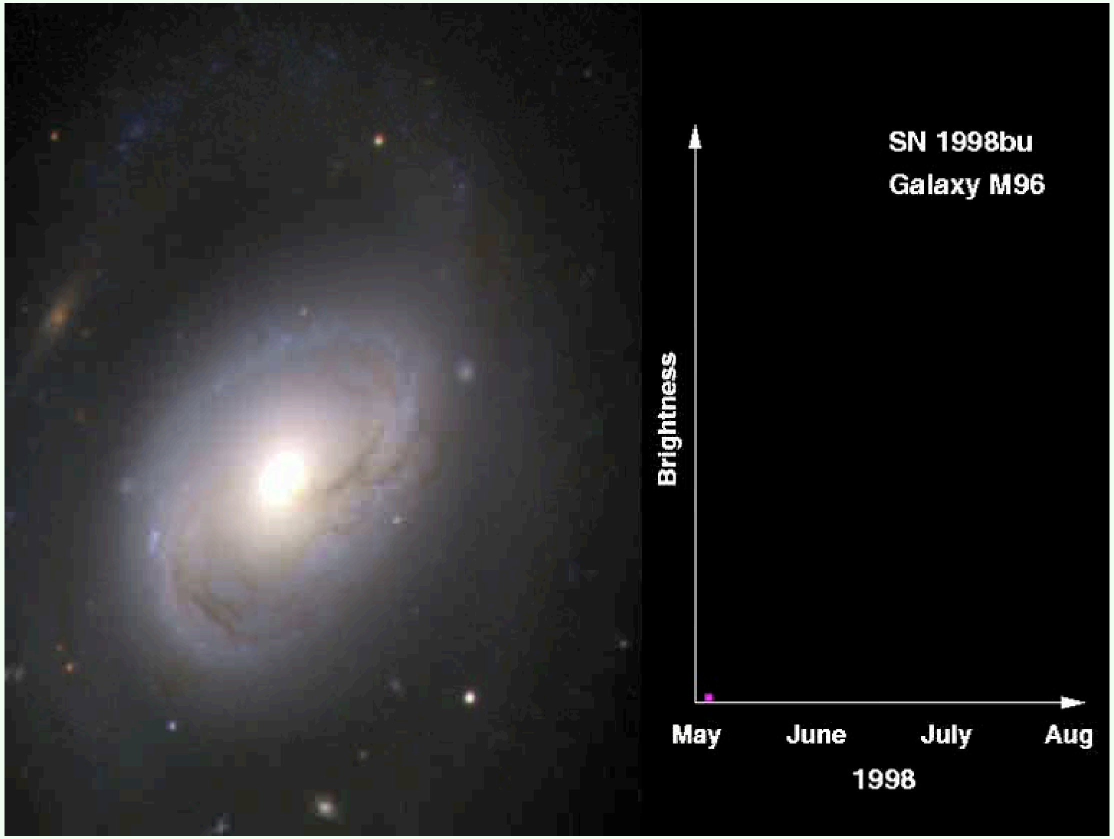
Supernovae
and other explosive transients

Paolo A. Mazzali



B-band

R-band

Supernovae

- One of the end points of stellar evolution
  - Stellar physics, massive stars, white dwarfs
- Main contribution to chemical enrichment of Universe: e.g. light powered by ^{56}Ni decay
  - Nuclear physics
- Cosmological lighthouses
  - Cosmology, Dark Energy
- Connection with High-Energy Astrophysics
  - Gamma-ray Bursts

Two main types of SNe

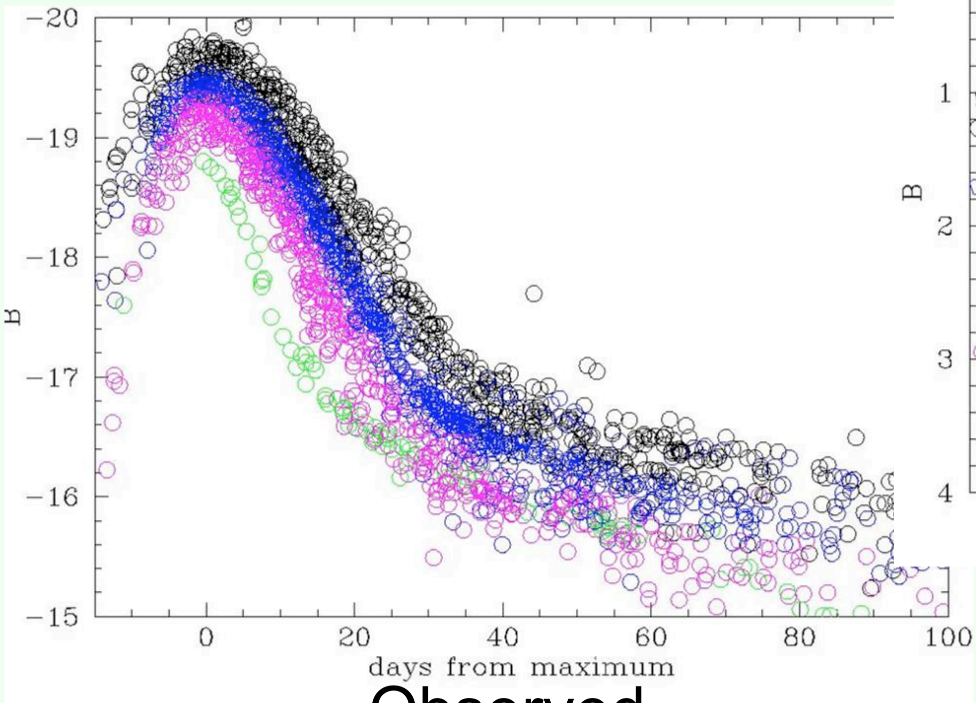
- Type Ia: exploding accreting White Dwarfs
  - Homogeneous events
  - normalisation, Cosmology
- (almost) all the rest: Core collapse
  - Highly variable in properties
  - a window into the physics of massive stars
- Other SN-like transients
  - Pair Instability SNe (very massive stars)
  - “Fast & Faint” (between Novae and SNe)

The case of SNe Ia

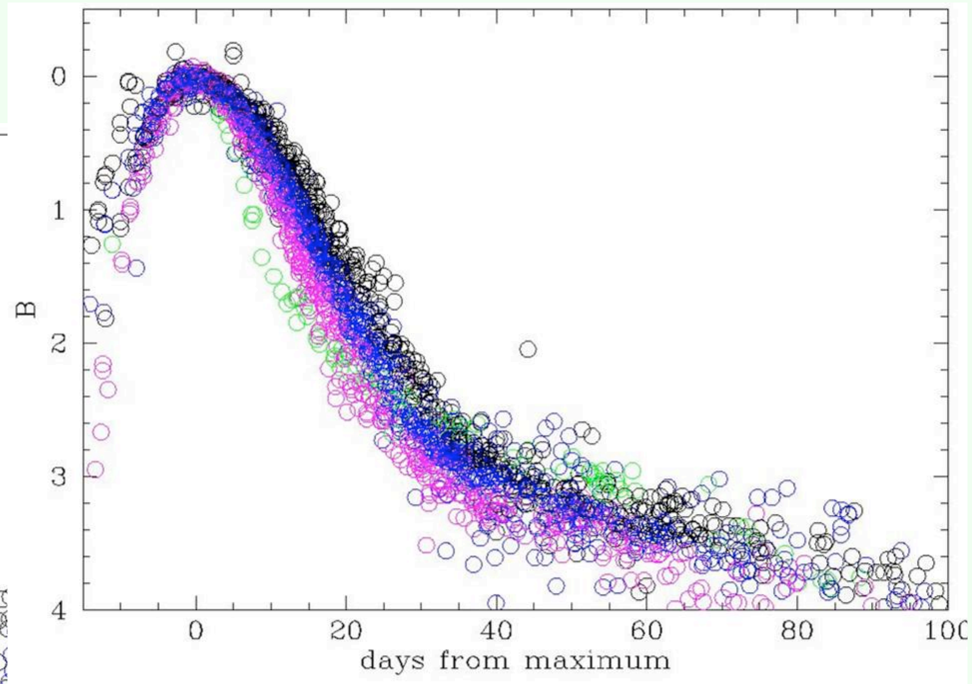
ASTRO: Calibration of SN luminosity

- Brighter SNe have broader LCs (Phillips 93)

PHYS: What causes Lum-light curve relation?



