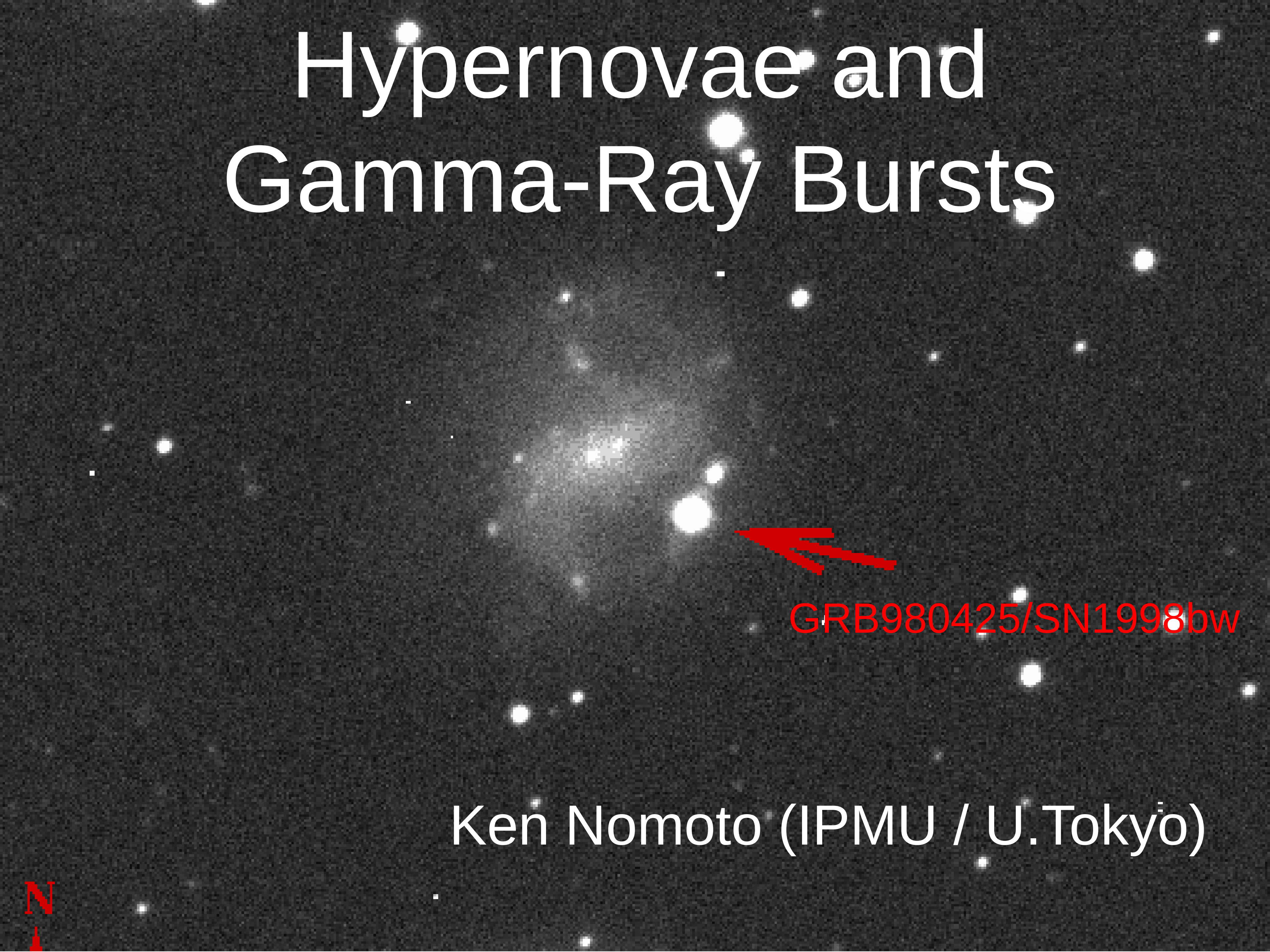
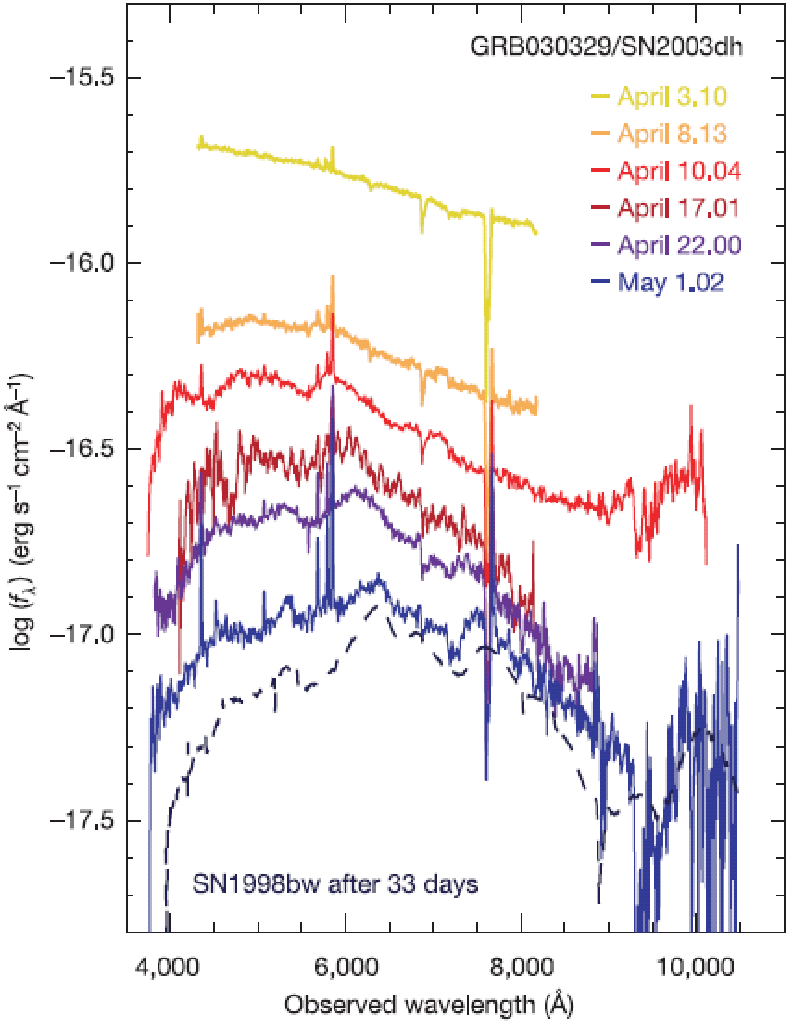
Hypernovae and Gamma-Ray Bursts

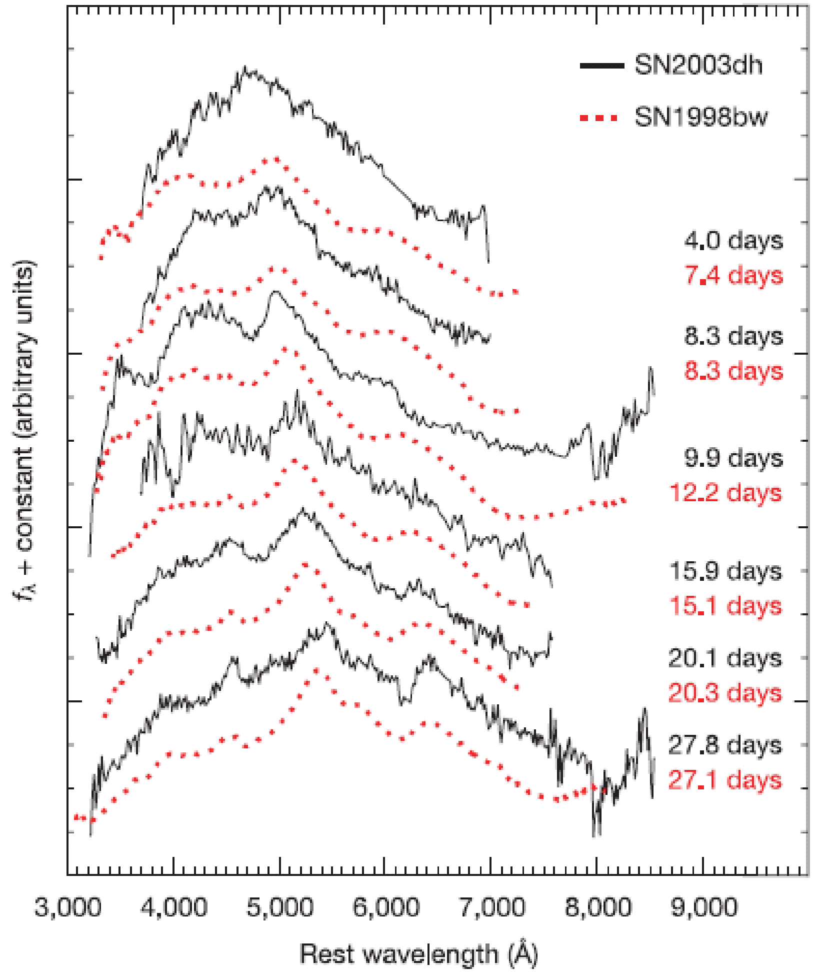


Ken Nomoto (IPMU / U.Tokyo)

GRB-SN Connection

(GRB 030329 / SN 2003dh)





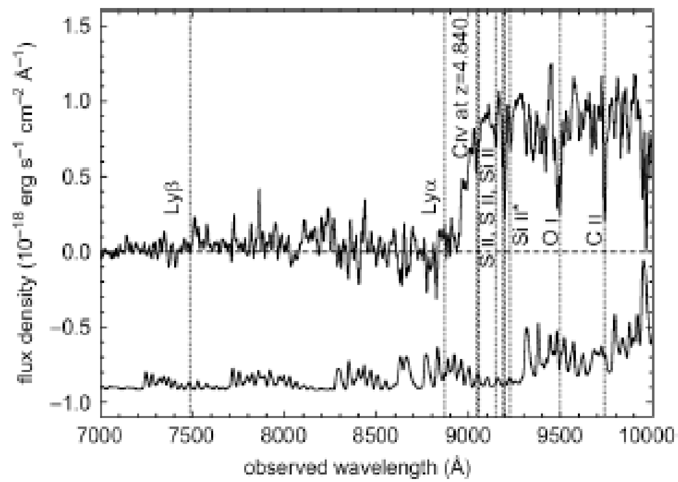
Stanek et al (2003) ;Hjorth et al (2003)

Unusual Spectra !

High Redshift GRBs

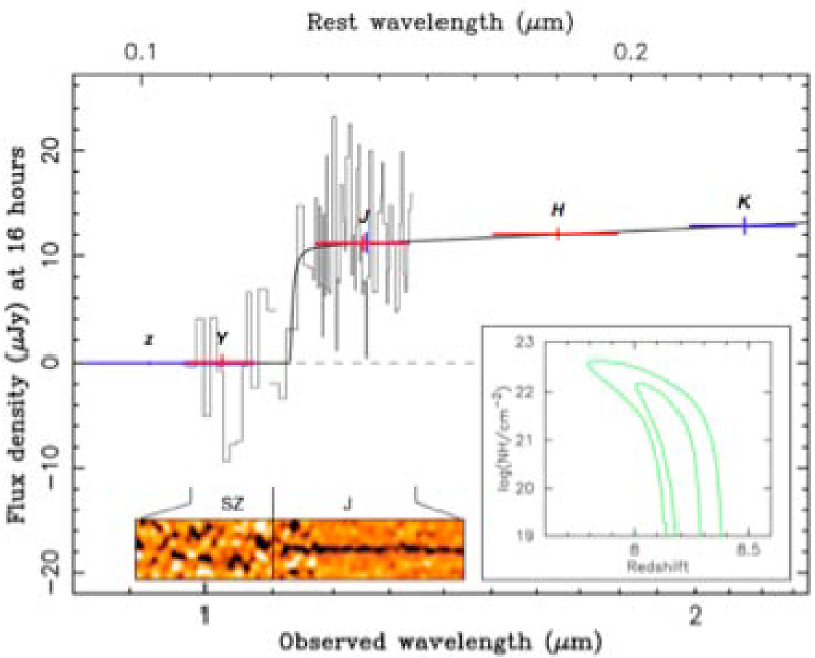
6 GRBs out of 500 at z>5

z = 6.29   GRB 050904



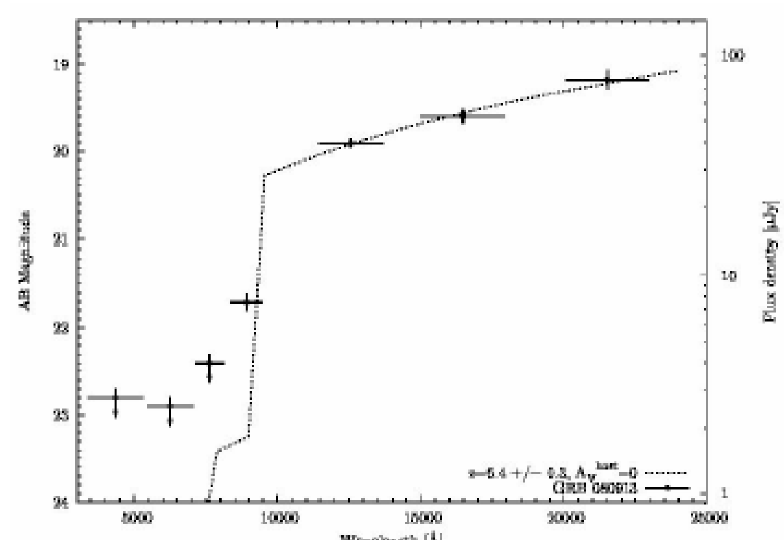
Kawai et al. 2006

z = 8.2   GRB 090423



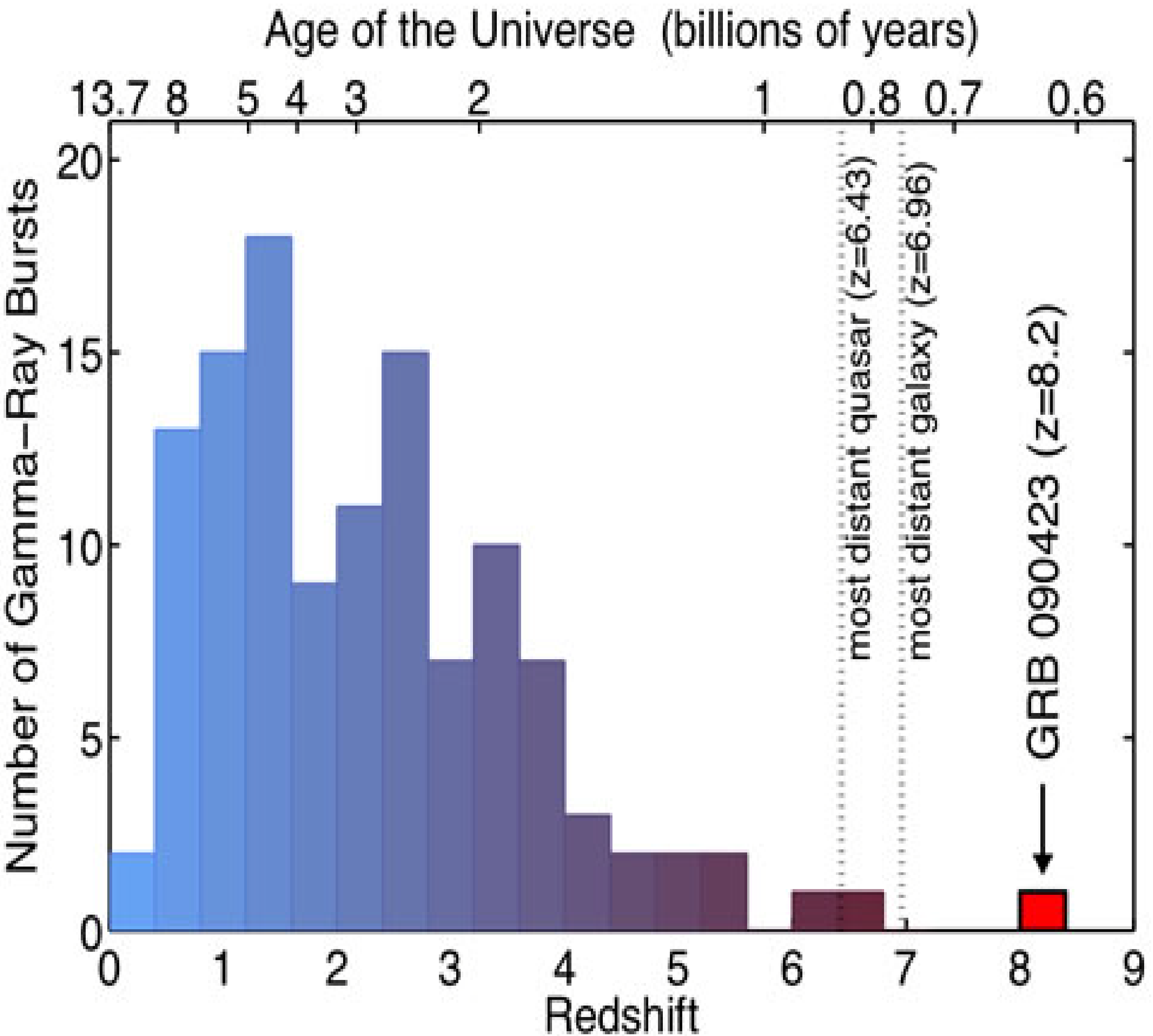
Tanvir et al. 2009   Salvaterra et al. 2009

z = 6.7   GRB 080913



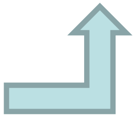
Greiner et al. 2009

Redshift Distribution of GRBs



:

Pop III GRB ?



