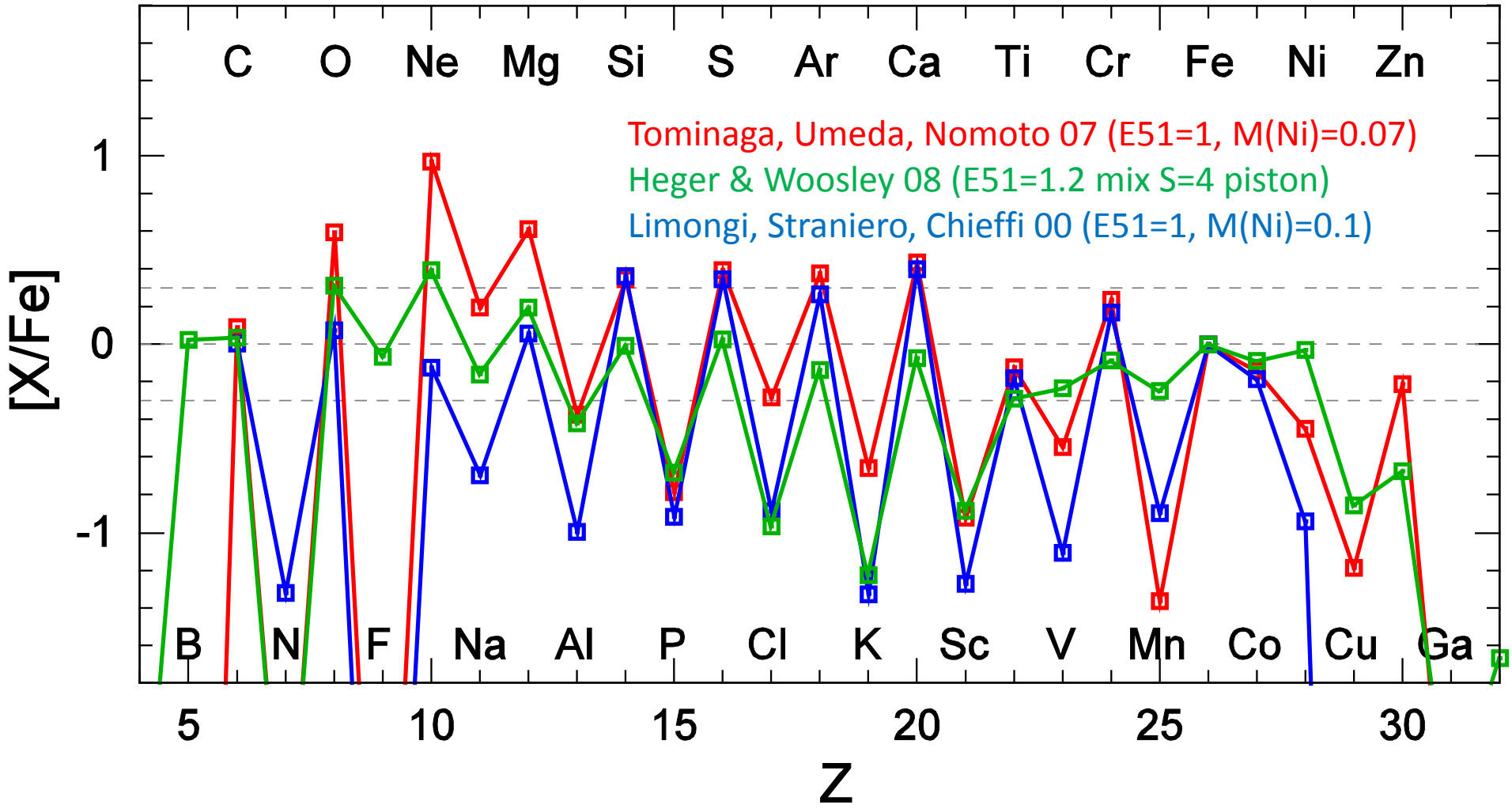
Nucleosynthesis in Hypernovae & Faint SNe

Ken Nomoto (IPMU, U. Tokyo)

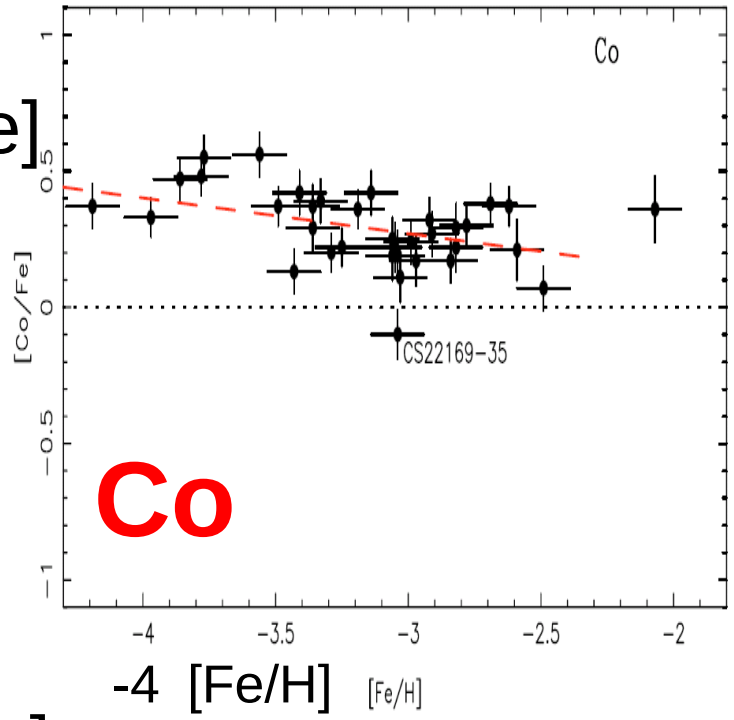
Importance of Mixing & Fallback & Aspherical Effects (Tominaga et al.)

$20M_{\odot}$, Z=0



[Co/Fe]

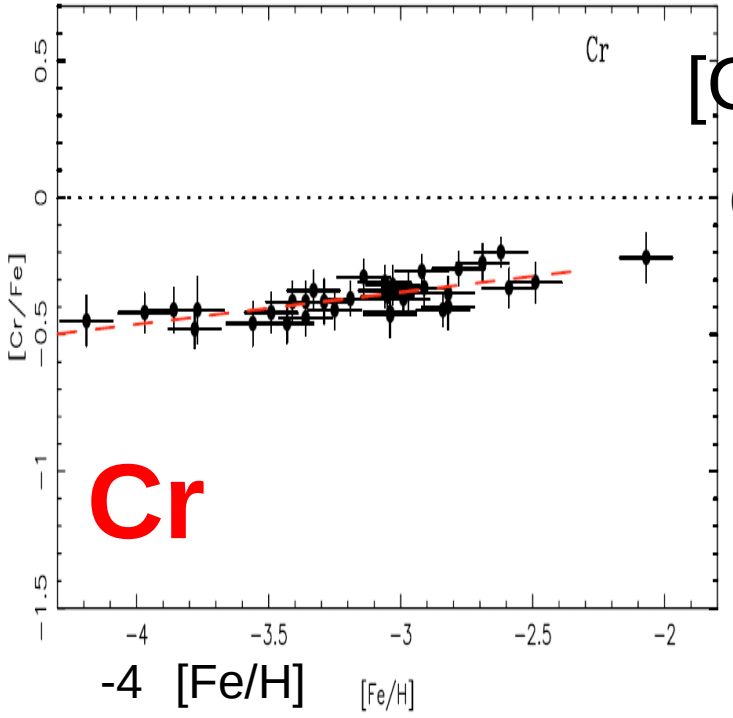
0



-4 [Fe/H]

[Cr/Fe]

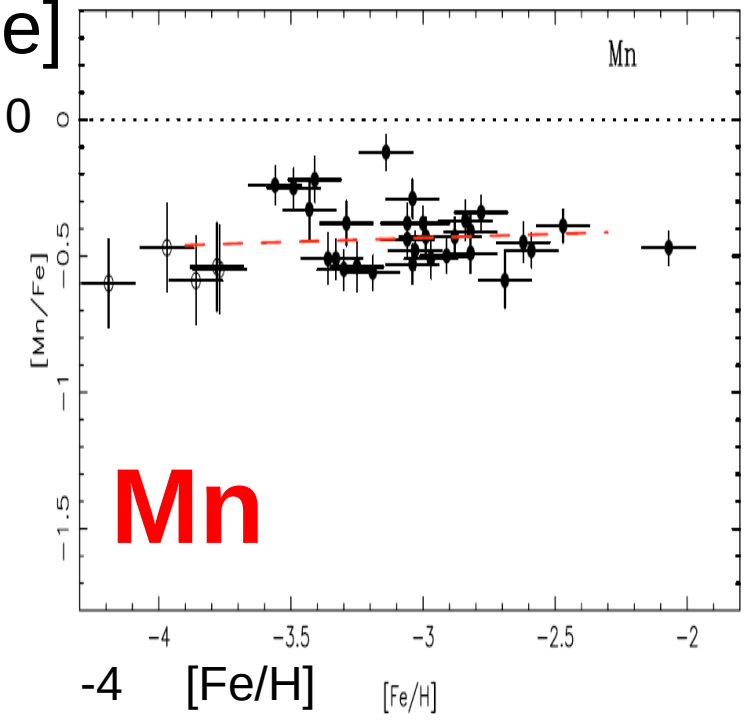
0



-4 [Fe/H]

[Mn/Fe]

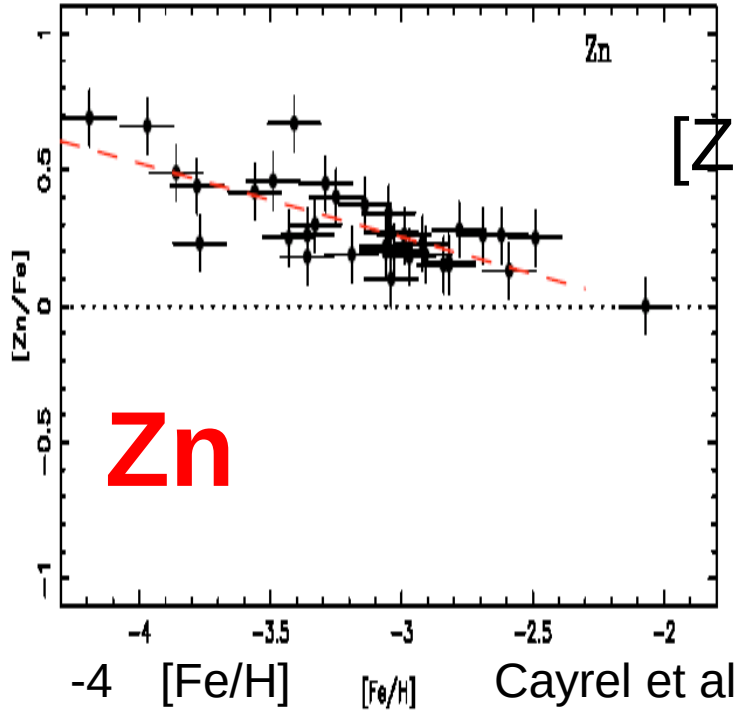
0



-4 [Fe/H]

[Zn/Fe]

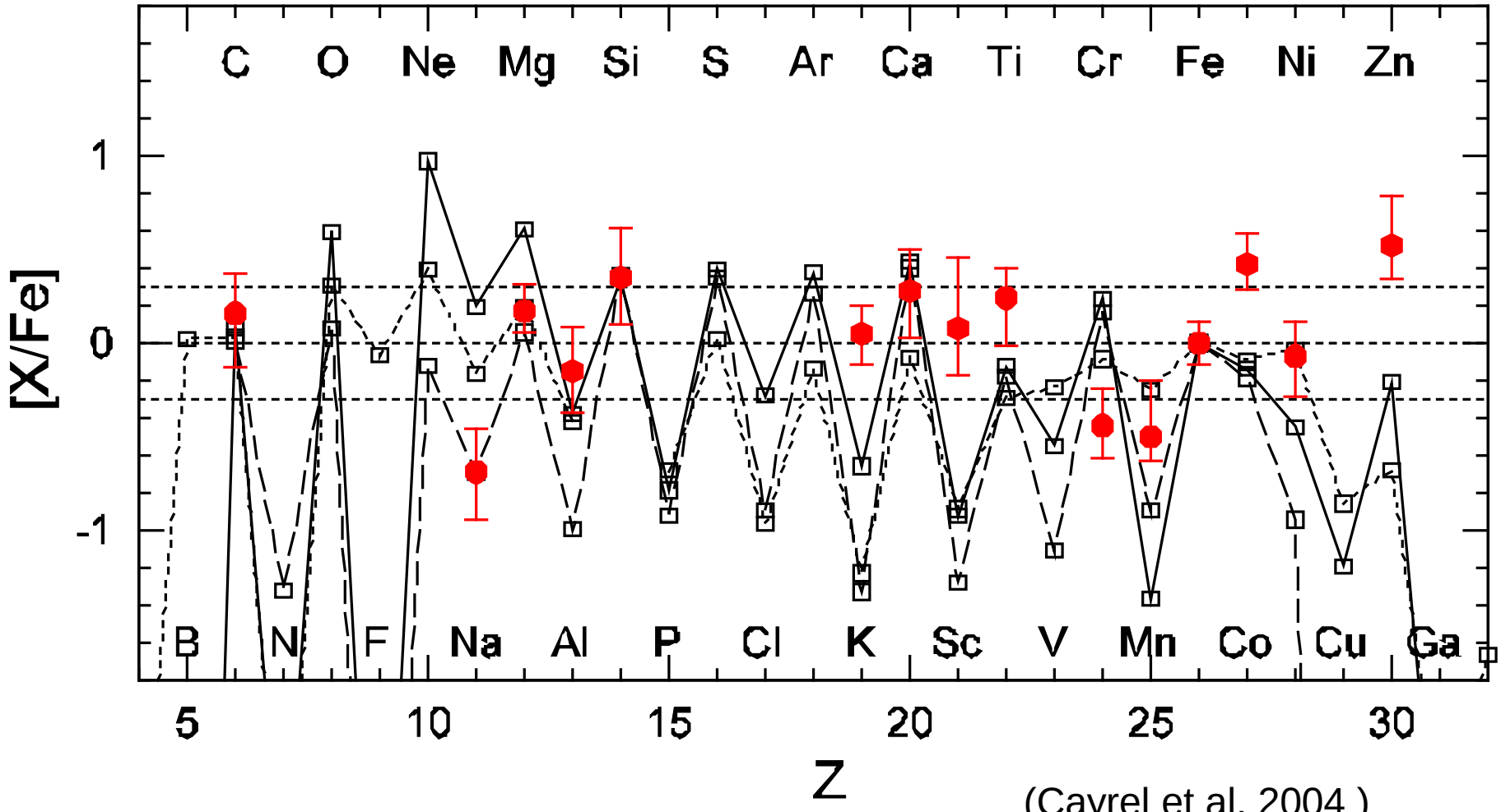
0



-4 [Fe/H]

