Core-Collapse Supernovae and Abundances in Extremely Metal-Poor Stars

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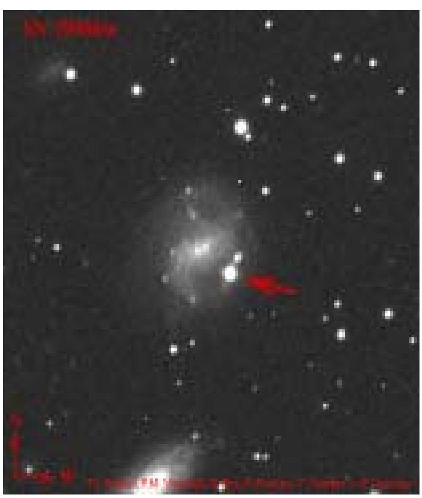
SN 1998bw (Hypernova)



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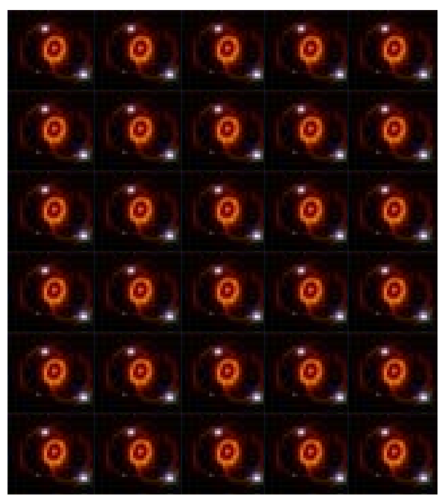
SN 1987A

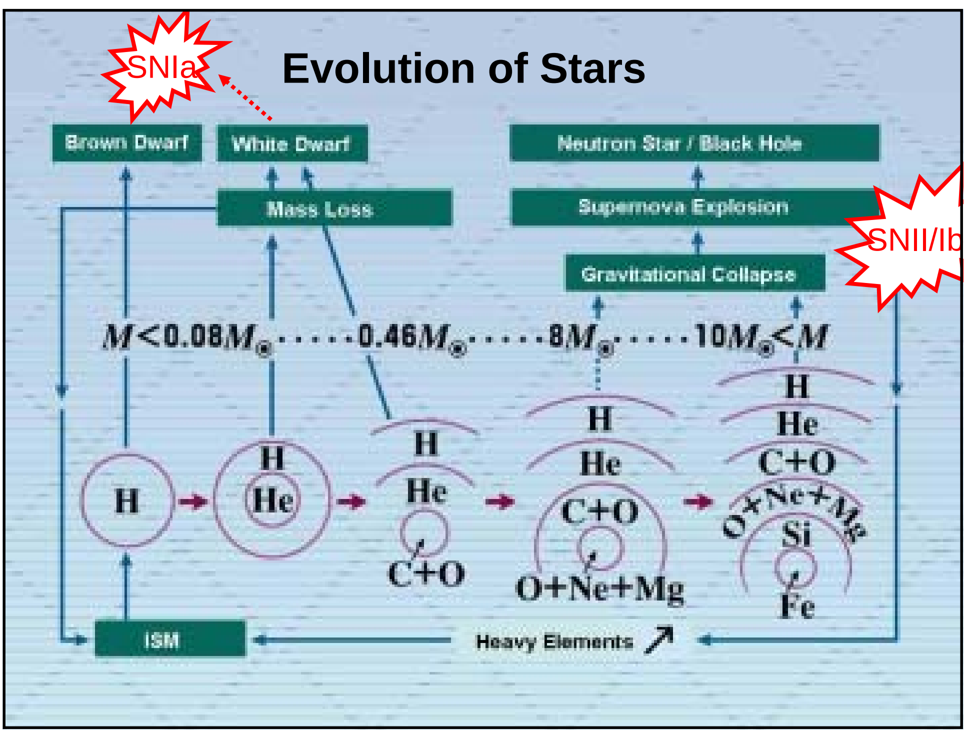


$E \sim 30 \times 10^{51}$ergs

$E \sim 1 \times 10^{51}$ergs

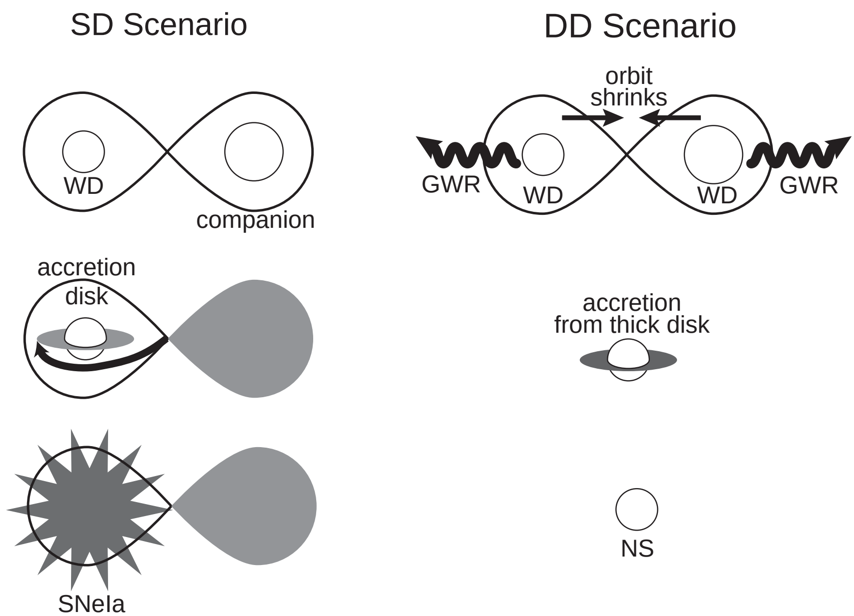
Explosion Mechanism? Nucleosynthesis? Galactic Chemical Evolution?

