Type Ia SNe

Observational Cosmology

NASSP course

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What good are exploding stars for cosmology?

- From the previous lecture, we can use "standard candles" to measure luminosity distances in cosmology
- *Type Ia Supernovae* (SNIa, SNeIa) are believed to be nearly perfect standard candles…
- They provided the first evidence for dark energy (in 1998) and…
- They are very bright, so can be measured to large distances.

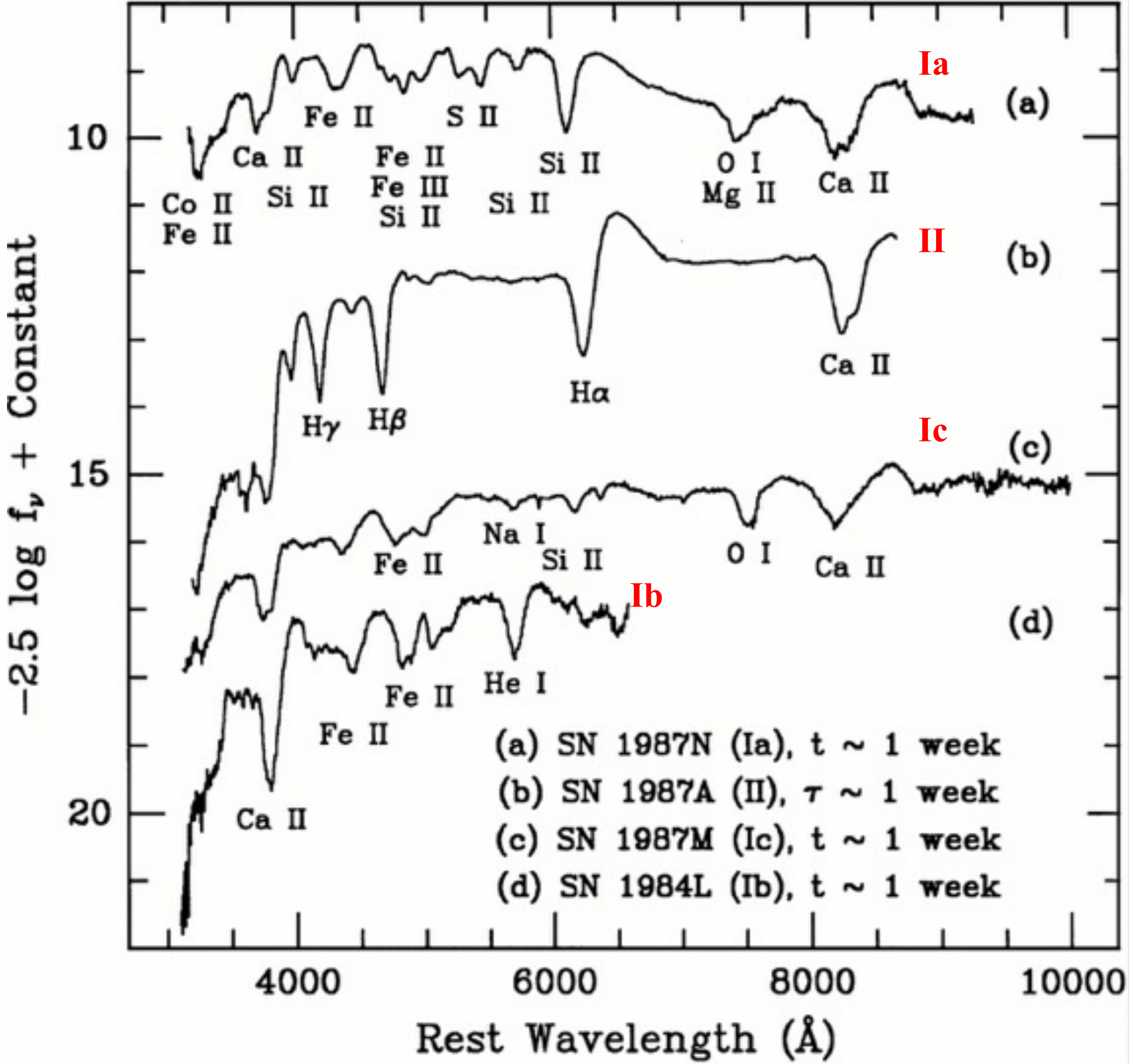
SNe Types

- There are several different types of SNe, each with a different explosion mechanism
- SNe are classified from their *spectral features*
- The classification dates back a long time, and thus is not particularly related to the type of explosion
- Only SNIa appear to be homogenous

