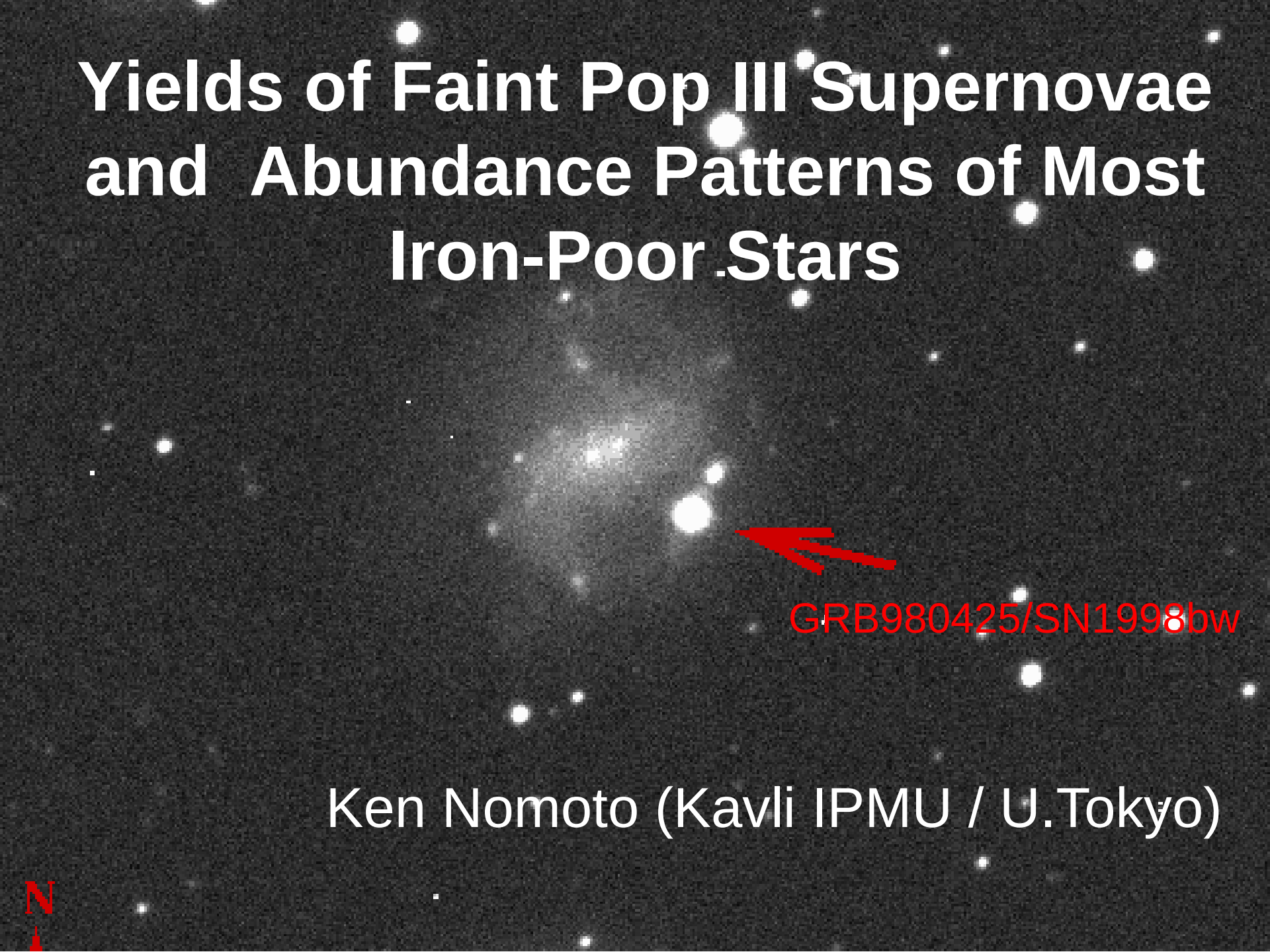
Yields of Faint Pop III Supernovae and Abundance Patterns of Most Iron-Poor Stars



Ken Nomoto (Kavli IPMU / U.Tokyo)

Tim, Welcome to the Red Vest Club !!

Recent Members 1

Recent Members 2

KITP/UCSB Supernova Workshop

(Santa Barbara 1997 July - December)

Organized by Adam Burrows, Friedel Thielemann, Ken Nomoto

KITP Supernova Workshop (1997)

KITP/UCSB Santa Barbara (1997 July – December)

Organized by Adam Burrows, Friedel Thielemann, Ken Nomoto

1) **EMP stars**: Abundance patterns of Mn, Cr, Ni, Fe, Zn

➔ Organizer's paper

2) Discovery of **SN 1997ef** (Sano; November 1997)

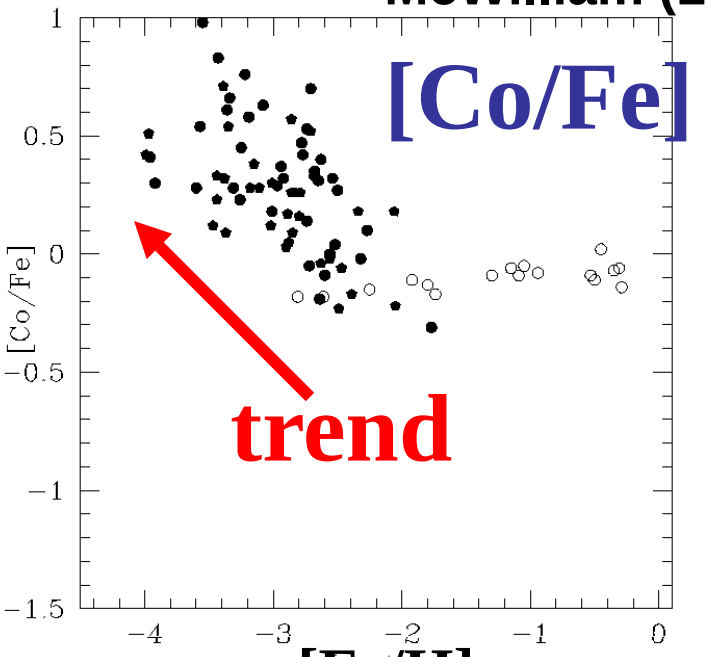
peculiar spectra ➔ **Broad-line SN Ic**

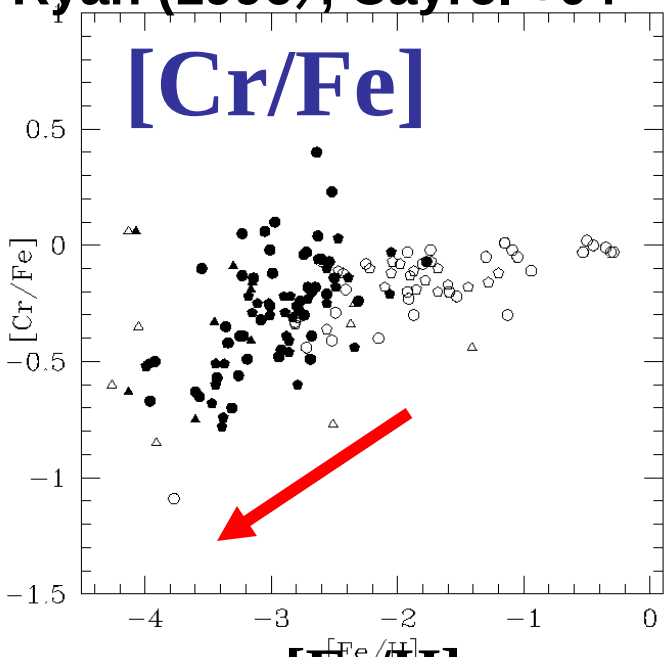
➔ Discovery of GRB980425 = SN 1998bw

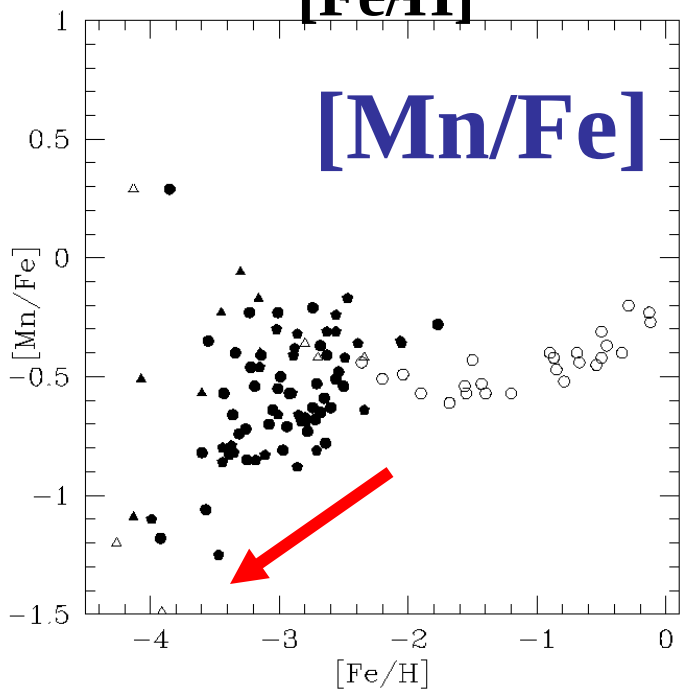
➔ Energetic Hypernova models

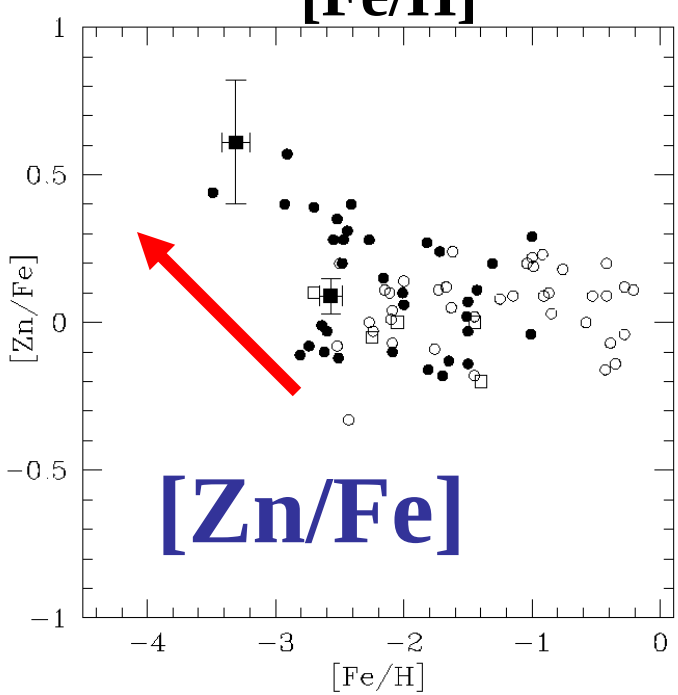
3) Connecting Hypernovae and EMP stars

McWilliam (1995), Ryan (1996), Cayrel +04

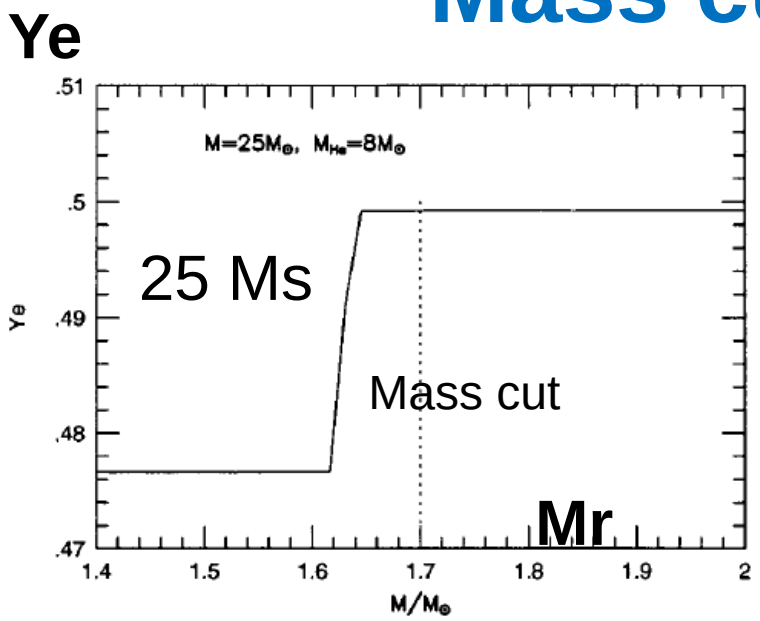


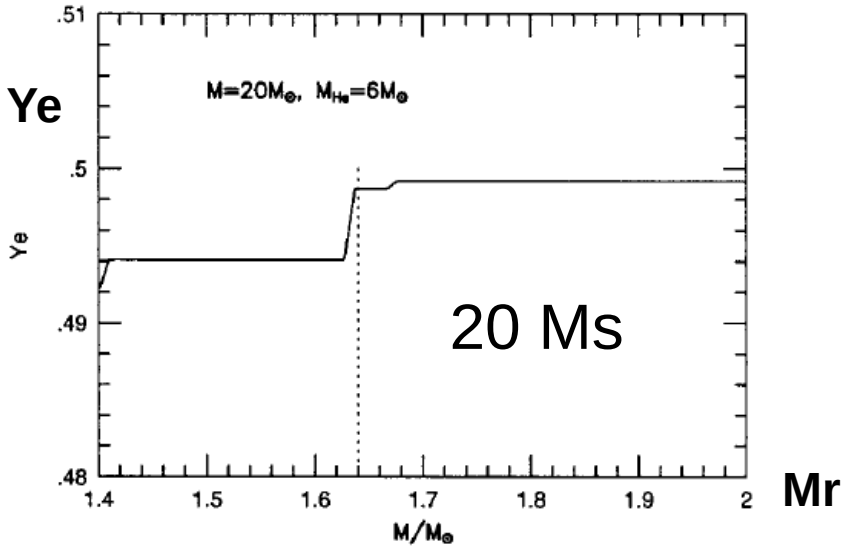


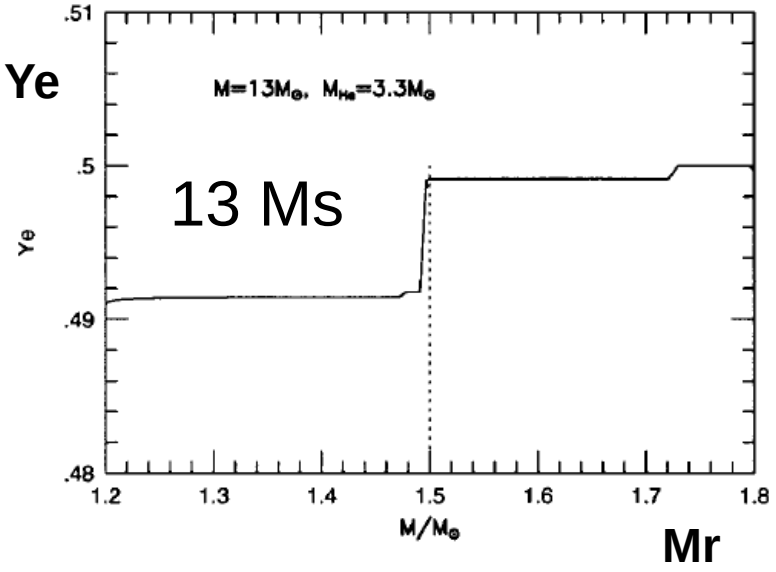


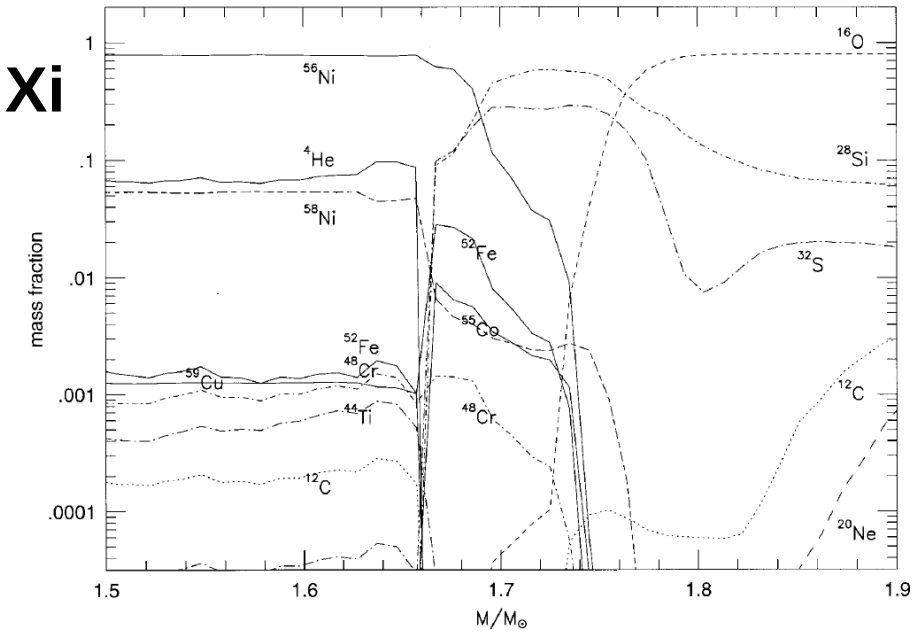


Mass cut ➔ Yields(Y_e)









