The structure and evolution of stars

Lecture14: Type Ia Supernovae

R. Kirshner

Learning Outcomes

In these final two lectures the student will learn about the following issues:

- What is a supernova
- Brief historical story of discovery of supernovae
- The difference between Type I and Type II supernovae
- The two physical mechanisms for producing supernovae
- The meaning of the terms core-collapse supernovae and thermonuclear supernovae
- What stars produce the typical Type II and Type Ia
- The best studied supernova - SN1987A
- Surveys of supernovae in the distant Universe - using Type Ia supernovae to measure the expansion of the Universe

Introduction and recap

Recap previous lecture

- Supernovae split into Type I and Type II
- The Type II come from core-collapse of massive stars with hydrogen rich atmospheres.
- Neutron star formed - core bounce and neutrino driven outflow
- Neutrinos account for 99% of energy of event
- Typical Type II supernovae have “plateau” phases, then radioactive tail phase showing decay of ^{56}Co
- Type I SNe lack hydrogen
- Type Ia are quite different to all the other types

The observed types of supernovae

Supernovae explosions classified into two types according to their *observed* properties. The two main types are ***Type I*** and ***Type II*** which are distinguished by the presence of hydrogen lines in the spectrum.

No hydrogen

↓

Type I

↙ ↓ ↘

Si | He | He or Si

↓ ↓ ↓

Ia | Ib | Ic

Hydrogen lines

↓

Type II

↓

Lightcurve and spectra properties

↓

II-P, II-L, IIn, IIb, II-p

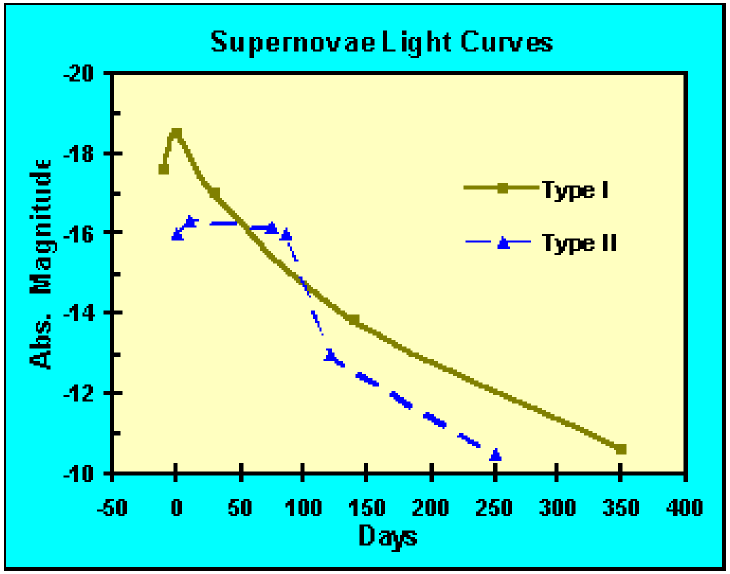
Type Ia supernovae

Type Ia supernovae are seen in galaxies with only older (>1Gyr) stellar populations e.g. elliptical galaxies. Hence they cannot be from the deaths of massive stars. They must come from low mass stars.

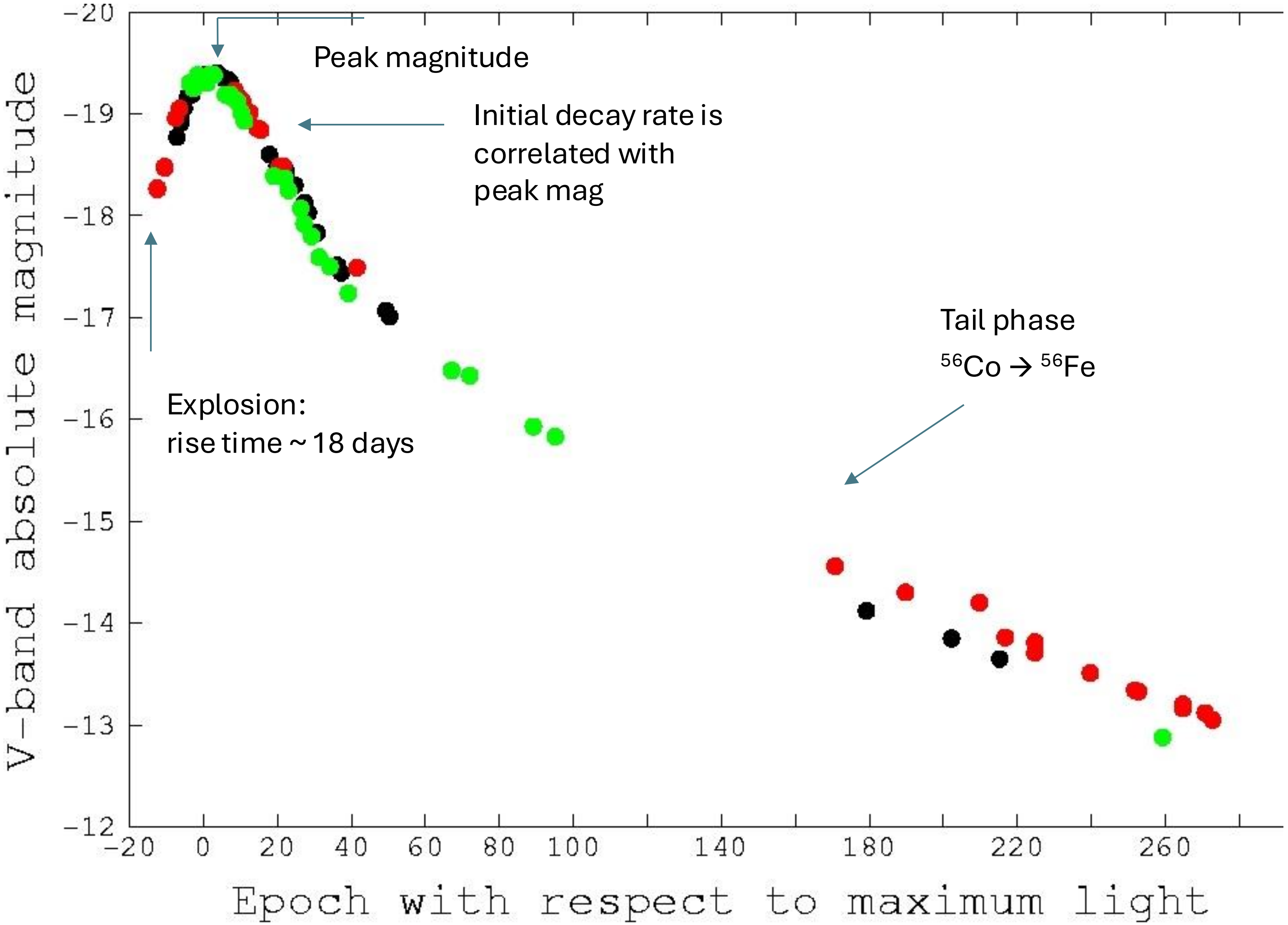
SN1994D in NGC4526 with HST

Type Ib and Ic are seen only in starforming galaxies, with young stellar populations. Note that the classification scheme predates any physical understanding of the mechanism causing explosion - potentially confusing !

Lightcurves are distinctly different from Type II SNe. But the Type Ia form quite a homogeneous group of events.



