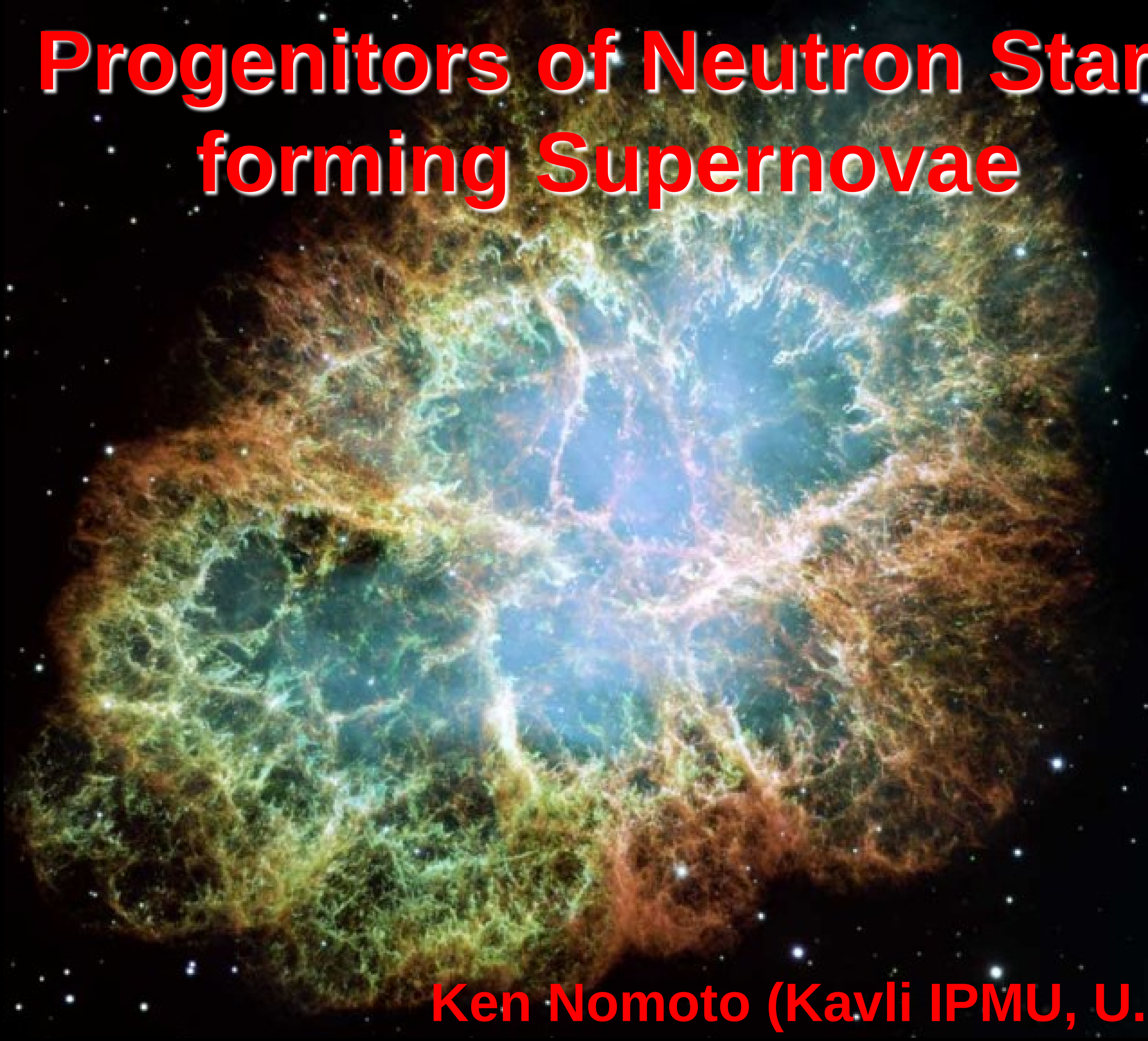
Progenitors of Neutron Star-forming Supernovae

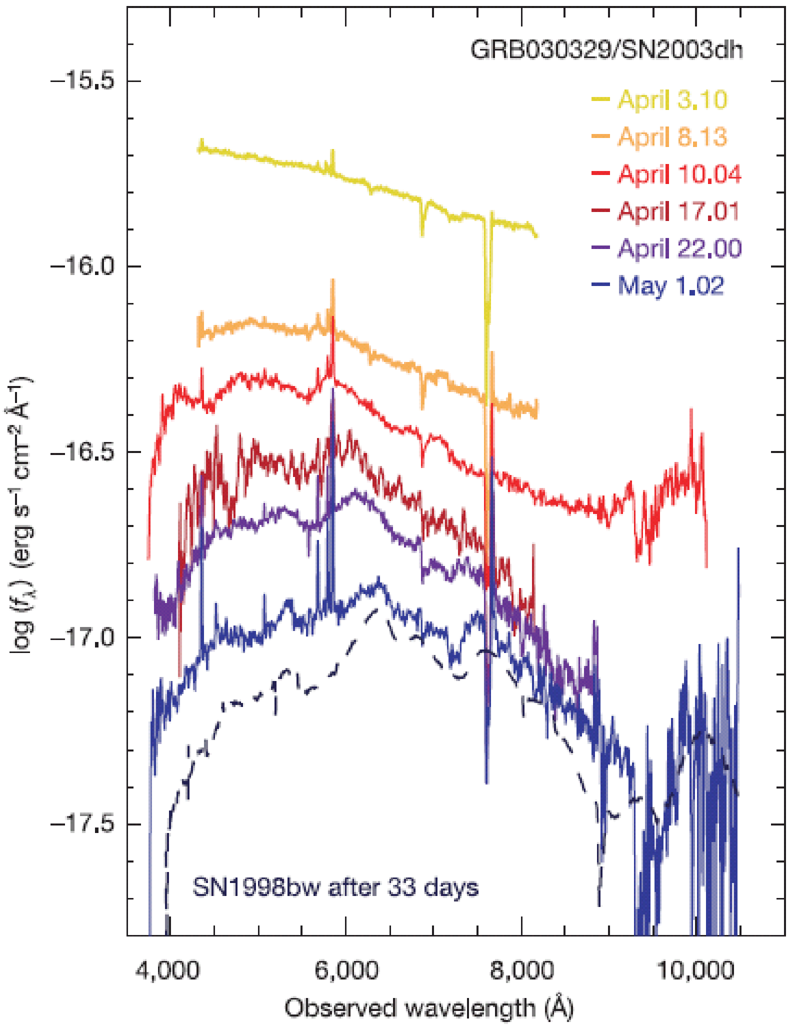


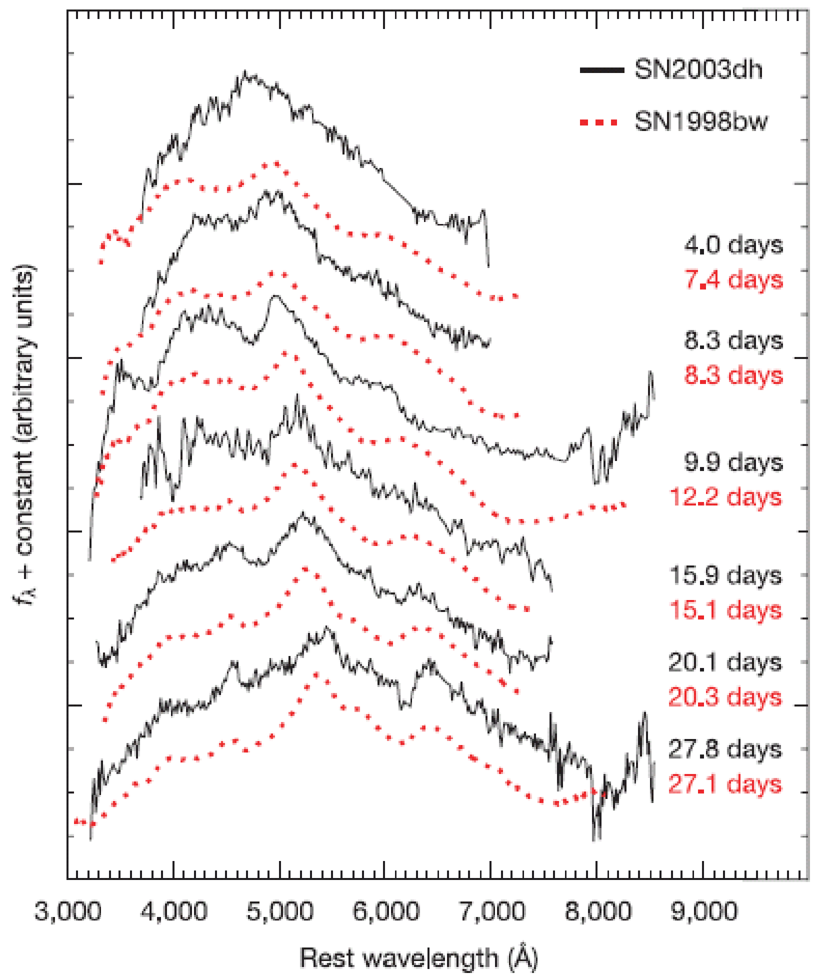
Ken Nomoto (Kavli IPMU, U. Tokyo)

Neutron star-forming supernovae

1) Magnetar-forming supernovae
   - GRB (XRF)-supernovae ?
   - Superluminous supernovae ?
2) Electron capture supernovae
3) Accretion induced collapse (AIC) of white dwarfs

GRB-SN Connection
(GRB 030329 / SN 2003dh)

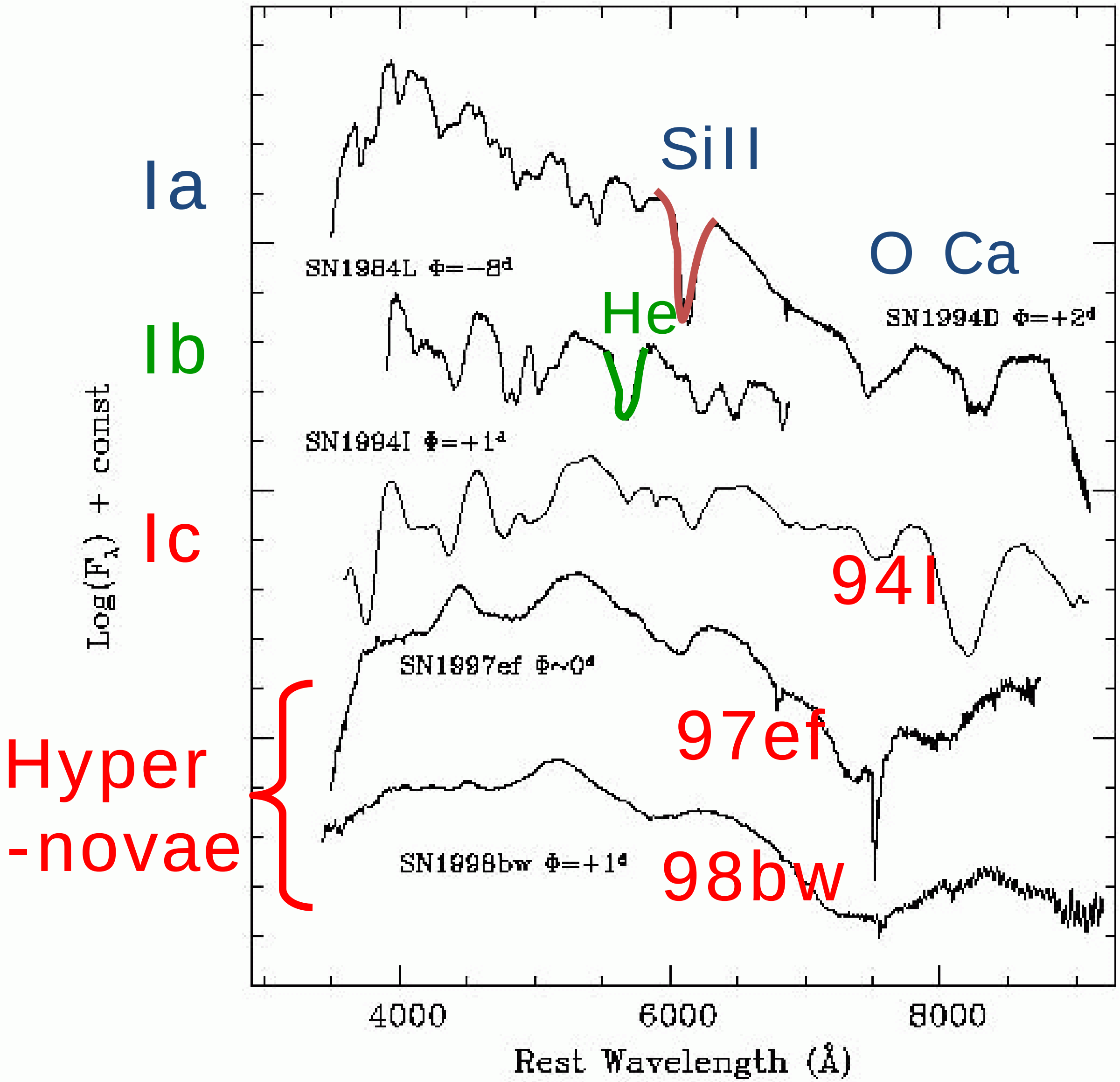




Stanek et al (2003) ;Hjorth et al (2003)

Broad Lines!

Spectraf Supernovae & Hypernovae



Ic: no H,

no strong He,

no strong Si

Hypernovae:

broad features

↑

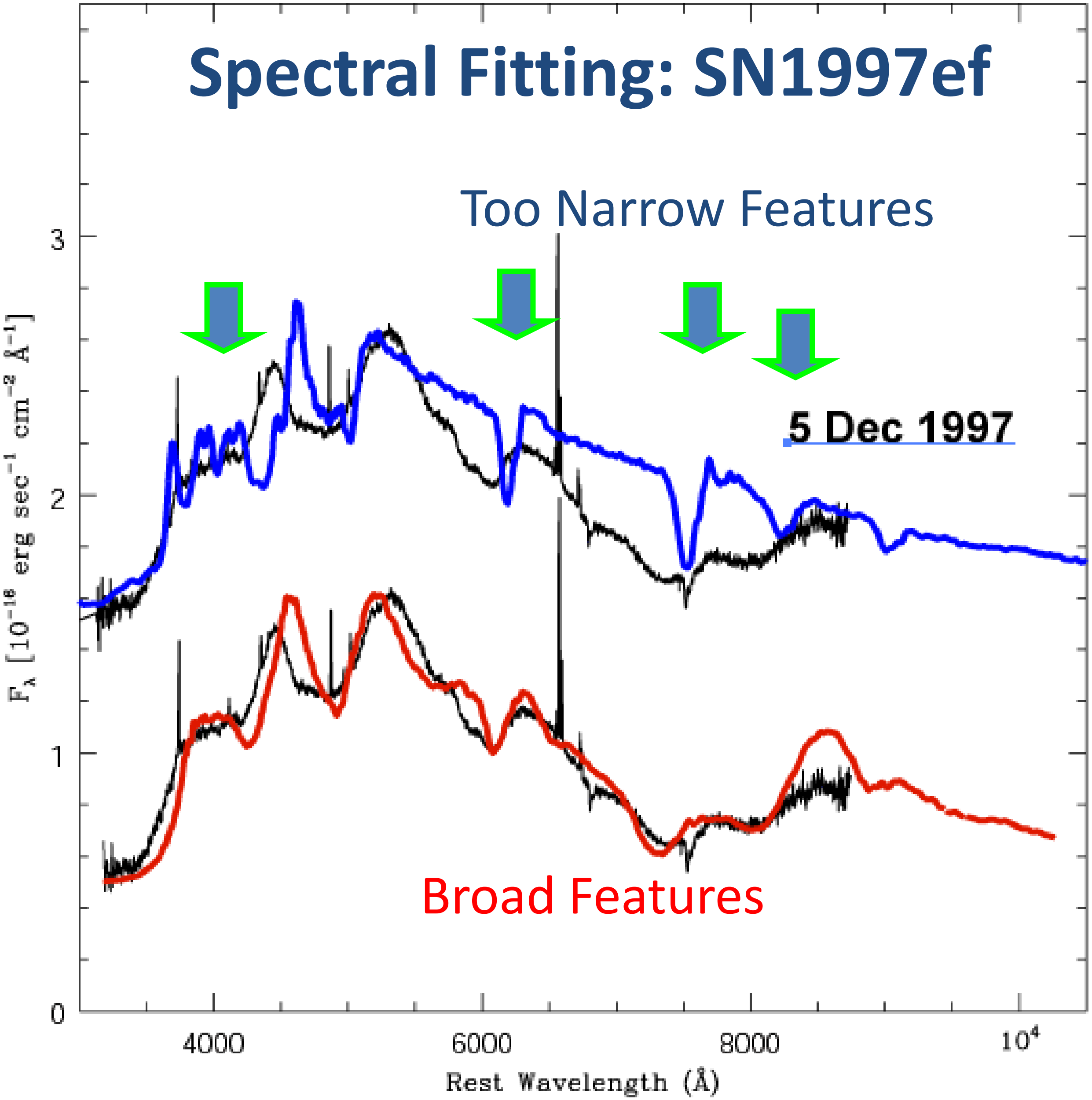
blended lines

↑

"Large mass at high velocities"