(Nakamura et al. 1999)

THE ASTROPHYSICAL JOURNAL, 517:193–208, 1999 May 20

NUCLEOSYNTHESIS IN TYPE II SUPERNOVAE AND THE ABUNDANCES IN METAL-POOR STARS

TAKAYOSHI NAKAMURA, HIDEYUKI UMEDA,[1] AND KEN'ICHI NOMOTO[1,2]
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Department of Astronomy, The University of Arizona, Tucson, AZ 85721
Received 1998 May 26; accepted 1998 December 18

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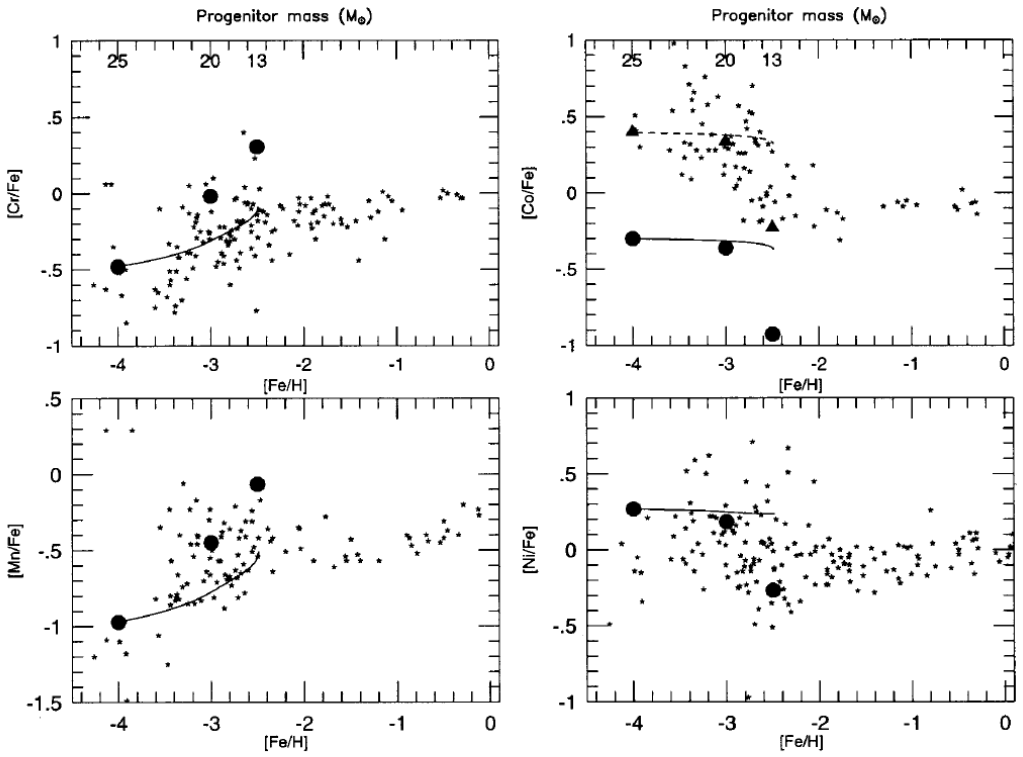
[Cr/Fe]

[Co/Fe]

[Mn/Fe]

[Ni/Fe]



[Fe/H]

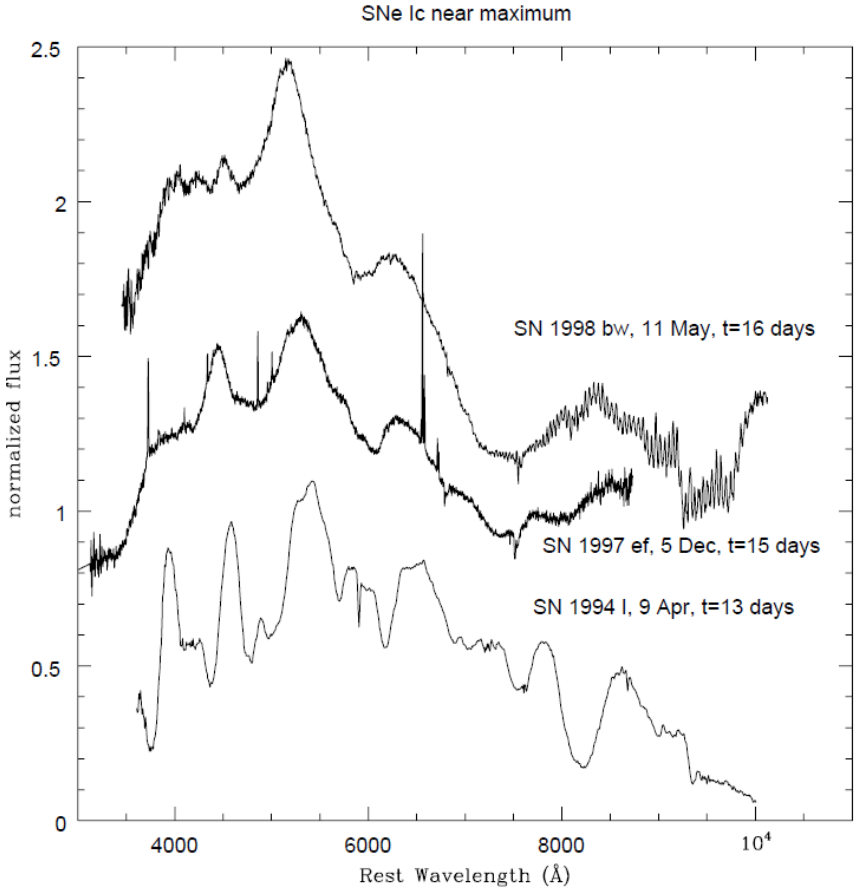
FIG. 11.—Same as Fig. 10, but with models for making stronger contrast in abundance ratios. The model set {A, G, I} in Fig. 9 and Table 5 is used for the solid lines and the filled circles. The dashed line and the filled triangles indicate the models for which the Co yield is multiplied by five for easier comparison with observed data.

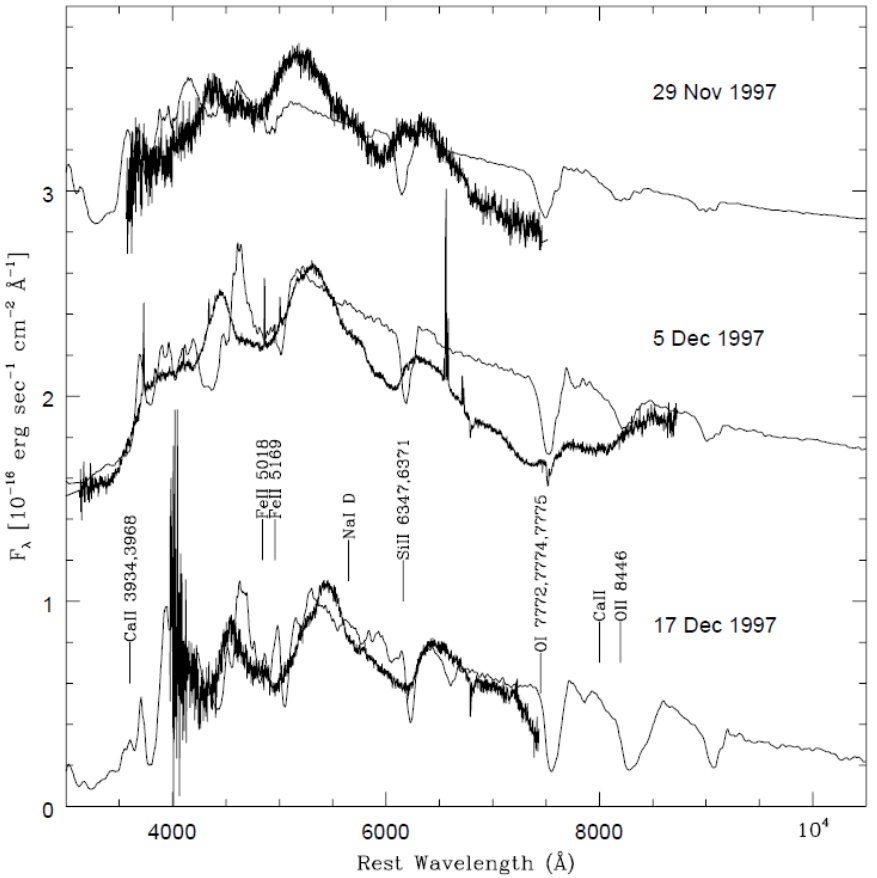
THE ASTROPHYSICAL JOURNAL, 534:660–669, 2000 May 10

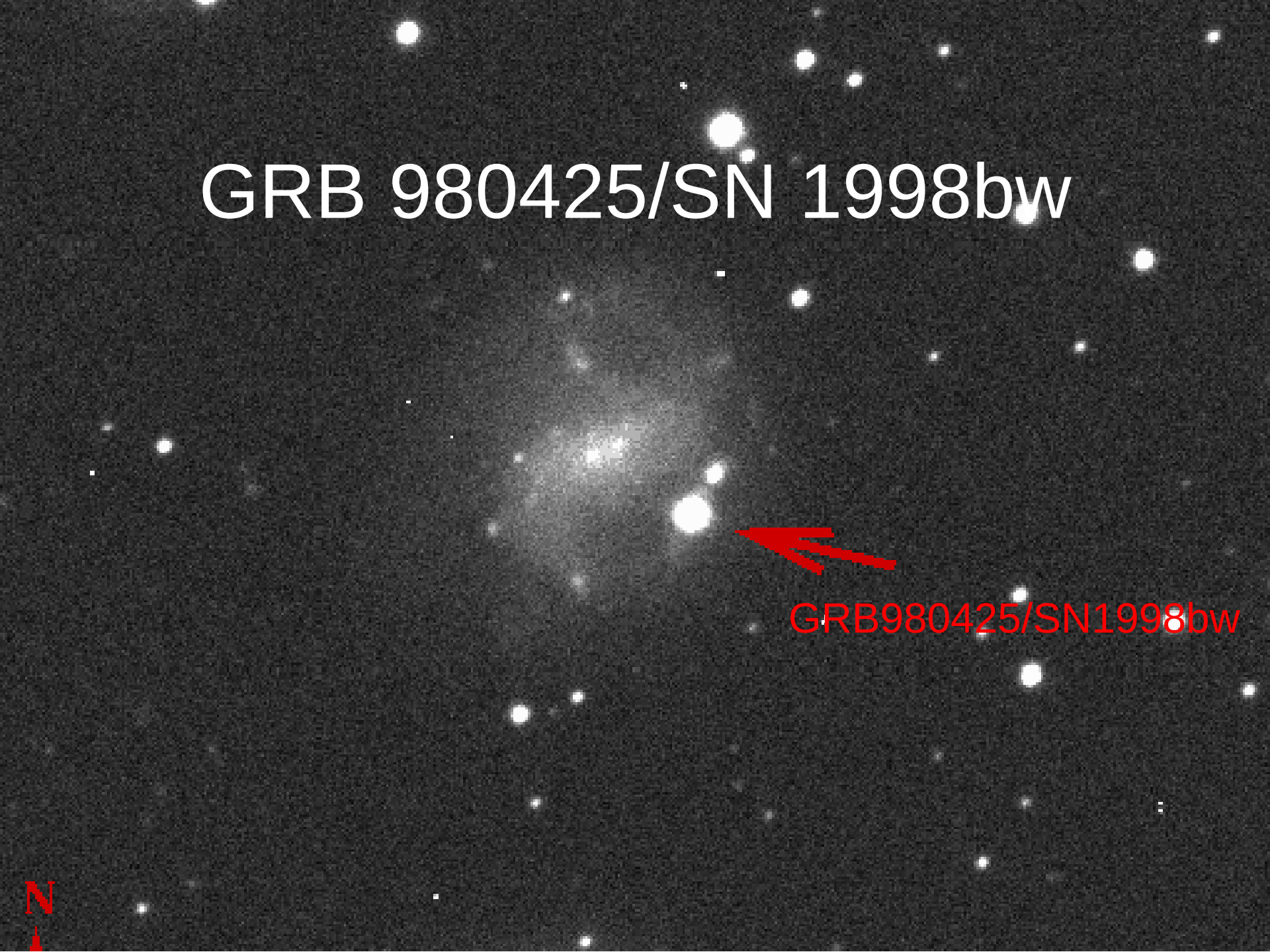
THE PECULIAR TYPE Ic SUPERNOVA 1997ef: ANOTHER HYPERNOVA

KOICHI IWAMOTO,[1] TAKAYOSHI NAKAMURA,[2] KEN'ICHI NOMOTO,[2,3] PAOLO A. MAZZALI,[3,4] I. JOHN DANZIGER,[4] PETER GARNAVICH,[5] ROBERT KIRSHNER,[5] SAURABH JHA,[5] DAVID BALAM,[6] AND JOHN THORSTENSEN[7]

