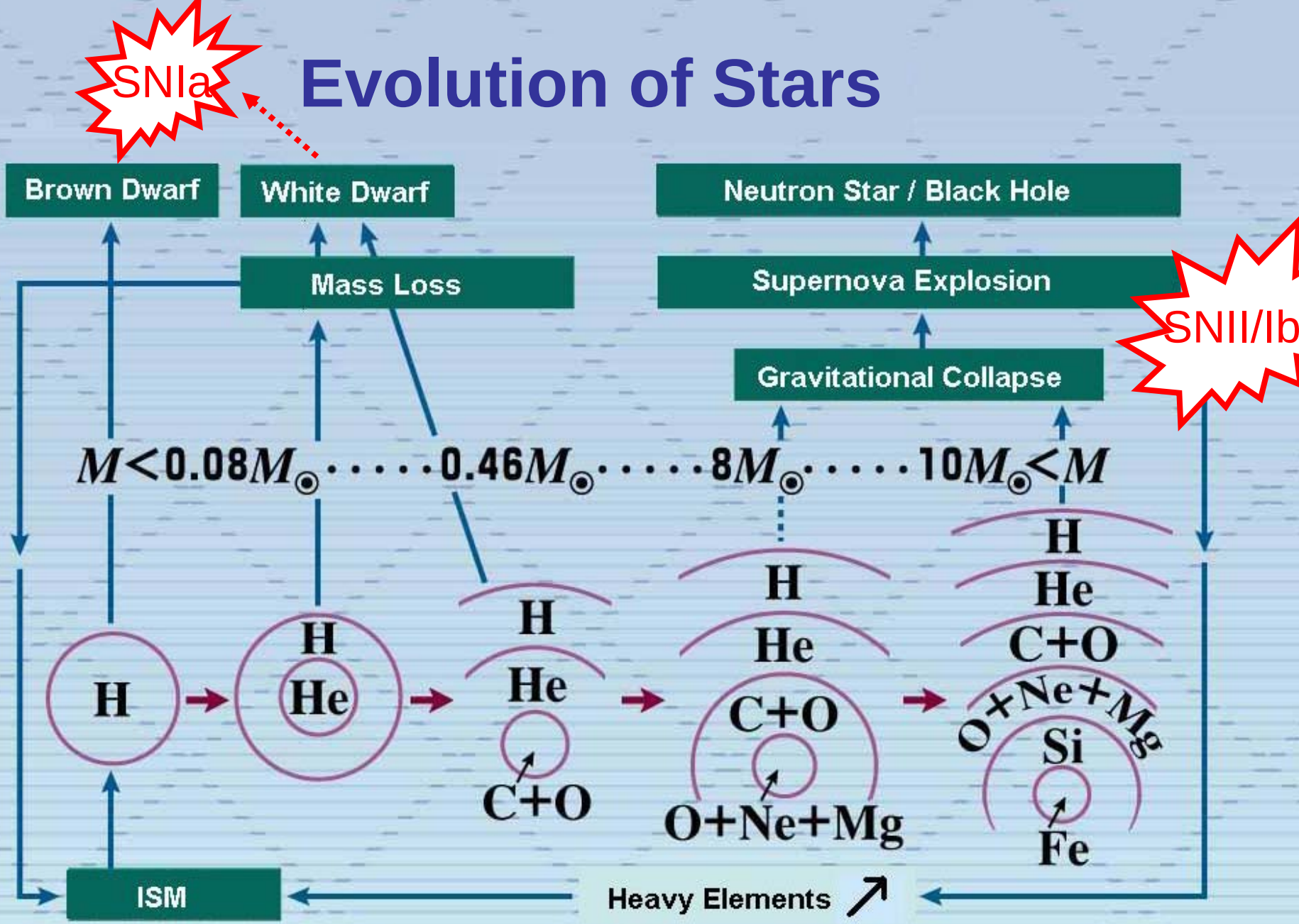
The Final Fates of Massive Stars

K. Nomoto (IPMU, U. Tokyo)

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)


観測装置制御計算機
Instrument Control Comput

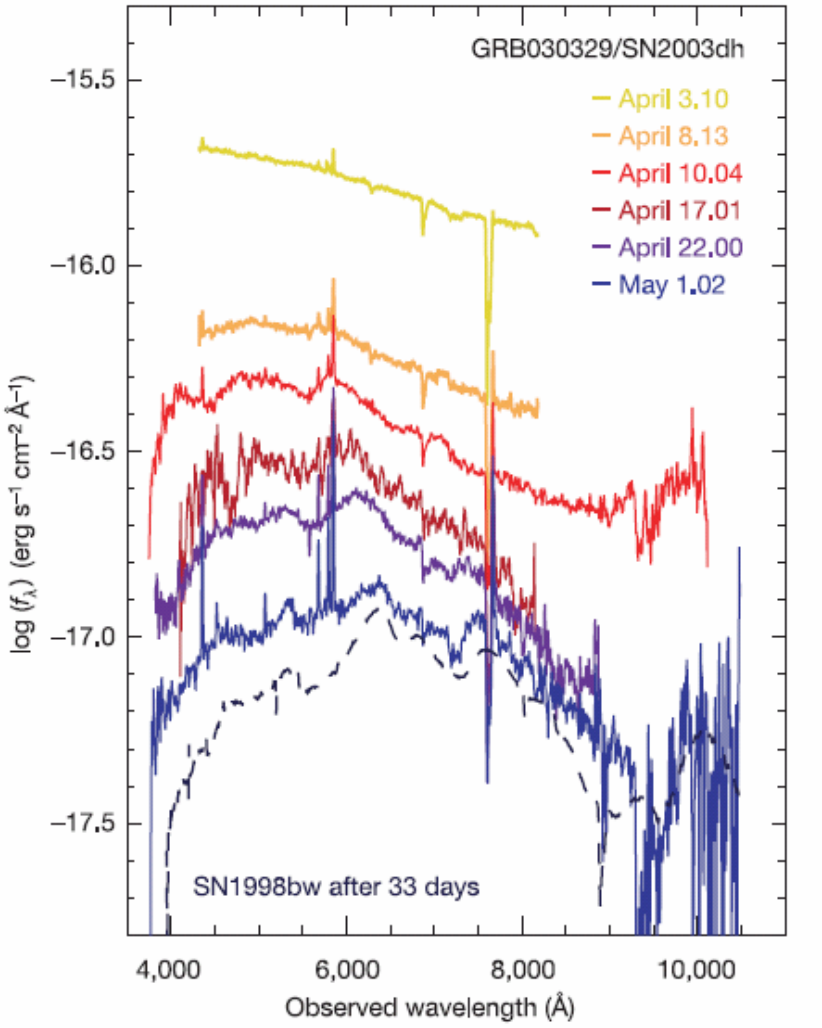
Supernova Observations

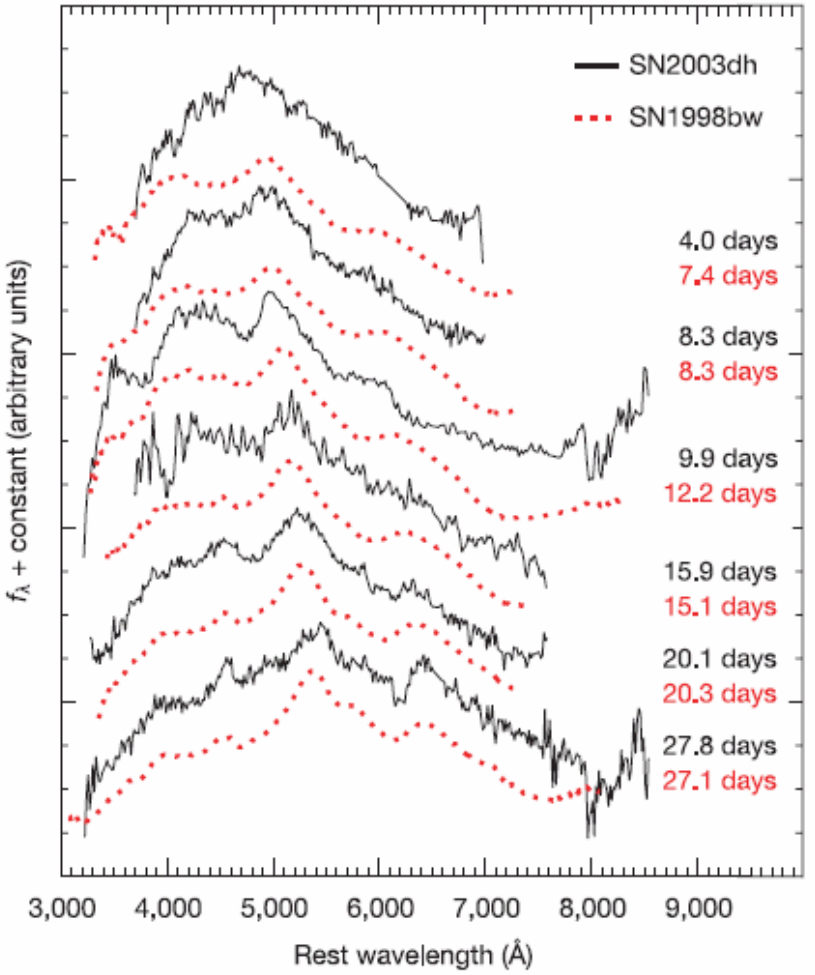
Distant SNe & Nearby SNe

- Photometry ➔ Light Curve (UBVRIJHK)
- Spectra (HDS, FOCAS, IRCS, OHS)
  - Circumstellar Matter : ToO
  - Early phase : ToO
  - Nebular phase
- Polarization

- SN Properties (Mass, Energy, Abundance, Distribution, Shape)
- Connections to:
  - Progenitors; GRBs; Metal-Poor Stars

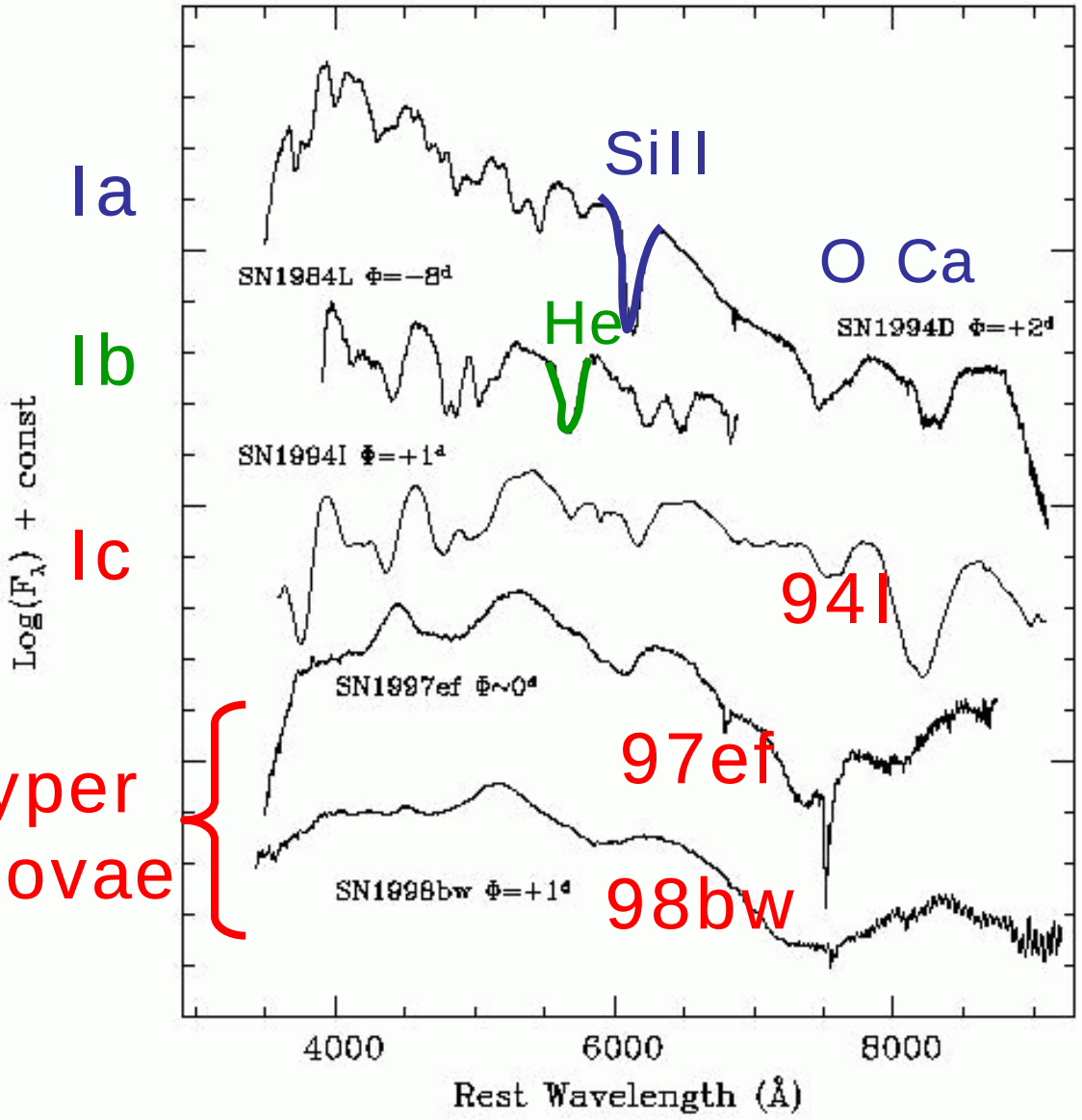
GRB 030329 / SN 2003dh





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

Early Spectra of Supernovae & Hypernovae



Ic: no H,

no strong He,

no strong Si

Hypernovae:

broad features

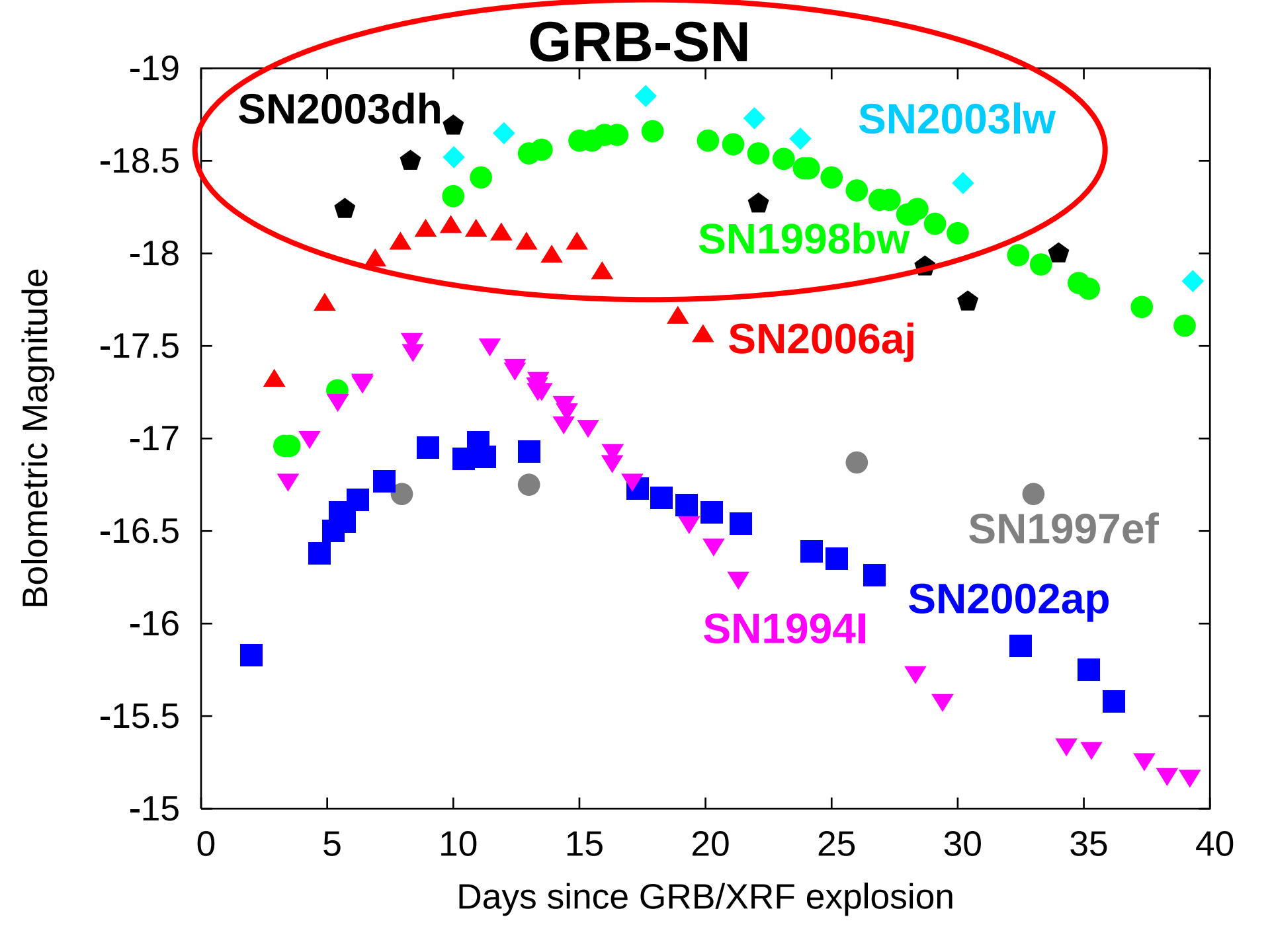
↑

blended lines

↑

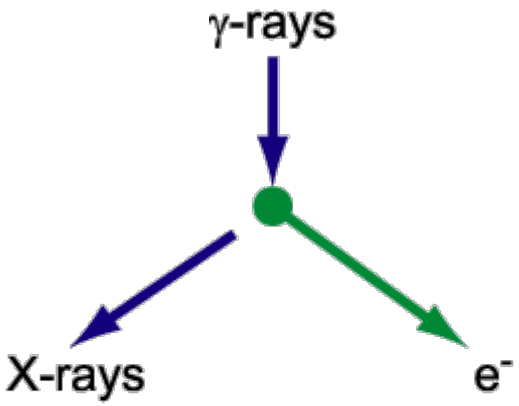
"Large mass at high velocities"

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

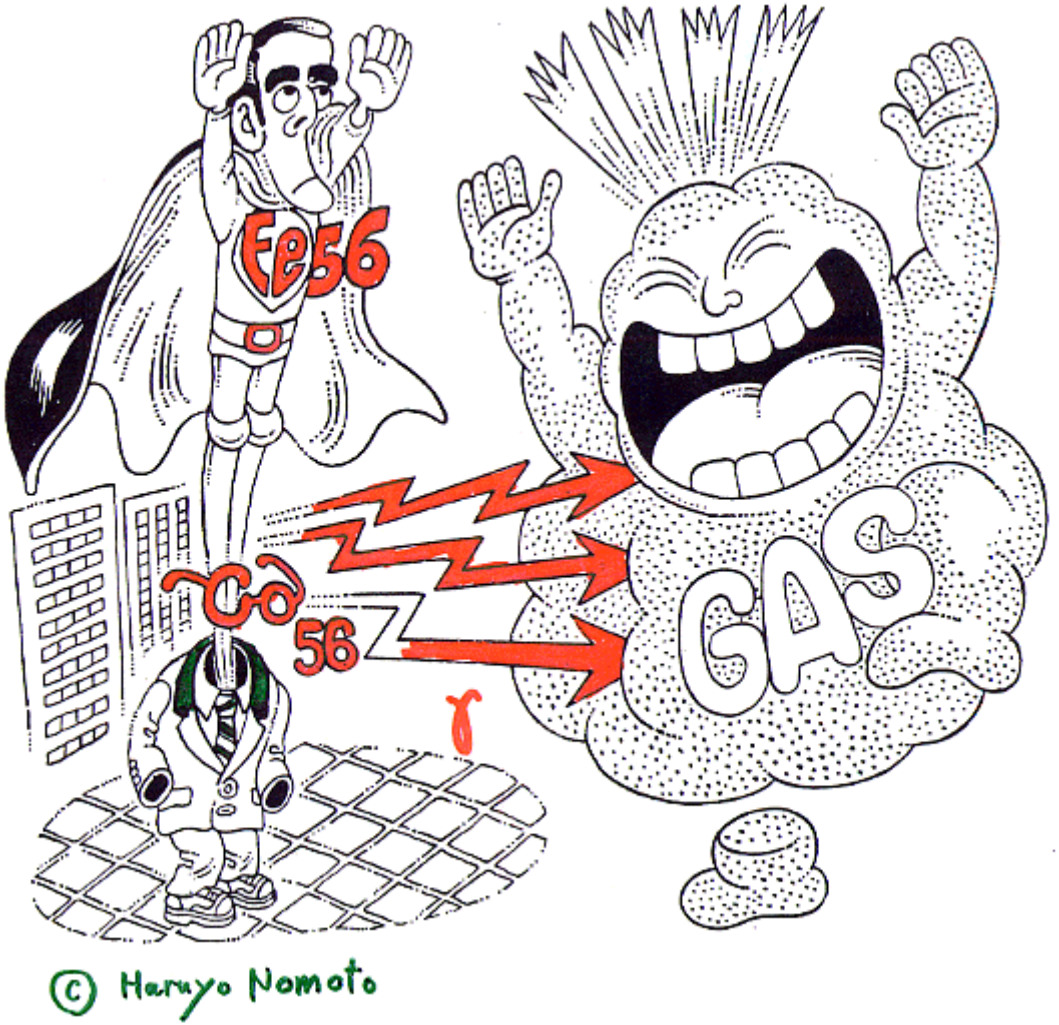
$^{56}Ni \xrightarrow[6.6d]{\gamma} {}^{56}Co \xrightarrow[78d]{\gamma} {}^{56}Fe$



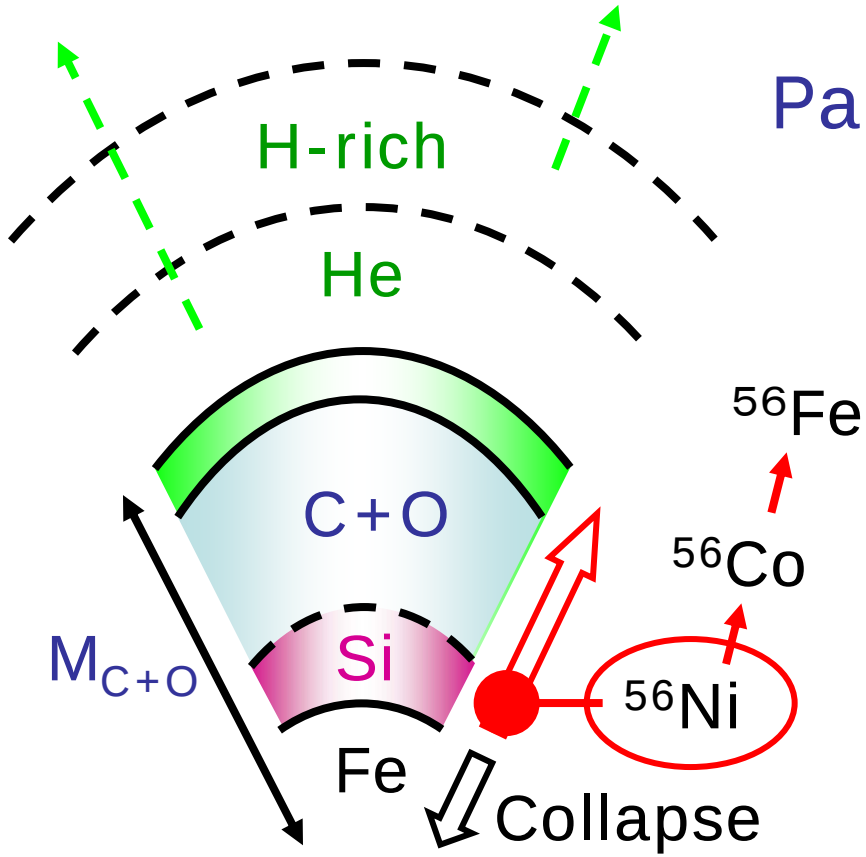
Photoabsorption Excitation/Ionization

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

Shape:M_{ej}



CO Star Models for SNe Ic



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

Light Curve | Spectra

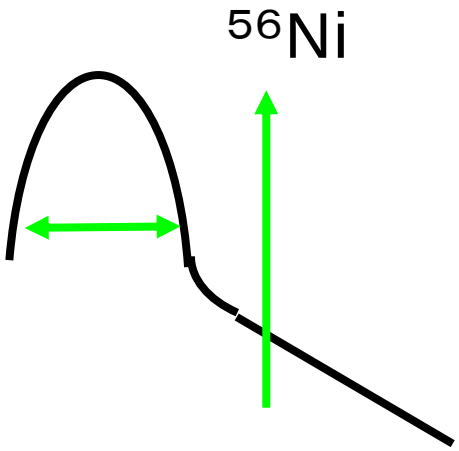
$$\tau \sim [\tau_{dyn} \bullet \tau_{diffusion}]^{1/2} \sim \left(\frac{R}{V} \bullet \frac{\kappa M_{ej}}{R c} \right)^{1/2}$$

