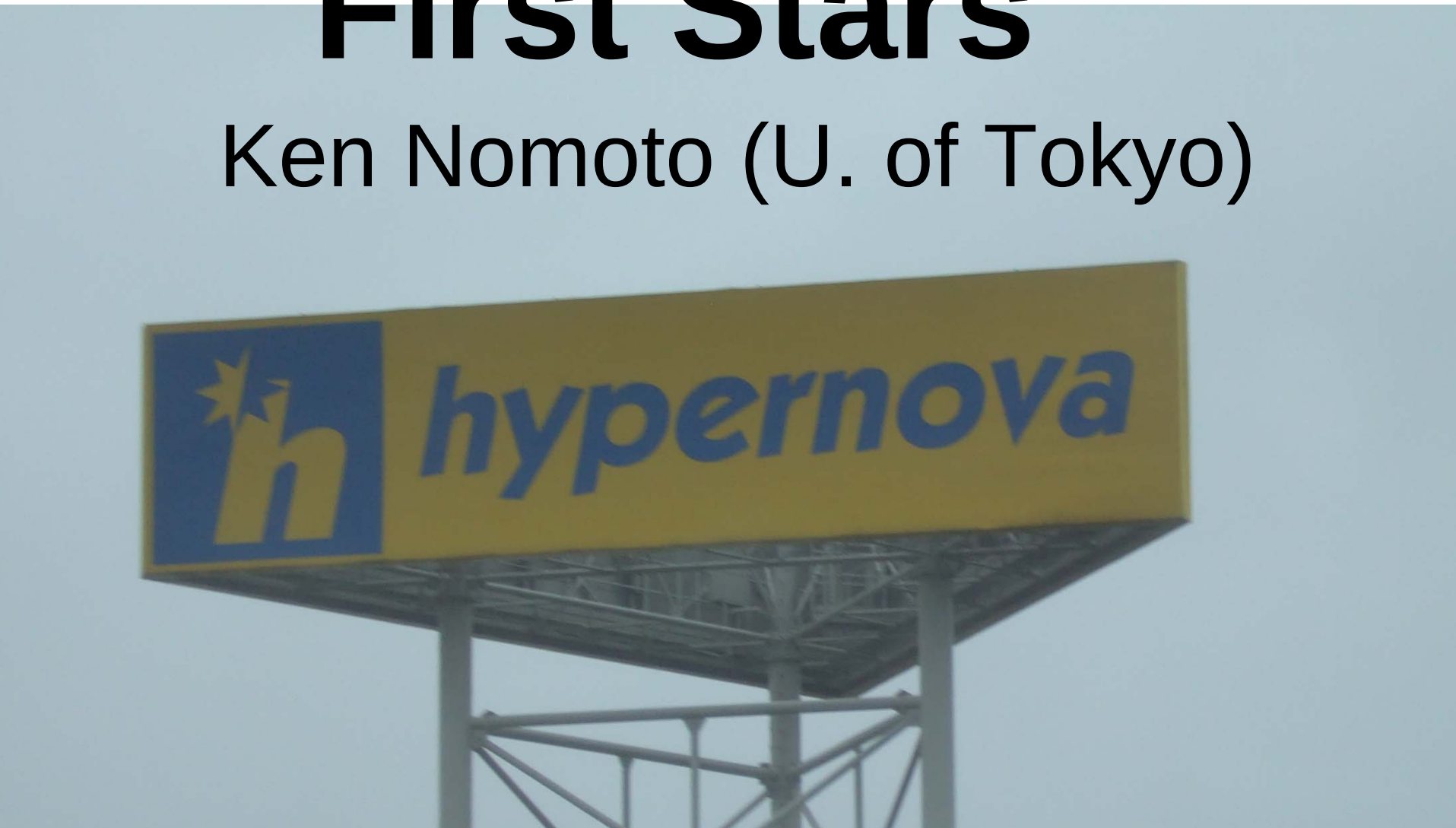
Hypernovae and First Stars

Ken Nomoto (U. 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**

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

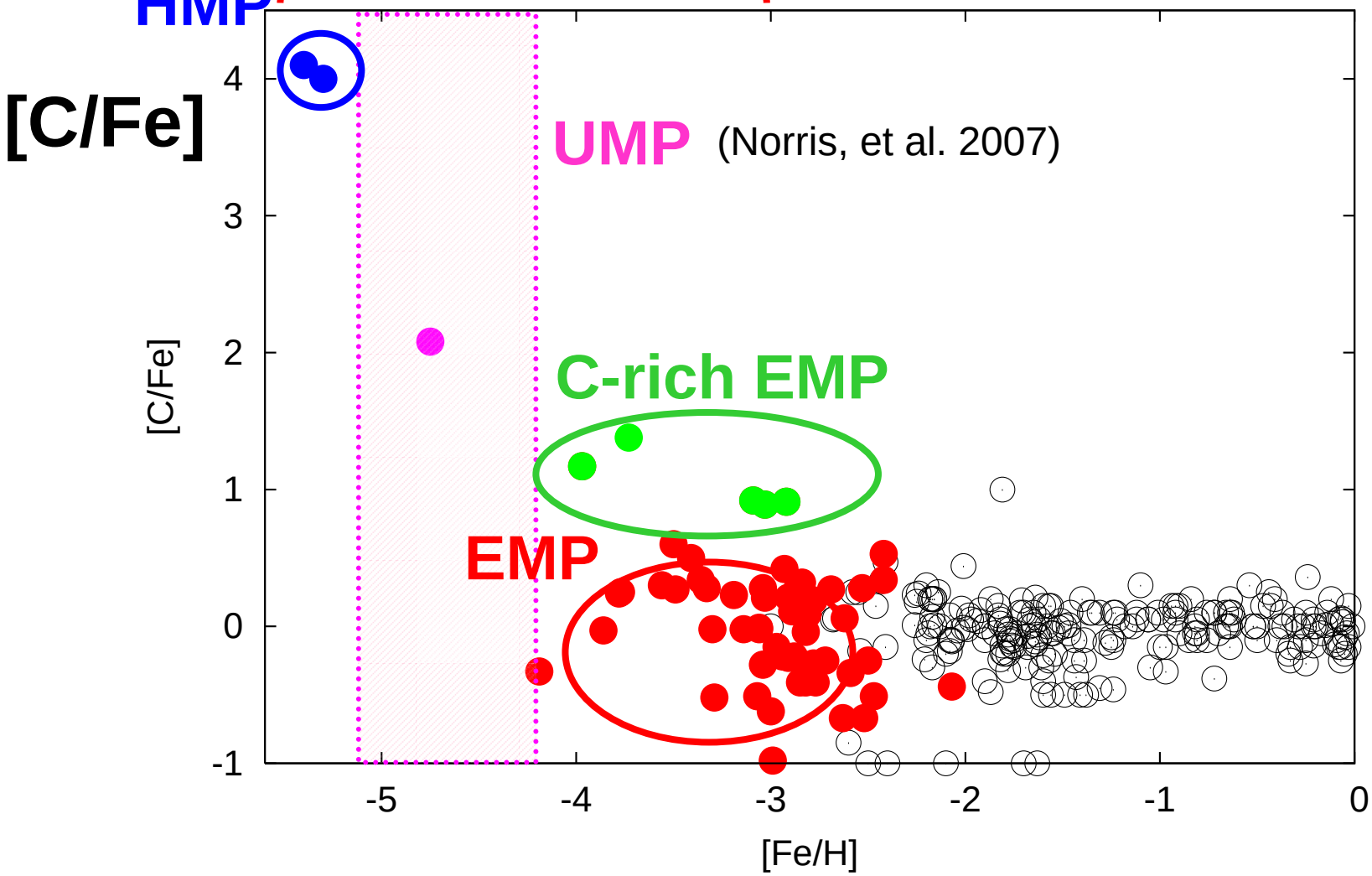
$$[Fe/H]=\log(Fe/H)-\log(Fe/H)_{\odot}$$

(Beers & Christlieb 2005)

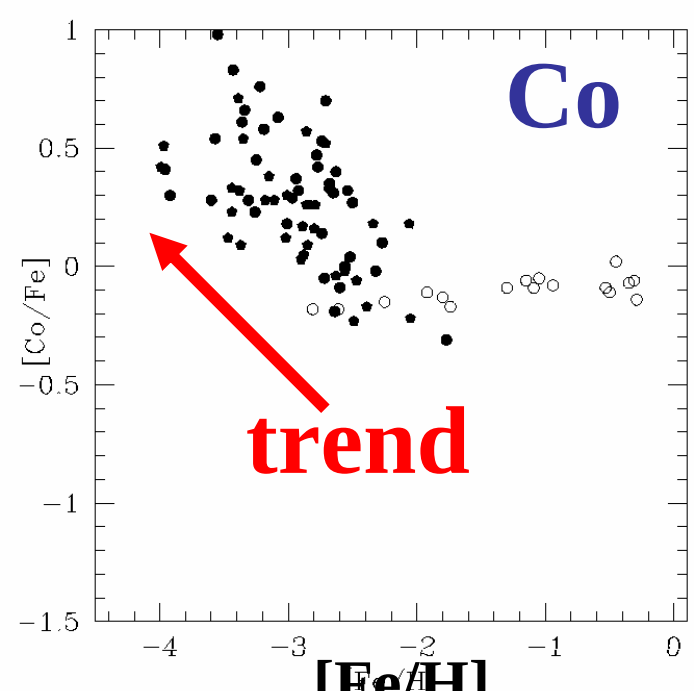
Metal-Poor Stars

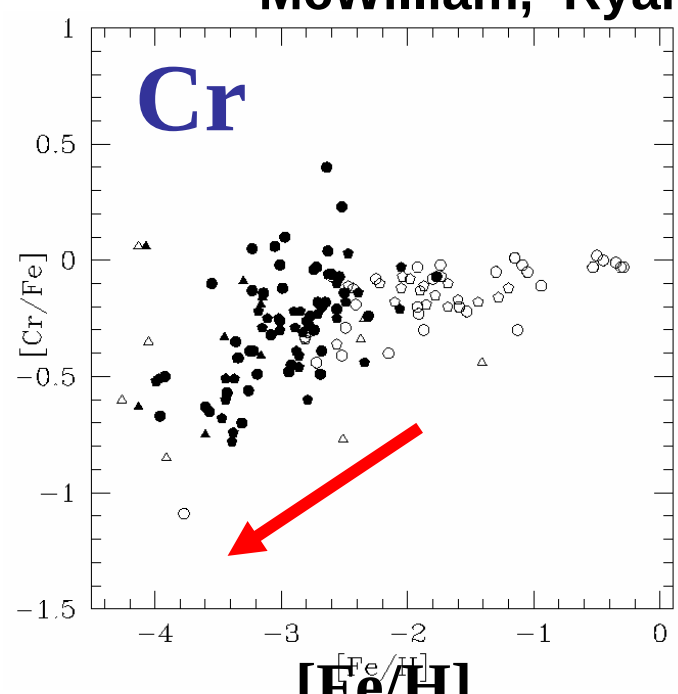
First Supernovae

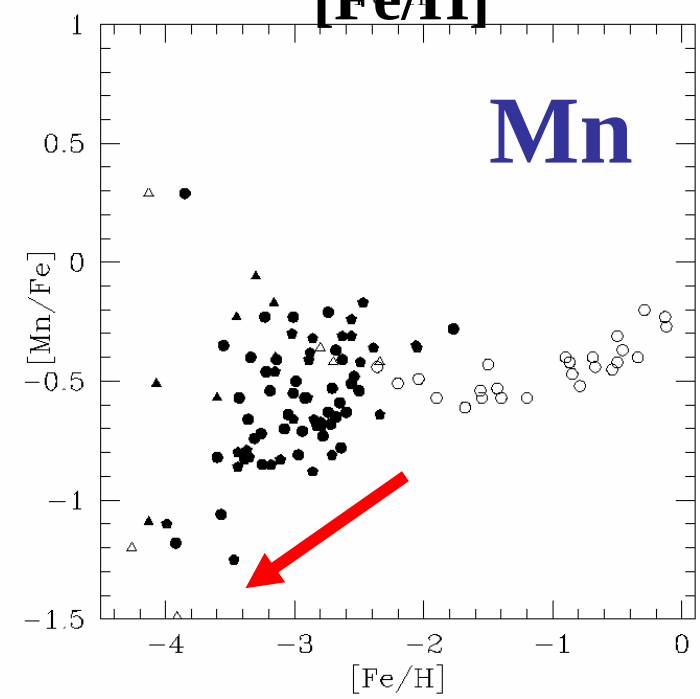
Beers, Christrieb (2005)

