Progenitors, Mass Loss, and Shock Breakout of Supernovae

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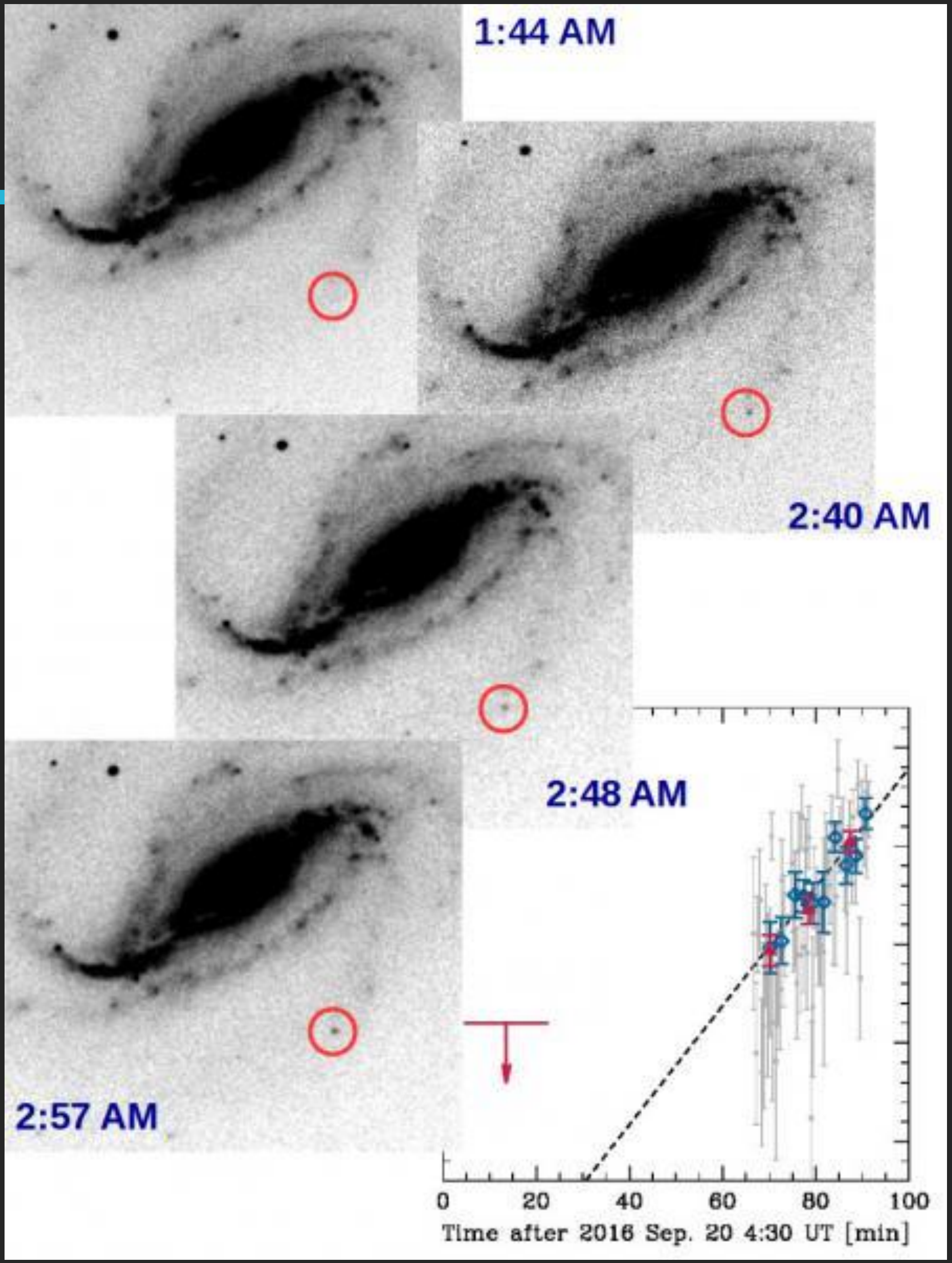
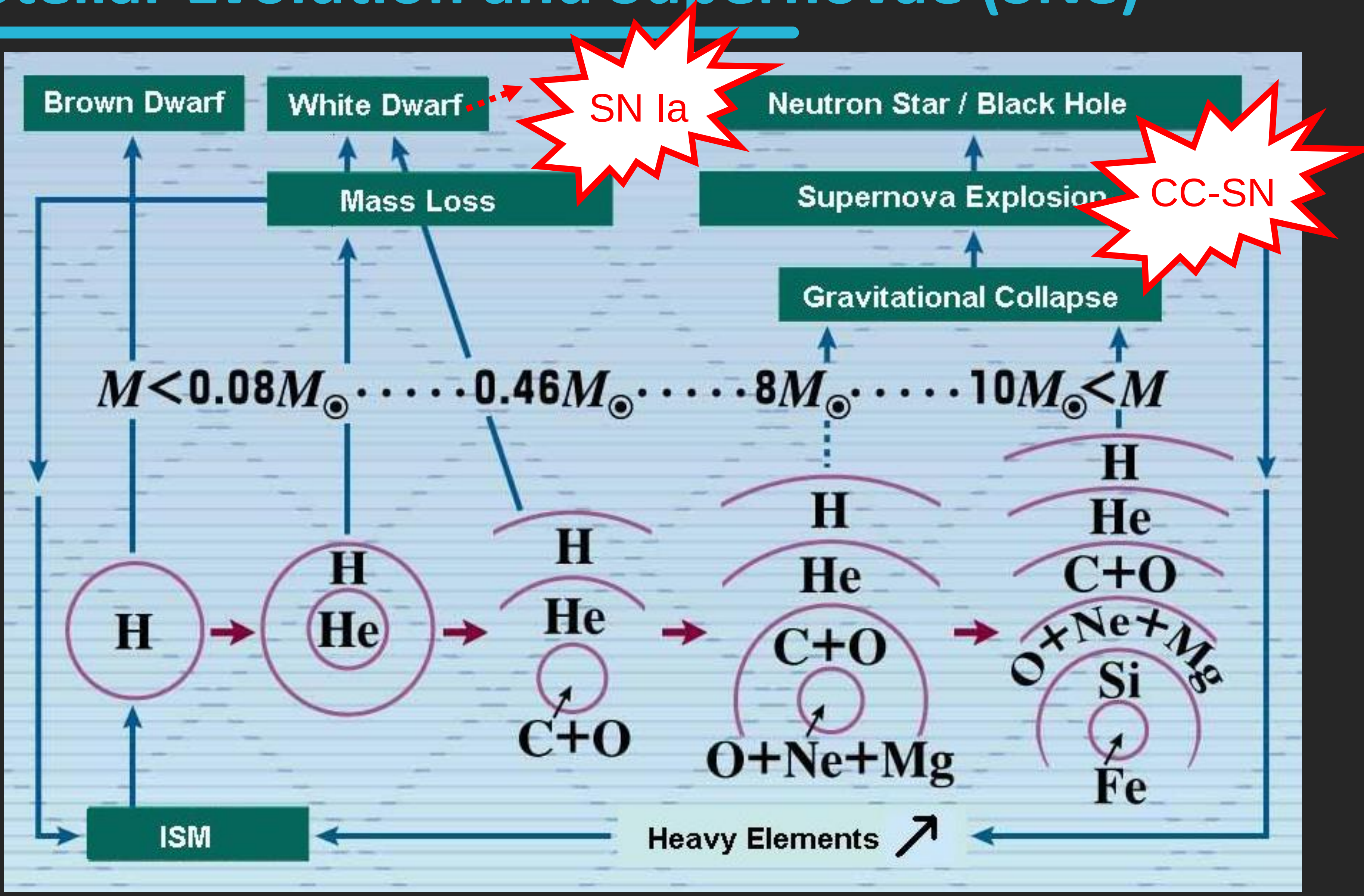
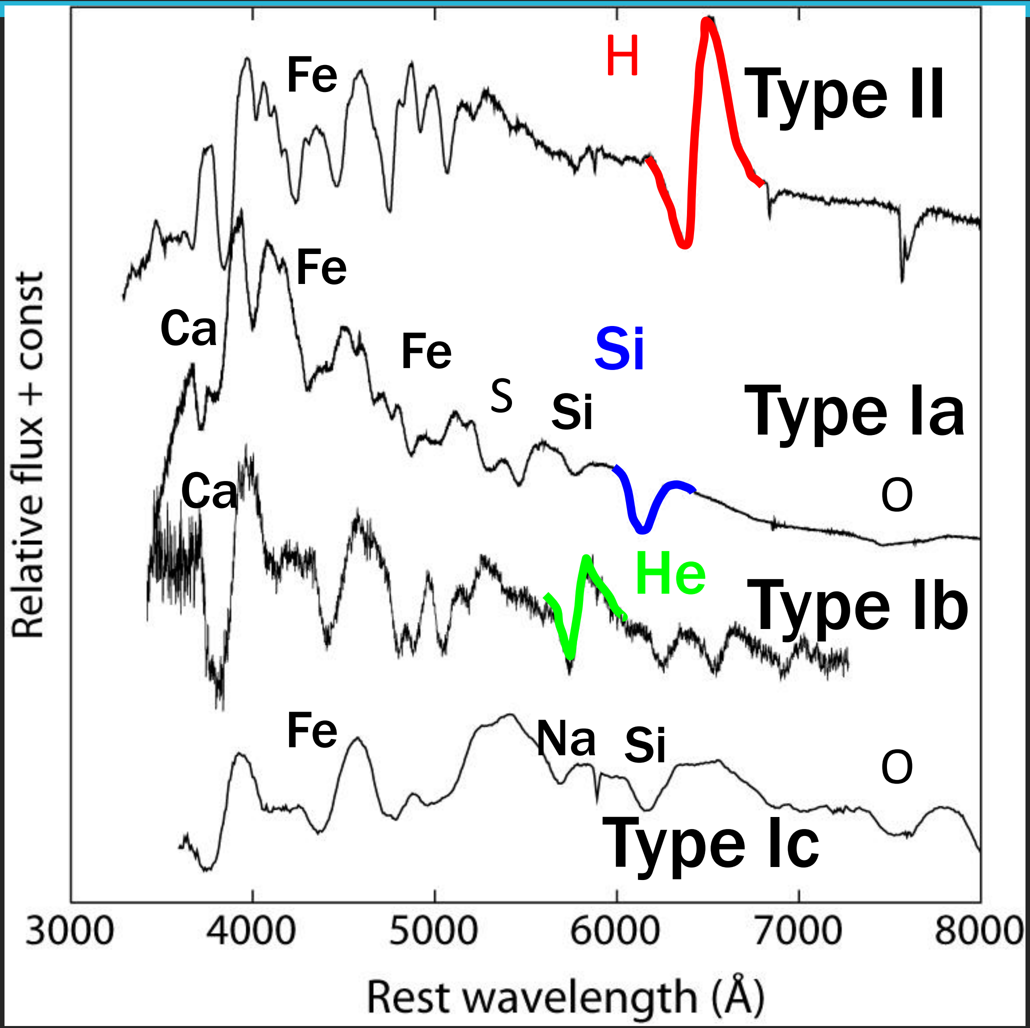


Stellar Evolution and Supernovae (SNe)



Supernova Classification

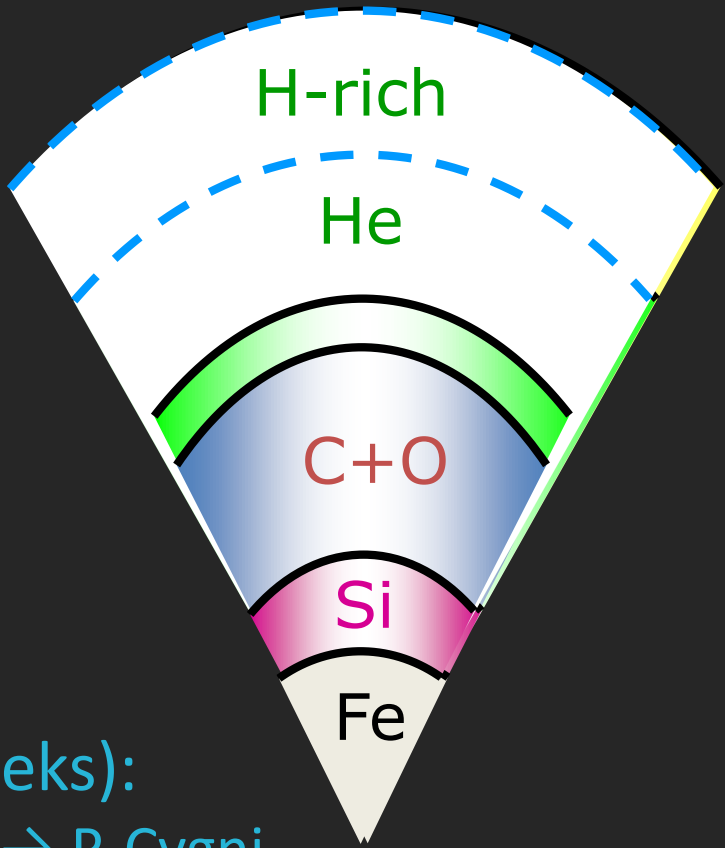


Ia

Thermonuclear exp. of a white dwarf (WD)

II/Ib/Ic

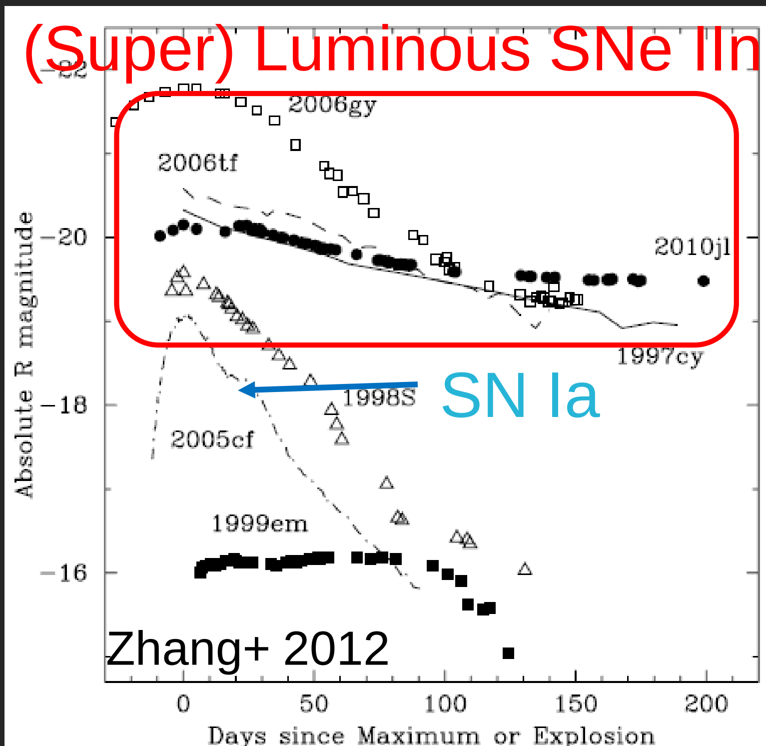
Core-Collapse (CC) of a massive star

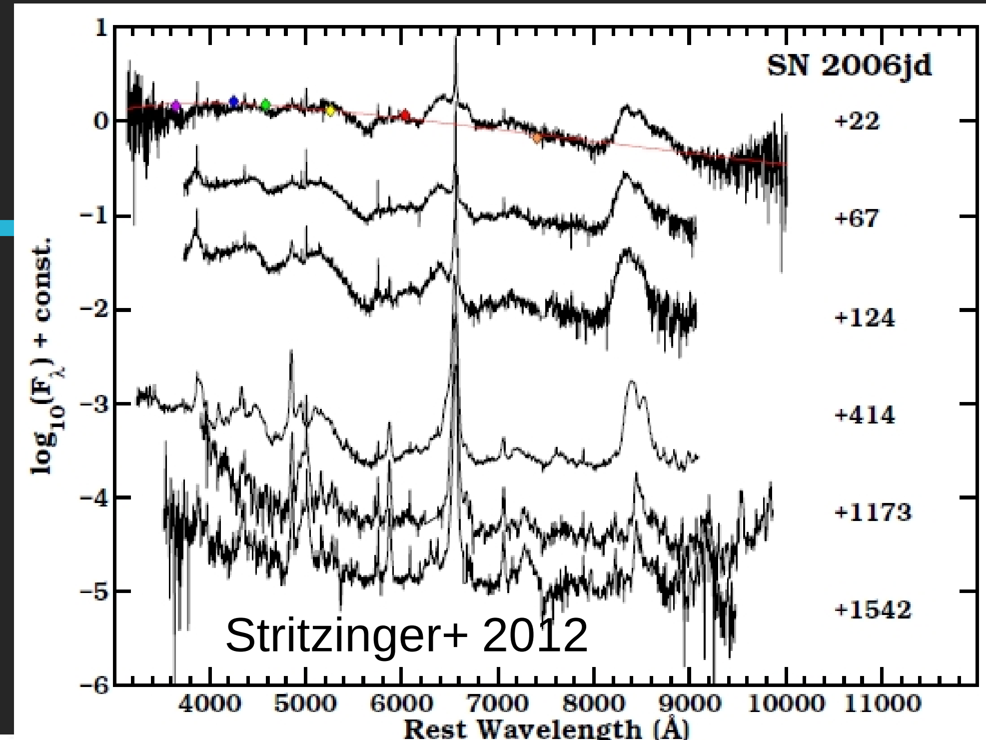


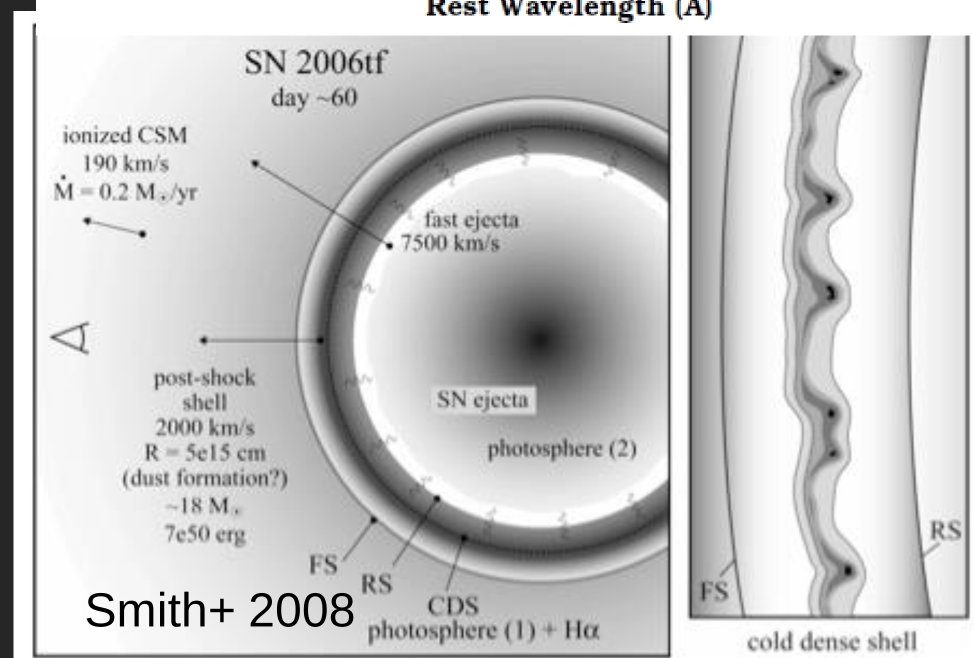
@ maximum brightness (~ a few weeks):

– Expanding optically thick medium → P-Cygni.

Type IIn SNe







Bright & Long-lasting

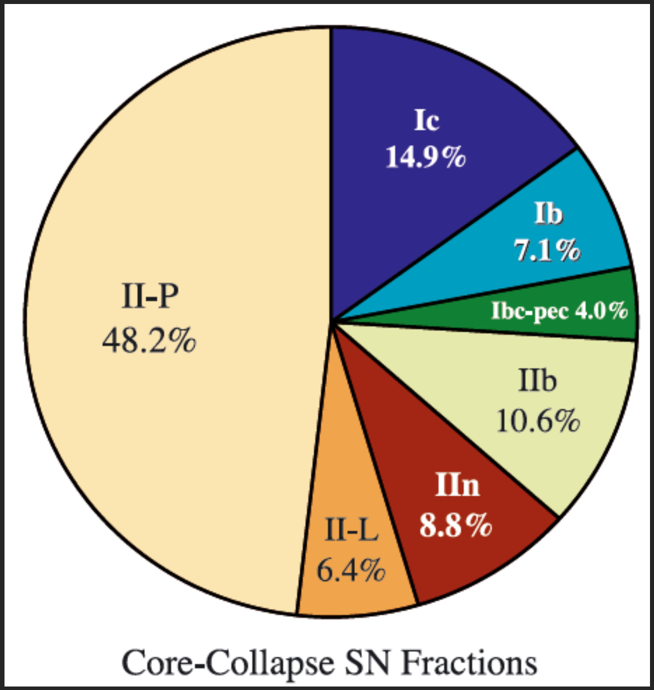
(sometimes E_{rad} **> 10^{51}erg**)

Emission lines

⇒ Interaction-powered

Dense CSM←mass loss

CCSN Populations



Nearby Volume-limited sample (Li+ 2011)

- Red Supergiant (RSG)→IIp, IIL
- He star (WR) → IIb, Ib
- C+O star (WR) → Ic

- ? w/ large mass loss → IIn (showing SN-CSM interaction)

