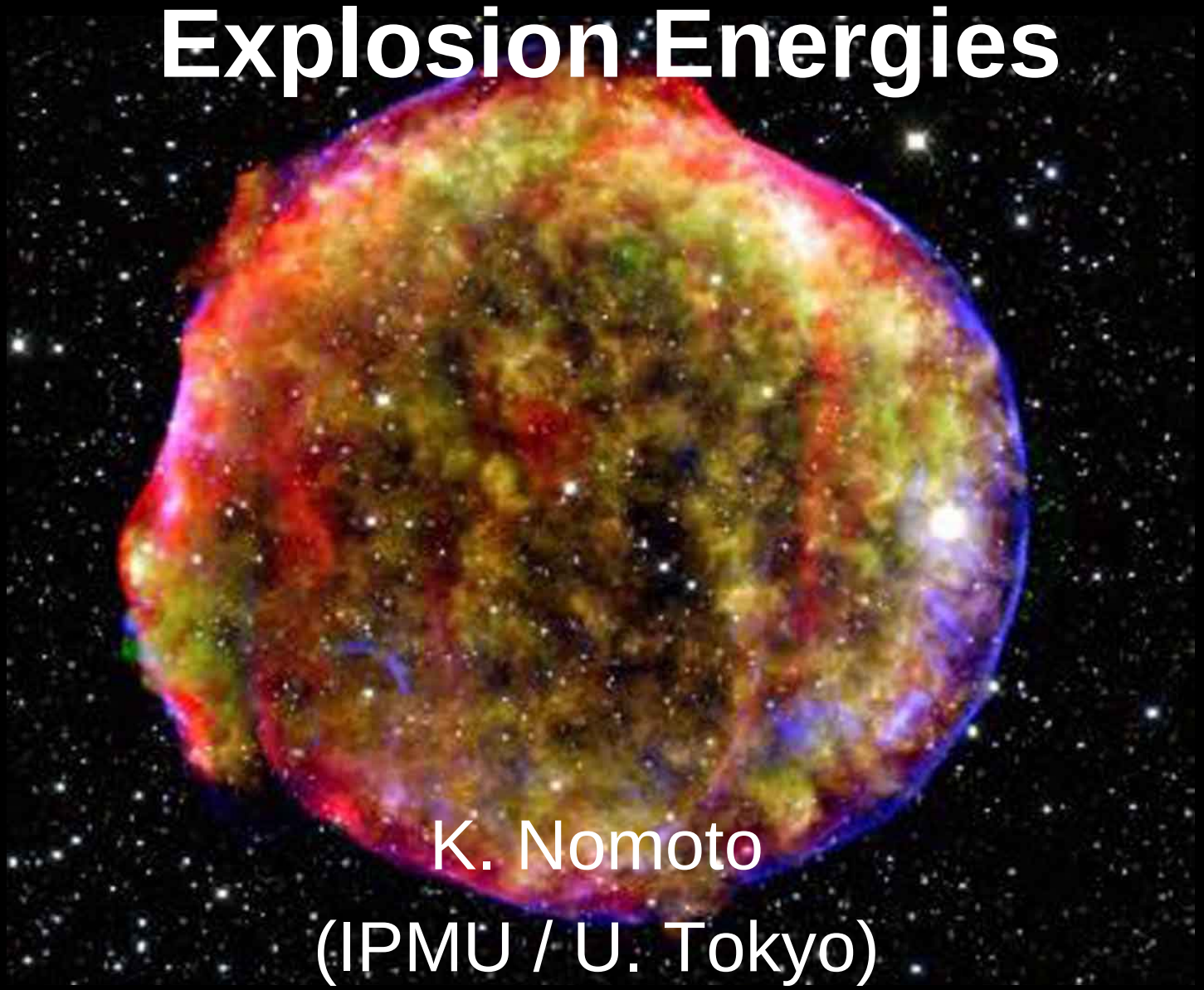
On the Range of Supernova Explosion Energies

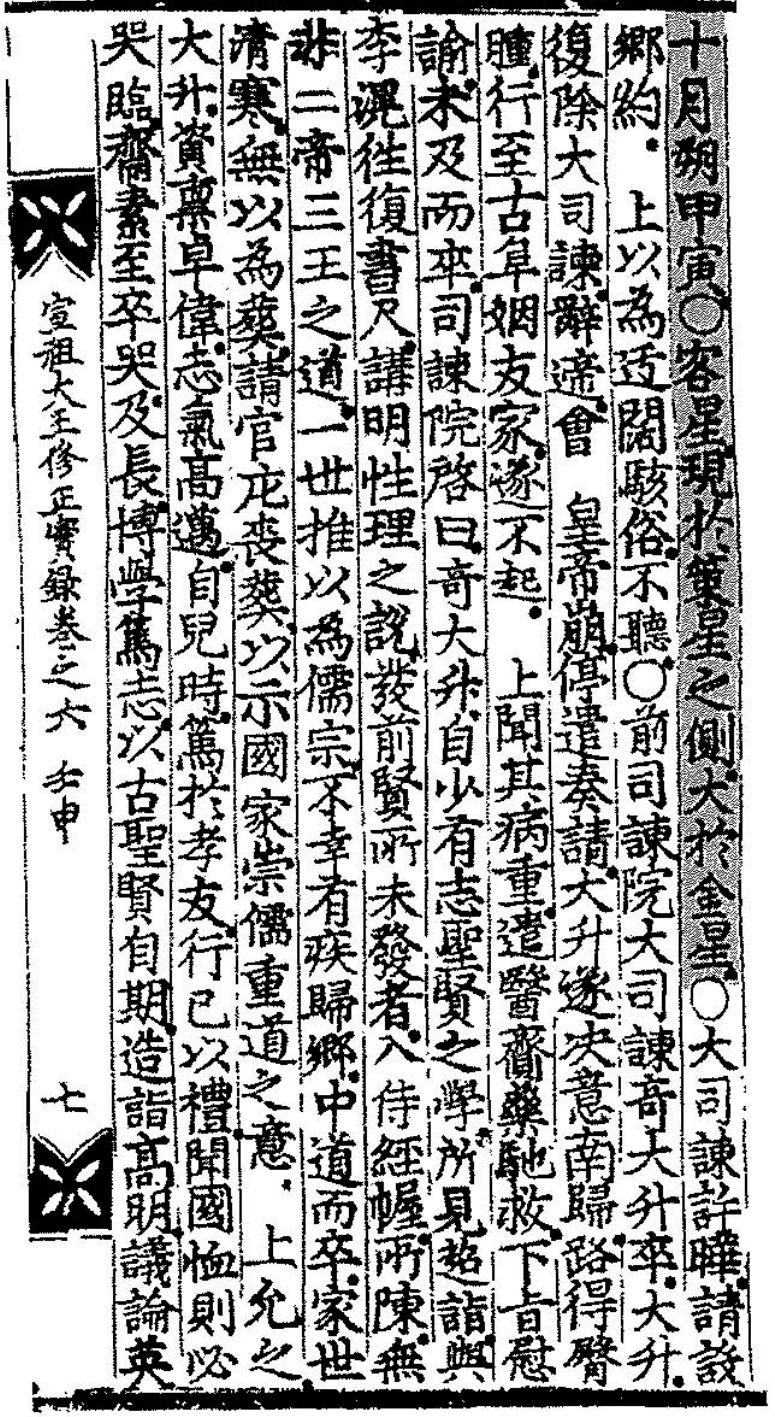


K. Nomoto
(IPMU / U. Tokyo)

AD 1572
Korean & Chinese Record

“Guest Star
as bright as Venus”

（Sonjo Sujong Sillok: Korea)

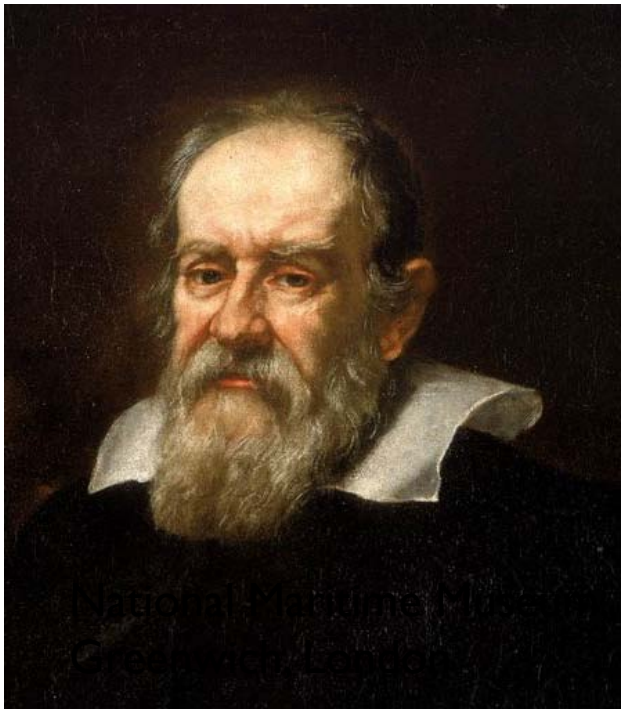

十月癸甲寅〇客星現於東皇之側大於金星〇大司諫許曄請設鄉約上以為迂闊駭俗不聽〇前司諫院大司諫奇大升卒大升復除大司諫辭遞會 皇帝崩停遣奏請大升遂決意南歸路得臀腫行至古阜姻友家遂不起 上聞其病重遣醫齎藥馳救下旨慰諭未及而卒司諫院啓曰奇大升自少有志聖賢之學所見超詣與李滉往復書只講明性理之說裁前賢所未發者入侍經幄所陳無非二帝三王之道一世推以為儒宗不幸有疾歸鄉中道而卒家世清寒無以為葬請官庀喪葬以示國家崇儒重道之意上允之大升資稟卓偉志氣高邁自兒時篤於孝友行已以禮閑國恤則必哭臨齋素至卒哭及長博學篤志以古聖賢自期造詣高明議論英

宣祖大王修正實錄卷之六 壬申 七

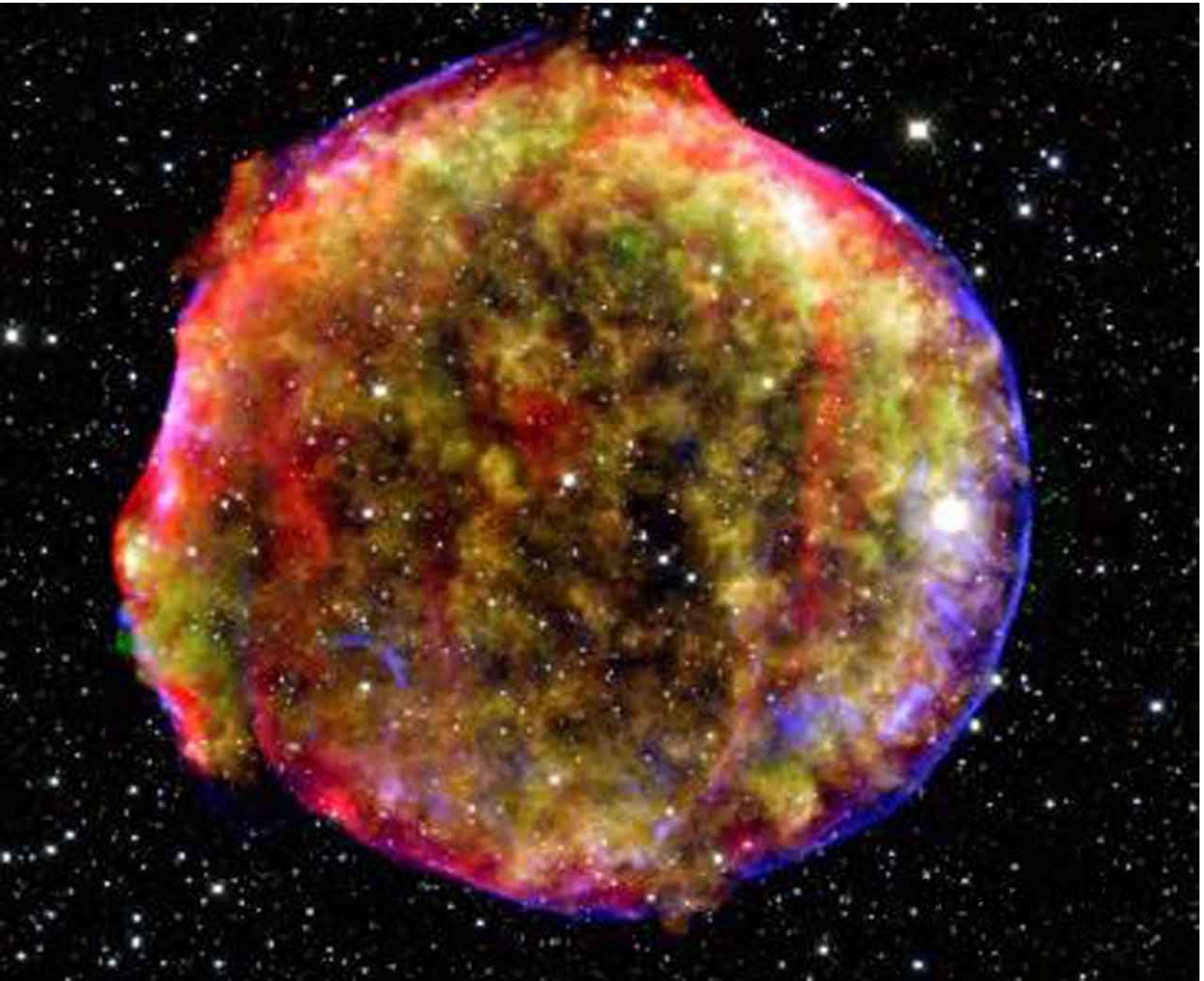
AD 1572
Tycho Brahe's Supernova

AD 1609
Galileo Galilei's Telescope


Istituto e Museo di Storia della Scienza, Florence



Remnant of Tycho's Supernova

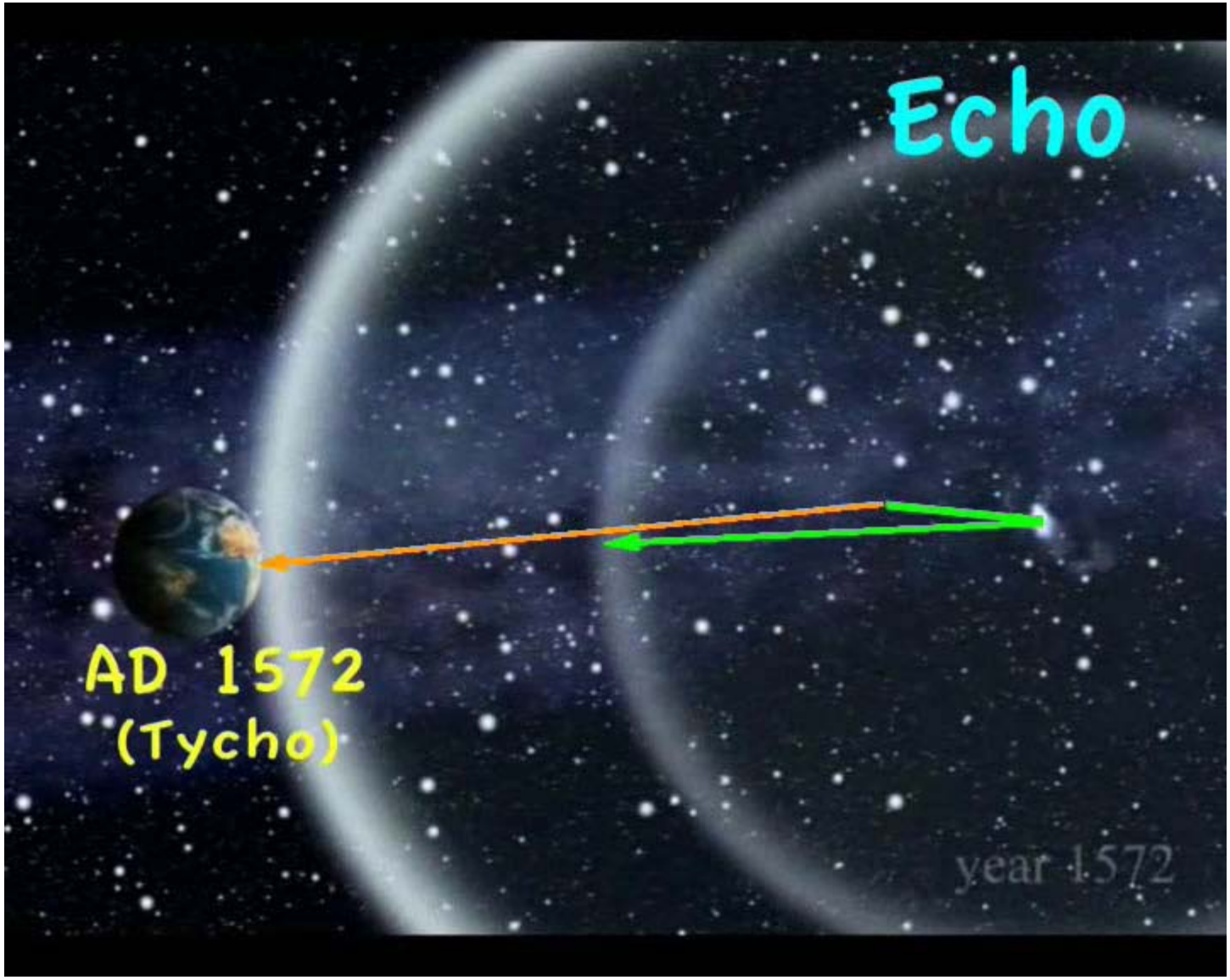


Green Yellow Blue
X-ray (Hot gas with millions of degree)

Red
Infrared
(Circumstellar/ Synthesized dust)

White
Optical
(Foreground/ background stars)

Observations of “SN Echo”



(Oort, Zwicky, ,,, Rest et al., Krause et al.)

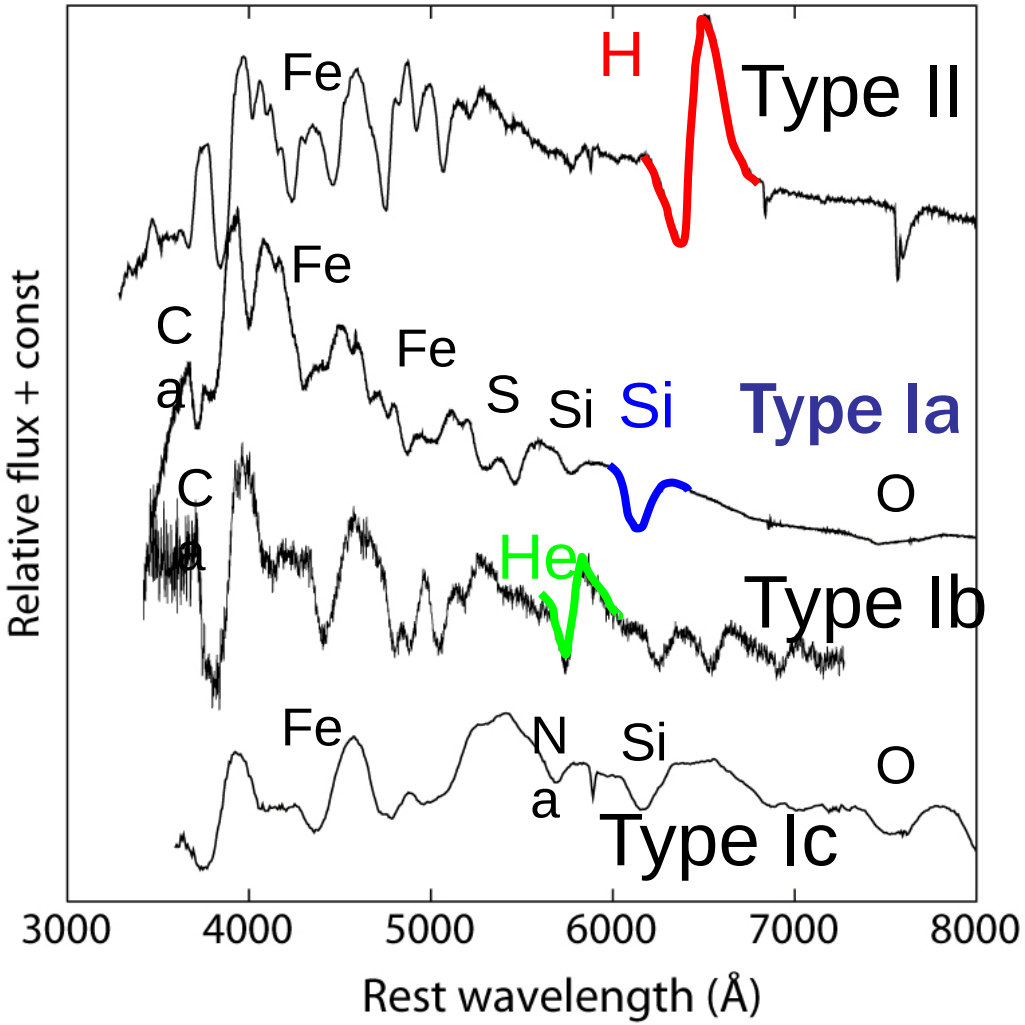
Modern Powerful Telescopes

Very Large Telescope (8.2m)

Subaru Telescope (8.2m)

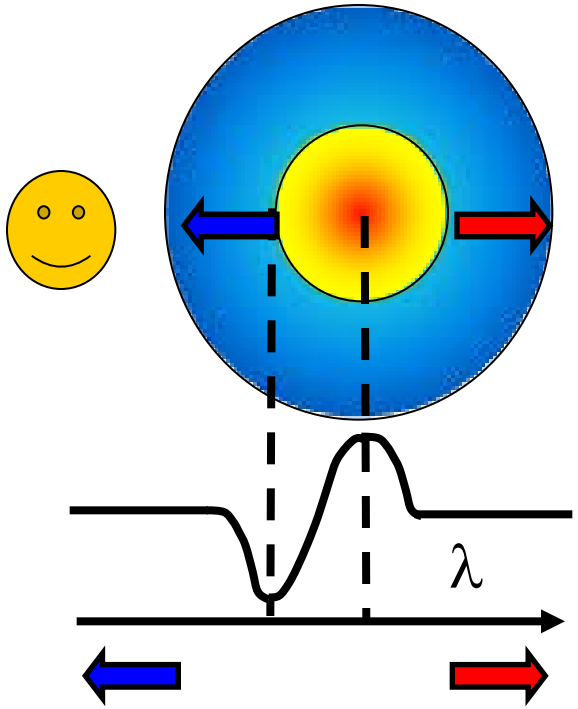
Keck Telescope (10m)

Supernova Spectra



Pseudo-continuum

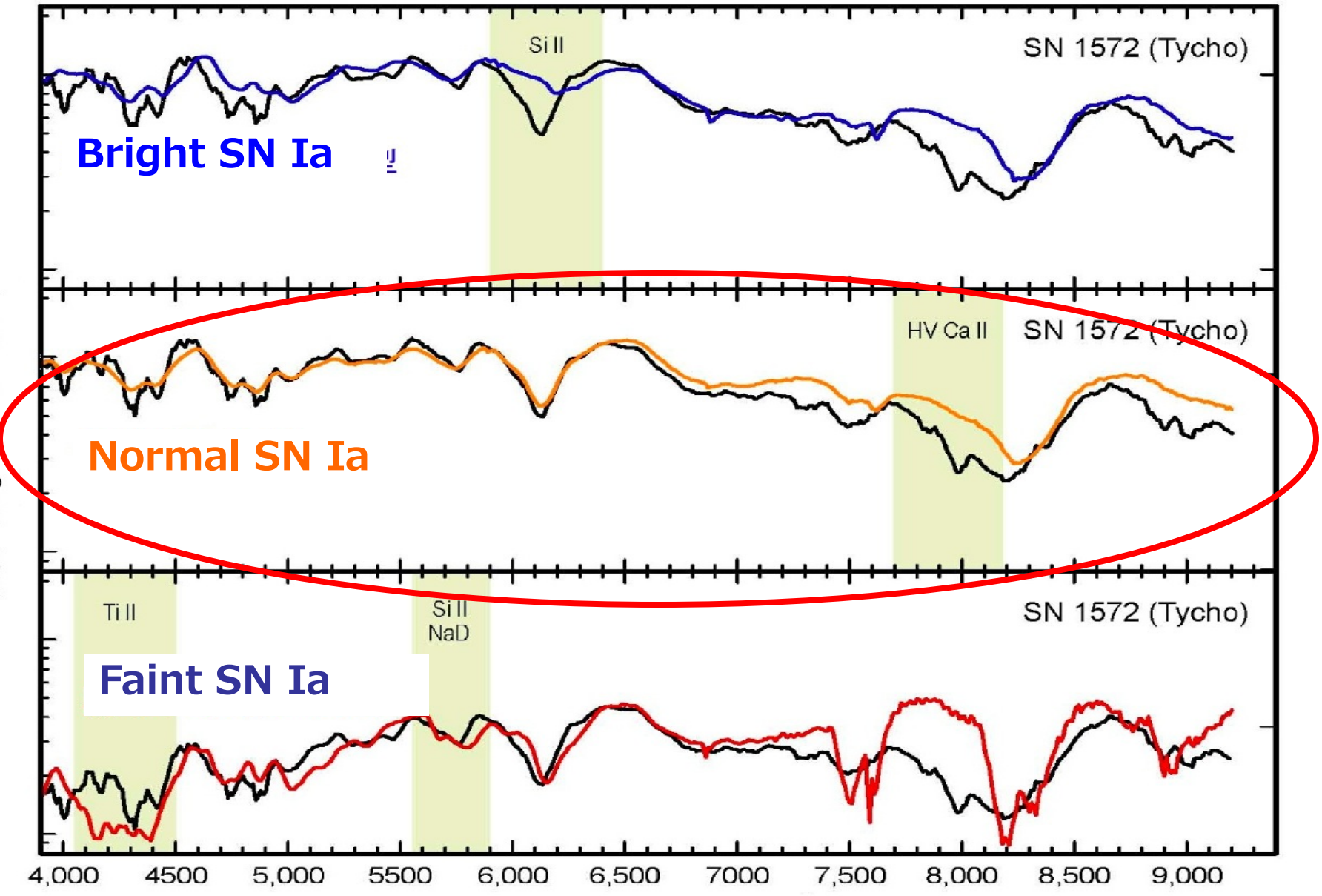
+ P-Cygni profile



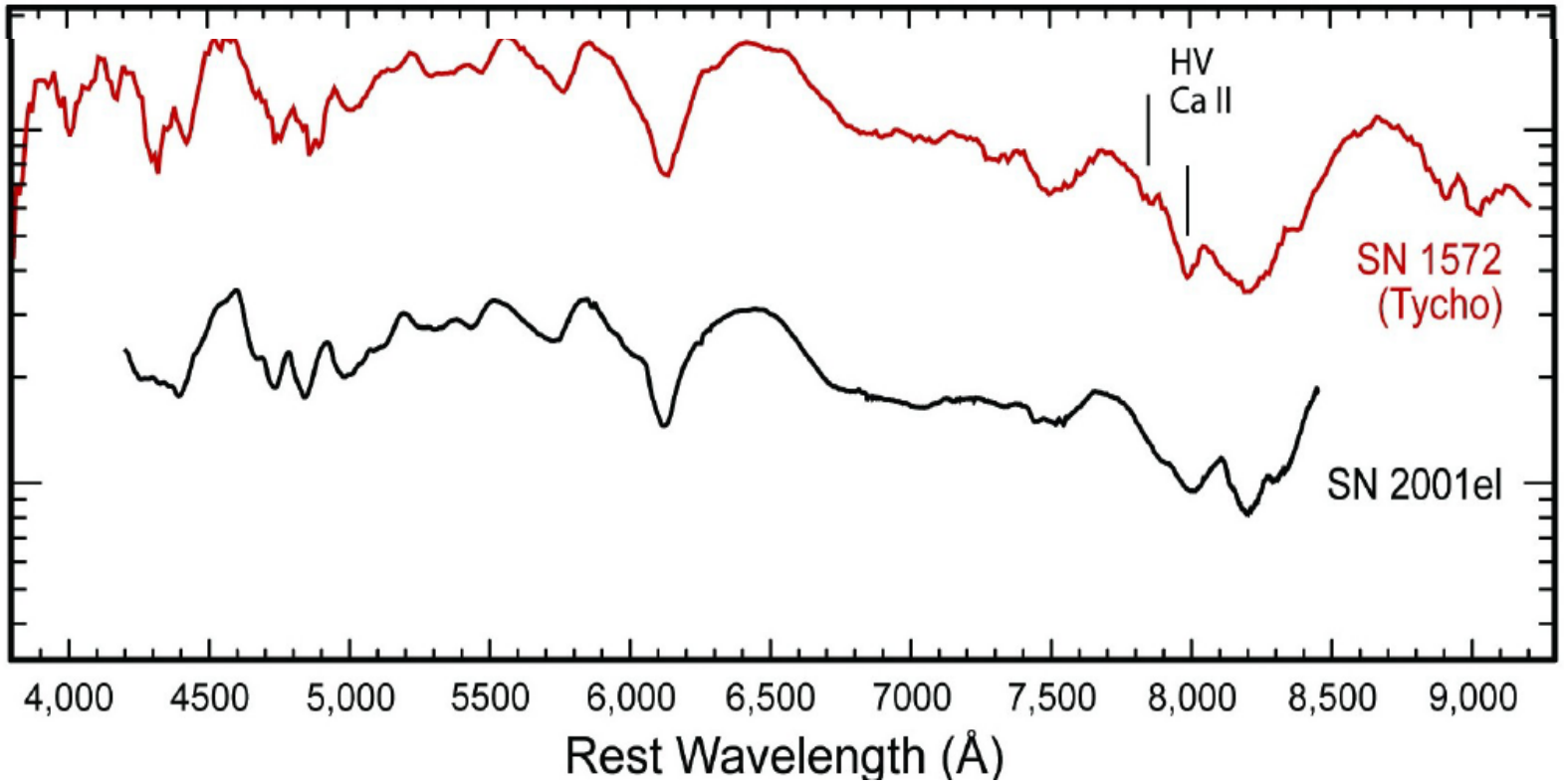
$v \propto (E/M_{ej})^{1/2}$

Spectra

(Krause, Tanaka, Goto, Usuda, Hattori, Birkmann, Nomoto '08)