Cayrel et al. (2004)

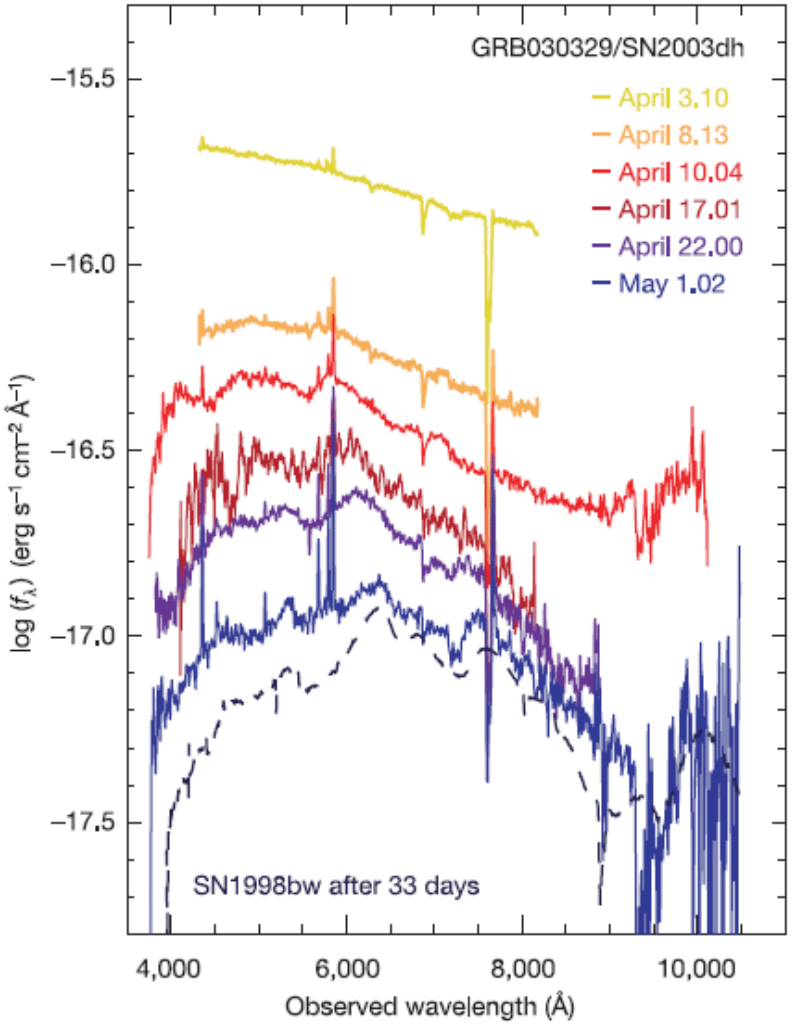
Poor Fit to Extremely Metal-Poor (EMP) Stars ➔ High Explosion Energy

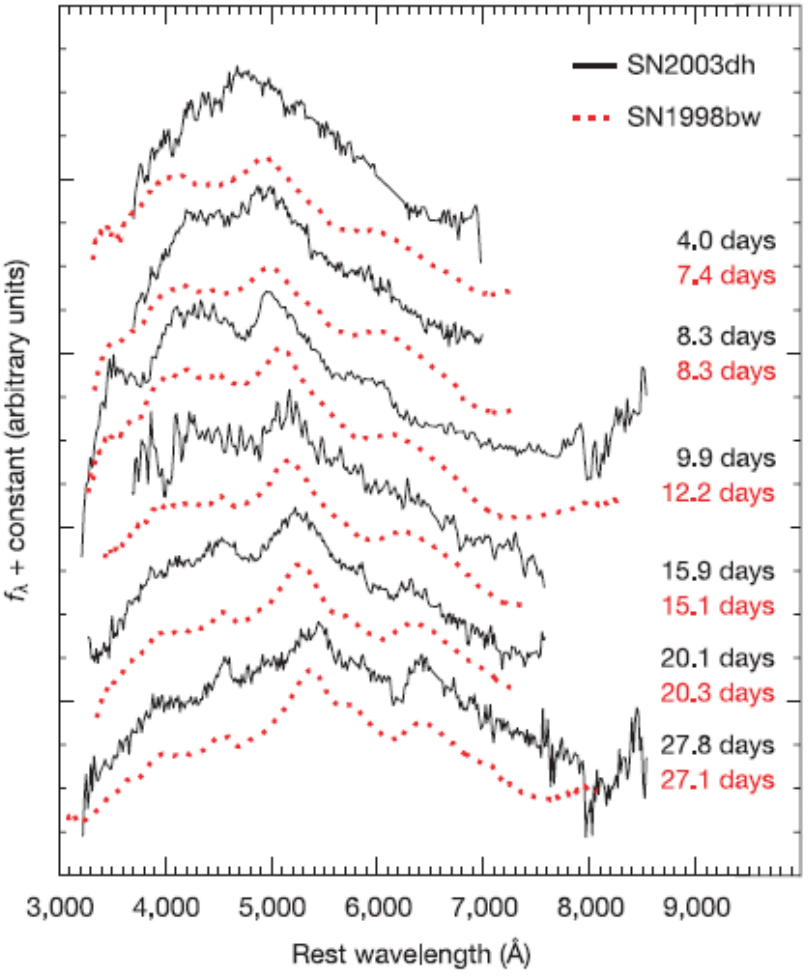


(Cayrel et al. 2004)

GRB-SN Connection

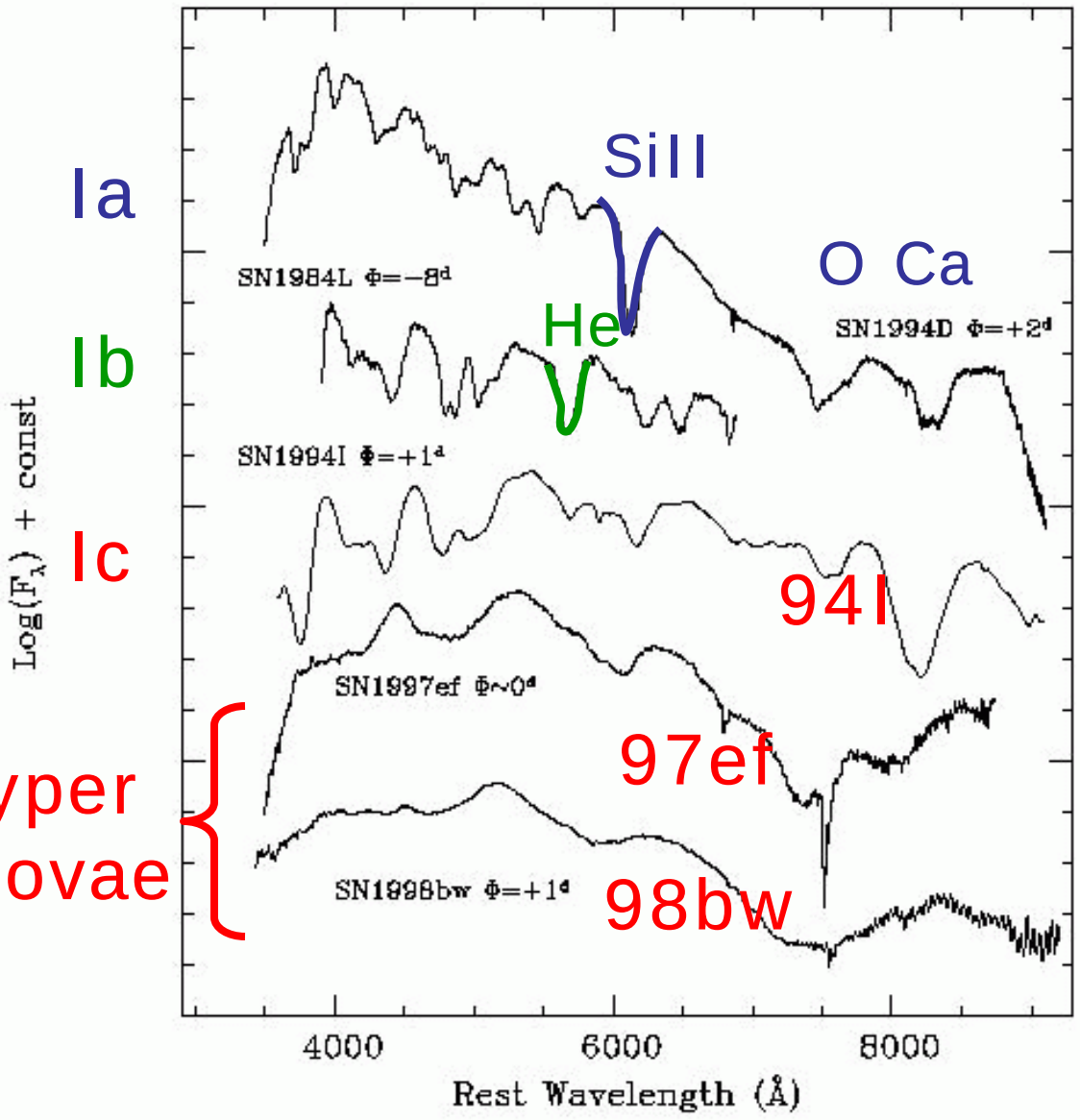
(GRB 030329 / SN 2003dh)





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

Spectra of Supernovae & Hypernovae



Ic: no H,

no strong He,

no strong Si

Hypernovae:

broad features

↑

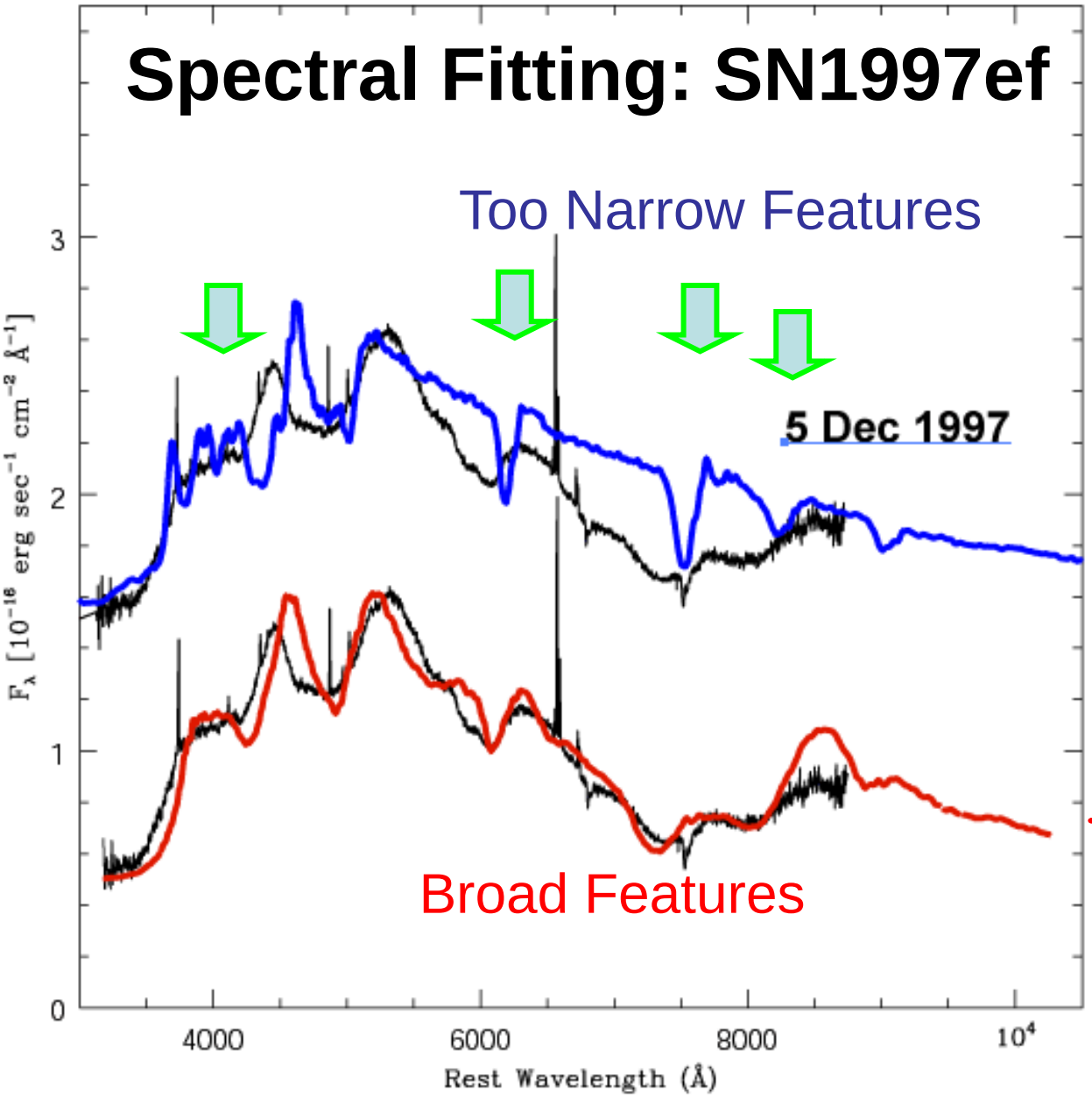
blended lines

↑

"Large mass at high velocities"

Patat et al. (1999)

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.

