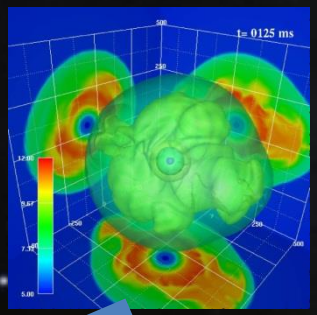
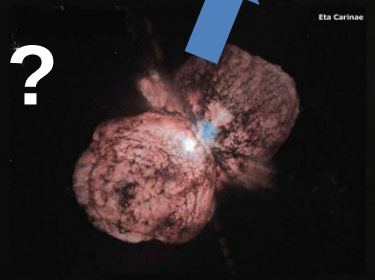
RIKEN SN-GRB, 26 August 2014



?



?

SN 2011dh

"Type I" Supernovae

Keiichi Maeda

Dept. Astron., Kyoto University

N group: A. Suzuki (JSPS), M. Yamanaka (ex.), T. Nagao (M1), N. Matsuo (

What do I/We (mainly) do?

- Theory.
  - Hydrodynamics after the shock launch (1 – 3D).
  - Nucleosynthesis.
  - UV/opt/IR Rad. transfer (1 – 3D, multi-v, t-dependent).
  - Non-thermal emission.
- Observation (From radio to MeV, not a complete list).
  - As PI:
    - Subaru (FOCAS-opt., IRCS-NIR/AO, HDS-opt/high-res.), ALMA (ToO).
  - As Co-I:
    - INTEGRAL (ToO), Chandra (ToO), Suzaku, HST, Subaru (FOCAS, Comics), Keck, VLT, Gemini, Magellan, VLA.

    + Smaller telescopes (e.g., see Yamanaka-san's talk).

Outline

- Emission from SNe (of type I).
  - Thermal vs. non-thermal.
  - Time-evolution in optical.

- Type Ia supernovae.
  - Various diagnostics for progenitor and explosion.
- Stripped-envelope SNe.
  - Highlight for SN IIb 2011dh.

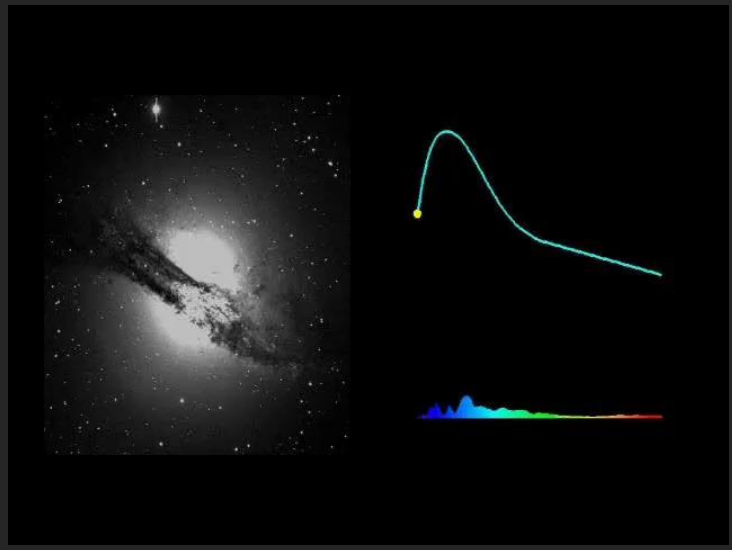
Observational Characteristics of Supernovae

- > 1000 discoveries a year (dep. on surveys).
  - **Only a part** (nearby) observed in detail.
- Distance > ~ 10 Mpc (extragalactic).

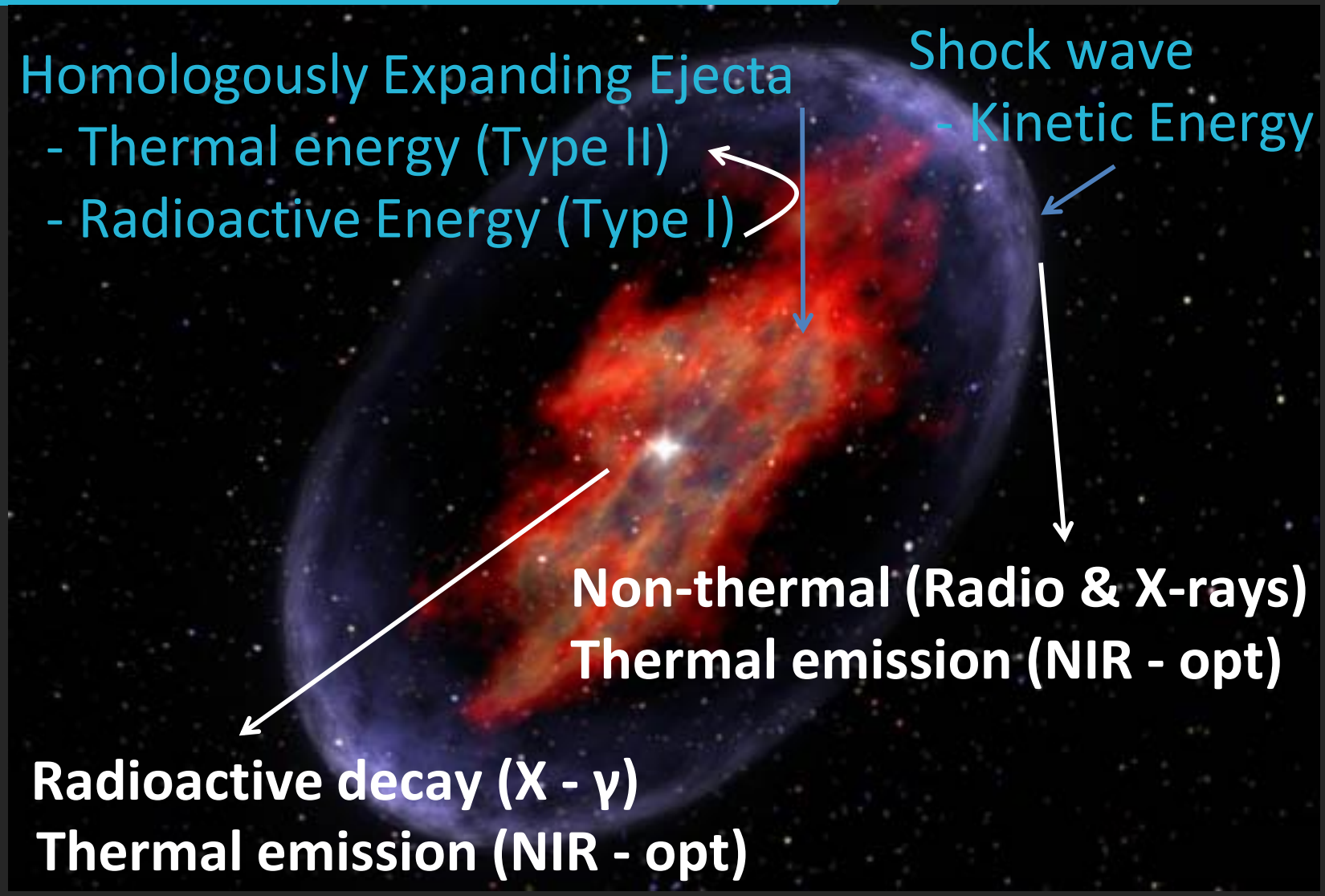
  - **Point sources** (except for a few by HST/AO/VLBI).
  - Typical maximum mag. V > ~ 16 mag（roughly）.
- Most of obs. = Optical.
  - Imaging + spectra (time-dep.)

⬇ Interpretation

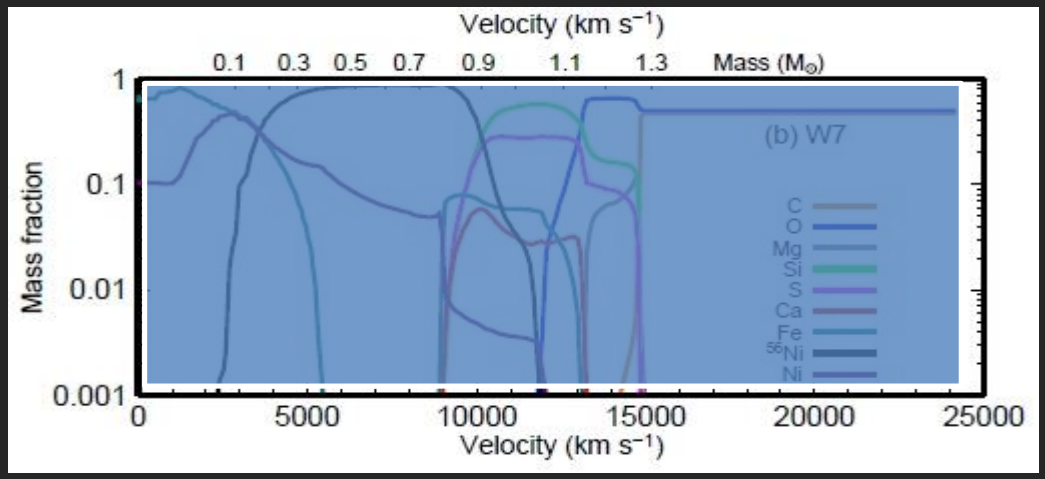
Supernova Physics
（e.g., exp. mech.）



Energy Budget in SNe ⇒ Emission



“Typical” SNe



R~Vt

$\rho \propto t^{-3}$

Thermal

E, M_{ej}, R

^{56}Ni→Co→Fe

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

CSM-int.

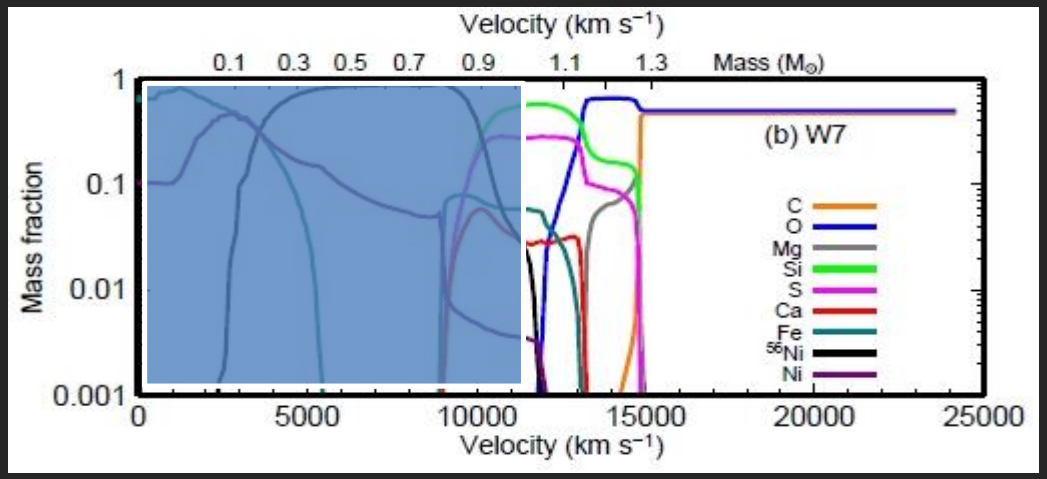
E, M_{ej}, CSM

Very Early… Outermost

UV/Opt

Opt/IR

X/Radio/Opt



R~Vt

$\rho \propto t^{-3}$

Thermal	^{56}Ni→Co→Fe	CSM-int.
E, M_{ej}, R	E, M_{ej}, M(^{56}Ni)	E, M_{ej}, CSM

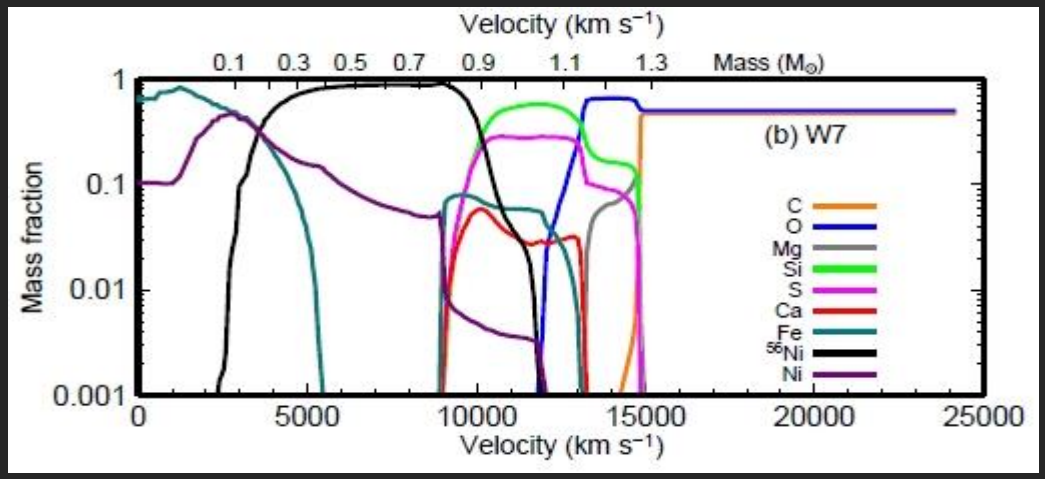
Very Early… Outermost

@Max… Outer→Inner

UV/Opt

Opt/IR

X/Radio/Opt



R~Vt

$\rho \propto t^{-3}$

Thermal	^{56}Ni→Co→Fe	CSM-int.
E, M_{ej}, R	E, M_{ej}, M(^{56}Ni)	E, M_{ej}, CSM

Very Early… Outermost

@Max… Outer→Inner

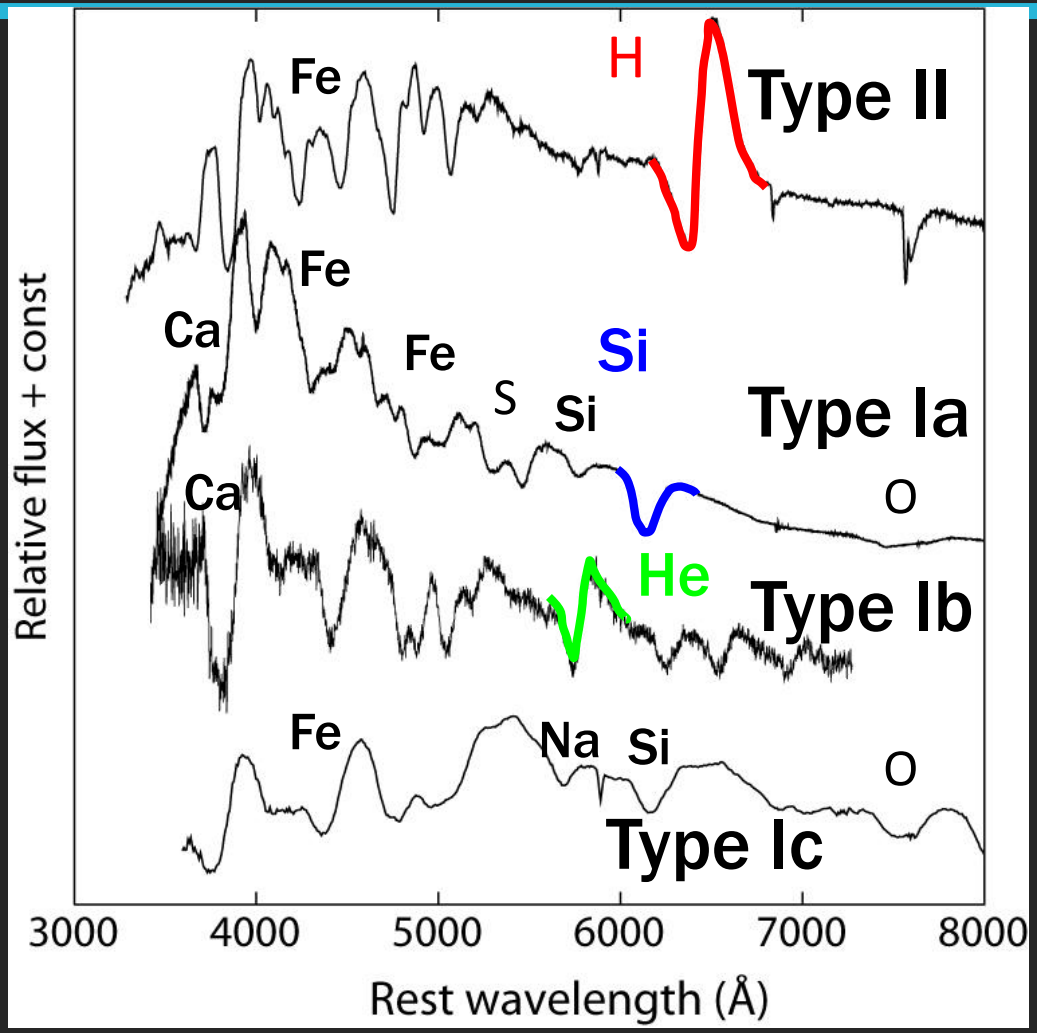
Late… Innermost

UV/Opt

Opt/IR

X/Radio/Opt

Supernova Classification

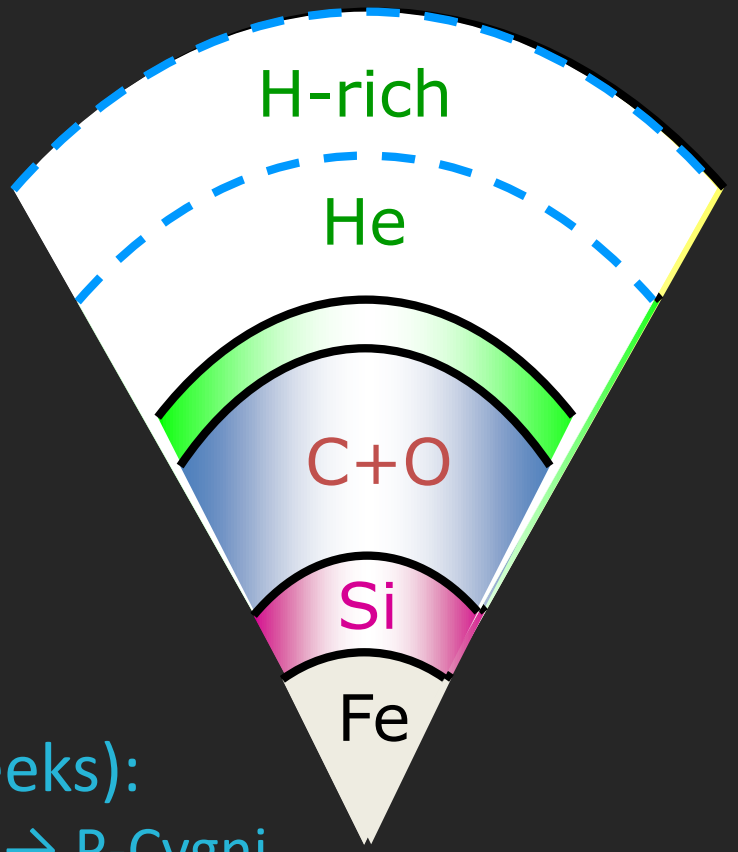


Ia

Thermonuclear exp. of white dwarf

II/Ib/Ic

Core-Collapse (CC) of massive stars



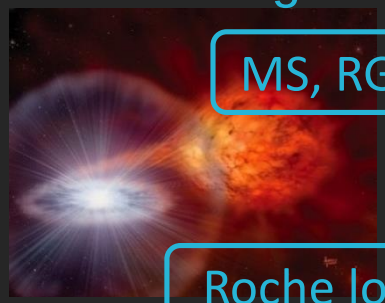
@ maximum brightness (~ a few weeks):

– Expanding optically thick medium → P-Cygni.

