Observational cosmology and Type Ia Supernovae

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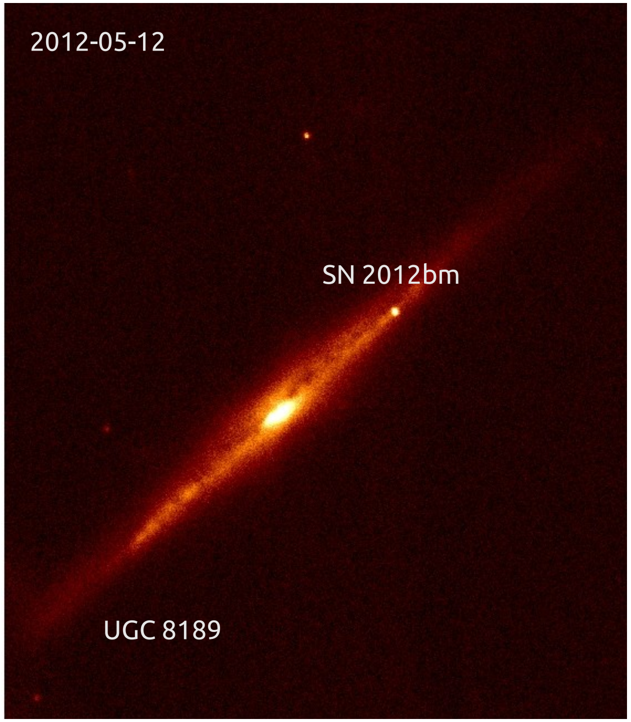
Physics at SU
Astronomy at SU
Physics at KTH

1. Identifying theoretically, and probing observationally, measurables related to dark energy to elucidate the nature of what is driving the accelerated expansion of the universe.

2. Searching experimentally for particle candidates of dark matter, which naturally means going beyond the standard model of particle physics, and if found, determining their properties and elucidating the underlying theoretical framework.

3. Investigating the physics of extreme objects, such as supernovae, neutron stars, and black holes. The work packages around these themes are formed by intertwining the applying teams within the AlbaNova University Centre in Stockholm.

Outline



NOTCam / Tanja Petrushevska

Part I: Cosmology – How to probe the expansion history of the Universe using Type Ia Supernovae

Part II: Astrophysics – Why it is not quite as simple as we would like...

Measuring distances

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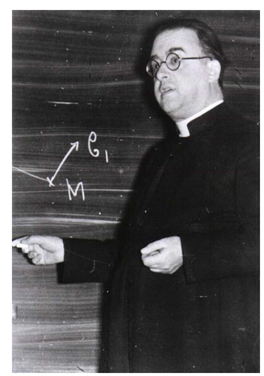
- Henrietta Leavitt (1912) – Period-Luminosity relation for Cepheids
- Knut Lundmark (1919) – Distance to Andromeda
- George Lemaitre (1927) – Theoretical arguments for expansion and estimating the Hubble constant
- Edwin Hubble (1929) – Universe is expanding!

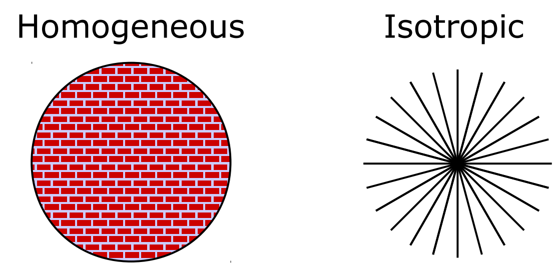

Leavitt


Lundmark


Lemaitre

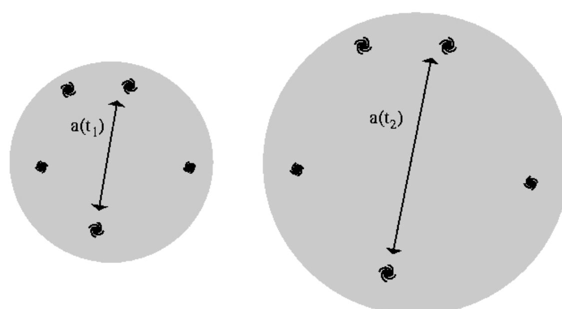

Hubble

The scale factor and the FLRW metric



Line element

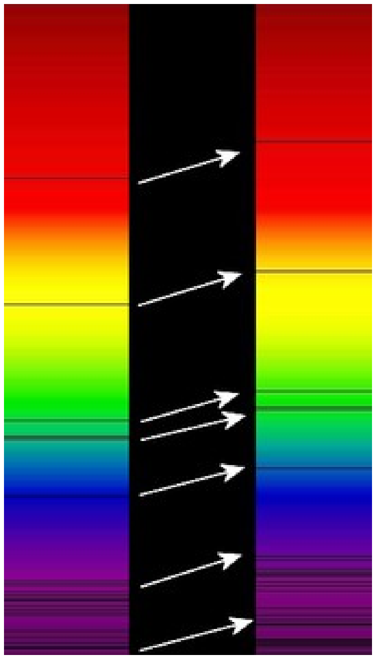
$$ds^2 = c^2\, dt^2 - a(t)^2 \left(\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta\, d\phi^2 \right)$$



The size of the universe is given by the scale factor, *a(t)*.

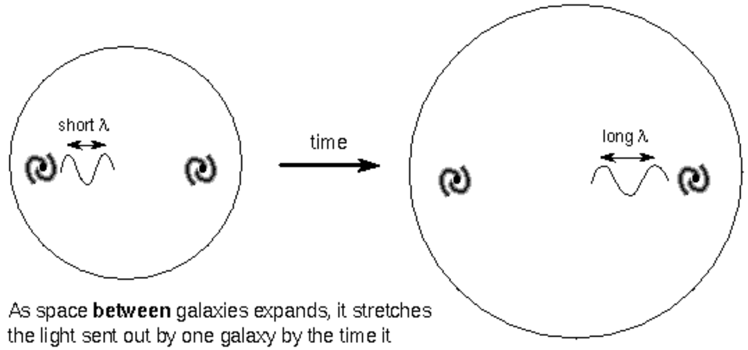
See Yashar's lectures!

Cosmological redshift



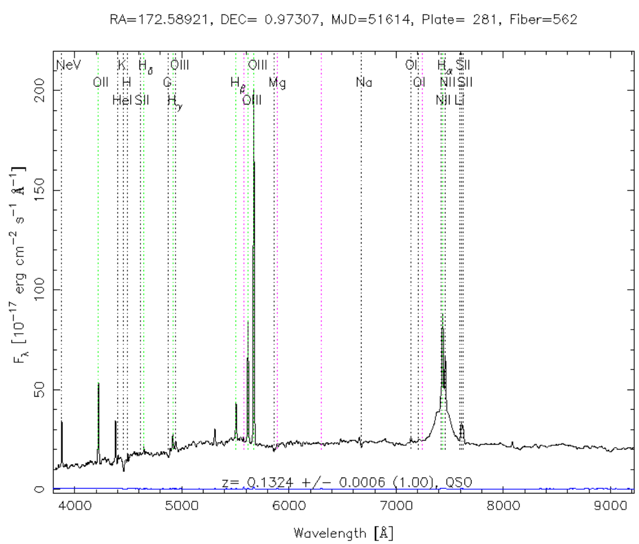
$$z = \frac{\lambda_{obs} - \lambda_{uts}}{\lambda_{uts}} \rightarrow 1 + z = \frac{\lambda_{obs}}{\lambda_{uts}}$$

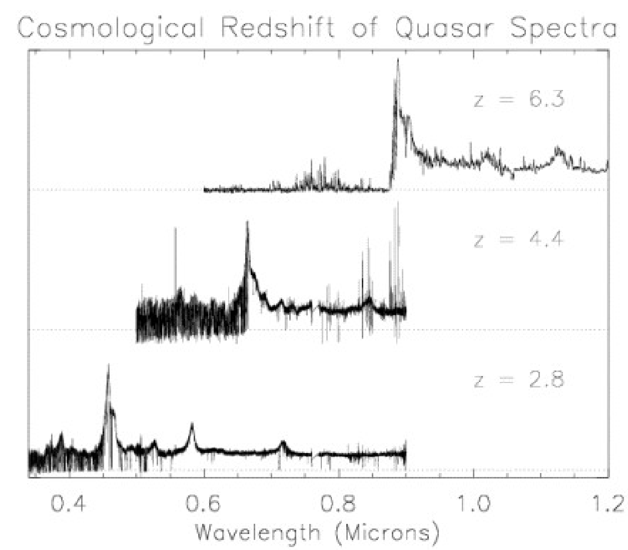
$$1 + z = \frac{a_{obs}}{a_{uts}}$$



As space **between** galaxies expands, it stretches the light sent out by one galaxy by the time it reaches another far away galaxy. Looks like **redshift**.

Easy to measure!





Cosmology from GR

Repulsive   Attractive

Geometry of space → $$G_{\mu\nu} = \Lambda g_{\mu\nu} + 8\pi G T_{\mu\nu}$$ ← **Energy-momentum tensor**
- energy
- matter
- radiation

Cosmological constant

Perfect fluid

$$p = w \cdot \rho$$

FLRW

$$ds^2 = c^2\, dt^2 - a(t)^2 \left(\frac{dr^2}{1 - kr^2} + r^2 d\theta^2 + r^2 \sin^2 \theta d\phi^2 \right)$$

Friedmann equation

$$\begin{aligned} H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 &= \frac{8\pi G}{3}(\rho - \rho_\Lambda) - \frac{k}{a^2} \\ &= H_0^2 \left[\Omega_M (1+z)^3 + \Omega_K (1+z)^2 + \Omega_\Lambda\right] \end{aligned}$$

See Yashar's lectures!

MEASURING COSMOLOGICAL DISTANCES

$$f = \frac{L}{4\pi r^2}$$

Find "standard candles" with $L \sim$ constant!