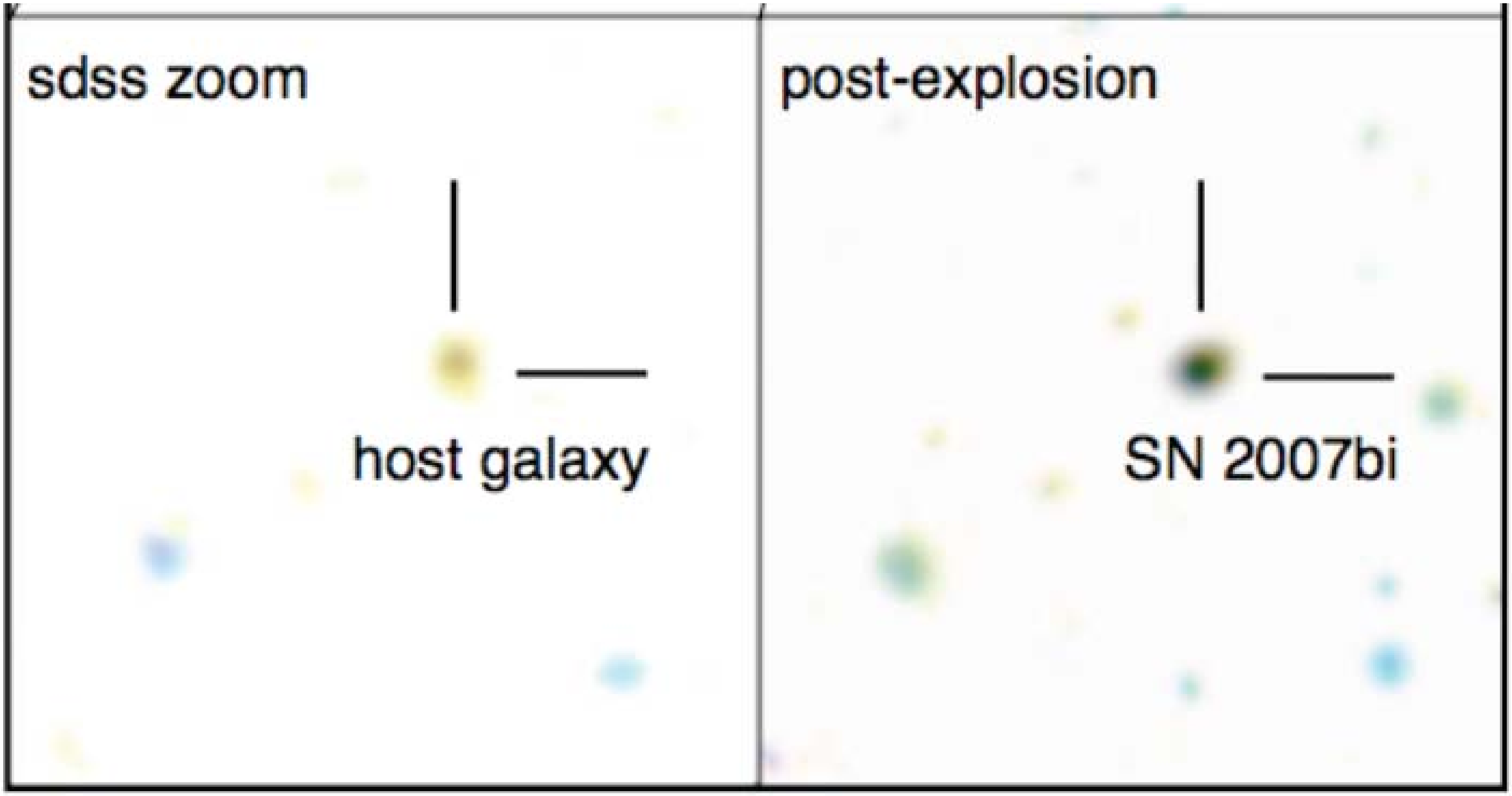
(Berger 09)

Unusual Supernovae

- Ultra-Luminous SNe (-23 mag)

- Ultra-Faint SNe (-14 mag)

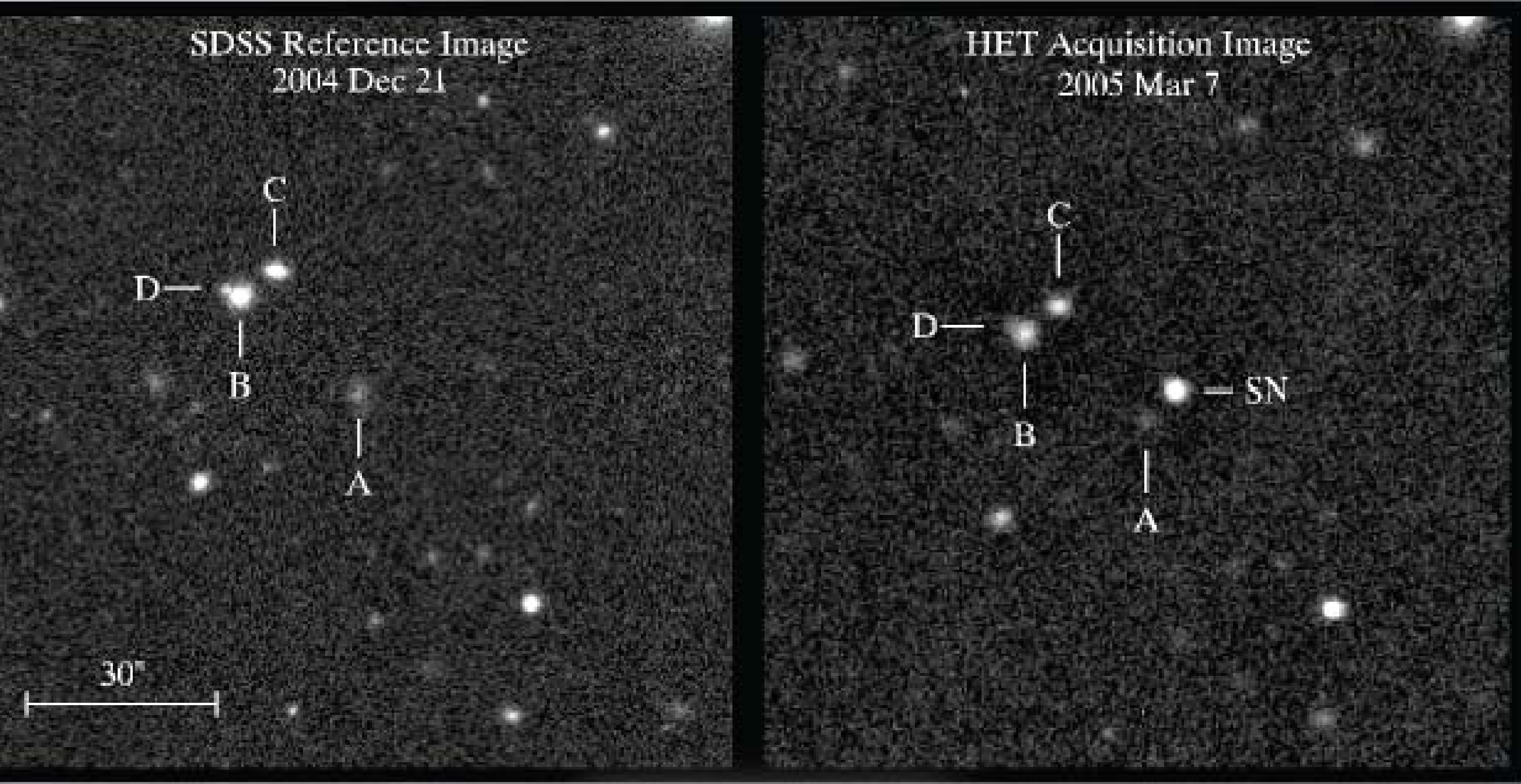
SN Ic 2007bi (PISN?)



(Young et al. 2009; Gal-Yam et al. 2009)

SN 2005ap

-22.7 mag



Quimby et al. 2007

Unusual Supernovae

- Ultra-Luminous SNe (IIn, II-L, Ic) (-23 mag)

  Pair Instability ?

  Core-Collapse ? GRB ?

  CSM Interaction ?

- Ultra-Faint SNe (IIn, Ic) (-14 mag)

  SN Impostor ? Super AGB ?

  Fallback SN ? non-SN GRB ?

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 ?**

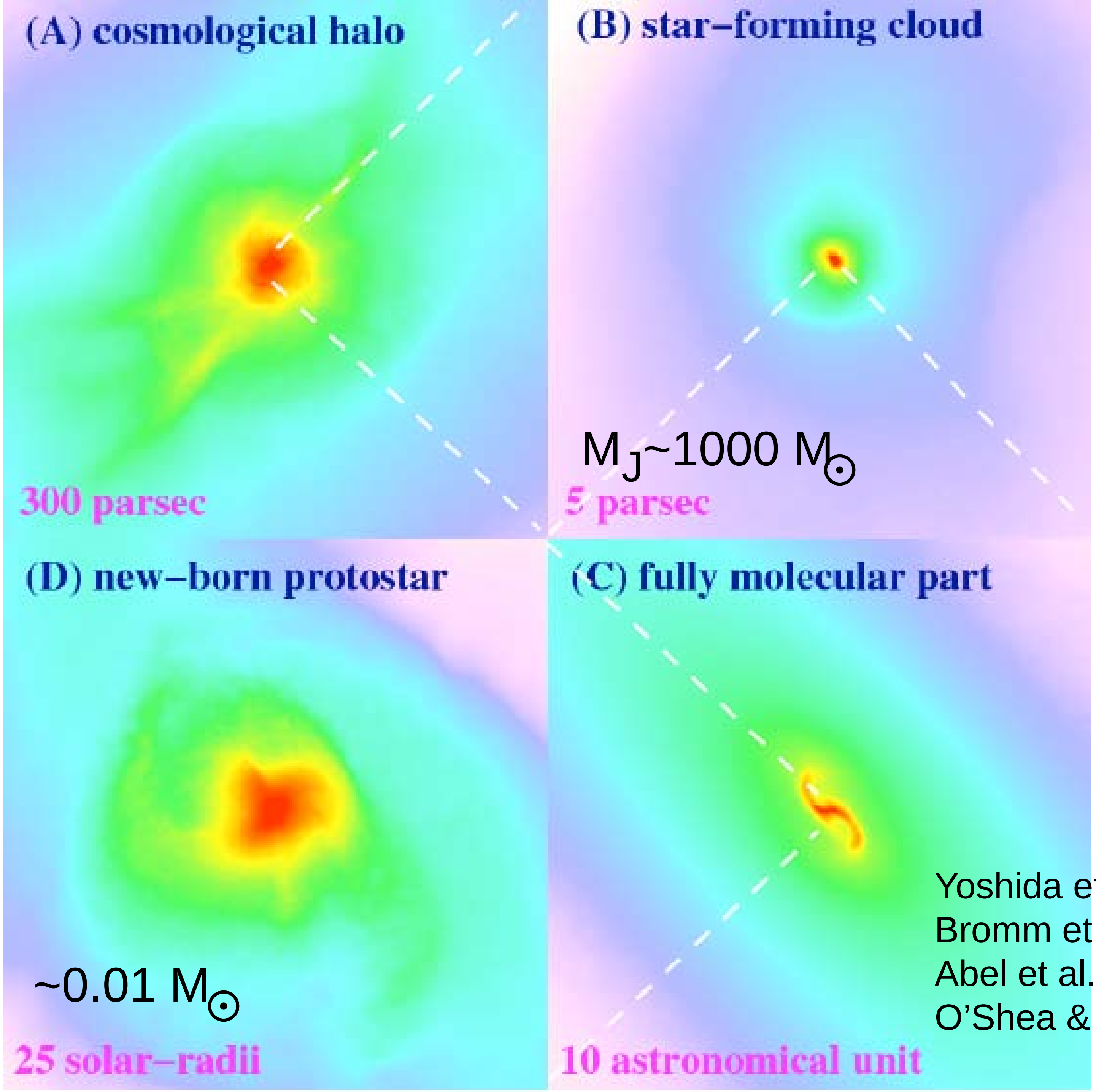
$M \sim 140 - 300 M_\odot$:

→ **Pair Instability SNe** → Complete Disruption

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

→ Core Collapse → **Pop III GRBs, Hypernovae**

→ **SNe II**



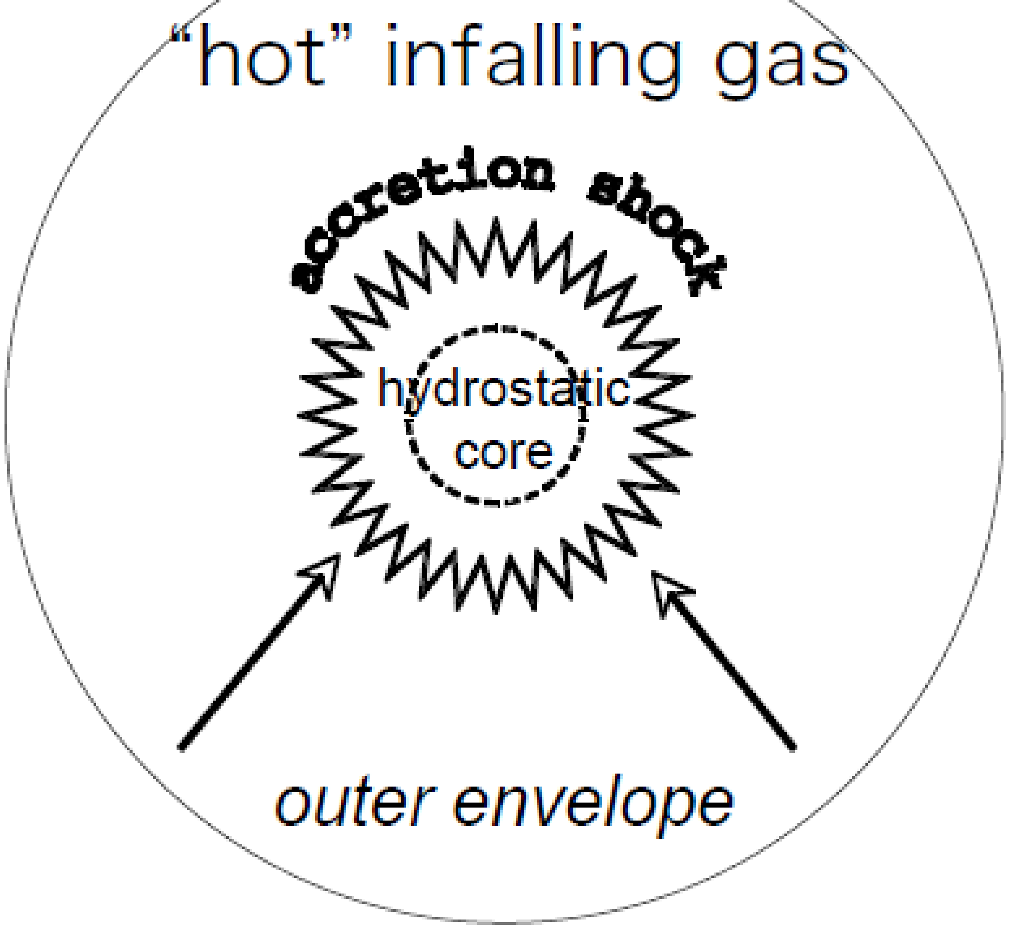
Yoshida et al.
Bromm et al.
Abel et al.
O'Shea & Norman

Formation of Pop III.1 Stars

- Dark Matter Halo (~10^6 $M_\odot$, z ~ 20)
- Primordial Cloud (~10^4 $M_\odot$)
- H_2 formation and cooling
- Collapsing Core (~10^3 $M_\odot$)
- Static Proto-Star (~0.01 $M_\odot$)
- Mass-Accretion
- Stellar Evolution, Explosion

Accretion onto Protostar → First Star

T ~ 500-10^4 K



Pop III.1 & Pop III.2

- Pop III.1
- Gas of primordial composition
- Initial conditions: purely cosmological

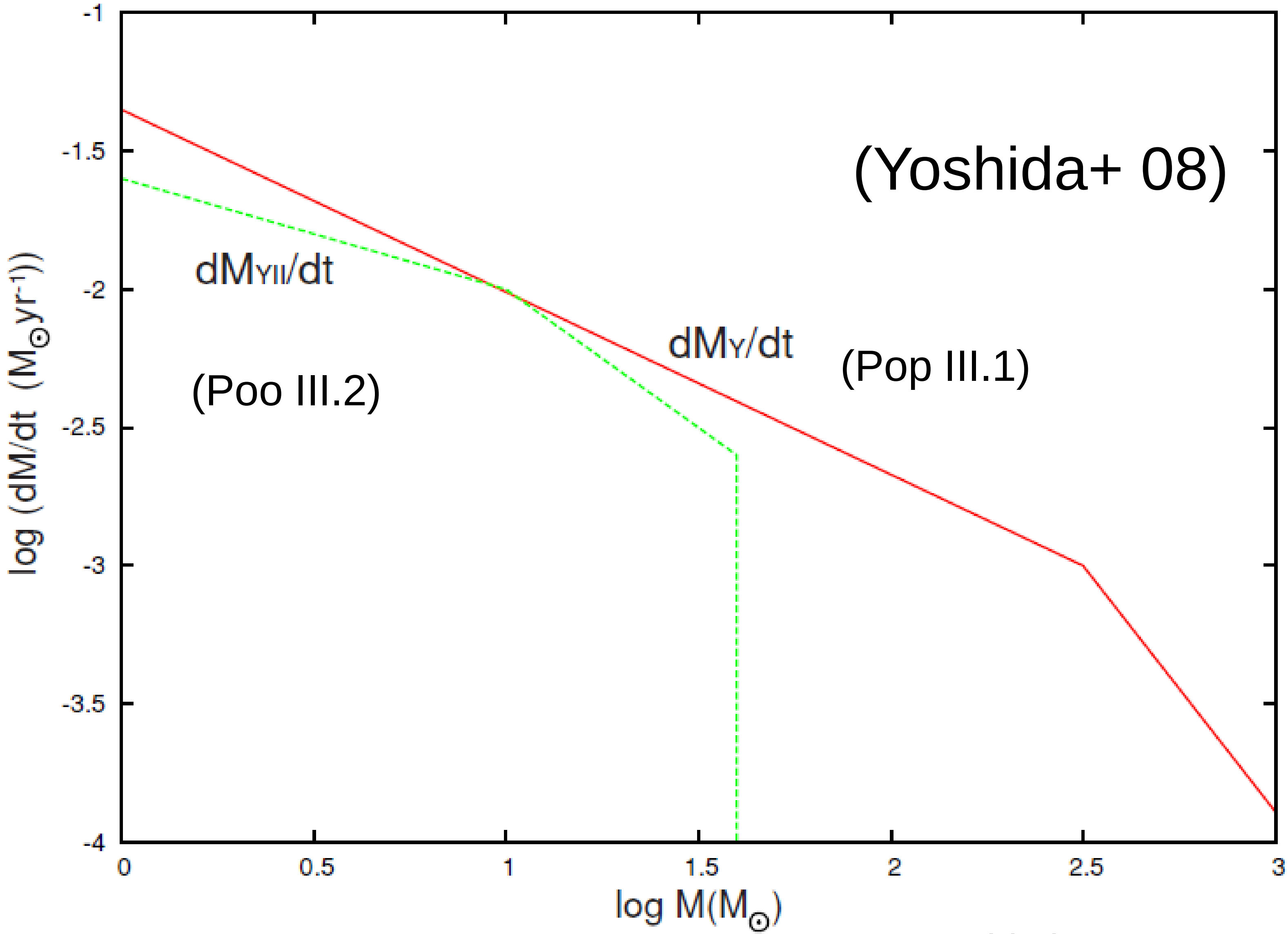
- Pop III.2
- Gas of primordial composition
- Initial conditions modified by radiative and kinetic feedback from a Pop III.1 star, but not chemical feedback

(McKee et al.)

