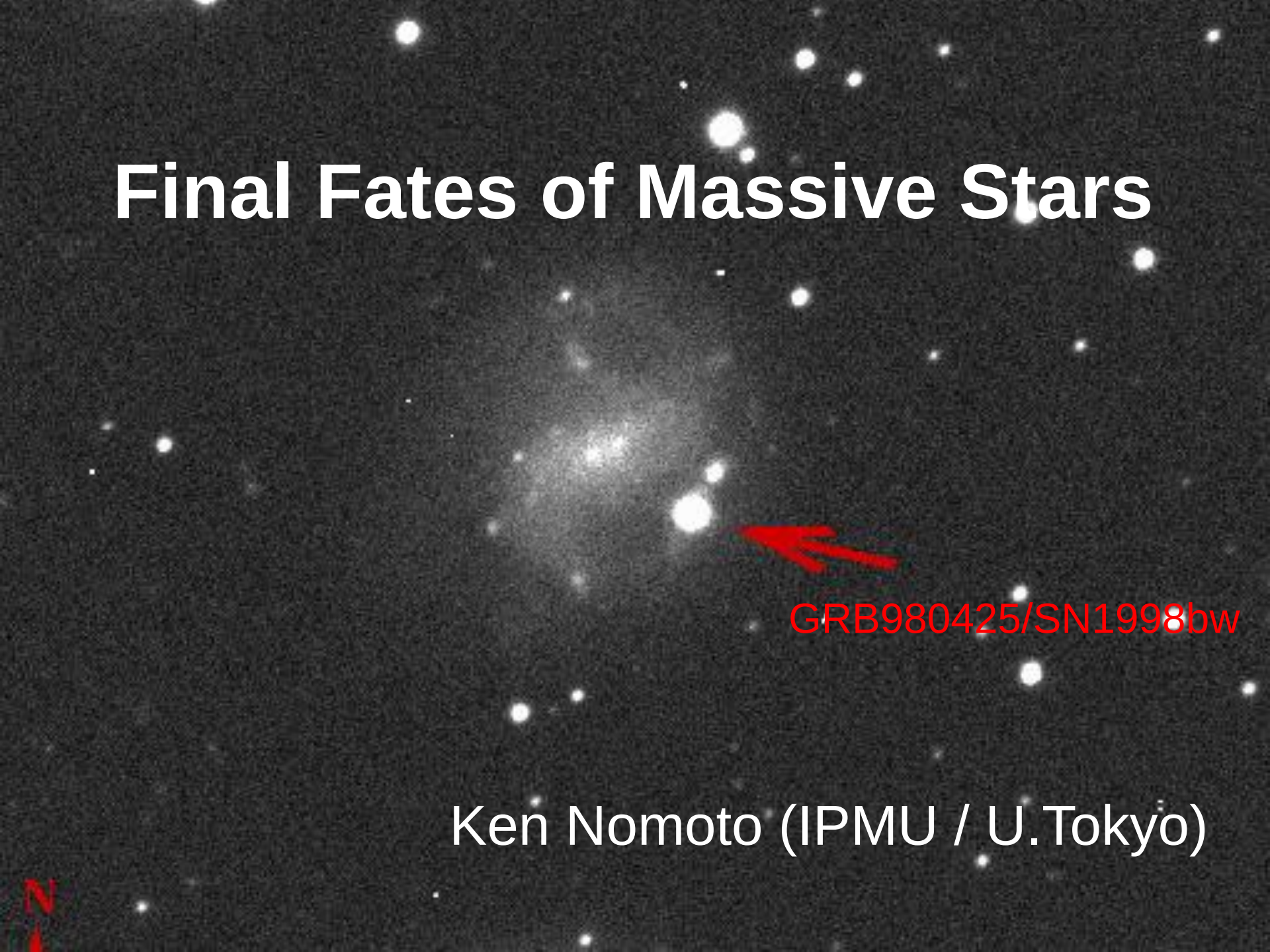
Final Fates of Massive Stars



Ken Nomoto (IPMU / U.Tokyo)

Evolution and Explosion of (Very) Massive Stars

- Pop III Stars : (very) massive?
- Superluminous supernovae

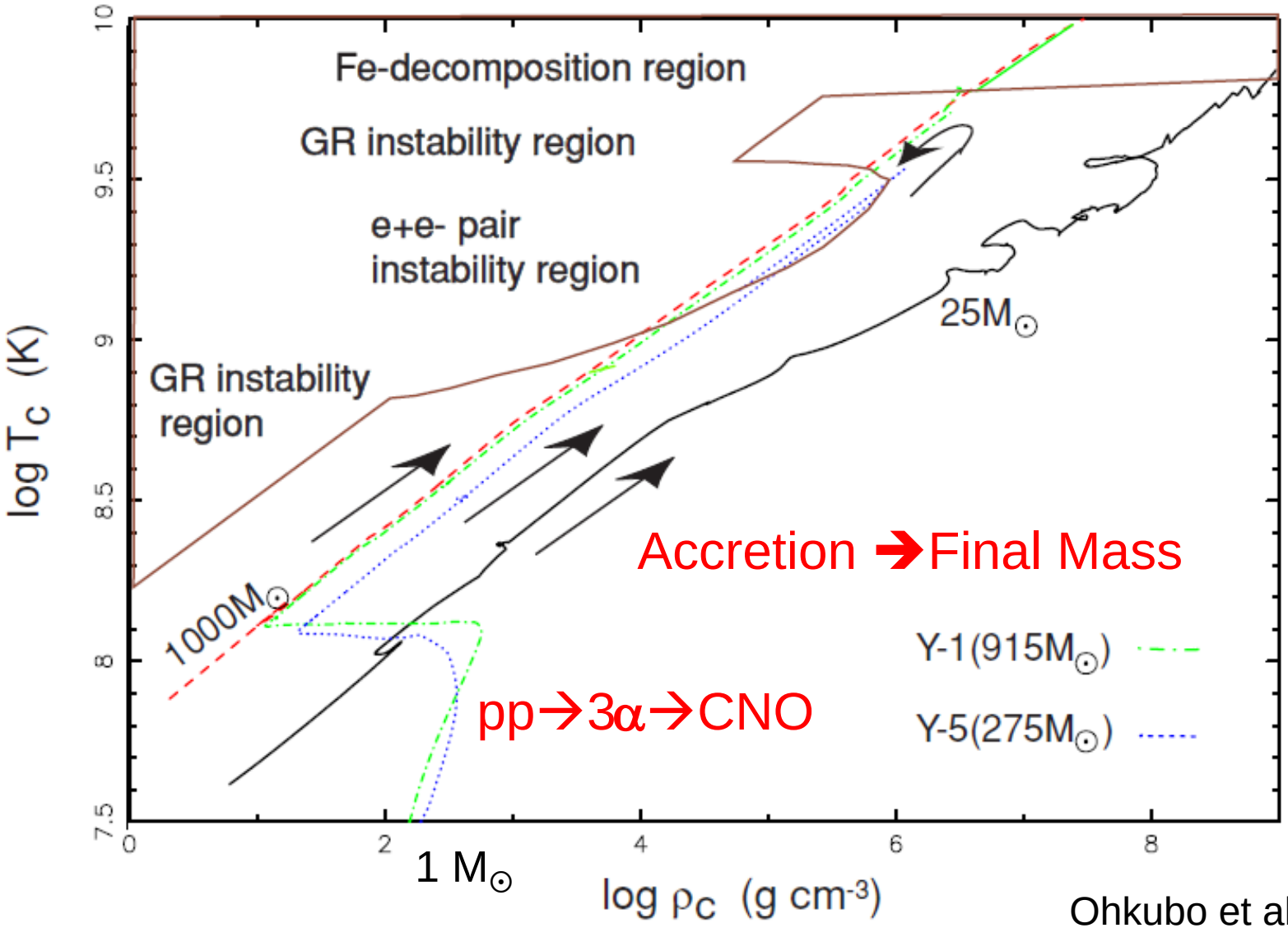
How massive ?

- Star Formation ➔ small core + CSM ➔ Mass Accretion (metallicity, feedback,,,,)
- Mass Loss (wind, instabilities, ,,,)
- Stellar Collisions in Dense Star Clusters

➔ Massive Star + (massive) CSM

Pop III Stars: Mass Accretion ➔

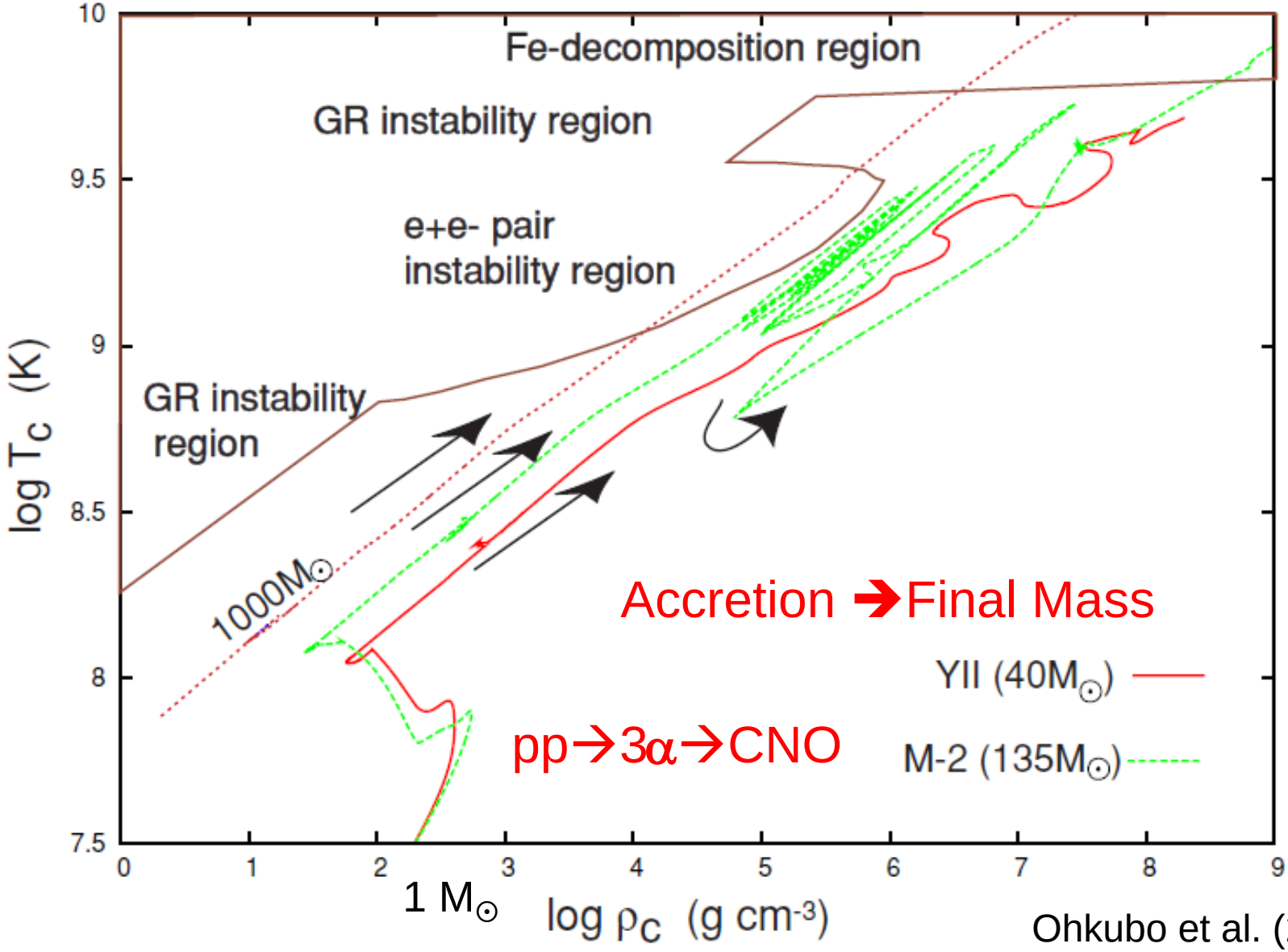
Pair-Instability (140-300 $M_\odot$) or **Core-Collapse**



Ohkubo et al. (2009)

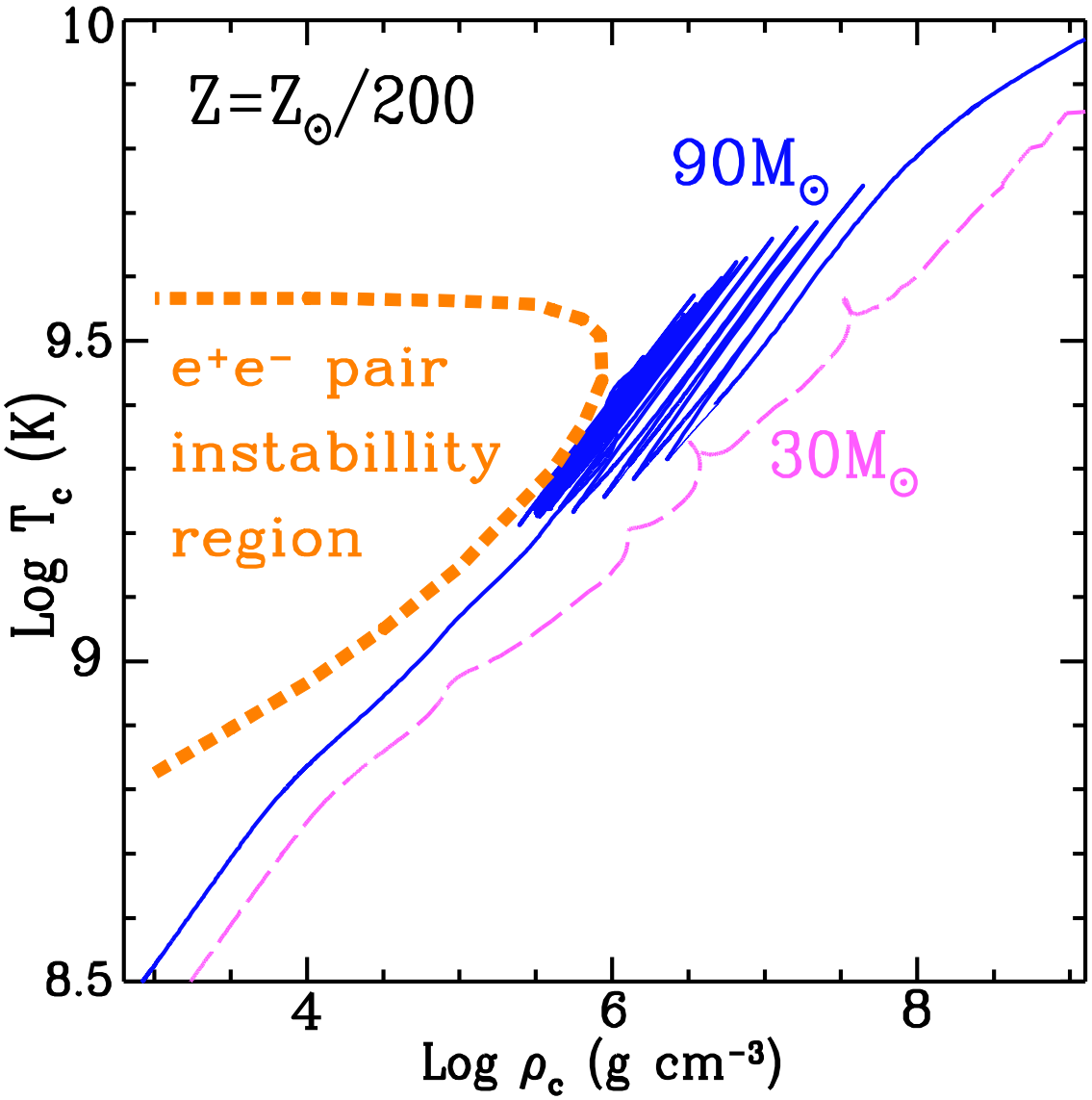
Pop III Stars: Mass Accretion ➔

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



Ohkubo et al. (2009)

