Day 1. Nucleosynthesis of massive stars and supernovae

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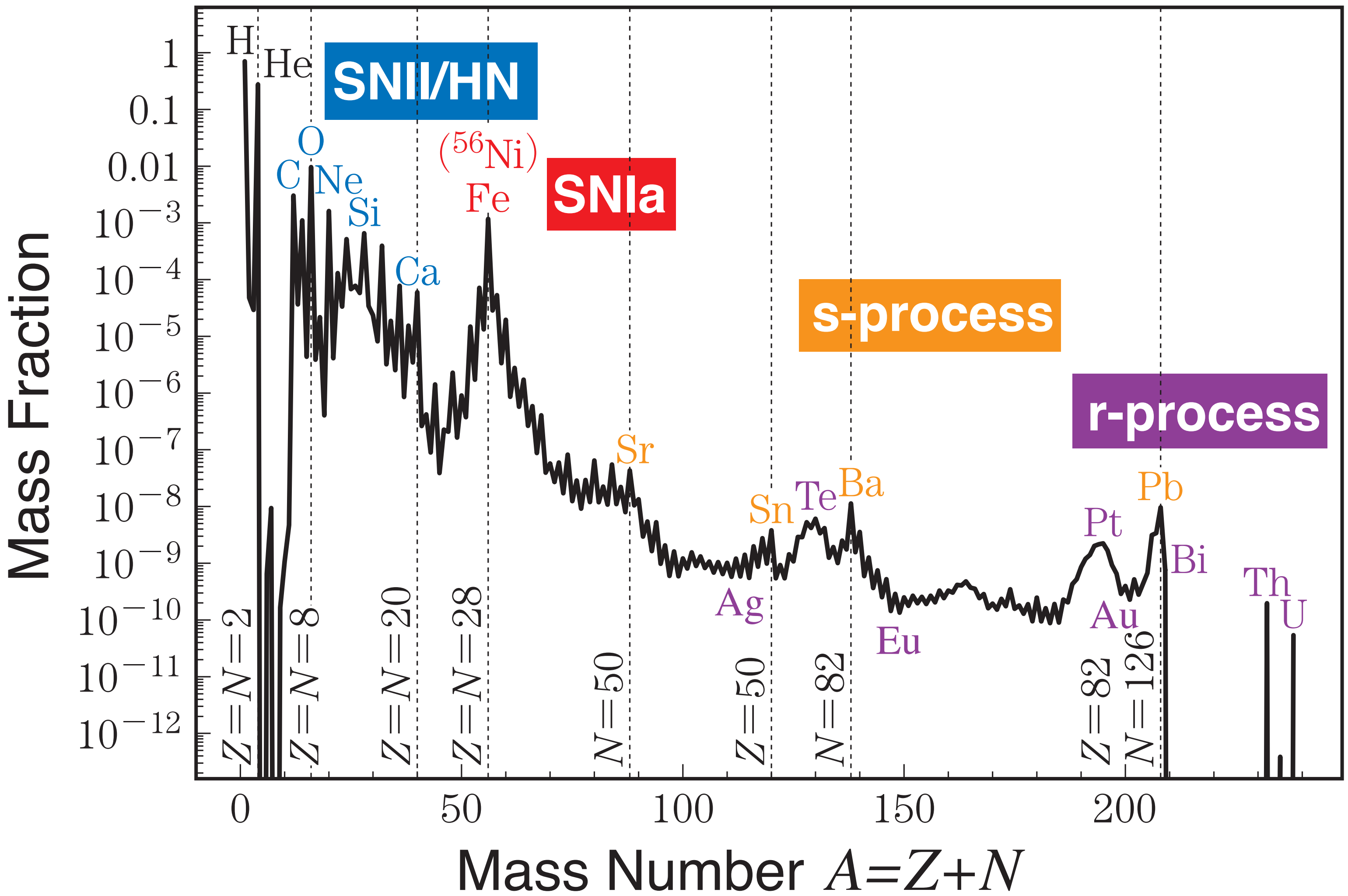
Origin of Elements

Big Bang Nucleosynthesis: 1H, 2H, 4He, 7Li



※ Metallicity Z = mass fraction of elements heavier than He

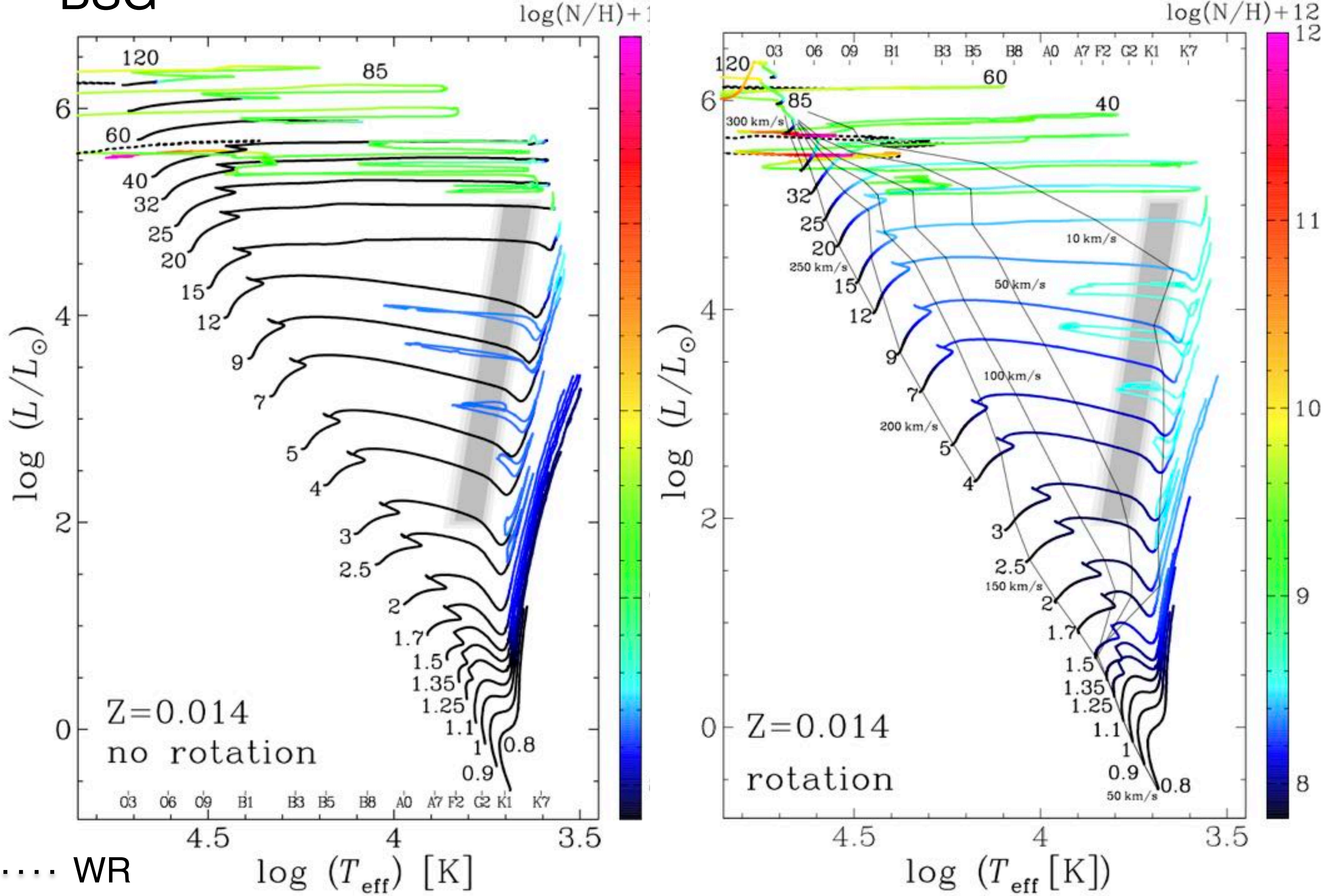
Contents

Core-collapse Supernoave

Rotation effect

Ekström+12

BSG



...... WR

Cepheid instability strip

Binary effect

Single stars

Binary stars (Eldridge et al. 2013)

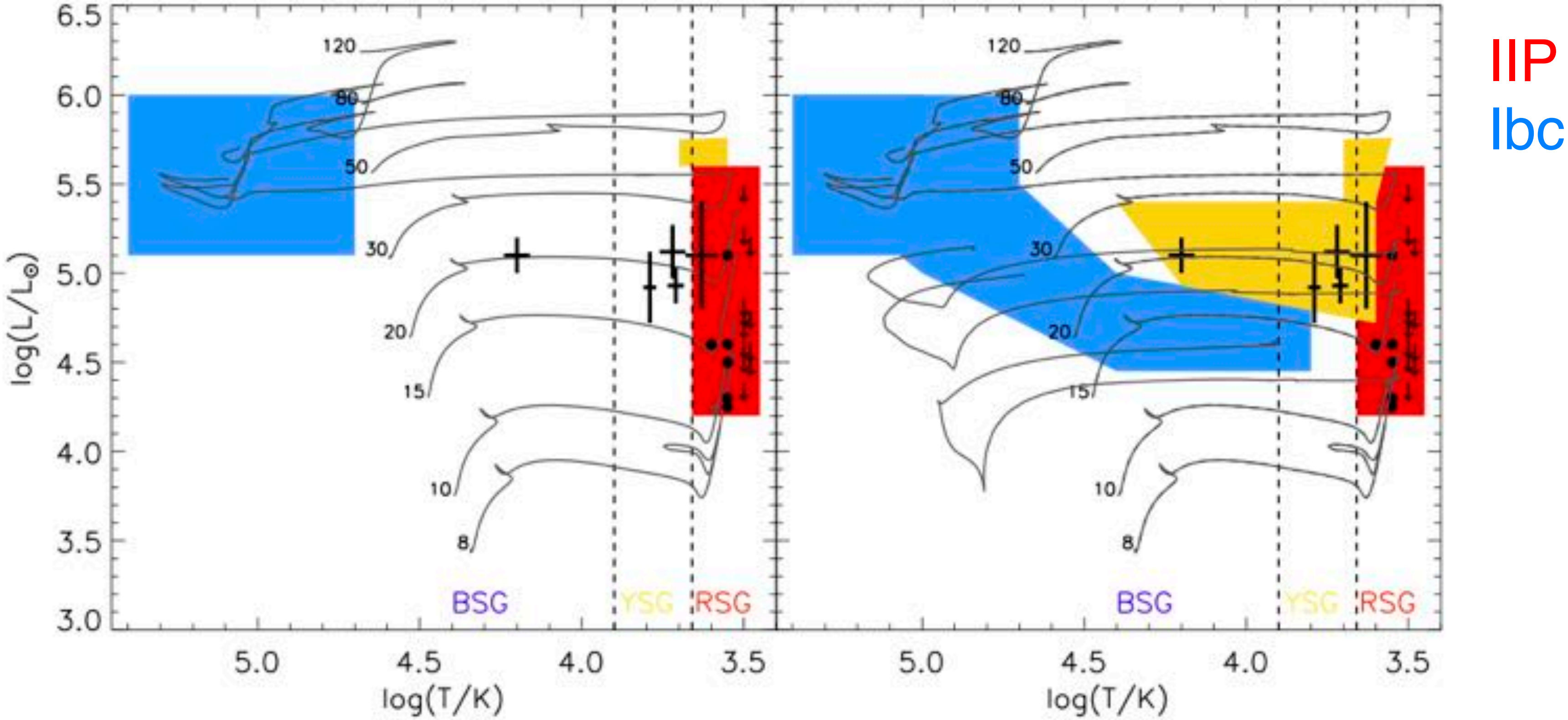
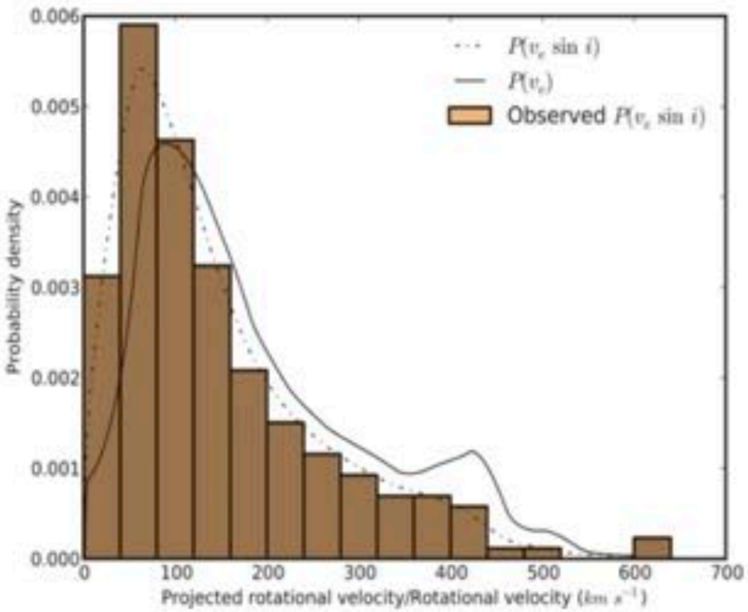


Figure 12. Cartoon HR diagrams of SN progenitors, the red, yellow and blue regions show the expected location of progenitors for type IIP, other type II and type Ib/c SNe. The left panel shows the single-star scenario. The solid lines show the evolution tracks for stars with masses given at their initial location. The right panel shows the binary scenario with the solid tracks at 10, 15 and 20$M_\odot$ showing binary evolution tracks and the dashed lines the single star tracks. In both plots the points with error bars show the locations of SNe 1987A, 1993J, 2008cn, 2009kr and 2011dh (Podsiadlowski 1992; Maund et al. 2004; Elias-Rosa et al. 2009a, 2010; Fraser et al. 2010b; Maund et al. 2011) respectively. The circles show the progenitor locations of observed type IIP progenitors and the arrows the upper limits for these progenitors (Smartt et al. 2009).

Rotation vs binary

Rotation distribution of single O star in 30 Dor



Ramirez-Agudelo+ 2013

Most / all high v sin i objects
due to binary interaction ?

if so …

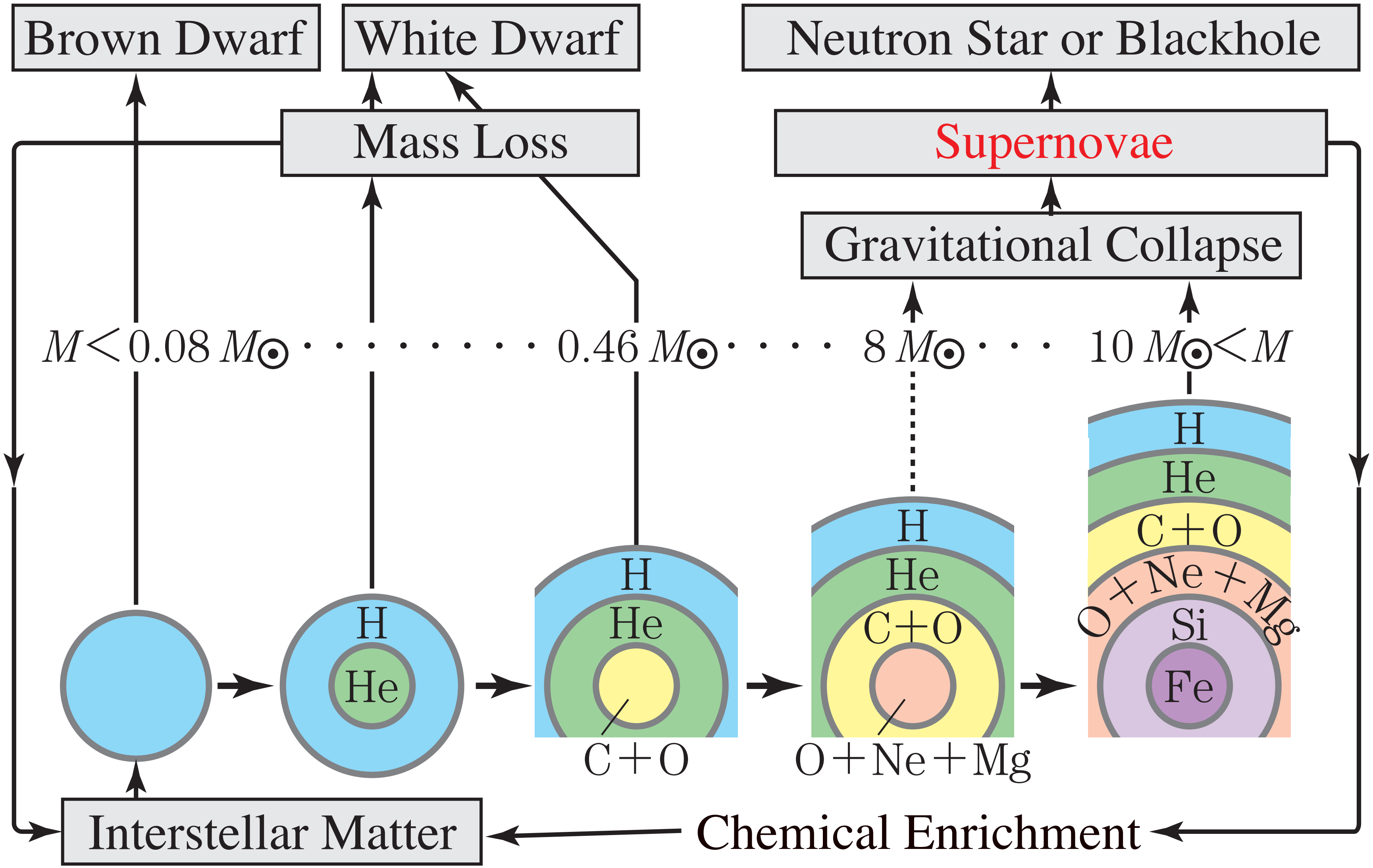
Outcome of massive star formation
* is *
moderately rotating stars
(100+/-30 km/s)

NO impact of rotation
on stellar evolution
before binary interaction

Ramirez-Agudelo+ , in prep.

Hugues Sana, talk at Binary Conference in Mongolia, Sep. 2014

Fate of Stars

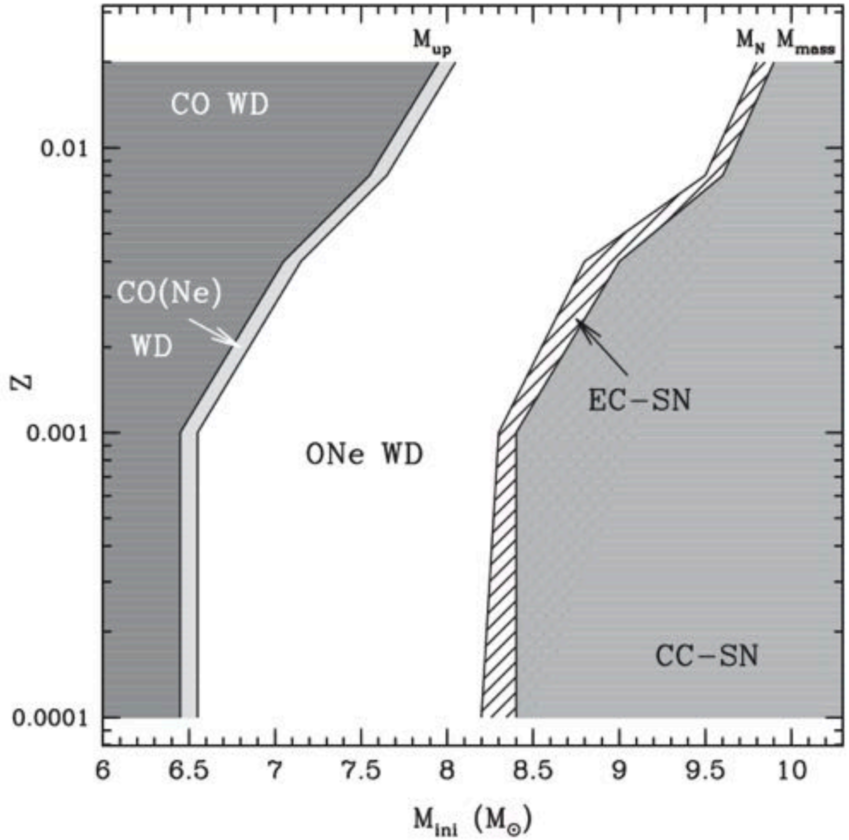


※ Solar Mass $M_{\odot}=2\times10^{33}$g

Super AGB & ECSN

- ~8-10$M_\odot$: semidegenerate C+O core
- ~8-9$M_\odot$: M_{core}=1.06$M_\odot$, off-center C ignition
- If the C burning does not propagates to the center, hybrid C+O+Ne WDs (Chen+14; Denissenkov+15), SN Iax?
- If C flame propagetes to the center, O+Ne+Mg core
- ~9-10$M_\odot$: central carbon ignition, O+Ne+Mg core
- If no Ne burning ignited, or if off-center Ne burning does not propagate to the center, ECSN
- >10$M_\odot$: M_{core}=1.37$M_\odot$, Ne ignition

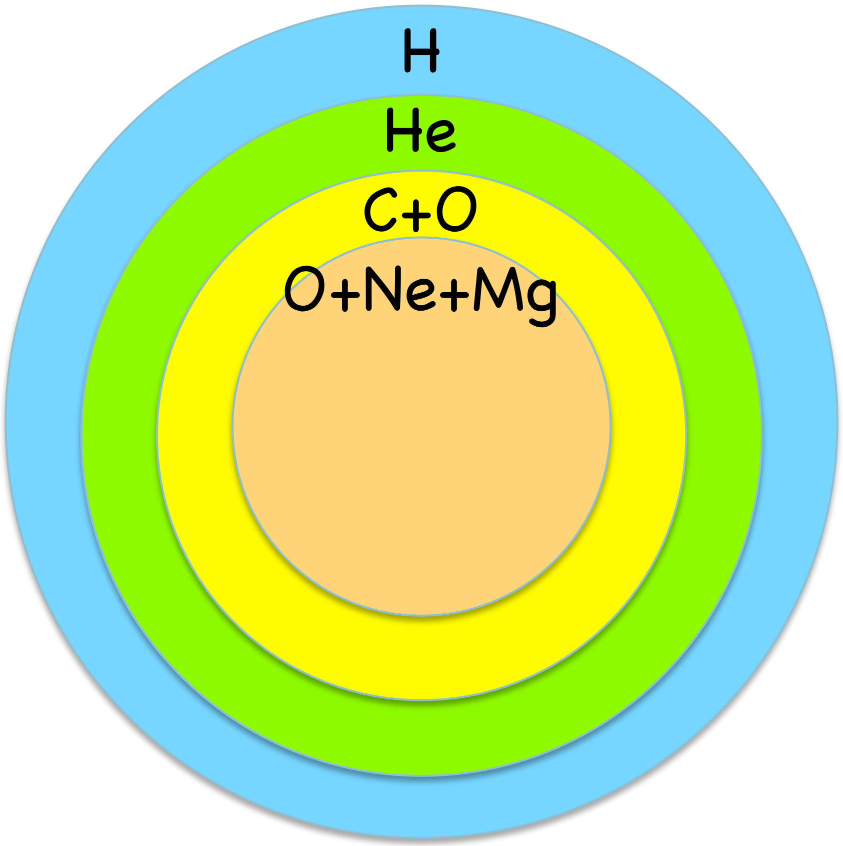
Nomoto 1984
Nomoto, CK, Tominaga 2013
CK, Hachisu, Nomoto 15



Doherty +15

Electron-capture SNe

$\sim$8-10$M_\odot$ @$Z_\odot$



H-He shell burning vs mass loss

↓

If M_{core}=1.38$M_\odot$, r=4x10^9 g/cm^3

↓

^{24}Mg(e$^-$, v) ^{24}Na (e$^-$, v) ^{20}Ne

^{20}Ne (e$^-$, v) ^{20}F (e$^-$, v) ^{20}O

↓

Gravitational collapse

Neutrino heating

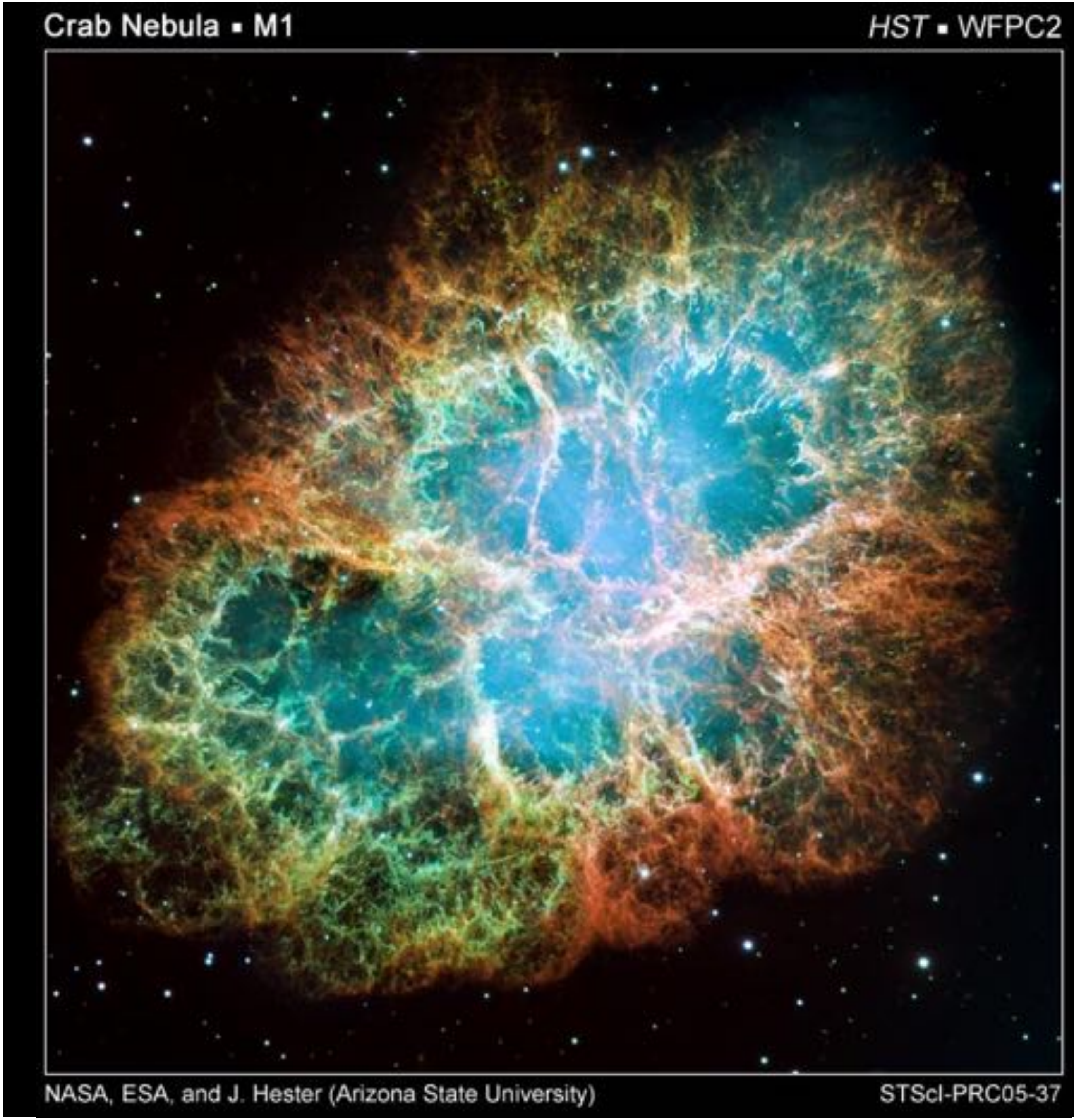
↓

Supernova explosion

M_Z~0.003$M_\odot$

↓

Neutron stars



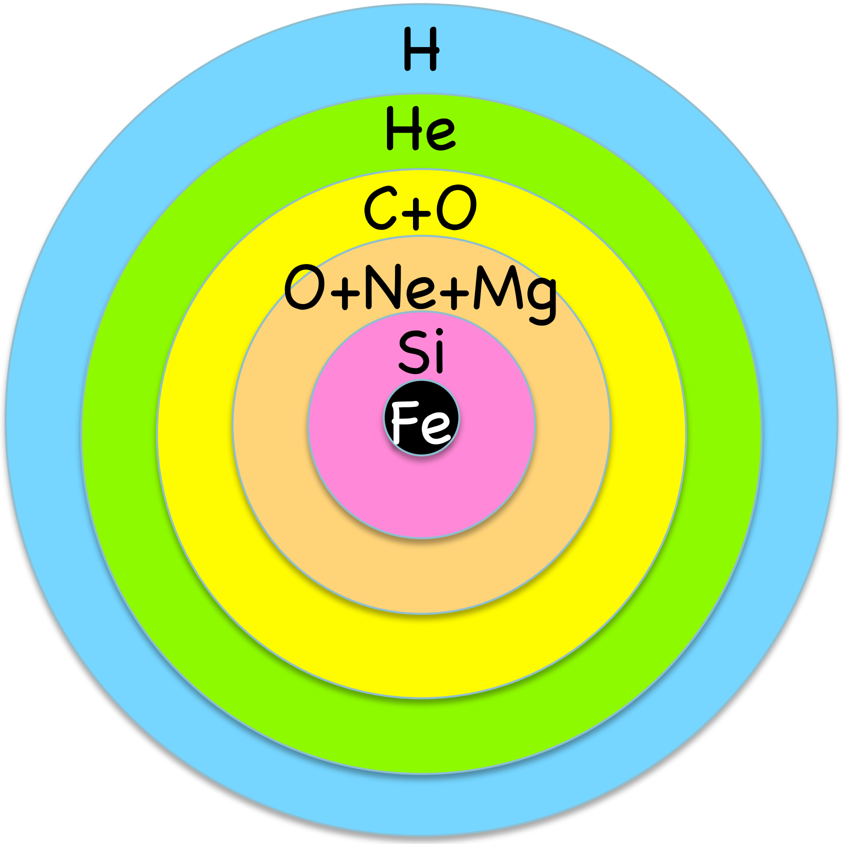
ECSN
(Nomoto+ 82)

PSR B0531+21
M_{NS}~$1.4M_{\odot}$

1054年
藤原定家「明月記」

Fe-core collapse SNe

$>10M_\odot$ @$Z_\odot$



Hydrostatic burning

$^{12}C(\alpha,\gamma)^{16}O$ if $T>5\times10^8$ K

…

↓

Photodissociation (Q<0)

$^{56}Fe \rightarrow 13\,^4He + 4n - 124.4MeV$

$^4He \rightarrow 2p + 2n - 28.3MeV$

↓

Gravitational collapse

Neutrino heating? MHD??

