PHYS2160 – Lecture 11 – The Distance Ladder - III

Last time

- Discovery of the Universe's expansion
- Measuring Distances & Standard Candles
- The Distance Ladder: Parallaxes ➔ Cepheids ➔ Tully Fisher (for spiral galaxies)

This Time

- Other Distance Indicators
  - Elliptical galaxies – surface-brightness fluctuations
  - Elliptical galaxies – Dn-σ or "Fundamental Plane"
- Supernovae
  - Type Ia supernovae and their use in cosmology.

Mid-term Exam will take place in **that room** (OMB230) next Wed, Sep 3 at 3pm.

- It will start at 3:05pm.
- It will be closed book and last 50 minutes.
- You will leave your bags (including mobile phones & other computing devices) at the front of the room and spread about the room to the maximum extent allowed.
- Exam booklets will be provided.
- You may use a scientific calculator.

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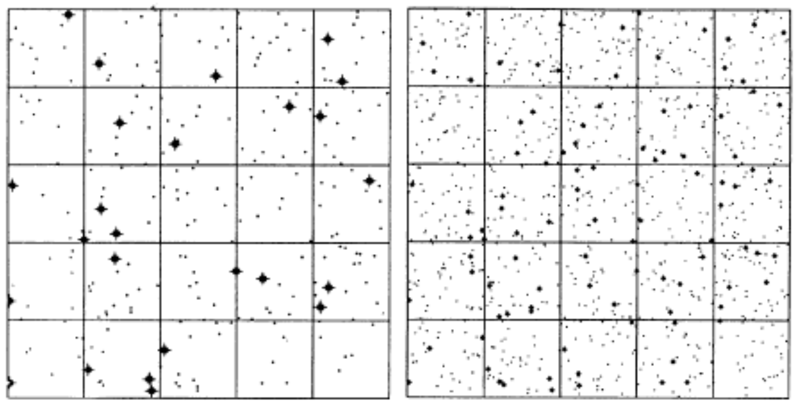
More Ladders – Elliptical galaxies – Surface-Brightness fluctuations

The technique (first proposed by John Tonry in the late 1980s) makes use of the fact that galaxy images will contain a finite number of stars per pixel, and that this number will vary from pixel-to-pixel, creating a noise-like fluctuation in the surface brightness distribution.

- The flux received from an elliptical galaxy is proportional to the distance as $1/r^2$.
- But the number of stars per pixel is proportional to the distance as r^2.
- Thus the surface brightness (the total flux received per pixel, or in this case flux per star times the number of stars) is independent of distance.
- But there is a difference between the nearby and faraway case – the more distant elliptical will look twice as smooth (i.e. the fluctuations between pixels will be smaller).

Thus by comparing the “smoothness” of two elliptical galaxies (one with known distance), using normalized fluxes (so they have both the same flux per pixel), one can obtain the distance of the other galaxy.

“Smoothness” will scale as $\sqrt{N}/N = 1/\sqrt{N} \equiv 1/\sqrt{d}$



Two example galaxy fields with the same surface brightness, but sampled at distances different by a factor of 2.   Jacoby et al. 1992, PASP, 104, 599

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Another Ladder – Supernovae

Supernovae are observationally classified into multiple classes, which (in the main) are considered to arise from different physical causes.

- SN Type II - the SN spectrum contains lines of hydrogen
- SN Type I - the SN spectrum contains no lines of hydrogen
  - SN Ia – spectrum has an Si II absorption line at 615nm near maximum
  - SN Ib – weak or no SiII, and shows a He I line at 587.6nm
  - SN Ic – weak or no SiII, and shows weak or no He

These types are *taxonomic* – i.e. they arise form observable differences*. But what do they mean?*

- All SNe except Ia are thought to arise from "core collapse" – when nuclear fusion suddenly become unable to sustain a star's core against its own gravity.
- Stars more massive than about $10M_\odot$ will develop an iron core larger than the Chandrasekhar limit (i.e. a gravitationally unstable mass large enough ($\gtrsim 1.4M_\odot$) that electron degeneracy pressure is unable to stop the core from collapsing into a neutron star or black hole).
- When a core is unable to gravitationally support itself it will collapse at speeds reaching up to >0.2c.
- For progenitor masses below about $25M_\odot$ the core's collapse will rapidly halt as it forms a neutron star (i.e. neutron degeneracy pressure eventually supports the core). The resulting "bounce" coverts up to 10% of the star's mass into neutrinos, as well as a blastwave that propagates out through the remaining stellar envelope.

