Spectral inferences from SNe Ia or…

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Spectrum is truth

I. Using observables to understand SNe Ia

Questions

- Properties of SNe Ia (eg Phillips rel'n)
- Mode of explosion (deflagration, delayed detonation, other even less reasonable modes…)
- Cosmology?

Methods

- Look at/model spectra & light curves

Supernova Spectra evolve: early

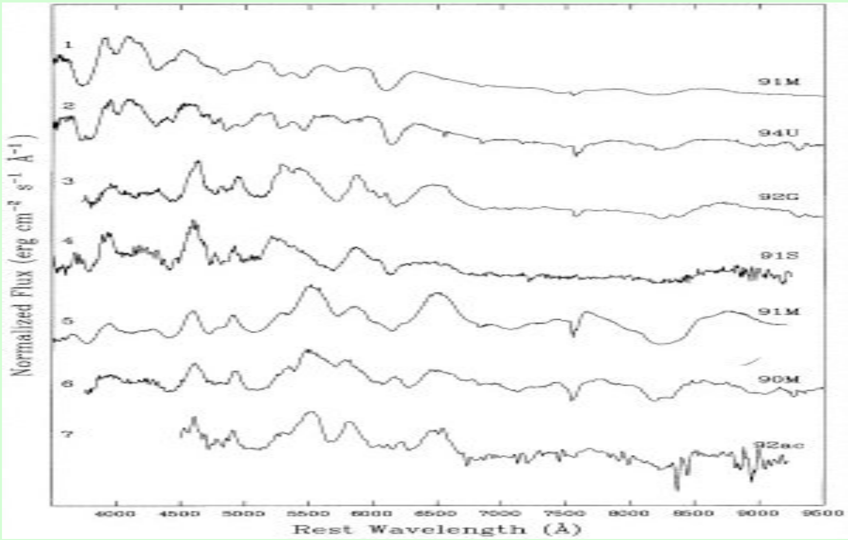
Soon after explosion (first few weeks), ejecta density is high enough for a

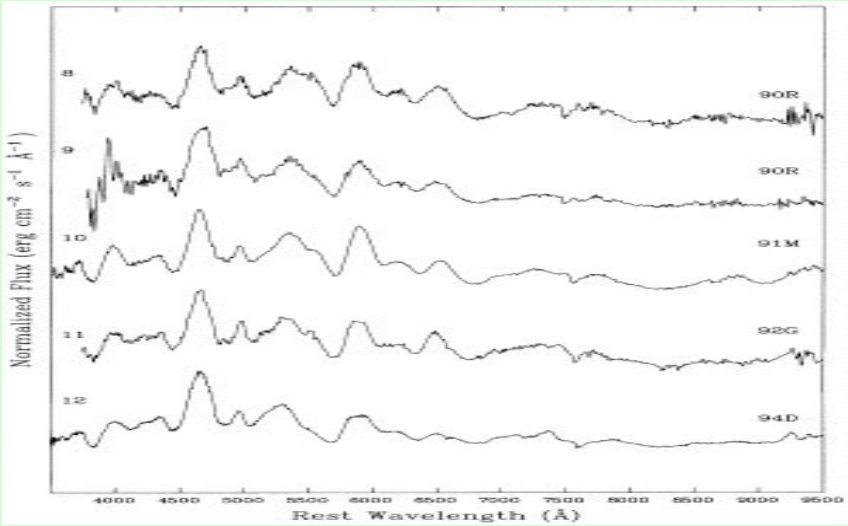
`pseudo-photosphere' to form.

"Photospheric Epoch"

(early time)

P-Cygni Profiles superposed on continuum





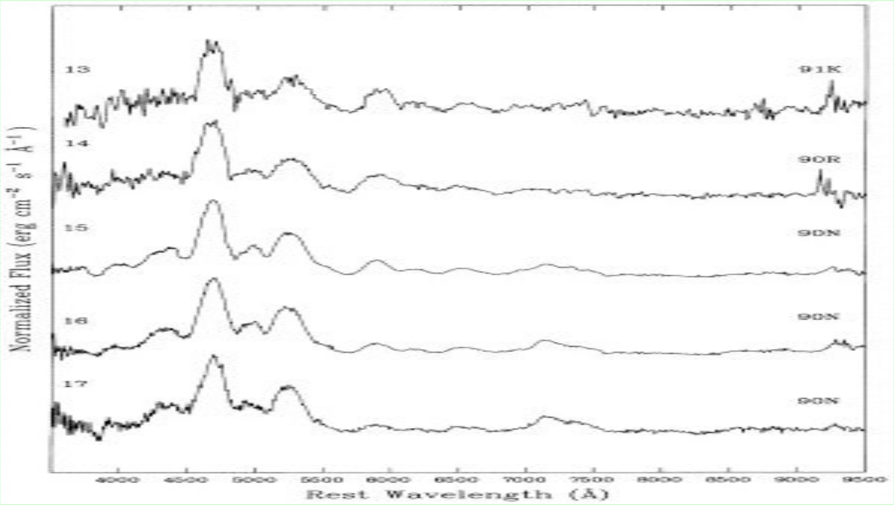
SNIa Spectral Evolution: late

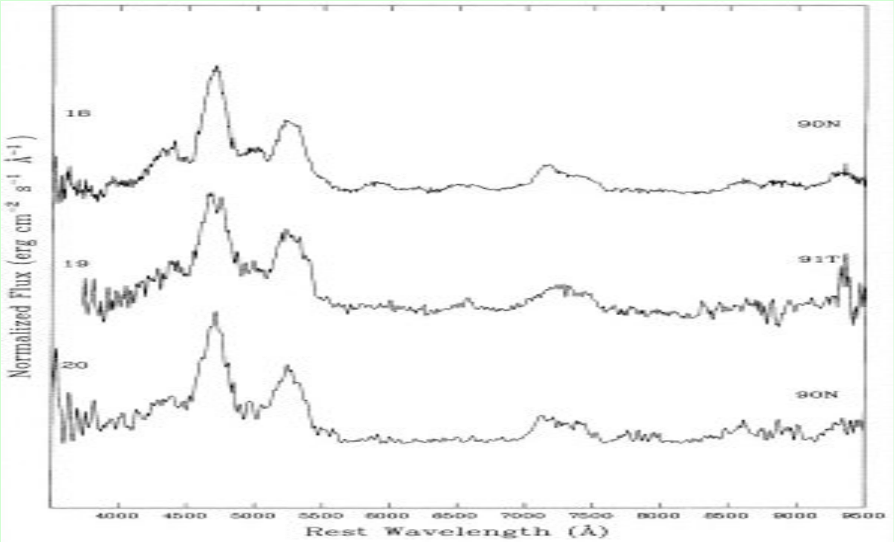
Later on, photosphere disappears as densities decrease.

"Nebular Epoch"

(late time)

Emission-line spectrum





Gomez & Lopez 1998

The Phillips Relation
(Absolute Magnitude - Decline Rate)

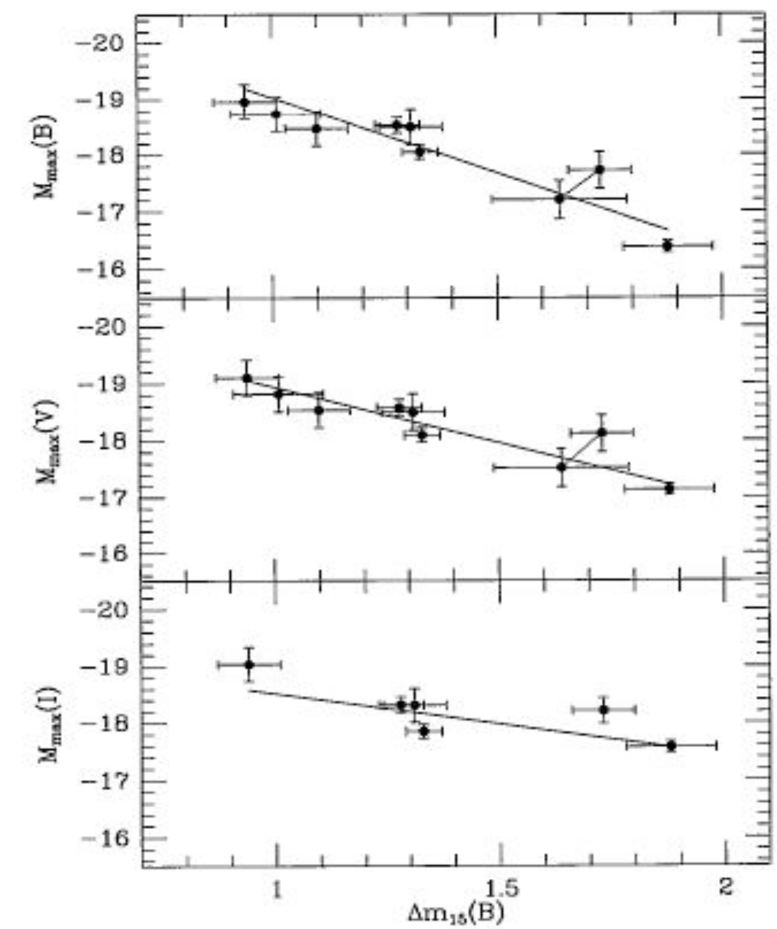
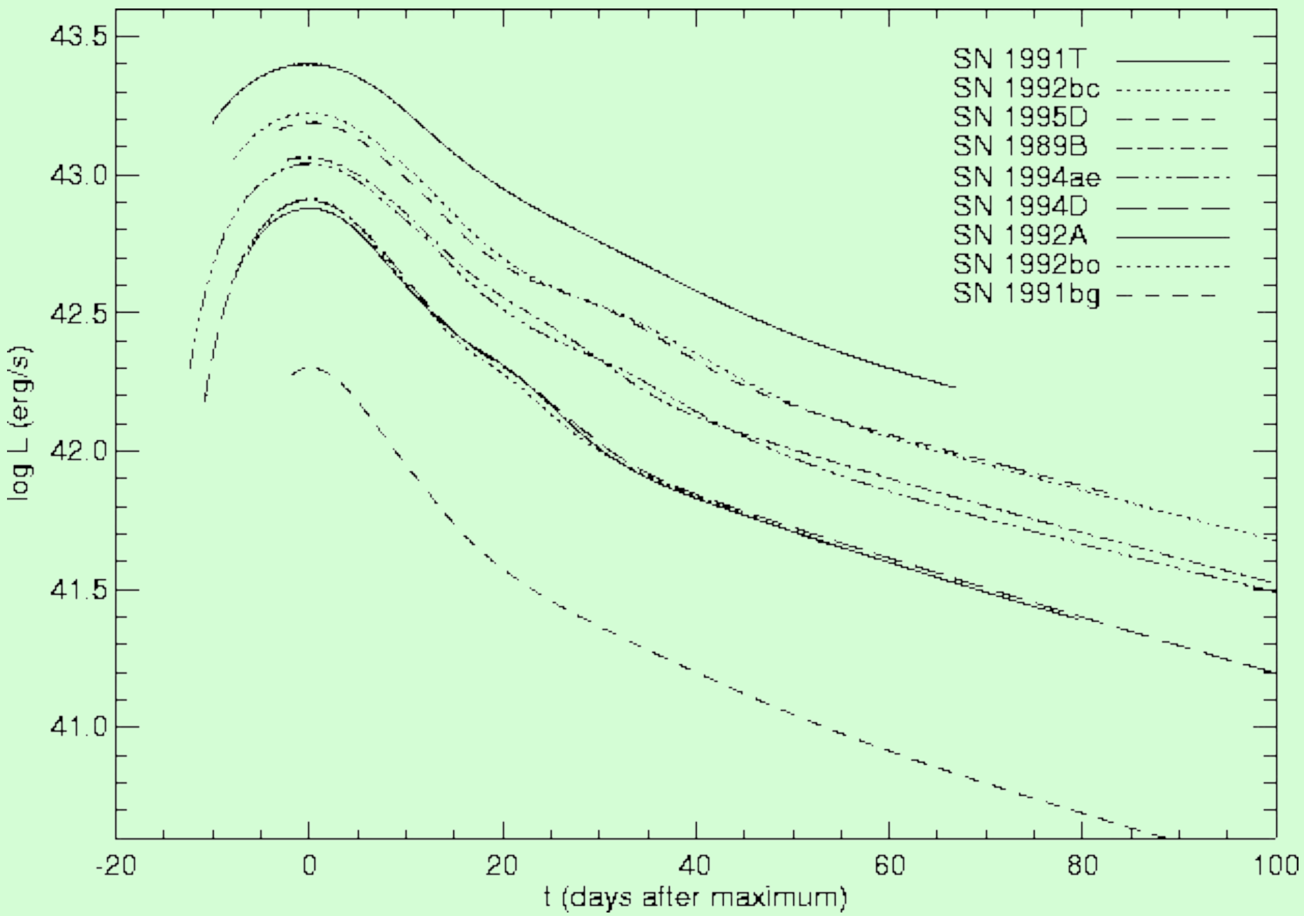


FIG. 1.—Decline rate–peak luminosity relation for the nine best-observed SN Ia's. Absolute magnitudes in B, V, and I are plotted vs. $\Delta m_{15}(B)$, which measures the amount in magnitudes that the B light curve drops during the first 15 days following maximum.

