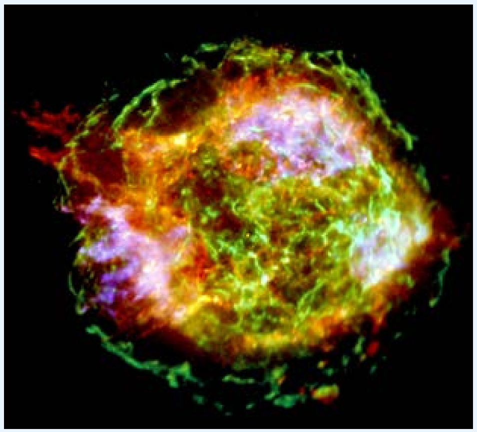
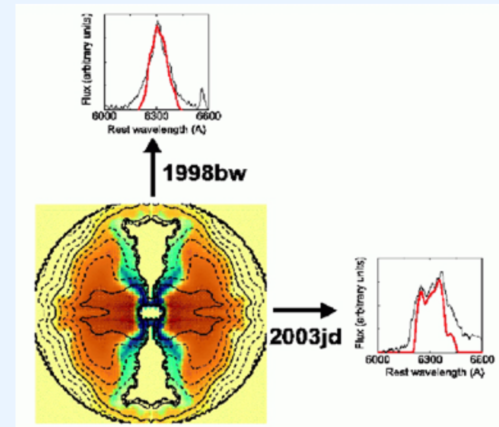
Recent progress in SN Science





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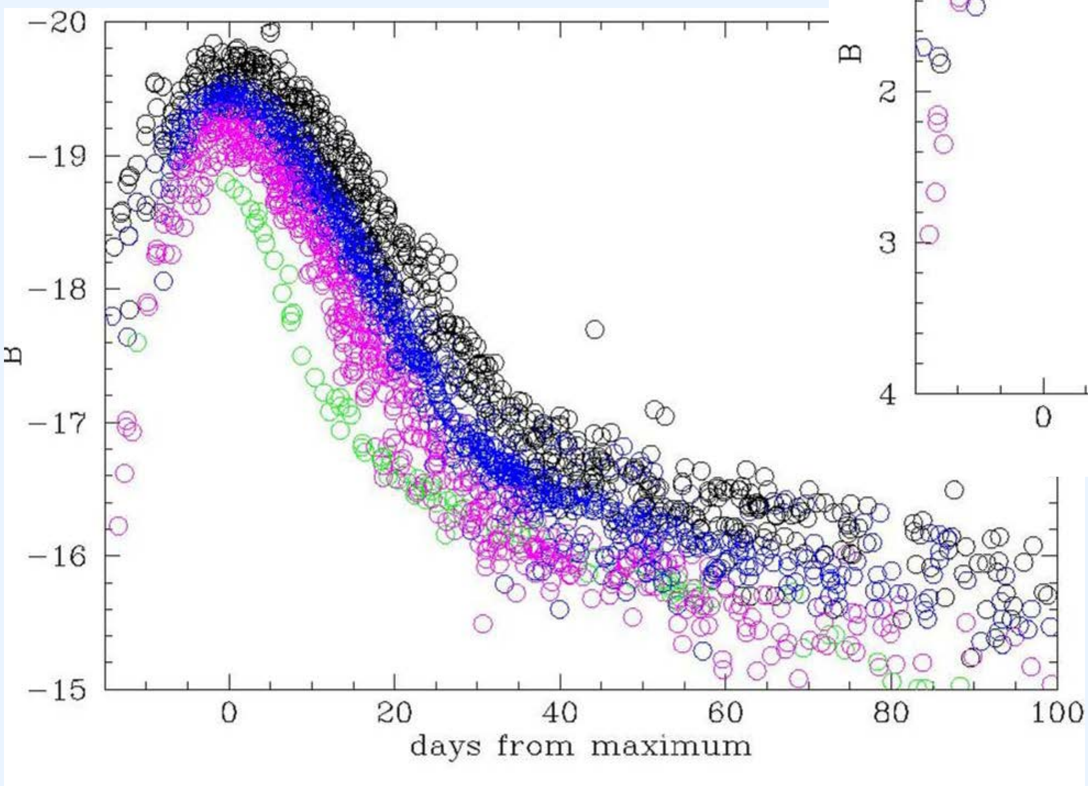
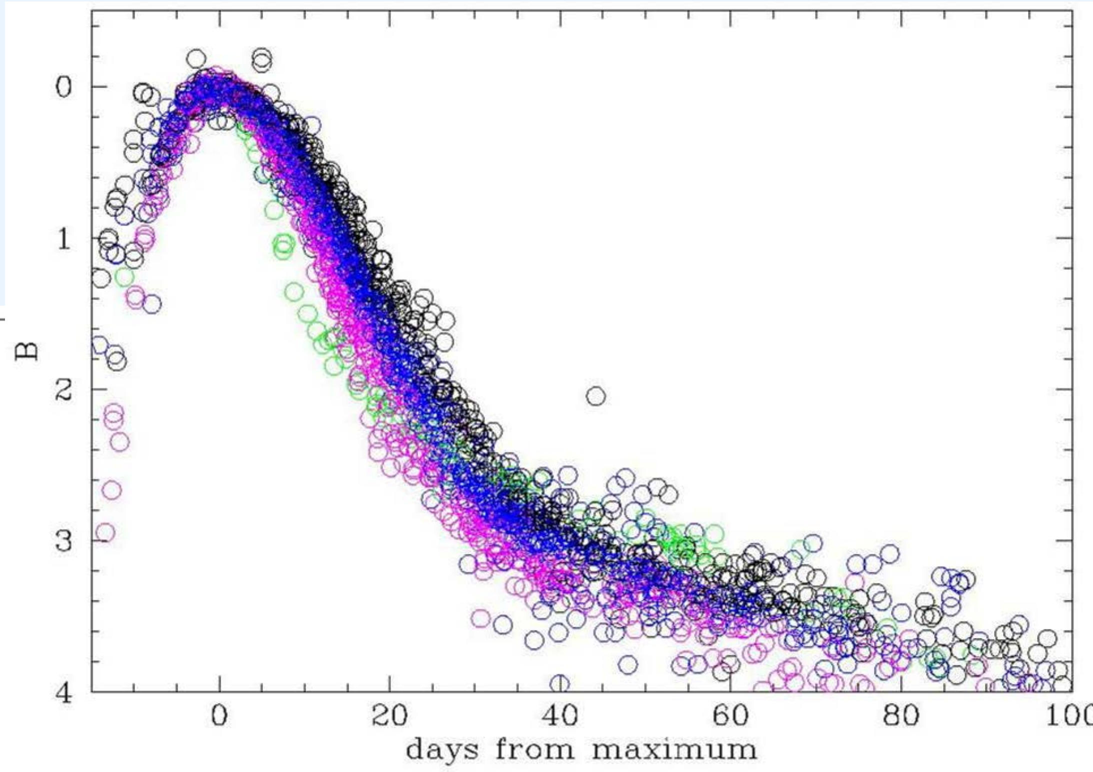
Supernova science is best done early

- Type Ia SNe: properties of outer ejecta → properties of progenitor (composition, physical nature – Single/Double Degenerate)
- GRB-SNe: outermost ejecta move fastest: they carry most of the Kin En, and signatures of any asymmetry (jets)
- Superluminous SNe: overall behaviour suggests physical mechanism

I. Type Ia SNe
B Light Curves: Observed v. Normalized



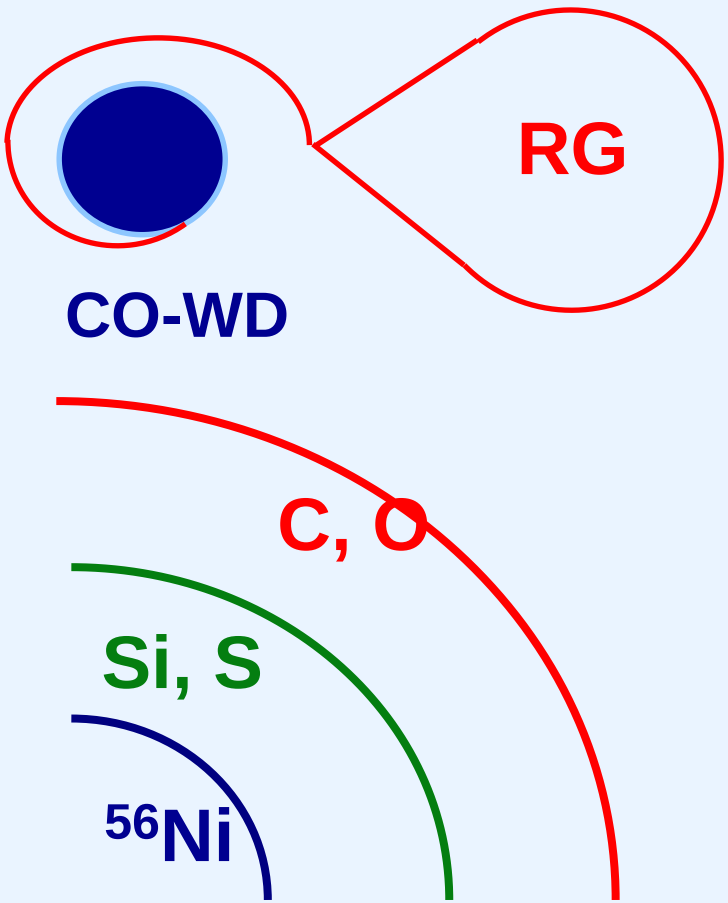


Standardizable candles

(Phillips 1993)

What are SNe Ia: Thermonuclear SNe

White Dwarf in Binary System



WD accretes H until M_{WD}~1.4M⊙, T~10^9K

- Thermonuclear burning (C burning) to NSE produces:
- Explosion (KE~10^{51} erg)
- Total disruption of WD
- ^{56}Ni synthesis (~0.7M⊙)

Using observables to understand SNe Ia

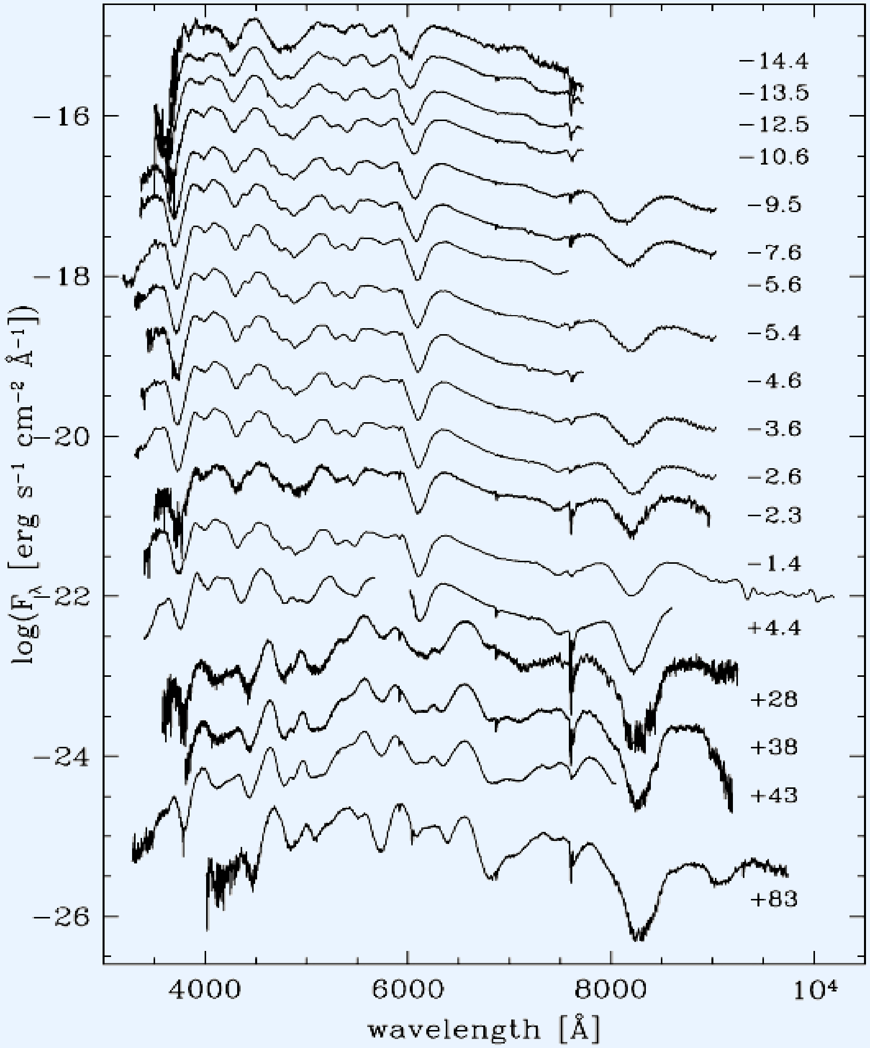
Questions

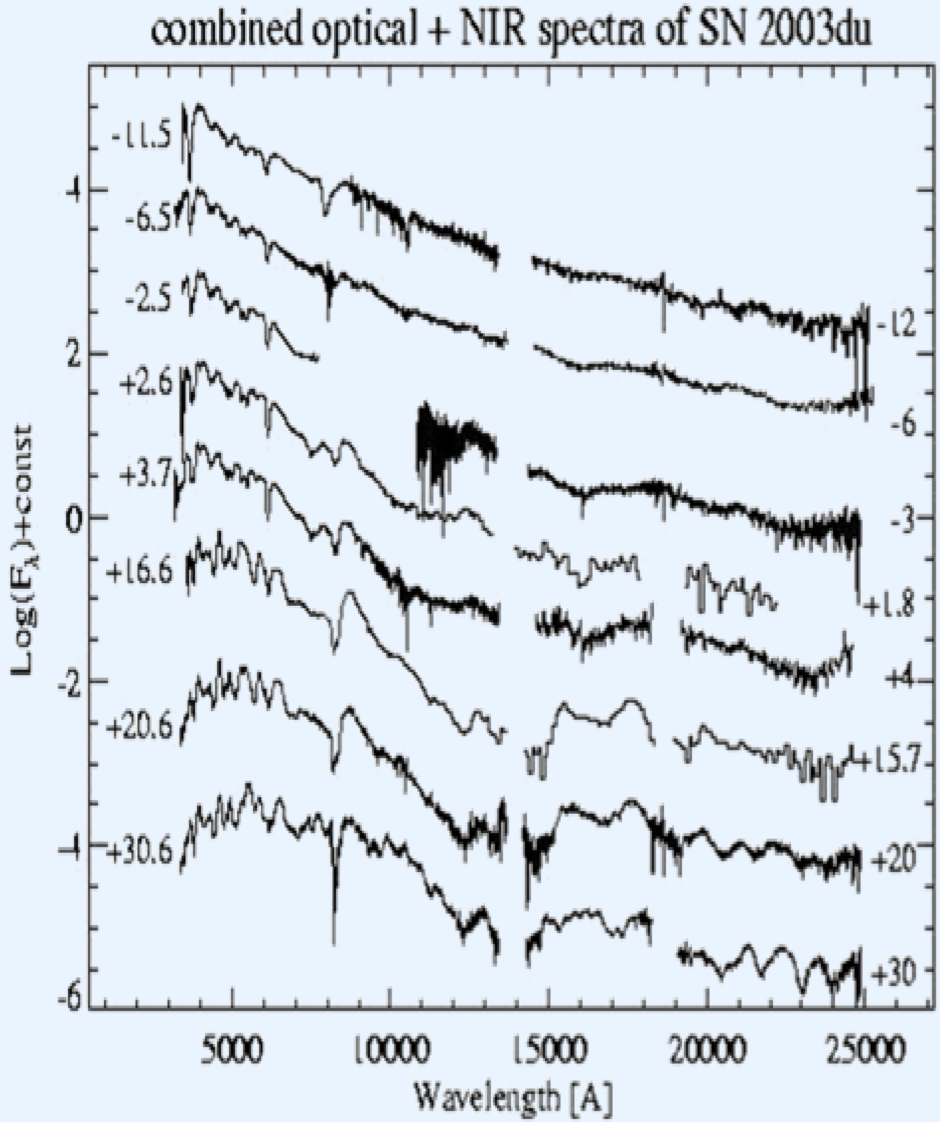
- Properties of SNe Ia (eg Phillips’ rel’n)
- Mode of explosion (deflagration, delayed detonation, other even less reasonable modes…)
- Progenitor (SD, DD?)
- Cosmology?

