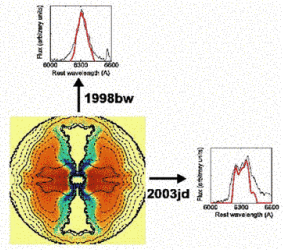
Asymmetries in Type Ic SNe



Paolo A. Mazzali

Max-Planck Institut für Astrophysik, Garching

Istituto Naz. di Astrofisica, Oss. Astron. Trieste

INAF

Astronomy Department and
RESearch Centre for the Early Universe,
University of Tokyo 東京大學

Type Ic SNe / Hypernovae

Broad lines

→ Large Kinetic Energy

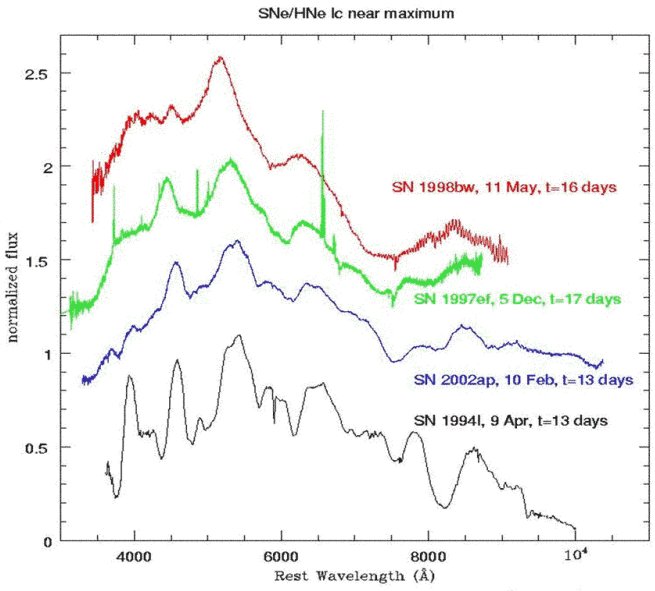
→ "Hypernovae"

(only SN1998bw was associated with a GRB)

Narrow lines

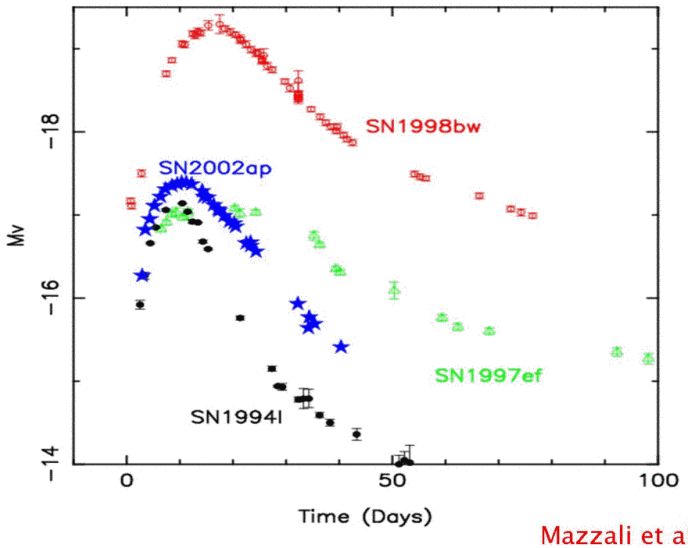
→ "normal" KE (1 foe)

→ Normal SN Ic



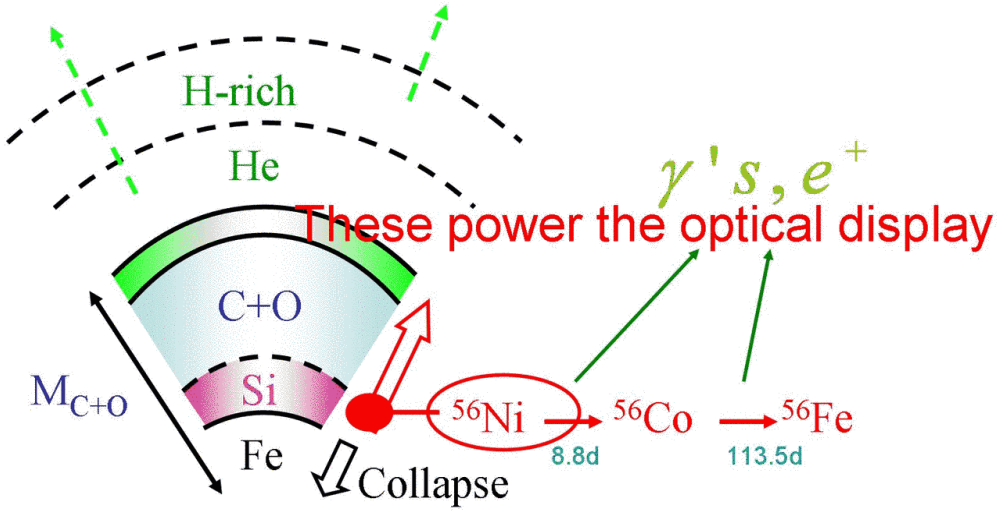
Mazzali et al. 2002

Hypernova light curves are brighter/more extended



Mazzali et al. 2002

CO Star Models for SNe Ic



Parameters [M_{ej}, KE, M(^{56}Ni)]

Explosion Parameters

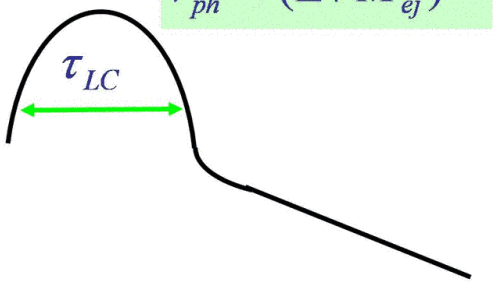
$$M_{ej}, M(^{56}Ni), KE$$

Light Curve | Spectra

$$\tau_{LC} \sim (\tau_{dyn} \cdot \tau_{diff})^{1/2} \sim \left(\frac{R}{V} \quad \frac{\kappa M_{ej}}{R c} \right)^{1/2}$$

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

$$v_{ph} \propto (E / M_{ej})^{1/2}$$

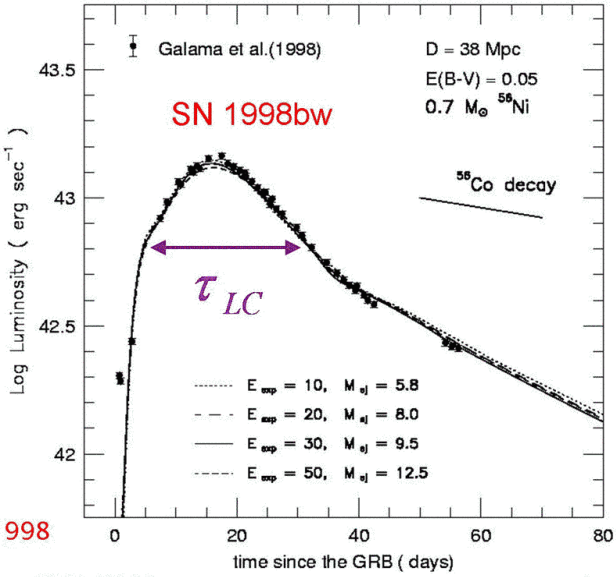


Determining the properties of SN 1998bw

Light curves can be degenerate if both M and E are allowed to vary

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

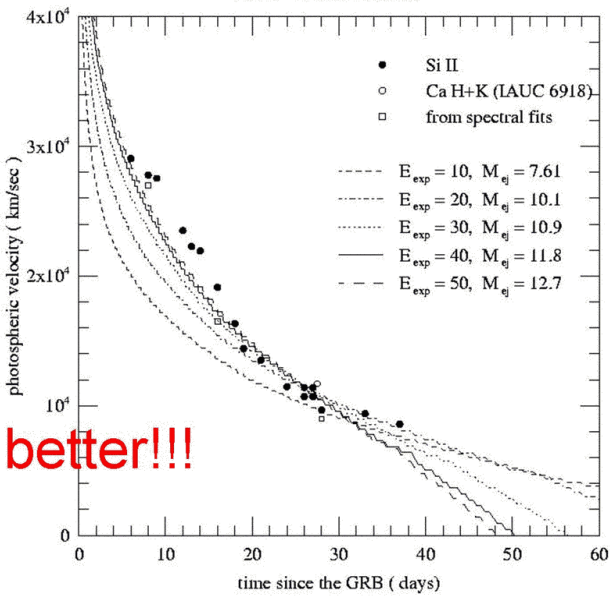
Iwamoto et al. 1998



Photospheric velocity useful to distinguish between models

$$v_{ph} \propto \left(\frac{E}{M_{ej}}\right)^{1/2}$$

SN 1998bw



…but spectra are better!!!

