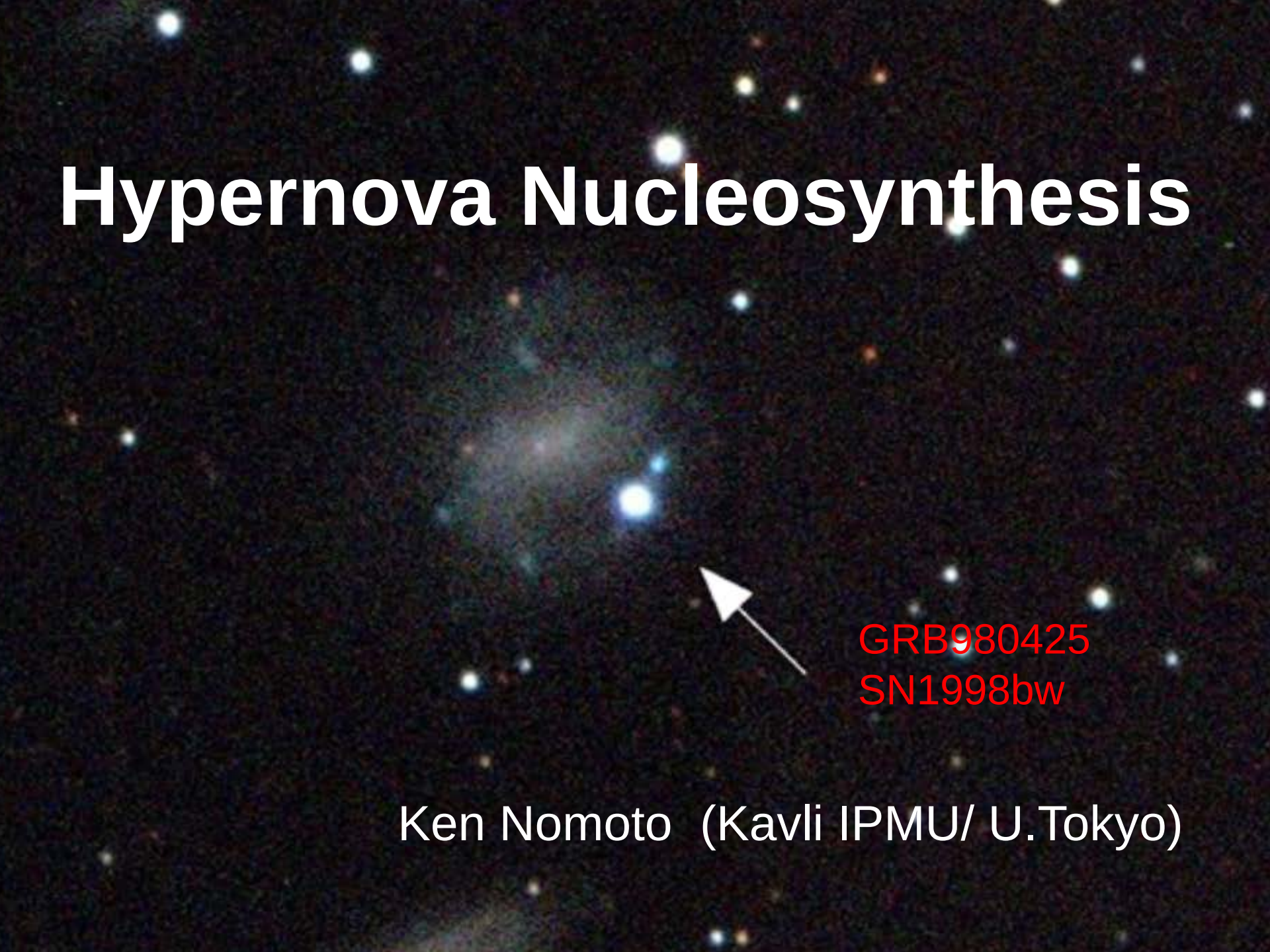
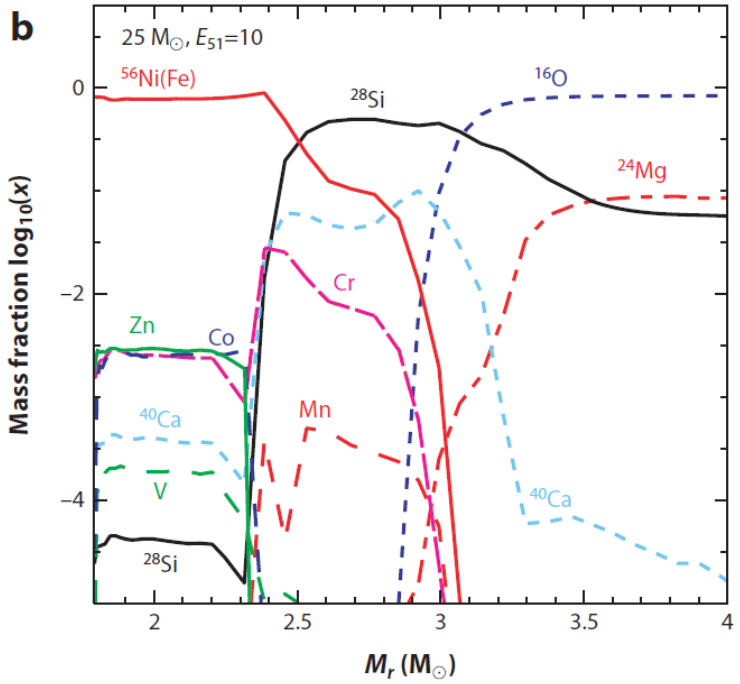
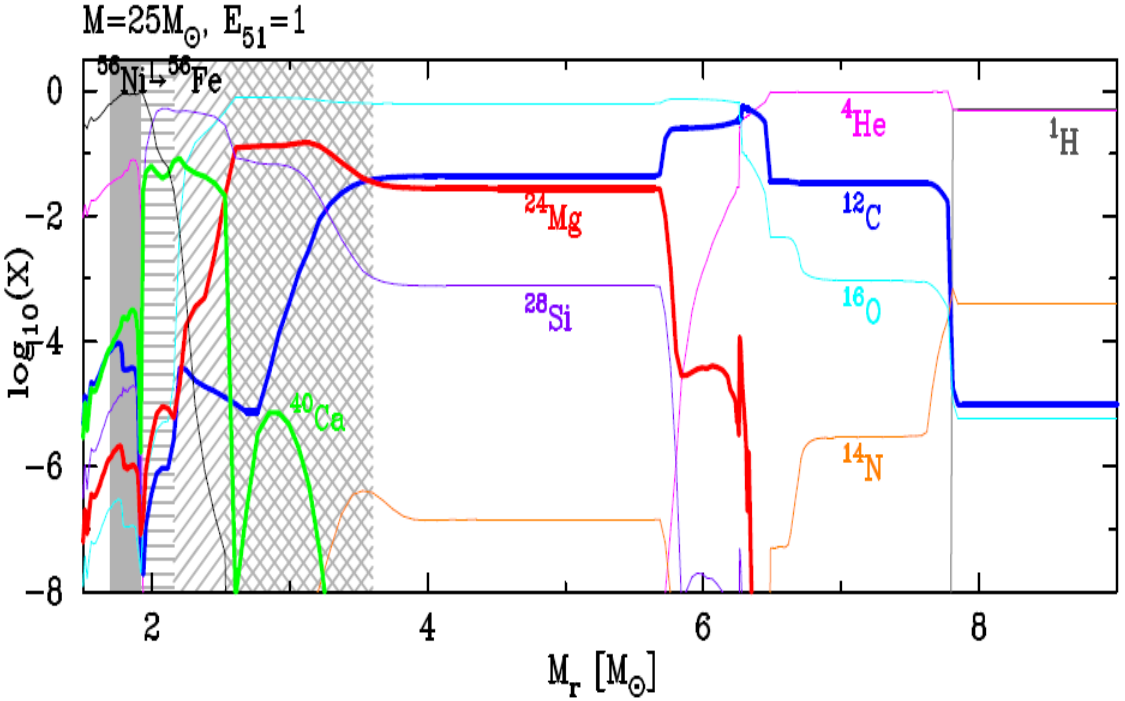
Hypernova Nucleosynthesis



Ken Nomoto (Kavli IPMU/ U.Tokyo)

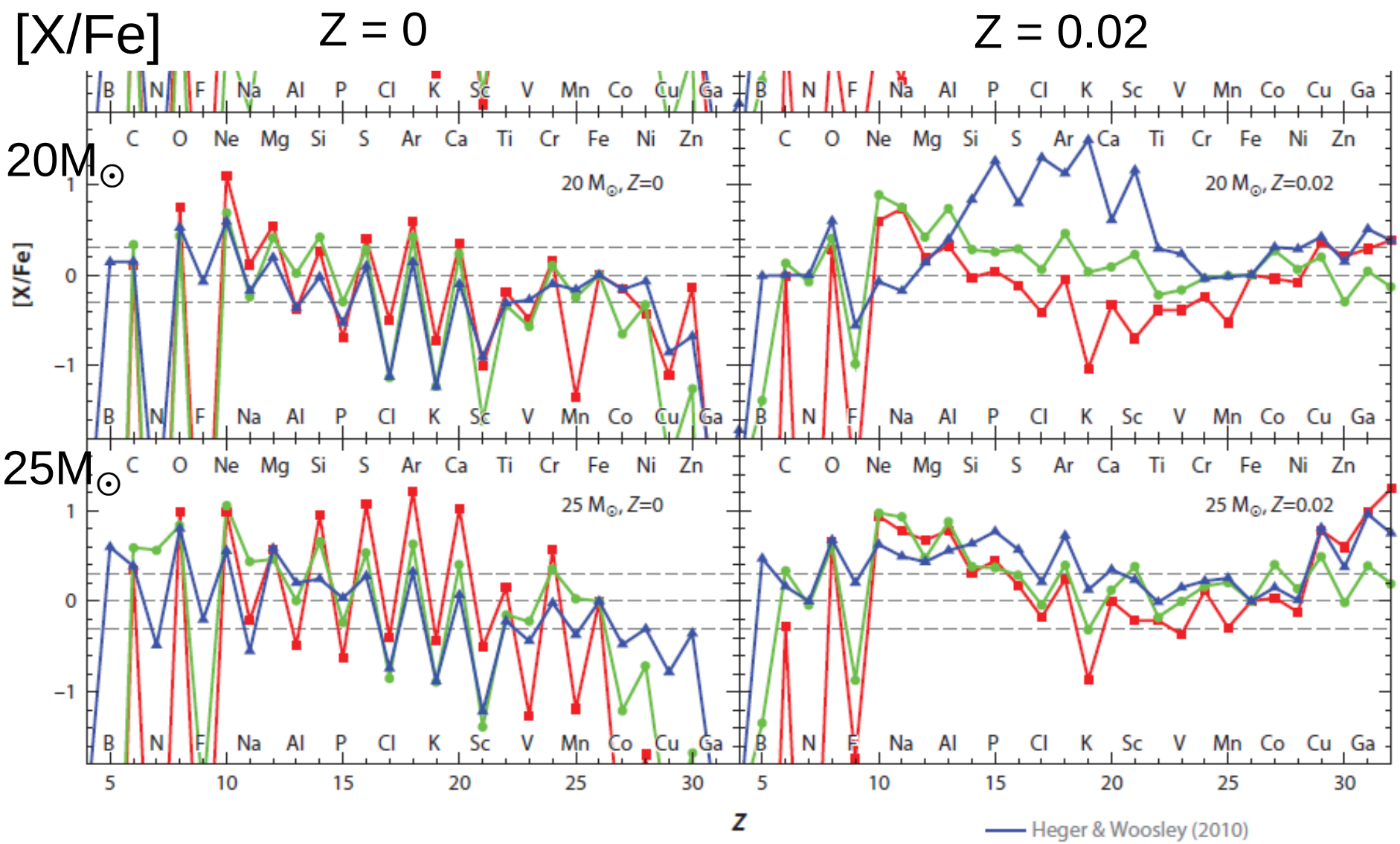
Supernova Nucleosynthesis





- Core Collapse Supernovae : C, O, Mg, Si, Ca, Fe, , ,
- Thermonuclear Supernovae : Fe, Si, ,
- Long Gamma-Ray Bursts --- Hypernovae ??
- Short Gamma-Ray Bursts --- Kilonovae ??

Yields from Core-Collapse SNe



(Nomoto, Kobayashi, Tominaga 2013 ARAA 51, 457-509)

Yields from Core Collapse Supernovae in Metal-Poor Environment

* Comparison with Extremely Metal-Poor Stars

➔Yield from an individual SN
[environment with much less contamination
less mixing]

→ Yields of unusually faint & luminious SNe

* First Stars, First SNe?

Metal Poor Stars

- Mega Metal Poor (MMP): [Fe/H] < -6
- Hyper Metal Poor (HMP): [Fe/H] < -5
- Ultra Metal Poor (UMP): [Fe/H] < -4
- Extremely Metal Poor(EMP) : [Fe/H] < -3
- Very Metal Poor (VMP): [Fe/H] < -2
- Metal Poor (MP) : [Fe/H] < -1
- Solar: [Fe/H] ~ 0
- Super Metal Rich(SMR): [Fe/H] > +0.5

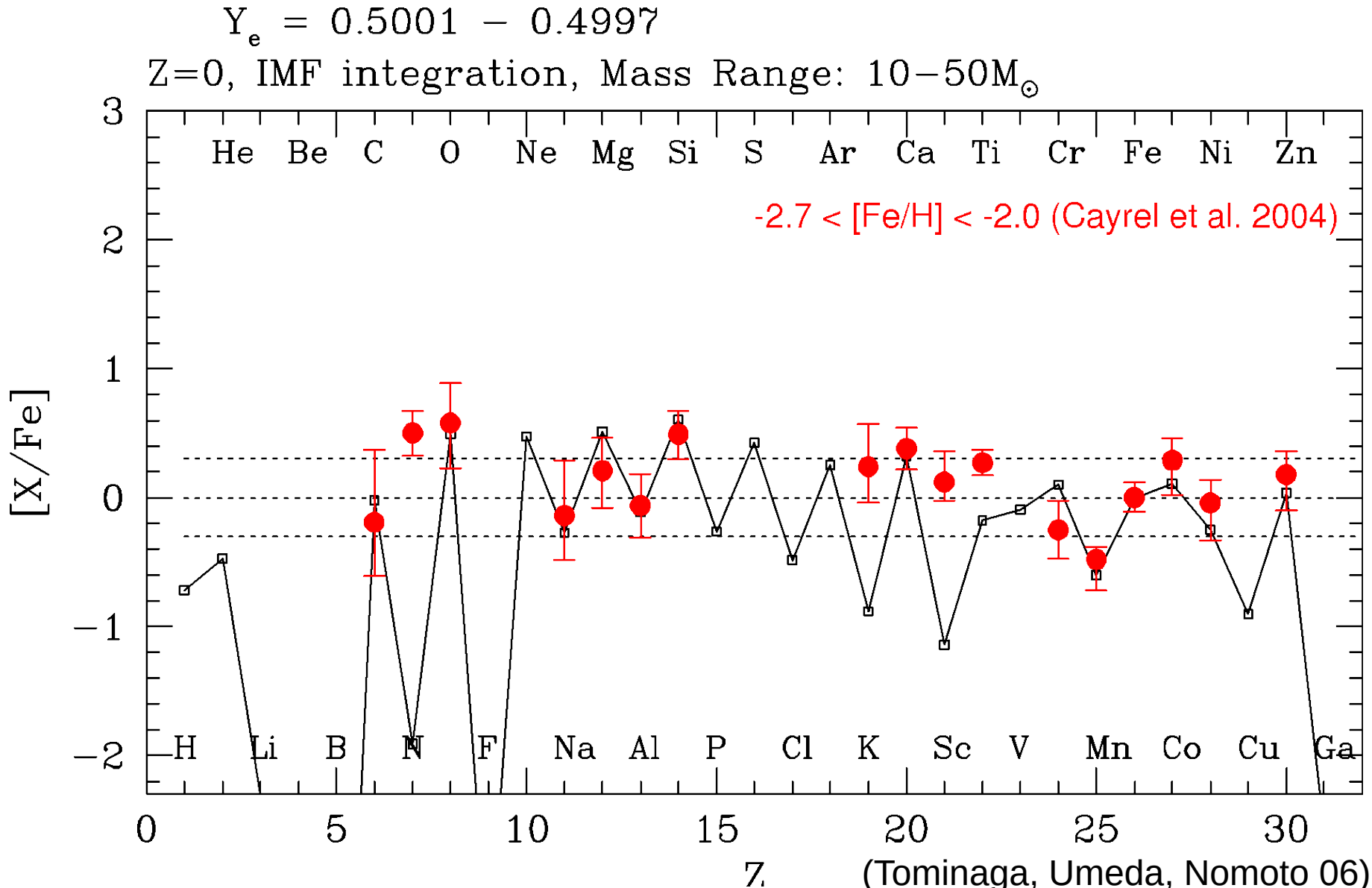
$$[Fe/H]=\log(Fe/H)-\log(Fe/H)_{\odot}$$

