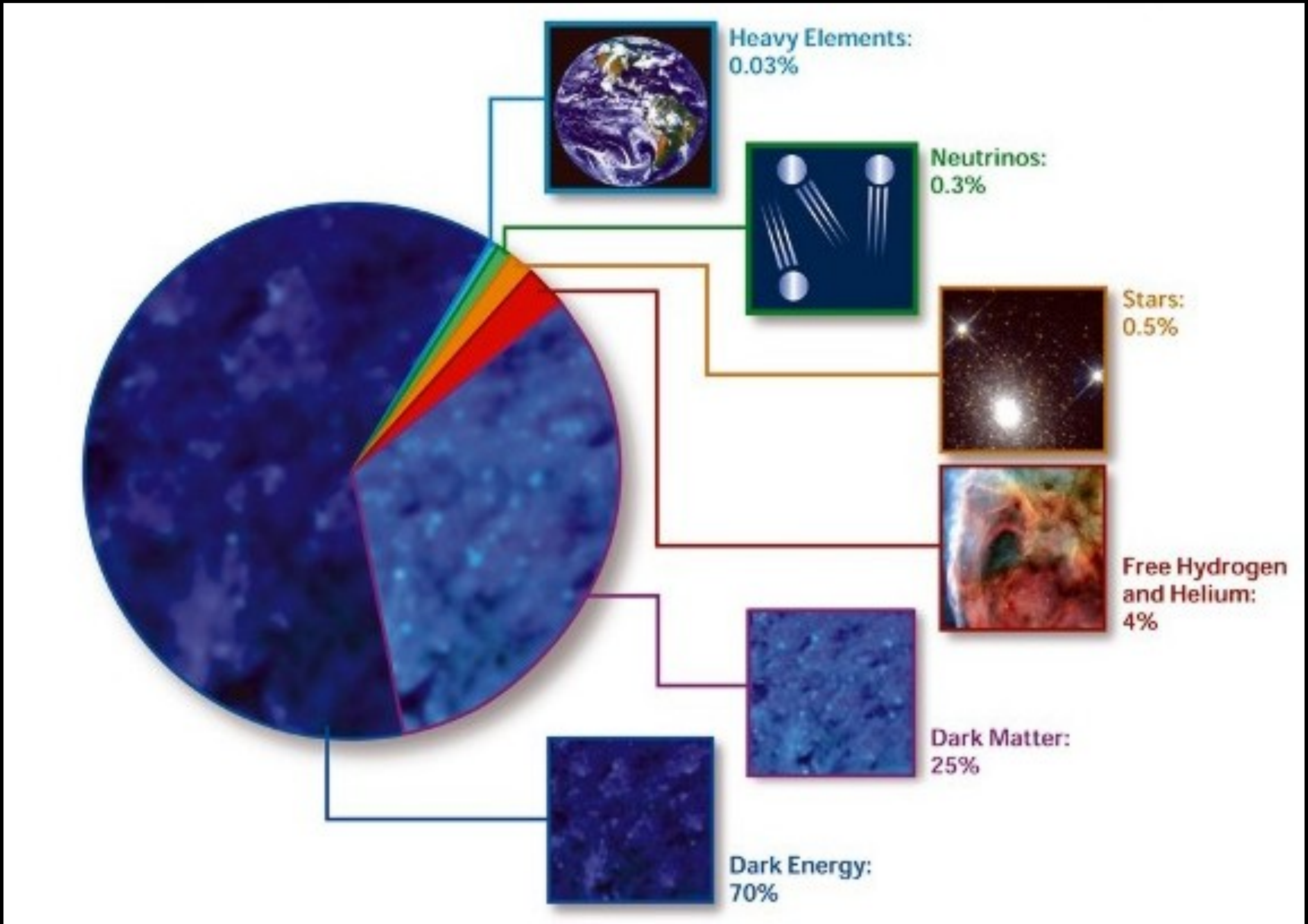
- This week: read Hawley and Holcomb, Chapters 13, 15.
- Today: Essay 2 due on HH, Chapter 8.
- Next Friday, Nov. 13: Essay 3 due on HH, Chap 13 and optional rewrite of Essay 1 (this will apply to Essay 1 only).

Contents of the Universe

- To determine the evolution of the Universe, we need to know what forms of matter and energy there are:
  - Ordinary (baryonic) matter (stars, gas, planets, …, made of atoms)
  - Neutrinos
  - Electromagnetic Radiation (Cosmic Microwave Background)
  - Dark Matter
  - Dark Energy
- and how much there is of each:

$$\Omega_i = \frac{\rho_i}{\rho_{crit}} = \frac{\rho_i}{(3H_0^2 / 8\pi G)}$$

Contents of the Universe



Dark Matter Properties: Clustering

Three `types' of Dark Matter distinguished by the objects they can be found in:

- Cold DM: clusters on all scales; particles slowly moving,... Candidates: Supersymmetric WIMPs, axions, …

- Hot DM: these particles moved at near the speed of light early on, and can only cluster in objects as big as clusters (or larger): would not expect to find them in individual galaxy halos
  Candidate: neutrinos

- Warm DM: clusters on scales of galaxies or larger.
  Candidate: heavy neutrinos (in certain cases)

Dark Matter & Large-scale Structure

These 3 different types of DM (cold, hot, warm) lead to different scenarios for the formation of galaxies and large-scale structures in the Universe (as we will discuss later in the course).

Observations of the large-scale distribution of galaxies (from galaxy surveys) indicate that the bulk of the DM is cold (or at most slightly warm).

The Expanding Universe

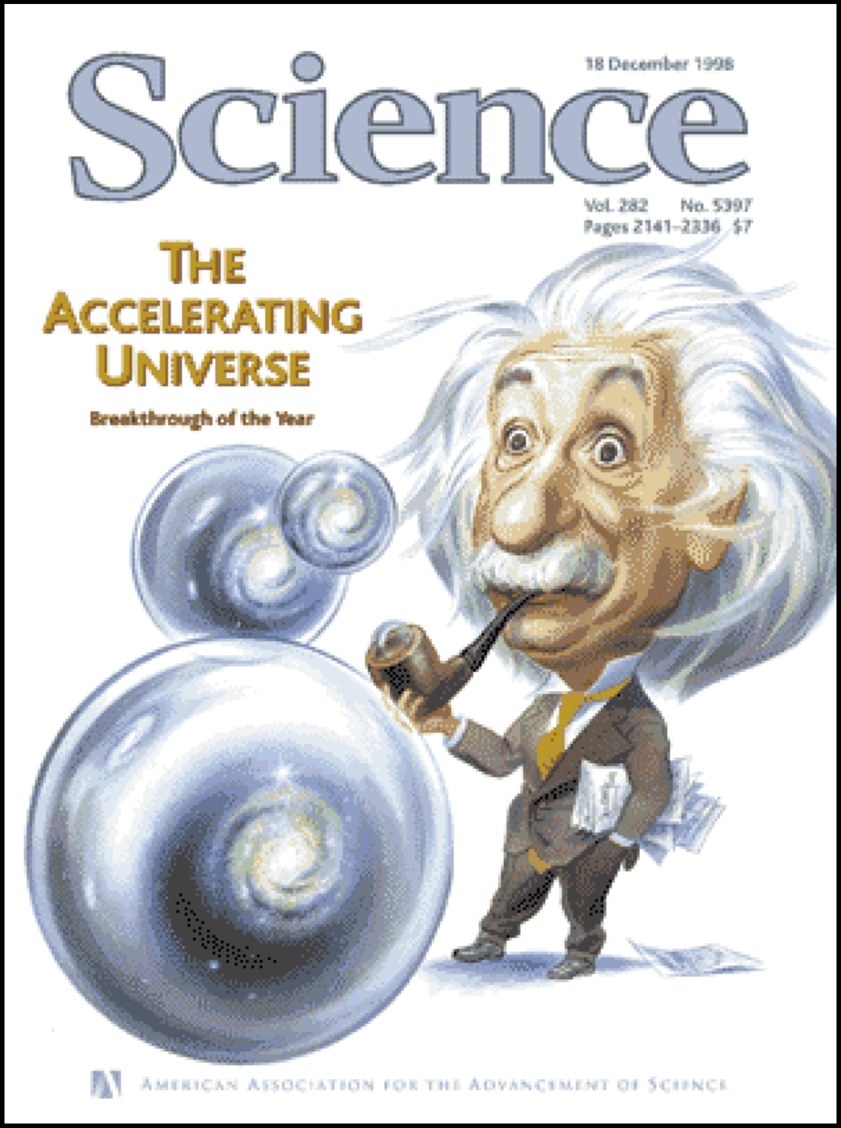
Does the recession speed of a distant galaxy increase or decrease with time?

Milky Way tugs gravitationally on it:
would naively expect it to slow down.

The Expansion is Speeding Up

Discovered in 1998 by 2 teams of astronomers.

Nobel Prize in 2011 for this discovery.

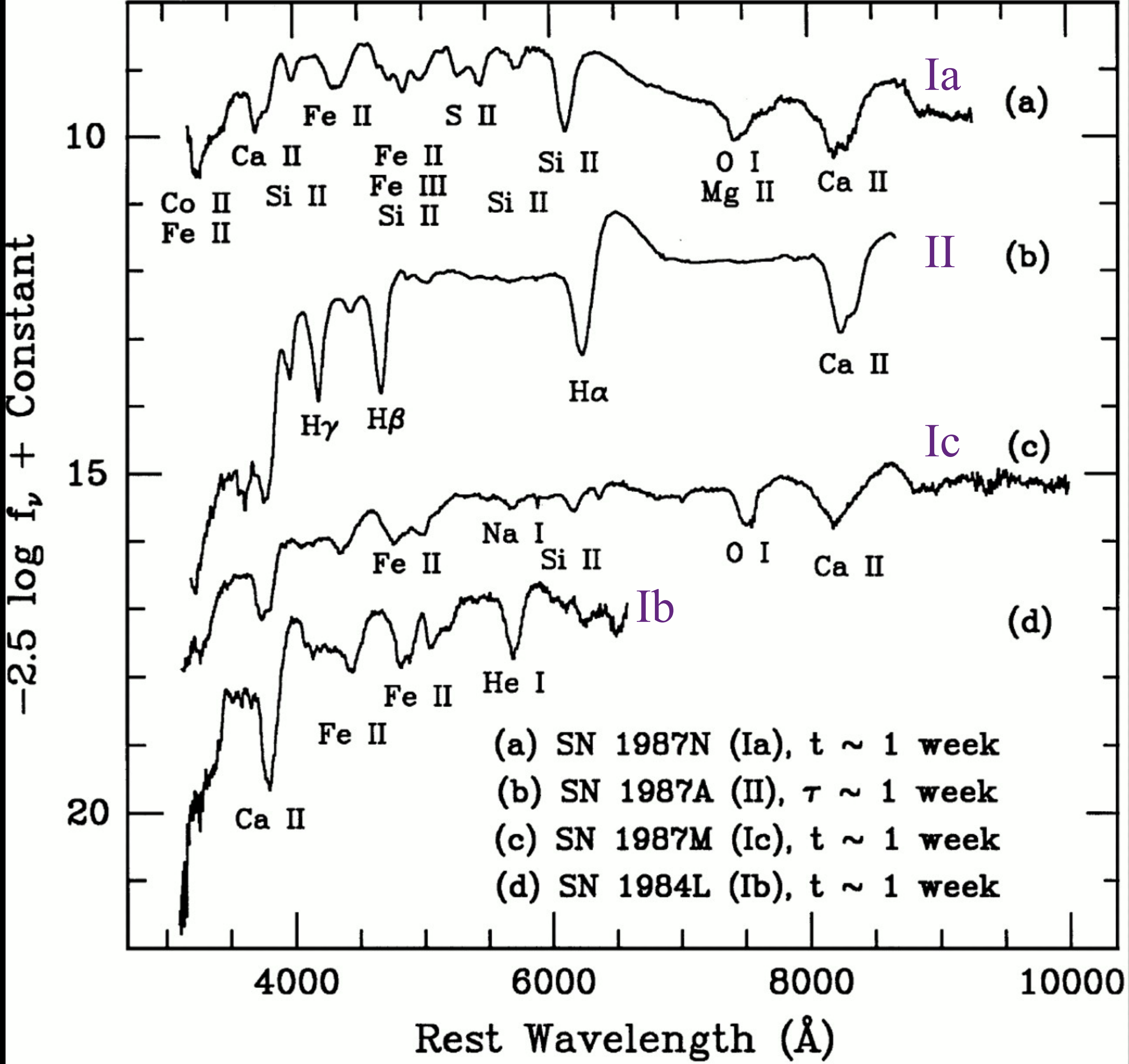


Type Ia Supernova: an exploding white dwarf star that for a few weeks shines as brightly as a typical galaxy.

Standardizeable candles: dispersion in peak brightness < 15%.

Occurs about once per century in a typical large galaxy, so monitor large number of galaxies to find them.