Formation of Pop III.2 Stars

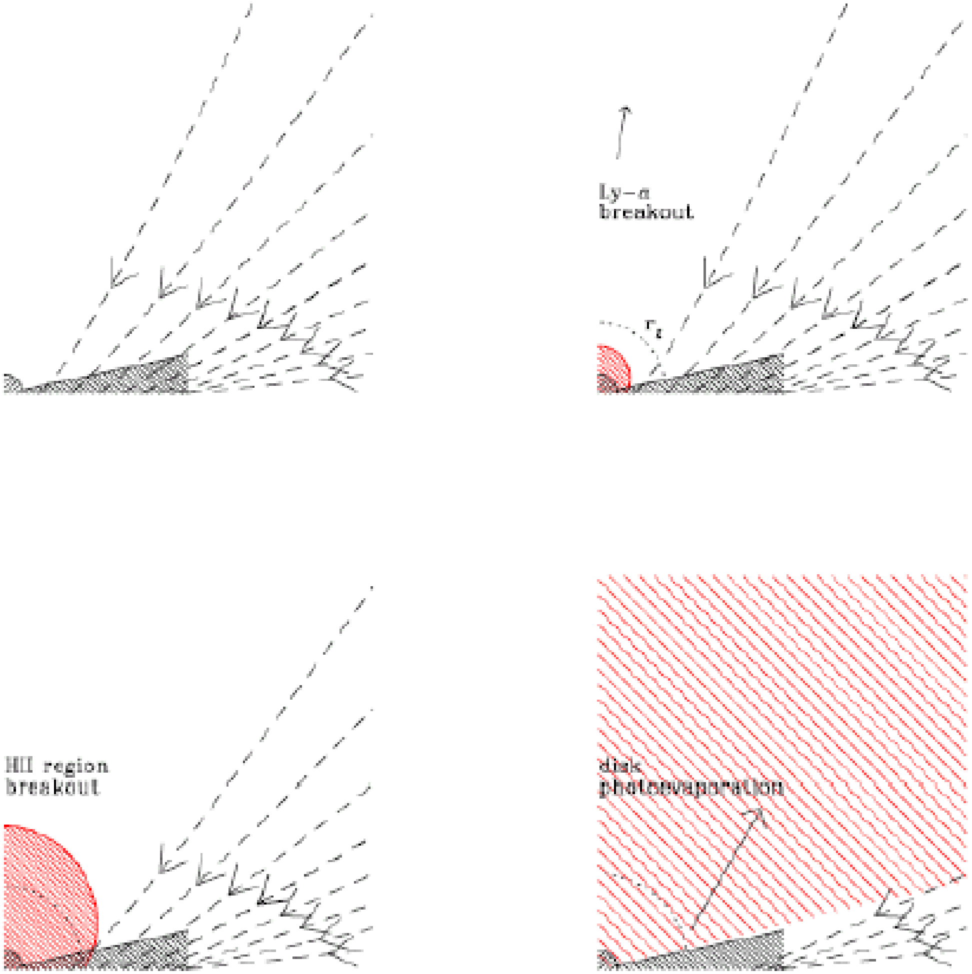
- Dark Matter Halo
- Primordial, reionized cloud
- H_2 & HD formation and line cooling
- Collapsing Core (~40 $M_\odot$)
- Static Proto-Star
- Mass-Accretion
- Stellar Evolution, Explosion

Accretion Rates



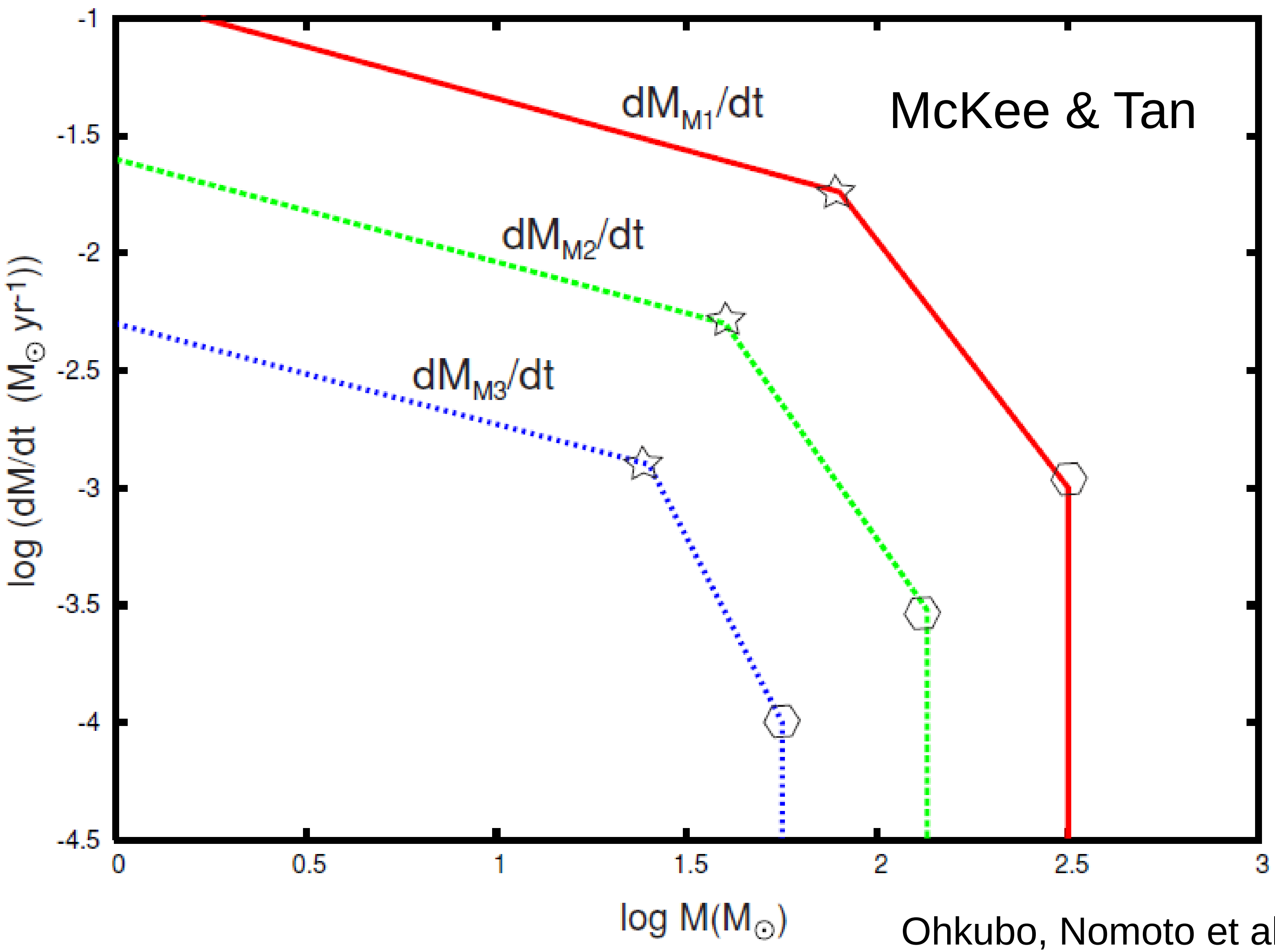
Ohkubo, Nomoto et al. (09)

Accretion rates with stellar feedback



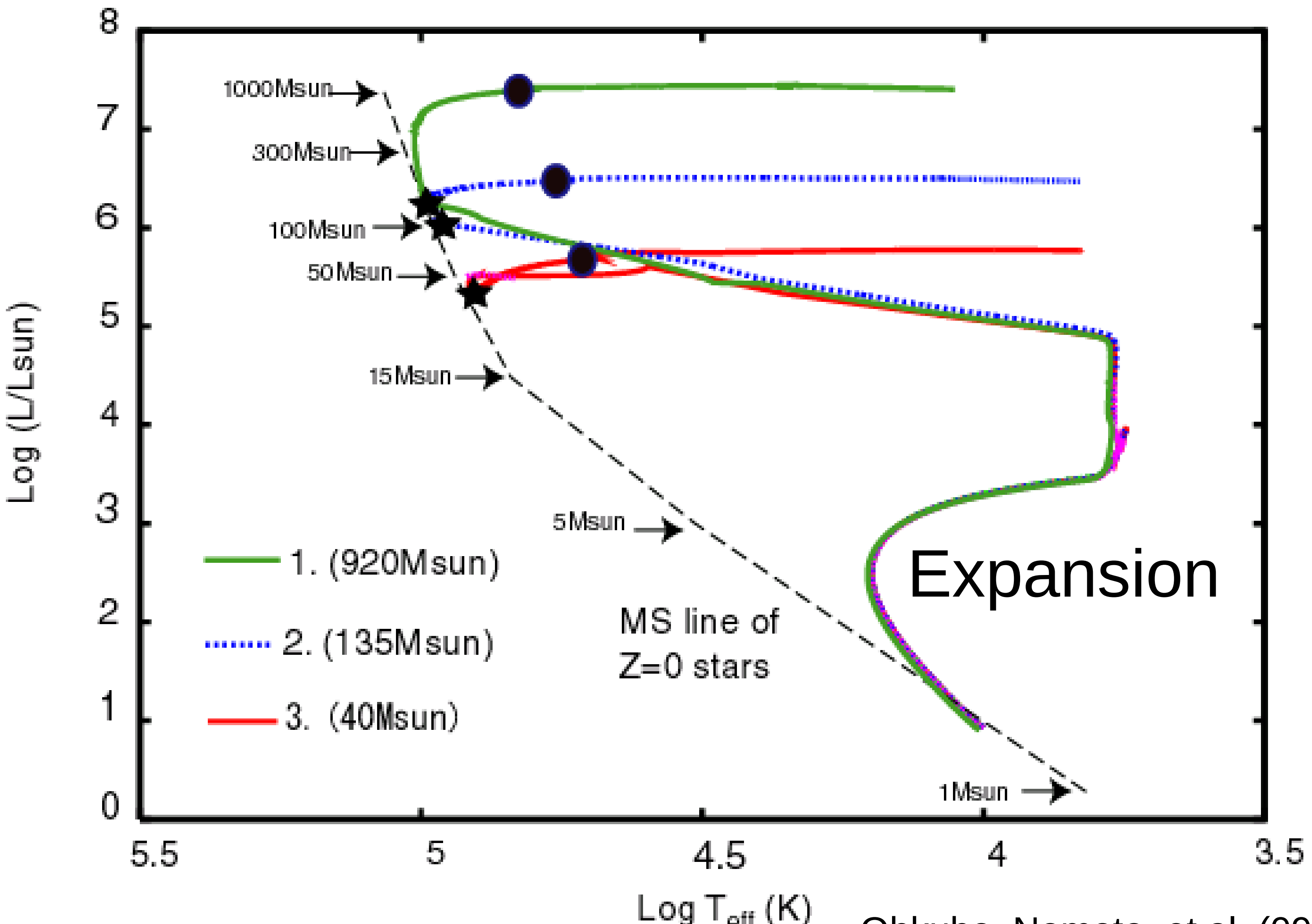
McKee & Tan (2008)

Accretion rates with stellar feedback



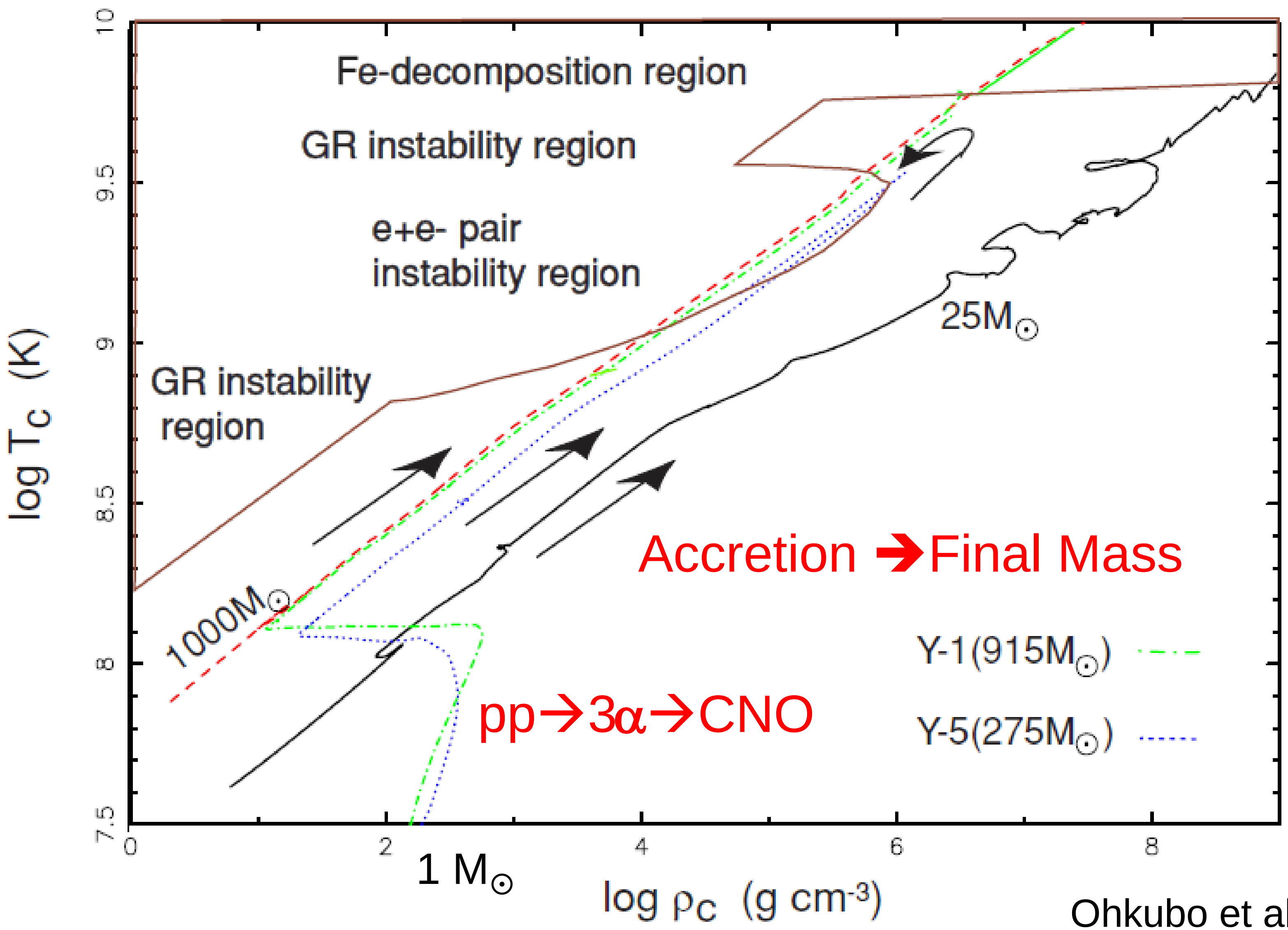
Ohkubo, Nomoto et al. (09)

Mass Accreting Pop III Stars



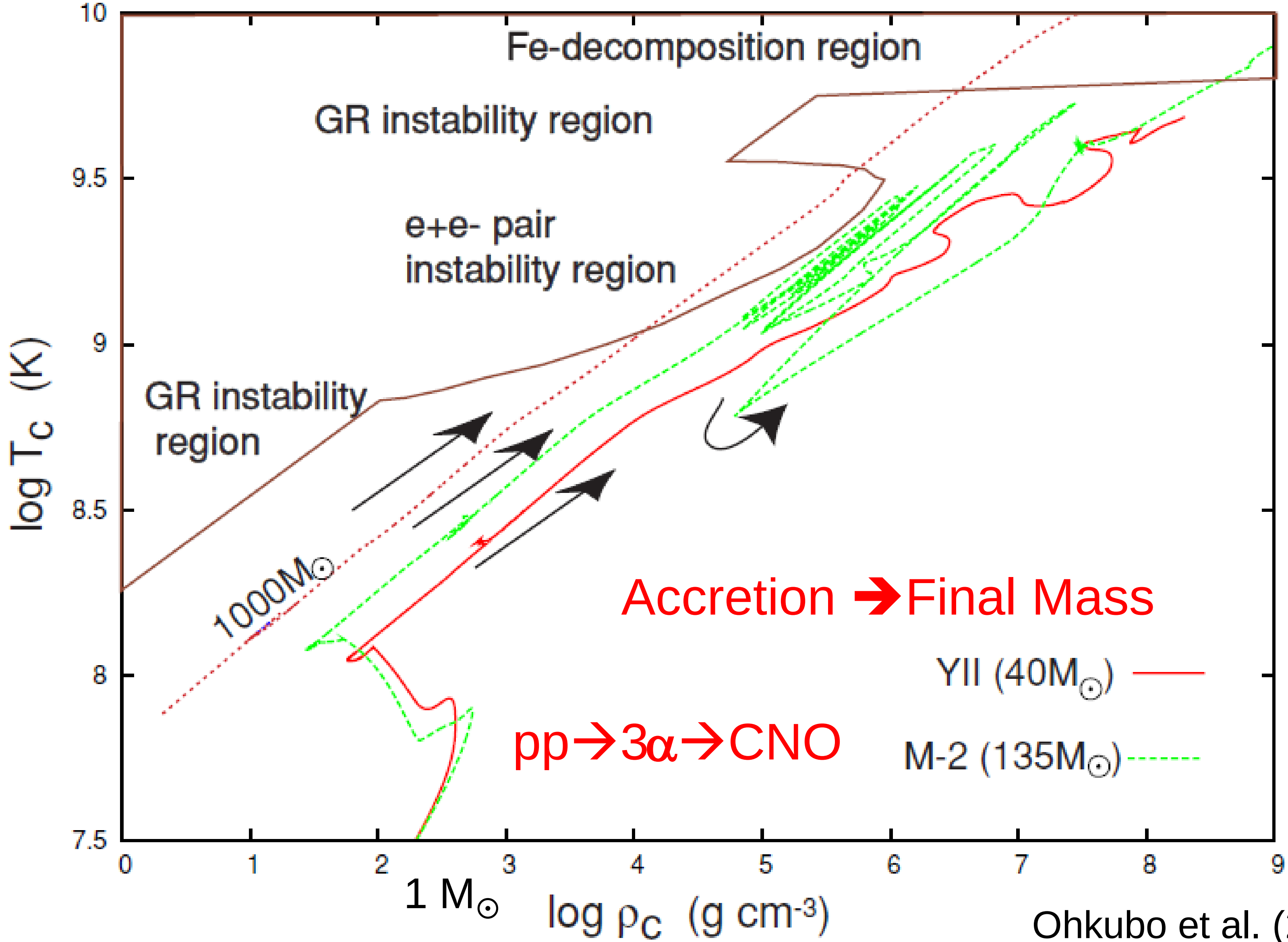
Ohkubo, Nomoto, et al. (09)