(Beers & Christlieb 2005)

VMP Stars vs. Normal SN II (10 - 50 $M_\odot$)

(-2.7 < [Fe/H] < -2.0)

(Salpeter IMF)

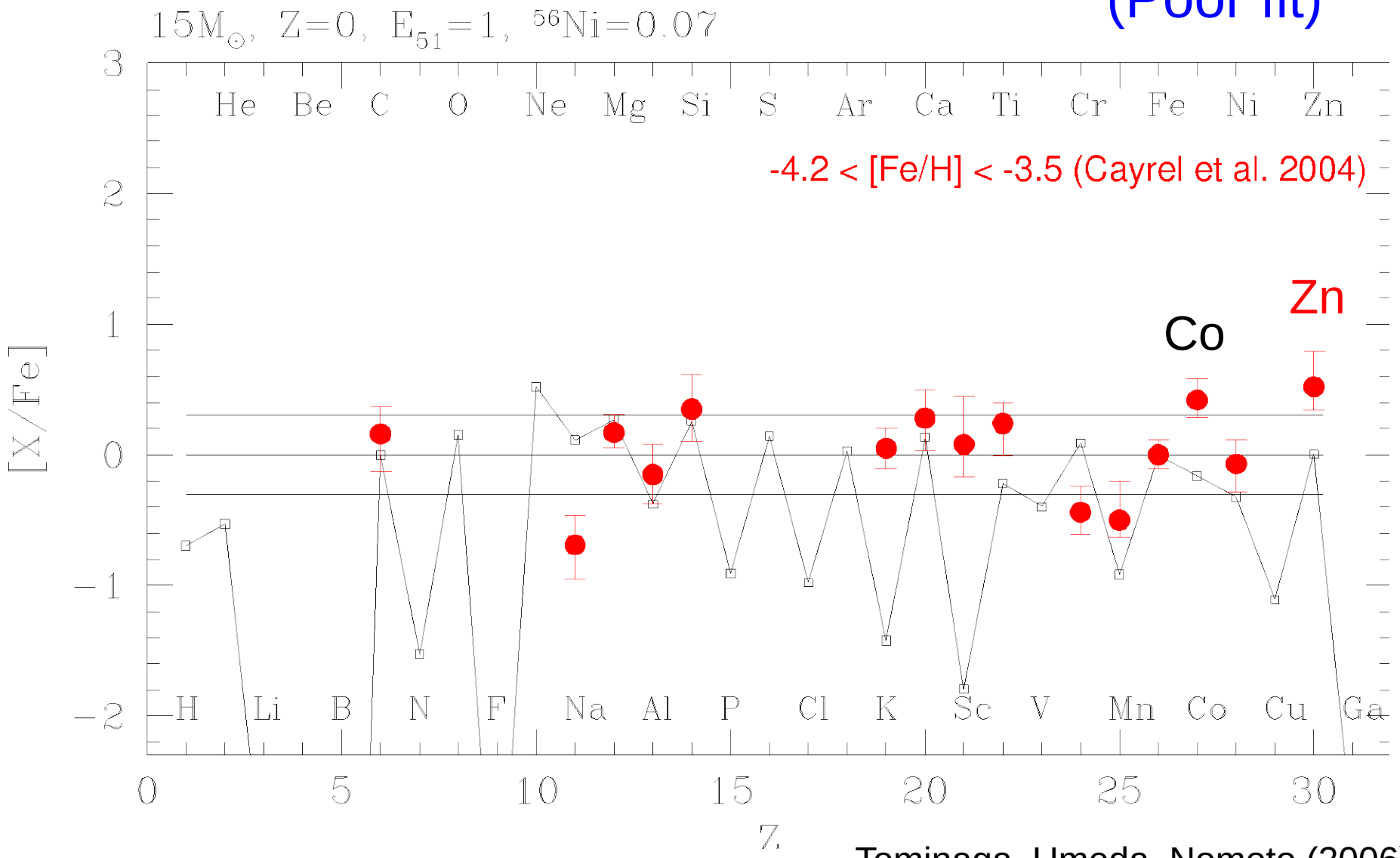


EMP Stars vs. Normal SN II

(-4.2 < [Fe/H] < -3.5)

(E_{51}=1)

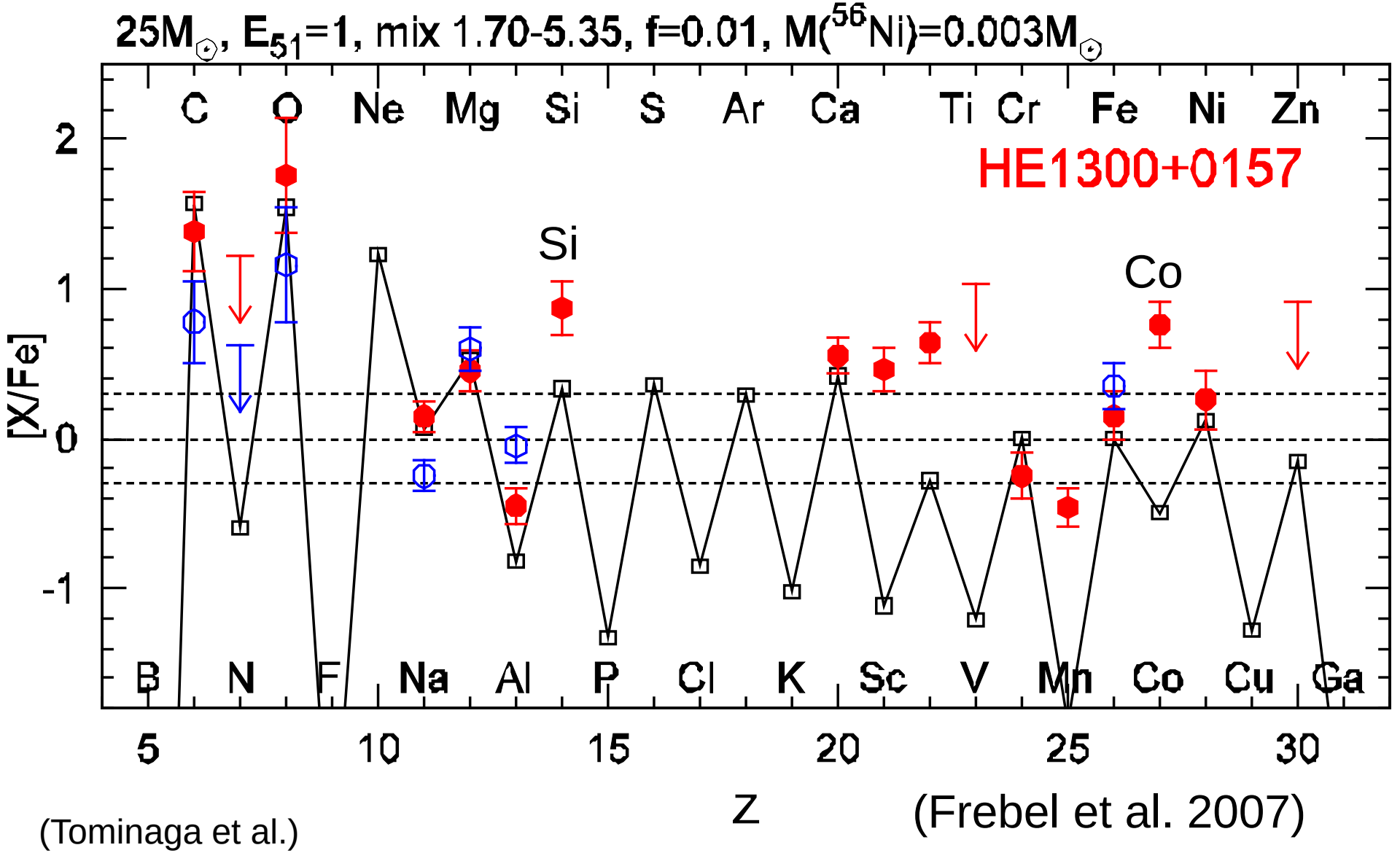
(Poor fit)



Tominaga, Umeda, Nomoto (2006)

CEMP-no Star (nomral + fallback SN)

(Poor fit)

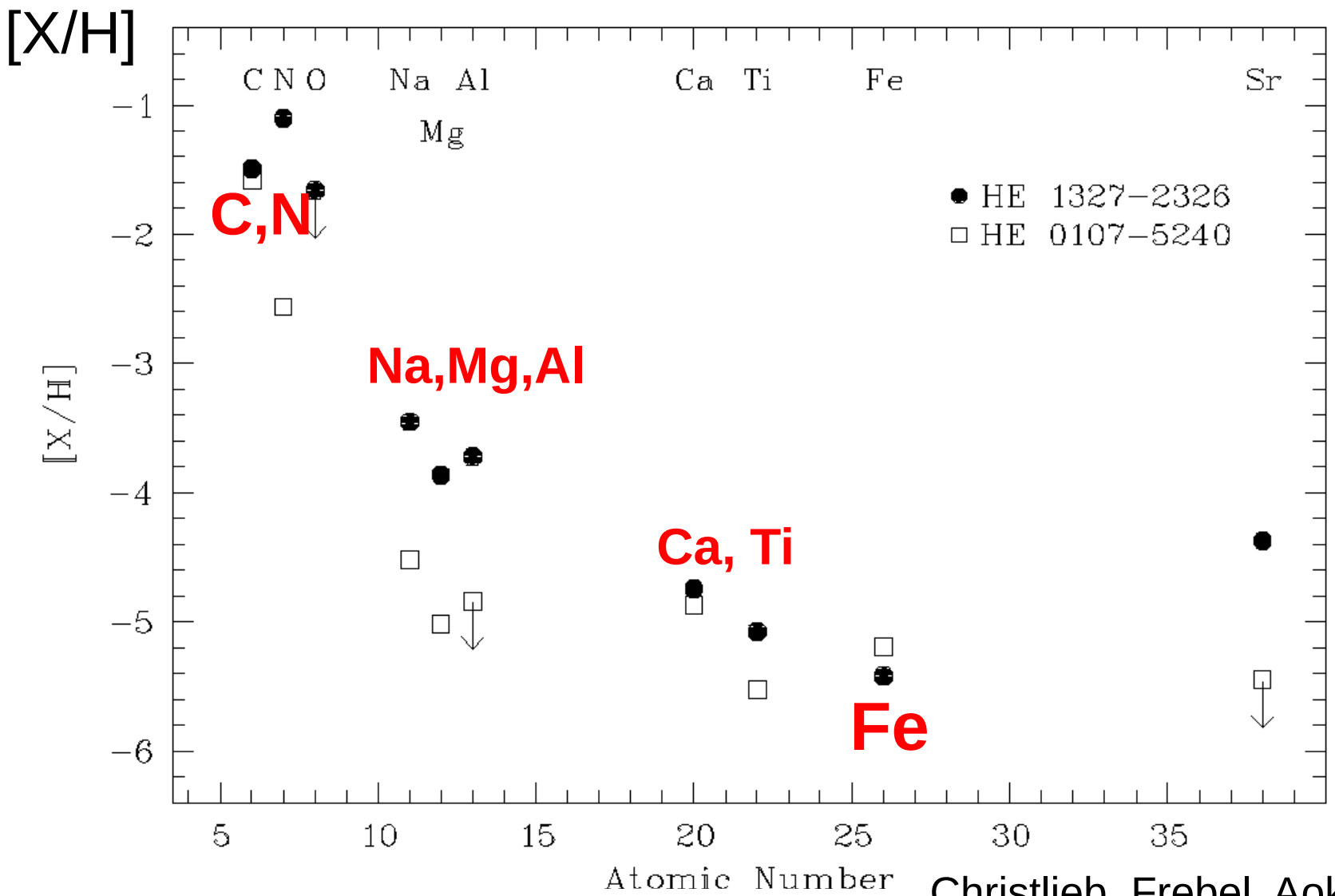


(Tominaga et al.)

(Frebel et al. 2007)

Hyper Metal-Poor (HMP) Stars

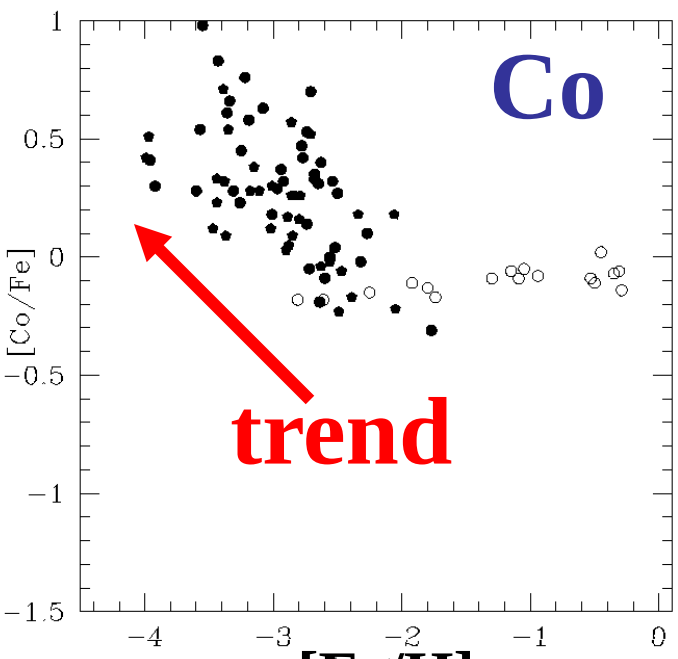
[Fe/H] < -5 [C, N, O/ Fe] > 3

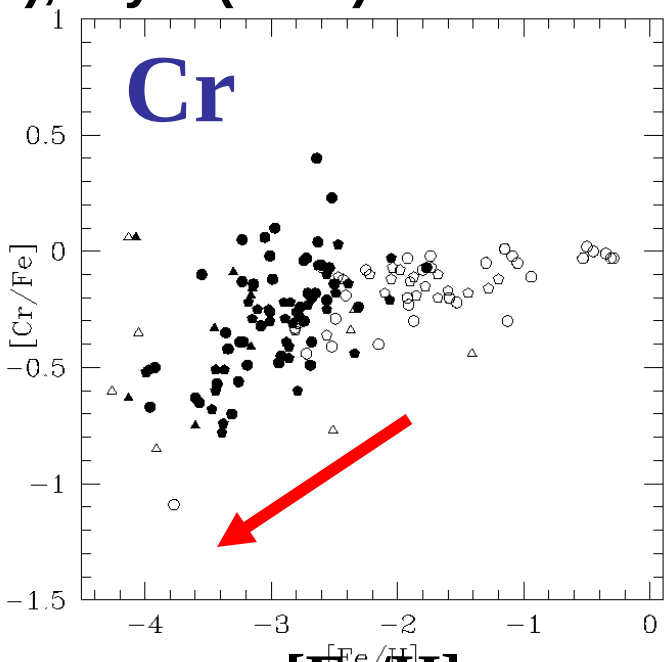


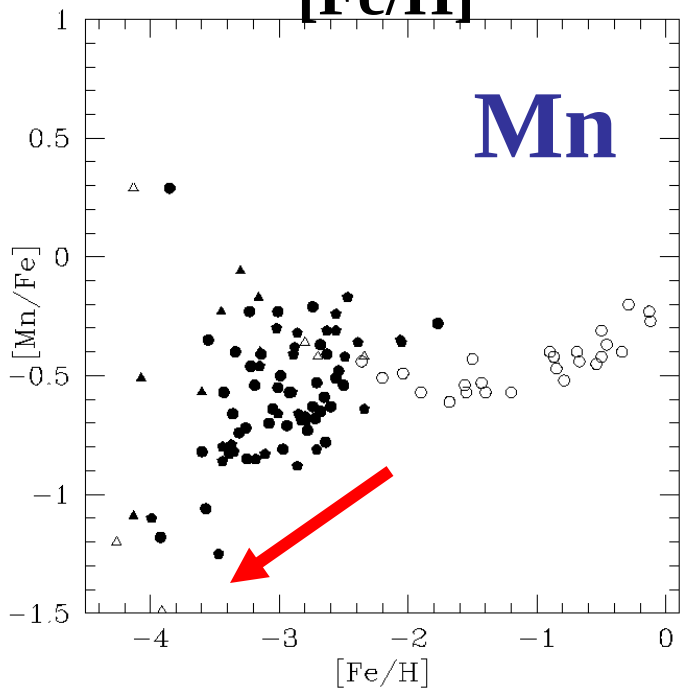
Christlieb, Frebel, Aoki, et al.