Supernova – GRB Connection

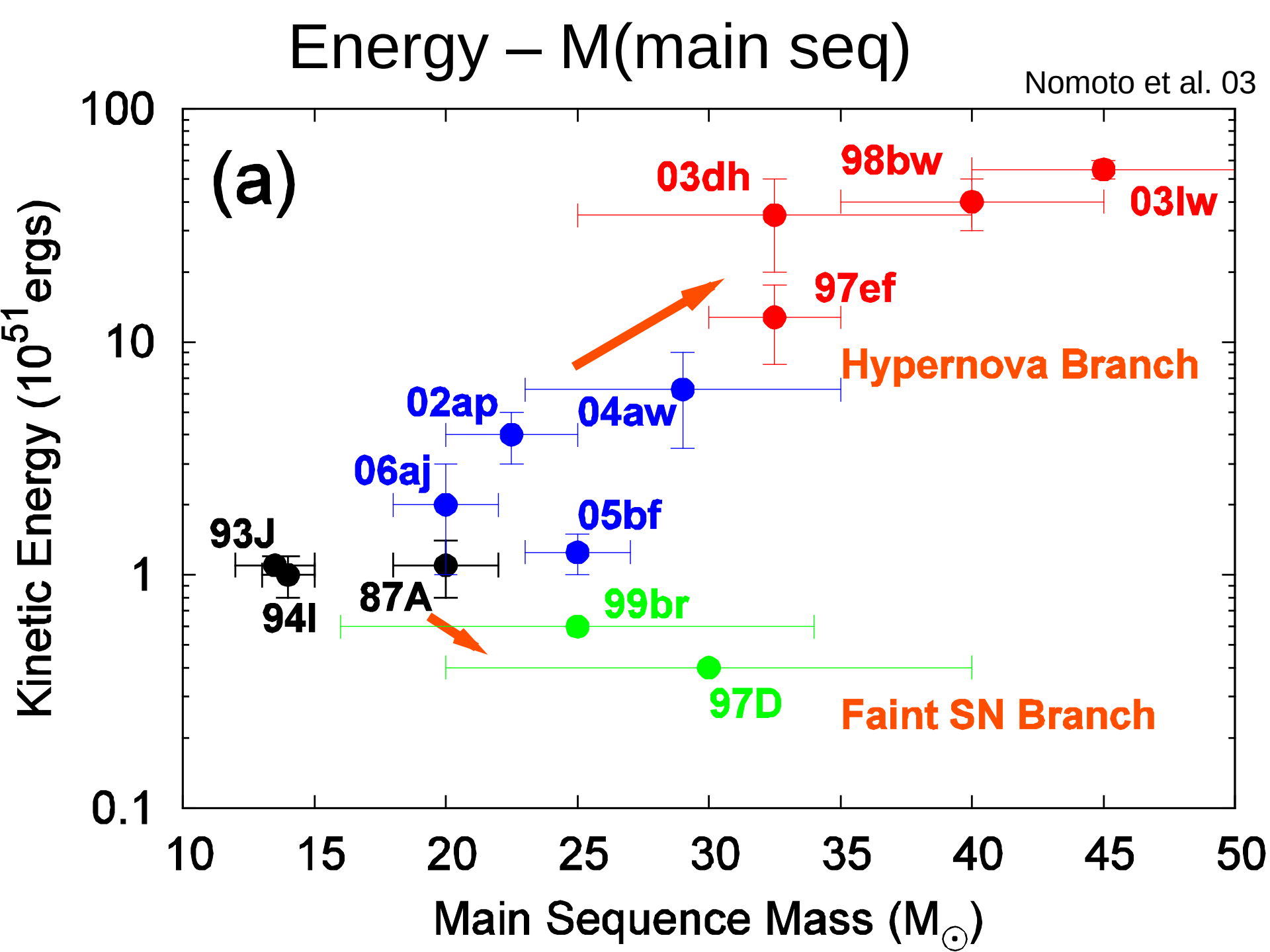
Three GRB－SNe = all Type Ic Hypernovae

$E > 10^{52}$ erg (～10×normal SN)

Large M_{ms} →Black Hole Forming SNe

Aspherical

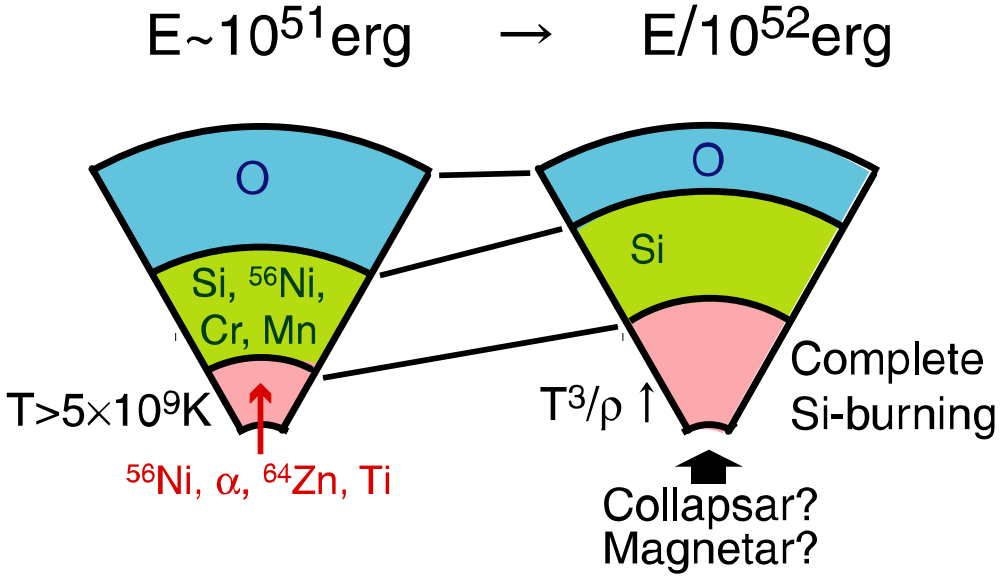
GRB	SN	$M_{CO}/M_{\odot}$	$M_{ms}/M_{\odot}$	$E/10^{51}$erg	$M(^{56}Ni)/M_{\odot}$
980425	1998bw	14	40	30	0.4
030329	2003dh	11	35	40	0.35
031203	2003lw	16	45	60	0.55


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

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 ↗

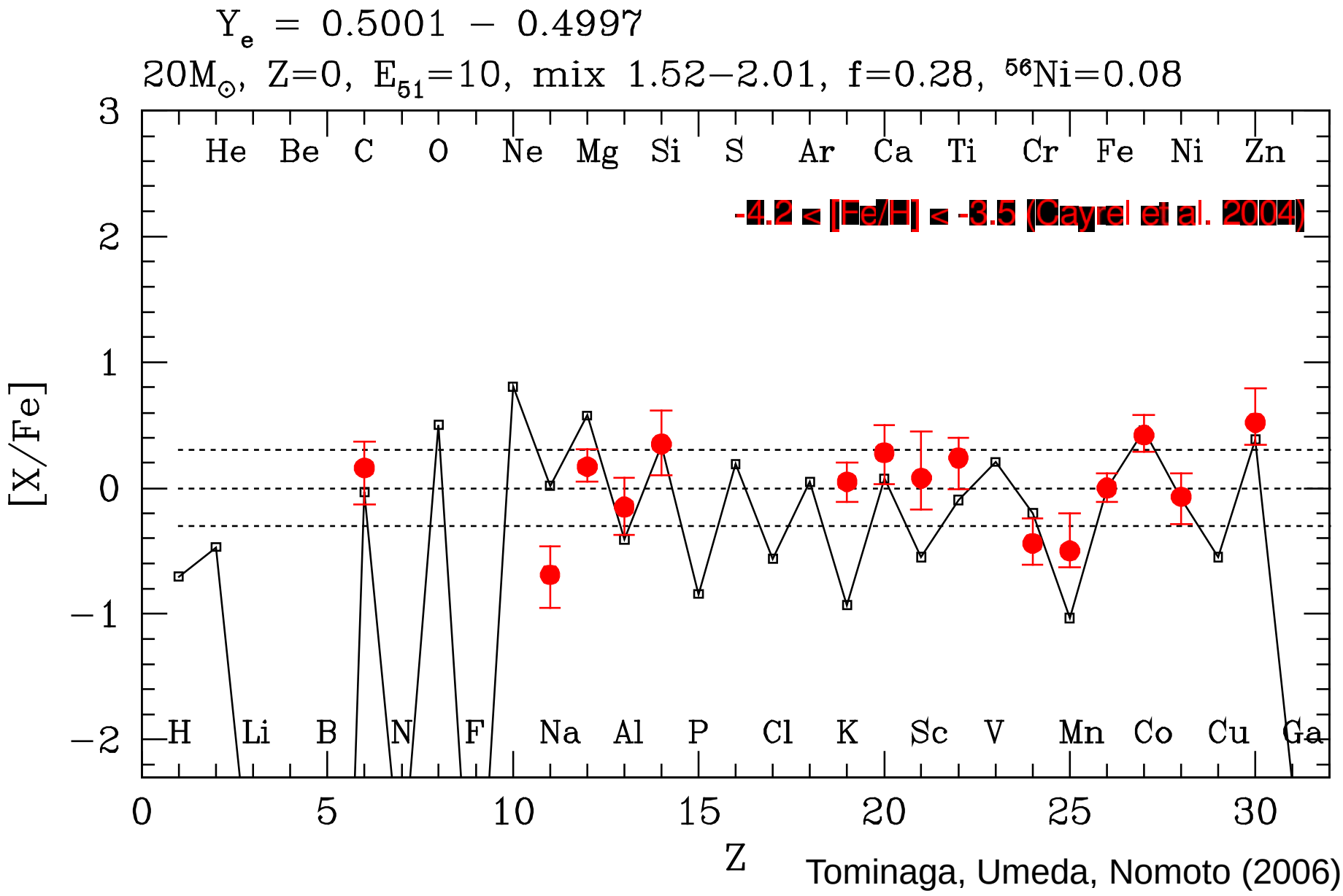
Zn/Fe ↗ ⇦ ^{64}Ge

Ti/Fe ↗

(3) More O burns

(Si, S, Ca)/O ↗

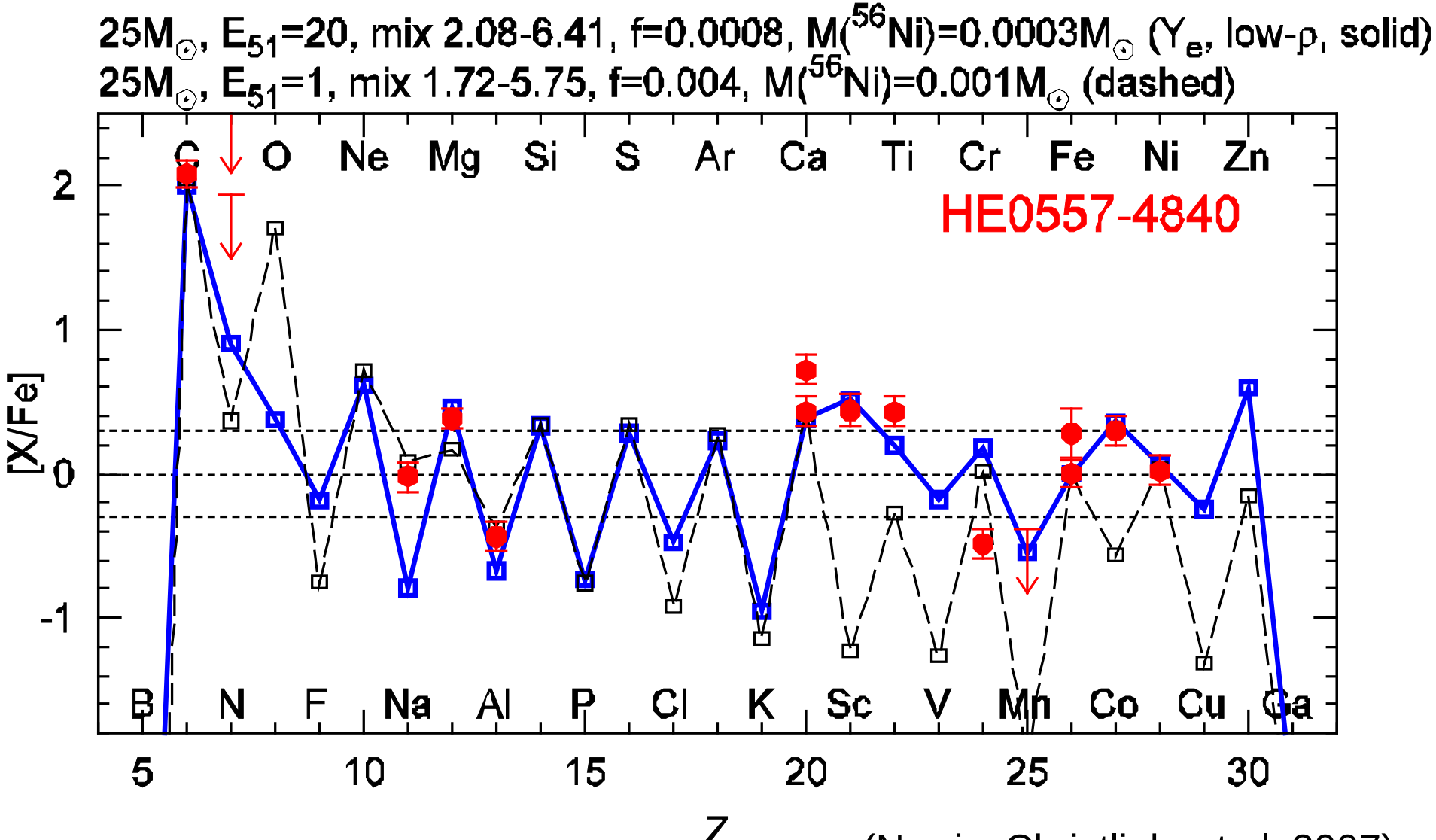
EMP stars vs. Hypernova (E_{51}=10)



Tominaga, Umeda, Nomoto (2006)

UMP Star : [Fe/H] = -4.75

Hypernova model (E_{51}=20:1D)➔Co

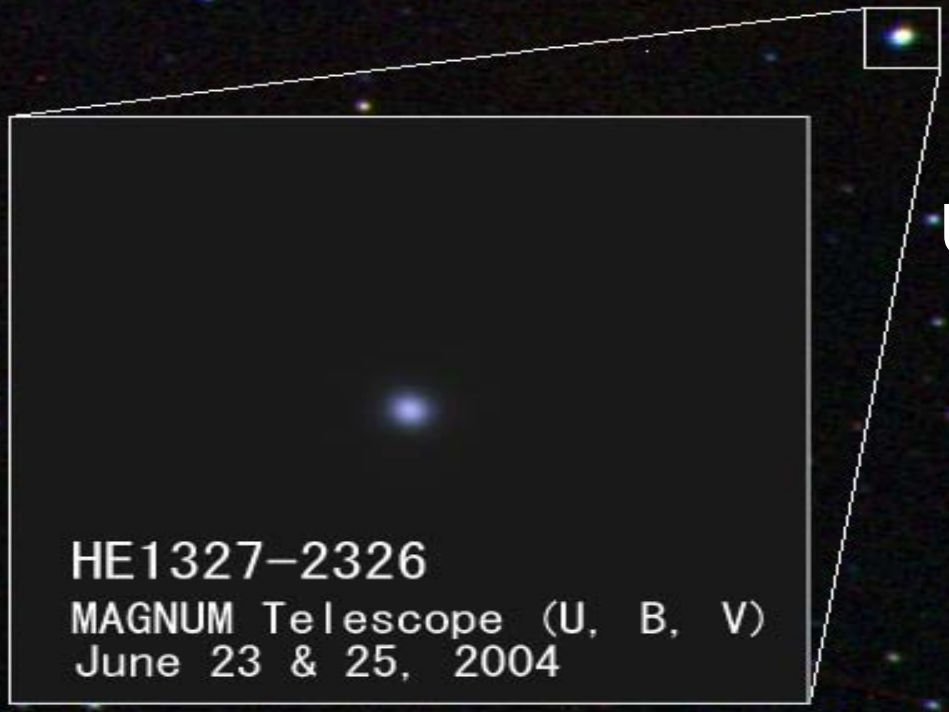


(Norris, Christlieb, et al. 2007)