High Velocity Ca Feature

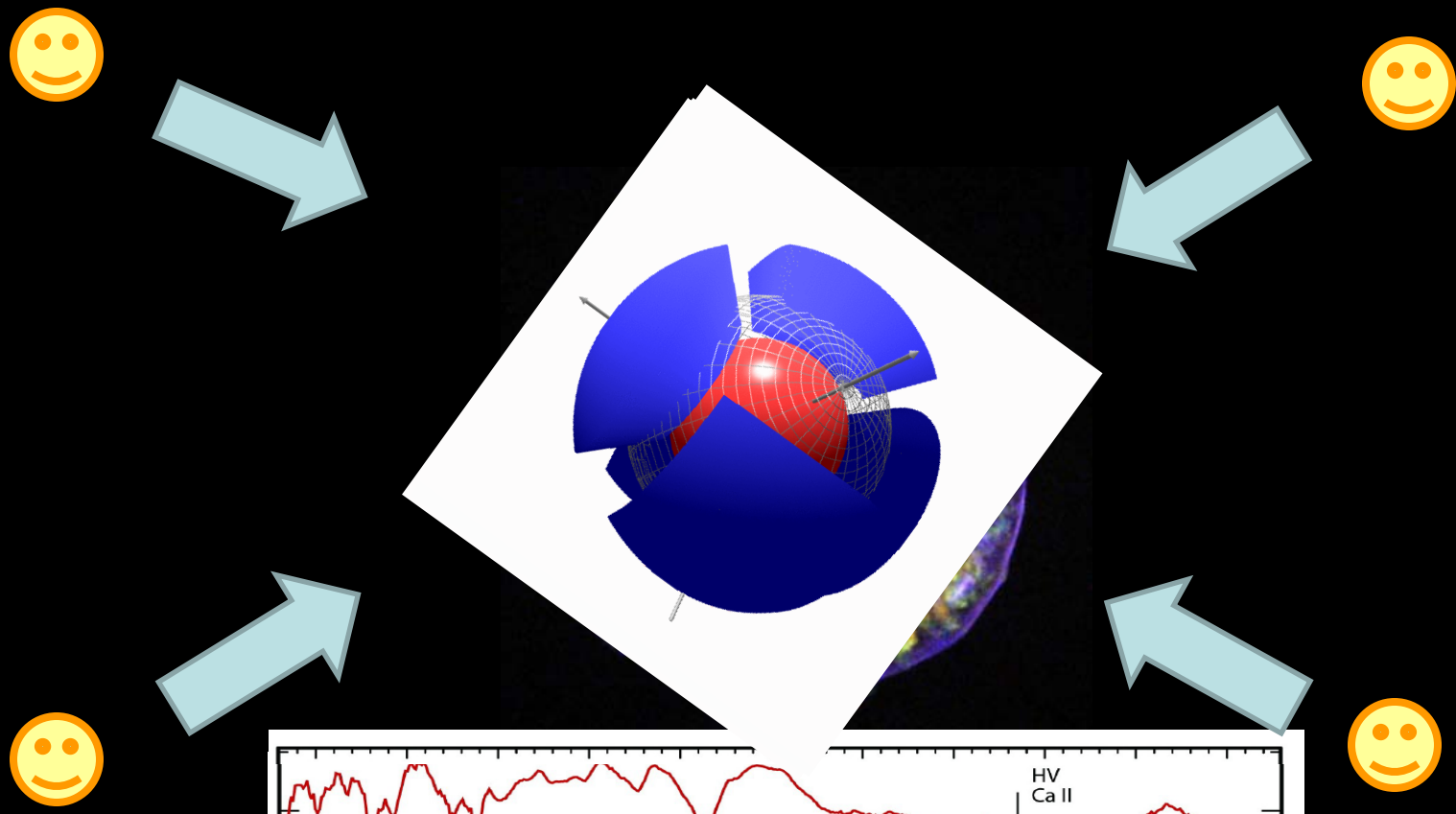


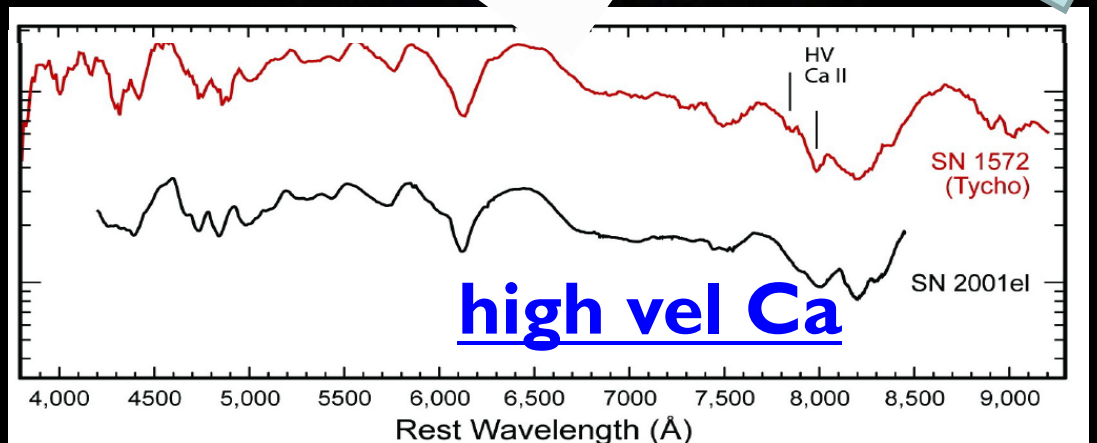
Origin of high velocity Ca ?

-- Circumstellar interaction ? (Gerardy+, Mazzali+)

-- Asphericity ? (← Echo)

Echo ⇨ Tycho's SN : 3D structure





Tanaka et al. 06,
ApJ, 645, 470

International weekly journal of science

nature

Tycho Brahe's 1572 supernova as a standard type Ia as revealed by its light-echo spectrum

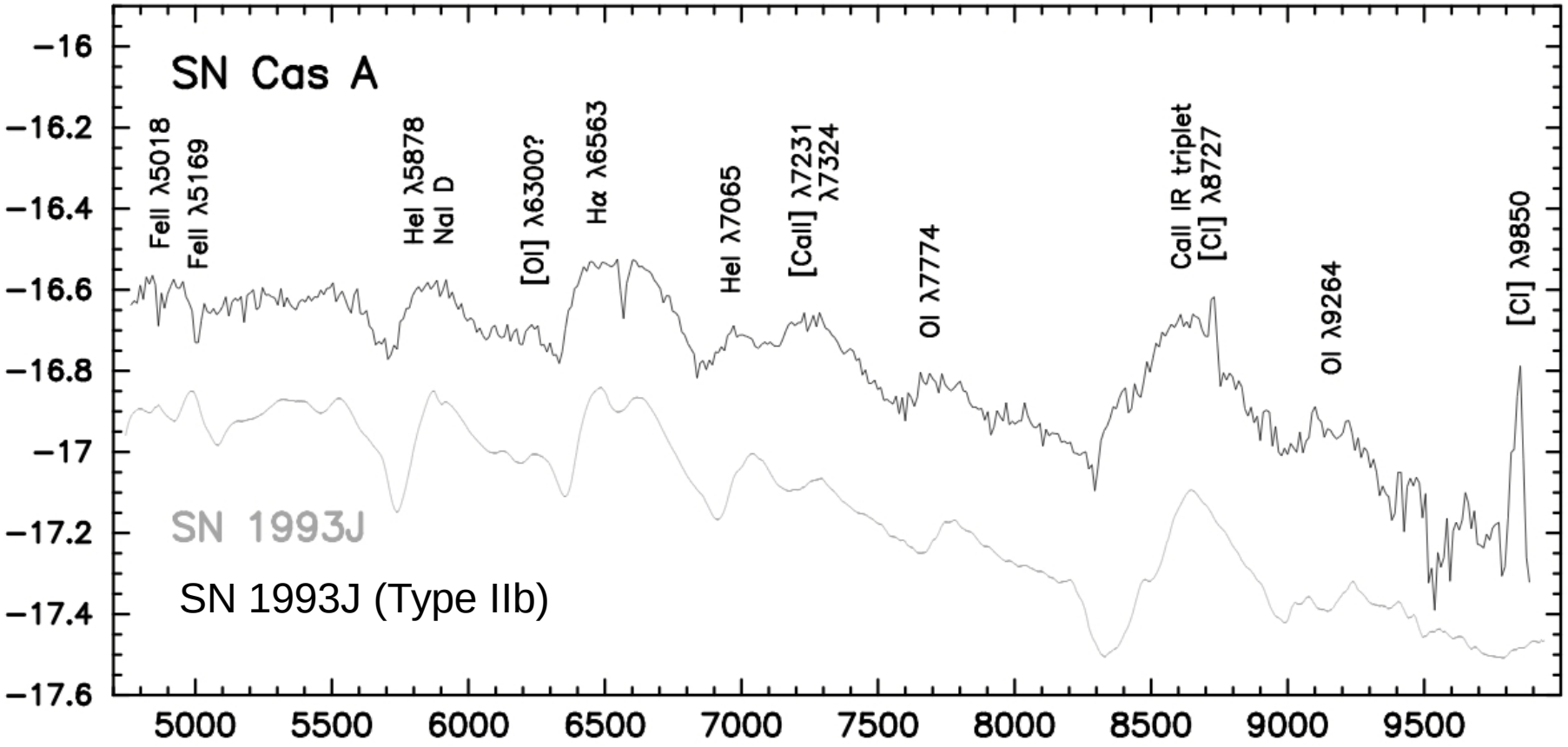
Oliver Krause[1], Masaomi Tanaka[2,3], Tomonori Usuda[4], Takashi Hattori[4], Miwa Goto[1], Stephan Birkmann[1,5] & Ken'ichi Nomoto[2,3]

[1]Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany. [2]Institute for the Physics and Mathematics of the Universe, University of Tokyo, Kashiwanoha 5-1-5, Kashiwa, Chiba 277-8568, Japan. [3]Department of Astronomy, Graduate School of Science, University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-0033, Japan. [4]SUBARU Telescope, National Astronomical Observatory of Japan, 650 North A'ohoku Place, Hilo, Hawaii, USA. [5]European Space Agency, Space Science Department, Keplerlaan 1, 2200 AG Noordwijk, The Netherlands.

Reprinted from Nature, Vol. 456, No. 7222, pp. 617–619 , 4 December 2008

MPIA, U. Tokyo, Subaru Telescope (2008)

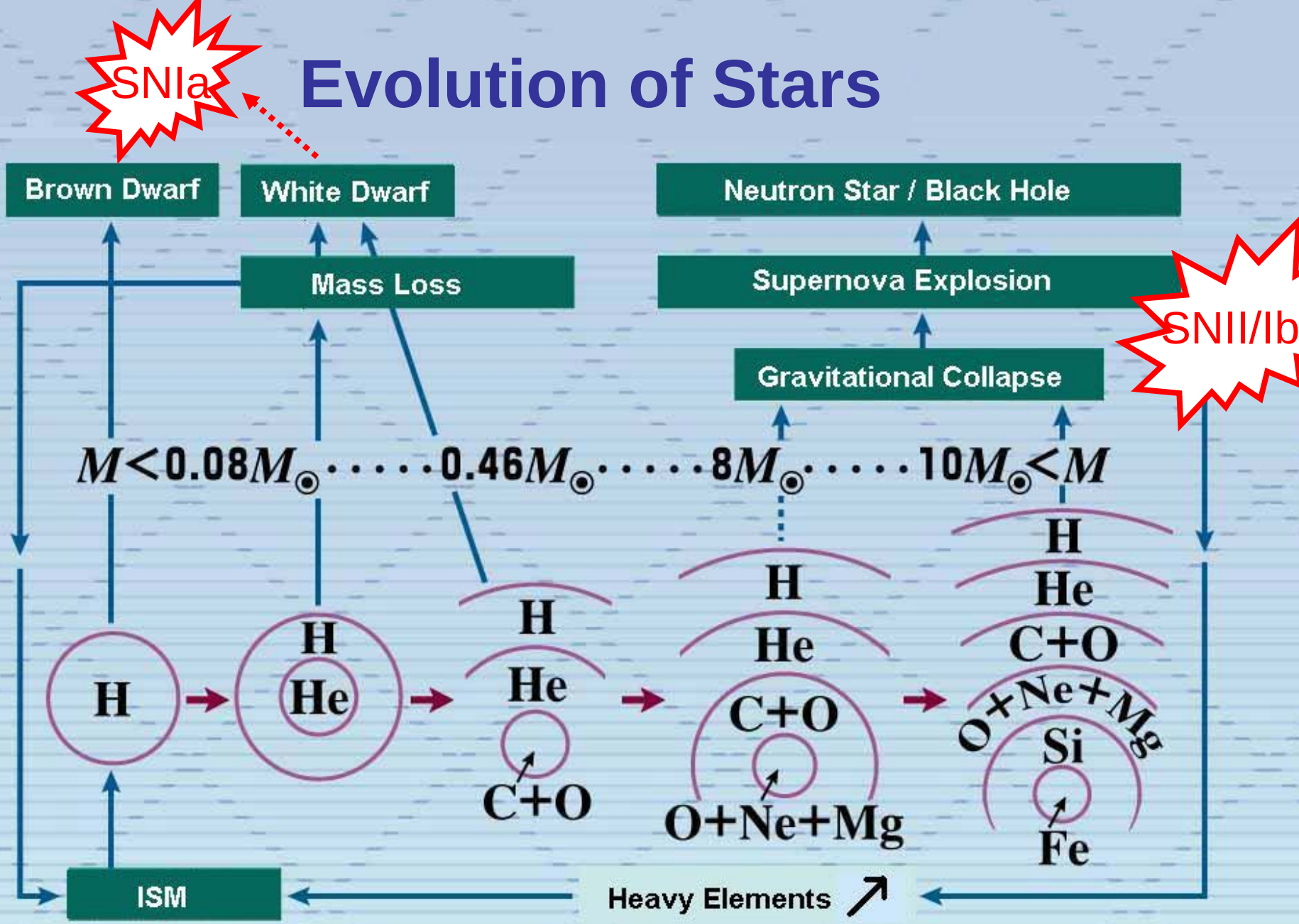
Light Echo ⇨ Cas A SN=Type IIb



SN 1993J (Type IIb)

Krause et al. (2008)

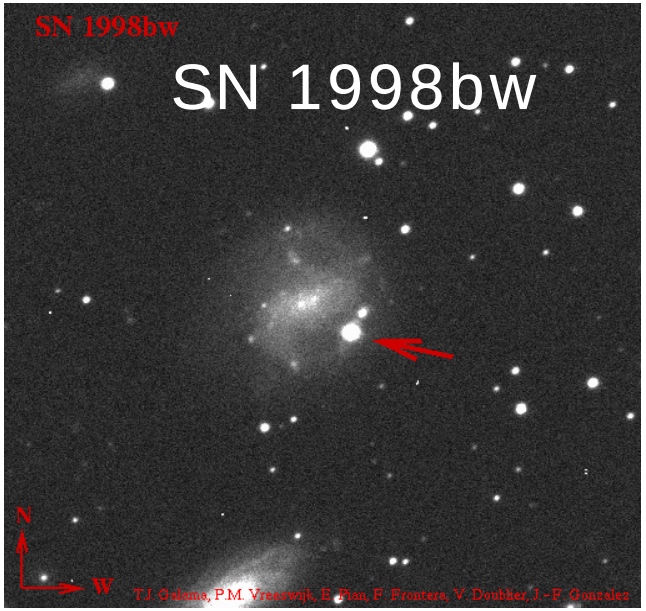
Evolution of Stars

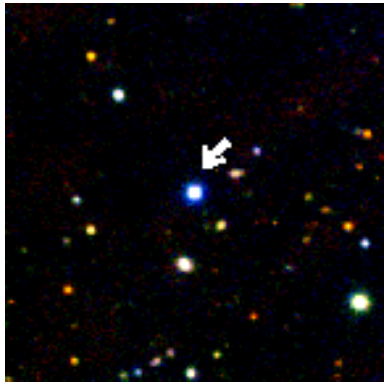


The Final Fates of Single Stars

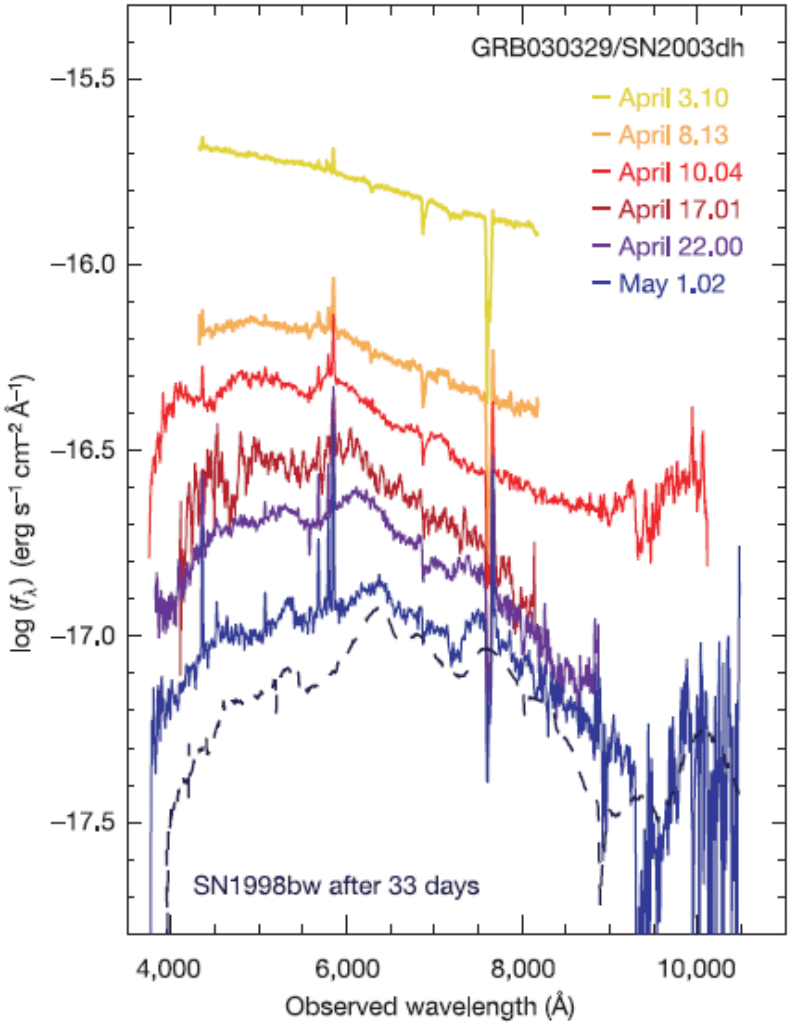
- $M < 0.08\ M_\odot$ Brown Dwarf
- $0.08 -- 0.46\ M_\odot$ He White Dwarf
- $0.46 -- 8\ M_\odot$ C+O White Dwarf
- $8\ M_\odot -- M_{up}$ O+Ne+Mg WD
- $M_{up} -- 10\ M_\odot$ ONeMg–cc-SN + NS
- $10\ M_\odot -- M_{ns}$ Fe-cc-Supernova + NS
- $M_{ns} -- 140\ M_\odot$ Fe-cc-Supernova + BH
- $140 -- 300\ M_\odot$ Pair Instability SN
- $300 -- 10^5\ M_\odot$ SN + BH
- $10^5\ M_\odot < M$ BH(H)

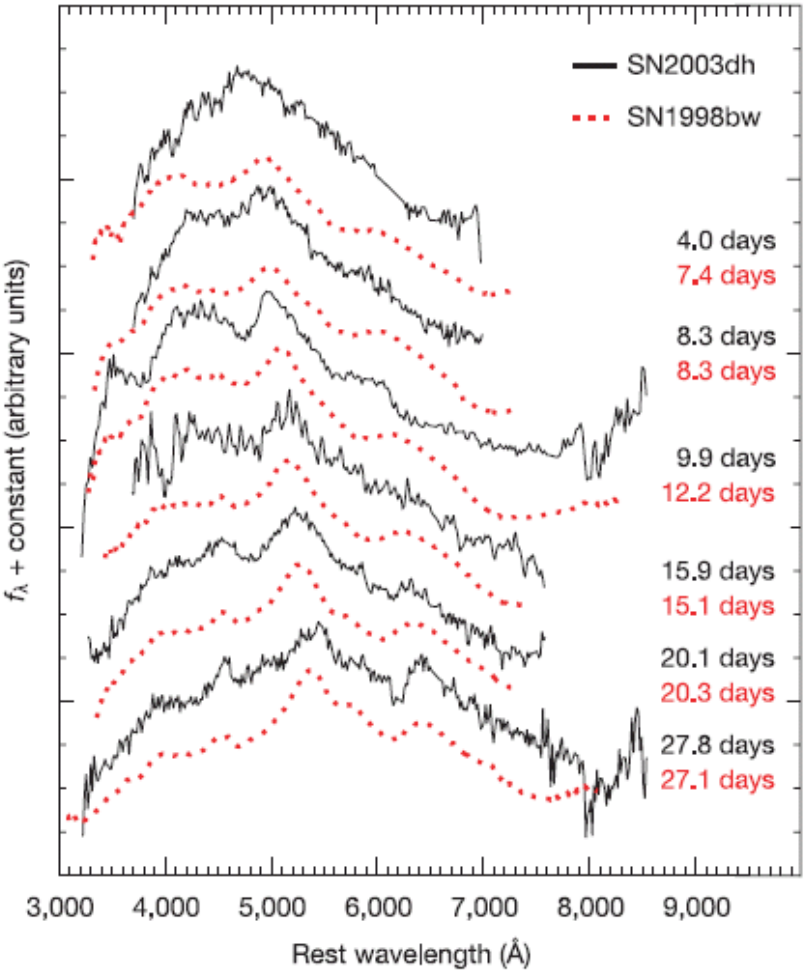
Supernova-GRB Connection





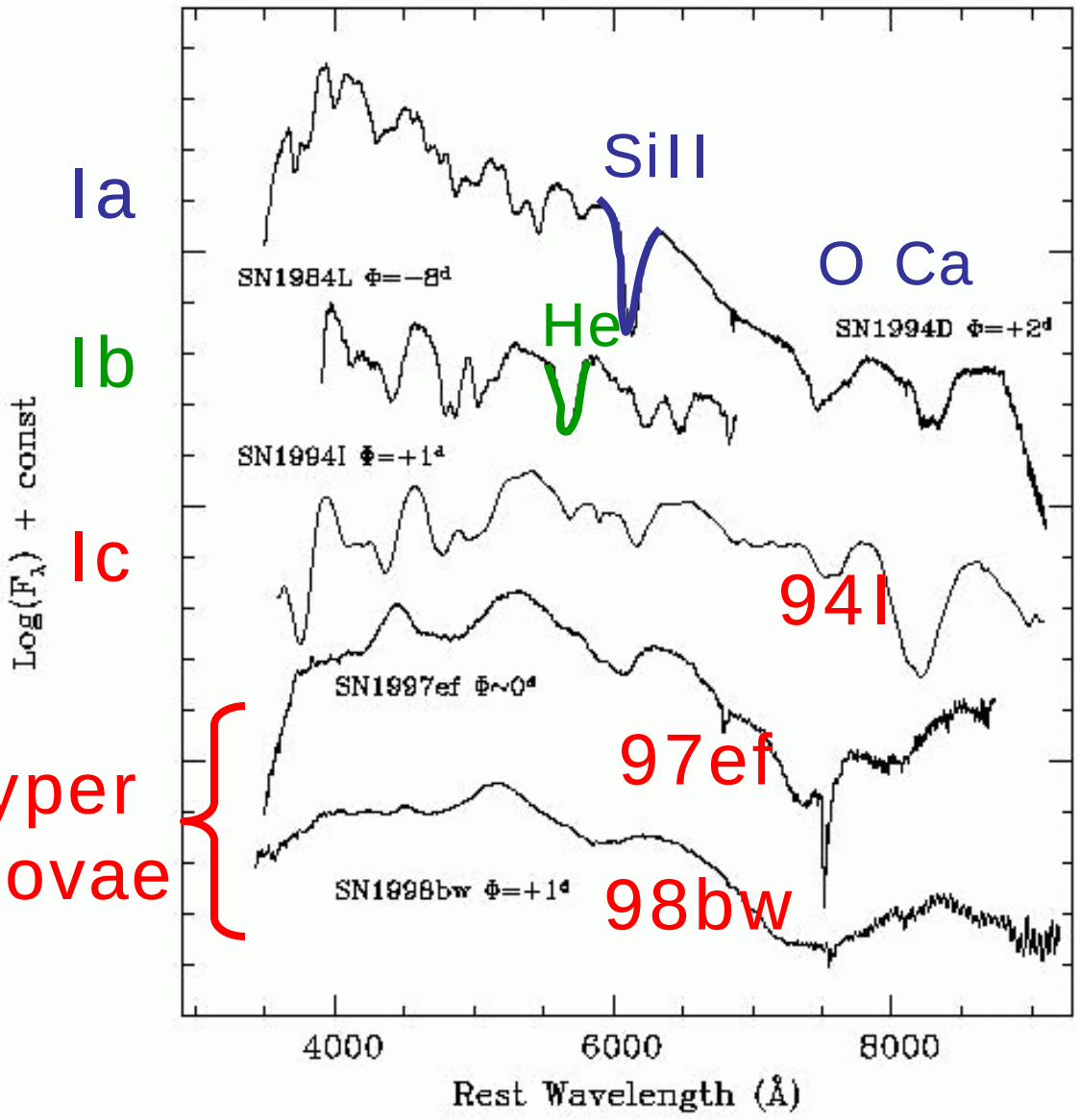
(1) GRB 030329 / SN 2003dh





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

Spectra of Supernovae & Hypernovae



Ic: no H,

no strong He,

no strong Si

Hypernovae:

broad features

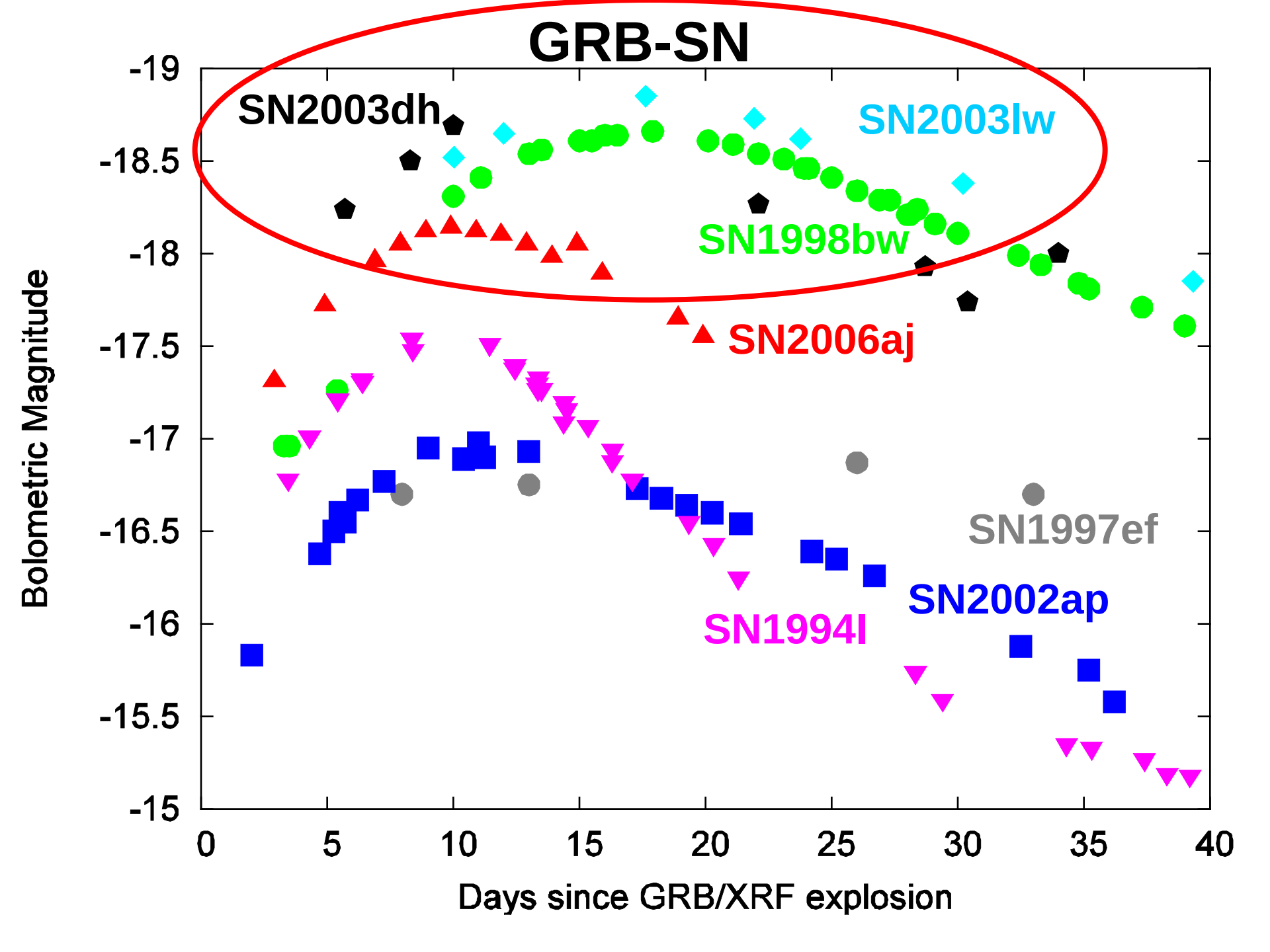
↑

blended lines

↑

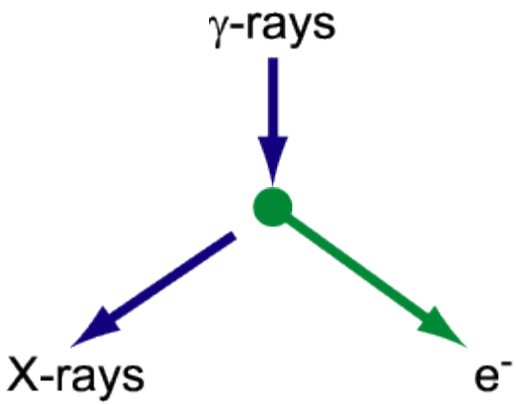
"Large mass at high velocities"

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

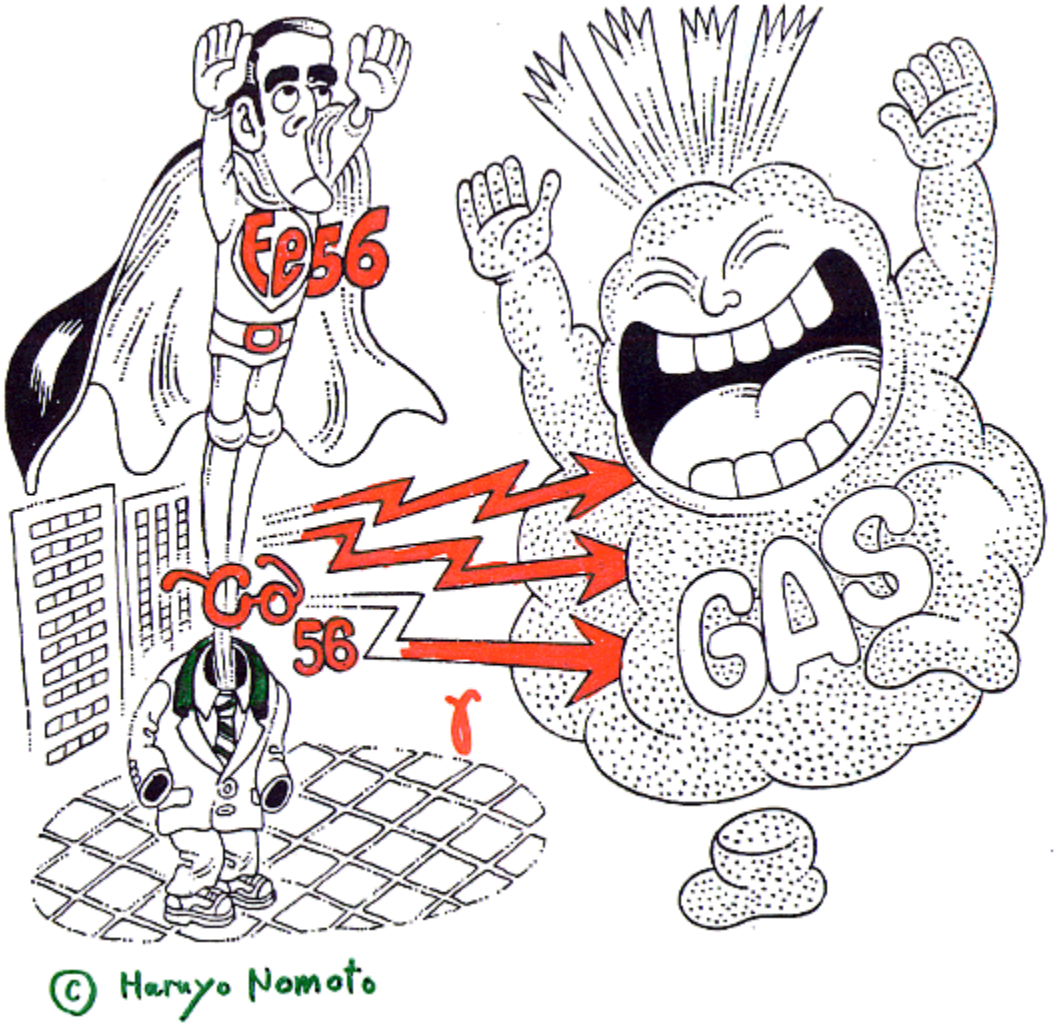
$^{56}Ni \xrightarrow[6.6d]{\gamma} {}^{56}Co \xrightarrow[78d]{\gamma} {}^{56}Fe$



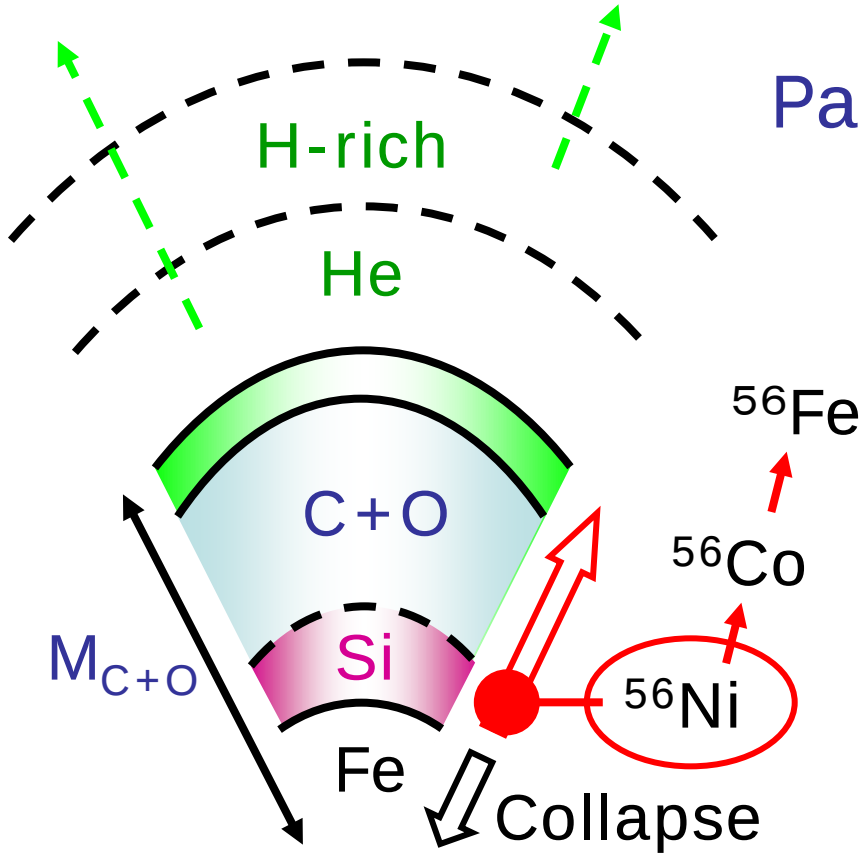
Photoabsorption Excitation/Ionization

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

Shape:M_{ej}



CO Star Models for SNe Ic



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

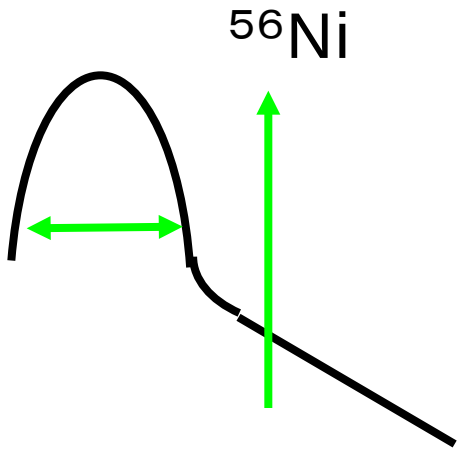
Light Curve — Spectra

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

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

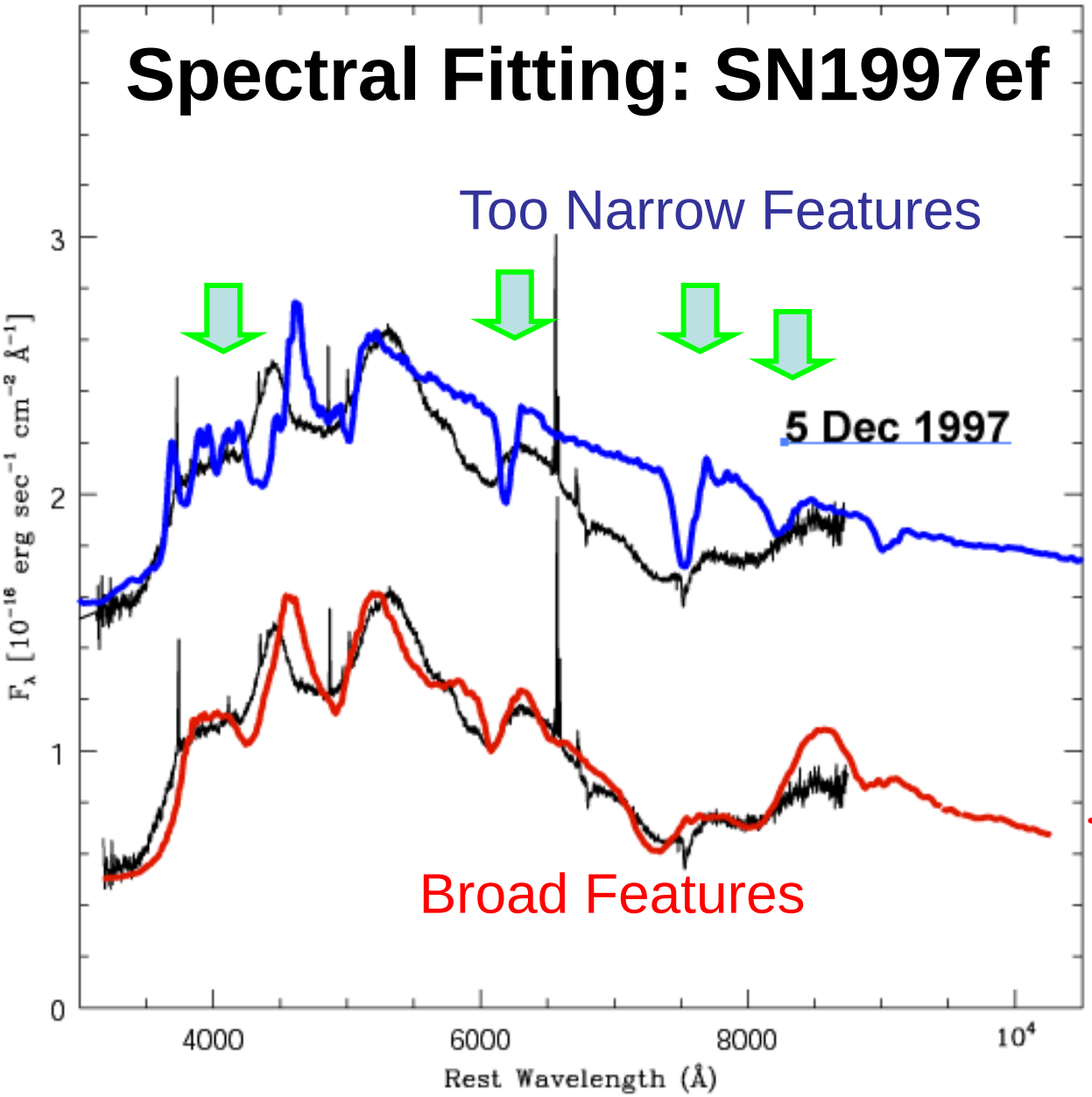
$$\propto \kappa^{1/2} M_{ej}^{3/4} E^{-1/4}$$

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



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

Supernova – GRB Connection

Three GRB－SNe = all Type Ic Hypernovae

$E > 10^{52}$ erg (～10×normal SN)

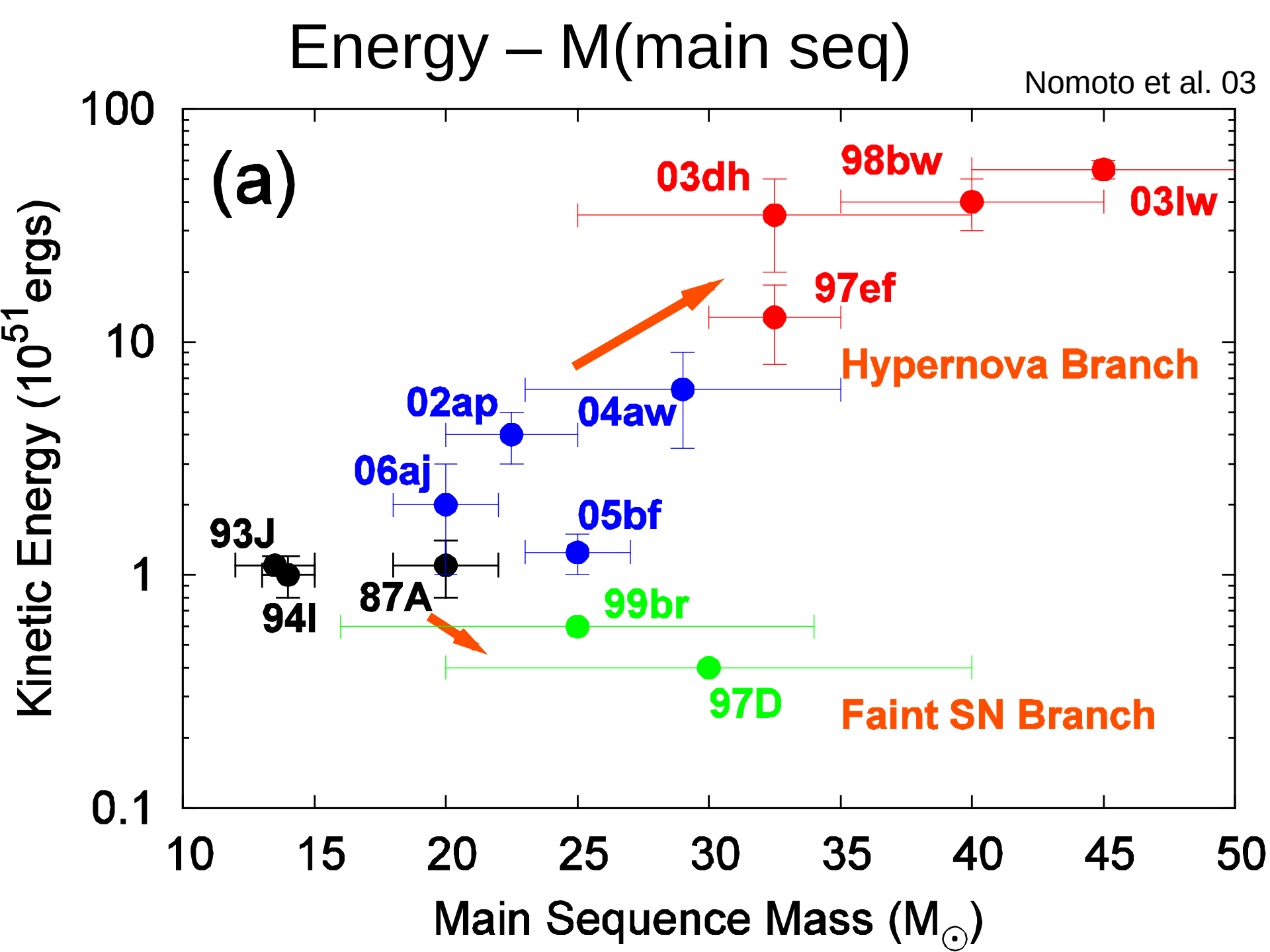
Large M_{ms} →Black Hole Forming SNe

Aspherical

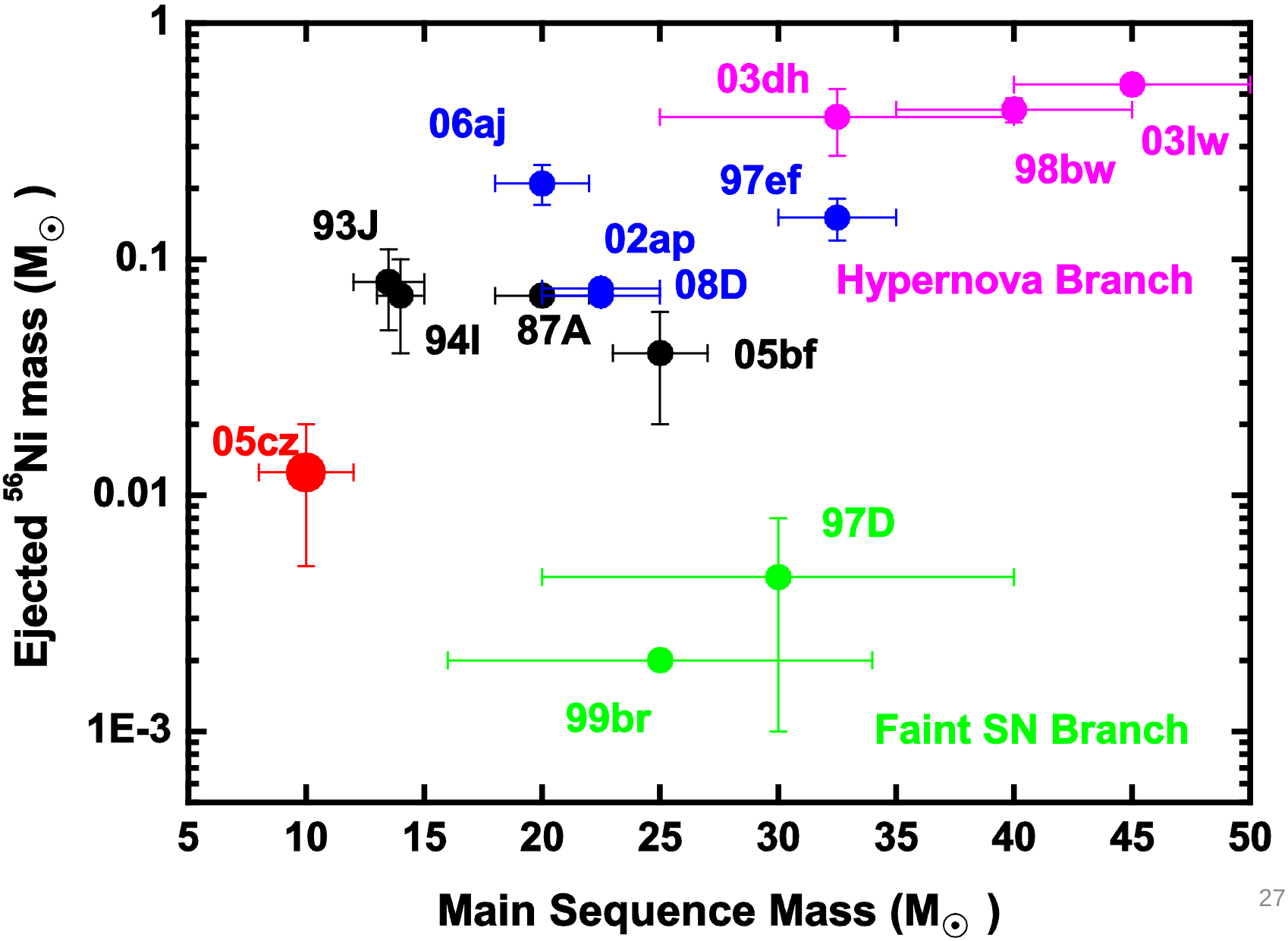
GRB	SN	$M_{CO}/M_{\odot}$	$M_{ms}/M_{\odot}$	$E/10^{51}$erg	$M(^{56}Ni)/M_{\odot}$
980425	1998bw	14	40	30	0.4
030329	2003dh	11	35	40	0.35
031203	2003lw	16	45	60	0.55

Hypernova in Prague

Hypernova in Prague

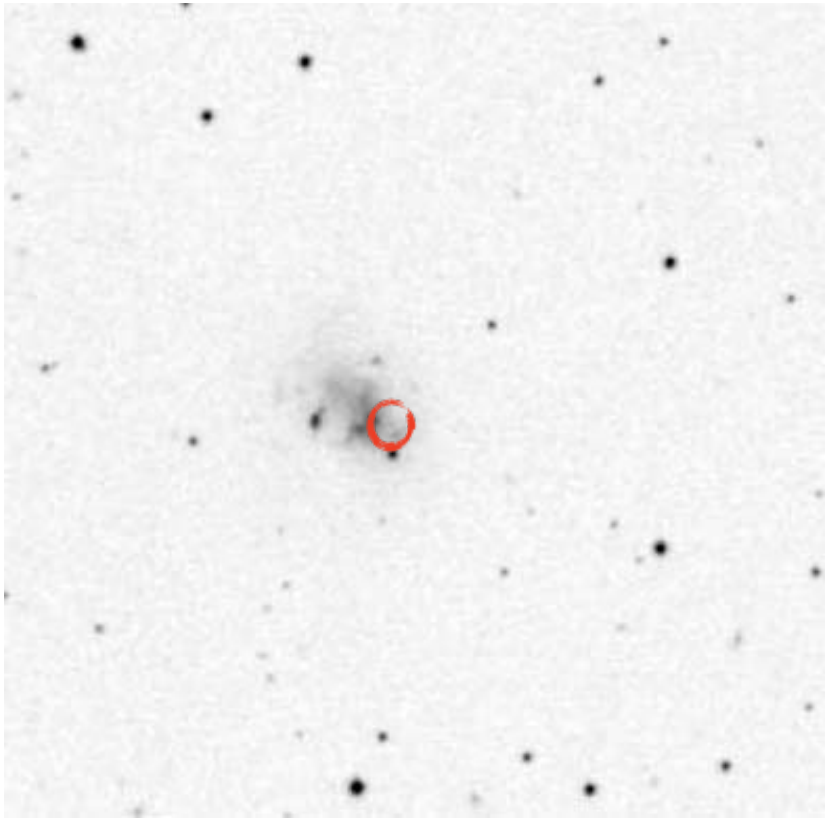

Energy – M(main seq)
Nomoto et al. 03
(a)
03dh
98bw
03lw
97ef
Hypernova Branch
02ap
04aw
06aj
05bf
93J
94I
87A
99br
97D
Faint SN Branch
Kinetic Energy (10^{51}ergs)
Main Sequence Mass ($M_\odot$)
100
10
1
0.1
10
15
20
25
30
35
40
45
50

M(^{56}Ni) - M(main seq)

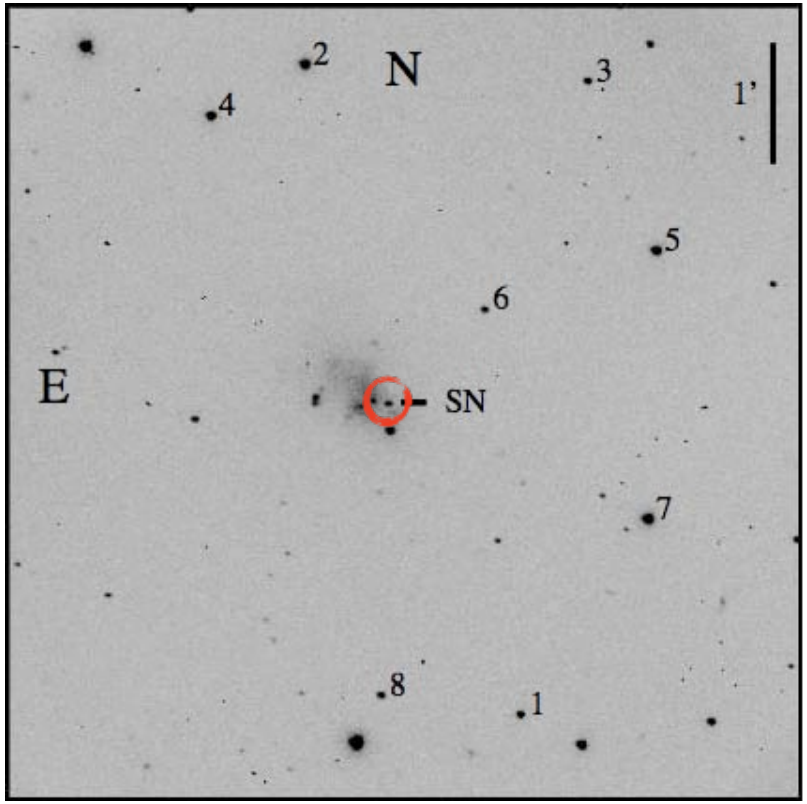


(3) Faint Supernovae

SNe 2008ha, 2005cz, 2008S



DSS



Foley et al. (2009)

SN 2008ha in UGC 12682 (~20 Mpc)

Faint Supernovae

SN 2008ha (I ?)