Phillips 1993

Bolometric Light Curves

Lpeak - decline rate or LC shape



Contardo et al. 2000

Light curve powered by ^{56}Ni decay

- $^{56}Ni \Rightarrow {}^{56}Co \Rightarrow {}^{56}Fe$
- γ-rays and e+ emitted in decay, thermalise and give rise to optical radiation
- Direct evidence from observation of emission line of Co, which decays in time relative to lines of Fe

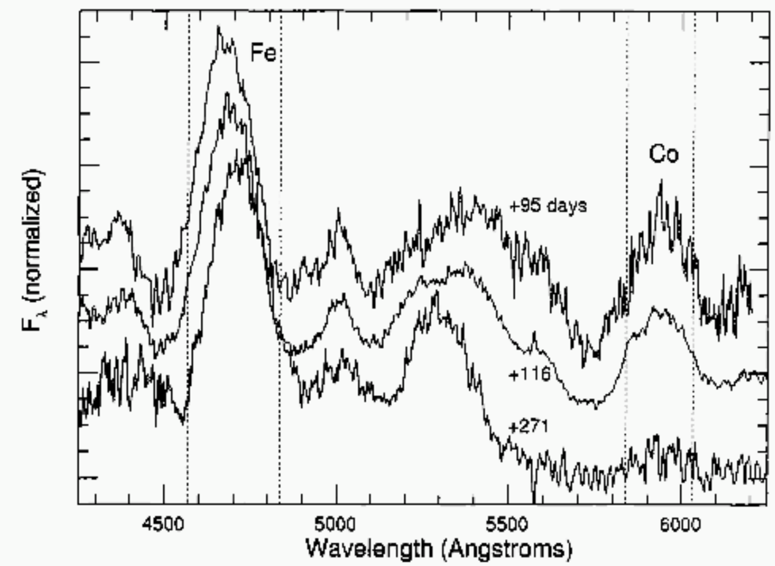
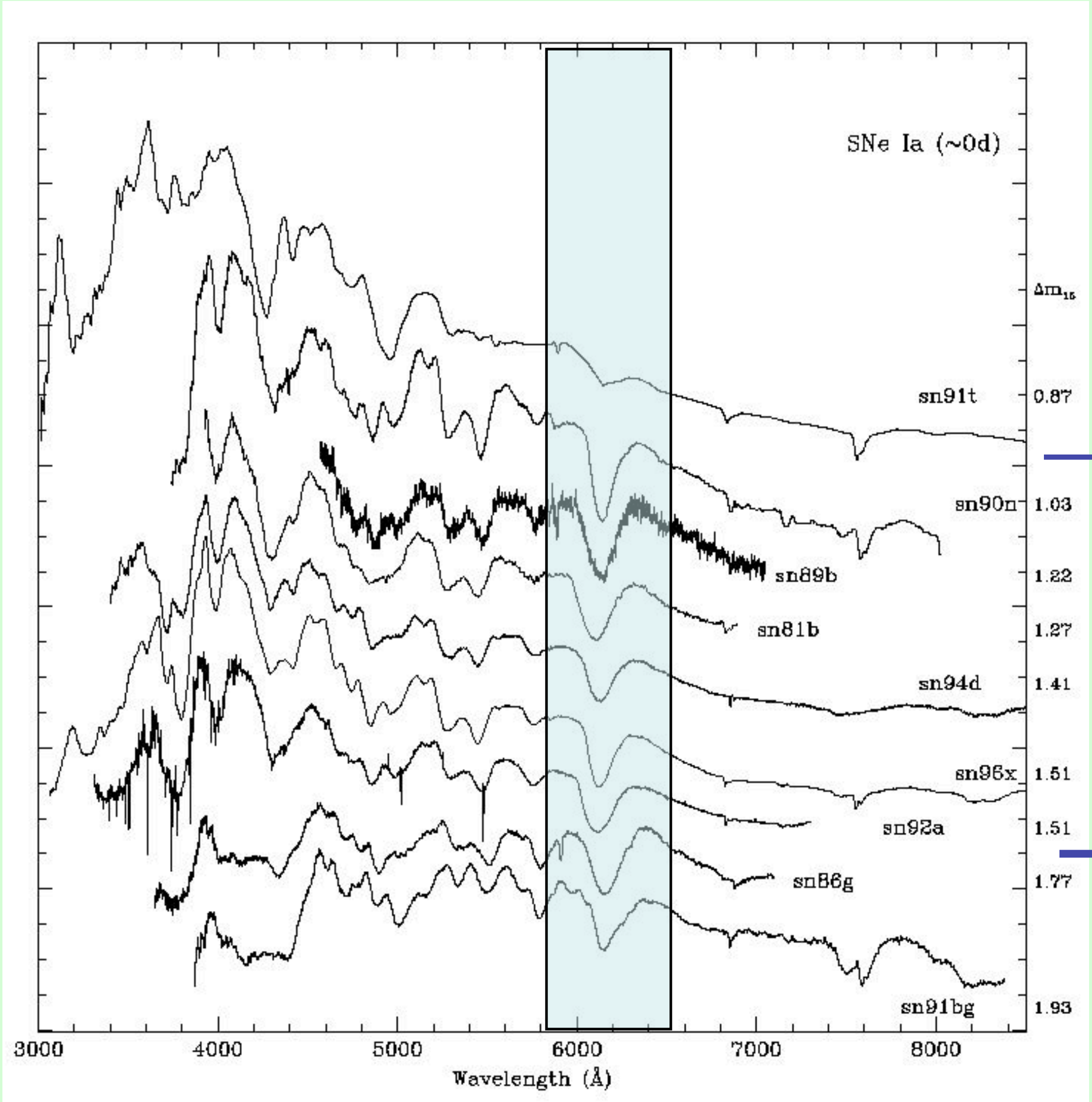


FIG. 1.—Normalized spectra of SN 1981B taken 95, 116, and 271 days after B maximum. Dotted lines indicate the limits of integration which define the Fe and Co features we measured. As the supernova ages, the decline of the cobalt feature relative to the iron feature is conspicuous.

Kuchner et al. 1994

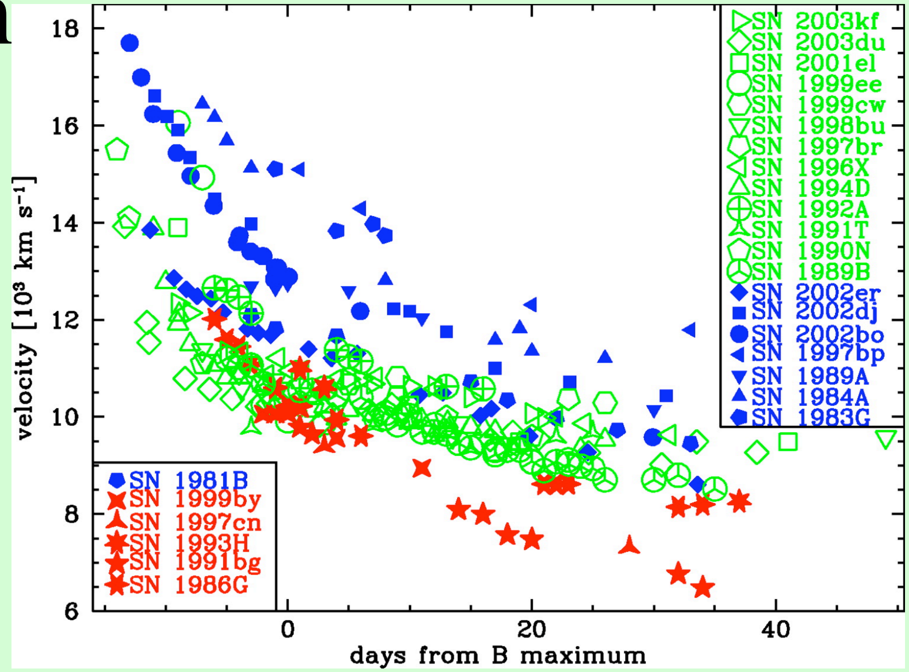
Happy b'day, Bob!

SNe Ia @ maximum



Spectroscopically "normal"

Velocity Gradients: an alternative SN Ia classification



Benetti et al. (2005):

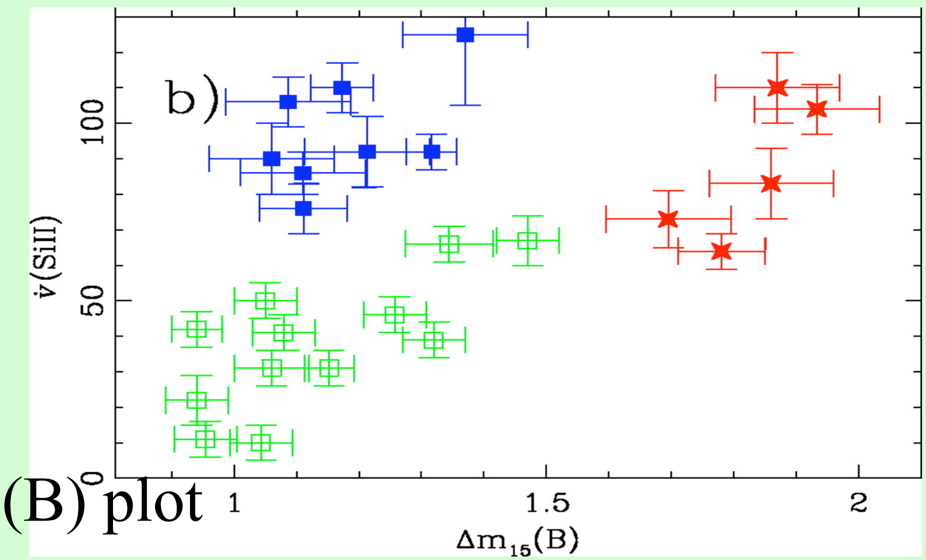
- Classify SNeIa according to rate of change of post-maximum photospheric velocity of SiII 6355

→ 3 SN groups:

High
Velocity Gradient Low
Velocity Gradient Faint

- Groups separate out

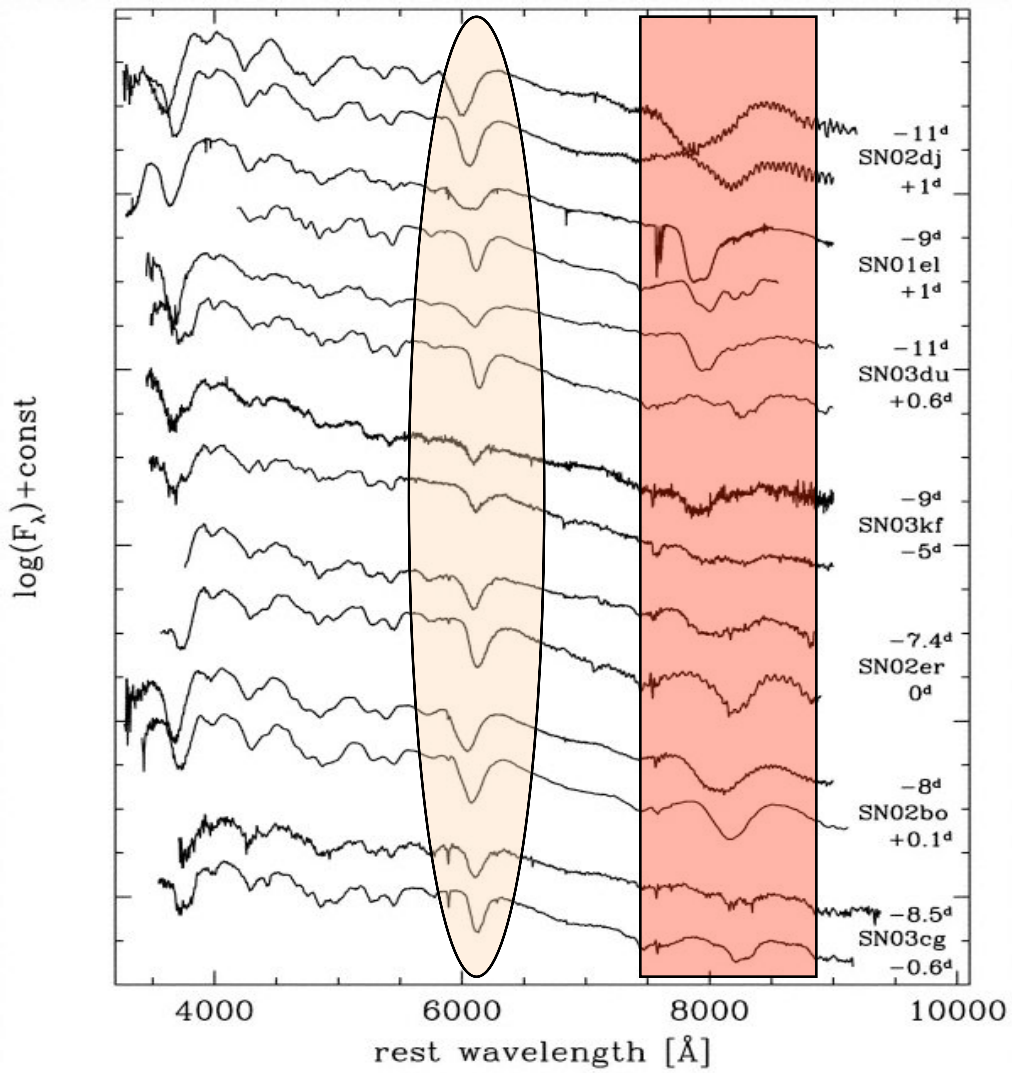
in dv/dt-ΔM15(B) plot



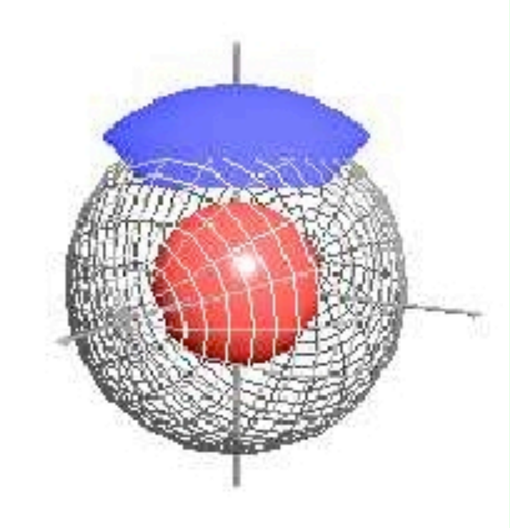
Outer regions of the ejecta: HVFs

- Nearly all SNe show very High Velocity (~20000 km/s) absorption Features (HVF) in Ca II (some also in Si II)