Hyper Metal-Poor Star

Fe/H ~ solar ratio / 200,000

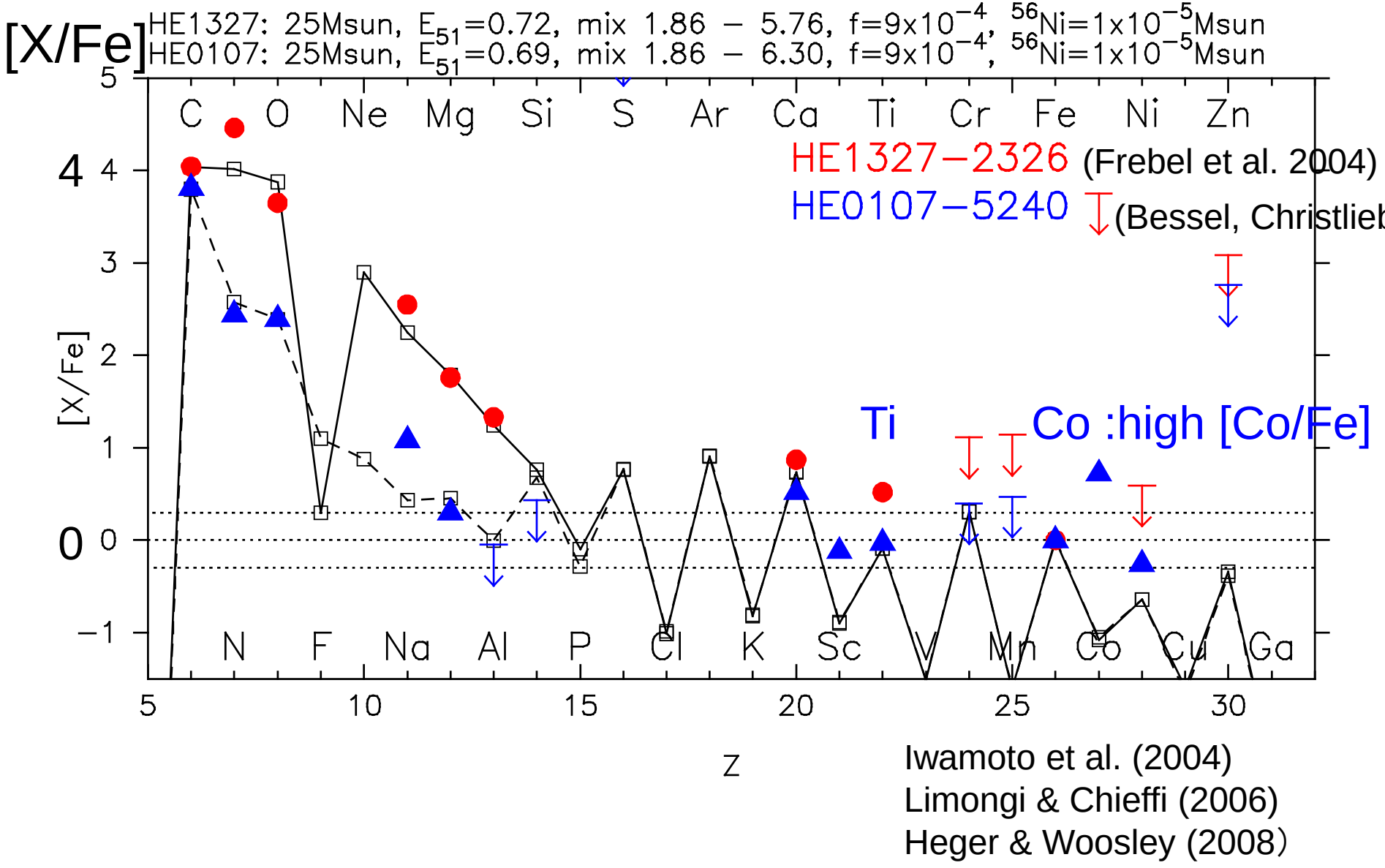
(A. Frebel et al.: Subaru Telescope)



Unique abundance pattern:
e.g., high (C, Co, Zn)/Fe

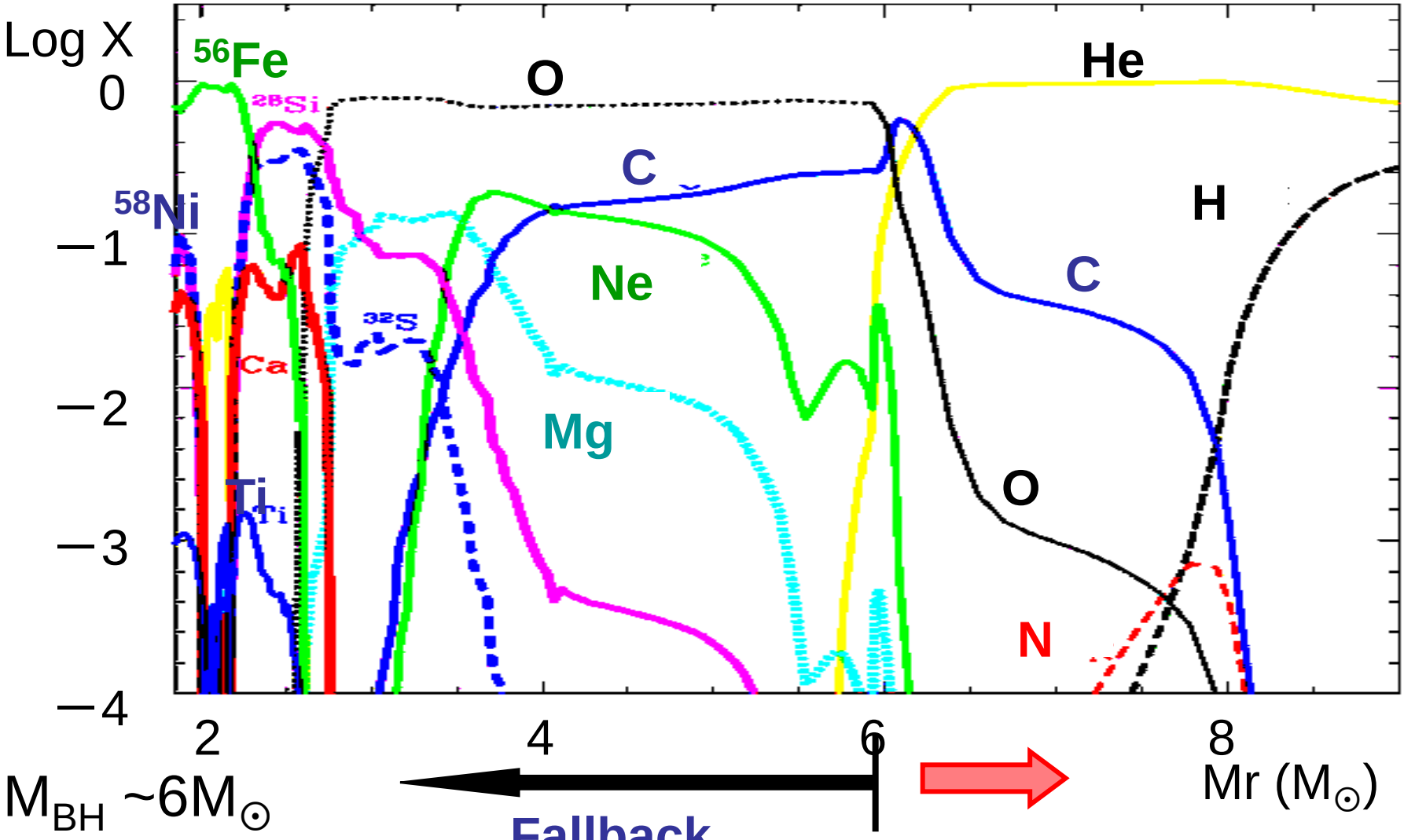
HMP stars: 1D Low E models (E_{51}< 1)

mixing & fallback ➔ low [Co/Fe]



Iwamoto et al. (2004)
Limongi & Chieffi (2006)
Heger & Woosley (2008)

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



Umeda & Nomoto (2003)

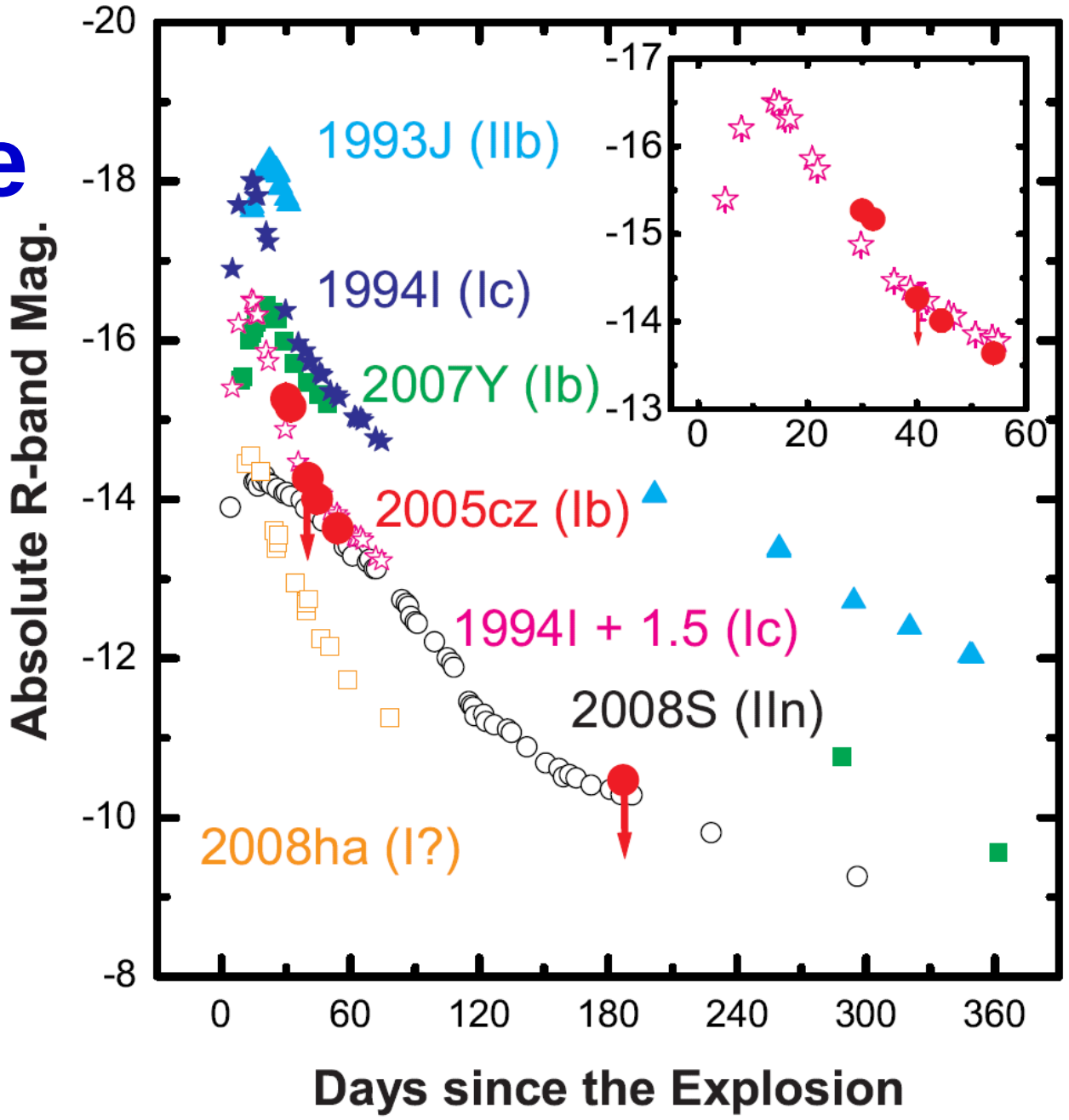
Faint Supernovae

SN 2008ha (I ?)

2005cz (Ib)
(Kawabata+)

2005E (Ib)
(Peretz+)

2008S (IIn)