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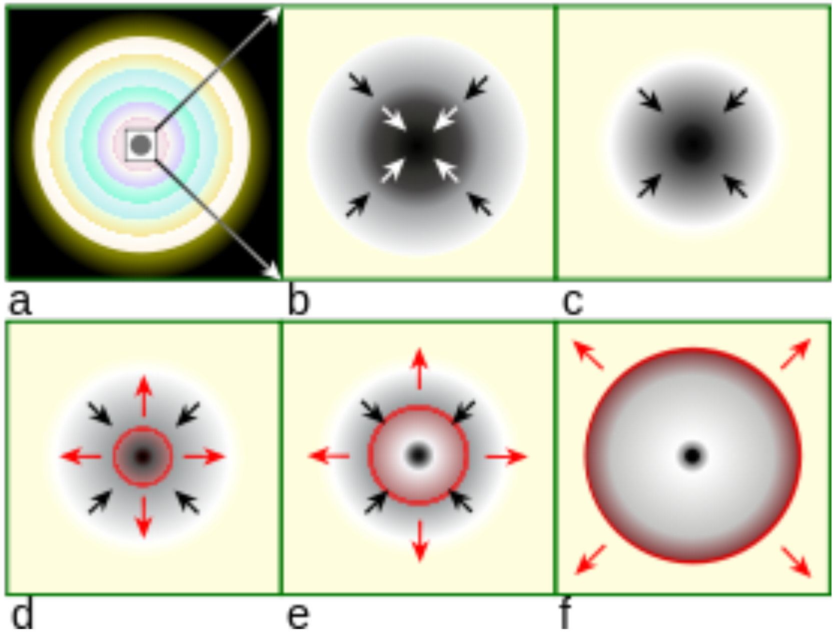
Supernovae

It is this blast that produces the vastly energetic explosion that we classify as SNe. (Current models predict a variety of variations on this theme of core collapse for masses above $25M_{\odot}$).



SN Type II - Within a massive, evolved star (a) the layered shells of elements undergo fusion, forming an iron core (b) that reaches the Chandrasekhar mass and starts to collapse. The inner part of the core is compressed into neutrons (c), causing infalling material to bounce (d) and form an outward-propagating shock front (red). The shock starts to stall (e), but it is re-invigorated by a process that may include neutrino interaction. The surrounding material is blasted away (f), leaving only a degenerate remnant.

(Note: The Chandrasekhar mass is the maximum core mass which can be supported against gravitational collapse by electron degeneracy pressure – two fermions cannot occupy the same quantum state, so in a dense sea of fermions (e.g. electrons) a repulsive force manifests as a pressure against the compression of matter into smaller volumes. Above the Chandrasekhar mass protons and electrons combine (via electron capture) to make neutrons. The corresponding neutron degeneracy liming mass is much larger, and poorly understood. Above this limit, the core will collapse into a black hole).

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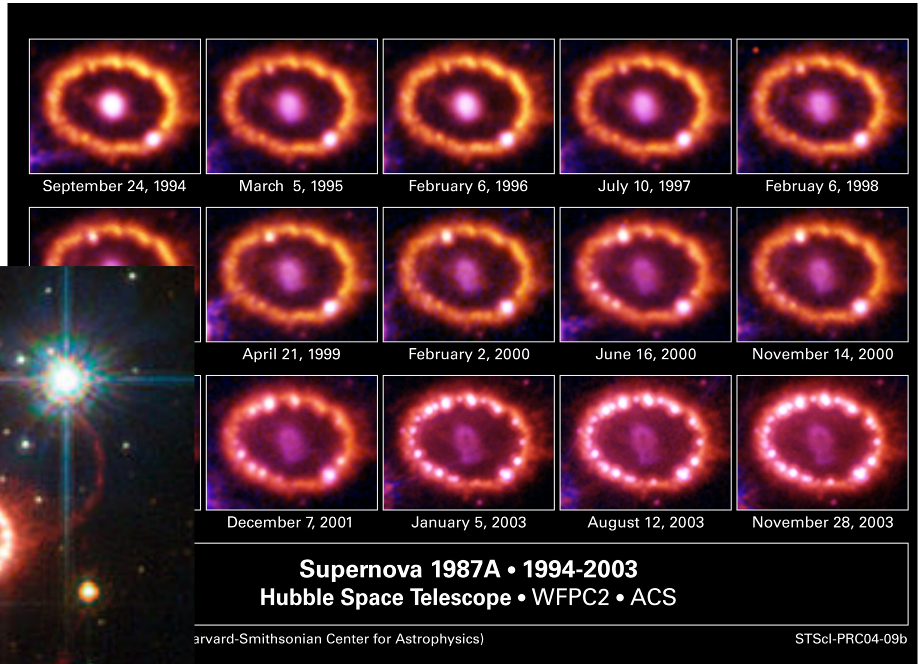
Supernovae – Type II

SN1987a exploded in the LMC on Feb 23-24 1987. Progenitor is though to have been an $18M_{\odot}$ B star. This very nearby SN is the only one for which the neutrino burst has been detected.



Because the neutrino burst *precedes* the emergence of optical radiation it was detected by looking *back* through neutrino detector data after the SN was discovered visually.

The "rings" are previously ejected material form the star being "lit up" over time by the blast wave from the SN.

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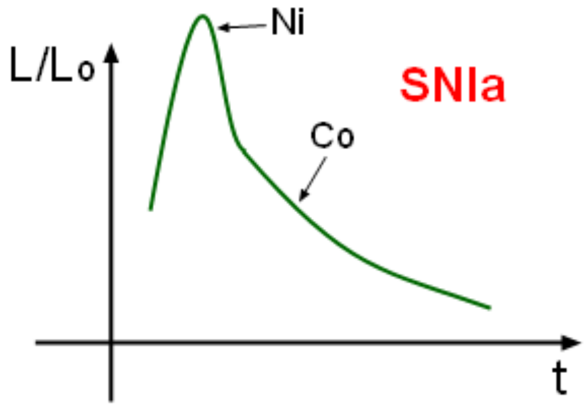
Supernovae – Type Ia

Except for SNe Ia – these SNe are thought to form via a variety of processes, all of which lead to matter being accreted onto a C-O (carbon-oxygen) white dwarf, such that nett mass exceeds ~$1.4M_{\odot}$. This much mass cannot sustain itself via electron degeneracy pressure and so the white dwarf will begin to collapse.

