Progenitors and Explosion Mechanisms of Stripped-Envelope Supernovae

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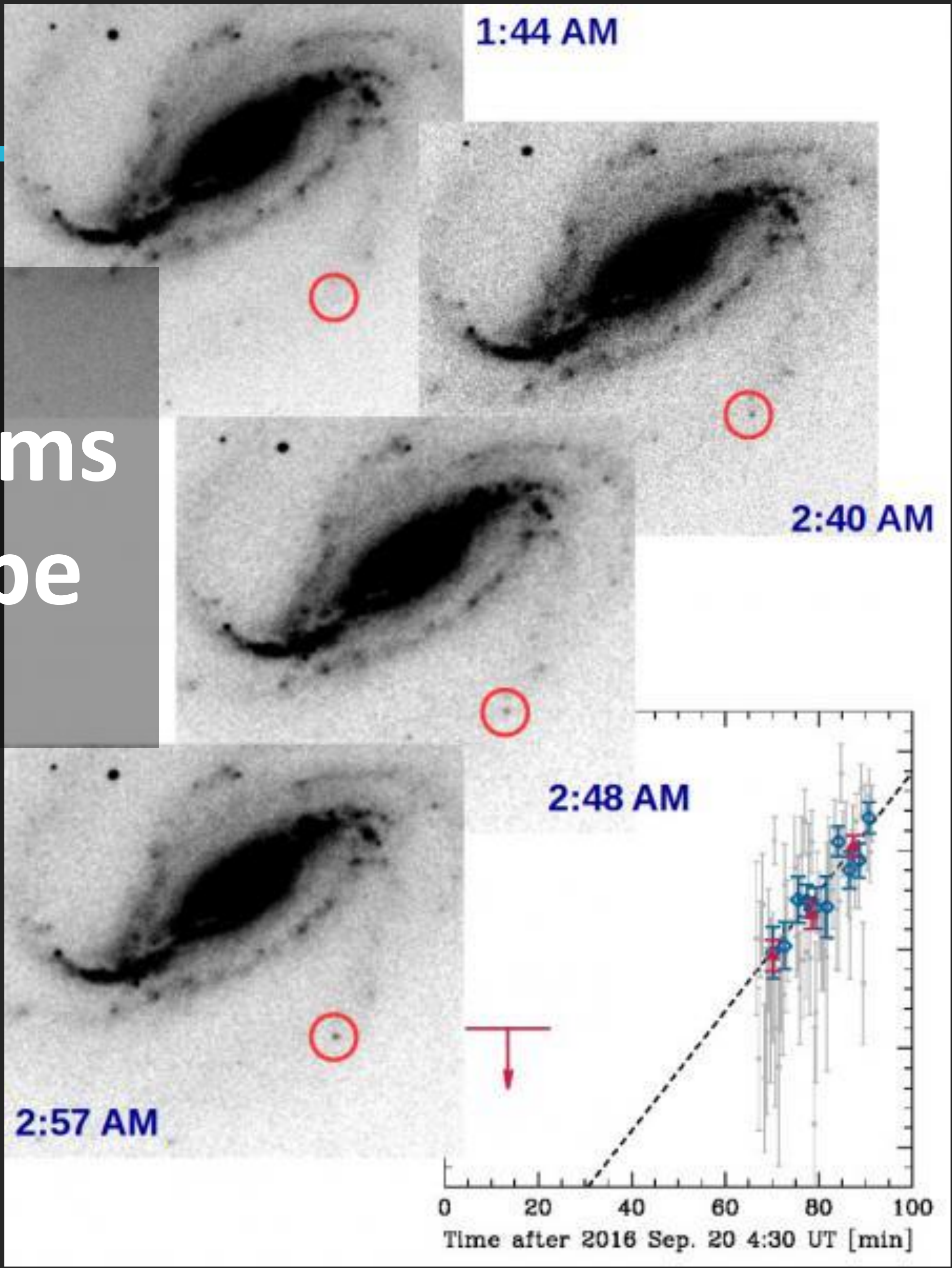
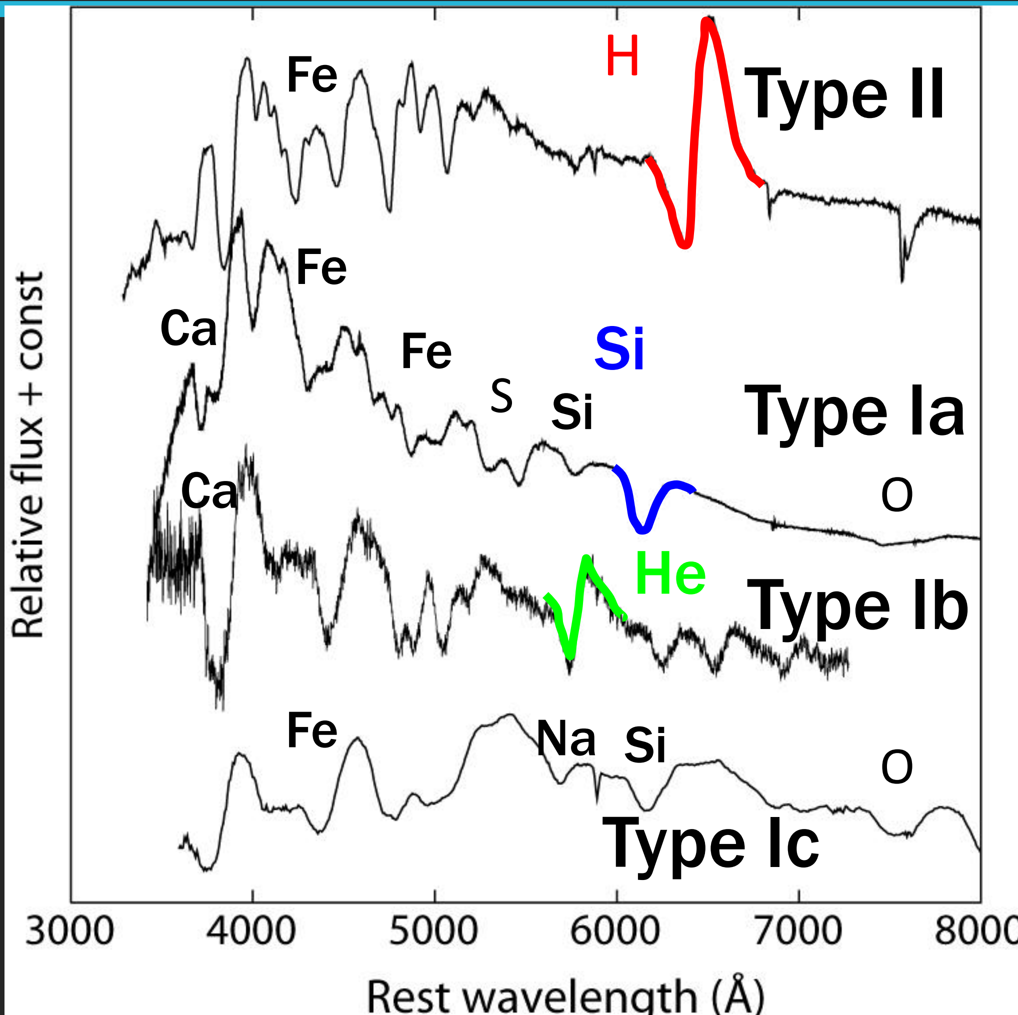
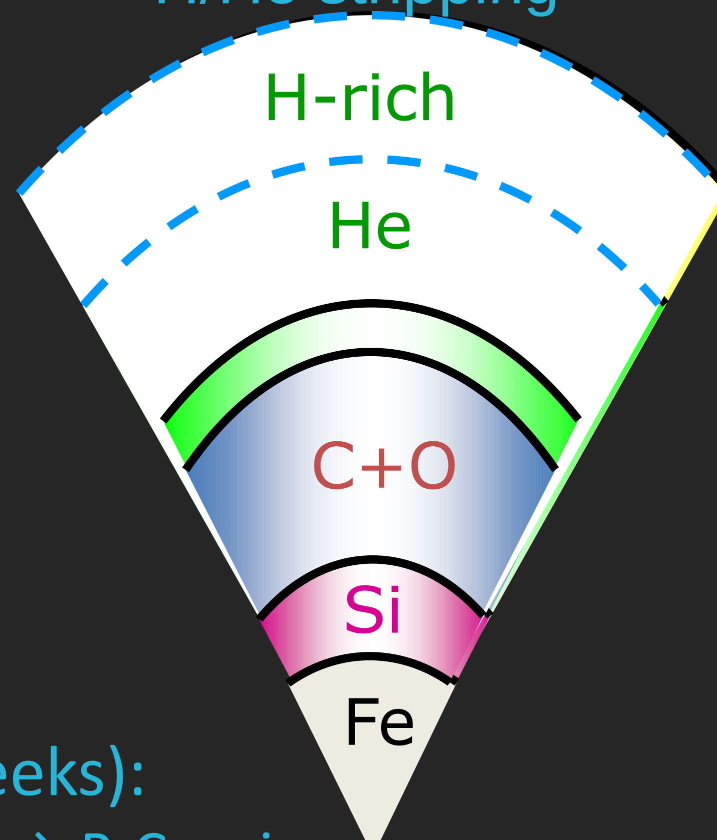


Stripped-Envelope SNe (SESNe)



SNe IIb/Ib/Ic

Core-Collapse (CC) of a massive star: H/He stripping



- @ maximum brightness (~ a few weeks):
  - Expanding optically thick medium → P-Cygni.

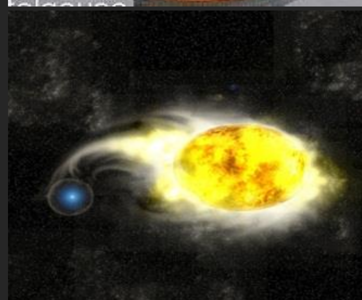
A Rough Picture

Progenitor

Mass loss

IIP/L

RSG



YSG

IIb

BSG

Ib

Ic

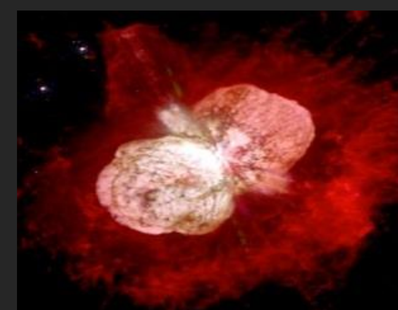
WR

Decreasing radius

More CSM (where?)

Dense CSM in the vicinity

IIn



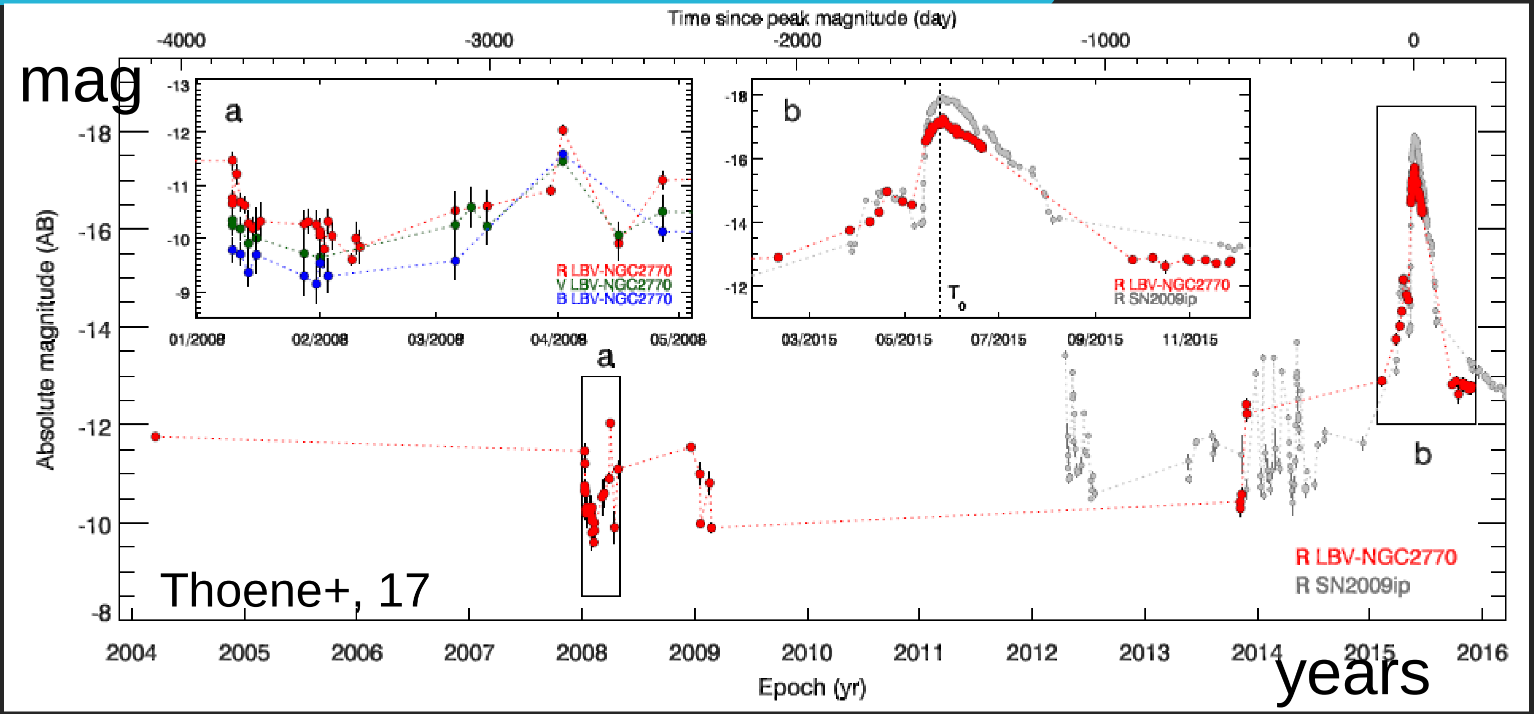
LBV (?)

Mass stripping sequence

Single star: Mass sequence

Binary: **Not** mass sequence

Beyond the standard mass loss



LBVs leading to a WR w/ a giant eruption in a few years?

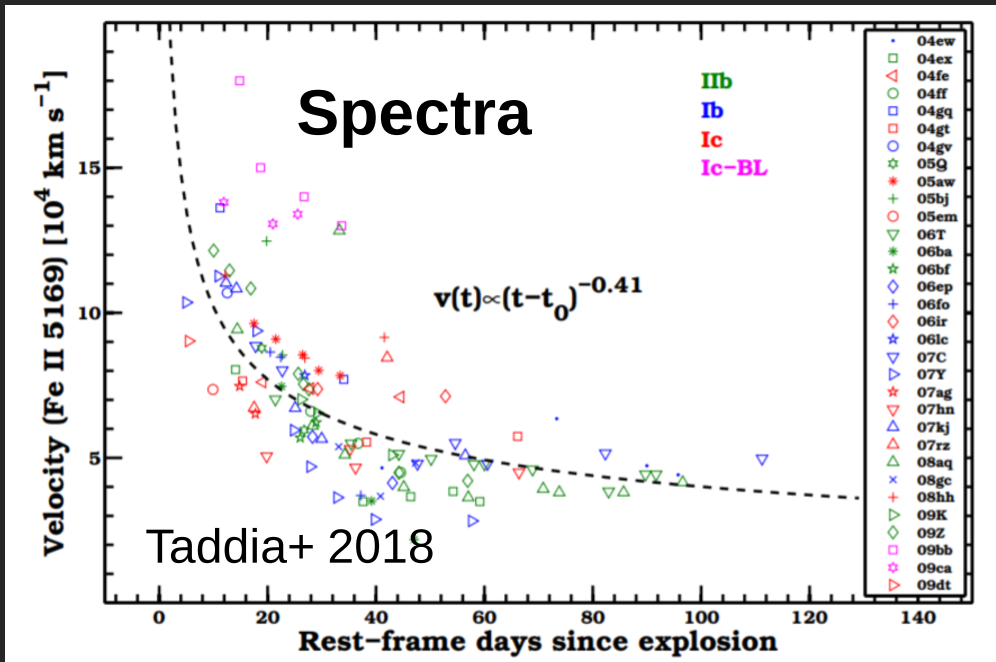
SNe 2009ip (Fraser+15, Graham+17), 2015bh (Elias-Rosa+16, Thoene+17), 2016bdu and 2005gl (Pastorello+17).

