Supernova Explosions of First Stars and their Nucleosynthesis

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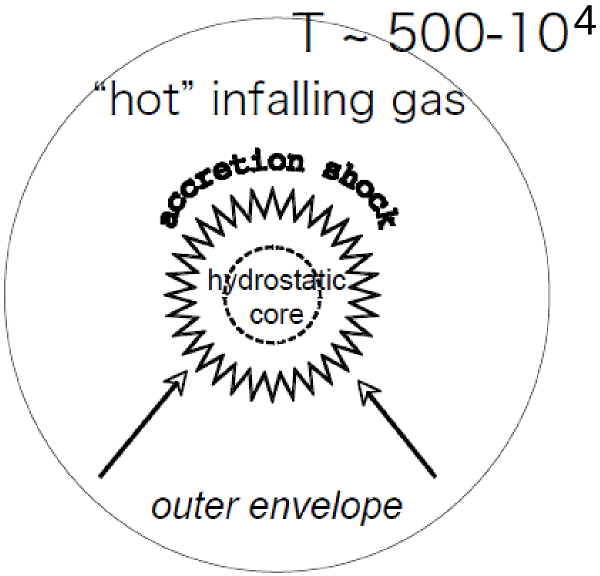
Big Bang to First Stars

The Big Bang ➔
Expanding Universe(Hubble-Lemaitre:redshift z)➔
Decrease in Temperature ➔
[Strong & Weak Forces] ➔
Primordial Nucleosynthesis ➔
H, He, Li ➔
The Dark Age
[Gravitational Force] ➔
First Stars (z~20) ➔
First Supernovae
Stellar Nucleosynthesis ➔
2nd generation Metal-Poor Stars ➔ ……….

First (PopIII) Stars & First Supernovae?



High-Redshift SNe

z = 3.9 (Cooke+ 2012)

First Stars: How massive ?

Star Formation

➔ small core + envelope

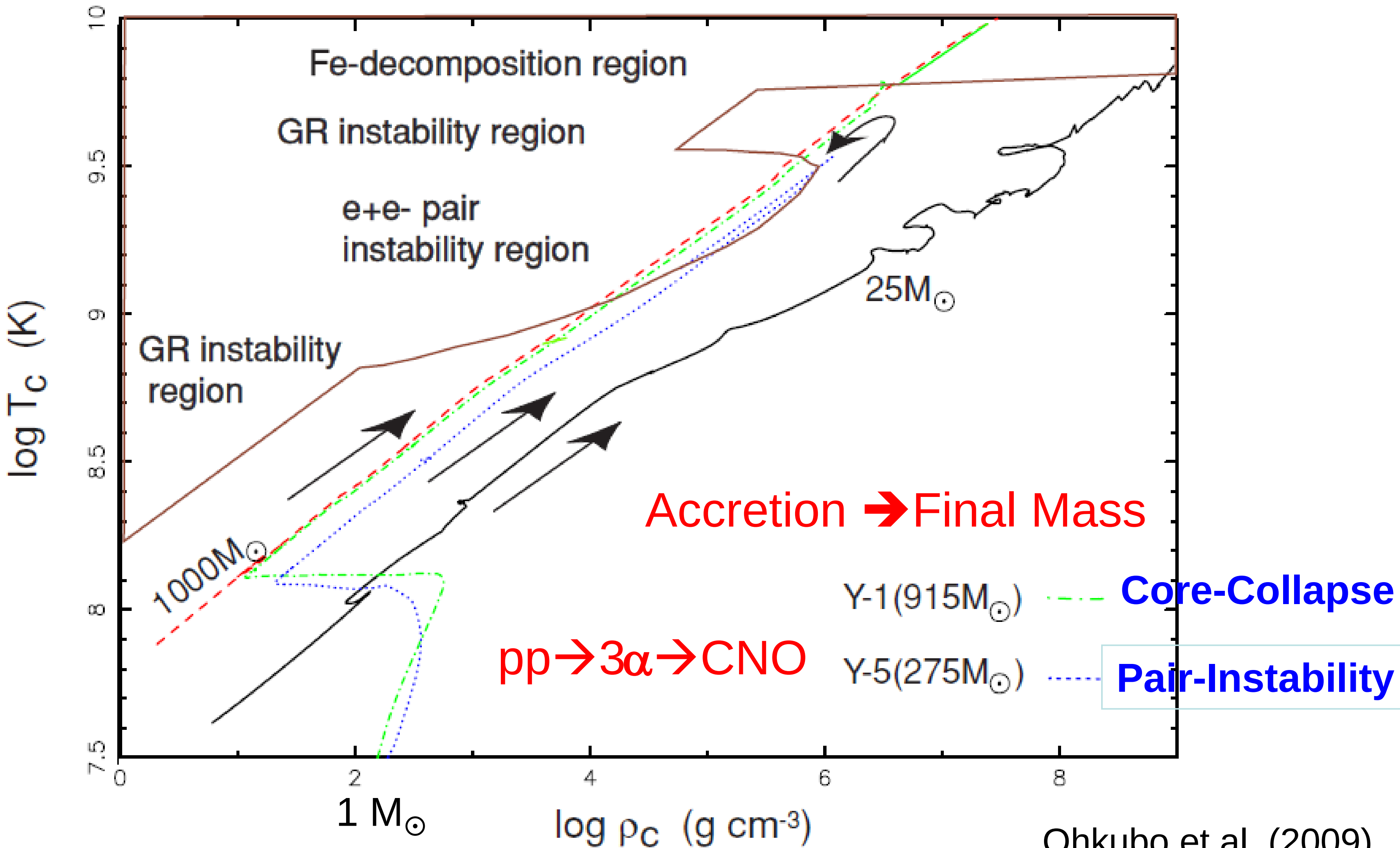
➔ **Mass Accretion** (Pop III.1 or III.2, Feedback, ,,,)

First Supernovae ?

Mass Estimates of Supernova Progenitors

- Nucleosynthesis signatures

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



Ohkubo et al. (2009)

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

$M(^{56}Ni) < 40\ M_\odot$

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

→ Core Collapse

Pop III GRBs, Hypernovae

SNe II **$M(^{56}Ni) < 10\ M_\odot$**

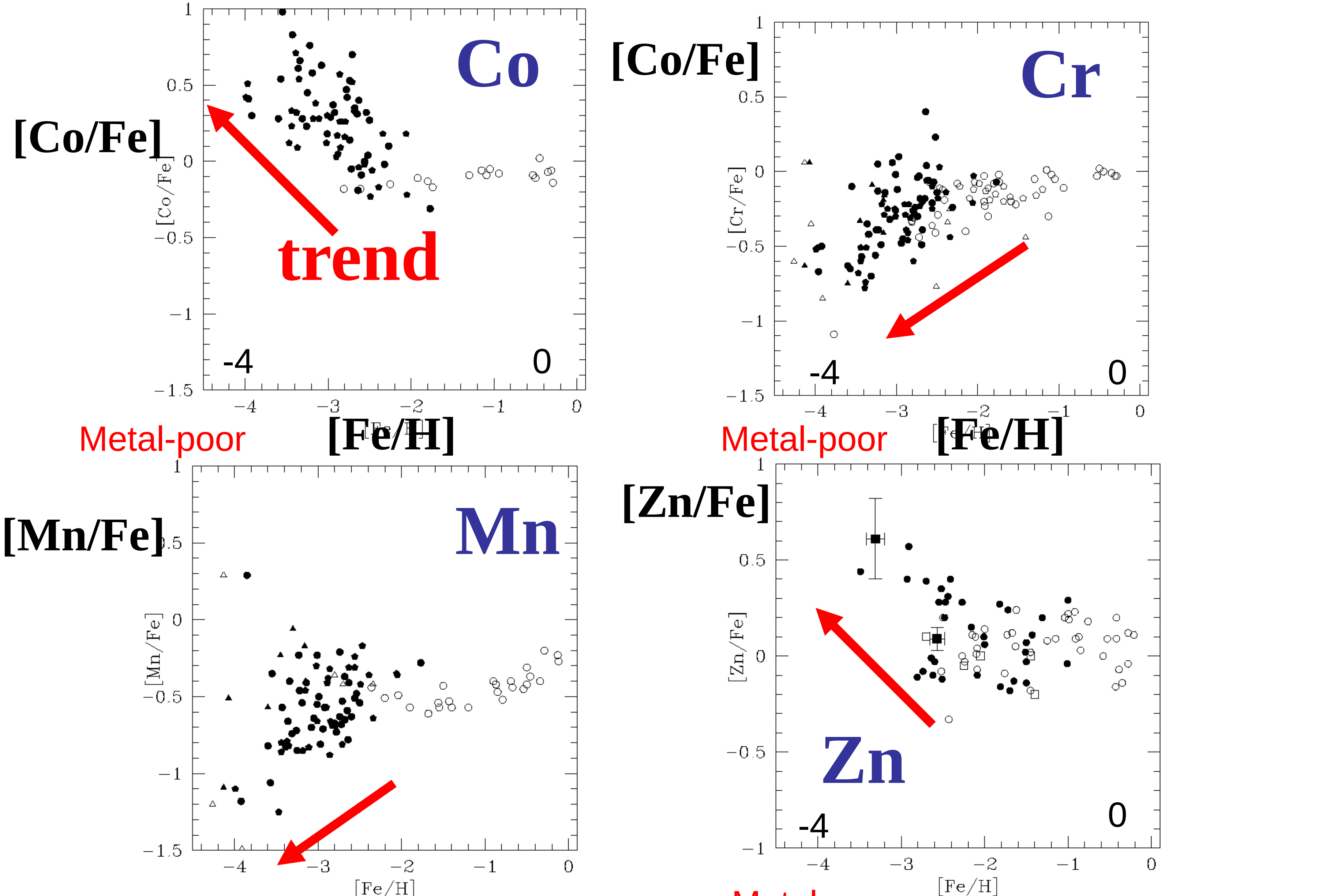
Metal Poor Stars

- 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)

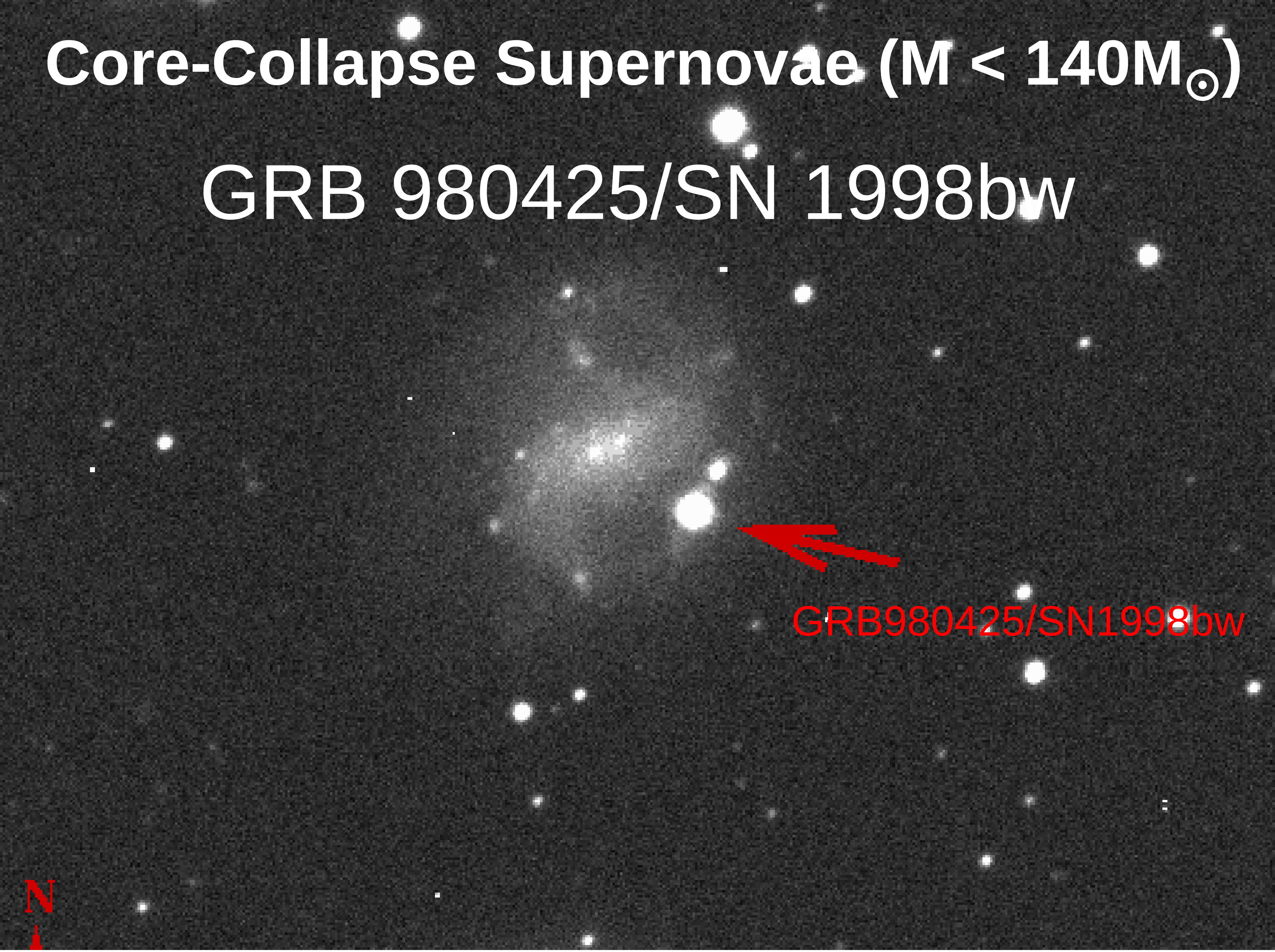
Unpredicted Abundance Ratios in Extremely Metal–Poor Stars