↓

Supernova explosion

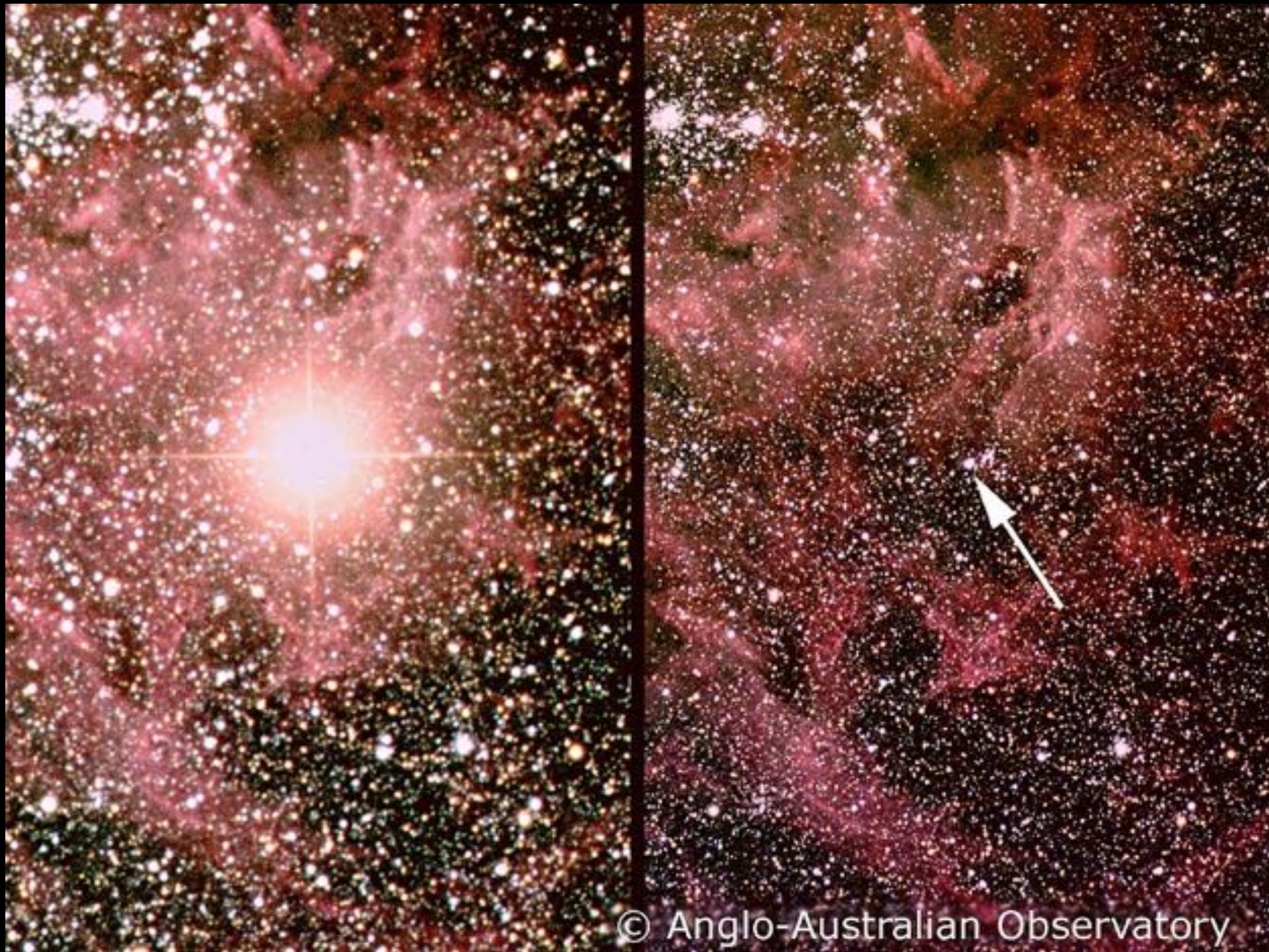
$^{56}Ni \rightarrow ^{56}Co + \nu_e + \gamma \rightarrow ^{56}Fe + 2\nu_e + 2\gamma$

Explosive nucleosynthesis

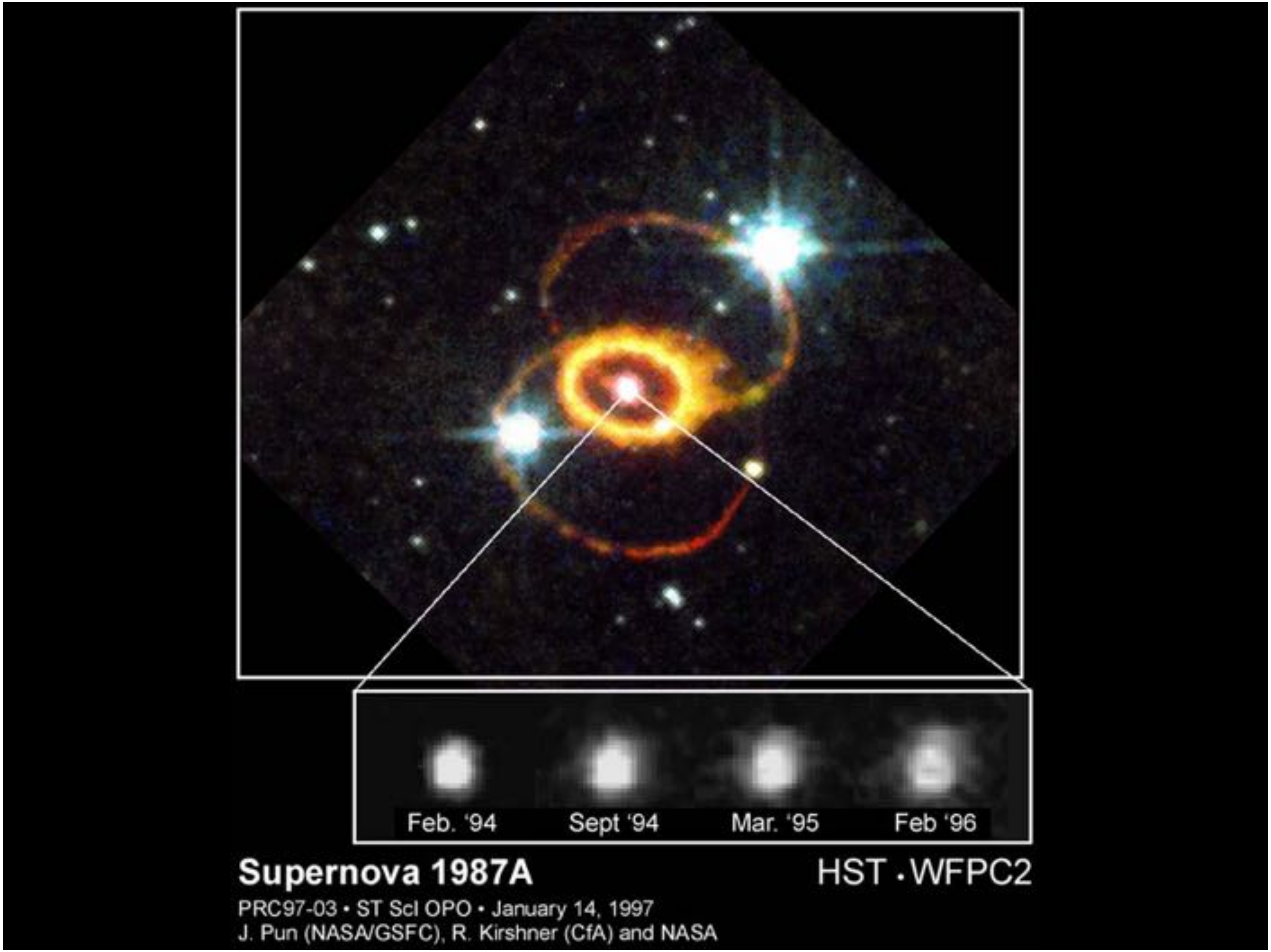
↓

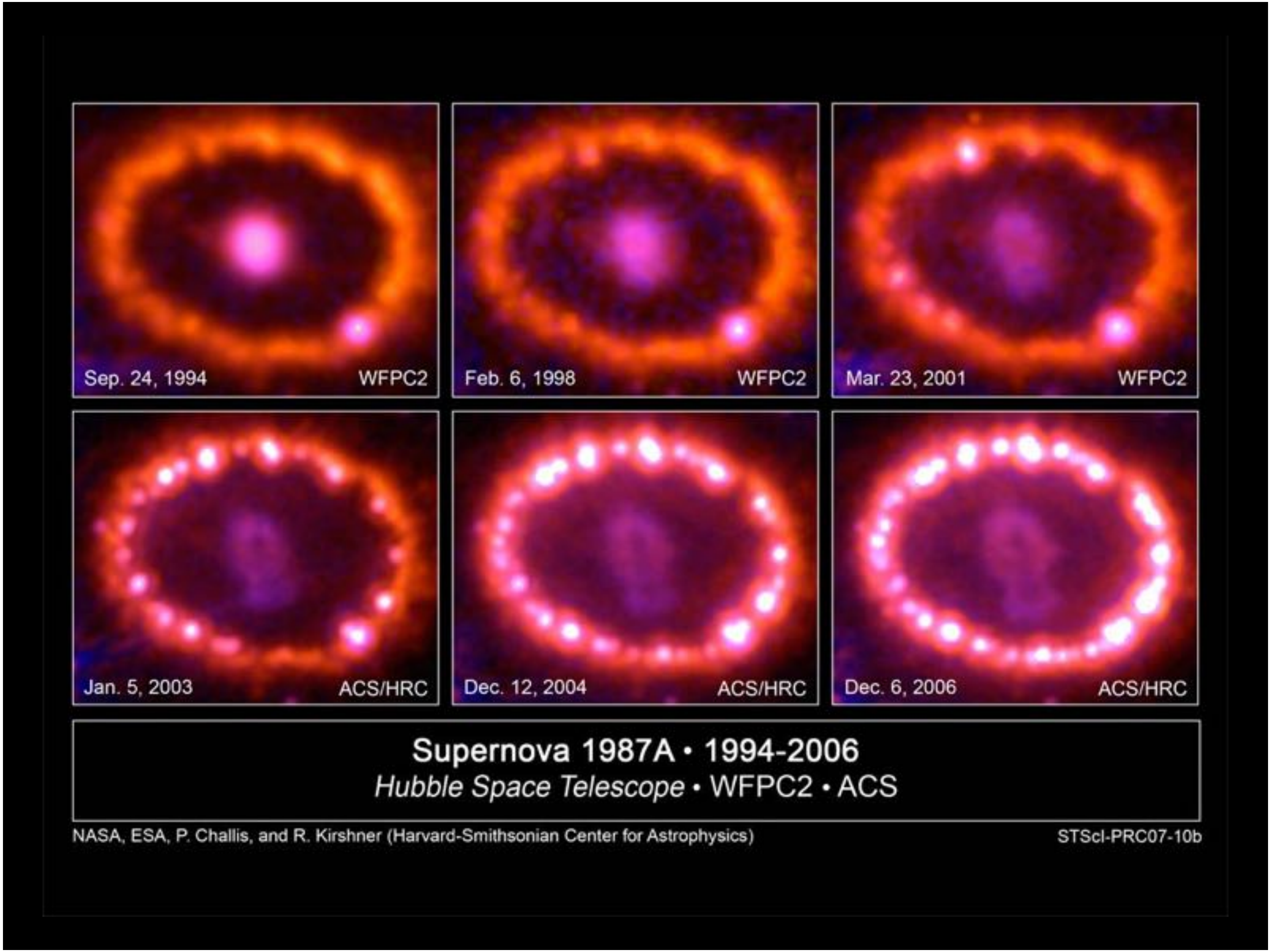
Neutron stars or Blackholes

SN1987A in LMC on 2/23/1987



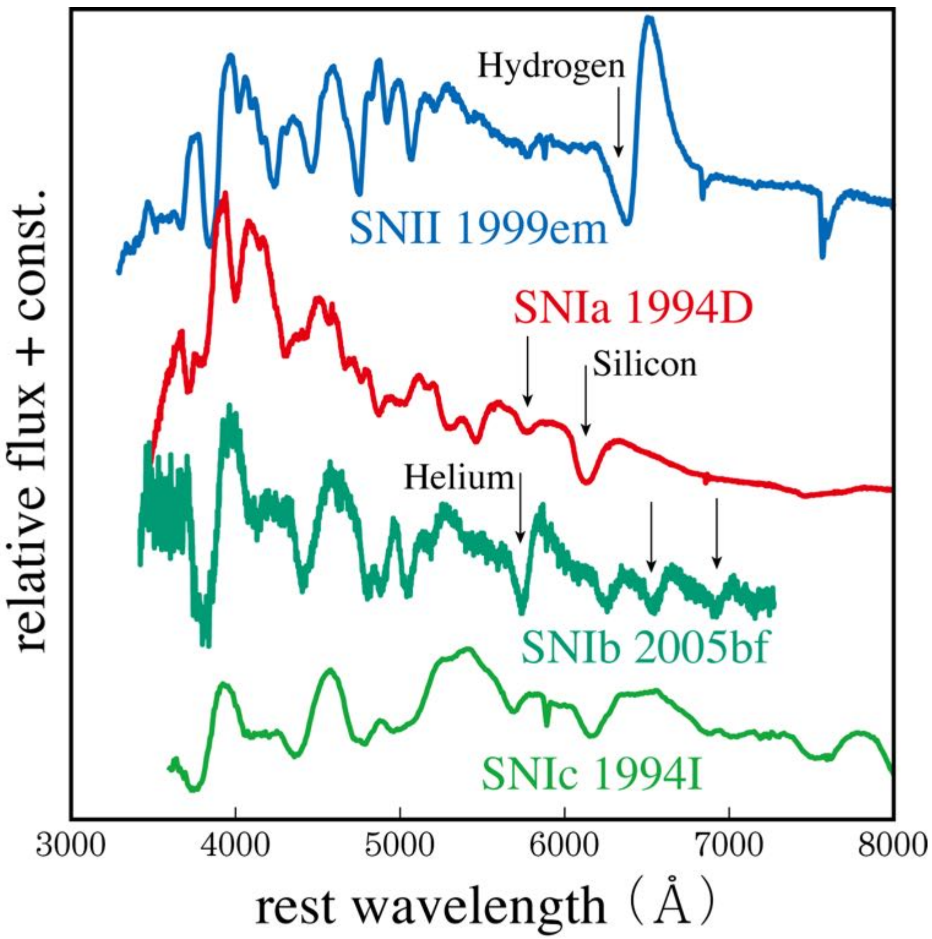
BSG


Feb. '94
Sept '94
Mar. '95
Feb '96
Supernova 1987A
HST • WFPC2
PRC97-03 • ST ScI OPO • January 14, 1997
J. Pun (NASA/GSFC), R. Kirshner (CfA) and NASA

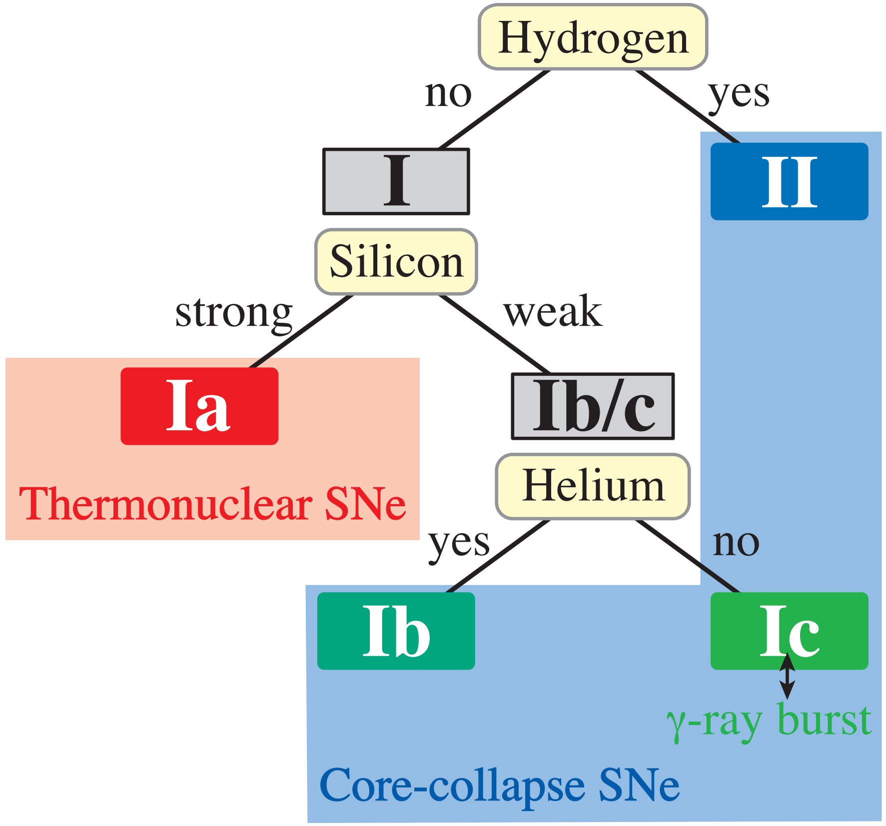

Sep. 24, 1994
WFPC2
Feb. 6, 1998
WFPC2
Mar. 23, 2001
WFPC2
Jan. 5, 2003
ACS/HRC
Dec. 12, 2004
ACS/HRC
Dec. 6, 2006
ACS/HRC
Supernova 1987A • 1994-2006
Hubble Space Telescope • WFPC2 • ACS
NASA, ESA, P. Challis, and R. Kirshner (Harvard-Smithsonian Center for Astrophysics)
STScI-PRC07-10b

Type of Supernovae

✷ Spectra



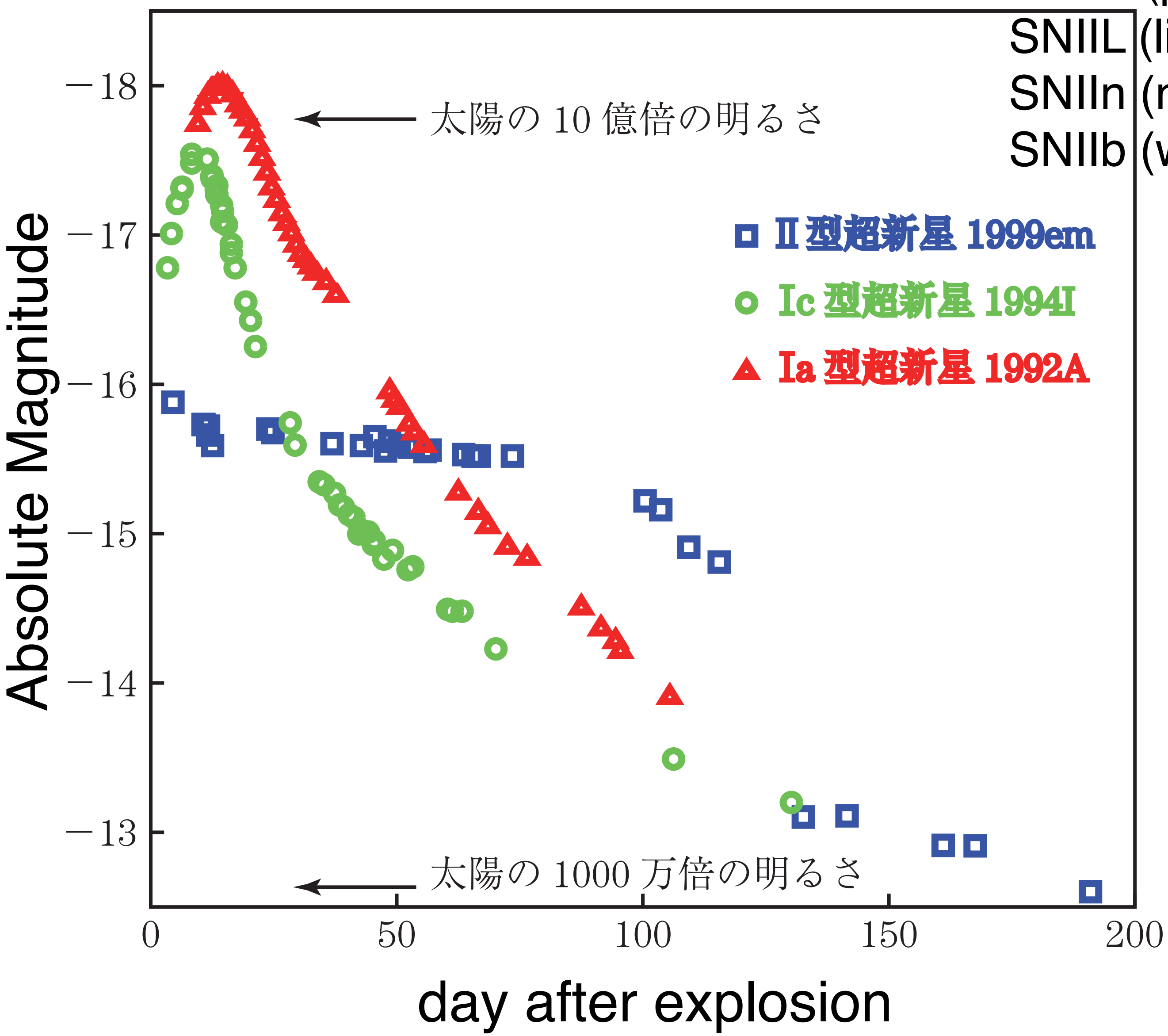
✷ Explosion



bright → Hypernovae

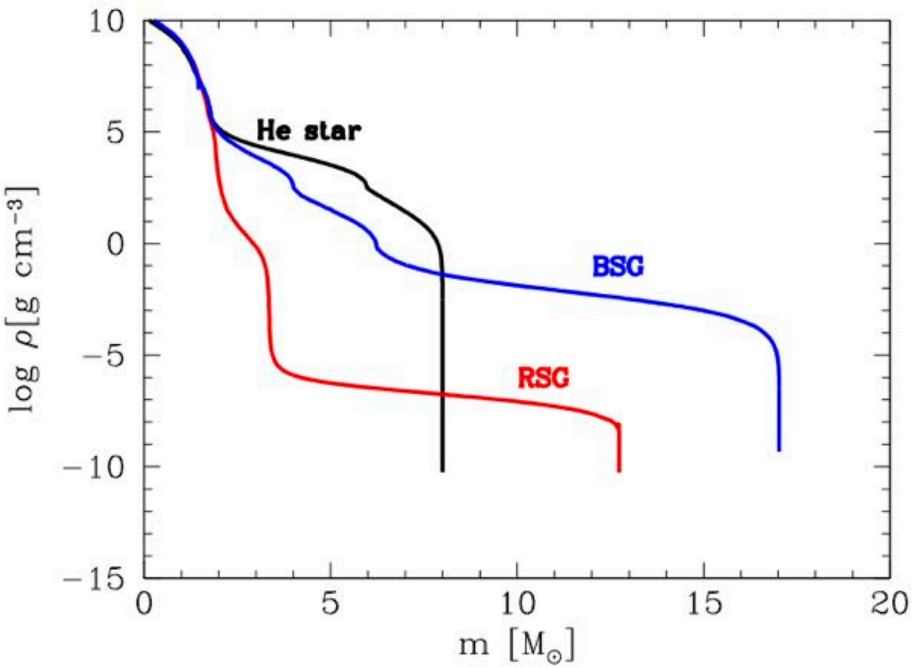
SN Light Curve (obs.)

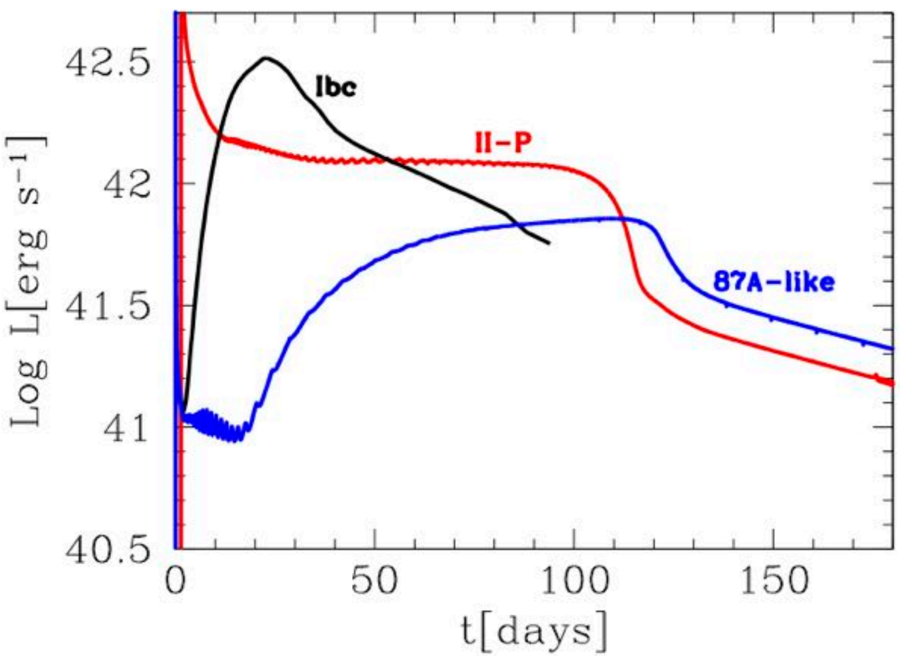
SNIIP (plateau)
SNIIL (linear)
SNIIn (narrow lines)
SNIIb (weak H line)



SN light curve (model)

- Hydrodynamics + Radiative-Transfer model
  - Circumstellar interaction
  - Mass-loss via rotation vs binary
  - both will depends on metallicity
- Yields should be similar → “**SNII” in this lecture**





M. Bersten talk at MIAPP Aug. 2016, Munich
also, KEPLER, Blinnikov, Mazzali, Maeda, Sim, etc

Fraction of SNe

Lick Observatory Supernova Search (Li+11)

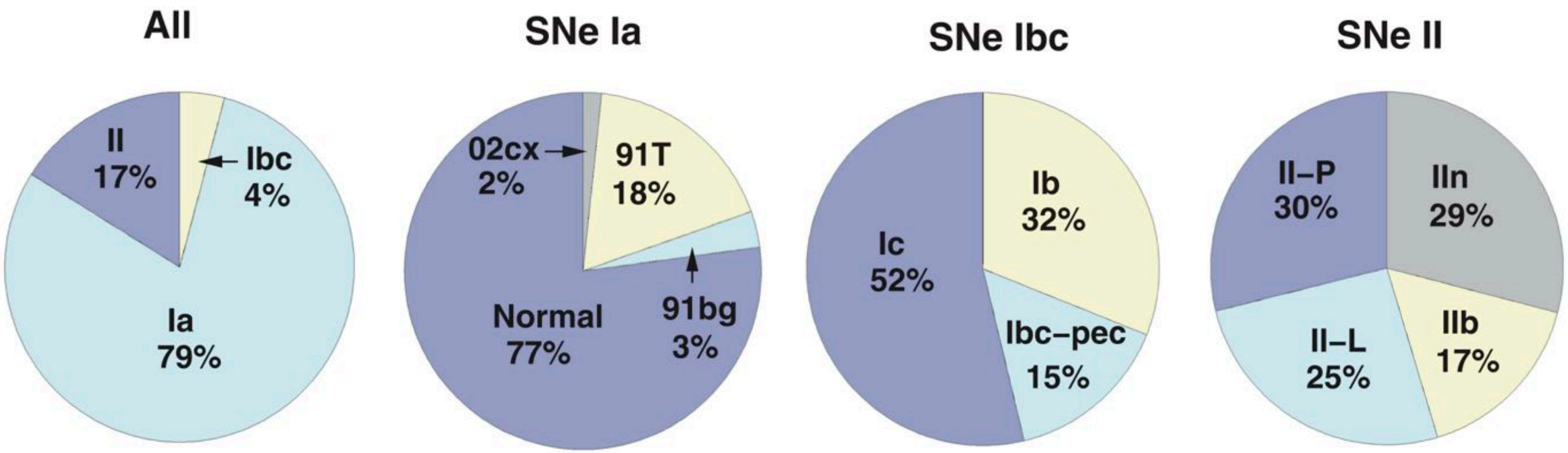
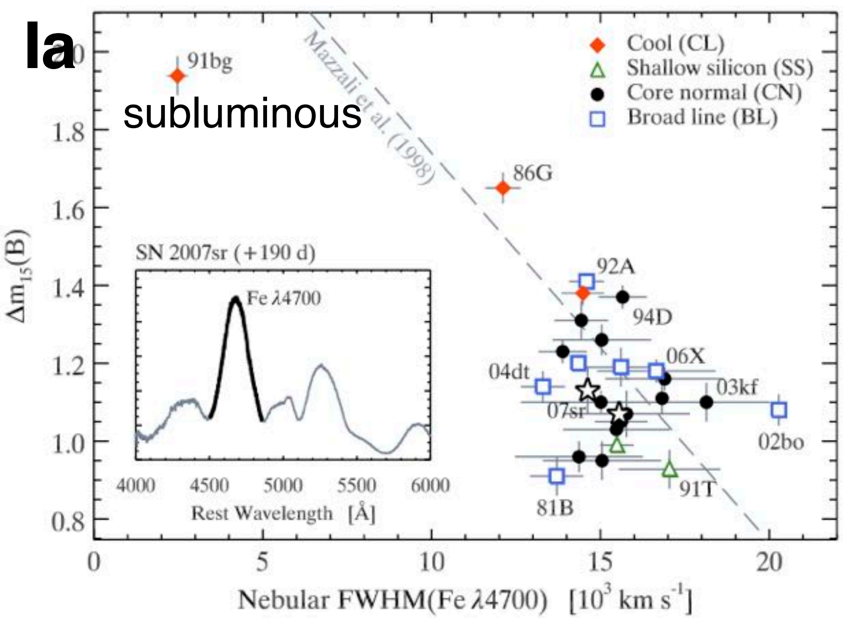


Figure 11. The observed fractions of the subclasses of SNe in an ideal magnitude-limited sample, illustrated as pie charts.



core-collapse

II-P (plateau)

II-L (linear)

IIn (narrow lines)

IIb (weak H line)

Ib (no H)

Ic (no H, no He)

Ibc-pec (Ca-rich or broad-line)

How does a supernova shine?