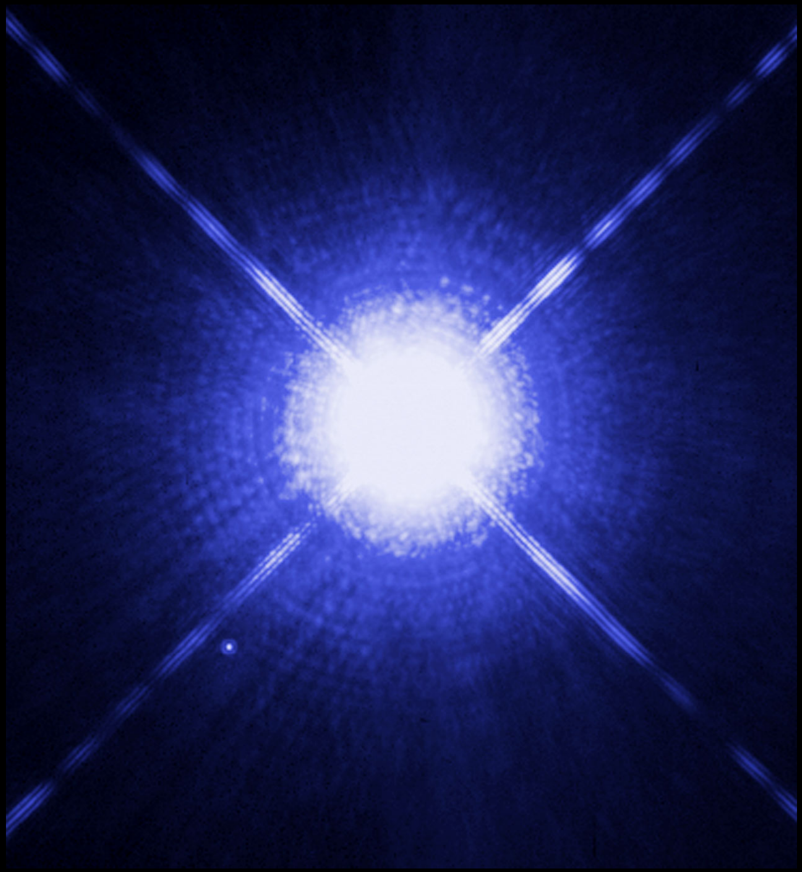
Spectrum of Light from different types of Super-novae



Classification of Supernovae

Type	Ia	Ib	Ic	II
Spectrum	No Hydrogen			Hydrogen
	Silicon	No Silicon		
		Helium	No Helium	
Physical mechanism	Nuclear explosion of low mass star	Core collapse of evolved massive star (may have lost its hydrogen or even helium envelope during red-giant evolution)		
Light curve	Reproducible	Large Variations		
Neutrinos	Insignificant	~ 100 × Visible energy		
Compact Remnant	None	Neutron star (typically appears as pulsar) Sometimes black hole ?		
Rate/h^2SNu	0.36 ± 0.11	0.14 ± 0.07		0.71 ± 0.34
Observed	Total ~ 2000 as of today (nowadays ~200/year)			

White Dwarf Stars



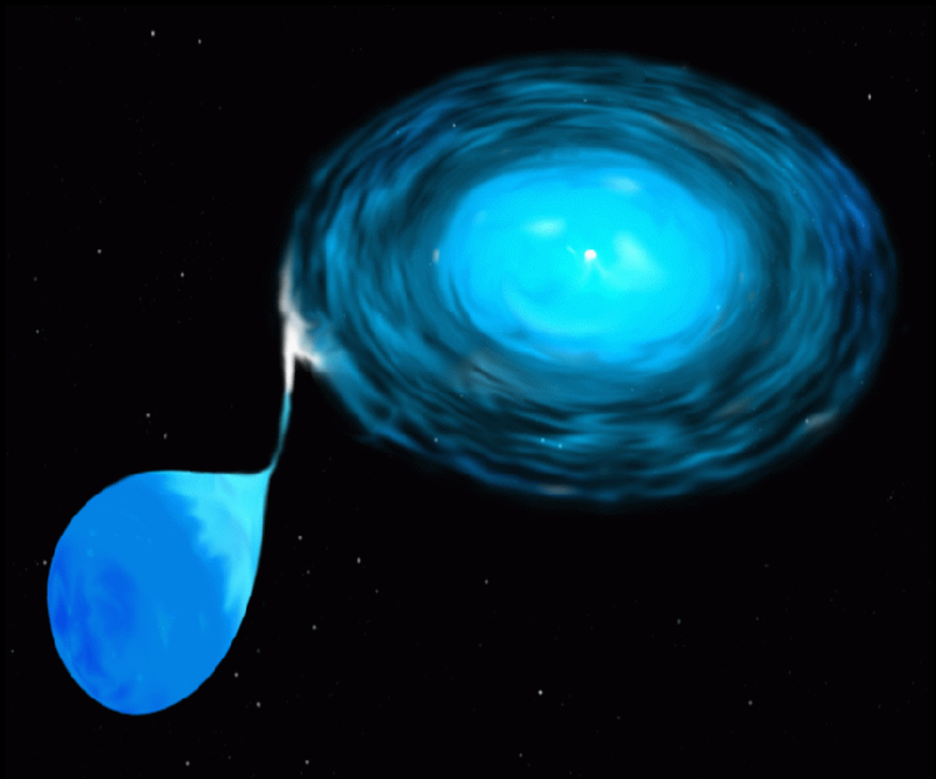
- Stars with about the mass of the Sun but with the size of the Earth:

  density~1000 kg/cubic centimeter

- The end state of most stars after they have finished burning Hydrogen and Helium to Carbon and Oxygen

Sirius A and B seen by the Hubble Space Telescope

Type Ia Supernova



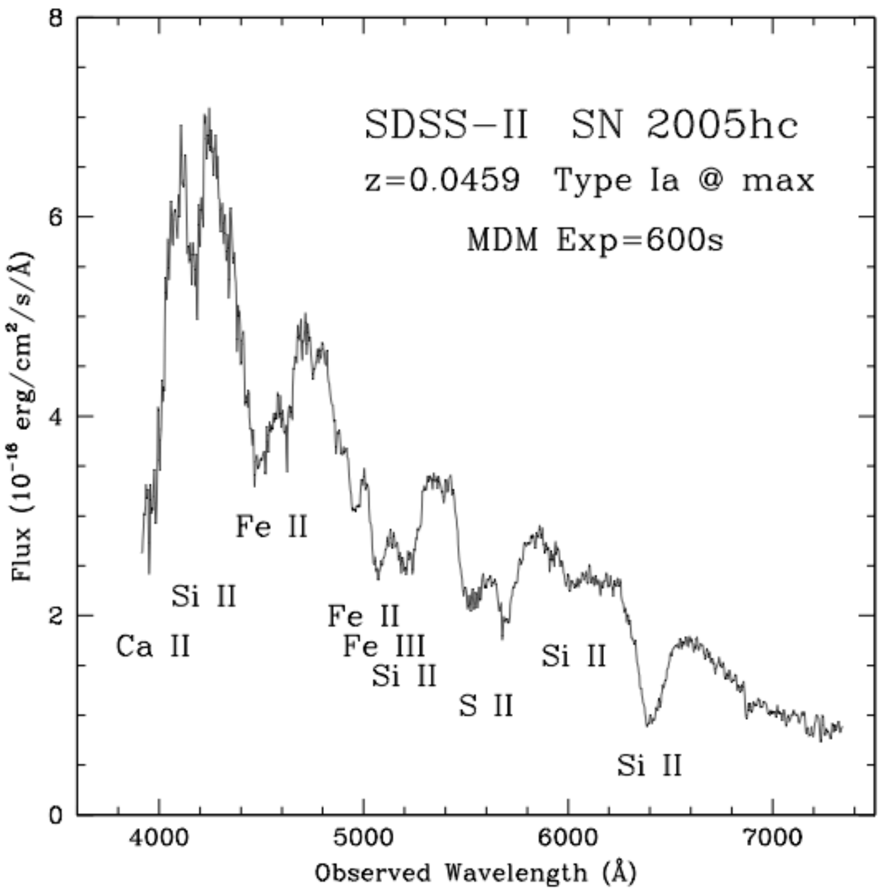
Thermonuclear explosion of White Dwarf star

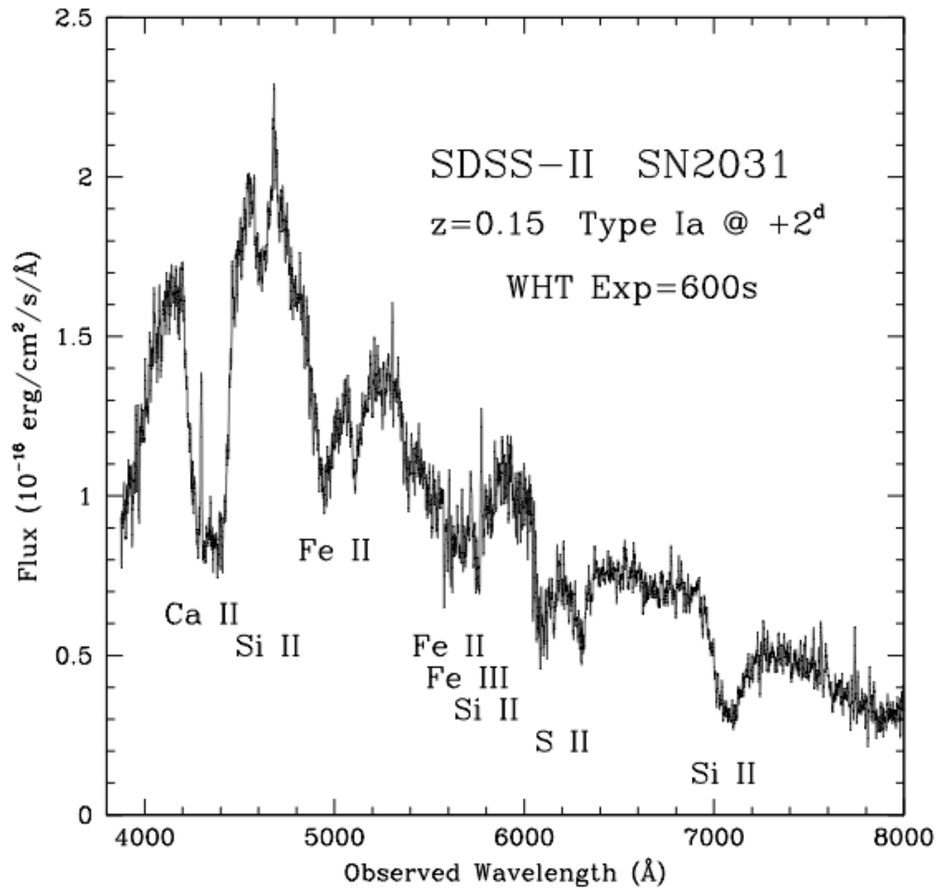
Accretes mass from a binary companion, grows to a critical mass (1.4 times the mass of the Sun, first calculated by S. Chandrasekhar) or else collides with another White Dwarf

After slow thermonuclear "cooking", a violent explosion is triggered; the star is completely incinerated within seconds; details are *not* understood

Radioactive decay of Nickel makes it shine for a couple of months

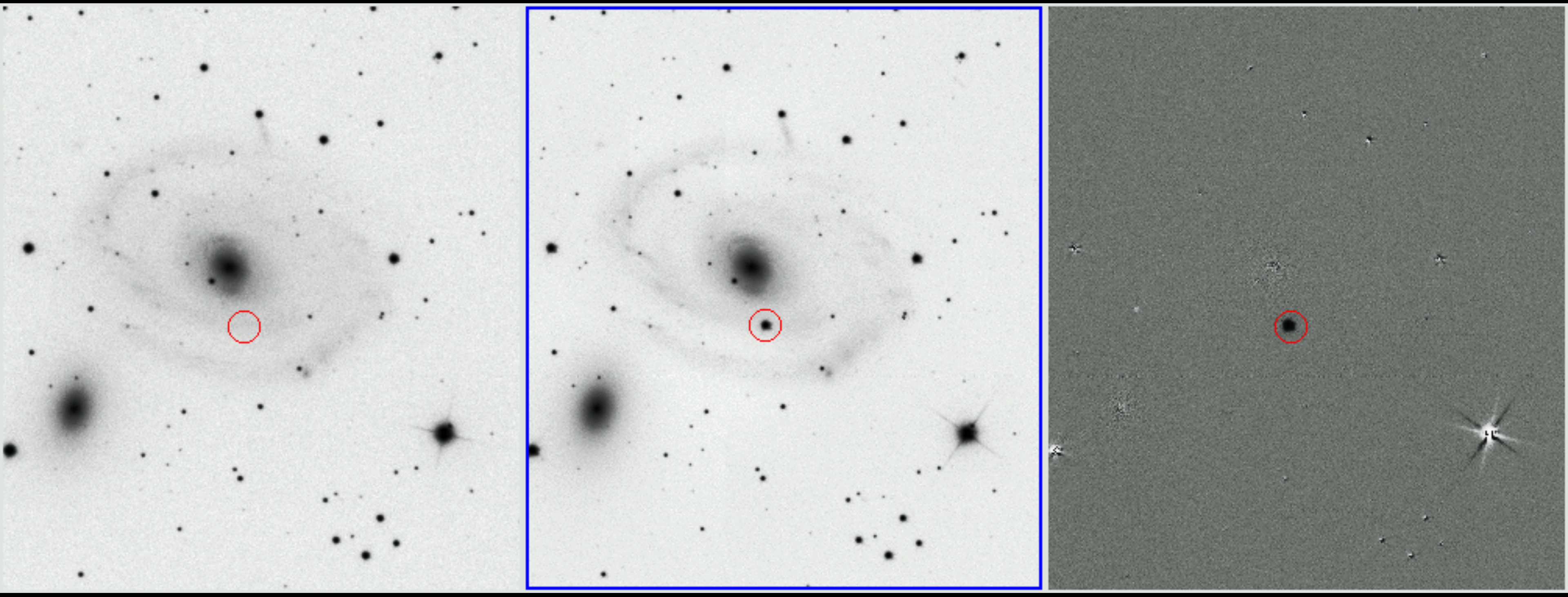
Type Ia Supernova Spectra: Homogeneous class of events