Evolution of the 90$M_\odot$ Star



Oscillation

↓

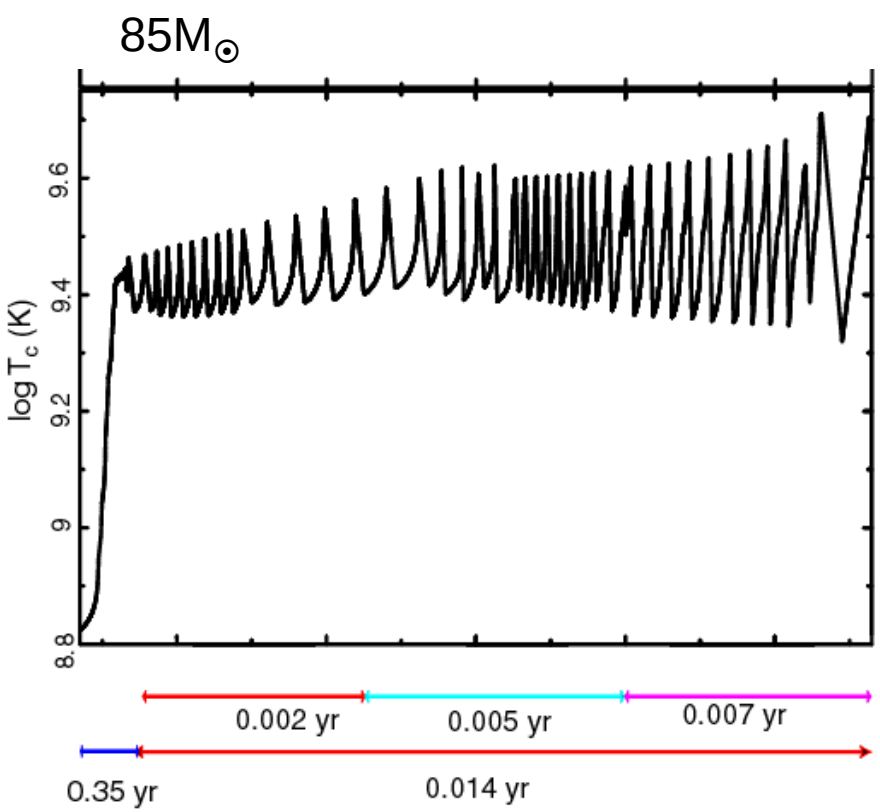
Fe core collapse

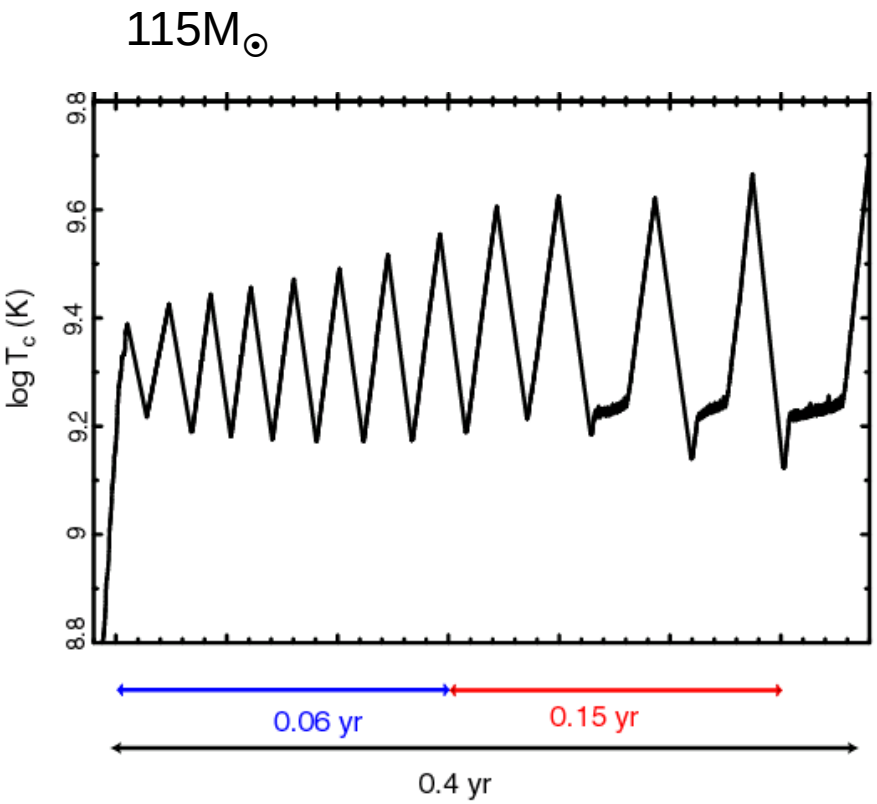
E_{51}=30

M(^{56}Ni)=5$M_\odot$

(Umeda & Nomoto)

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



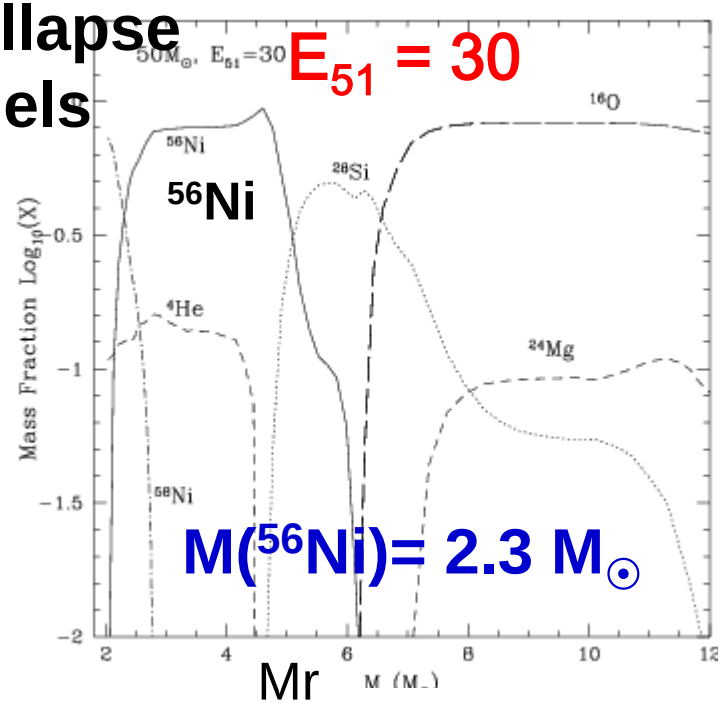


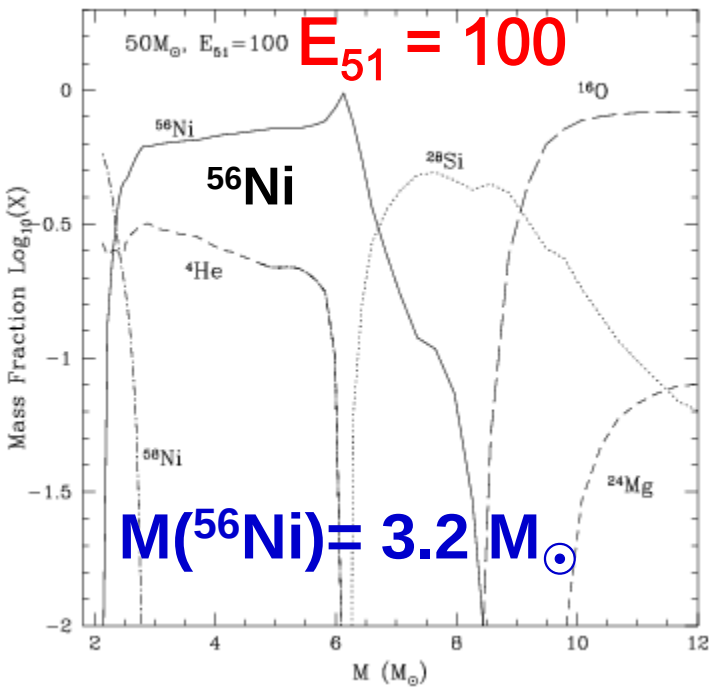
→ Fe Core Collapse

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

Core-Collapse SN Models

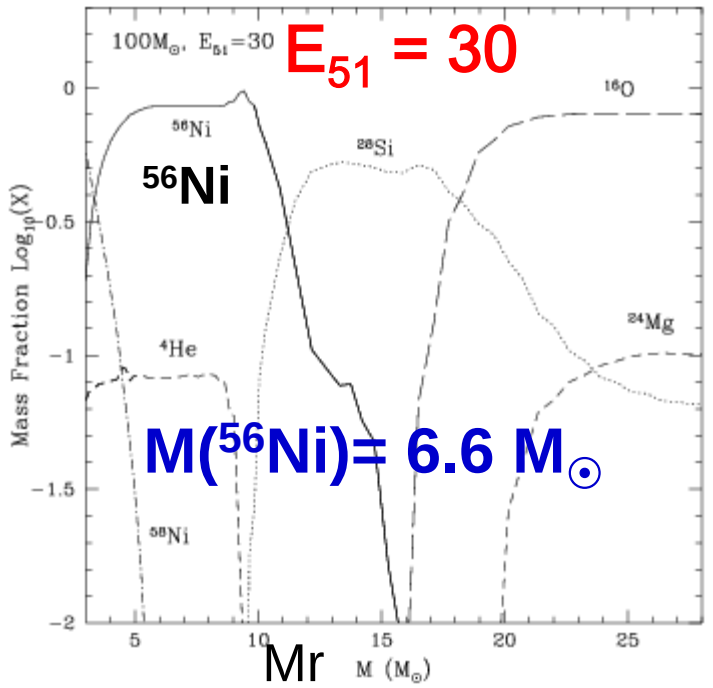
Log (Mass Fraction)

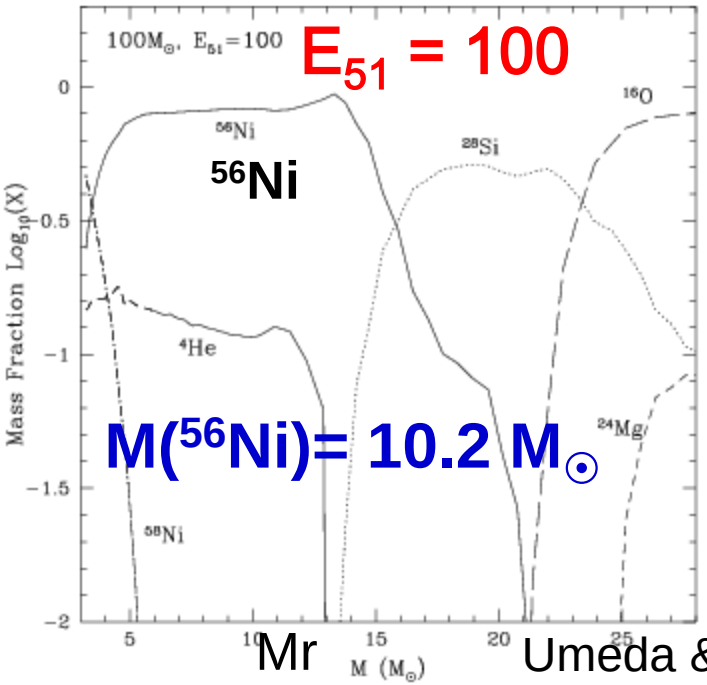




M = 50M⊙

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

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

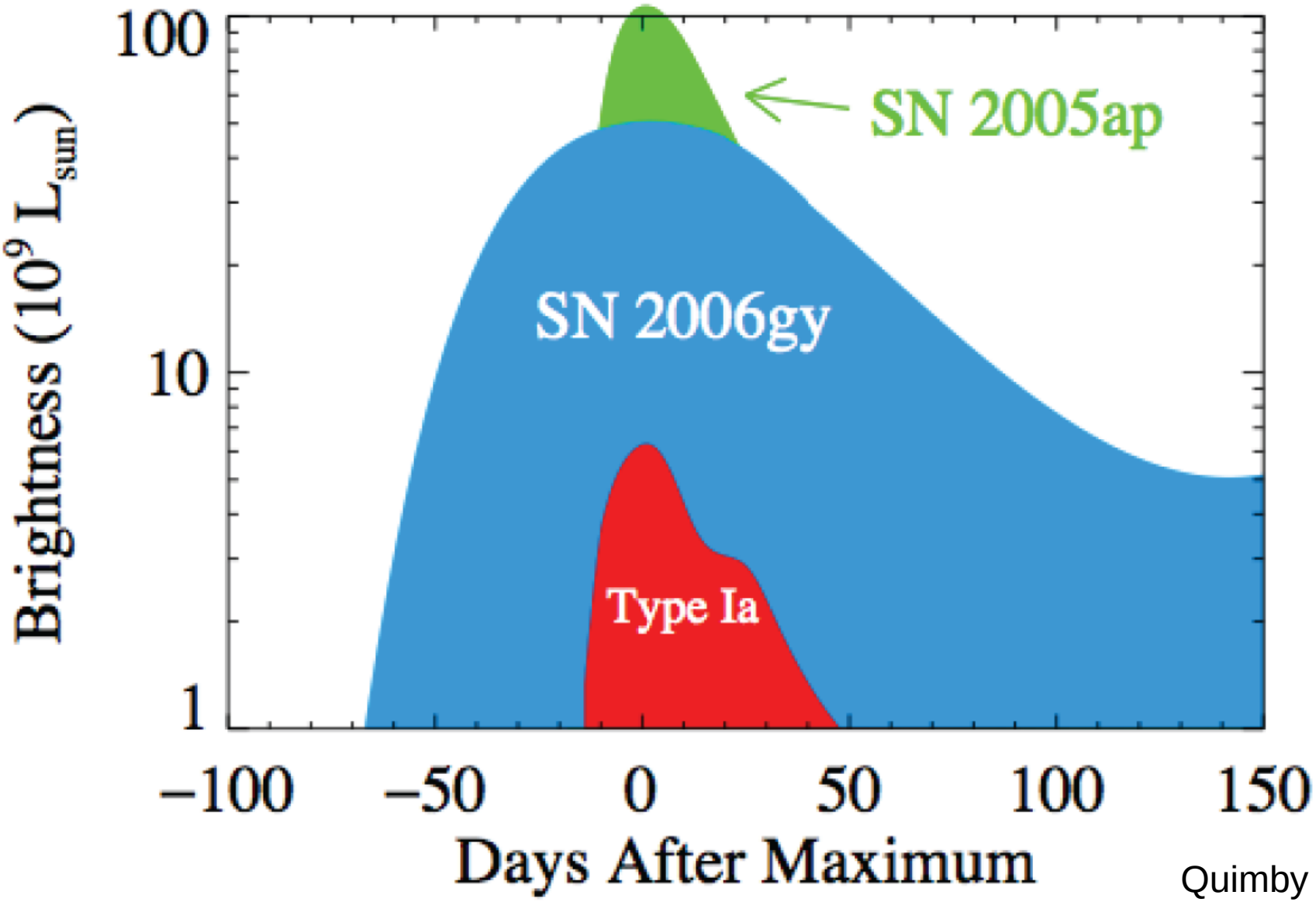
$M \sim 8 - 140 M_\odot$:

→ Core Collapse

↗ **Pop III GRBs, Hypernovae**

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

Superluminous Supernovae



Quimby

Unusual SNe —---Pop III SNe ?

