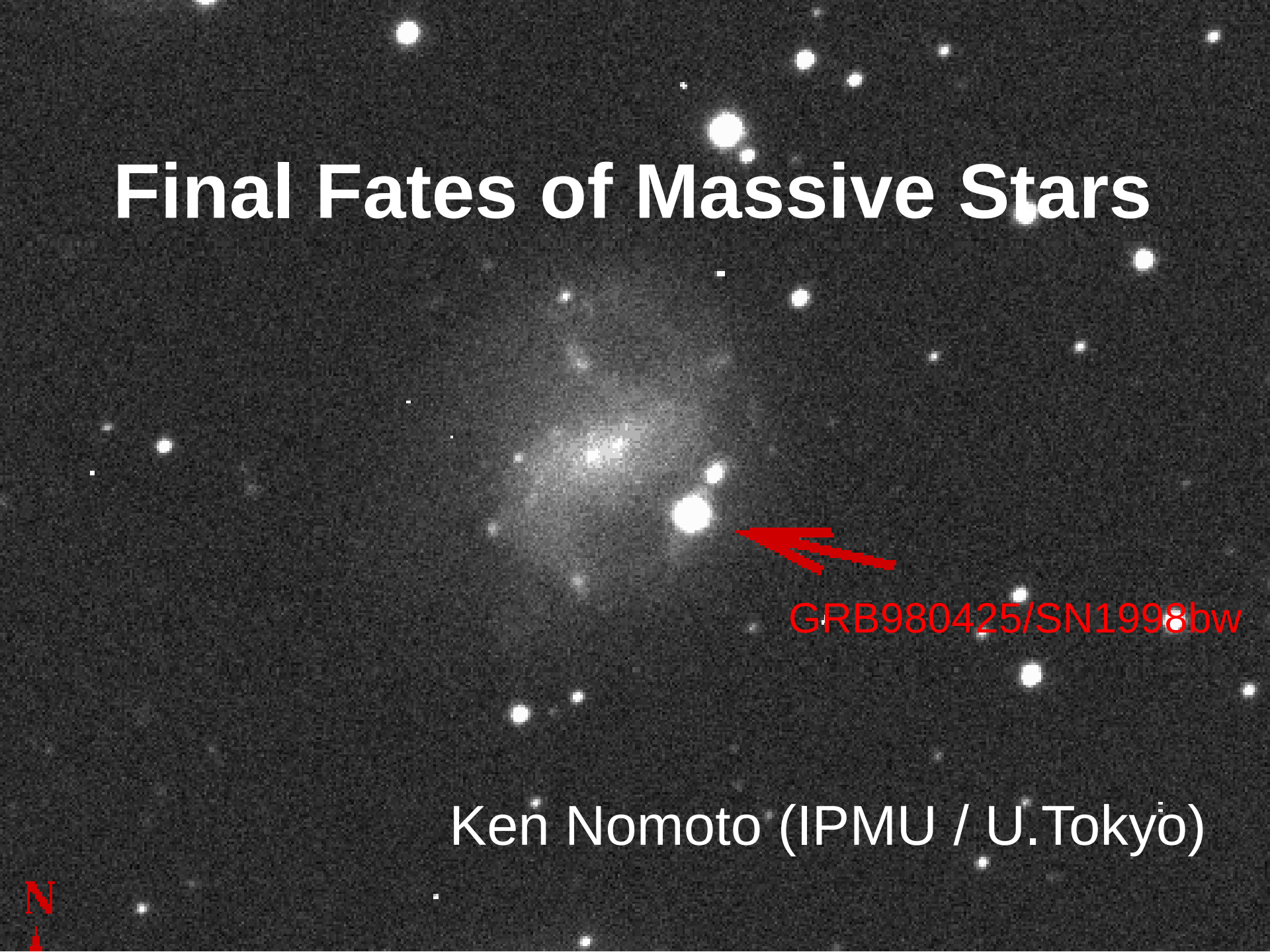
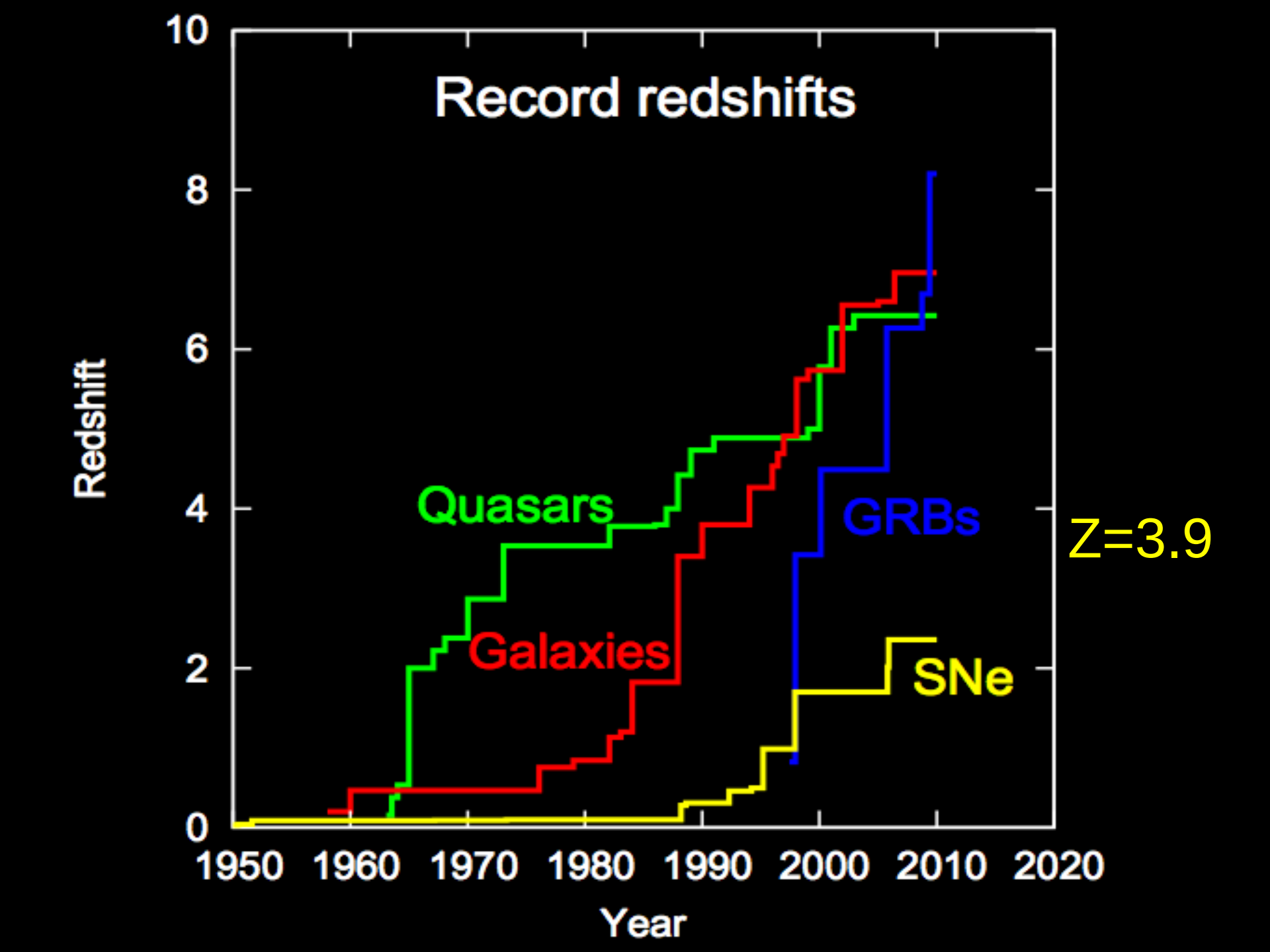
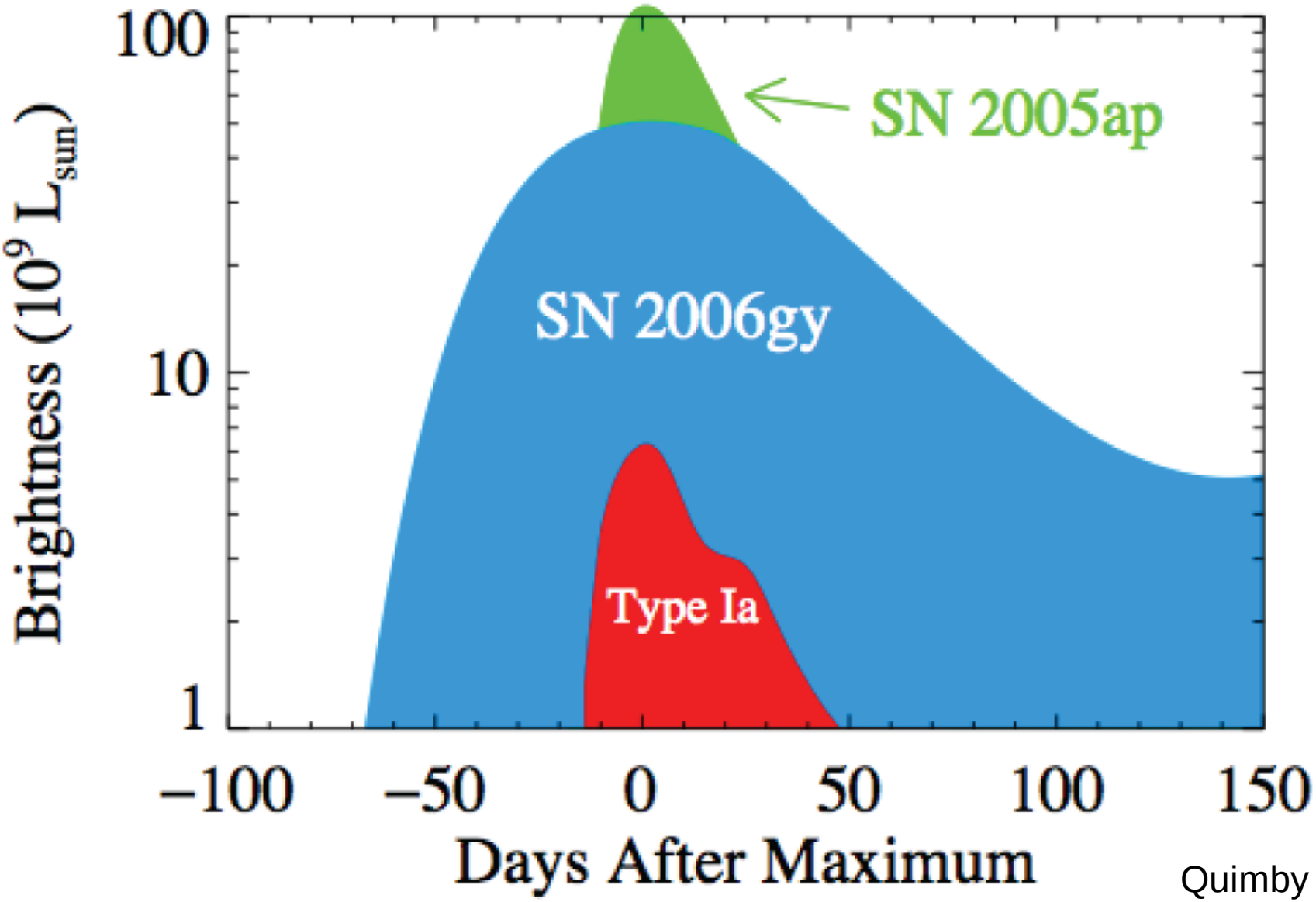
Final Fates of Massive Stars



Ken Nomoto (IPMU / U.Tokyo)


Record redshifts
Redshift
Year
10
8
6
4
2
0
1950
1960
1970
1980
1990
2000
2010
2020
Quasars
Galaxies
GRBs
SNe
Z=3.9

Superluminous Supernovae



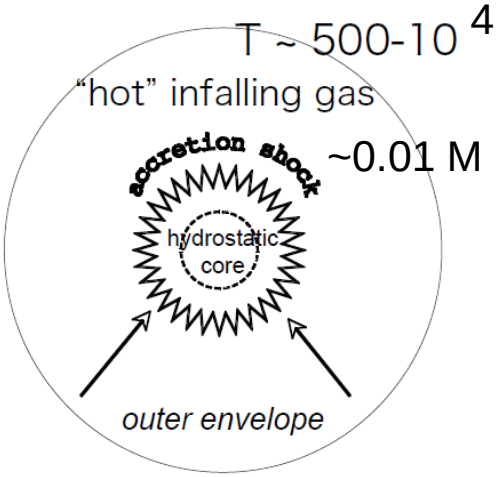
Quimby

Evolution and Explosion of (Very) **Massive** Stars

- First (Pop III) Stars :

  (very) massive?

- Superluminous supernovae



e.g., Omukai

How massive ?