Patat et al. (1999)

Spectral Fitting: SN1997ef

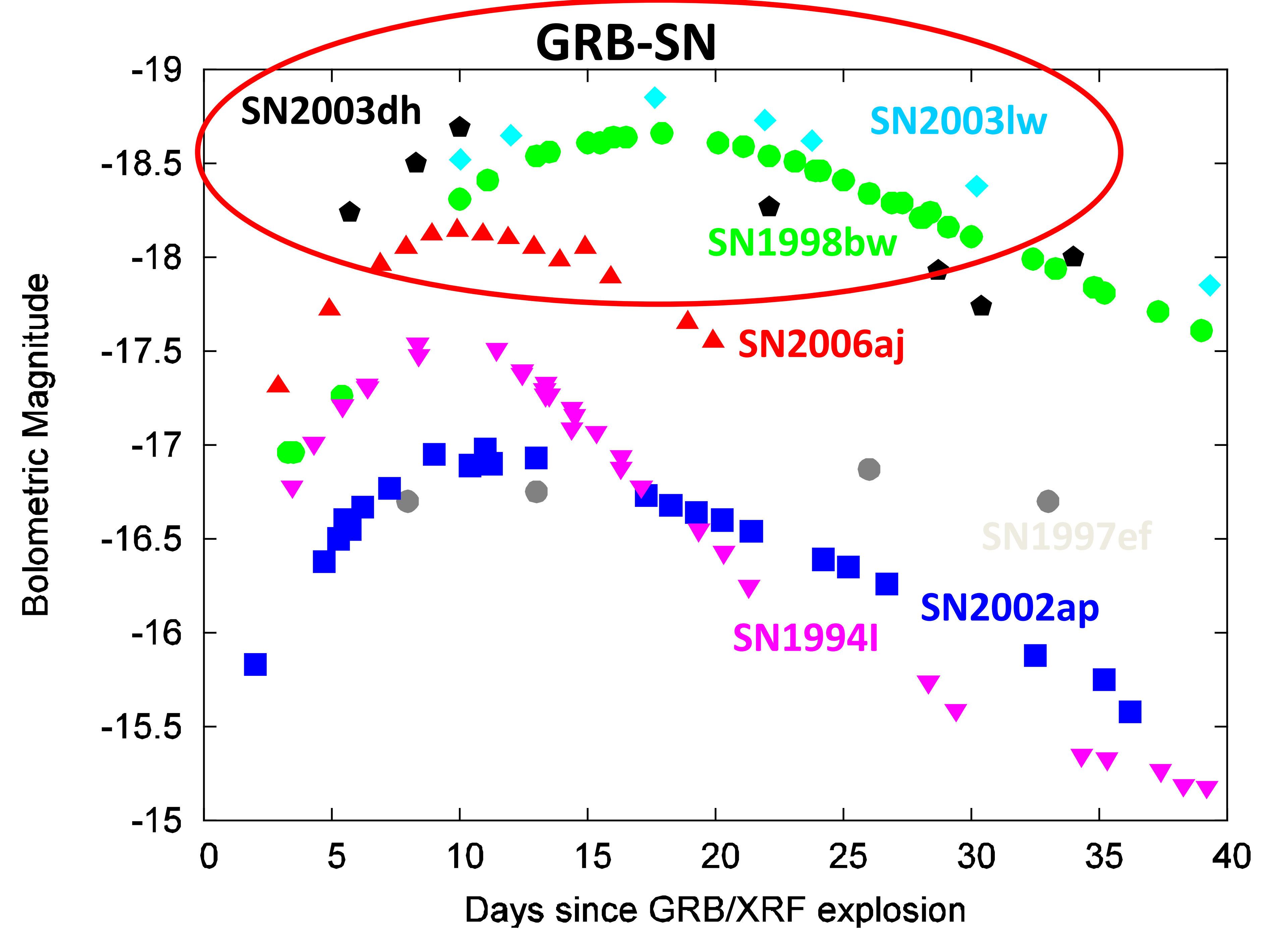


Iwamoto et al. (2000)

$E_{51}=E/10^{51}$ erg

Normal SN
($E_{51}=1$)
Small M_{ej}

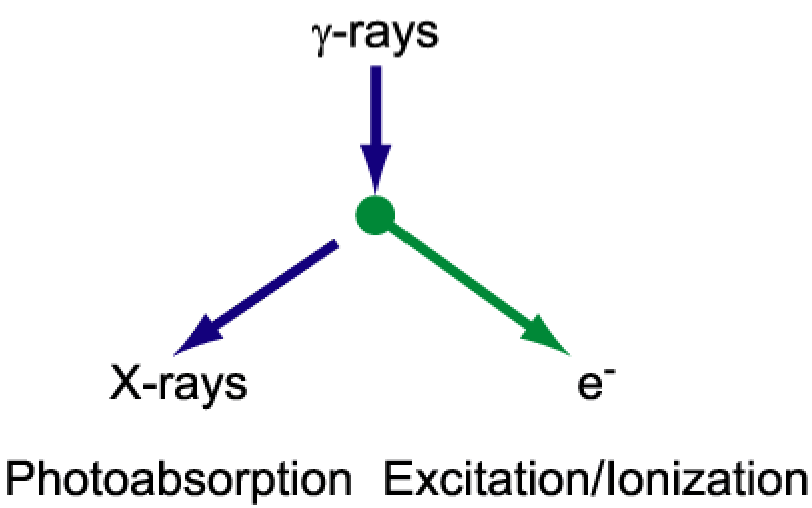
Hypernova
($E_{51}=20$)
Large M_{ej} at High Vel.



GRB-SN
SN2003dh
SN2003lw
SN1998bw
SN2006aj
SN1997ef
SN2002ap
SN1994I
Bolometric Magnitude
-19
-18.5
-18
-17.5
-17
-16.5
-16
-15.5
-15
0
5
10
15
20
25
30
35
40
Days since GRB/XRF explosion

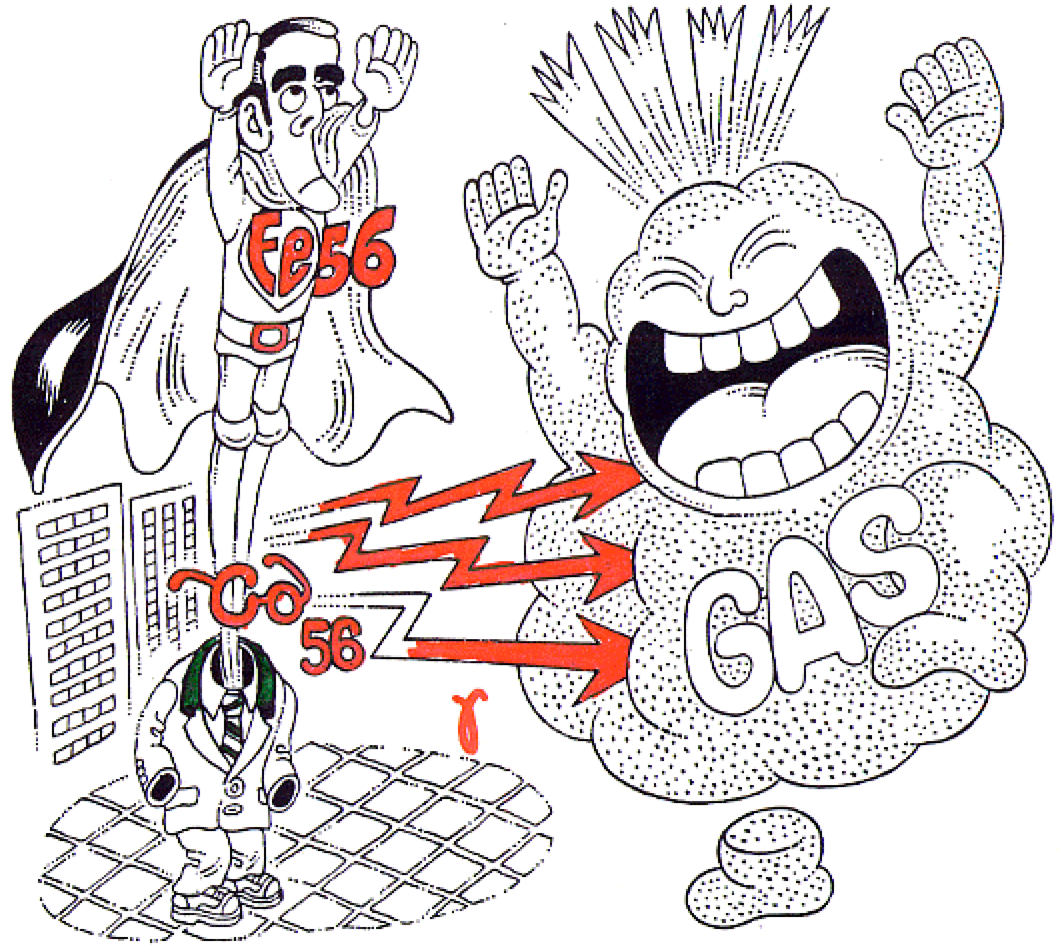
^{56}Co-decay

$$^{56}\mathrm{Ni} \xrightarrow[6.6\mathrm{d}]{\gamma} {}^{56}\mathrm{Co} \xrightarrow[78\mathrm{d}]{\gamma} {}^{56}\mathrm{Fe}$$

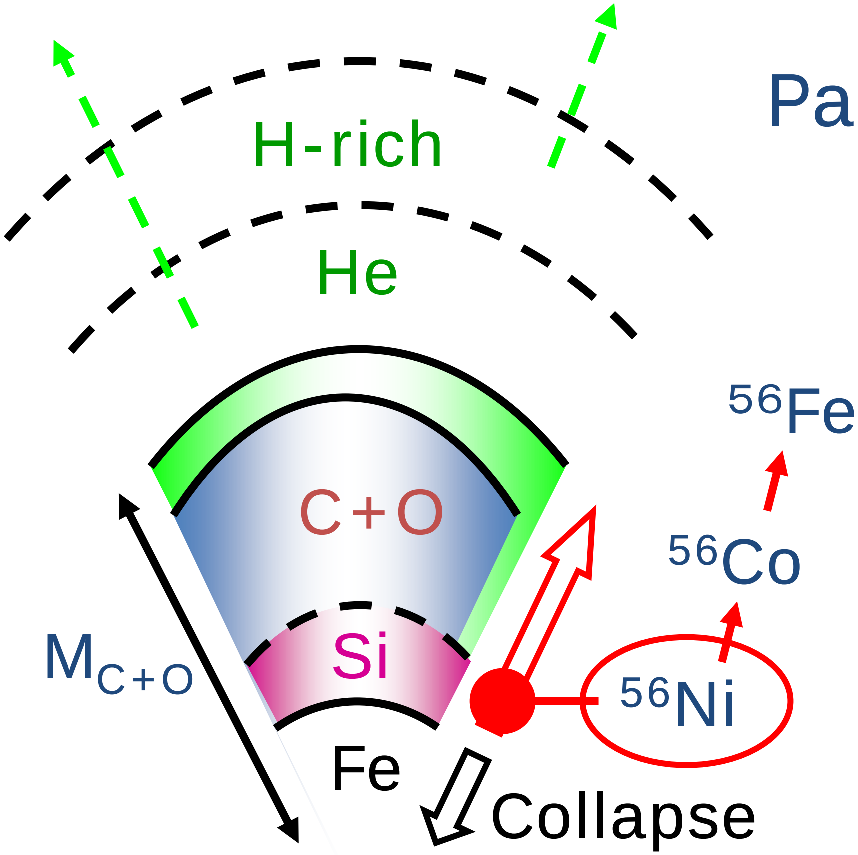


$L \propto M(^{56}\mathrm{Ni})$

Shape: M_{ej}



CO Star Models for SNe Ic



$M_{ms}/M_\odot$	$M_{C+O}/M_\odot$
~ 40	13.8
~ 35	11.0
~ 22	5.0

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

Light Curve | Spectra

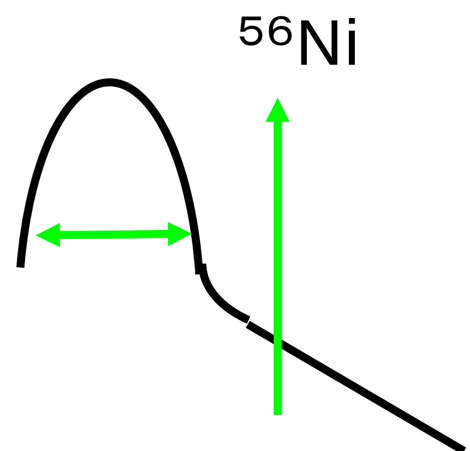
$E \propto M_{ej}$

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

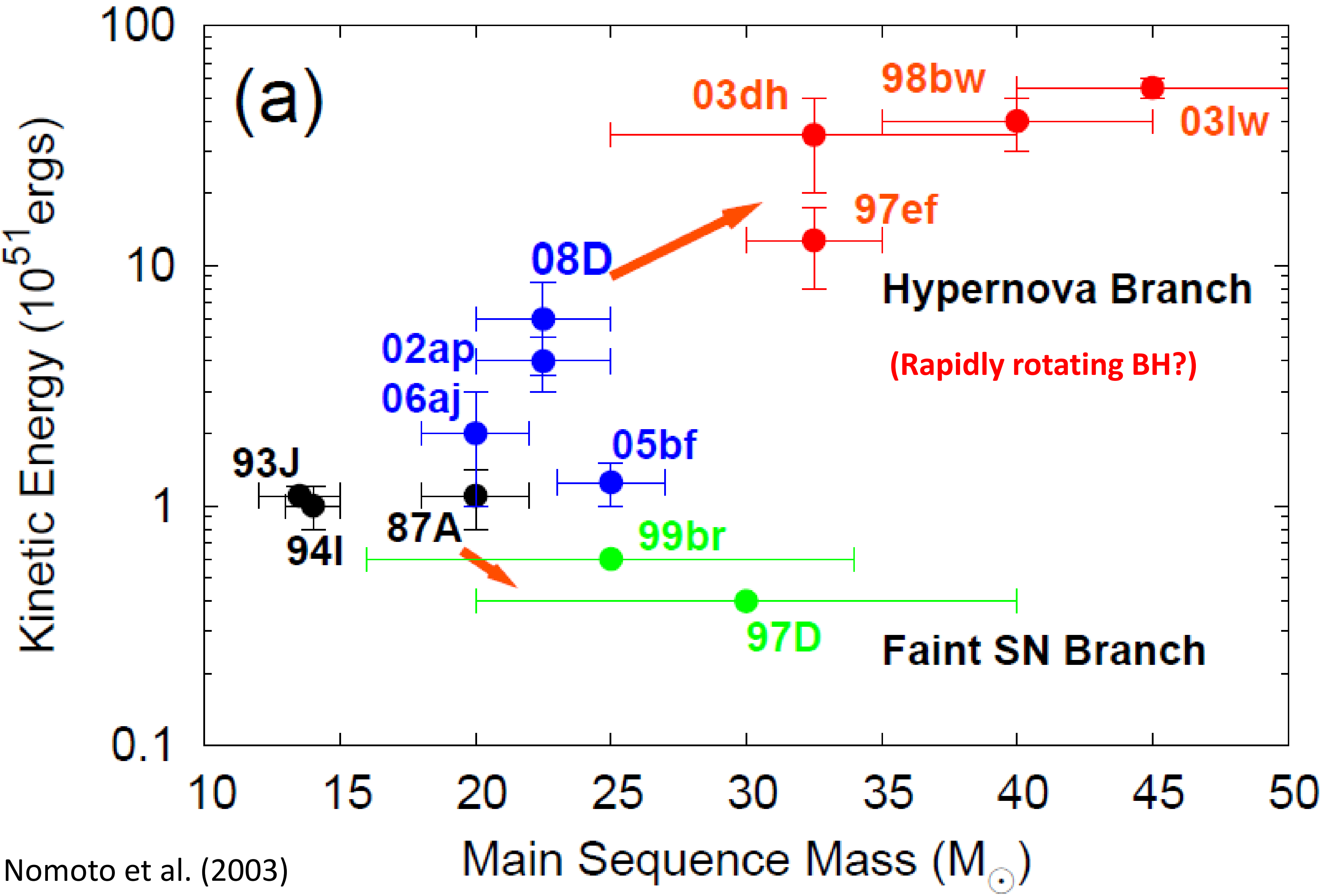
$$\sim \left(\frac{R}{V} \bullet \frac{\kappa M_{ej}}{R c} \right)^{1/2}$$

