電磁波で探る超新星の性質

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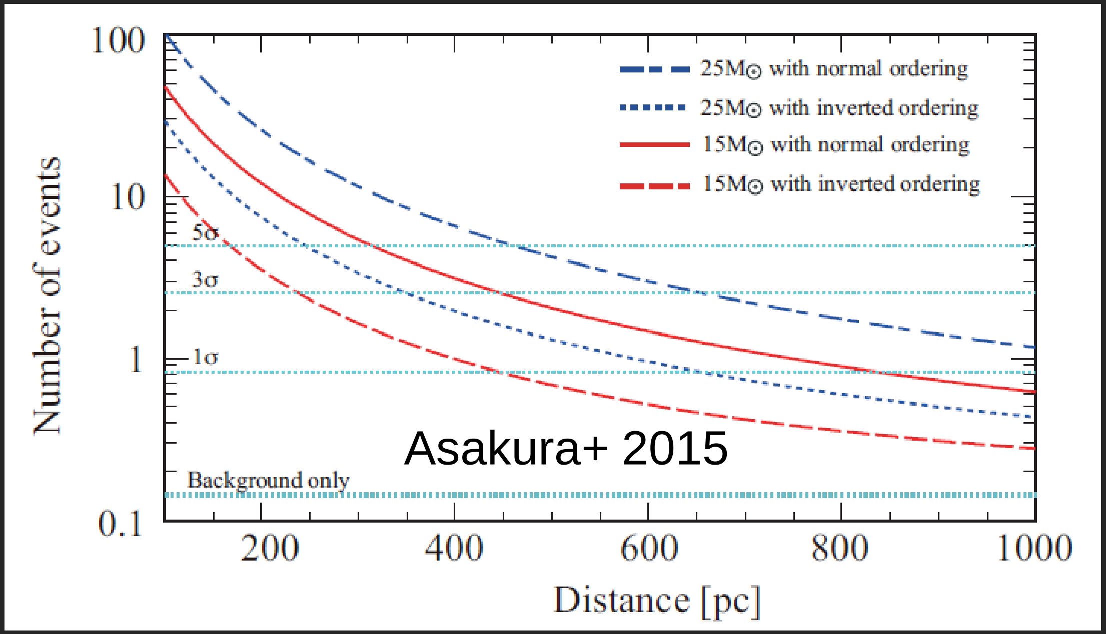
第2回超新星ニュートリノ研究会, 2016/1/6-7

Let's Go Supernova: A putative SN at ~200pc

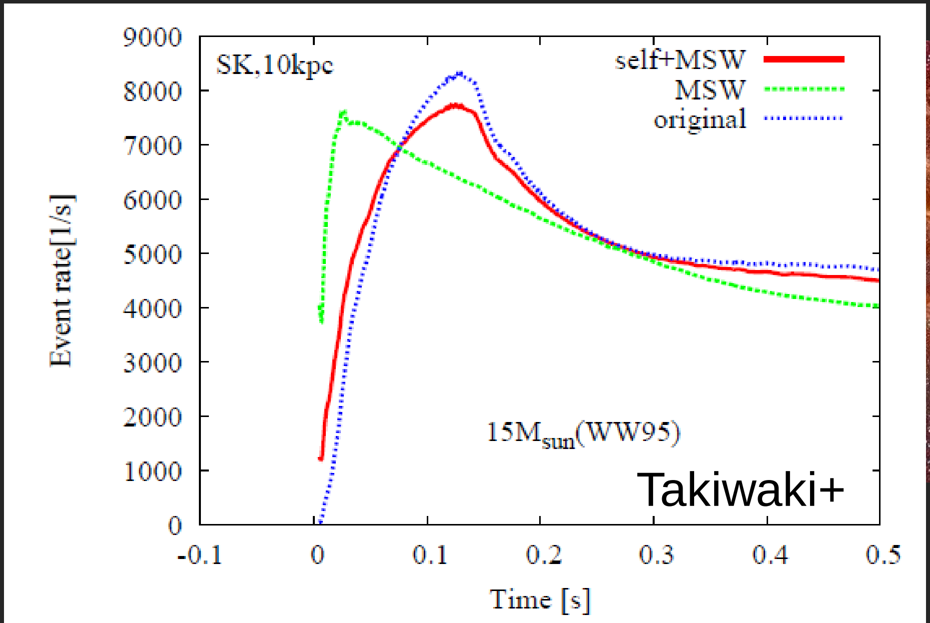
- Pre-SN neutrinos.

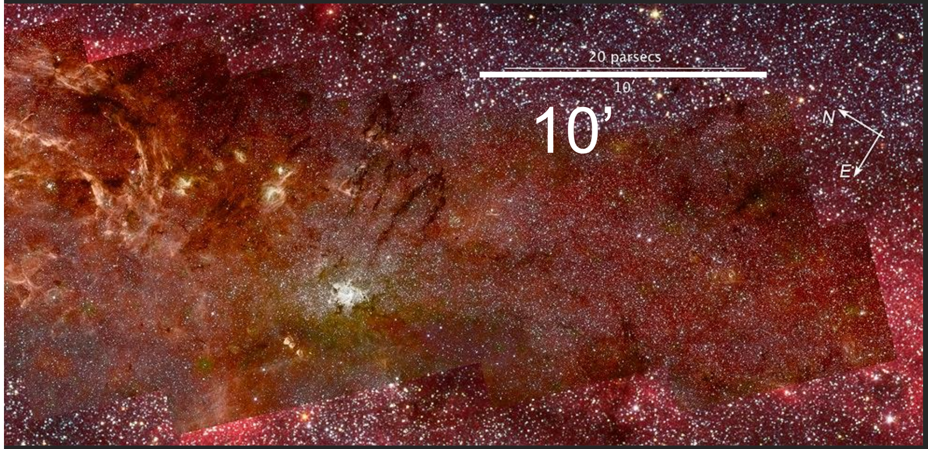


- Identifying the star to explode **before a few days** (will not be many optical counterparts, relatively easy).

⇒A wealth of information on a **progenitor** and explosion.

Let’s Go Supernova: at the Gal. Center (~8 kpc)

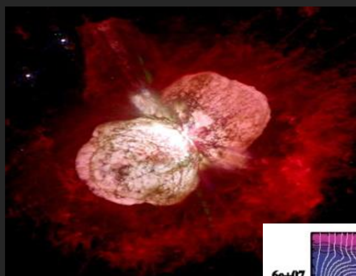




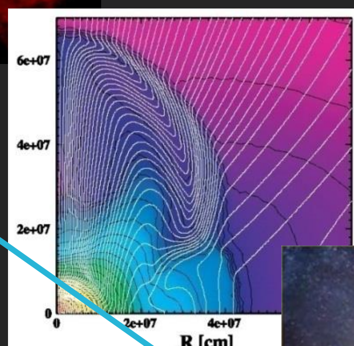
- Identifying the moment of an SN **before EM signals** (will be many stars + huge absorption ⇒ wide-field NIR/X-ray follow-up better than optical?).

⇒A wealth of information on a progenitor and **explosion**.

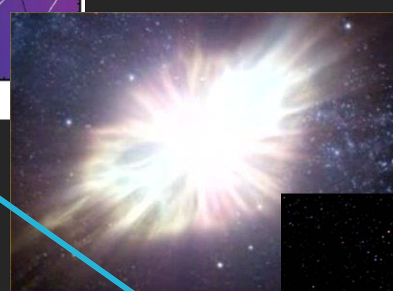
Evolution of SNe and observational signatures



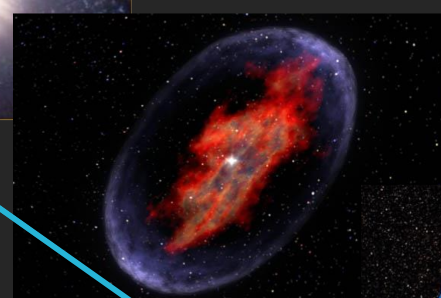
Opt-IR
ν



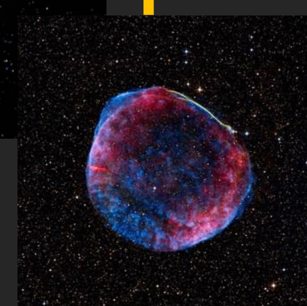
GW
ν



UV-X



Opt-IR
Radio, X
γ



Opt-IR
Radio
X
VHE γ

ms - sec

sec - day

day - year

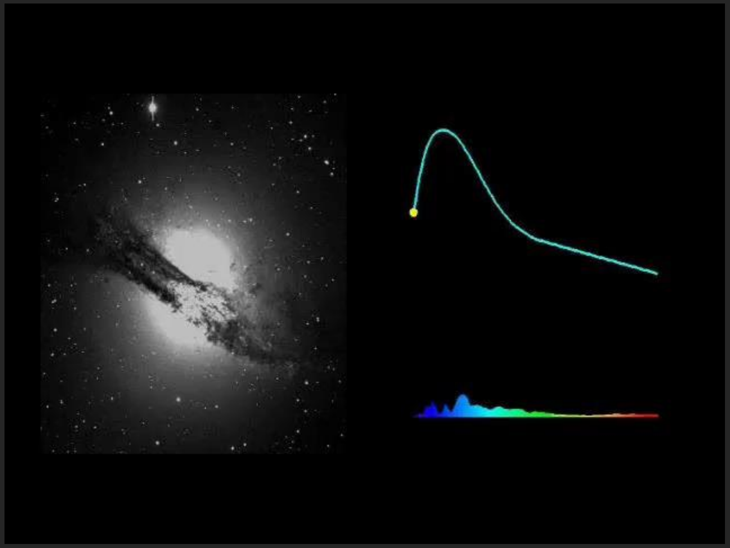
decade - centuries

Observational Characteristics of Supernovae

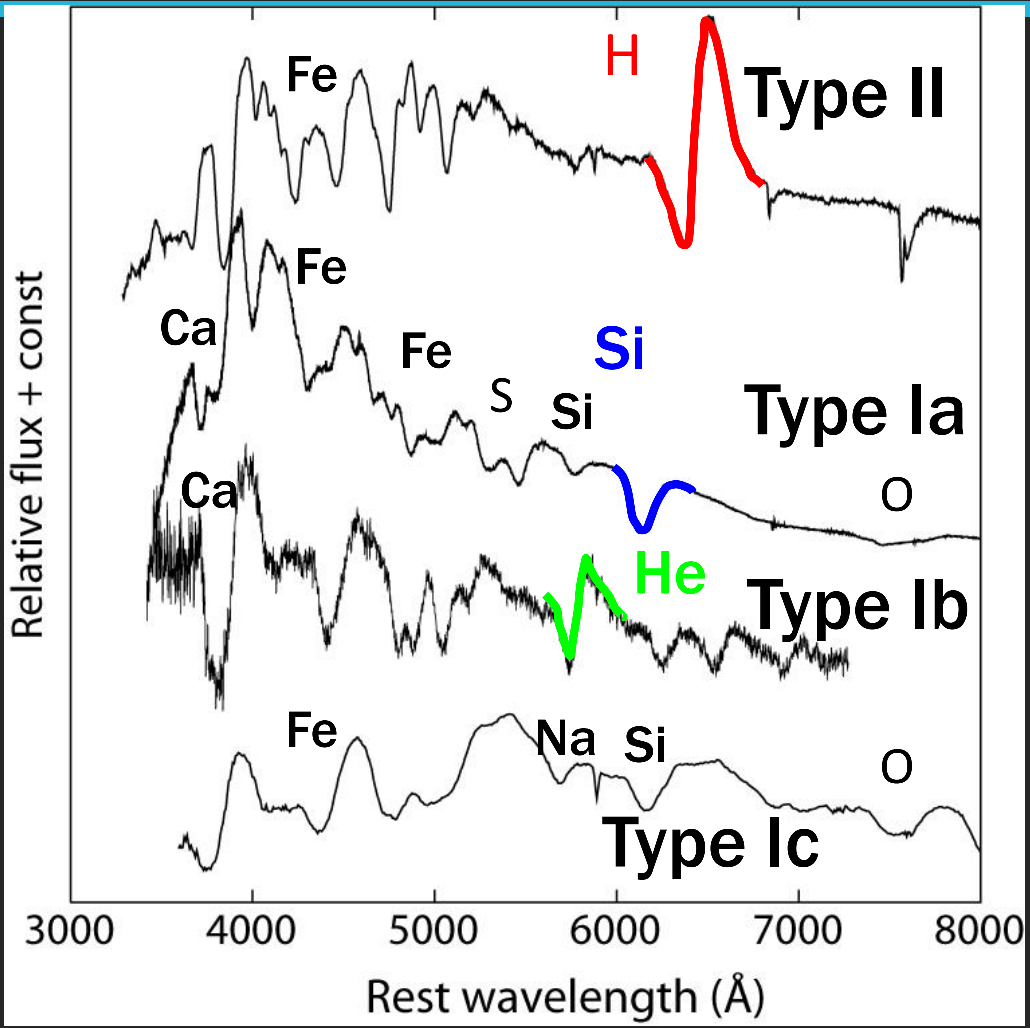
- \> 1000 discoveries a year (dep. on surveys).
  - **Only a part** (nearby) observed in detail.
- Distance > ~ 10 Mpc (extragalactic).
  - **Point sources** (except for a few by HST/AO/VLBI).
  - Typical maximum mag. V > ~ 16 mag（roughly）.
- Most of obs. = Optical.
  - Imaging + spectra (time-dep.)

⬇ Interpretation

Supernova Physics
（e.g., exp. mech.）



Supernova Classification

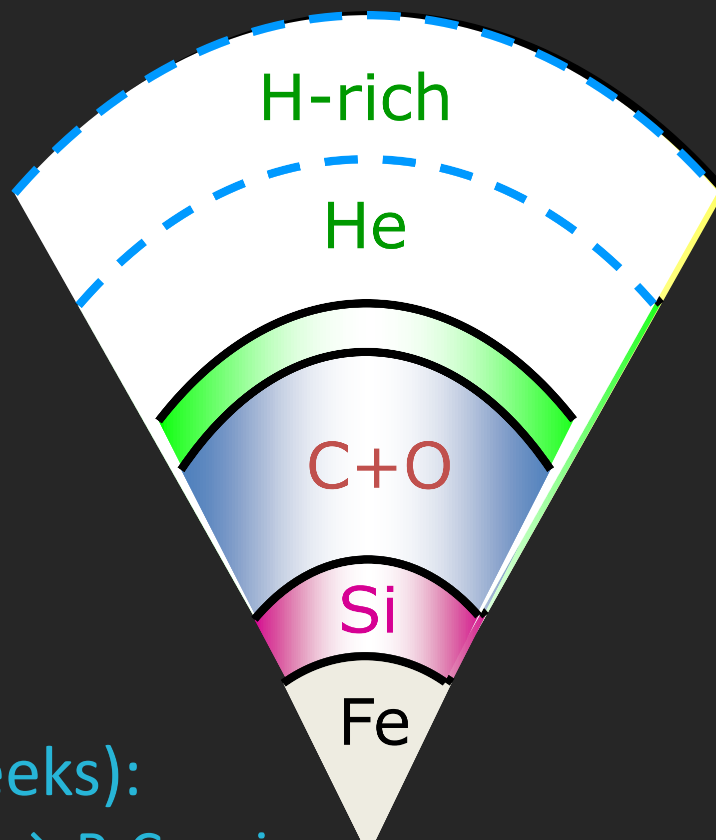


Ia

Thermonuclear exp. of a white dwarf (WD)

II/Ib/Ic

Core-Collapse (CC) of a massive star



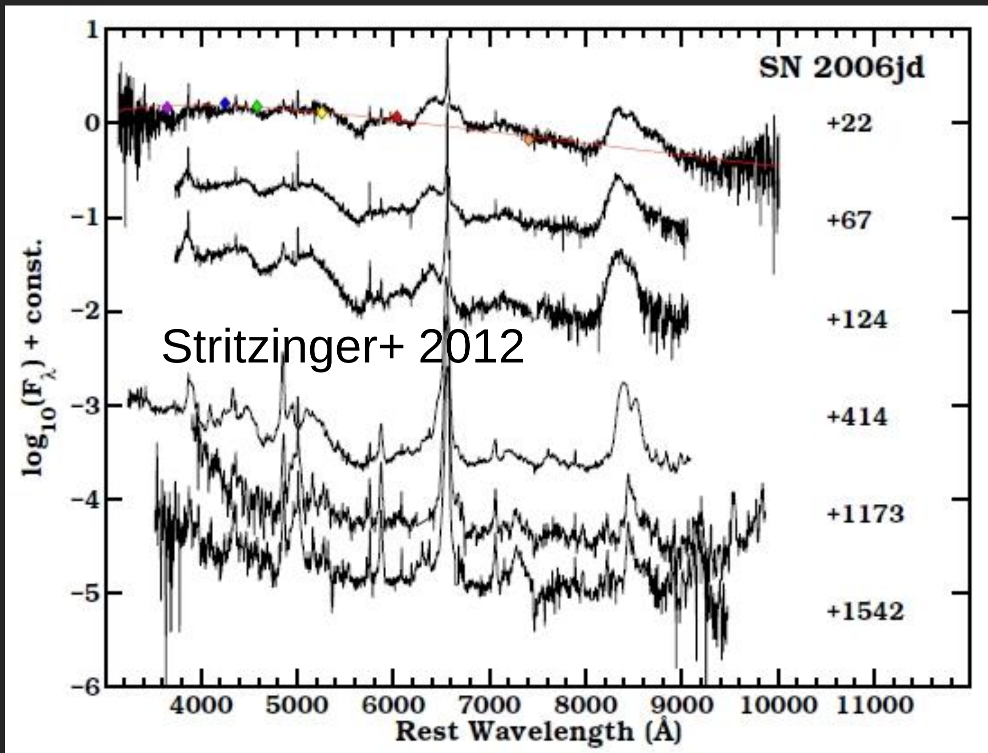
@ maximum brightness (~ a few weeks):

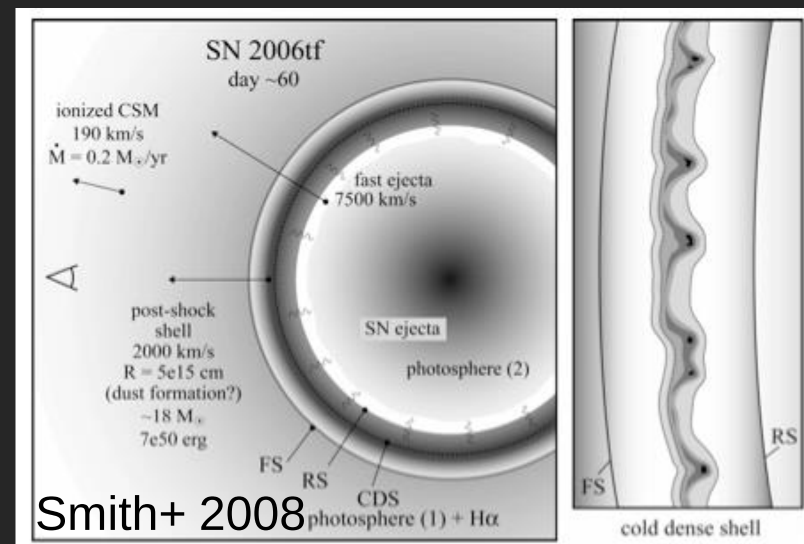
– Expanding optically thick medium → P-Cygni.

SN Classification

IIn

Core-Collapse (CC) of a massive star



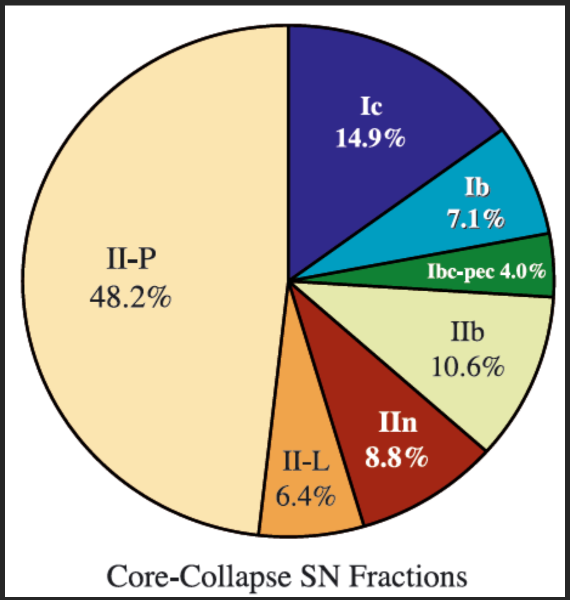


Emission lines of hydrogen

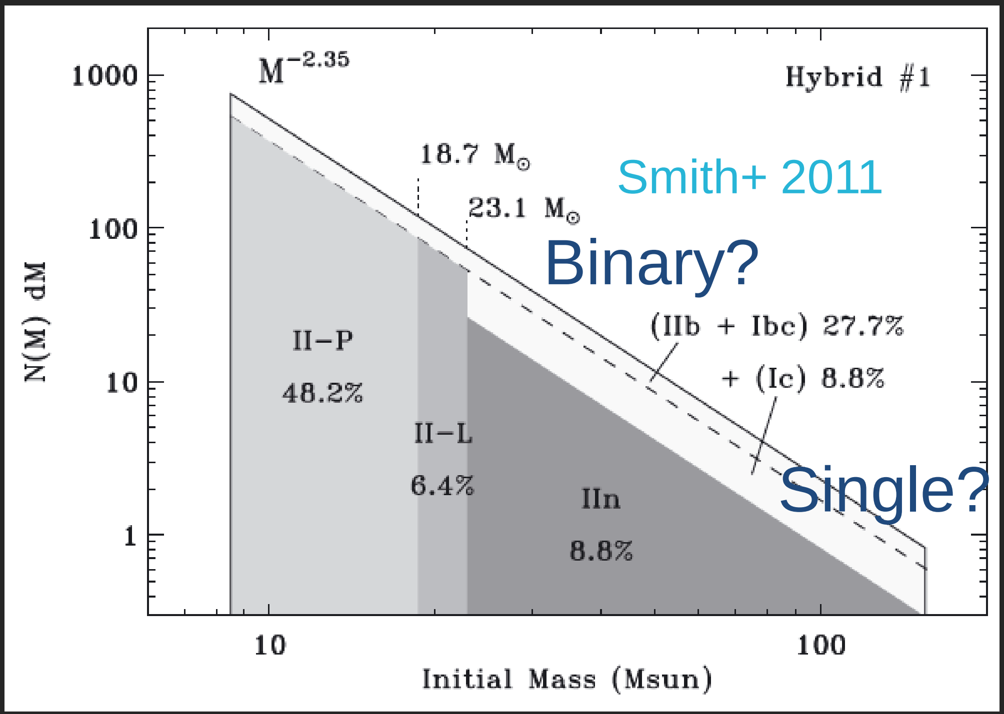
⇒ **Interaction-powered** (Crash between the SN ejecta and CSM, i.e., pre-SN wind/mass loss)

The nature of SN material is largely hidden.

End of massive star's life (observationally)



Nearby Volume-limited sample
(Core-collapse only: Li+ 2011)



Mass loss (wind or binary):

IIn: explosions of what? Huge mass loss: ???

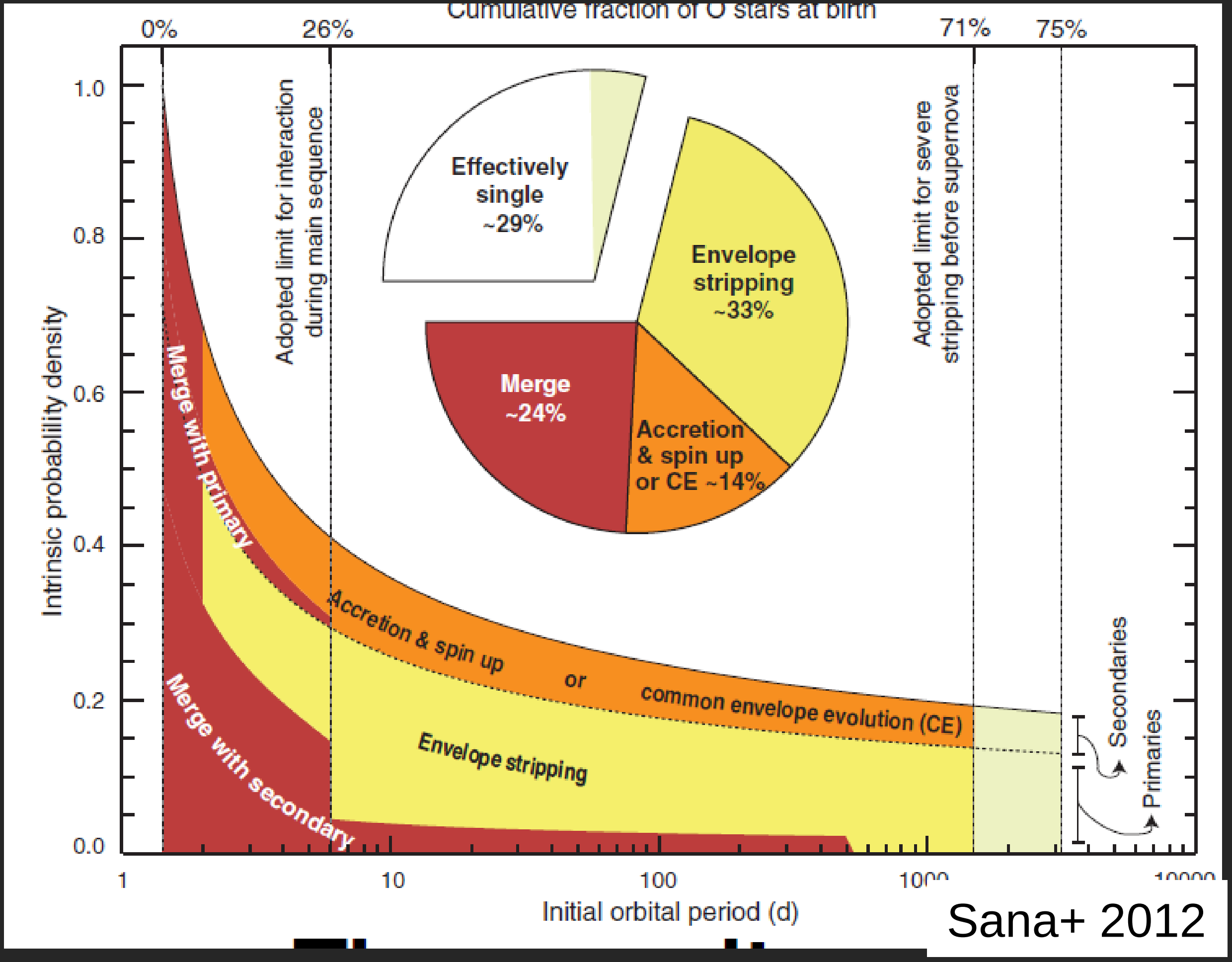
Ib/Ic: explosions of He/C+O stars (Wolf-Rayet, WR?): Small

IIb: A small amount of H-envelope (< 1 $M_\odot$): Medium?

IIp/IIL: explosions of RSGs (Red SuperGiants): Large

Binary Important, but not well-known

Fraction of binary interaction

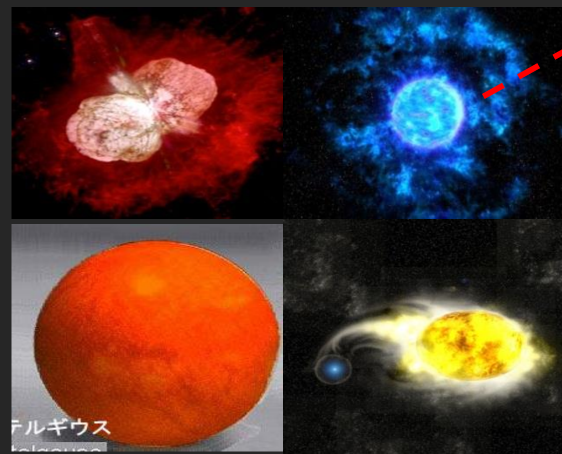


Initial orbital period

More than half of massive stars experience strong binary interaction during their evolution.

Progenitor – CSM - Explosion

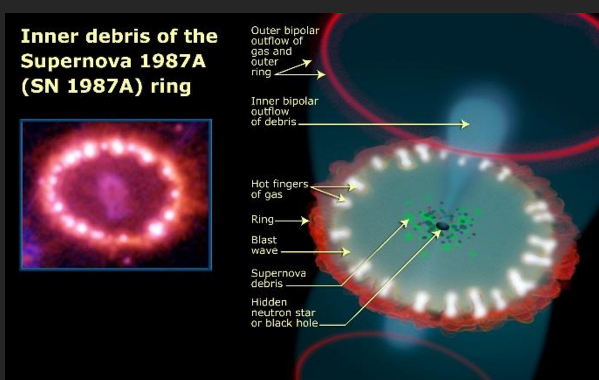
Neutrinos



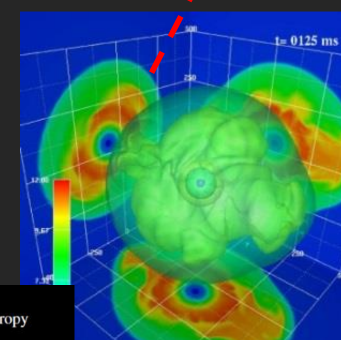
Mass
Metallicity
Rotation
Binary
…

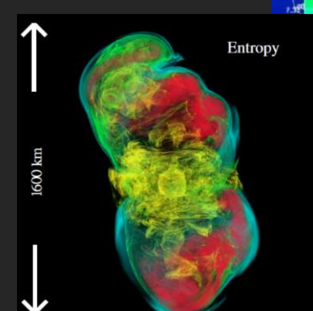
Neutrinos

Mass loss by
stellar wind
Instabilities
Binary



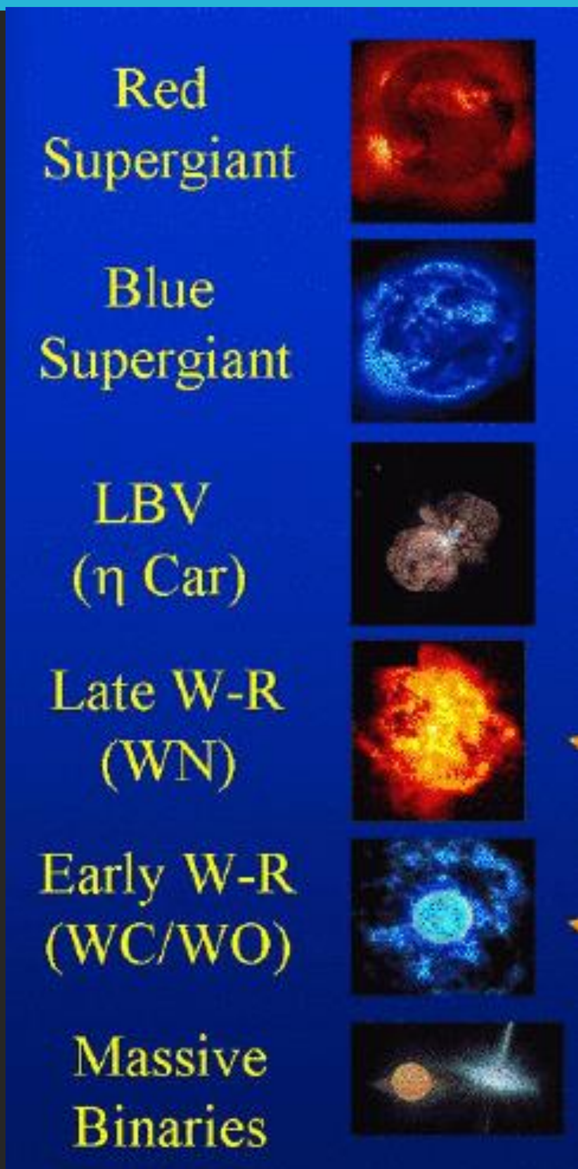
Diversity within the same mechanism.
Even different mechanisms.