Type Ia Supernovae

- Thermonuclear explosion of (nearly Chandrasekhar-mass) C+O WD(s).

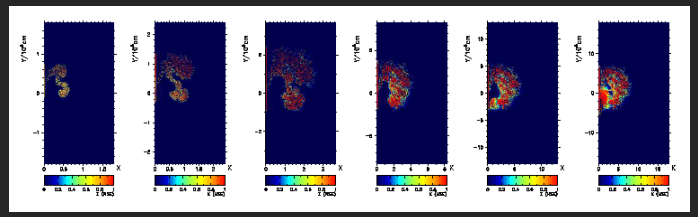
Single Degenerate (SD)
WD + non-degenerate

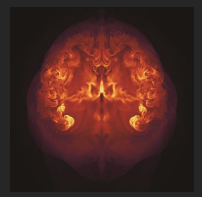


MS, RG, He star?

Roche lobe, Wind-fed?

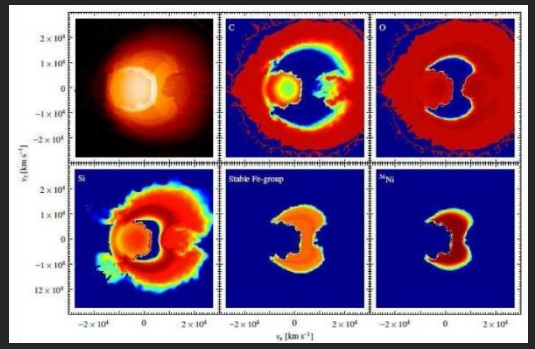
Central ignition?
Surface detonation?
Asymmetry?





Double Degenerate (DD)
WD + WD

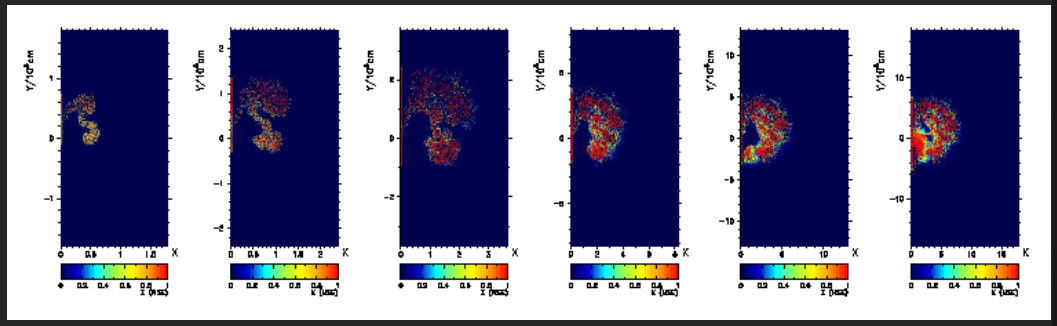
Masses?

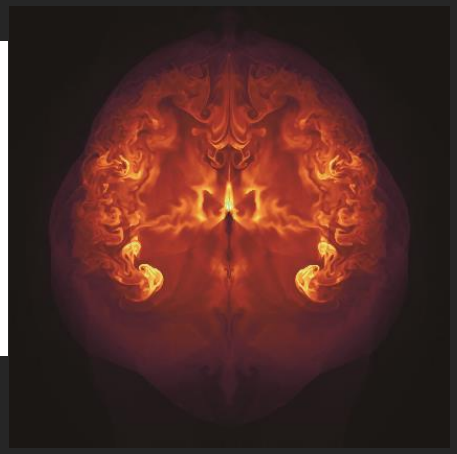


KM, Roepke+ 2010

Roepke+ 2012

Examples of explosion models





Single Degenerate

Chandrasekhar WD

Central (off-center) ignition

KM, Roepke+ 2010

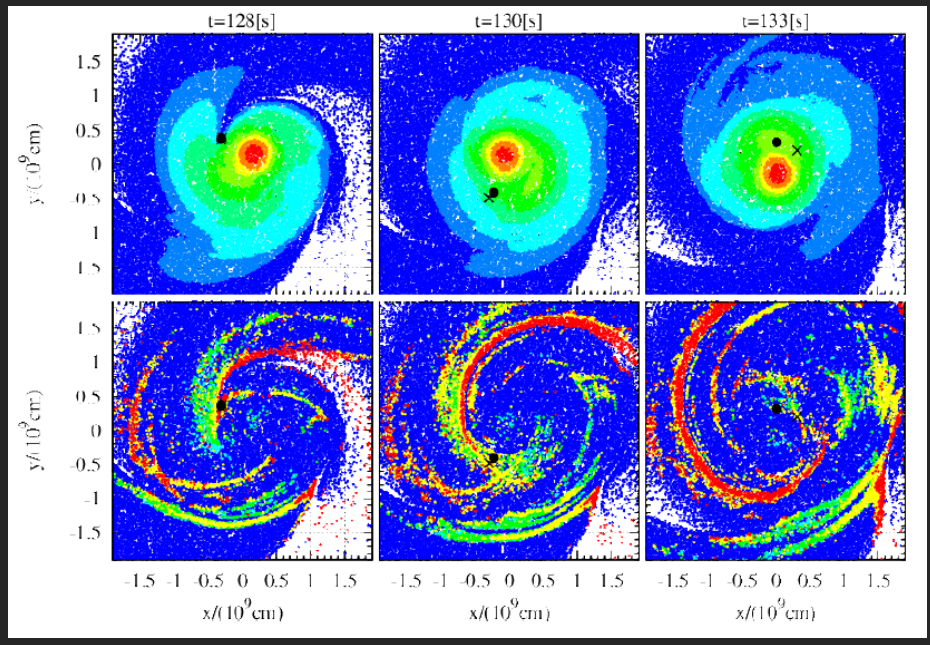
Double Degenerate

Various WD+WD masses

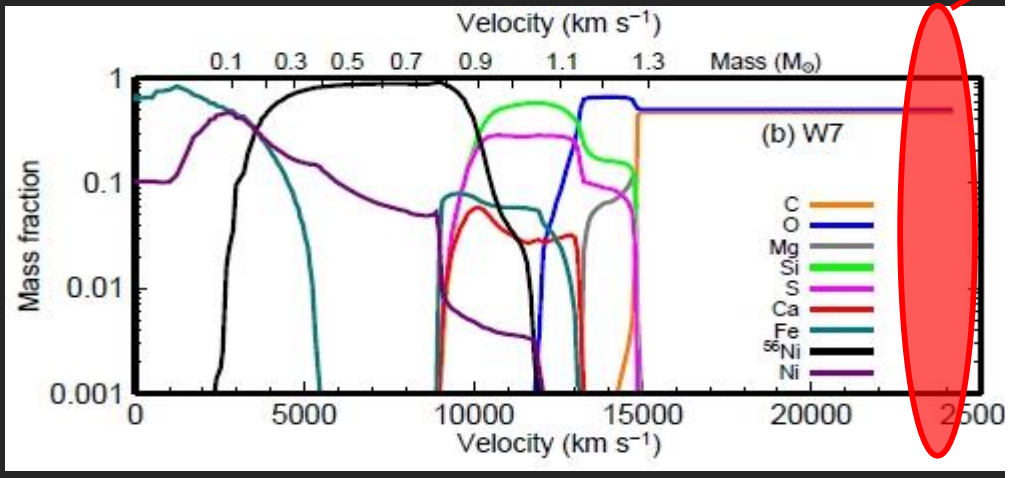
Explosion not yet

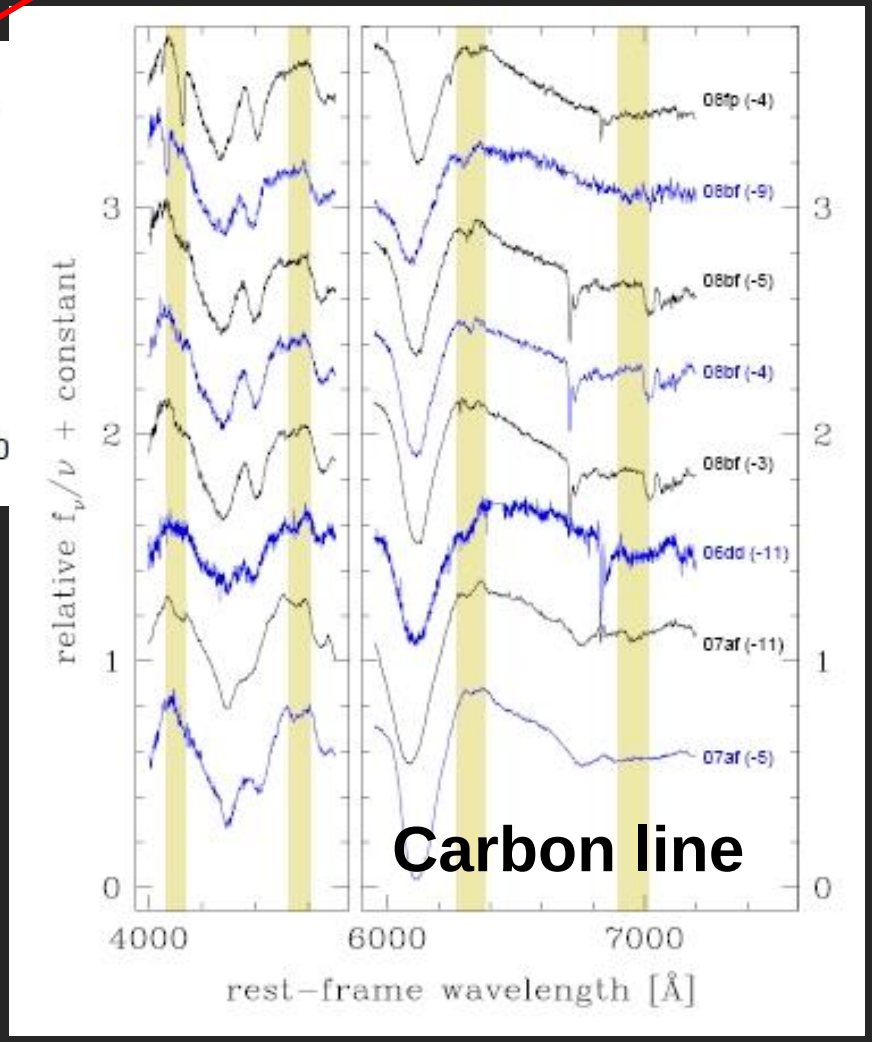
Tanigawa+ (w/ KM) in prep.

Sato+ (w/ KM) in prep.



Very Early Phase - progenitor





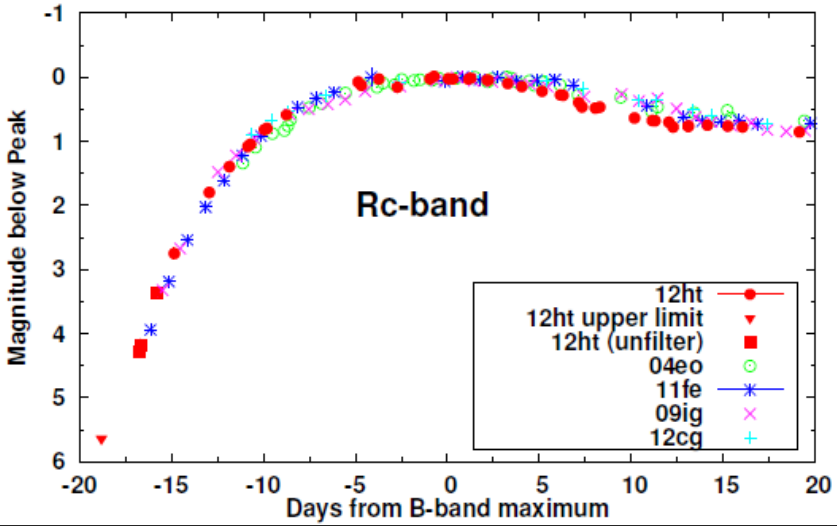
C in the outermost layer?
Perhaps common in SNe Ia.

Folatelli+ (w/ KM) 2012, Parrent+ 2011

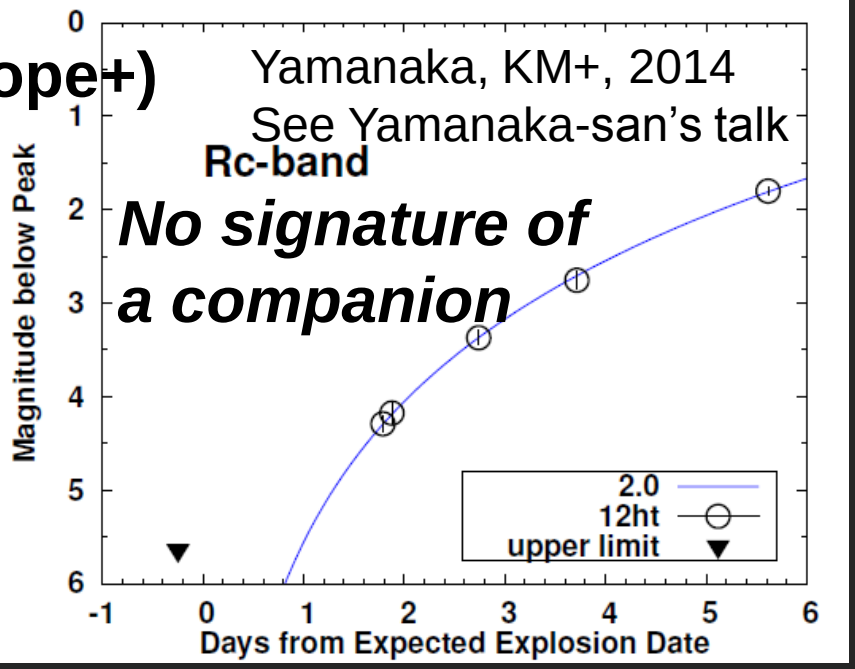
C left after the thermonuclear explosion.

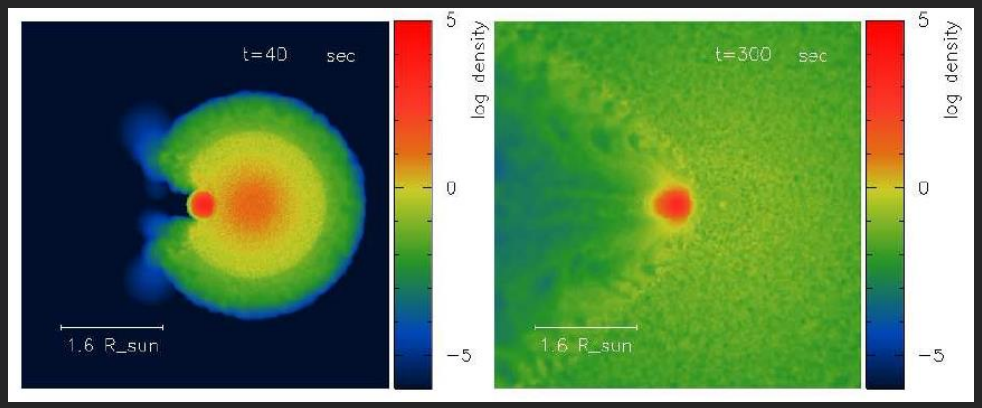
Very Early Phase - companion

SN Ia 2012ht (Kanata Telescope+)



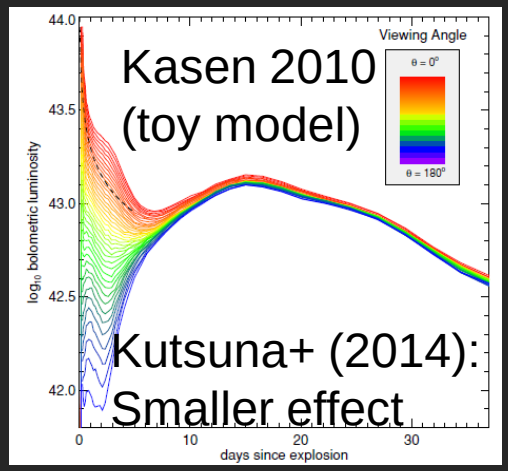
Yamanaka, KM+, 2014
See Yamanaka-san's talk





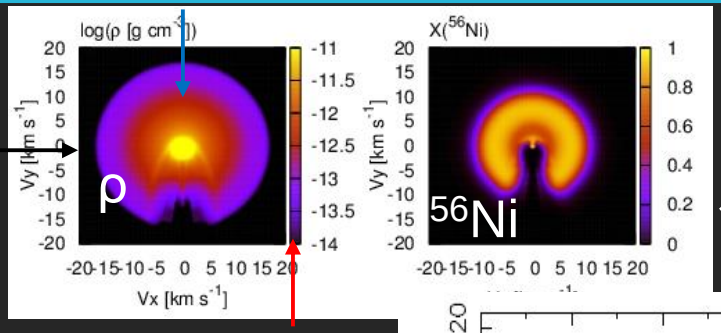
Liu+ (w/ KM), 2013 (hydro)

?