Mazzali et al (2005)

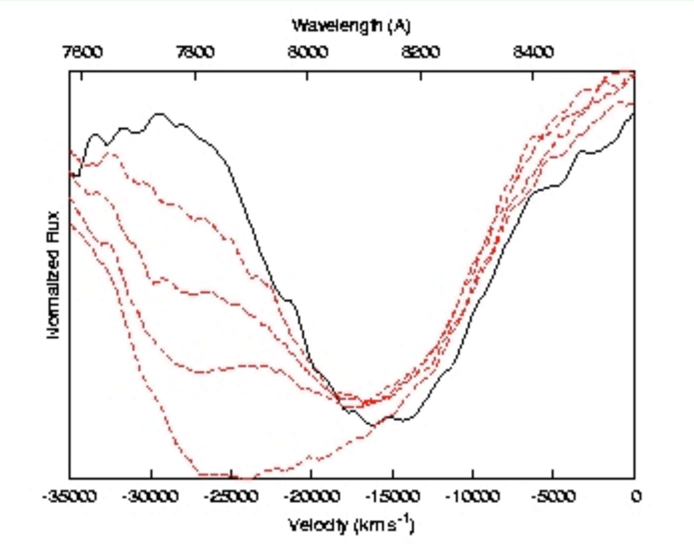


HVFs trace the outer explosion



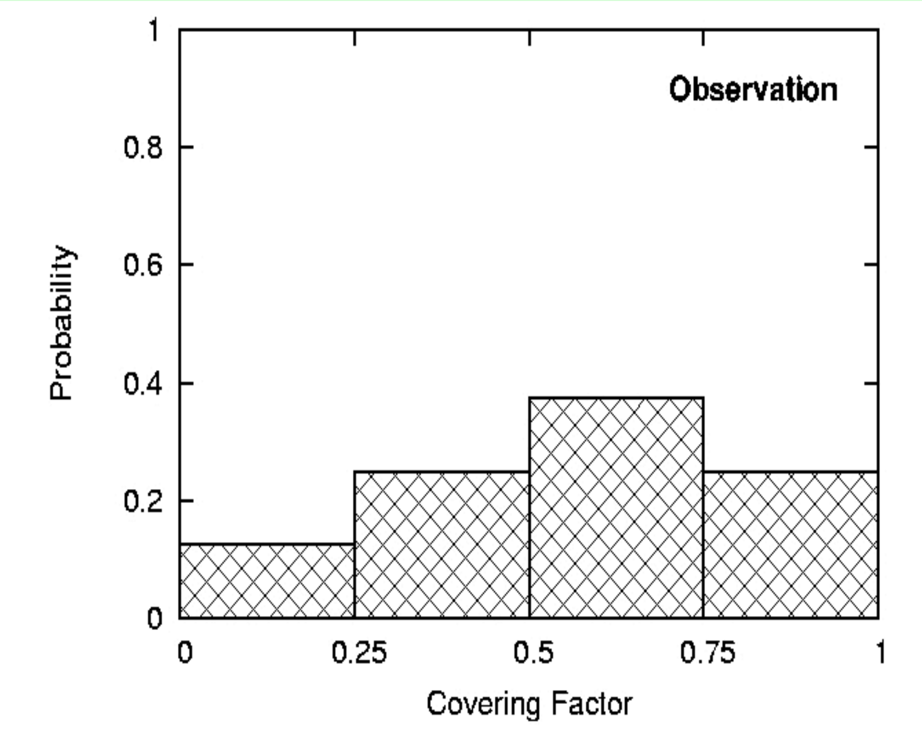
What makes the HVFs?

- Abundance enhancement unlikely
- Density enhancement more reasonable (incl. H)
- Ejection of blobs or CSM interaction?
- Blobs: line profiles depend on orientation

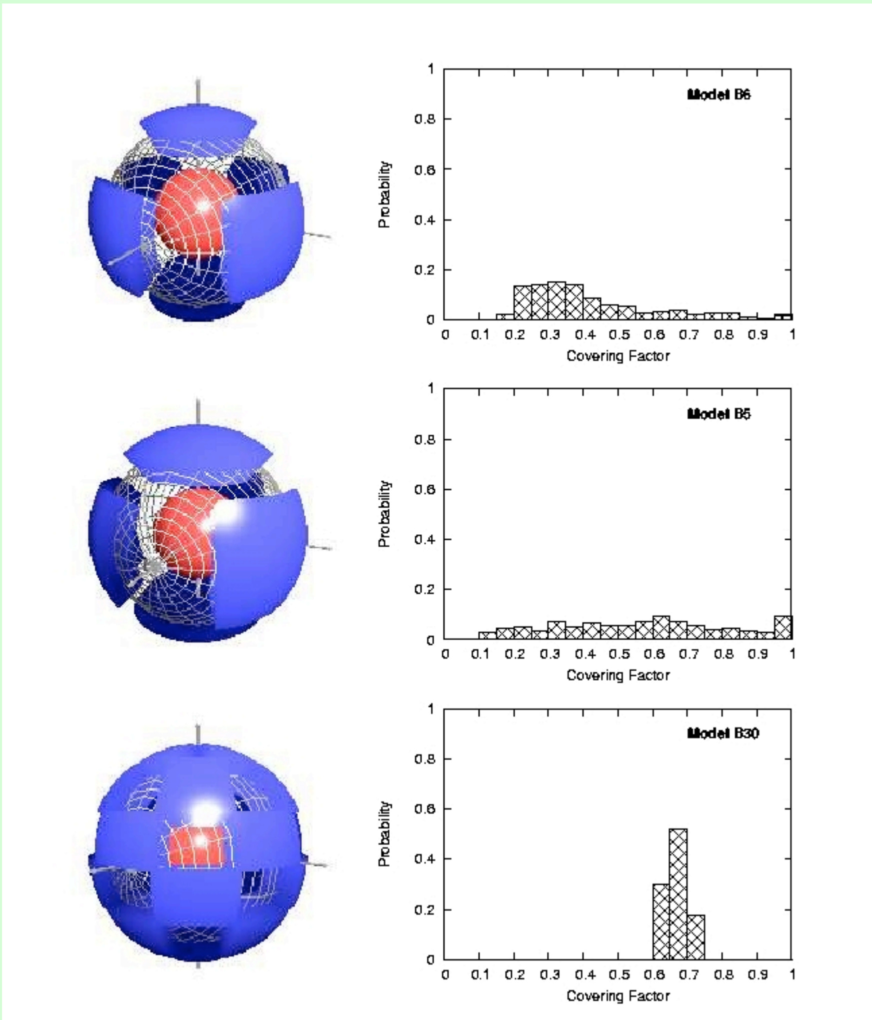


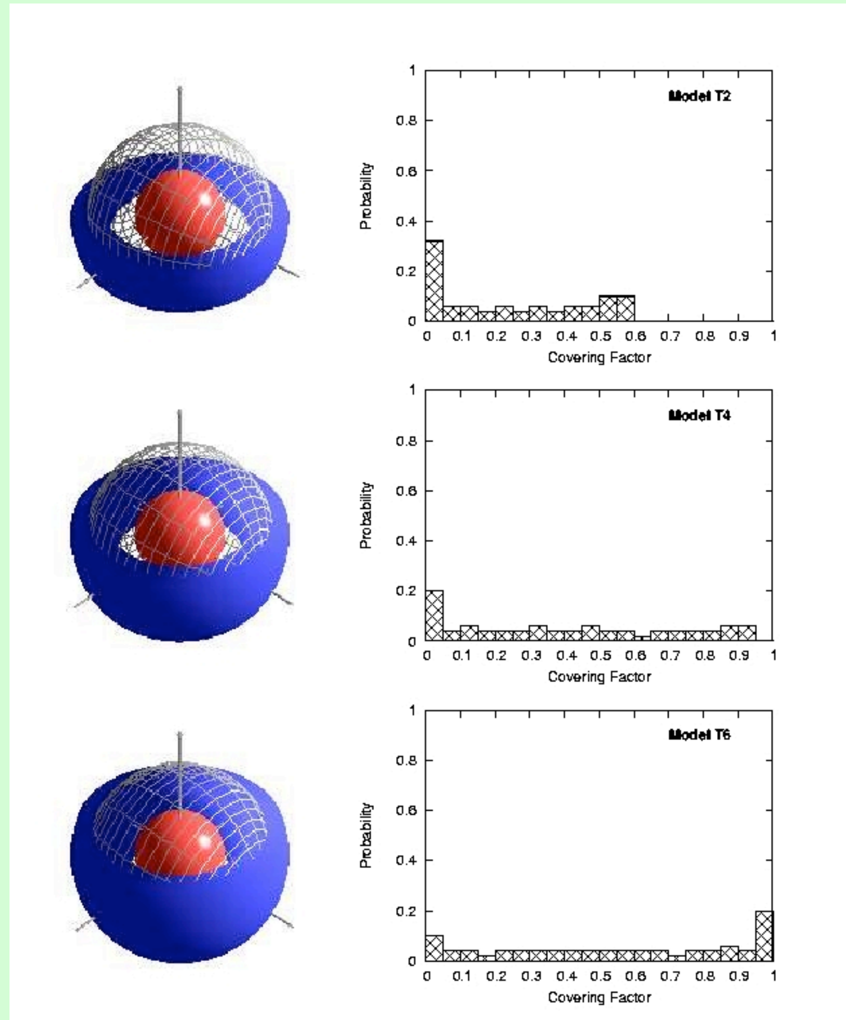
Distribution of HVFs

- Any model should reproduce the observed distribution of HVF wavelength (blob velocity) and strength (optical depth, covering factor)
- Single blob does not