$E \propto M_{ej}$

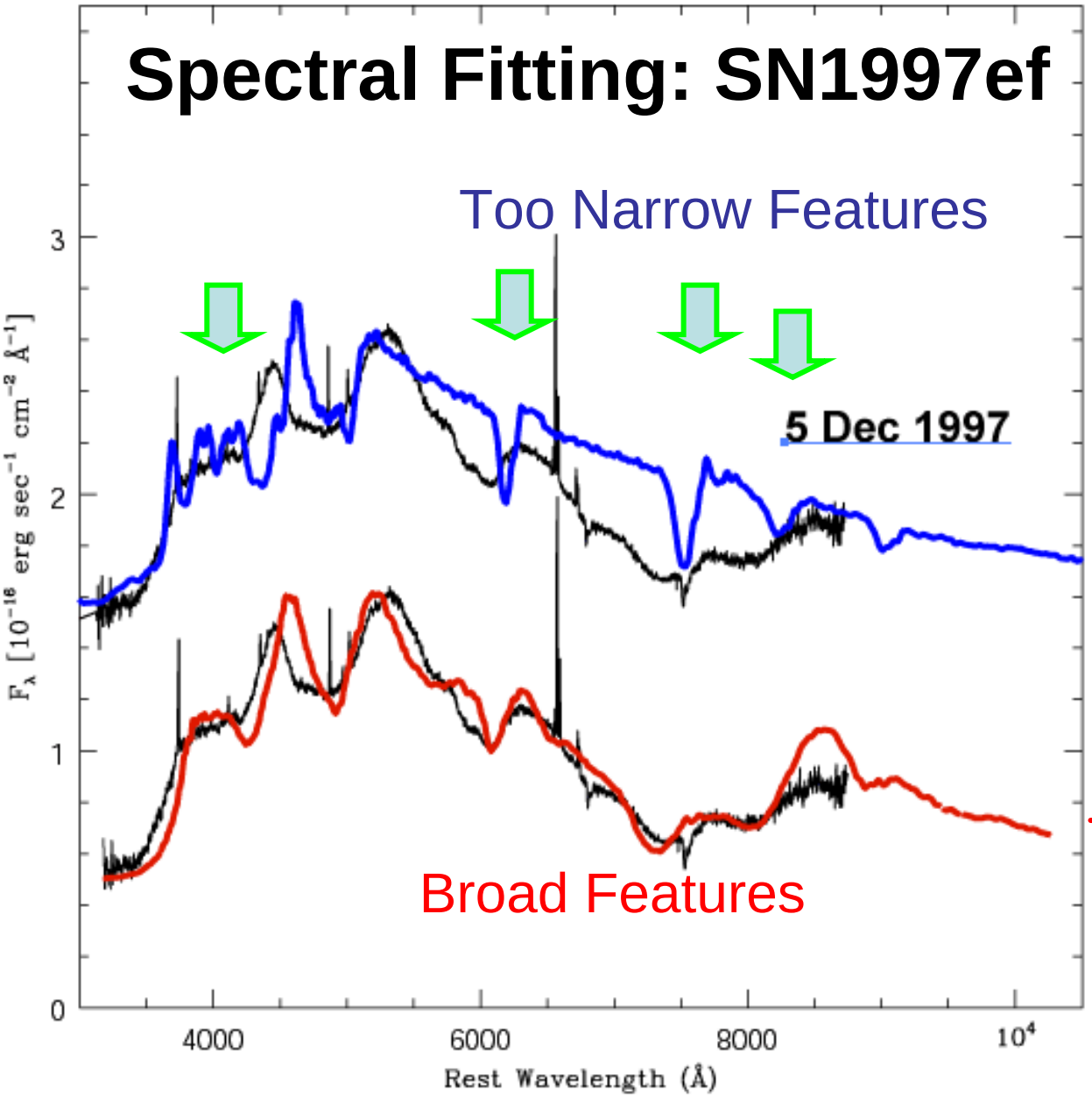
$$\propto \kappa^{1/2} M_{ej}^{3/4} E^{-1/4}$$

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

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

GRB-Supernovae

Three GRB－SNe = all Type Ic Hypernovae

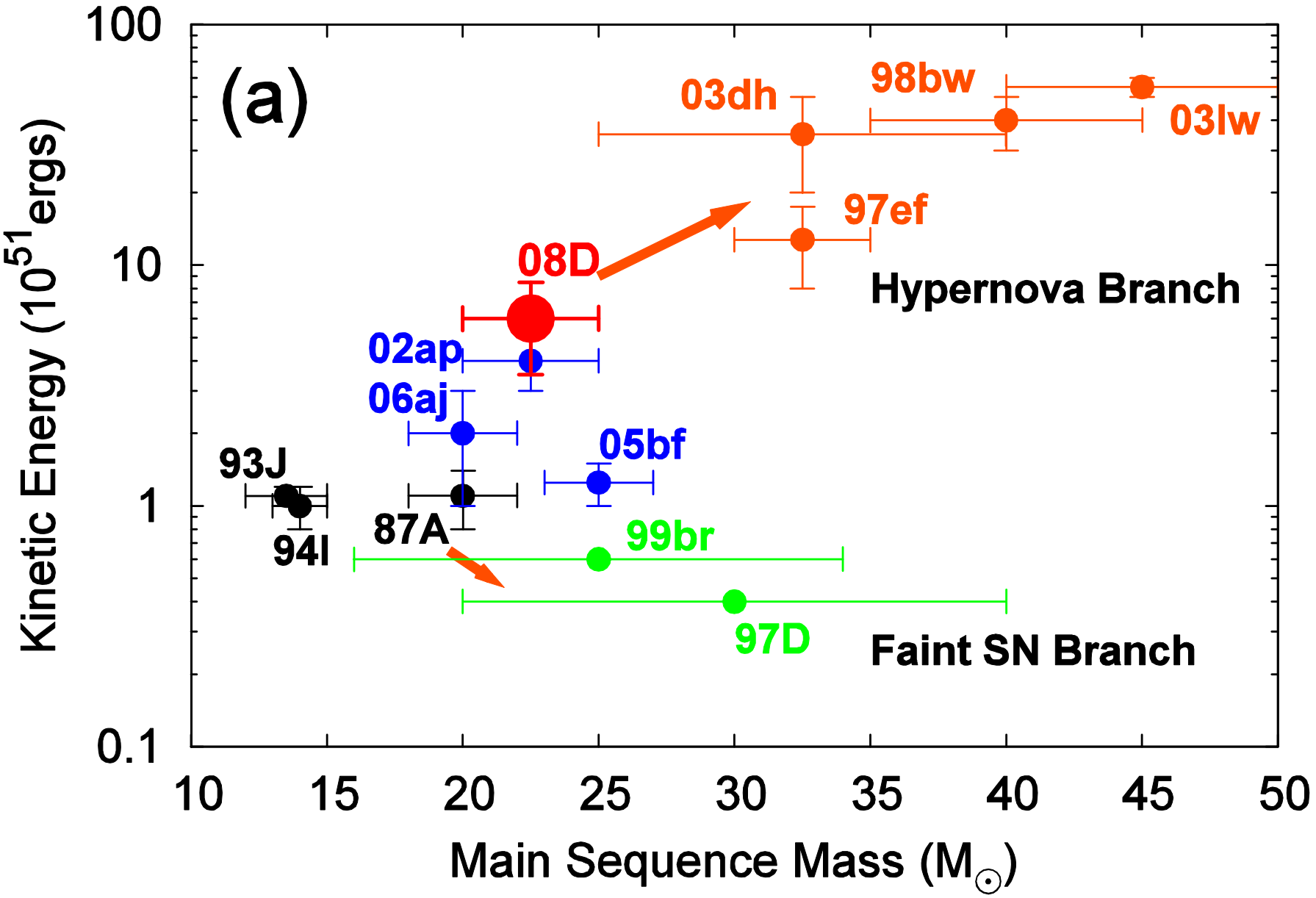
$E > 10^{52}$ erg (～10×normal SN)

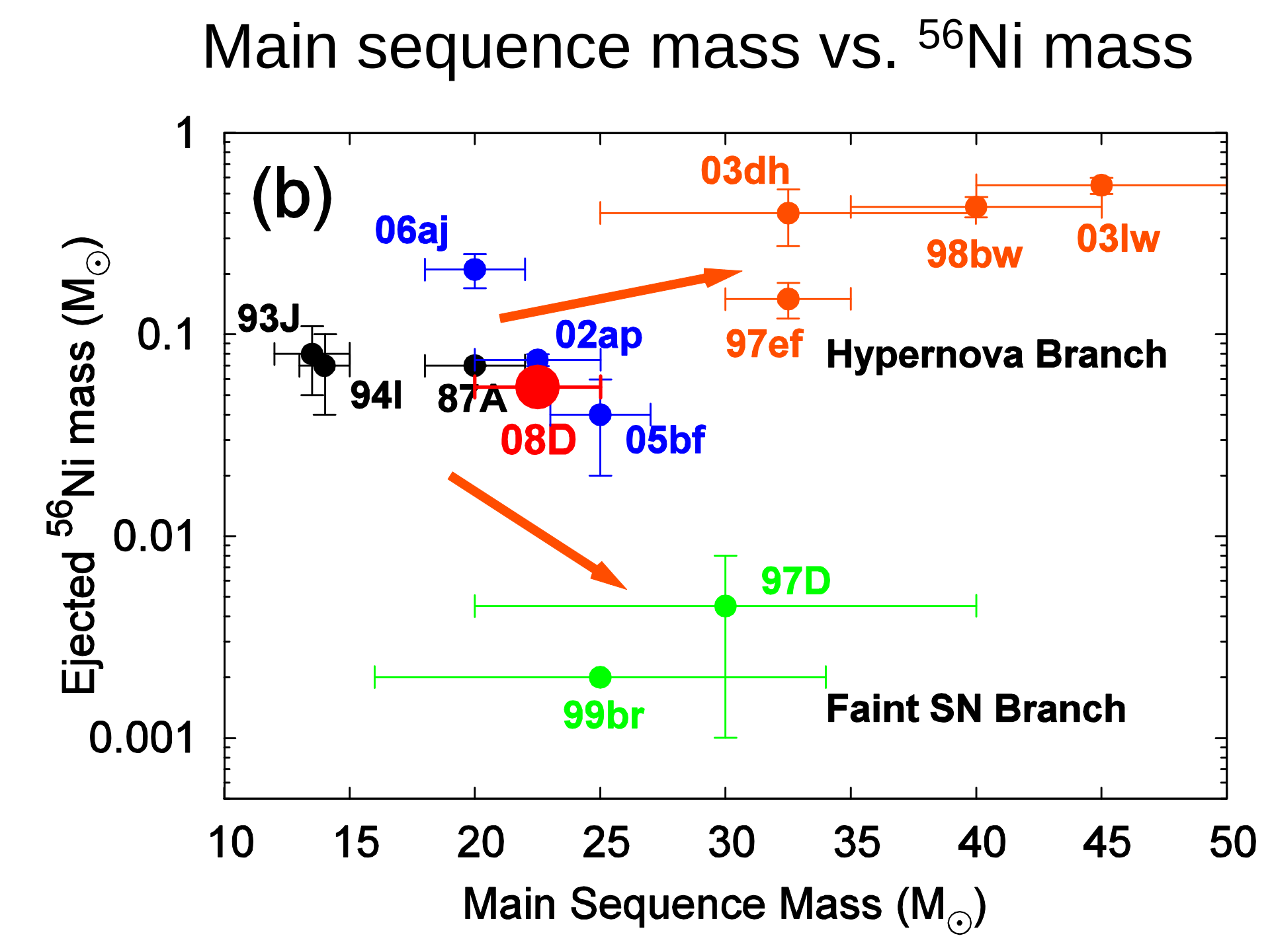
Large M_{ms} →Black Hole Forming SNe

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

Main sequence mass vs. Kinetic energy



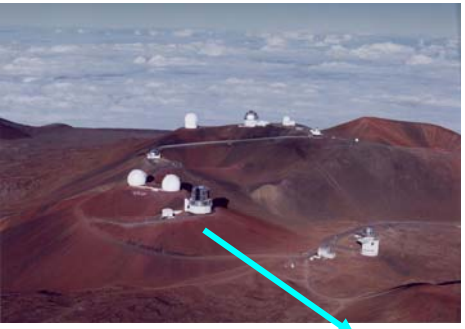

Main sequence mass vs. ^{56}Ni mass
(b)
03dh
06aj
98bw
03lw
93J
02ap
97ef
Hypernova Branch
94I
87A
08D
05bf
97D
99br
Faint SN Branch
Ejected ^{56}Ni mass ($M_\odot$)
Main Sequence Mass ($M_\odot$)
1
0.1
0.01
0.001
10
15
20
25
30
35
40
45
50