KM, Kutsuna, Shigeyama, 2014, ApJ, accepted (arXiv:1408.4211)

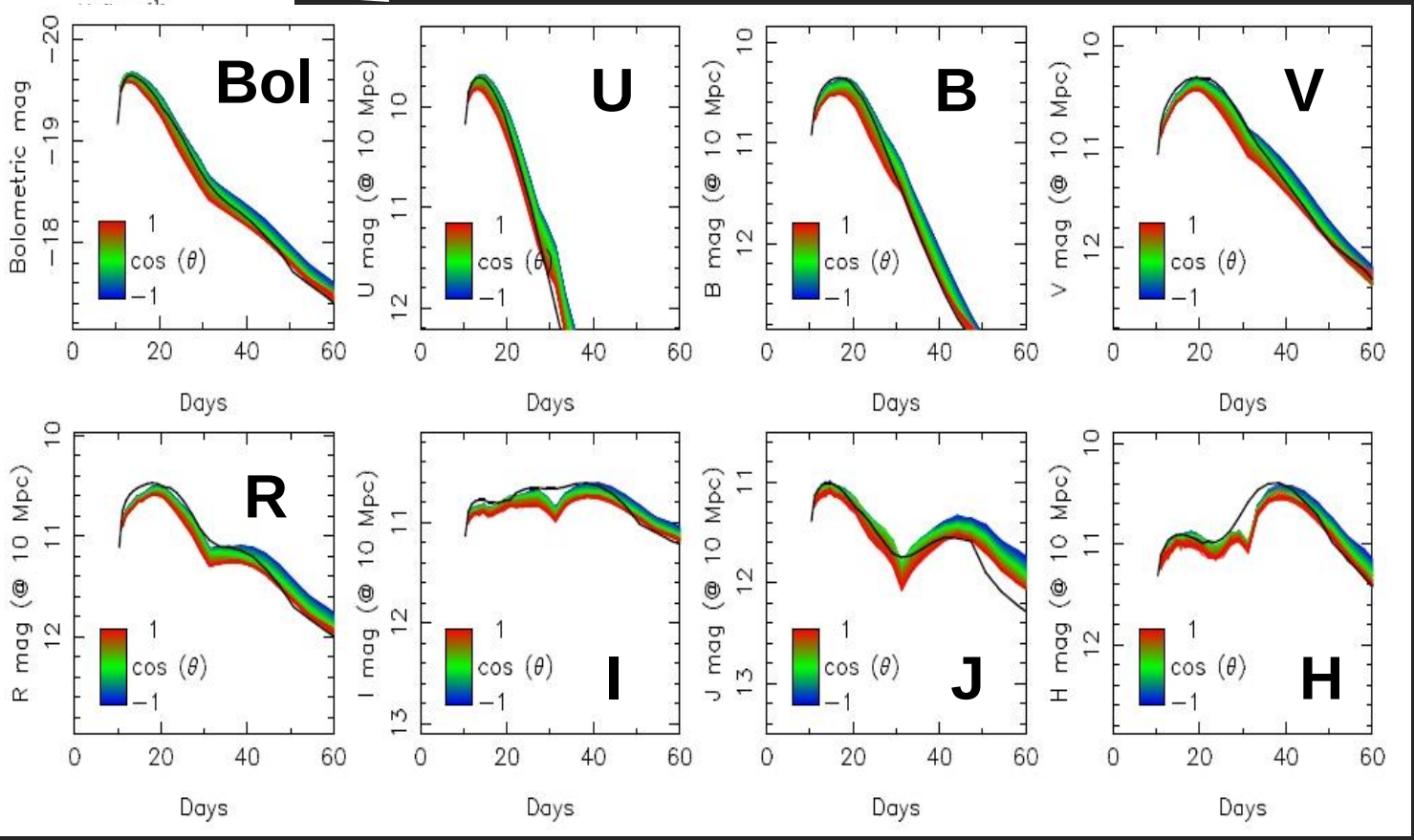
Can we see a companion at max/post-max?



Radiation Hydro (w/ simplified transfer)

Detailed multi-D transfer (frequency-dependent w/ 0.5M transitions)

Companion
No companion
Opposite



~0.1 mag level

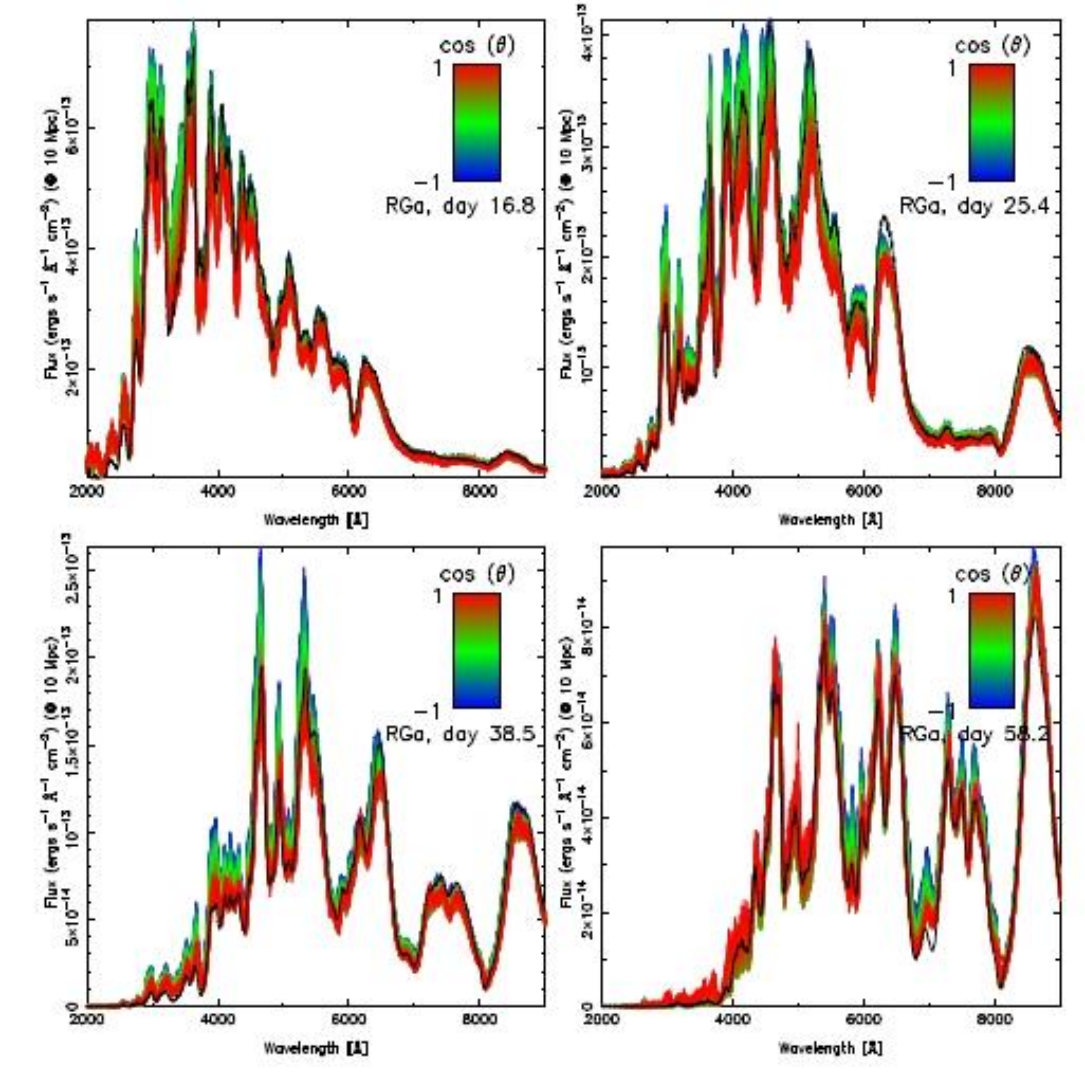
Companion **not** rejected

Spectral Evolution

Companion

No companion

Opposite



The companion direction is redder (small flux in blue).

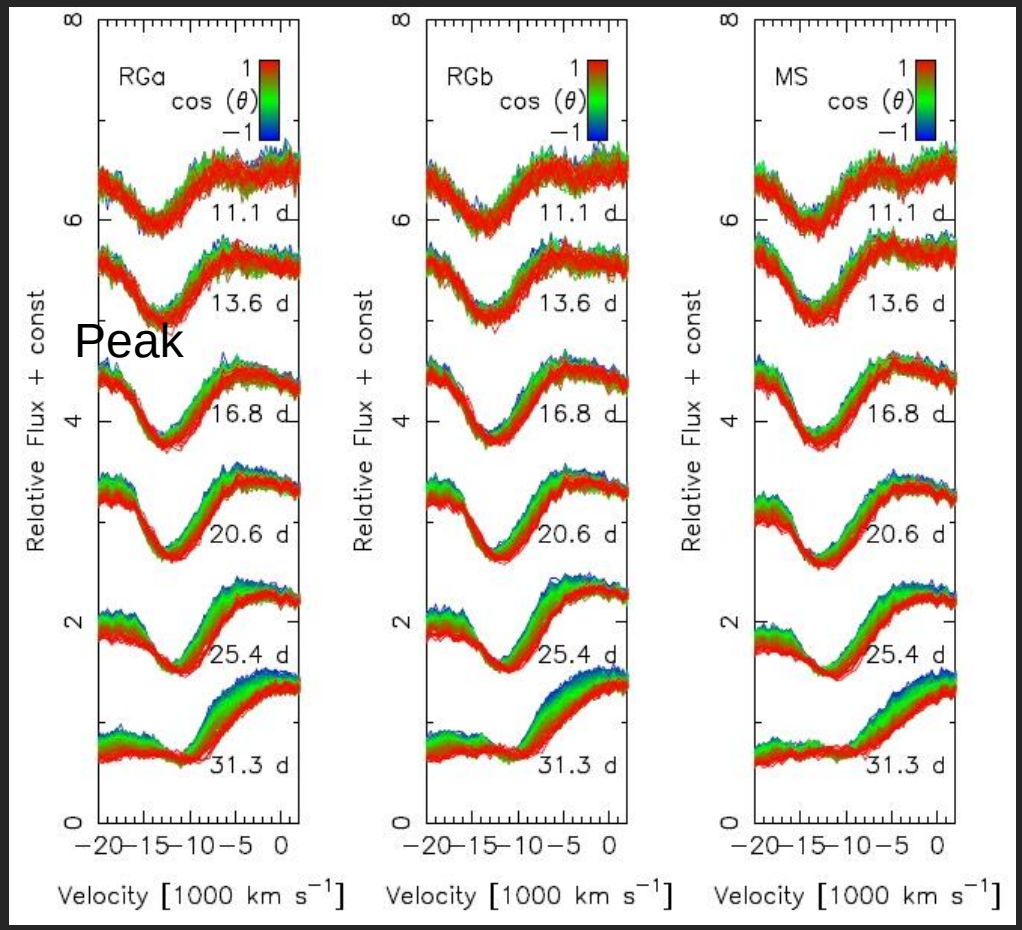
0.1 mag level.

Opposite to Kasen+ (2004). [companion – blue, 91T-like.]

No 91T-like in our simulations.

Line velocity (Si II6355 as an example)

Time



Companion
No companion
Opposite

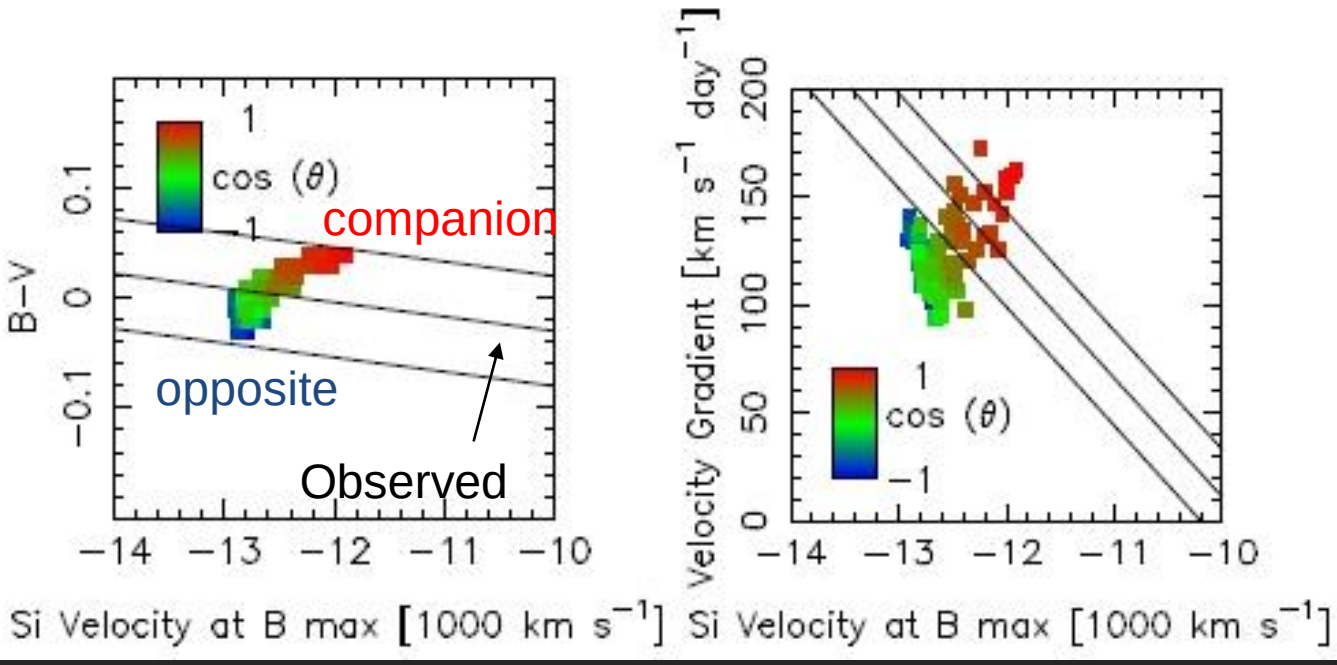
No variation

Companion = Slower

Rapid decrease for the companion direction

Observationally accessible.

Diagnostics @ Maximum



Opposite to the observed relations.

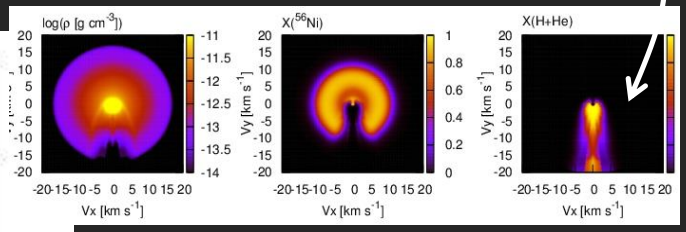
The companion-induced asymmetry-angle variation cannot be a source of the relations.

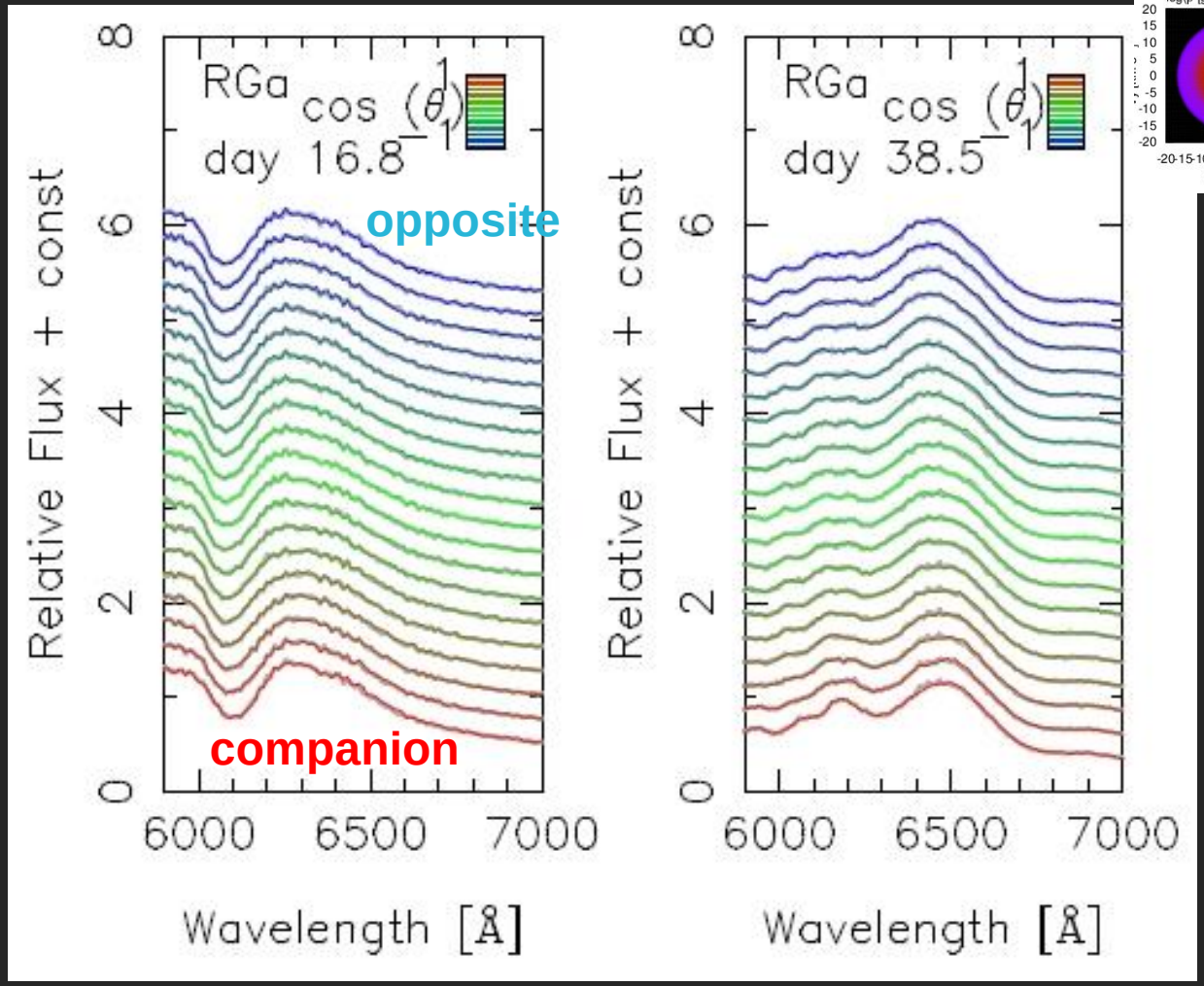
Still within currently observed scatters.