- Gravitational Energy

$$E_{\rm Grav} = \frac{GM_{\rm NS}^2}{R_{\rm NS}} = 3\times 10^{53}\,{\rm erg}\left(\frac{M_{\rm NS}}{M_{\rm sun}}\right)^2\left(\frac{R_{\rm NS}}{10\ {\rm km}}\right)^{-1}$$

$$E_{\rm kin} \sim 10^{51}\,{\rm erg} \equiv 1\ {\rm foe}$$

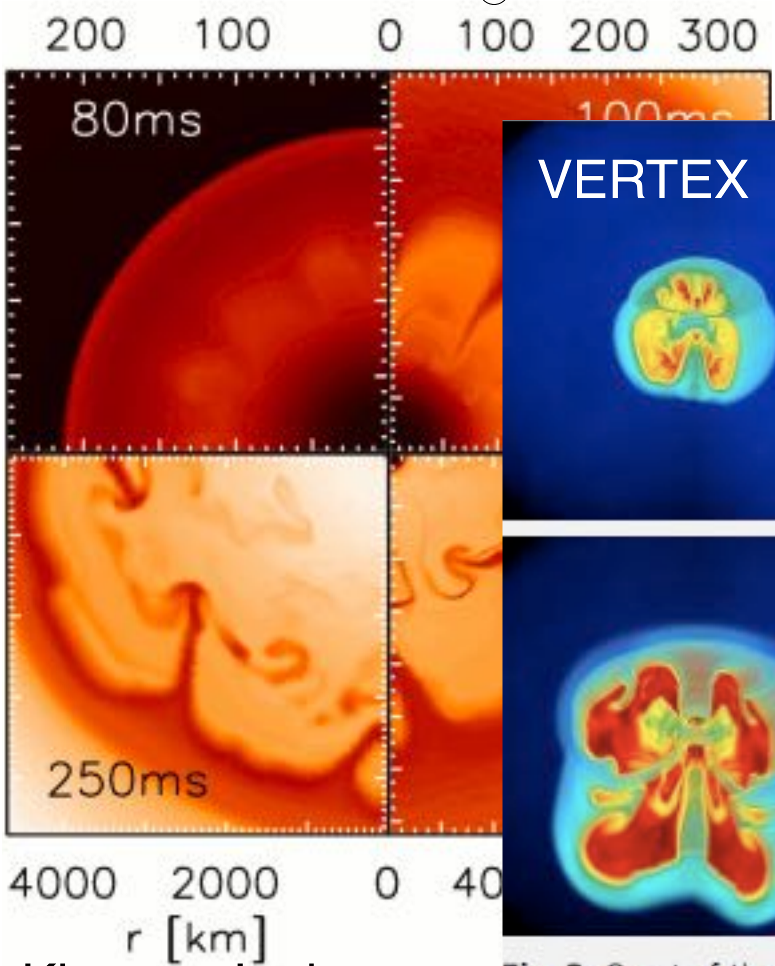
- 99% of energy is released in the form of neutrino
  - Neutrino heating (Colgate & White 1966)
  - SASI (Standing Accretion Shock Instability, Blondin et al. 2003)
- Core-bounce → **Shock** - heating → Expansion – cooling
- **Radioactive Decay**
  - ^{56}Ni (6days) → ^{56}Co (77days) → ^{56}Fe
- **Interaction with circumstellar matter**
  - SNIIP-IIL-IIb-IIn-Ib-Ic??
  - progenitor mass range? binary effect? metallicity effect?

2D/3D simulations

8.8 $M_\odot$

✷ Few parameters. Central parts?

12-25$M_\odot$



Kitaura, Janka, Hillebrandt 06 (2D)

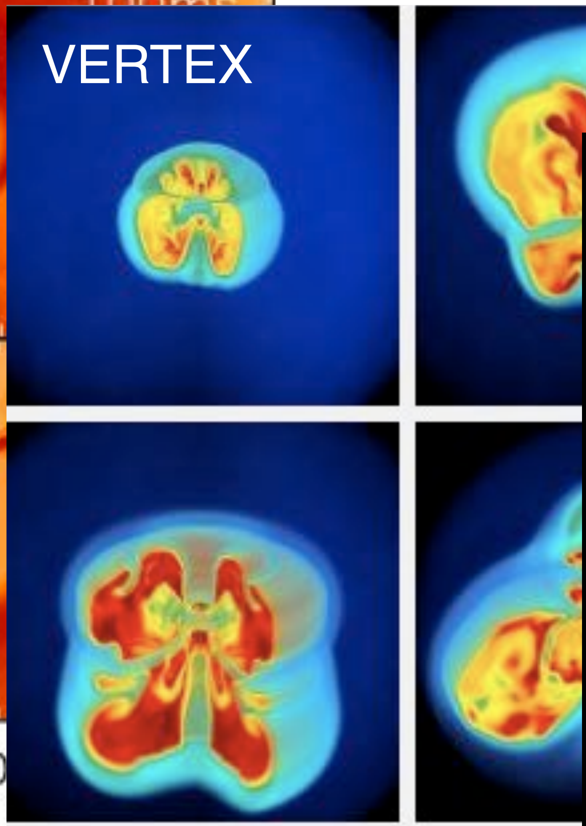


Fig. 2: Onset of the supernova explosion o
solar masses. The images show a sequence
from the computer simulation at 0.53, 0.6
seconds (from top left to bottom right) aft
core has collapsed to a neutron star.

Marek & Janka 09

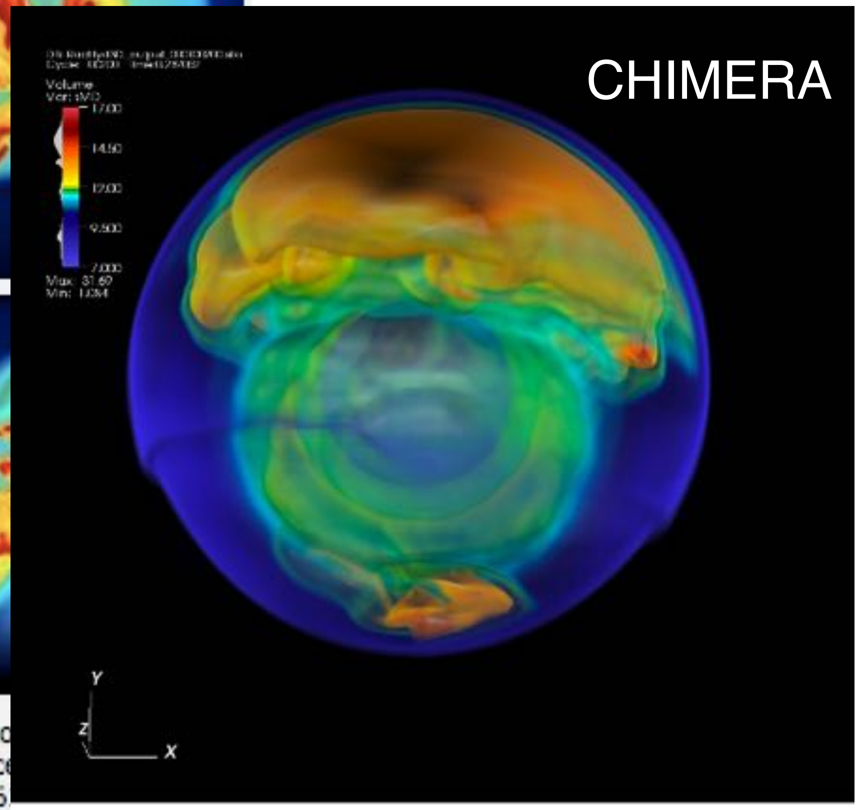
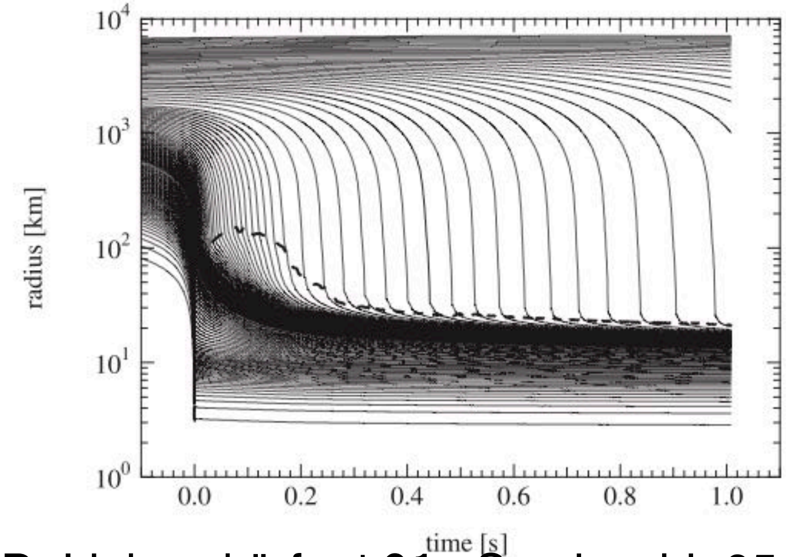


Figure 2. Snapshot of the entropy distribution of the 15 $M_\odot$ 3D simulation at 132 ms post-bounce time.

Bruenn, Mezzacappa+ 09,13

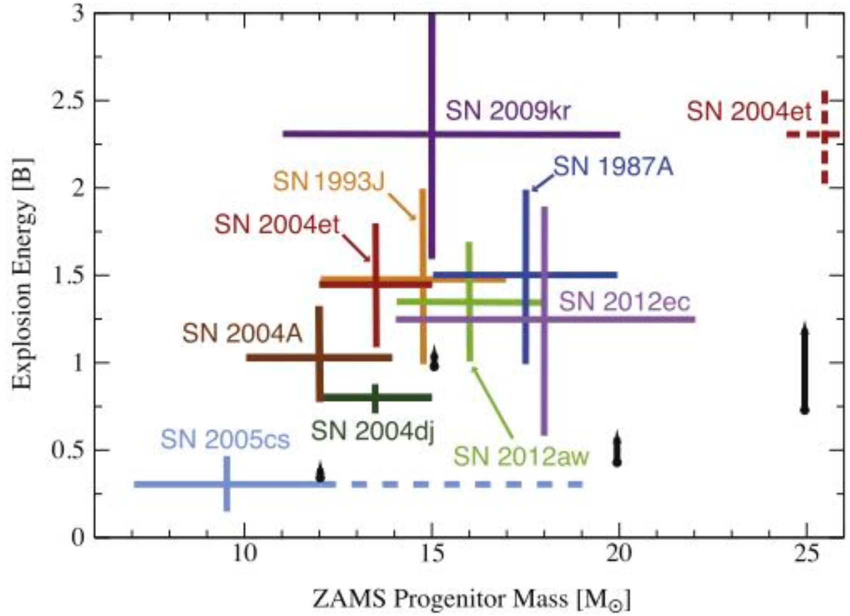
Also, Burrows+ 07
Takiwaki, Kotake, Suwa 12

1D/2D/3D failure & success

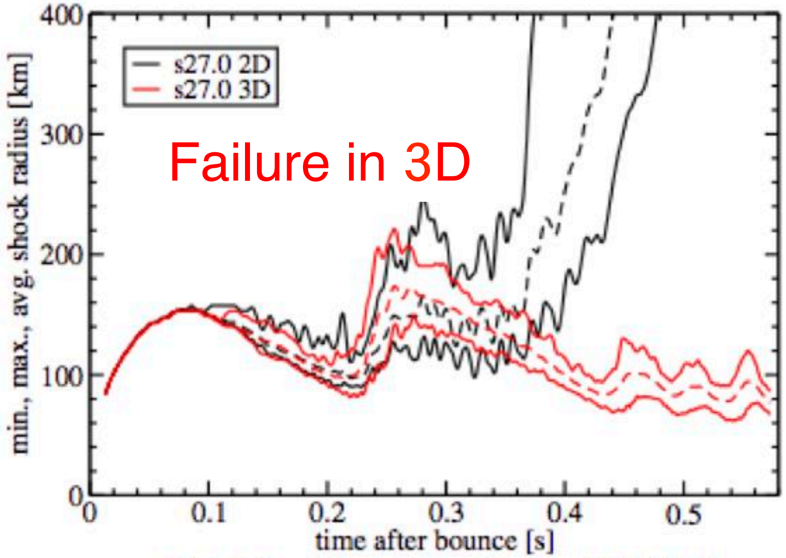


1D: Liebendörfer+01; Sumiyoshi+05 (fig)

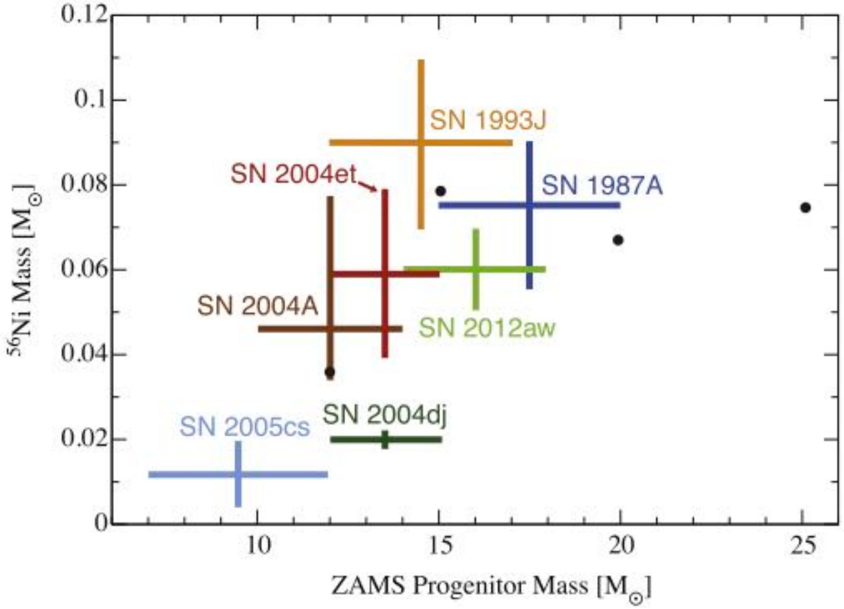
FIG. 1.—Radial trajectories of mass elements of the core of a 15 $M_\odot$ star as a function of time after bounce in model SH. The location of shock wave is displayed by a thick dashed line.



2D: Bruenn+ 16, with nucleosynthesis



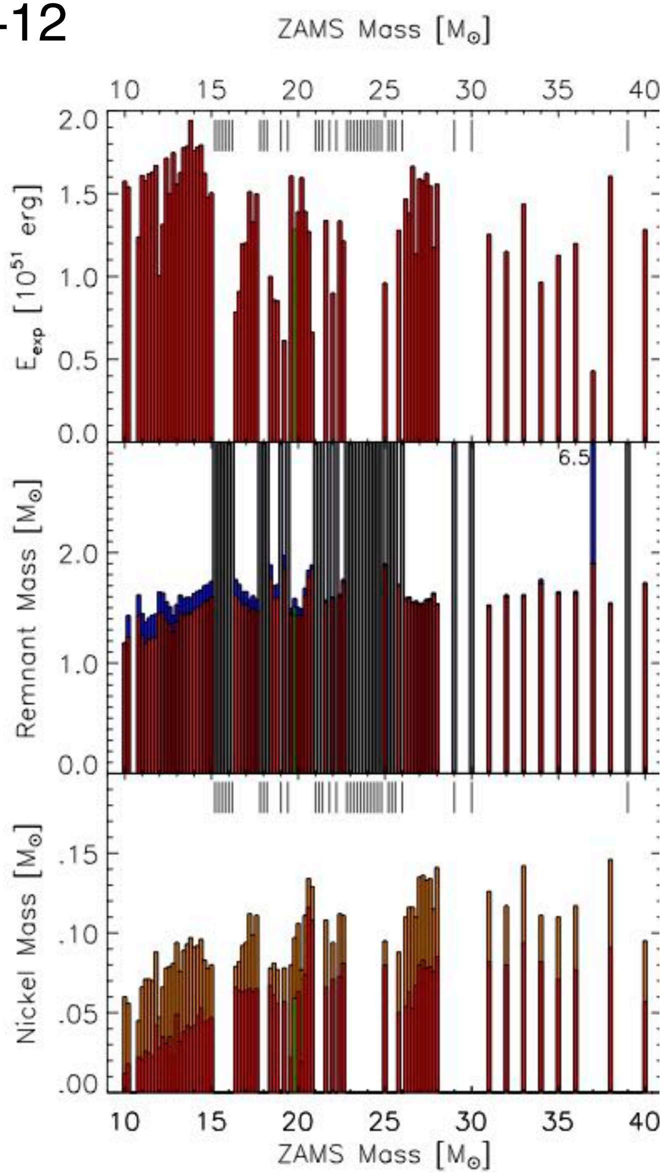
27 $M_\odot$ Hanke et al. (2013)



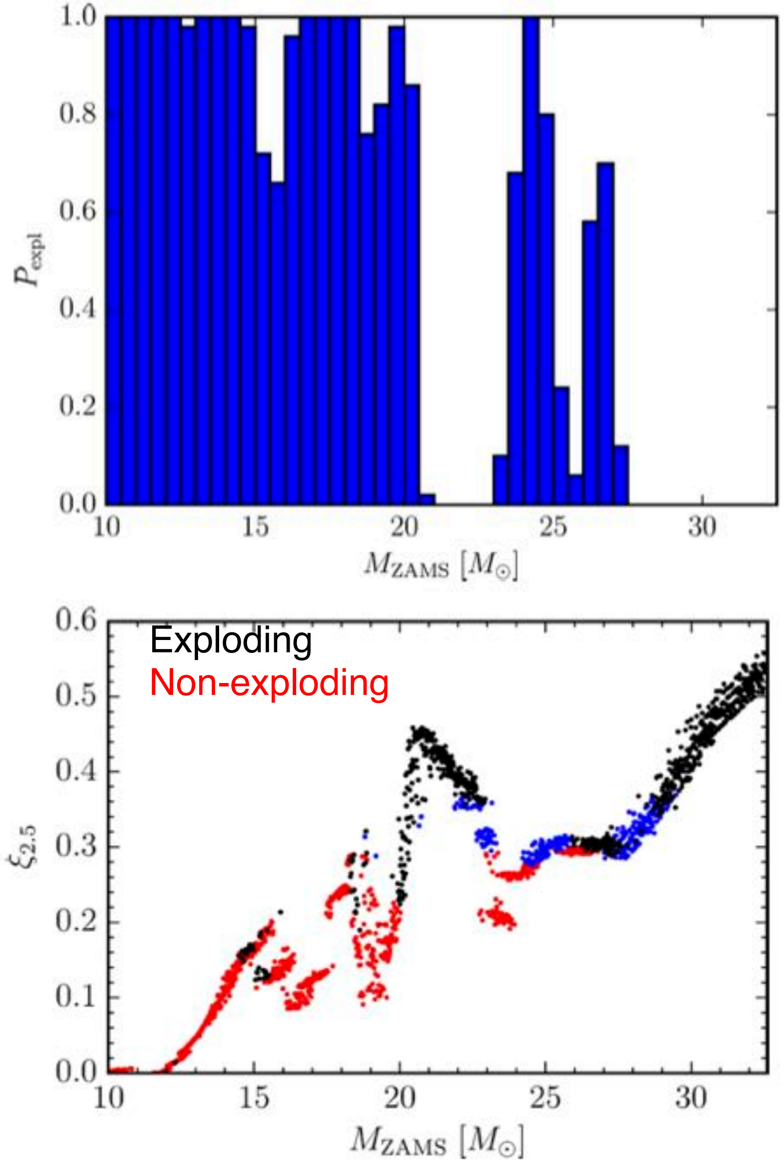
Systematics with 1D

with Heger & Woosley (2010) stellar evolution models, $Z_\odot$

Ugliano+12

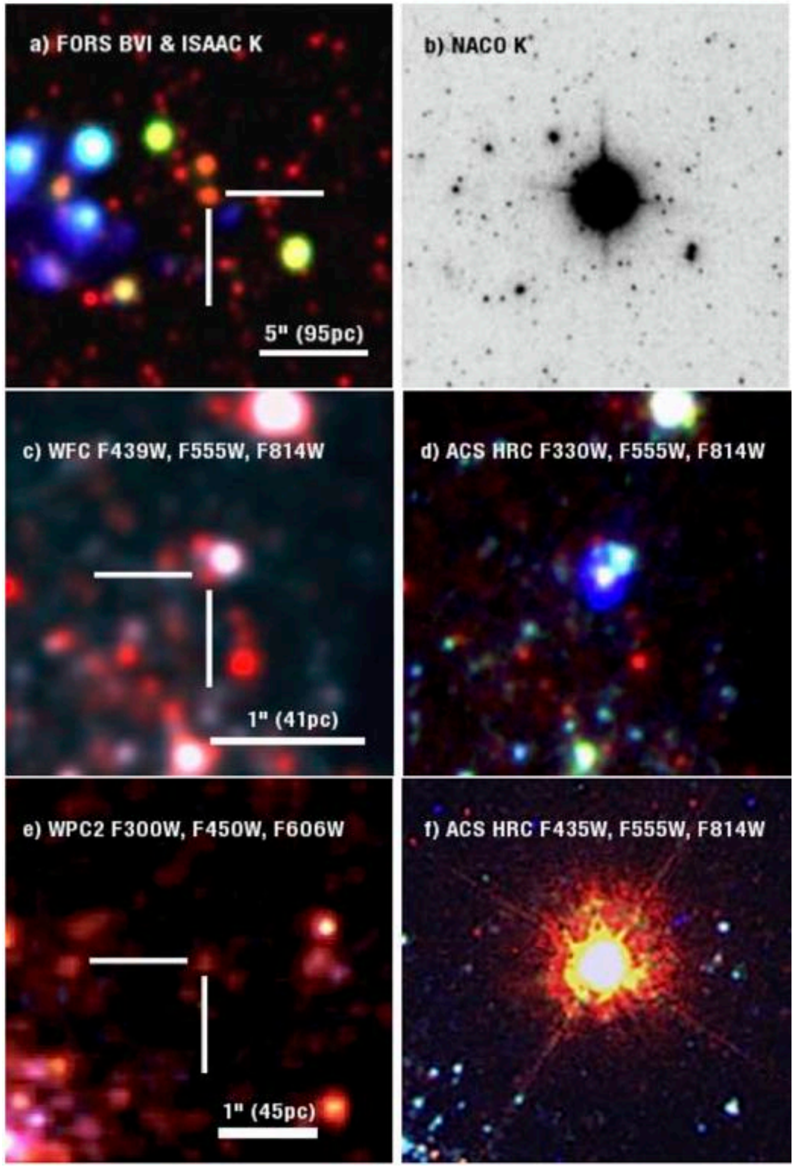


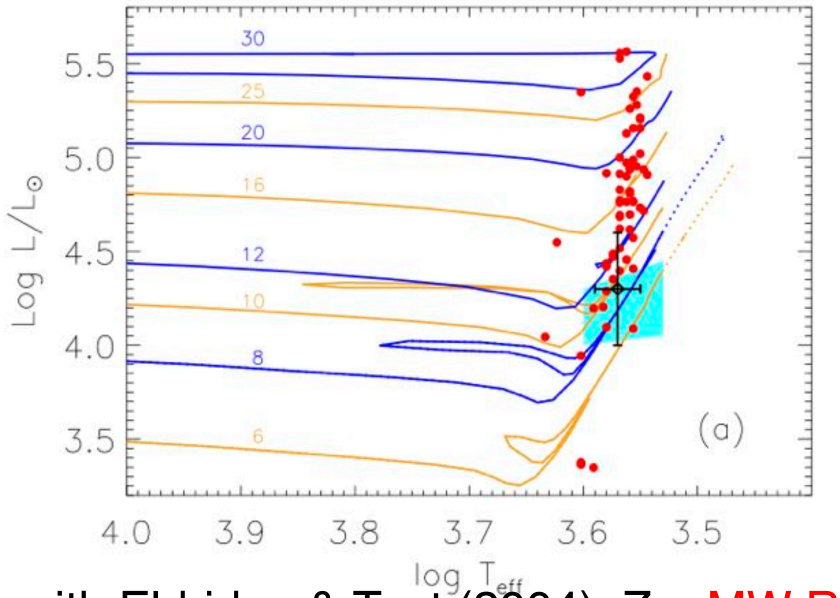
Müller+16



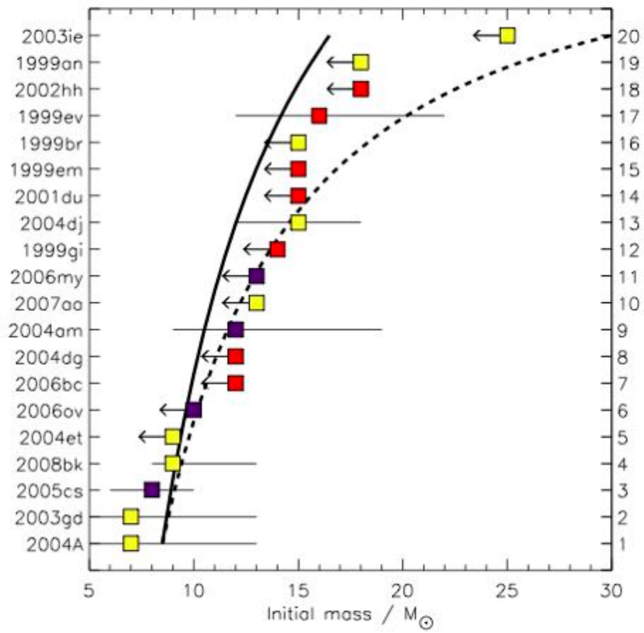
Failed Supernovae >20M$_\odot$

Smartt (2099), ARAA



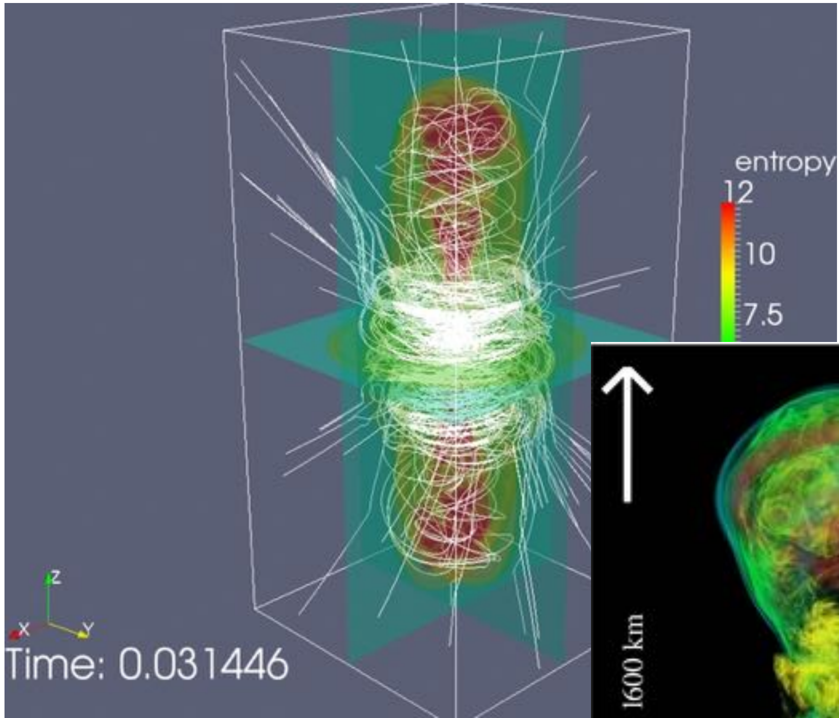


with Eldridge & Tout (2004), Z$_\odot$, MW RSGs



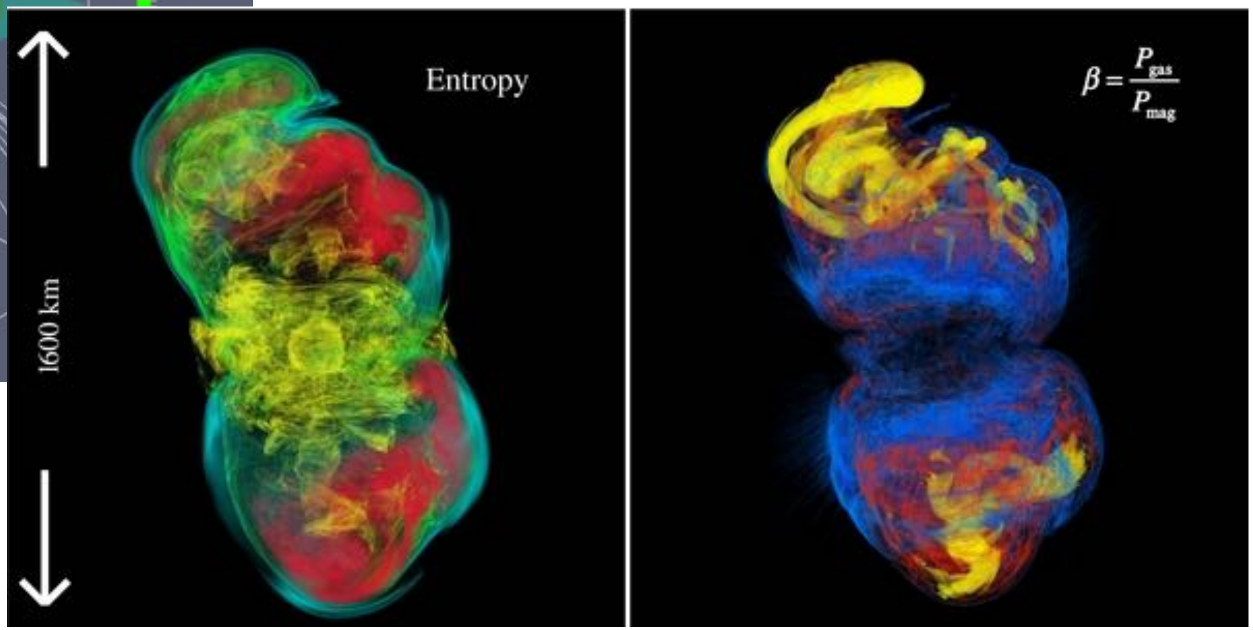
MHD-driven HNe

- neutrino-driven mechanism give <2x10^{51} erg
- 2D MHD simulations (Shibata et al. 2006; Burrows et al. 2007; Takiwaki & Kotake 2011…) and 3D:



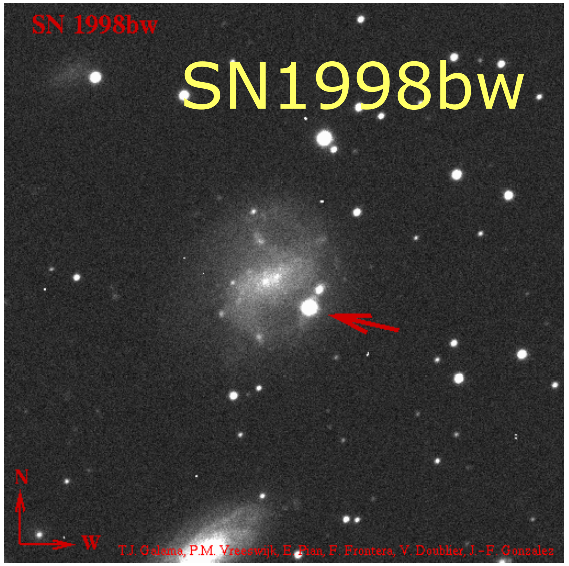
←Winteler et al. 2012
r-process nucleosynthesis
with tracer particles

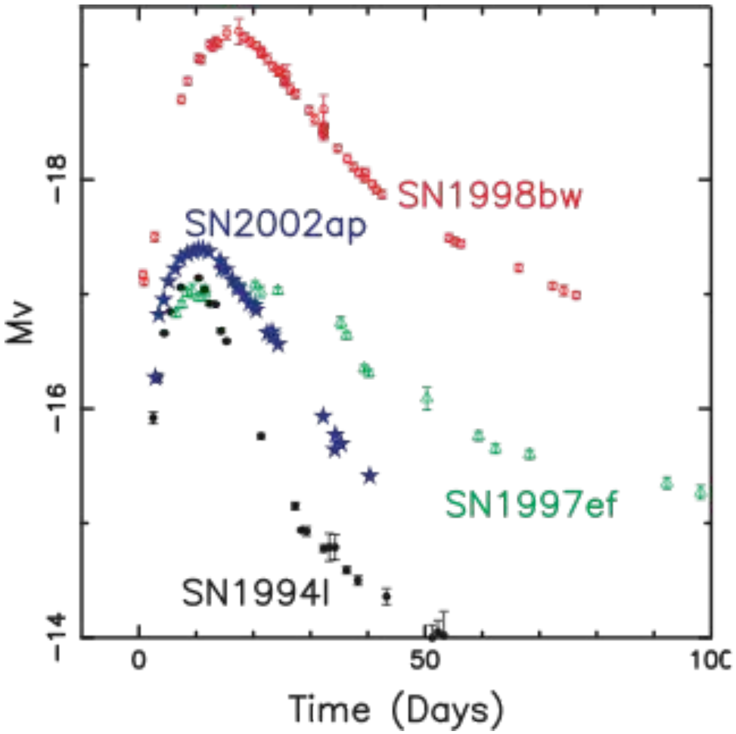
↓GRMHD: Mösta et al. 2014

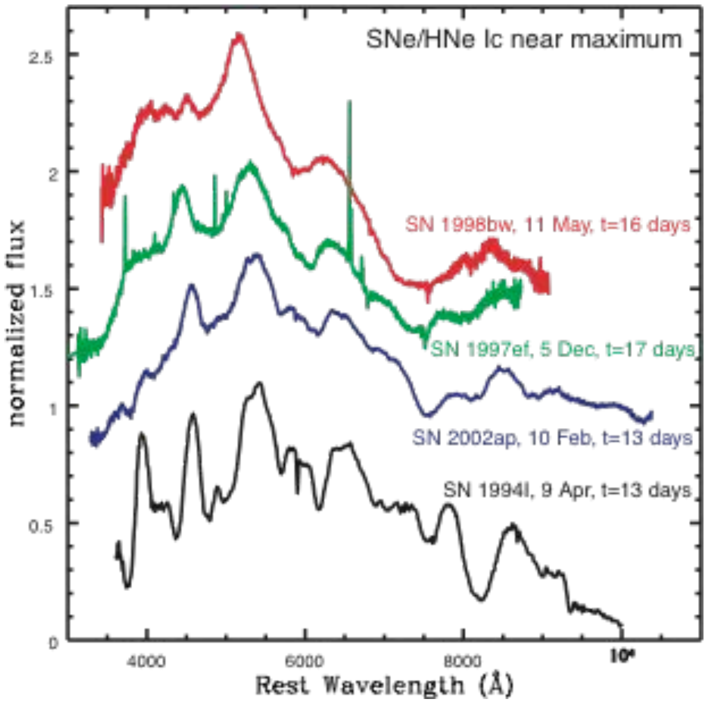


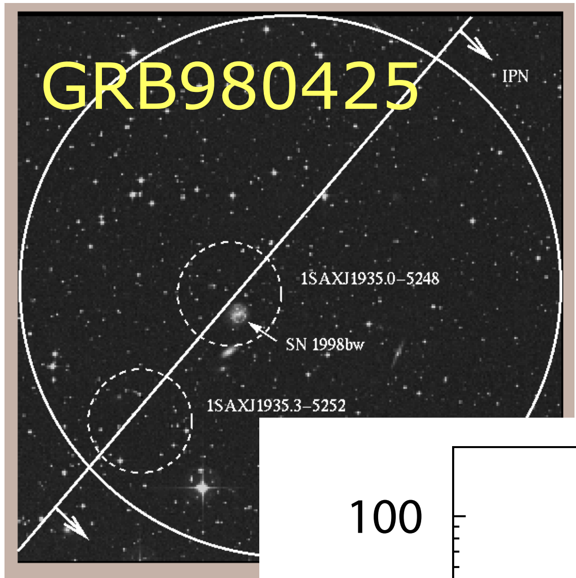
Hypernovae

- SN Light Curve & Spectra
- bright, broad, blended line
- $\rightarrow E>10^{52}$erg,M(Fe)>$0.1M_\odot$



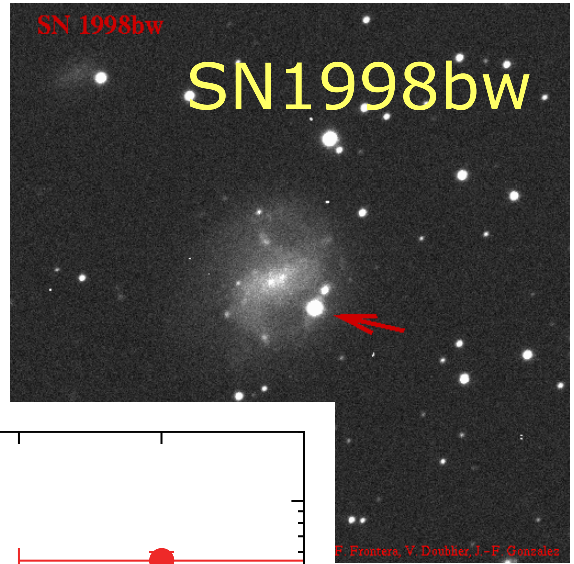


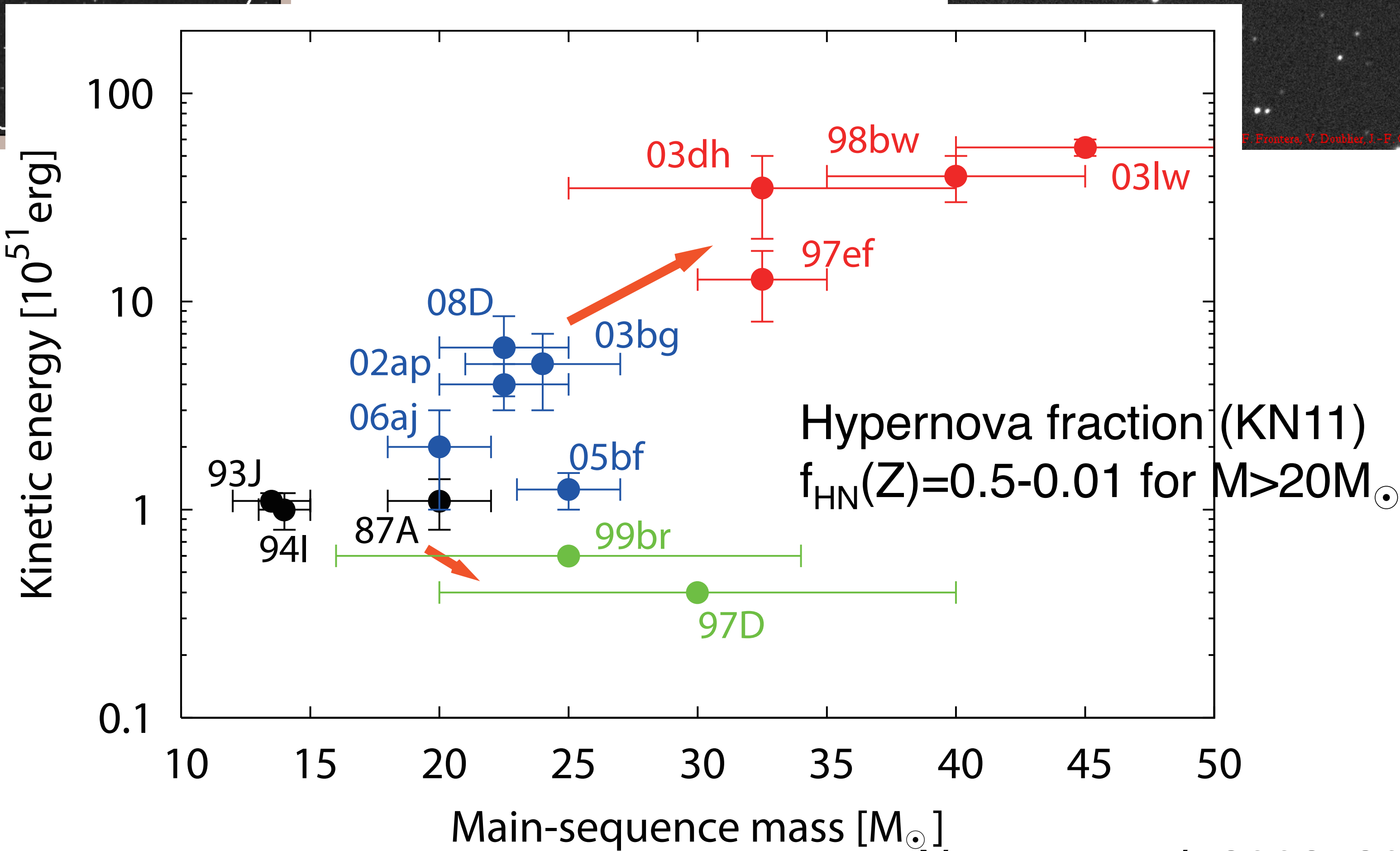




Hypernovae

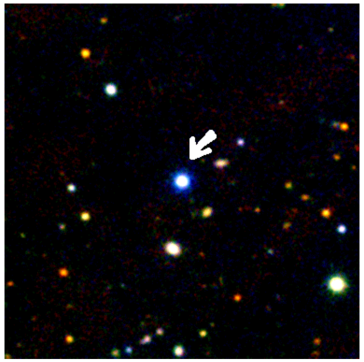
- SN Light Curve & Spectra
- bright, broad, blended line
- $\rightarrow E > 10^{52}$ erg, $M(Fe) > 0.1 M_\odot$



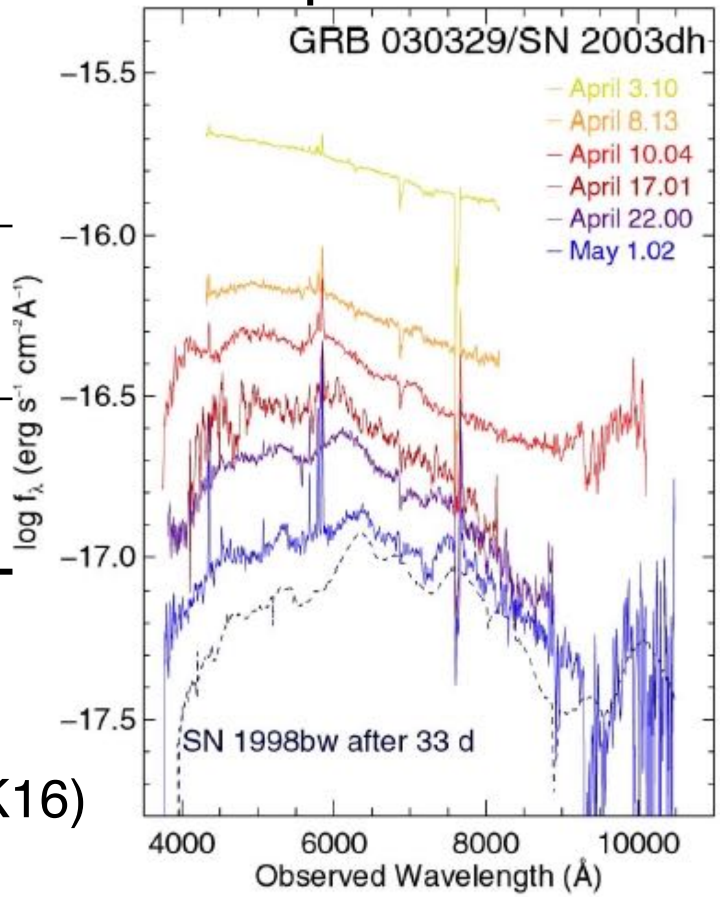


Nomoto et al. 2002, 2013

HN - GRB Connection

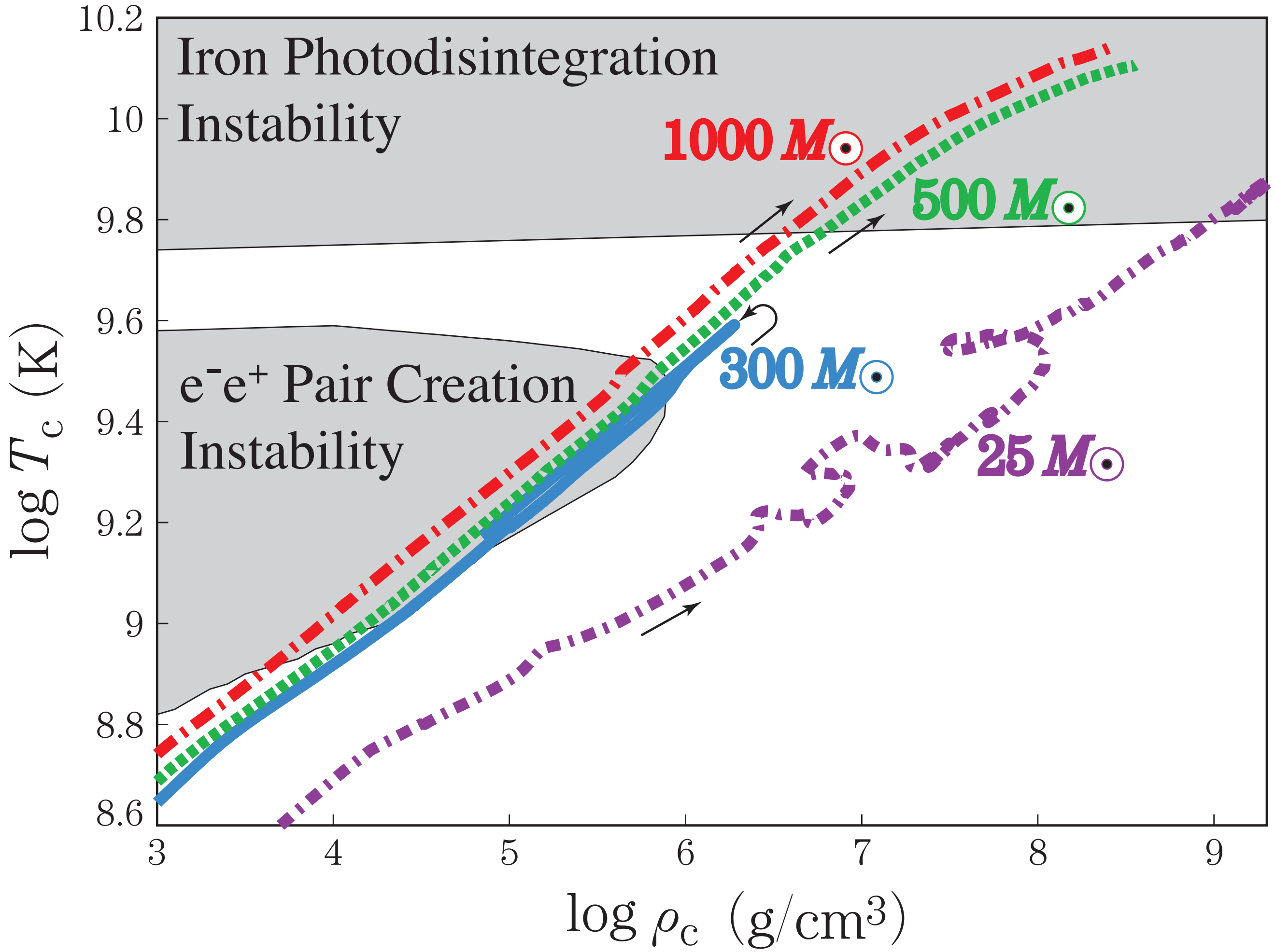


	HN	HN only (low-mass HN)
long GRB	1998bw/980425, 2003dh/030329, 2003lw/031203, 2012bz/120422A, ~10 photometry only: 980326, ...	1997ef ($35M_\odot$), 2002ap ($20M_\odot$), 2003jd ($30M_\odot$?), ...
GRB only (dark HN?)	060505 (long?), 060614 (long?,high-z?)	
HN? & X-ray flash	2006aj/060218, 020903	



long GRBs ~ massive & metal-poor HNe?? (CK16)

Pair Instability Supernova (PISN)

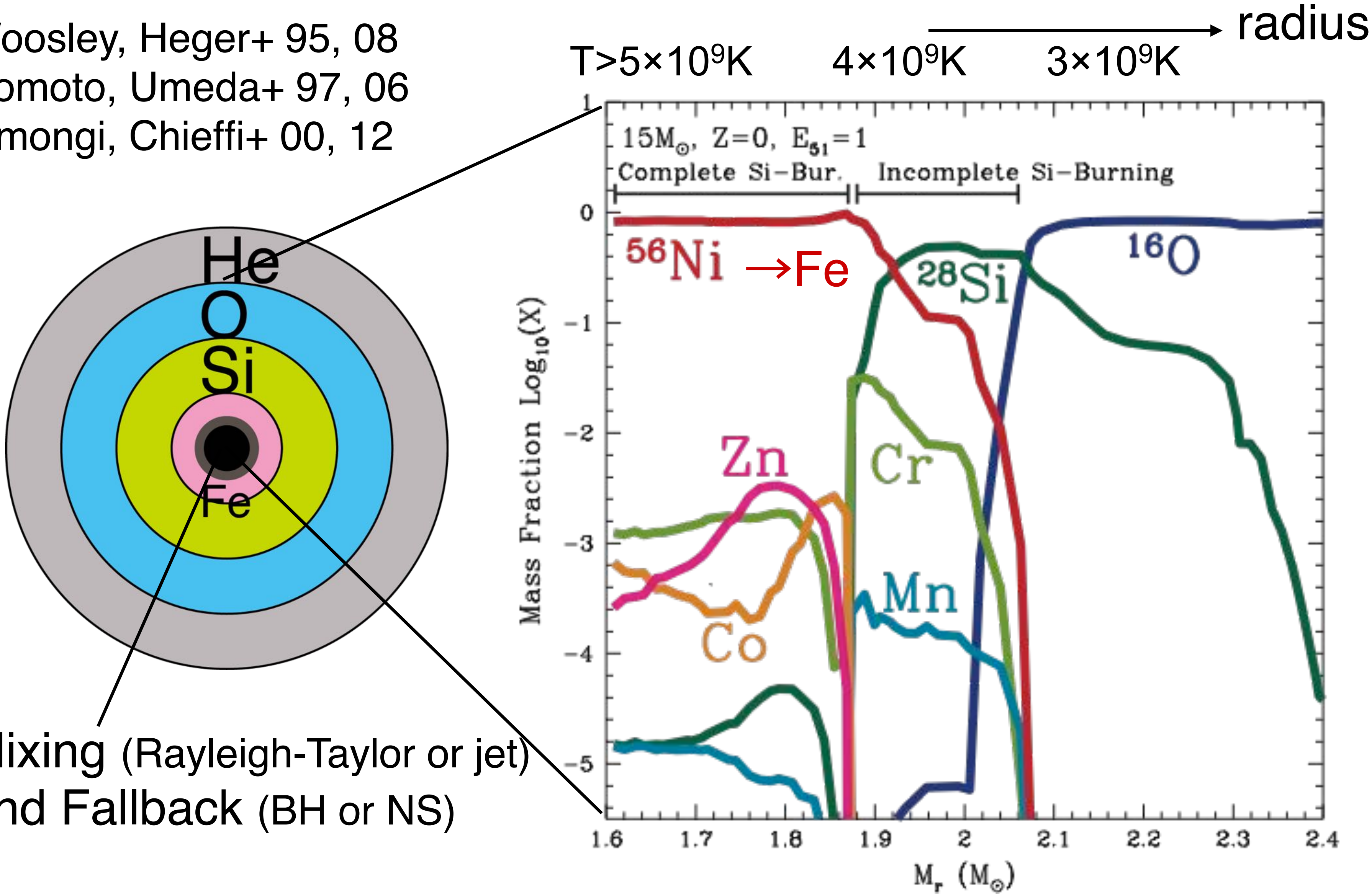


- **SN 2006gy** (SNIIn)**, 2007bi** (Gal-Yam et al. 2009), but could be normal SNII with circumstellar interaction (Moriya, Nomoto et al.)

Explosive Neucleosynthesis

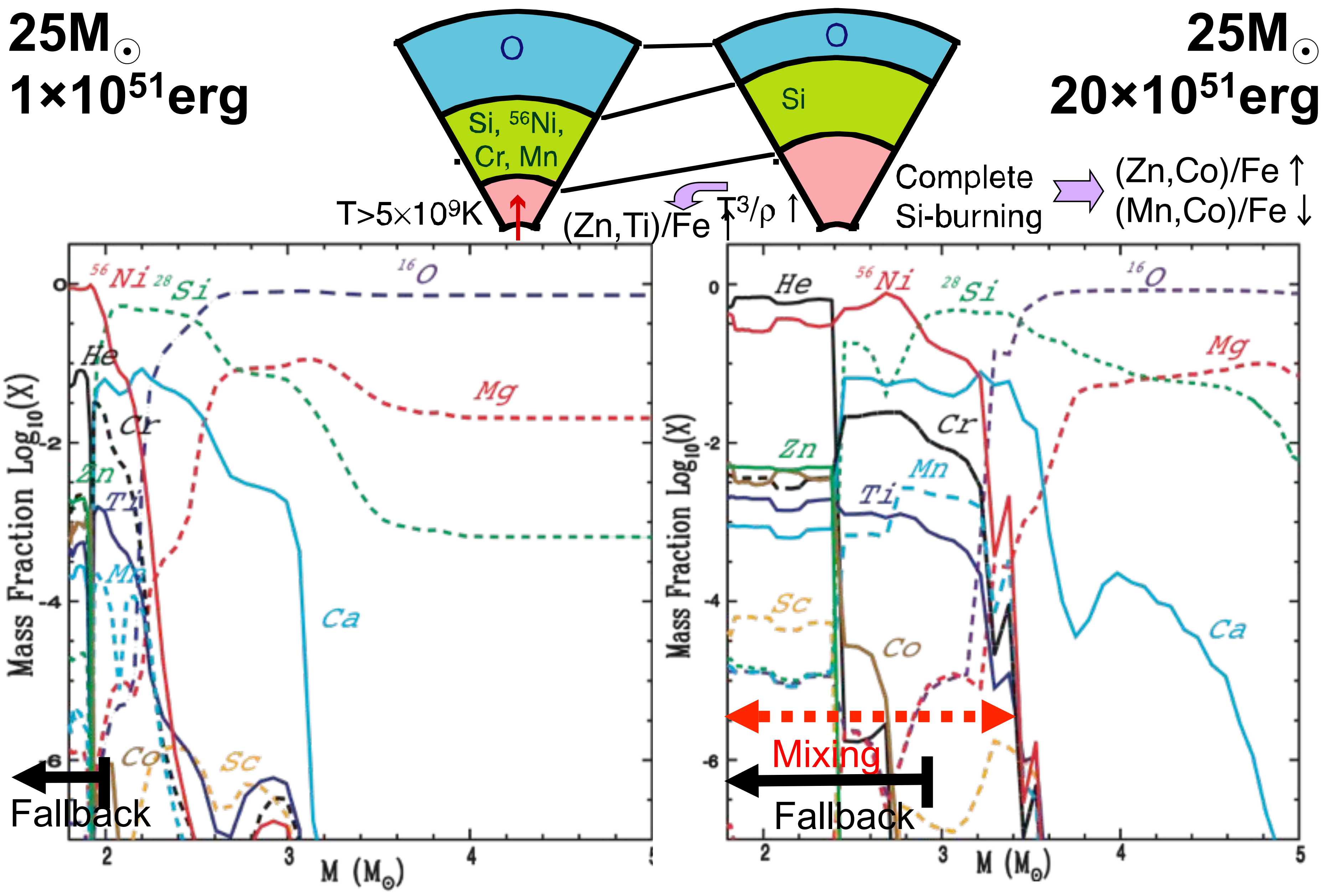
Explosive Nucleosyntheis

Woosley, Heger+ 95, 08
Nomoto, Umeda+ 97, 06
Limongi, Chieffi+ 00, 12



Mixing (Rayleigh-Taylor or jet)
and Fallback (BH or NS)

SN/HN Nucleosynthesis



Mixing-Fallback Model

Umeda & Nomoto 2002; Tominaga et al. 2007 (fig)

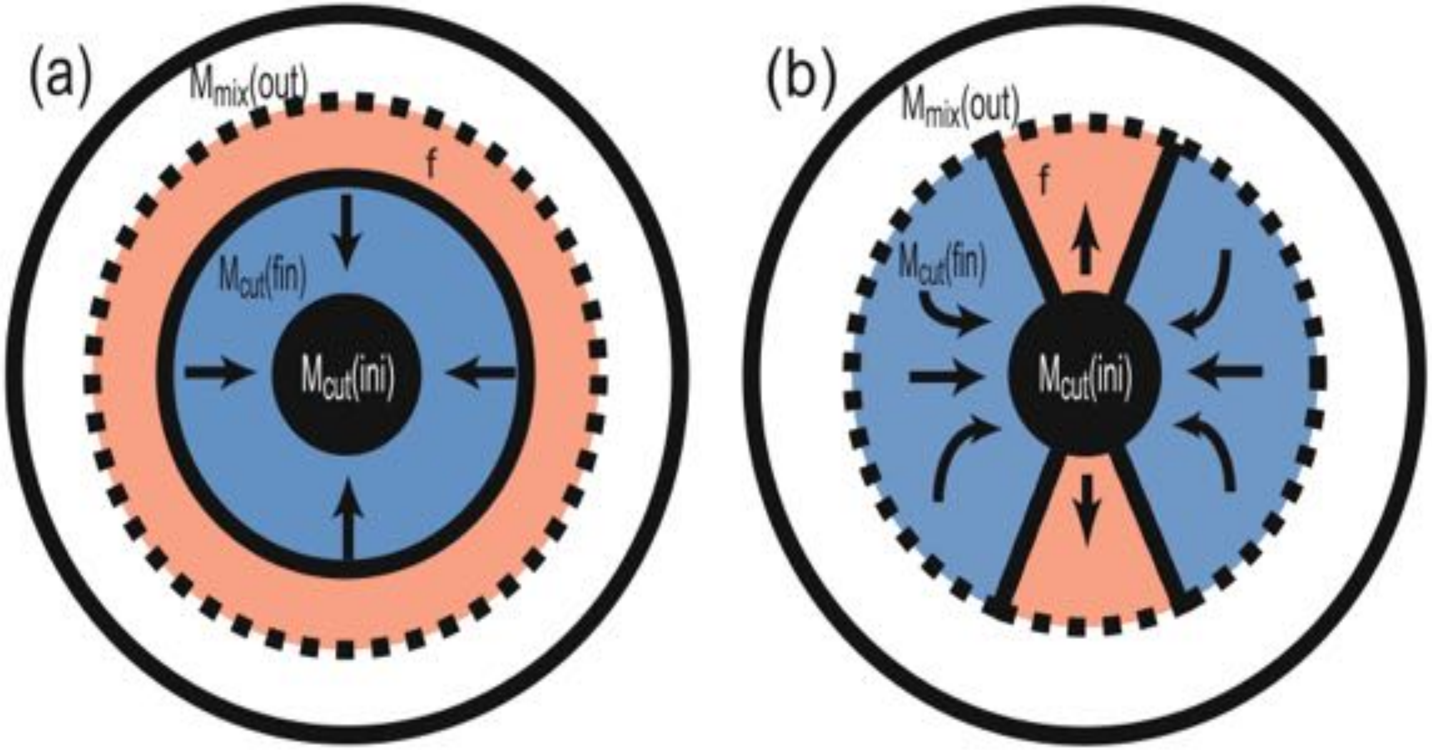


FIG. 12.—Illustration of the mixing-fallback model. The central black region is the initial mass cut, that is, inside the inner boundary of the mixing region, M_{cut}(ini). The mixing region is enclosed with the dotted line. A fraction f of the materials in the mixing region are ejected to the interstellar space. The rest of the materials, located in the blue region, fall back into the central remnant. (*a*) One-dimensional picture. The materials are mixed up to a given radius, and a part of the materials are ejected. (*b*) Two-dimensional picture. While the all materials in the outer region above M_{mix}(out) are ejected, the materials in the mixing region may be ejected only along the jet axis. In the jetlike explosion, the ejection factor f depends on the jet parameters (e.g., an opening angle and an energy deposition rate).