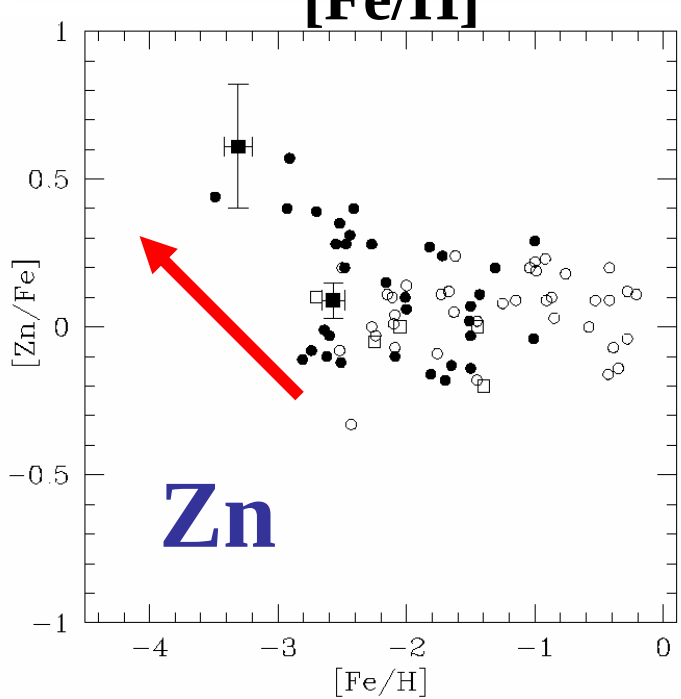


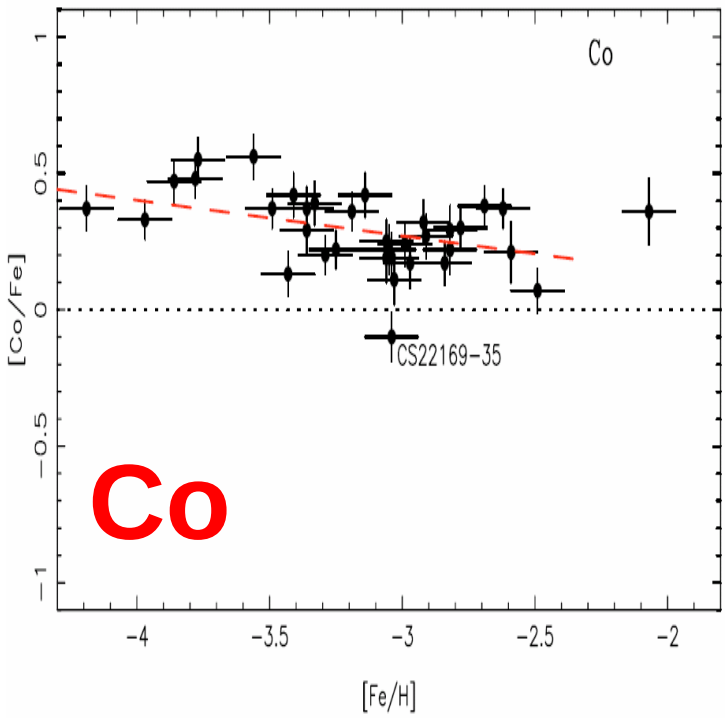
McWilliam, Ryan

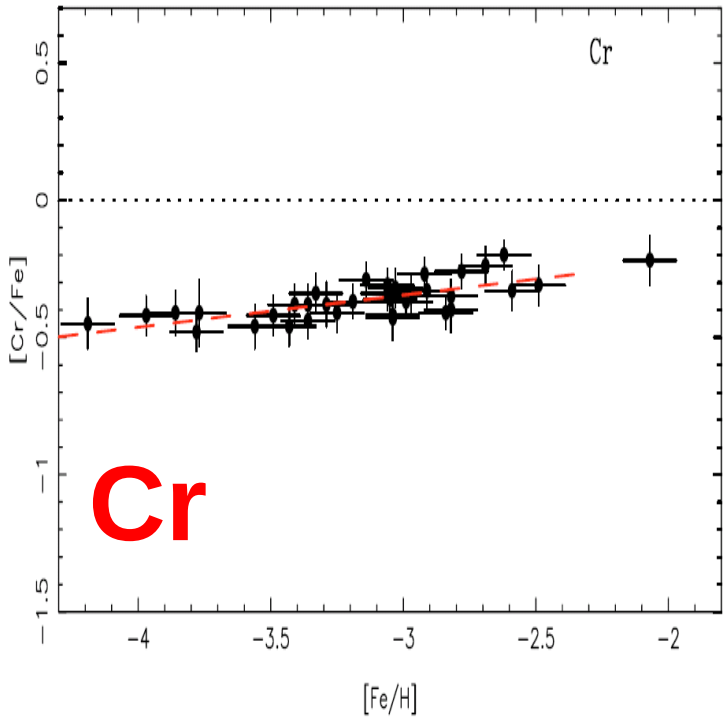


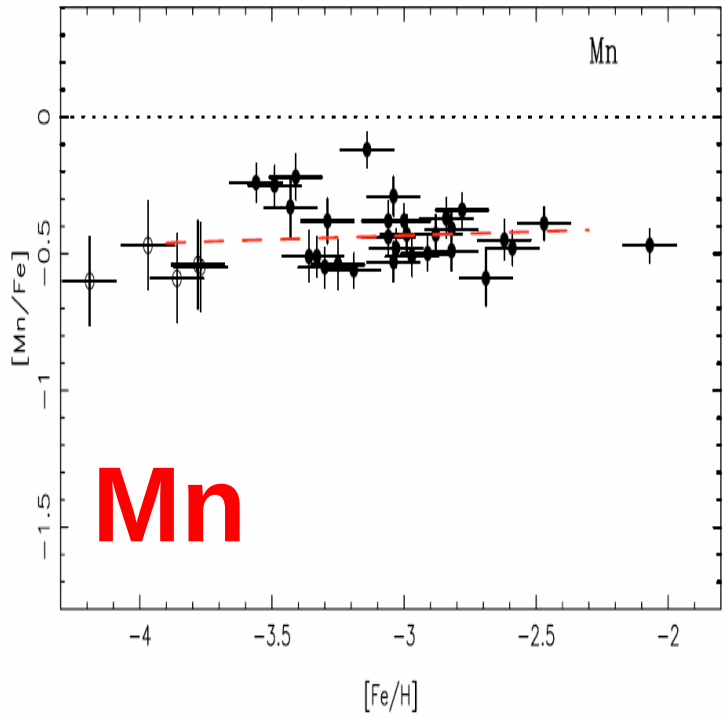


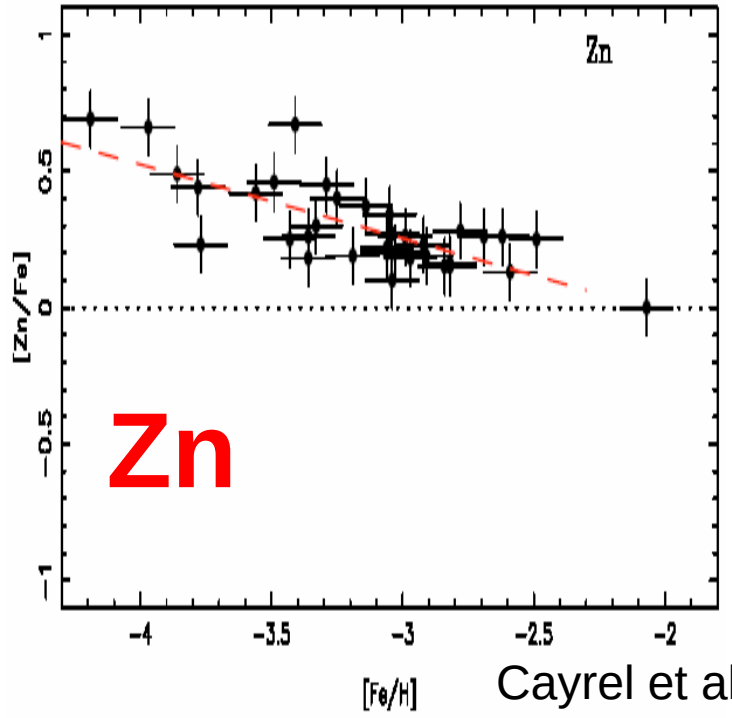




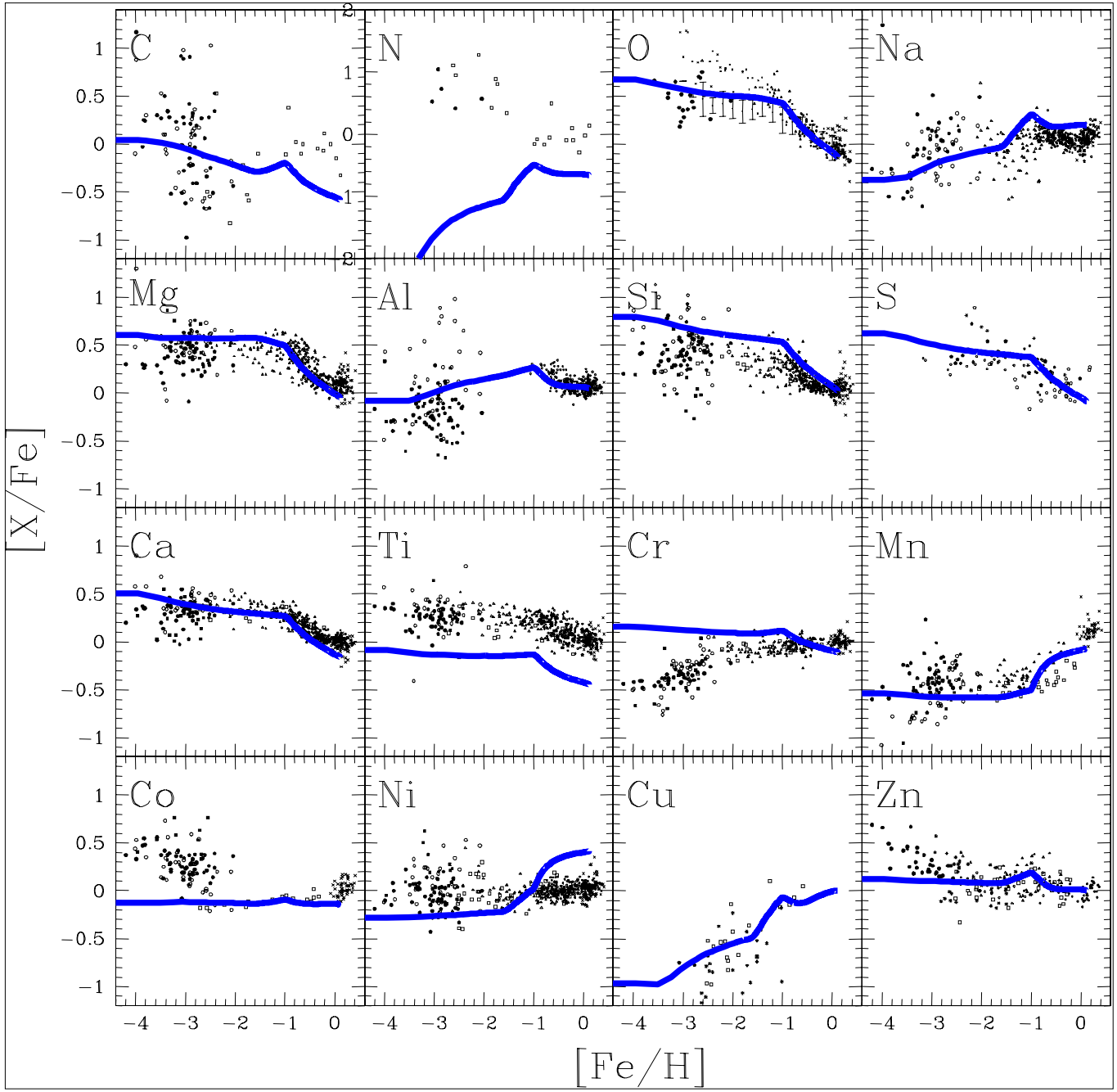








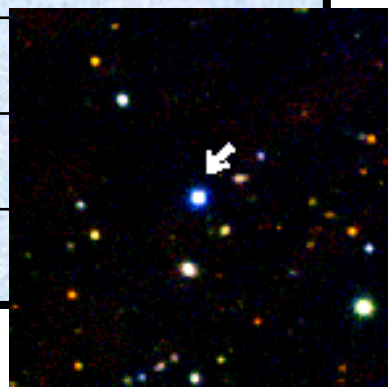
Cayrel et al. (2004)

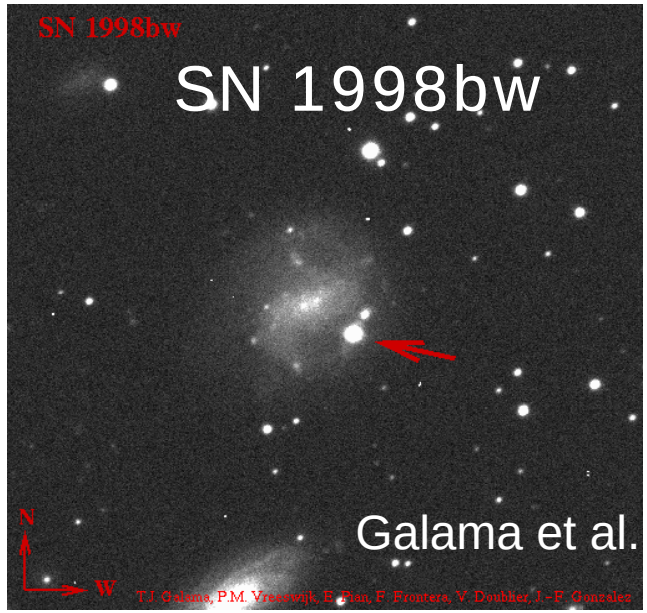


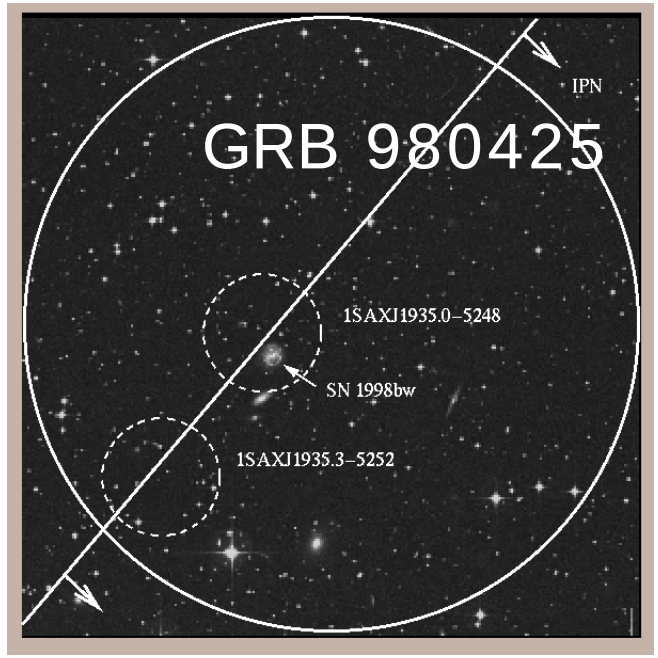
Kobayashi, Umeda, Nomoto et al. 2006

GRB-Supernova Connection

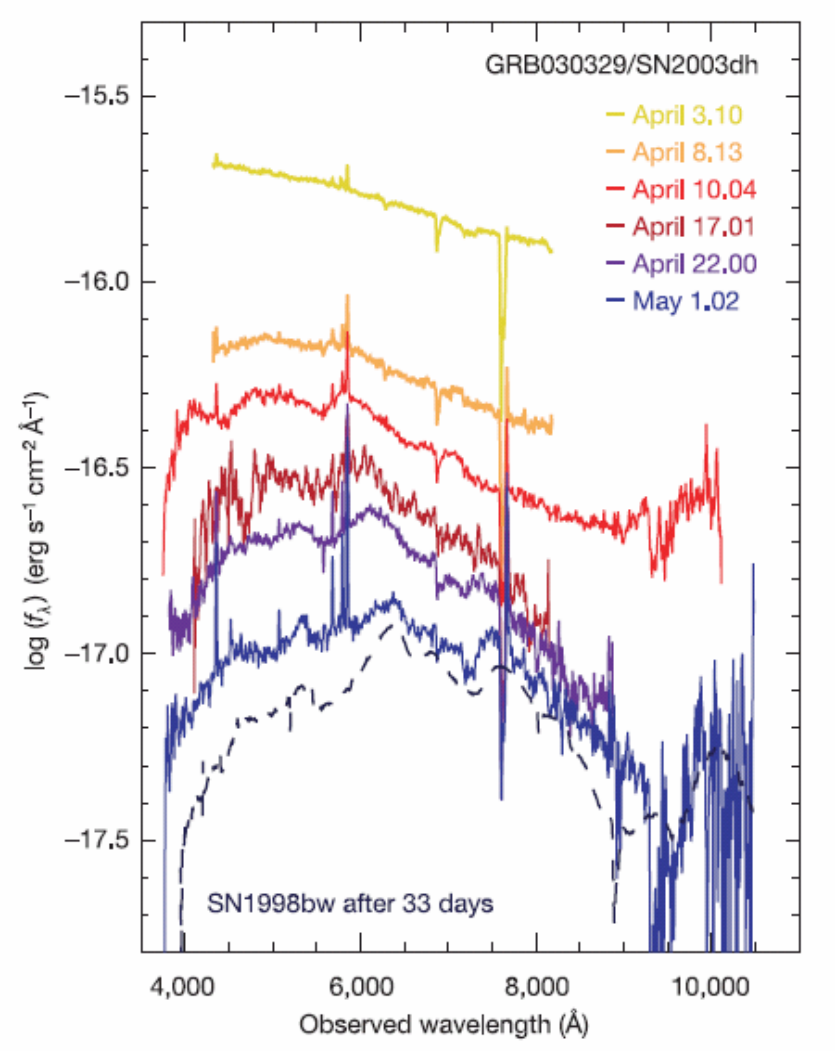
SNe Ic	
SN	GRB
1998bw	980425
1997ef	(971115)
2002ap	
2003dh	030329
2003lw	031203