Superluminous SNe (IIn, II-L, **Ic**) (-22 mag)

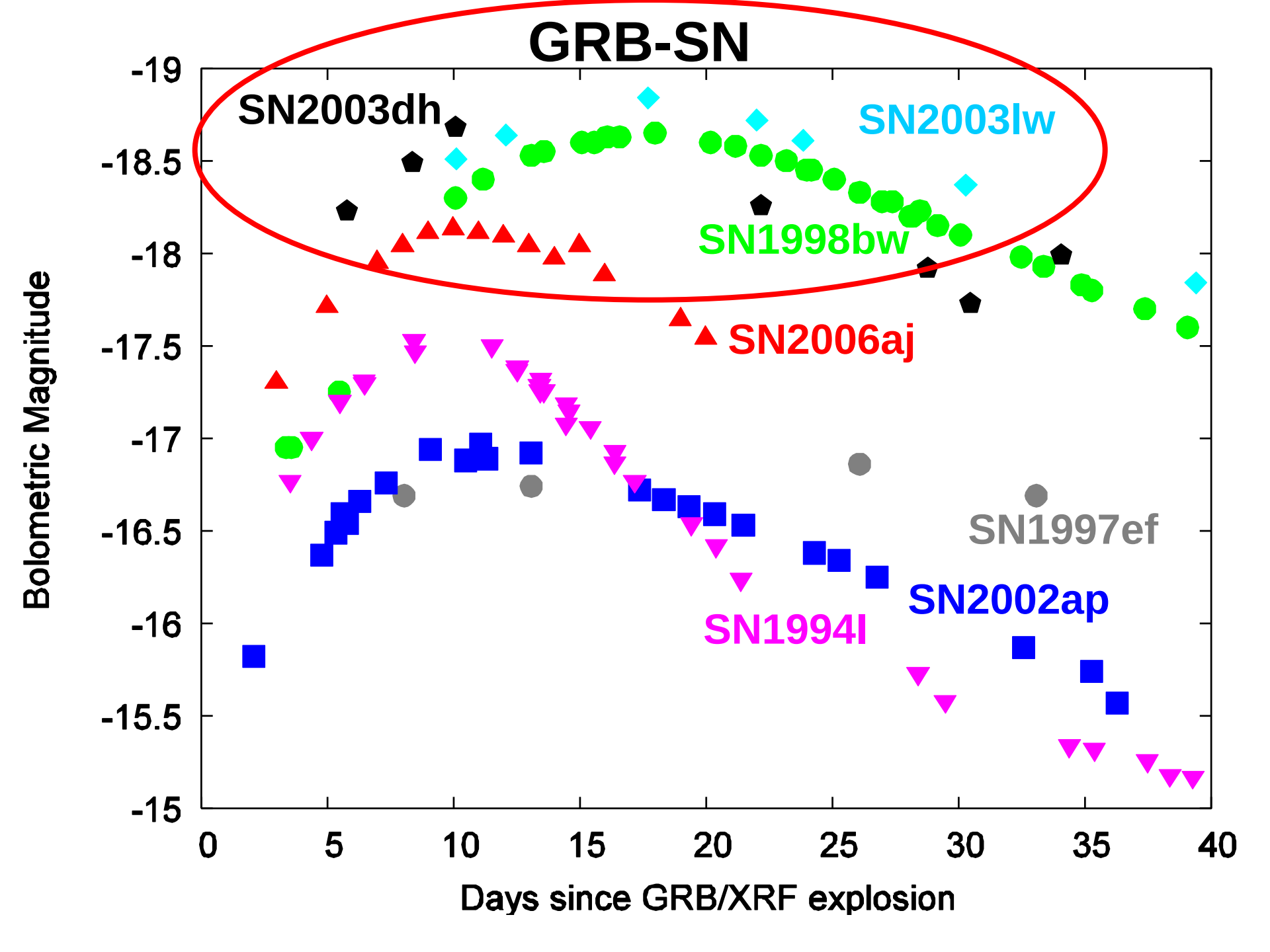
Pair Instability ? $M(^{56}Ni) < 40\ M_{\odot}$

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

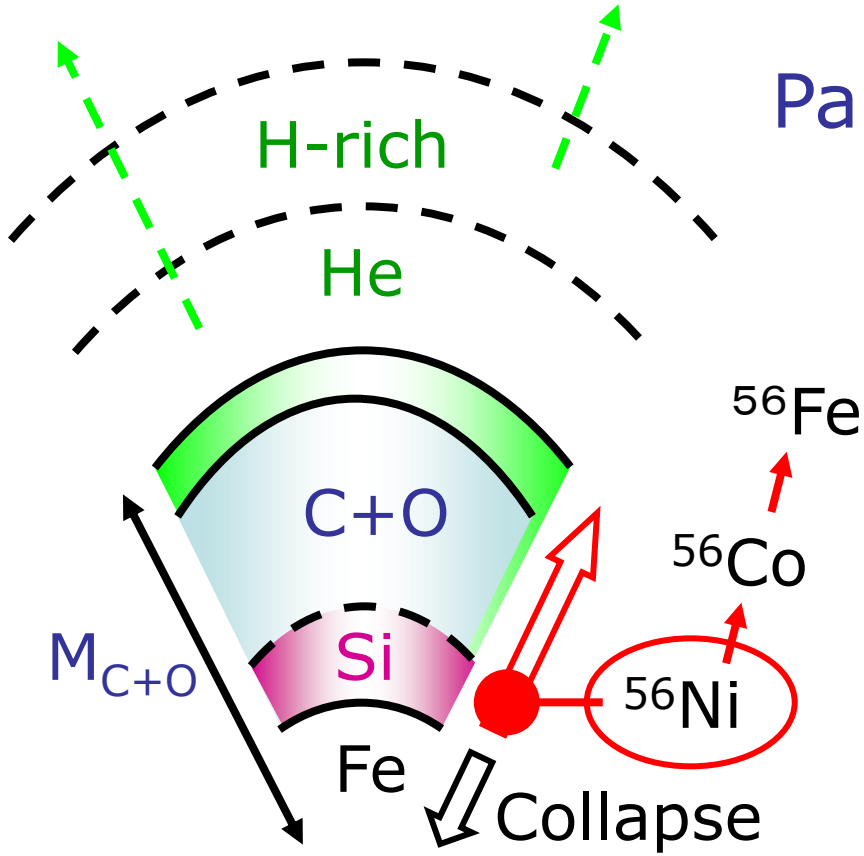
Magnetar ? **XRF ?**

Circumstellar Interaction ?

SN 1999as ?


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

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)]

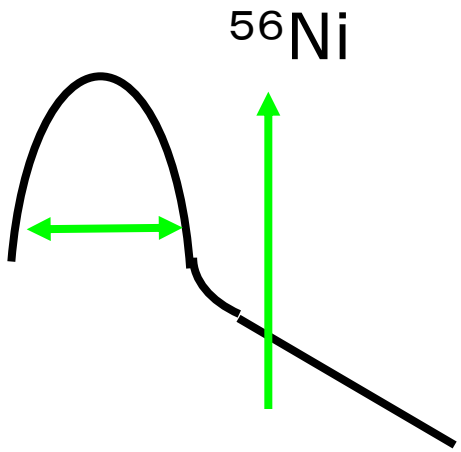
Light Curve — Spectra

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

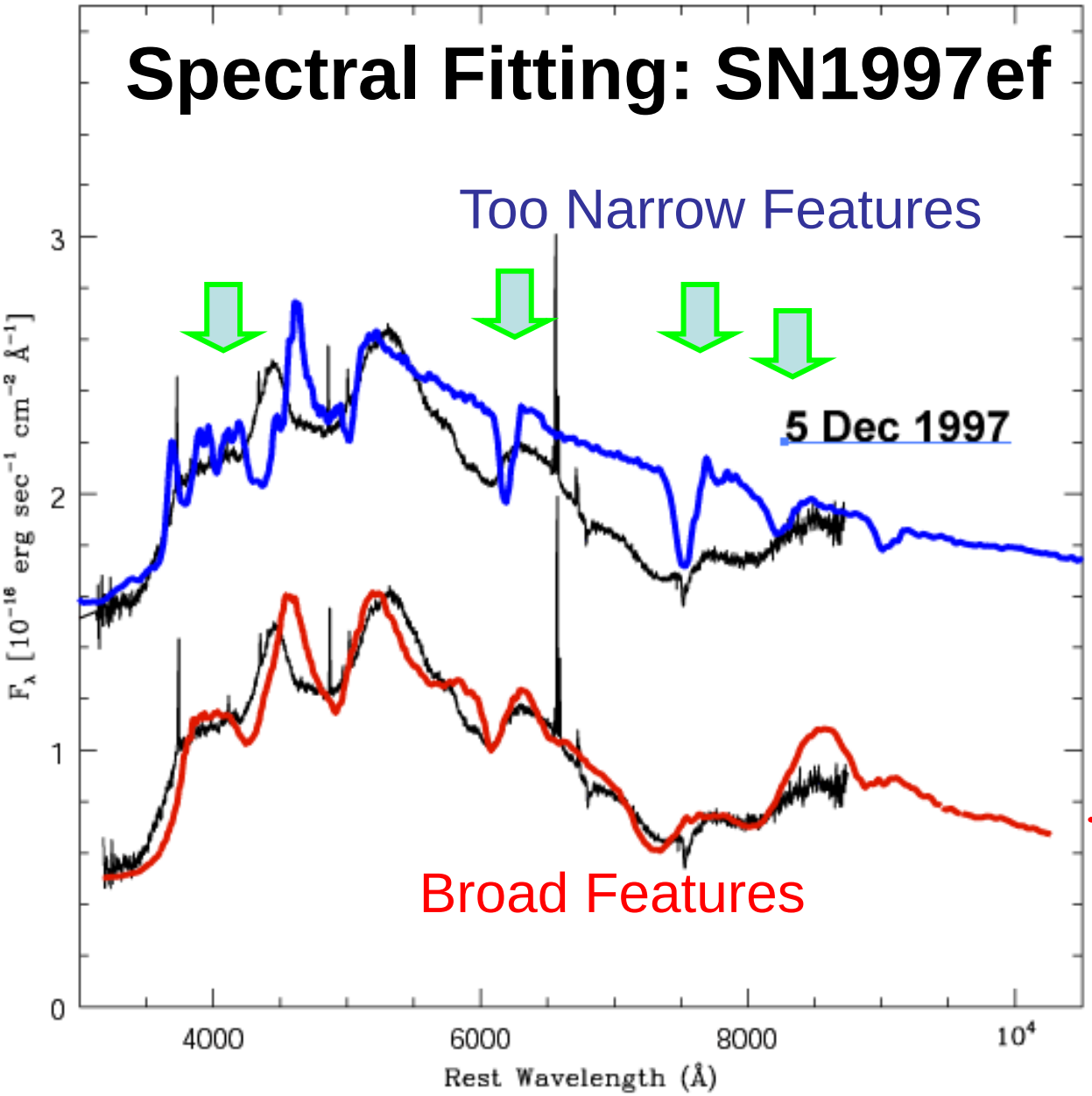
$$\propto \kappa^{1/2} M_{ej}^{3/4} E^{-1/4}$$

$E \propto M_{ej}$

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



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-Supernovae

Three GRB－SNe = all Type Ic Hypernovae

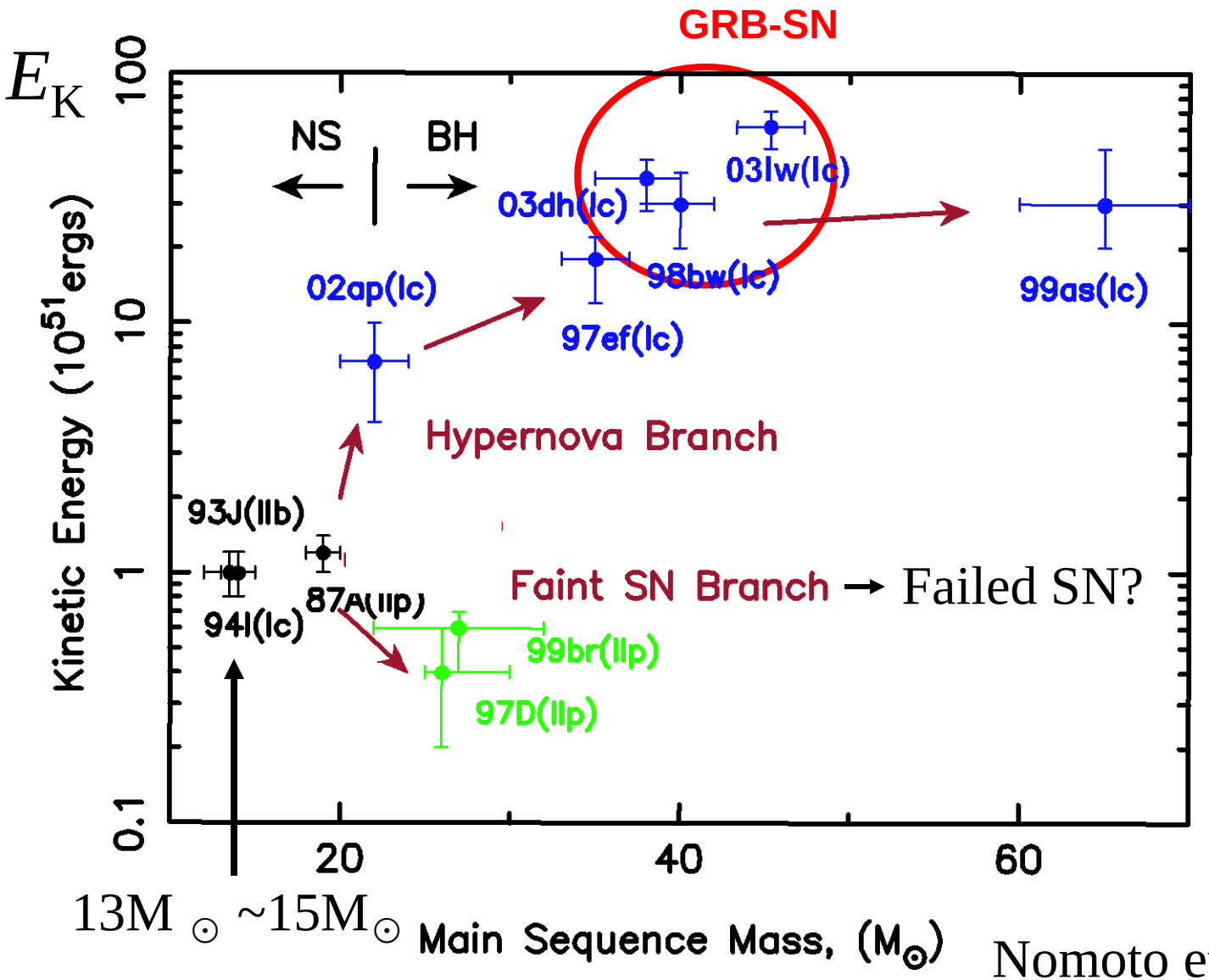
$E > 10^{52}$ erg (～10×normal SN)

Large M_{ms} →Black Hole Forming SNe

Aspherical

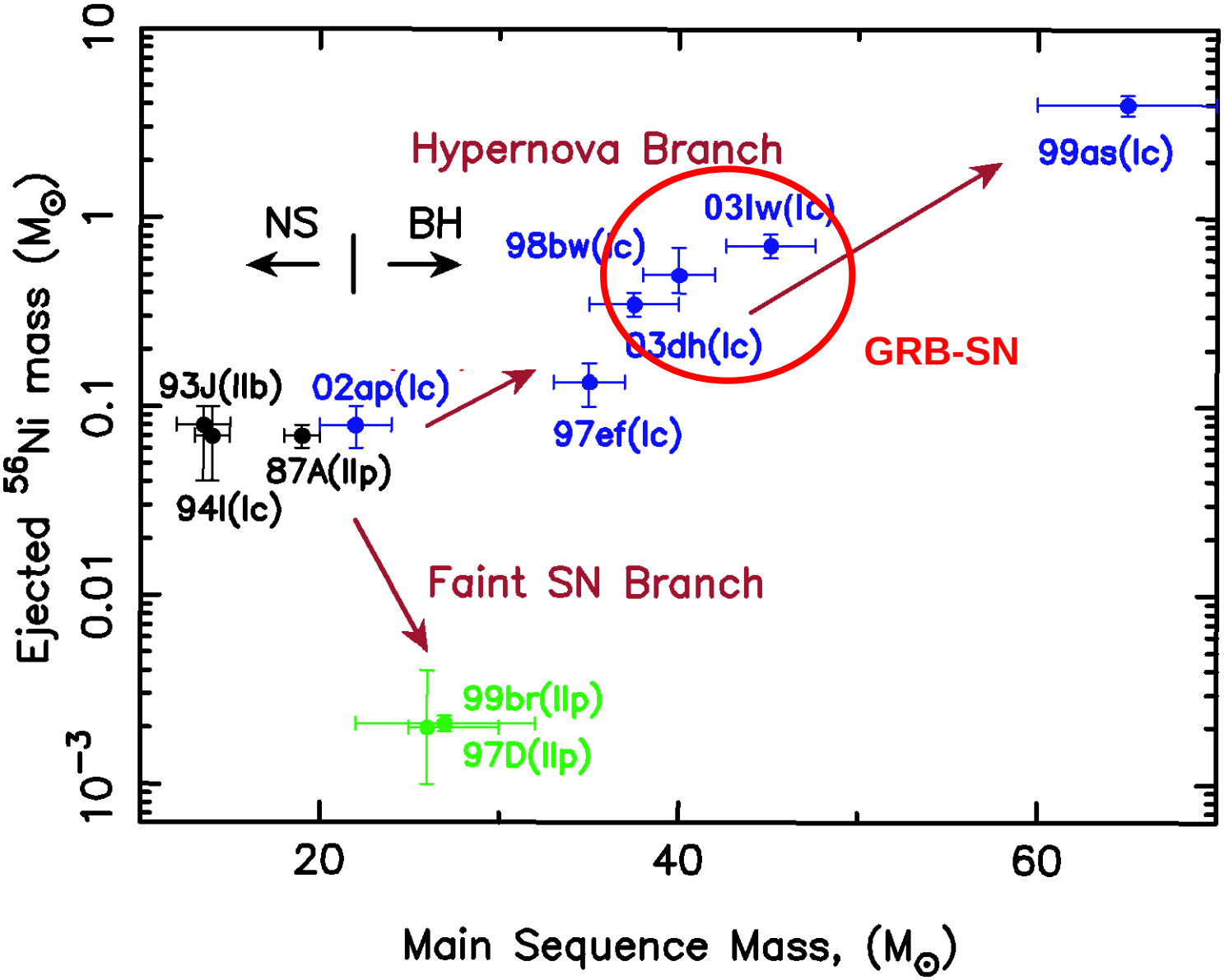
GRB	SN	$M_{CO}/M_{\odot}$	$M_{ms}/M_{\odot}$	$E/10^{51}$erg	$M(^{56}Ni)/M_{\odot}$
980425	1998bw	14	40	30	0.4
030329	2003dh	11	35	40	0.35
031203	2003lw	16	45	60	0.55

