Supernova Nucleosynthesis

Keiichi Maeda

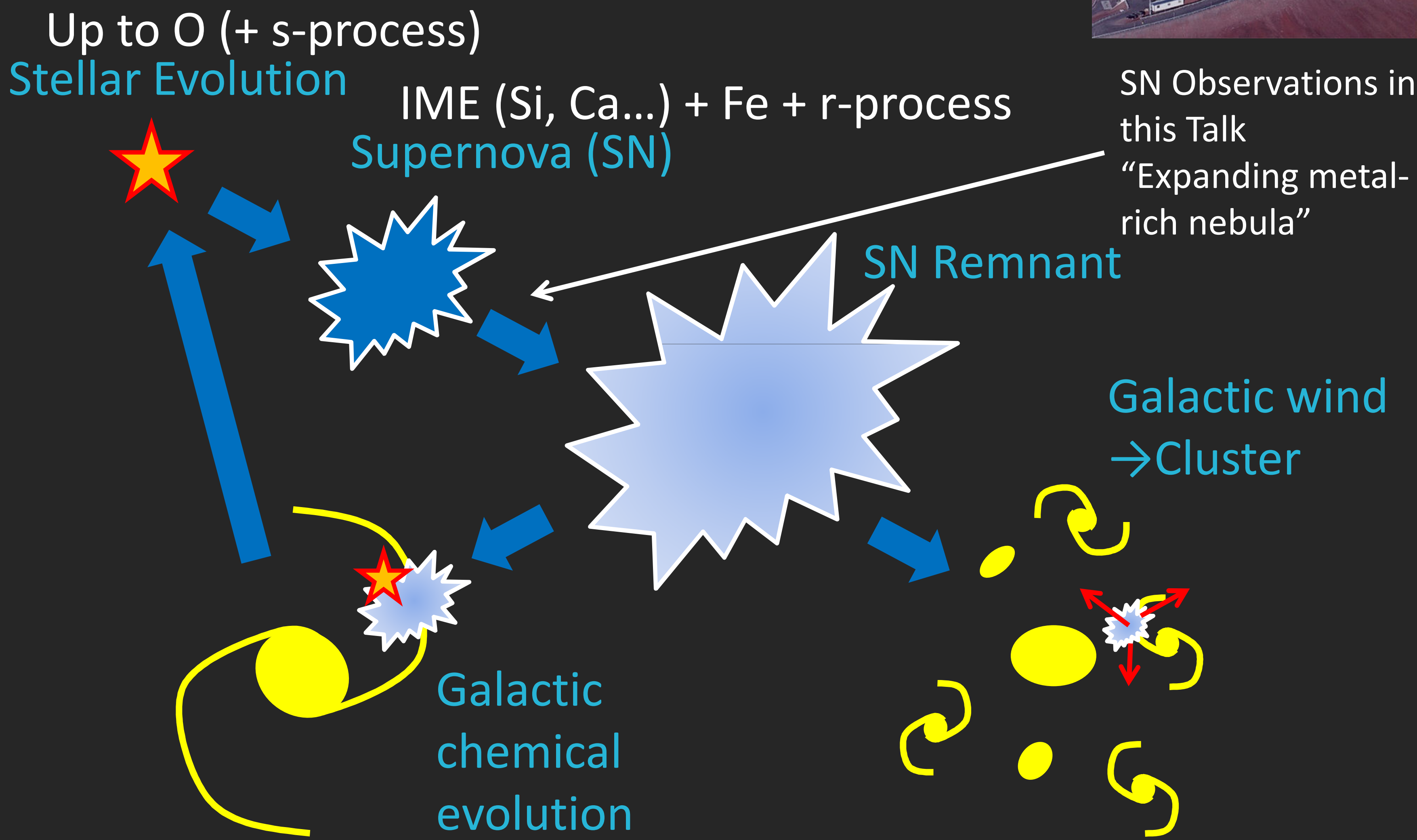
Inst. for the Phys. and Math. of the Universe (IPMU),

University of Tokyo

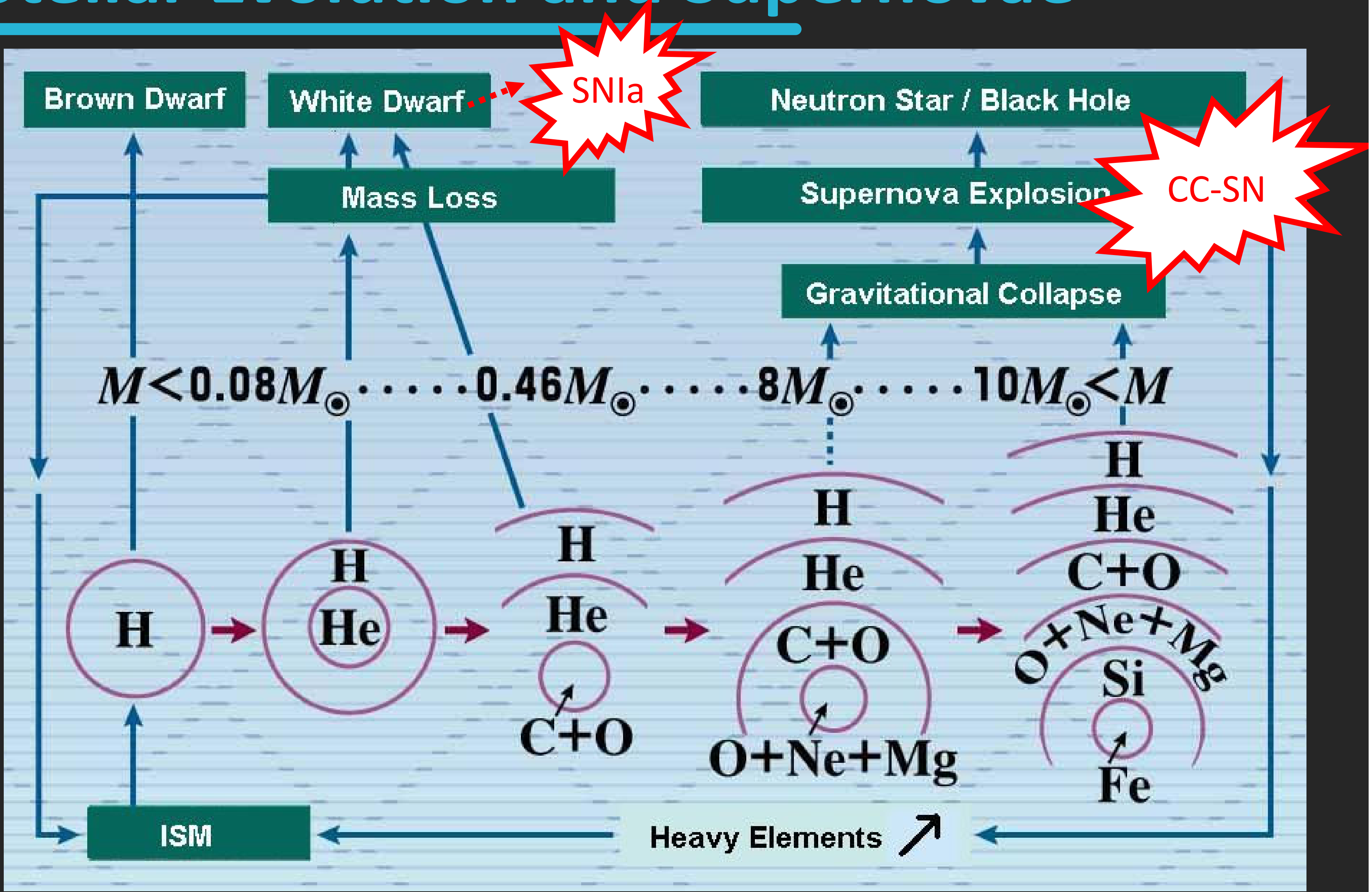
IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

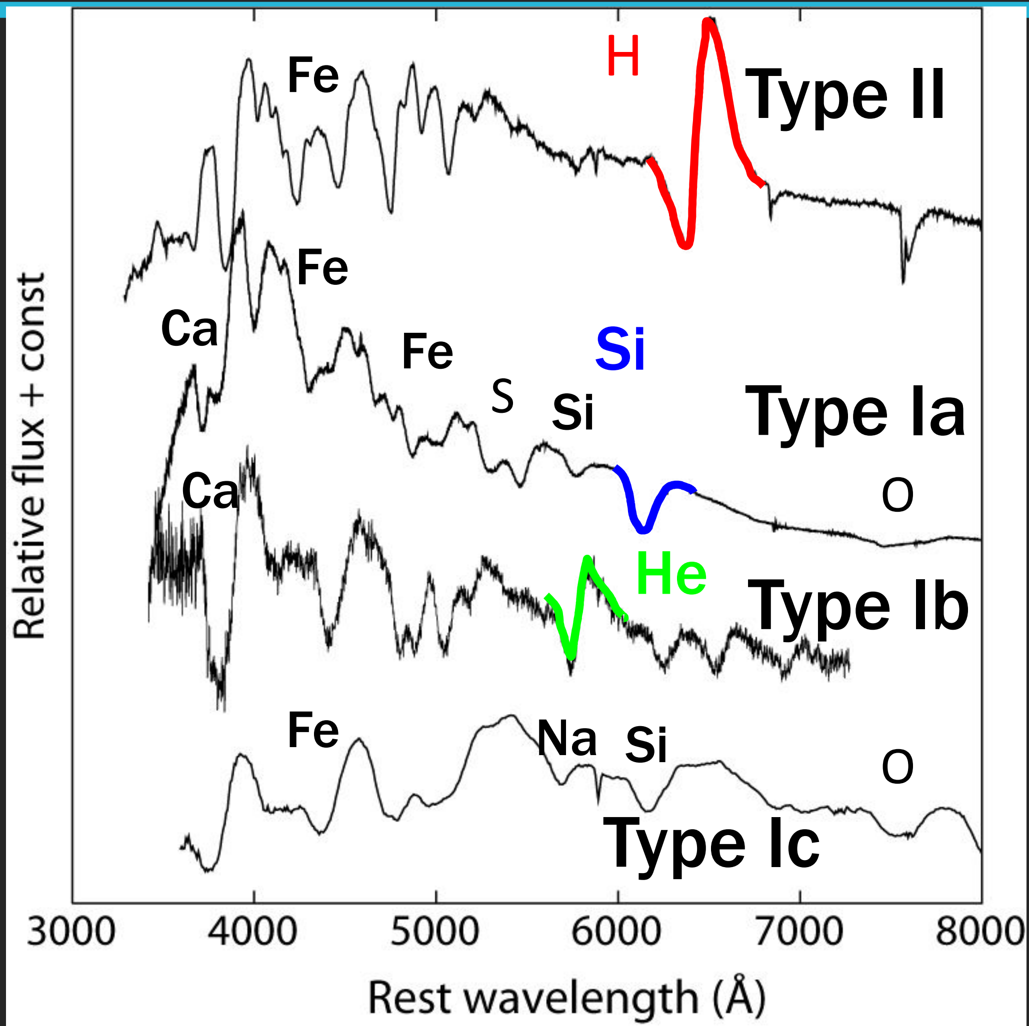
SNe as the Origin of Elements



Stellar Evolution and Supernovae



Supernova Classification

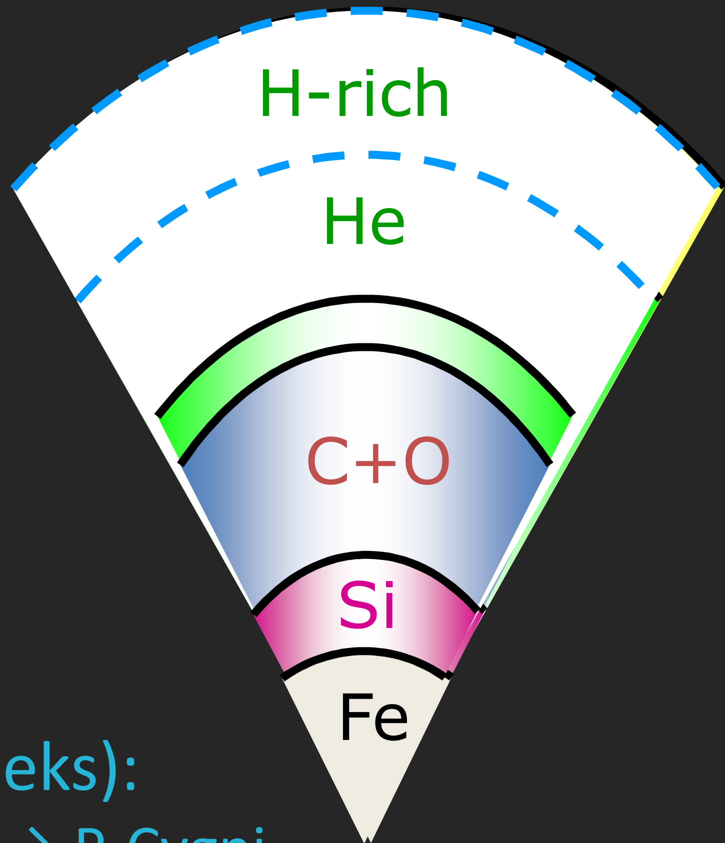


Ia

Thermonuclear exp. of white dwarf

II/Ib/Ic

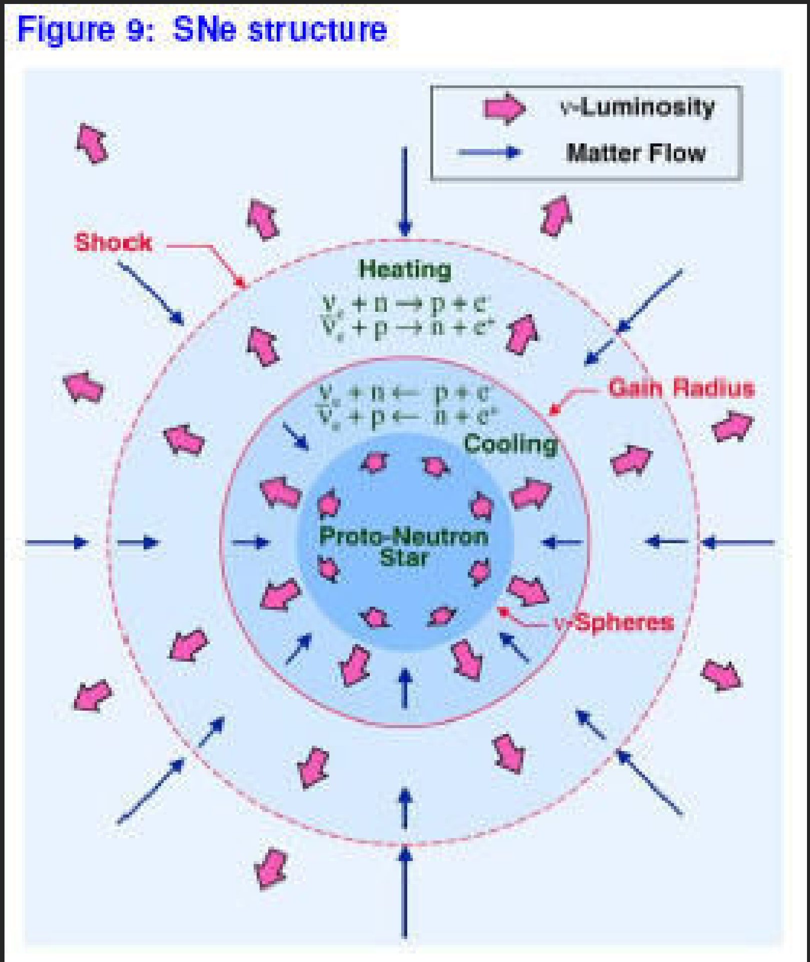
Core-Collapse (CC) of massive stars



@ maximum brightness (~ a few weeks):

– Expanding optically thick medium → P-Cygni.

Core-collapse SN – Standard Picture



- Core-collapse
  → proto NS + bounce shock
  → shock stalled
  (ram pressure + Fe dissociation)
  →ν from proto NS (~ 3 × 10^{53} erg)
  →1% of ν deposited, shock revival
  → explosion w/ ~ 10^{51} erg.

- **Caveat**
  - do **not** explode in (1D) sims.
  - Multi-D effects favored.