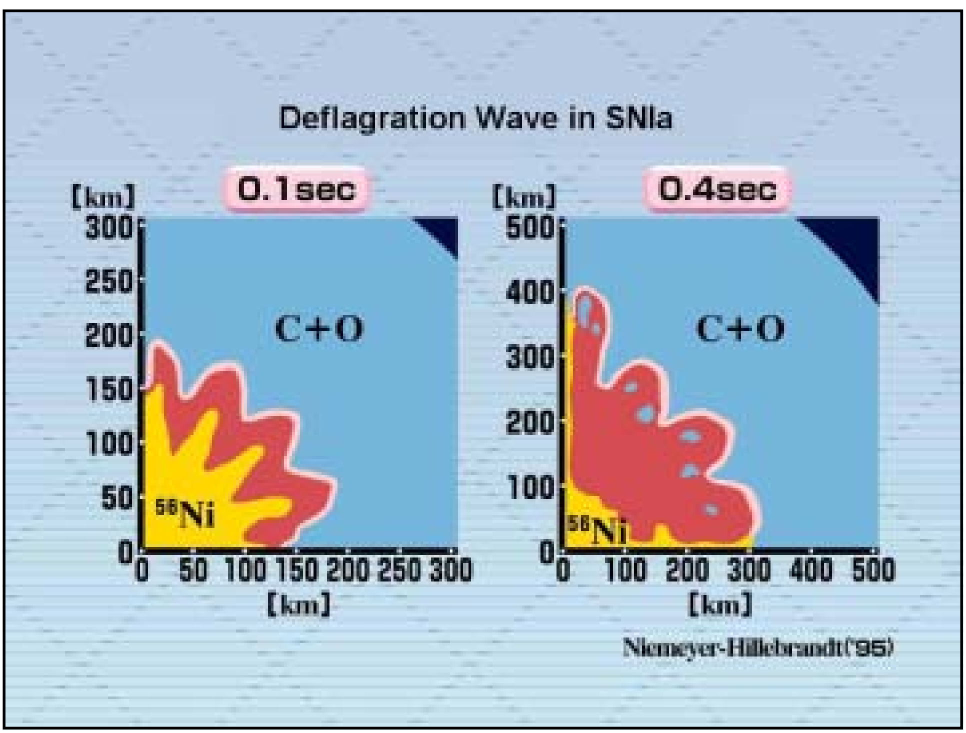
Contents



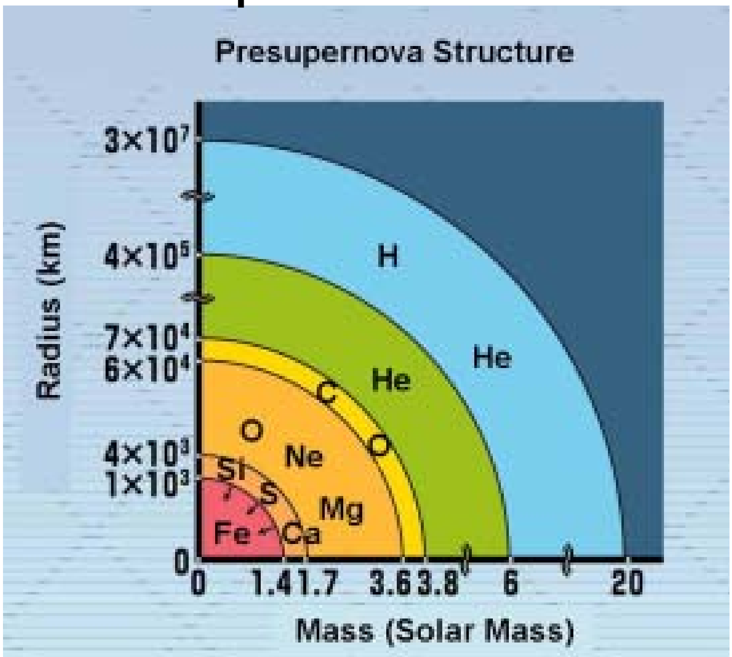
Evolution of Stars
SNIa
Brown Dwarf
White Dwarf
Neutron Star / Black Hole
Mass Loss
Supernova Explosion
Gravitational Collapse
SNII/Ib
$M<0.08M_\odot$ ····· $0.46M_\odot$ ····· $8M_\odot$ ····· $10M_\odot<M$
H
H He
H He C+O
H He C+O O+Ne+Mg
H He C+O O+Ne+Mg Si Fe
ISM
Heavy Elements

SNe Ia: Accreting White Dwarfs

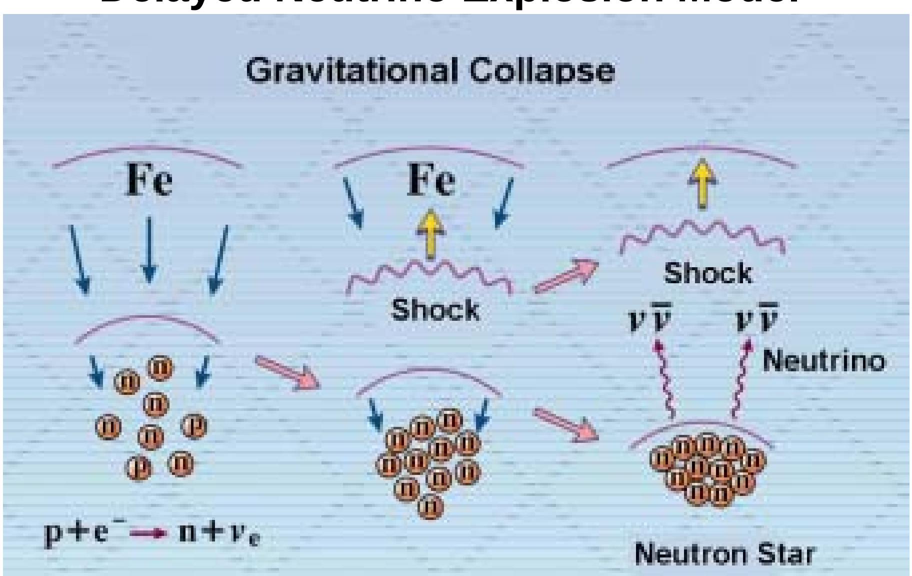




Core-Collapse SNe: Massive Stars



Delayed Neutrino Explosion Model



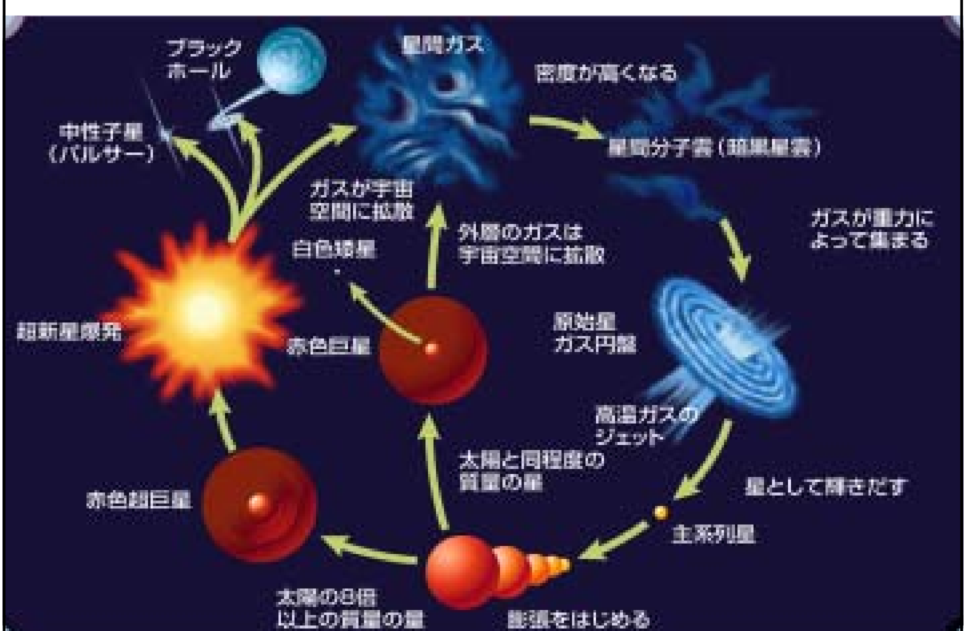
Marginally Explains Energetic of
(Normal) Core-Collapse SNe (10^{51}ergs)