Pop III Stars: Mass Accretion ➔
Pair-Instability (140-300 $M_\odot$) or **Core-Collapse**



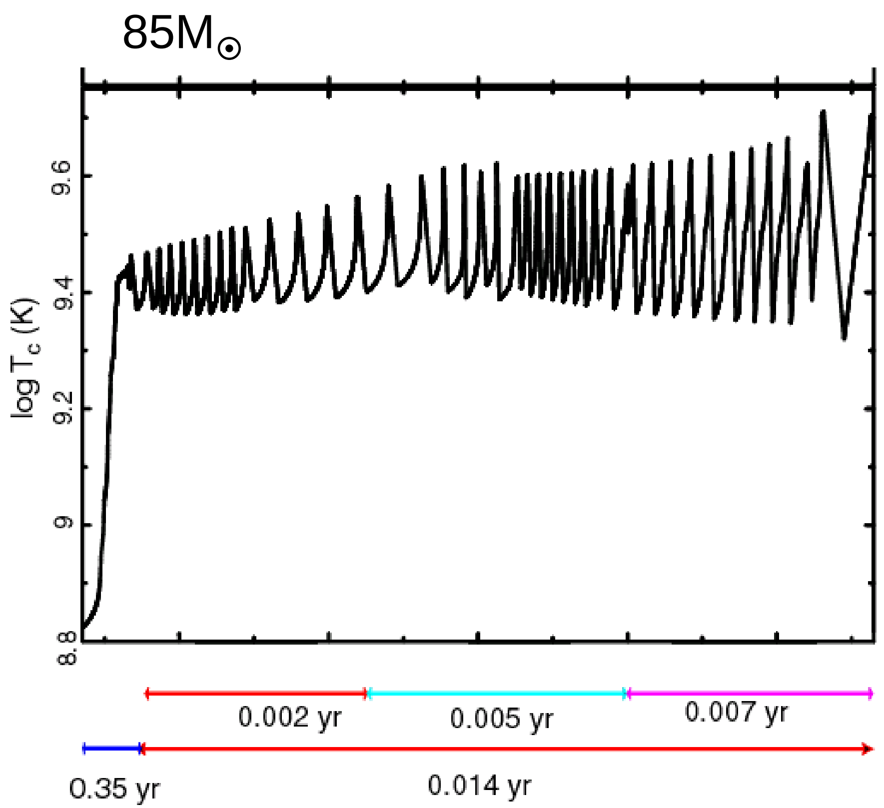
Ohkubo et al. (2009)

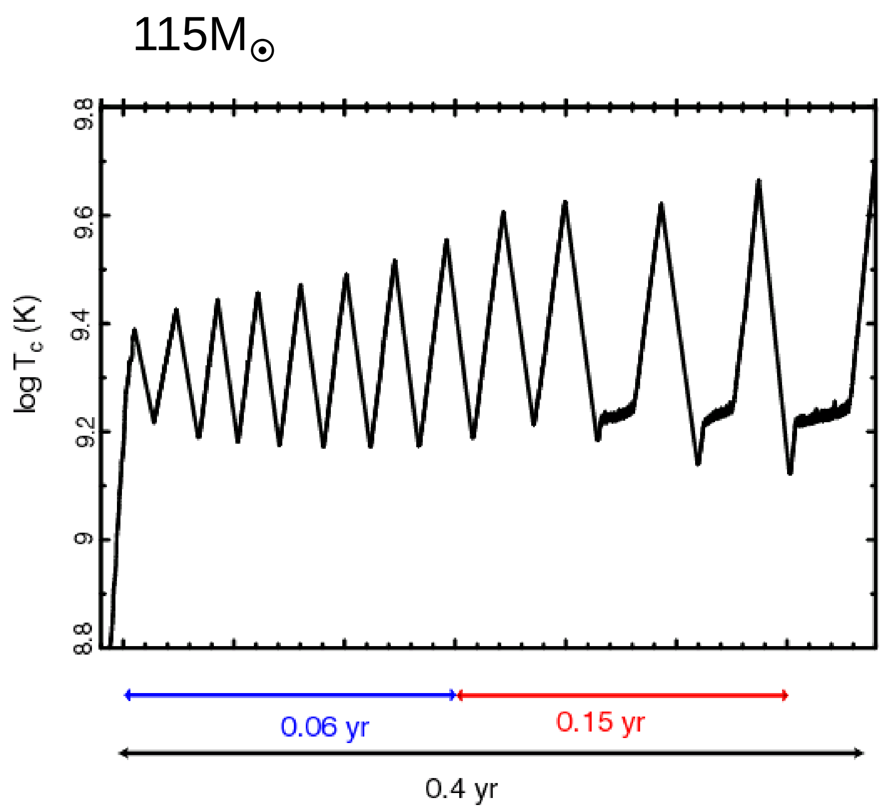
Pop III Stars: Mass Accretion ➔ Core Collapse (40-140 $M_\odot$) ➔ LSN & GRB ?



Ohkubo et al. (2009)

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





→ Fe Core Collapse

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

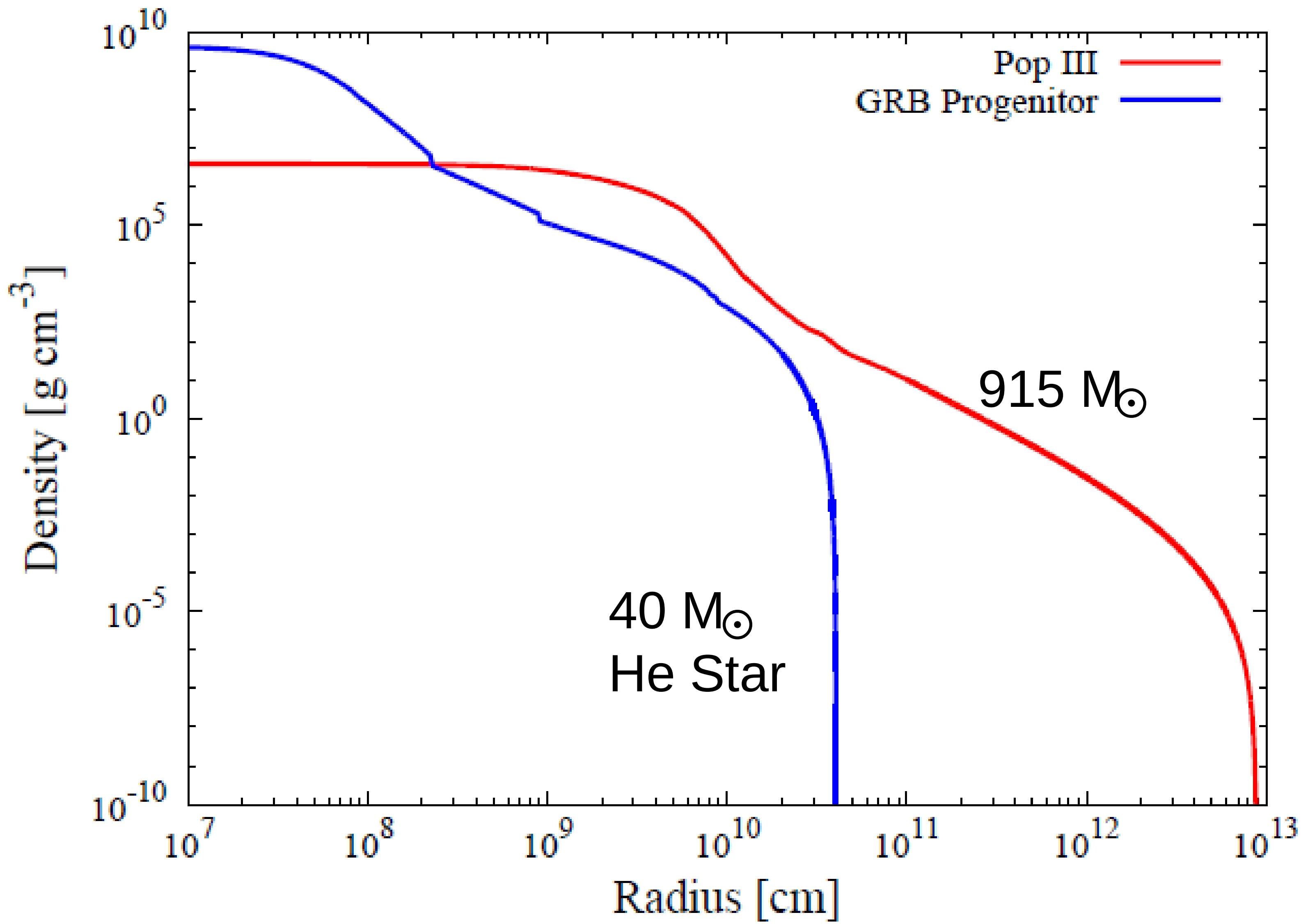
Final Fates of Accreting Pop III Stars

- Hypothetical Scenario: (dM/dt : uncertain)
  (stellar feedback)

- Pop III.1 → $M > 300\ M_\odot$ Core Collapse
  → PISN

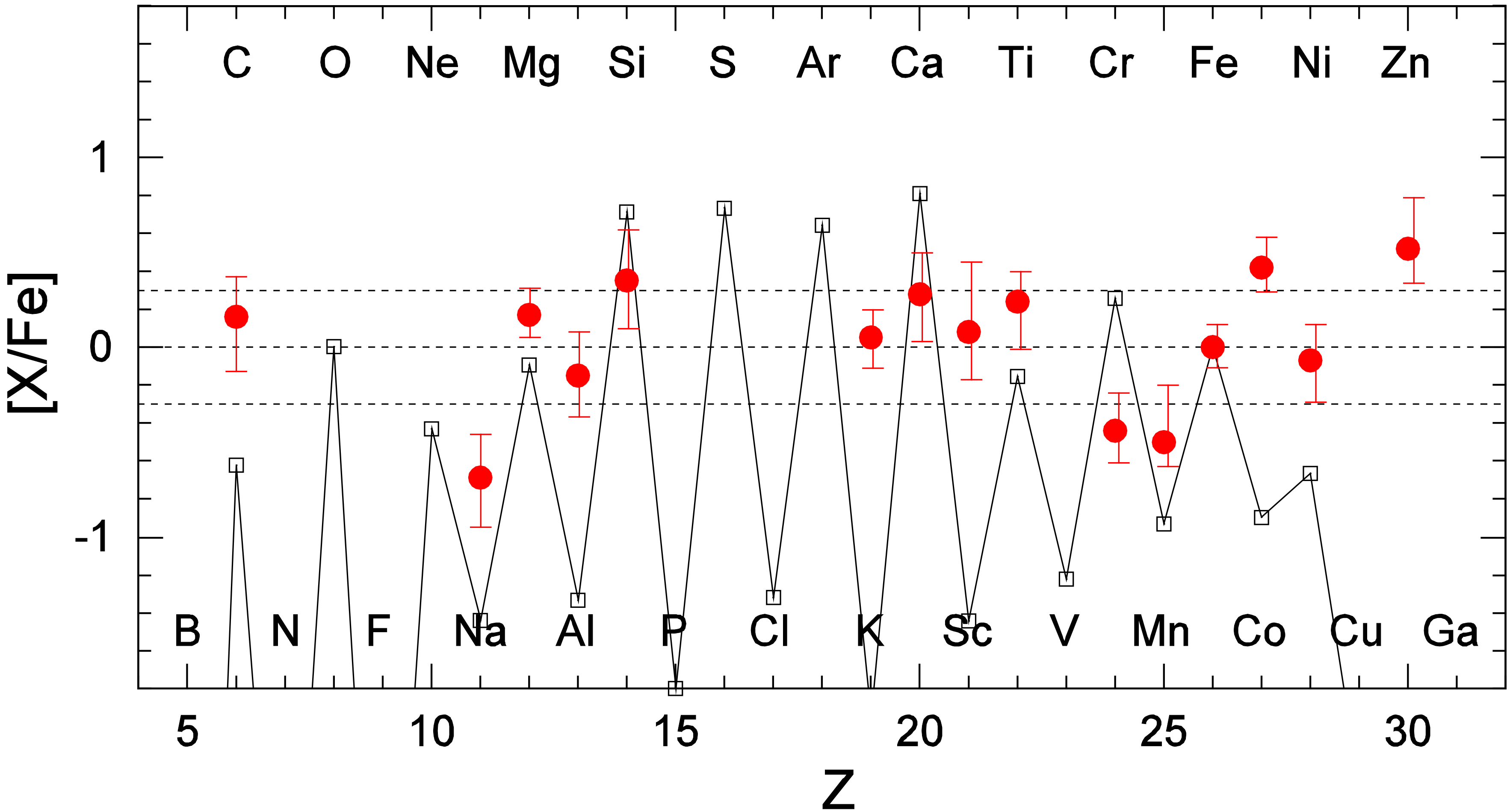
- Pop III.2 → $M < 50\ M_\odot$ Core Collapse

Pop III GRBs ?



(Suwa 2010)

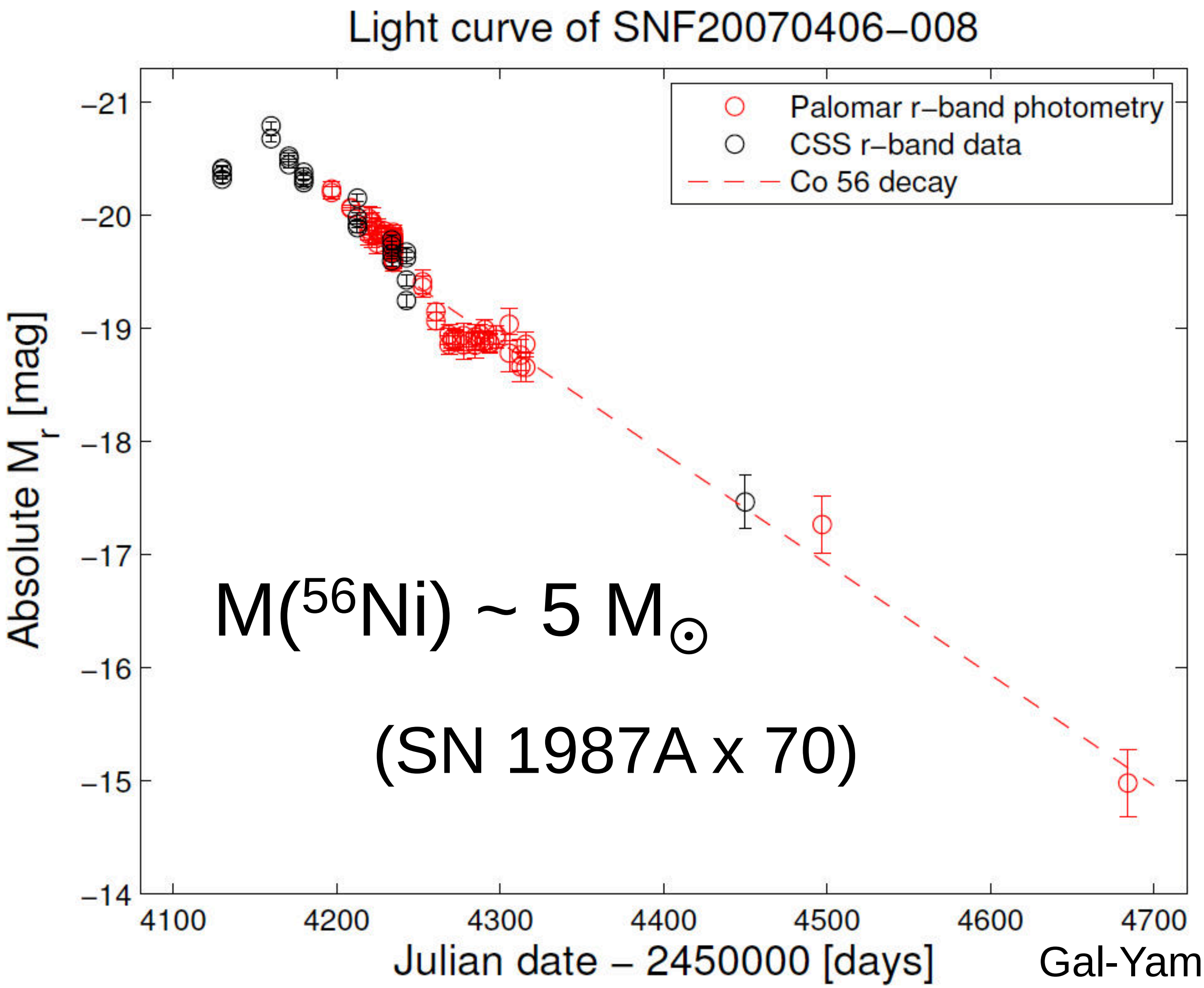
Pair Instability SN vs EMP stars



Umeda & Nomoto 2002

Extremely Luminous SNe

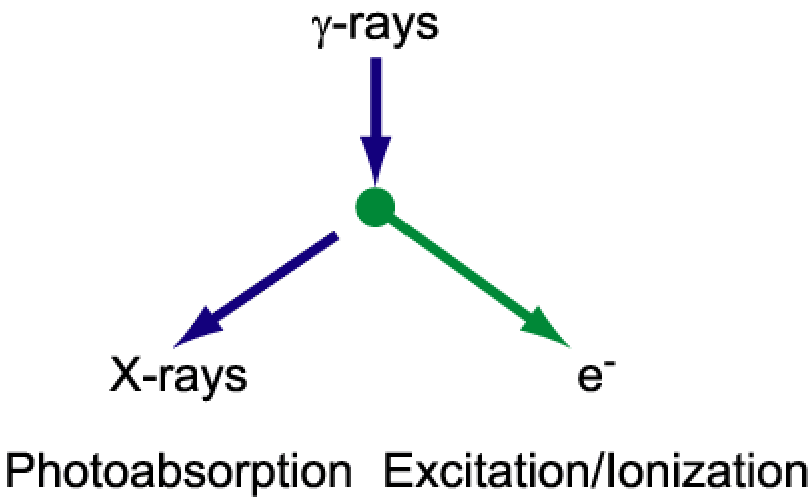
SN Ic 2007bi (Pair-Instability?)