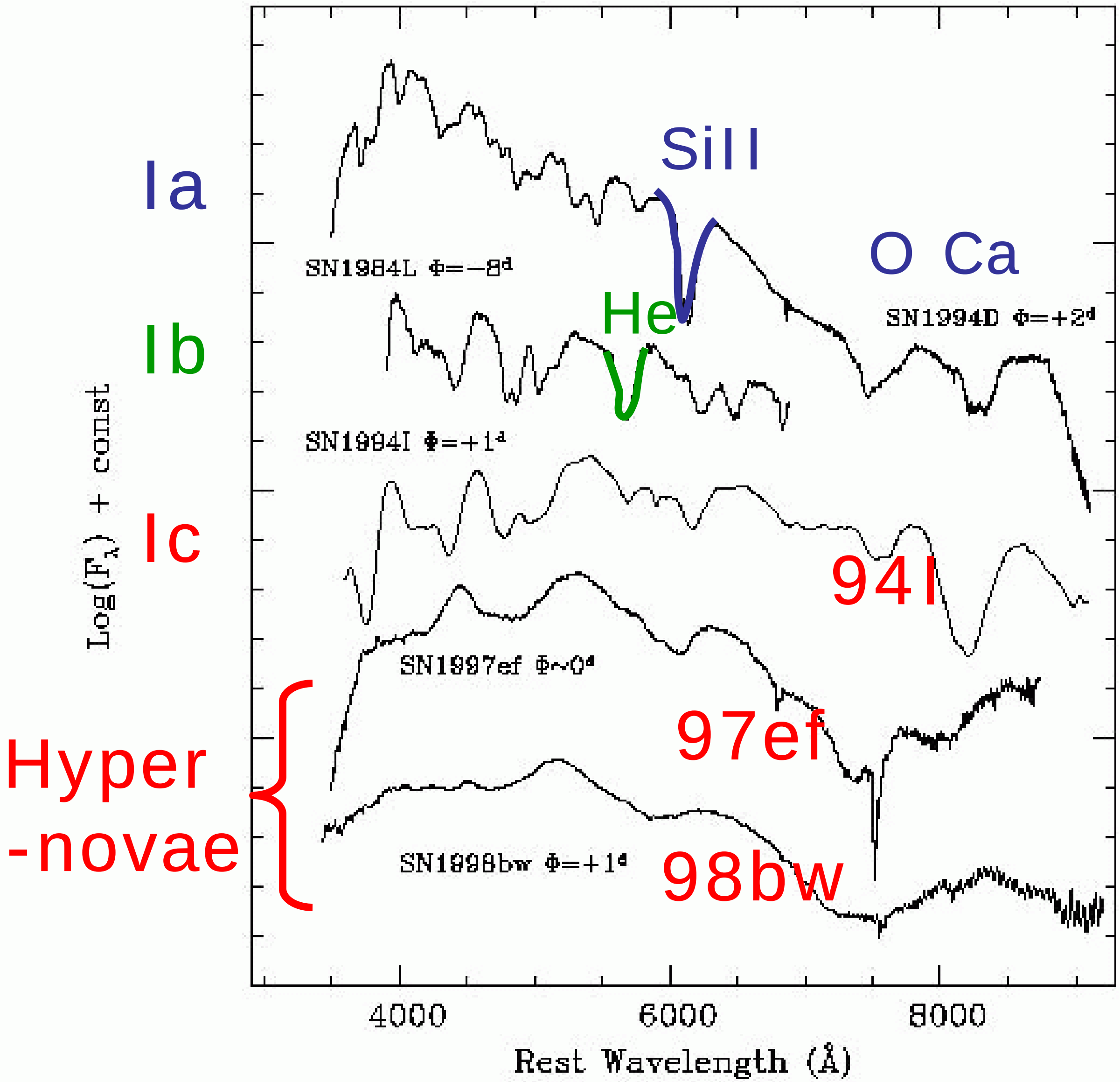
McWilliam(1995), Ryan(1996)

Core-Collapse Supernovae ($M < 140M_{\odot}$)

GRB 980425/SN 1998bw



Spectra of Supernovae & Hypernovae



Ic: no H,

no strong He,

no strong Si

Hypernovae:

broad features

↑

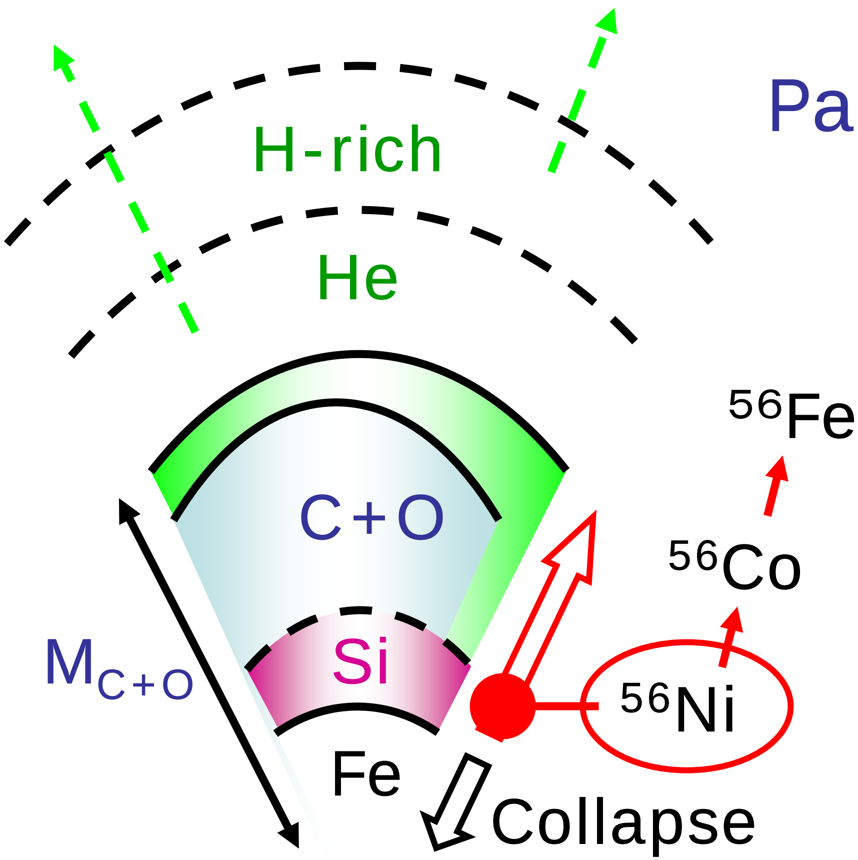
blended lines

↑

"Large mass at high velocities"

Patat et al. (1999)

CO Star Models for SNe Ic



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

Light Curve | Spectra

$E \propto M_{ej}$

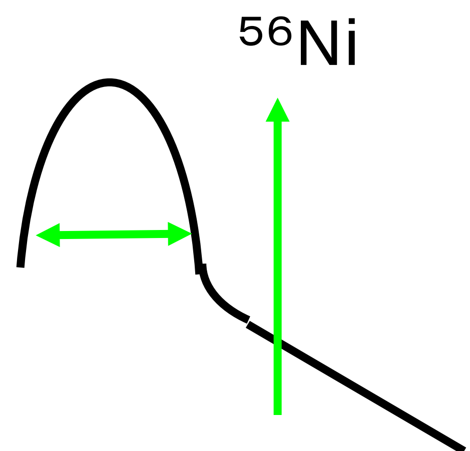
$$\tau \sim [\tau_{dyn} \bullet \tau_{diffusion}]^{1/2}$$

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

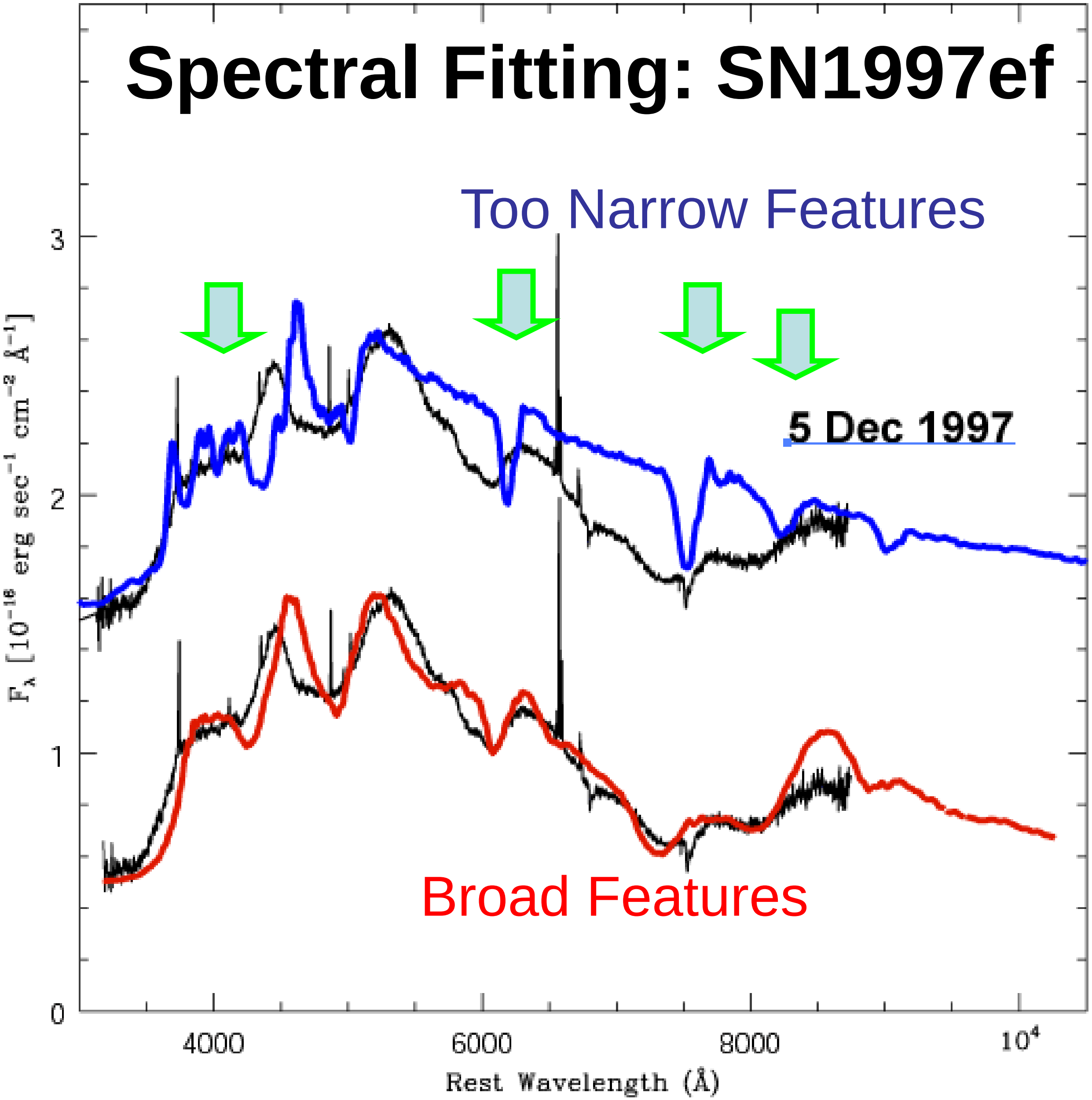
$$\propto \kappa^{1/2} M_{ej}^{3/4} E^{-1/4}$$

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

$E \propto M_{ej}^3$



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.

^{56}Co-decay

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

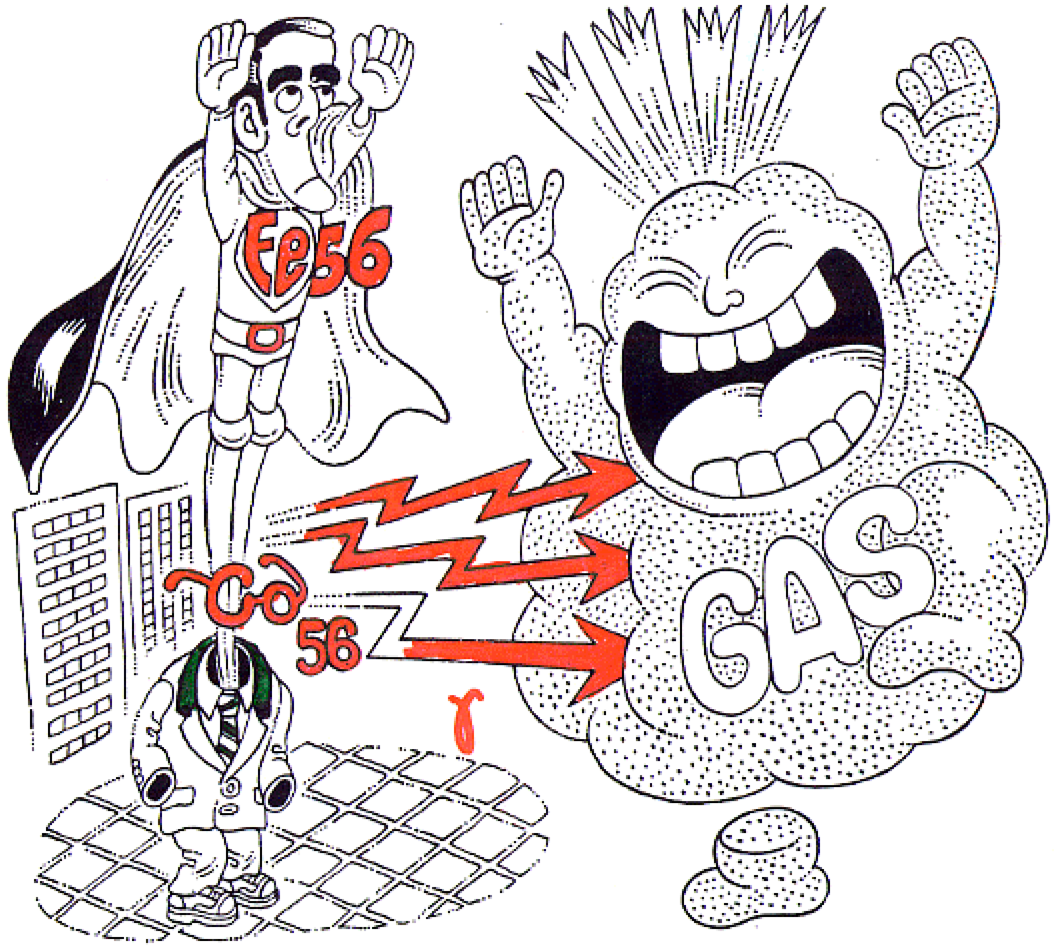
γ-rays

X-rays $\quad$ e^-

Photoabsorption $\quad$ Excitation/Ionization

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

Shape: M_{ej}



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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

XXVIth
General Assembly

Hypernova in Prague

Type II-P
SN 1997D

Very narrow lines.

V < 1000 km s^{-1}.