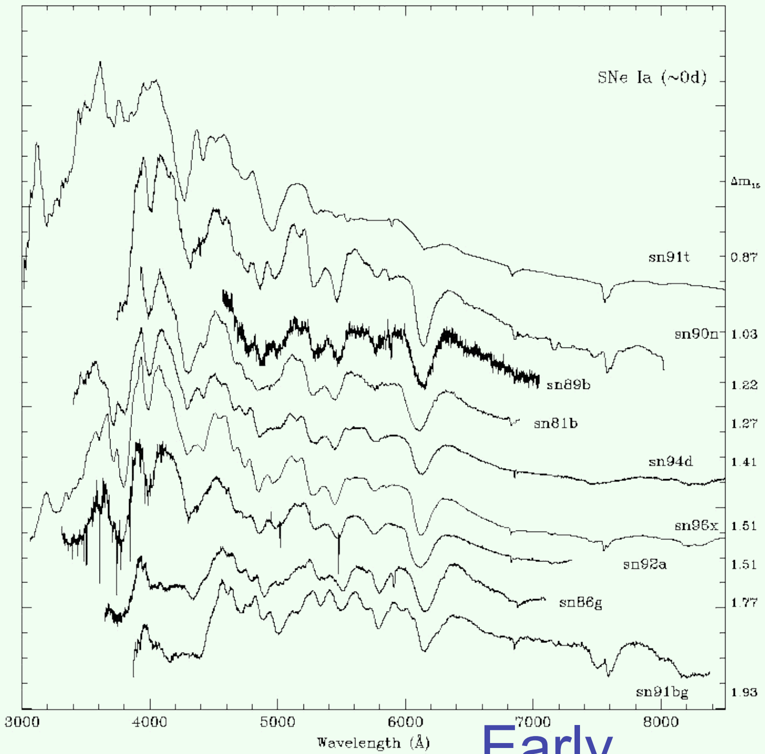
Observed



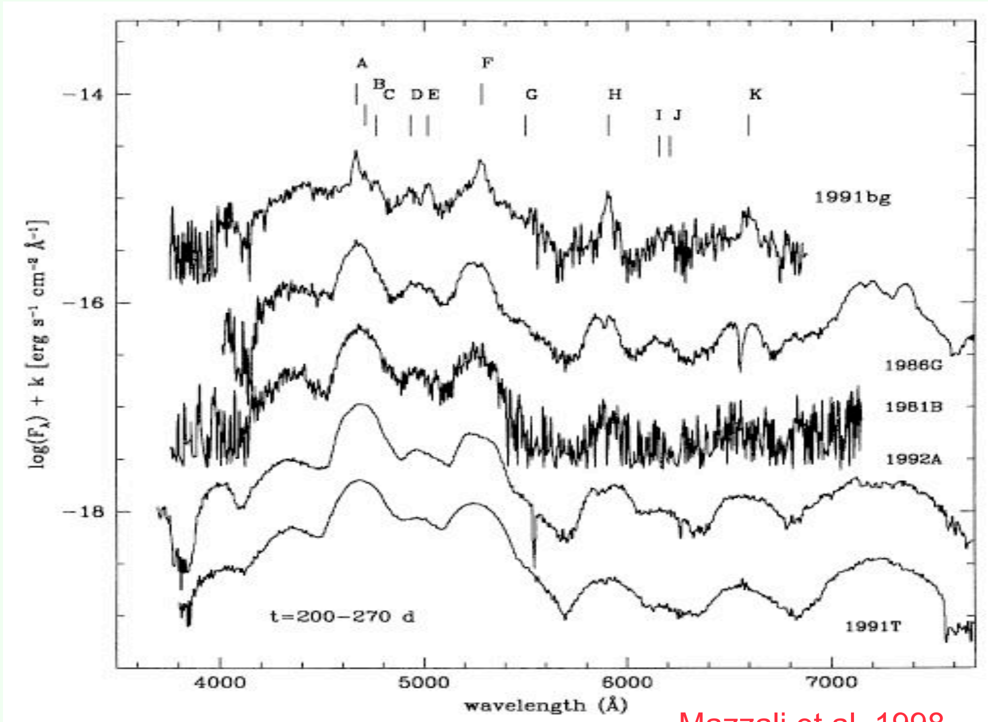
normalised

The case of SNe Ia

- Observations near maximum
  - Composition of outer layers, energetics
- Importance of late, nebular phase
  - Properties of inner layers, dominated by ^{56}Ni



Early

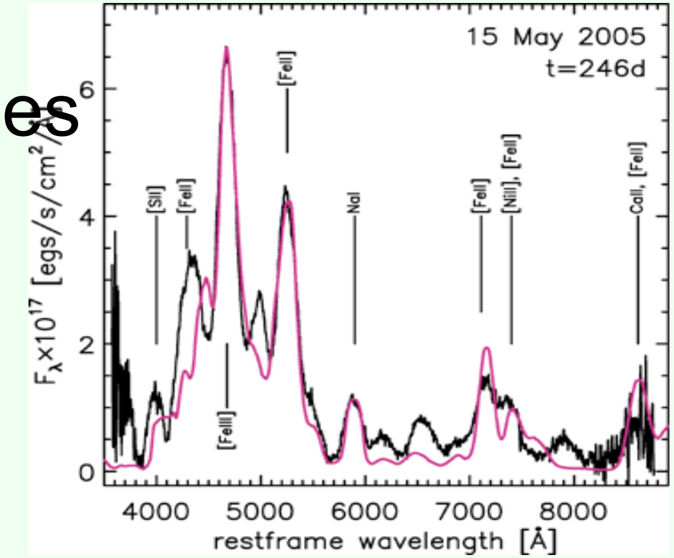


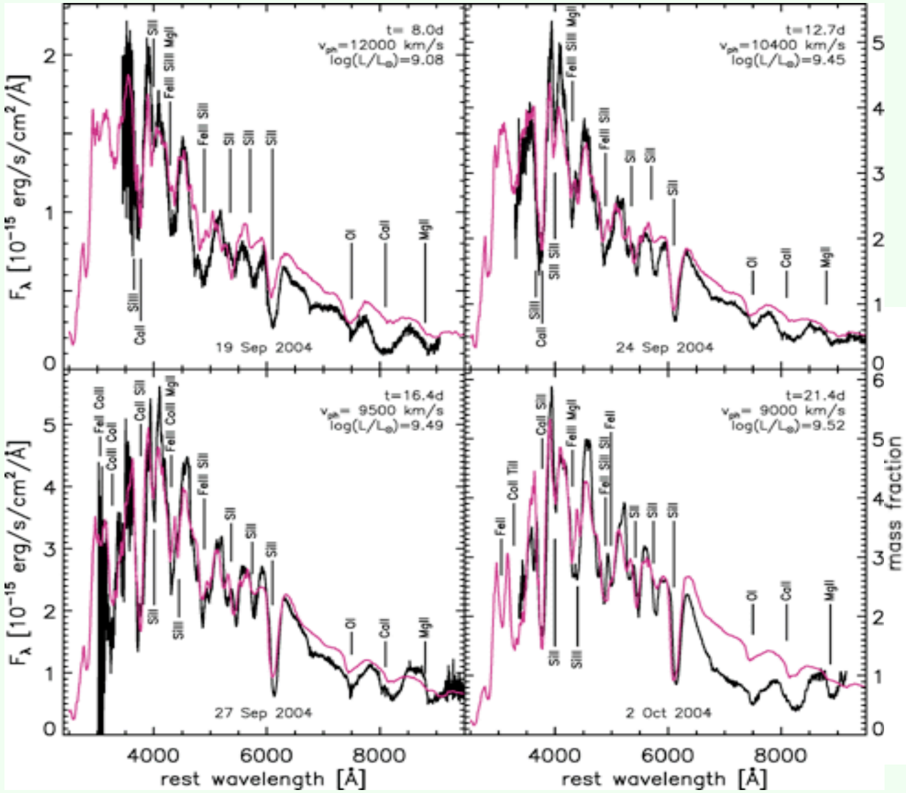
Mazzali et al. 1998

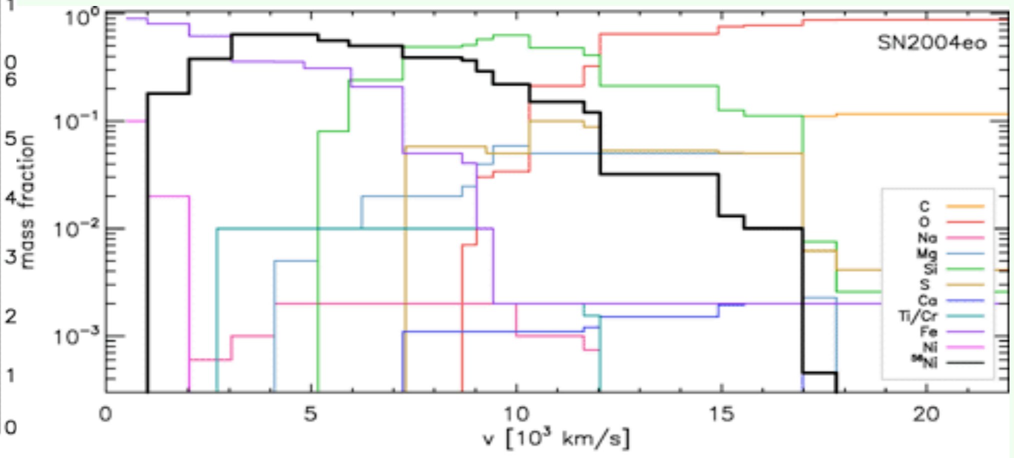
Late

The case of SNe Ia

- Abundance tomography
  - Model time series of spectra
  - Montecarlo and NLTE techniques
  - Complete description of SN