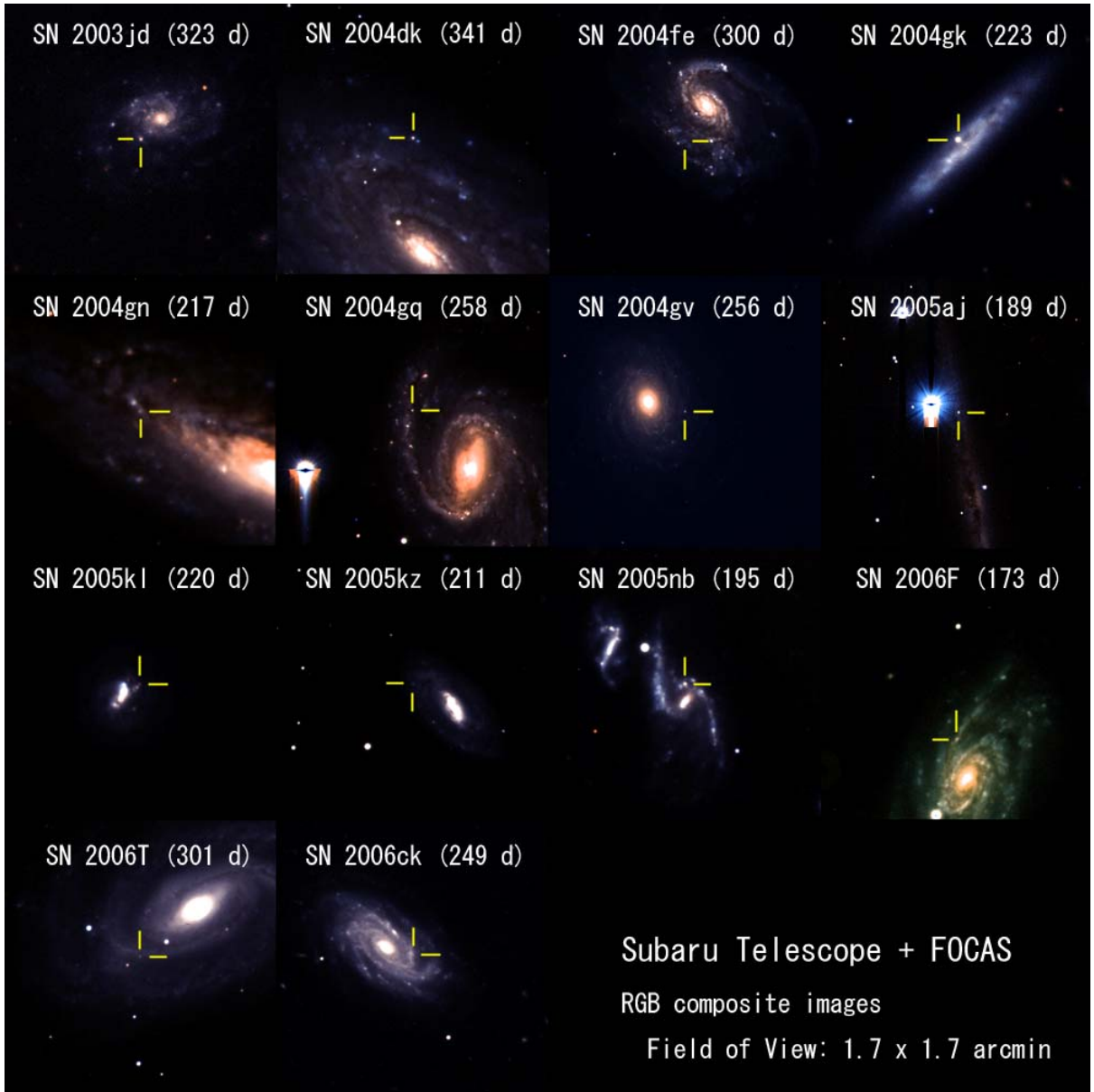
Hypernova in Prague

Hypernova in Prague

Nebular Spectra of SNe Ibc

15 SNe Ibc. Previously, only 3!

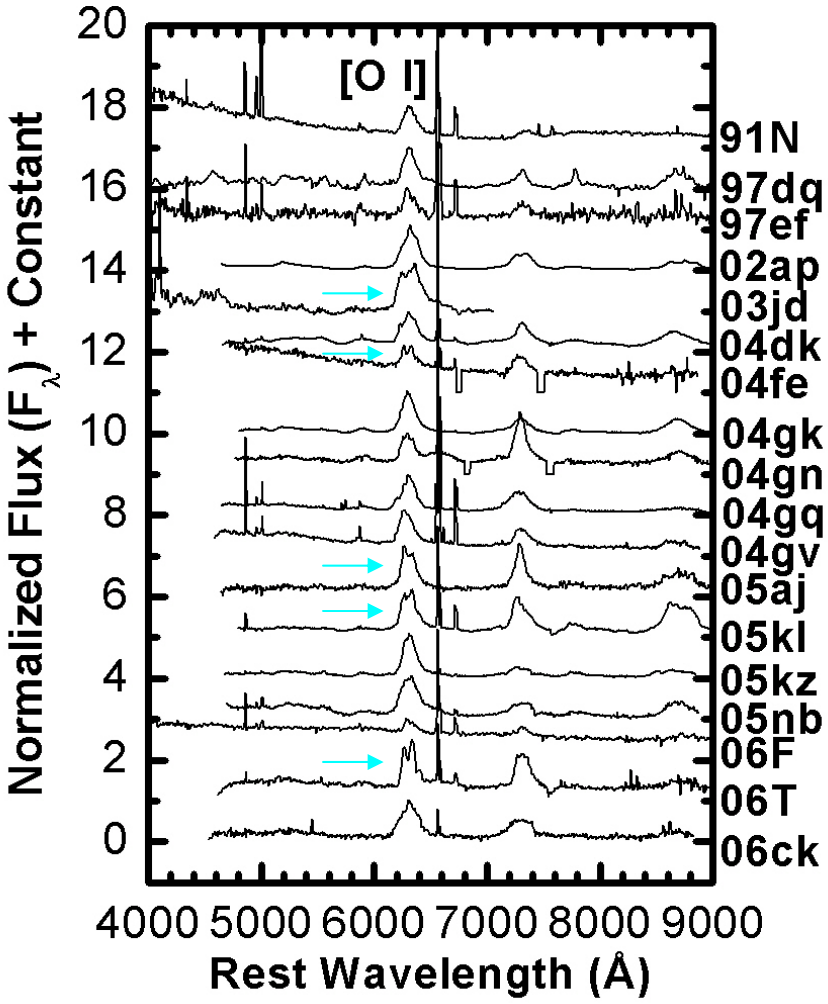


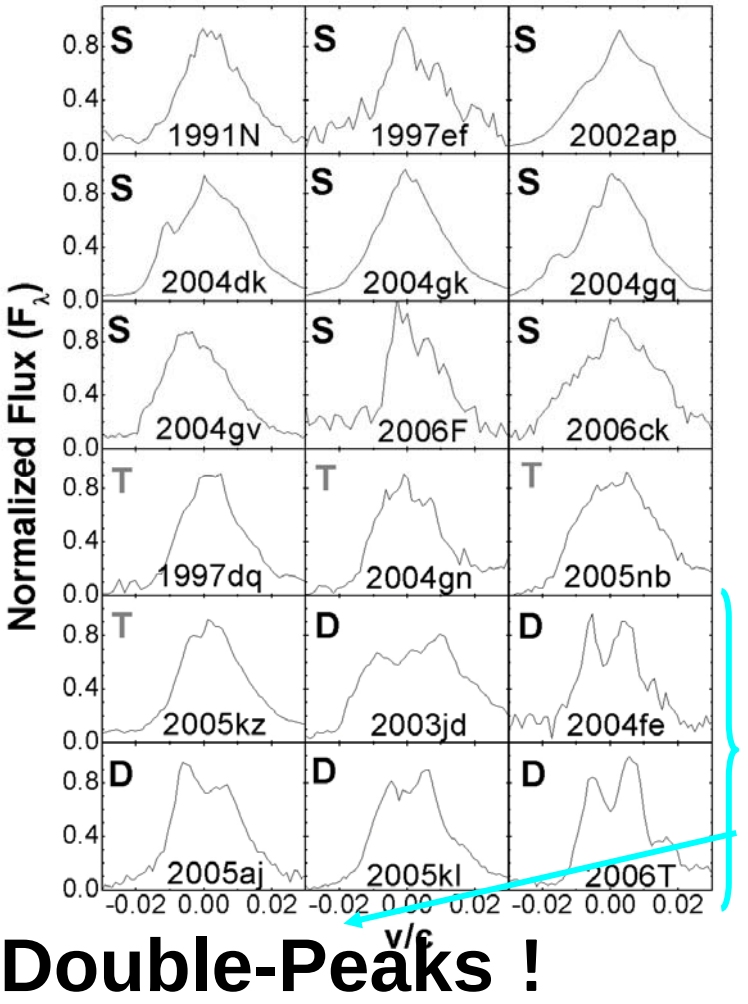


Maeda et al. (2008: Science)

Late-Time Spectroscopic Data

[OI] emission line



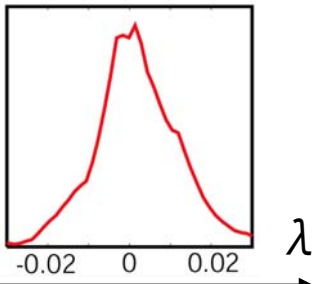


Double-Peaks !

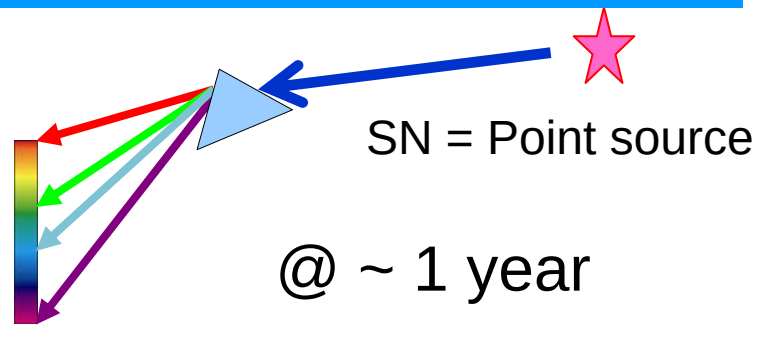
- Asphericity is COMMON to core-collapse SNe!

Bipolar vs. Spherical: How distinguished?

“Single-peak”



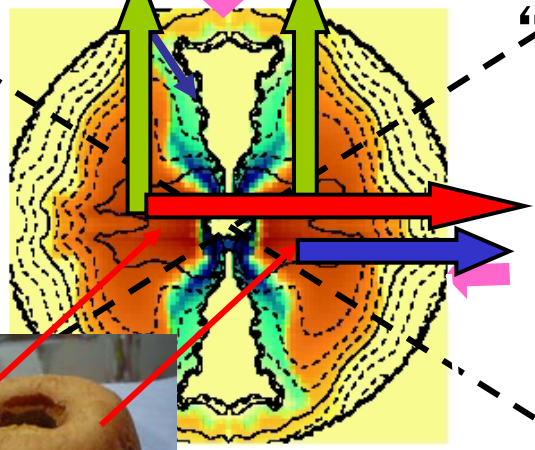
Geometry



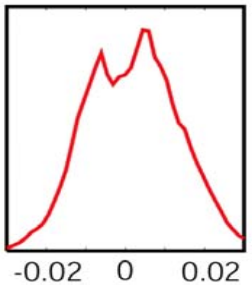
@ ~ 1 year

[OI] 6300

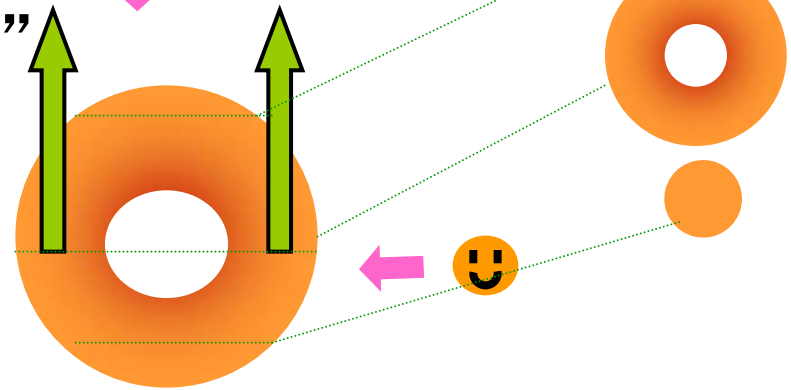
Fe (^{56}Ni)