Potentially limit such a model in the future.

Can we see Hydrogen: Hα?

Companion **H** contaminated



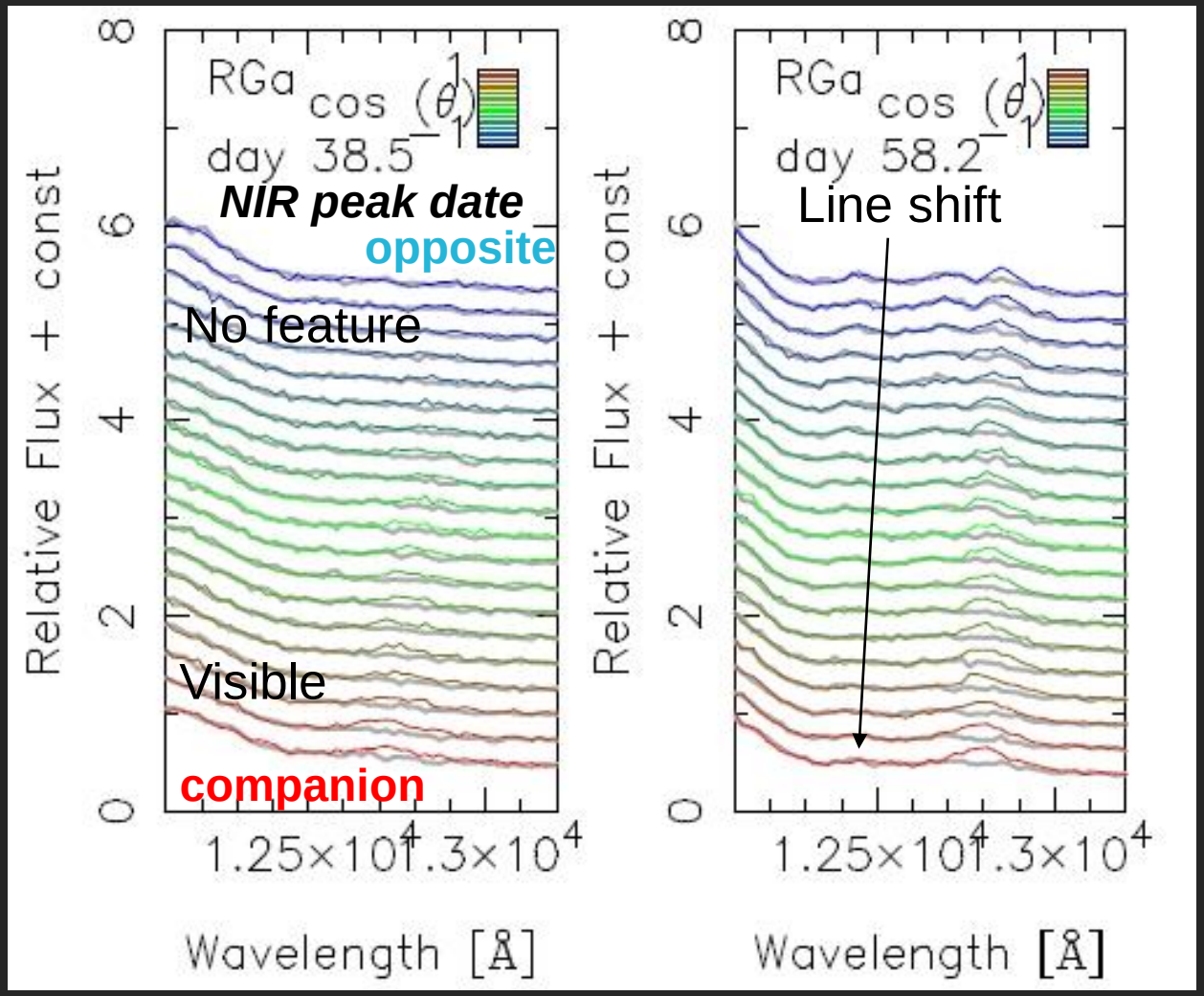


Weak, and contaminated by other metal lines.

Observationally not practical.

Black: No companion model (overlapping)

Can we see Hydrogen: Pβ?



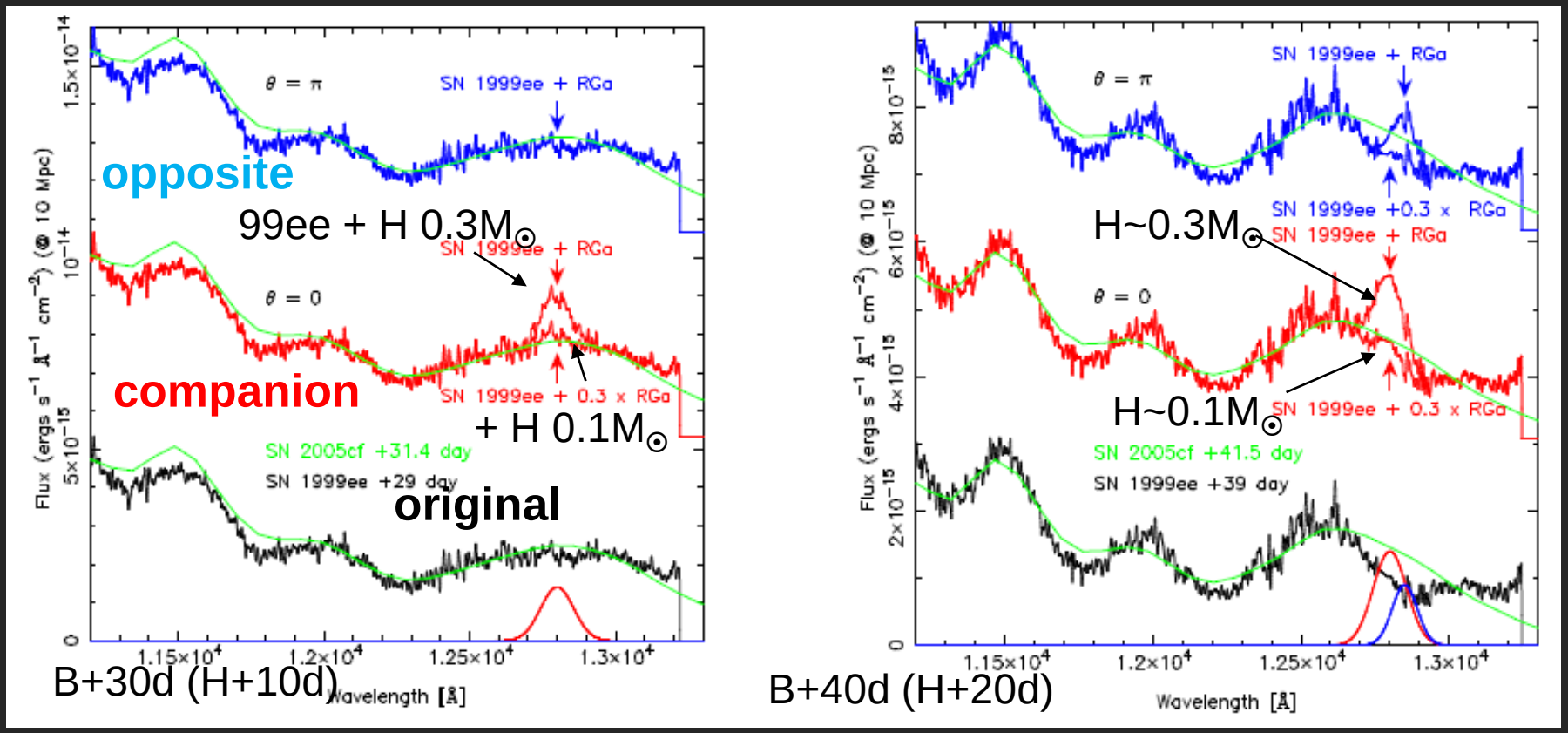
Black: No companion model

NIR clean and Pβ stronger than Hα.

Observationally possible.

Investigating Pβ in NIR?

1999ee vs. 2005cf



H > ~ 0.1 – 0.2$M_\odot$ ruled out.

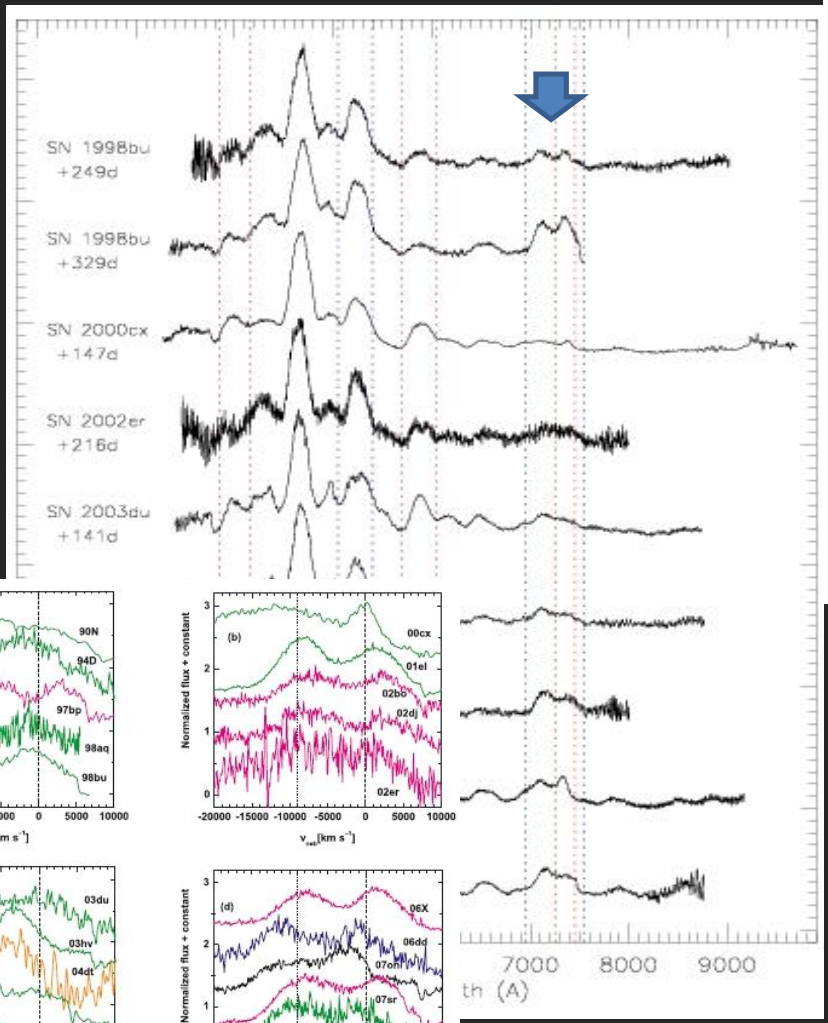
Indeed shows the difference @ Pb?

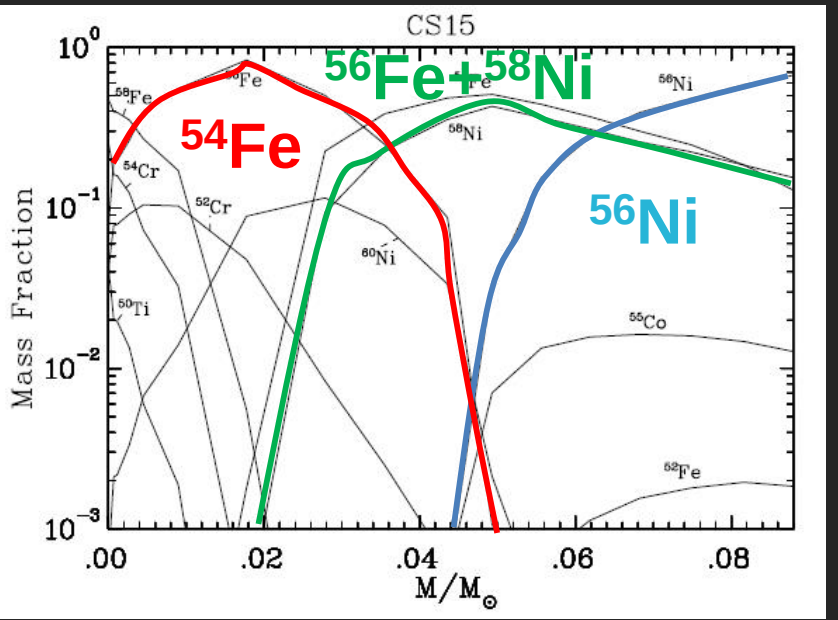
⇒ Consistent w/ RG (w/ 0.1 – 0.2$M_\odot$ envelope stripped)?

Just illustration

Late-time: Innermost region of SNe Ia

W7 model (Nomoto)





Stable Fe/Ni in the innermost(?) region

← Exp. Mech.

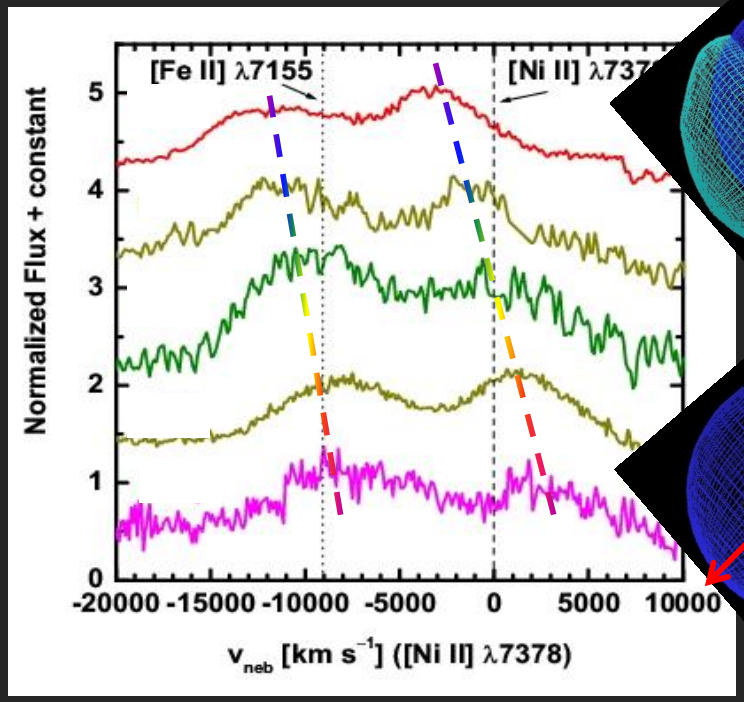
KM, Taubenberger Sollerman+ 10
KM, Benetti, Stritzinger+ 10
KM, Leloudas, Taubenberger+ 11

Type Ia Supernovae are not spherical

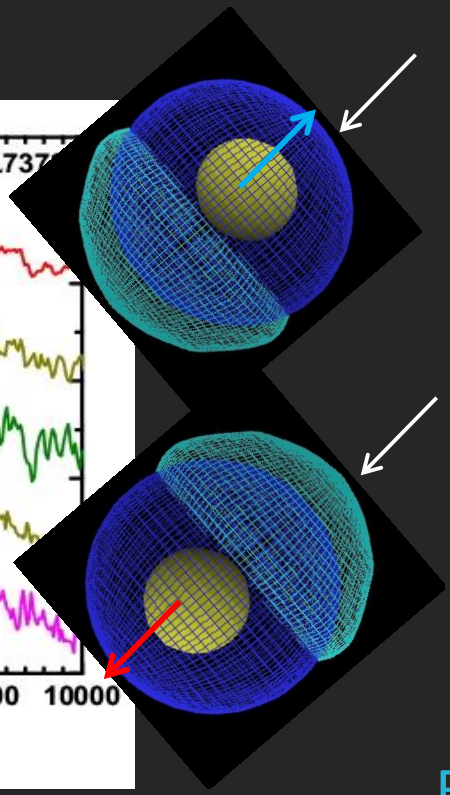
Early-phase "**spectral diversity**" = **viewing angle**?