However, since this is a C-O white dwarf, this collapse generates the pressures and temperatures required to initiate C burning, and within a few seconds a substantial fraction of the matter in the white dwarf will undergo fusion, releasing sufficient energy to unbind the star. An expanding shock wave is generated, expelling material at up to 0.03c.

Type Ia SNe display a characteristic light curve after their explosion. This luminosity is generated by the radioactive decay of ^{56}Ni through ^{56}Co to ^{56}Fe. (The Ni is generated from Si burning in explosion; Si➔S➔Ar➔Ca➔Ti➔Cr➔Fe➔Ni; which itself follows O burning, which follows Ne burning, which follows C burning).



Amazingly, the peak luminosity of the light curve is extremely consistent across normal Type Ia SNe, having a maximum absolute magnitude ~ −19.3. This allows them to be used as a secondary standard candle to measure the distance to their host galaxies.

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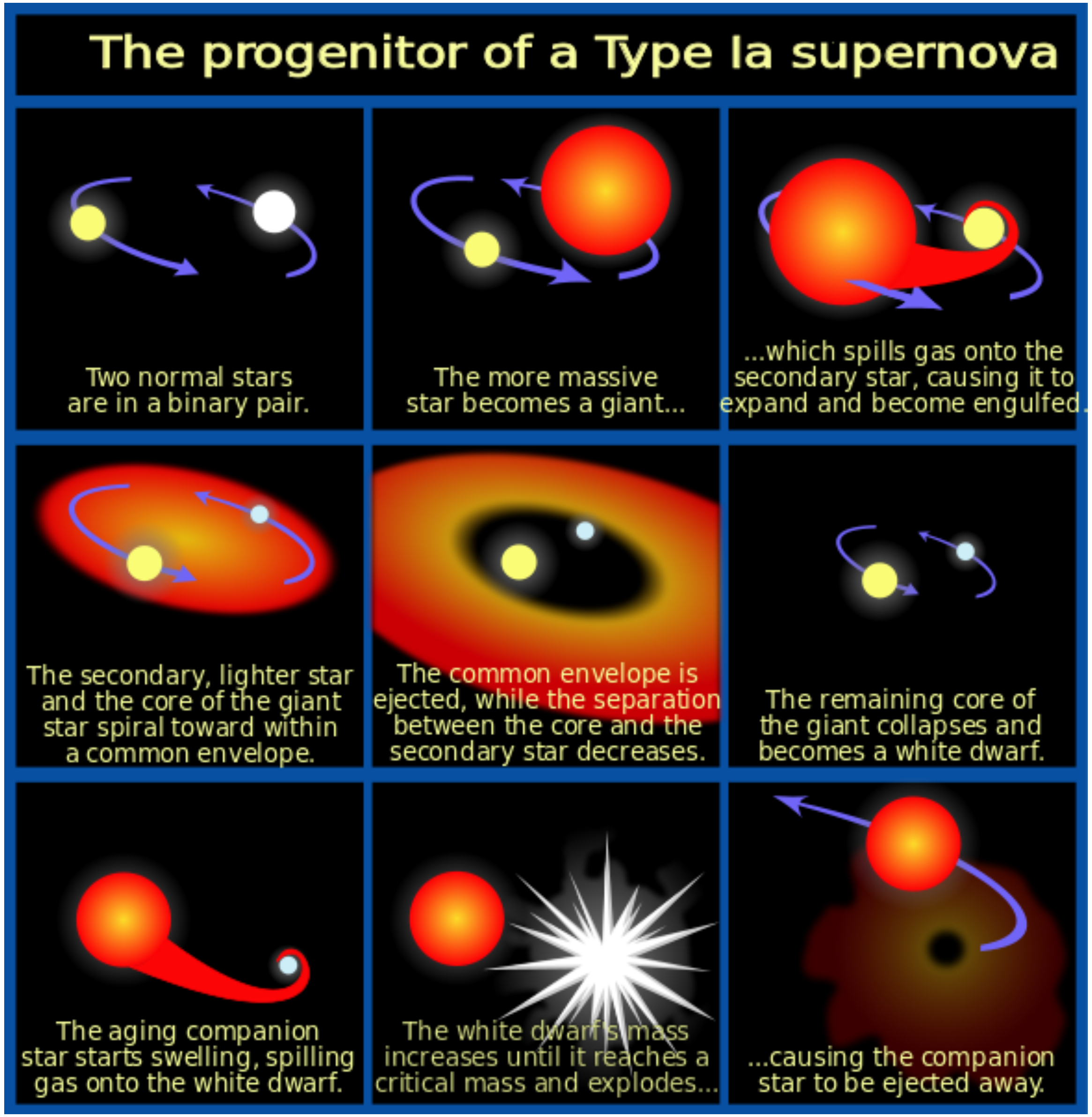

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Supernovae – Type Ia as Distance Indicators

Actually using SN Ia as a distance indicators, however, is just a little more complicated than this simple picture. The galaxy in which the SN resides may host dust which lies between us and the SN, which will (a) redden the light curve and (b) produce a fainter maximum luminosity.