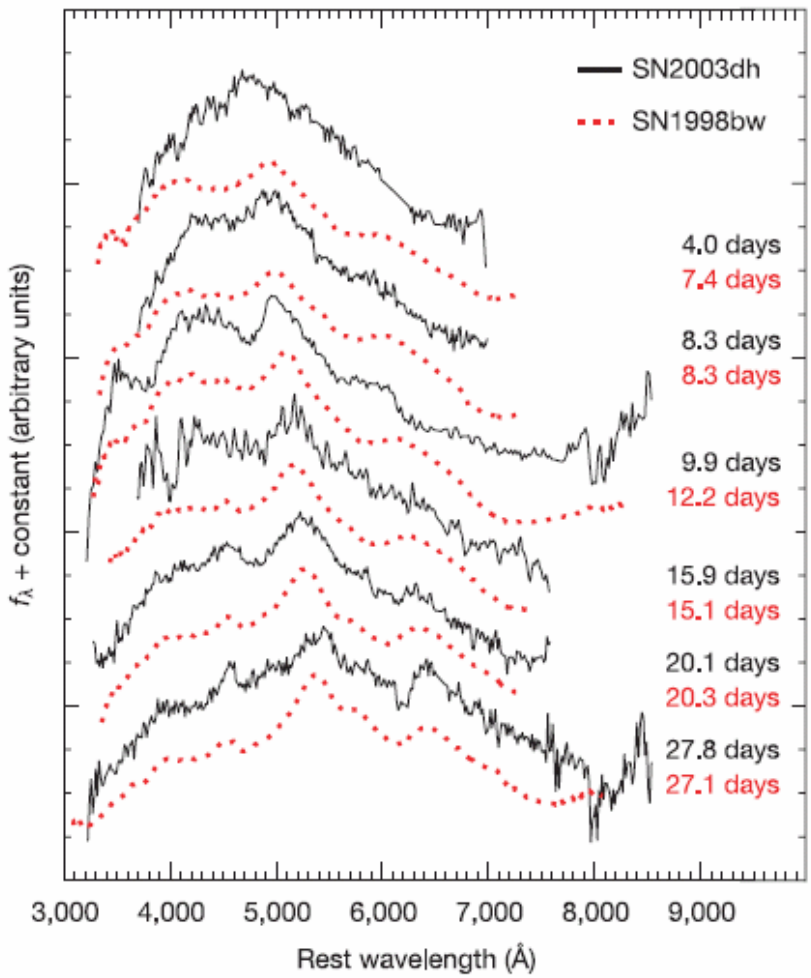






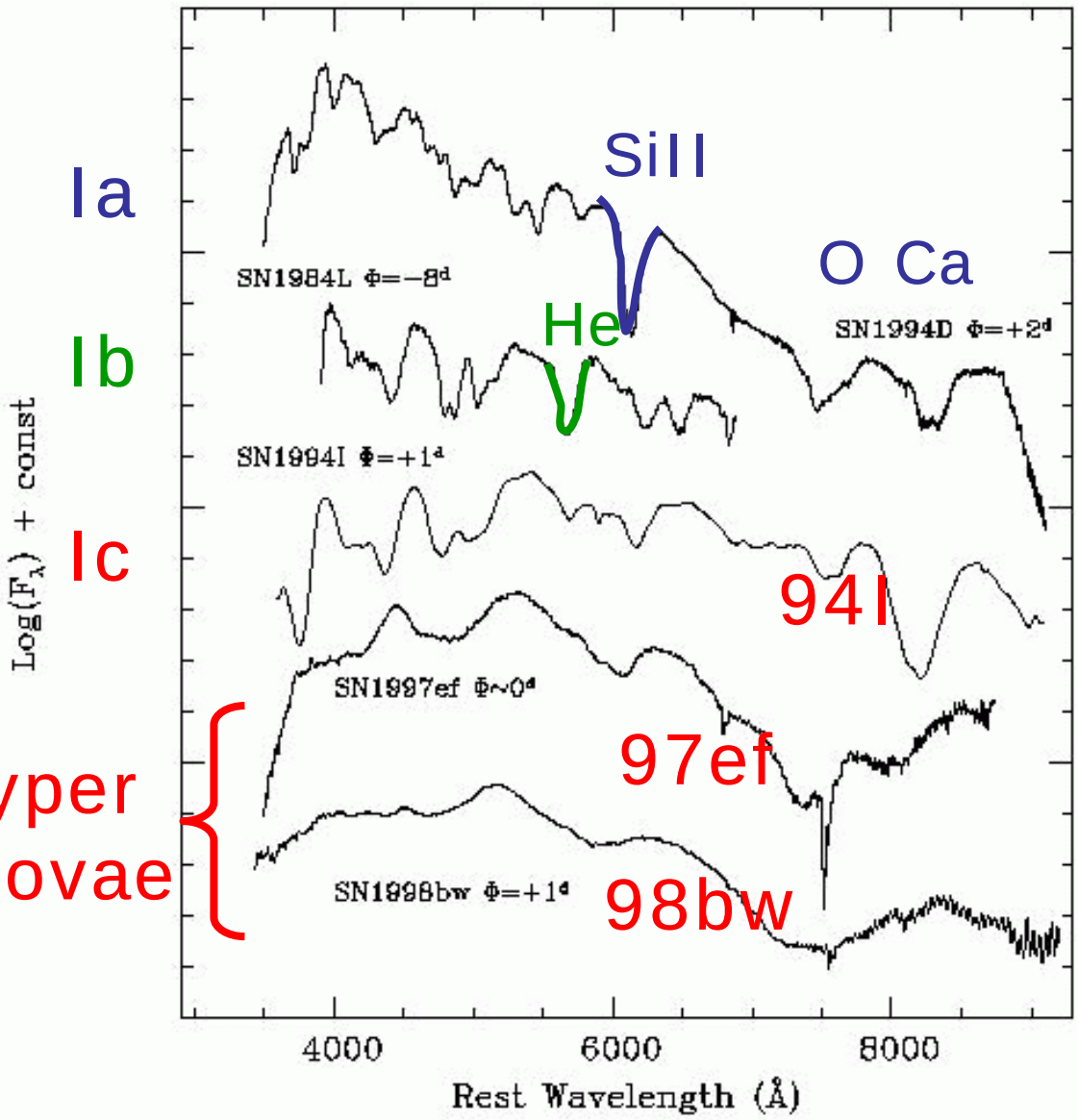
GRB 030329 / SN 2003dh





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

Spectra of Supernovae & Hypernovae



Ic: no H,

no strong He,

no strong Si

Hypernovae:

broad features

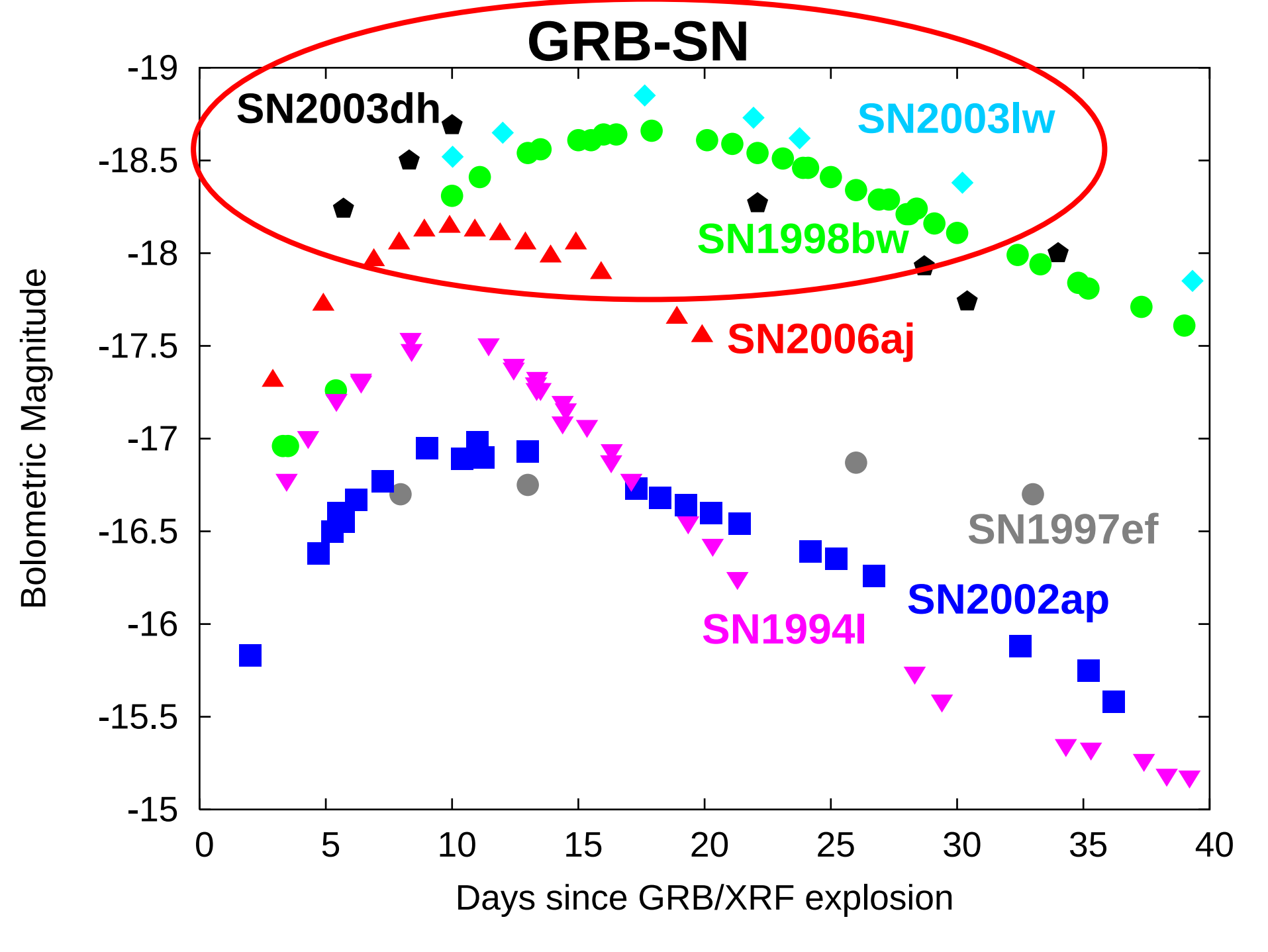
↑

blended lines

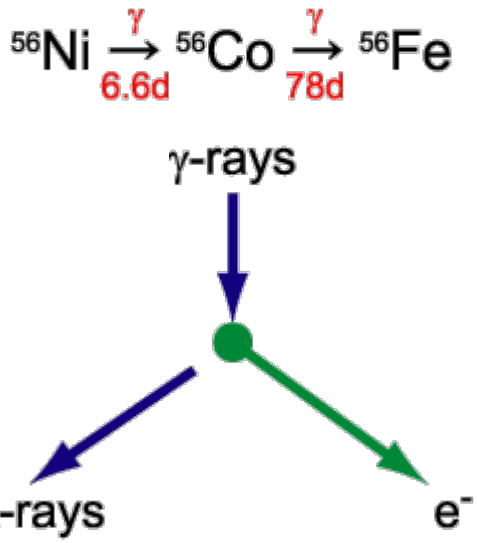
↑

"Large mass at high velocities"

Patat et al. (1999)


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

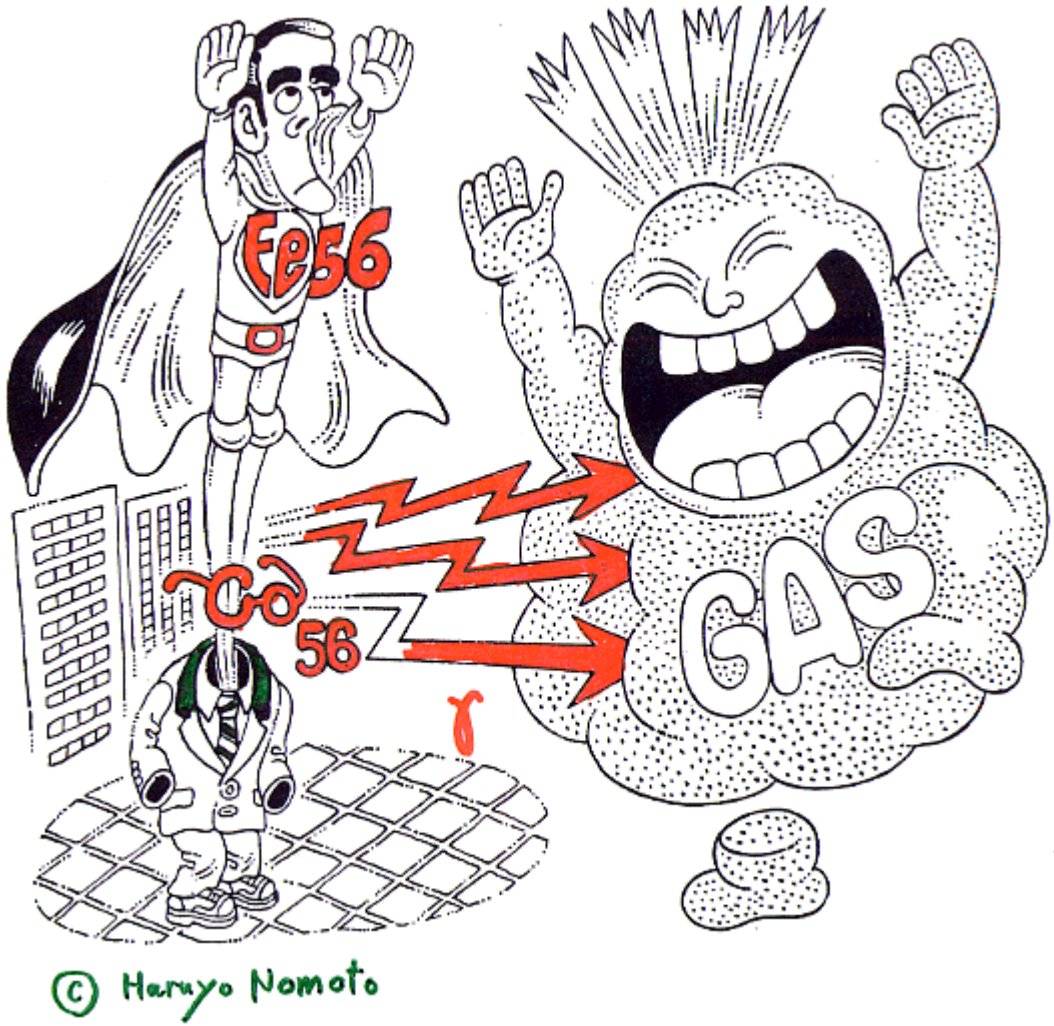
^{56}Co-decay



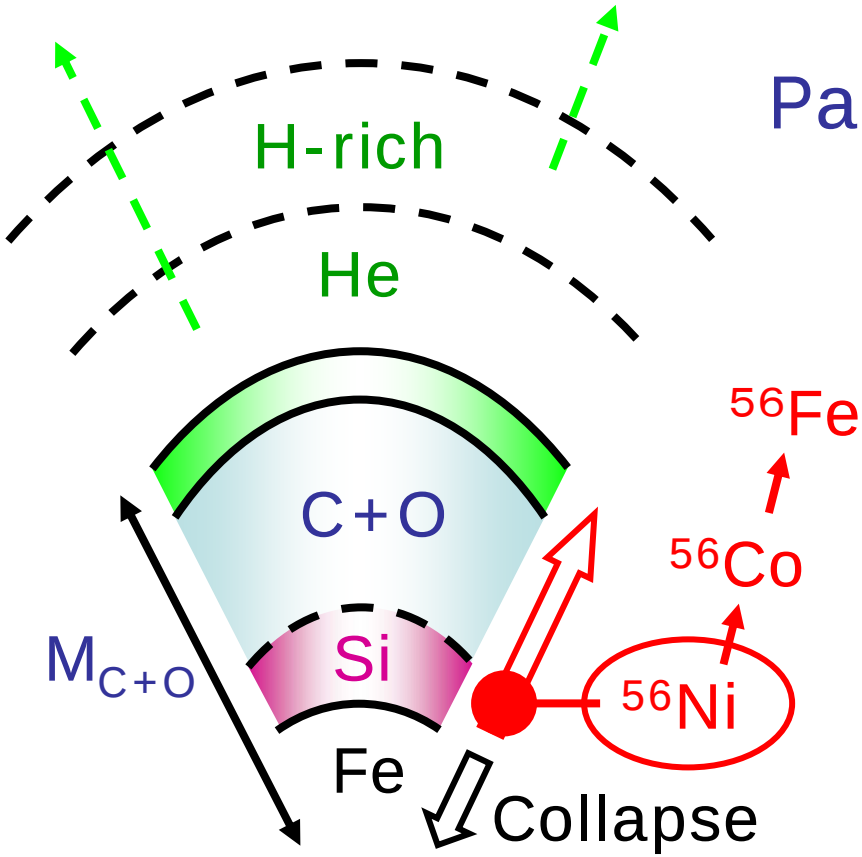
Photoabsorption Excitation/Ionization

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

Shape:M_{ej}



CO Star Models for SNeIc



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

Light Curve — Spectra

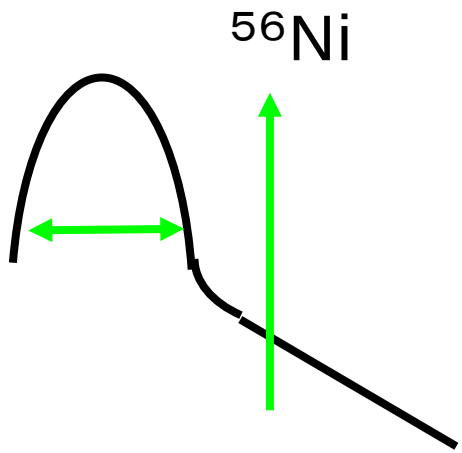
$$\tau \sim [\tau_{dyn} \bullet \tau_{diffusion}]^{1/2} \qquad E \propto M_{ej}$$