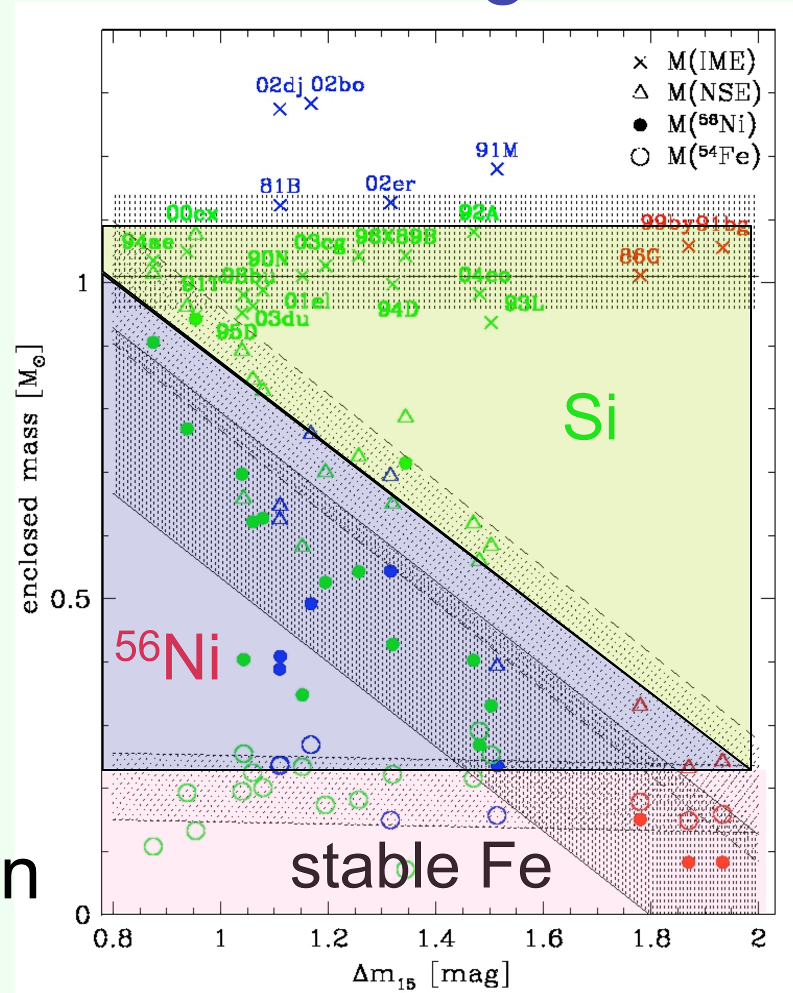
(Mazzali et al. 2008)

The case of SNe Ia

- The key to understanding SN Ia behaviour
  - Study many SNe
  - Mass (Ni + Si) ~ const
    - Mass burned ~ const
    - KE ~ const
    - Lum $\propto$M(^{56}Ni)
    - LC width $\propto$ opacity
    - $\qquad\qquad\propto$ M(Fe group)

  - Links to progenitor/ explosion

Zorro diagram



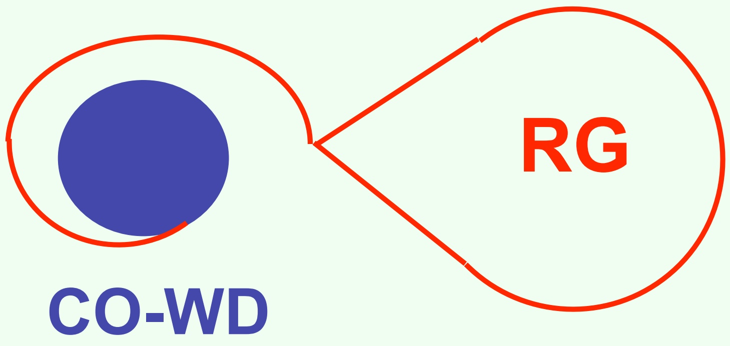
Mazzali et al. (2007)

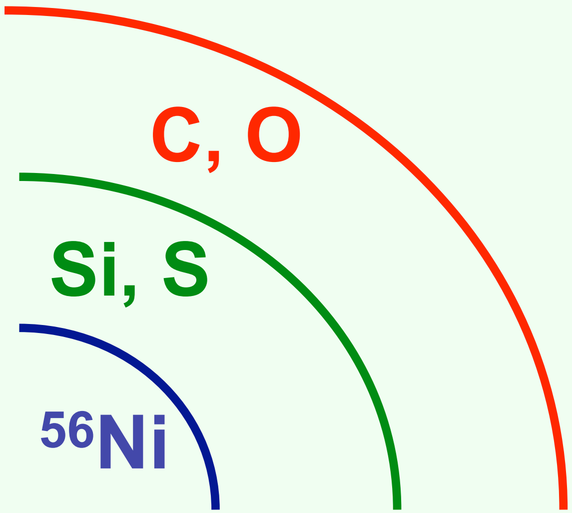
The progenitors of SNe Ia

- Observational evidence:
  - no H
  - no preference for association with spiral arms
  - ∴ low mass, no H-envelope
- Possible progenitors:
  - Main sequence stars:
    - if M >10M⊙: association w/ spiral arms
    - If M < 8M⊙: single stars do not explode: $M_{core}<M_{Ch}$
      - » This can only happen if core accretes from He envelope
    - 8 < M < 10M⊙: core collapse, probably w/ H-envelope:
      - Accretion Induced Collapse
      - if H lost in binary interaction, weak explosion, little 56Ni

What are SNe Ia: Thermonuclear SNe

White Dwarf in Binary System





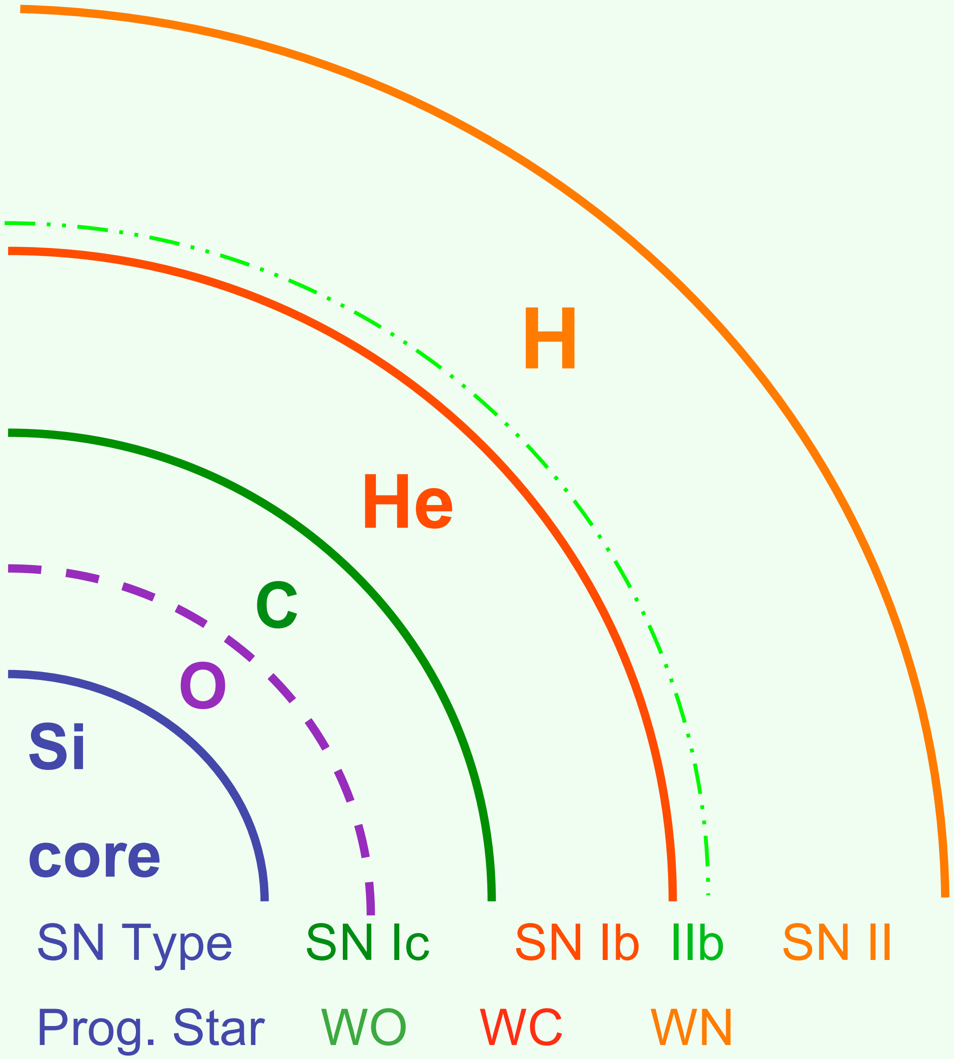
WD accretes H until M_{WD}~1.4M☉, T~10^9K

- Thermonuclear burning (C burning) to NSE
- Explosion (KE~10^{51} erg)
- Total disruption of WD
- ^{56}Ni produced (~0.7M☉)
- What is the companion?

