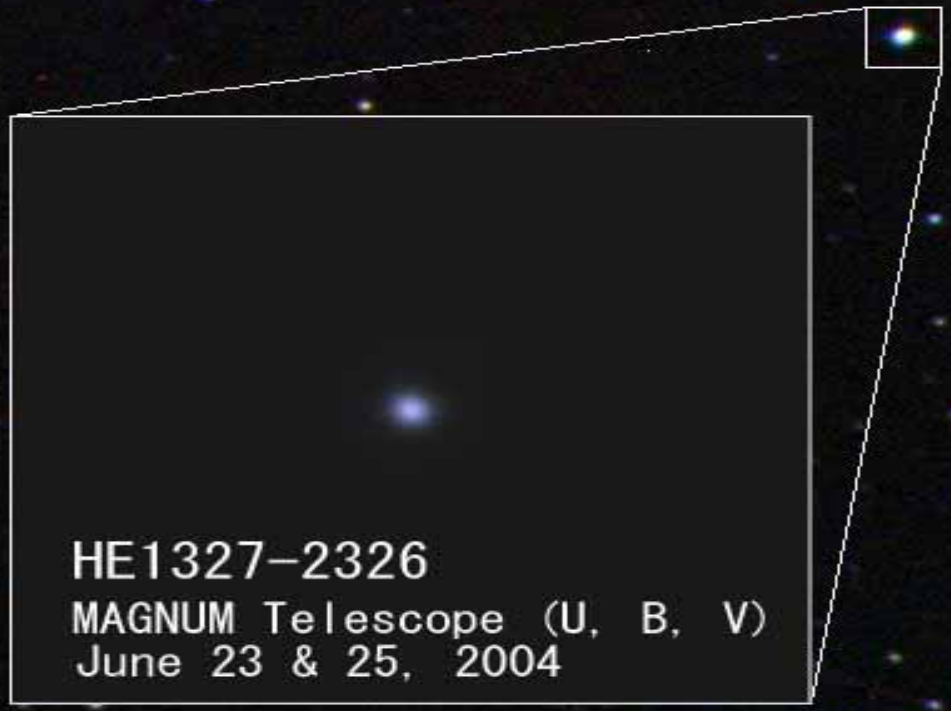
Nucleosynthesis in First Supernovae

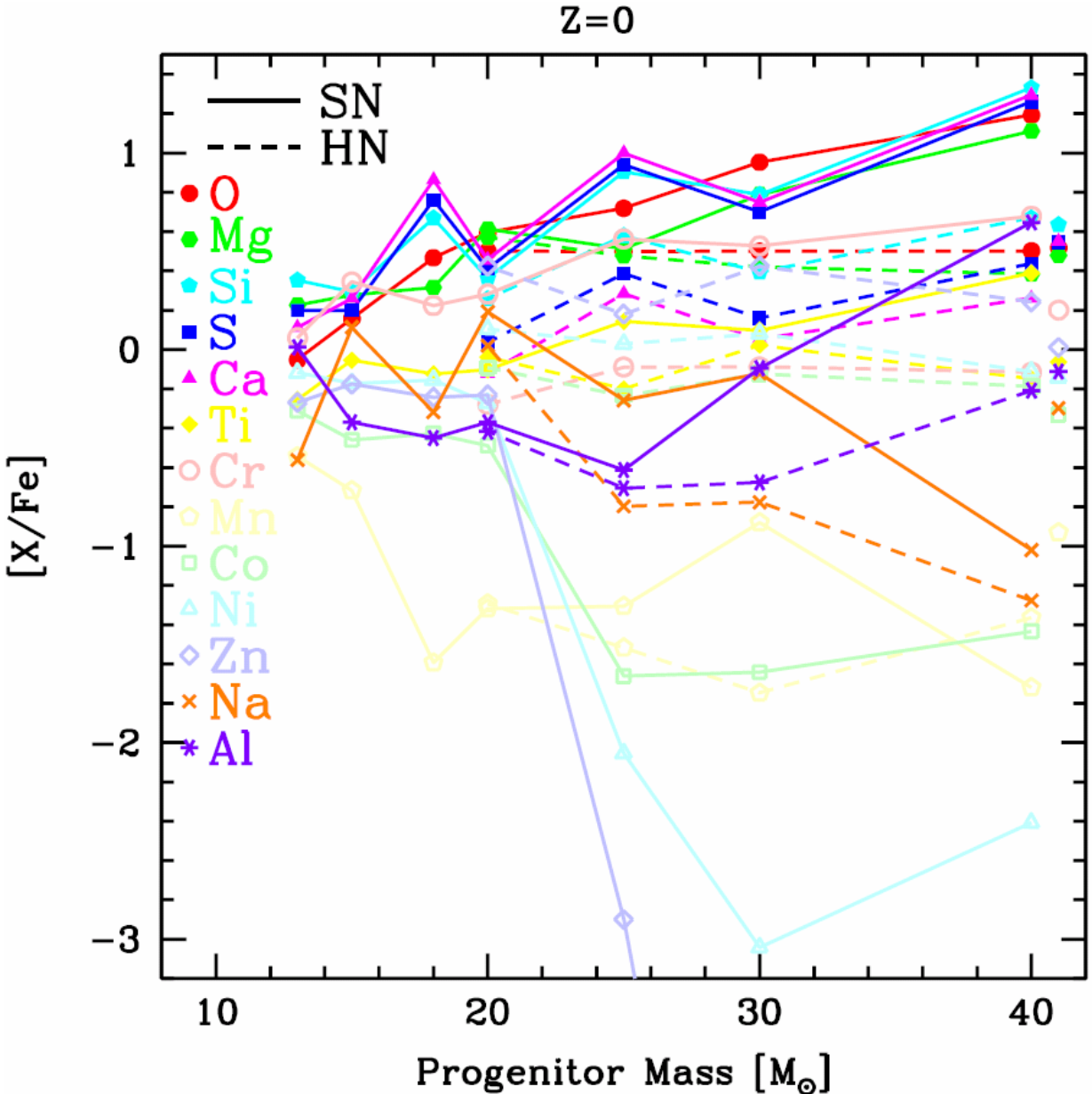


Ken'ichi Nomoto
(Univ. of Tokyo)

The First Stars ?

- **First Stars (IMF ?)** ⇨ **Reionizing Source**
- **First Supernovae** (Type II, Ibc, Hypernovae, Pair)
- **Metal-Enrichment**
- **Abundance Ratios @high z, low Z**
  - EMP (Extremely Metal-Poor) Stars: Halo, dSph
  - DLA, ICM, ...
  - **α-elements: [(C, N, O, Mg, Si, Ca)/Fe], [Si/O]**
  - **Fe-peak elements: [(Ti, Cr, Mn, Co, Ni, Zn)/Fe]**
  - **R-process, s-process elements**

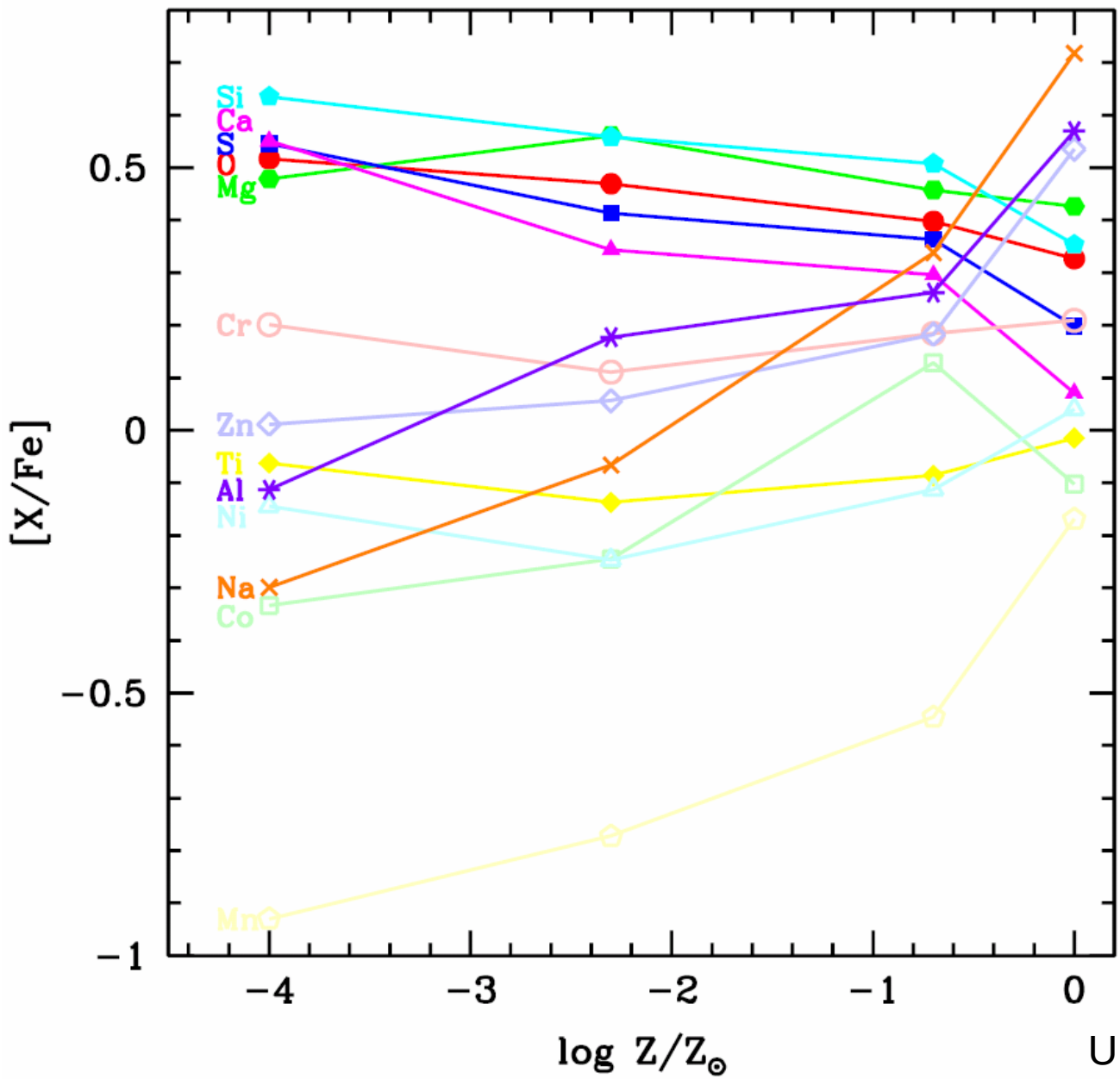
SN II Yields (Pop III)



Tominaga et al.(2005)

Woosley Weaver (1995)
Chieffi Limongi (2002)
Umeda Nomoto (2002)

SN II Yields



Umeda et al.(2005)

Yields of Core Collapse Supernovae

Parameters in the Explosion Models

* Explosion Energy : 10^{49} – 10^{53} erg

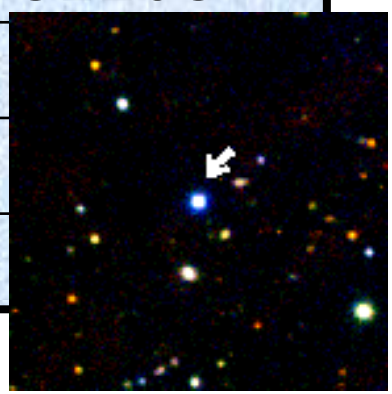
  Crab - Hypernovae

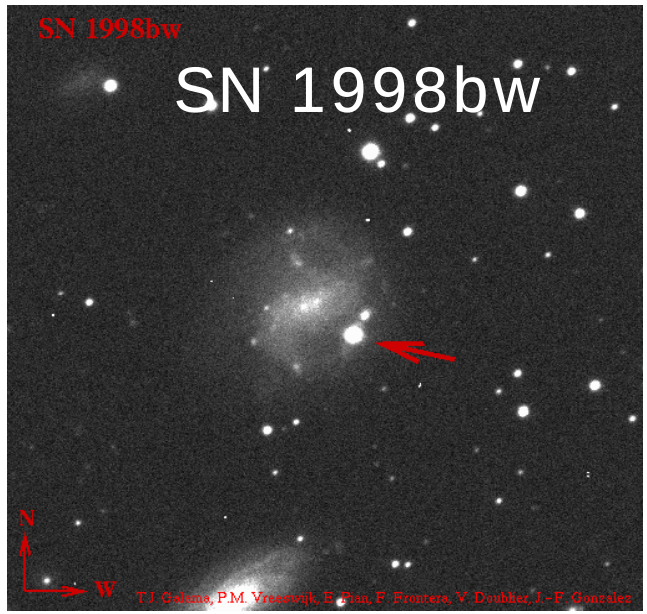
* Mass Cut
* Y_e: neutrino process (e.g., Frohlich et al. 2005)
* Compact Star : NS vs BH → r-process
* Mixing & Fallback :
* Asphericity : Disk, Jets

Hypernova Candidates

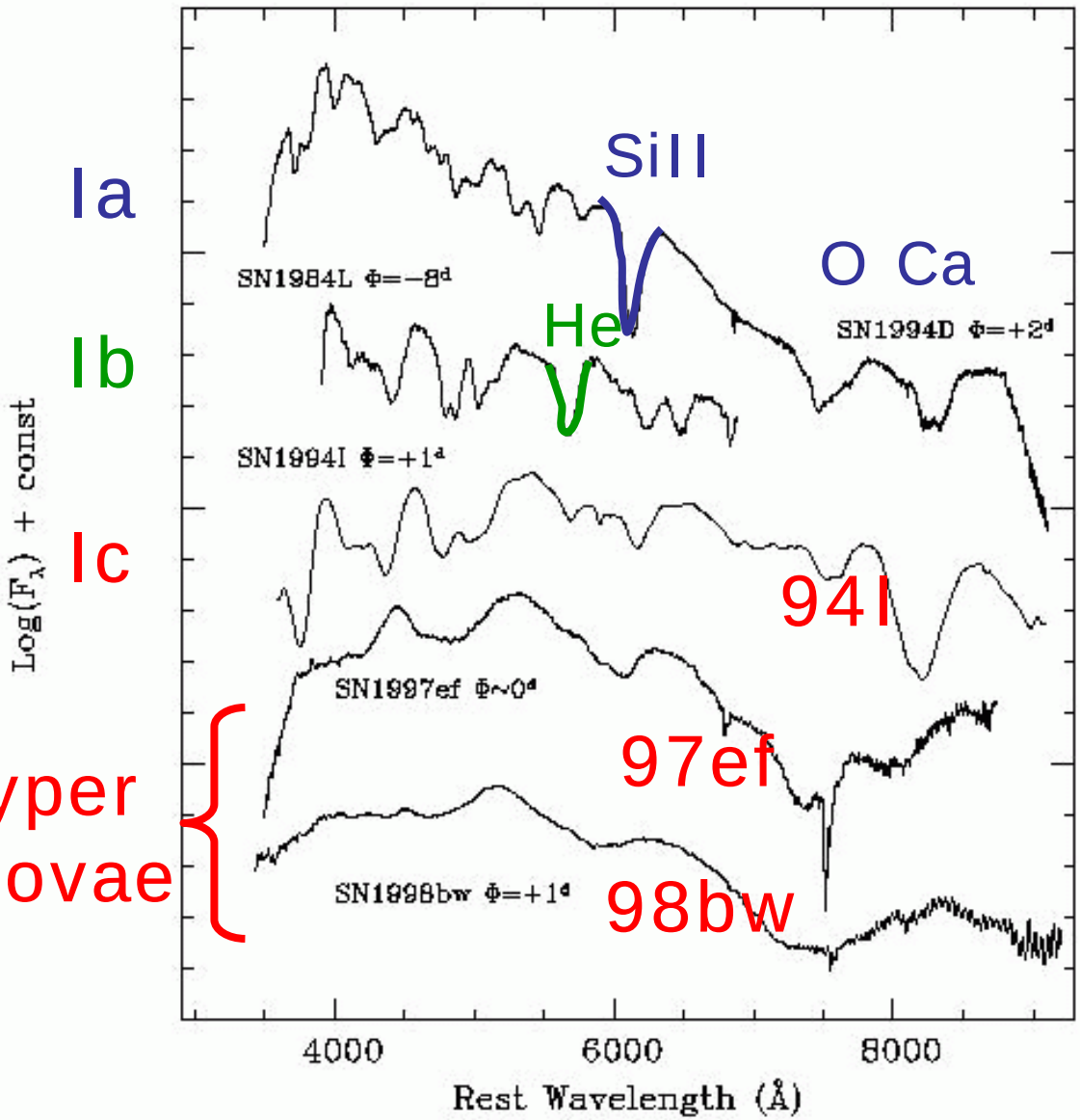
$E_{kinetic} > (5\text{-}10) \times 10^{51}$ ergs