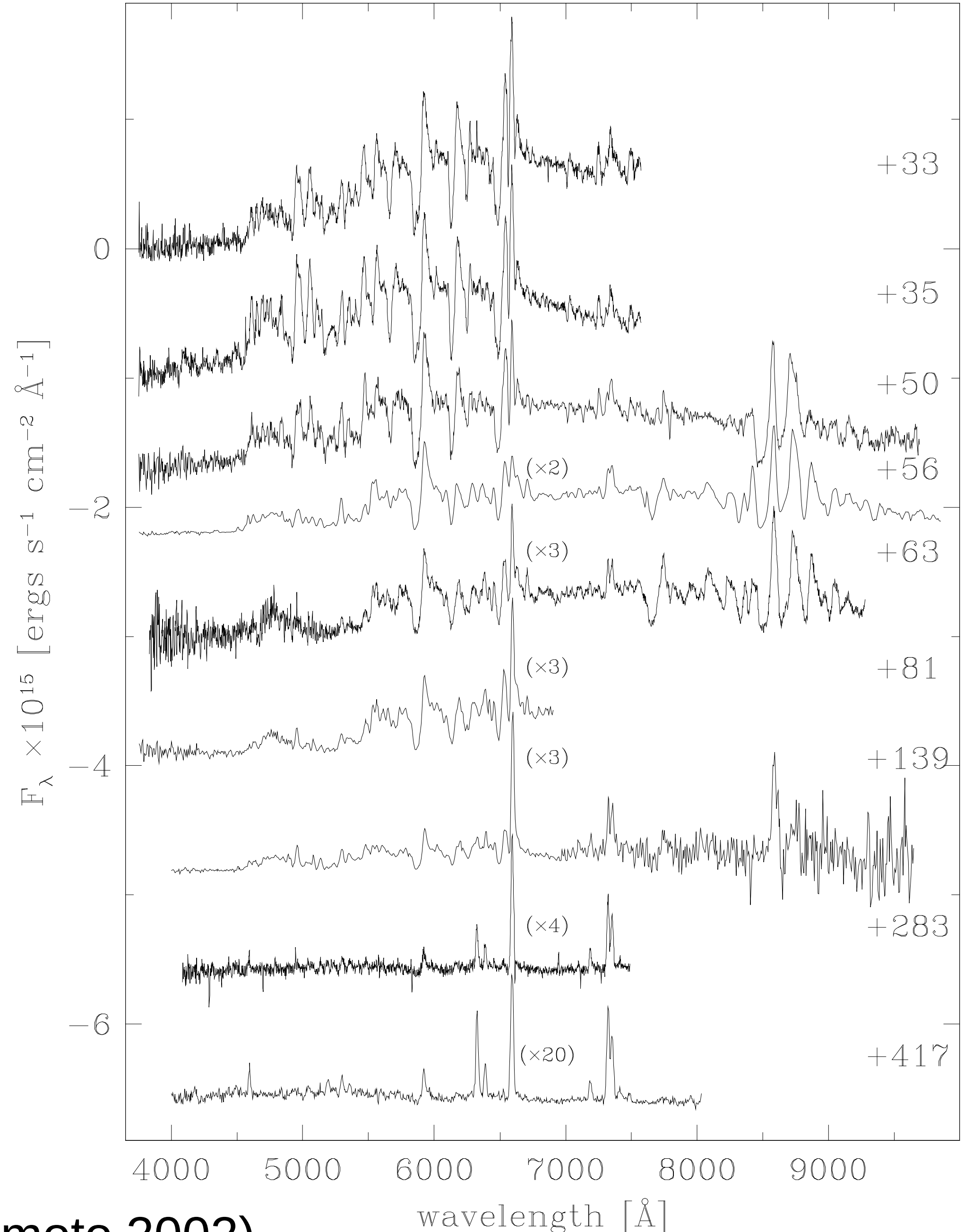
E_K=1-4 × 10^{50}ergs.

V~1000km s^{-1}

2002gd, 1999br

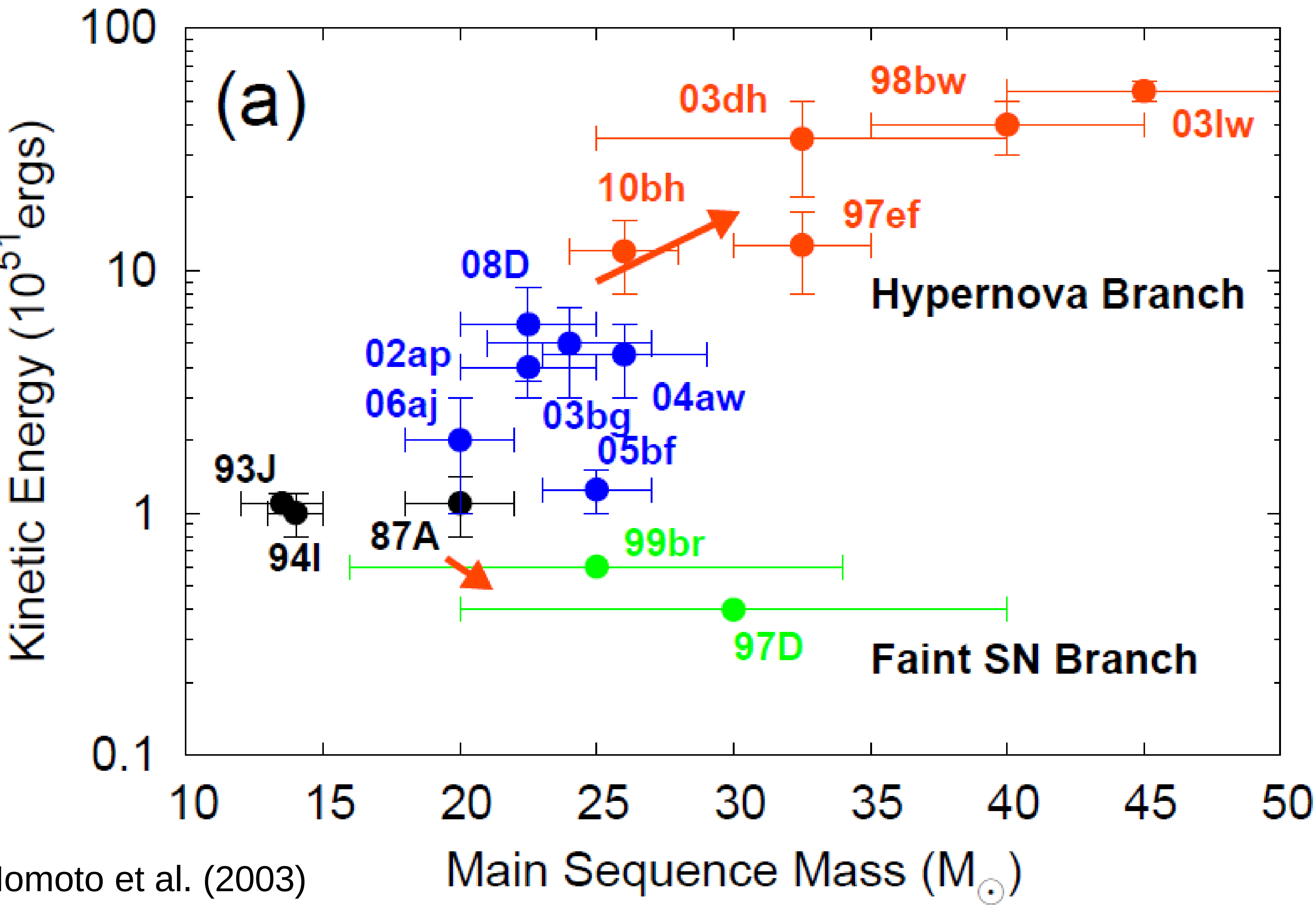
Faint

M(^{56}Ni)~2 × $10^{-3}M_\odot$



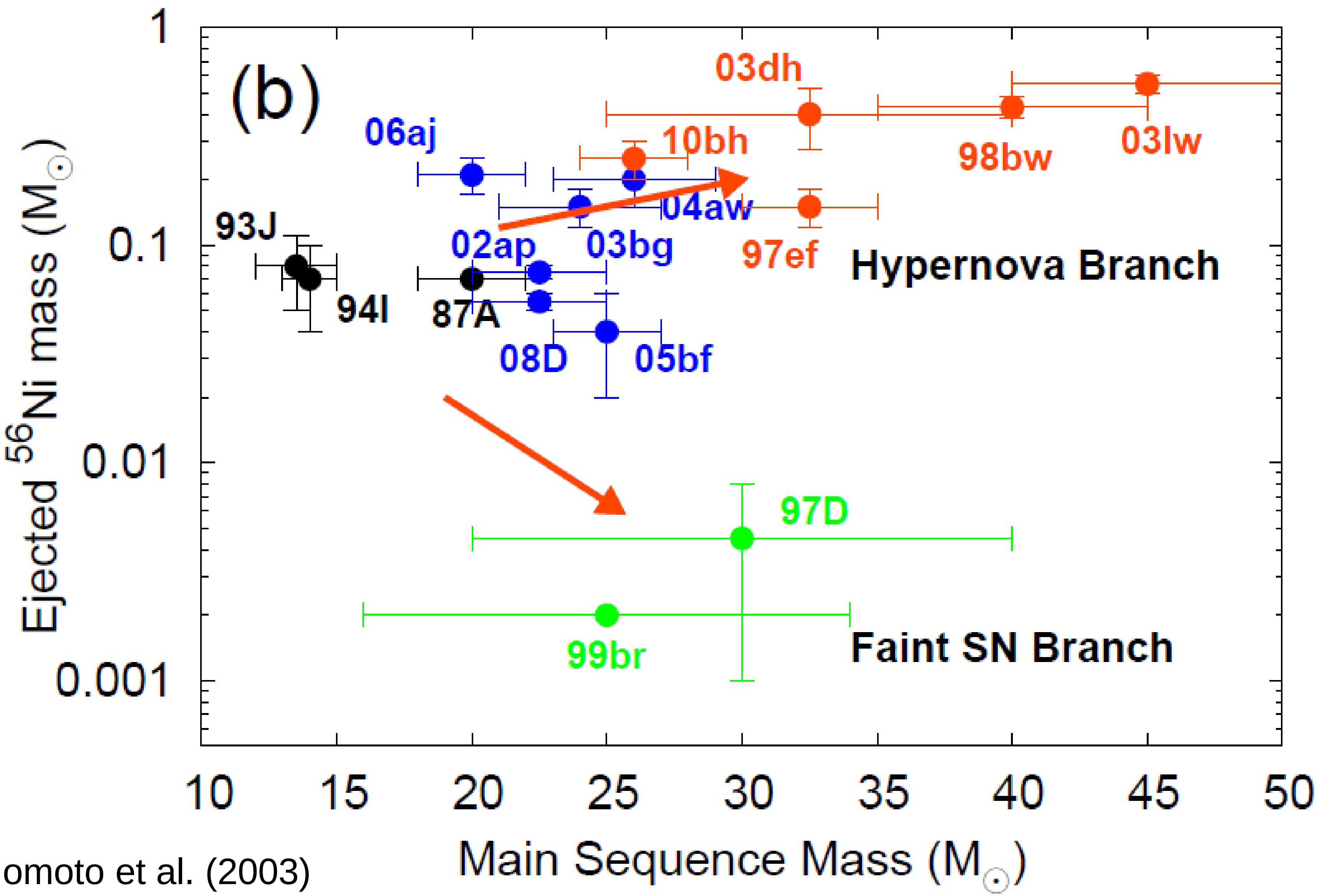
(Turatto, Mazzali, Young, Nomoto 2002)

SNe [M_{ms}-E relation]



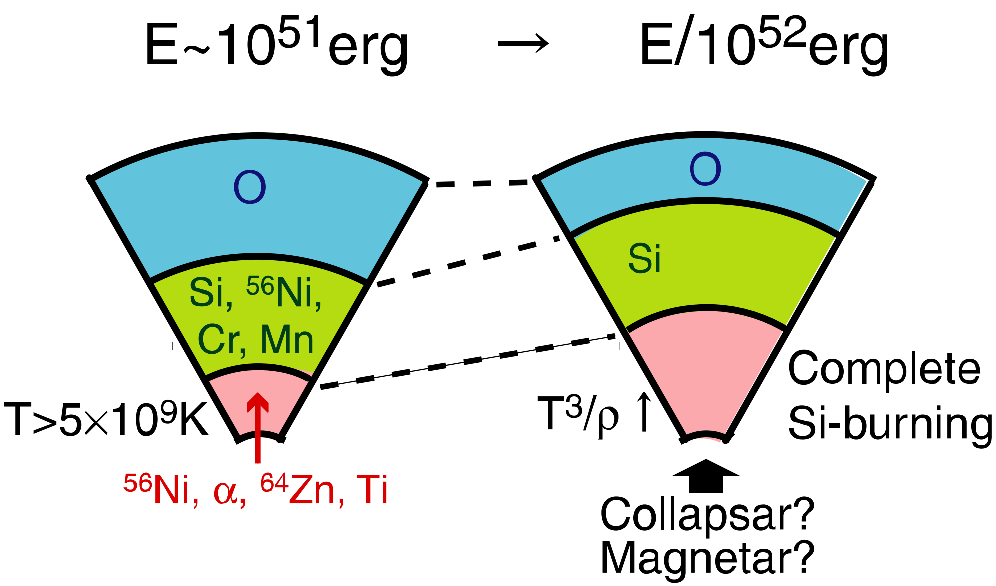
Nomoto et al. (2003)

SNe [M_{ms}- ^{56}Ni mass 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 ↗