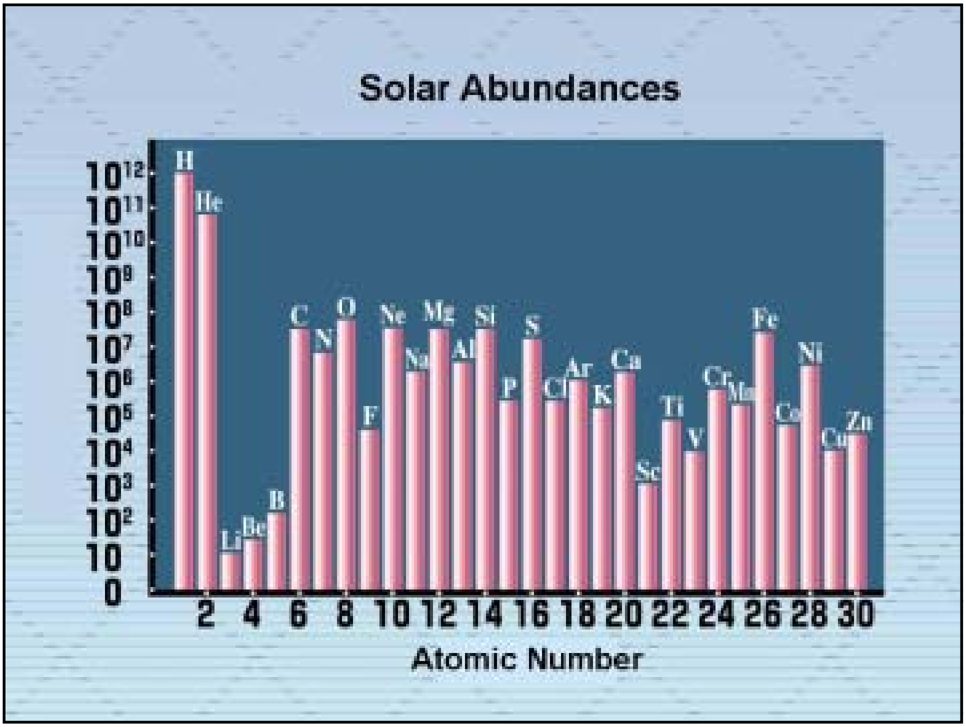
e.g., Janka et al. 2002

Fate of Massive Stars

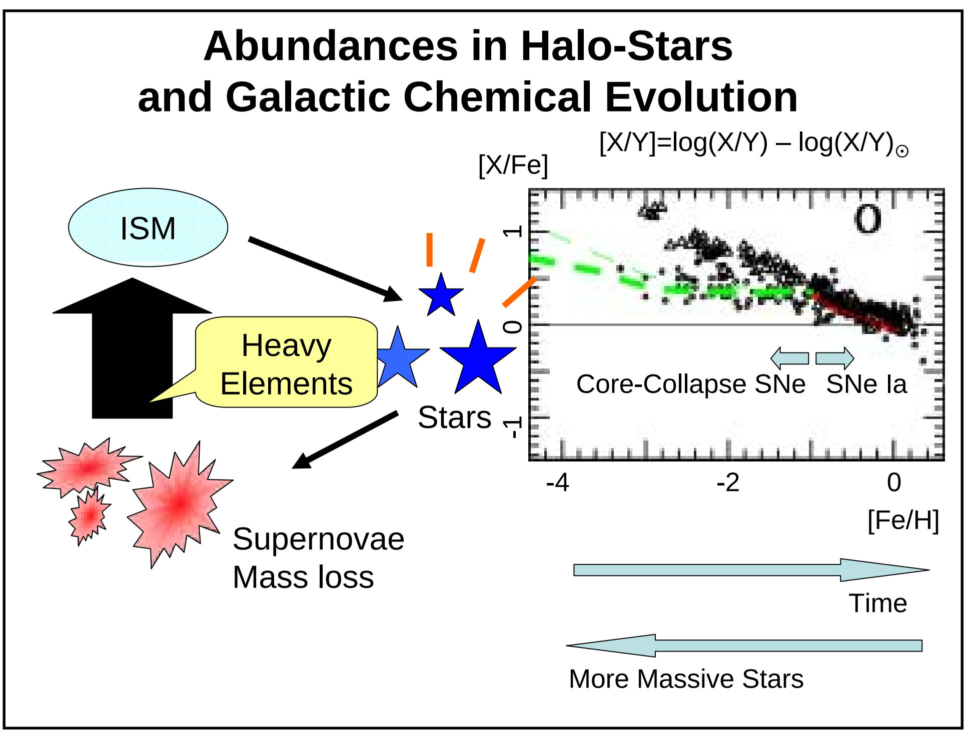
- ～12－25$M_{\odot}$: Core-Collapse Supernovae (Neutron Star Formation)
- ～25－100？$M_{\odot}$: Supernovae/Hypernovae (Black Hole Formation?)
- ？－130？$M_{\odot}$: Direct Collapse to a BH (Black Hole Formation?)
- ～140－270$M_{\odot}$: Pair Instability SNe (PISNe) (No Central Remnant)
- ～300$M_{\odot}$以上: Direct Collapse to a BH? BH + Explosion?

Cycle in the Galaxy/Universe





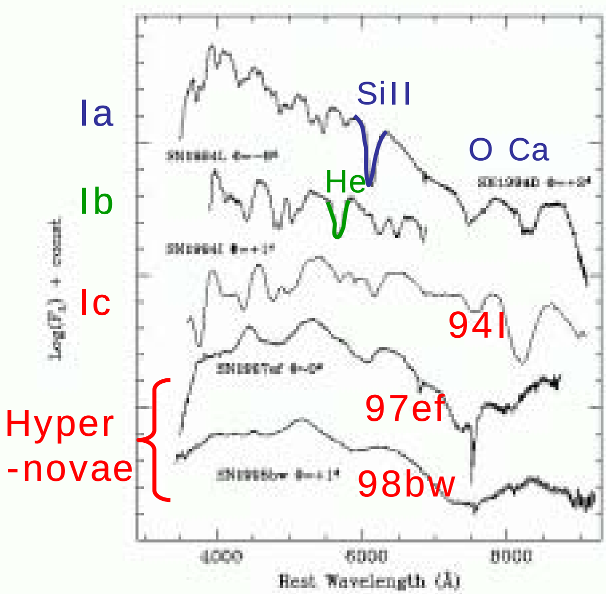
Solar Abundances
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10
0
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Atomic Number



Abundances in Halo-Stars
and Galactic Chemical Evolution
[X/Y]=log(X/Y) – log(X/Y)$_\odot$
[X/Fe]
ISM
Heavy
Elements
Stars
Supernovae
Mass loss
O
1
0
-1
Core-Collapse SNe
SNe Ia
-4
-2
0
[Fe/H]
Time
More Massive Stars

Observational Properties of Hypernovae

Spectra of Supernovae & Hypernovae



Ic: no H,

no strong He,

no strong Si

Hypernovae:

broad features

↑

blended lines

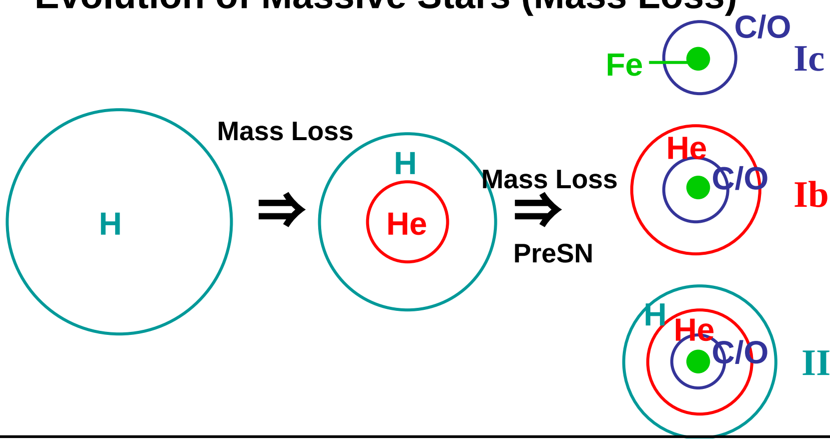
↑

"Large mass at high velocities"

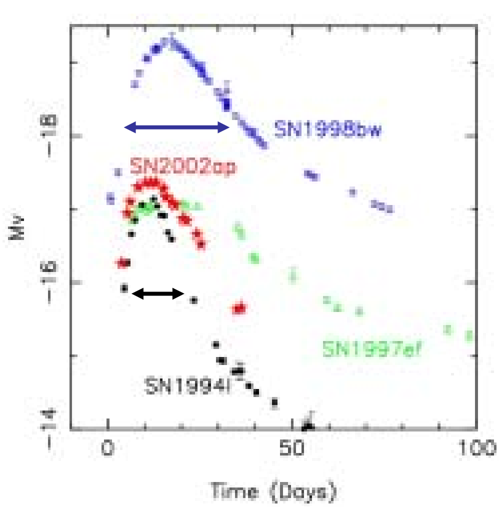
Classification of Supernovae

SN
- SNI -- no H
  - Ia -- Si line -- Exploding WD
  - Ib -- He lines
  - Ic -- no He, Si
  - (Ib, Ic) -- Core-Collapse
- SNII -- H line

・Evolution of Massive Stars (Mass Loss)



Light Curves of Supernovae & Hypernovae



Light Curve Broadness

SN1998bw >> SN1994I

↓

Ejected Mass

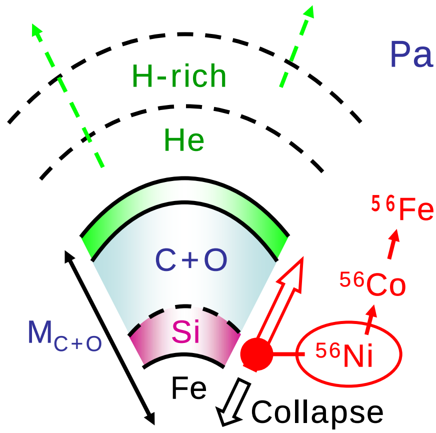
SN1998bw >> SN1994I

↓

Progenitor's Mass

SN1998bw >> SN1994I

CO Star Models for SNeIc



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

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

Light Curve | Spectra

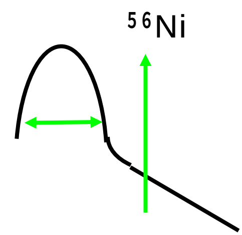
$E \propto M_{ej}$

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

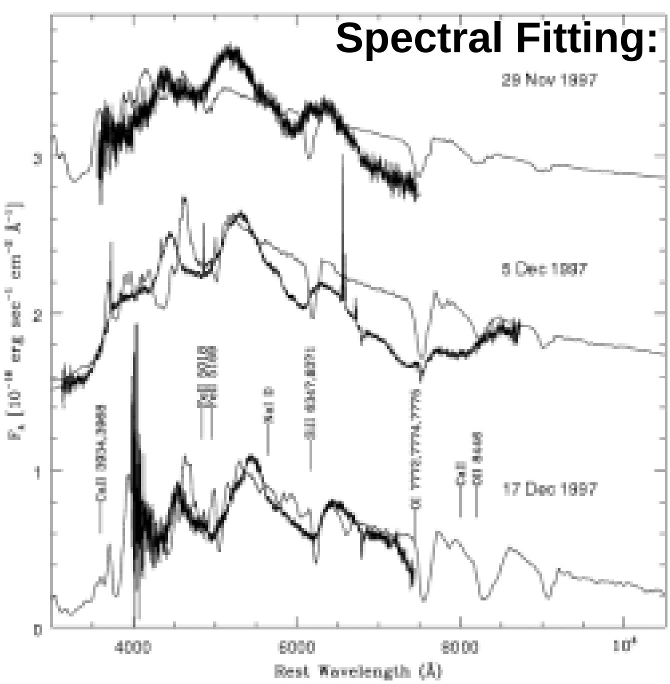
$$\sim \left(\frac{R}{V} \bullet \frac{\kappa M_{ej}}{R c}\right)^{1/2}$$