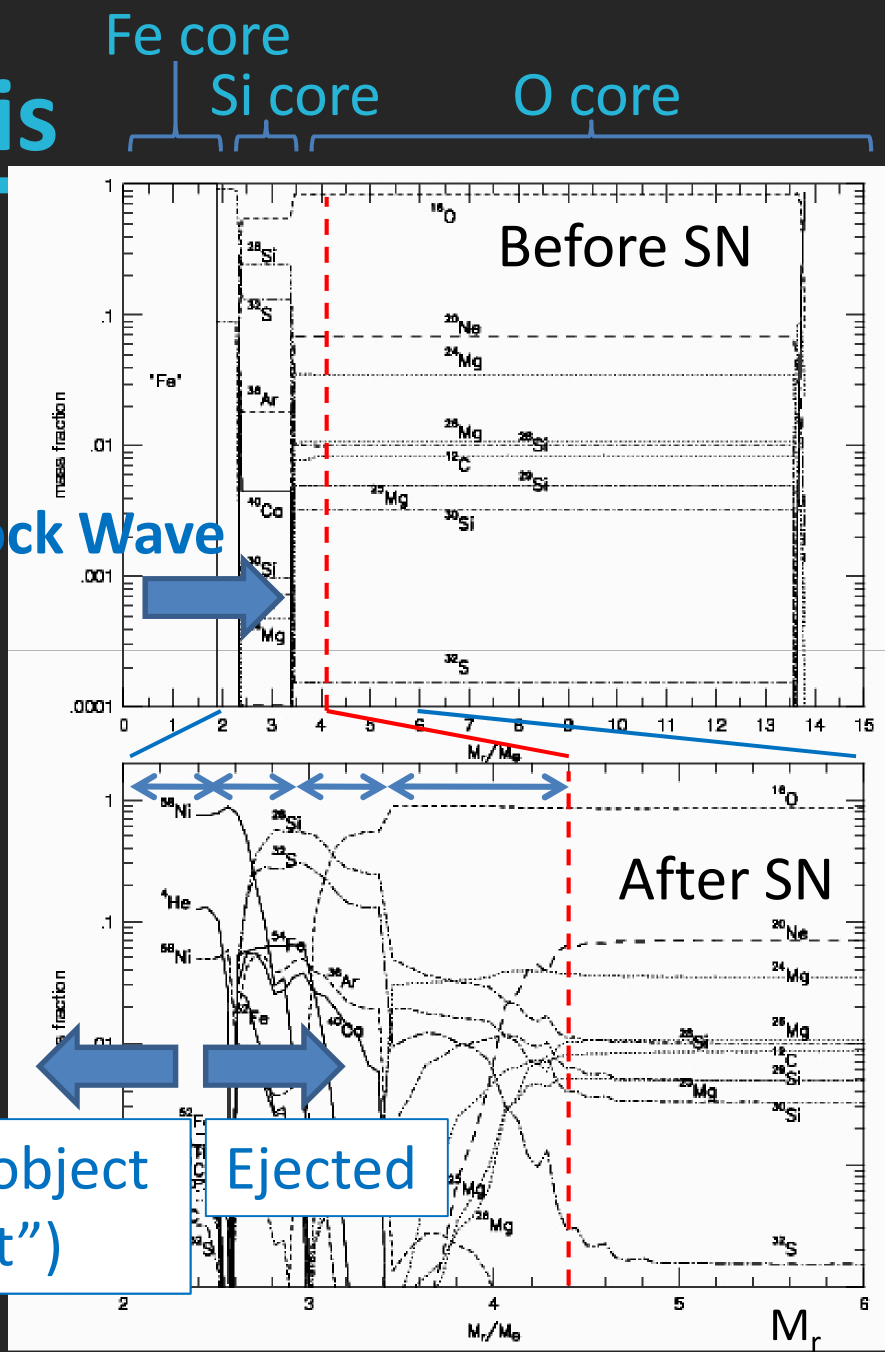
Inside Fe core (typically decoupled from the envelope)

CC-SN Nucleosynthesis

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

Depends on

- E_K, "mass cut", and M_{ms}.
- \+ Asymmetry (later).



^{56}Ni important in theory & observation

- Theory:
  - Produced in the **innermost** region.

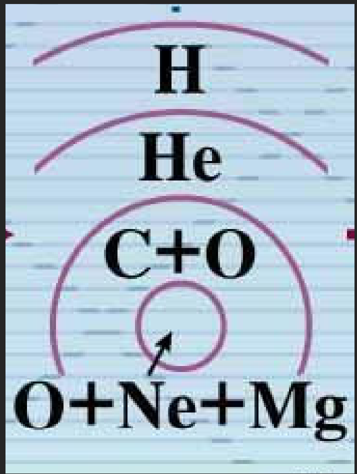
- Observation.
  - SNe Ia/b/c powered by **^{56}Ni→^{56}Co→^{56}Fe**.

~ week **~ 100 days**

Flow

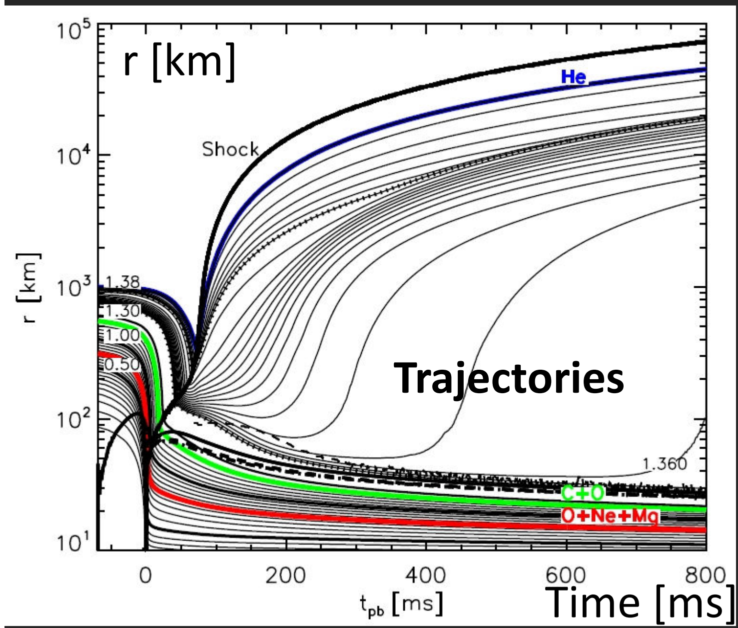
- 8-10$M_\odot$
- 10 - 20(?)$M_\odot$
- 20 -100$M_\odot$
- 100 – 300$M_\odot$
- >300$M_\odot$
- White Dwarf

8-10M$_\odot$: ONeMg Core-Collapse



Nomoto 1984

- Degenerate **ONeMg** core.
  - T not reached to neon ignition.
  - **Electron capture**→Collapse→**NS**.
    - ^{24}Mg(e$^-$, ν)^{24}Na(e$^-$, ν)^{20}Ne.
    - ^{20}Ne(e$^-$, ν)^{20}F(e$^-$, ν)^{20}O.



Kitaura+ 2006

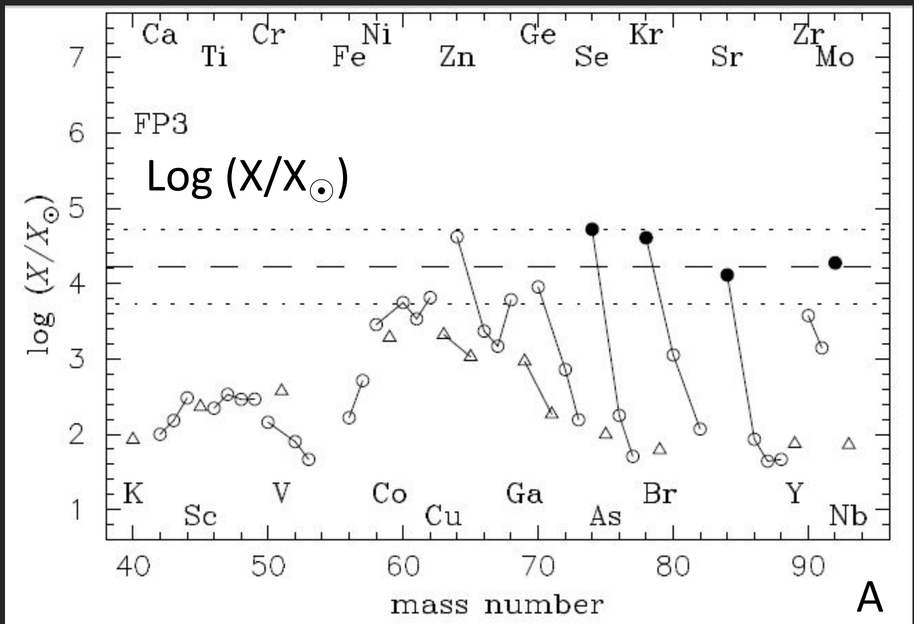
- **Explosion** even in 1D simulations.
  - Standard ν-driven explosion.
  - Small binding energy in the envelope + steep density gradient.
  - $E_K < 10^{50}$ erg.
  - M(^{56}Ni) < 0.015M$_\odot$ Kitaura+ 2006

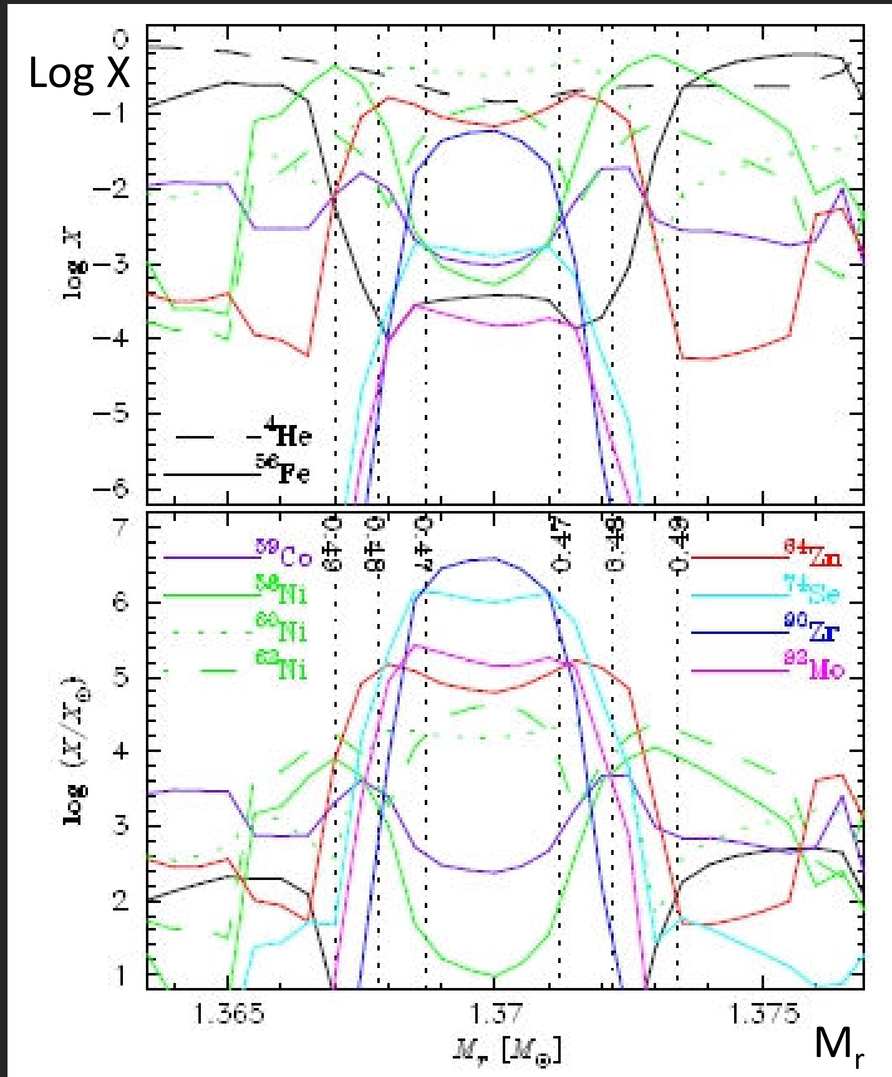
    ~ 0.002 – 0.004M$_\odot$ Wanajo+ 2009

8-10M$_\odot$: ONeMg Core-Collapse

Wanajo+ 2009

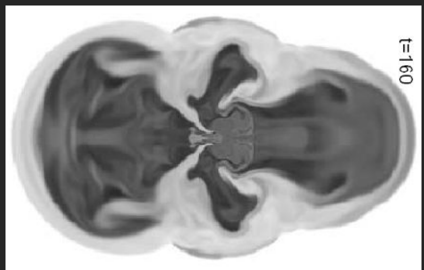
- Mostly Fe-peak.
- **Neutron-rich** isotopes.
  - **Little IME** (density too low in envelope).





$10\text{-}100M_{\odot}$: Fe CC

- Simulations do not produce SNe as energetic as observed..., anyway they explode **observationally**.
- 2D/3D effects?



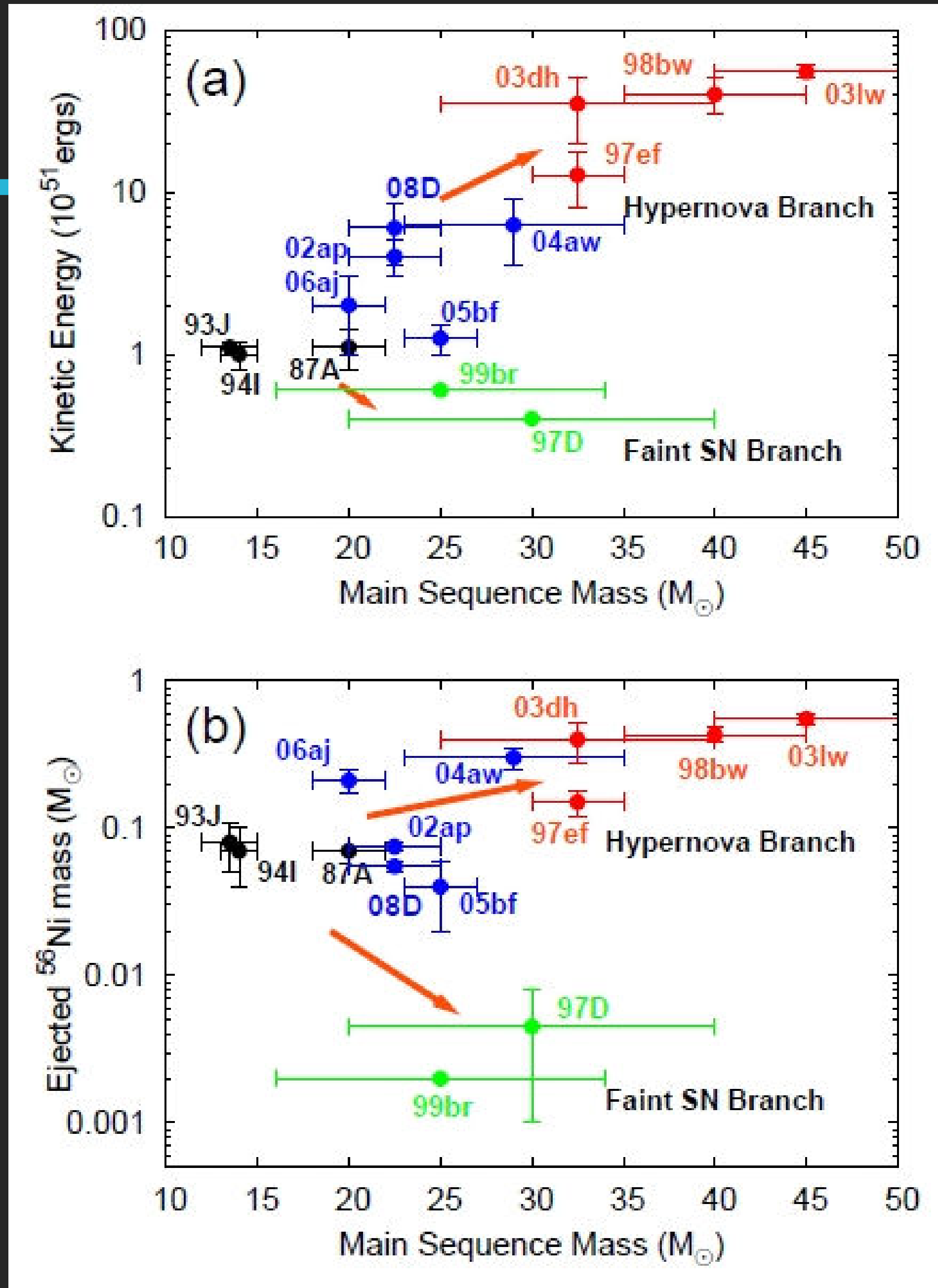
Blondin+ 2003
"SASI - Standing Accretion Shock Inst."

"Observational"

E_K and $M(^{56}Ni)$ vs. M_{ms} →

M_{ej} derived by modeling obs.

$M_{ej} \rightarrow M_{ms}$ assumes evo. Model.