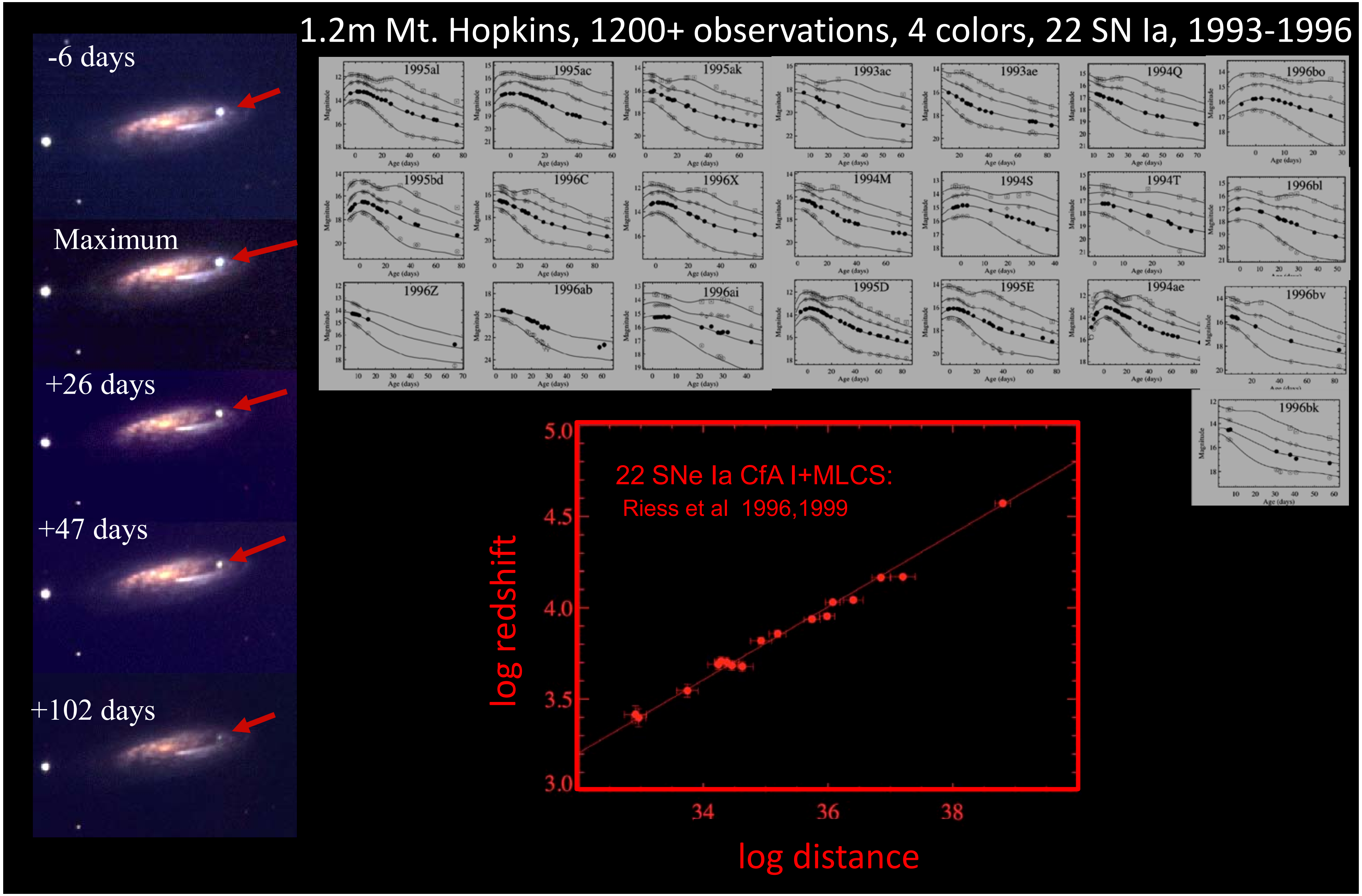
In the 1990s two teams were working hard at the problem of how to calibrate Ia Sne (a team led by Saul Perlmutter at Berkeley, and the High-Z team led by Brian Schmidt and Adam Riess).

As their analysis techniques developed, it turned out that Ia SNe really were remarkable distance indicators. And because a SN is a **very** bright event, it makes distance measurement at much larger distances feasible. Indeed all the way out to z=1 and beyond (equivalent to v=300,000km/s which is ~4300Mpc if we think H_0 is 70km/s/Mpc).

This is a sufficiently large distance that it becomes feasible to look for **changes** in the Hubble constant with time/distance, and so to probe the cosmology of our Universe.