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Using standard cosmology and assuming a constant universe.

$$f = \frac{L}{4\pi (a(t_0)\cdot r_E)^2} \qquad \left(\begin{matrix}\text{from now on} \\ a(t_0) = a_0\end{matrix}\right)$$

f is power/area. Think of the light source as something sending out flashes of a given wavelength. In an expanding universe:

i) Photons are redshifted by $(1+z)$

ii) Time between flashes is dilated by $(1+z)$

$$f = \frac{L}{4\pi \underbrace{a_0^2 r_E^2 (1+z)^2}_{d_L^2}} = \frac{L}{4\pi d_L^2} \qquad (1)$$

Astronomers measure brightness in magnitudes:

$$m = -2.5 \log_{10}\left(\frac{f}{F}\right) + M$$

F is flux measured at 10 pc

$$\left[\frac{f}{F} = \frac{L}{4\pi d_L^2} \cdot \frac{4\pi (10\,pc)^2}{L}\right]$$

$$m - M = 5 \log_{10}\left(\frac{d_L}{10\,pc}\right) \qquad \text{"Distance modulus"}$$

How do we connect this to cosmological parameters?

From (1) $\quad d_L = a_0 \cdot r_E \cdot (1+z) \qquad (2)$

The FLRW metric with a wisely chosen $(c=1)$ coordinates $(d\theta = d\varphi = 0)$, for a light beam $(ds^2 = 0)$ gives.

$$\frac{dt}{a} = \frac{dr}{\sqrt{1-kr^2}}$$

(If you are confused set $k=0$, $c=c$ and you can relax...)

Multiply by a_0:

$$\frac{a_0}{a}\,dt = a_0 \frac{dr}{\sqrt{1-kr^2}}$$

$$(1+z)\,dt = a_0 \frac{dr}{\sqrt{1-kr^2}} \qquad (3)$$

From the Friedmann equation:

$$H = \frac{\dot a}{a} = \frac{\dot a}{a_0}\cdot\underbrace{\frac{a_0}{a}}_{=1+z} = (1+z)\frac{d}{dt}\left(\frac{a}{a_0}\right) = (1+z)\frac{d}{dt}(1+z)^{-1} =$$

$$= -\frac{1}{1+z}\frac{dz}{dt}$$

Inserting this into eq. (3) we can replace dt by dz:

$$-\frac{dz}{H(z)} = a_0\frac{dr}{\sqrt{1-kr^2}}$$

Integrating from emission, z_e, to today

$$\int_{z_e}^{0} -\frac{dz}{H(z)} = \int_0^{z_E}\frac{dz}{H(z)} = a_0\underbrace{\int_0^{r_E}\frac{dr}{\sqrt{1-kr^2}}}_{=r_E \text{ (for a flat universe, } k=0)}$$

Recall eq. (2)

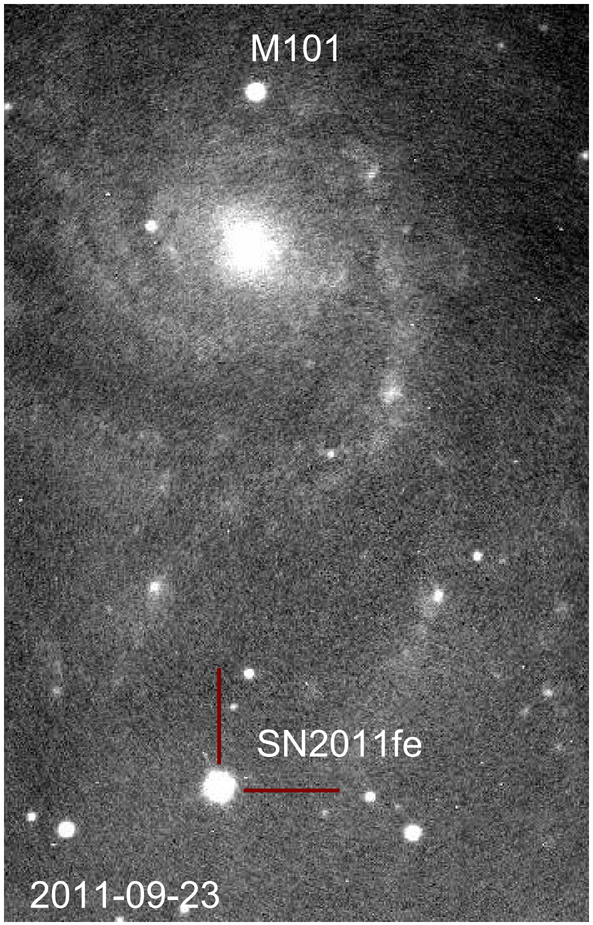
$$d_L = a_0\cdot r_E\cdot(1+z) = (1+z)\int_0^{z_E}\frac{dz}{H(z)} =$$

$$= (1+z_E)\int_0^{z_E}\frac{dz}{H_0\left[\Omega_M(1+z)^3+\Omega_K(1+z)^2+\Omega_\Lambda\right]^{1/2}}$$

From before:

$$m - M = 5\log_{10}\left(\frac{d_L(z;\Omega_M,\Omega_\Lambda,\Omega_K)}{10\,pc}\right)$$

Measuring distance using standard candles – Type Ia Supernovae



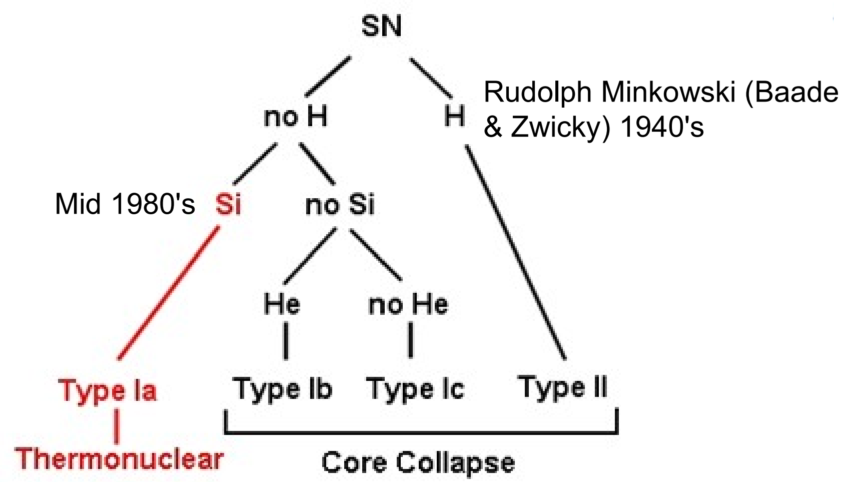
Mattias Ergon & Joel Johansson

Alexis Brandeker

(G. Miicheva, S. Gelato and the telescope group at Albanova)

Historical supernova classification

- Empirical
- Presence or absence of certain features in their optical spectra taken near maximum light



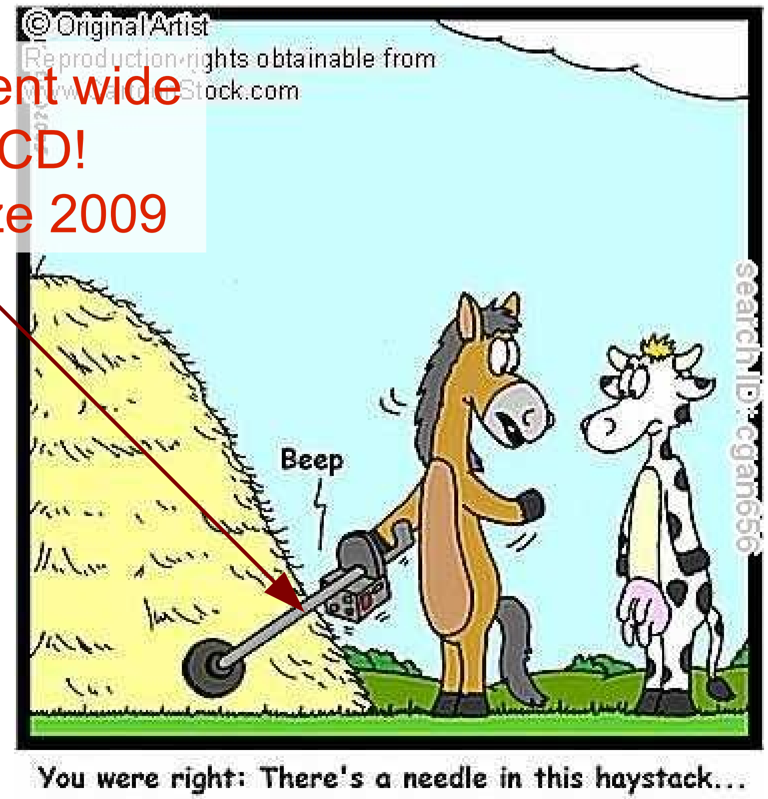
Supernovae and cosmology

- First proposed by Baade and Zwicky
- Bright enough to be seen over cosmological distances

Why did it take so long?!

How to find supernovae?

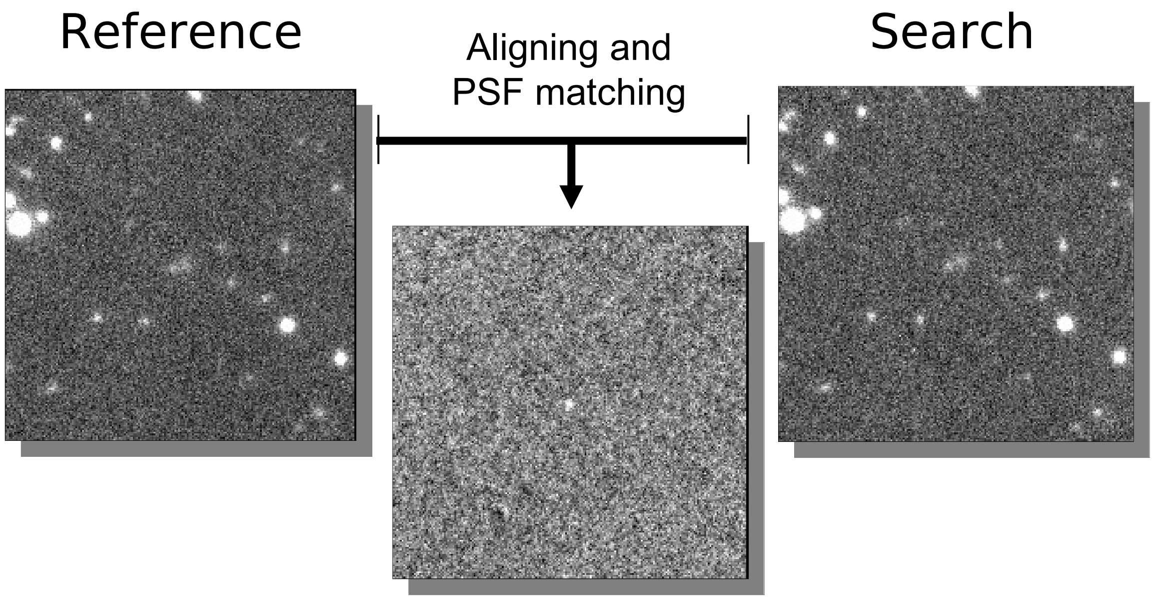
High efficient wide field CCD!
Nobel prize 2009