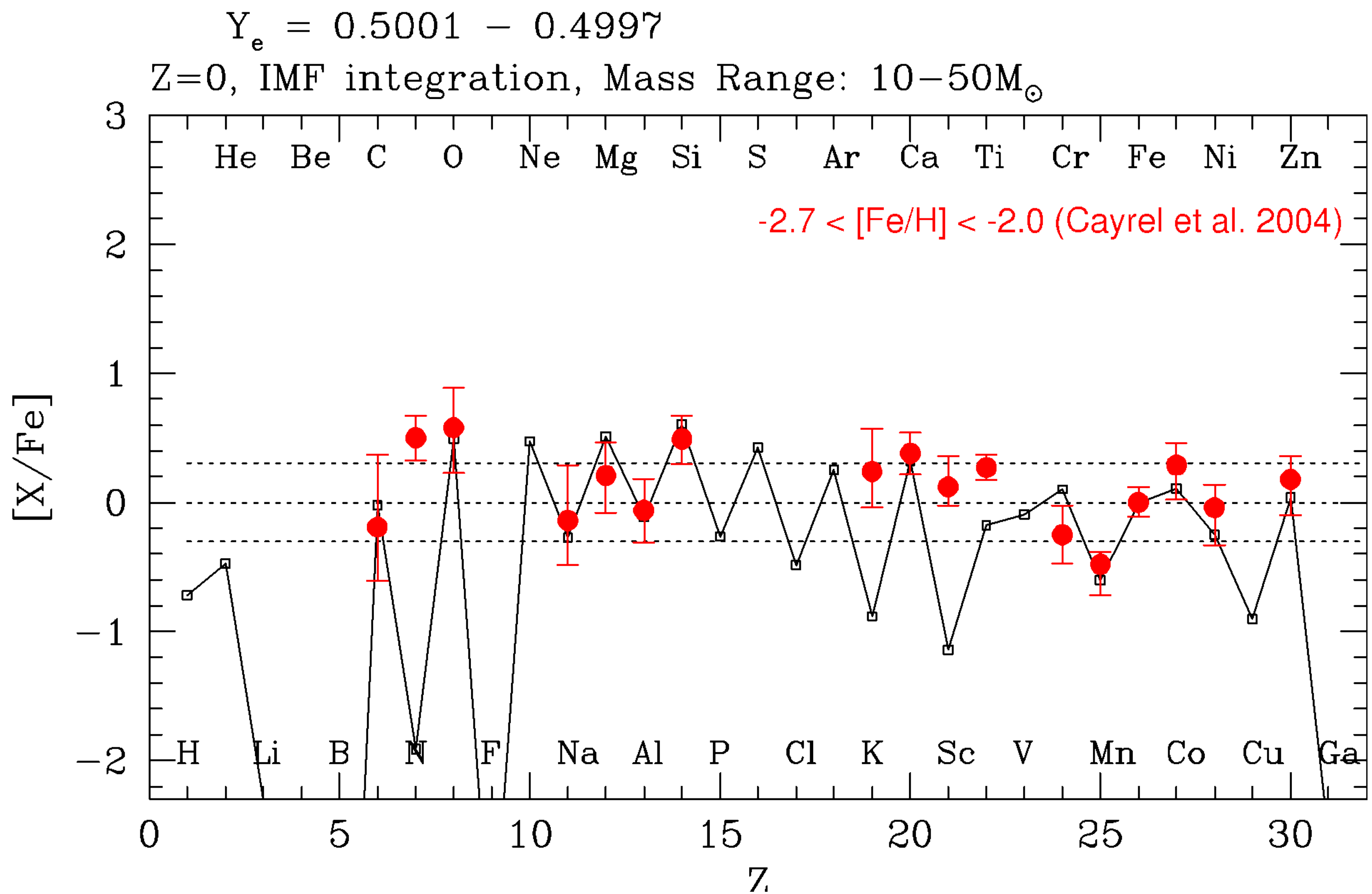
Zn/Fe ↗ ⇦ ^{64}Ge

Ti/Fe ↗

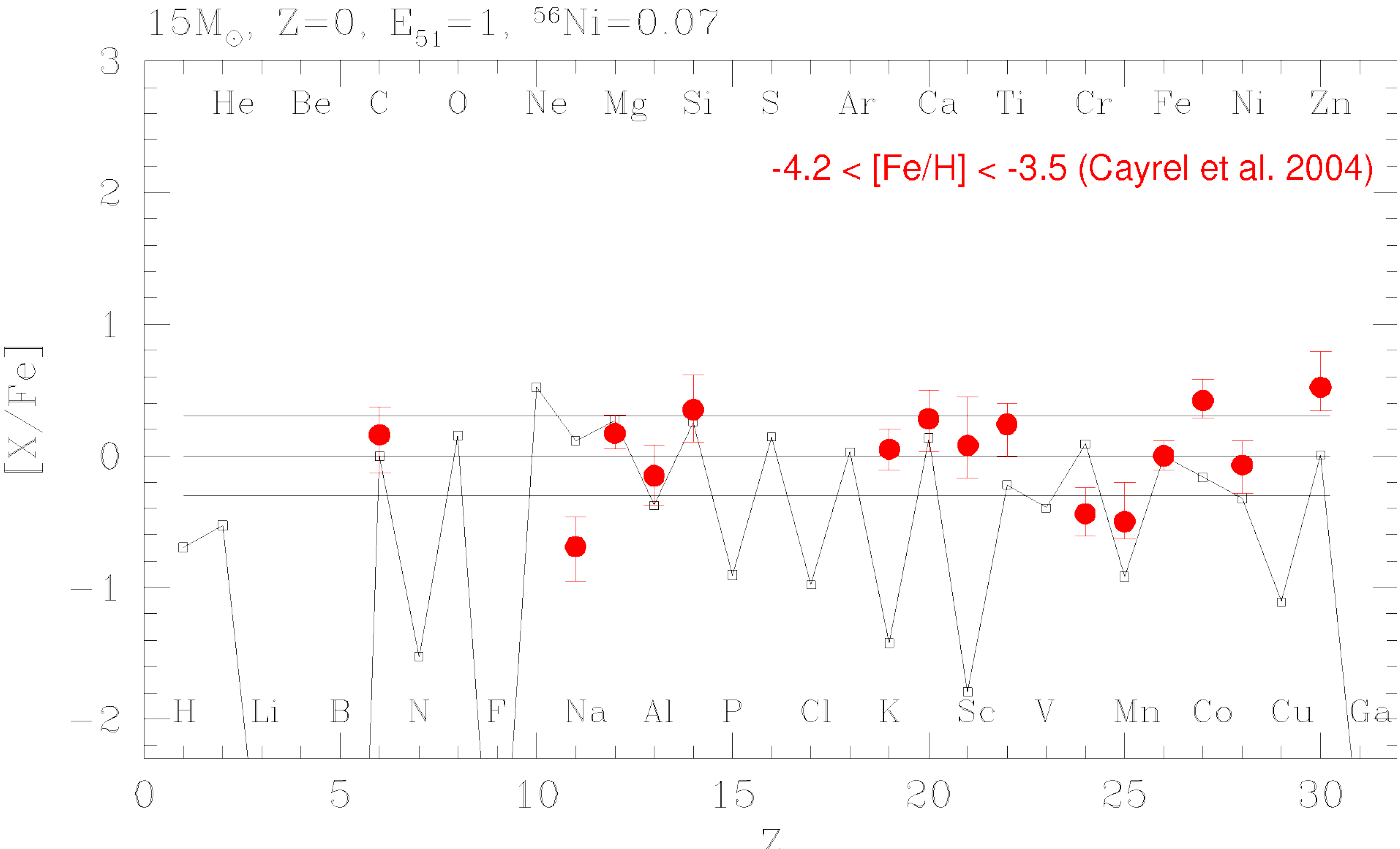
(3) More O burns

(Si, S, Ca)/O ↗

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

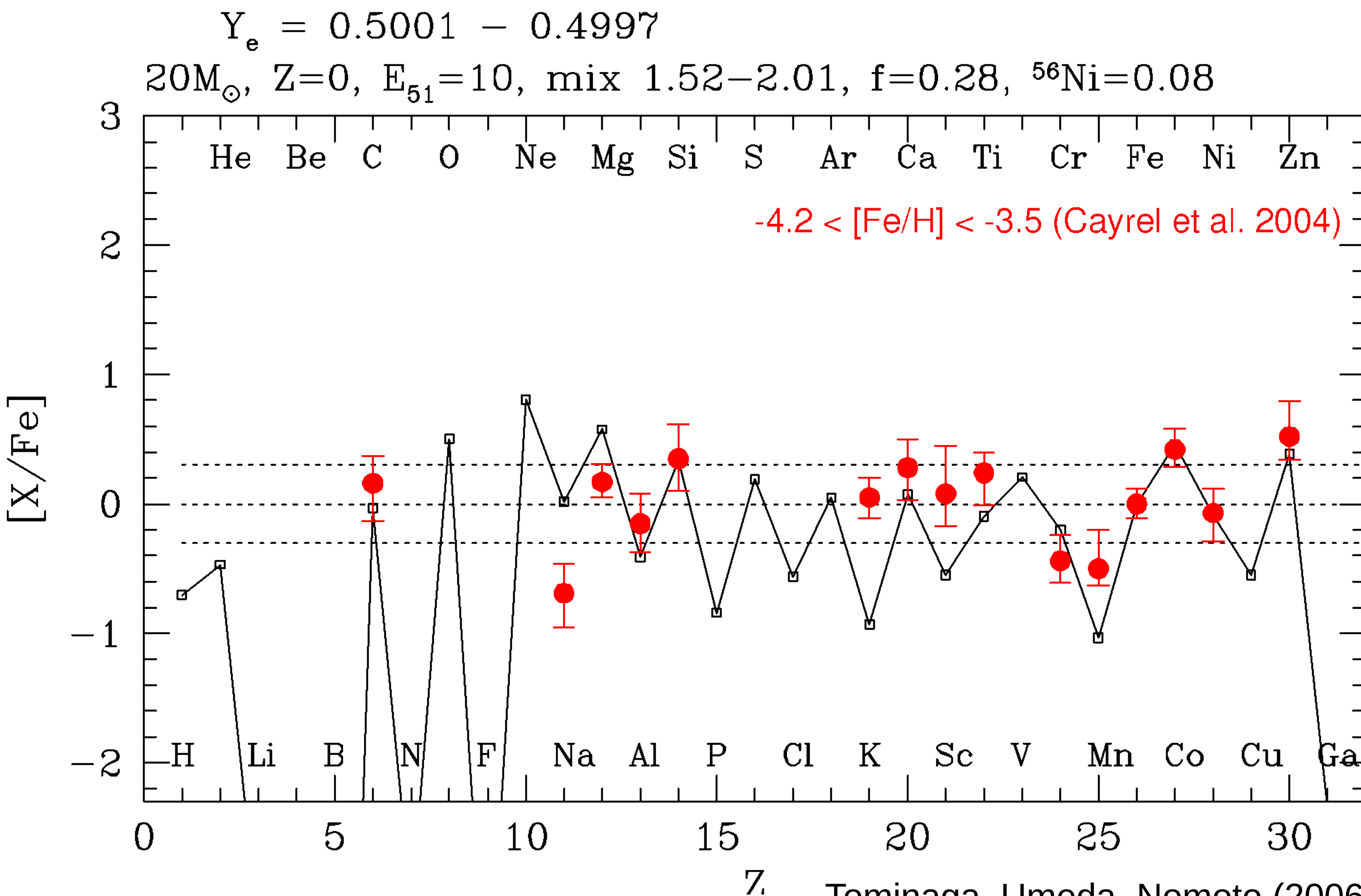


EMP stars vs. Normal SN II: Poor Fit



Tominaga, Umeda, Nomoto (2006)

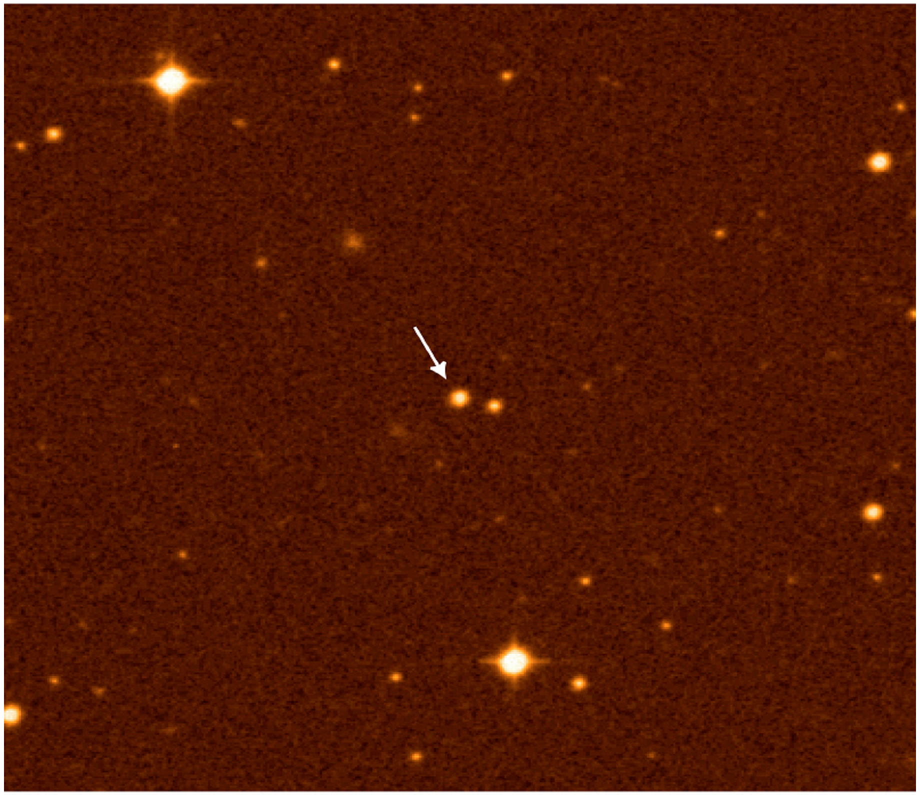
EMP stars vs. Hypernova (E_{51}=10)



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?