Figures 12*a* and 12*b* illustrate these parameters for spherical and aspherical models. The final remnant mass, M_{cut}(fin), is determined by the above three parameters,

Final BH mass $$M_{cut}(\mathrm{fin}) = M_{cut}(\mathrm{ini}) + (1 - f)[M_{mix}(\mathrm{out}) - M_{cut}(\mathrm{ini})]. \quad (A1)$$

Need for mixing-fallback

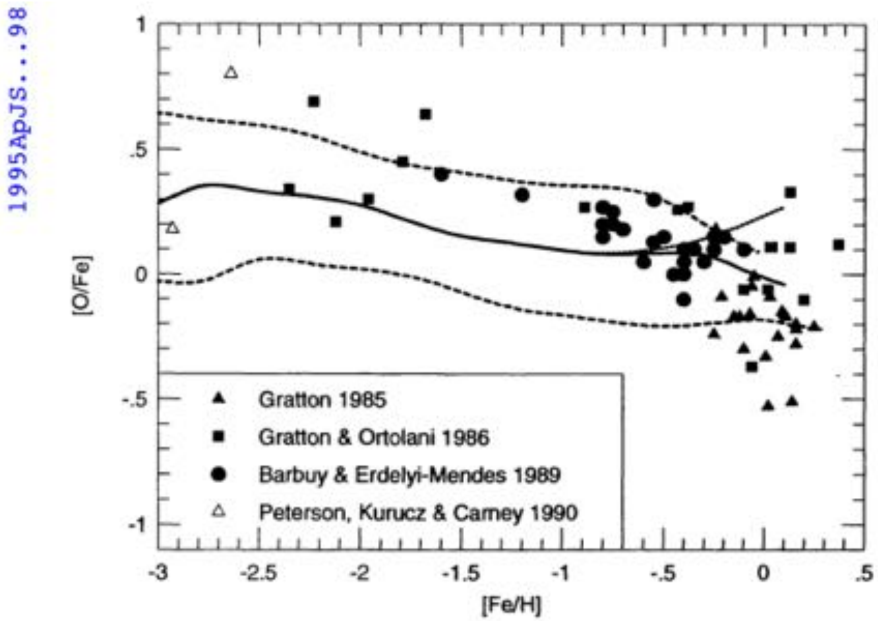
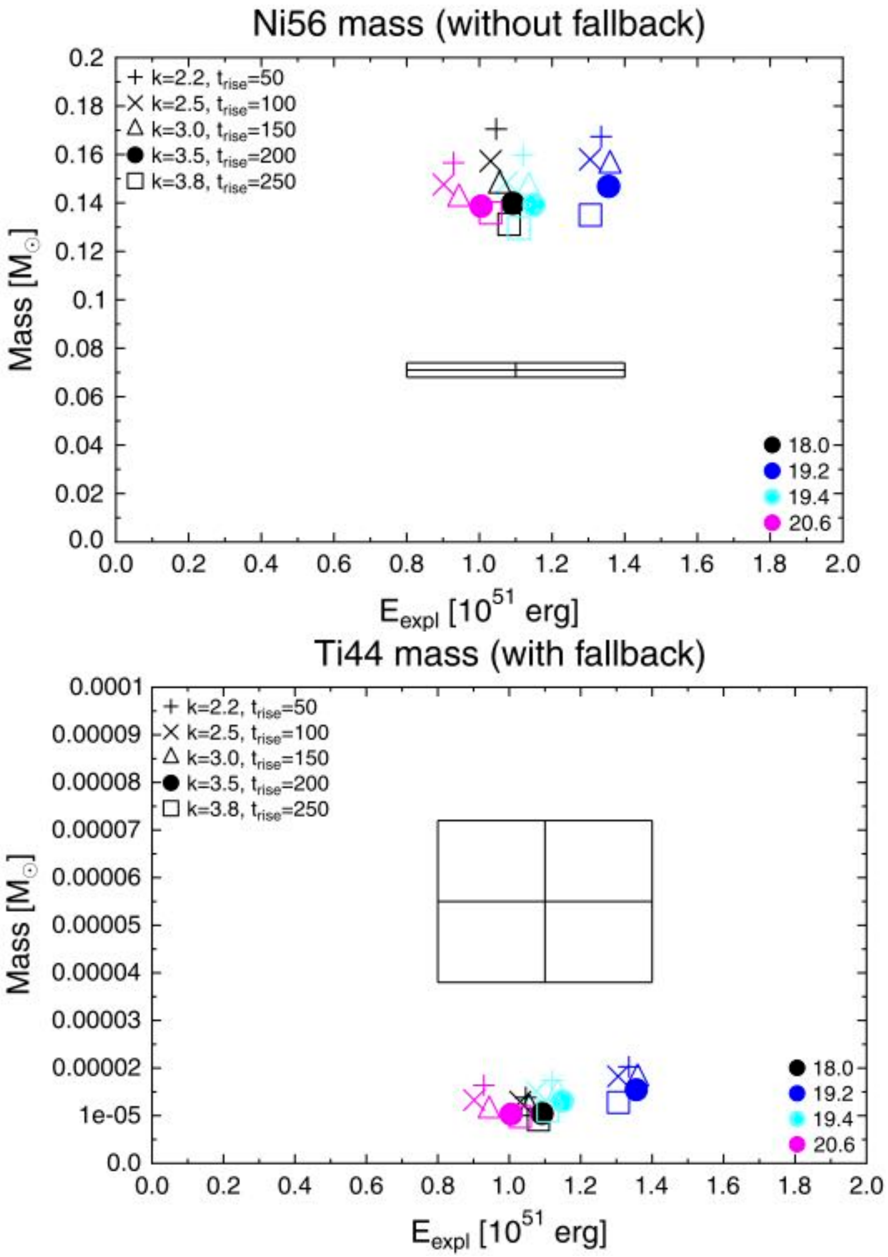


FIG. 11.—Evolution of the oxygen-to-iron ratio, [O/Fe], as a function of [Fe/H]. The solid line shows the calculation, the dashed lines indicate factor of 2 variations in the iron yields from massive stars, and the dotted line shows the results when Type Ia supernovae are excluded. Several sets of observations are shown in the figure and discussed in the text. The [O/Fe] is largest at very low metallicities, with the small dip at [Fe/H] $\simeq -3.0$ dex caused by the uncertainty in the iron yields of the $M \gtrsim 30\ M_{\odot}$ extremely metal-poor massive stars. The oxygen-to-iron ratio then slowly decreases due to small mass and metallicity effects. Intermediate-mass stars begin to dominate contributions to the interstellar medium later on, but because they produce very little oxygen and no iron, the [O/Fe] ratio is not affected. Type Ia supernovae begin to inject large amounts of iron and negligible amounts of oxygen into the interstellar medium after $\simeq 10^9$ yr, causing the downturn of the [O/Fe] ratio to its solar value. This effect is shown by comparing the solid line in the figure (which includes both Type II and Type Ia supernovae) with the dotted line (which excludes Type Ia supernovae). The best fit to the [O/Fe] observations may be a systematic reduction of the iron yields by a factor of 2. The reduced iron yields are consistent with the SN 1987A observations and the uncertainty in modeling the explosion. Factor of 2 increases in the iron yields are excluded.

- **WW95**'s iron yield should be reduced by a factor of 2 (Timmes, Woosley, Weaver 95).
- This reduction is applied to many GCE & hydro simulations.
- But, not only Fe but also other iron-peak elements should be reduced.

Need for mixing-fallback



- Recent 1D model ***PUSH*** including detailed neutrino physics (Perego et al. 15)
- ^{56}Ni is too high without fallback (upper panel)
- ^{44}Ti (→ ^{44}Ca) is too low with fallback (lower panel)

Observations: error bar box, Seitenzahl et al. 2014

K06 Yields

Kobayashi, Umeda, Nomoto, Tominaga, Ohkubo 2006, ApJ, 653, 1145

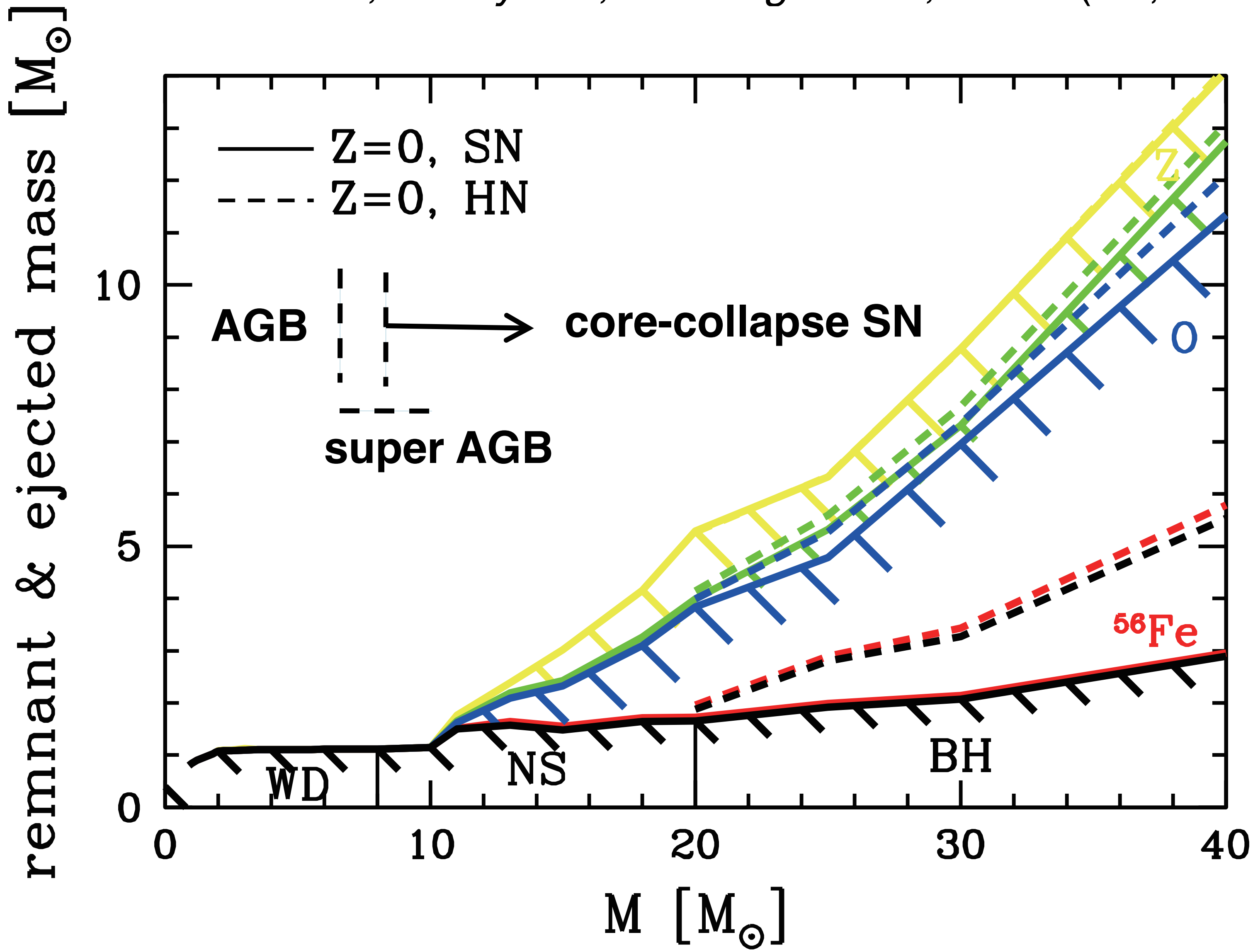
- Stellar Evolution Model: Umeda, Nomoto, et al 1999
- Nuclear Reaction Network: Hix & Thielemann 1996
- M = 13, 15, 18, 20, 25, 30, 40 $M_\odot$
- Z = 0, 0.0001, 0.004, 0.02, (0.05)*
- E = 1, 10, 10, 20, 30 foe for 20, 25, 30, 40 $M_\odot$

	13$M_\odot$, Z=0, 1foe	**25$M_\odot$, Z=0, 1foe**	**25$M_\odot$, Z=0, 10foe**	**40$M_\odot$. Z=0, 30foe**	**25$M_\odot$, Z=0.02, 10foe**	**SNIa (W7)**
H	6.6	11	11	14	8.4	0
He	4.0	8	8	12	7.3	0
O	0.45	2.8	2.4	6.3	2.2	0.14
Fe	0.07	0.07	0.10	0.26	0.09	0.61
Zn	1.3e-4	2.5e-6	2.6e-4	6.9e-4	1.4e-4	1.2e-5

- There models updated in CK+11; Z=0.05 included in NKT13, ARAA

Stellar Yields

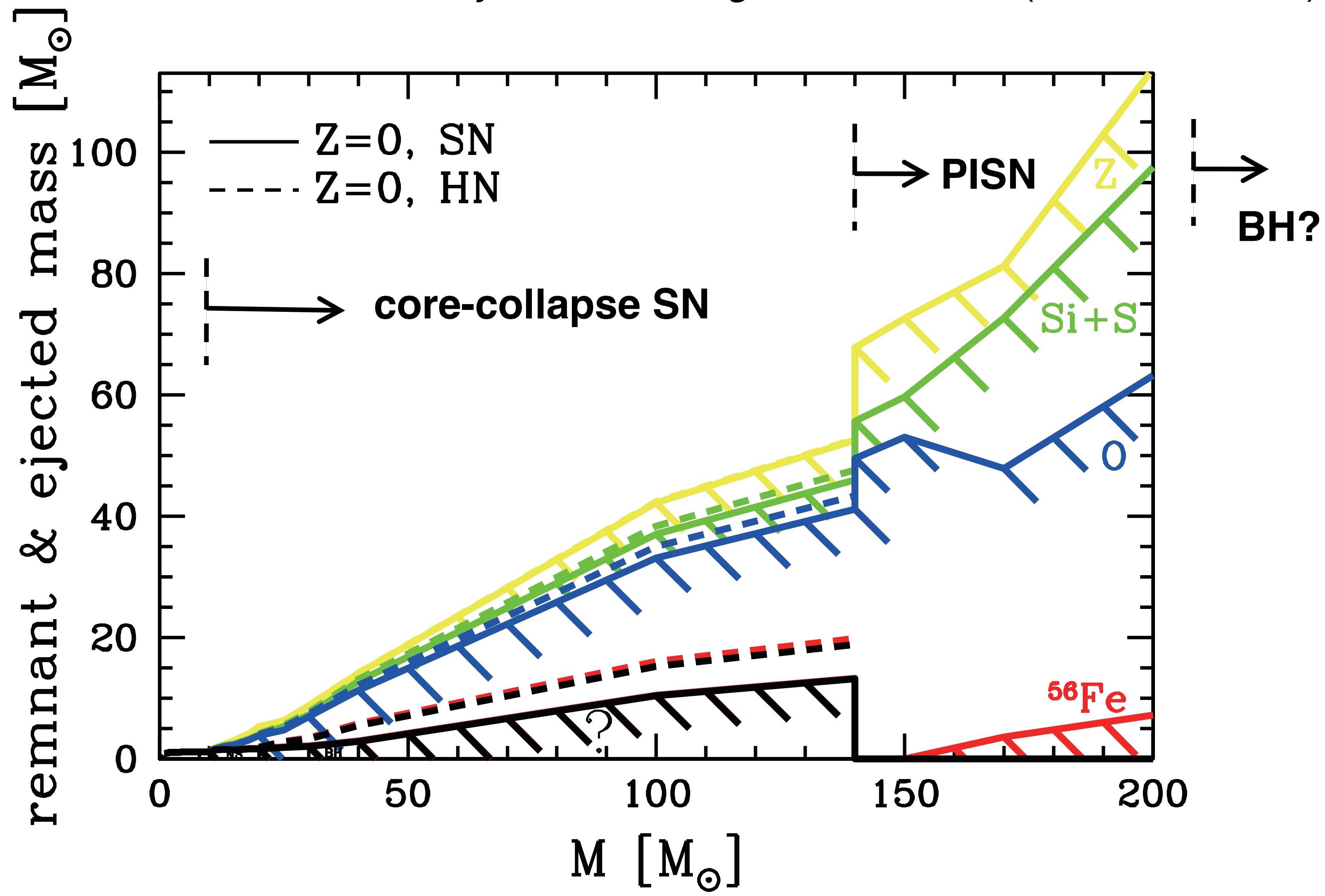
Nomoto, Kobayashi, Tominaga 2013, ARAA (1D, no rotation)



Also, Woosley & Heger; Limongi & Chieffi

Stellar Yields

Nomoto, Kobayashi, Tominaga 2013, ARAA (1D, no rotation)