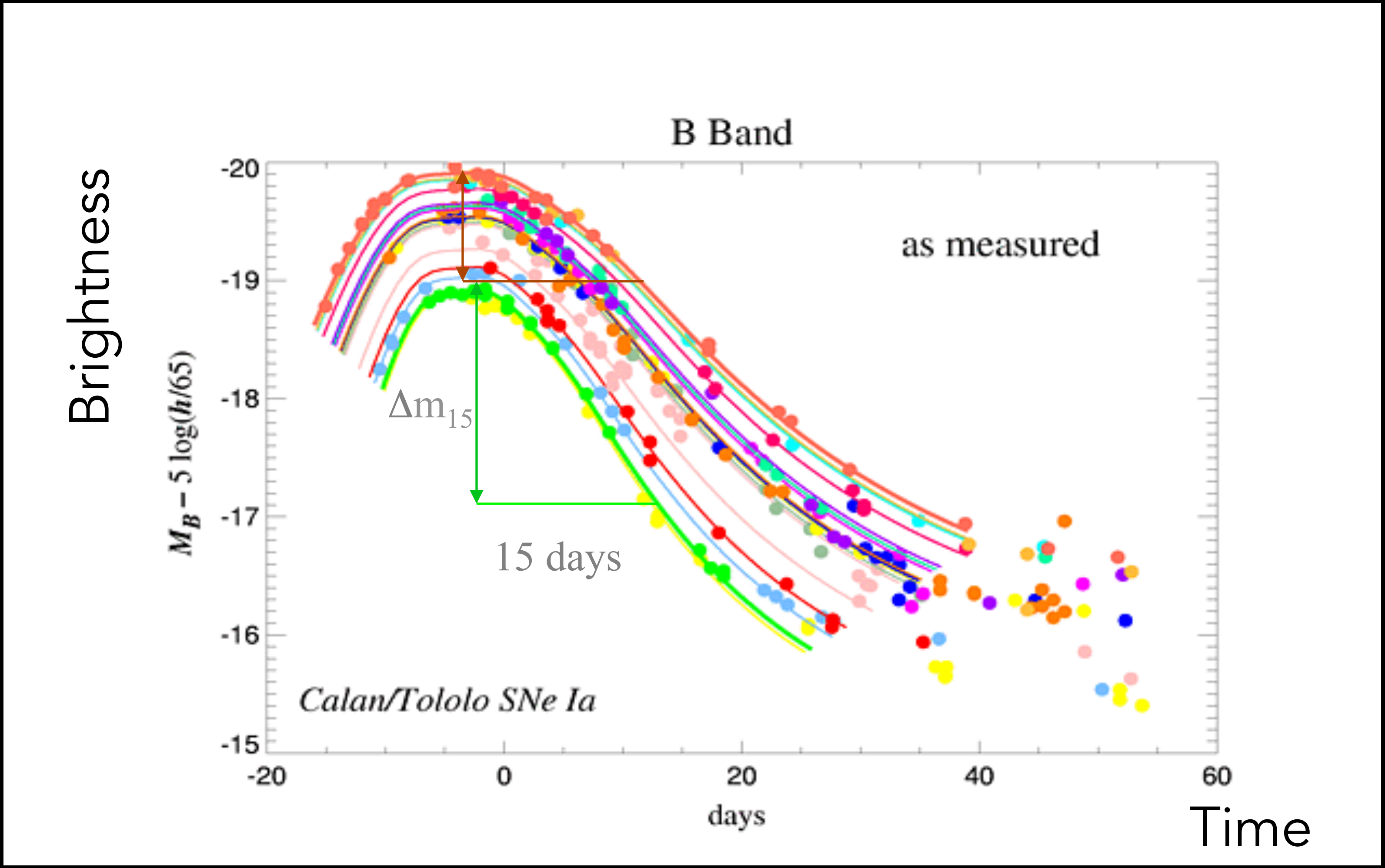
from SDSS Supernova Survey

Finding Supernovae: Image Subtraction



Before After Difference

SN 2002ha (Ia) $z = 0.014$

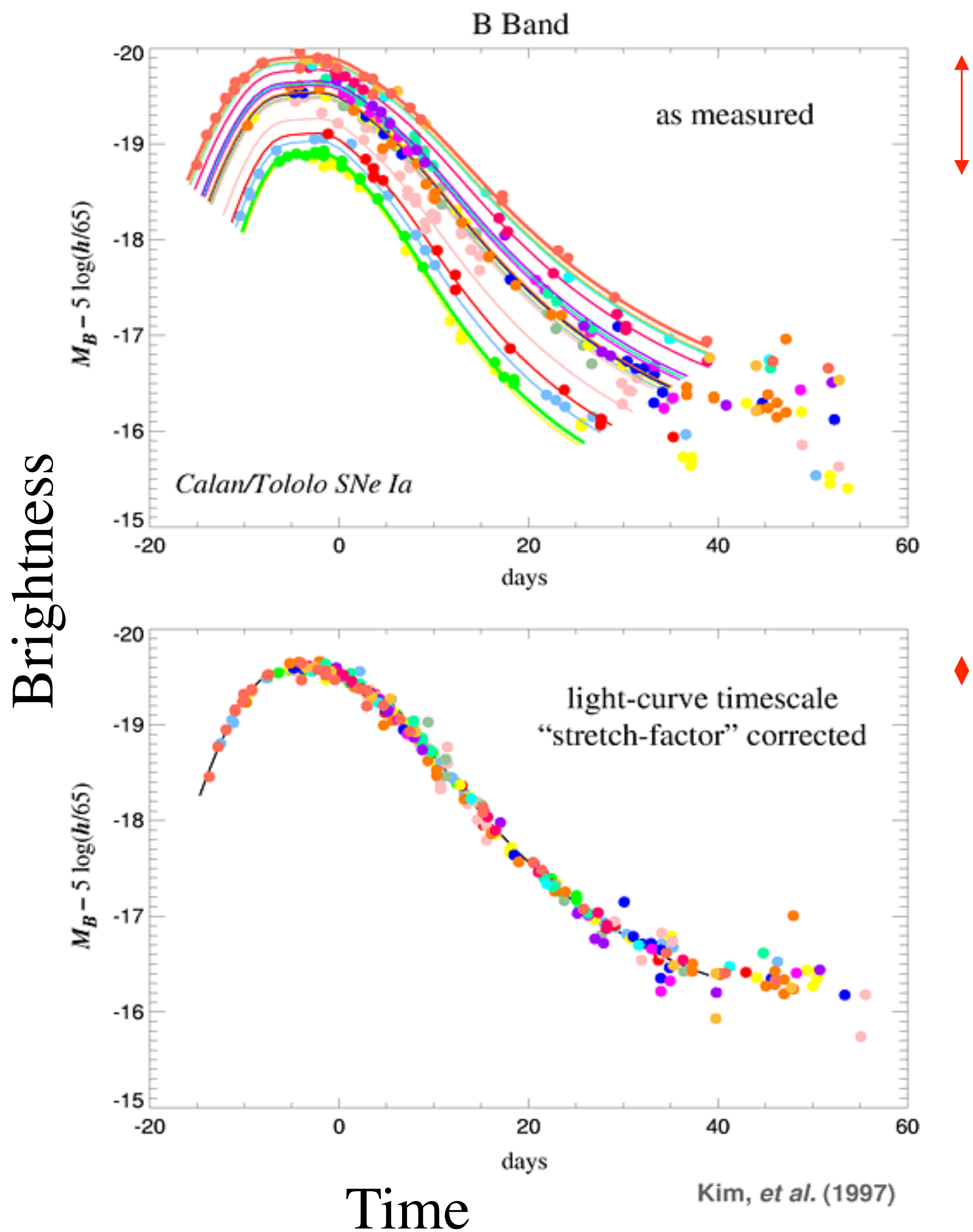


Brighter supernovae decline more slowly

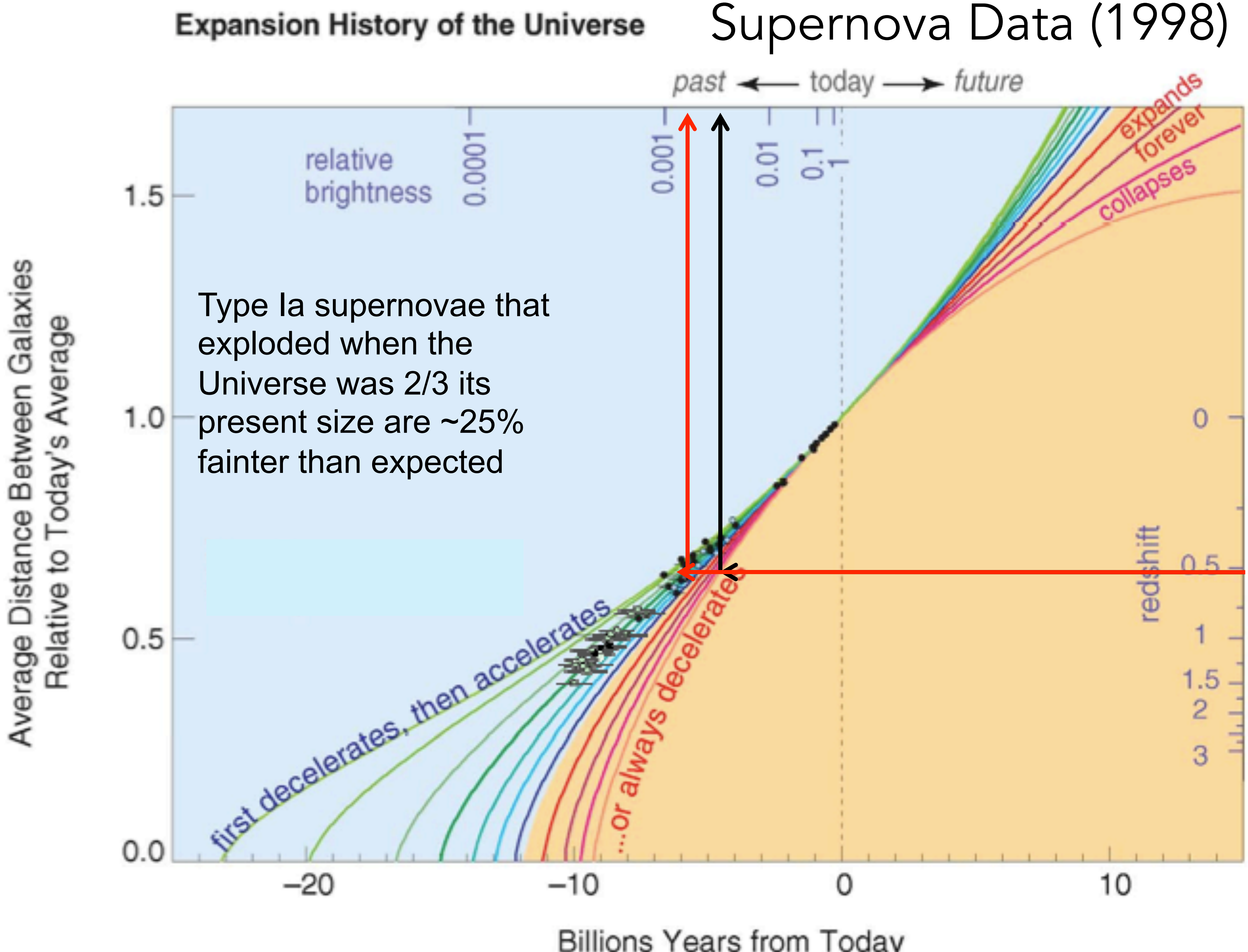
Type Ia SN
Peak Brightness
is a calibrated
`Standard
Candle'

Peak brightness
correlates with
decline rate

Use this to measure
supernova
distances to a
precision of 7%



Supernova Data (1998)



Type Ia supernovae that exploded when the Universe was 2/3 its present size are ~25% fainter than expected

Why is this a mystery?

When you throw a ball straight up in the air, imagine it first slows down but then, instead of falling back to Earth, it starts speeding up and rockets out of the atmosphere. That's what the Universe appears to be doing.

What causes Cosmic Speed-up?

Two possibilities:

1. The Universe is filled with stuff that gives rise to `gravitational repulsion'. We now call this

   Dark Energy

2. Our understanding of gravity (Einstein's General Relativity) is wrong on the largest scales:

   Modified Gravity
   (*not* the same as MOND)

Expansion Dynamics

- Friedmann equations of General Relativity:

$$H^2 = \left(\frac{1}{a}\frac{\Delta a}{\Delta t}\right)^2 = \frac{8\pi G\rho}{3} - \frac{k}{a^2} + \frac{\Lambda}{3}$$

$$\frac{1}{a}\frac{\Delta}{\Delta t}\left(\frac{\Delta a}{\Delta t}\right) = -\frac{4\pi G}{3}\rho + \frac{\Lambda}{3}$$

- For acceleration, $\Delta a/\Delta t$ is increasing with time: the cosmological constant term Λ introduced by Einstein must dominate over all other forms of mass and energy.