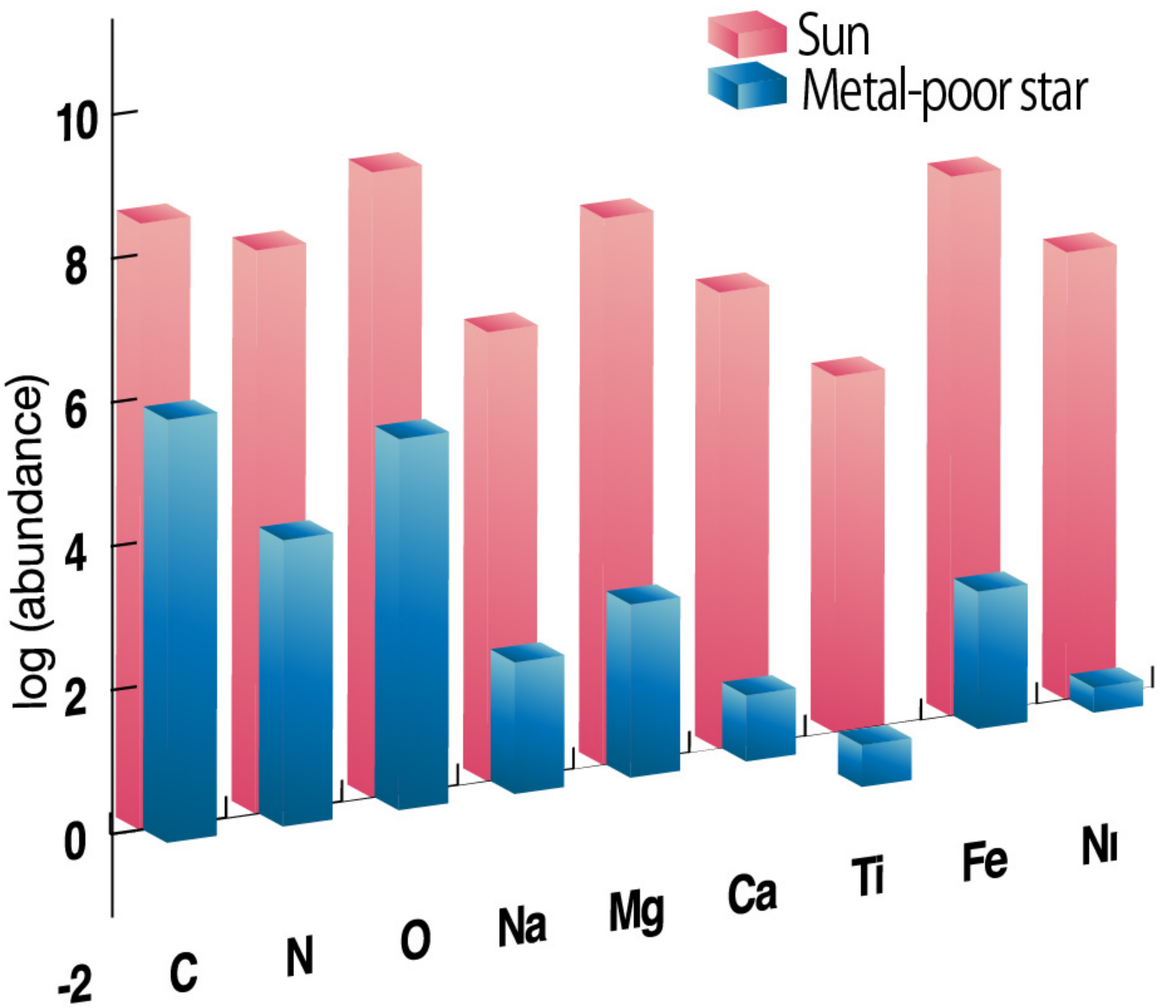


The Very Metal-Deficient Star HE 0107-5240

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

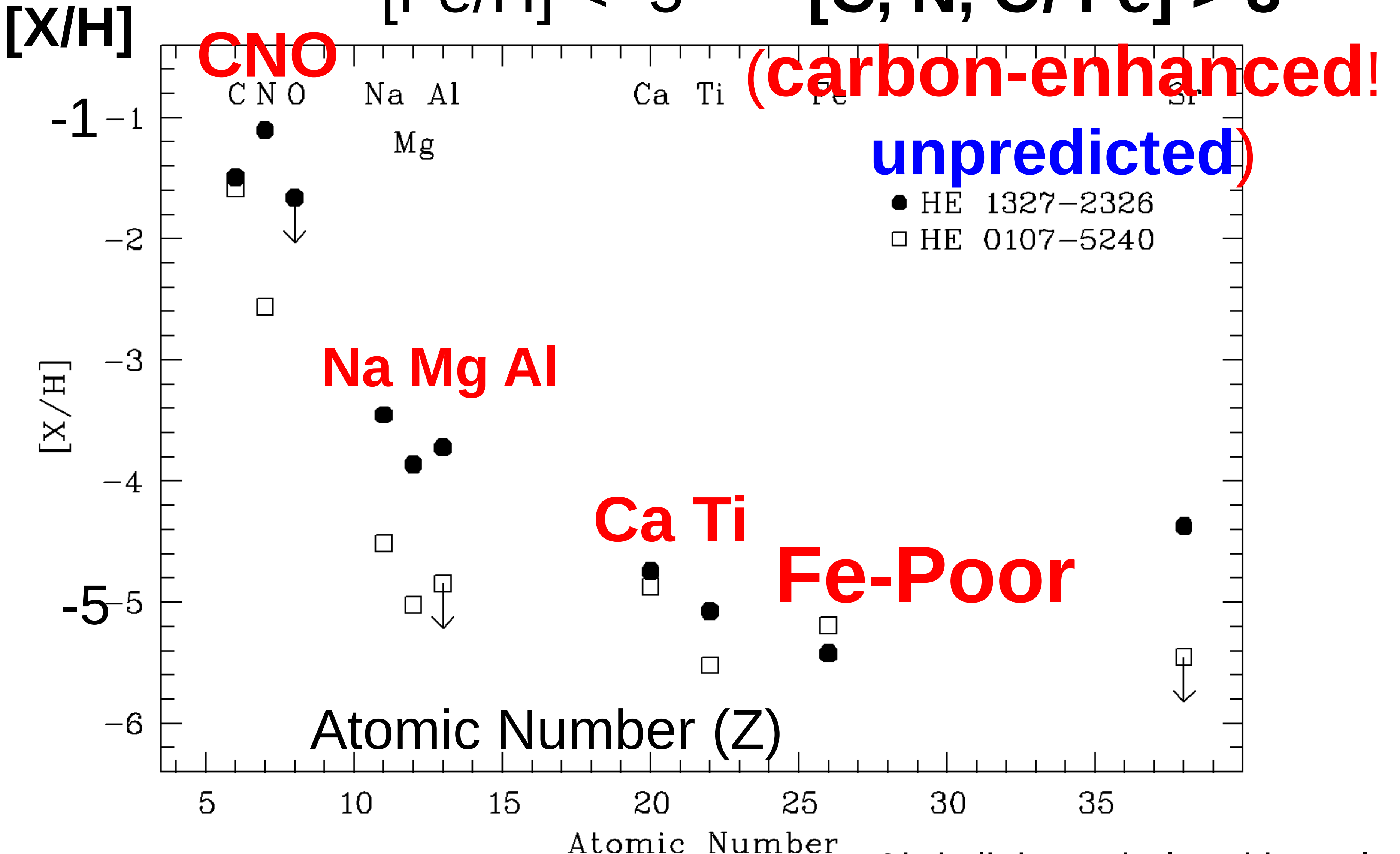
CEMP-no Stars

(Carbon Enhanced Metal Poor)
(no-s process enhancement)



Hyper Metal-Poor (HMP) Stars

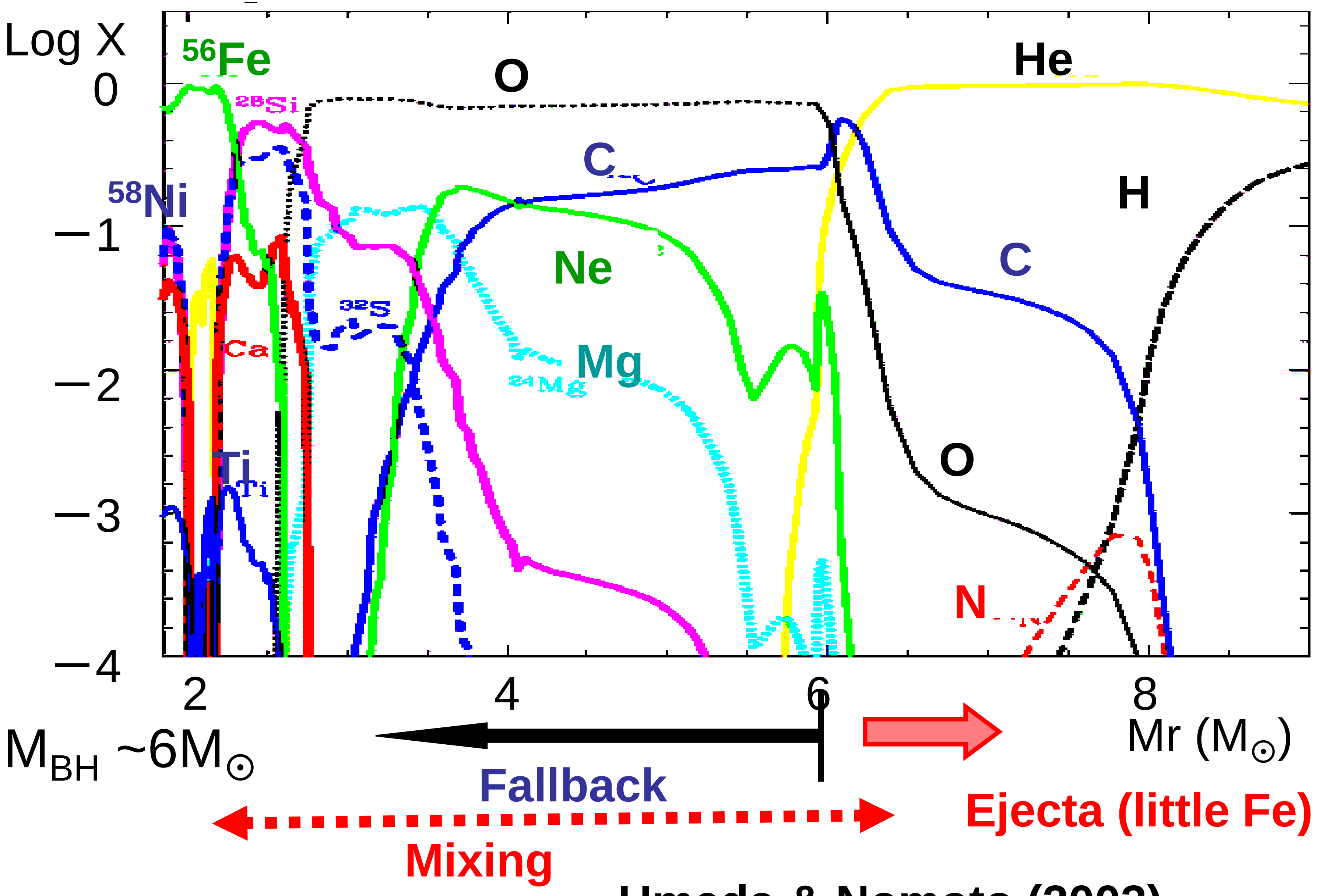
[Fe/H] < -5   **[C, N, O/ Fe] > 3**



Christlieb, Frebel, Aoki, et al.

Mixing and Fall-back Model

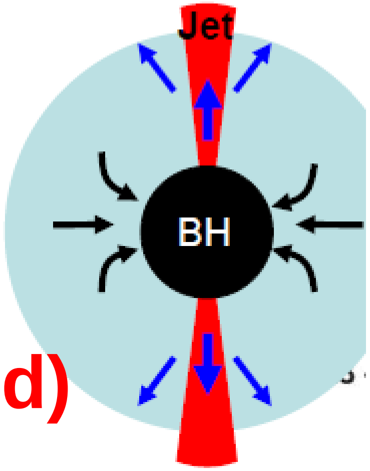
M=25M$_\odot$, [Fe/H]=−5.3



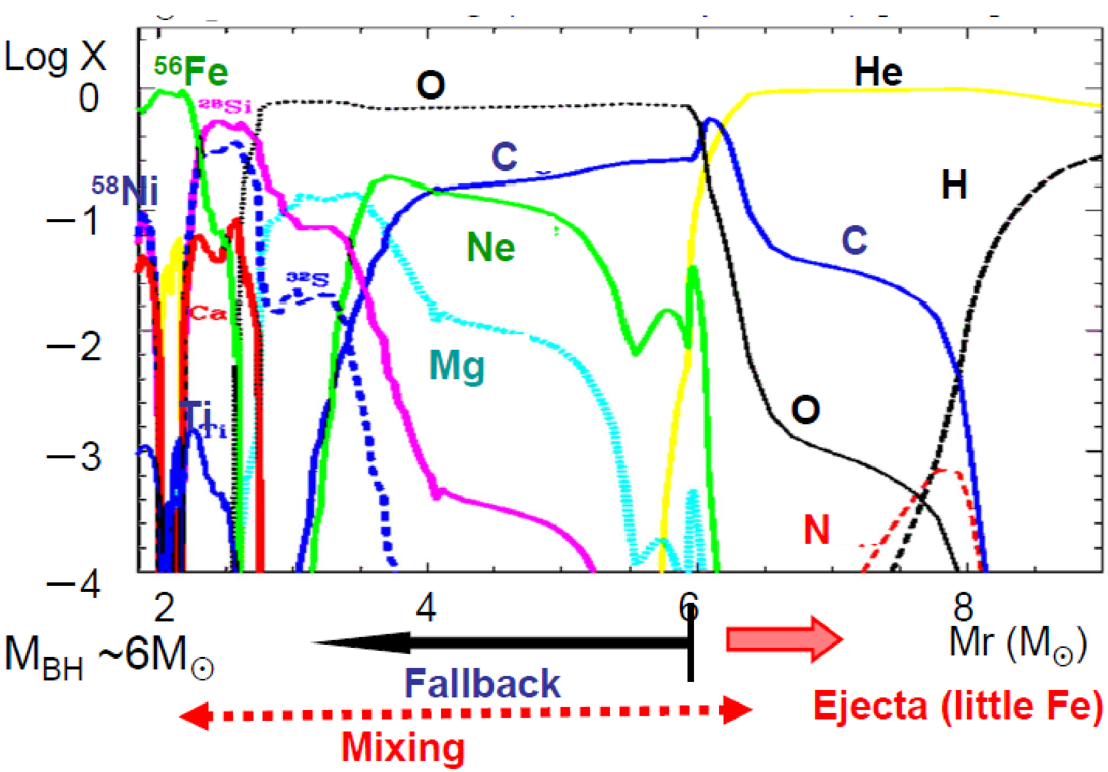
Umeda & Nomoto (2003)

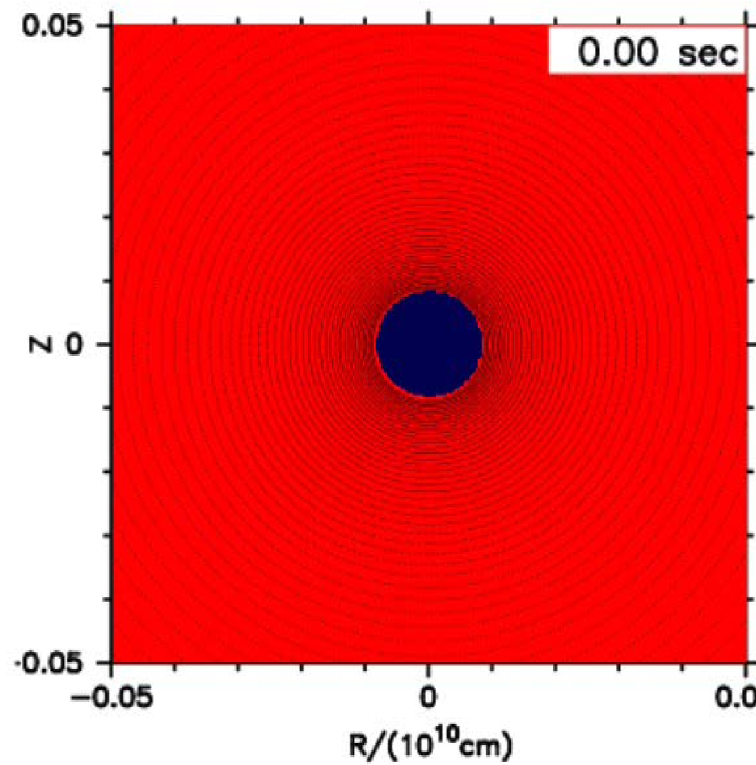
Mixing & Fallback Supernova

➔ Carbon Enhanced Metal Poor (CEMP) Stars



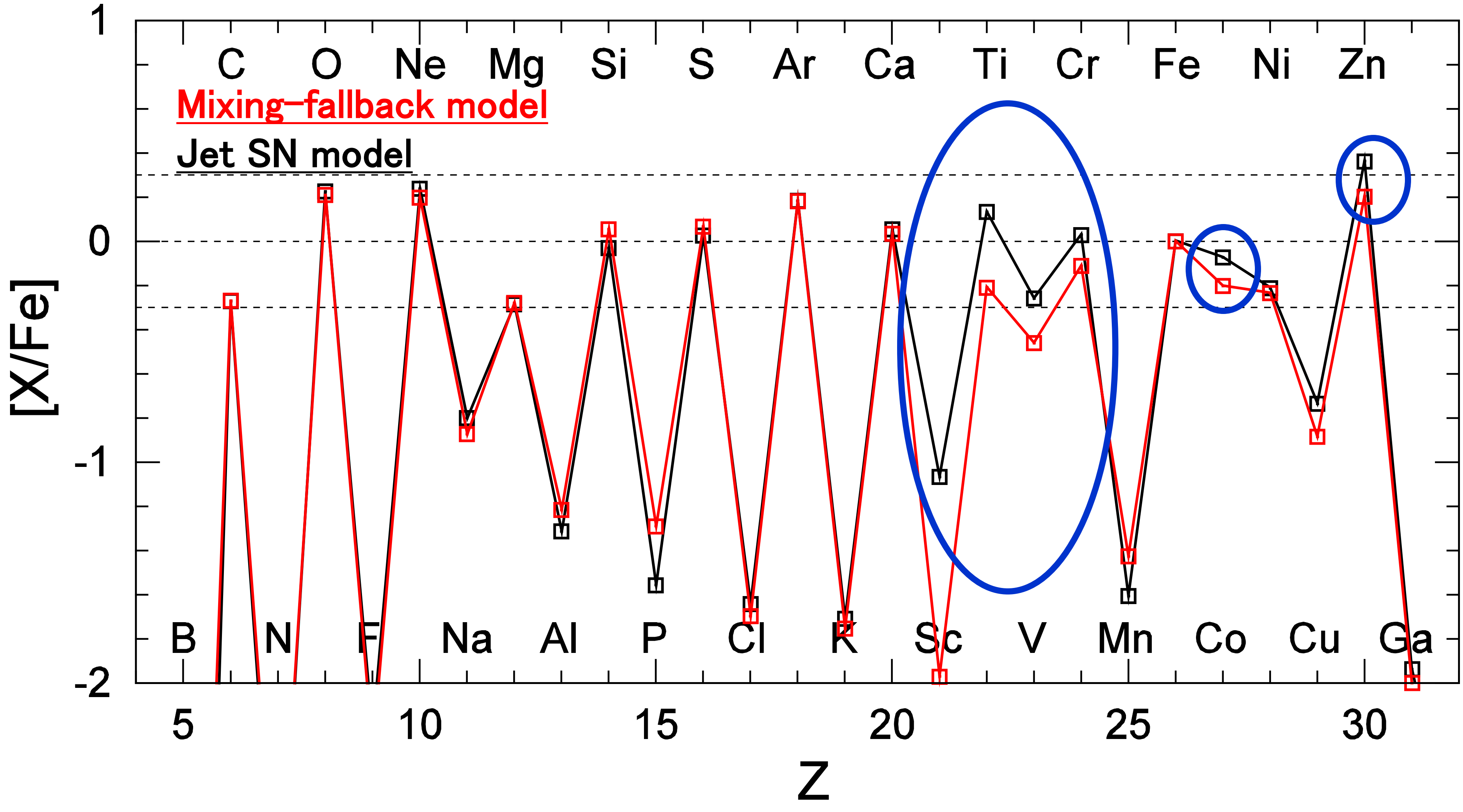
M(Fe) small ➔ Faint SN (Jet-induced)





Mixing-fallback vs. Jet SN model

High entropy due to the energy concentration.