Iwamoto et al. 1998

Must fit LC and spectra simultaneously

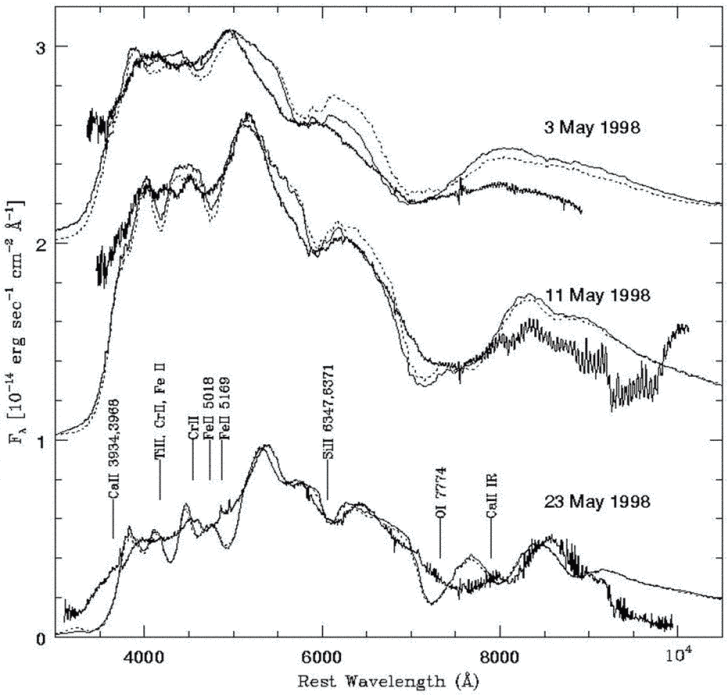
SN 1998bw

Early-time spectra

Model CO138

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

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



Iwamoto et al. 1998

Fe lines broader than O lines!

SN 1998bw

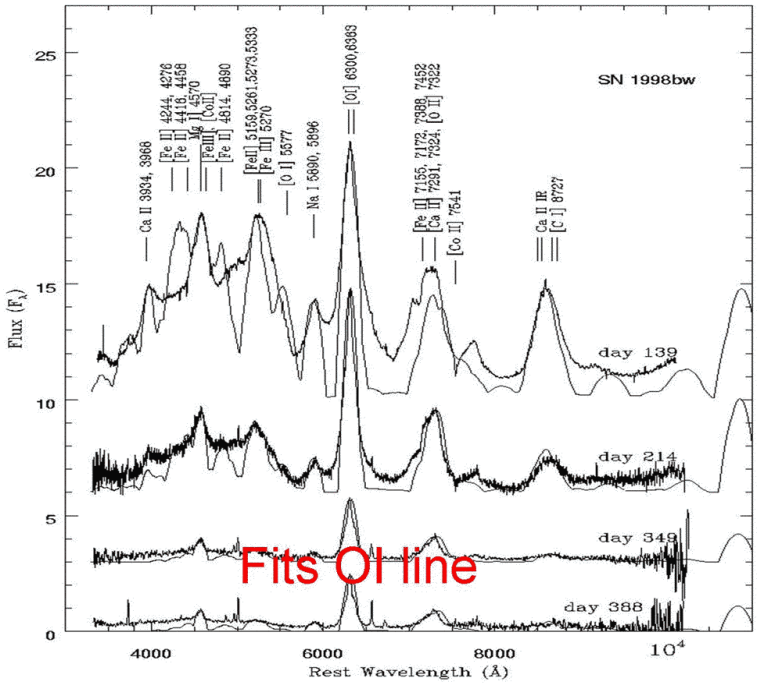
Late-time spectra

`narrow-line' models

v~6,000 km/s

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

Mazzali et al. 2001



Fits OI line

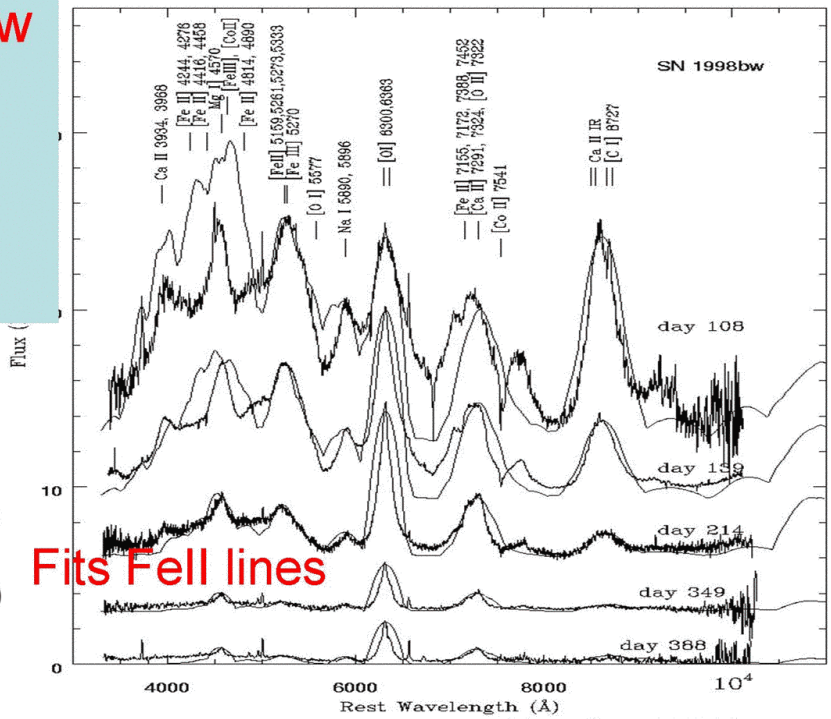
SN 1998bw

Late-time spectra

`Broad-line' models

v~10,000 km/s

$M(^{56}Ni) \sim 0.6 M_{\odot}$

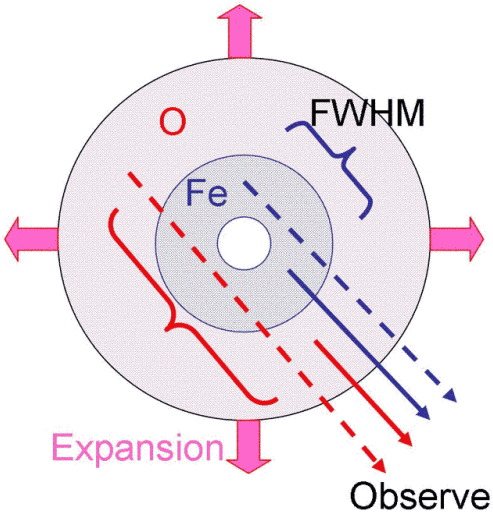


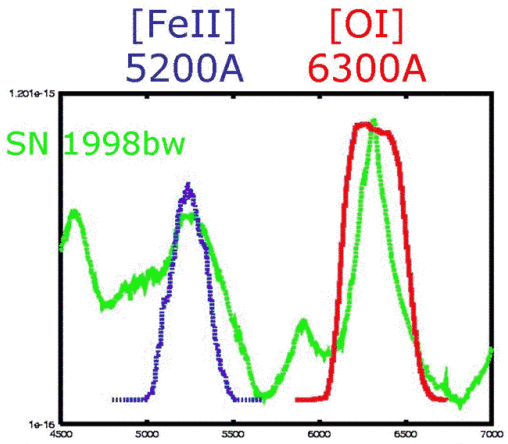
Fits FeII lines

Mazzali et al. 2001

Spherical Explosion of Massive Star:

O lines are broader than Fe lines



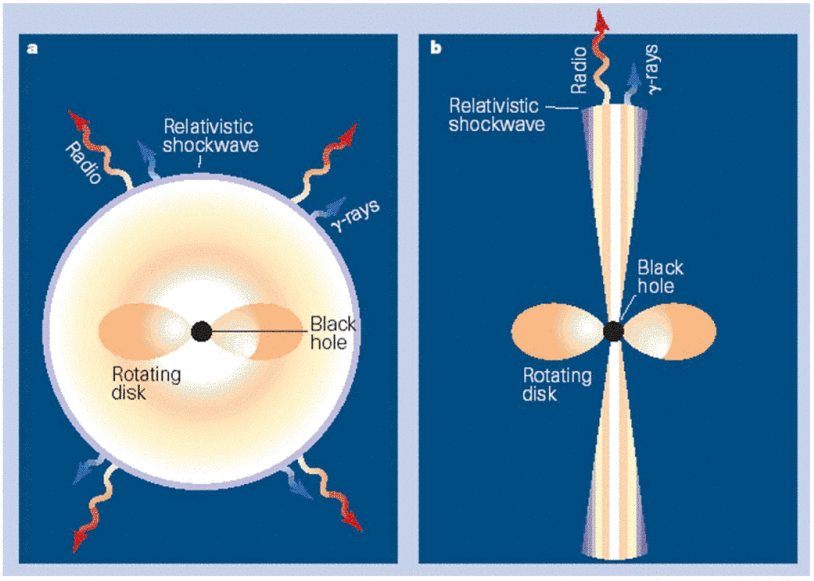


A Spherical Model cannot match SN 1998bw

Maeda et al. 2002

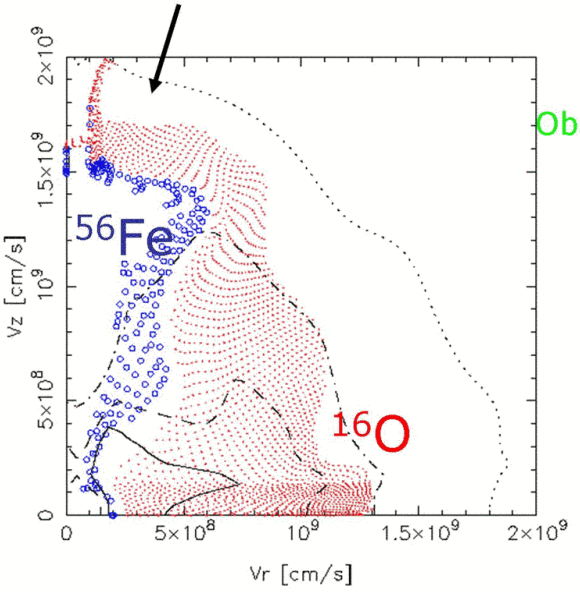
Indications that explosion was asymmetric