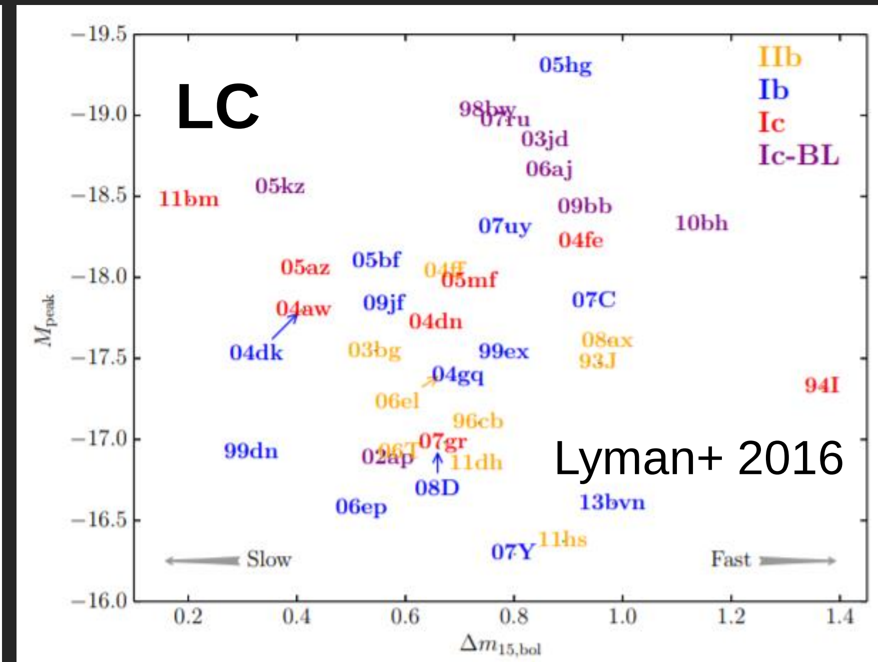
2005gl w/ progenitor (LBV progenitor for IIn) (Gal-Yam+Leonard 09).

 # Relation to SESNe?

 # Late burning stages? **(how envelope reacts? See Ouchi's poster)**

SN properties





The LC time scale + velocity (roughly) similar.

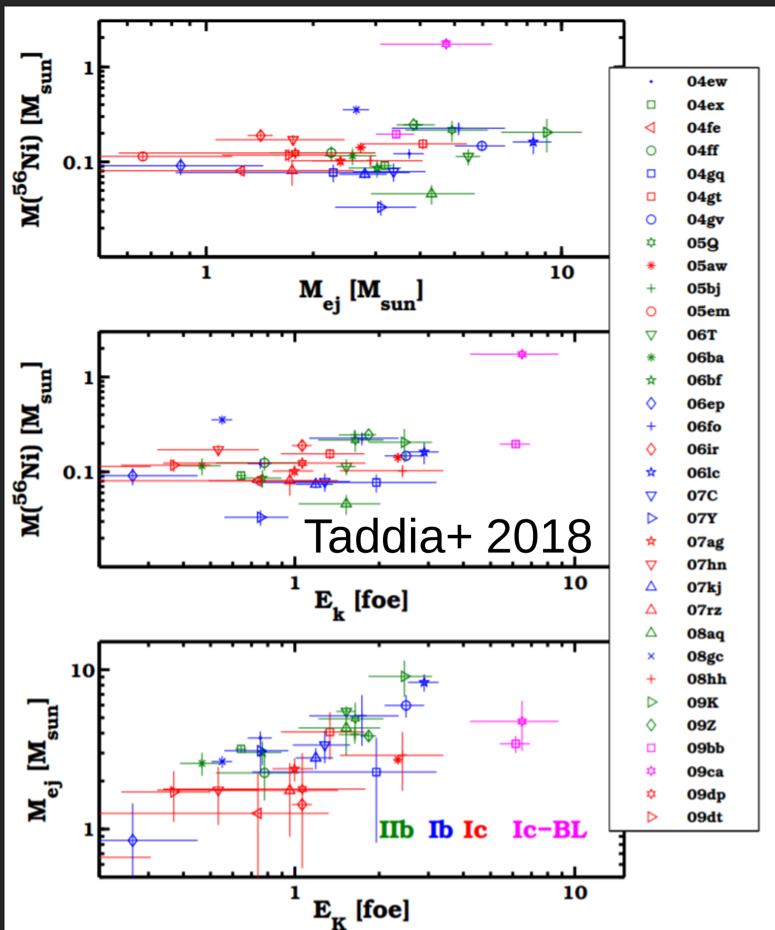
⇒ **Similar Ejecta mass and Explosion Energy.**

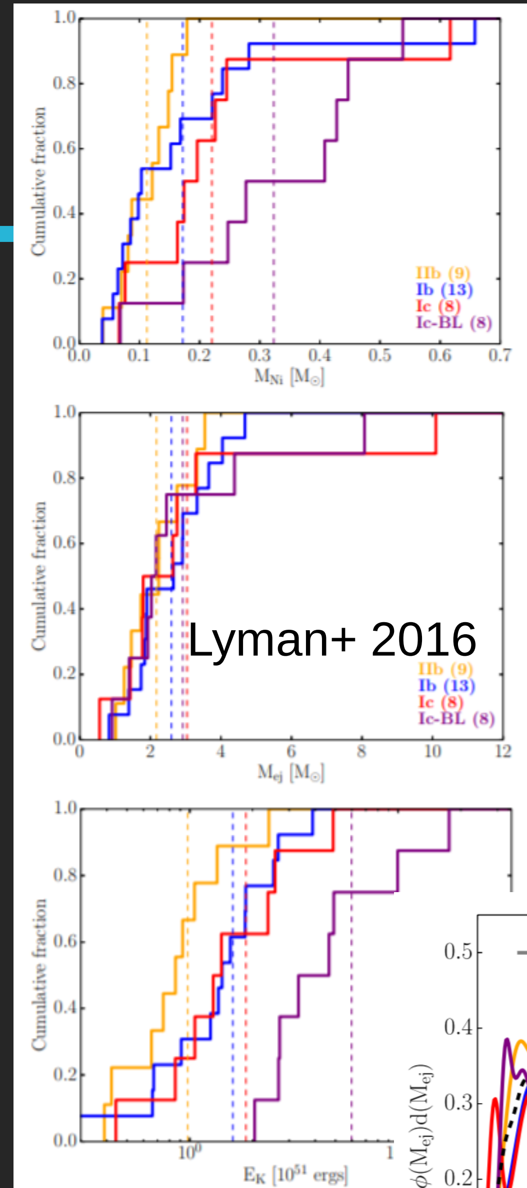
The peak luminosity slightly higher for SNe Ic.

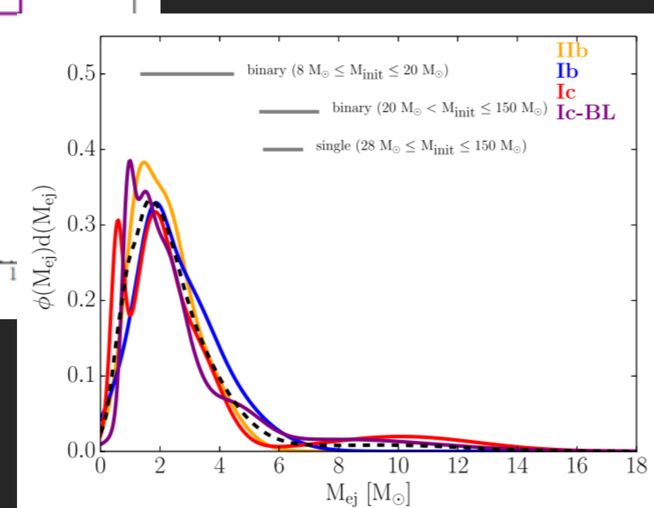
⇒ **(Relatively) larger M(^{56}Ni) for SNe Ic (?).**

Exception: Broad-lines SNe Ic (not for this talk).

SN Properties





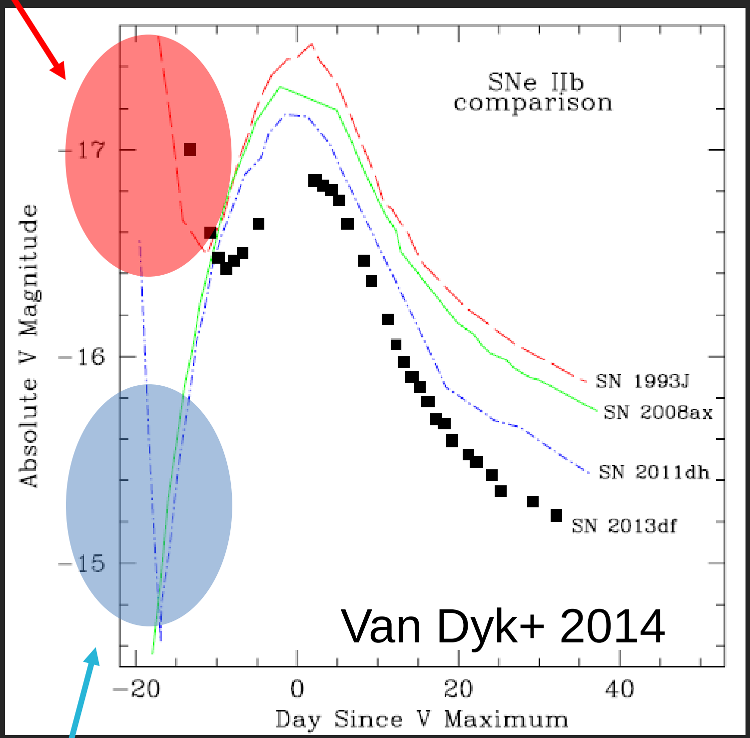


Similar, details depend on analysis.

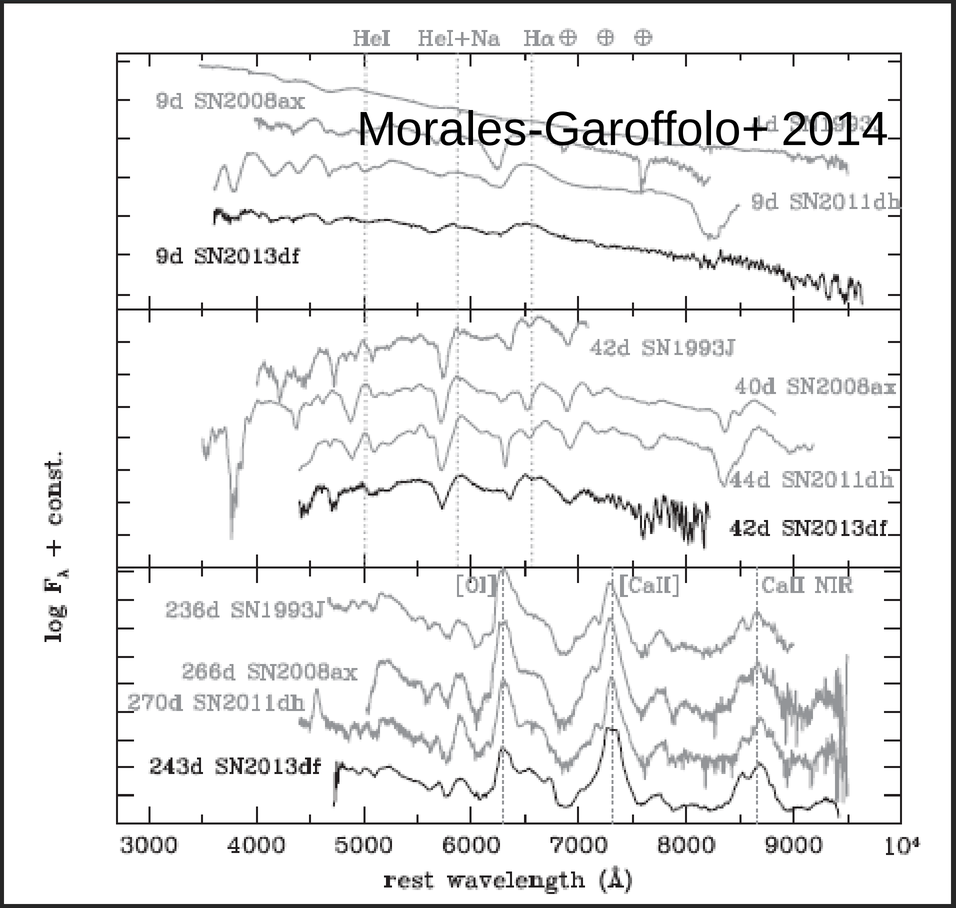
$M_{ej} < 4M_{\odot} \Rightarrow M_{ms} < 20M_{\odot} \Rightarrow$ binary (?)

SNe IIb: The best studied SESNe

“Strong” cooling (extended H)
1993J & 2013df



“weak/no” cooling (compact H)
2008ex & 2011dh
2016gkg in between.