Vacuum Energy and the Cosmological Constant

- Einstein introduced the cosmological constant Λ to obtain a static Universe, then abandoned it when Hubble presented evidence for cosmic expansion.
- Lemaitre reinterpreted Λ as the energy density of empty space (the vacuum), something to be experimentally determined rather than introduced or removed by hand.
- In classical physics, if I remove all matter (particles, radiation) from a volume, it contains no energy. But in quantum physics, empty space carries energy and pressure.

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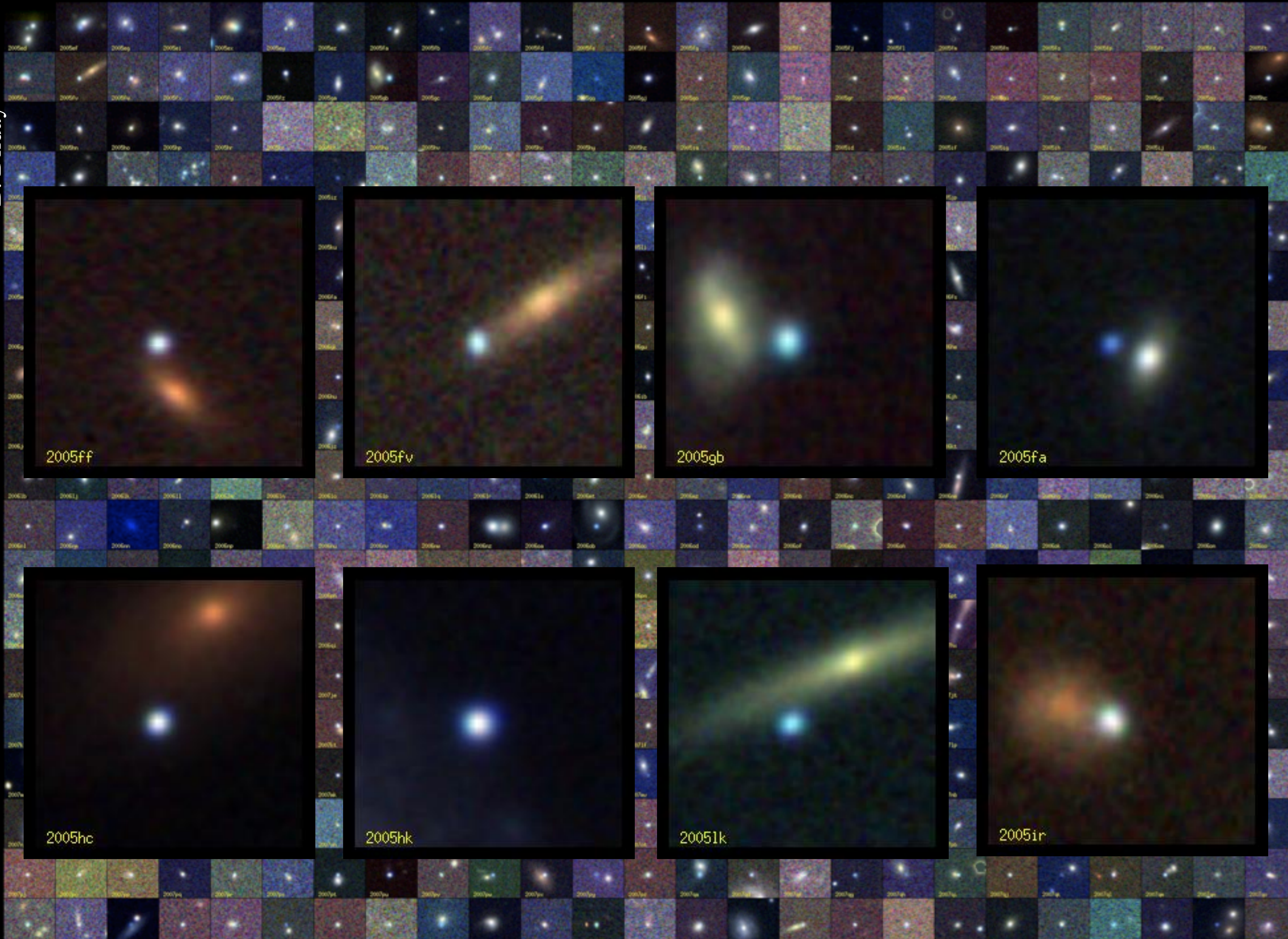
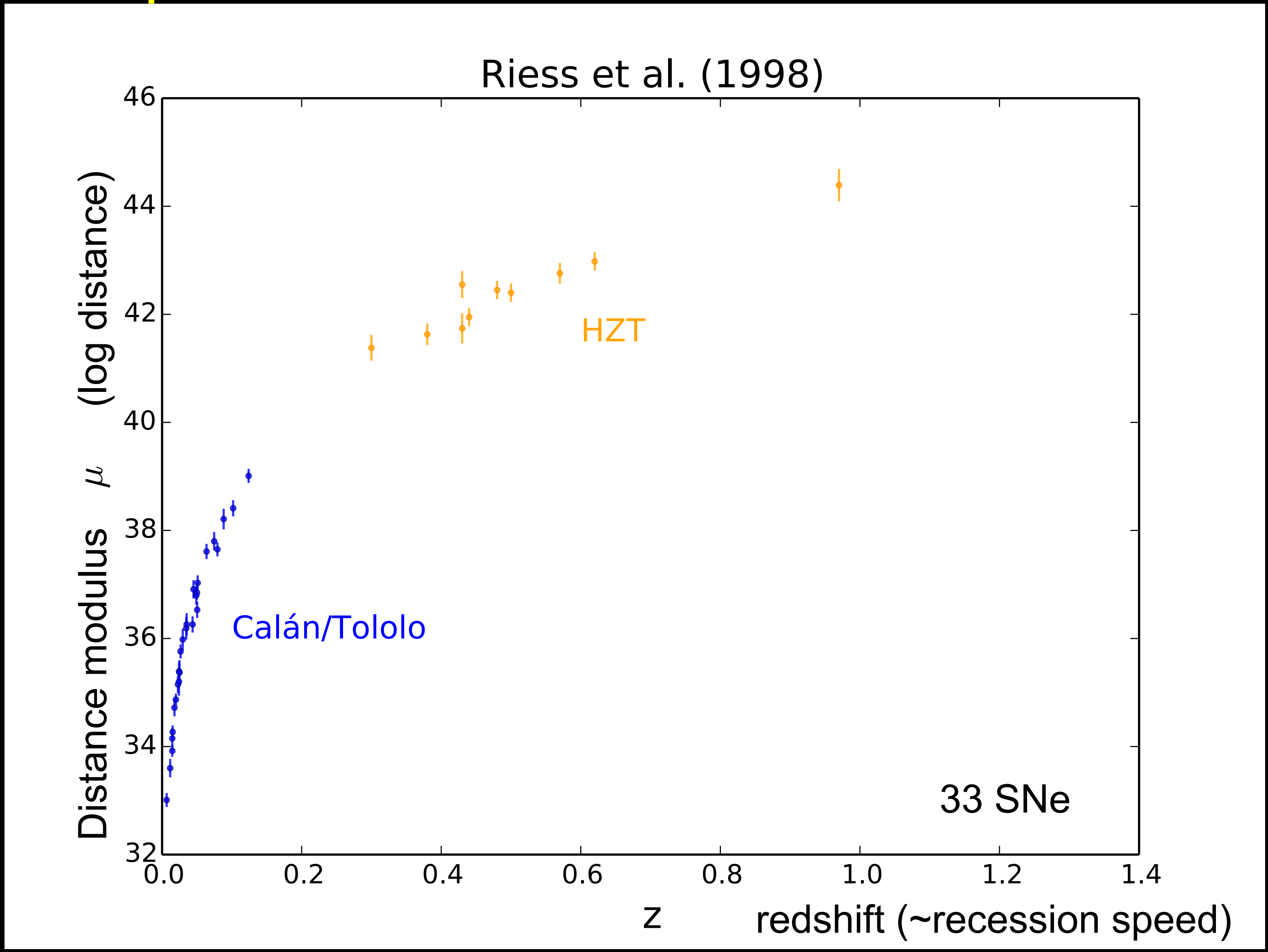
$$p_{vacuum} = -\rho_{vacuum} = -\frac{\Lambda}{8\pi G} = \text{constant}$$



B. Dilday

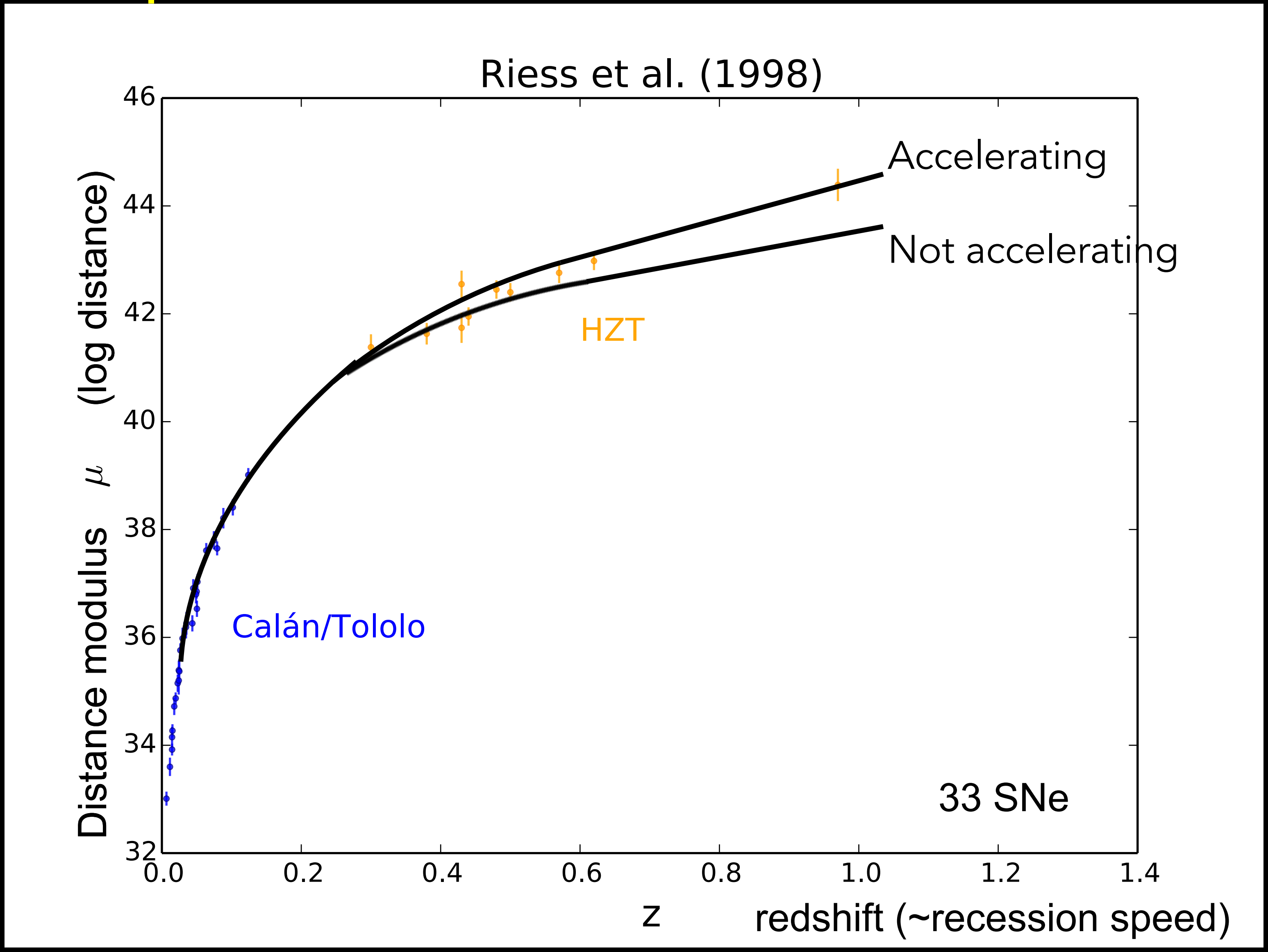
500 supernovae from SDSS-II survey 2005-2007