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

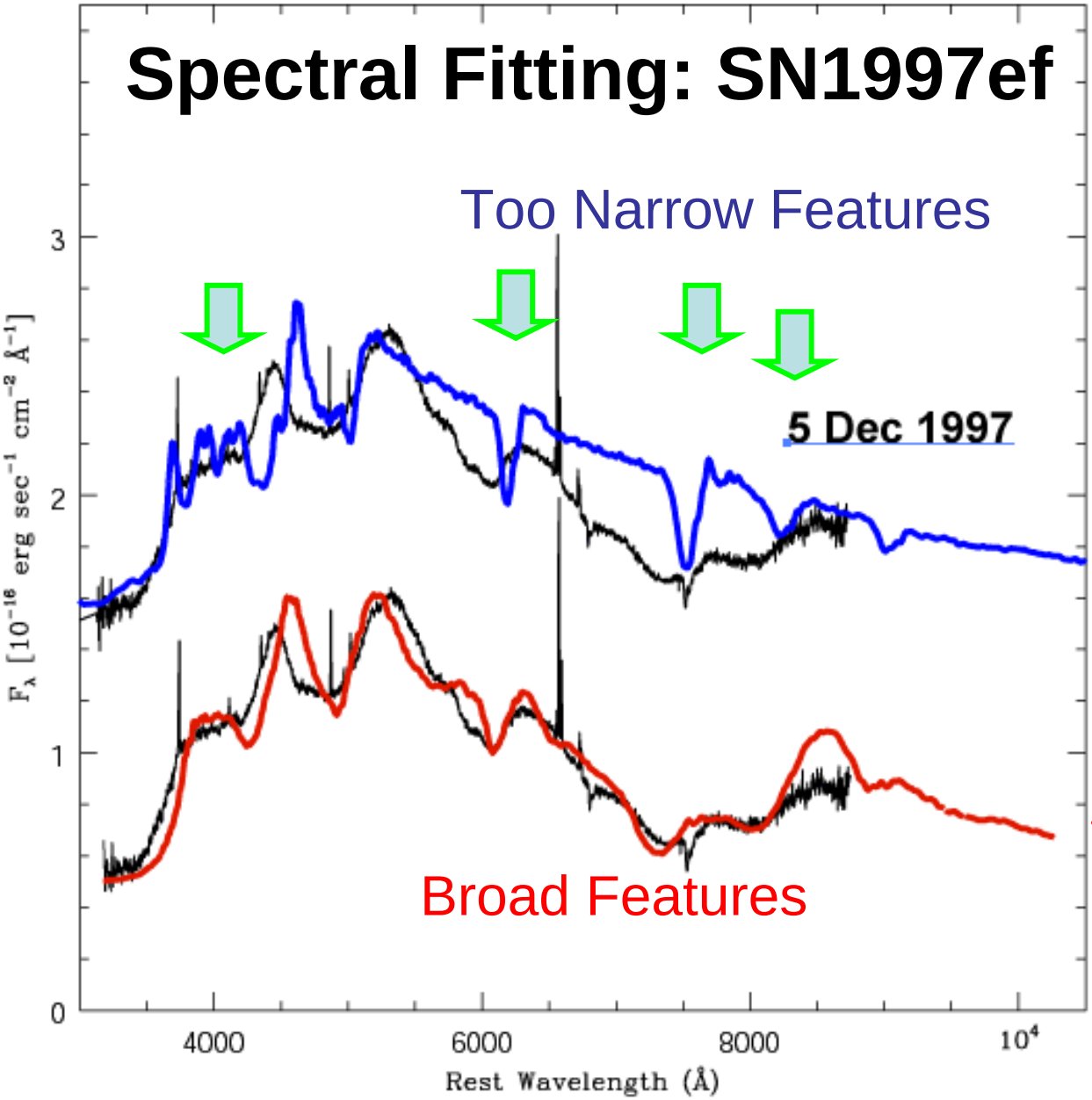
$$\propto \kappa^{1/2} M_{ej}^{3/4} E^{-1/4}$$

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

$M_{ms}/M_{\odot}$	$M_{C+O}/M_{\odot}$
~ 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.

Supernova – GRB Connection

Three GRB－SNe = all Type Ic Hypernovae

$E > 10^{52}$ erg (～10×normal SN)

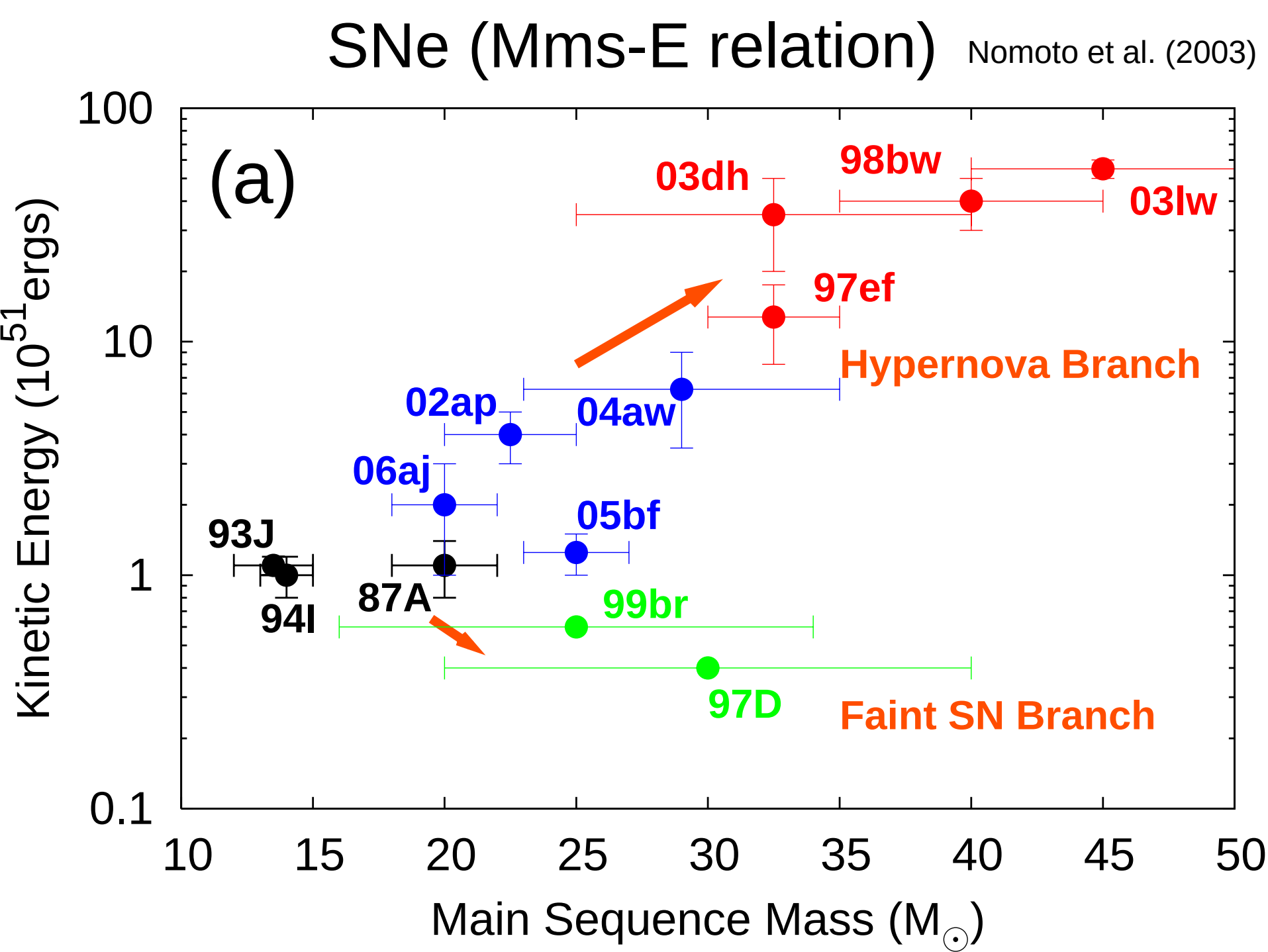
Large M_{ms} →Black Hole Forming SNe

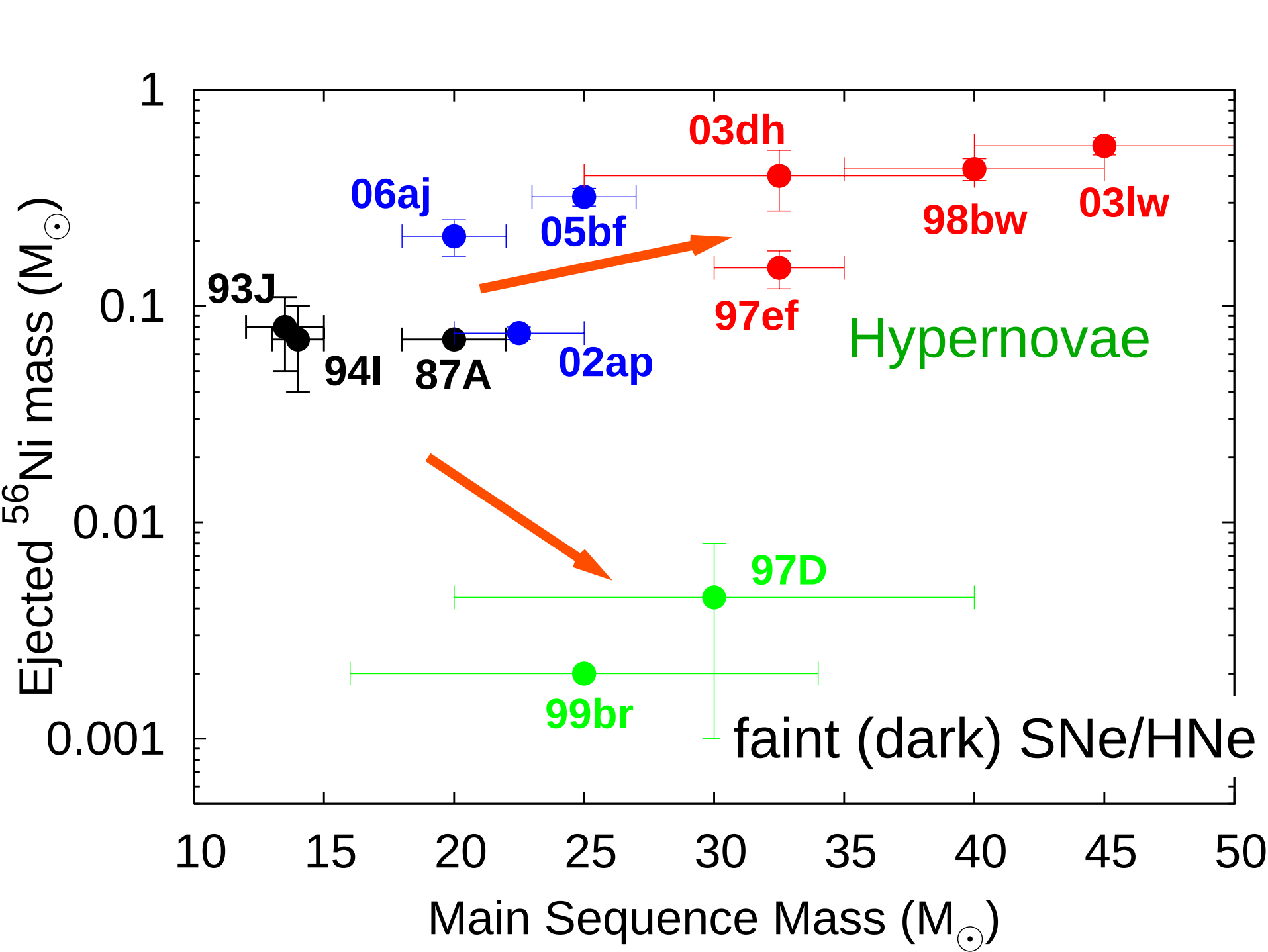
Aspherical

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

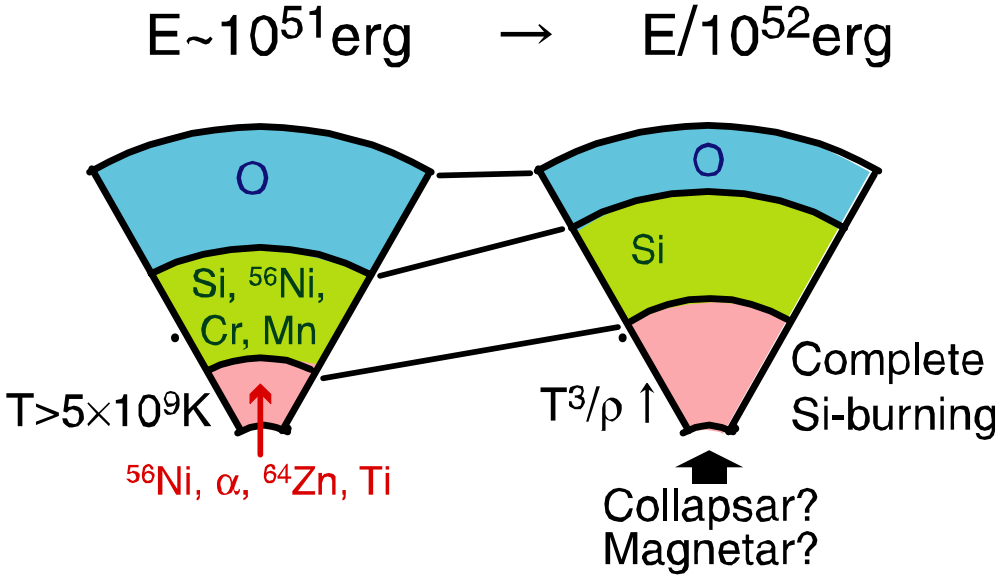
Hypernova in Prague

Hypernova in Prague


SNe (Mms-E relation)
Nomoto et al. (2003)
(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


1
0.1
0.01
0.001
Ejected ^{56}Ni mass ($M_\odot$)
10
15
20
25
30
35
40
45
50
Main Sequence Mass ($M_\odot$)
03dh
06aj
05bf
98bw
03lw
97ef
93J
94I
87A
02ap
Hypernovae
97D
99br
faint (dark) SNe/HNe