Similar spectra & peak LC
⇒ similar progenitor mass
and energetics

Progenitor diversity (no RSG, no WR)

Disappearance
+Companion

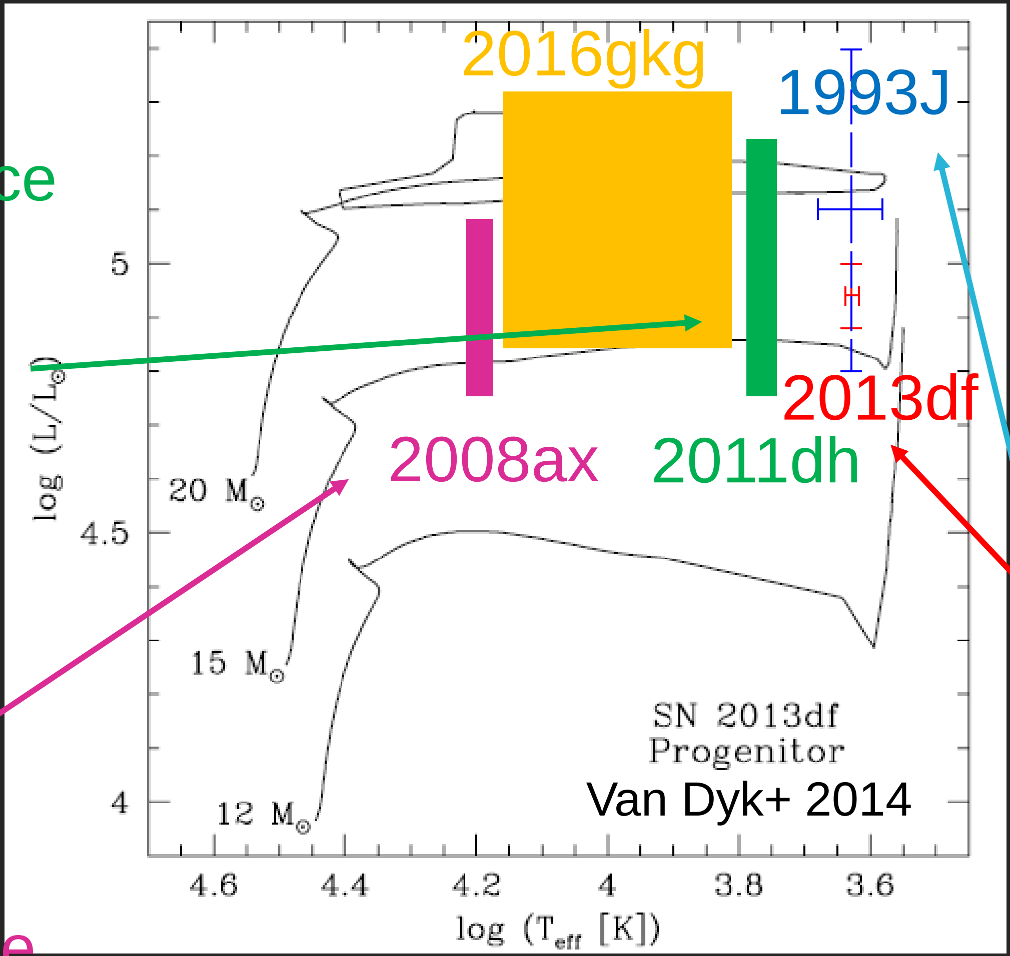
YSG

~ 200R⊙

BSG

~ 50R⊙

Disappearance



Disappearance
+Companion

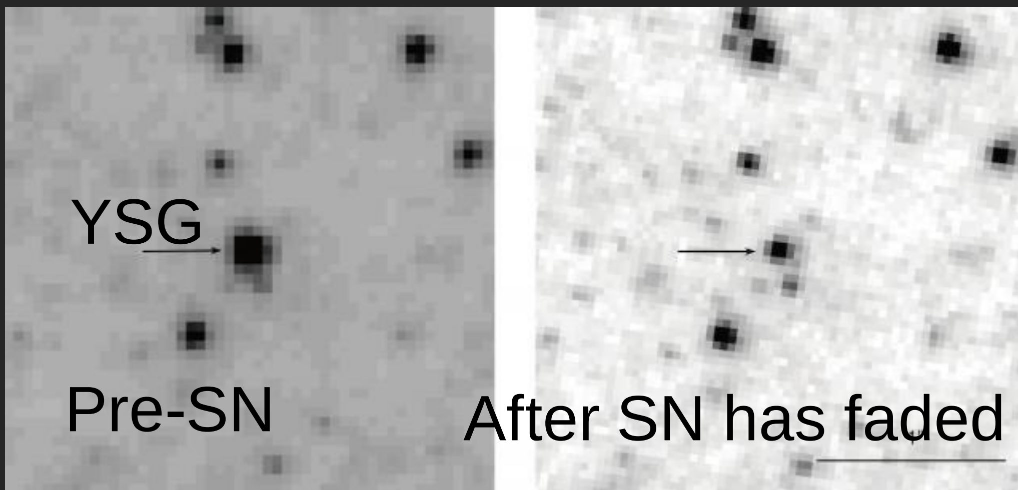
Pre-SN only

YSG

~ 600R⊙

The progenitor mass range largely consistent with SNe IIp.
Hydrogen stripping sequence ~ Diversity in radius

4 YSG progenitors among 5 best-studied cases

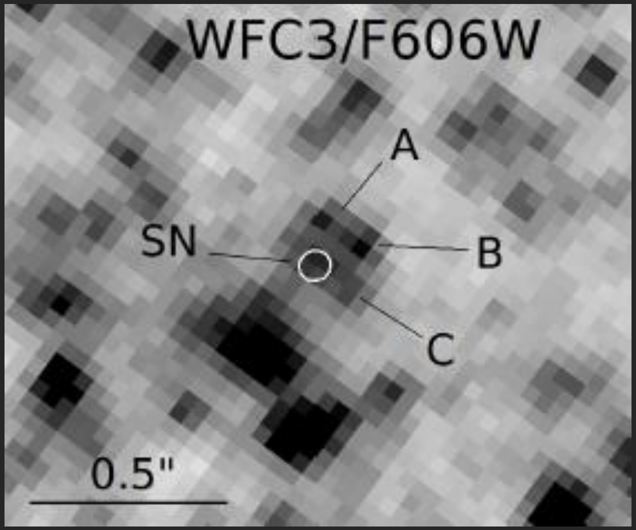


SN 2011dh:
Van Dyk+ 2013

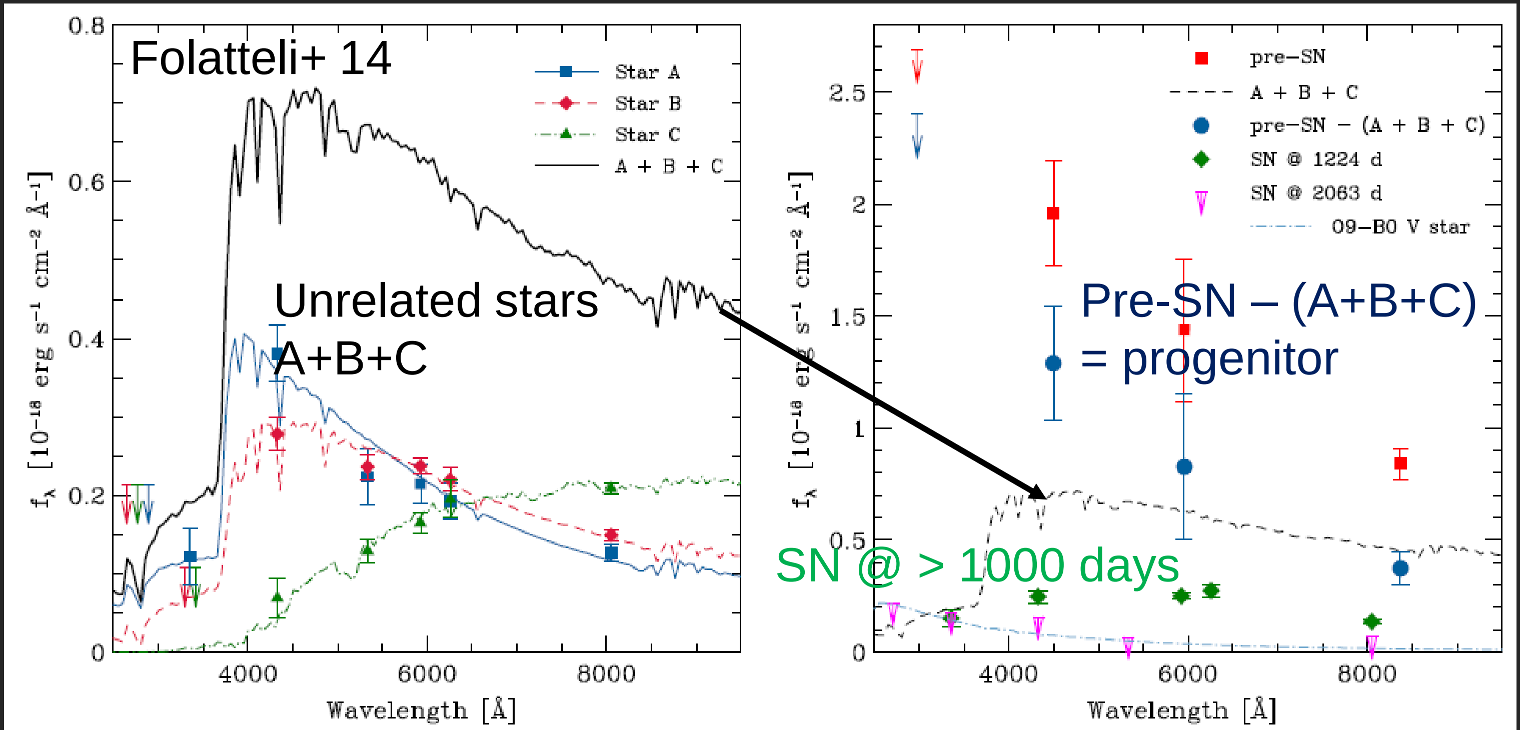
"Classical" YSG:
Expanding ***rapidly towards red supergiants*** after leaving the main sequence, spending ***only a few thousand years in that phase***.

(Originally) not considered as a "SN progenitor", but most of IIb progenitors.

BSG progenitor: SN 2008ax



Pre-SN point source (Crockett+ 2008) indeed consists of multiple stars (need for deep post-SN disappearance image).
SN had faded below the “progenitor“ flux
⇒ **Blue Supergiant progenitor.**

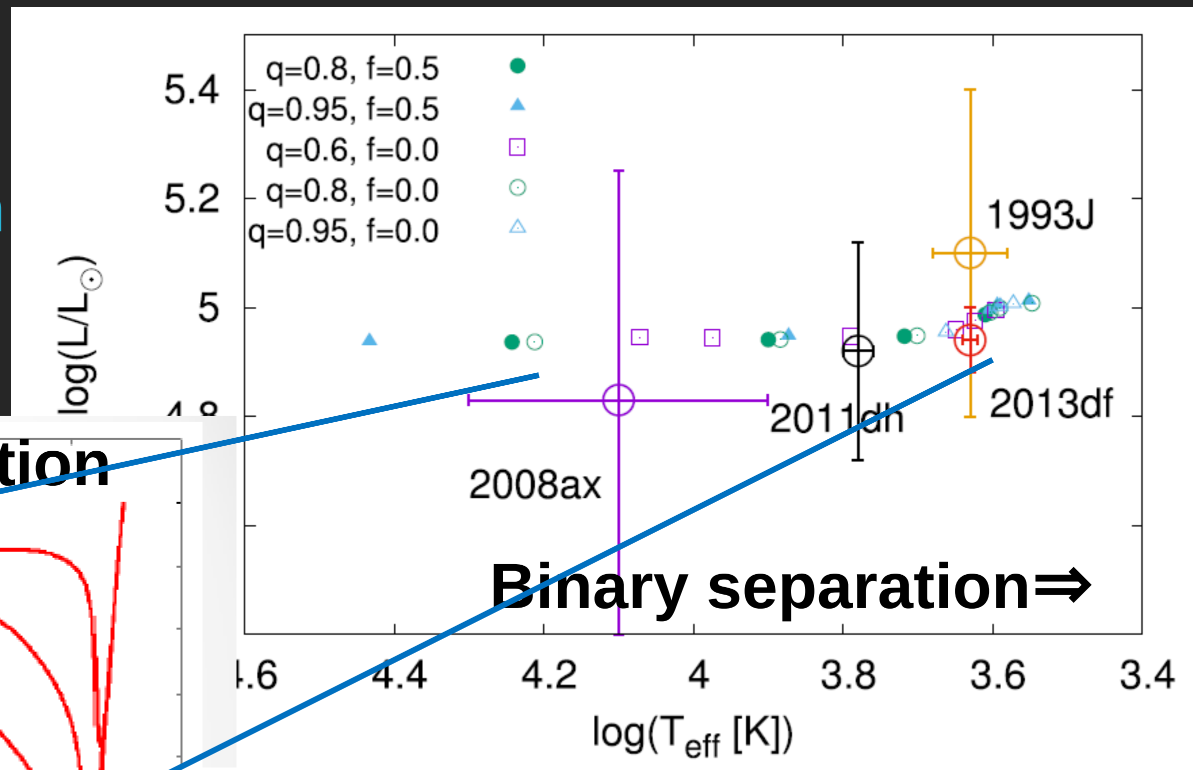


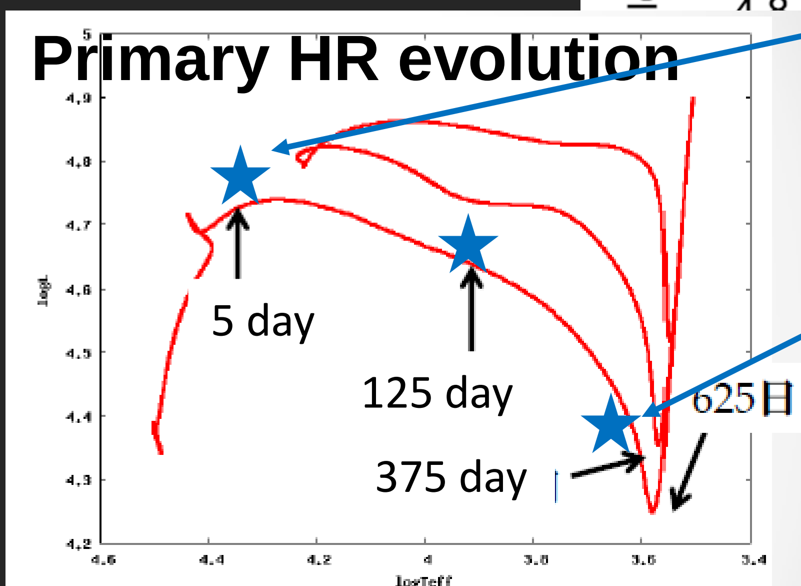
Binary Evolution Model: Progenitors

“Standard” binary models naturally explain/predict the diversity in the progenitors.

- Roche lobe
- No common env.
- Non-deg. companion

Ouchi & KM 2017



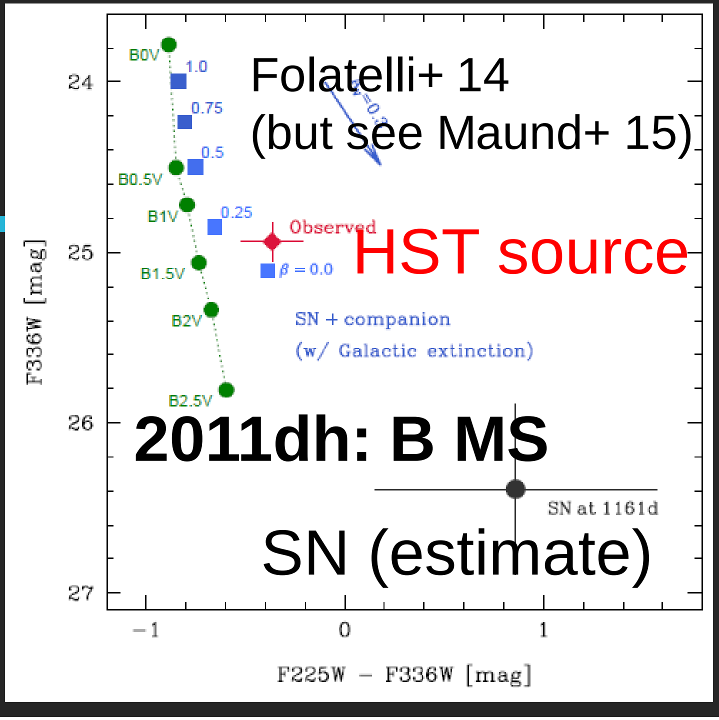


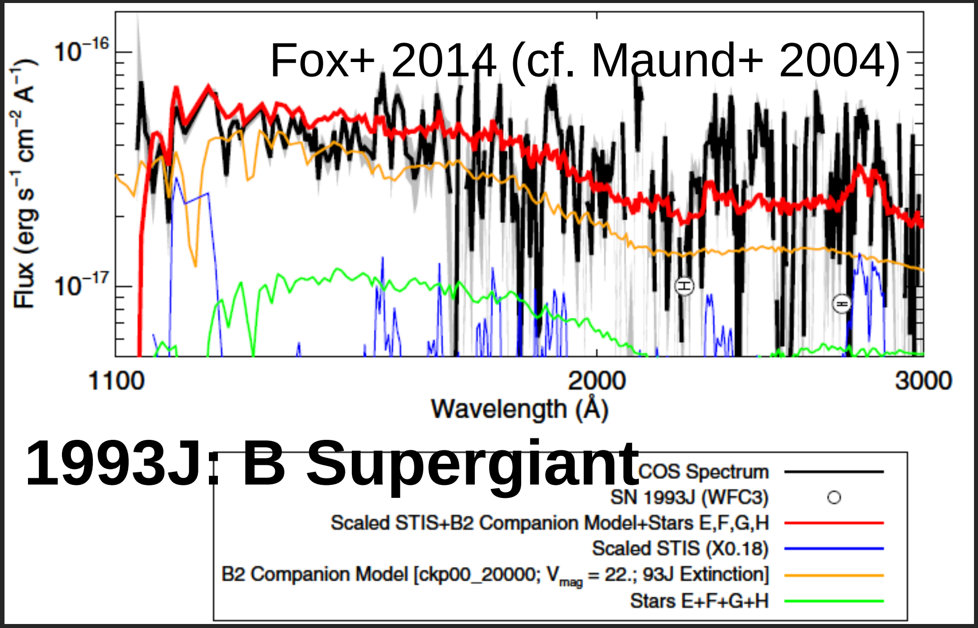
Variation controlled by initial separation:
See also Yoon+, Benvenuto+, Eldridge+.