KM+ 2010, Nature, 466, 82

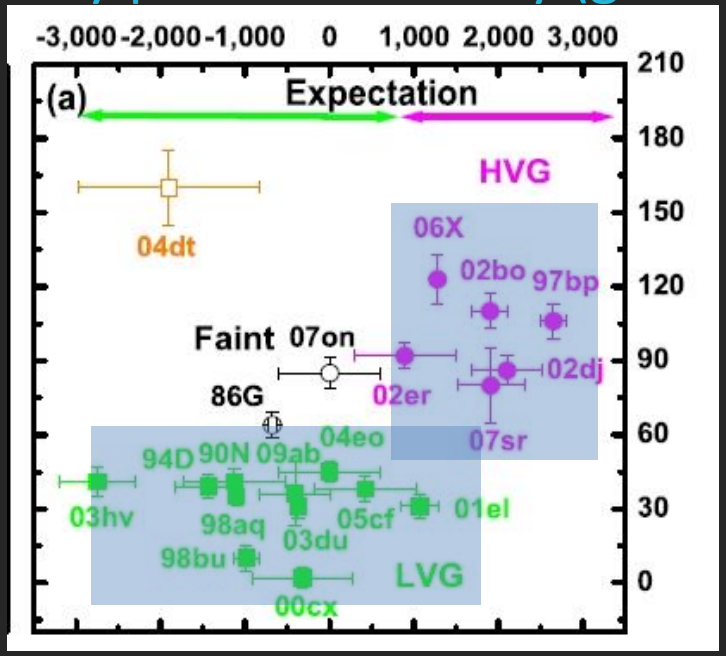
KM+ 2011, MNRAS



Blueshift ← Redshift →



Early phase Si velocity (gradient)

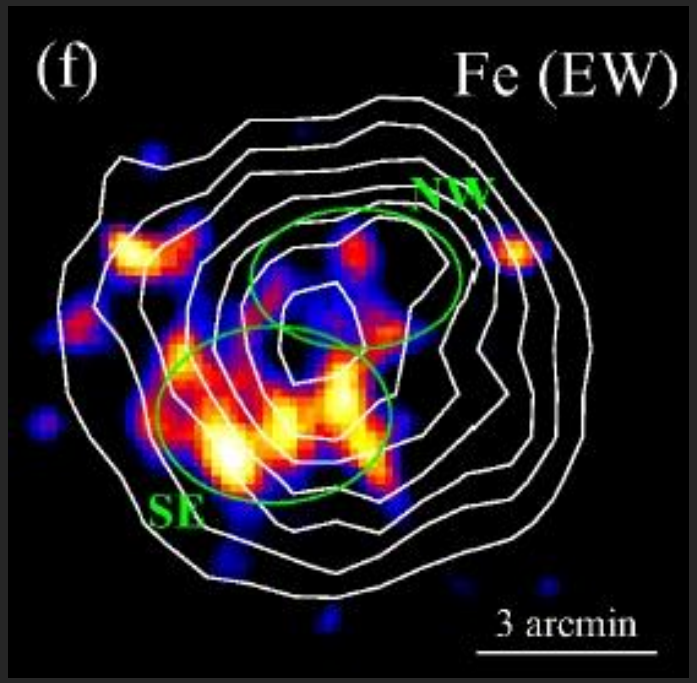


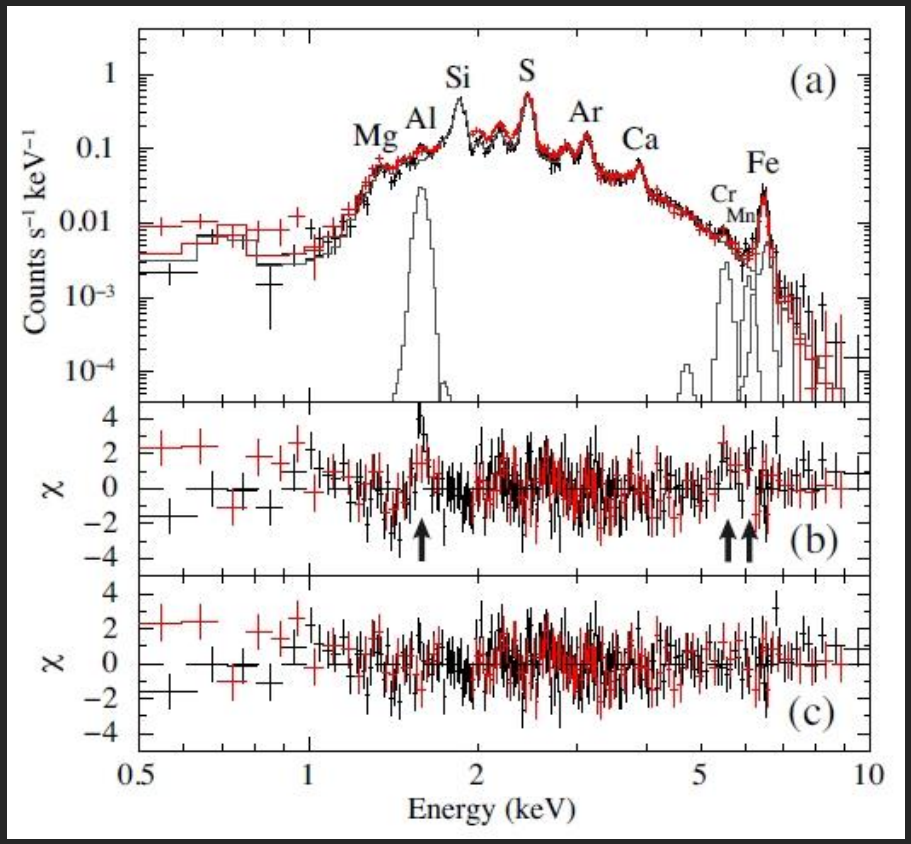
Blueshift ← Redshift →

c.f., Blondin+ 2012, Silverman+ 2012

c.f., Uchida+ 2013 for SN 1006

Asymmetry in SN Ia Remnant?



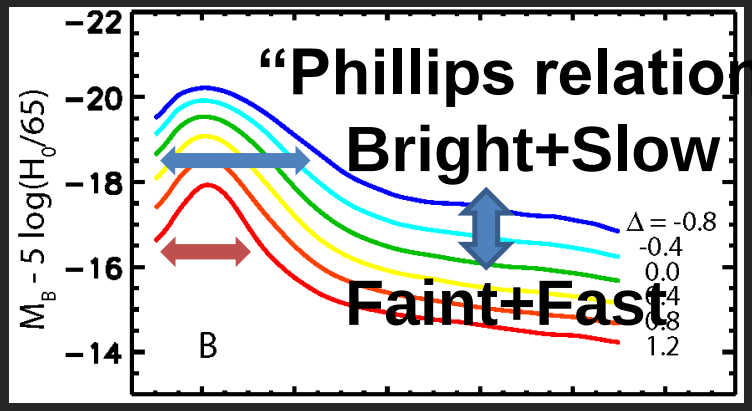


Yamaguchi, Tanaka, KM+ 2012

G344.7-0.1 by Suzaku

Off-axis Fe ⇒ CC classification, but
Fe-rich spec. ⇒ Ia favored.
+ Mn, Cr, Al (complementary to optical SN study)

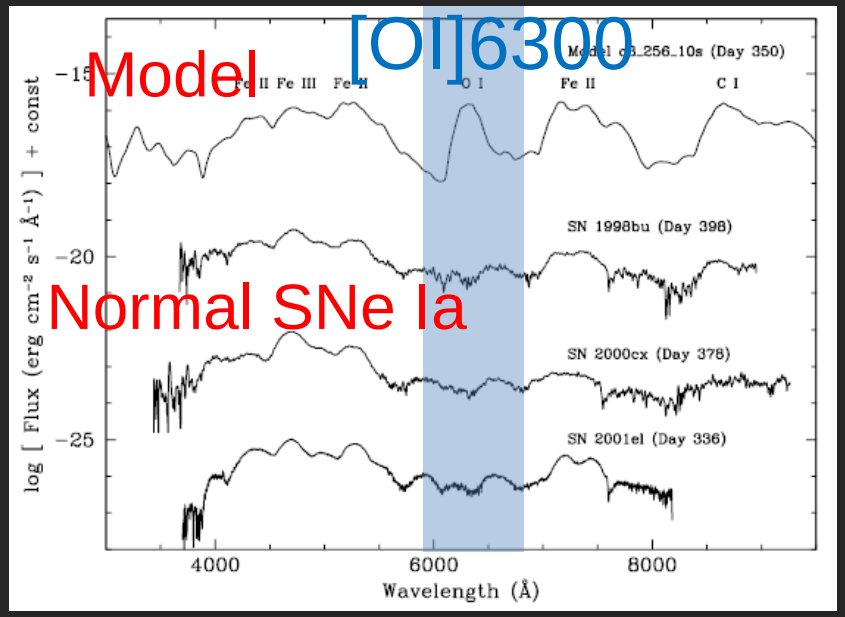
Unburned materials @ inner region of SNe Ia?



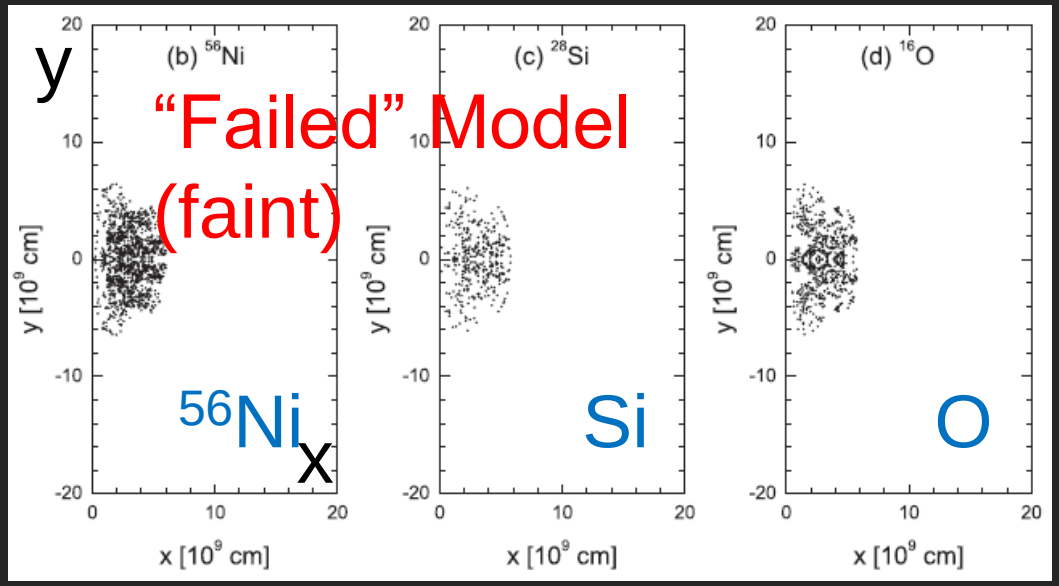
Synthesized + **unburned** ~ $1.4M_\odot$

^{56}Ni (~ $0.6M_\odot$) →Luminosity

Faint →Unburned Oxygen? Where?



Kozma+ 2005



KM, Roepke, Fink+ 2010

Taubenberger+ (w/KM) 2013, VLT/FORS2

Oxygen in a peculiar faint SN Ia 2010lp

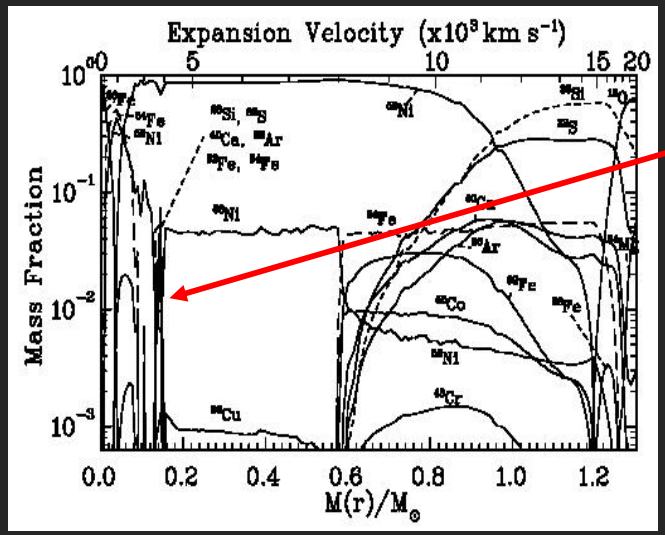
SN 1991bg-like:

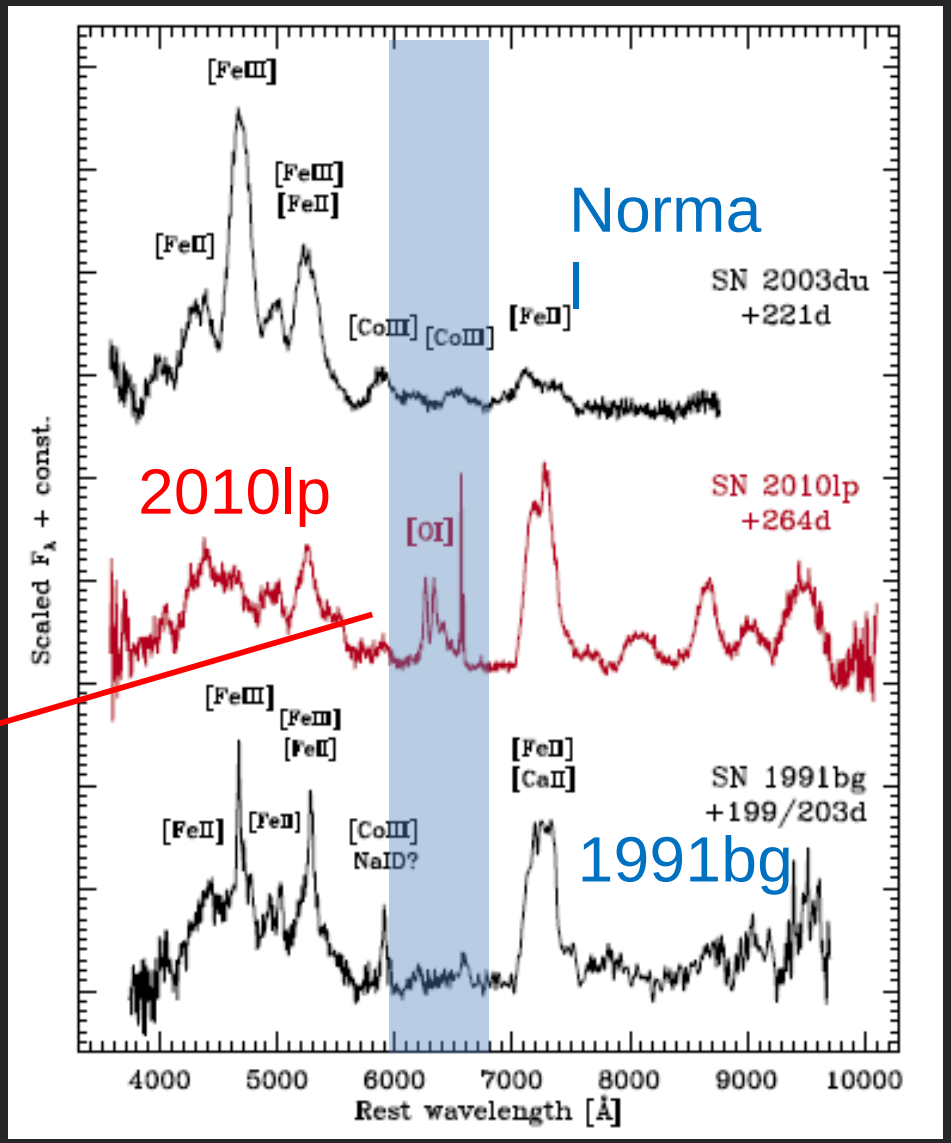
Faint end of SNe Ia

L and ^{56}Ni smaller by ~ 5.

So far no [OI] detected (within a small sample).

→ [OI] detected (first among SNe Ia in the CCD era).