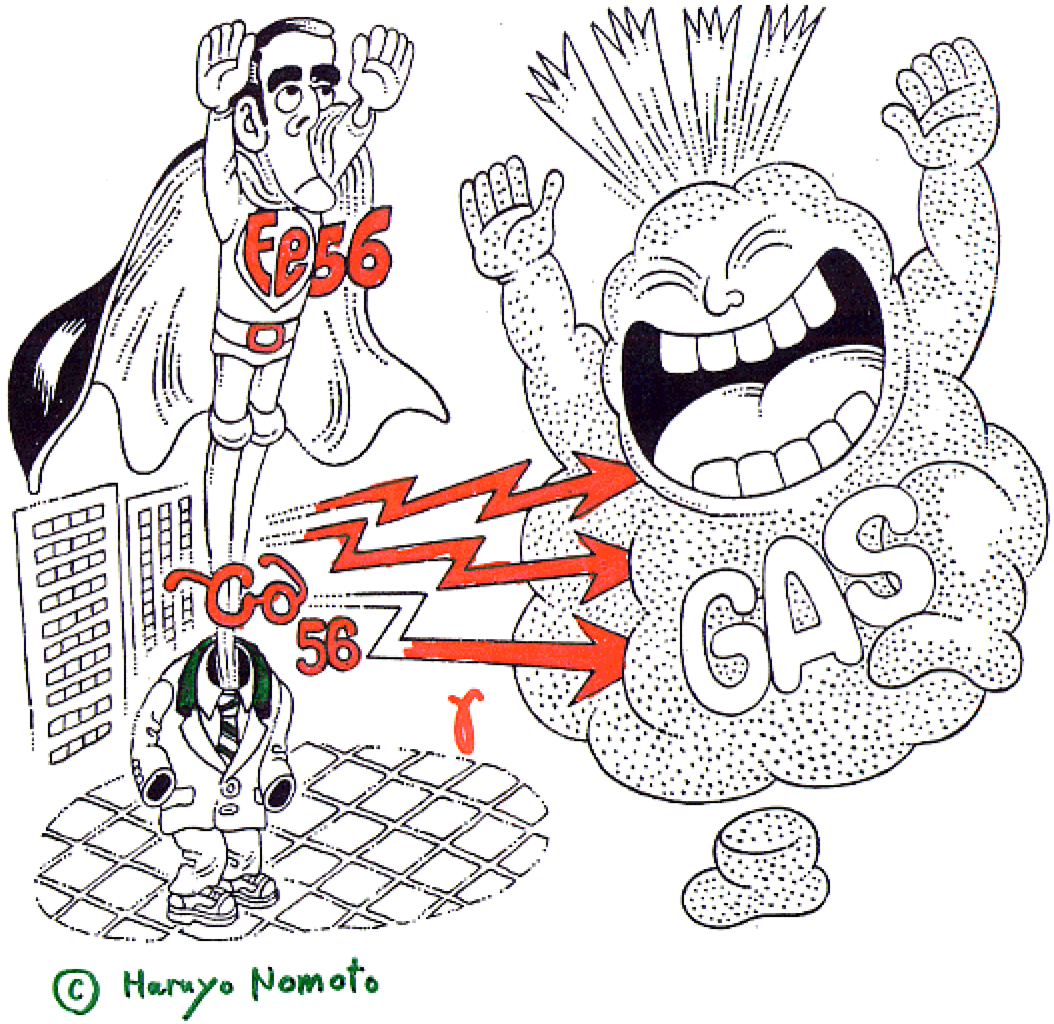
Gal-Yam et al. 2009

^{56}Co-decay

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



$$\left\{ \begin{array}{l} L \propto M(^{56}\mathrm{Ni}) \\ \mathrm{Shape}: M_{ej} \end{array} \right.$$



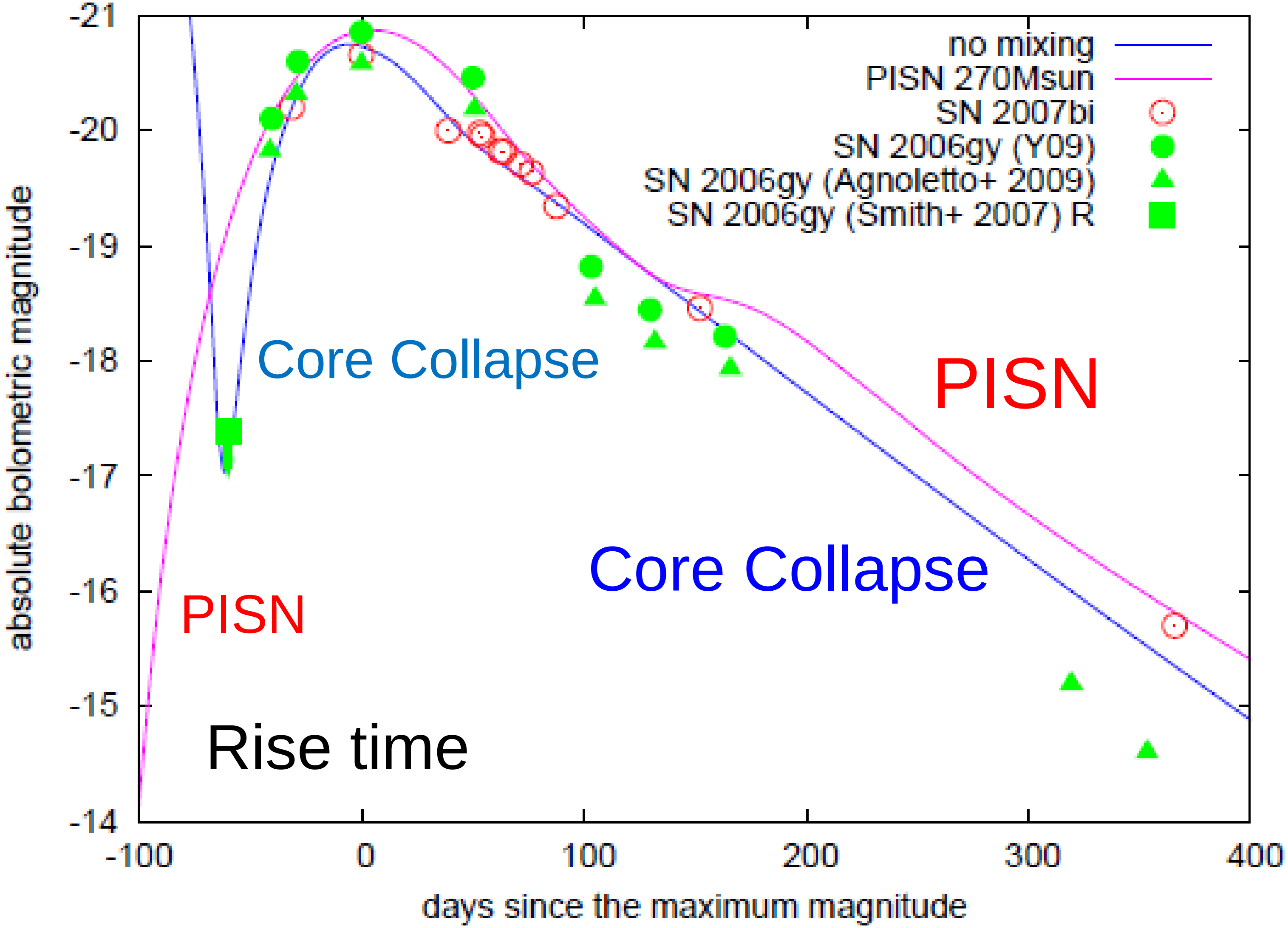
Models for Luminous SNe

	Core-Collapse	PISN
M (ms) =	100 $M_\odot$	270 $M_\odot$
M (C+O core) =	43 $M_\odot$	121 $M_\odot$
M (ejecta) =	39 $M_\odot$	121 $M_\odot$
E (kin) =	3.3 E52 erg	7E52 erg
M (^{56}Ni) =	6.1 $M_\odot$	9.8 $M_\odot$

- LC: Rise time = 52 - 85 days 150 days
- Jet-induced Explosion

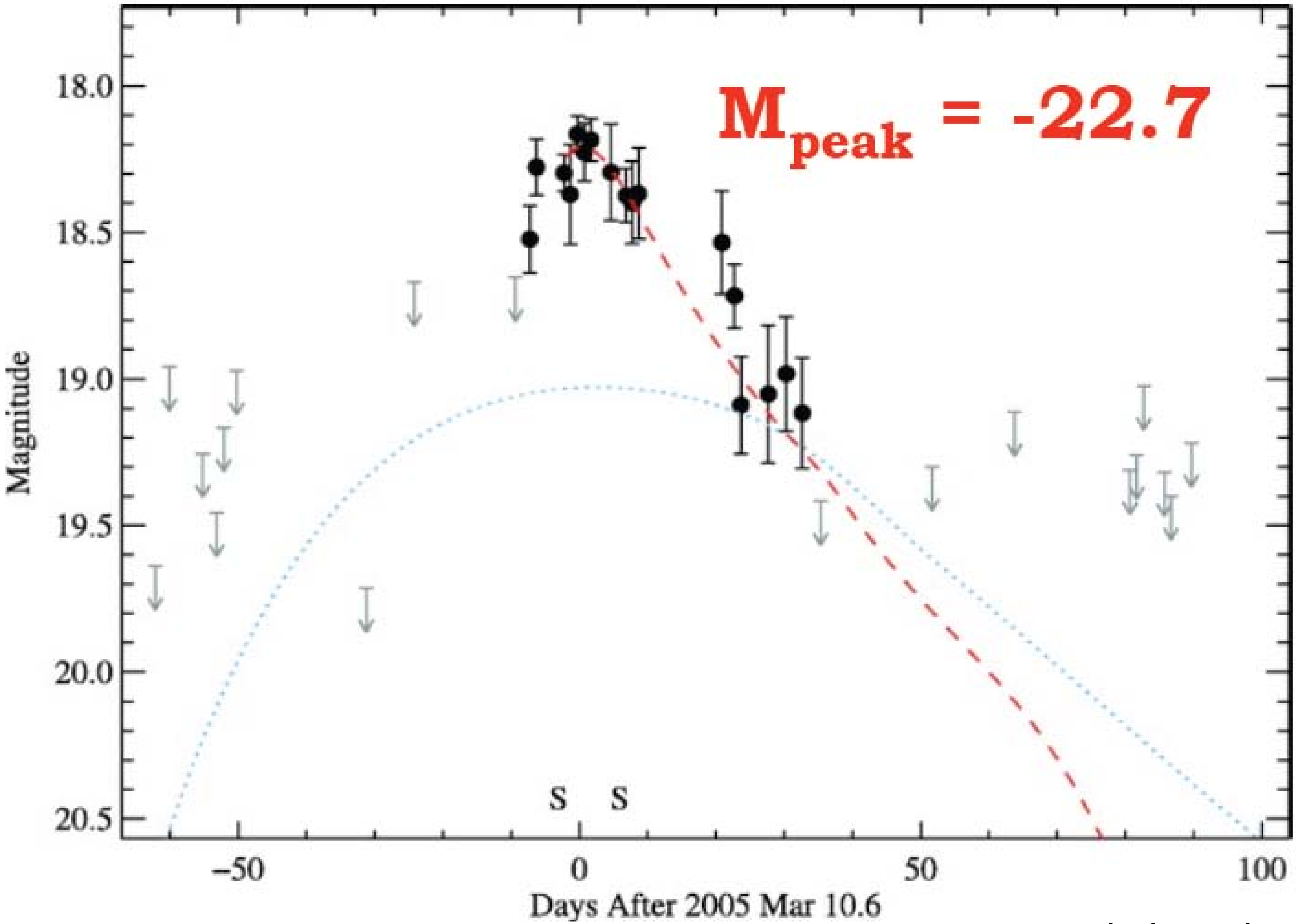
→ Aspherical Hypernova → GRB?

SNe 2007bi, 2006gy
Core-Collapse vs. PISN



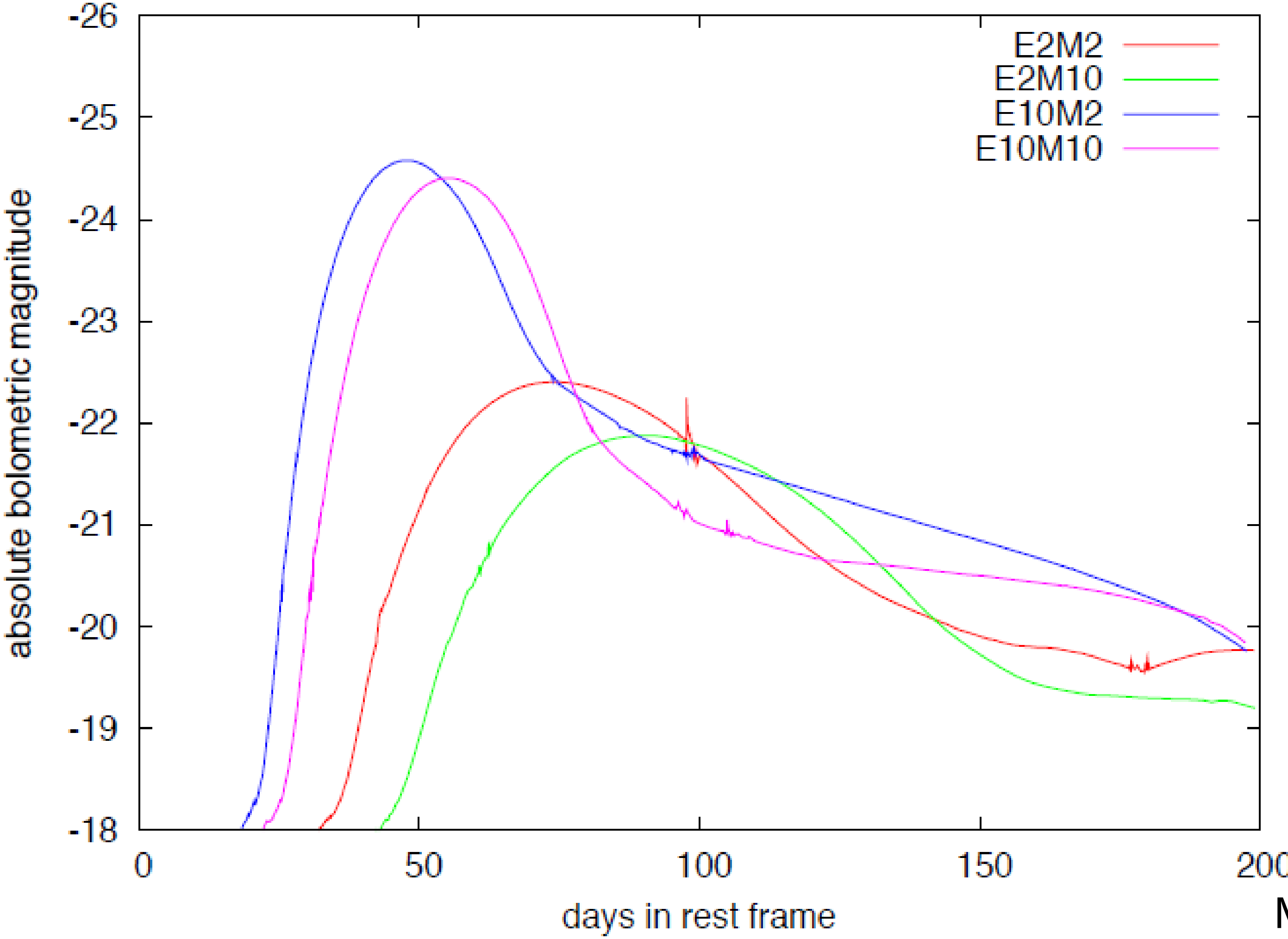
Moriya et al.