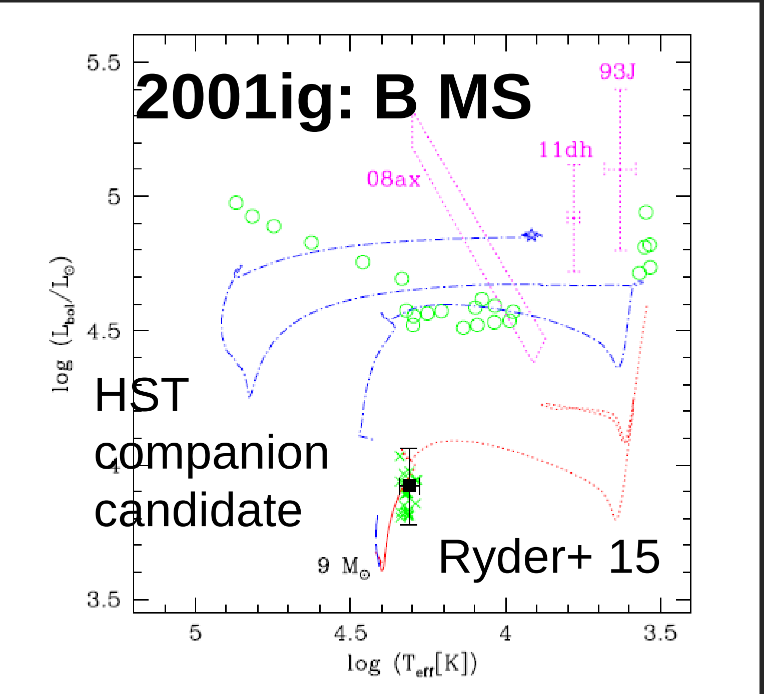
Companion (candidates)

Binary predictions: O/B companion (mass transfer should be there)

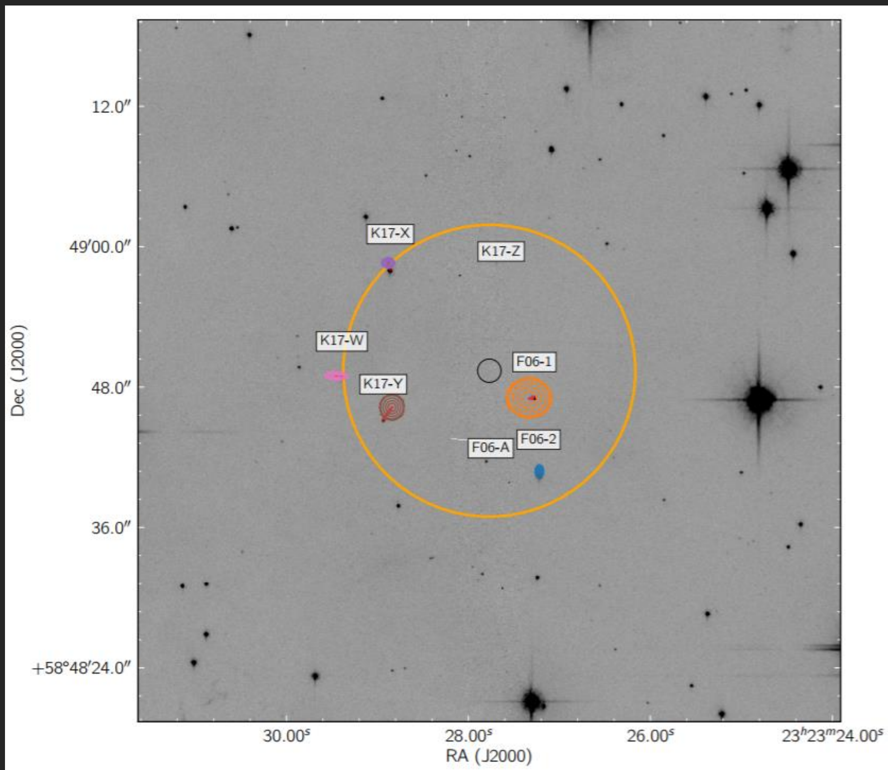
Companion candidates commonly seen (at least no negative evidence, except for one object…)

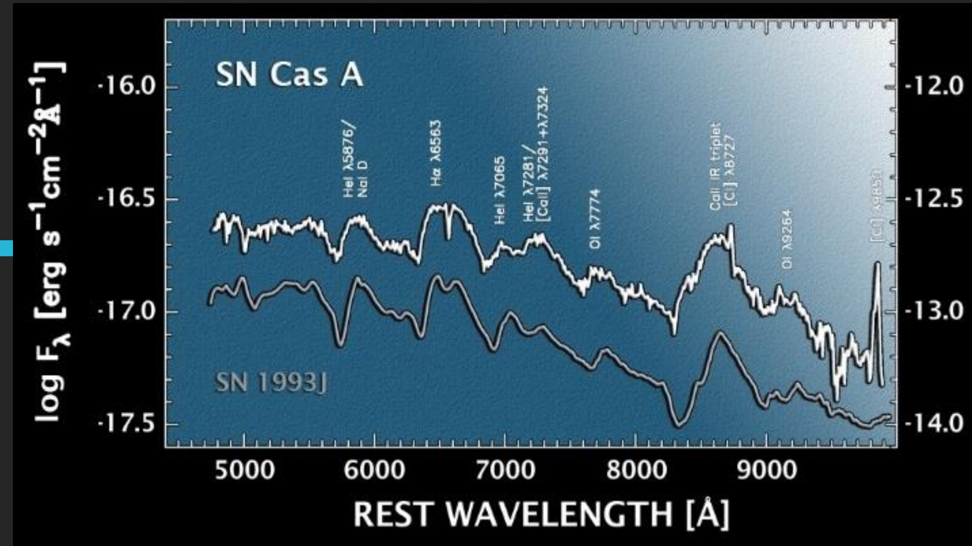






A big issue – Cas A





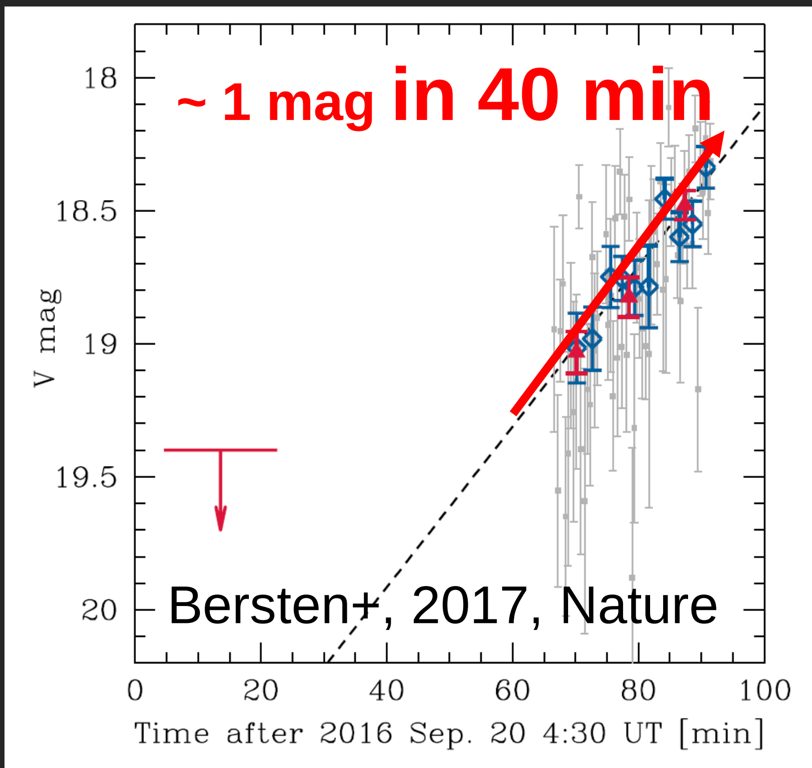
	A_V=10.6 mag	A_V=15 mag
Main Sequence companion	below M0	below K5
Stripped Stars	not allowed	
White Dwarfs	allowed	
Single Star	Stars with $> 30M_\odot$ exist in the neighbourhood	
Disrupted binary	allowed	
Pre-explosion Merger	allowed	
Neutron Star	allowed	
Black hole	allowed	

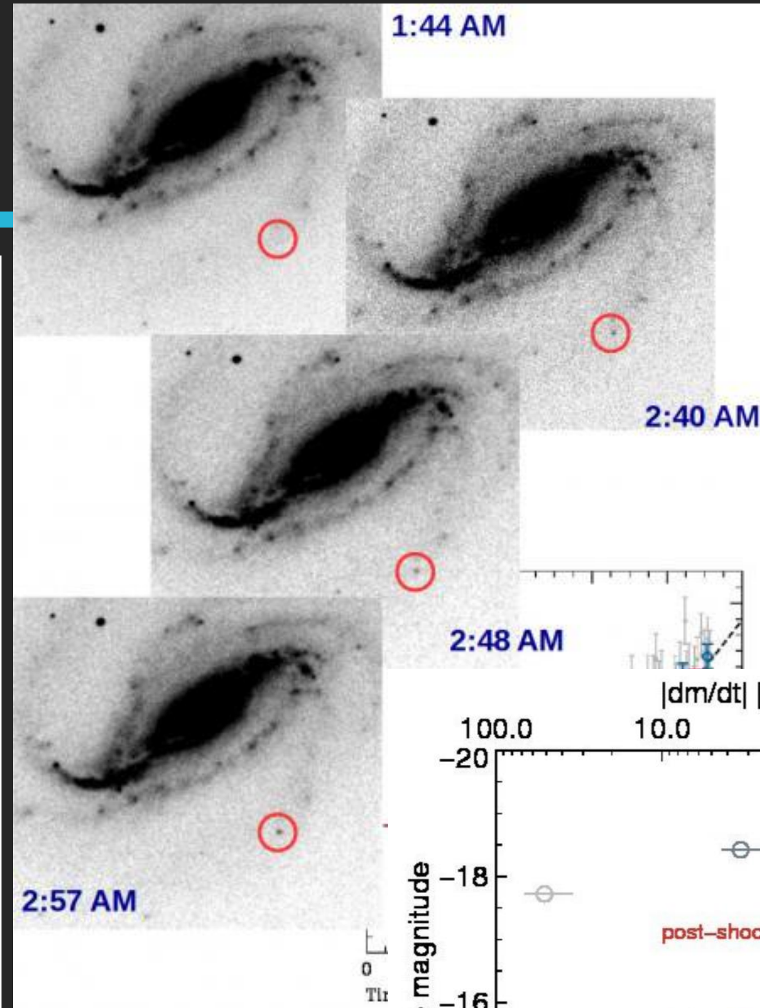
Table 4: Progenitor scenarios that are not ruled out by the presented data for two estimates of extinction

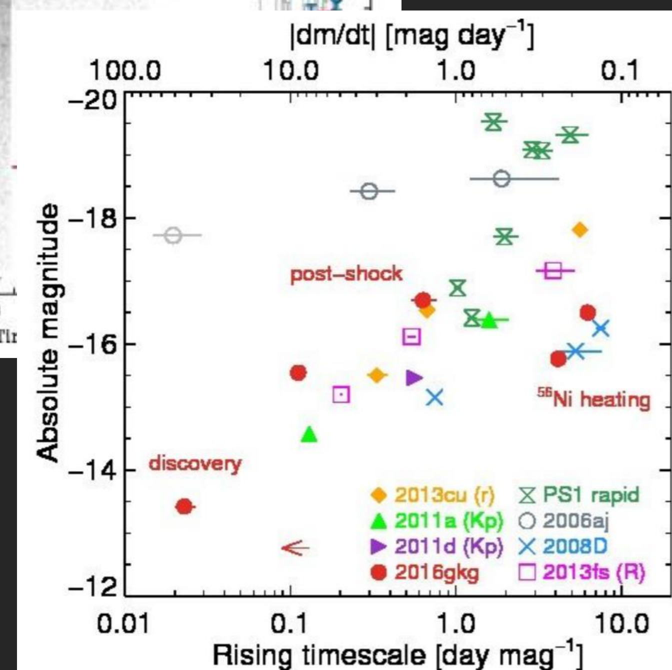
No bright companion detected.
Deep upper limit.

Kerzendorf+ 17, Kochanek 17

Shock breakout





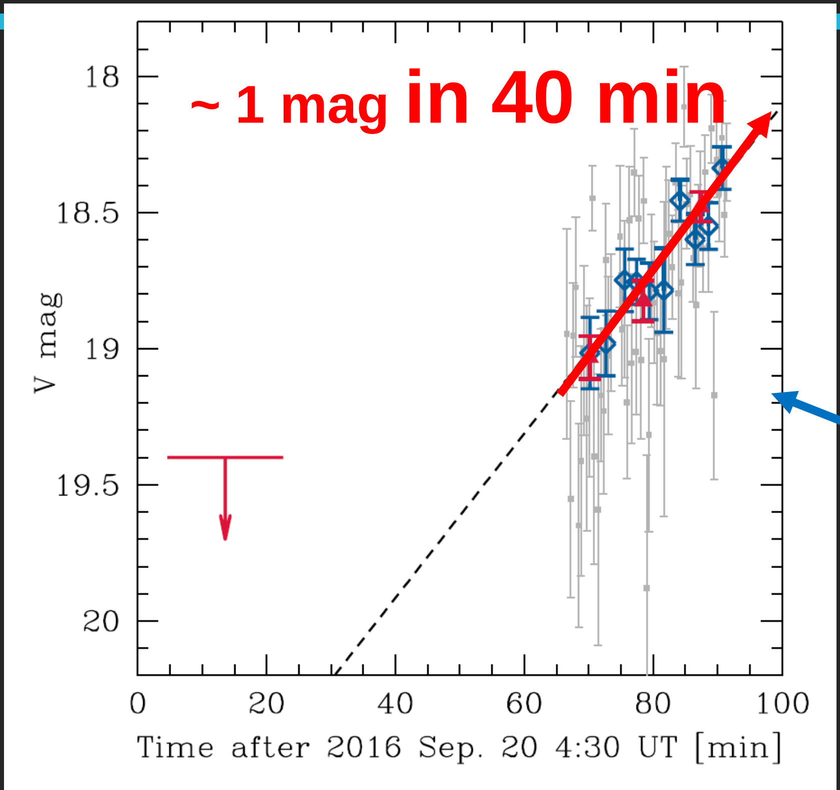


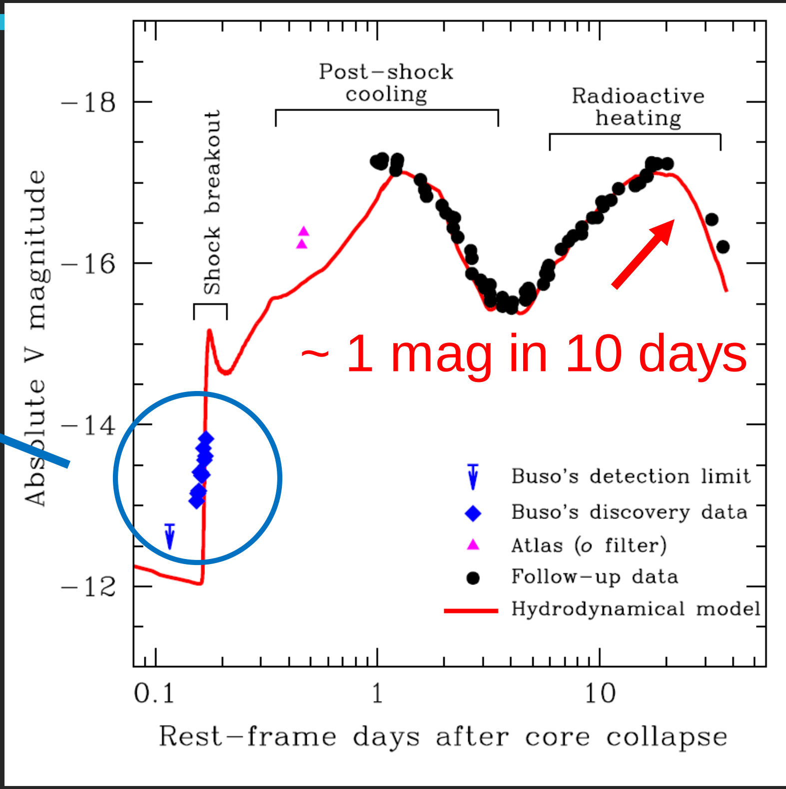
An armature's discovery by luck.