Problems with Single Degenerate scenario

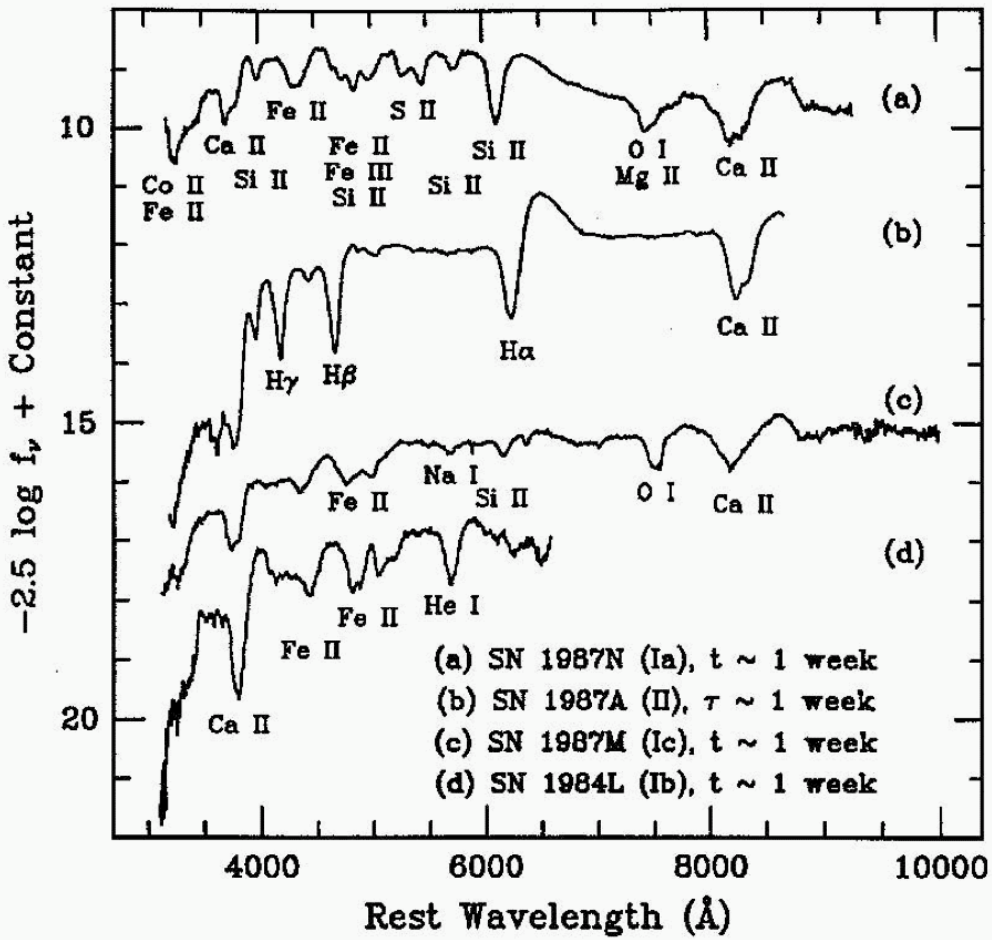
- Lack of progenitors
  - Most WDs come from low-mass stars, and have M ~ 0.4-0.8 $M_\odot$
- Where is the accreting H ?
  - Searches in both early and late-time spectra so far have failed
- Where is the companion?
  - No signatures in light curves, no evidence of interaction (almost always)
- What to do…
  - Double degenerate merger?
    - Thought to give rise to massive core and undergo AIC
    - Most WDs have M ~ 0.6 $M_\odot$: hard to reach M(Ch)
    - Only model that (possibly) works is “violent” merger of 2 0.8$M_\odot$ CO WDs

Massive Stars ($>8M_\odot$)



- Si burning → Fe core
- Core collapse
- Compact object (NS/BH)
- ν emission
- KE deposited ($\sim 10^{51}$erg)
- Nucleosynthesis
  → ^{56}Ni ($\sim 0.1 M_\odot$)
- envelope ejection
- SN type depends on degree of stripping
  - Role of binarity?