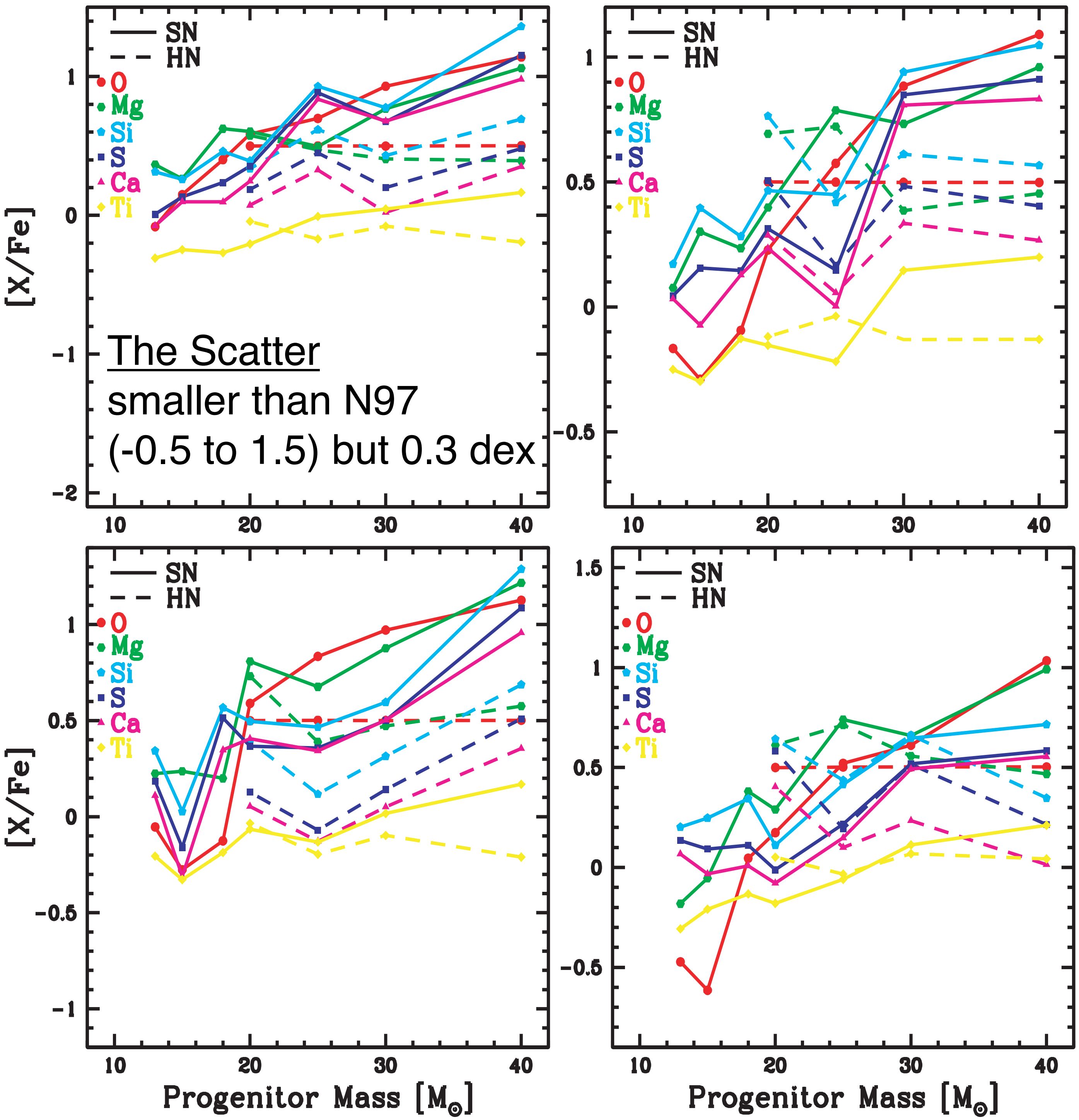
Also, Woosley & Heger

Z=0

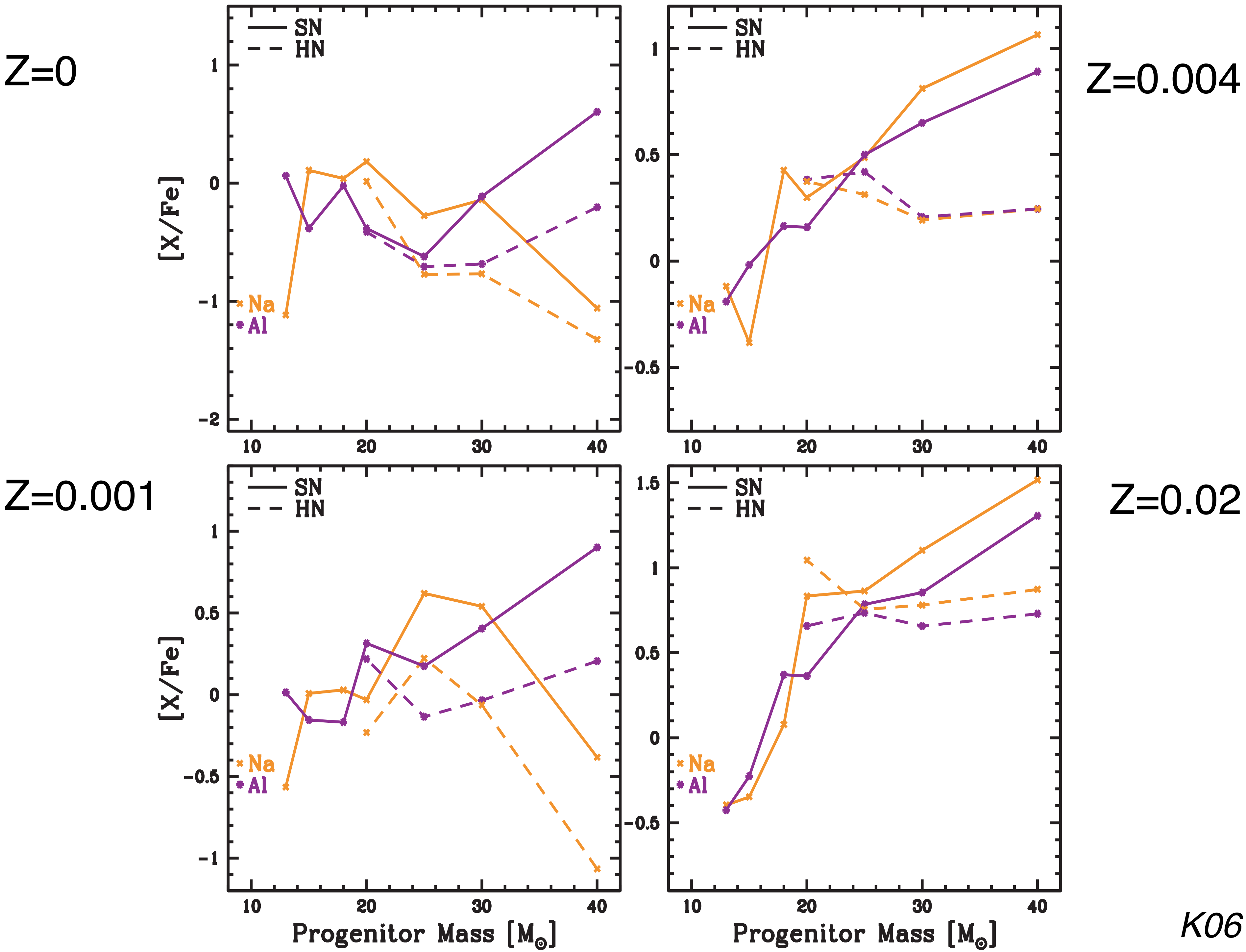
Z=0.004

Z=0.001

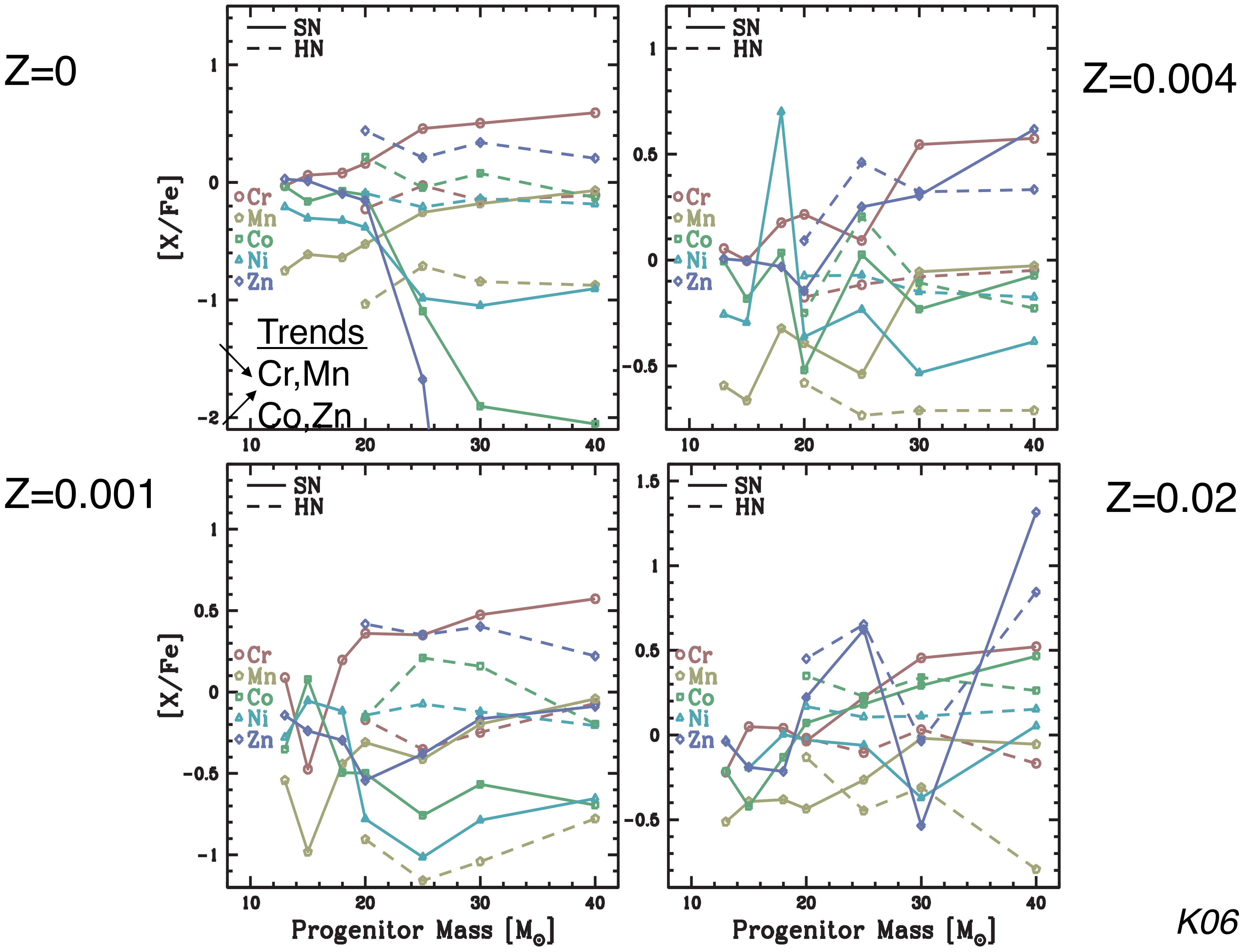
Z=0.02



K06

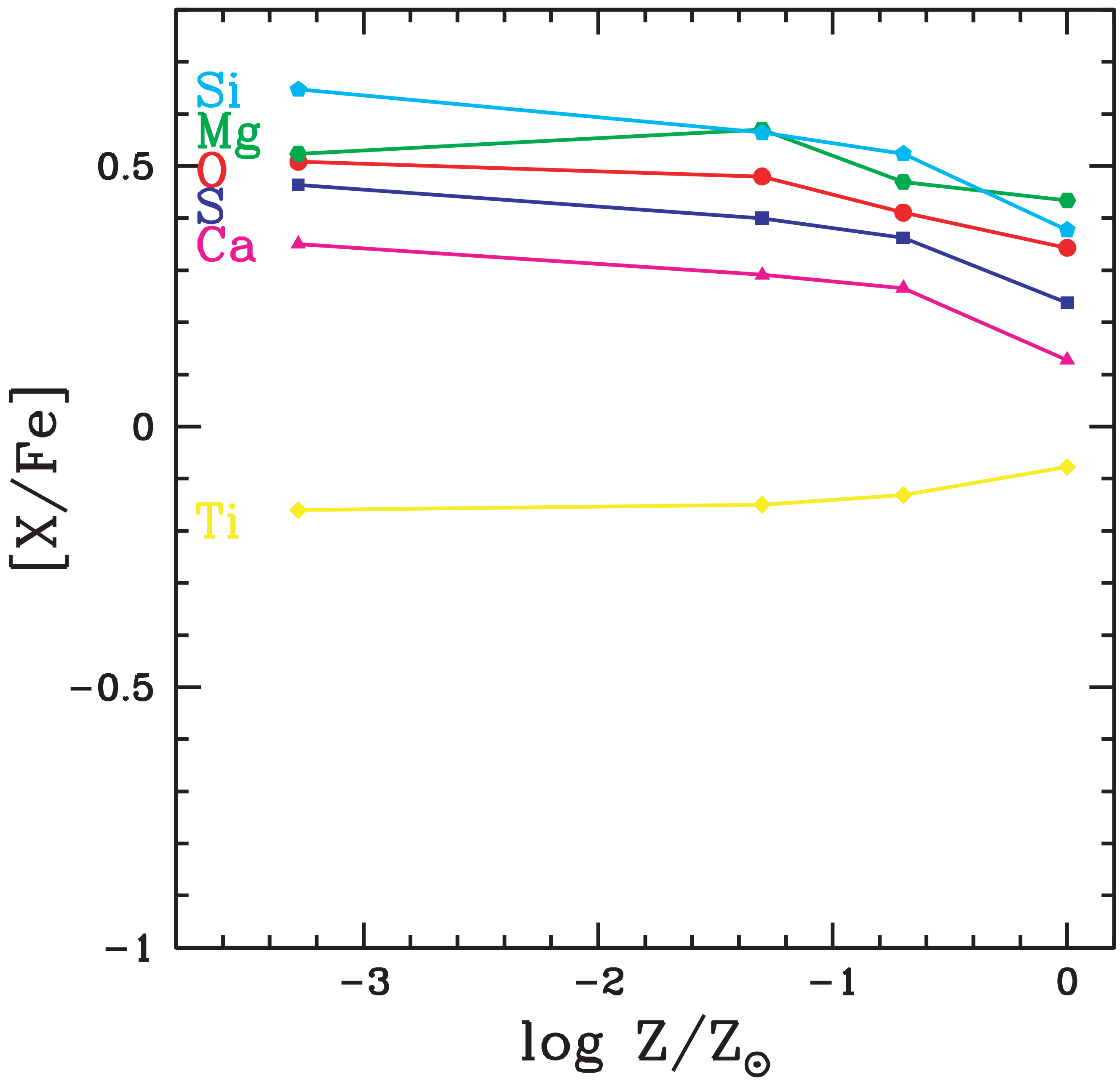


Z=0
Z=0.004
Z=0.001
Z=0.02
SN
HN
Na
Al
[X/Fe]
Progenitor Mass [M⊙]
K06



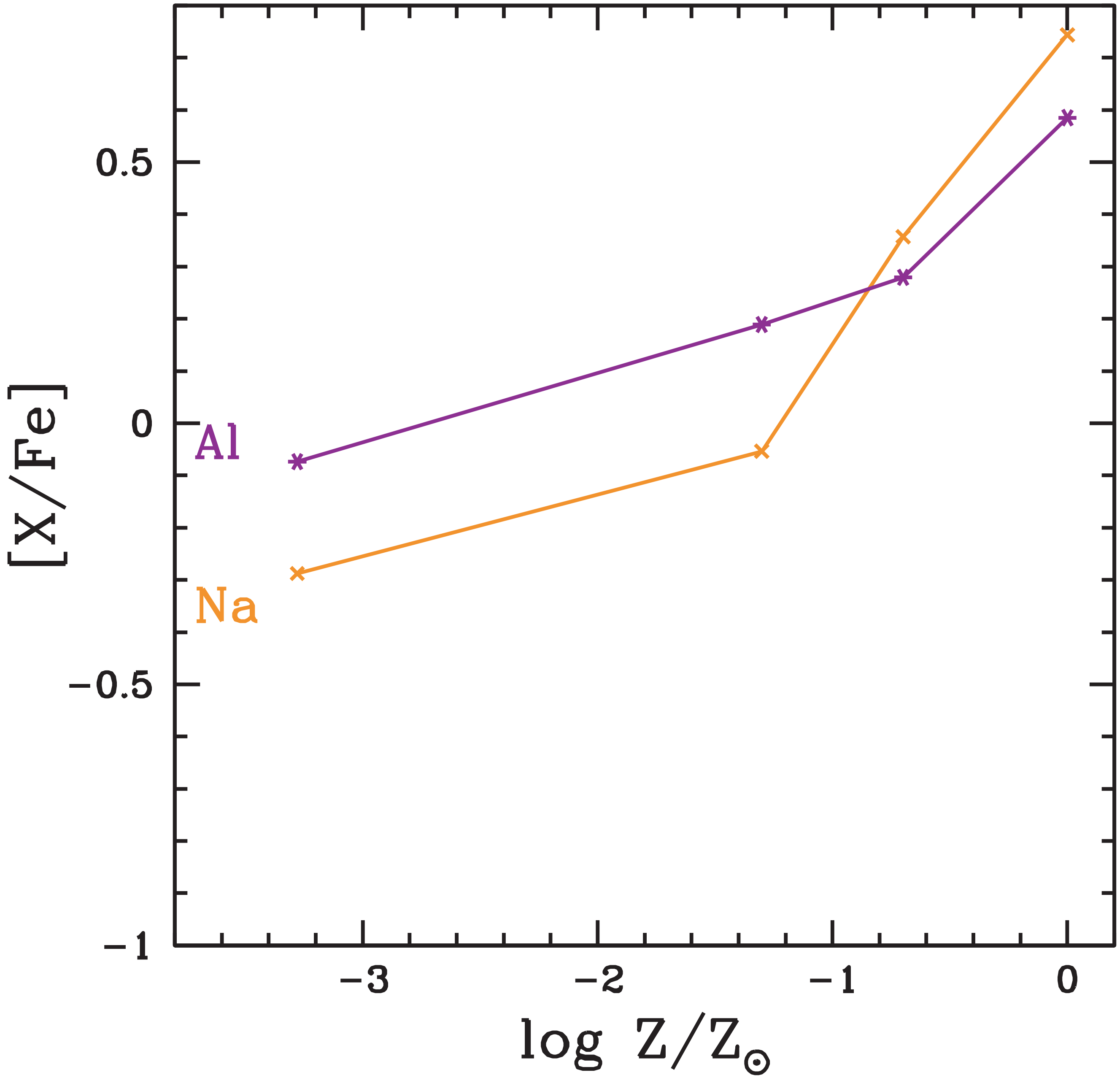
Z=0
Z=0.004
Z=0.001
Z=0.02
SN
HN
Cr
Mn
Co
Ni
Zn
[X/Fe]
Trends
Cr,Mn
Co,Zn
Progenitor Mass [M⊙]
K06

Metallicity Dependence



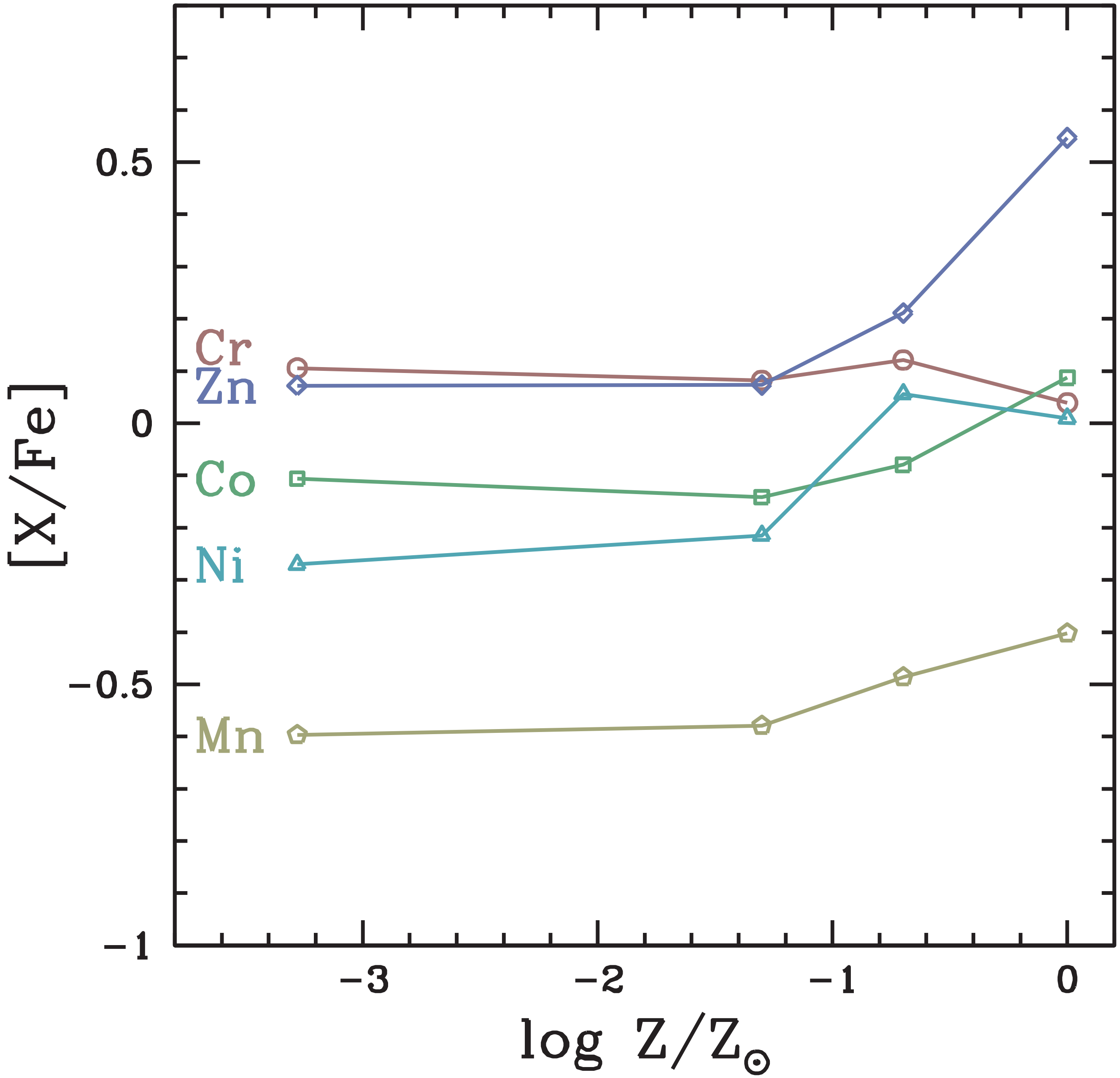
K06

Metallicity Dependence



K06

Metallicity Dependence

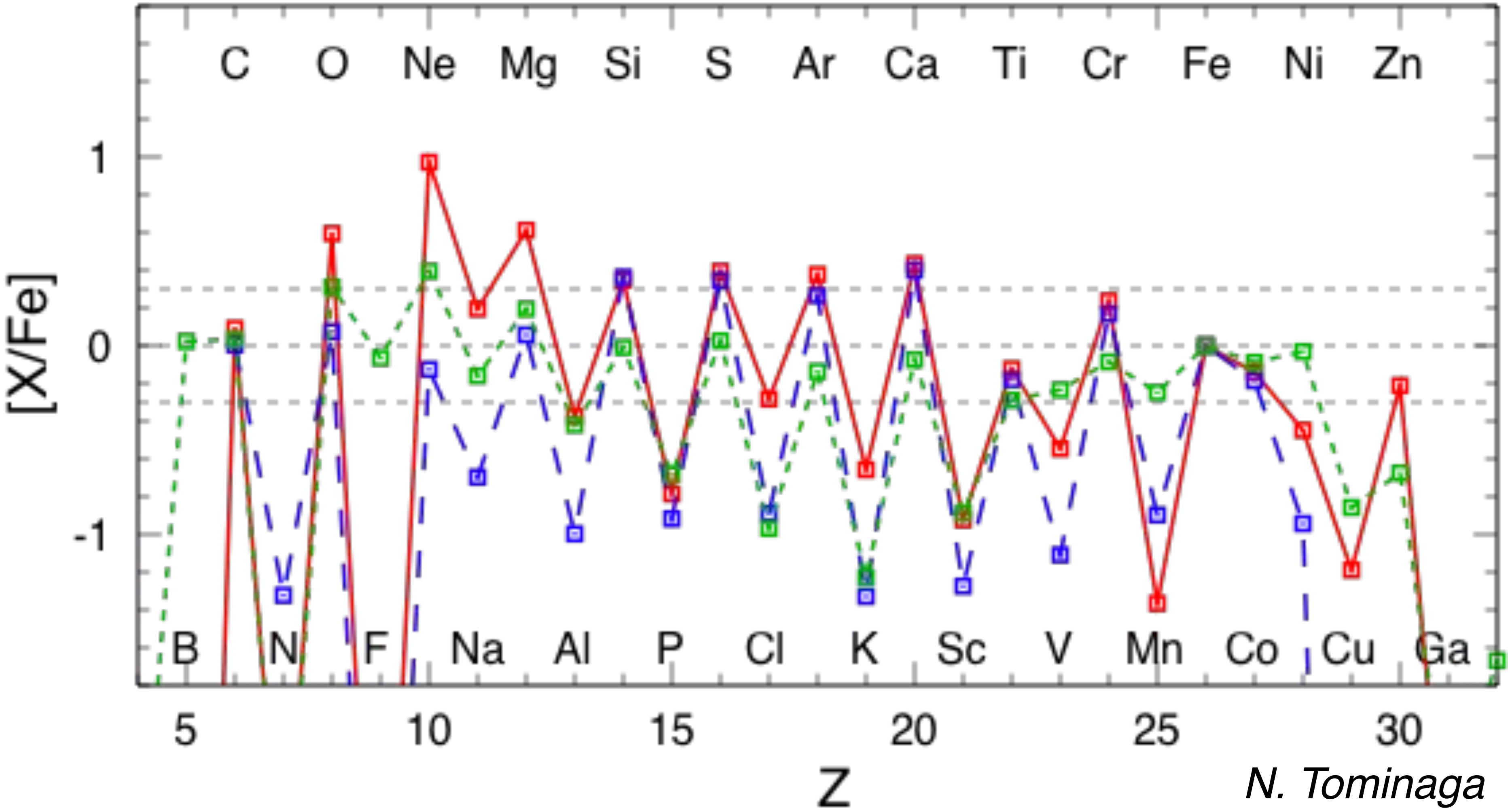


K06

SN Yields from different groups

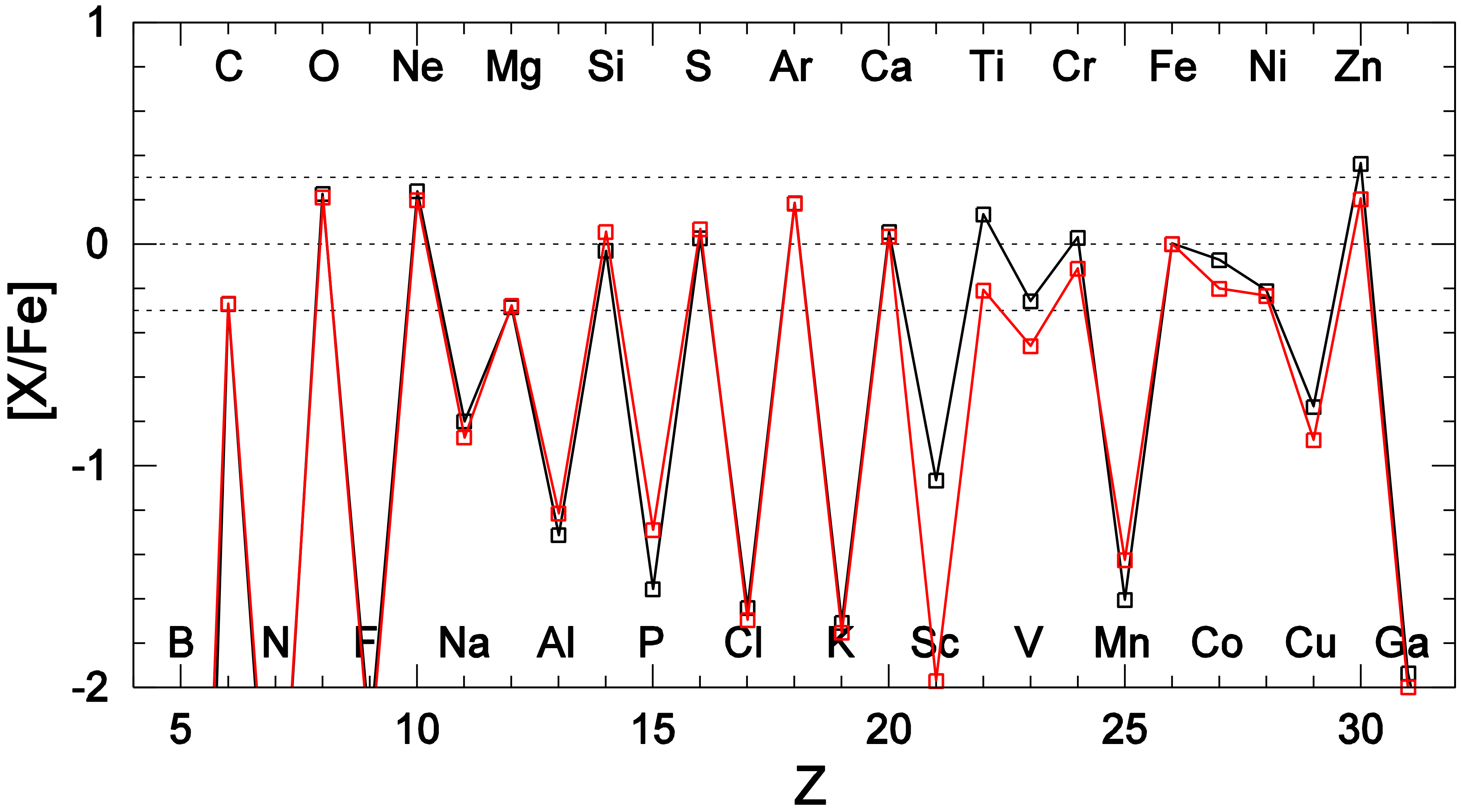
$20M_{\odot}$ Z=0 E=1foe

Tominaga, Umeda, Nomoto 2007
Heger & Woosley 2008
Limongi, Straniero, Chieffi 2000



N. Tominaga

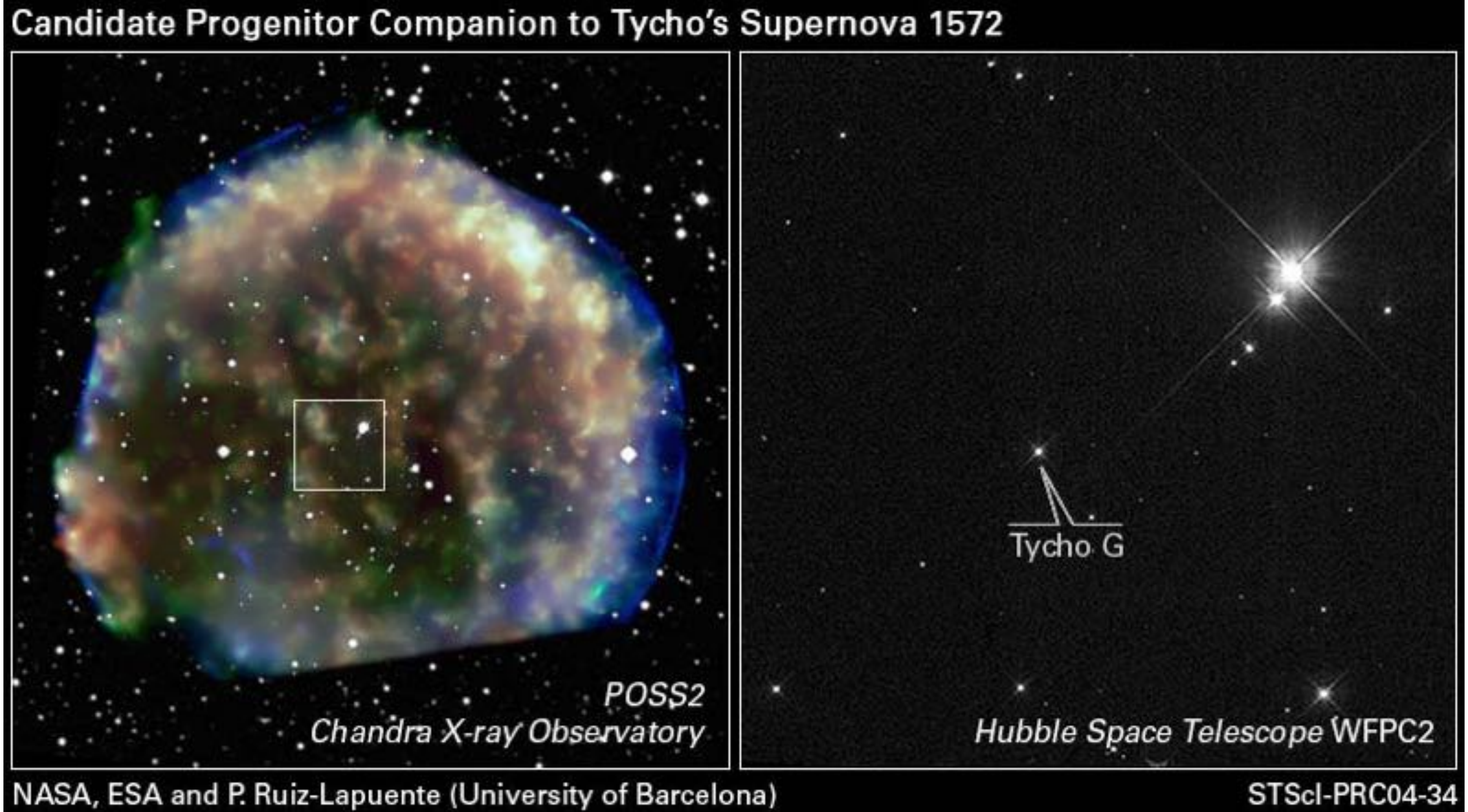
1D model vs 2D (Jet-induced SN) model



Maeda & Nomoto 2003; N. Tominaga

Type Ia Supernovae

Type Ia Supernovae

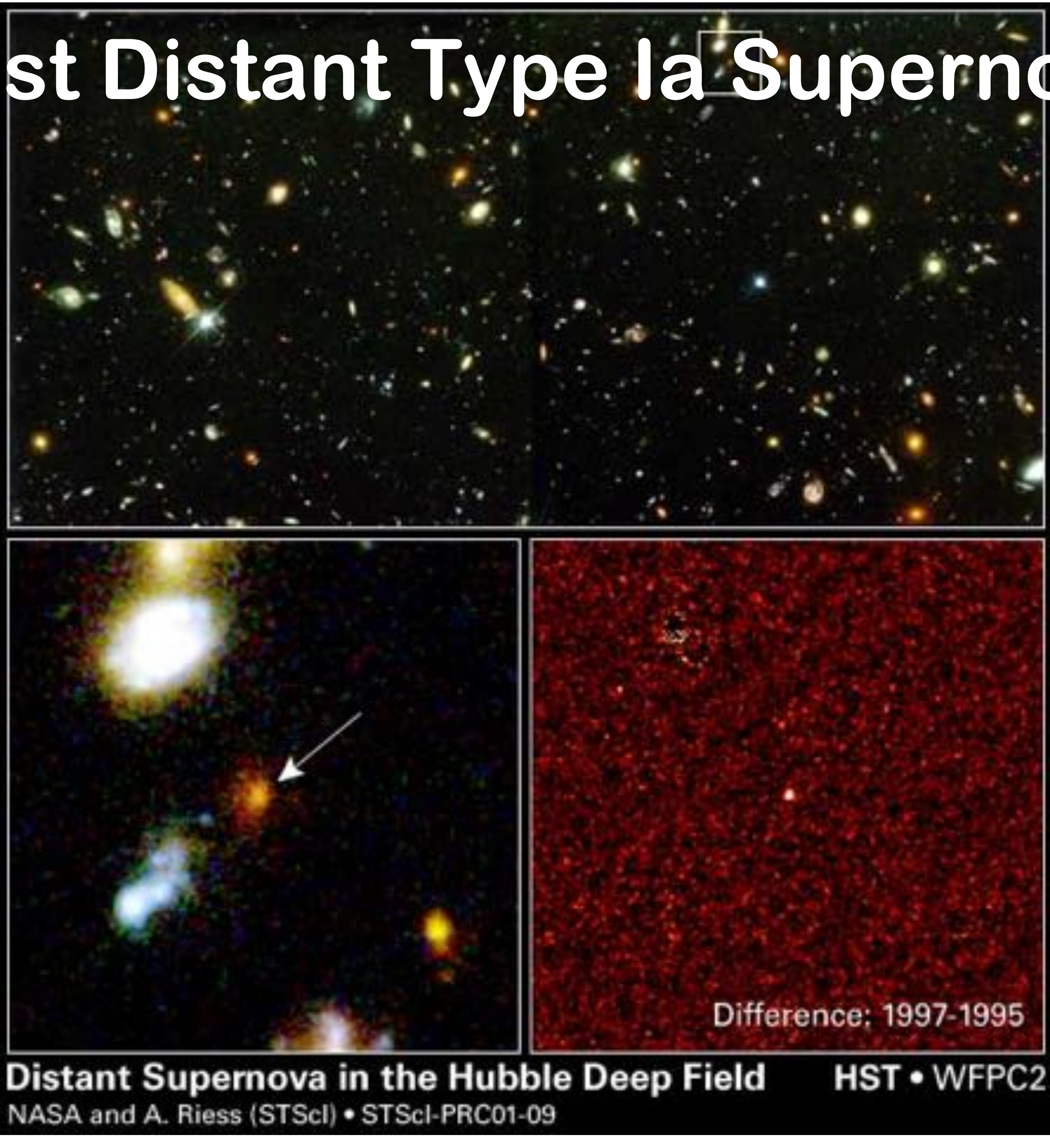


but see Kerzendorf et al. 2009

2 SNe Ia in Elliptical Galaxy

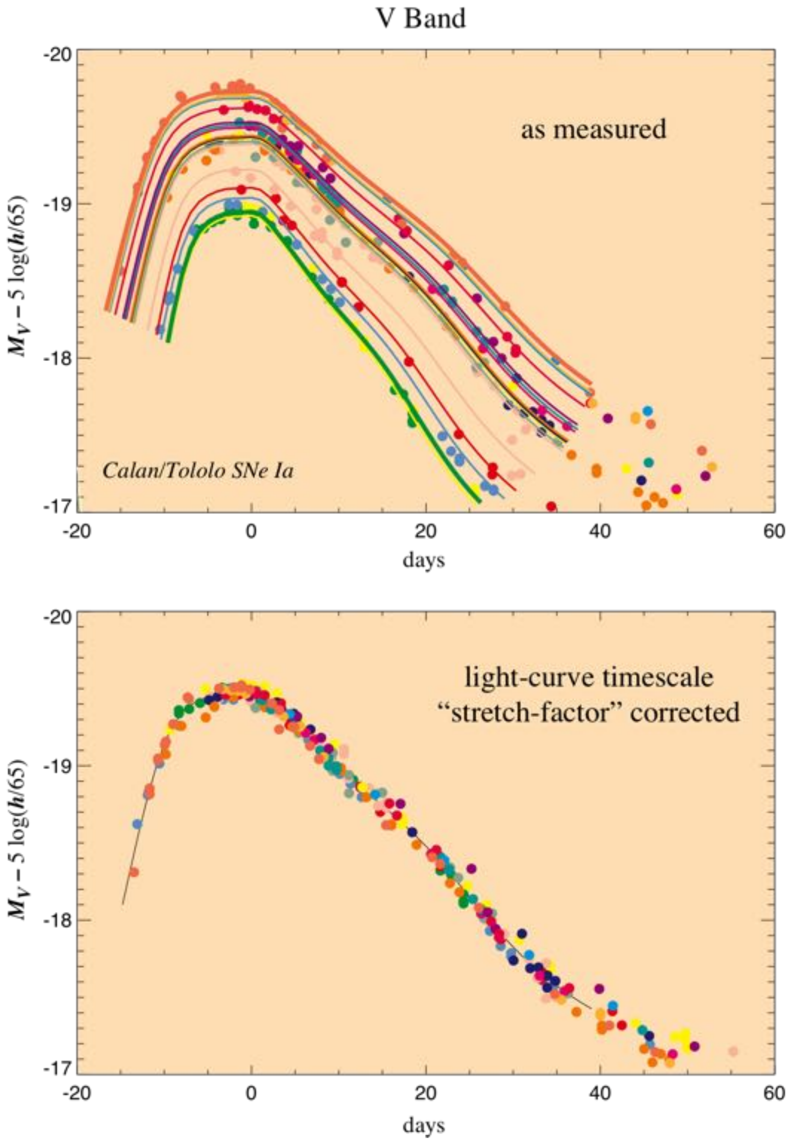
NASA/Swift; NGC 1316, SN2006dd & 2006mr

Most Distant Type Ia Supernova

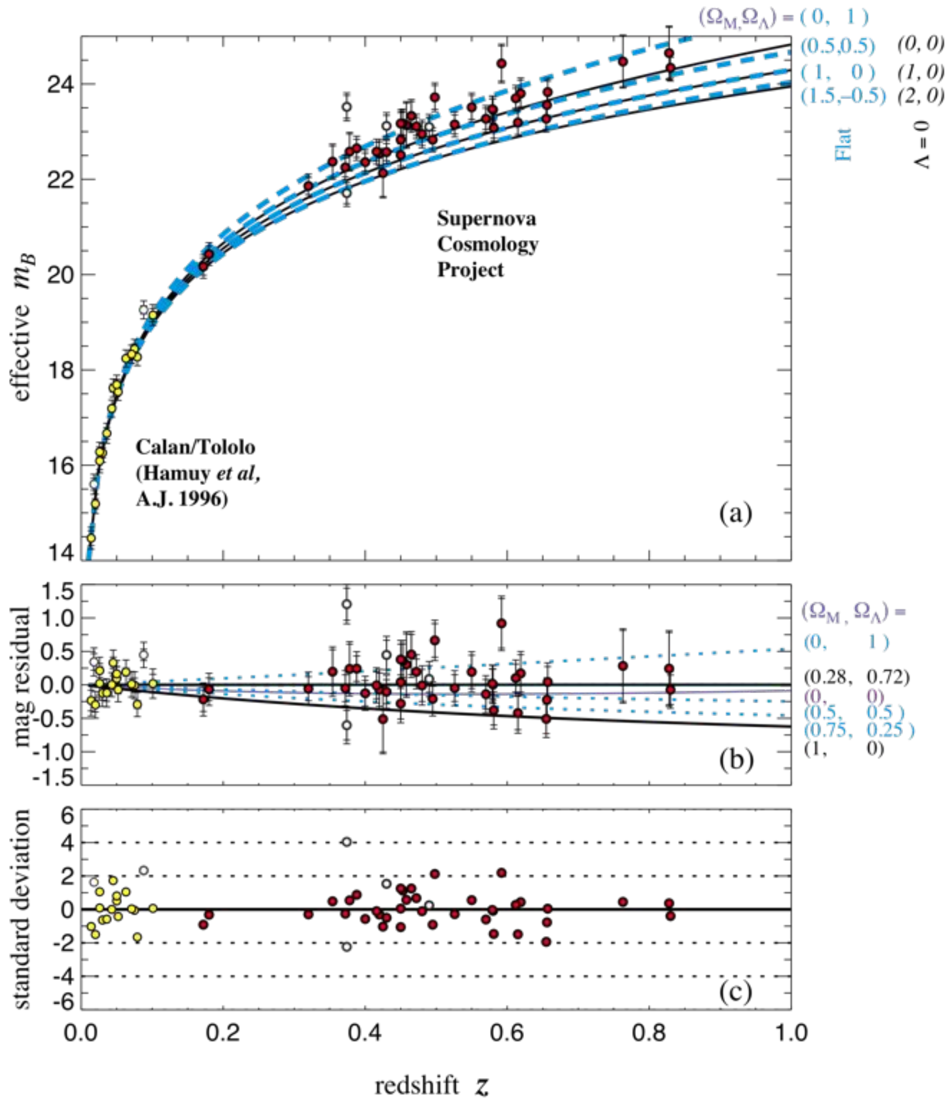


SN1997ff
z=1.7

SNIa cosmology



Perlmutter et al. 99



Accelerating Universe

H_0=65, Ω_m=0.28, Ω_λ=0.72

SNIa progenitor scenarios

	Pro	Con
SD (Nomoto, Podsiadlowski)	- Naturally Ch-mass - CSM for some - UV-pulse detection for 2 SNe	- Narrow range Mdot (Nomoto 82) - No detection of radio/X-ray - No detection of companion stars (Kerzendorf) - Phillips relation (Sim+13)?
DD (Maoz, Badenes)	- Binary population synthesis (BPS) (Iben & Tusukov 84)? - Delay-time distribution (DTD)? - too short timescale for GCE	- Accretion induced collapse in 1D (Nomoto & Kondo 91) - Not enough WD binaries (SPY project) - sun-Ch in simulations - too low Mn
double.det (Hillebrandt)	- BPS (Ruitter) - DTD	- sub-Ch by definition - He should be hidden - too low Mn