Extremely fast rise: ~ 1 mag in 40 min

(⇔ ~ 1 mag in 10 days in SN peak, even faster than the post-breakout "cooling").

Confirming the basic picture of breakout





Estimated progenitor:

He core ~ 5 $M_\odot$, H env.~ 0.1$M_\odot$, R~300$R_\odot$, M_{ms}~20$M_\odot$

Consistent with the detected progenitor candidate.

Confirming the basic mechanism of the SB.

(but could be some CSM: ~ 6 x 10^{-4} $M_\odot$/yr in the final hrs?)

Progenitor radius

days

“post-breakout cooling: Shock-deposited energy”

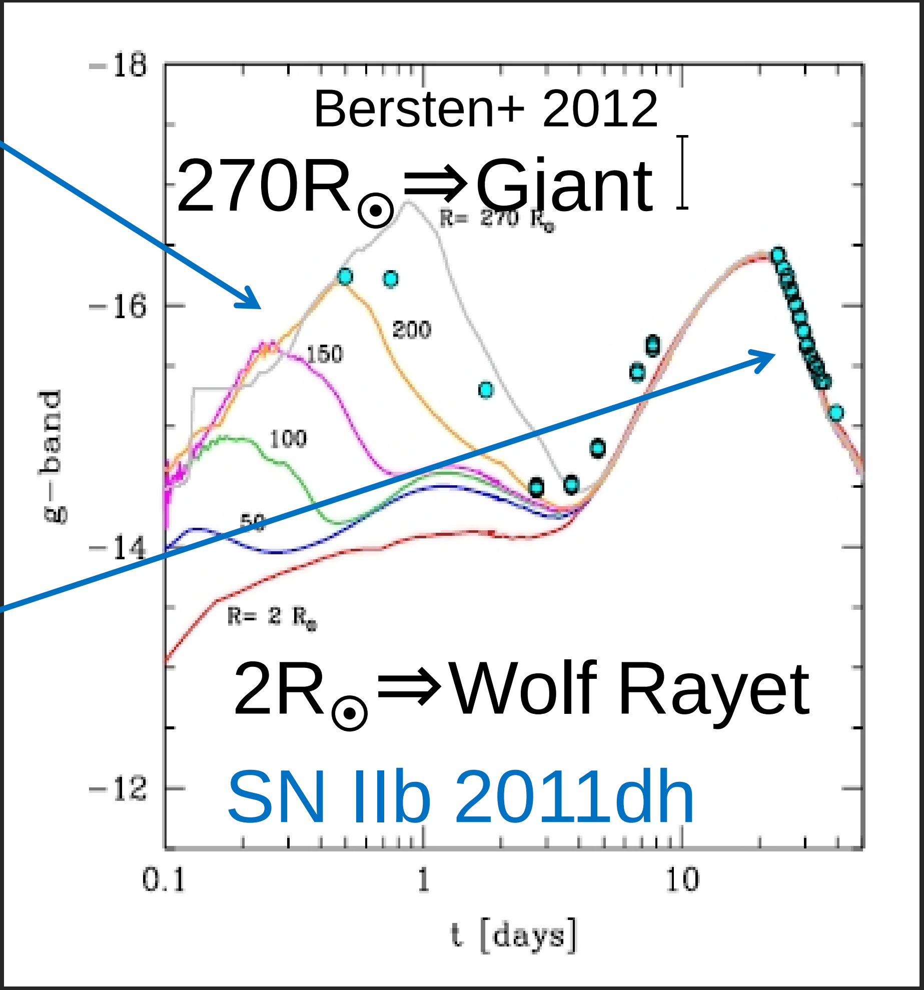
$T \propto (Vt/R_0)$

Brighter for larger

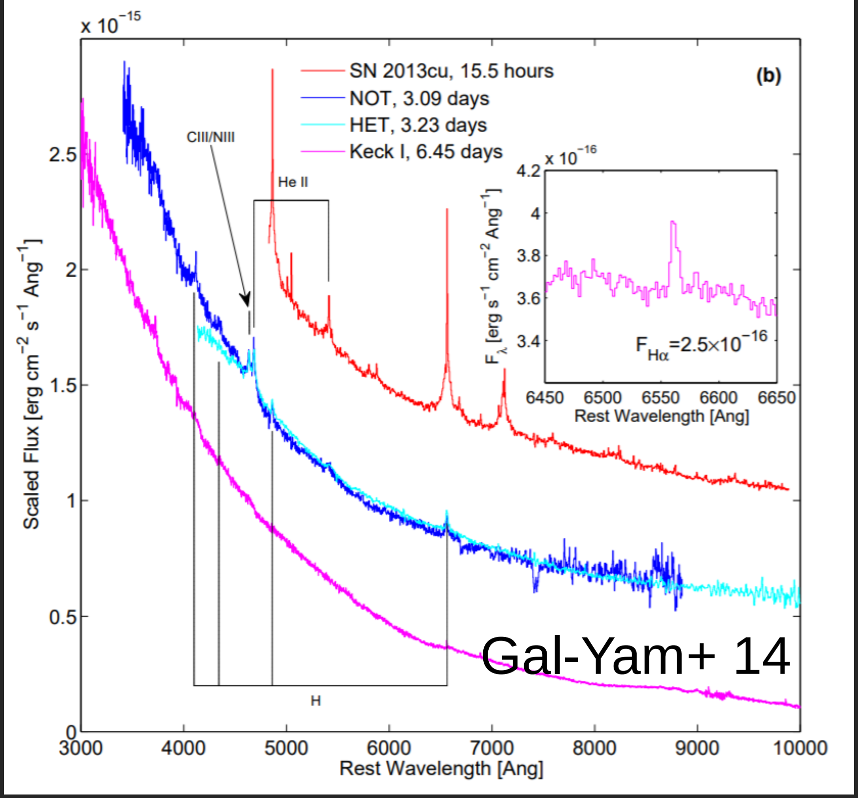
weeks

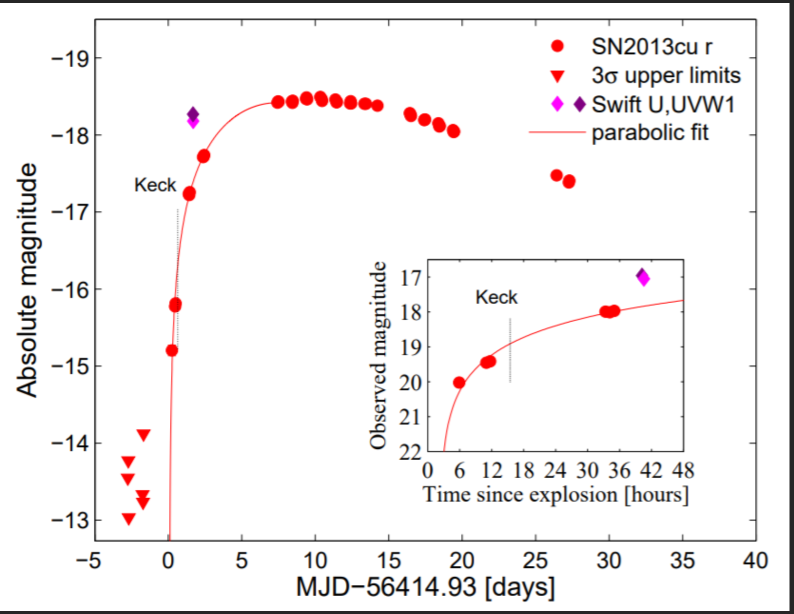
“^{56}Ni-heating”

No information on the progenitor radius



Enhanced mass loss in the final decades?





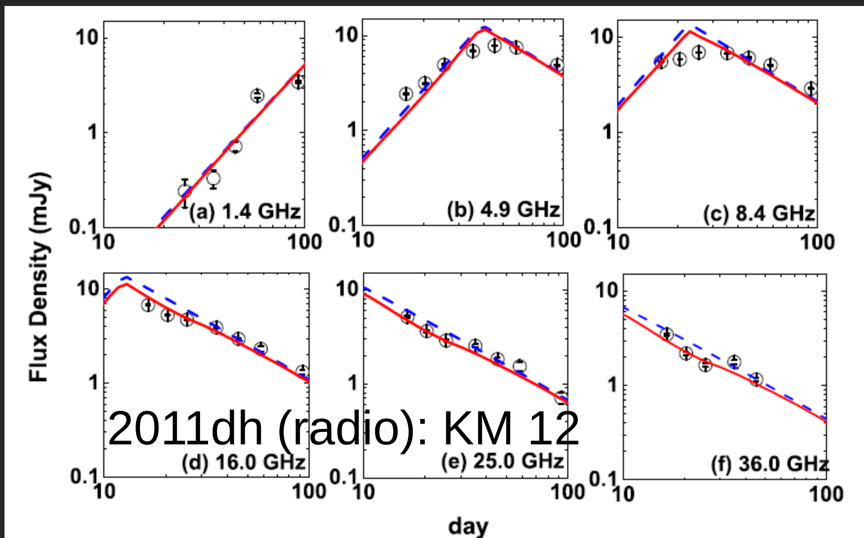
~ $3 \times 10^{-3} M_{\odot}$/yr (100 km/s); Groh 14

The first "flash spectroscopy" as reported for SN IIb 2013cu.
Follow-up samples all for SNe II (Yaron+ 17, Khazov+ 17, …).

Simply bias? (other SNe IIb spectra after > 2 days)

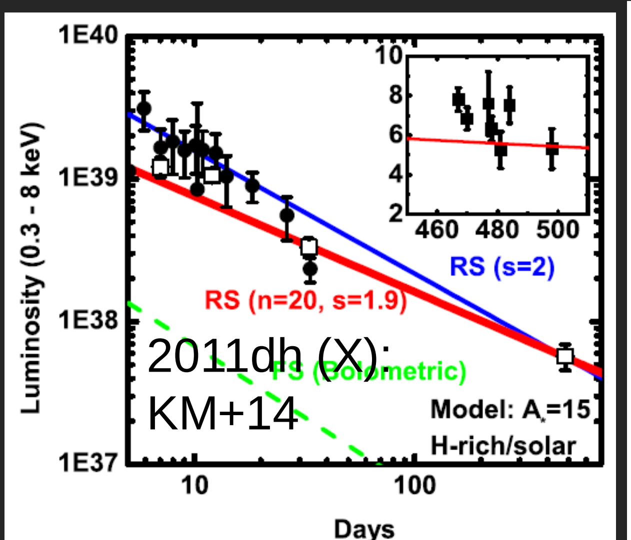
⇒ need more "first 24hrs" for SESNe.

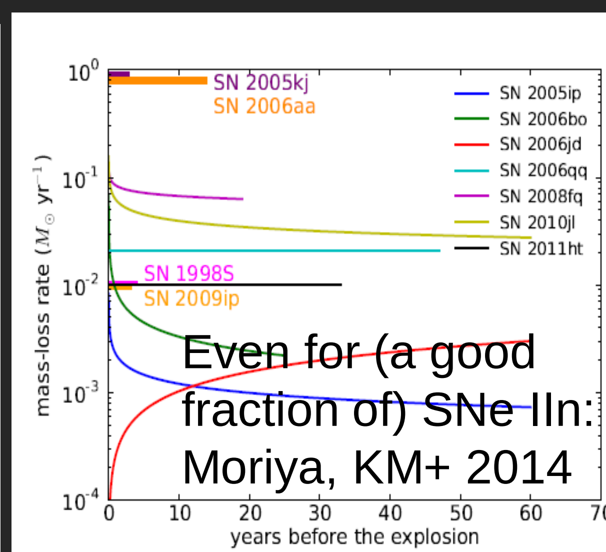
"Smooth" mass loss in the larger scale



Even for SNe Ib/c: Chevalier+Fransson 06

Supernova	α	β	Age (days)	References
1983N	−1.0	−1.6	30 – 300	1
1984L	−1.0	−1.5	100 – 200	2
1990B	−1.1	−1.3	70 – 200	3
1994I	−1.0	−1.3	20 – 800	4
2001ig	−1.06	−1.5	70 – 700	5
2002ap	−0.9	−0.9	4 – 20	6
2003L	−1.1	−1.2	100 – 400	7
2003bg	−1.1	−2	60 – 1000	8