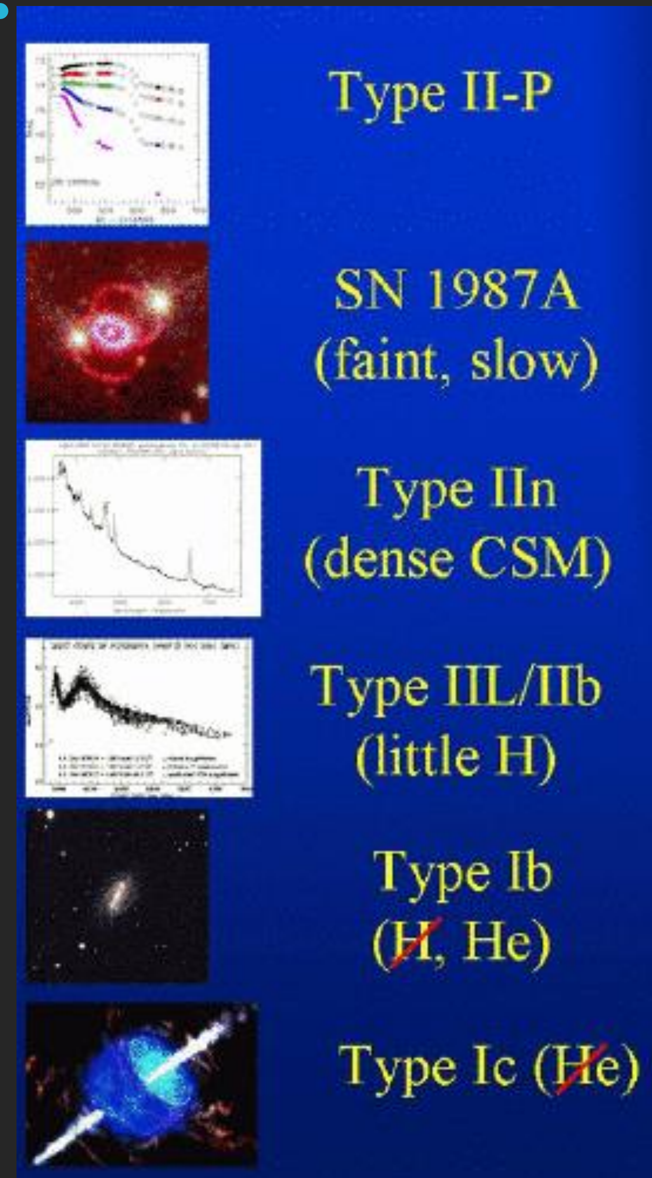


Observations of supernova progenitors (and progenitor systems)

Progenitors ⇔ Supernovae

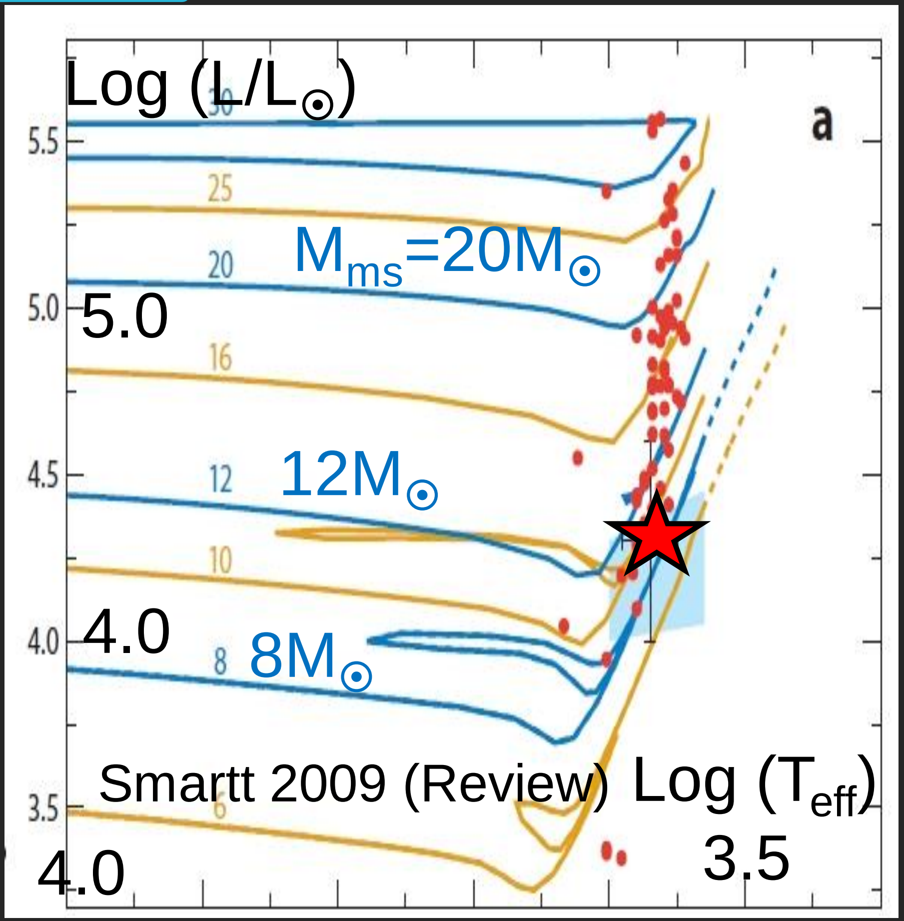


?



Typically a few years before the SN

Progenitor search in **past** images



Progenitor Detection

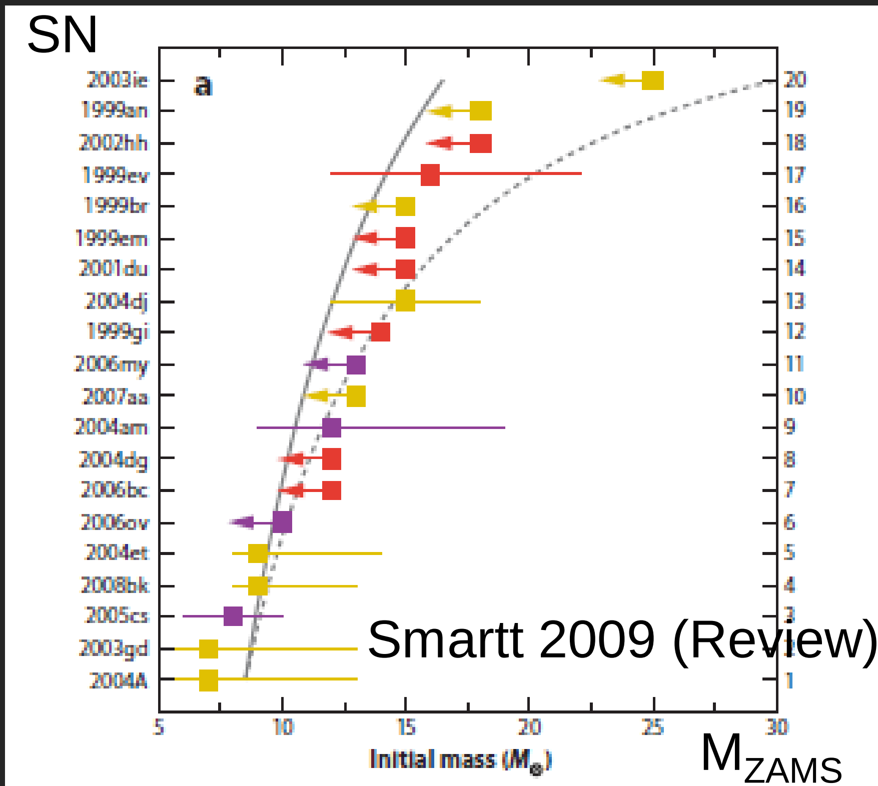
< ~ 30 Mpc with HST (Hubble).

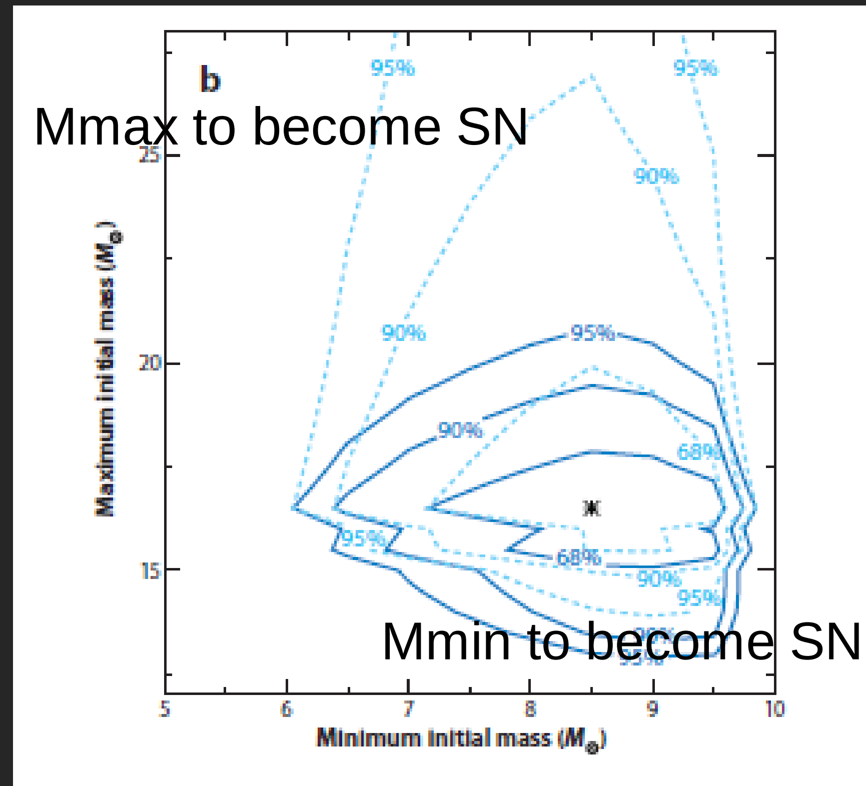
Good for SNe IIp (Giant, bright in optical)

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





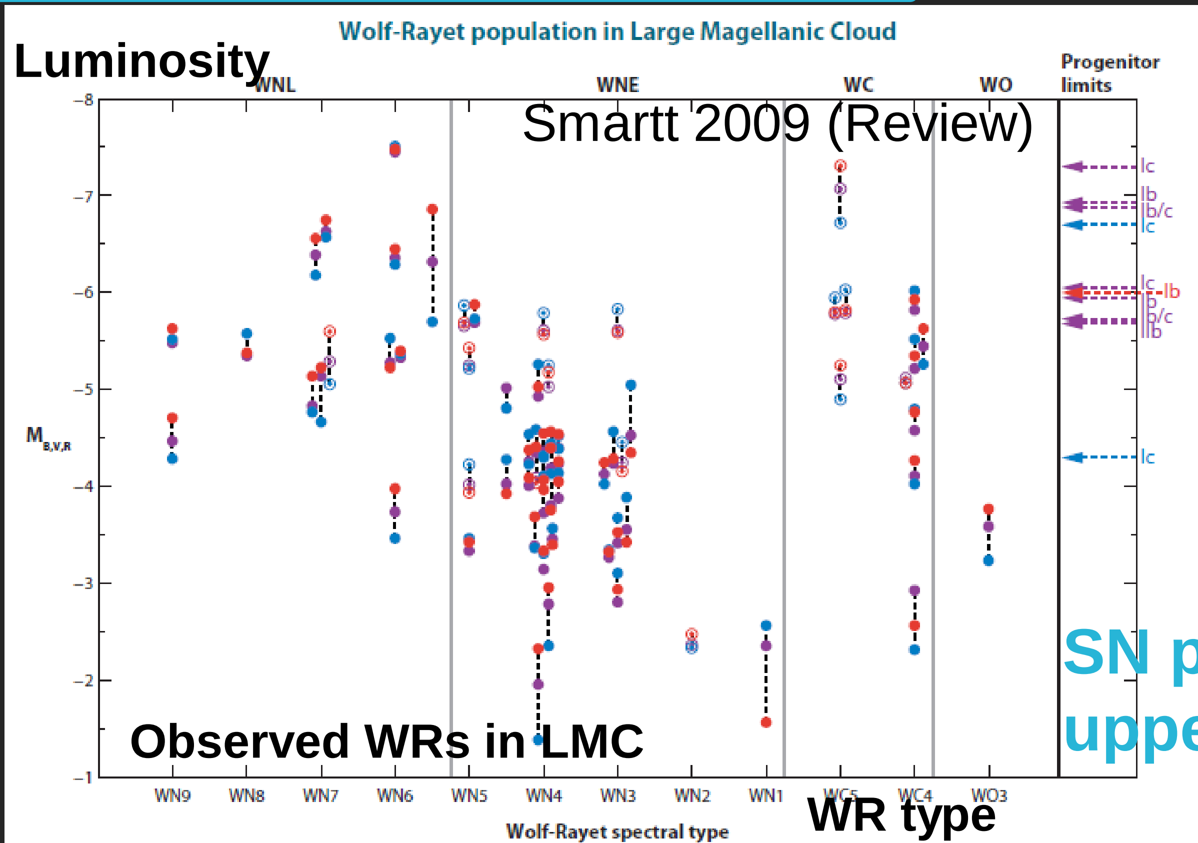
Assuming Salpeter IMF,

M_{min} ~ 8.5$M_\odot$ (±1.5) → ECAP-SN IIp, or no ECAP-SNe?

M_{max} ~ 16.5$_\odot$ (±1.5) → RSG problem (There are RSG > M_{max})

⇒Horiuchi-san?

WR progenitor for SNe Ib/c? (no detection)



More should have been detected if the progenitors are known WR populations.

⇒ Something unclarified is happening within << 10^6 yrs ?
(a challenge to stellar evolution theory)

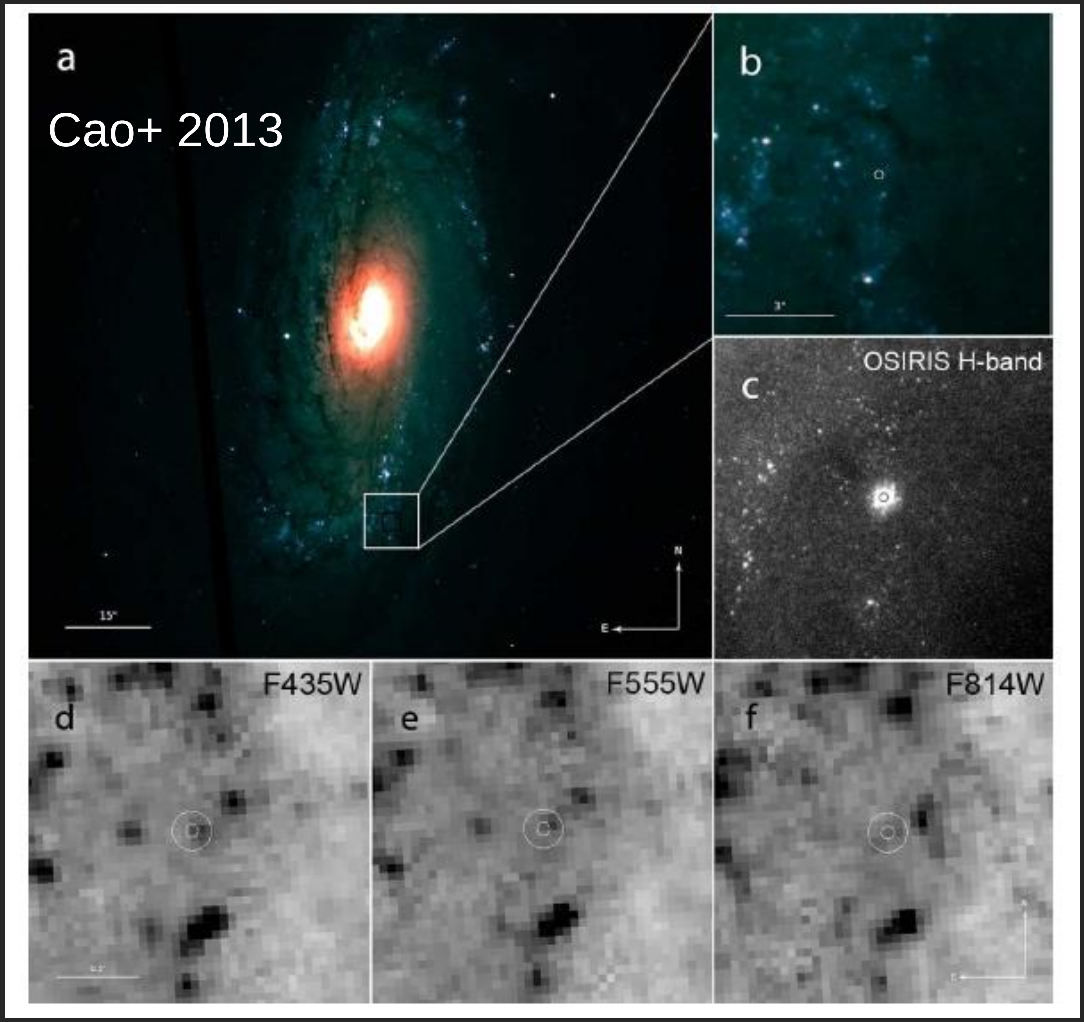
A candidate progenitor of SNe Ib/c

The first detection of a candidate in 2013: iPTF13bvn

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

SN Light curve indicates a compact progenitor, but less massive (Kuncarayakti, KM+ 2014). Controversy.

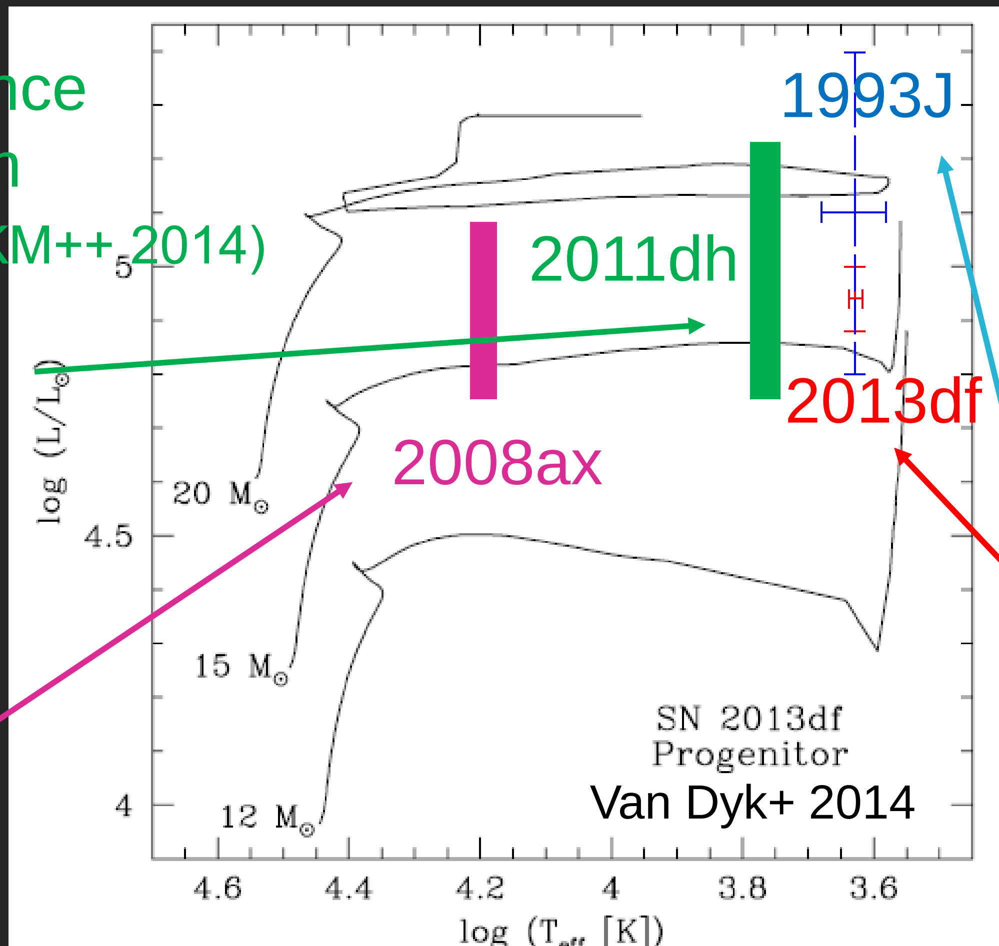
Further HST observations in last August, now analyzing
(Folatelli, …, KM+ in prep.)



Progenitor search for SNe IIb (no RSG, no WR!)

Disappearance
+Companion
(Folatelli, …, KM++ 2014)

YSG
~ 200R⊙



Disappearance
+Companion

Pre-SN only

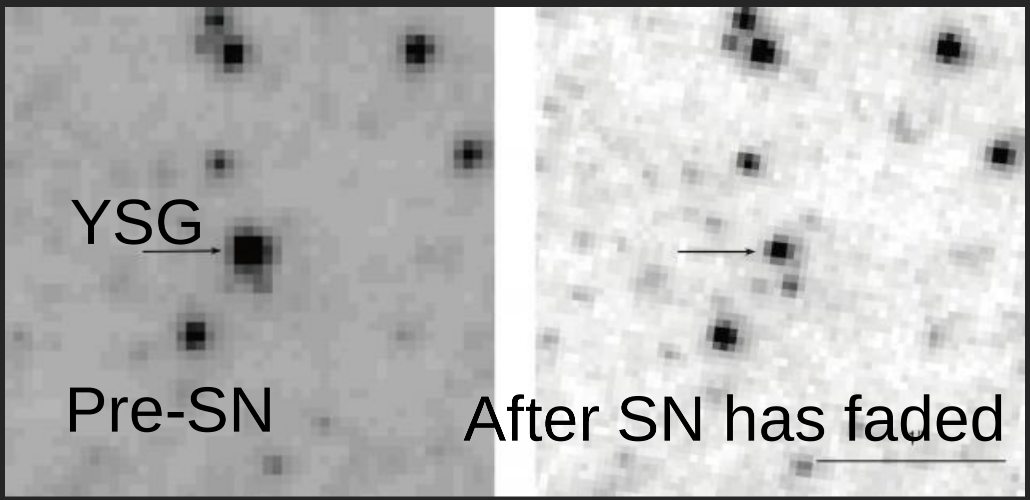
YSG
~ 600R⊙

BSG
~ 50R⊙

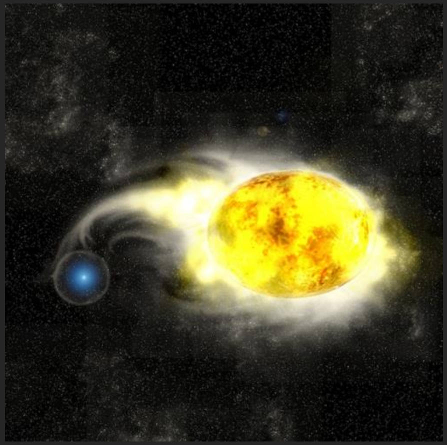
Disappearance
(Folatelli, …, KM++ 2015)

BSG=Blue Supergiant
YSG=Yellow Supergiant

YSG Progenitors for 3 SNe IIb (out of 4)



"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

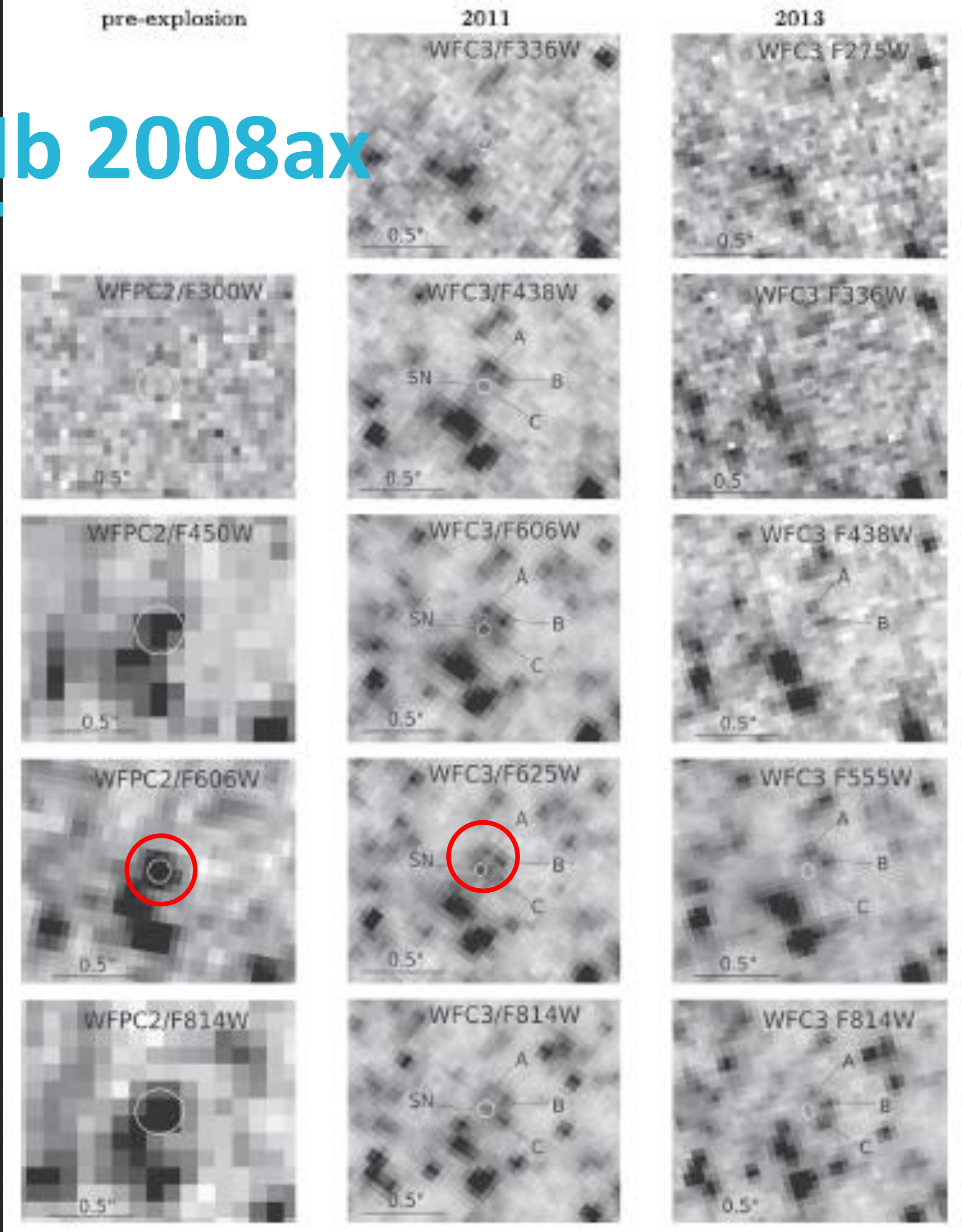
Not considered as a "SN progenitor", but one third of IIb progenitors! Indication: Binary.

Another one: SN IIb 2008ax

Pre-SN point source
Crockett+ (2008)

Analyses of late-time HST images by us show that it consists of multiple stars.
Folatelli, …, KM+ (2015)

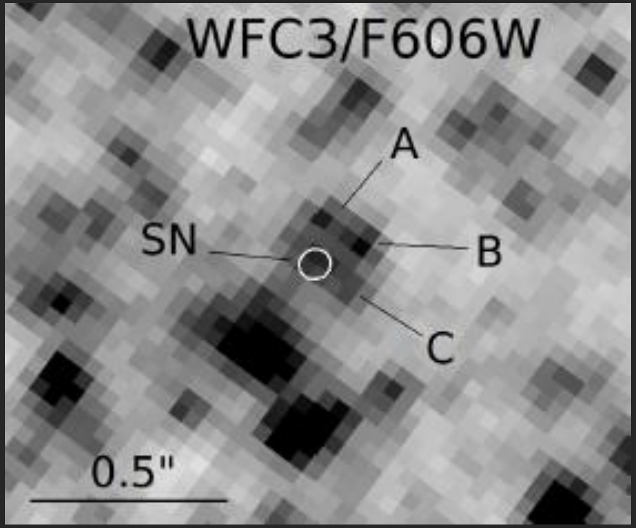
Now, the SN has faded.
A fraction of light gone.
⇒ Progenitor.