Supernova Ia Hubble Diagram



figures by A. Conley

Supernova Ia Hubble Diagram



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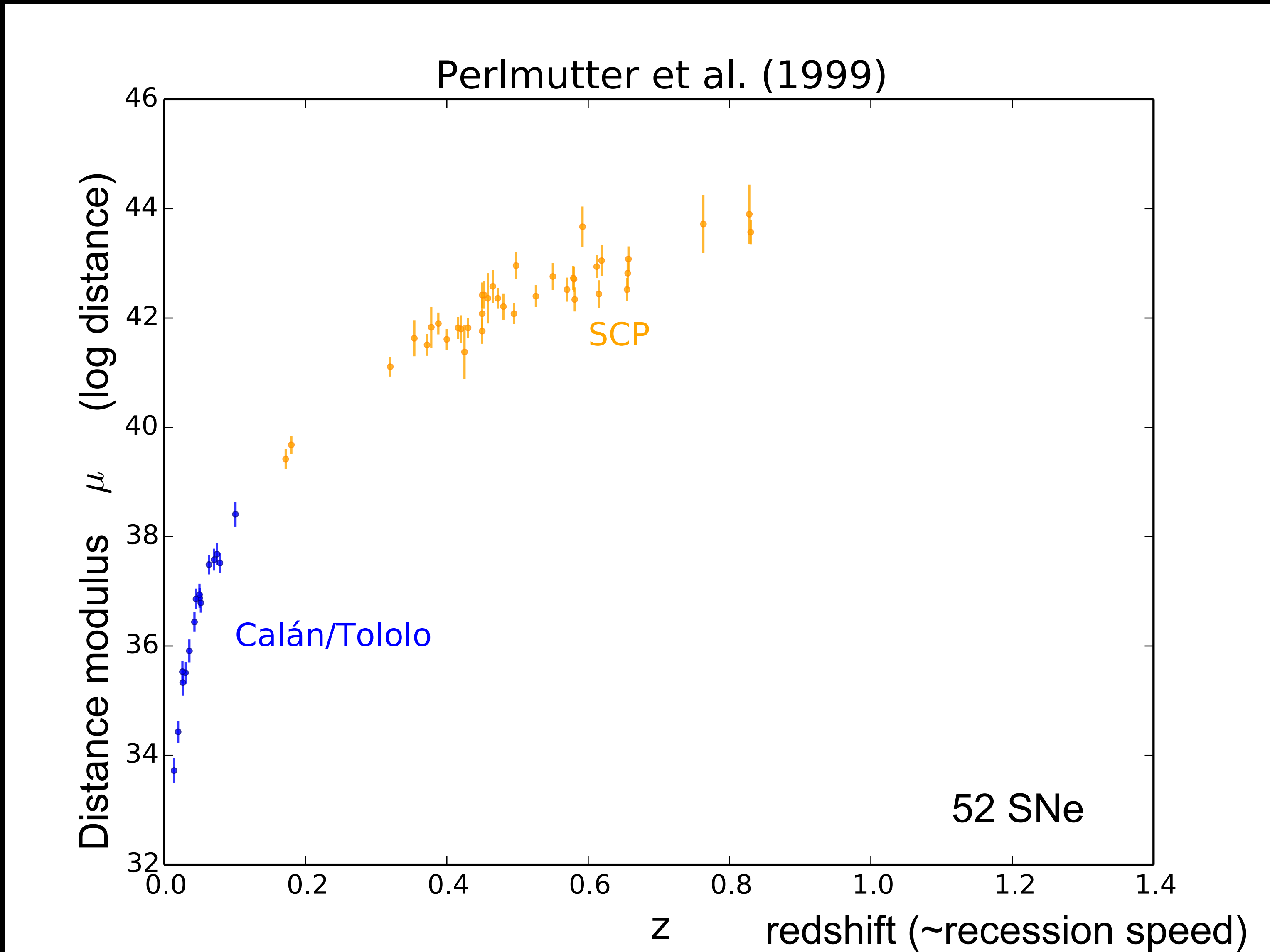
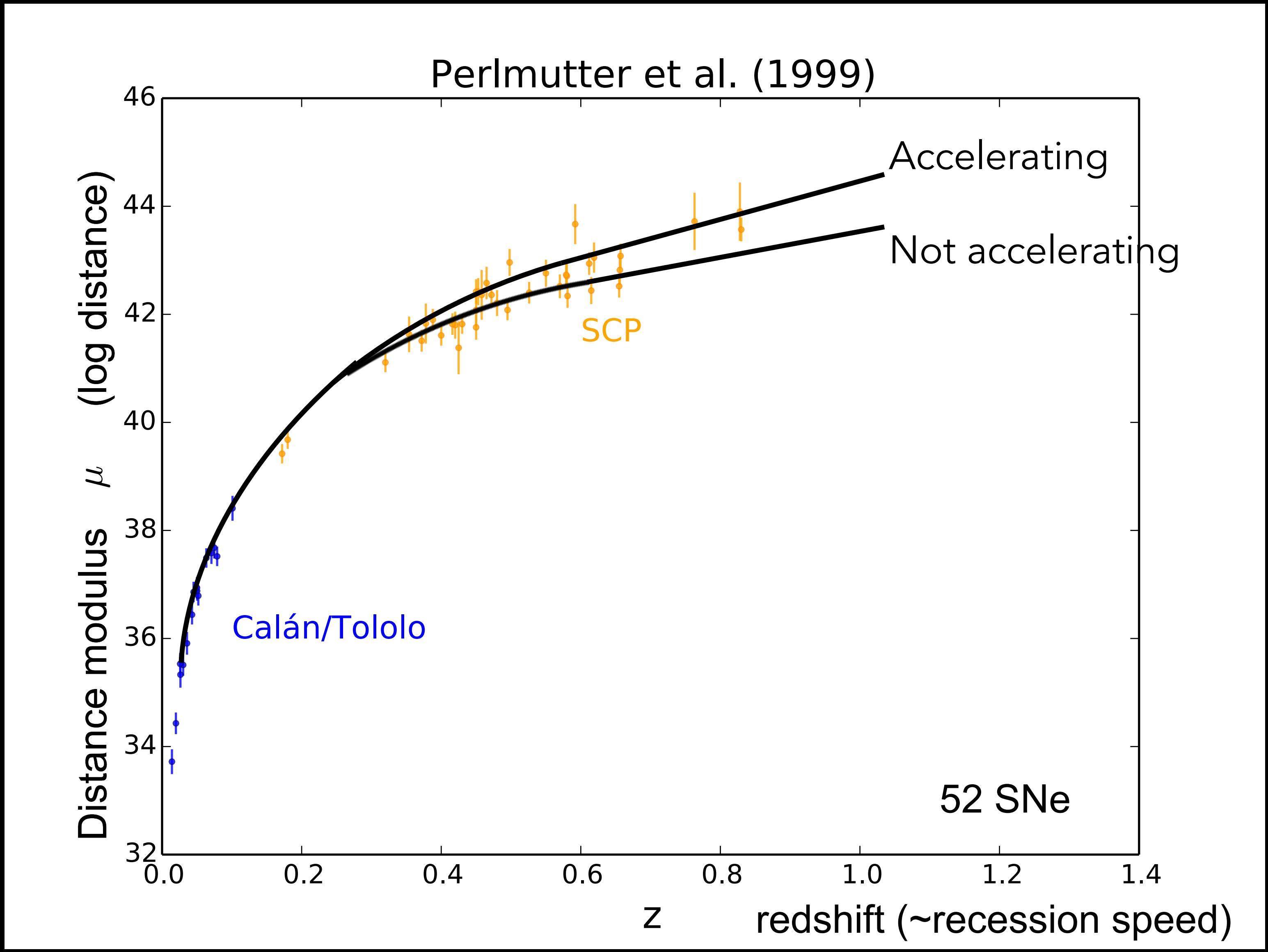


Perlmutter et al. (1999)
Distance modulus μ (log distance)
46
44
42
40
38
36
34
32
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
z redshift (~recession speed)
SCP
Calán/Tololo
52 SNe