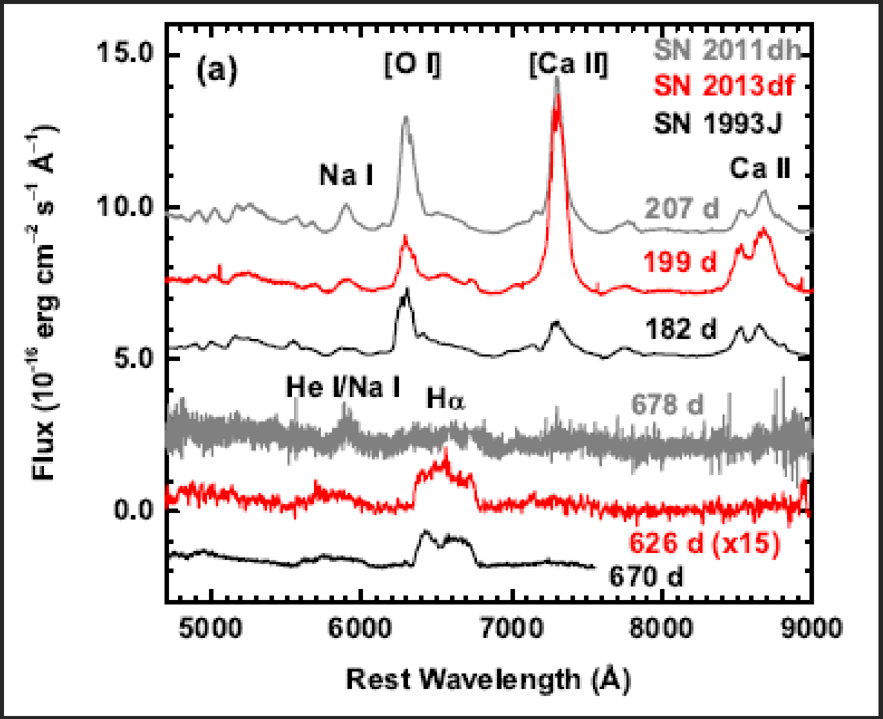


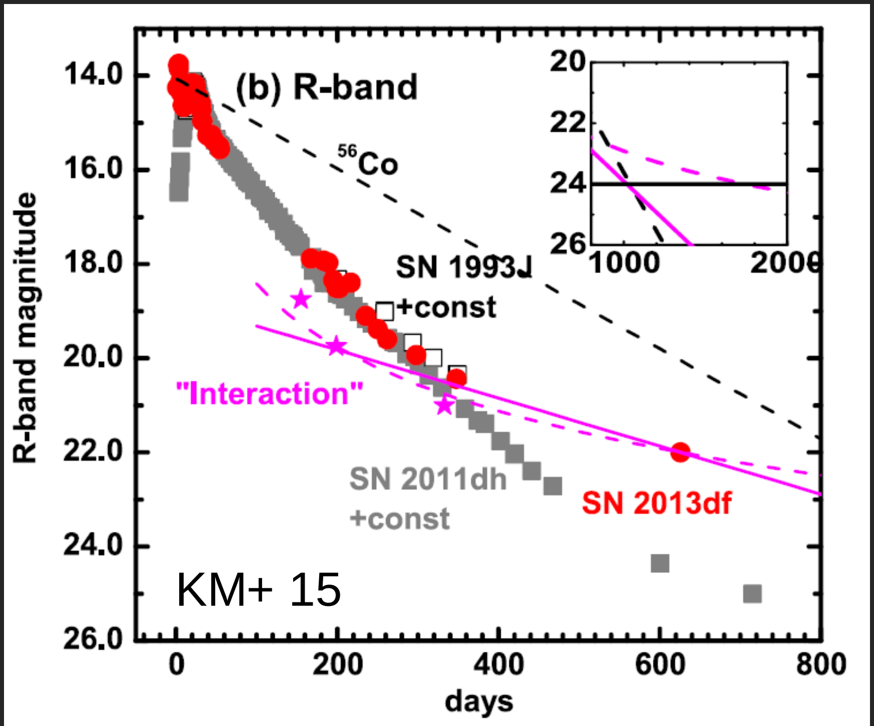


Some Modulations (e.g., Wellons+ 12) and outliers, but largely follow ~ r^{-2}.

Smooth mass-loss responsible for the stripping, or a sequence of eruptions in ~ 1000 yr timescale?

SNe IIb w/ strong late-time CSM interaction



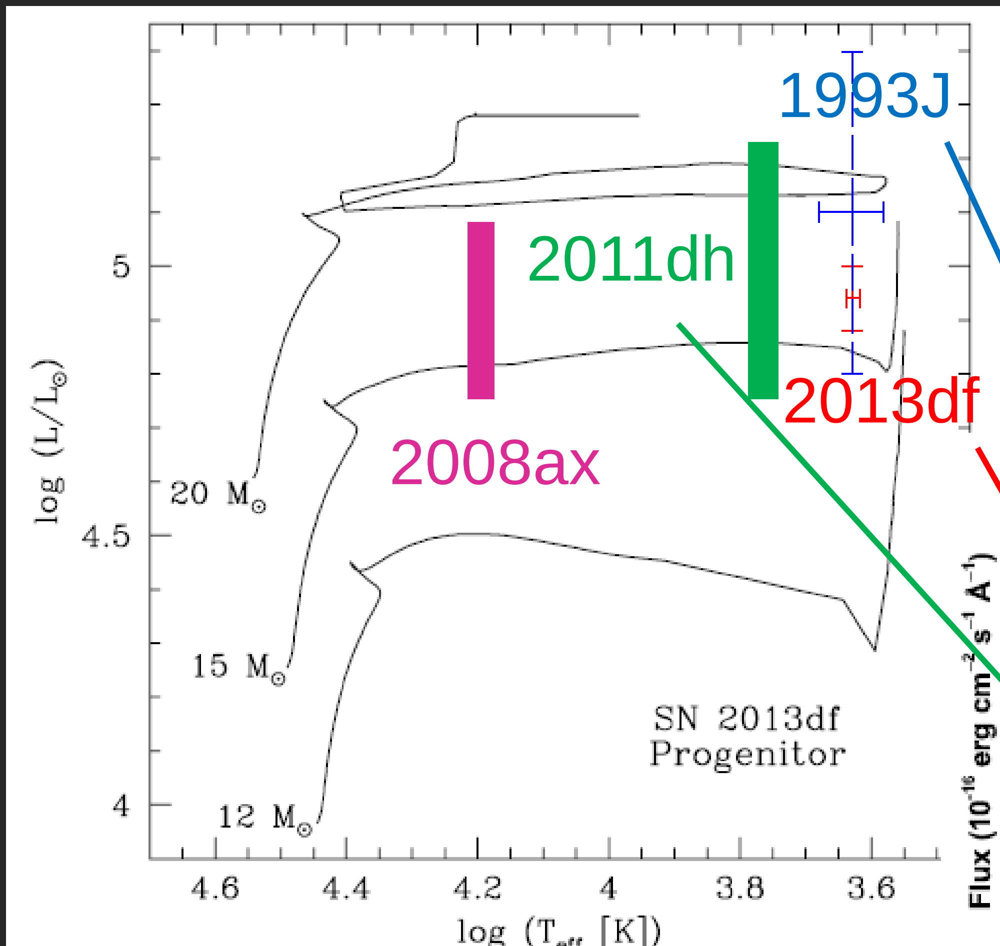


SNe IIb 1993J & 2013df: CSM interaction visible at ~ 1 year.
It is consistent with the smooth r^{-2} distribution.

For their CSM density, CSM becomes dominant @ ~ year.

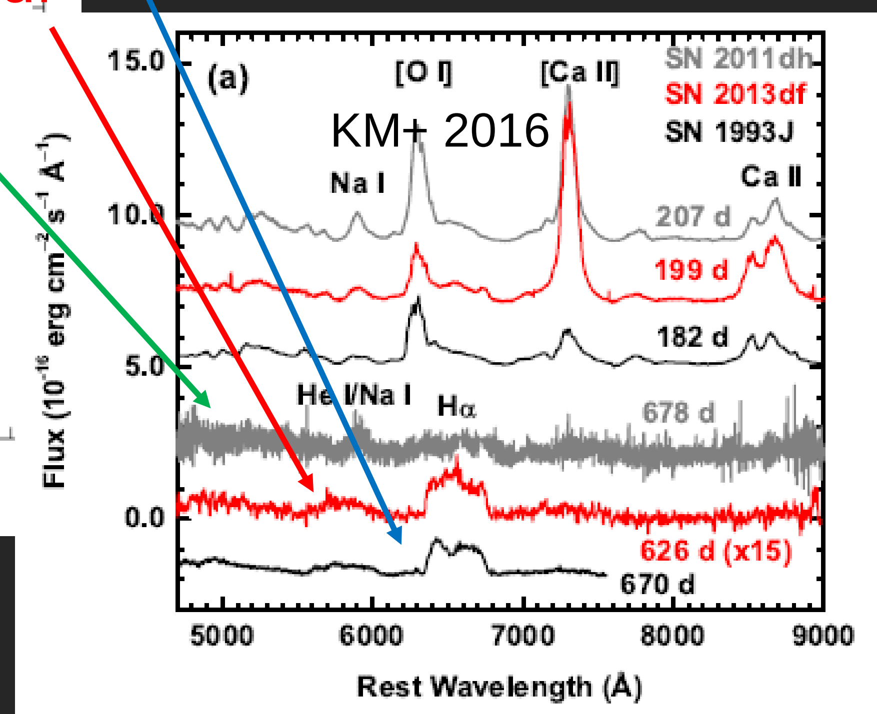
Radio is smooth, no strong variation (≠ eruption).

Progenitor HR vs. CSM (in the last 100 yrs)

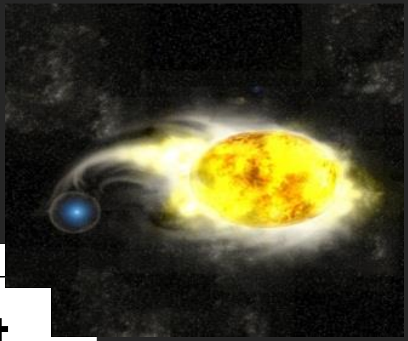


Hα from SN-CSM interaction @ ~ 1 yr

Extended progenitor = massive CSM (mass loss)



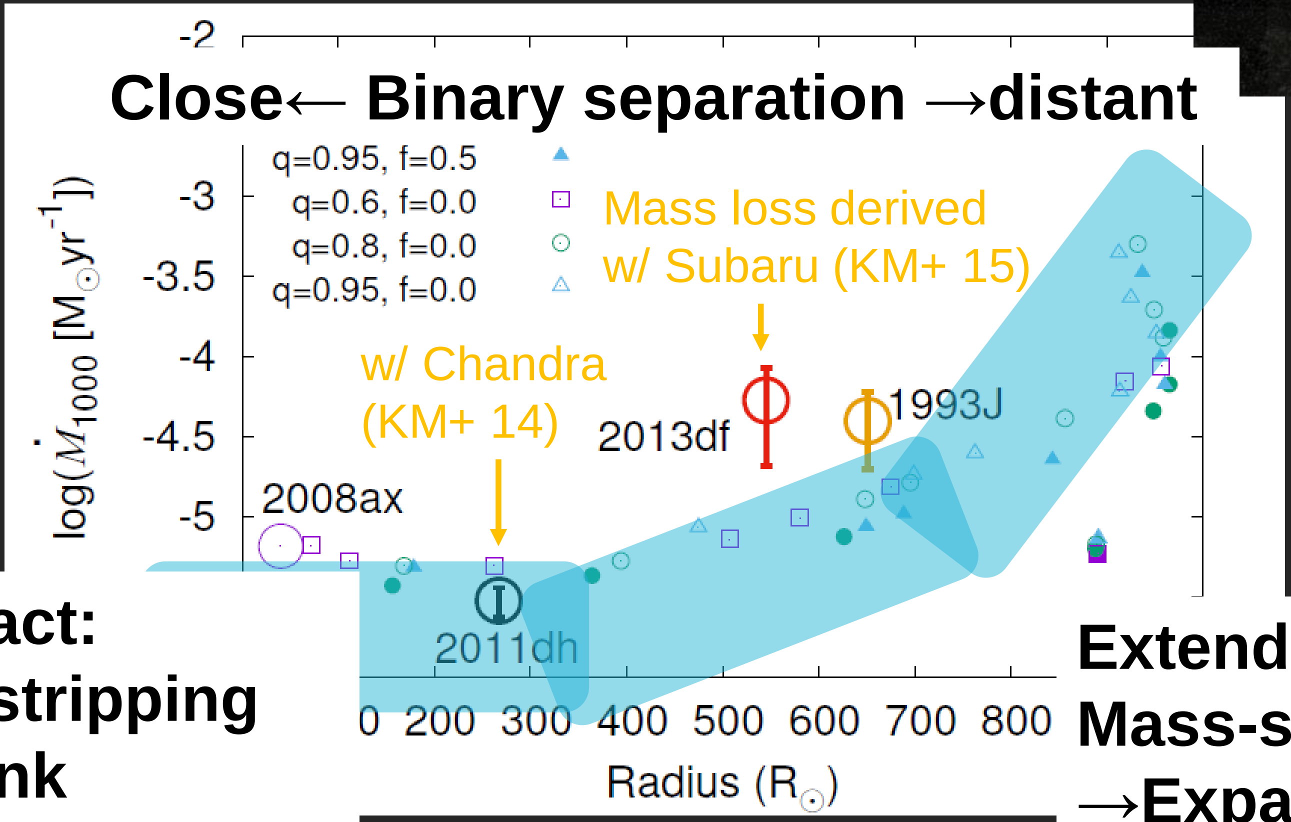
Ouchi & KM 17



Binary Evolution Model: CSM

Progenitor R vs. mass loss

Close← Binary separation →distant



Compact: Mass-stripping →Shrink

Extended: Mass-stripping →Expand

Binary does predict

1. Diversity in progenitor radius (different H-stripping)
2. the R - mass loss relation (in the last 100 yrs).

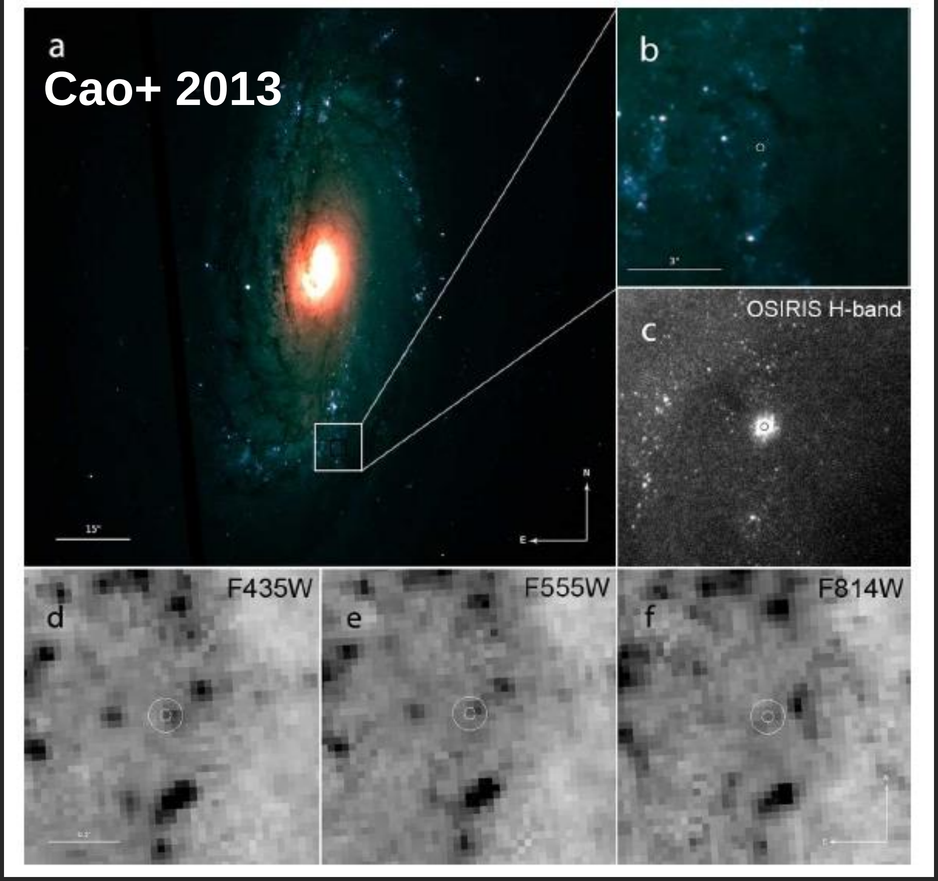
A candidate progenitor of SN Ib

Direct detection difficult (expected progenitor too blue).
The first detection of a candidate in 2013: iPTF13bvn