“Double-peak”



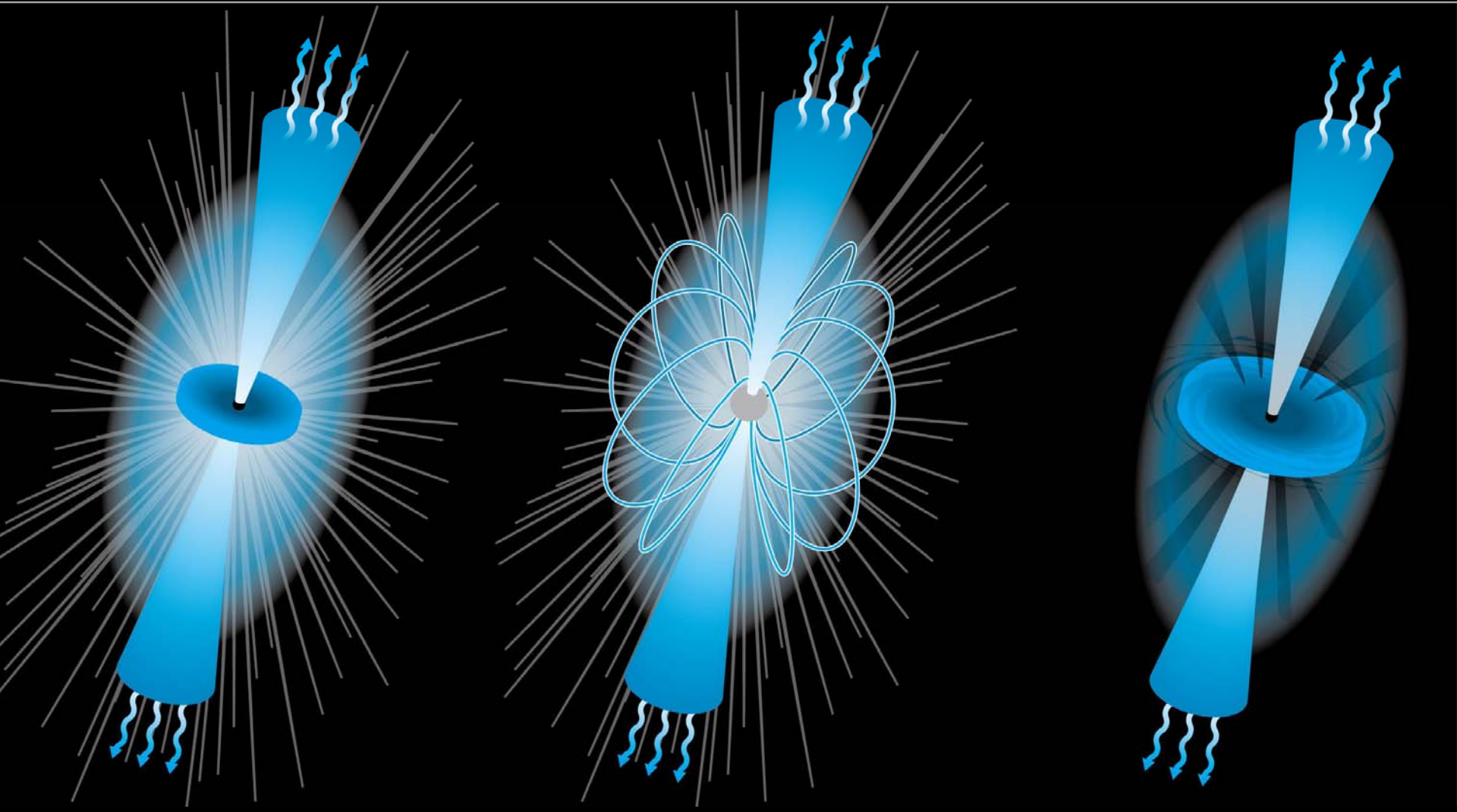
“Single-peak”



“Single-peak”

Doppler shift

SN-GRB Connection

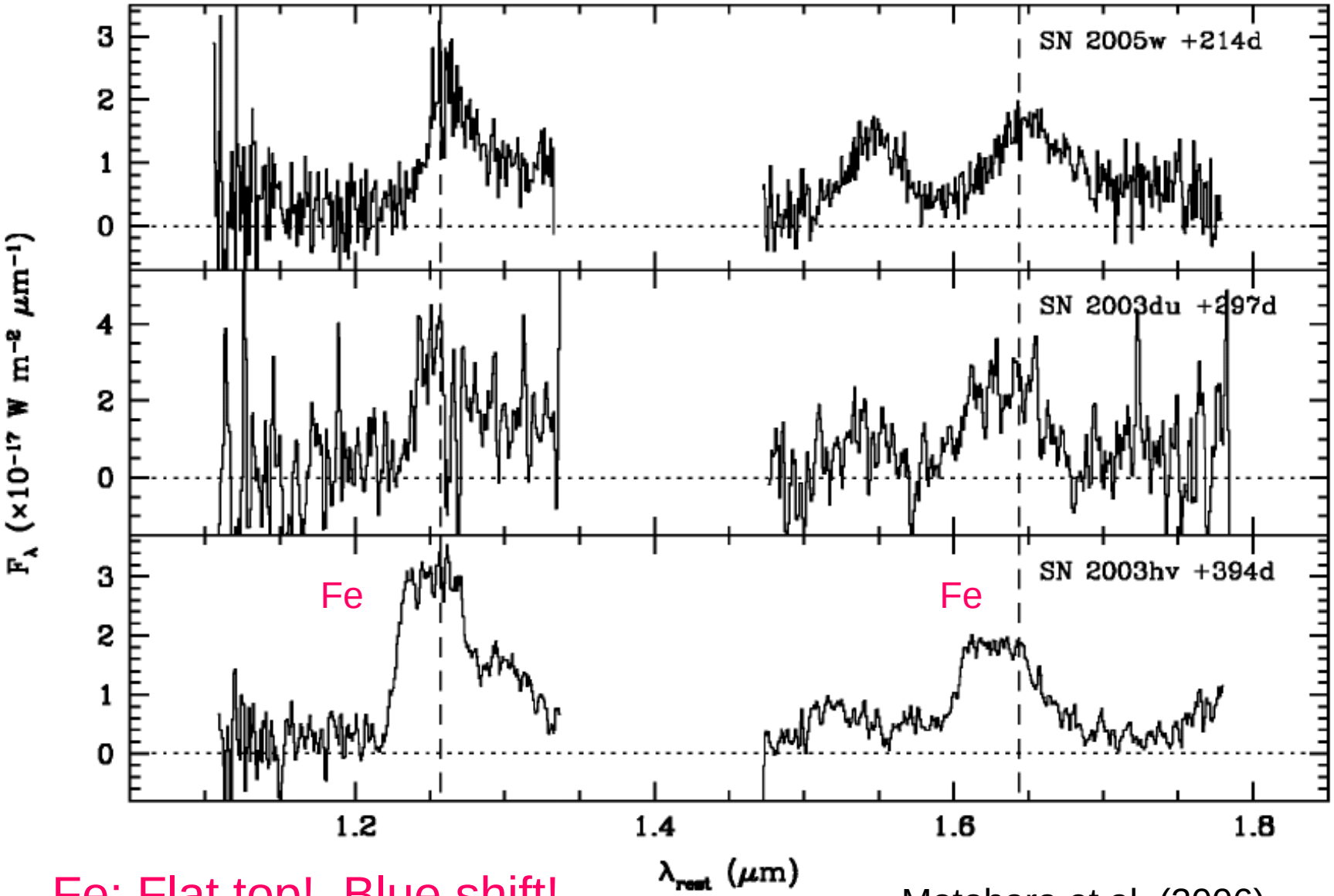


GRB-HN

Magnetar

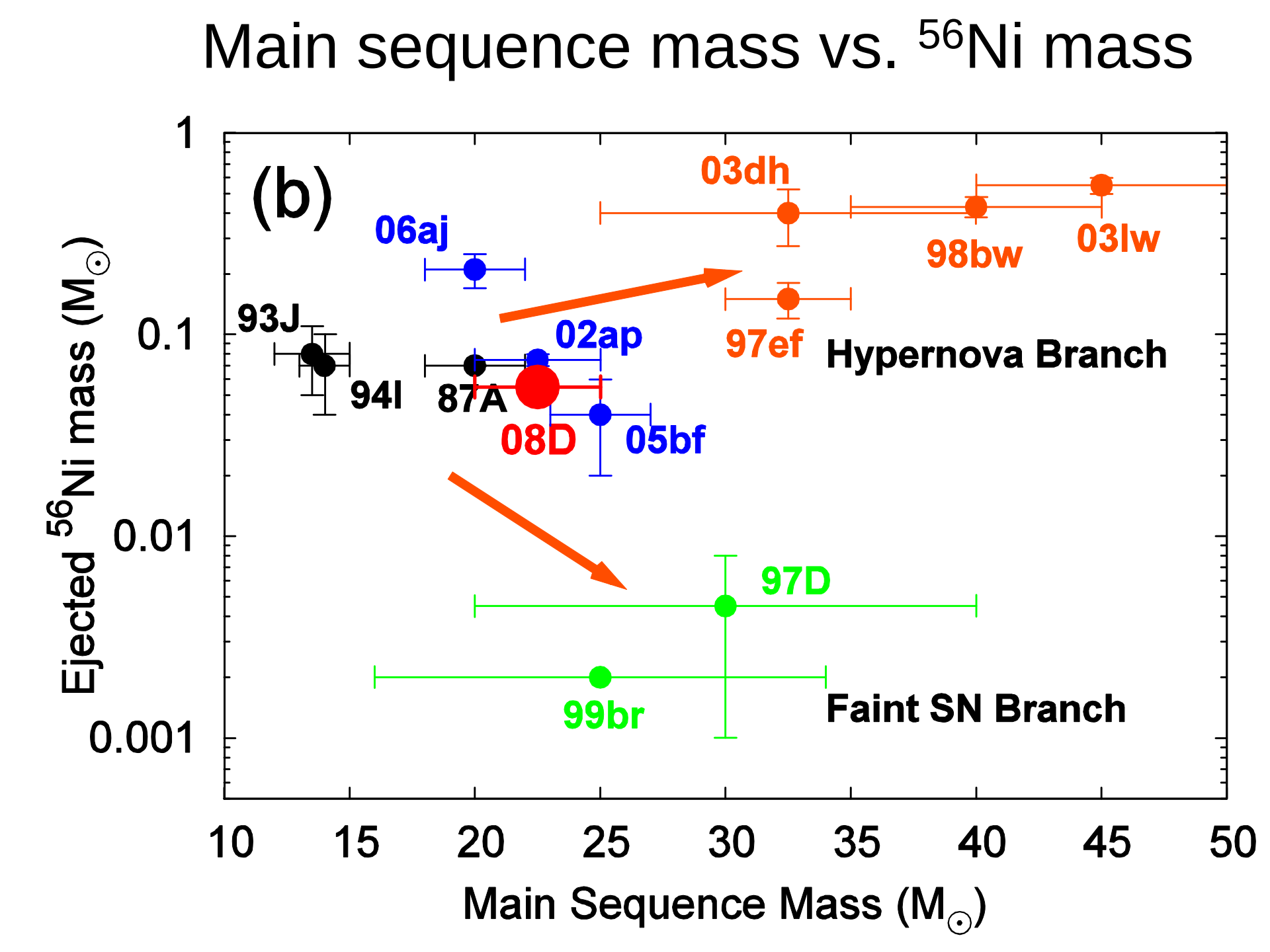
Non-SN GRB

SUBARU/OHS observations of SNe Ia 05W, 03du, 03hv



Fe: Flat top! Blue shift!