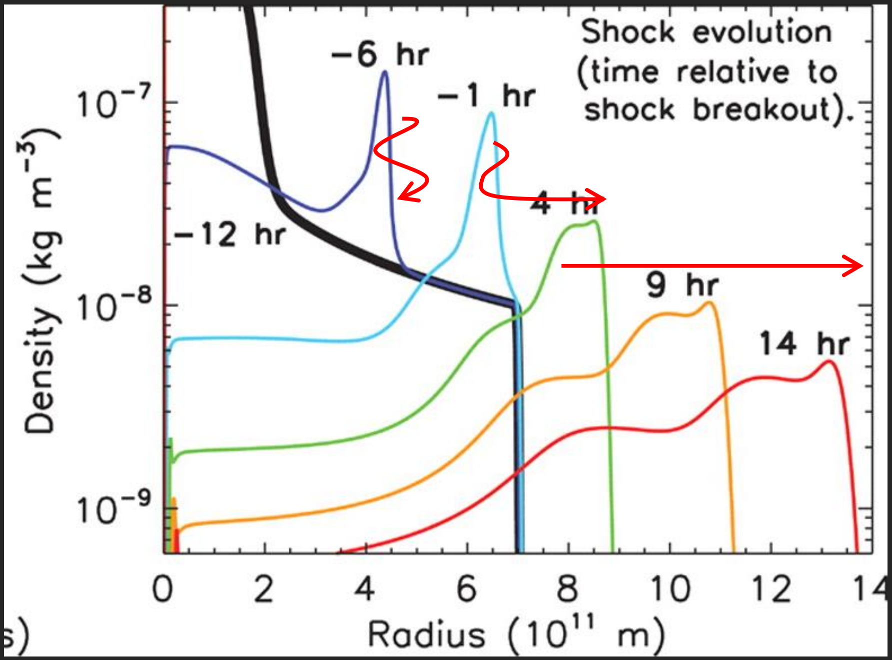
Mass stripping sequence

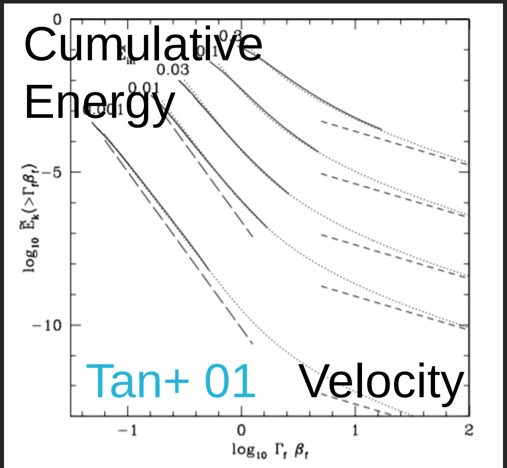
Single star: Mass sequence

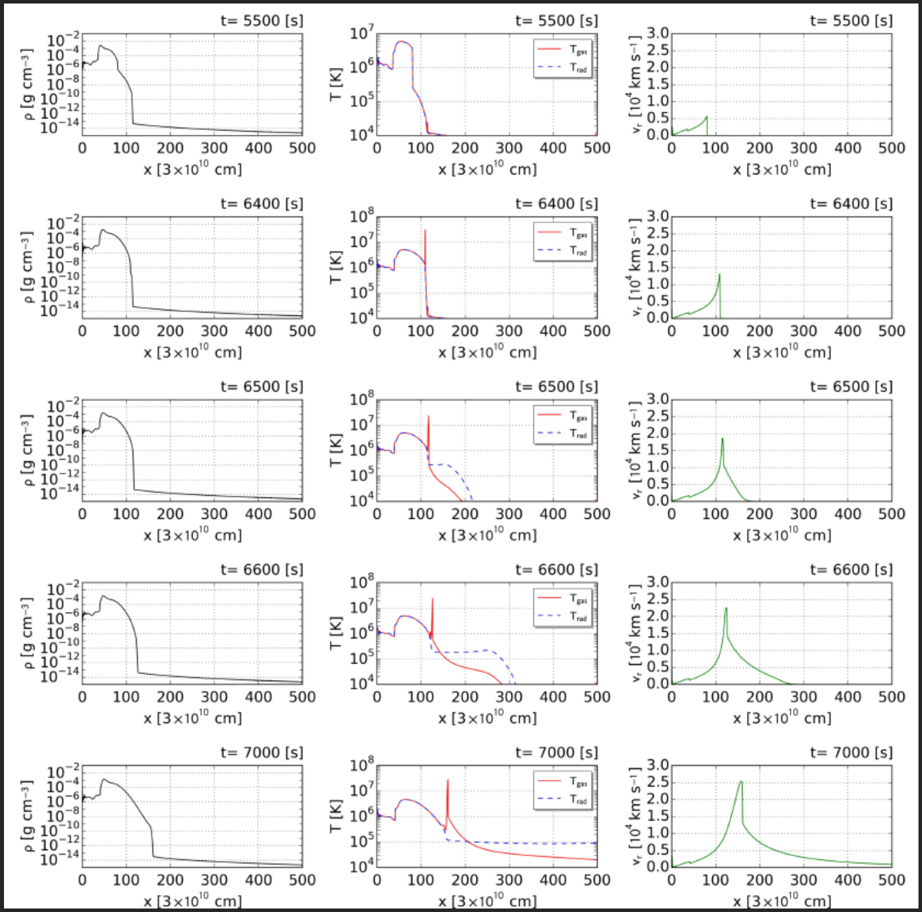
Binary: **Not** mass sequence

CCSNe: Shock Breakout

Original idea:
Falk & Arnett 1977
Klein & Chevalier 1978





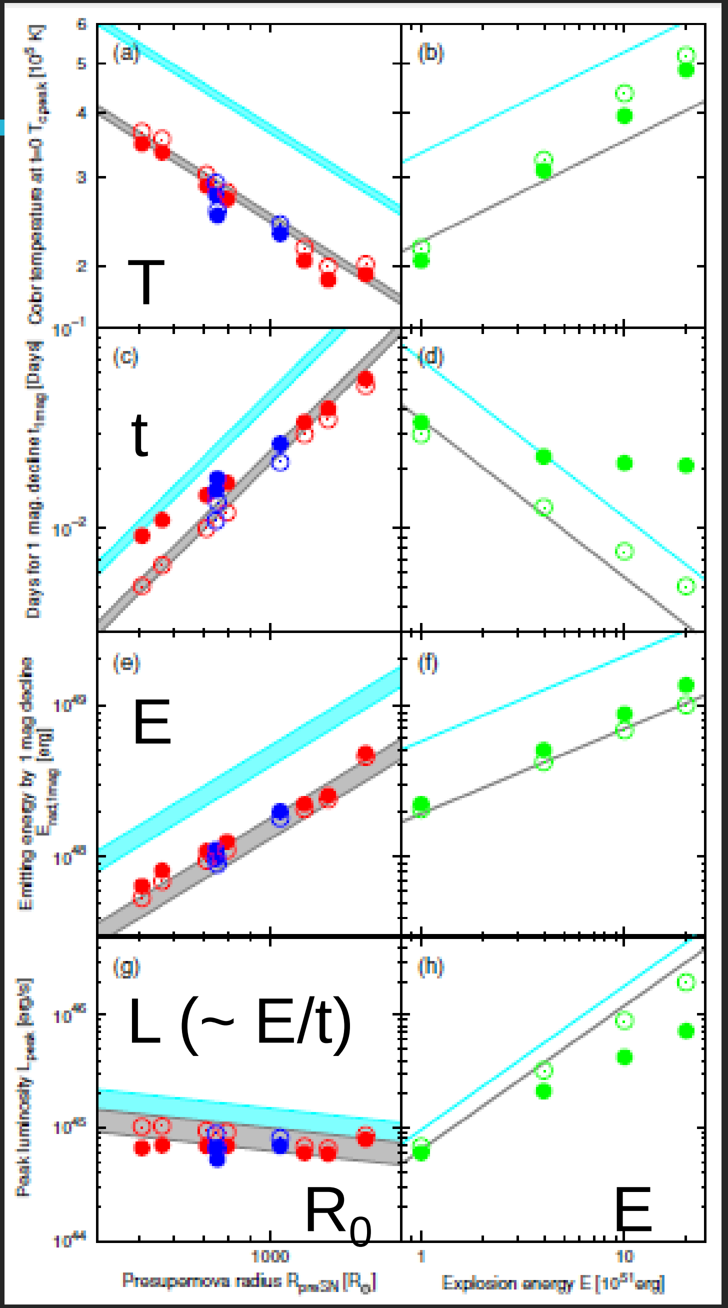


Suzuki, KM, Shigeyama 16

A probe to the progenitor.

Shock Breakout

Numerical (radiation-hyd.): Tominaga+ 2011



Semi-Analytic (adiabatic): Matzner+1999

$$T_{se} = 5.55 \times 10^5 \left(\frac{\kappa}{0.34\ \mathrm{cm^2\ g^{-1}}}\right)^{-0.10} \left(\frac{\rho_1}{\rho_*}\right)^{0.070} \times \left(\frac{E_{in}}{10^{51}\ \mathrm{ergs}}\right)^{0.20} \left(\frac{M_{ej}}{10\ M_\odot}\right)^{-0.052} \times \left(\frac{R_*}{500\ R_\odot}\right)^{-0.54} \mathrm{K} \quad \left(n = \frac{3}{2}\right),$$

UV for RSG
X for WR
(faint in optical)

$$E_{se} = 1.7 \times 10^{48} \left(\frac{\kappa}{0.34\ \mathrm{cm^2\ g^{-1}}}\right)^{-0.87} \left(\frac{\rho_1}{\rho_*}\right)^{-0.086} \times \left(\frac{E_{in}}{10^{51}\ \mathrm{ergs}}\right)^{0.56} \left(\frac{M_{ej}}{10\ M_\odot}\right)^{-0.44} \times \left(\frac{R_*}{500\ R_\odot}\right)^{1.74} \mathrm{ergs} \quad \left(n = \frac{3}{2}\right),$$

~ 10^{48} erg

$$t_{se} = 790 \left(\frac{\kappa}{0.34\ \mathrm{cm^2\ g^{-1}}}\right)^{-0.58} \left(\frac{\rho_1}{\rho_*}\right)^{-0.28} \times \left(\frac{E_{in}}{10^{51}\ \mathrm{ergs}}\right)^{-0.79} \left(\frac{M_{ej}}{10\ M_\odot}\right)^{0.21} \times \left(\frac{R_*}{500\ R_\odot}\right)^{2.16} \mathrm{s} \quad \left(n = \frac{3}{2}\right),$$

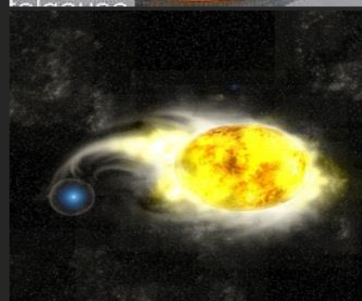
+ light travel time
~ hrs for RSG
~ a few sec for WR

Shock Breakout – Progenitor - CSM

Breakout

Progenitor

RSG



YSG

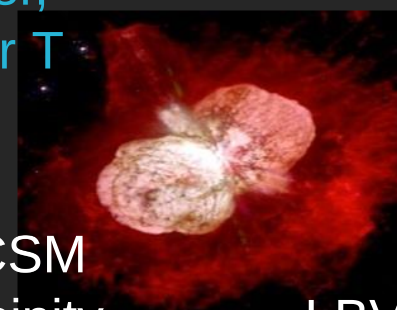
BSG

WR

Shorter, higher T

Decreasing radius

Longer, Lower T

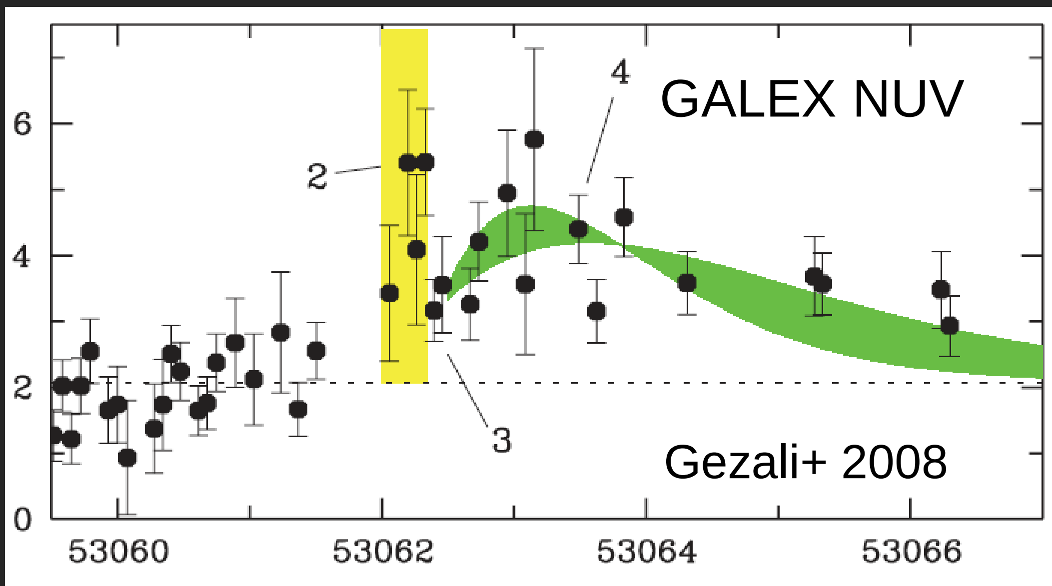


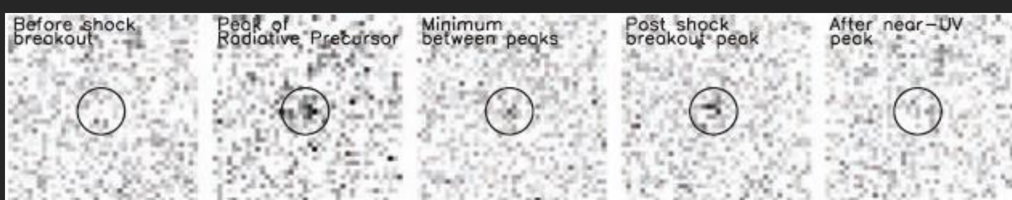
Dense CSM in the vicinity

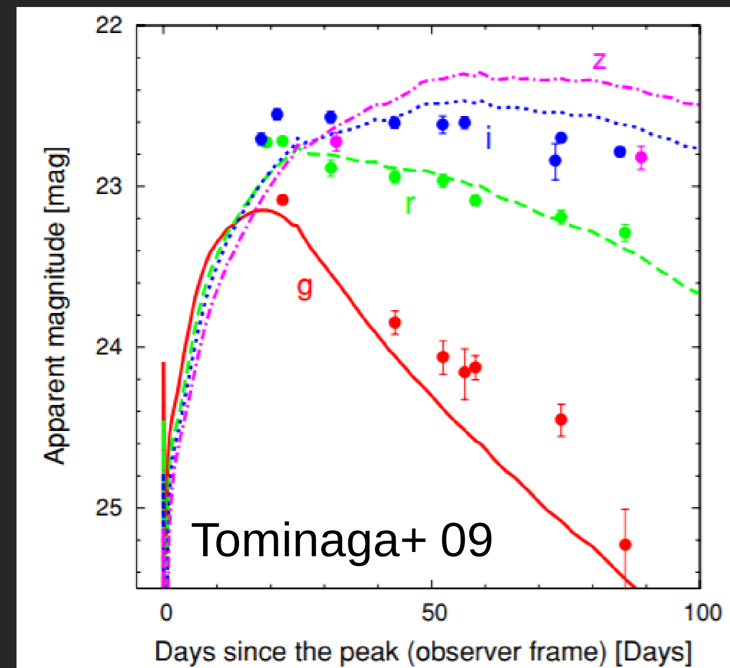
LBV (?)

GRB outliers? (Suzuki-san)

Shock Breakout: robust candidate @ UV







SN IIp SNLS-04D2dc

UV, ~ 6 hrs ⇒ **RSG**.

Consistent with the “classical” picture.

Model params:

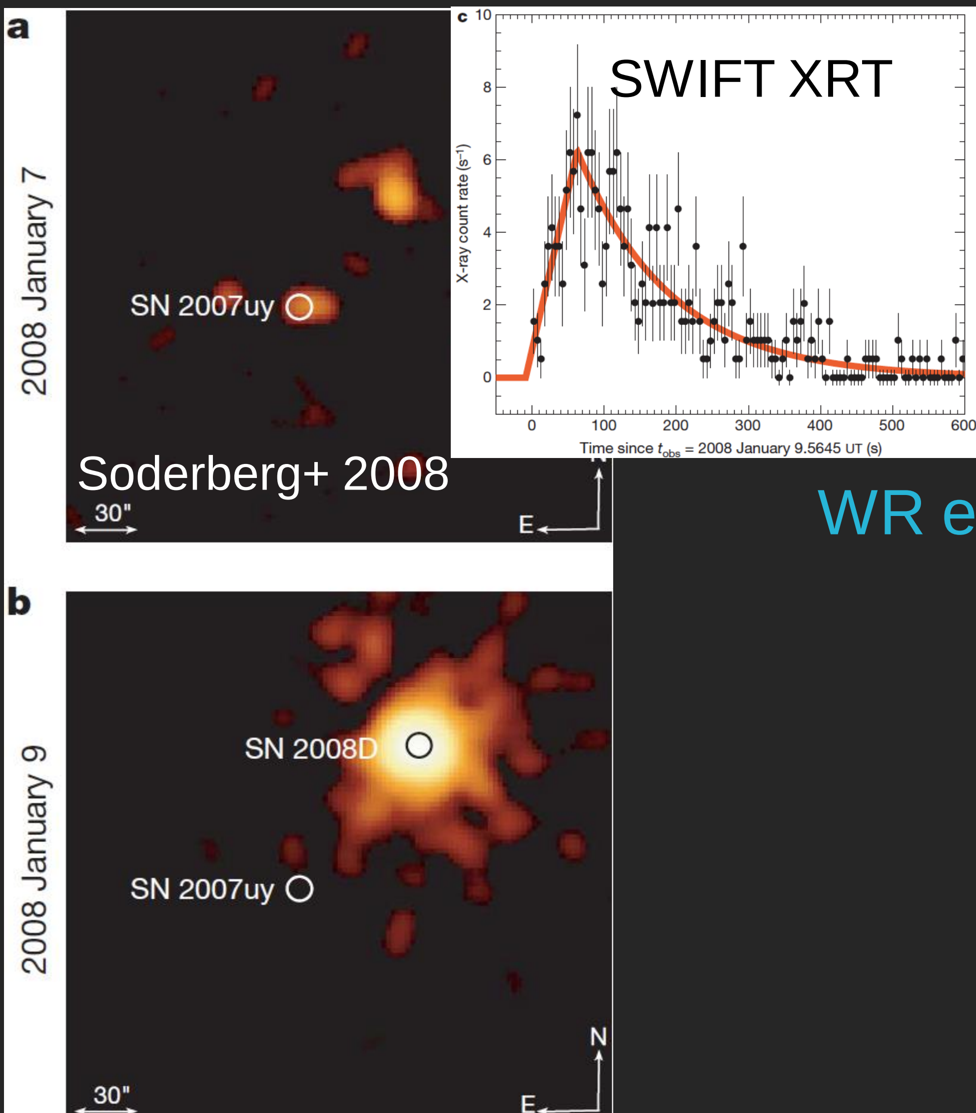
$M_{ms}=20M_\odot$

$M_{presn}=18.4M_\odot$

$M_{henv}=13.4M_\odot$

$R=800R_\odot$

Shock Breakout: robust candidate @ X

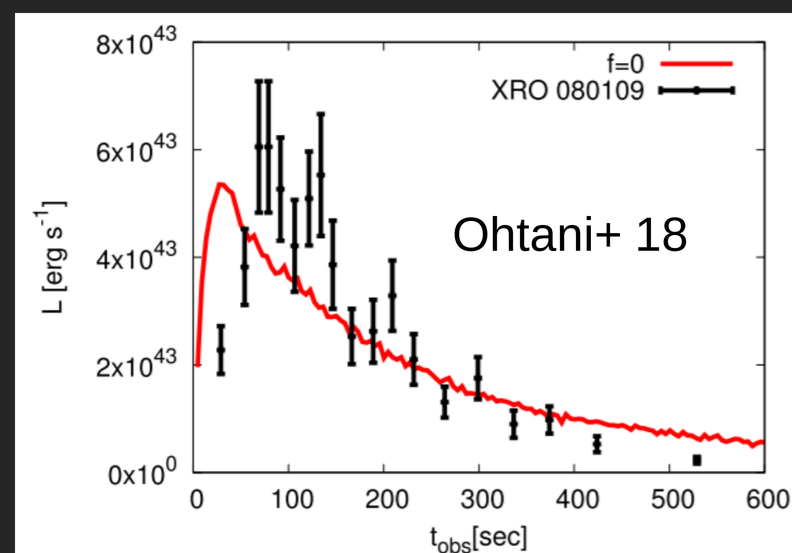


SN Ib 2008D

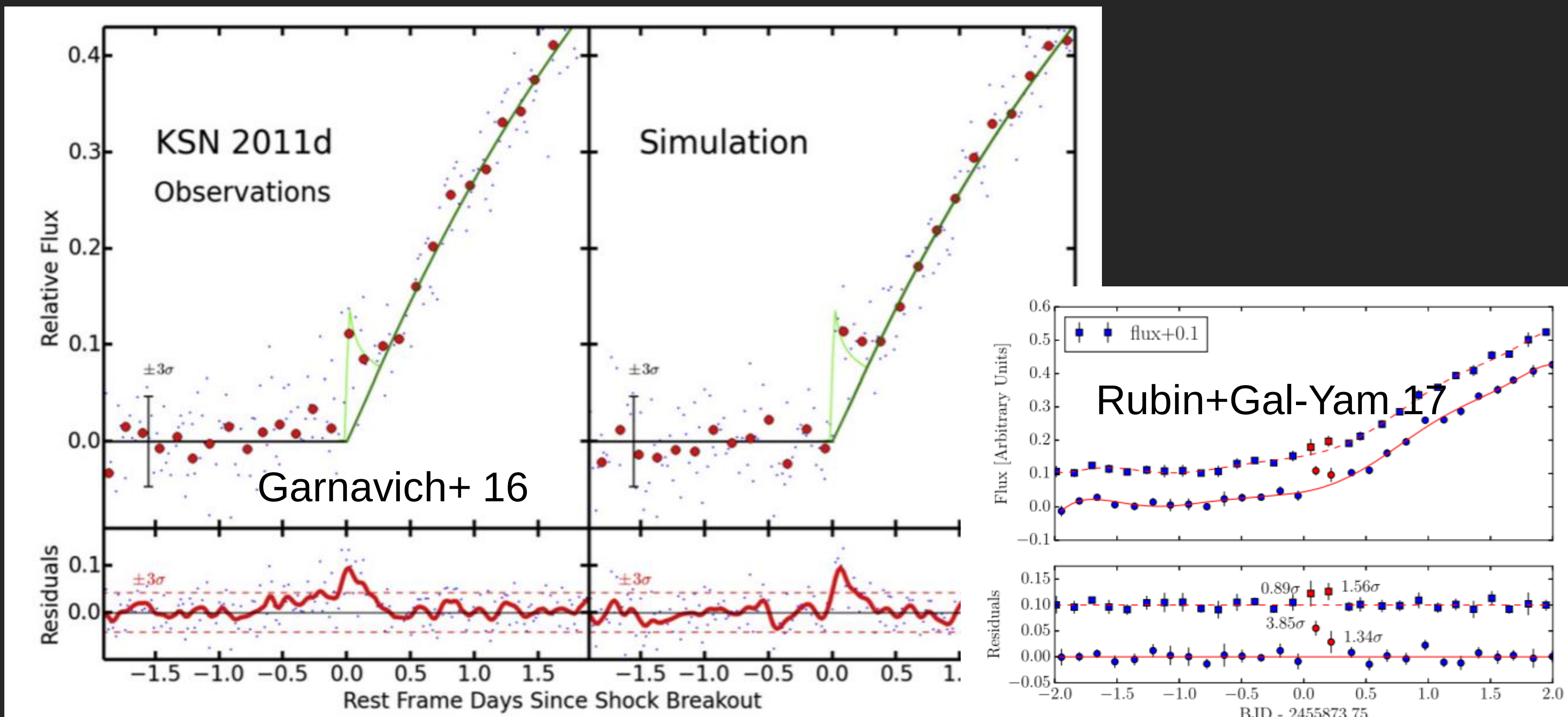
X, ~ a few 100 sec

⇒ compact, but >> WR?