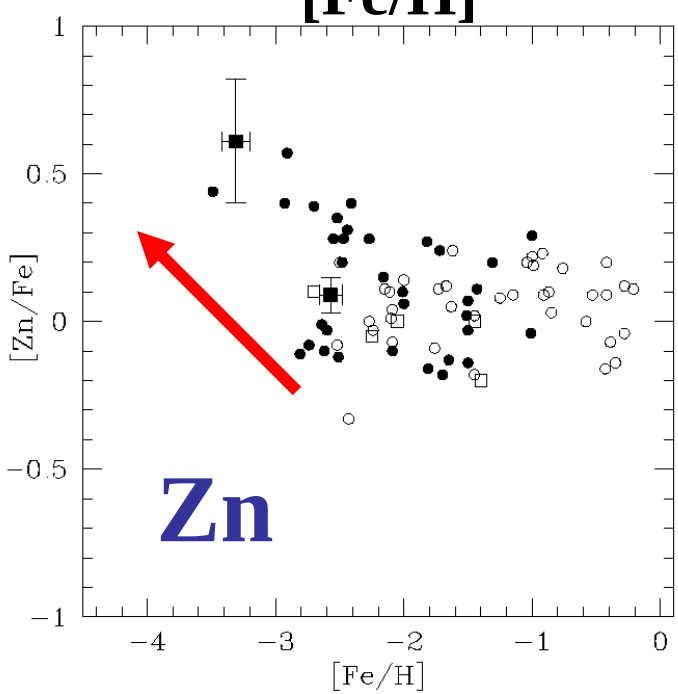
EMP stars

McWilliam(1995), Ryan(1996)



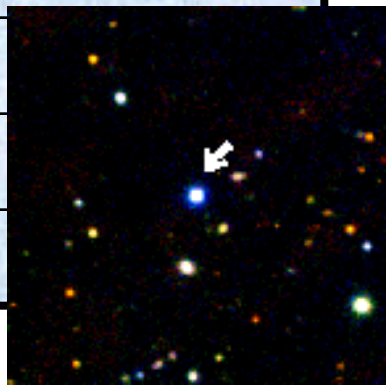


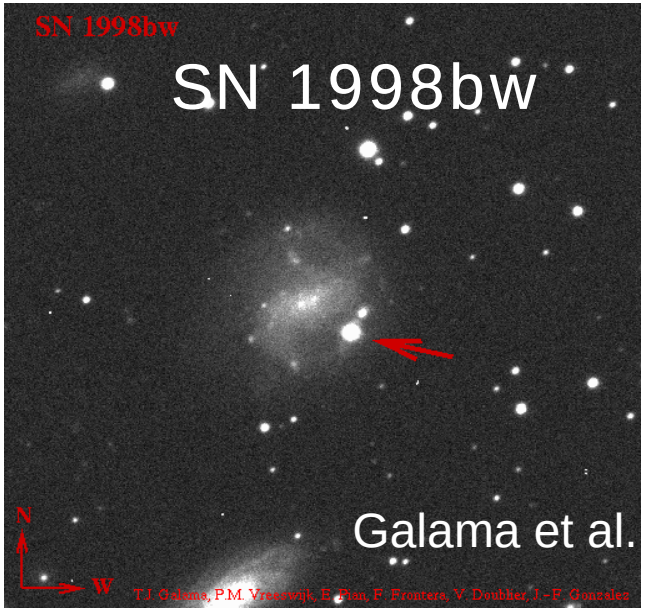




GRB-Supernovae

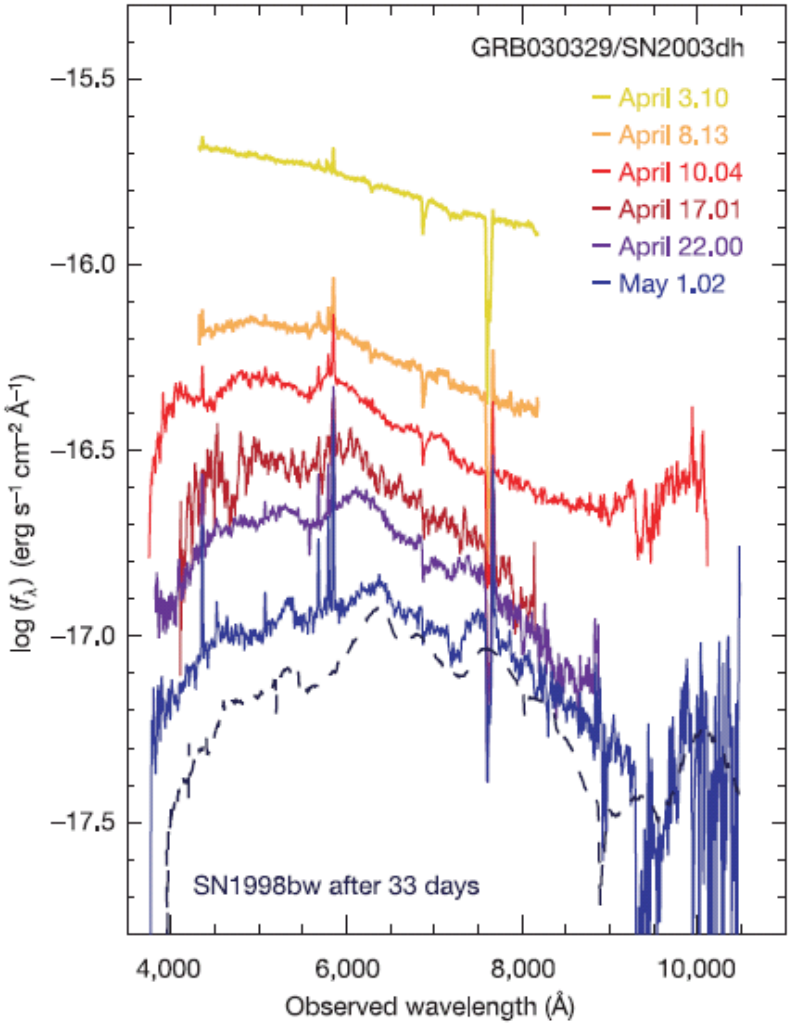
SNe Ic	
SN	GRB
1998bw	980425
1997ef	(971115)
2002ap	
2003dh	030329
2003lw	031203

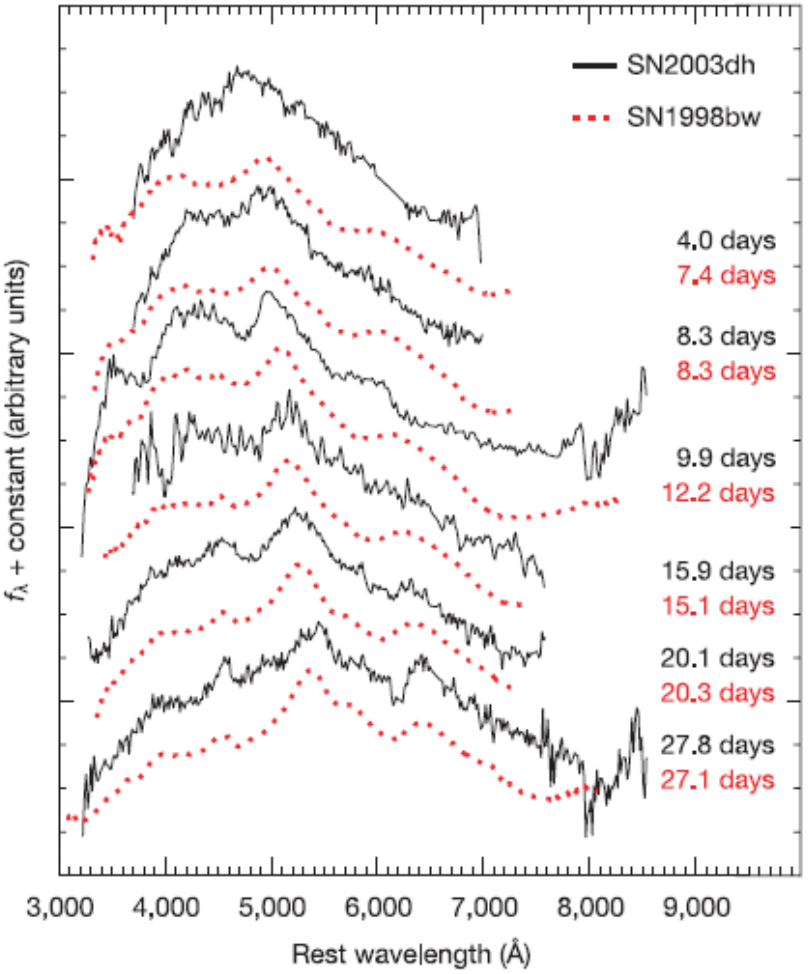




GRB-SN Connection

(GRB 030329 / SN 2003dh)

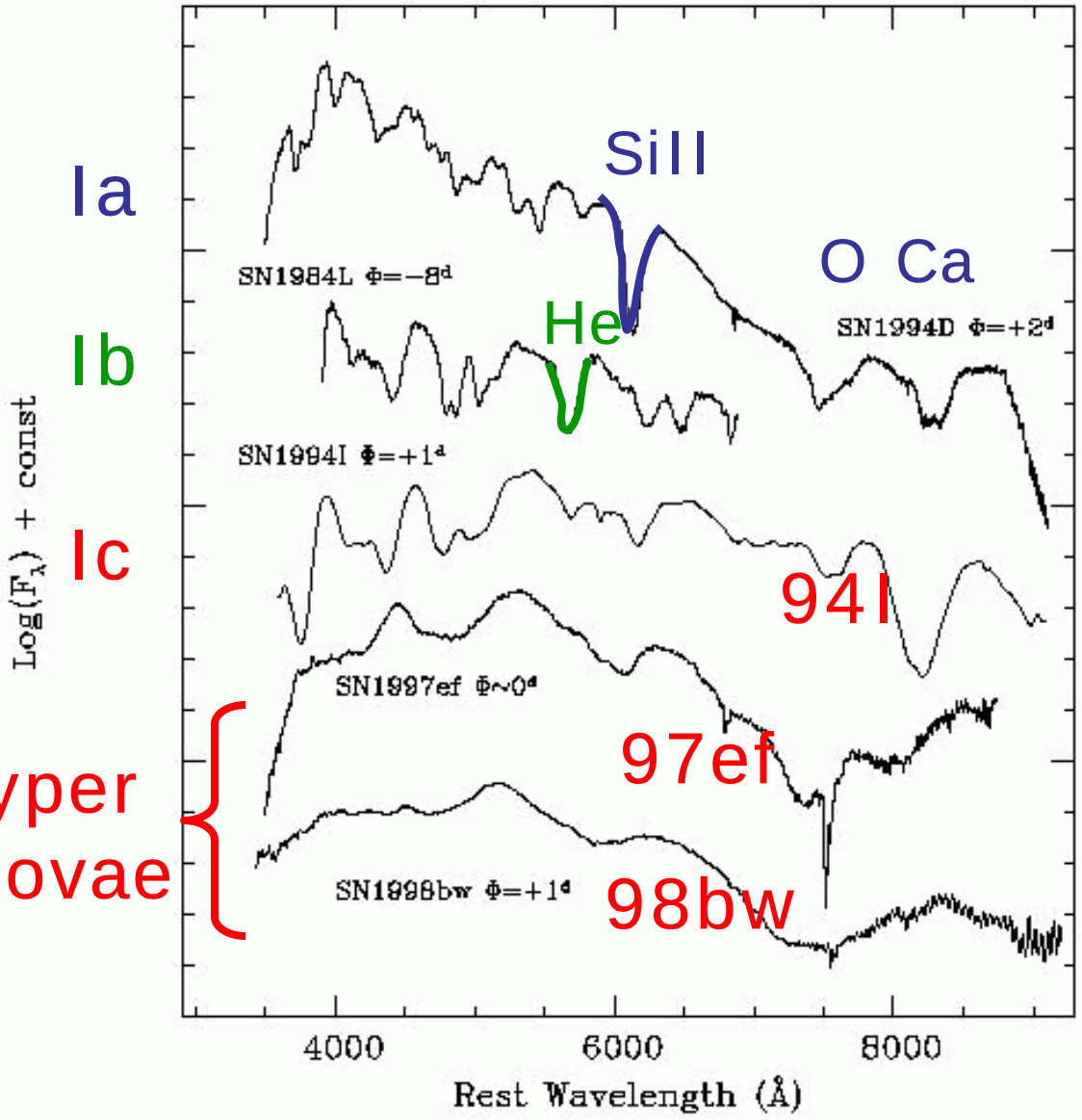




Stanek et al (2003) ;Hjorth et al (2003)

Broad Lines!