Classification of Supernovae

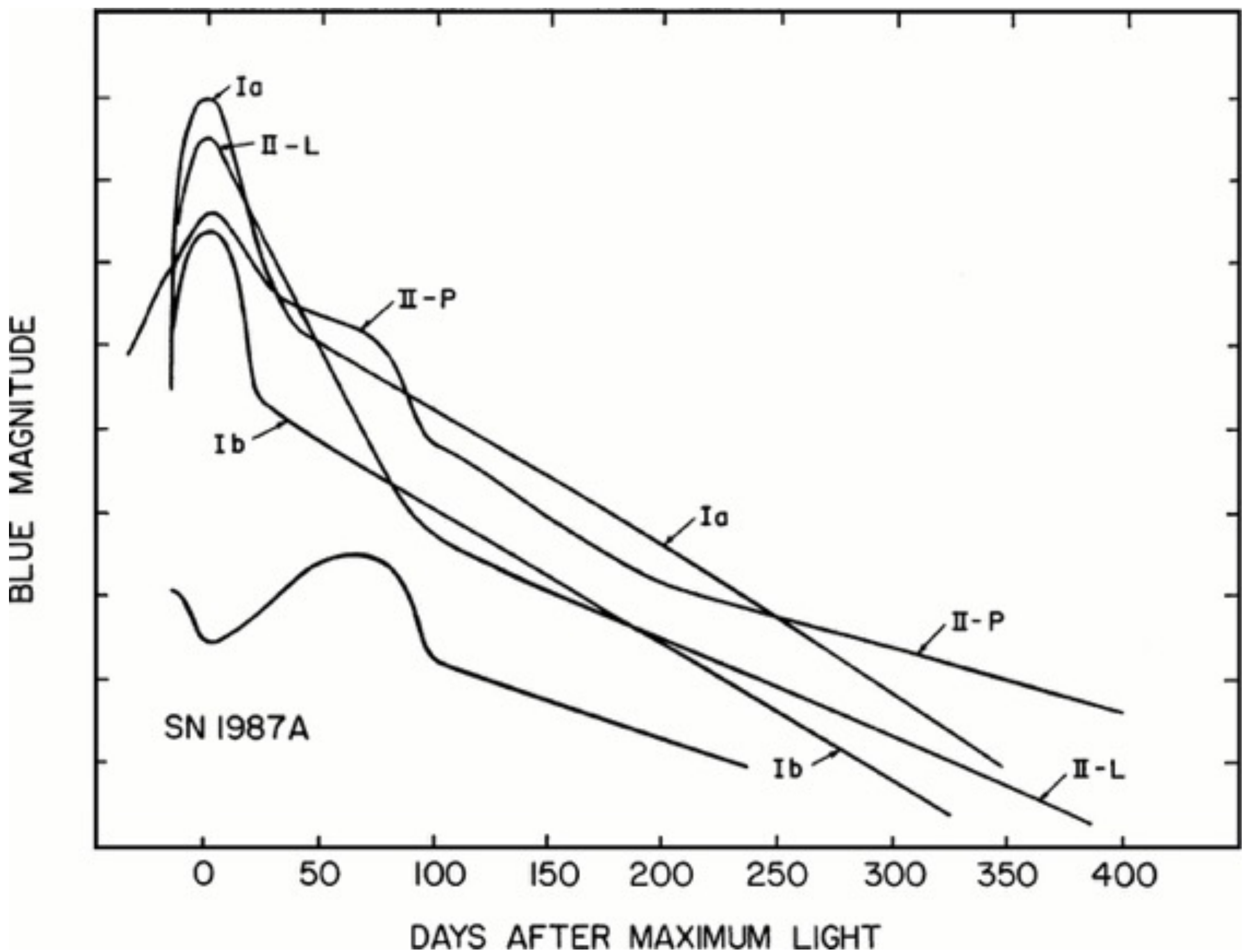
Type	Ia	Ib	Ic	II
Spectrum	No Hydrogen			Hydrogen
	Silicon	No Silicon		
		Helium	No Helium	
Physical mechanism	Nuclear explosion of low mass star	Core collapse of evolved massive star (may have lost its hydrogen or even helium envelope during red-giant evolution)		
Light curve	Reproducible	Large Variations		
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)			

Early
SN
Spectra



Filippenko 1997

Light-curves of different SNe



Type Ia Supernovae

General properties:

Homogeneous class* of events, only small (correlated) variations

Rise time: ~ 15 – 20 days

Full decay time: many months

Bright: M_B ~ – 19.5 at peak

No hydrogen in the spectra

Early spectra: Si, Ca, Mg, ...(absorption)

Late spectra: Fe, Ni,…(emission)

Very high velocities (~10,000 km/s)

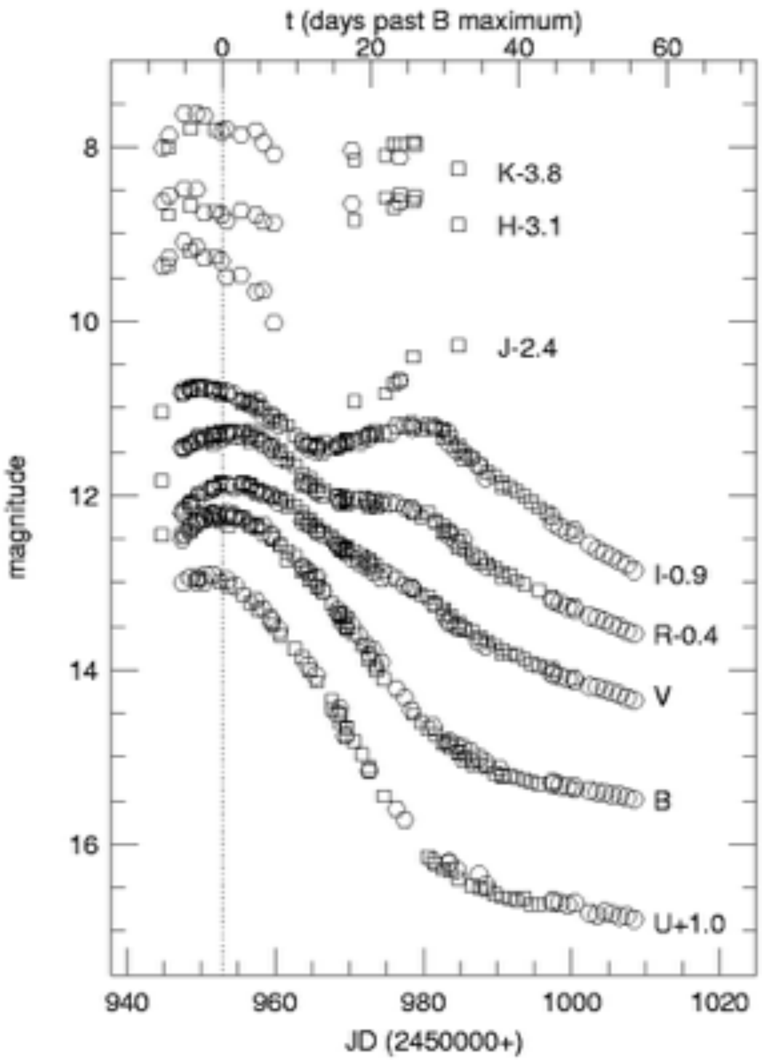
SN Ia found in all types of galaxies, including ellipticals

Hence progenitor systems must have long lifetimes – WHY?