Time

~1990

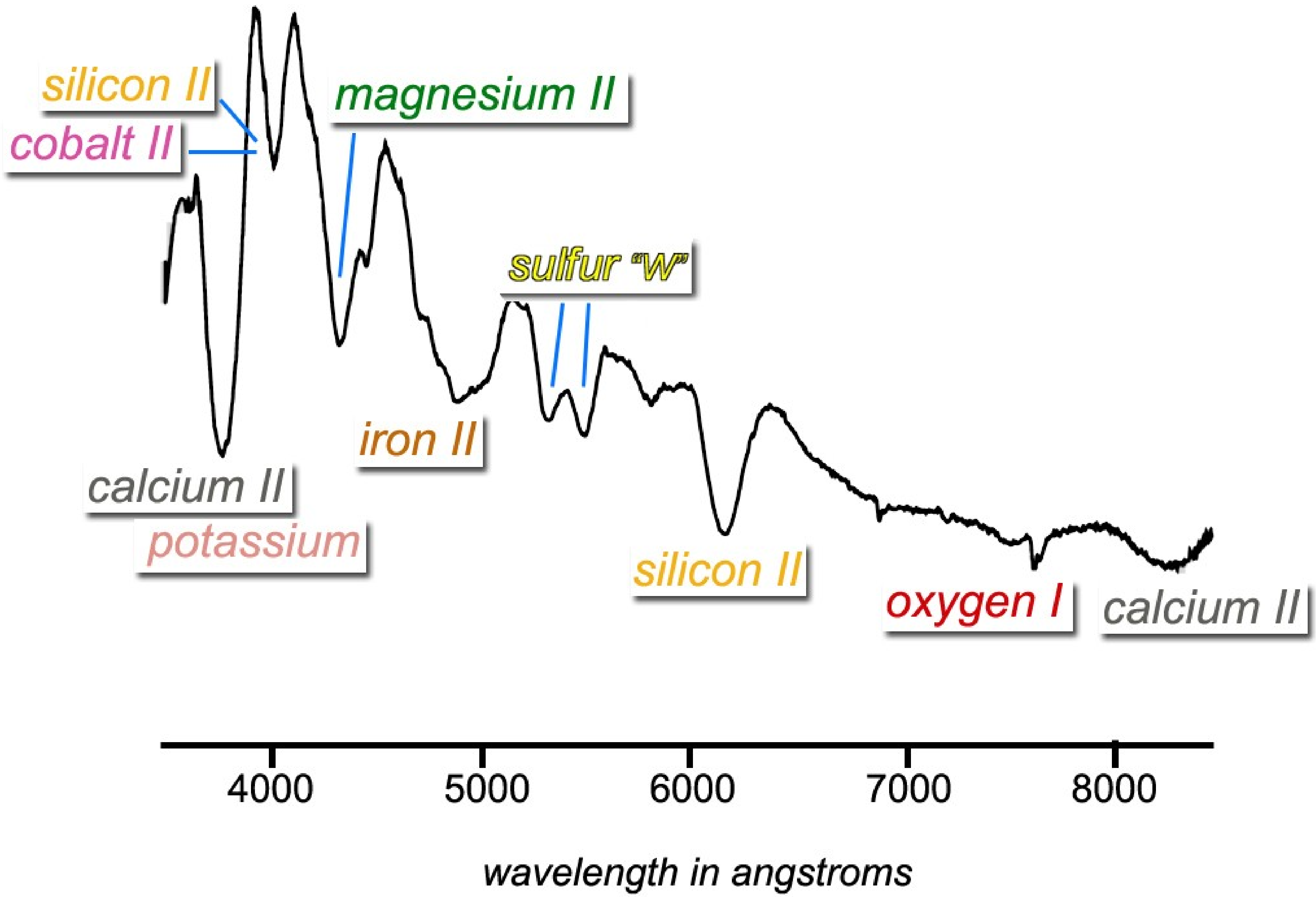
Finding transients and SNe



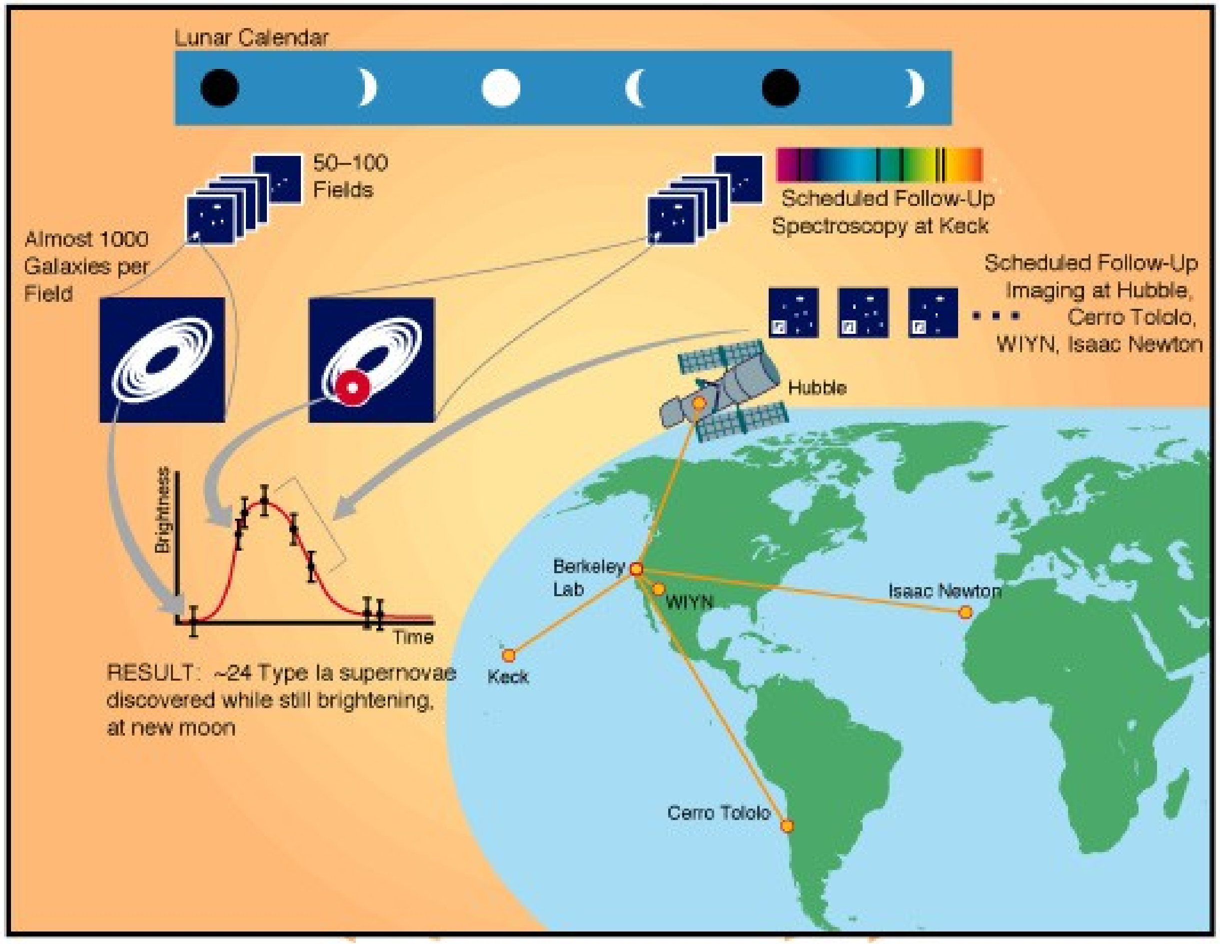
Technique for finding transients since the early 1990's.

First high-z (z=0.31) SN Ia was Danish (Nørgaard-Nielsen et al. 1989)!

What did you find?