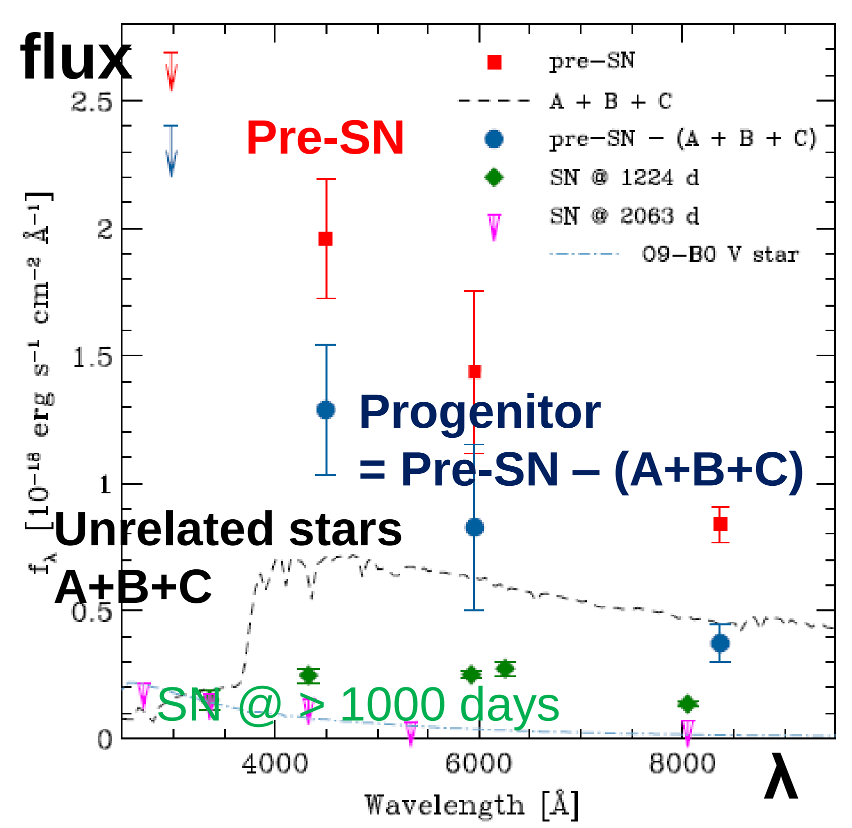


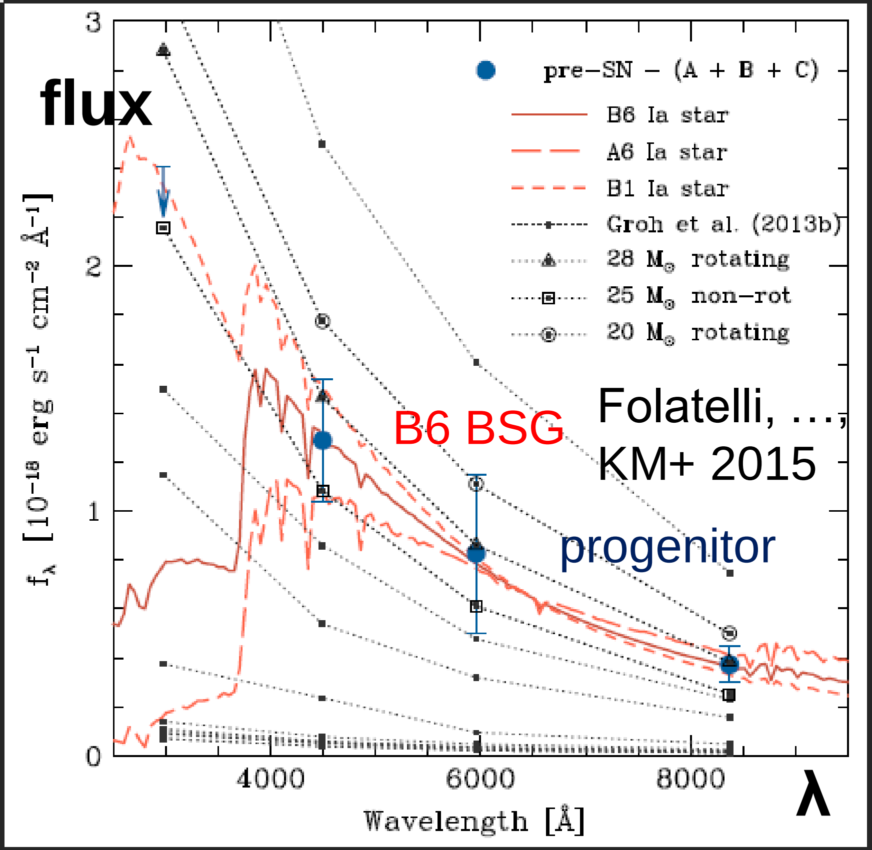
Progenitor of 2008ax

SN had faded below the "progenitor" flux

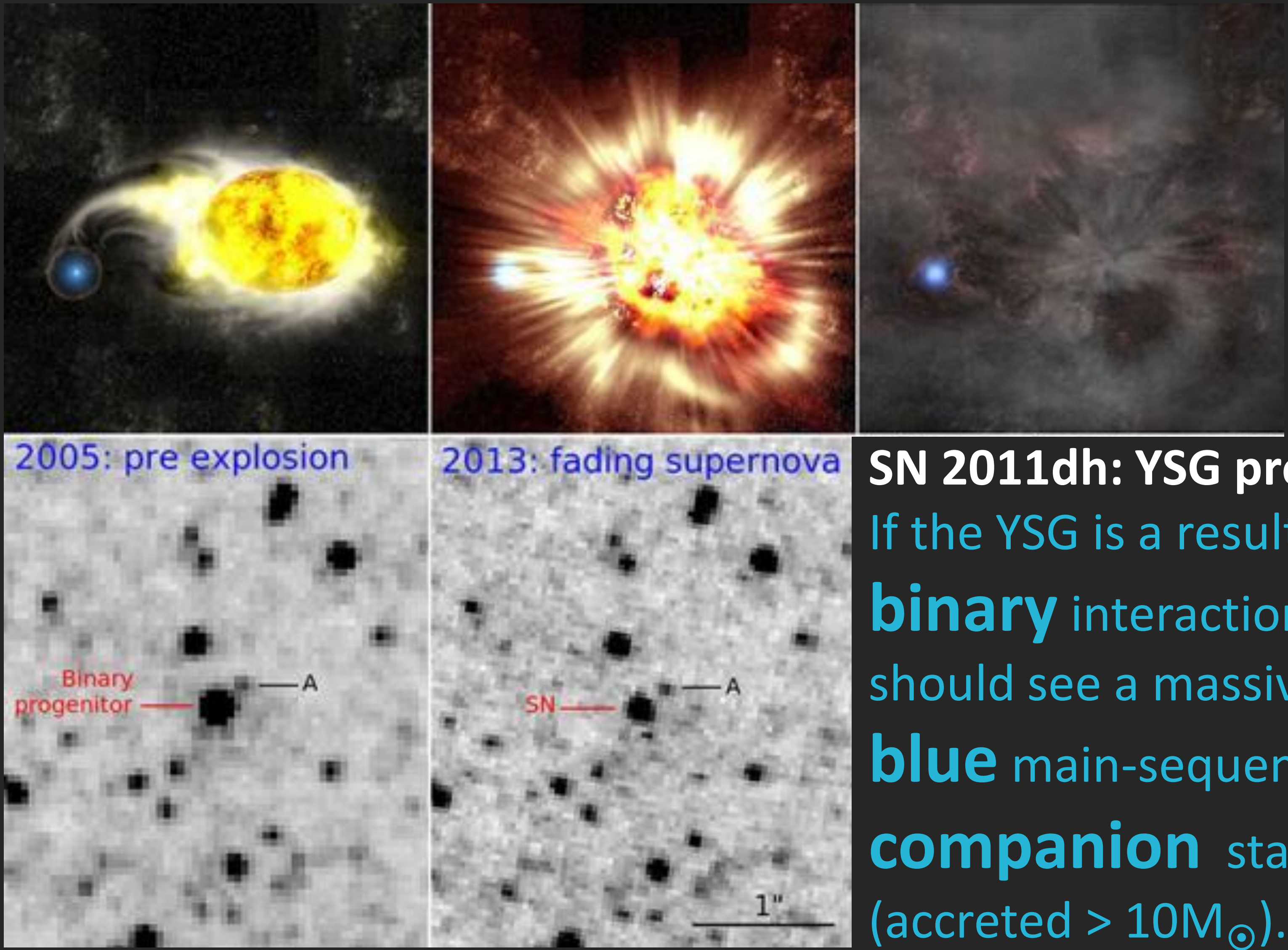
⇒ **Real progenitor was a Blue-supergiant (BSG ~ SN 1987A!).**







Direct Detection of Companion (Candidate)

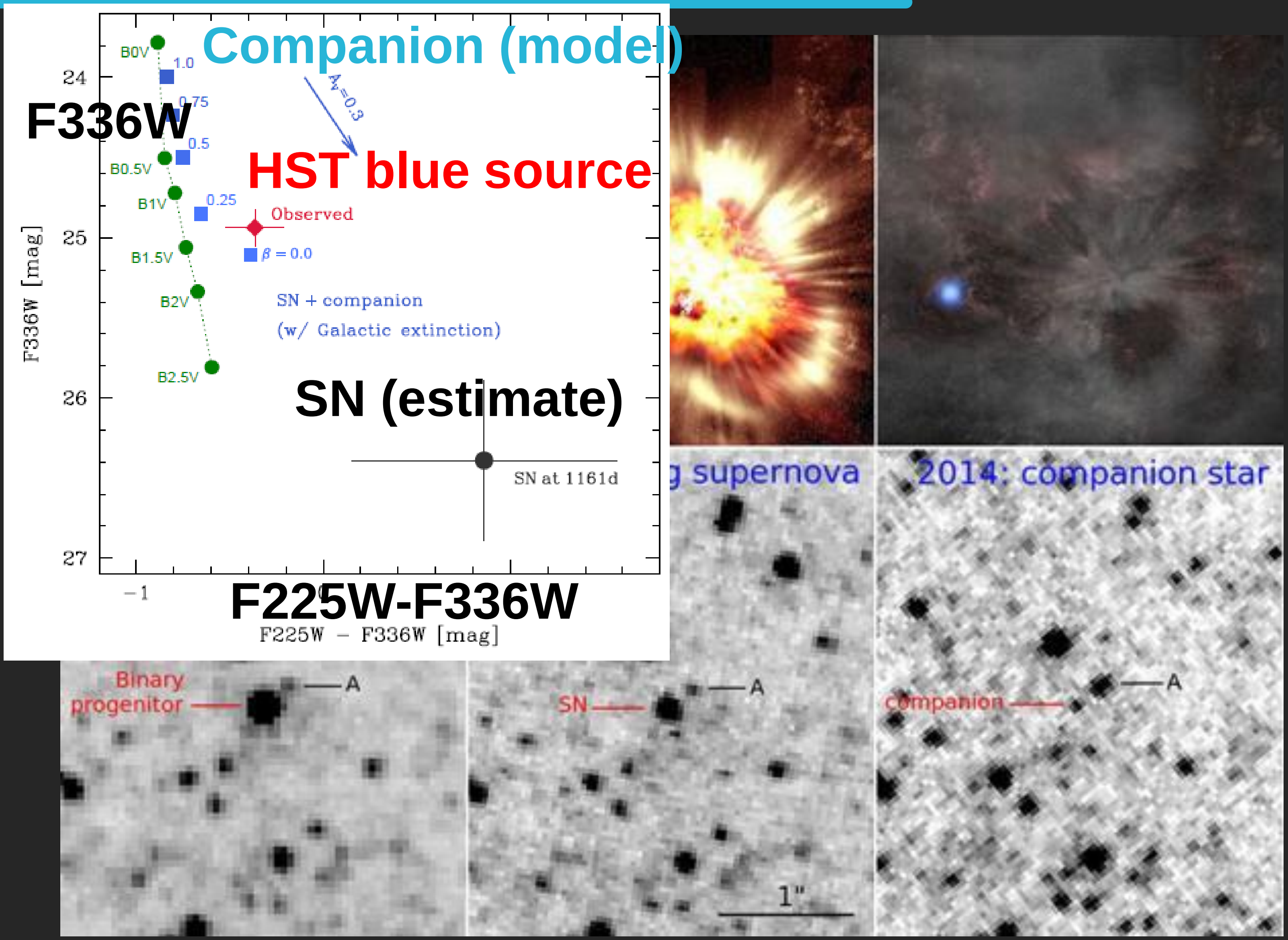


SN 2011dh: YSG progenitor

If the YSG is a result of a **binary** interaction, we should see a massive & **blue** main-sequence **companion** star in **UV** (accreted > $10M_{\odot}$).

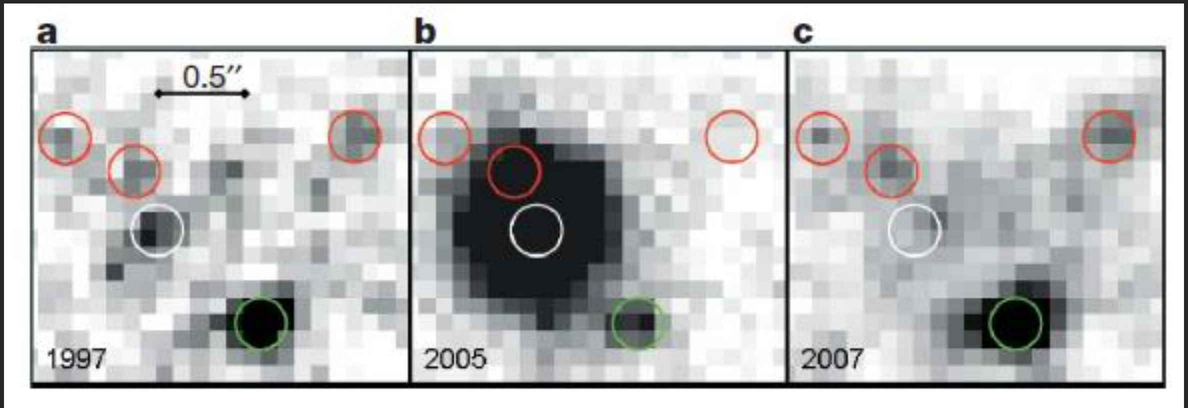
Folatelli, …, KM+ 2014, ApJ, 793, L22

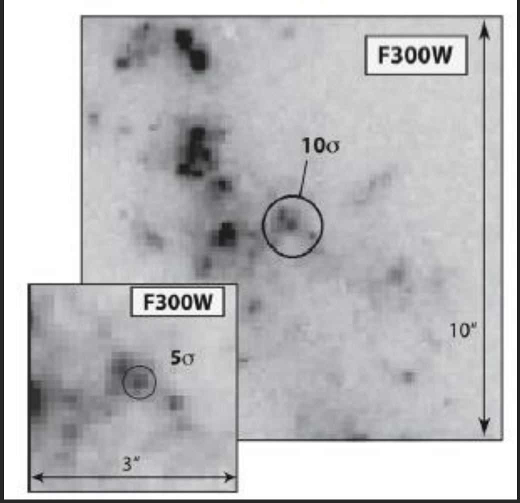
Direct Detection of Companion (Candidate)



Caveat: very diverse, may come from multiple populations

SN IIn Progenitors and Environments

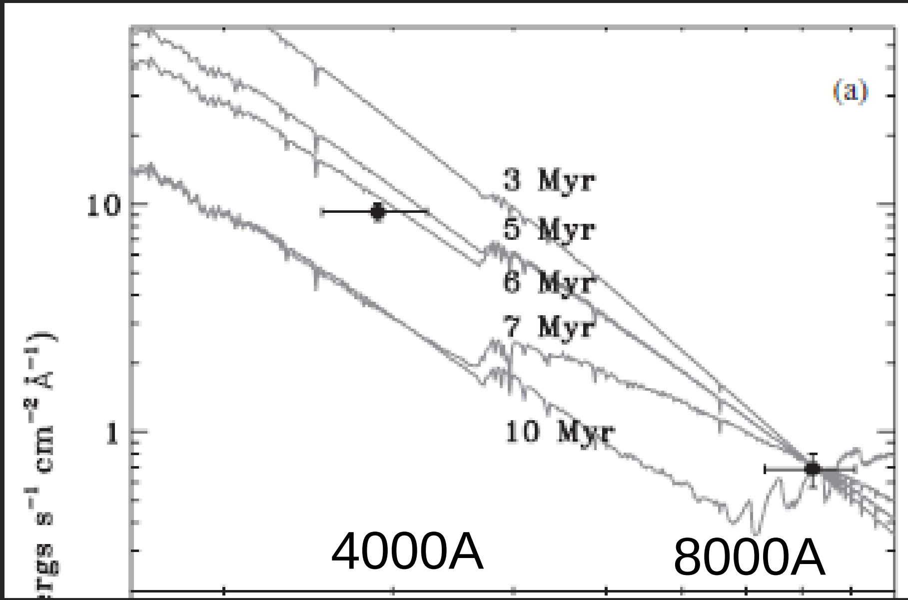




~$10^6 L_\odot$: Luminous Blue Variable (?) > $50 M_\odot$

SN 2005gl
Gal-Yam & Leonard 2009

A challenge: LBV (RSG⇒WR) is **not** regarded as an SN progenitor in theory (again!).



Low-metallicity: ~ $0.3 Z_\odot$
Life-time: ~ 3-5 Myr

SN 2010jl
Smith+ 2011

Pre-burst activities of some SN (?) IIn

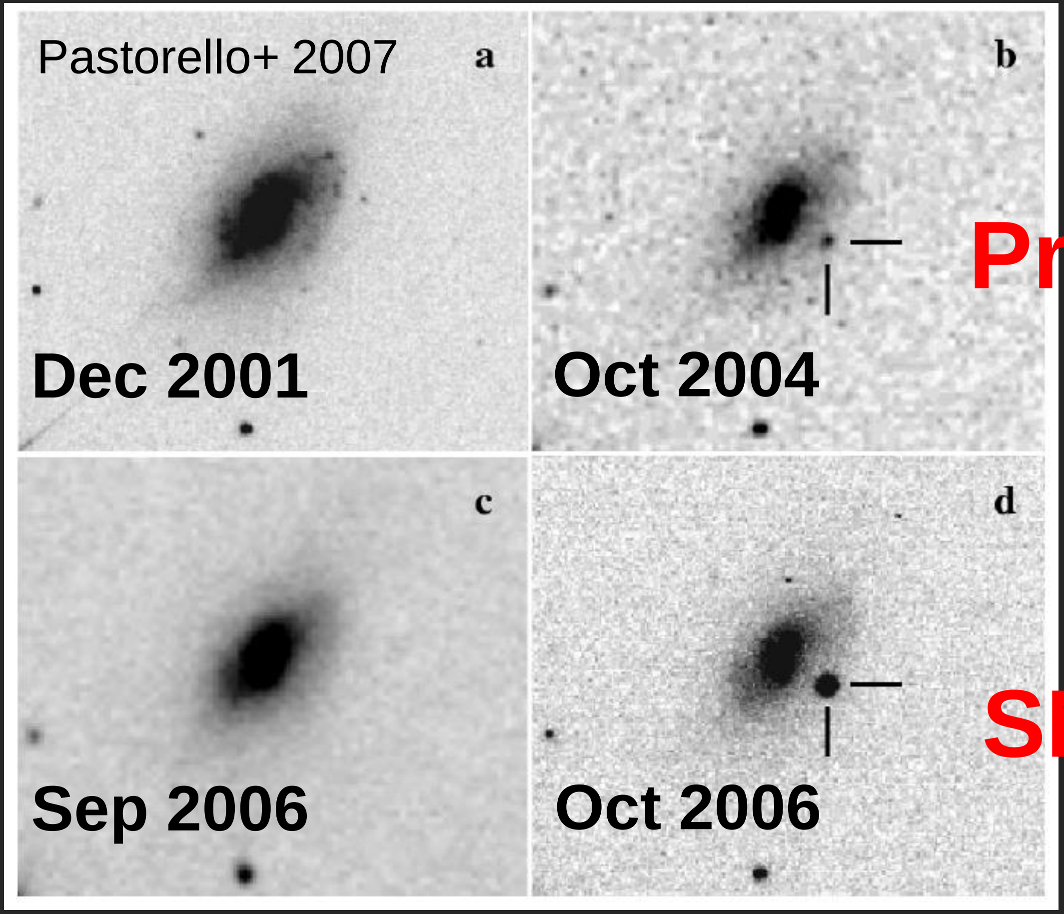
(At least) Two "SNe IIn" showing **pre-burst activities.**

SN or not (whole star disrupted or not) ?

SN 2009ip ("SN" in 2011) now below the pre-burst luminosity in 2015 (Thoene, …, KM+, 2015, ATEL #8417)。

Another example: Type "Ibn"

SN Ibn 2006jc



Pre-SN burst

2 years

SN

SN 2006jc resembles type IIn (emission line dominated) but He (not H): Thus termed Ibn

⇒He-rich mass-loss, 2 yrs before the SN.

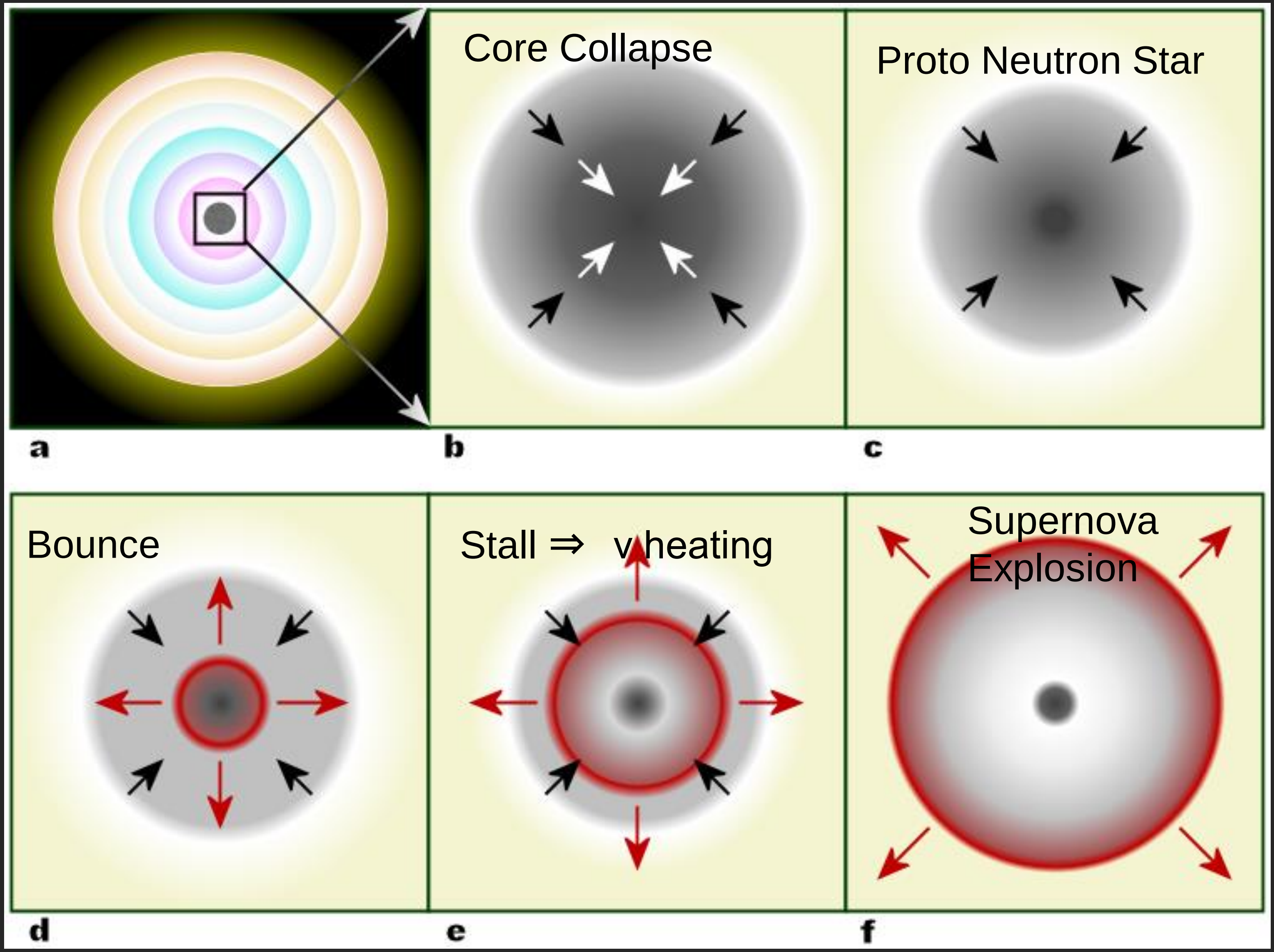
Summary for the direct progenitor obs.

- SNe IIp: RSGs as expected, but is it the whole story? (e.g., RSG problem)
- SNe Ib/Ic: Seems to be compact, but not like a WR star we know. Binary? Final evolution?
- SNe IIb: Huge diversity, YSG, BSG… Binary?
- SNe IIn: Really LBV? Evolutionary path totally unclear.
- “SNe” IIn/Ibn: Pre-SN activities… what?

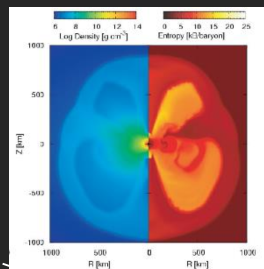
Pre-SN progenitor within a few days to explode (pre-SN ν!) will revolutionize our understanding of the final evolution toward SNe (currently ~ year or so before the SN).

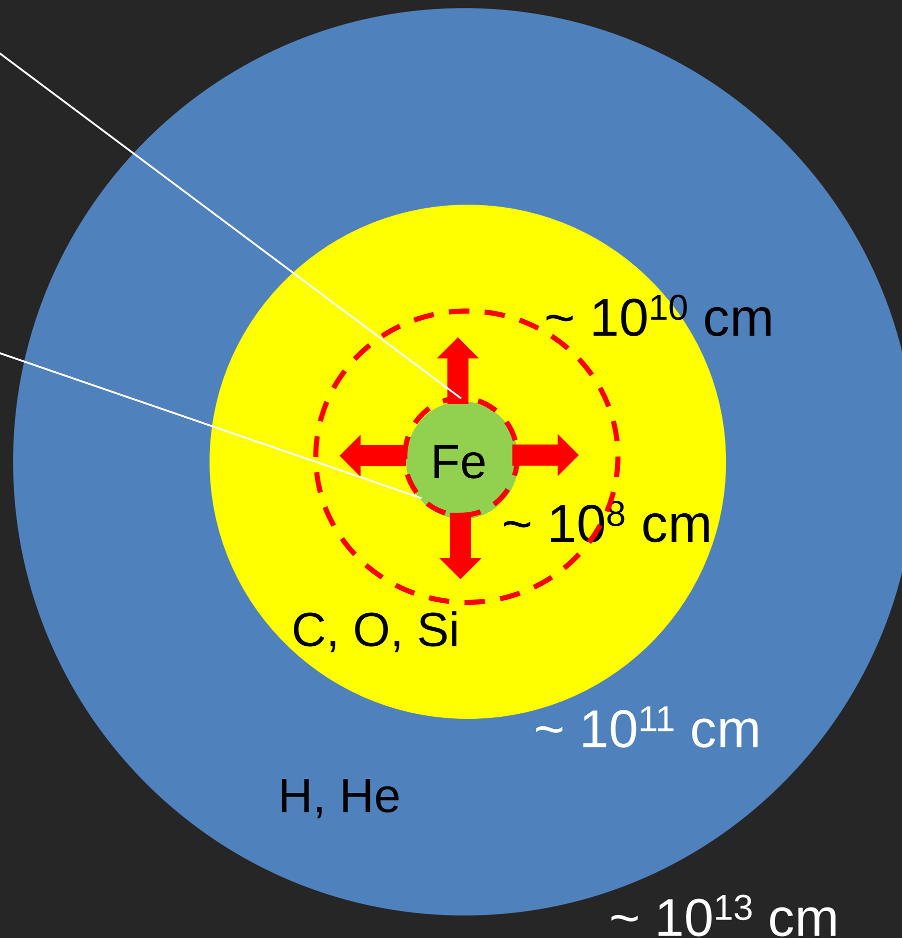
Observations of supernovae

After the Fe-core collapse (> $10M_\odot$)



Explosive Nucleosynthesis at the shock



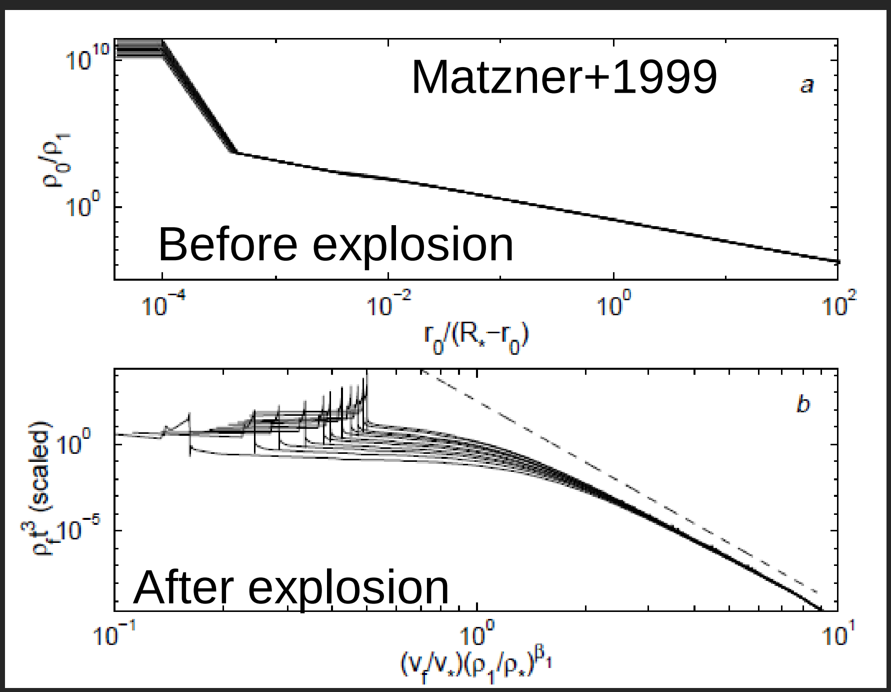


The shock penetrates into the outer layers. The high temperature there induces explosive nucleosynthesis above the Fe core.

Dynamics [$\rho(r,t)$, $T(r,t)$]
⇒ Nuclear reactions [$X_i(r, t)$]

From the collapse to shock breakout

- Fe-core Collapse ⇒ Shock reaching to the surface.
- The ν burst ⇒ Electromagnetic radiation.



- $V \sim (E/M)^{1/2}$.
- $\Delta t \sim R/V$

~ 100 sec $(R/R_\odot)(E/10^{51}\mathrm{erg})^{-1/2}\ (M/M_\odot)^{1/2}$

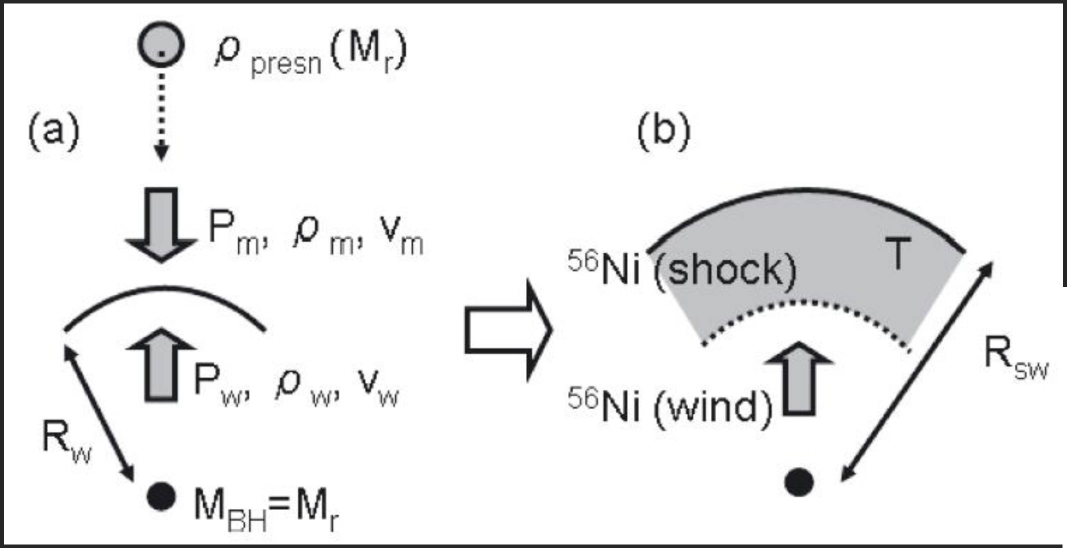
- RSG (IIp): $1000R_\odot$, $10M_\odot$

⇒ a few hours.