More Luminous SN 2005ap



Quimby + (2009)

Interaction with Dense Circumstellar Matter



• wind radius = 5e15 cm

name	E_{kin}	M_{ej}
E2M2	2	2
E2M10	2	10
E10M2	10	2
E10M10	10	10

units : 10^{51} erg, $M_{\odot}$

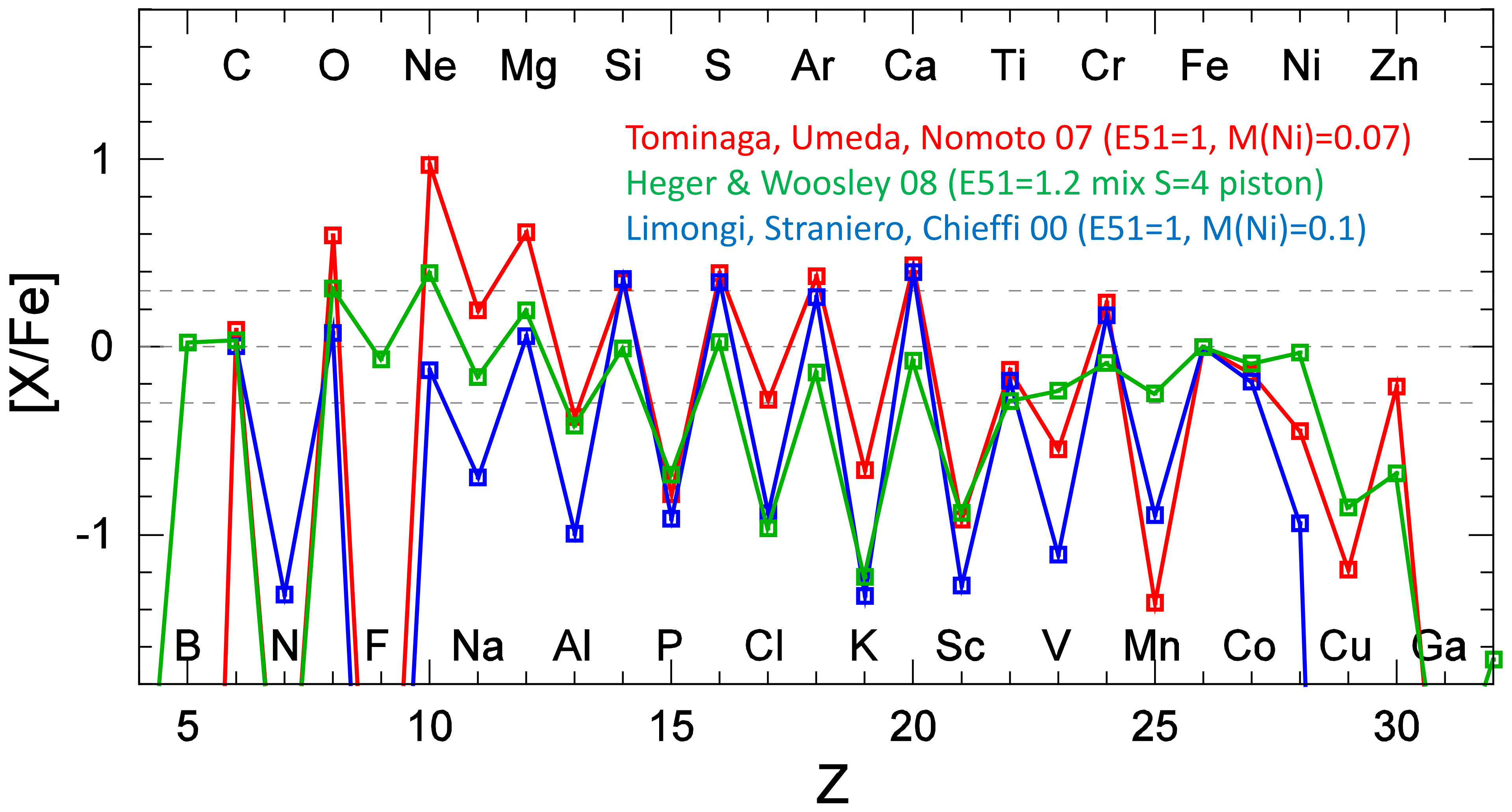
dM/dt=0.1 Ms/y

Accreting matter?

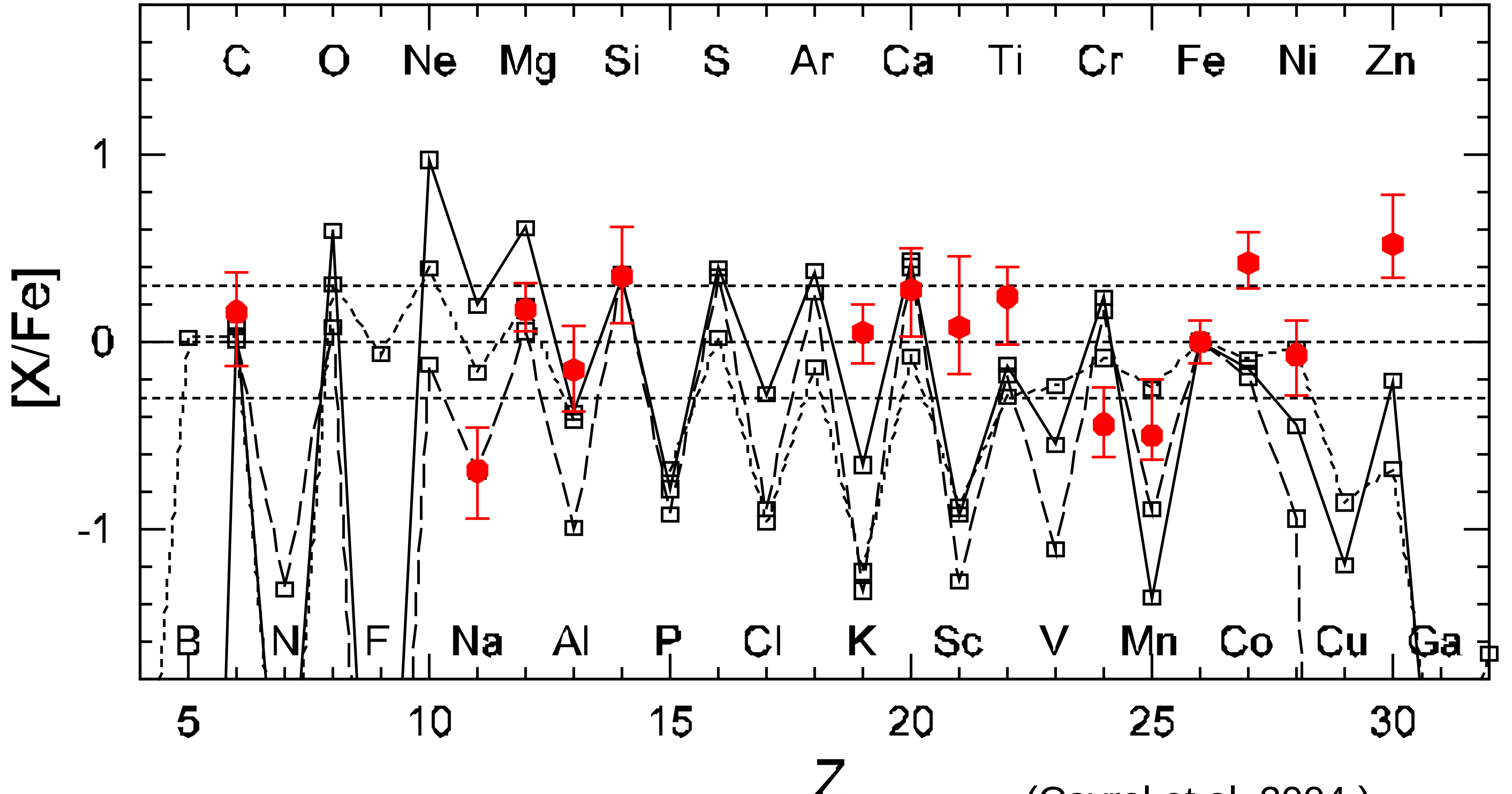
Moriya et al. (2010)

Pop III.2: Core Collapse SN

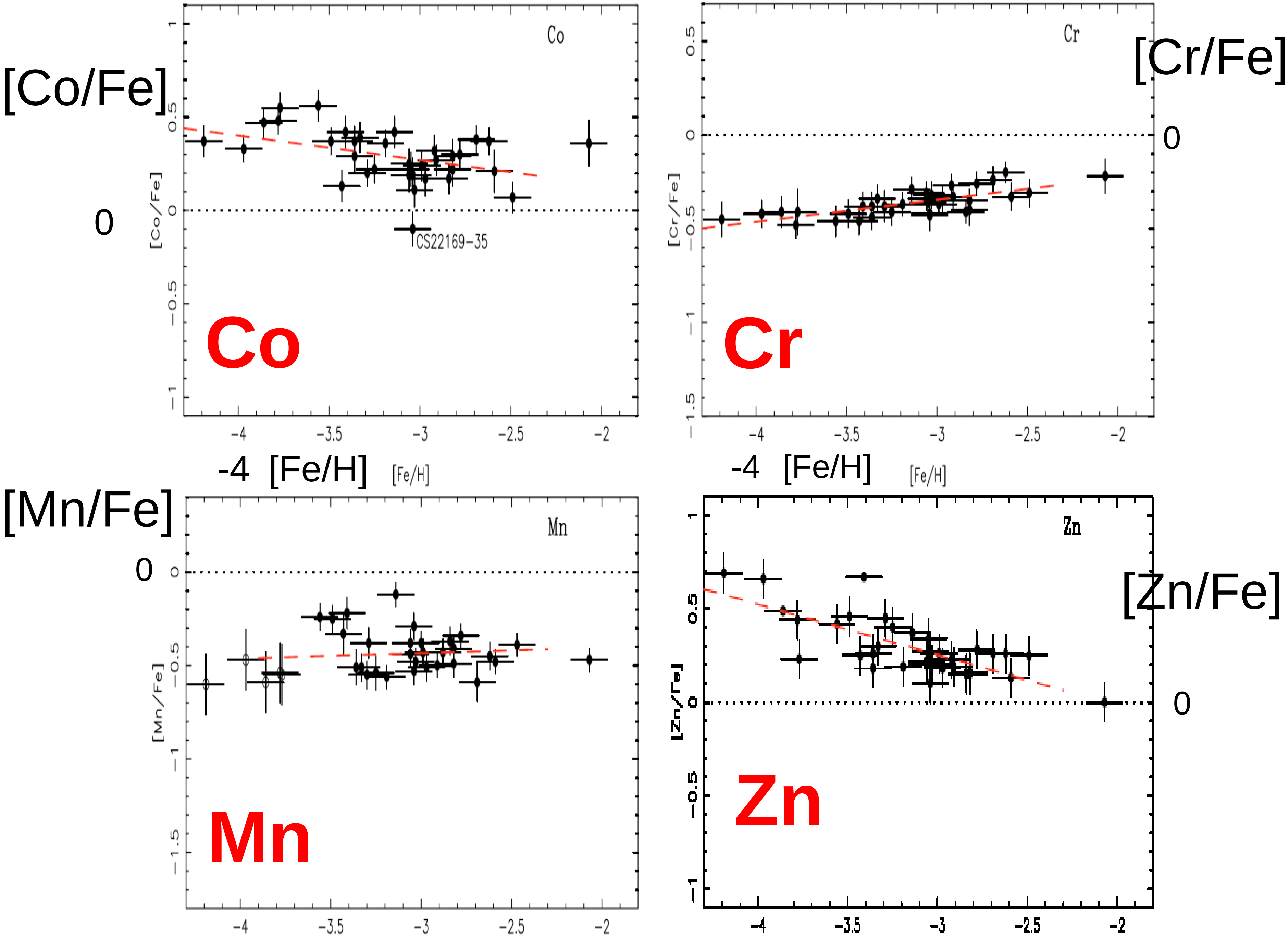
($20M_{\odot}$, $Z=0$, $E_{51}=1$)



Poor Fit to Extremely Metal-Poor (EMP) Stars → High Explosion Energy

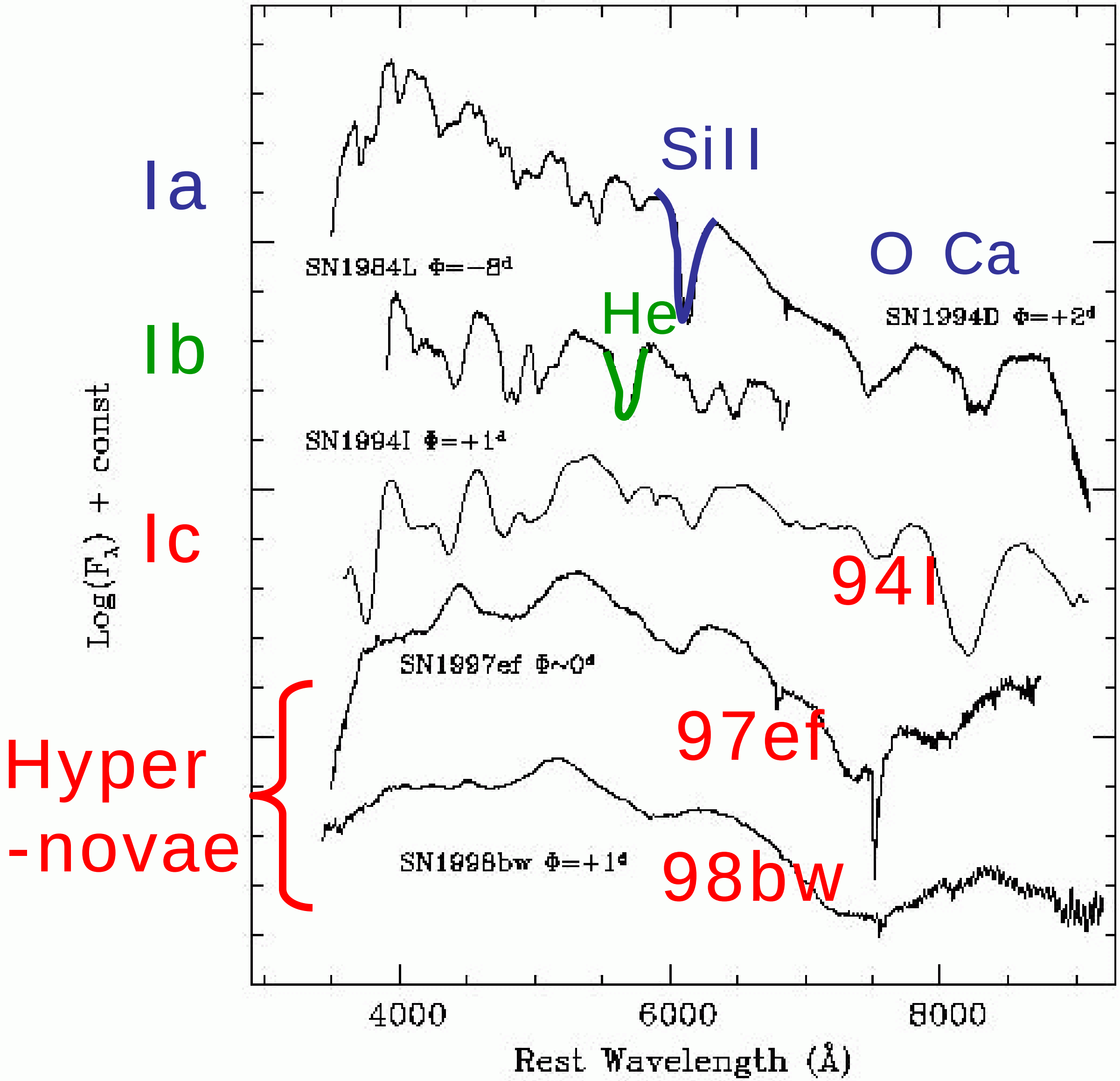


(Cayrel et al. 2004)



Cayrel et al. (2004)

Spectra of 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)

Supernova – GRB Connection

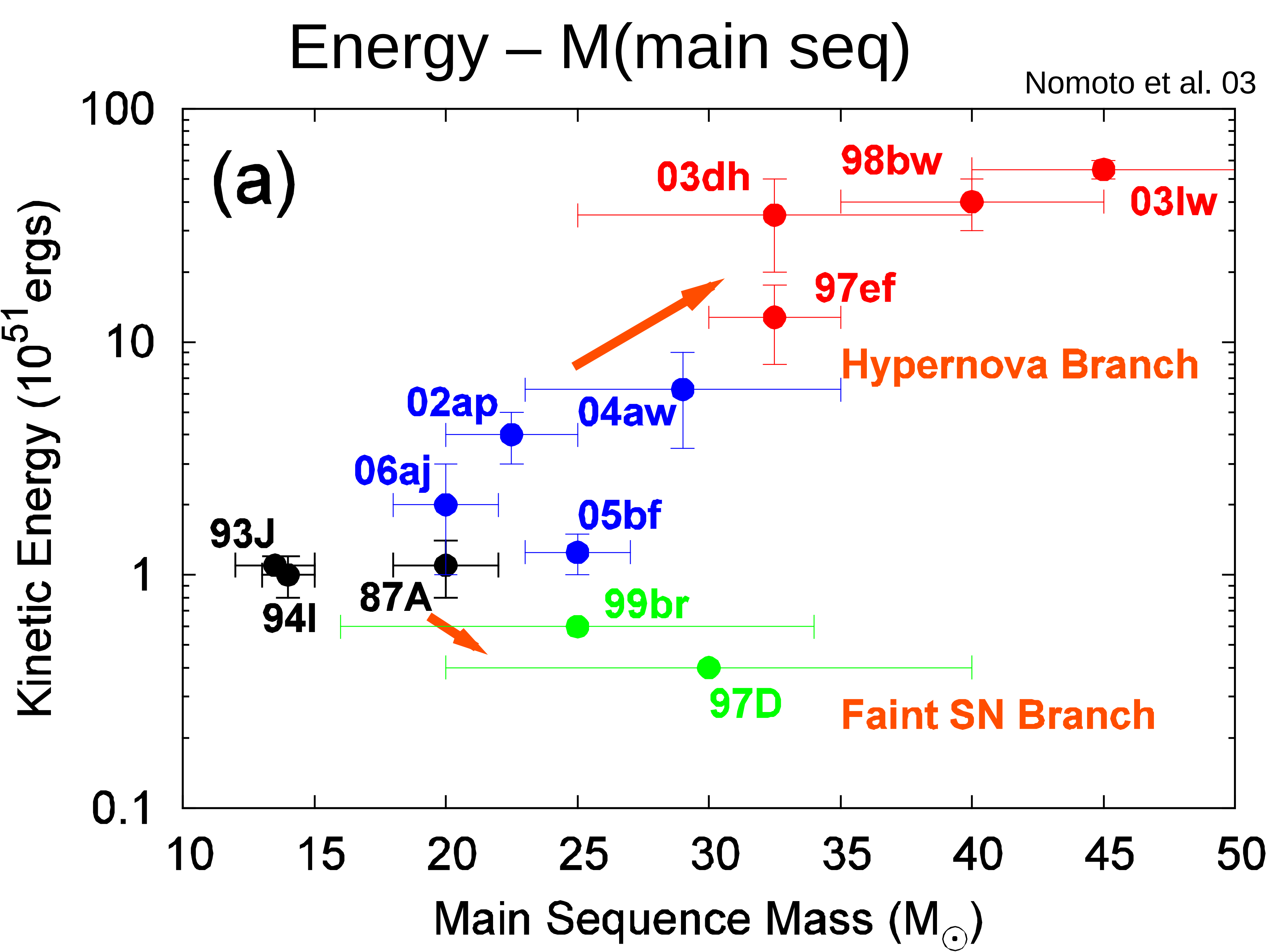
Three GRB－SNe = all Type Ic Hypernovae

$E > 10^{52}$ 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

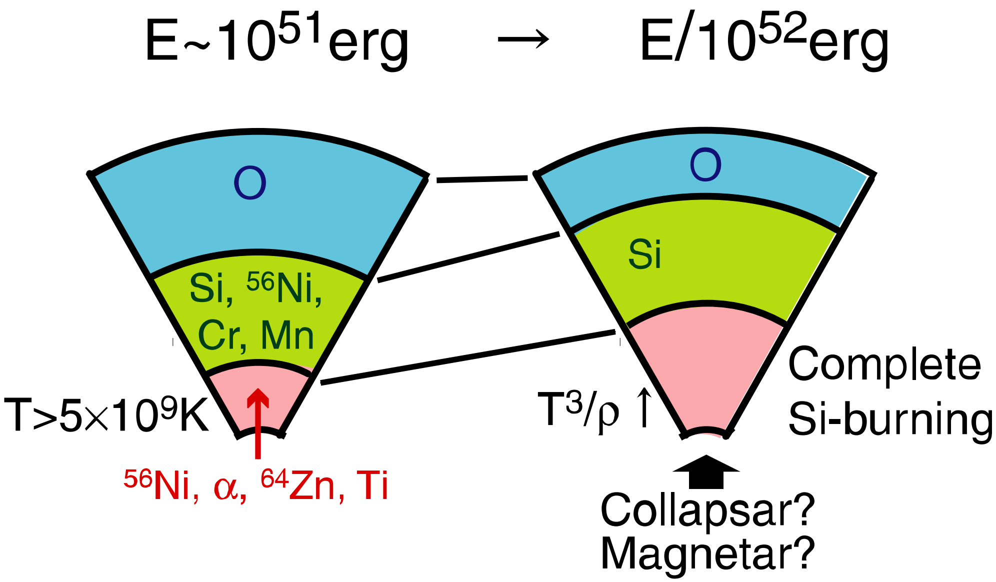


Energy – M(main seq)
Nomoto et al. 03
(a)
100
10
1
0.1
Kinetic Energy (10^{51}ergs)
10
15
20
25
30
35
40
45
50
Main Sequence Mass ($M_\odot$)
98bw
03dh
03lw
97ef
Hypernova Branch
02ap
04aw
06aj
05bf
93J
87A
94I
99br
97D
Faint SN Branch