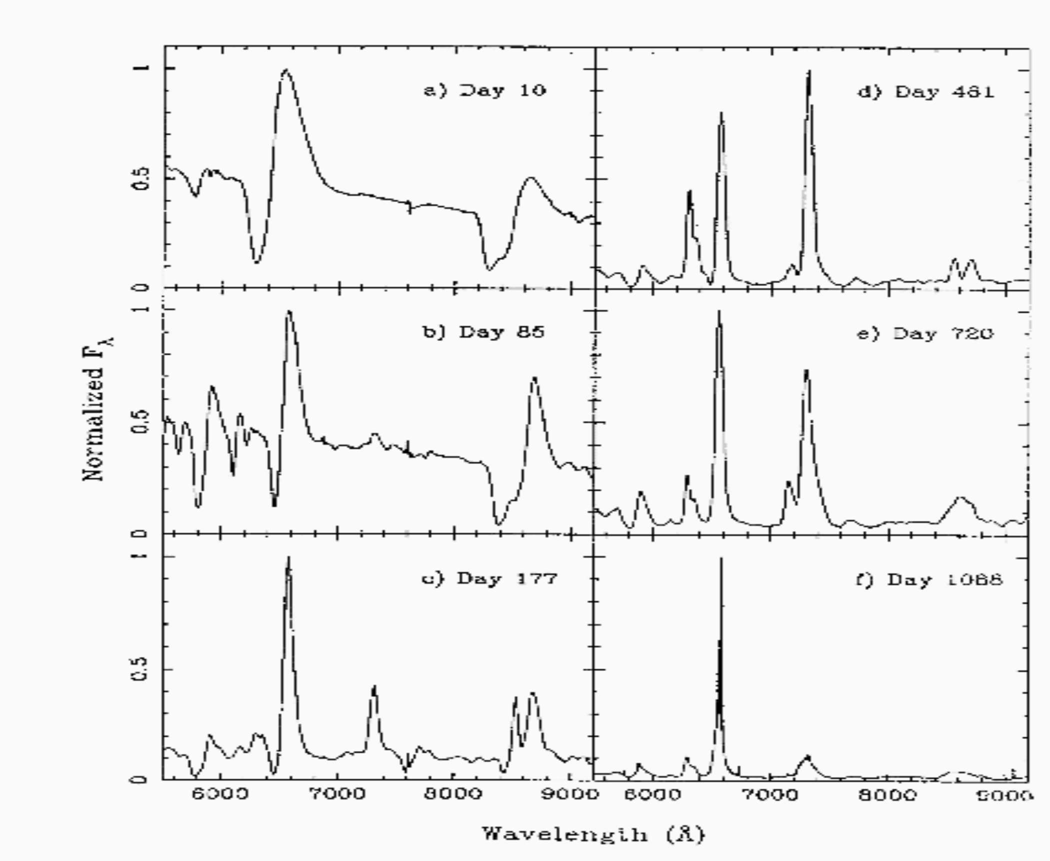
Spectral Classification



Type I: no H lines
Ia: strong Si
Ib: strong He
Ic: no/weak He, Si

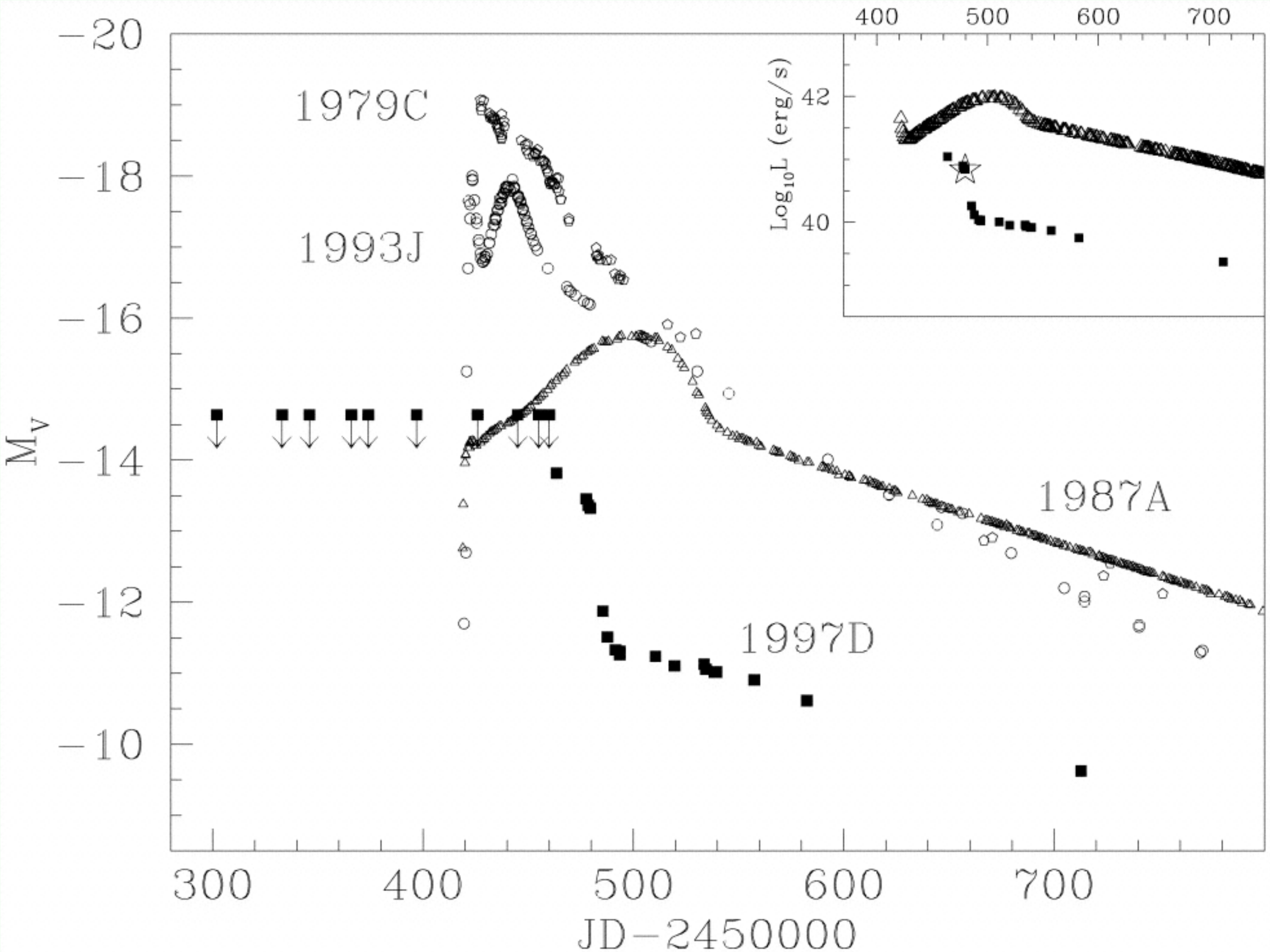
Type II: H lines

M ~ 8 - 15 M☉: SNe II



H lines dominate at all times

Type II SNe



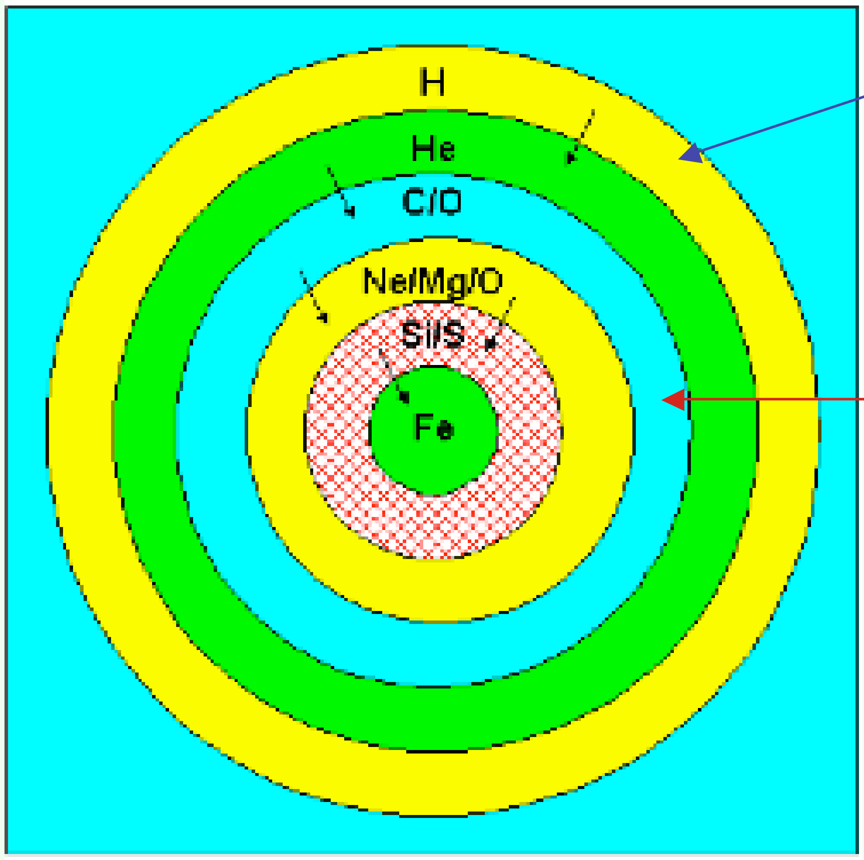
79C: IIL
(small H env.
- no Rec. Phase)

93J: Ib
(very small H env.:
He lines)

87A: IIP-pec
(BSG prog
- small R)

97D: IIP (faint)
(large envelope,
small KE
- long plateau)

SNe II: spectral evolution reflects structure of massive star

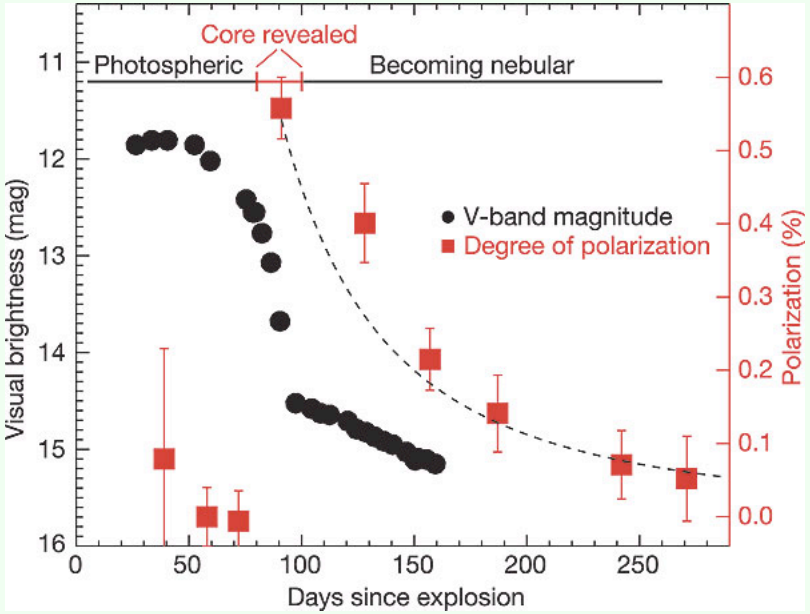


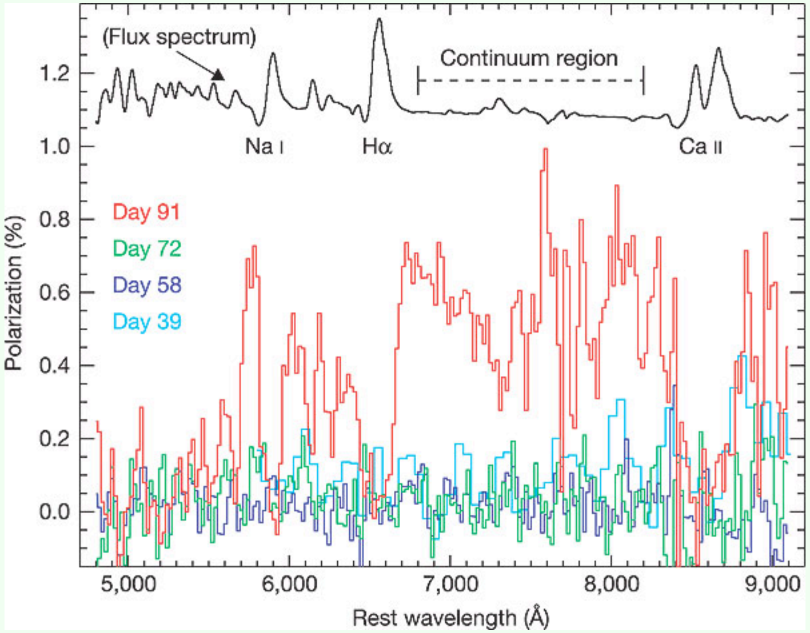
Early times:
outer layers visible

Late times:
inner part exposed

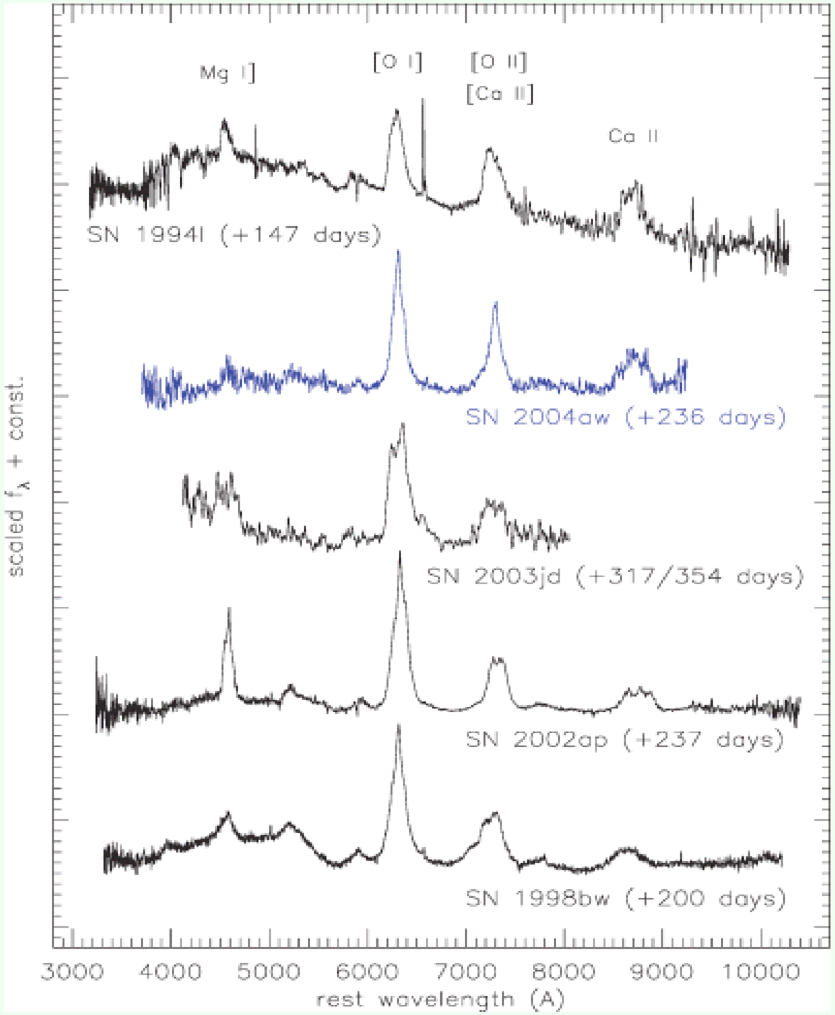
SNe II: aspherical core

- Polarization data show:
- SNe Ib/c (no envelope) are more polarized than SNe II (H envelope)
- Polarization of SNe II increases when light comes from inner layers
  (Leonard et al. 2006)