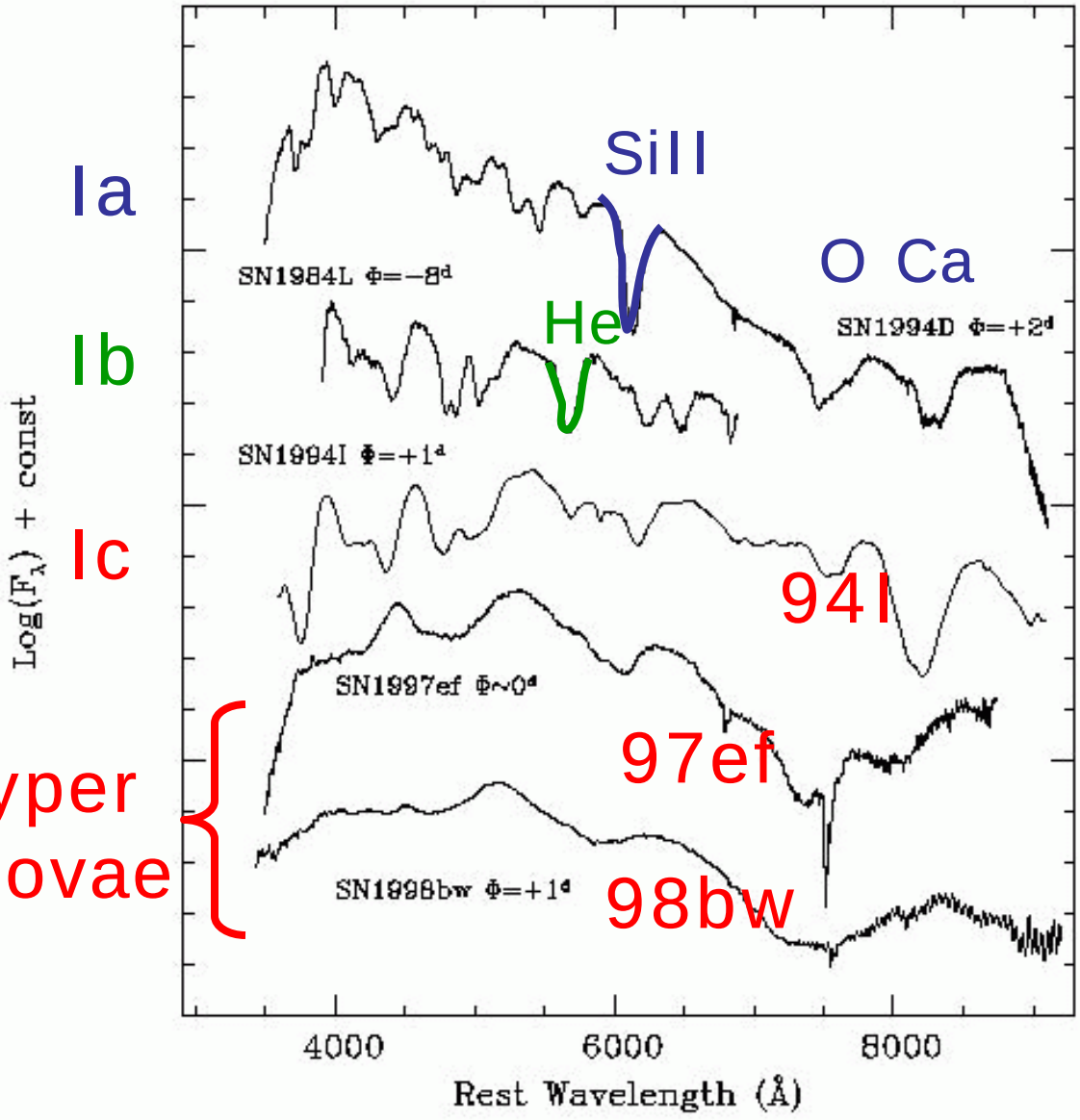
Received 1998 May 26; accepted 2000 January 4






GRB 980425/SN 1998bw
GRB980425/SN1998bw
N

Spectra of Supernovae & Hypernovae



Ic: no H,

no strong He,

no strong Si

Hypernovae:

broad features

↑

blended lines

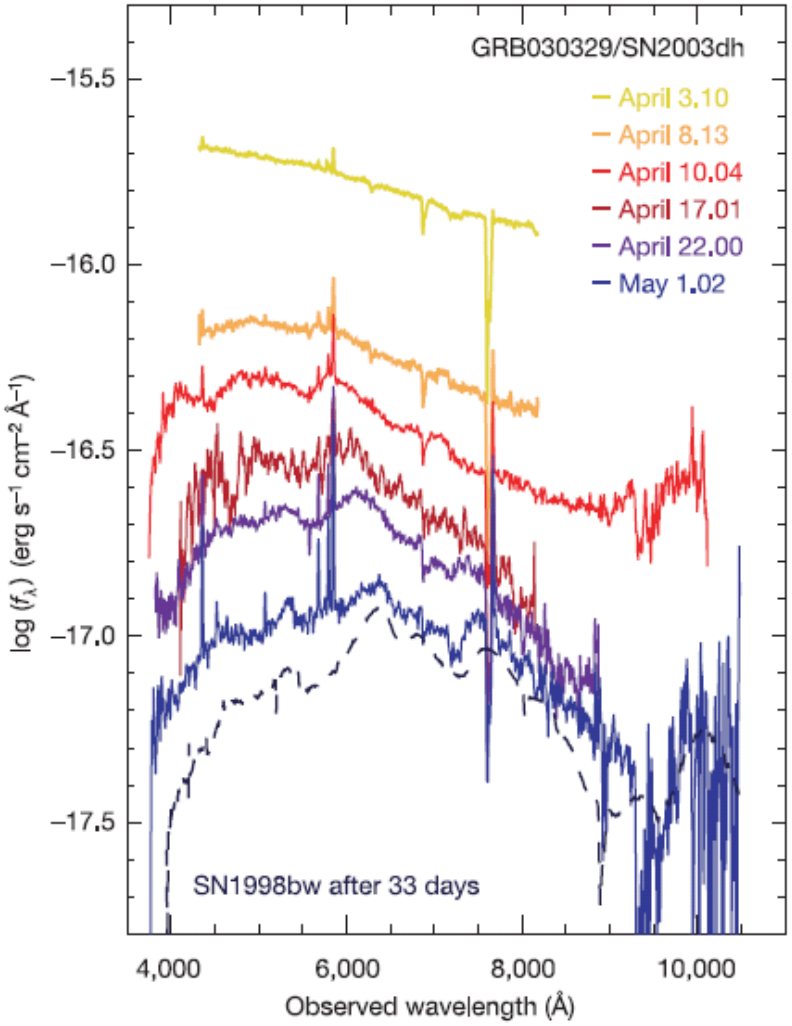
↑

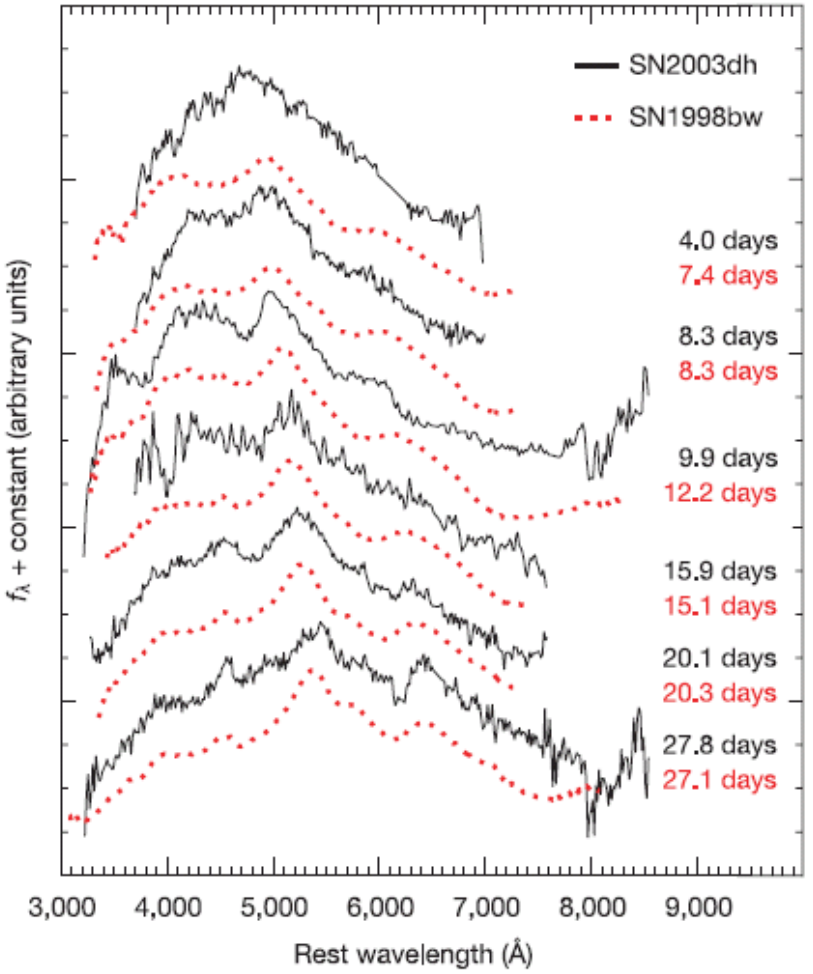
"Large mass at high velocities"

Patat et al. (1999)

GRB-SN Connection

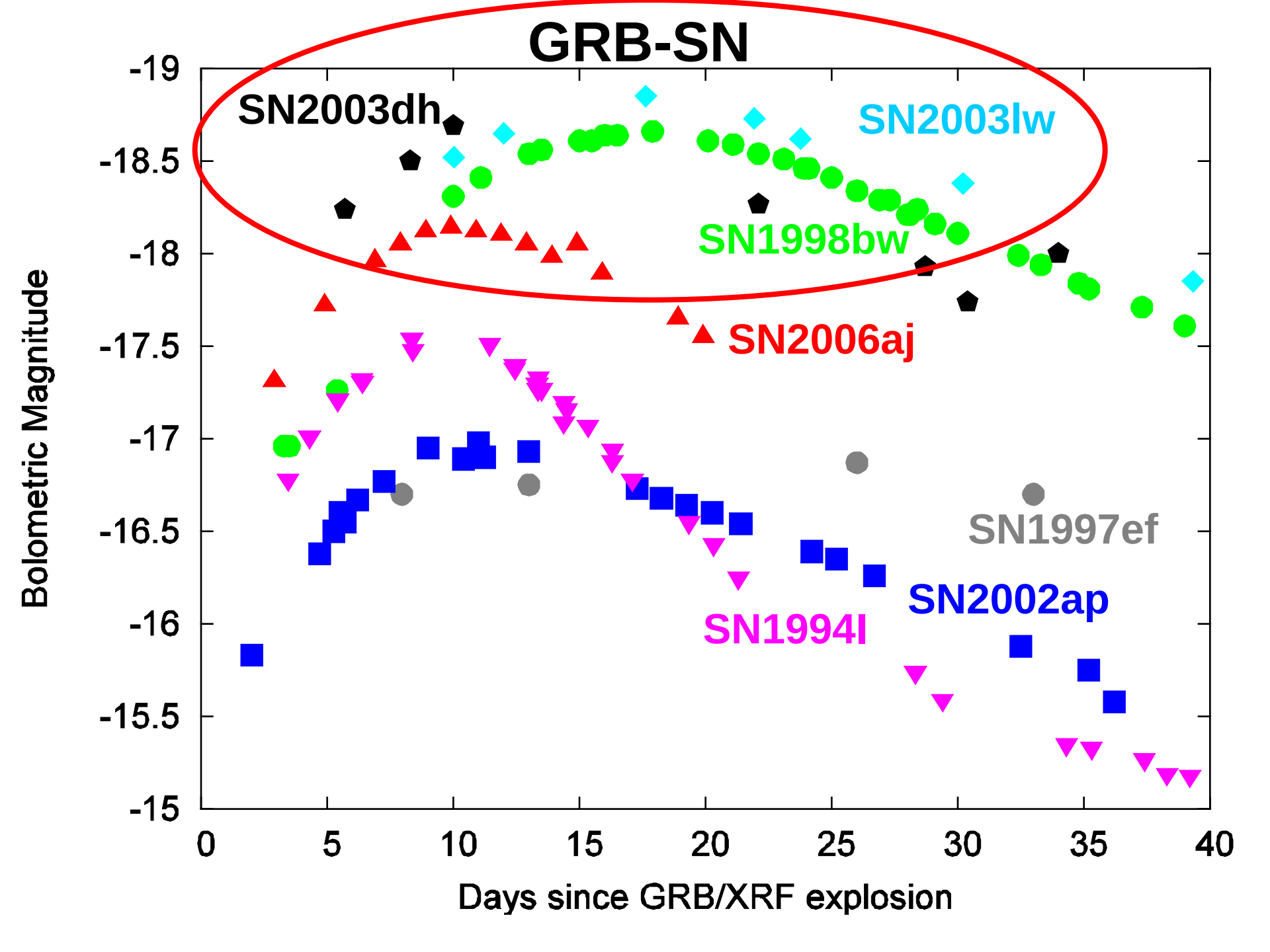
(GRB 030329 / SN 2003dh)





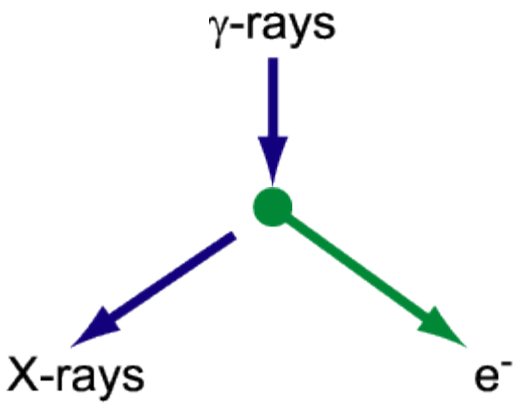
Stanek et al (2003) ;Hjorth et al (2003)

Broad Lines!


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

^{56}Co-decay

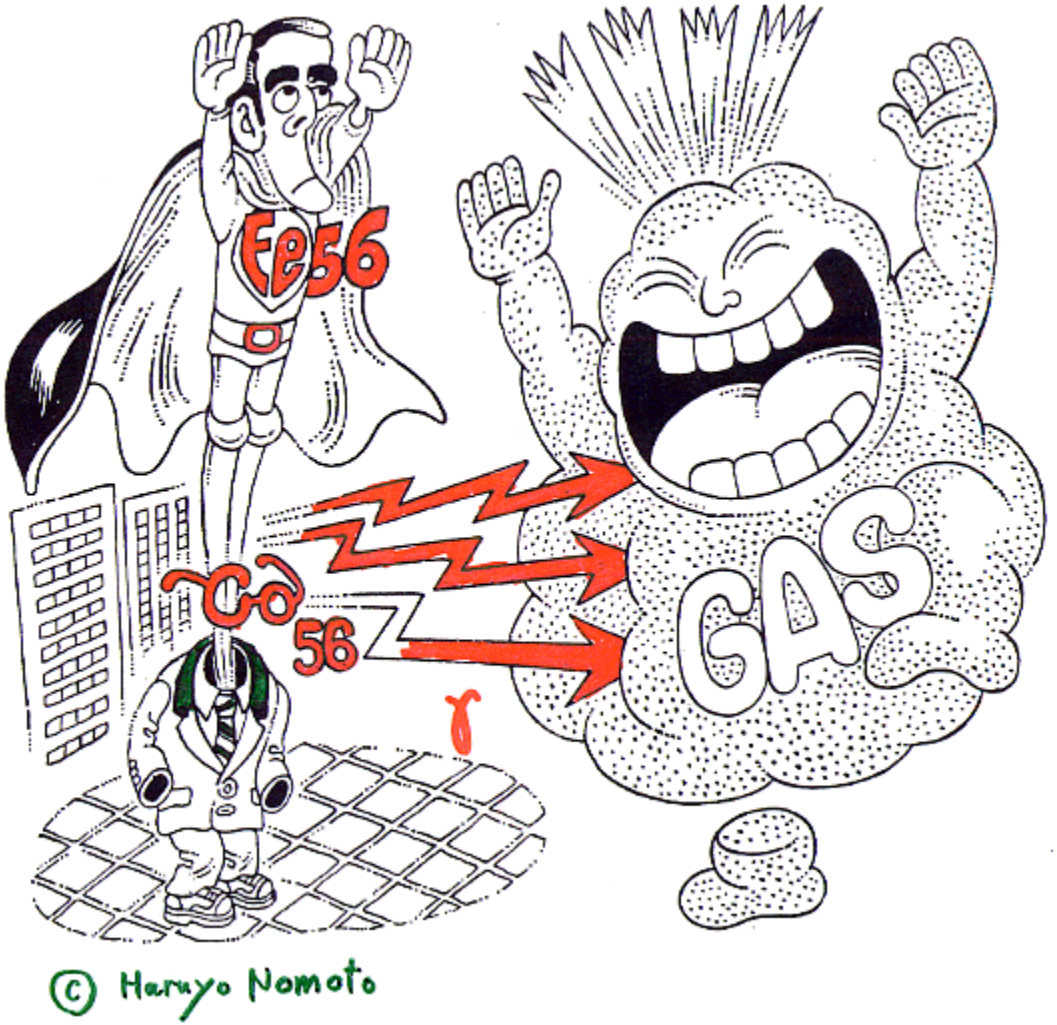
$^{56}Ni \xrightarrow[6.6d]{\gamma} {}^{56}Co \xrightarrow[78d]{\gamma} {}^{56}Fe$



