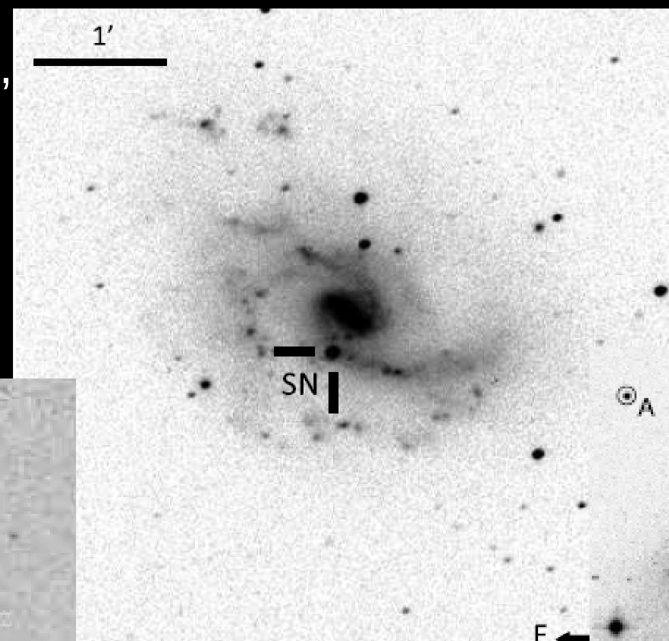
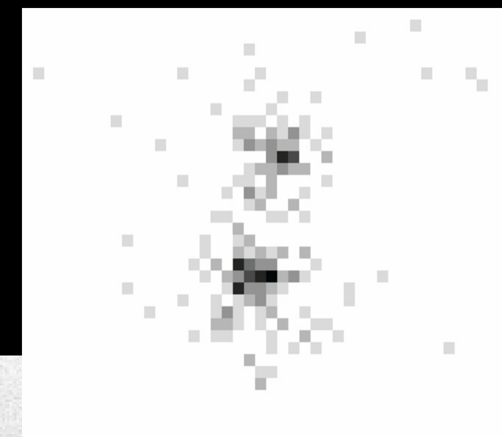
# Unveiling the structure of progenitors of Sne-IIP through multiwaveband observations.

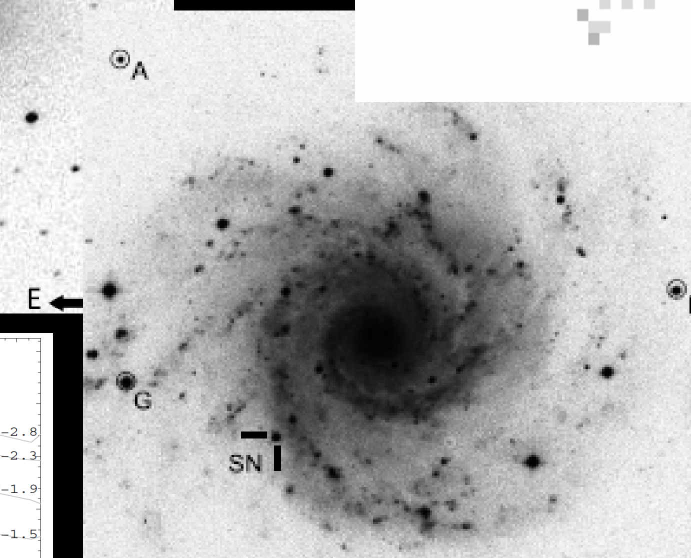
**Firoza Sutaria** (Indian Institute of Astrophysics, Bangalore)

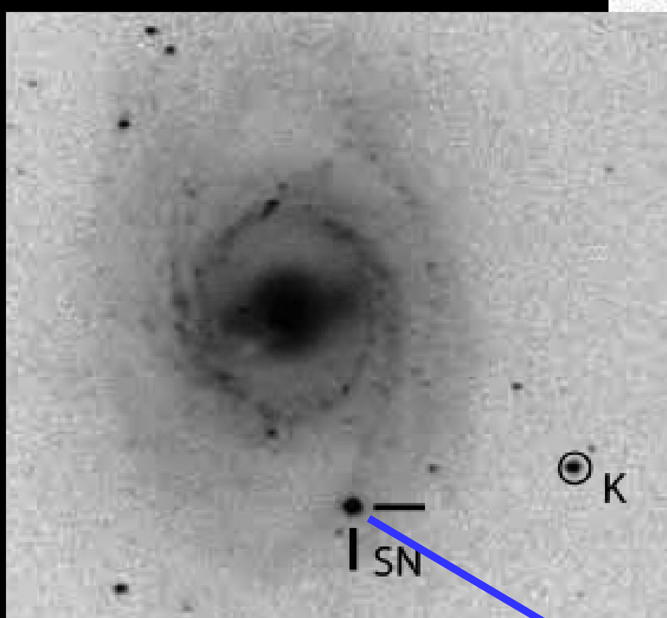
SN2013ab in NGC 5669 (V), (104 cm ARIES/ST). ►



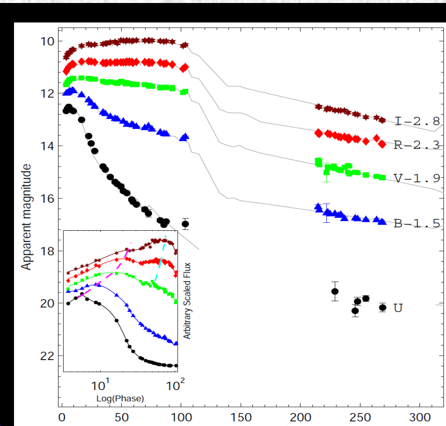



▲ SN2011ja (Chandra ACIS-I)




▲ SN2012aw in NGC 3551 (V), (104 cm ARIES/ST).




SN2013ej in NGC0628 (BR band; Composite). (104cm ARIES/ST).

# Instruments and Collaborators:

**IIA (India): M. Safonova, Chinthak Murali**

**ARIES (India): S.Bose, B. Kumar, B. Kumar, K. Misra, H. Chandola, M. Singh, S. Pandey**

**TIFR (India): S. Chakraborti, N. Yadav, A. Ray**

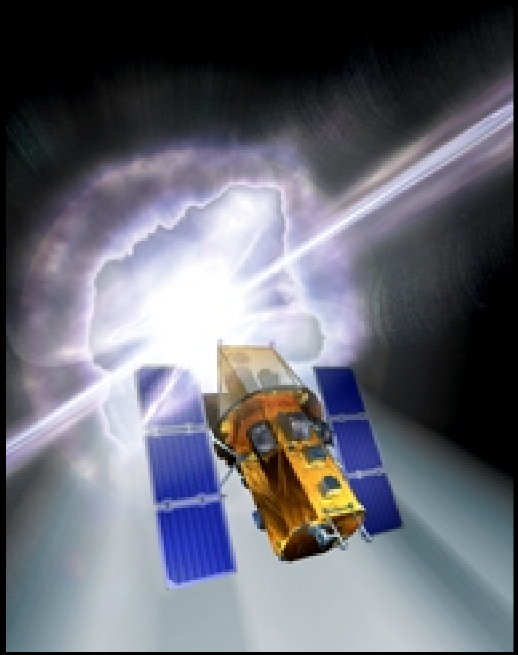
**LCGOT/UCSB: S. Valenti, M. Graham, A. Howell**

**INAF: A. Pastrorello, P. Ochner**

**U. Chicago: V. Dwarkadas, D. York**

▲2m HCT (IIA, India).

◄2.3m at Vainu Bappu Telescope (IIA, India)



◄Swift/UVOT

▼1.04m ST (ARIES, India)

# A blast wave that lights up the past – evolution of the SN shock

- Core rebound initiates shock wave through progenitor envelope.
- Blast wave propagates out, sweeps up CSM / ISM material in front it.
- Free Expansion phase ($10^2$ to $10^3$ yr):
  Supersonic, adiabatic expansion/cooling, $r_{shock} \propto t^{-3}$
- Reverse shock forms at
  $M_{CSM} \simeq M_{ejecta.;}$
  moves inwards,
  expansion slows,
  reheating
- Sedov-Taylor expansion ($10^4$ yr):
  Adiabatic cooling dominates.
- Snow plow phase: $10^6$-$10^9$ yr
  Radiative cooling dominates.
- Mixing of ISM and ejecta

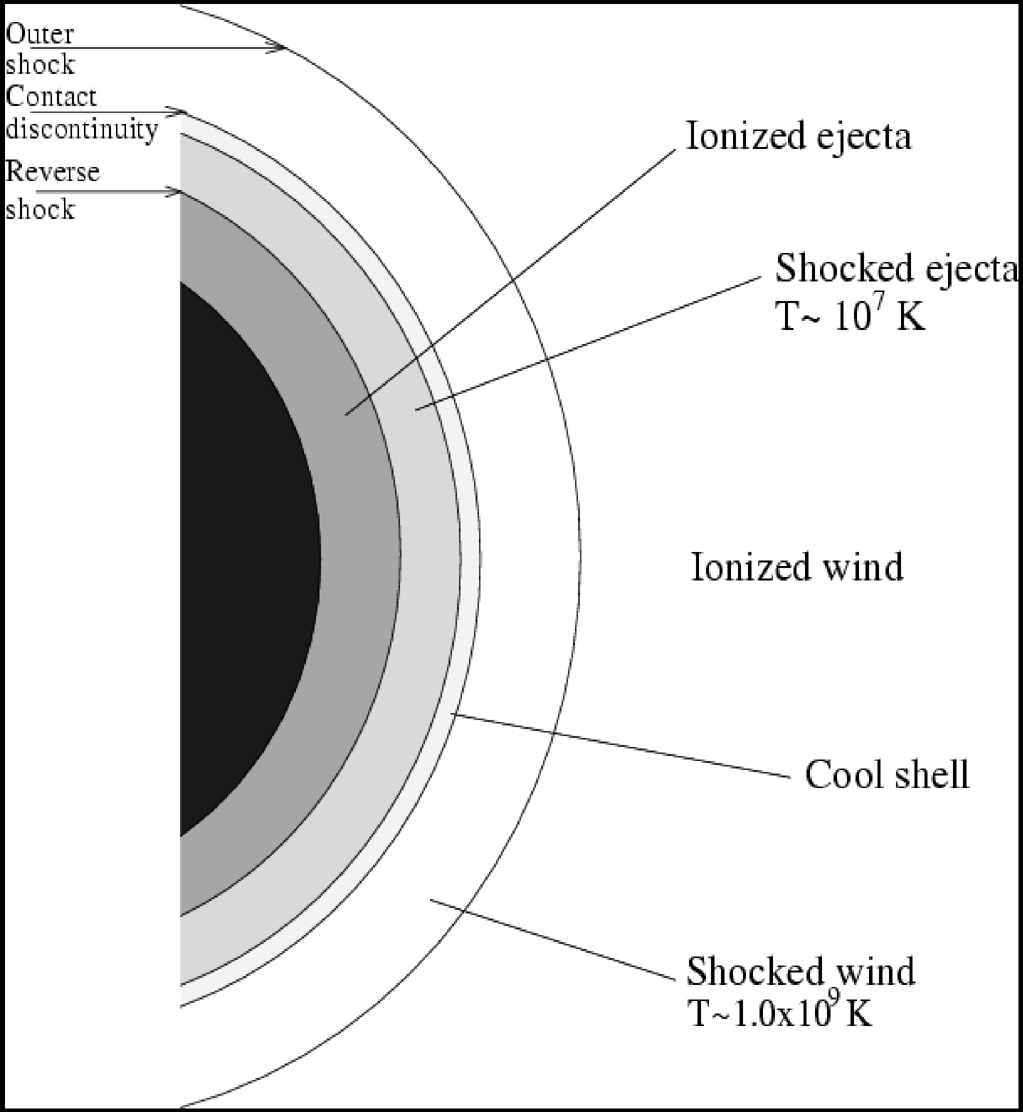



Image credit: Nymark, Fransson & Kozma, 2006, A &A

# CSM as fossil evidence of progenitor evolution

Tracks:

- Various nuclear burning stages
- How / why was material ejected from progenitor
  - LBV (2009ip) ?
  - Pair instability (2006gy, 2007bi) ?
  - Red Super Giant (RSG)?
- The mass of the progenitor.
- Metallicity of the progenitor.