Methods

- Look at model spectra & light curves

Data: e.g. SNe 2002bo, 2003du

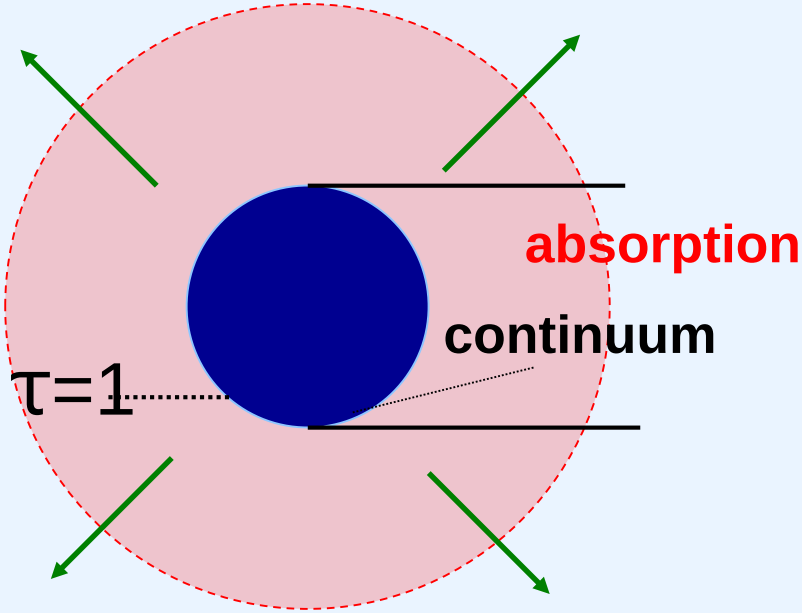




Early-time spectrum

Homologous expansion

(v ≈ R)



- Ejecta are dense

"Photospheric Epoch"

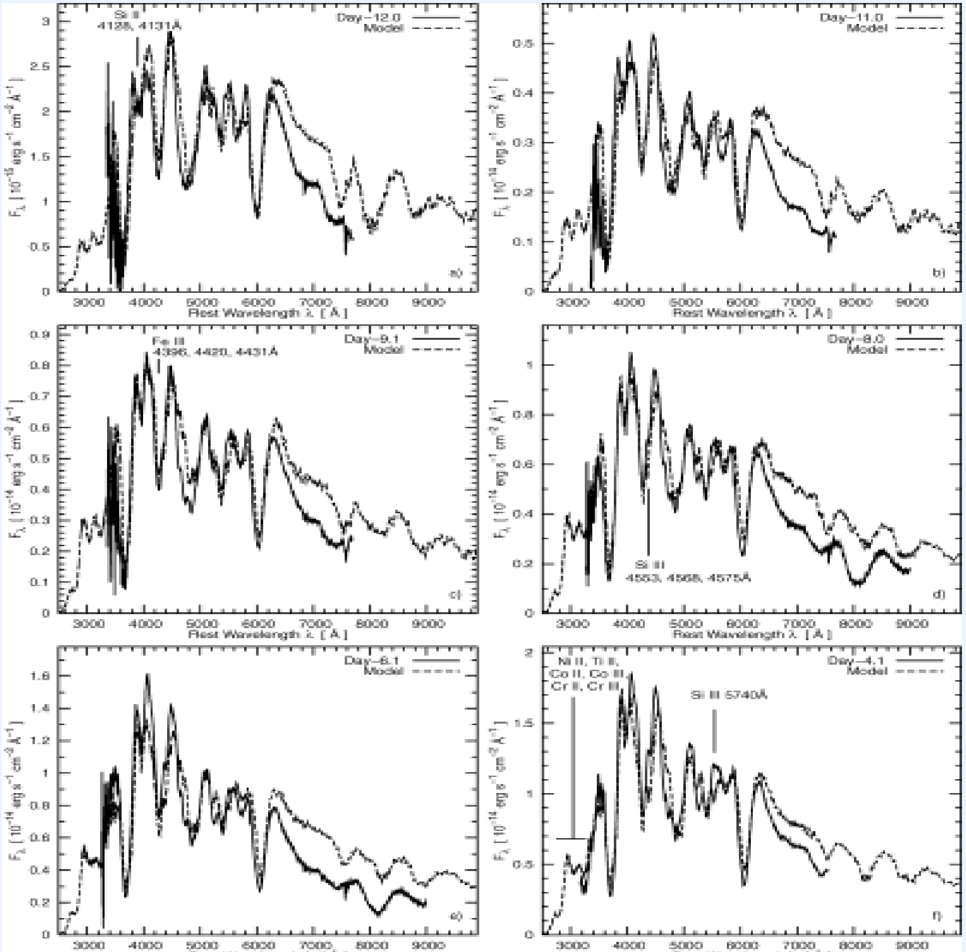
- P-Cygni profiles

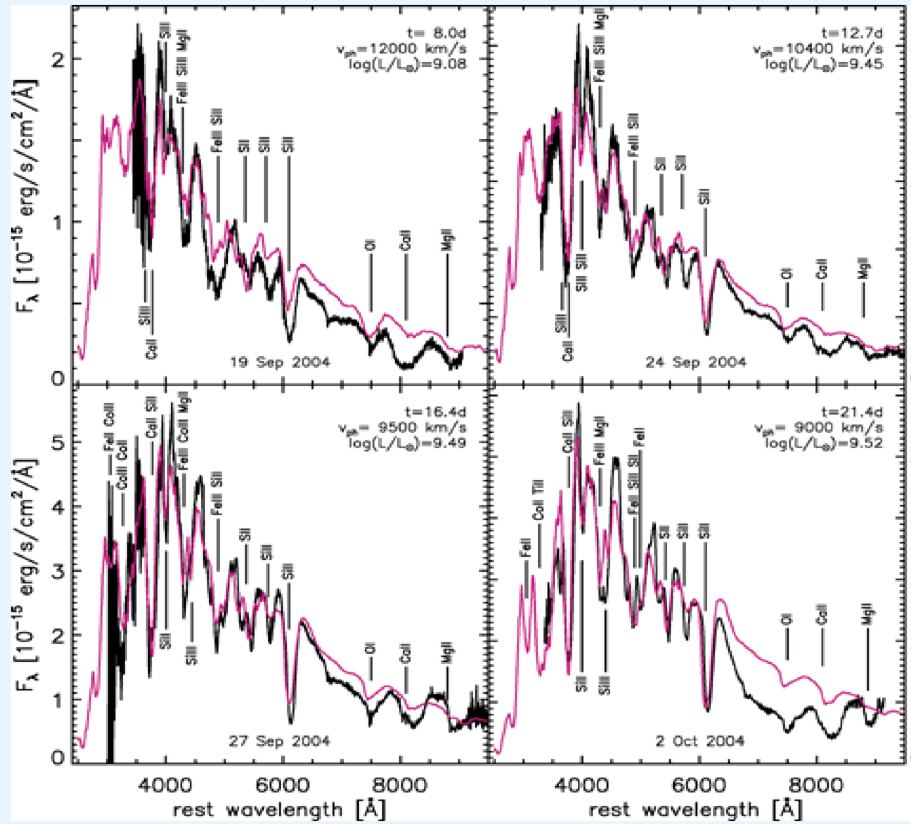
$$L = 4\pi R_{ph}^2 \sigma T_*^4$$

$$R_{ph} = v_{ph} t$$

Abundance Stratification

Models of spectral sequence reveal composition layering





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

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

(Stehle et al. 2005)

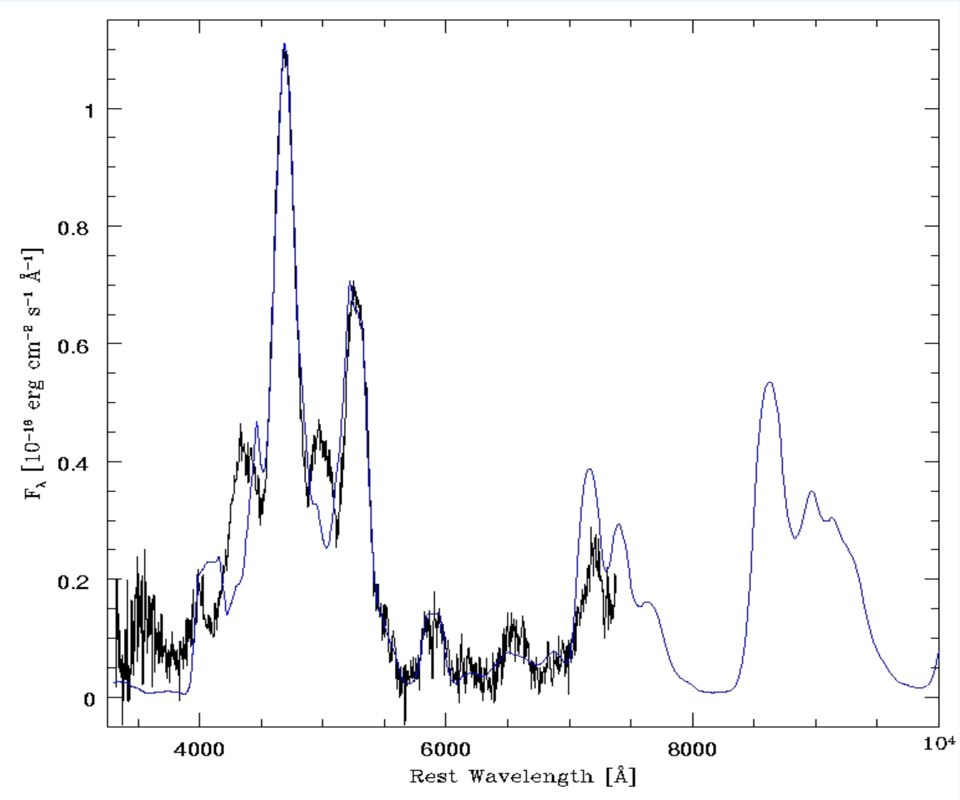
(Mazzali et al. 2008)

Late-time spectra

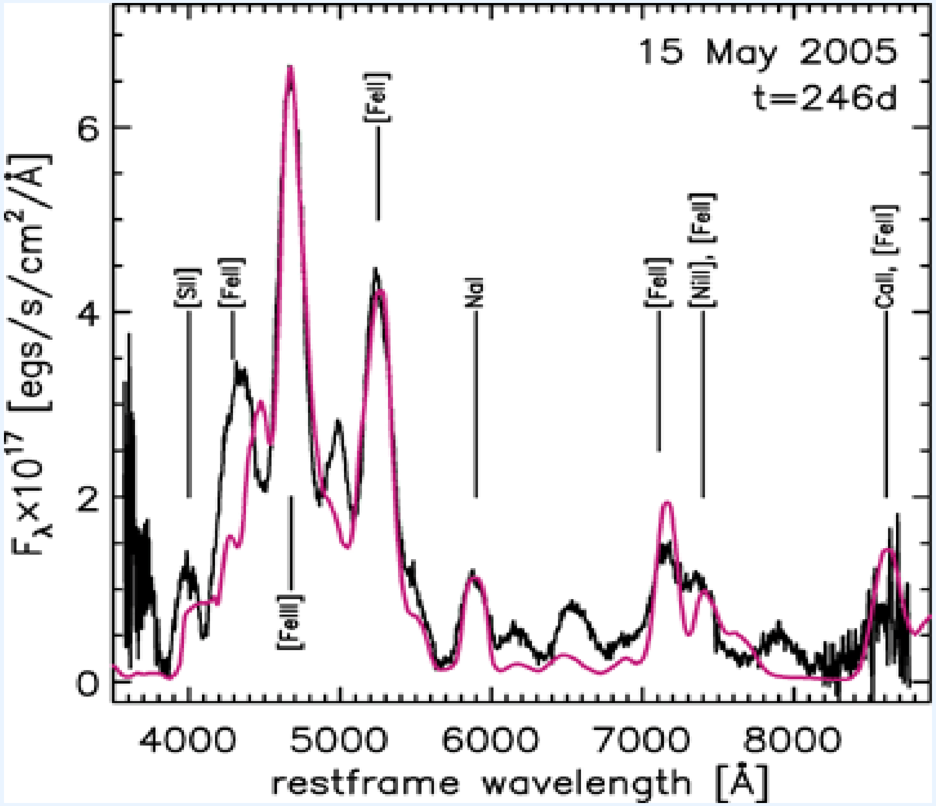
Full view of inner ejecta (^{56}Ni zone)

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

→ Estimate masses (both ^{56}Ni and ejecta)



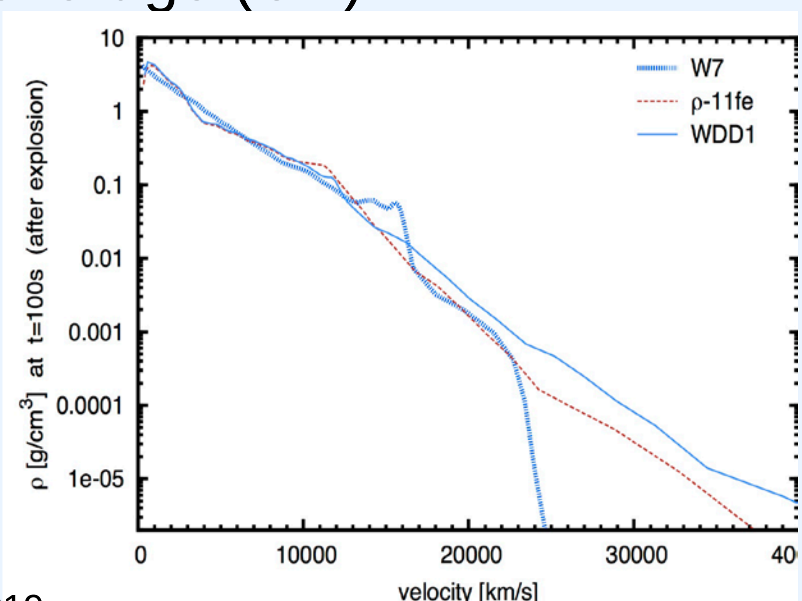
SN 2002bo



SN 2004eo (narrower lines)

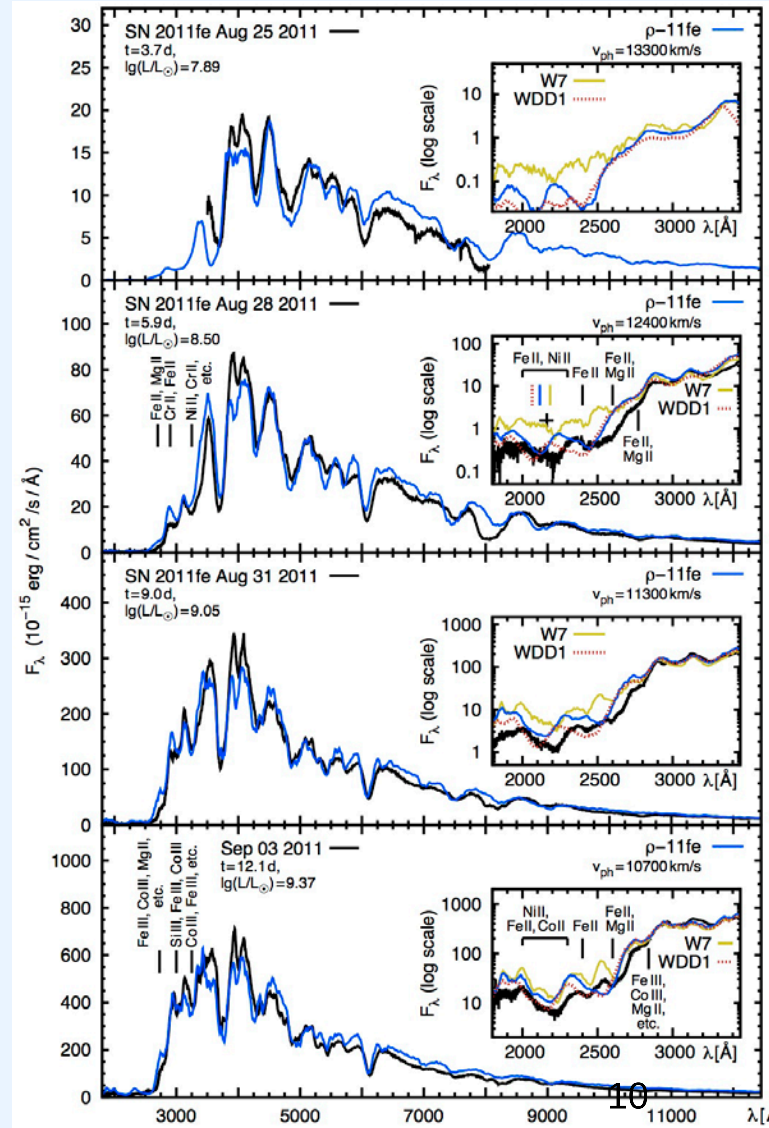
SN2011fe: one of the nearest recent SNe Ia

- Discovered very early: early spectra allow us to constrain outer density (explosion model) and progenitor metallicity
- Normal SN Ia
- $\Delta m_{15}(B)$~1.1 mag
- HST coverage (UV)