Spectra of Supernovae & Hypernovae



Ic: no H,

no strong He,

no strong Si

Hypernovae:

broad features

↑

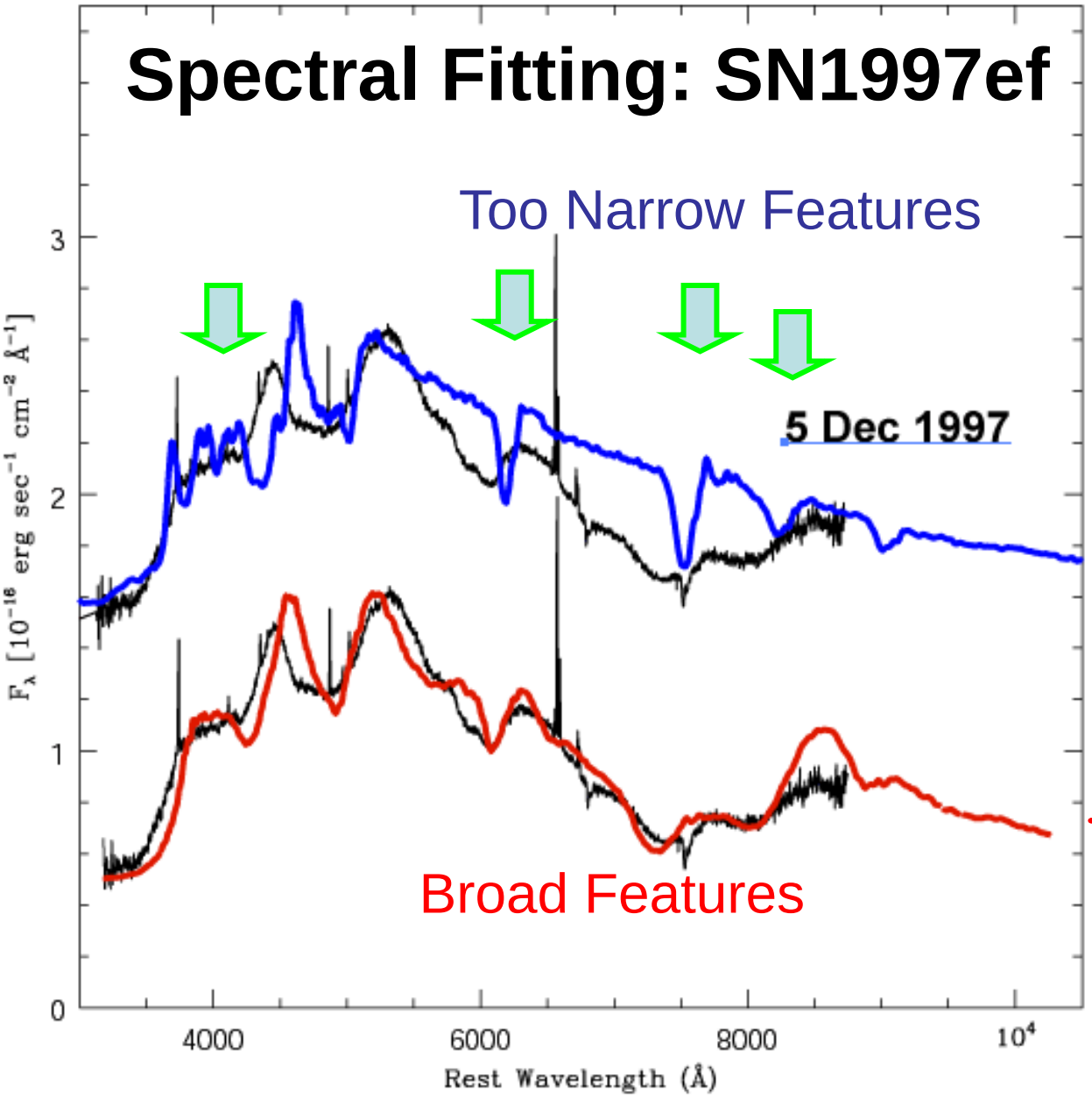
blended lines

↑

"Large mass at high velocities"

Patat et al. (1999)

Spectral Fitting: SN1997ef



Iwamoto et al. (2000)

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

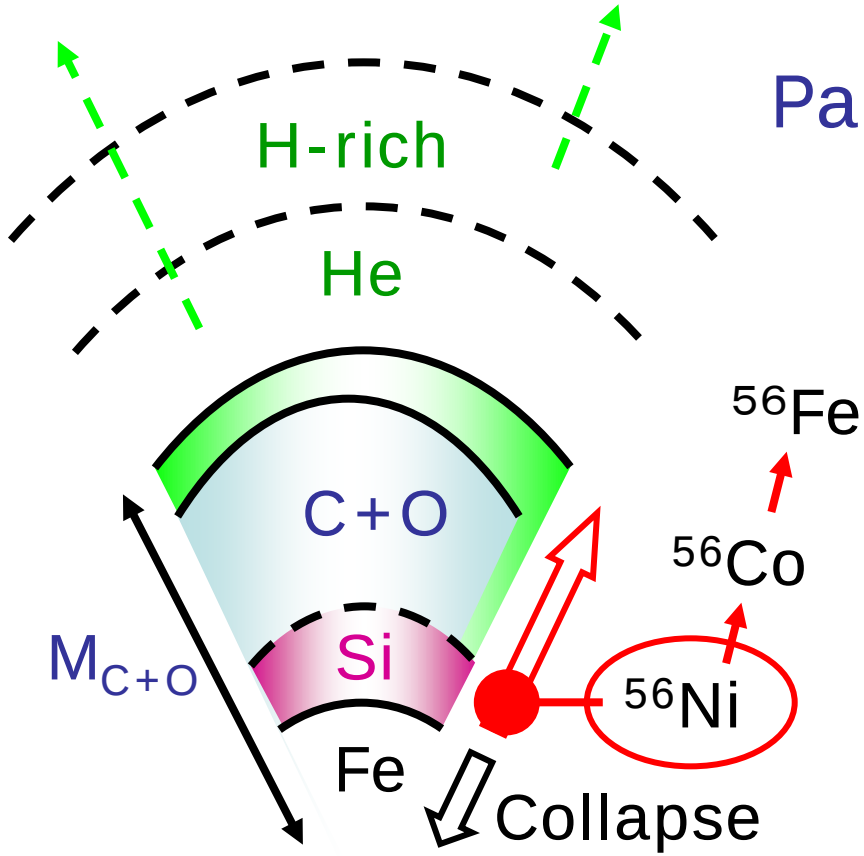
Normal SN
(**$E_{51}=1$**)

Small M_{ej}

Hypernova
(**$E_{51}=20$**)

Large M_{ej}
at High Vel.

CO Star Models for SNe Ic



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

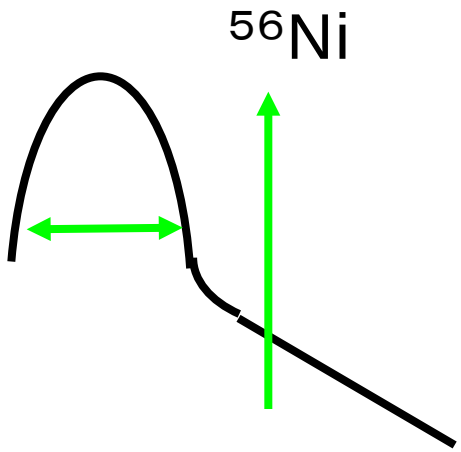
Light Curve — Spectra

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

$E \propto M_{ej}$

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

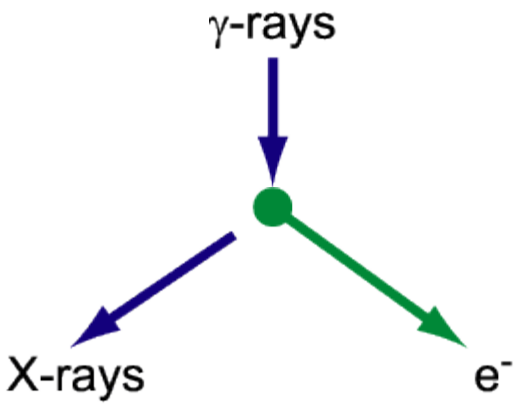
$E \propto M_{ej}^{3}$



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

^{56}Co-decay

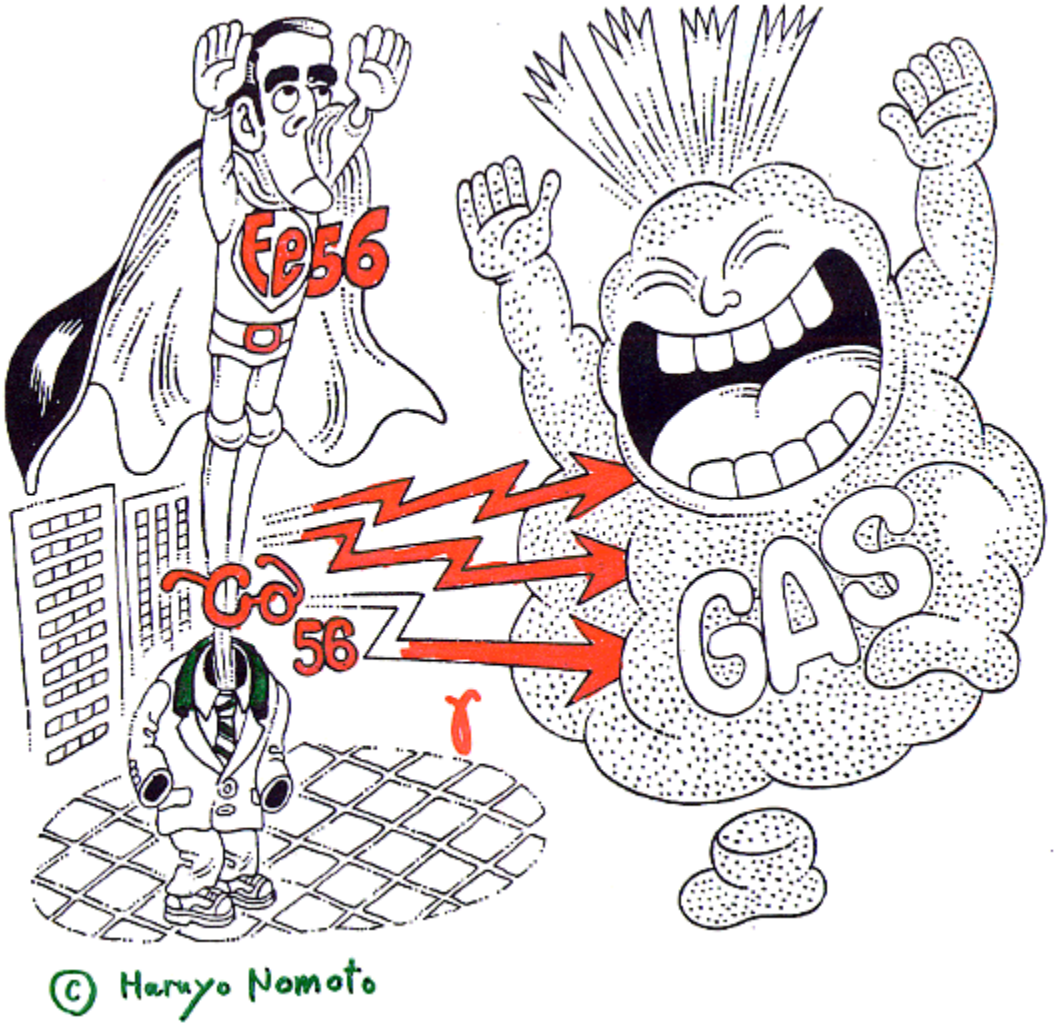
$^{56}Ni \xrightarrow[6.6d]{\gamma} {}^{56}Co \xrightarrow[78d]{\gamma} {}^{56}Fe$

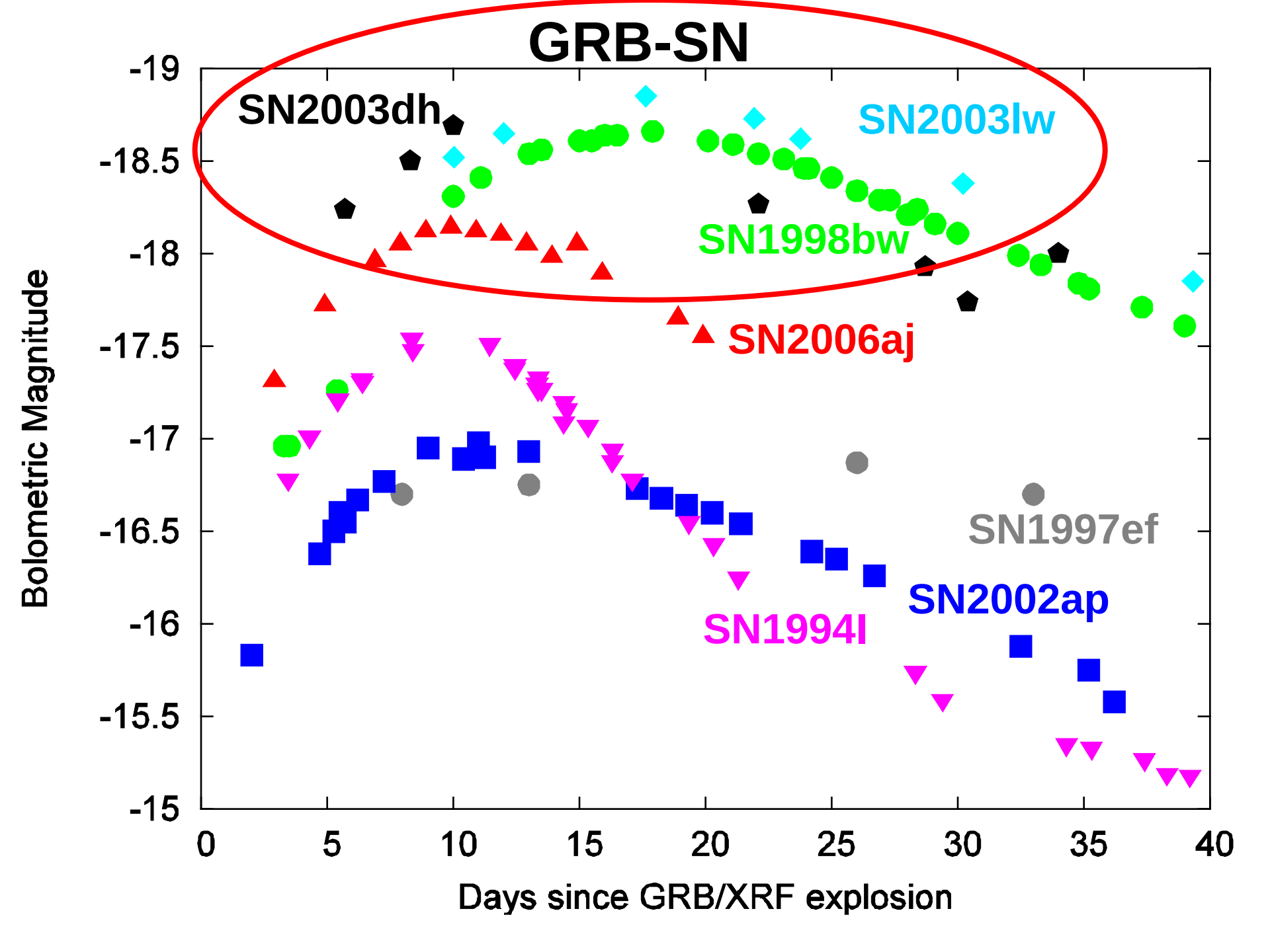


Photoabsorption Excitation/Ionization

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

Shape:M_{ej}




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

Hypernova – GRB Connection

Three GRB－SNe = all Type Ic Hypernovae

$E > 10^{52}$ erg (～10×normal SN)