# Supernovae responsible for dusty Universe?

- Nucleosynthesis & recycling of heavy elements.
- Massive progentiors ($M > 8\ M_{\odot}$) ⇒ Large mass loss (dusty CSM?)

+ Short lifetimes, + dust production before / during / after explosion?

- Source of dust ($\geq 10^{8}\ M_{\odot}$) in high z (≥ 6) galaxies?
- If typical $M_{dust} \sim 10^{-2}\ M_{\odot}$, what is the primordial star formation rate?

# SNe-IIP and SNe-IIL – extreme ends of a single class?

**SN2012aw:** Early detection (max. 48 hrs after shock breakout),
Early identification,
Bright (peak $M_V$= -18.3)
Early X-ray + Early radio emission
Continuum polarized at level of 0.3%
⇒ substantial asymmetry in outer ejecta.
HST archival images set $M_{prog}$ < 15.5 M⊙.

**SN2013ab:** Early detection (max 60 hrs after shock breakout),
Early identification,
Bright ( peak $M_V$= -17.4),
No early (or late time) X-ray or Radio emission.
No archival observations to estimate $M_{prog}$.

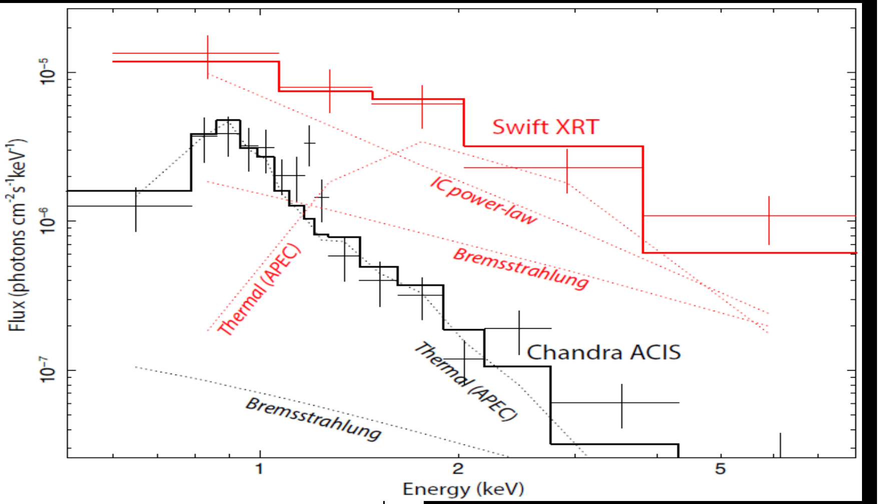
**SN2013ej:** Early detection (max. 14 hrs after shock breakout),
Early identification,
Bright ( peak $M_V$= -17.5),
Early X-ray emission,
HST archival images set 8 < $M_{prog}$ < 15.5 M⊙.

# Tracing the reverse shock:  X-ray observations of Sne-IIP 2011ja and  2013ej:

**Prompt X-ray emission observed from both 2011ja and 2013ej.**

**SN2013ej: Prolonged X-ray emission, from 12d to 145d post explosion in SN2013ej.**
**SN2013ej: (0.3-8) keV  flux drops from $9\times10^{-15}$ erg/cm$^2$/s to ~$4\times10^{-15}$ erg/cm$^2$/s.**

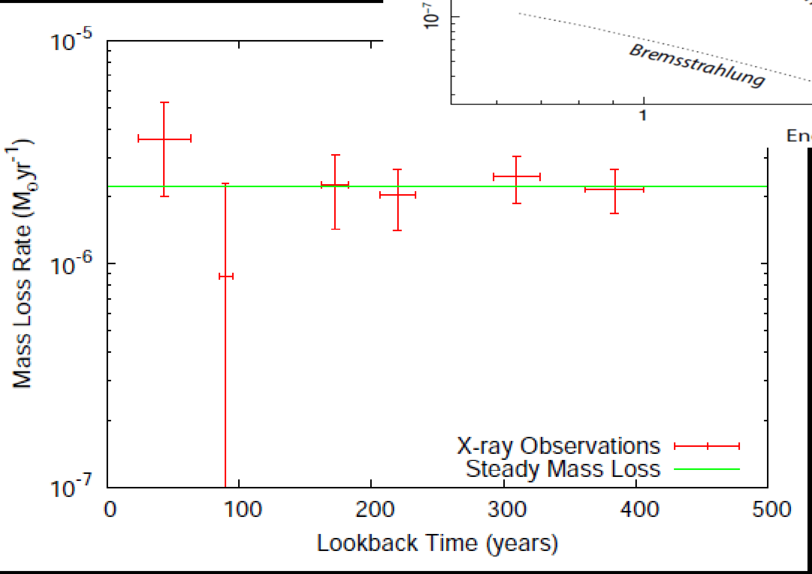
**SN2011ja: Prolonged X-ray emission, from 18d post explosion to 113 d post explosion.**
**SN2011ja:  (0.3-8) keV  flux increases from $9.8\times10^{-15}$ erg/cm$^2$/s to ~$4.08\times10^{-14}$ erg/cm$^2$/s.**




**Multicomponent X-ray emission:**

- **Forward shock (~100 keV) when ejecta plows in to CSM.**
- **Reverse shock (~1 keV) when the outflow is decelerated by the CSM pressure.**
- **Model consists of self-absorbed, hot, Plasma + thermal bremms. + Inverse Compton process.**

**Progenitor of 2013ej:**
**ZAMS mass M = 13.3 ±0,3 M⊙.**

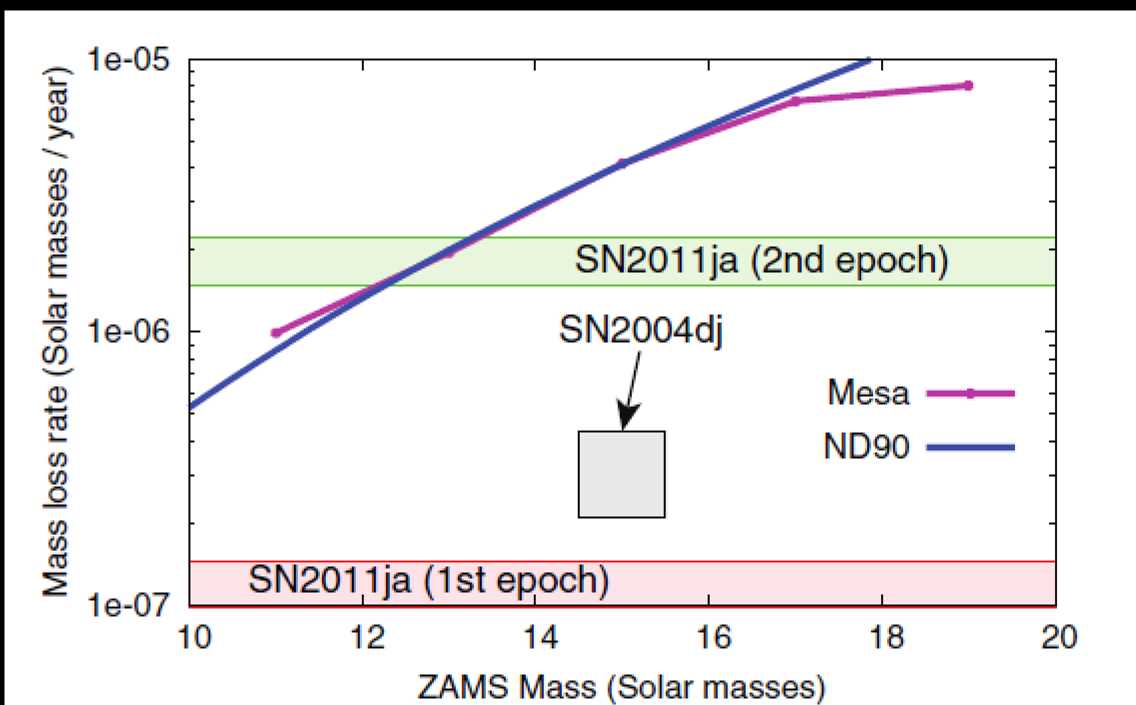



**◄▲SN2013ej at 5 epochs.**
**(Chakraborti... Sutaria... etal, 2015, ApJ, in prep.)**

# Evidence of CSM interaction in Radio and X-rays

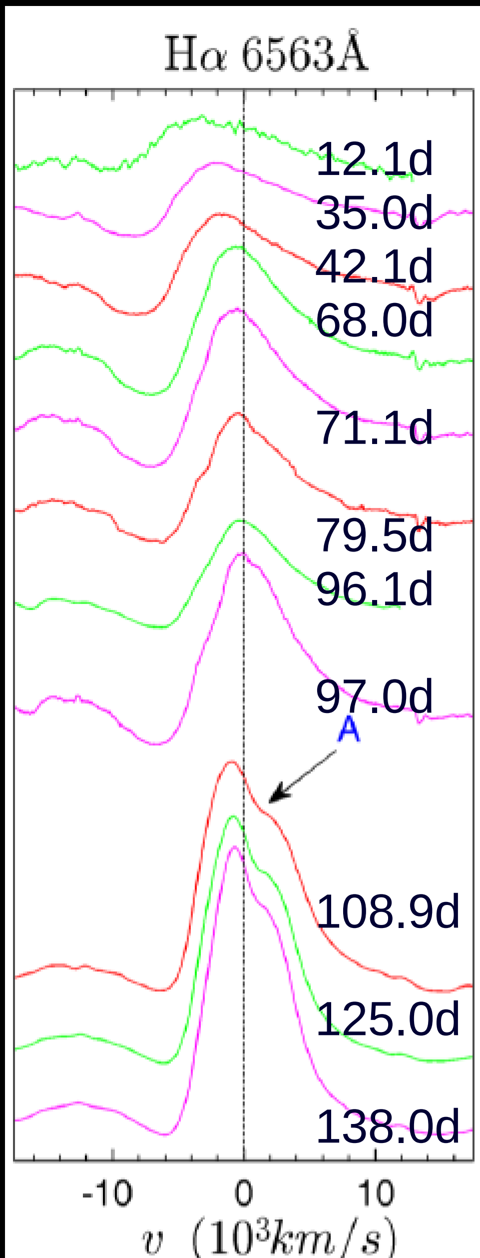
**Type IIP SN2011ja** : X-ray + Radio observations at up to 84 d post-explosion ⇒CSM bubbles caused by the hot progenitor wind, or progenitors with episodic mass loss. **(Chakraborti...Sutaria et al. 2013)**