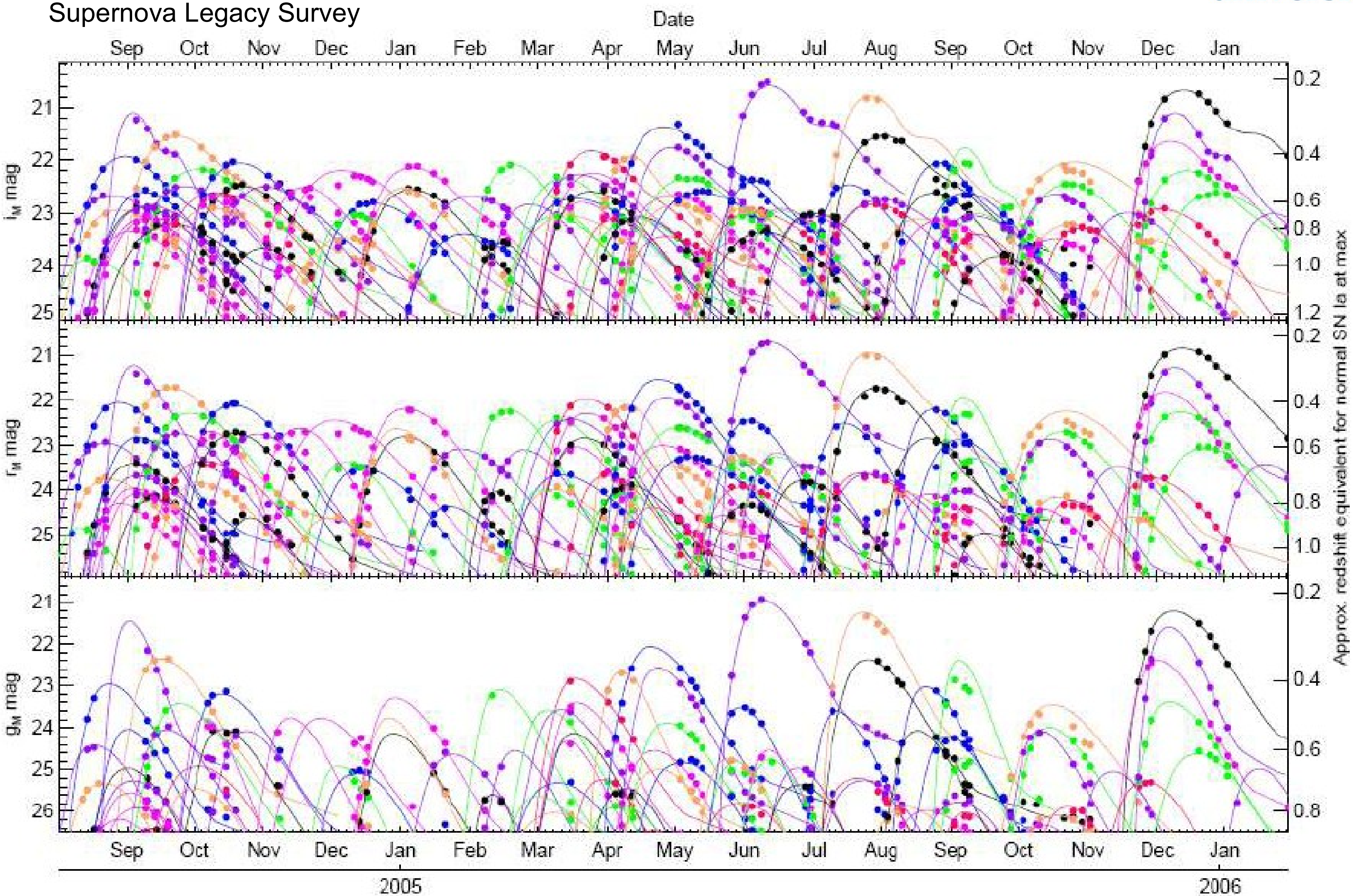
Strategy



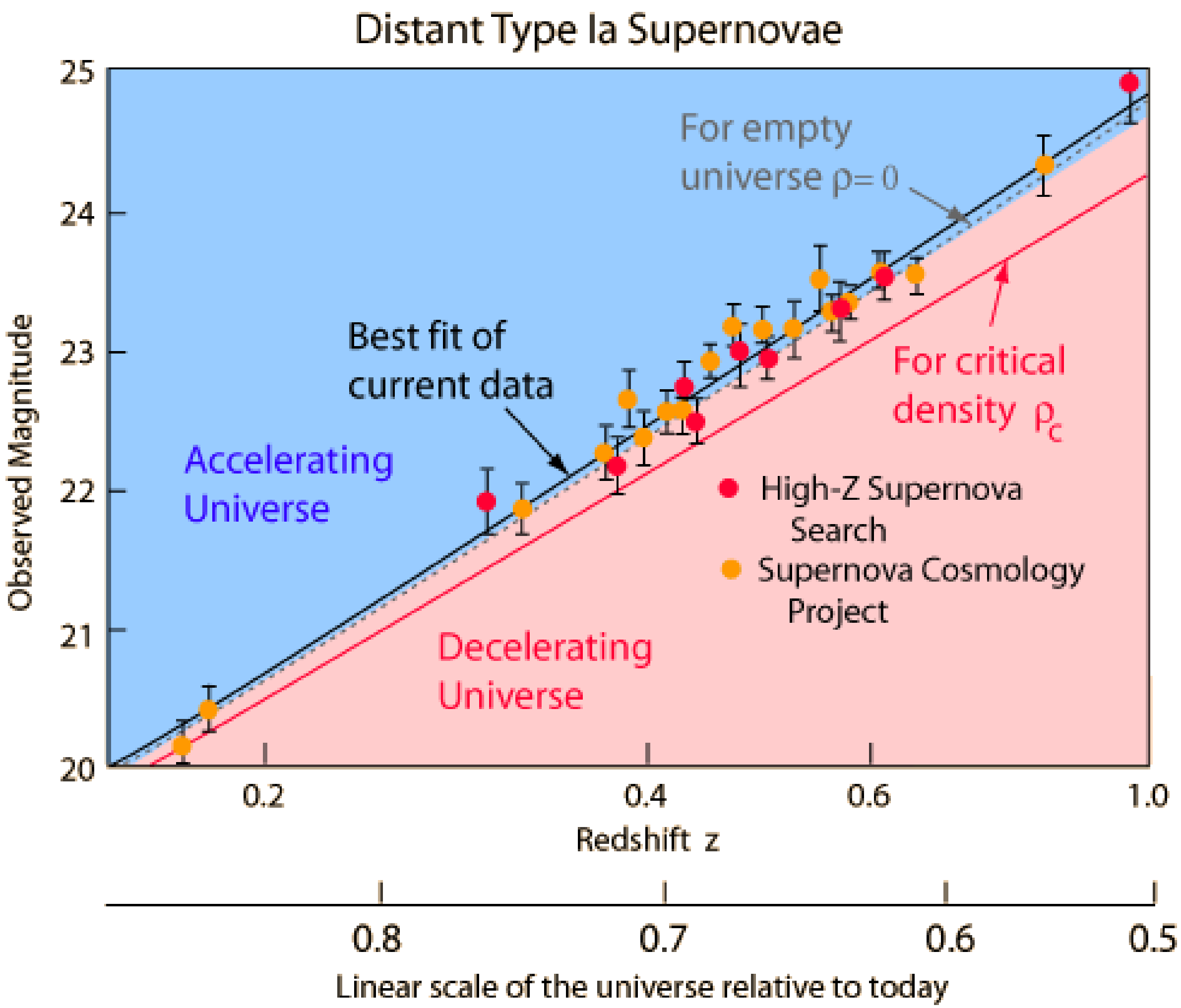
Perlmutter, et al., in Thermonuclear Supernovae, NATO ASI, v. 486 (1997)

Today: “rolling search”

Supernova Legacy Survey



The universe is accelerating (1998)!



Carroll and Ostlie, An Introduction to Modern Astrophysics, 2nd Ed., 2007

Nobel Prize in physics 2011

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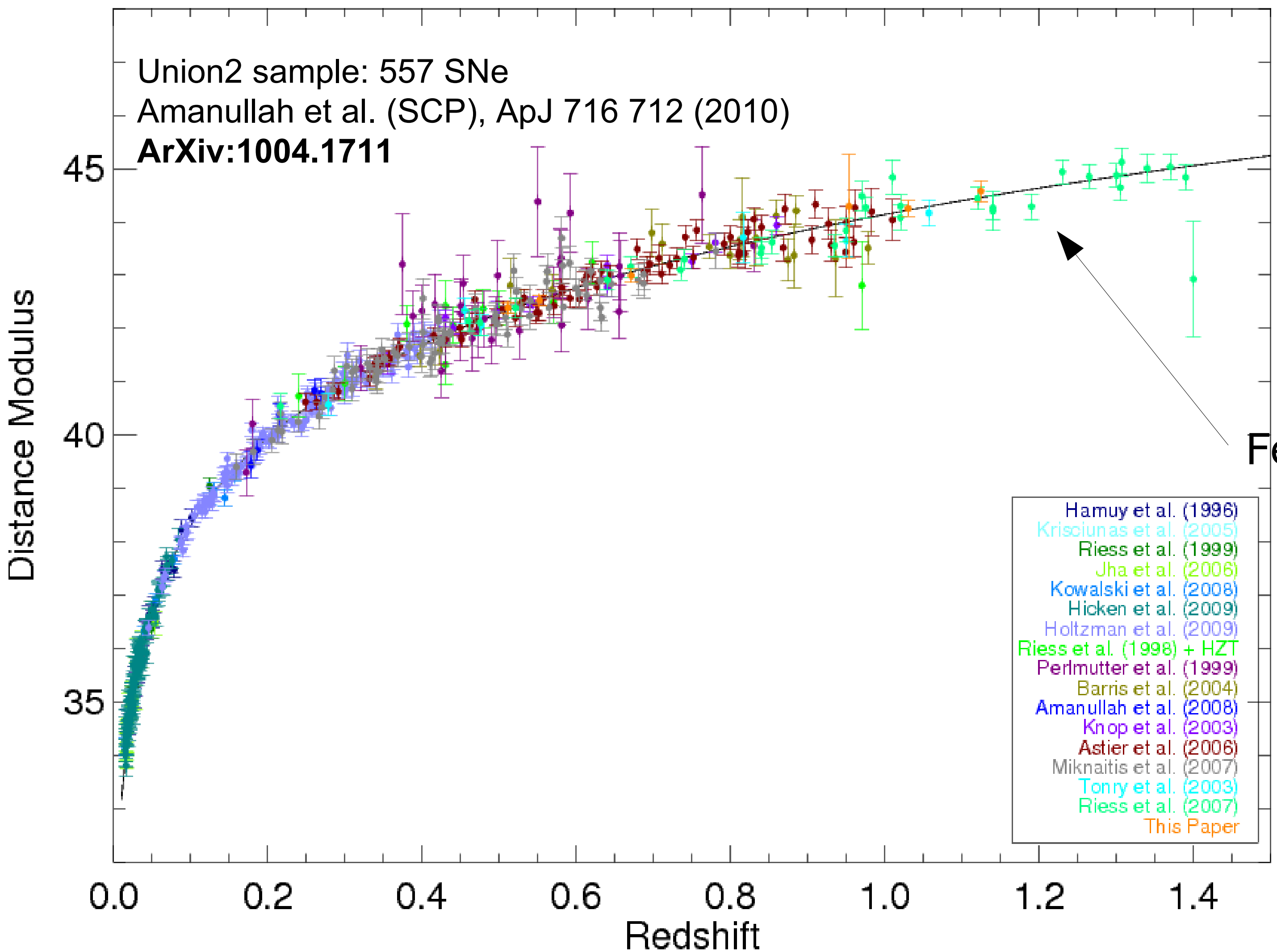
Saul Perlmutter