2005cz (Ib)

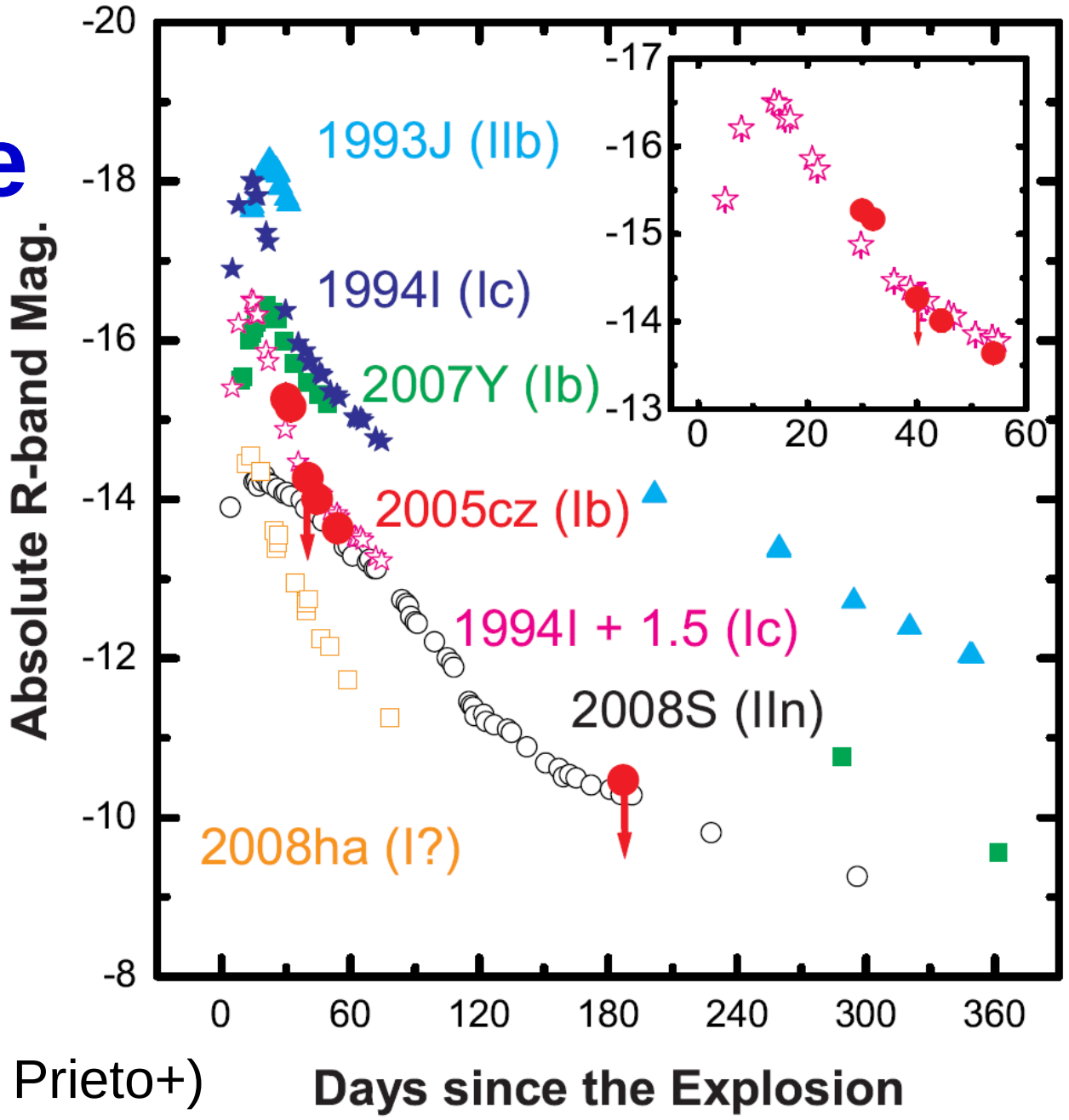
(Kawabata+)

2005E (Ib)

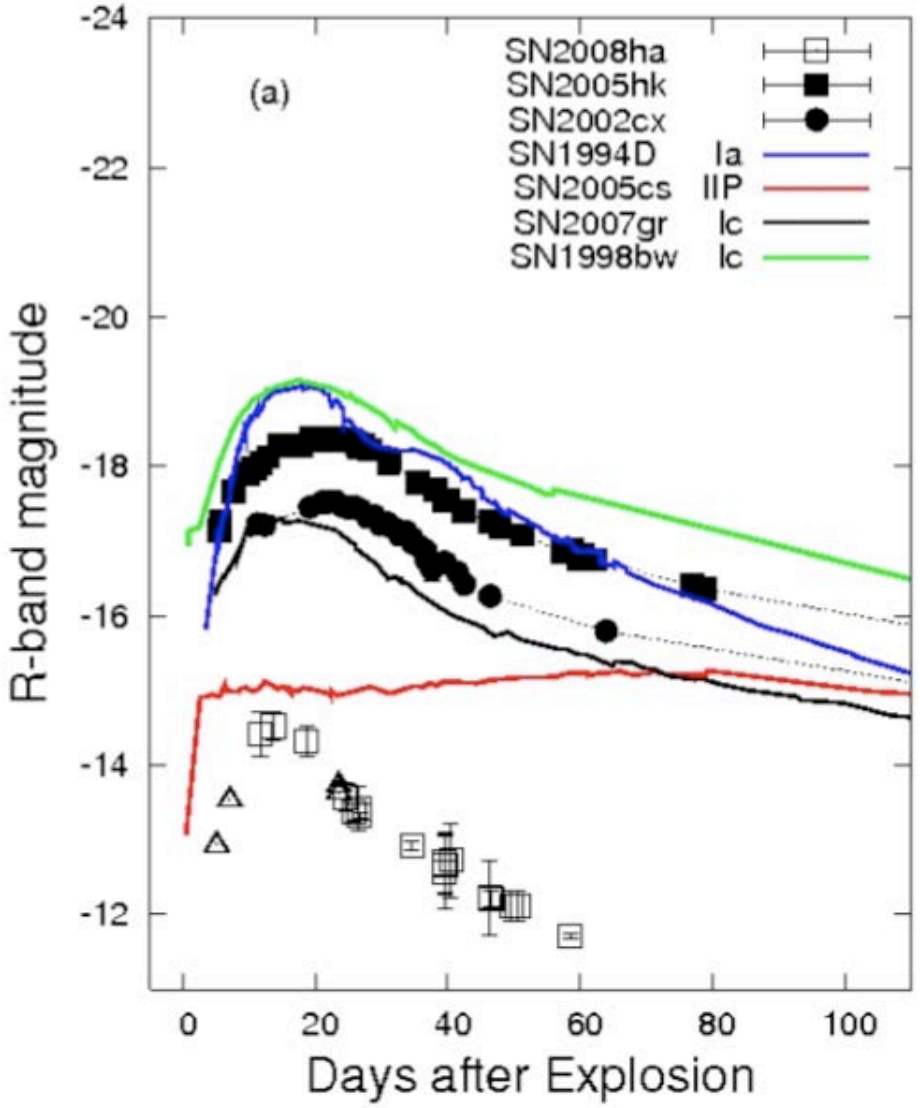
(Peretz+)

2008S (IIn)

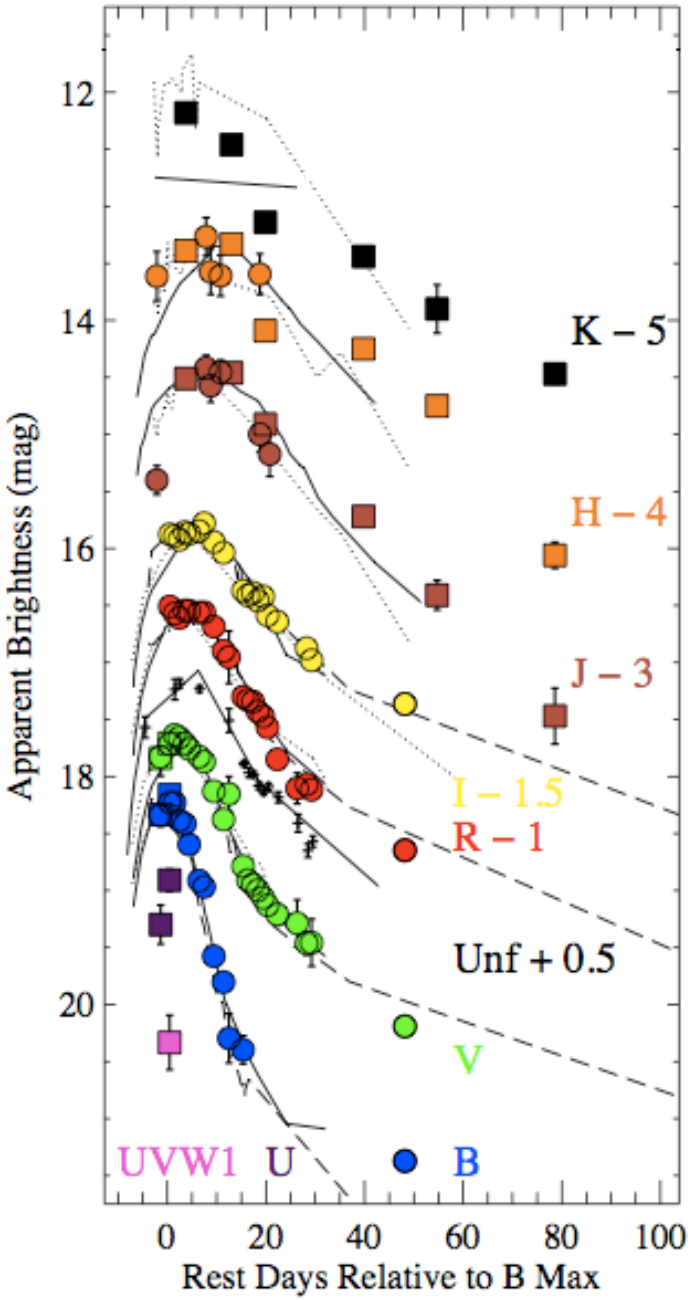
(8-10Ms AGB; Prieto+)



SN2008ha:Light Curve

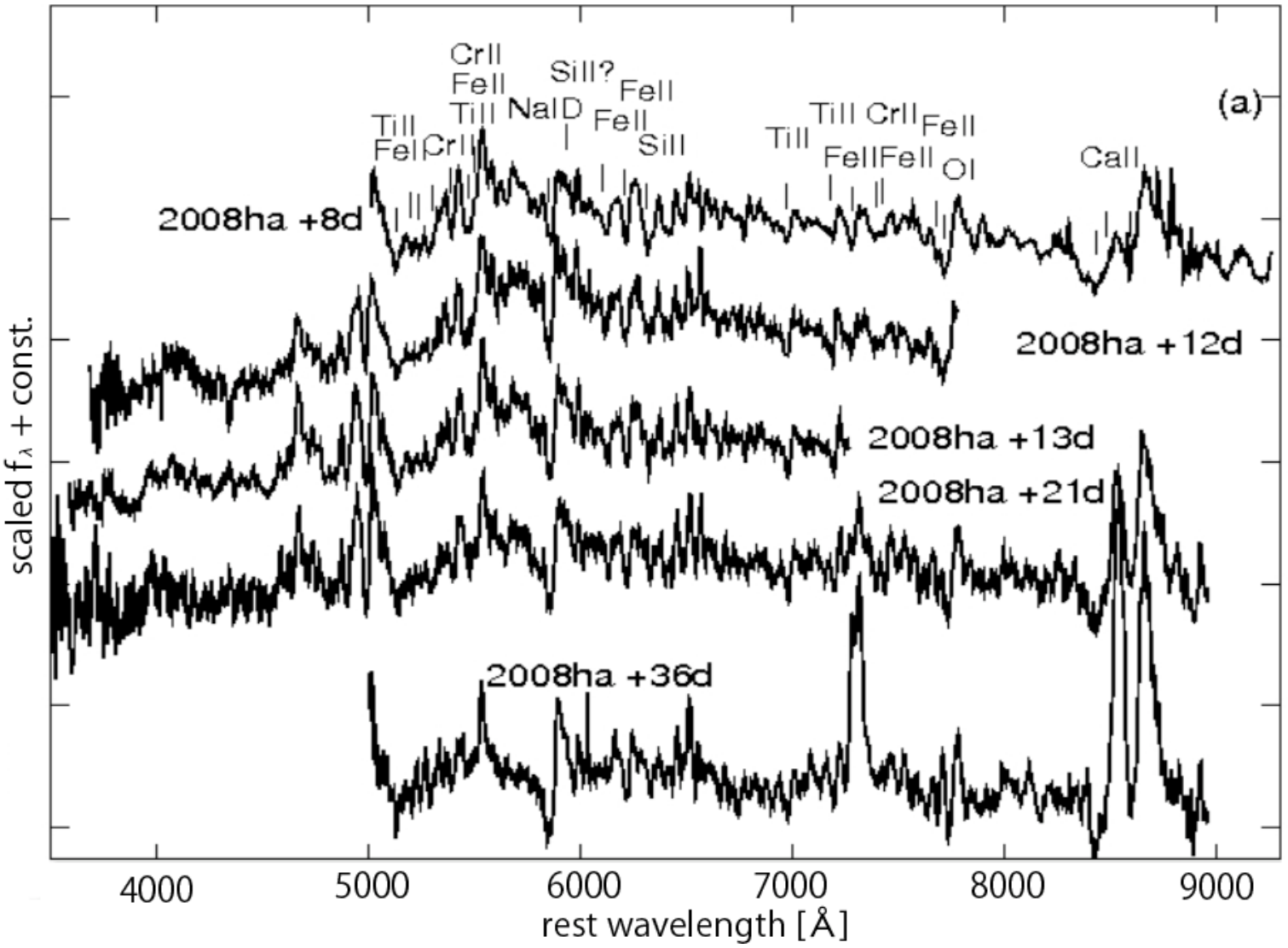


Valenti et al. (2009)



Foley et al. (2009)

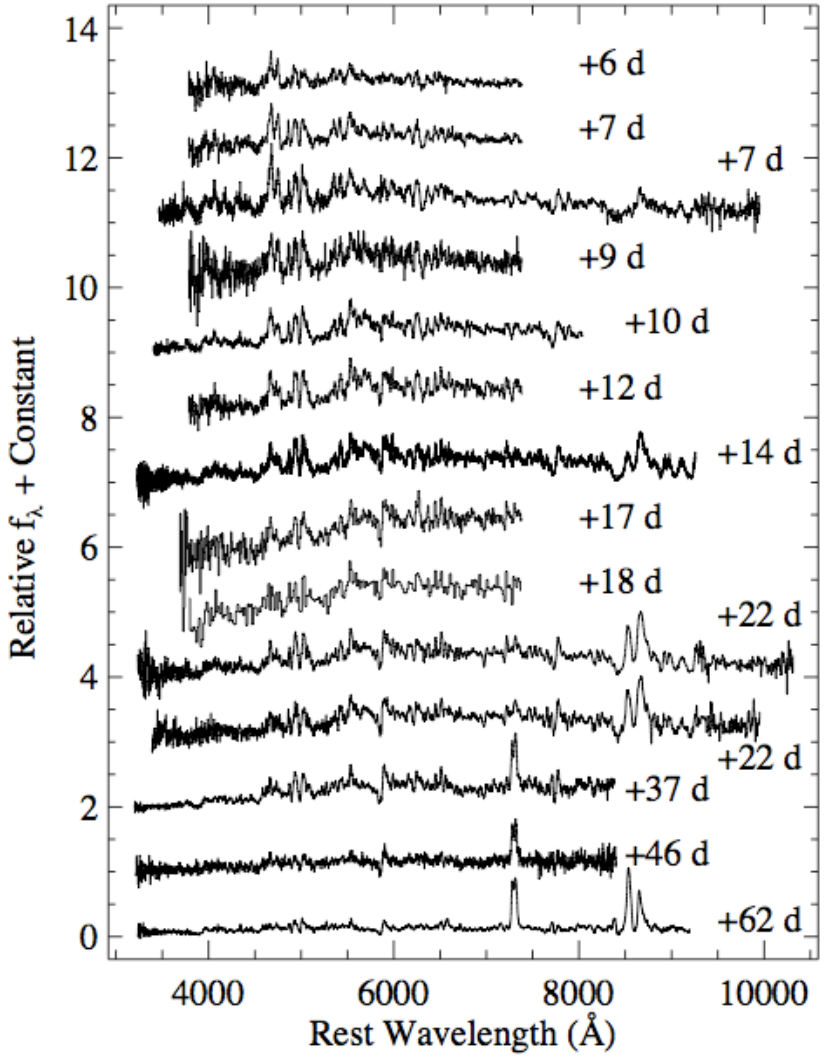
SN 2008ha: Spectra (type I)



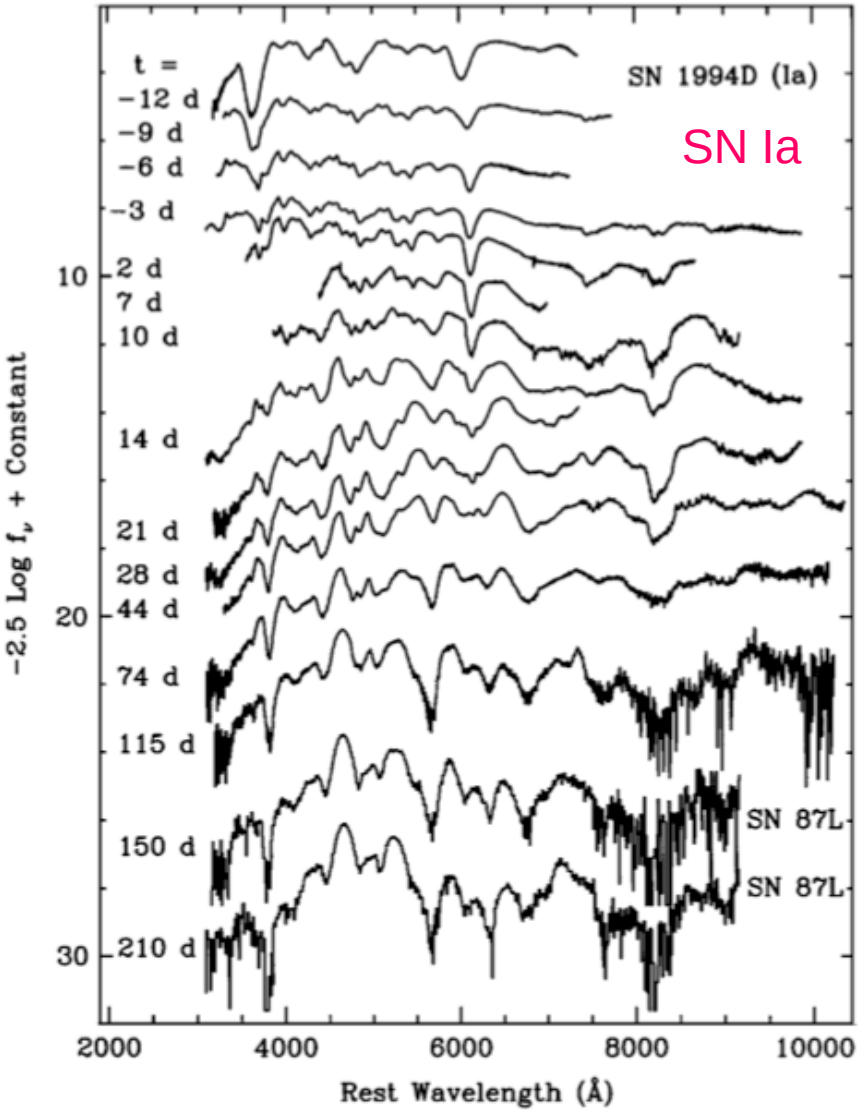
Valenti et al. (2009)

Faint SN 2008ha: Spectra(narrow)

SN I 2008ha



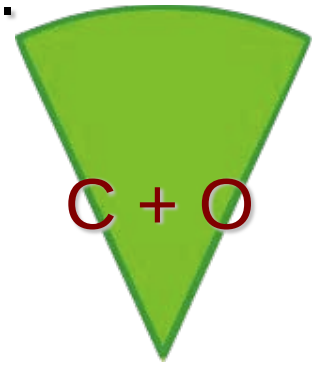
Foley et al. (2009)



Filippenko (1997)

Fallback Supernovae

1.



2.

Injection of energy

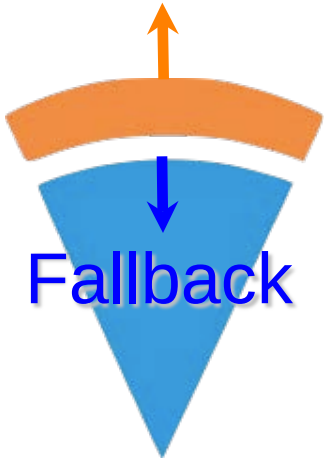
3.

Propagation of shock

4.

Inner layer does not exceed escape velocity

5.