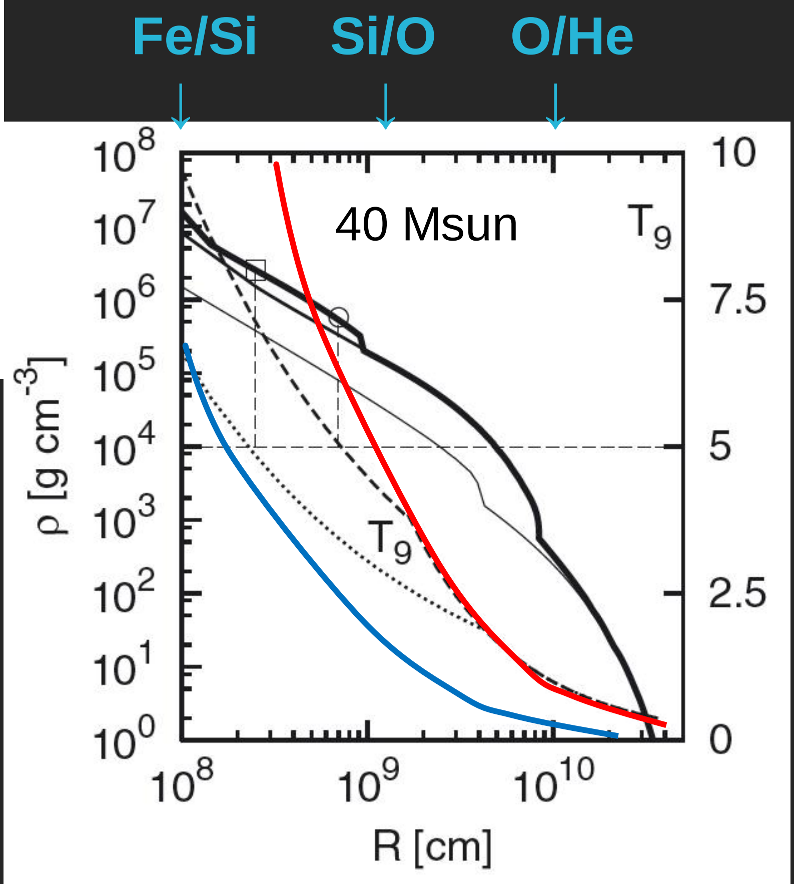
- WR (Ib/c?): $1R_\odot$, $1\text{-}10M_\odot$

⇒ a few 100 sec.

Temperature behind the shock (above Fe-core)



$T_9 = T/10^9$K at the passage of the shock (i.e., peak T)



- Assuming the shock emerges out of the Fe core.

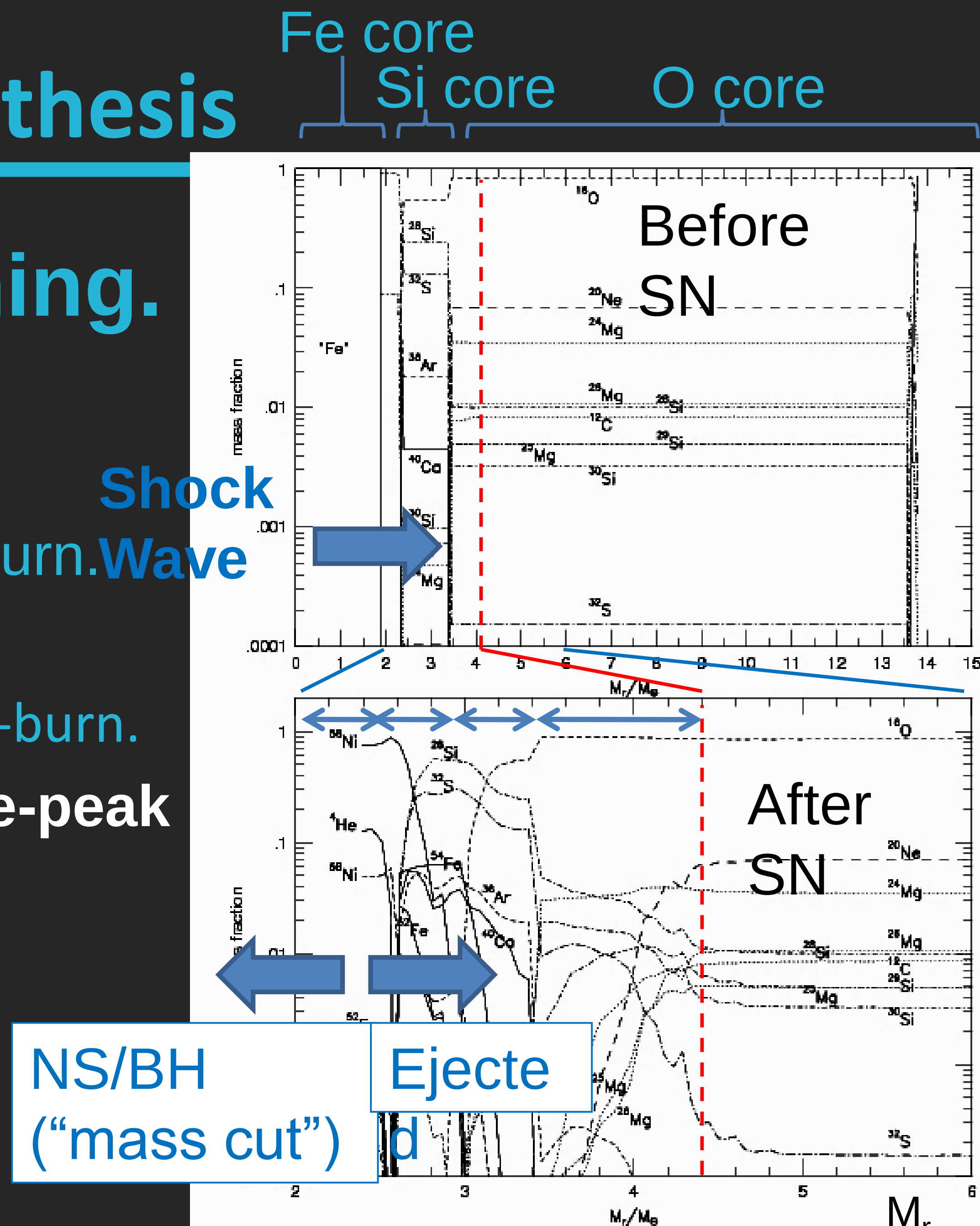
A simple (very rough) estimate:

- $E_K \sim (4\pi/3)\, R^3 aT^4$
- $T \propto (E_K/R^3)^{1/4}$

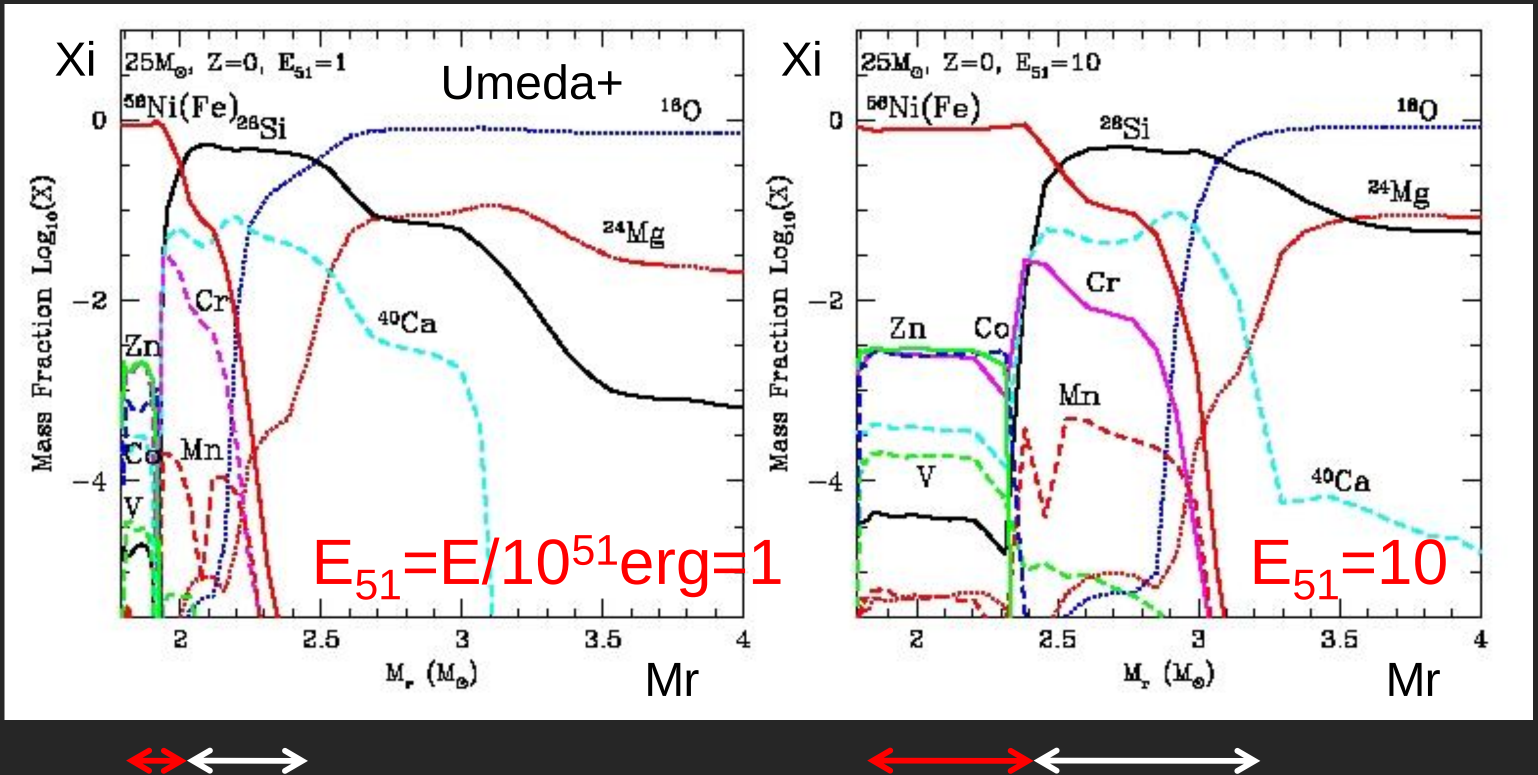
KM, Tominaga, 2009

CC-SN Nucleosynthesis

- **Explosive burning.**
  - **$T \propto (E_K/R^3)^{1/4}$**
    - $T_9 = T/10^9 K > 5$: Si-burn.
      ^{56}Ni, He, Fe-peak
    - T_9 = 4-5: incomplete Si-burn.
      Si, S, Fe, Ar, Ca, Fe-peak
    - T_9 = 3-4: O-burn.
      O, Si, S, Ar, Ca
    - T_9 = 2-3: C,Ne-burn.
      O, Mg, Si, Ne



Supernova Nucleosynthesis (in 1D)



Fe-peak IME (Si, Ca…)

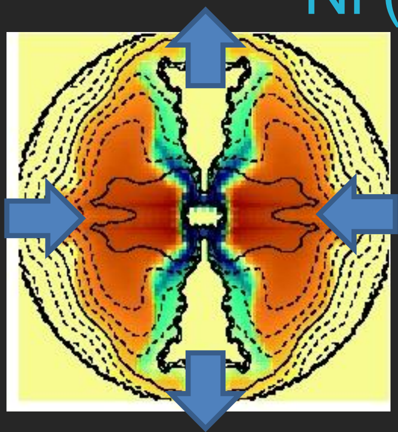
Mass: Larger IME (for larger mass)

Energy: Larger Fe (for larger E) + Fe-peaks (e.g., Zn, Ti)

+ non 1D effect (mixing, global asymmetry)

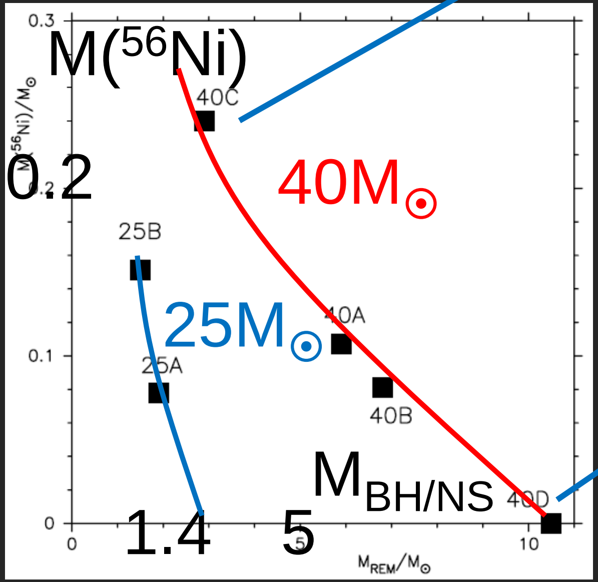
Supernova Nucleosynthesis (asymmetric)

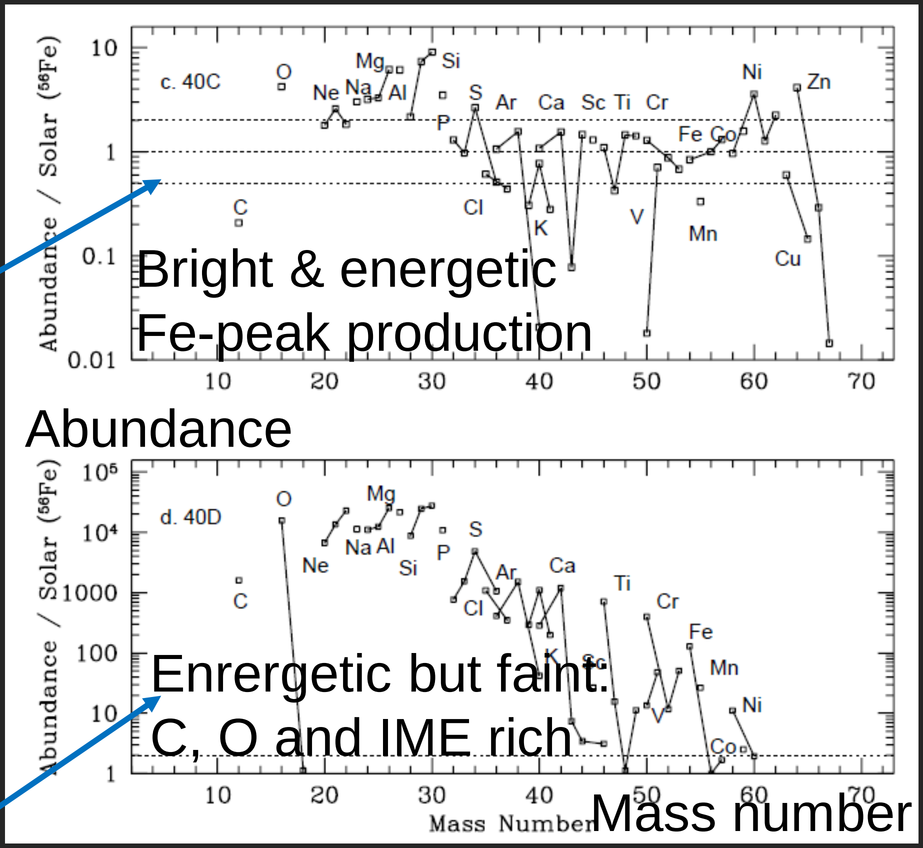
^{56}Ni (Fe), Zn, … "Black-box" jet-like Model,



C, O, …

KM & Nomoto 2003

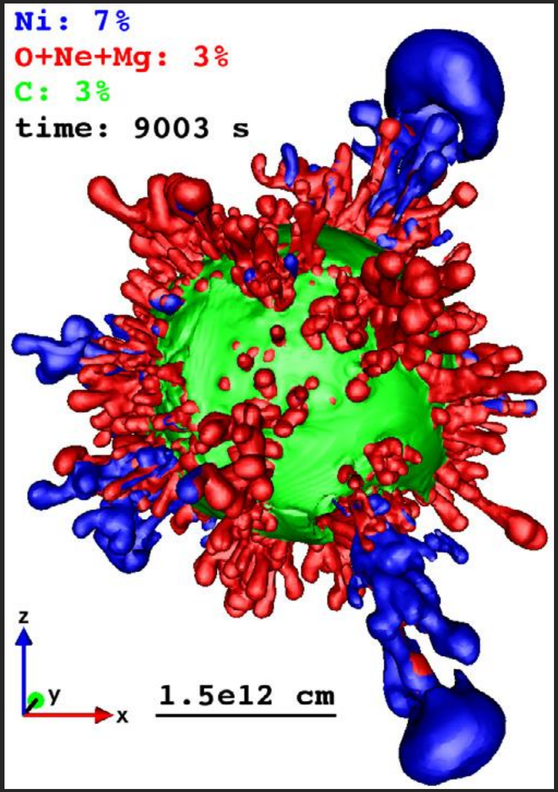




See also Tominaga, KM+ 2007

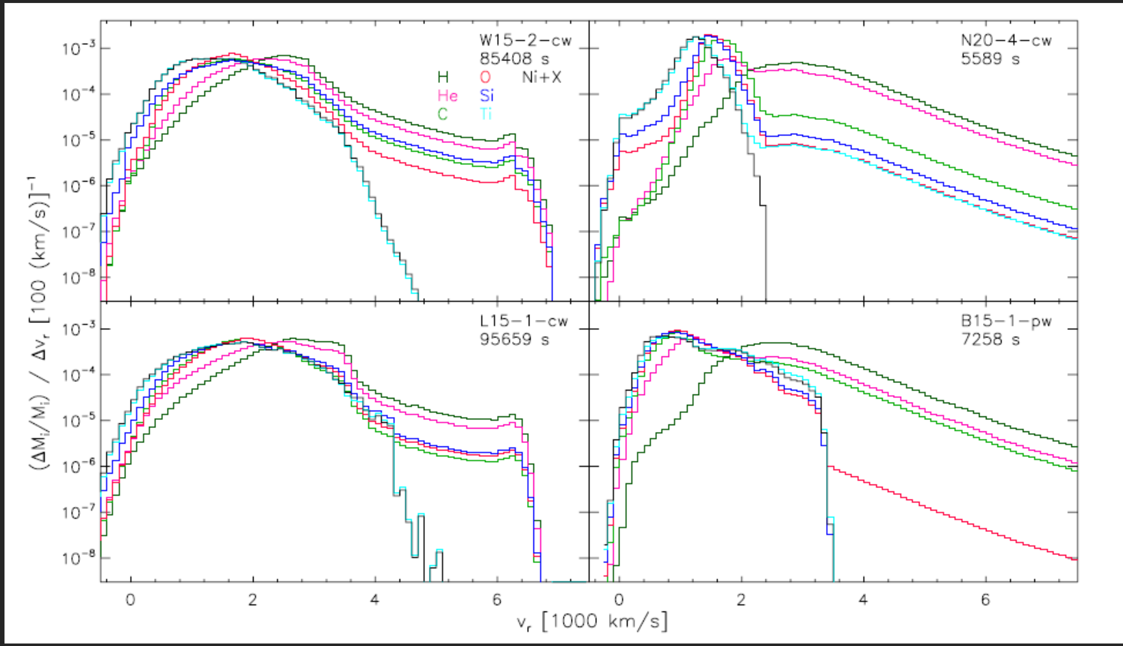
[Zn, Co/Fe]↑, [Mn, Cr]↓ for [Fe/H]↓

Supernova Nucleosynthesis (3D ν-driven)



ν-driven with hydro-instability

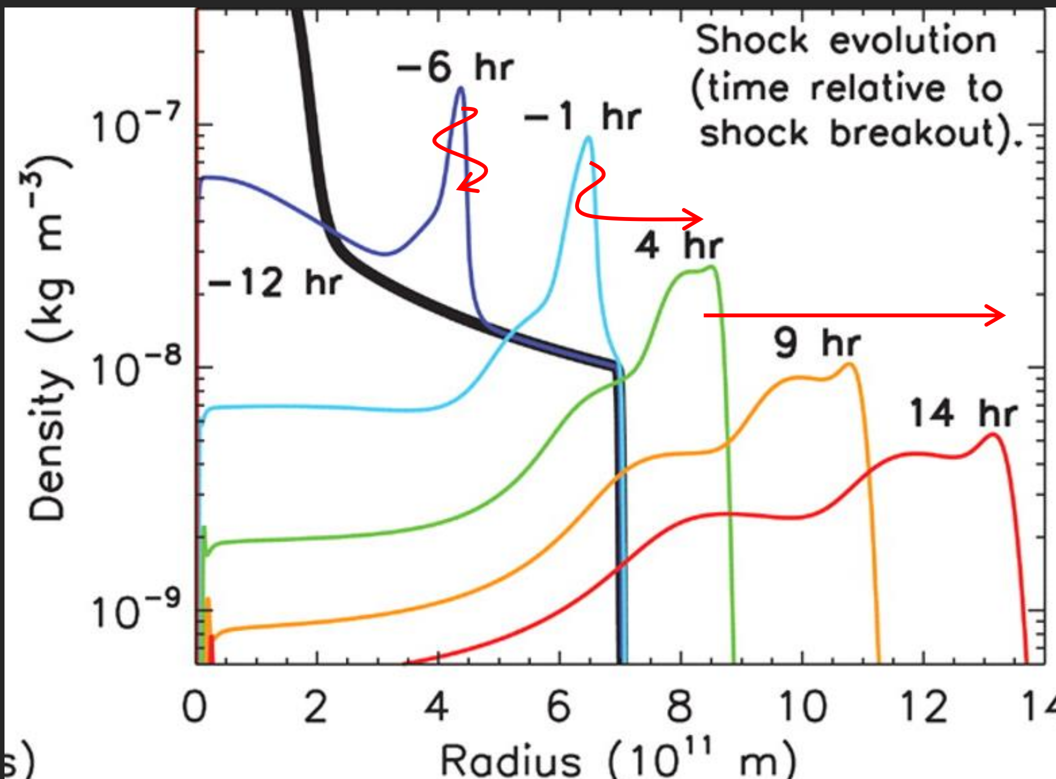
Wongwathanarat+ 2015



More and more sophisticated models being available (Takiwaki-san, Horiuchi-san's talks).

Shock Breakout

Original idea:
Falk & Arnett 1977
Klein & Chevalier 1978



Semi-Analytic (adiabatic):
Matzner+1999

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

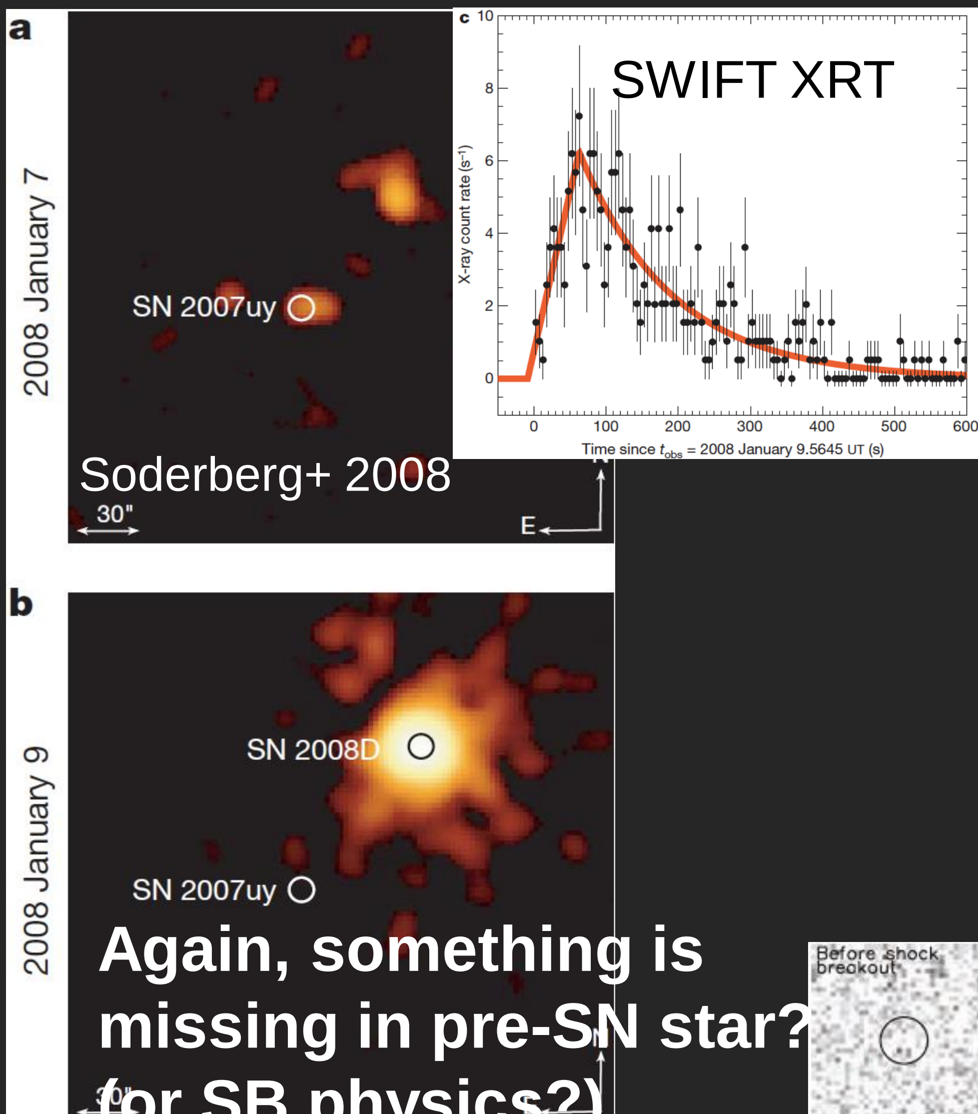
$$E_{se} = 1.7 \times 10^{48} \left(\frac{\kappa}{0.34\ \mathrm{cm^2\ g^{-1}}}\right)^{-0.87} \left(\frac{\rho_1}{\rho_*}\right)^{-0.086} \times \left(\frac{E_{in}}{10^{51}\ \mathrm{ergs}}\right)^{0.56} \left(\frac{M_{ej}}{10\ M_\odot}\right)^{-0.44} \times \left(\frac{R_*}{500\ R_\odot}\right)^{1.74}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

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

RSG (R ~ 1000$R_\odot$)
T~ $10^{5\text{-}6}$ K (→ UV)
t ~ 1000 sec

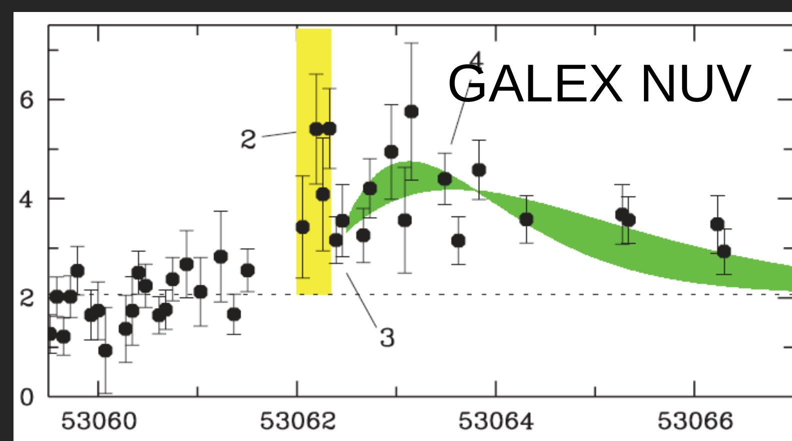
Wolf-Rayet (~ $R_\odot$)
T ~ 10^7 K (→ X)
t ~ a few sec

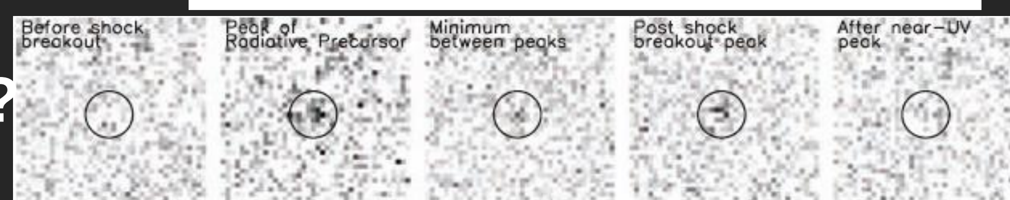
Shock Breakout: detected cases



SN Ib 2008D
X, ~ a few 100 sec
⇒ compact, but >> WR?

SN IIp SNLS-04D2dc
UV, ~ 6 hrs ⇒ RSG.