Brian Schmidt

Adam Riess

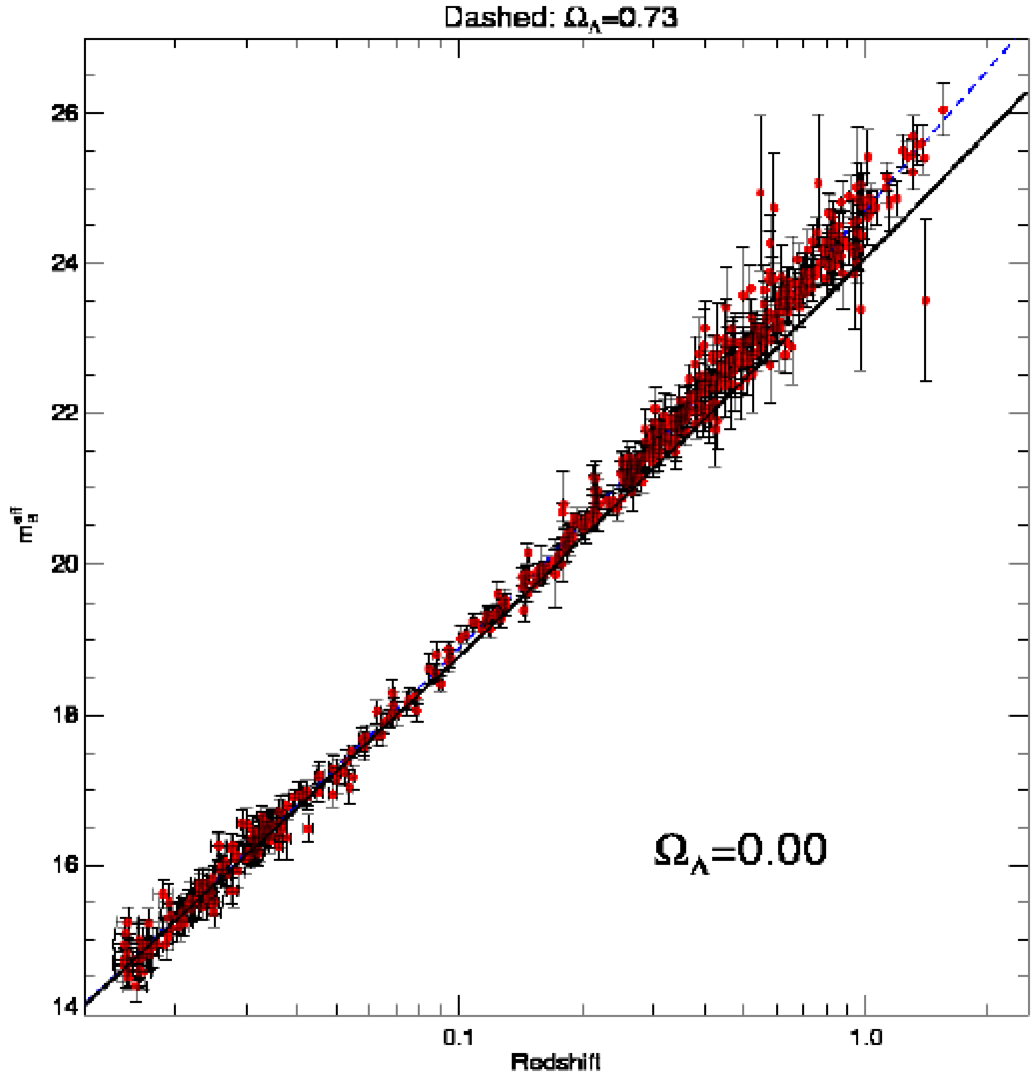
"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"