Hypernovae/Faint SNe



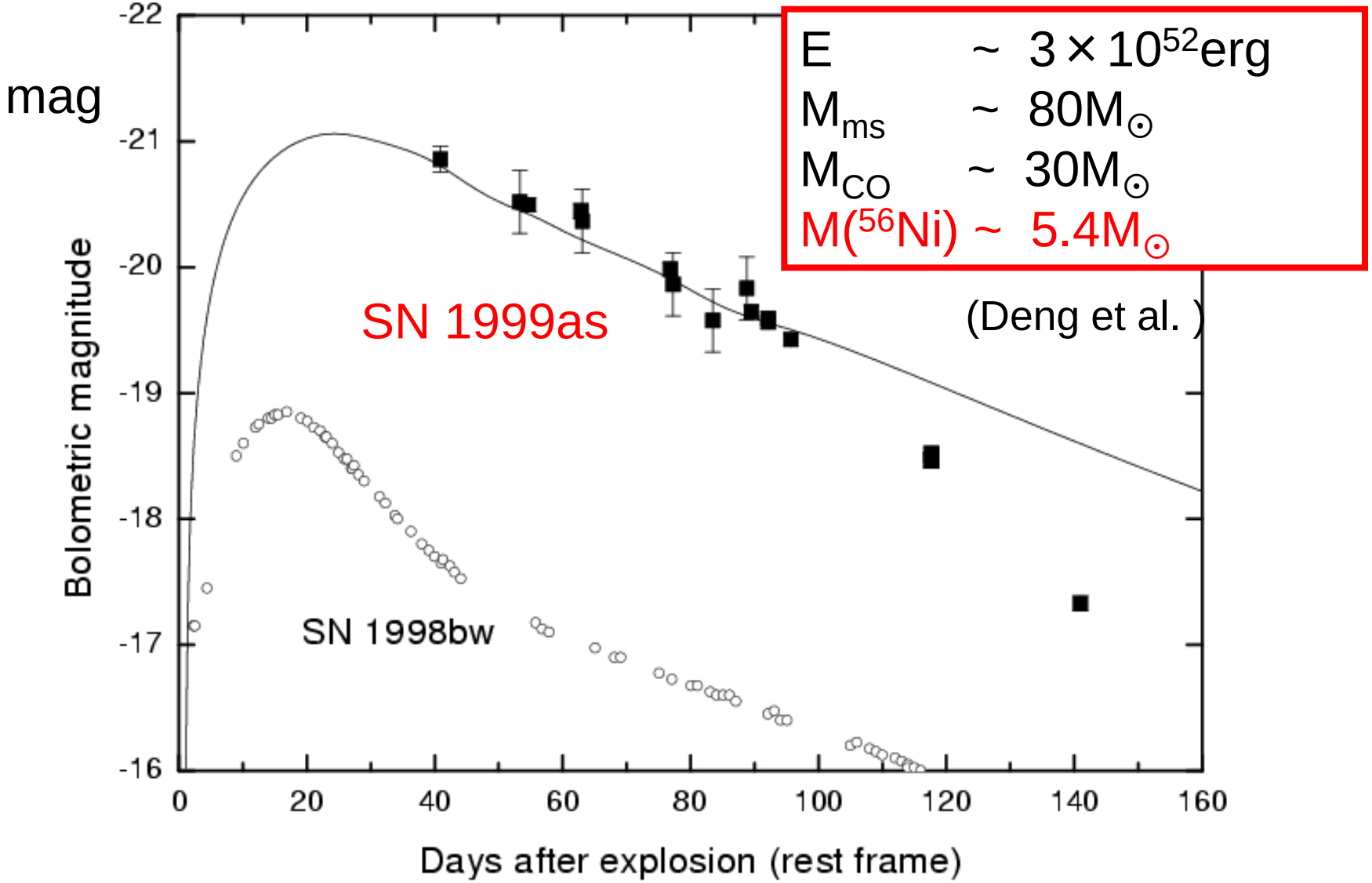
Nomoto et al. (2003)

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



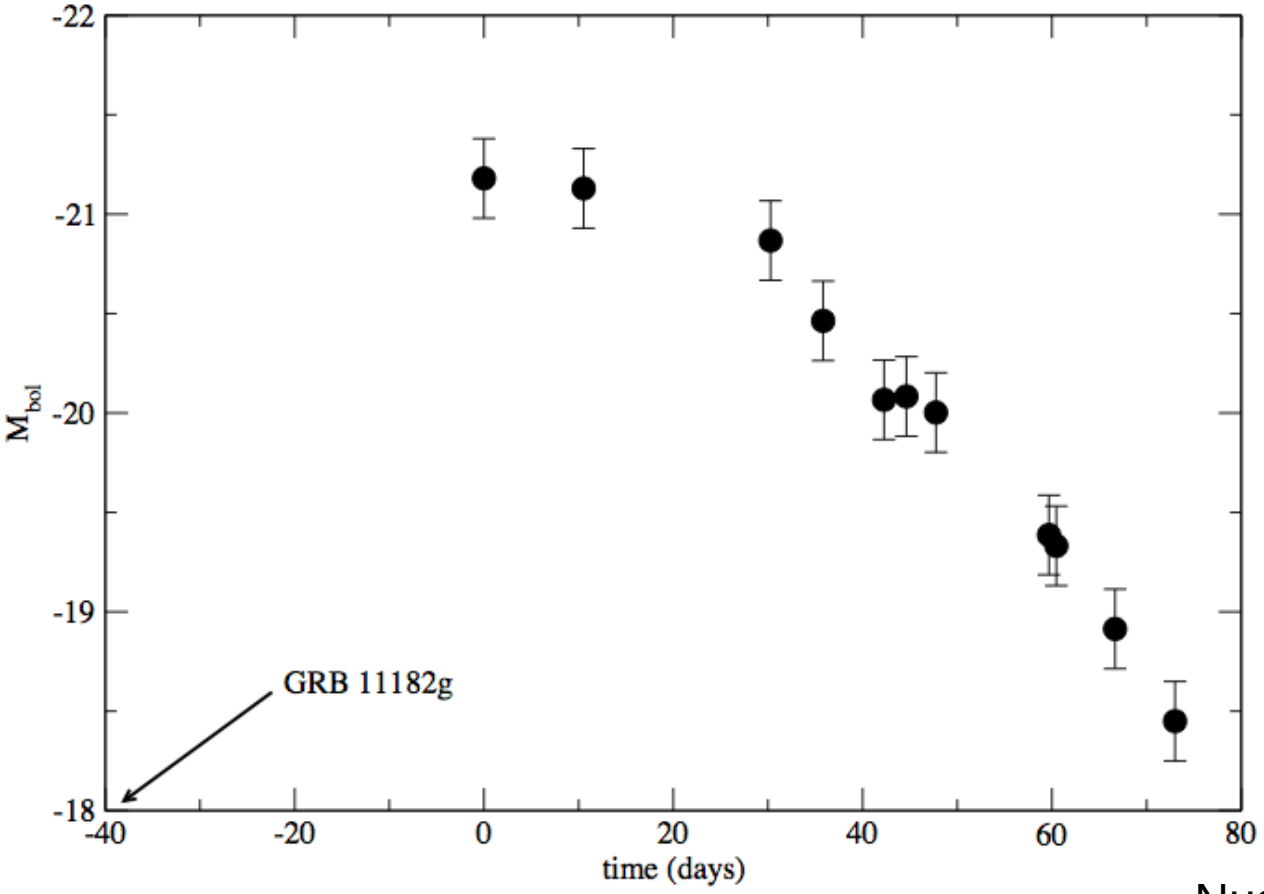
Superluminous SNe: 1999as @z=0.127

(Knop et al.)



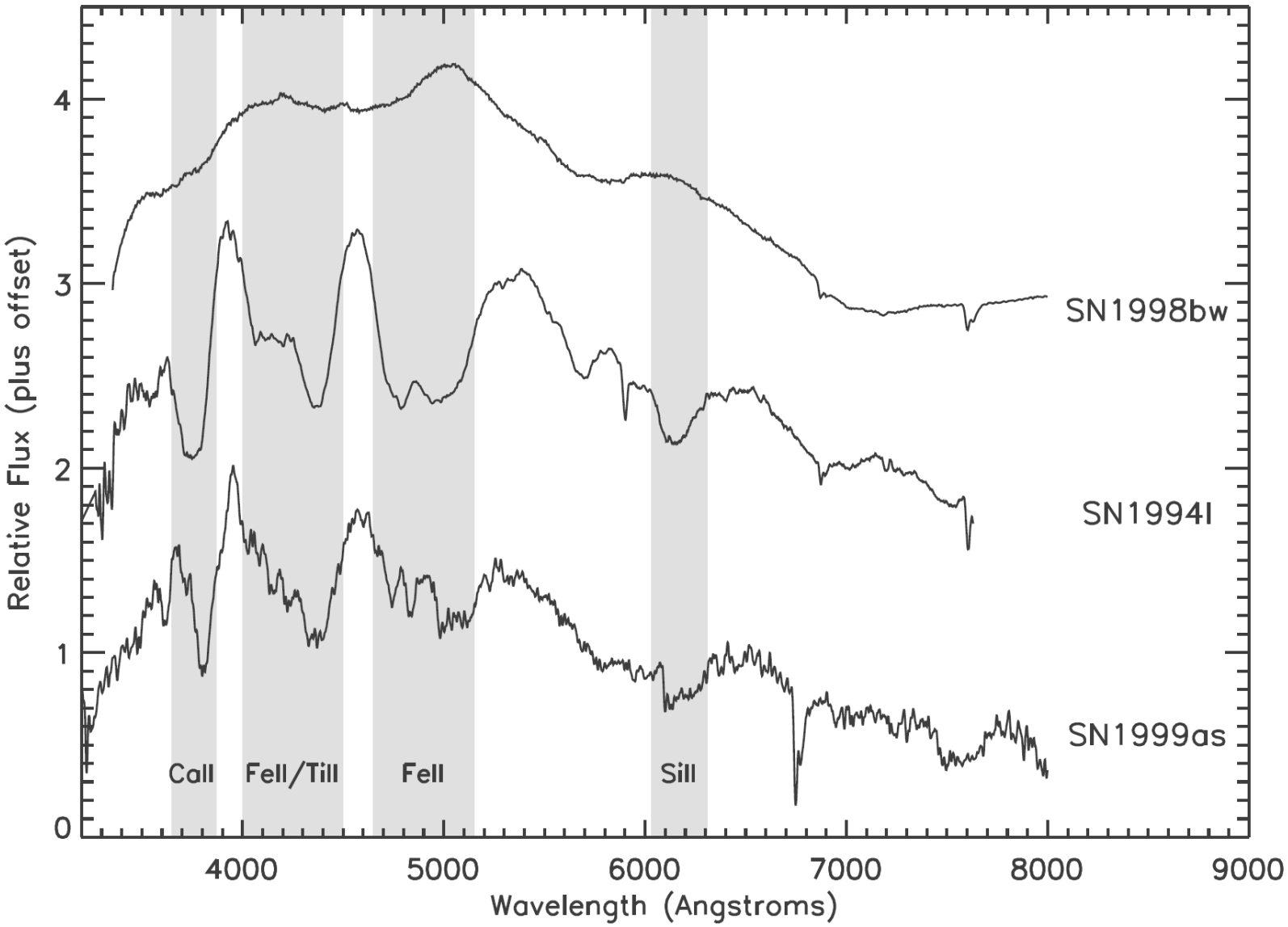
SN 1999as: Possible GRB….

Name	TJD	Peak Flux	RA	Dec	sig(deg)
11182g	85552.	0.236	131.7	3.5	30.9



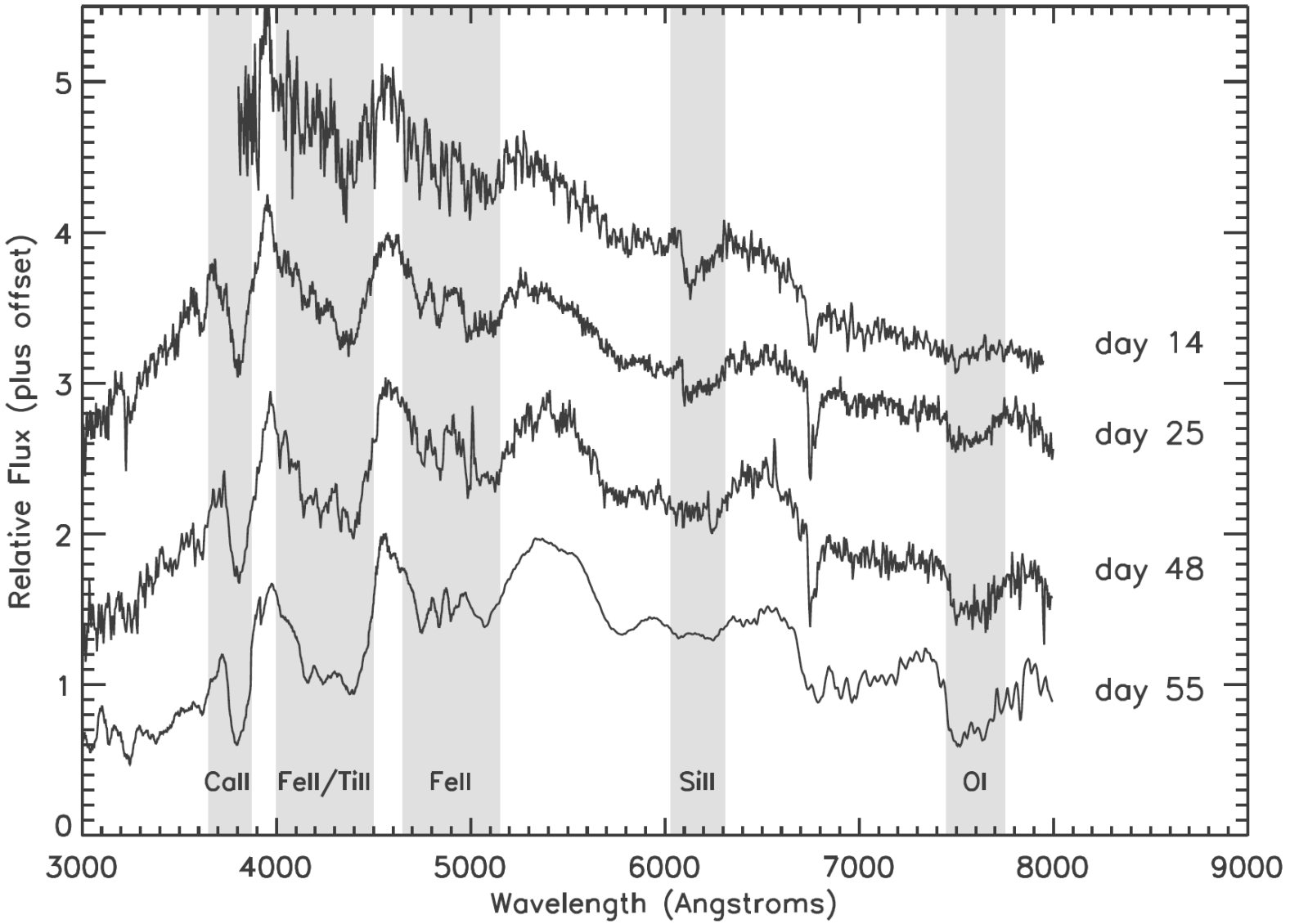
Nugent et al.

SN 1999as: SN Ic Spectrum



Nugent et al.