WR explosion within a dense CSM

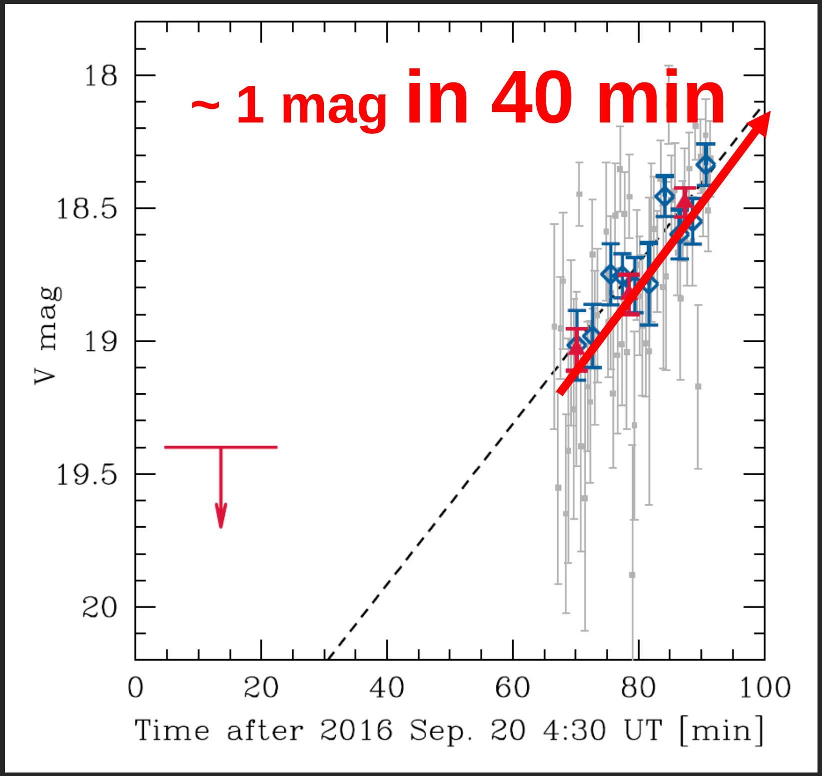


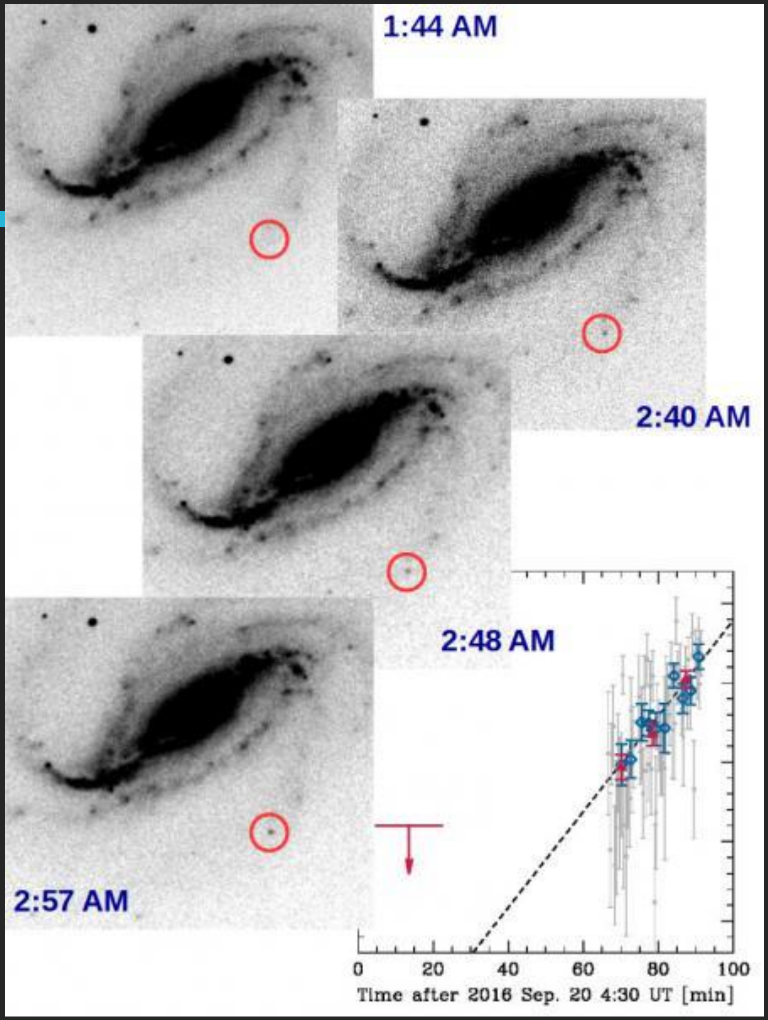
Shock breakout: candidate @ optical?



High-cadence light curve by the Kepler telescope:
Indication of a “spike”: Garnavich+ 16
But poison noise? : Rubin+ Gal-Yam 17

Robust candidate in optical: SN IIb 2016gkg

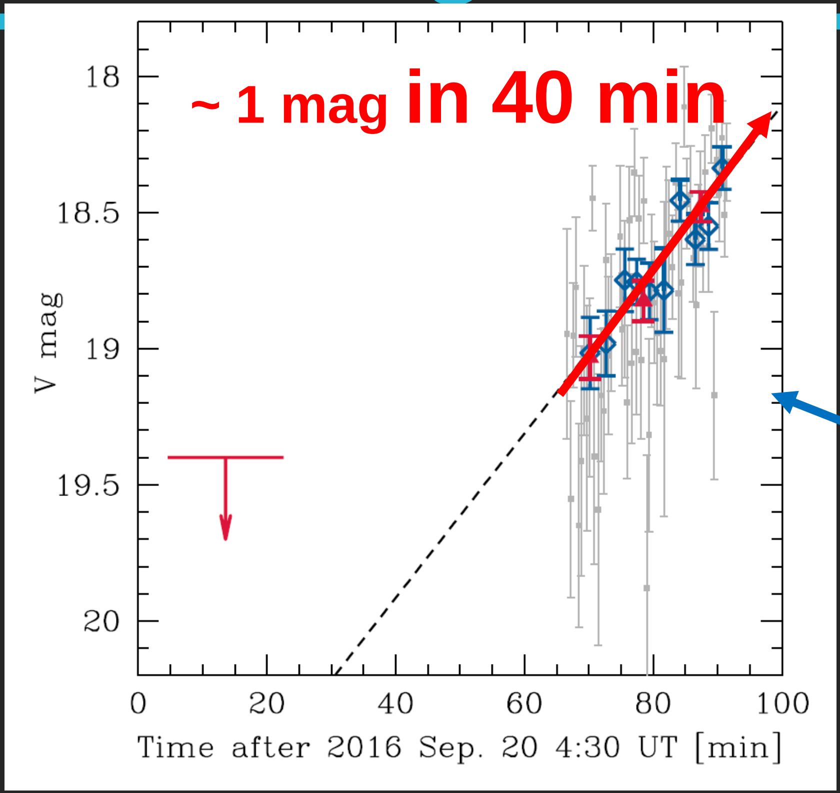


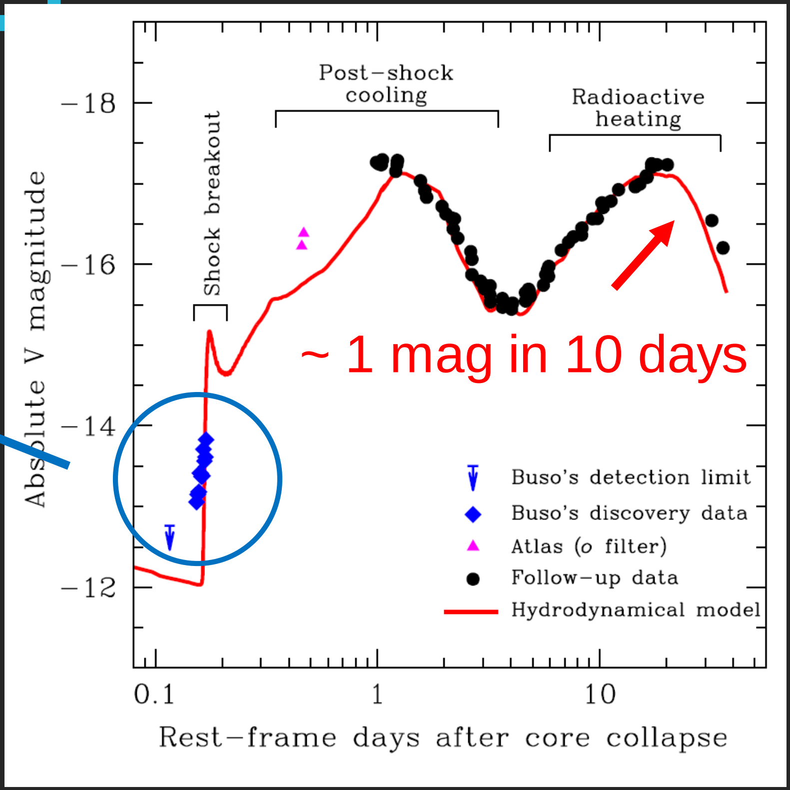


Discovery of an armature astronomer by a luck.
An extremely fast rise: ~ 1 mag in 40 min
(⇔ ~ 1 mag in 10 days in the main part of SNe)

Bersten+, 2017, Nature

Confirming the basic picture of the SB





Estimated progenitor:

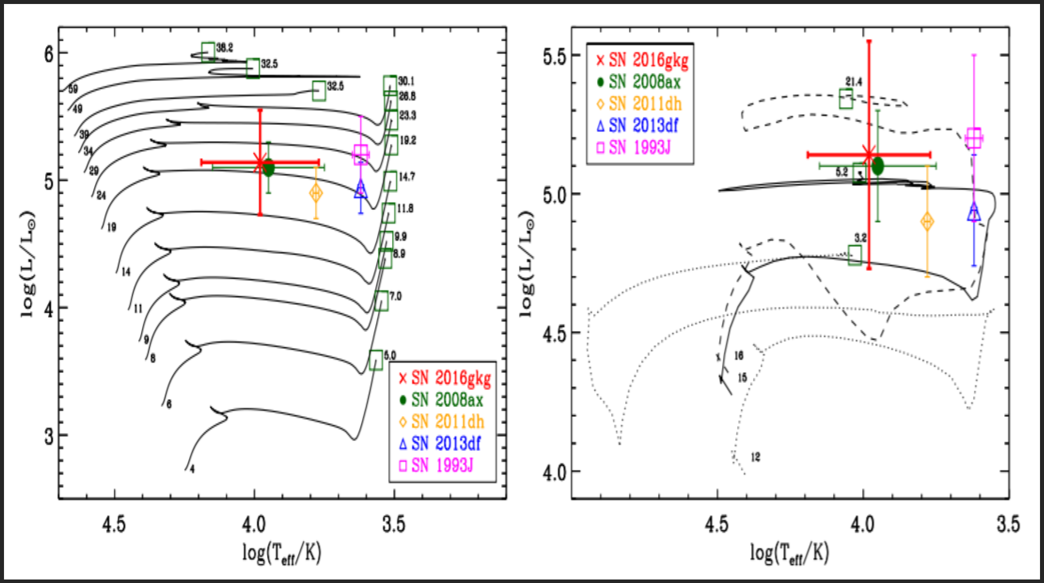
He core ~ 5 $M_\odot$, H env.~ 0.1$M_\odot$, R~300$R_\odot$, M_{ms}~20$M_\odot$

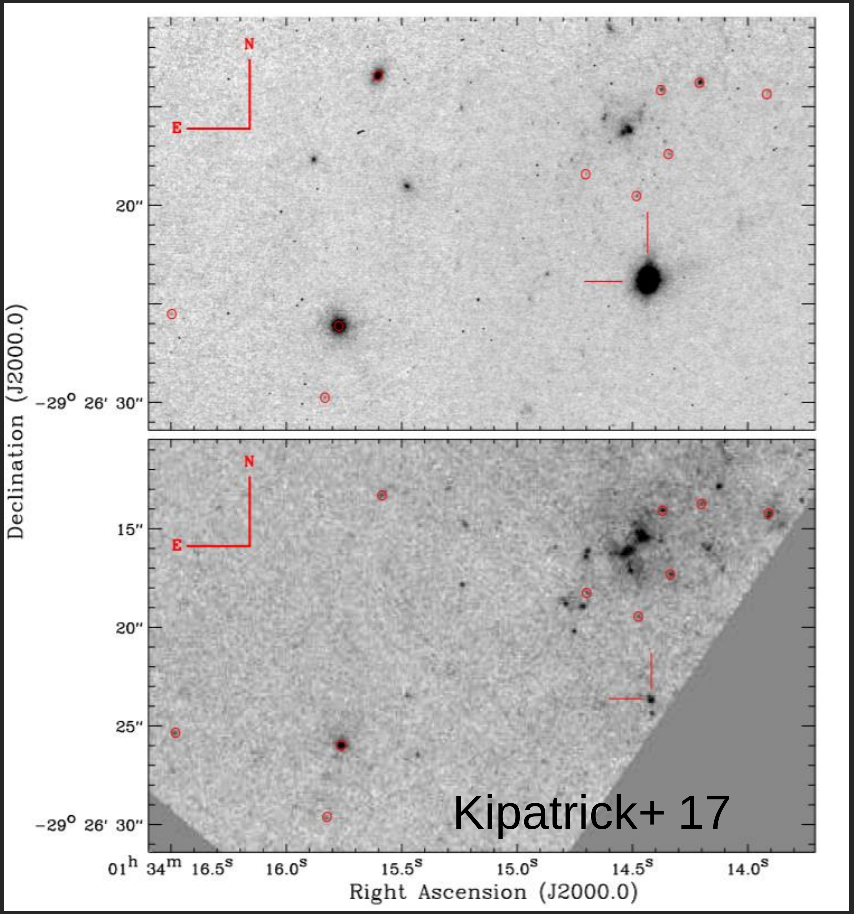
Consistent with the detected progenitor candidate.

Confirming the basic mechanism of the SB.

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

Progenitor (candidate) of SN 2016gkg



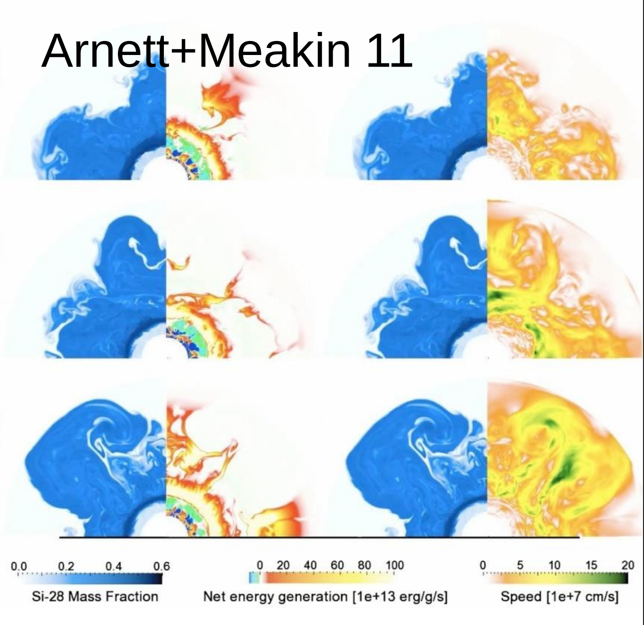


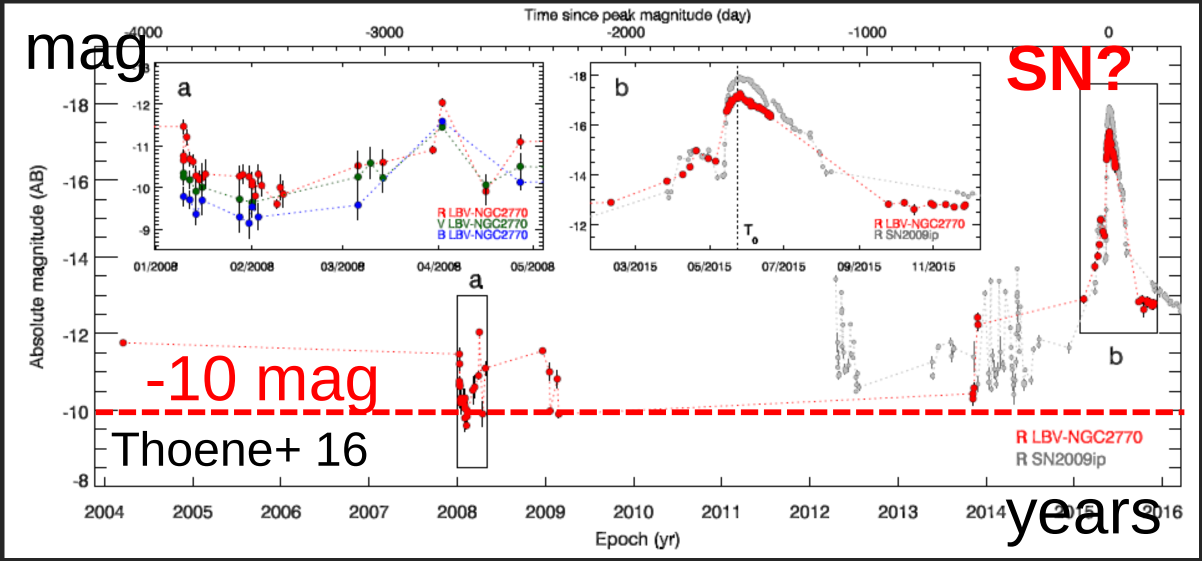
Progenitor radius ~ $250R_{\odot}$
"Yellow Supergiant" as commonly found for SNe IIb (→later)

⇔He core ~ 5 $M_{\odot}$, H env.~ $0.1M_{\odot}$, R~$300R_{\odot}$, M_{ms}~$20M_{\odot}$
Consistent with the detected progenitor candidate.

Unresolved problems for Core Collapse SNe (CC SNe)

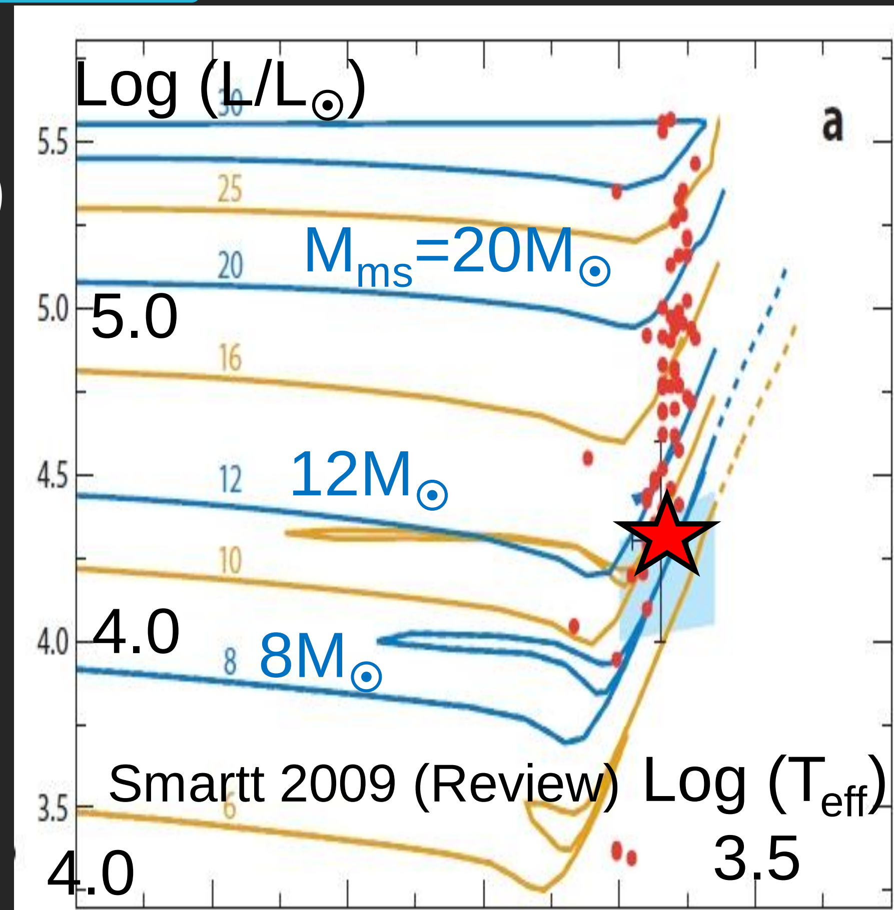
- **Explosion mechanism.**
- **Final evolution of massive stars (single & binary).**
  - Progenitor **at the time** of the explosion.
  - Mass loss in the **final decades.**





Typically a few years before the SN

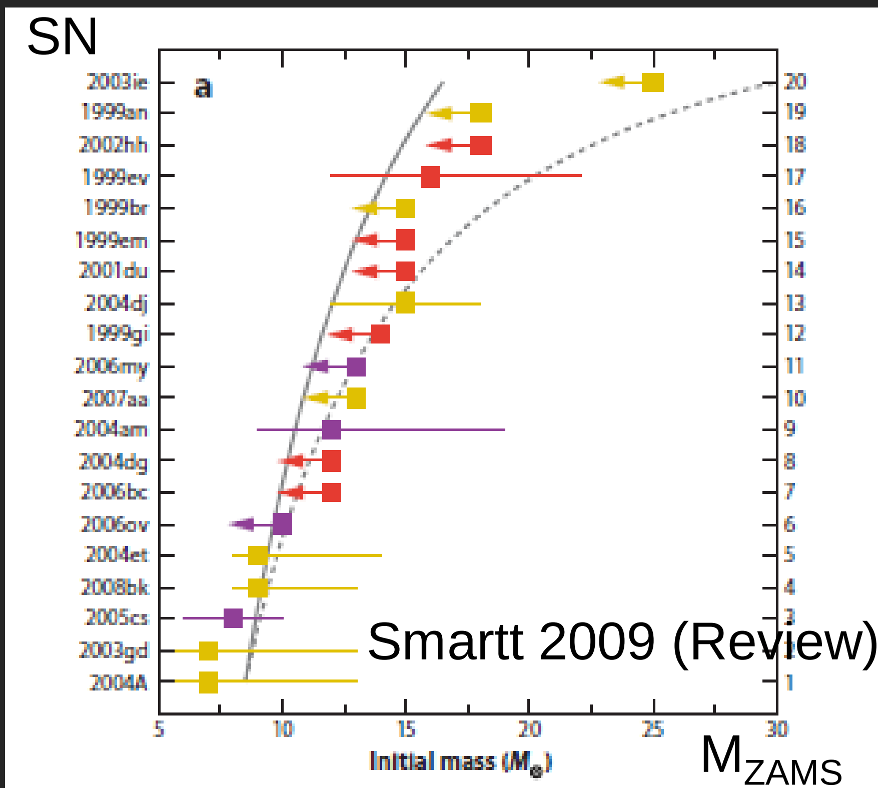
SN IIp Progenitor search in past images

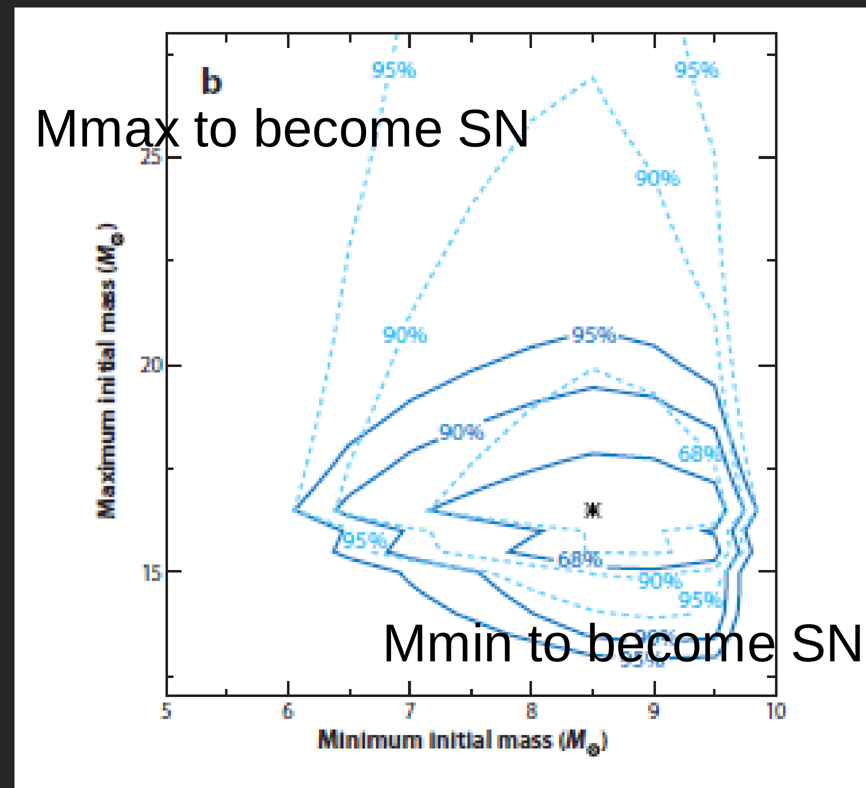


Progenitor Detection

< ~ 30 Mpc with HST (Hubble).
Good for SNe IIp (Giant, bright in optical).
Bad for SNe Ib/Ic (Wolf –Rayet, bright in UV, not in opt.).
The best cases = The progenitor "candidates" gone after the SN.