**Type IIP SN2012aw:** Radio (GMRT, up to 184 days after explosion) + optical: Rare case of Compton cooling dominating over Synchrotron self absorption (SSA) in the CSM. Possibly due to a progenitor with low mass loss rate $1.9 \times 10^{-6}$ M☉/yr. **(Yadav...Sutaria et al. 2014)**

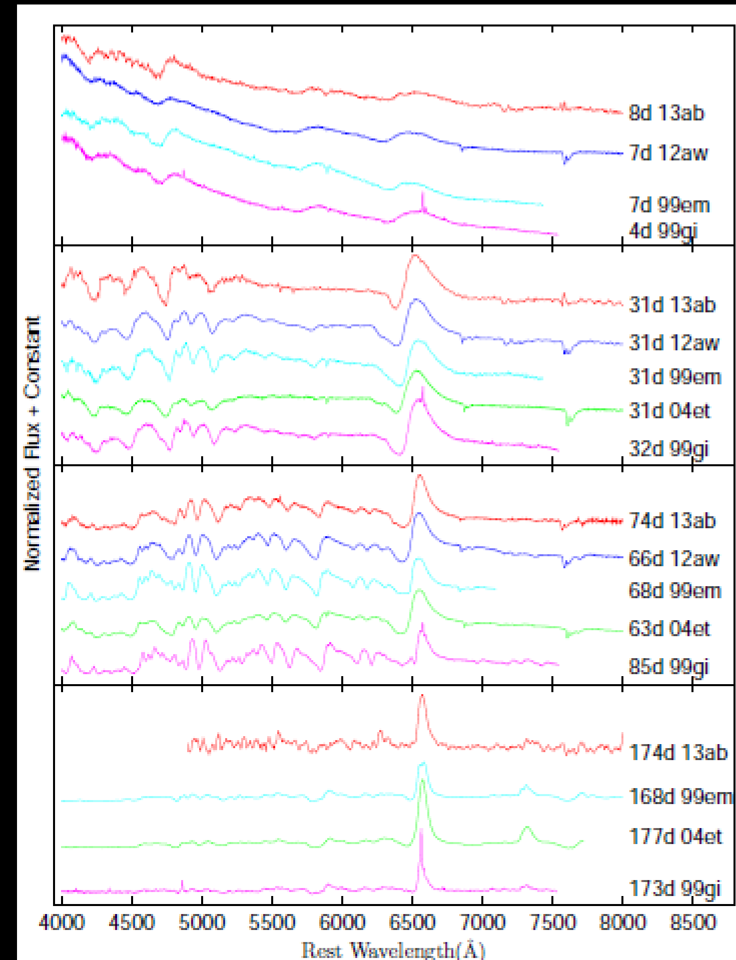



SN2011ja: ZAMS and wind mass-loss rate (last 100 yr) for MESA runs (magenta), and theoretical line (blue) (Nieuwenhuijzen & de Jager 1990; R = 103 R) plotted for comparison. Shaded boxes are 1σ confidence intervals for the mass-loss rate observed in SN 2011ja (corresponding to B = 0.1) first epoch (red), second epoch (green), and SN2004dj from Chakraborti et al. (2012) (gray). Progenitor possibly underwent variable mass loss during the final phases of stellar evolution.

# Evidence of early CSM interaction in SNe-IIP



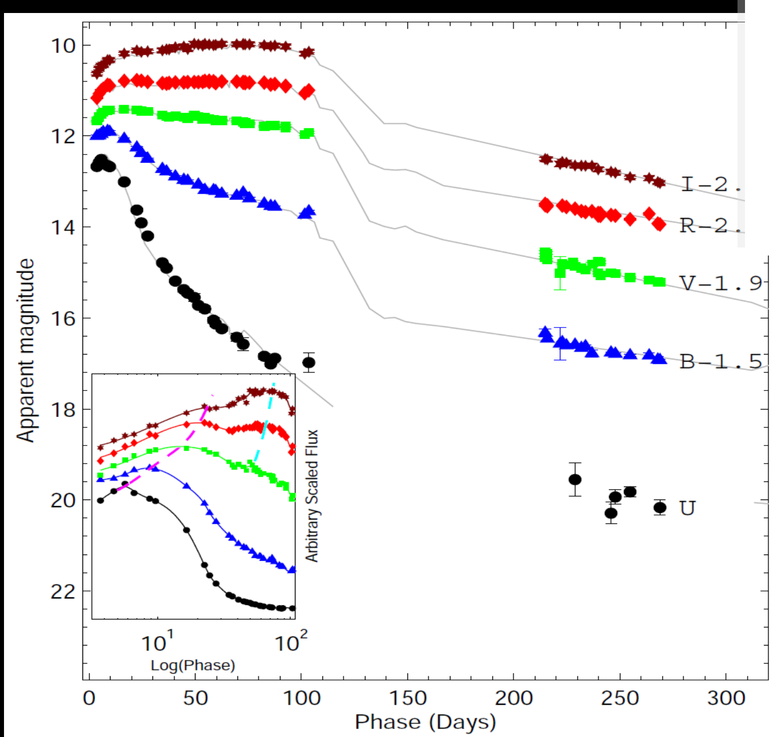

◄Comparison of H-α line velocities in **SN2013ej**. An additional feature (marked A) appears at ~ 108 d, corresponding to the start of the nebular phase.

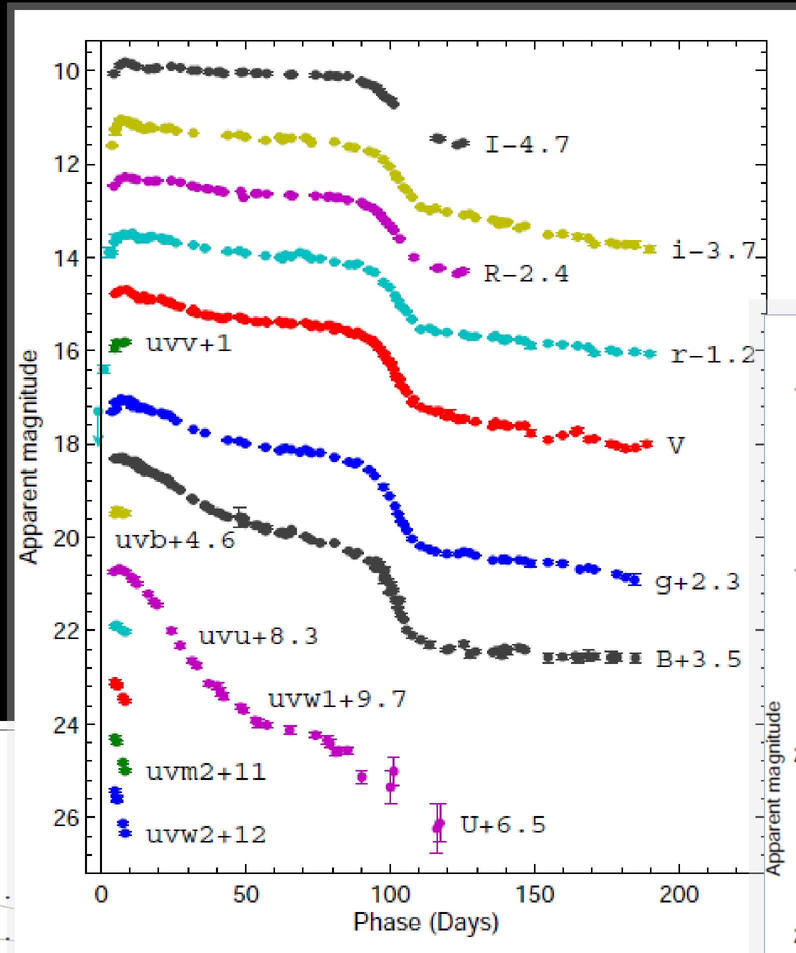



▲Comparison of early (8d), plateau (31d, 74d) and nebular (174d) phase spectra of **SN 2013ab** with other well-studied type IIP **SN 2012aw,** SNe 1999em , 1999gi and 2004et.
**Bose et al. 2014)**

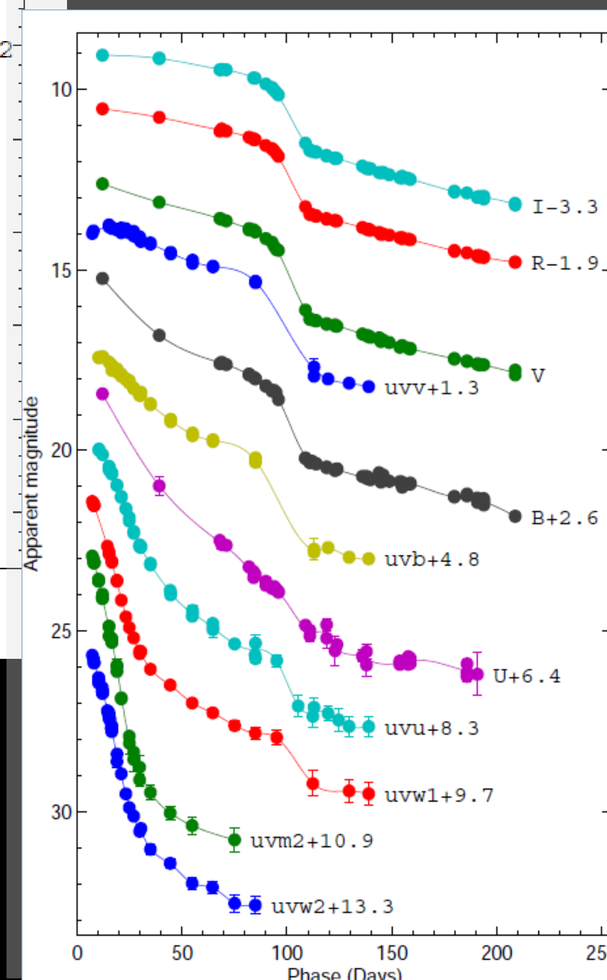
# A look at the light curves:

SN2012aw in UBVRI.
SN1999em in grey lines.
Inset: Early time evolution of 2012aw with the evolution of Primary and Secondary peaks marked. ▼



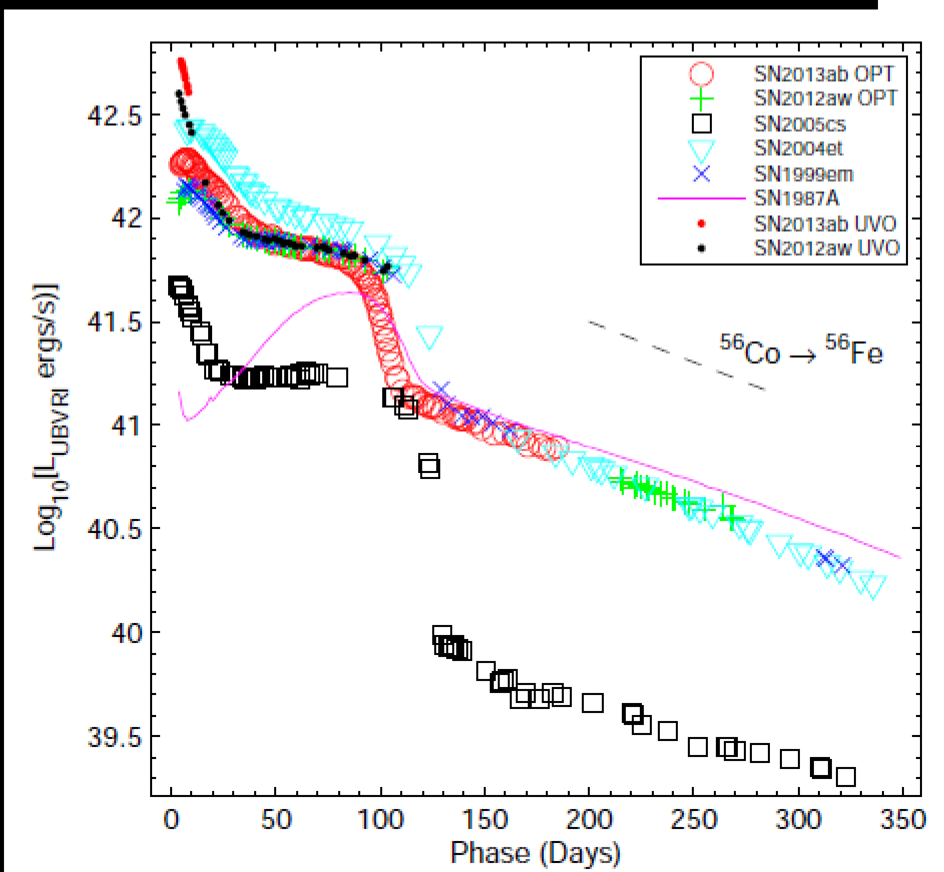

▲ SN2013ab UBVRI and Swift/UVOT light curves.

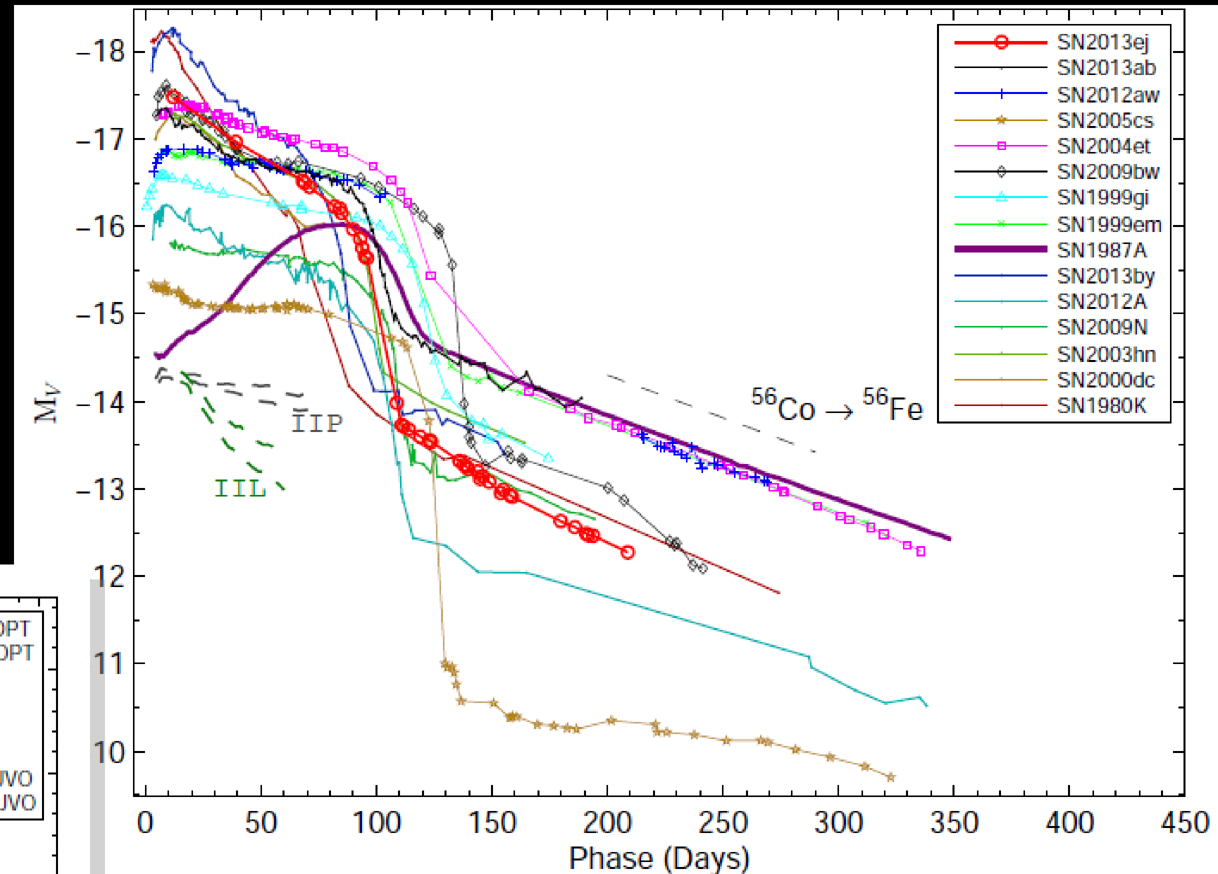



▲ SN2013ej UBVRI + *Swift* u, b, uvw1, uvm2, uvw2.

# Comparing $M_V$ & $M_{bol}$:

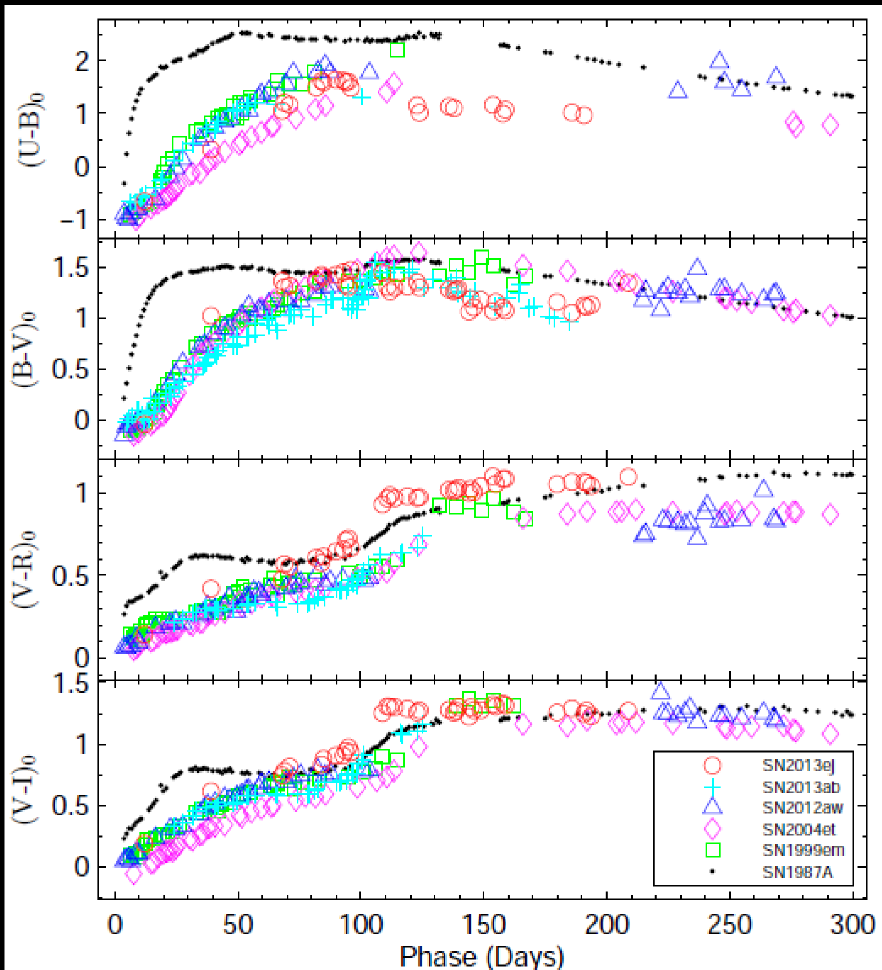
The bolometric light curves across various SNe-II. ▼



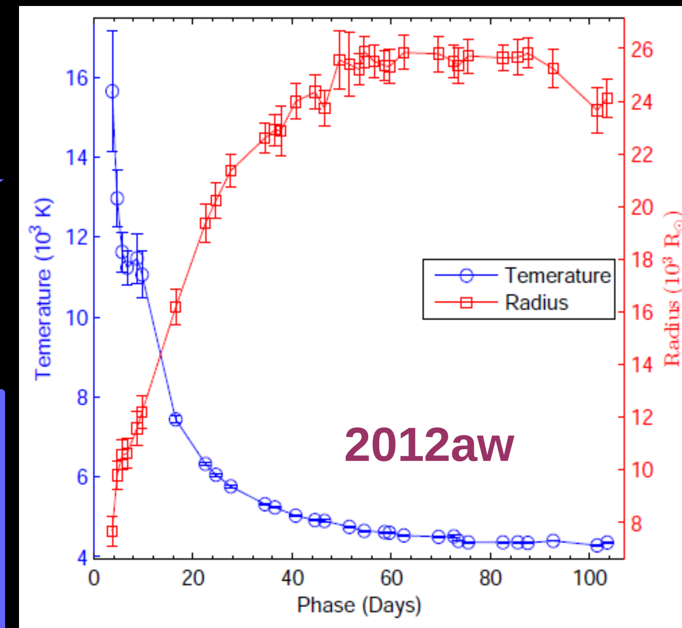

▲Comparing the absolute mag. ($M_V$) of SN2012aw, 2013ab and 2013ej.