SN 1999as: Spectral Evolution

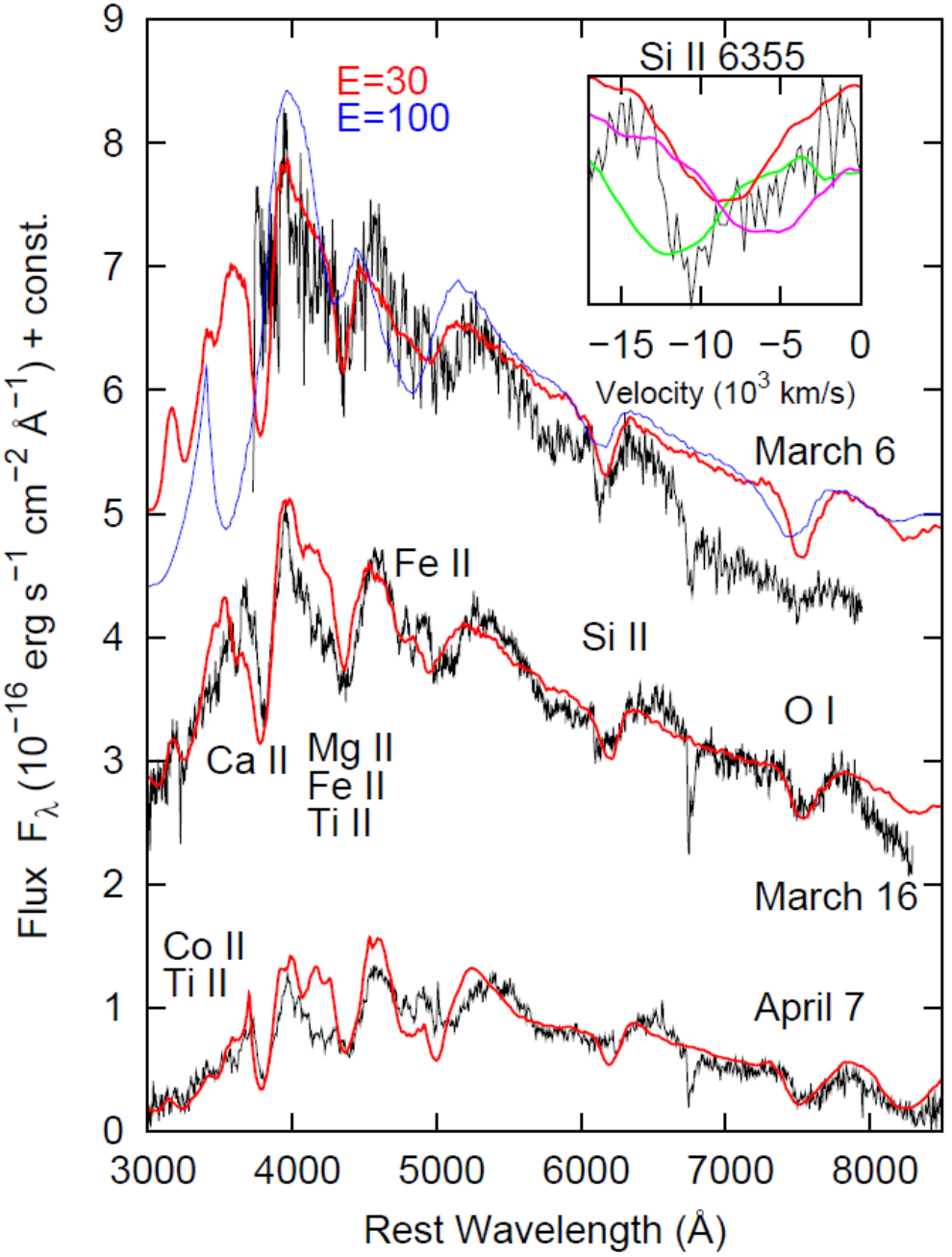


Nugent et al.

SN 1999as :

Synthetic Spectra

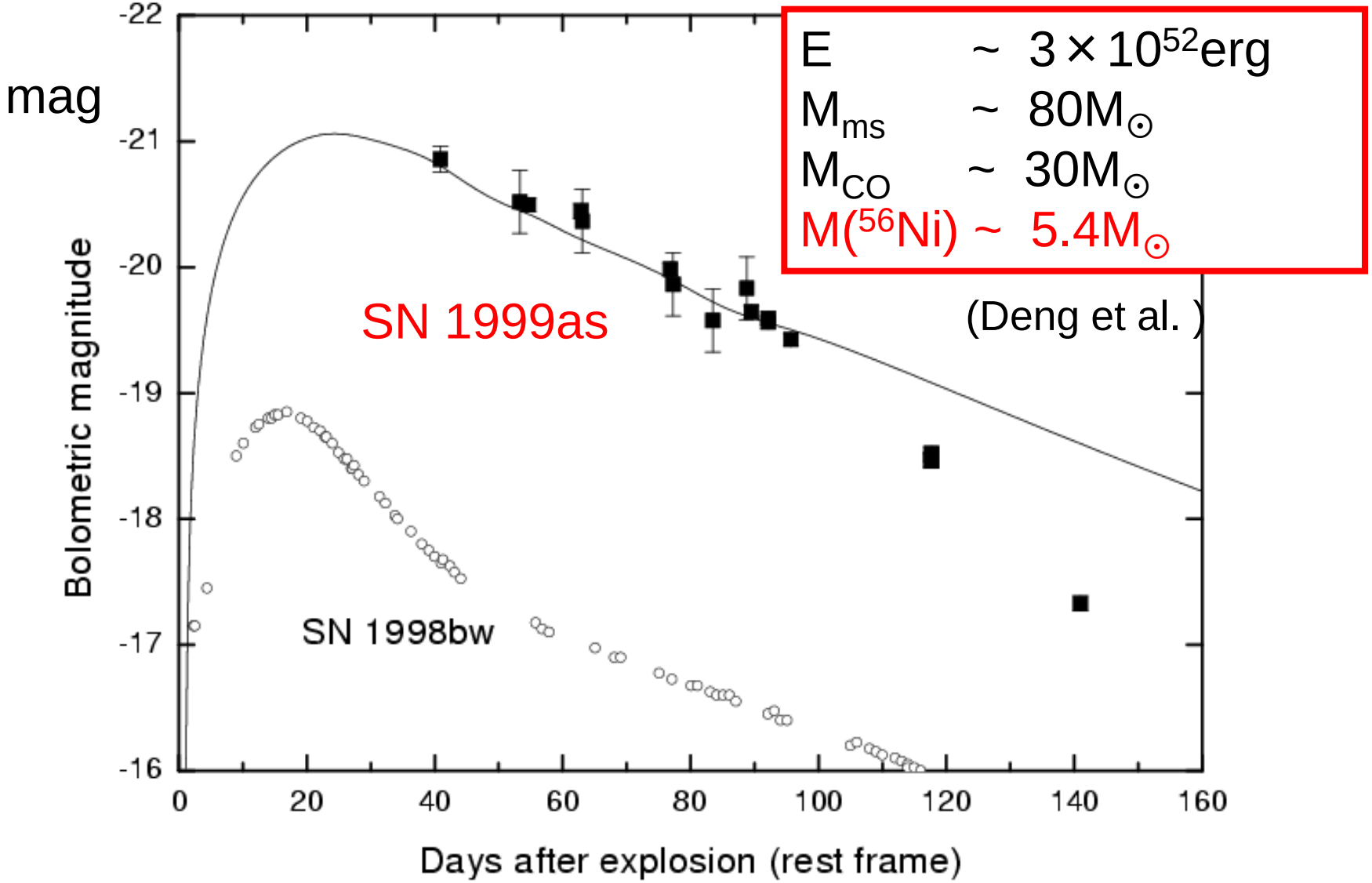
- E = 3e52 erg
- Mc+o = 30 $M_{\odot}$



Deng et al.

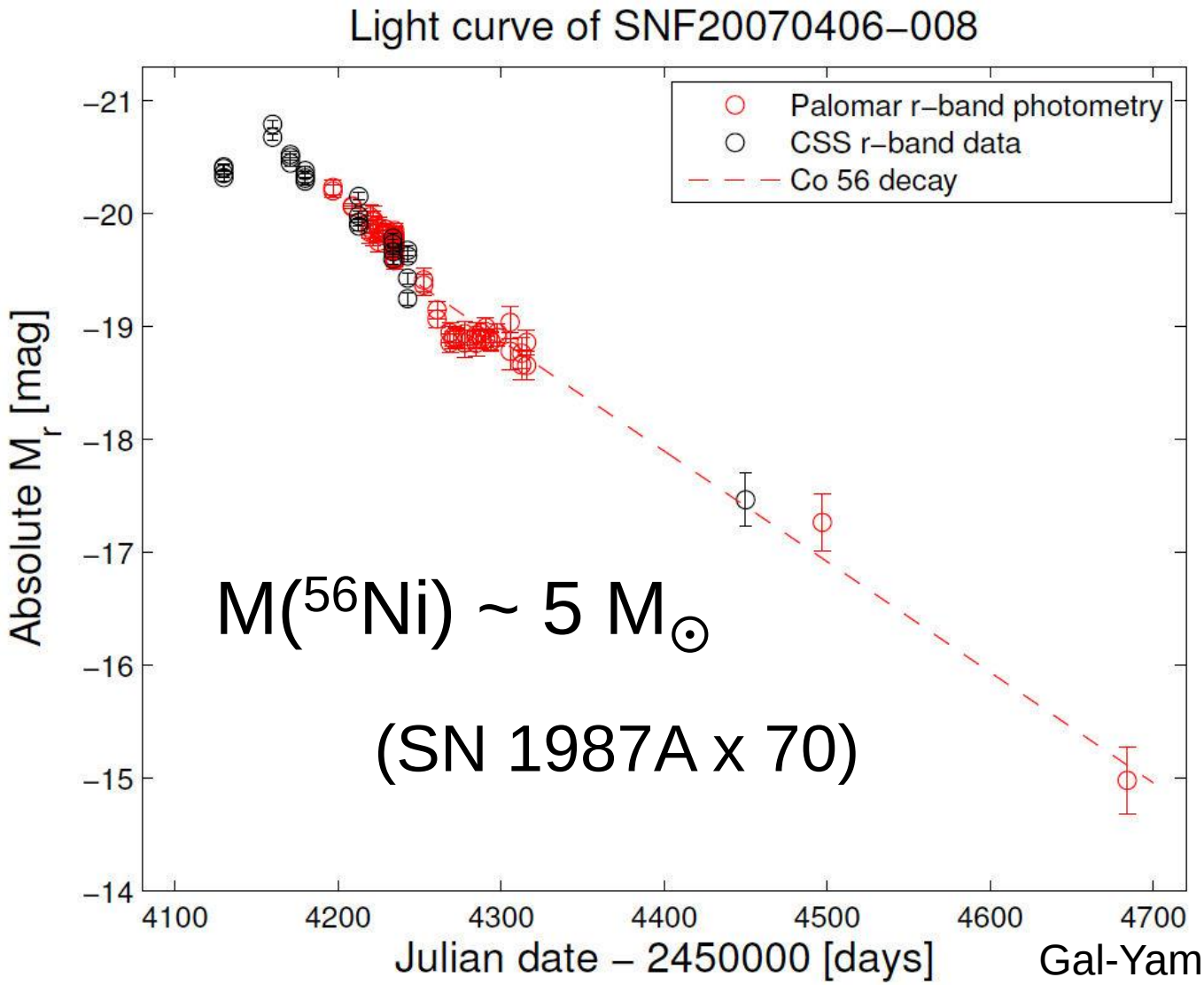
Superluminous SNe: 1999as @z=0.127

(Knop et al.)



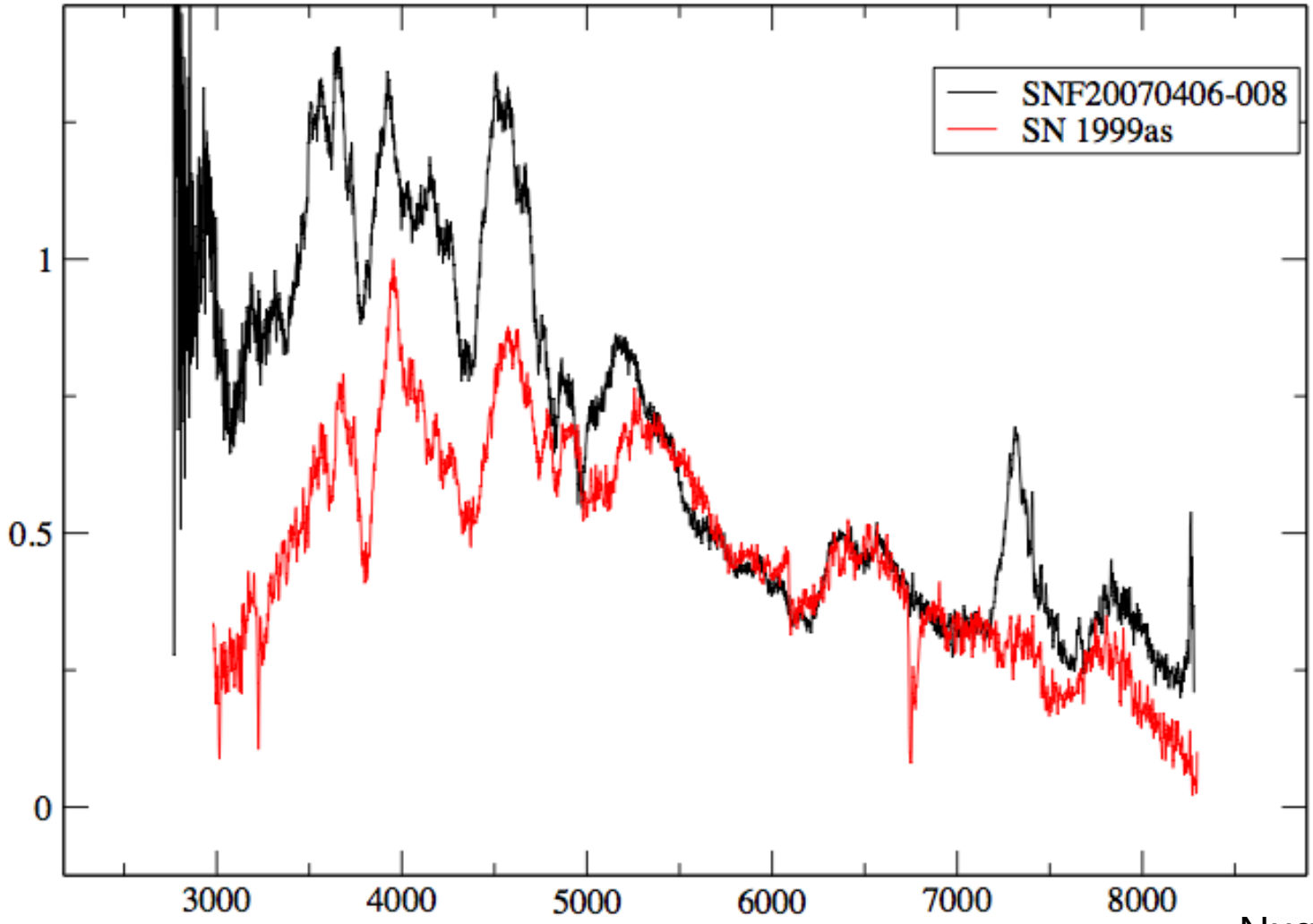
Superluminous SN

SN Ic 2007bi (Pair-Instability?)



Gal-Yam et al. 2009

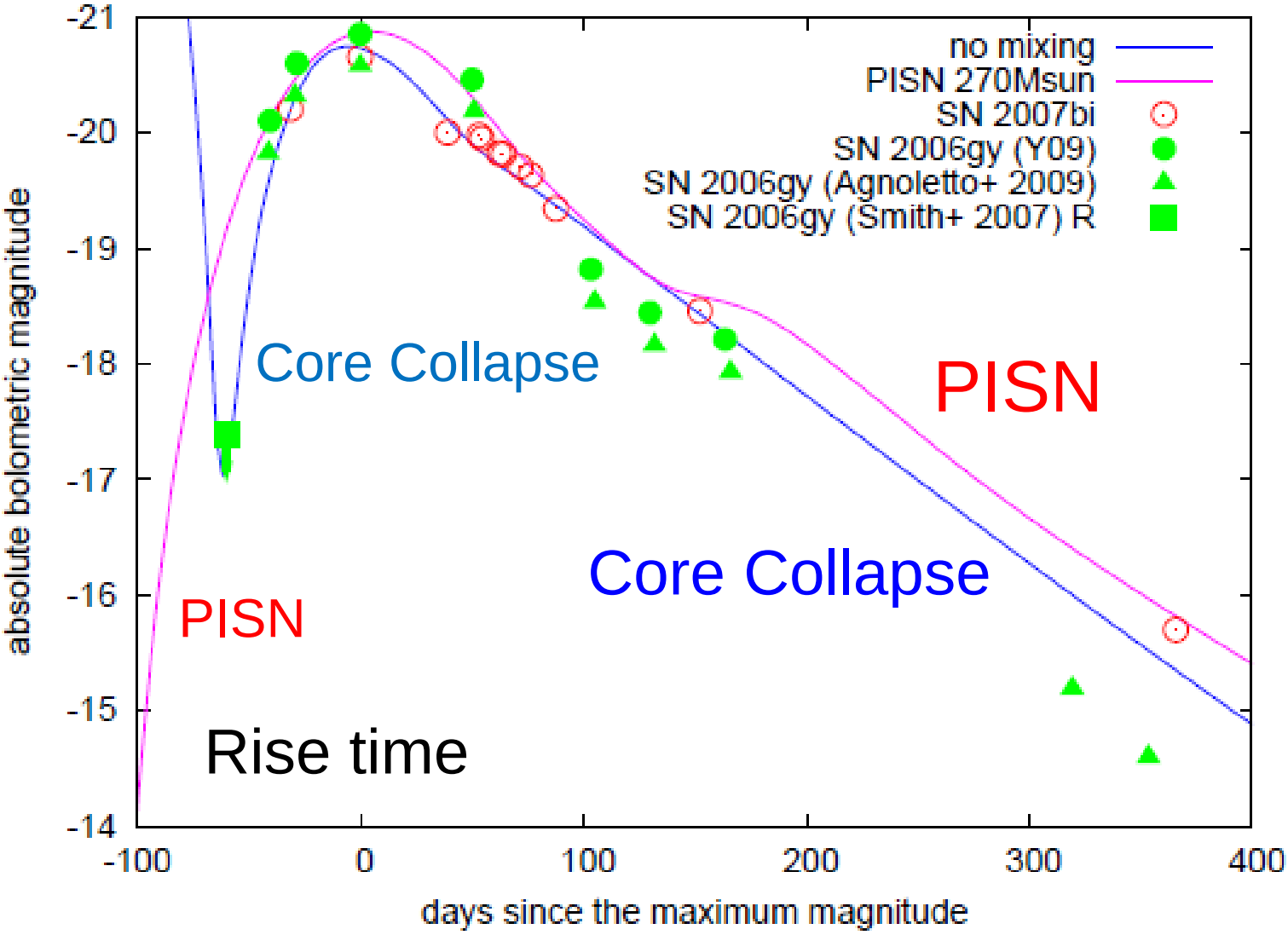
SNe 2007bi vs. 1999as



Nugent et al.