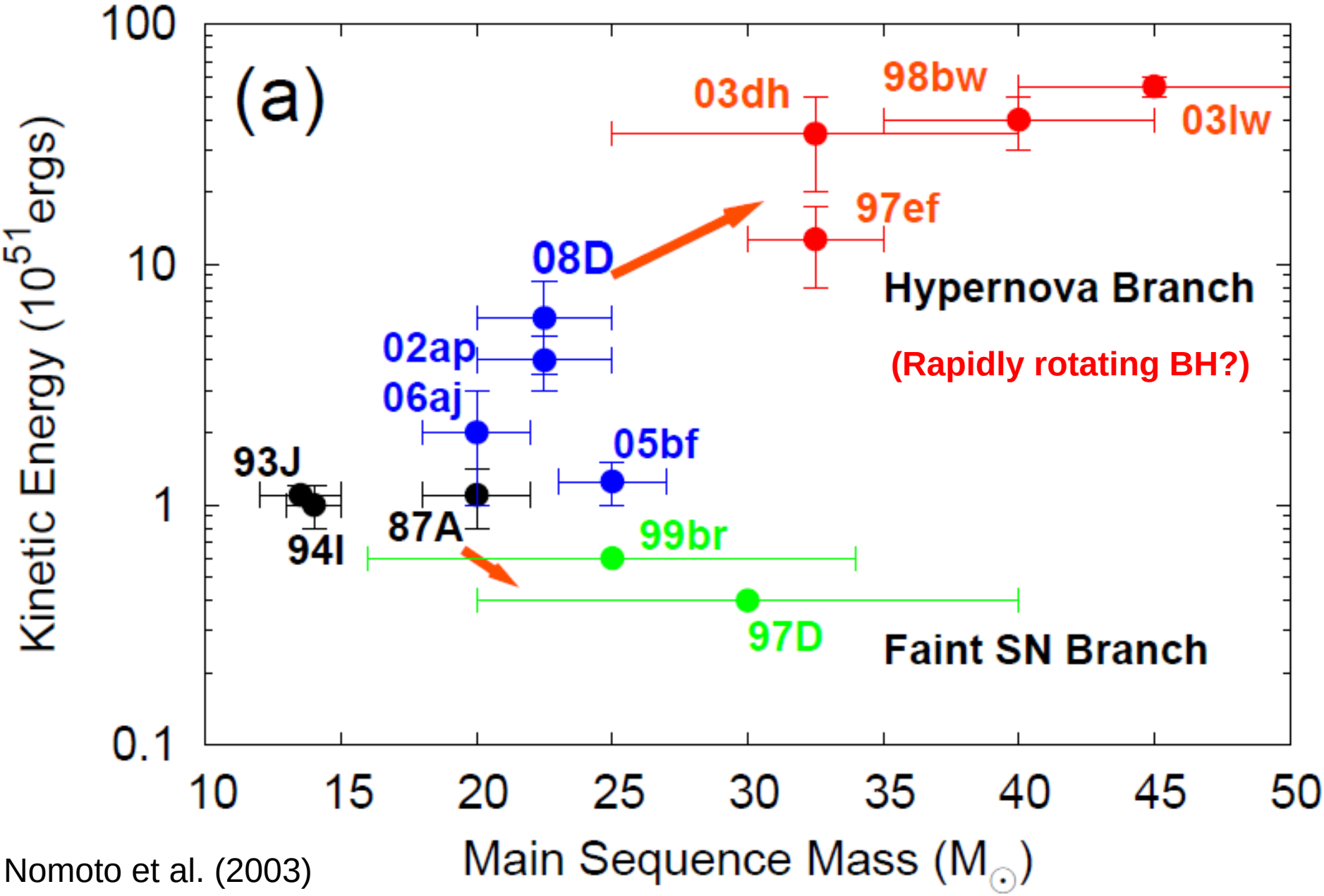
Large M_{ms} →Black Hole Forming SNe

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

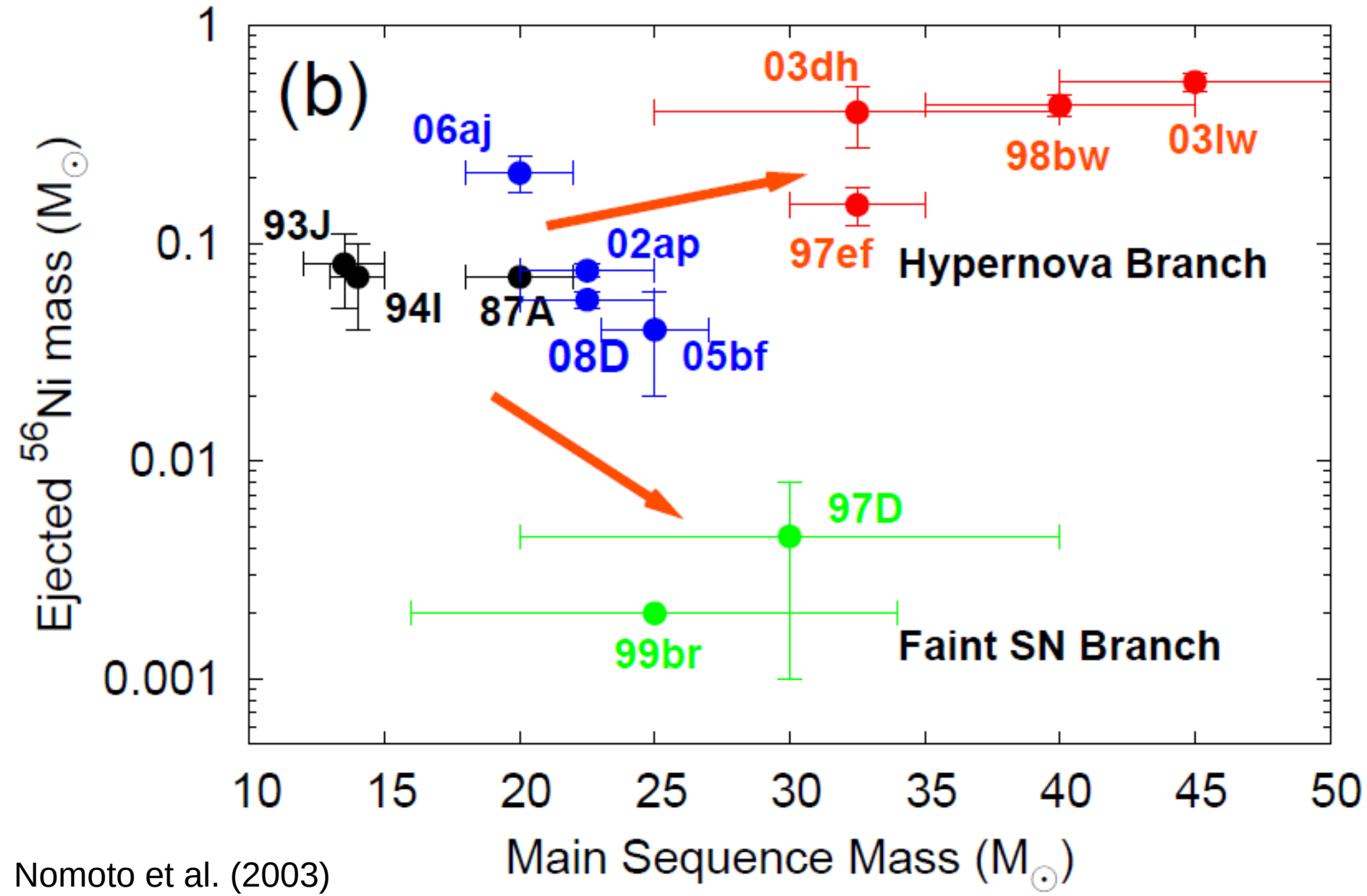
Hypernova in Prague

SNe [M_{ms}-E relation]



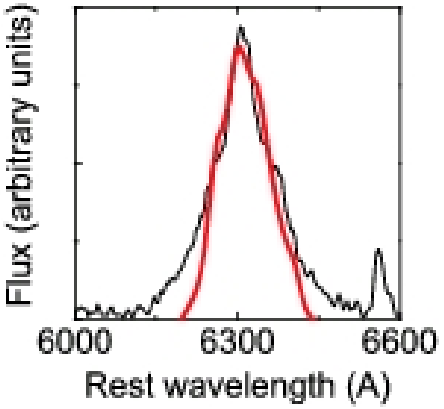
Nomoto et al. (2003)

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



Nomoto et al. (2003)

Type Ibc SNe: Bipolar Explosion



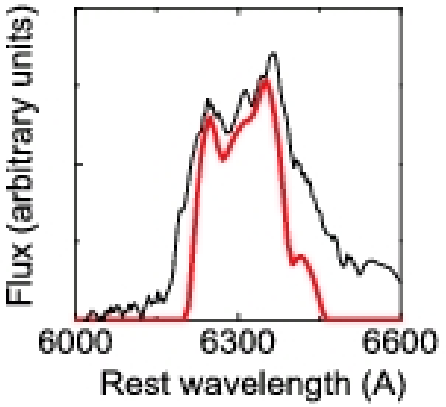
^{56}Fe

1998bw

^{16}O

2003jd

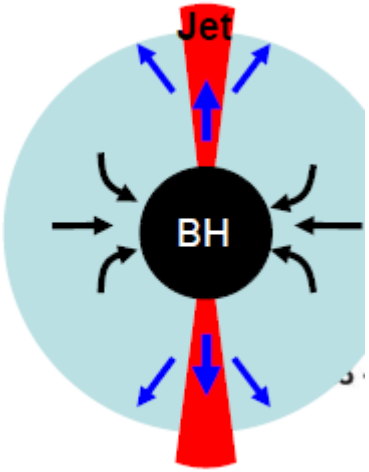
[OI] 6300A (SUBARU)



Maeda et al. (2002, 2005)

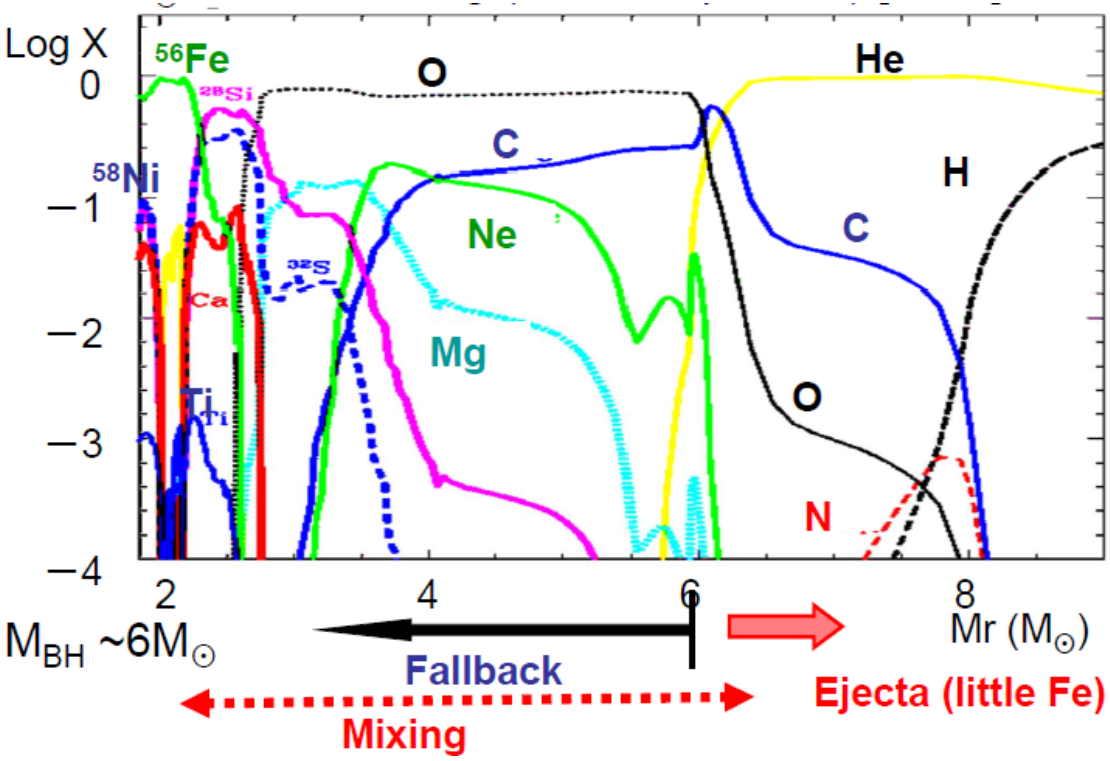
Mixing & Fallback Supernova

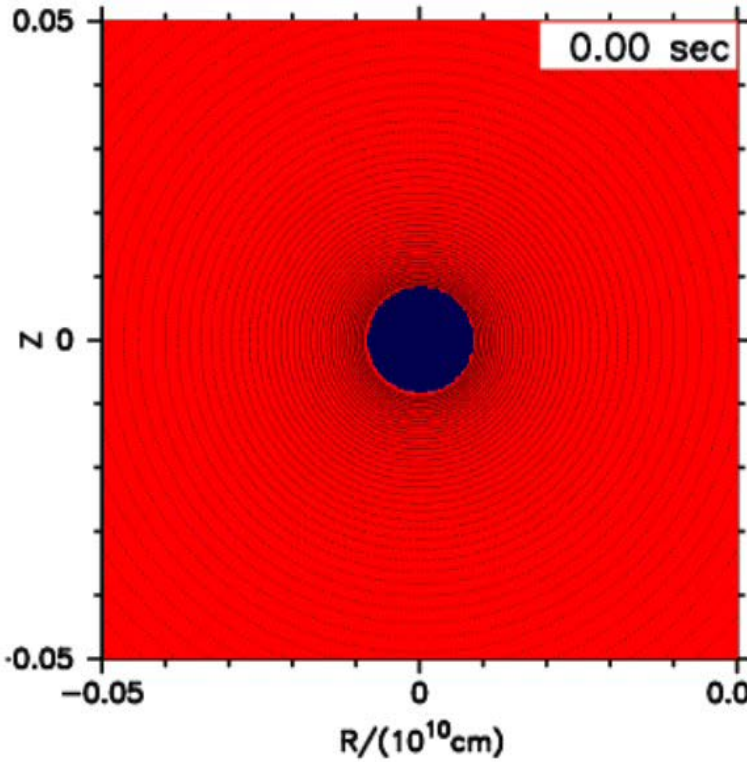
➔ Carbon Enhanced Metal Poor **(CEMP)** Stars



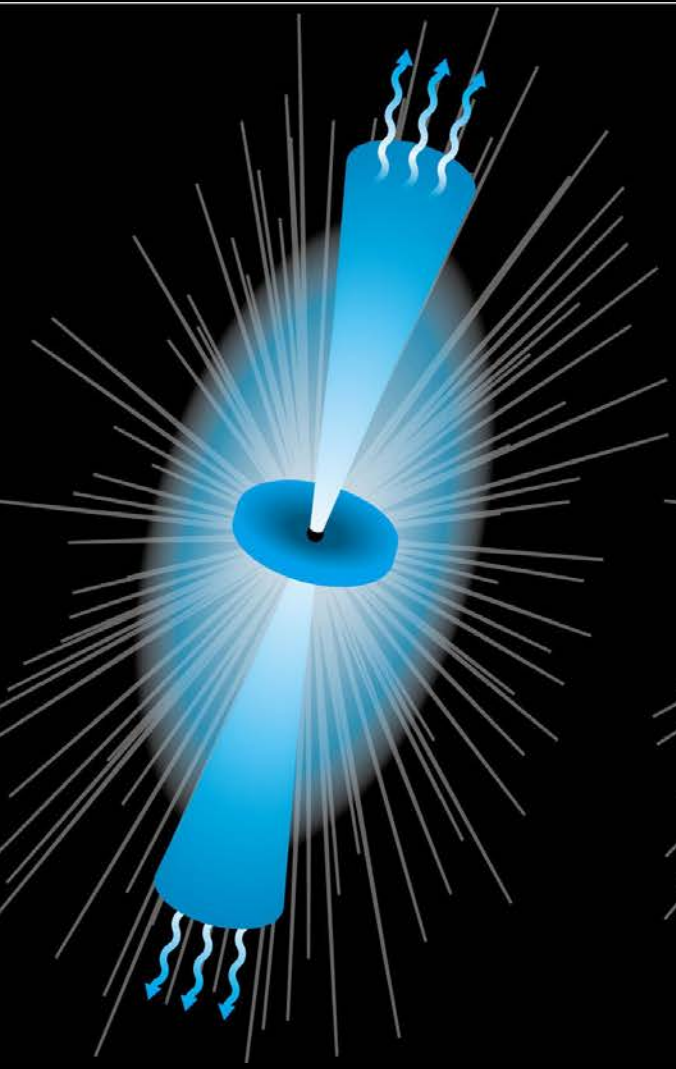
➔ M(Fe), M(BH)

(Jet-induced)