- Star Formation ➔ small core + envelope ➔

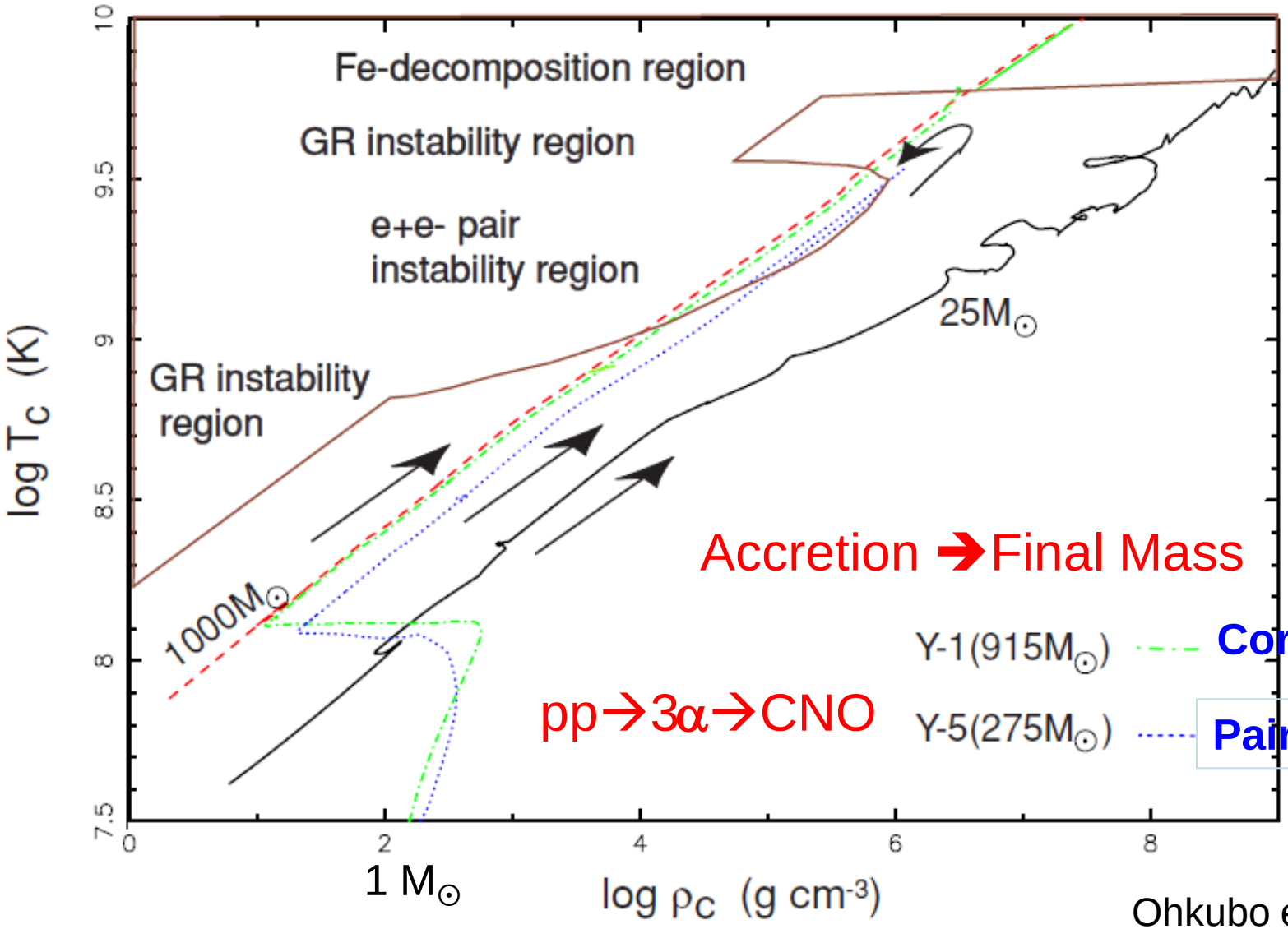
  Mass Accretion (metallicity, feedback,,,,)

- Mass Loss (wind, instabilities, ,,,)
- Stellar Collisions in Dense Star Clusters

➔ Massive Star + (dense) Circumstellar Matter

Pop III Stars: Mass Accretion ➔

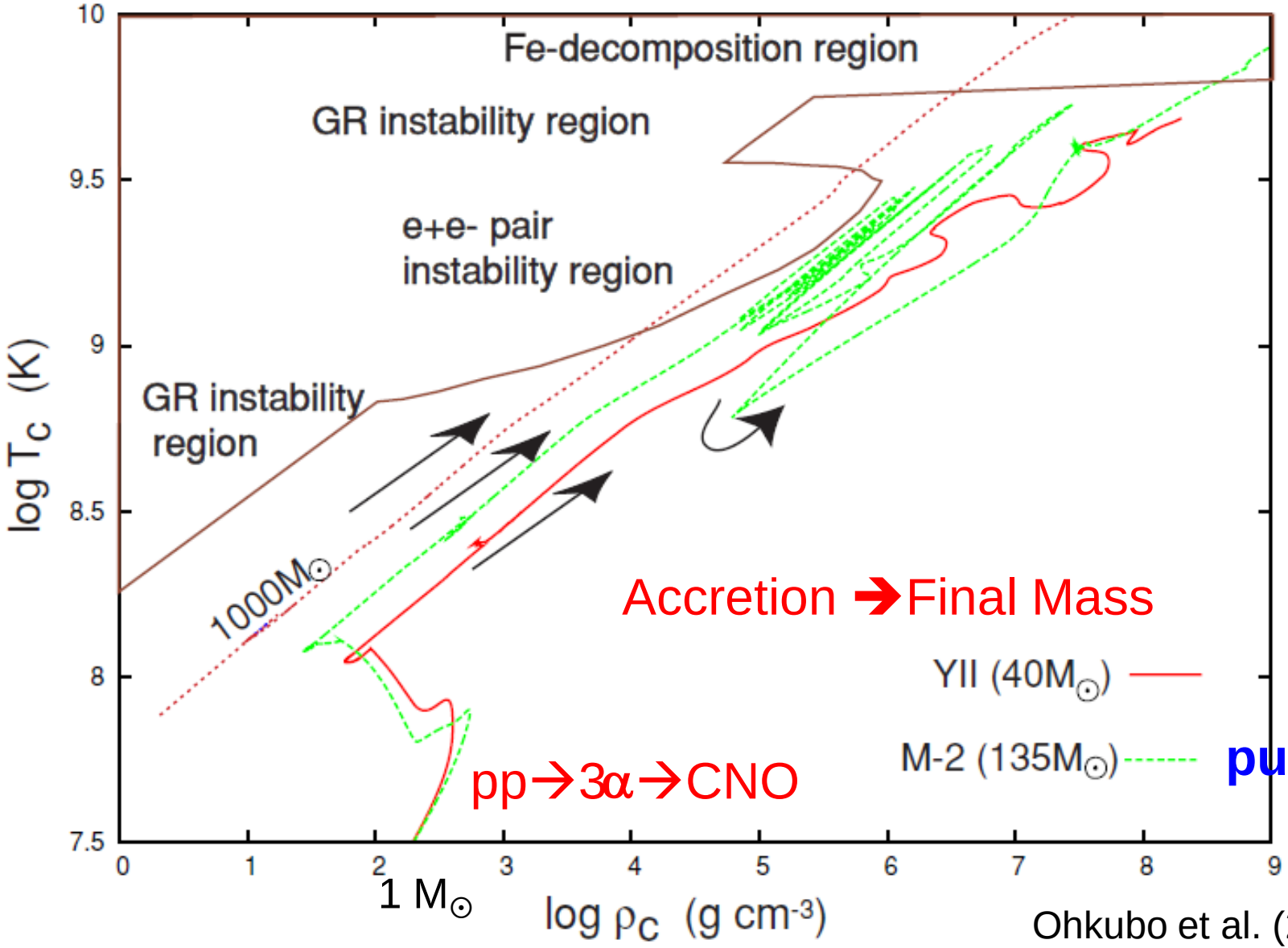
Pair-Instability (140-300 $M_\odot$) or **Core-Collapse**



Ohkubo et al. (2009)

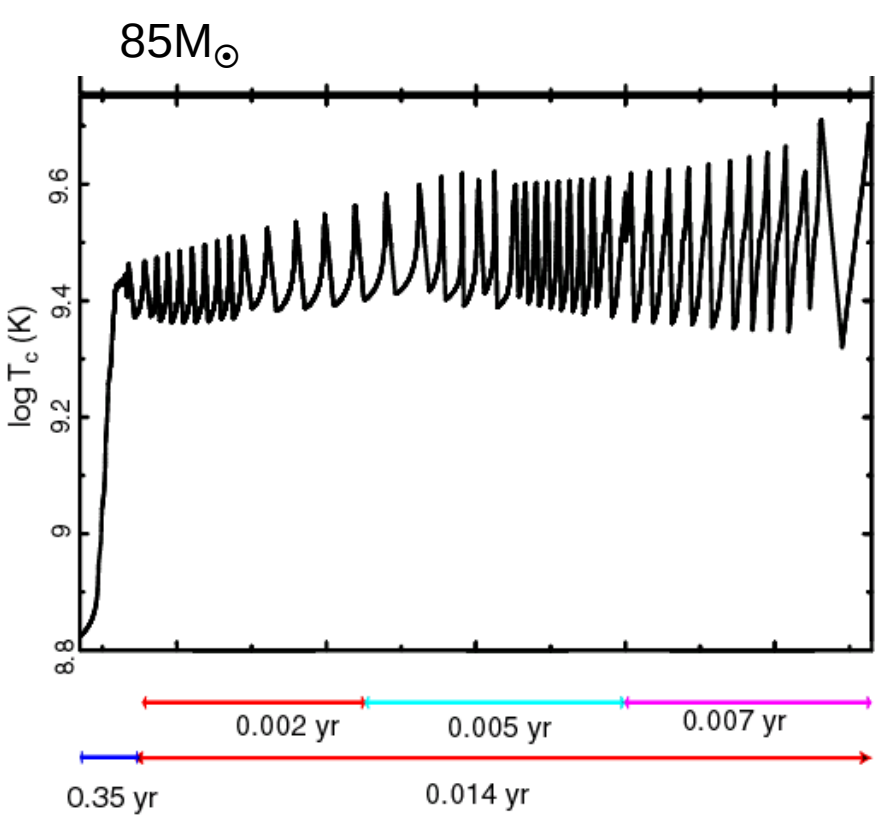
Pop III Stars: Mass Accretion ➔

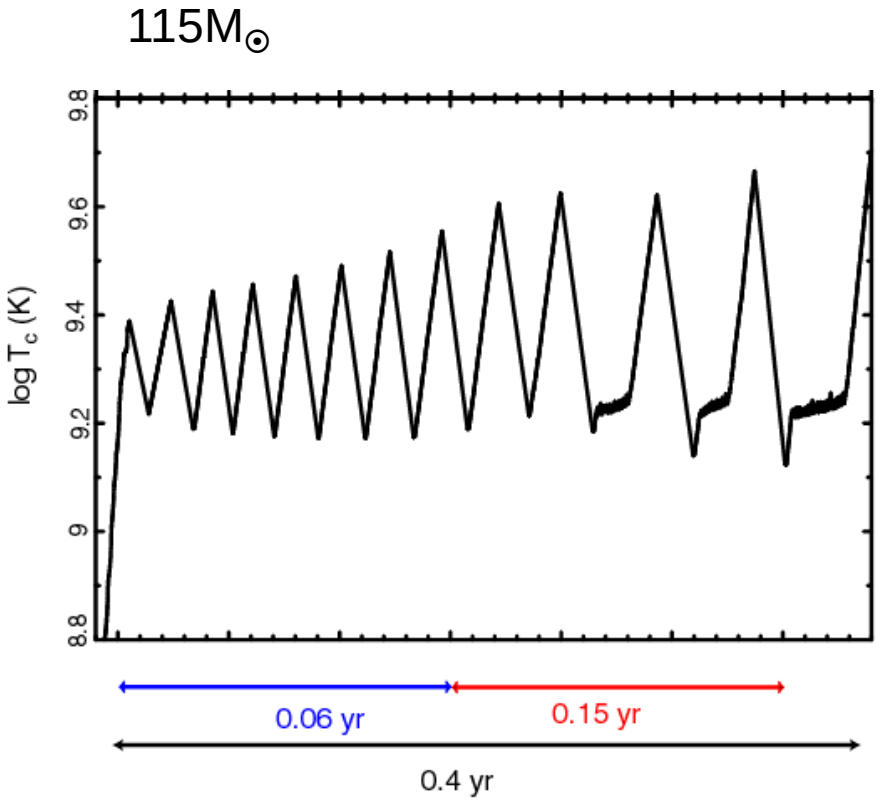
Core Collapse (40-140 $M_\odot$) ➔ LSN & GRB ?



Ohkubo et al. (2009)

Pulsation ($80M_\odot$<M<$140M_\odot$)



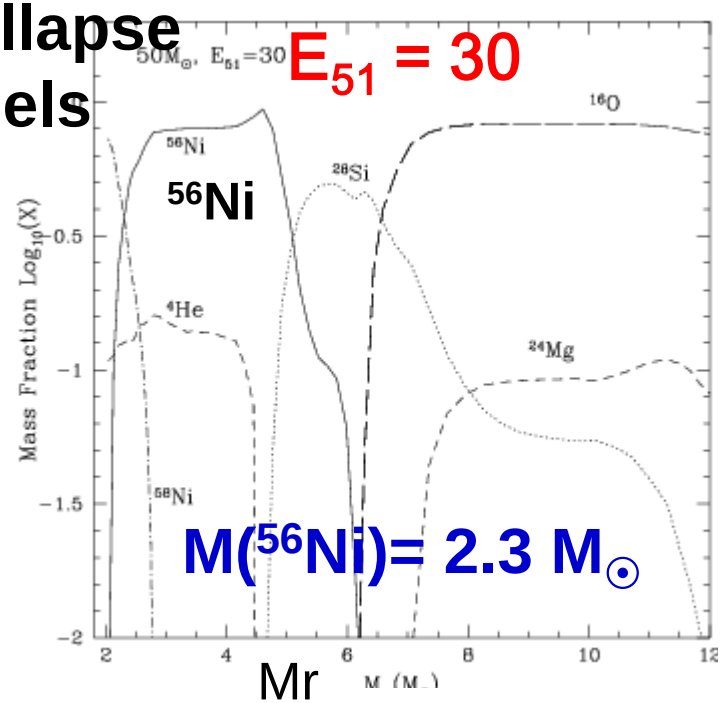


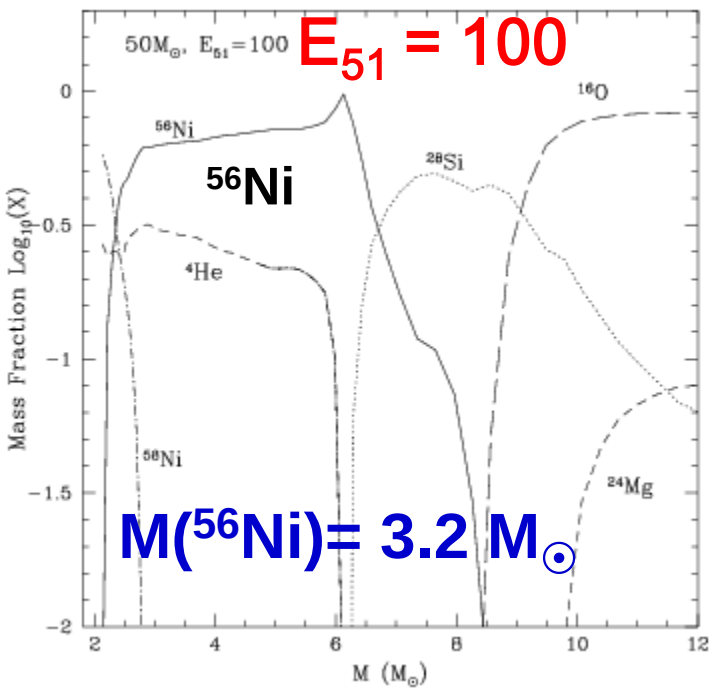
→ Fe Core Collapse

Ohkubo, Nomoto et al. (2009)
Heger & Woosley (2002)