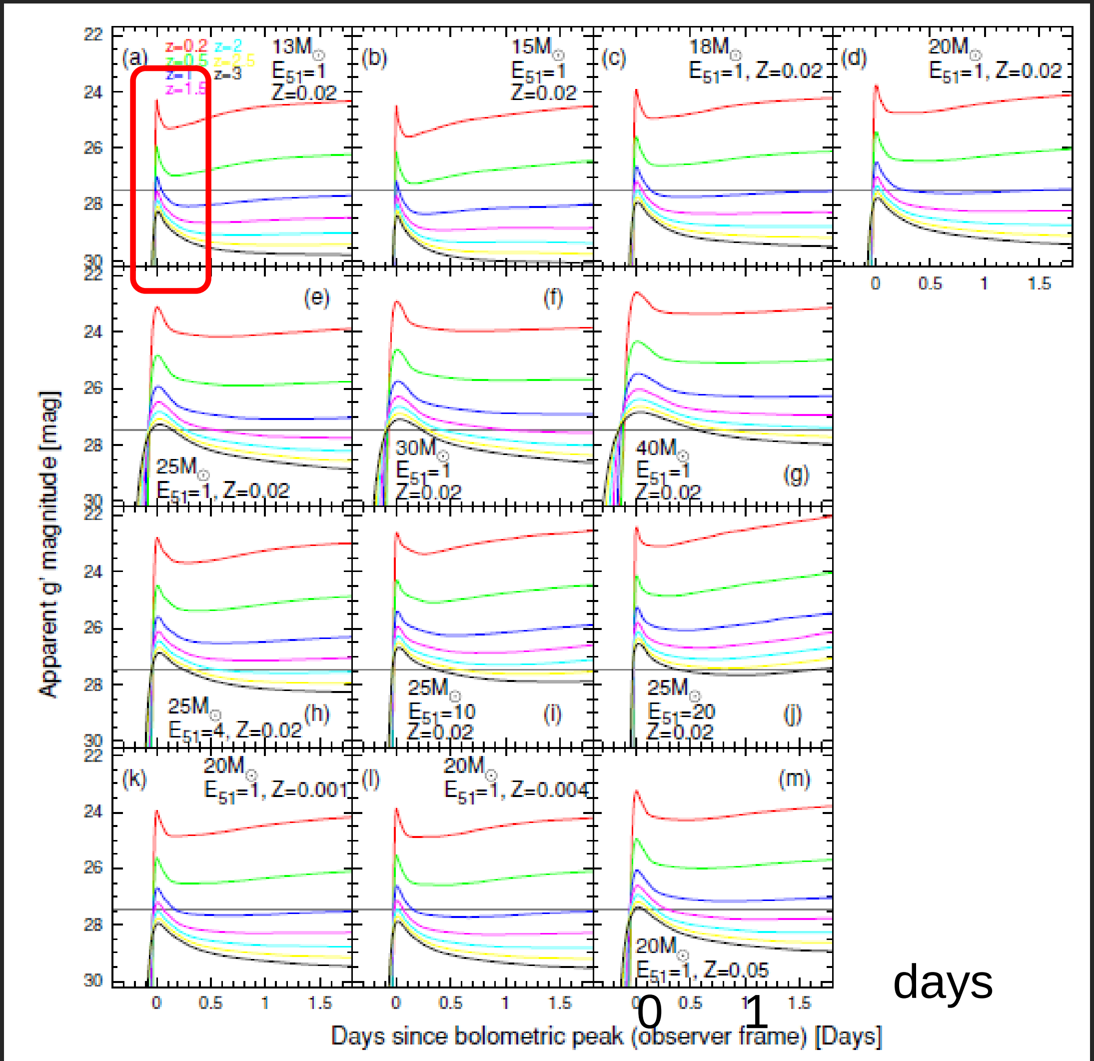




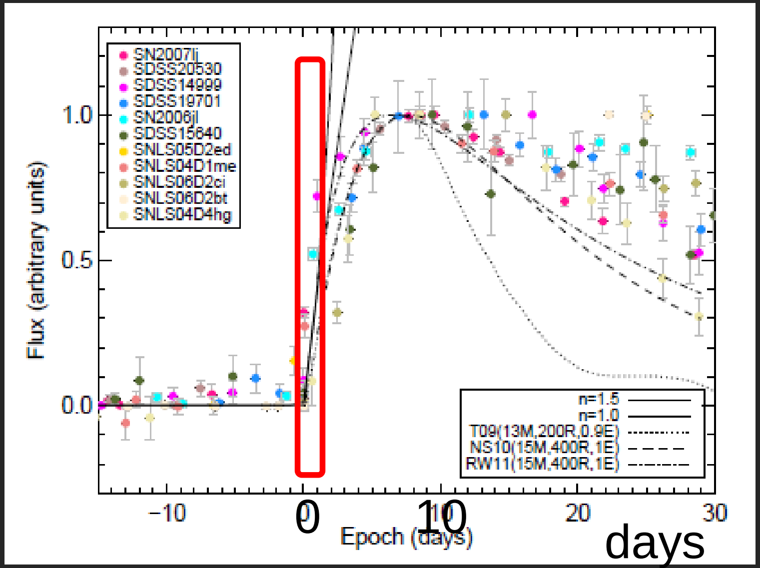
Again, something is missing in pre-SN star?
(or SB physics?)

Shock Breakout (in optical)

Numerical (radiation-hyd.): Tominaga+ 2011



Gonzalez-Gaitan, Tominaga+ 2015
Compilation of nearby SNe IIp

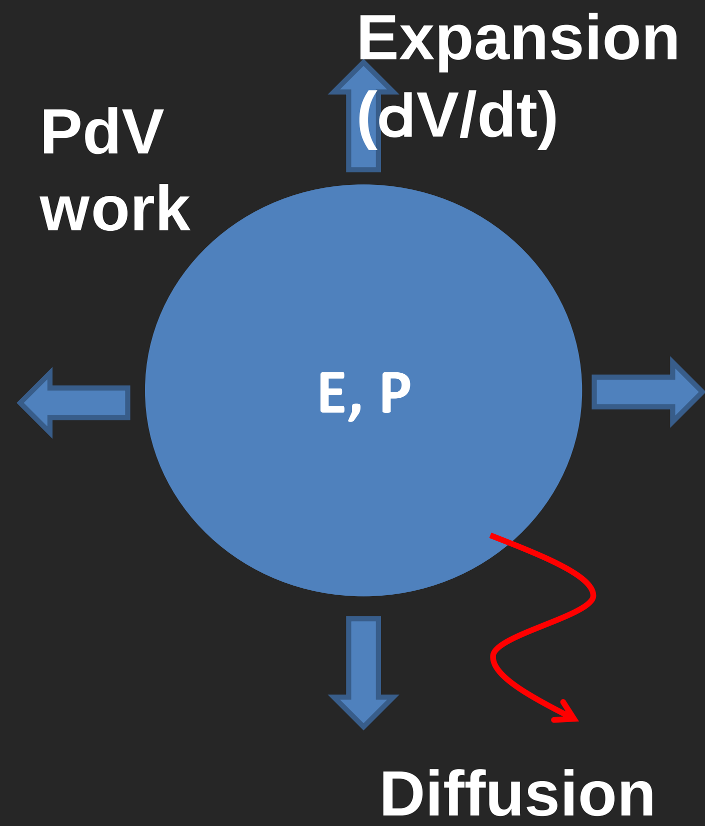


No solid detection in optical so far.

Ongoing surveys (incl. Kiso, Subaru/HSC: Tominaga+)

“Post” Shock Breakout (Adiabatic Cooling)

$$\dot{E} + P\dot{V} = \epsilon - \frac{\partial L}{\partial M} \sim 0$$



Temperature

$$E, P \propto T^4$$

$$\frac{\dot{T}}{T} \sim -\frac{\dot{R}}{R} \sim -\frac{v}{R}$$

$$T \propto R^{-1} \propto t^{-1}$$

Luminosity

$$\frac{\partial L}{\partial M} \sim \frac{L}{M} \sim \frac{E}{\tau_{diff}}$$

$$\tau_{diff} \sim \frac{\kappa M}{\beta c R}$$

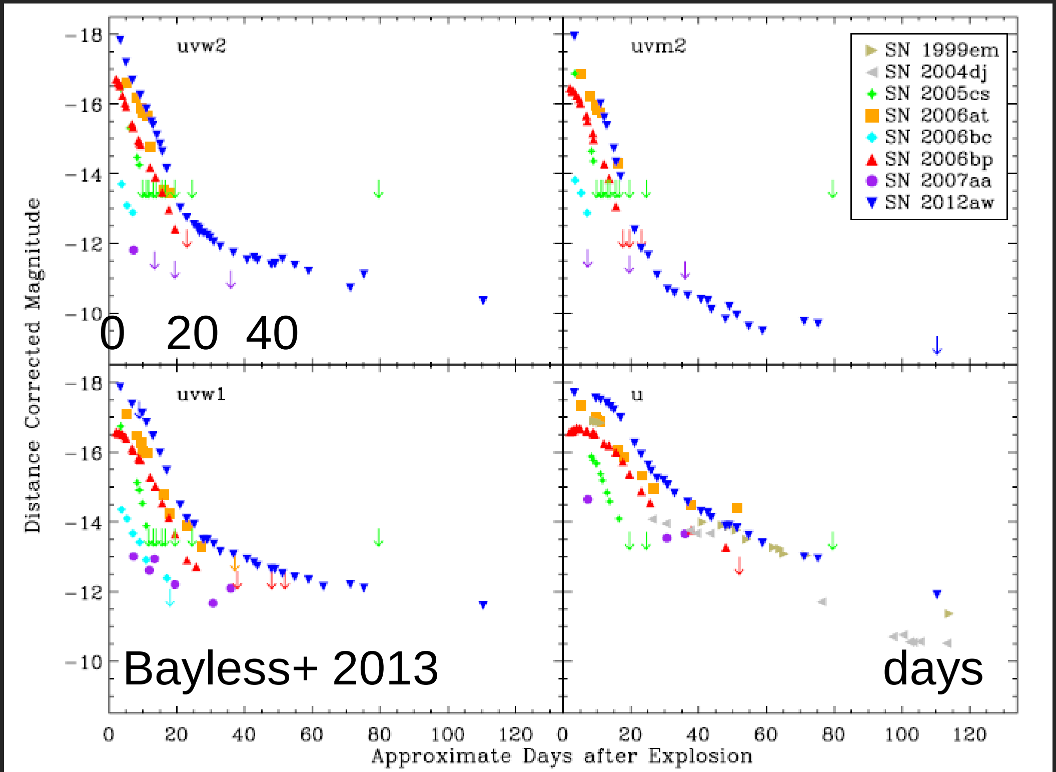
$$L \sim \frac{1}{2}\frac{E}{M} R \frac{\beta c}{\kappa} e^{-f(t)}$$

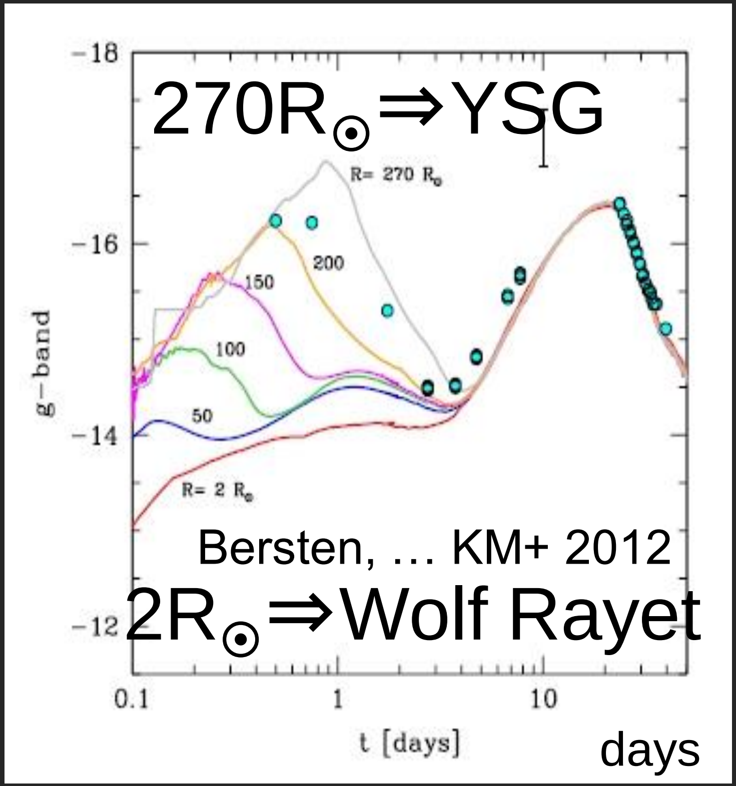
First phase:
Fully Optically thick
Cooling by Adiabatic loss
Photon diffusion

"Post" shock breakout ⇒ Progenitor radius

SNe IIp (RSG)

SN IIb 2011dh (YSG)

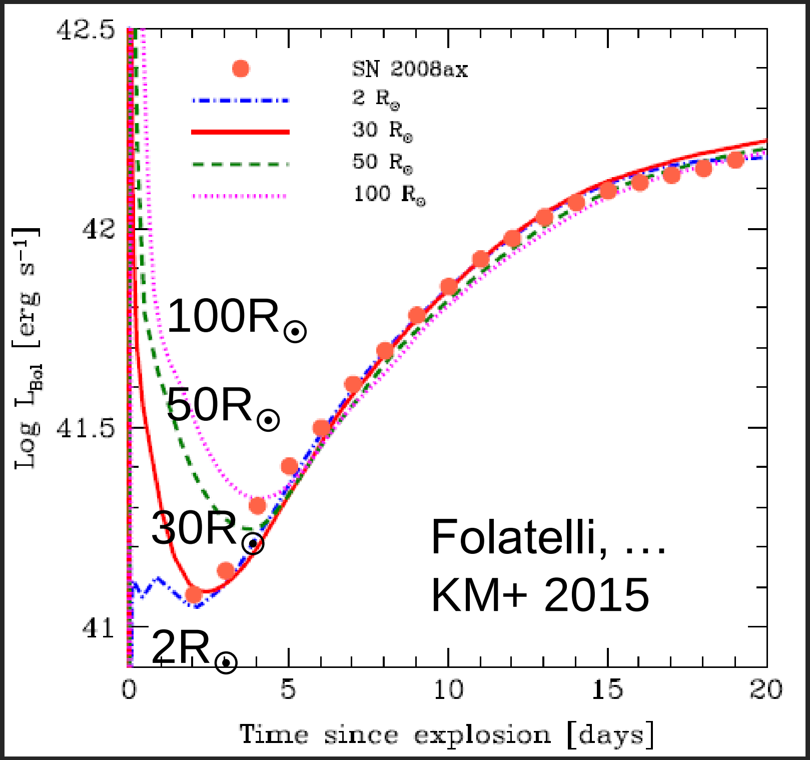


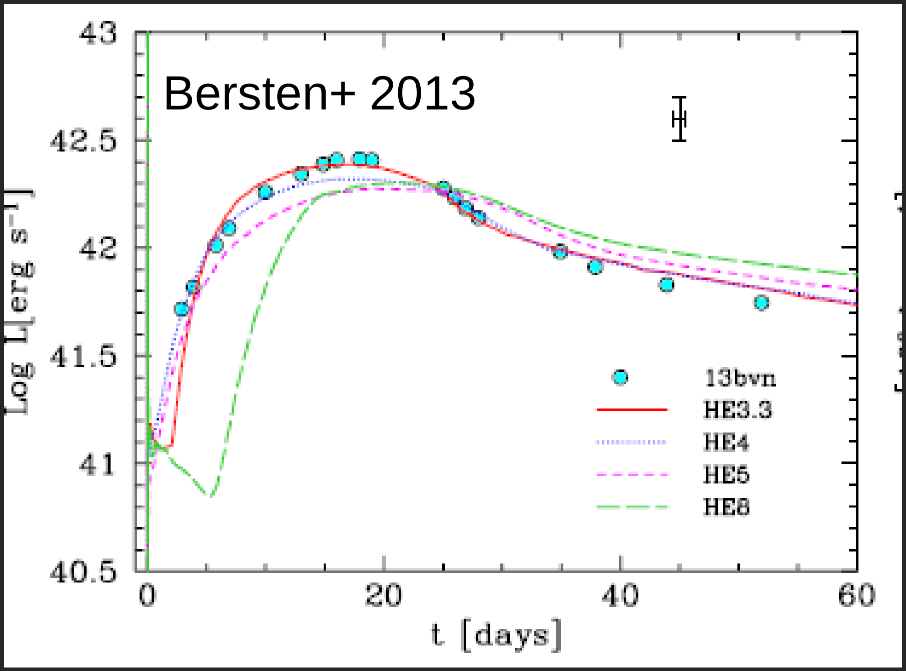


Largely consistent w/ Progenitor radius from the "direct" detection.

SN IIb 2008ax (BSG)

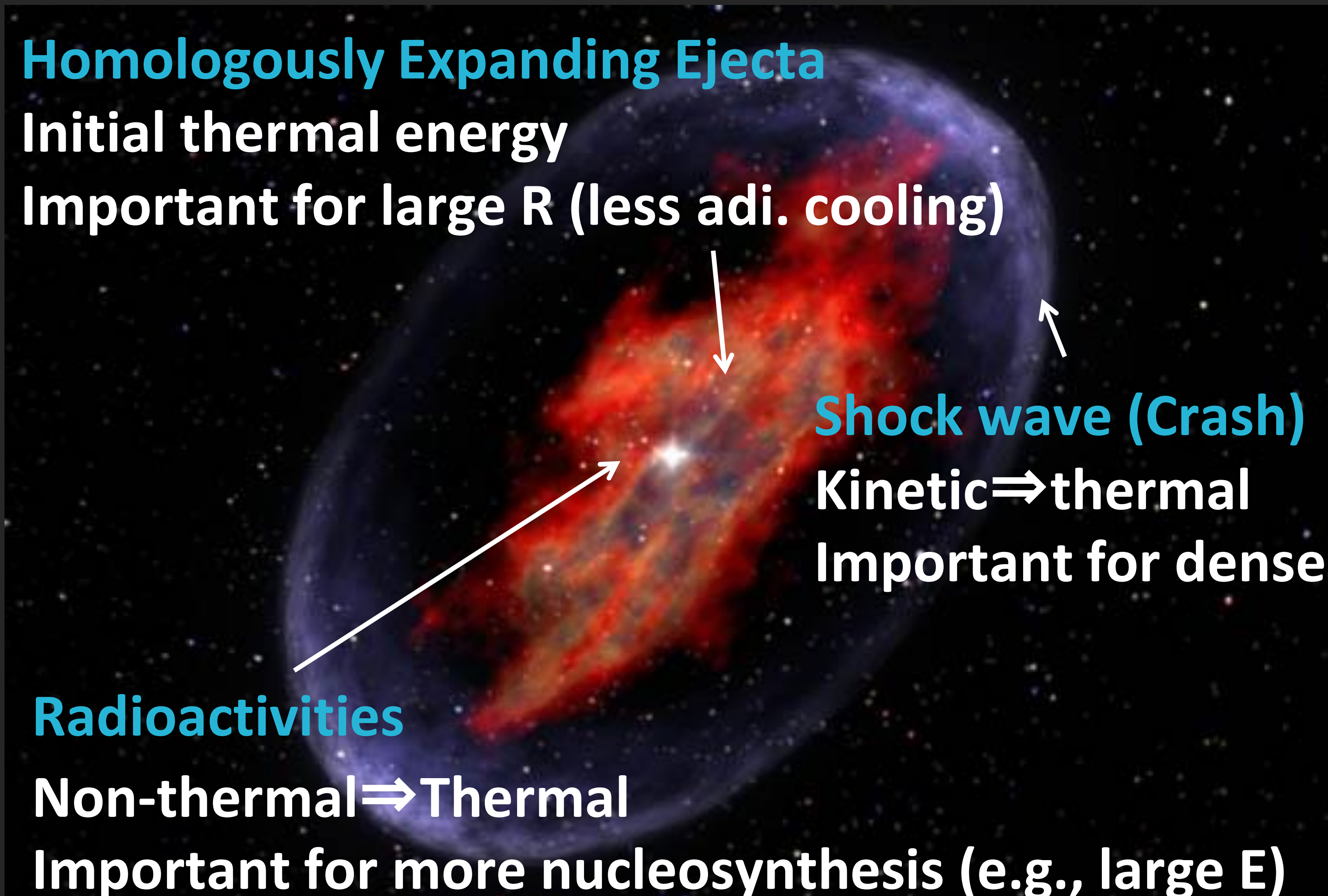
SN Ib iPTF13bvn (WR?)





Largely consistent w/ Progenitor radius from the “direct” detection.

Further Energy Budget for EM radiation



Homologously Expanding Ejecta

Initial thermal energy

Important for large R (less adi. cooling)

Shock wave (Crash)

Kinetic⇒thermal

Important for dense CSM

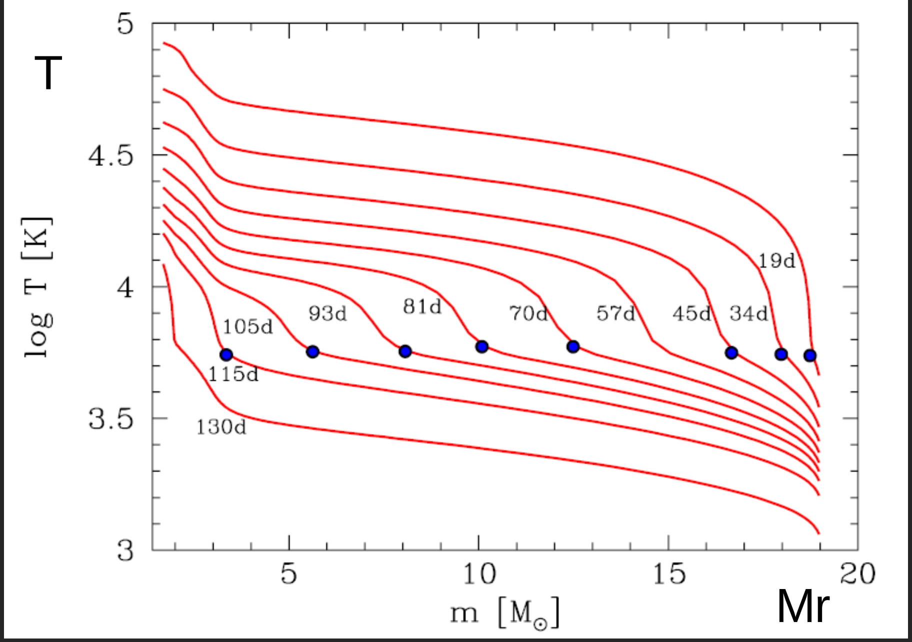
Radioactivities

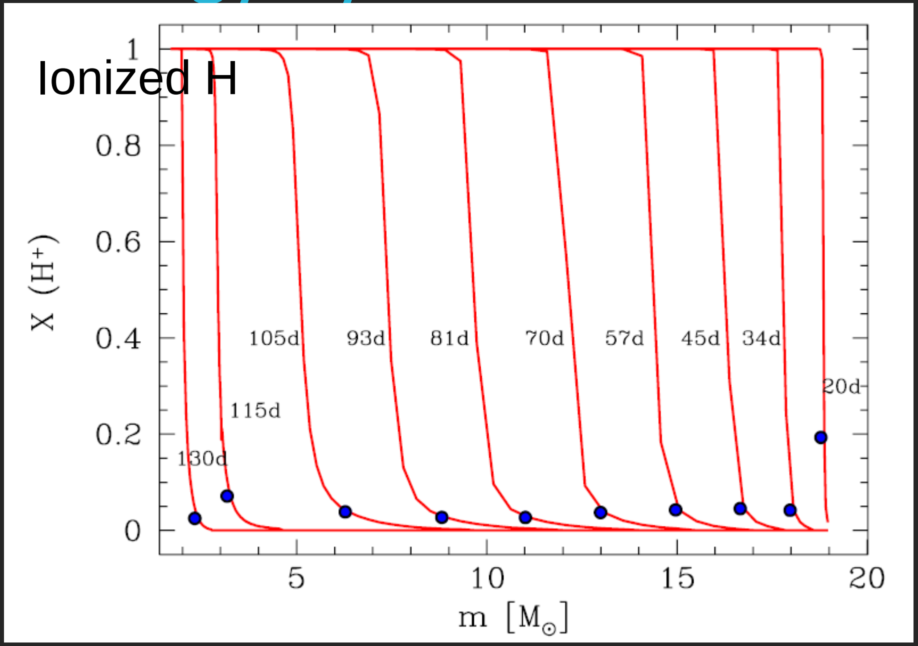
Non-thermal⇒Thermal

Important for more nucleosynthesis (e.g., large E)

SNe IIp: Recombination (initial thermal E)

- Hydrogen-rich envelope (RSG).
- $\kappa = \sigma_T/m_H \sim 0.4\ \mathrm{cm^2\,g^{-1}}$ if H^+, but ~ 0 if H^0.
- Keep/Trap the thermal energy by Thomson scat.



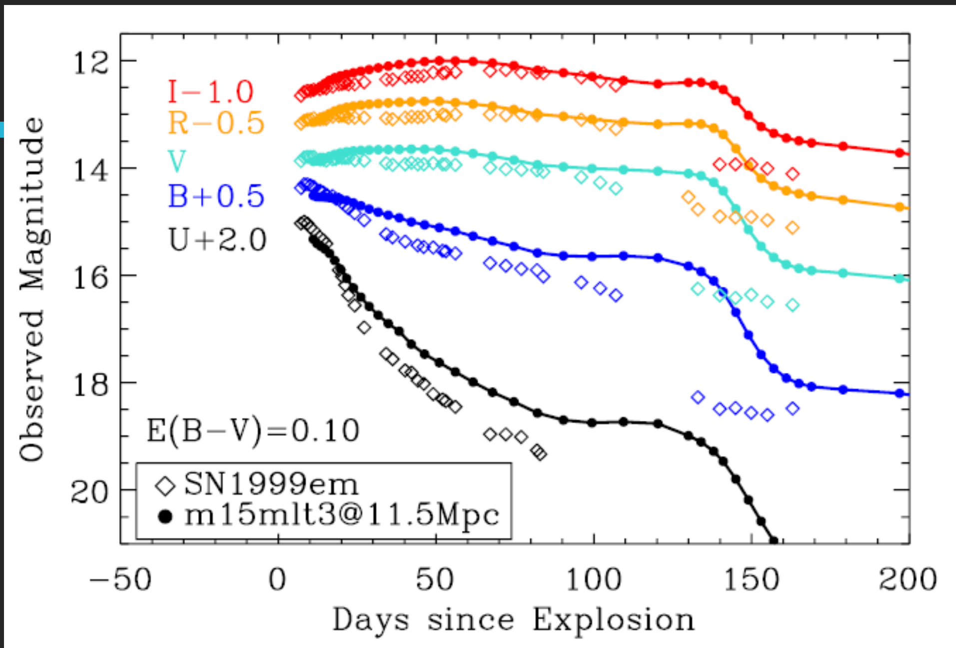


Bersten+ 2011

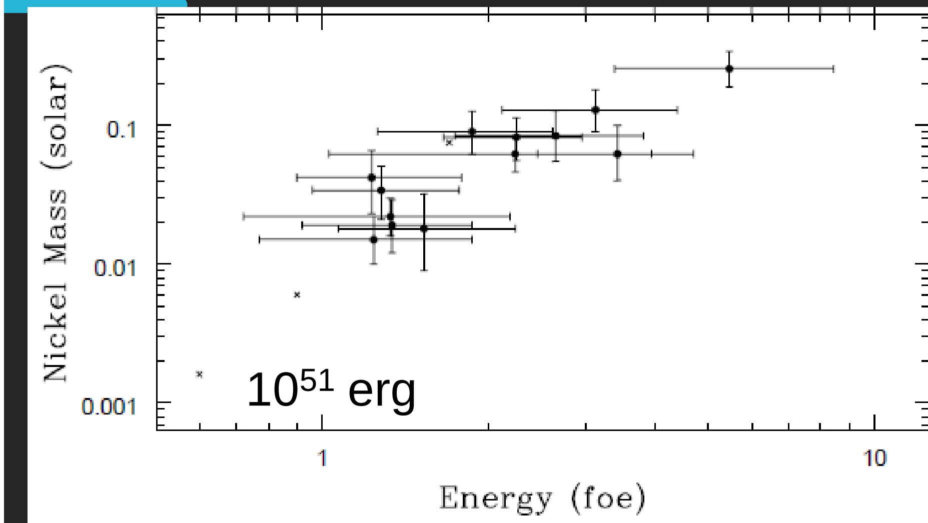
T~ const ~ 6,000K
R ~ const

$L \sim 4\pi R^2 T^4$ ~ const
Color (T) ~ const

Dessart+ 2013



Hamuy+ 2003



Bose+ 2013

Name	t_0 (245 0000+)	Δt_p (d)	t_p (d)	M_V^p (mag)	v_p (km s^{-1})	E_0 ($\times 10^{50}$ erg)	M_{ej} ($M_\odot$)	R_0 ($R_\odot$)
SN 1999em	1475.6	92 ± 8	55 ± 4	−16.69 ± 0.01	3512 ± 122	7 ± 2	11 ± 3	399 ± 54
SN 1999gi	1522.3	97 ± 8	58 ± 4	−16.26 ± 0.02	2746 ± 217	4 ± 1	10 ± 3	421 ± 99
SN 2004et	3270.5	87 ± 8	63 ± 4	−17.01 ± 0.03	3630 ± 142	6 ± 2	9 ± 2	591 ± 90
SN 2012aw	6002.6	96 ± 11	57 ± 6	−16.67 ± 0.03	3631 ± 200	9 ± 3	14 ± 5	337 ± 67

Not always consistent w/ detected progenitor mass?
E-M(^{56}Ni) related? (calibration w/ v-burst detection!).

Radioactivity

Isotopes	W7	C-DEF	C-DDT	O-DDT
^{22}Na	2.01E−08	1.01E−07	1.46E−07	5.40E−08
^{26}Al	5.18E−07	1.69E−06	2.47E−06	8.77E−07
^{36}Cl	2.08E−06	4.74E−07	5.22E−06	2.06E−06
^{39}Ar	6.79E−09	1.53E−09	1.69E−08	7.75E−09
^{40}K	4.34E−08	7.17E−09	7.75E−08	3.90E−08
^{41}Ca	4.35E−06	1.10E−06	1.18E−05	8.85E−06
^{44}Ti	8.37E−06	1.93E−06	3.21E−06	1.59E−05
^{48}V	4.32E−08	1.68E−08	9.76E−08	1.09E−07
^{49}V	1.05E−07	1.00E−07	3.07E−07	2.69E−07
^{53}Mn	1.64E−04	4.93E−04	3.38E−04	2.25E−04
^{55}Fe	1.79E−03	4.17E−03	2.89E−03	1.93E−03
^{60}Fe	3.33E−09	9.86E−15	2.29E−13	6.93E−12
^{55}Co	4.89E−03	3.18E−03	3.07E−03	5.40E−03
^{56}Co	1.21E−04	1.18E−04	1.06E−04	1.04E−04
^{57}Co	9.52E−04	1.94E−03	1.40E−03	9.37E−04
^{60}Co	4.32E−08	5.30E−10	1.19E−09	3.30E−09
^{56}Ni	6.40E−01	2.45E−01	2.46E−01	5.40E−01
^{57}Ni	2.46E−02	1.06E−02	1.09E−02	1.71E−02
^{59}Ni	4.66E−04	7.24E−04	5.78E−04	4.22E−04
^{63}Ni	4.82E−08	4.28E−11	1.85E−10	1.22E−09

←Ia (Delayed-Detonation of Chandrasekhar WD)

KM+ 2010

Active works by several groups (e.g., Umeda+)

State-of-art models to come (Takiwaki/Horiuchi-san's talk?)