SN IIp Progenitors: Mass range





Assuming Salpeter IMF,

M_{min} ~ 8.5$M_\odot$ (±1.5), M_{max} ~ 16.5$_\odot$ (±1.5)

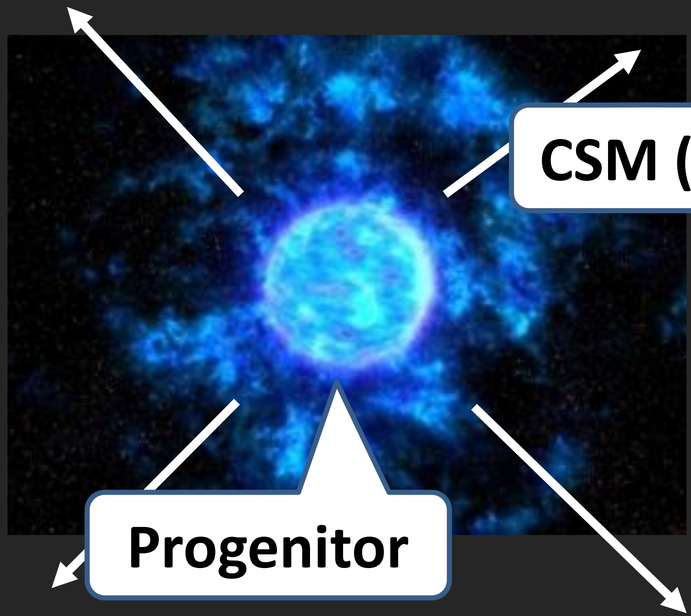
→ largely consistent w/ stellar evolution theory, but

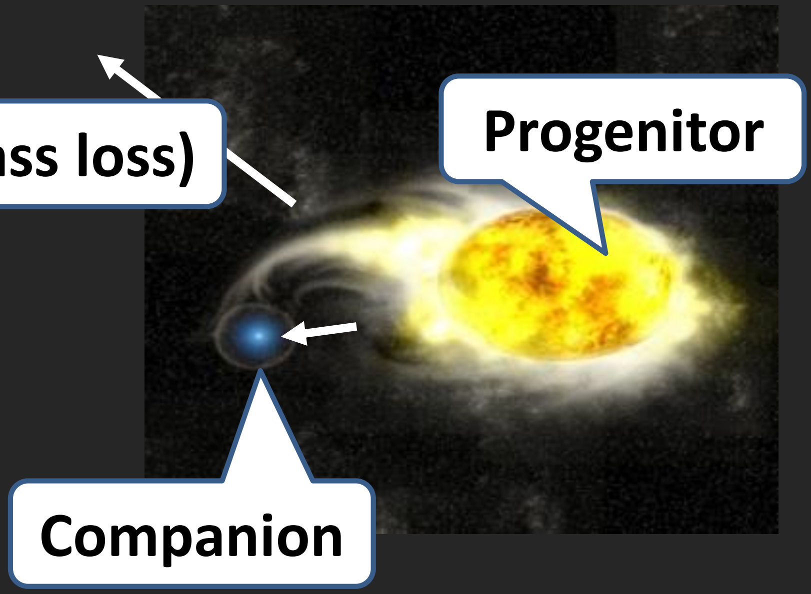
RSG problem (There are Galactic RSGs w/ > M_{max})

Stripped Envelope SN (SNe IIb/Ib/Ic)

- Stripped Envelope-SNe:
  - An explosion of a massive, bare He (or CO) star.
  - How to get rid of the H envelope.

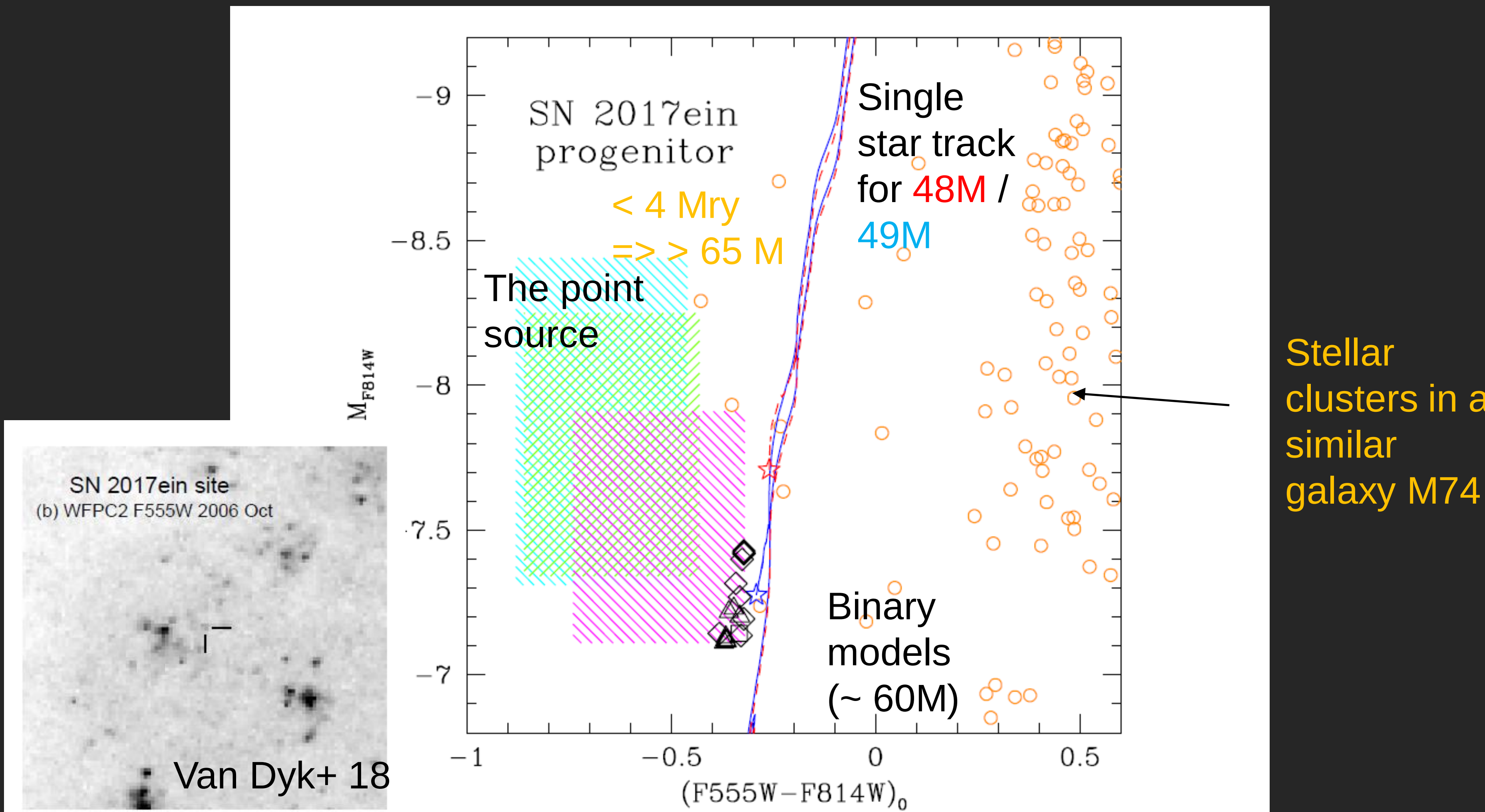
Single or Binary?



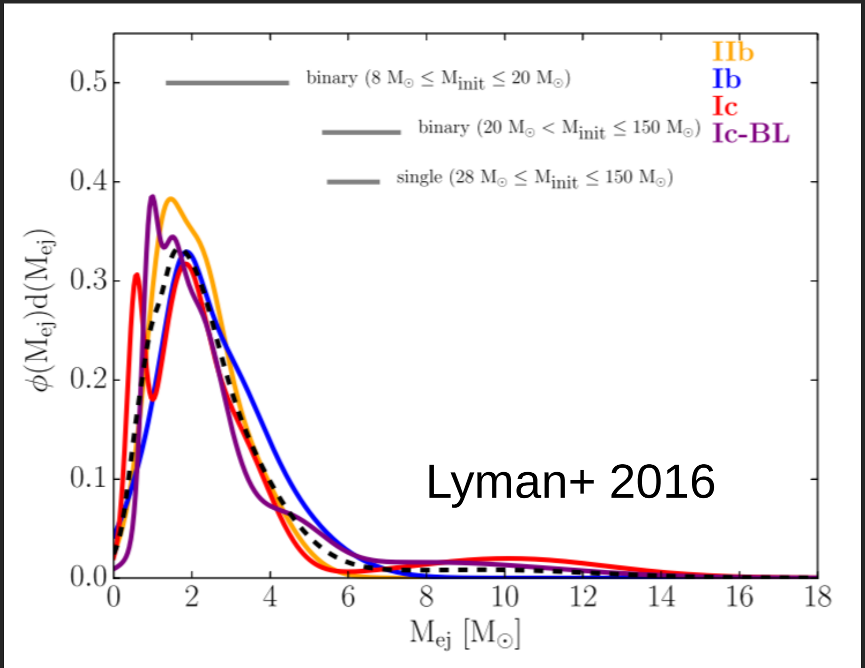


A (first) candidate progenitor of SN Ic

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



Real progenitor?



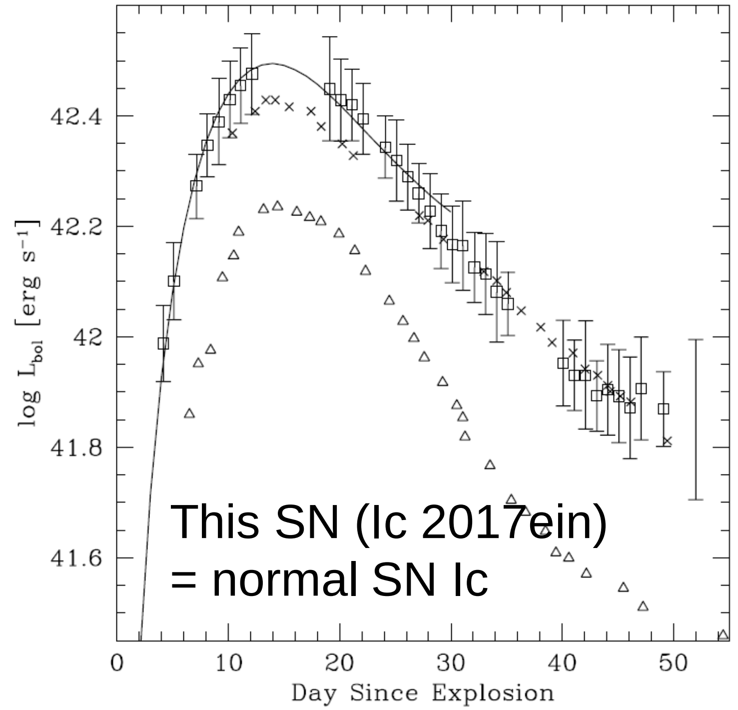


Figure 7. Quasi-bolometric light curve of SN 2017ein (open squares), assuming the bolometric corrections for SESNe from Lyman et al. (2014). The uncertainties shown with each data point arise primarily from the photometric measurements and from the uncertainties in the bolometric corrections. An error 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 and not the youngest in it; this can happen without the disappearance confirmation…)

A candidate progenitor of SN Ib

Direct detection difficult (expected progenitor too blue).

The first detection of a candidate in 2013: iPTF13bvn

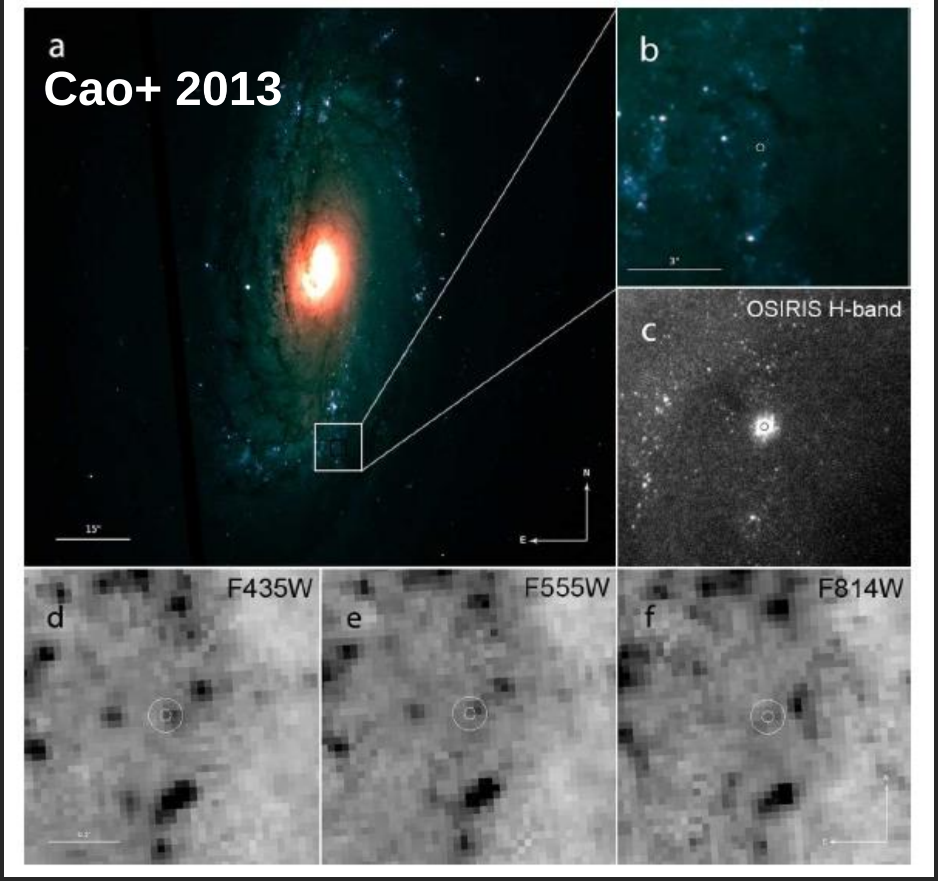
Massive Wolf-Rayet?

($M_{ms} > 20M_{\odot}$) (Cao+ 13)

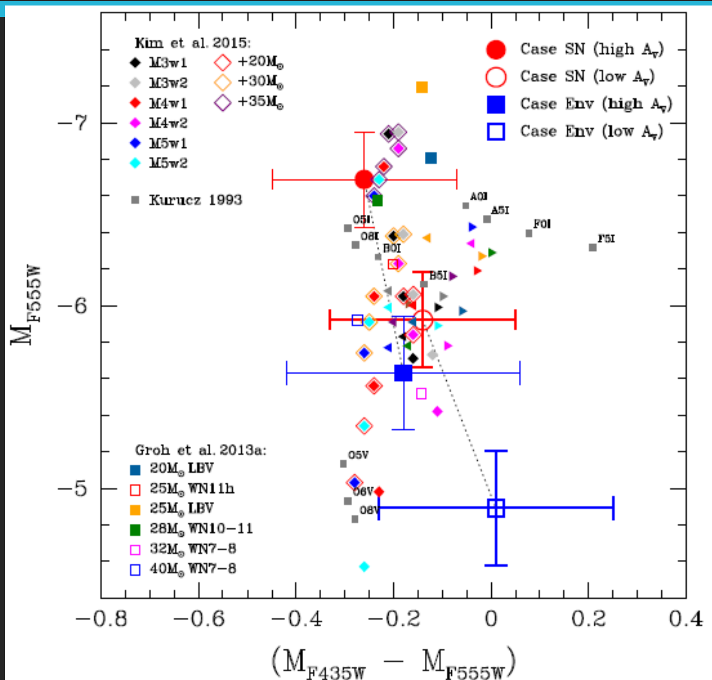
SN emission indicates a compact progenitor, but less massive

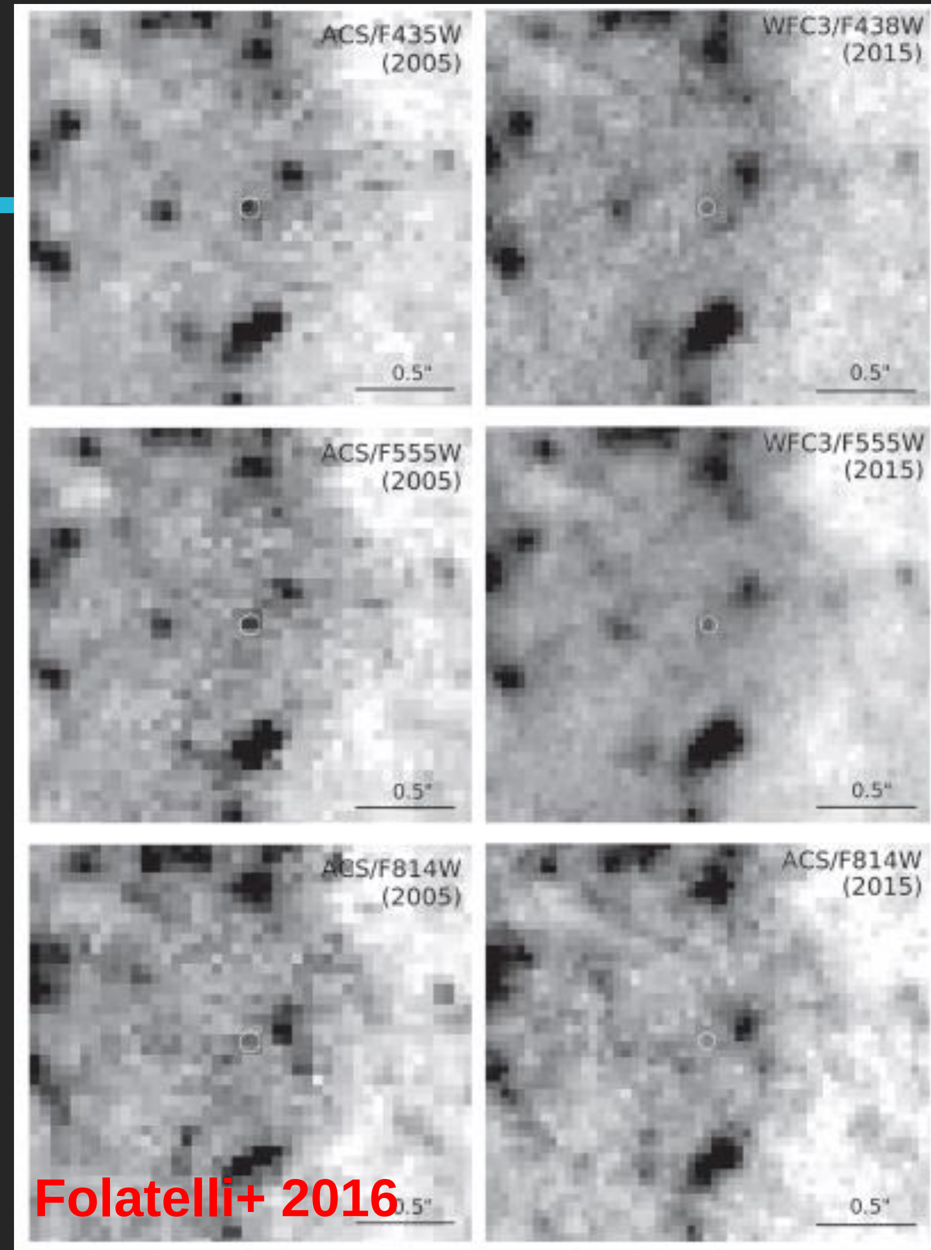
(e.g., Bersten+14, Kuncarayakti+ 14).

Controversy?



SN Ib iPTF13bvn





HST observation at ~2 yrs.

Progenitor gone.

Revised phot.→less massive.

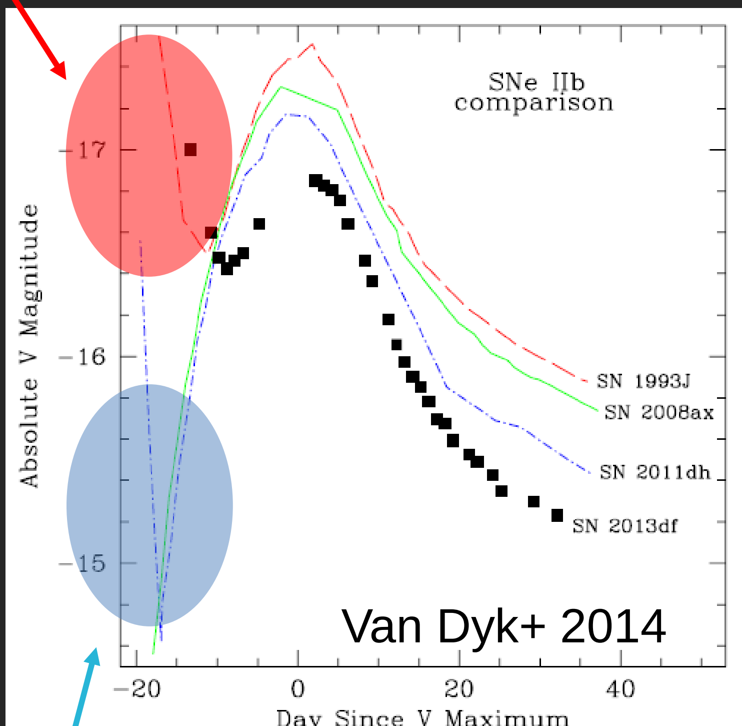
(Folatelli+ 16; Eldridge+Maund 16).