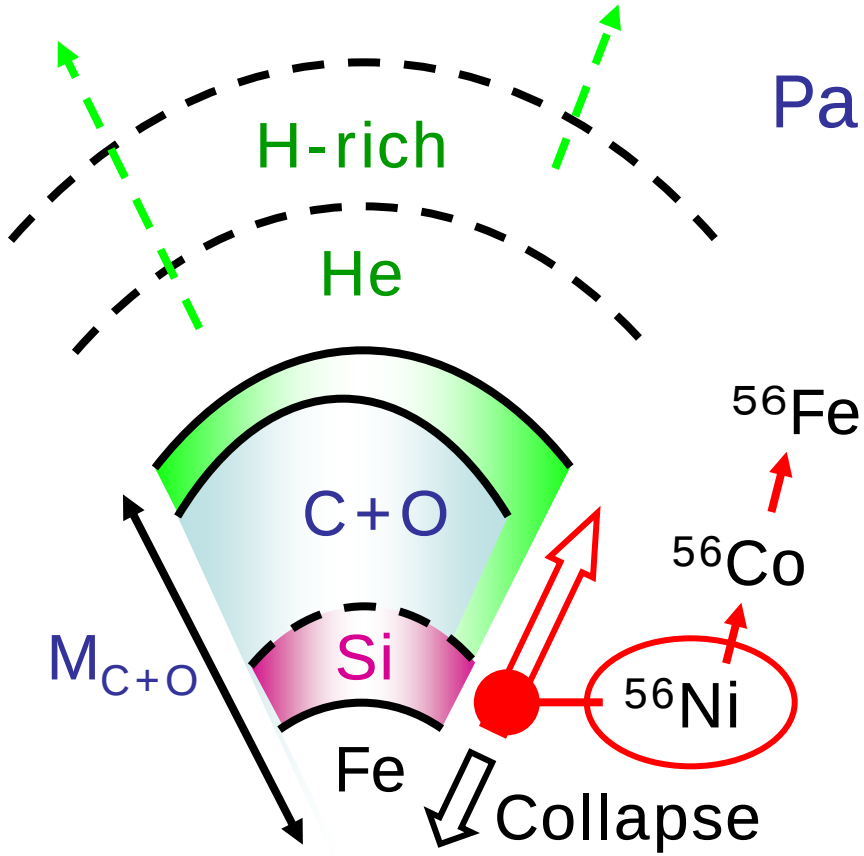
Photoabsorption Excitation/Ionization

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

Shape:M_{ej}



CO Star Models for SNe Ic



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

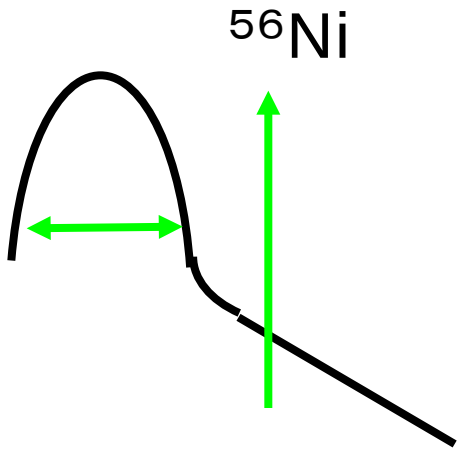
Light Curve — Spectra

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

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

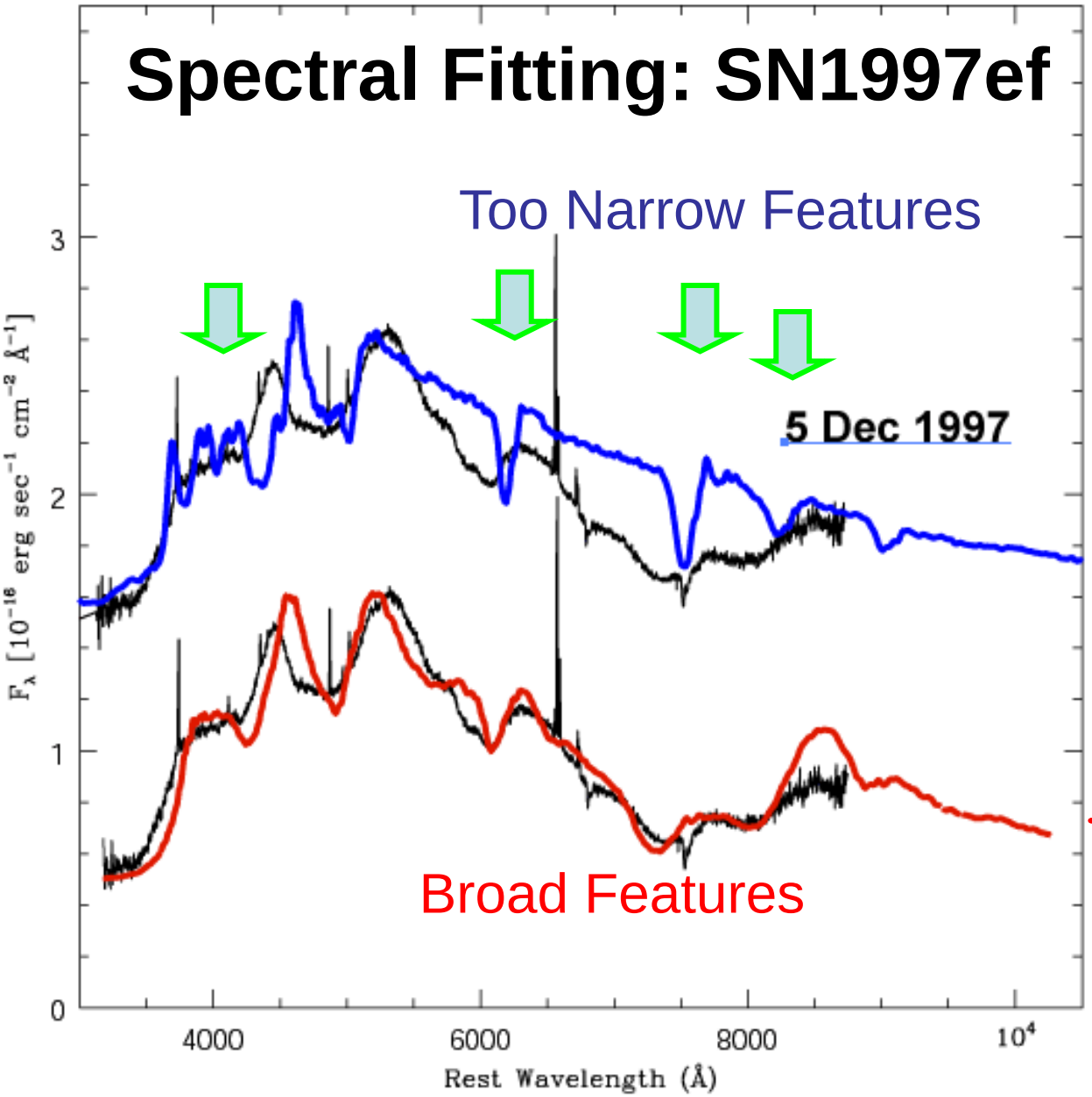
$$\propto \kappa^{1/2} M_{ej}^{3/4} E^{-1/4}$$

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



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

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.

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

Hypernova in Prague

Type II-P
SN 1997D

Very narrow lines.

V < 1000 km s^{-1}.

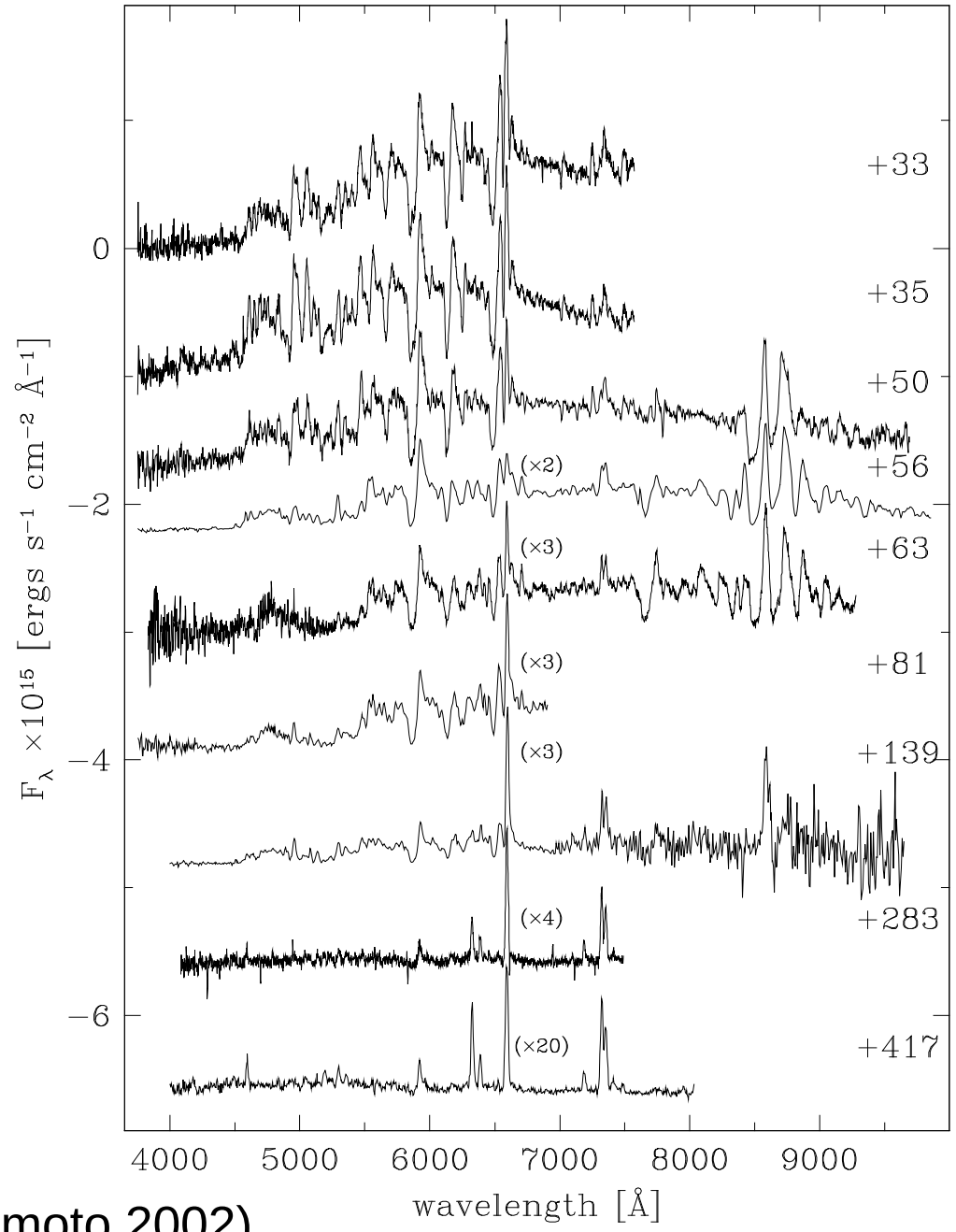
E_K=1-4 × 10^{50}ergs.