*luminosity, color, spectra at max. light

Light curves of a SNIa in different bands

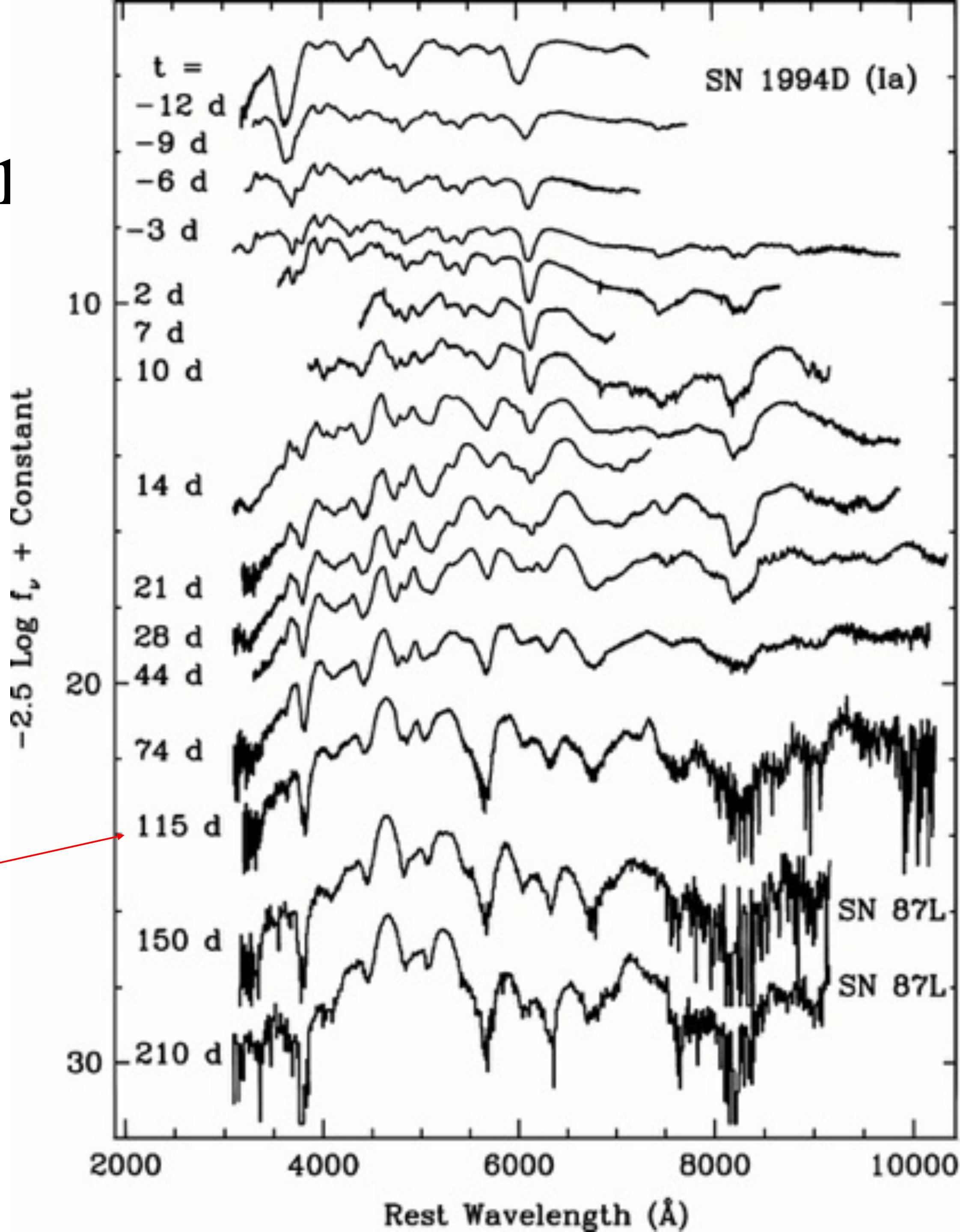
SN1998bu
Light curve

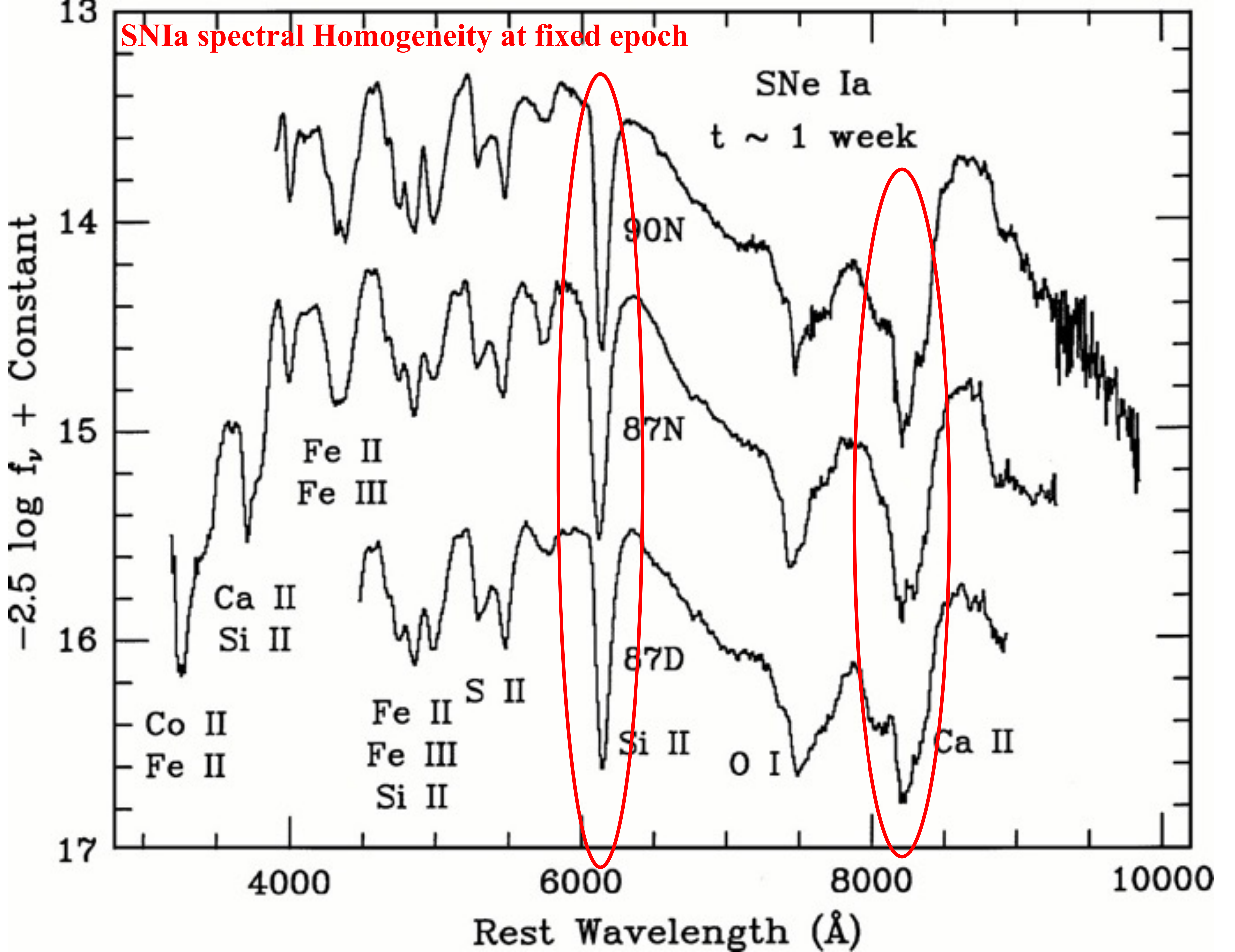


Suntzeff, et al
Jha, et al
Hernandez, et al

Spectral evolutio

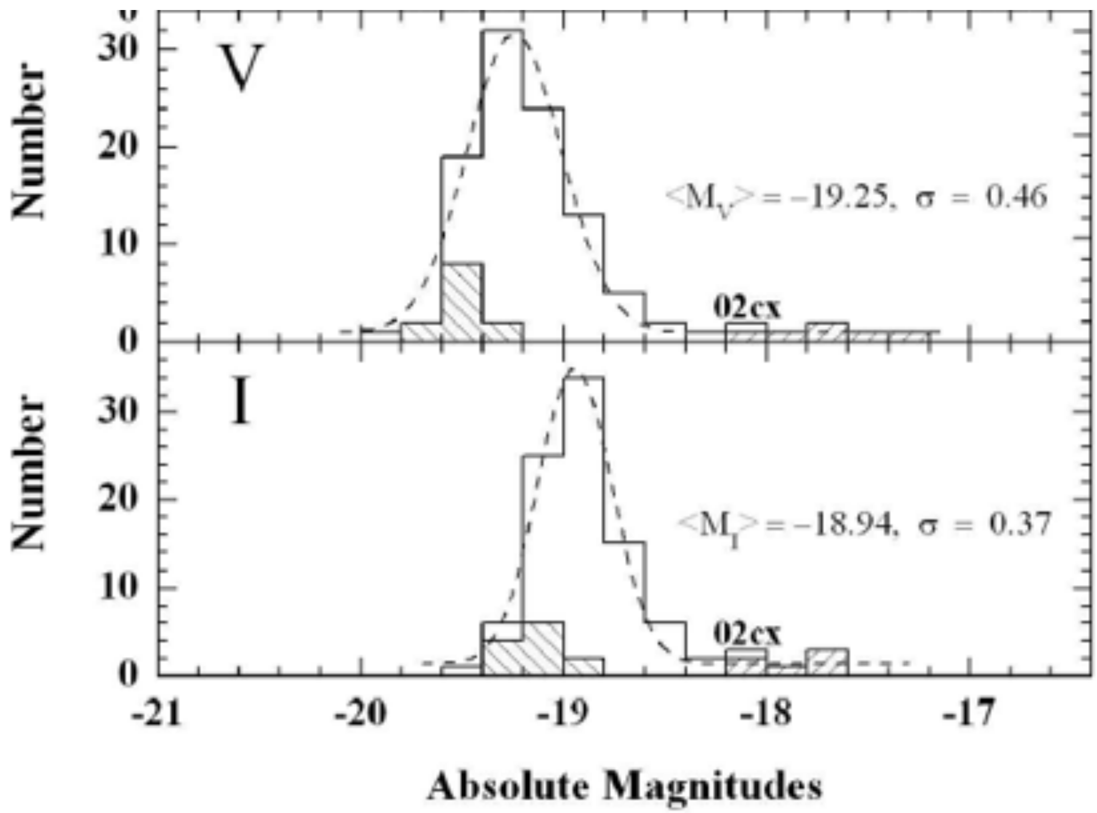
- The spectrum of a SNIa changes with time reflecting the fact that one is looking at different parts of the explosion…
- Days (e.g. –2d, 12d) are quoted relative to date of B-band maximum.




SNIa spectral Homogeneity at fixed epoch
SNe Ia
t ~ 1 week
90N
87N
87D
Fe II
Fe III
Ca II
Si II
Co II
Fe II
Fe II
Fe III
Si II
S II
Si II
O I
Ca II
13
14
15
16
17
4000
6000
8000
10000
−2.5 log f$_\nu$ + Constant
Rest Wavelength (Å)