Motohara et al. (2006)


Main sequence mass vs. ^{56}Ni mass
(b)
03dh
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Faint SN Branch
Ejected ^{56}Ni mass ($M_\odot$)
Main Sequence Mass ($M_\odot$)
1
0.1
0.01
0.001
10
15
20
25
30
35
40
45
50

Faint Supernovae - EMP Stars

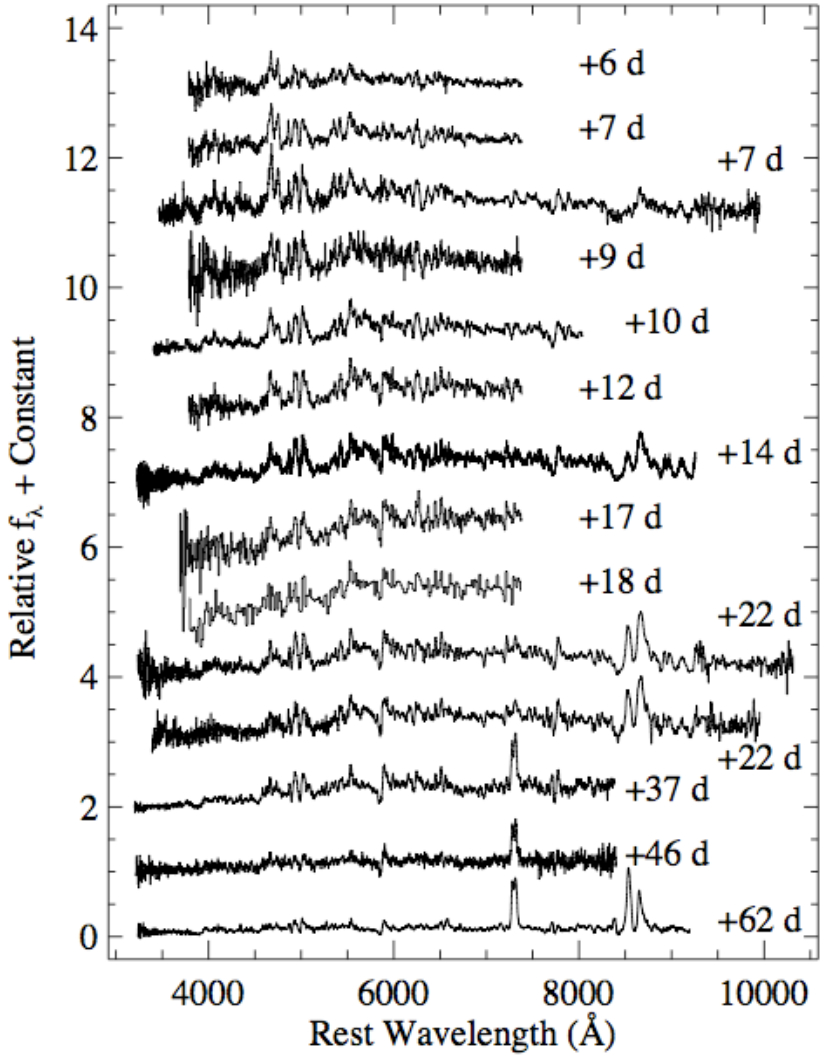
Fallback: small M(Ni)
large [CNO/Fe] ➔ CEMP

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

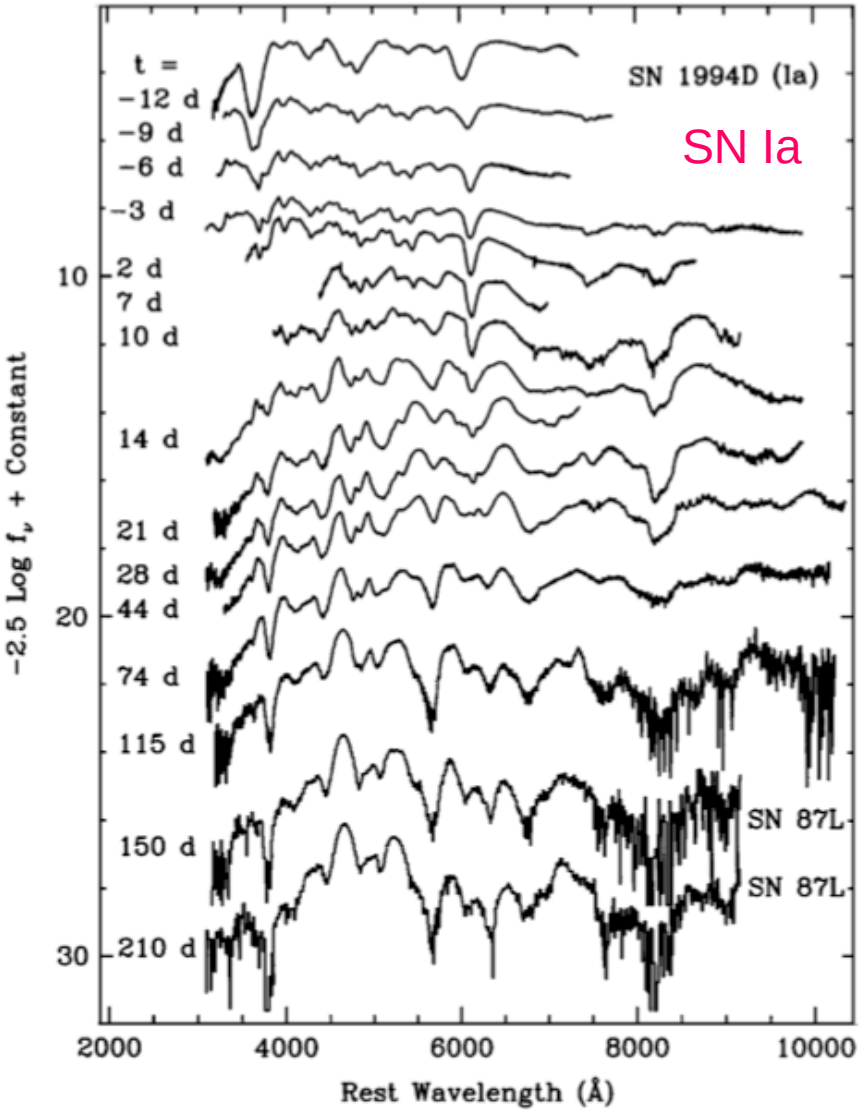
(2) Weak Explosion
Mixing & Fallback

Faint SN 2008ha: Spectra(narrow)

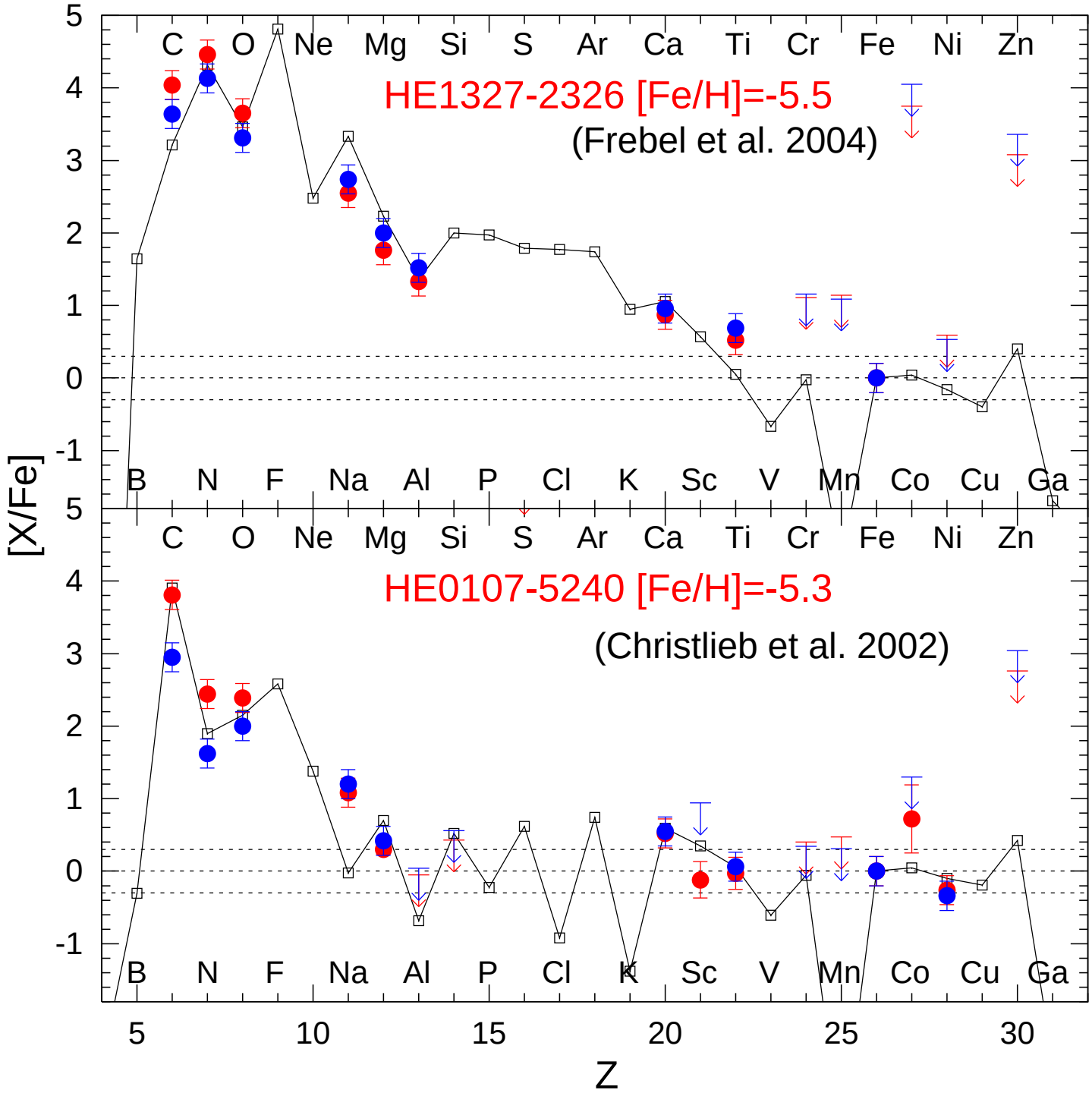
SN I 2008ha (v ~ 700 km/s)



Foley et al. (2009)



Filippenko (1997)



HMP Stars

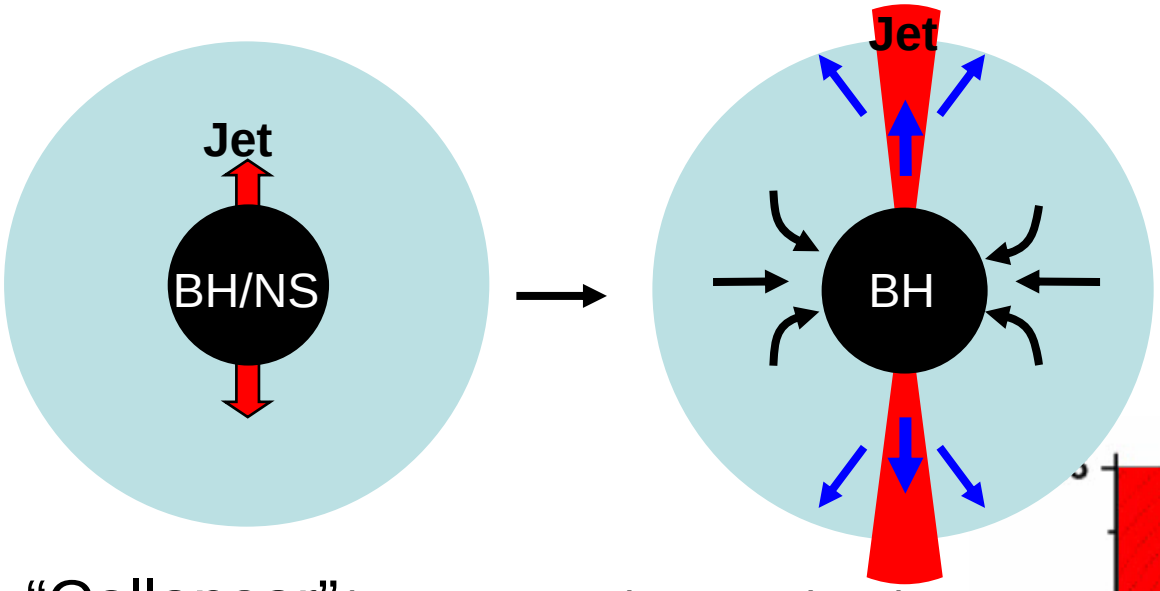
Jet-induced SN models

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

Dark Hypernova

Tominaga et al. 2007

Jet-induced Nucleosynthesis



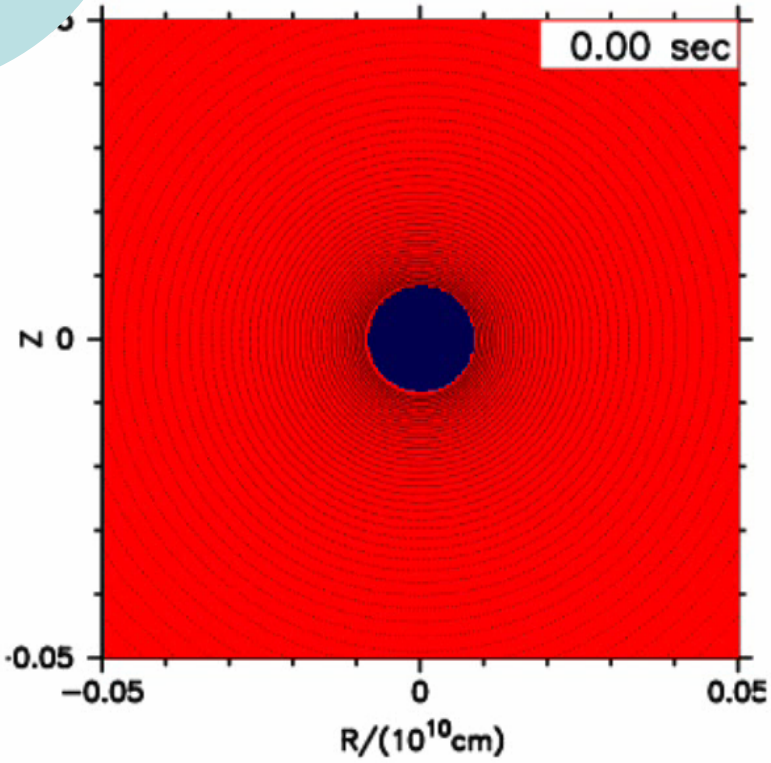
Special relativistic hydrodynamics (Tominaga et al. ApJL 2007)