Consistent w/ binary, but

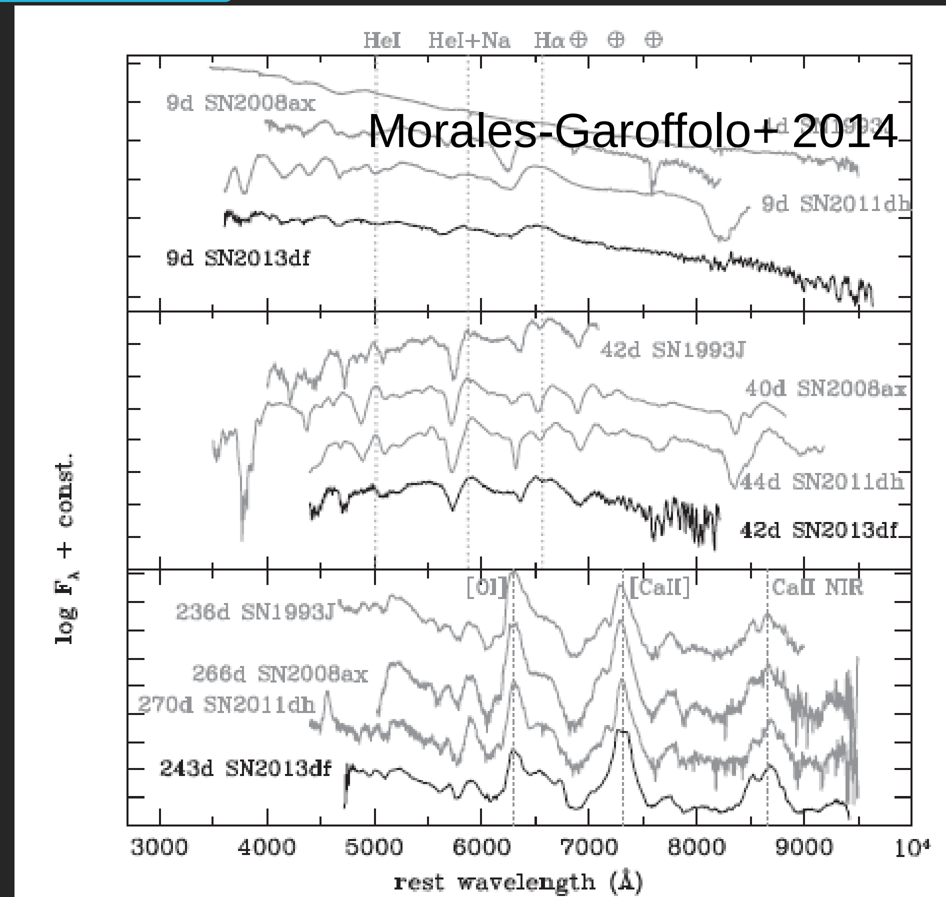
UV limit for a companion (< 20M$_\odot$) [again in HST Cycle 25; Van Dyk+].

SNe IIb: The best studied (interesting) cases

"Strong" cooling (extended H)
1993J & 2013df



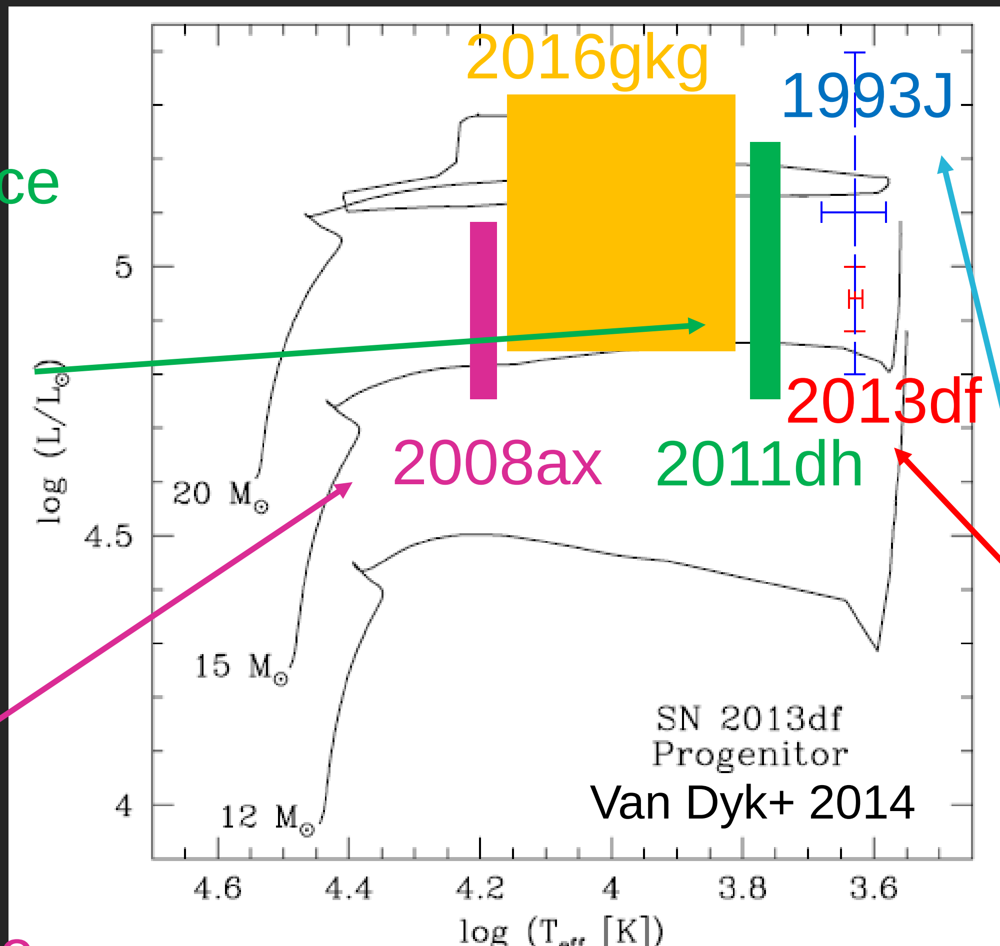
"weak/no" cooling (compact H)
2008ex & 2011dh
2016gkg in between.



Similar spectra & peak LC
⇒ similar progenitor mass
and energetics

Progenitor diversity (no RSG, no WR)

Disappearance
+Companion
YSG
~ 200R⊙



Disappearance
+Companion

Pre-SN only

YSG
~ 600R⊙

BSG
~ 50R⊙
Disappearance

BSG=Blue Supergiant
YSG=Yellow Supergiant

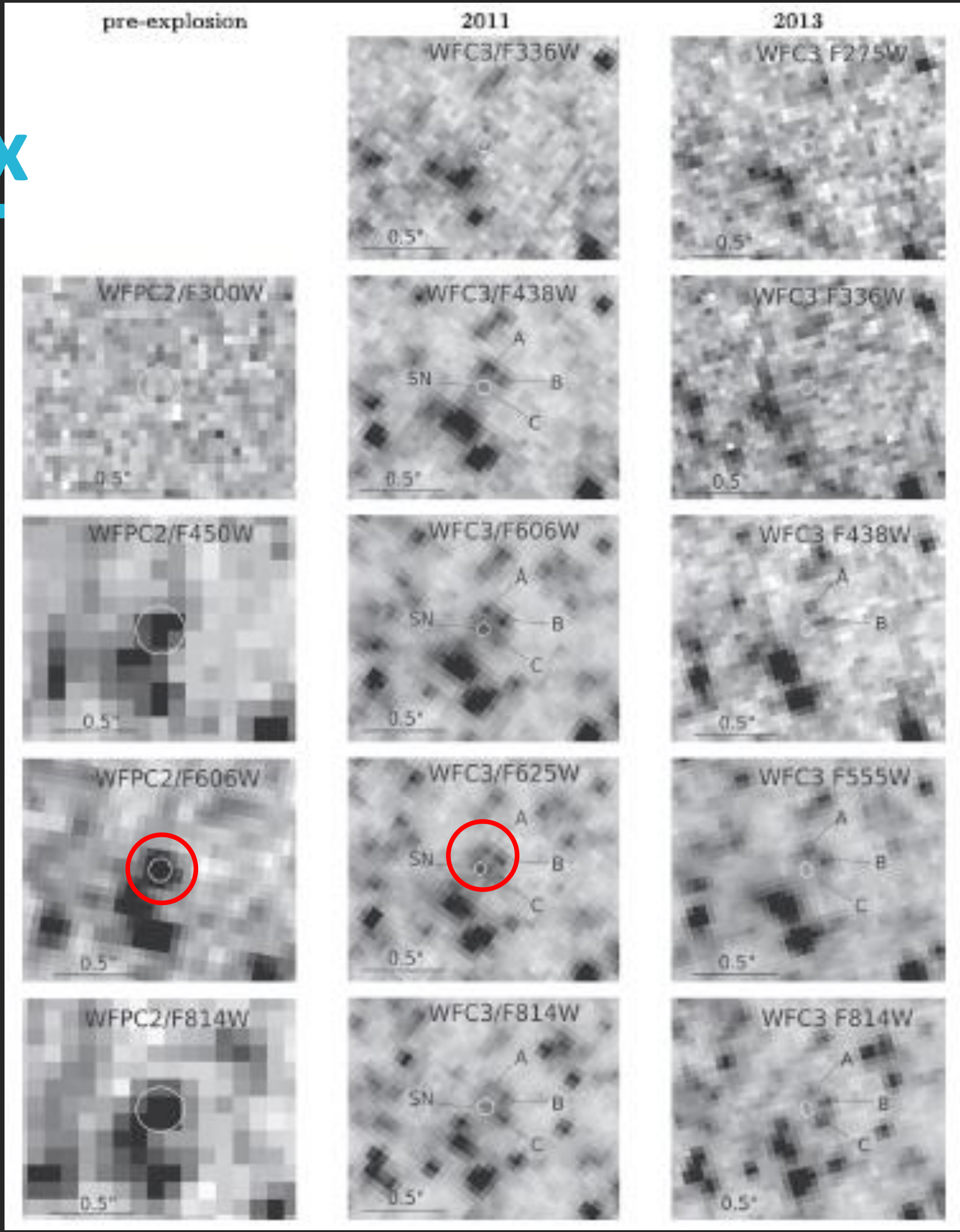
2016gkg: will go for the disappearance in HST cycle 25 (Folatelli+).

BSG: SN IIb 2008ax

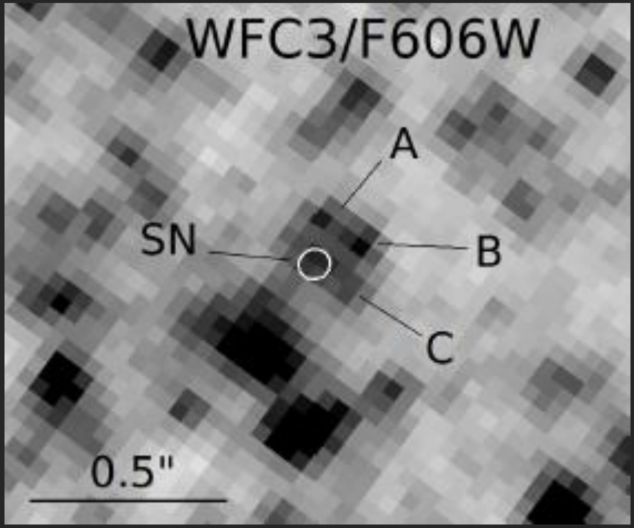
Pre-SN point source
Crockett+ (2008)

Analyses of late-time HST images shows that it consists of multiple stars.
Folatelli+ (2015)
[Another need for post-SN deep imaging]

Now, the SN has faded.
A fraction of light gone.
⇒ Progenitor.



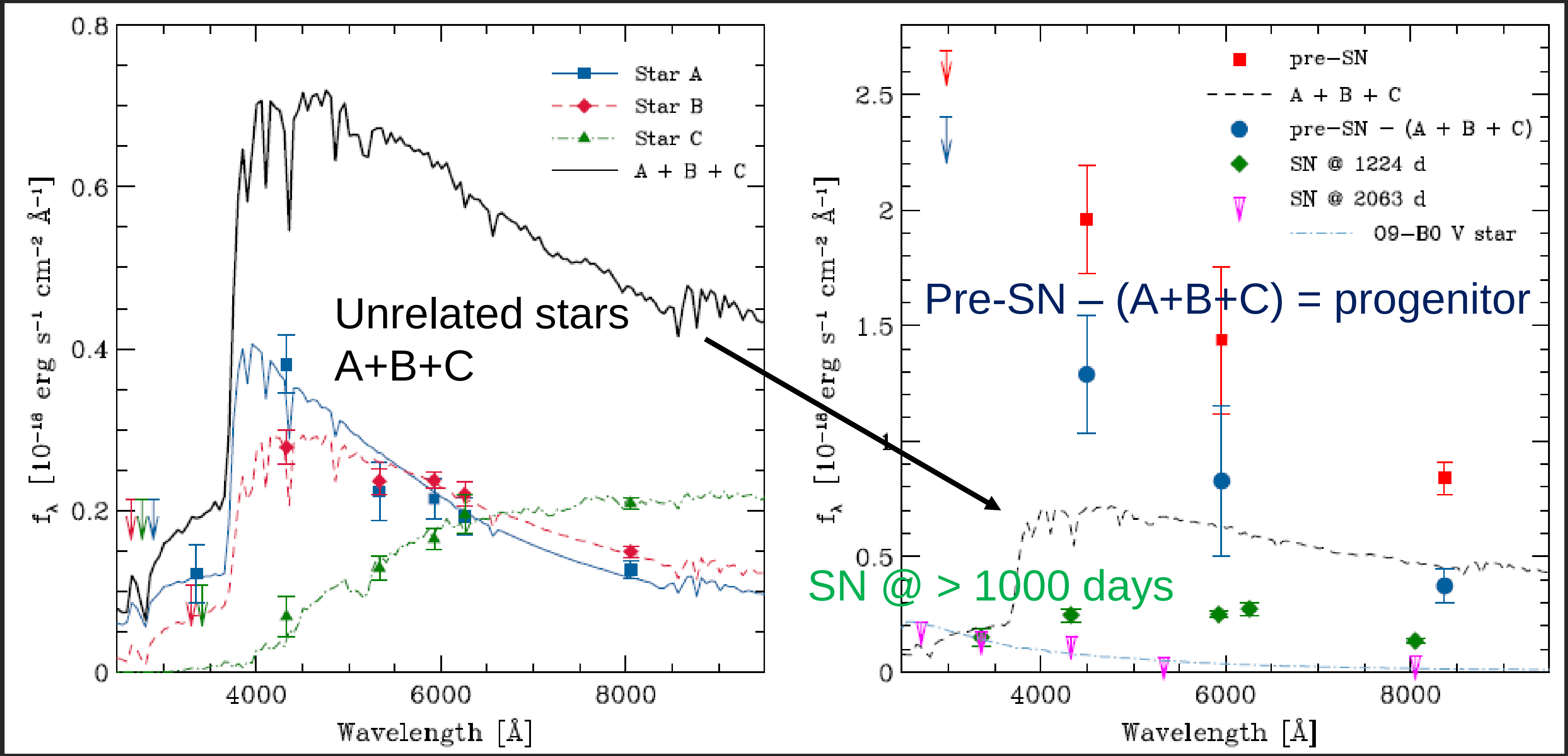
BSG progenitor: SN 2008ax



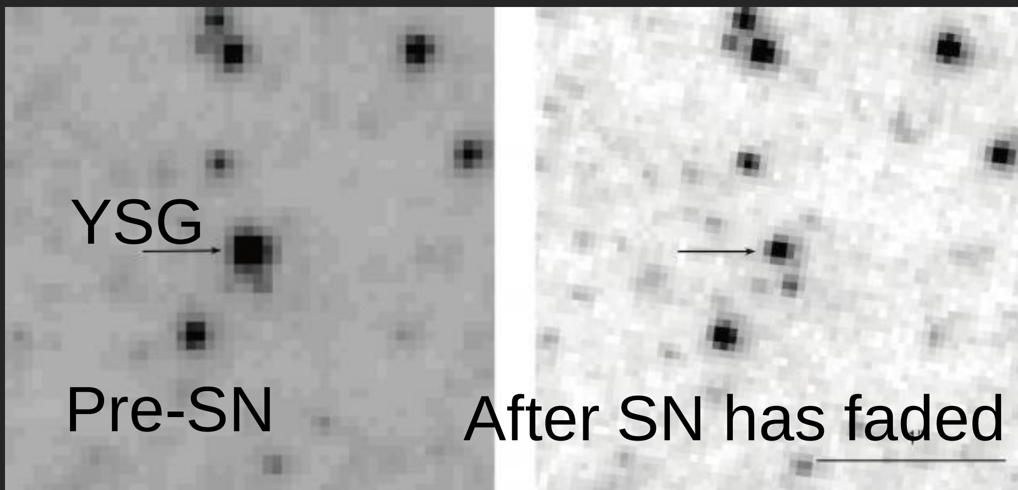
SN had faded below the "progenitor" flux

⇒ **Blue Supergiant progenitor.**

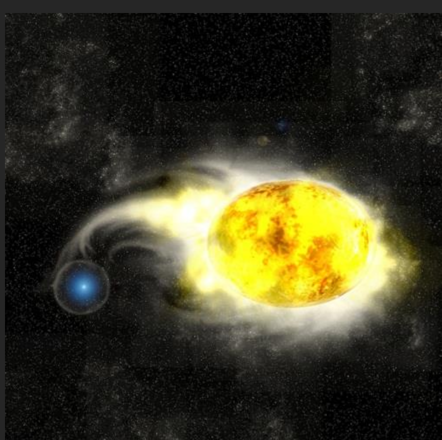
Folatteli+ 14



The other three (four w/gkg) = YSGs



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



Progenitor = YSG
Van Dyk+ 2013

Not considered as a “SN progenitor”, but one third of IIb progenitors! Indication: Binary?

Progenitor radius

days

“post-breakout cooling: Shock-deposited energy”

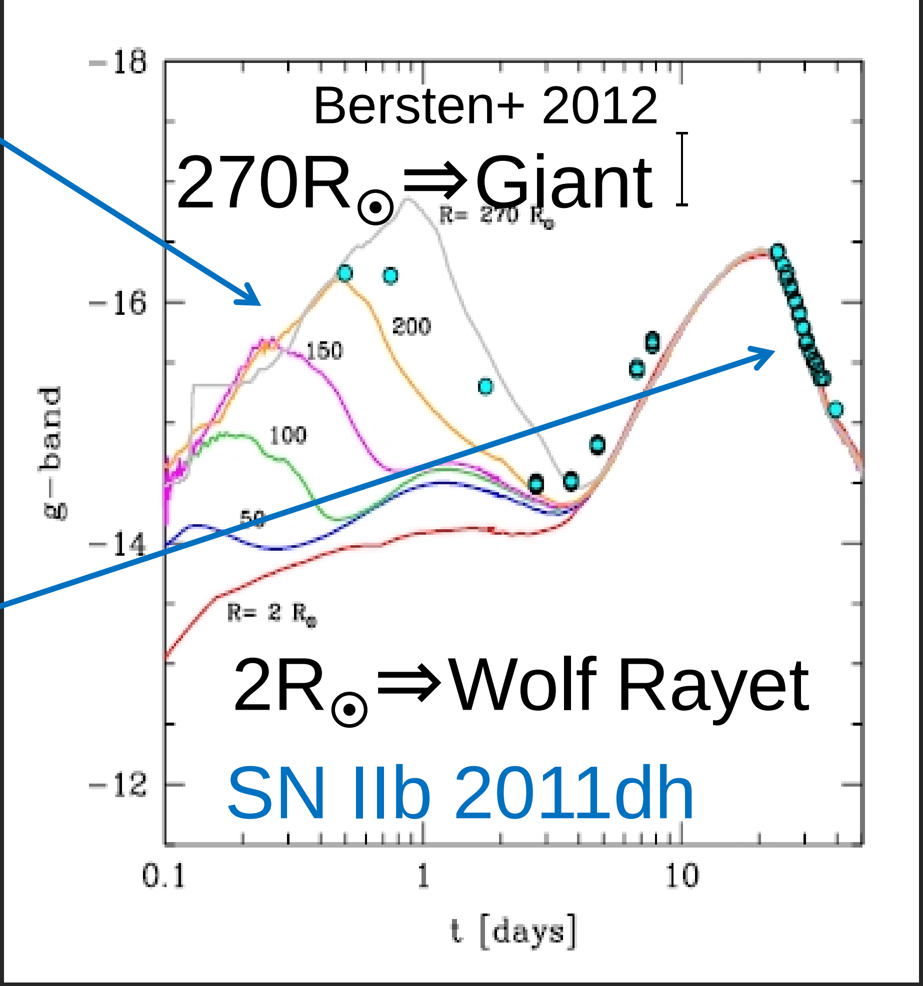
$T \propto (Vt/R_0)$

Brighter for larger

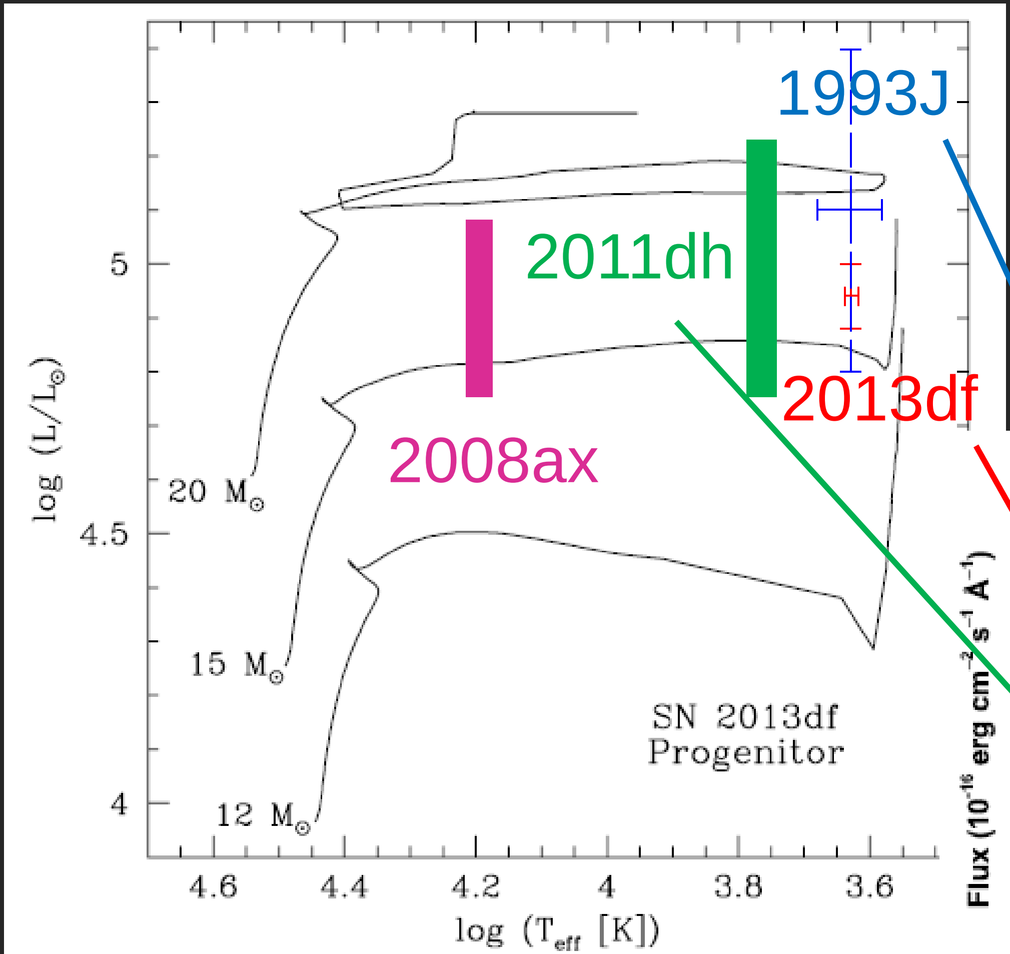
weeks

“^{56}Ni-heating”