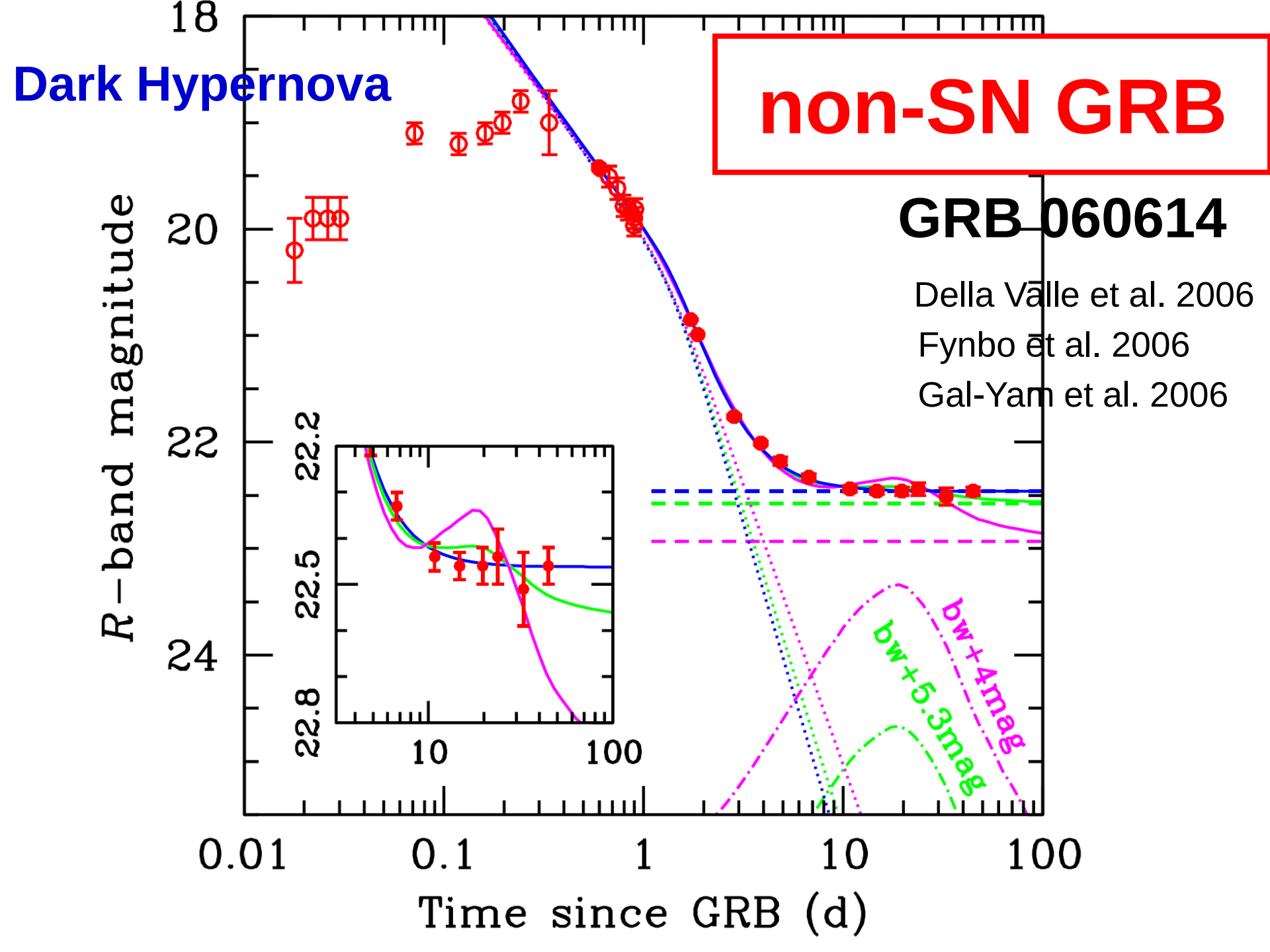


Dark Hypernova

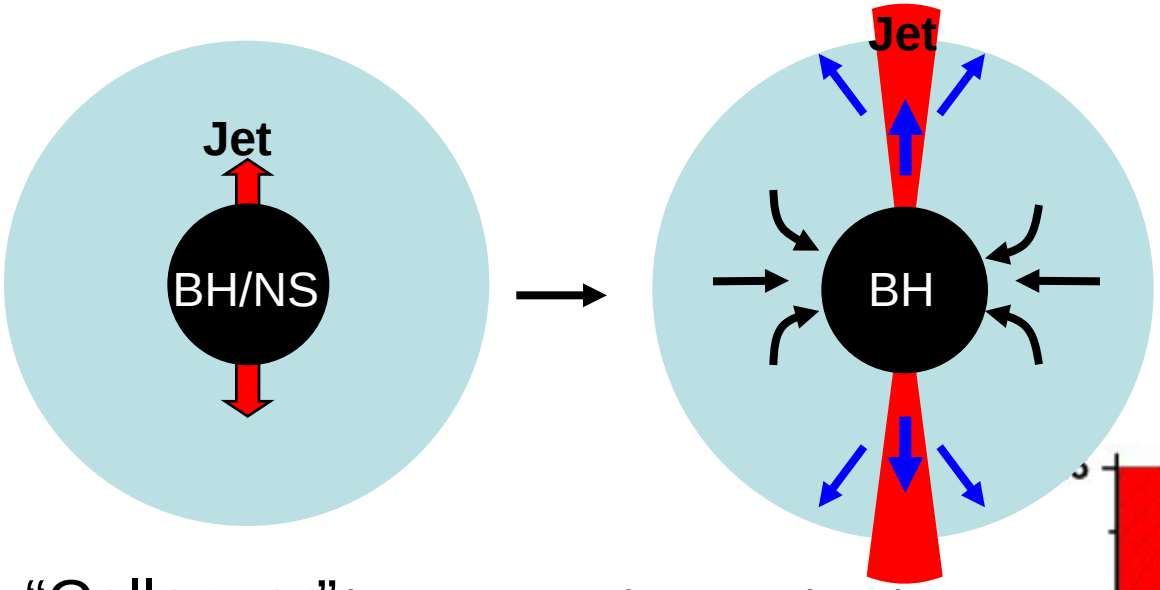
non-SN GRB

GRB 060614

Della Valle et al. 2006
Fynbo et al. 2006
Gal-Yam et al. 2006



Jet-induced Nucleosynthesis



Special relativistic hydrodynamics (Tominaga et al. ApJL 2007)

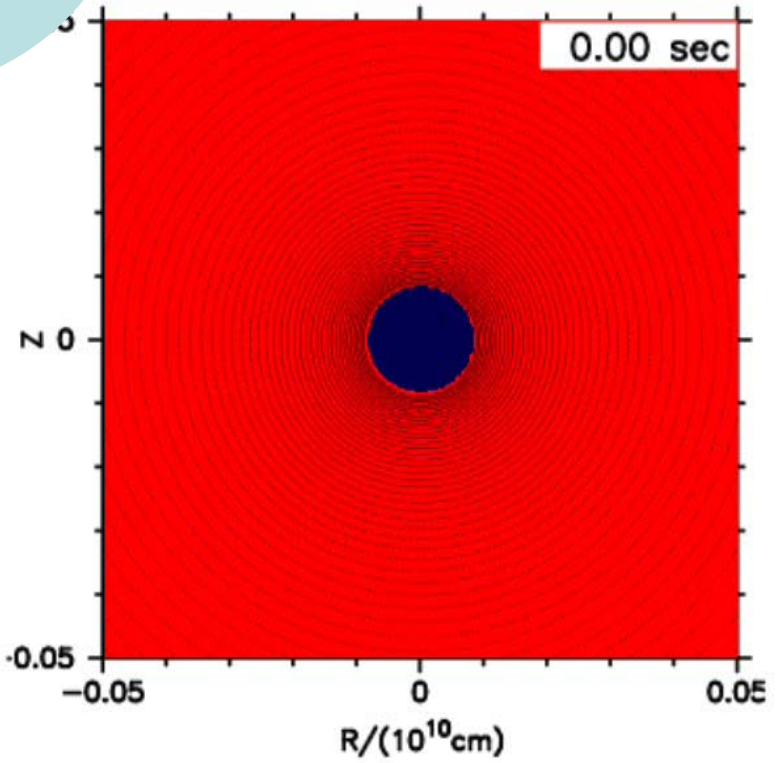
cf. "Collapsar"(e.g., MacFadyen et al. 01)

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

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

Same mass and explosion energy

$40M_\odot$ 1.5×10^{52}erg

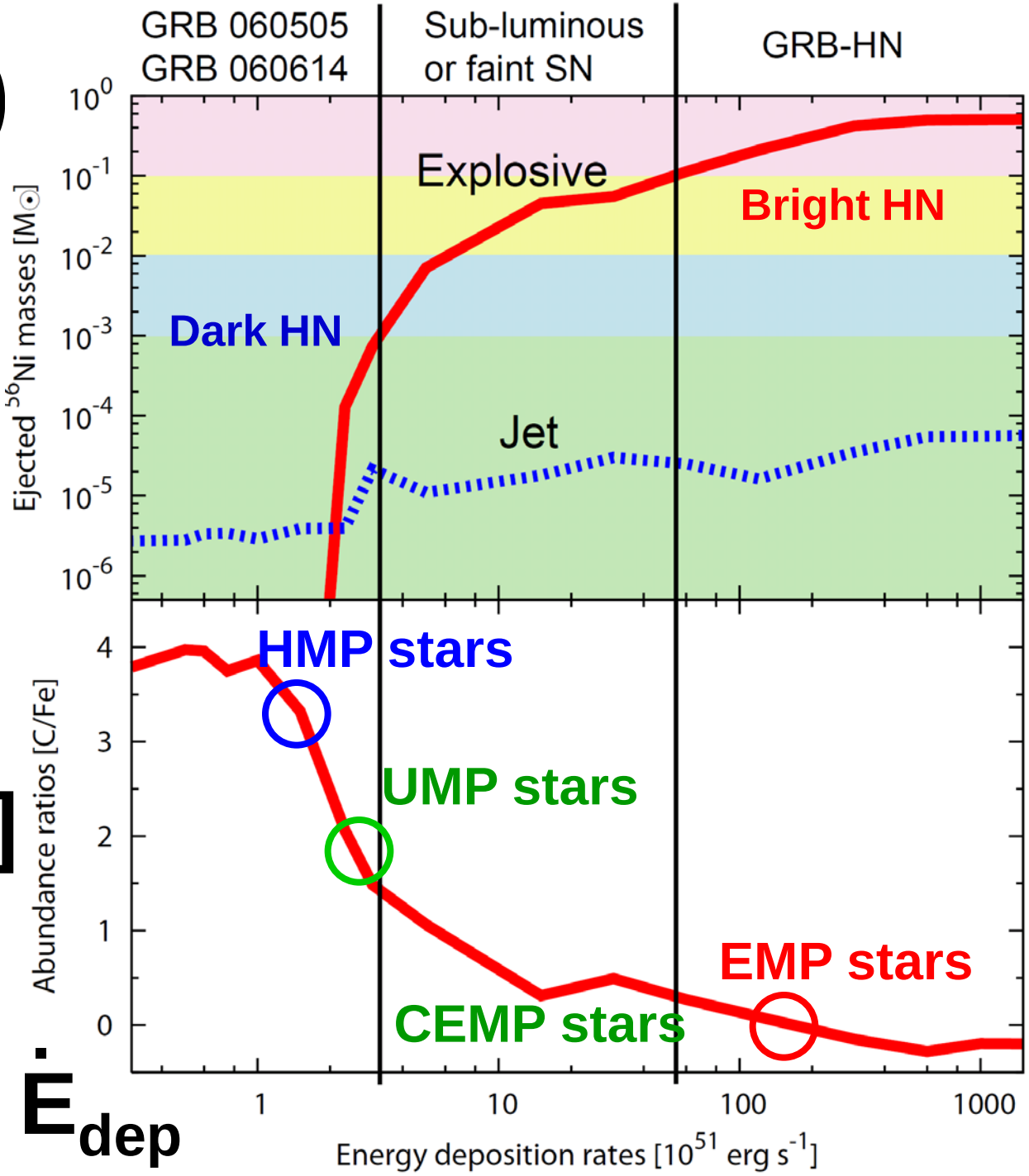


$M(^{56}Ni)$

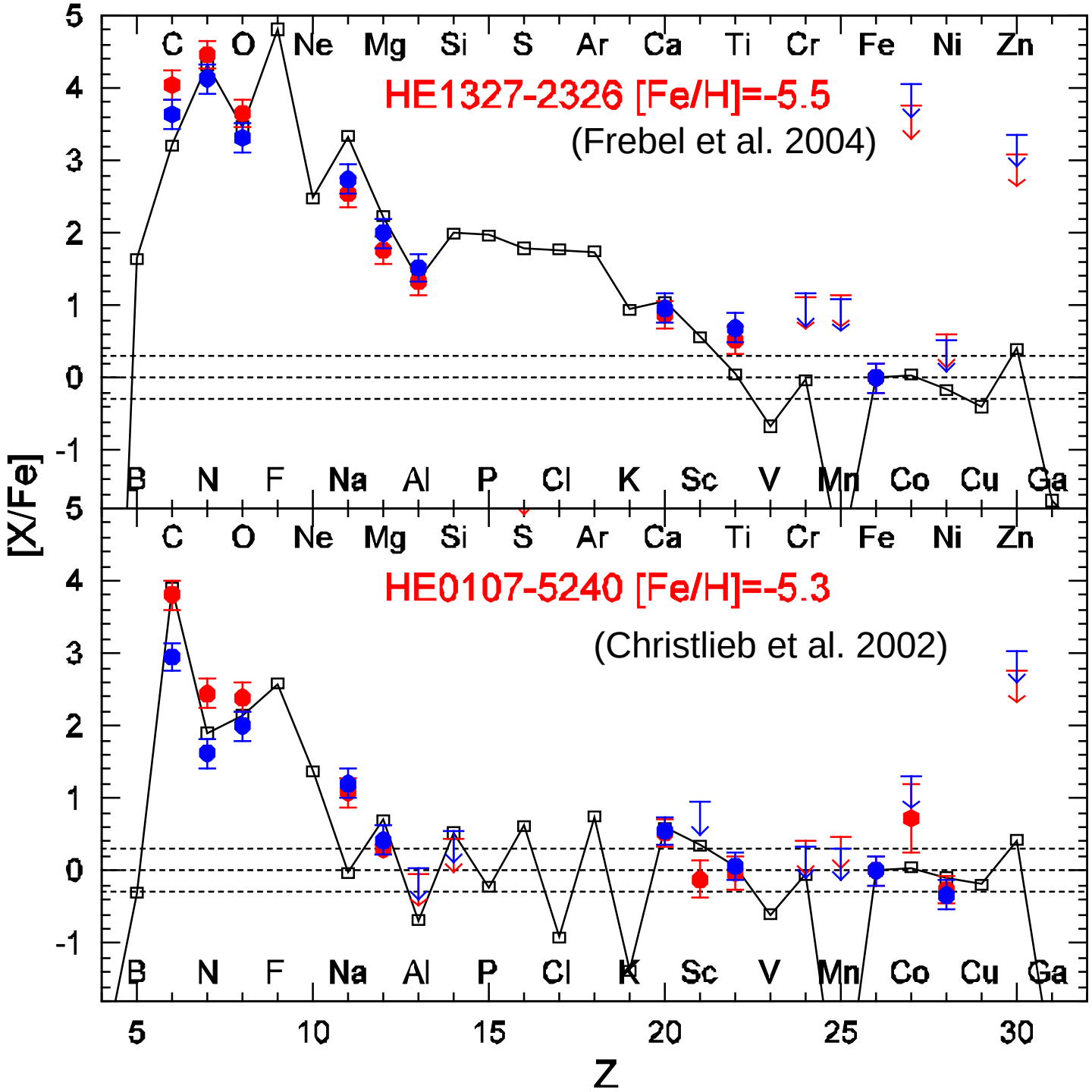
Smaller $\dot{E}_{dep}$ ➔
smaller $M(^{56}Ni)$
and
larger [C/Fe]

[C/Fe]

High E ➔ Fallback



Tominaga et al. (2007)



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-like Energetic Explosion

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

(2) Weak Explosion

Mixing & Fallback

Diversity & Peculiarities of Supernovae

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

  Pair-Instability ? Core-Collapse ?

- Ultra-Faint SNe (IIn): AGB progenitors?

  (Ibc): Fallback SNe ?

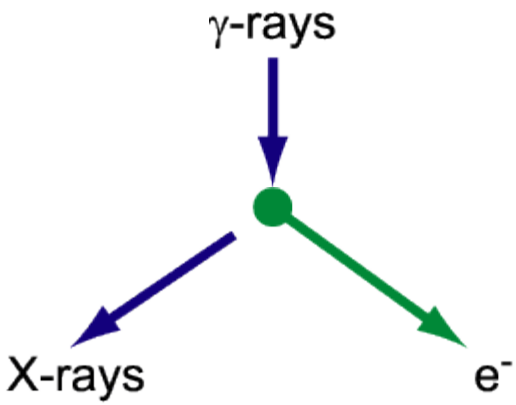
* Ic: GRB-SNe, Hypernovae; aspherical

* Ib: Energetic (HN-like); aspherical

LBV, WR connection ?