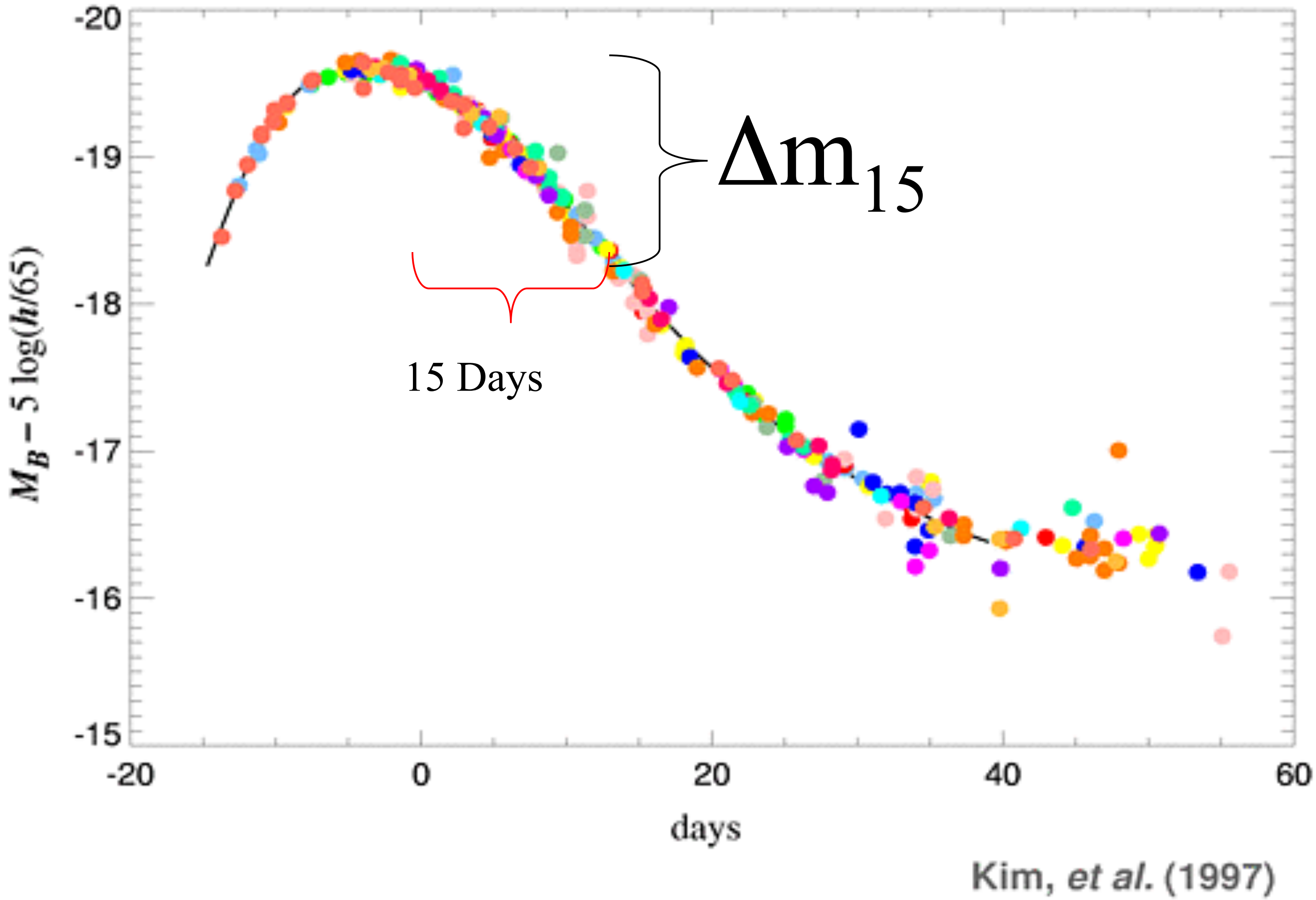
Are SNIa perfect standard candles?

- On average there is still some variation in intrinsic luminosity – hence they are no perfect standard candles…