SNe Ic	
SN	GRB
1998bw	980425
1997ef	(971115)
2002ap	
2003dh	030329
2003lw	031203
1997dq	
1998ey	
1992ar	





Spectra of Supernovae & Hypernovae



Ic: no H,

no strong He,

no strong Si

Hypernovae:

broad features

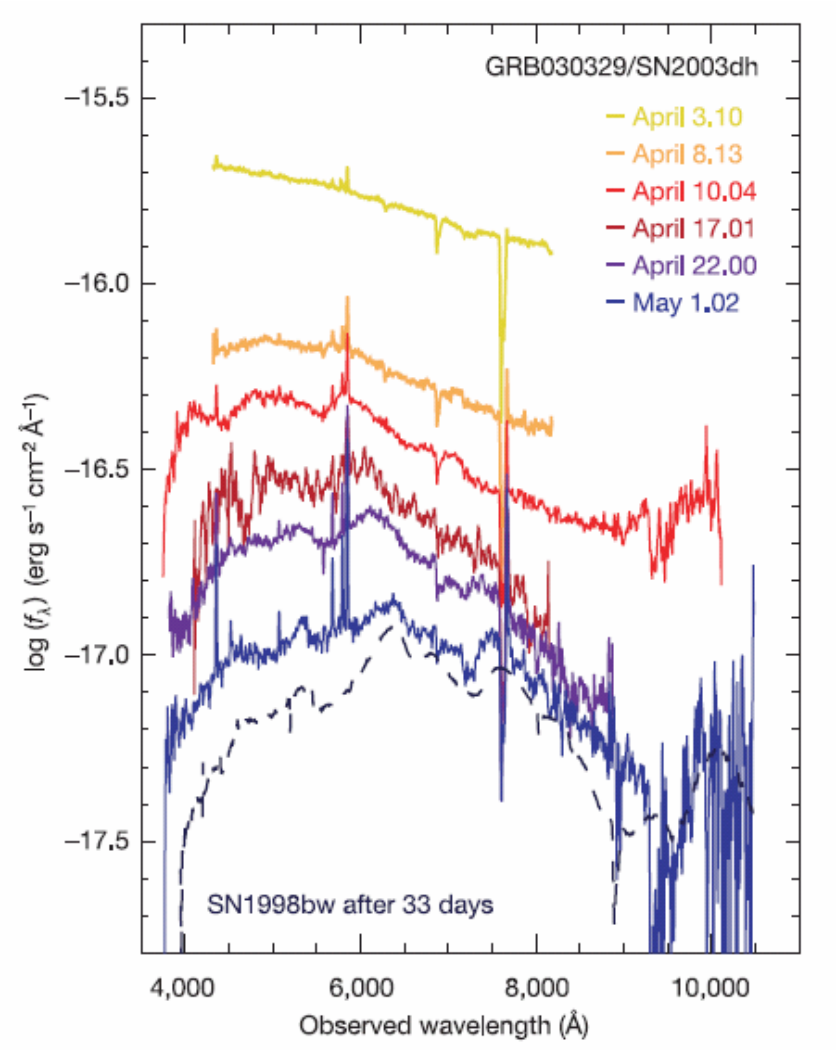
↑

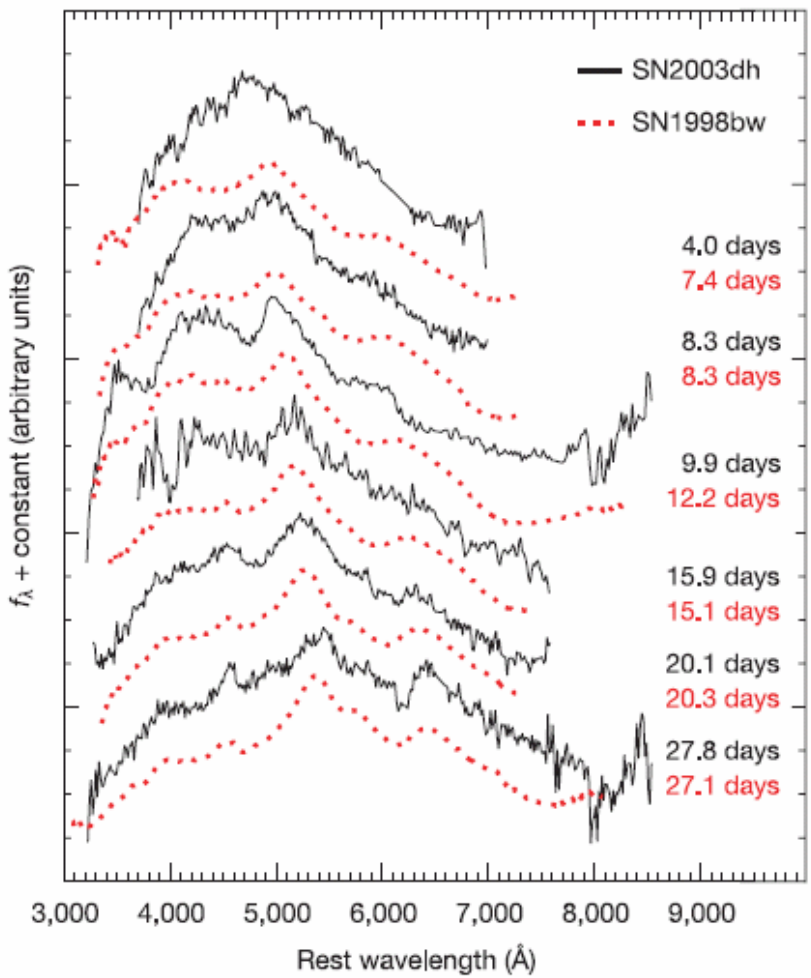
blended lines

↑

"Large mass at high velocities"

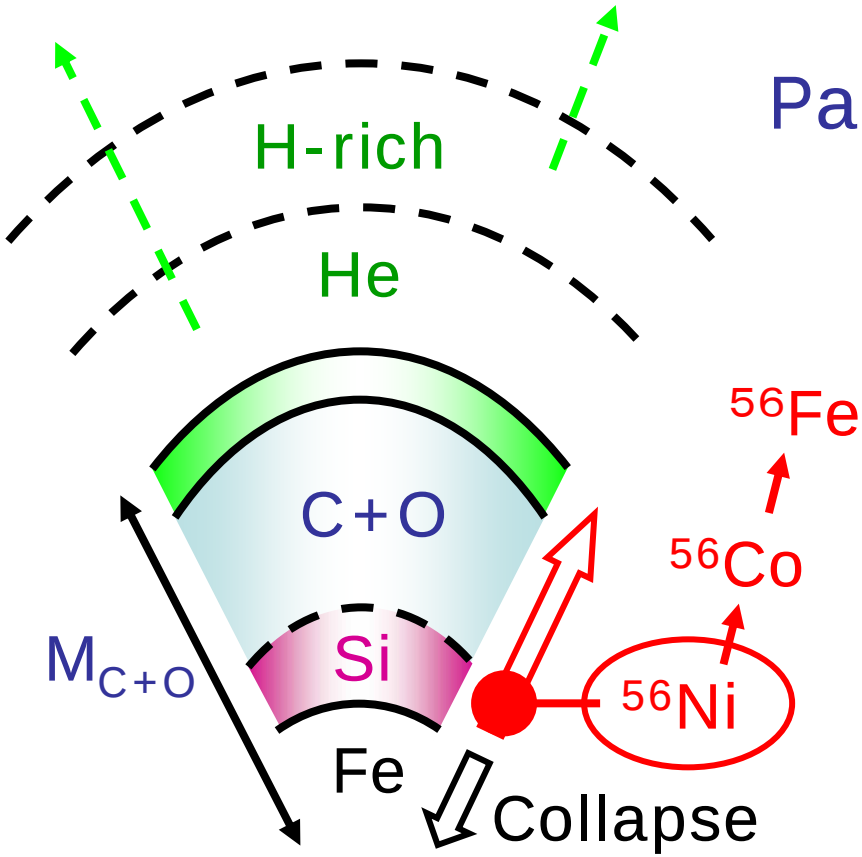
GRB 030329 / SN 2003dh





Hjorth et al (2003)

CO Star Models for SNeIc



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

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

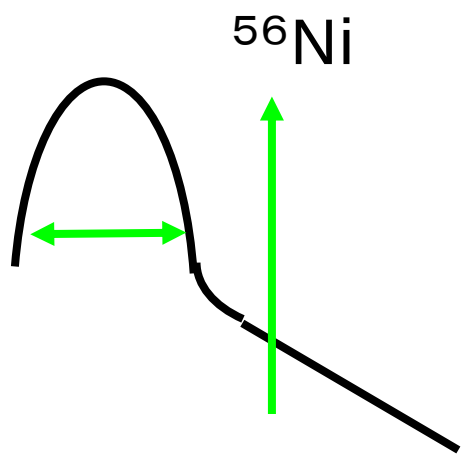
Light Curve — Spectra

$$\tau \sim [\tau_{dyn} \bullet \tau_{diffusion}]^{1/2} \quad E \propto M_{ej}$$

$$\sim \left(\frac{R}{V} \bullet \frac{\kappa M_{ej}}{R c} \right)^{1/2}$$

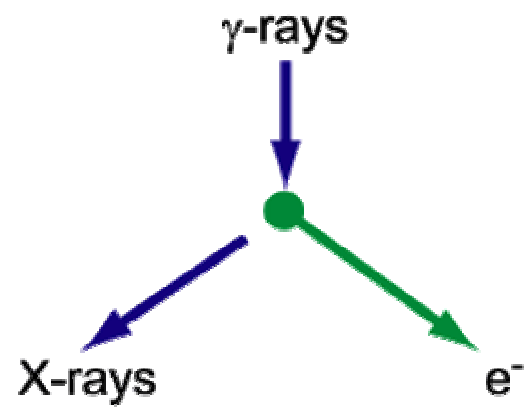
$$\propto \kappa^{1/2} M_{ej}^{3/4} E^{-1/4}$$

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



^{56}Co-decay

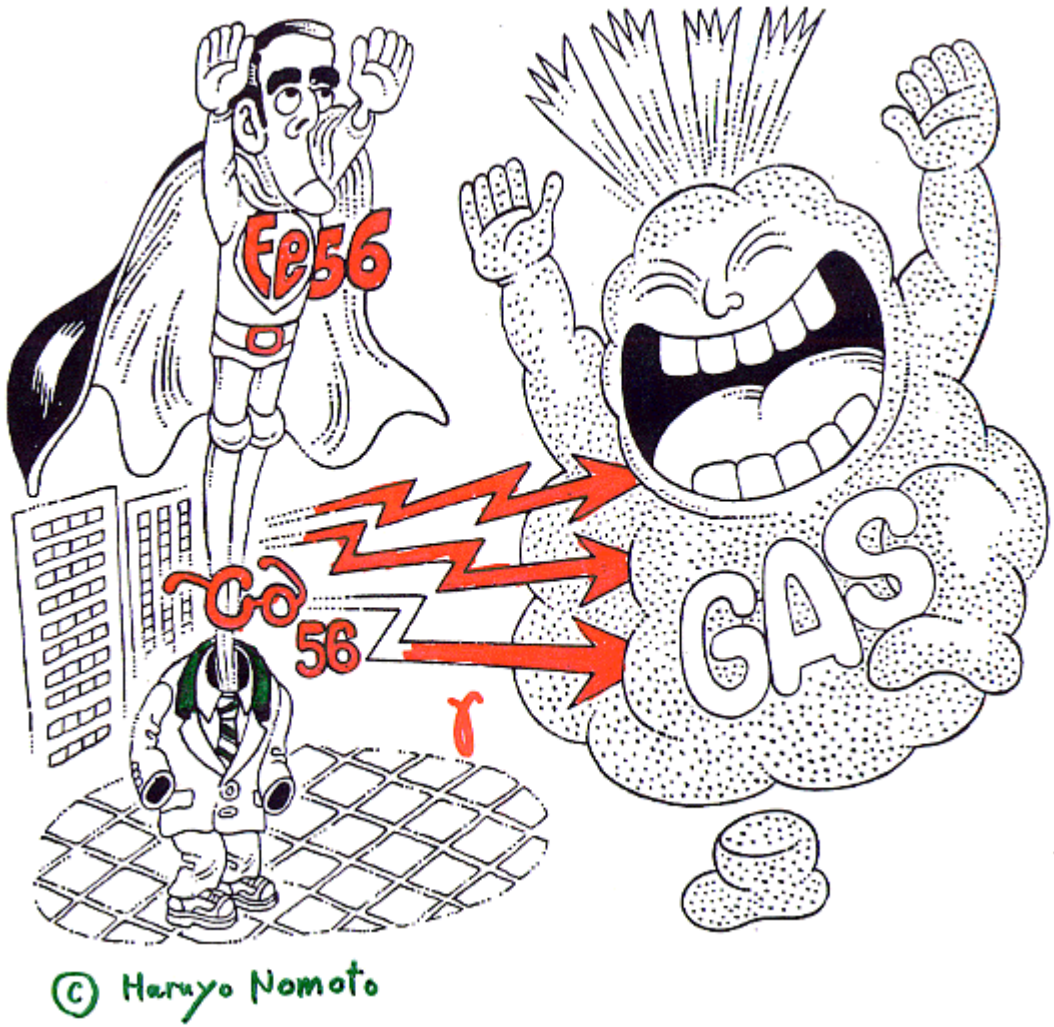
$^{56}Ni \xrightarrow[6.6d]{\gamma} {}^{56}Co \xrightarrow[78d]{\gamma} {}^{56}Fe$



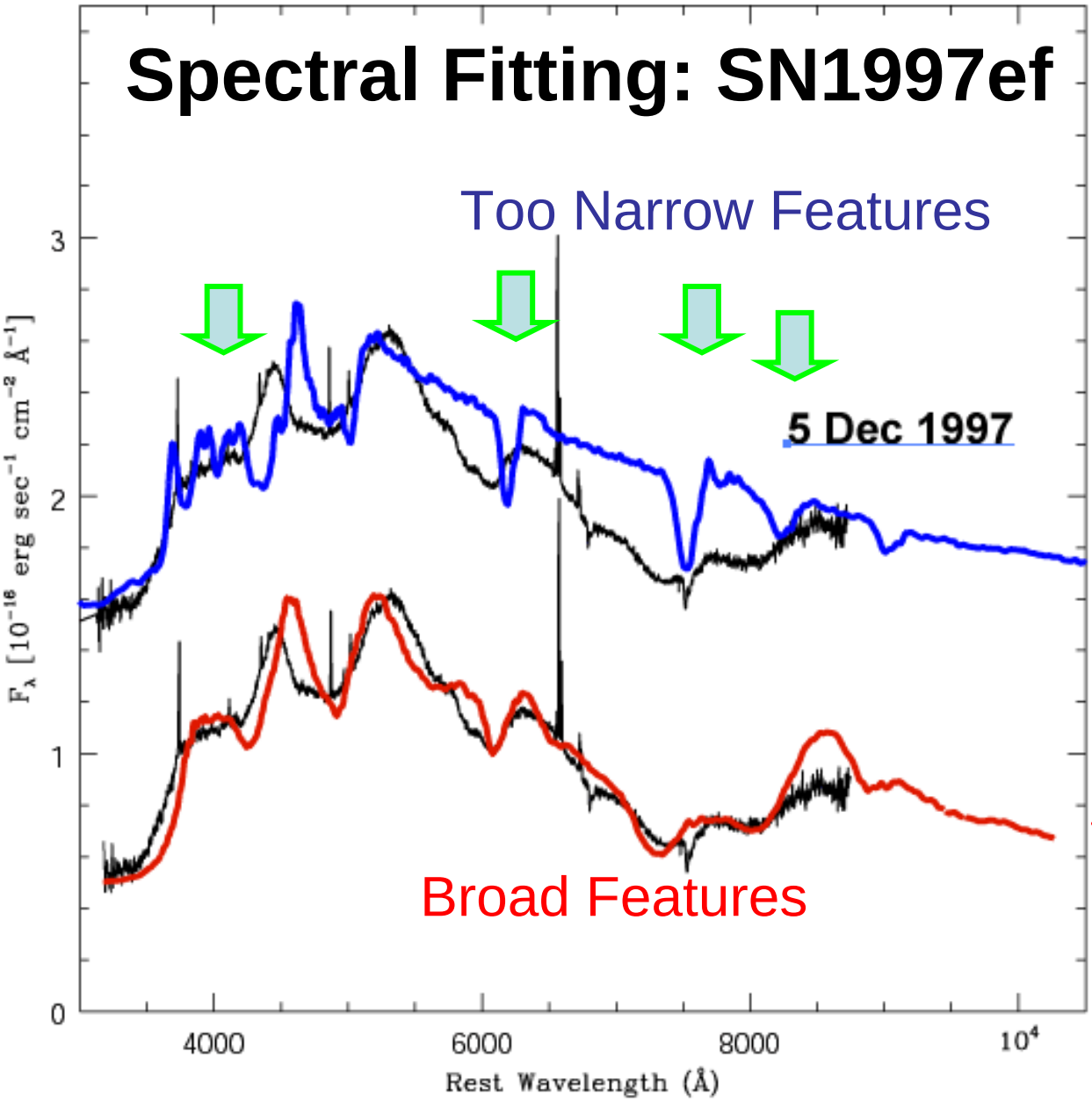
Photoabsorption Excitation/Ionization

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

Shape:M_{ej}



Spectral Fitting: SN1997ef



Iwamoto et al. (2000)