Multi-Colour Light Curve Shapes (MCLS)

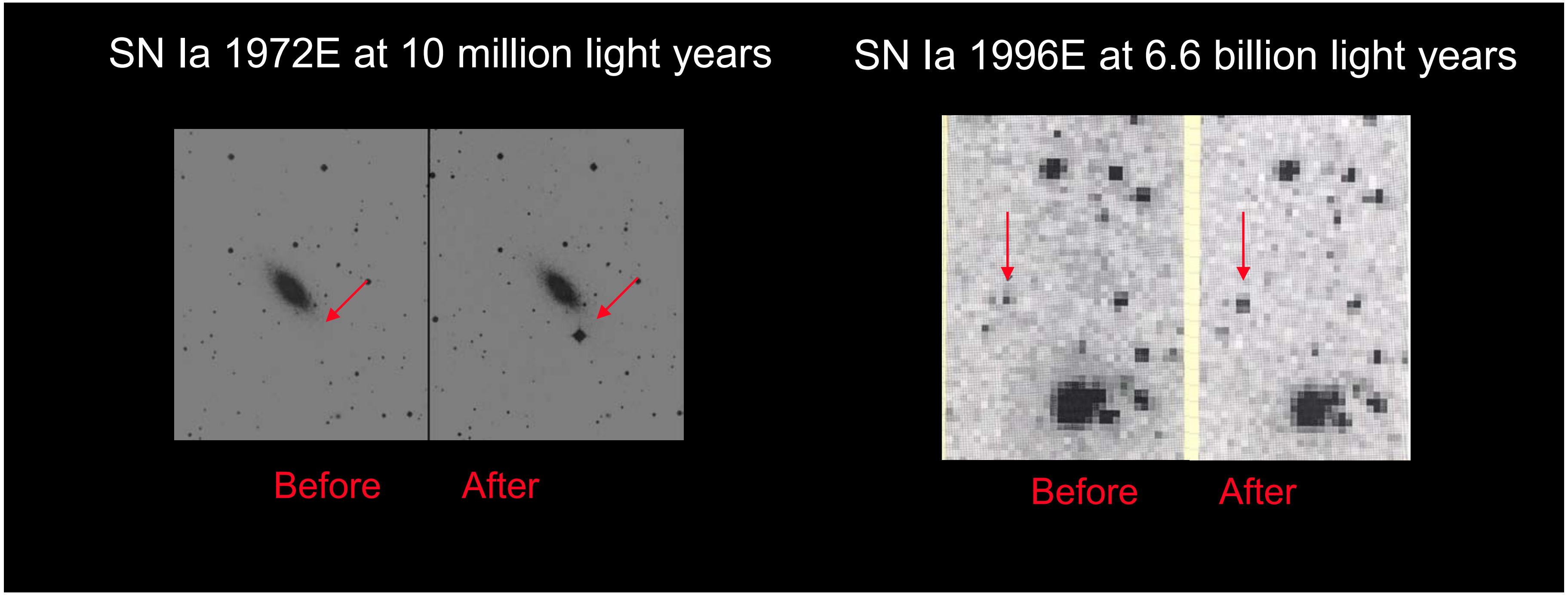
(Slide from Adam Reiss' Nobel Lecture 2011)



Multi-Colour Light Curve Shapes (MCLS)

(Slide from Adam Reiss' Nobel Lecture 2011)

Though at large distances, these observations become very challenging!



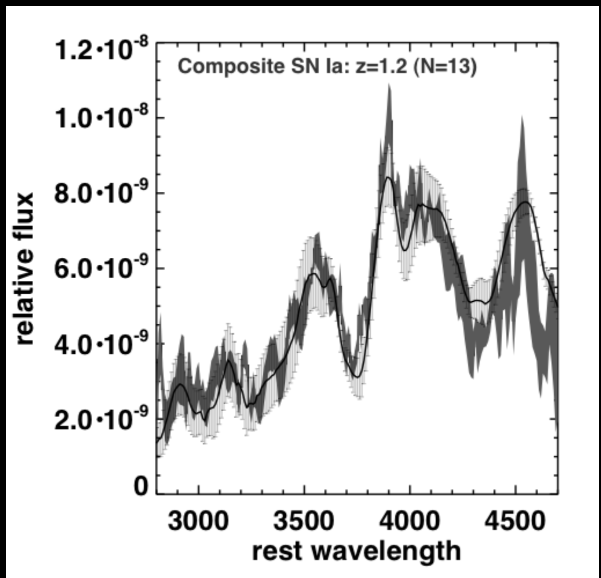
(Recall ly ~ 3.3pc, so 6.6 Gly is ~2000Mpc)