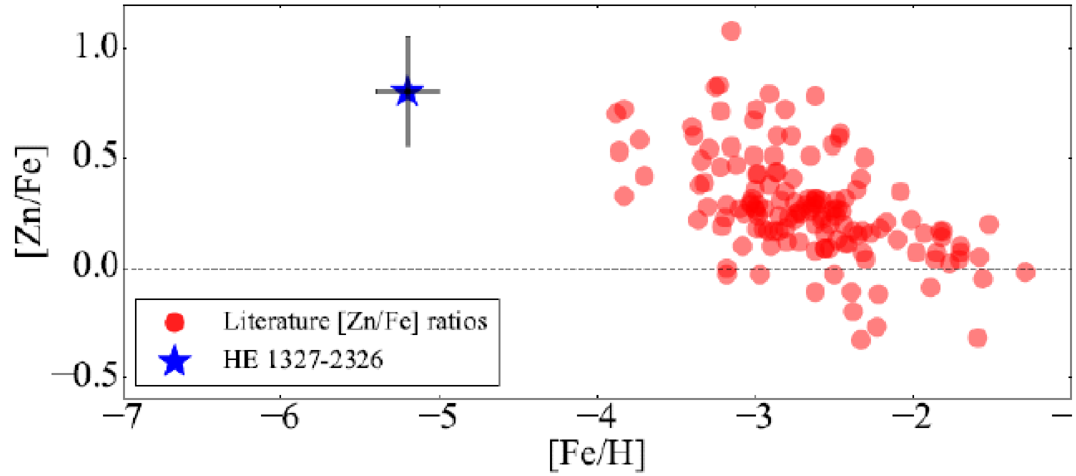
HMP star
with high [Zn/Fe]

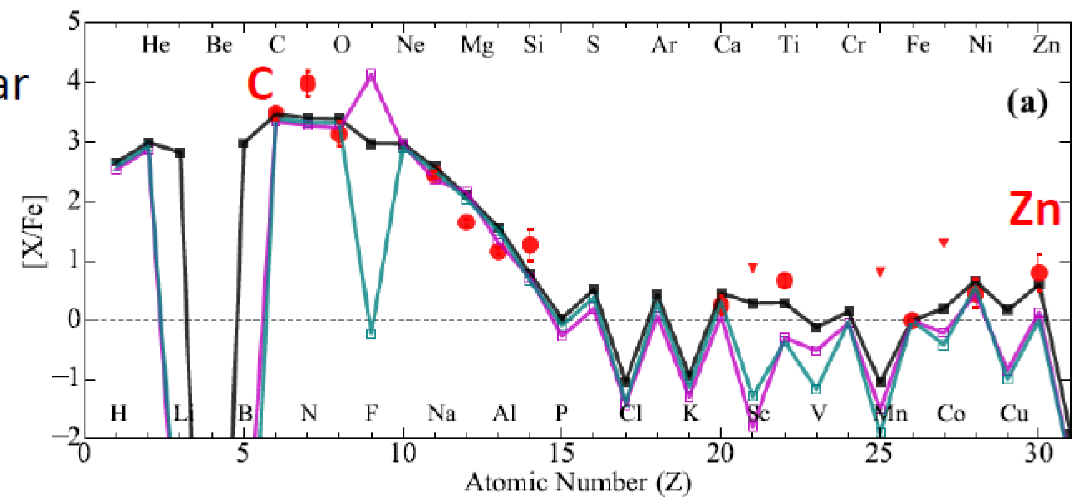
UV spectrum with HST
[Fe/H] = -5.2
[Zn/Fe] = 0.80 +- 0.25

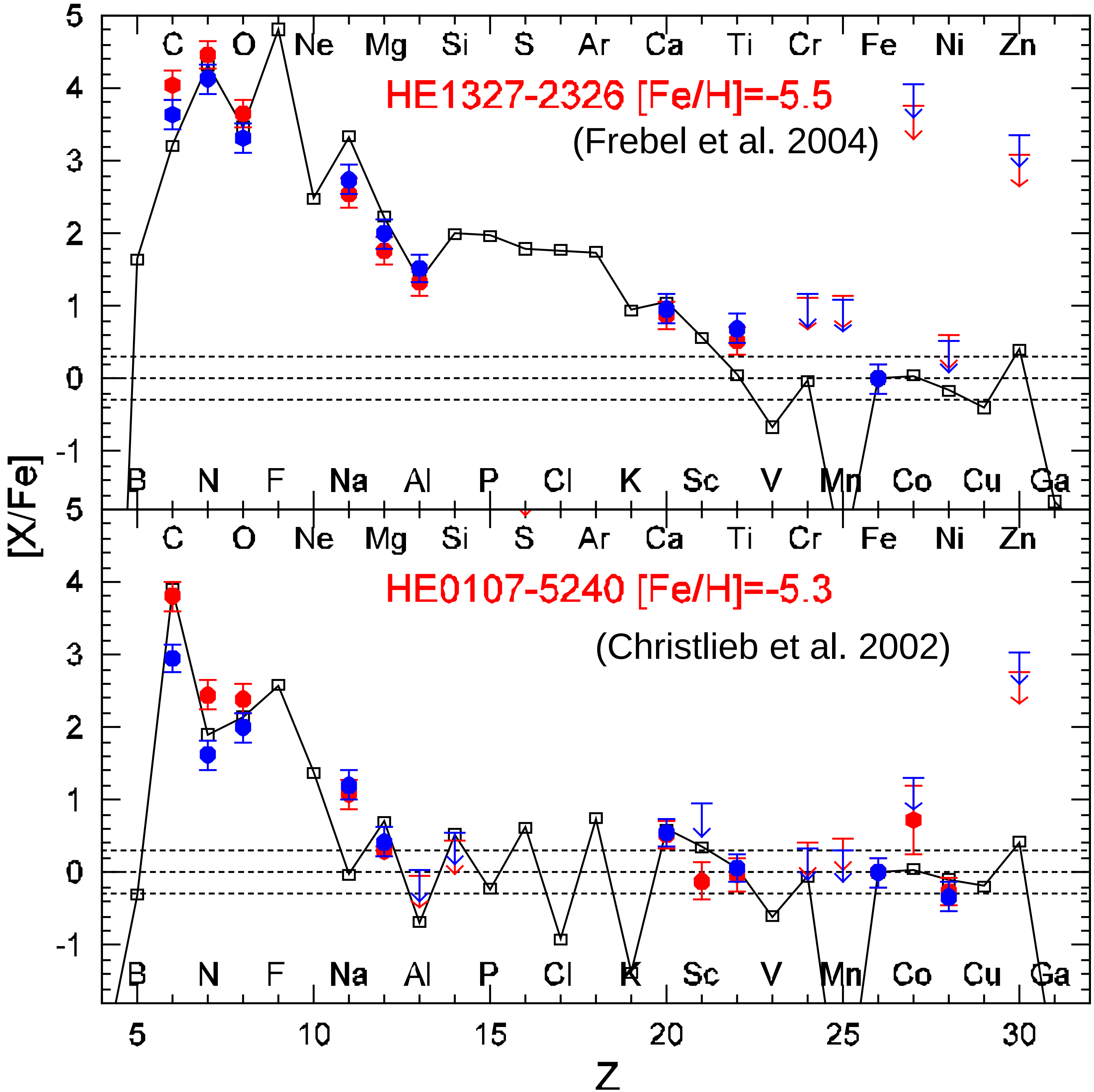
Carbon-Enhanced (CEMP) star

Aspherical (**Jet**) Model
M = 25 $M_\odot$
E = 5 x 10^{51} erg

(Ezzeddine, Frebel,.. KN,.. 2019 ApJ)







HMP Stars

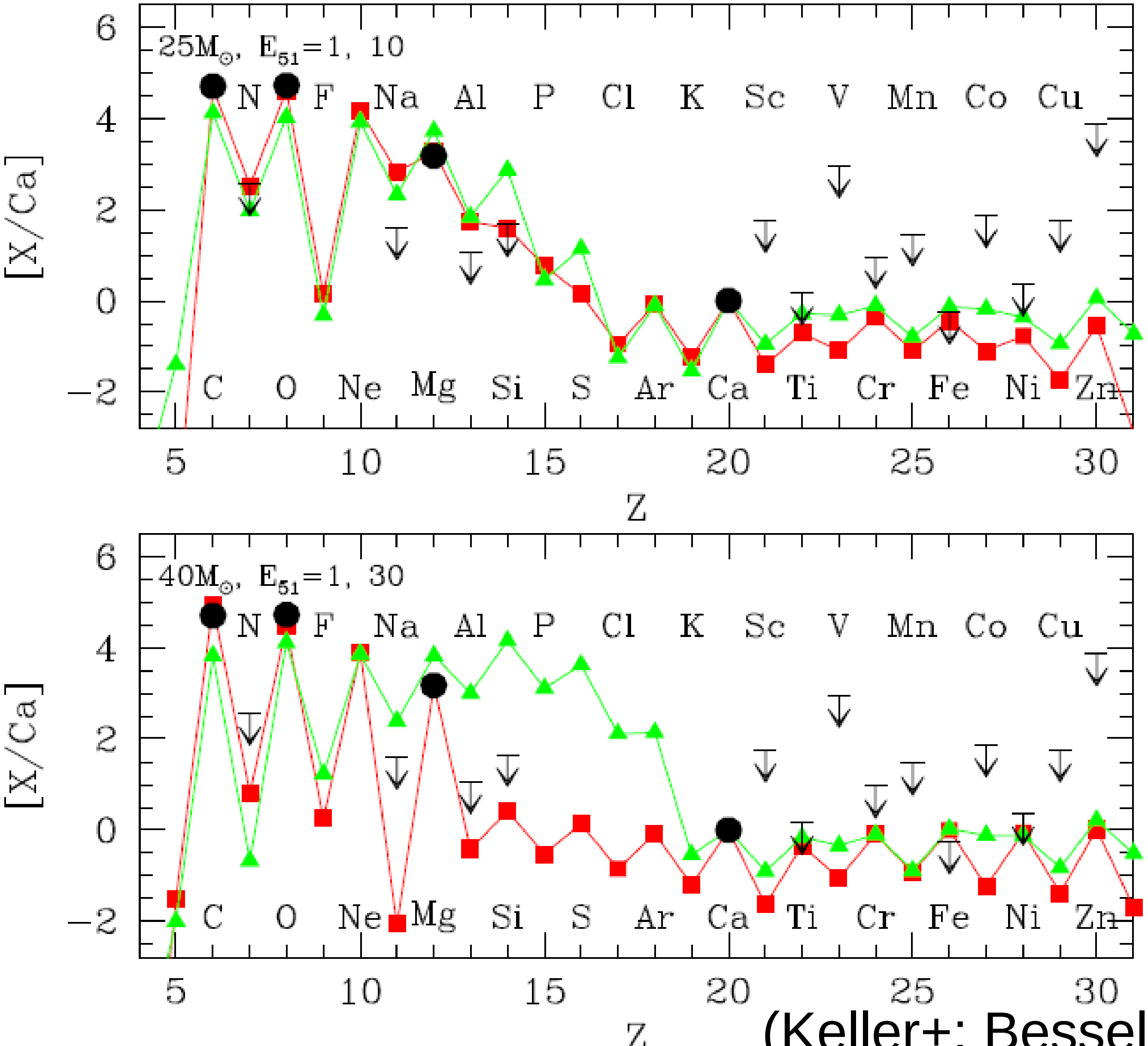
Jet-induced SN models

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

Dark Hypernova

Tominaga et al. 2007

SM0313-6708 ([Fe/H] < -7.52): Mixing-Fallback model :



M ~ 25 – 40 $M_\odot$

[Fe/H] < -7.52

[Ca/H] = -7.26

[Mg/H]= -4.08

[O/H] = -2.53

[C/H] = -2.55

(O & incomplete Si burning → Ca)

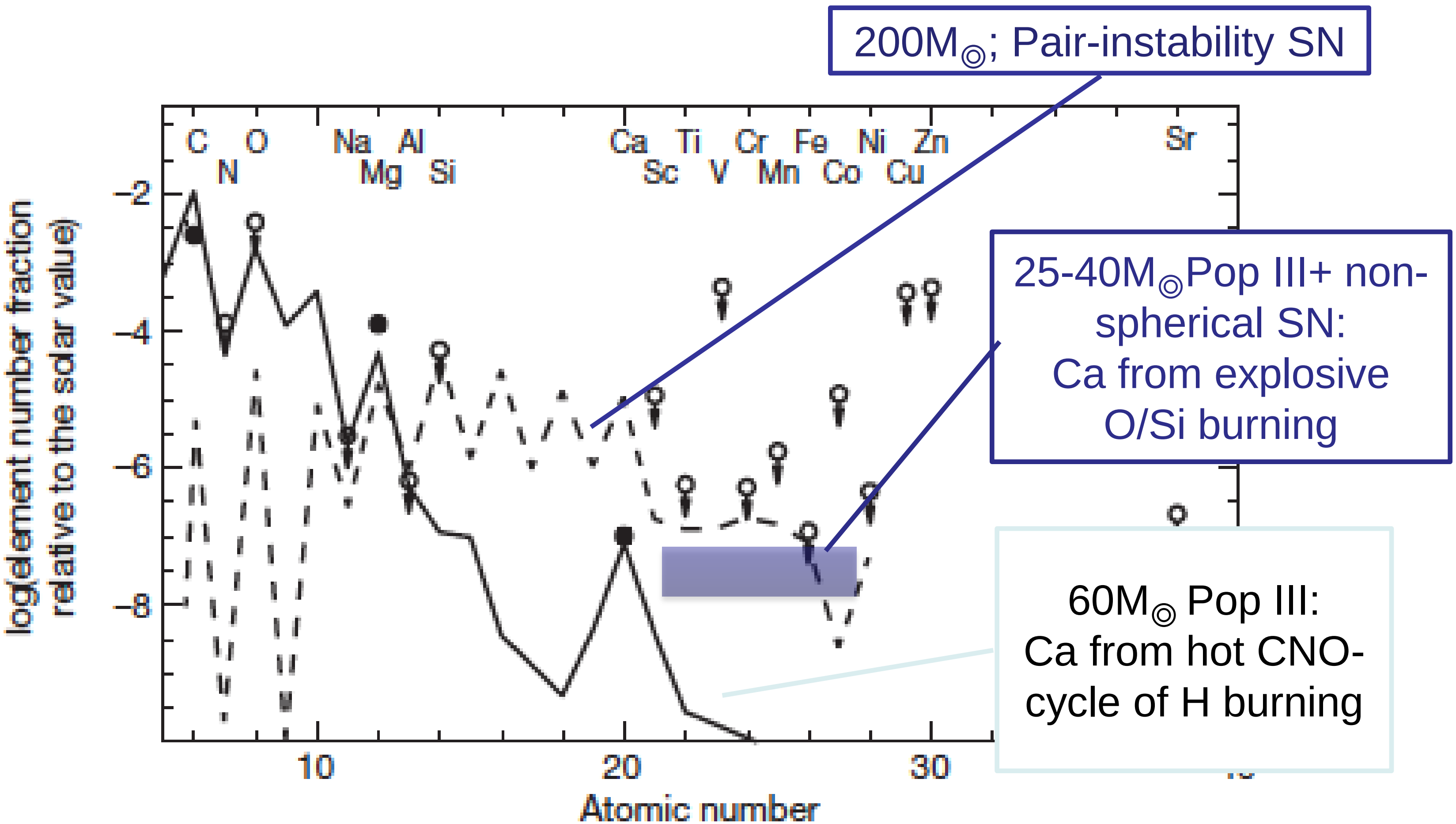
M(BH) ~ 6 $M_\odot$

(Ishigaki+15)