V~1000km s^{-1}

2002gd, 1999br

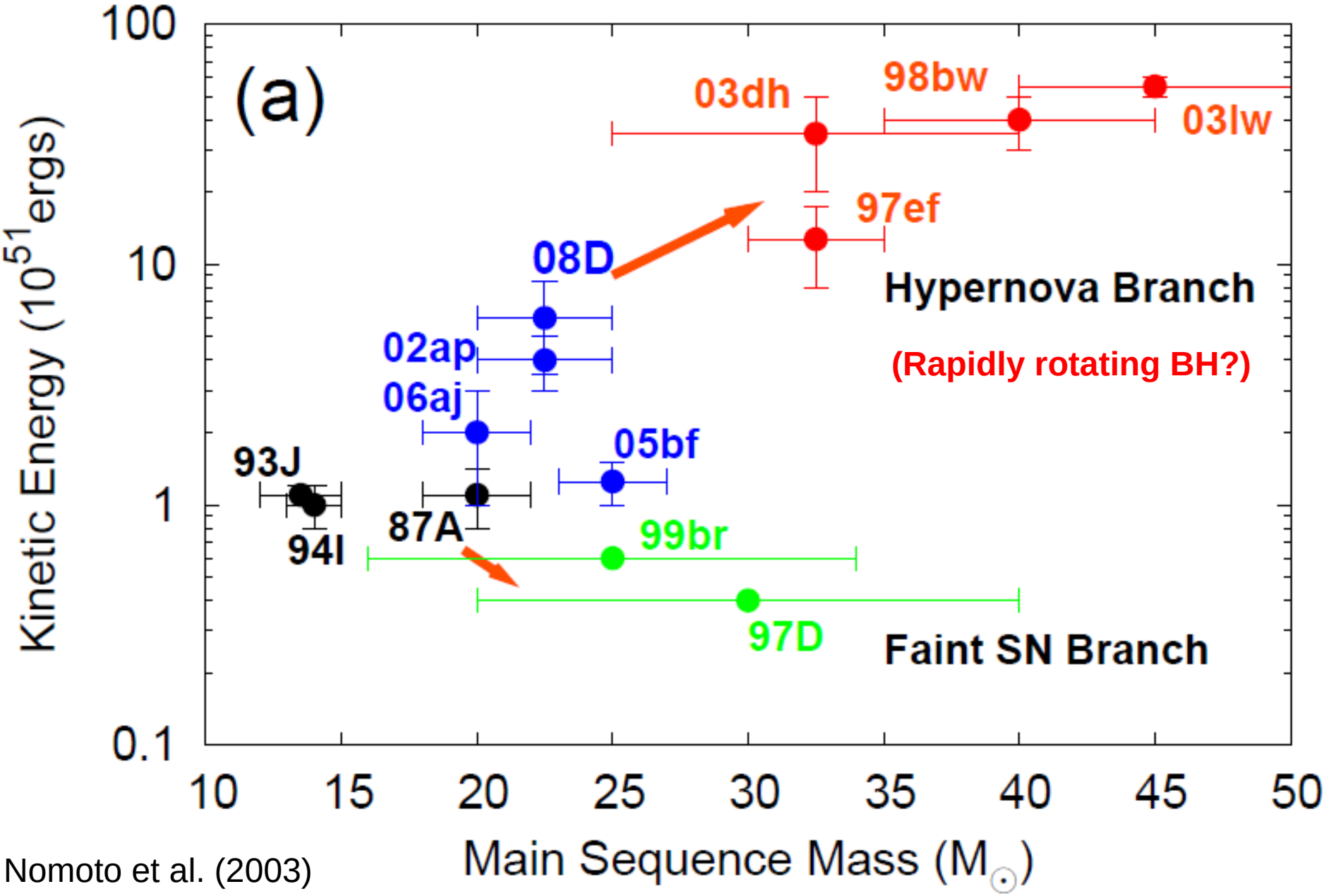
Faint

M(^{56}Ni)~2 × $10^{-3}M_{\odot}$



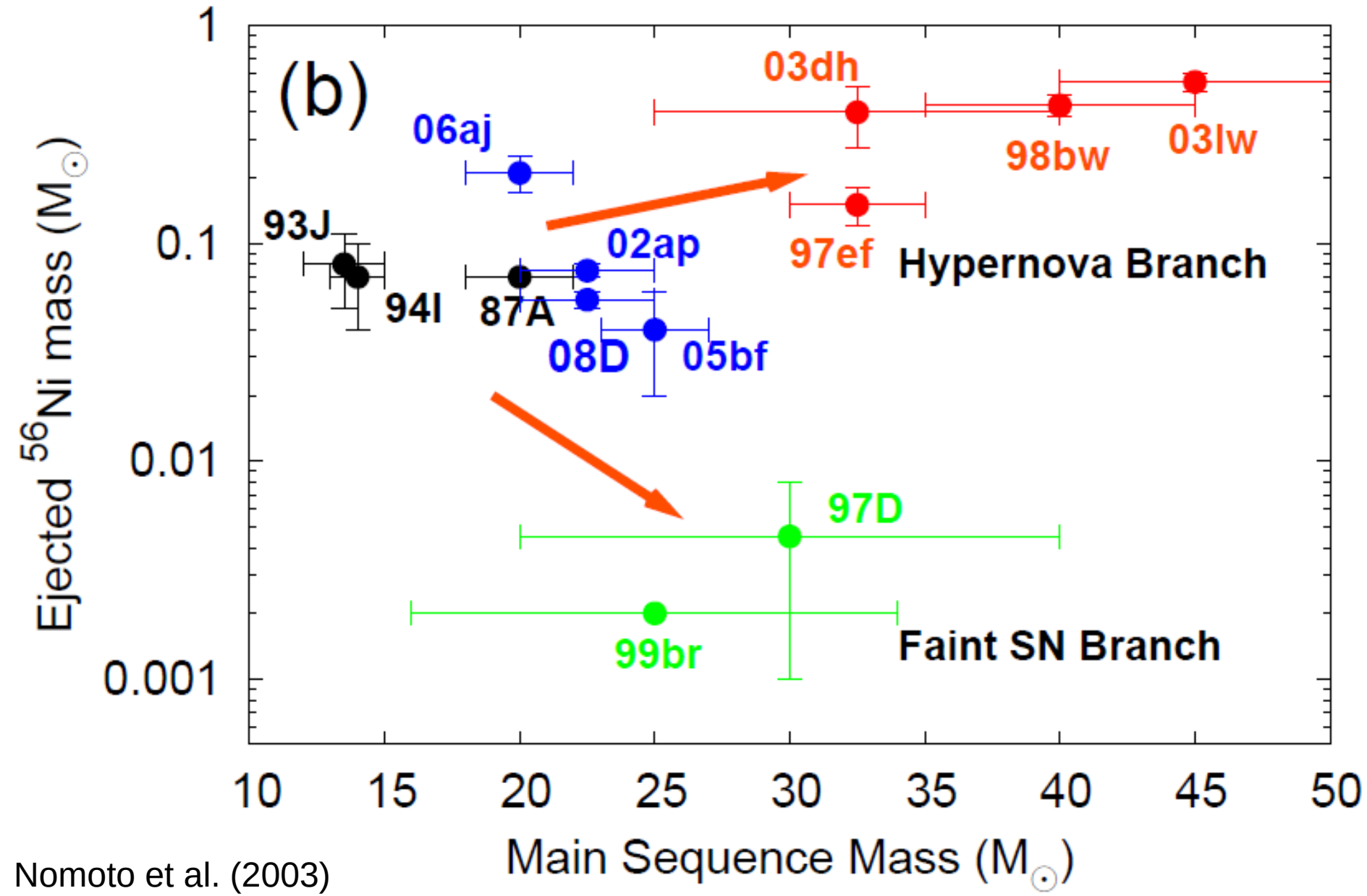
(Turatto, Mazzali, Young, Nomoto 2002)

SNe [M_{ms}-E relation]



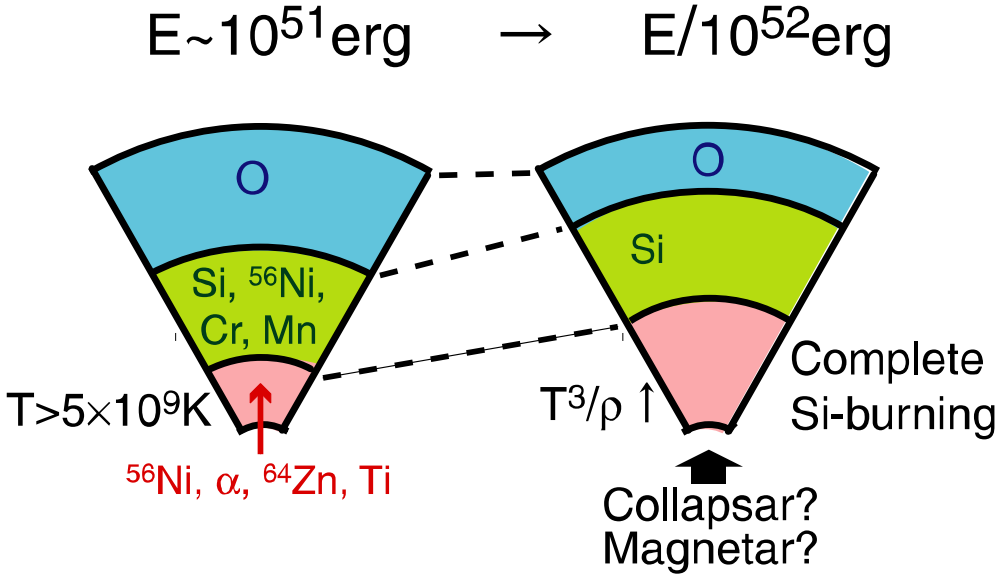
Nomoto et al. (2003)

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



Nomoto et al. (2003)

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 ↗

Normal SNe vs Hypernovae

THE ASTROPHYSICAL JOURNAL, 565:385–404, 2002 January 20

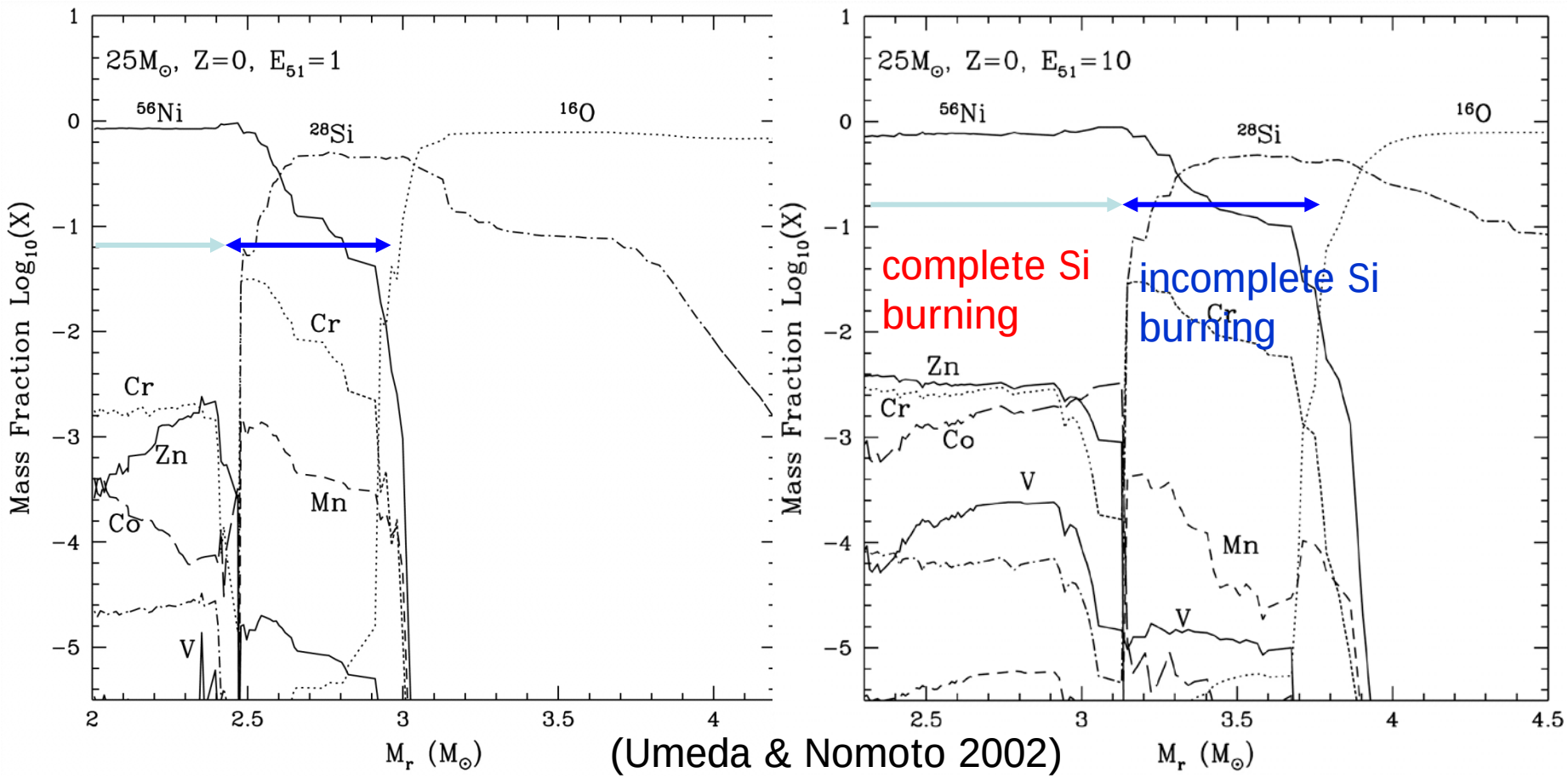
NUCLEOSYNTHESIS OF ZINC AND IRON PEAK ELEMENTS IN POPULATION III TYPE II SUPERNOVAE: COMPARISON WITH ABUNDANCES OF VERY METAL POOR HALO STARS

HIDEYUKI UMEDA AND KEN'ICHI NOMOTO

3.5. *Mixing and Fallback*

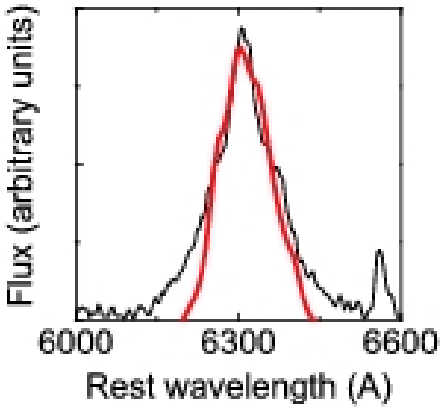
Normal SNe

Hypernovae



(Umeda & Nomoto 2002)

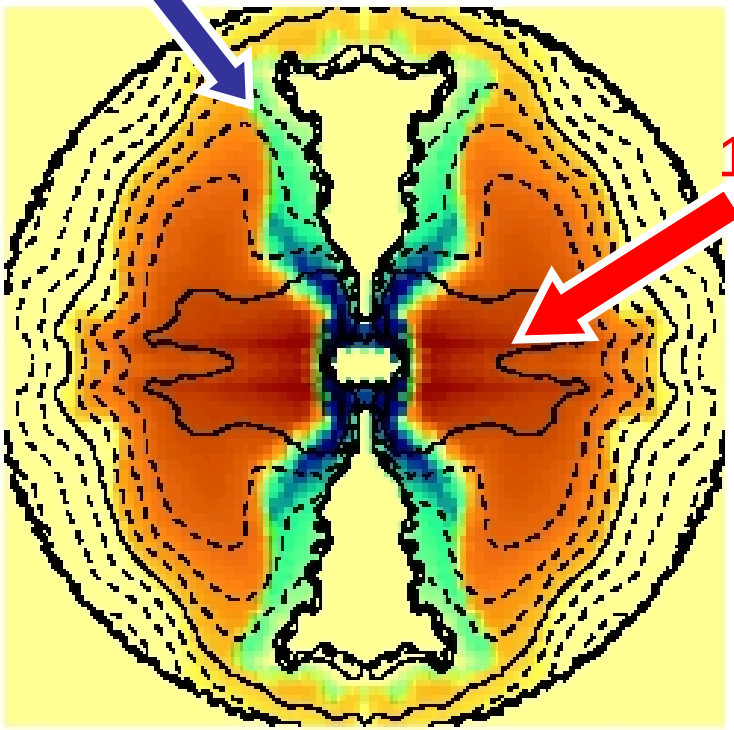
Type Ibc SNe: Bipolar Explosion



[Jet + Fallback ➔ Mixing and Fallback]

^{56}Fe

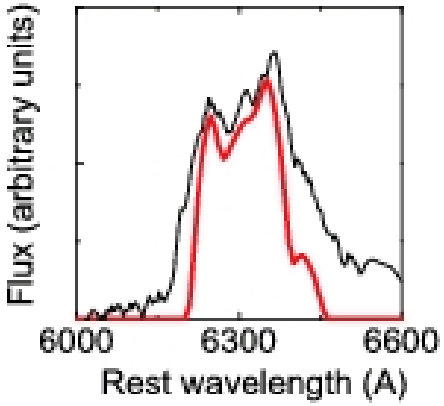
1998bw



^{16}O

2003jd

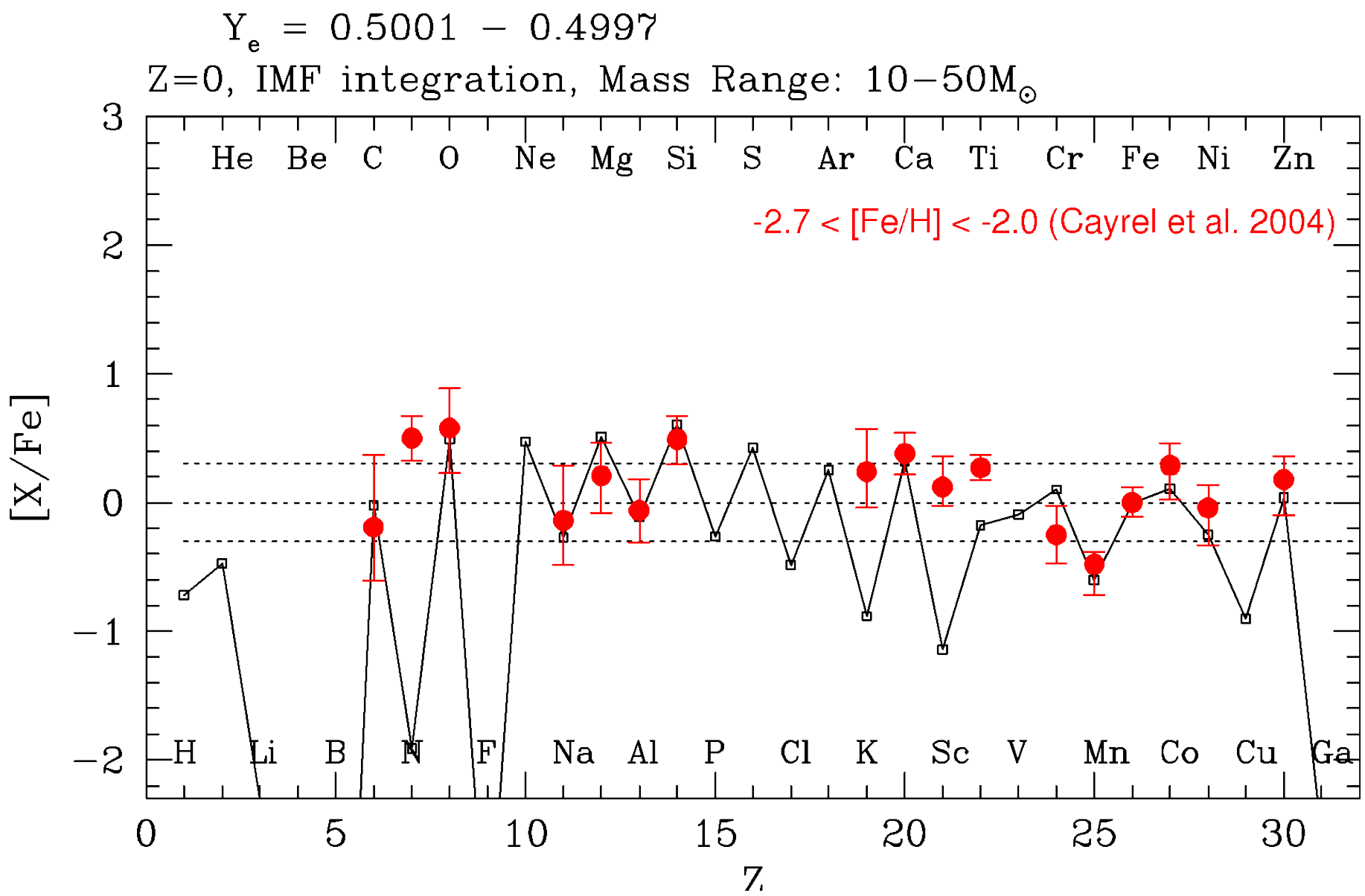
[OI] 6300A (SUBARU)