SN Ia cosmology today, Union2

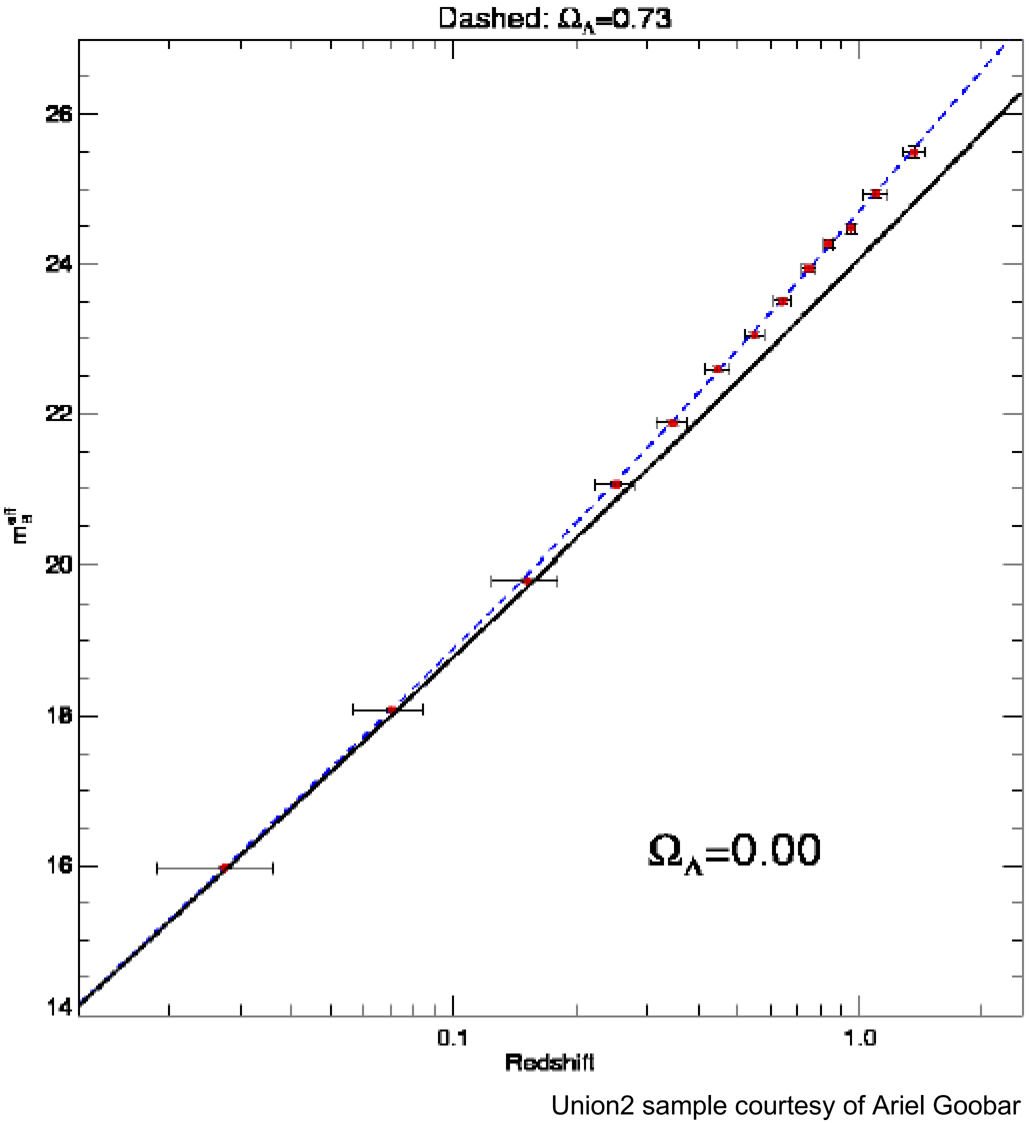


Hubble Space Telescope

Few events at $z > 1$

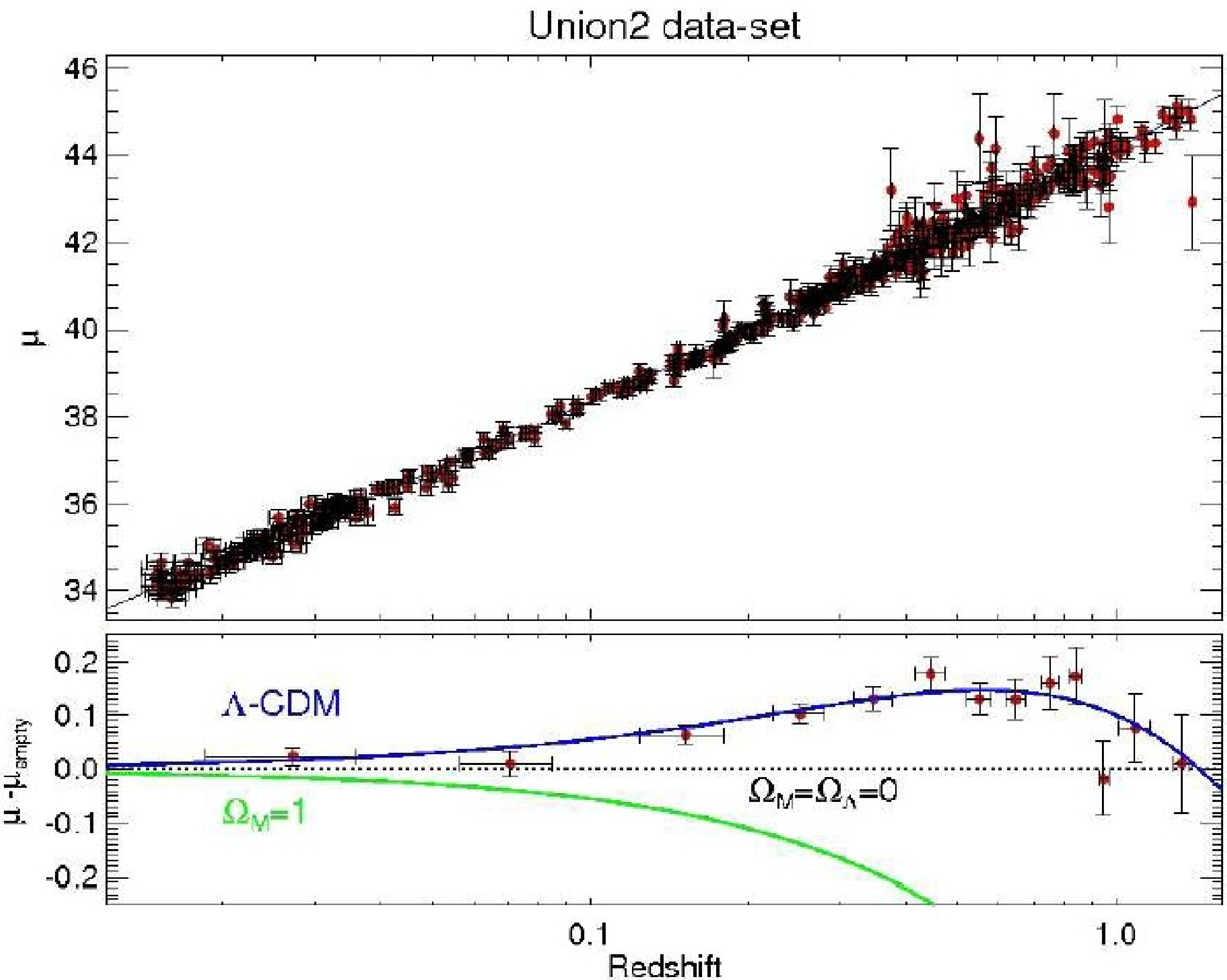


Union2 sample courtesy of Ariel Goobar



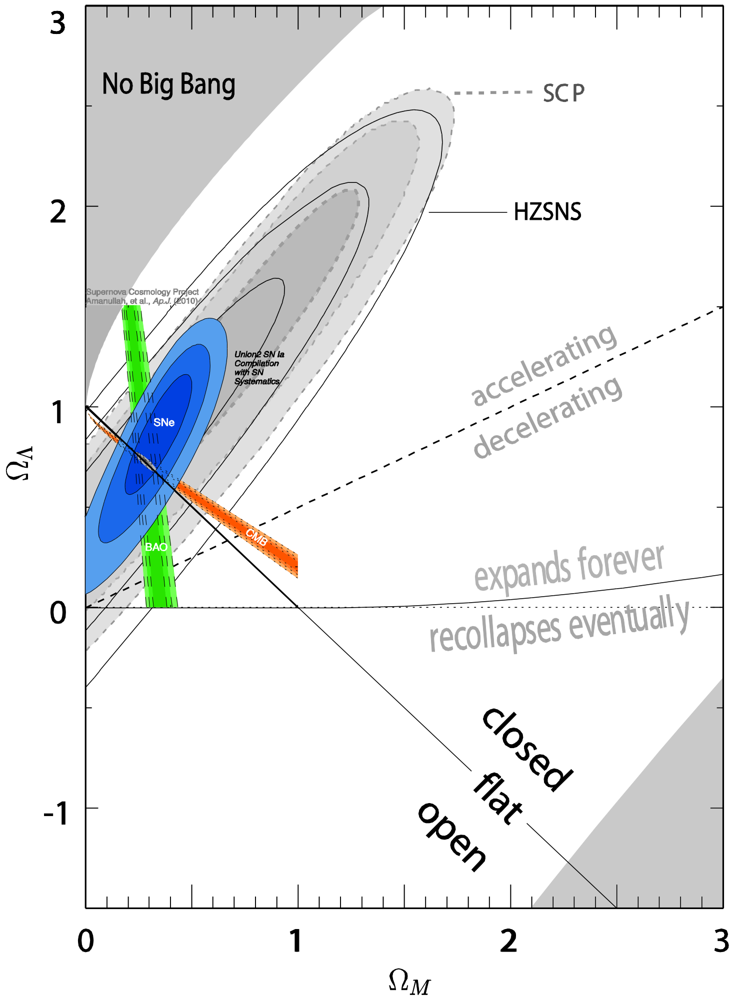
Union2 sample courtesy of Ariel Goobar

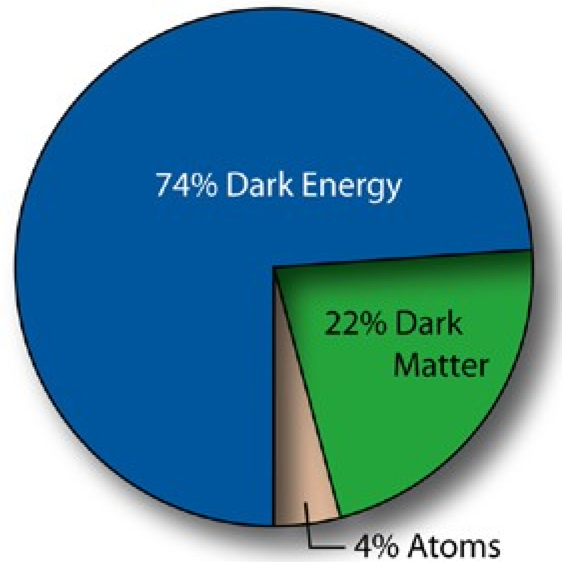
ΛCDM is an excellent fit to the data



Union2 sample courtesy of Ariel Goobar

The energy budget of the universe





See lectures by Hans Kristian & Tomi!

Cosmological constant?

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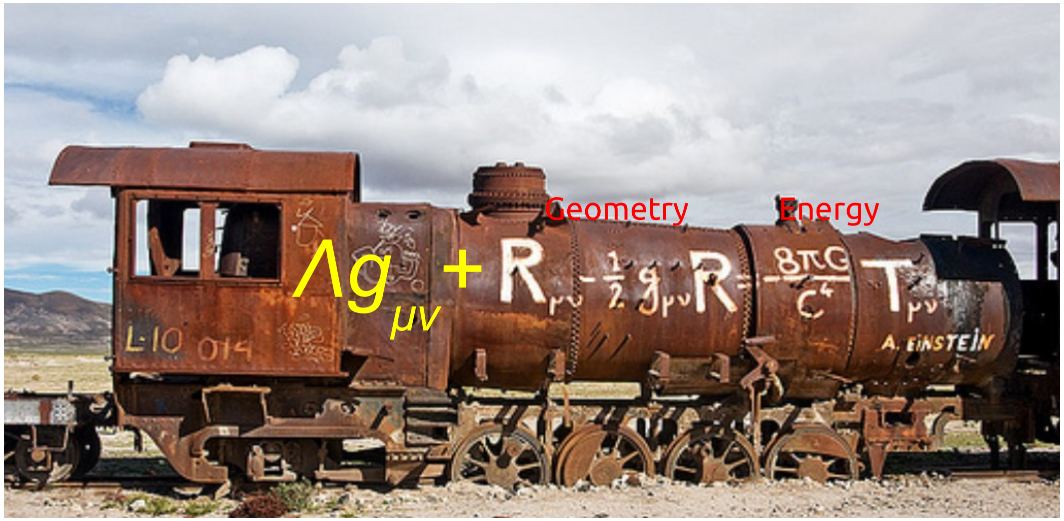
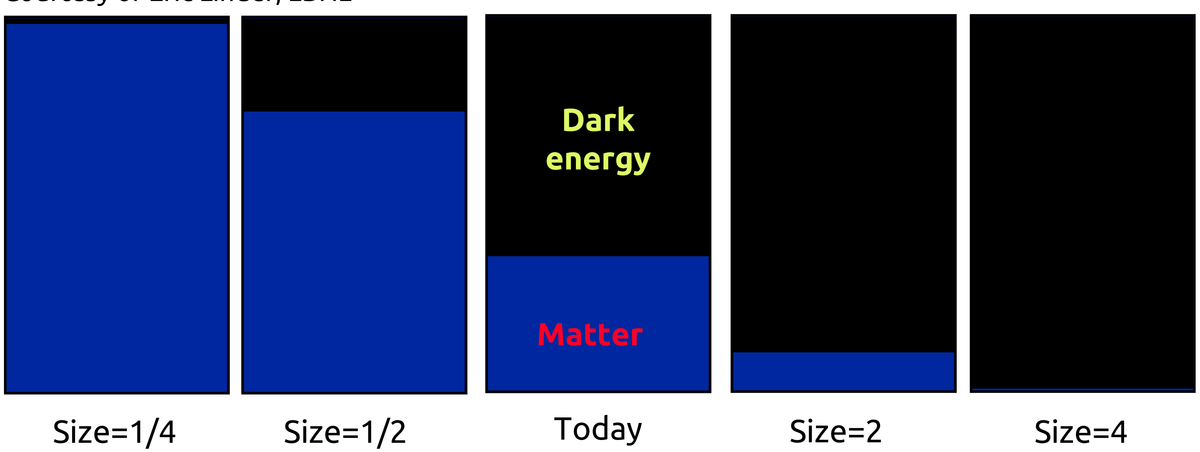


Why is Λ at least 10^{120} times smaller than we would expect?

We think there was an epoch of time varying vacuum once – inflation.

Courtesy of Eric Linder, LBNL



Think of the energy in Λ as the level of the fluid. At most times in history, matter is either drowned or dry.

See Tomi Koivisto's lectures!

What is causing the acceleration?

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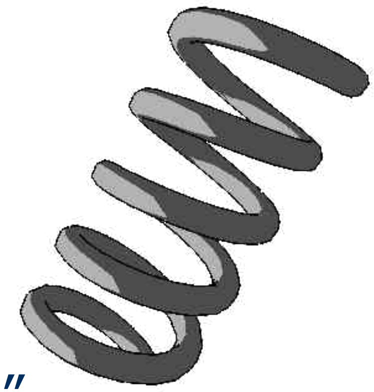

- What could it be?
  - Cosmological constant?
  - Scalar fields?
  - Massive gravity?
  - Extra dimensions?
- Measure the properties of the "missing energy"

$$p = w \cdot \rho$$

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

Constraints on dark energy

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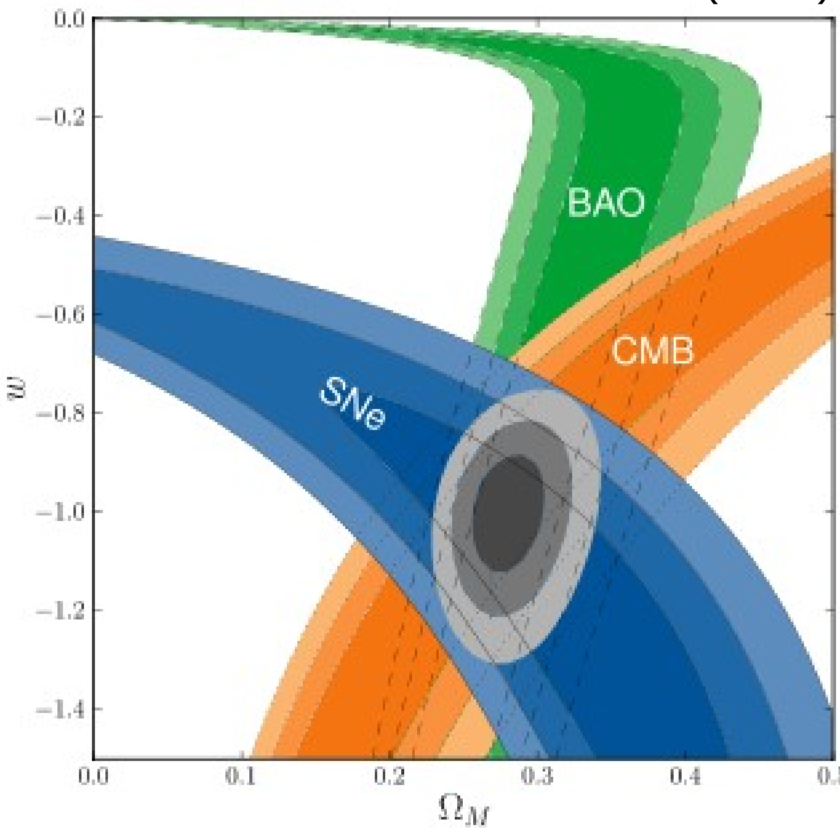
Assuming a time-independent *w* and a flat Universe.