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

$E \propto M_{ej}^3$

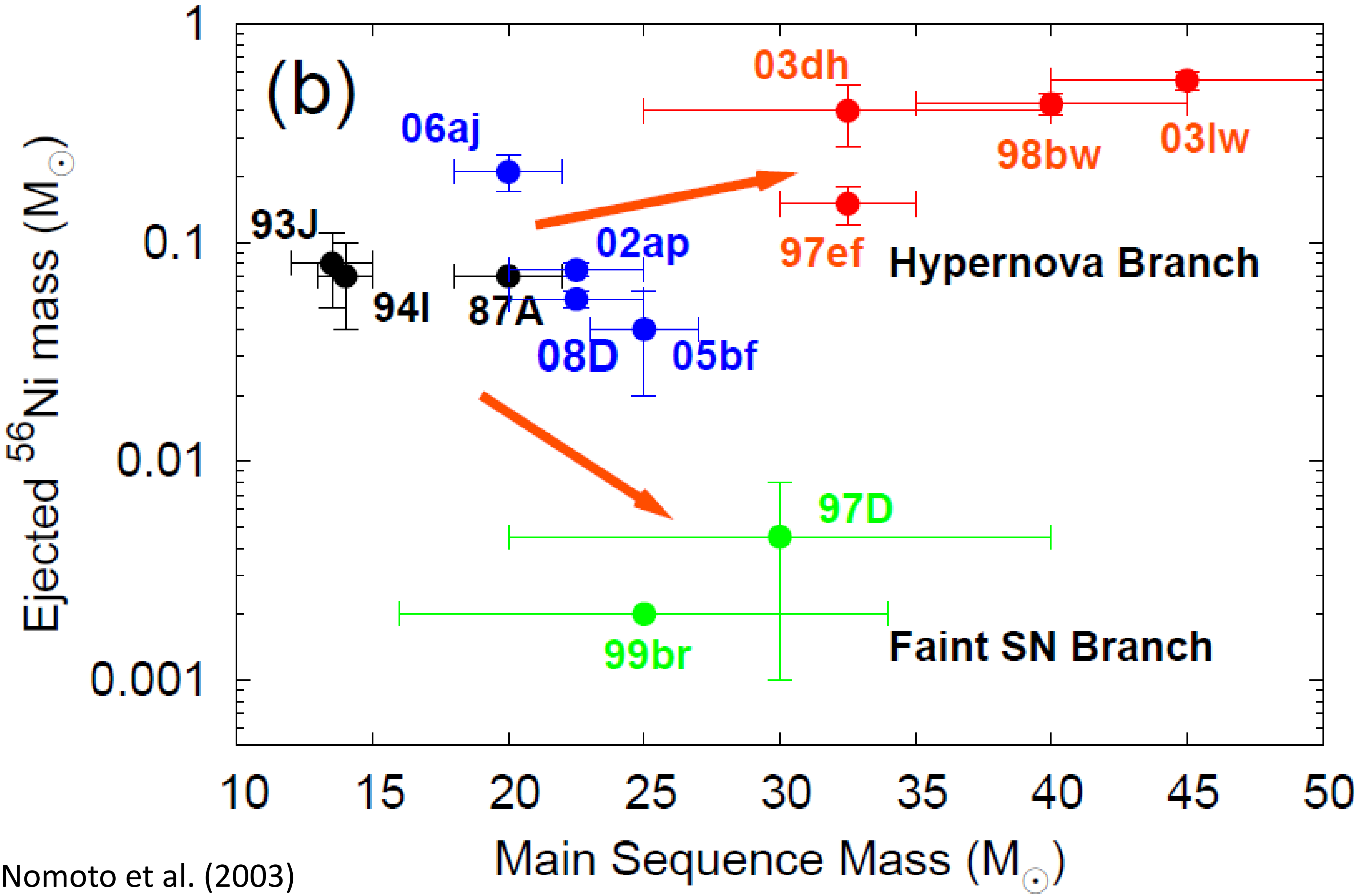


SNe [M_{ms}-E relation]



Nomoto et al. (2003)

SNe [M_{ms}-M(^{56}Ni) relation]



Nomoto et al. (2003)

Magnetar – X Ray Flash – Optical Light Curve ?

- **XRF 060218/ SN 2006aj (& XRF100316D/SN 2010bh)**

(Pian+, Chornock+, Bufano+)

Small Oxygen Mass < 1.3 $M_\odot$

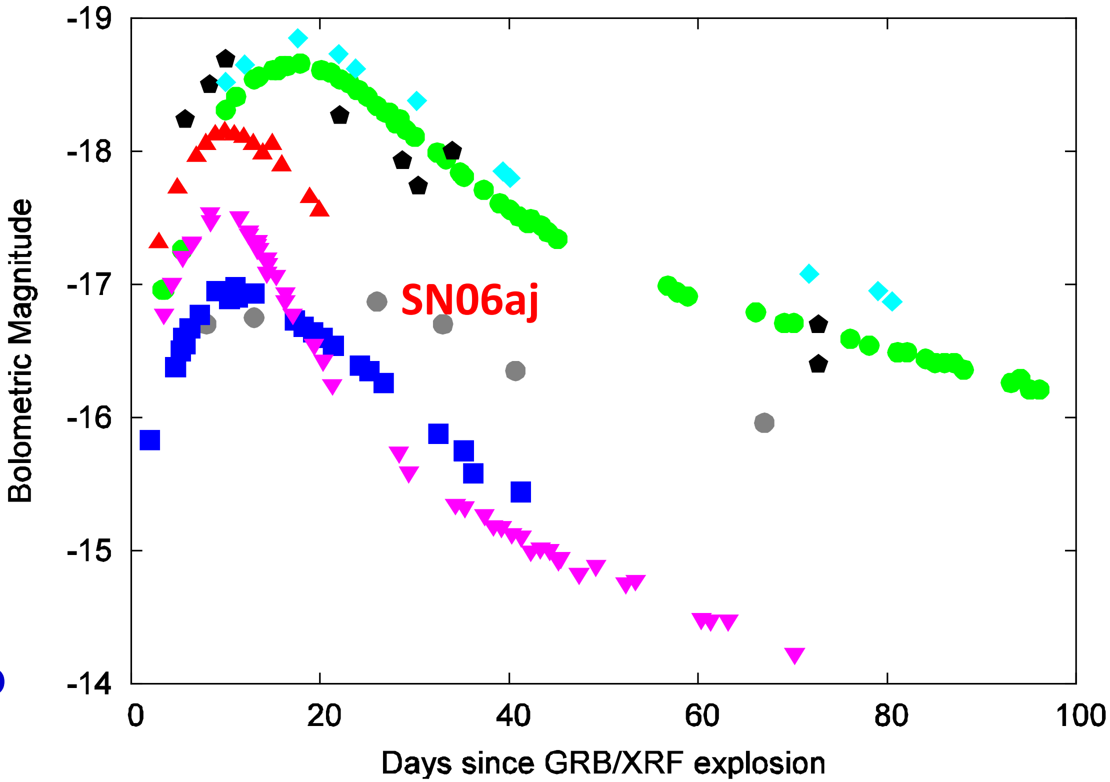
M_{ej} ~ 2 $M_\odot$ (M_{ms} ~ 20 $M_\odot$)

E ~ 2 x 10^{51} erg

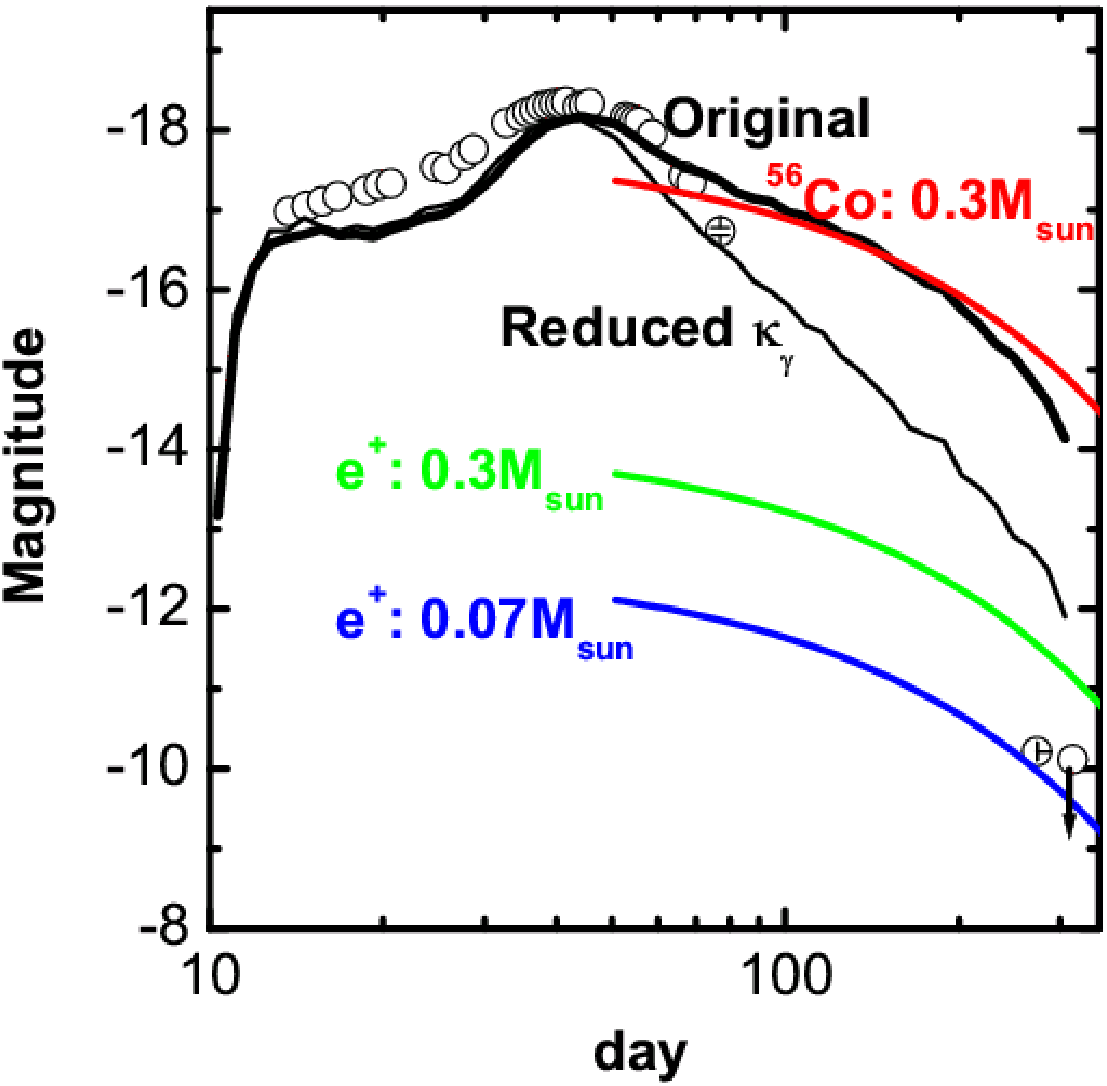
$M(^{56}Ni)$~0.2$M_\odot$

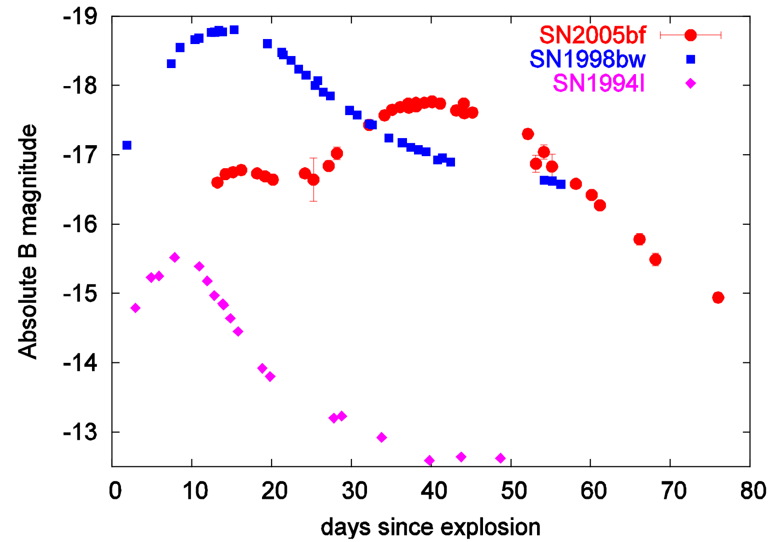
- Neutron Star-forming SN ?
- Magnetar-driven XRF ?

  Magnetar-powered LC?



SN Ib 2005bf: **Double Peak Light Curve**



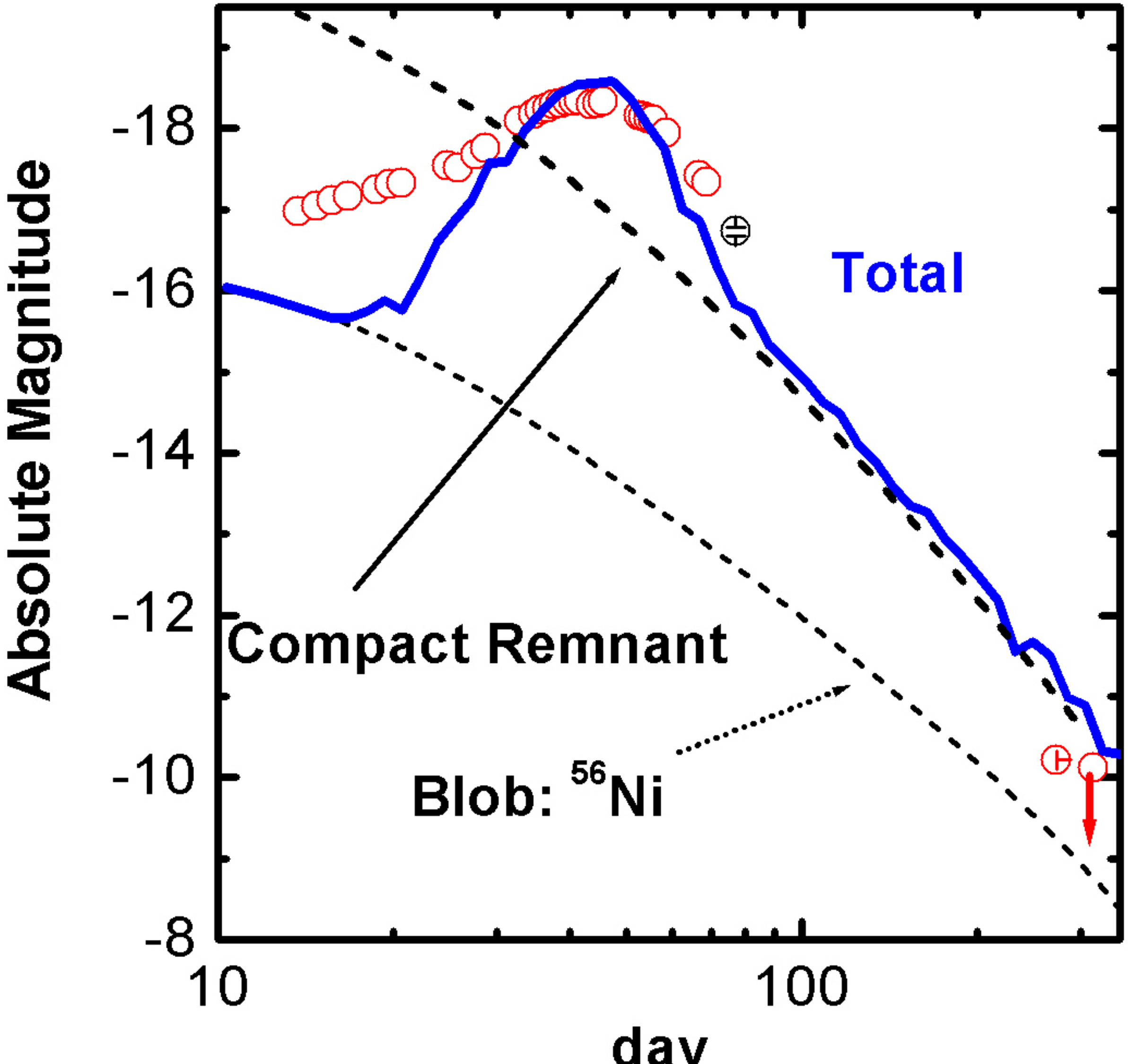


SUBARU observations

M(^{56}Ni) < 0.07 M$_\odot$

Maeda et al. (2007)

SN Ib 2005bf: 1st peak: ^{56}Ni decay
2nd peak: Magneter ?