(Keller+; Bessel+)

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

(Keller et al. 2014)



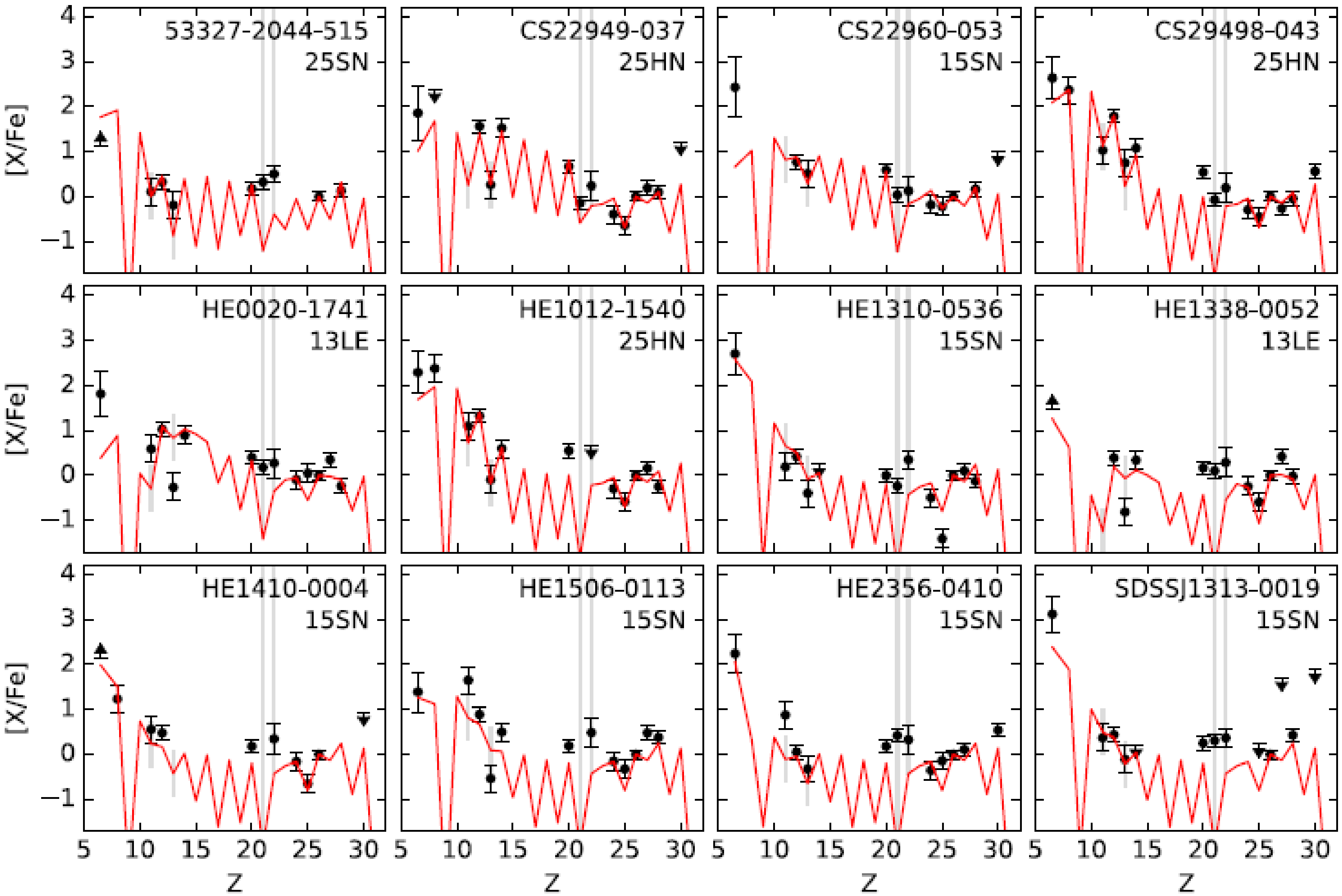
If [Ca/Fe] > 1 ➔ Ca = hot CNO cycle ➔ Tc > 10^8 K

➔ Z ~ 10^{-8} $Z_\odot$ ➔ Pop III (Mori, KN, Ishigaki 2019)

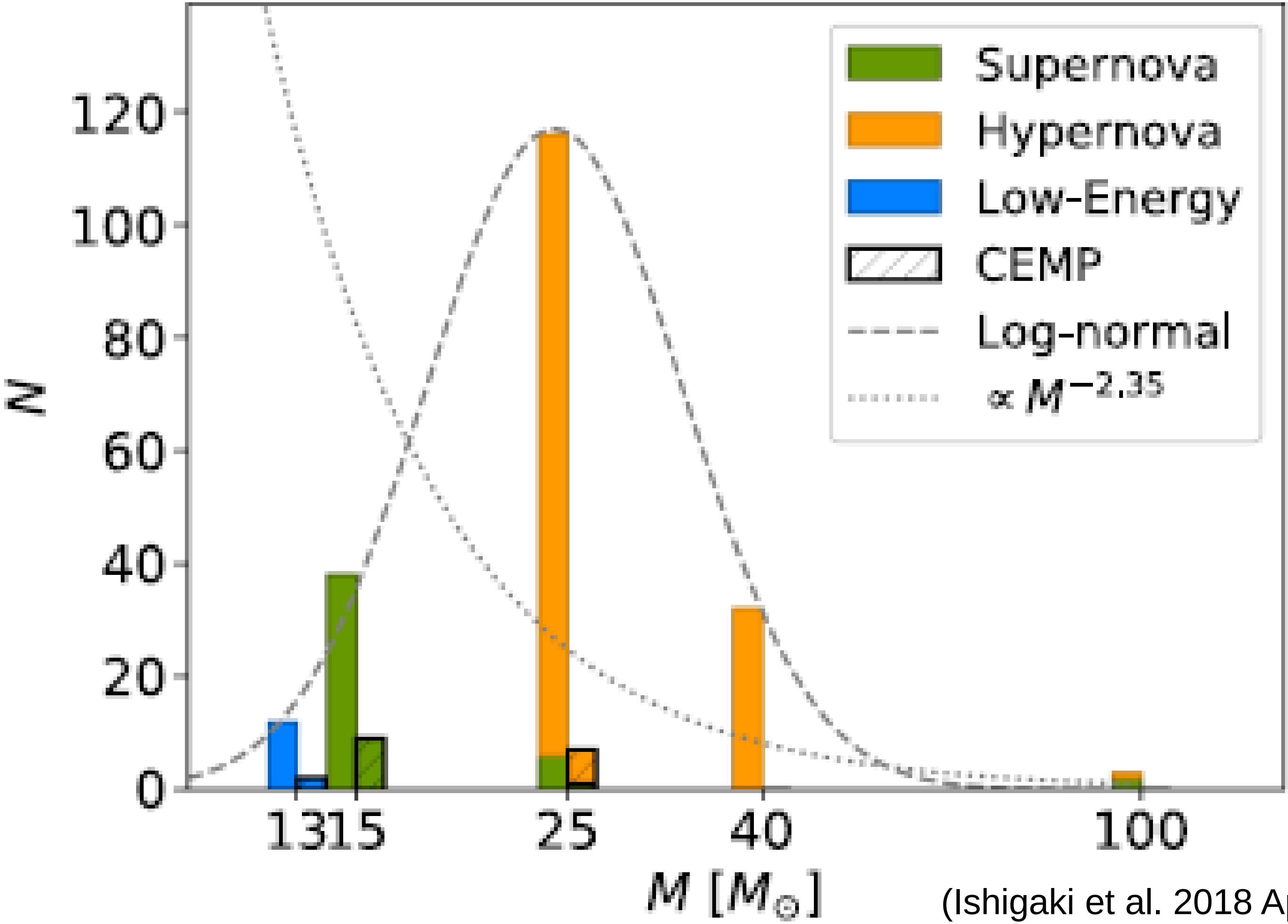
If [Ca/Fe] ~ 0 ➔ Ca from SN explosion ➔ not necessarily Z = 0

Best fit models

(Ishigaki et al. 2018 ApJ)



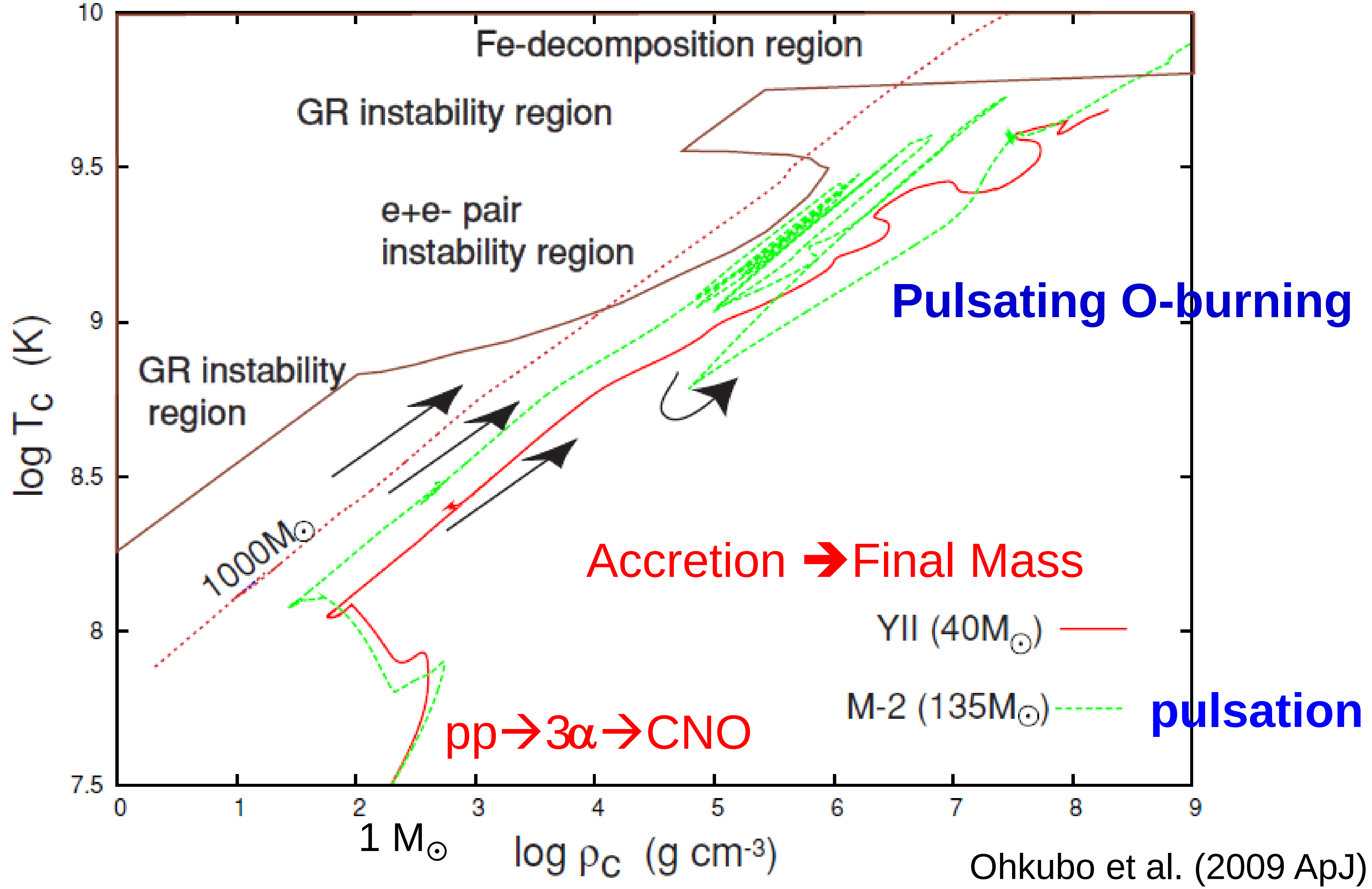
Mass distribution



(Ishigaki et al. 2018 ApJ)

Pulsating O & Si Burning ➔ CSM ?