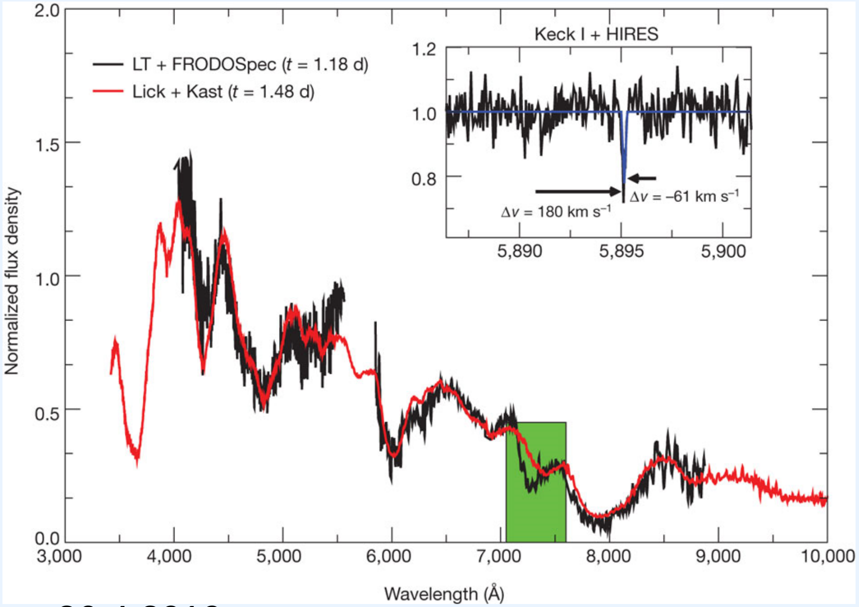
PM et al 2014

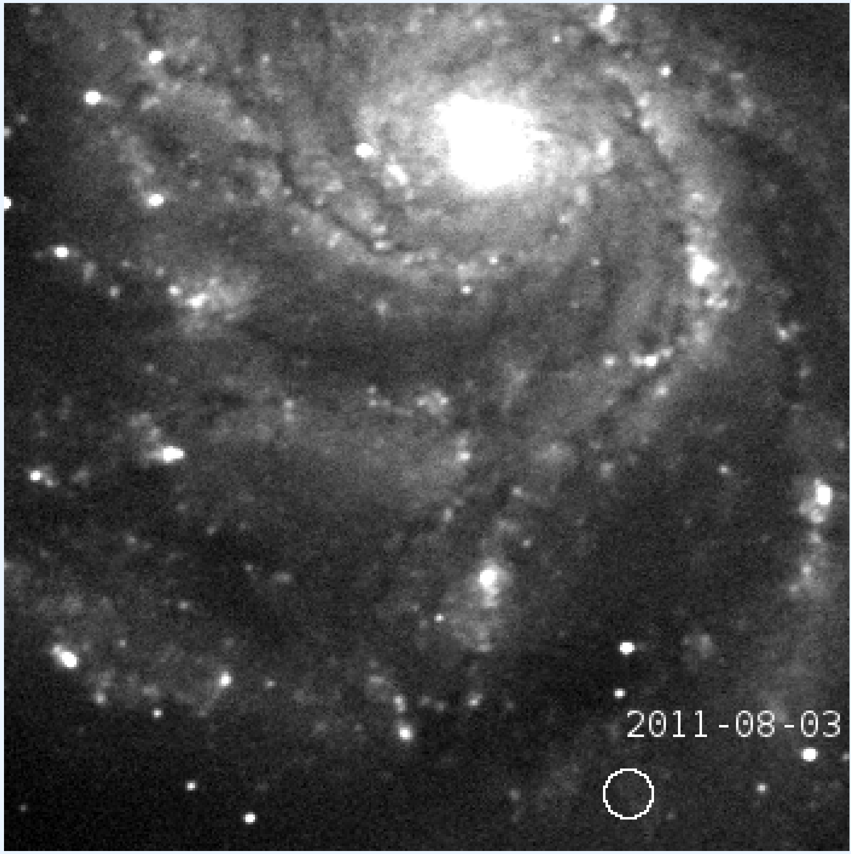
- A weak delayed-detonation ?



SN Ia 2011fe in M101

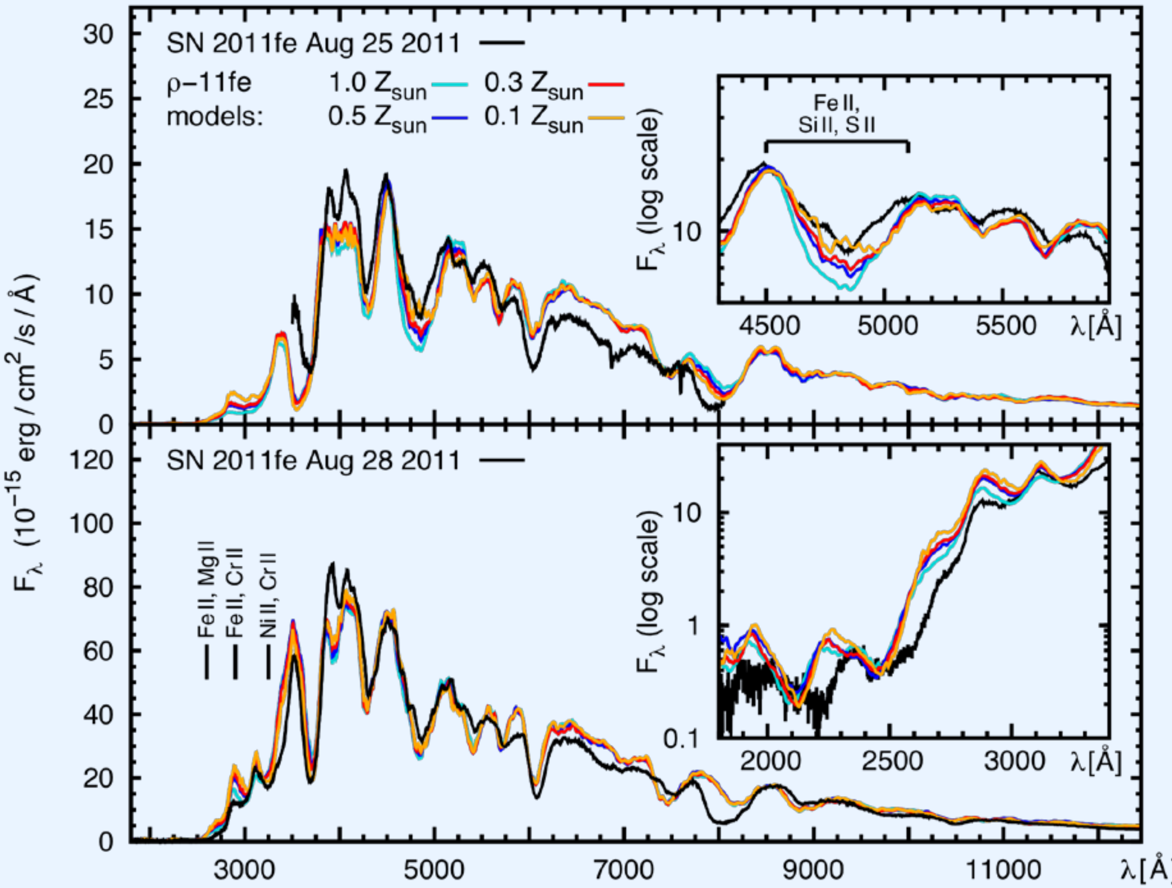
- Discovered very early: early spectra allow us to constrain outer density (explosion model) and progenitor metallicity
- Liverpool Telescope took 1st spectrum the day after discovery (Nugent et al. 2011, Nature)





What was the progenitor metallicity?

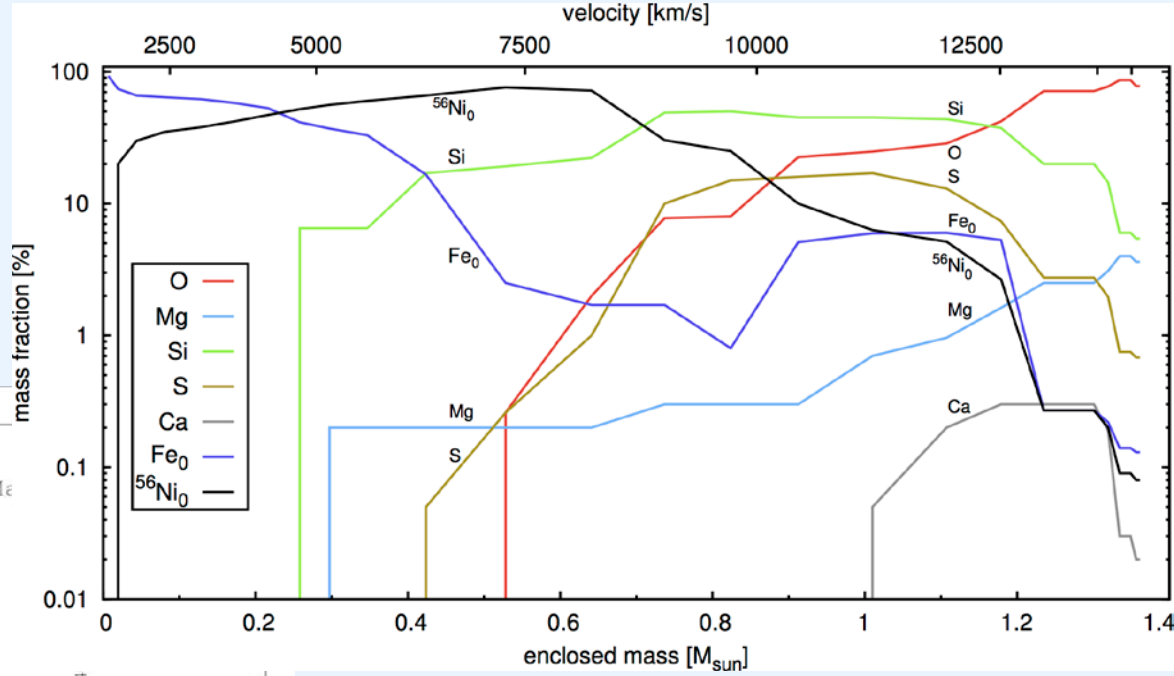
- Outer layers carry progenitor information:
- NEED VERY EARLY SPECTRA
- Best metal content ~ 1/3 solar (in agreement with galaxy estimates)

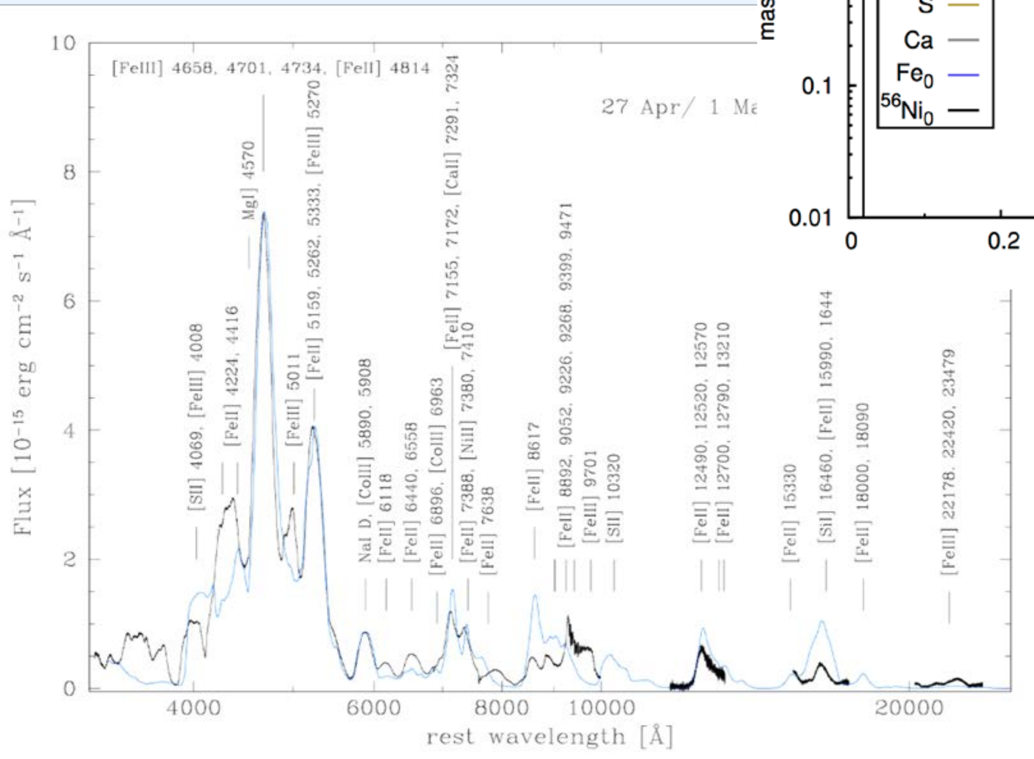


PM et al 2014

SN 2011fe: Abundance Tomography

- Add model of late-time spectra
- Inner layers dominated by ^{56}Ni, stable Fe-gp

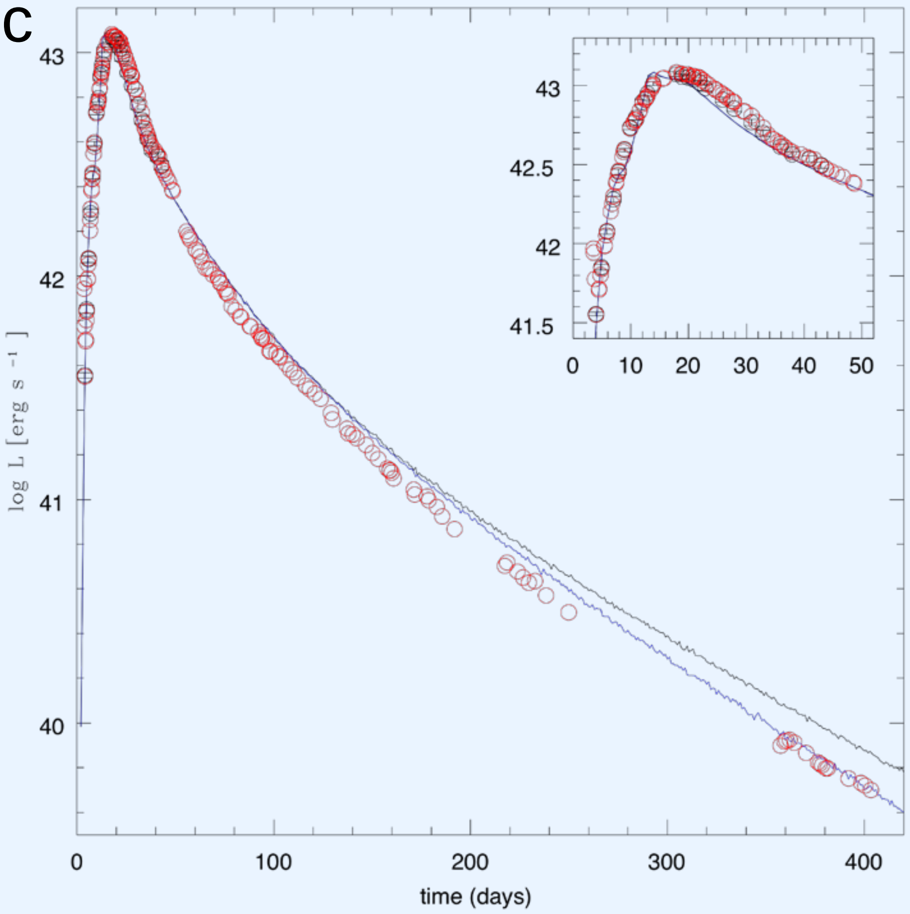




(PM et al 2015)