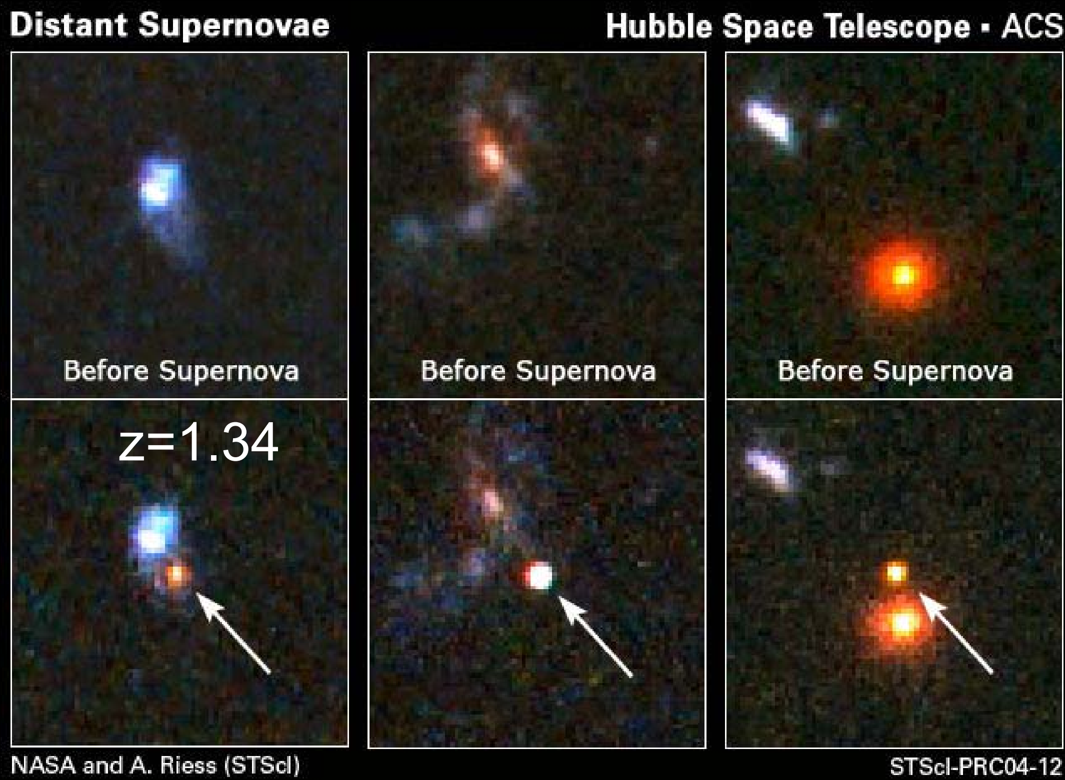
High-Z Type Ia

(Slide from Adam Reiss' Nobel Lecture 2011)

HUBBLE SPACE TELESCOPE

- In 2002 Astronauts install ACS
- From 2002-2007 the *Higher*-z Team measured 23 new SNe Ia at z>1





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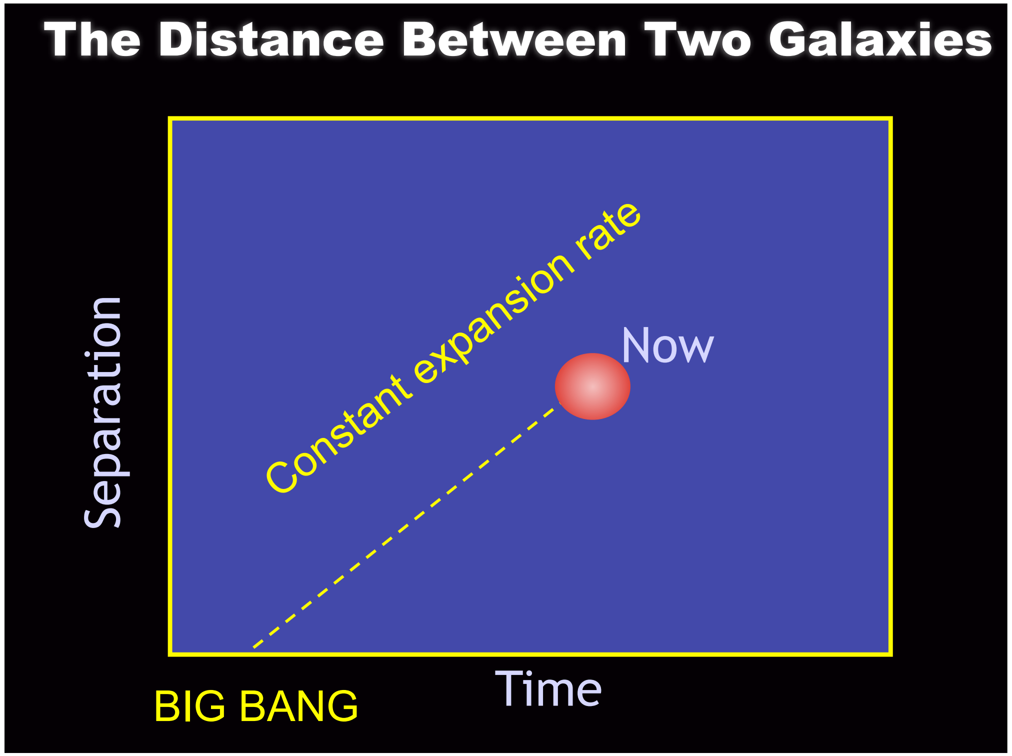
Interpreting Type Ia SNe Distances

Imagine we probe the evolution of the Universe by measuring the distance between two galaxies today. If the Universe has been expanding at a constant rate, then we can extrapolate back to when that scale was zero to determine when the Big Bang was (as we did earlier).