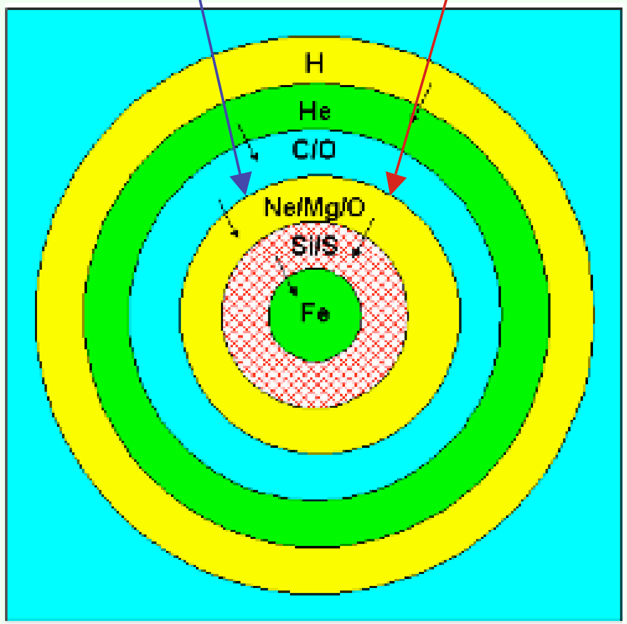
Stripped stars better: SNe Ib/c



Early times: see CO core
H- and H envelopes lost

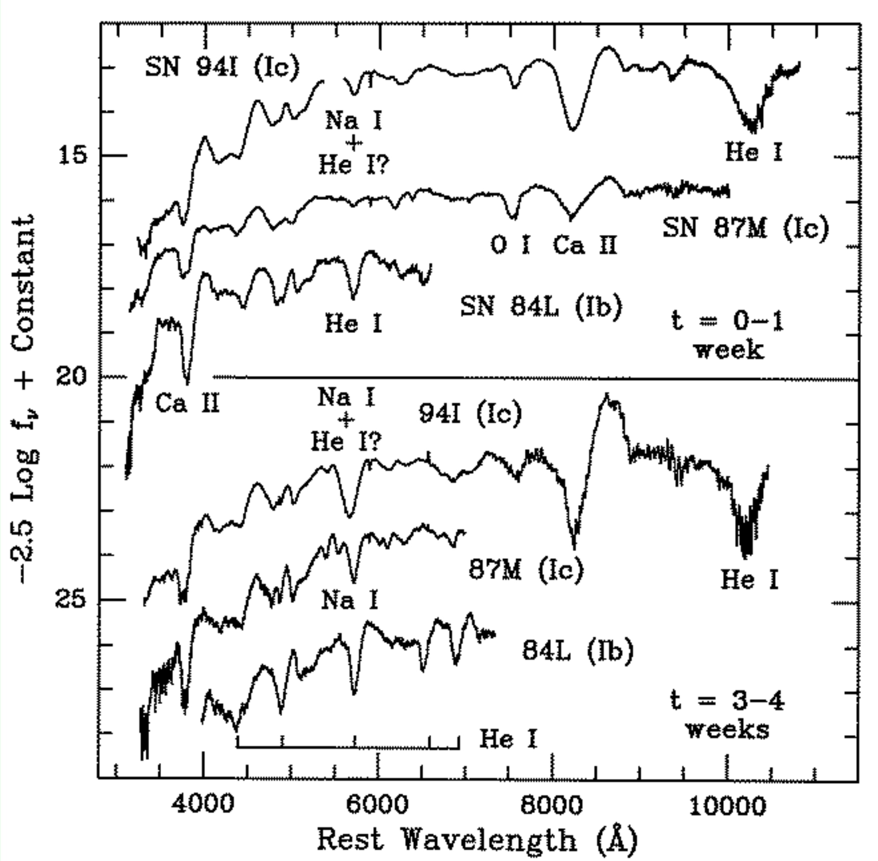
Late times:
see CO core, as in SNe II, Ib