$L=L_0(t/t_0)^{\beta}$

$L_0=8x10^{43}$erg/s(*)

T_0=60day

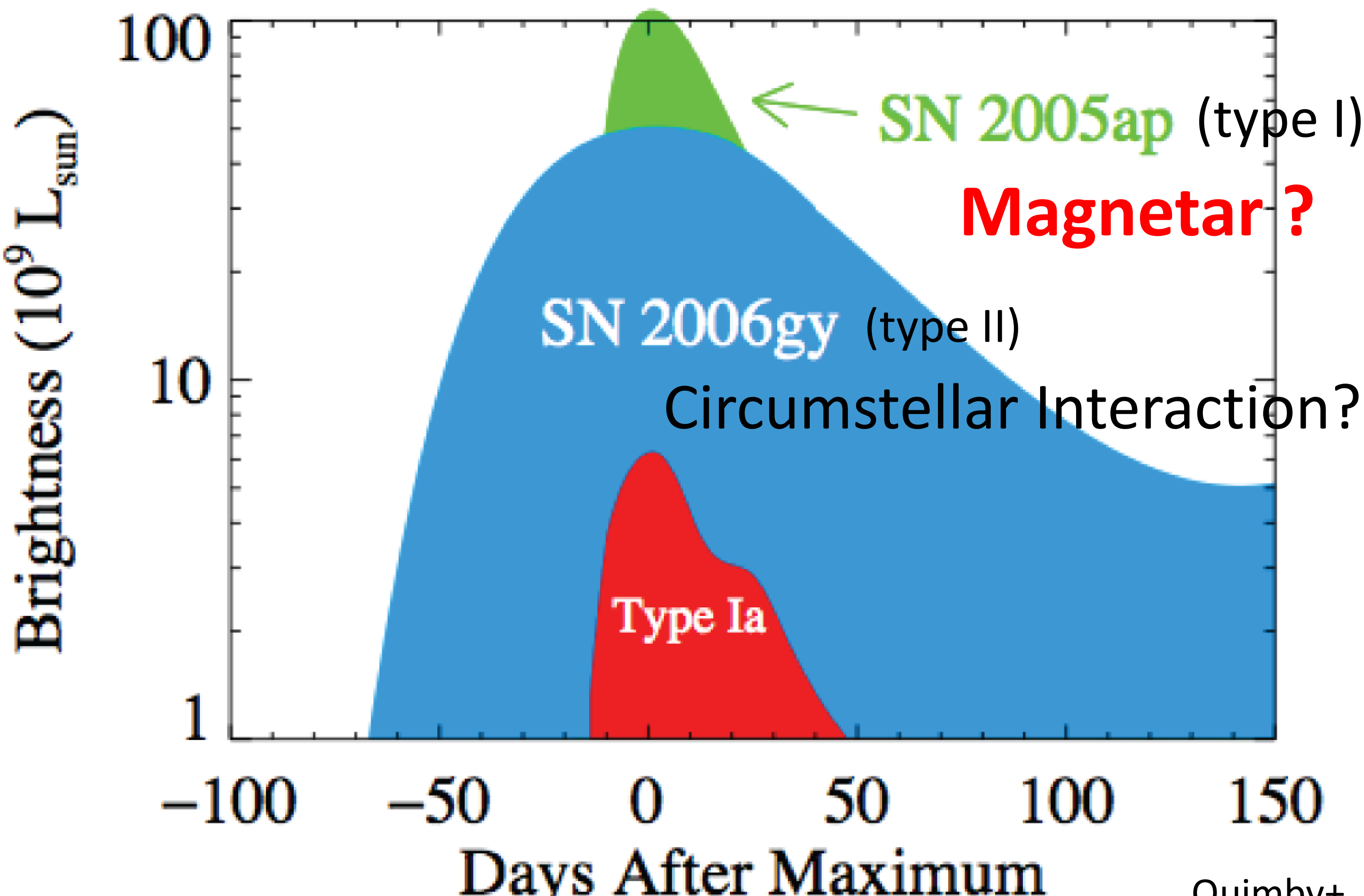
β = -4 (n = 2)

(*) If dipole, e.g.,

B_0~10^{15} G, P_0~10 ms

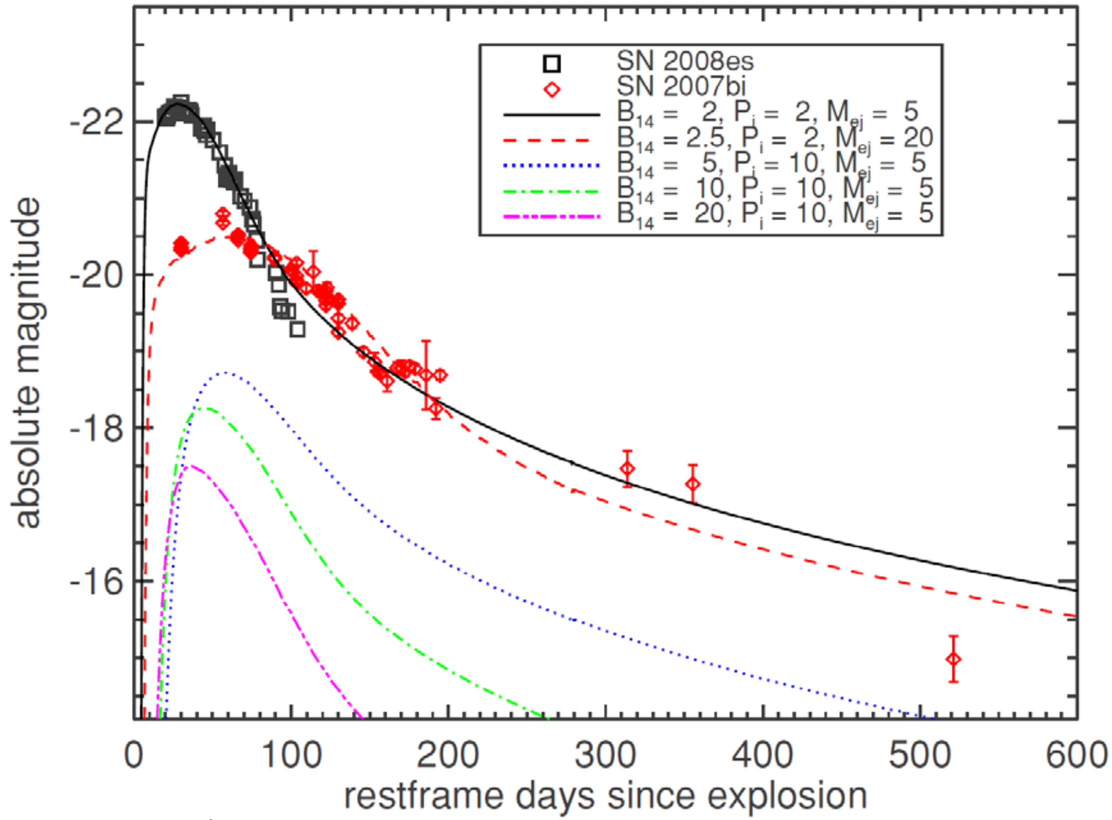
Maeda et al. (2007)

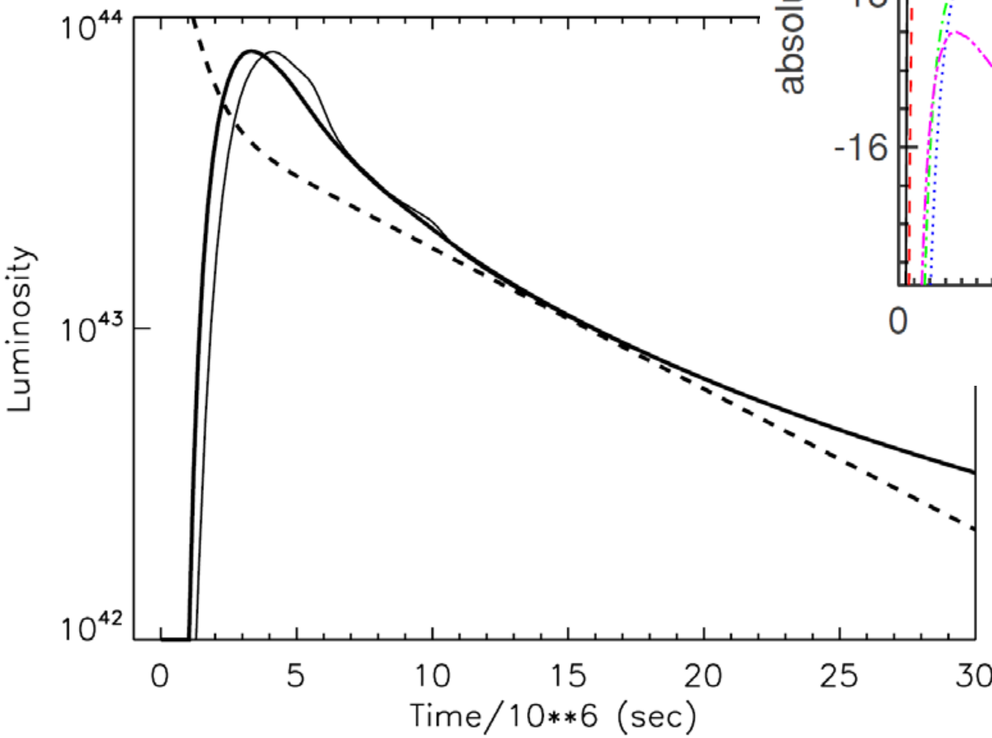
Superluminous Supernovae



Quimby+

Magnetar models for Superluminous SNe

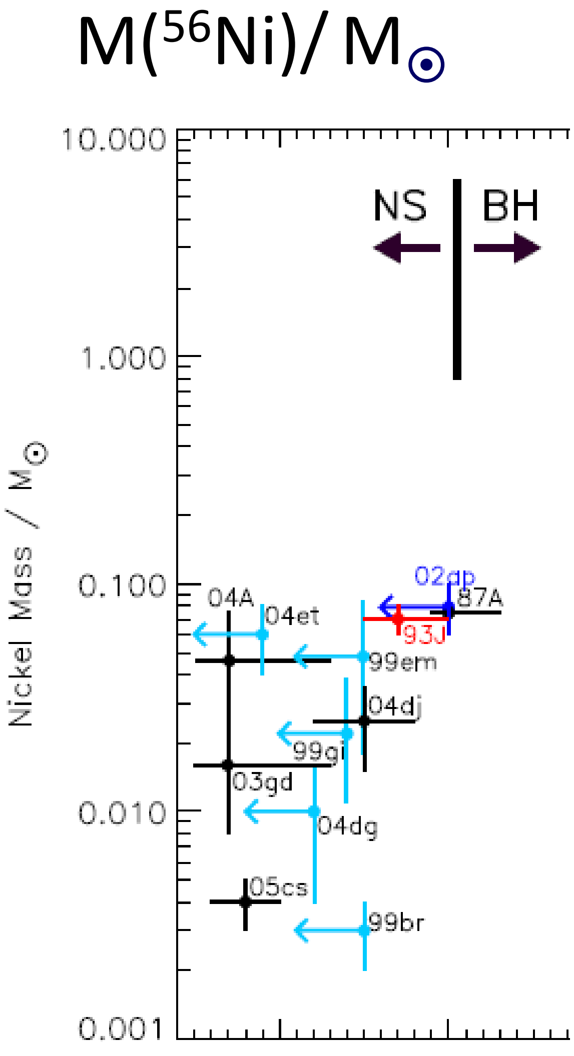




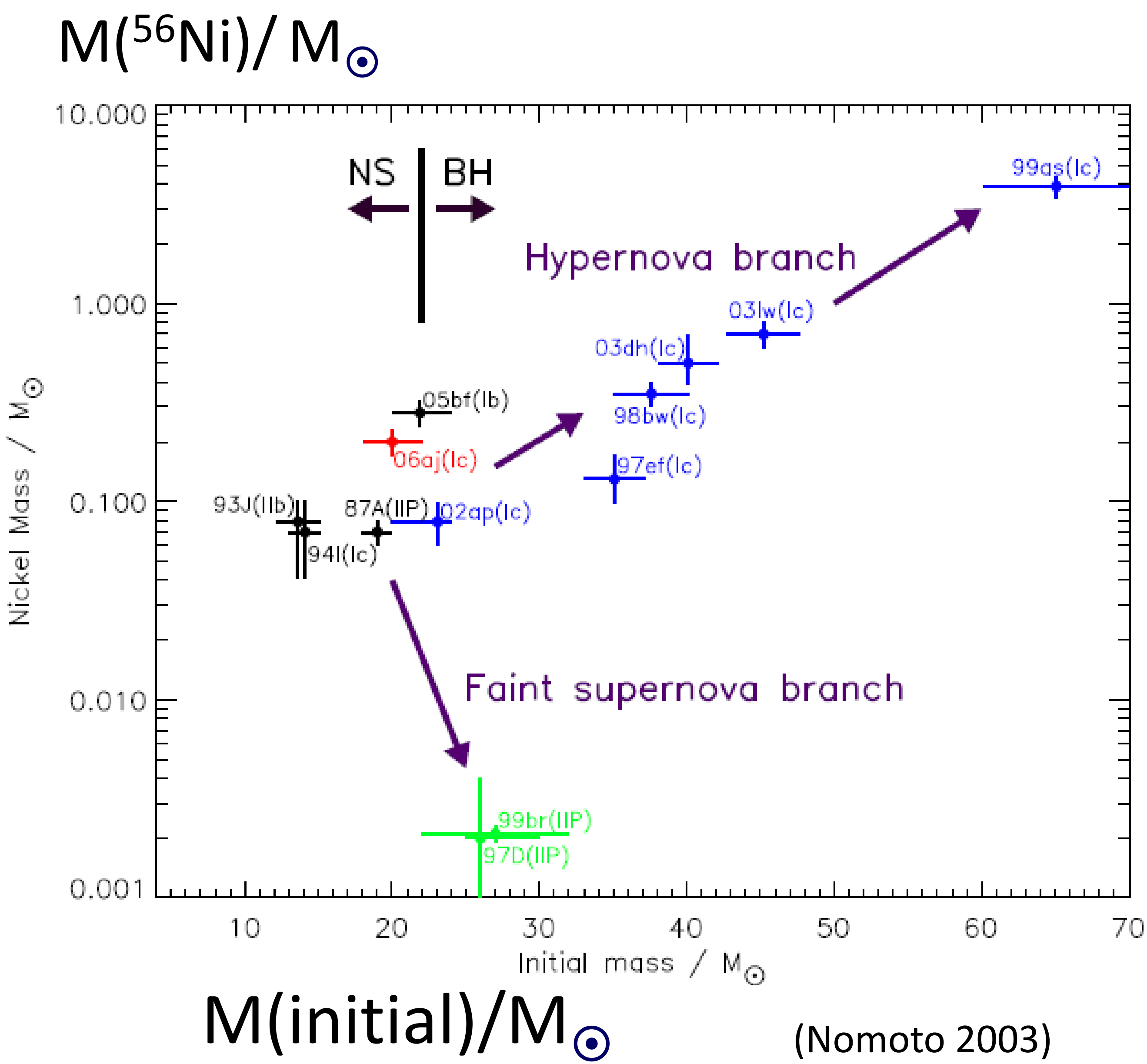
Kasen & Bildsten 2010

Woosley 2010

Faint Supernovae



(Smartt 2005)



(Nomoto 2003)

Neutron star-forming supernovae

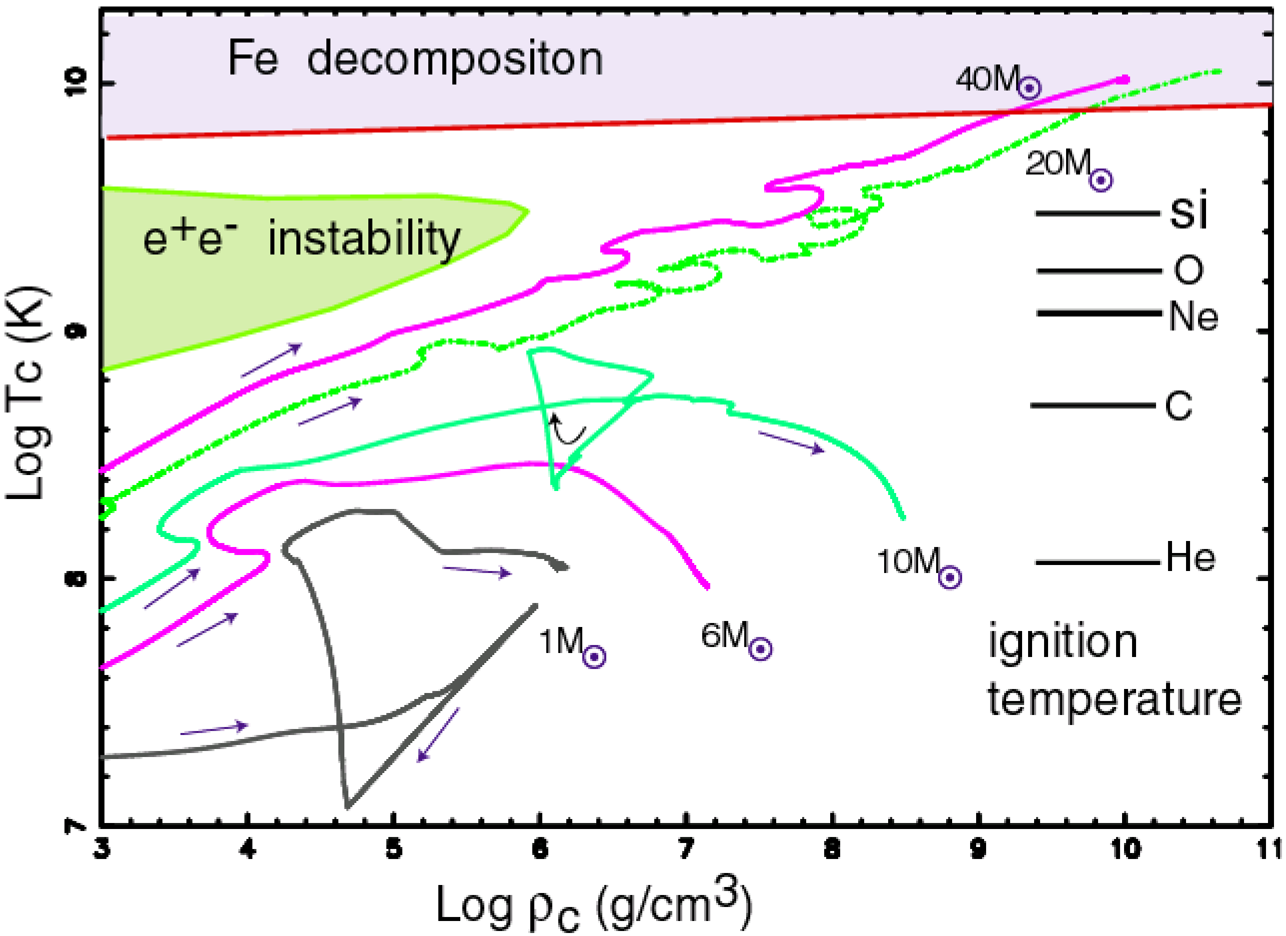
1) Magnetar-forming supernovae -
   - GRB (XRF)-supernovae ?
2) Electron capture supernovae
3) Accretion induced collapse (AIC) of white dwarfs

Final Fates of Stars:

$M < 8\ M_\odot$ → Electron-Degenerate Core → White Dwarf

$M = 8 - 10\ M_\odot$ → Electron-Degenerate ONeMg Core → ??