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

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

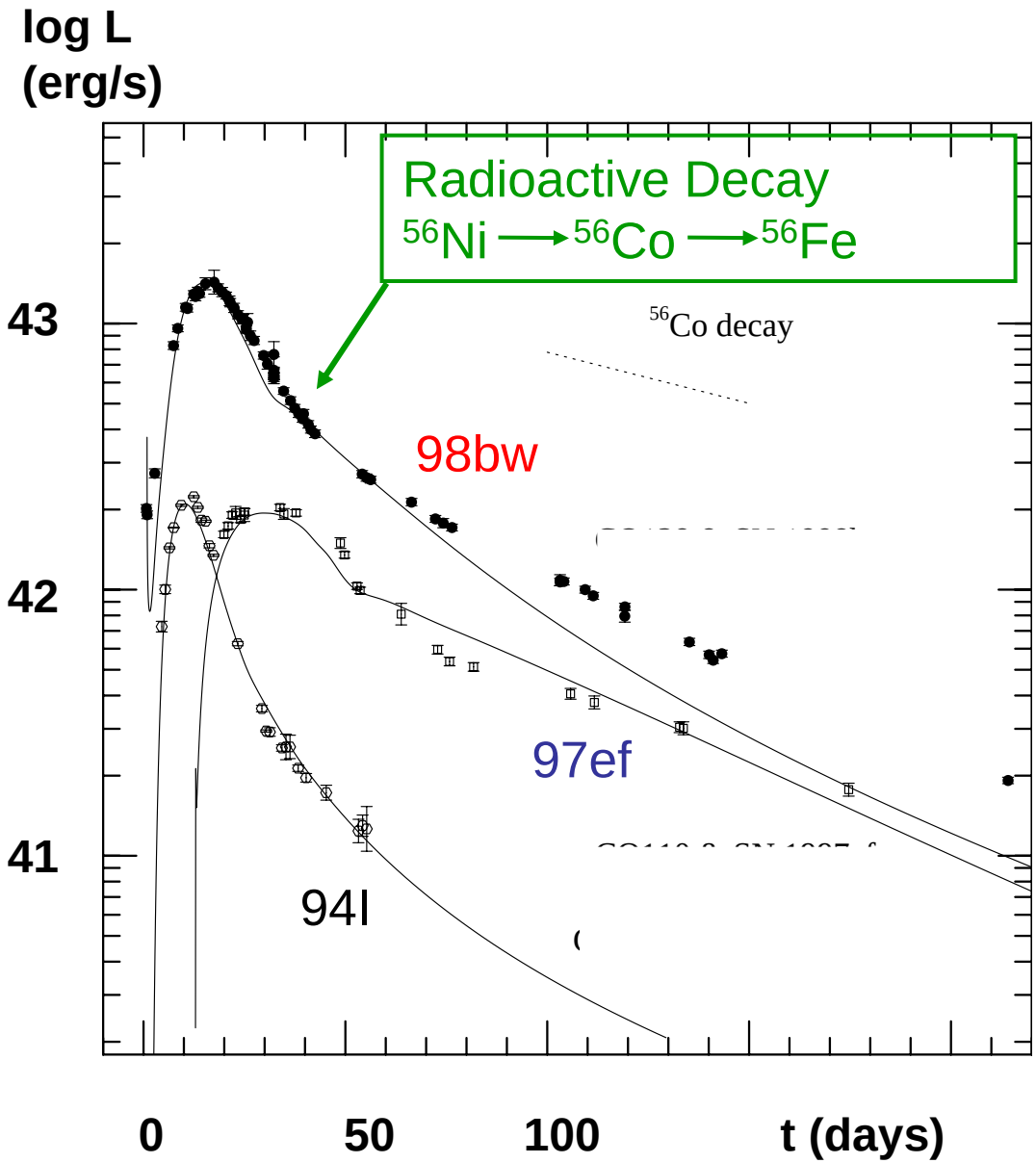
Small M_{ej}

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

Large M_{ej}
at High Vel.

Light curves of Hypernovae & SNeIc

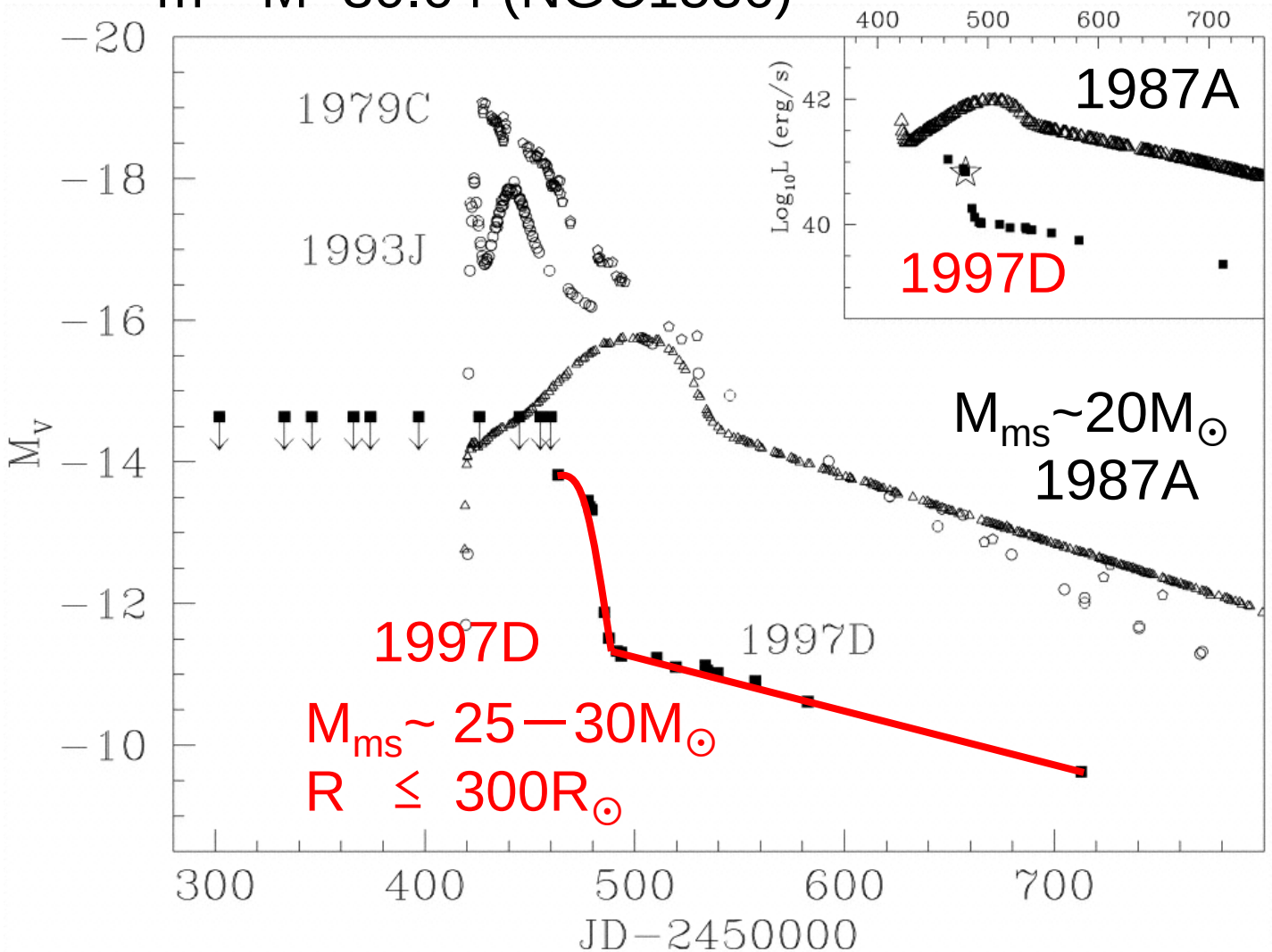
C+O Star Models			
	98bw	97ef	94I
M_{ms} ($M_\odot$)	40	35	15
M_{C+O} ($M_\odot$)	13.8	10.0	2.1
E_K (10^{51}erg)	30	20	1
M(^{56}Ni) ($M_\odot$)	0.5	0.15	0.07



SN Ⅱ 1997D: Faint SN

Turatto, Mazzali, Young, Nomoto, Iwamoto et al. (1998)

m−M=30.64 (NGC1536)



M(^{56}Ni)