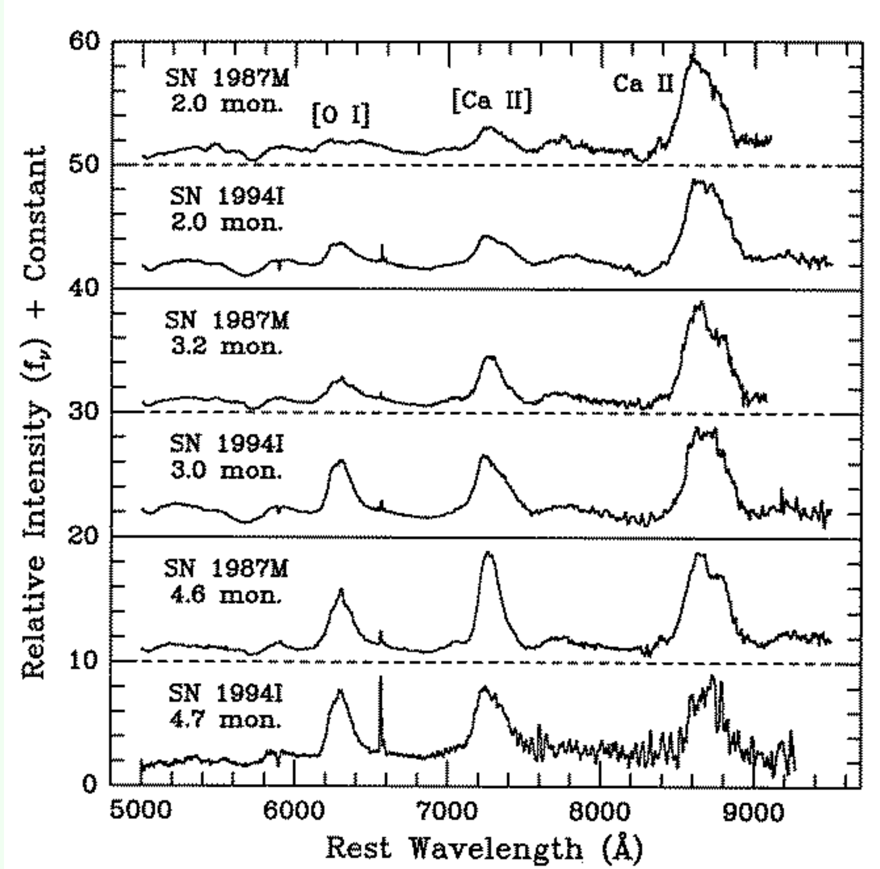
Star more stripped



Late: O, Ca, Mg

SNe Ib/c



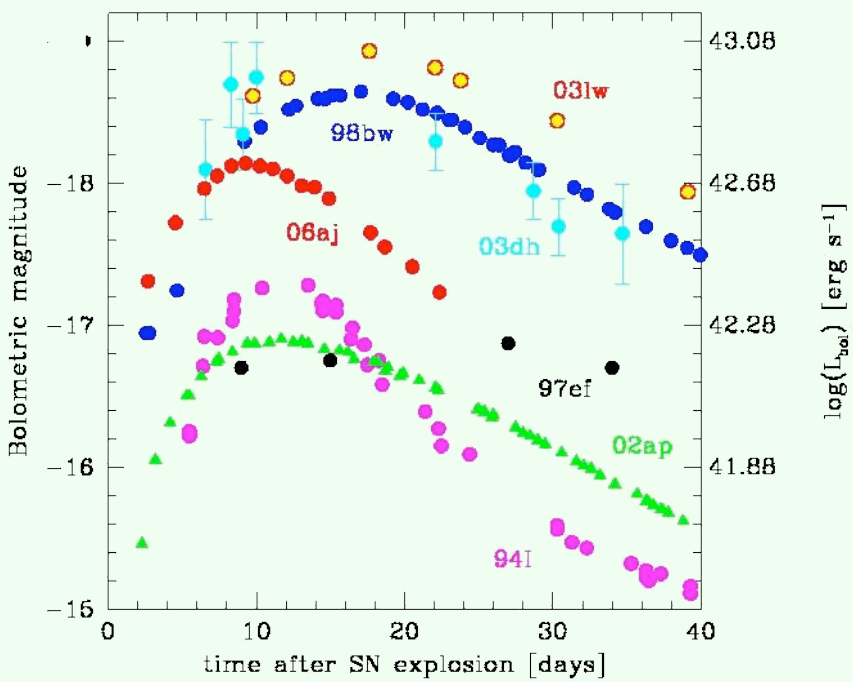


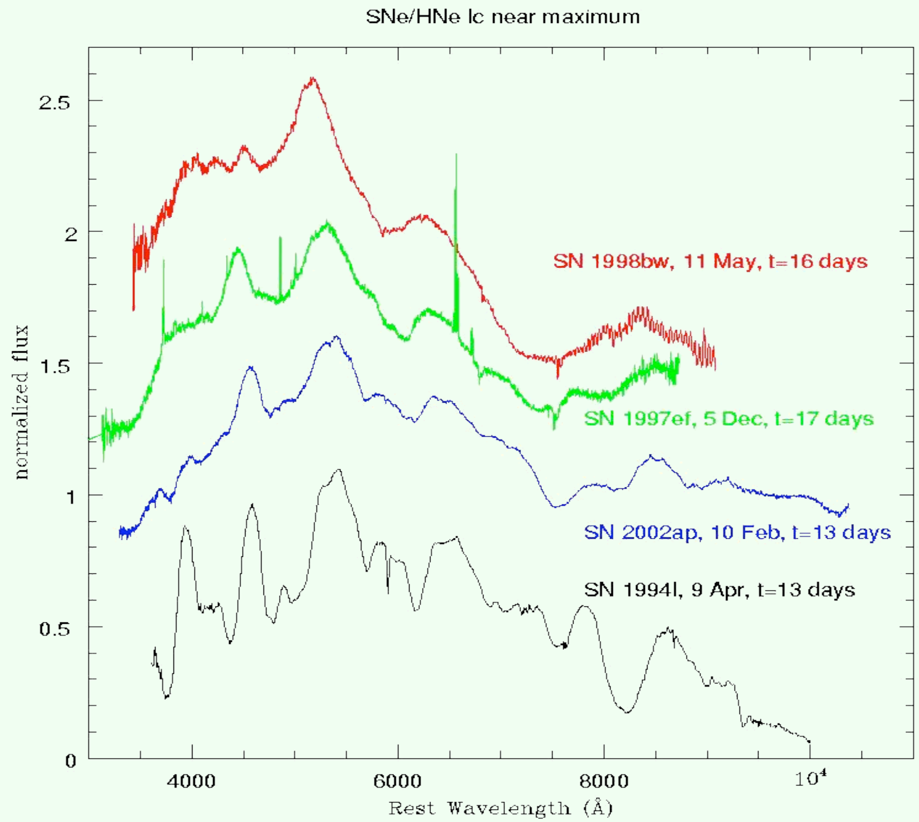
Early: He (Ib), Ca, Si, some O

Late: O dominates, Ca

Properties of SNe Ib/c

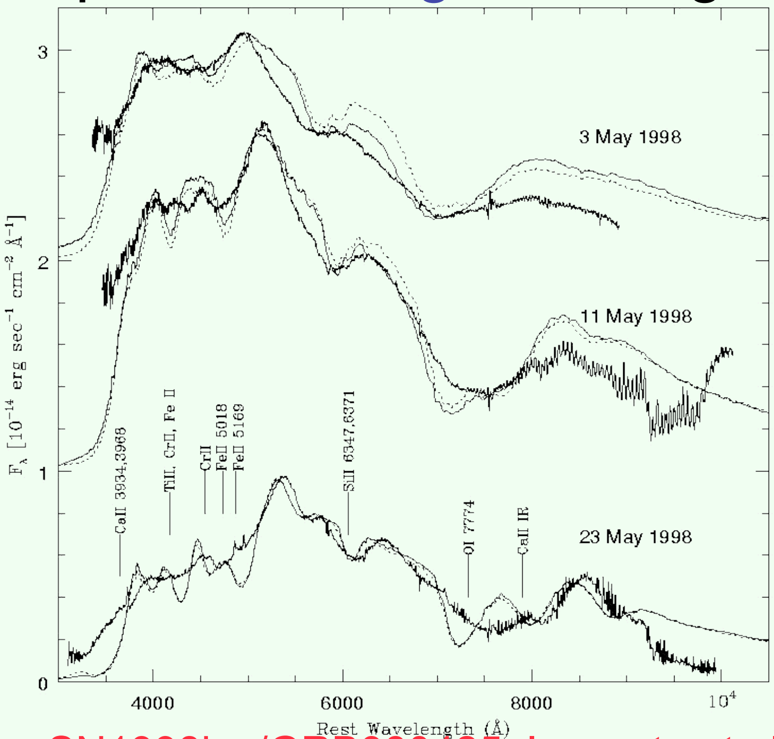
- SNe Ib/c come with a range of properties
- Different line width
  - different Kinetic Energy
- Different Luminosity
  - Variable production of ^{56}Ni



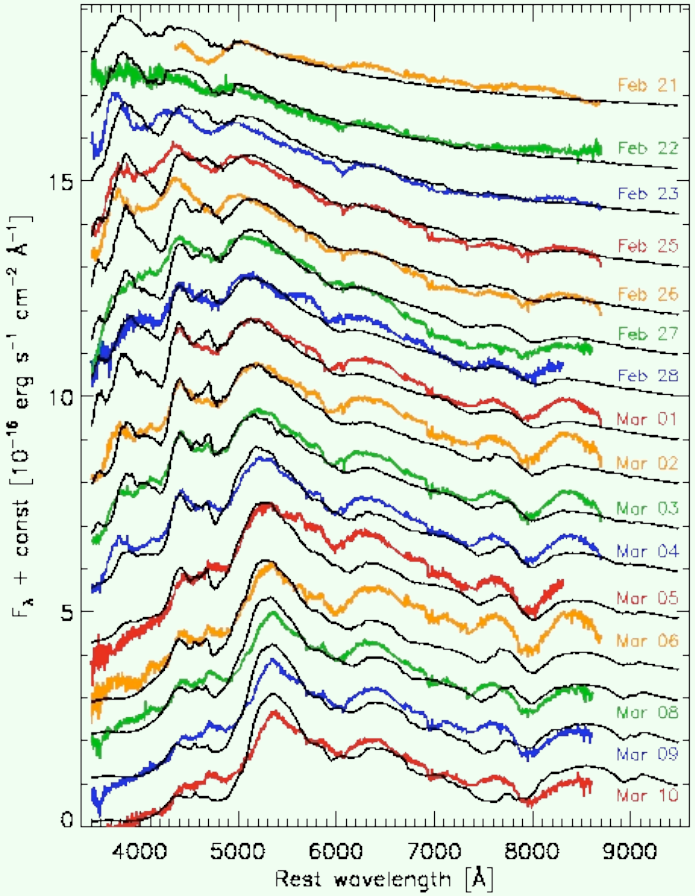


The case of GRB/SNe

- Modelling early-time spectra: SN1998bw/GRB980425
  – determine KE (>10^{52} erg), composition, mass (M_{ZAMS}>35 M☉)
- Extend study to SNe accompanied by X-ray Flashes:
  – lower Mass, KE, Lum
  – possible Magnetar origin



SN1998bw/GRB980425, Iwamoto et al. 1998

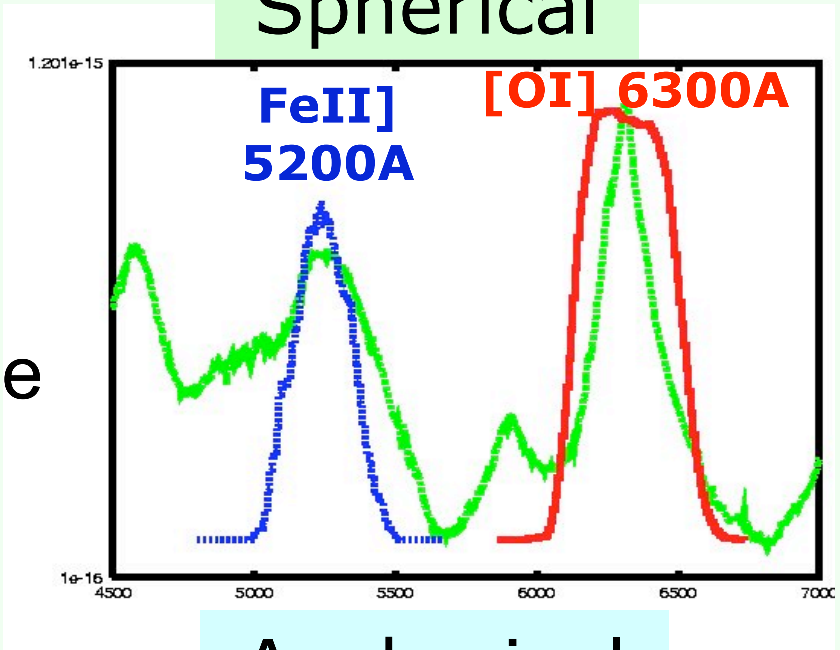


SN2006aj/XRF060218, PM et al. 2006

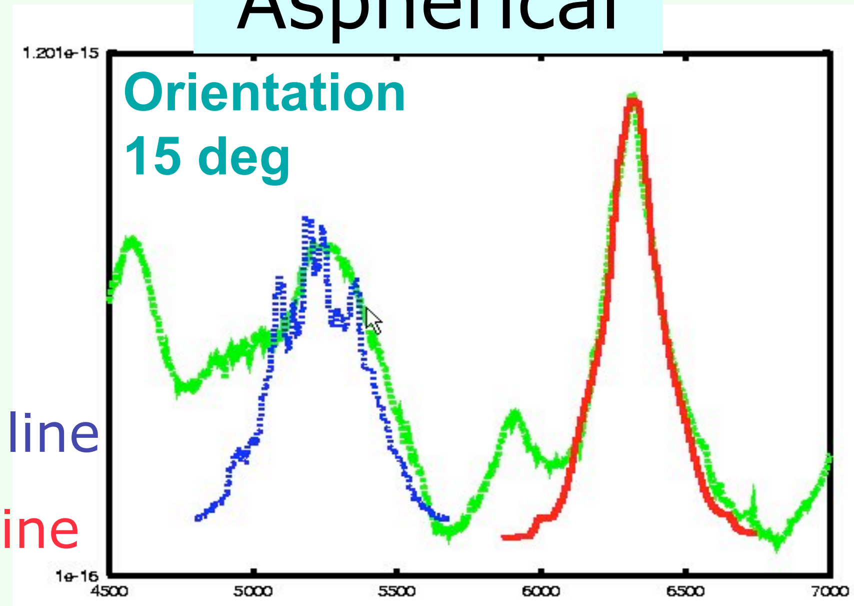
The case of GRB/SNe

- Importance of Nebular phase (>100 days after explosion)
  - –Ejecta are transparent: morphology of ejecta
- Spectra of SN 1998bw
  - – [v(Fe) > v(O)]: explosion was aspherical