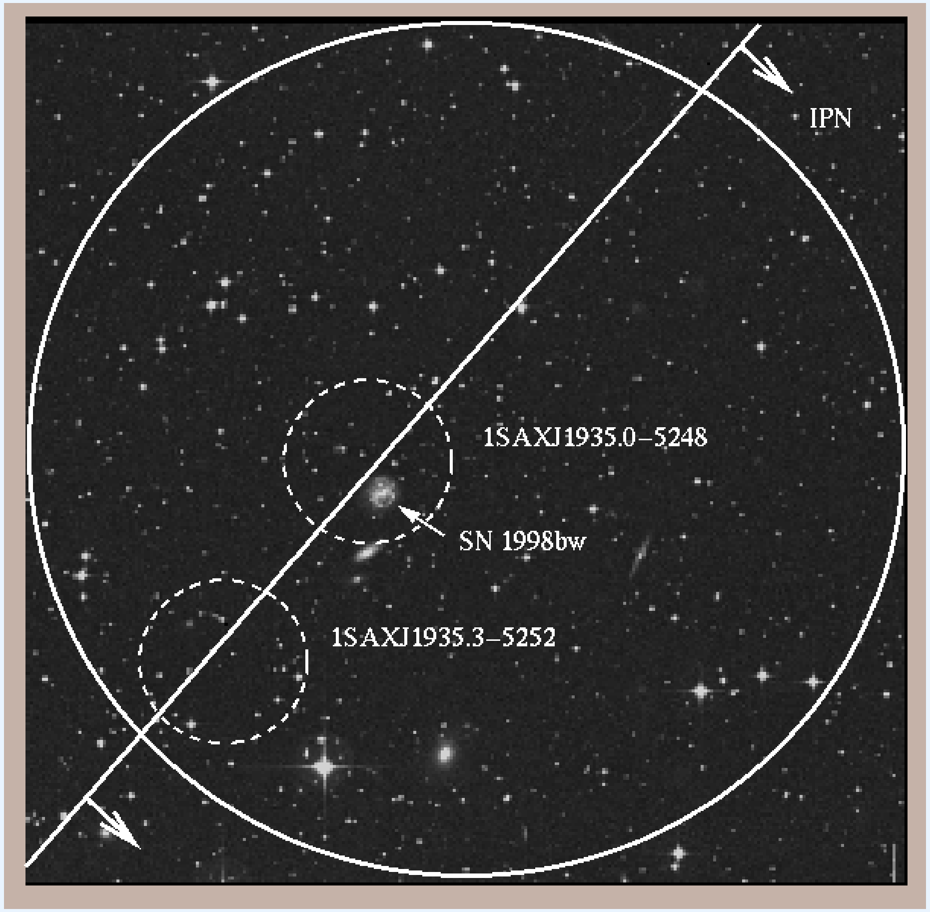
Test results with Light curve

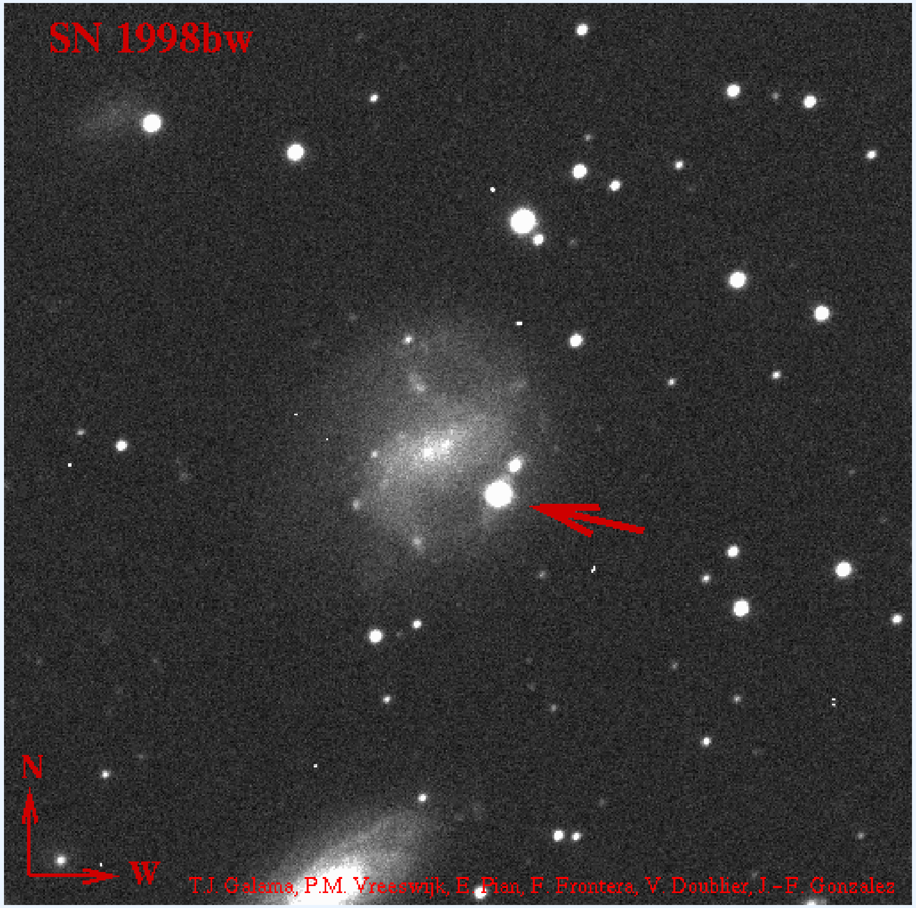
- Use density and abundance distribution to compute synthetic bolometric LC with Montecarlo method
- Successful match confirms results: Normal SN Ia
  - Mass ~ M(Ch)
  - Ek ~ 1.25 10^{51} erg
  - M(^{56}Ni) ~ 0.47 $M_\odot$
  - M(NSE) ~ 0.70 $M_\odot$
  - M(IME) ~ 0.42 $M_\odot$
  - M(CO) ~ 0.24 $M_\odot$



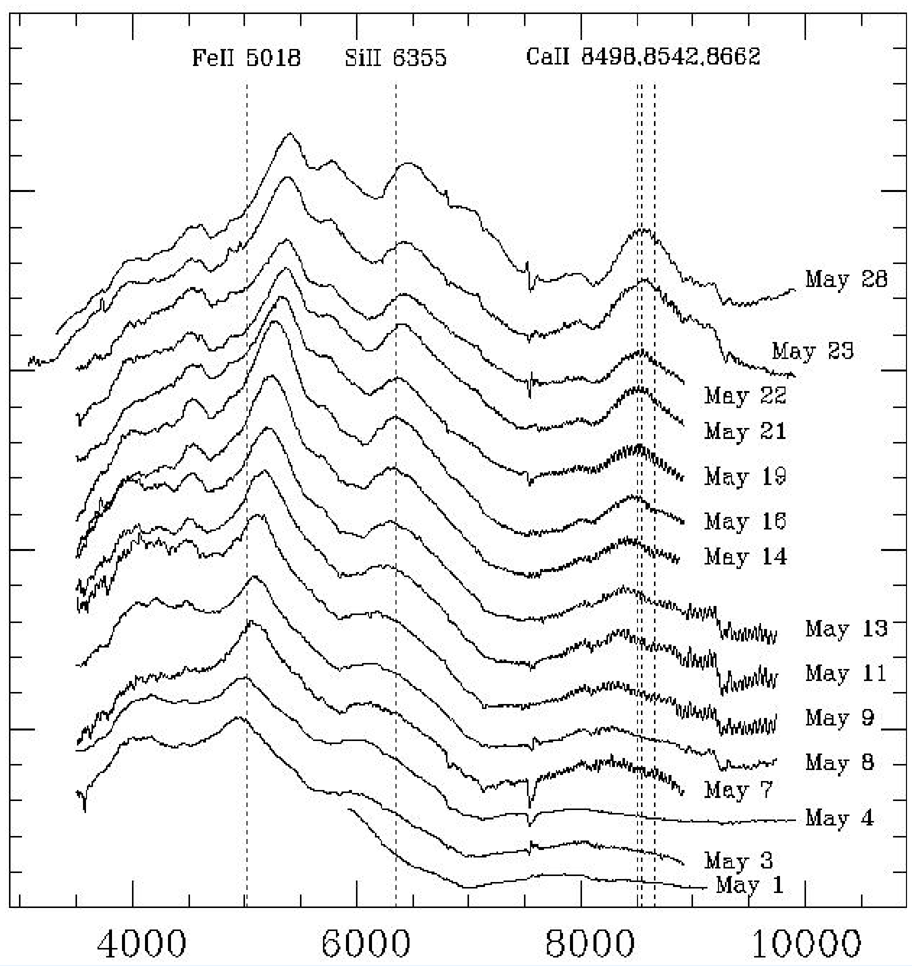
II. Long Gamma-Ray Bursts/Supernovae

GRB980425: the first optical counterpart



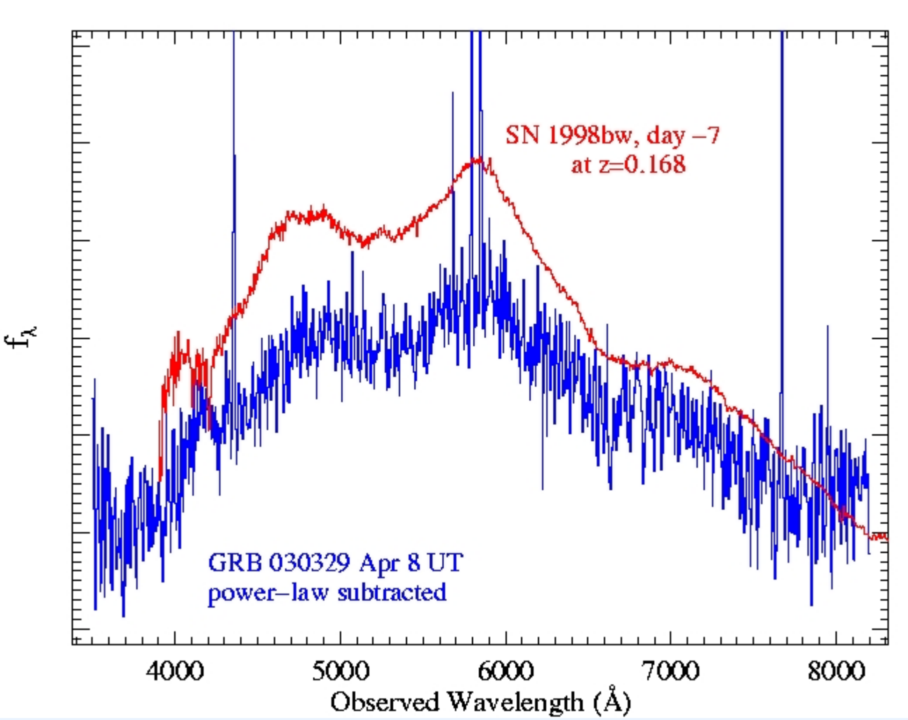


GRB/SNe are Broad-lined SNe Ic



SN 1998bw / GRB980425

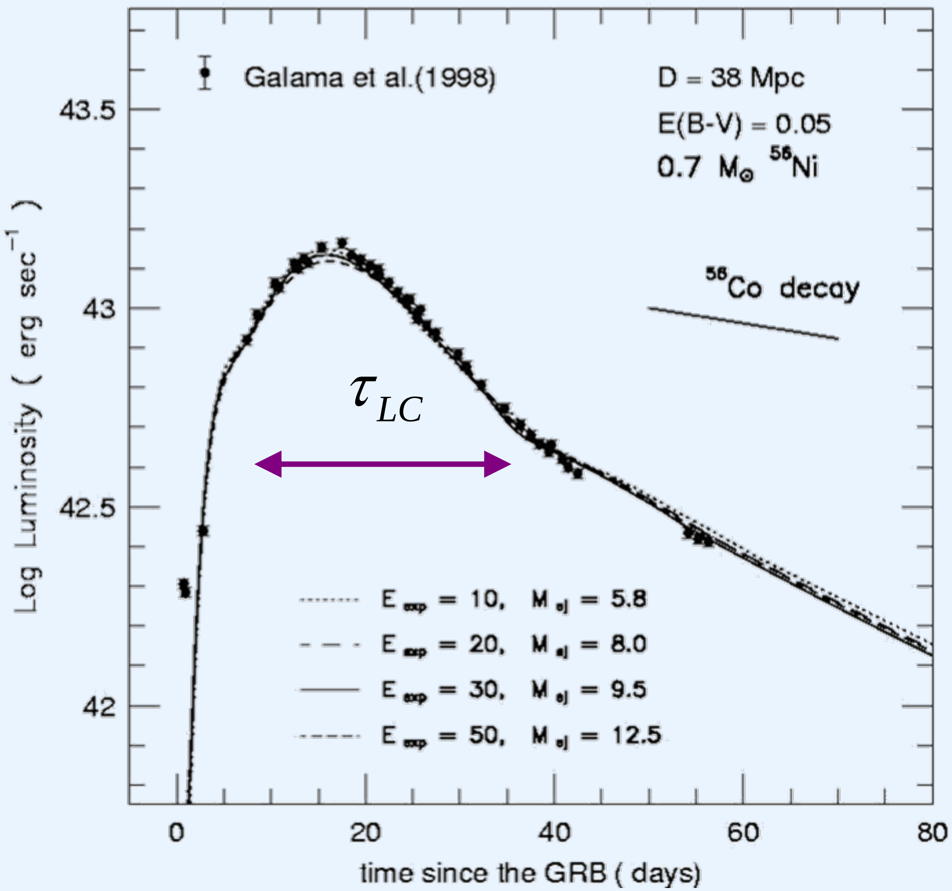
Patat et al. 2001

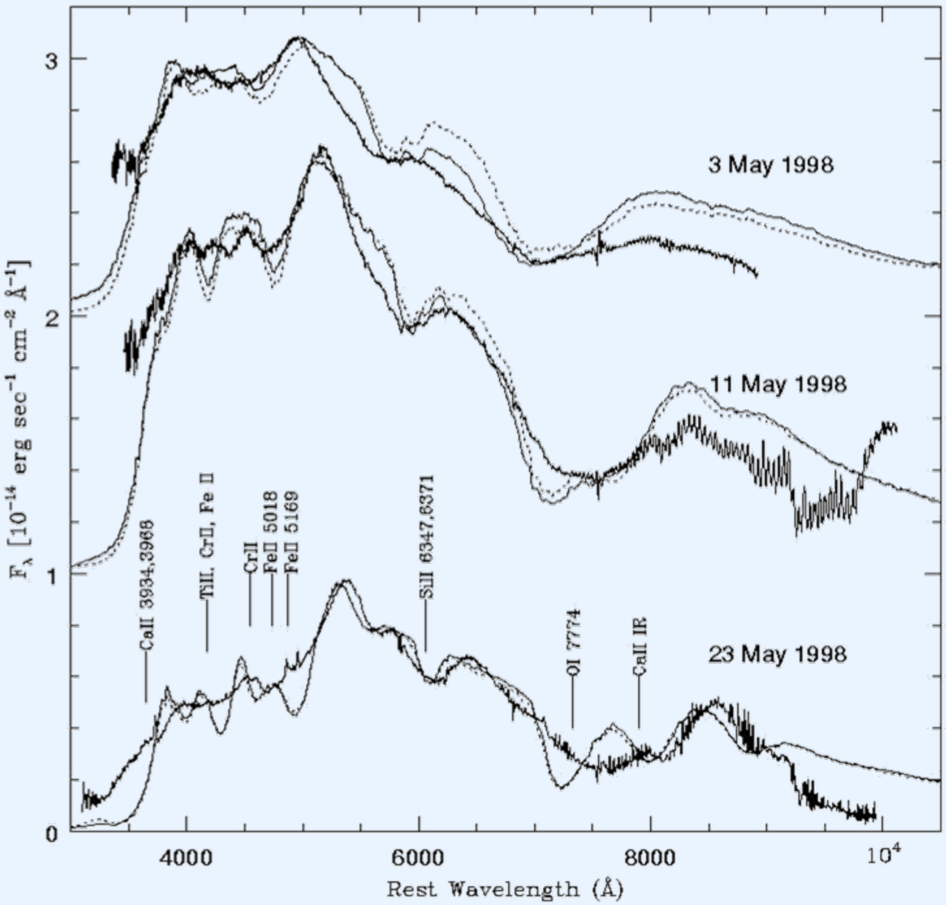


SN2003dh / GRB030329

Matheson et al. 2003

SN 1998bw: high mass and KE





$$\tau_{LC} \propto \frac{\kappa^{1/2} M^{3/4}}{E^{1/4}}$$

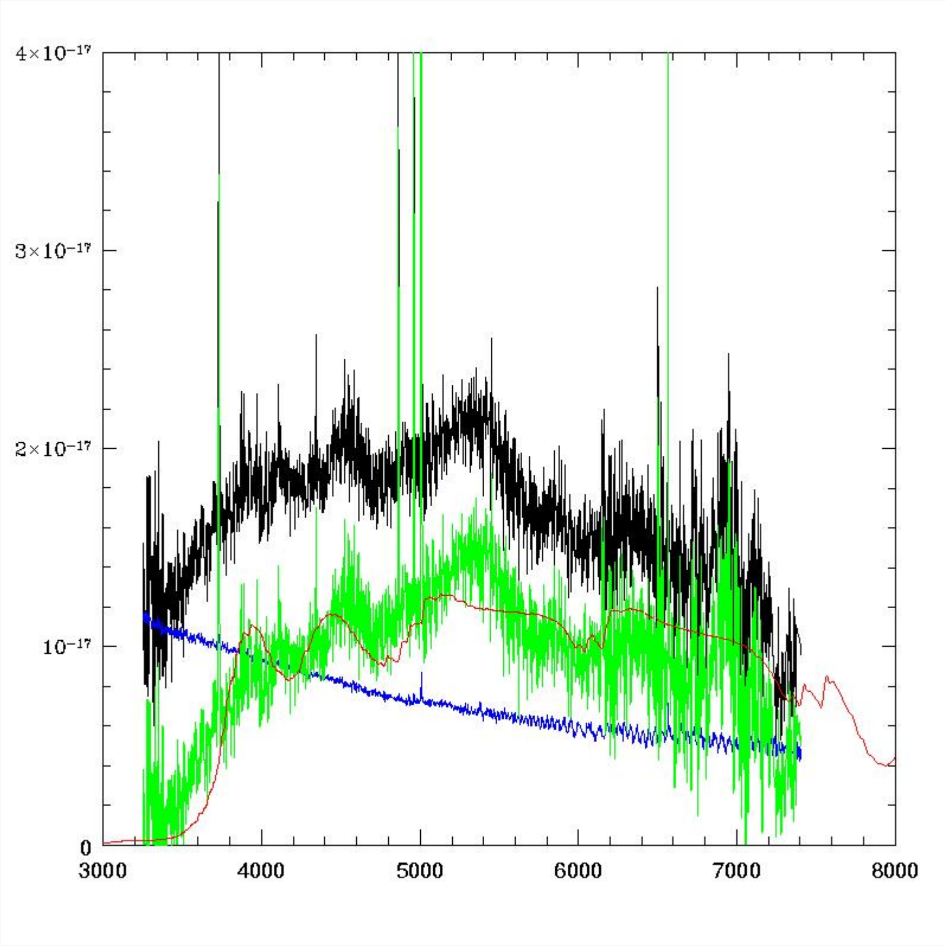
$$M_{ej} = 10.9 M_\odot$$

$$M(^{56}\mathrm{Ni}) = 0.5 M_\odot$$

$$KE = 5\times10^{52}\, erg$$

Iwamoto et al. 1998

GRB/SNe are all similar SN 2003dh/GRB030329



SN 2003dh was almost as bright and powerful as SN 1998bw:

KE = 3.8 10^{52} erg

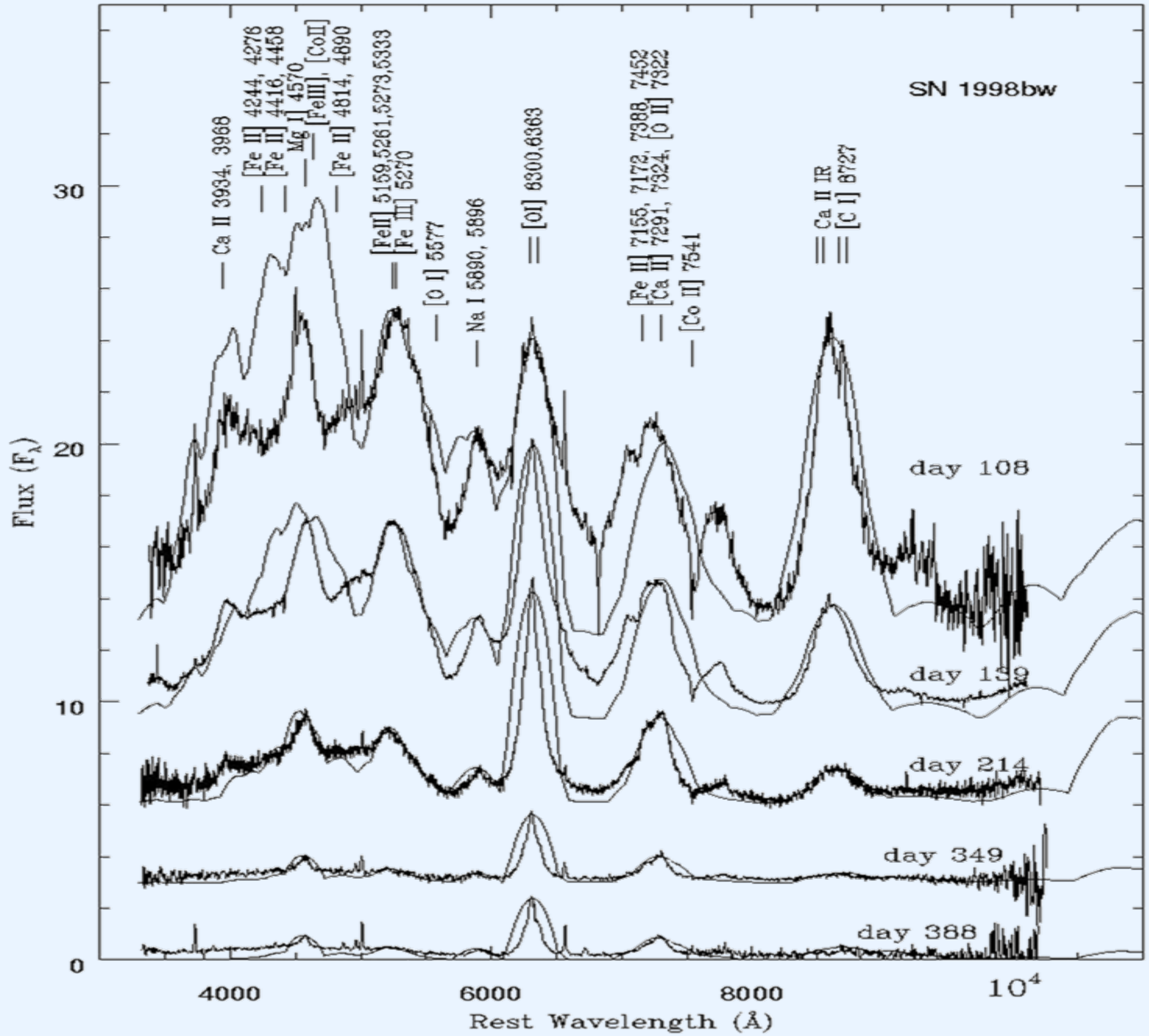
$$M(^{56}Ni) \sim 0.35 M_{\odot}$$

$$M_{ej} \sim 8 M_{\odot}$$

Mazzali et al. 2003

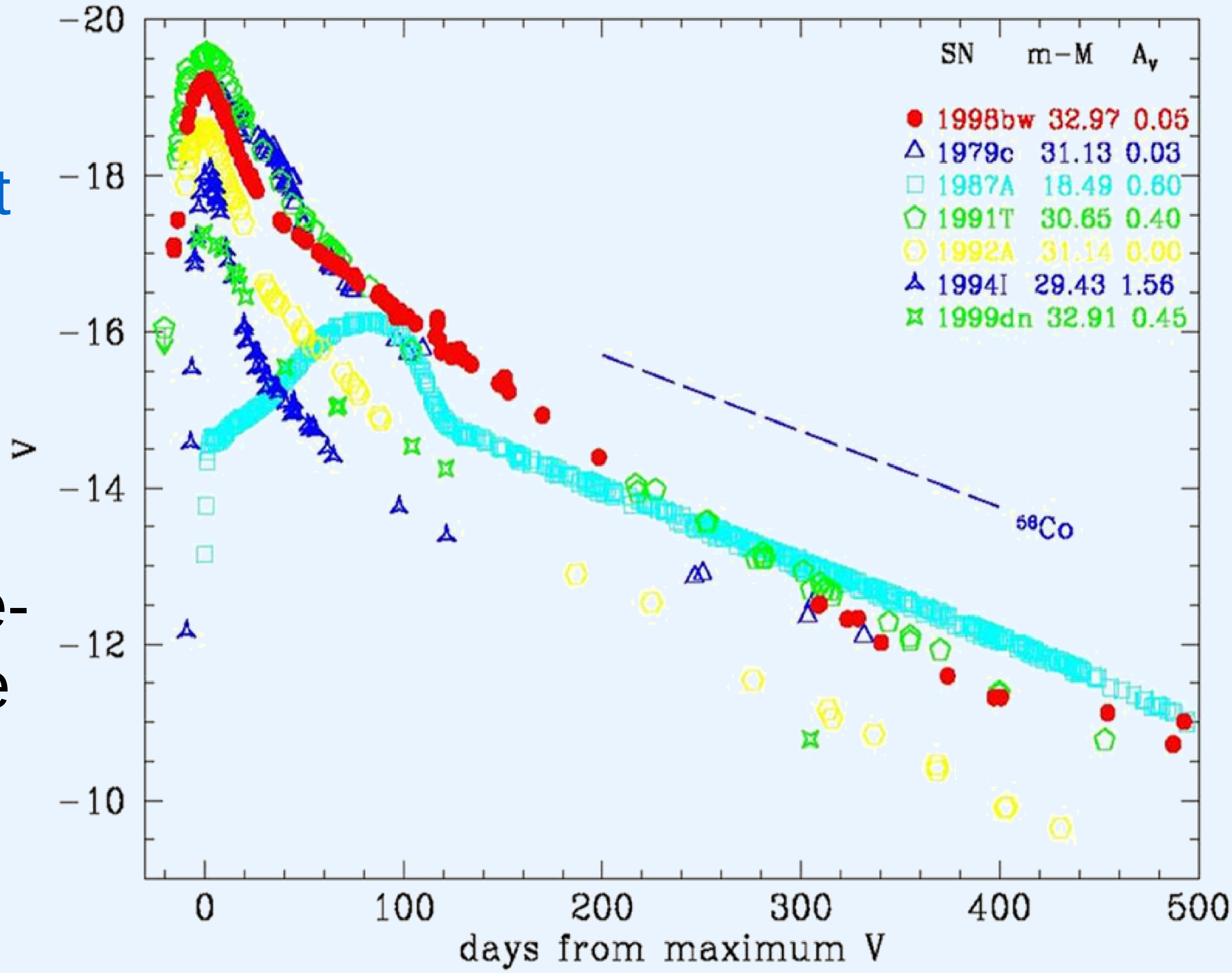
GRB/SNe are driven by ^{56}NI

- Strong nebular Fe lines in nebular spectrum resemble SNe Ia, and testify to the large amount of ^{56}Ni synthesised
- Oxygen line are broader than Fe lines, indicating an aspherical explosion (Mazzali et al. 2001)

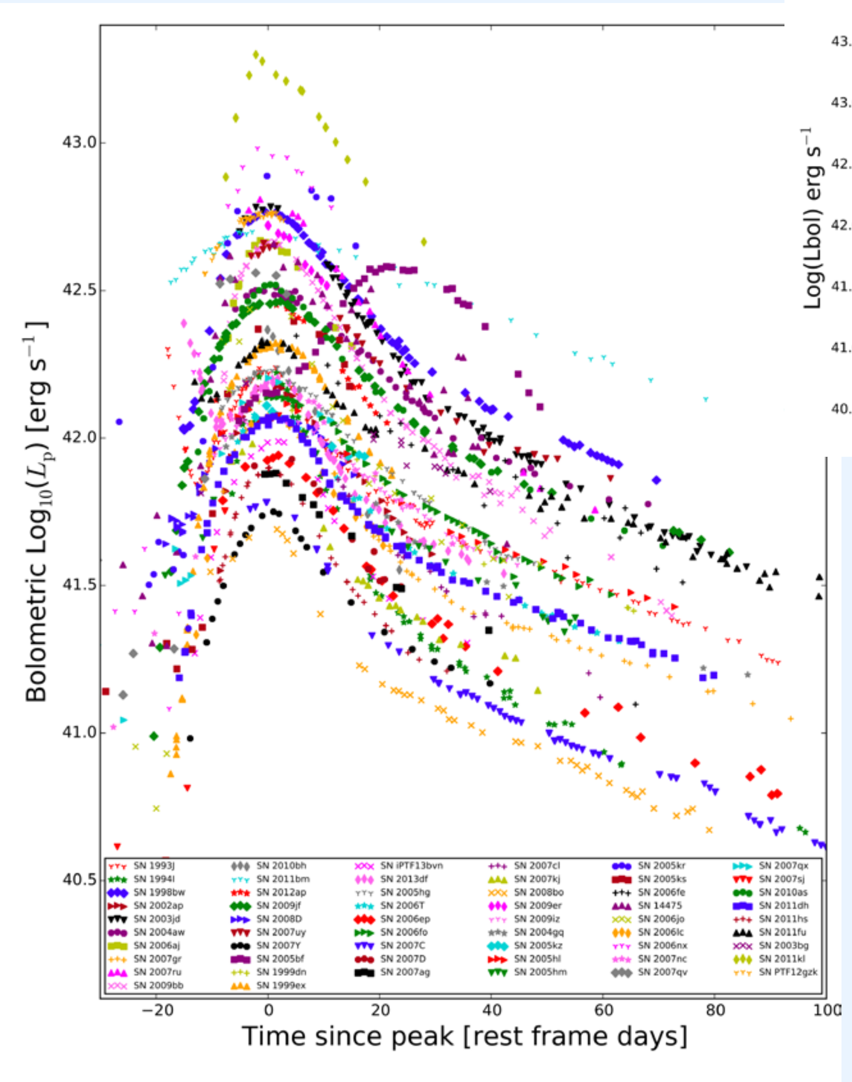


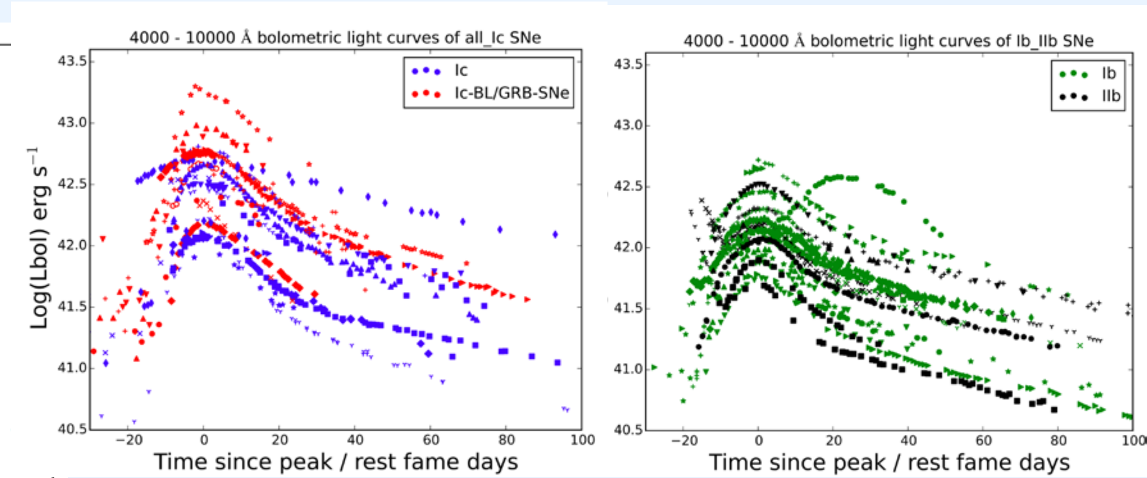
GRB/SNe are luminous

- SN1998bw was as bright as a SN Ia
- It produced much more ^{56}Ni than `normal' core-collapse SNe (~ 0.5 M⊙)