No information on the progenitor radius

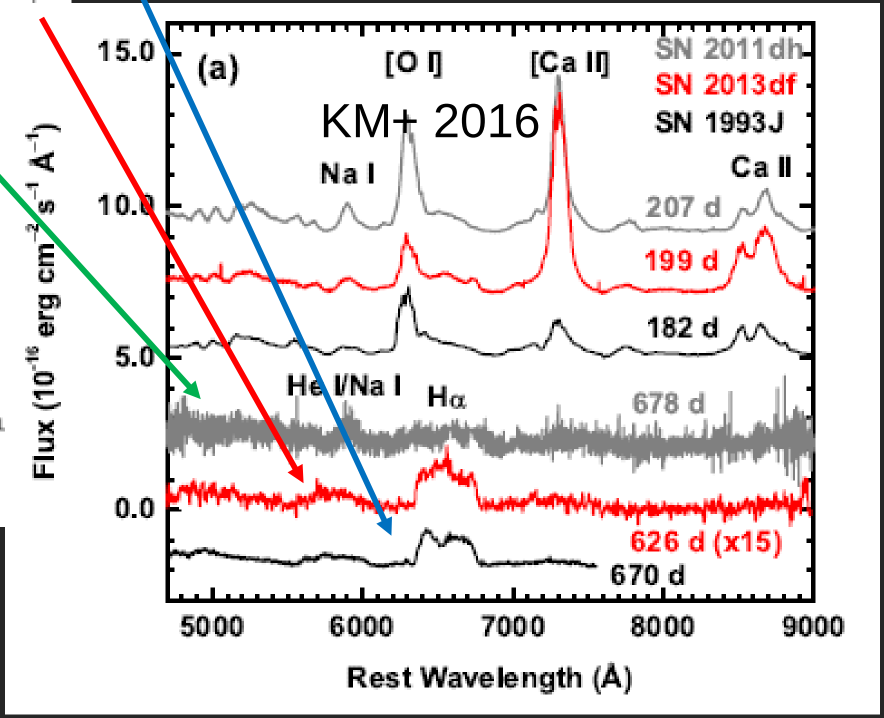


Progenitor HR vs. CSM (in the last 100 yrs)

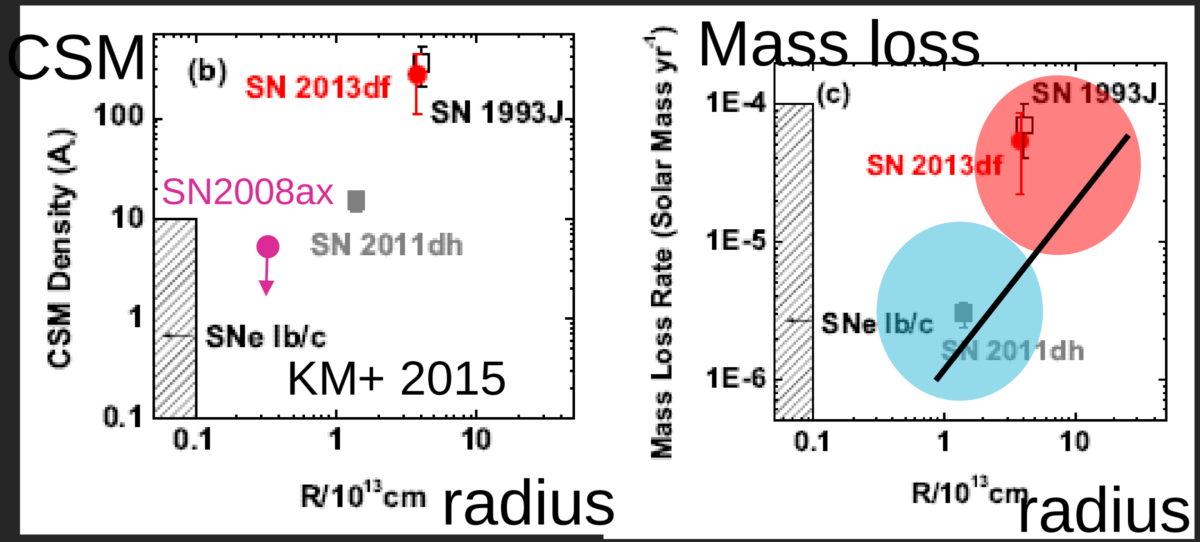


Hα from SN-CSM interaction @ ~ 1 yr

Extended progenitor = massive CSM (mass loss)



Progenitor – CSM relation fro SNe IIb?



Robust estimate of the CSM density by radio/X and/or optical, compared to the direct progenitor detection.

KM+ 2015, 2016

More extended progenitors are associated w/ **larger** mass loss rate?

Note that more extended progenitors tend to have a more massive H-rich envelope (less stripping ⇒ naively, **smaller** mass loss?).

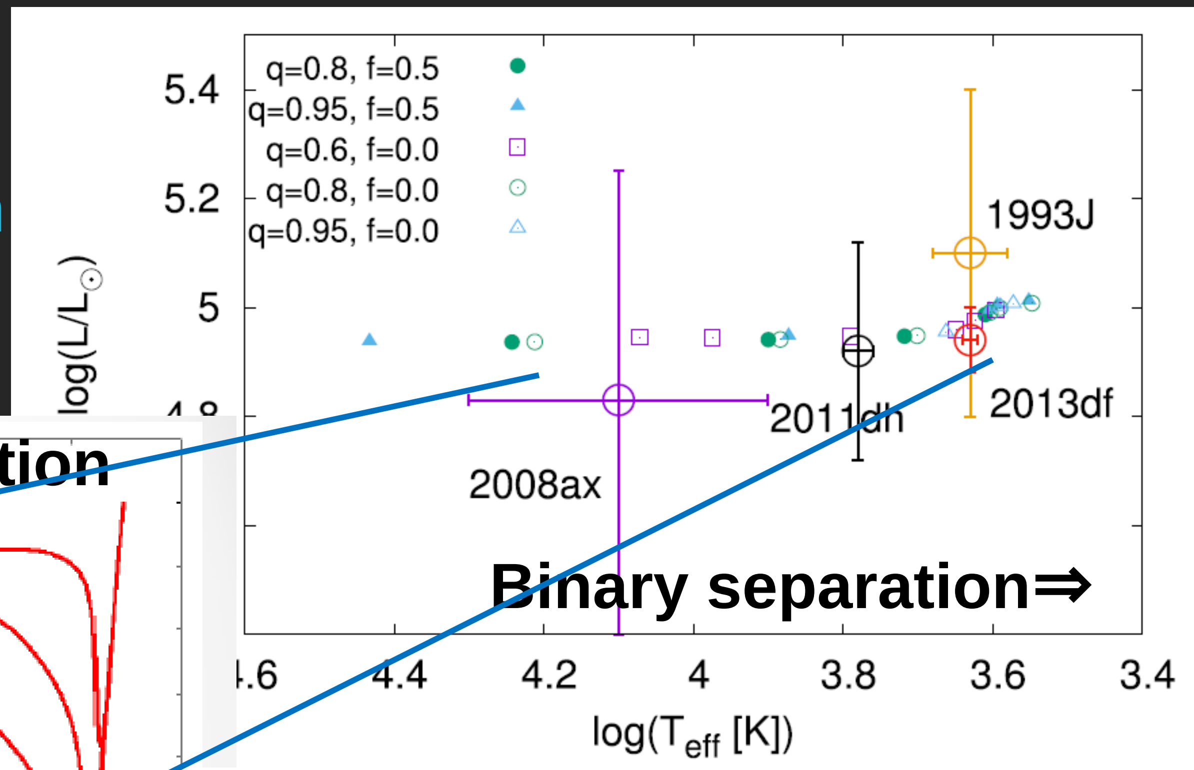
 # It is for the mass loss in the last 100 yrs, not a few yrs.

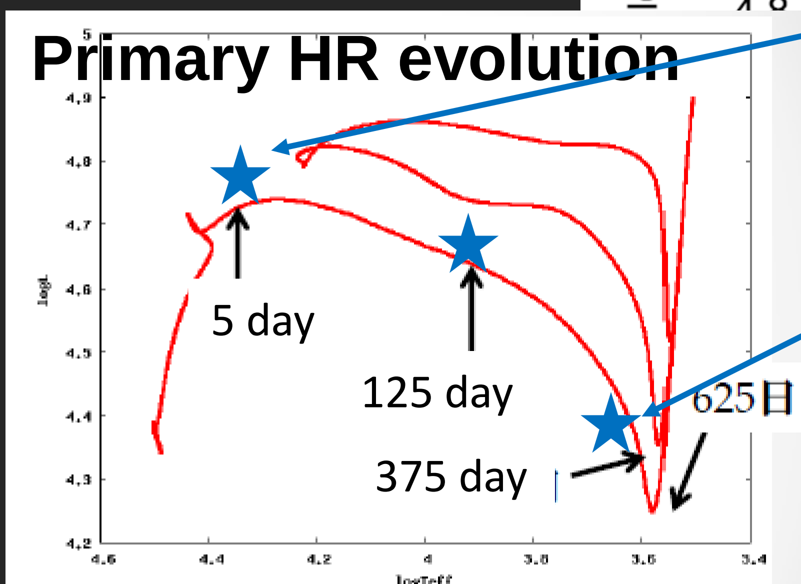
Binary Evolution Model: Progenitors

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

Roche lobe
No common env.
Non-deg. companion

Ouchi & KM 2017



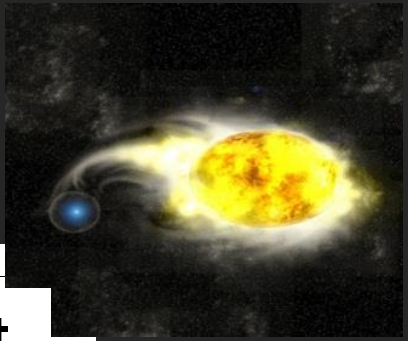


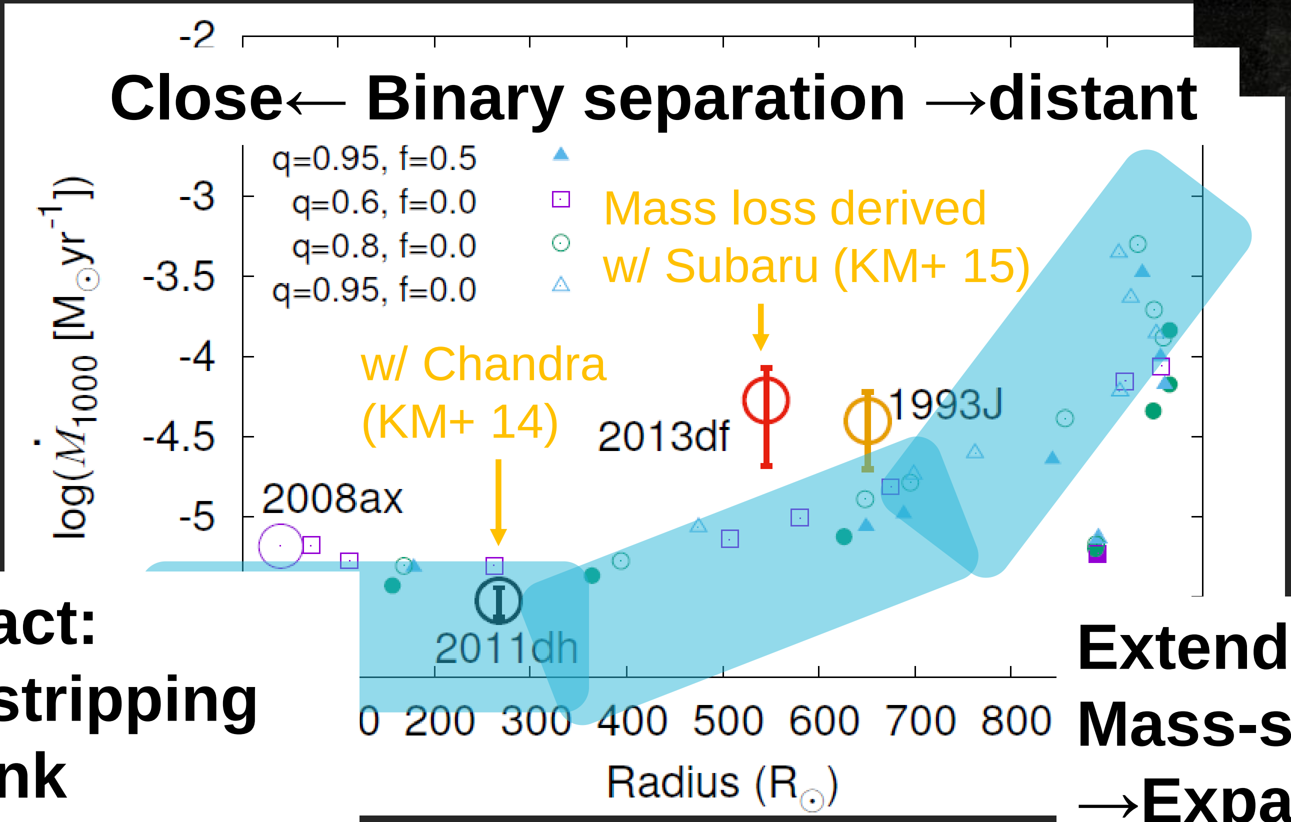
Variation controlled by initial separation (see also Yoon+ 17).

Ouchi & KM 17

Binary Evolution Model: CSM

Progenitor R vs. mass loss





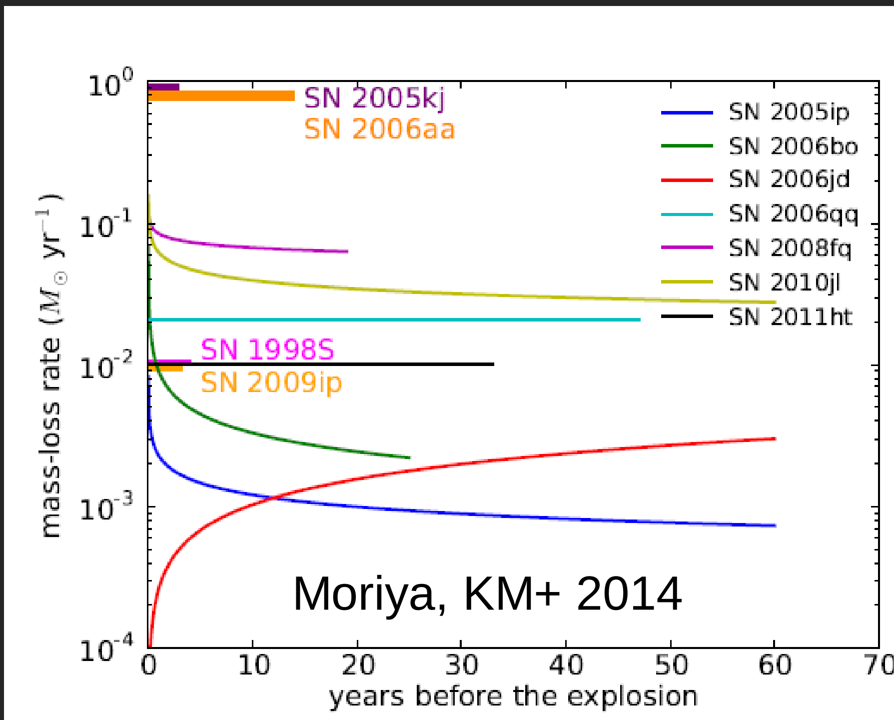
Compact: Mass-stripping →Shrink

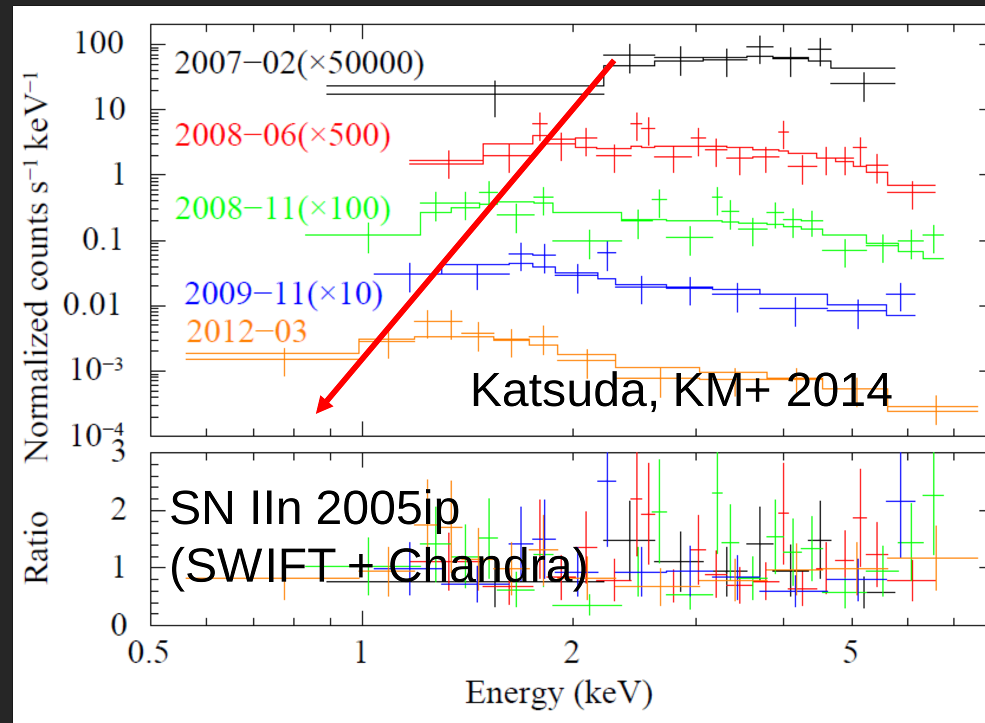
Extended: Mass-stripping →Expand

Binary does predict

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

Beyond the standard mass loss: SNe IIn





Optical light curves for ~ 10 SNe IIn

> 10^{-3} $M_\odot$/yr for all SNe IIn

Mostly steady state mass loss, not eruptive events (≠ LBVs???).

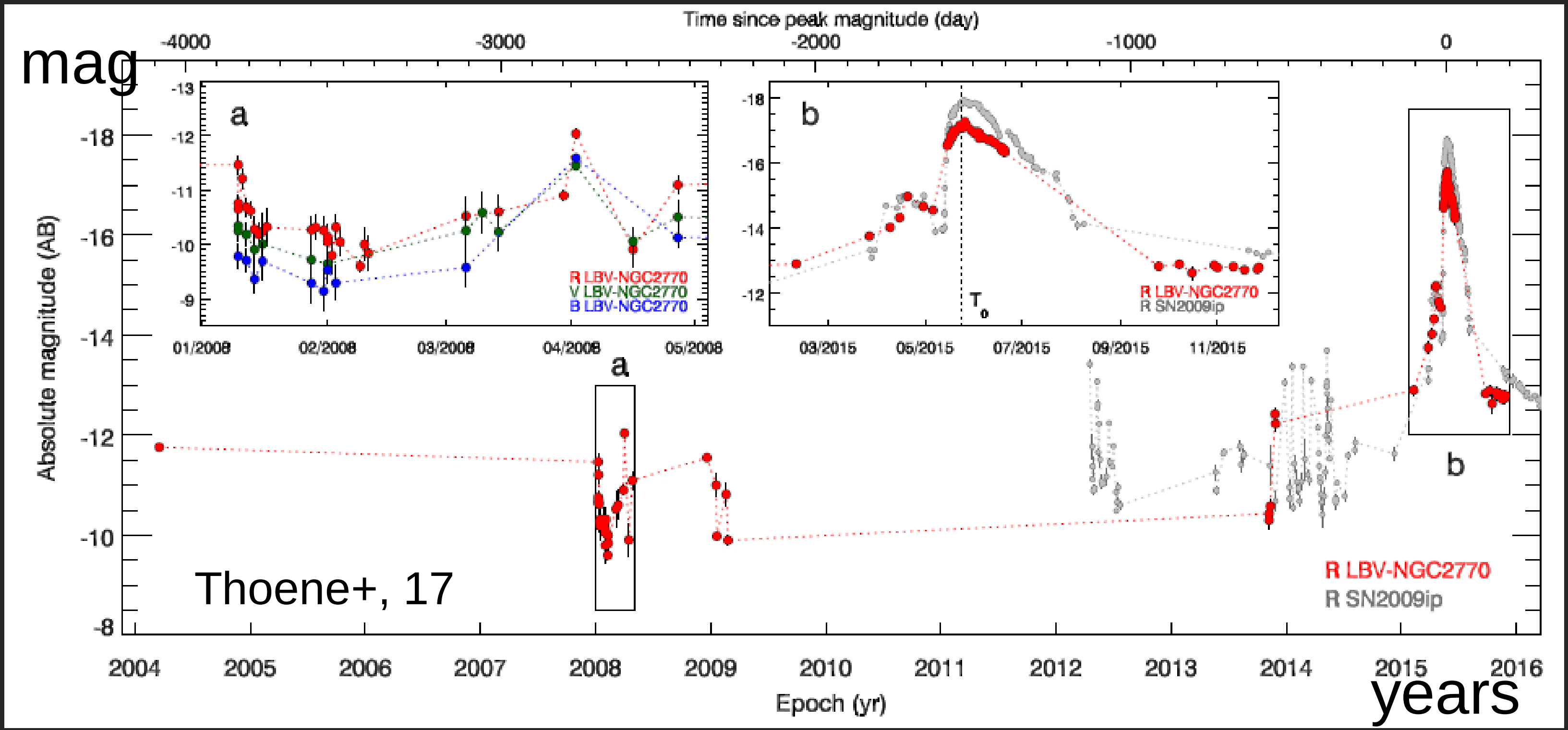
X-rays (rare detection)

~ 10^{-2} $M_\odot$/yr for 2005ip

Decreasing CSM density

e.g., Chandra+ 2012 (2006jd)

Beyond the standard mass loss: pre-SN activity



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

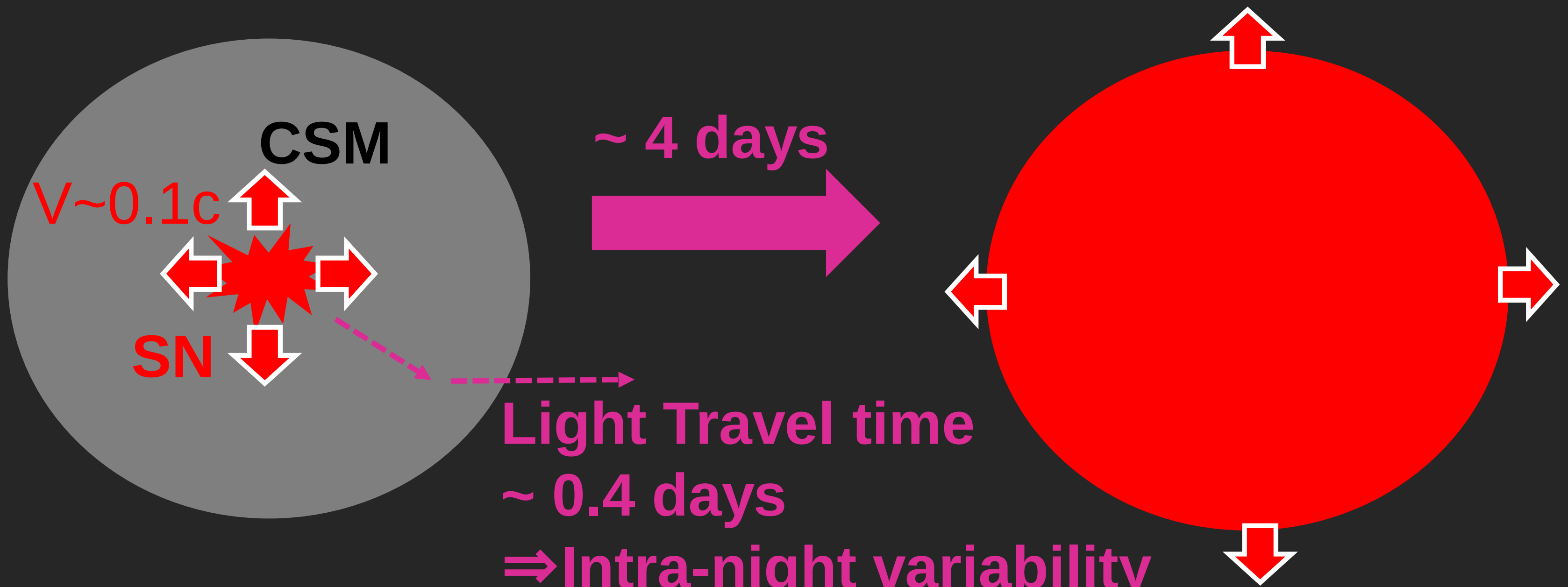
SNe 2009ip (Fraser+15, Graham+17), 2015bh (Elias-Rosa+16, Thoene+17), 2016bdu and 2005gl (Pastorello+17).