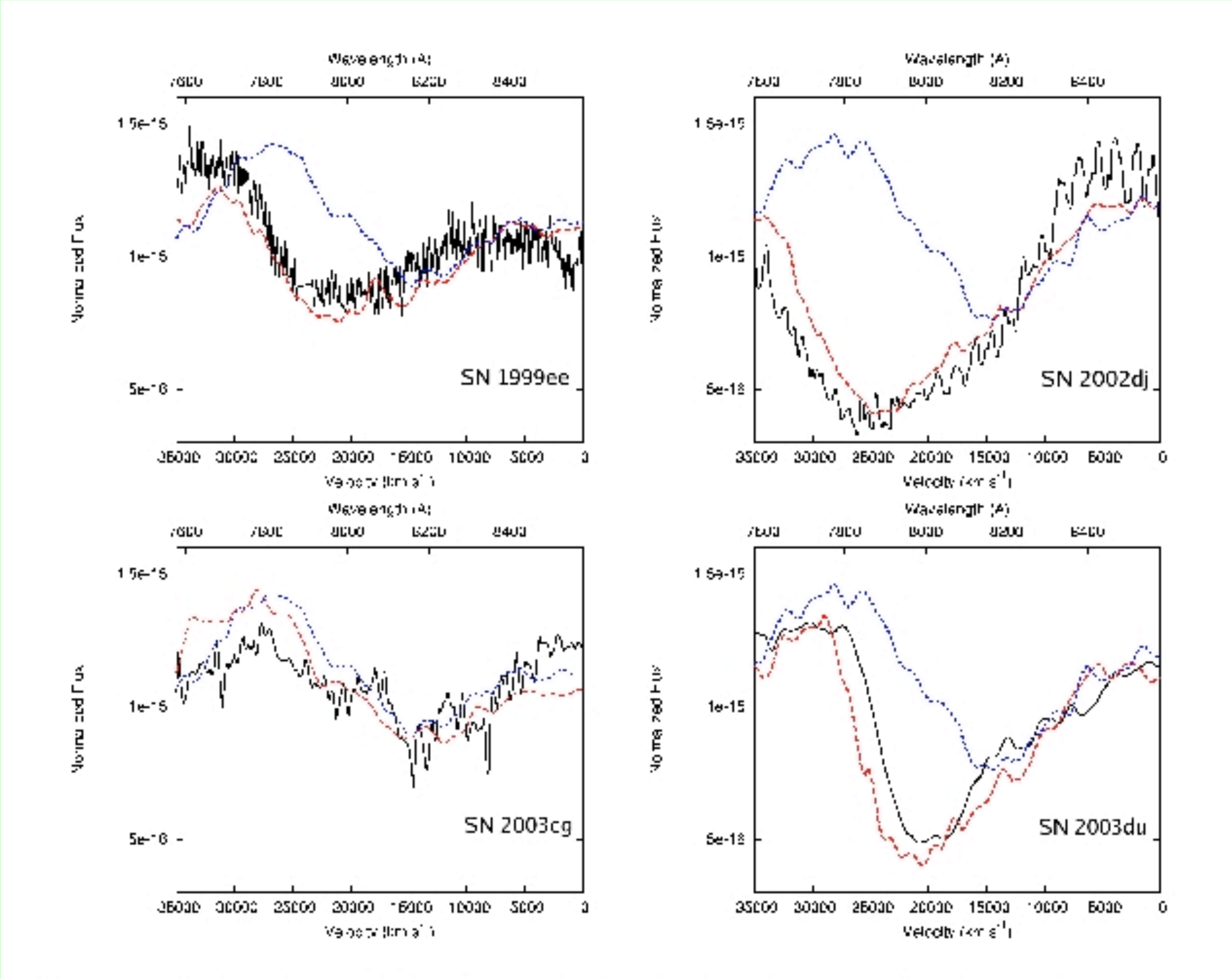


Need a few blobs or a thick torus



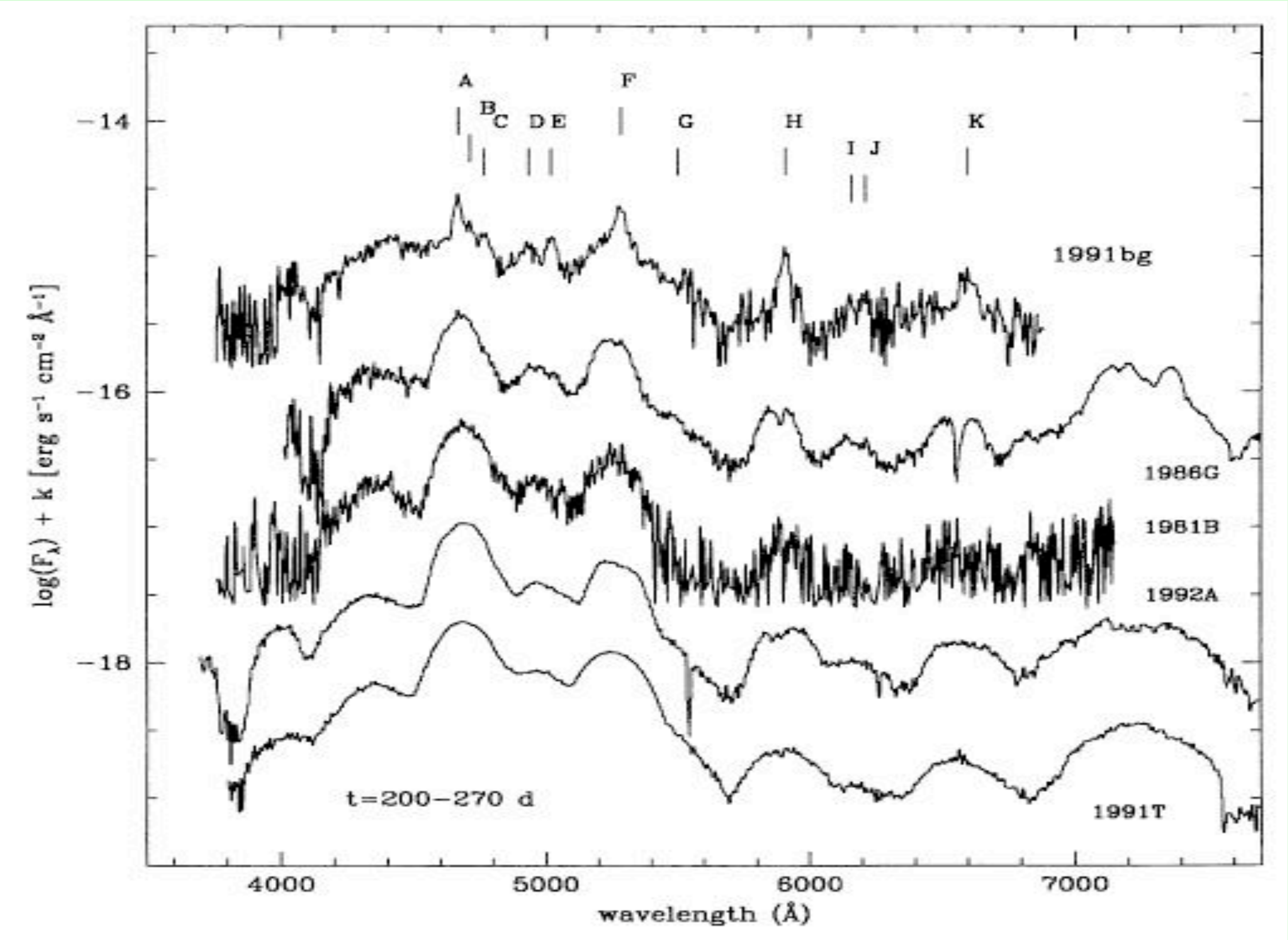


Use blobs to fit spectra



Tanaka et al. 2006

SNe Ia: late-time spectra



Δm15(B)

1.93

1.77

1.27

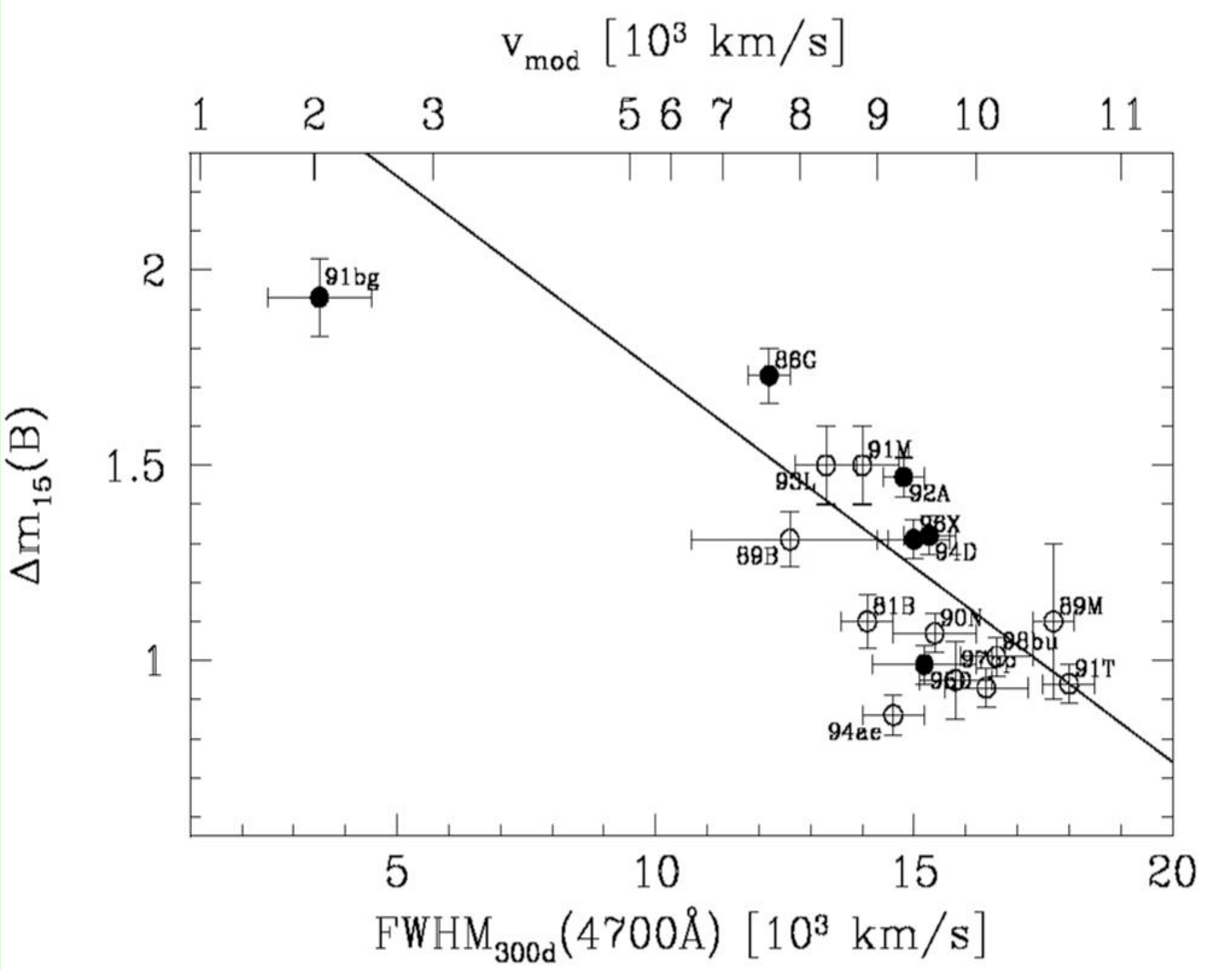
1.51

0.87

Mazzali et al. 1998

Nebular line width - decline rate

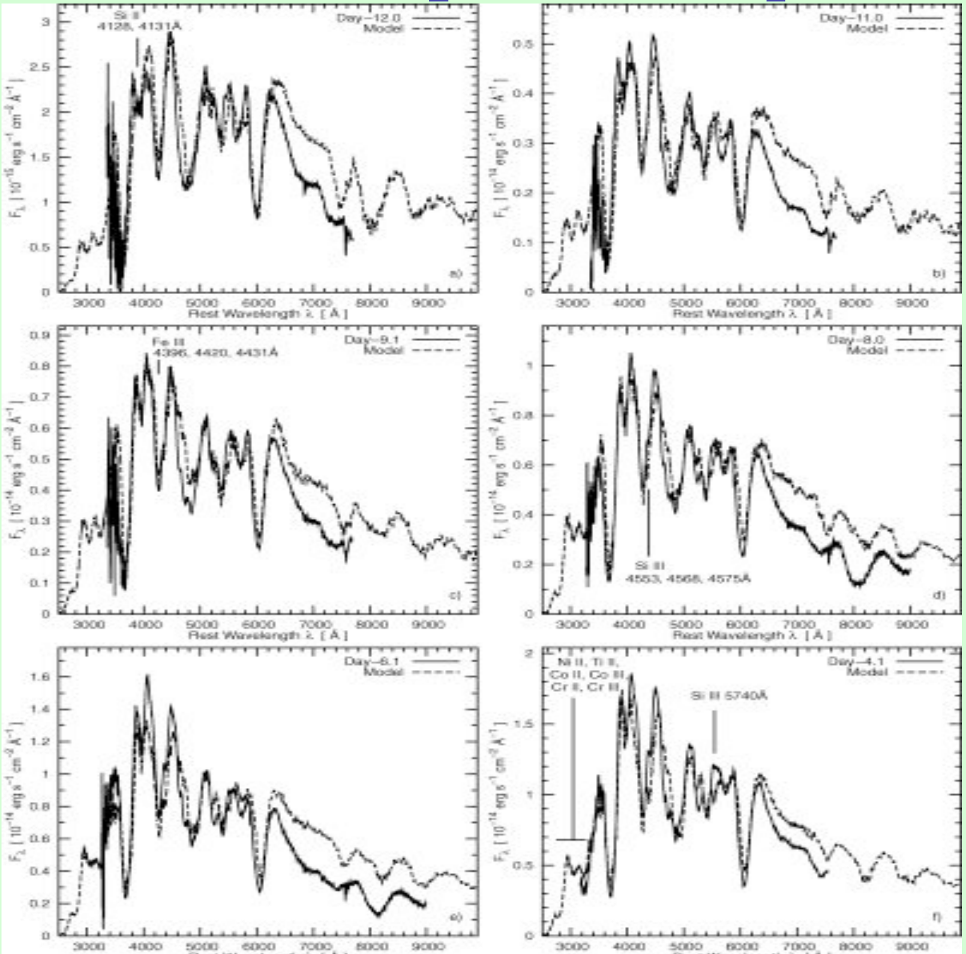
^{56}Ni mass and distribution and decline rate (≡Luminosity) are related

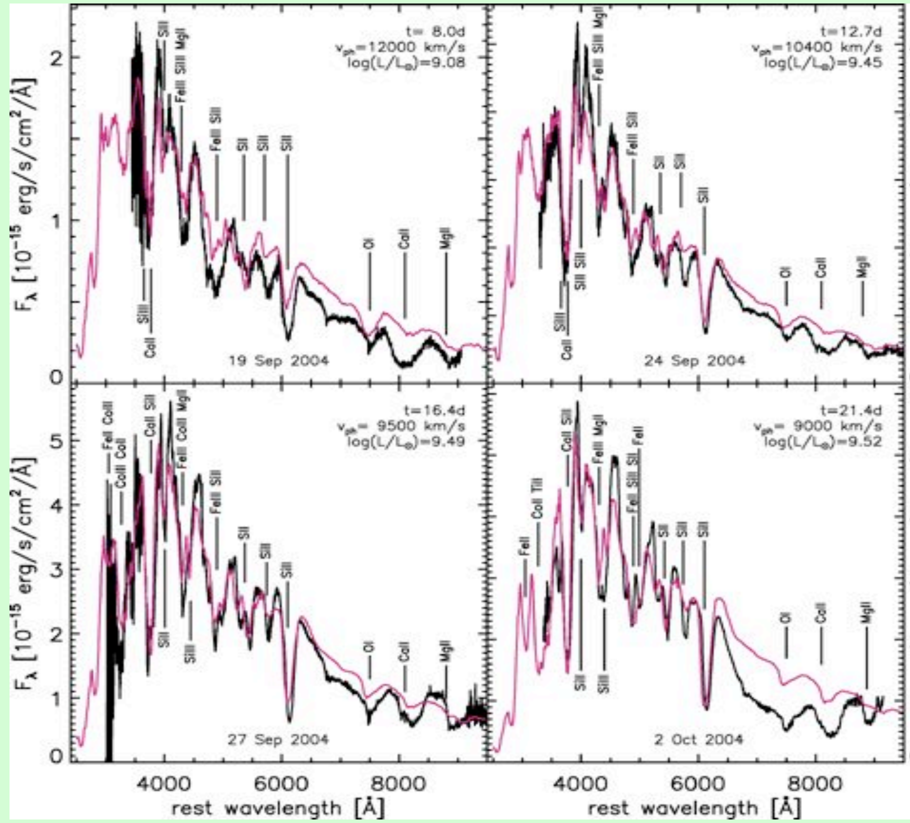


after Mazzali et al. 1998

Abundance Stratification

Models of spectral sequence give composition layering





SN 2002bo: bright [$\Delta m_{15}(B)$=1.15] SN 2004eo: dim [$\Delta m_{15}(B)$=1.45]