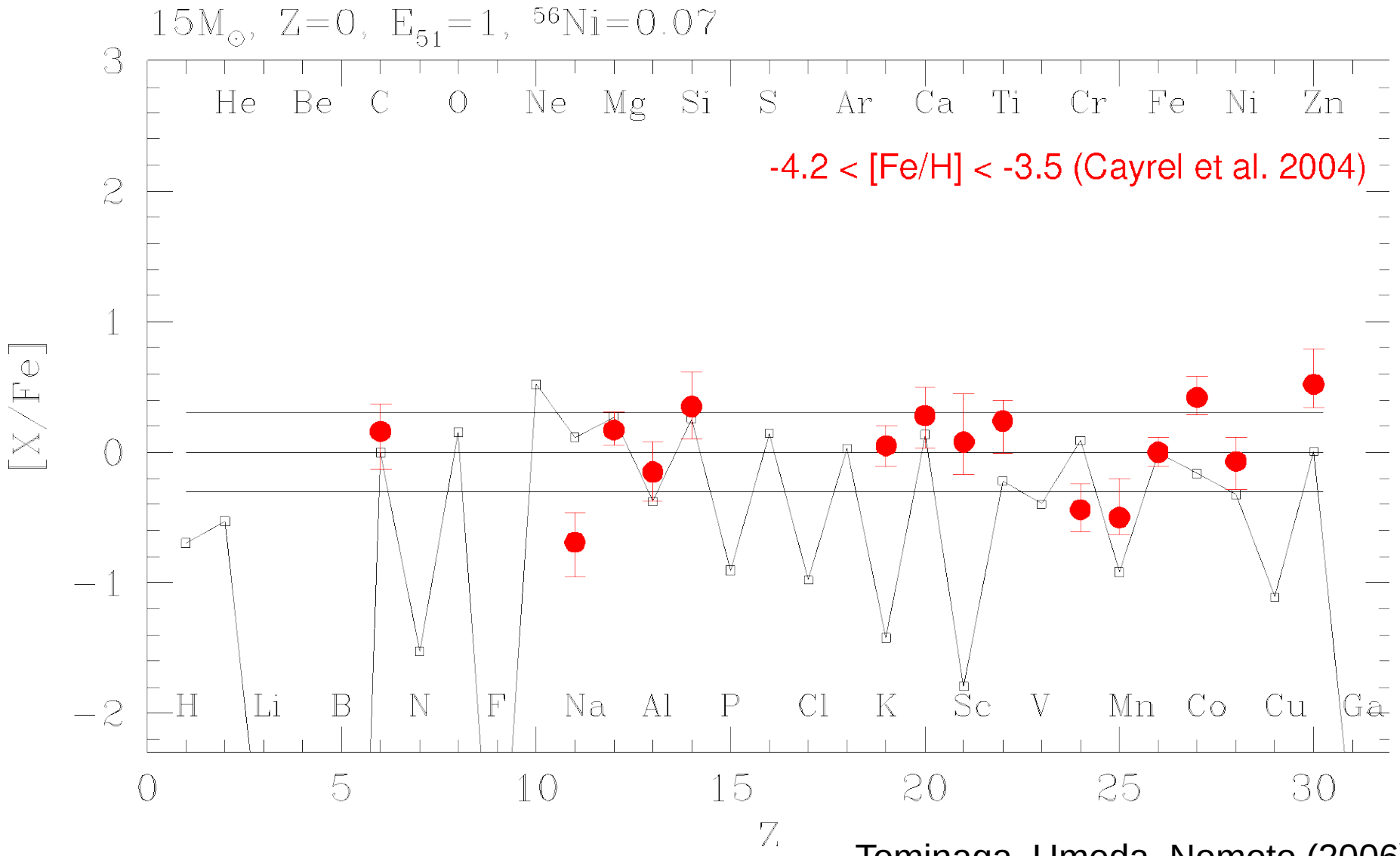
Double Peaks

Maeda et al. (2002, 2005)

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

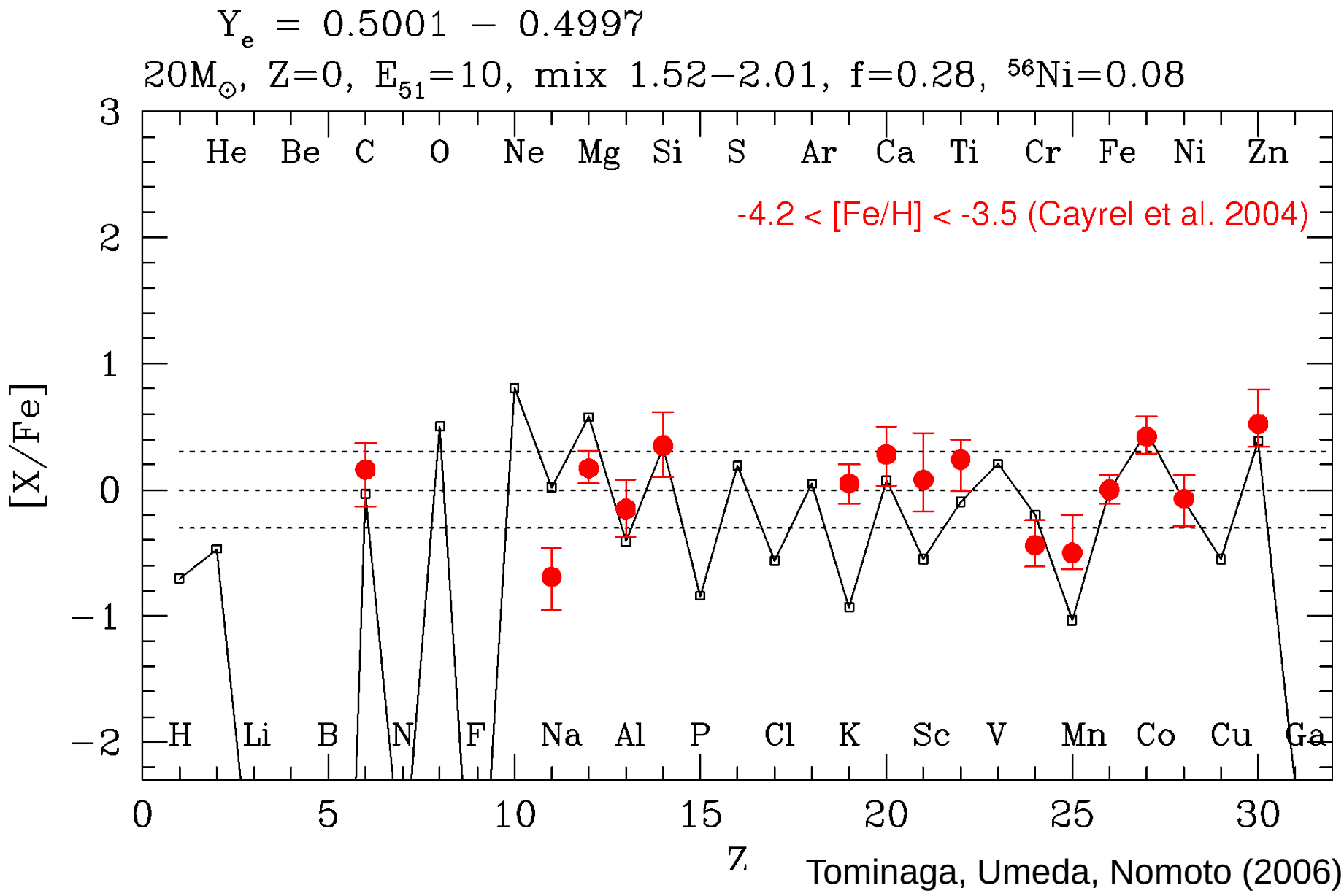


EMP stars vs. **Normal** SN II: Poor Fit



Tominaga, Umeda, Nomoto (2006)

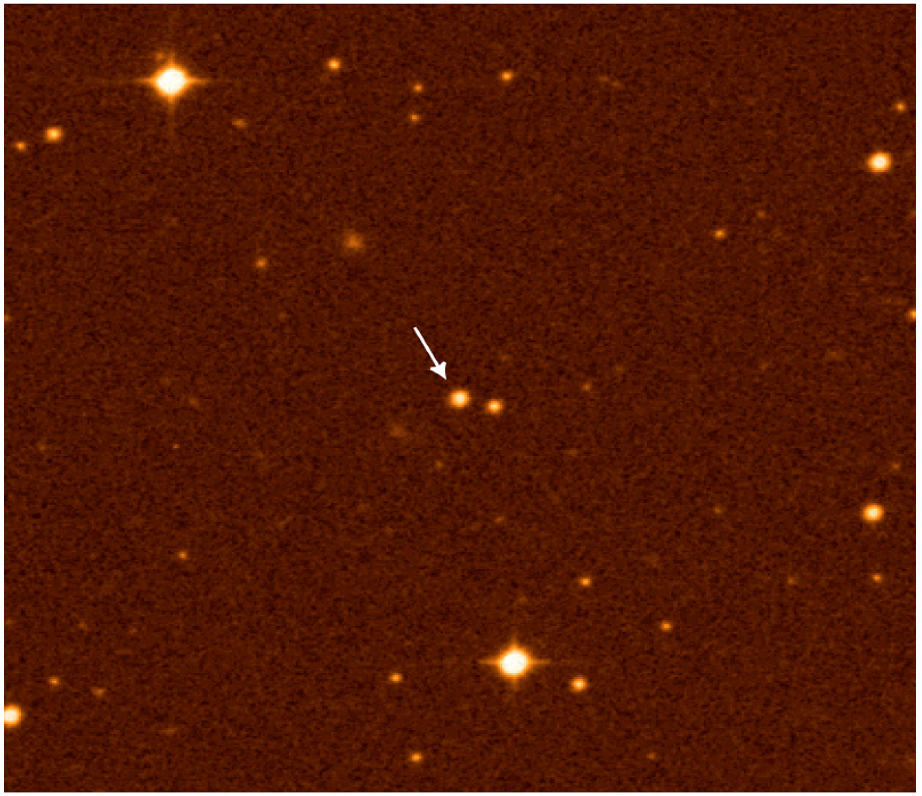
EMP stars vs. **Hypernova** (E_{51}=10)



Tominaga, Umeda, Nomoto (2006)

Hyper Metal Poor star: HE0107-5240

- Discovery:
  (Christrieb et al. 2002)
- Red-giant ~ 0.8 $M_{\odot}$
- **[Fe/H] ~ - 5.7**
  [C/Fe] ~ + 4
- Pop III (first generation) or Second generation?
- Formation of Pop III low mass star?

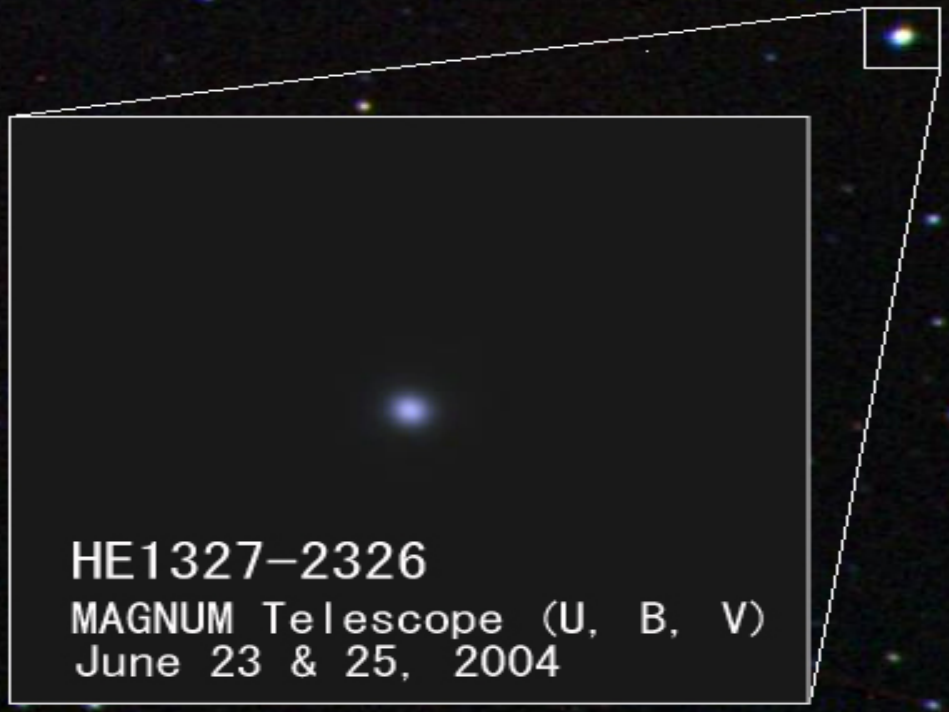


The Very Metal-Deficient Star HE 0107-5240

ESO PR Photo 25a/02 (30 October 2002)