All available SN Ib/c data





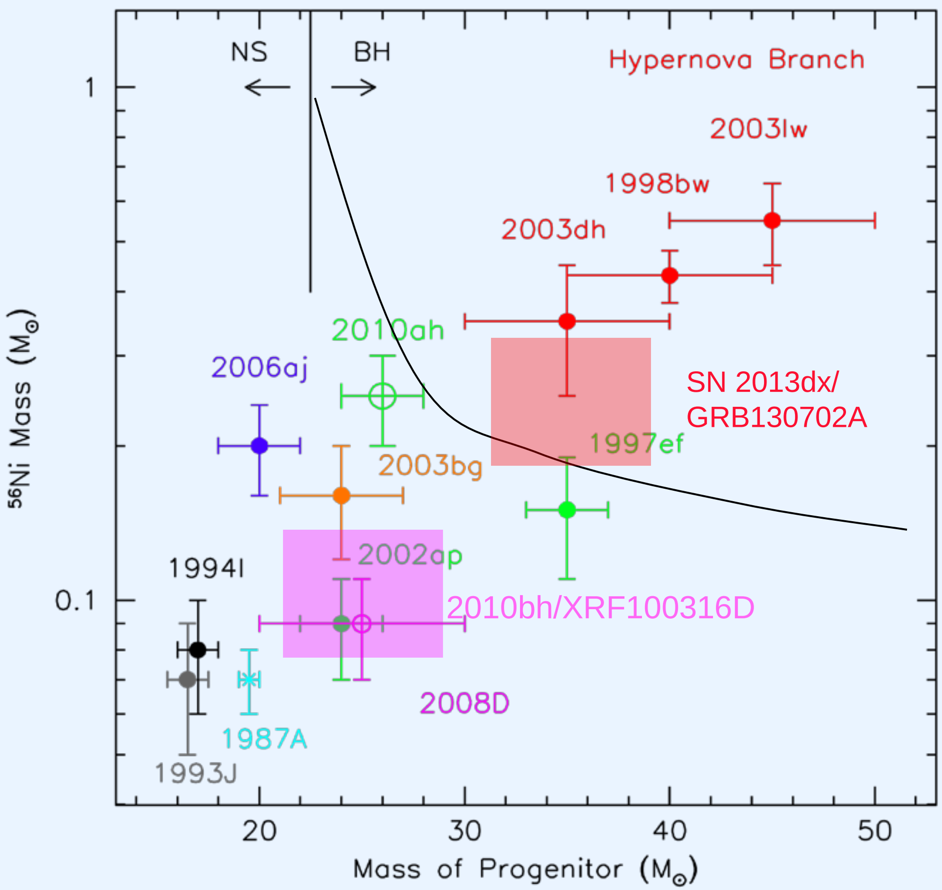
85 SNe Ib/c + IIb

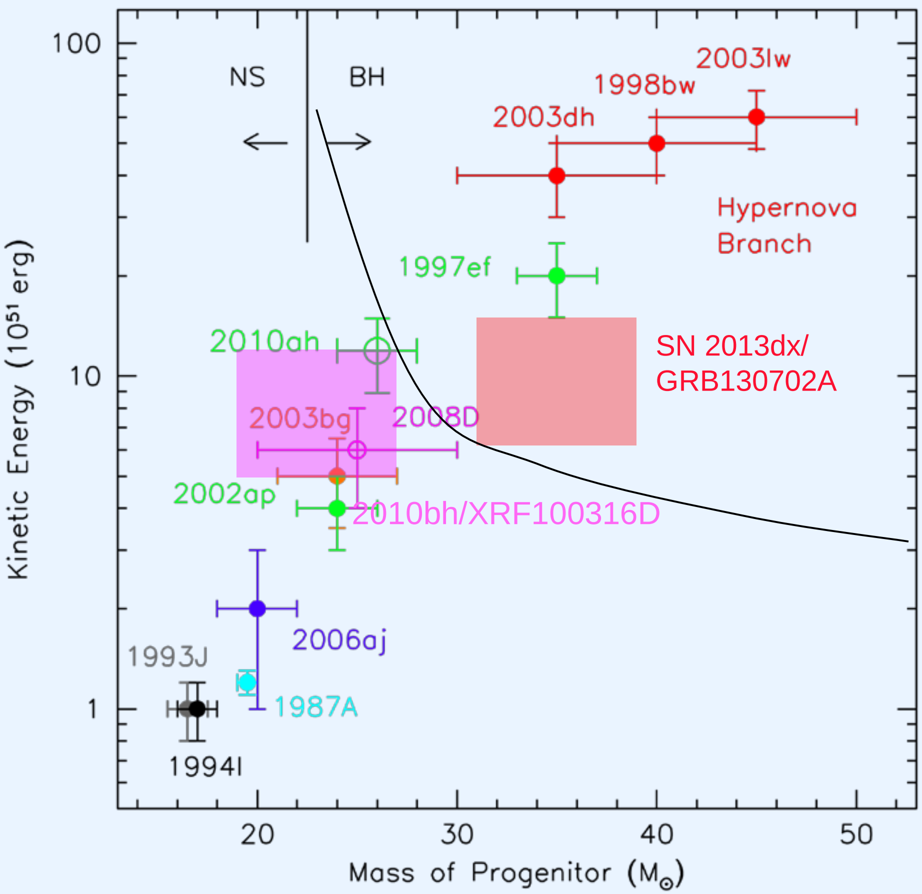
Ic + GRB/SNe more luminous than Ib/IIb

Light curve useful for M(^{56}Ni), need spectra for Mej/Ek estimates

Prentice et al. 2016

Props of SNe Ibc as f(prog. mass)

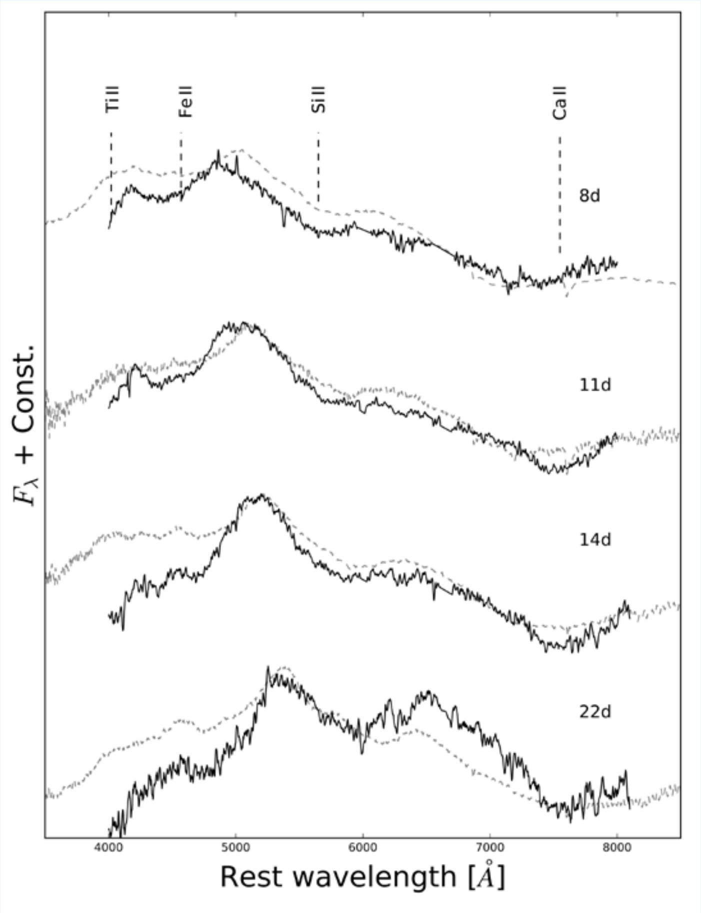




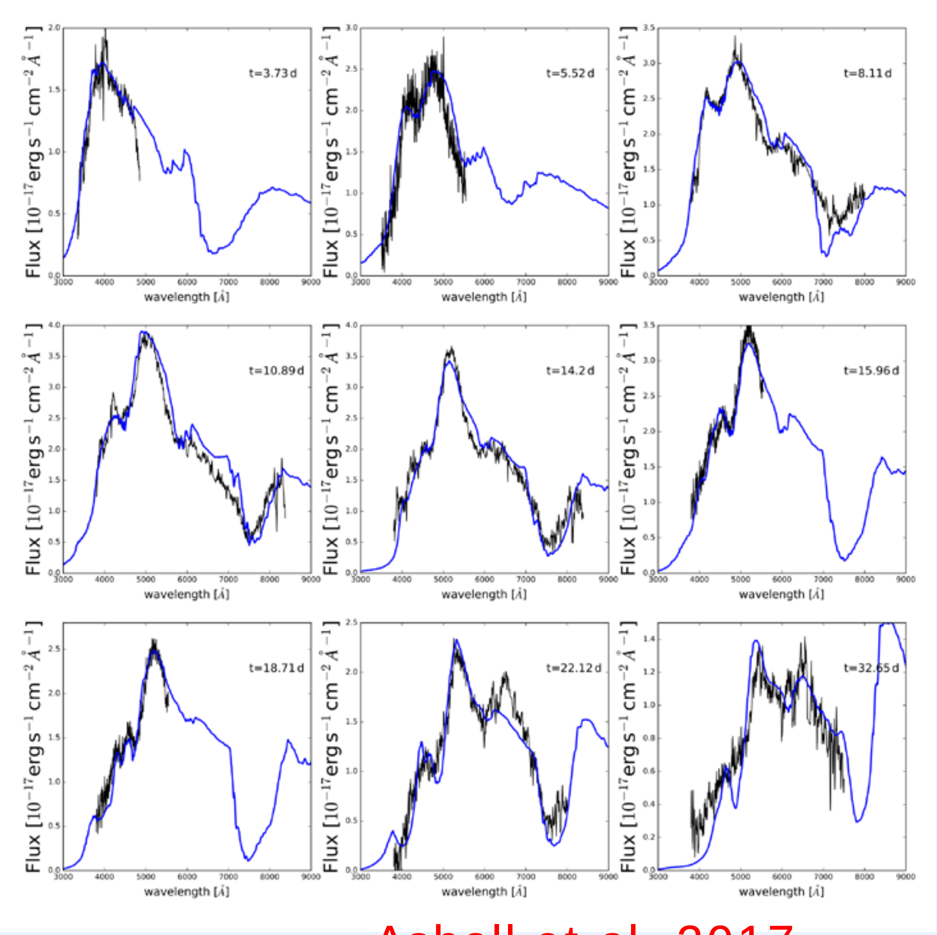
A minimum mass and energy seem to be required for GRBs

SN2016jca/GRB161219B

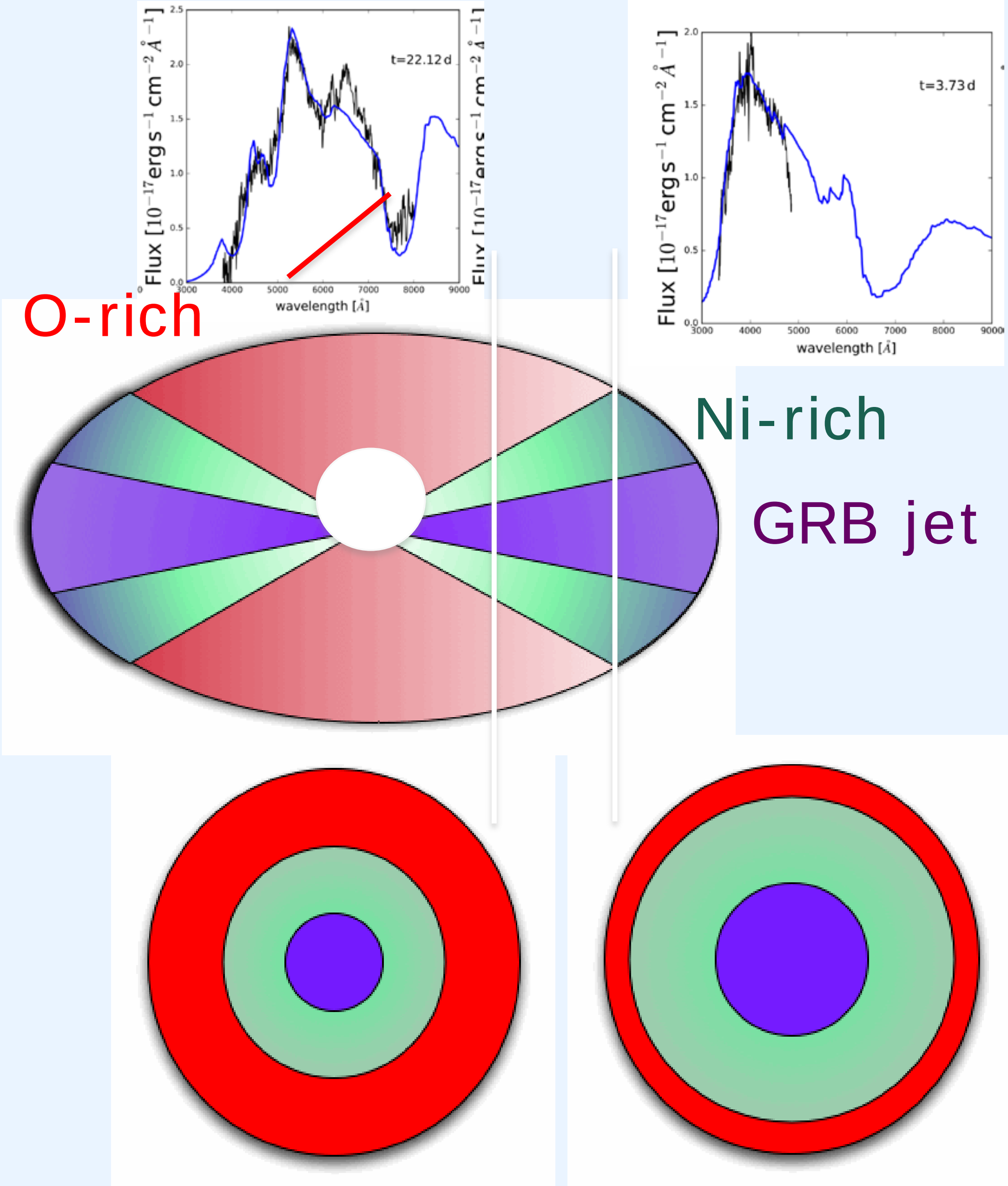
Higher velocities than 1998bw, UV suppressed: more Ni



Very early data allow better models: increasing O ab. at low velocities, indicative of aspherical props.