# ... and colors...

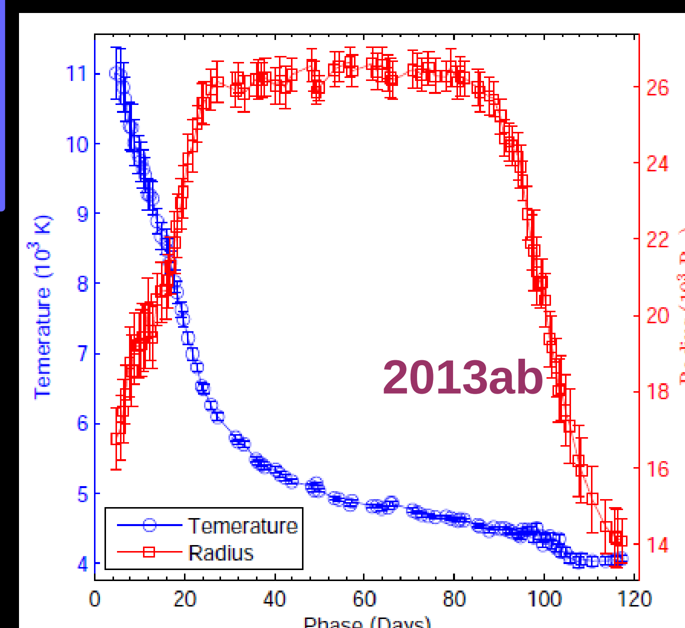



▲Color evolution of 2012aw, 2013ab and 2013ej compared with that for SN1999em and SN2004et.

▼ Temporal evolution of $T_{phot}$ & $R_{phot}$ from BB fits to observed fluxes from 170 to 880 nm.

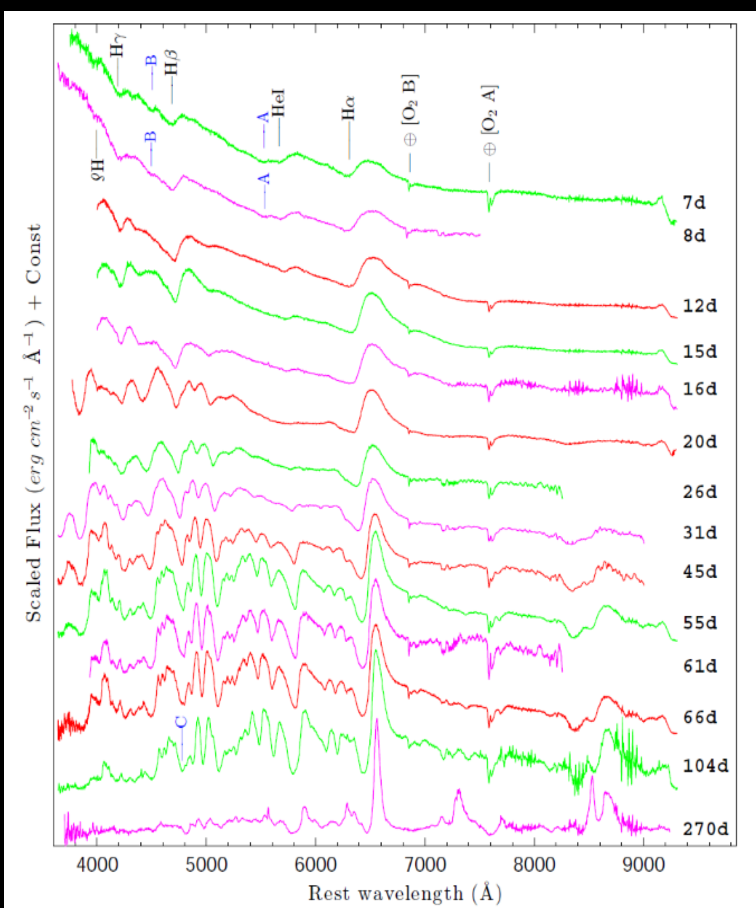



**The outward moving SNe-shock, and The inward moving recombination front reveal themselves...**

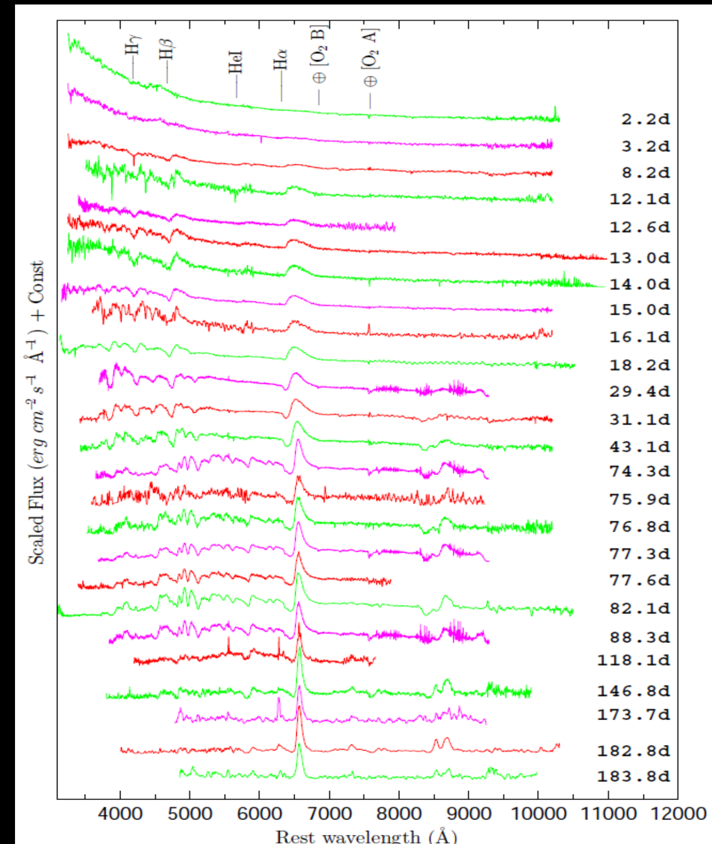


# Spectral analysis:

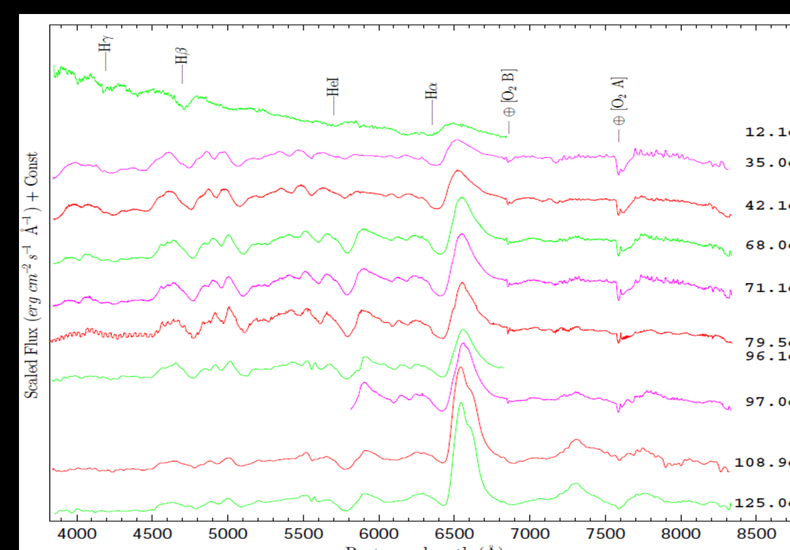
▼**SN2012aw:** (A) High velocity He I at 17665 km/s on 7 d slows down to 16643 km/s on 8d.
(B) HV H-β feature also slows From 21785 km/s to 21477 km/s.
(C) HV feature of H-β blended with Ba II and Sc II lines on 104 d.



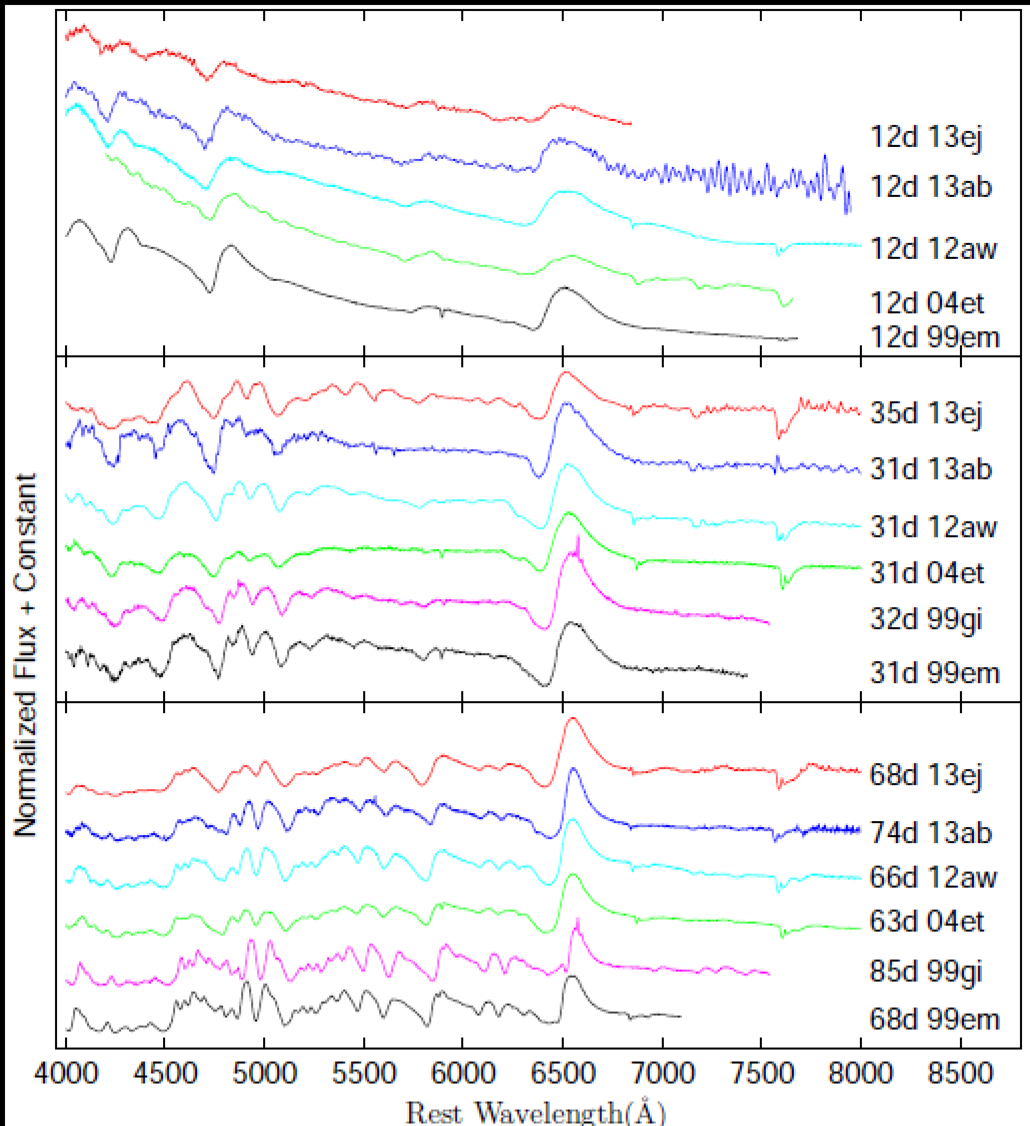

◄**SN2013ab:** No HV features in spectra.