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

$E \propto M_{ej}^3$



Spectral Fitting: SN1997ef



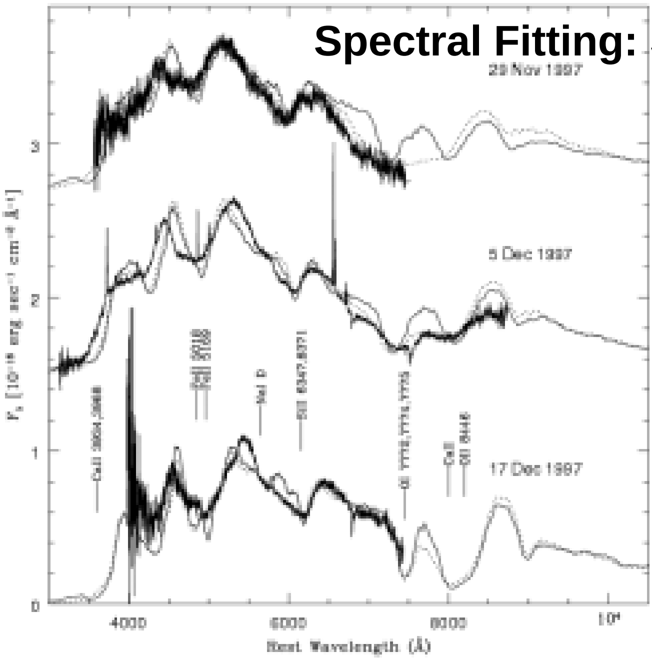
Model

Normal SN

Small M_{ej}

Too Narrow Features

Spectral Fitting: SN1997ef



Model
Hypernova
Large M_{ej}

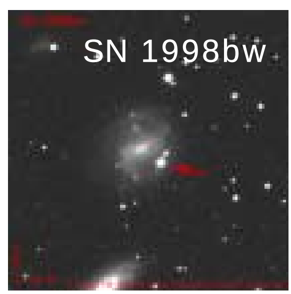
⇩

Broad
Features

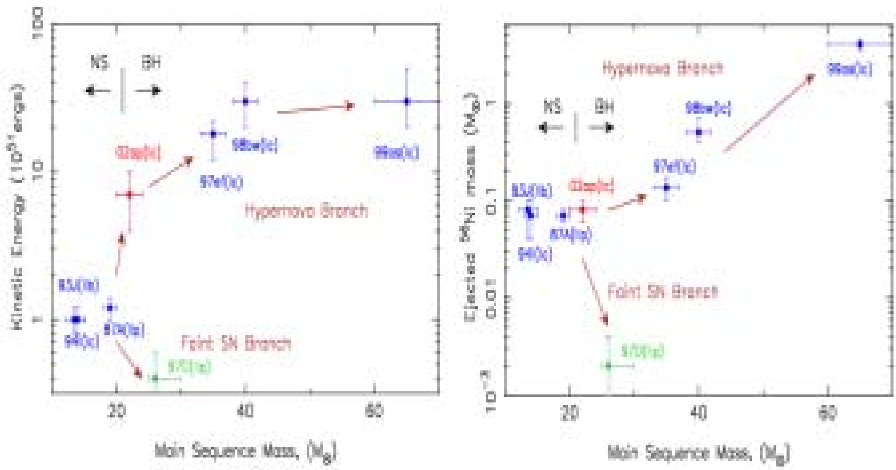
Hypernova Candidates

$E_{kinetic}$ > (5-10)×10^{51}ergs

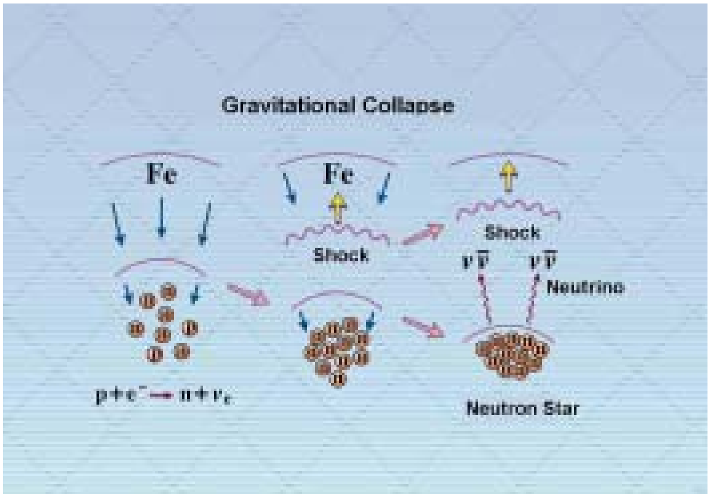
SNe Ic		SNe IIn	
SN	GRB	SN	GRB
1998bw	●980425	1997cy	970514
1997ef	971115	1999E	980910
1999as		1988Z	
2002ap		1999eb	991002
1997dq			
1998ey			
1992ar			



Progenitors' Mass – E – M(^{56}Ni)



Evidence
of
Asphericity and **Black Hole** Formation
in
Hypernova explosions

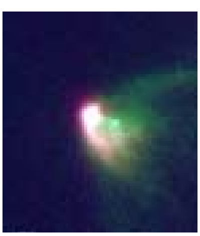


$E_{grav} \sim GM_{REM}^2/R_{REM} \sim G(1.5M_\odot)^2/(10\text{km}) \sim 6\times10^{53}$ergs

E_{grav} / $E_{Supernova}$ ~ 0.002 ; Marginally attained in simulations.

E_{grav} / $E_{Hypernova}$ ~ 0.02 (NS), 0.002 (BH) ; ???

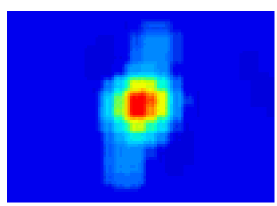
Jets in the Universe



L1551-IRS5

SUBARU/NAO

Young Stars



v4641 Sgr

Hjellminget et al.

VLA/NRAO

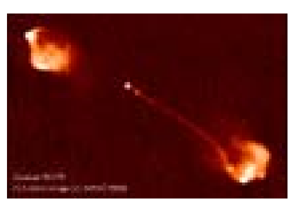
Stellar Mass Black Holes

Centaurs A

NASA/CXC/SAO

AURA/NOAO/NSF

Galaxies



3C175

Bridle

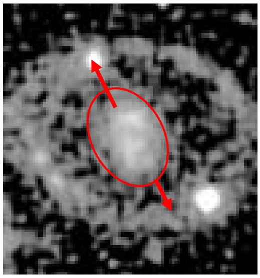
VLA/NRAO/NSF

Quasars

1) Asphericity in Core-collapse SNe (in general)

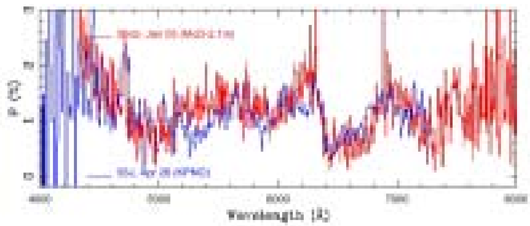
SN1987A: Asymmetrical, but not spherical, ejecta

Optical Polarization in core-collapse SNe > 0.5 %
(in SNe Ia < 0.2 - 0.3%)