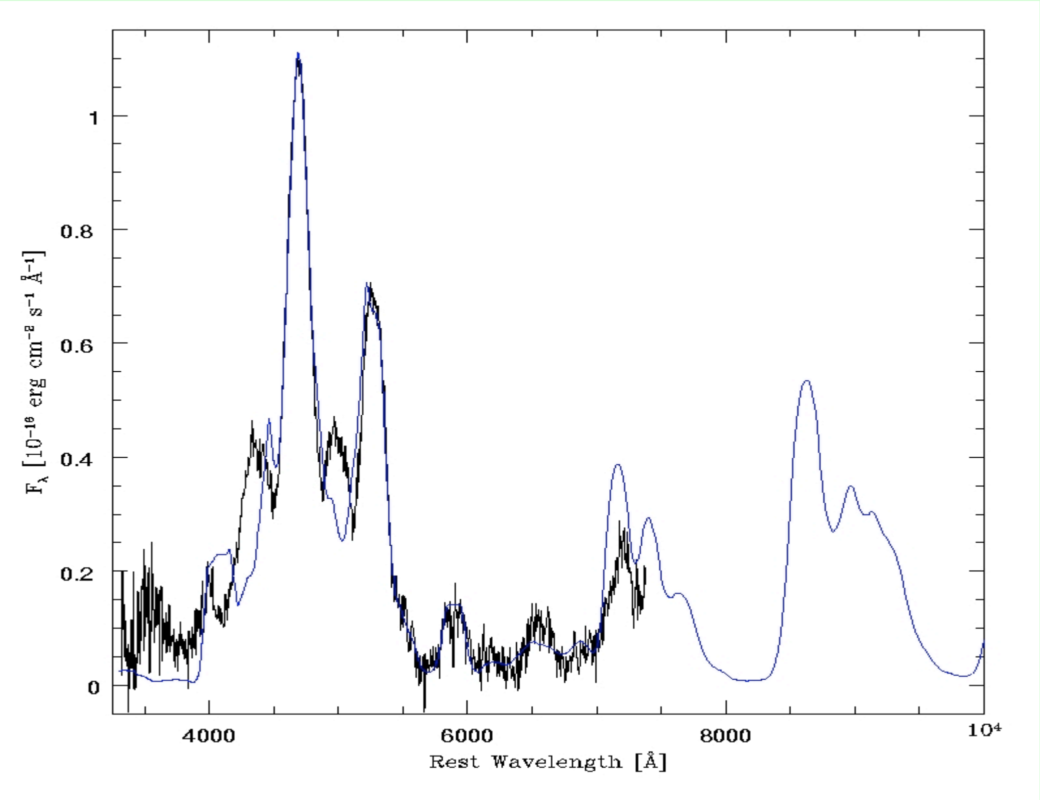
(Stehle et al. 2005) (Mazzali et al. 2008)

Late-time spectra

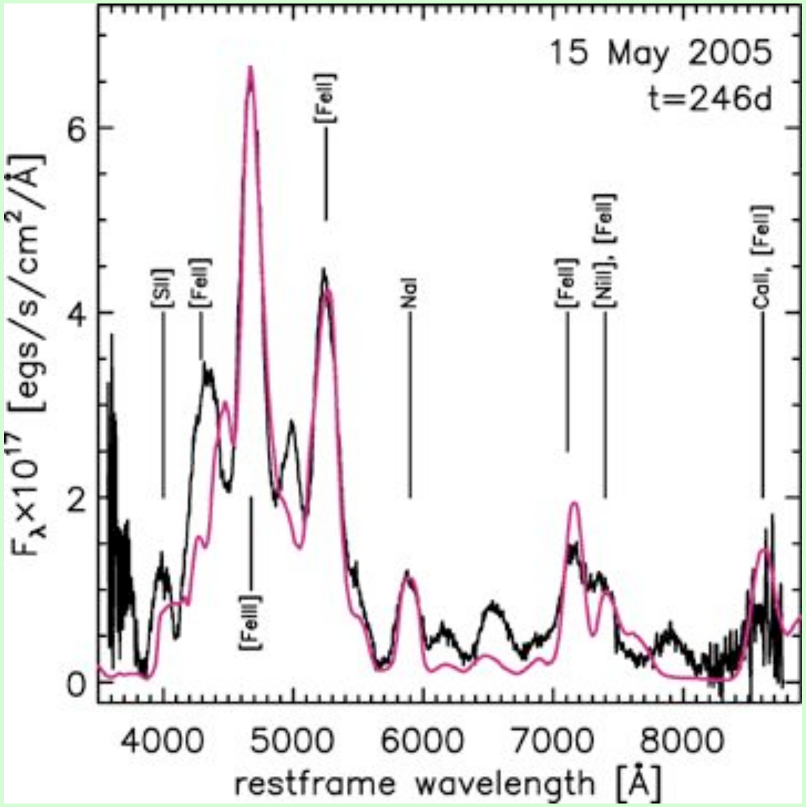
Full view of inner ejecta (^{56}Ni zone)

Monte Carlo LC code + NLTE nebular code (no radiative transfer)

- Estimate masses



SN 2002bo

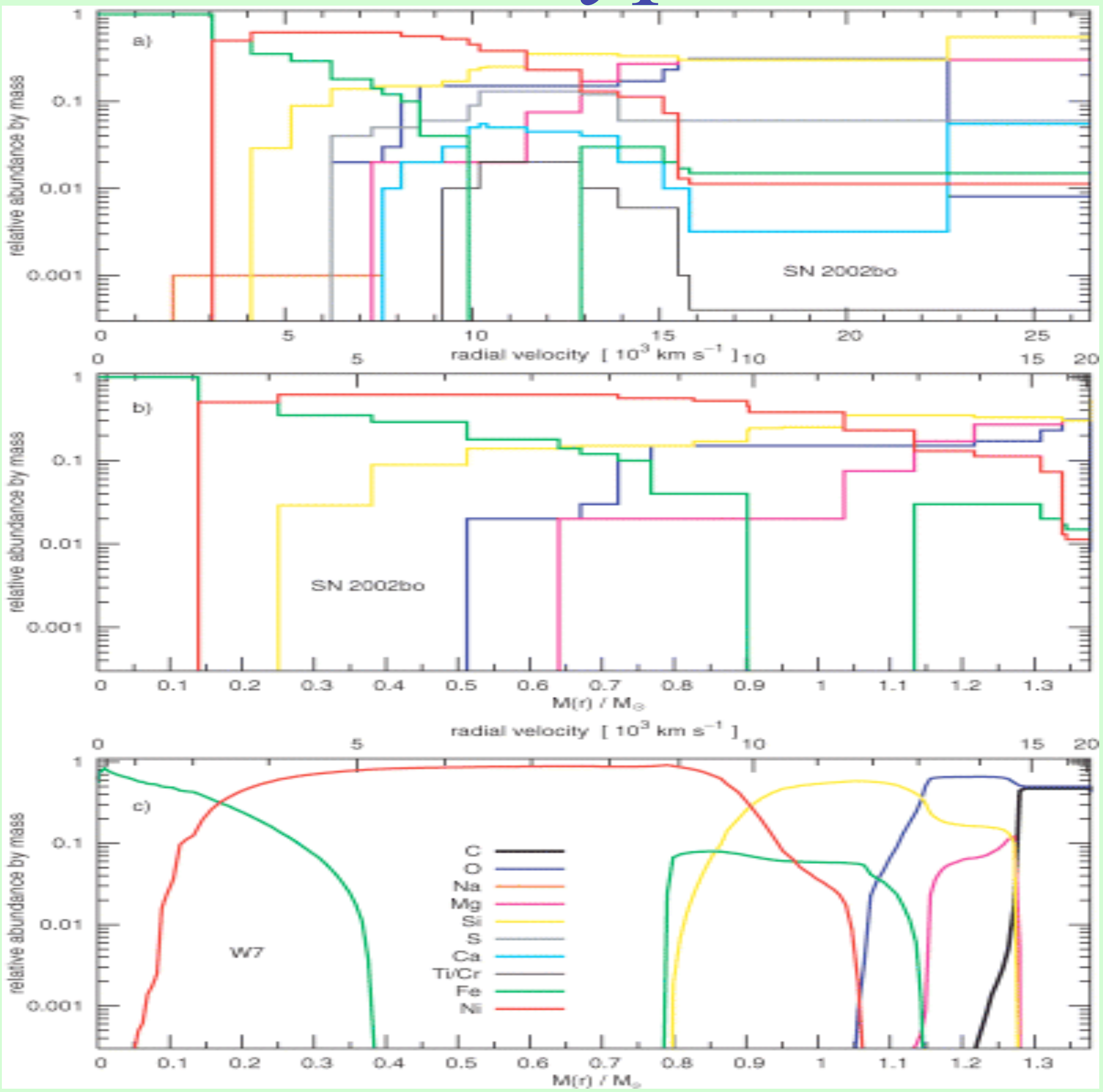


SN 2004eo (narrower lines)

Result: Composition in a typical SN Ia

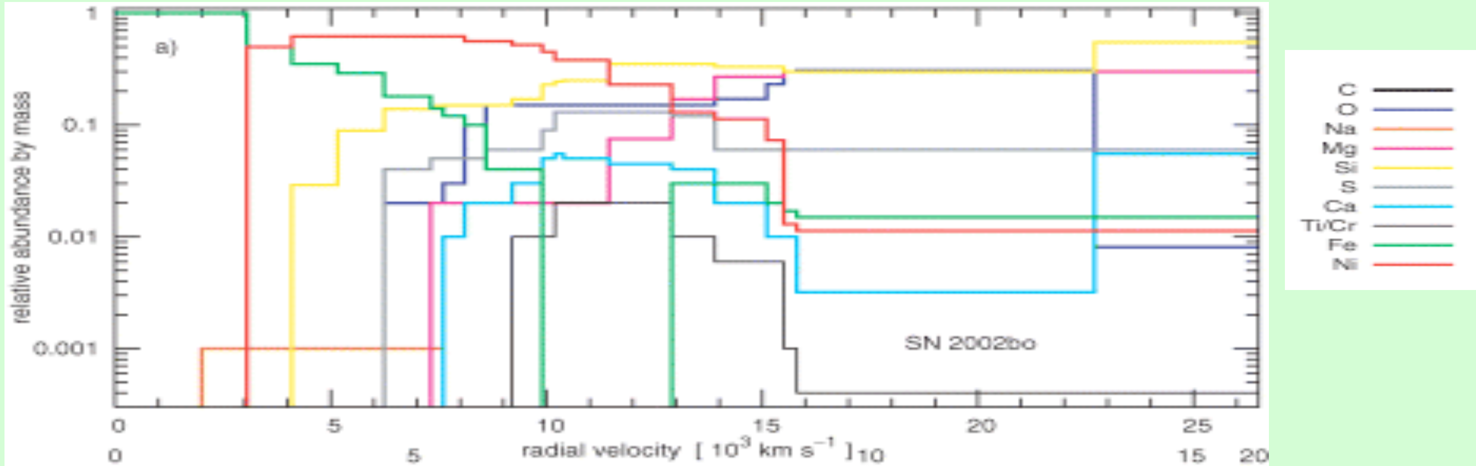
- SN 2002bo
  $\Delta m_{15}(B)=1.15$
  (average)