Ejection of the outer layer

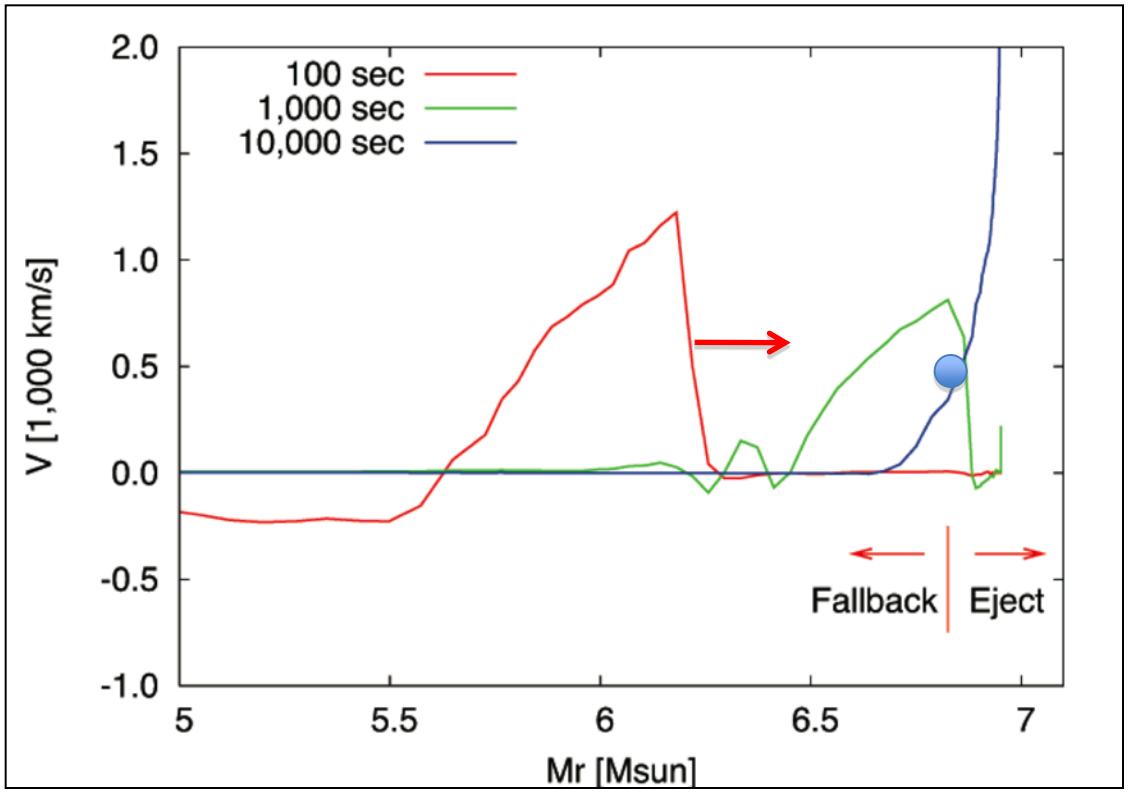
Fallback Supernova

$$M_{\rm MS} = 25\ M_\odot \ \rightarrow\ \text{mass loss} \ \rightarrow\ M_{\rm He} = 6.95\ M_\odot$$

weak explosion $\quad E_{\rm kin} = 1.0 \times 10^{48}$ erg

$v(\text{fallback}) \sim 500$ km/s at $10,000$ sec (blue circle)

$$\rightarrow\ M_{\rm fallback} = 6.83\ M_\odot,\ M_{\rm ej} = 0.12\ M_\odot$$

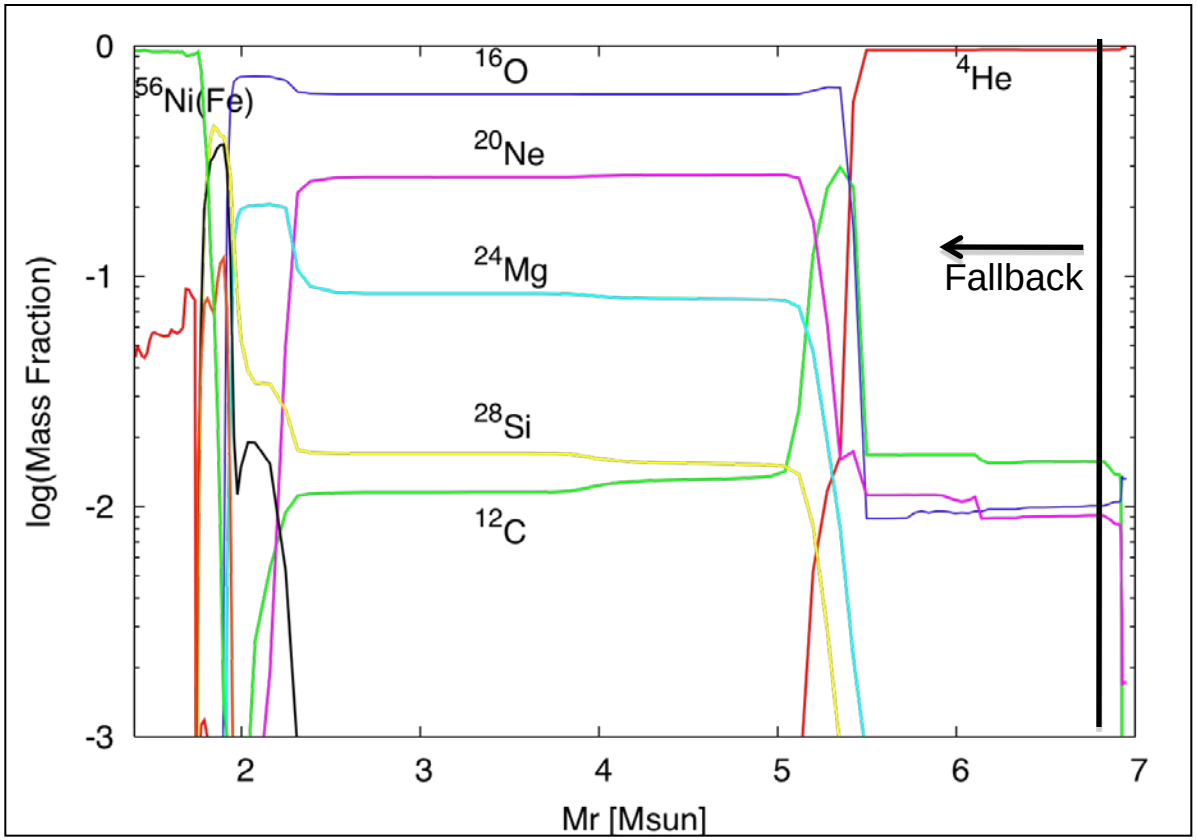


Moriya et al. 09

Fallback Supernova

- abundance distribution

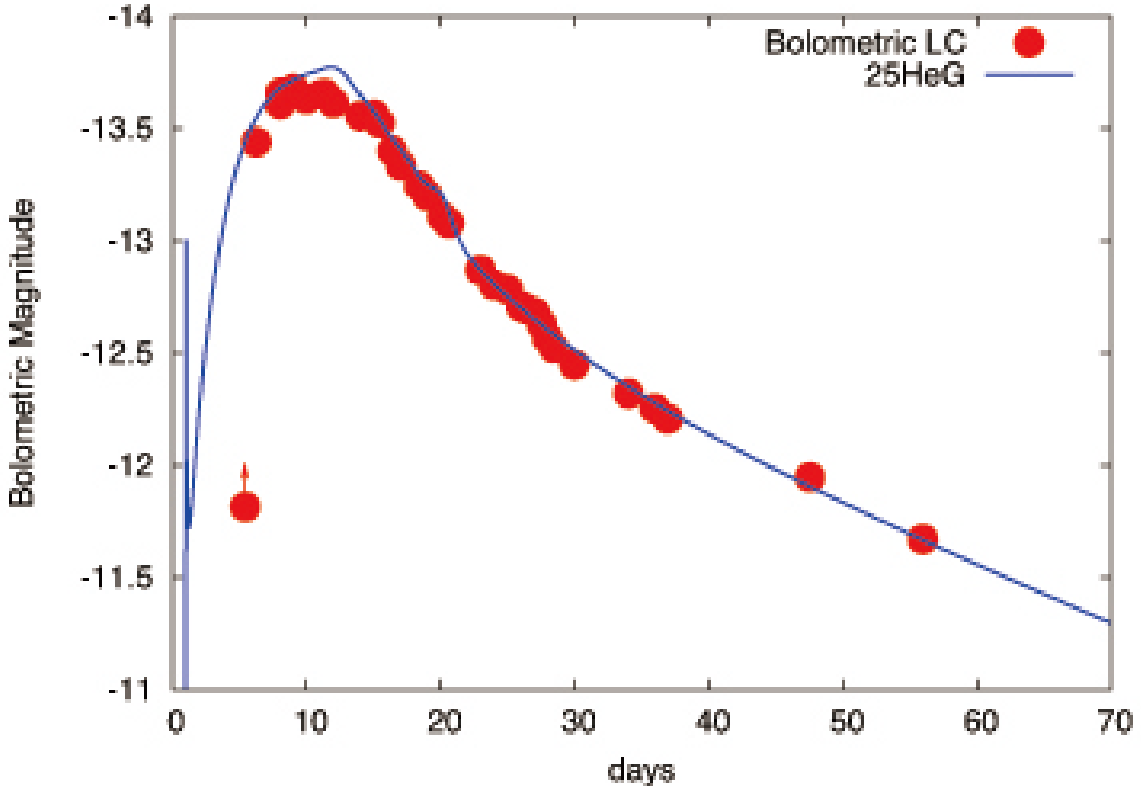
Mixing and Fallback



Moriya et al. 2009

Fallback models for SN 2008ha

- He star core-collapse model (25 $M_\odot$ → 7 $M_\odot$)



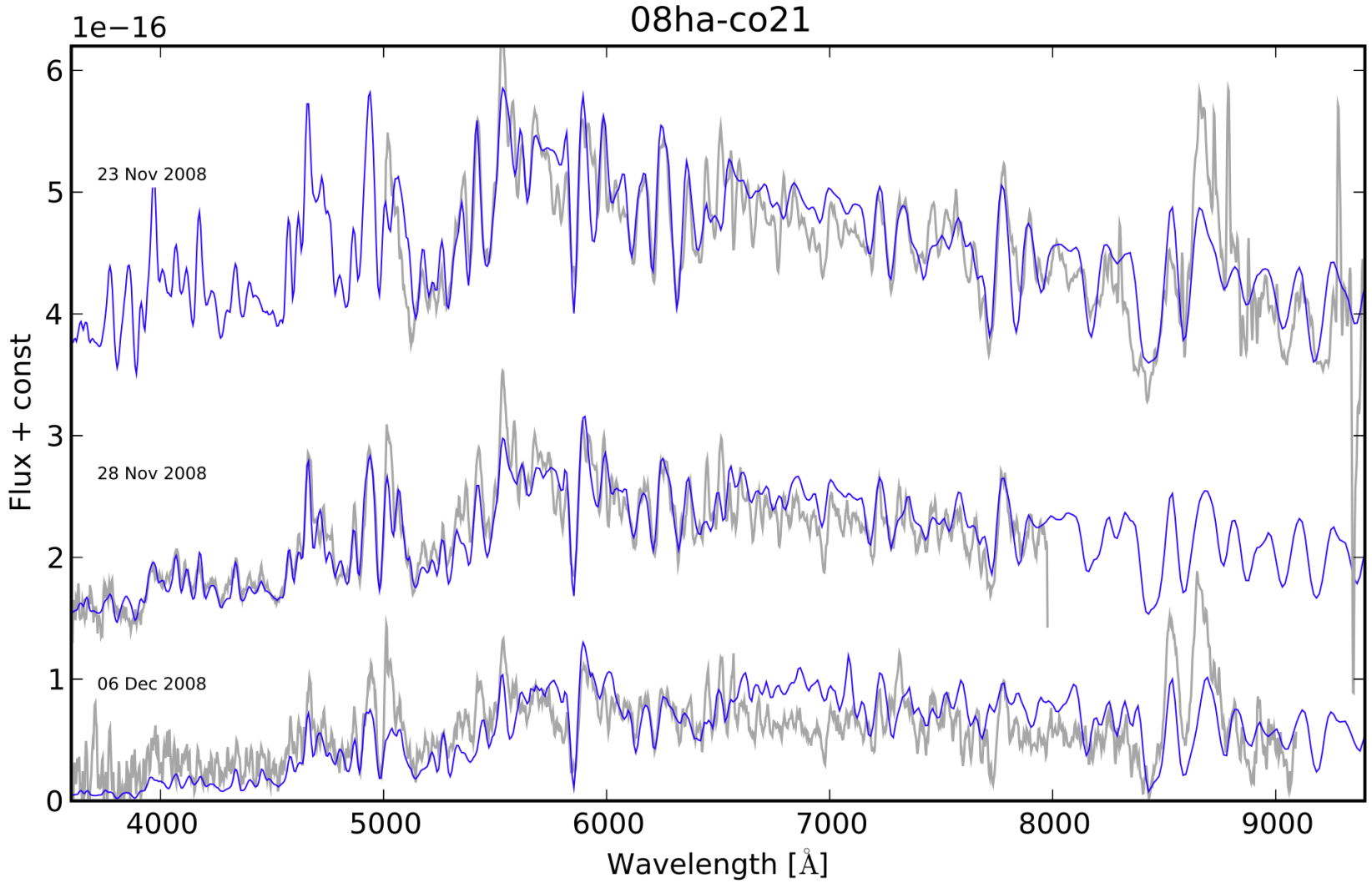
Moriya et al.

$$E_{\rm kin} = 1.0 \times 10^{48}\ {\rm erg} \quad M_{\rm ej} = 0.1\ M_\odot \quad M_{^{56}{\rm Ni}} = 0.003\ M_\odot$$

- CO star core-collapse model (13 $M_\odot$ → 2.7 $M_\odot$)

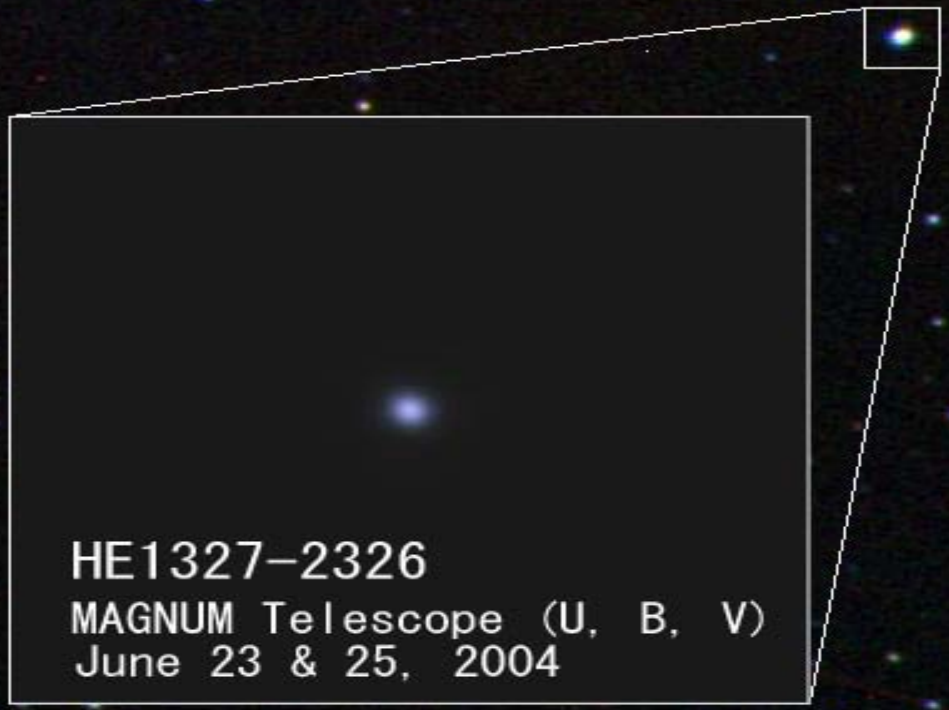
$$E_{\rm kin} = 1.4 \times 10^{48}\ {\rm erg} \quad M_{\rm ej} = 0.08\ M_\odot \quad M_{^{56}{\rm Ni}} = 0.003\ M_\odot$$

SN 2008ha: Synthetic Spectra



Sauer et al. 2009

Hyper Metal Poor Star



Frebel et al. (2005)

Faint Supernovae – EMP (extremely metal-poor) Stars

Fallback: small M(Ni)
large [CNO/Fe] ➔ CEMP

(1) Jet-like Energetic Explosion
Zn, Co enhanced

(2) Weak Explosion
Mixing & Fallback

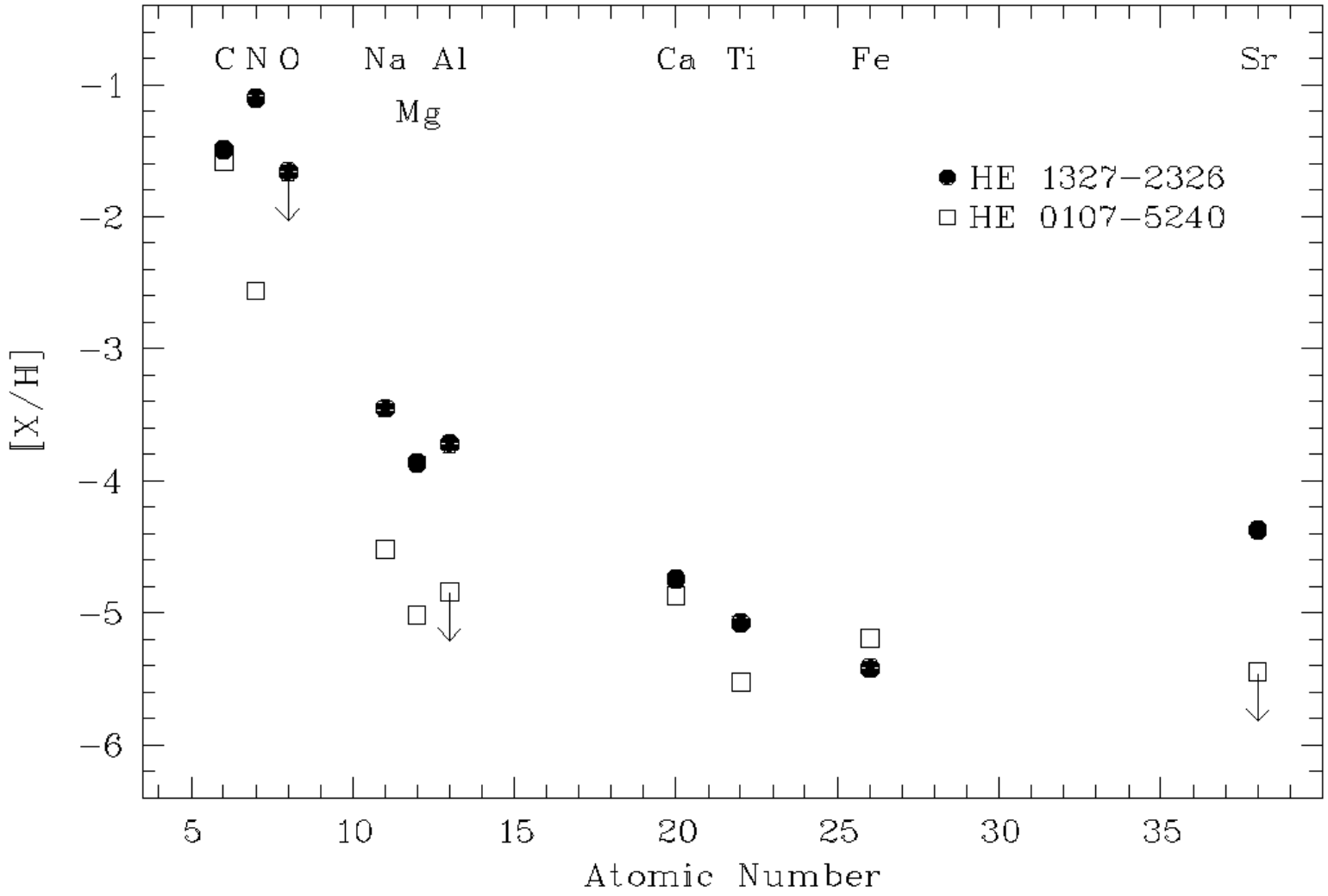
Metal Poor Stars

- 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; CEMP
- 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

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

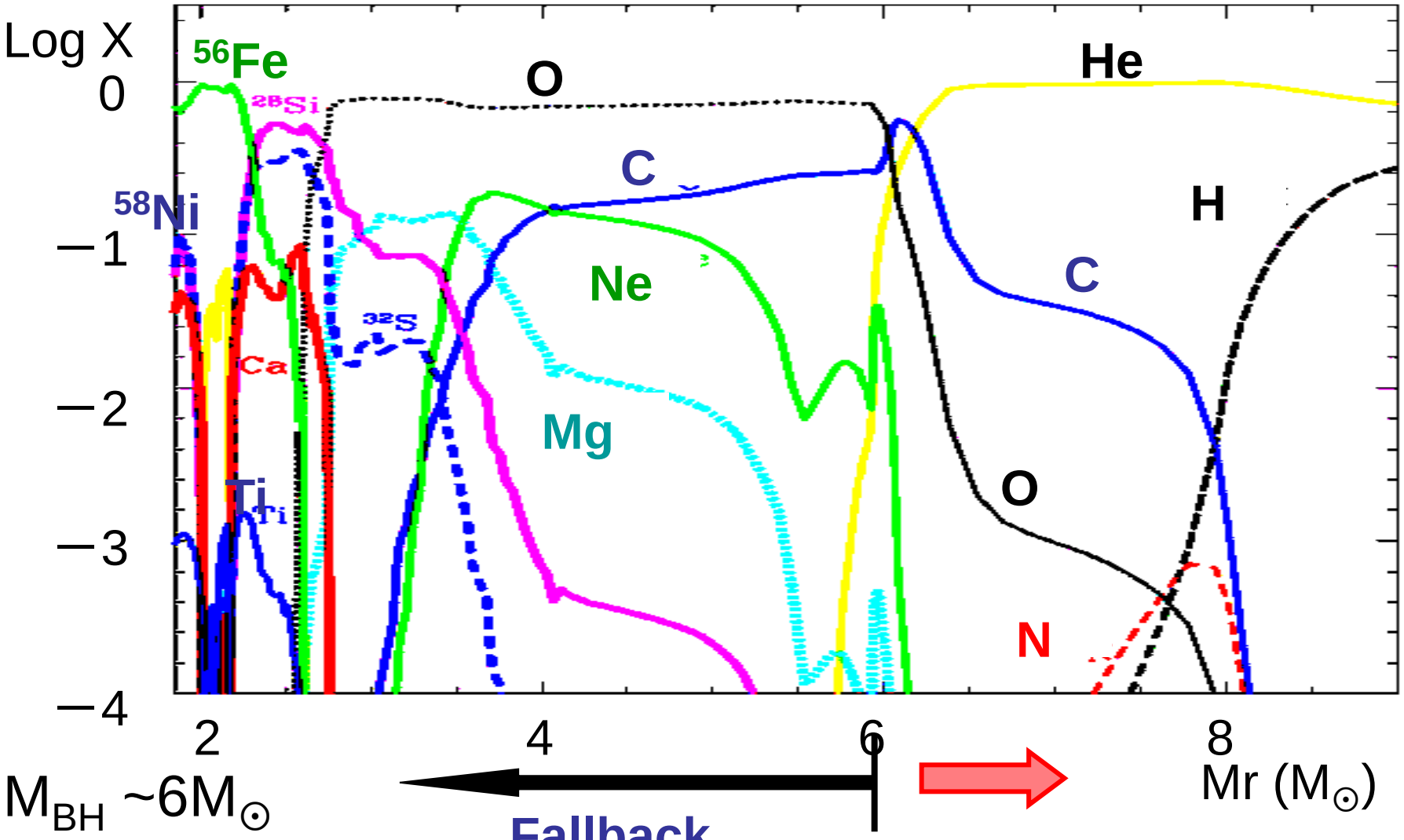
(Beers & Christlieb 2005)

Hyper Metal-Poor Stars



Frebel, Aoki, et al.

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



M_{BH} ~$6M_\odot$

Fallback

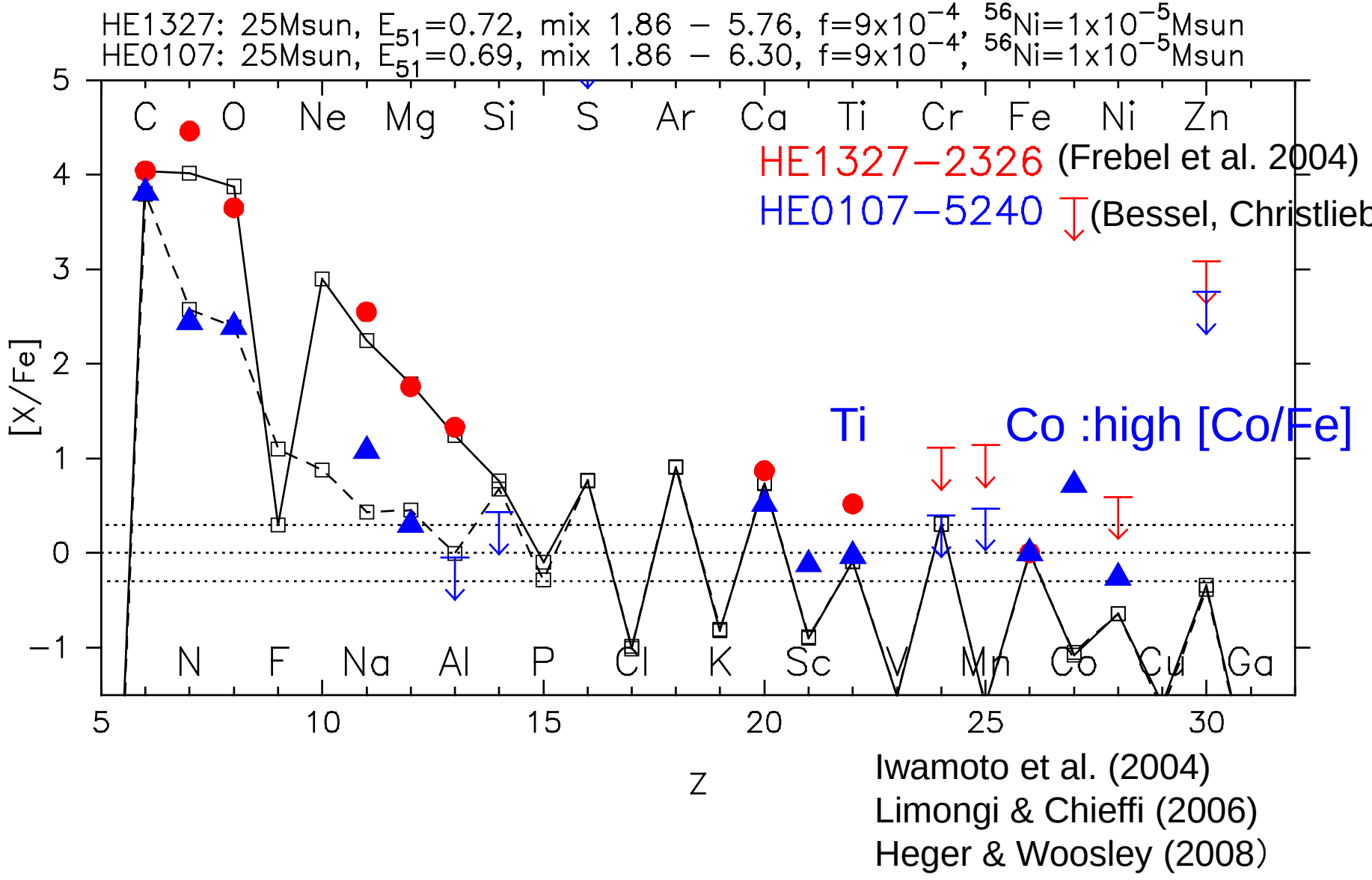
Mixing

Ejecta (little Fe)

Umeda & Nomoto (2003)

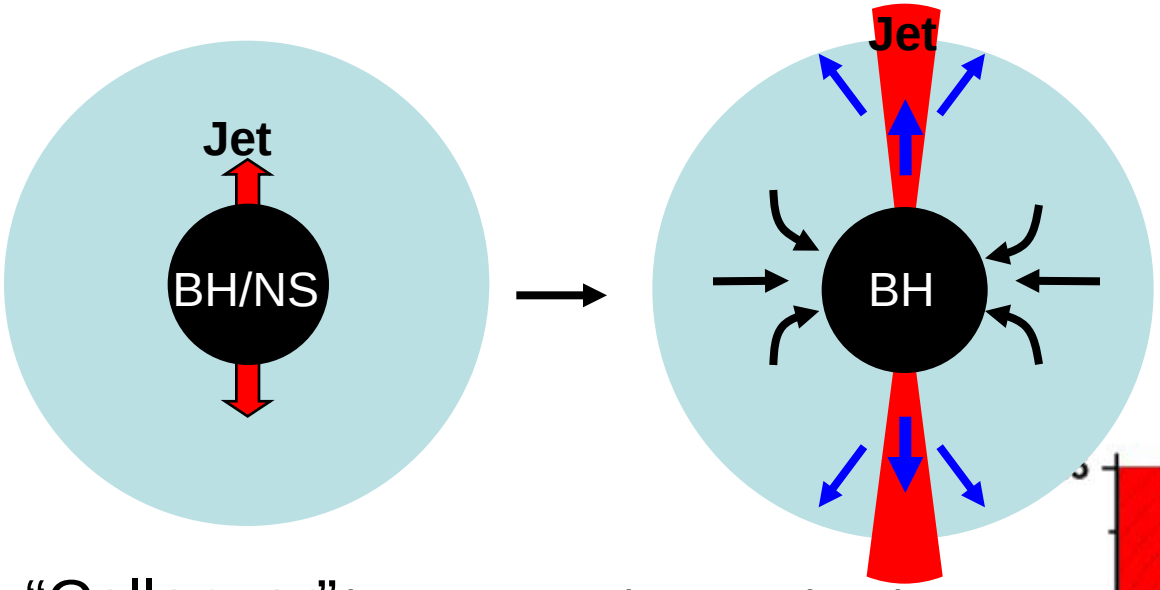
HMP stars: 1D Low E models (E_{51}< 1)

mixing & fallback ➔ low [Co/Fe]



Iwamoto et al. (2004)
Limongi & Chieffi (2006)
Heger & Woosley (2008)

Jet-induced Nucleosynthesis



Special relativistic hydrodynamics (Tominaga et al. ApJL 2007)

cf. "Collapsar"(e.g., MacFadyen et al. 01)

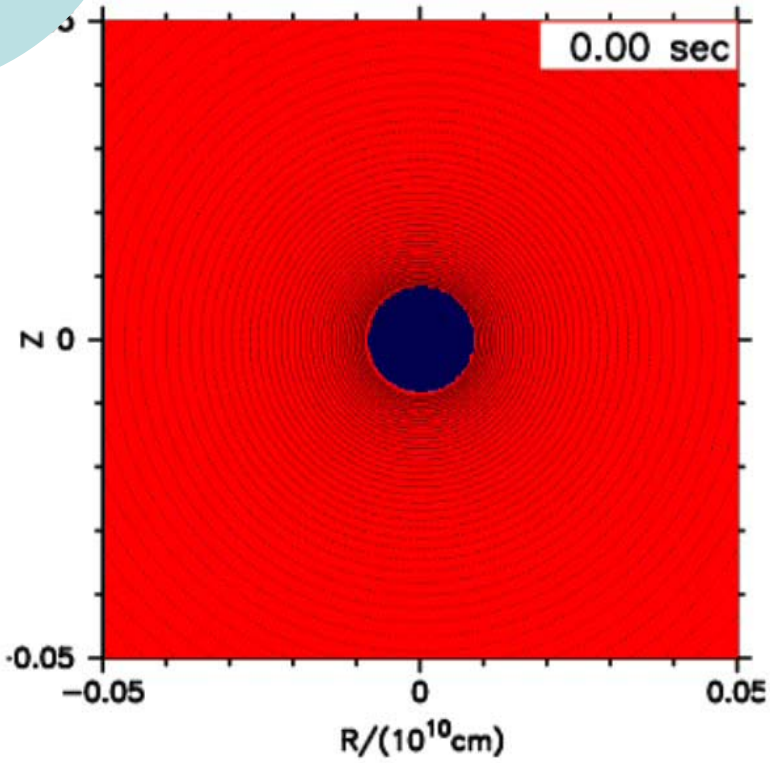
Magnetorotational Supernovae

(e.g., Moiseenko et al. 06)

$\dot{E}_{\rm dep}$:
Energy deposition rate
(Rotation, ***B*** etc.)