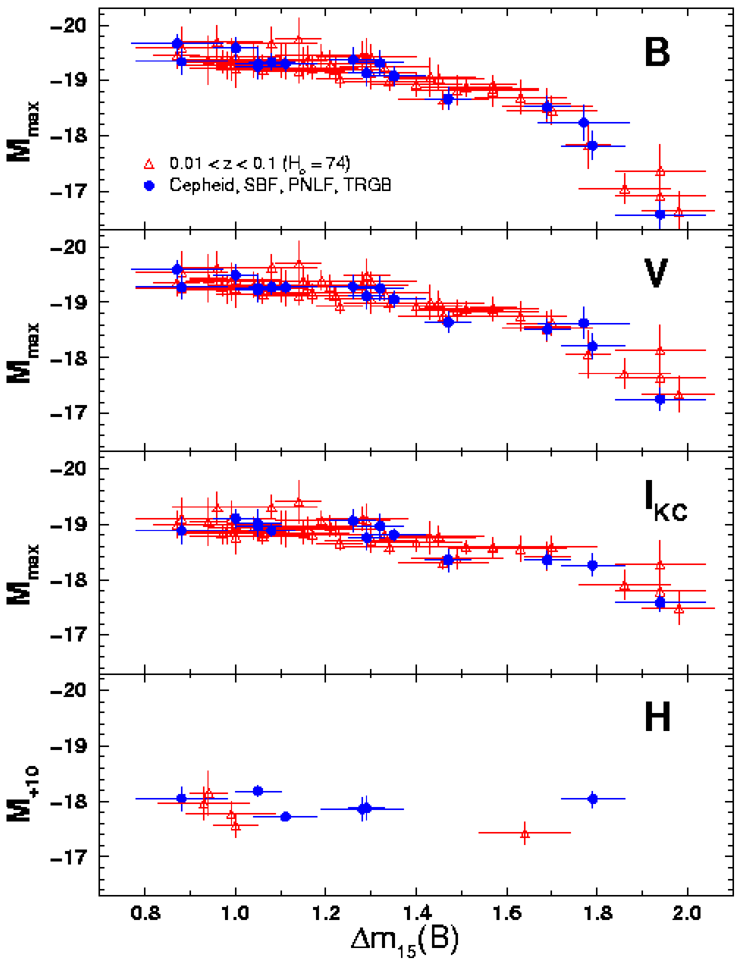
Typical lightcurve for Type Ia SNe

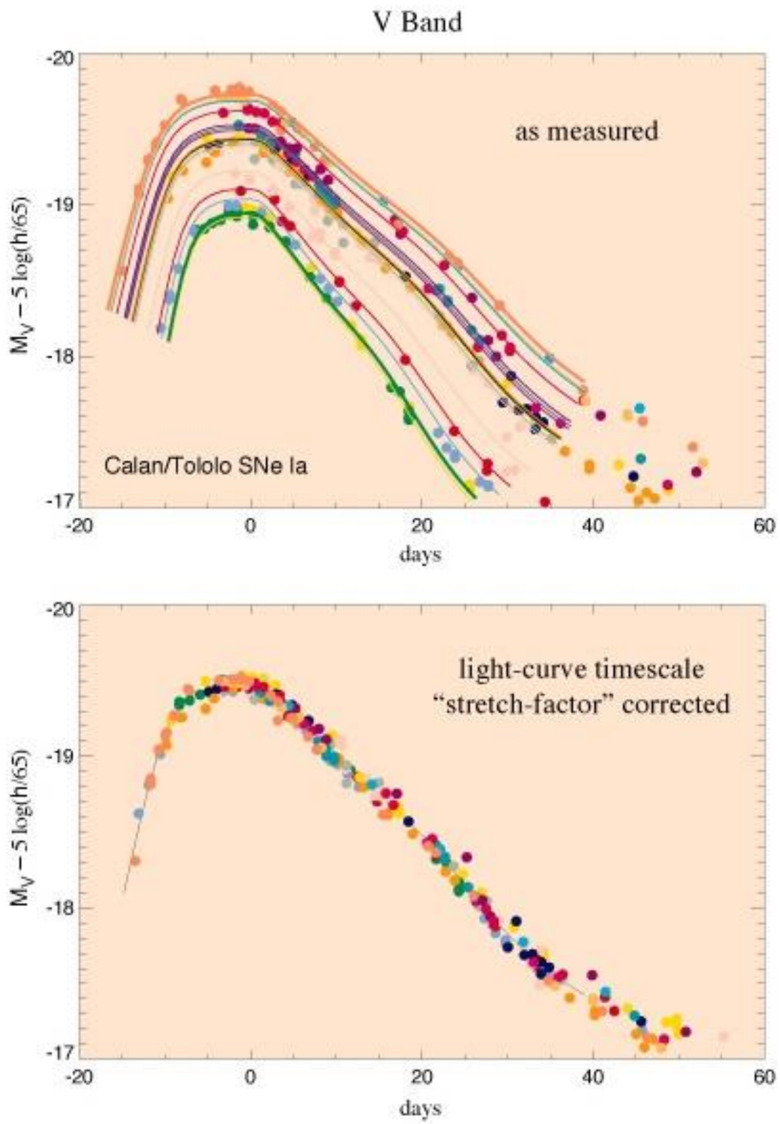


Composite lightcurve from three typical SNe Ia.

SN2002er, SN1990N, SN1996X. All shifted to peak mag of SN2002er

The Phillips decline rate relation





$$M_{\max}(B) = -21.726 + 2.698\Delta m_{15}(B).$$

Chandrasekhar mass WDs

M_{Ch}=1.46$M_\odot$

Recall the Chandrasekhar mass is the maximum possible mass for a white dwarf star. An isolated WD cools off with measured relation and fades for rest of time.

If we add mass to a WD to push it over M_{Ch} then it will be come unstable. The mass comes from an accreting binary companion in a close interacting binary system. Once M_{Ch} reached then e^- degeneracy pressure no longer enough to hold star up:

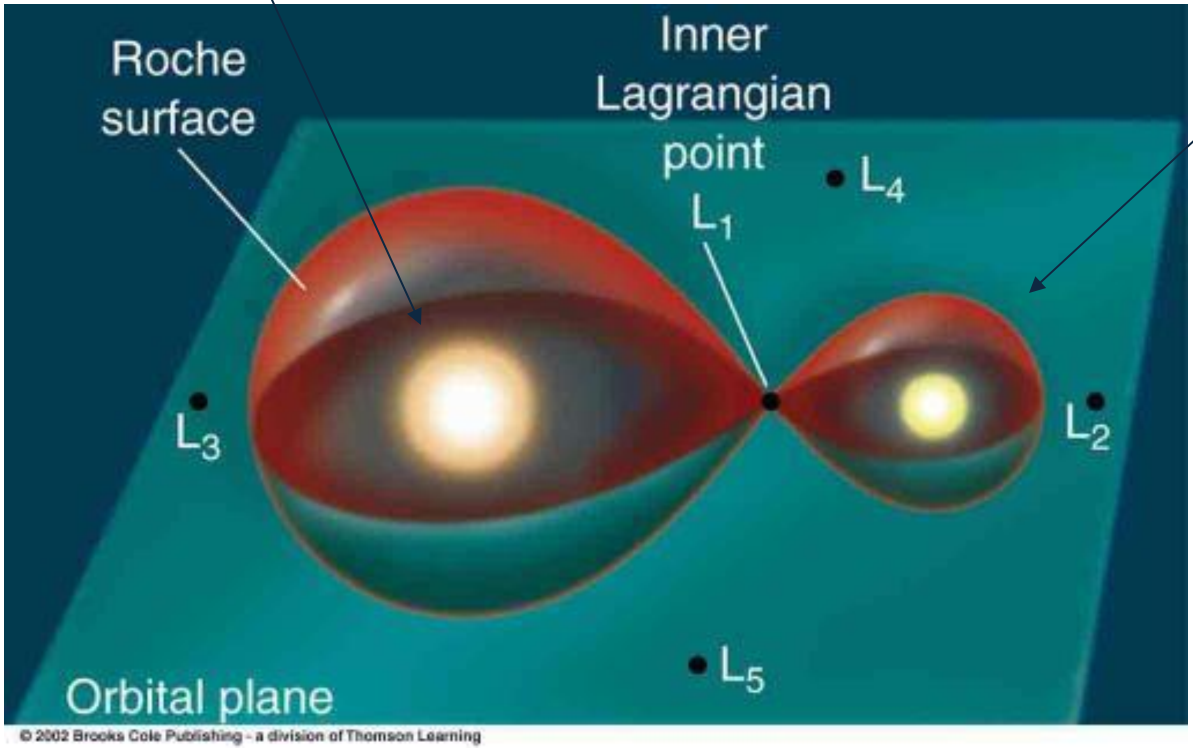
$\rightarrow$ C ignited under degenerate conditions - nuclear burning raises T but not P

$\rightarrow$ Thermonuclear runaway

$\rightarrow$ Incineration and complete destruction of star

Companion star
expanding to fill
its Roche Lobe

WD with mass
close to M_{Ch}



“Roche lobe” : region within which matter is gravitationally bound to the star. The Roche lobe of the primary and secondary meet at the Langrangian point. Matter can be transferred.