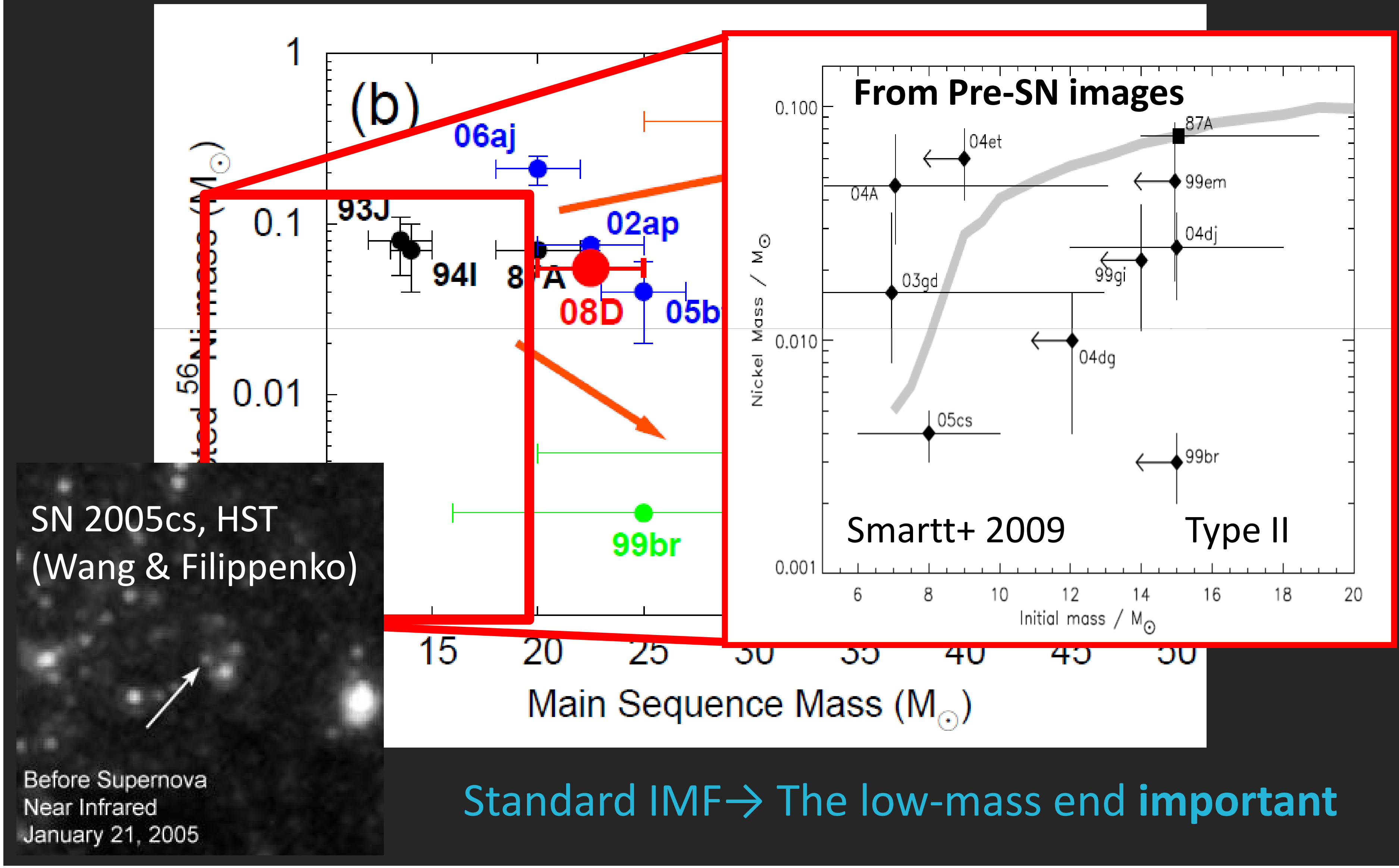
The low mass end of CC-SNe?

- 8-12$M_{\odot}$
- 12 - 20(?)$M_{\odot}$
- 20 -100$M_{\odot}$
- 100 – 300$M_{\odot}$
- >300$M_{\odot}$
- White Dwarf$_{\odot}$

Why matter?

They may not be dramatic, but should be numerous.

The low mass end of CC-SNe?

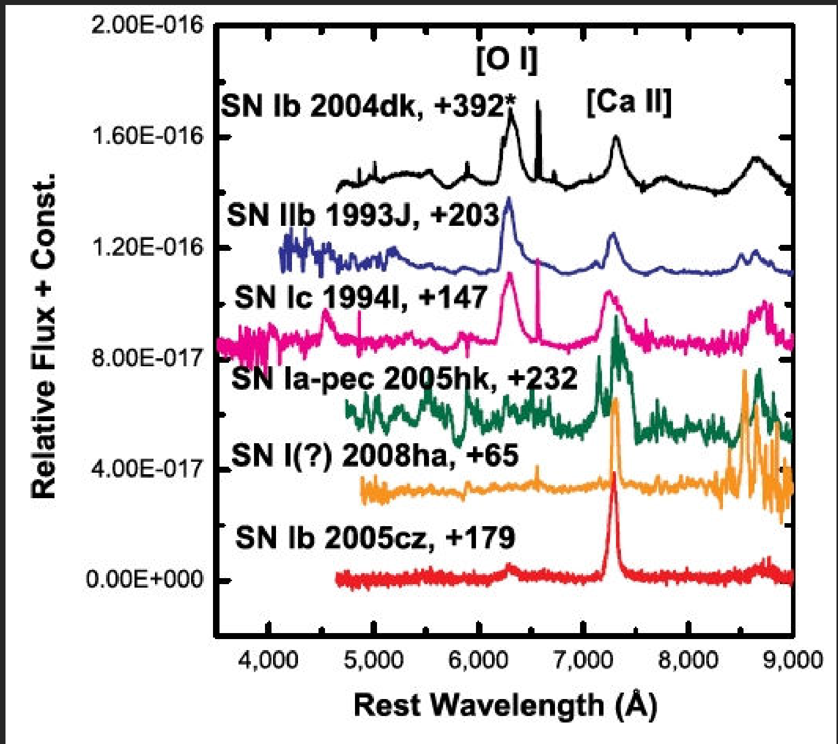


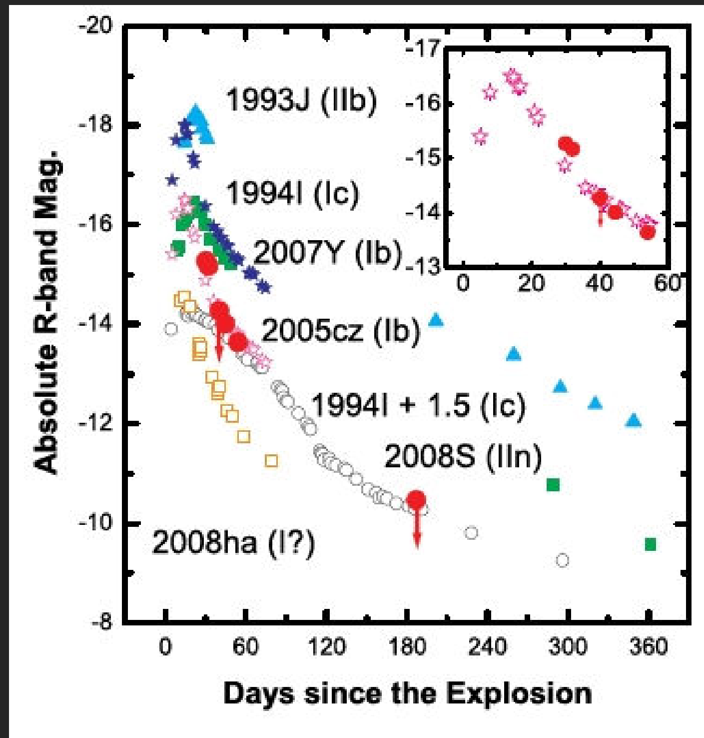
Standard IMF→ The low-mass end **important**

The low mass end of CC-SNe?

- SN Ib 2005cz in an elliptical.

Kawabata, **KM**, Nomoto+, 2010, Nature, 465, 326

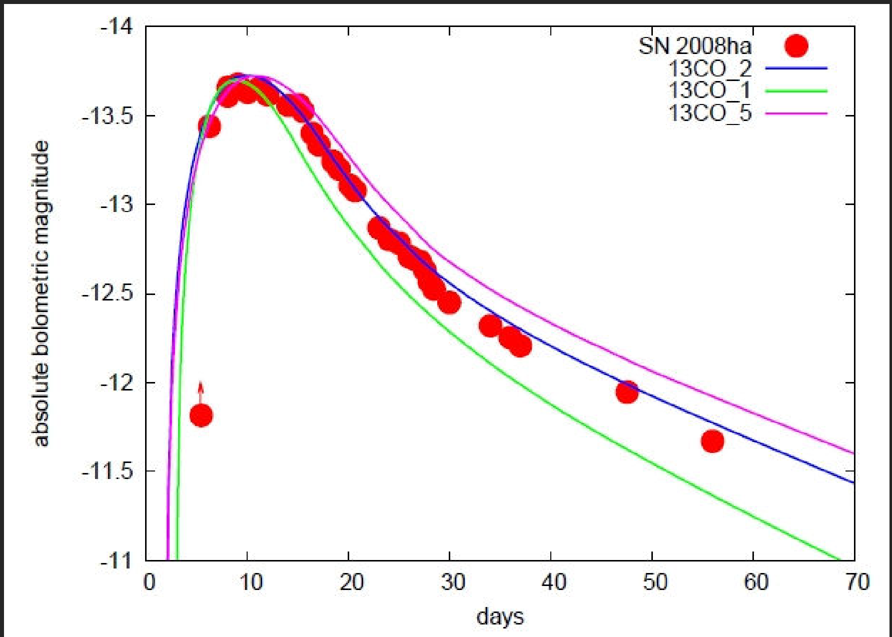




- Small O/Ca → Small O-core: M_{ms} ~ 8 – 12$M_\odot$.
- EK << 10^{51} erg, M(^{56}Ni) < 0.02$M_\odot$ (ONeMg-CC? Fe-CC?).

The low mass end of CC-SNe?

- Very faint SN I(?) 2008ha. Valenti+09; Foley+ 09



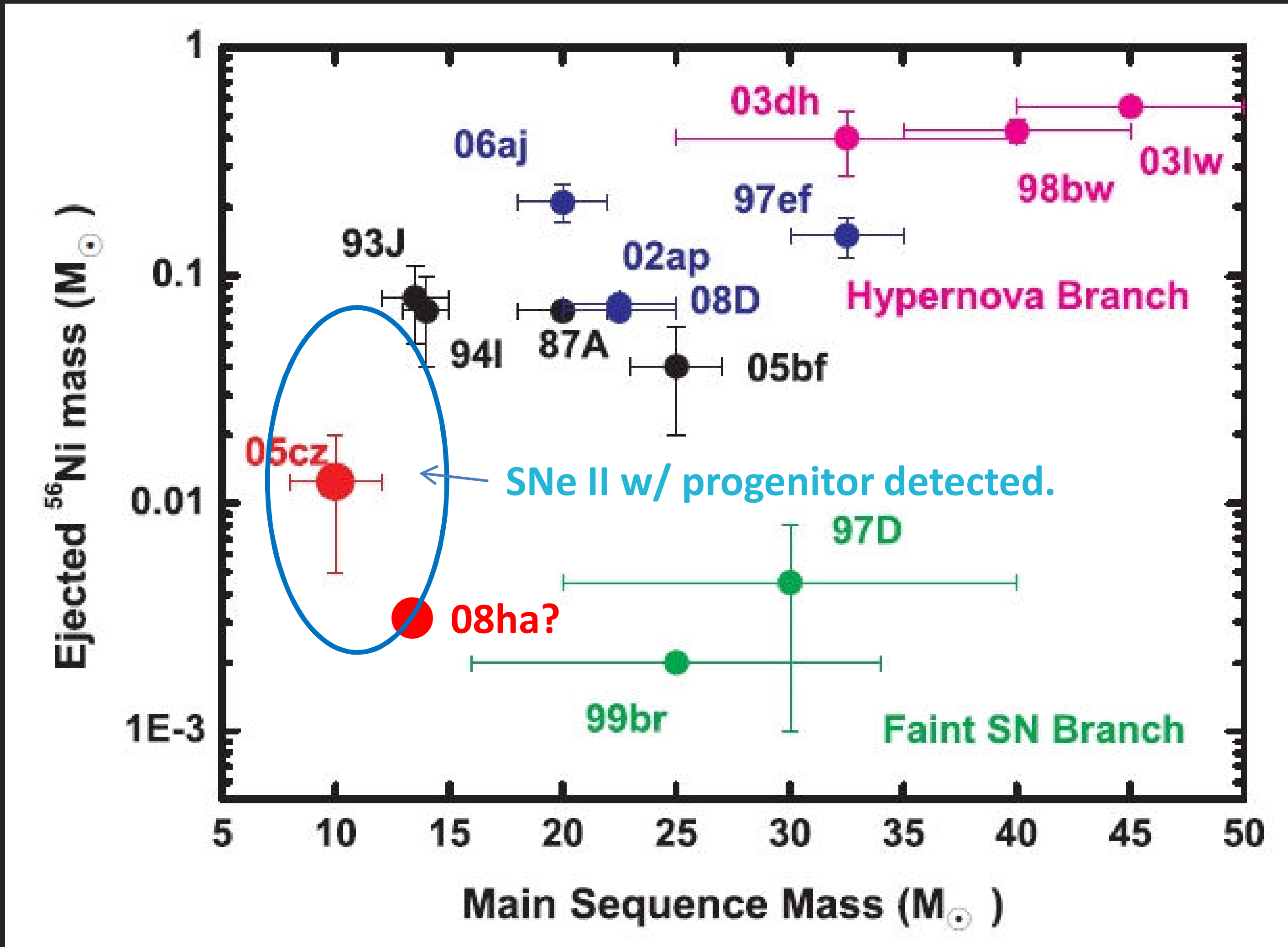
- A fallback CC-SN model. Moriya+2010
  - $M_{ms} \sim 13M_\odot$.
  - $E_K = 1.2 \times 10^{48}$ erg.
  - $M_{ej} = 0.074M_\odot$.
  - $M(^{56}Ni) = 0.003M_\odot$.
  - **NS→BH formation?**

Mass fractions = M_i / M_{ej} (Moriya, Tominaga, Tanaka+ 2010)

^{4}He	^{12}C	^{16}O	^{20}Ne	^{24}Mg	^{28}Si	^{32}S	^{36}Ar	^{40}Ca	^{44}Ti	^{48}Cr	^{52}Fe	^{56}Ni
0.037	0.20	0.32	0.14	0.066	0.063	0.034	0.0065	0.0045	0.00051	0.0017	0.011	0.12

NOTE. — The mass fraction of each element is shown.

The low mass end of CC-SNe?



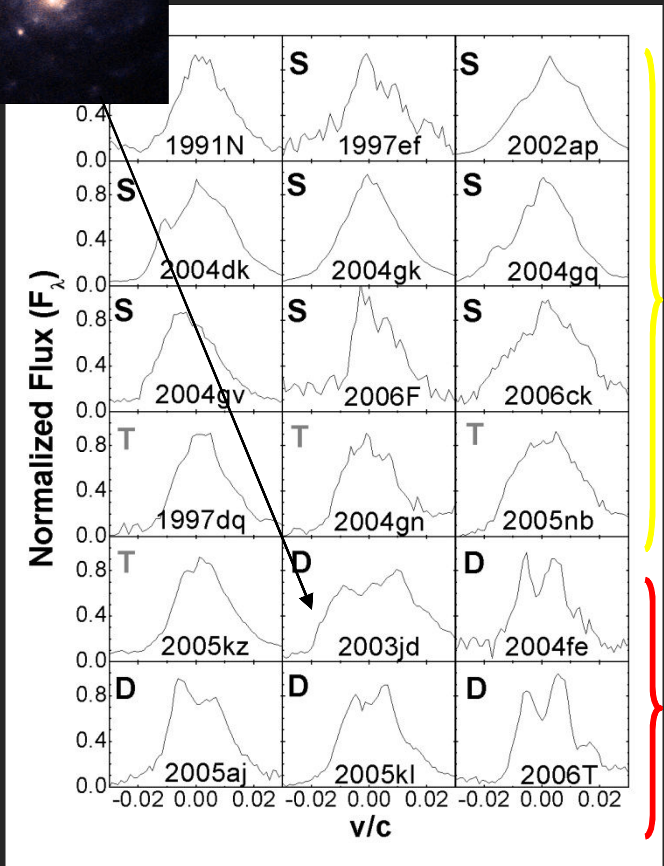
Asymmetry in SN explosions ($> 10M_\odot$)

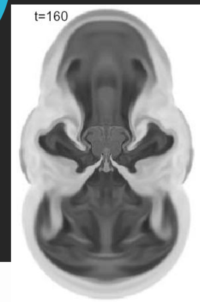
- $8\text{-}10M_\odot$
- $10 - 20(?)M_\odot$
- $20(?) - 100M_\odot$
- $100 – 300M_\odot$
- $>300M_\odot$
- White $\text{Dwarf}_\odot$