**SN2013ej:** H-α at ~108 d shows signs of CSM Interaction.►



# Comparing spectra at similar epochs.




**1999gi data from Leonard et al. 2002, ApJ, 124.**
**1999em data from Leonard et al. 2002, PASP,114.**
**2004et data from Sahu et al. 2006, MNRAS, 372.**

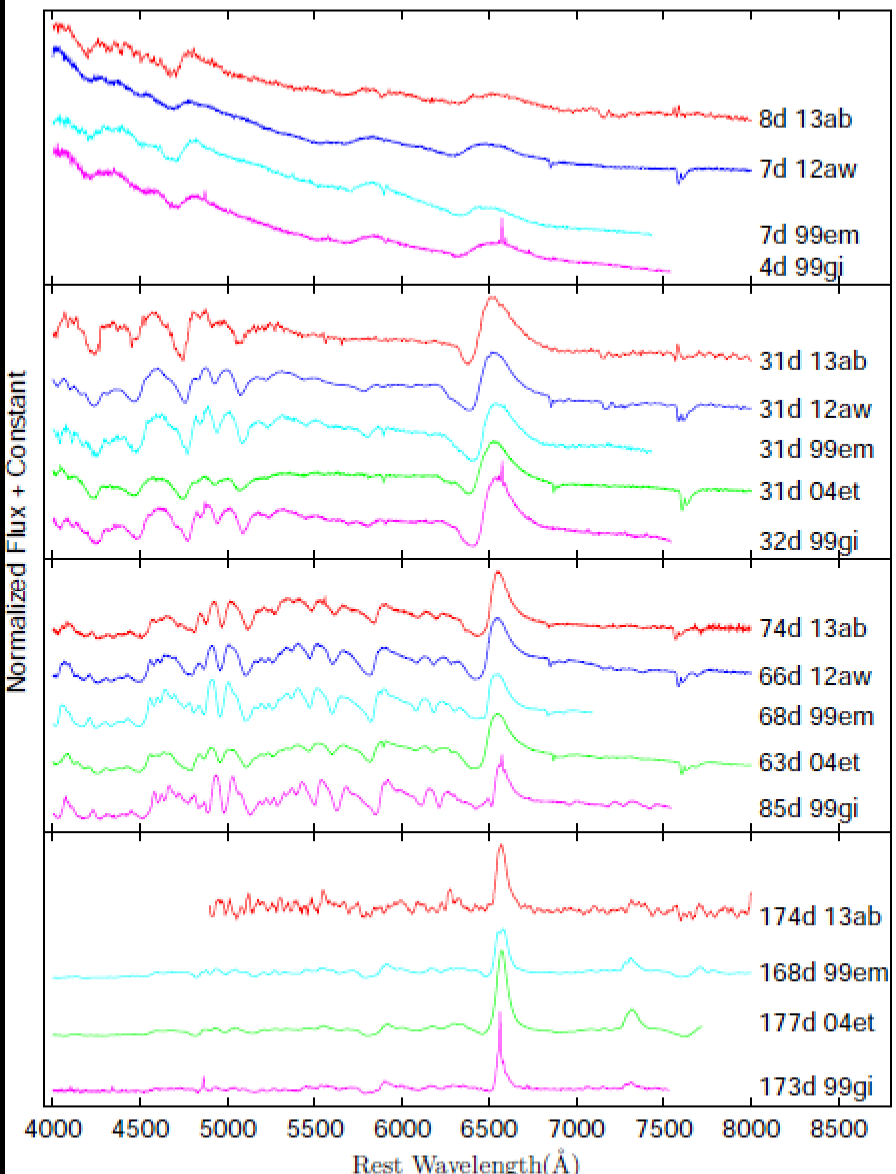
**SN 2013ej:**
- **Dip in H-alpha at 6170 A.**

**Si II (6347, 6371 A)?**
**Early CSM interaction?**
**Also seen at 35d, 45d.**
- **Modelled by SYNOW as Si II feature.**

**SN2013ab: No unusual feature.**

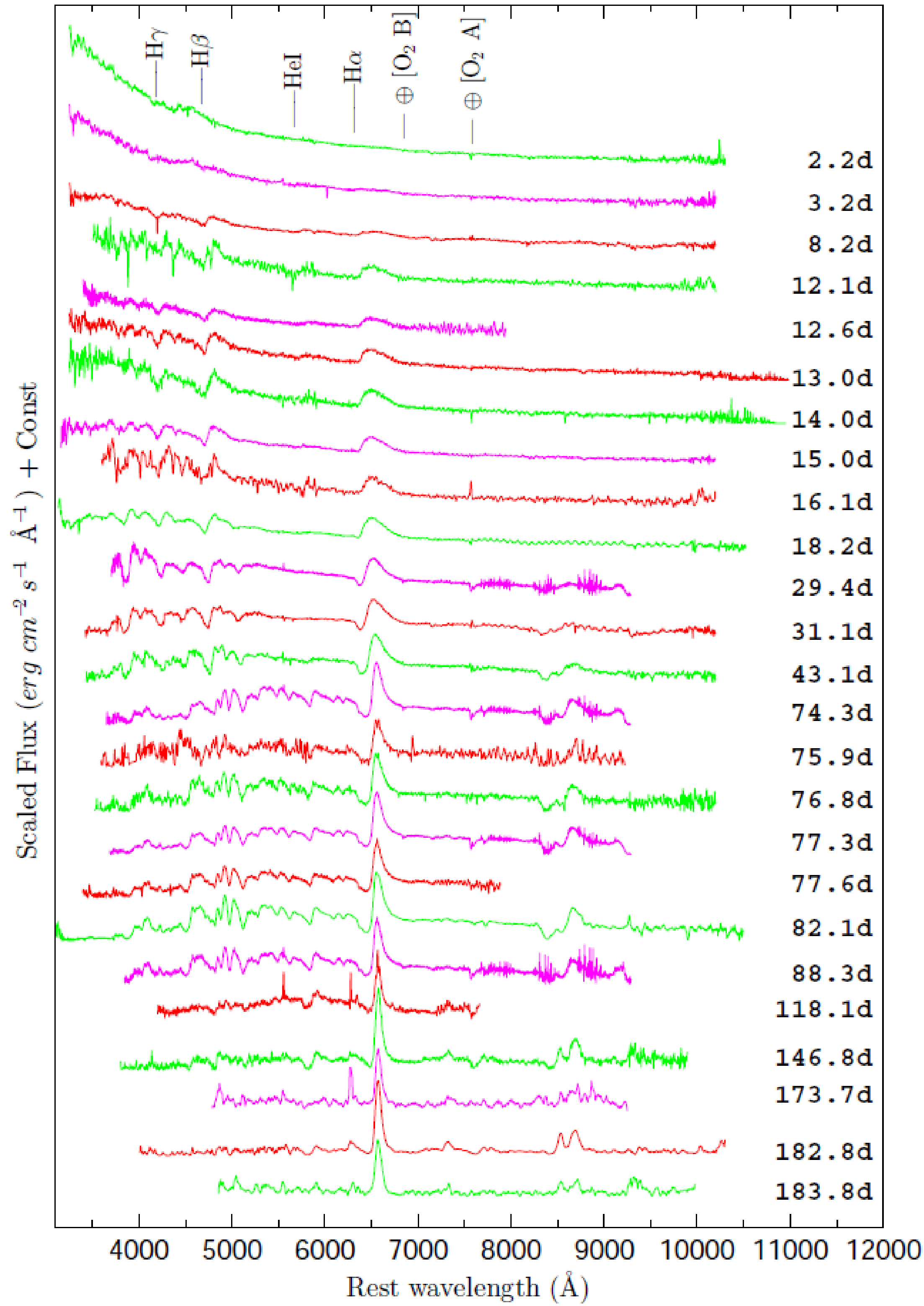
**SN2012aw:**
- **NII lines (4623, 5679 A) seen at 8 d, disappear by 12d.**

**No HV features present in 1999em and 1999gi at 60d -- HV features present in 2012aw, Similar to that 2004et. HV Features often emerge at start of Nebular phase.**

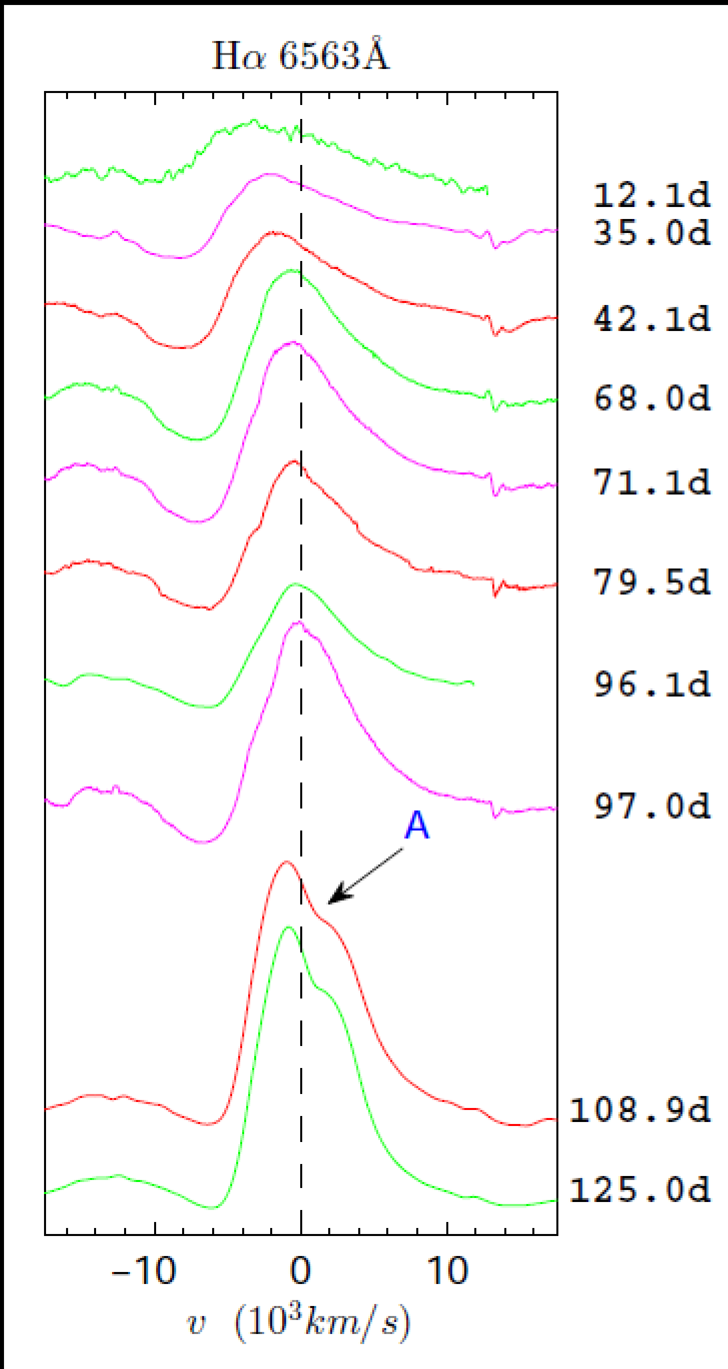



▲Comparison of spectra at select epochs For SNe 13ab, 12aw, 99em, 04et, 99gi.