Roche lobe is gravitational equipotential surface

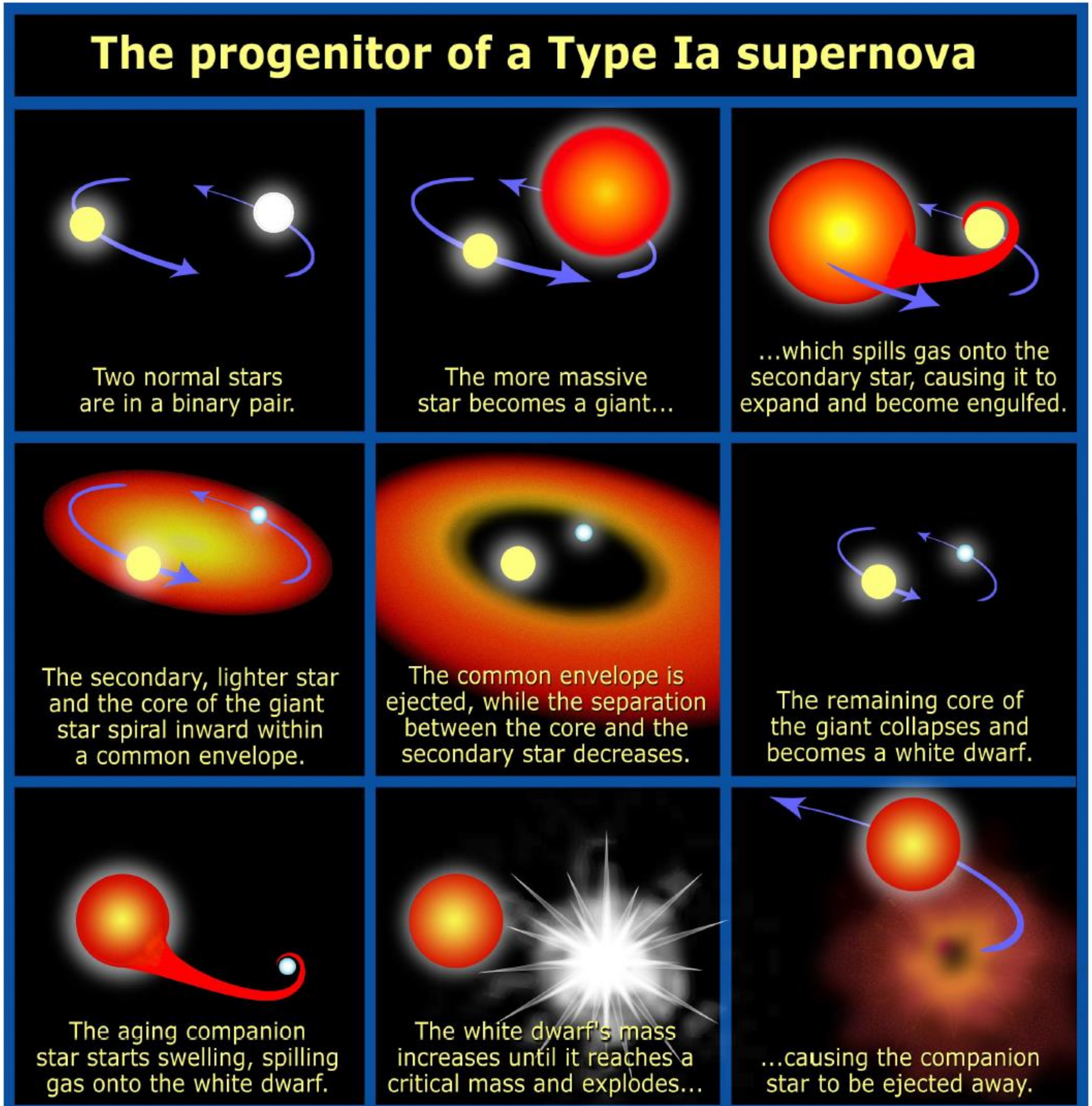
Exceeding the Chandrasekhar mass

There are three models for accreting the required matter - none of them are yet proven

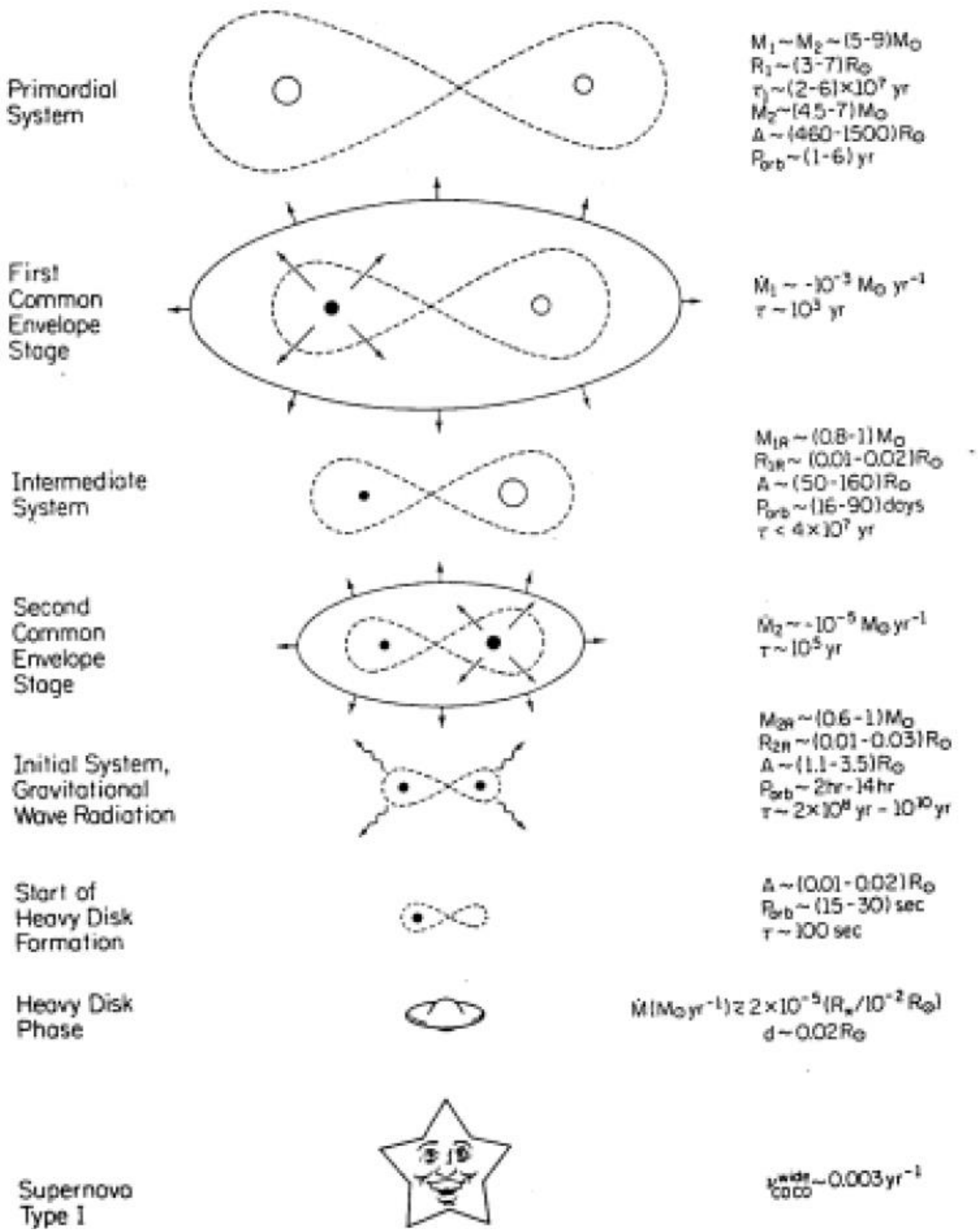
1. WD + main-sequence star companion: slow accretion of mass from a binary companion on the main-sequence e.g. cataclysmic variable systems (M~1$M_\odot$ and below). But observed accretion rate is slow, timescales possibly too long e.g. U Scorpii (recurrent nova) M_{WD}=1.5±0.2$M_\odot$ M_{MS}=0.9±0.2$M_\odot$

2. WD + red giant: the initially more massive star becomes WD. The lower mass companion (~1-2$M_\odot$) evolves into red giant. Mass transferred to WD. Such systems are well known to produce ***novae***. But mass transfer must be at just the right rate.