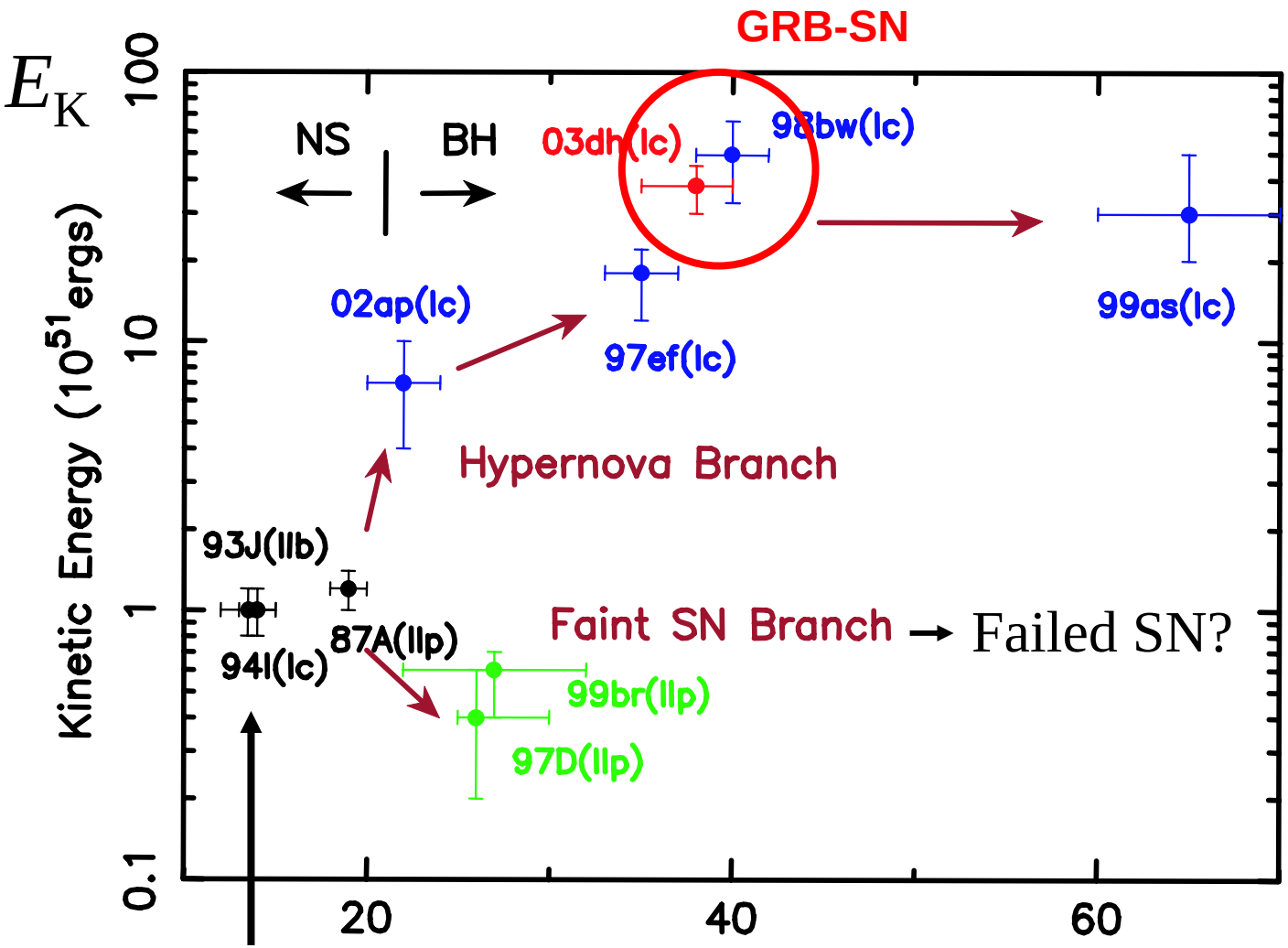
0.07$M_\odot$

0.002$M_\odot$

E~4×10^{50}erg

narrow lines

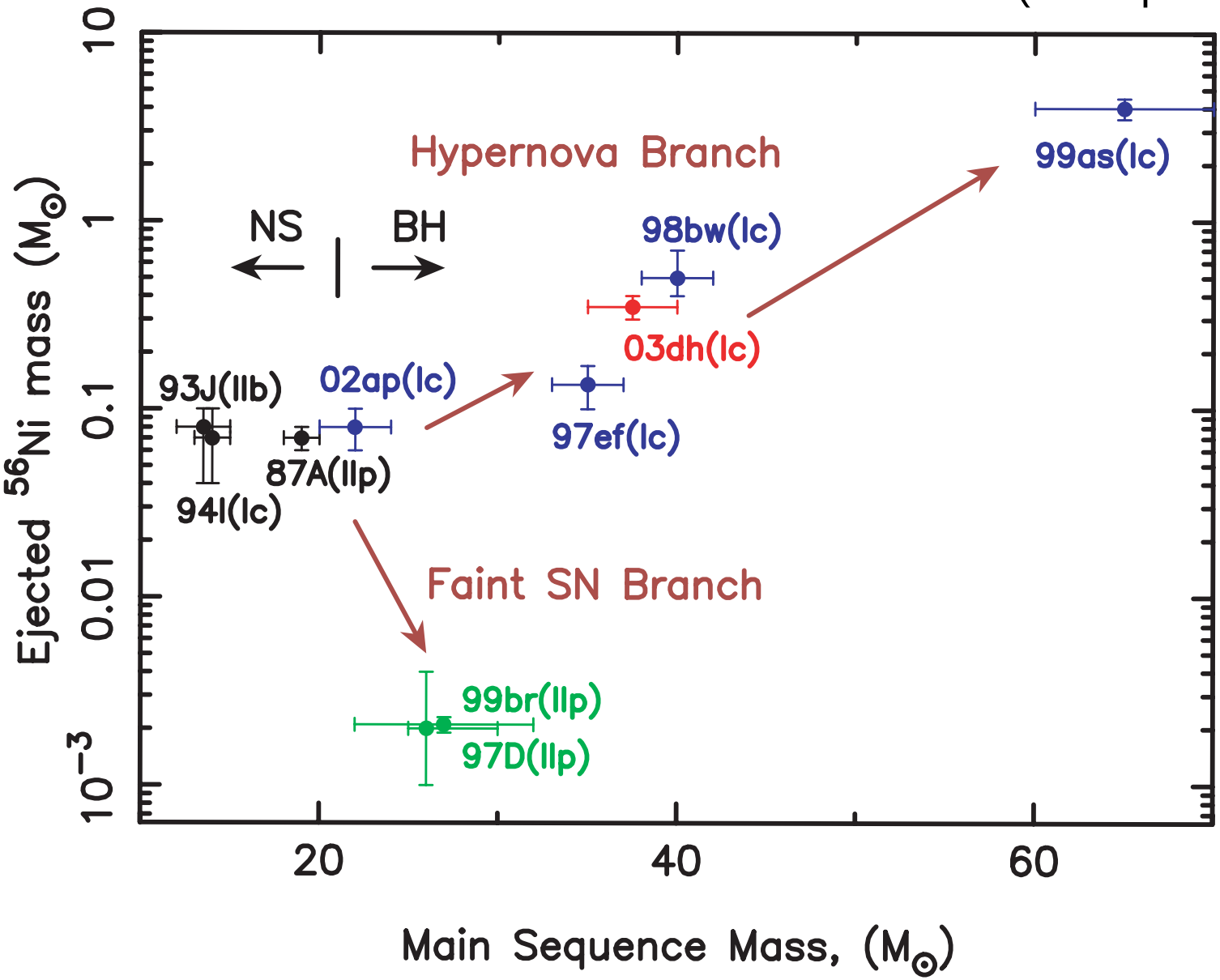
Hypernovae/Faint SNe



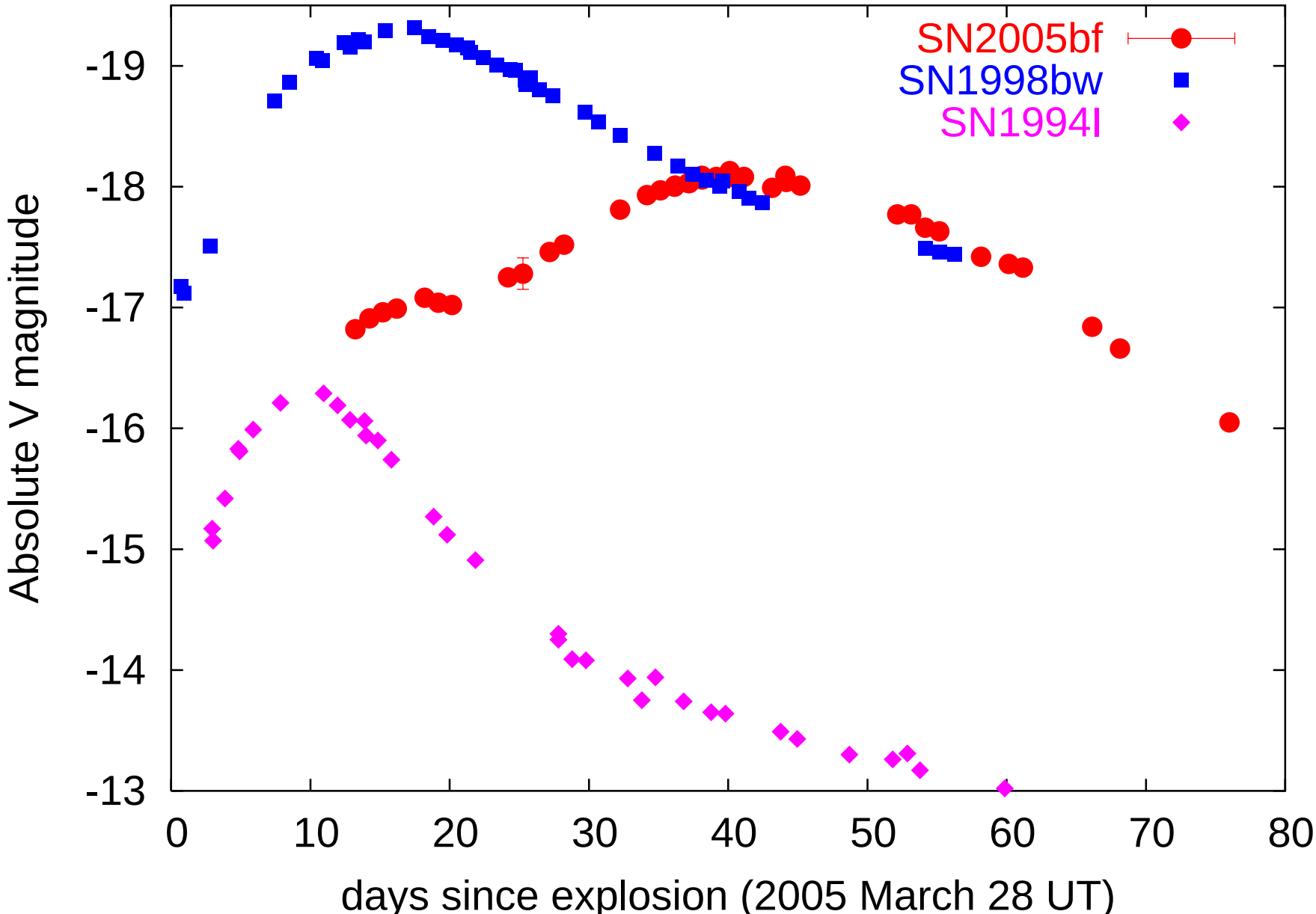
Nomoto et al. (2003)

Hypernova and Faint SN (^{56}Ni mass)

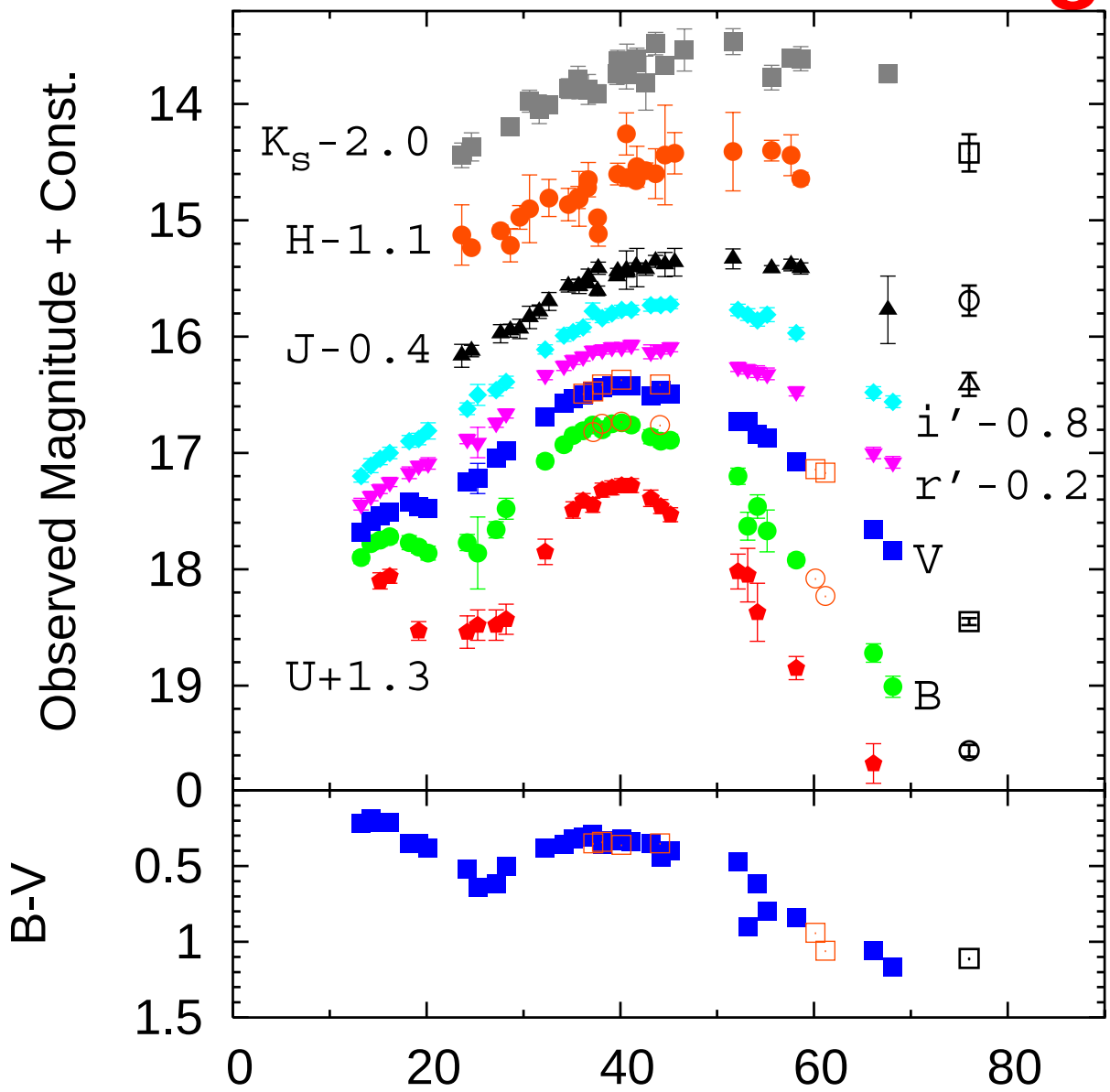
Nomoto et al. (astro-ph/0308136)