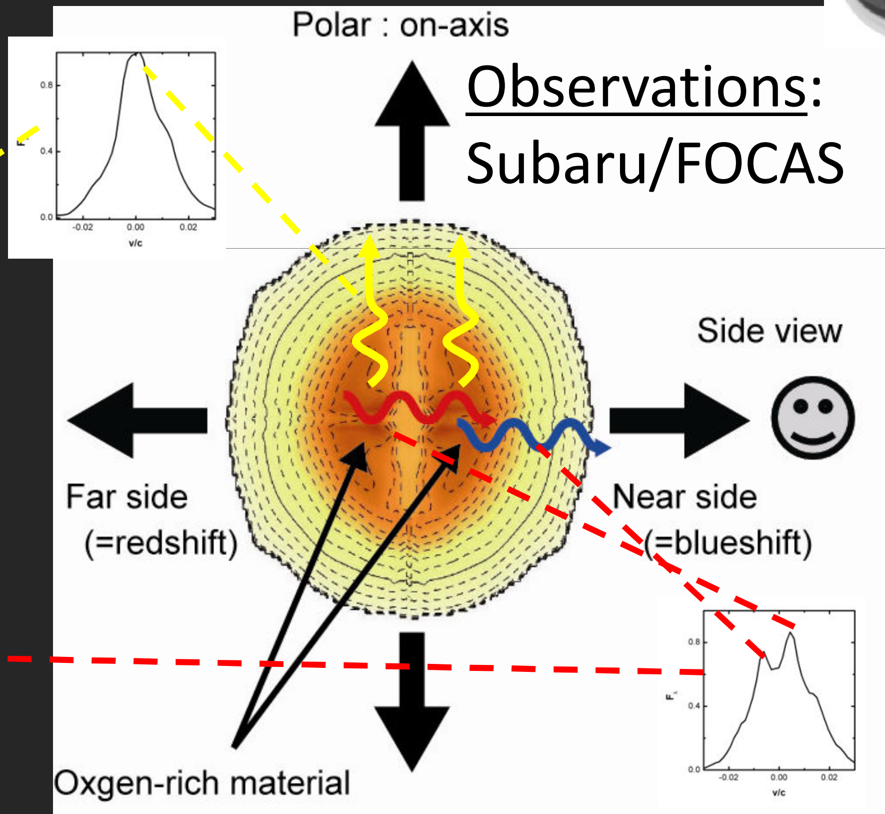
Asymmetry – Observations (> 10M$_\odot$)

KM, Kawabata, Mazzali+ 2008, Science, 319, 1220

[OI]6300 @ 1 year for 18 SNe



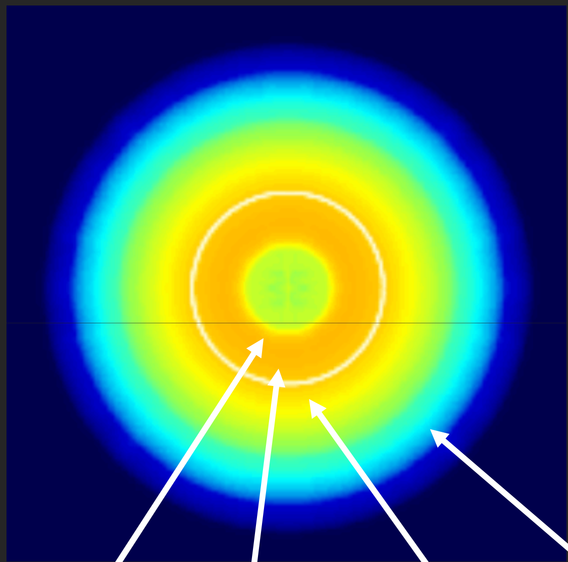




Accumulating evidences… e.g., Polarization (**Tanaka**, Kawabata, KM+ 2008, 2009)

Nucleosynthesis in "bipolar" CC-SNe

Spherical



$$T_{shock} \sim 24 E_{52}^{1/4} r^{-3/4}$$

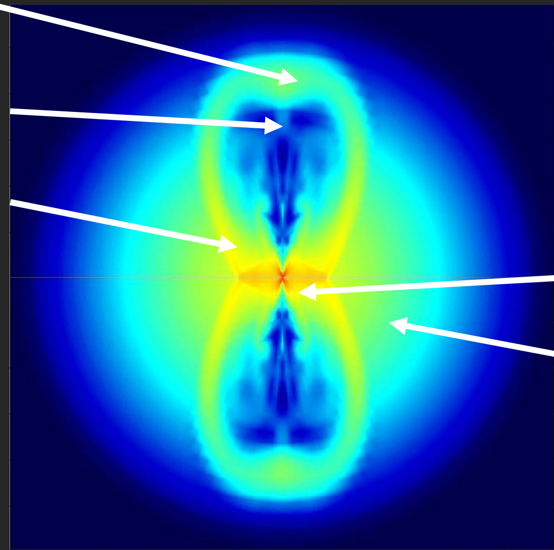
$$V \propto \sqrt{E/M}$$

E(isotropic) ↑ → Tshock ↑ & V ↑

Heavier elm.

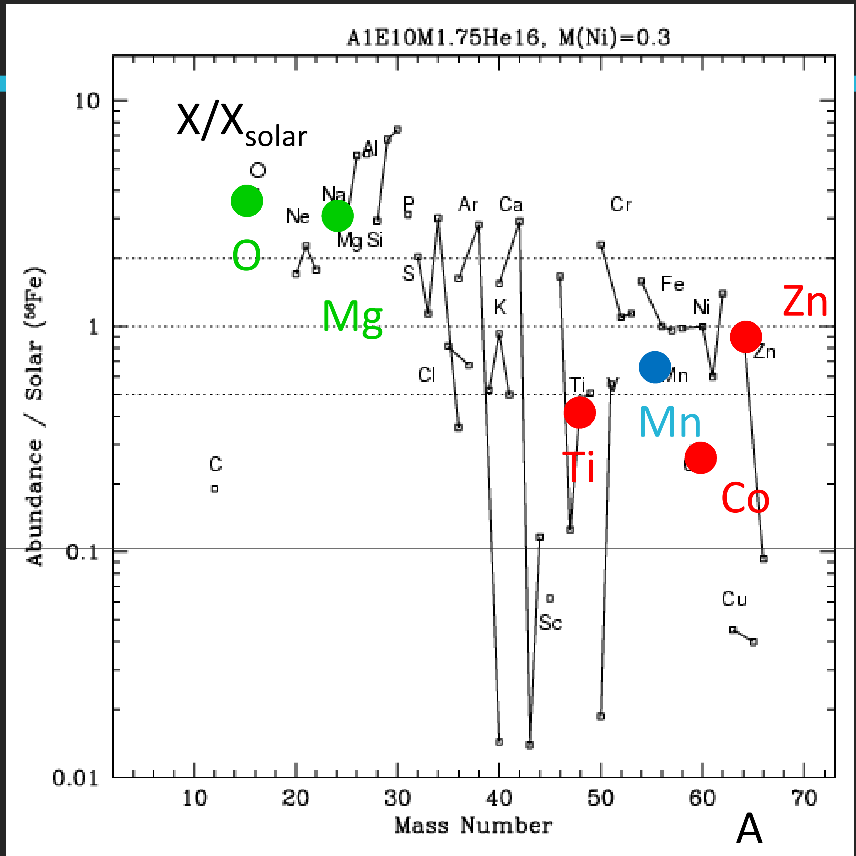
Easier to be ejected.

Bipolar

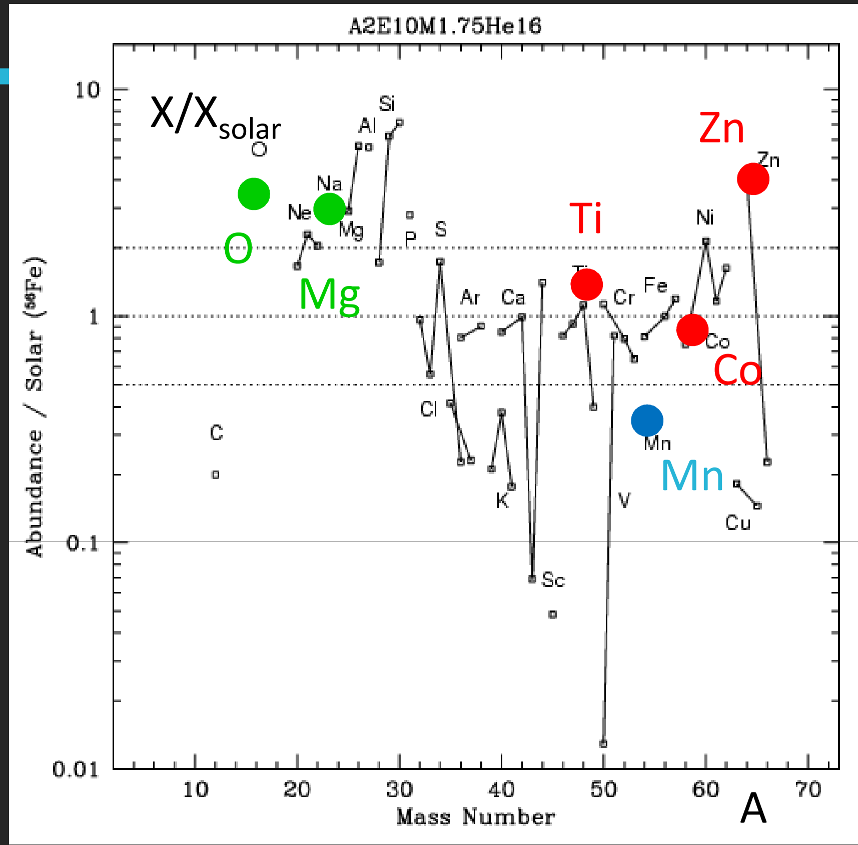


Nagataki+97; KM+ 2002, ApJ, 565, 405; KM & Nomoto, 2003, ApJ, 598, 1163; Tominaga, KM, Umeda+ 2007, Tominaga 2009

Spherical



Bipolar



KM & Nomoto 2003

SN→ISM→Star

- (Zn,Co,Ti)/Fe↑, (Mn,Cr)/Fe↓
  - Similar trends seen in **metal-poor halo stars** (early chemical evolution).
  - “Asphericity” may be an important function in understanding the Chemical Evo.
  - KM & Nomoto 2003; Tominaga, KM+, Umeda+ 2007; Tominaga 2009

20(?)-100$M_\odot$: Fe CC "Hypernovae"

- 8-10$M_\odot$
- 10 - 20(?)$M_\odot$
- 20(?) -100$M_\odot$
- 100 – 300$M_\odot$
- >300$M_\odot$
- White Dwarf$_\odot$

From Supernovae to Hypernovae.

20(?)-100$M_\odot$: Fe CC

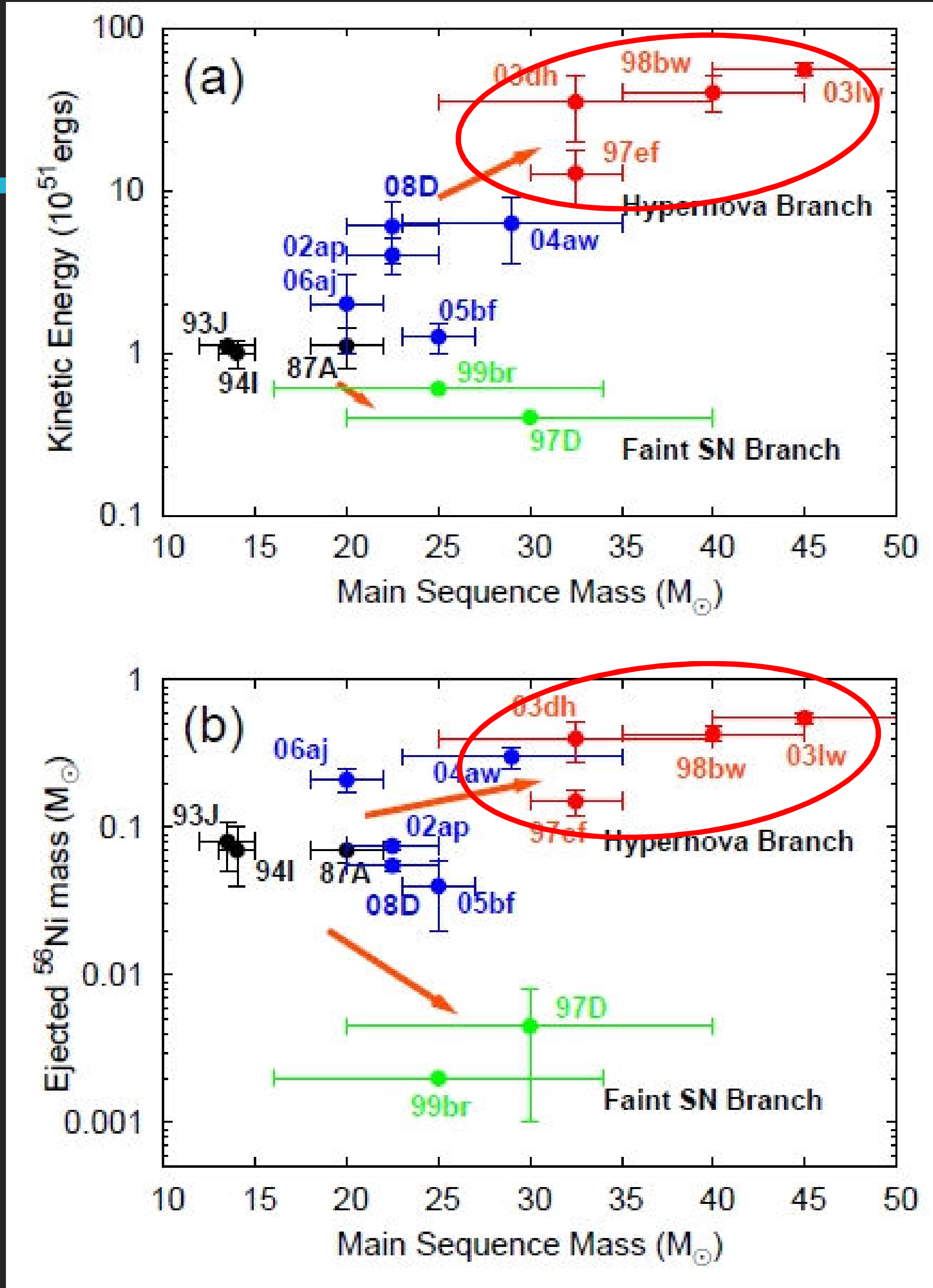
- "Traditional" idea:
  - M_{ms} > 20-30$M_\odot$ → **BH, No SN.**
- **New Observations:**
  - They **do explode**.
  - Energetic – **"Hypernovae"**
  - Sometimes w/ GRBs.

"Observational"

E_K and $M(^{56}Ni)$ vs. M_{ms} →

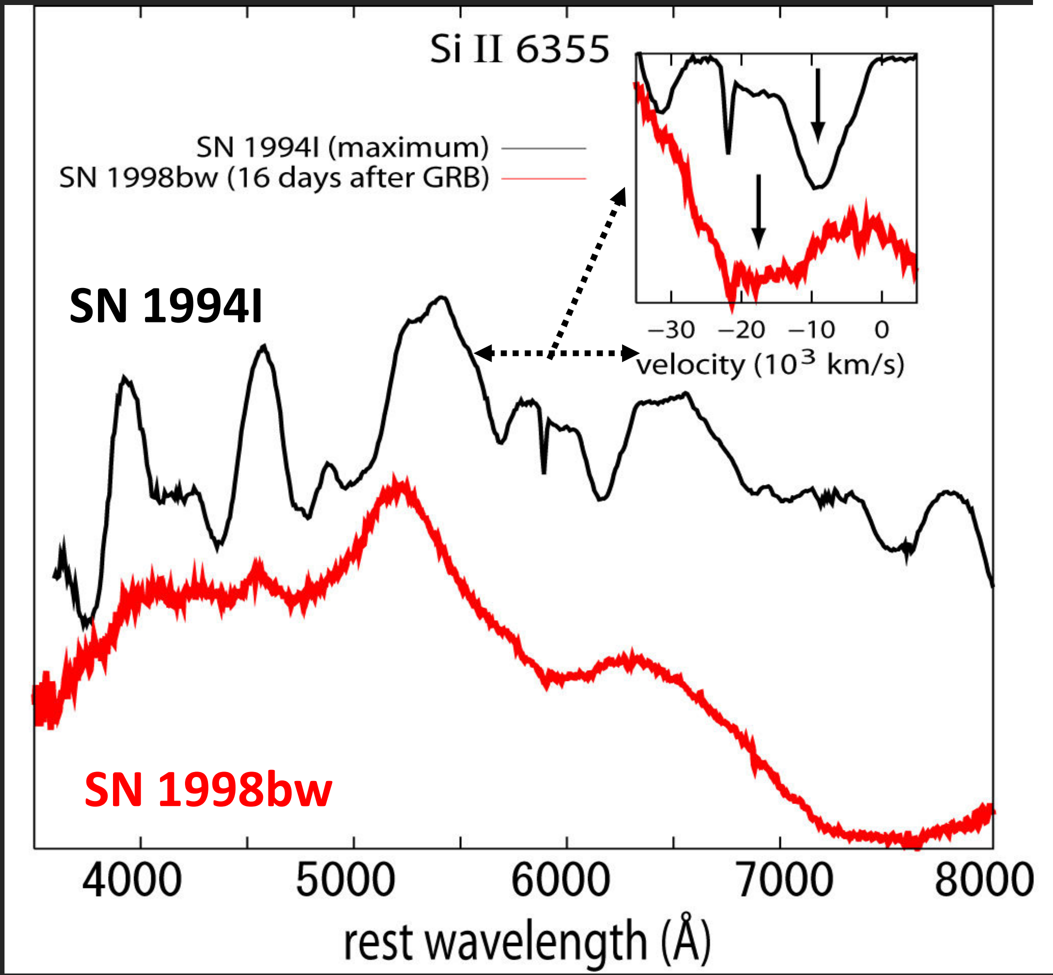
M_{ej} derived by modeling obs.