Spherical



Aspherical



Observed

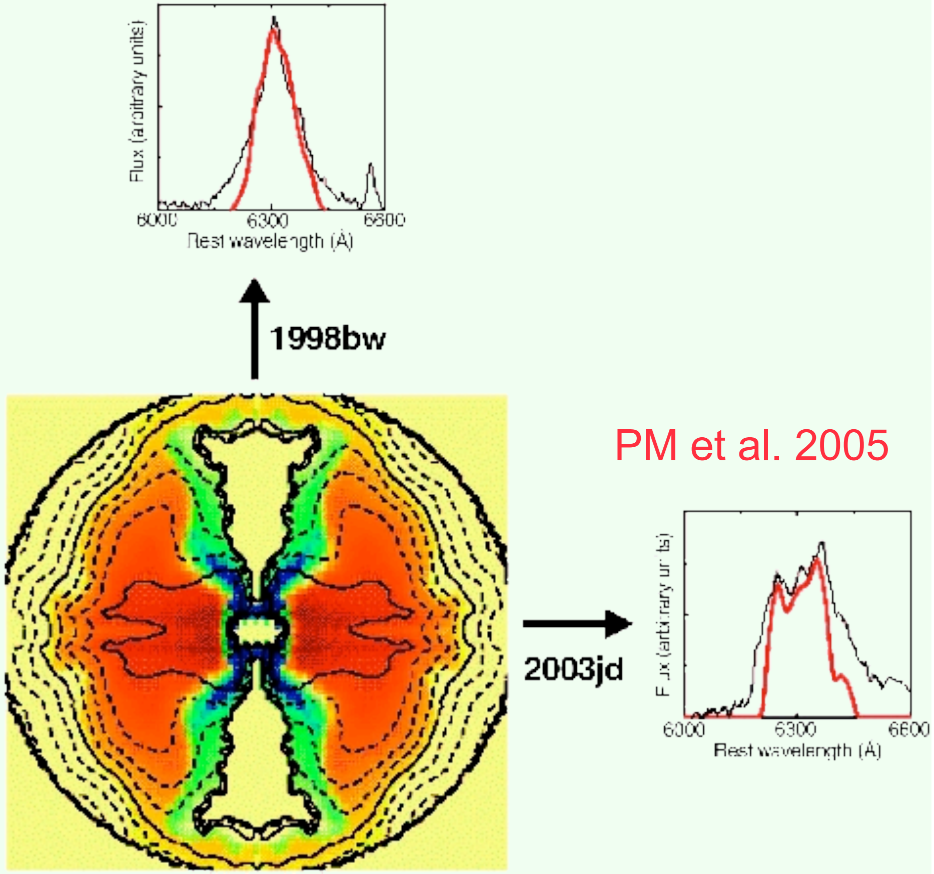
Model Fe line

Model O line

PM et al. 2001, Maeda et al. 2002

The case of GRB/SNe

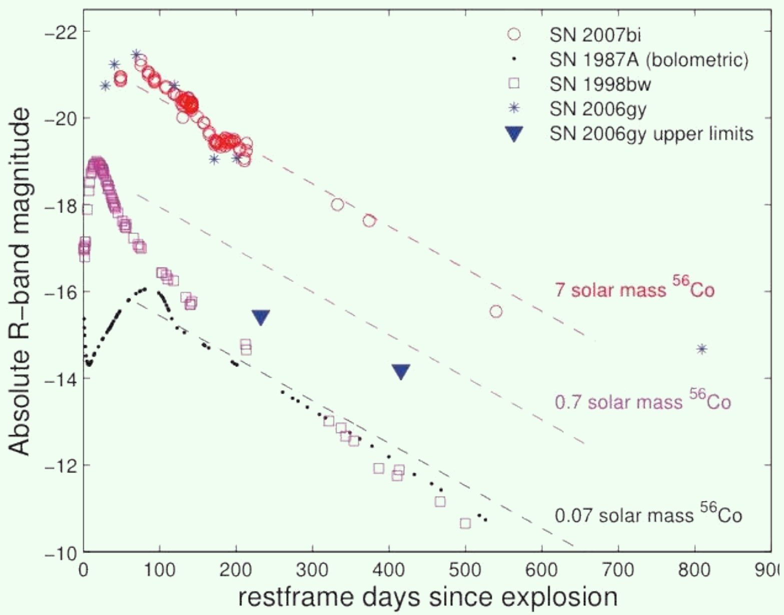
- Asphericity: successful search for off-axis events (SN, no GRB) through nebular spectroscopy
  - All SNe Ib/c are aspherical to some degree
  - GRB/SNe are the most aspherical

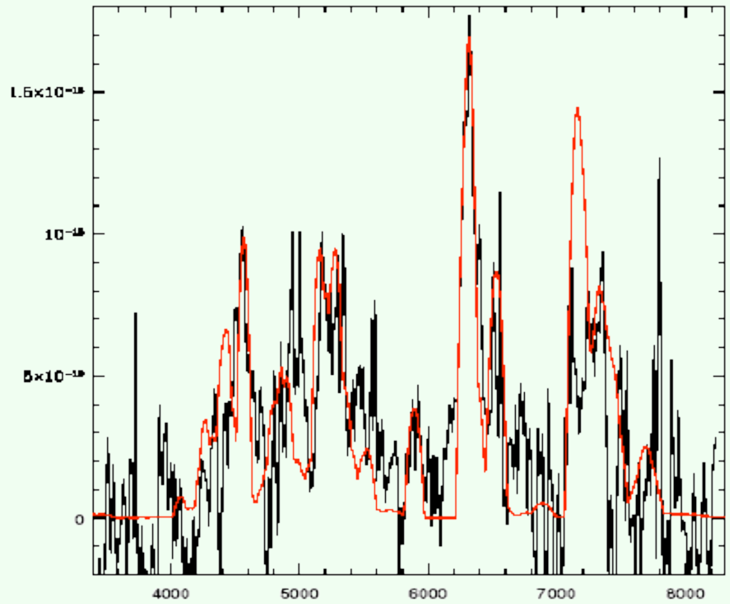


PM et al. 2005

Other types of Supernovae

- Pair Instability : $M > 100\ M_{\odot}$ (first stars)
  - Too massive for even a BH: whole star explosion
  - Very bright SNe
  - Predicted by theory, not found locally
  - SN2007bi: >50M⊙ of Oxygen, 3 M⊙ of ^{56}Ni



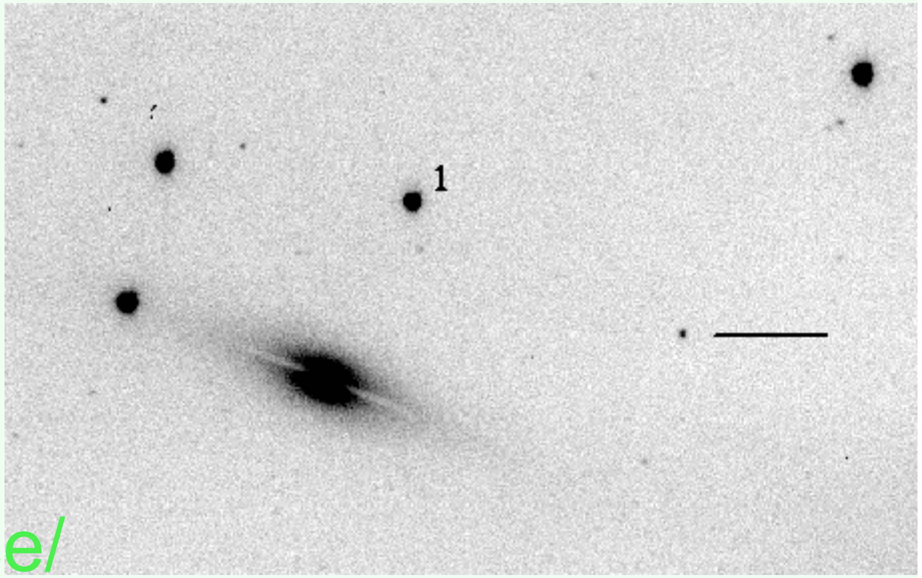


Other types of Supernovae

"Fast and Faint"

E.g. 2005E: a SN Ib found outside an E-galaxy

- Low-mass ejecta (0.3 $M_\odot$)
- Only 0.003 $M_\odot$ of ^{56}Ni
- Rich in Ca, Ti
- Incomplete burning



- Accretion-induced collapse/ Electron Capture SNe (8-10 $M_\odot$)
- Explosion of He shells on low-mass stars (2-5 $M_\odot$)

Summary

- SNe Ia
  - Detailed study through spectroscopy and modelling
    - Distribution of abundances, mass
    - “the white dwarf knows how to explode”
- SNe Ib/c
  - GRB/SNE are brightest, most energetic
  - GRBs and XRFs have progenitors of different mass
  - SNe Ib/c are aspherical
- Other types of explosions
  - PISNe
  - Shell explosions

Future prospects

- SNe Ia
  - Progenitor: different channels? (single/double degenerate?)
    - need large datasets to compare SNe with similar LC
    - Early data essential to see progenitor (e.g. PTF11kly=SN2011fe)
- SNe Ib/c
  - Role of jets, asymmetries
  - Mass function: link to progenitor
- GRB
  - cosmology
- Other types of explosions
  - PISNe
  - "Fast & Faint" (may have different nucleosynthesis, not ^{56}Ni)
  - Other classes of transients discovered by new surveys