^{56}Co-decay

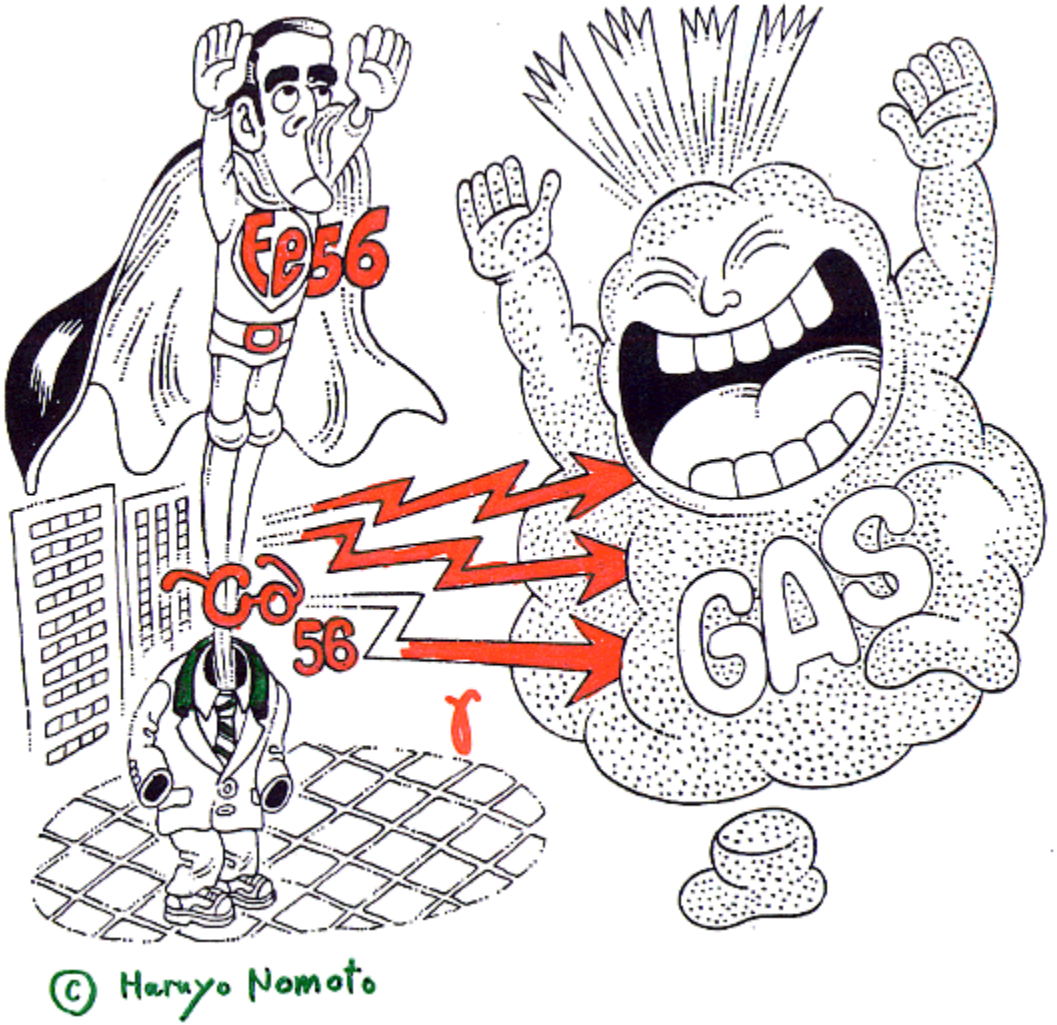
$^{56}Ni \xrightarrow[6.6d]{\gamma} {}^{56}Co \xrightarrow[78d]{\gamma} {}^{56}Fe$



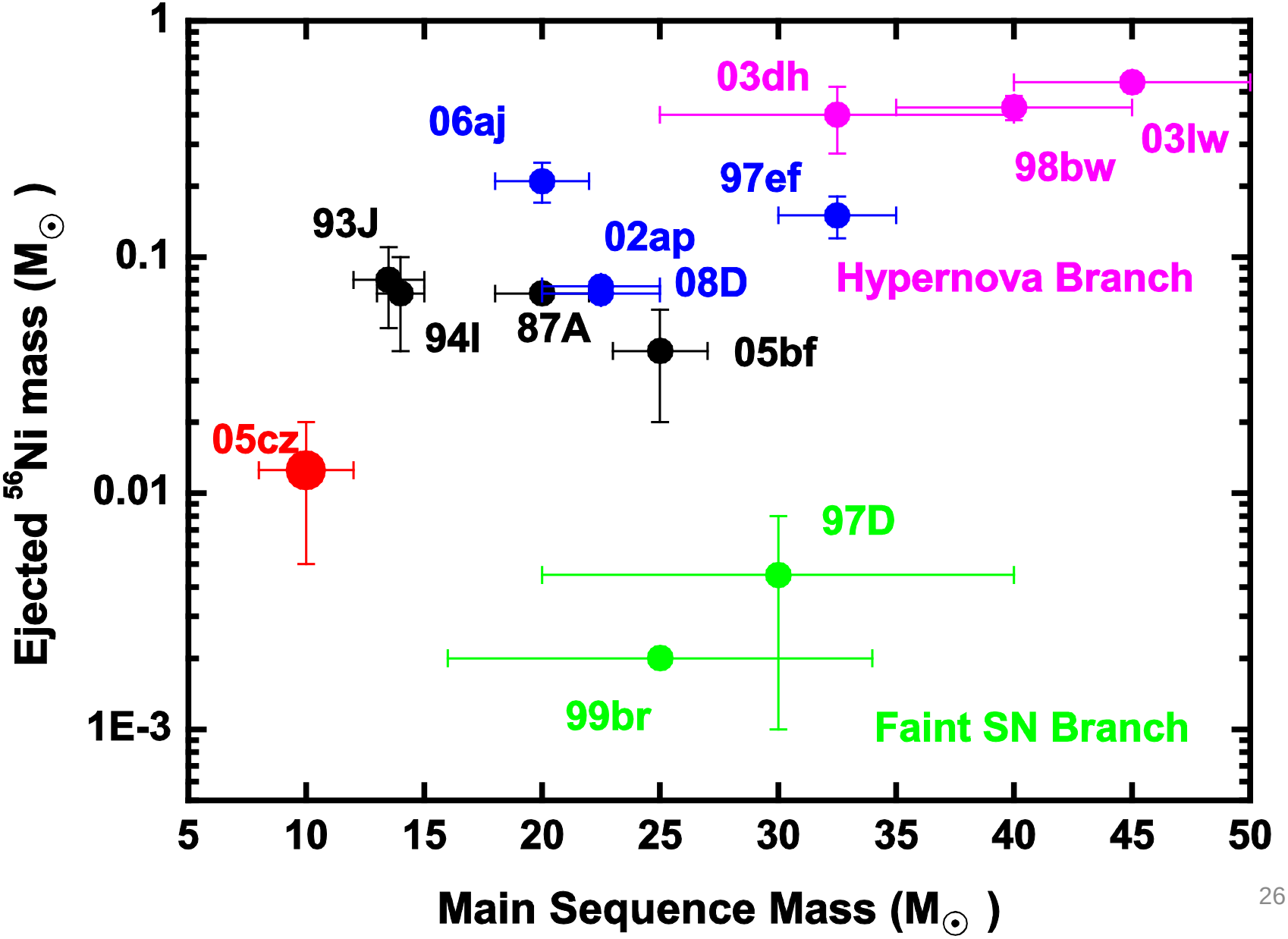
Photoabsorption Excitation/Ionization

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

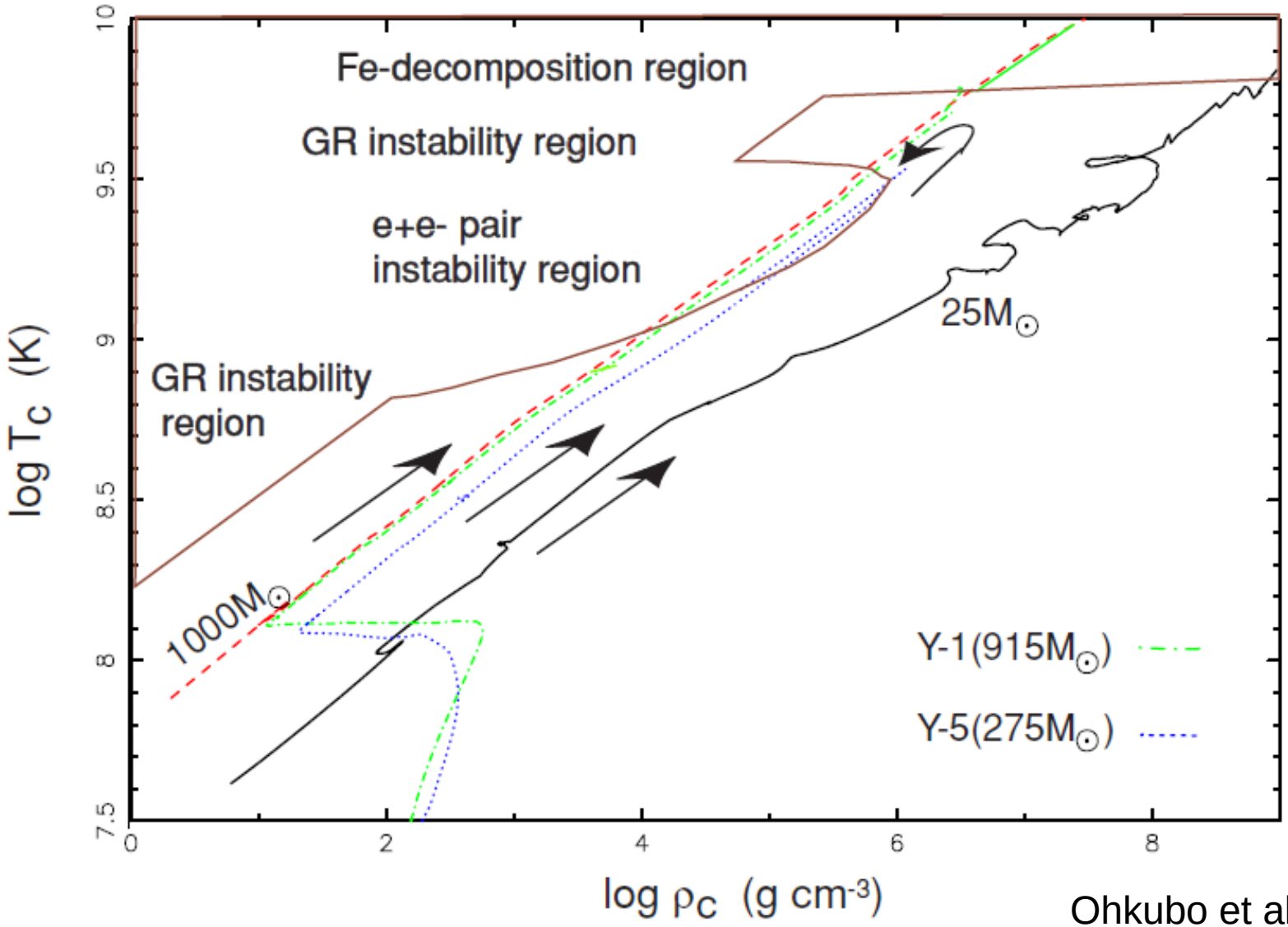
Shape:M_{ej}



M(^{56}Ni) - M(main Seq)

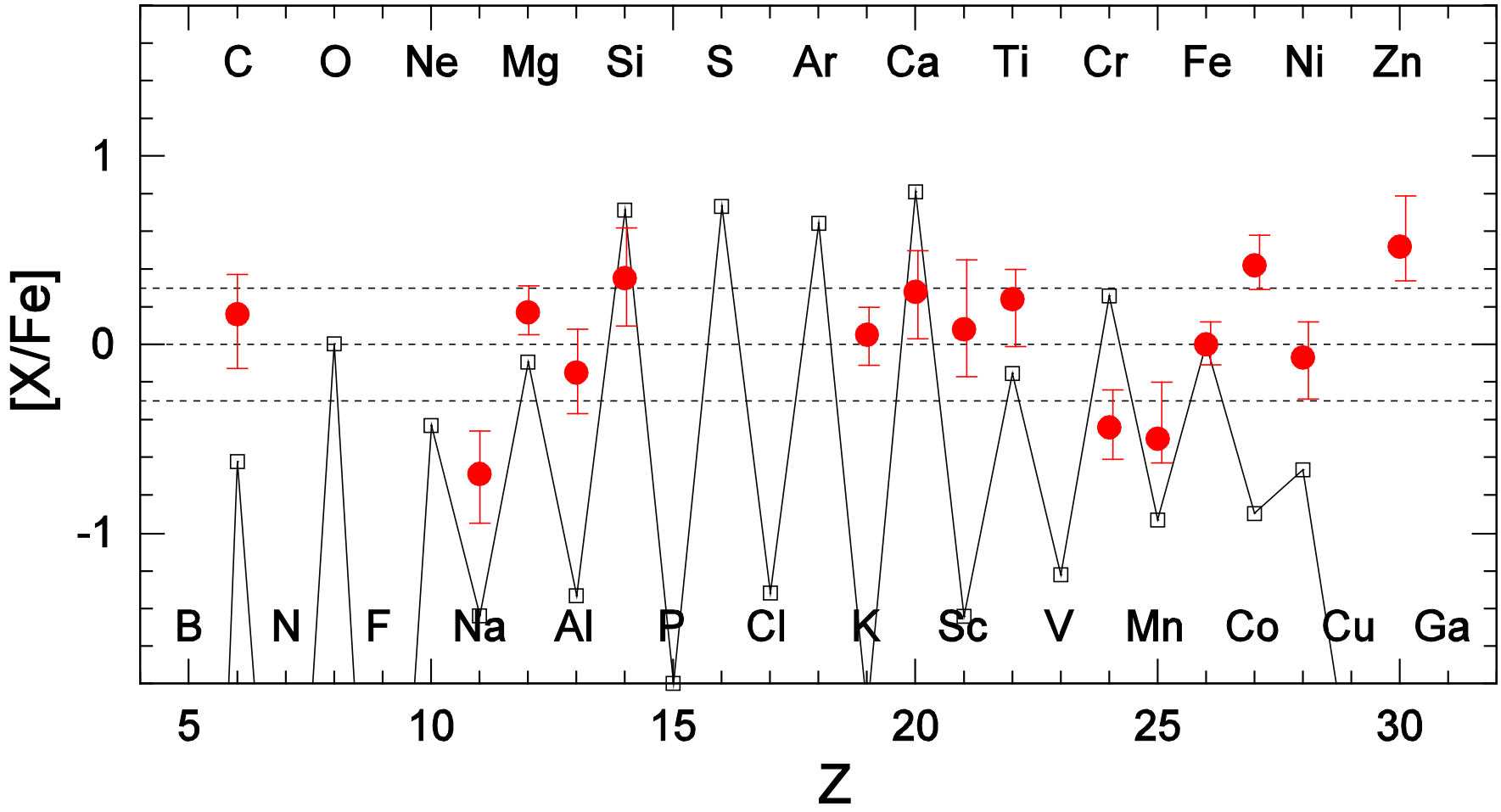


Pair-Instability SNe (140-300 $M_\odot$)