Core-Collapse SN Models

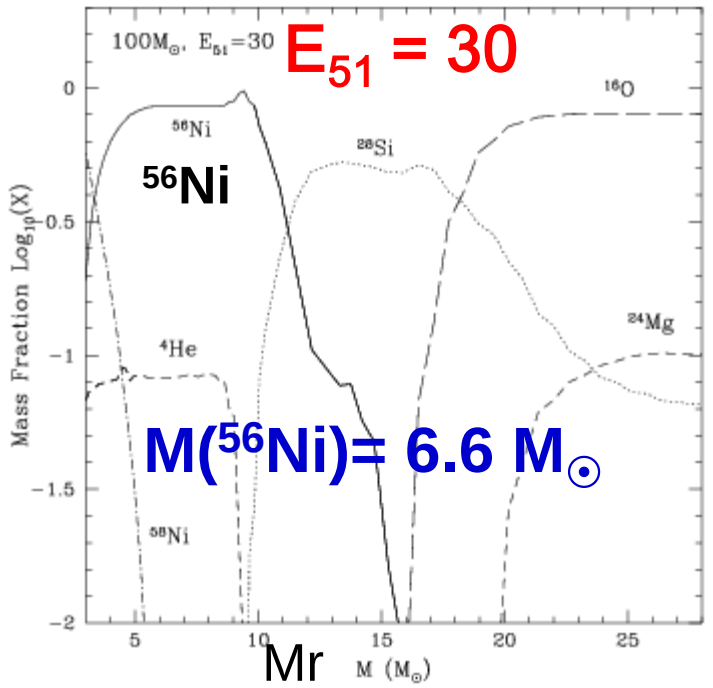
Log (Mass Fraction)

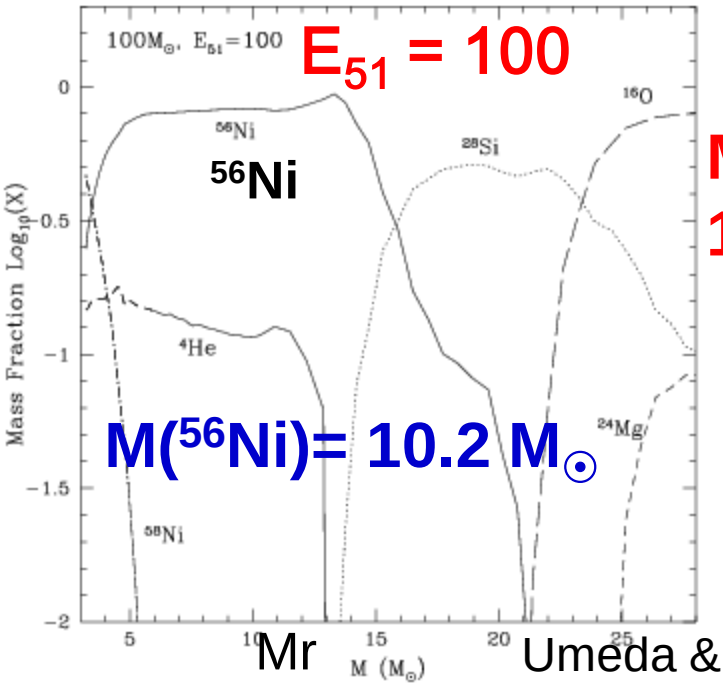




M = 50M⊙

Log (Mass Fraction)





M = 100M⊙

Umeda & Nomoto

Pop III Stars – Pop III GRBs – Pop III SNe ?

$M > 10^5 M_\odot$:SMS (Super Massive Stars)

→ GR instability → Collapse

$M \sim 300 - 10^5 M_\odot$:

→ Collapse (& Explosion) → IMBH → SMBH ?

→ **Pop III GRBs ?**

$M \sim 140 - 300 M_\odot$:

→ **Pair Instability SNe** → Complete Disruption

$M(^{56}Ni) < 40\ M_\odot$

$M \sim 8 - 140 M_\odot$:

→ Core Collapse

→ **Pop III GRBs, Hypernovae**

→ **SNe II** **$M(^{56}Ni) < 10\ M_\odot$**

~ 40 – 140 $M_\odot$ Stars

- Nuclear Instability (O,Si burning)
  Pulsational Mass Ejection
  (core materials ?)
  LBV-connection ?
- Formation of Dense Circumstellar Matter
- Propeties of GRBs ? (also M >300 $M_\odot$)

Unusual SNe vs. Very Massive Stars

Superluminous SNe (type Ic, II) (stellar mass?)

Pair Instability ? $M(^{56}Ni) < 40\ M_{\odot}$

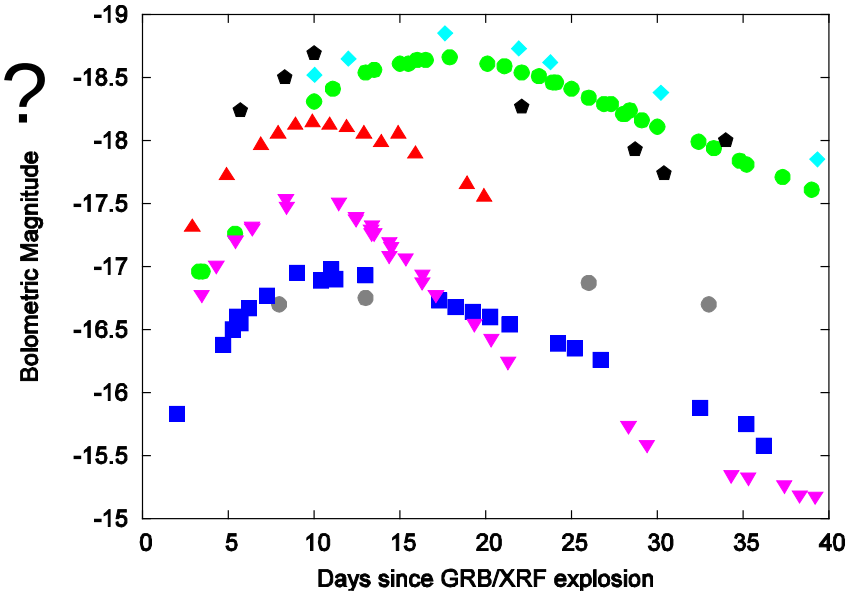
Pulsational Instability ? ➔ Interaction ?

Core-Collapse ? **GRB ?** $M(^{56}Ni) < 10\ M_{\odot}$

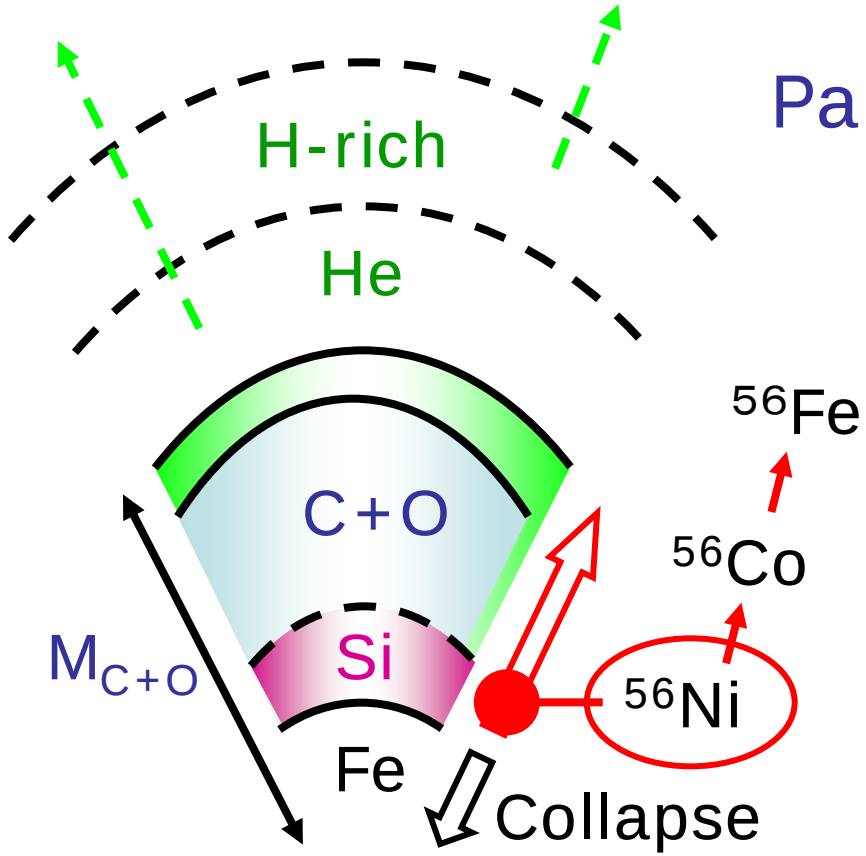
Magnetar ? **XRF ?**

Circumstellar Interaction ?

SN 1999as ?



CO Star Models for SNe Ic



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

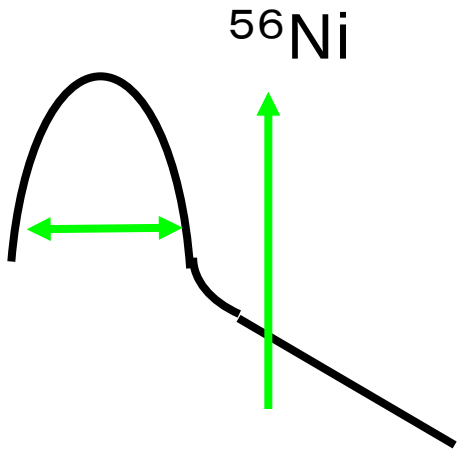
Light Curve — Spectra

$$\tau \sim [\tau_{dyn} \bullet \tau_{diffusion}]^{1/2} \sim \left(\frac{R}{V} \bullet \frac{\kappa M_{ej}}{R c}\right)^{1/2}$$

$E \propto M_{ej}$

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

$E \propto M_{ej}^{3}$



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

GRB-Supernovae

Three GRB－SNe = all Type Ic Hypernovae

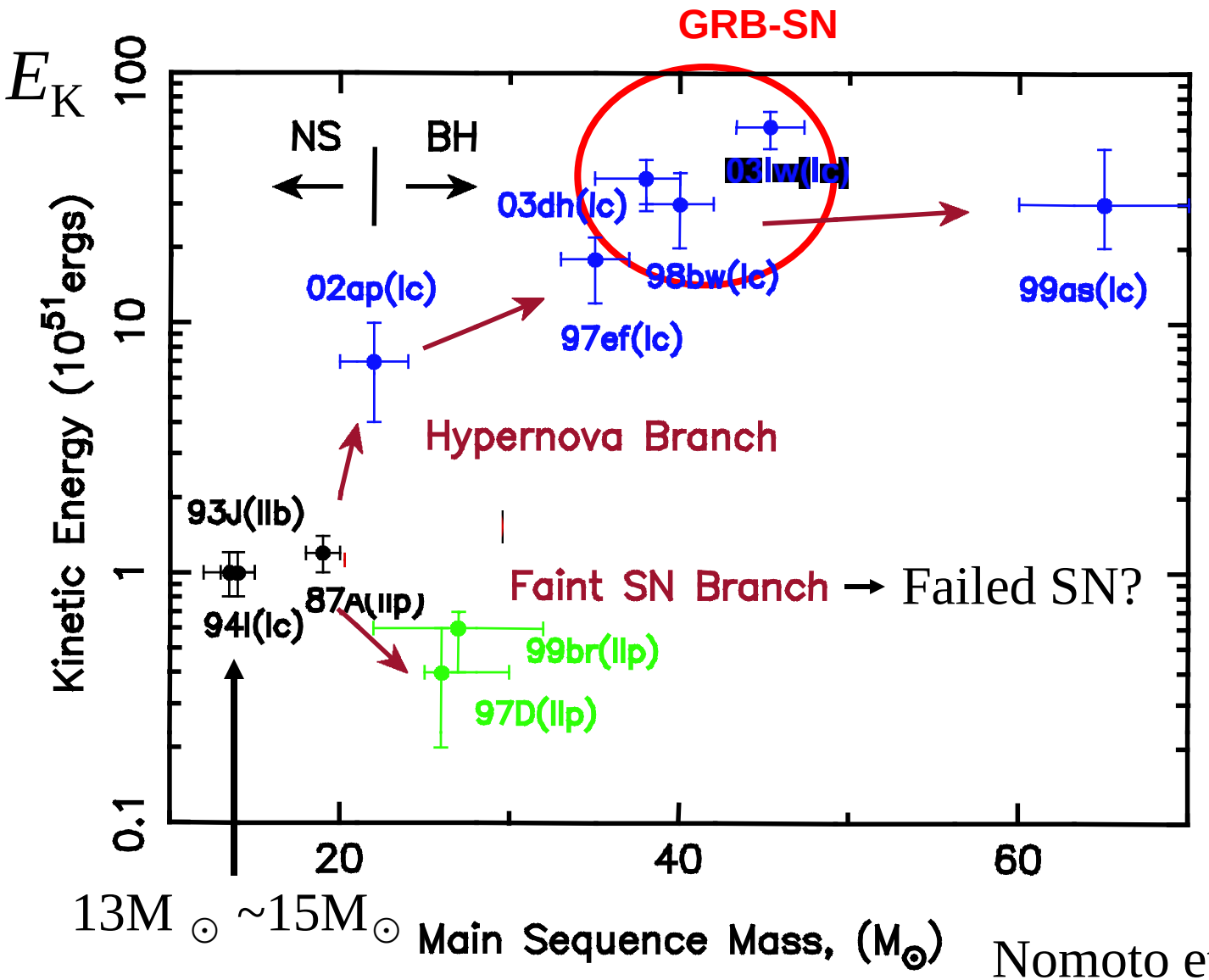
$E > 10^{52}$ erg (～10×normal SN)