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

Magnetorotational Supernovae

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

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

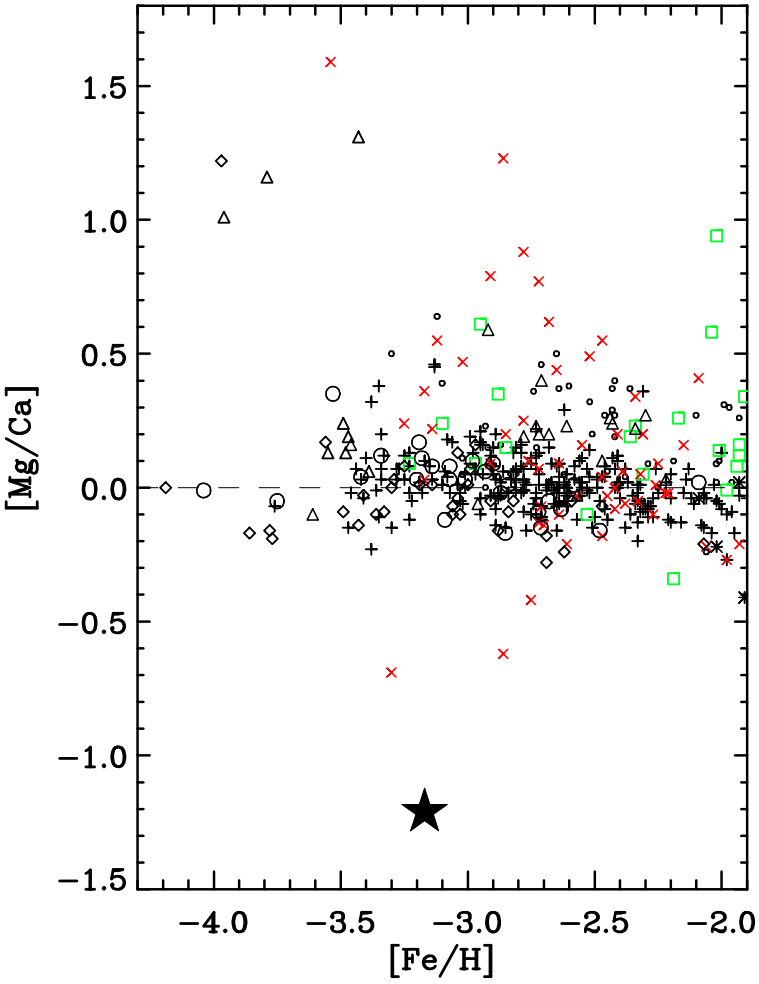


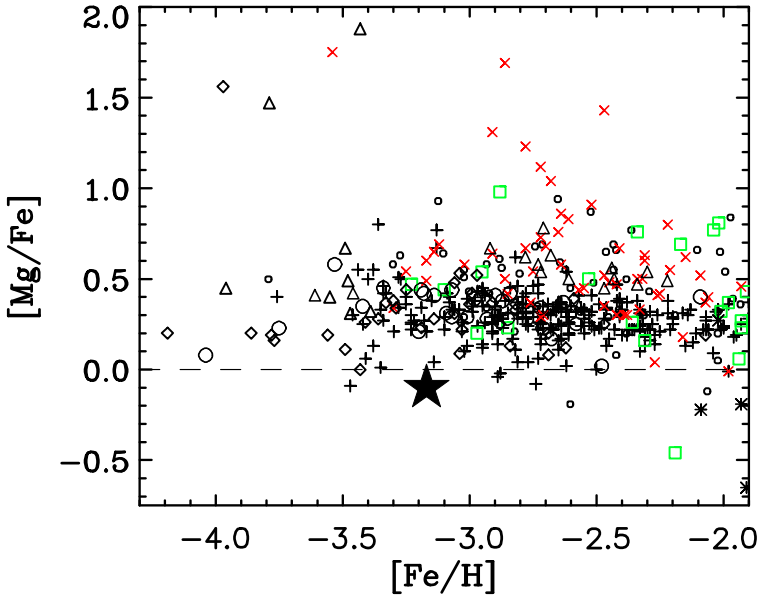
Same mass and explosion energy

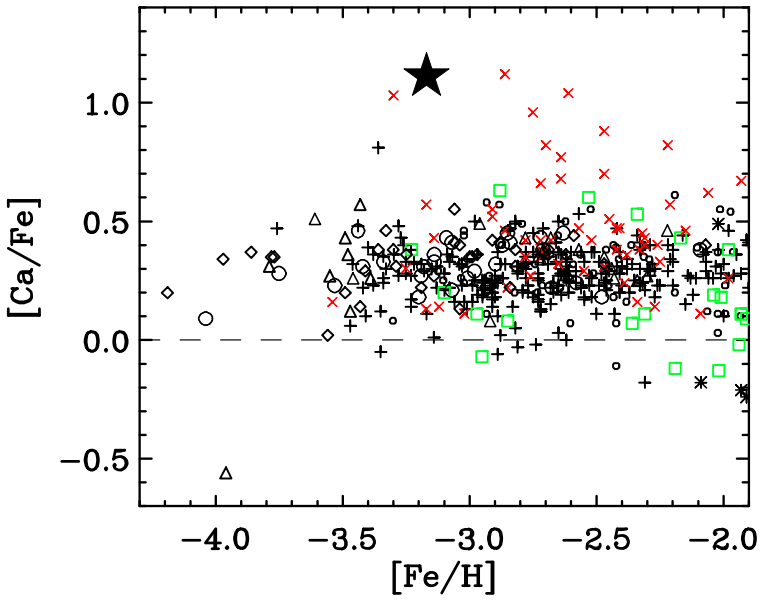
$40M_{\odot}$ 1.5×10^{52}erg

Ca-rich EMP Star

(Lai et al. 2009)







EPM stars in dSph Sextans

- Low [Mg/Fe]

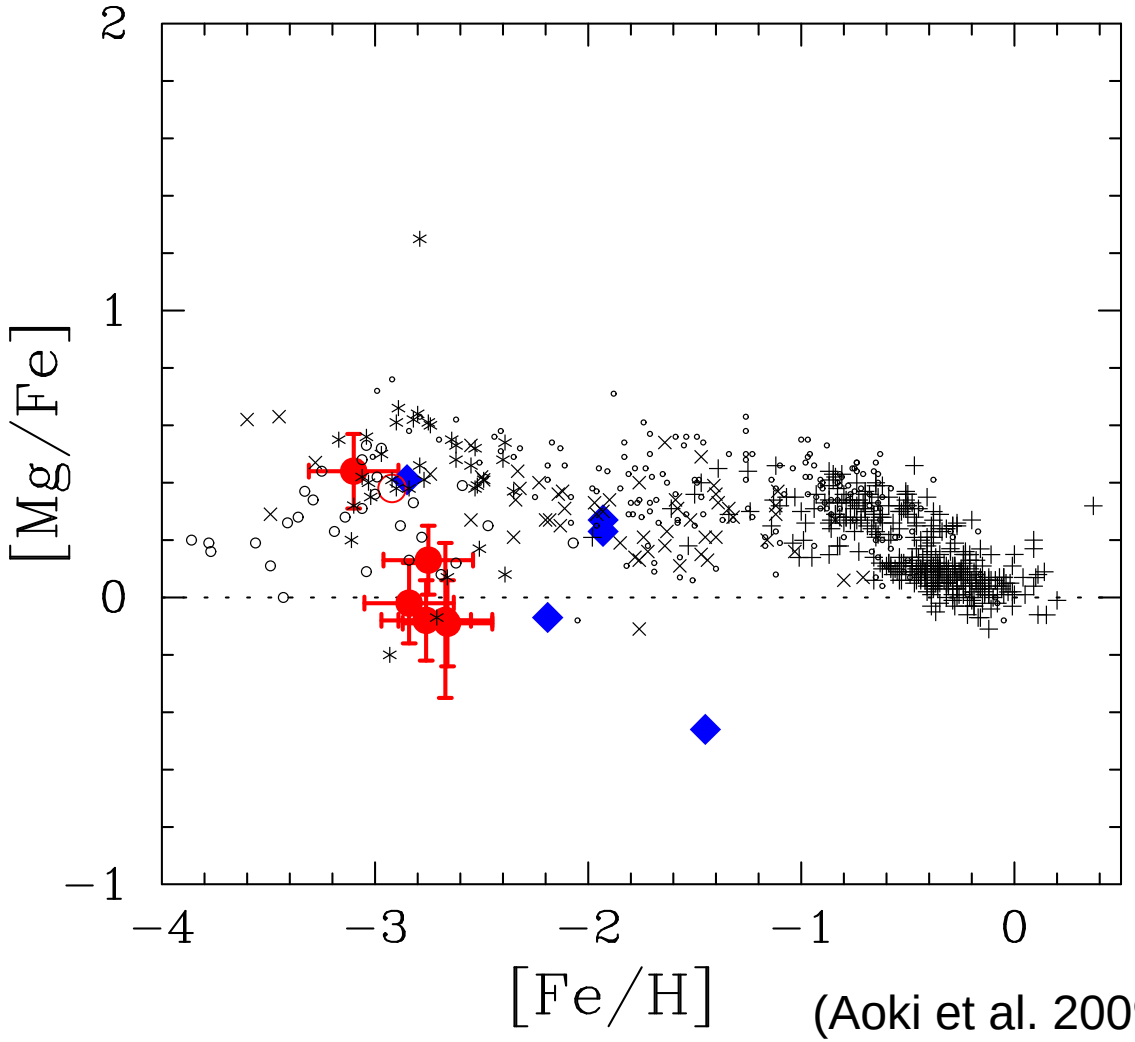
at [Fe/H] =-2.8

SN Ia ?

SN II ?

~10 $M_\odot$?

~25 $M_\odot$?