HST Image of SN1987A

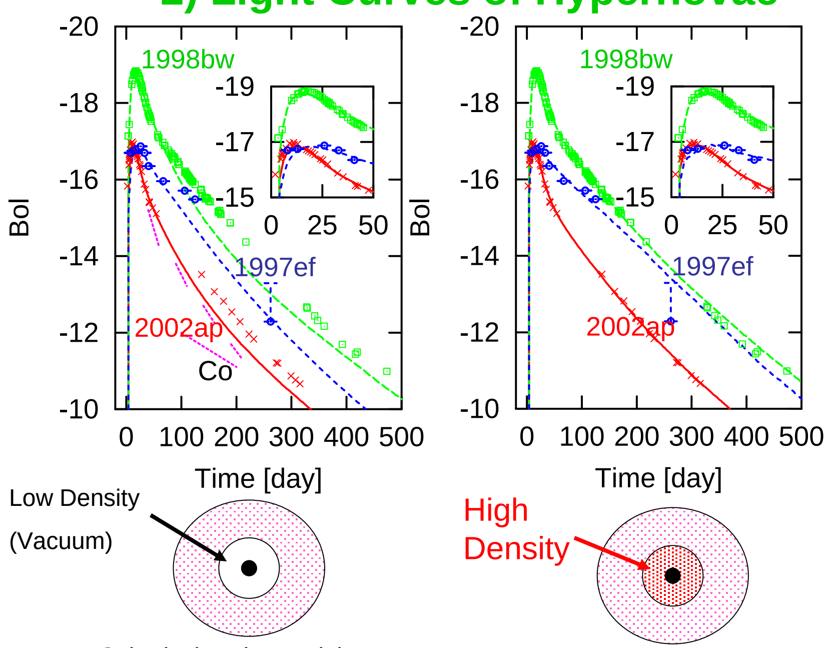
Wang et al. 2002



Optical Spectropolarimetry of

SNe 1993J, 1996cb, Wang et al. 1999

2) Light Curves of Hypernovae

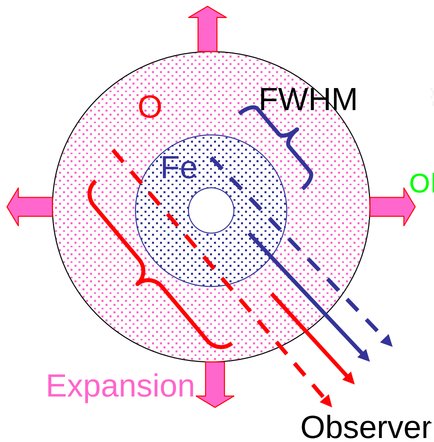


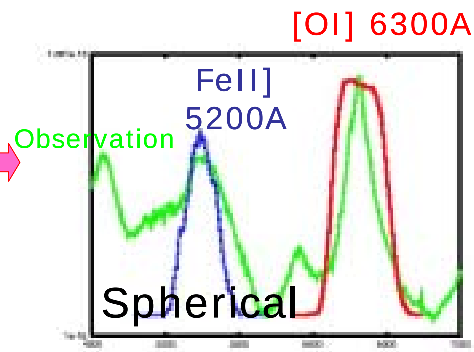
Spherical Hydro Model

Maeda et al. 2003, ApJ, submitted

3) Late time spectra of SN1998bw

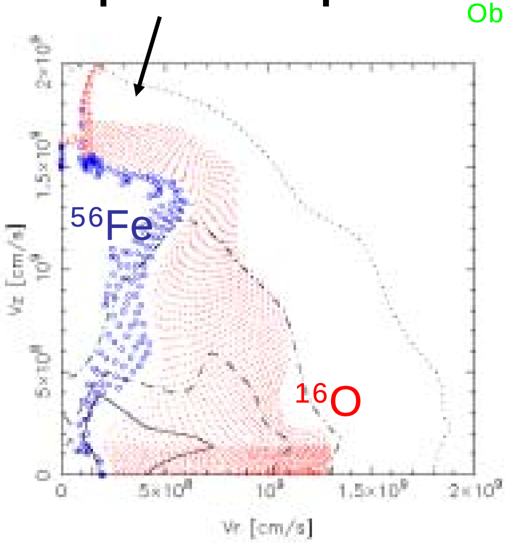
Line Width Inversion of Fe and O



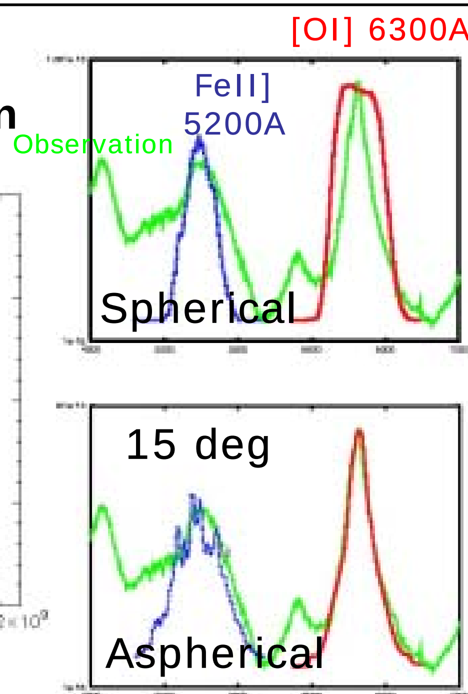


Broader Fe lines than O lines in the observations.

Interpretation as an Aspherical explosion



Maeda et al. 2002



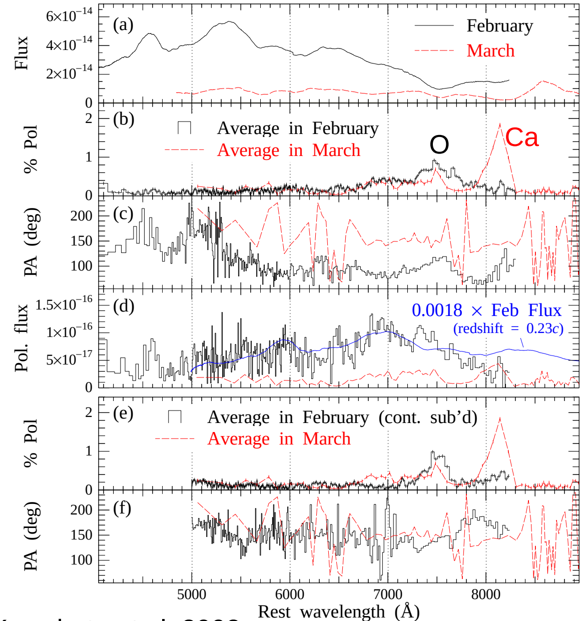
4) Optical Polarimetry of SN2002ap

Feb, 2002
<1% at OI7773
Outer Region
March,2002
<2% at CaII IR
Inner Region

↓

1)Different asphericity in different depths.

2)The Polarized flux is well fitted by radiation redshifted by 0.23c.



Kawabata et al. 2002

A Hypothetical 'Jet' Interpretation

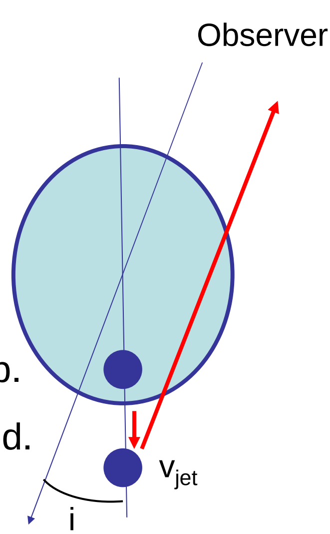
$$P_{jet}(\lambda) = f * \frac{F[\lambda(1 - V_{red}/c)]}{F(\lambda)}$$

$V_{red} = V_{jet}(1 + \cos i) = 0.23$ c,

Thus $V_{jet} > 0.115$c.

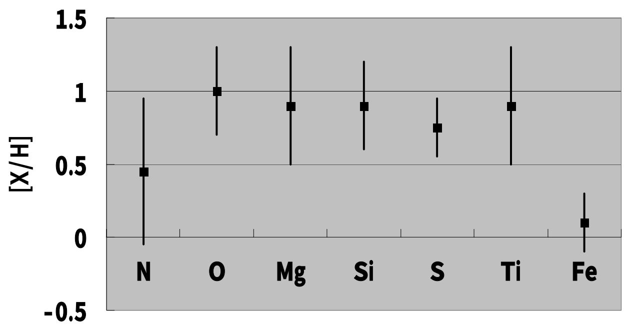
The jet could be a ^{56}Ni-rich blob.

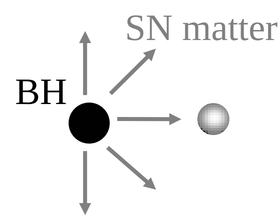
High ionization state is expected.



5) BH Formation in a HN explosion

Abundances in Nova Sco $[X/H]=\log_{10}(X/H)-\log_{10}(X/H)_\odot$

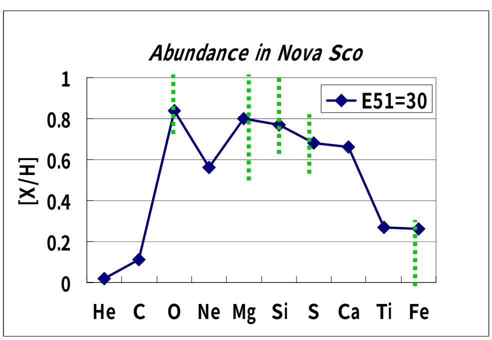




- Enhancement of O,Mg,Si,S,Ti by a factor of 6-10.