UV pulse from donor star

subluminous Ia **iPTF14atg** (Cao el al. 2015, Nature)
also normal Ia, **SN2012cg** (Marion et al. 15)

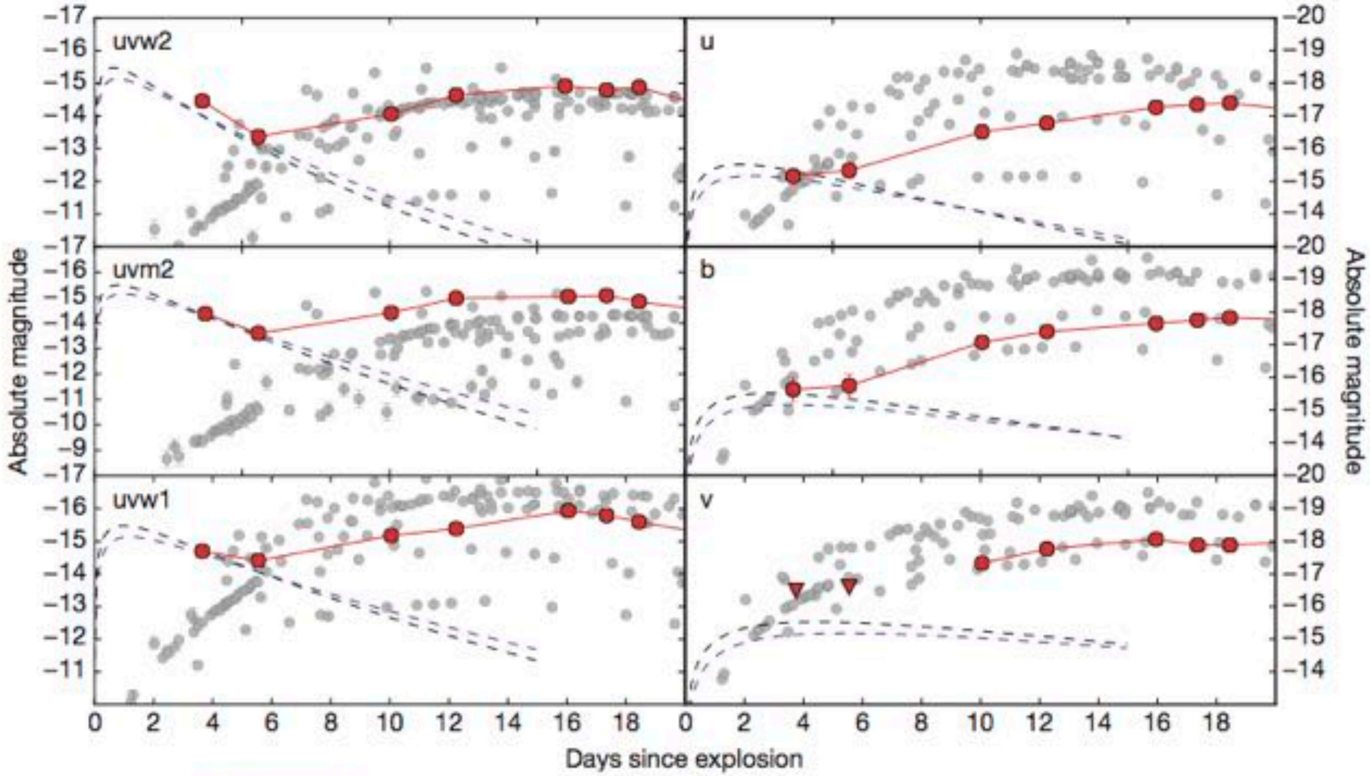
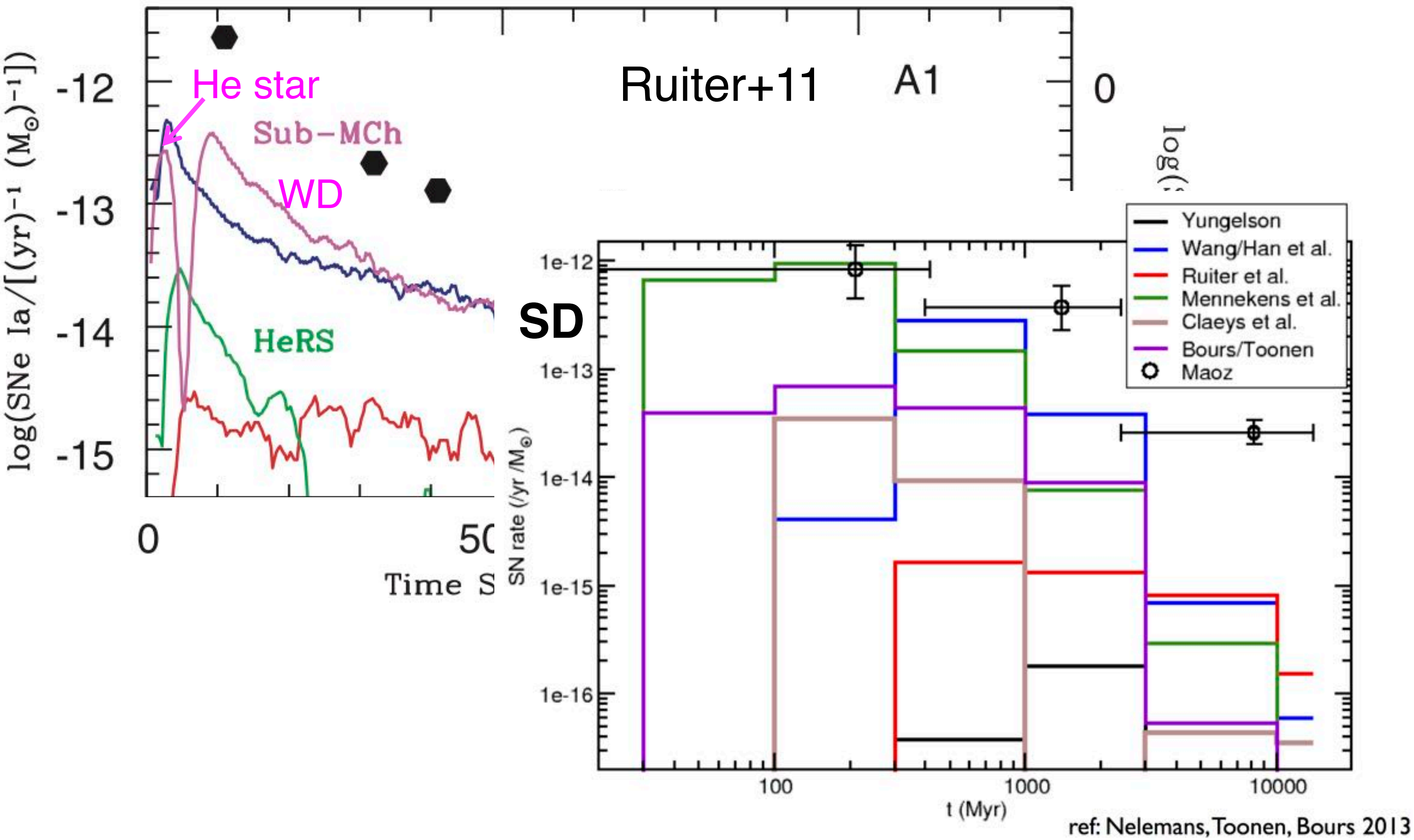


Figure 1 | Swift/UVOT lightcurves of iPTF14atg. iPTF14atg lightcurves are shown with red circles and lines and are compared with those of other type Ia supernovae (grey circles). The magnitudes are in the AB system. The 1σ error bars include both statistical and systematic uncertainties in measurements. Lightcurves of other supernovae and their explosion dates are taken from previous studies[13,26]. In each of the three ultraviolet bands (uvw2, uvm2 and uvw1), iPTF14atg stands out as exhibiting a decaying flux at early times. The blue and black dashed curves show two theoretical lightcurves derived from companion interaction models[9].

SD in Binary Population Synthesis

- SDS DTD can be much higher (Nelemans+13)



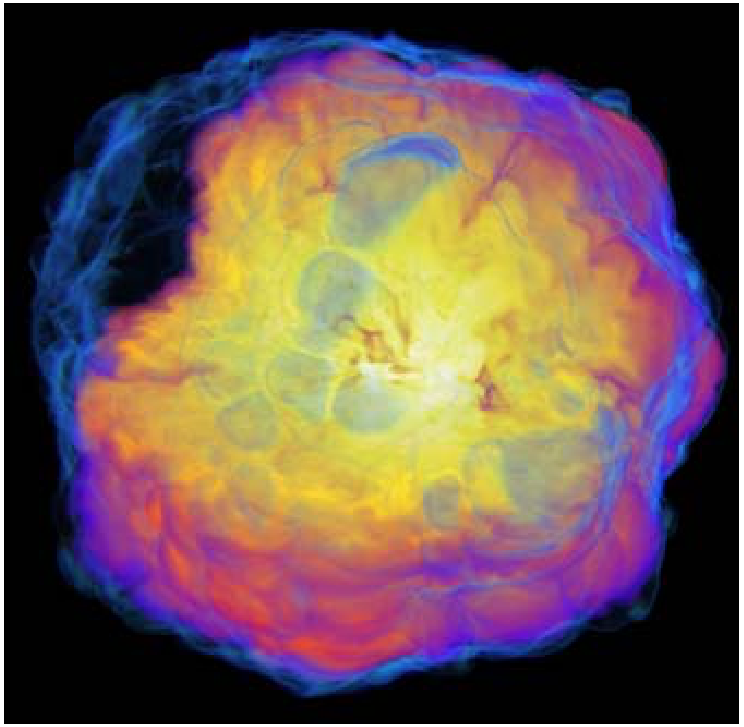
3D simulations of SNIa explosion

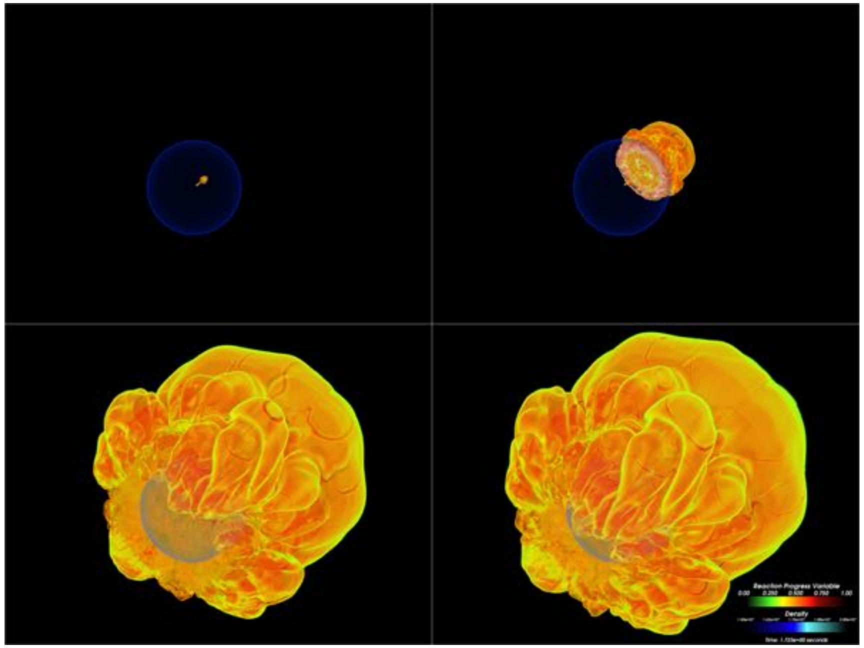
MPA

- F. Roepke 2004
- pure deflagration
- or, delayed detonation (Roepke et al. 12)

Chicago

- Jordan et al. 2007, FLASH
- gravitationally confined detonation (GCD)

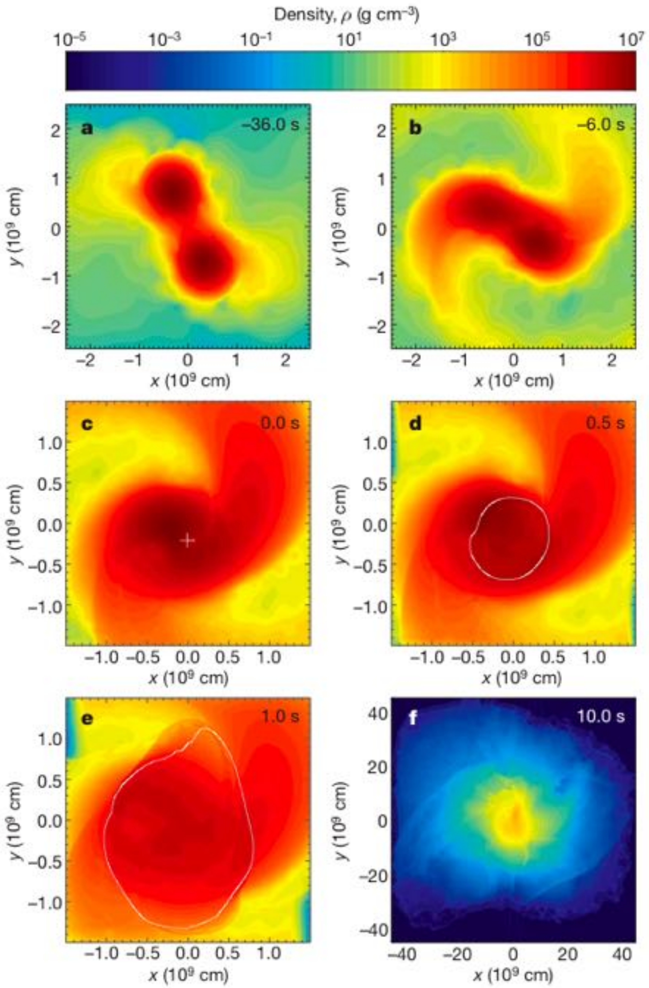




WD merger simulations – subluminous?

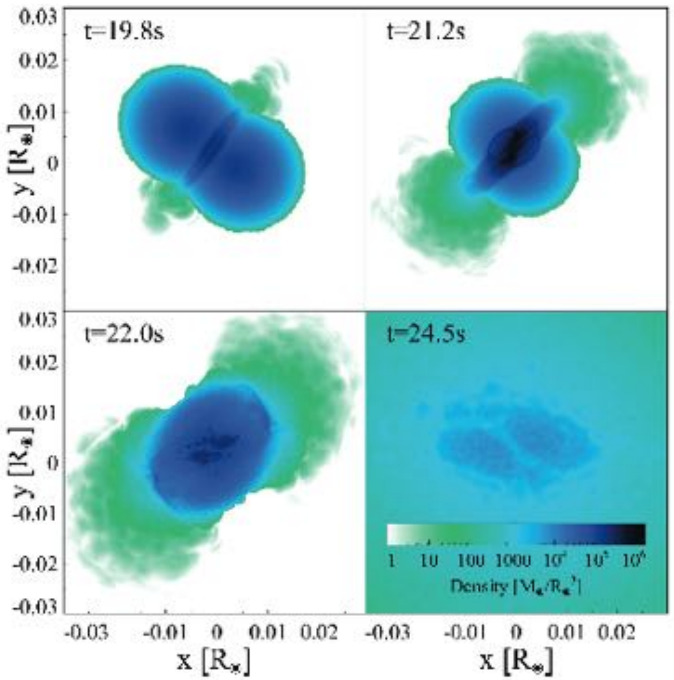
MPA

- Pakmor et al. (2009) Nature, Gadget2→grid
  - ★ $0.83M_\odot + 0.9M_\odot \rightarrow M(^{56}Ni) = 0.1M_\odot$



LANL

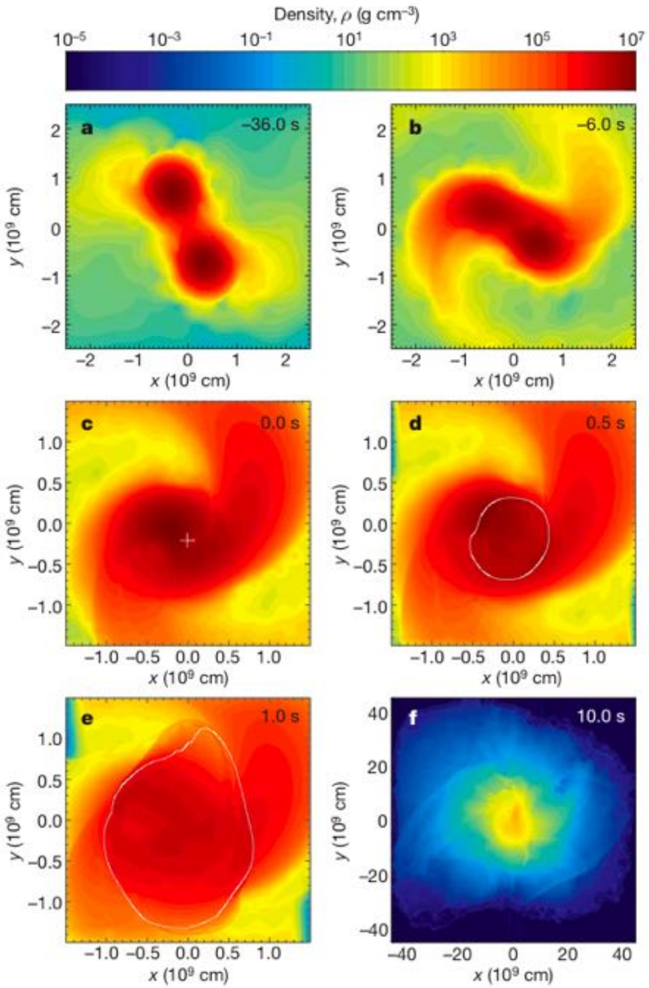
- Raskin et al. (2009), SNSPH (Fryer et al. 06)
  - ★ $0.6M_\odot + 0.6M_\odot \rightarrow M(^{56}Ni) = 0.3M_\odot$



WD merger simulations – subluminous?

MPA

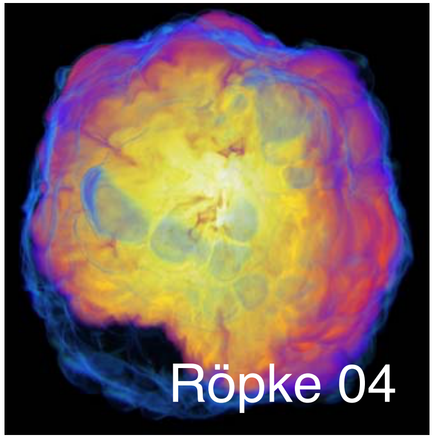
- Pakmor et al. (2009) Nature, Gadget2→grid **sub-Ch**
  - 0.83$M_\odot$+0.9$M_\odot$→M(^{56}Ni)=0.1$M_\odot$



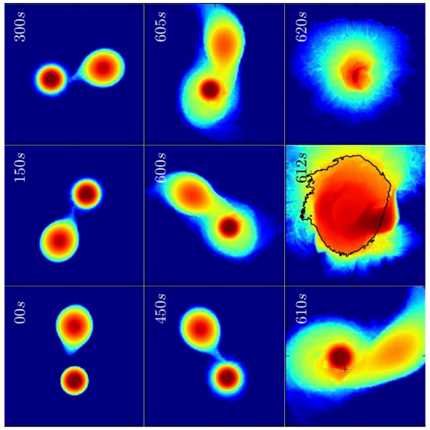
LANL

- Raskin et al. (2009), SNSPH (Fryer et al. 06)
  - 0.6$M_\odot$+0.6$M_\odot$→M(^{56}Ni)=0.3$M_\odot$
- **Violent merger** (Pakmor et al. 12)
  - 0.9$M_\odot$+1.1$M_\odot$→M(^{56}Ni)=0.62$M_\odot$
  - normal Ia, but M(O)=0.5
- M_1>0.8$M_\odot$: **Double-det**, triggered by He (Raskin+12; Pakmor+13; Shen & Moore 14) **sub-Ch**
- Tanigawa, Nomoto+ (2016) SPH

SN Ia progenitors / explosions



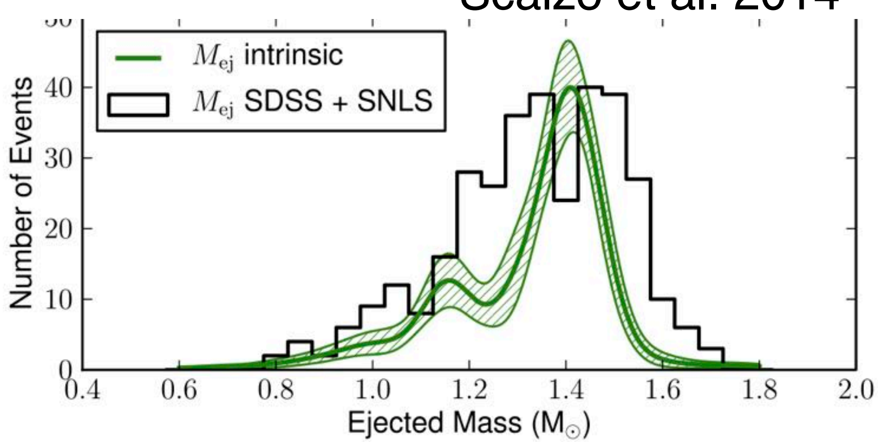
- Ch-mass deflagration or delayed detonation
- sub-Ch double detonation from He-star (Ruiter+14)
- sub-Ch double detonation from H accretion (Yungelson+95, CK+15)
- Ch-mass deflagration of CONe WD (Meng & Podsiadlowski 14, CK+15, Kromer+15)



- CO WD+CO WD merger, likely to be sub-Ch
- sub-Ch double detonation from He-WD (Ruiter+14)
- triple merger

Pakmor+ 11,12

Scalzo et al. 2014



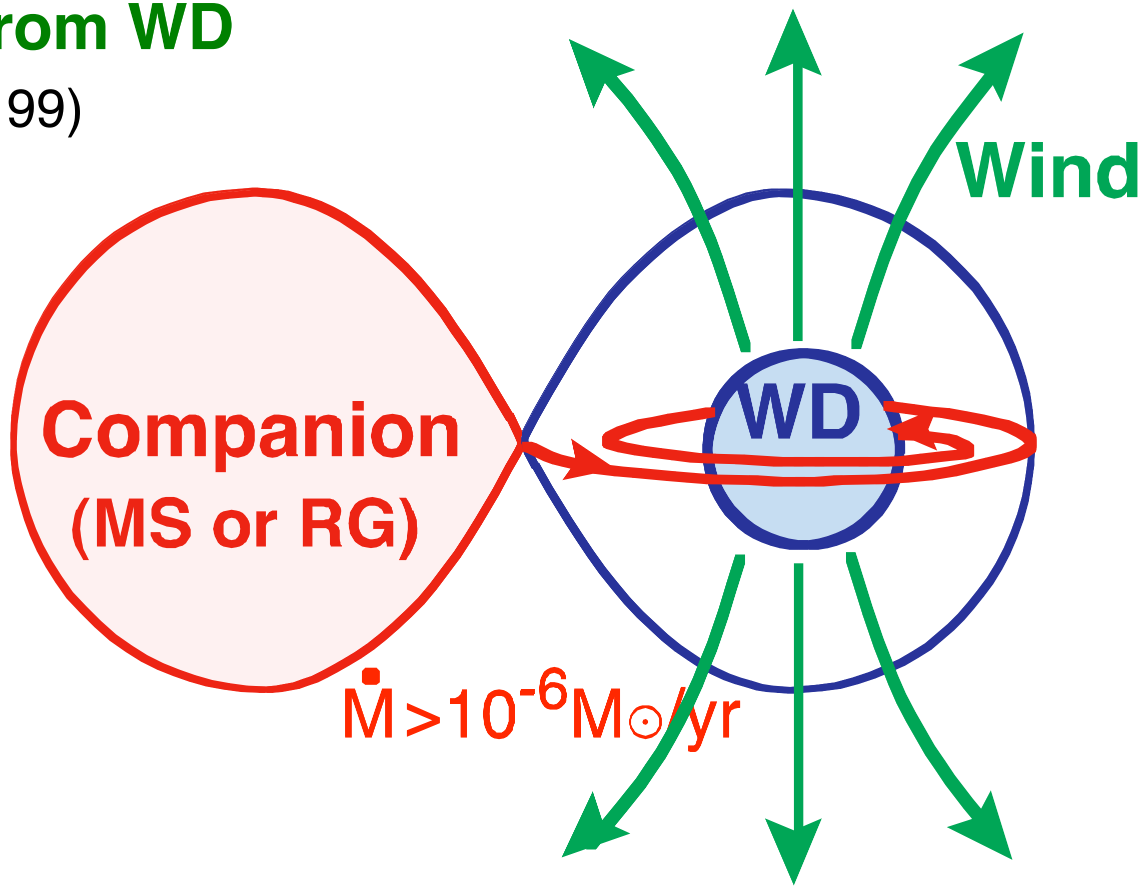
The majority of SNe Ia have ~1.4$M_\odot$.