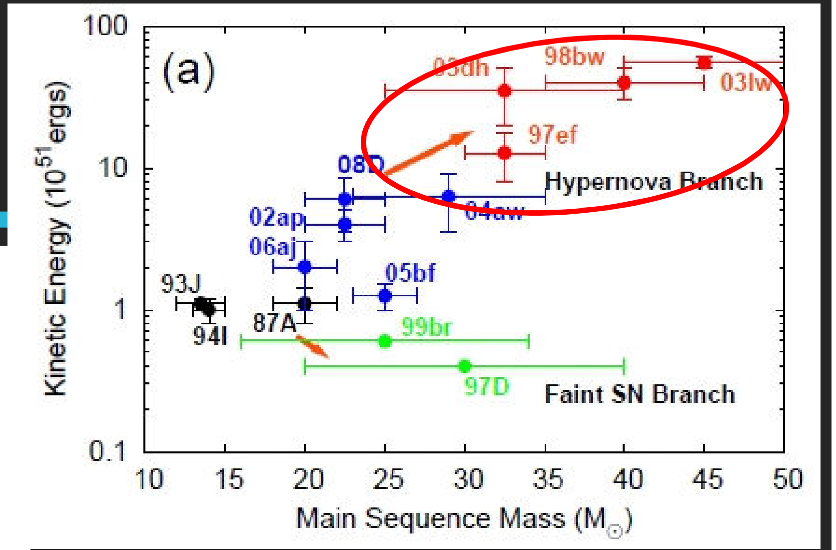
M_{ej}→M_{ms} assumes evo. Model.

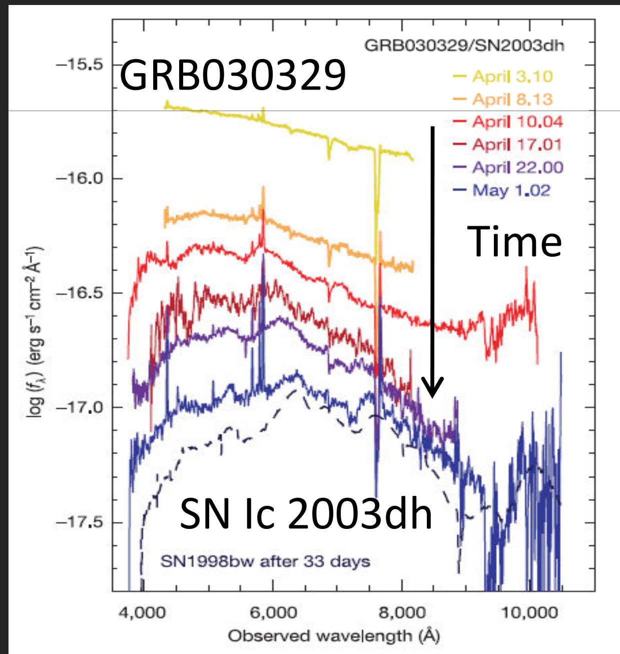


Iwamoto+ 1998

Hypernovae







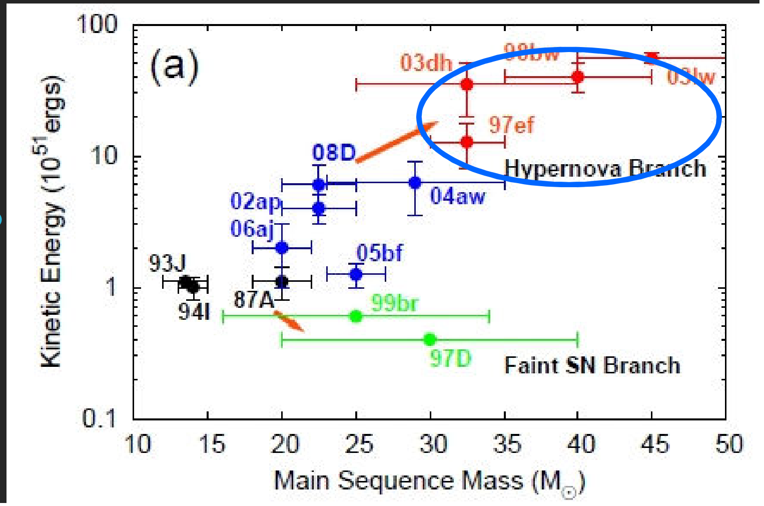
Line Width $\propto E_K^{1/2} Mej^{-1/2}$

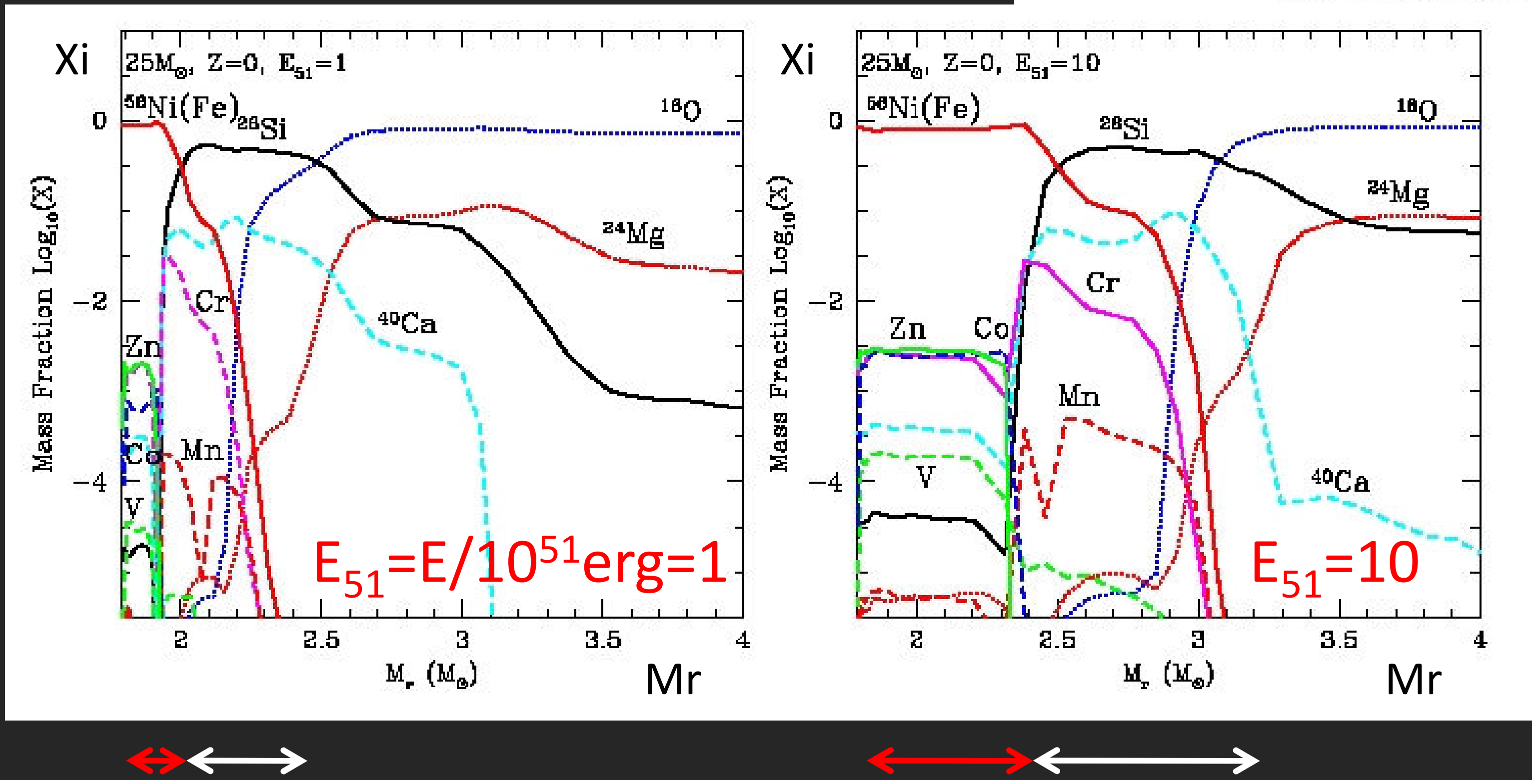
- Some w/ GRBs.

Galama+ 1998; Hjorth+2003; Stanek+2003

Hypernova Nucl. syn.

- Larger E_K
  - Larger amount of Fe-peak and IME.



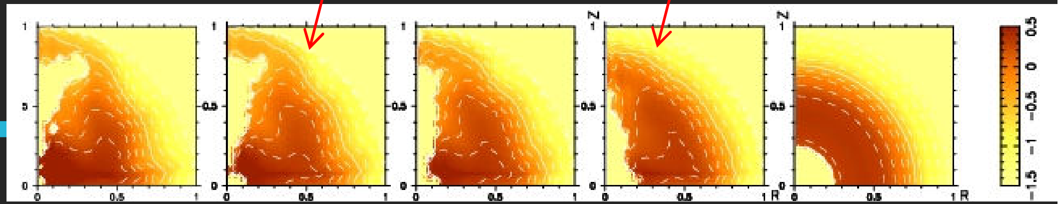


Fe-peak IME (Si, Ca...)

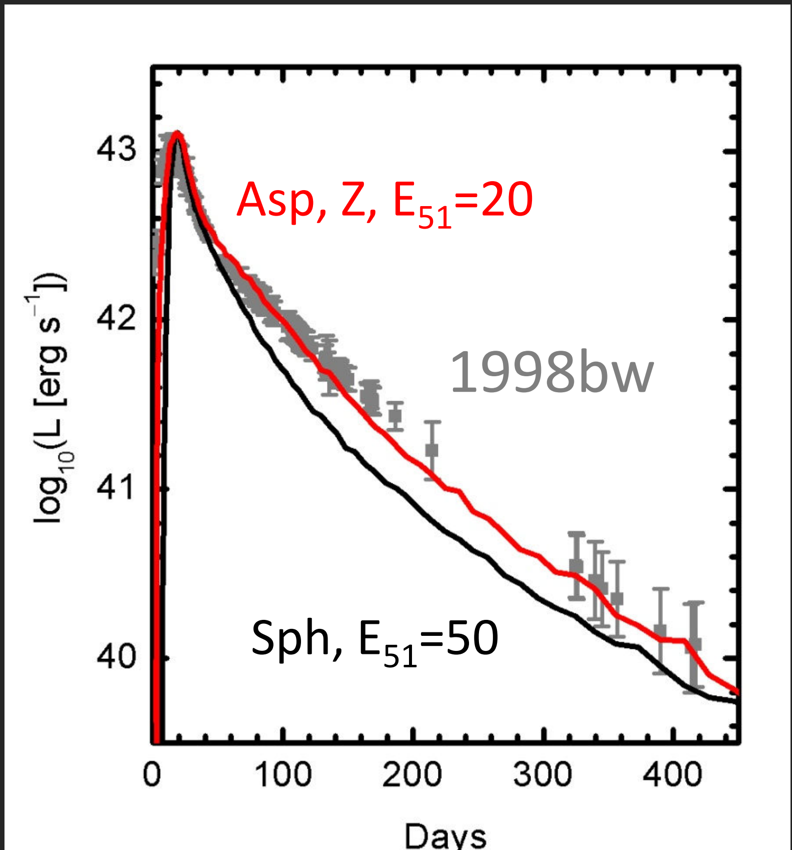
Nakamura+01, Umeda+02

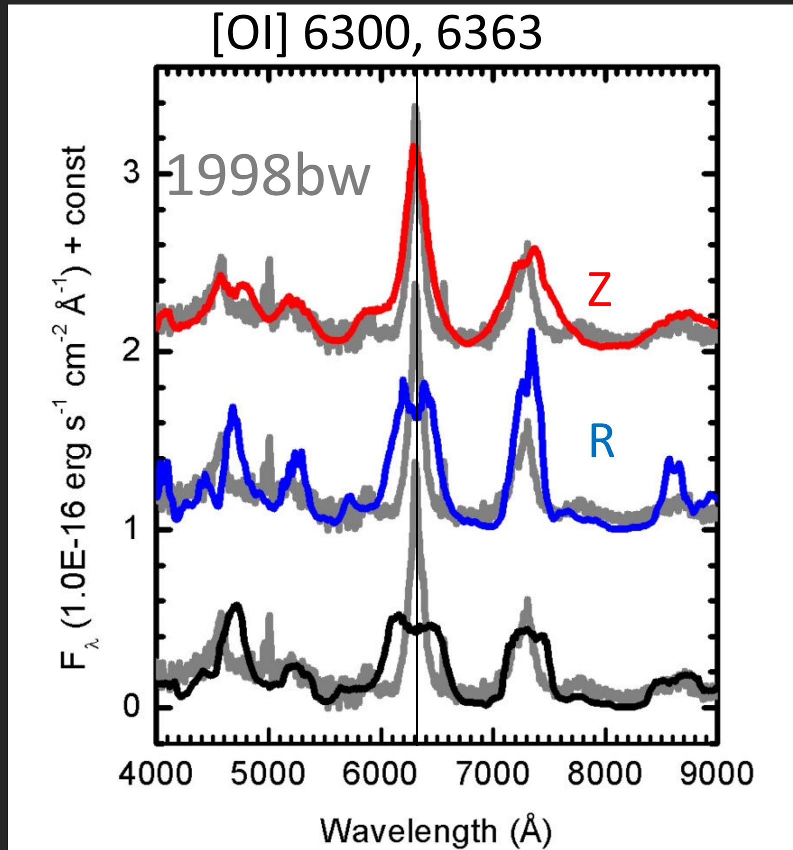
Asymmetry again

SN 1998bw   Typical SN



KM+, 2006ab





30°

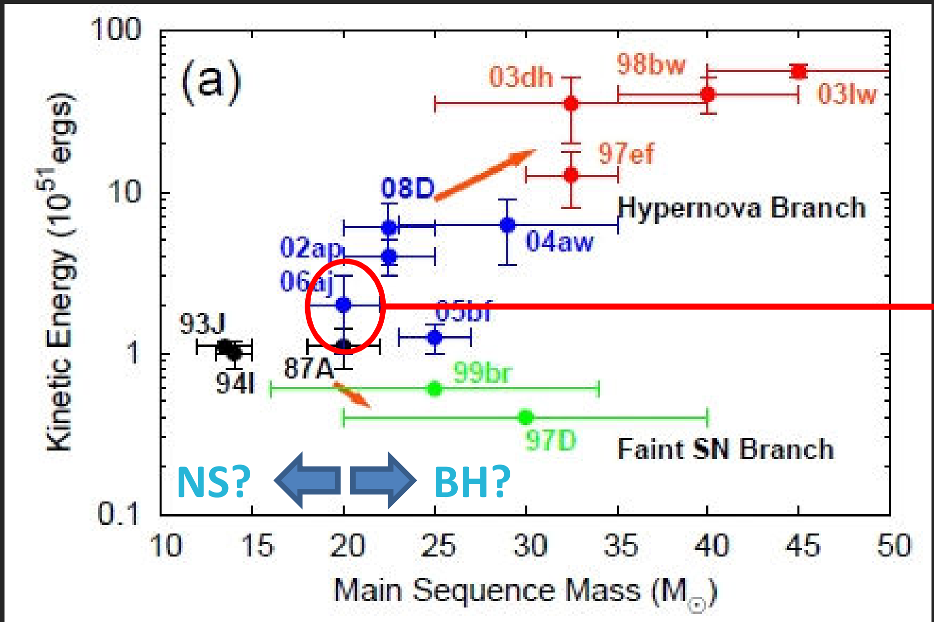
- Hypernovae seem to have **larger asphericity** than others.
  - Both **"Energy" & "asphericity"** important in nucleosynthesis.