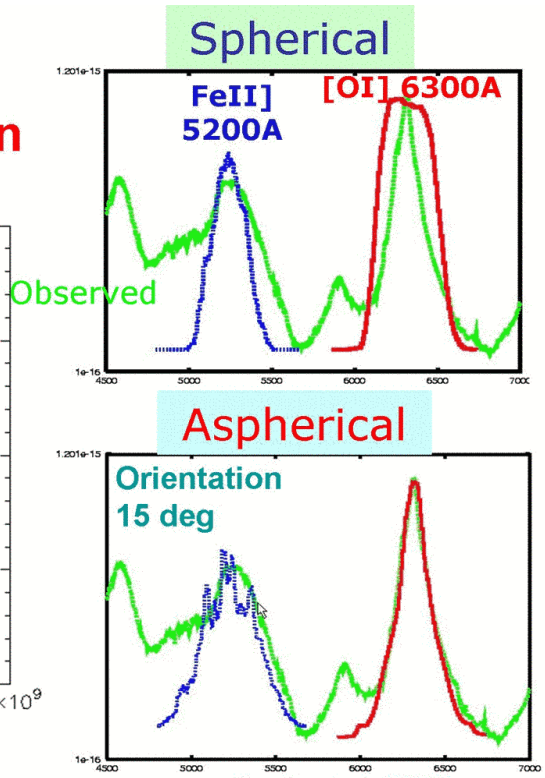
Link to GRB's



Baron 1998

Interpretation as an Aspherical explosion

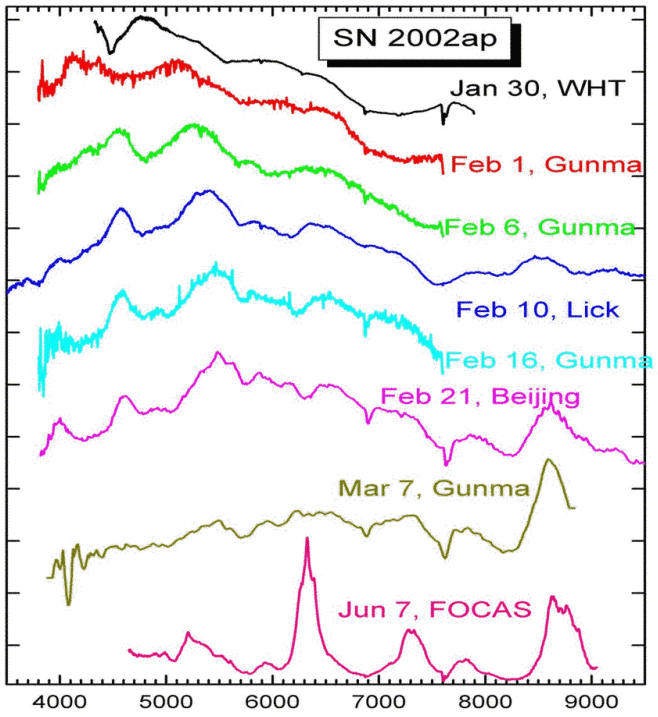




Maeda et al. 2002

SN Ic 2002ap

in M74



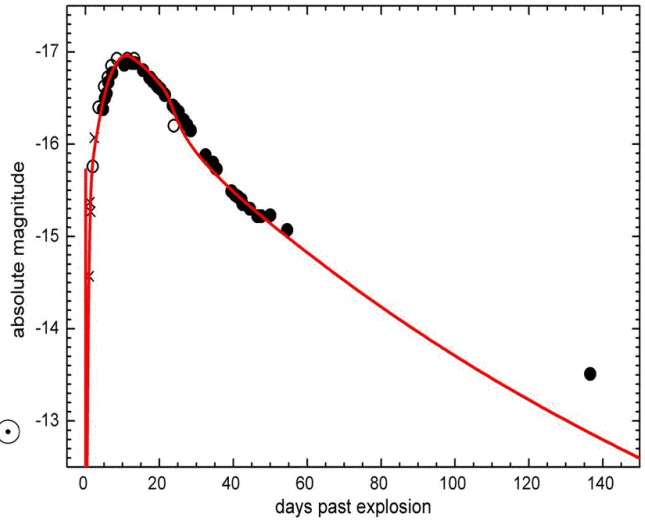
SN2002ap: modelling the light curve

Model CO100/4

KE = 4 foe

$M_{ej} = 2.5 M_\odot$

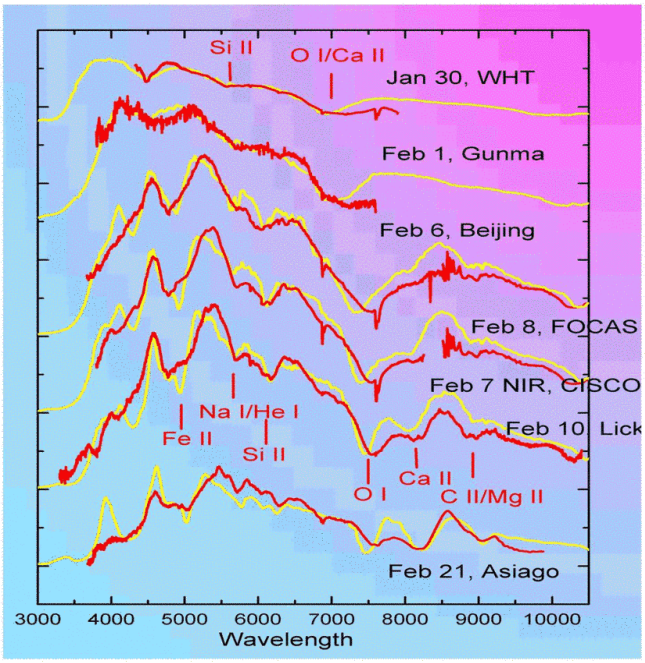
$M(^{56}Ni) \sim 0.07 M_\odot$



Mazzali et al.2002

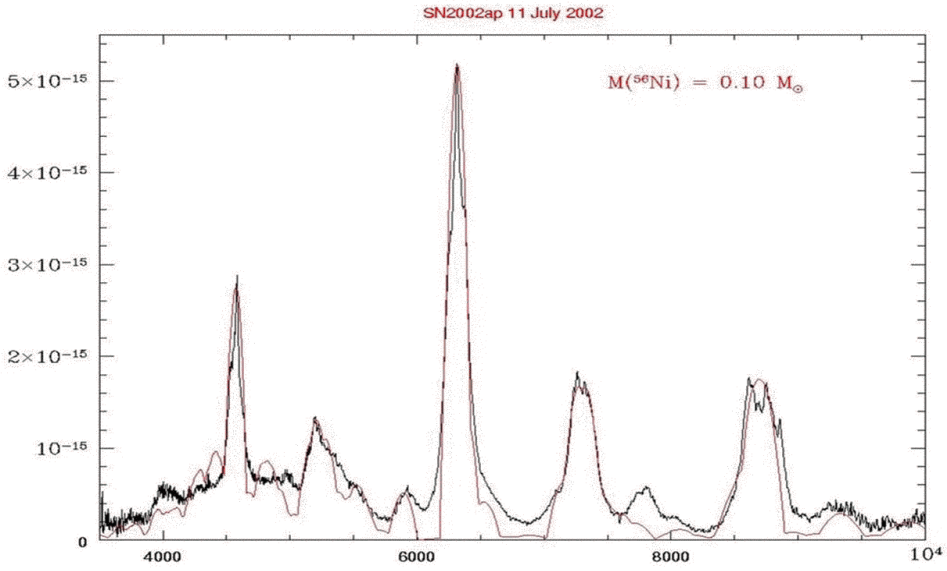
SN 2002ap: early spectral models

Model CO100/4



Mazzali et al 2002

SN 2002ap: nebular models

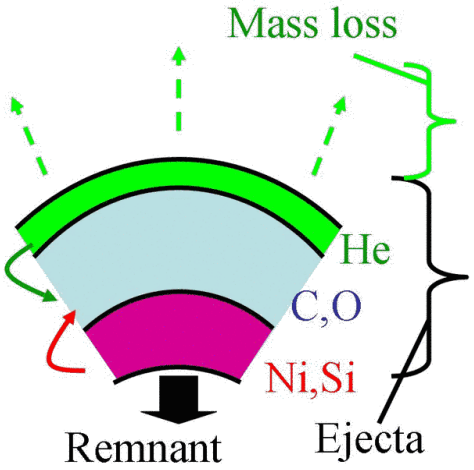


Foley et al. 2003

The properties of SN 2002ap

- M_{ejecta} ~ 2.5 $M_\odot$ - 5 $M_\odot$
- M(^{56}Ni) ~ 0.07-0.1 $M_\odot$
- KE ~ 4 – 10 foe

- M_{ZAMS} ~ 20 - 25 $M_\odot$
  - **SN/HN Boundary?**
- M_{REM} > 2 $M_\odot$
  - **BH/NS Boundary**

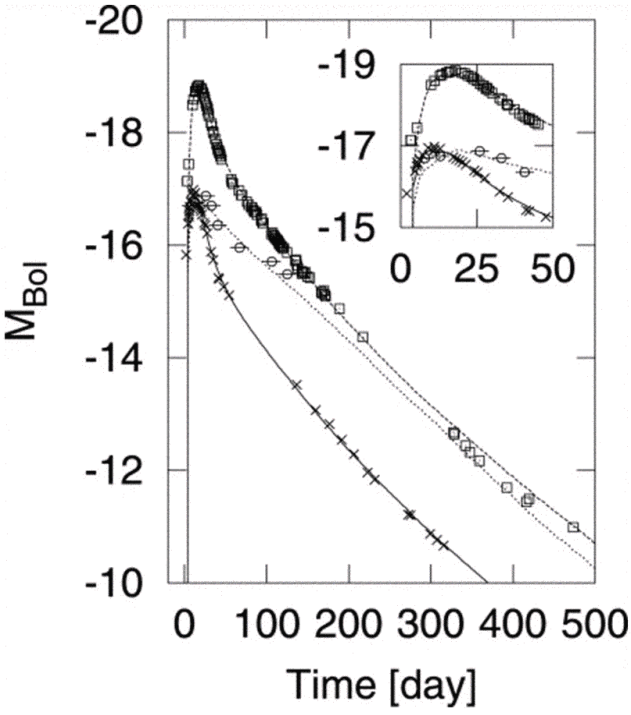


- Matter Mixing
  - He: Outer Layer ⇒ Mixed In.
  - ^{56}Ni: Deepest Region ⇒Surface.

  (He coexists with O, Rapid Rise in LC)

Properties of Type Ib/c Super/Hypernovae

SN	83N	94I	02ap	97ef/dq	98bw
type	Ib	Ic	Ic (Hypernovae)		
M_{ZAMS}	15	15	21	34	40
M_{He}	4	4	6.6	13	16
M_{CO}	2	2	4.5	11	14
M_{Expl}	4	2.1	4.6	11.1	13.8
M_{Rem}	1.25	1.2	2.1	1.6	2.9
M_{Ej}	2.75	0.9	2.5	9.5	10.9
M_{He}	2.0	---	0.1	---	---
M_{CO}	0.5	0.6	1.8	5.3	8
$M_{IME(Si,S)}$	0.1	0.2	0.5	4	2
M_{Ni}	0.15	0.07	0.1	0.13	0.7
E_{51}	1	1	5	19	50
GRB	X	X	X	X	√

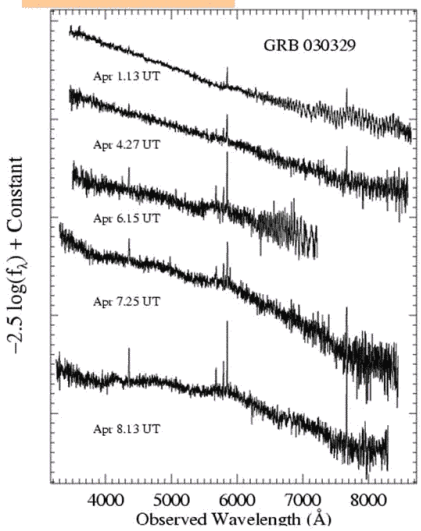


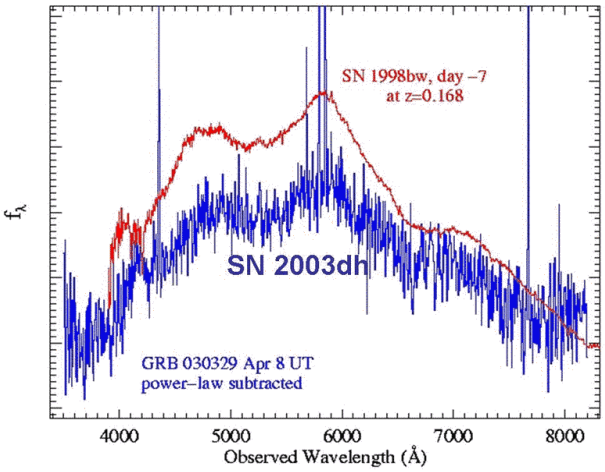
HN LCs require dense massive core
(Maeda et al 2003)

→ Indication of aspherical explosion?