Type Ib SN 2005bf: Light Curve

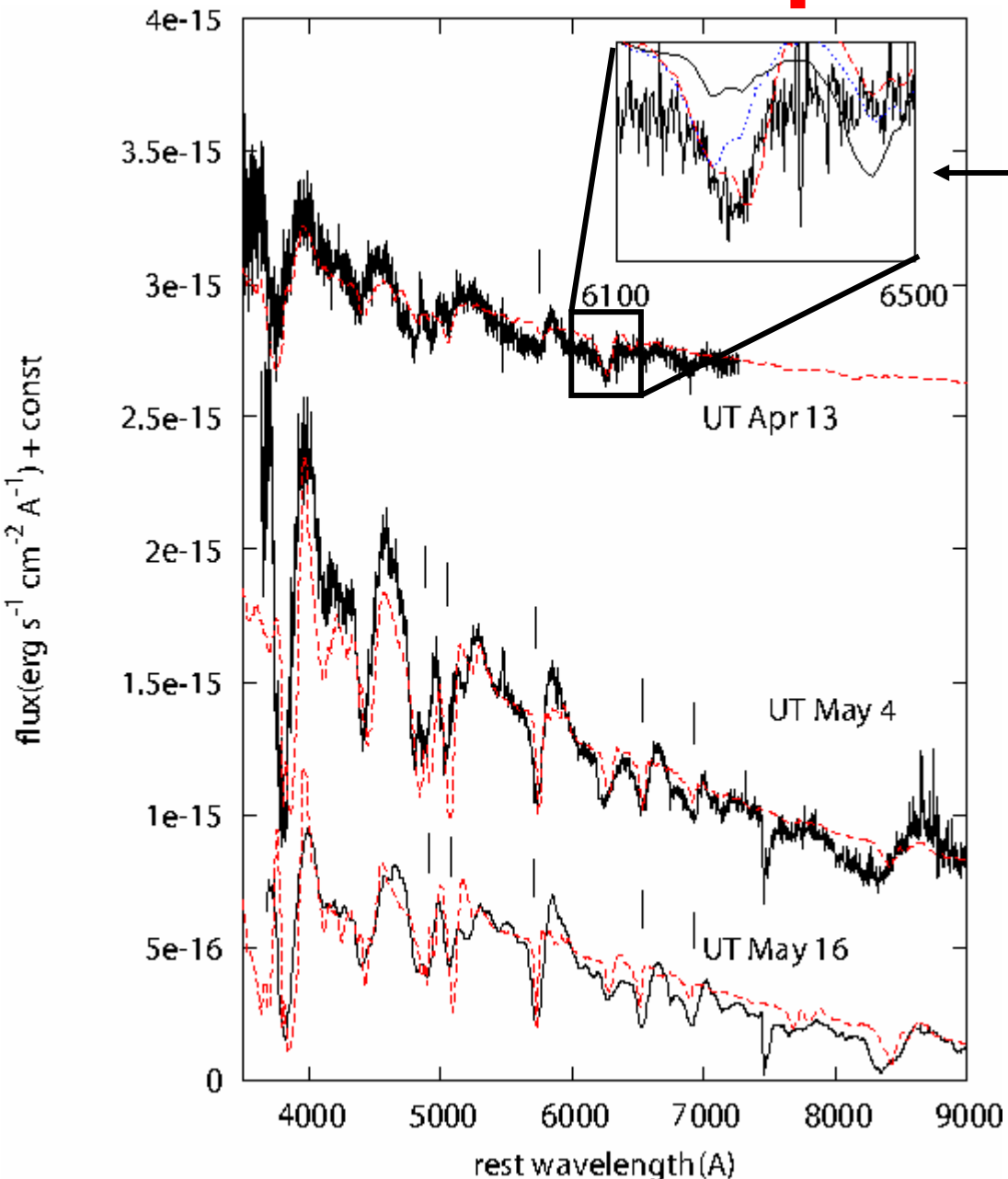


SN 2005bf: Observed Light Curves



Tominaga et al. 2005

SN 2005bf: Spectra

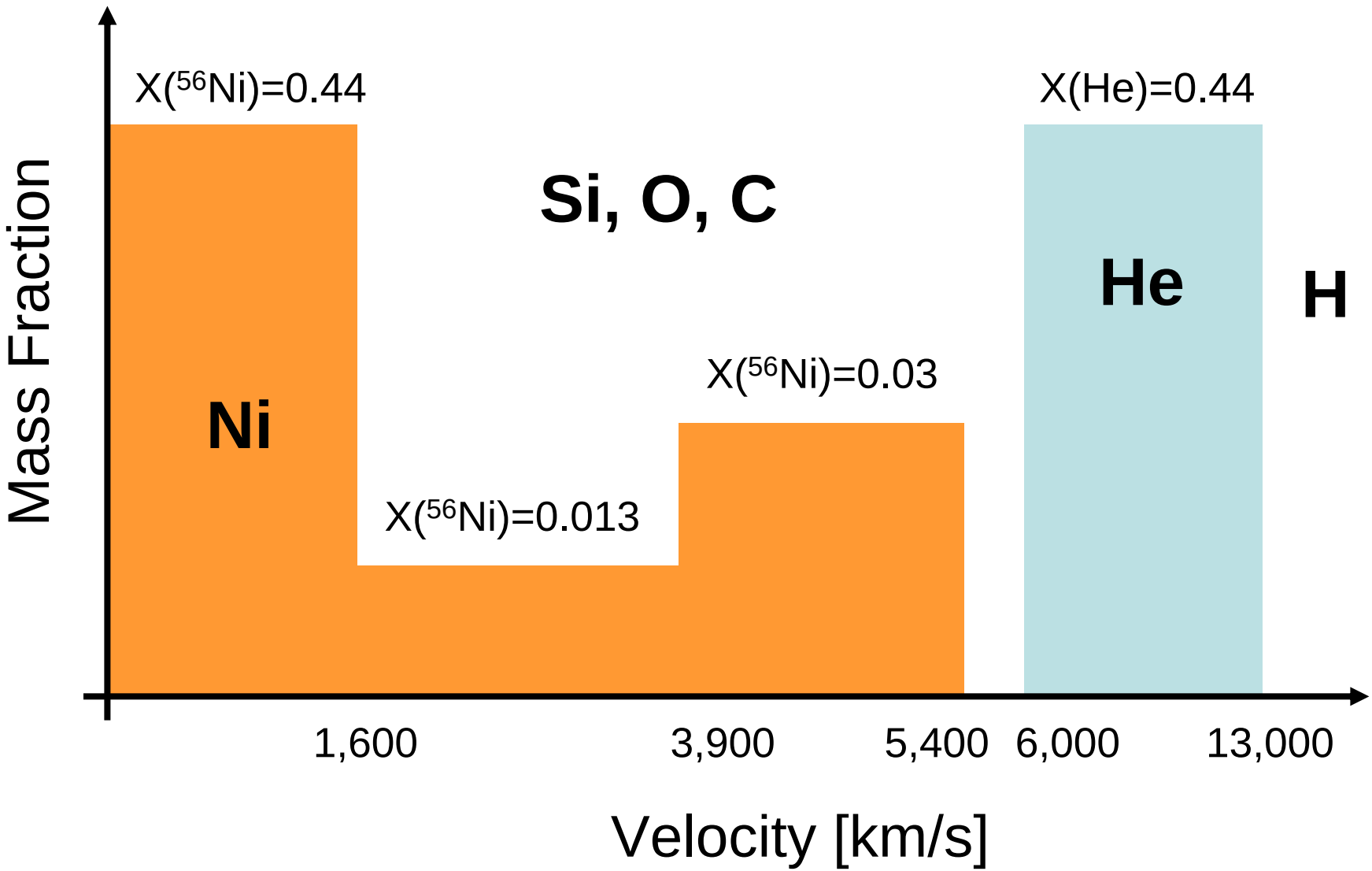


H feature

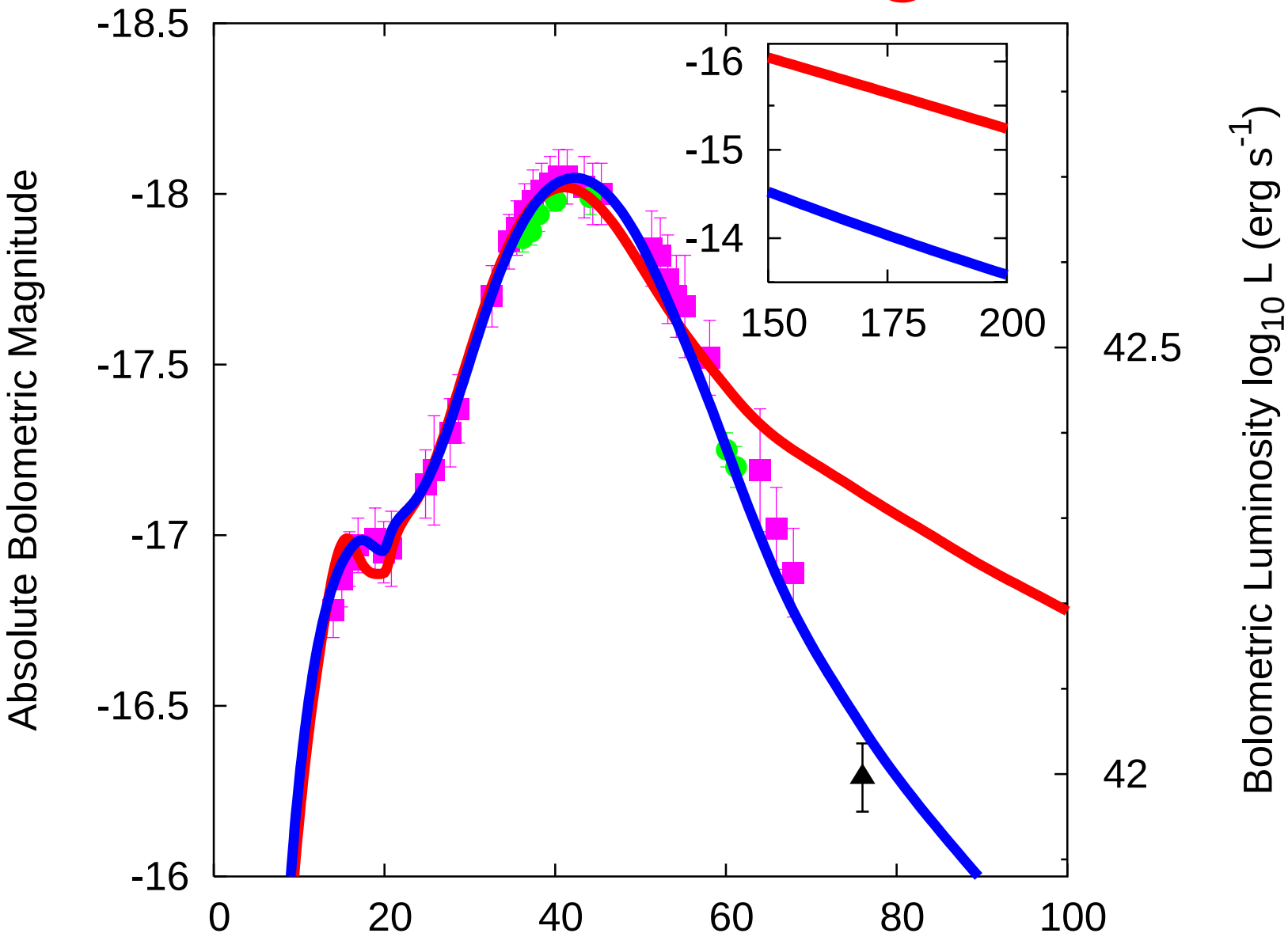
He

Tominaga et al. 2005

SN 2005bf: Abundance Distribution



SN 2005bf: Model Light Curves



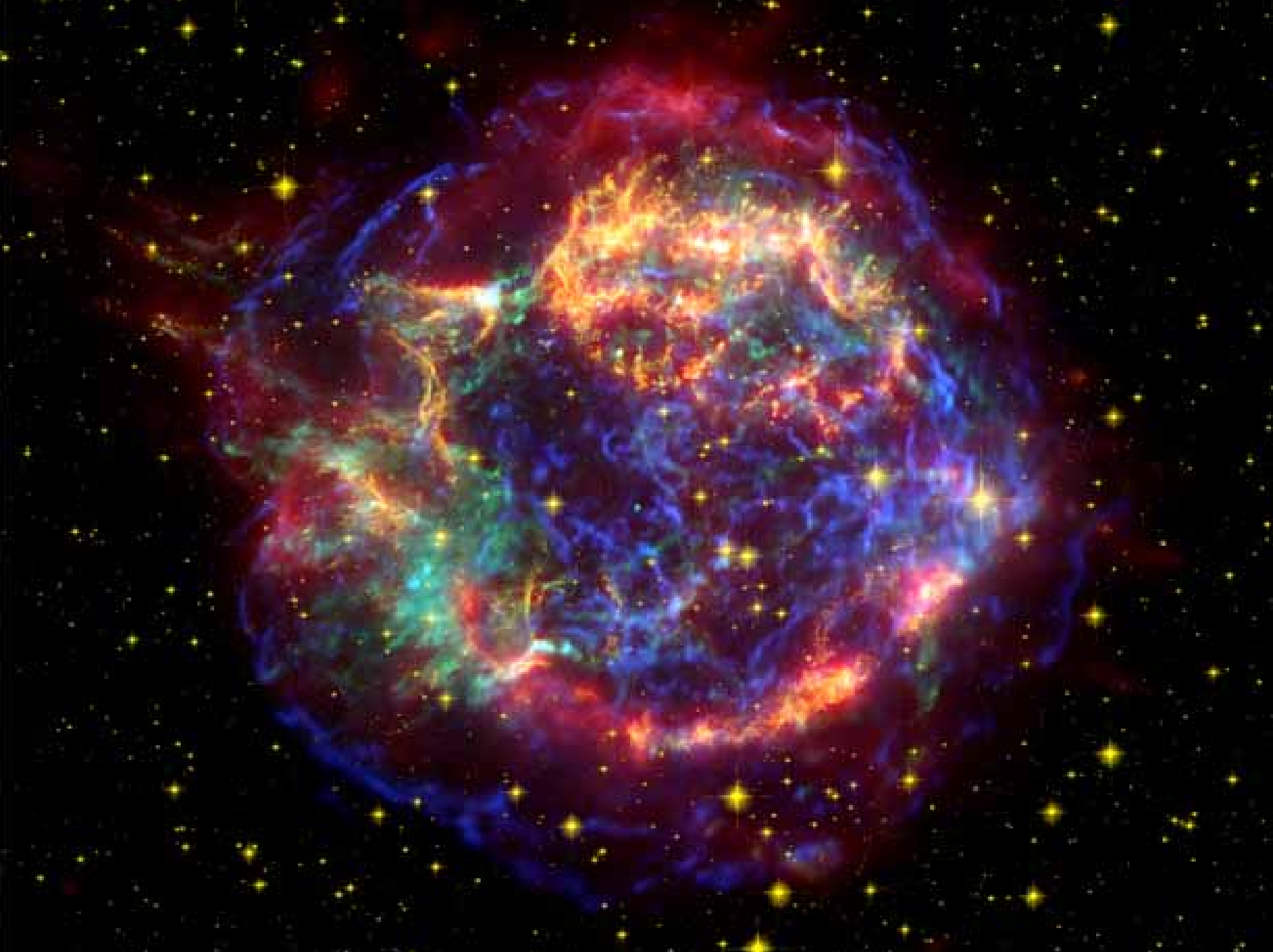
Tominaga et al. 2005

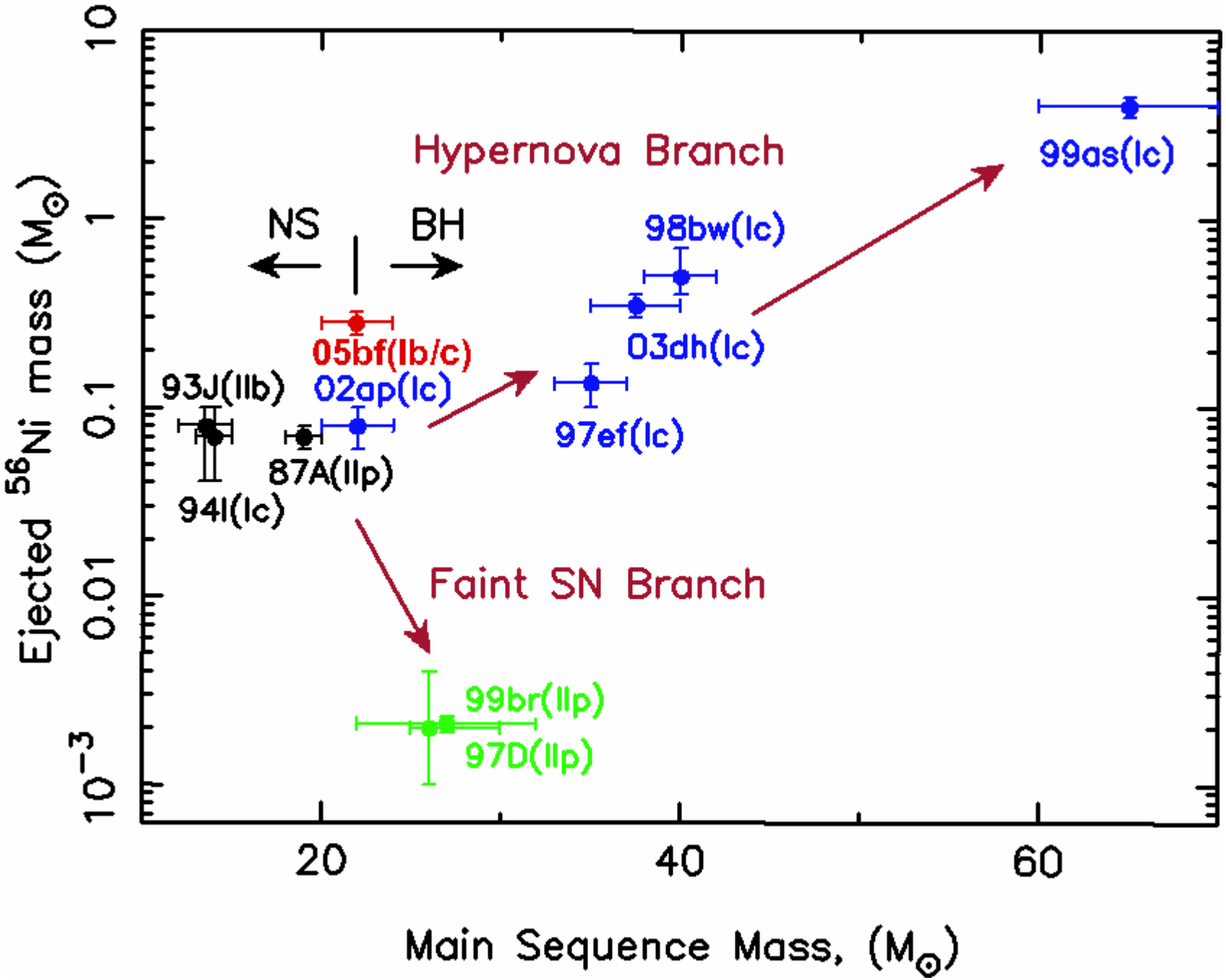
The Unique Type Ib SN 2005bf

- Peculiar Light Curve
  - Double peaks
  - Slow rise to the 2nd peak (~40 days)

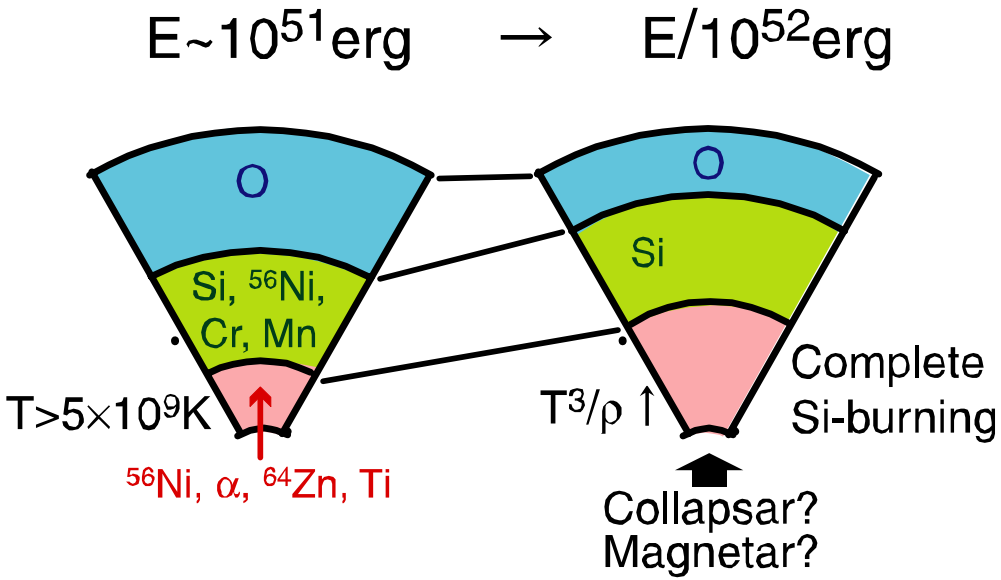
↓

- Double peaked ^{56}Ni distribution → **Jets?**
- M_{ej} ~ 6 – 7 $M_\odot$ (M_{ms} ~ 25 – 30 $M_\odot$)
- E ~1.3 x 10^{51} erg & M(^{56}Ni)~0.3$M_\odot$ **> NS?**
- Explosion of a WN star He, H features
- Cas A? Magnetar?