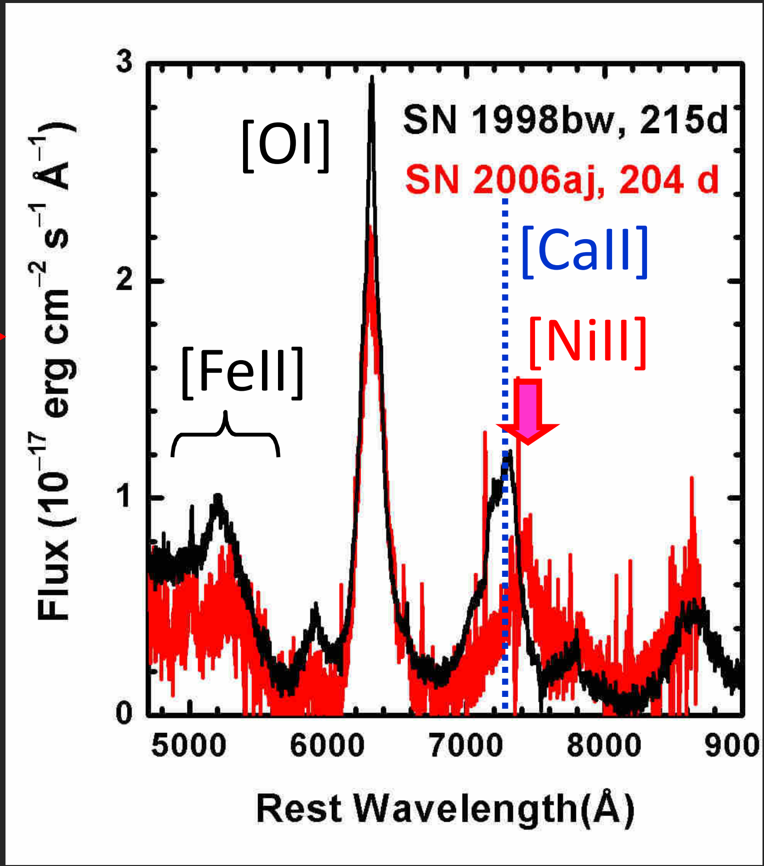
Theory… e.g., Fryer+ 1999

NS or BH?

KM+, 2007, ApJ, 658, L5

- Important functions in nucleosynthesis.
  - Energy, asphericity, **“mass cut”** vs. M_{ms}.





Transition at ~20$M_\odot$? SN 2006aj.

M(^{58}Ni) ~ 0.05$M_\odot$

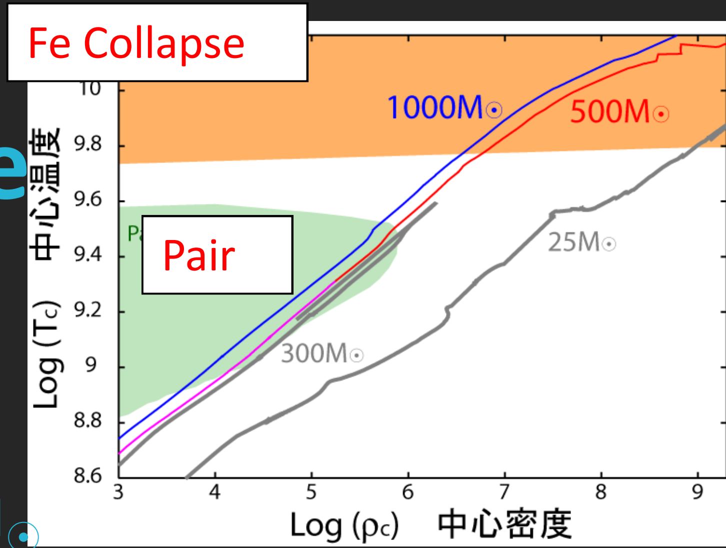
n-rich⇒**NS formation**(?)

> $100M_\odot$: PISN and beyond

- $8\text{-}10M_\odot$
- $10 - 20(?)M_\odot$
- $20(?) -100M_\odot$
- $100 – 300M_\odot$
- $>300M_\odot$
- White Dwarf

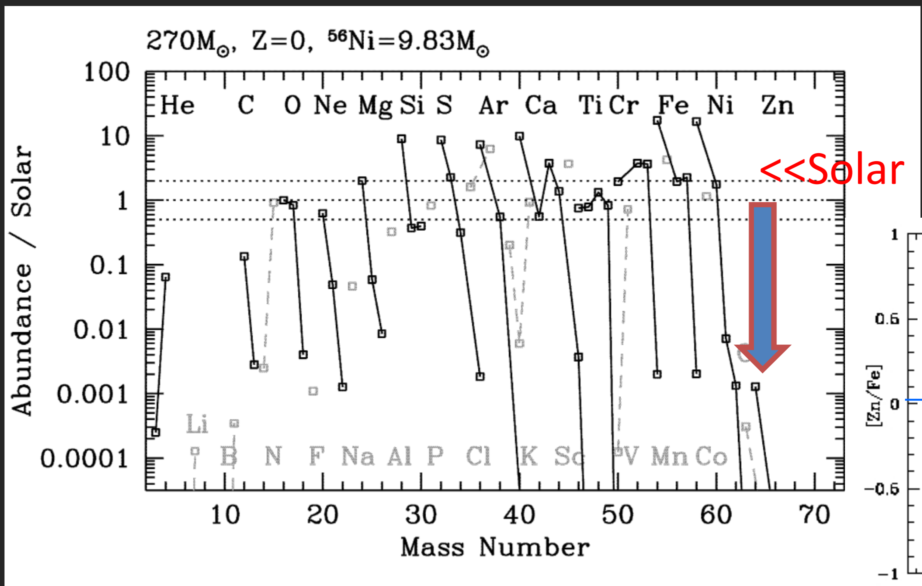
100-300$M_\odot$: Pair Inst. SNe

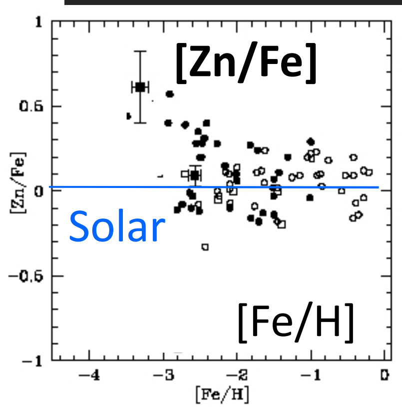
- Radiation dominated: $P \propto \rho^{\gamma} = \rho^{4/3}$
- e- e+ creation→Γ<4/3, Collapse
  →O-burn runway→$M(^{56}Ni)$ = 0.05 – 30$M_\odot$



No Indication
- Metal Poor Stars (Early Universe)
- Nearby SNe (Present Universe)?

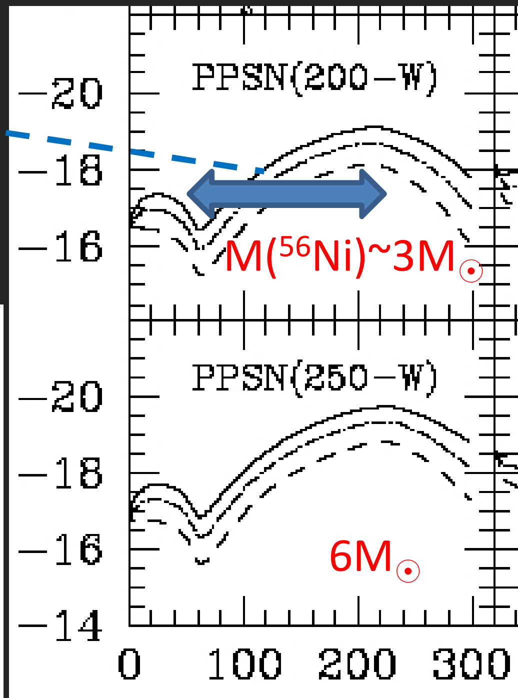
Umeda & Nomoto 2002





Scannapieco+ 2005

~200day!



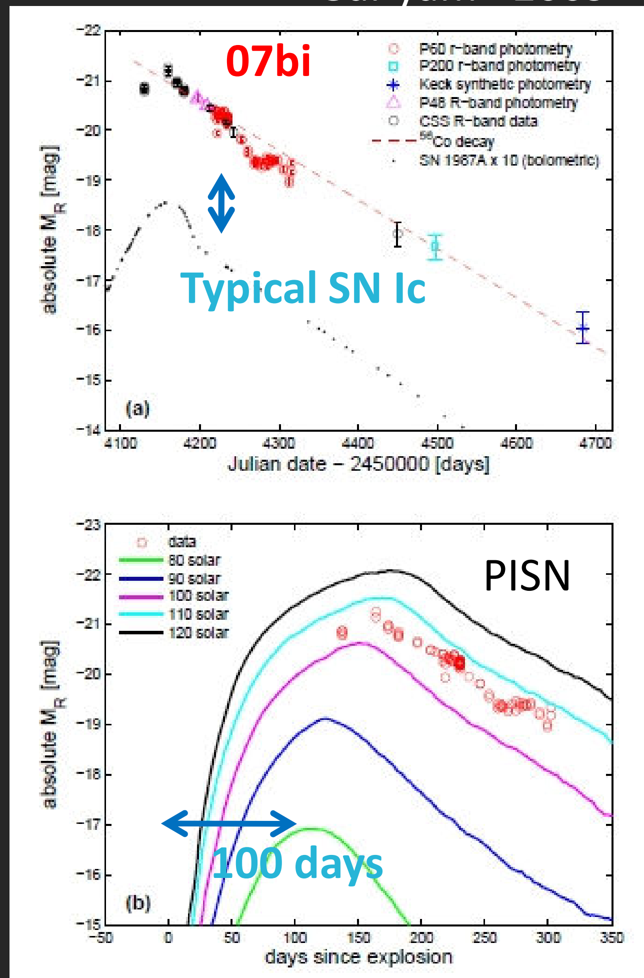
PISN – Observational counterpart?

- SN Ic 2007bi = bright + ^{56}Ni/Co/Fe heating.
  - $M_{ej} > 40M_{\odot}$, $M(^{56}Ni) > 6M_{\odot}$.
  - Cons. w/ PISN. Gal-yam+ 2009

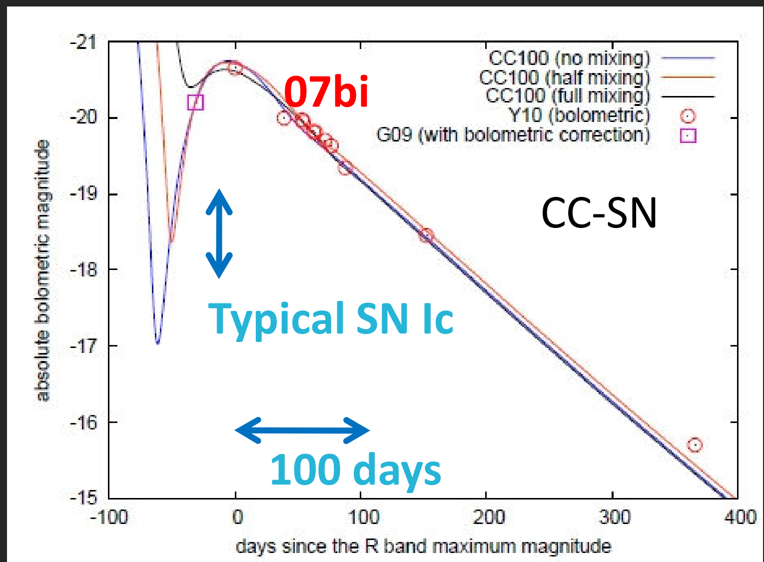
⇕ **Not** conclusive yet.

- CC-SN w/ M_{ms} ~ $100M_{\odot}$.

Gal-yam+ 2009

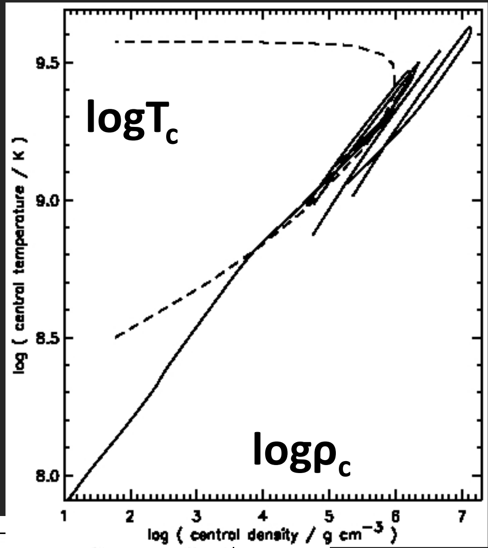


Moriya, Tominaga, Tanaka+ 2010b

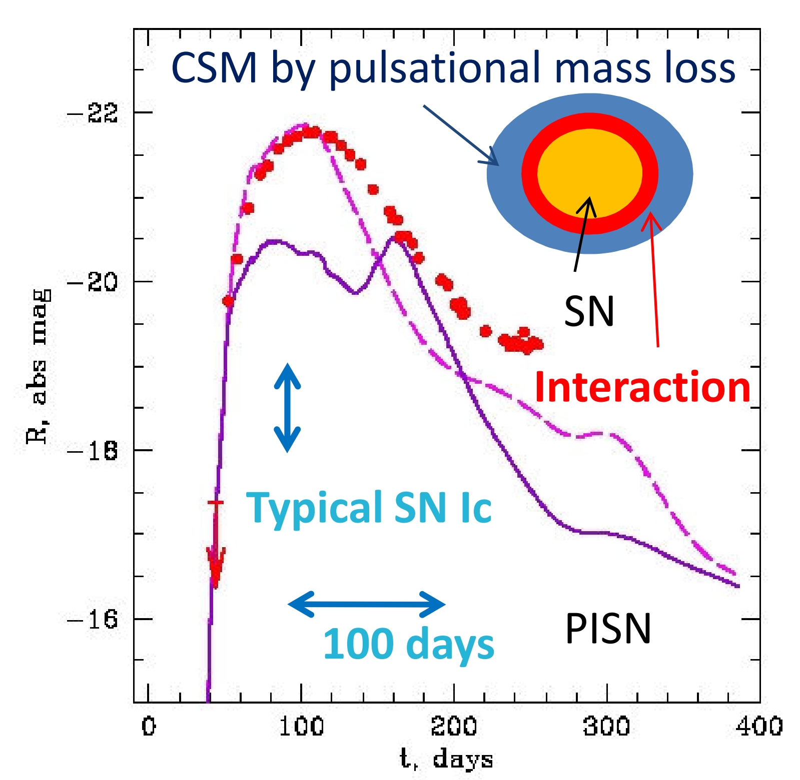


Another candidate for a PISN?

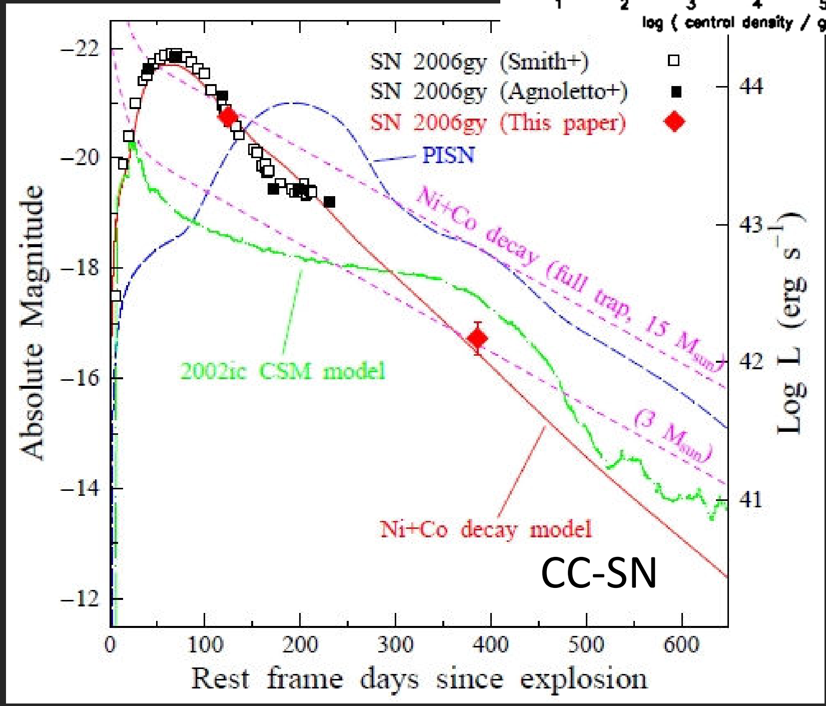
- SN IIn 2006gy = bright + interacting.



Not conclusive yet.