The Confirmation: GRB030329 / SN2003dh (HN)

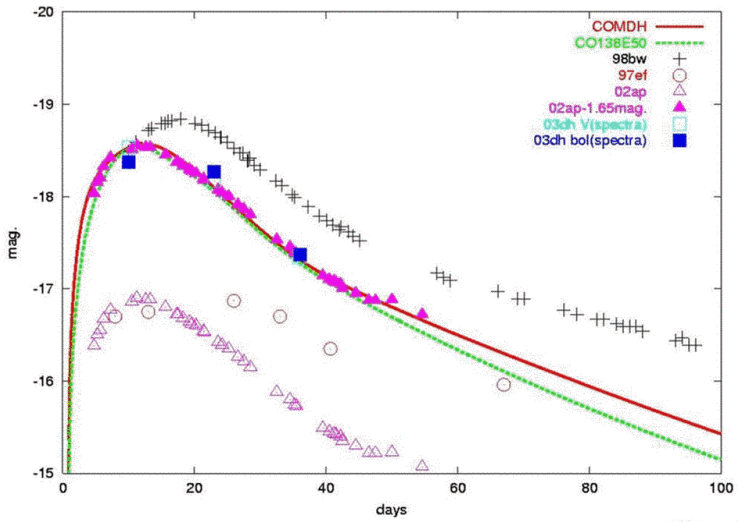
Z = 0.167





Stanek et al. 2003

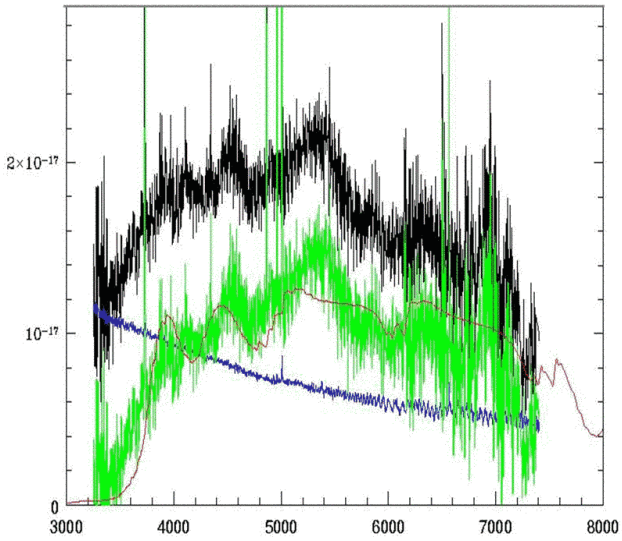
SN 2003dh: the light curve



SN 2003dh is somewhat dimmer than SN 1988bw, but much brighter than both SNe 1997ef and 2002ap

Mazzali et al. 2003

SN 2003dh: another Hypernova



SN 2003dh is 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

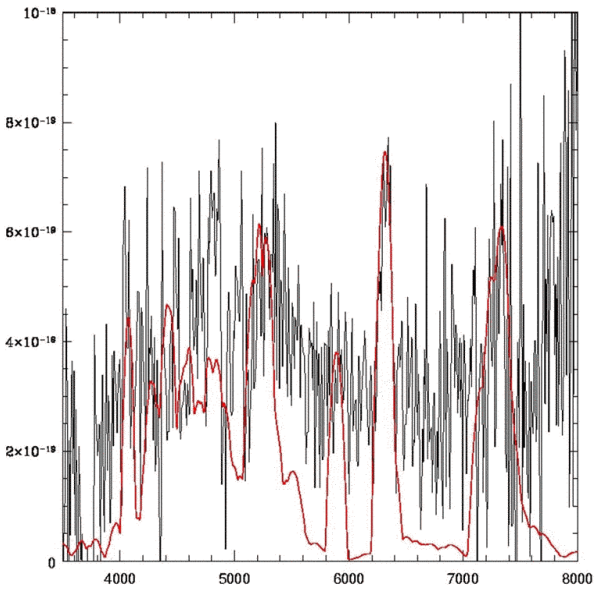
SN2003dh: the nebular phase

The nebular spectrum shows a strong but narrow [O I]6300 line, like SN1998bw.

Model:

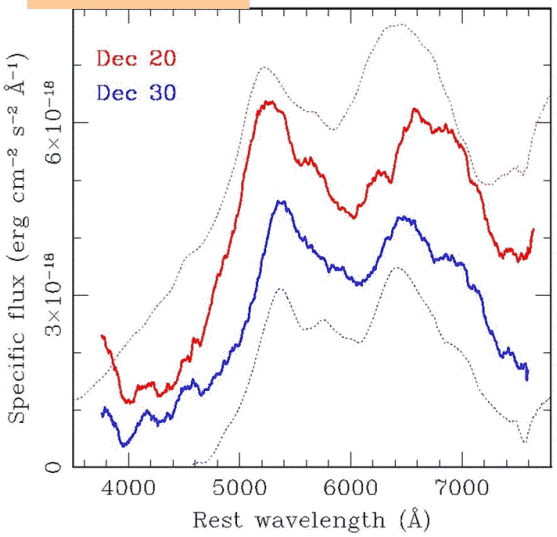
v = 5000 km/s

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



The Nail in the Coffin: GRB031202 / SN2003lw (HN)

z = 0.105



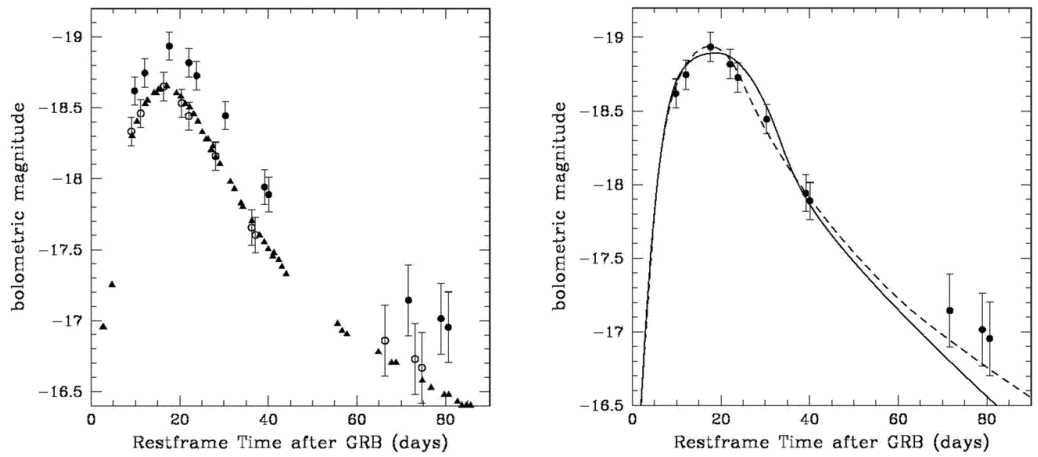
Highly reddened, but a close analogue of SN1998bw