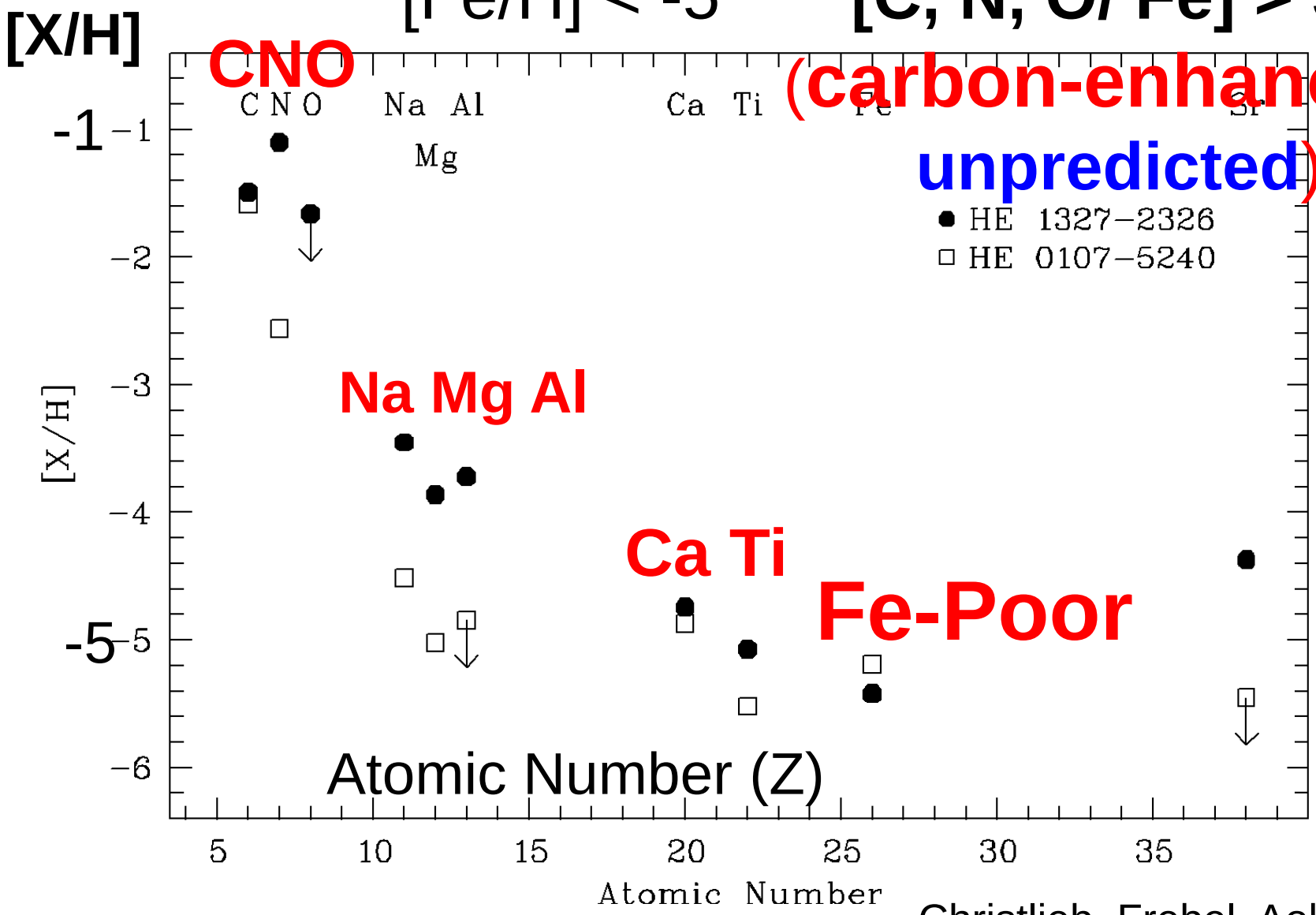
HMP Star: HE1327-2326

(Frebel et al. 2005)



Hyper Metal-Poor (HMP) Stars

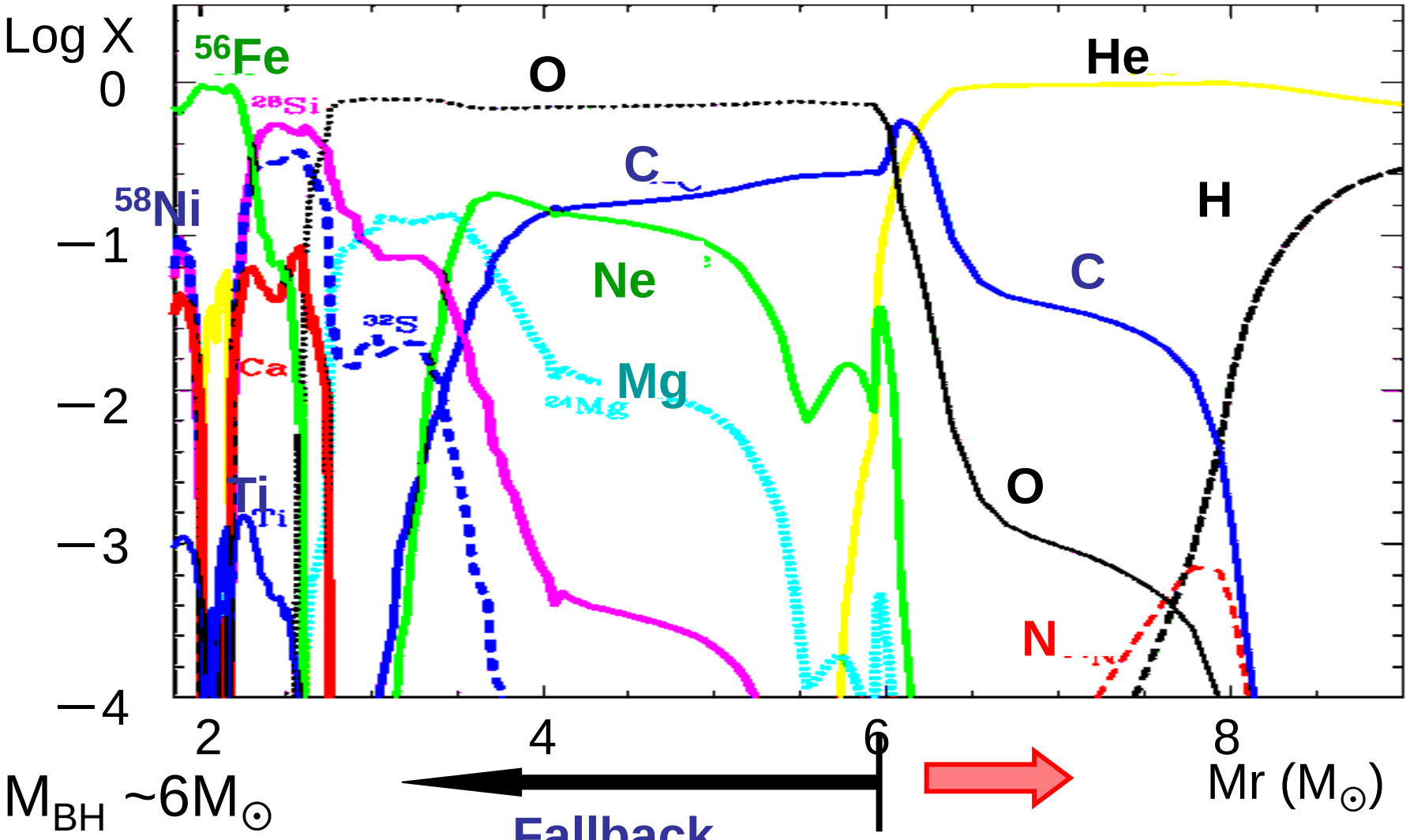
[Fe/H] < -5 **[C, N, O/ Fe] > 3**



Christlieb, Frebel, Aoki, et al.

Mixing and Fall-back Model

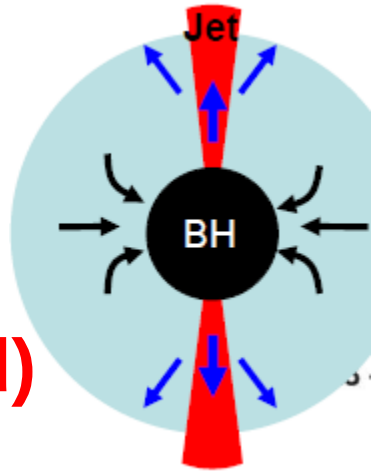
$M=25M_{\odot}$, [Fe/H]=−5.3



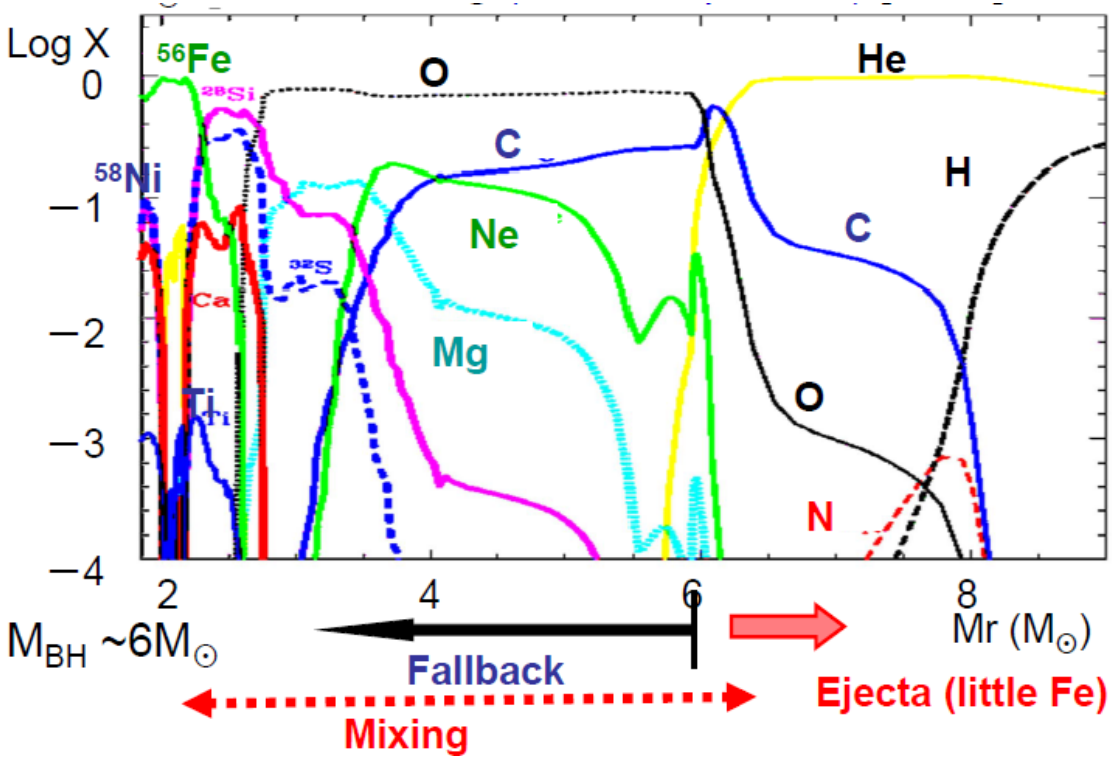
Umeda & Nomoto (2003)

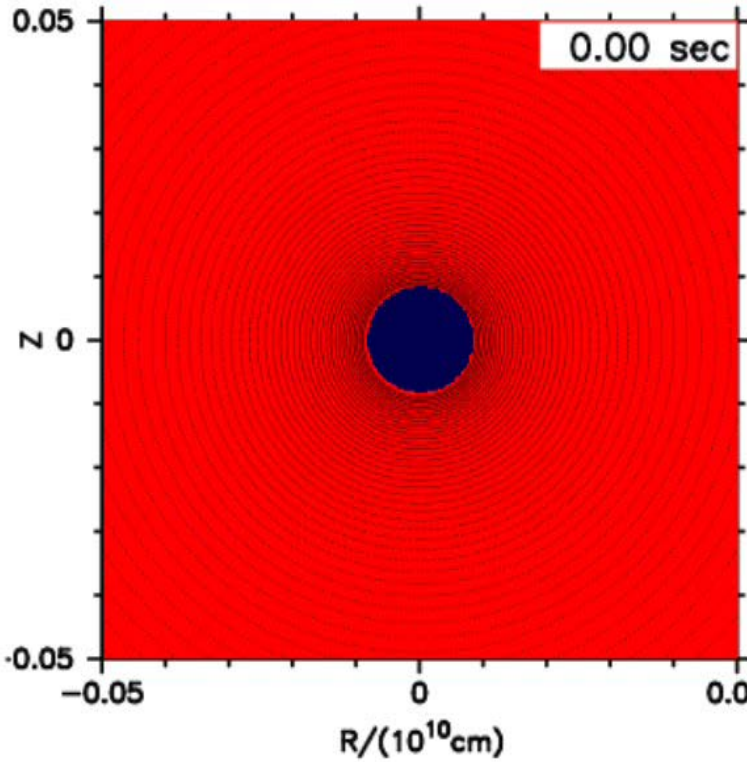
Mixing & Fallback Supernova

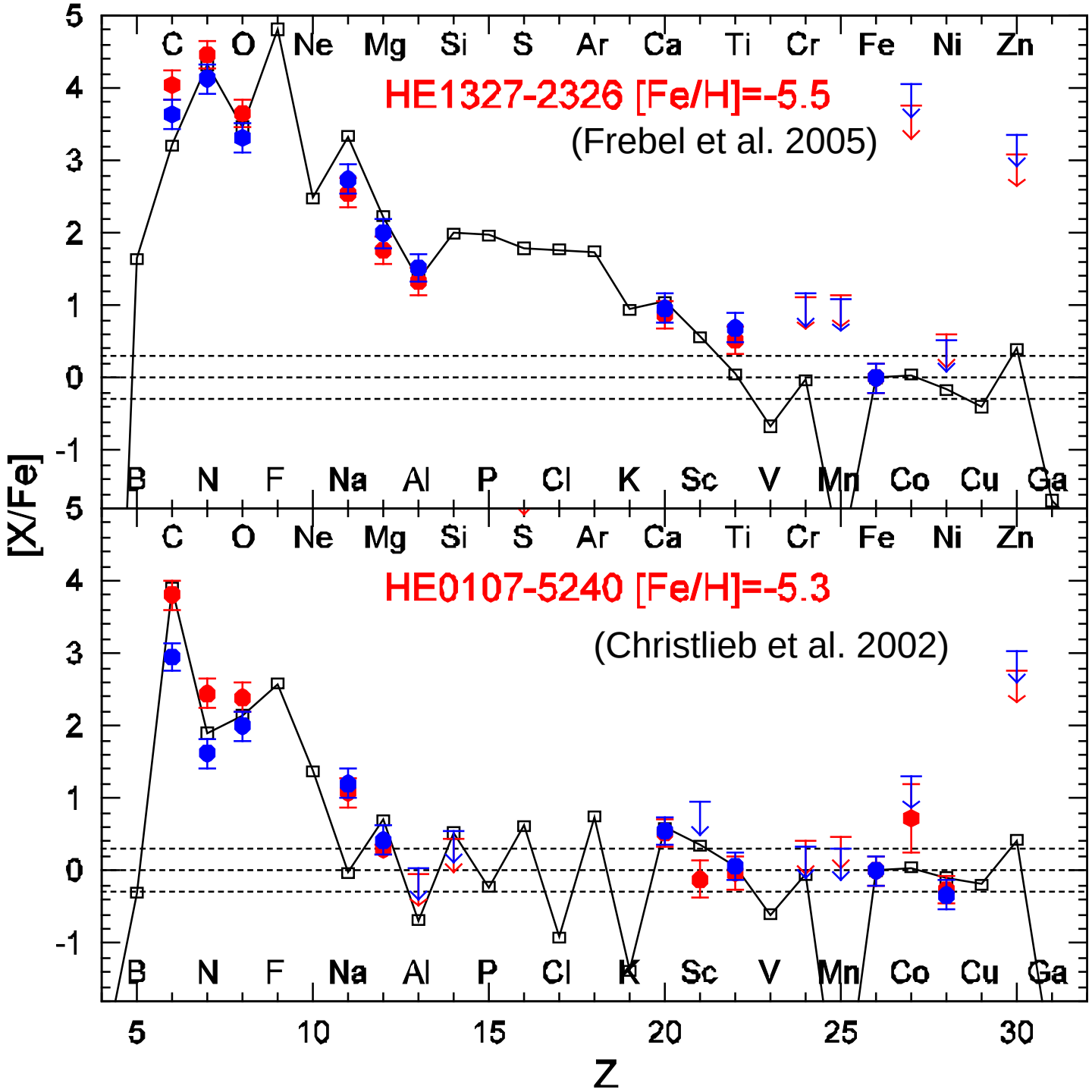
➔ Carbon Enhanced Metal Poor **(CEMP-no)** Stars