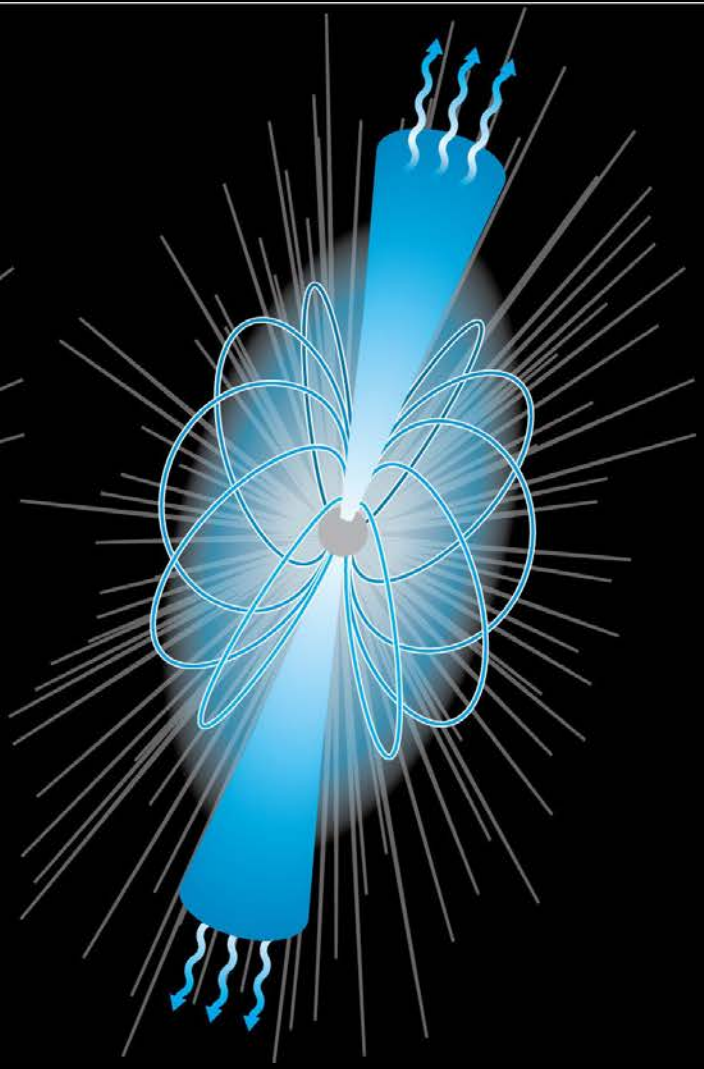




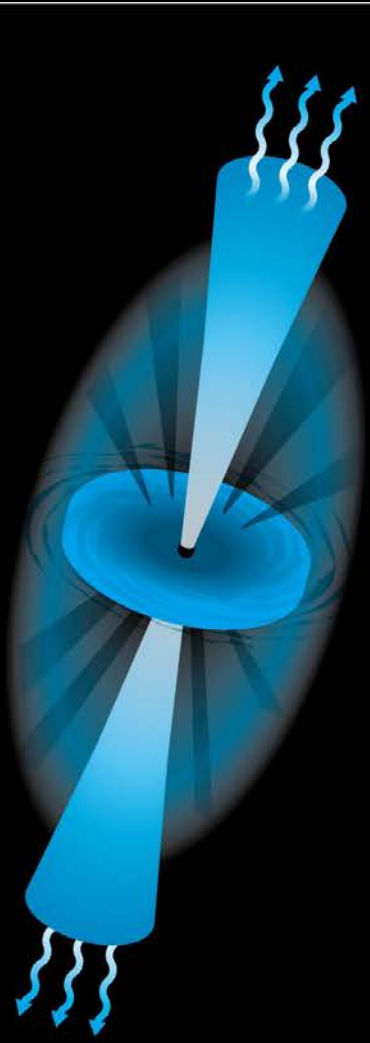
SN-GRB Connection



GRB-HN



Magnetar



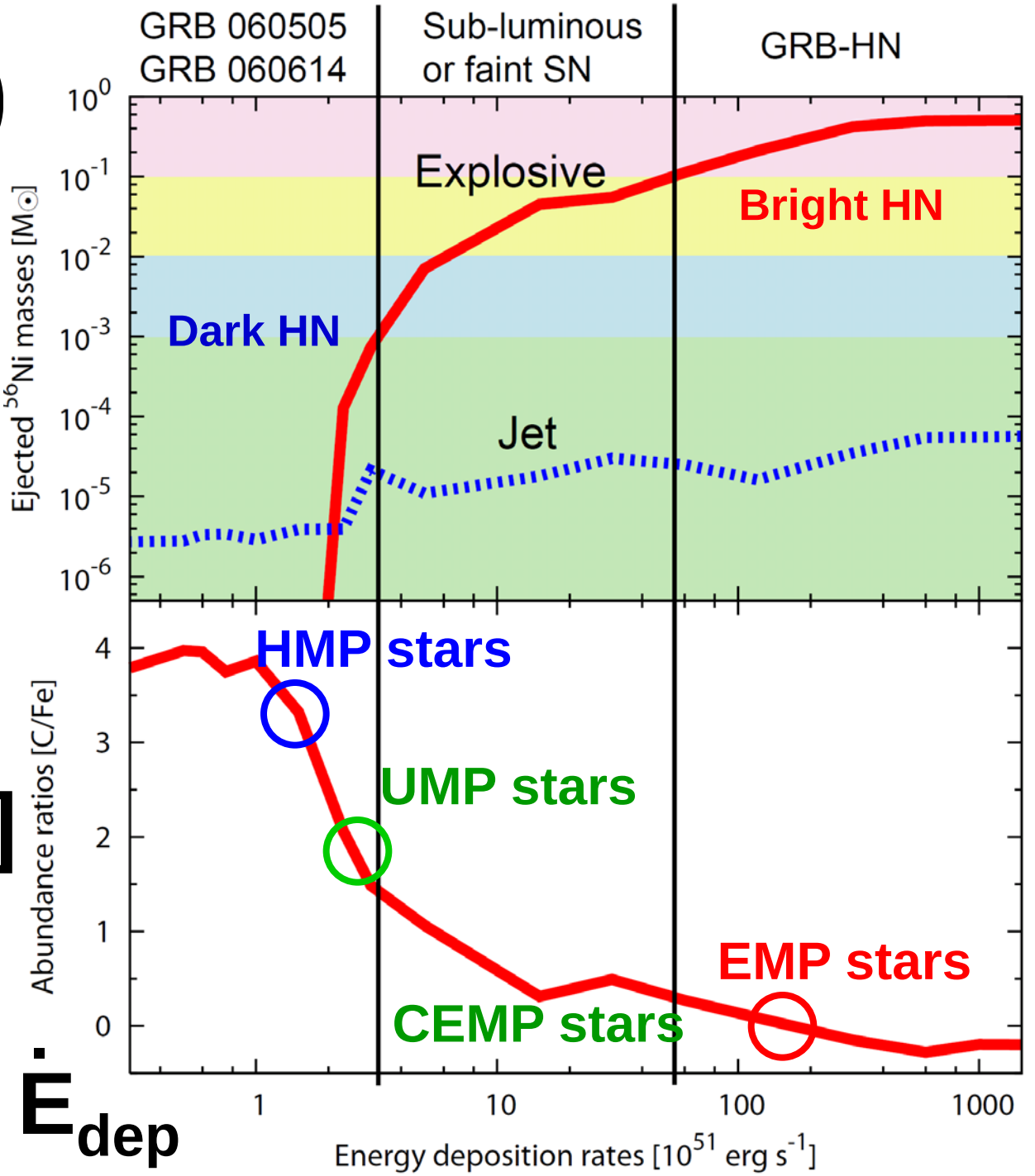
Non-SN GRB

$M(^{56}Ni)$

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

[C/Fe]

High E ➔ Fallback



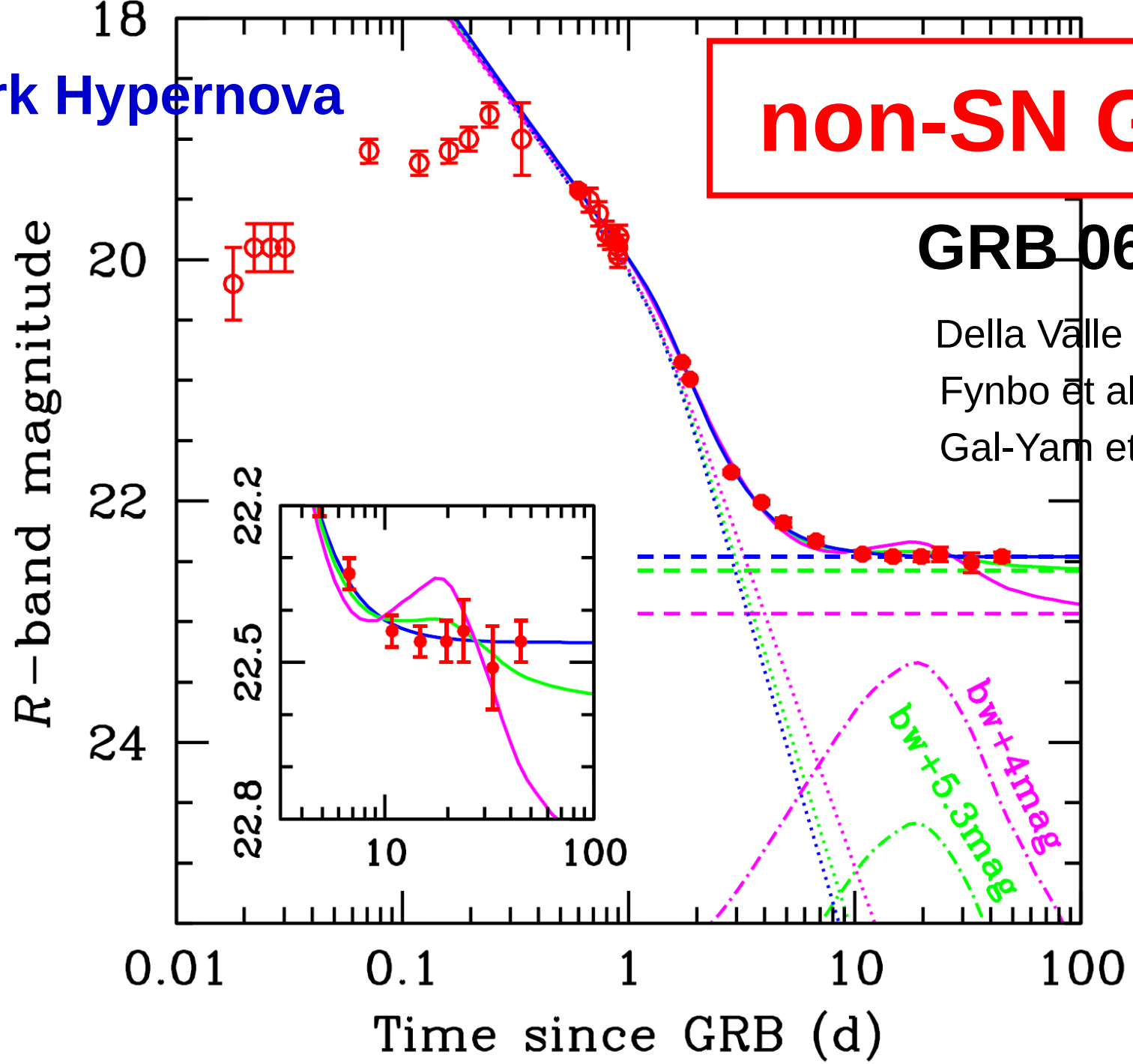
Tominaga et al. (2007)

Dark Hypernova

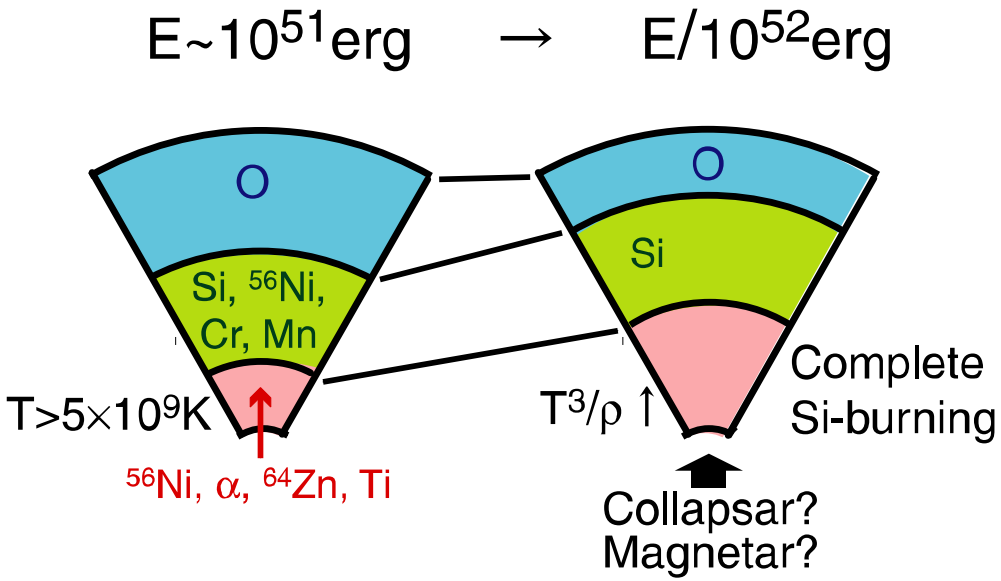
non-SN GRB

GRB 060614

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



Hypernova Nucleosynthesis



(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 ↗

Jet + Fallback

~ Mixing & Fallback

(3) More O burns

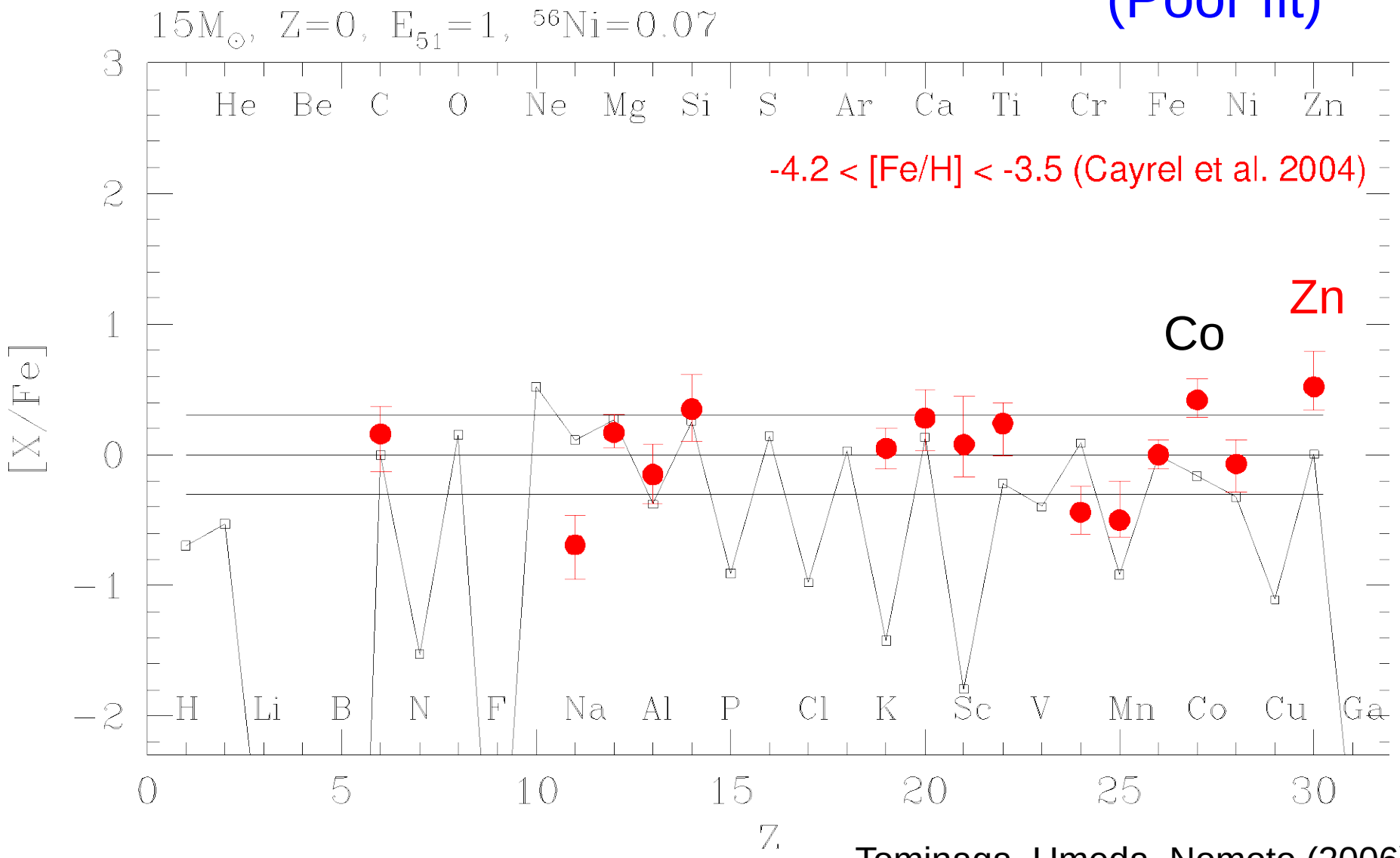
(Si, S, Ca)/O ↗

EMP Stars vs. Normal SN II

(-4.2 < [Fe/H] < -3.5)