Pul. PISN Model (Interaction w/ wind)
Woosley, Blinnikov, Heger, 07



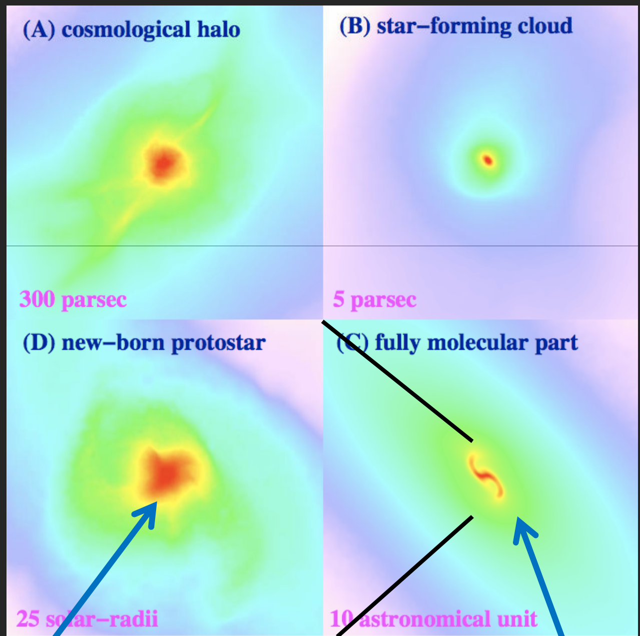
Core-Collapse Model
(^{56}Ni heating) Kawabata+ 2009

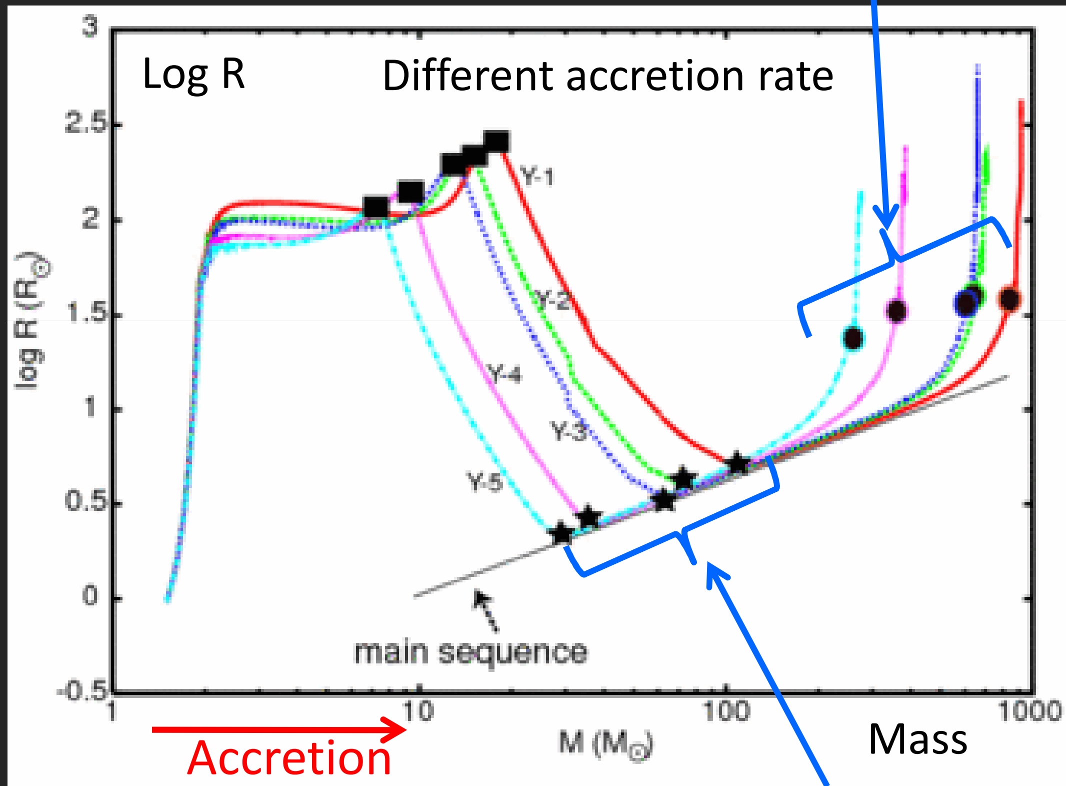
> 300$M_\odot$: Fe Core-collapse

~ 300 – 1000$M_\odot$ at leaving MS

Ohkubo+, 2009

Yoshida+, 2008





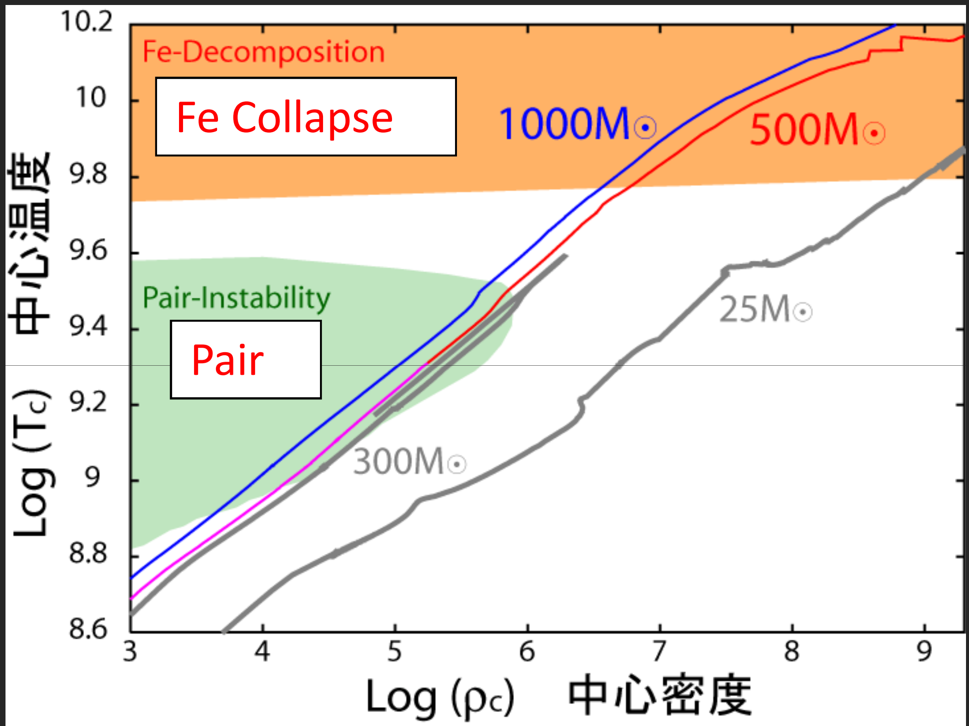
Proto-star core ~ $10^{-2}M_\odot$

~ 30 – 100$M_\odot$ at ZAMS

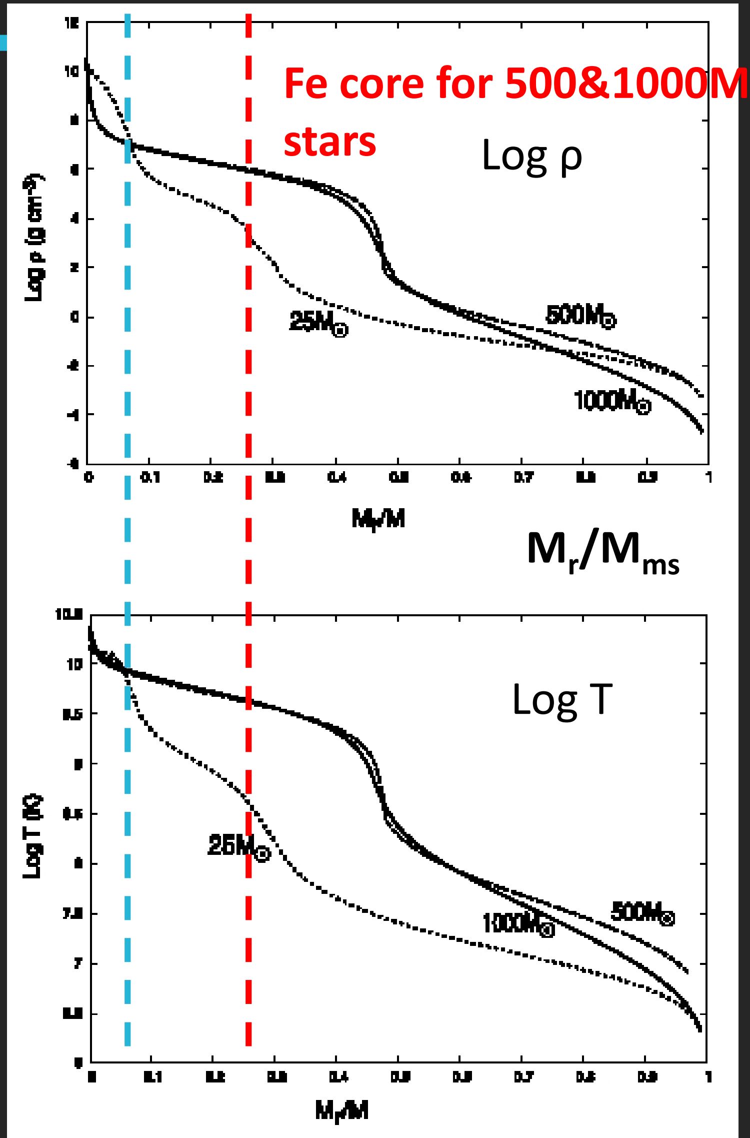
Primordial cloud ~ 10^3 - $10^5M_\odot$

High Accretion Rate (>$10^{-3}M_\odot$/year) … Only for “Zero” Metal

> 300M$_\odot$: Fe CC



Fe core for 25M star

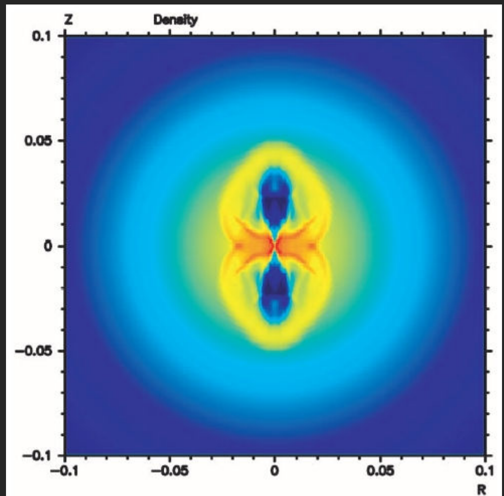


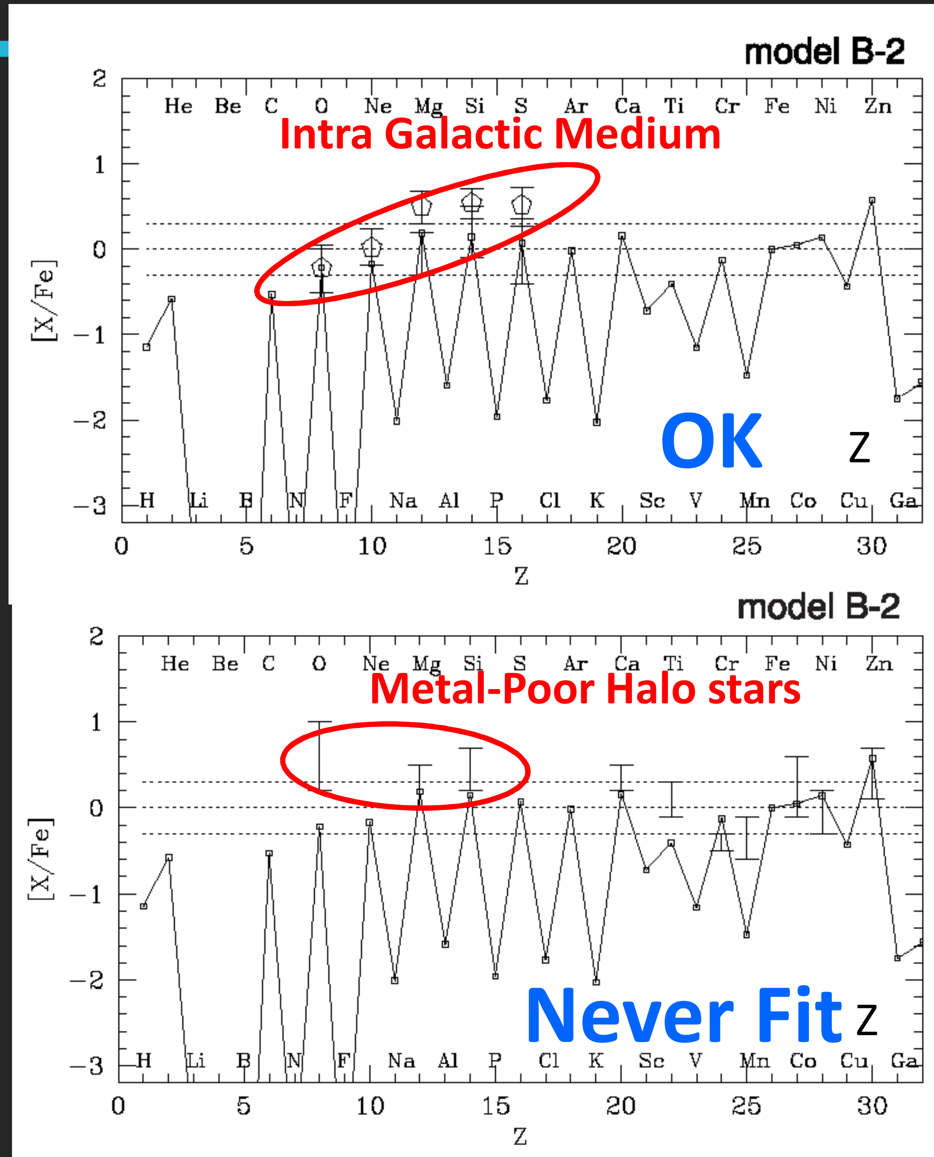
t~2 10^6 yr ~ 10-30% of M$_{ms}$~13 – 25M$_\odot$

Ohkubo, Umeda, KM+, 2006, ApJ, 645, 1352

Hypothesized exp.

[X/Fe] Ohkubo+ 2006





- $M(^{56}Ni)=5M_\odot$
- $M(Si)=4M_\odot$
- $M(O)=24M_\odot$
- $M(He)=280M_\odot$
- $M(H)=190M_\odot$
- $M_{BH}=480M_\odot$

Nucleosynthesis ← E, Geometry → M(BH)

Atomic Number

Thermonuclear SNe (Type Ia)

- 8-10$M_\odot$
- 10 - 20(?)$M_\odot$
- 20(?) -100$M_\odot$
- 100 – 300$M_\odot$
- >300$M_\odot$
- White Dwarf

Type Ia SN = Distance ladder

Thermonuclear SNe (Type Ia)

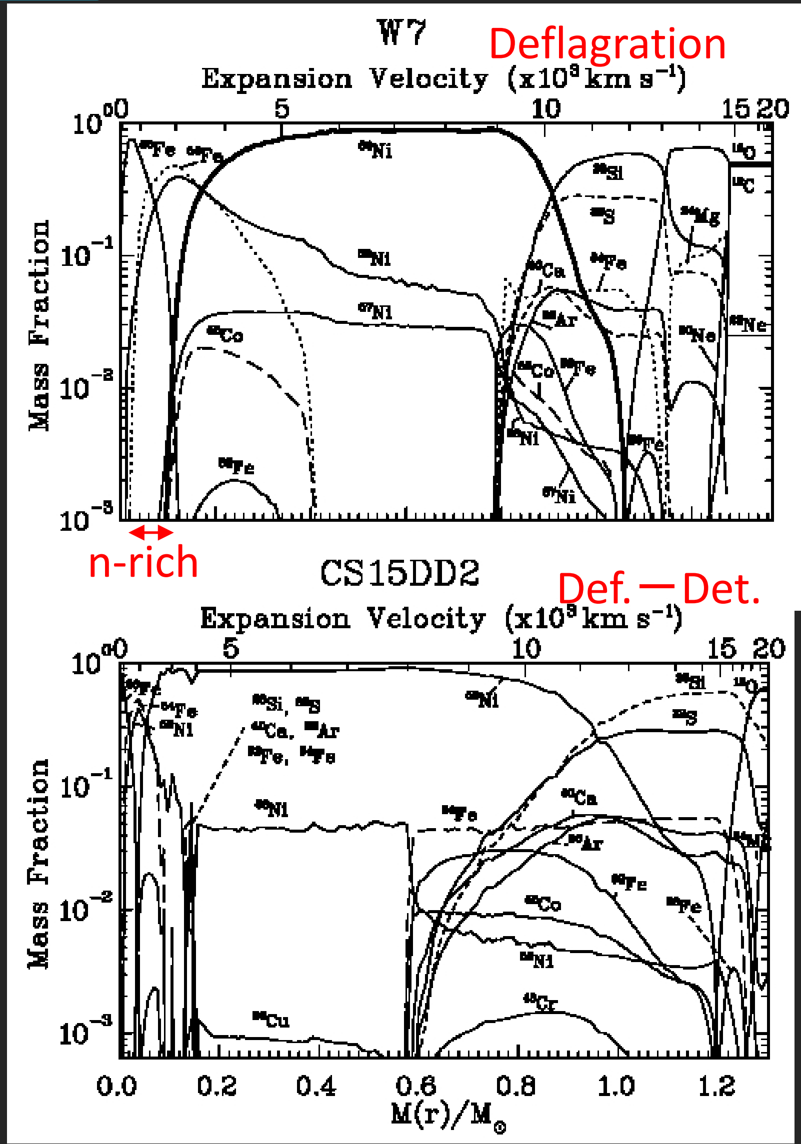
- **Consensus:**
  - **Chandrasekhar-mass white-dwarf** (~$1.4M_\odot$).
  - **Thermonuclear** explosion.
  - **No** central object left.
  - **Fe** producer, typically $M(^{56}Ni) \sim 0.6M_\odot$.
  - **Standard candles** (luminosity estimate possible).