Large M_{ms} →Black Hole Forming SNe

Aspherical

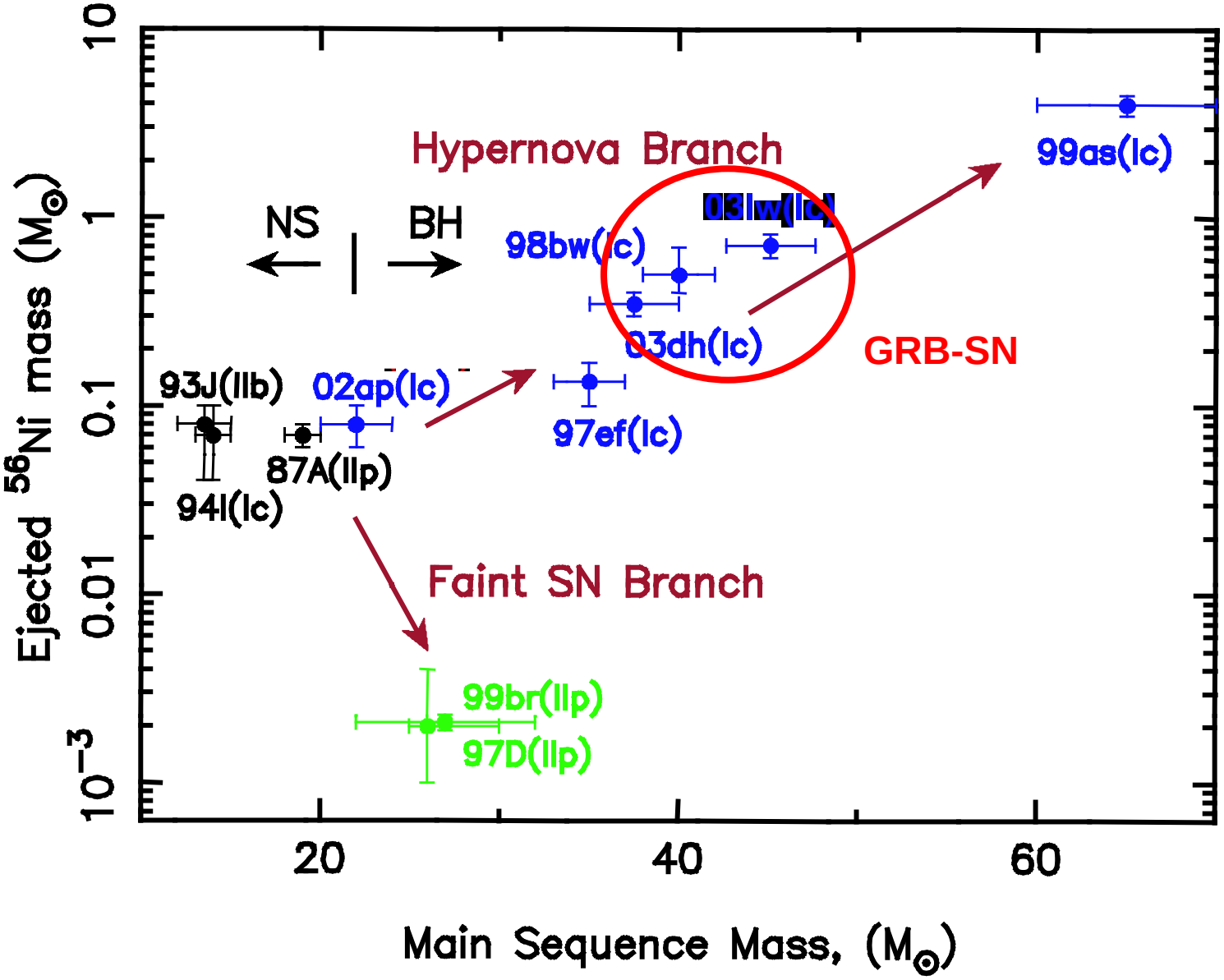
GRB	SN	$M_{CO}/M_{\odot}$	$M_{ms}/M_{\odot}$	$E/10^{51}$erg	$M(^{56}Ni)/M_{\odot}$
980425	1998bw	14	40	30	0.4
030329	2003dh	11	35	40	0.35
031203	2003lw	16	45	60	0.55

Hypernovae/Faint SNe



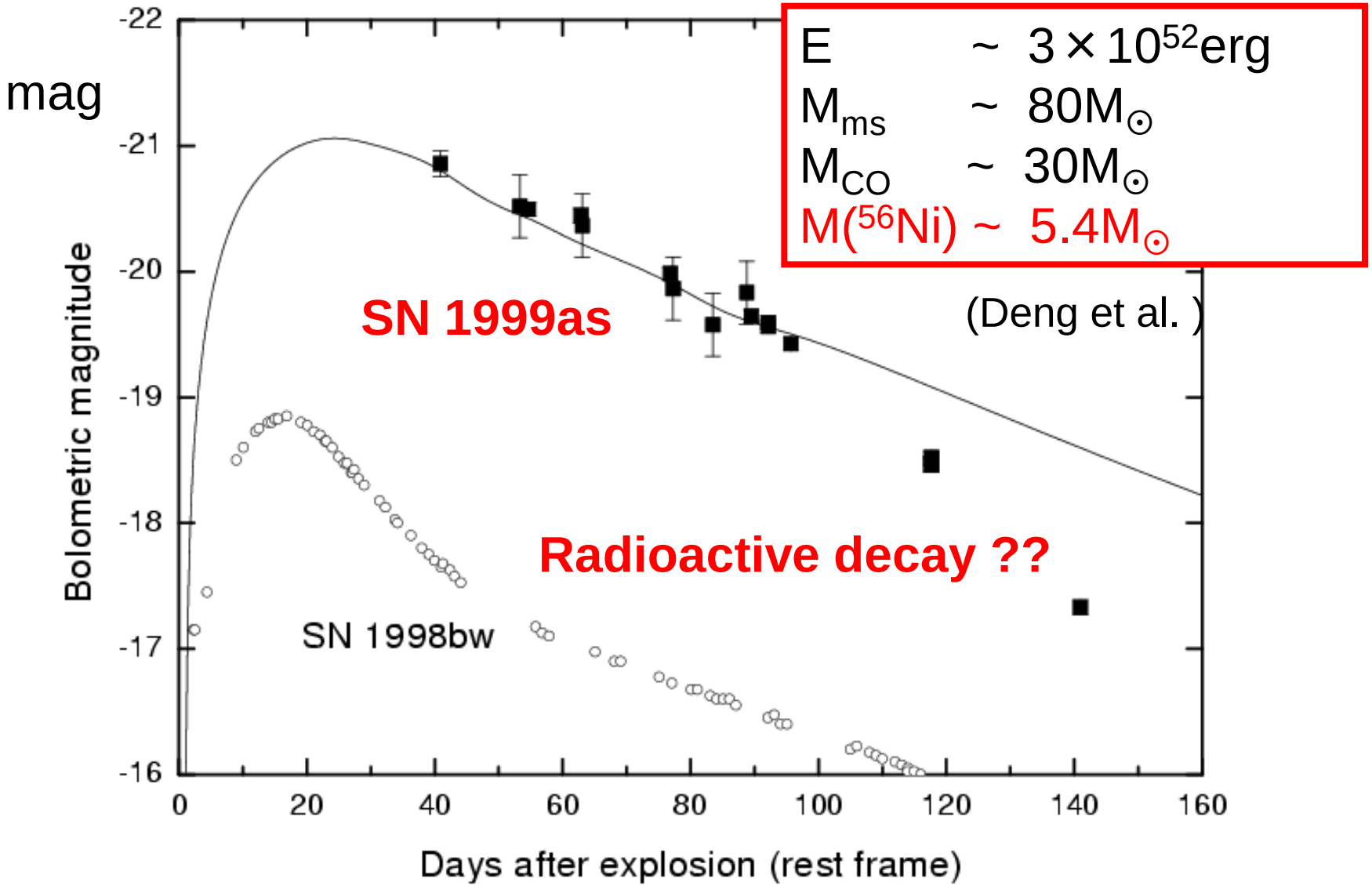
Nomoto et al. (2003)

Hypernovae/Faint SNe (^{56}Ni mass)

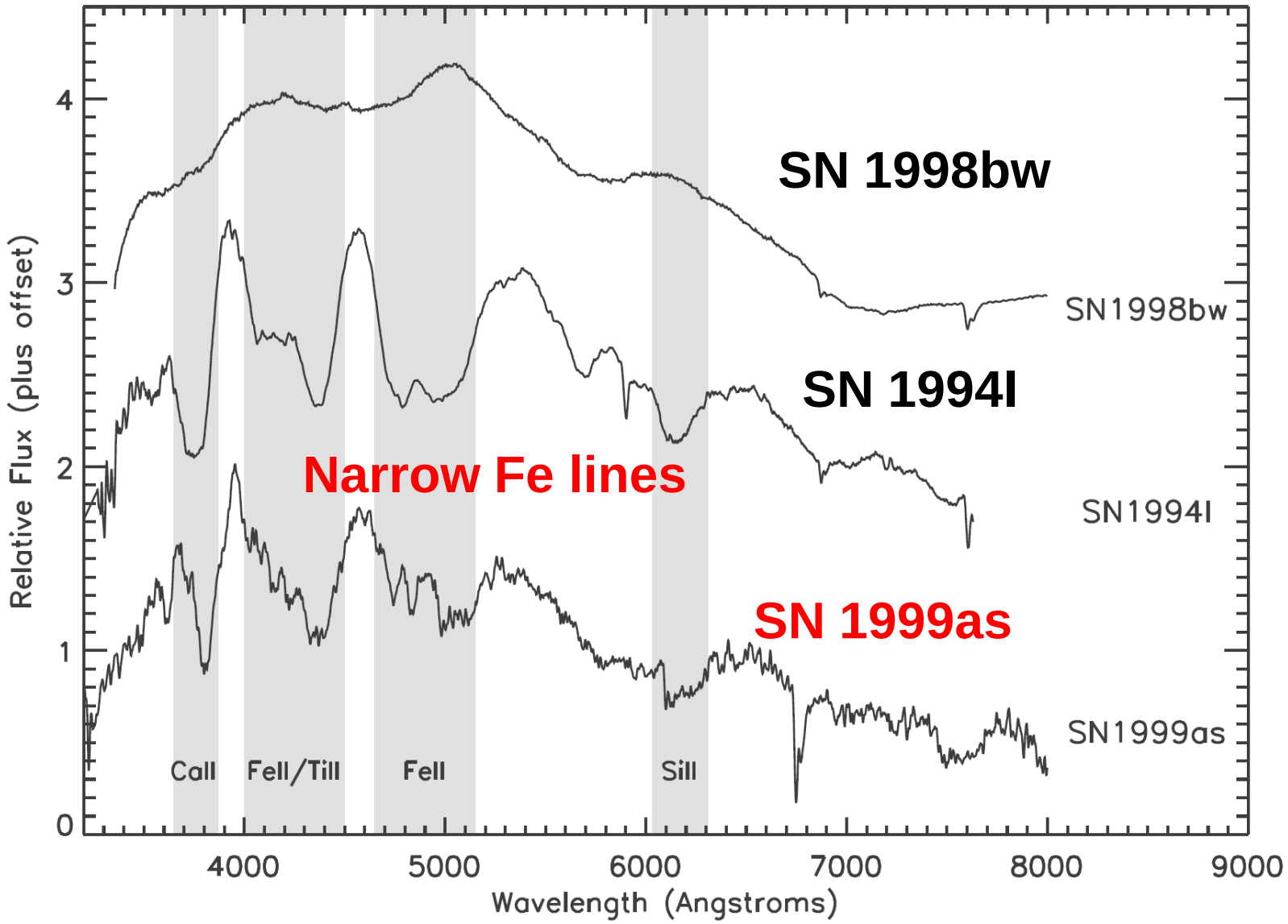


Superluminous SN: 1999as @z=0.127

(Knop et al.)



SN 1999as: Type Ic Spectrum

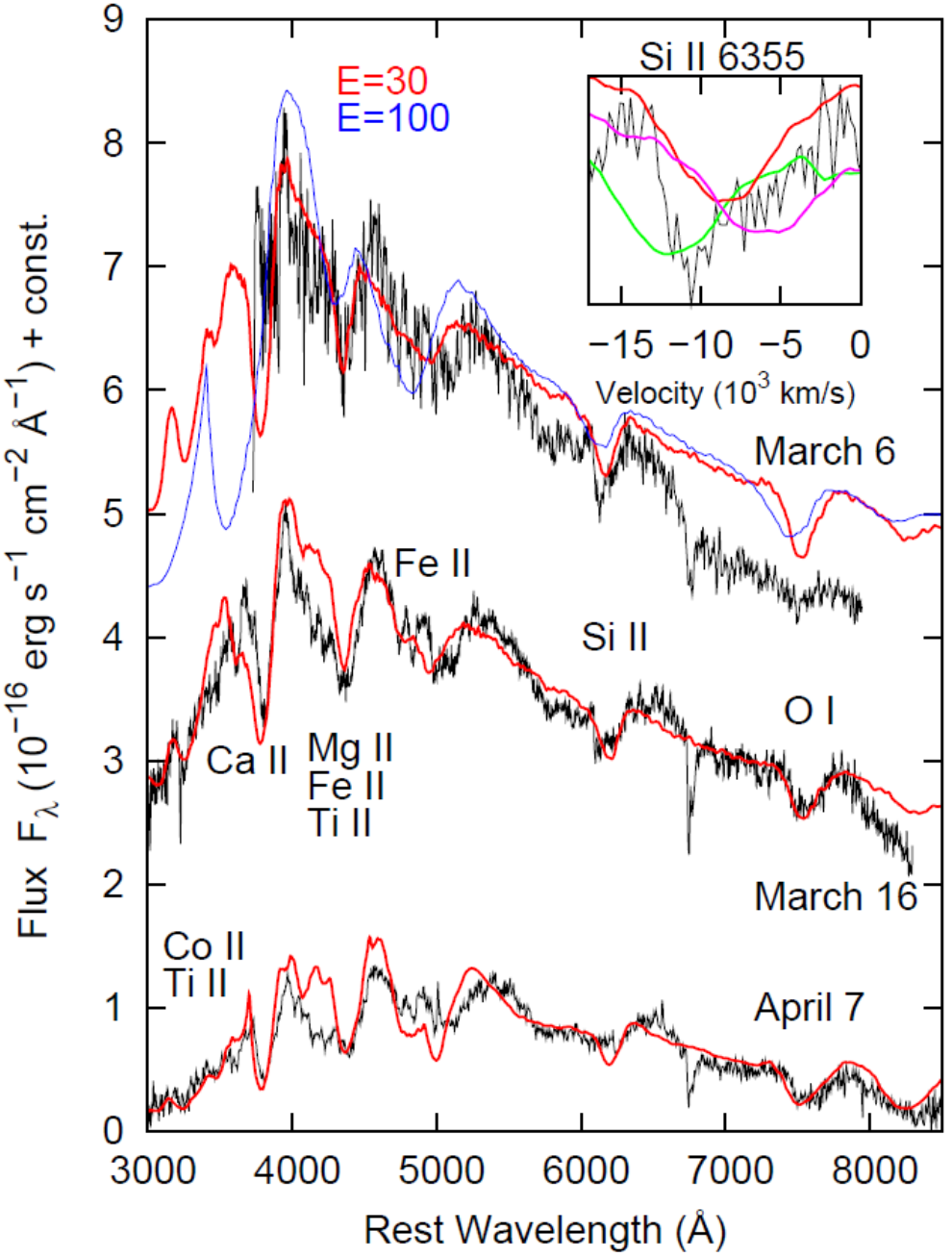


Nugent et al.