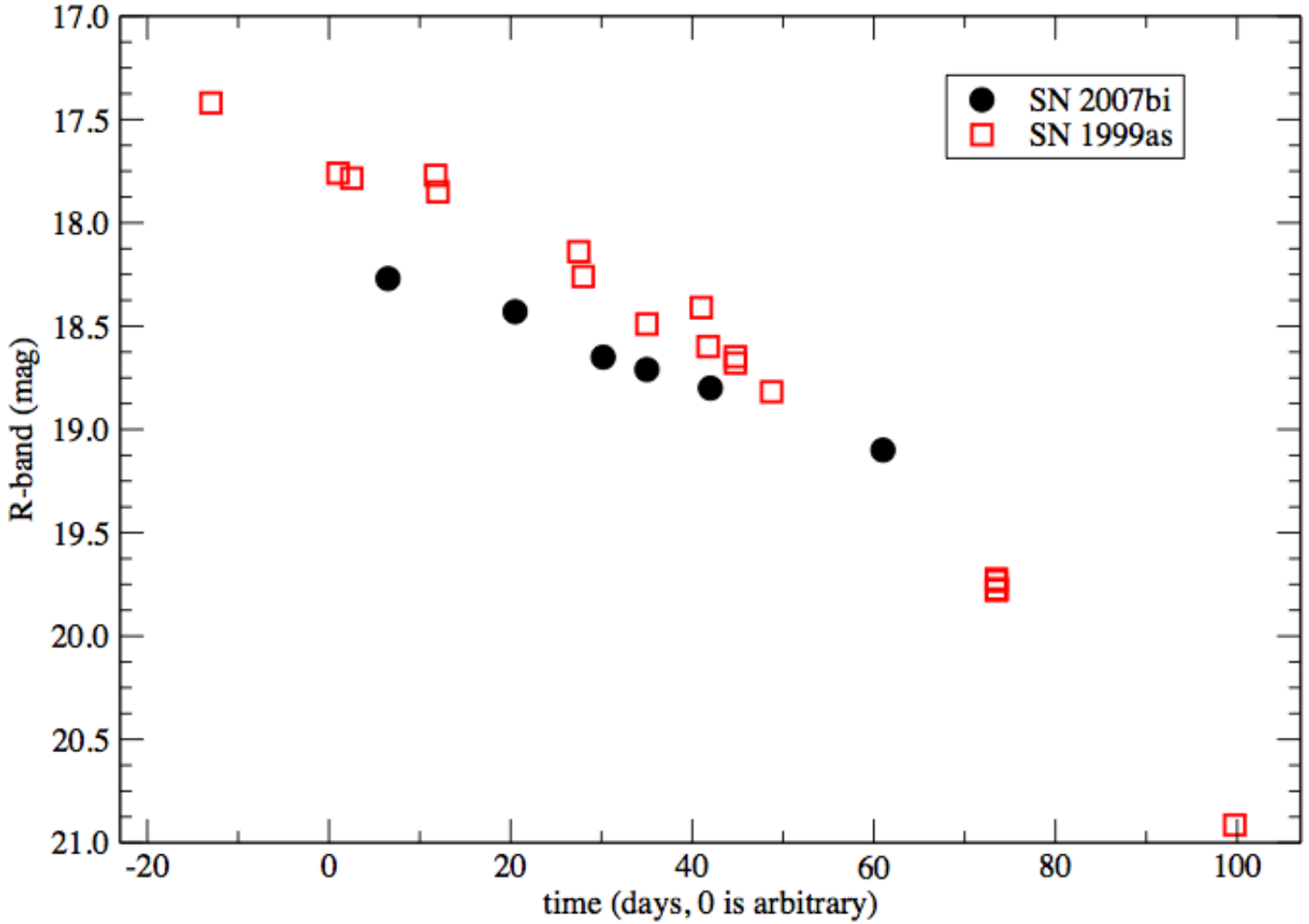
SNe 2007bi, 2006gy

Core-Collapse vs. PISN



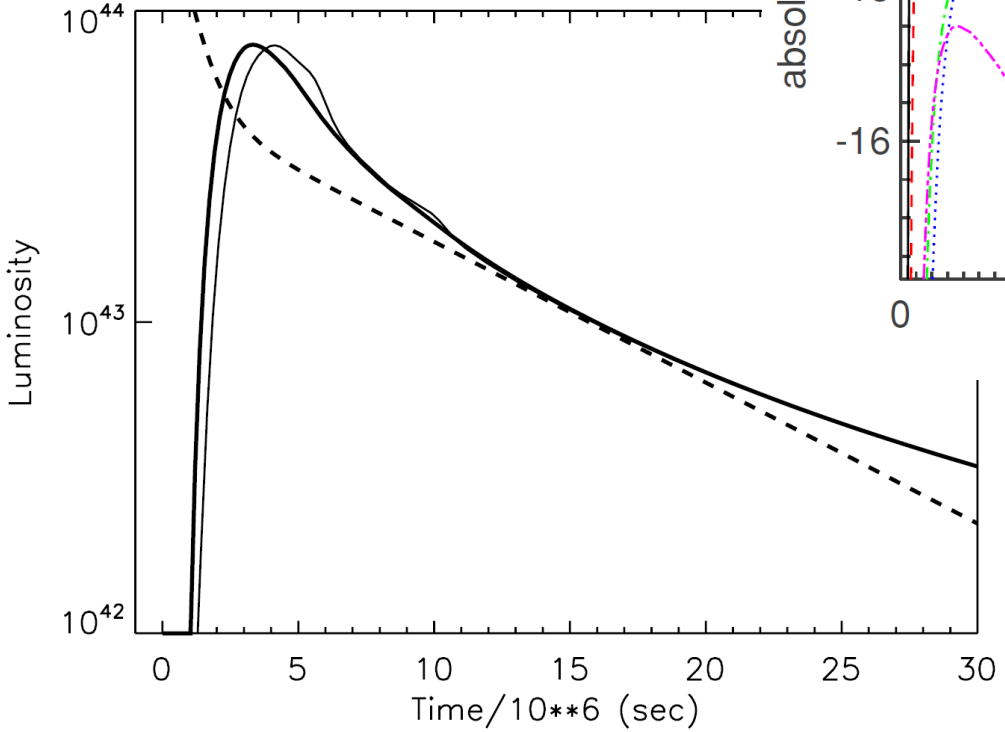
Moriya et al.

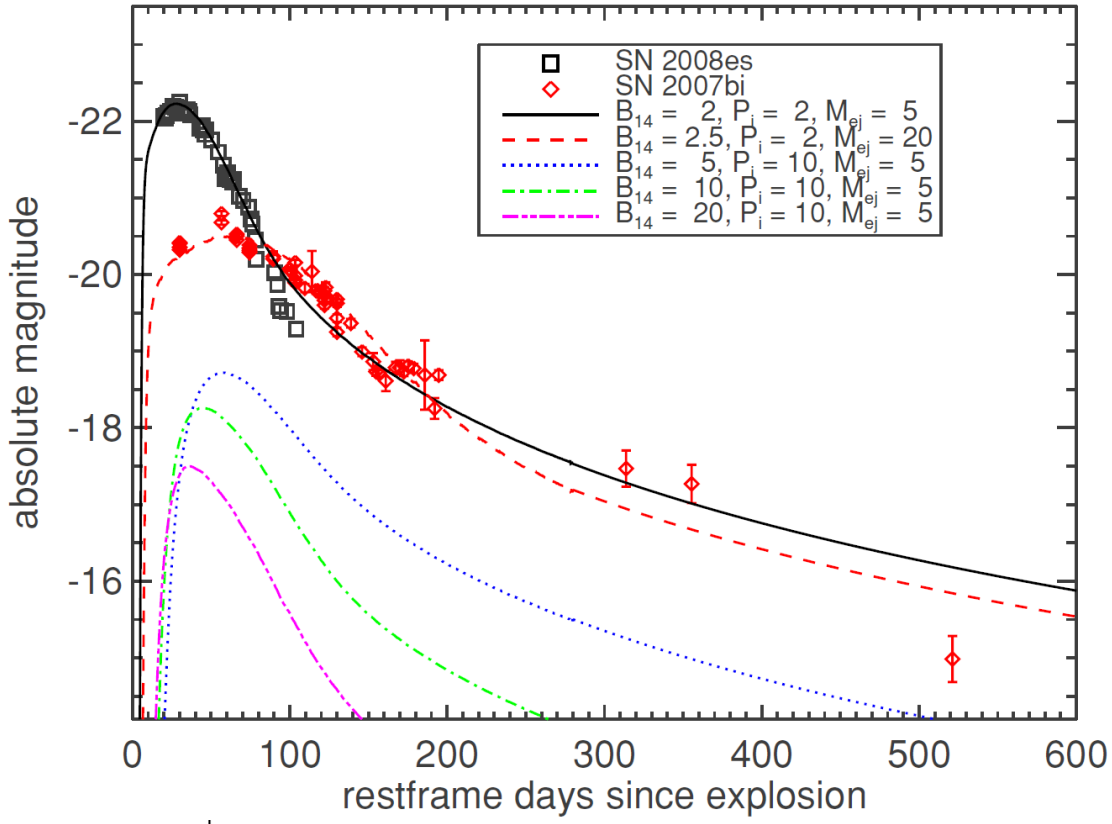
SNe 1999as vs. 2007bi



Nugent et al.

Magnetar model

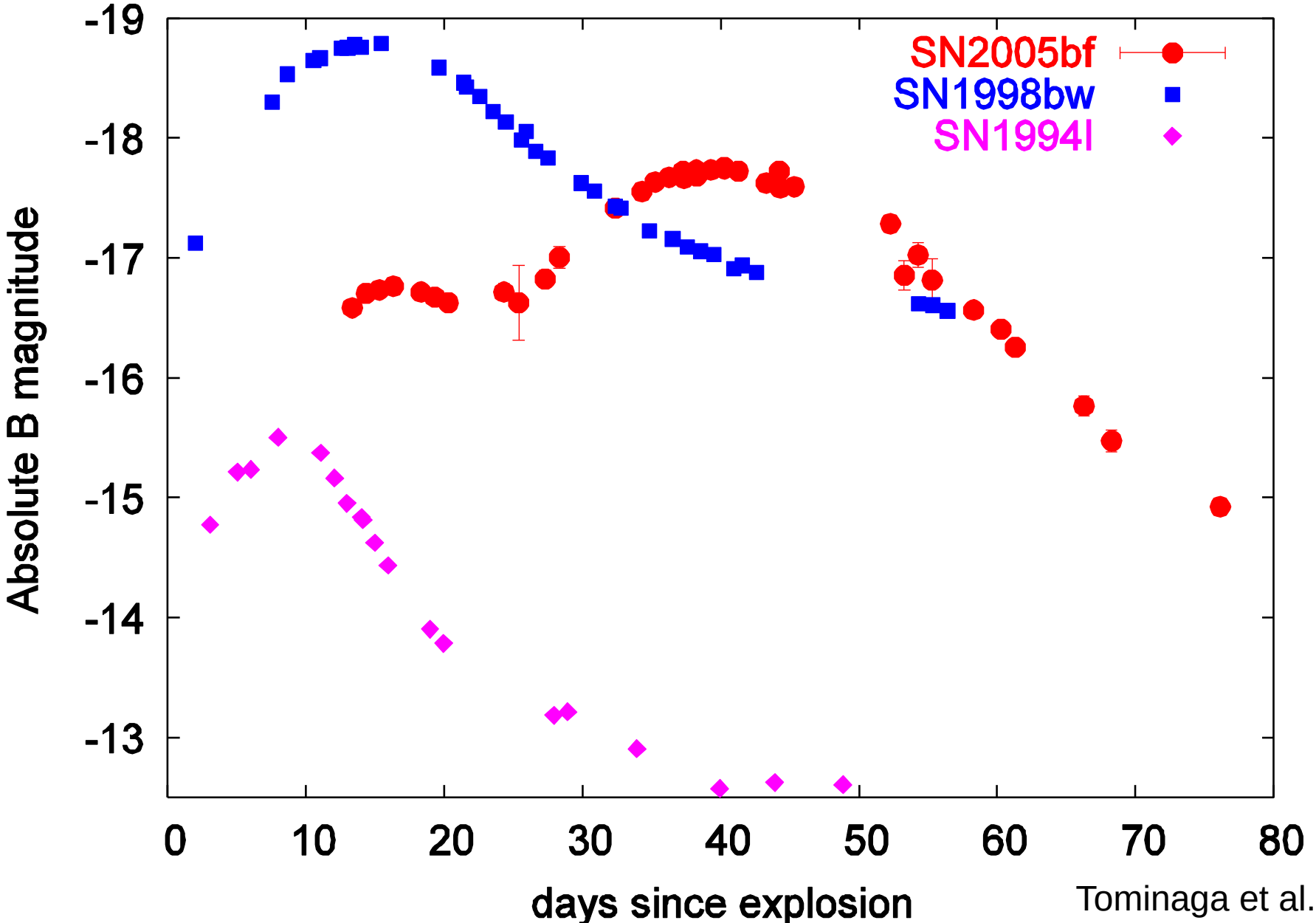




Kasen & Bildsten 2010

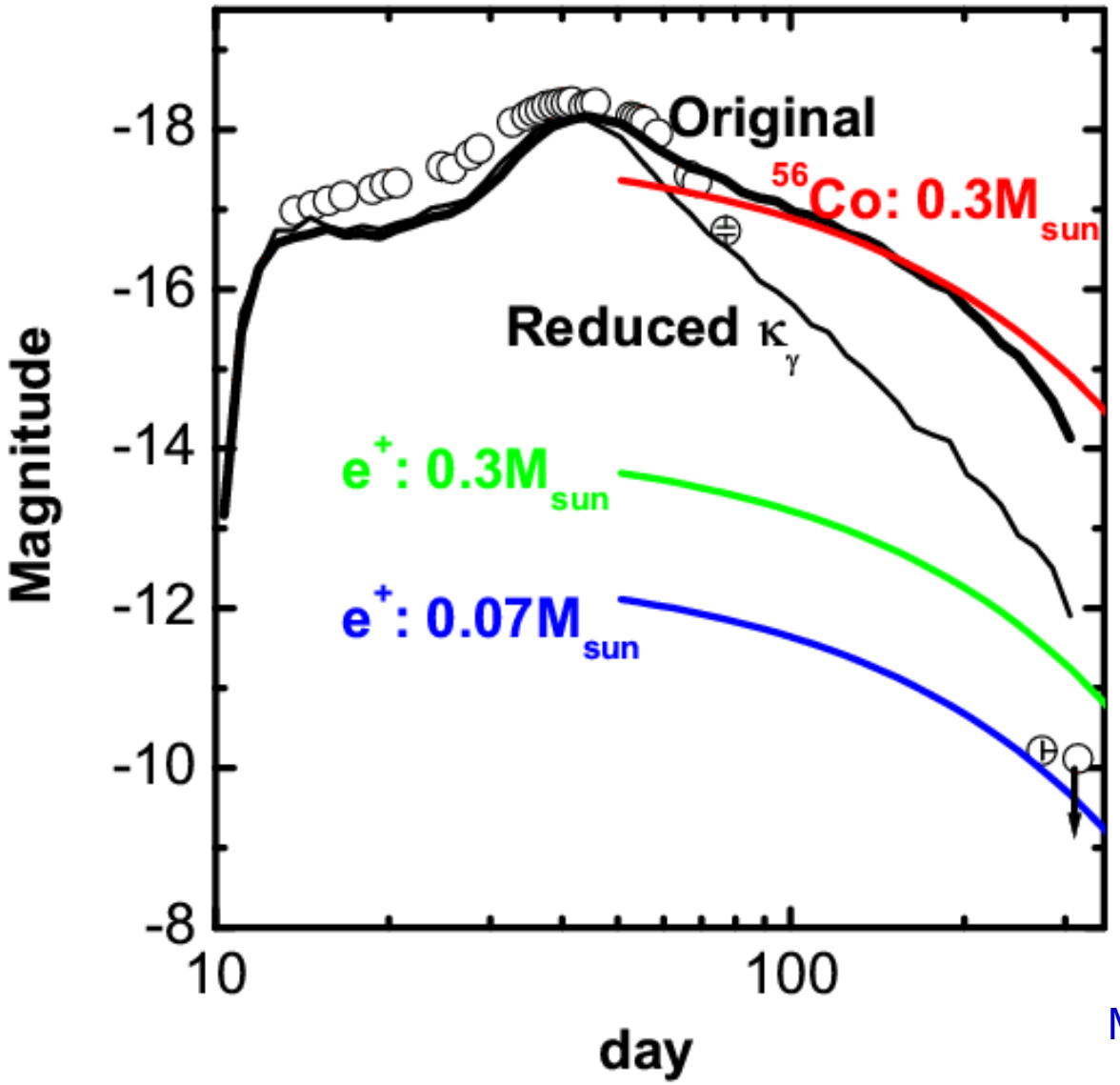
Woosley 2010

SN Ib 2005bf: Double Peaks



Tominaga et al.