$M > 10\ M_\odot$ → Fe Core → Collapse (NS or BH)



$M > 10\ M_\odot$:
Ne ignition

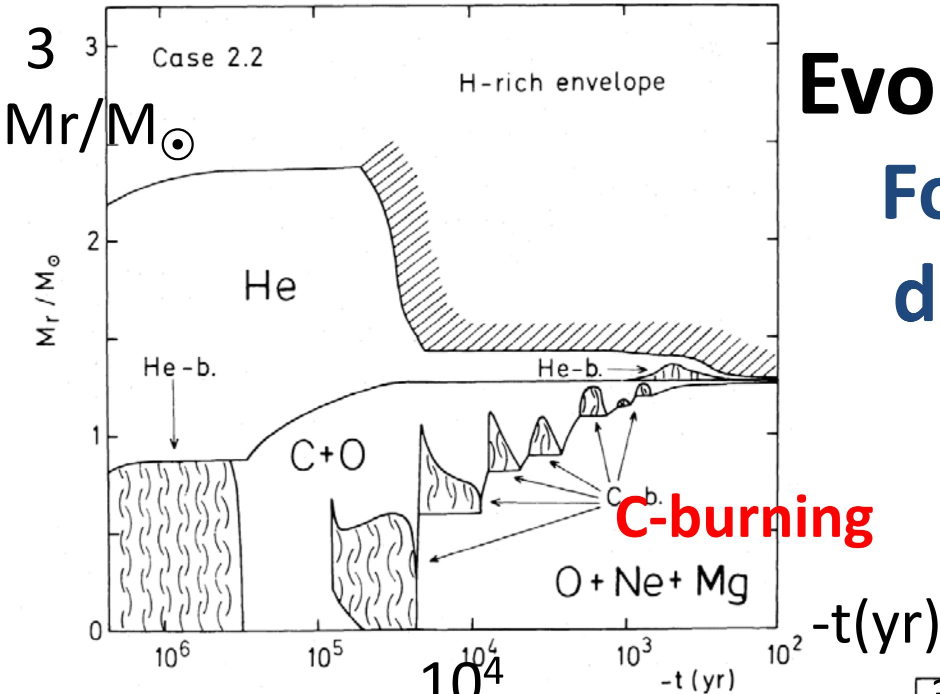
$M > 8\ M_\odot$:
C ignition

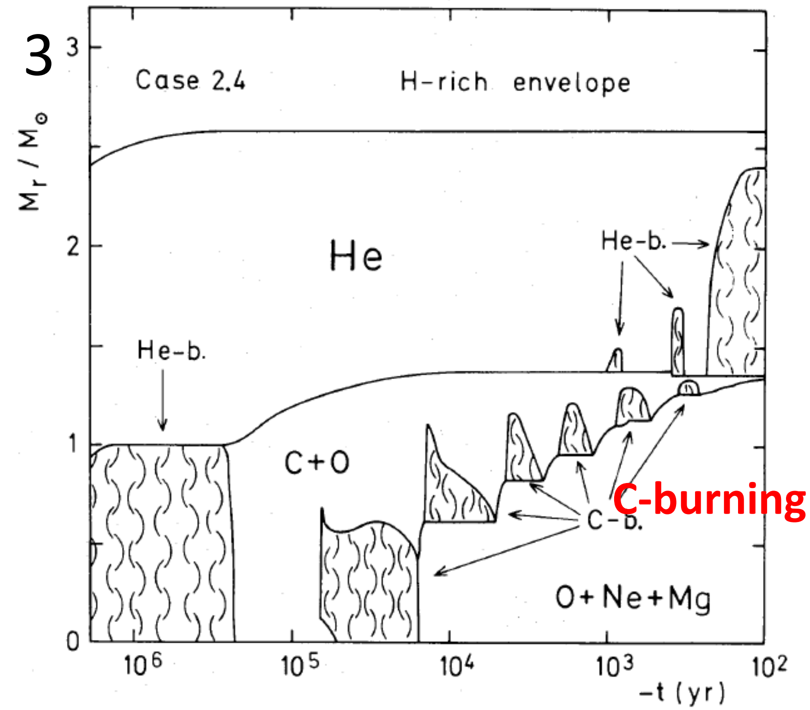
Jones, Hirschi,Nomoto+ 13
Toki,Suzuki,Nomoto+ 13
Tominaga, Blinnikov, Nomoto+ 2013

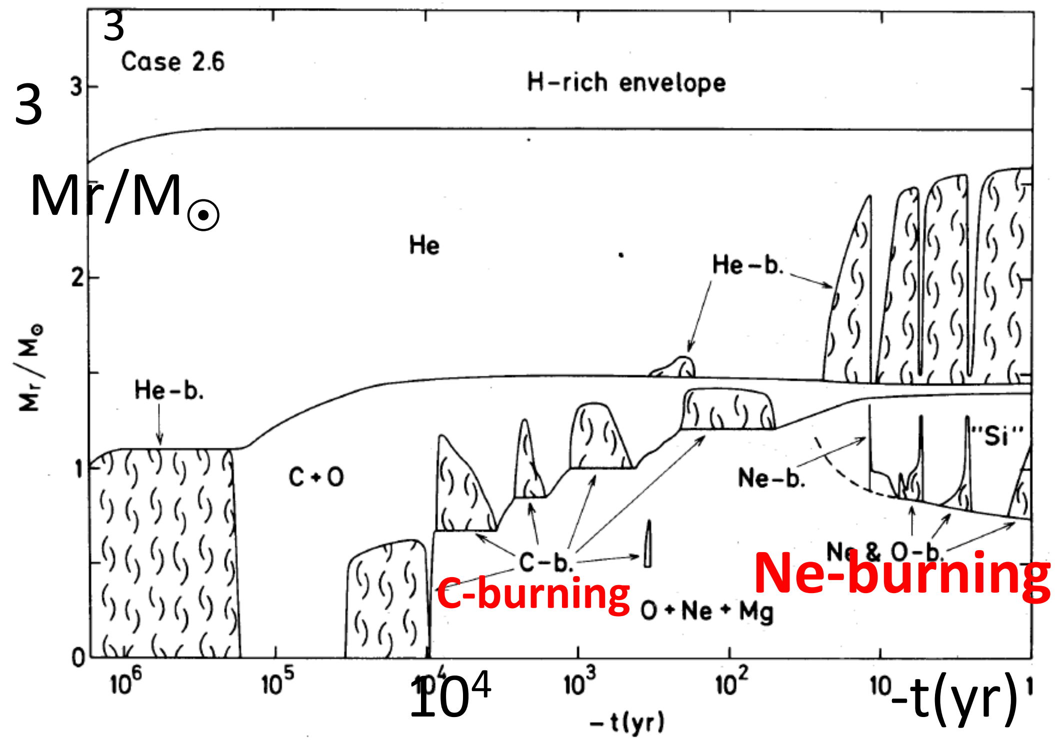
Evolution of 8-10 $M_\odot$ Stars:

Formation of an electron degenerate ONeMg core

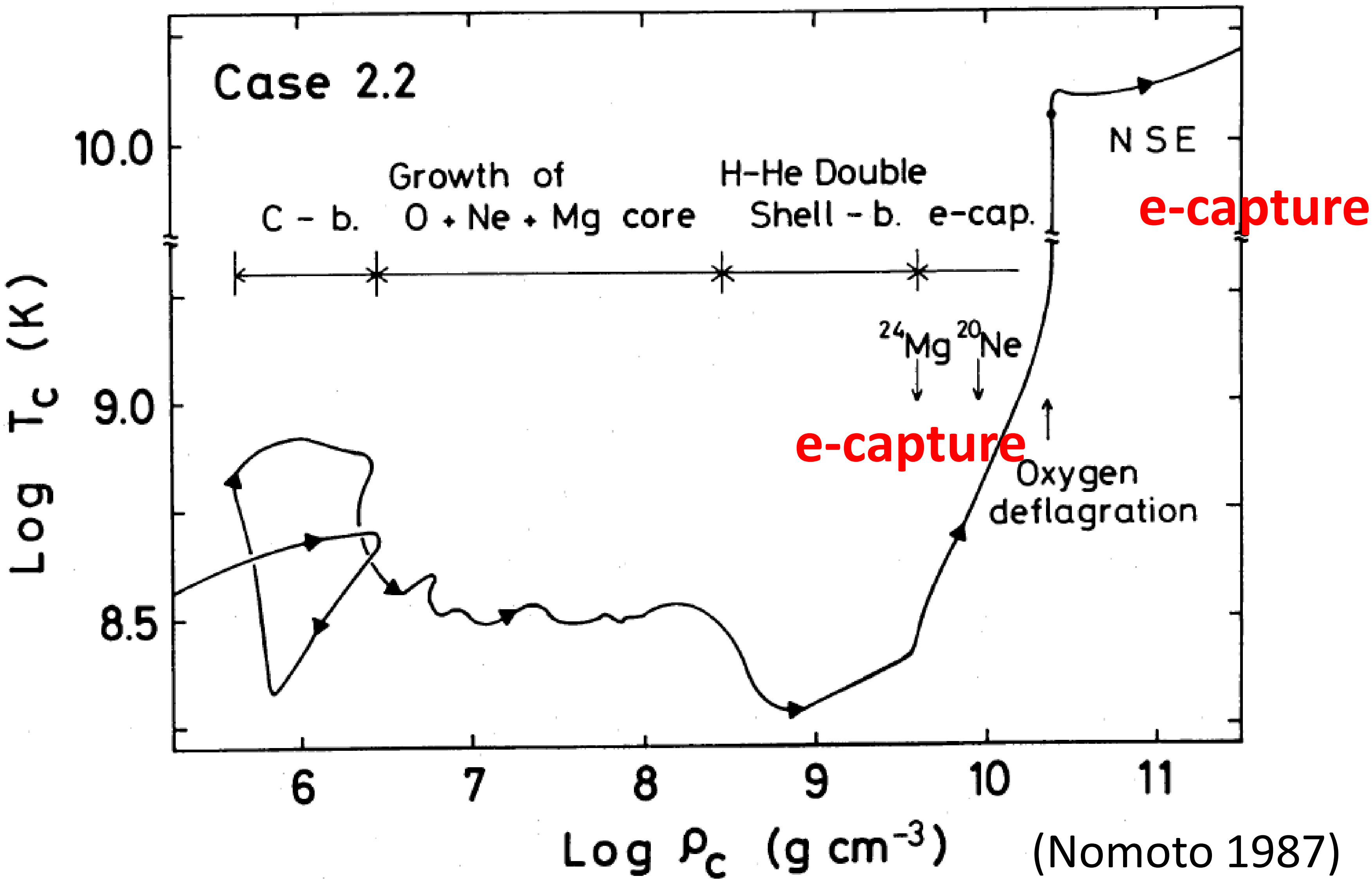
(Nomoto 1982, 84, 87)







Evolution of the central density & temperature of 8.8 $M_\odot$ star ➔ Collapse



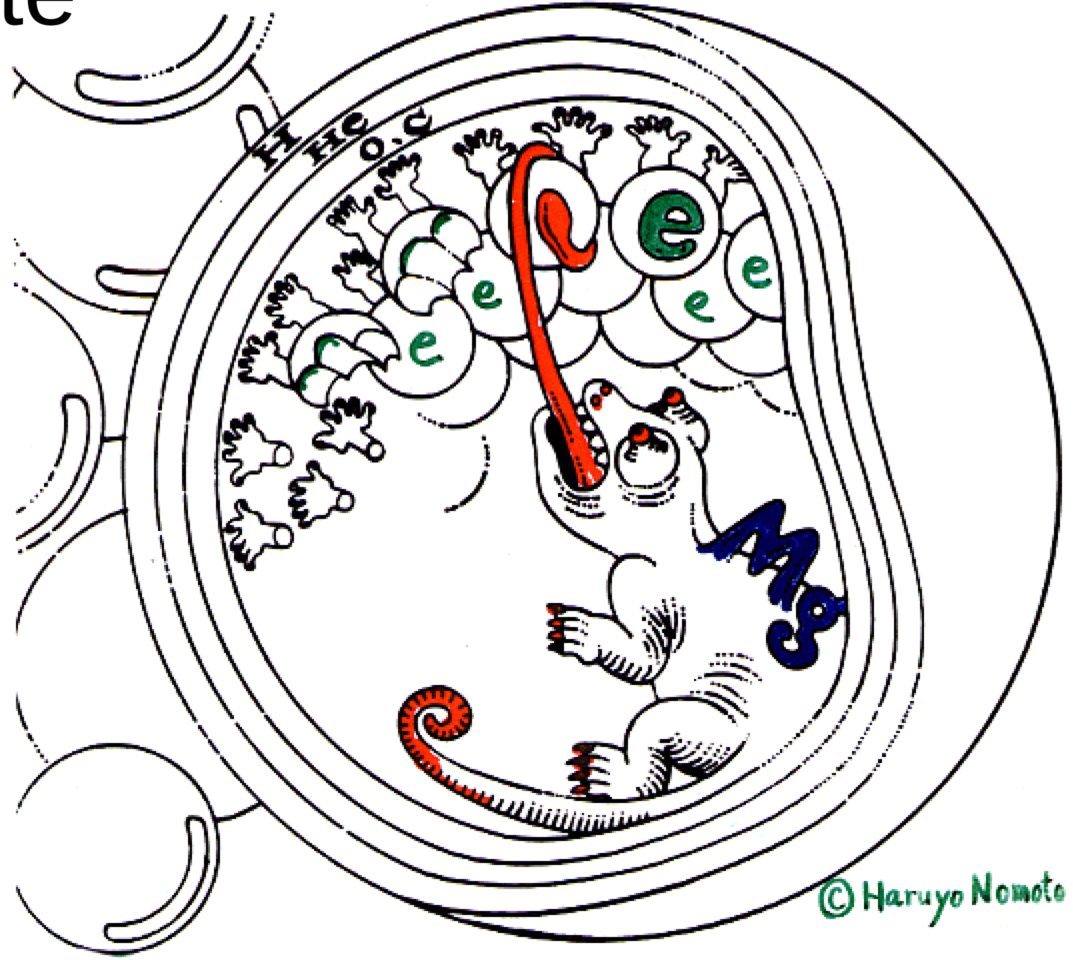
(Nomoto 1987)