Perlmutter et al. (1999)
Accelerating
Not accelerating
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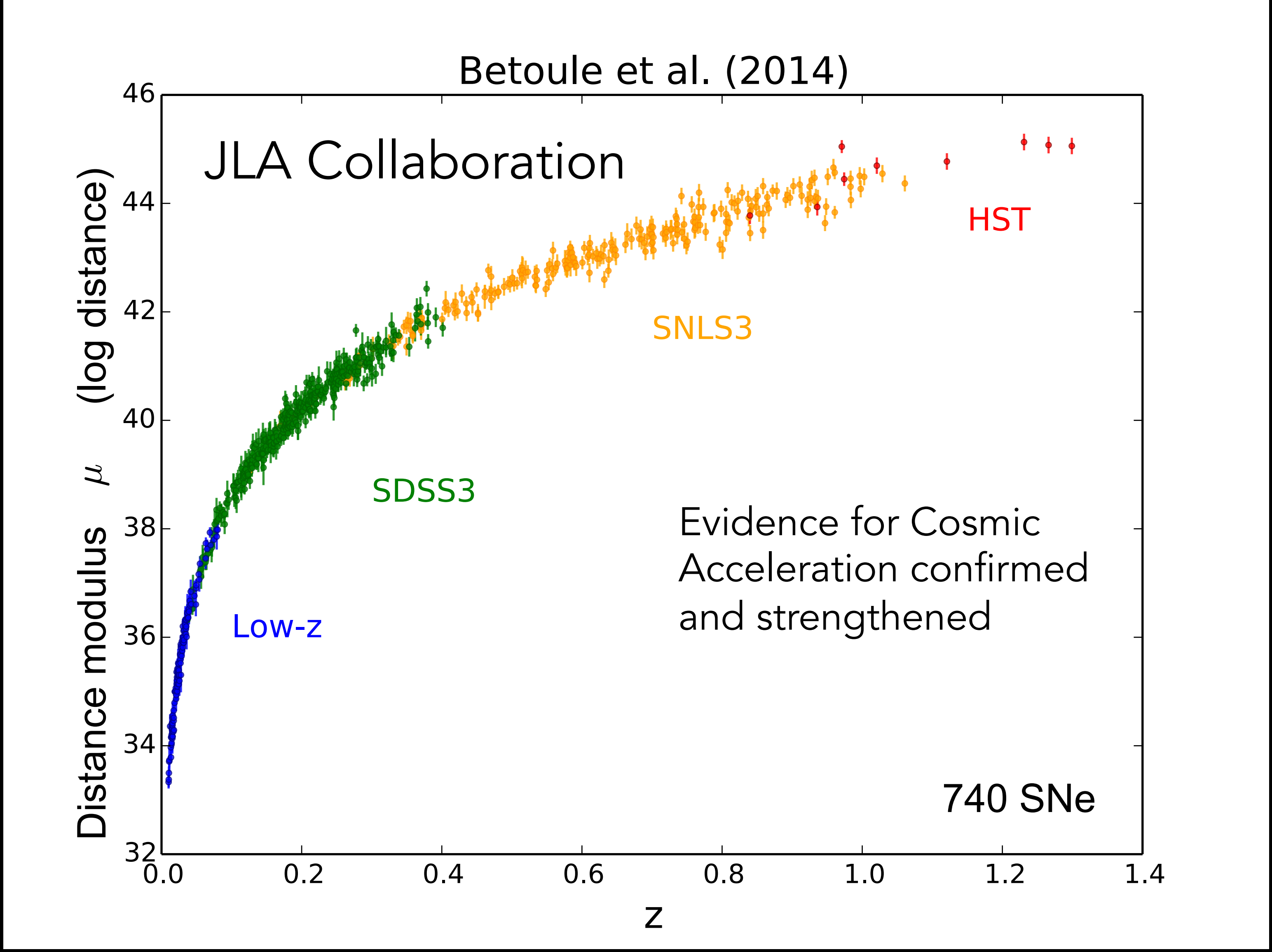
Betoule et al. (2014)
JLA Collaboration
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Low-z
Evidence for Cosmic Acceleration confirmed and strengthened
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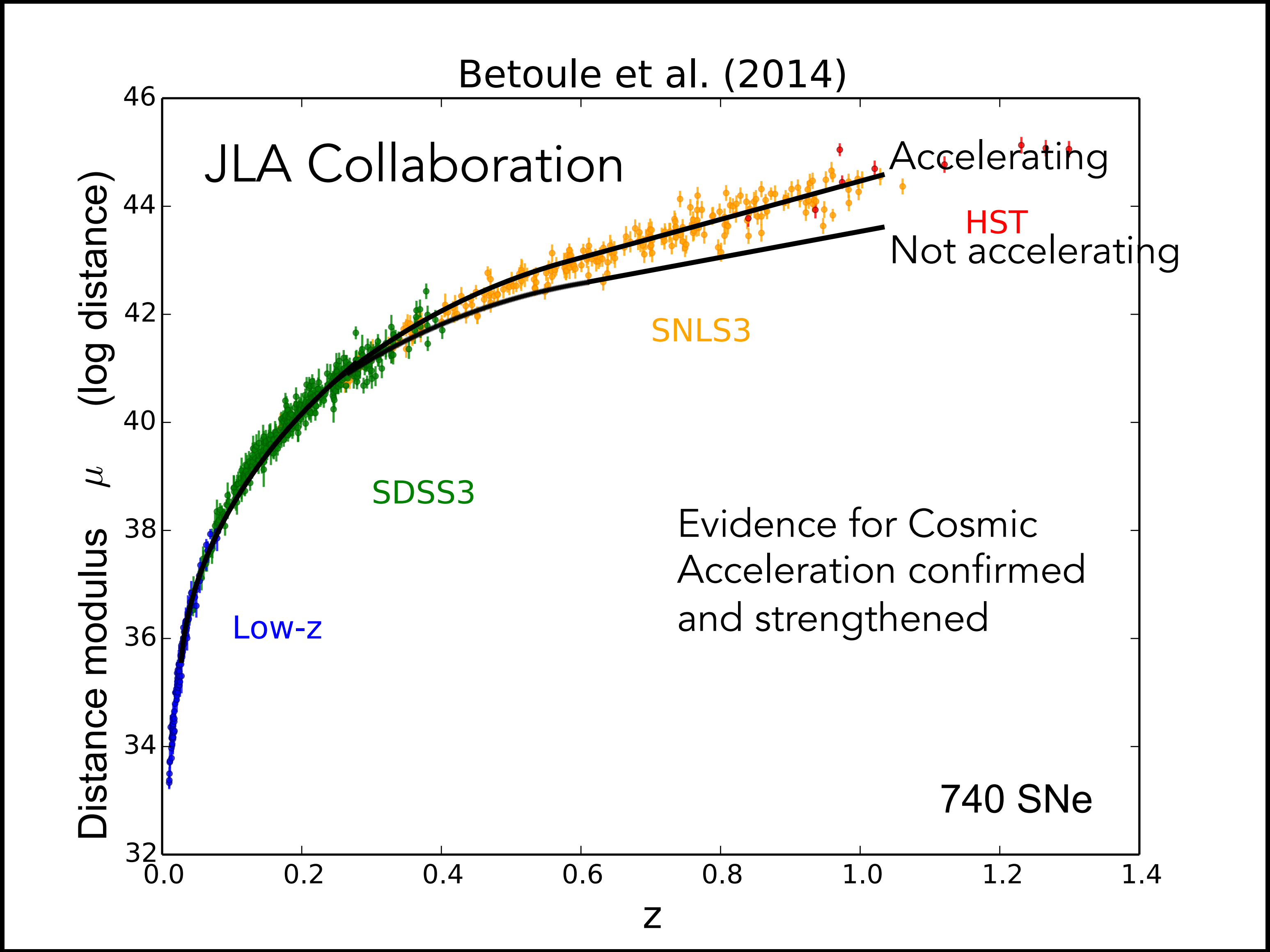
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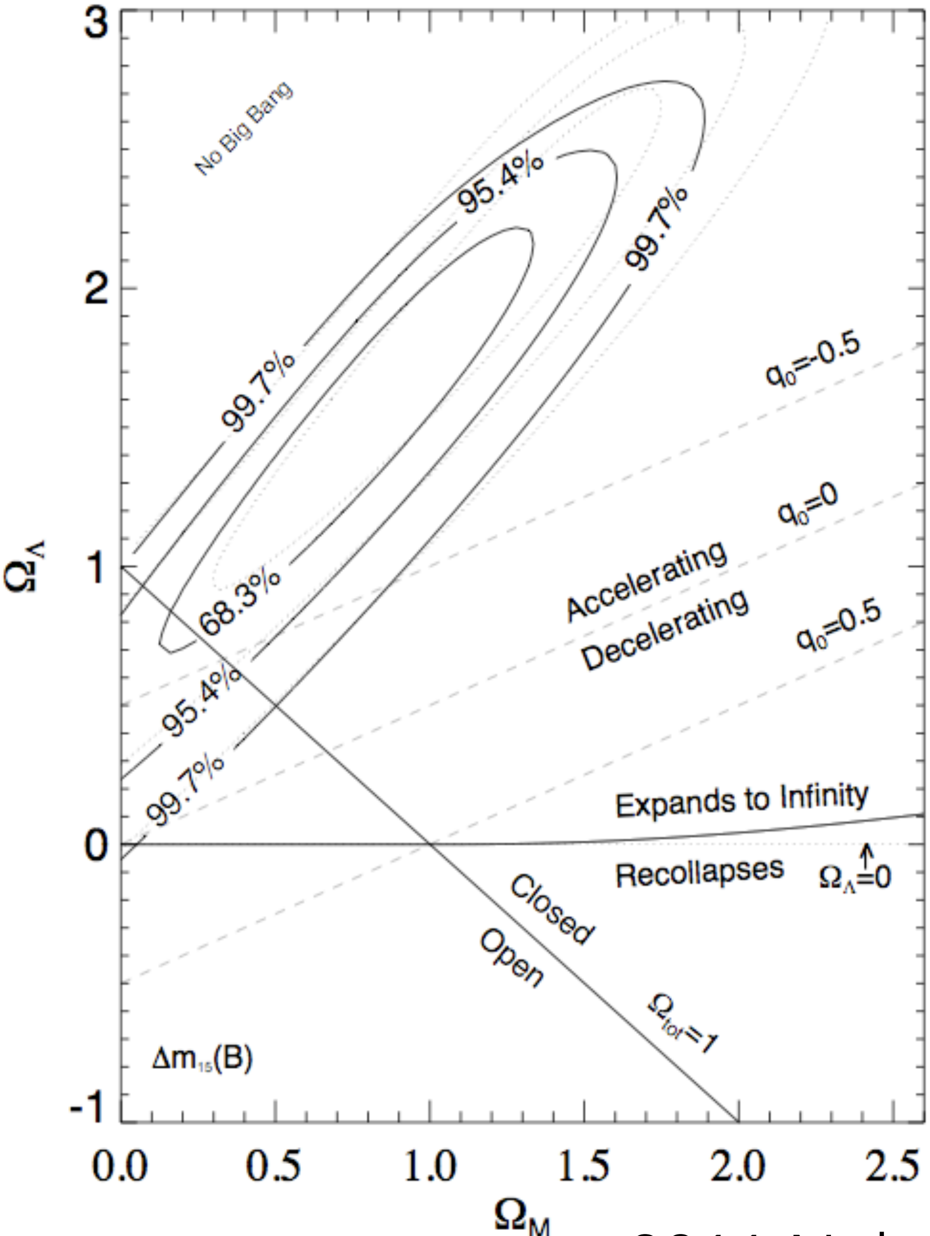
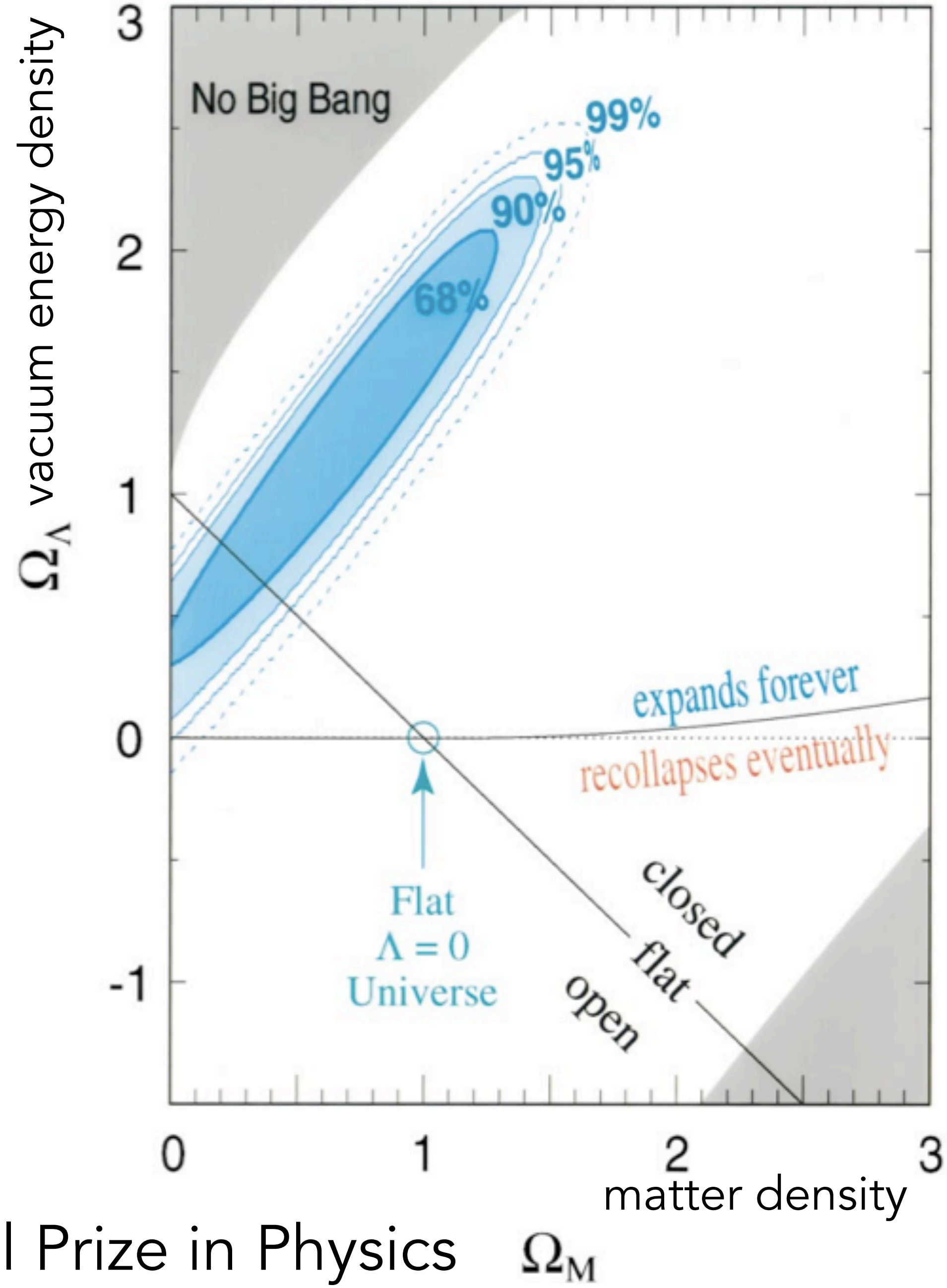
Riess et al. (1998, AJ)

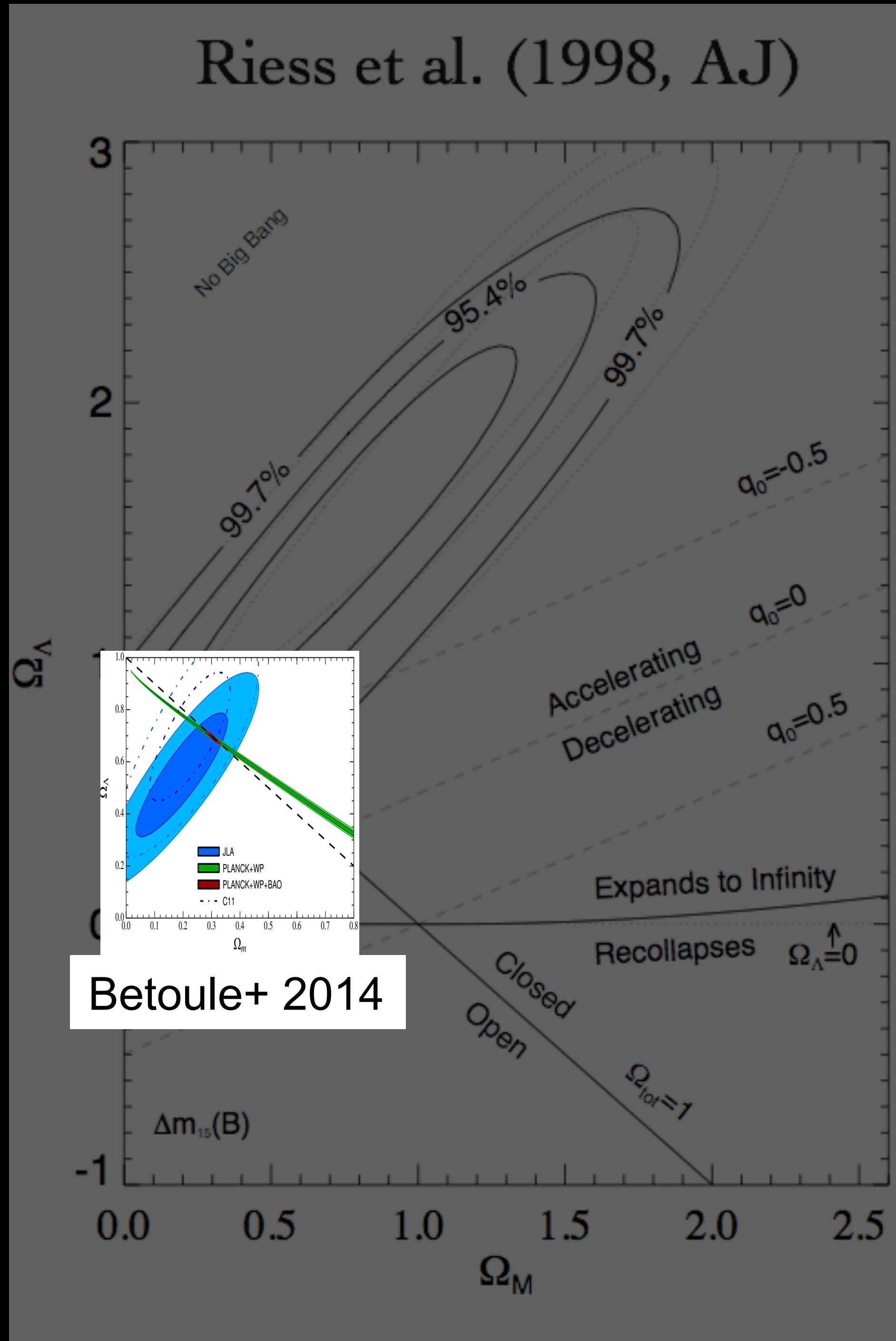


Perlmutter et al. (1999, ApJ)



2011 Nobel Prize in Physics

Progress over the last 17 years



Supernovae

Cosmic Microwave Background (Planck, WMAP)

CMB+BAO

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Dark Energy and Expansion

- Dark Energy (DE): more general concept than vacuum energy. Any form of mass-energy with sufficiently negative pressure, $p_{DE} < -\rho_{DE}/3$.
- If $w = p_{DE}/\rho_{DE} = -1$, i.e., vacuum energy, then ρ_{DE}=constant in time, but for other values of w the DE density evolves in time.