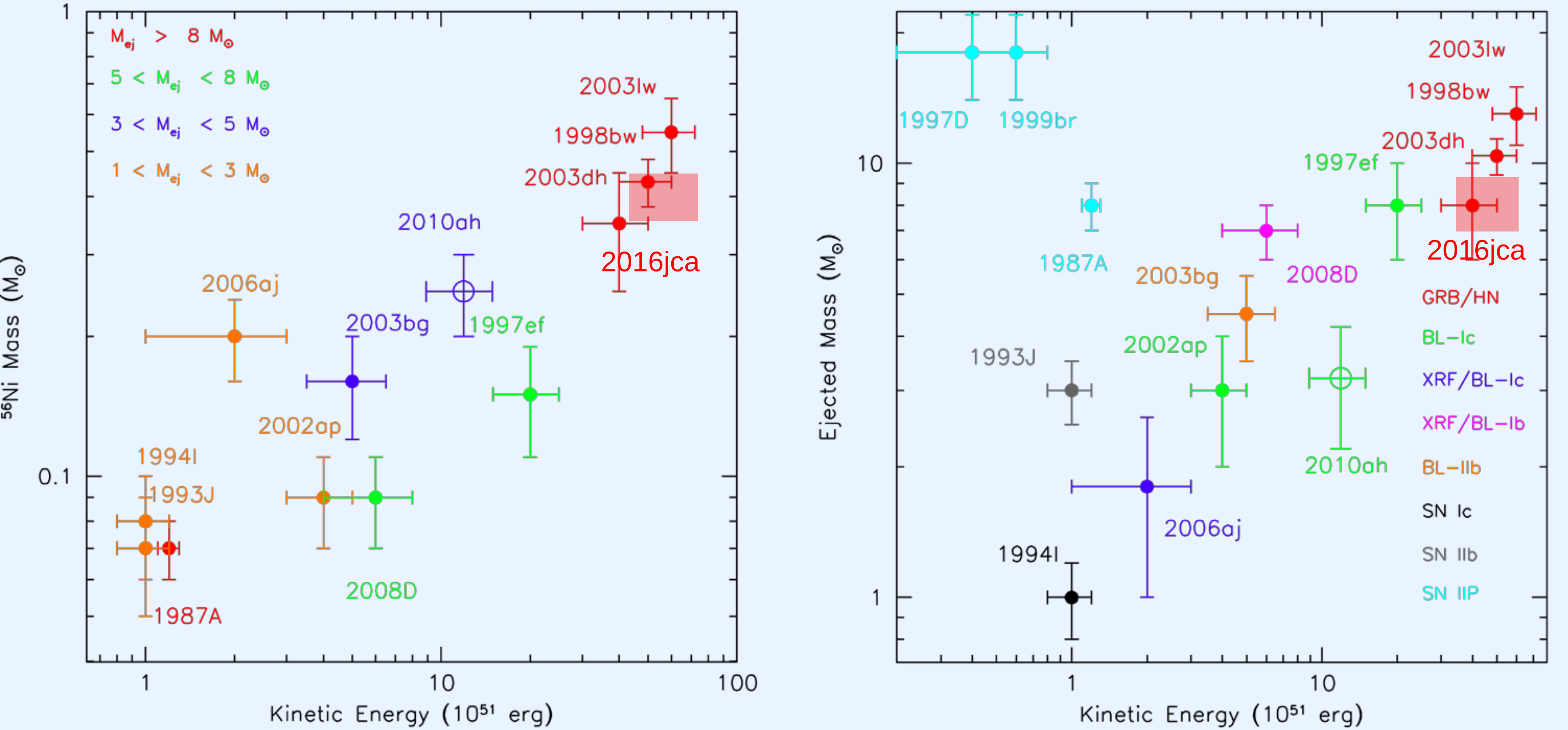
Ashall et al. 2017



SN 2016jca: More ^{56}Ni early on: head-on Ni jet

As time passes, see deeper into aspherical ejecta

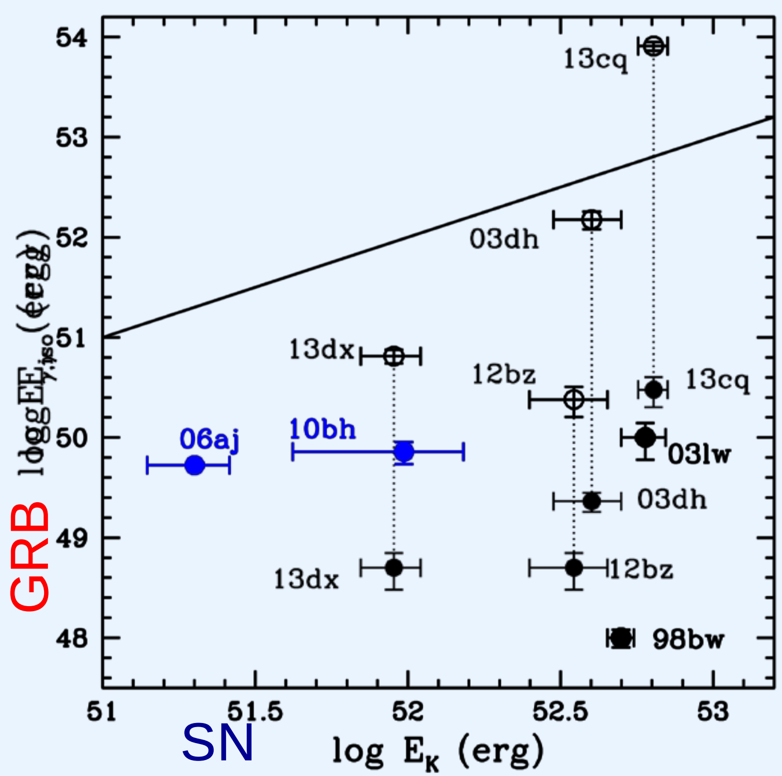
SNe Ib/c: Modelling results

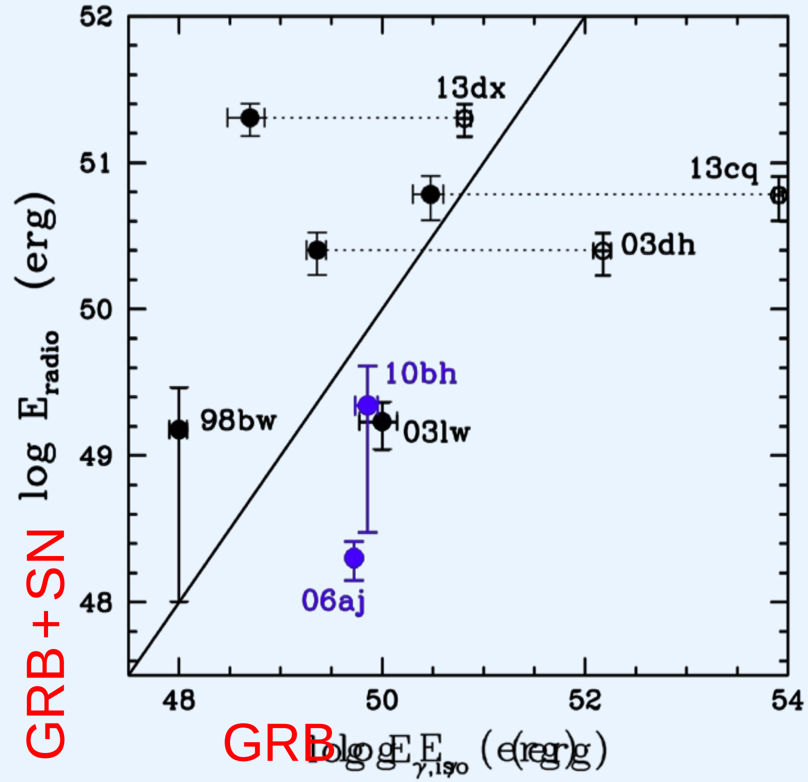


A minimum mass and energy seem to be required for GRBs

SN 2016jca was (again) similar to all other GRB/SNe

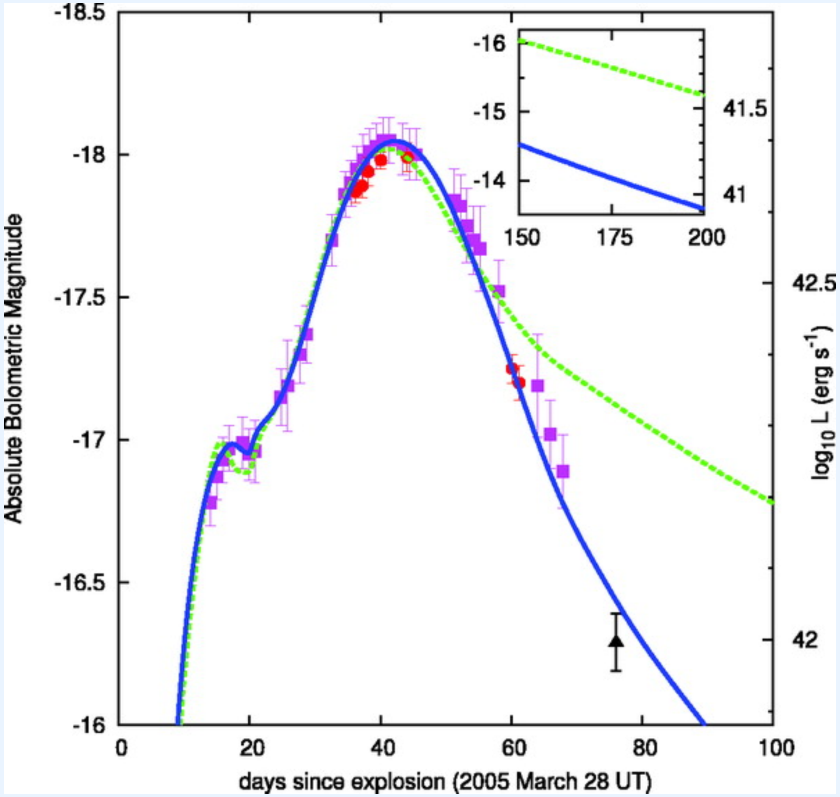
What is the "driving force"?
Compare energies of GRBs and SNe

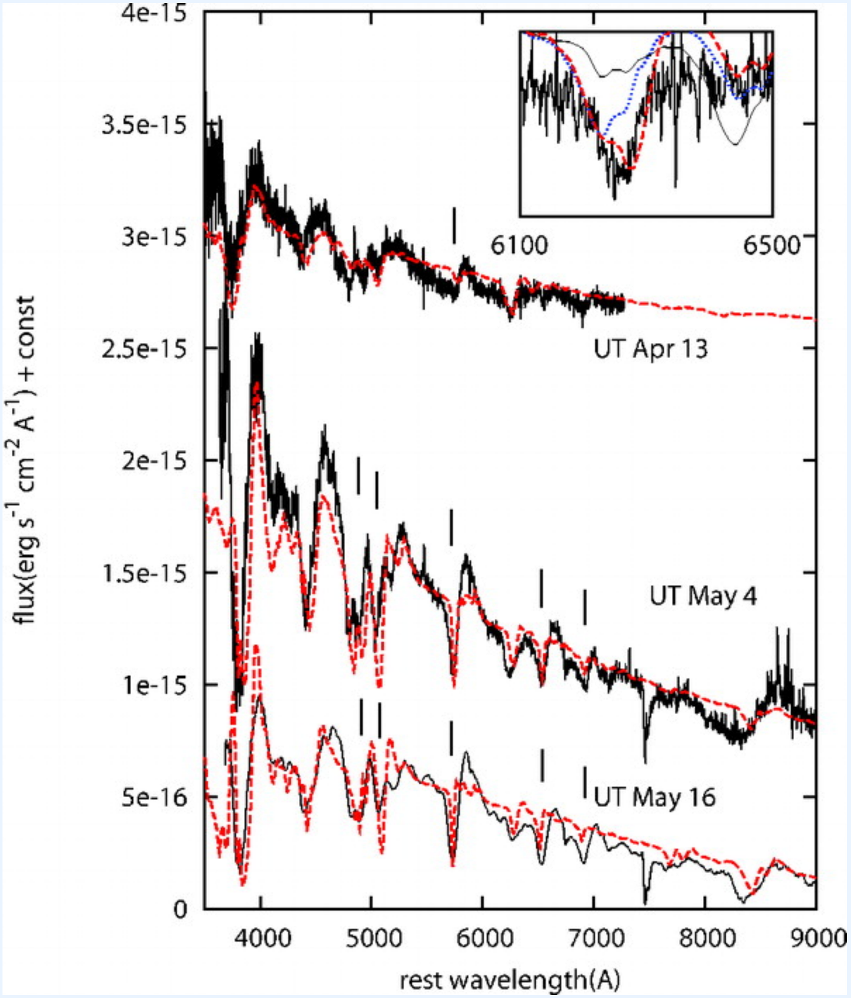




SN kinetic energy always dominates, and it is close to the maximum magnetar energy (PM+2014)

A Magnetar in SN Ib 2005bf?



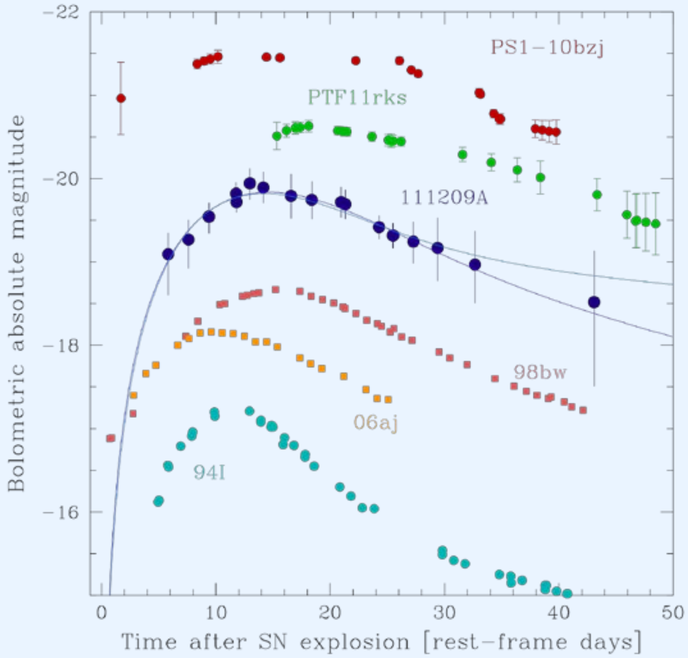


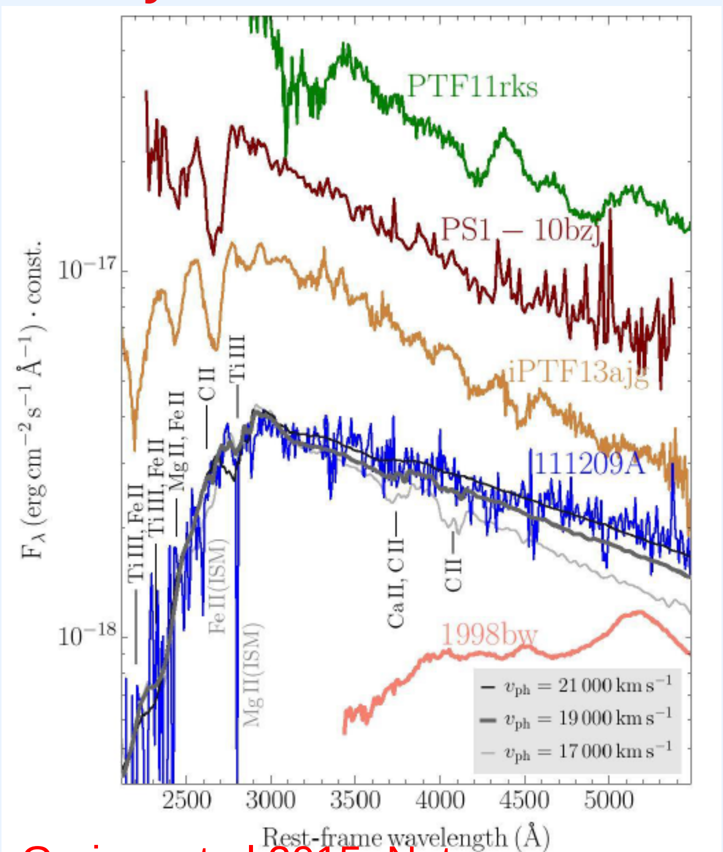
SN 2005bf (Tominaga et al. 2007)
showed a bright, late 2nd LC peak

Magnetar activity may have been responsible for the rebrightening
(Maeda et al. 2007)

III. SLSNe and ULGRBs?

- Ultra-long (>10^4 s) GRB111209 showed a SN bump (SN2011kl)
- SN LC intermediate in Lum between GRB/SNe and SLSNe
- Blue spectrum, consistent with high velocity SLSN





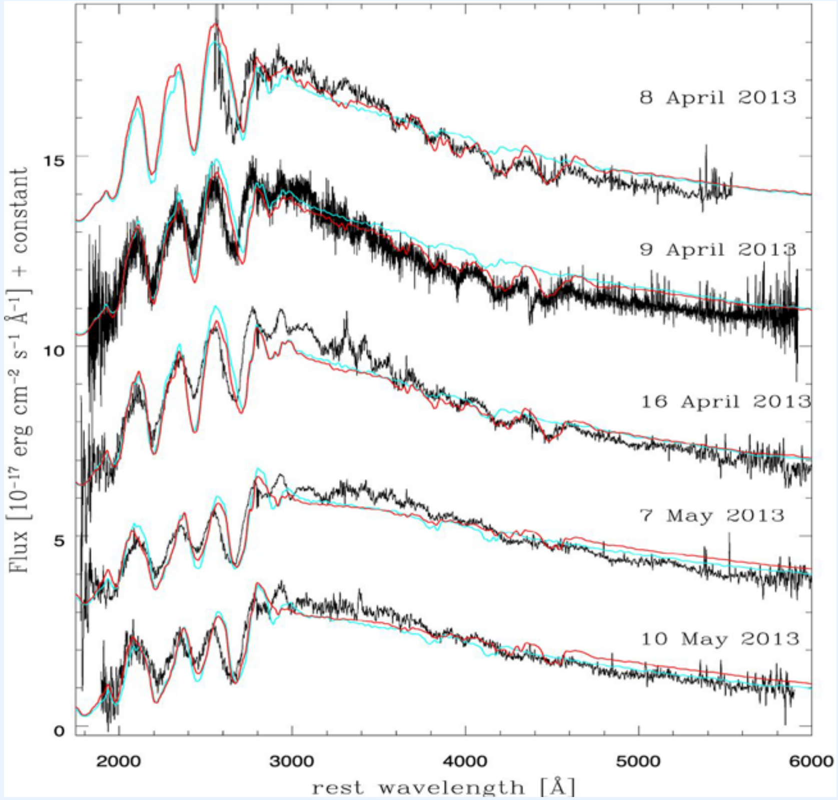
Consistent with Magnetar powering

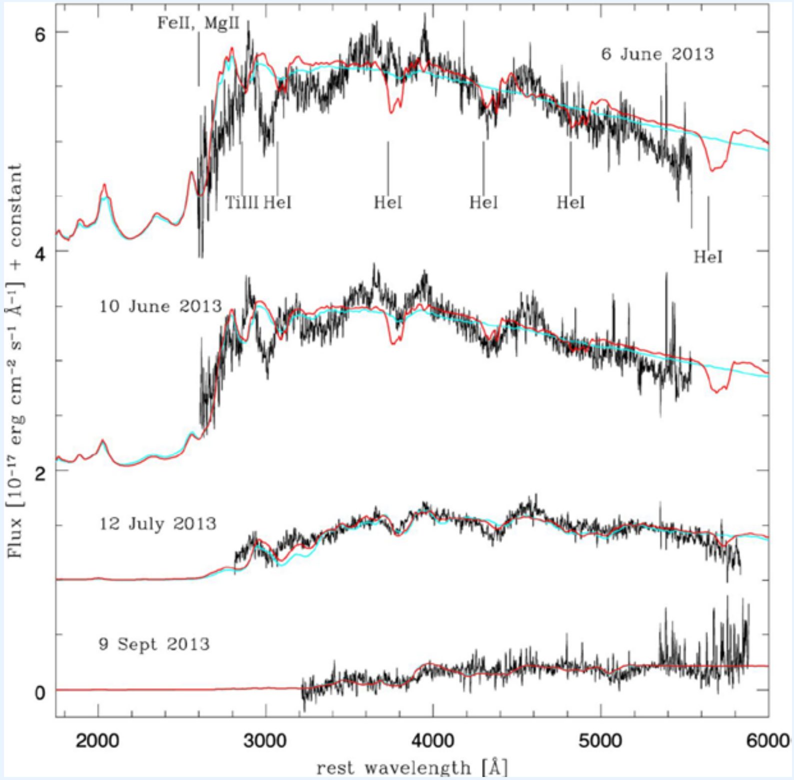
Are all luminous SNe magnetars?