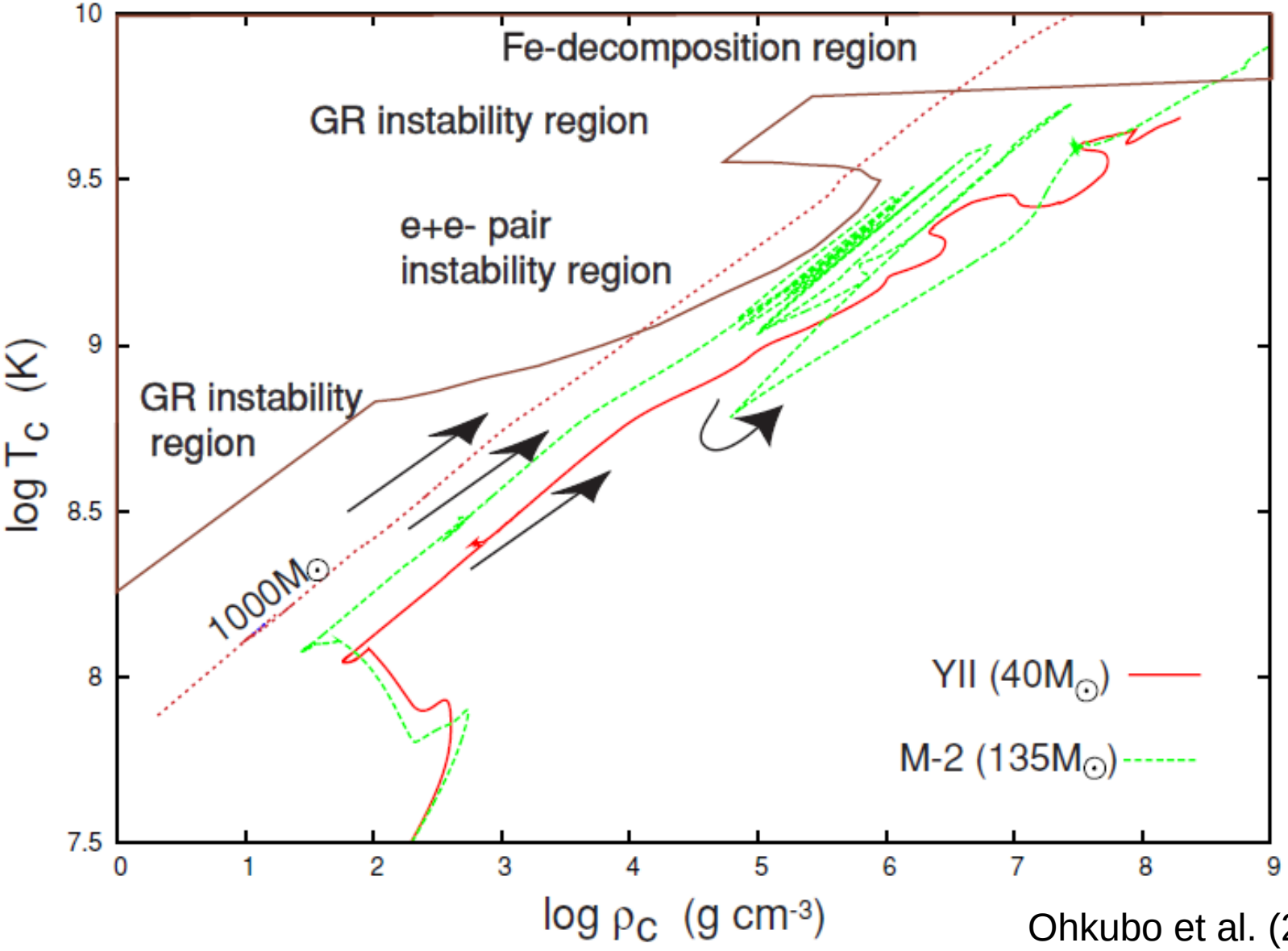
Ohkubo et al. (2009)

Pair Instability SN vs EMP stars



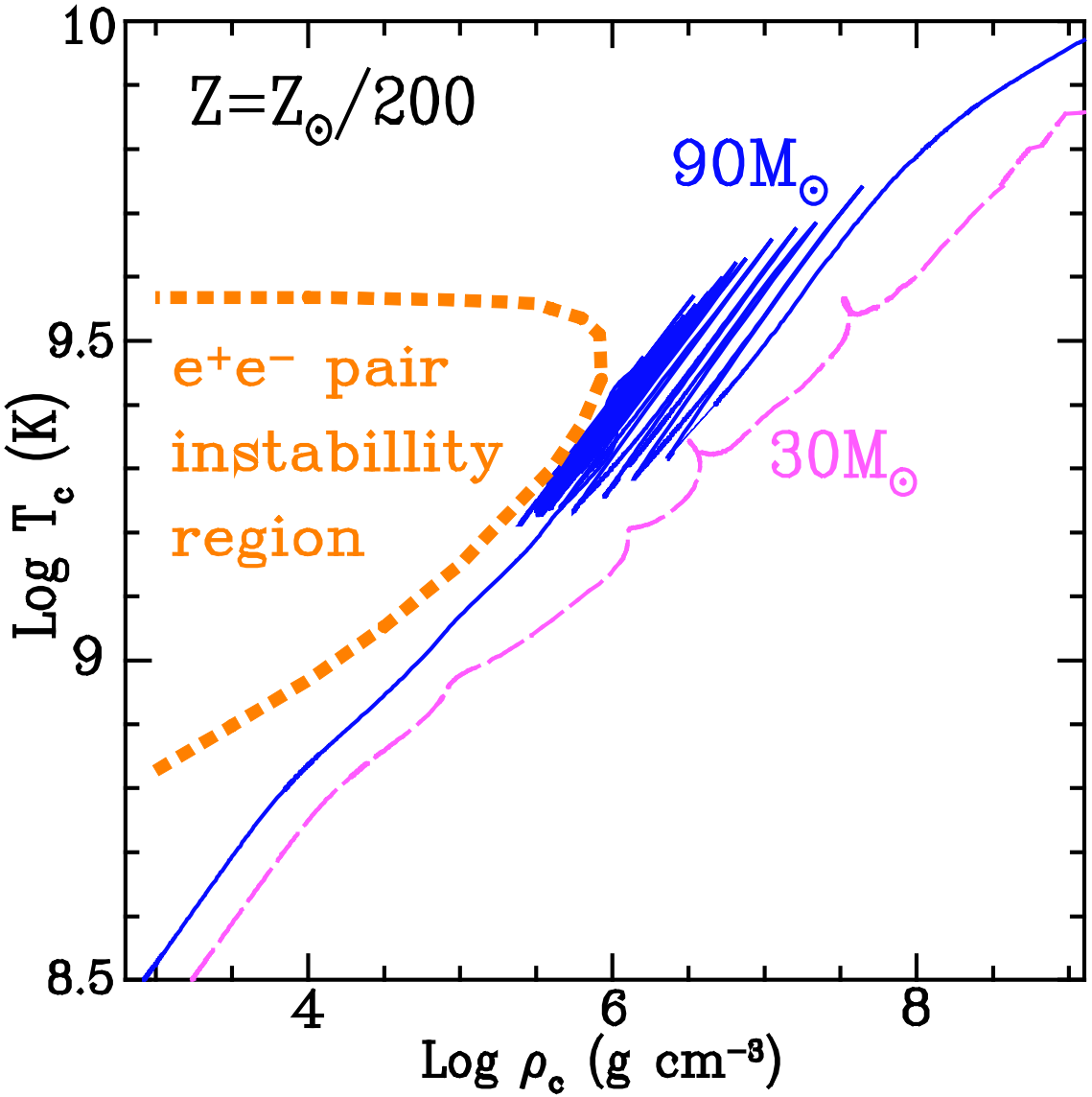
Umeda & Nomoto 2002

Pulsation of O, Si Core (80-140$M_\odot$)



Ohkubo et al. (2009)

Evolution of the 90$M_\odot$ Star



Oscillation

↓

Fe core collapse

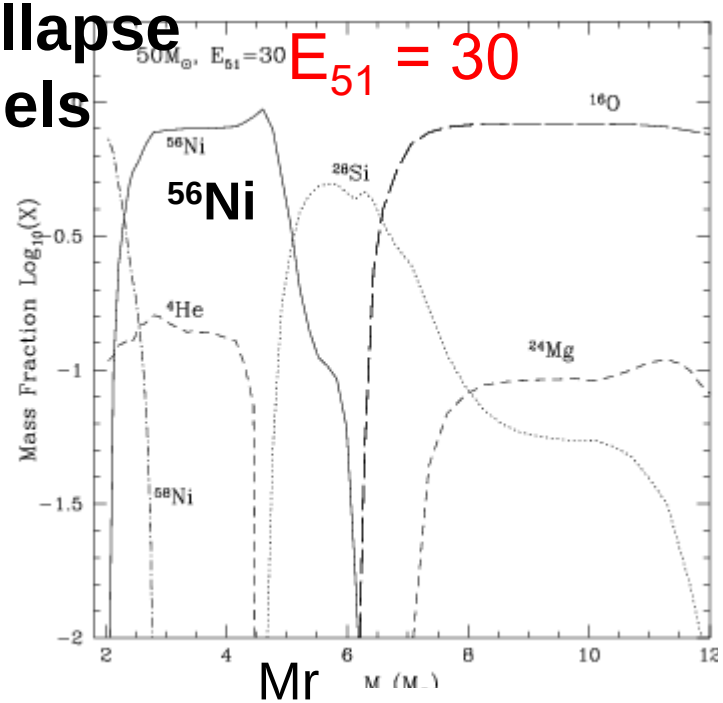
E_{51}=30

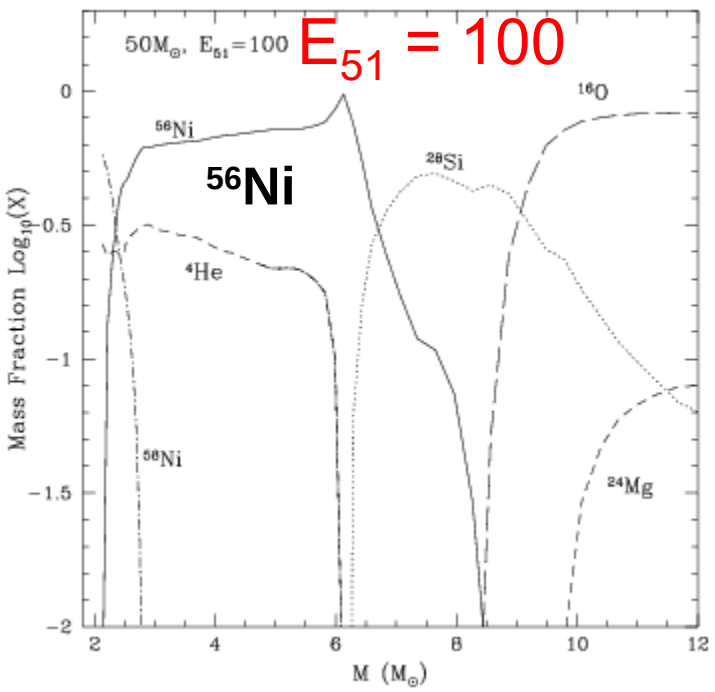
M(^{56}Ni)=5$M_\odot$

(Umeda & Nomoto)

Core-Collapse SN Models

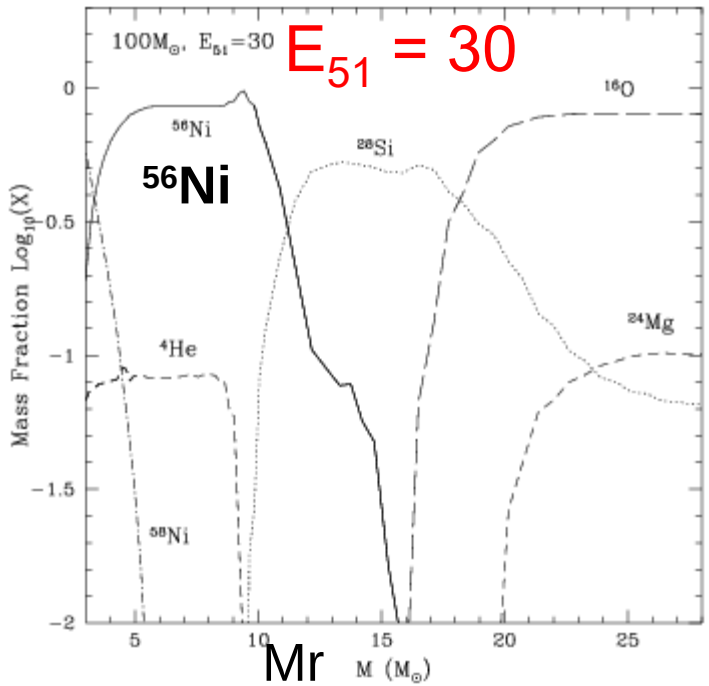
Log (Mass Fraction)

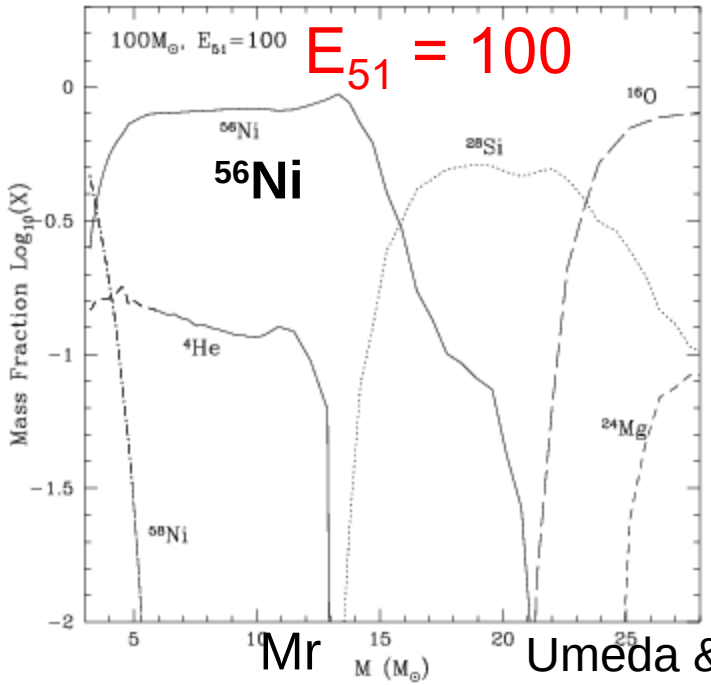




M = 50M⊙

Log (Mass Fraction)