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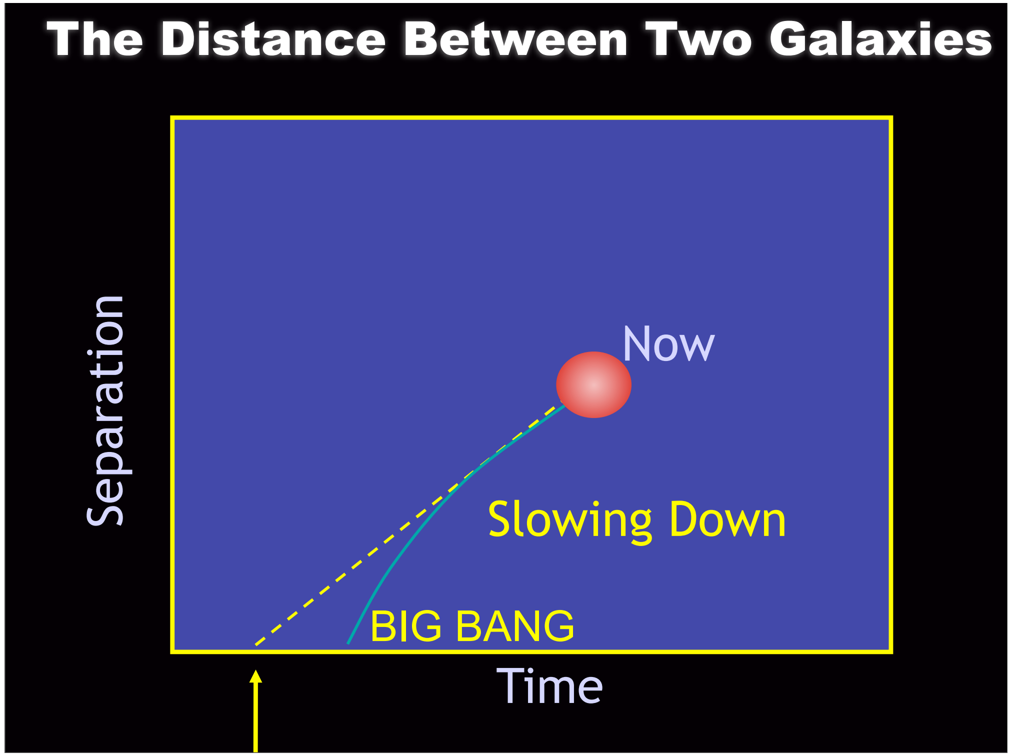
Interpreting Type Ia SNe Distances

But if the expansion is not constant (e.g. if it is slowing down – which is what we believe is happening because the presence of baryons and dark matter in the Universe will tend to slow the expansion), then the Big Bang will have happened more recently than the simple linear extrapolation of H_0 predicts.



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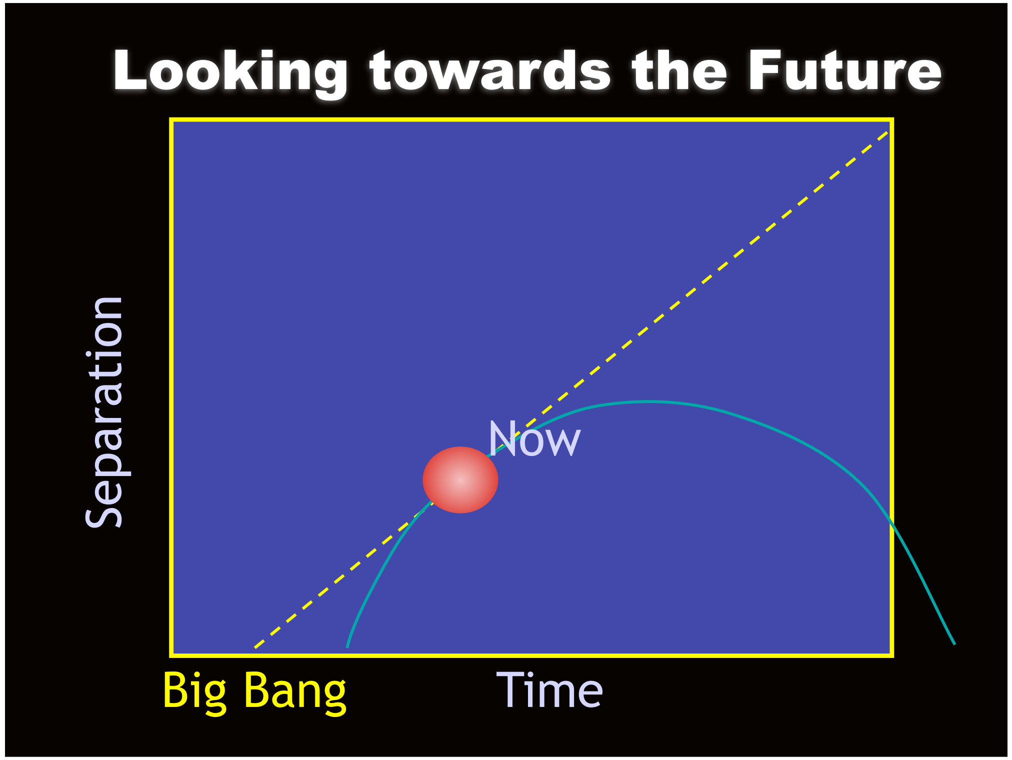
Interpreting Type Ia SNe Distances

We can also try to imagine what will happen in the future. If there is enough matter in the universe, the expansion will reverse and the Universe will collapse. Distance measurements allow us to probe the expansion of the Universe and determine into which regime it falls. If we measure the change in the Hubble constant with time and find we are below the blue line, then gravity wins and the Universe will recollapse.