Hypernova Branch
NS
BH
98bw(Ic)
99as(Ic)
03dh(Ic)
05bf(Ib/c)
02ap(Ic)
93J(IIb)
97ef(Ic)
87A(IIp)
94I(Ic)
Faint SN Branch
99br(IIp)
97D(IIp)
Ejected ^{56}Ni mass ($M_\odot$)
Main Sequence Mass, ($M_\odot$)
10
1
0.1
0.01
10^{-3}
20
40
60

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 ↗

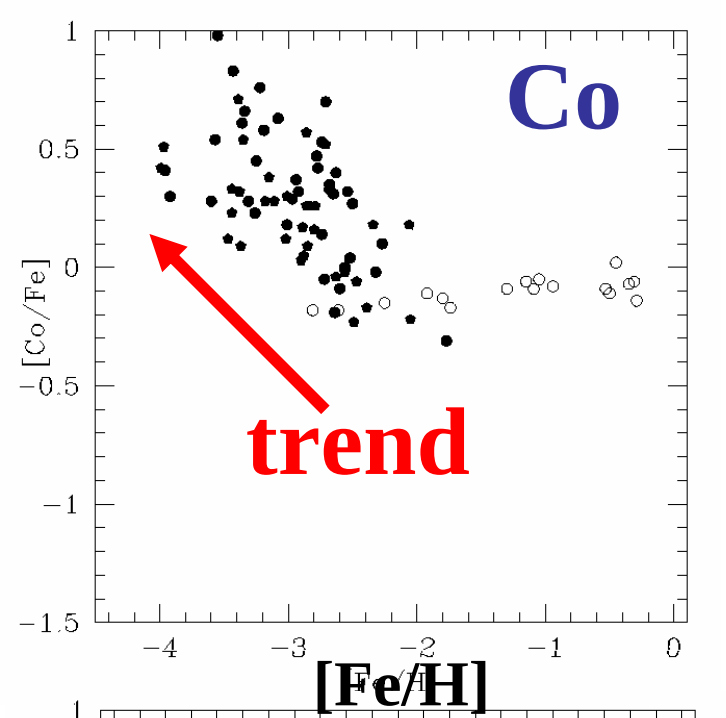
Zn/Fe ↗ ⇦ ^{64}Ge

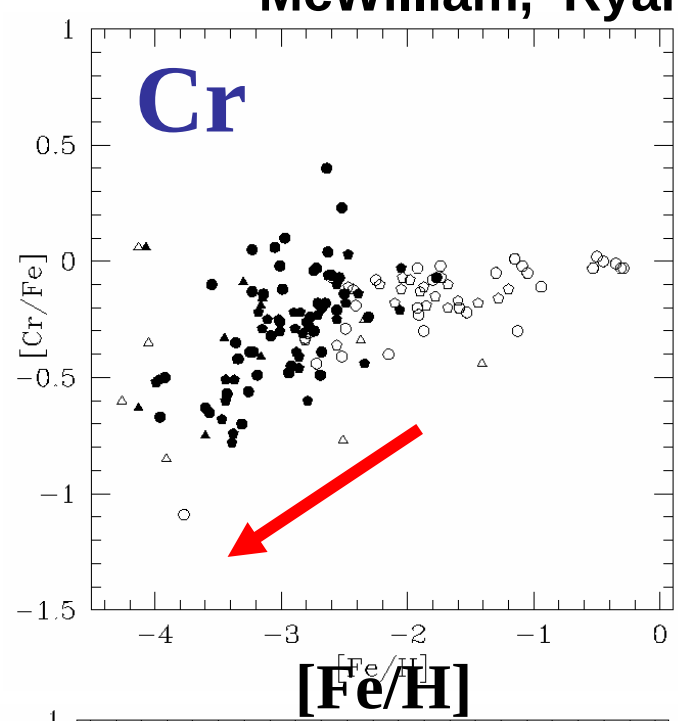
Ti/Fe ↗

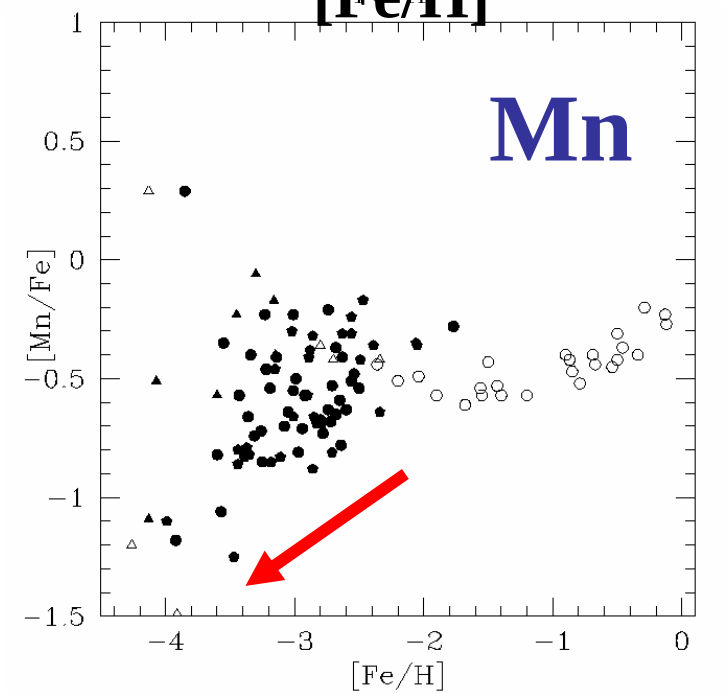
(3) More O burns

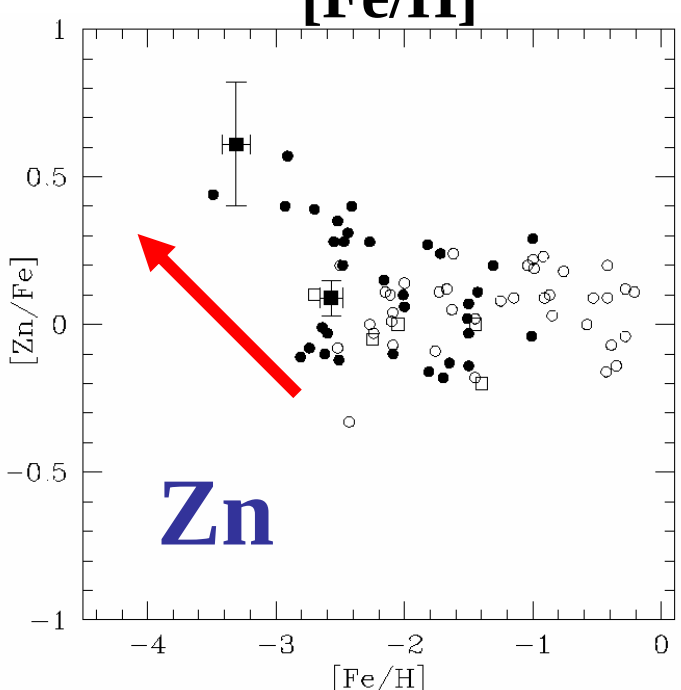
(Si, S, Ca)/O ↗

McWilliam, Ryan

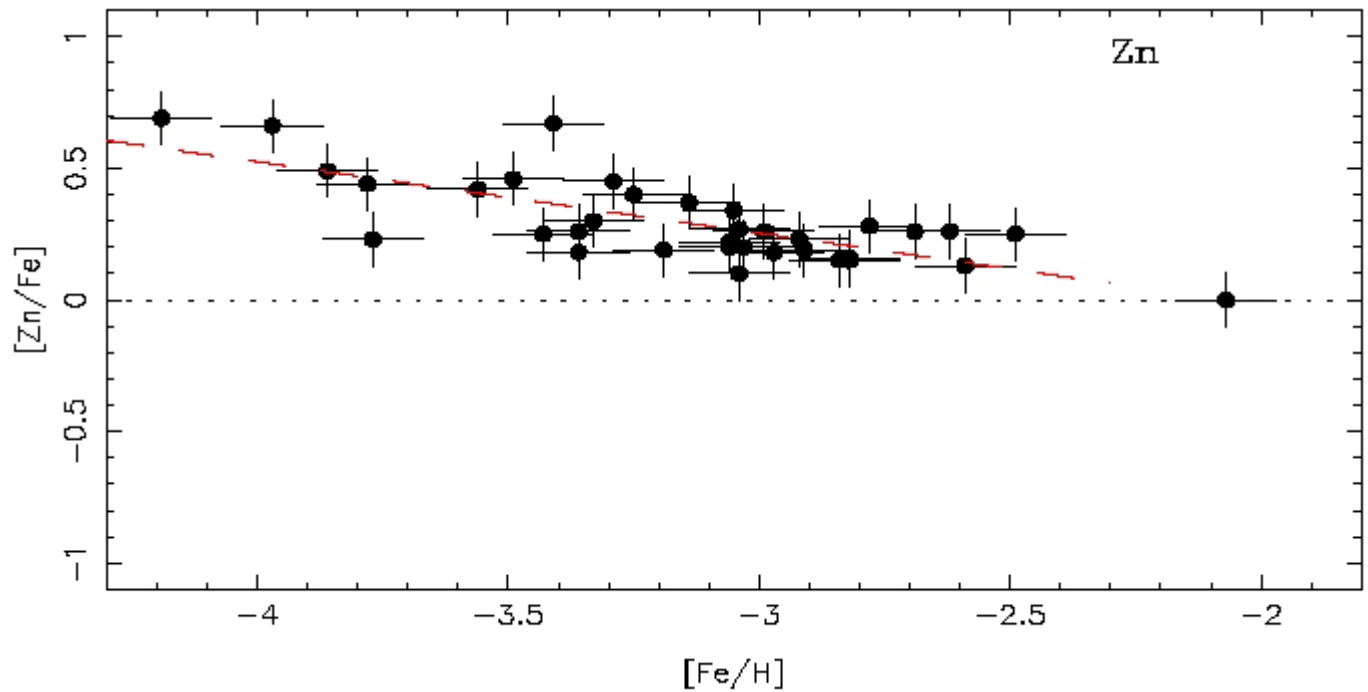




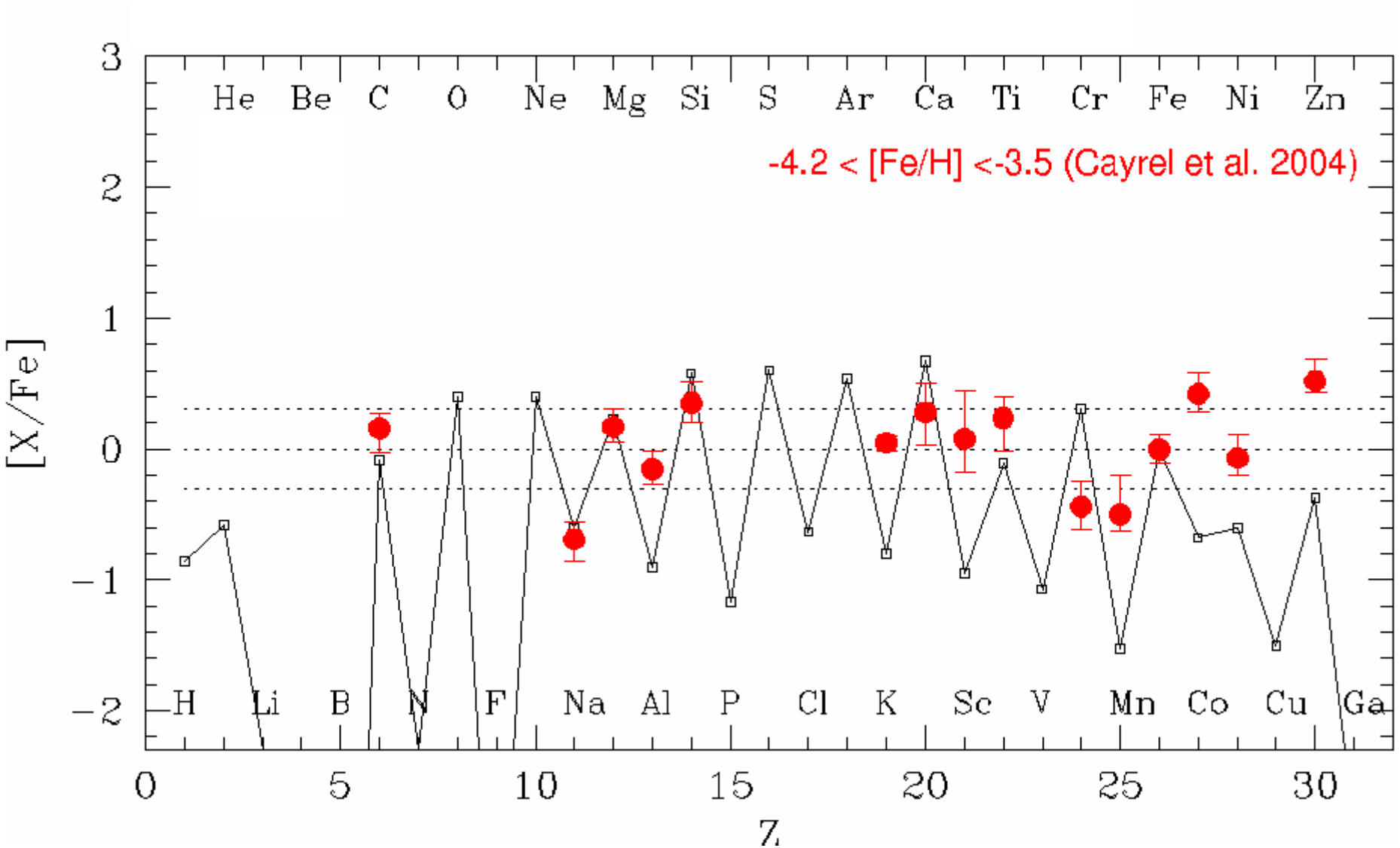




[Zn/Fe]: Cayrel et al. (2003)

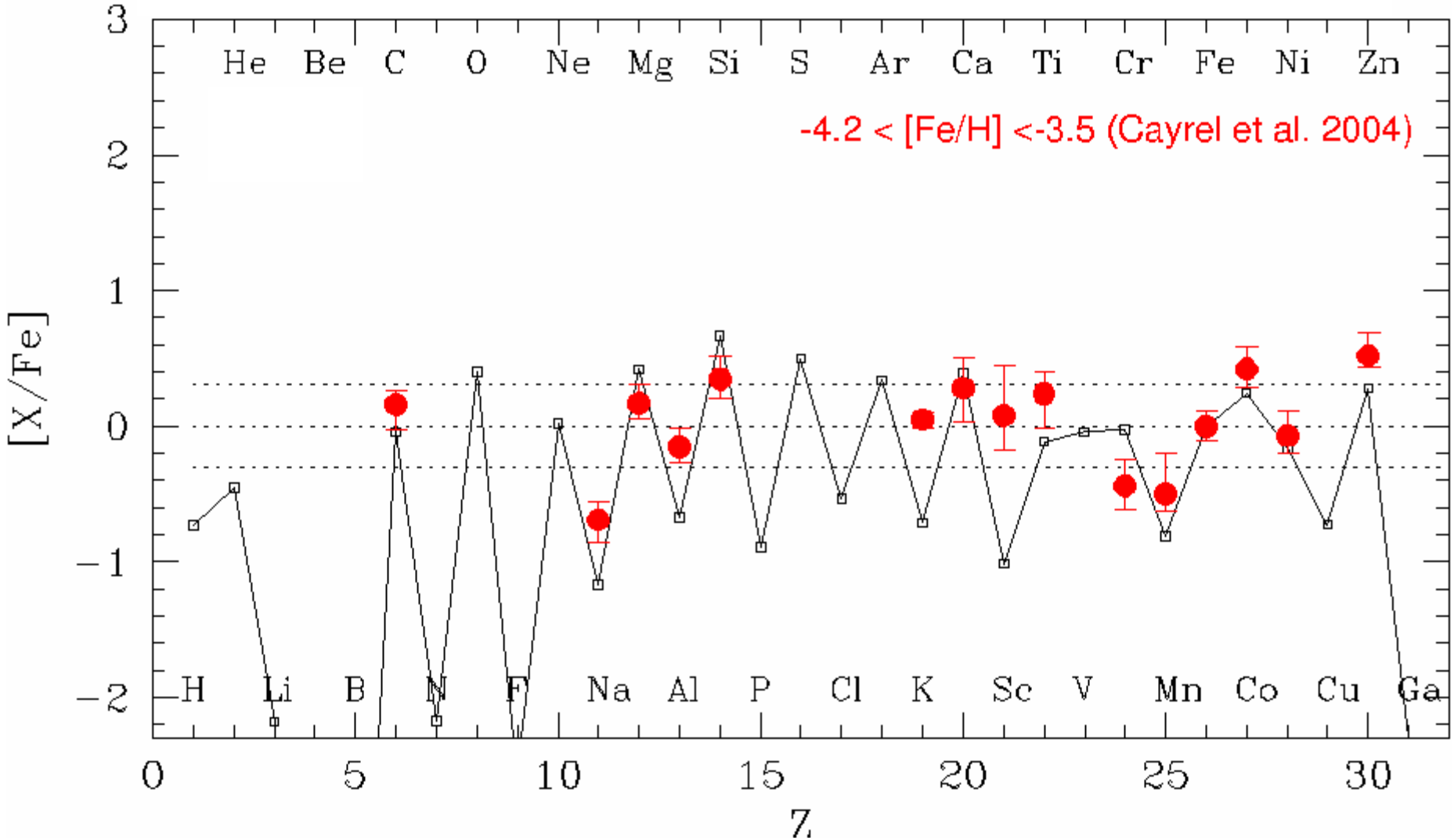


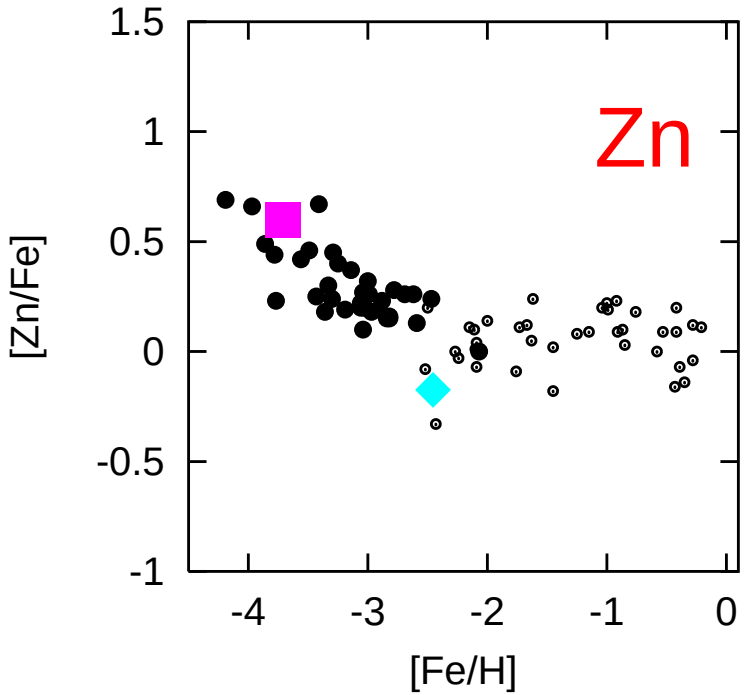
EMP stars $25M_{\odot}$, E_{51}=1.5, $M(Fe)=0.14M_{\odot}$