- Elements more mixed than in typical 1D models

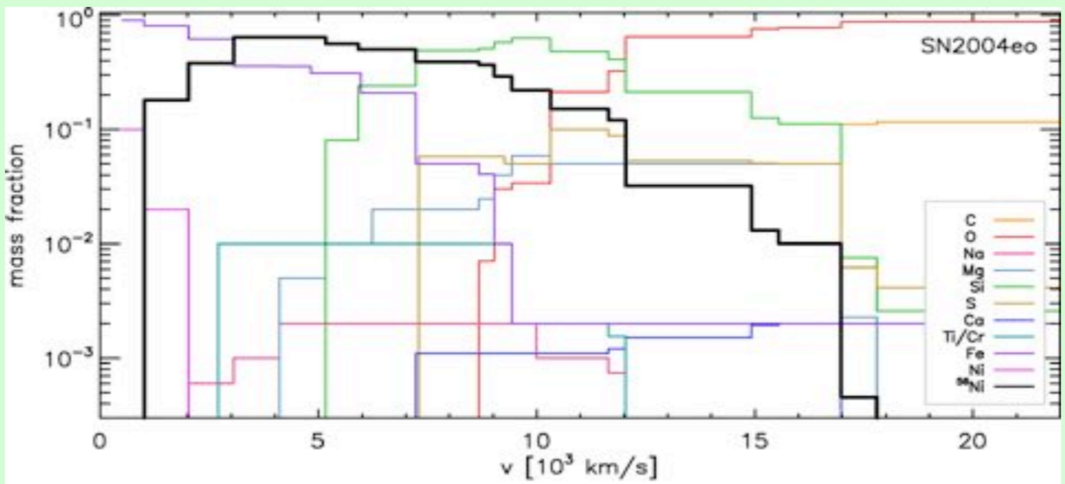


Compare two different SNe

SN 2002bo



SN 2004eo



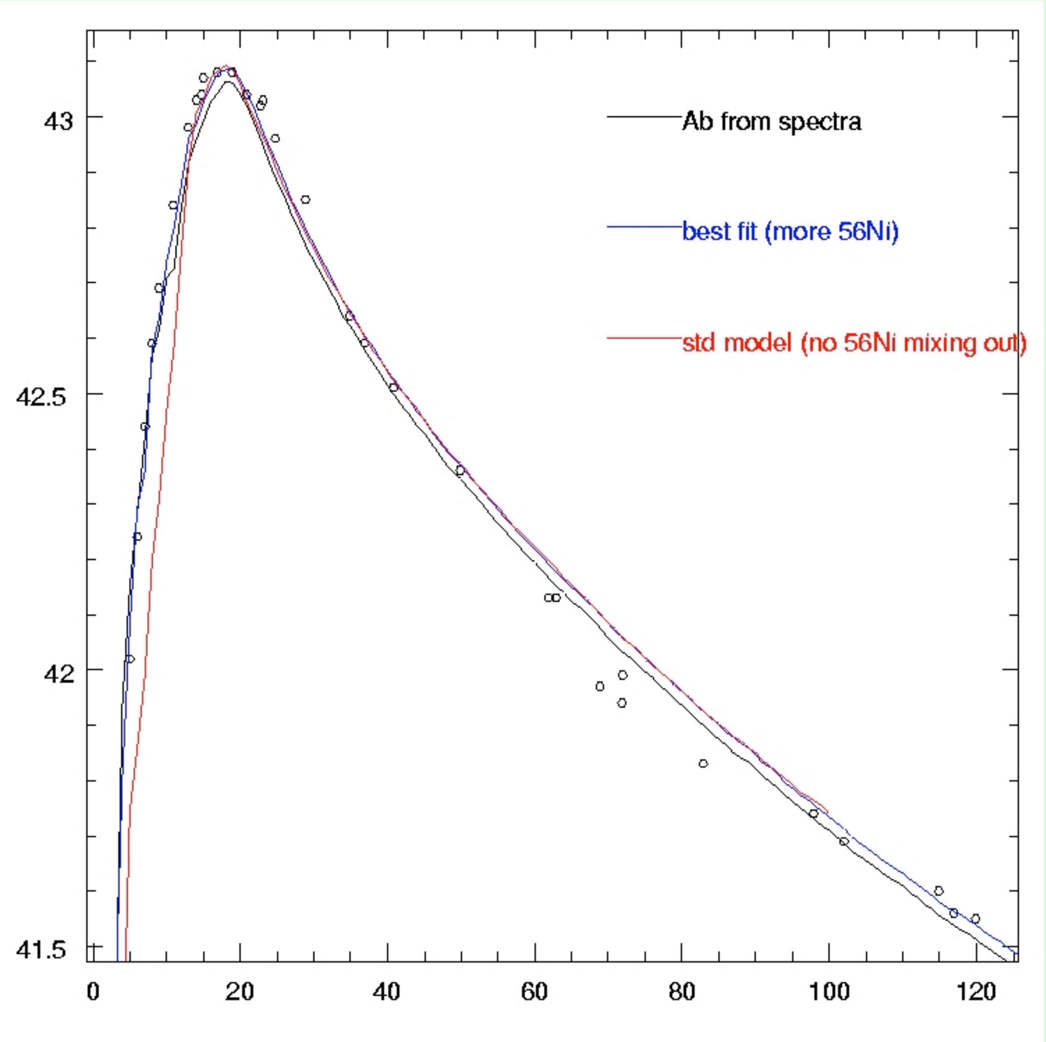
SN2002bo (brighter) has more burning

Test: Modelling Light Curve

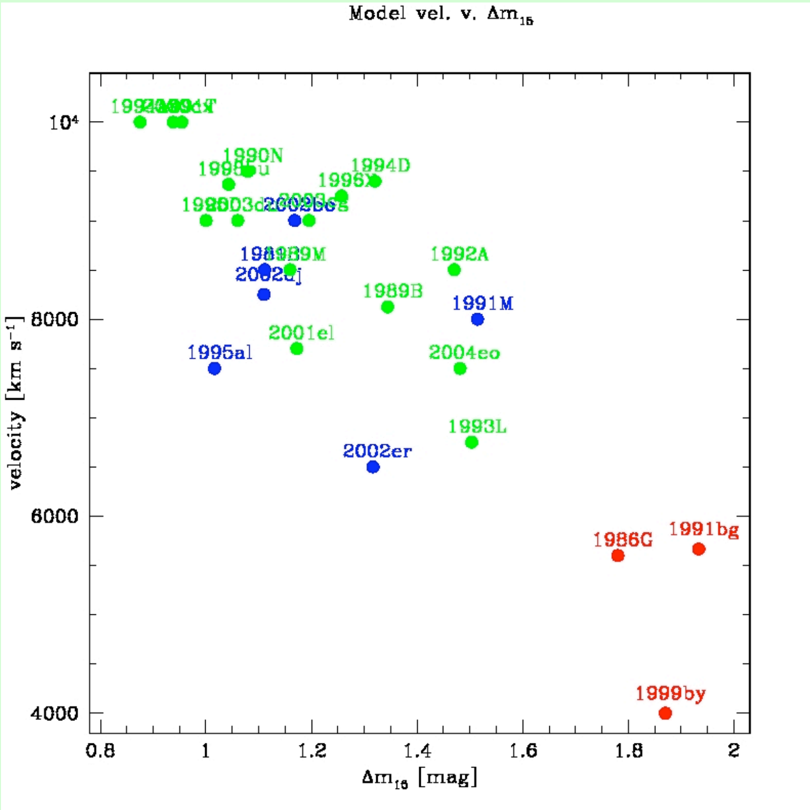
Monte Carlo code

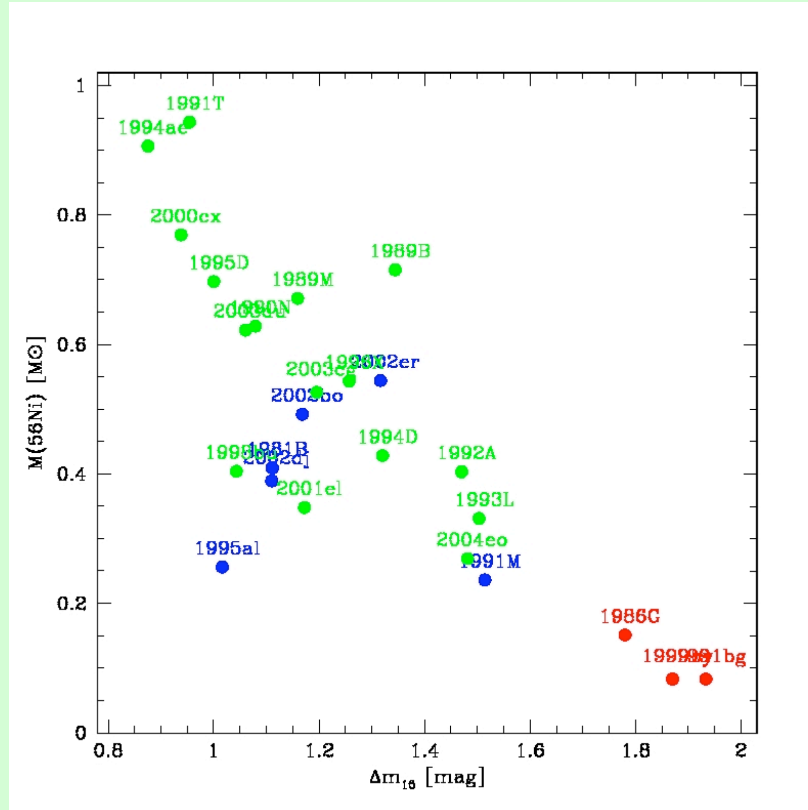
- Use W7 density
- Composition from tomography
- ^{56}Ni ~0.50M⊙

→ Model LC matches data very well



The Global View

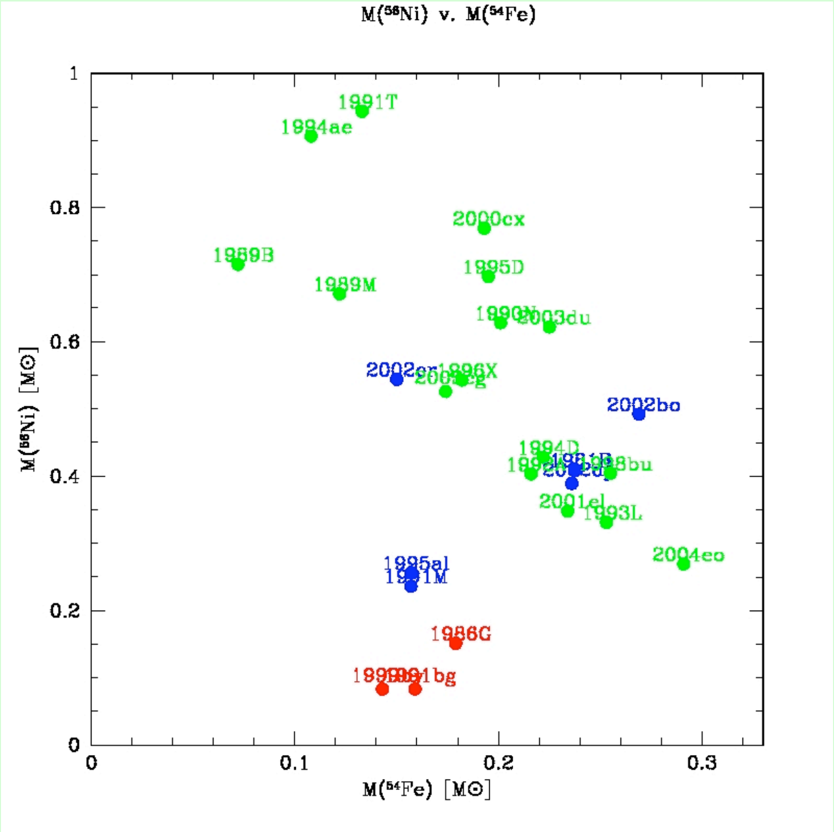


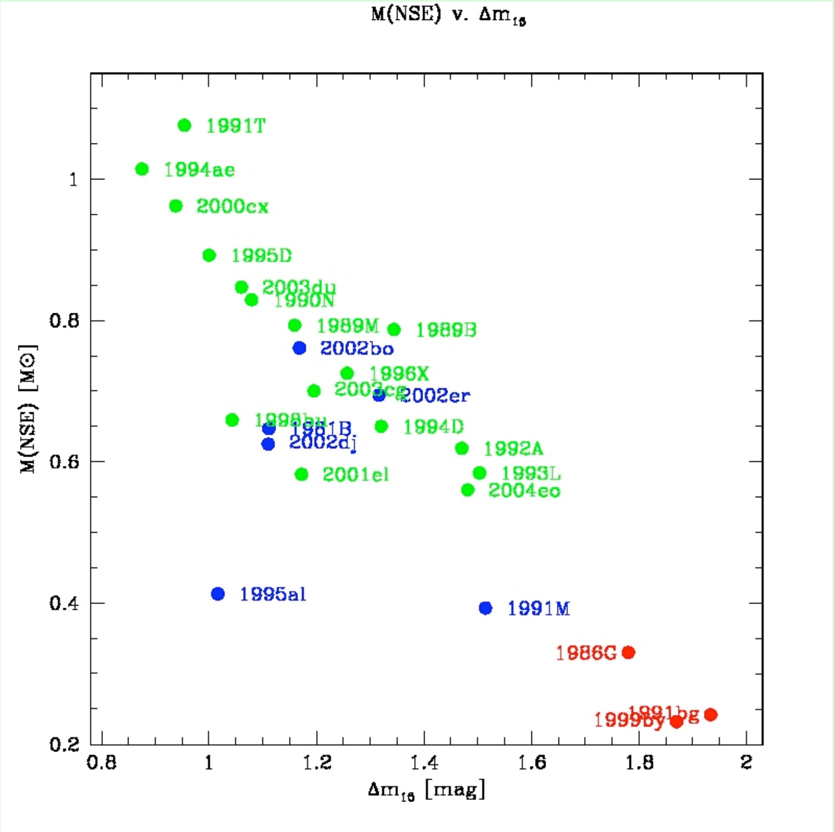


- Late time spectra suggest

$M(^{56}\mathrm{Ni}) \propto \Delta m_{15}(B)$ [$\propto$ M(Bol)

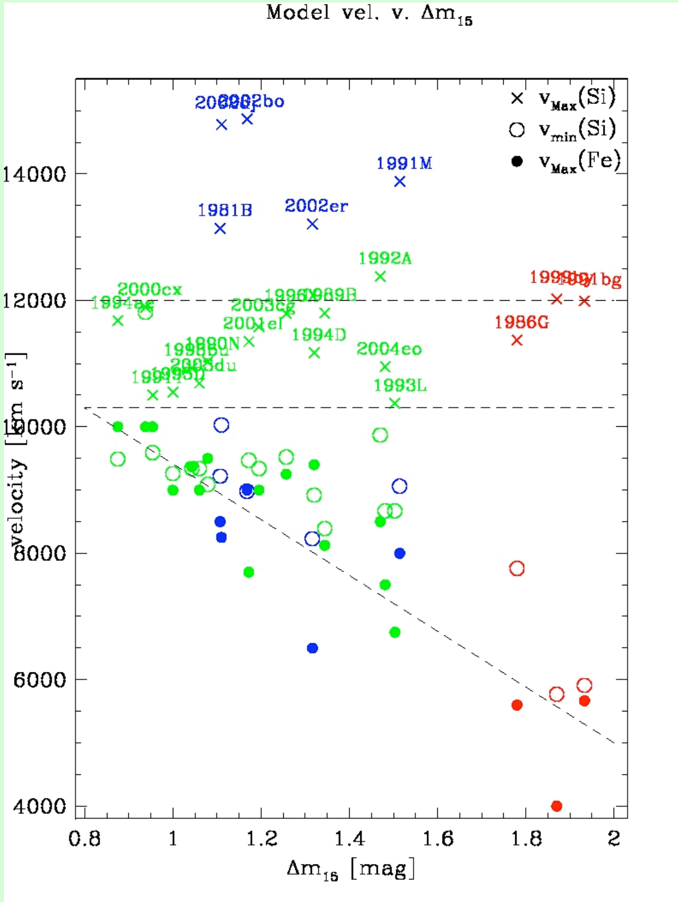
Role of ^{54}Fe, ^{58}Ni

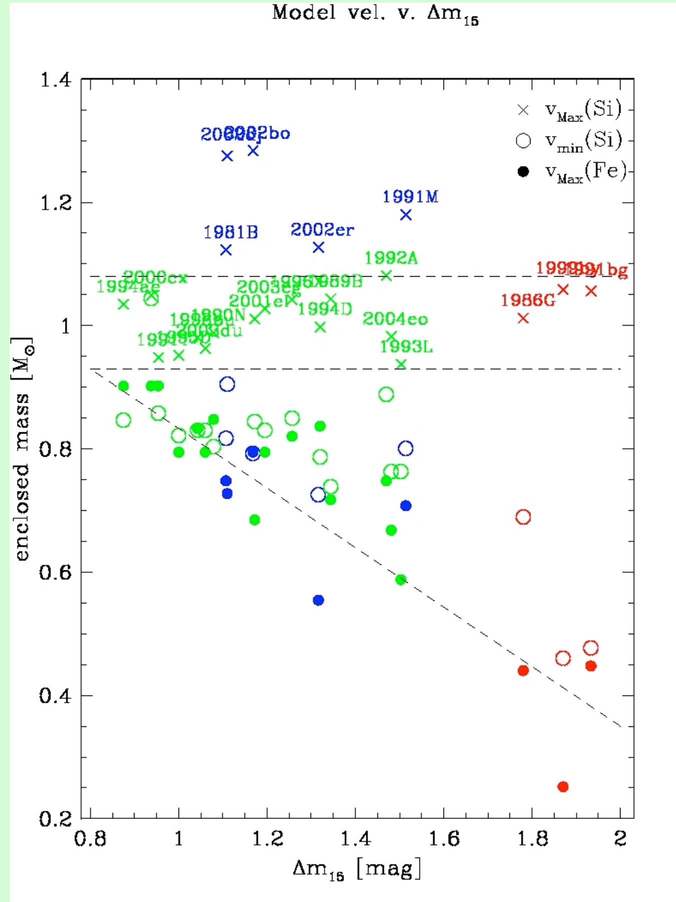




- Stable Fe group isotopes radiate but do not heat
- Some anticorrelation between ^{56}Ni and (^{54}Fe, ^{58}Ni)
- Very good correlation beween Σ(NSE) and Δm_{15}(B)

Composition Layering





- Outer extent of NSE zone varies (∝ Δm_{15}(B), Lum)
- Inner extent of IME matches outer extent of NSE
- Outer extent of IME ~ const.