↓Core-collapse

KM+ 2010

Species	Models											
	40A	40B	40C	40D	40SHa	40SHb	40SLa	40SLb	25A	25B	25Sa	25Sb
^{26}Al	3.39E−05	3.10E−05	5.45E−05	1.40E−05	5.70E−05	5.52E−05	5.36E−05	5.35E−05	1.10E−02	1.23E−02	1.22E−02	1.22E−02
^{41}Ca	5.30E−06	4.05E−06	1.50E−05	9.05E−07	8.65E−06	7.40E−06	2.27E−05	2.24E−05	1.95E−06	1.41E−06	2.06E−06	2.06E−06
^{44}Ti	1.64E−04	1.50E−05	4.26E−04	7.52E−08	1.18E−03	6.67E−06	6.52E−06	8.72E−06	1.31E−04	3.66E−05	2.14E−04	5.73E−05
^{56}Ni	1.07E−01	8.11E−02	2.40E−01	6.28E−08	5.44E−01	9.01E−02	4.38E−01	9.07E−01	7.81E−02	1.51E−01	1.64E−01	9.07E−02
^{57}Ni	3.25E−03	1.45E−03	7.68E−03	6.90E−08	1.81E−02	1.39E−03	1.18E−03	2.16E−03	2.12E−03	2.65E−03	4.18E−03	2.55E−03

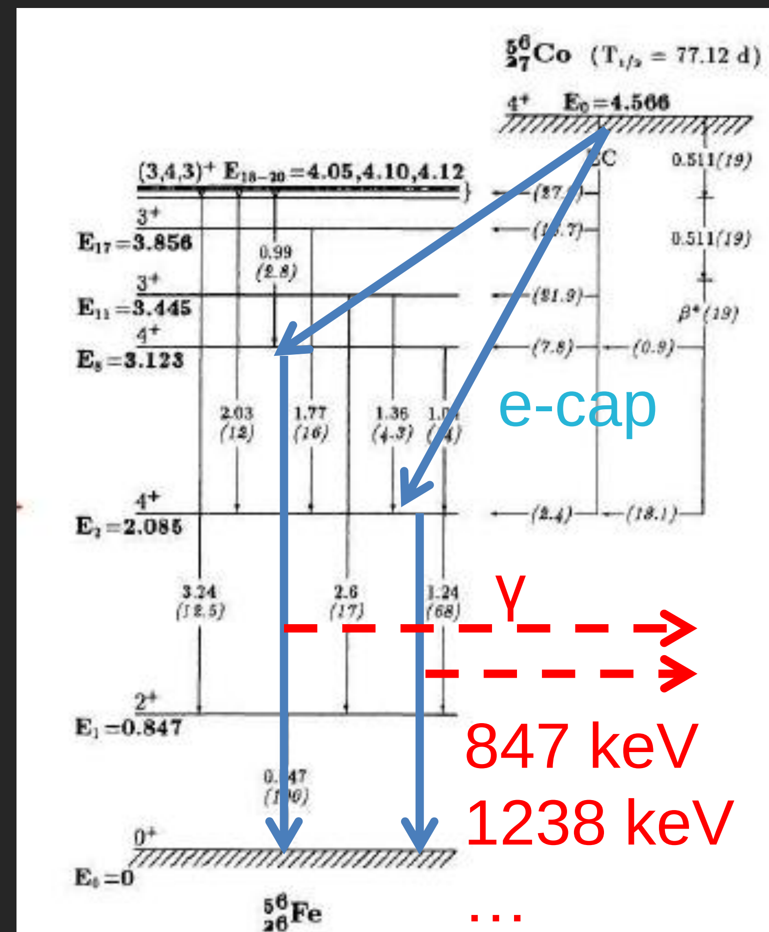
^{56}Ni→Co→Fe

- ~ 0.6 $M_\odot$ in each SN Ia.
- ~ 0.1 $M_\odot$ in each CC-SNe.
- ^{56}Ni→^{56}Co→^{56}Fe.
  ~1 week ~100 days

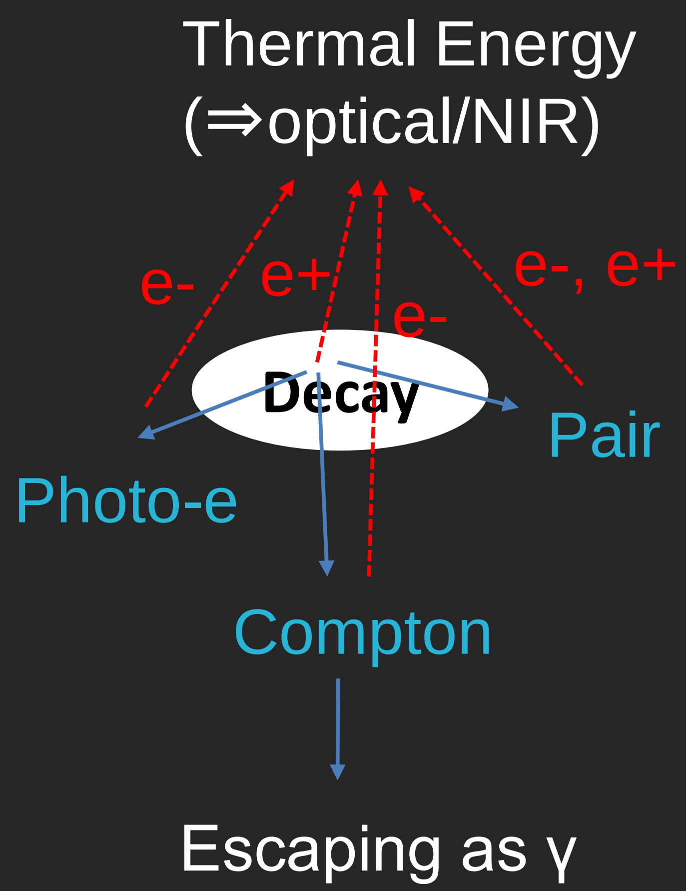
$$L_{\rm peak} \approx 7.8 \times 10^{43}\ M_{56{\rm Ni},\odot} \exp\left(\frac{-t_{\rm peak}}{8.8\ {\rm days}}\right)\ {\rm erg\ s^{-1}}$$

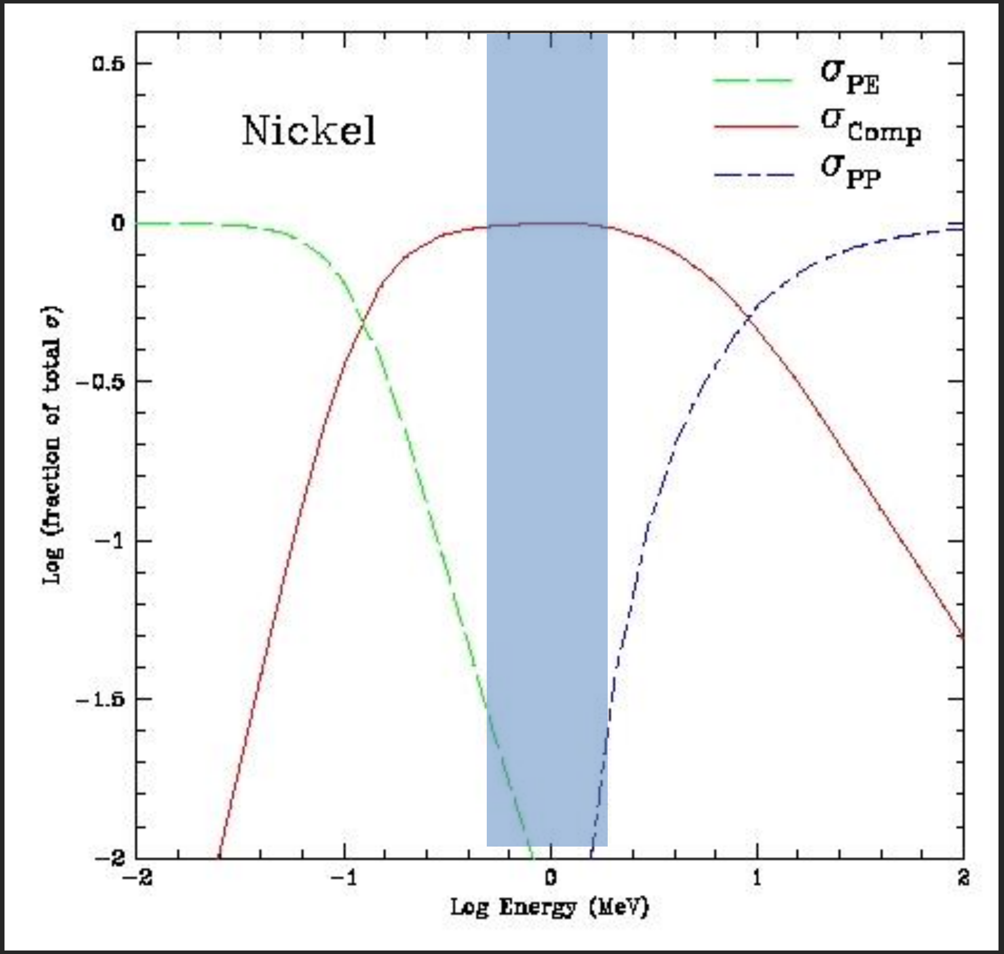
$$L_{\rm tail} \approx 1.3 \times 10^{43}\ {\rm erg\ s^{-1}}\, M_{56{\rm Ni},\odot} \times (\tau_\gamma + 0.035 f_{e+}) \exp\left(\frac{-t_{\rm tail}}{113.5\ {\rm days}}\right)$$

^{56}Fe ^{56}Co



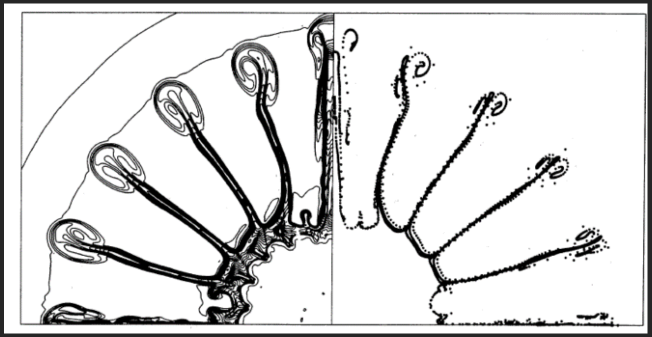
Decay Gamma-ray
(Nuclear Levels ~ MeV)





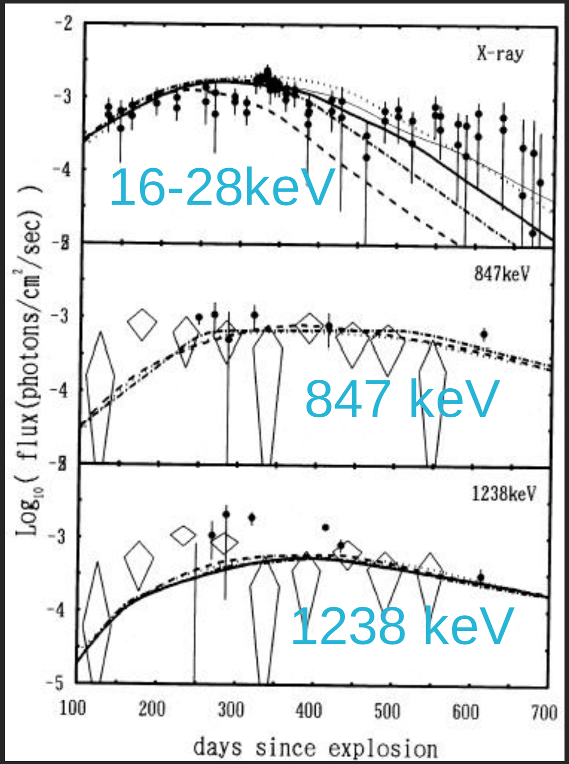
Radioactivity: SN 1987A

- $M(^{56}Ni) \sim 0.07 M_\odot$
- $M(^{57}Ni)/M(^{56}Ni) \sim 1.5\ [X(^{57}Fe)/X(^{56}Fe)]_\odot$
- $M(^{44}Ti)/M(^{56}Ni) < \sim 2.9\ [X(^{44}Ca)/X(^{56}Fe)]_\odot$



Hachisu+ 1992

Kumagai+ 93

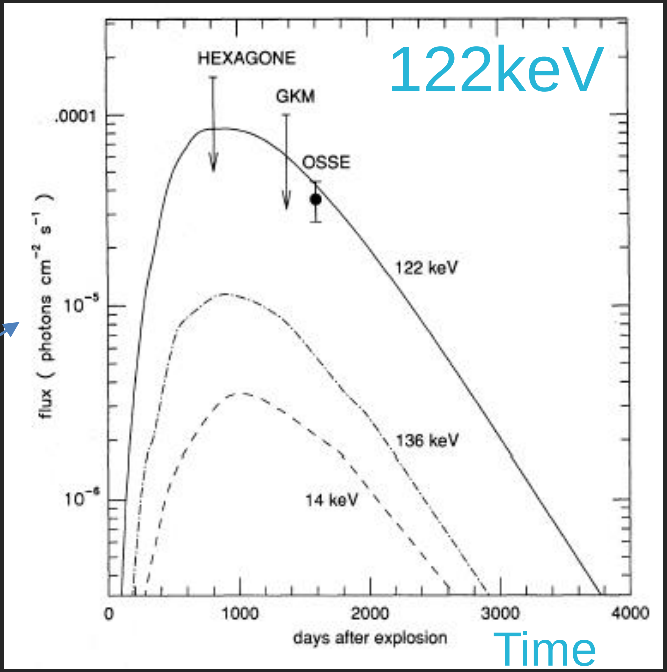


Kumagai+ 1989

^{56}Co/Fe

^{57}Co/Fe

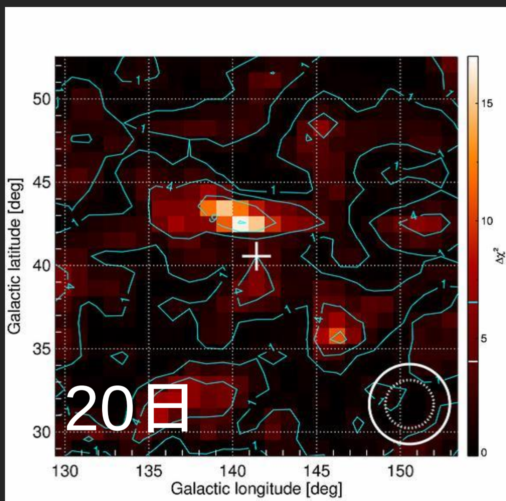
Time (100 – 700 day)

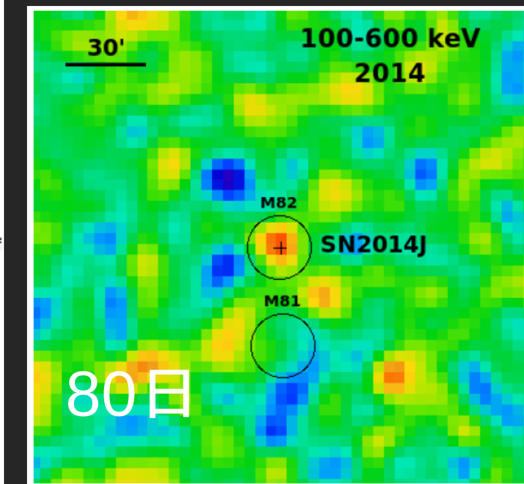


Time (0 - 4000 day)

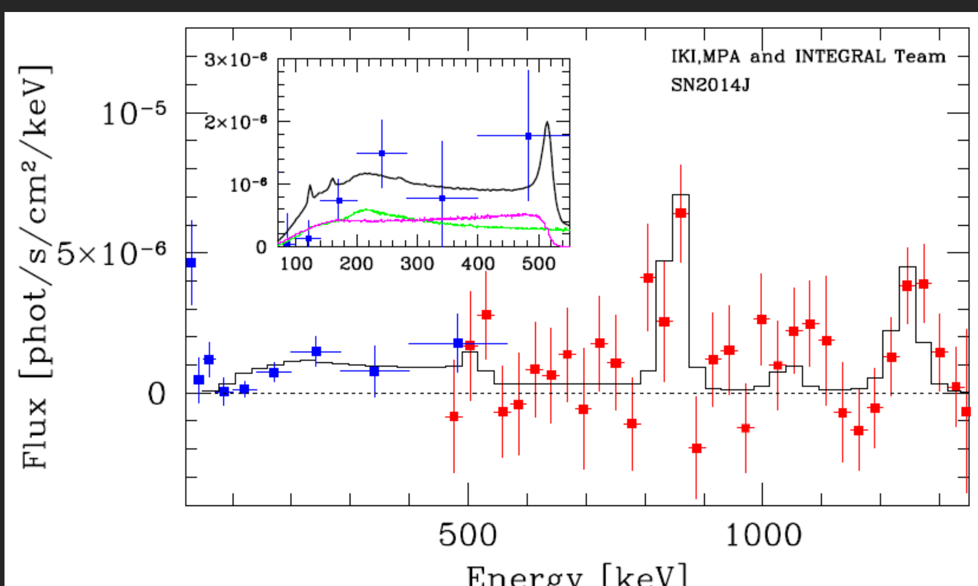
New insights: e.g., need for R-T mixing (pure 1D models too opaque).

Another example: SN Ia 2014J





SN Ia 2014J @M82, 3.8Mpc



@ 20 days (INTEGRAL):
Diehl, …, KM+ et al., 2014, Science

@ 50 – 100 days (INTEGRAL):
Churazov et al., 2014, Nature

@ 75 days (Suzaku):
Terada, KM+, submitted

Gamma from a next Galactic SN

Astro-H simulation

(for Ia, though)

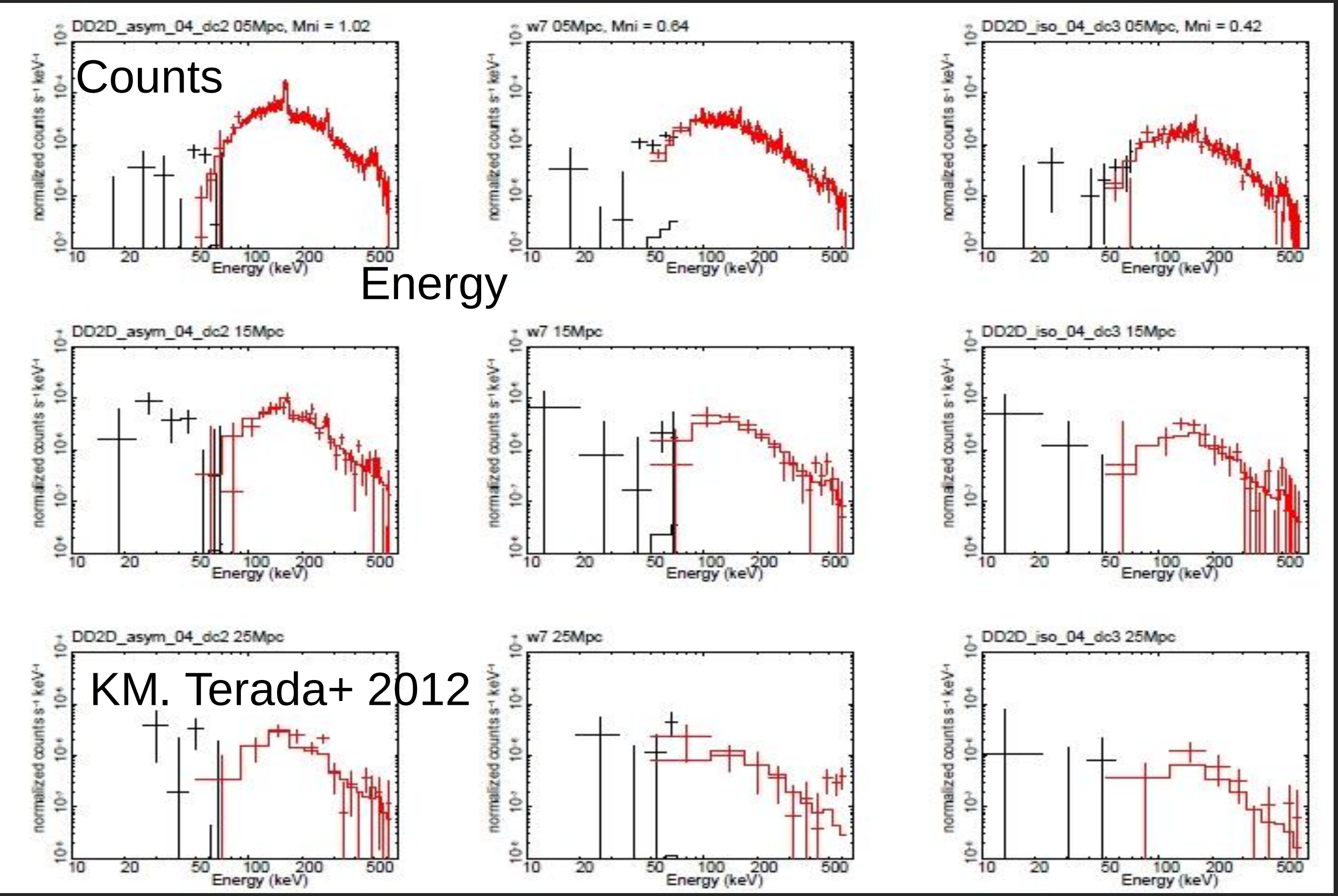
- Should be **easy** detection, w/ very **good** S/N ratio.

M(^{56}Ni)=1M$_\odot$(DDT)   0.6M$_\odot$ (W7)   0.4M$_\odot$(DDT)

5 Mpc

15 Mpc

25 Mpc



Diffusion of radioactive-powered optical radiation (for SNe Ib/c)

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

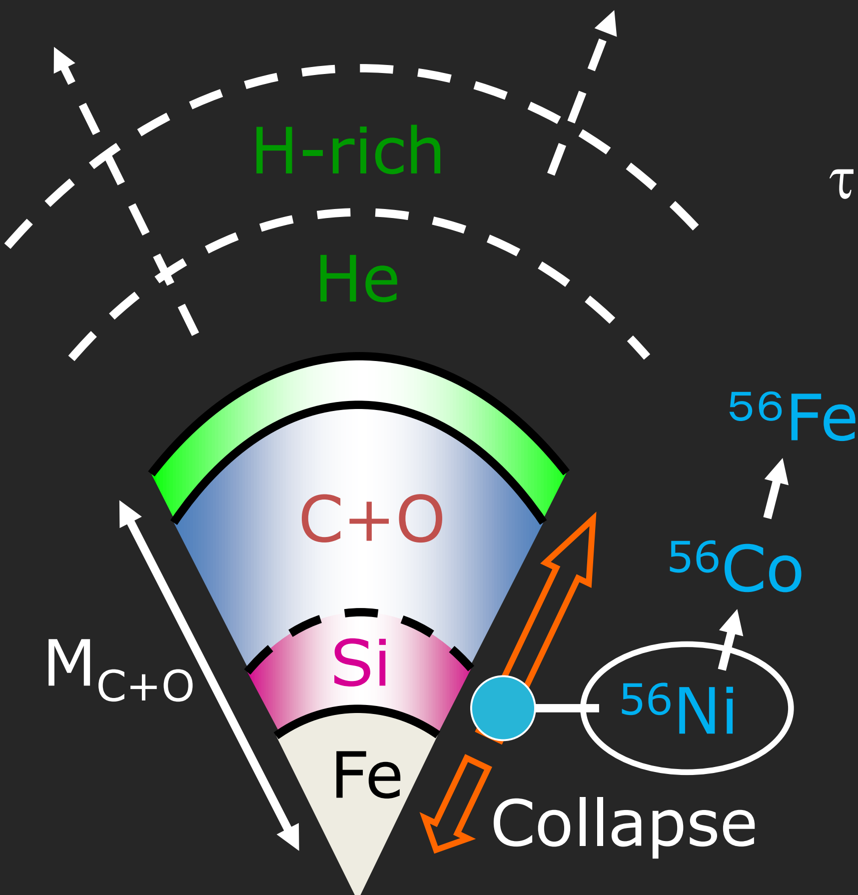
Light Curve | Spectra

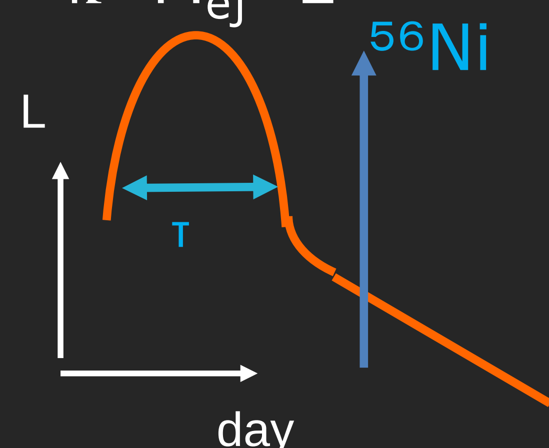
$$\tau \sim [\tau_{dyn} \bullet \tau_{diffusion}]^{1/2}$$

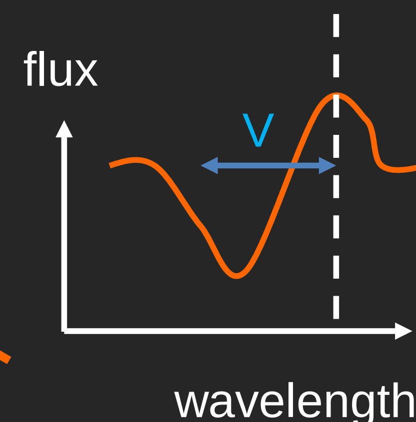
$$\sim \left(\frac{R}{V} \bullet \frac{\kappa M_{ej}}{R c} \right)^{1/2}$$

$$\propto \kappa^{1/2} M_{ej}^{3/4} E^{-1/4}$$

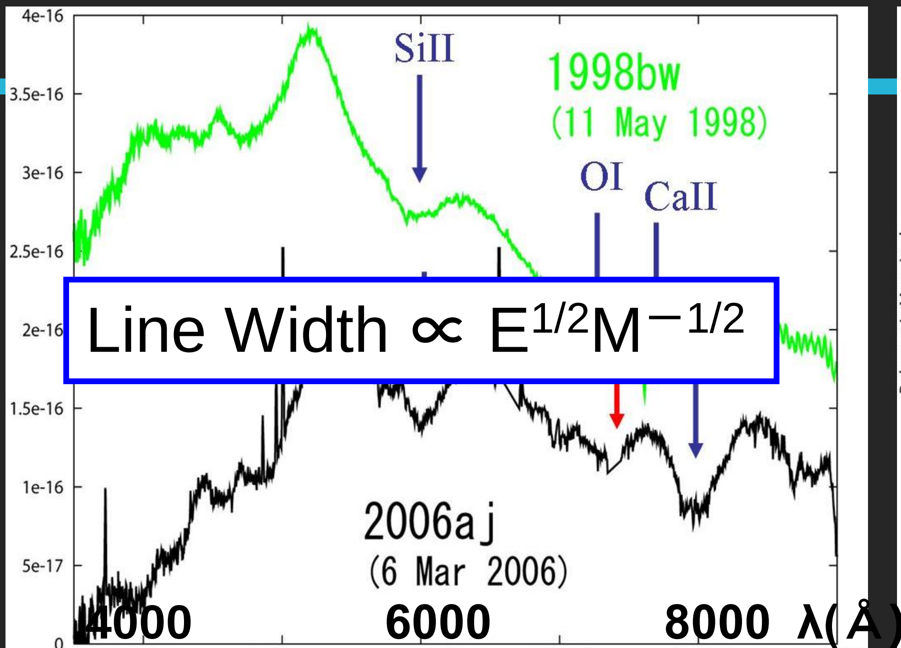
$$V \sim [E/Mej]^{1/2}$$



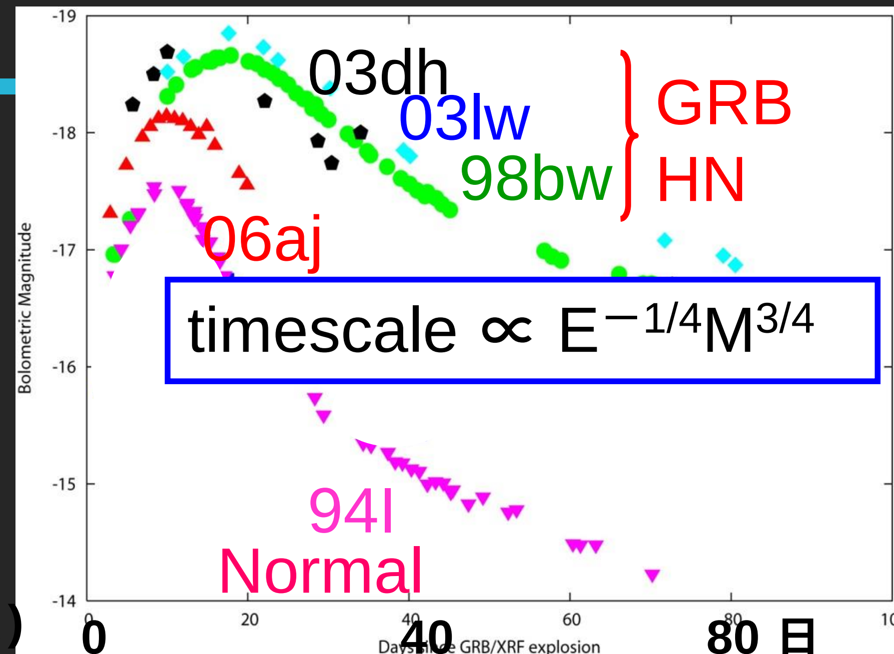




Spectra @ ~ 2 weeks



Light Curve @ 1st month



	1994I	2006aj	1998bw
High-E event	none	XRF	GRB
$M_{ej}/M_{\odot}$	~1	~2	~10
M_{ms}	10-15	20-25	35-45
E_{51} (10^{51}erg)	1	2	20
M(^{56}Ni)	0.07	0.3	0.4