SN Ic1999as :

Synthetic Spectra

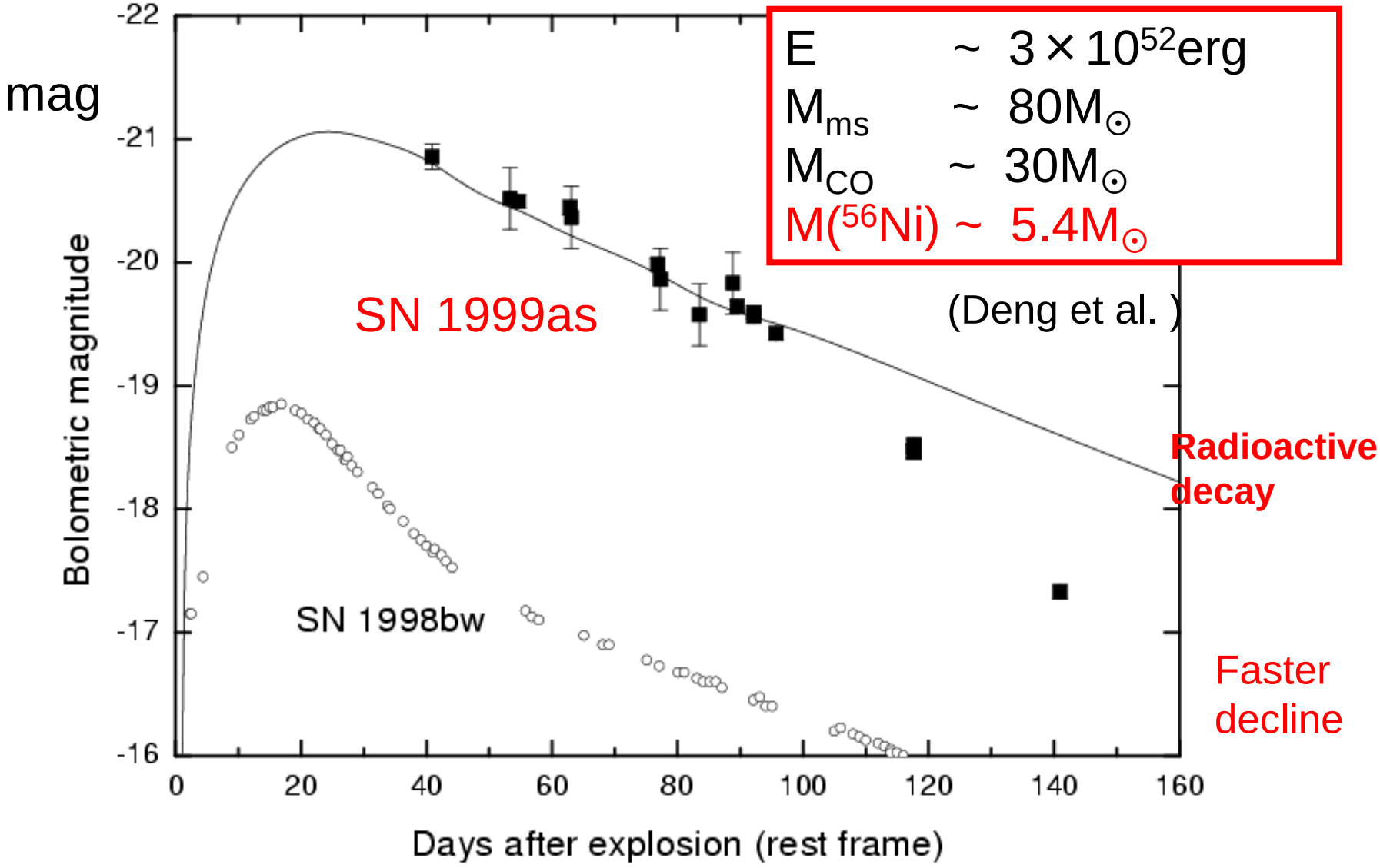
- E = 3e52 erg
- Mc+o = 30 $M_{\odot}$



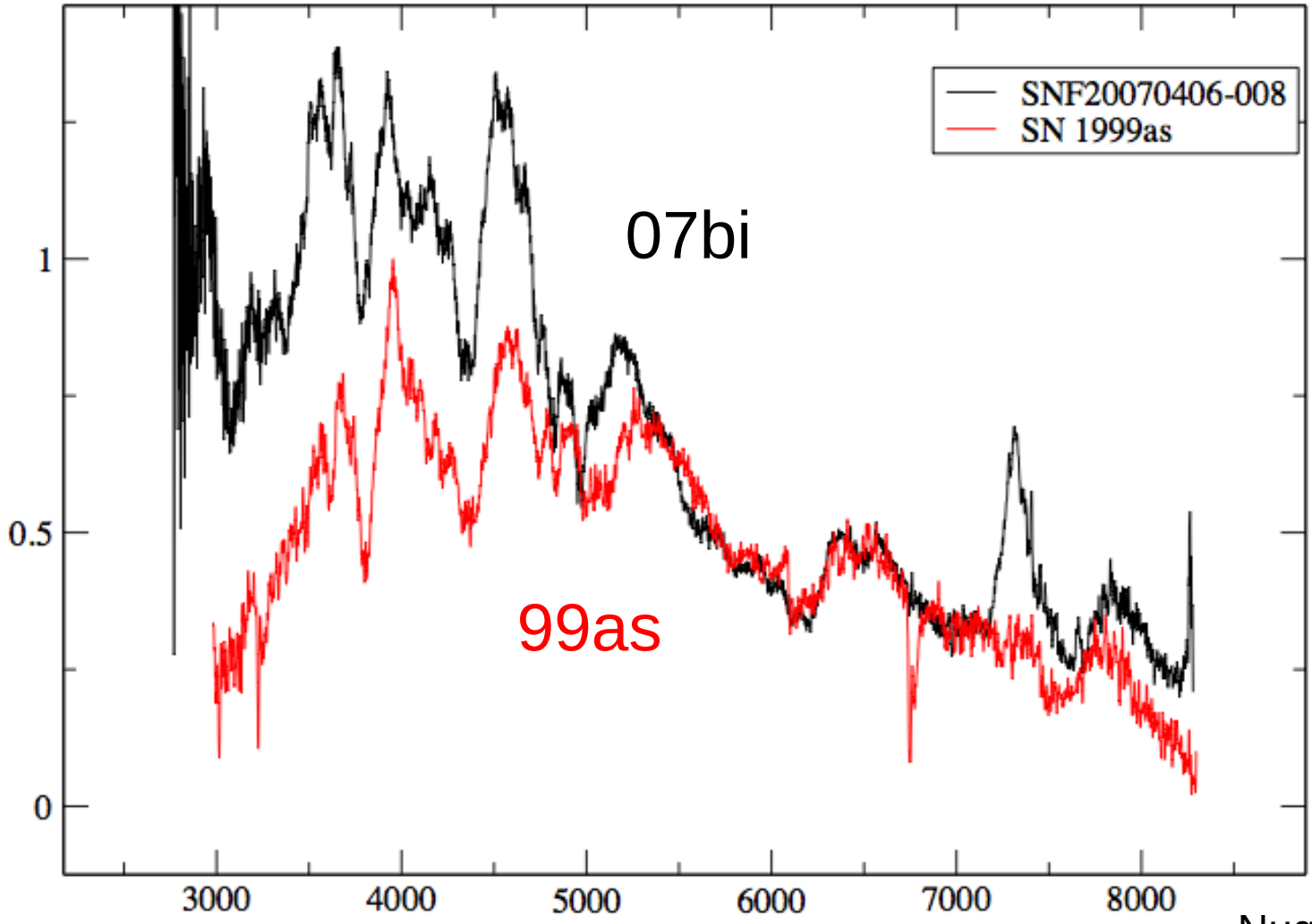
Deng et al.

Superluminous SN: 1999as @z=0.127

(Knop et al.)



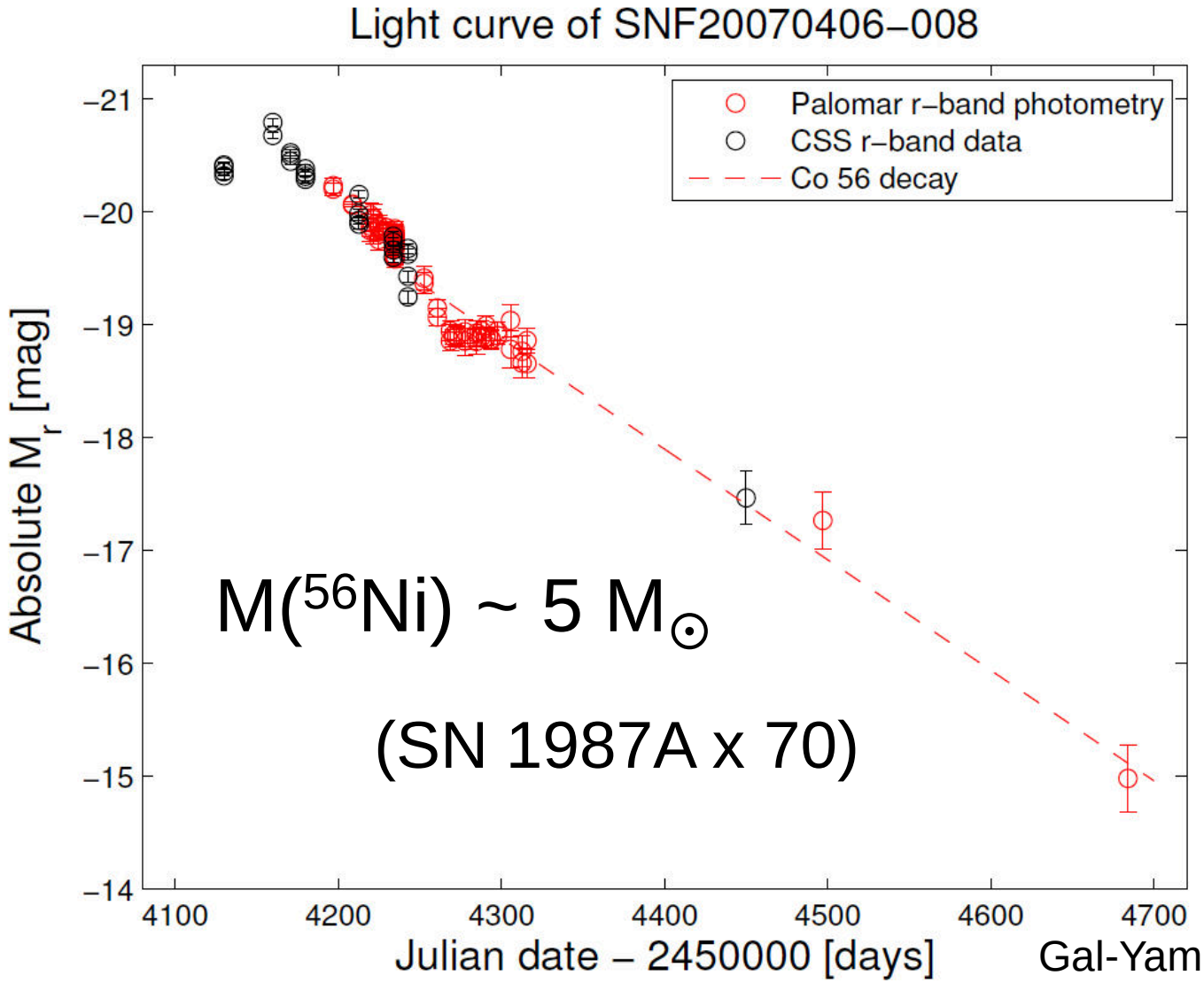
SLSNe Ic 2007bi vs. 1999as



Nugent et al.