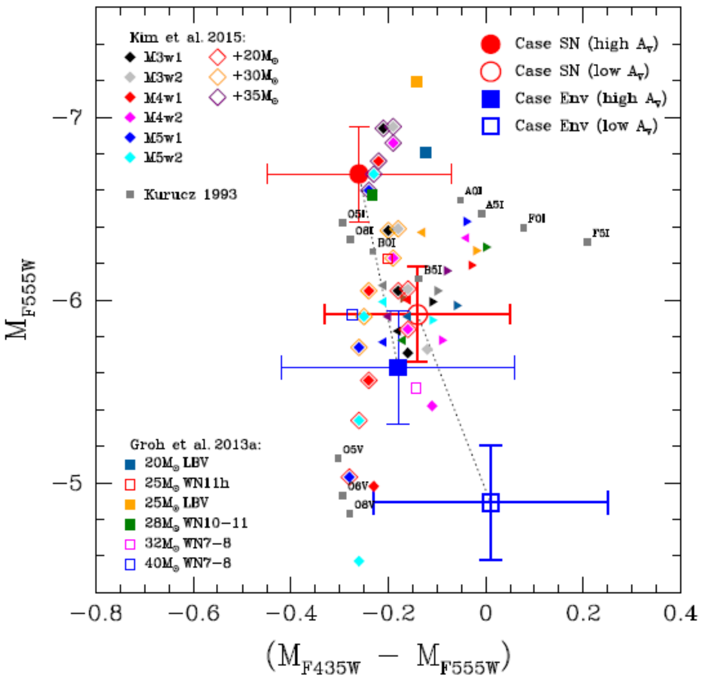
Massive Wolf-Rayet?
($M_{ms} > 20M_{\odot}$) (Cao+ 13)

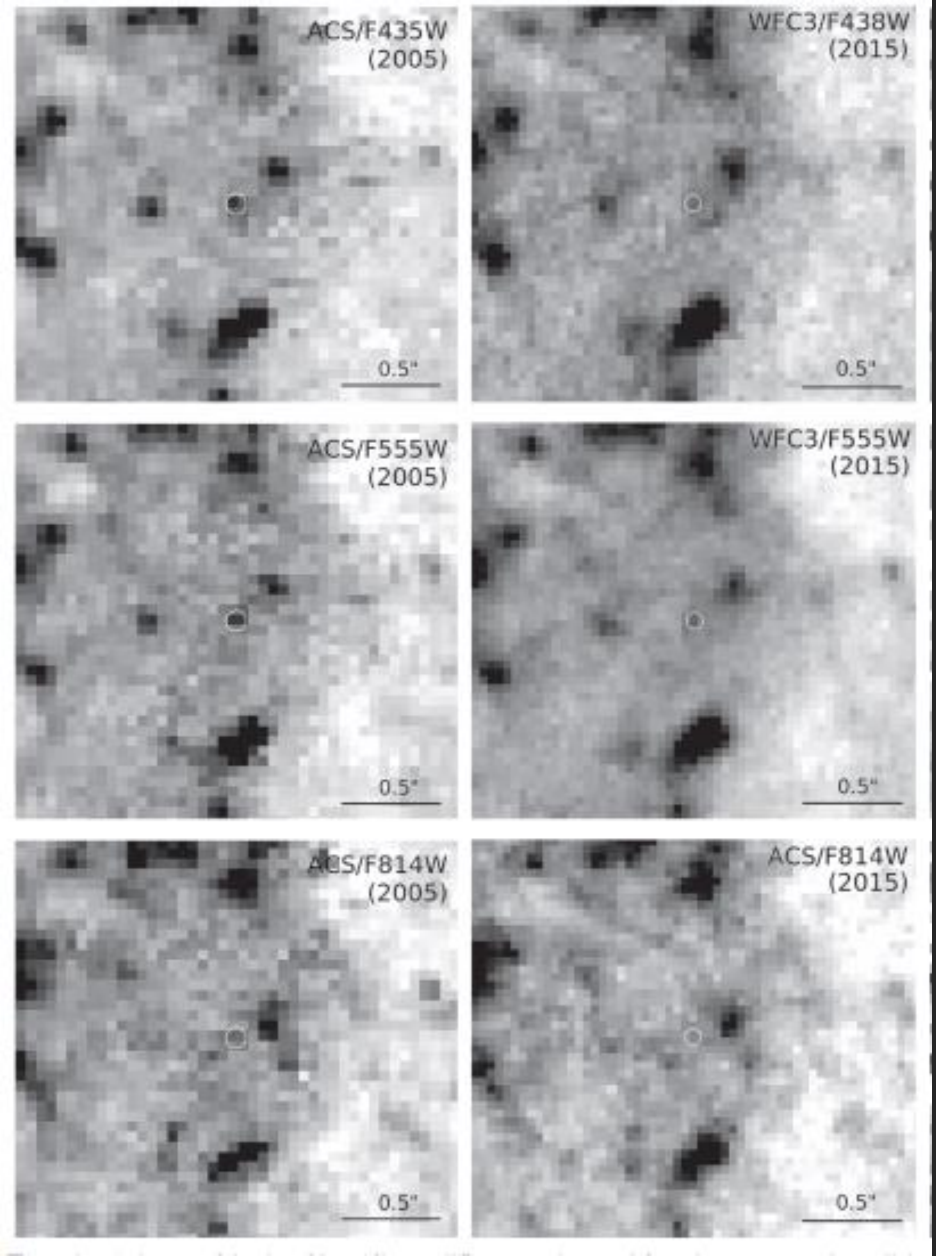
SN emission indicates a compact progenitor, but less massive
(e.g., Bersten+14, Kuncarayakti+ 14).

Controversy?



SN Ib iPTF13bvn





HST observation at ~2 yrs.

Progenitor gone.

Revised phot.→less massive.

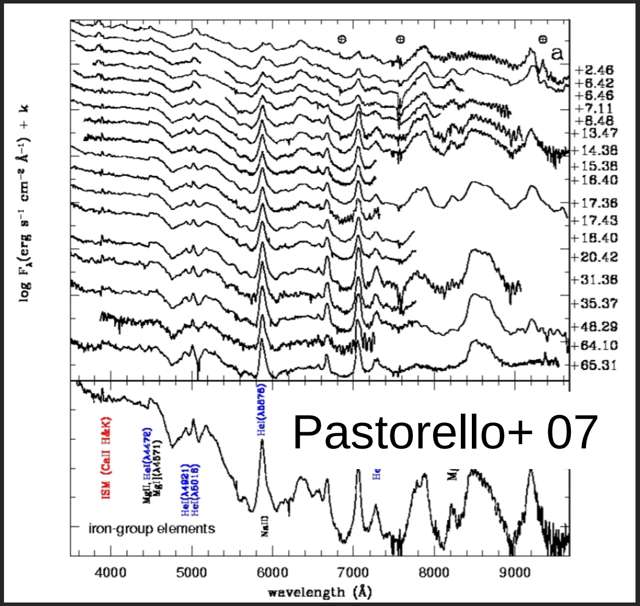
(Folatelli+ 16; Eldridge+Maund 16).

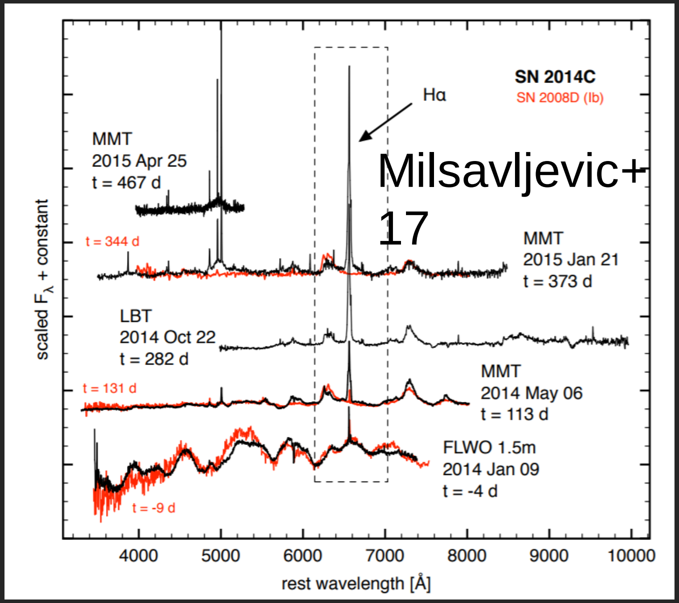
Consistent w/ binary, but

UV limit for a companion ($< 20M_\odot$)

Folatelli+ 2016

SNe Ib w/ strong CSM interactoin





SN "Ibn" 2006jc: He emission lines (He-rich CSM).

Pre-burst in 2004. SN Ibn "variety".

Some Ibn different than canonical SNe Ib? (e.g., Moriya+KM 16)

SN Ib 2014C: Strong Halpha developed at ~ 0.5 yr.

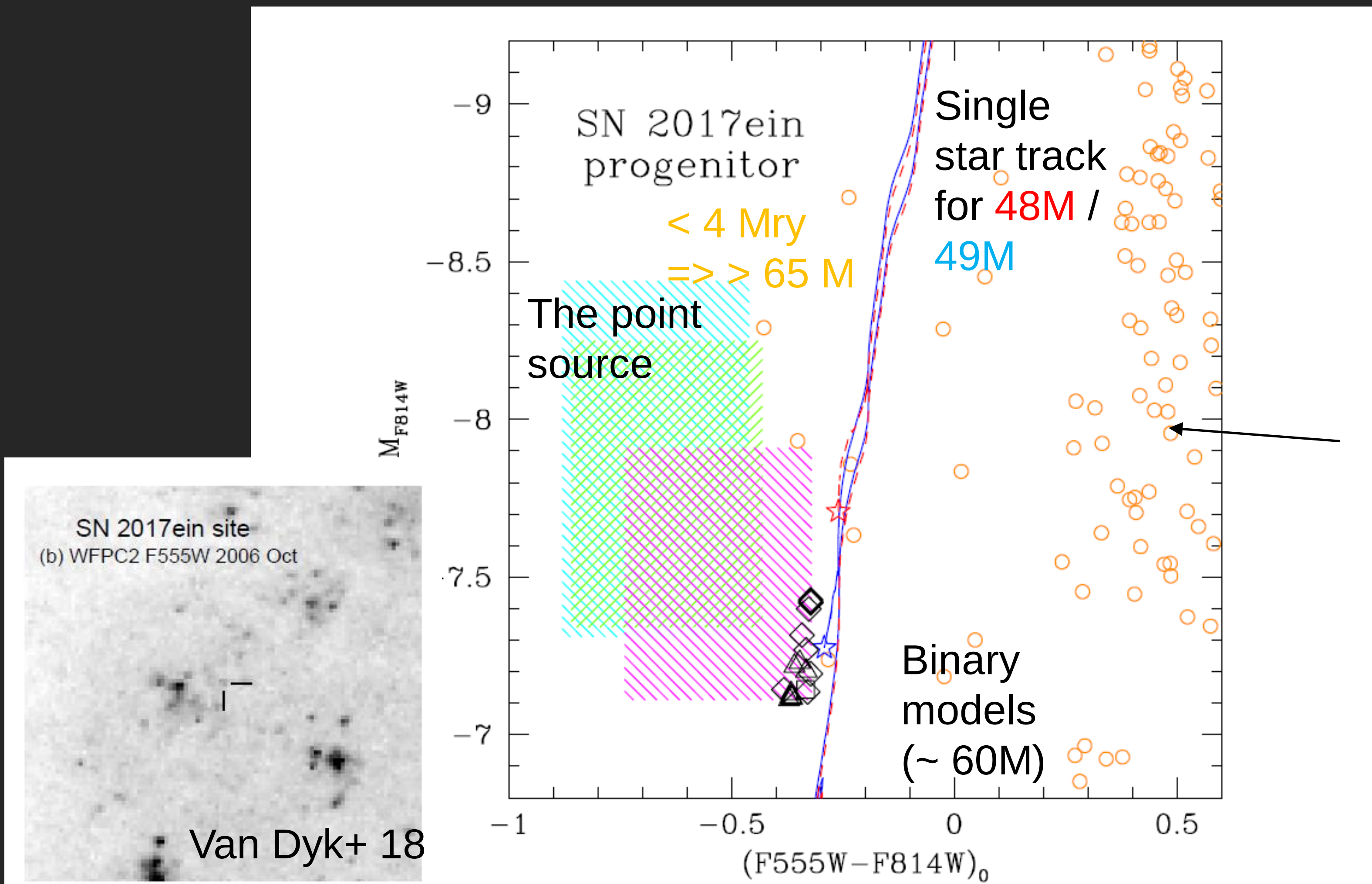
Cavity? Not like He-rich CSM.

More like normal, timing of "eruptions"? (Margutti+ 17)

SNe IIb ⇒ *Ib→IIn* ⇒ Ib ⇒ *Ibn* ⇒ Ic or different population?

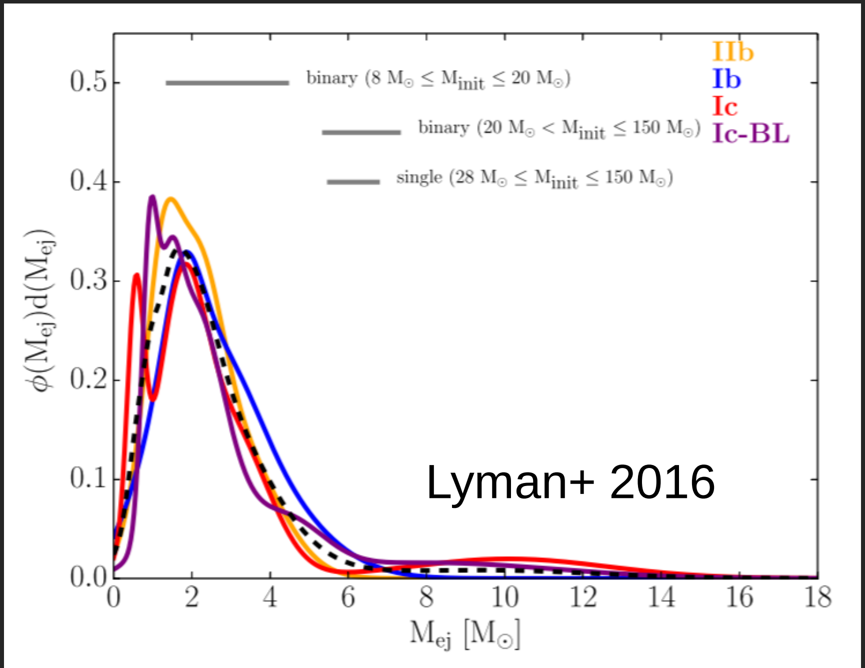
A (first) candidate progenitor of SN Ic

M_{ms} ~ 47-80$M_{\odot}$? (⇔a tension to a sample of SN Ic properties)



Stellar clusters in a similar galaxy M74

Real progenitor?