3. WD+WD merger (double degenerates): merging of two WD in binary systems, We see WD binary systems.
   e.g KPD 1930+2752: M_{tot}=1.47± 0.01$M_\odot$: looses angular momentum by gravitational radiation, merges within 200 x 10^6 yrs


The progenitor of a Type Ia supernova
Two normal stars are in a binary pair.
The more massive star becomes a giant...
...which spills gas onto the secondary star, causing it to expand and become engulfed.
The secondary, lighter star and the core of the giant star spiral inward within a common envelope.
The common envelope is ejected, while the separation between the core and the secondary star decreases.
The remaining core of the giant collapses and becomes a white dwarf.
The aging companion star starts swelling, spilling gas onto the white dwarf.
The white dwarf's mass increases until it reaches a critical mass and explodes...
...causing the companion star to be ejected away.

FORMATION FREQUENCIES OF SNI PRECURSORS



Nucleosynthesis in Type Ia SNe

Evidence for nuclear burning

1. At peak we see O, Mg, Si, S, Ca. Rapid fusion of C and O

$$^{12}C + ^{12}C \rightarrow ^{24}Mg + \gamma$$

$$^{16}O + ^{16}O \rightarrow ^{32}S + \gamma$$

$$\rightarrow ^{28}Si + \alpha$$

$$\rightarrow ^{24}Mg + 2\alpha$$

1. Later spectrum dominated by iron and other heavier elements (as in massive star burning, on explosive timescale)
2. Inner parts of ejected matter form Fe-group, outer parts from C+O burning which only reaches Mg, Si, S, Ca.
3. Denser regions burn all way to Fe-group, outer parts only to lighter elements. Computational simulations reproduce this pattern with exploding CO WD.

Late-time lightcurve and ^{56}Ni production

As in Type II explosions

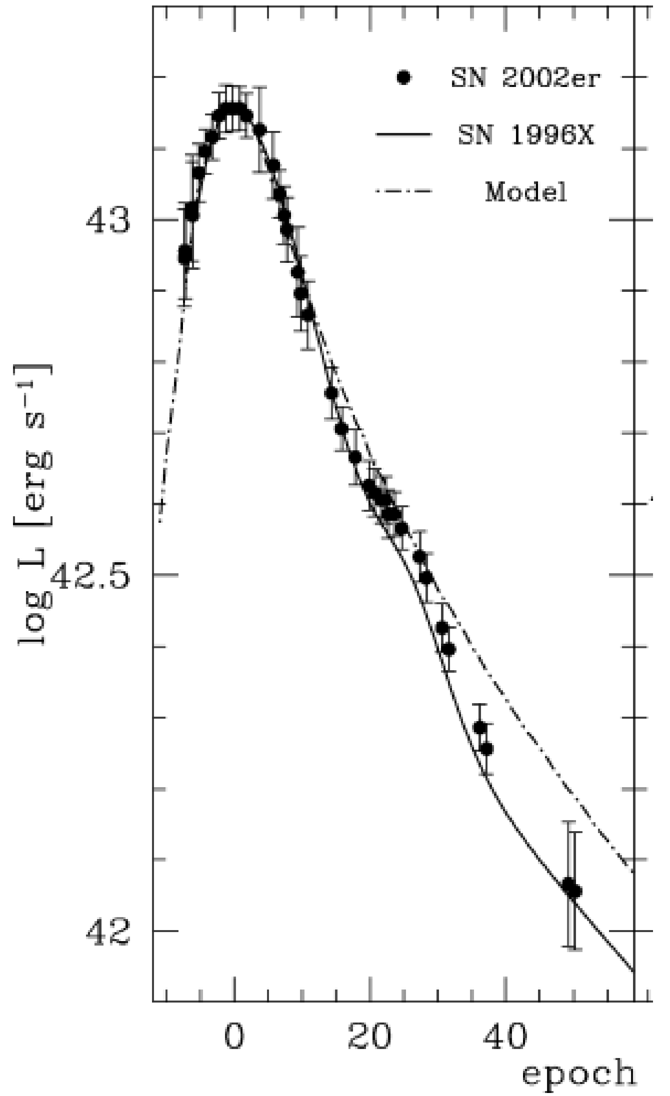
- But main product is ^{56}Ni rather than Fe
- Timescale too short for β-decays to occur to change ratio of p/n
- Fuel (e.g. ^{28}Si) has Z/A=1/2 ⇒ product must have Z/A=1/2
- ^{56}Ni has Z/A=1/2 but ^{56}Fe=26/56<1/2

$$^{56}Ni \rightarrow {}^{56}Co + e^{+} + \nu_e + \gamma \quad (\tau_{1/2} = 6 \text{ days})$$

$$^{56}Co \rightarrow {}^{56}Fe + e^{+} + \nu_e + \gamma \quad (\tau_{1/2} = 77.1 \text{ days})$$

SN1987A: M(^{56}Ni)= 0.075$M_\odot$

Typical M(^{56}Ni) for SNe Ia ~ 0.7-1$M_\odot$



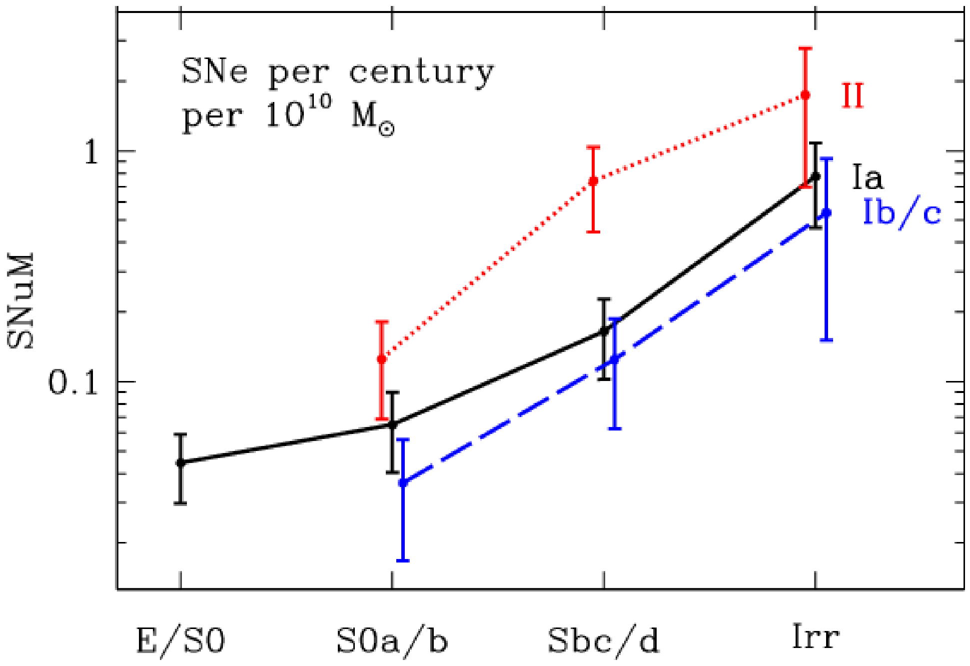
Observed SN rates

Standard results over all galaxy types:

	Ia	Ib/c	II	All
SN rate in SNu	0.2	0.08	0.40	0.68

1SNu= 1 SN $(100yr)^{-1}$ $(10^{10} L_{\odot}{}^{B})^{-1}$

Recent results as a function of galaxy type: spirals and irregular are high starformation rate galaxies