Electron Capture (EC) in 8-10 $M_\odot$ Stars

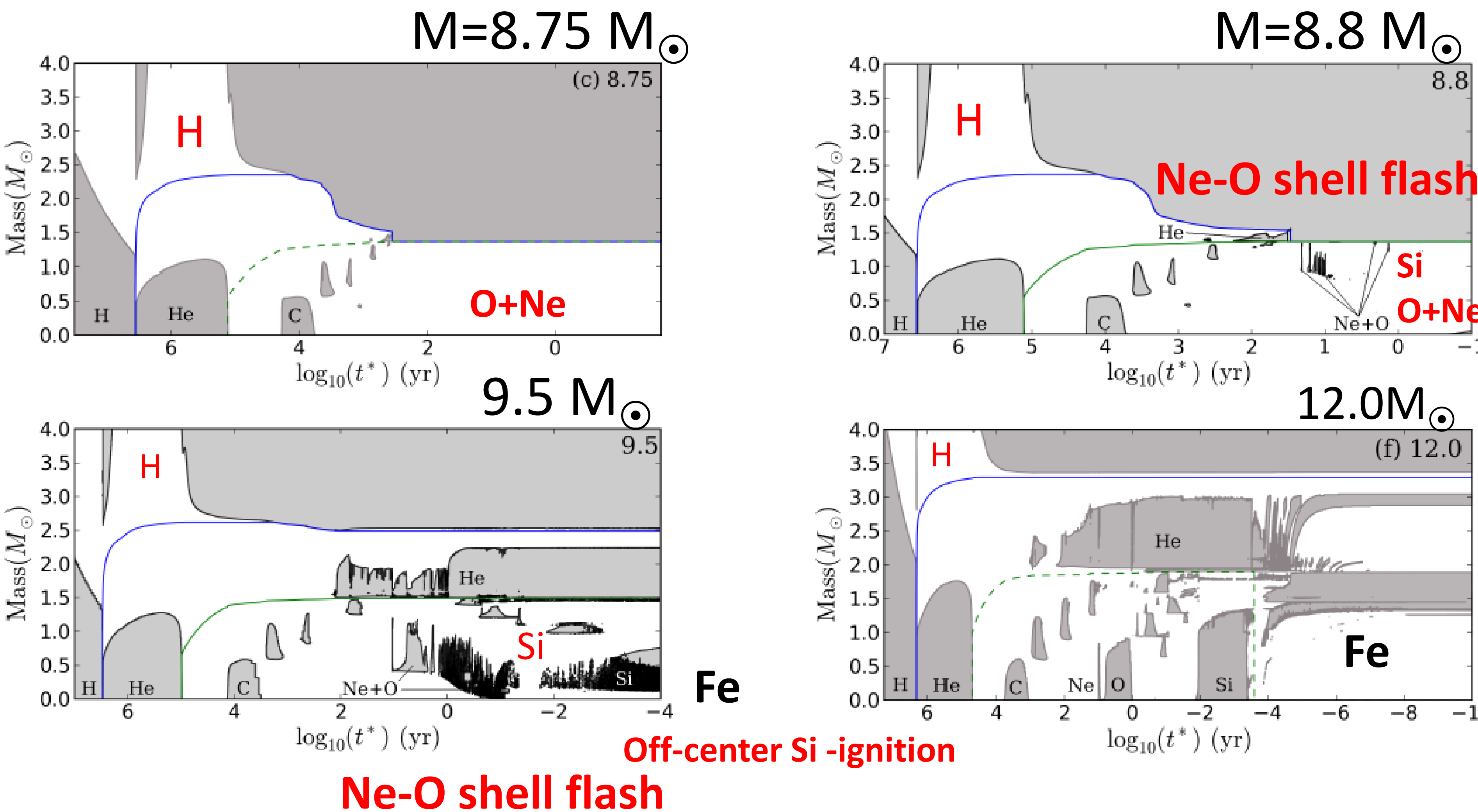
Electron-degenerate
O+Ne+Mg Core

- $^{24}Mg(e^-,\nu)^{24}Na$
  $(e^-,\nu)^{24}Ne$
- $\rho>4.0\times10^9 gcm^{-3}$
- →collapse

(Nomoto 1984)



Evolution of 8 – 12 $M_\odot$ Stars



(Jones, Hirschi, Nomoto+ 13; Takahashi+13; Ritossa+99)

Evolution of the O+Ne Core

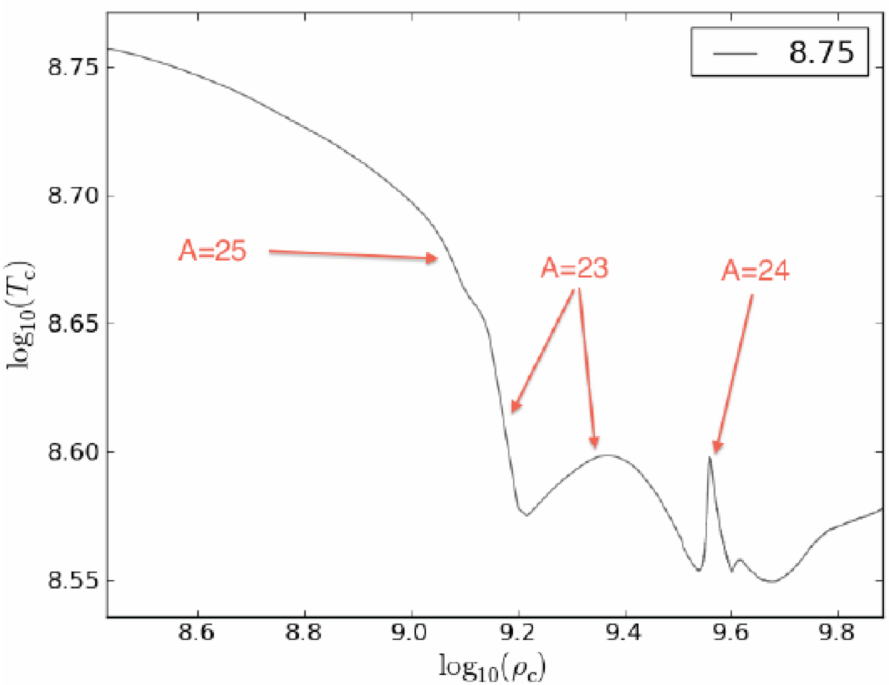
Carbon burning ($^{12}C+^{12}C$) ➔

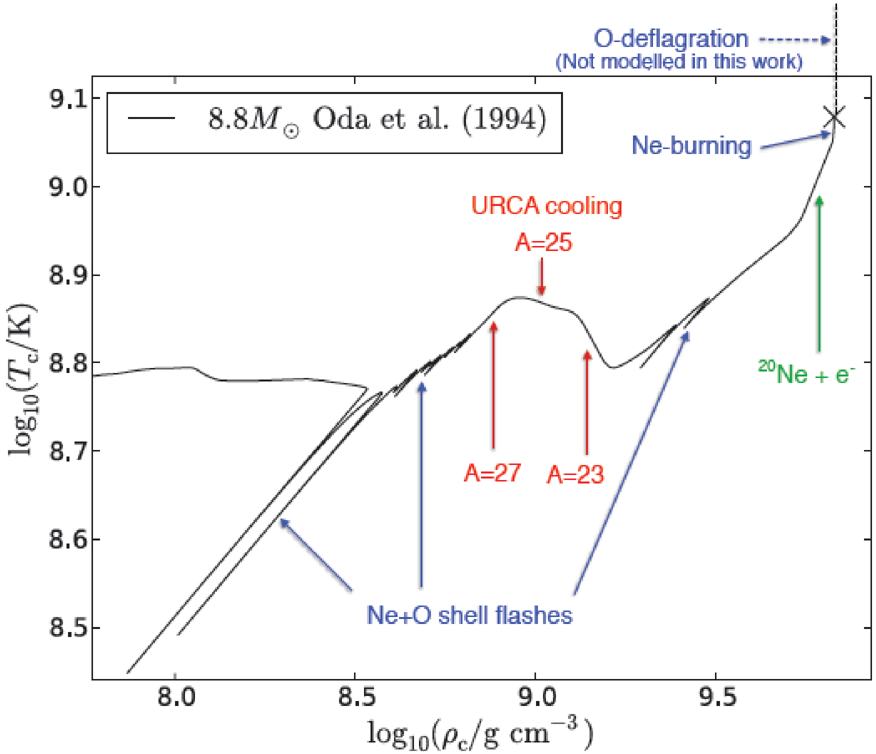
$X(^{16}O)=0.57$, $X(^{20}Ne)=0.34$, $X(^{23}Na)=0.06$, $X(^{24}Mg)=0.01$, $X(^{25}Mg)=0.02$

URCA Cooling: **e-capture** $(i) \quad {}^{A}Z + e^- \rightarrow {}^{A}(Z-1) + \nu$

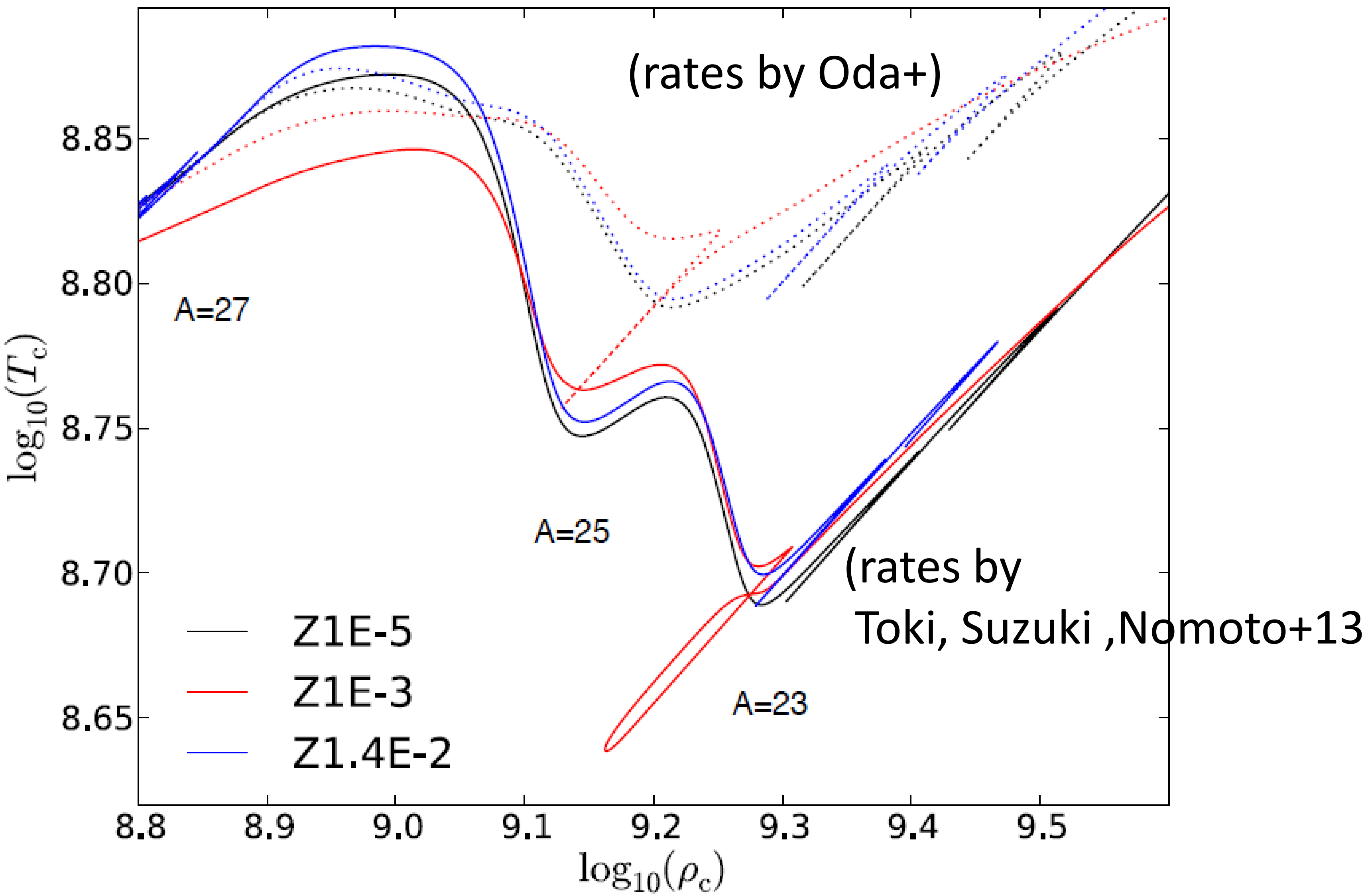
Beta-decay $(ii) \quad {}^{A}(Z-1) \rightarrow {}^{A}Z + e^- + \bar{\nu}$

URCA pairs: $^{27}Al \leftrightarrow {}^{27}Mg$; $^{25}Mg \leftrightarrow {}^{25}Na$; $^{23}Na \leftrightarrow {}^{23}Ne$



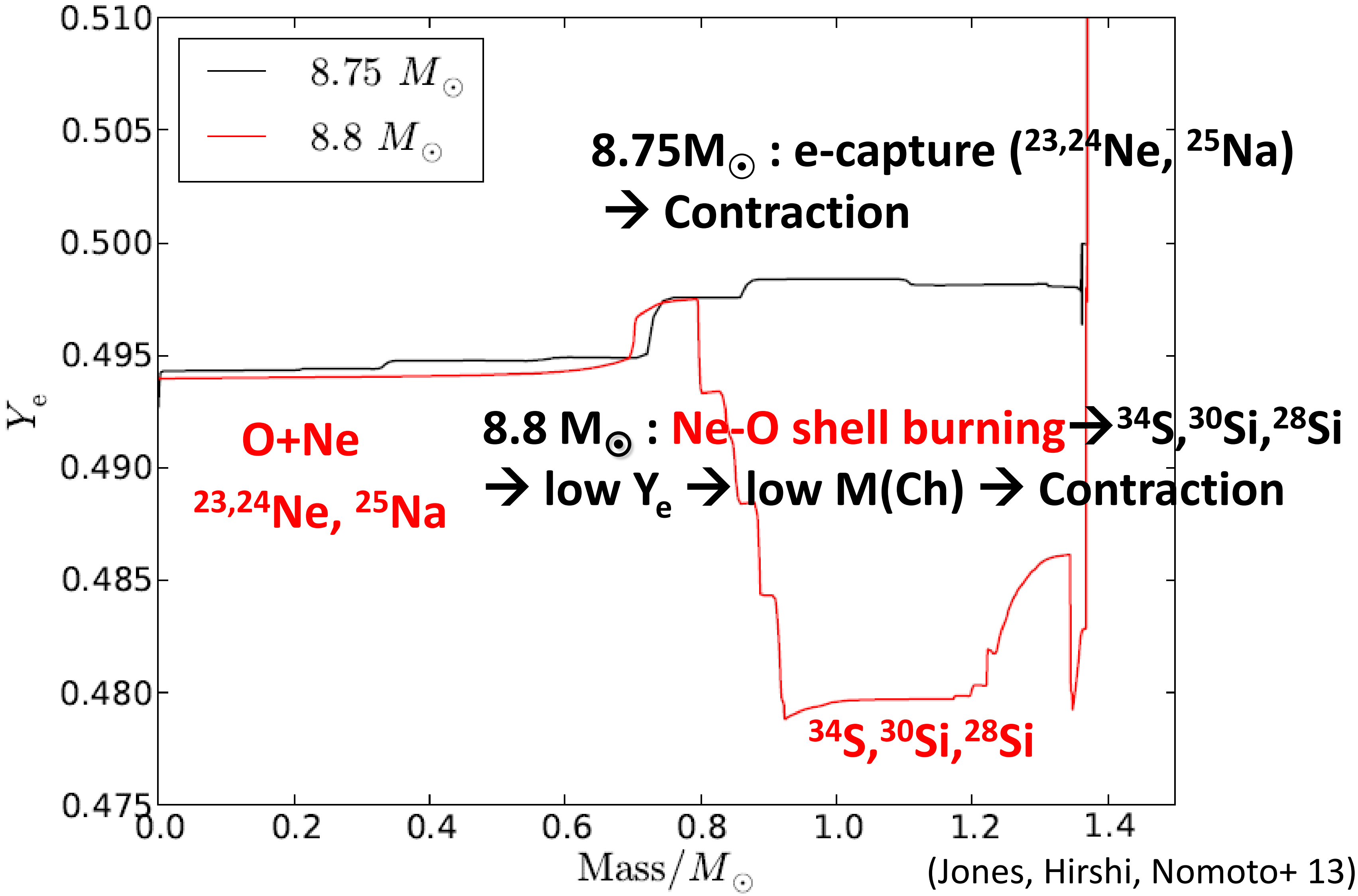


URCA Cooling ➔ Higher Ignition Density



(Jones, Hirschi, Nomoto+13)

Ne-O shell burning (n-rich S, Si) & e-capture (n-rich Ne, Na) → Contraction



(Jones, Hirshi, Nomoto+ 13)

Final Fates of Stars:

$M < 8\ M_\odot$ → Electron-Degenerate Core → White Dwarf

$M = 8 - 8.8\ M_\odot$ → Mass Loss → O+Ne White Dwarf

→ Electron Capture (EC) Supernova

$M \sim 8.8 - 9.5\ M_\odot$

Ne-O flame → does not reach the center

formation of a degenerate O+Ne core

EC Supernova

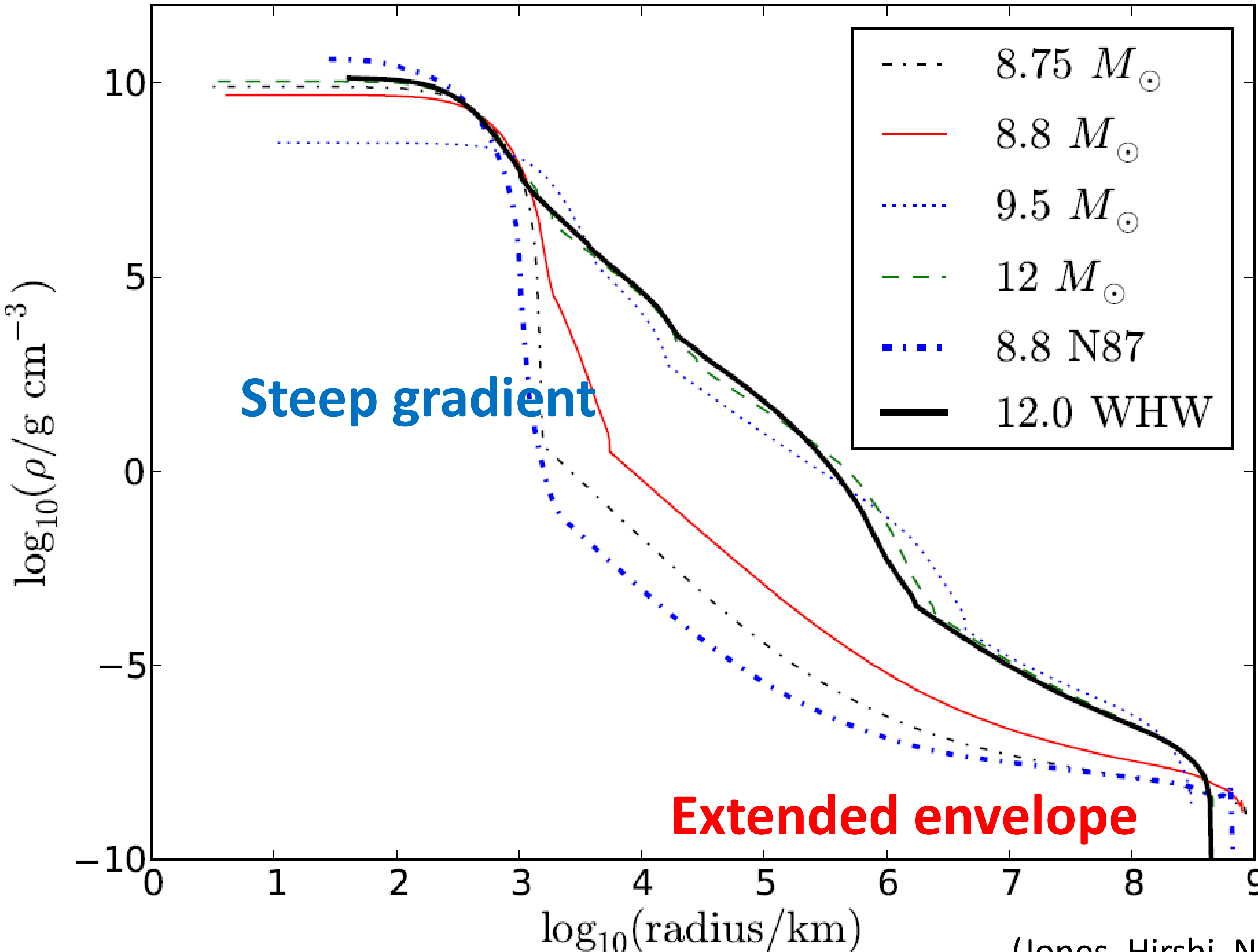
$M \sim 9.5 - 11\ M_\odot$

Ne-O flame → reaches the center (?)

formation of an Fe core

$M > 11\ M_\odot$ → central Ne-burn → Fe Core → NS or BH

Presupernova density profiles



(Jones, Hirshi, Nomoto+13)

$9M_\odot$ Star
Neutrino Heating → Weak Explosion

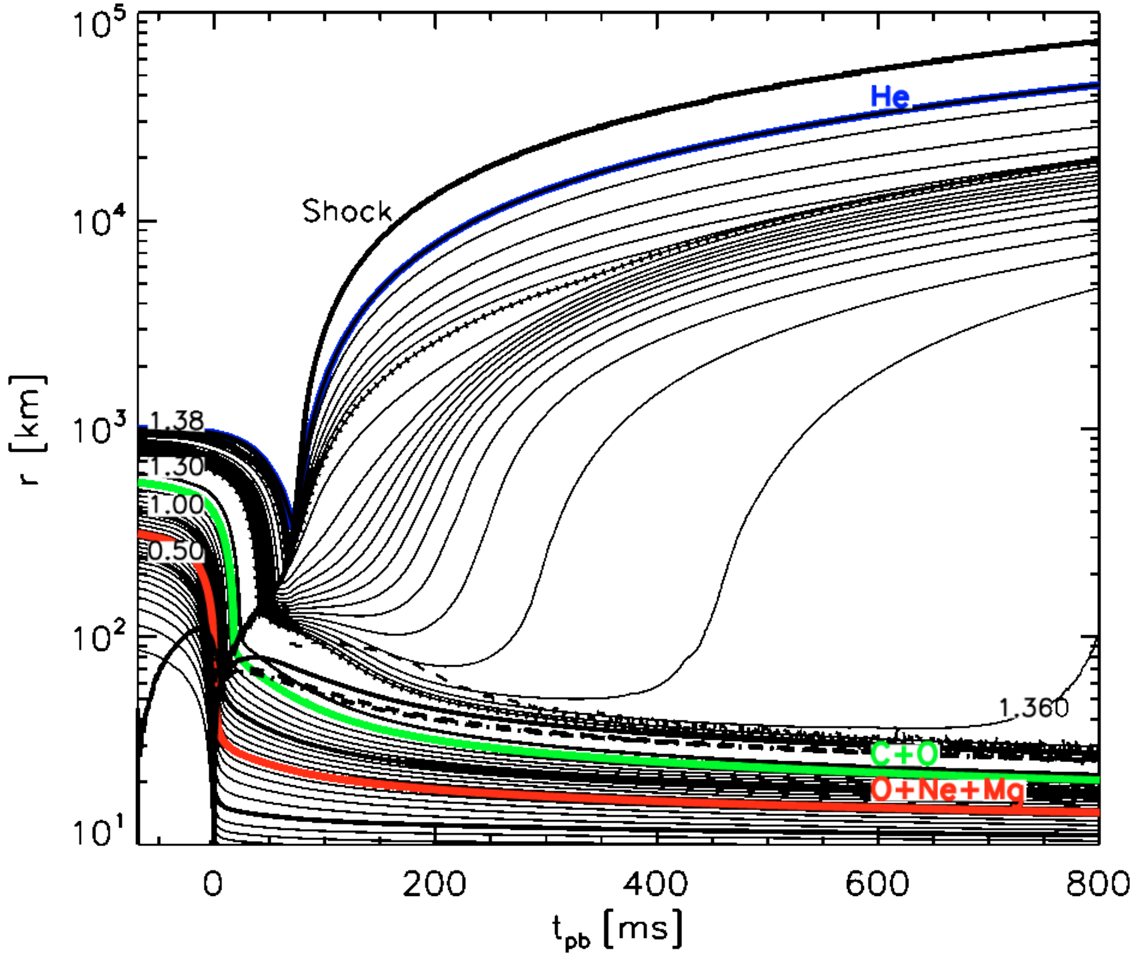
Steep Density Gradient

→ $E_{exp} = 1 \times 10^{50}$ erg
$M_{ej} = 0.011 M_\odot$

→ Super-AGB star's
H-He-rich Envelope
(~0.5 - $5M_\odot$)
Planetary Nebula-like

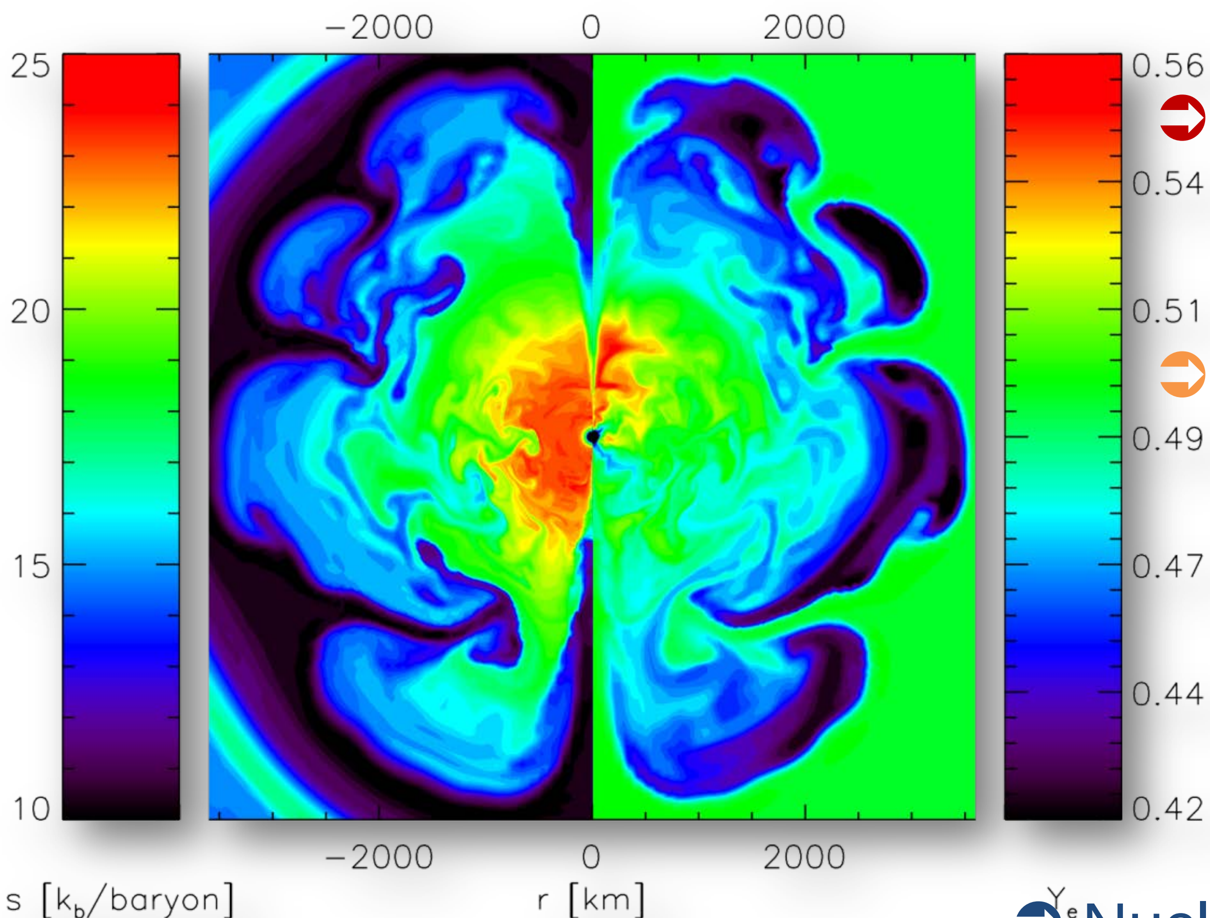
→ Nucleosynthesis Constraints

(Hoffman+ 08, Wanajo+09,11,13)



Kitaura, Janka, & Hillebrandt (2006)

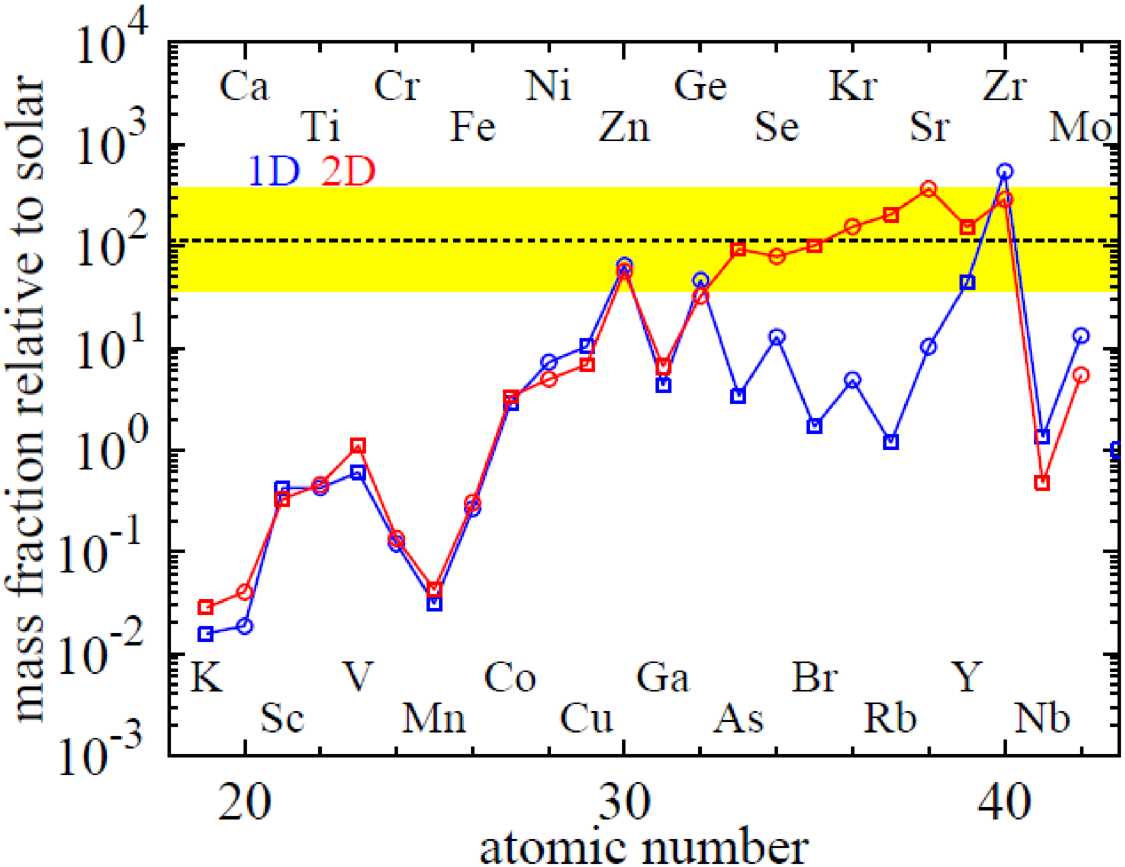
2D explosion model of Electron Capture (EC) SN (9$M_\odot$ star)



(B. Müller & H.-T. Janka 2011)

- ➲ convective n-rich lumps (down to $Y_{e,\,min}$ = 0.40)
- ➲ n-rich lumps have low entropy ~13-16 k_B per nucleon
- ➲ Nucleosynthesis: Y_e= 0.40-0.56: weak r-process?