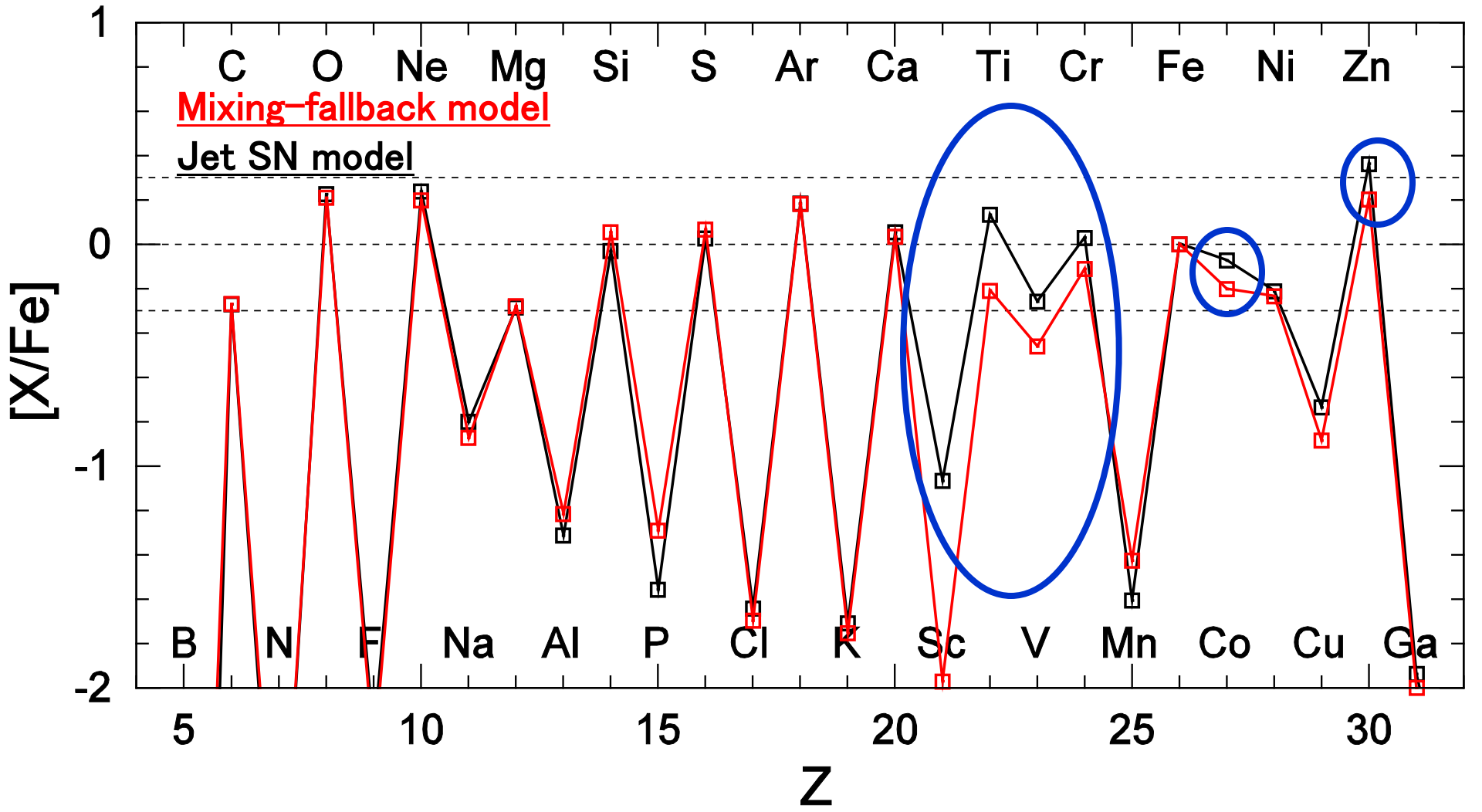
Same mass and explosion energy

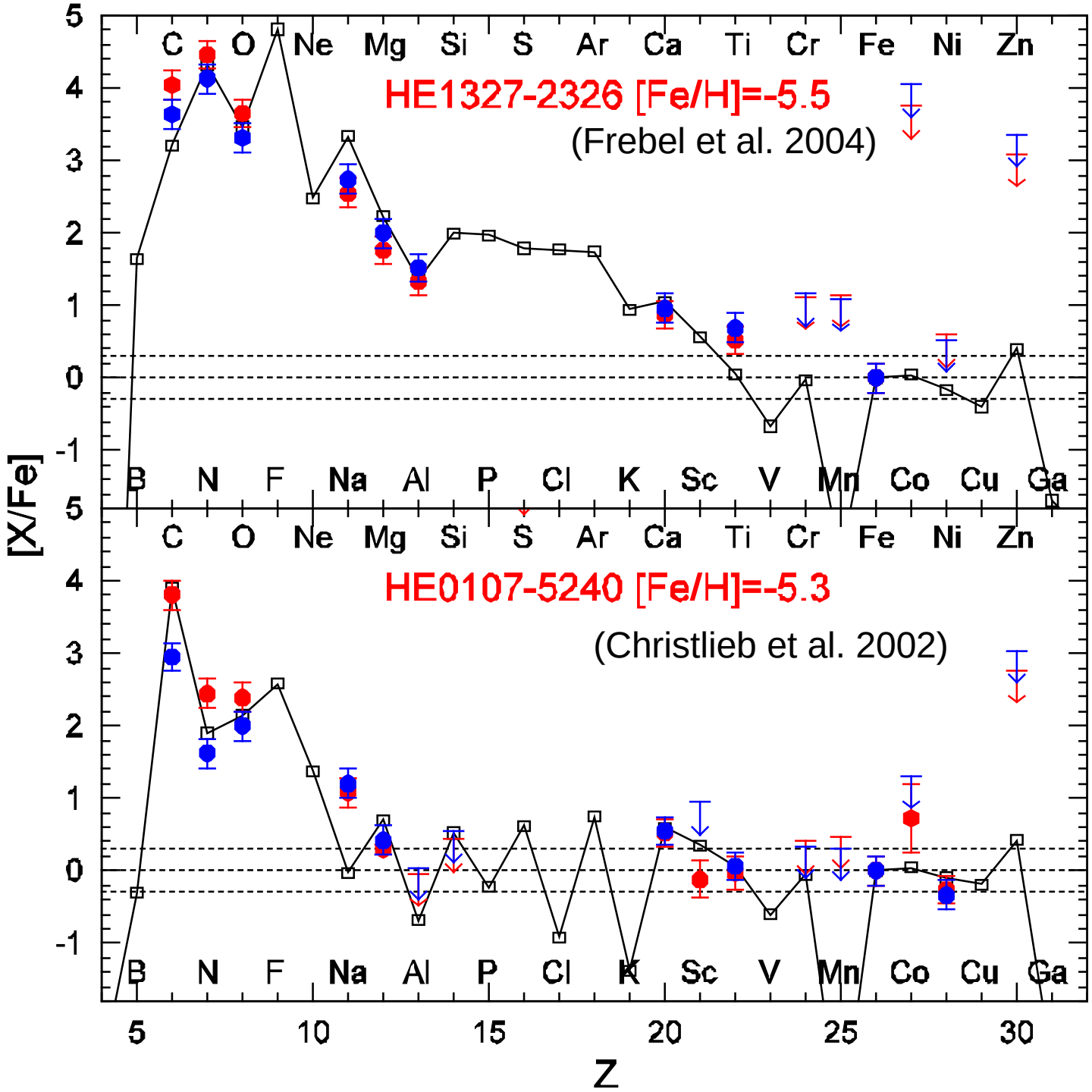
$40M_\odot$ 1.5×10^{52}erg



Mixing-fallback vs. Jet SN model

High entropy due to the energy concentration.





HMP Stars

Jet-induced SN models

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

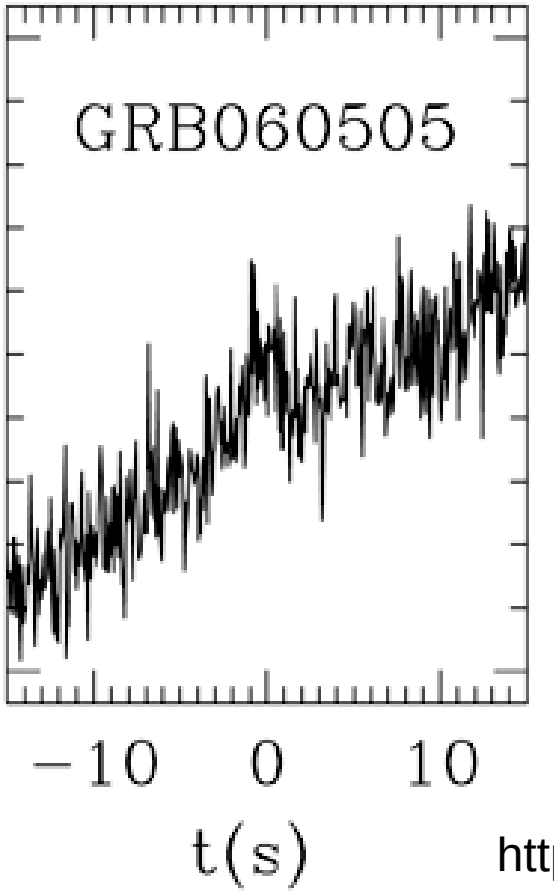
Dark Hypernova

Tominaga et al. 2007

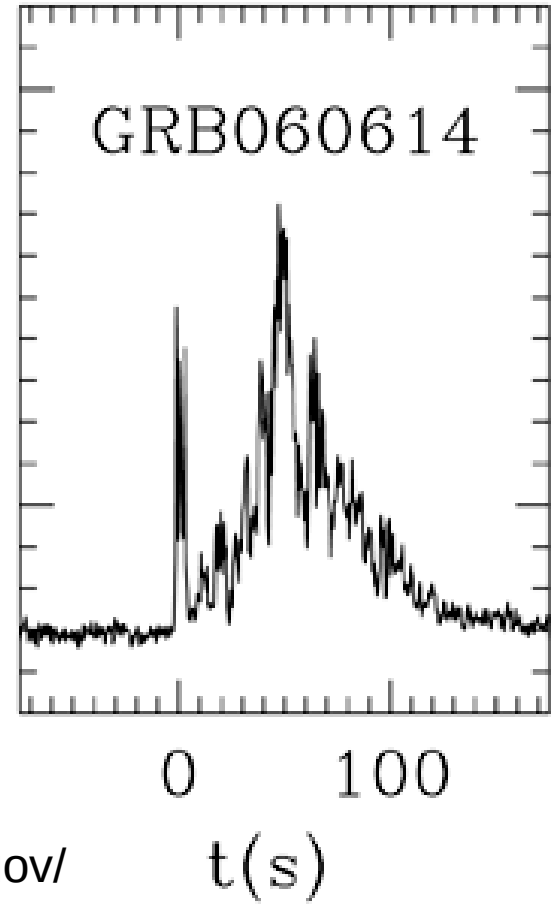
(2) No-SN GRBs

Della Valle et al. 06, Gal-Yam et al. 06,
Fynbo et al. 06, Gehrels et al. 06

GRB 060505 at z=0.089



GRB 060614 at z=0.125



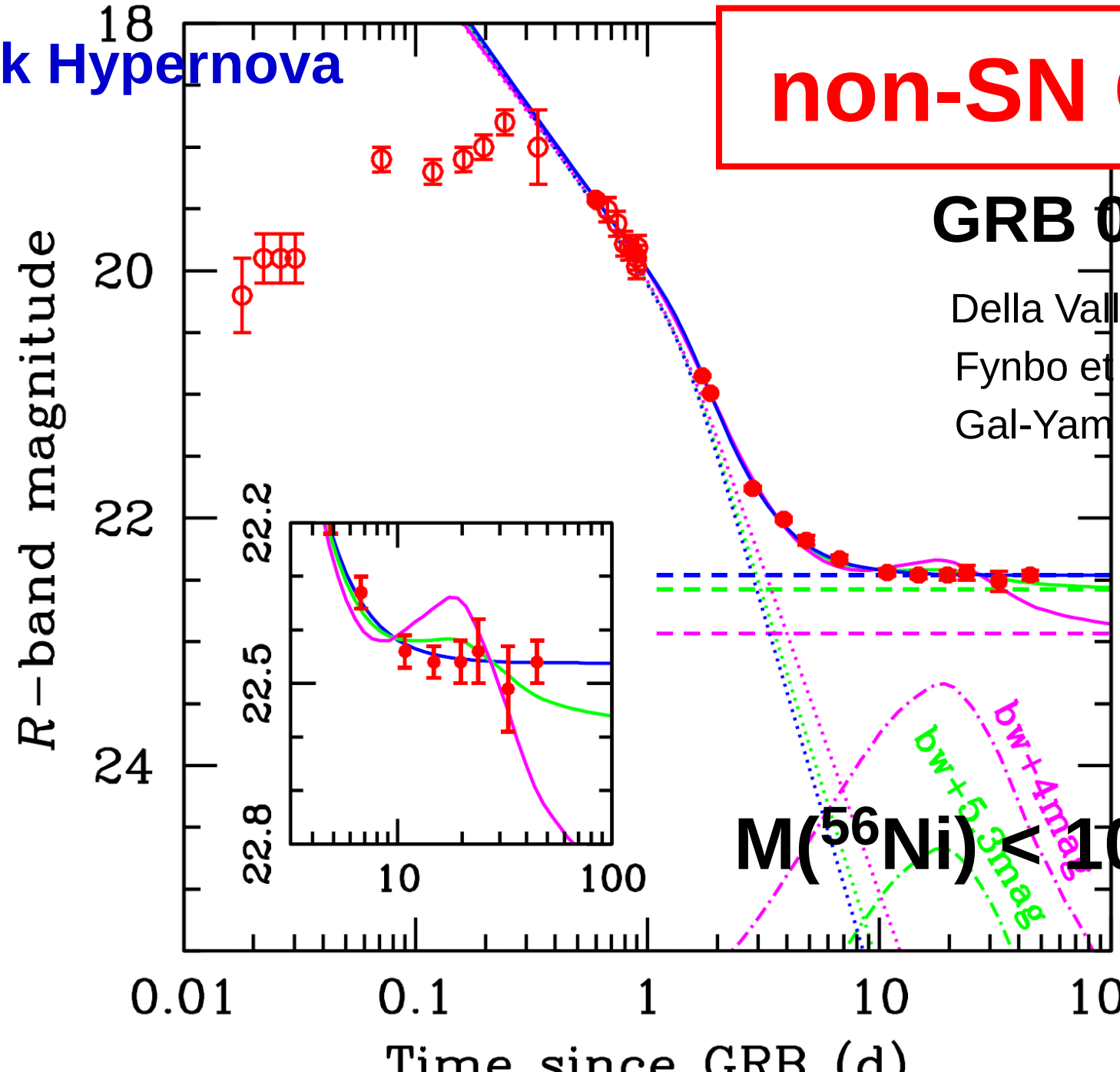
http://swift.gsfc.nasa.gov/

Dark Hypernova

non-SN GRB

GRB 060614

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

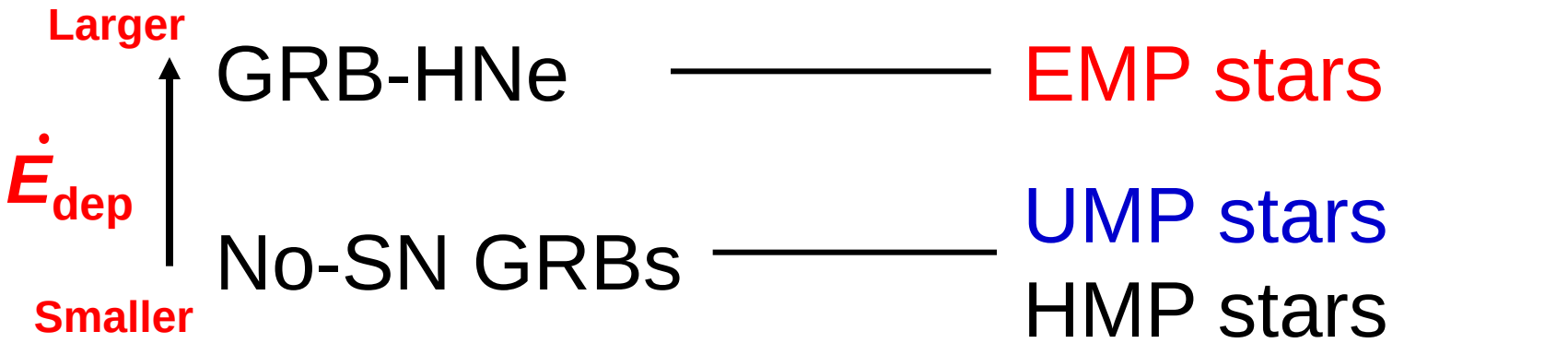


$M(^{56}Ni) < 10^{-3}$ Ms

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

Hypernovae with relativistic jets

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



8 – 10 $M_\odot$ Stars

Super AGB Stars (1.07 $M_\odot < M_{core} < M_{Ch}$)

degenerate ONeMg core

- 8 $M_\odot < M < M_{up}$

  ONeMg White Dwarfs

  $M_{up} \sim 9\ M_\odot$ (Z)

- $M_{up} < M < 10\ M_\odot$ ($M_{core} \sim M_{Ch}$)

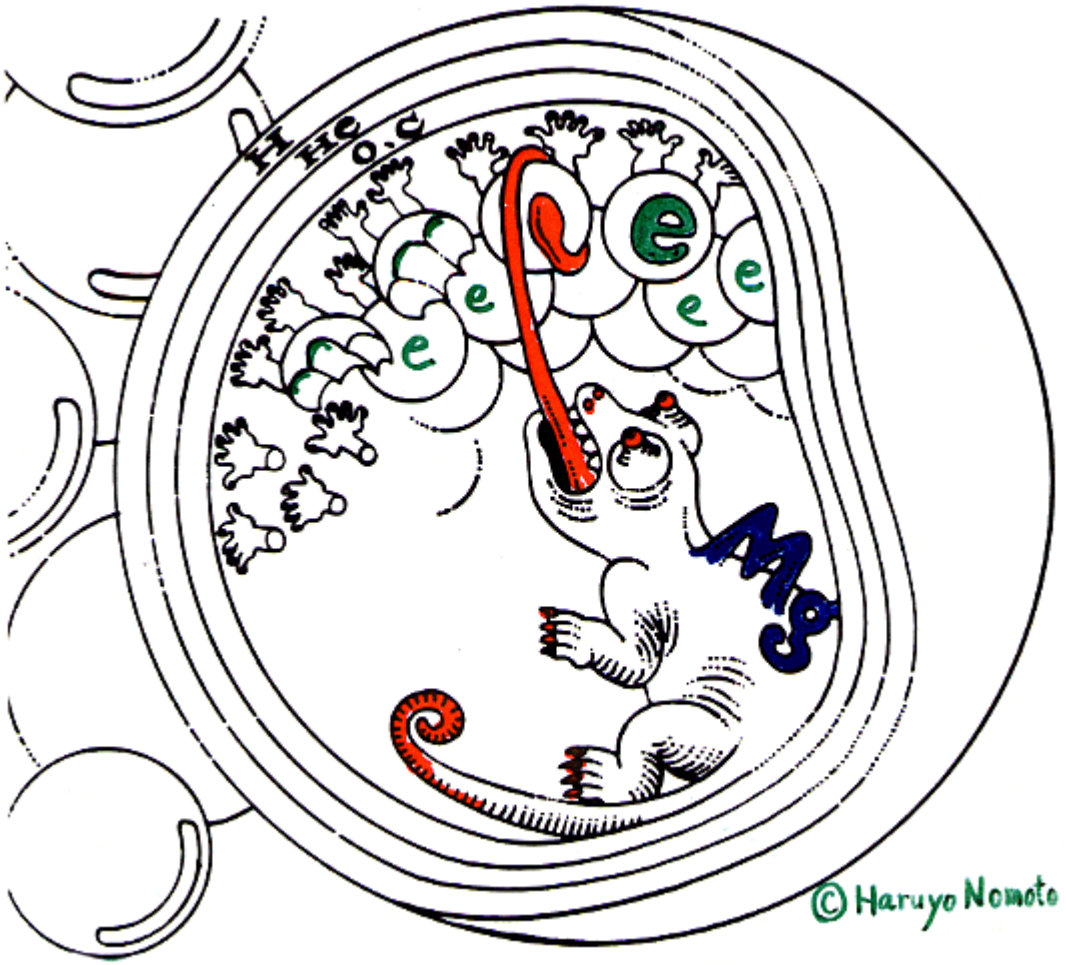
  ONeMg Core Collapse SNe II

  due to Electron Capture

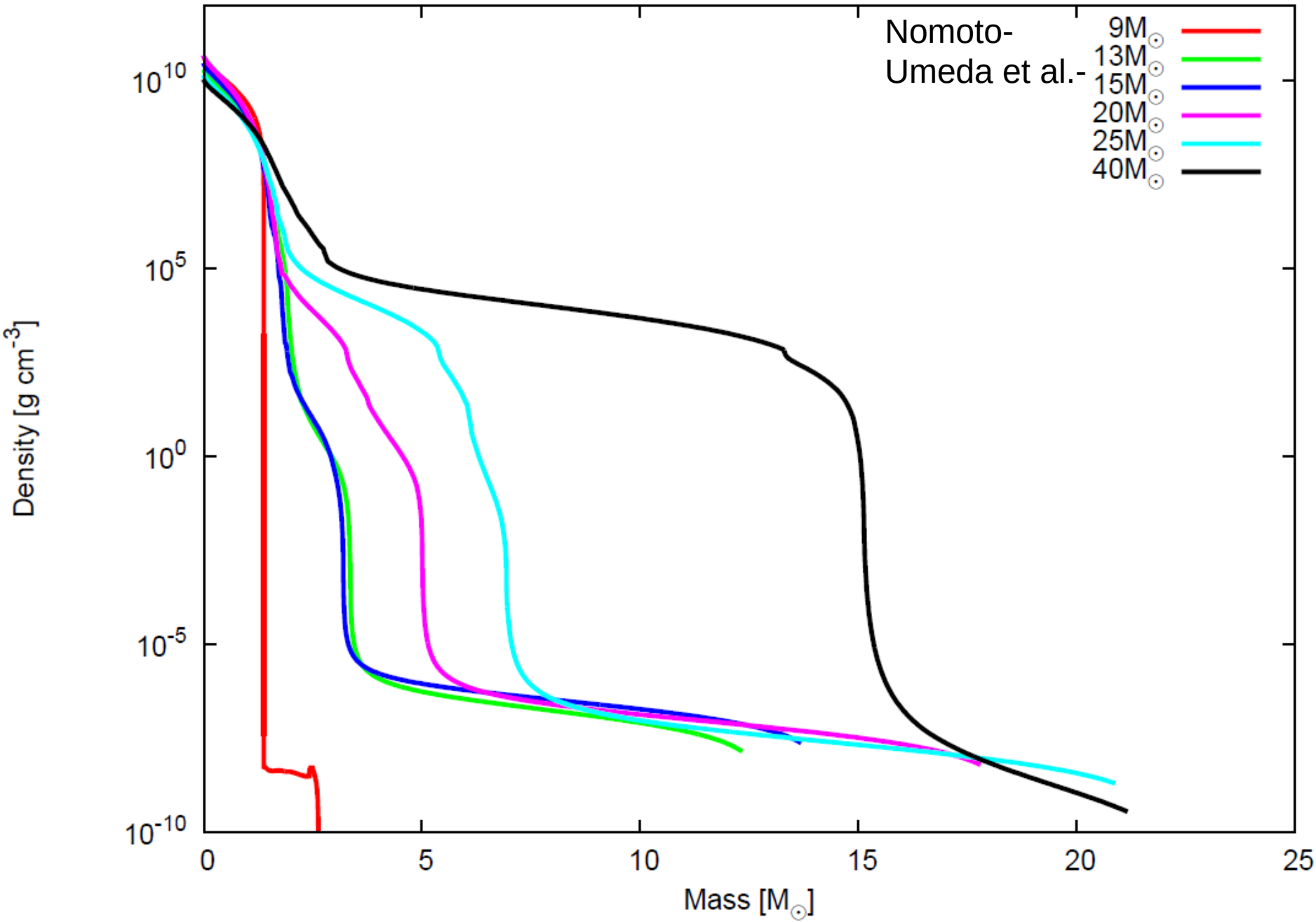
Nomoto 1984

Electron Capture in ONeMg Core

- $^{24}Mg(e^-,\nu)^{24}Na(e^-,\nu)^{24}Ne$
- $\rho > 4.0 \times 10^9 gcm^{-3}$
- $\rightarrow$collapse