Superluminous SN

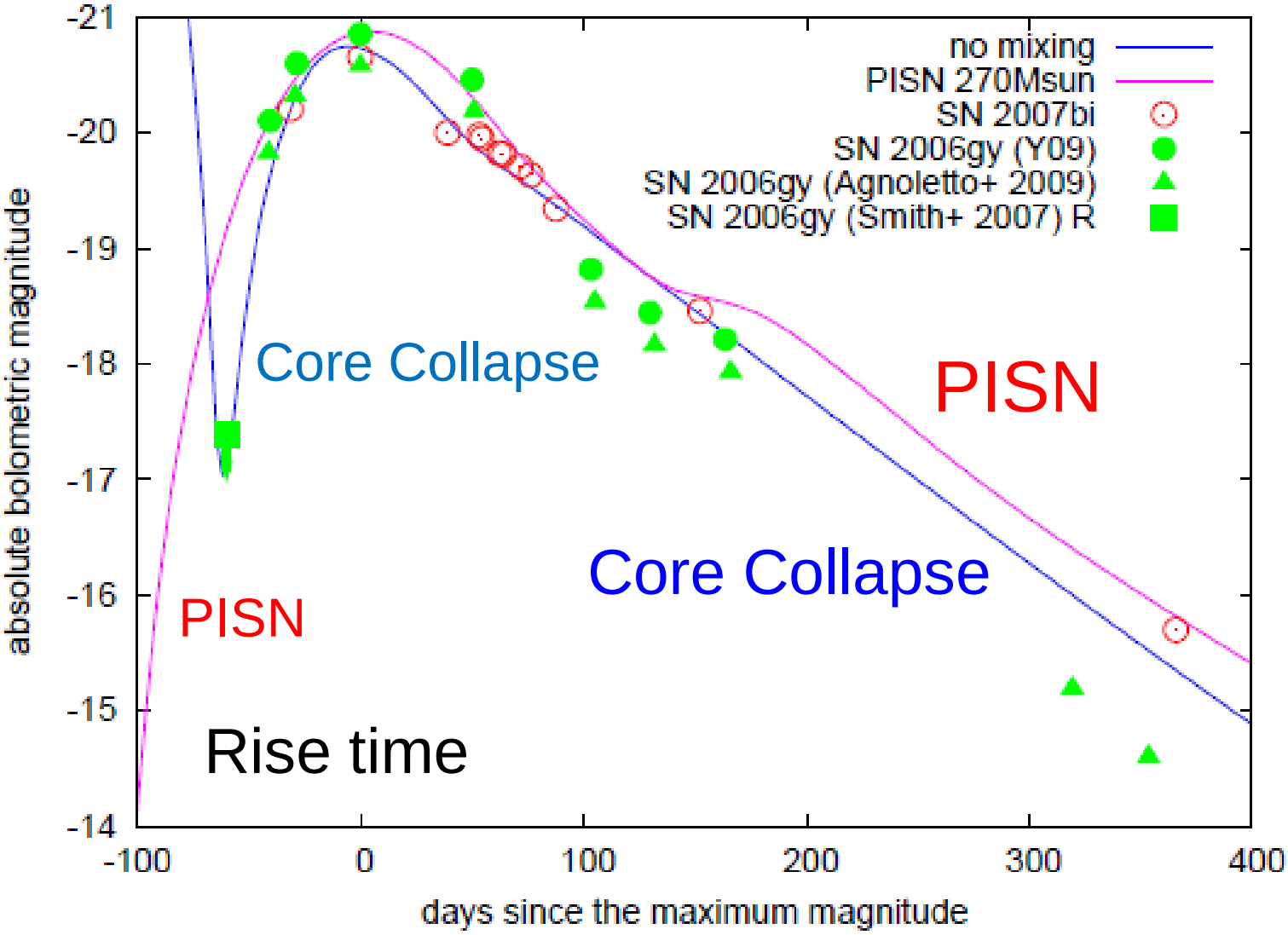
SN Ic 2007bi (Pair-Instability?)



Gal-Yam et al. 2009

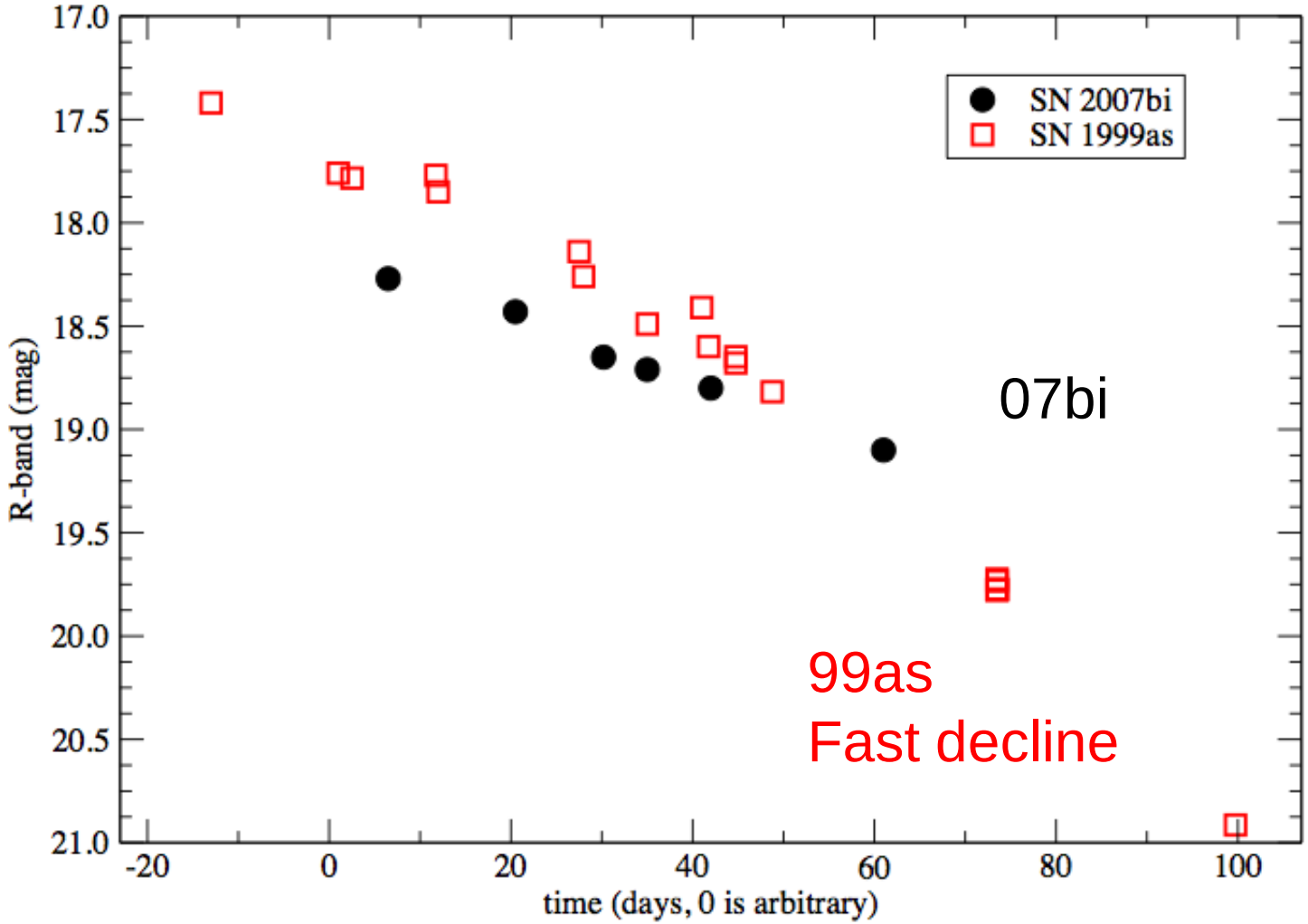
SN 2007bi

Core-Collapse vs. PISN



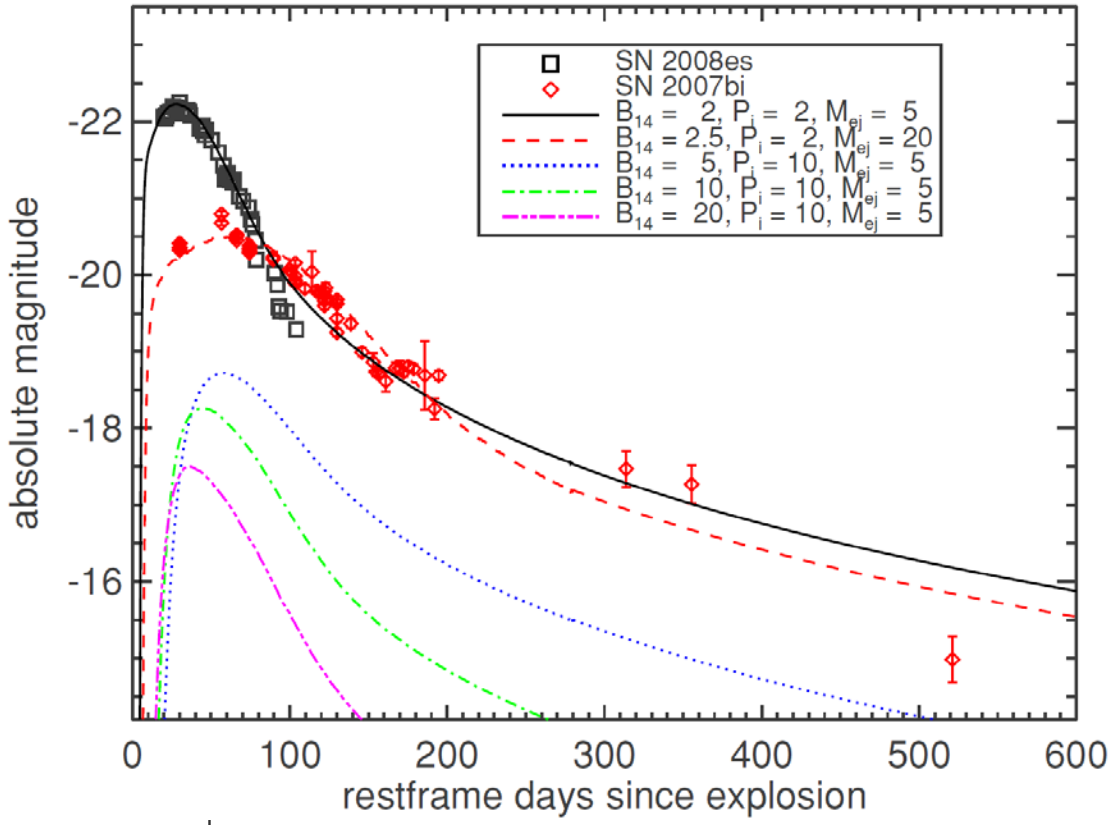
Moriya et al.

SNe 1999as vs. 2007bi

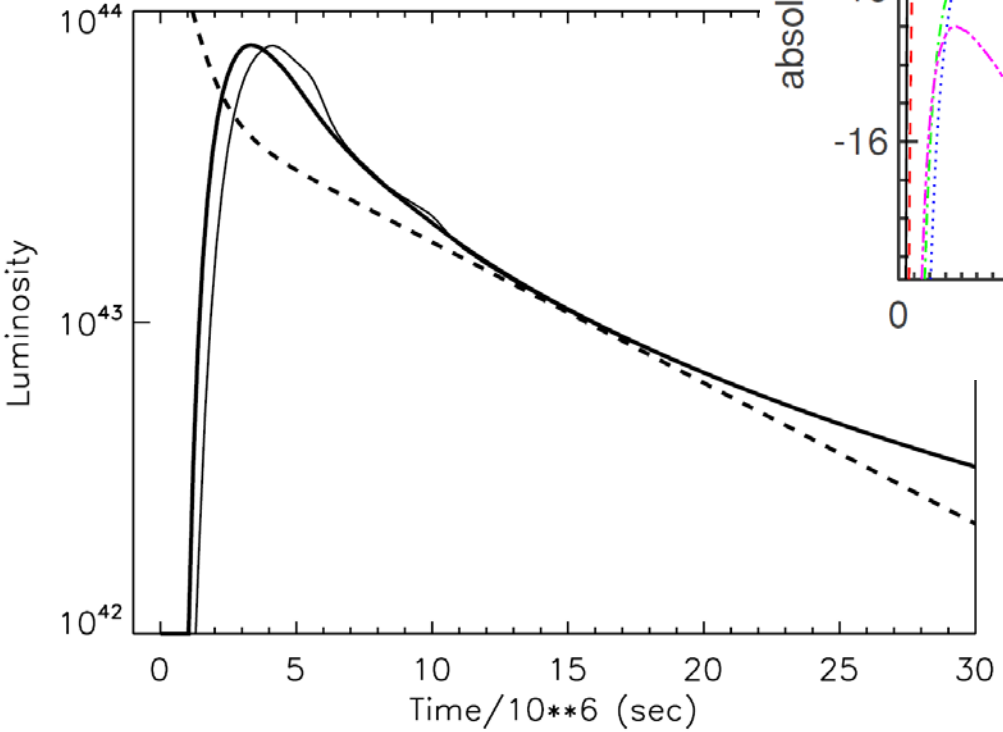


Nugent et al.