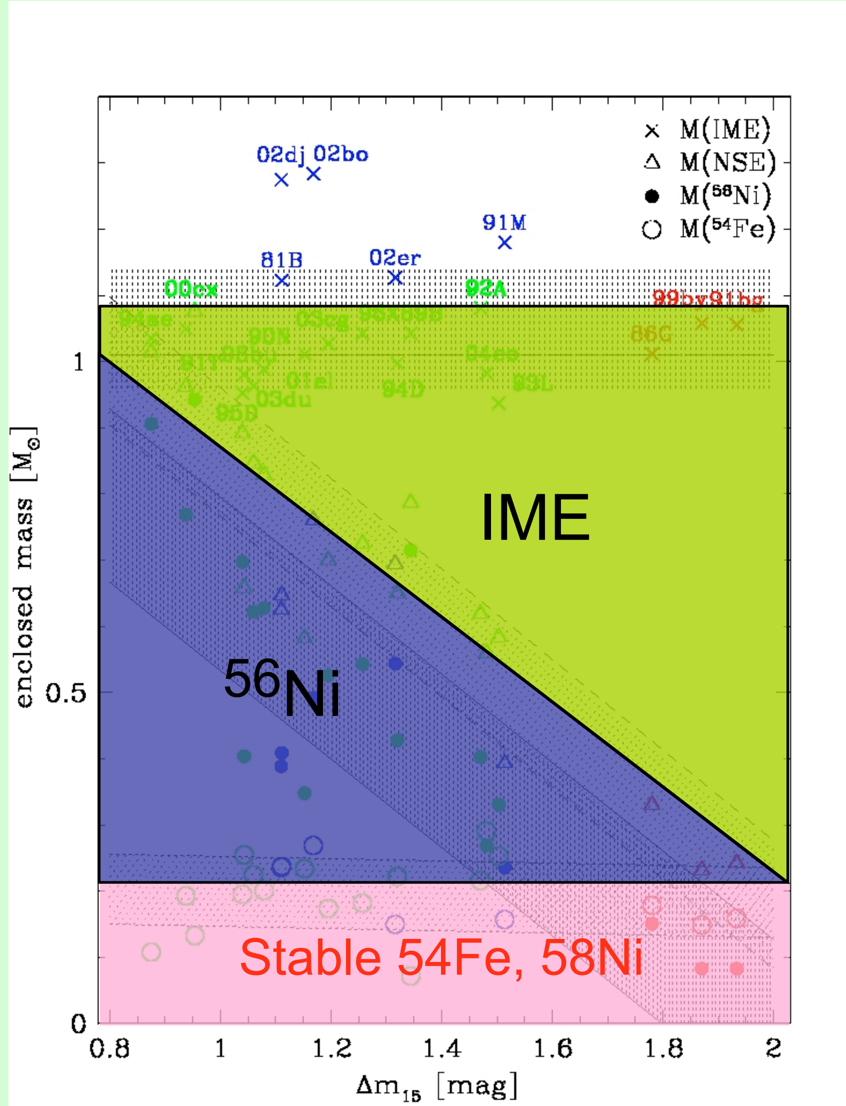
Putting it all together: "Zorro" diagram

A basic property of SNe Ia

Mass burned ~ constant

→ Progenitor mass also probably constant: MCh

→KE ~ const



Mazzali et al. (2007), Science

What does it all mean?

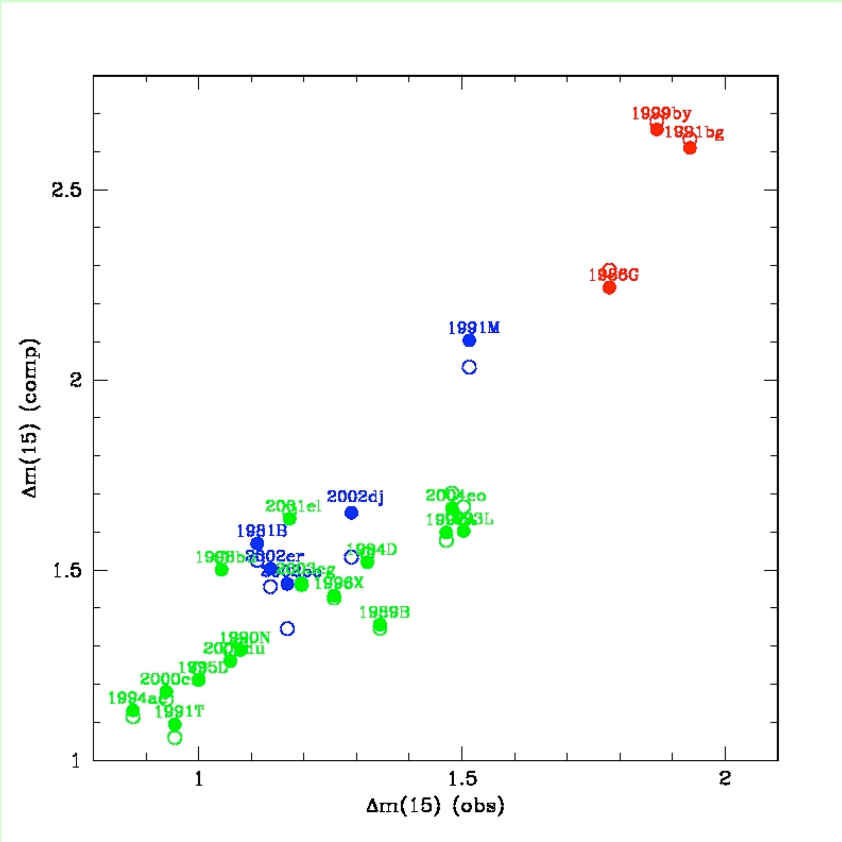
- Delayed detonation?
- Multi-spot ignited deflagration?
- Other possibilities….?

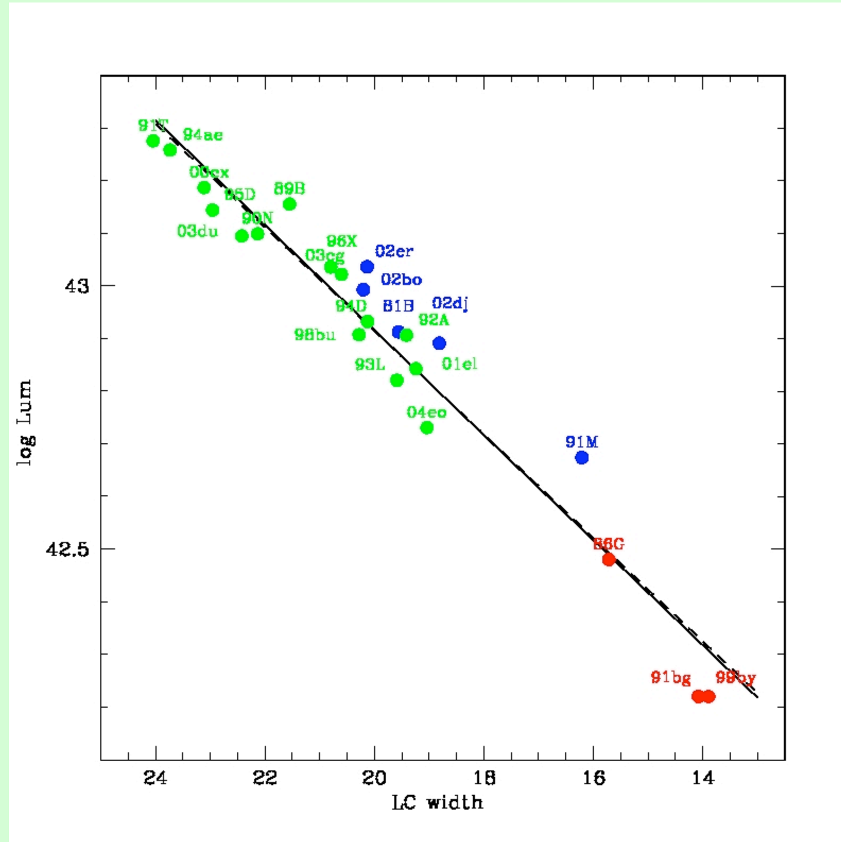
Using Zorro to reconstruct Phillips' Rel'n

- Use composition to compute LC parameters
  - $L = 2 \times 10^{43} M(^{56}\mathrm{Ni})$
  - $\tau \propto \kappa^{\frac{1}{2}} E_k^{-\frac{1}{4}} M_{ej}^{\frac{3}{4}}$
  - $E_k = [1.56M(^{56}\mathrm{Ni}) + 1.74M(stable\mathrm{NSE}) + 1.24M(\mathrm{IME}) - 0.46] \times 10^{51}\mathrm{erg}$
  - $\kappa \propto M(\mathrm{NSE}) + 0.1M(\mathrm{IME})$

- Derive Phillips Relation

Using Zorro to reconstruct Phillips' Rel'n





- Use composition to compute LC parameters √
- Derive Phillips Relation √

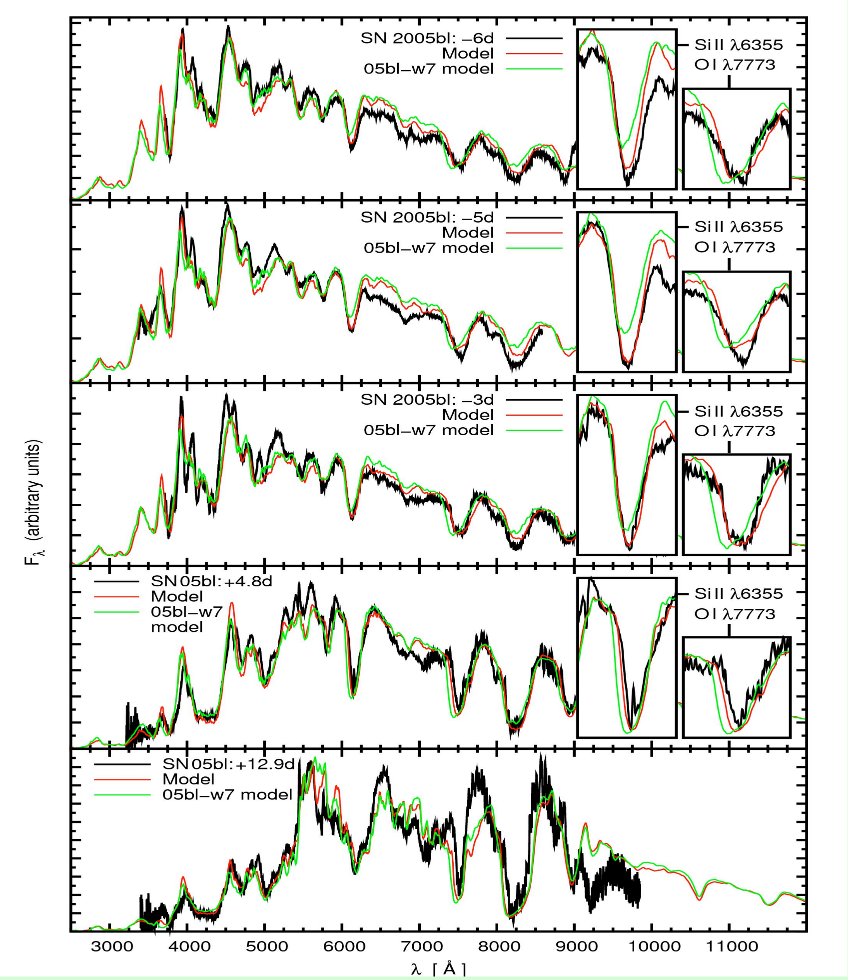
End of story? …maybe not

- Is SN 1991bg consistent with MCh?
- PM et al. 97 suggested that a smaller mass may give better spectral fits at peak.
- Study 91bg-like SN 2005bl by means of "super" tomography: play with both abundances and density distribution (rescaling W7 profile depending on Mass, Energy):