(E_{51}=1)

(Poor fit)

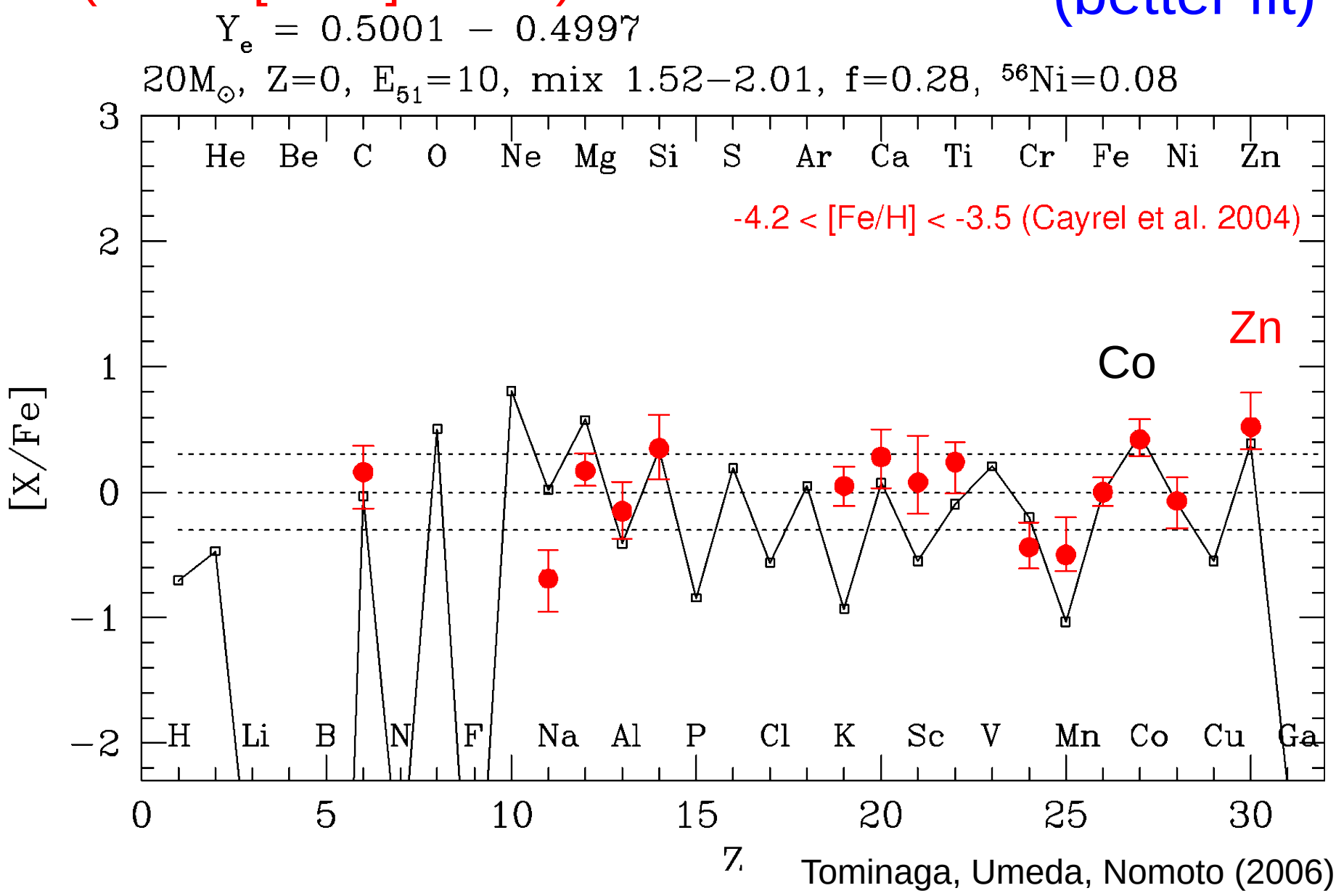


Tominaga, Umeda, Nomoto (2006)

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

(-4.2 < [Fe/H] < -3.5)

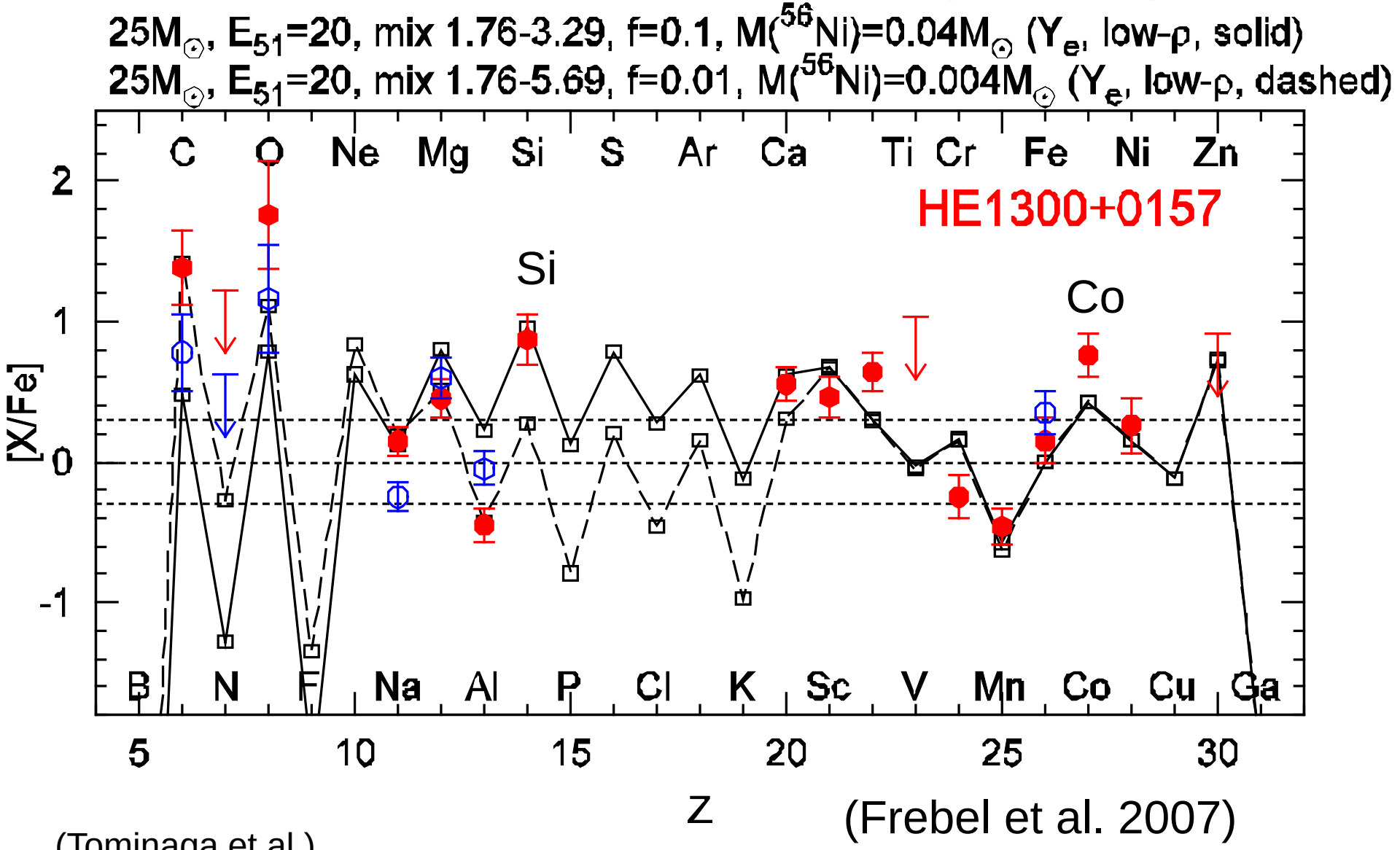
(better fit)



Tominaga, Umeda, Nomoto (2006)

CEMP-no-s Star (Hypernova with fallback)

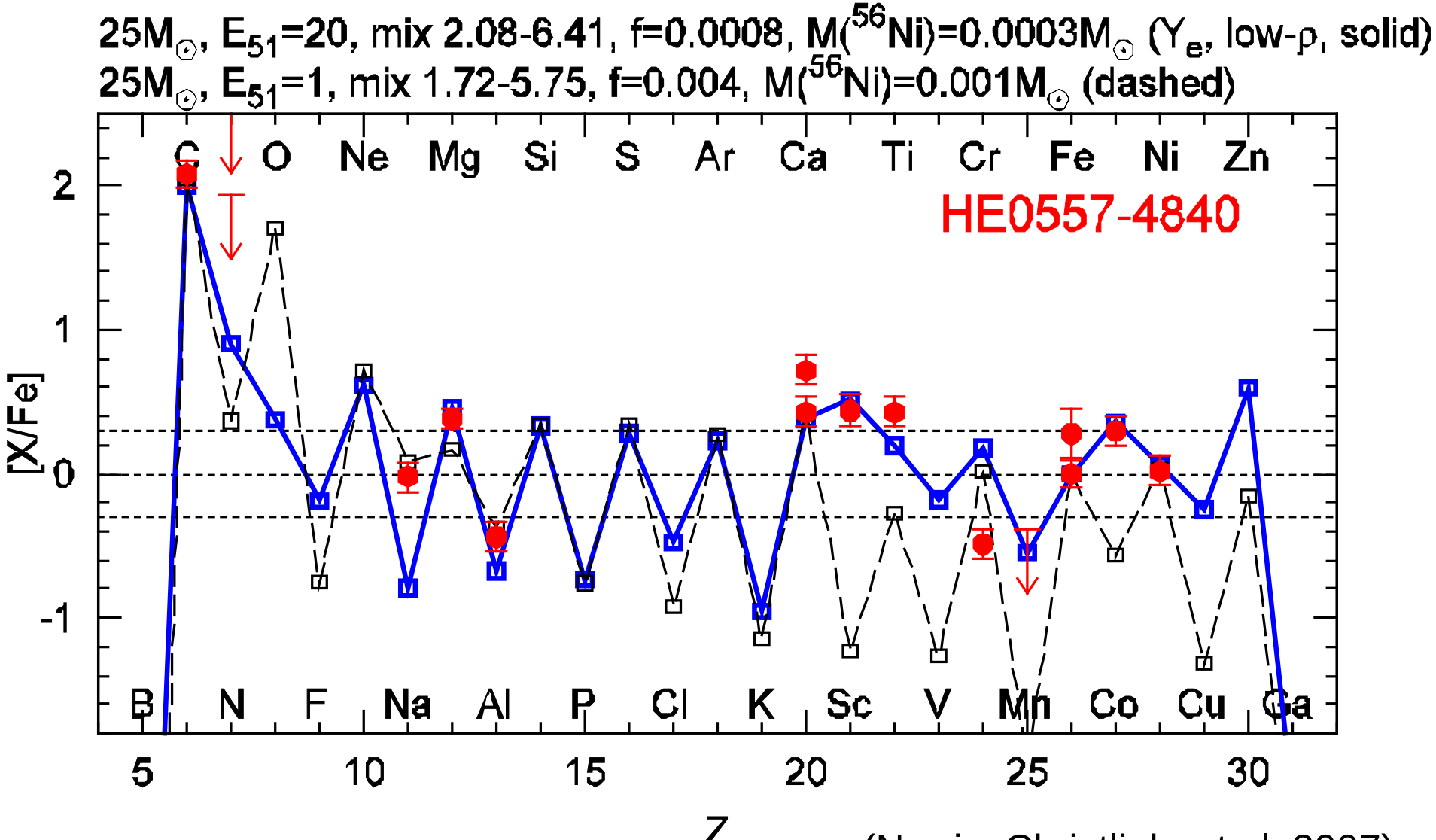
(better fit)



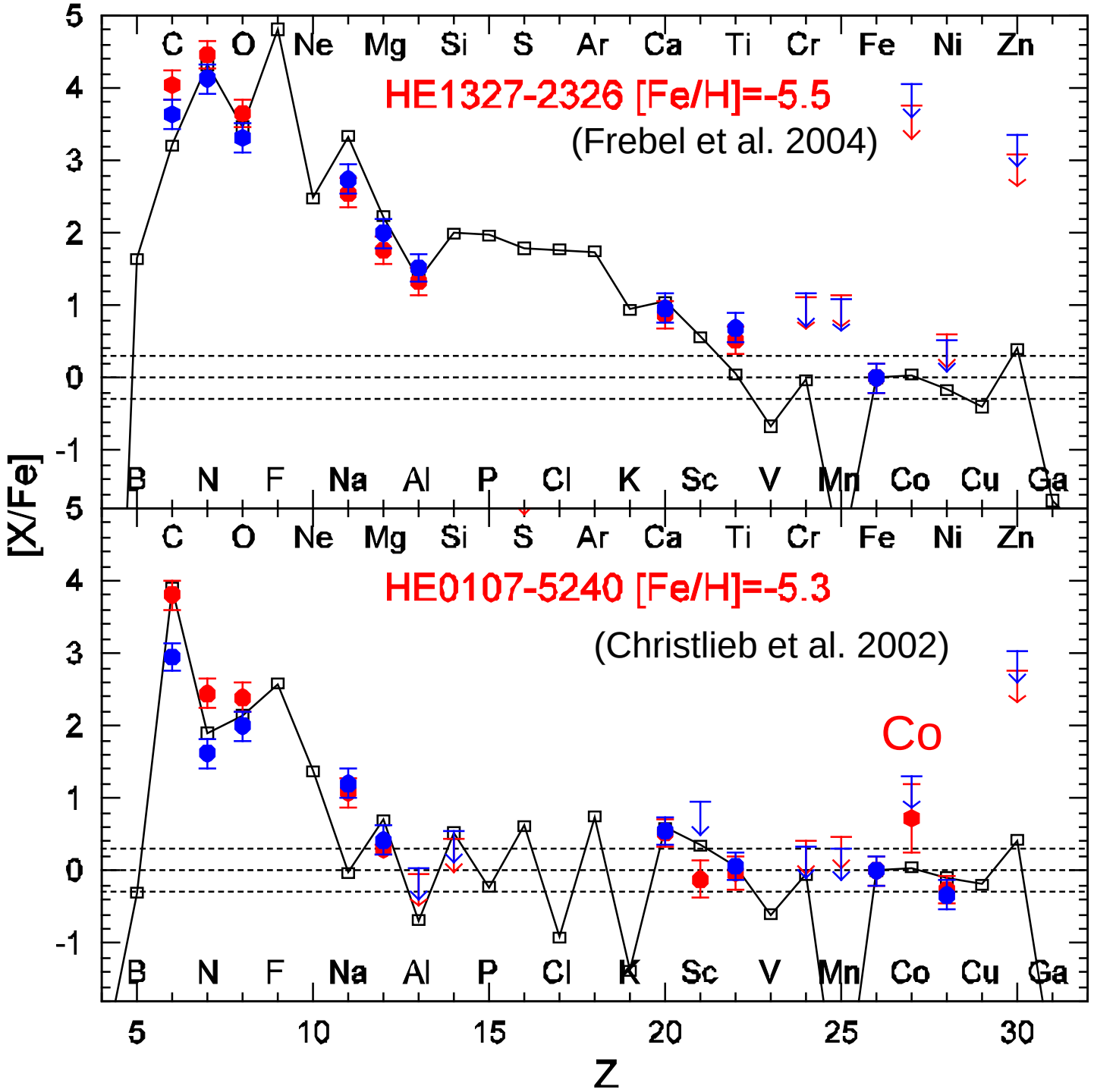
(Tominaga et al.)