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 ↗

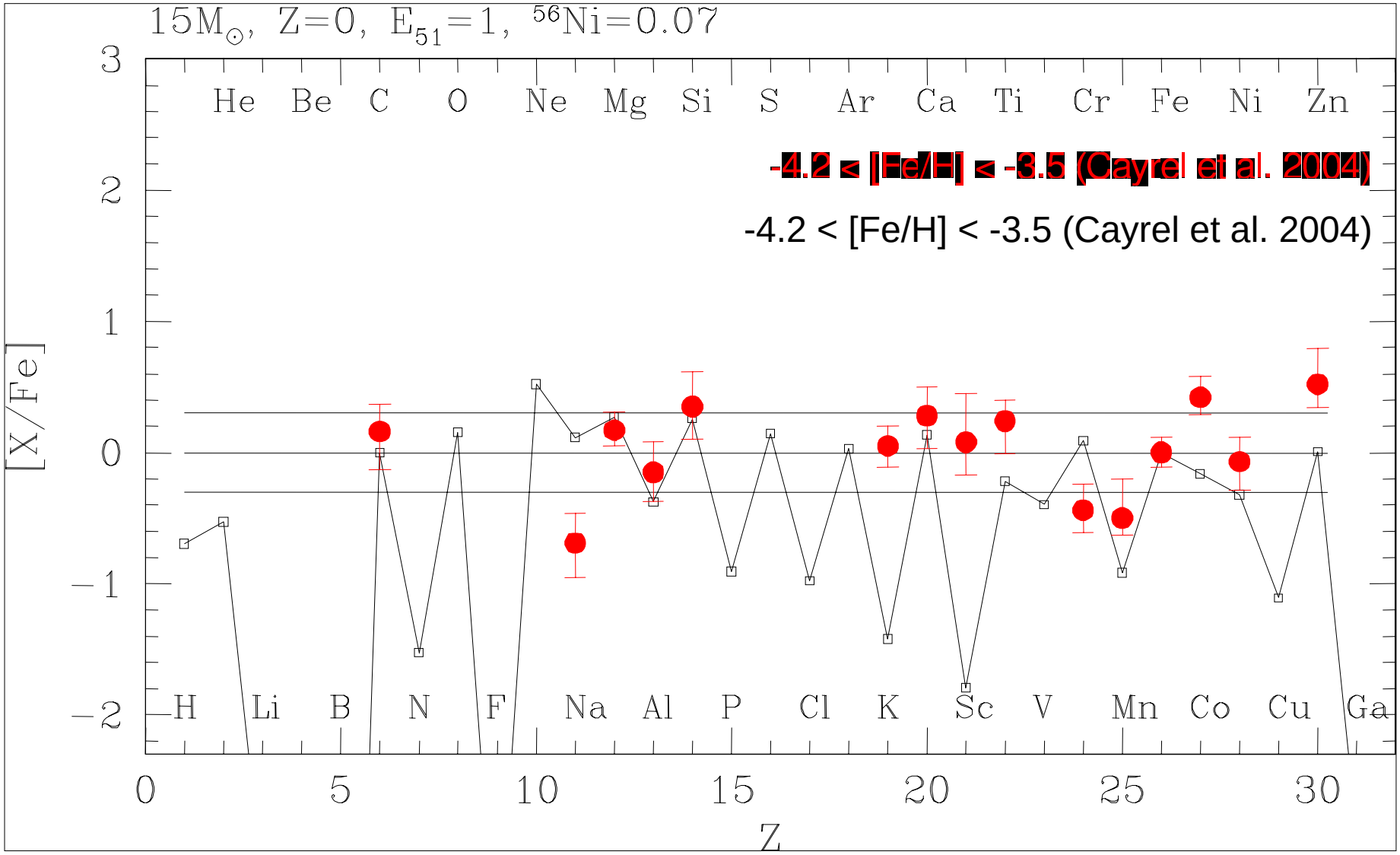
Zn/Fe ↗ ⇦ ^{64}Ge

Ti/Fe ↗

(3) More O burns

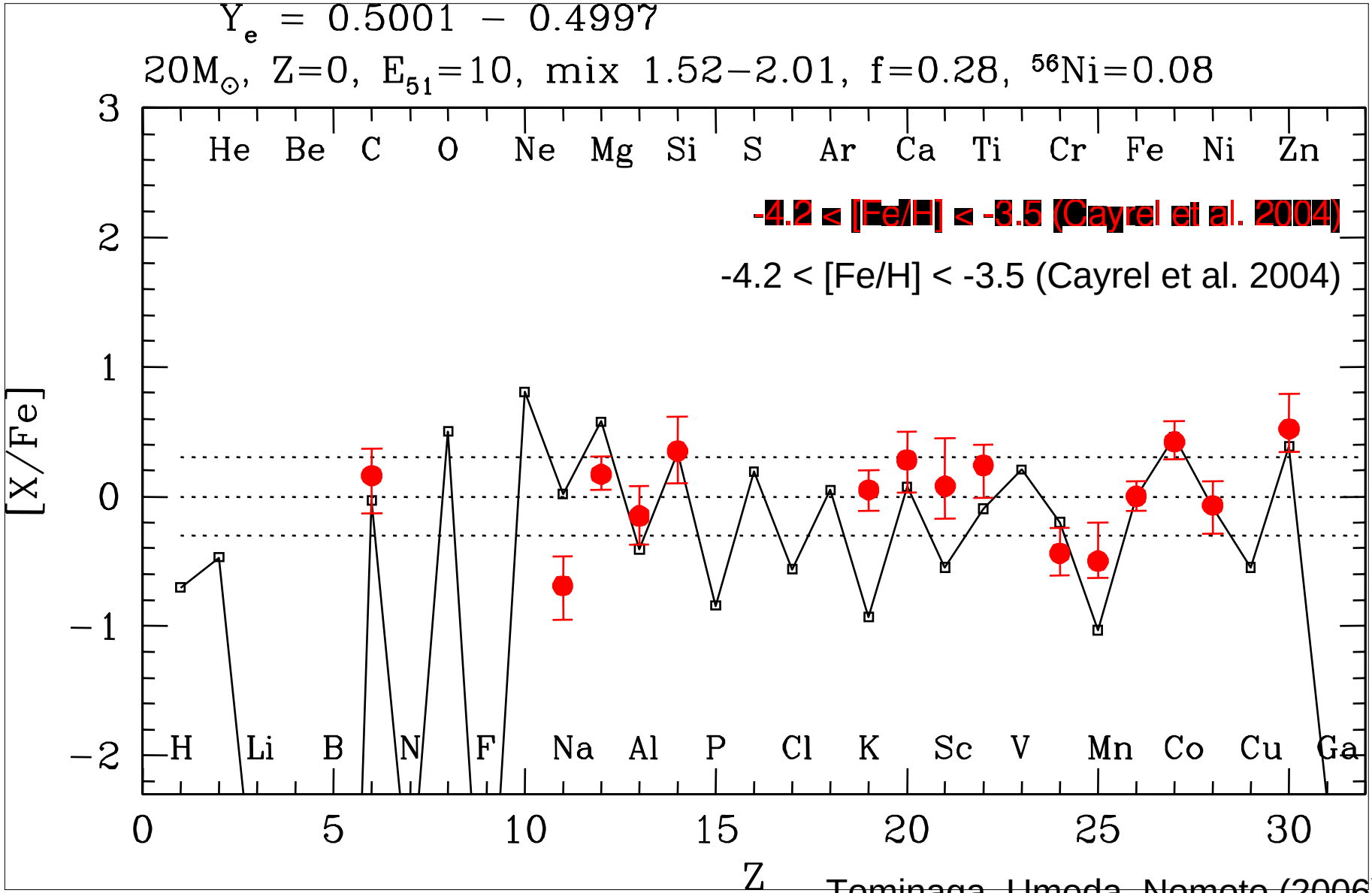
(Si, S, Ca)/O ↗

EMP stars vs. Normal SN II



Tominaga, Umeda, Nomoto (2006)

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



Tominaga, Umeda, Nomoto (2006)

SN-induced Star Formation

(M, E, mass cut)

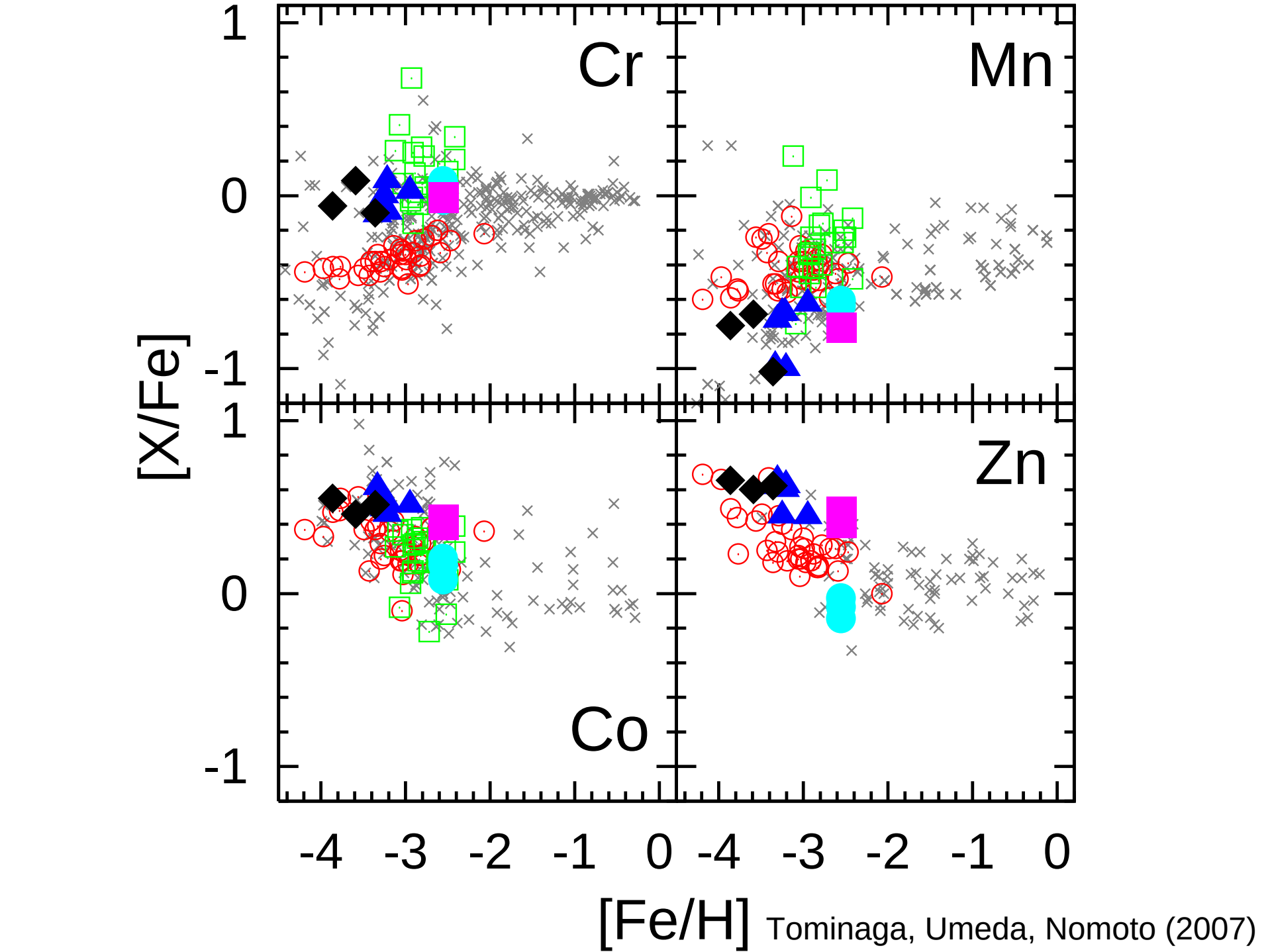
- → **[X/Fe] - [Fe/H]**

Fe/H ∝ M(Fe)/M(H)∝ M(Fe)/E

M(Fe): Fe mass in SN ejecta

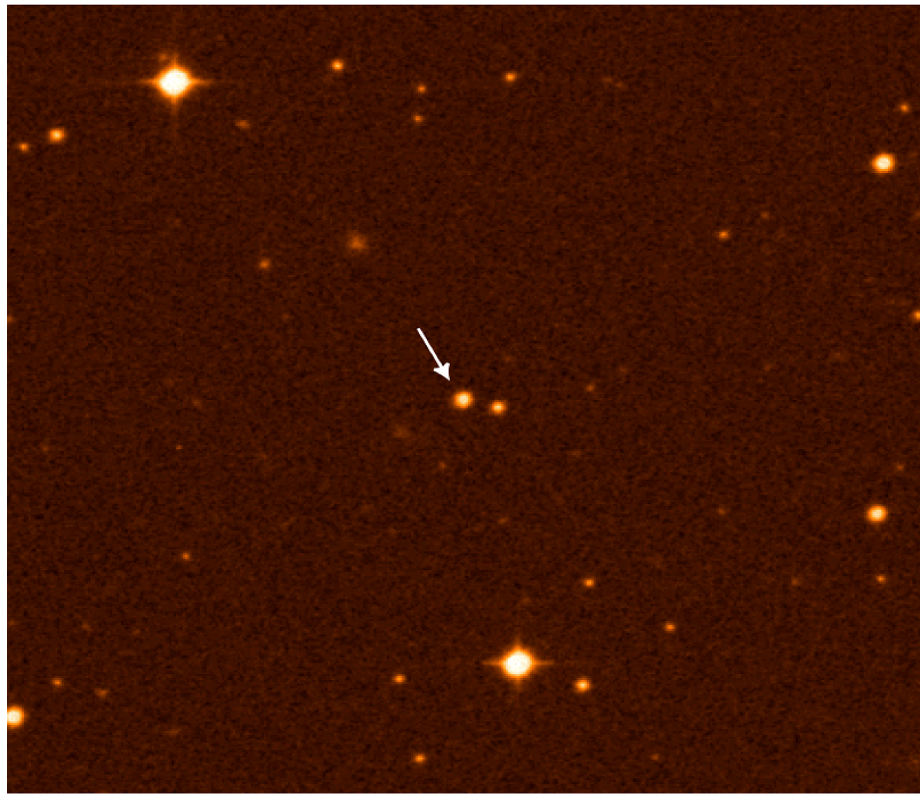
M(H): Mass of swept up H ∝ E

E: Explosion Energy


Cr
Mn
Co
Zn
[X/Fe]
[Fe/H]
1
0
-1
-4
-3
-2
-1
0
Tominaga, Umeda, Nomoto (2007)

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?