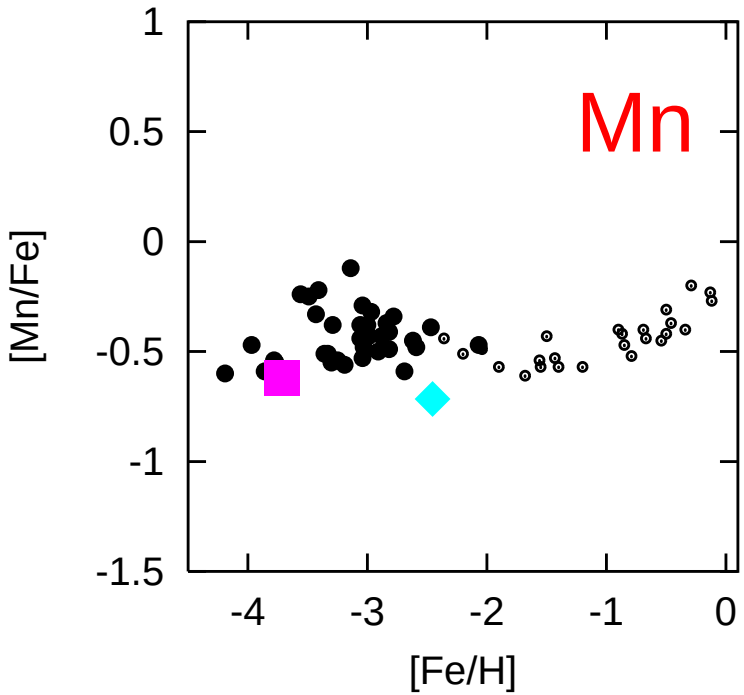


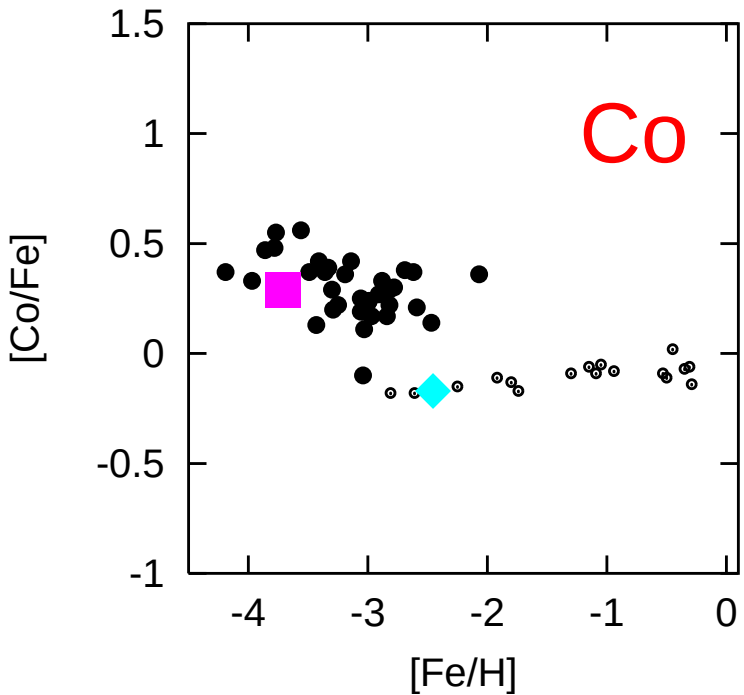
EMP stars

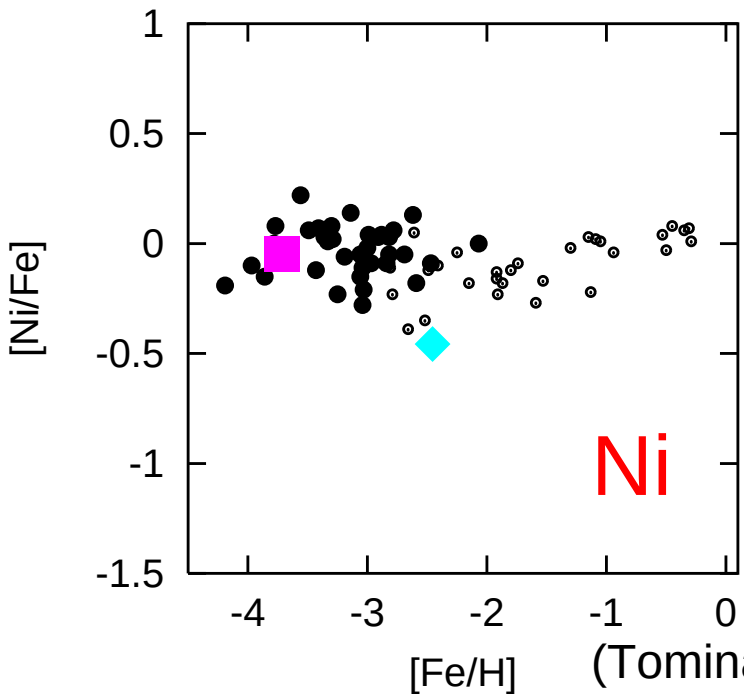
Mixing-Fallback Model
$25M_{\odot}$, E_{51}=20, M(Fe)=$0.10M_{\odot}$







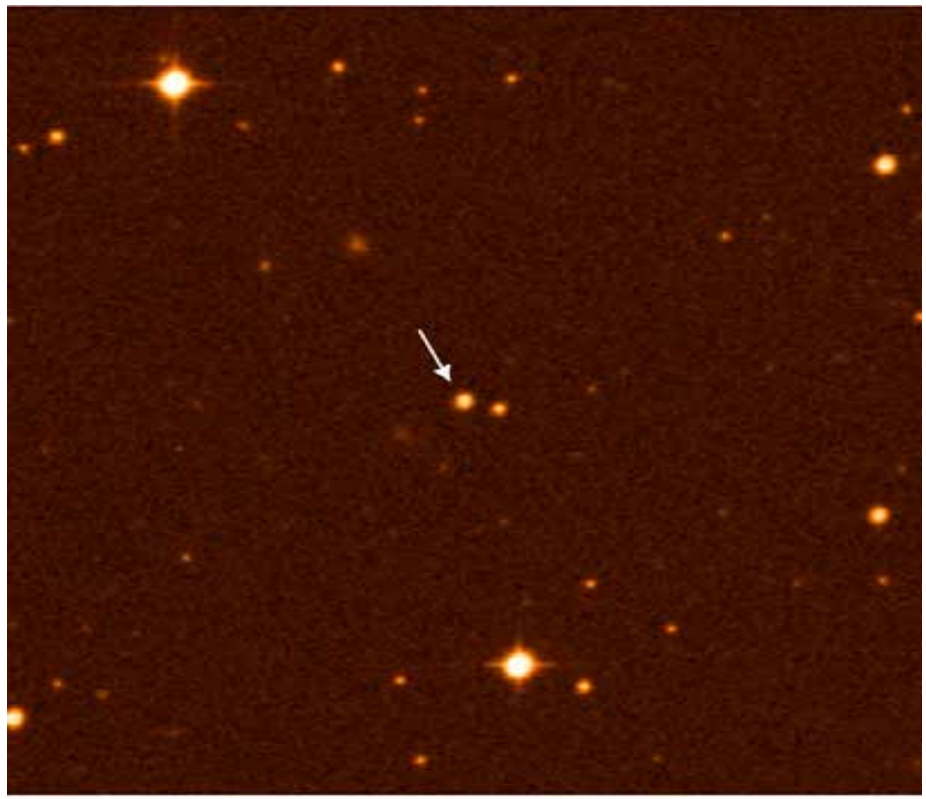




(Tominaga et al.)

Hyper Metal Poor star: HE0107-5240

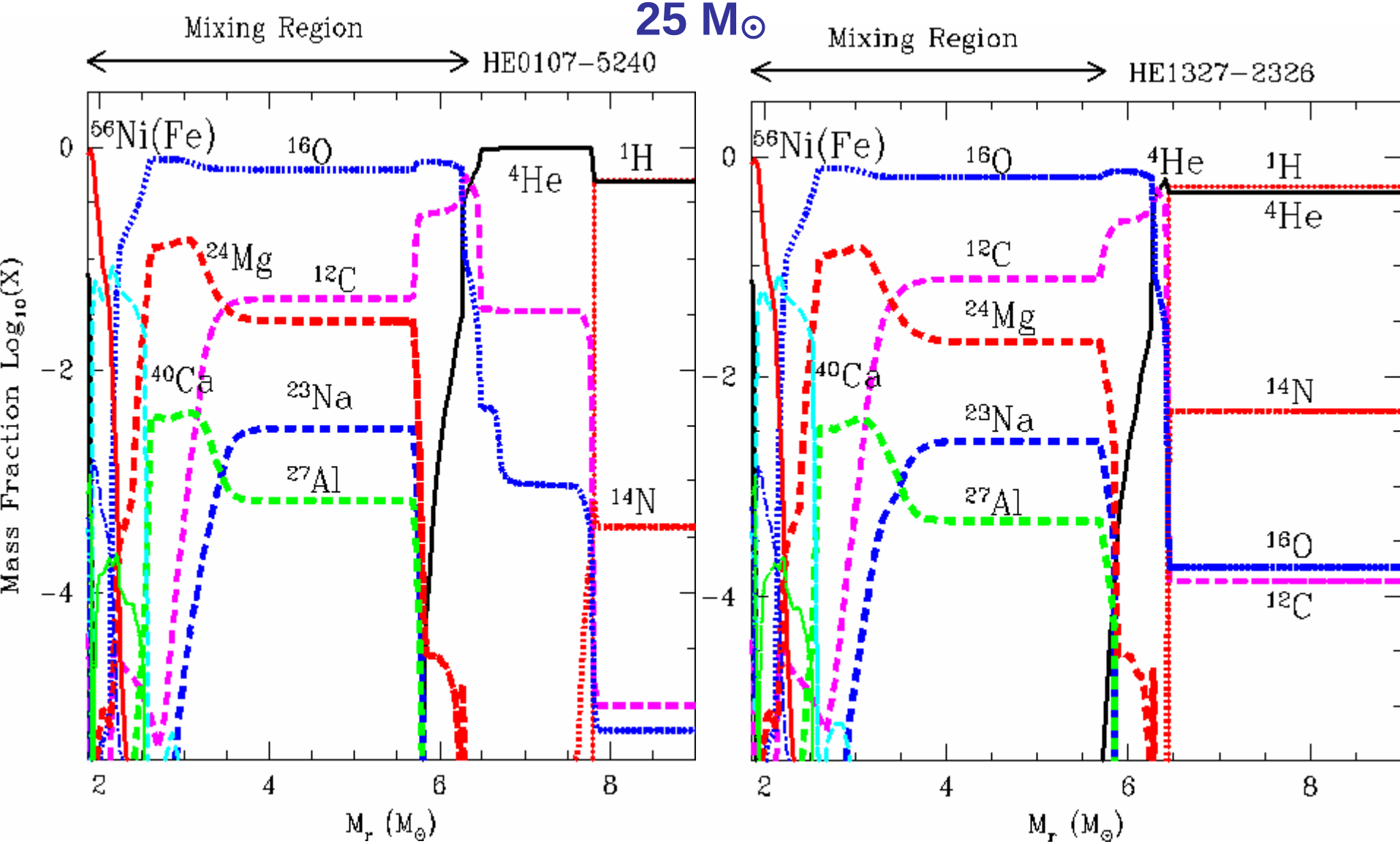
- Discovery:
  (Christrieb et al. 2002)
- Red-giant ~ 0.8 $M_{\odot}$
- **[Fe/H] ~ - 5.2**
  [C/Fe] ~ + 4
- Pop III (first generation) or Second generation?
- Formation of Pop III low mass star?



Abundance distribution

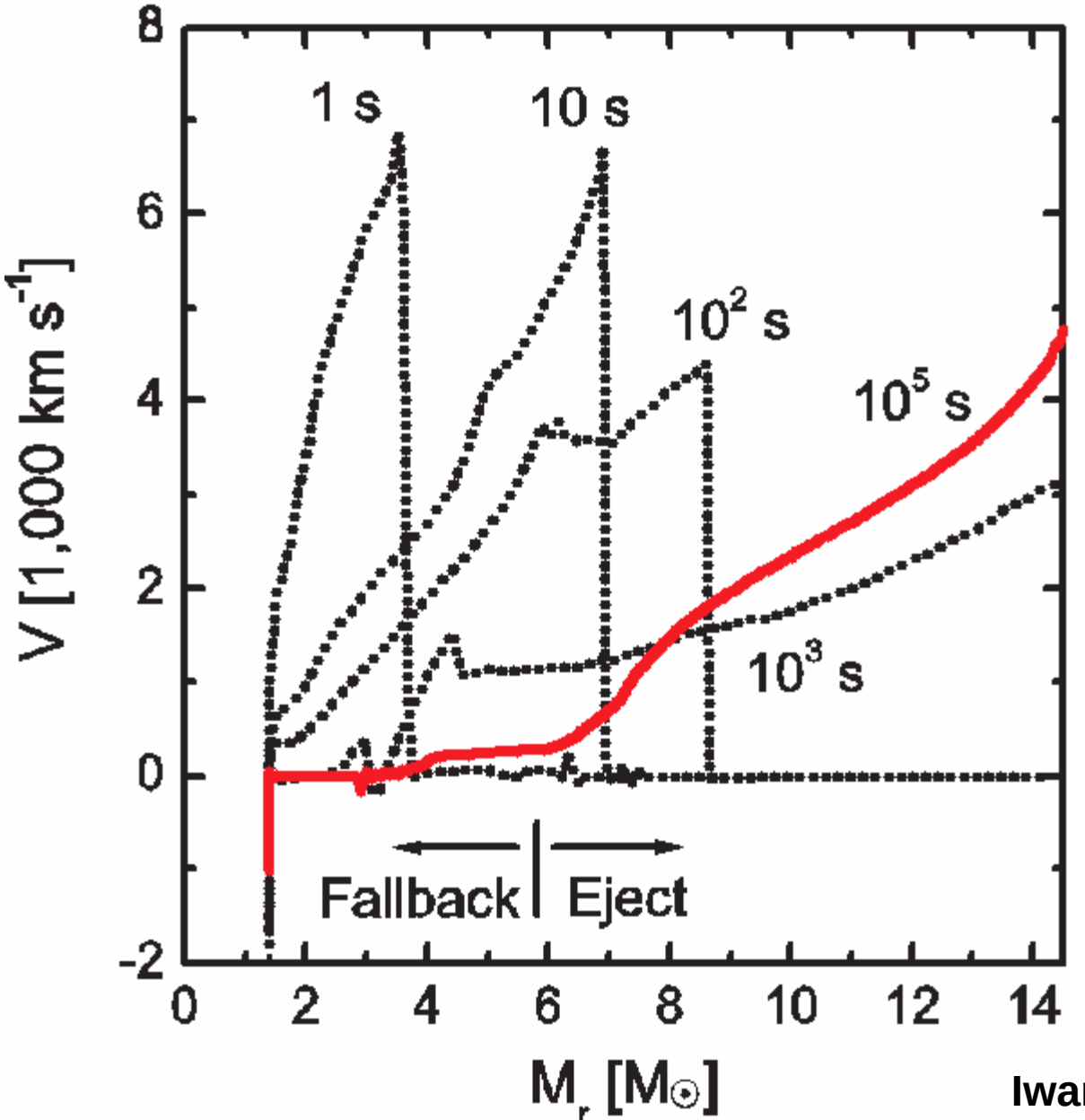
HE01075240(E_{51}=0.71) **HE1327-2328(E_{51}=0.74)**