A quick definition: Δm_{15}

The change in *m* in the 15 days after maximum

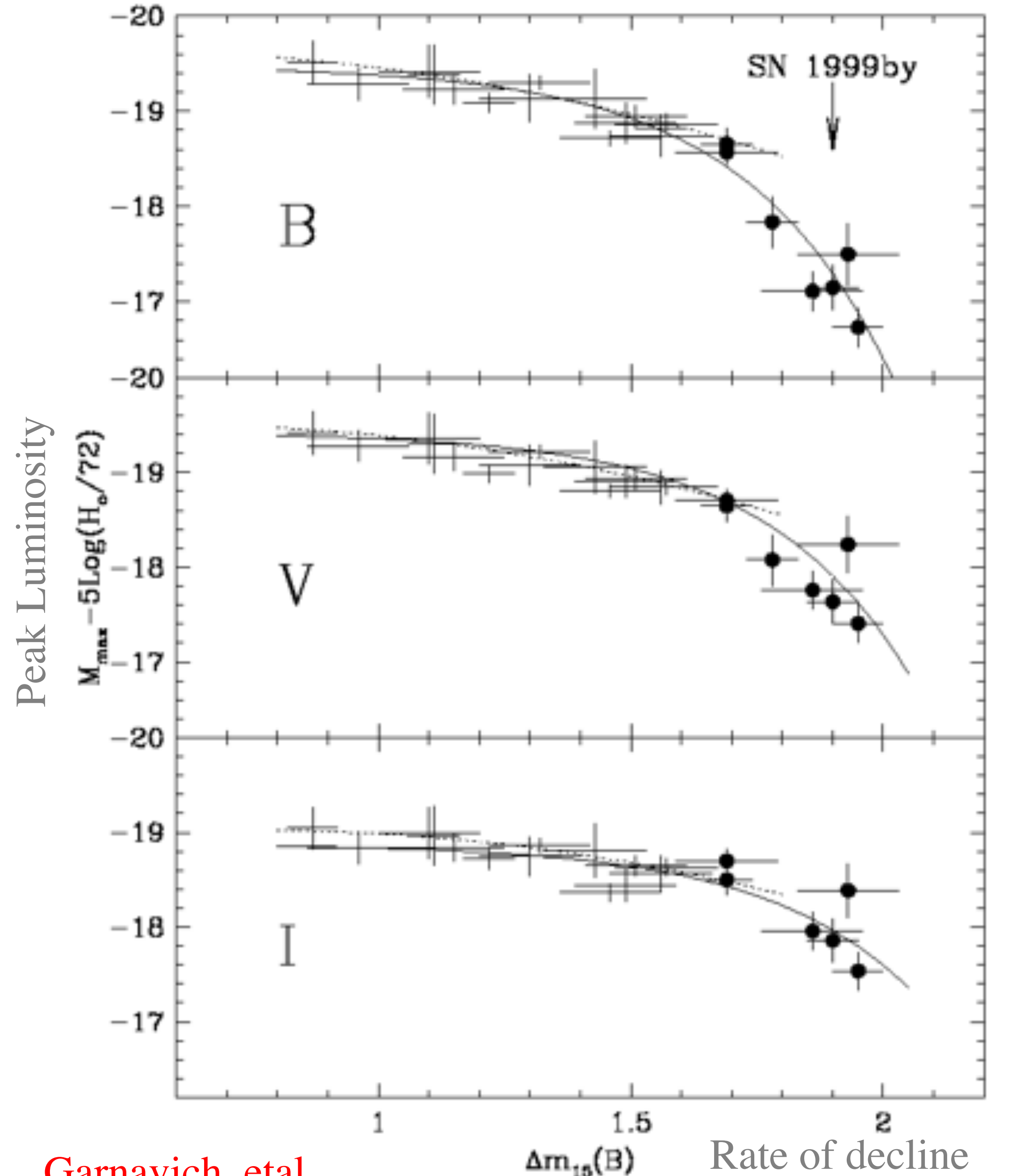


SN Ia Peak Luminosity Empirically correlated with Light-Curve Decline Rate

Brighter ←→ Slower

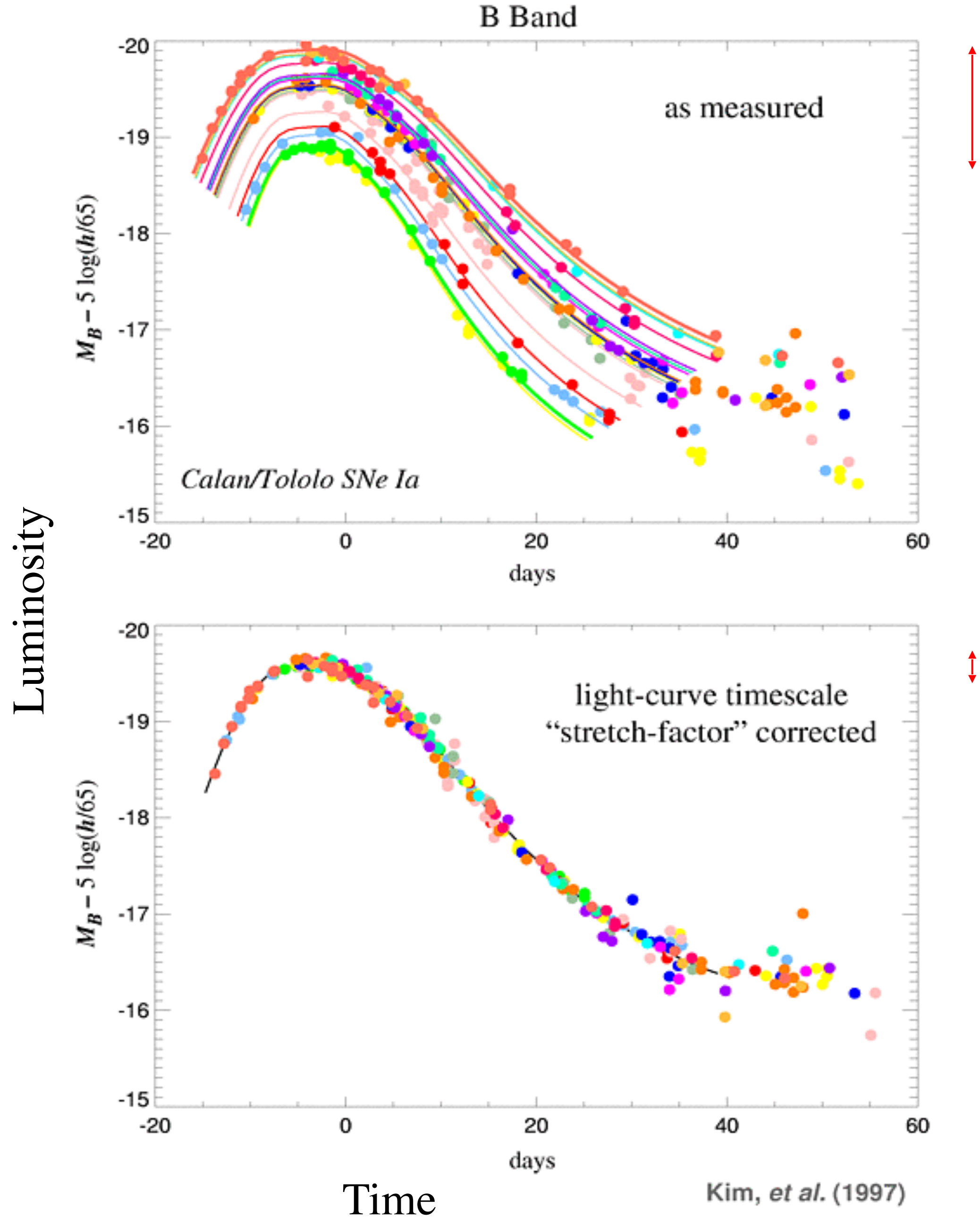
Use to reduce Peak Luminosity Dispersion