→ Broader
- Line width
- LC width

Iwamoto et al. 98
Mazzali et al. 06
Maeda et al. 06

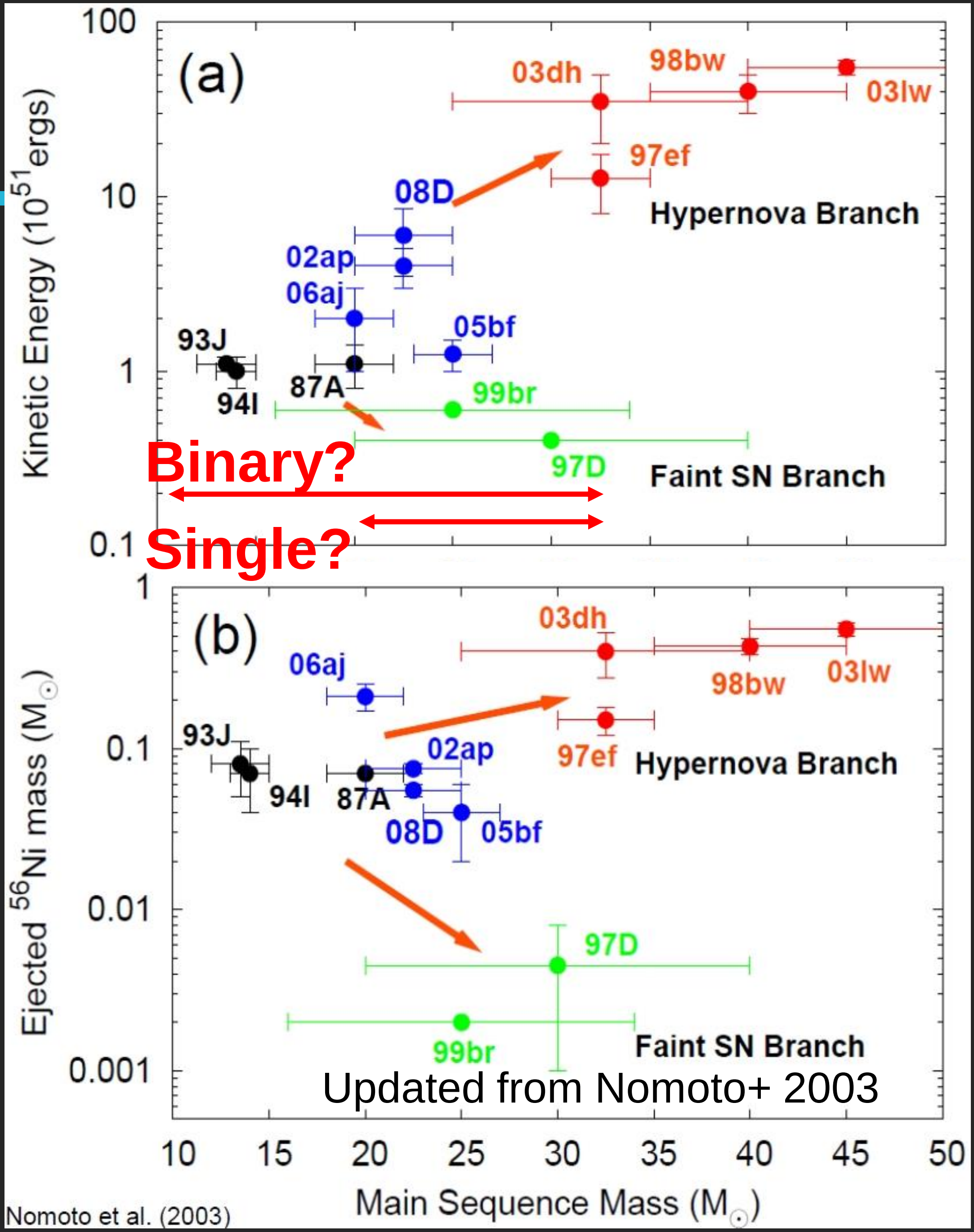
Global properties

Light curve + spectral modeling
⇒Progenitor mass
Explosion energy

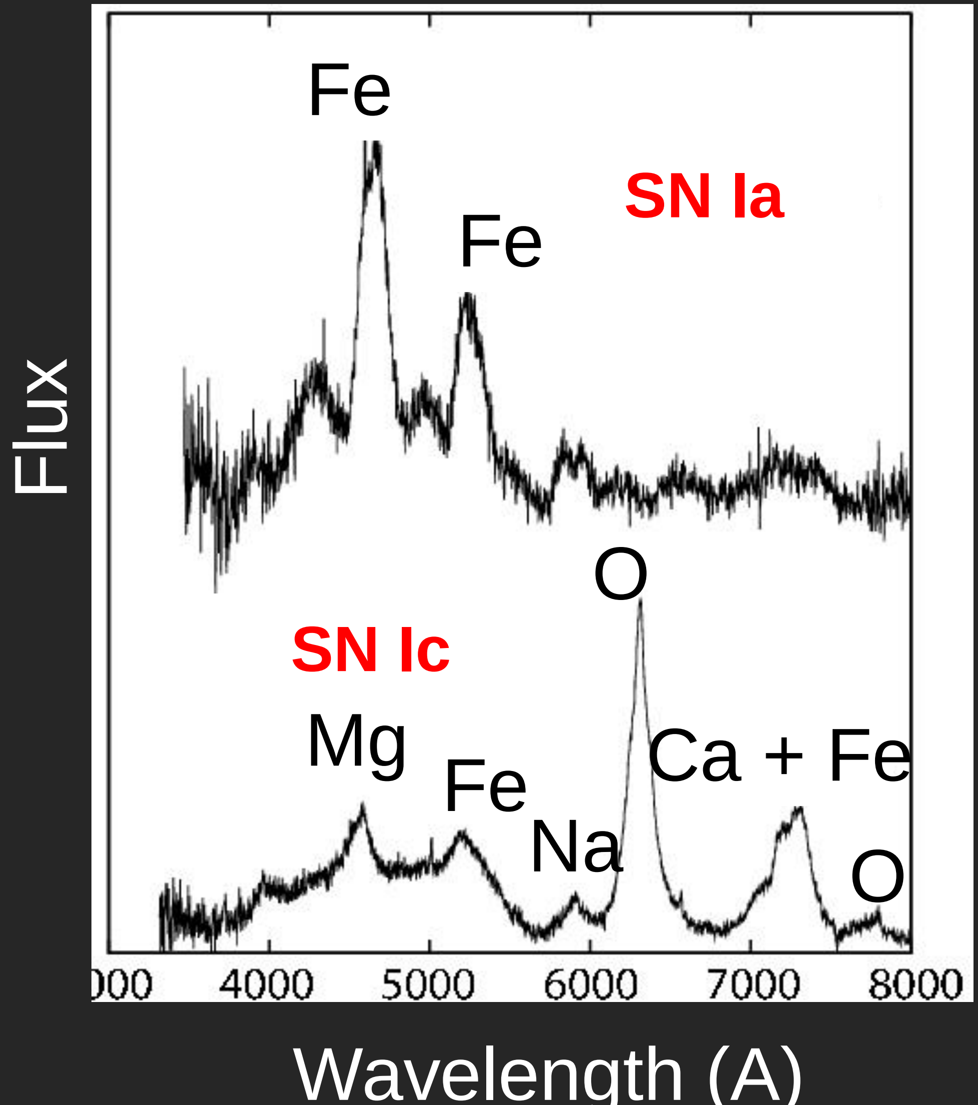
Luminosity
⇒M(^{56}Ni)

Diversities.
A good fraction from a binary path?

E-M(^{56}Ni)-M related?
(calibration w/ ν-burst detection!).



SN optical emission: ~ a year

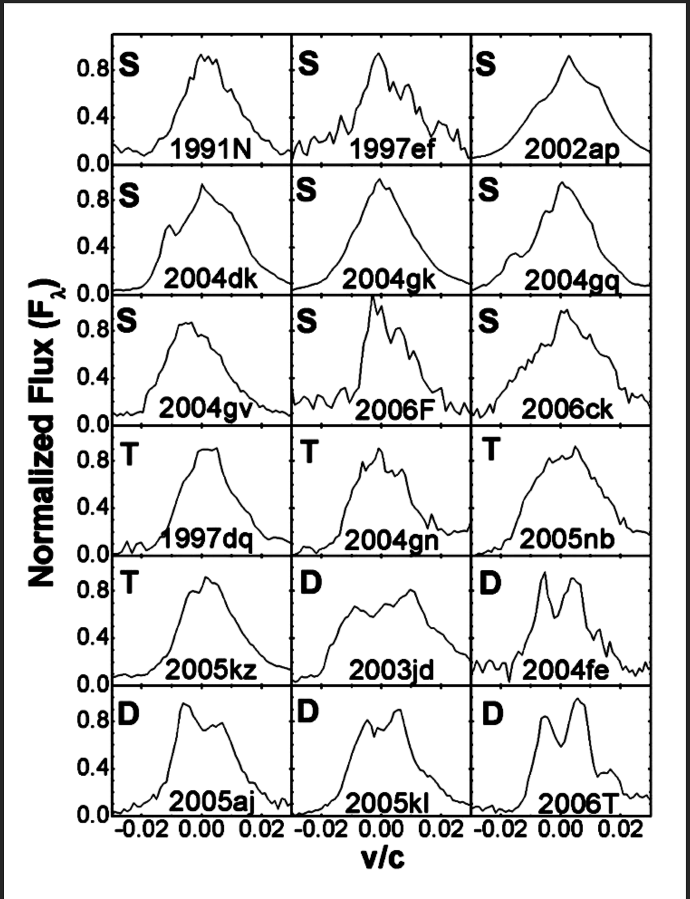


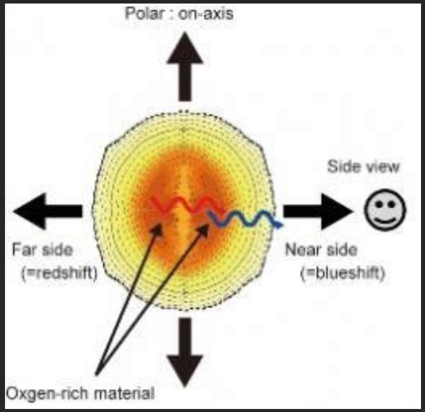
- Optically thin.
  - $\rho \propto t^{-3}$
- **Innermost** region.
- Elements synthesized **at the explosion.**
  - SNe Ia → Fe
  - CC-SNe → Fe, Ca, O.

cf: 8m-Subaru obs. for the inner composition.
KM+ 2007ab, 2009, …, ApJ
Kawabata, KM+ 2010, Nature

Kinematics (late-time spec.)

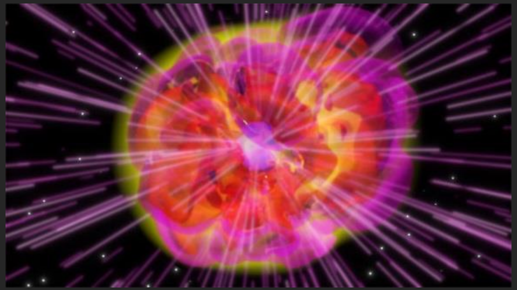
Abunance+Kinematics→explosion





A powerful way to probe explosion from EM radiation.

Takiwaki+ 2014



Core-collapse SNe are aspherical

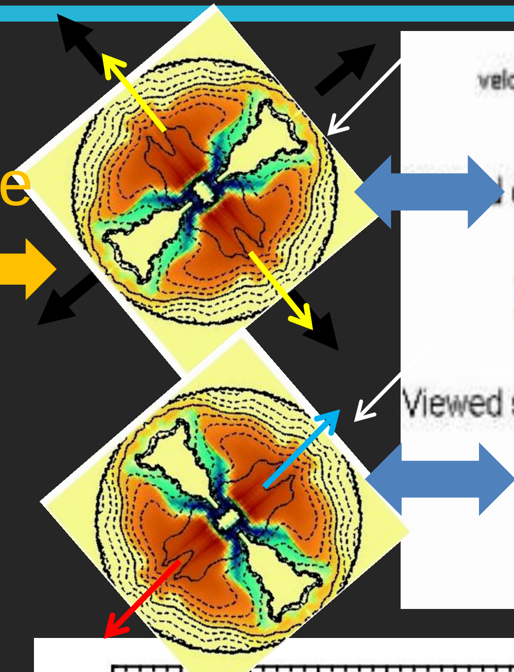
KM, Kawabata+ 2008←**Subaru/FOCAS**

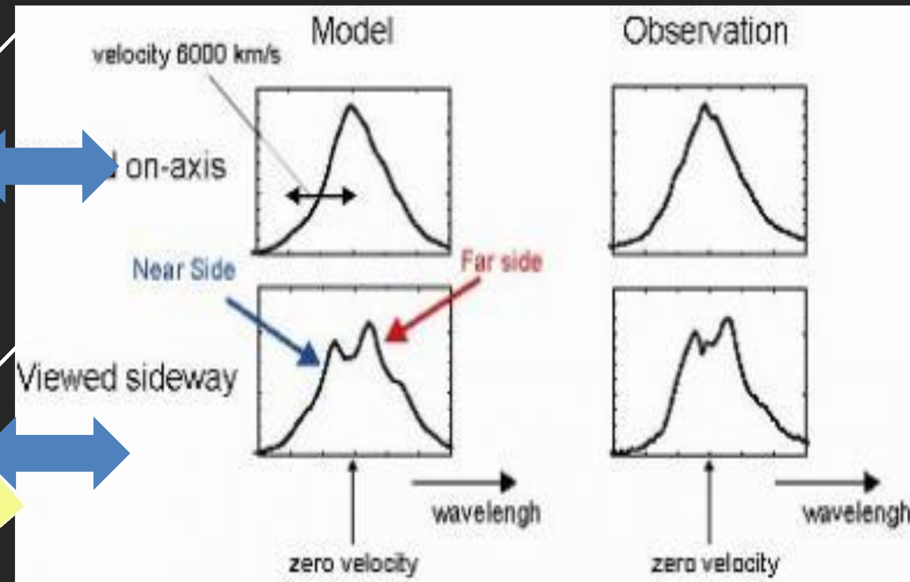
Kinematics (late-time spec.)

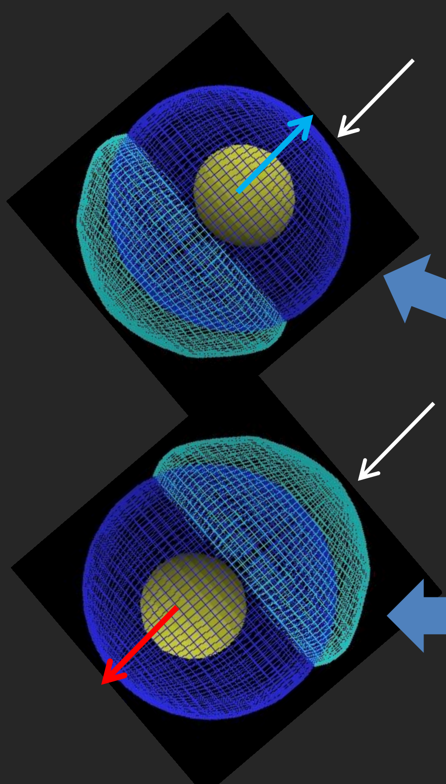
Core-collapse

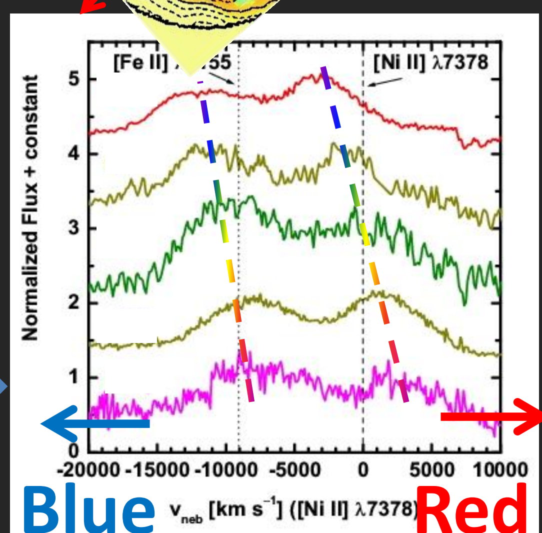
KM+ 2008, Science

Subaru (8m)









Type Ia SNe

KM+ 2010, Nature

Gemini (8m) etc.

Different type of explosion geometry ⇔ v signal

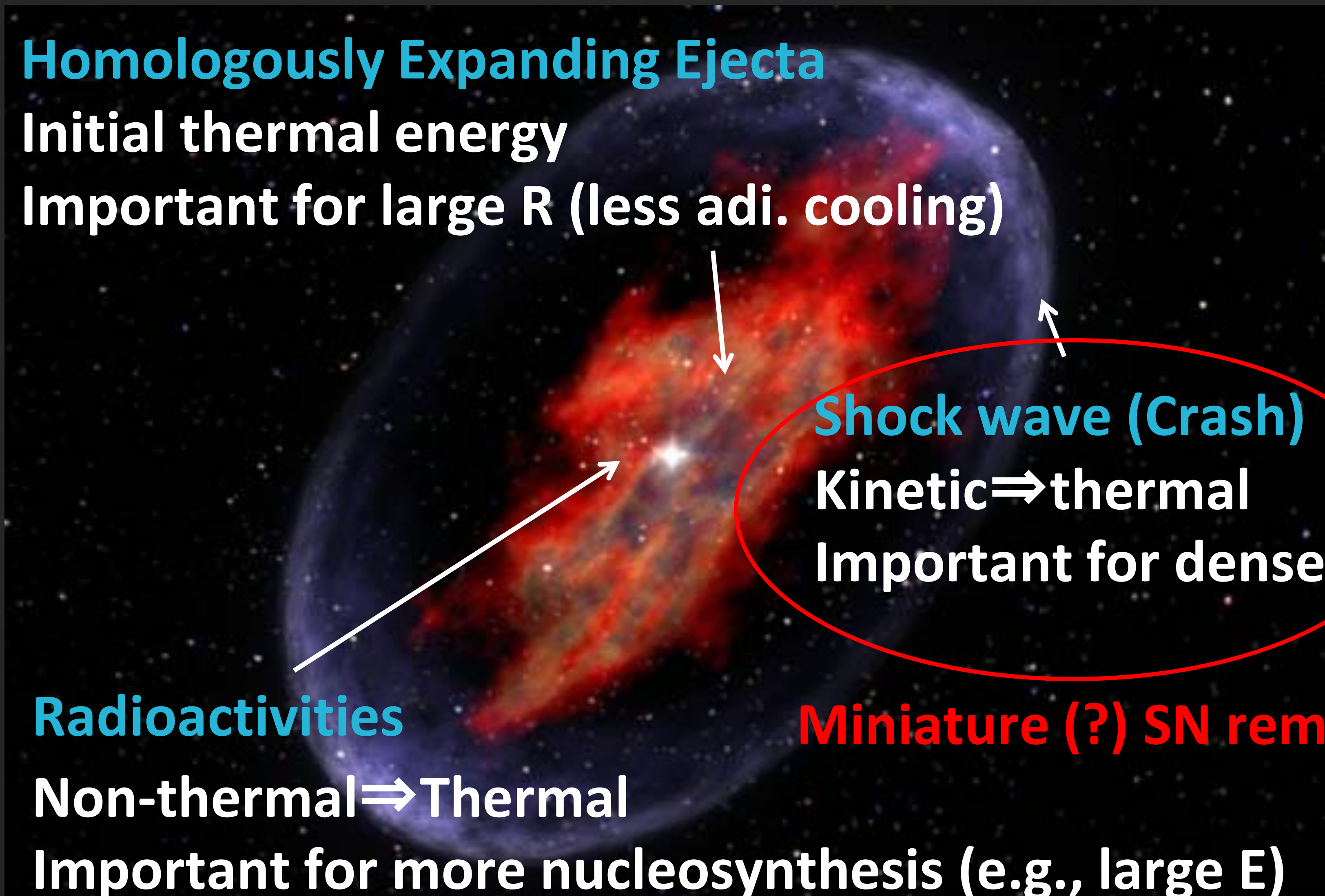
Summary for the SN observation.

- Shock breakout, post-SB ⇔ progenitor radius: qualitatively consistent with progenitor detection (?), but discrepancy especially for SNe Ib/c.
- "Peak" phase ⇔ mass, energetics, ^{56}Ni: Relations between these quantities. Explosion Mechanism?
- "Late" phase ⇔ kinematics, nucleosynthesis @ explosion: Strong probe for explosion from EM radiation.
- Little information on the SN nature for SNe IIn.
- Radioactive decay: Easy to get for a Galactic SN.

Connecting ν burst to EM signals will be key in understanding the explosion mechanism (will give an important calibrations for all the EM method!).

Observations of supernova on-site environment/Cicumstellar matter (= mass loss in the last decades to centuries)

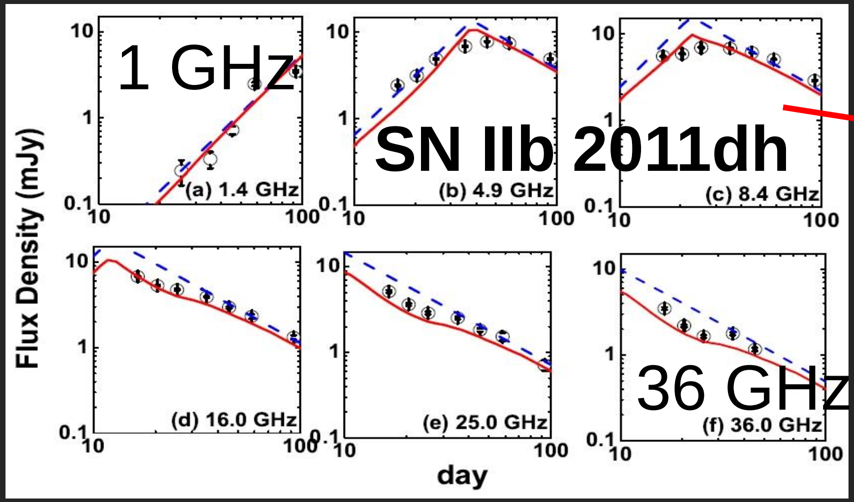
Further Energy Budget for EM radiation



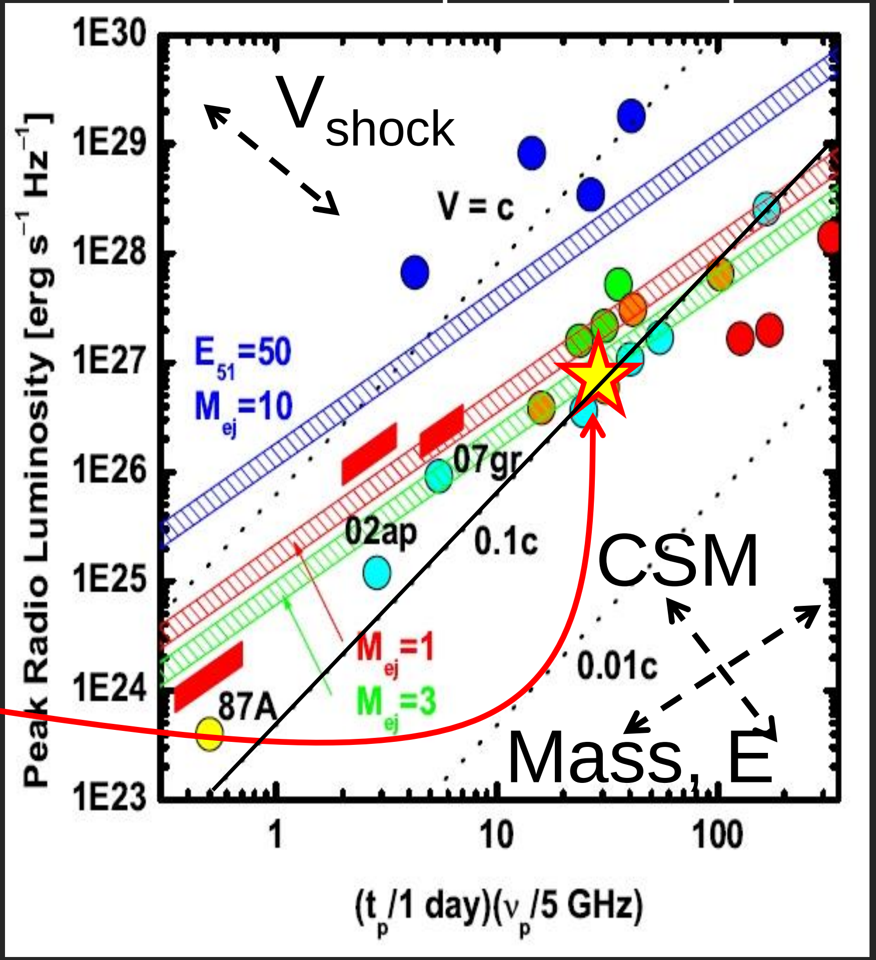
KM 2012b, 2013a, ApJ

SN radio emission (collision w/ surroundings)

- Days - **weeks**
  - – **Progenitor + breakout.**
- Weeks - months
  - – **Ejecta mass + Energy.**
  - – **CSM/ISM density.**
  - – **Cosmic ray acceleration.**



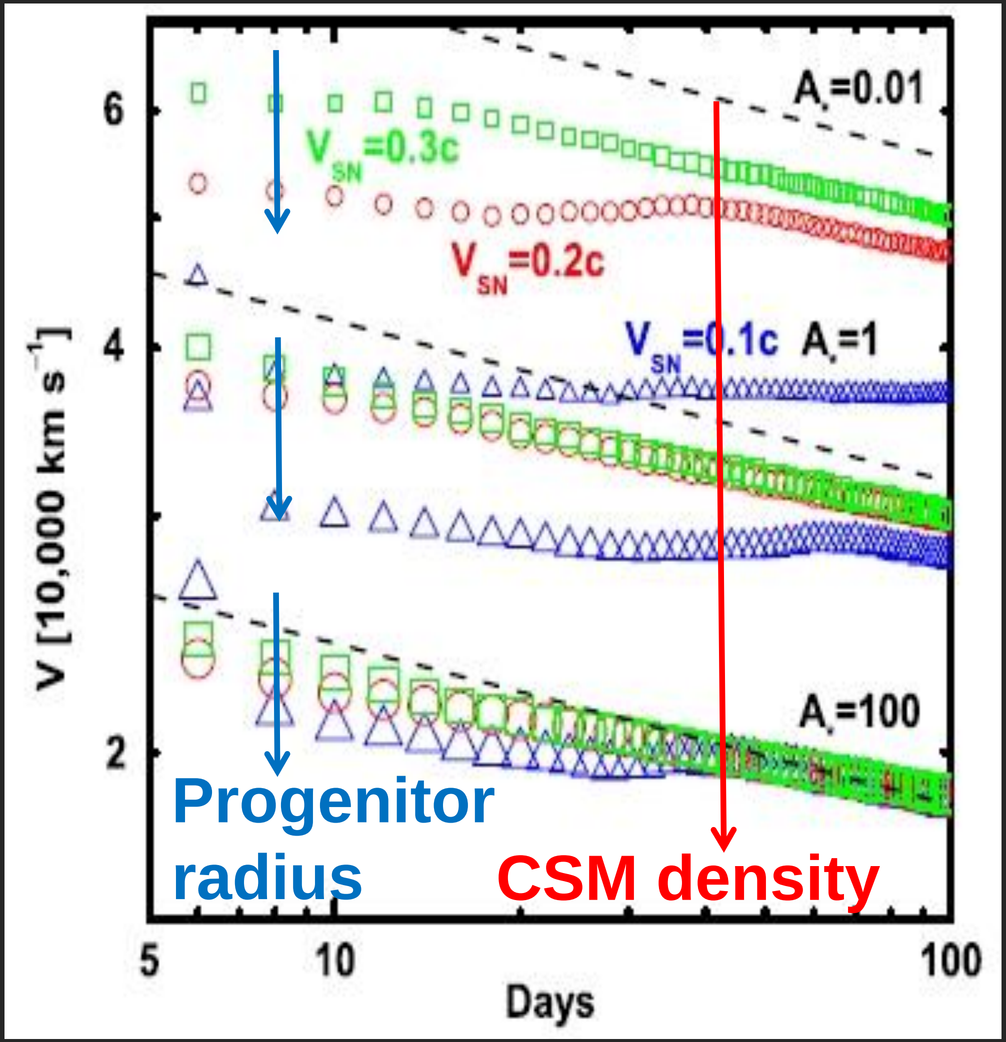
Radio t_{peak} vs. L_{peak}



ALMA ToO conducted (KM+)

KM 2013, ApJ, 762, 14

Early-Phase Radio & Progenitor



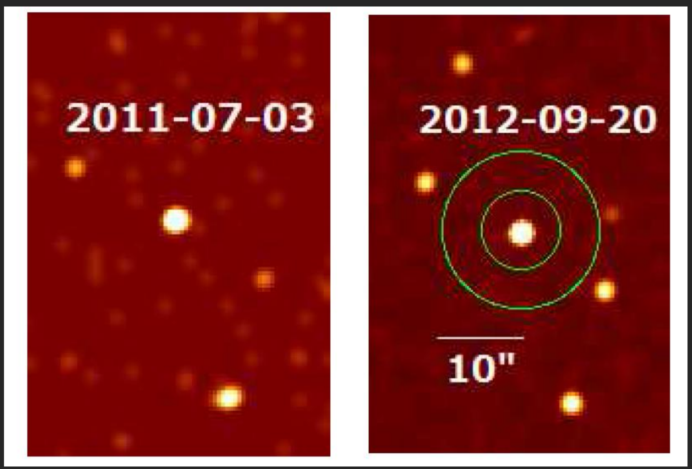
Assuming a next SN @ galactic center, radio follow-up may be complementary to NIR (huge abs in opt. & radio sky is more quiet).