25 $M_\odot$



Iwamoto et al. (Science 2005)

Fallback & BH formation

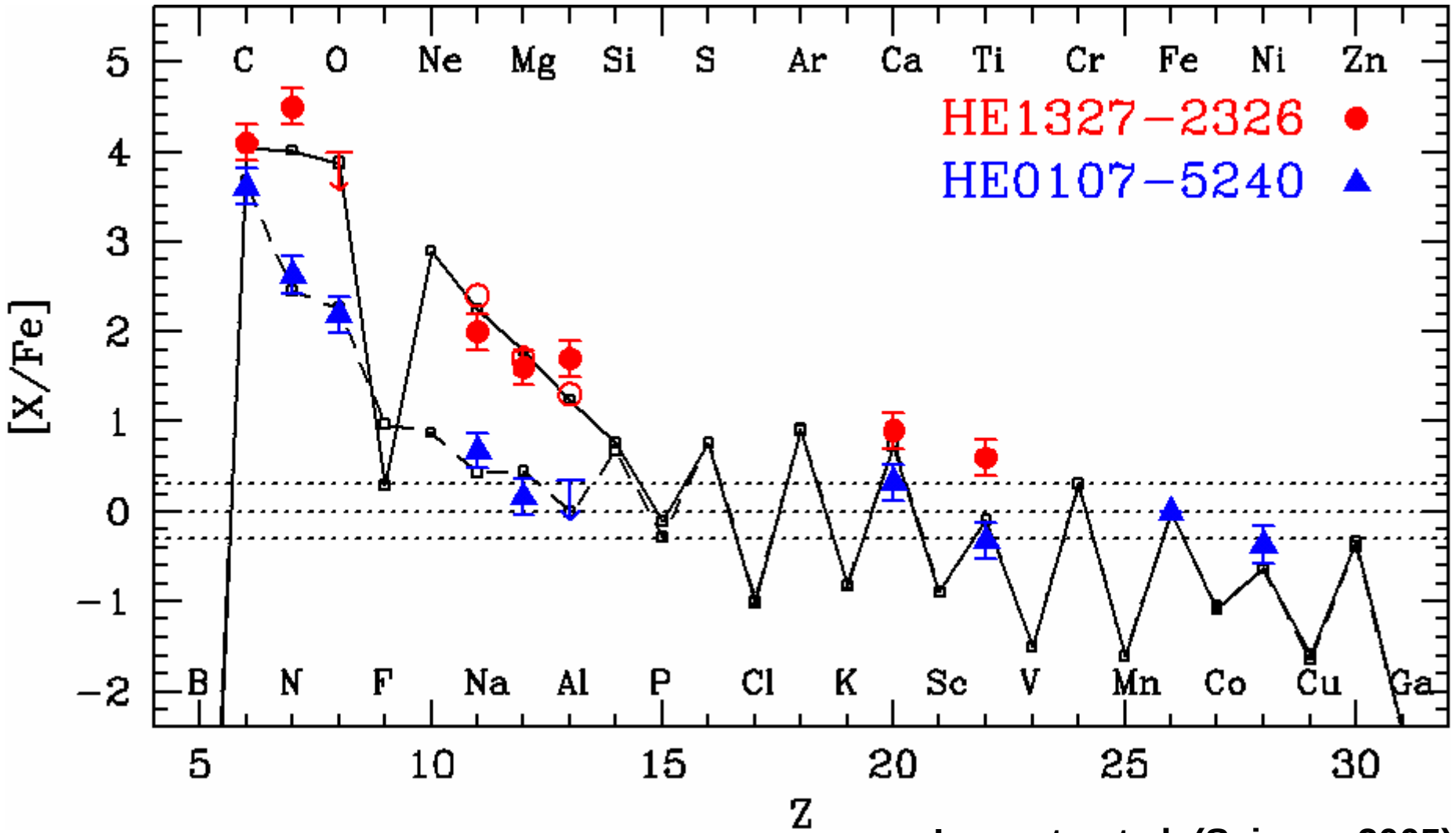


M=25 $M_\odot$

E_{51} = 0.74

Iwamoto et al. (2005)

Hyper Metal Poor (HMP) stars



Iwamoto et al. (Science 2005)

The First Star Candidates

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

→ GR instability → Collapse

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

→ Collapse (& Explosion)

→ IMBH → ICM, IGM ○

$M \sim 130 - 300 M_\odot$:

→ Pair Instability → Nuclear Explosion

[Zn/Fe] < −0.8

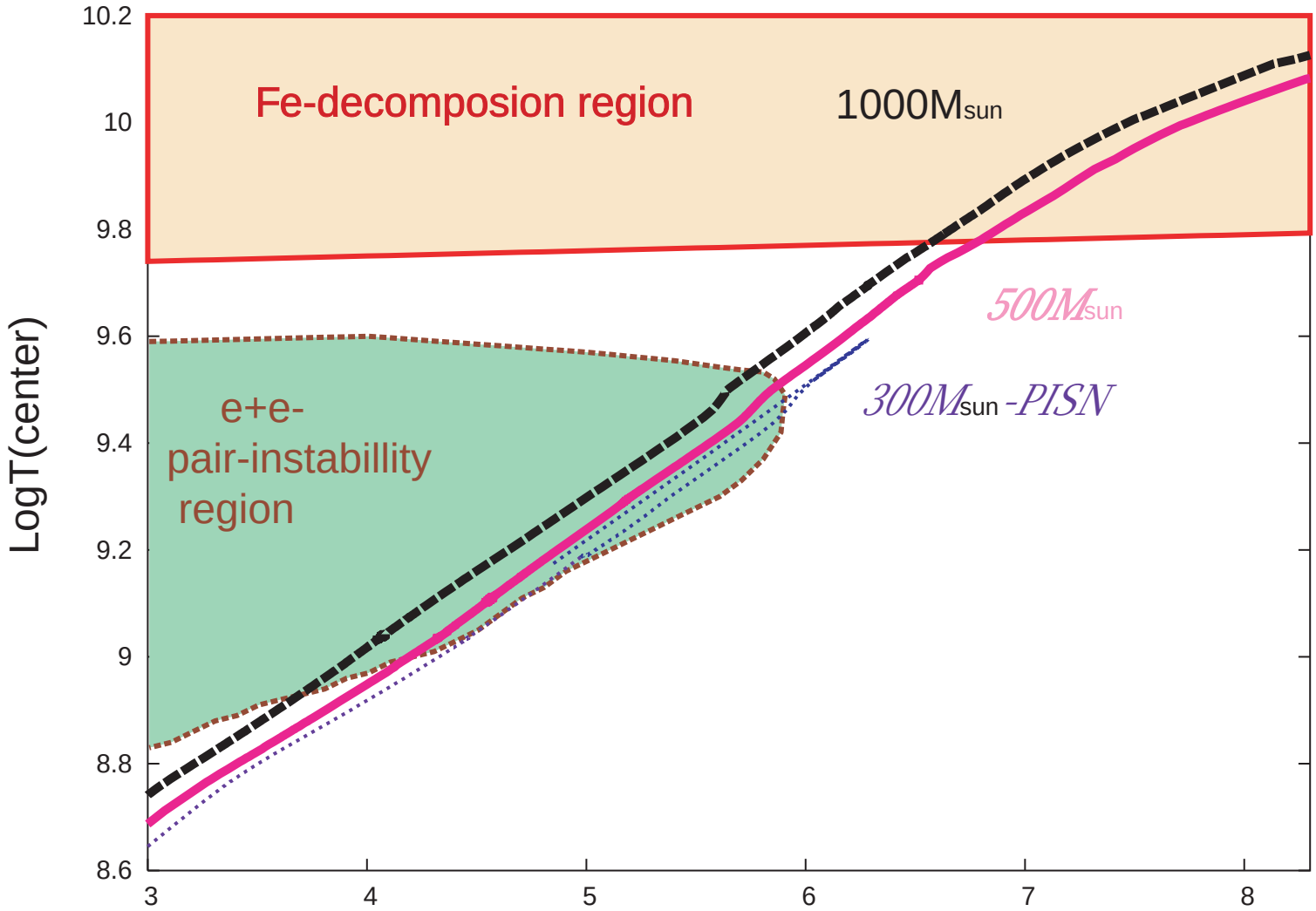
[C/Fe] < 0 too much Fe

$M \sim 8 - 130 M_\odot$:

→ Core Collapse → **Hypernovae**

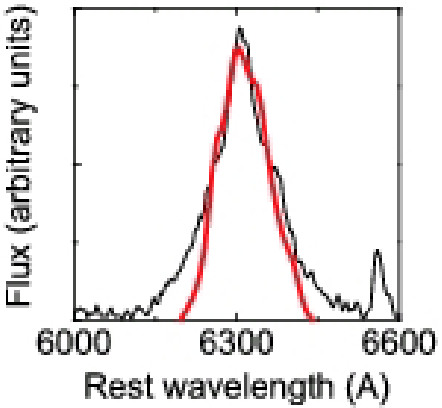
→ **SNe II**

Very Massive Stars: Collapse → Jet-induced explosion ?



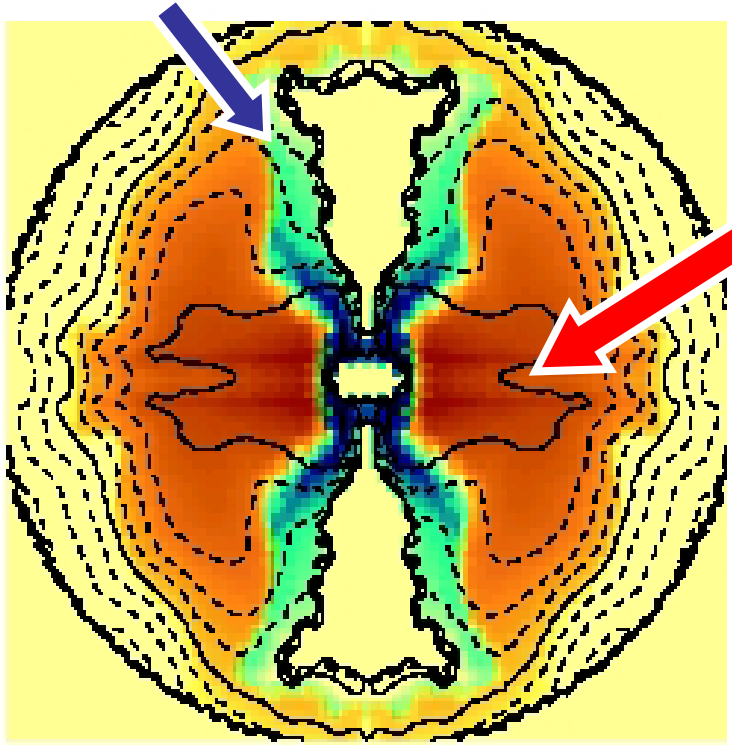
Fryer et a. 2001 Ohkubo et al. 2005

Hypernova: Bipolar Explosion



^{56}Fe

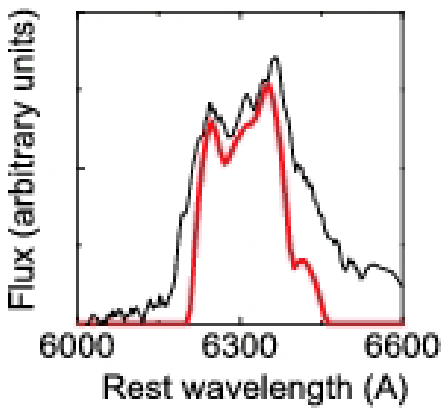
1998bw



^{16}O

2003jd

[OI] 6300A (SUBARU)

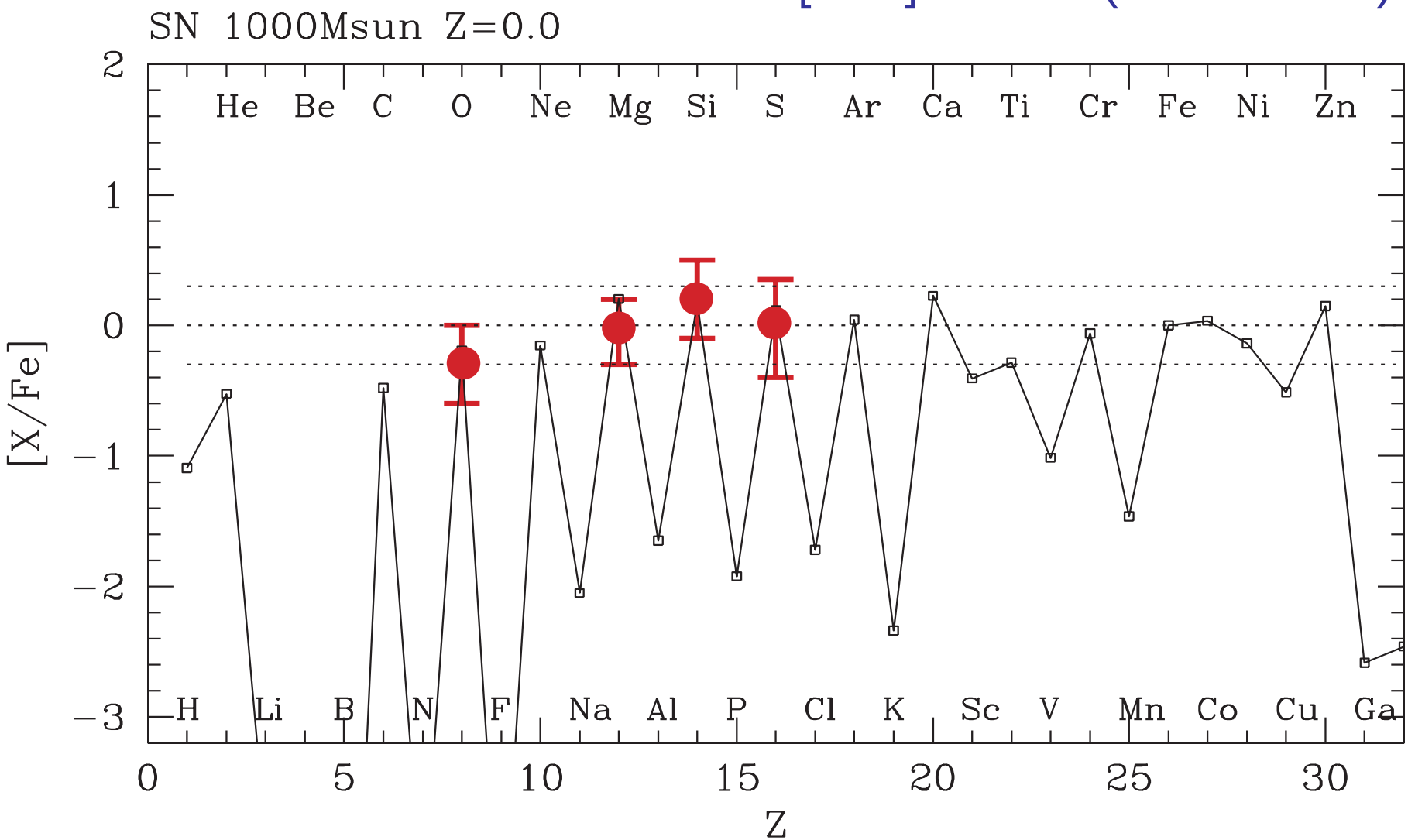


Maeda et al. (2002, 2005)
Mazzali et al. (Science 2005)

Core Collapse VMS vs. ICM, IGM

E ~ 2e54 erg; M(Fe) ~ 5 Ms

[C/Si] ~ - 0.7 (- 0.2 in IGM)



First Supernovae

[Fe/H] : -5 -4 -3 -2.5

Faint SNe

Hypernovae

Normal SNe

Black-Hole Forming Supernovae (20-130$M_\odot$)

⇒ **First Black Hole** > 2~6$M_\odot$

Faint SNe (High and Low energy) ⇒ **C,O-rich ejecta**

⇒ **Efficient Cooling of ISM**

⇒ **Formation of Low Mass C,O-rich 2nd Generation Stars**