M = 100M⊙

Umeda & Nomoto

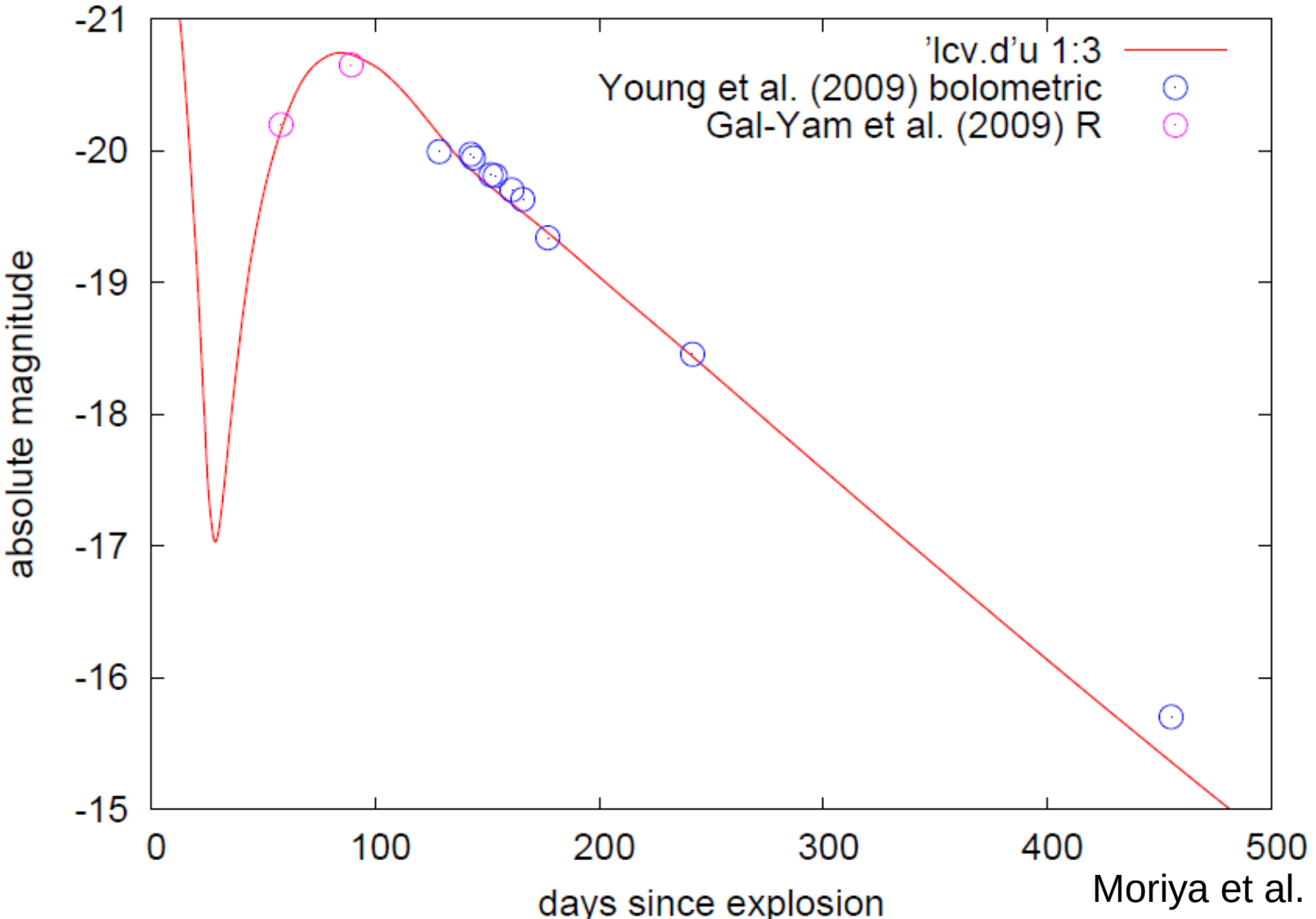
Models for Luminous SNe

	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 (56Ni) =	6.1 $M_\odot$	9.8 $M_\odot$
• LC: rise time =	52 - 85 days	150 days

- Jet-induced Explosion

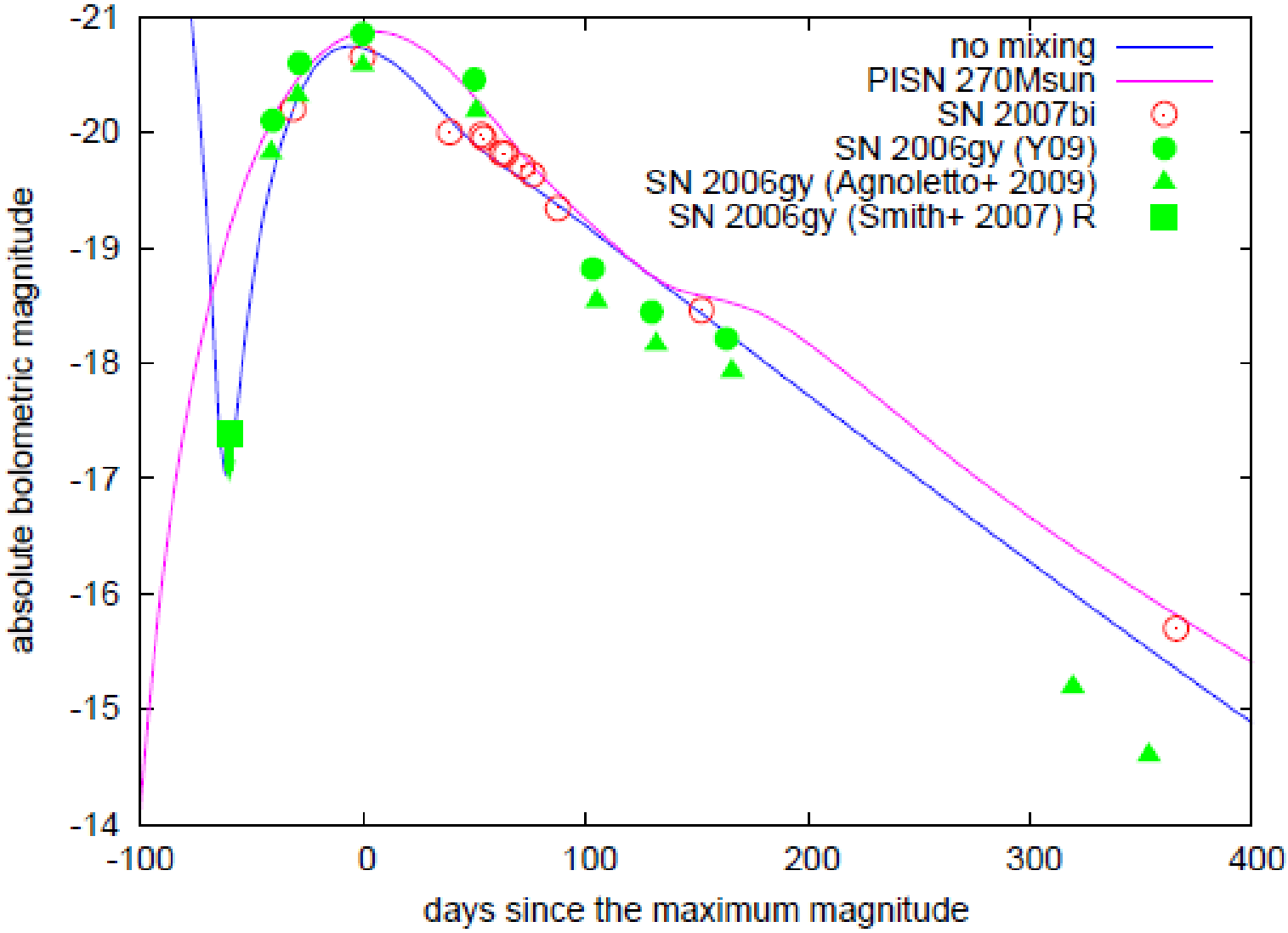
→ Aspherical Hypernova → GRB?

SN Ibc 2007bi (core-collapse Hypernova)



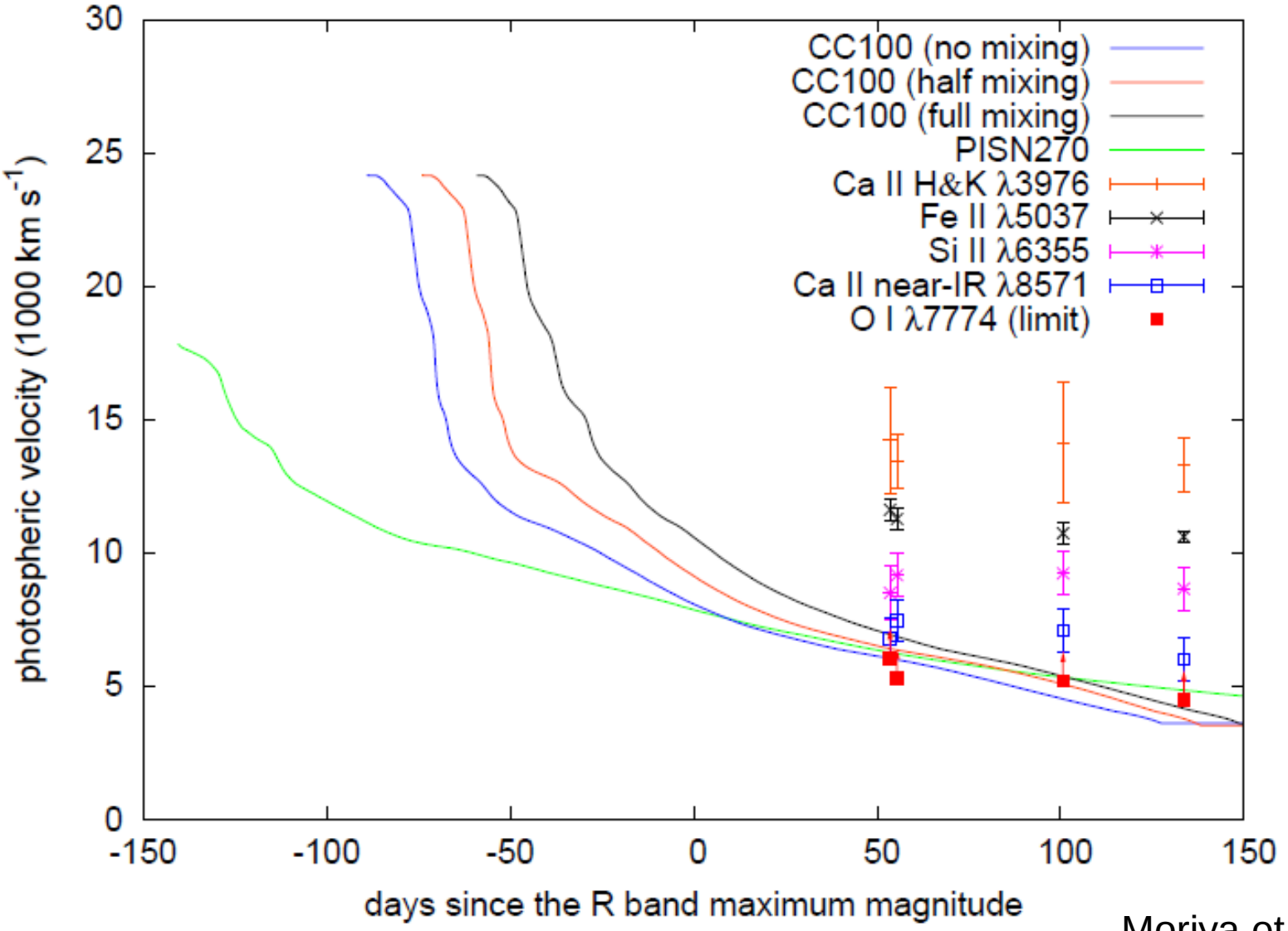
Moriya et al.

SN IIn 2006gy



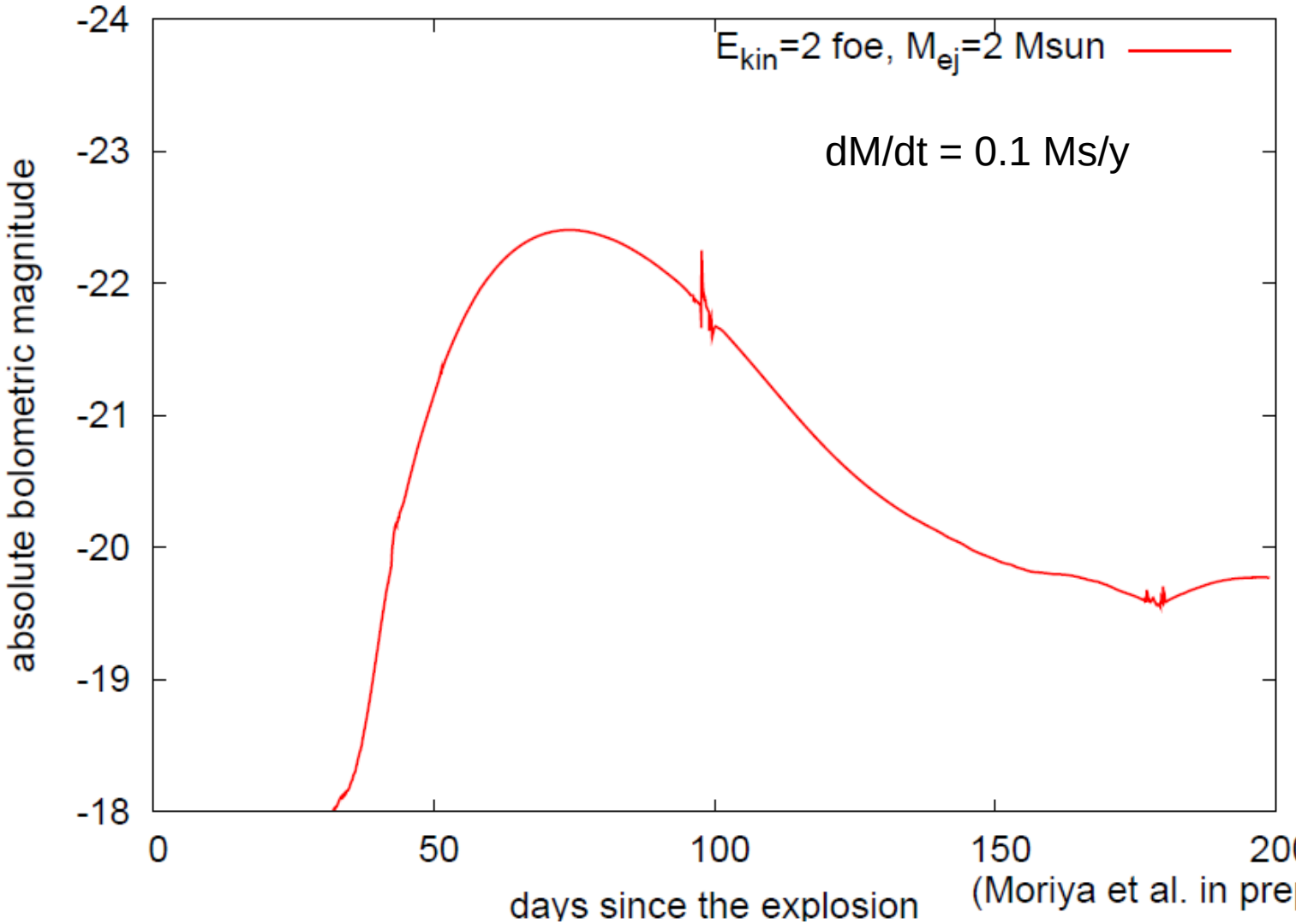
Moriya et al.

Photospheric Velocity (SN 2007bi)



Moriya et al.

Interaction with Dense Circumstellar Matter (mass accreting star ?)



(Moriya et al. in prep.) →poster

HMP/CEMP/EMP Stars

Peculiar Abundance Patterns:

large [C/Fe]: (HMP, CEMP)

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

Possible Source of Peculiarities

(1) Hypernovae (GRB-SN)

(2) Non-SN GRB (Dark Hypernovae)

(3) Faint (& Weak) Supernovae

Fallback SN (after Mixing)

Nucleosynthesis in First Supernovae

* Metal-Poor Stars : peculiar abundance patterns
  Hypernova contribution (Zn, Co, Ti..)

* Fallback Supernovae : ➔ Faint Supernovae
  Weak Explosion
  Jet-induced Hypernovae

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