SN 2005bf: Light Curve @ Late Phases



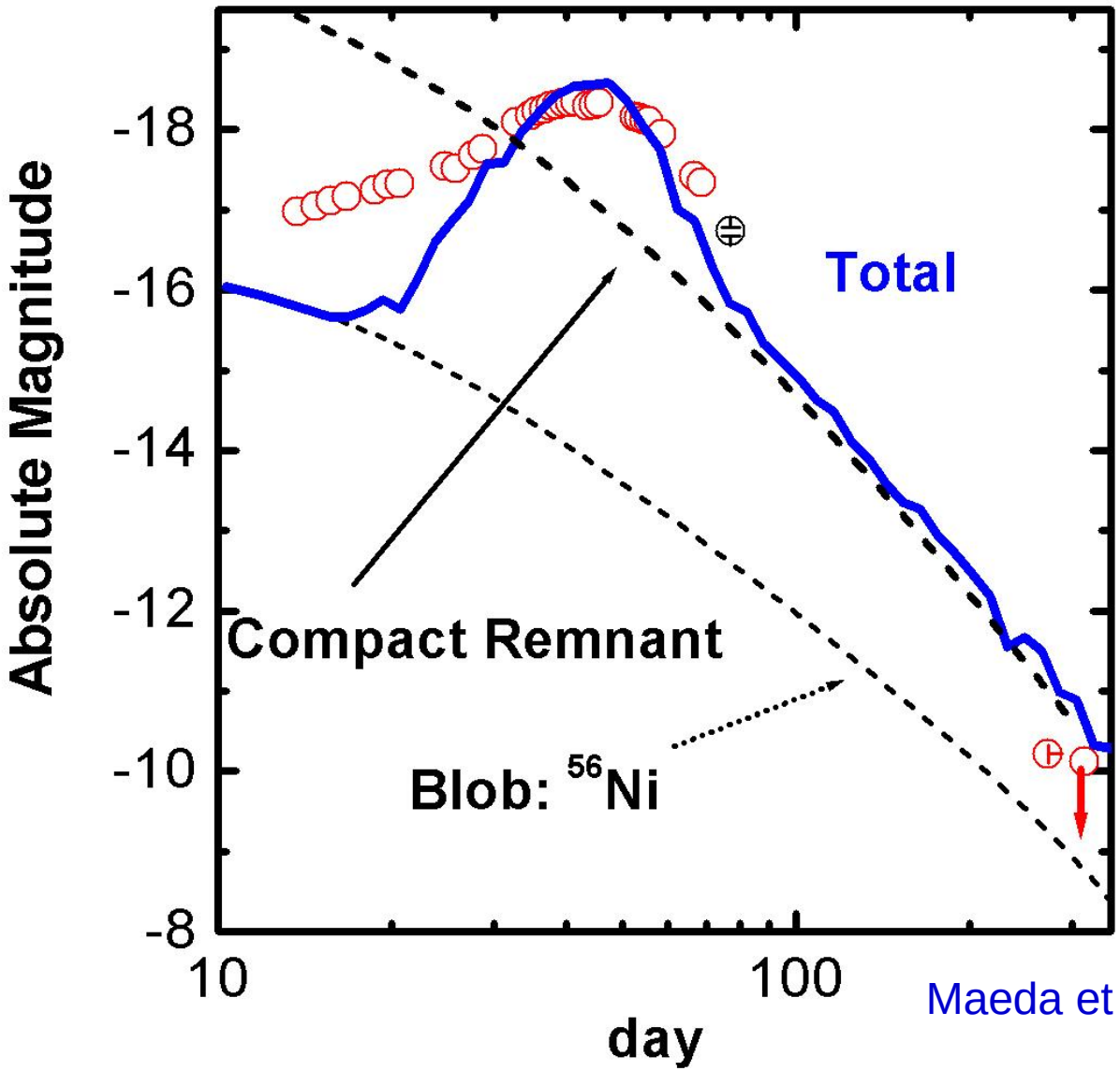
SUBARU obs

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

Maeda et al. (ApJ 2007)

1st peak: ^{56}Ni decay

2nd peak: Magnetized Pulsar ?



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

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

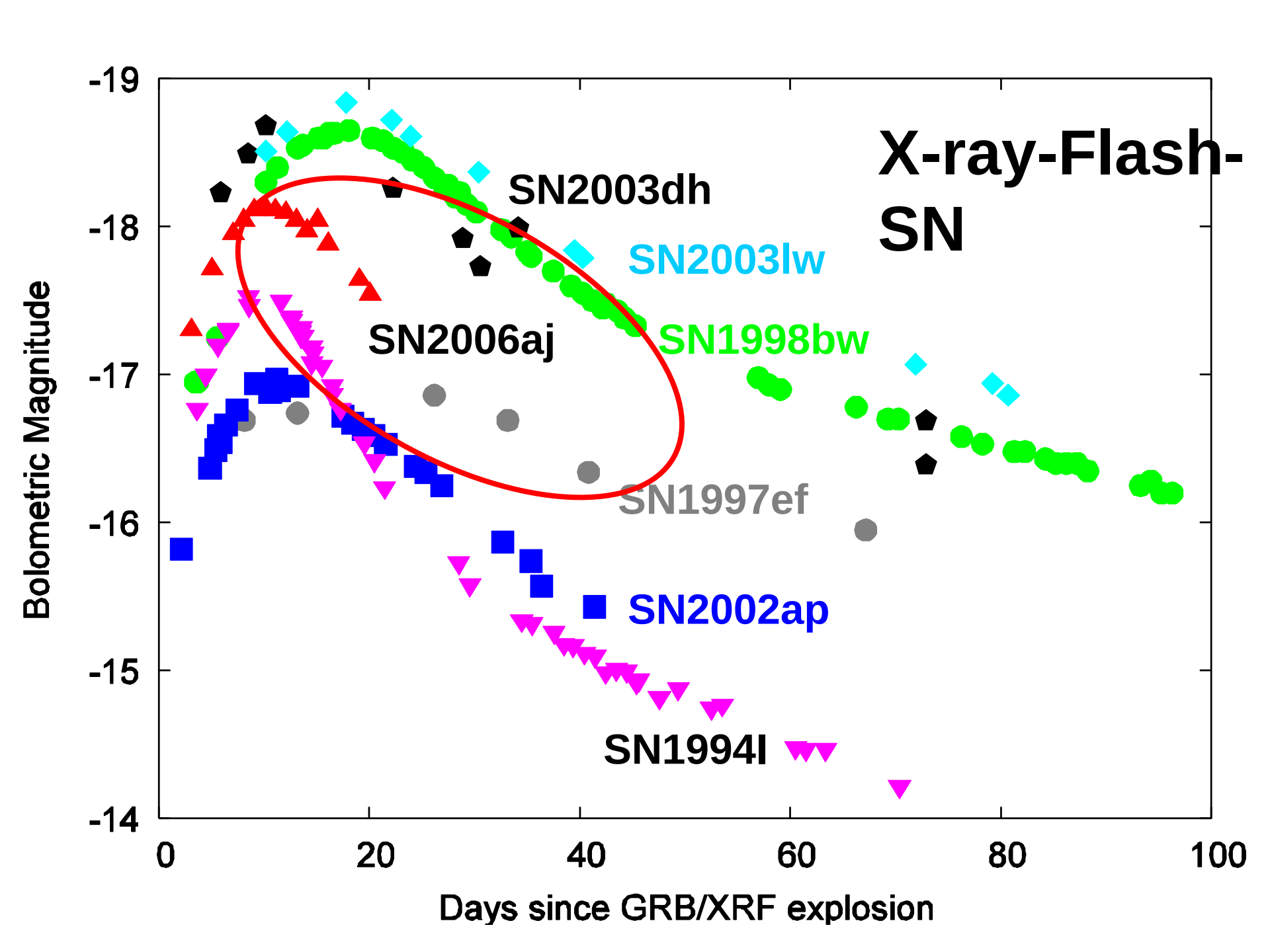
$T_0=60$day

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

(*) If dipole, e.g.,

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

Maeda et al. (2007 ApJ)

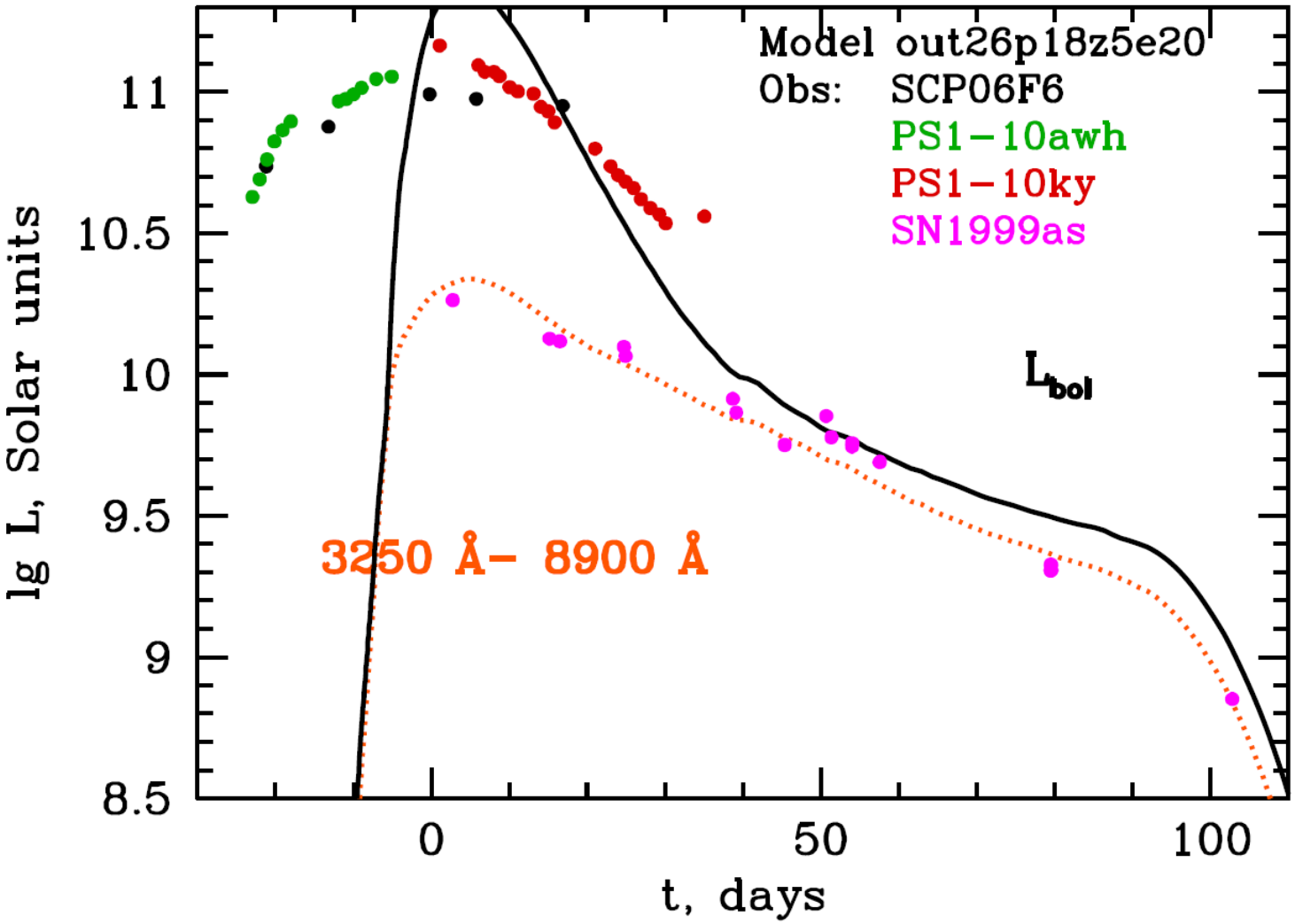

X-ray-Flash-SN
SN2003dh
SN2003lw
SN1998bw
SN2006aj
SN1997ef
SN2002ap
SN1994I
Bolometric Magnitude
Days since GRB/XRF explosion
-19
-18
-17
-16
-15
-14
0
20
40
60
80
100

XRF 060218/ SN 2006aj

- **Small Oxygen Mass < 1.3 $M_\odot$**
- $M_{ej} \sim 2\ M_\odot$ ($M_{ms} \sim 20\ M_\odot$)
- $E \sim 2 \times 10^{51}$ erg
- $M(^{56}Ni) \sim 0.21 M_\odot$

- Neutron Star forming SN ?
- Magnetar-driven XRF ?
- Mass Loss Rate ? Shell ?
- Cas A – connection ?