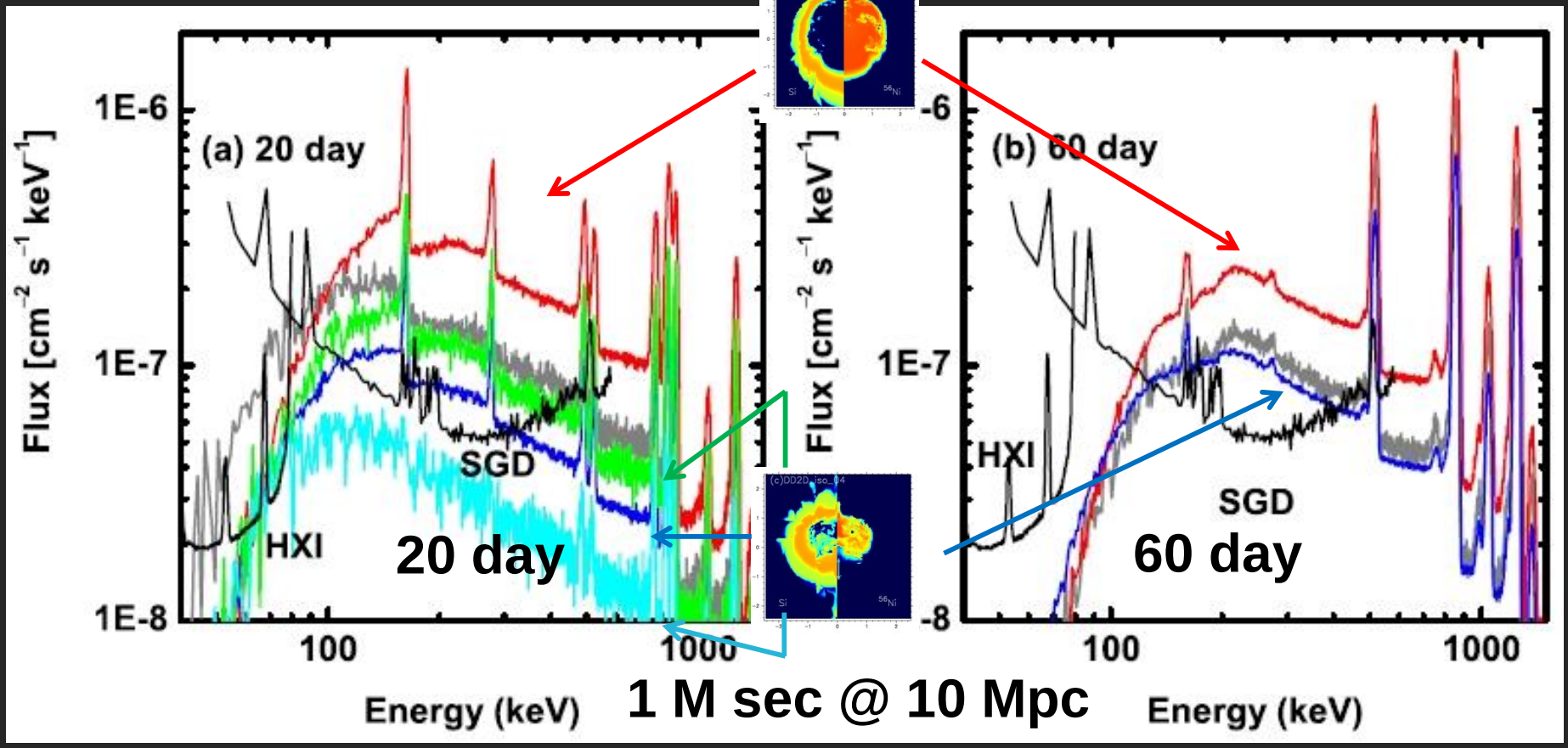




HXI/SGD sensitivities: Takahashi SPIE 2010, Tajima SPIE 2010

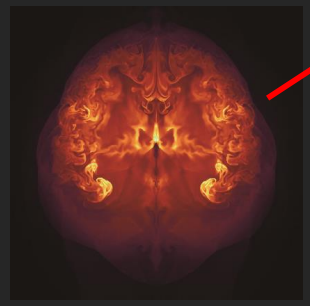
High-E: Radioactive Decay

KM, Terada+ 2012

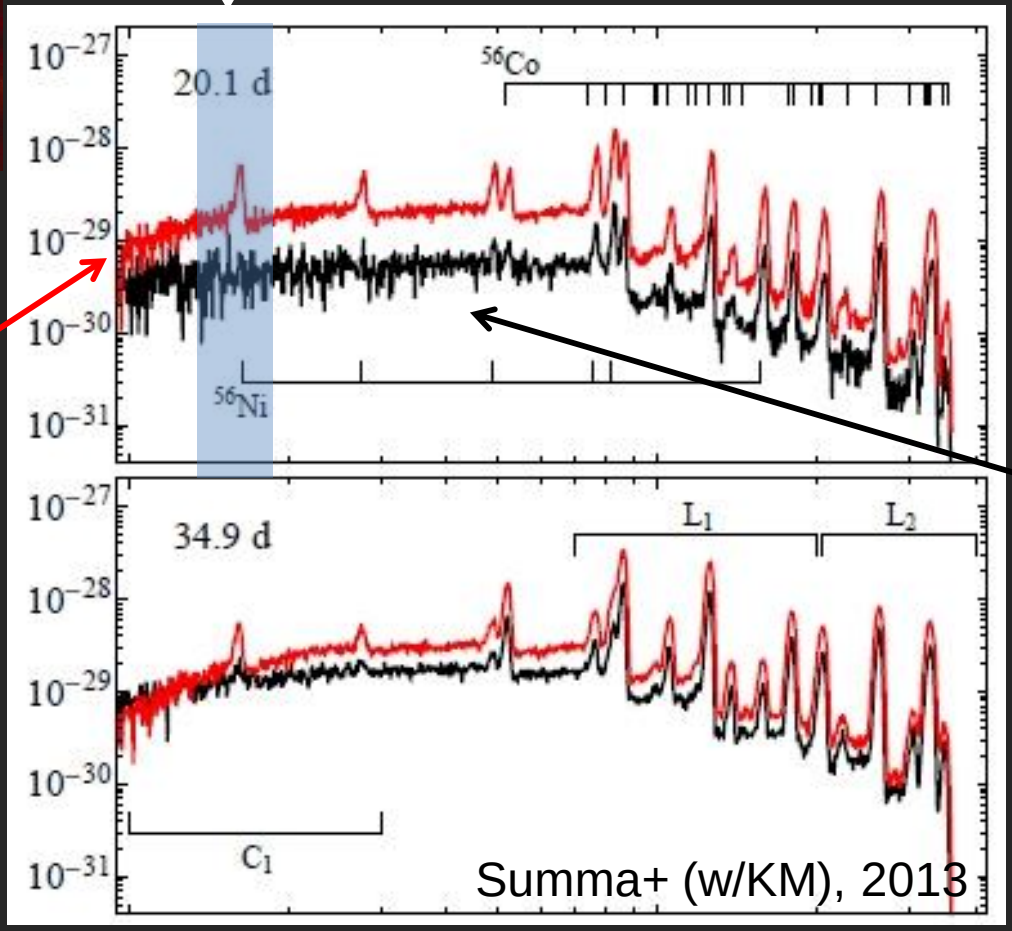


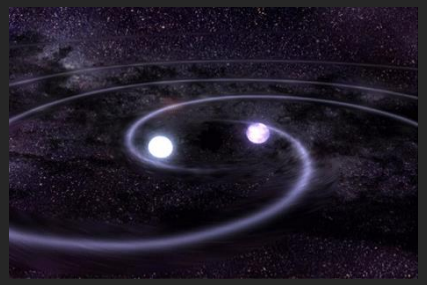
No Detection of radioactive decay from SNe Ia before 2014.
^{56}Ni/Co/Fe will be detectable up to ~ 15 Mpc by SGD/Astro-H.

MeV Diagnostics for progenitor?



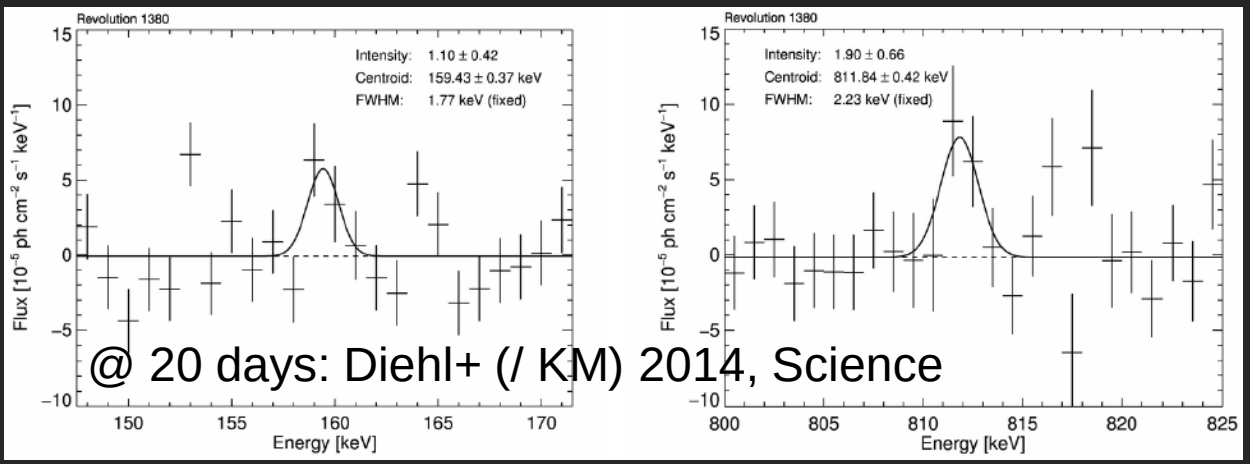
^{56}Ni decay, 158 keV



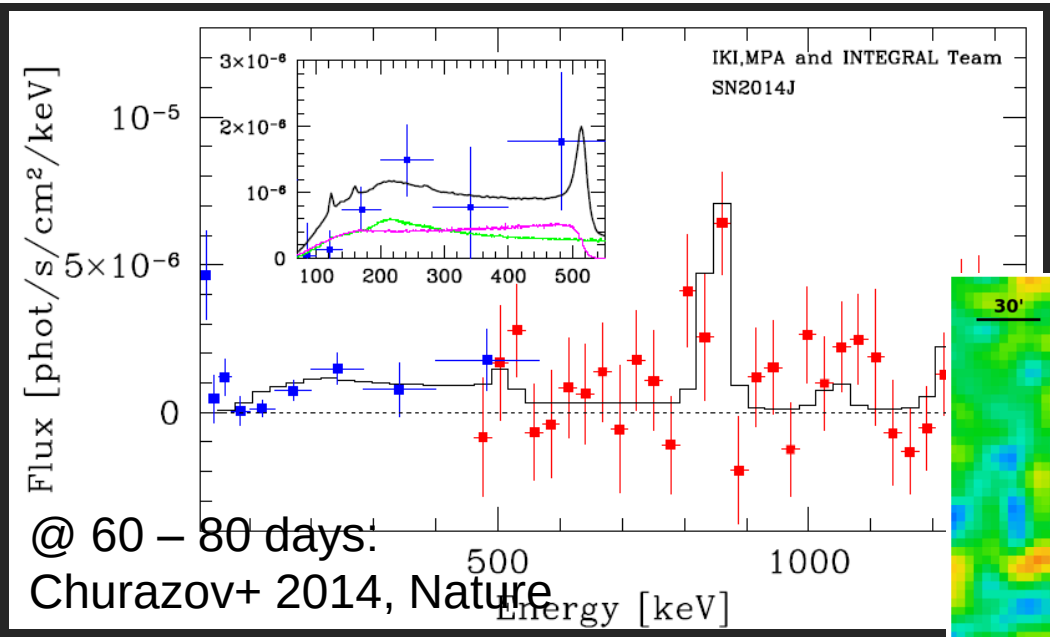


INTEGRAL detection of MeV γ from SN Ia 2014J (~ 6 Ms in total)

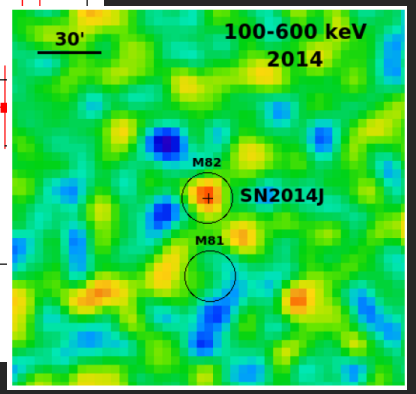
Supernova Radioactivity in 2014



@ 20 days: Diehl+ (/ KM) 2014, Science



@ 60 – 80 days:
Churazov+ 2014, Nature



日経（8/1）

超新星爆発、仕組み解明

京大など 星の表面でも核反応

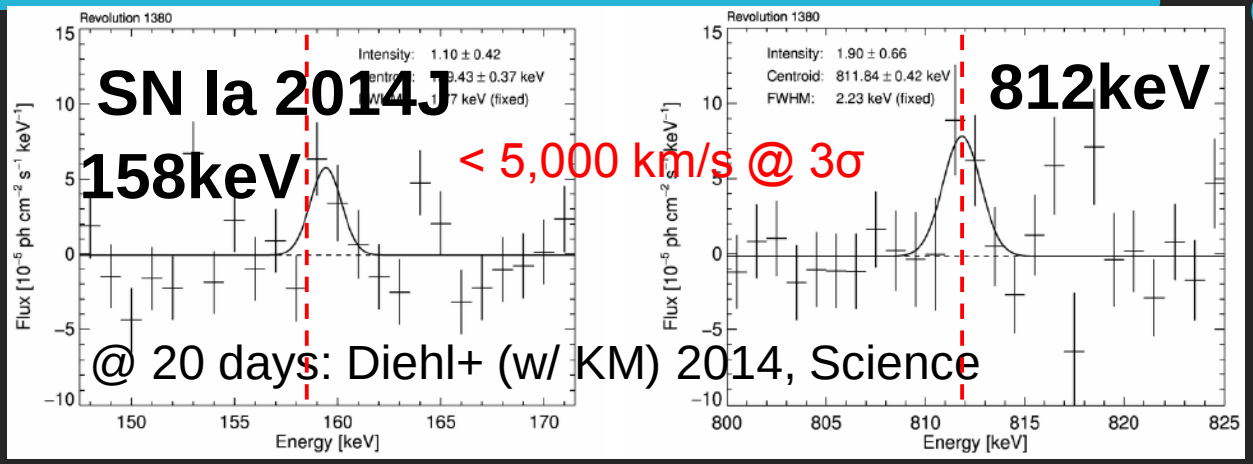
SN Ia 2014J
@M82
Most nearby
SN Ia
since 1986

The first detection of ^{56}Ni/Co decays from SNe Ia.

Confirmation of basic concept of thermonuclear explosion, **but…**

Seen both in IBIS and SPI
SPI analyzed by two independent groups

MeV Diagnostic Power: SN explosion physics



SN Ia 2014J

158keV

< 5,000 km/s @ 3σ

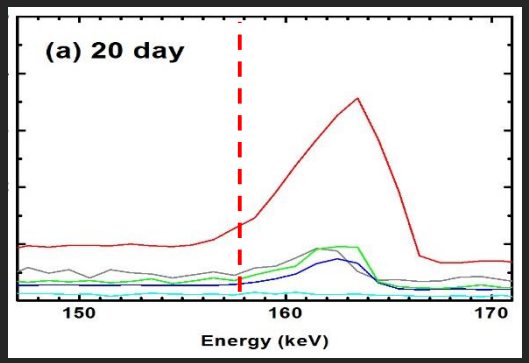
812keV

@ 20 days: Diehl+ (w/ KM) 2014, Science

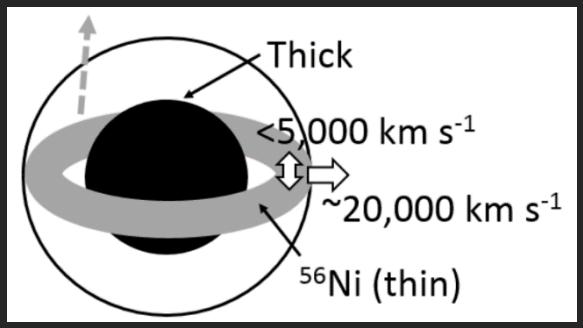
Challenge to theories
- Early emergence
- Small Doppler shift

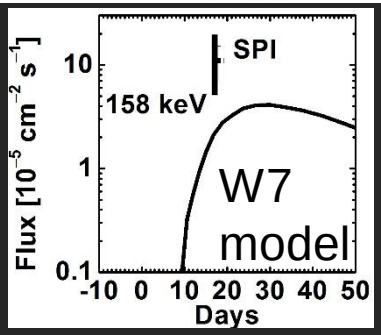
⇒ Suggested scenario
- WD + He donor
- Surface He ignition

(**not** a leading model!)



Model Prediction
KM, Terada+ 2012





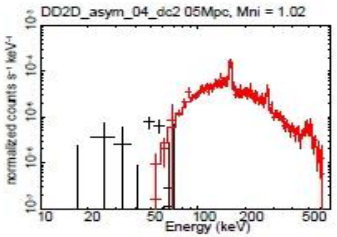
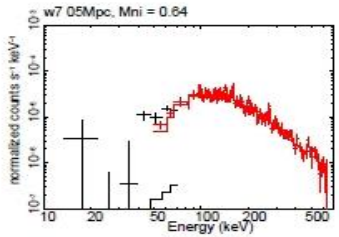
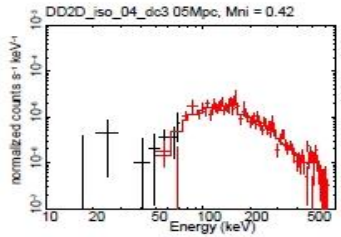
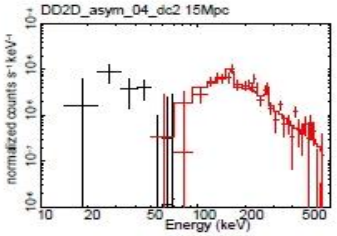
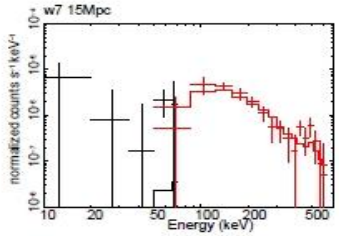
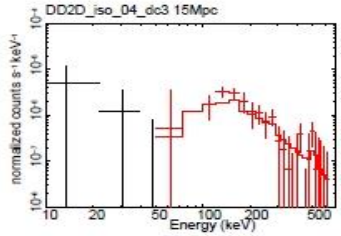
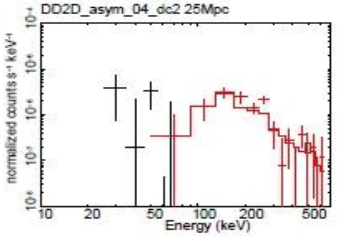
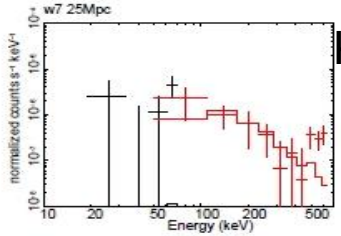
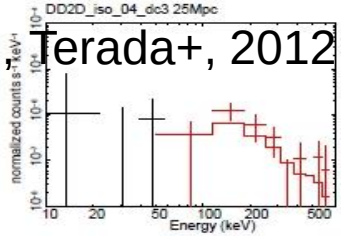
MeV, that Unique

SN 2014J looks like quite normal in optical.
- The model applies to SNe Ia in general?
- Variations even if optical is identical?

⇒ **Need at least another few SNe detected.**

Sensitivity curve from Takahashi SPIE 2010

Radioactive decay in Astro-H era

	$M(^{56}Ni)=1M_{\odot}$(DDT)	$0.6M_{\odot}$ (W7)	$0.4M_{\odot}$(DDT)
5 Mpc			
15 Mpc			
25 Mpc			

KM, Terada+, 2012

1 Ms exp., at ~ 20 days (~ 158 keV peak: $^{56}Ni \rightarrow Co$)

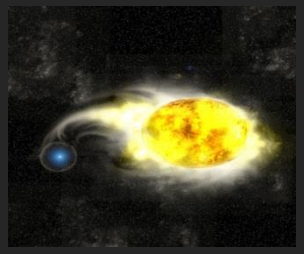
Detection up to ~ 15 - 20 Mpc at 158 keV

Stripped-envelope SNe

- Gravitational collapse of a massive star.
- H-envelope lost before the explosion.