Presupernova Density Structure

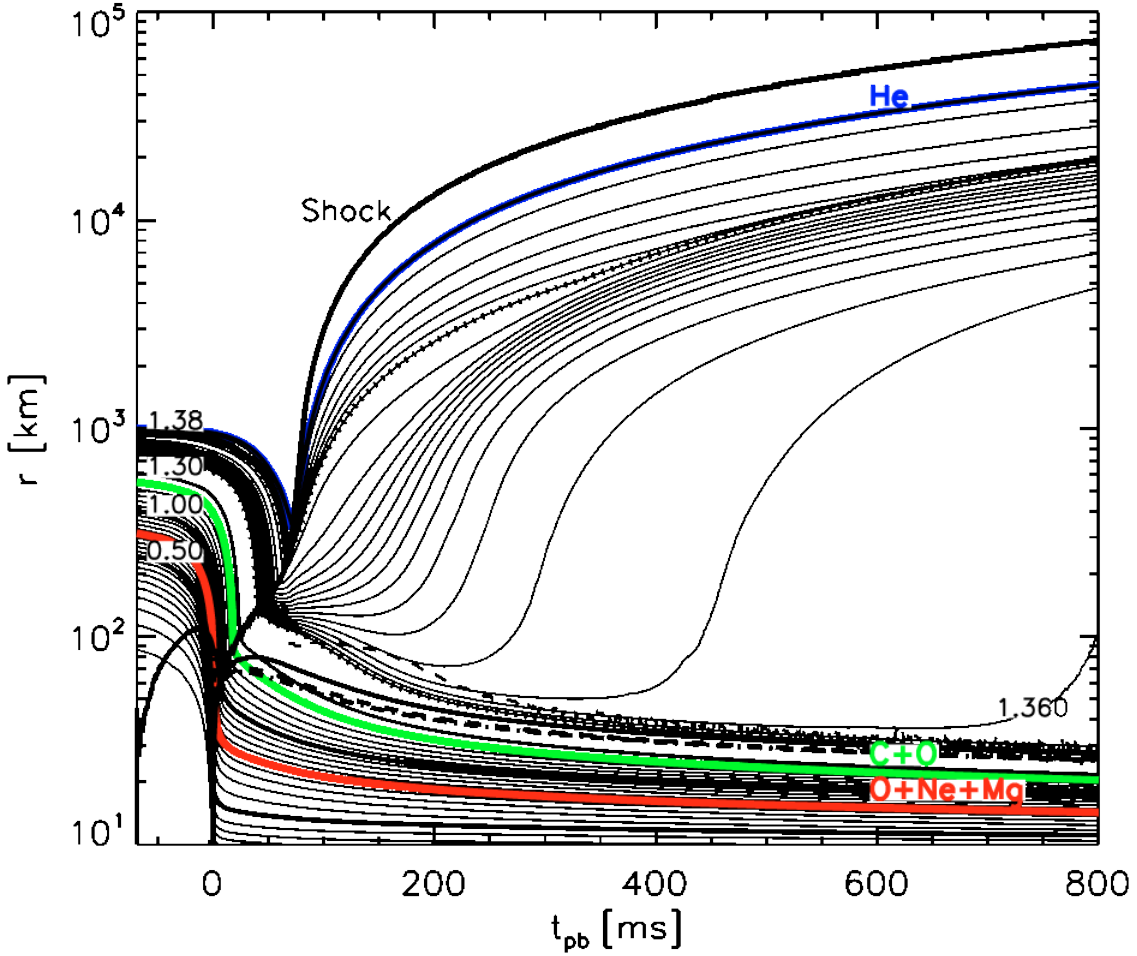


$9M_\odot$ Star
Neutrino Heating → Weak Explosion

Steep Density Gradient

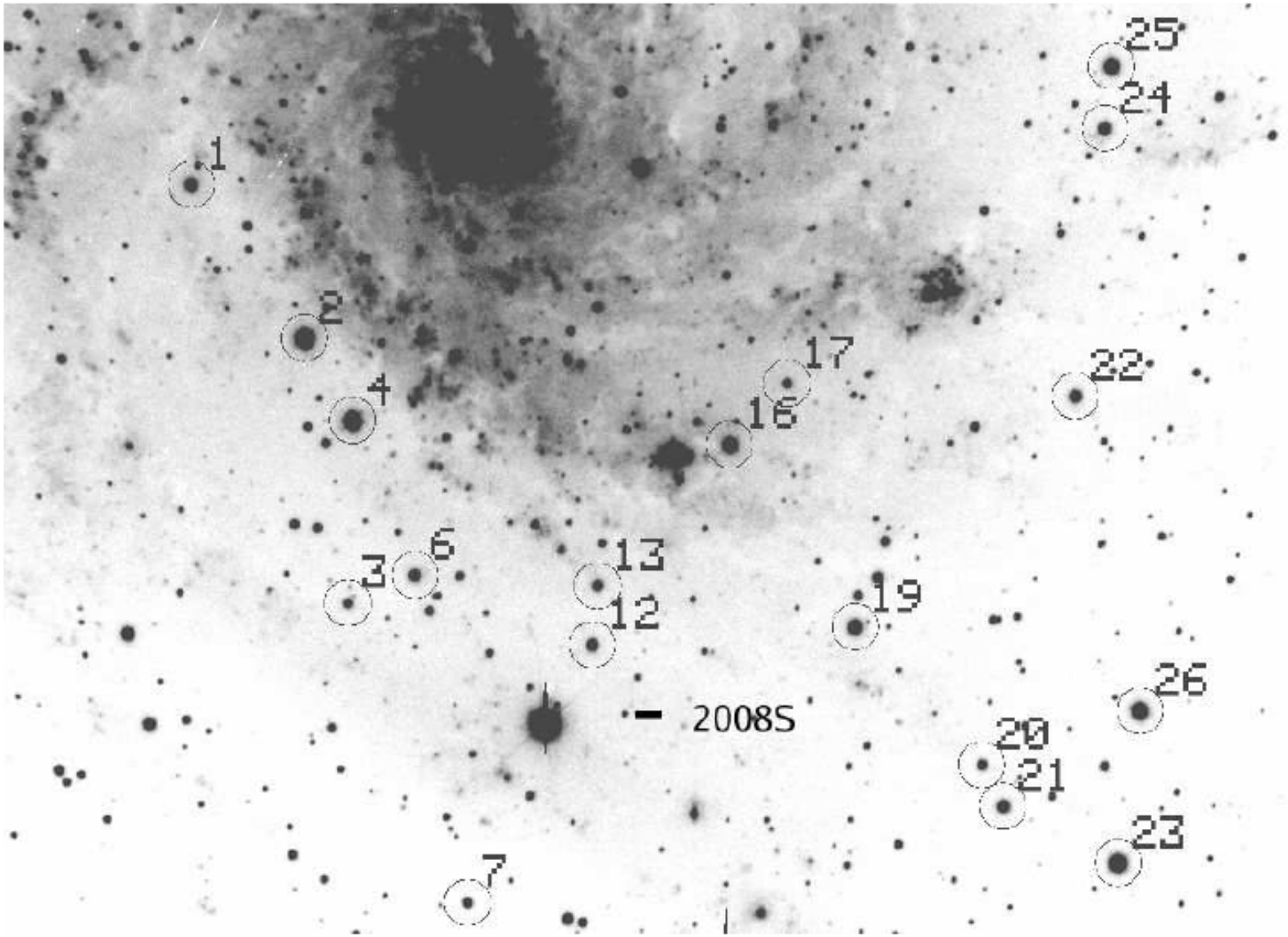
→ $E_{exp} = 1 \times 10^{50}$ erg

$M_{ej} \sim 0.002 M_\odot$



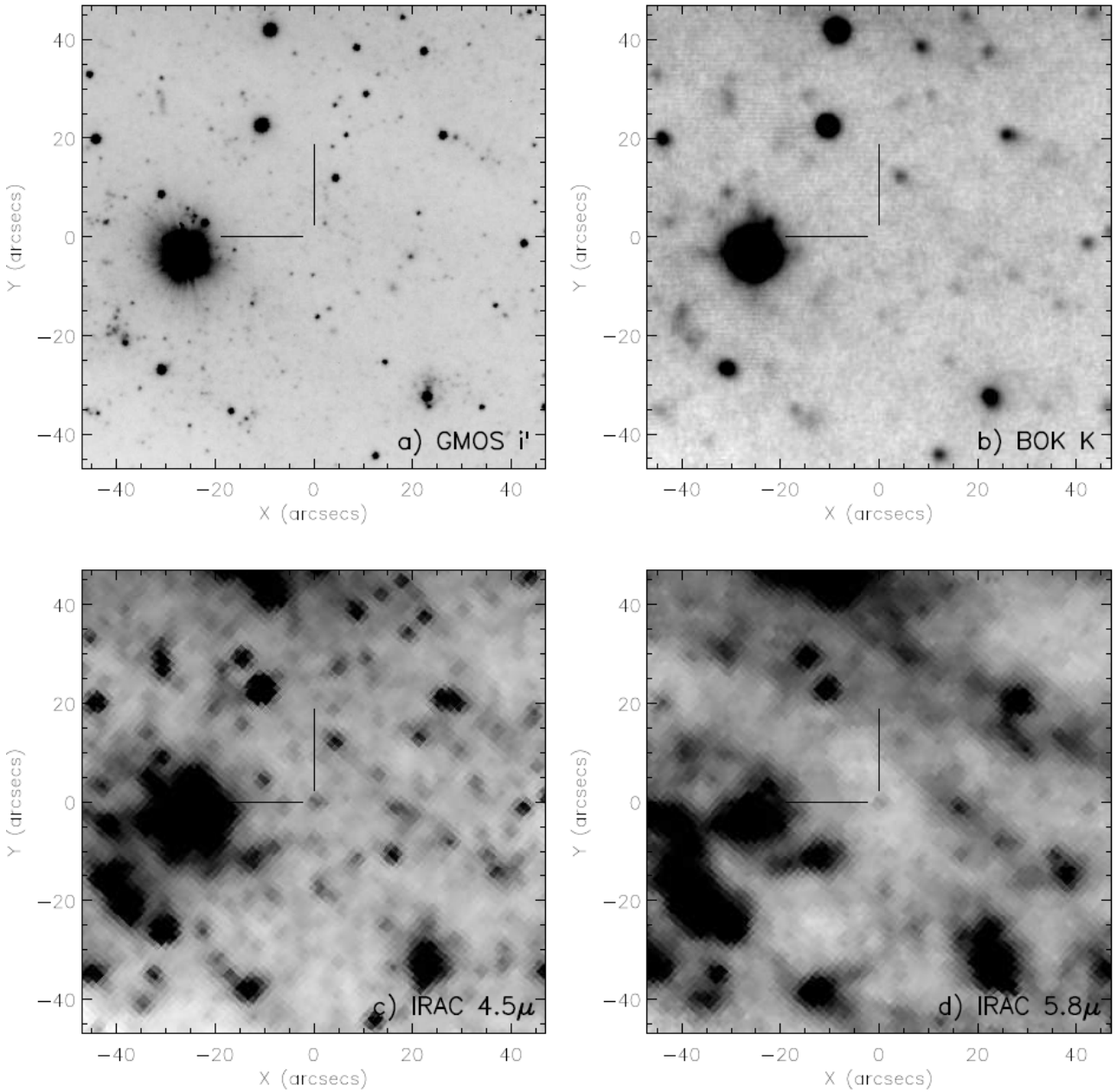
Kitaura, Janka, & Hillebrandt (2006)

SN 2008S



Botticella et al. 2009

Progenitor of SN 2008S



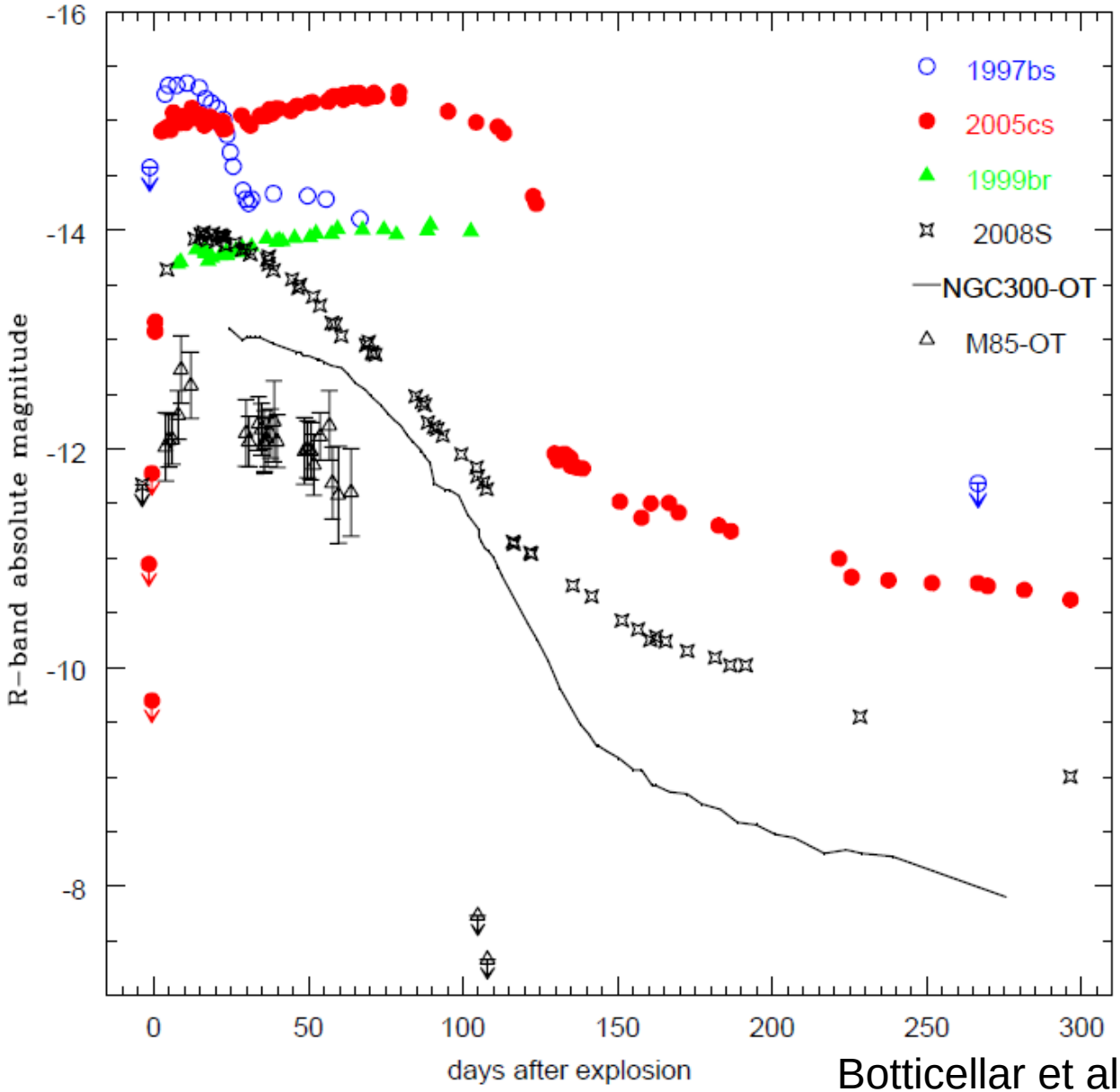
No detection in NIR
a) GMOS /Gemini
b) Bok K

Detection in MIR
Spitzer/IRAC
c) 4.5 micron
d) 5.8 micron

Dust-enshrouded progenitor

Botticella et al. 2009
Prieto et al. 2008, 09

Faint SNe IIn: SN 2008S, NGC300-OT



(Della Valle et al. 08;
Pastorelle 08;
Botticella et al. 09)

Progenitor =
Super AGB star ?

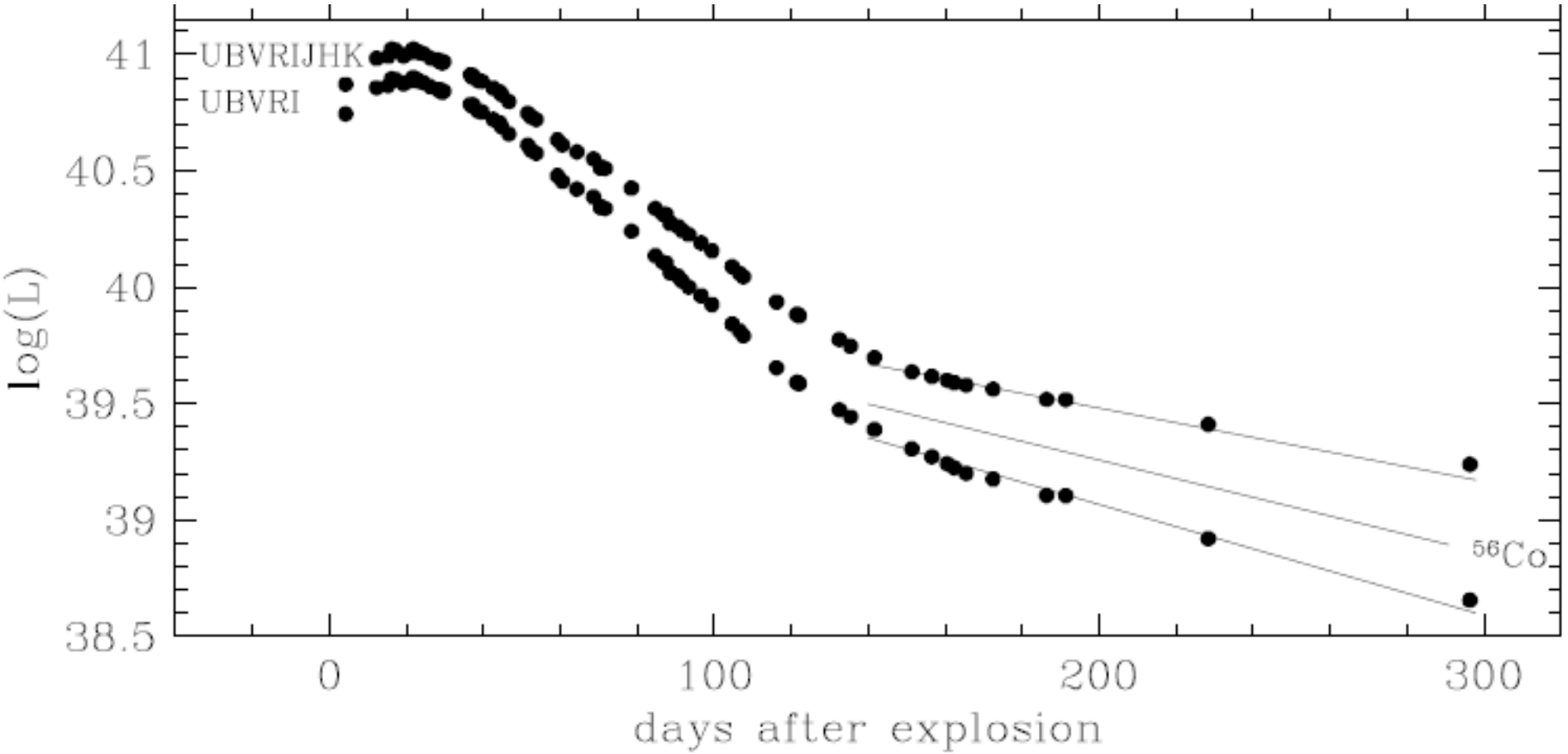
(Prieto et al. 08,09
Thompson et al. 08)

SN Impostor ?

(Smith et al. 09
Bond et al. 09
Berger et al. 09)

Botticellar et al. 2009

SN 2008S



Botticella et al. 2009

Faint Supernovae

SN 2008ha ~ Core collapse - Fallback SN ?

~ SNe 2002cx, 2005hk-like ?

narrow line feature

~ SNe 2005E, 2005cz-like ?

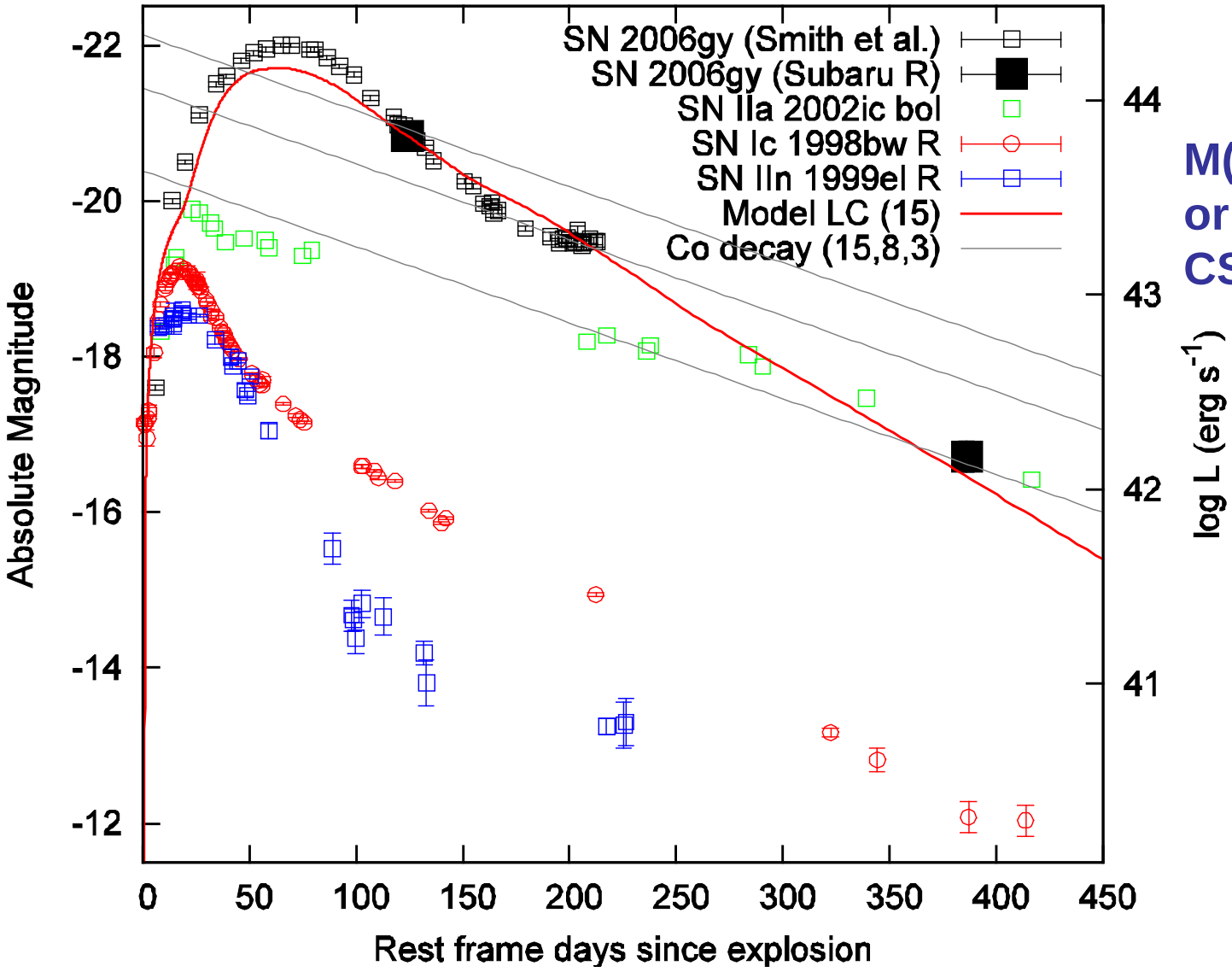
large [Ca/O]

SN 2008S-like ?

Thermonuclear, Core Collapse, or Impostor ?

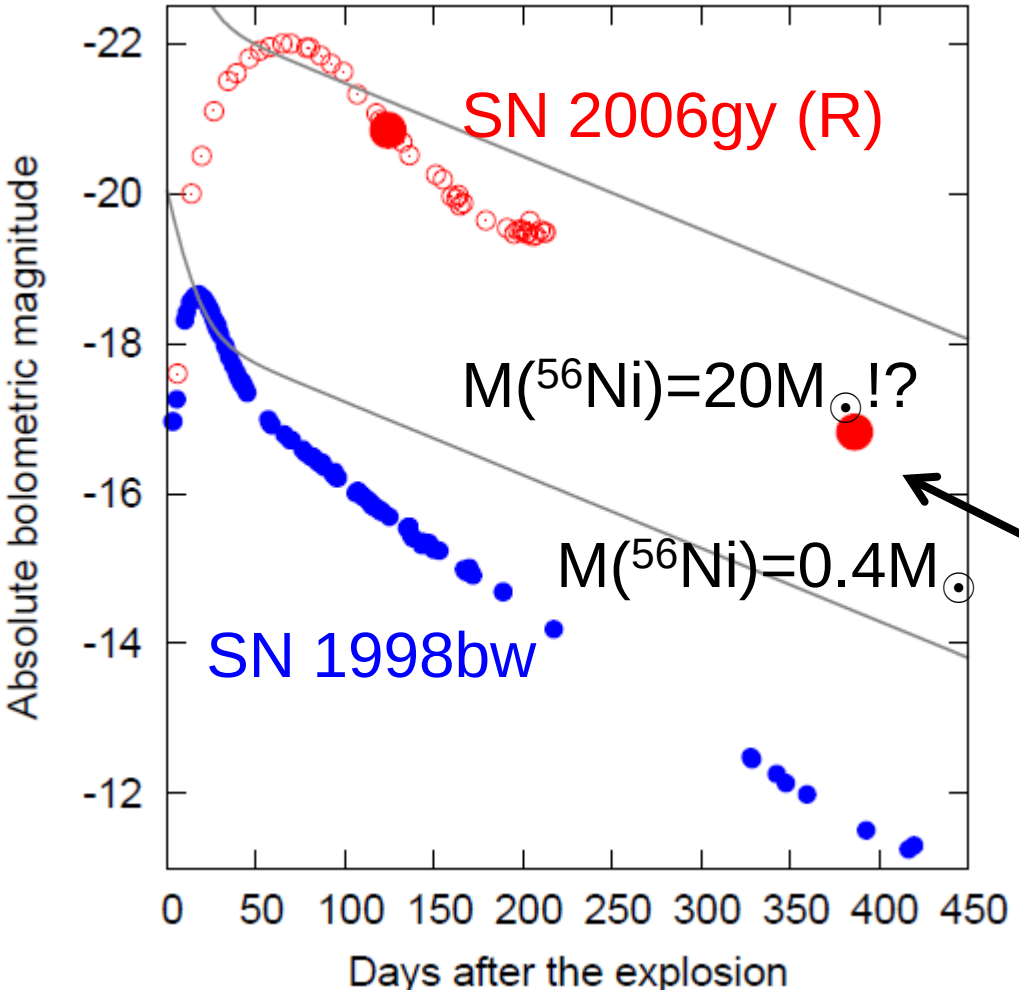
EMP star-connection [Ca/O, O/Fe] ?