➔ **M(Fe) small** ➔ **Faint SN (Jet-induced)**







HMP Stars

Jet-induced SN models

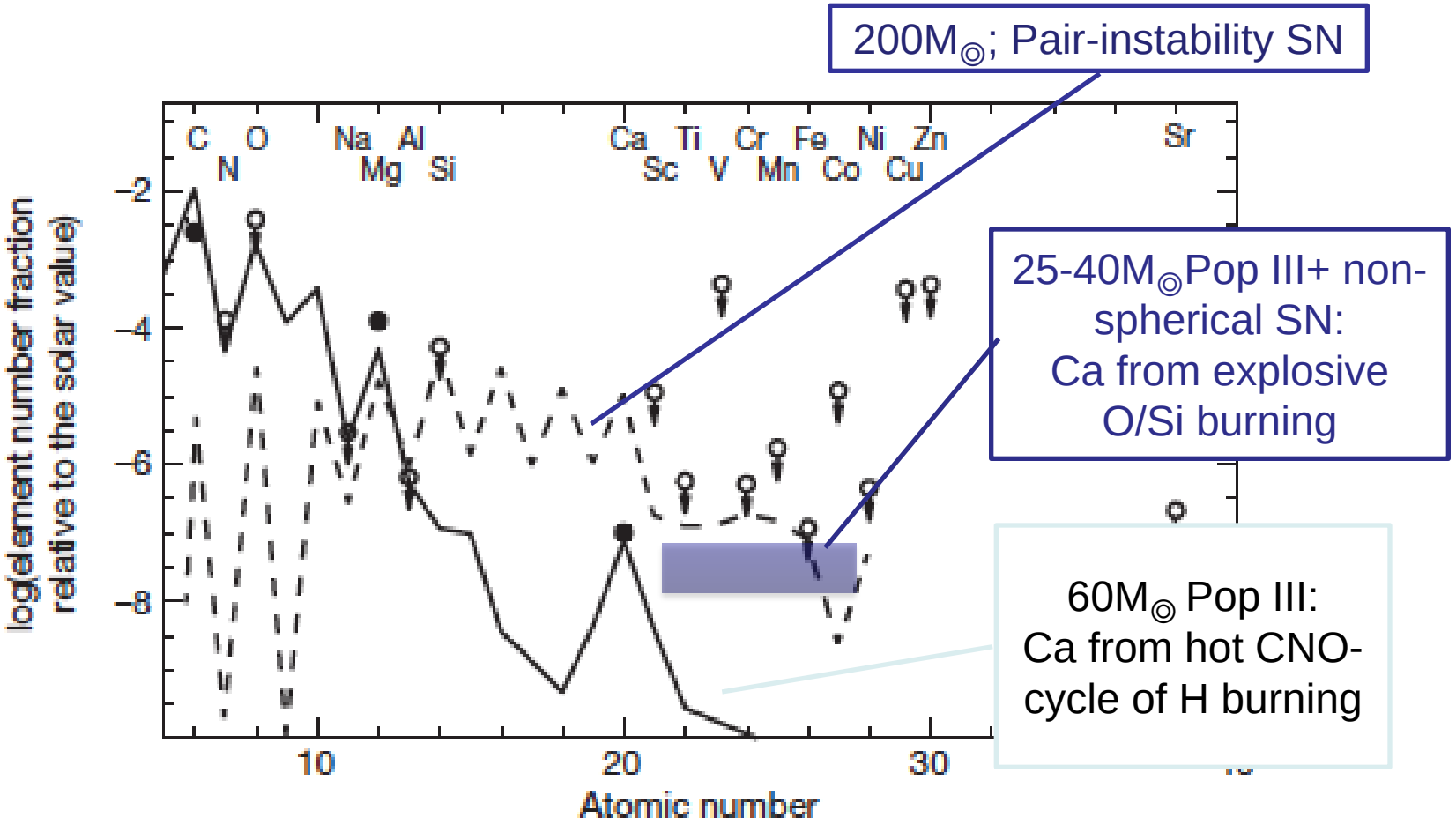
High E ➔ High Co/Fe ➔ **Fallback** ➔ Small Fe

Dark Hypernova

Tominaga et al. 2007

Constraints on masses of the Pop III with SMSS 0313-6708

(Keller et al. 2014)

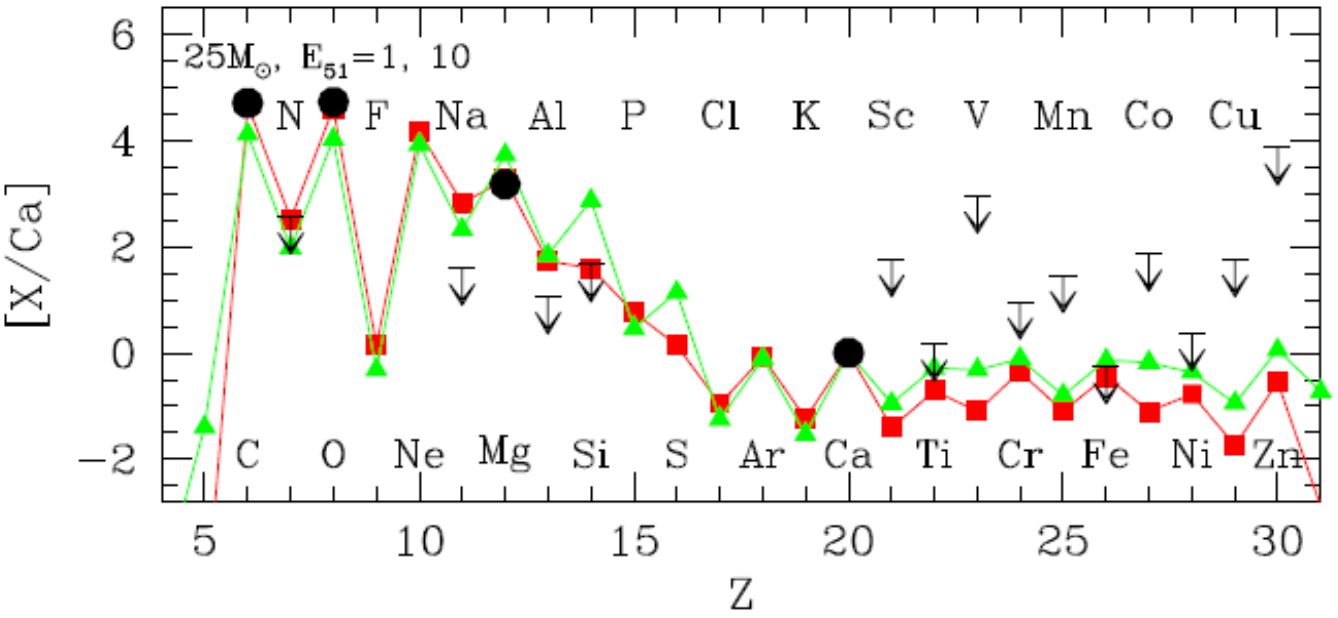


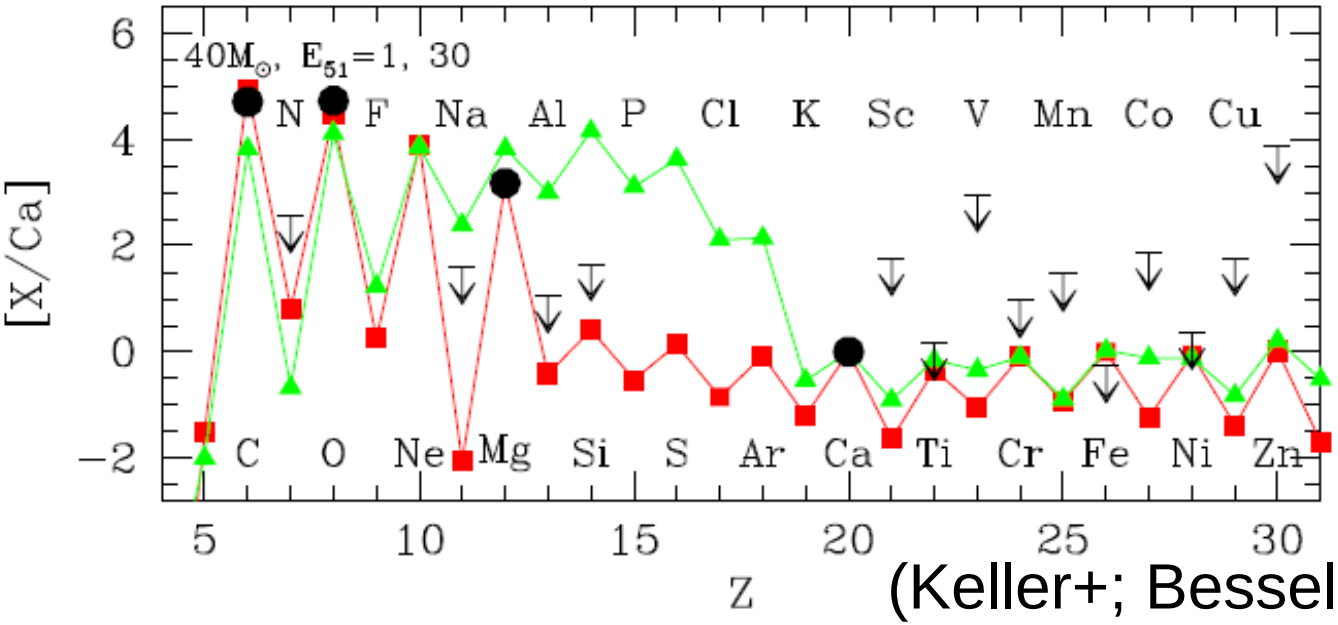
If [Ca/Fe] > 1 ➔ Ca = hot CNO cycle ➔ Tc > 10^8 K

➔Z ~ 10^{-10} $Z_\odot$ ➔ Pop III

If [Ca/Fe] ~ 0 ➔ Ca from SN explosion ➔ not necessarily Z = 0

SM0313-6708 ([Fe/H] < -6.5):





(Keller+; Bessel+)

Mixing-Fallback model :

M ~ 25 – 40 $M_\odot$

[Fe/H] < -7.52

-7.8? -6.5?

[Ca/H] = -7.26

[Mg/H]= -4.08

[O/H] = -2.53

[C/H] = -2.55

(O & incomplete Si burning ➔ Ca)

M(BH) ~ 6 $M_\odot$

(Ishigaki+15)

First Supernovae – **CEMP-no** Stars

Fallback Supernovae: ejecting small Fe

large [CNO/Fe] ➔ CEMP-no

(1) Jet-like Energetic Explosion ?

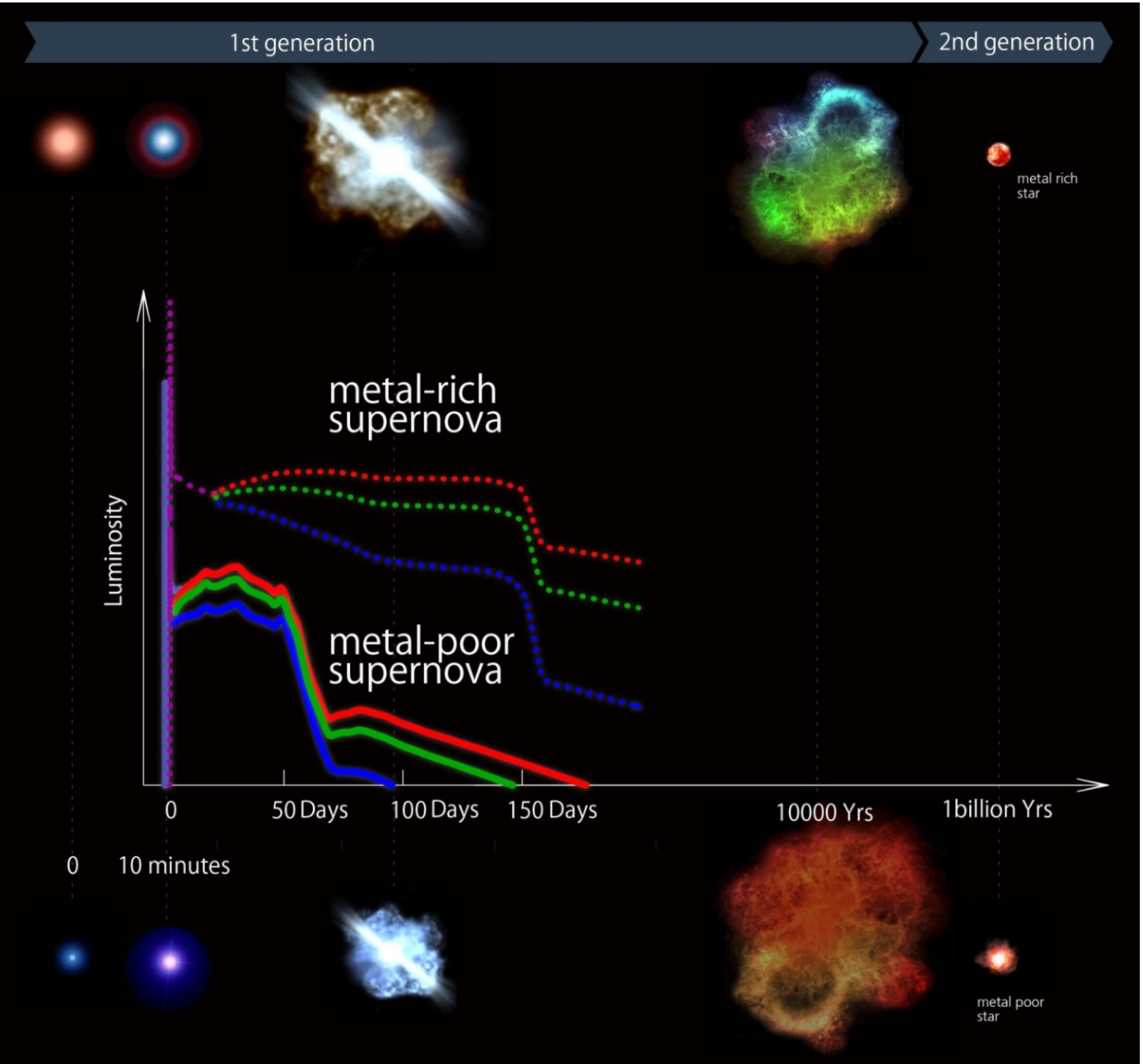
large **[Zn/Fe],** [Co/Fe], [Ti/Fe]

(correlation with [Ni/Fe] (Ye))

(2) Weak Explosion ?

Mixing & Fallback

Fallback Supernova ➔ Faint Supernovae



Light curve of 25 – 40 $M_{\odot}$ stars :

- *fainter
- *shorter
- *bluer

Tolstov et al. (2016) ApJ 821, 124

Discussion

[Zn/Fe] : larger for lower [Fe/H] ?
indicator of jet-induced nucleosynthesis
[Fe/H] : mixing of SN ejecta (jet?) with ISM

If [Ca/Fe] > 1 ➔ Ca = hot CNO cycle ➔ Tc > 10^8 K
➔ Z ~ 10^{-10} $Z_\odot$ ➔ Pop III
If [Ca/Fe] ~ 0 ➔ Ca from SN explosion
➔ not necessarily Z = 0

Nucleosynthesis in aspherical explosions
PISN ?
Mass function of First stars & Black holes

Black-Hole-forming Supernovae ?

- First Stars ➔Fallback supernovae
  - ➔ Jet-induced Mxing & Fallback= Hypernovae?
  - ➔ Extremely metal-poor stars
- Hypernovae (GRB, XRF)
- **Superluminous Supernovae**

  (any connection to EMP stars ??)

- Black Hole forming vs. Magnetar forming

Nucleosynthesis in Stars and the Chemical Enrichment of Galaxies

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(Annual Review Astron. Astrophys. 51, 457, 2013)

Nucleosynthesis in Stars and the Chemical Enrichment of Galaxies

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Abstract