SN 2009ip now below the pre-burst luminosity (Thoene+17).

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

Beyond the standard mass loss : the final yrs

- **Final evolution of massive stars may be dynamical w/ non-stationary mass loss in days – years.**



Light Travel time
~ 0.4 days
⇒Intra-night variability possible.

No probe anymore

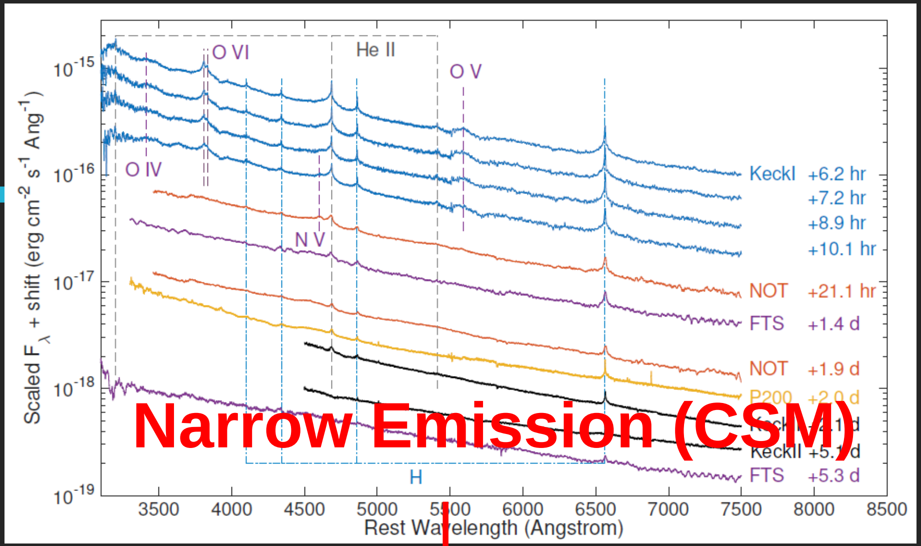
eg. ~10^{15} cm
⇒Mass loss in the final
~100 days (w/ 1,000 km/s: WR)
~30 years (w/ 10 km/s: RSG)

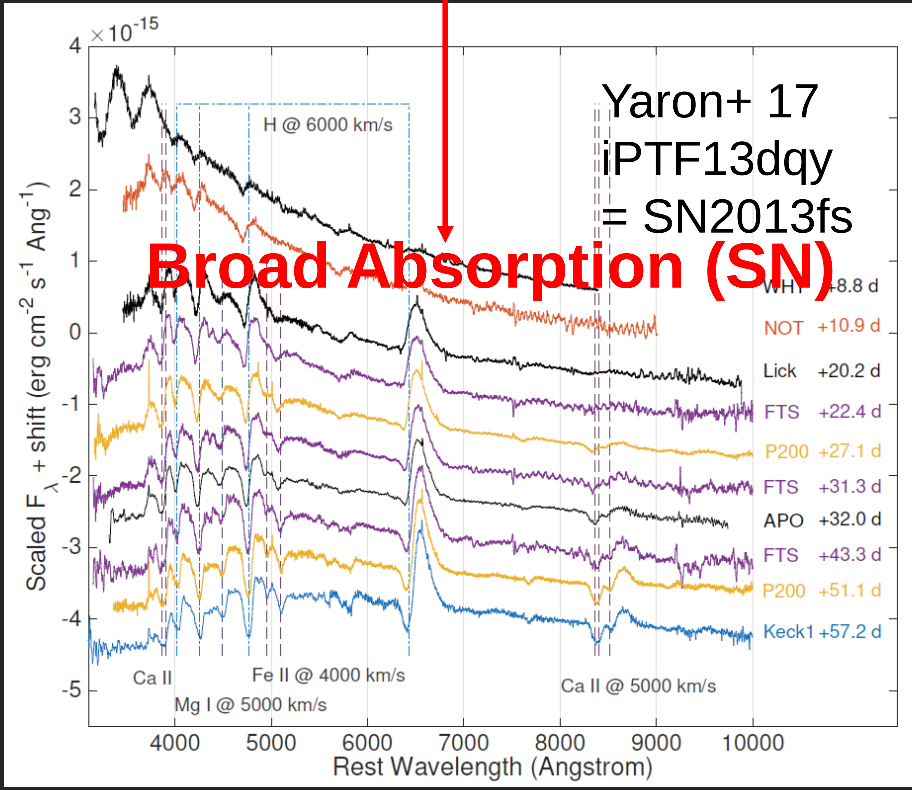
Can potentially be seen in the SN data in the first few days.

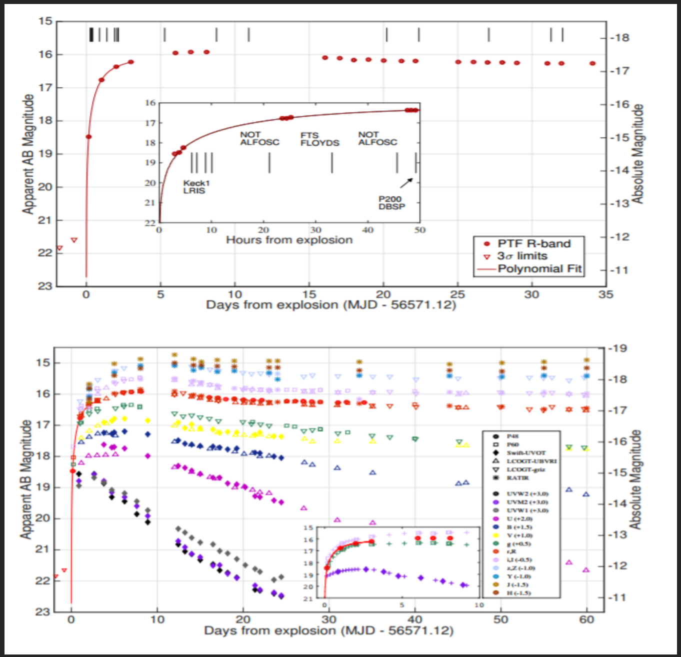
“Flash” spectroscopy

Recombination from the massive CSM near the SN??? （so far detected in one SN Ib and some SNe II）

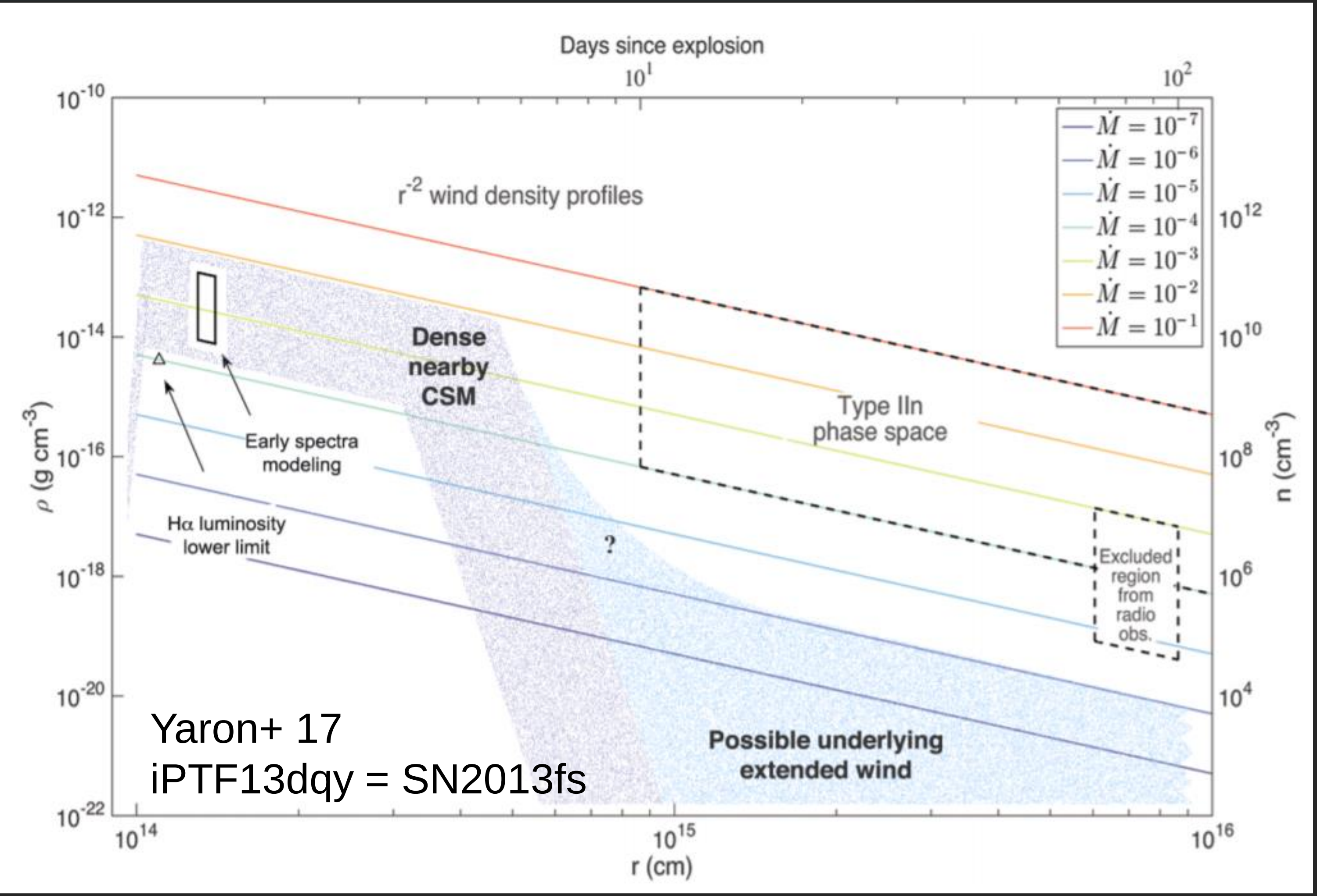
→ **New probe of CSM.**





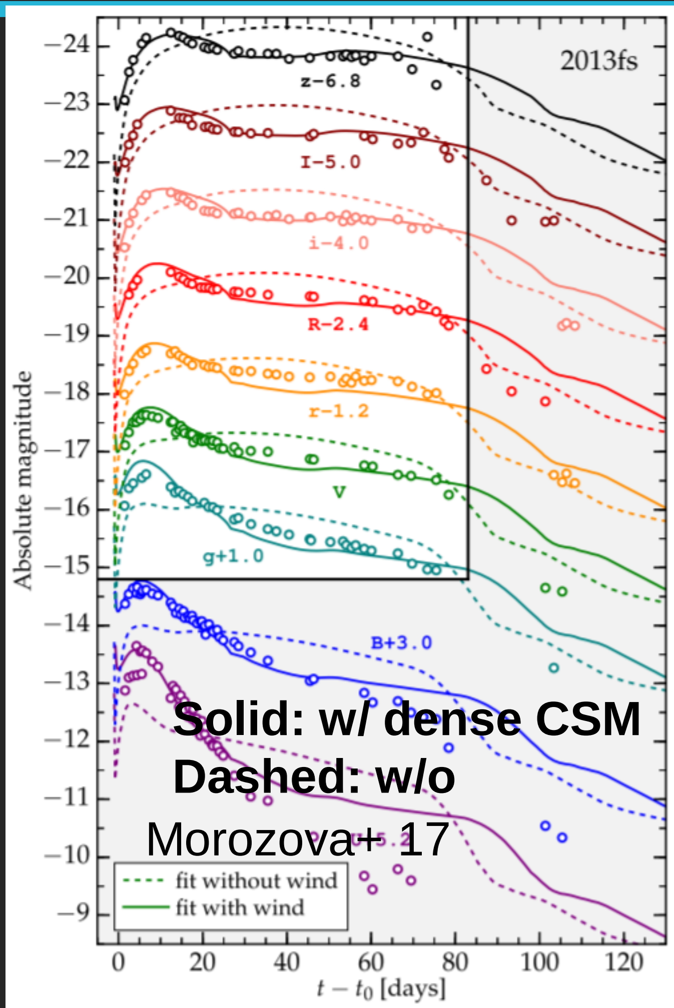


Mass loss in the final days to decades (< 10^{15}cm)

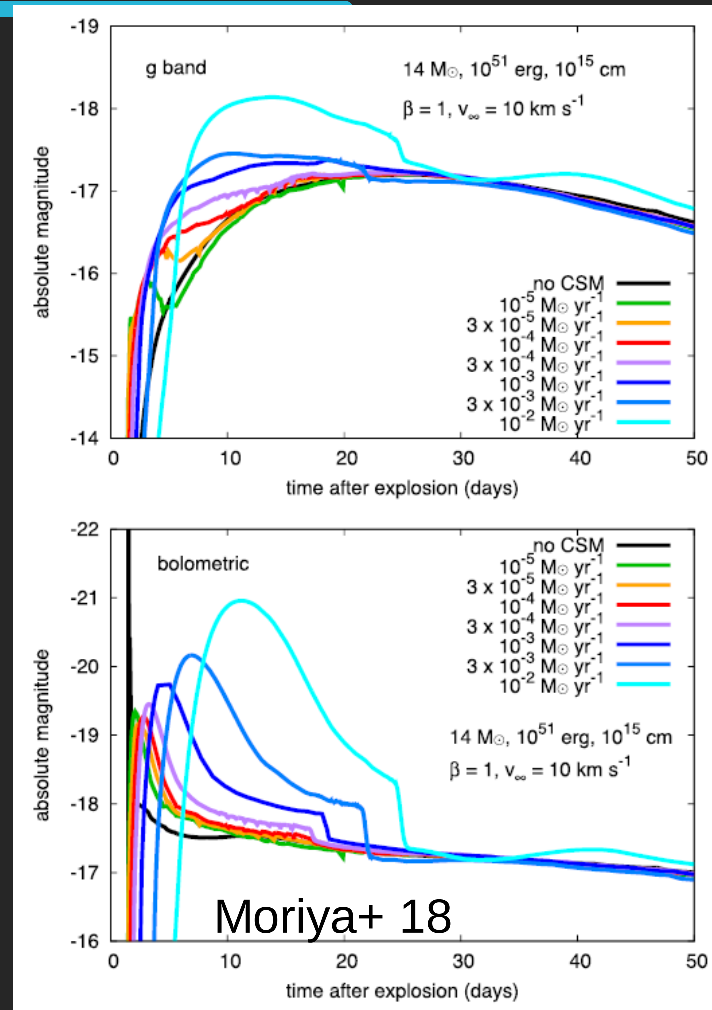


A similar dense & confined CSM may also be there for low-luminosity SNe IIp (a case for SN IIp 2016bkv; Nakaoka+ 18).

Wind breakout common?



SN w/ the “flash spectrum”

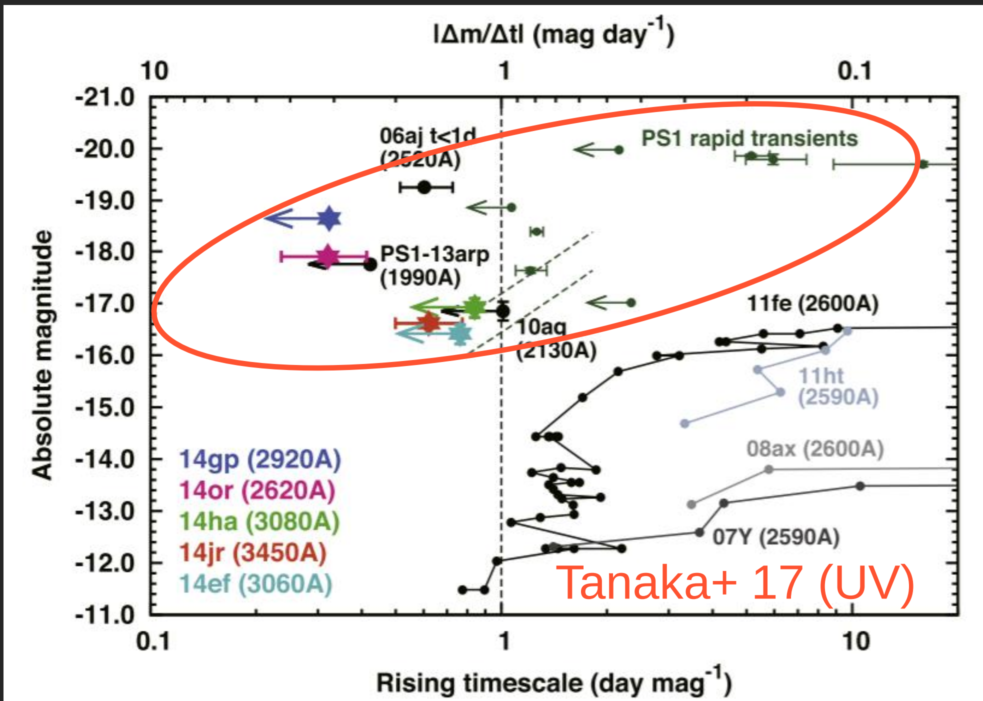


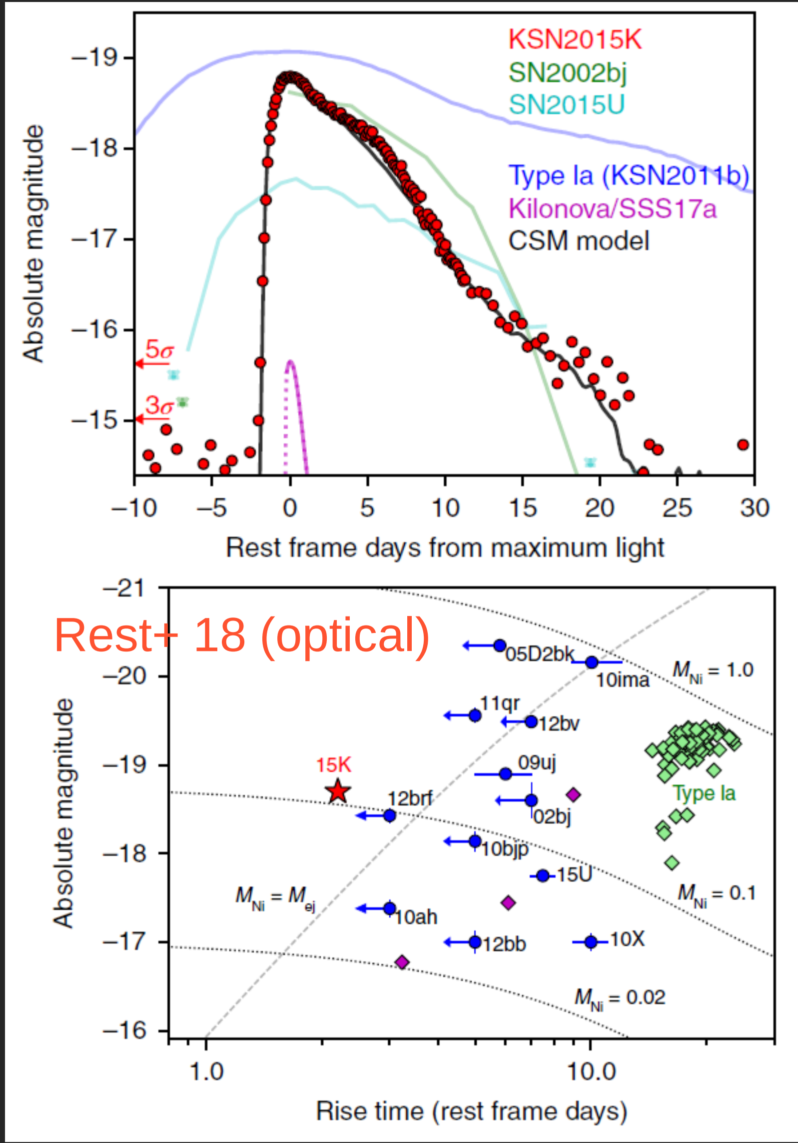
Effect of the dense/confined CSM

We might already be seeing the “wind breakout” for a good fraction of SNe II.

Wind breakout: unidentified candidates?