Single massive star

Binary evolution



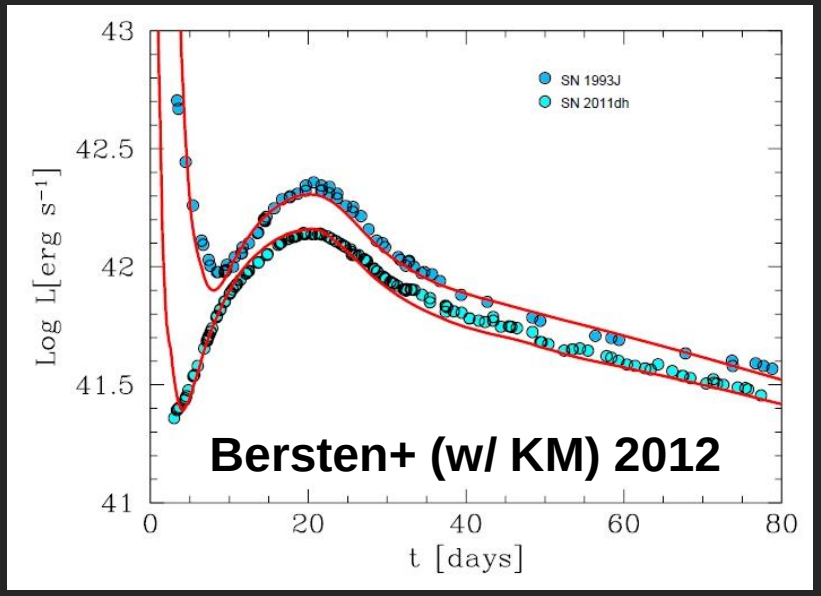
Progenitor?
- RSG?
- YSG?
- Wolf-Rayet?
- Mass?

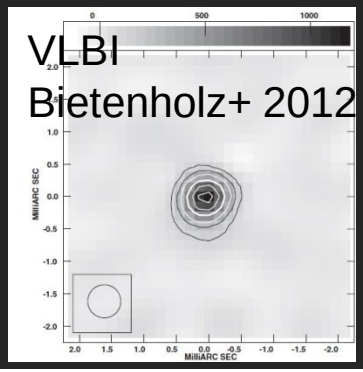
Explosion Mechanism?
- Energetics?
- Asymmetry?

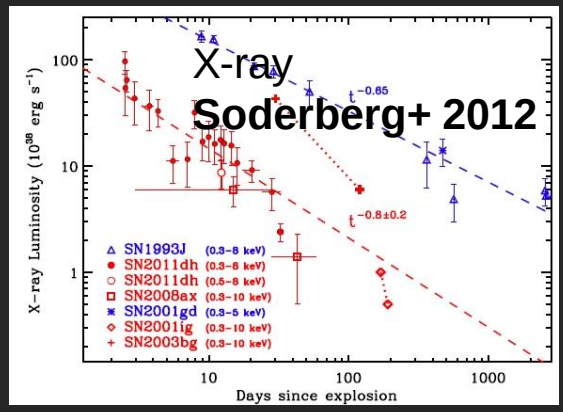
SN IIb 2011dh – One of Best Cases

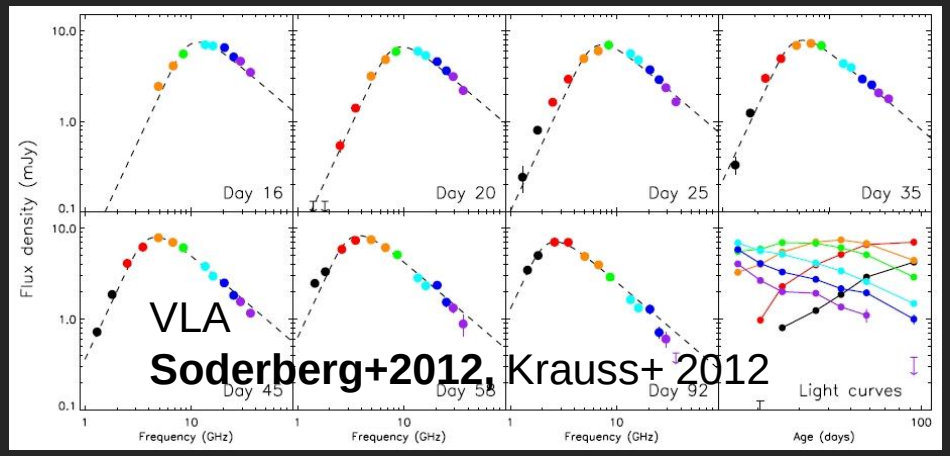
Nearby M51 (@ 8 Mpc)
Intensive radio and X-ray followup
Intensive optical followup + detailed models

10^{51}erg, ejecta mass ~ 2 $M_\odot$
3-4 $M_\odot$ He star
⇒ 15-18 $M_\odot$@ MS

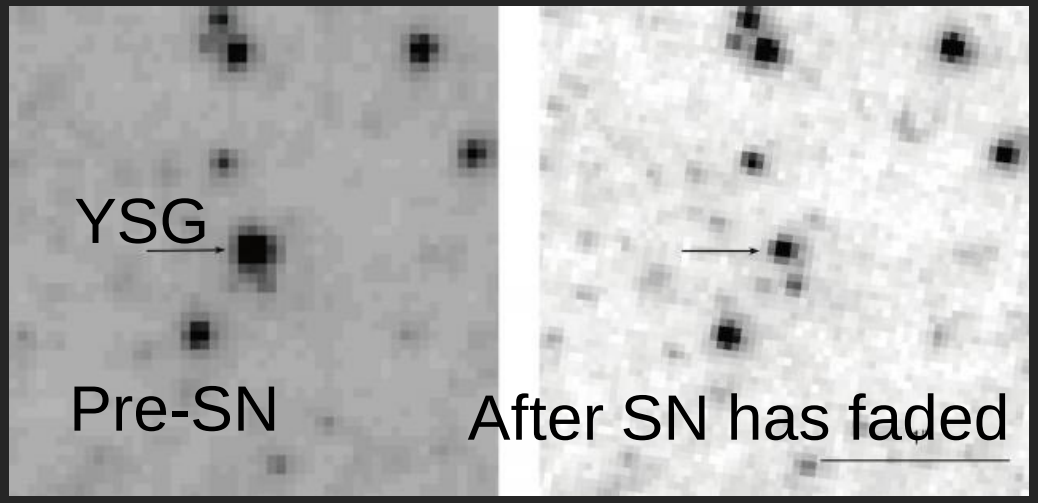




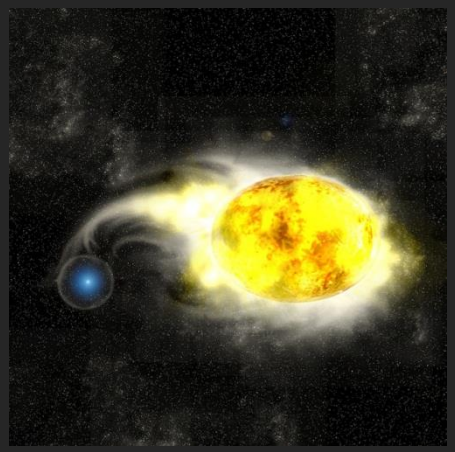




Progenitor debate



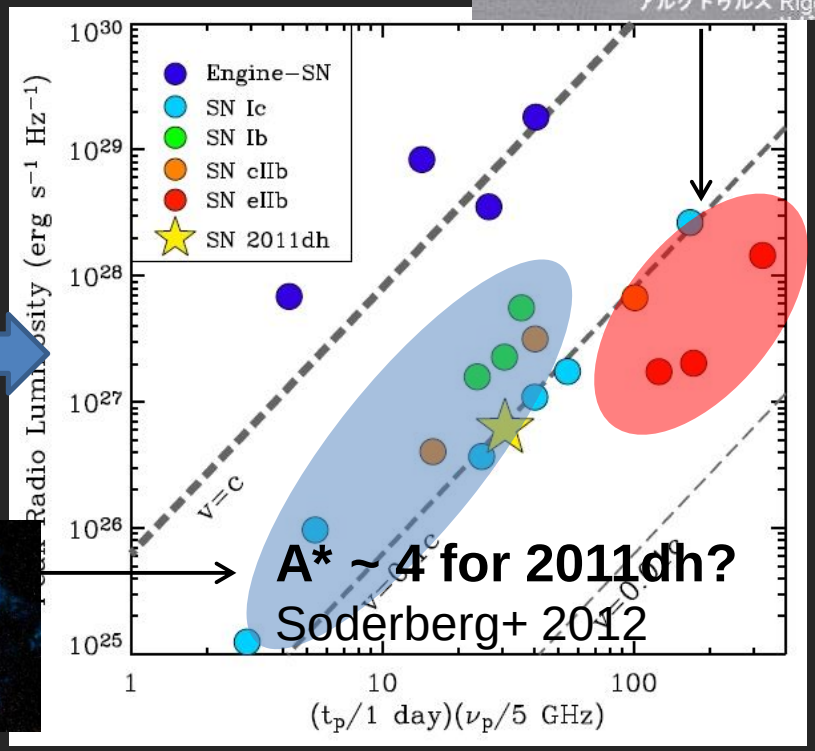
RSG



Progenitor = YSG

Van Dyk+ 2013

WR



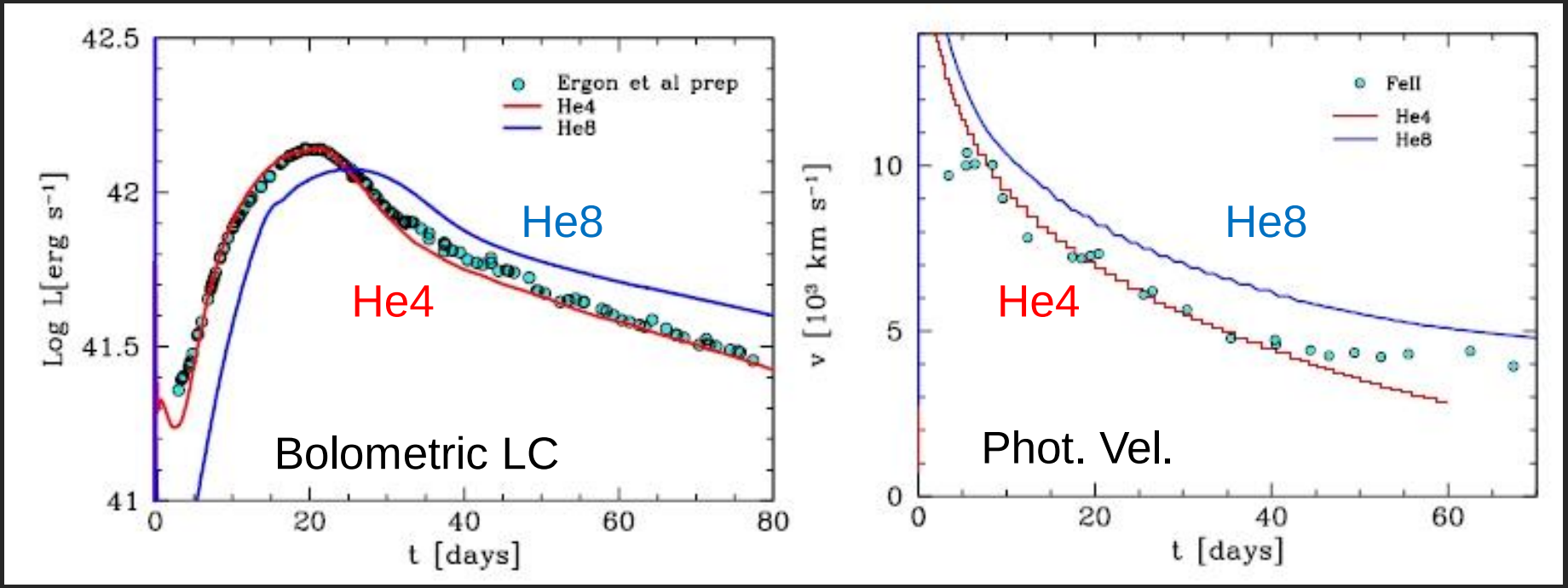
A* ~ 4 for 2011dh?

Soderberg+ 2012

Progenitor mass: binary needed

YSG in pre-SN image. Progenitor?

Bersten+ (w/ KM) 2012



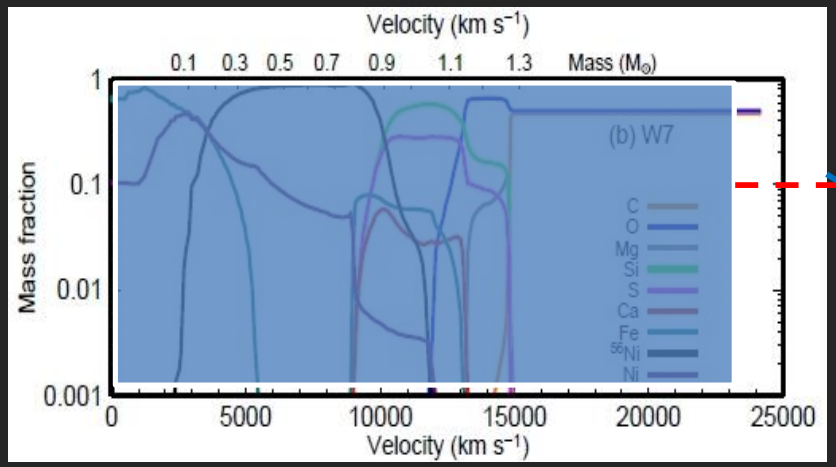
$M(He) \sim 4M_\odot \Rightarrow M_{ms} = 12\text{-}15M_\odot$.

$E \sim 0.8 \times 10^{51}$erg, $M(^{56}Ni) \sim 0.06M_\odot$.

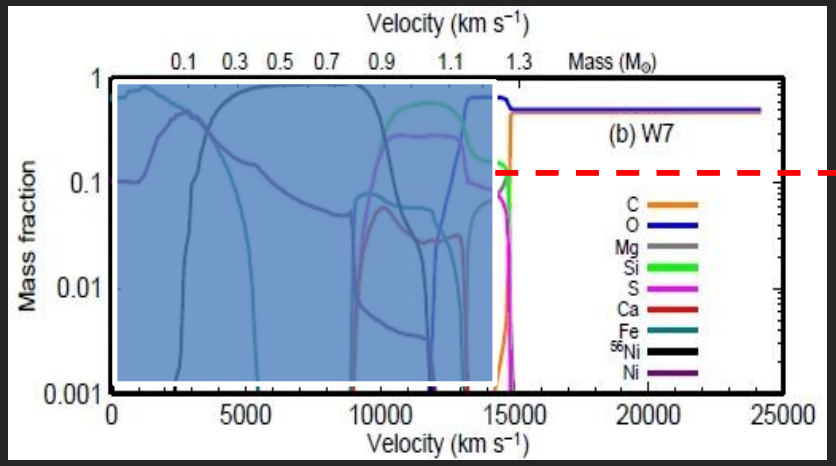
Need binary evolution!

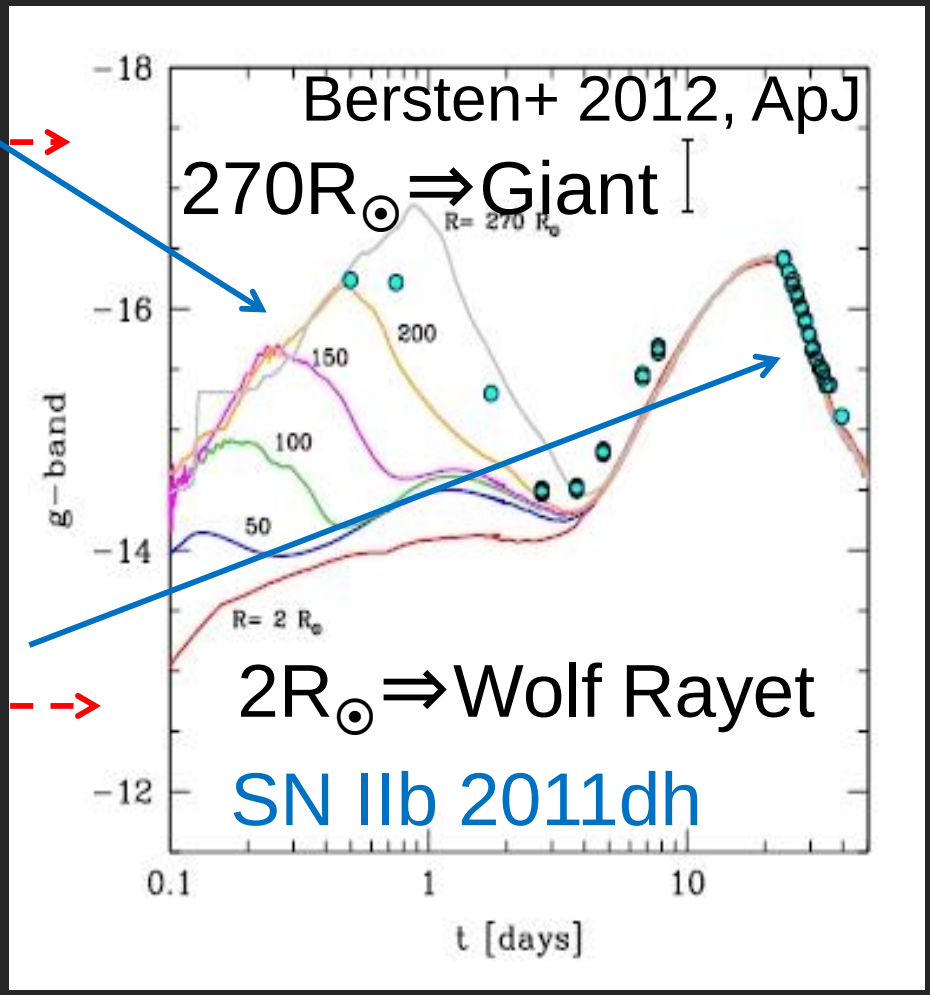
Progenitor radius: It is YSG!