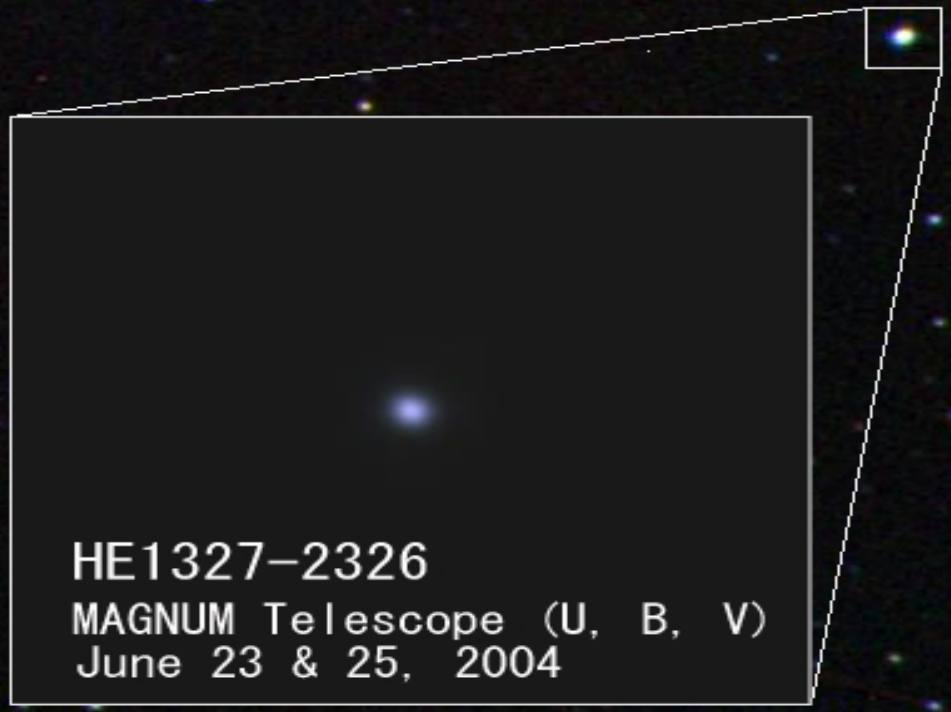


The Very Metal-Deficient Star HE 0107-5240

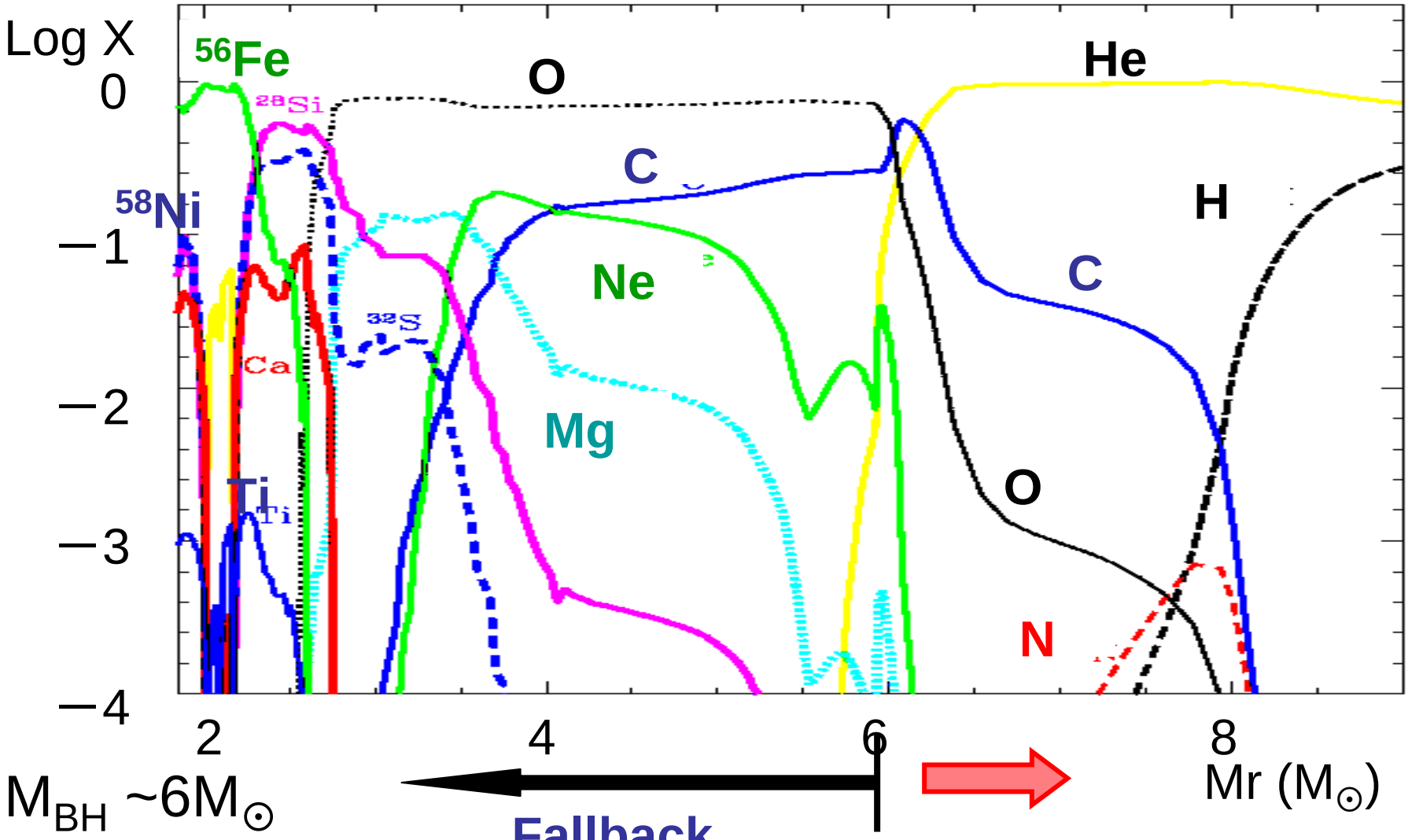
ESO PR Photo 25a/02 (30 October 2002)

First Star – Hypernova Connection:

Abundance Patterns of Extremely Metal-Poor Stars



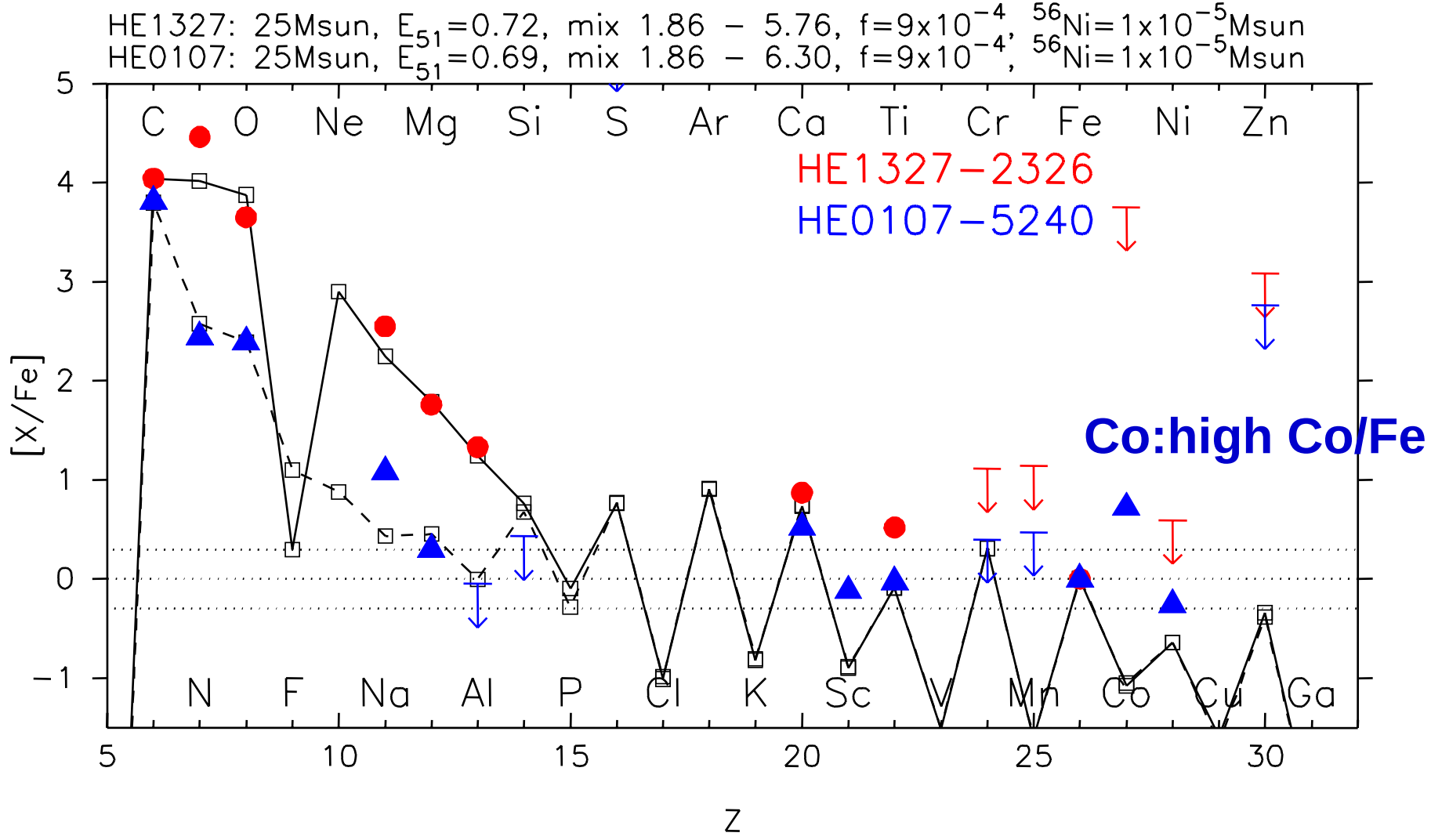
$M=25M_{\odot}$, $E=7\times10^{50}$erg (Weak Explosion) [Fe/H]=−5.3



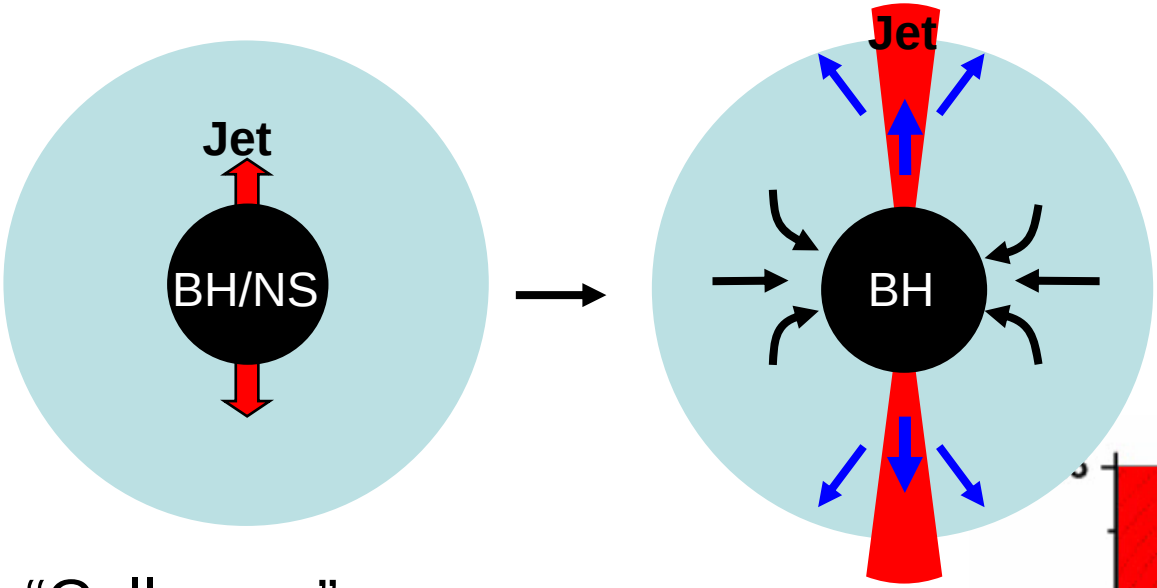
Umeda & Nomoto (2003)

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

mixing & fallback ➔ low [Co/Fe]



Jet-induced Nucleosynthesis



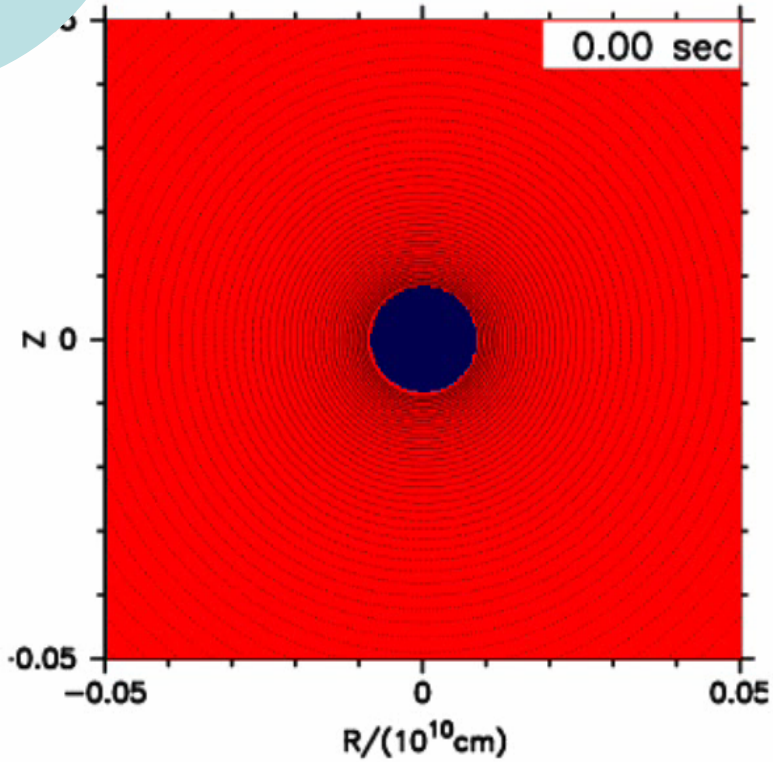
Special relativistic hydrodynamics (Tominaga et al. ApJL 2007)