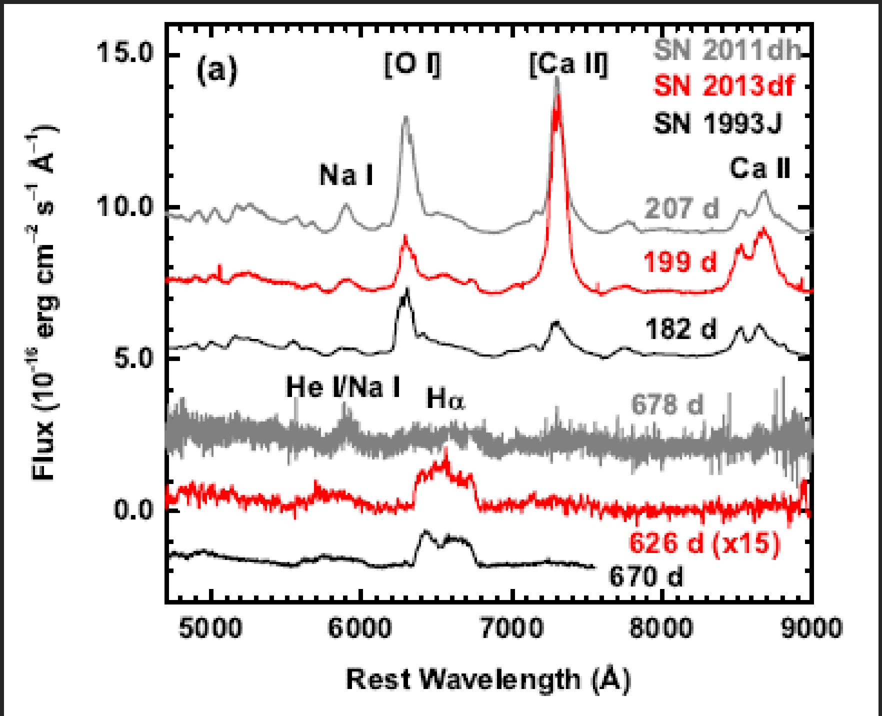
Luminous & Fast Transients

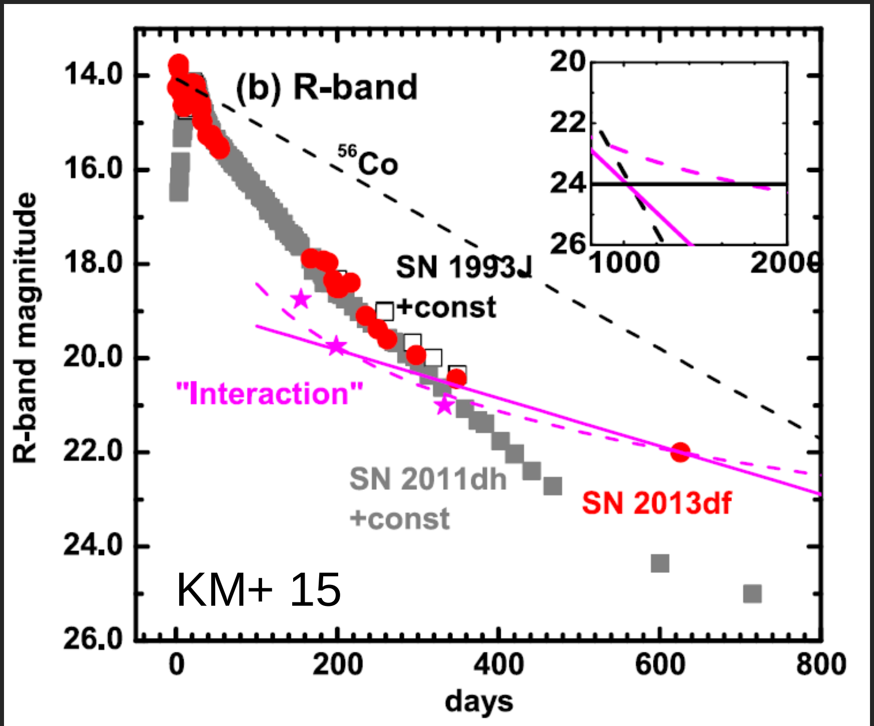




No good statistics yet, perhaps ~ 10% of CC SNe?

SNe IIb w/ strong CSM interaction





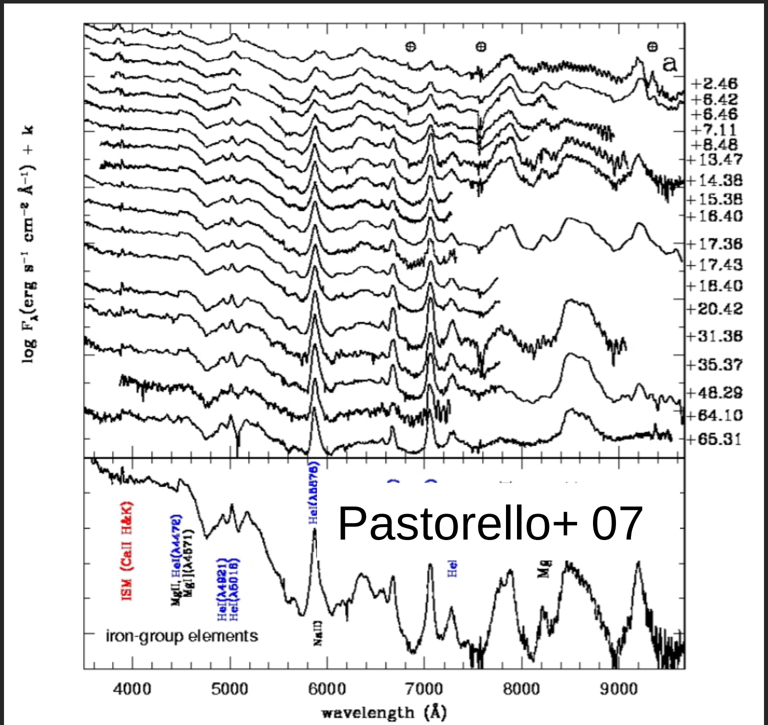
SNe Iib 1993J & 2013df: CSM interaction visible at ~ 1 year.

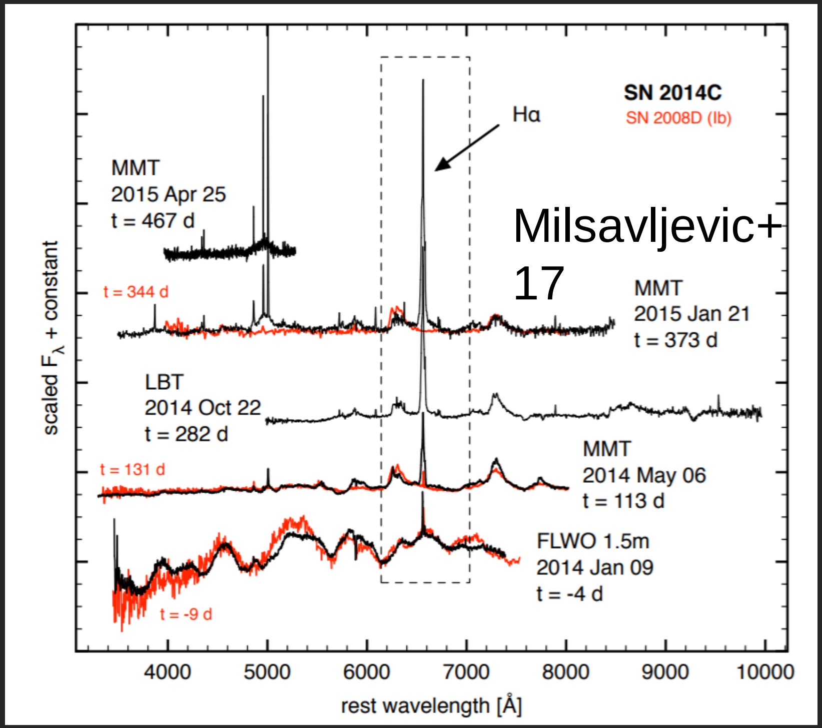
It is consistent with the smooth r^{-2} distribution,

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

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

SNe Ib w/ strong CSM interactoin



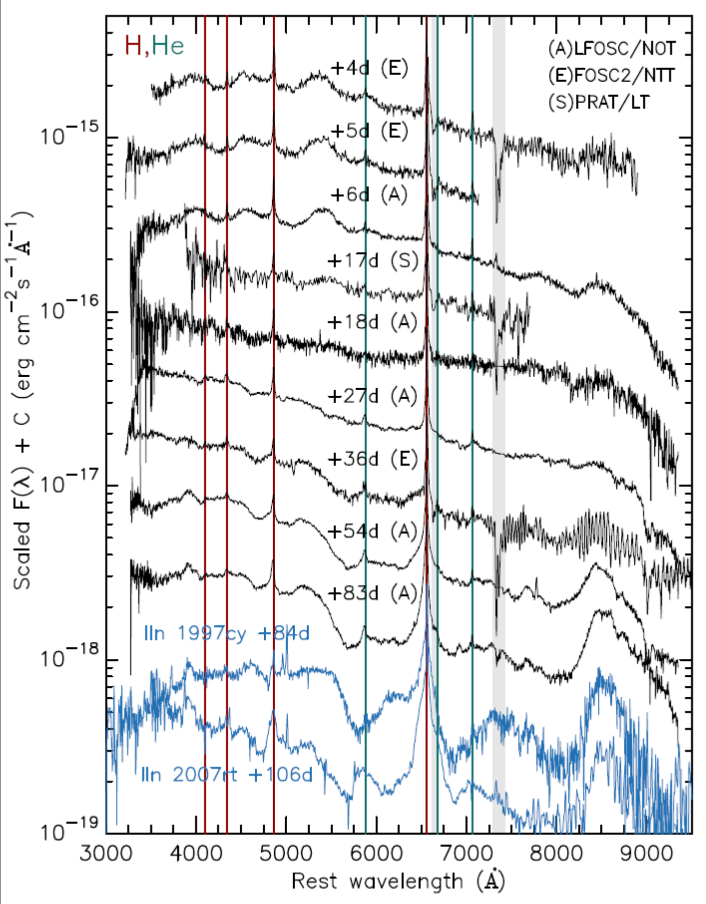


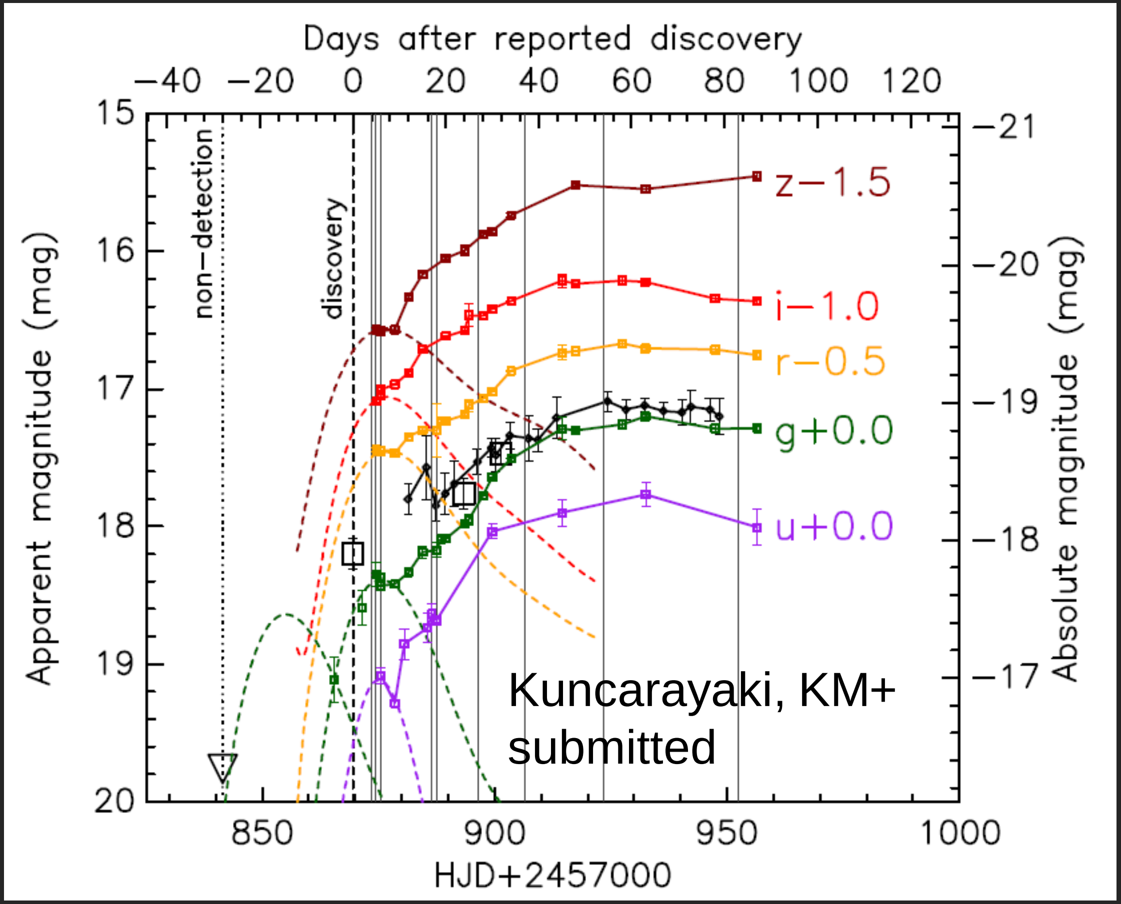
SN “Ibn” 2006jc: He emission lines (He-rich CSM).
Pre-burst in 2004

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

WR explosion crushing into H/He-rich CSM.

SN Ic w/ strong CSM interaction





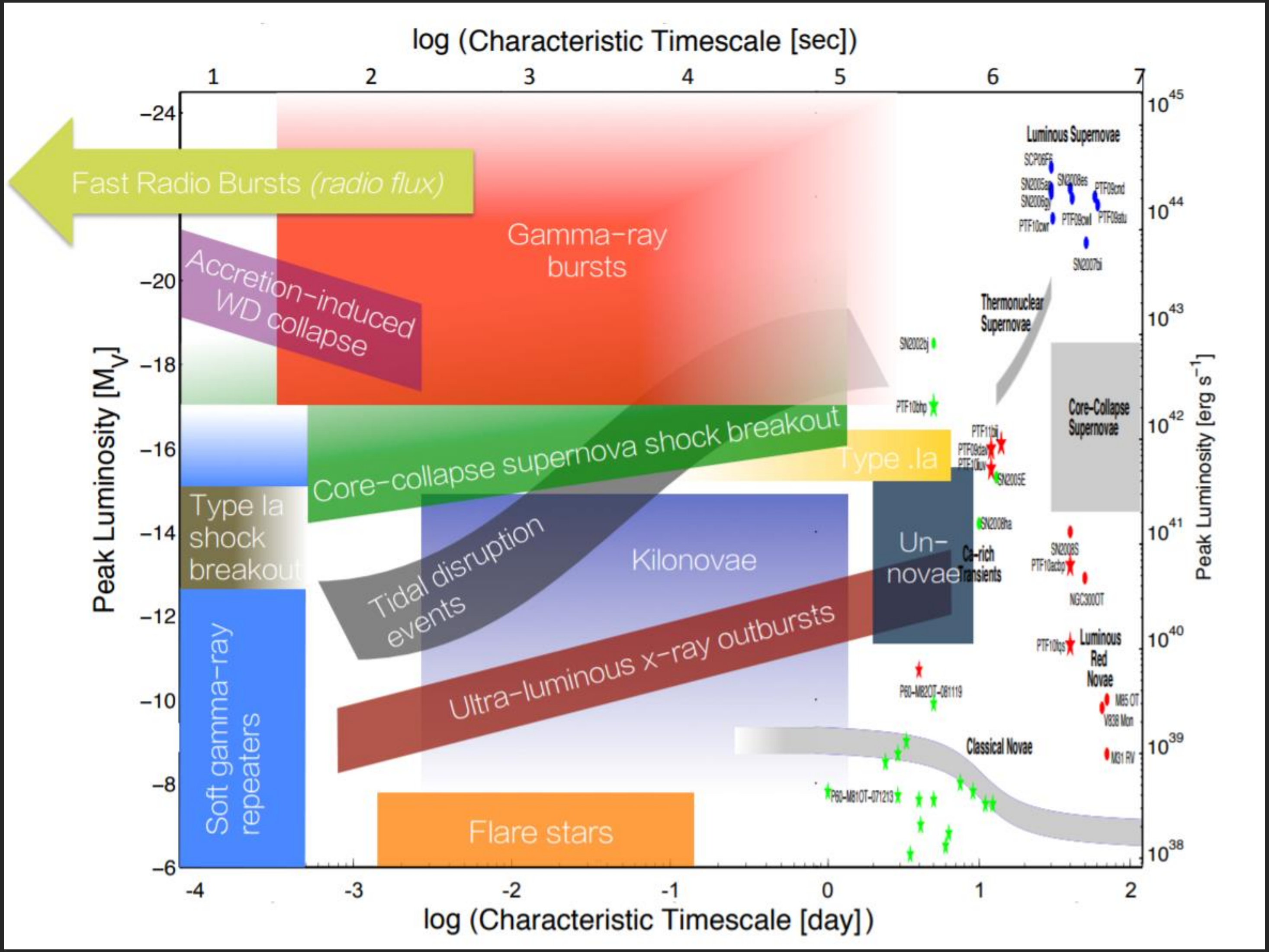
SN Ic 2017dio: SN Ic, evolved into SN IIn in a month.

CSM increasing outward.

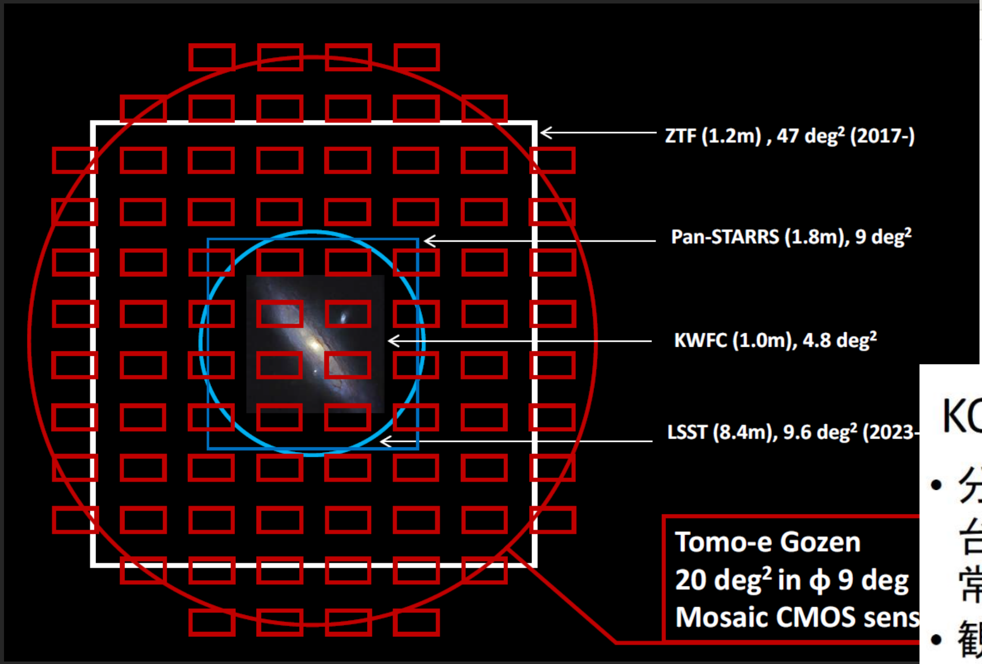
Some SNe IIn may host SNe Ic (WR, C+O).

New Time-Domain

Cooke+ 2015



Prospects for observations (2018-)



朝日新聞 DIGITAL

トップニュース　スポーツ　カルチャー　特集・連載　オピニオン　ラ

新着　天声人語　社会　政治　経済・マネー　国際　テック＆サイエンス　環境・エネルギー　地域　朝

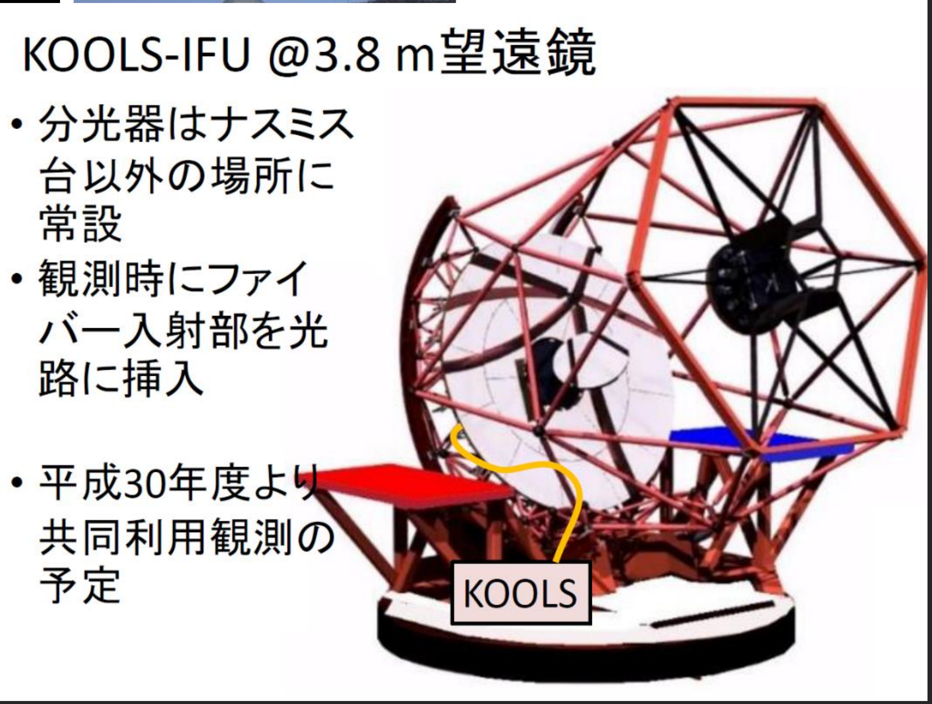
朝日新聞デジタル ＞ 記事　　社会　サイエンス　宇宙・天文

京大望遠鏡、愛称「せいめい」　陰陽師安倍晴明にちなみ

野中良祐　2018年4月19日10時30分

シェア 0　ツイート list　B!ブックマーク 6　メール　印刷

京都大は１８日、岡山県内で今夏から観測を始める東アジア最大の望遠鏡について、愛称を「せいめい」に決めたと発表



Hope to develop a key project on “rapid discovery + quick SN follow-up”.

Summary: Breakout – Progenitor -CSM

- Mutually linked, a big unresolved problem.
- Shock Breakout:
  - **Robust candidates: RSG (IIp), WR+wind (Ib), YSG (IIb).**
  - **Basics of SB calibrated by SN IIb 2016gkg.**
- Progenitor:
  - **Well calibrated for SNe IIp (confirm) and IIb (surprise).**
  - **Only a few candidates for SNe Ib/Ic.**
- CSM:
  - **The final yrs yet to be understood.**
  - **Relations to Progenitor/ SN types (beyond IIn) and SB?**