With GRB031202/SN2003lw,

ALL 3 nearest GRBs are Hypernovae

Malesani et al. 2004

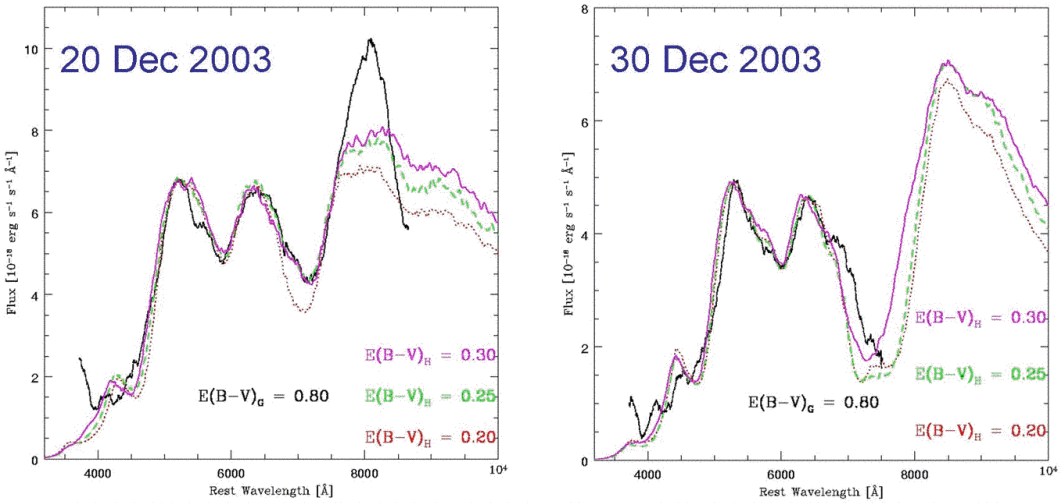
SN2003lw: the Light Curve



LC(03lw) ~ LC(98bw)*1.15 (stretch), but ~0.3 mag brighter

Model similar to CO138, but more massive: M=13Mo, E~60 foe (Mazzali et al. 2006)

SN2003lw: models for different host reddenings [$E(B-V)_H$=0.20;0.25;0.30]



Similar to SN1998bw and SN2003dh, but more massive

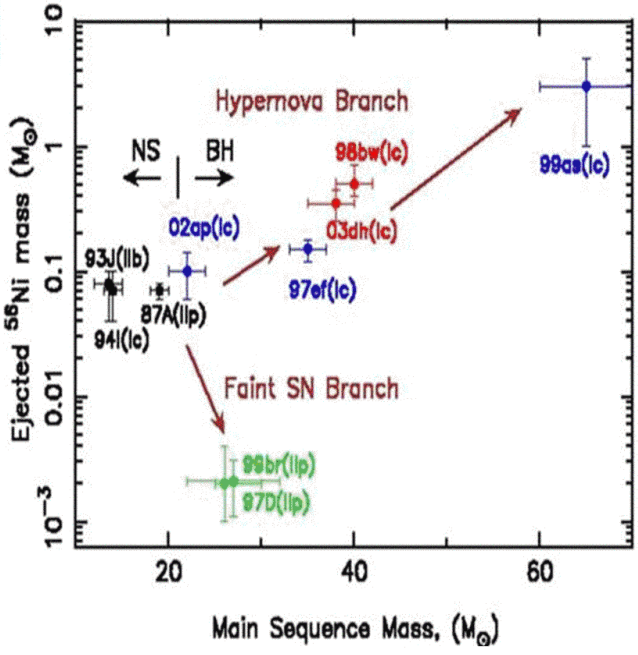
$M(^{56}Ni) \propto M_{MS}$?

`bright' branch:

Hypernovae

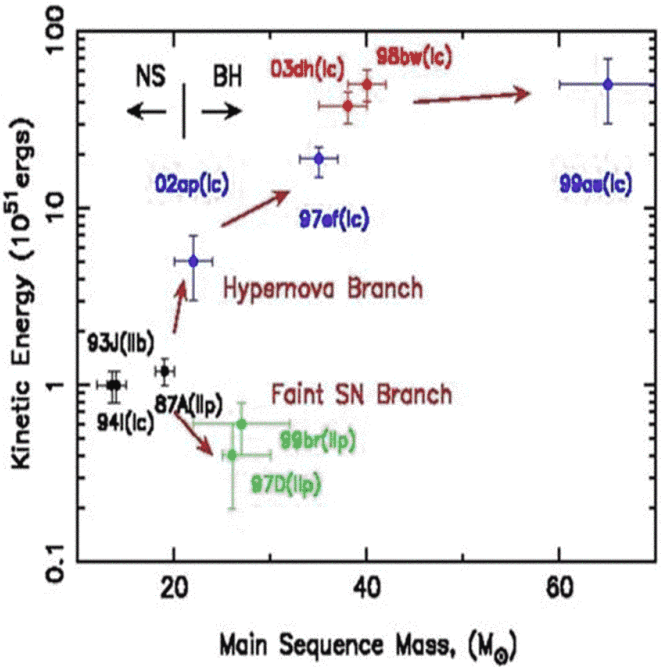
`faint' branch:

SN1997D etc.



$KE \propto M_{MS}$?

Again two branches



Rates of GRBs and HNe

GRBs:

Observed: $R_{obs} = 10^{-7}\ yr^{-1}$

Beaming factor: $2\Omega/4\pi$

($\sim 10^{-2}$ for jet opening angle $\omega = 8^\circ$)

$\Rightarrow$ R(GRB) $\sim 10^{-5}\ yr^{-1}$

HNe:

CC SNe: $7\times10^{-3}\ yr^{-1}$

of these, SNe Ib/c: $10^{-3}\ yr^{-1}$

HNe: 5% of SNe Ib/c, but 3 - 5× brighter

$\Rightarrow$ R(HNe) $\sim 10^{-5}\ yr^{-1}$

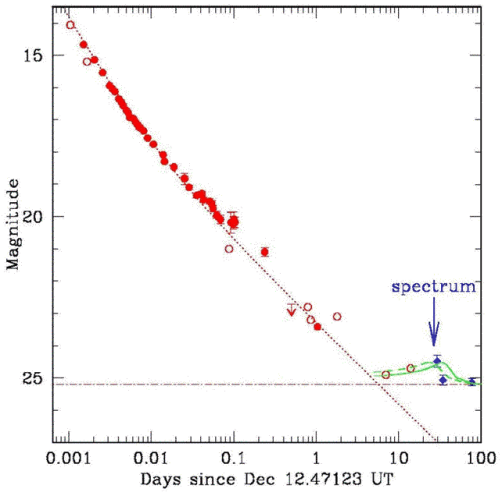
These are lower than rate of SNe from massive stars:

$R(SN; M > 80M_\odot) = 2 \times 10^{-4} yr^{-1}$

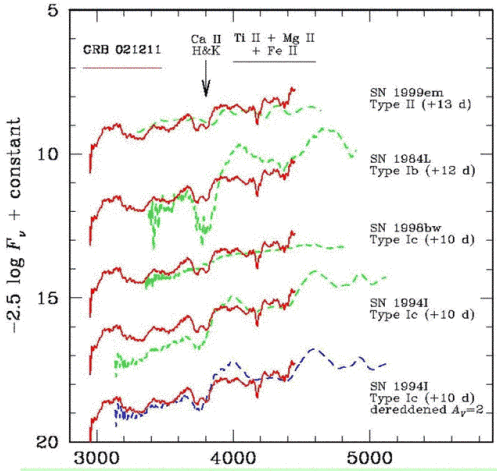
Podsiadlowski et al. 2004

A Caveat: a non-HN in a GRB?