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

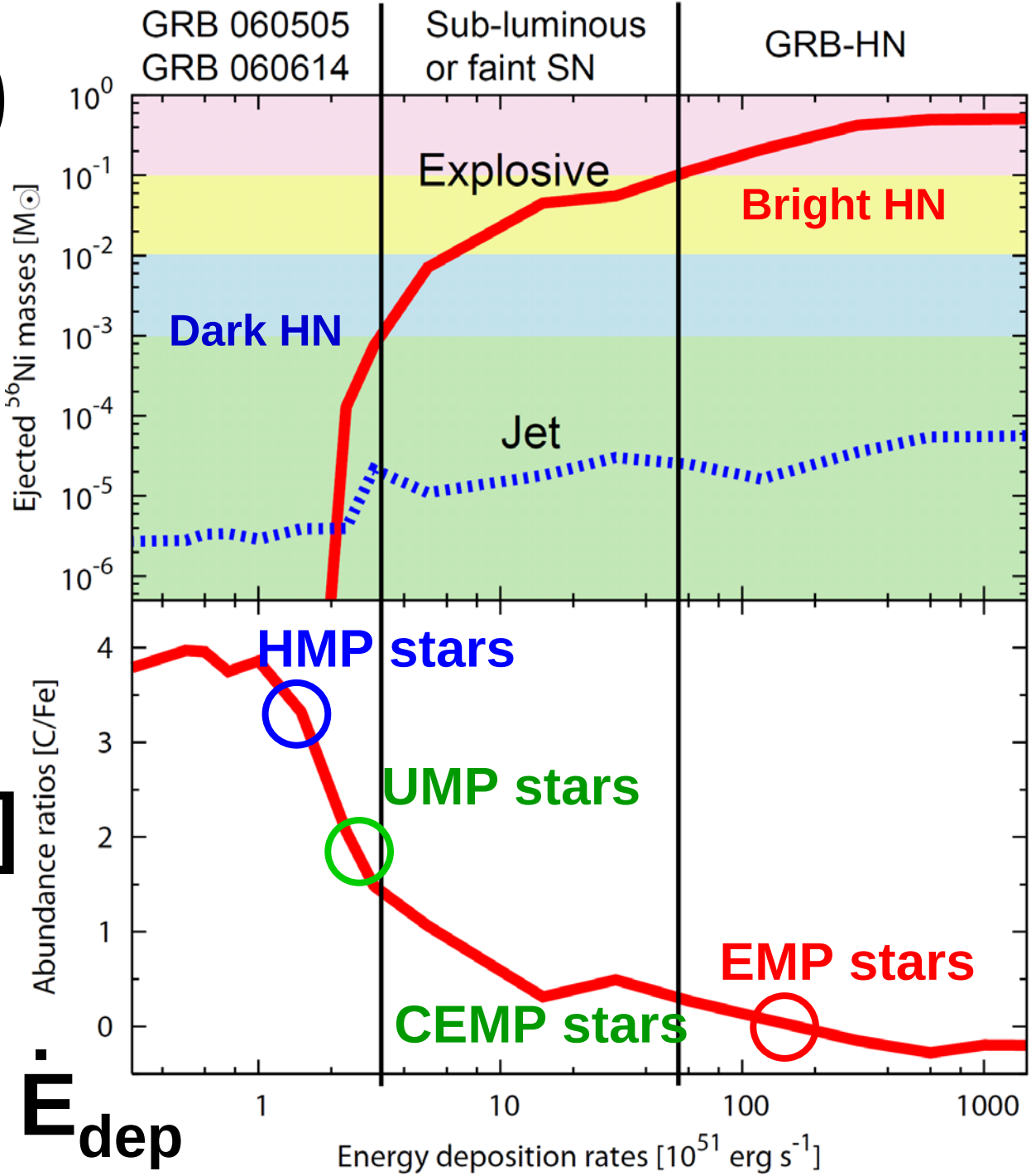
$40M_{\odot}$ 1.5×10^{52}erg

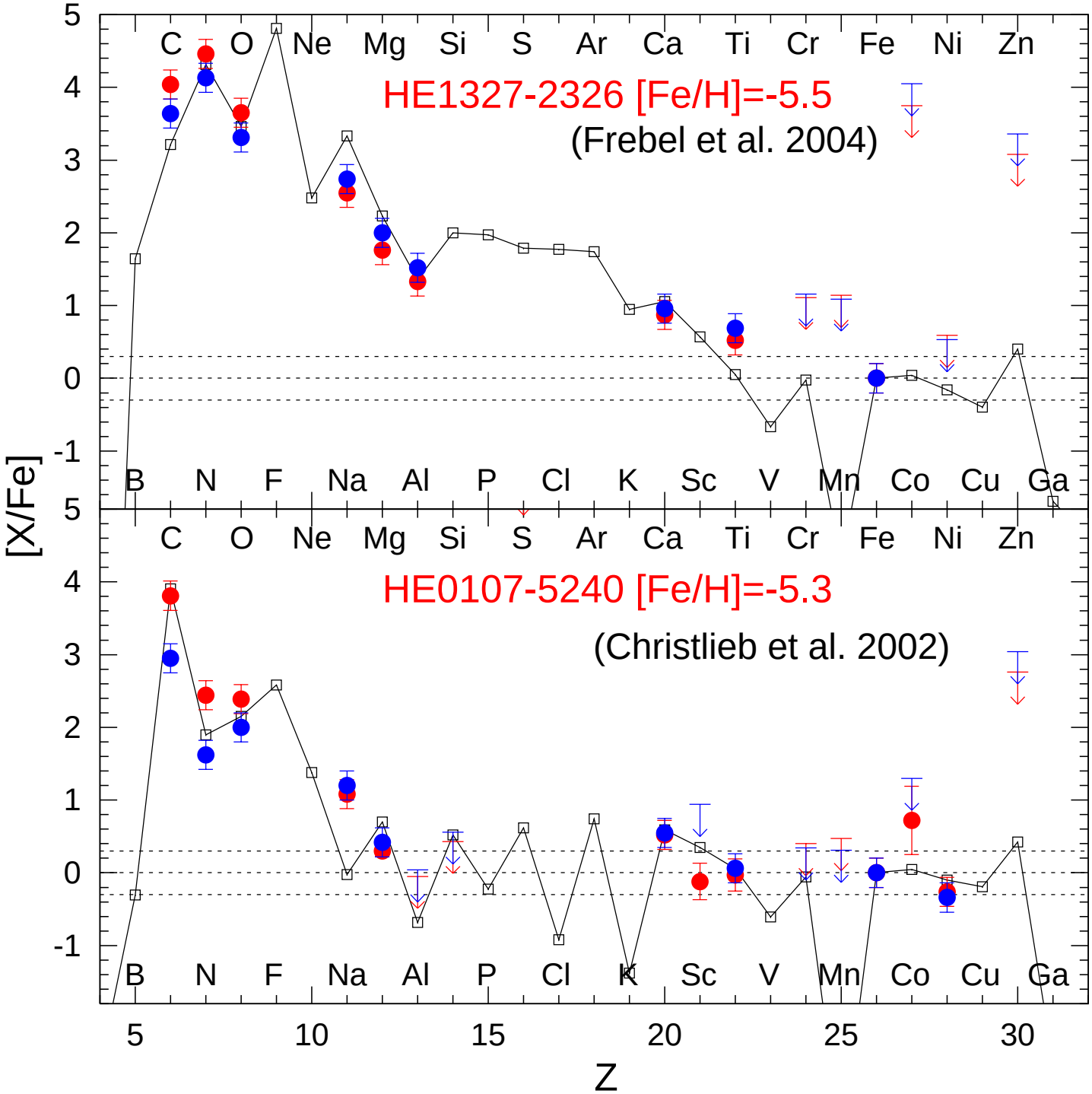
$M(^{56}Ni)$

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

[C/Fe]

High E ➔ Fallback





HMP Stars

Jet-induced SN models

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

Dark Hypernova

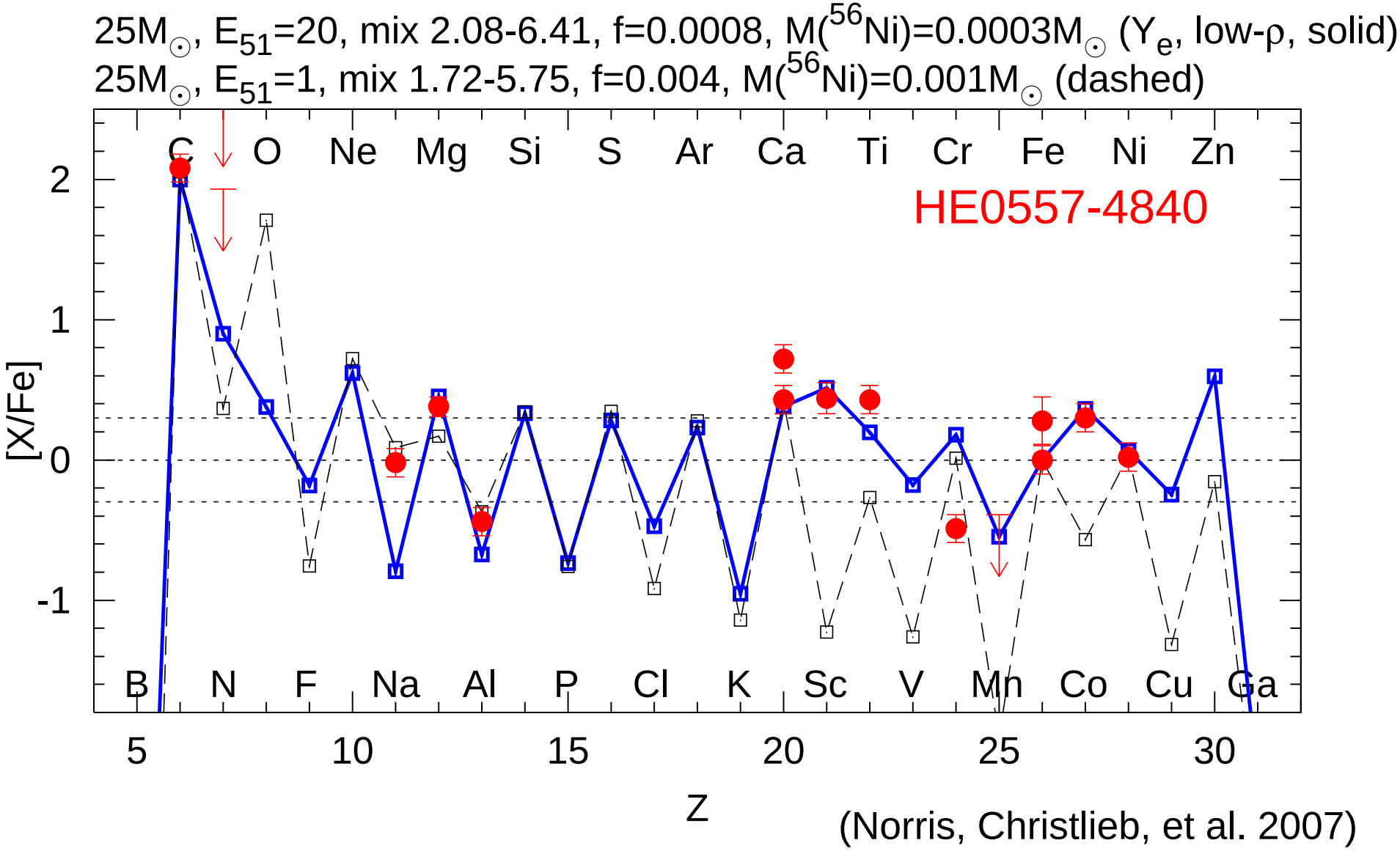
Tominaga et al. 2007

HMP/UMP/EMP stars

Star	[Fe/H]	Features	Authors
HE0107	-5.7	**C**-rich, [Mg/Fe]~0 , **Co**-rich	Christlieb et al. Bessel & Christlieb
HE1327	-5.4	**C**, O, Mg-rich	Frebel et al. Aoki et al.
HE0557	-4.75	**C**,Ca,Sc,Ti-rich, **Co**-rich	Norris et al.
HE1300	-3.88	**C**, Si, Ca,Sc,Ti, **Co**-rich	Frebel et al.
HE1424	-3.96	Si,Ca,Cu-poor, **Co**,Mn-rich	Cohen et al.
CS22949	-4.0	**C**,N,O,Mg,**Co,Zn**-rich	Depagne et al.
CS29498	-3.5	**C**,N,O,Mg-rich, [**Co**/Fe]~0	Aoki et al.
BS16934	-2.78	C-poor , O,Mg-rich	Aoki et al.

UMP Star : [Fe/H] = -4.75

Hypernova model (E_{51}=20:1D)➔Co



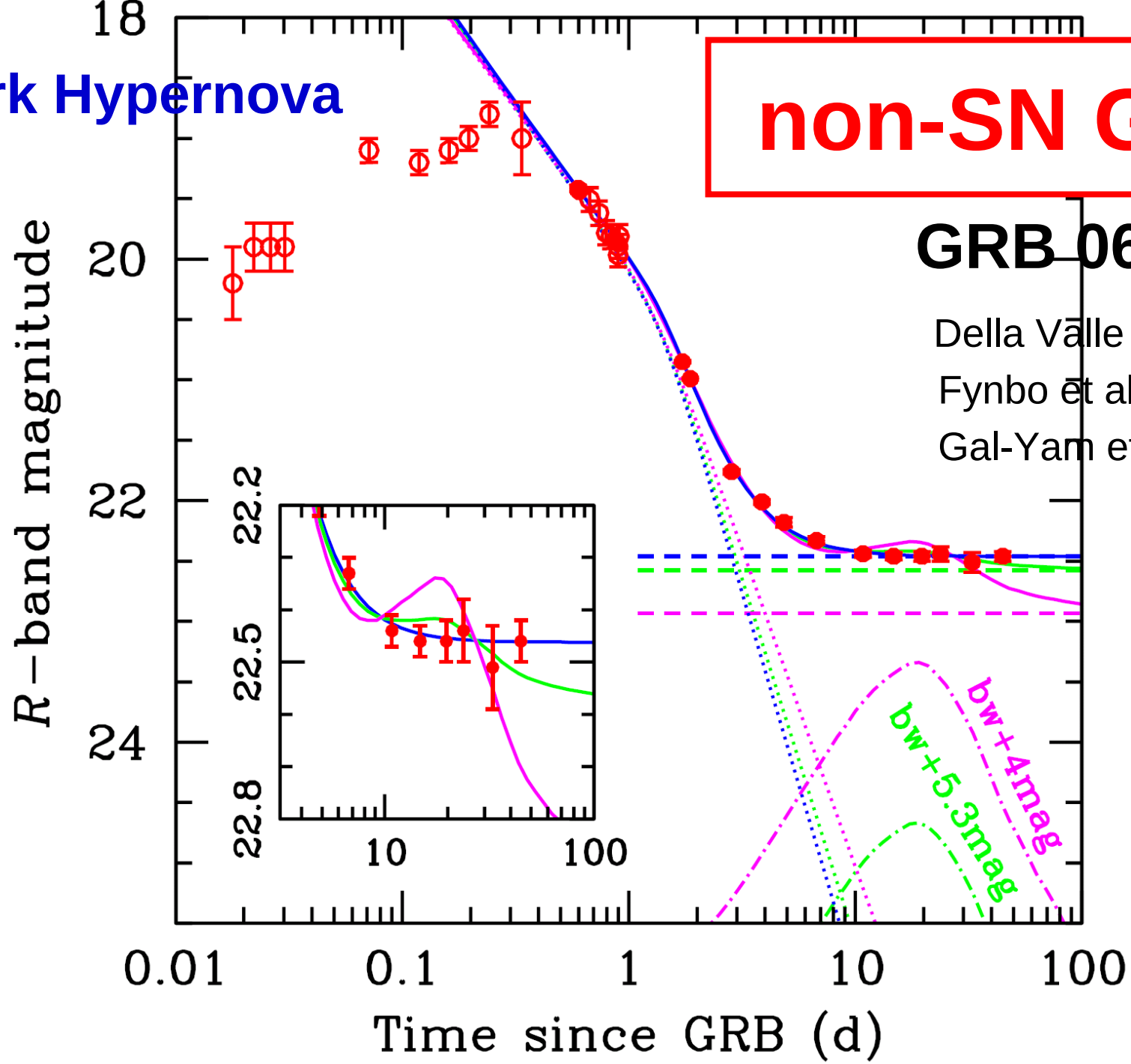
(Norris, Christlieb, et al. 2007)

Dark Hypernova

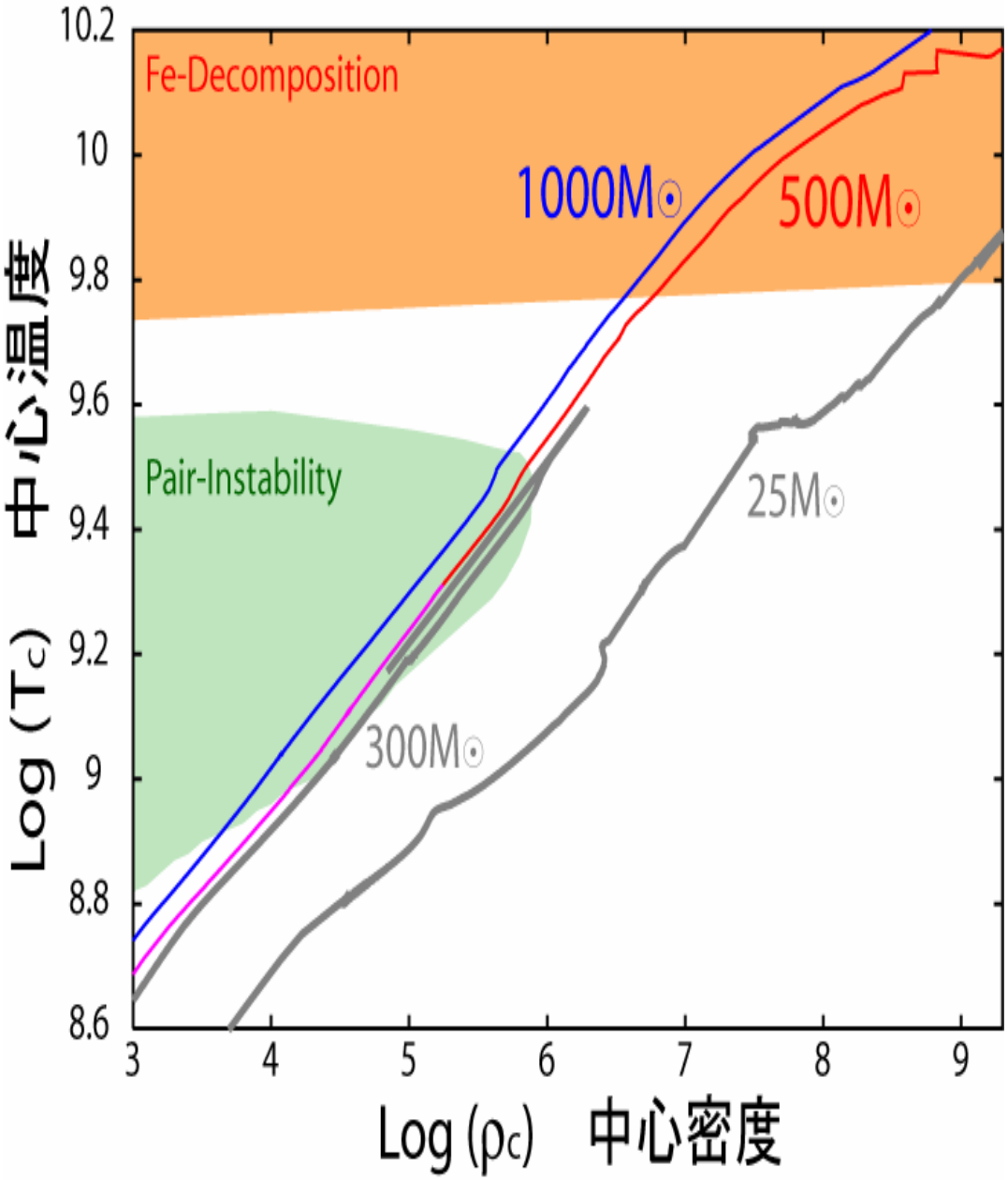
non-SN GRB

GRB 060614

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



Pair Instability Supernovae ($130M_\odot - 300M_\odot$)