SNe Ia – classical picture

- **Two modes** of flames.
  - **Deflagration** (subsonic).
  - **Detonation** (supersonic).
- Favored scenarios:
  - **Pure deflagration.**
    - e-capture.
      - n-rich stable Fe-peak.

        W7 by Nomoto+ 1984
  - **Delayed det. (Def. →det.).**
    - Little e-capture (Ye = const.).
      - ^{56}Ni/stable-Fe set by progenitor.
    - C, O-burning outside.

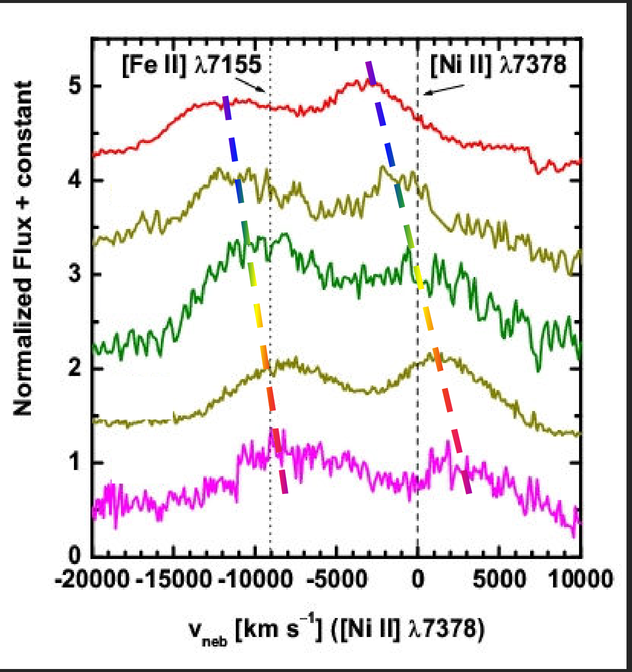
      Khokhlow 1991; Iwamoto+ 99



KM, Taubenberger, Sollerman+ 2010, ApJ, 708, 1703

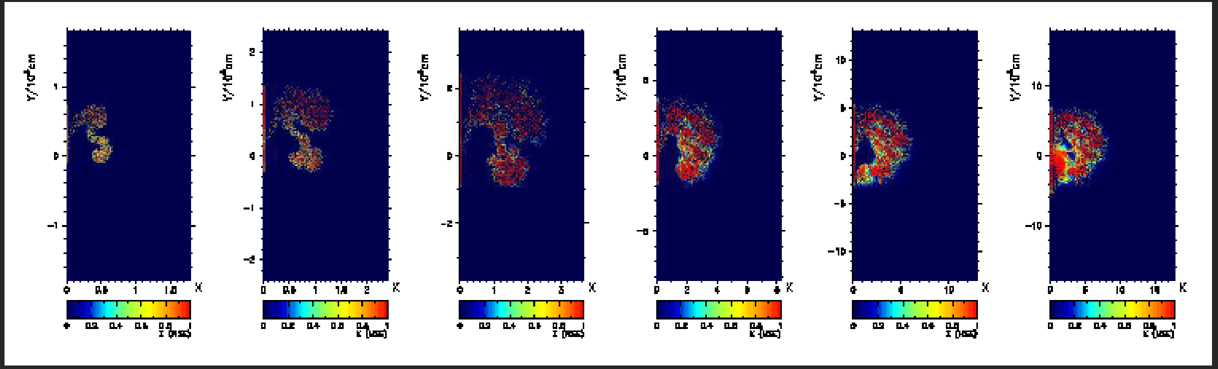
Asymmetry

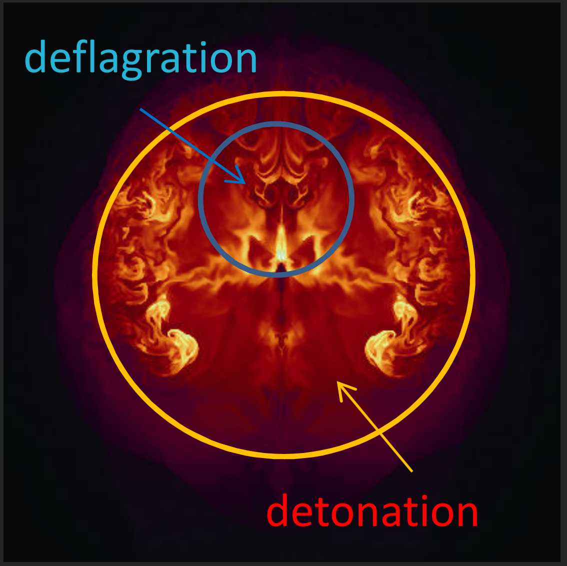
- **“Off-set”** ignition.
    - Doppler shifts in late-phases.
    - Solves “unresolved” spectral diversity.



Fe-peak elements

Deflagration → Detonation →





time →

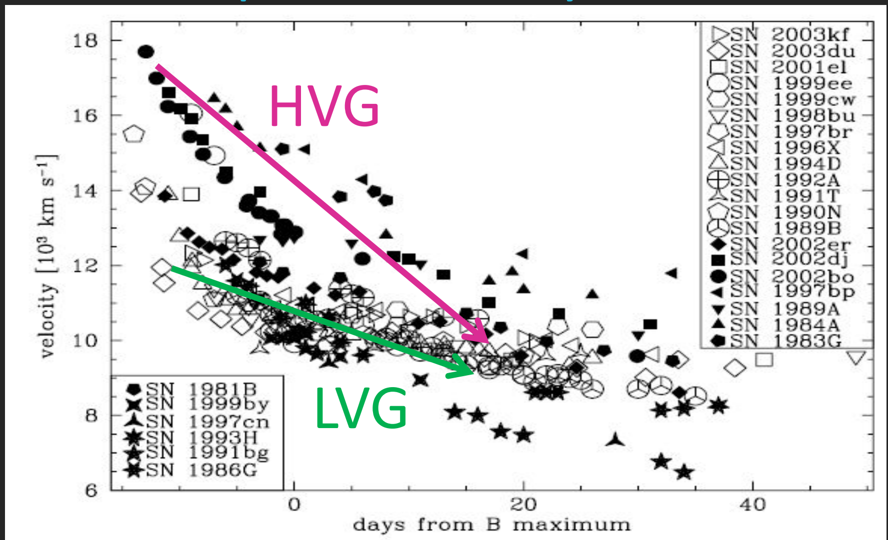
KM, Roepke, Fink+ 2010, ApJ, 712, 624 (cf. Kasen+ 2009)

Asymmetry

- "**Off-set**" ignition.
  - Doppler shifts in late-phases.
  - Solves **"unresolved" spectral diversity.**

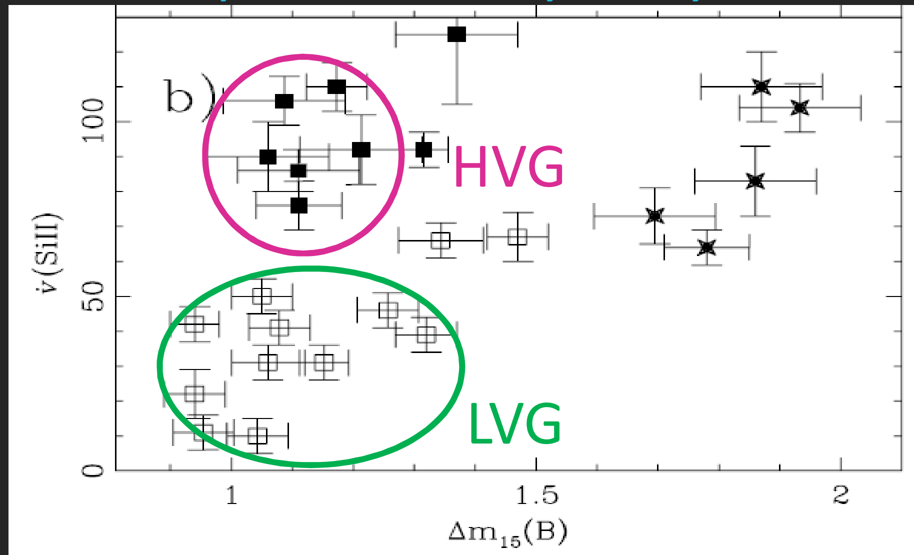
Branch+ 1988; Benetti+ 2005

Si II absorption velocity



Days

Si II absorption velocity / day

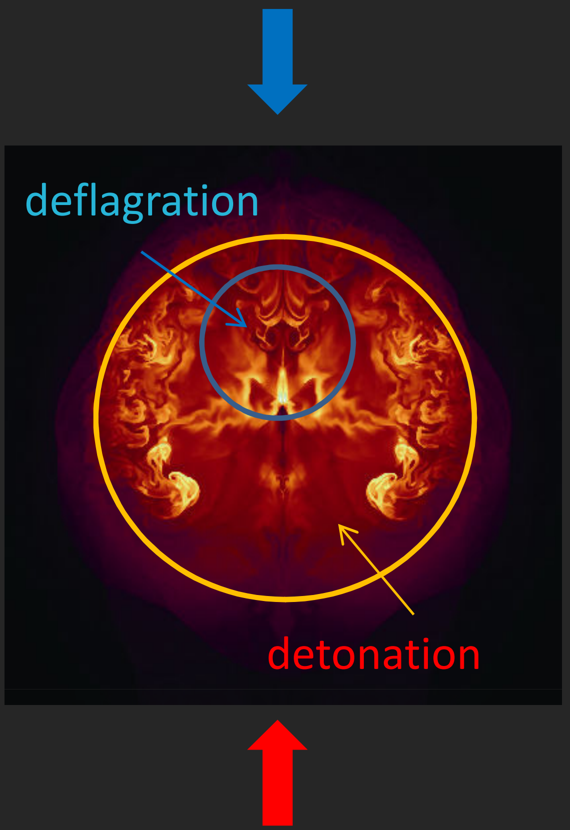


Decline Rate = Luminosity indicator

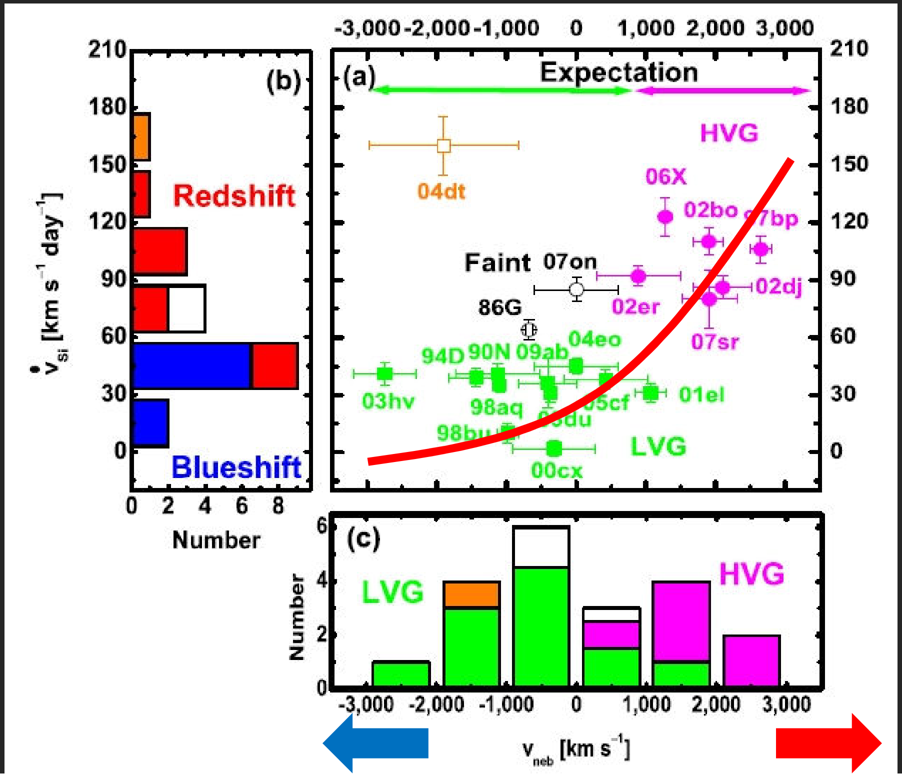
- Spectral evolution do **not correlate** with the "luminosity".

Asymmetry

- "**Off-set**" ignition.
  - Doppler shifts in late-phases.
  - Solves "unresolved" spectral diversity.



Velocity gradient

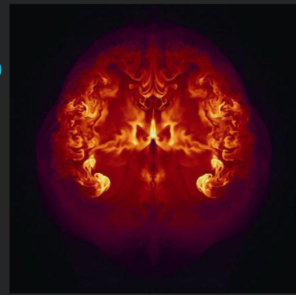


KM, Benetti, Stritzinger+ 2010, Nature, 466, 82

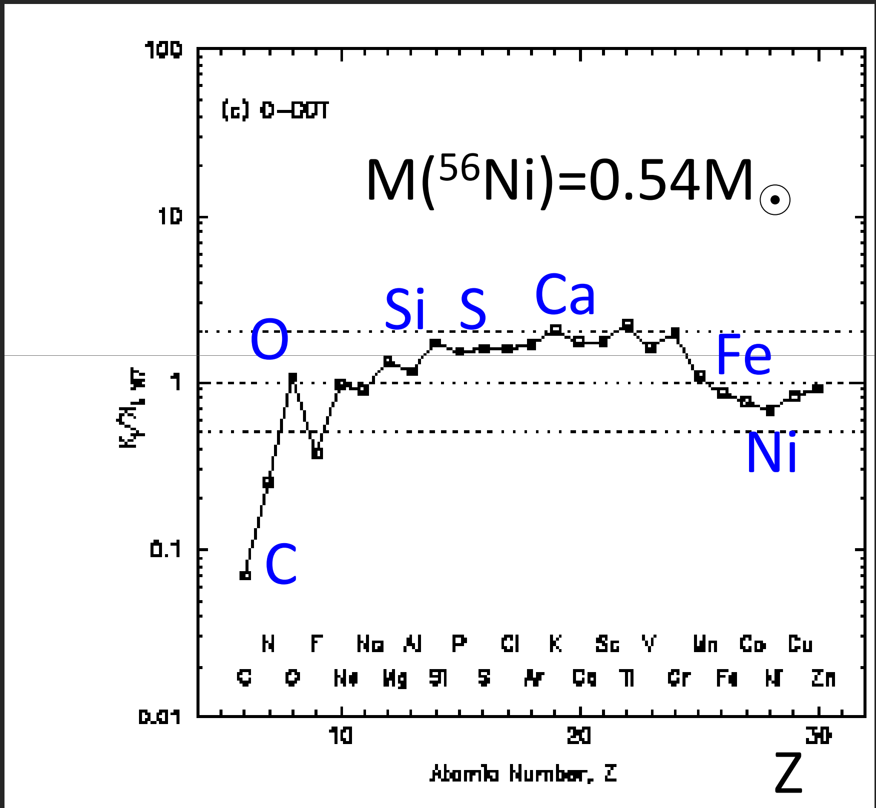
viewing angle (←Doppler shift in late-phases)

KM, Roepke, Fink+ 2010, ApJ, 712, 624 (cf. Kasen+ 2009)

SN Ia Nucleosynthesis: 2D delayed det.



X/X_{W7}: **Normalized** by the classical 1D **W7** model.



- Consistent with 1D W7 within a factor of 2.

Problems in 1D def.

- Low C.
  - C-burning outside.
- Low Ni/Fe (^{58}Ni/^{56}Ni).
  - Strong det. (^{56}Ni) despite weak def. (^{58}Ni) .

- Similar to 1D delayed det. Model, indeed.
  - Differences in details, though (e.g., Ni/Fe ratio ⇔ M(^{56}Ni)).

Summary

Mass ($M_\odot$)	SN	Obs?	E_{51}	Asymmetry	Comp. rem.
8-10	CC	perhaps probably	0.001 ~ 0.1	? ?	BH? NS
10-12	CC	Yes	0.01 - 1	?	NS
12-20(?)	CC	yes	~1	moderate, likely bipolar	NS
20(?)-100	CC	yes	~ 5 - 50	Extreme, likely bipolar	BH?
100-300	PISN	maybe	7 - 80	?	No
WD	Ia	yes	1 - 1.5	One-sided	No

Key quantities in SN Nucleosynthesis