Greiner et al 2015, Nature

SLSNe:ULGRB = SNeIc:GRB/HNe

Can get spectra of SLSNe ("I") with same model as SN2011kl, just lower Ek





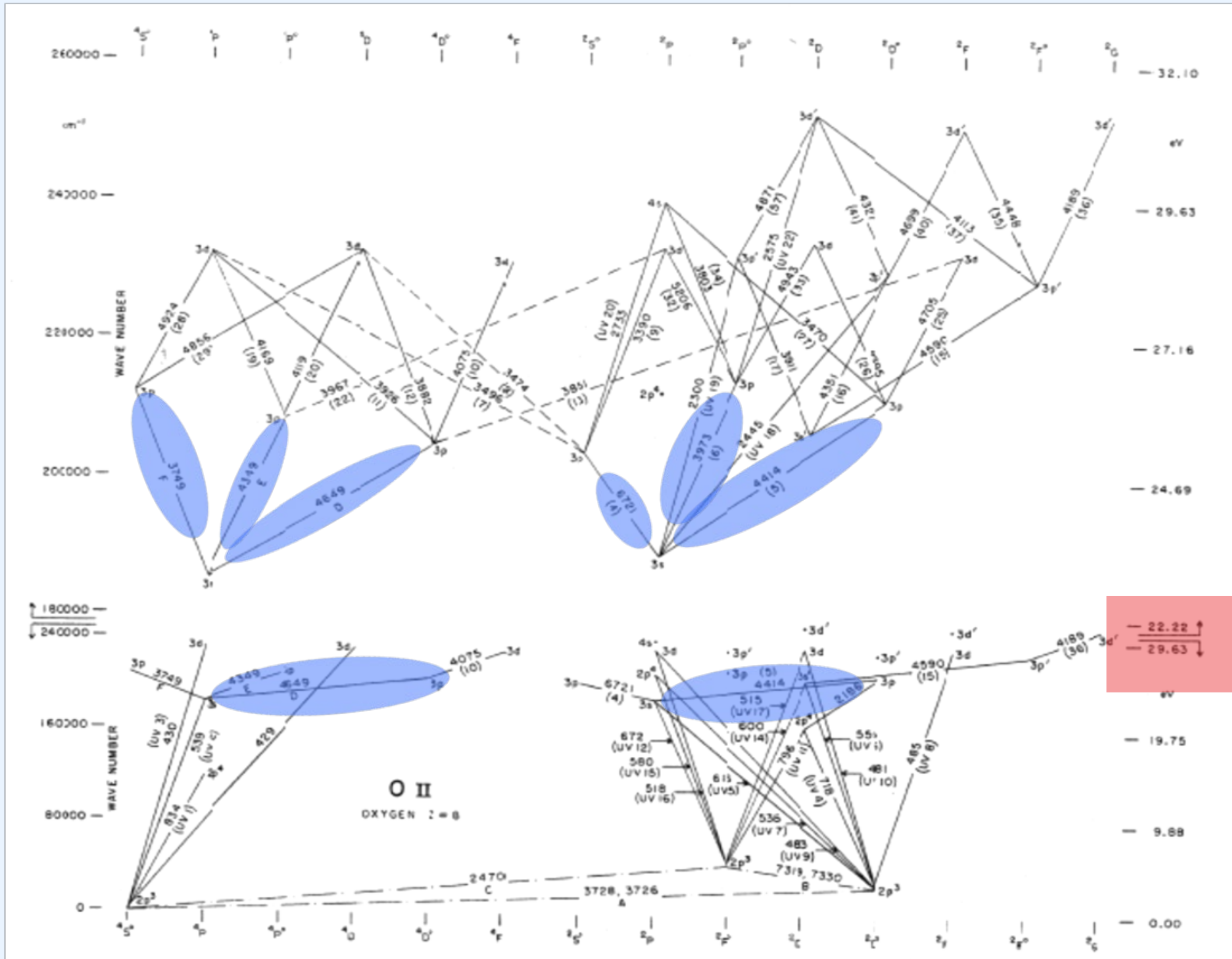
"peculiar" OII lines are result of non-thermal excitation/ionization at high Temp

HeI lines appear via same process only later, when Temp is "right" (lower)

The OII ion

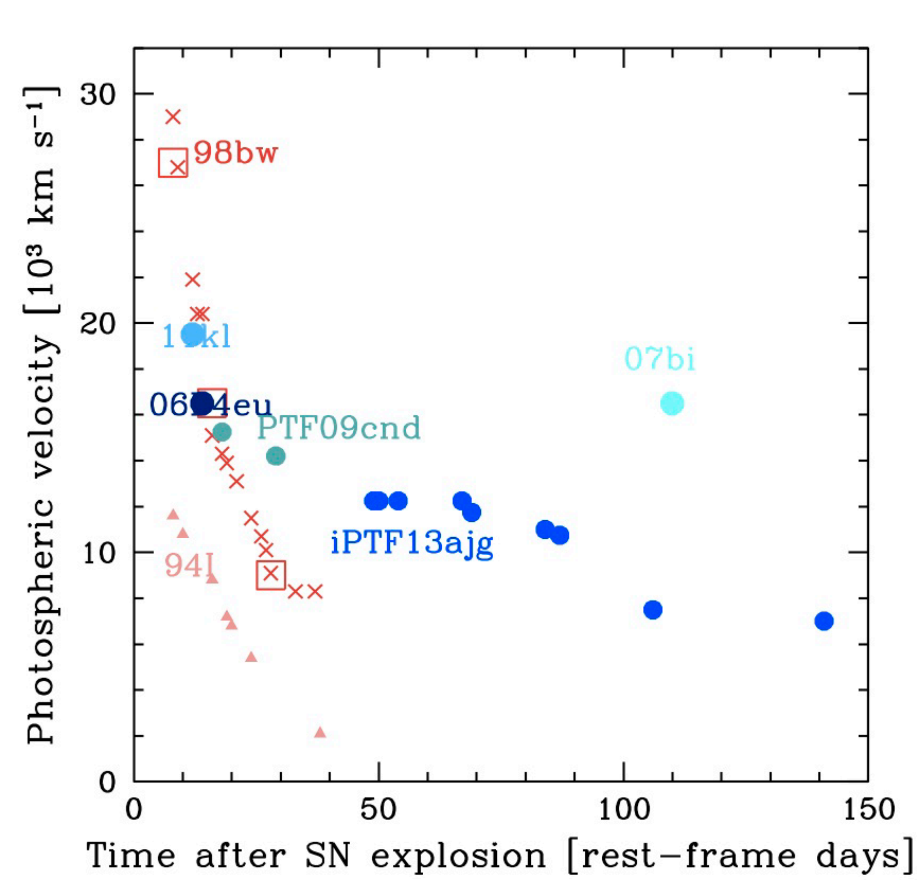
Optical OII lines come from lower levels with higher excitation energy than HeI (>22eV).

Not thermally excited

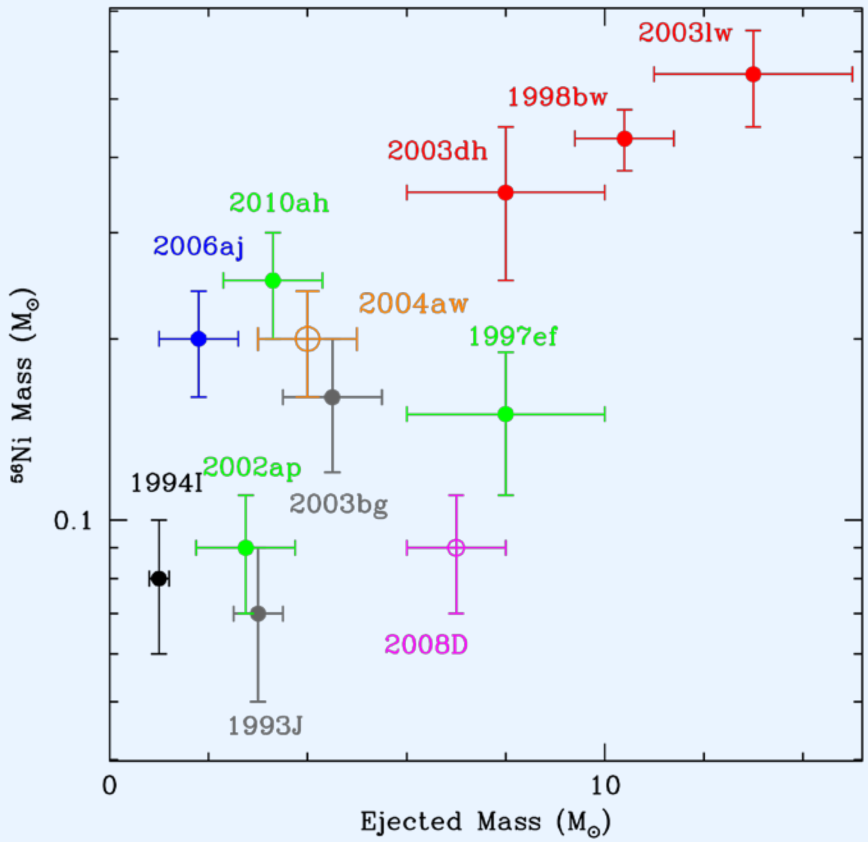


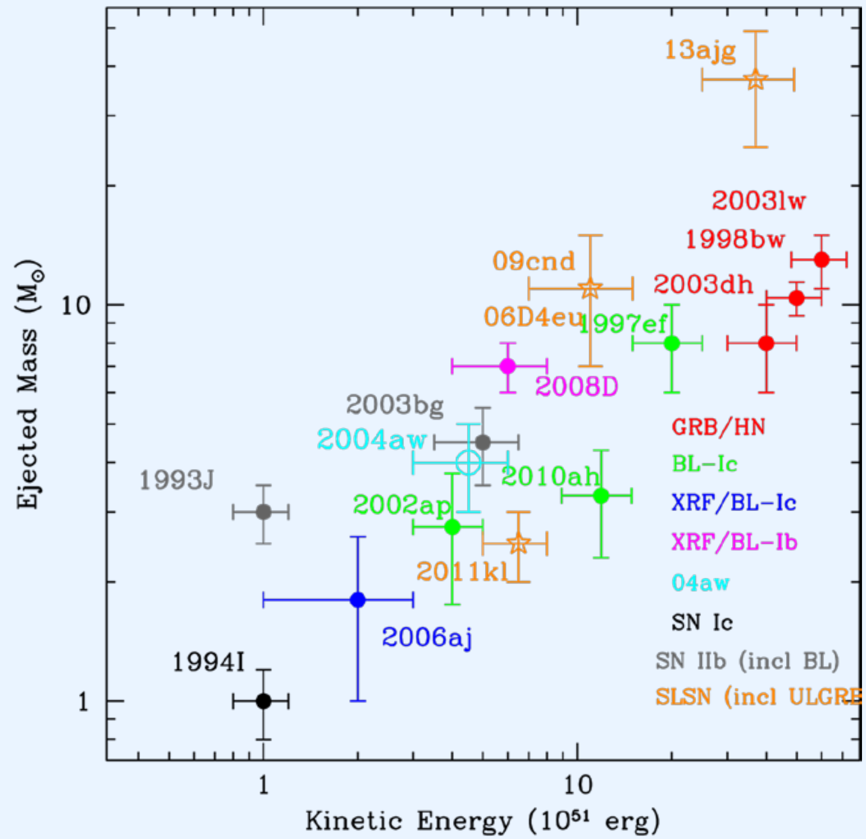
Velocity evolution

- Both SLSNe and HNe have high velocities,
- but in SLSNe high vel is sustained over a much longer time
- Slow decline suggestive of Magnetar powering in SLSNe



Comparing SNe Ib/c and SLSNe-I





- SNe Ib/c: ejected mass correlates with both ^{56}Ni mass and E
- SLSNe: - similar Ek range as SNe Ib/c; may reach larger Mej
  - Ek and Mej correlate; Ek/M typically ~1 (as in low-E SNe Ic)
  - ULGRB/SN is the exception; little info on M(^{56}Ni) (yet).

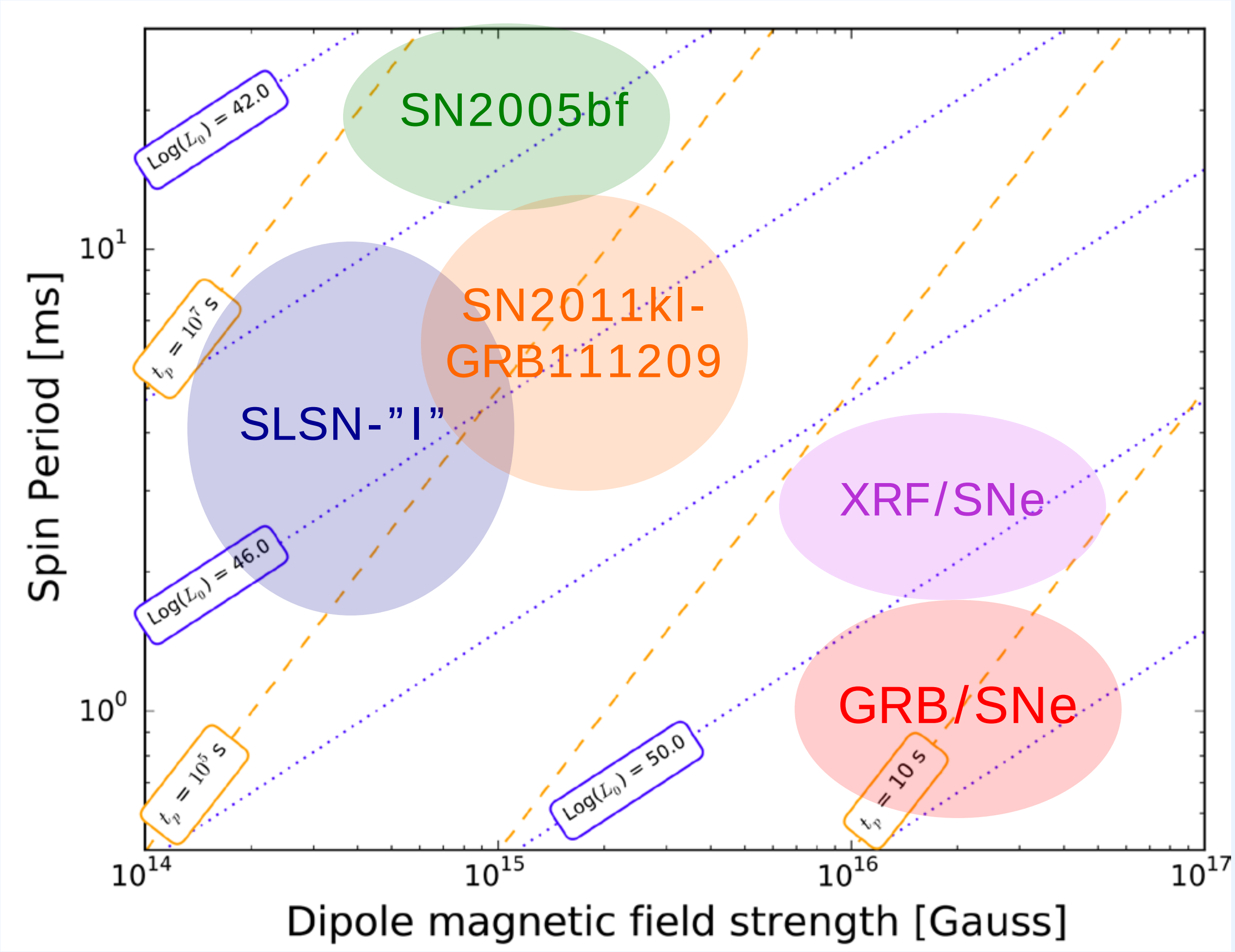
Comparing properties

	M_{ej} ($M_\odot$)	Ek (10^{51}erg)	Ek/Mej		M_{ej} ($M_\odot$)	Ek (10^{51}erg)
SNe Ic-7,6,5	1-4	1-4	~1	SLSNe-"I"	5-40	5-40
SNe Ic/BL	4-8	4-20	1-2			
GRB/HNe	8-12	20-50	3-5	ULGRB/SN	2-3	5-8

- ULGRB/SNe can have He and H (like SNe Ib/c, IIb)
- Highly excited OII (and He I) lines due to non-thermal excitation
- These are all cores of massive stars (binaries?)
- GRB/SNe, ULGRB/SNe have the highest Ek, Ek/Mej
- ULGRB/SNe NOT at massive end of range
- GRB/SNe driven by ^{56}Ni, ULGRB/SNe probably not.
- Magnetar powering likely in both GRB/HNe and ULGRB/SNe

Magnetar parameters?

- GRB, XRF require rapid energy injection, large E/M
- SLSNe powered by interaction: late injection



After Metzger+ 2015

Conclusions

- Type Ia SNe: early and late observations can reveal properties of progenitor/explosion.
- GRB/SNe: we know energetics and morphology, but what is the engine?
  A ``super-magnetar''?
- SLSNe: these seem to be different by having high Lum but not high E/M.
  Can we disentangle a classical SN?
  Is a Magnetar responsible for the LC?