days Surface→Radius, Composition→**Progenitor**



weeks ⇩ $\rho \propto t^{-3}$



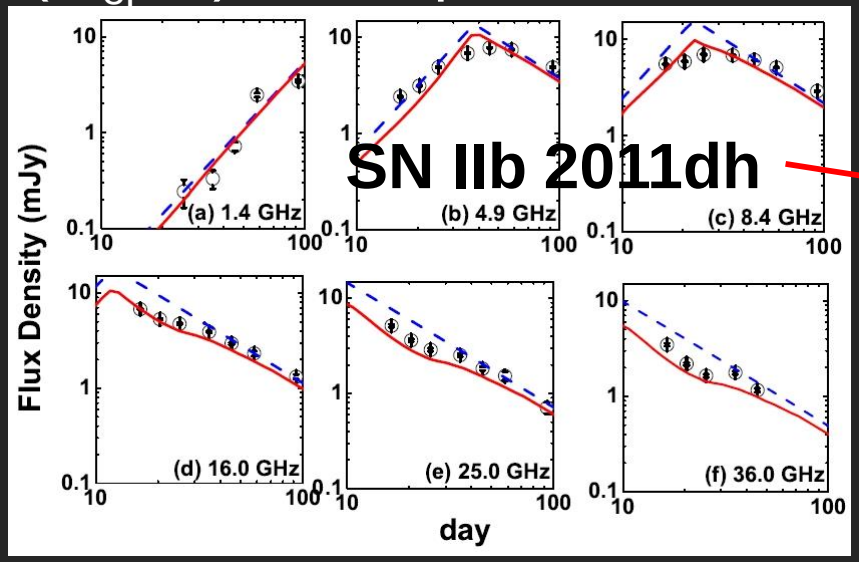


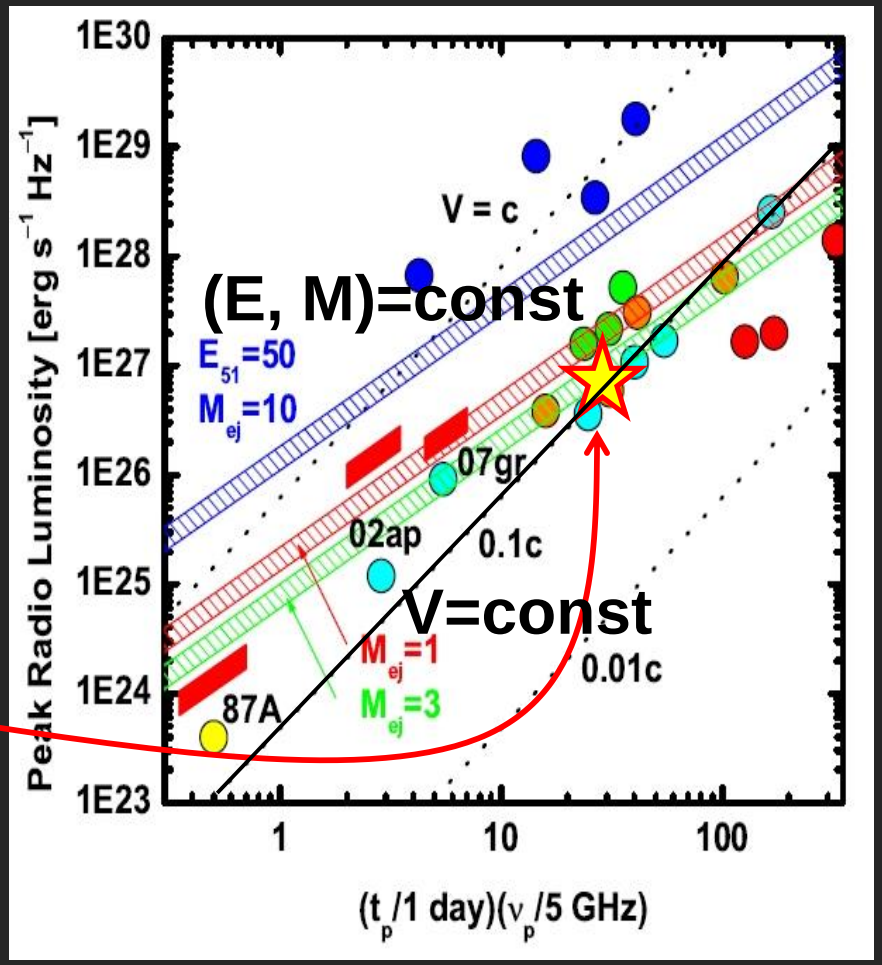
Radio also points to the low-mass progenitor

- (M_{ej}, E) from radio.
- Most SNe IIb/Ib/Ic have $M_{ej} \sim 1 - 5 M_\odot$

$\Rightarrow M_{ms} < 25 M_\odot$. **Binary?**

(M_{ej}, E) from optical model.



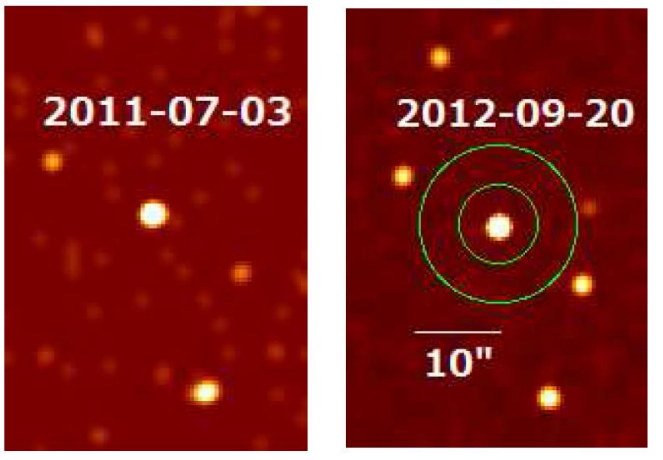


KM 2013, ApJ, 762, 14

KM 2012, ApJ, 758, 81

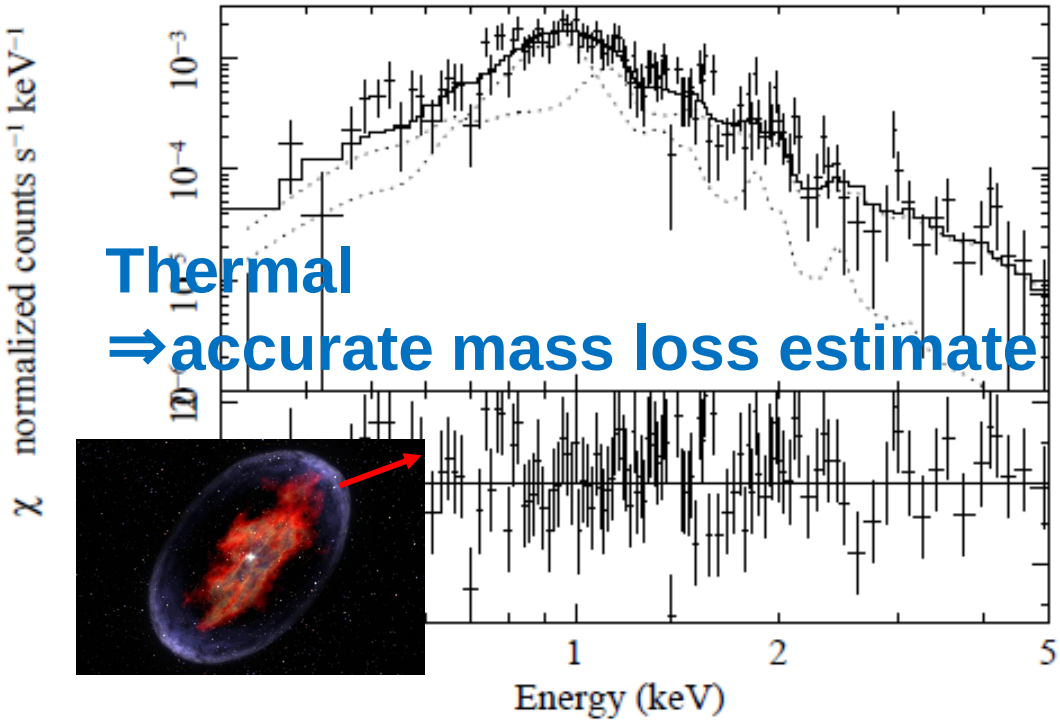
KM, Katsuda, Bamba, Terada, Fukazawa, 2014, ApJ

X-ray from SN 2011dh: binary needed



SN 2011dh @ 500 days

Chandra **750 ksec**



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

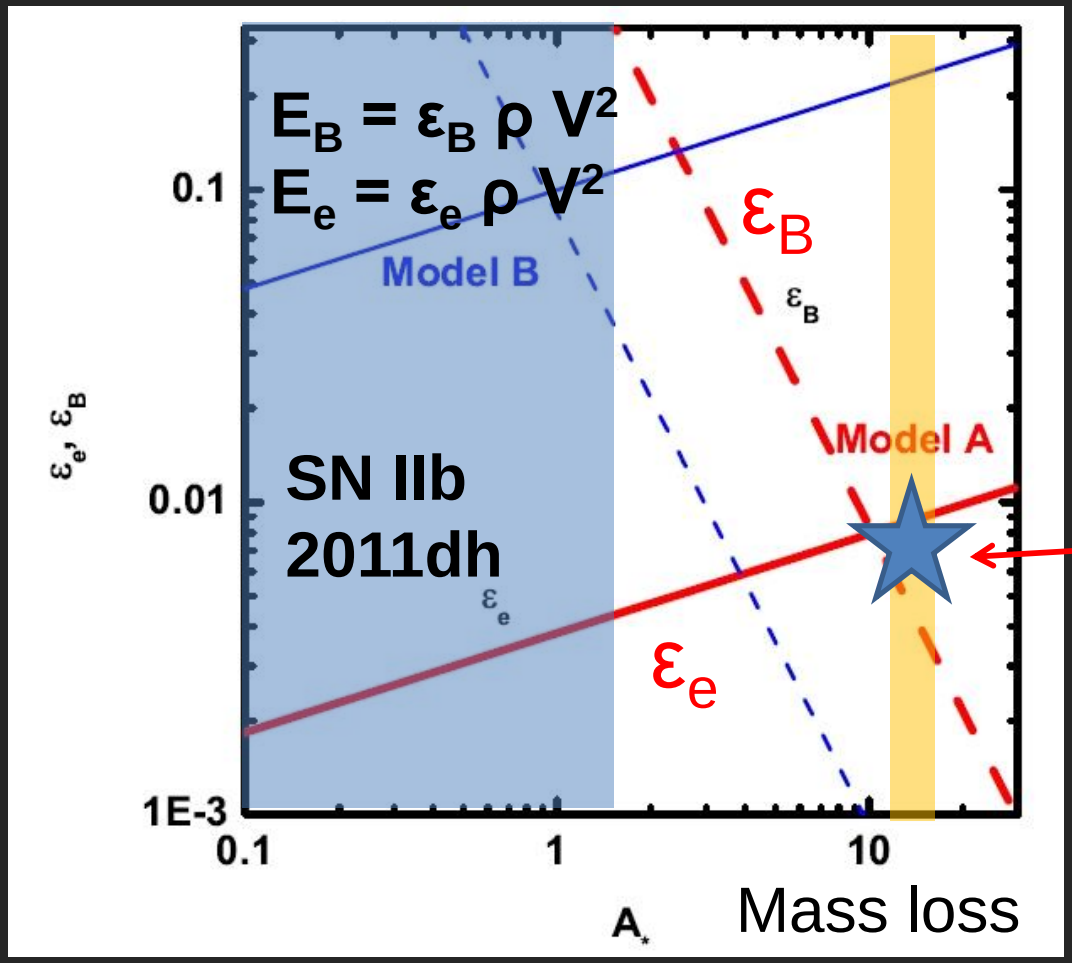
(Obviously) the first mass loss determination for an YSG SN-progenitor (also rare for SNe Ib/c in general).

Not enough to get rid of all the H-envelope

⇒Binary interaction in the past.

KM 2012, ApJ, 758, 81

Byproduct: Electron acceleration

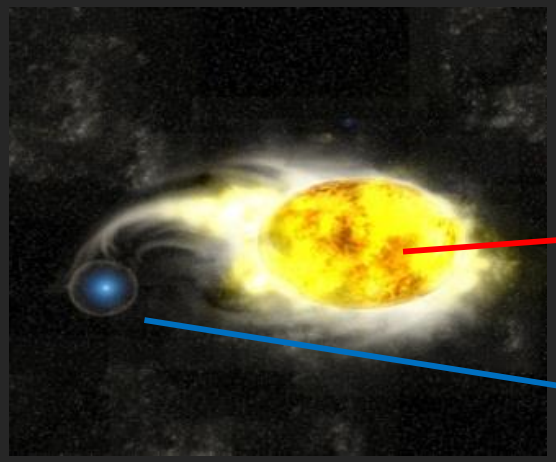


Mass loss determined (very rare for SE-SNe) ⇒Unique solution for radio emission

$\varepsilon_e \sim \varepsilon_B \sim 0.01$
→ lower than believed (in SN community).

$\rho_{CSM} \propto A^* r^{-2}$, A* ~1 for WR, A*~10 for YSG

Binary evolution for the YSG progenitor

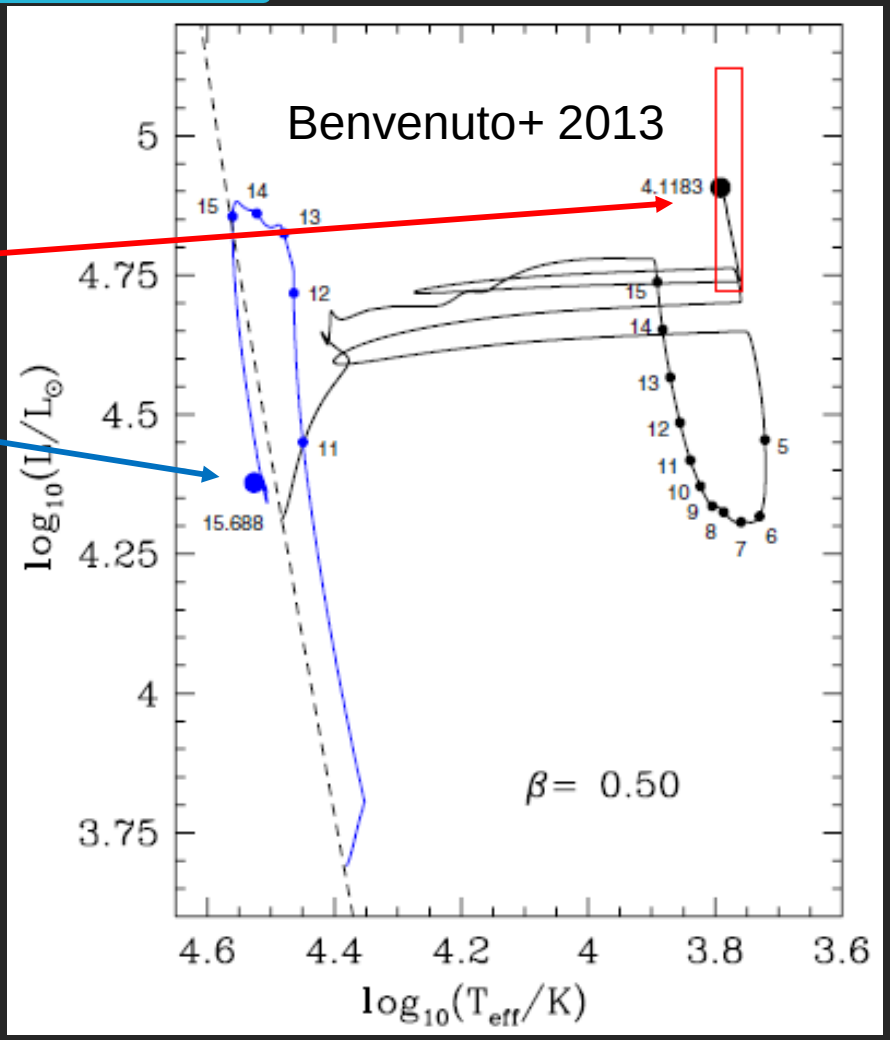


Should be an O or B companion there.

Final piece = direct detection of the companion.

Too blue for optical.

Go for UV.



Latest news: Companion candidate detected

Folatteli+ (w/ KM), submitted

HST UV obs. On 2014 August
(Folatteli, KM+)

Magnitude and color exactly
as predicted.
⇒ Stay tuned!

What do I/We (mainly) do?

- Theory.
  - Hydrodynamics after the shock launch (1 – 3D).
  - Nucleosynthesis.
  - UV/opt/IR Rad. transfer (1 – 3D, multi-v, t-dependent).
  - Non-thermal emission.
- Observation (From radio to MeV, not a complete list).
  - As PI:
    - Subaru (FOCAS-opt., IRCS-NIR/AO, HDS-opt/high-res.), ALMA (ToO).
  - As Co-I:
    - INTEGRAL (ToO), Chandra (ToO), Suzaku, HST, Subaru (FOCAS, Comics), Keck, VLT, Gemini, Magellan, VLA.

    + Smaller telescopes (e.g., see Yamanaka-san's talk).

What do I/We (mainly) do?

- Theory.
  - Hydrodynamics after the shock launch (1 – 3D).
  - Nucleosynthesis.
  - UV/opt/IR Rad. transfer (1 – 3D, multi-v, t-dependent).
  - Non-thermal emission.
- Observation (From radio to MeV, not a complete list).
  - As PI:
    - Subaru (FOCAS-opt., IRCS-NIR/AO, HDS-opt/high-res.), ALMA (ToO).
  - As Co-I:
    - INTEGRAL (ToO), Chandra (ToO), Suzaku, HST, Subaru Keck, VLT, Gemini, Magellan, VLA.

    + Smaller telescopes (e.g., see Yamanaka-san's talk).