UMP Star : [Fe/H] = -4.75

Hypernova model (E_{51}=20:1D)➔Co



(Norris, Christlieb, et al. 2007)



HMP Stars

([Fe/H] < -5)

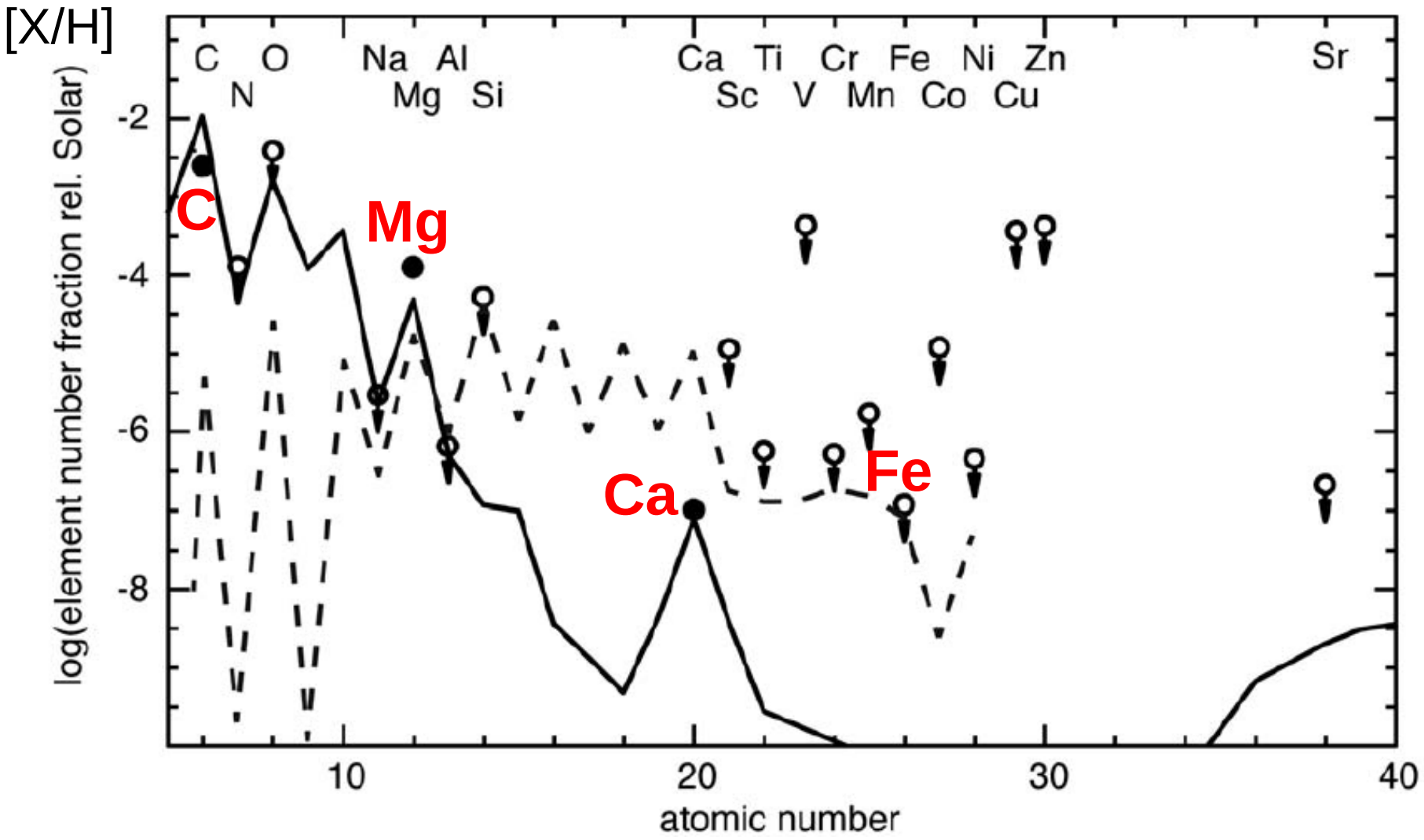
Jet-induced SN models

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

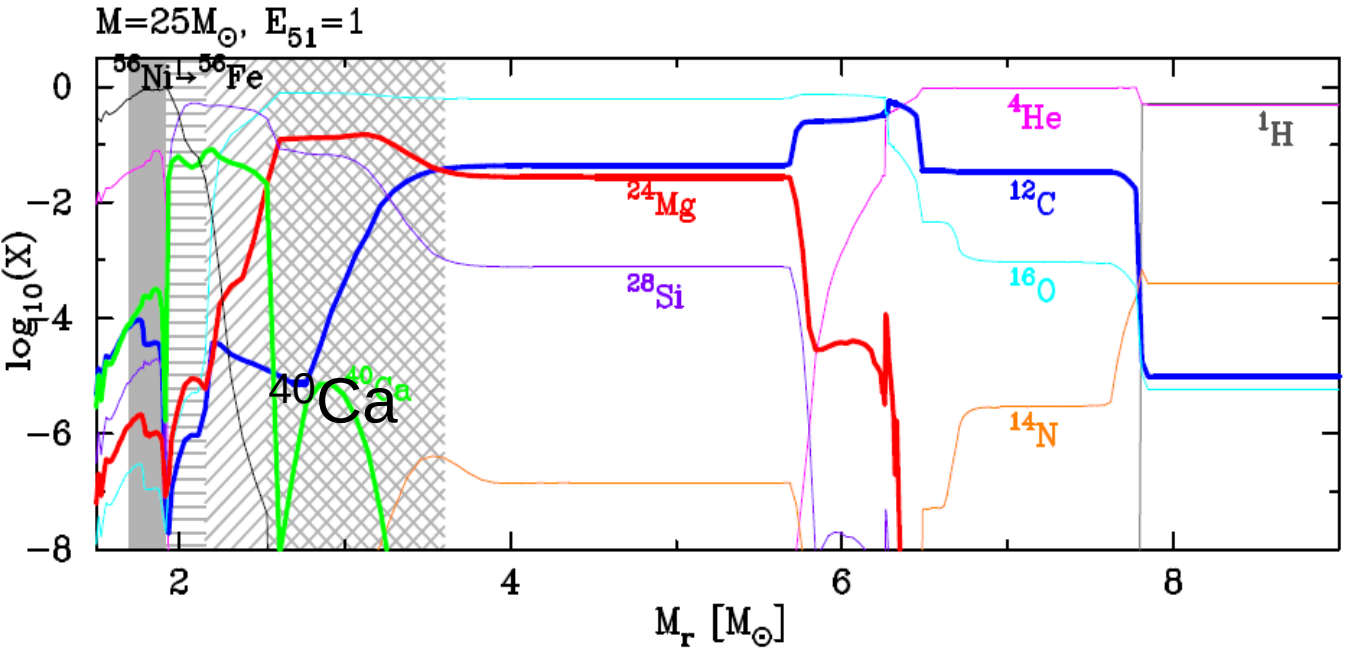
Dark Hypernova

Tominaga et al. 2007

Mega Metal-Poor Star : [Fe/H] < -7.1



pre-SN hot CNO cycle ➔ **Ca** ($M > 60\ M_{\odot}$) (Keller+14)

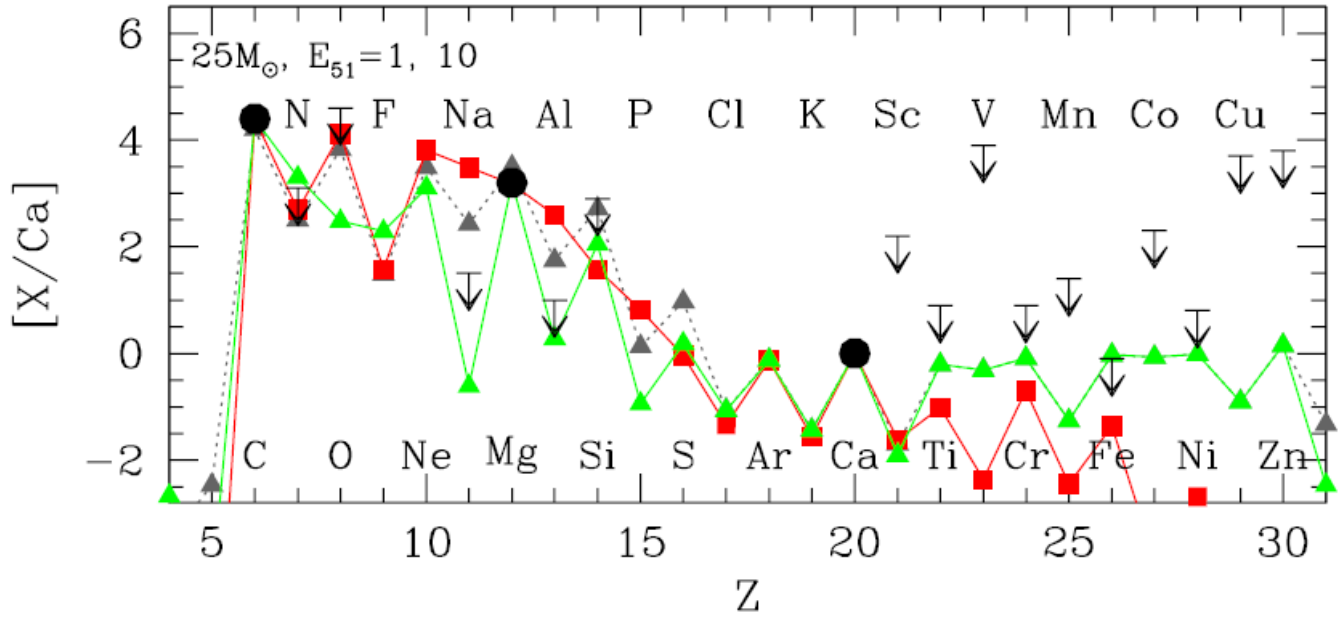


[Fe/H] < -7.1

Explosive O b. & Incomplete Si-b. ➔ Ca

Mixing & Fallback ➔ M(BH) ~ 5.6 $M_\odot$

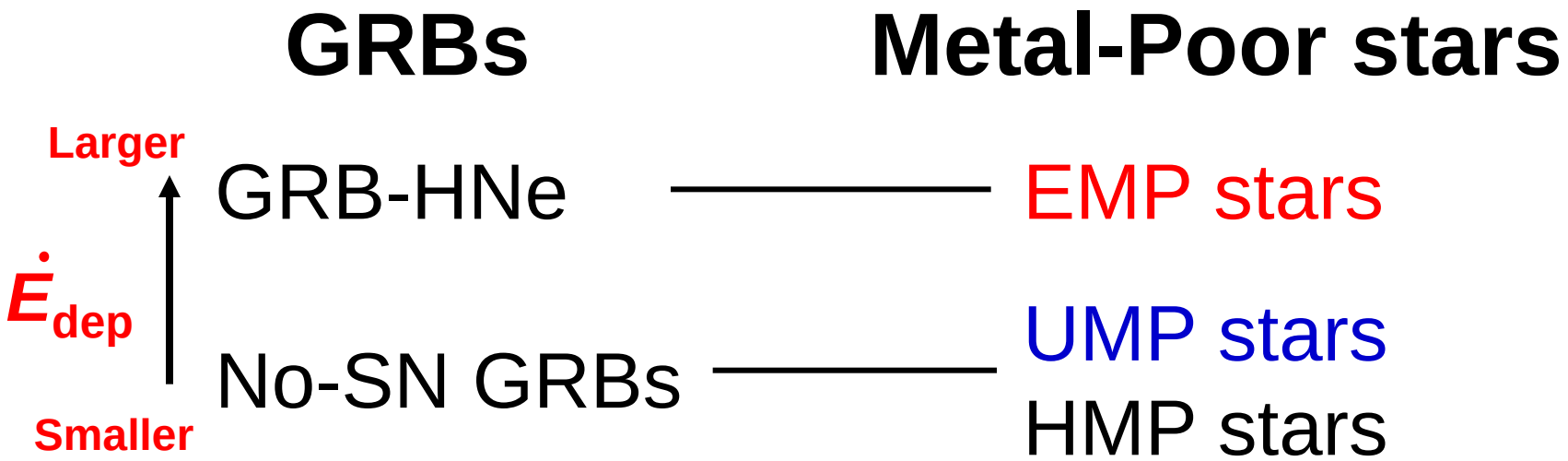
(Ishigaki + 14)



First stars --Metal-poor stars -- GRB connection

Hypernovae with relativistic jets

$M_{ms} \sim 20 - 130\ M_{\odot}$

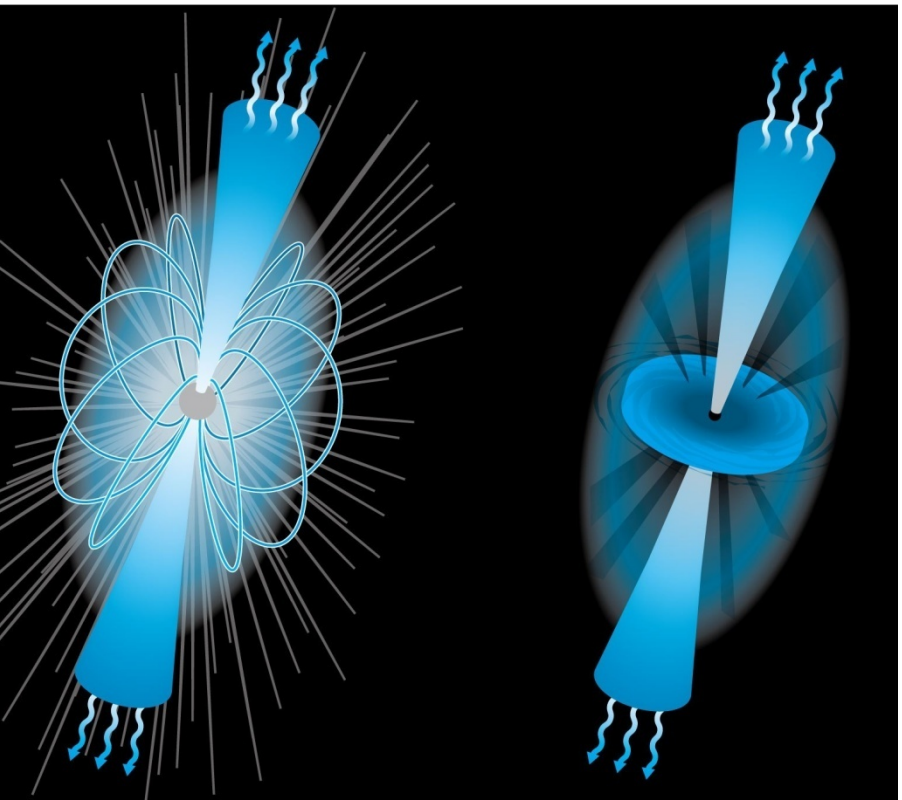


Hypernova Nucleosynthesis

- Central Engine ??

  Outflow from Disk ? (McLaughlin +)

  Magnetar ?



Materials in Jets: Ye ?

r-process elements ?

Correlation with

Fe-peak elements

(Zn, Co) ?