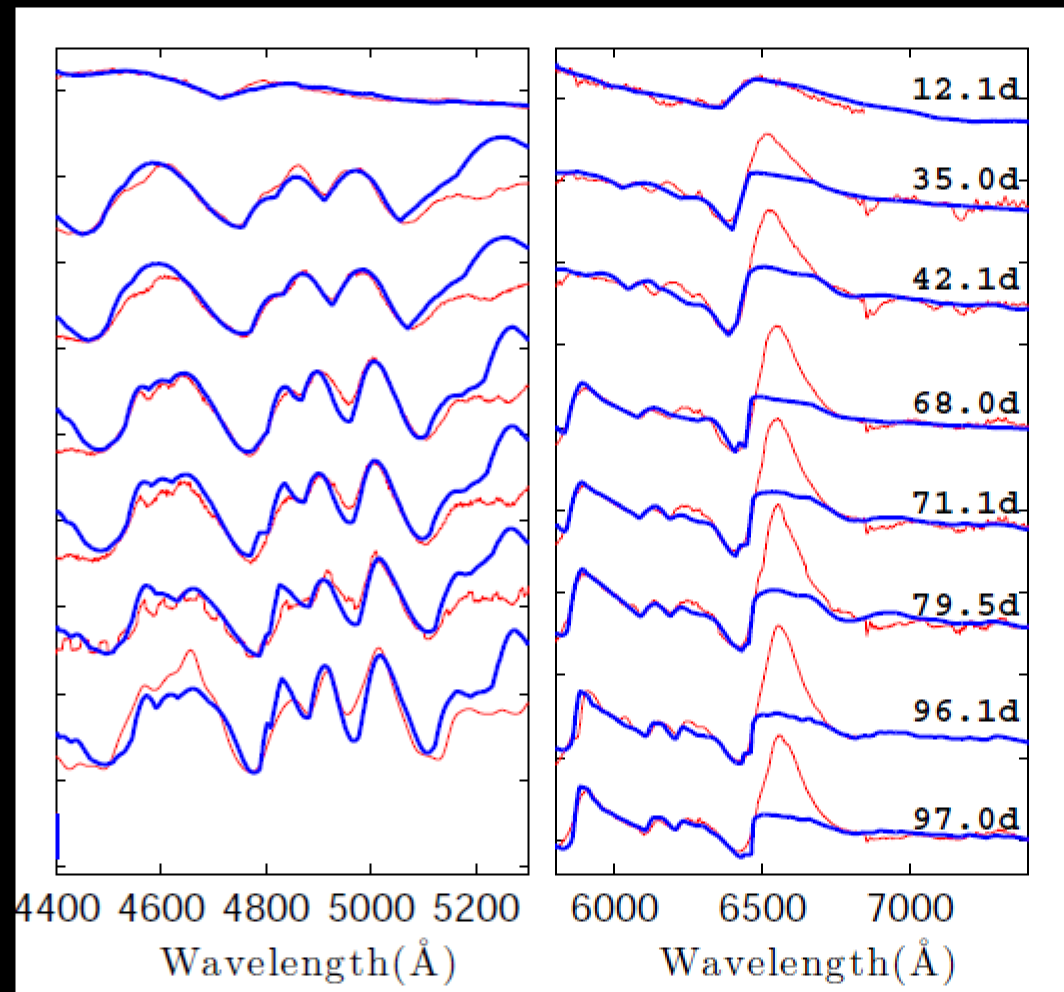
Spectral Evolution of SN2013ab. Spectra at Extreme blue and red ends have poor S/N. ►



# The evolution of line profiles: SN2013ej

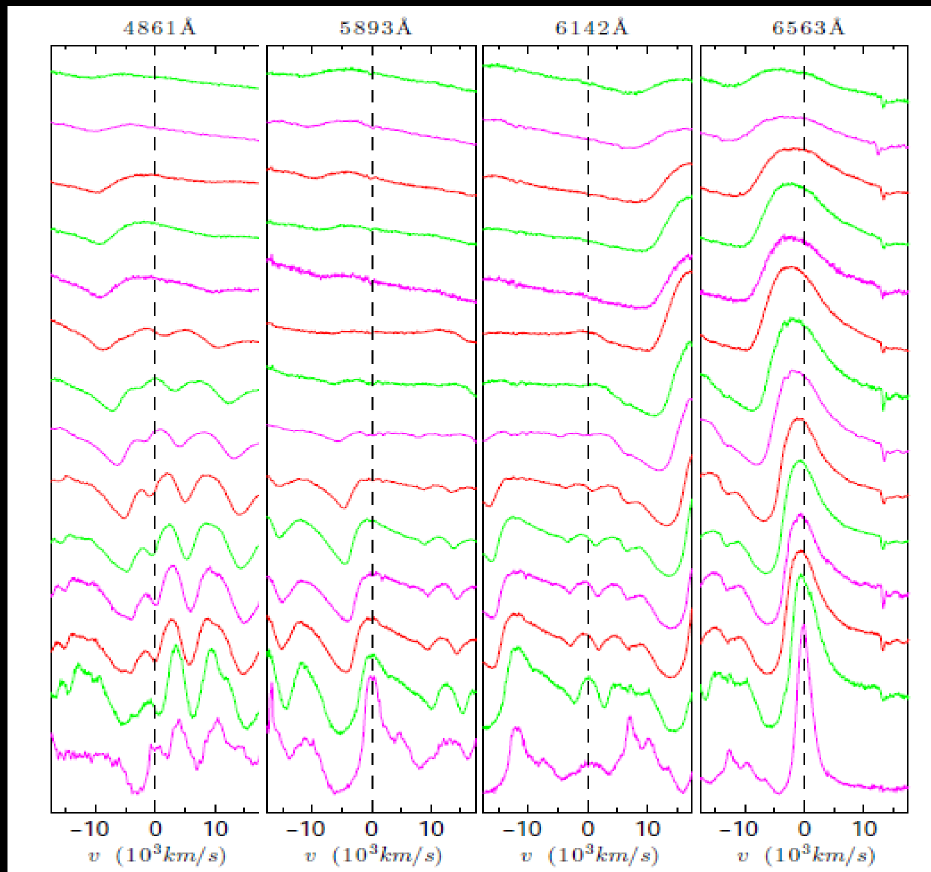



◄Evolution of the H-alpha profile of SN2013ej.

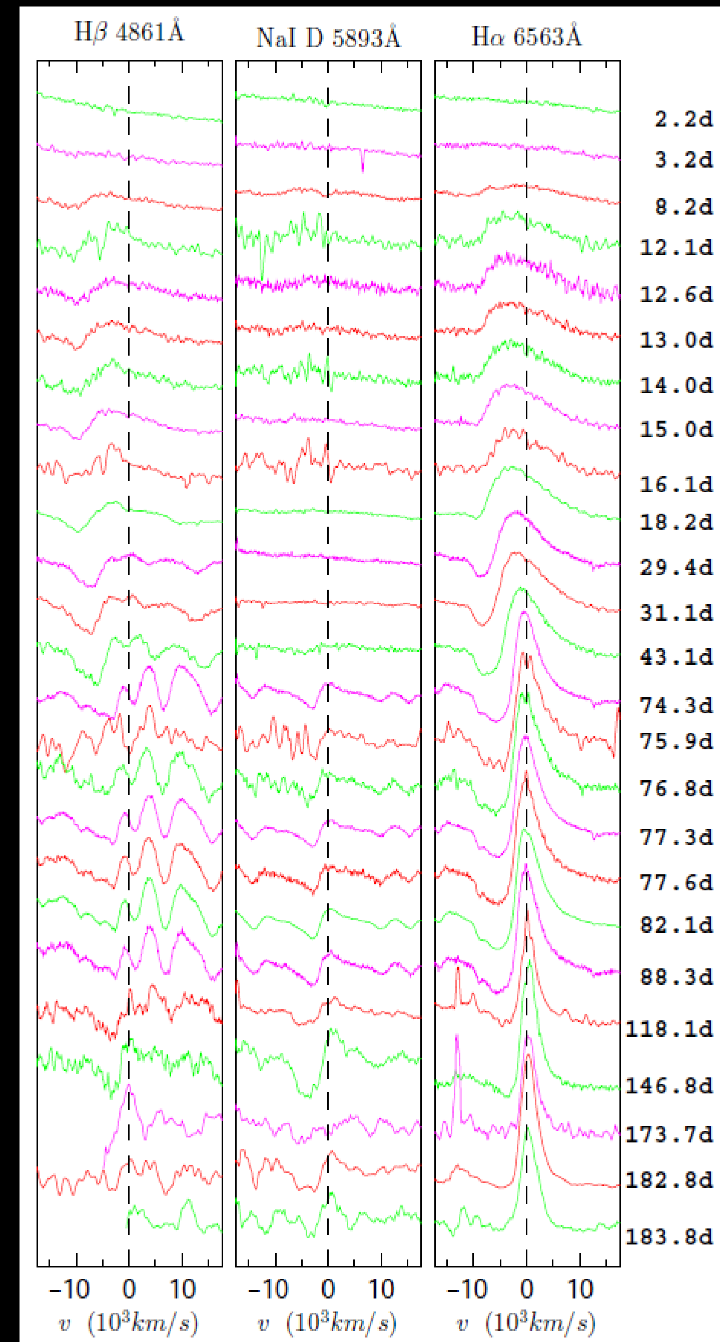



▲SYNOW chi-by-eye fits to Fe-II (l) and H-alpha(r) Profiles in the case of SN2013ej.

# The evolution of line profiles: SN2013ab and 2012aw




SN2012aw: The evolution of line profiles H-β, NaI D, Ba II and H-α. The phases are 7, 8, 12, 15, 16, 20, 26, 31, 45, 55, 61, 66, 104 and 270 d (top to bottom).