Hypernova in Prague

Hypernova in Prague

Hypernova Nucleosynthesis



Low energy High energy

(1) M(Complete Si-burning) ↗

(Zn, Co)/Fe ↗

(Mn, Cr)/Fe ↘

Fe/(O, Si) ↗

(2) More α-rich ⇐ entropy ↗

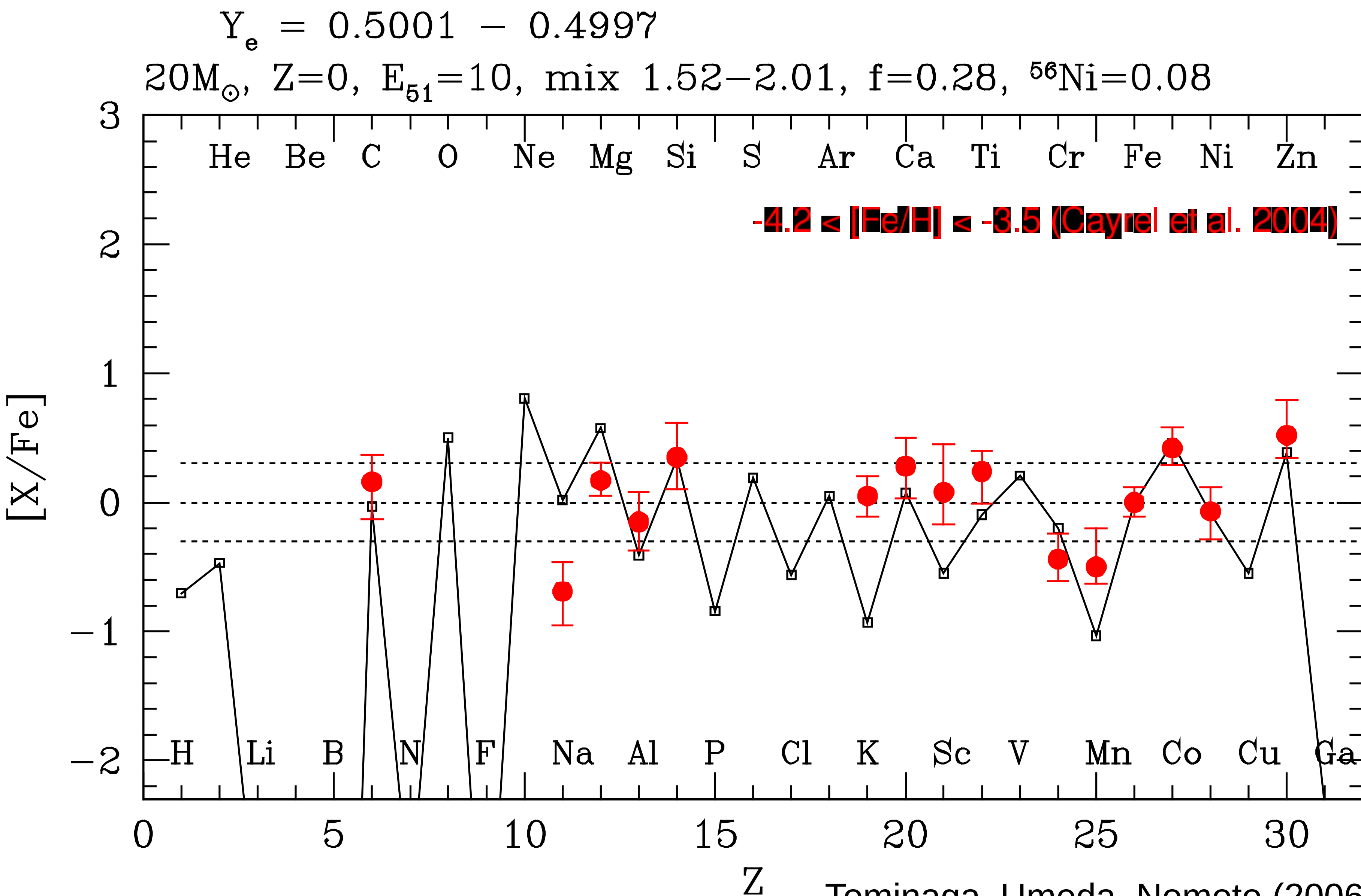
Zn/Fe ↗ ⇐ ^{64}Ge

Ti/Fe ↗

(3) More O burns

(Si, S, Ca)/O ↗

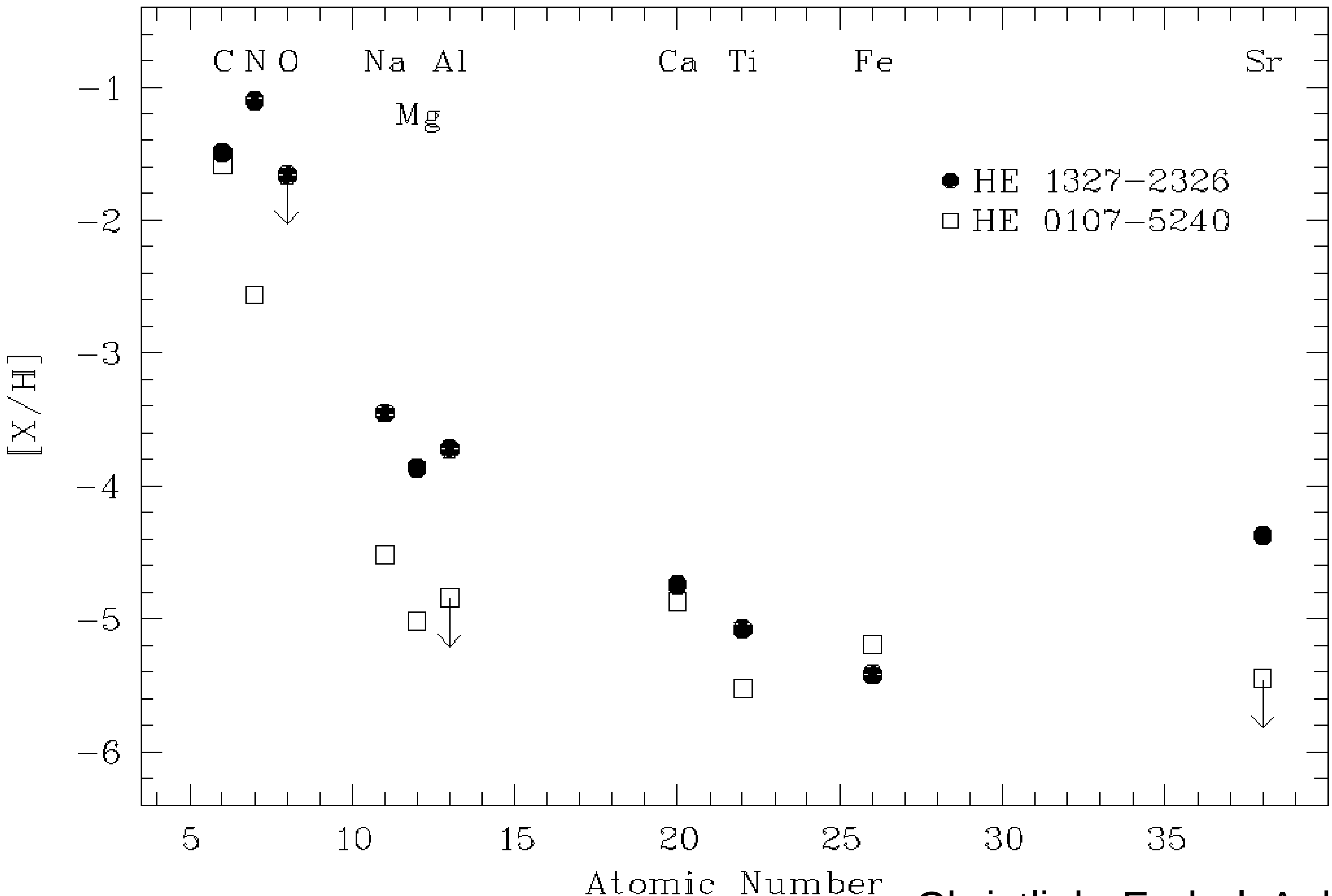
EMP stars vs. Hypernova (E_{51}=10)



Tominaga, Umeda, Nomoto (2006)

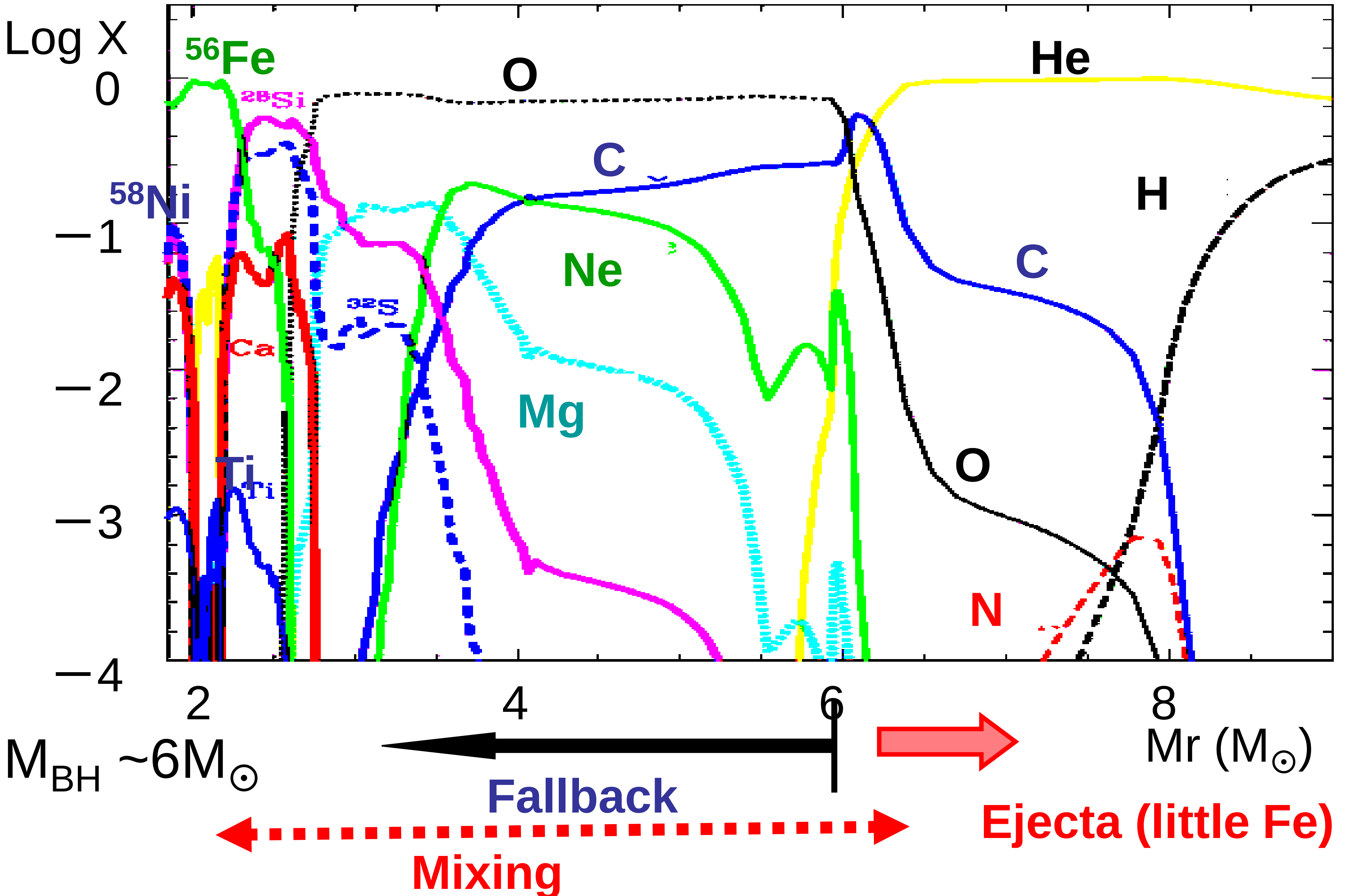
Hyper Metal-Poor (HMP) Stars

[Fe/H] < -5 [C, N, O/ Fe] > 3



Christlieb, Frebel, Aoki, et al.

$M=25M_\odot$, $E=7\times10^{50}$erg (Weak Explosion) [Fe/H]$=-5.3$



Umeda & Nomoto (2003)

Faint Supernovae

SN 2008ha (I ?)

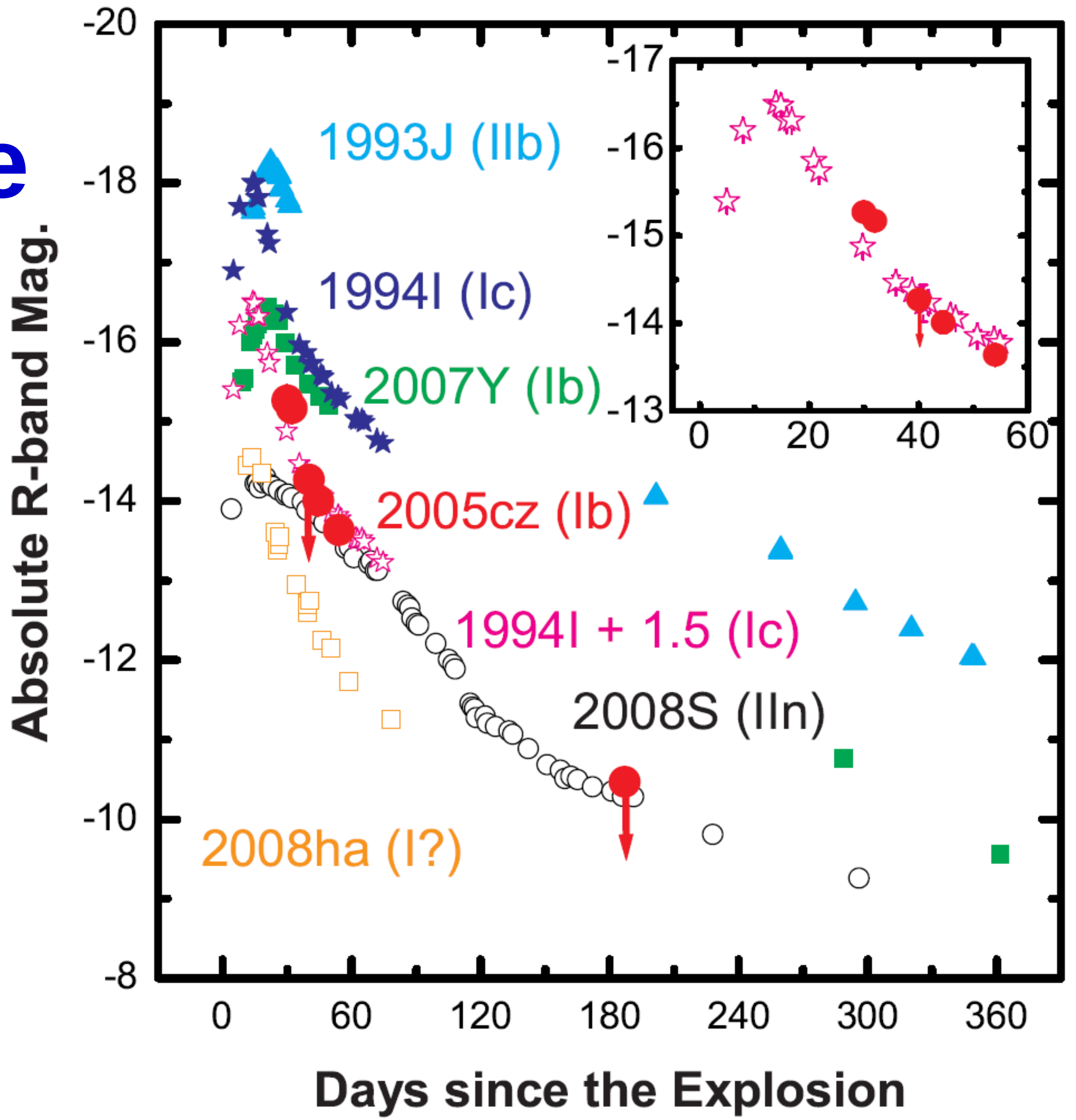
2005cz (Ib)