GRB021211 / SN2002lt



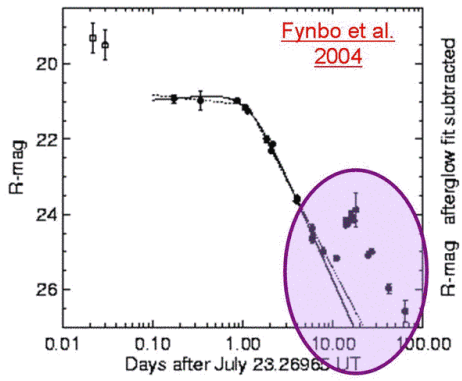
Della Valle et al. 2003



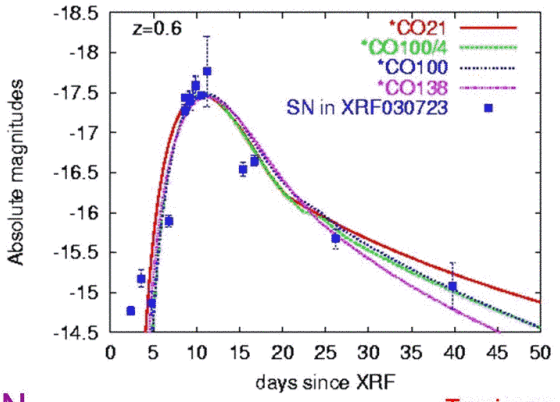
The spectrum is similar to the "normal" SN Ic 1994 or to SN 2002ap

A SN in XRF030723?

XRFs are the weak (X-ray dominated) analog of GRBs



Bump in LC interpreted as a SN

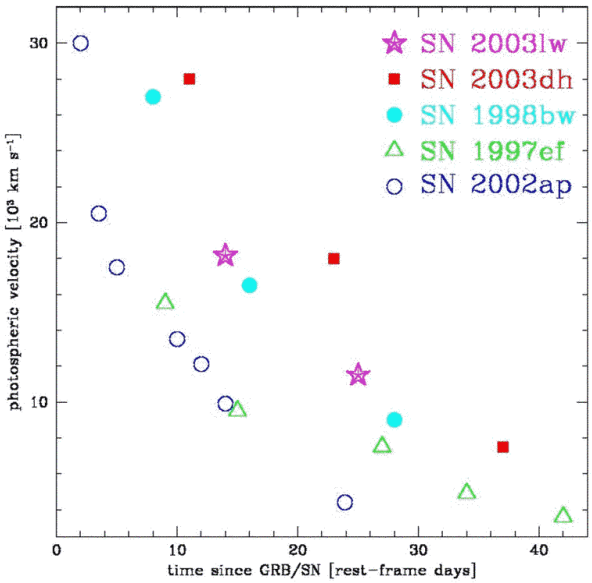


Tominaga et al. 2004

LC Fits: a normal SN Ic or a low-E HN like SN2002ap at z~0.6

Properties of GRB/HNe: Photospheric velocities

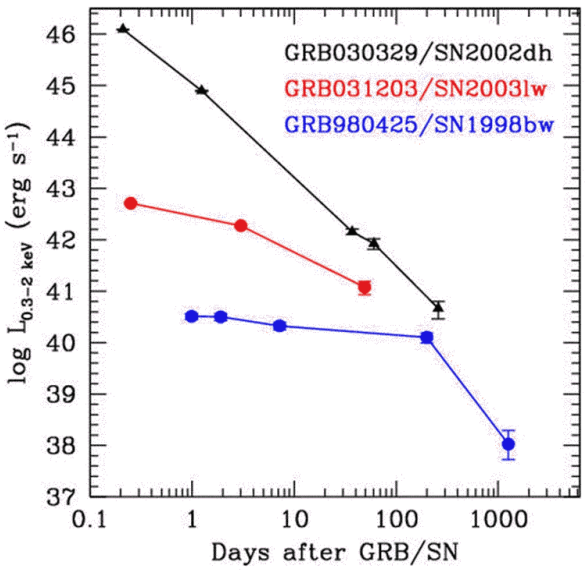
- Velocity also seems to be proportional to global properties: GRB/SNe have the highest velocities



3 HNe/GRB

Same SN properties, but very different X-ray light curves (and radio properties)

→ What is the diagnostic value?



Hypernovae - Summary

- Hypernovae are energetic (KE >10^{52} erg) SNe Ic
- HN produce more ^{56}Ni than 'normal' core-collapse SN
  and they have more massive progenitors (BH form.?)
- M(^{56}Ni), KE, M_{ej}, M_{ZAMS} probably correlate
  (also in SNe II)
- major contribution to Chemical Evolution at high-z ?
- HNe are linked to GRB's
  Rate of HNe ~ Rate of GRB's (Podsiadlowski et al. 2004)
  → They are probably asymmetric explosions
- Observed differences: intrinsic or due to orientation?
  → Need 2D codes

Signatures of Asphericity

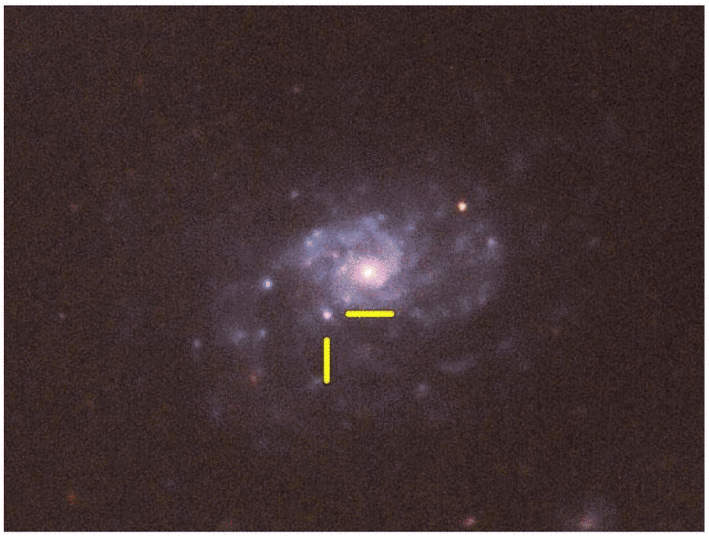
- Presence of inner dense core
- Fe lines broader than [OI] line

- [O I] line in SN2003dh narrower than in SN1998bw

→Either SN2003dh is more aspherical than SN1998bw,
or the viewing angle is even closer to the jet angle.
Latter possibility suggested by properties of GRB

- Are GRB/SNe the only aspherical SNe Ic?
- No: normal SNe Ic are polarised
- Still, GRB/SNe are probably the most aspherical SNe, which is probably related to the presence of GRBs

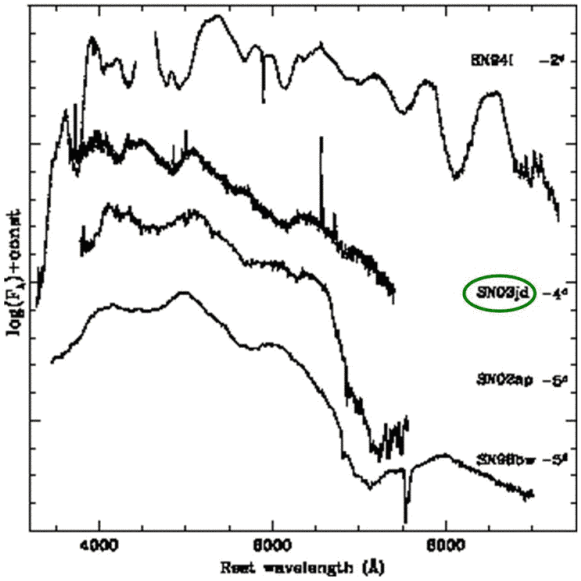
The bright Type Ic SN 2003jd



The bright Type Ic SN 2003jd

- SN 2003jd was as bright at peak as SN1998bw (Mv = -18.7)
- Early-time spectra had broad lines, similar to HN SN2002ap
- No GRB or XRF