$$H^2 = \left(\frac{1}{a}\frac{\Delta a}{\Delta t}\right)^2 = \frac{8\pi G(\rho_{matter} + \rho_{DE})}{3} - \frac{k}{a^2}$$

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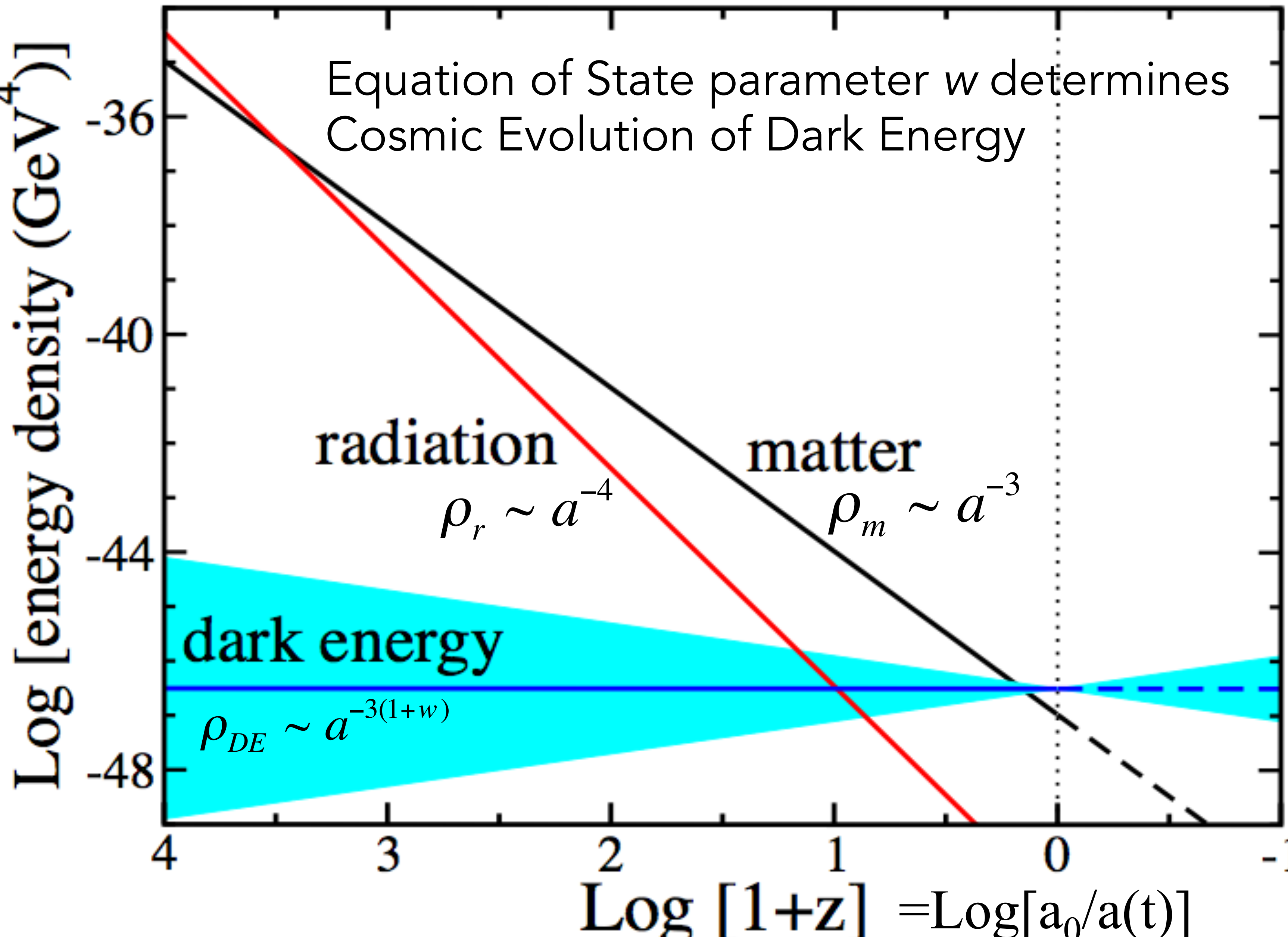
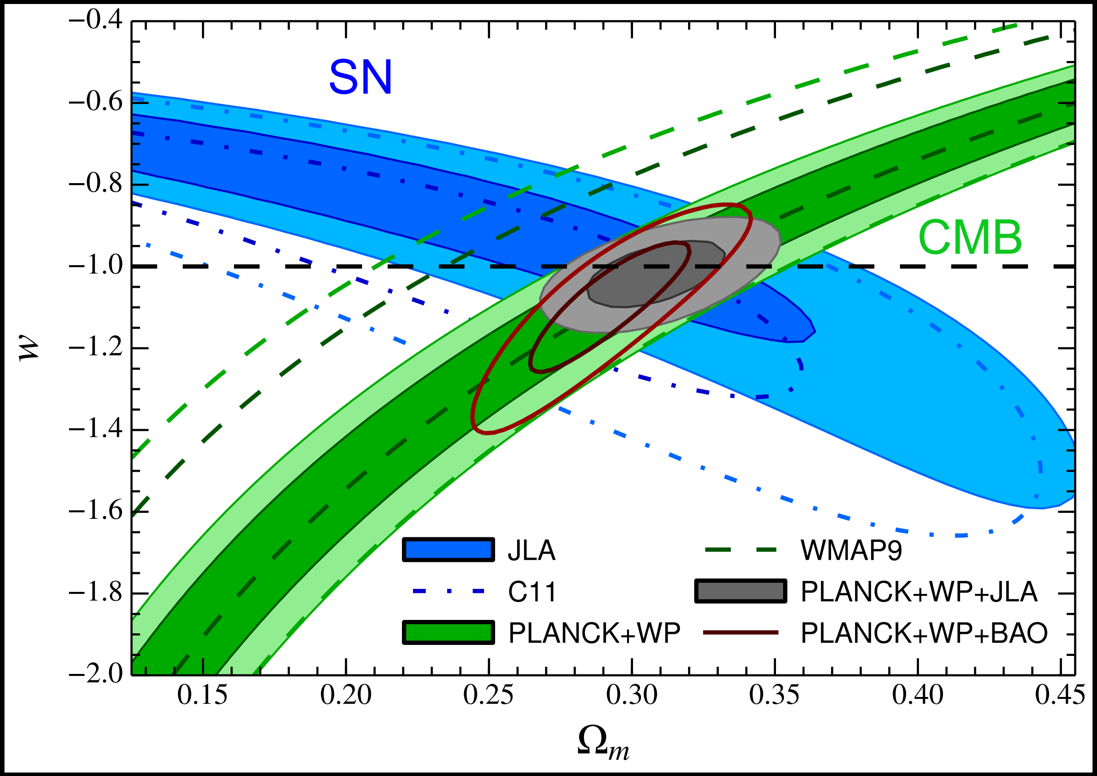


Equation of State parameter w determines
Cosmic Evolution of Dark Energy
radiation
$\rho_r \sim a^{-4}$
matter
$\rho_m \sim a^{-3}$
dark energy
$\rho_{DE} \sim a^{-3(1+w)}$
Log [energy density (GeV^4)]
-36
-40
-44
-48
4
3
2
1
0
-1
Log [1+z] =Log[a$_0$/a(t)]

Current Dark Energy Constraints from Supernovae, CMB, and Large-scale Structure

Assuming constant *w*: $w = -1.027 \pm 0.055$

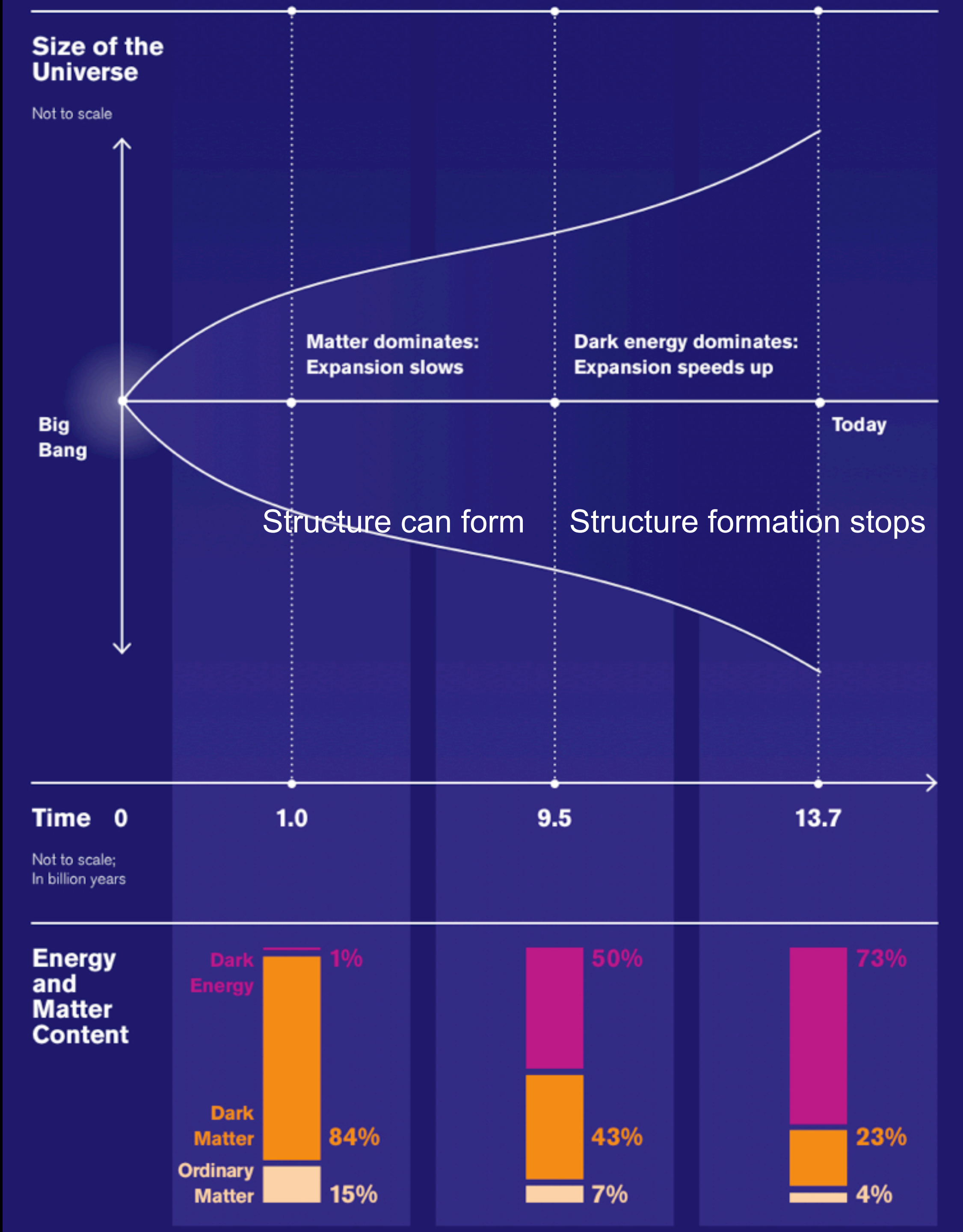


Betoule etal 2014

Consistent with vacuum energy (Λ): w=−1, but need better precision

History of Expansion

Once DE starts to dominate, it pulls matter apart faster than gravity can pull it together: formation of galaxies and large-scale structure effectively ceases.

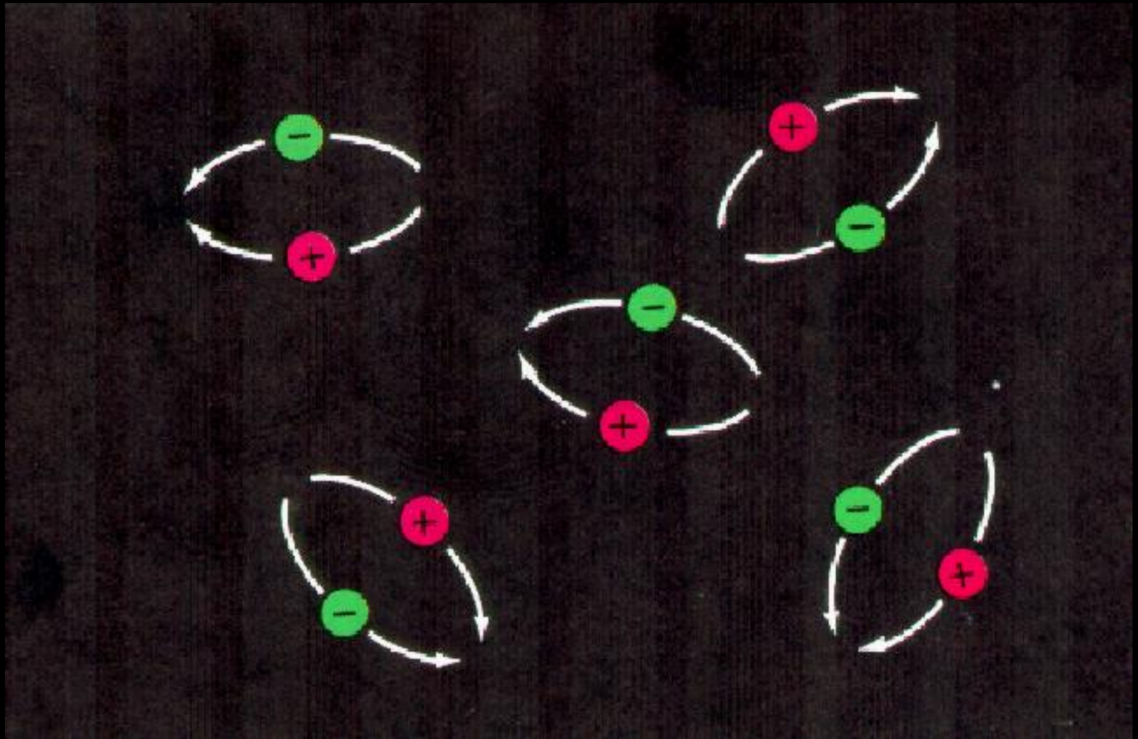


What is Dark Energy?