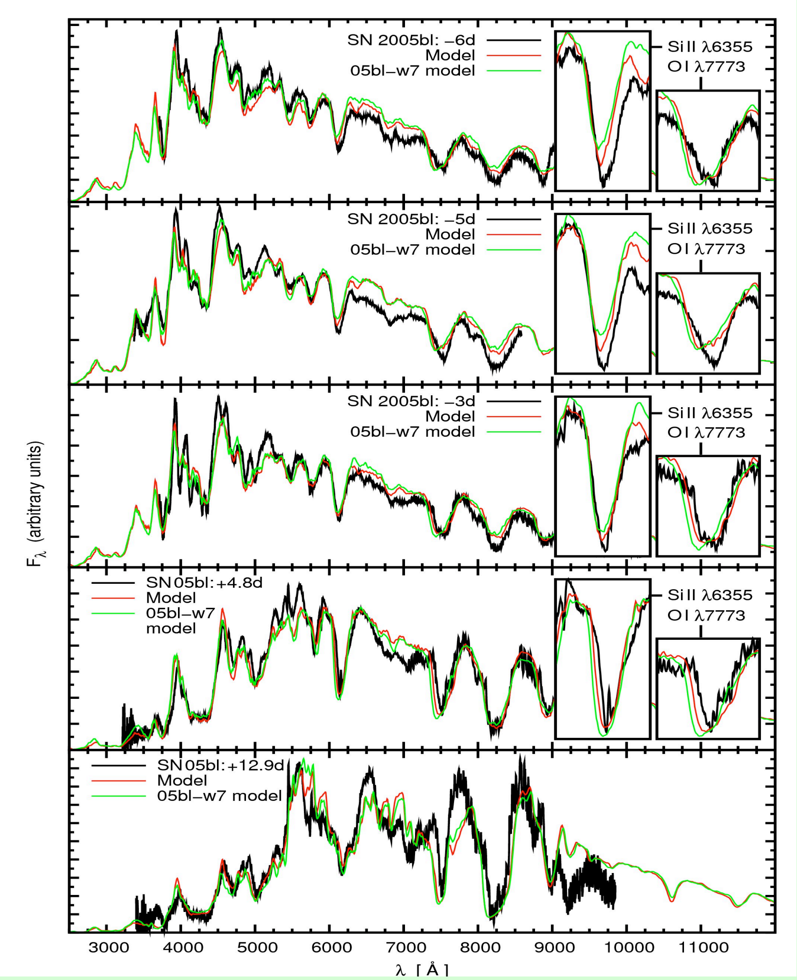
$$\rho' = \rho_{W7} \left(\frac{E'_k}{E_{k,W7}} \right)^{-3/2} \left(\frac{M'}{M_{W7}} \right)^{5/2}$$

$$v' = v_{W7} \left(\frac{E'_k}{E_{k,W7}} \right)^{1/2} \left(\frac{M'}{M_{W7}} \right)^{-1/2}$$

Results for SN 2005bl



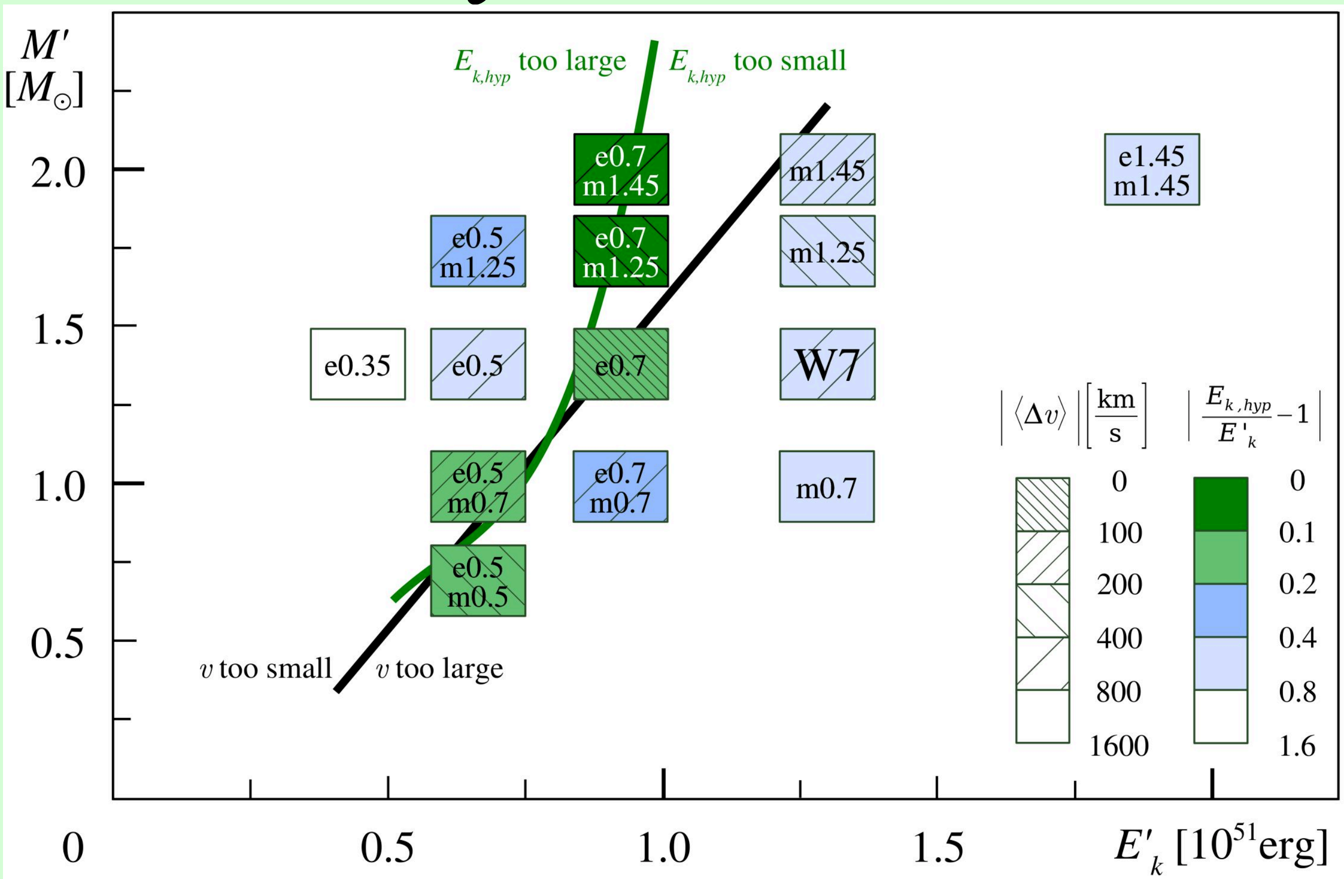
M=M_{Ch}, E=0.7W7



M=1.25M_{Ch}, E=E(W7)

- Models with a smaller E/M preferred

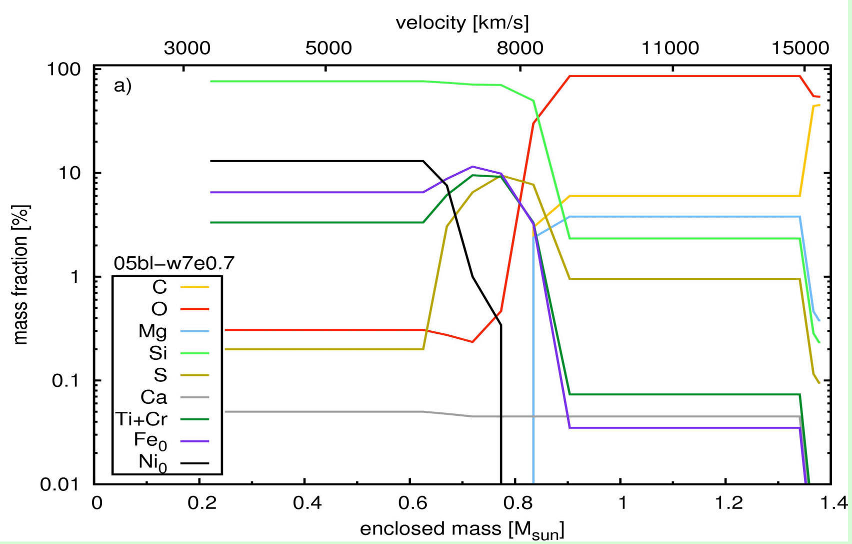
Consistency of models

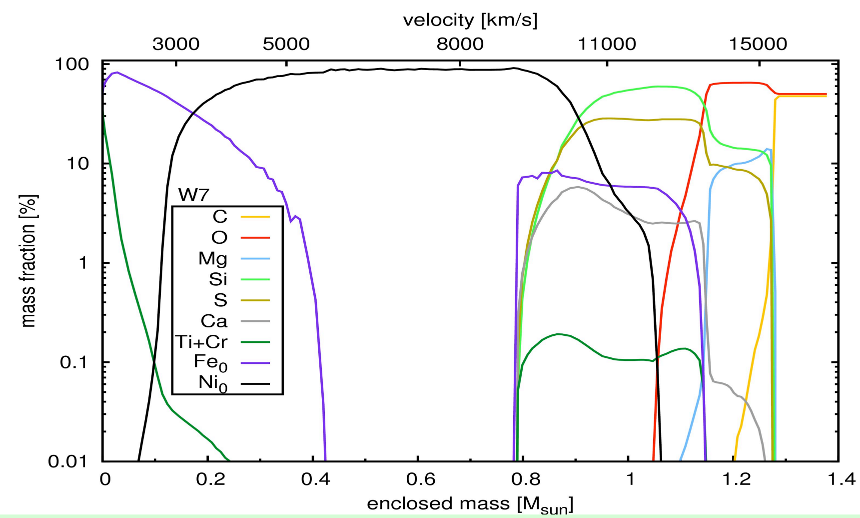


- Spectral fit
- Energetics (KE from burning - binding energy of WD)
- Expected LC props (Hachinger et al. 2009)

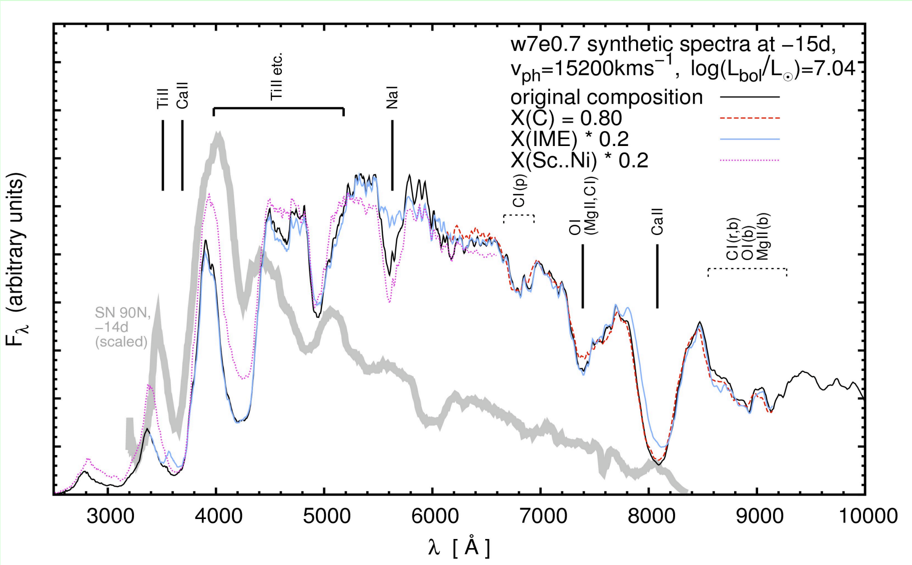
Abundance distribution

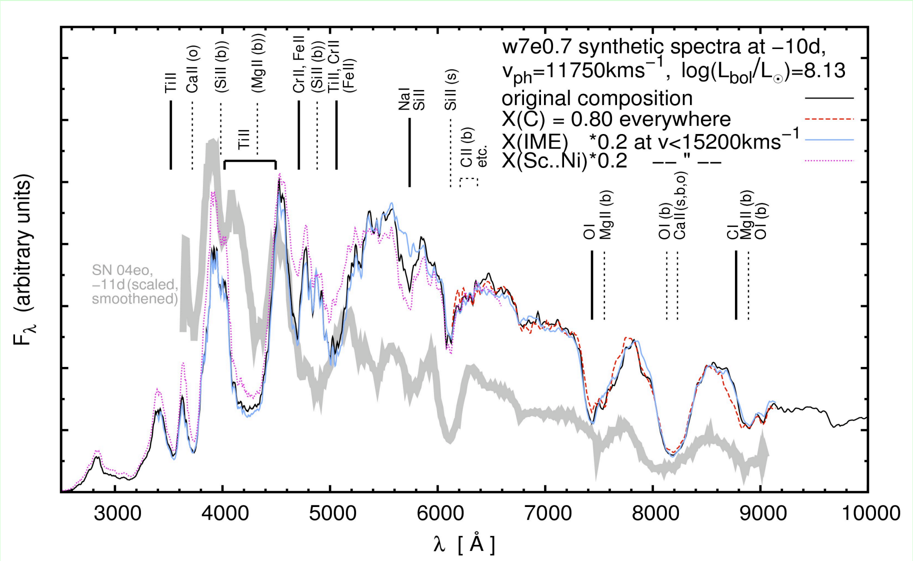
- Much smaller Fe-group zone
- IME extend down to lower velocities
- Significant presence of O down to ~9000 km/s
- Different progenitor/explosion mode?
- 91bg-like SNe preferentially associated with old populations (Hamuy et al. 2000)





A prediction: SN1991bg at the earliest times





- Extrapolating abundances and LC evolution, expect 91bg at the earliest times to be quite different from maximum and from other SNe Ia at similar epochs

Conclusions

- "Inverse approach" is a powerful method to extract general SN properties
- Ejecta reflect stratified composition of models
- Total mass burned is approximately constant
- ^{56}Ni determines luminosity
- Total NSE determines LC shape
- 91bg-like SNe have smaller E/M,
  may have M $\neq$MCh
- Further test for other subtypes may bring new surprises