Israelian et al. 1999

Hypernova model for the formation of the BH in Nova Sco



BH mass in the model

4.8M at the explosion

5.4M now (Post SN)

M_{MS}=40, M_{He}=16, E_{51}=30

M_{BH} at the explosion ~ 5M

Black hole formation with Hypernova explosion.

Podsiadlowski et al. 2002

The properties of hypernova explosions

- High velocity material (Fe)
- Low velocity & high density material (O)
  - Contrary to conventional spherical models.
- forms a black hole, but explodes with large E_{51} (>10).
  - Black hole formation does not always leads to a failed supernova.

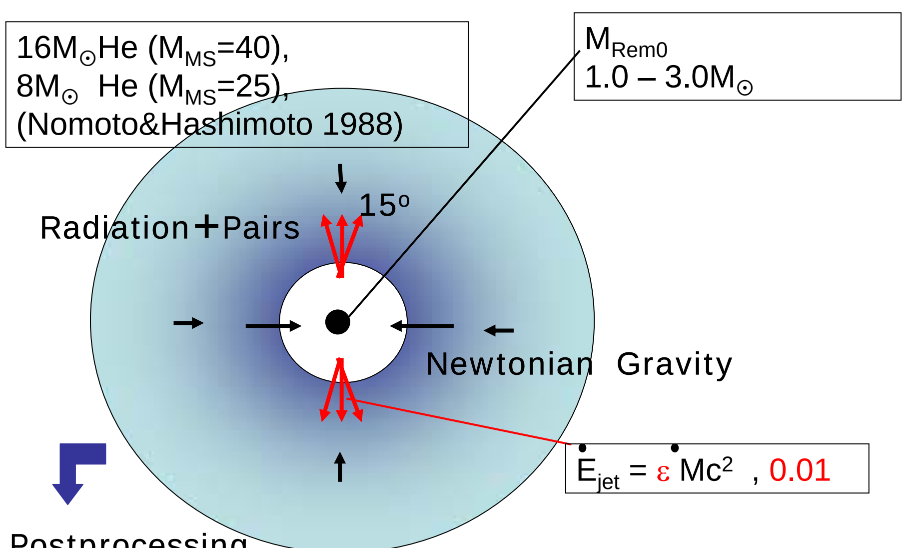
Do jet-induced explosions satisfy these conditions?

Jet-induced explosion model

Previous Works

	Energy Input	Mass cut	Yields	
Many	Prompt Spherical	By hand	Done	8-300M E_{51}=1-100
Nagataki 1998&2000	Prompt Asphperical	Byhand (No Accretion)	Done	SN1987A 20M, E_{51}=1
Maeda et al. 2002	Prompt Asphperical	By hand (No Accretion)	Done	SN1998bw 40M, E_{51}=1-30
Khoklov et al. 1999	Jet induced (By hand)	Hydro (By Accretion)	No	15M, E_{51}=1
This Work	Jet induced (accretion)	Hydro (By Accretion)	Done	20M,40M E_{51}=1-30

Model: Jet-induced Explosion



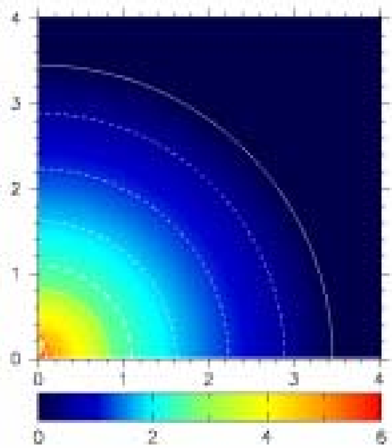
Postprocessing

222 isotopes (Tielemann et al.)

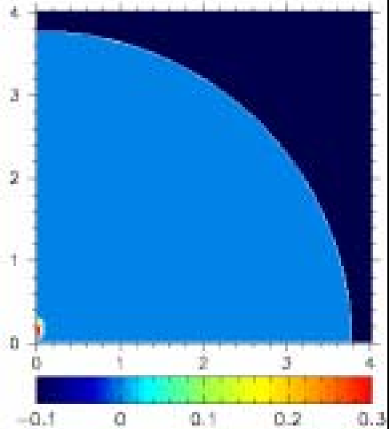
K. Maeda, in preparation

Hydrodynamics

Log (Density[g cm^{-3}])



Radial Velocity/c



R/10^{10}cm

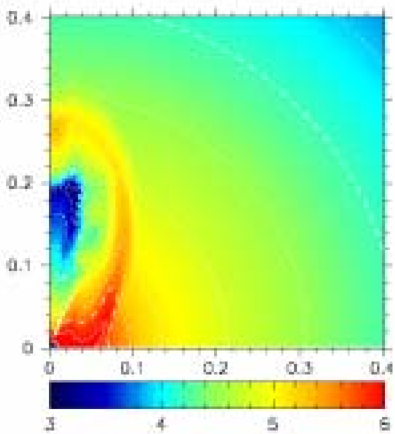
Collimated jets (Z) + Bow shock (All direction)

$\dot{M} \searrow$

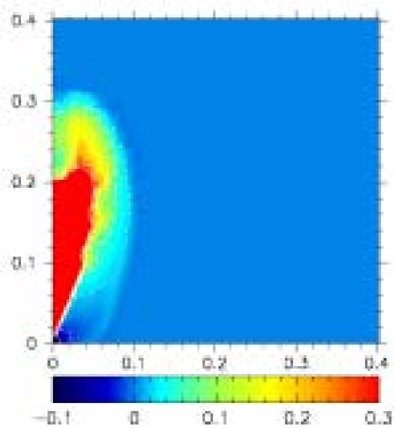
Lateral expansion

Hydrodynamics (Center)

Density



Radial Velocity

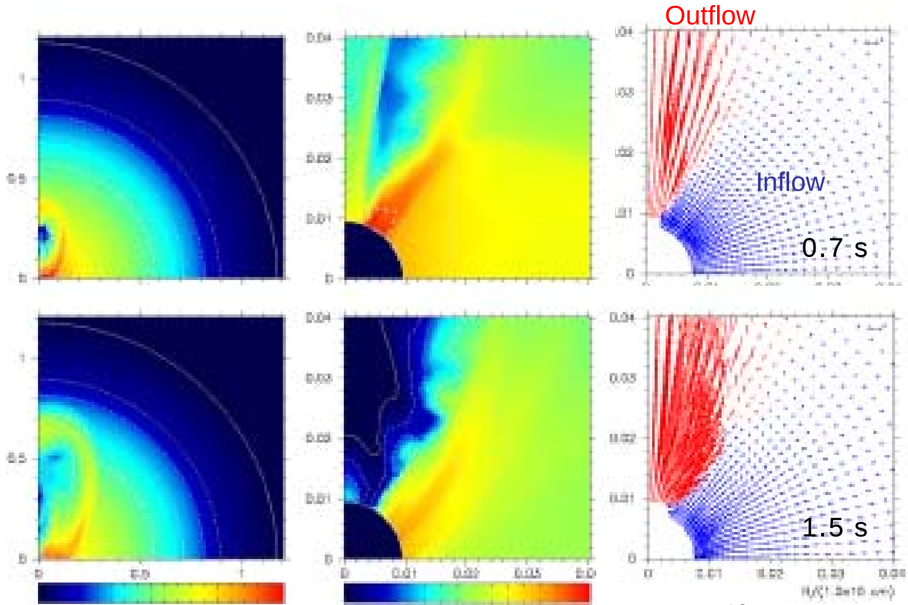


R/10^{10}cm

Accretion from the side

Continue to accrete, $M_{BH} \nearrow$

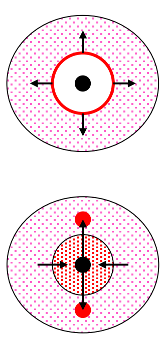
E_{51}=11, M_{BH}(final)=5.9M, M(^{56}Ni)=0.11M