(Aoki et al. 2009)

SN – GRB – EMP star Connections

- GRB-SNe = Hypernovae
- Faint SNe – EMP stars (CEMP, Zn, Co)
  Weak SNe
  "Dark" Hypernovae ➔ Non-SN GRB

- Faint SNe -- Ca-rich SN
  -- Ca-rich EMP
- dSph low Mg/Fe

Diversity in SN properties:

- ONeMg (AGB)-SN --- SN 2008S (faint IIn)
- Most Luminous SN 2006gy (Kawabata's poster)

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)

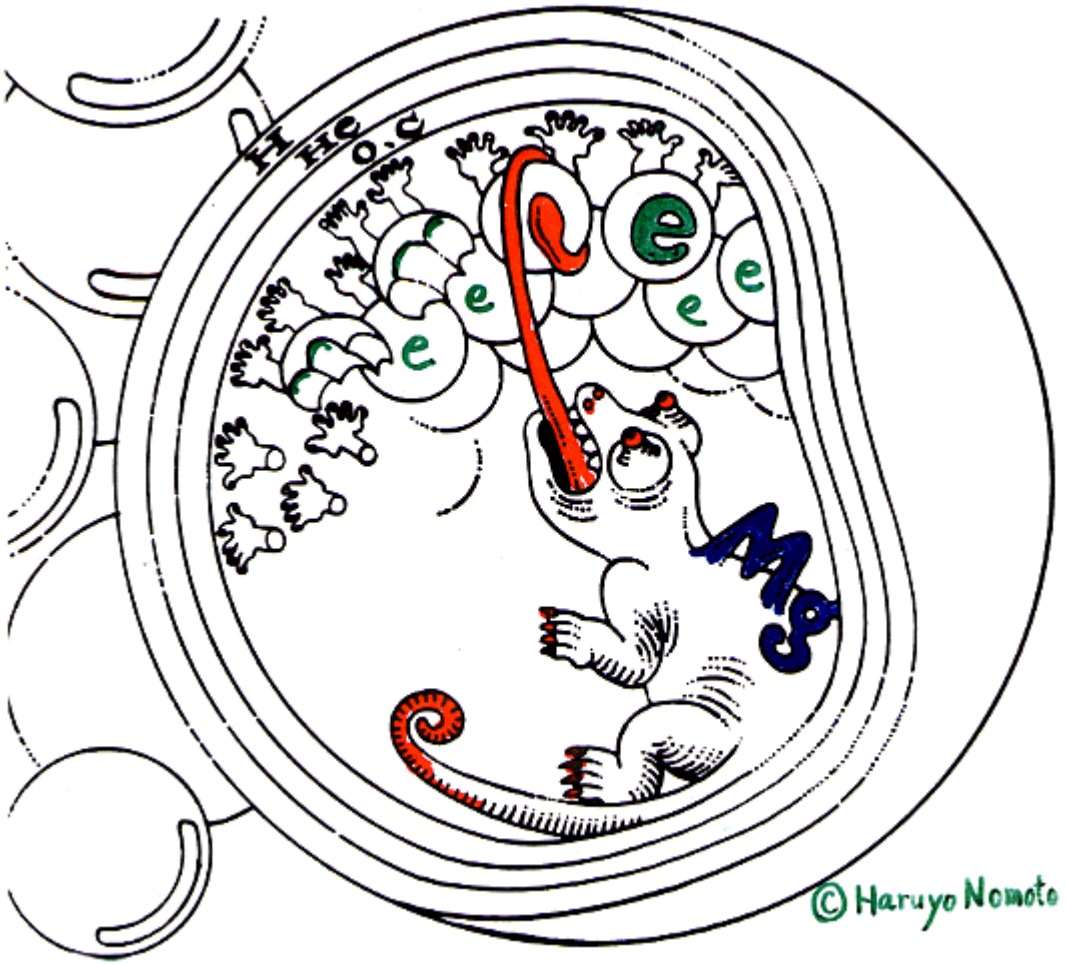
- $M_{up} < M < 10\ M_\odot$ ($M_{core} \sim M_{Ch}$)

  ONeMg Core Collapse SN II

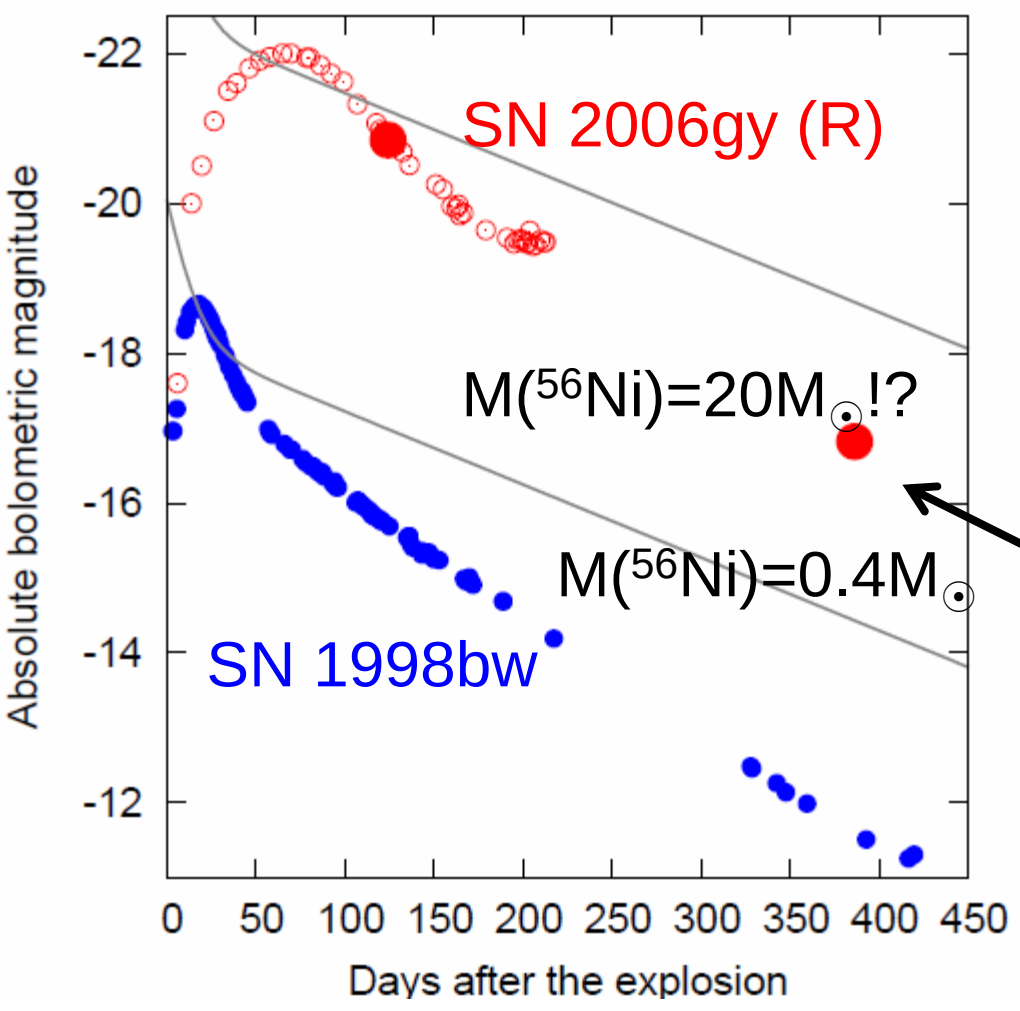
  due to Electron Capture

Electron Capture in ONeMg Core

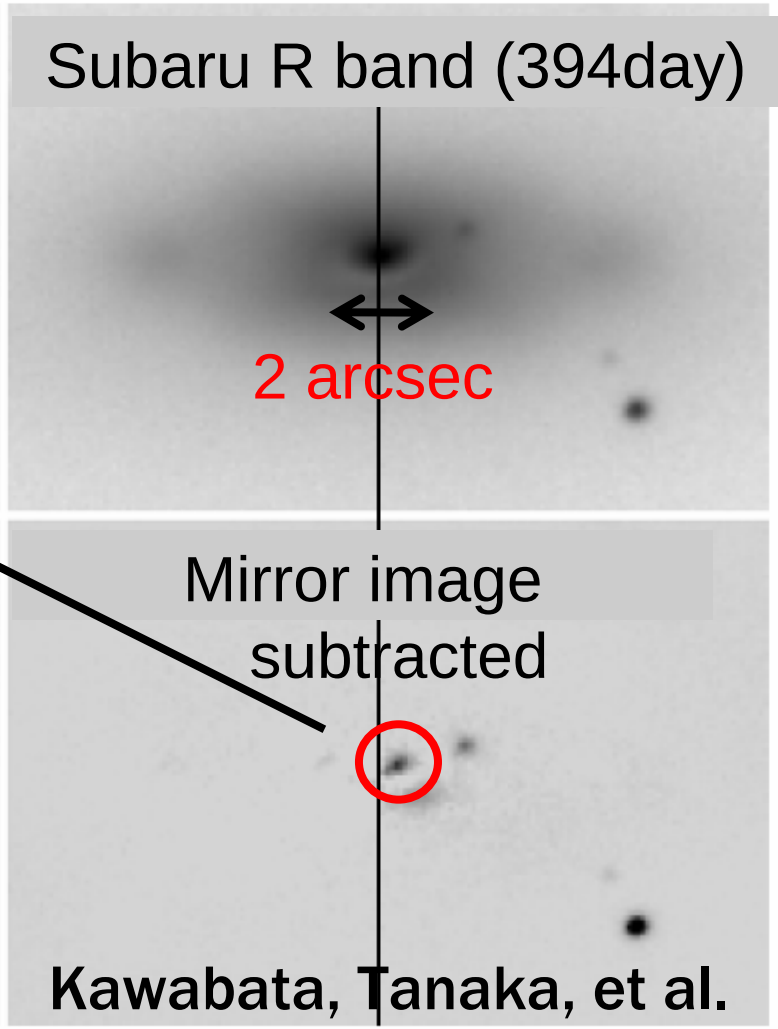
- $^{24}Mg(e^-,\nu)^{24}Na$ $(e^-,\nu)^{24}Ne$
- $\rho > 4.0 \times 10^9 gcm^{-3}$
- →collapse



Most Luminous Supernova 2006gy

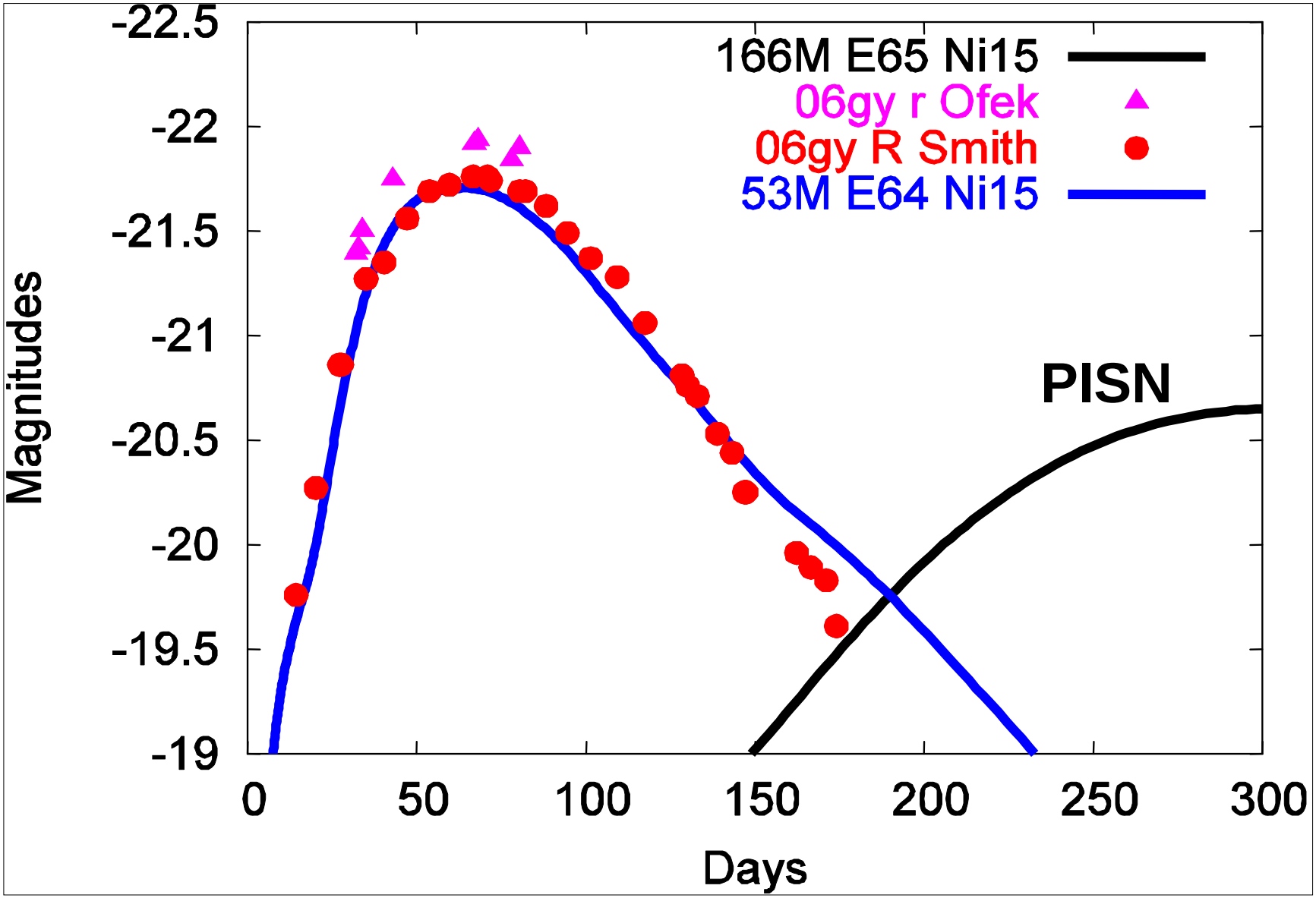


Also Agnoletto et al. (08)



(ApJ 2009; also Poster)

SN2006gy vs PISN



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 ?