Phillips 1993



Garnavich, etal

Type Ia SN
Peak Brightness
as calibrated
Standard Candle

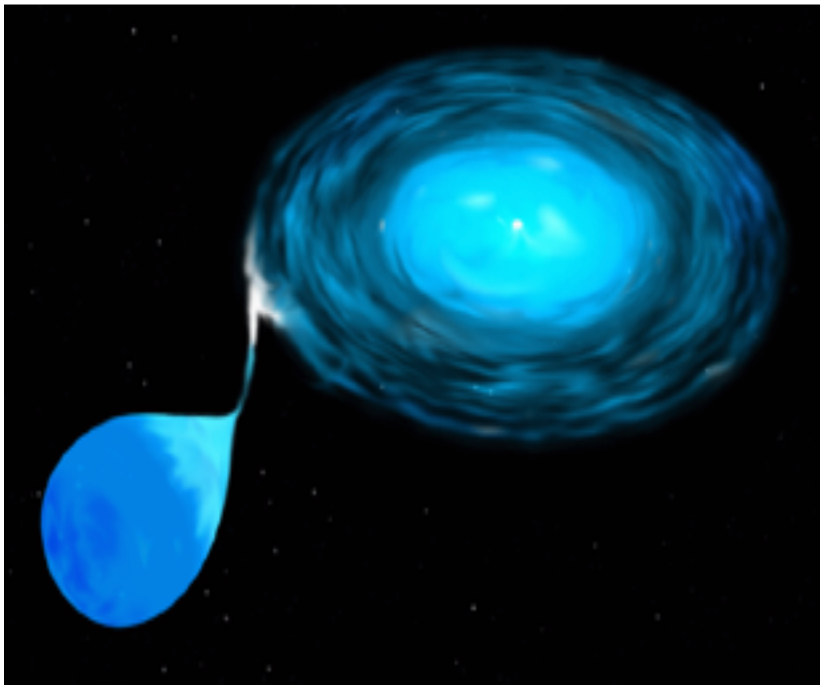


Peak brightness
correlates with
decline rate

SNIa as true standard candles

- After correction, the dispersion is only about $\sigma \sim 0.15$ mag!
- This corresponds to an uncertainty in the true distance of about ~7% which is very good.
- But, there could be problems: the correlation between intrinsic luminosity and decay time is calibrated at low redshift. What if there is evolution with redshift? This would cause problems.
- How can we explain the brightness-decay time correlation?

SN Ia Theory:



“Standard model”:

SNe Ia are thermonuclear explosions of C+O white dwarf (WD) stars.

Evolution to criticality:

Accretion from a binary companion leads to growth of the WD to the critical Chandrasekhar mass (~ 1.4 solar masses).

After ~1000 years of slow thermonuclear “cooking”, a violent explosion is triggered at or near the center, and the star is completely incinerated within seconds, no compact remnant is left.

In the core of the star, light elements are burned in fusion reactions to form Nickel.

The radioactive decay of Nickel and Cobalt makes it shine for a couple of months

Chandrasekhar Mass Models

- The WD accretes H or He from the companion star, burns it on the surface to C+O

- When $M = M_{Ch} = 1.4$ solar masses (Chandrasekhar mass)

thermonuclear instability: C, O burn explosively to ^{56}Ni (n=p) in the core

$\rightarrow$ explosion driven by E_{kin} released from fusion reactions in a few seconds. Free expansion of ejecta thereafter, with velocities ~10^4 km/sec.
Outer regions burn to Si, Ar, Ca,… as seen in early spectra.

Radioactive decays: $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$ + MeV photons (days)
γ's downscatter, `thermalize' and escape as optical/NIR light: light curve that we see.

SNIa as standard candles - I

- We can explain why SNIa have roughly the same intrinsic luminosity if we assume that **all** of the Chandrasekhar mass,: M_{Ch} , is fully burned → $M_{Ni} \sim 0.6$ M_{sun}

  → \`fixed' L_{peak}
- Why is there some variation in L_{peak}? Well spread in progenitor Mass (1– 7 M_{sun})

  → spread in C/O ratio
  → spread in M_{Ni} produced & E_{kin}
  → spread in L_{max}

Other diversity factors: varying accretion rates, rotation speeds, magnetic fields, metallicity etc…

SNIa as standard candles - II

- How can we explain the crucial brightness-decay time (L_{peak} - Δm_{15}) correlation?
- Basic idea: increased mass in **nickel** affects both peak luminosity and decline rate:

1. Increase M_{Ni} → increase L_{peak}

- Increase M_{Ni} → increase T → increase opacity → increase photon diffusion time → longer decline

There has been recent progress in 3D…

From the FLASH centre – the first Self-consistent SNIa explosion…via Compressional heating…