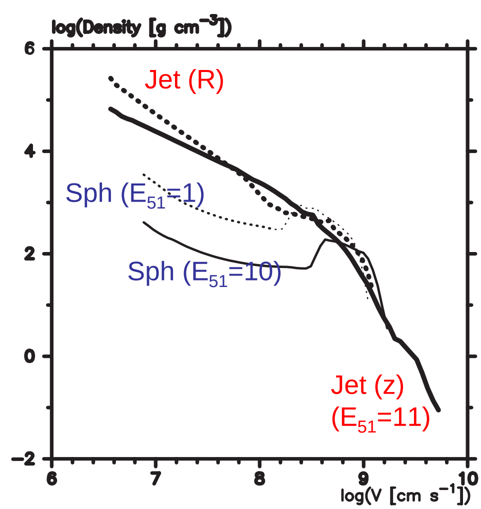


Density Distribution

High density core at the central region

High velocity material along z

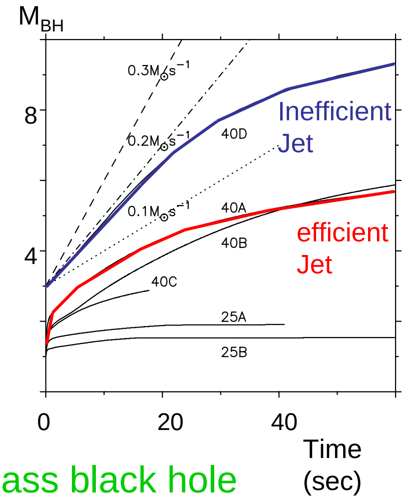




Growth of a central remnant

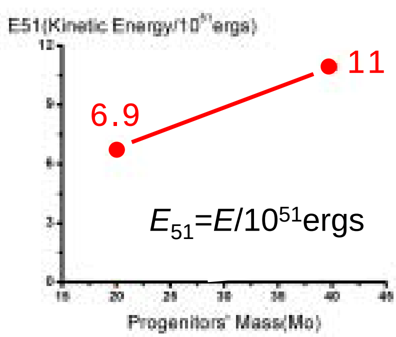
M_{REM} can be ~ 5 – 10$M_\odot$, starting from 1.5 – 3$M_\odot$.

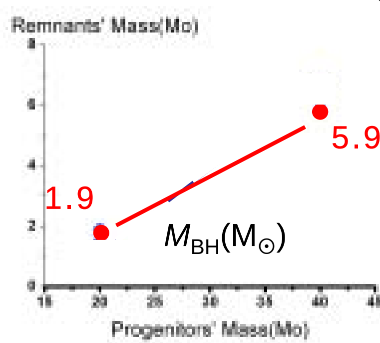
Still a strong explosion follows (E_{51}>10).



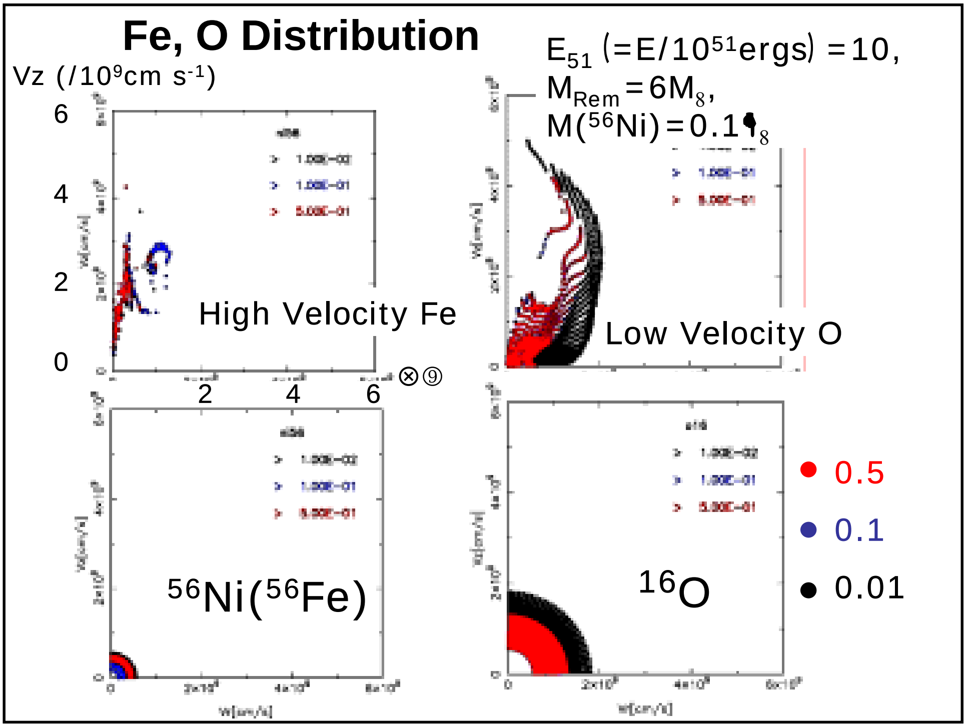
A hypernova with a stellar mass black hole (X-ray Novasco; Large Si,S with black hole formation).

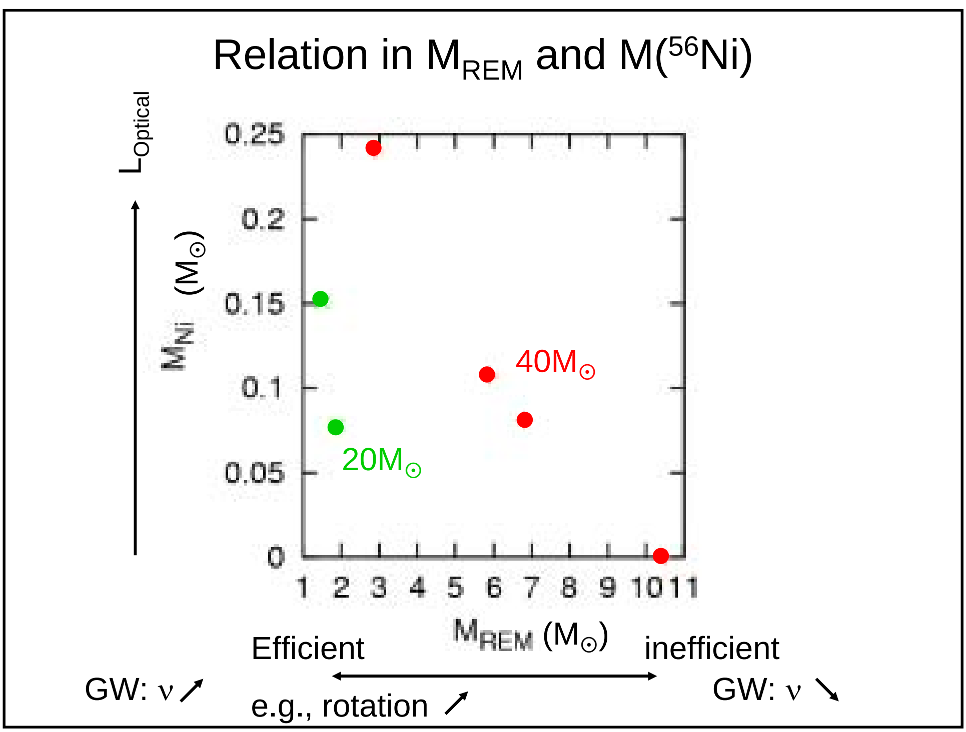
Final Remnants' masses and Kinetic Energies





- A more massive star makes a more energetic explosion (As seen in 'Hypernova Branch').


Fe, O Distribution
Vz (/10⁹cm s⁻¹)
E51 (=E/10^51 ergs) =10,
MRem =6M⊙,
M(56Ni)=0.1M⊙
High Velocity Fe
Low Velocity O
56Ni(56Fe)
16O
0.5
0.1
0.01
6
4
2
0
2
4
6


Relation in MREM and M(56Ni)
LOptical
MNi (M⊙)
0.25
0.2
0.15
0.1
0.05
0
1 2 3 4 5 6 7 8 9 10 11
40M⊙
20M⊙
MREM (M⊙)
Efficient
inefficient
e.g., rotation ↗
GW: ν ↗
GW: ν ↘

Jet-Driven Explosion Model

- High velocity material (Fe)
- Low velocity & high density material (O)
  - Contrary to conventional spherical models.
- forms a black hole, but explodes with large E_{51} (>10).
  - Black hole formation does not always leads to a failed supernova.