Pulsational Pair-Instability (80-140 $M_\odot$)



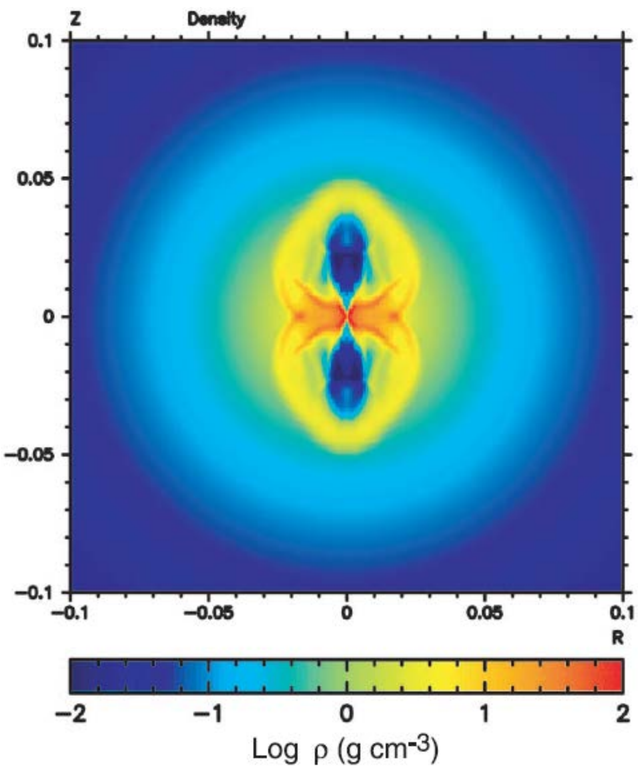
Ohkubo et al. (2009 ApJ)

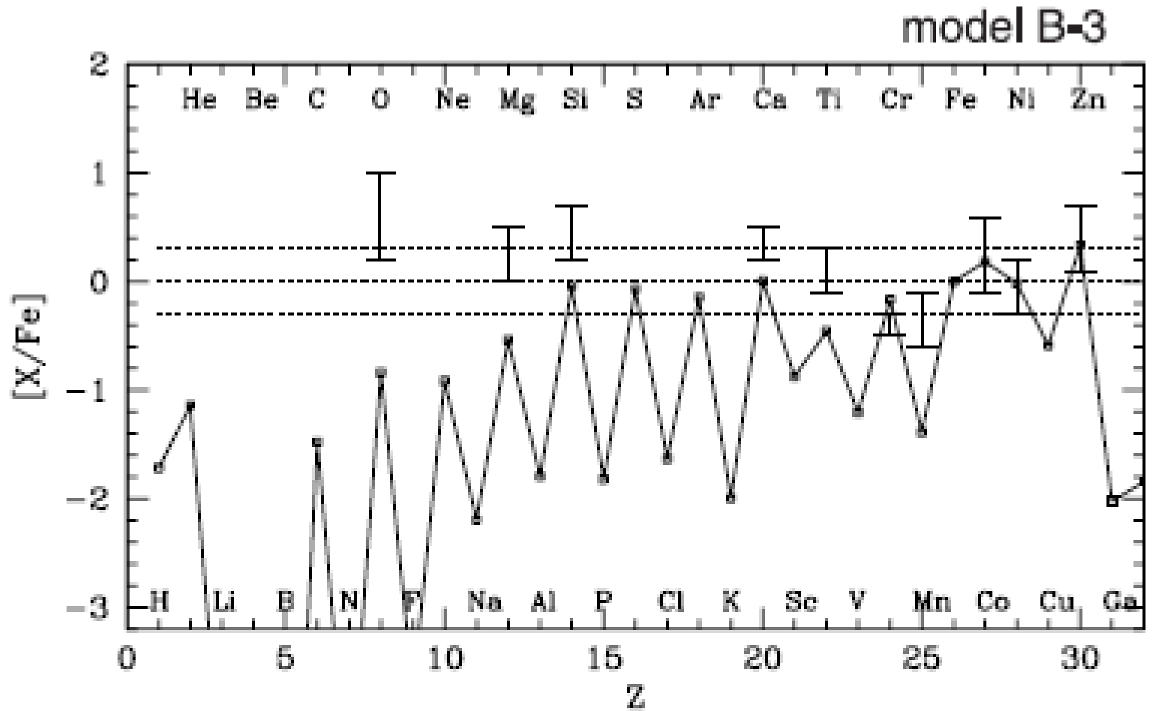
M = 500 $M_\odot$ (- 1000 $M_\odot$)

Black Hole forming explosion:

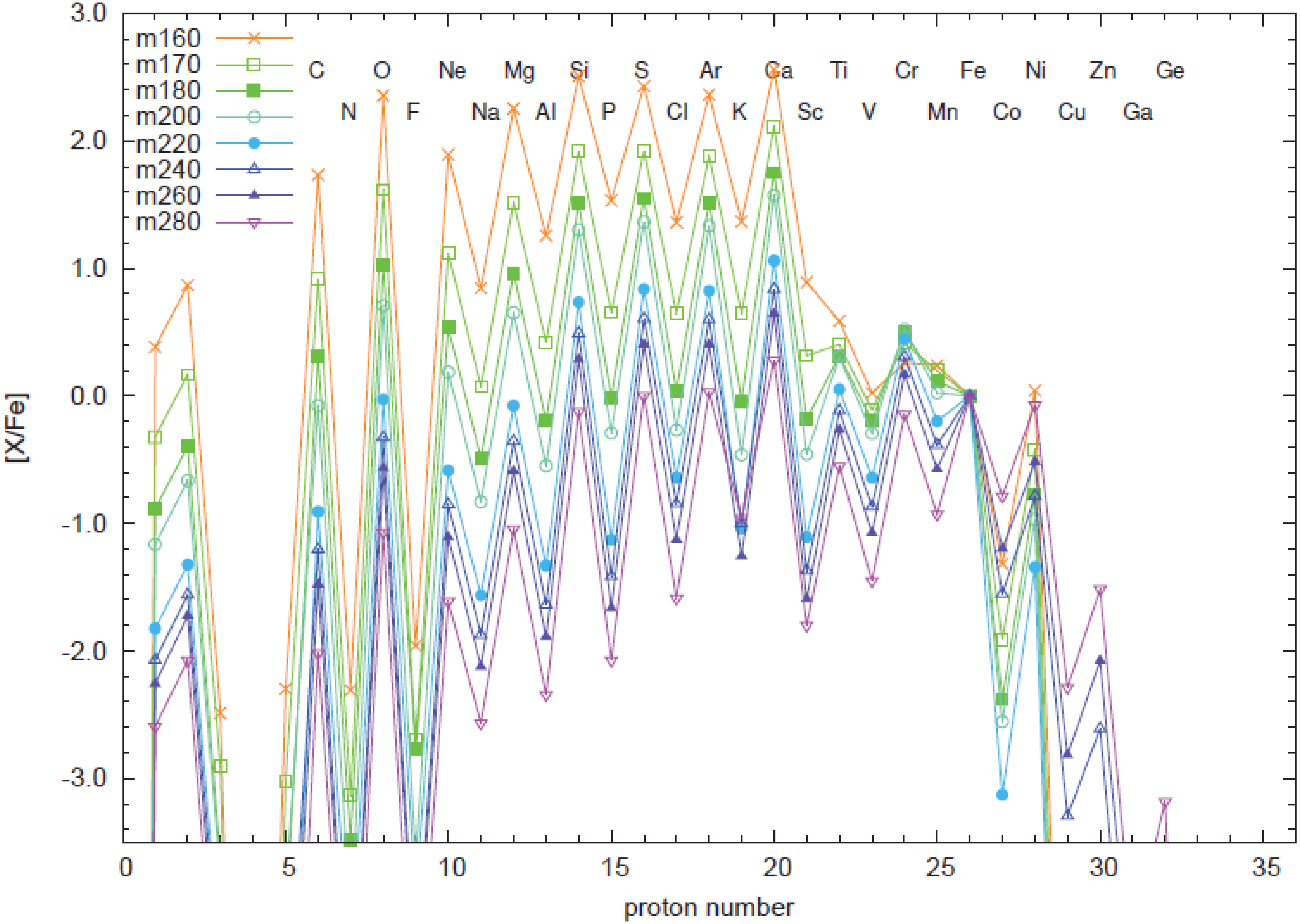
[O/Fe] : much smaller than EMP stars

(Ohkubo +07)



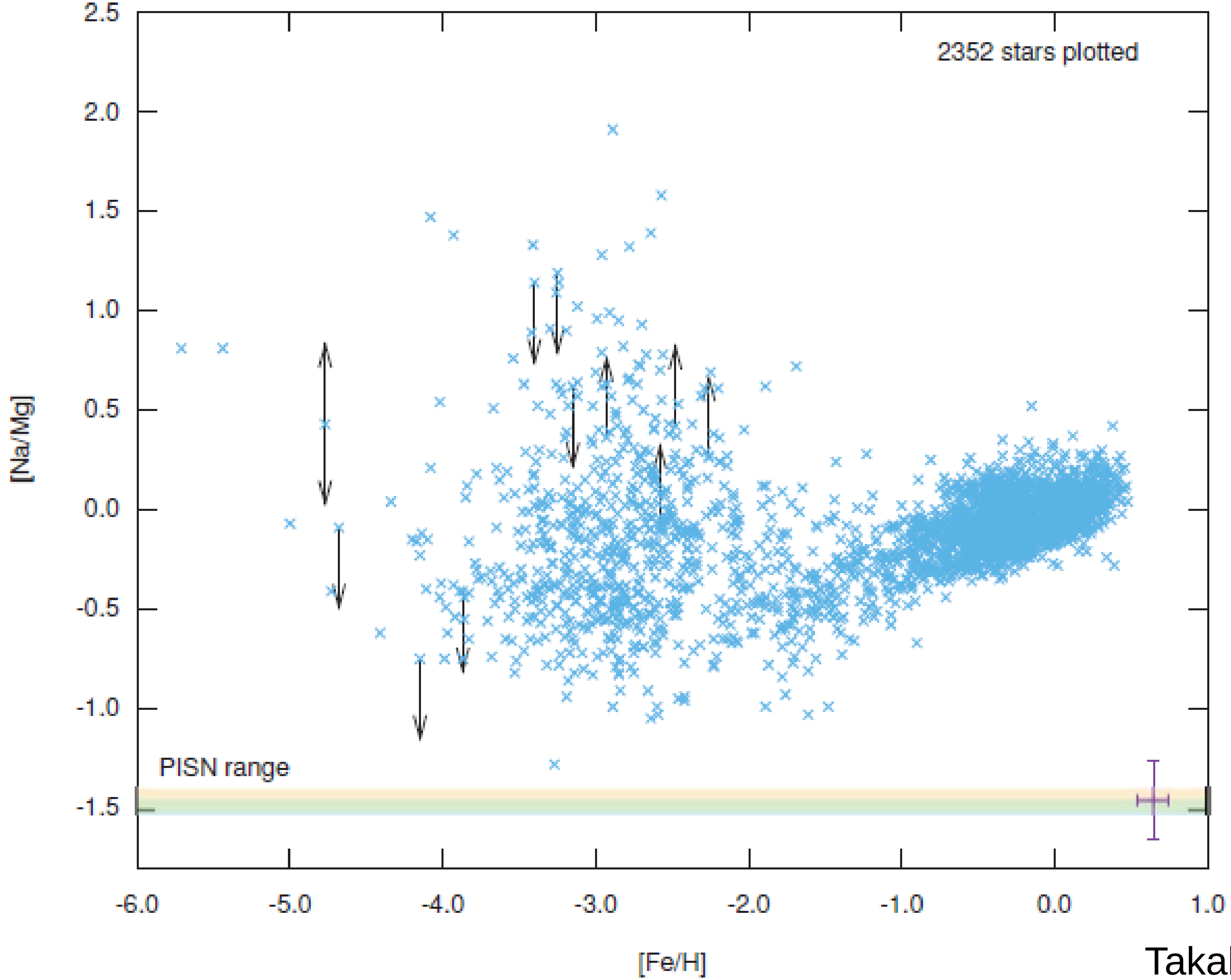


Pair-Instability SN yields: large odd/even Z



Takahashi+18

Pair Instability SN: [Na/Mg] too small



Takahashi+18

~80 – 140 $M_\odot$ Stars

$M(He) \sim 50 – 62\ M_\odot$

Pulsational Pair-Instability (PPI)

➔ Pulsational Mass Ejection

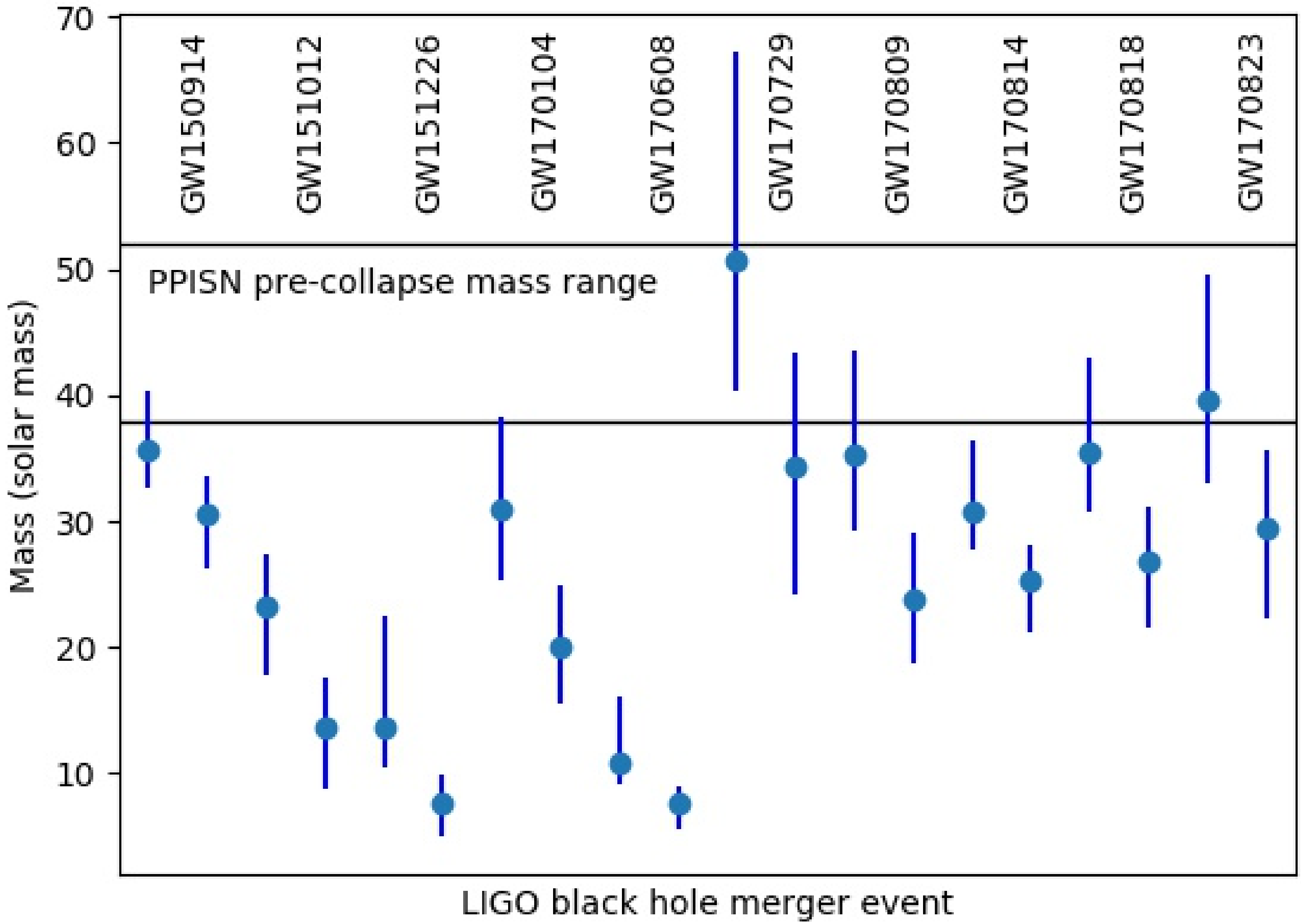
➔ Dense Circumstellar Matter

$M(ej) \sim 4 – 40\ M_\odot$

➔ **Collapse (BH formation):** $M(^{56}Ni) < 10\ M_\odot$

e.g., Barkat et al. (1967)
Heger & Woosley (2002)
Ohkubo, Nomoto et al. (2009)
Yoshida et al. (2016)
Woosley (2017)

LIGO BH masses vs. PPISN masses



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

Hypernovae with relativistic jets

(M_{ms} ~ 20 – 80 M_{sun})

	GRBs		Metal-Poor stars
Larger	GRB-HNe		EMP stars
$\dot{E}_{dep}$			
Smaller	No-SN GRBs		UMP stars HMP stars

Fallback SNe ➔ Black-Hole-forming SNe ?

Superluminous Supernovae

(any connection to EMP stars ??)