Magnetar model



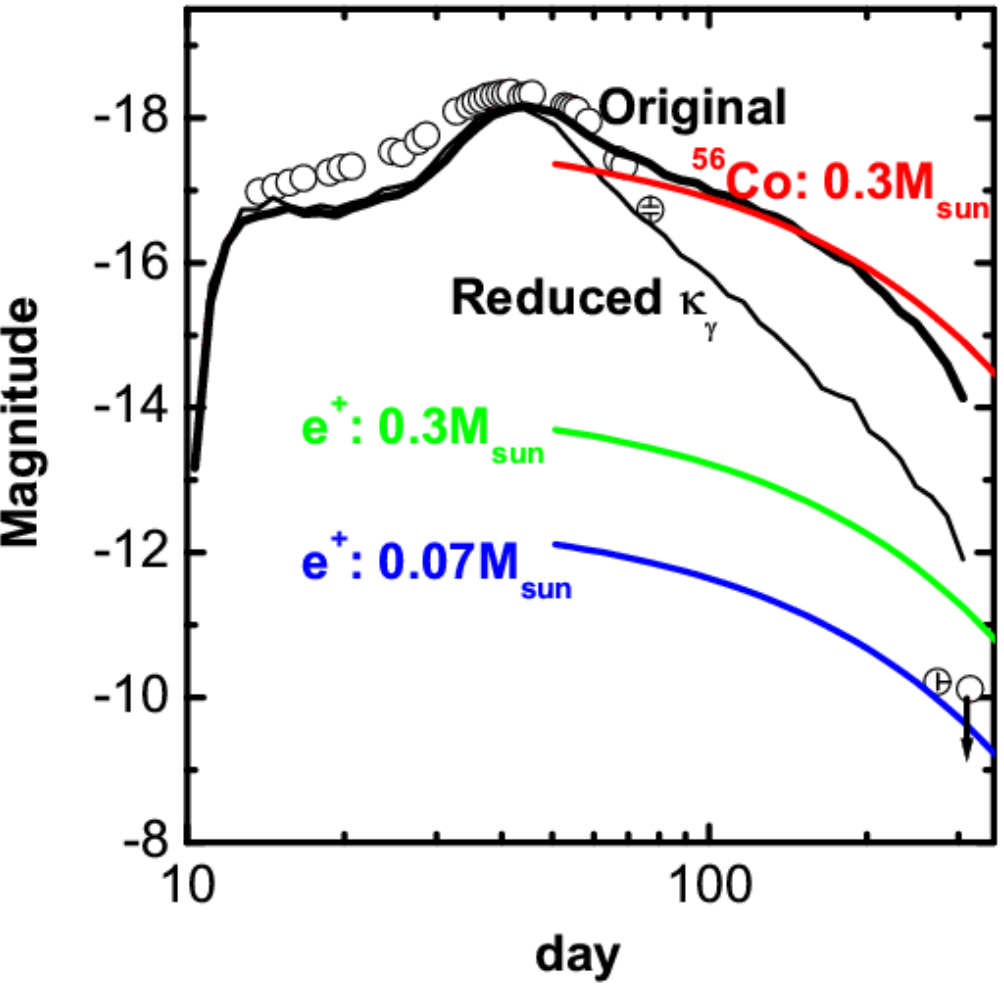
Kasen & Bildsten 2010

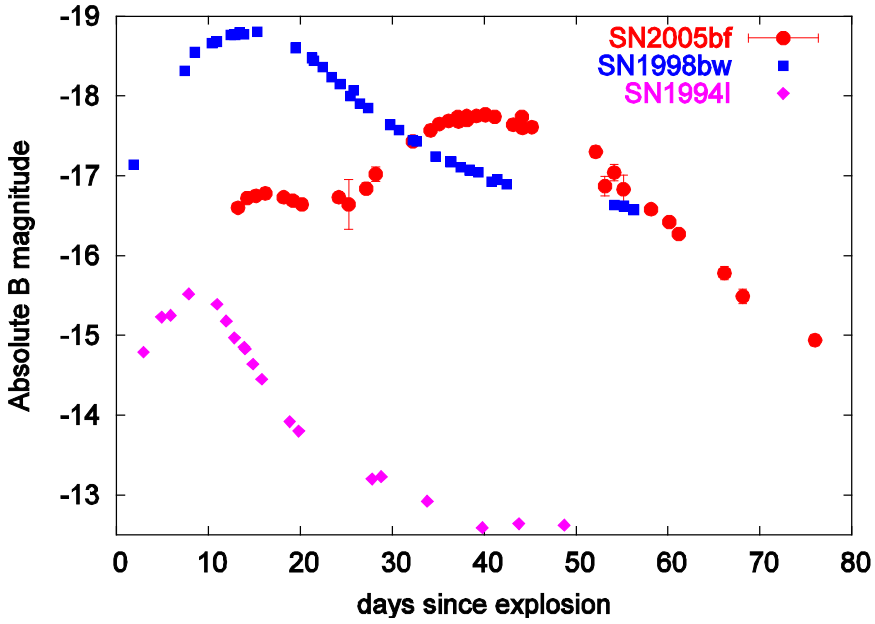


Woosley 2010

Magnetar ??

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





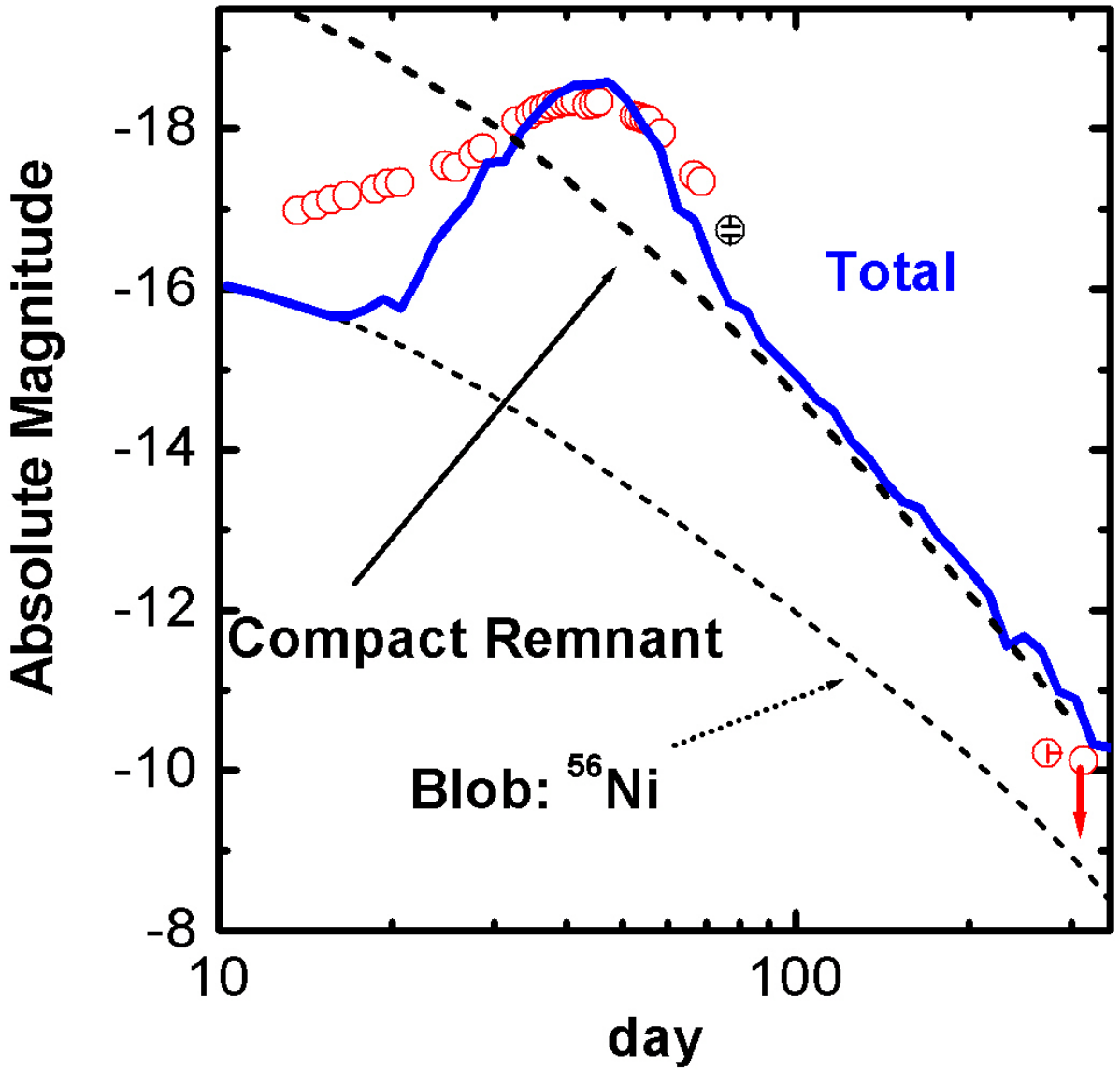
SUBARU obs

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

Maeda et al. (2007)

1^{st} peak: ^{56}Ni decay

2^{nd} peak: Magneter ?



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

$L_0=8\times10^{43}$erg/s(*)

$T_0=60$day

$\beta = -4$ (n = 2)

(*) If dipole, e.g.,

$B_0\sim10^{15}$ G, $P_0\sim10$ ms

Maeda et al. (2007)

Magnetar – X Ray Flash – Optical Light Curve ?

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

  Small Oxygen Mass < 1.3 $M_\odot$ (Pian+, Chornock+ Bufano+)

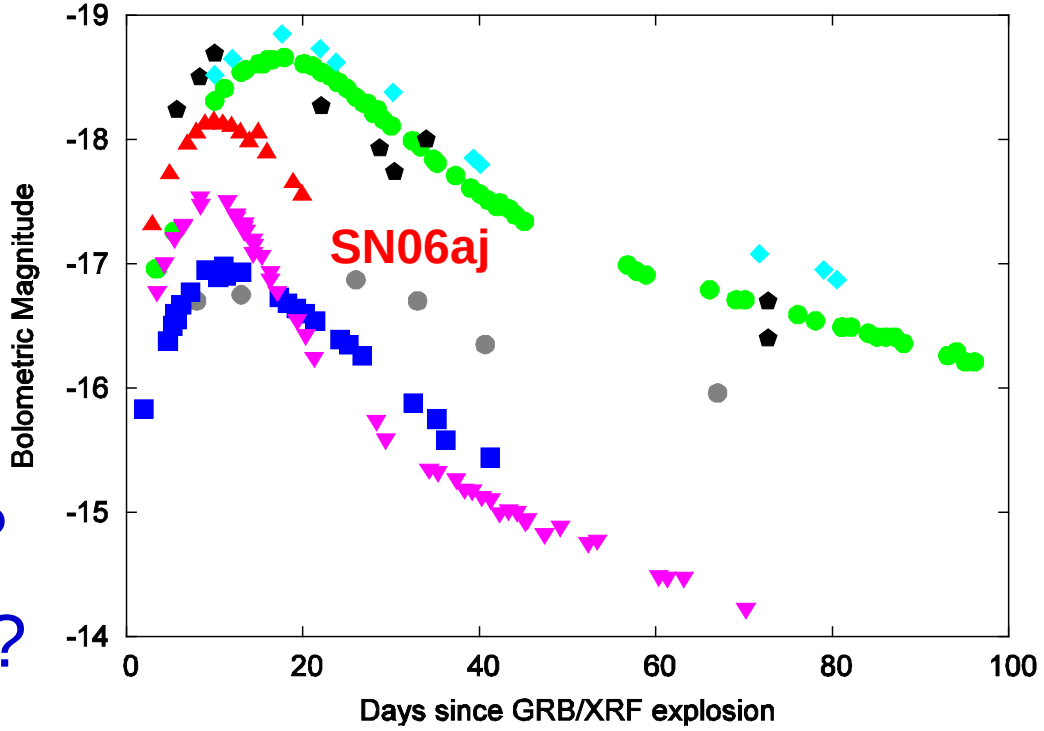
  $M_{ej} \sim 2\ M_\odot$ ($M_{ms} \sim 20\ M_\odot$)

  $E \sim 2 \times 10^{51}$ erg

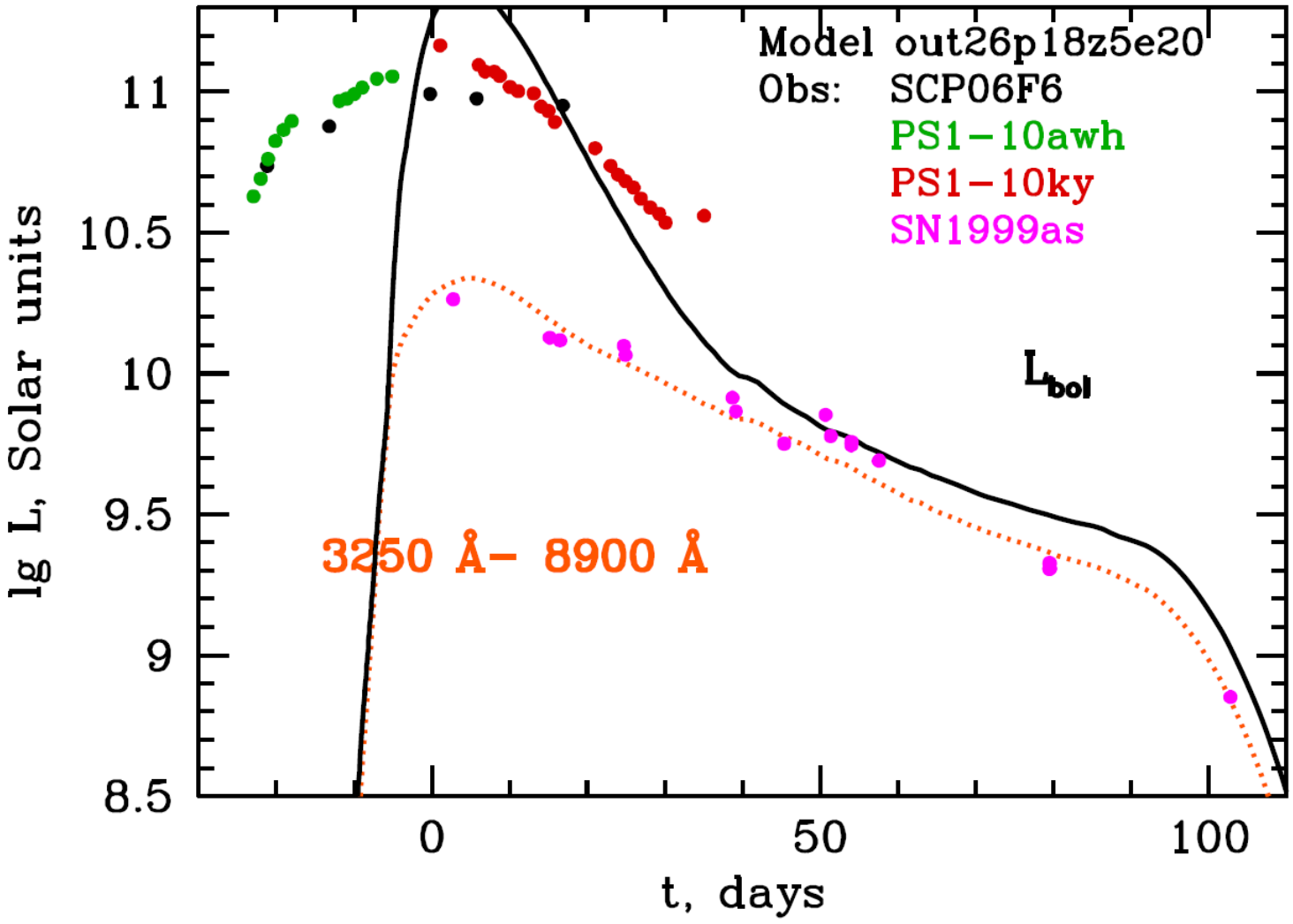
  $M(^{56}Ni) \sim 0.2 M_\odot$

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

  Magnetar-powered LC?