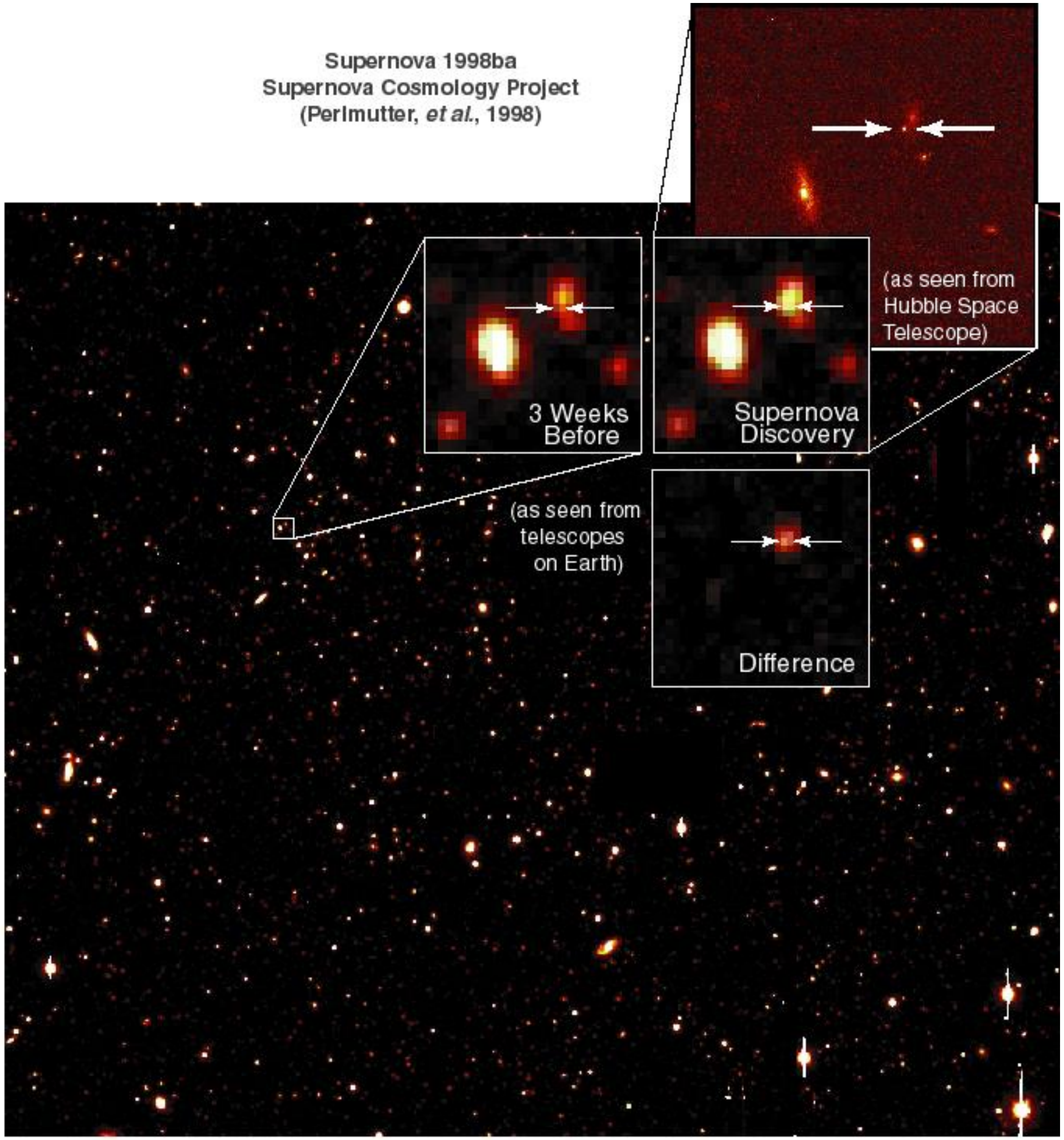


ellipticals → spirals → irregulars

Observed SN rates

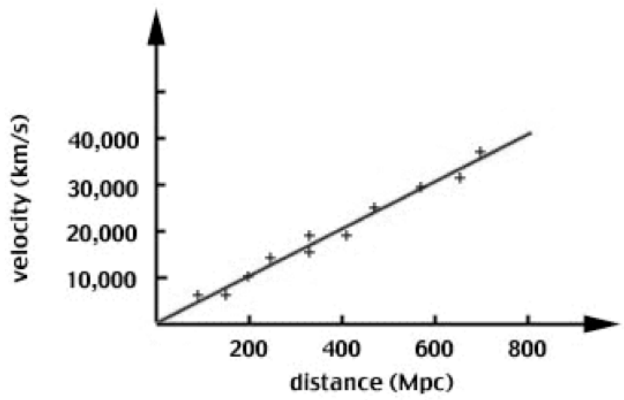
So in surveys of fixed areas of sky, why do we see many more SNe Ia than II ?

See Assignment 2 for calculation of rates within a magnitude limited area.



Using standard candles for cosmology

- What is a standard candle and how is it used to determine distance?
  A standard candle is an object whose luminosity can be determined without knowledge of its distance. We can therefore determine the distance to standard candle by measuring its apparent brightness and applying the luminosity-distance formula

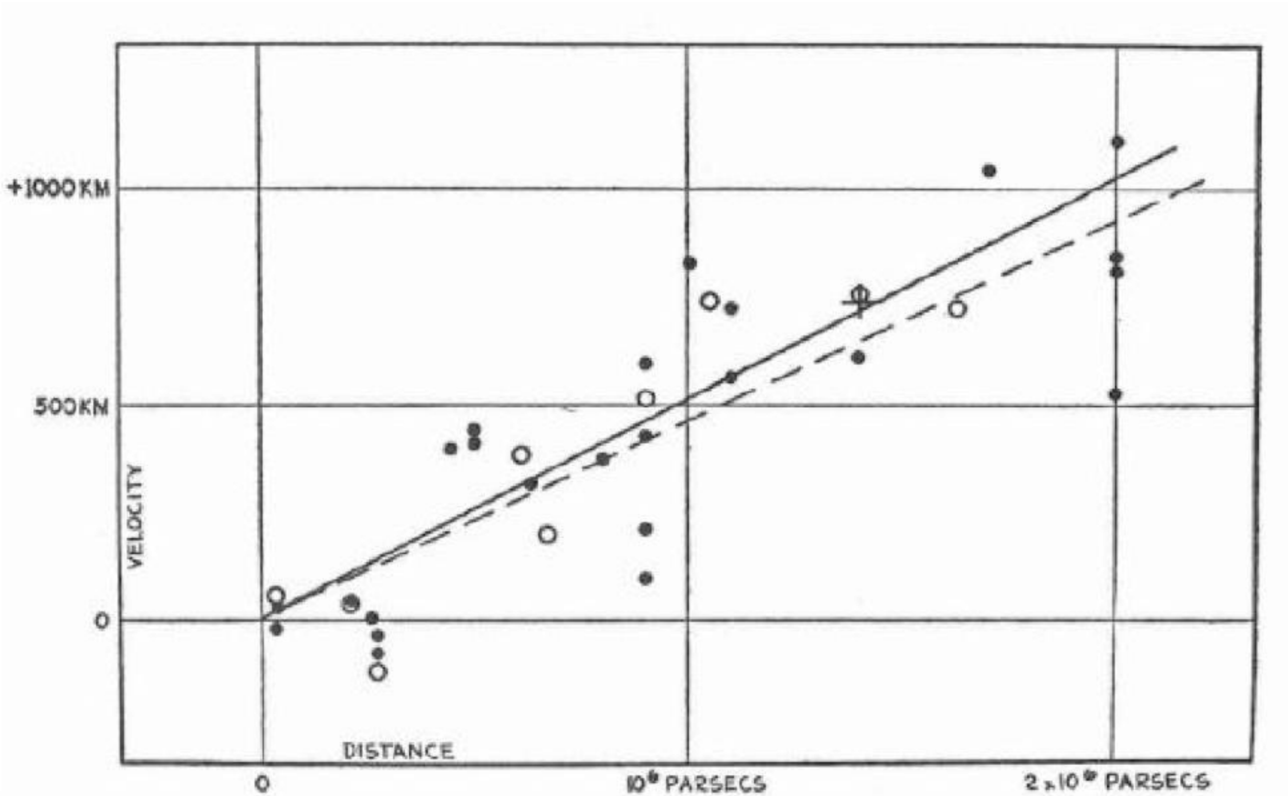


Phillips relation means type Ia SNe are ***calibratable standard candles***.