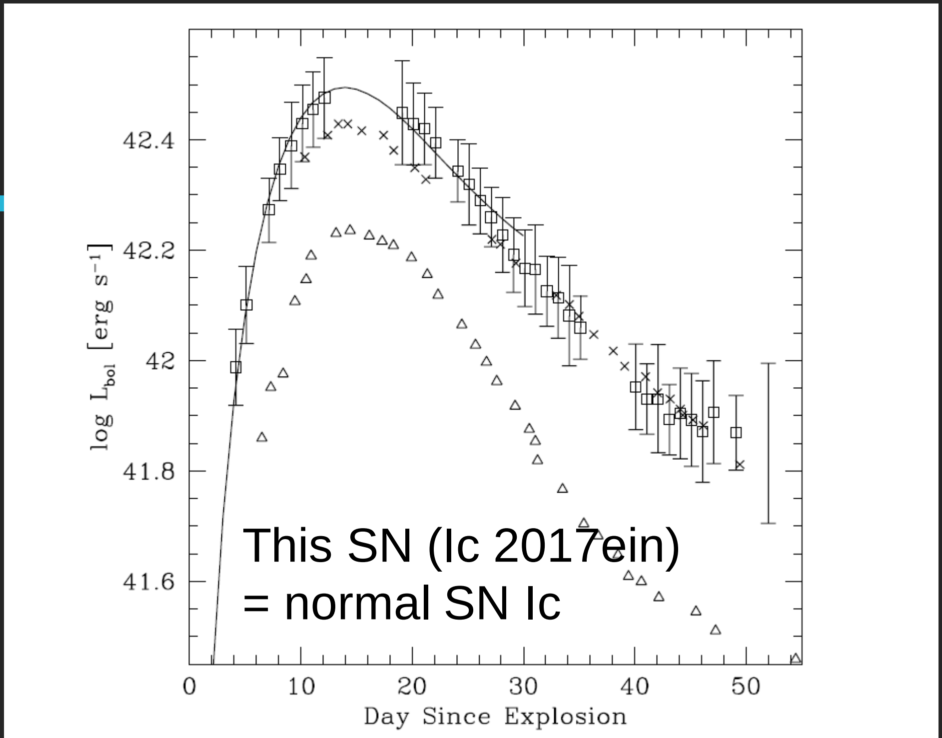
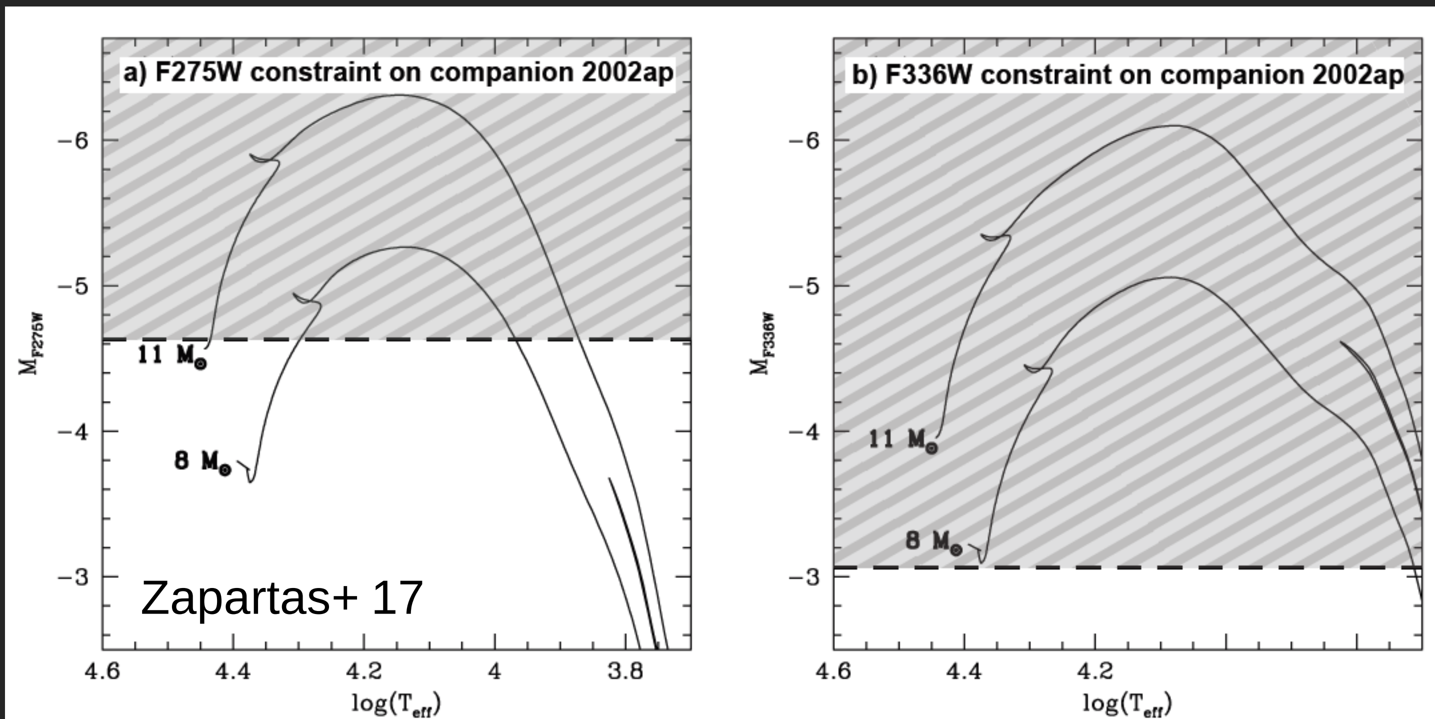


Figure 7. Quasi-bolometric light curve of SN 2017ein (open squares), assuming the bolometric corrections for SESNe from Lyman et al. (2014). The uncertainties shown with each data point arise primarily from the photometric measurements and from the uncertainties in the bolometric corrections. An error bar is also given, representing the additional uncertainty in both the reddening and the distance. For comparison we show the bolometric light curves for SN 2007gr (Hunter et al. 2009; Chen et al. 2014; open triangles) and SN 2004aw (Taubenberger et al. 2006; crosses). Additionally, we display the mean best-fit Arnett (1982) semi-analytical model (solid curve), powered by radioactive decay of ^{56}Ni and ^{56}Co.

"Optically-found" SNe Ib/c seem to have the ejecta of < $4M_\odot$.
If $M_{NS} \sim 1.4M_\odot$, $M_{CO} < 5\text{-}6M_\odot$ ($M_{ms} < \sim 25M_\odot$).
… But similar properties w/ other SNe.
More likely a less massive progenitor?
(cluster member or multiple stars? e.g., situation for 08ax).

An upper limit for companion of SN Ic 2012ap

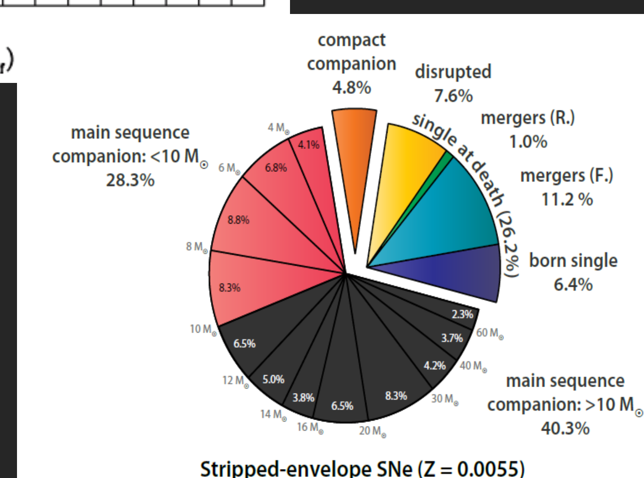


No good companion candidate detected for SNe Ib/c so far.

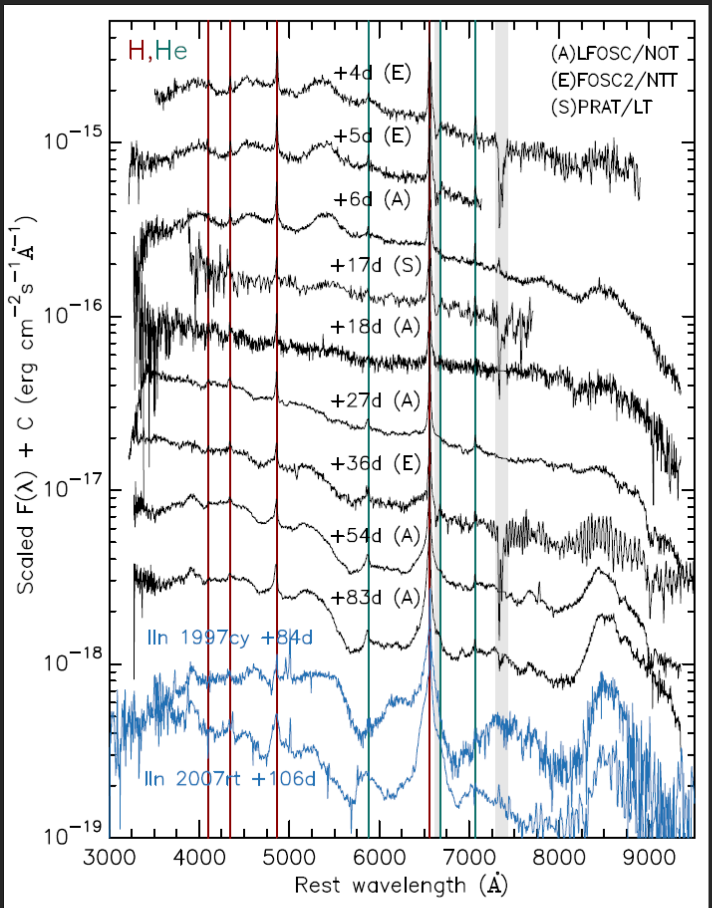
2012ap (Ic-BL): < ~10$M_\odot$ MS (Zapartzs+ 17)

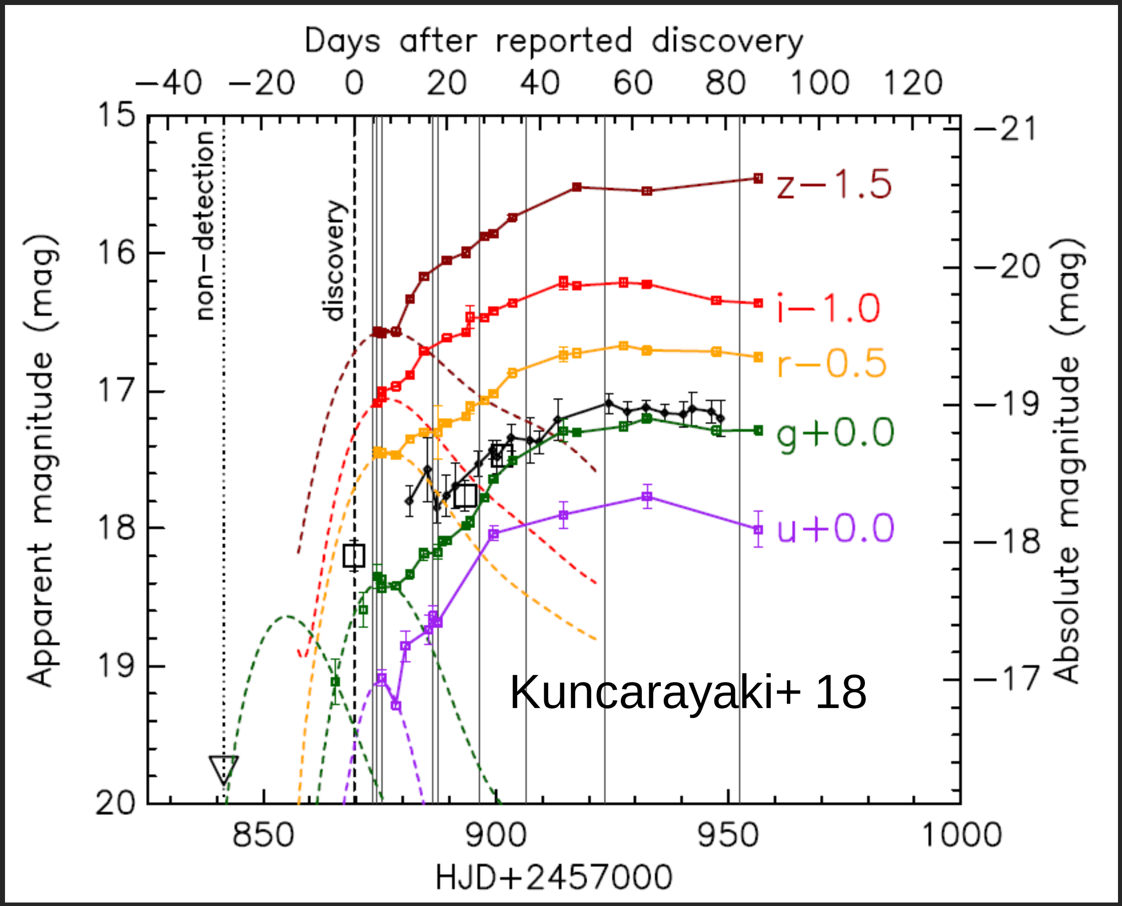
iPTF13bvn (Ib): < ~20$M_\odot$ MS (Folatelli+ 16)

Binary model survives; we need detection.



SN Ic w/ strong CSM interaction



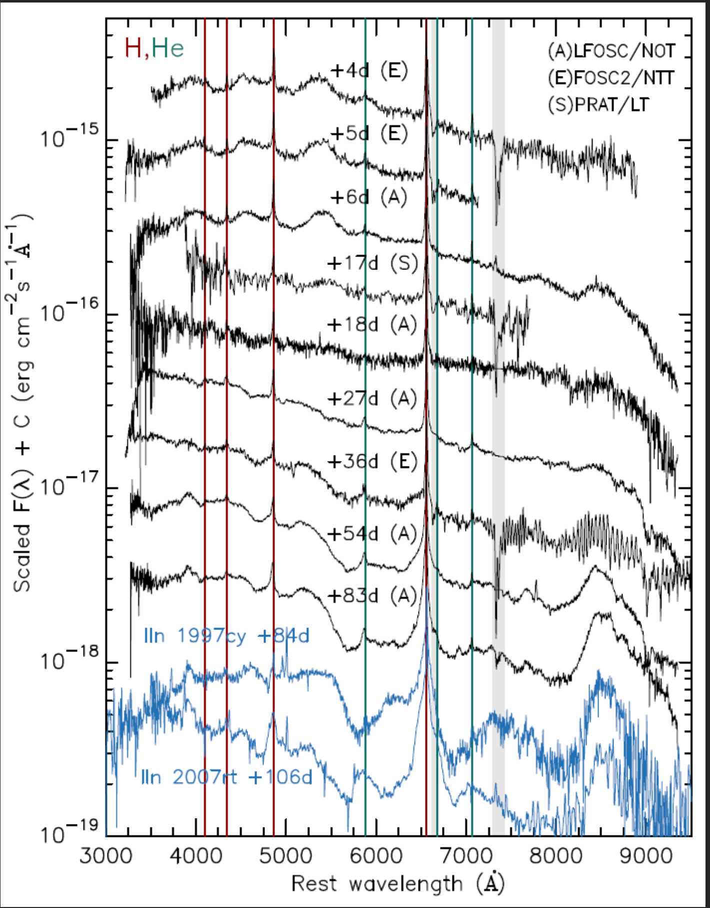


SN Ic 2017dio: Evolved into SN IIn in a month (Ic⇒IIn).

CSM increasing outward (not r^{-2}).

Some SNe IIn may host SNe Ic (WR, C+O).

SN Ic w/ strong CSM interaction



Not much mass between "SN Ic" and "H-rich CSM"
⇒ Where is He???
1. Revisit to the He-rich CSM interaction characteristics
But Ibn is there.
2. Perhaps binary companion
How the companion knows the primary is going to explode.
3. Otherwise, further unknown in the (single star) final evolution?
but not the "final" eruption.

And, how common is it? (could be abundant behind SNe IIn?)

Summary

- SNe IIb/Ib/Ic share similar properties as SNe (at least to the first order).
- Binary scenario well-developed for SNe IIb.
  - Progenitor, companion, mass loss.
  - Largely "smooth" CSM for the last ~ 10-1000 yrs.
  - No particular need of the eruption for the H-rich envelope stripping, but does not reject it.
- Less clear for SNe Ib/c; no strong argument against binary interaction scenario, but may require something else.
  - SN Ib ⇒ IIn may indicate a role of the eruption? Ibn???
  - SN Ic ⇒ IIn: further challenge, perhaps companion mass-loss important for SNe IIn.