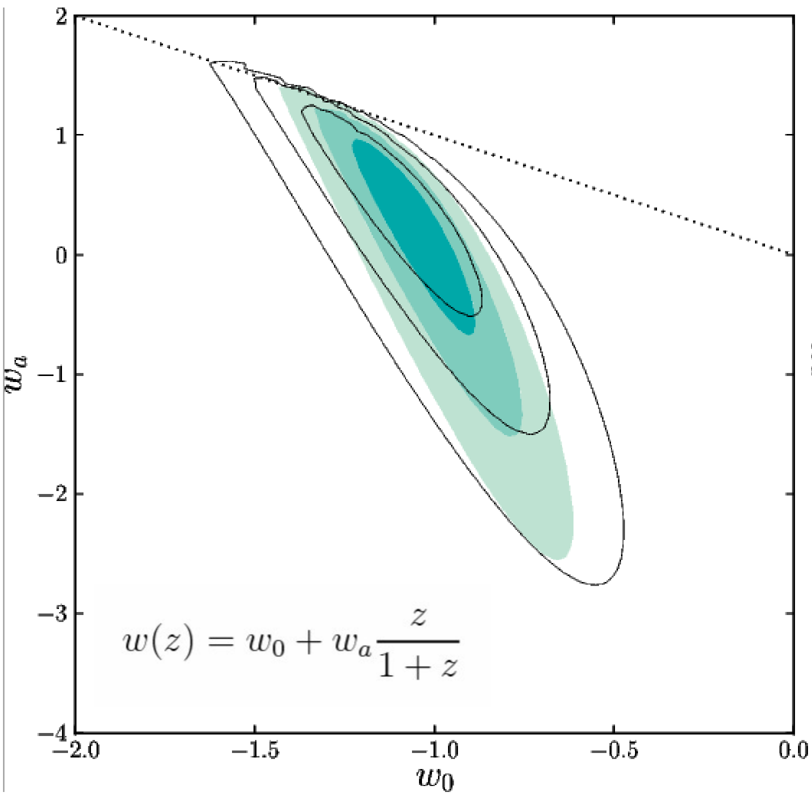
$$w = -0.977^{+0.050(+0.077)}_{-0.054(-0.082)}$$

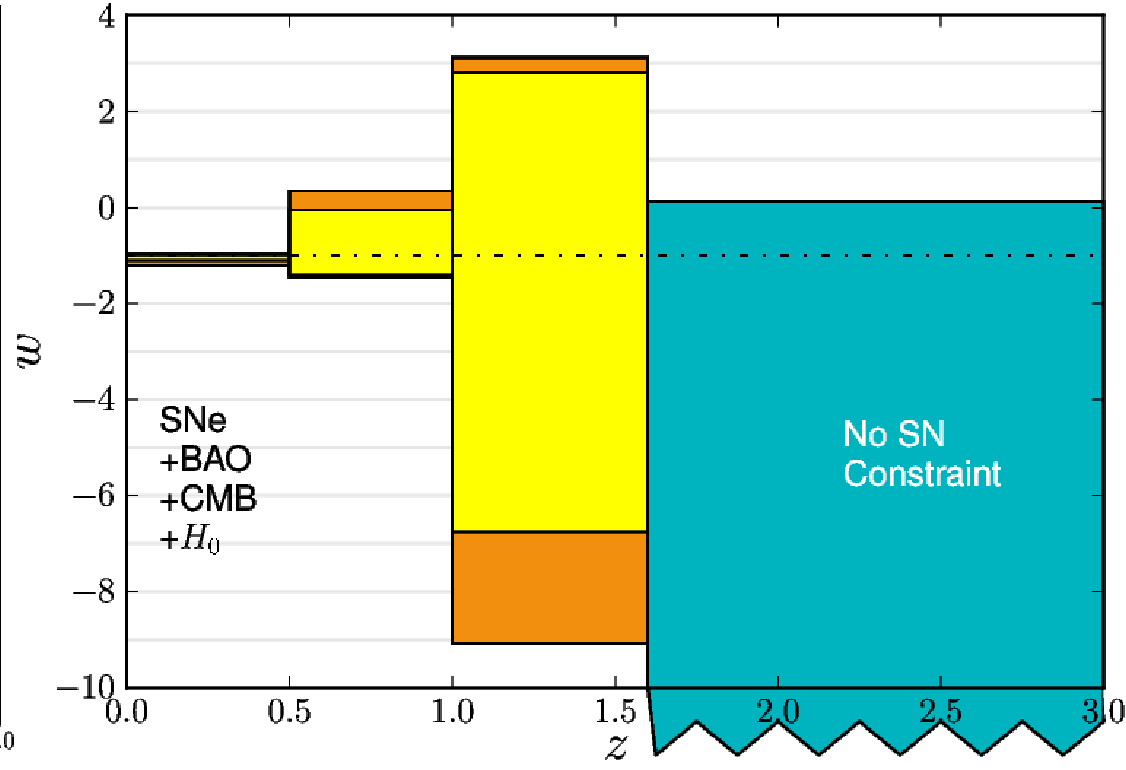
Amanullah et al. (2010)



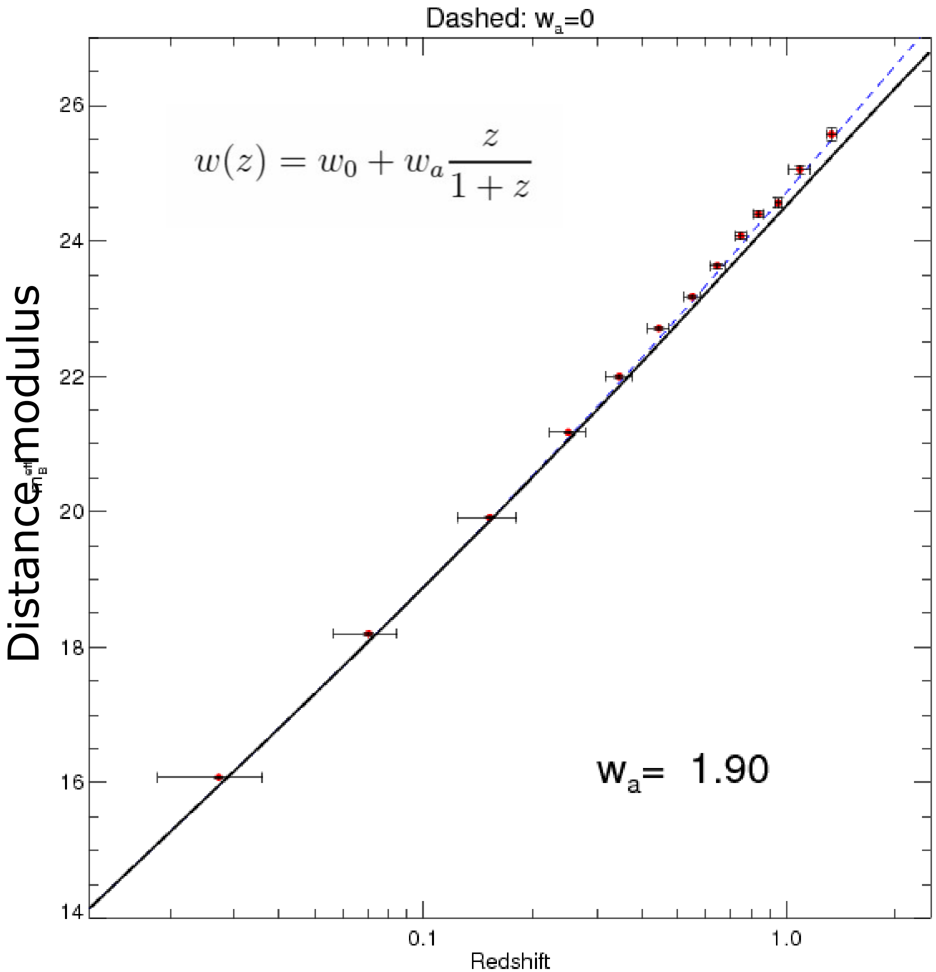
Time-dependent DE equation of state, *w(z)*

Amanullah et al. (2010)