Supernova Cosmology Project and **High-Z Team**:

Competing teams working on using Ia SNe in medium redshift Universe to measure expansion.

Hubble's original Hubble diagram

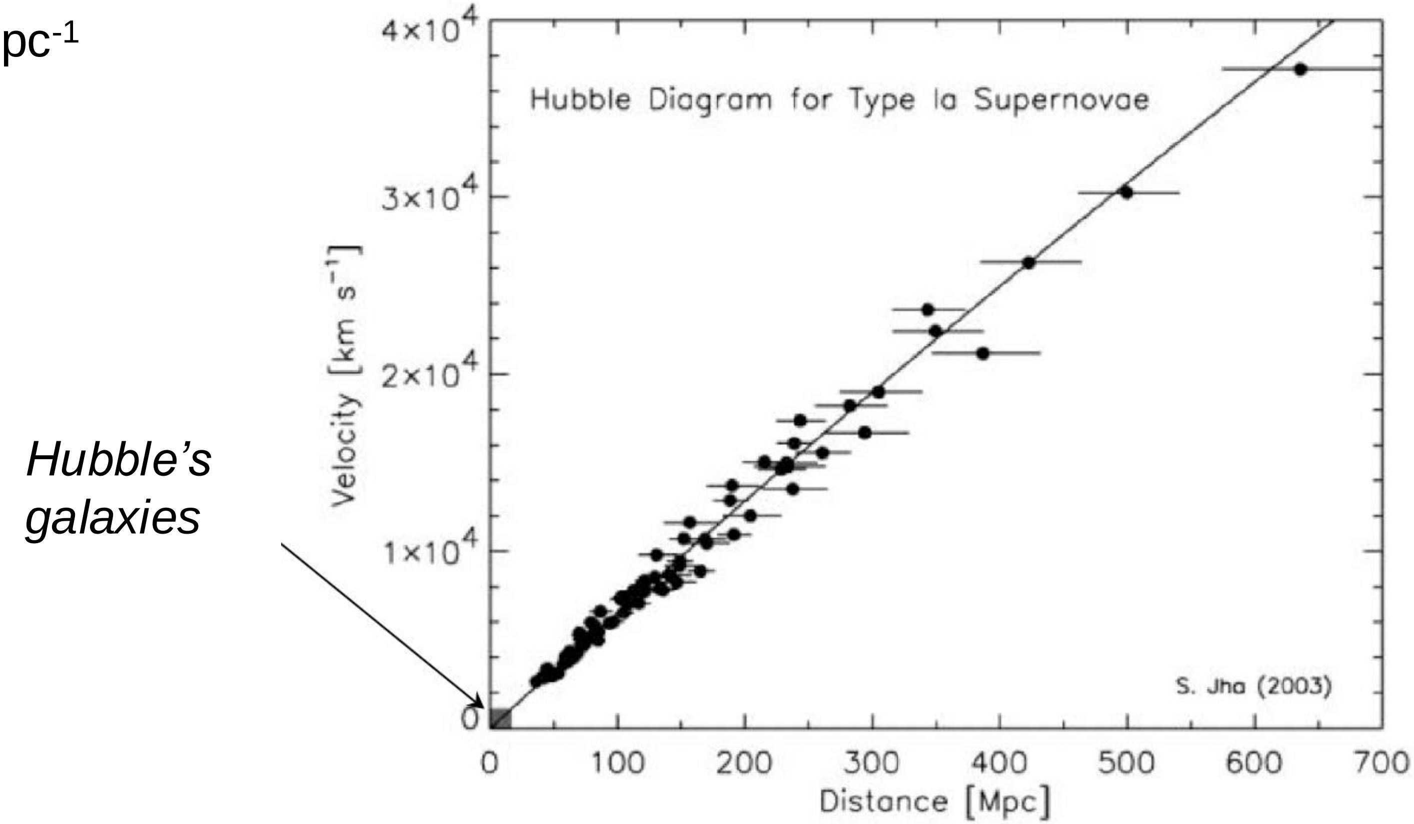


First determination of the Hubble Constant: H_0~500 $kms^{-1}Mpc^{-1}$

$$H_0 = \frac{v}{d}$$

Today's best Hubble diagram

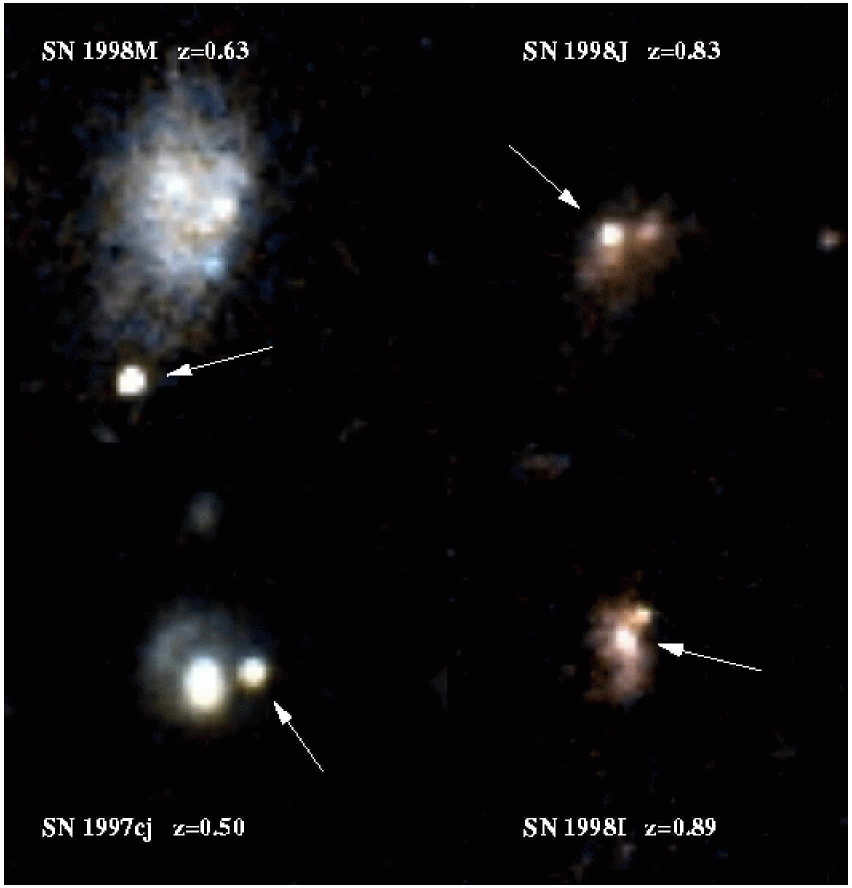
$H_0 = 72 \pm 7$ $kms^{-1}Mpc^{-1}$



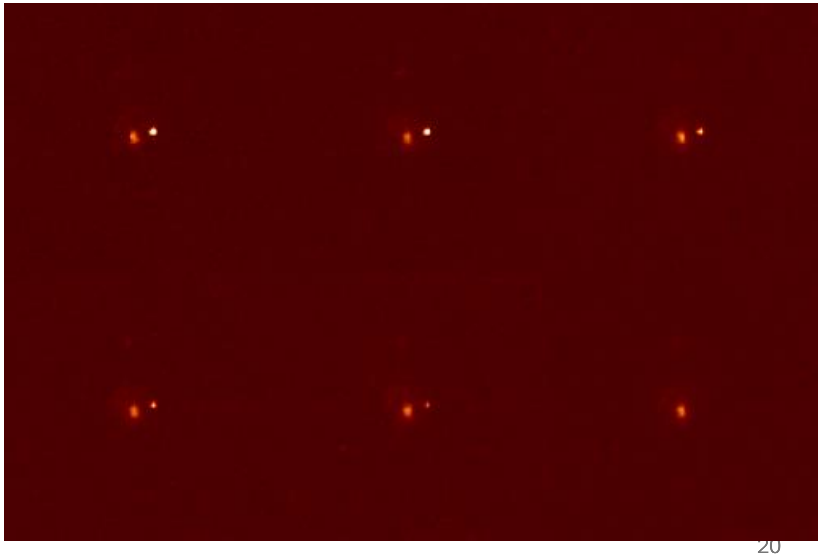
As we get further away, we now plot *redshift* rather than velocity. **Note: The Cosmological Redshift is a redshift caused by the expansion of space**

$$z = \frac{\lambda_o - \lambda_{rest}}{\lambda_{rest}}$$

Images from HST of distant SNe:

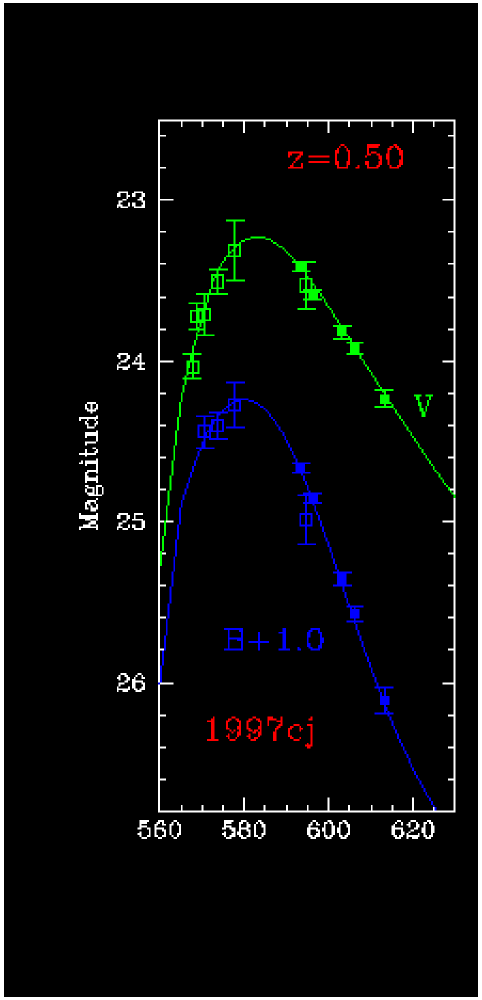


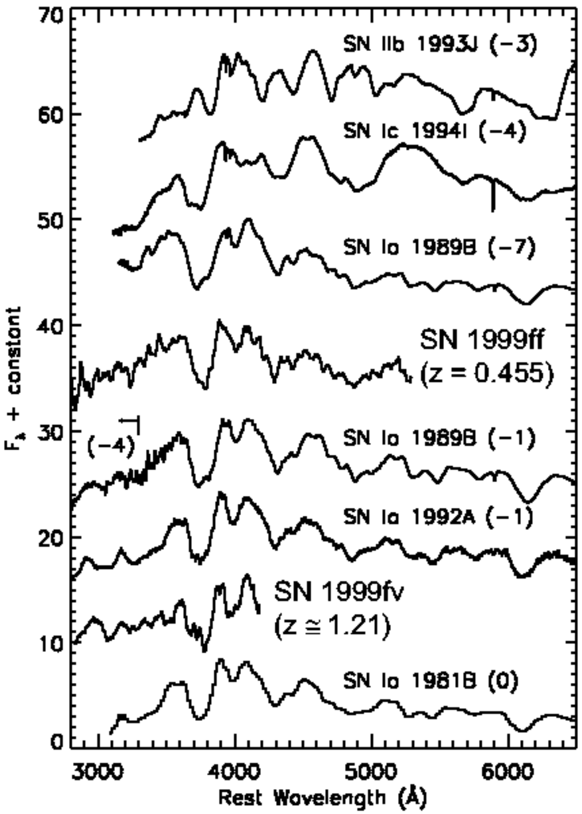
Fading of SN1999cy



High Z team example data

Sample lightcurves and spectra





What does expansion look like at high *z* ?