SN99as: **Circumstellar Interaction ??**



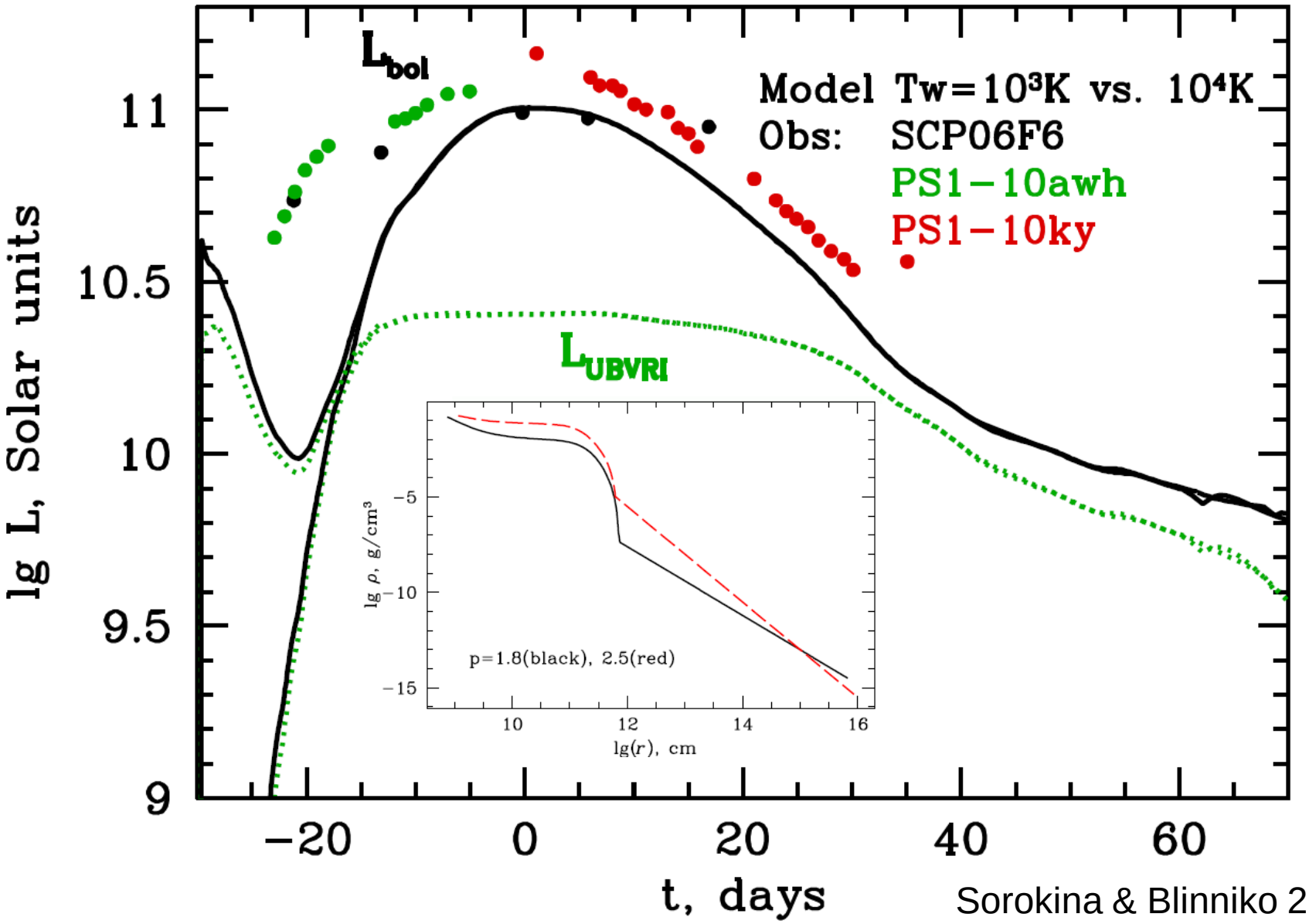
Dense C+O CSM

M(csm) = $5M_{\odot}$
E = 2 e51 erg

UV bright

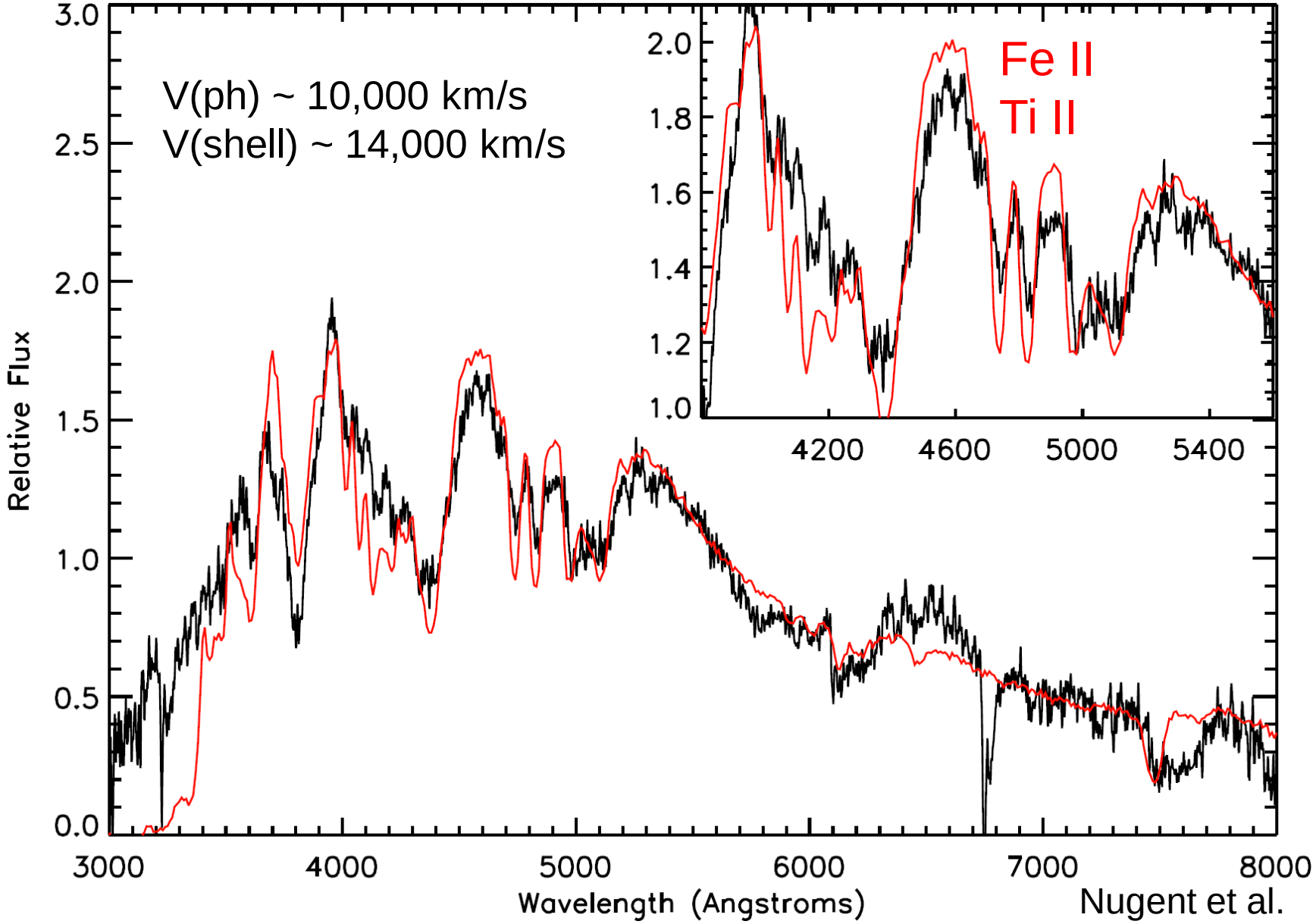
Sorokina & Blinnikov 2012

Non-H Superluminous SNe



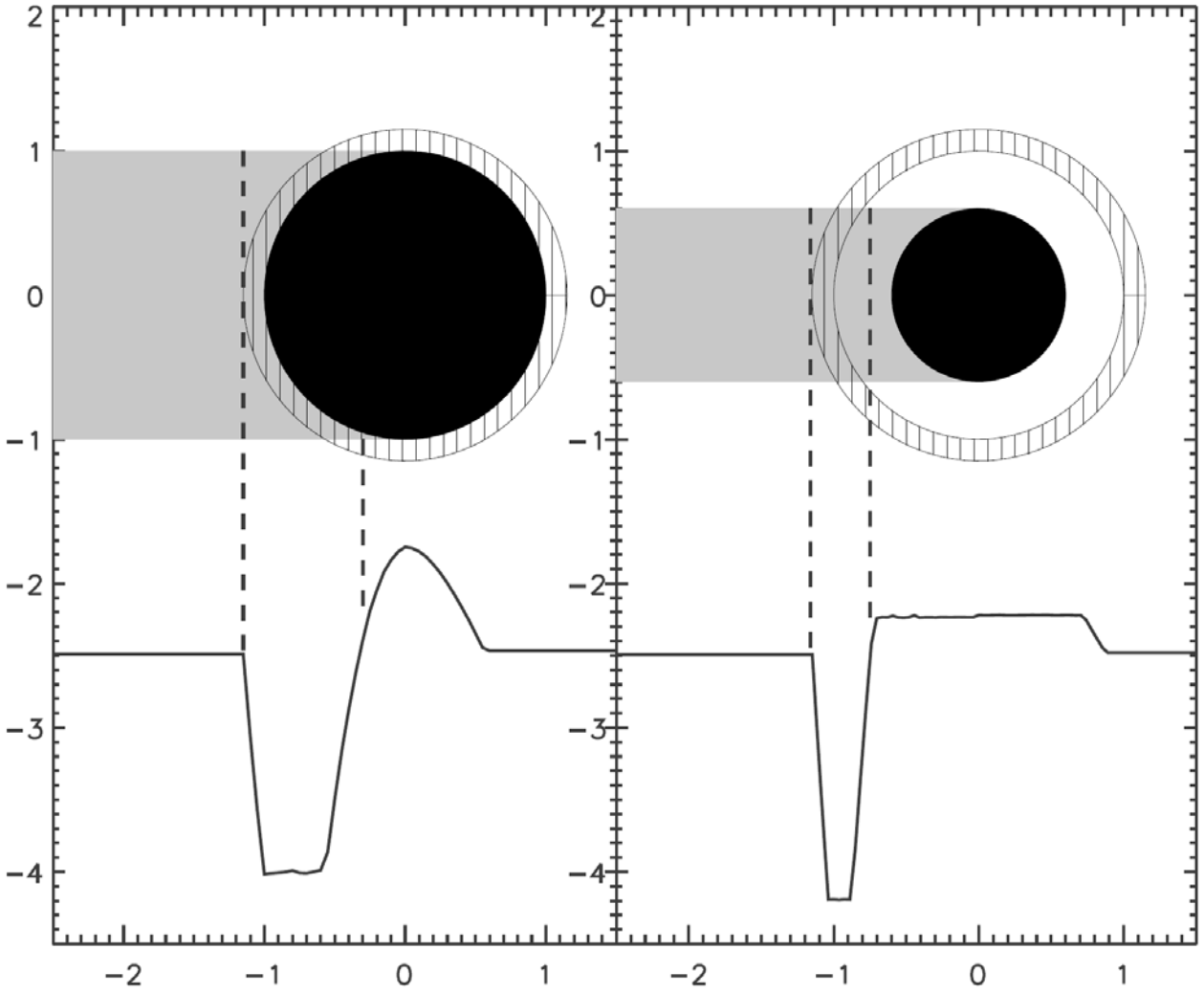
Sorokina & Blinnikov 2012

SN1999as: Narrow Lines



Nugent et al.

A Detached Shell Model



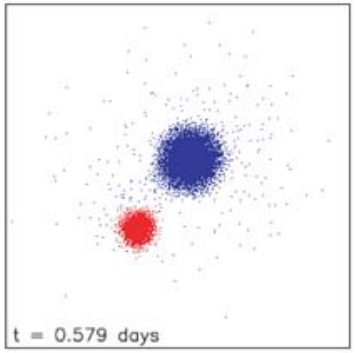
V(ph) ~ 10,000 km/s
V(shell) ~ 14,000 km/s
M(shell) ~ 0.2 $M_{\odot}$

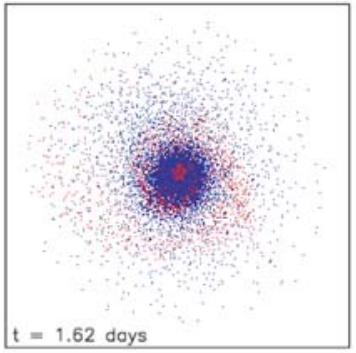
Shell Ejection ?

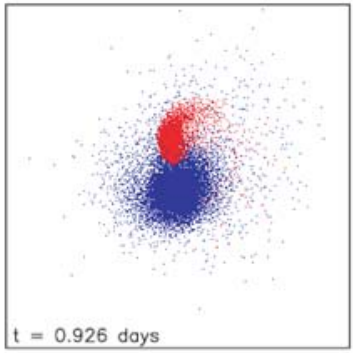
Circumstellar Interaction?

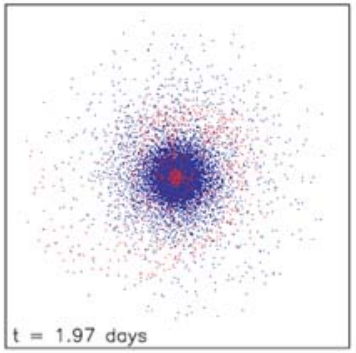
Nugent et al.

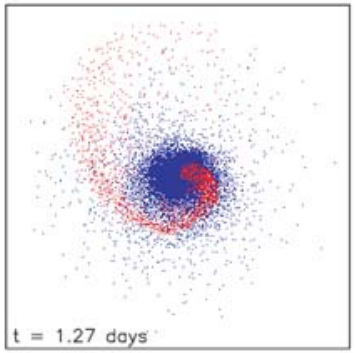
Multiple Stellar Collisions in Dense Star Cluster

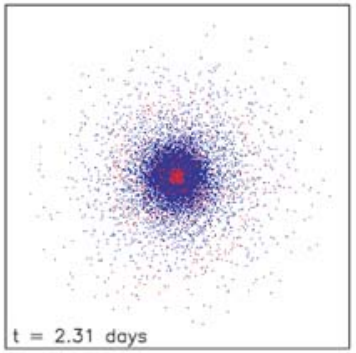












➔

Formation of Massive Stars & Massive Circumstellar Matter

88.5 $M_\odot$ + 27.9 $M_\odot$ ➔
106.1$M_\odot$ (Star) + 10.3 $M_\odot$ (CSM)

If evolved, or if rotation-induced mixing
➔ H-depleted Star

Wolf-Rayet + Wolf-Rayet
➔
Wolf-Rayet + CSM (non-H) ??

Suzuki, Nakasato, et al.

Fates of (Very) Massive Stars

Pair Instability SN: disruption $M(^{56}Ni) < 40\ M_{\odot}$

Black Hole-forming SN: **GRB ?** $M(^{56}Ni) < 10\ M_{\odot}$

Magnetar-forming SN: connection to **XRF ?**

(Late time spectra ?)

Dense Circumstellar Matter (esp. non-H) ?

LBVs ?

Pulsational Instability ? ➔ Shell ejection ?

Multiple Stellar Collisions?

- Fallback SN ➔ Faint SN , Non-SN GRB