- We don't know. A component with relativistic negative pressure: $w = p/\rho c^2 < -1/3$
- Most conservative hypothesis is that it's the energy of empty space (vacuum zero-point energy of virtual particles: Heisenberg uncertainty principle). In this case, $w = -1$.
- However, quantum theory predicts vacuum energy density should be infinite.
- Other ideas even more speculative (e.g., "quintessence": very light scalar field).

The Cosmological Constant Problem

Vacuum zero-point fluctuations: in quantum theory, empty space is filled with pairs of virtual particles and antiparticles that continuously fluctuate into and out of the vacuum. Experimental effects of these fluctuations have been observed.



The Cosmological Constant Problem

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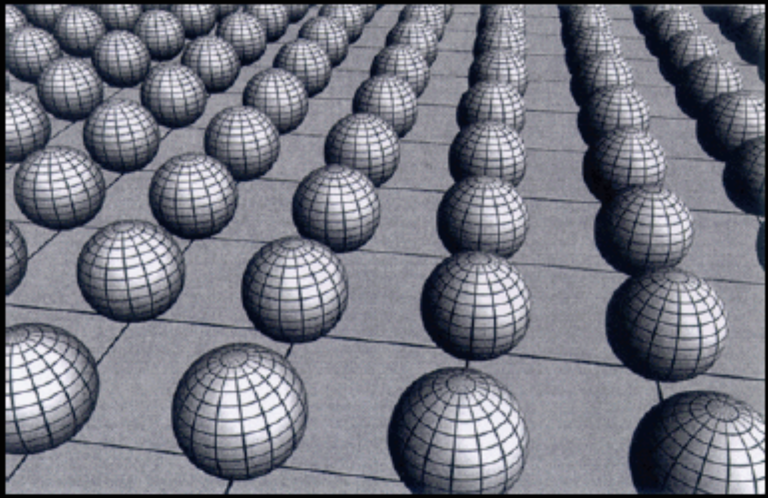
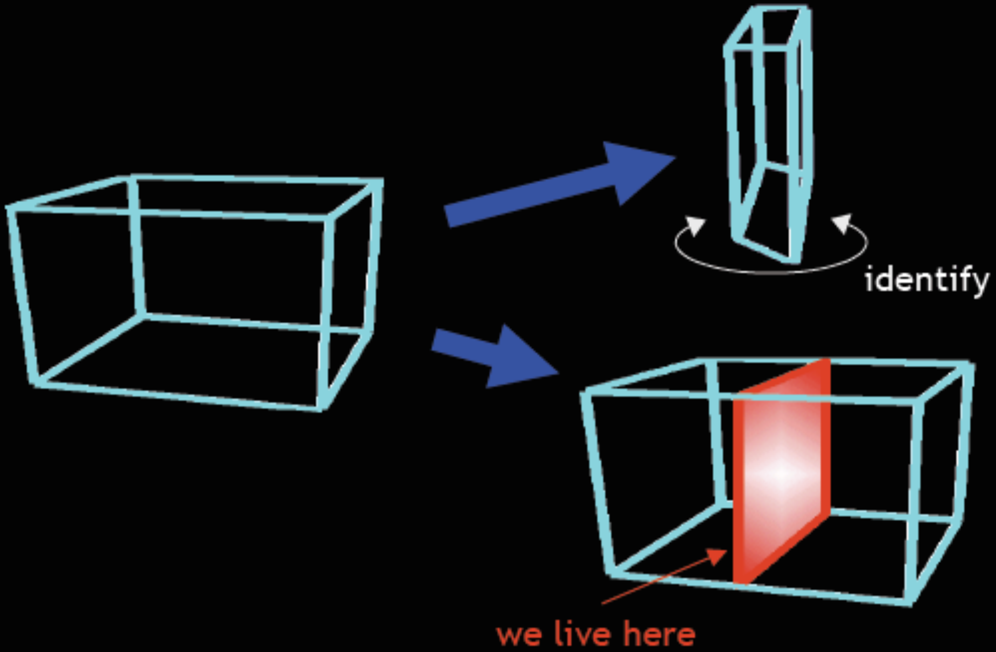
These fluctuations carry energy. When we calculate that energy (per unit volume), we get infinity. When we try to fix that problem, we still get an answer that is too big by a factor of about 10^{120}. Really hard to make a math error this big.

This problem continues to stump particle physicists and string theorists.

Extra dimensions of spacetime

String theory does predict that there are extra dimensions which we can't see. They might alter the way in which vacuum energy influences spacetime curvature.





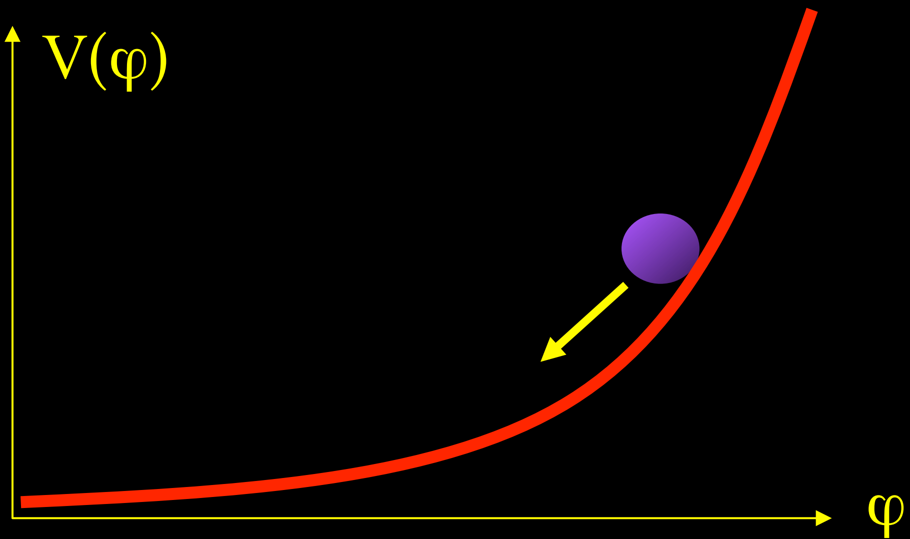
Old-school compactification:
curl up dimensions until they're too small to see (Kaluza & Klein)

New-fangled approach:
imagine we are confined to a "brane"

S. Carroll

Scalar Field as Dark Energy (aka Quintessence, alas)

- Dark Energy could be due to a very slowly rolling (evolving in time) `scalar field'.
- This particle must be many orders of magnitude less massive than other elementary particles.
- Evidence suggests an earlier period of cosmic acceleration shortly after the Big Bang, possibly also due to a scalar field (``primordial inflation")



Why is Dark Energy important?

- Nature of Dark Energy will determine the future evolution of the Universe (but its effects on Earth or in our galaxy are now extremely tiny).
- It's 70% of the Universe.
- Mapping the Universe can give us clues to nature of Dark Energy (determine *w*) or tell if something strange is going on with gravity.

Dark Energy and the Fate of the Universe

- Nature of Dark Energy determines future evolution of the Universe

- Continued acceleration: the ~billion galaxies in the Universe beyond the Local Group of galaxies (Milky Way, Andromeda, and their satellites) will disappear beyond the horizon in ~100 billion years. Won't be able to tell Universe is expanding. Need to do astronomy now!

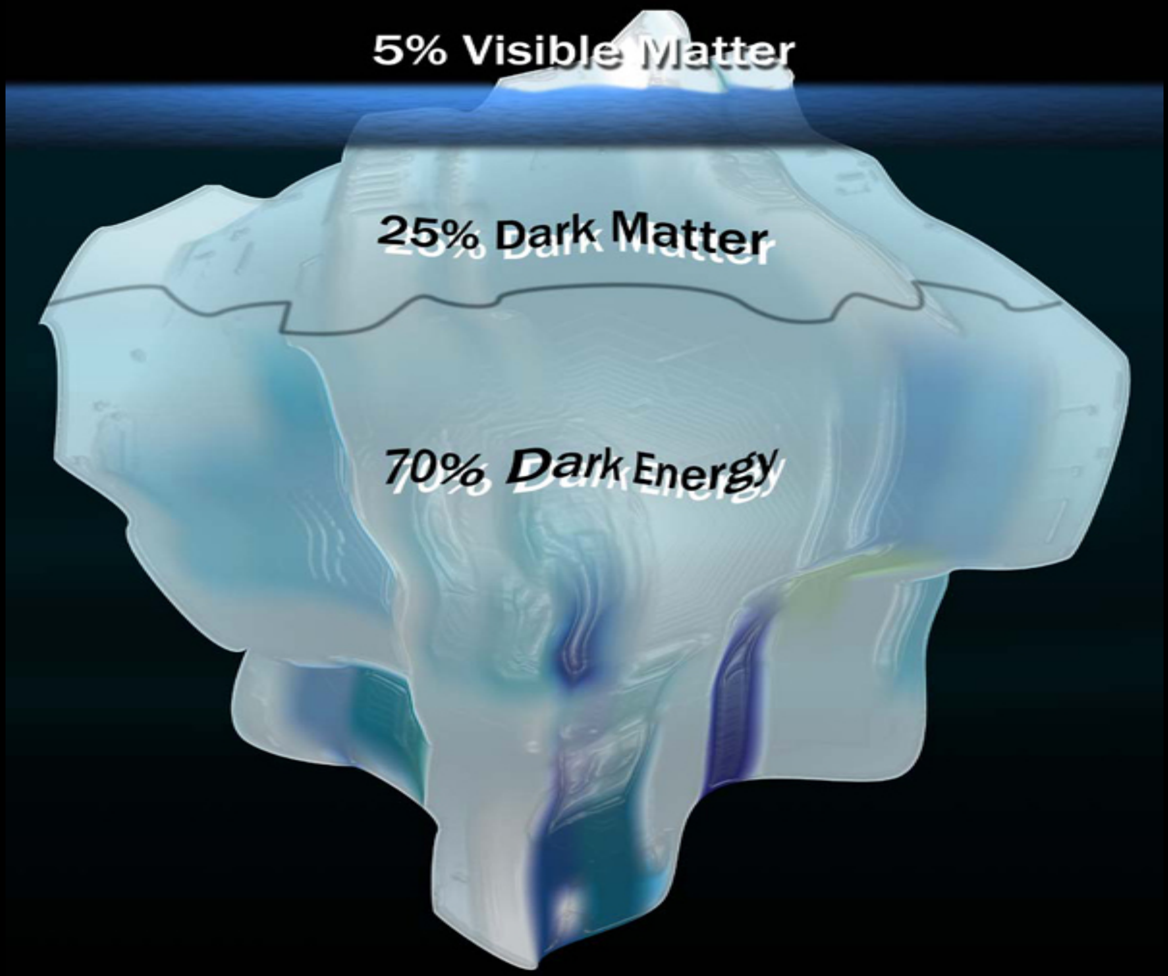
- `Phantom Dark Energy': in some models, dark energy density *increases* in time, leading to ever-increasing expansion rate: eventually galaxies, stars, atoms would be split apart in a Big Rip.

95% of the Universe is Dark

Ordinary Matter: atoms

Dark Matter: holds galaxies together, helps them form

Dark Energy: `gravitationally repulsive' stuff that speeds up cosmic expansion



Modified Gravity and Expansion

- Modified Gravity: acceleration might arise 'naturally' in a different theory of gravity from General Relativity (GR), without the need for Dark Energy. This theory must agree with GR where it has been tested (bending of light by the Sun, Mercury's orbit,…)

$$H^2 = \left(\frac{1}{a}\frac{\Delta a}{\Delta t}\right)^2 = \frac{8\pi G(\rho_{matter} + \rho_{DE})}{3} - \frac{k}{a^2}$$

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$$H^2 + f\left(a, H, \frac{\Delta H}{\Delta t}, \ldots\right) = \frac{8\pi G \rho_{matter}}{3} - \frac{k}{a^2}$$

Dark Stuff vs. Modifying Gravity

- Anomalies in orbit of Uranus (1800's): new ("dark") planet or deviation from Newton's law of Gravity? Discovery of Neptune (Le Verrier, 1846)

- Anomalies in orbit of Mercury (1900's): new planet or deviation from Newton's law of Gravity? Discovery of General Relativity (Einstein, 1915)

- Anomalies in orbits of stars in galaxies and of galaxies in clusters (1930's, 1970's): dark matter or deviation from Newtonian dynamics (MOND)? Preponderance of evidence for dark matter (2000's)

- Cosmic Acceleration: dark energy or deviation from General Relativity? Stay tuned.