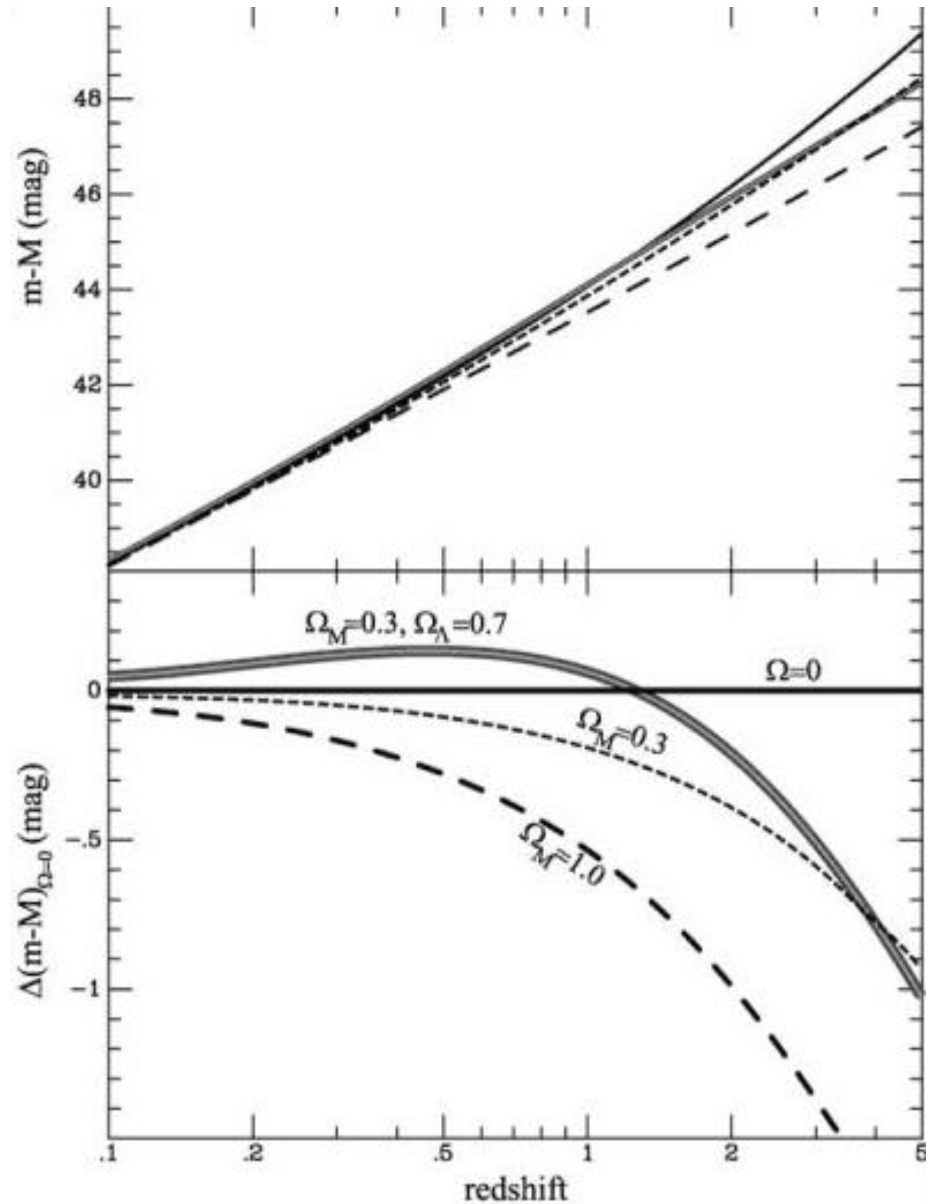
If matter density of the Universe

$\Omega=0$

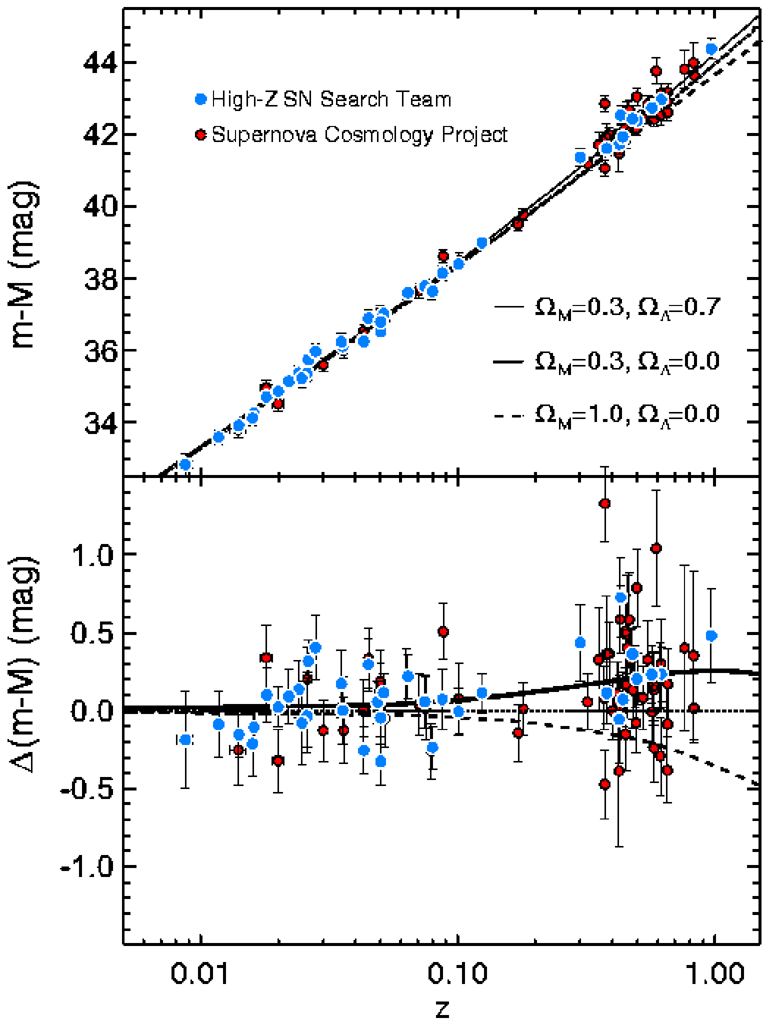
Universe will expand at current rate, constantly forever.

If $\Omega_M=1.0$ then there is enough matter to slow and halt expansion

These projects thought they would measure the slowing down of the Universe due to influence of dark matter - big surprise !



The Accelerating Universe



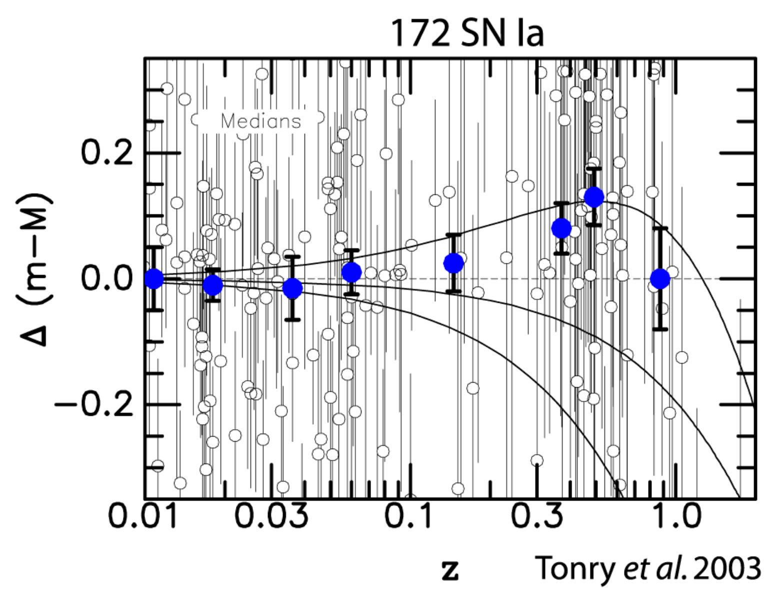
Approx lookback time: **$0.1t_H$** **$0.5\ t_H$ 0.65_{tH}**

The distances to supernovae in the redshift range 0.1 < *z* < 1.0

Typical dispersion in SNe Ia mags:

σ_{Ia}~0.2 mag. Need to discriminate by 0.2 mag !

Implies large numbers of objects required, take medians



Tonry *et al.* 2003

Dark energy ?

Now two other pieces of evidence for the model of Ω_Λ=0.7 , Ω_M=0.3

Cosmic microwave background - measured by WMAP (Wilkinson Microwave Anisotropy probe)

The total mass measured in Clusters of galaxies (I.e. visible + dark matter).

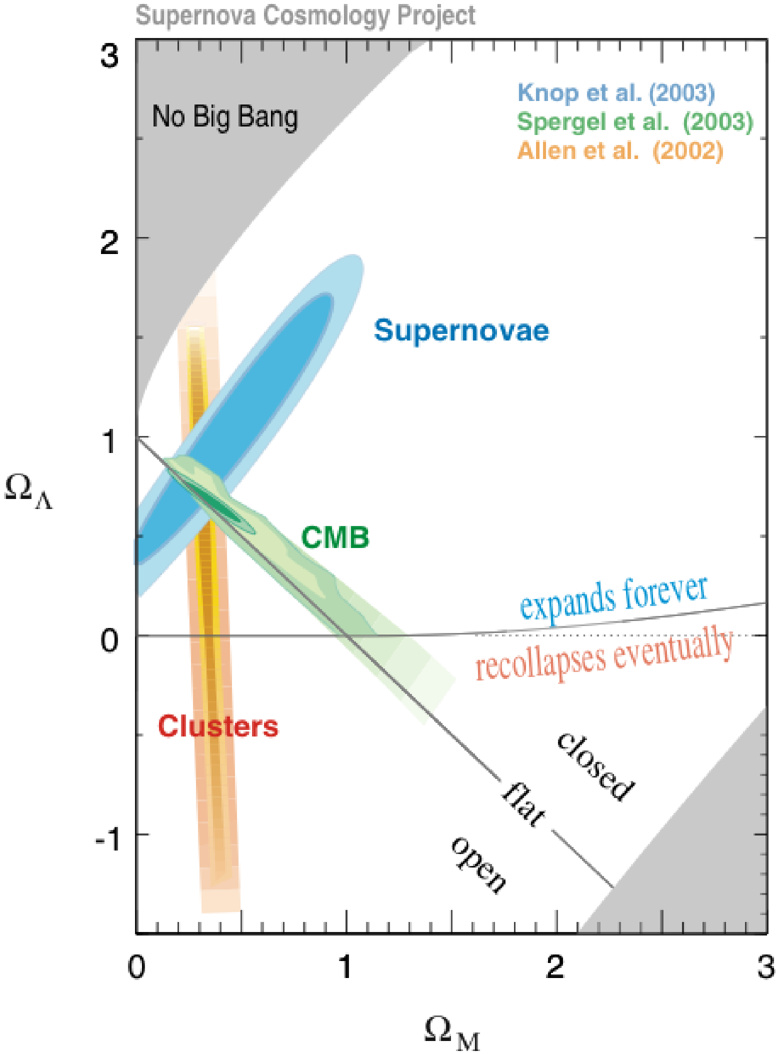
Current summary of Universe contents:

73% dark energy

23% dark matter

4% normal baryons

Type Ia SNe from Chandrasekhar mass WDs crucial to understanding Universe.



Summary of supernovae lectures

- Type II SNe: understand the broad outline of evolution of massive star to form Fe collapsing cores. Current difficulty in understanding how collapse produces explosion
- Type Ia: unanimous agreement amongst theorists that they are thermonuclear explosions in WD. But what are the progenitor systems ? How does the WD accrete at the right rate ?
- Thermonuclear SNe come from WDs pushed over M_{Ch}
- Very homogeneous in their properties
- Lightcurve is powered by ^{56}Ni at all stages, unlike type II-P
- Can be used as calibratable standard candles in the medium redshift Universe
- Were the first evidence of the existence of dark energy
- Now a concordance is emerging in the estimation of cosmological parameters