Most Luminous Supernova 2006gy

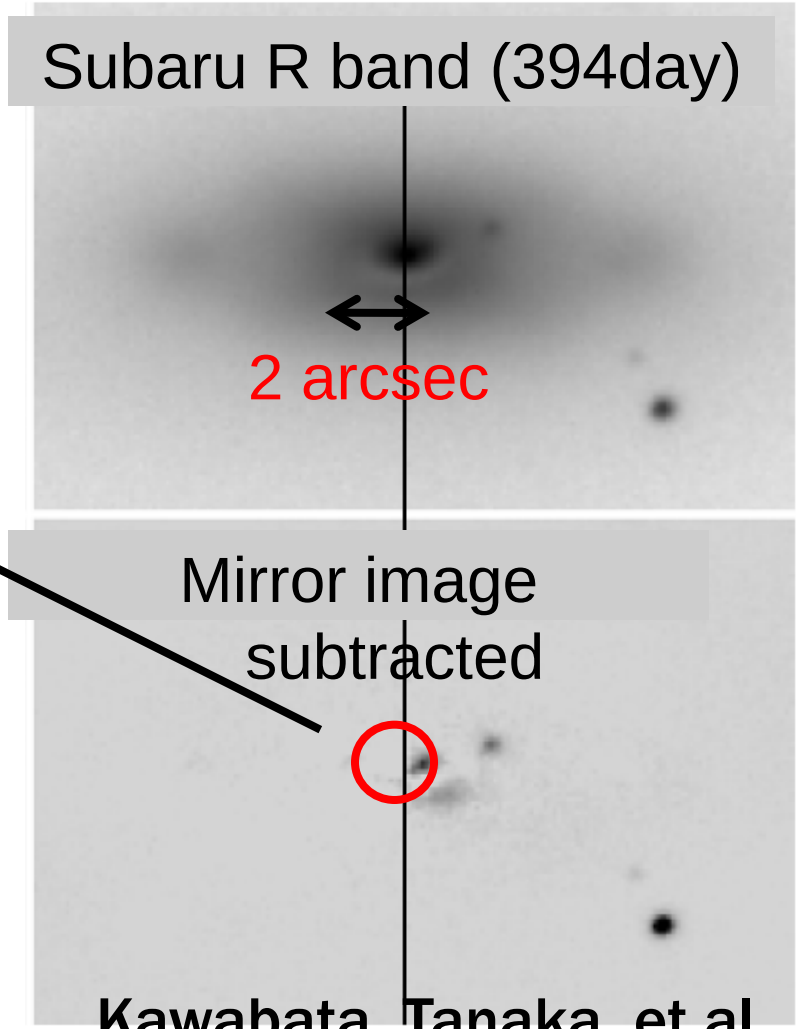


M(^{56}Ni)~15M$_\odot$
or
CSM interaction

SN 2006gy



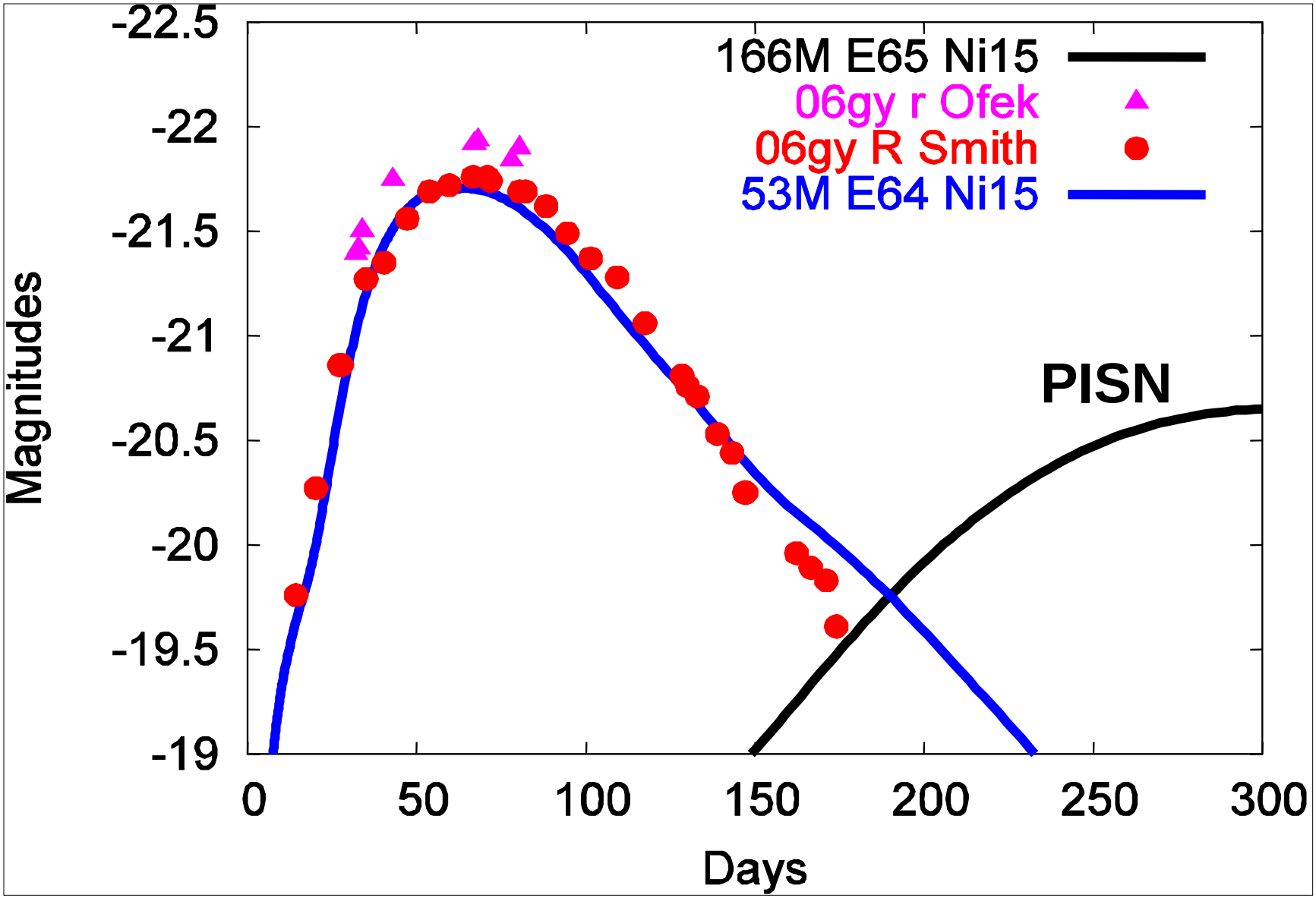
Also Agnoletto et al. (08)



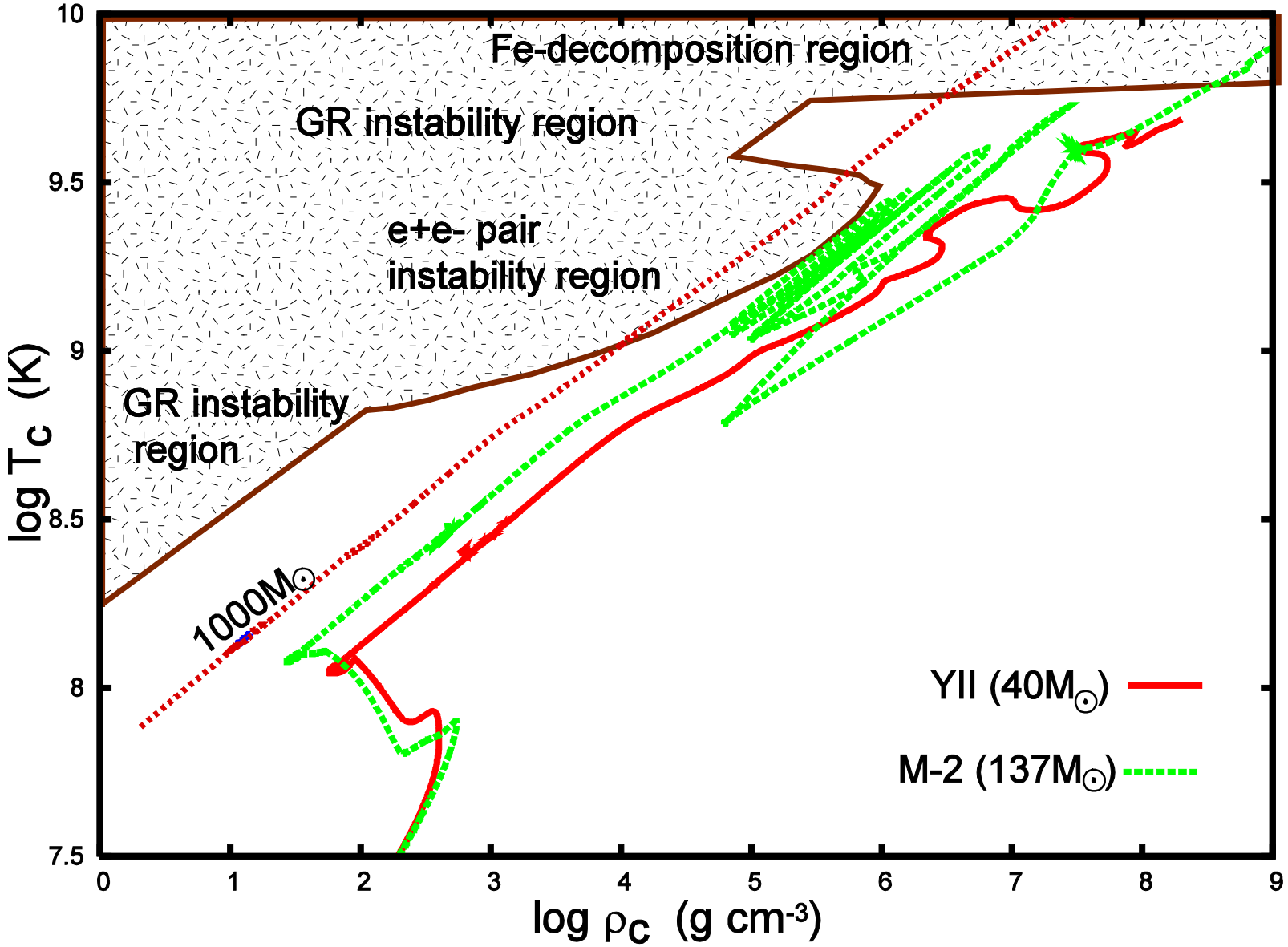
Kawabata, Tanaka, et al.

(ApJ 2009)

SN2006gy vs PISN

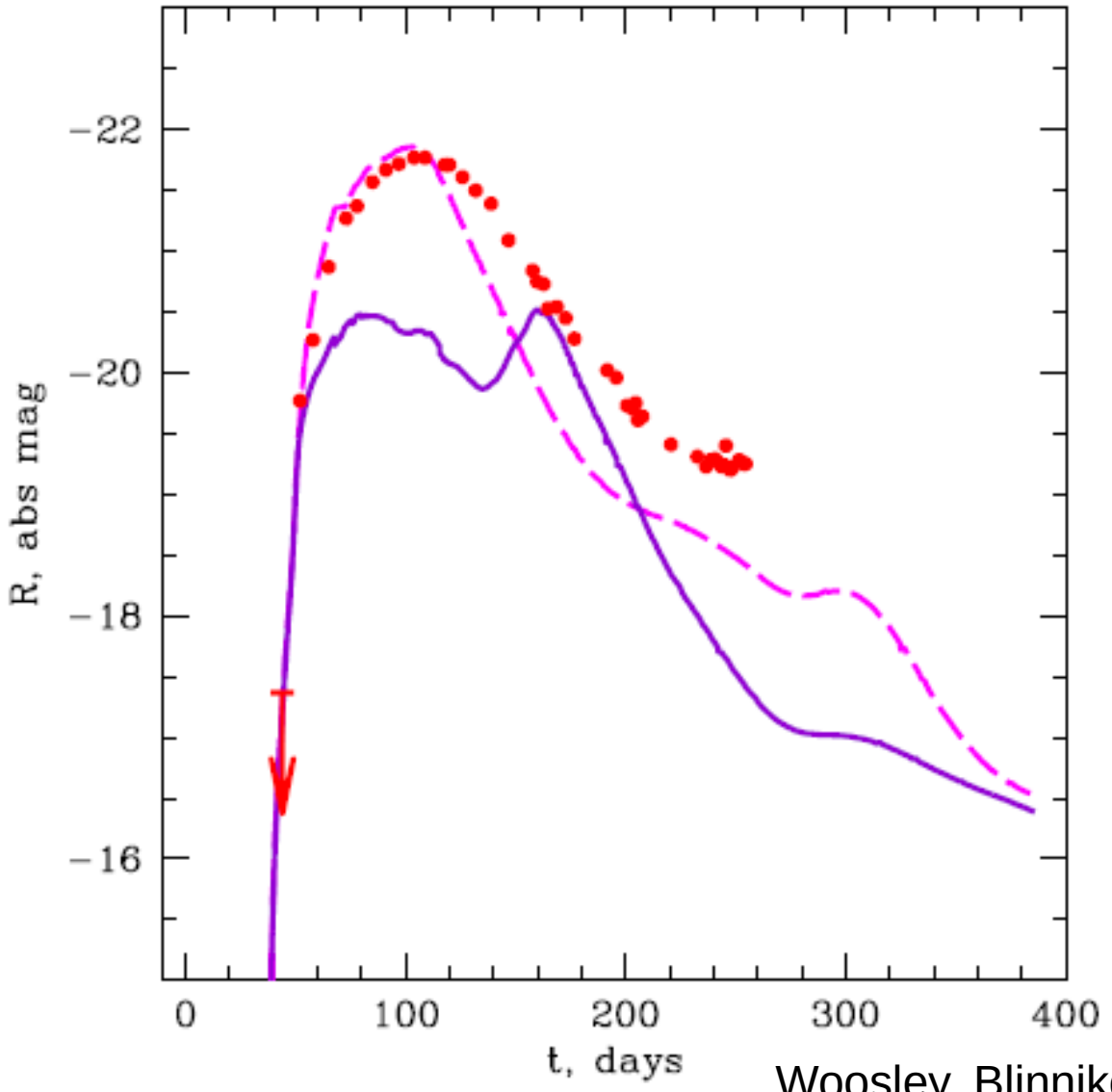


Nuclear Instability (O, Si- burning)



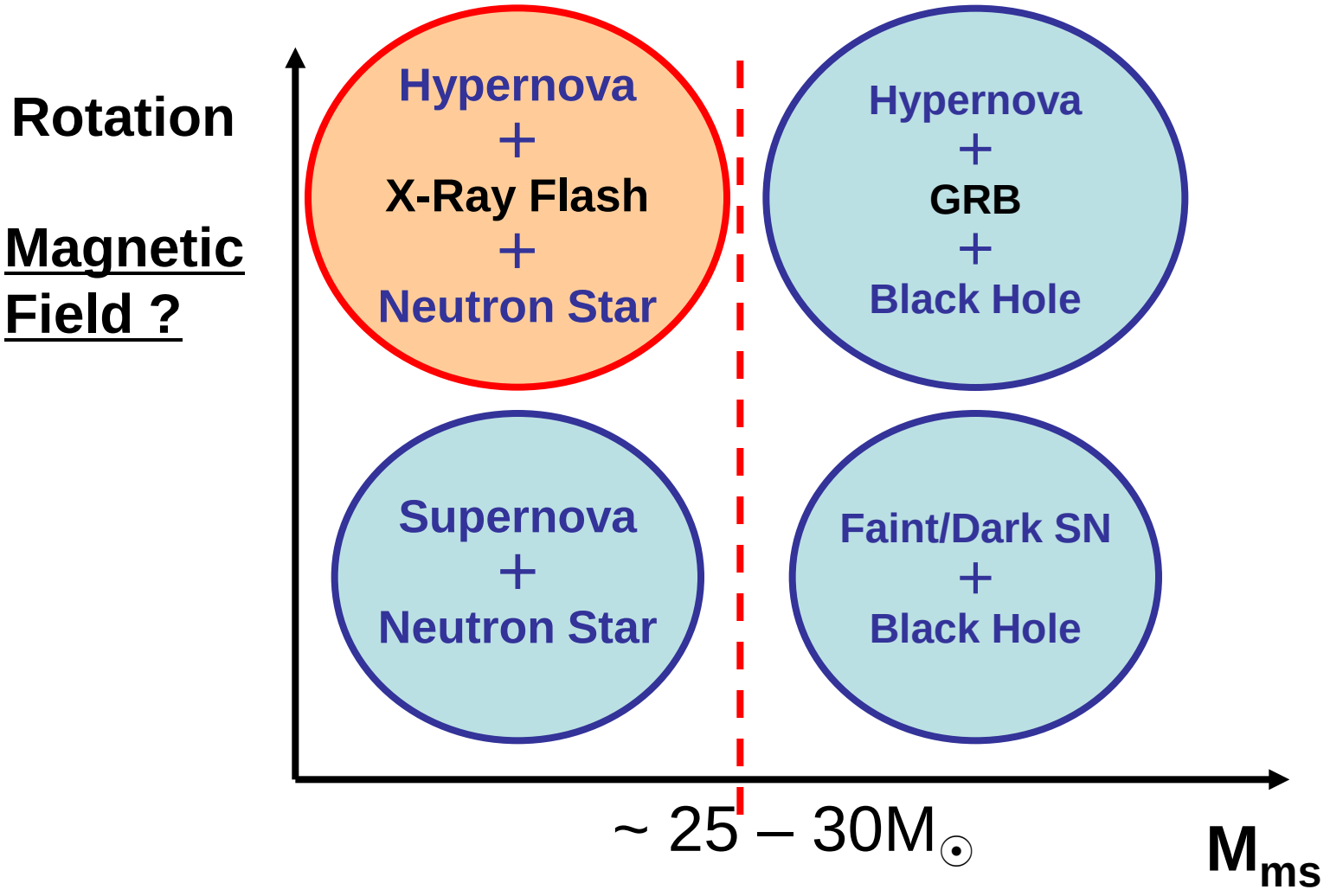
Ohkubo, Nomoto, et al.

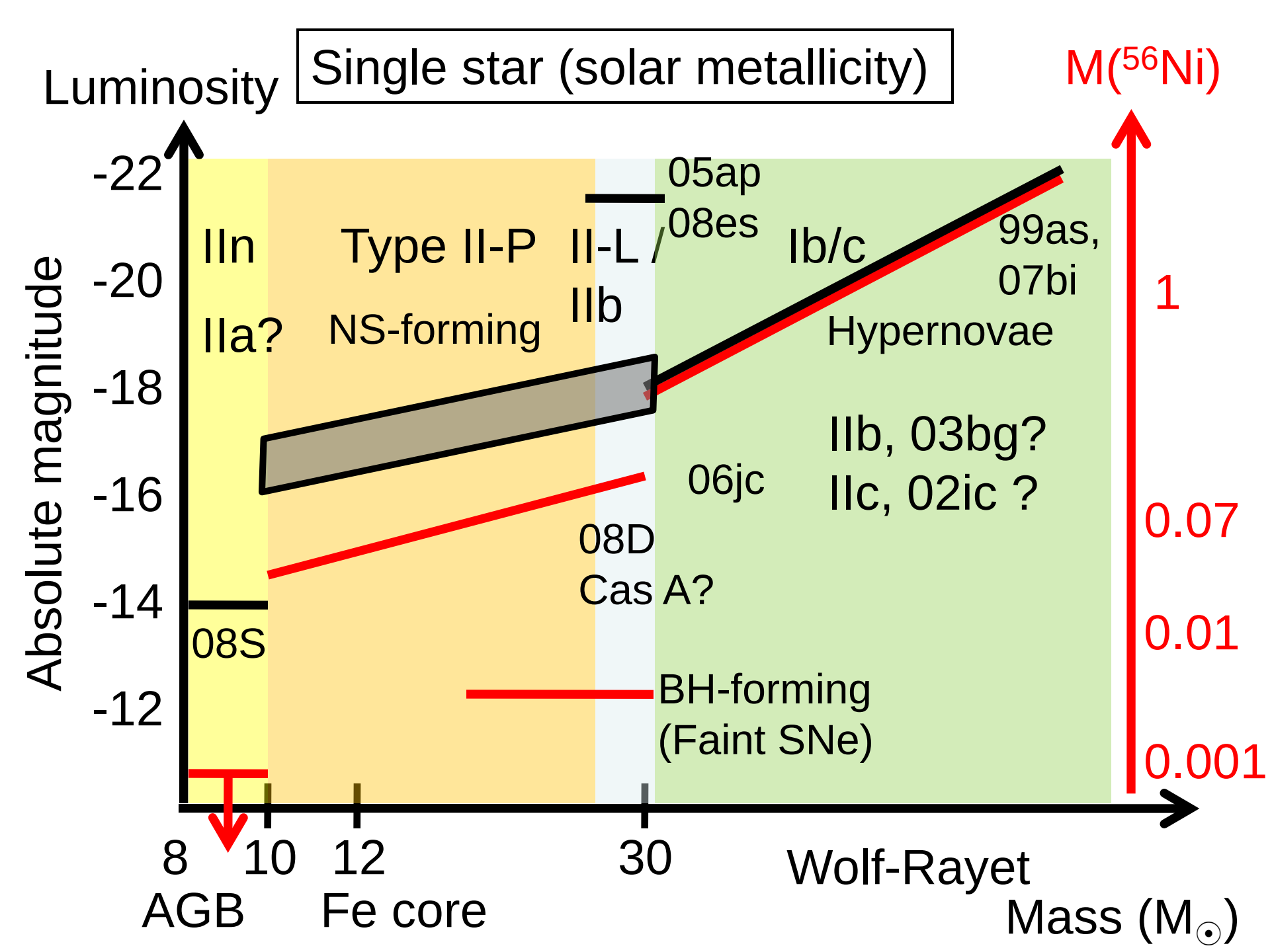
100-130 $M_\odot$: Nuclear Instability

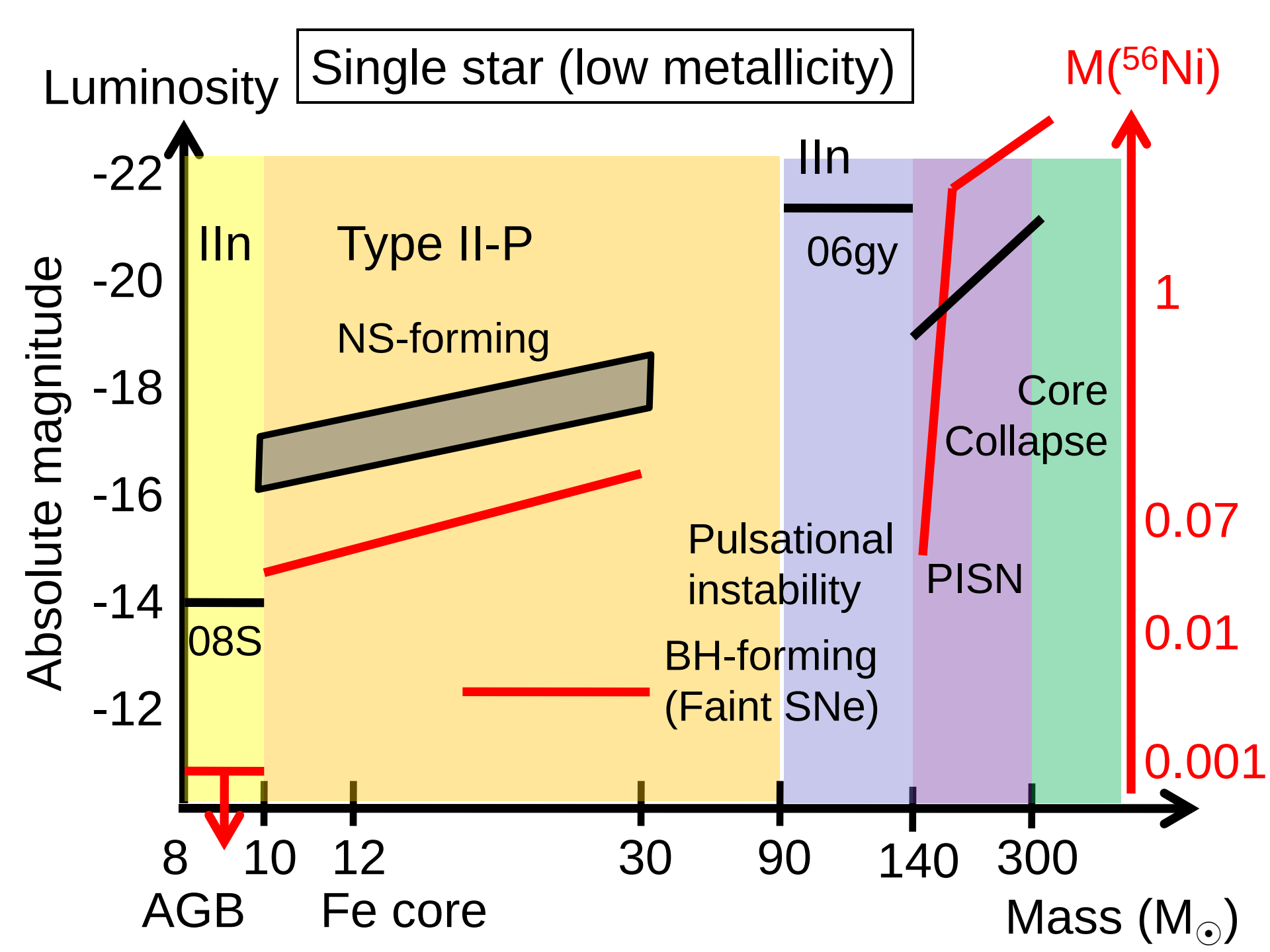


Woosley, Blinnikov, Heger (2007)

Final Fates of Massive Stars




Single star (solar metallicity)
Luminosity
M(56Ni)
-22
-20
-18
-16
-14
-12
Absolute magnitude
IIn
IIa?
Type II-P
NS-forming
II-L / IIb
05ap
08es
Ib/c
99as, 07bi
Hypernovae
IIb, 03bg?
IIc, 02ic ?
06jc
08D
Cas A?
08S
BH-forming
(Faint SNe)
1
0.07
0.01
0.001
8
10
12
30
AGB
Fe core
Wolf-Rayet
Mass (M⊙)


Single star (low metallicity)
Luminosity
M(56Ni)
-22
-20
-18
-16
-14
-12
Absolute magnitude
IIn
Type II-P
NS-forming
IIn
06gy
Core
Collapse
1
0.07
0.01
0.001
Pulsational
instability
PISN
08S
BH-forming
(Faint SNe)
8
10
12
30
90
140
300
AGB
Fe core
Mass (M⊙)

Diversity & Peculiarities of Supernovae vs. Progenitors, Mechanisms

* Ultra-Luminous SNe (IIn, II-L, Ic)
* Ultra-Faint SNe (IIn): AGB progenitors?

* Ic: GRB-SNe, Hypernovae; aspherical
* Ib: Energetic (HN-like); aspherical
  Dusty
  LBV, WR connection ?