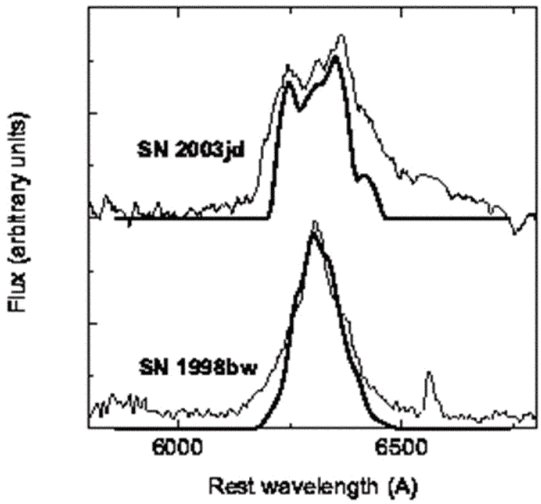
Mazzali et al. (2005)

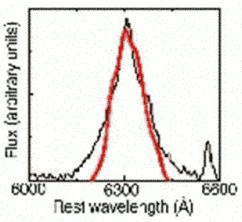


SN 2003jd:
an aspherical SN viewed off-axis

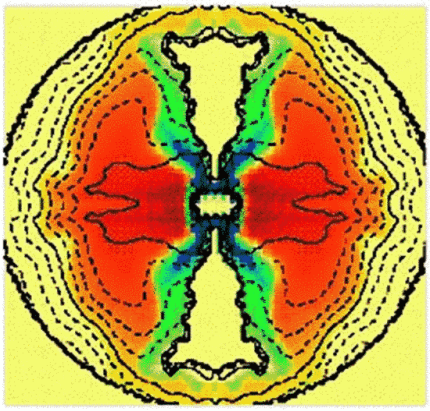
- The [O I] 6300A line shows a double peak, suggesting an explosion similar to SN1998bw but viewed ~70° from the axis

(Subaru and Keck data, Mazzali et al. 2005)

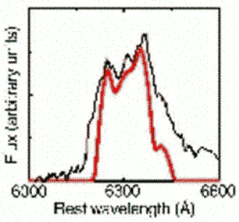




1998bw



2003jd



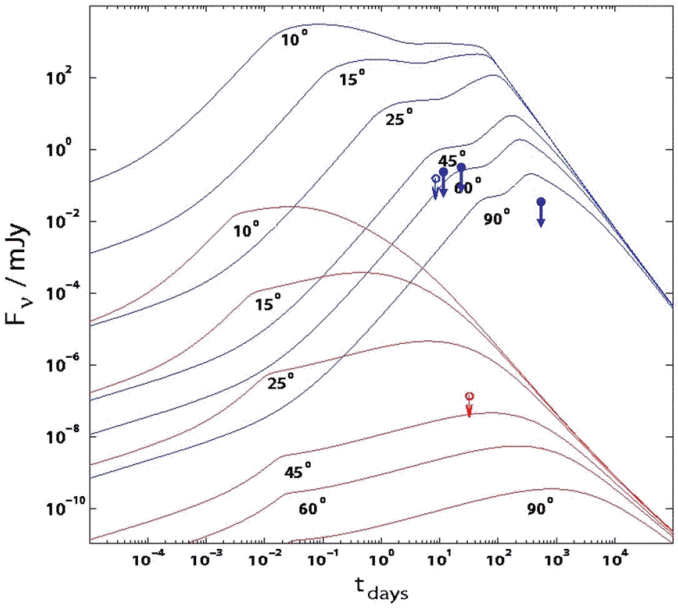
What we see depends on where we look…

(von oben Gammablitz, von der Seite Supernova?)

Mazzali et al. (2005)

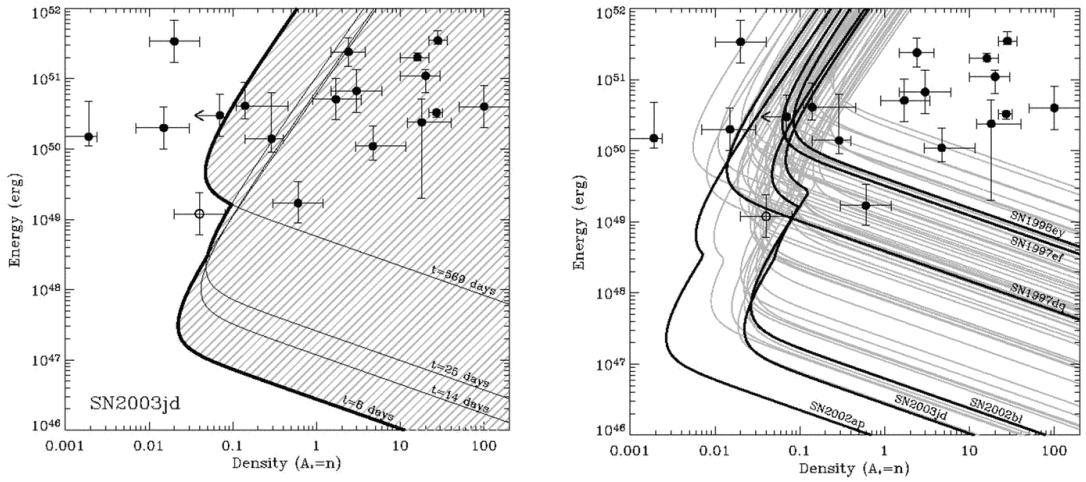
Was SN 2003jd also a GRB/HN?

- X-ray and Early Radio upper limits are not in contradiction with a GRB viewed off-axis
- Later Radio upper limits (Soderberg et al 2005) indicate no jet



Mazzali et al. 2005

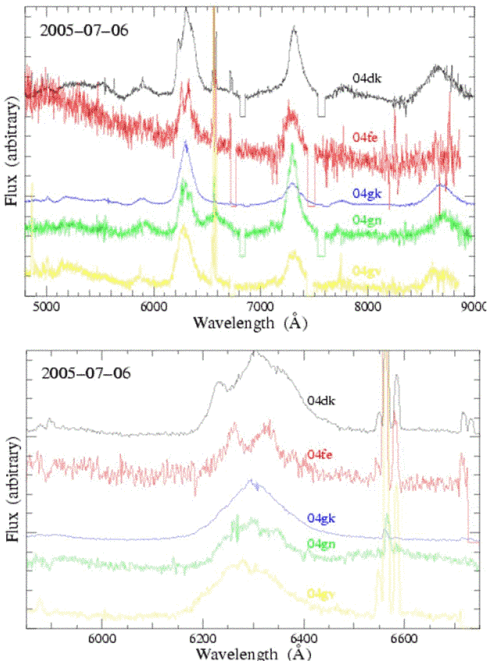
Radio Properties of SNe Ibc

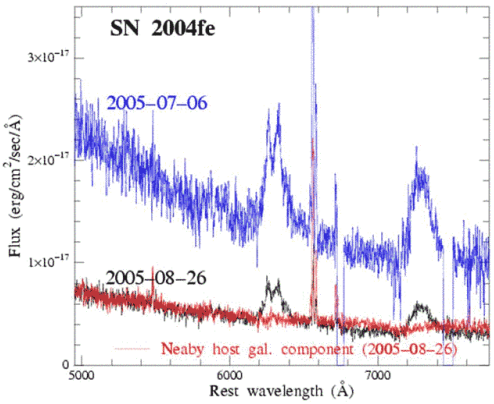


Most HNe show no radio (Soderberg et al 2005)

Either no jet, or a low-density environment (wind)

SNe Ic show a variety of nebular [O I] profiles:
asymmetry is commonplace and viewing angle matters





Three basic q's

1) Are ALL long-GRBs HNe?
   - why are GRBs w/HNe weak in γ, X-ray, radio?
   - are GRBs @ z~1 a different family (Shri)?
   → find GOOD SN in GRB @ z~1, or rule out w/ confidence

2) What are the off-axis props of GRBs? (for the theorists)
   - are XRFs off-axis GRBs?
   - where is the radio in the off-axis HNe?
   - why is radio only ever seen when γ-rays are seen?
   .....is there a jet at all in GRB/SNe?

3) What are the z~5 GRBs?