The challenge of SN Ia cosmology

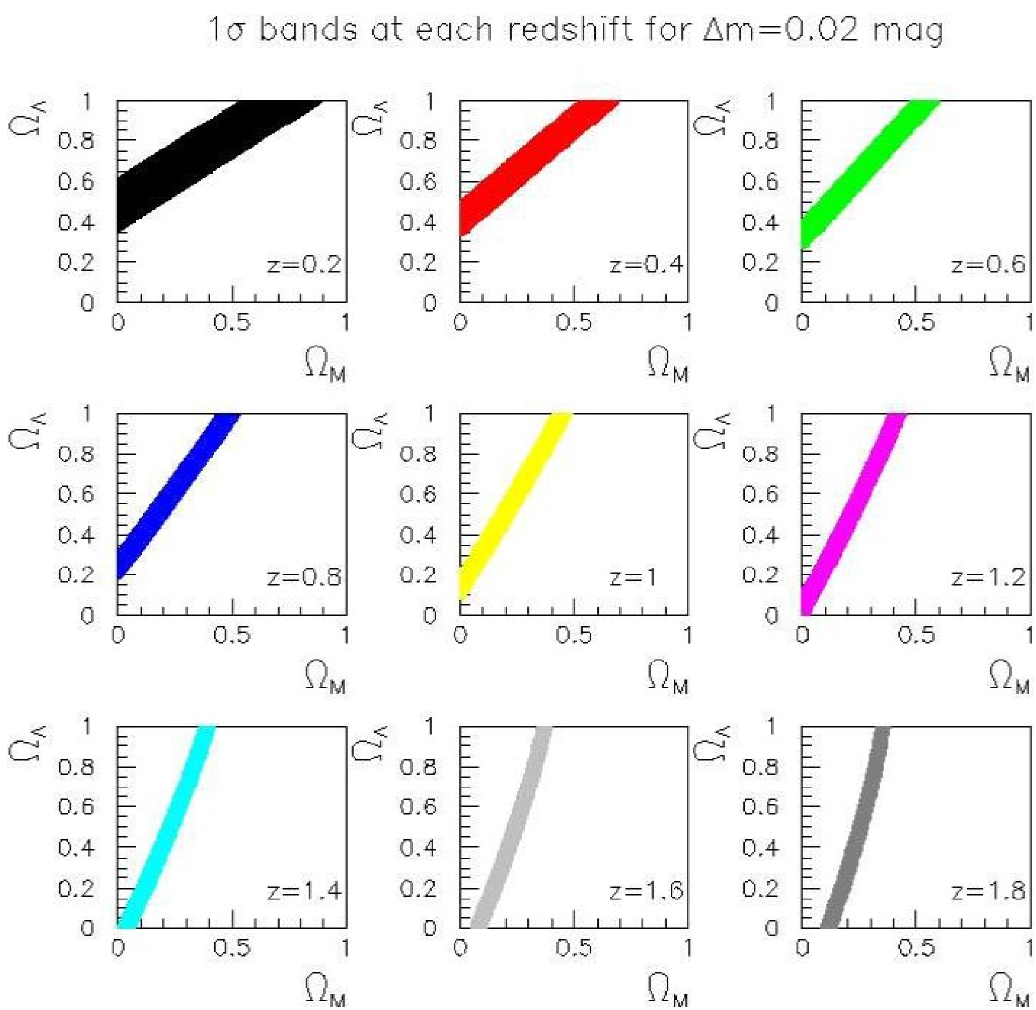


Union2 sample courtesy of Ariel Goobar

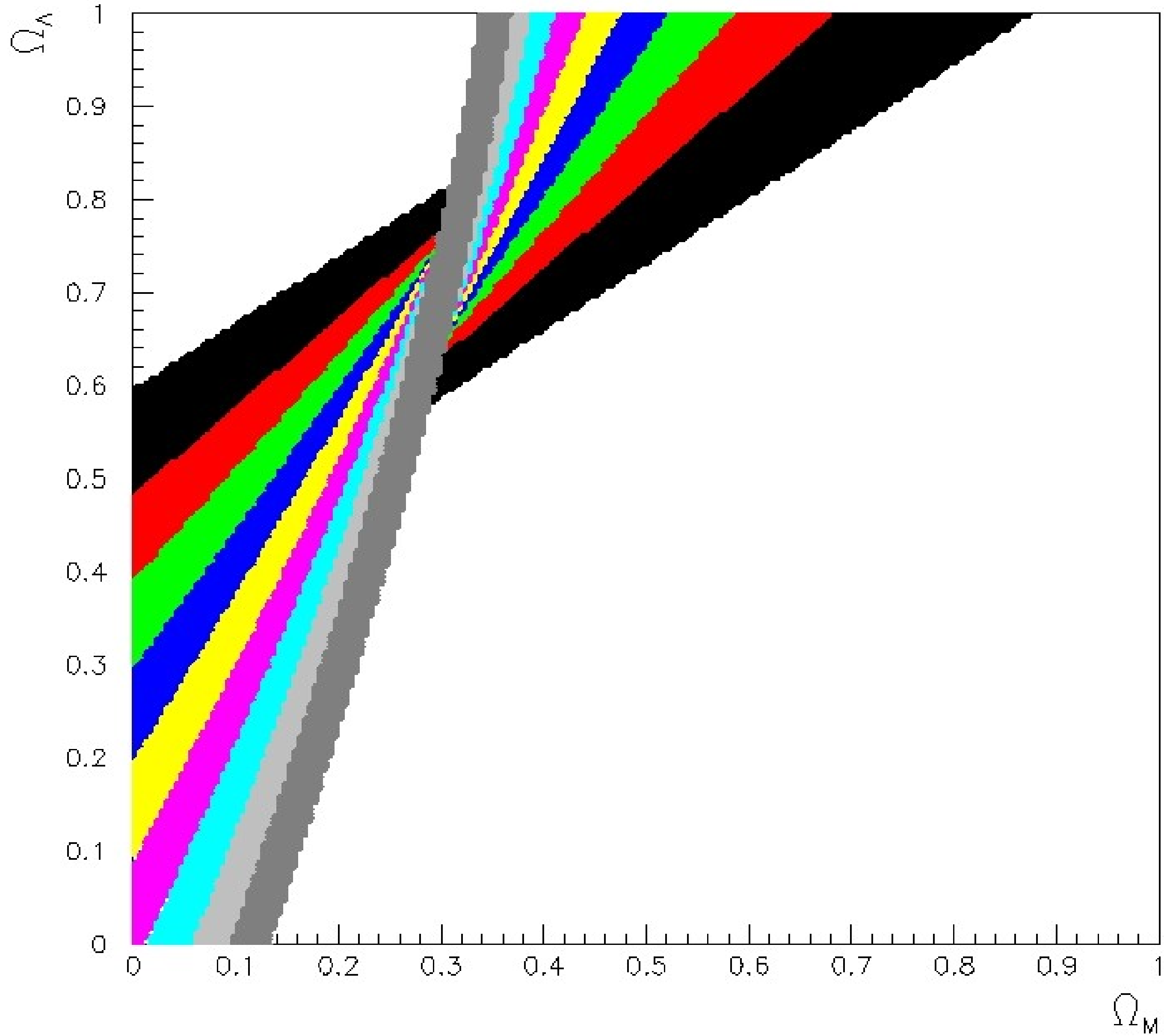
A 5% change in w corresponds to a 1% change in distances out to z=1!

- Improve SNe Ia as standard candles
- Extend observations to higher redshifts
- Reduce systematic errors

Degeneracy between parameters



Goobar & Perlmutter (1995)



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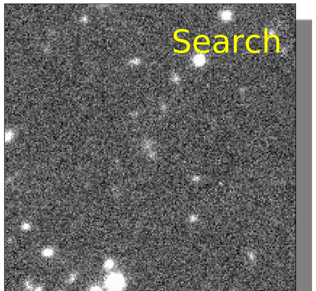
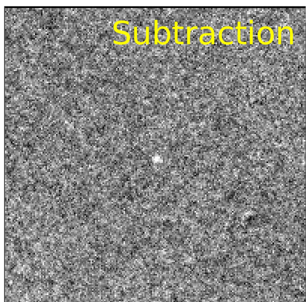
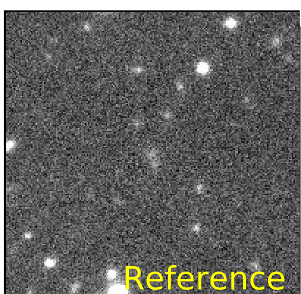
Goobar & Perlmutter (1995)

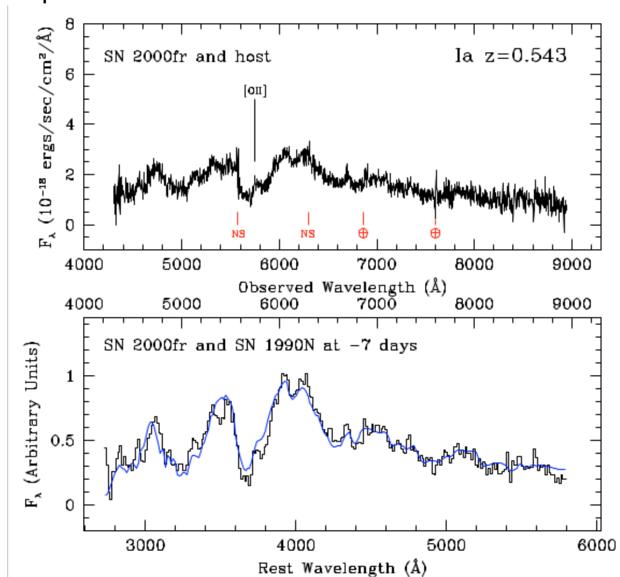
How to win a Nobel Prize



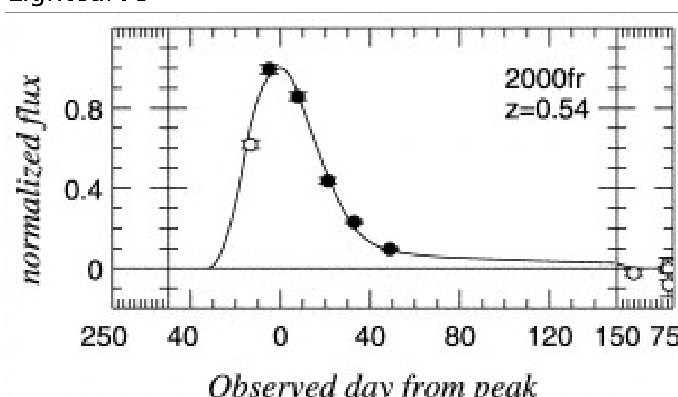




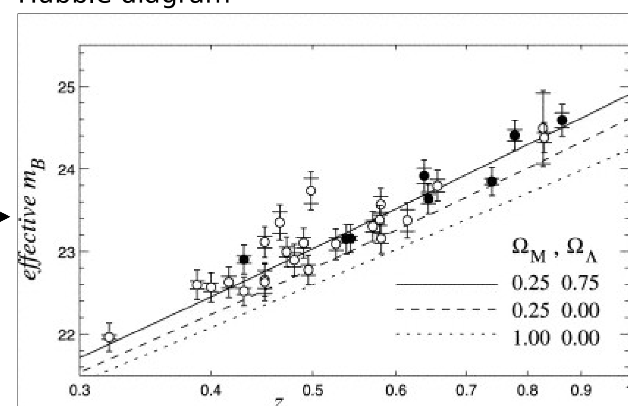
Spectrum



Lightcurve



Hubble diagram



Cosmology fits