(Kawabata+)

2005E (Ib)

(Peretz+)

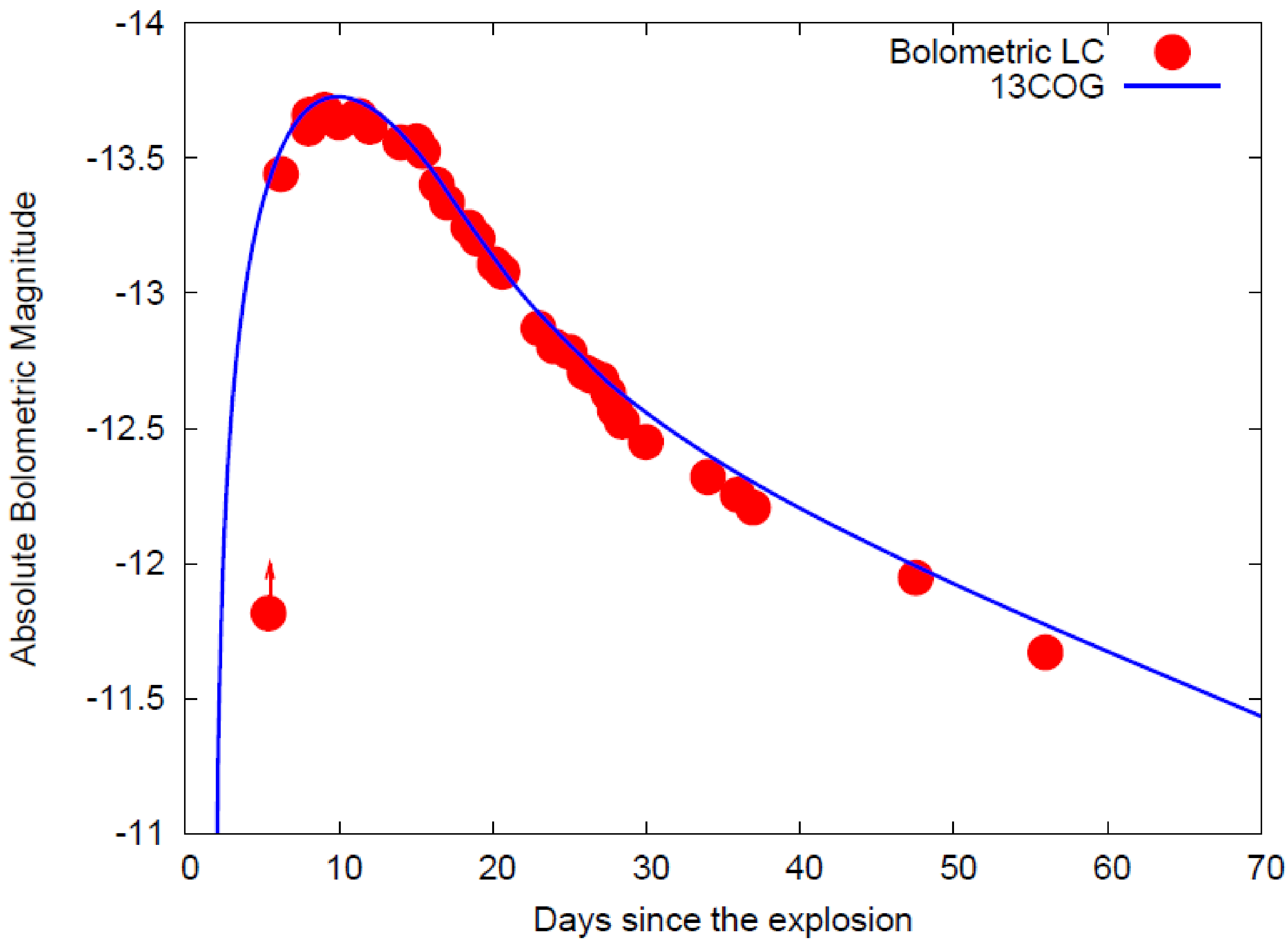
2008S (IIn)



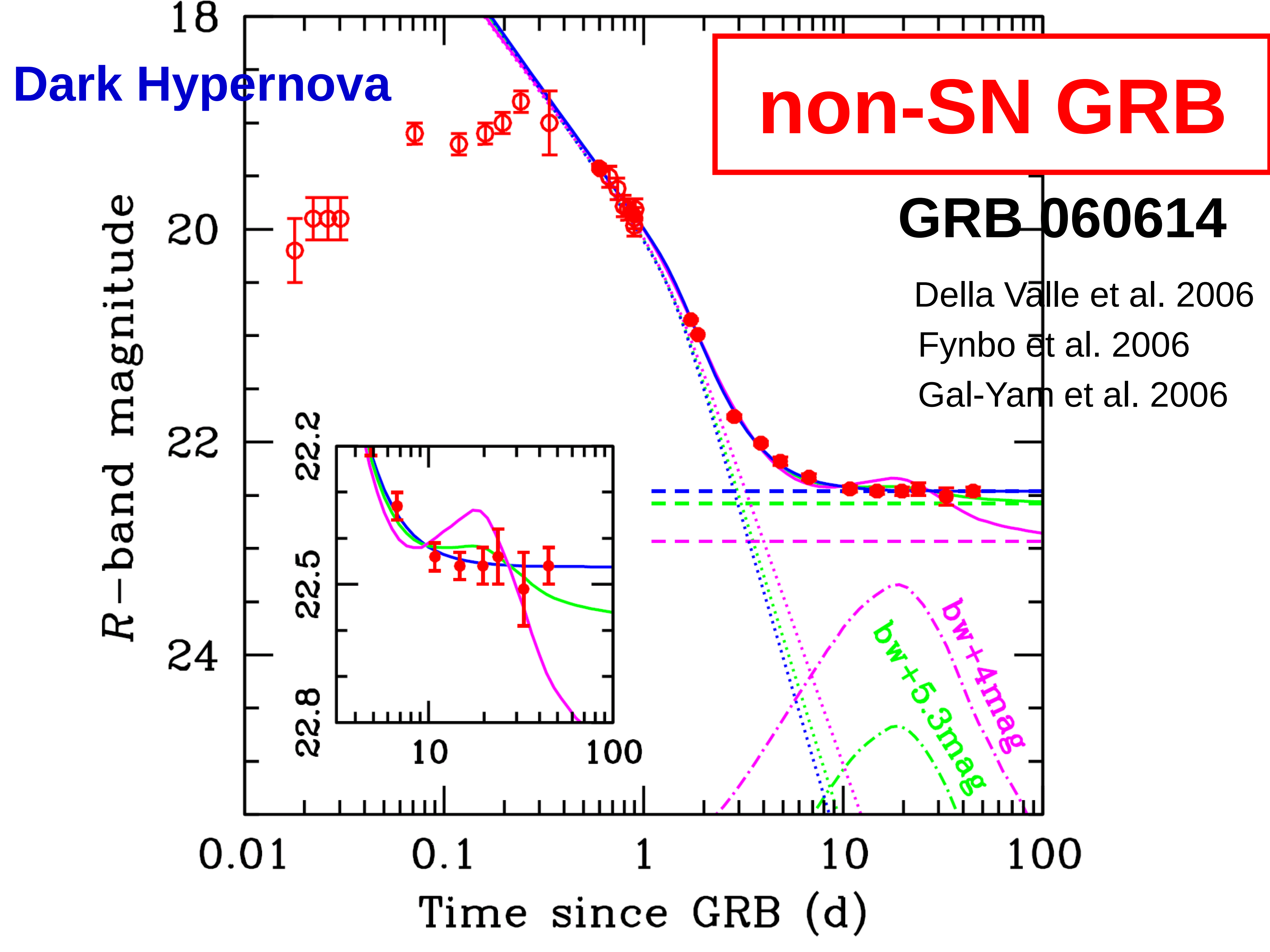
Fallback model for SN 2008ha

- CO star core-collapse model (13 $M_\odot$ → 2.7 $M_\odot$)

$$E_{\rm kin} = 1.4 \times 10^{48}\ {\rm erg} \qquad M_{\rm ej} = 0.08\ M_\odot \qquad M_{^{56}{\rm Ni}} = 0.003\ M_\odot$$

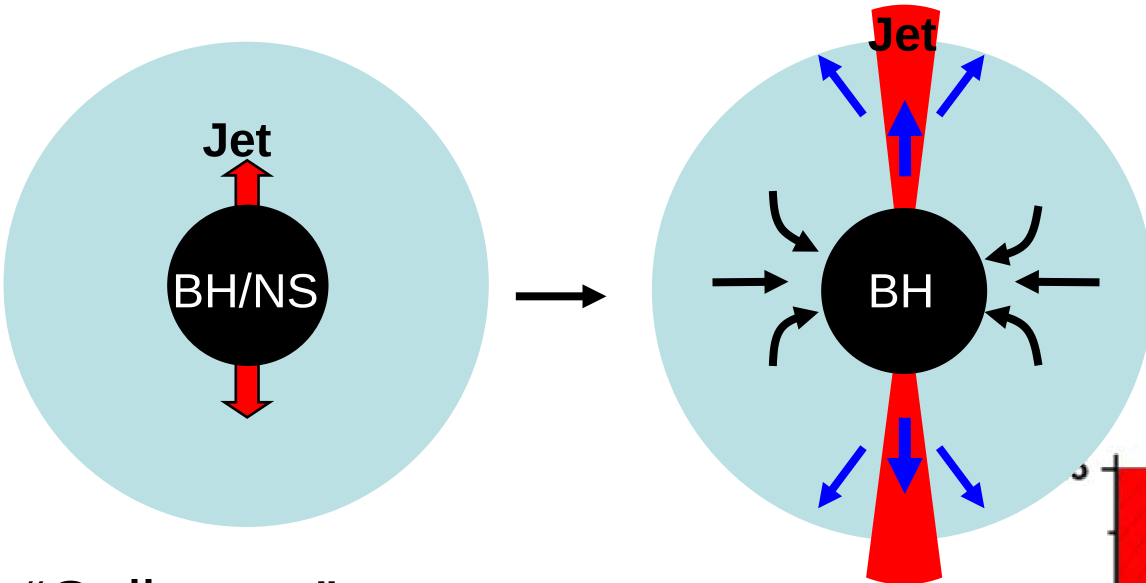


Moriya et al.



Dark Hypernova
non-SN GRB
GRB 060614
Della Valle et al. 2006
Fynbo et al. 2006
Gal-Yam et al. 2006
R − band magnitude
Time since GRB (d)
18
20
22
24
0.01
0.1
1
10
100
22.2
22.5
22.8
10
100
bw+4mag
bw+5.3mag

Jet-induced Nucleosynthesis



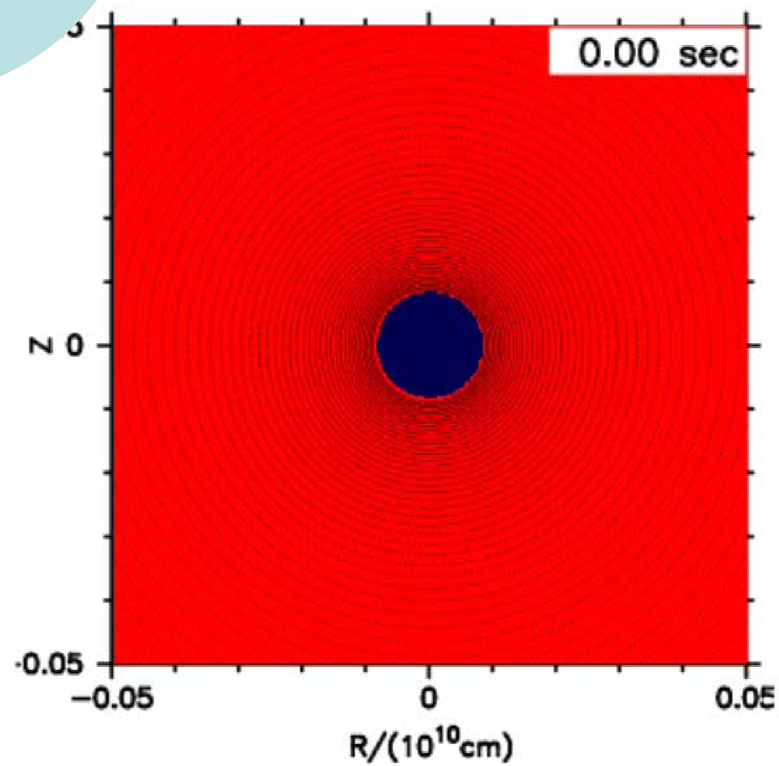
Special relativistic hydrodynamics
(Tominaga et al. ApJL 2007)

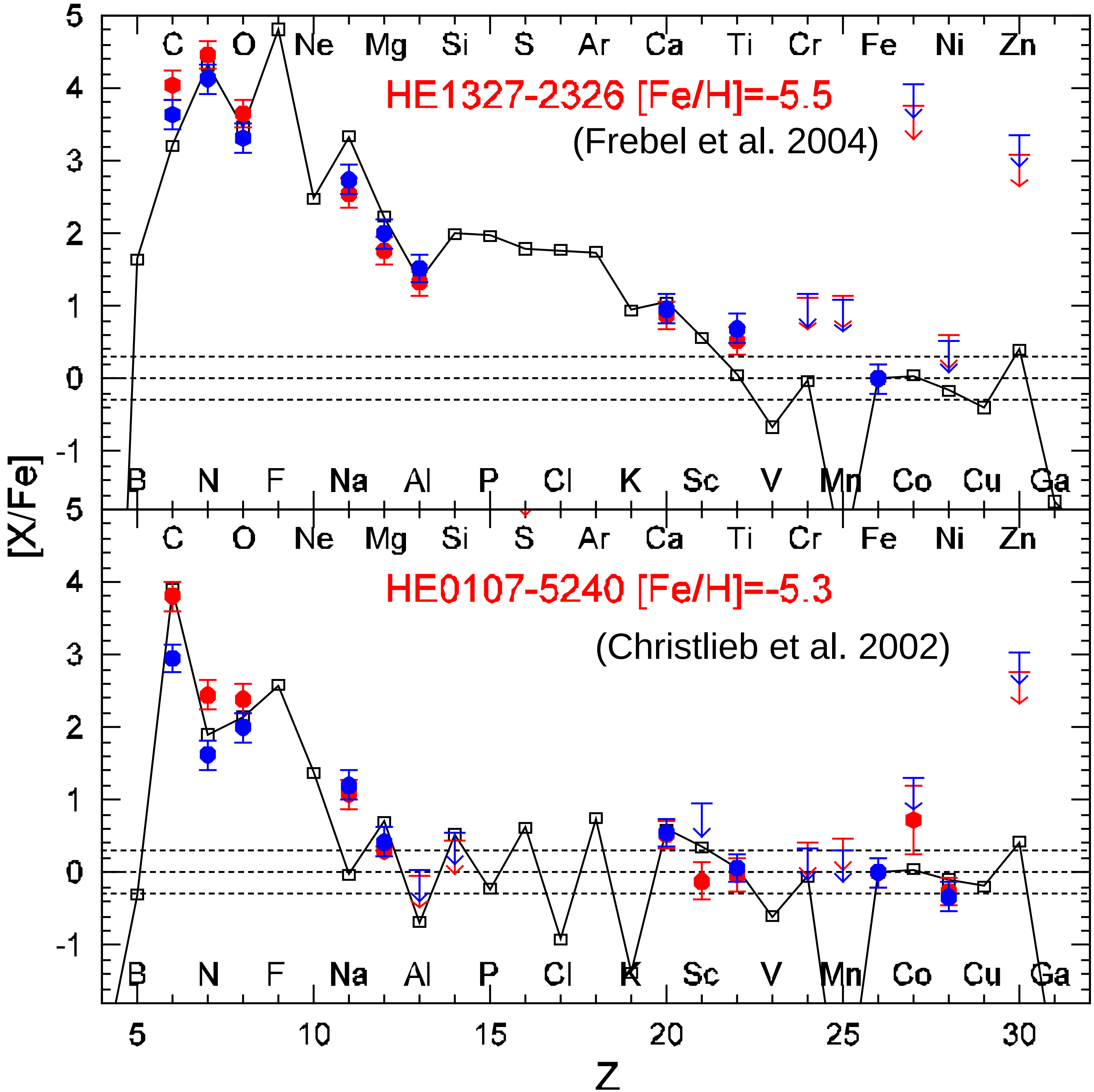
cf. “Collapsar”(e.g., MacFadyen et al. 01)

Magnetorotational Supernovae
(e.g., Moiseenko et al. 06)

$\dot{E}_{\mathrm{dep}}$:
Energy deposition rate
(Rotation, ***B*** etc.)

Same mass and explosion energy
$40M_{\odot}$ 1.5×10^{52}erg





HMP Stars

Jet-induced SN models

High E ➔ High Co/Fe ➔ **Fallback** ➔ Small Fe

Dark Hypernova

Tominaga et al. 2007

Faint Supernovae – EMP (extremely metal-poor) Stars

Fallback Supernovae: small M(Ni)

large [CNO/Fe] → CEMP

(1) Jet-induced Hypernovae

large [Zn/Fe], [Co/Fe], [Ti/Fe]

(2) Weak Explosion

Mixing & Fallback

Final Fates of Accreting Pop III Stars

- Hypothetical Scenario: (dM/dt : uncertain)

- Pop III.1 → $M > 300\ M_\odot$ Core Collapse
  IMBH ? GRB ?

- Pop III.2 → $M < 50\ M_\odot$ Core Collapse
  SNe, HNe ? GRB ?

* Extremely Luminous Supernovae:
PISNe vs. Core-Collapse Hypernovae(GRB?)
Circumstellar Interaction ?

Final Fates of Massive Stars