Complete Si-burning ↘

⇩

[Zn/Fe] < −0.8

[Co/Fe] < −0.2

alpha/Fe

Too much Fe

no r-process

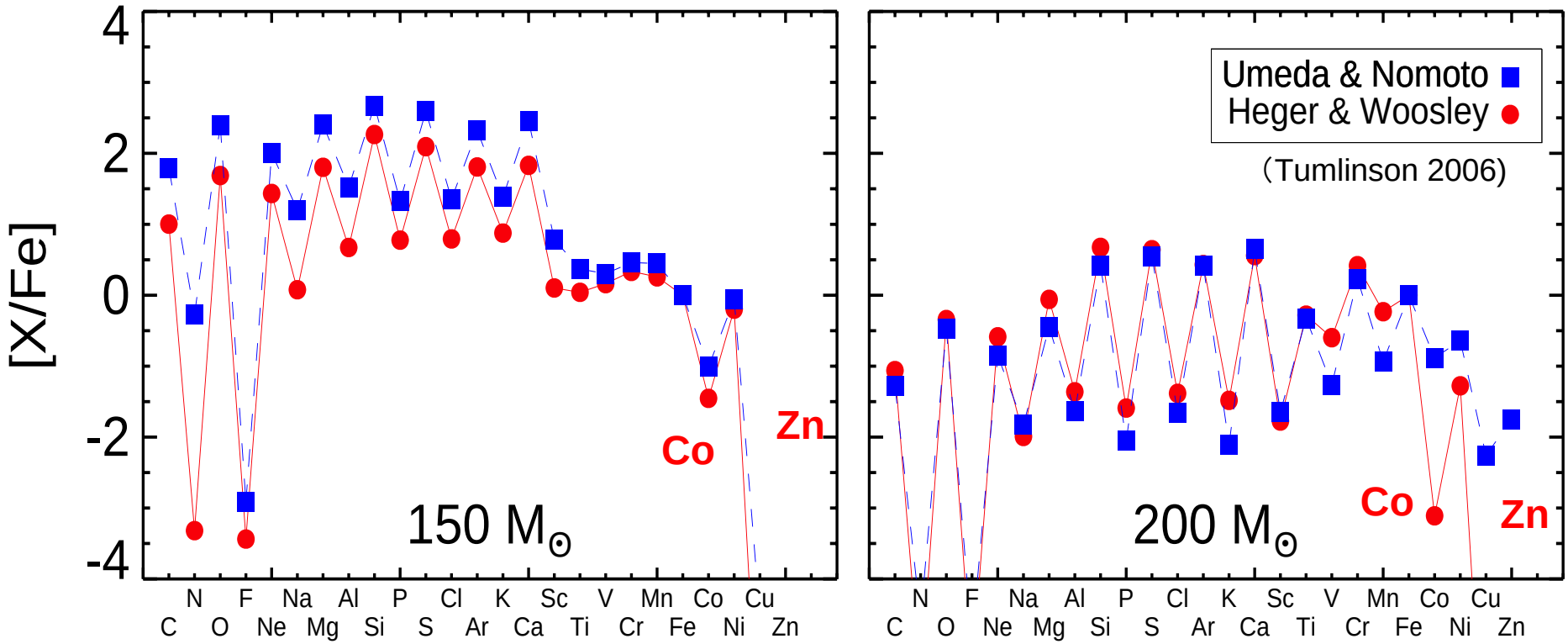
Umeda & Nomoto 2002, ApJ, 565, 385

Heger & Woosley 2002, ApJ, 567, 532

Ohkubo et al. 2006 ApJ

Pair Instability Supernovae

- Strong Odd-Even effect
- [Zn/Fe], [Co/Fe] << 0



The First Star Candidates & IMF

$M > 10^5 M_\odot$: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

Strong odd-even effect

[Co/Fe] , [Zn/Fe] << 0 , no r-process

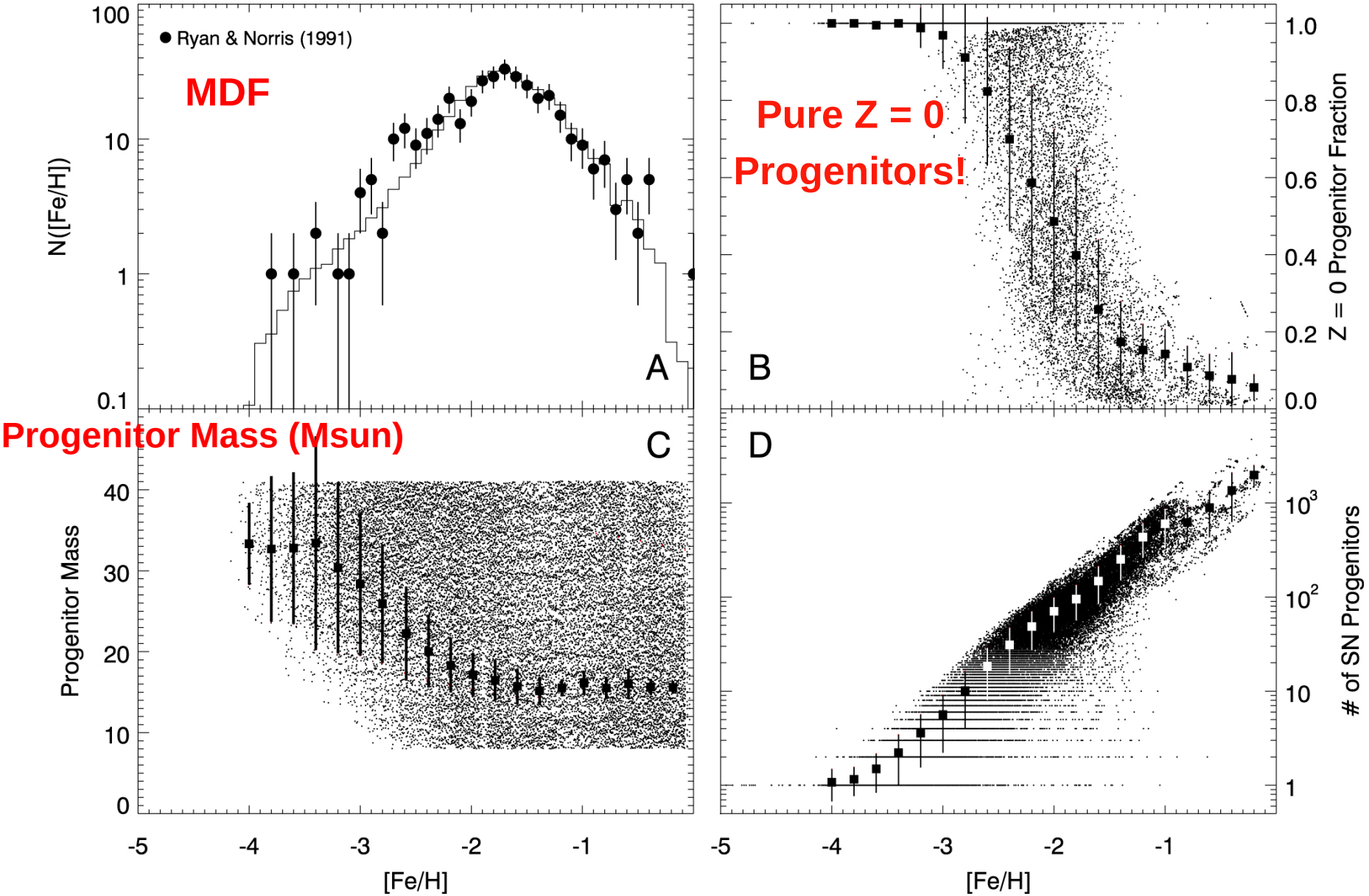
$M \sim 8 - 130 M_\odot$:

→ Core Collapse → **Hypernovae**

→ **SNe II**

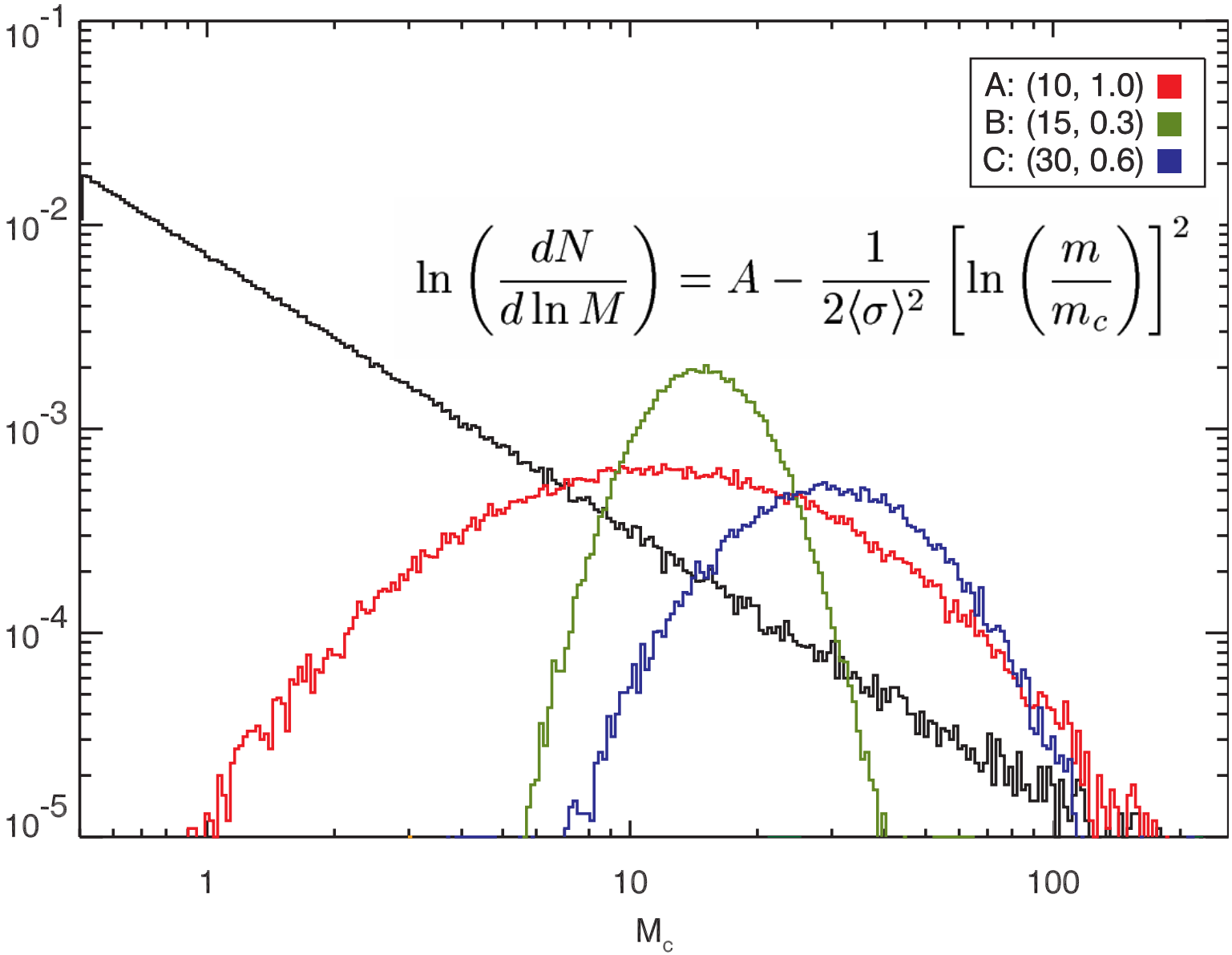
Inhomogeneous Chemical Evolution (Tumlinson 2006)

(Ionization, r-process, Zn/Fe, MDF)



The First Stars IMF? (Tumlinson 2006)

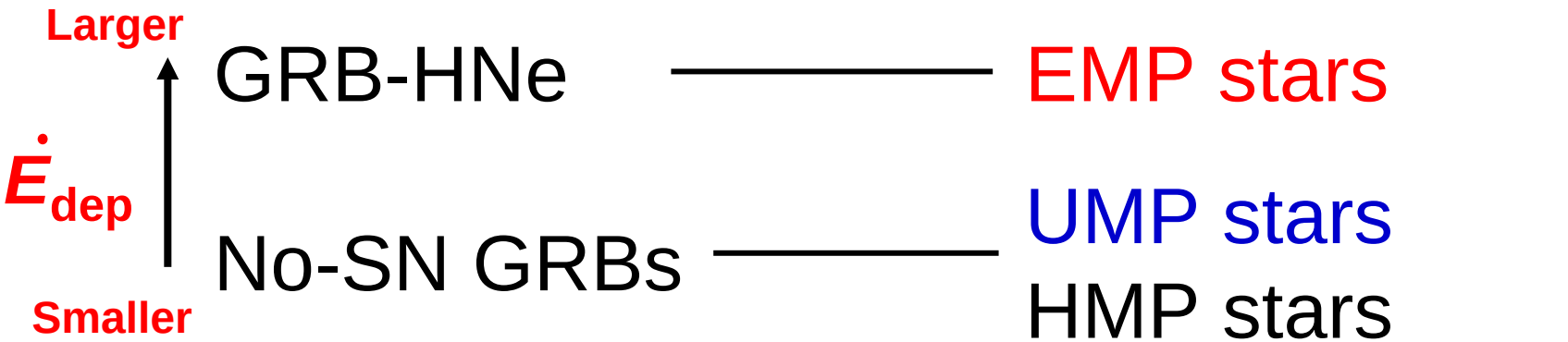
(Ionization, r-process, Zn/Fe, MDF)



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

Hypernovae with relativistic jets

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



First Supernovae

Jet-induced Hypernovae ➔ [Fe/H] < -2.5 :
EMP-HMP stars

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

(M > 130 $M_\odot$: Pair Instability SNe: minor)

E > 10^{52} erg **(strong feedback)**

Normal SNe ➔ -2.5 < [Fe/H] < -1 : VMP stars

M ~ 8 - 20 $M_\odot$ (Neutron Star Forming)

E ~ 10^{51} erg