→ SD scenario + delayed detonation

CSM/companions can be hidden…

SNIa Progenitor Scenario

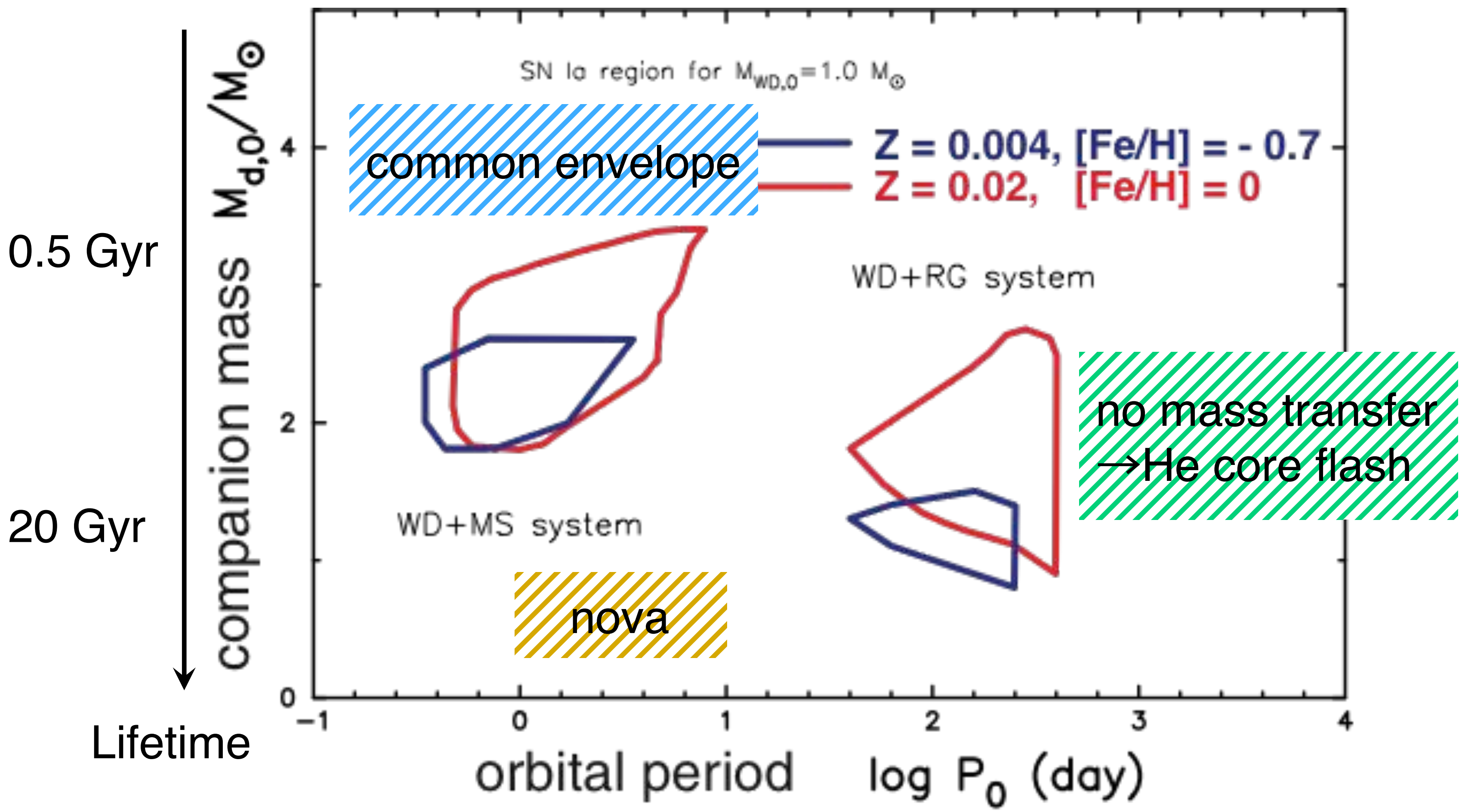
- **Single Degenerate (SD)** vs Double Degenerate (DD)
- Accretion of H-rich matter
- **Optically thick winds from WD**
  (Hachisu, Kato, Nomoto 96, 99)
- **Metallicity Effect**
  No SN Ia @ [Fe/H]<-1.1
  (Kobayashi+ 98)
- **Stripping Effect**
  (Hachisu+ 07; KN09)
- **Lifetime** 0.1-20 Gyr
  depending on metallicity



Kobayashi, Tsujimoto, Nomoto, Hachisu & Kato 1998

Metallicity Effect of SNe Ia

- SNIa lifetime～lifetime of secondary star
- Lifetime Distribution depends on metallicity

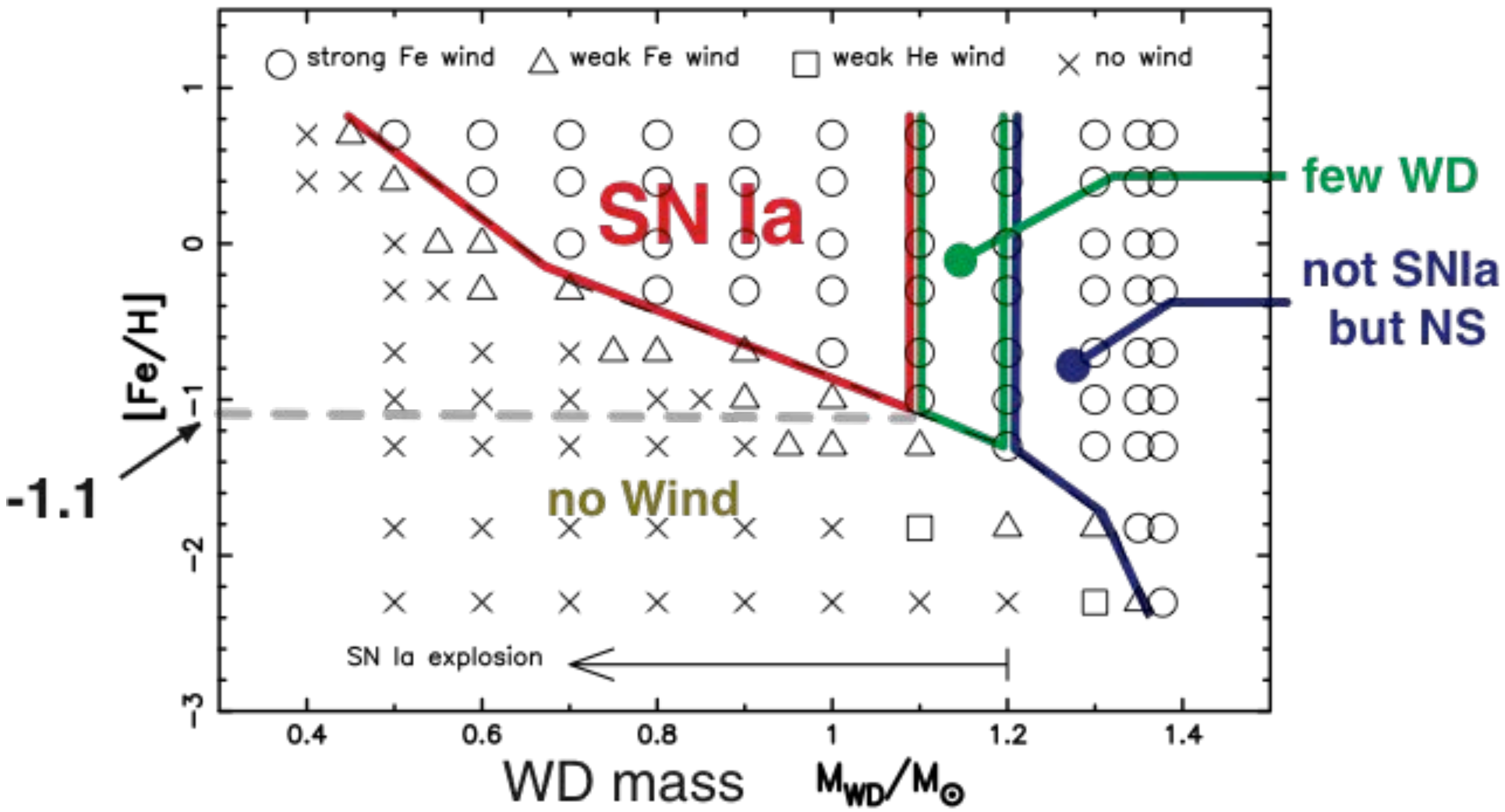


Kobayashi, Tsujimoto, Nomoto, Hachisu & Kato 1998

Low-Metallicity Inhibition of SNe Ia

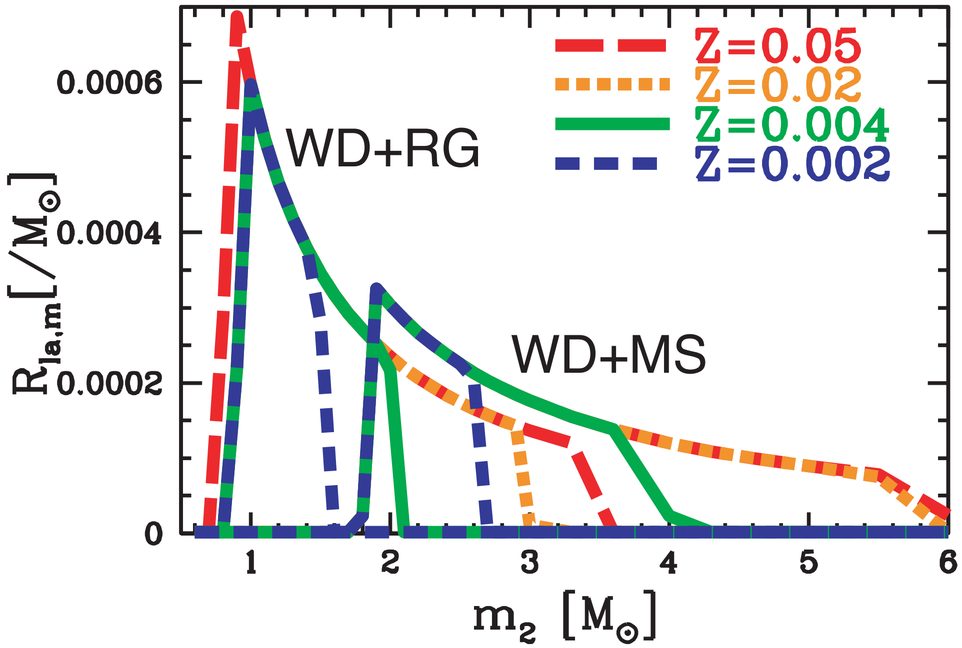
no SN Ia at [Fe/H] < -1

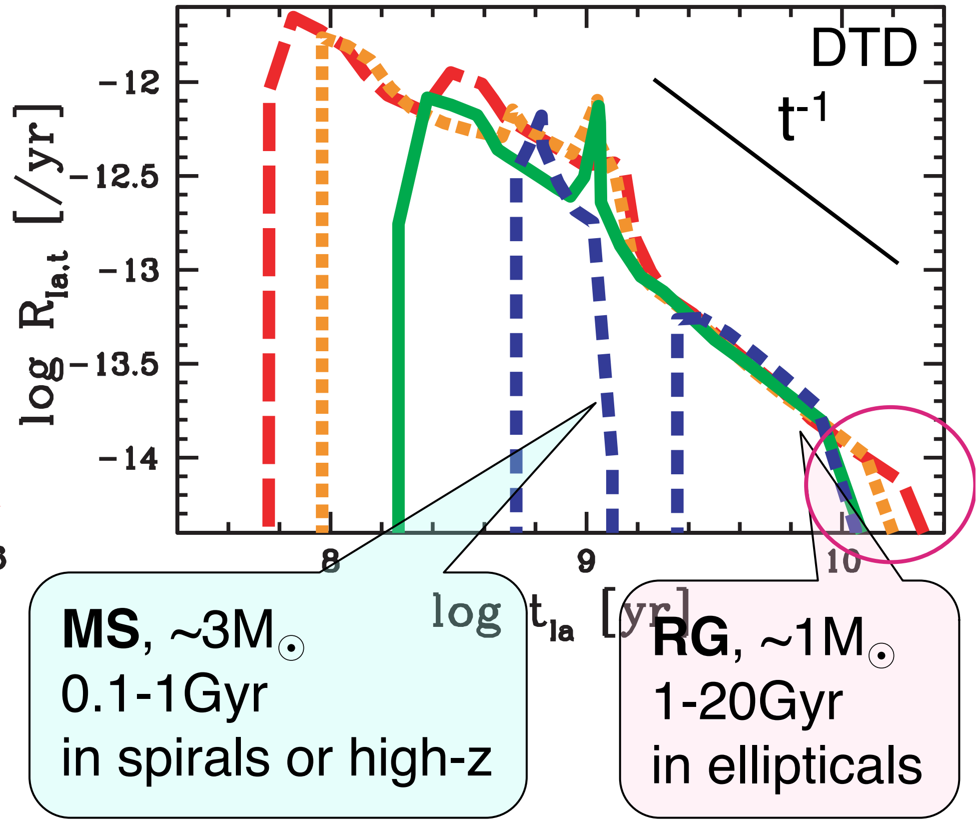
(Kobayashi, Tsujimoto, Nomoto, Hachisu & Kato 1998)



SN Ia Lifetime

- Single Degenerate Scenario
- SNIa Lifetime ~ lifetime of companion star
- Companion mass ranges from binary calculation (Hachisu, Kato, Nomoto)





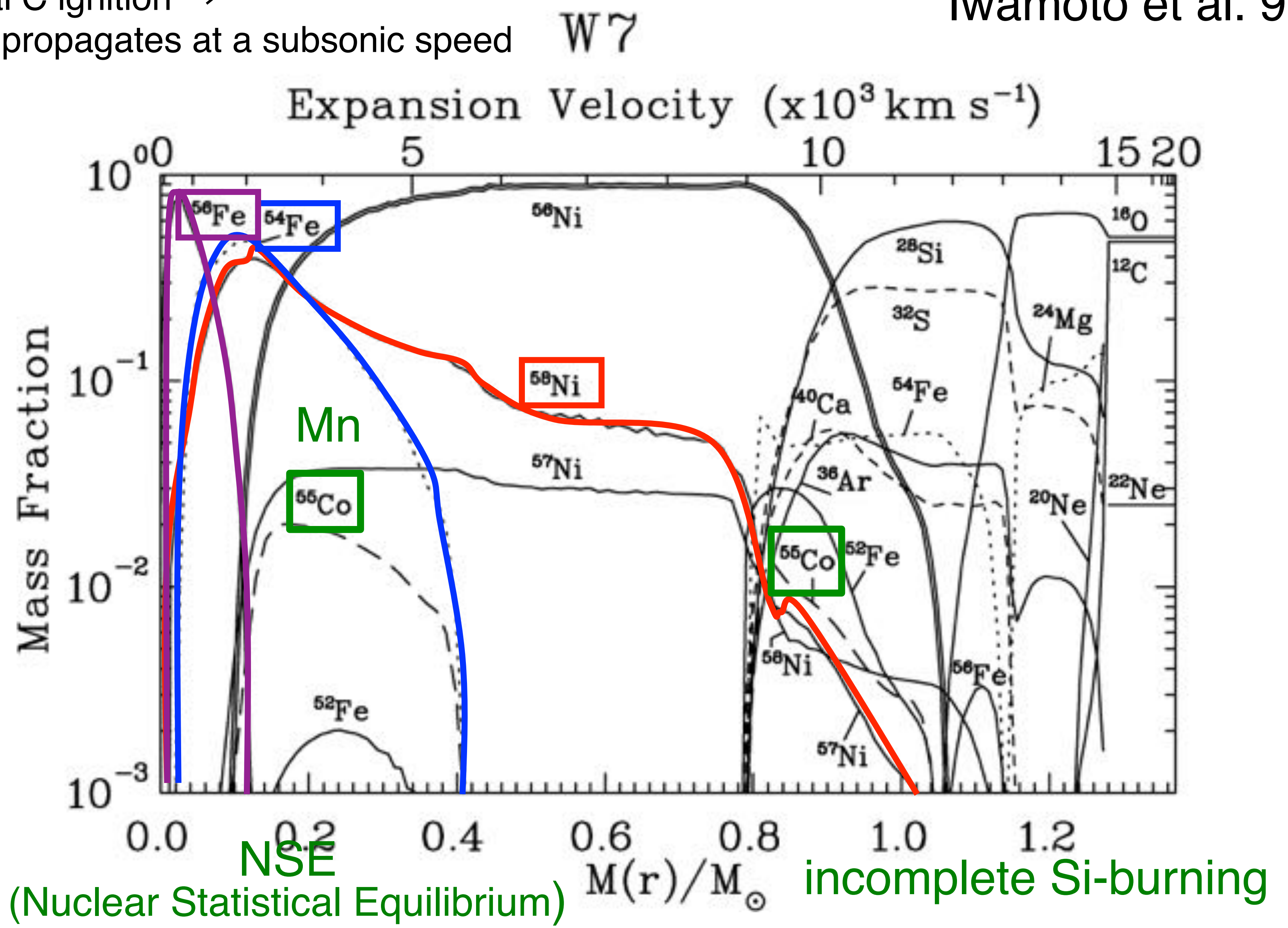
CK & Nomoto (2009)

SNIa
Neucleosynthesis

Deflagration Model

central C ignition →
flame propagates at a subsonic speed

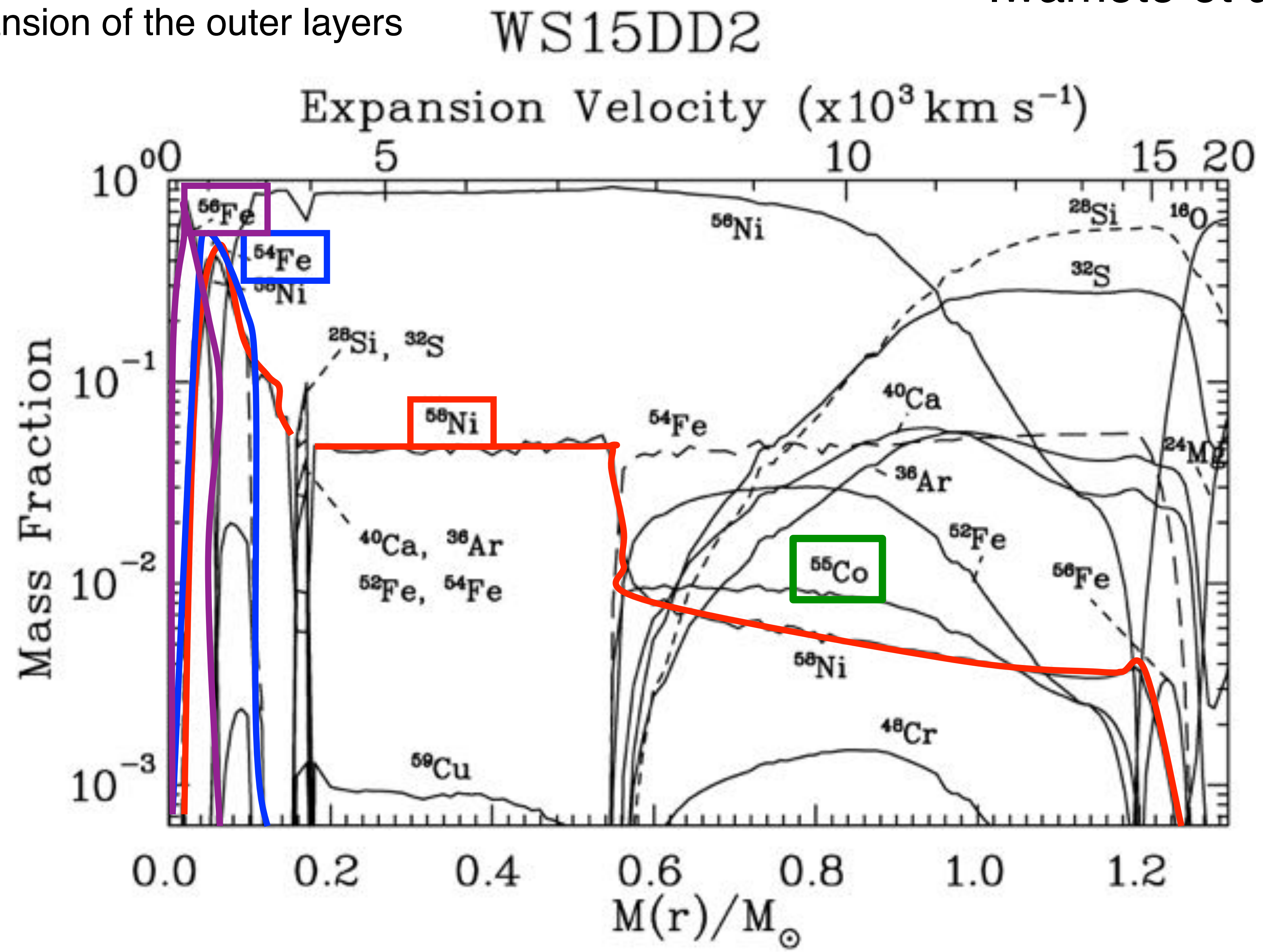
Iwamoto et al. 99



Delayed Detonation Model

slower deflagrations cause an earlier expansion of the outer layers

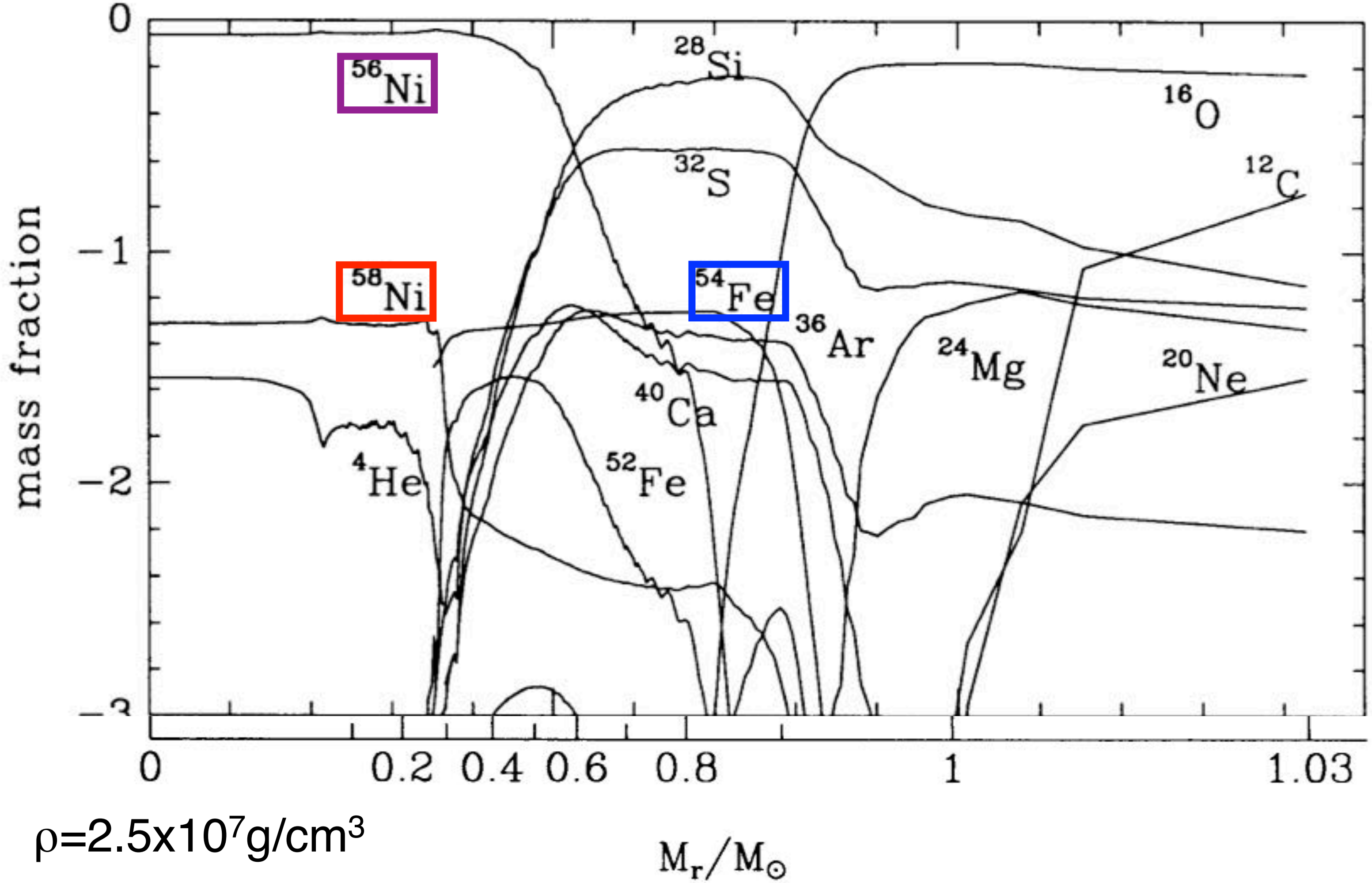
Iwamoto et al. 99



Sub-Chandrasekhar mass Model

Shigeyama et al. 92

CDT3 1.03$M_\odot$

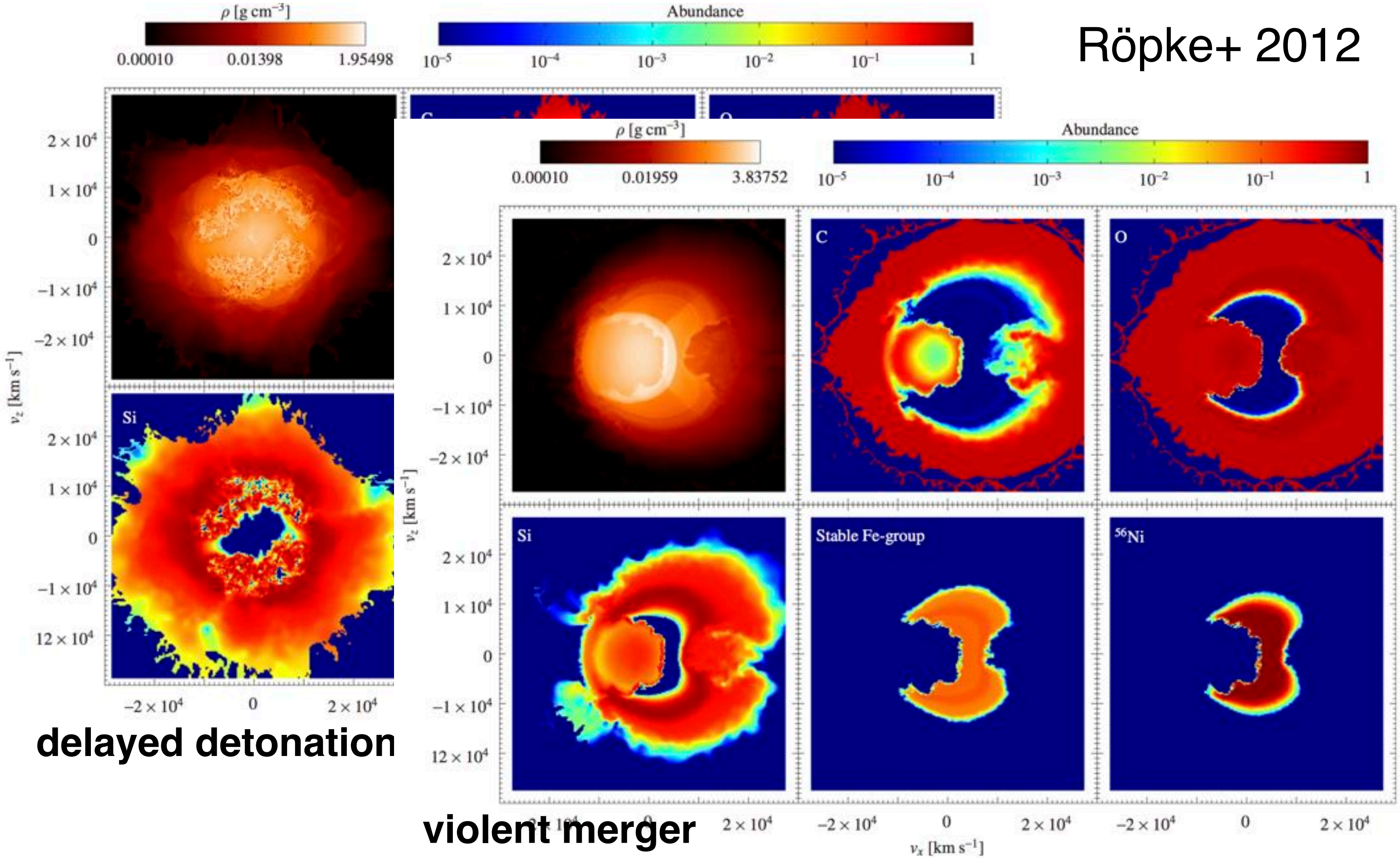


$\rho=2.5\times10^7 g/cm^3$

no NSE → low Mn production

Unburned CO in merger

Röpke+ 2012



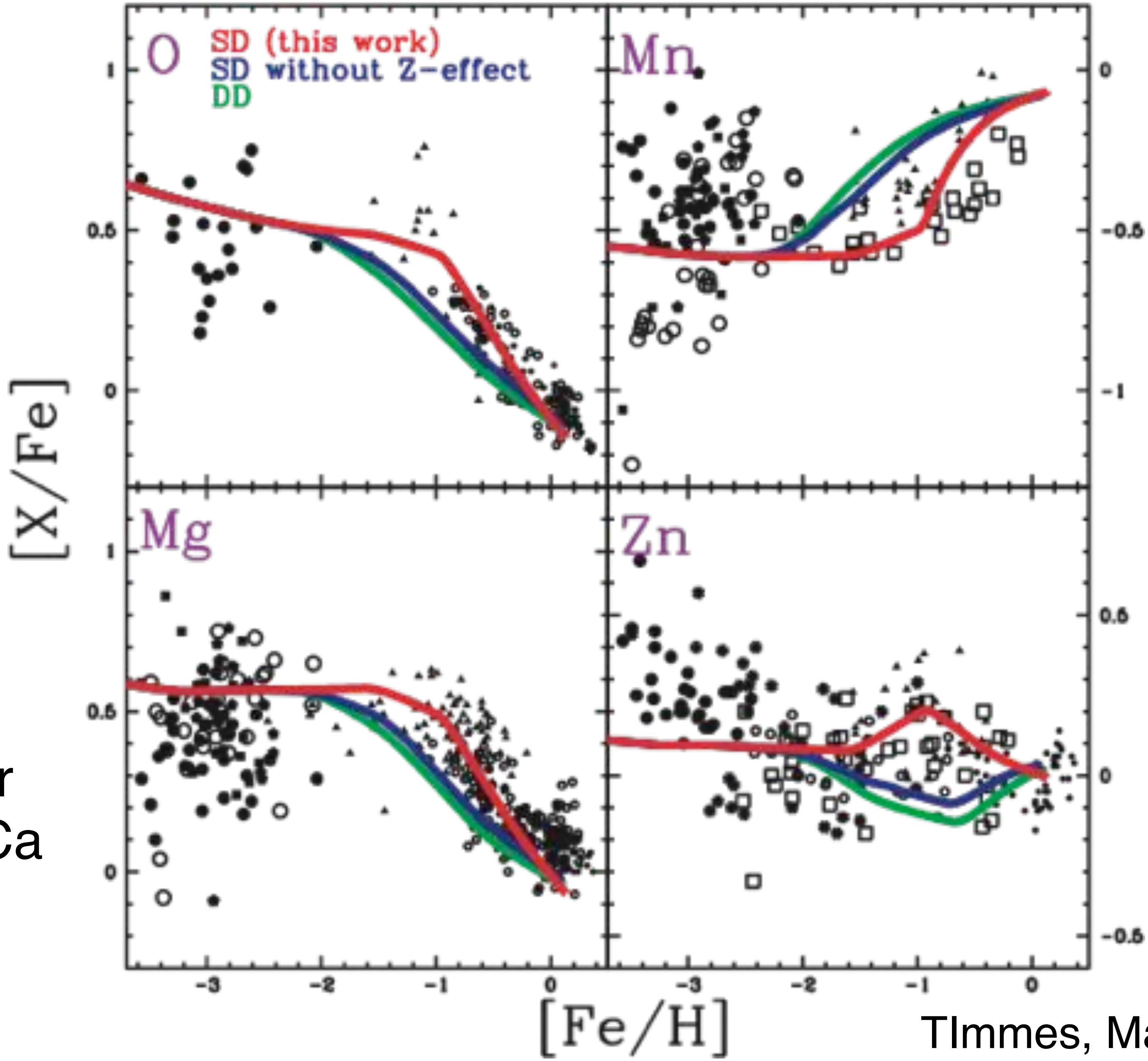
✷ To get the observed low [O/Fe], a higher rate is required.

Nucleosynthesis Yields of SNe Ia

	M(Fe) [$M_\odot$]	M(O) [$M_\odot$]	[Mn/Fe]
Mch, Deflagration (W7)	0.613	0.143	0.15
Deflagration (Fink+13, N5def)	0.158	0.06	0.36
Mch, Delayed Detonation (Röpke+12, N100)	0.604	0.101	0.33
GCD	?	?	?
Sub-Mch, Double Detonation (Sim+10, 1.06$M_\odot$)	0.56	0.08	–0.13 ✗
Violent Merger (Röpke+12, 1.1+0.9$M_\odot$)	0.616	0.492 ✗	–0.15 ✗
tamped merger (Raskin+14)	~0.7-0.8	~0.4 ✗	?
Collision	?	?	?
core degenerate merger	?	?	?

Mn values are from Seitenzahl+ 13b

one-zone GCE models (CK & Nomoto 2009)



Also for
Si, S, Ca

See also
TImmes, Matteucci,…