Radio in first few days
⇒ Shock velocity
⇒ Progenitor radius

Radio in > 10 days
⇒ CSM density

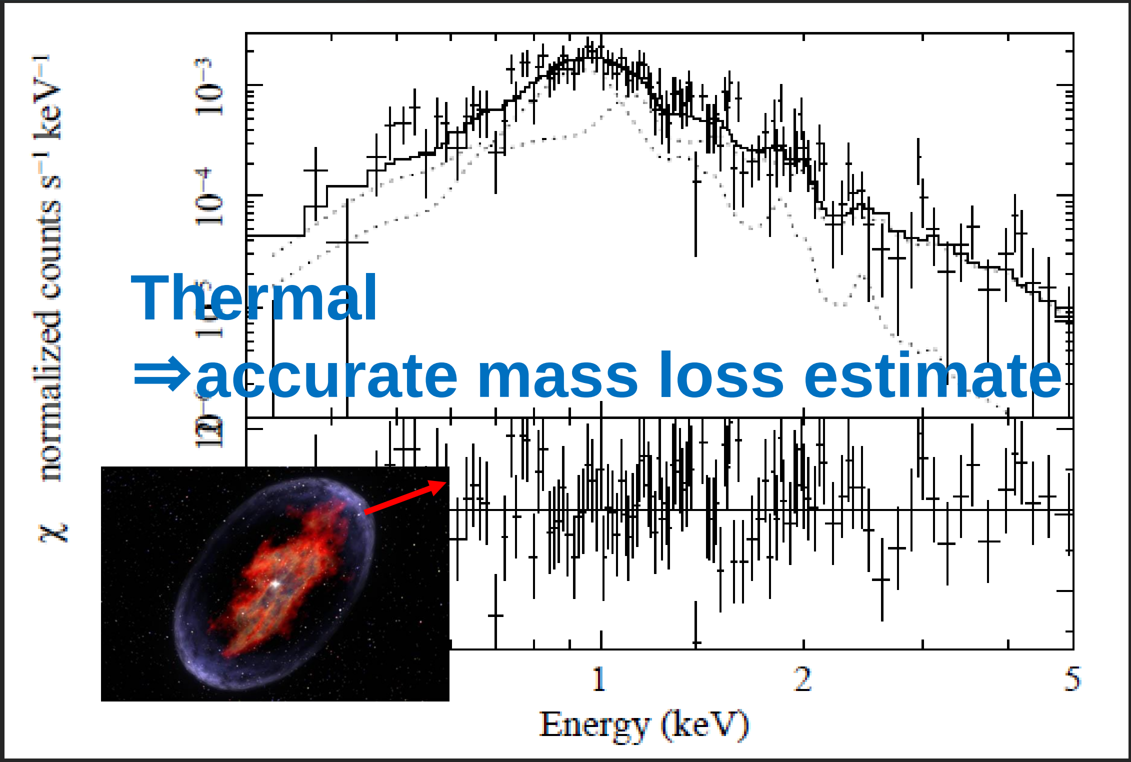
KM, Katsuda, Bamba, Terada, Fukazawa, 2014, ApJ

CSM as seen X-rays: example SN IIb 2011dh (YSG)



SN 2011dh @ 500 days

Chandra 750 ksec



Thermal
⇒accurate mass loss estimate

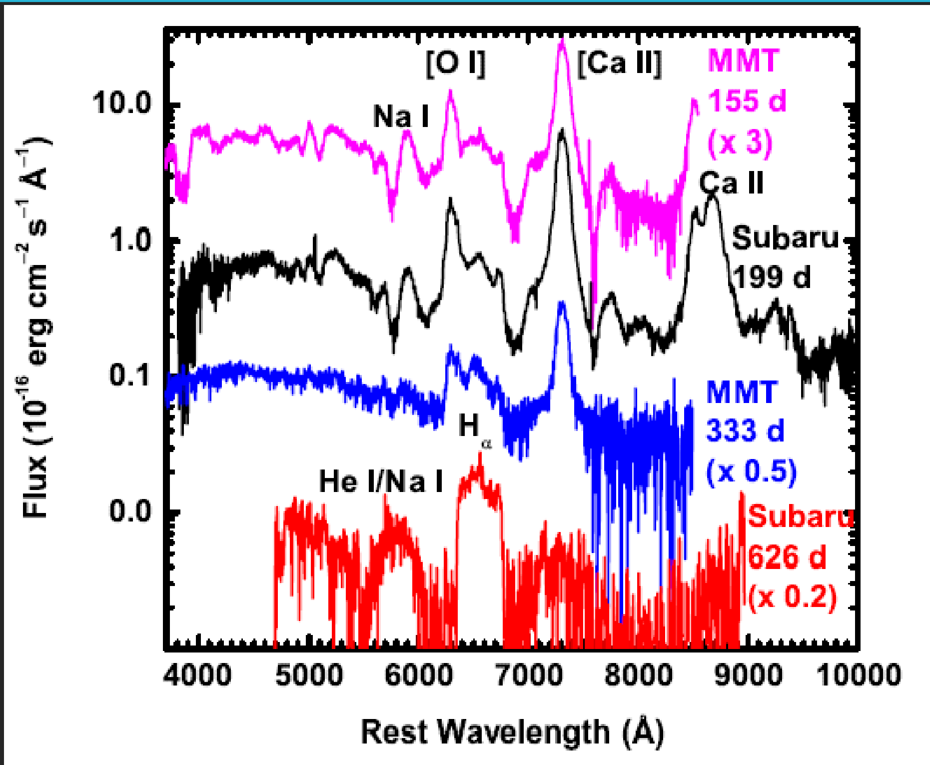
~ 3 x 10^{-6} $M_{\odot}$/yr in the final ~ 1,000 yrs (for v ~ 20 km/s)

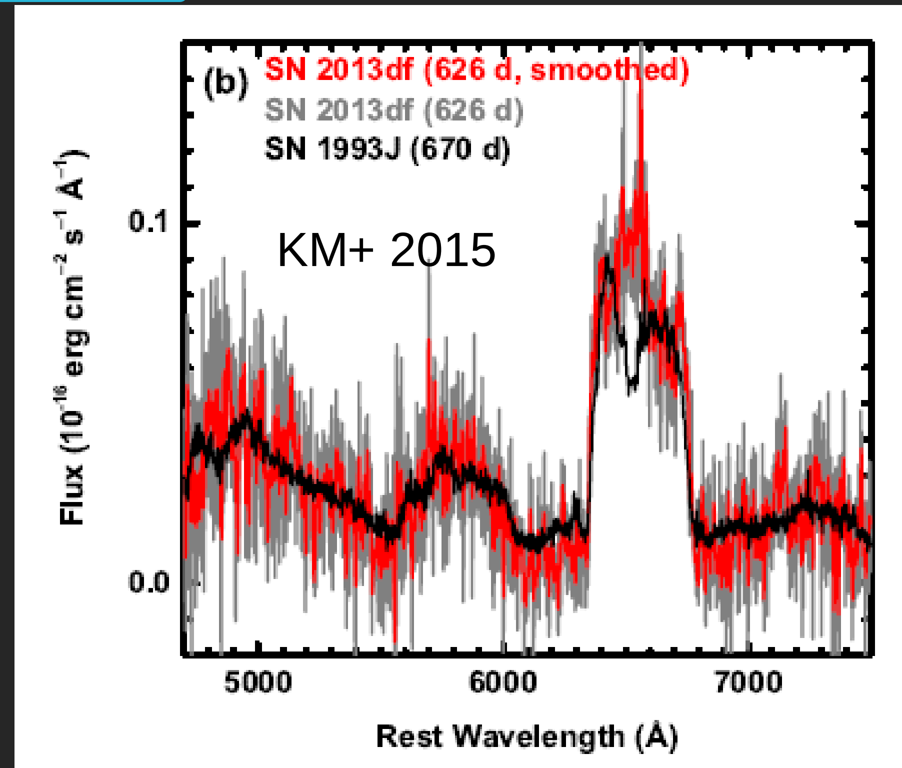
Consistent with “single stellar wind” from YSG.

However, not enough to get rid of all the H-envelope

⇒Binary interaction in the past (delay to the explosion).

CSM as seen in optica: SN IIb 2013df





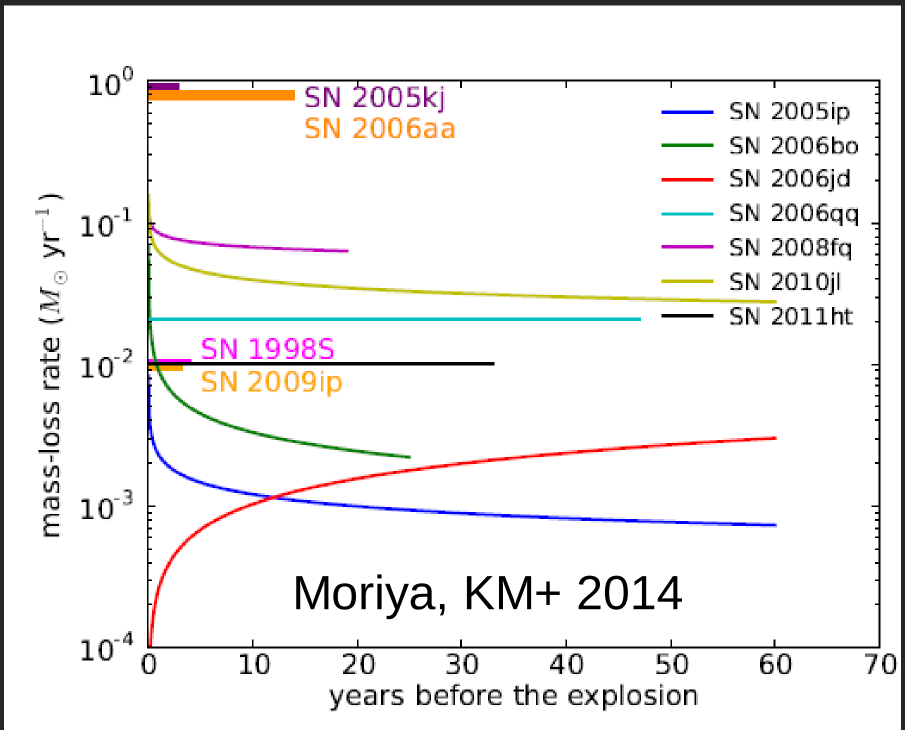
Hα ⇒Mass loss: ~ 5 10^{-5} $M_{\odot}$ yr^{-1} for 20 km s^{-1} (> 10 x 2011dh!)

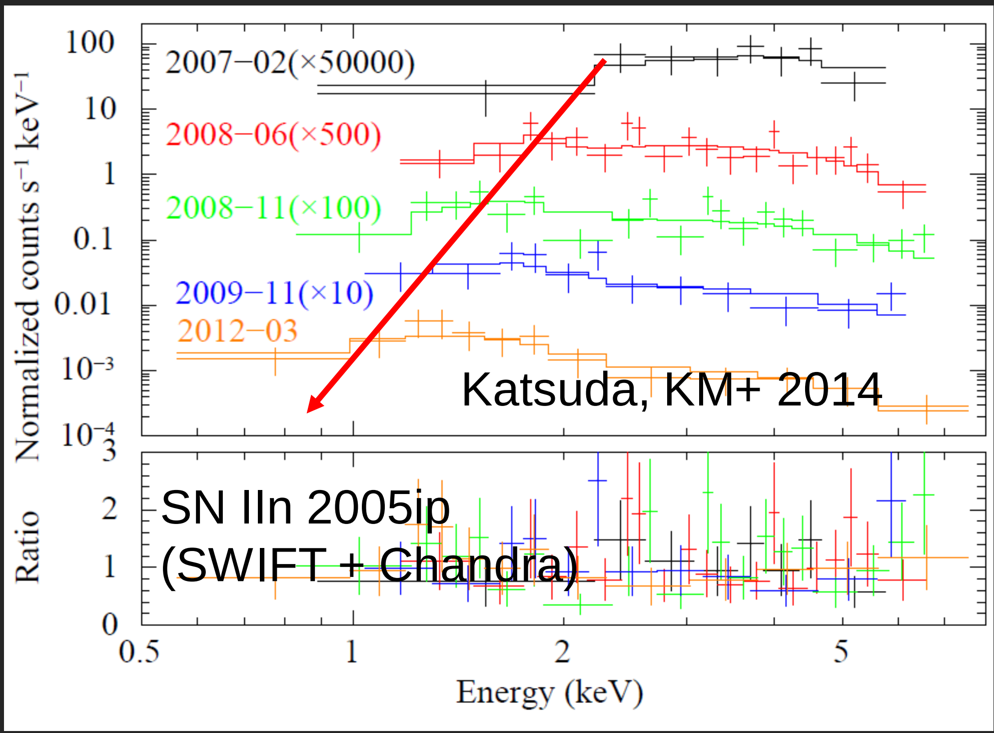
Progenitor (candidate) detected for SNe IIb 2013df and 2011dh

R ~ $600R_{\odot}$ (2013df) vs. $200R_{\odot}$ (2011dh):

Relation to Progenitor and mass loss (know **no** model prediction!)

Huge CSM around SNe IIn (what to make it?)





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

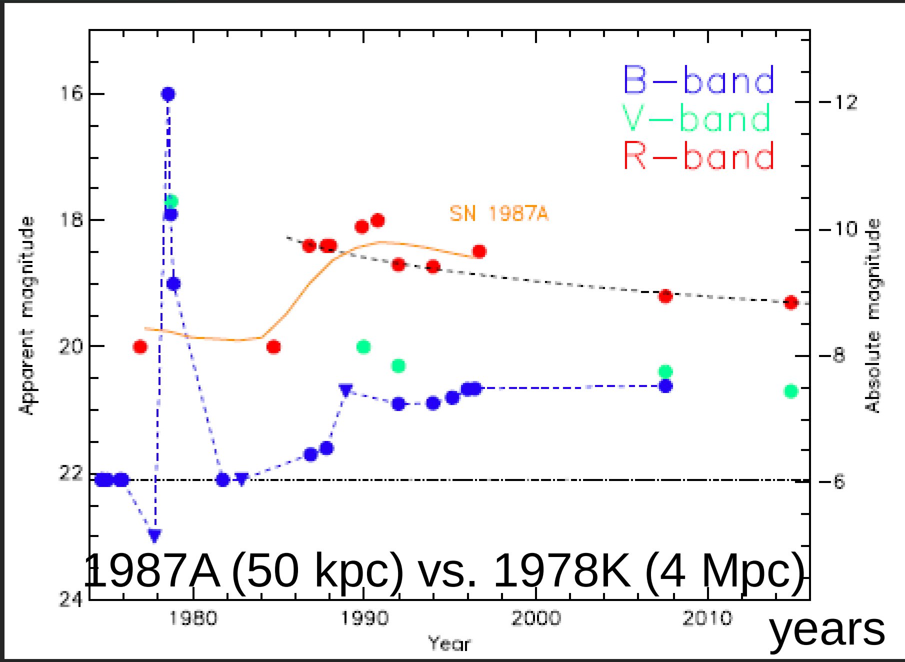
Decreasing CSM density

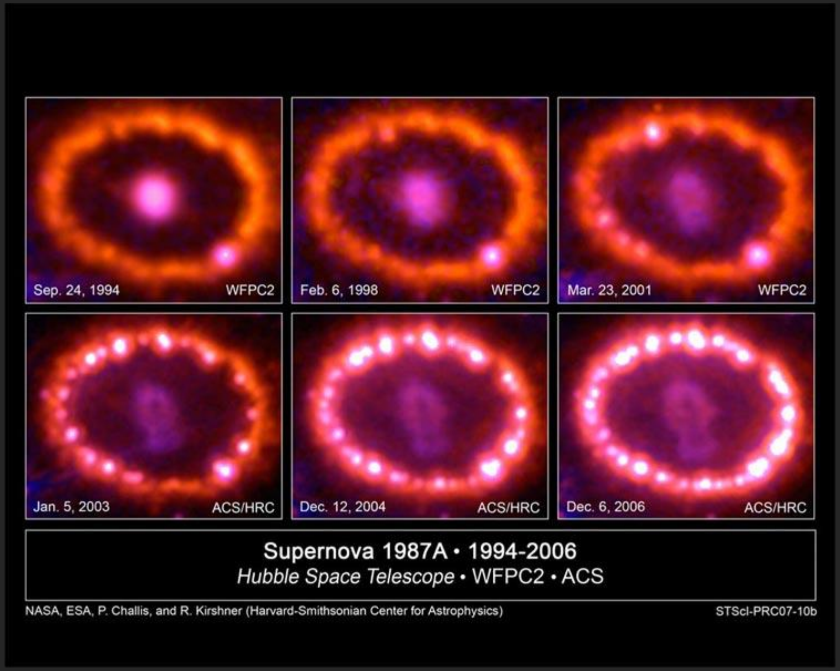
e.g., Chandra+ 2012 (2006jd)

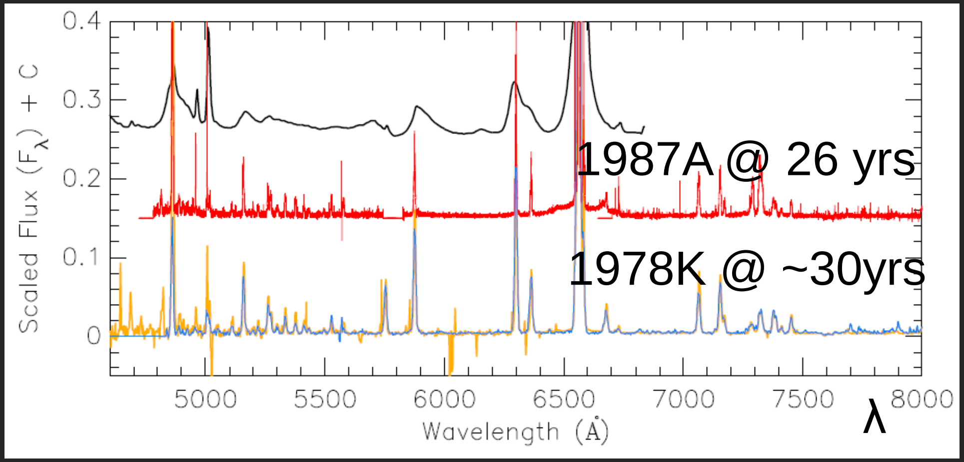
SN evolving into Remnant

Kuncarayakti, KM+, submitted

- And of course we (?) can observe a galactic SN for many centuries.







Summary for the CSM observation.

- Basically sensitive to the CSM density and environment: Many unresolved problems regarding the progenitor evolution in the final days to centuries.
- Connection between the progenitor and mass loss for SNe IIb/Ib/Ic, crazy huge mass loss for SNe IIn.
- For an SN @ Galactic center, radio (and X) may be a good alternative to optical counterpart search.
- Radio an for example provide an independent measure of progenitor radius if observed in the first few days.

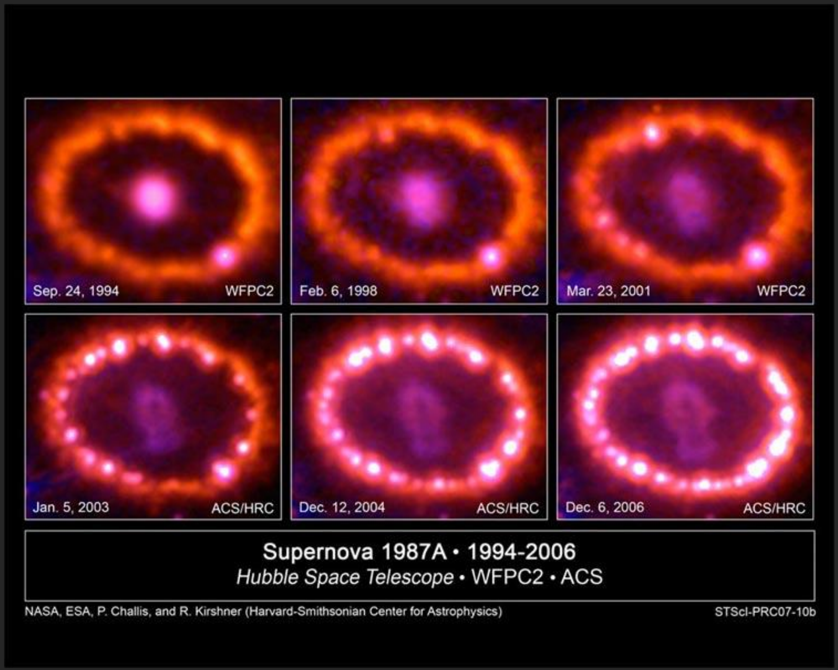
Again, especially pre-SN ν detection can be a key.

Yet further for a next galactic SN

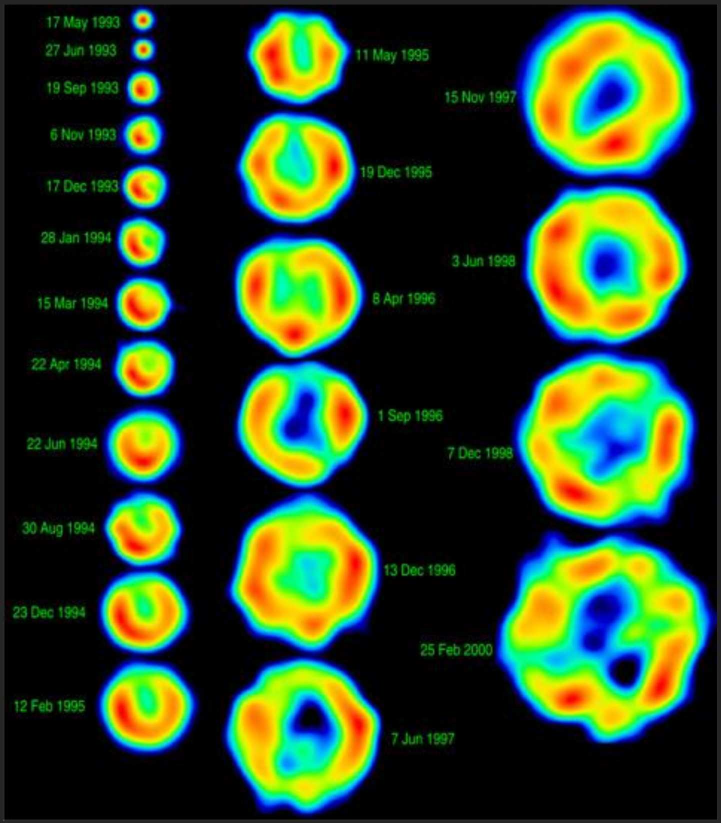
- So far mostly for SNe @ > a few Mpc (except for SN 1987A @ 50 kpc).
- Of course there are many diagnose observations (almost) only possible for a Galactic one – so a few examples (among many)

Resolved Imaging/spectroscopy

Optical: SN 1987A (50 kpc)



Radio: SN 1993J (2.6 Mpc)



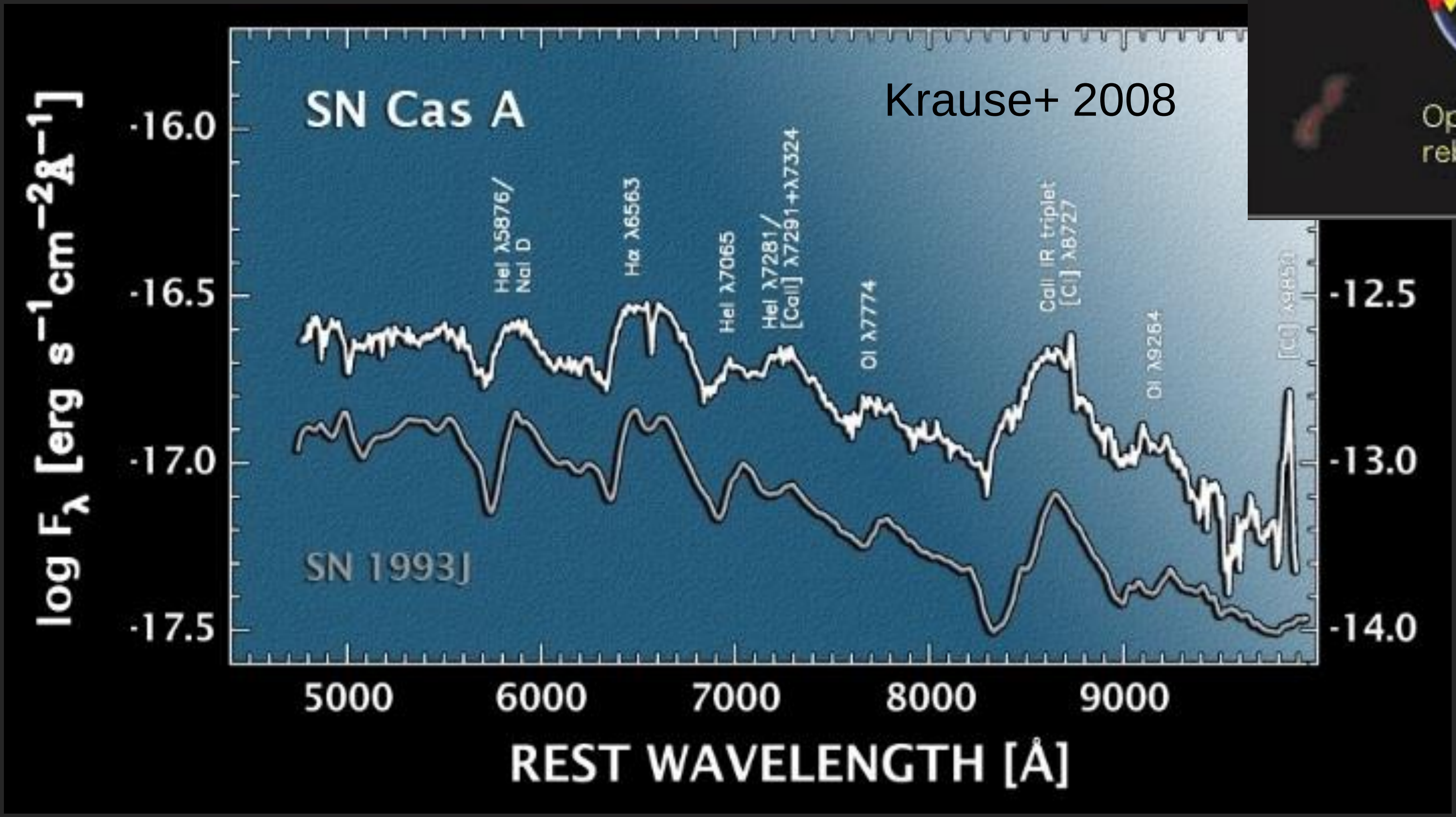
R ~ 0.01 pc (V/10,000 km/s) (t/1yr)

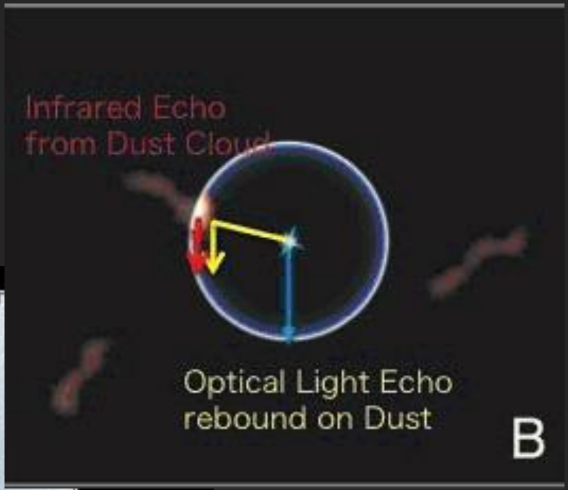
0.04 pc/1” @ Galactic center

HST or 8m AO: ~ 0.15” ⇒ Spatially resolved in the first year

30m AO (e.g., TMT, 2021-?): ~ 0.01”!!! (0.0004 pc @ GC)

Echo: Fully 3D diagnostics



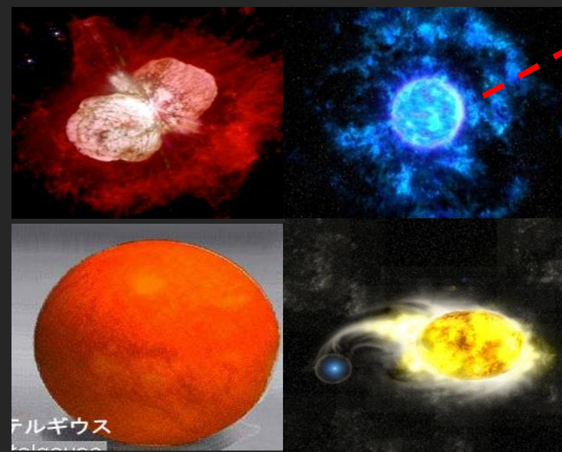


Especially around Galactic center, many scattering clouds.

Collect the light emitted at “all” the directions (3D nature in the explosion⇔ν burst).

Summary

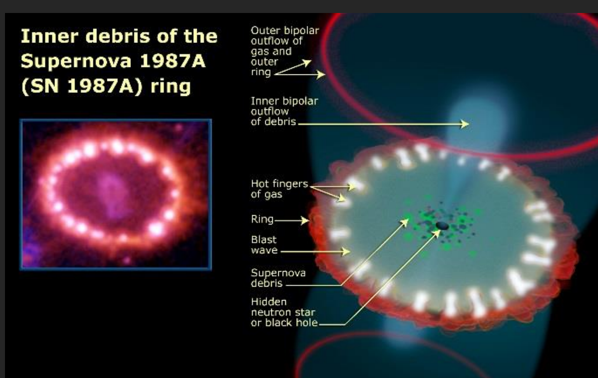
Neutrinos



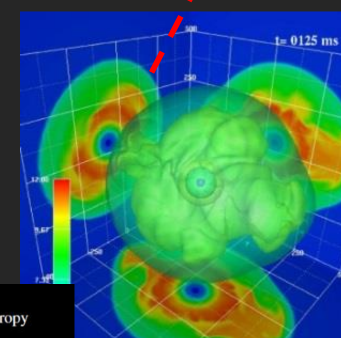
Mass
Metallicity
Rotation
Binary
…

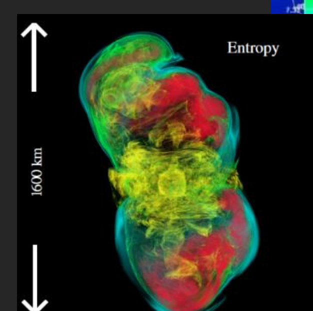
Neutrinos

Mass loss by
stellar wind
Instabilities
Binary



Diversity within the same mechanism.
Even different mechanisms.



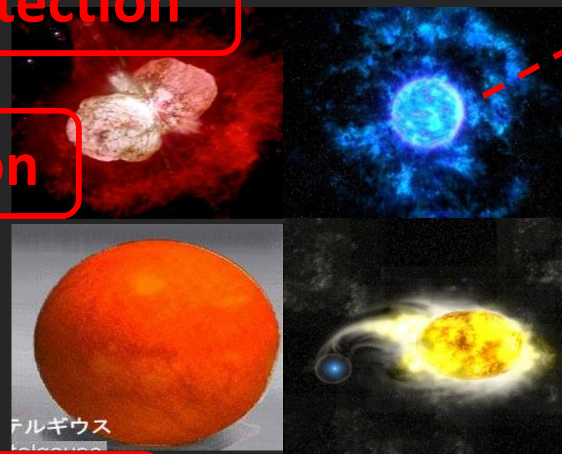


Summary

(post-) Breakout
(opt. & radio)

Neutrinos

Progenitor detection



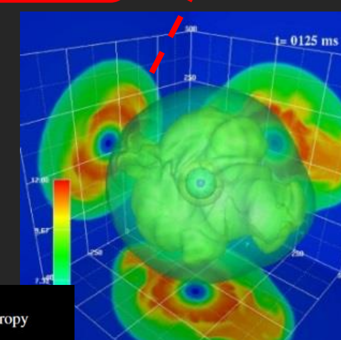
Companion detection

Mass
Metallicity
Rotation
Binary
...

Neutrinos

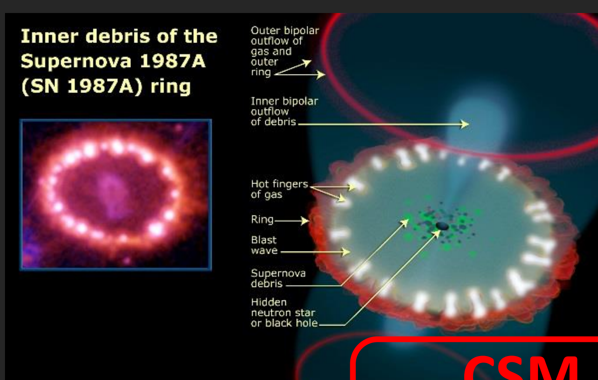
Mass loss by
stellar wind
Instabilities
Binary

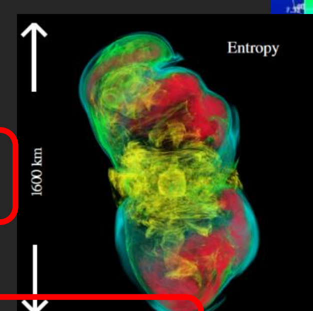
Opt. @ peak



Pre-SN activity

Diversity within the same mechanism.
Even different mechanisms.





Spatially resolved

Opt. @ late

CSM crush
(radio, opt., X)

γ-rays

3D Echo

Let's Go Supernova

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京都大学　宇宙物理学教室

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