Yields from EC-SNe (relative to solar)



(2D hydro models: B. Muller & T. Janka)

1D model (Wanajo, Nomoto+09)

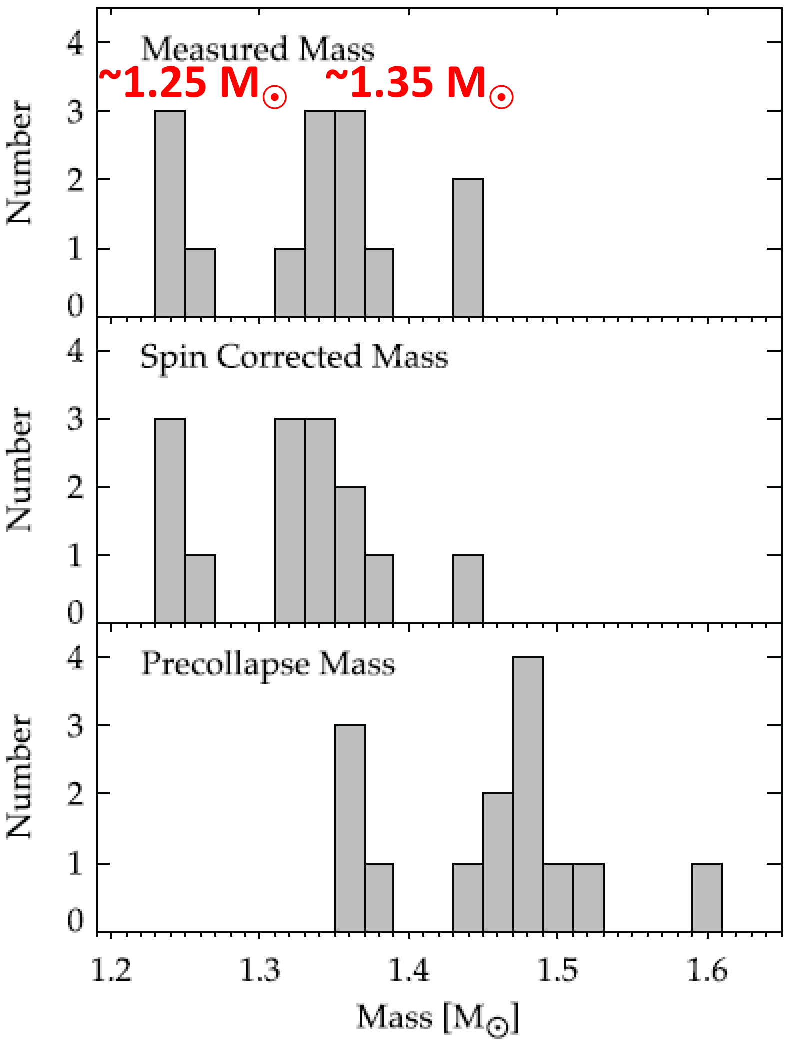
- ➲ only up to $N = 50$ ($A = 90$)
- ➲ only Zn, Ge, and Zr

2D model (Wanajo+11, 13)

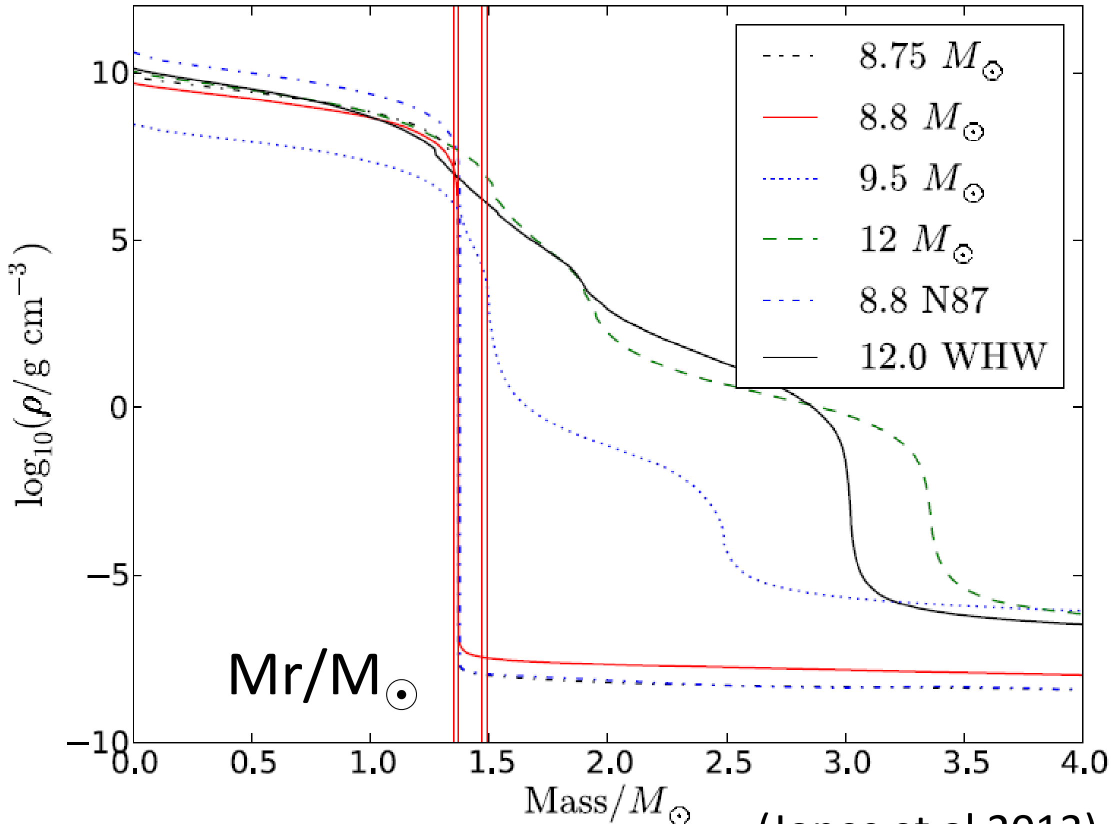
- ➲ still up to $N = 50$
- ➲ but can be the source of
- ➲ Zn,Ge, As, Se, Br, Rb, Sr, Y, Zr
- ➲ **^{48}Ca, ^{60}Fe**
- ➲ little Fe (^{56}Ni) mass $= 0.003\ M_\odot$
- ➲ **Faint SNe**

Neutron Star Masses

- Bimodal NS mass distribution (Schwab et al., 2012)



log (density)



(Jones et al 2013)

M(ms) → M(C+O) ~ M(NS)

8.8 M⊙ → 1.38 M⊙ ~1.25M⊙

9.5 M⊙ → 1.49 M⊙ ~1.35 M⊙

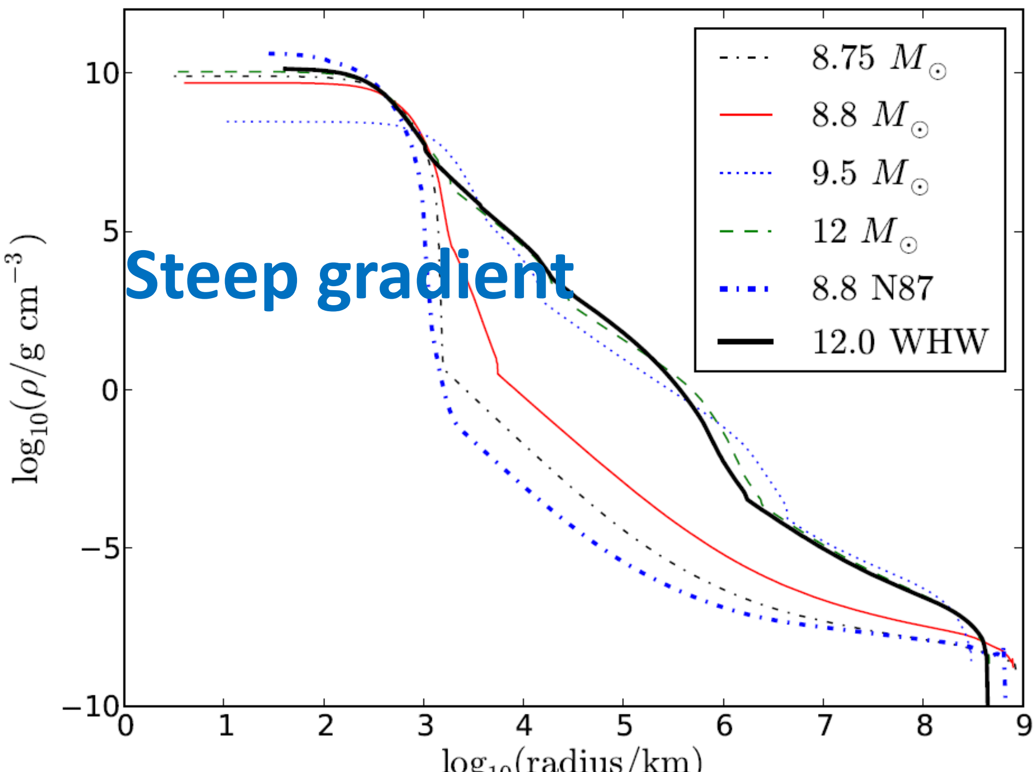
Neutron star-forming supernovae

1) Magnetar-forming supernovae
   - GRB (XRF)-supernovae ?
2) Electron capture supernovae
3) Accretion induced collapse (AIC) of white dwarfs

AIC & Explosion of ONeMg WD

Close Binary: ONeMg WD + Companion

Accretion ➔ M(WD) → M(Chandra) ➔ Electron Capture Supernova



$E_{exp} = 1 \times 10^{50}$ erg

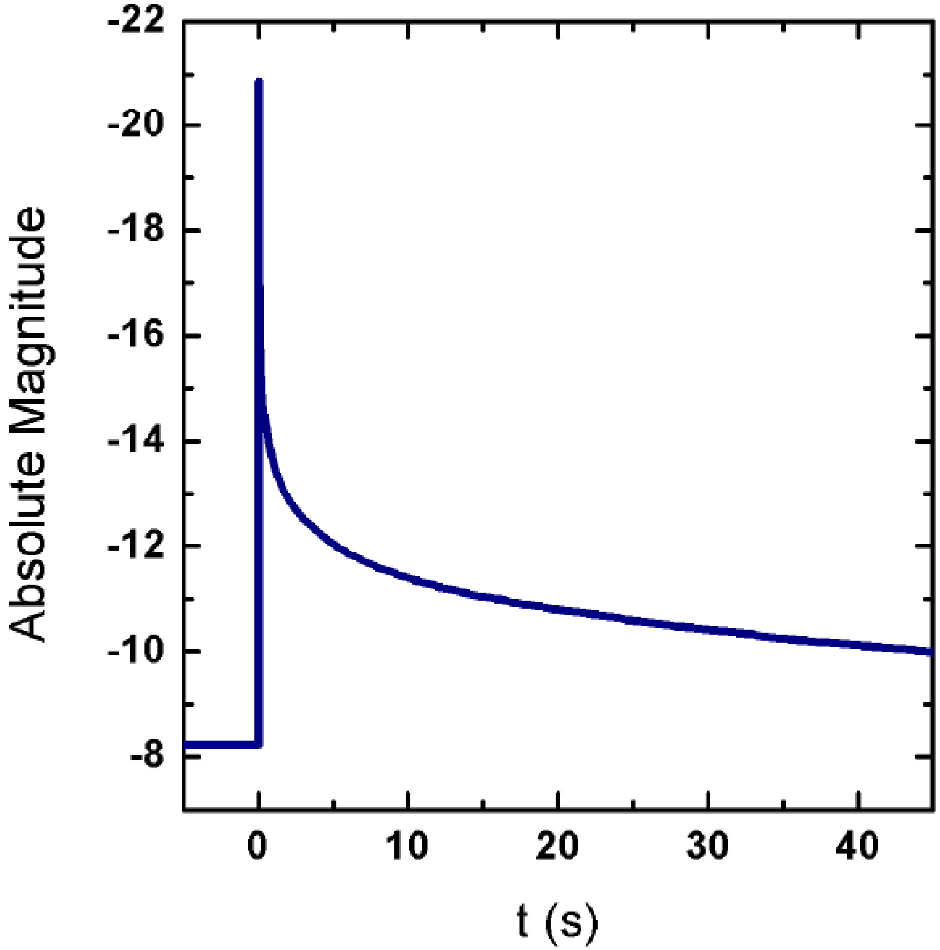
$M_{ej} = 0.011 M_\odot$

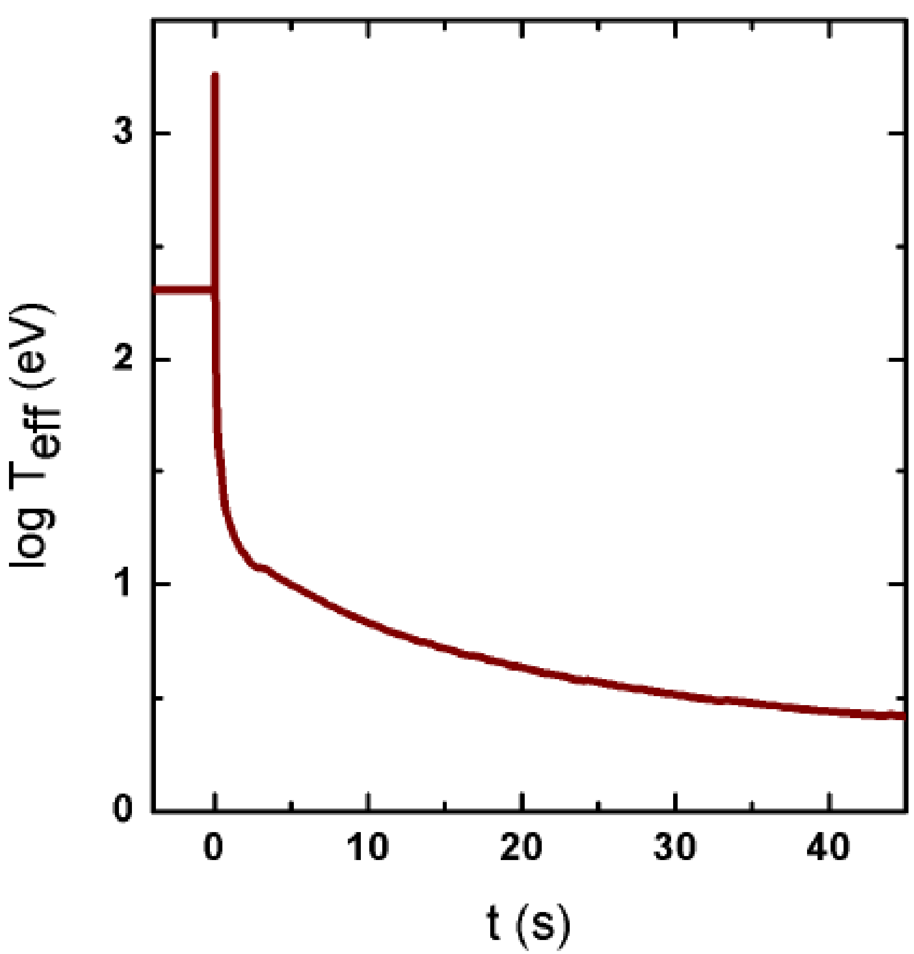
Fe (^{56}Ni) mass = $0.003 M_\odot$

Zn, Ge, As, Se, Br, Rb, Sr, Y, Zr

(Tolstov et al. 14)

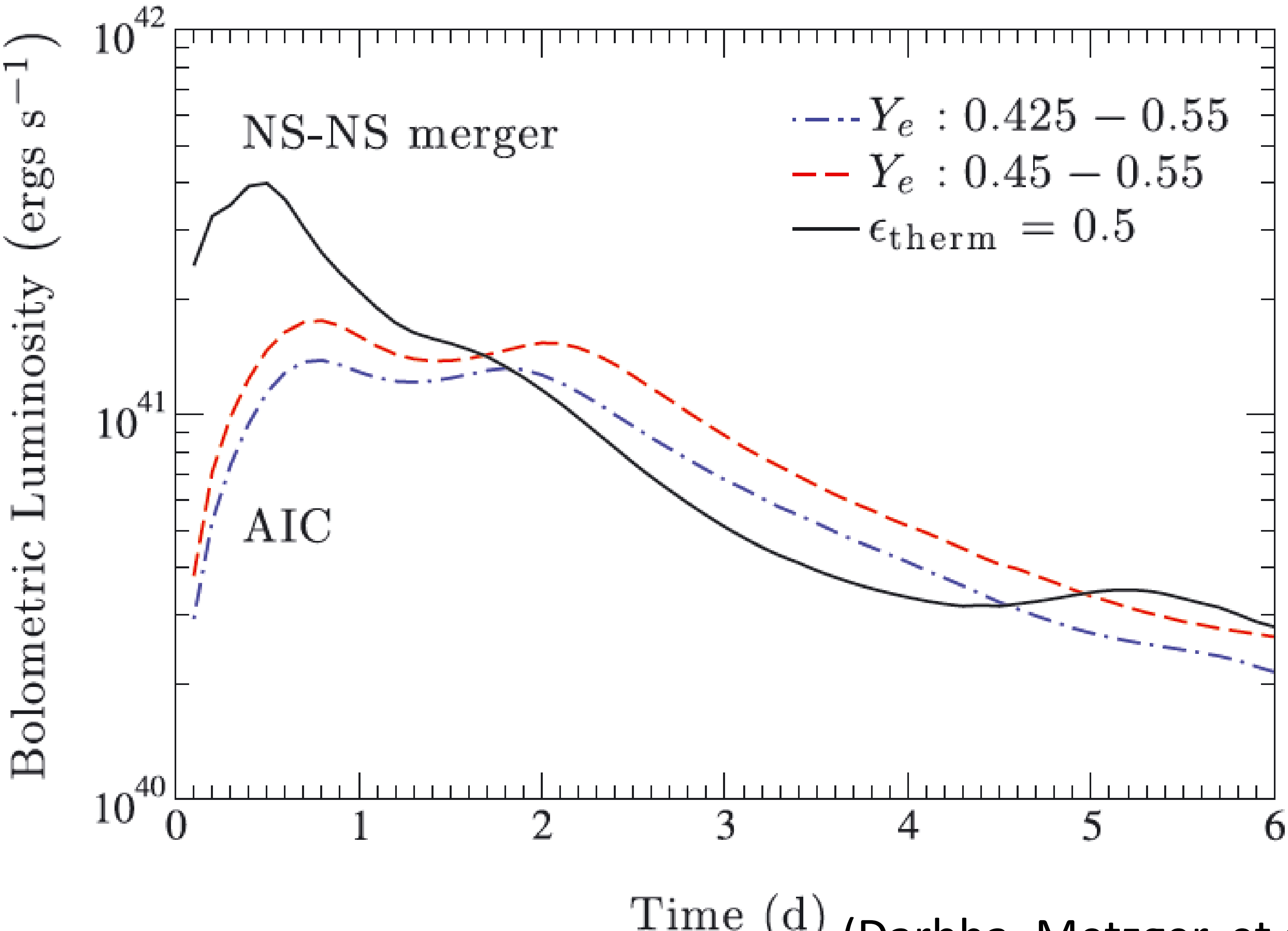
Shock Breakout of AIC:
X-ray, UV Transients





(Tolstov et al. 14)

AIC vs. NS merger



(Darbha, Metzger, et al. 10)

Neutron star-forming supernovae

1) Magnetar-forming supernovae
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2) Electron capture supernovae
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4) Close Binary Evolution → Double NSs