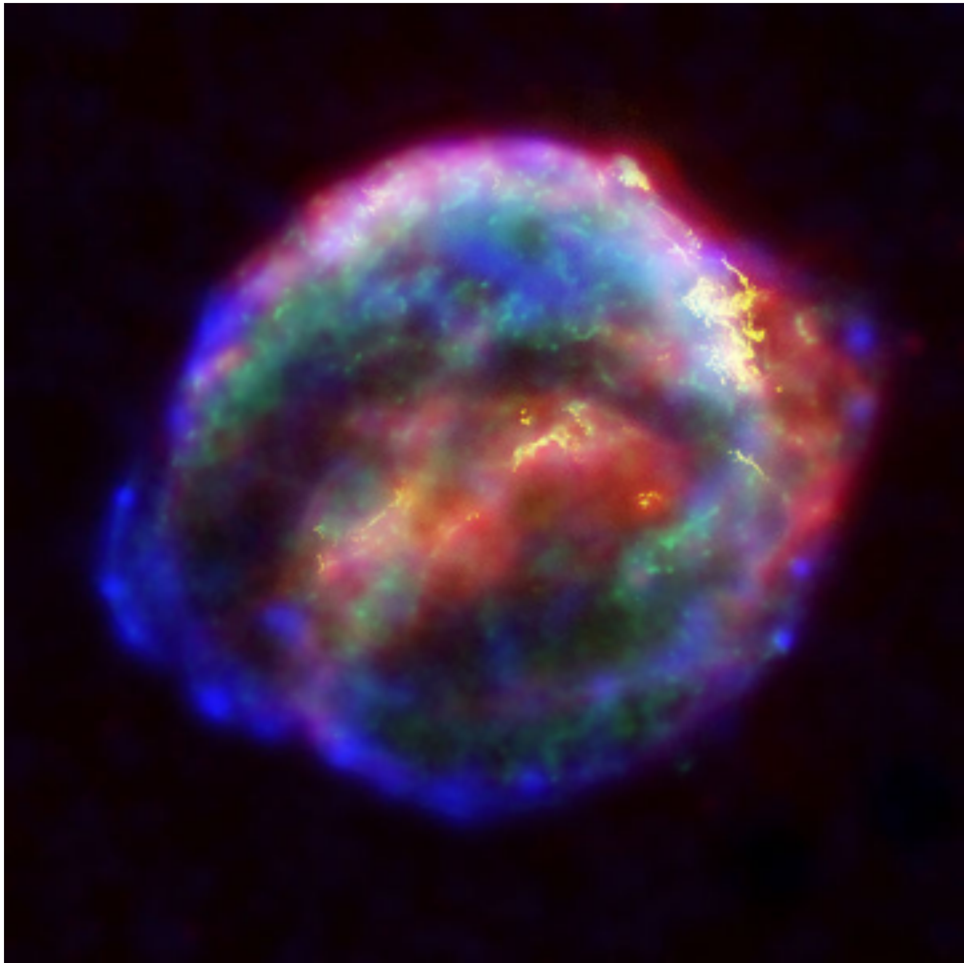
Details…

- The bubble, initially measuring approximately 10 miles in diameter, rises more than 1,200 miles to the surface of the star in one second.

- In another second, the flame crashes into itself on the opposite end of the star, triggering a detonation.

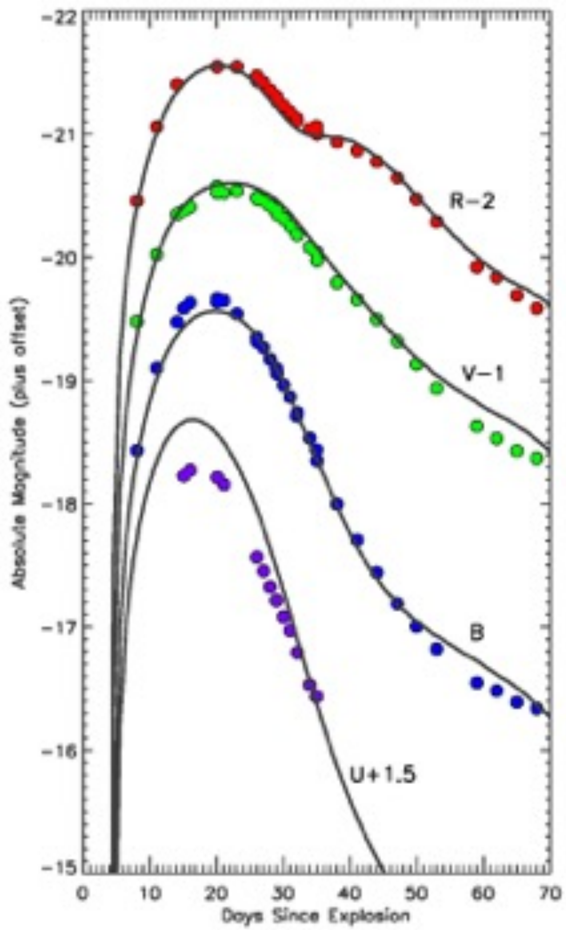
- This process simulates no more than three seconds. The Flash Center team ran its simulation on two supercomputers. Just one of the jobs ran for 75 hours on 768 computer processors, for a total of 58,000 cpu hours.

So far so good…but a much better understanding of SNIa are required for the future as we push them to the limit for cosmology…



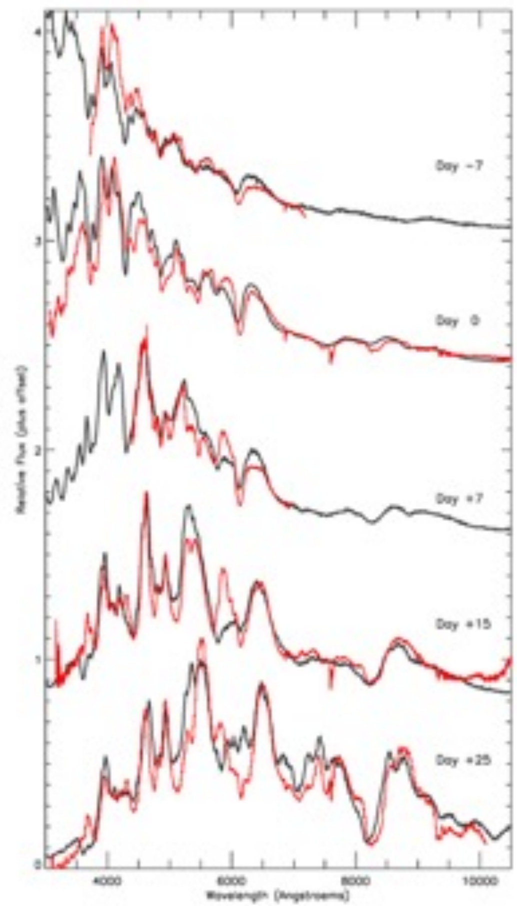
Kepler's SNIa remnant as seen by Chandra

Comparison of Predicted and Observed Light Curves and Spectra



Comparison of U, V, B, R light curves predicted by GCD model and obs. of Type Ia Supernova SN 2001el

Kasen & Plewa (2006)



Comparison of spectra predicted by GCD model and obs. of Type Ia supernova SN 1994D

Moving into an era where comparisons of high-fidelity, 3D, whole-star stimulations and high-quality observations will allow us to discriminate among proposed explosion mechanisms

Some problems

- Whilst some simulated models of SNIa explosions are now available, reproducing the observed light-curves and spectra is only just beginning
- Computationally it is impossible to run enough simulations to consider all possible scenarios
- 3-D modelling is very much in it's infancy – off-centre explosions are only just being considered
- A few SNe progenitor systems have been found, but they are very difficult to find and study
- So we shall have to cope with an empirical relationship for a while longer.

QUESTIONS
you should now be able to answer…

1. Why are SNIa useful for cosmology?
2. What are the distinctive spectral features of SNIa?
3. What is the current model for SNIa explosions?
4. Why are SNIa approximately standard candles?
5. What correlation do we use to make them more standard?
6. What are some of the challenges for the future of SNIa science?