If it lies between the blue line and the yellow dotted line, then the Universe will continue to expand indefinitiely.

If it lies above the yellow dotted line, then something is making the Universe accelerate!



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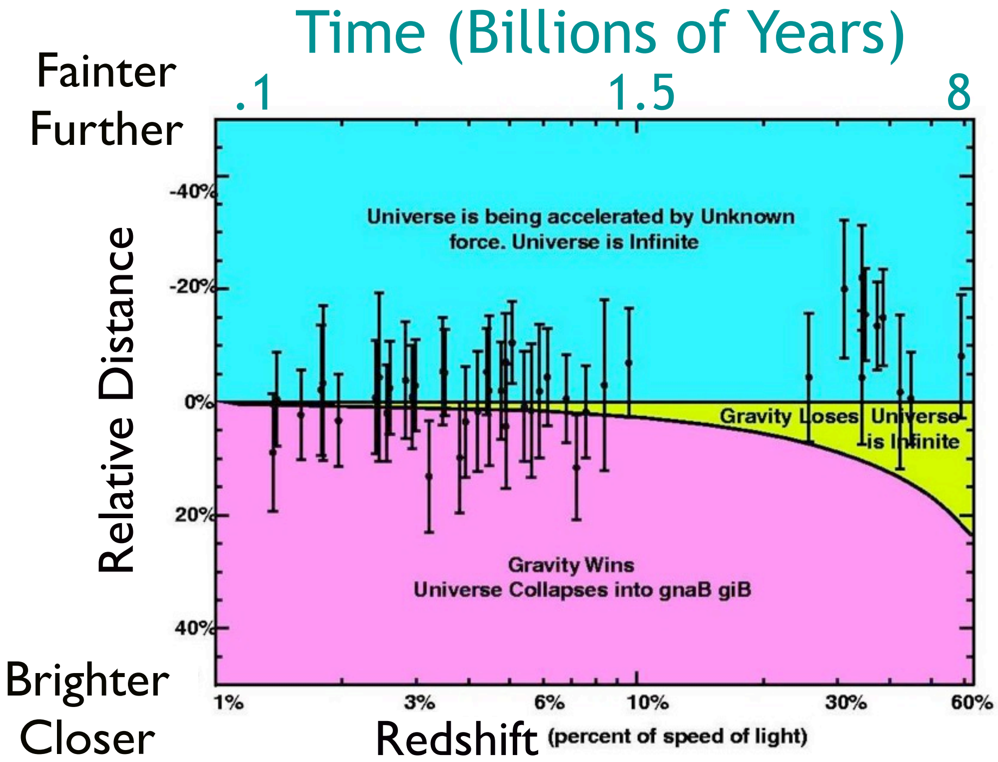
And the Nobel Prize goes to …

SN Type Ia distances have shown that the last case is what is happening … if we plot change in the Hubble constant (here denoted "Relative Distance") vs Redshift (equivalent to time looking back into the Universe), we find that the trend is that the Universe is accelerating. Something is causing its expansion to increase, rather than contract. The cause of this acceleration has been christened "Dark Energy"



(Plot from Brian Schmidt's Nobel Lecture, 2011)

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- References
  - Adam Ríess (http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/riess-lecture.html) and Brian Schmidt (http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/schmidt-lecture.html) Nobel Prize lectures (text and slides available at these pages). Between them these give a good introduction to both SN as distance indicators, and their use for cosmology.
- Bibliography

Useful constants, units, and formulae:

Gravitational constant	G	$=$	6.67	$\times$	10^{-11}	N m^2 kg^{-2}
Speed of light	c	$=$	3.00	$\times$	10^{8}	m s^{-1}
Planck constant	h	$=$	6.626	$\times$	10^{-34}	J s
Boltzmann constant	k	$=$	1.38	$\times$	10^{-23}	J K^{-1}
Stefan-Boltzmann constant	σ	$=$	5.67	$\times$	10^{-8}	W m^{-2} K^{-4}
Mass of the hydrogen atom	m_H	$=$	1.67	$\times$	10^{-27}	kg

Solar mass	$M_\odot$	$=$	1.99	$\times$	10^{30}	kg
Solar radius	$R_\odot$	$=$	6.96	$\times$	10^{8}	m
Earth mass	$M_\oplus$	$=$	5.98	$\times$	10^{24}	kg
Equatorial radius of Earth	$R_\oplus$	$=$	6.378	$\times$	10^{6}	m
Mass of moon	M_{moon}	$=$	7.3	$\times$	10^{22}	kg
Astronomical unit	AU	$=$	1.496	$\times$	10^{11}	m
Parsec	pc	$=$	3.086	$\times$	10^{16}	m
Hubble's constant	H_0	$=$	70			km s^{-1} Mpc^{-1}

Distance modulus	$m - M$	$=$	$5\log d - 5$ (d in pc)
Apparent magnitude	$m_2 - m_1$	$=$	$2.5\log\frac{f_1}{f_2}$
For small recession velocities	v/c	$=$	$\Delta\lambda/\lambda$
Definition of redshift	$(1+z)$	$=$	$\lambda_{obs}/\lambda_{rest}$
Energy and frequency	E	$=$	$h\nu$
Frequency and wavelength	c	$=$	$\nu\lambda$