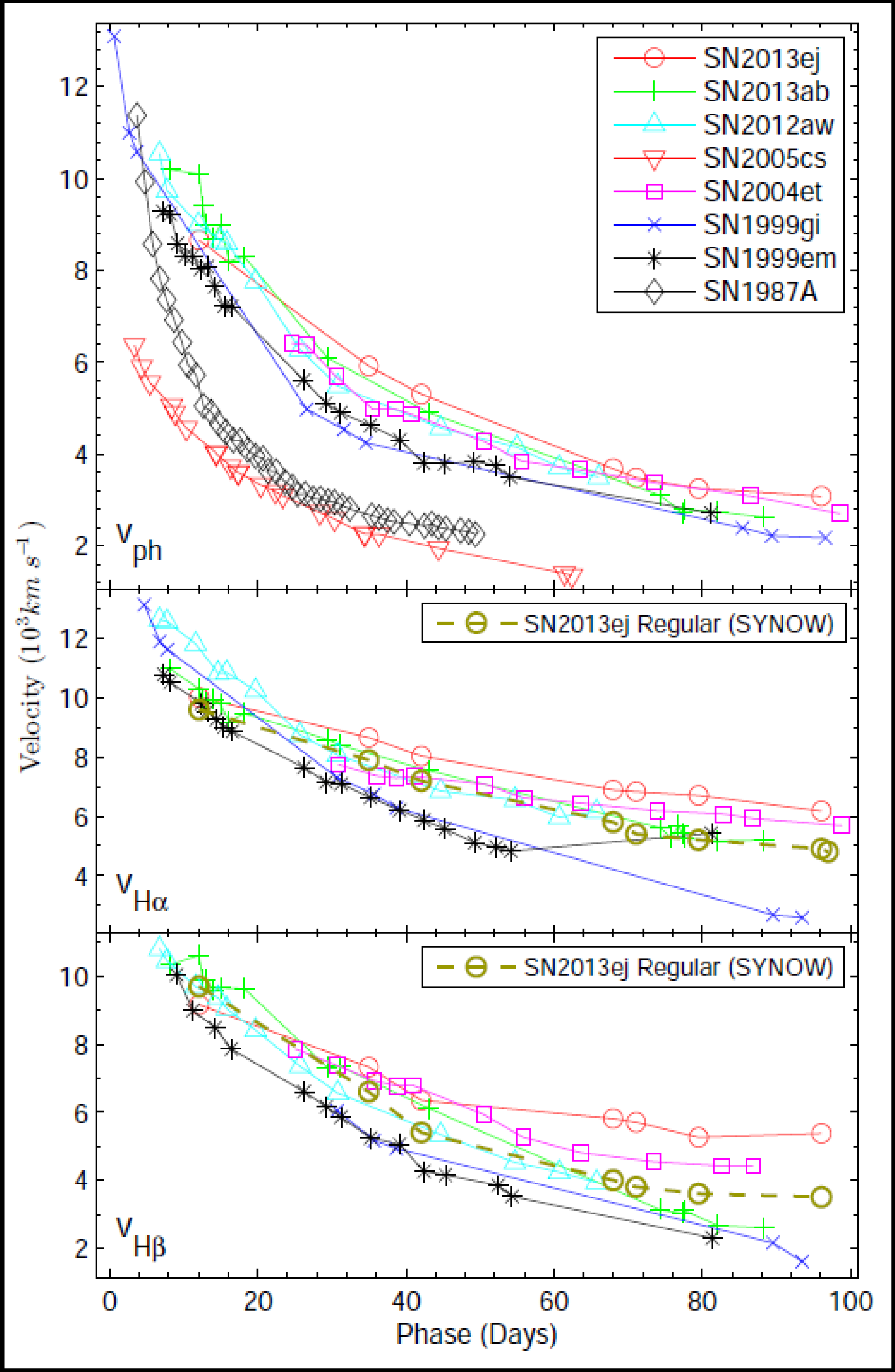



SN2013ab: Evolution of the line profiles of SN2013ab, for the H-β, NaI D and H-α. ►

# Comparing the "photospheric" velocities:

**Velocities estimated from SYNOW (Sobolev approximation) models, No HV features included.**

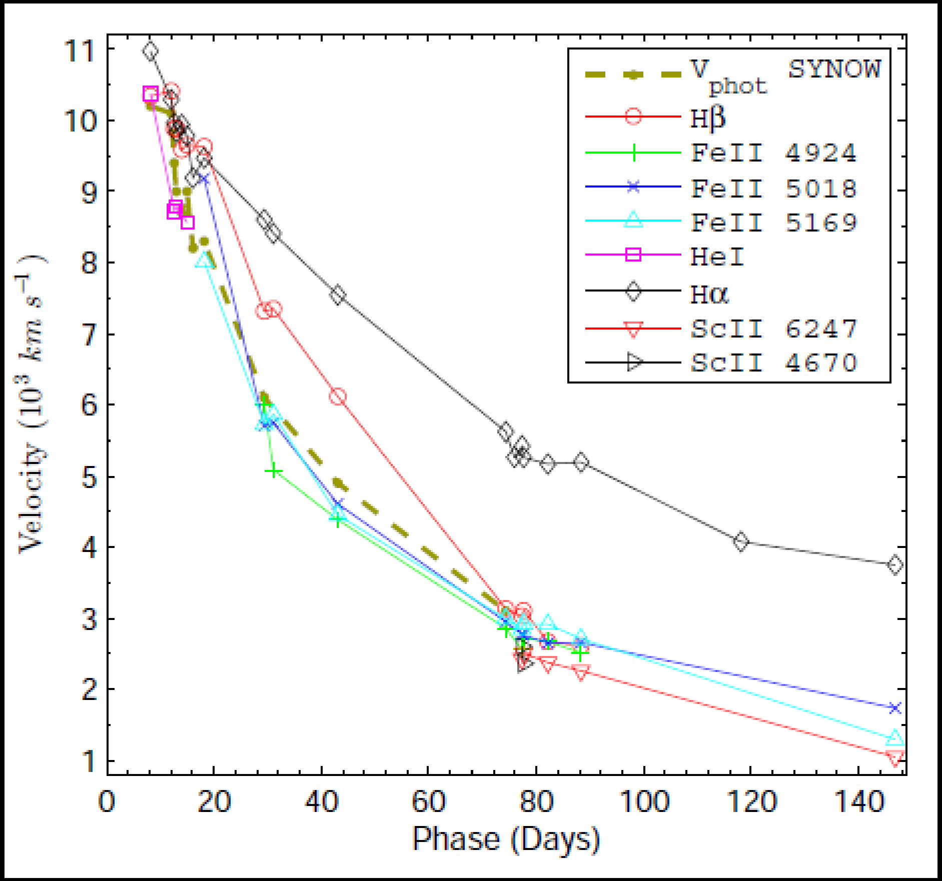
**Direct measurements:**
**from Fe II (4924, 5069, 5169 A)**
**from H-α, H-β absorption features.**

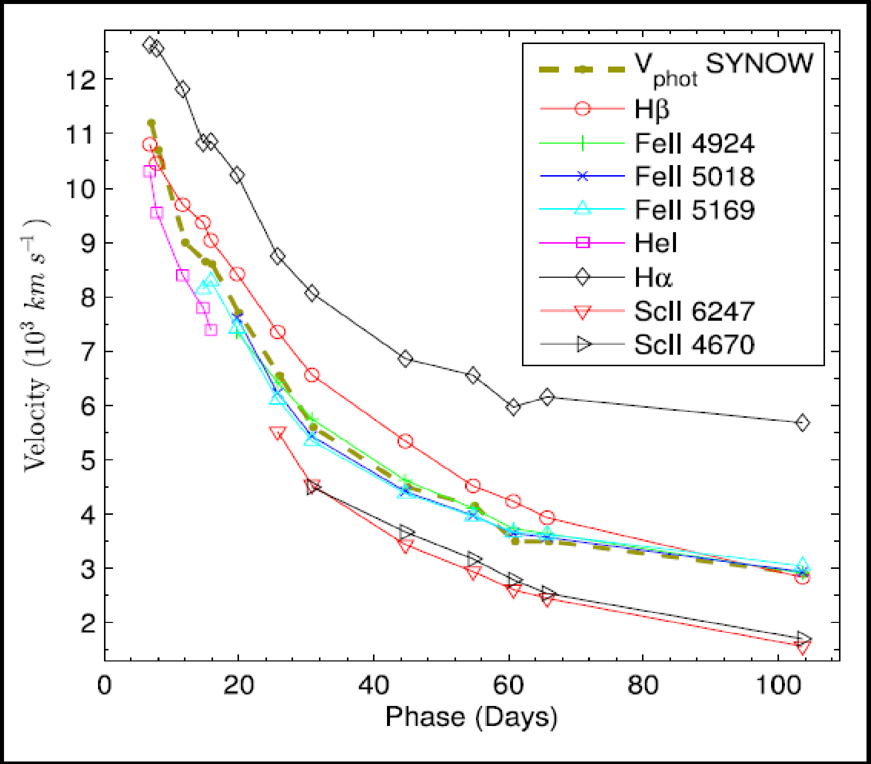



**Top:** $v_{ph}$ from FeII at late phases & HeI at early phases)
**Center:** P-cygni absorption trough Velocity from H-α
**Bottom:** P-cygni absorption trough Velocity from H-β.

# More velocity comparisons:

▼Line velocities for SN2013ab, measured from absorption troughs of various spectral features, and from SYNOW.




▲Line velocities for SN2012aw, measured from absorption troughs of various spectral features & from SYNOW.

## Results, conclusions and points to ponder:

- The emergence of very bright SNe, even in the “isolated progenitor” class. New mechanisms for mass loss?

Modelling of the light curves and spectra suggests that:

- SN2012aw is a super luminous SN-IIP with ~15 $M_\odot$ progenitor, which underwent extensive and episodic mass loss in the late evolutionary stage. Explosion energy is 1-2 f.o.e., and $M_{Ni}$=0.06 Msun**.**
- SN 2013ab reveals itself as "typical" event with ~9 $M_\odot$ progenitor with a highly extended envelope (~ 600 $R_\odot$).
- SN2013ej, which was identified as a type-IIP early in its evolution, shows up as transitionary event between classes, as it shows late time characteristics of Sne-IIL. HV features near nebular stage suggest possible bipolar distribution of $^{56}$Ni. X-ray evidence of circumstellar interaction at late stages. Progenitor ZAMS ~14 $M_\odot$, ~450 $R_\odot$ and explosion with 2.3 f.o.e.

Events like SN2013ej, SN2011ja demonstrate the need for spectral followup of SNe at several epochs, especially when classifying events for the determination of the cosmological SNe rate, as a function of the supernova type.

Merci beaucoup, IAU!