SN99as: Circumstellar Interaction Model



C+O CSM

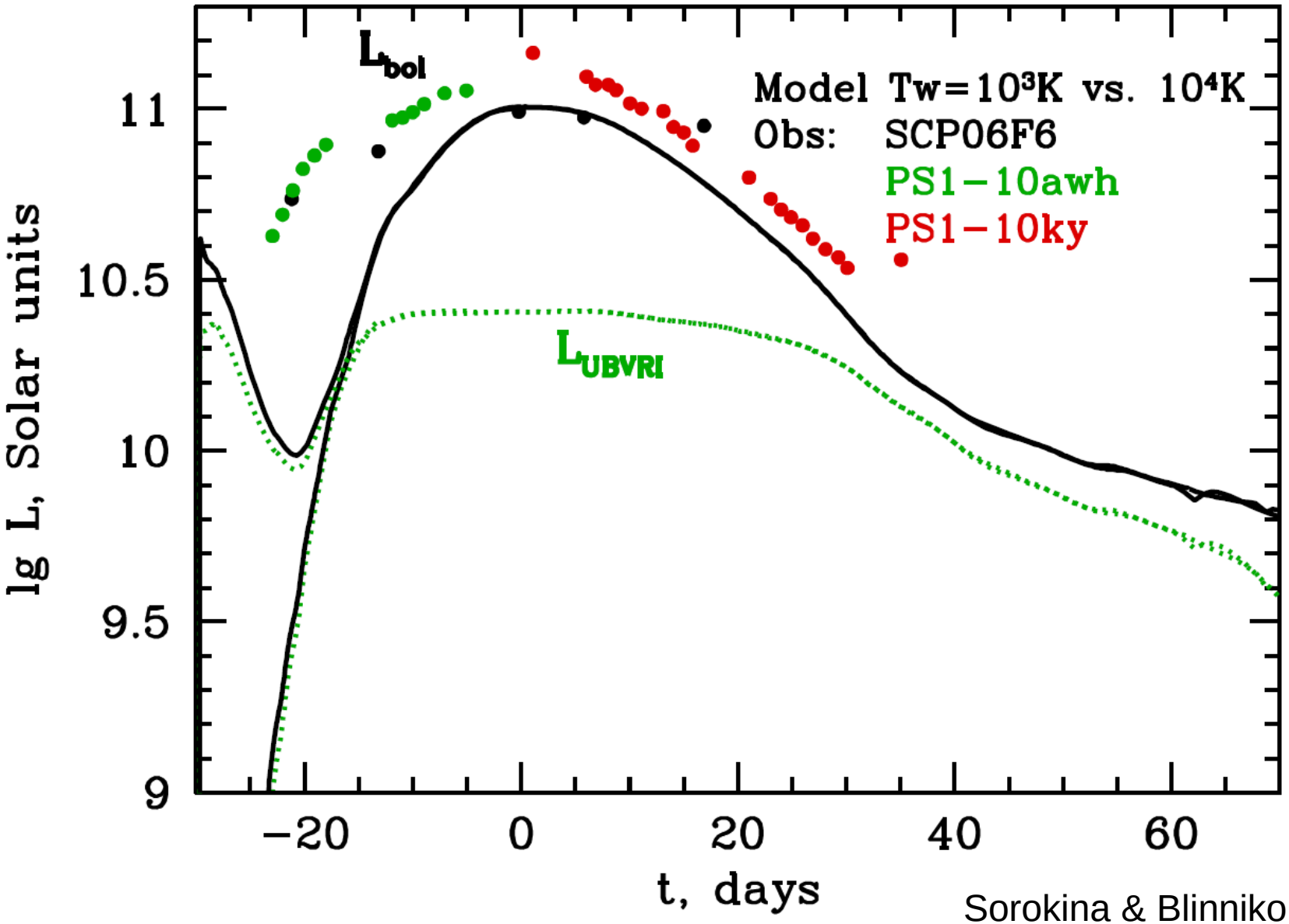
M(csm) = $5M_{\odot}$

E = 2 e51 erg

UV bright

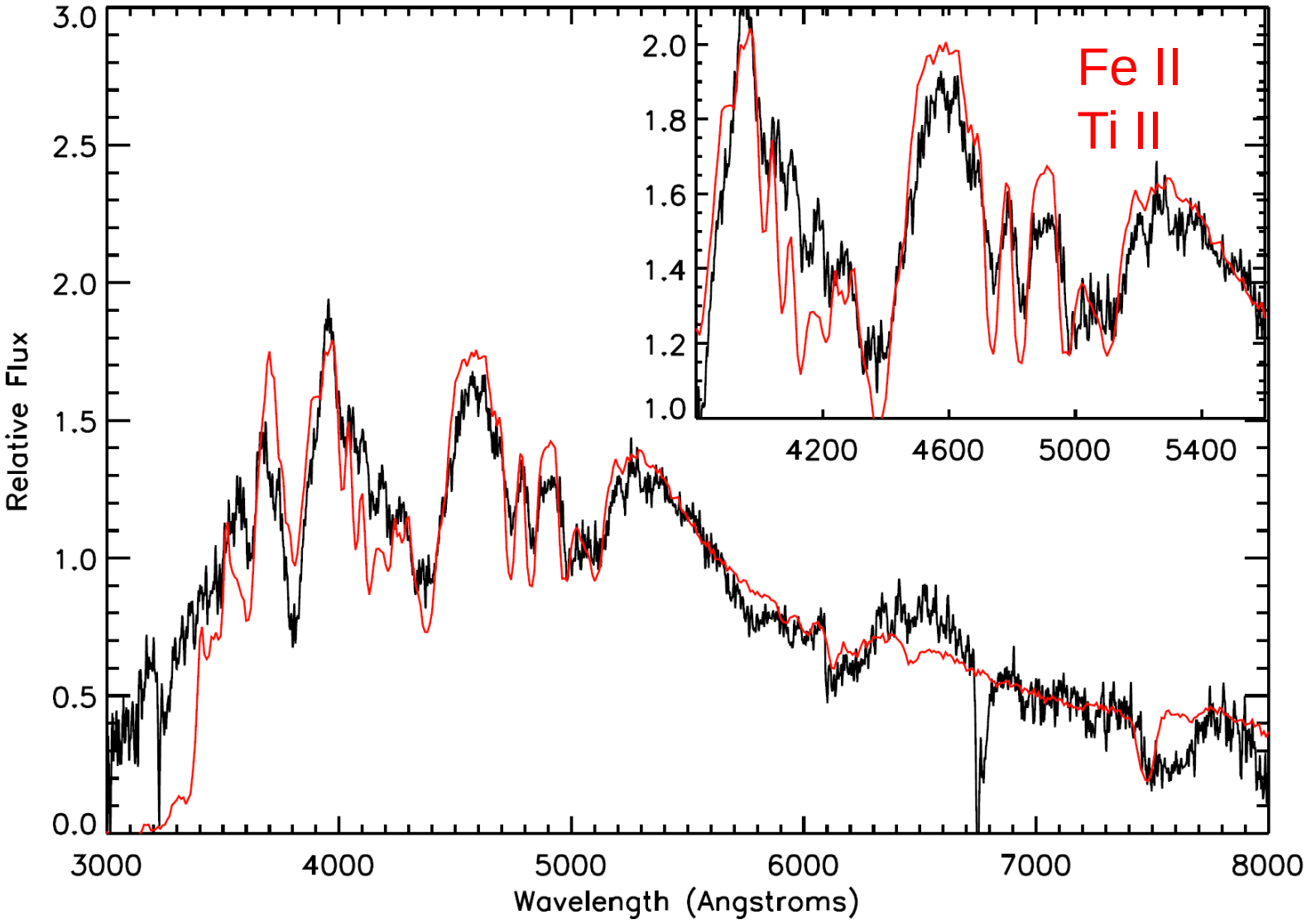
Sorokina & Blinnikov 2012

Non-H Superluminous SNe



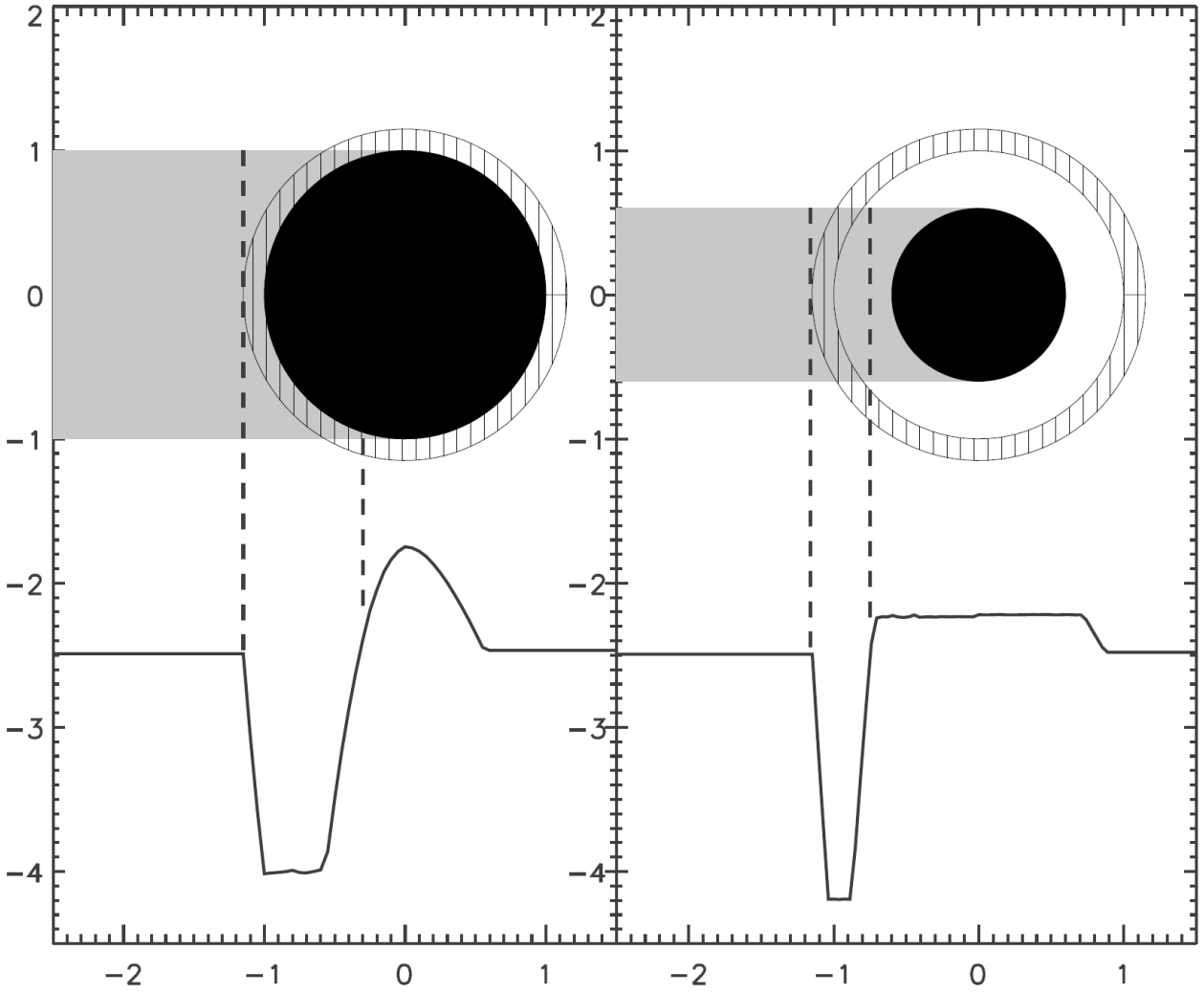
Sorokina & Blinnikov 2012

SN1999as: Narrow Lines



Nugent et al.

A Detached Shell Model



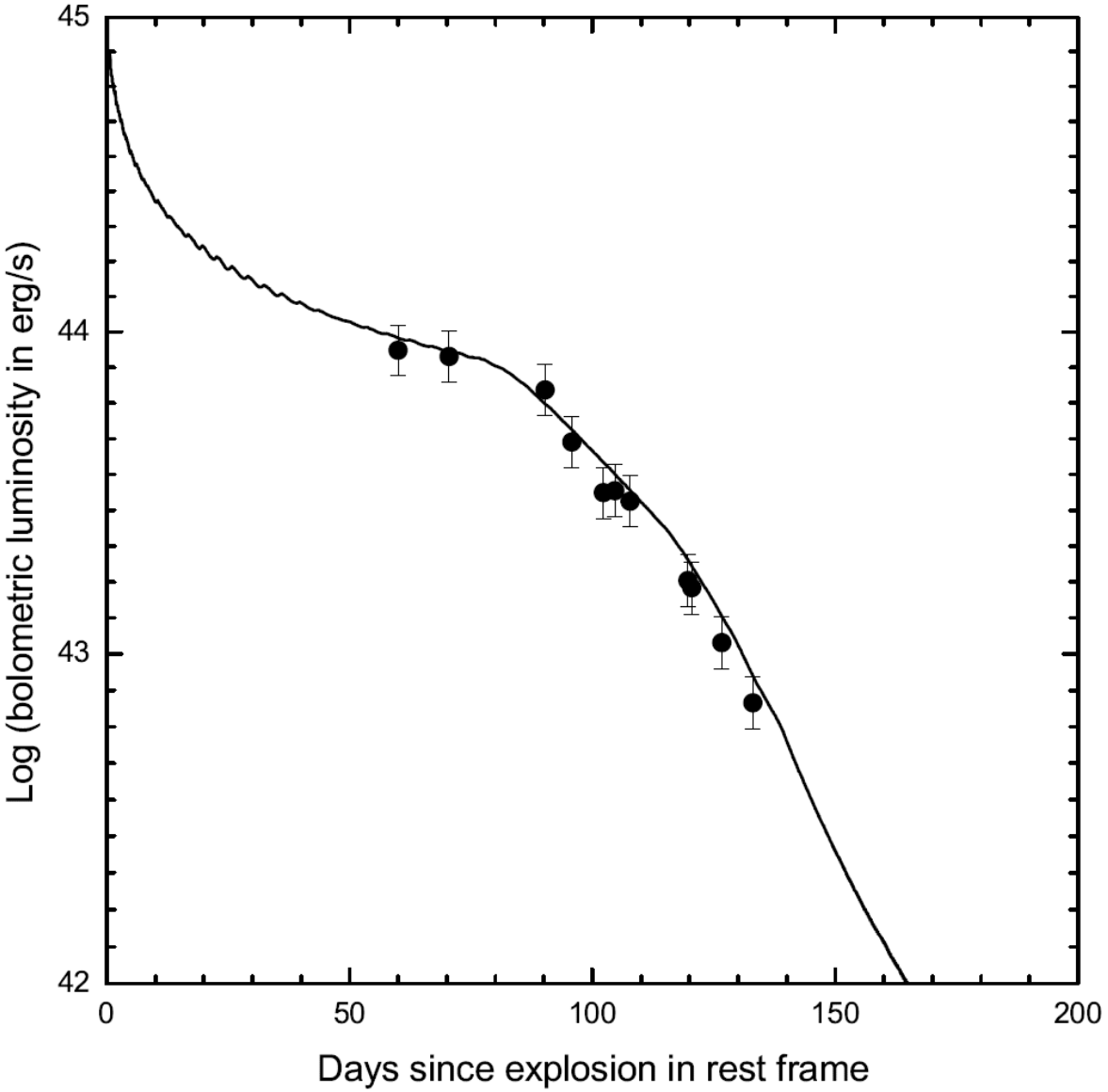
V(ph) ~ 10,000 km/s
V(shell) ~ 14,000 km/s
M(shell) ~ 0.2 $M_{\odot}$

Shell Ejection ?

CSM Interaction?

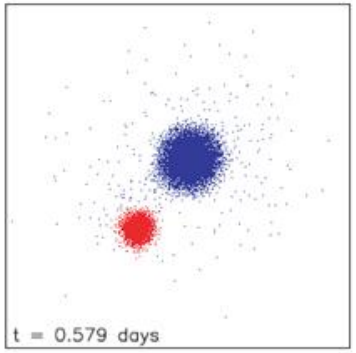
Nugent et al.

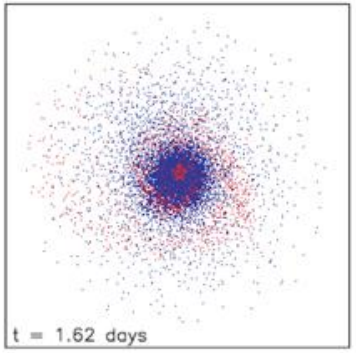
SN1999as: reverse shocked ejecta

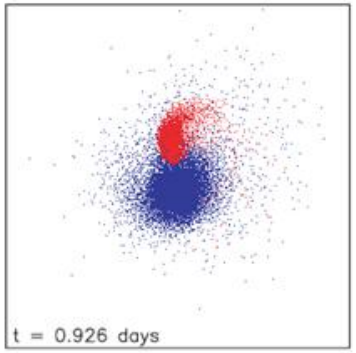


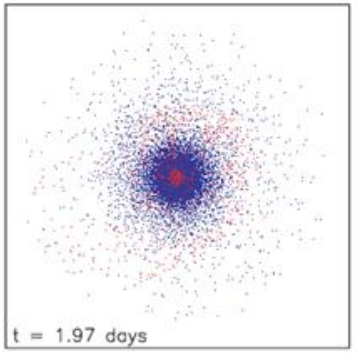
Deng et al.

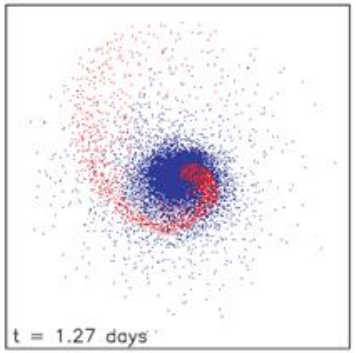
Multiple Stellar Collisions in Dense Star Cluster

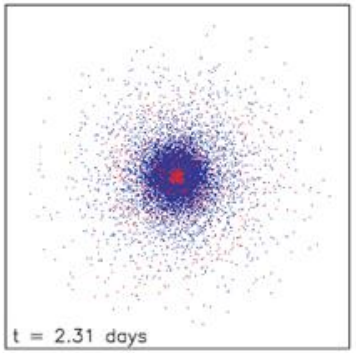












Suzuki, Nakasato, et al.

➔

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 IRotation-induced mixing
➔ H-depleted Star

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

Superluminous SNe (Ic) ?

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

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

Magnetar ? **XRF ?**

Circumstellar Interaction ?

SN 1999as : Shell ejection?

Late time spectra ?

Multiple Stellar Collisions in Dense Star Clusters ?

~ 40 – 140 $M_\odot$ Stars

- Nuclear Instability (O,Si burning)
  Pulsational Mass Ejection?

  even the core materials ?

  LBV?
- Interaction with Dense Circumstellar Matter
- GRBs ?