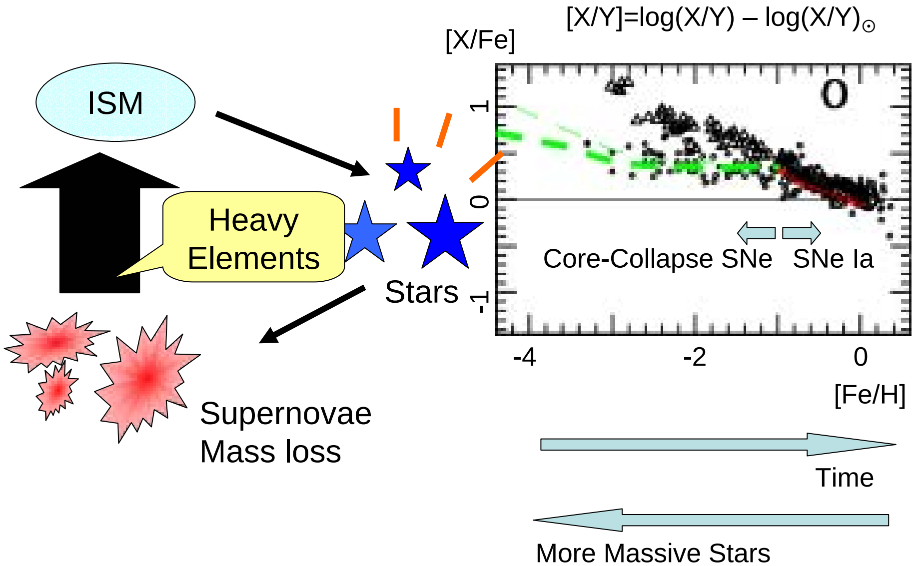
⇩

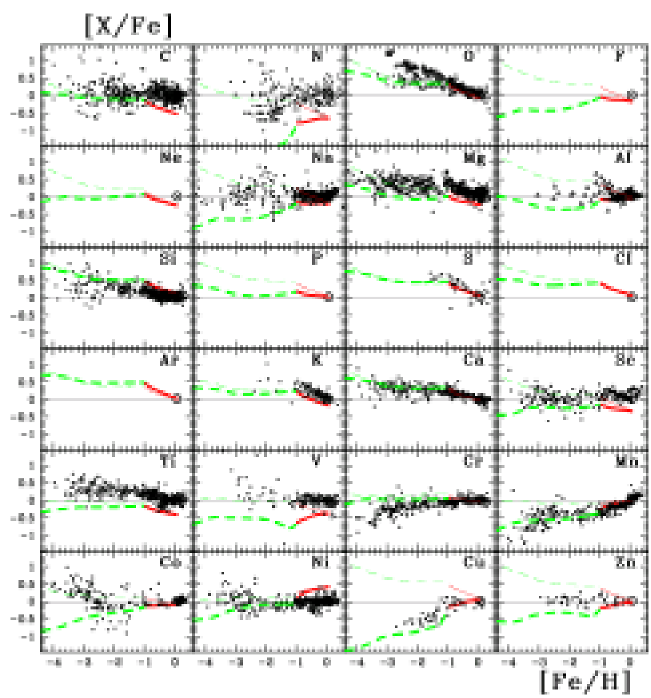
These conditions can be satisfied.

⇨ Nucleosynthesis features?

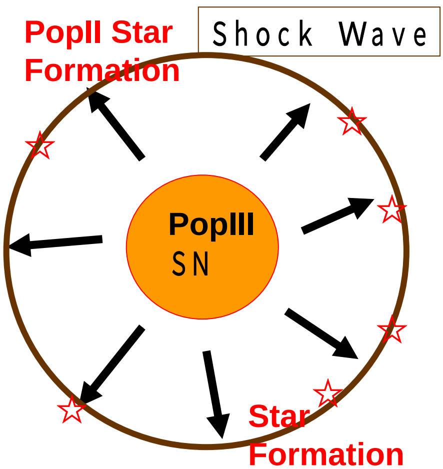
Abundances in Extremely Metal-Poor stars
and
Early Galactic Chemical Evolution

Abundances in Halo-Stars and Galactic Chemical Evolution





Abundances in Extremely Metal-Poor Stars as Relics of SN Explosions in the Early Galactic Evolution



Only one explosion likely produced metal- poor stars with [Fe/H]= −4 ~ −2.5

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

(Ryan et al. 1996, Shigeyama & Tsujimoto 1998, Nakamura, Umeda, Nomoto, Thielemann, Burrows 1999)

The abundance of these stars are determined by the nucleosynthesis in individual Core-Collapse SNe.

The SNe should be massive because of their short lifetime.

The First Stars (Pop III, metal-free)

↓

Shallow IMF

↓

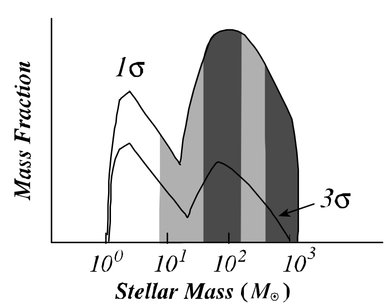
Massive Stars

↓

Pre-galactic Metal-enrichment?

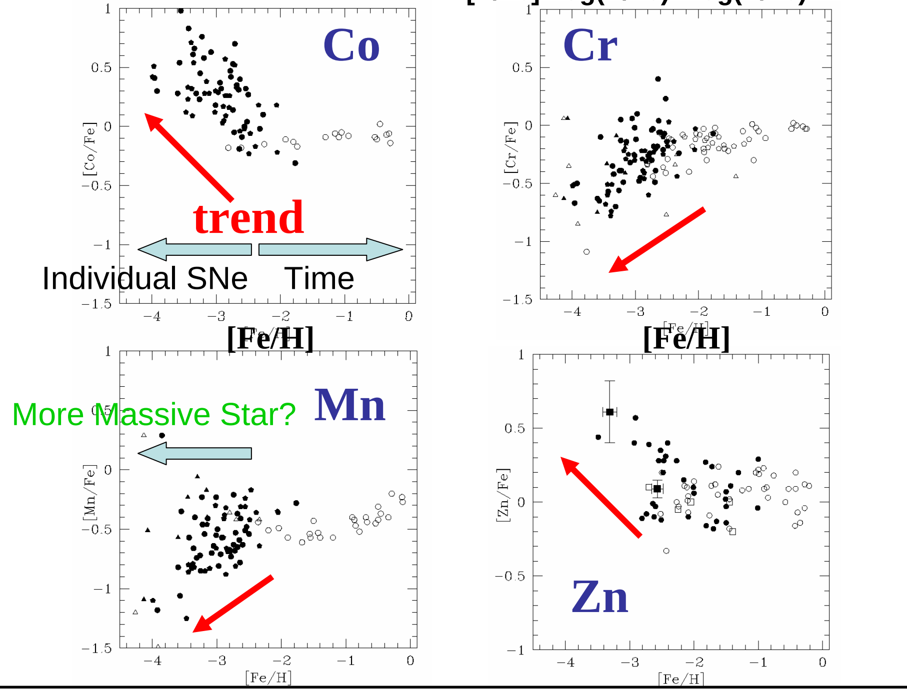
Reionizing Source?

(z=0, T_{eff}~10^5K)



Nakamura & Umemura 2001

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



More Massive Star ⟺ Smaller [Fe/H]

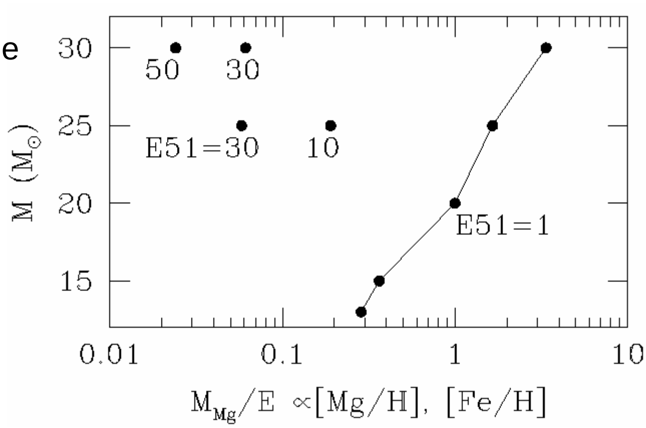
Fe/H= Fe ejected by individual Core-Collapse SN/
H swept up by the Shock wave
$\propto$ ~M(Fe)/E (Ryan et al 1996; Shigeyama & Tsujimoto 1998)

Fe: depends on the mass cut

⇩

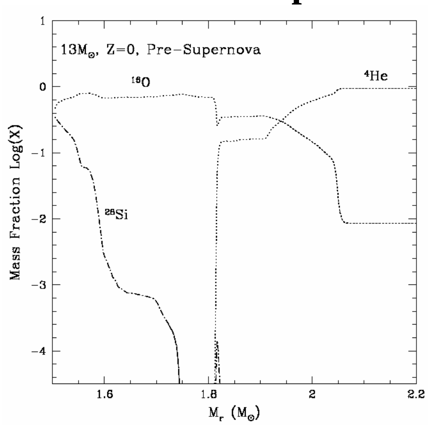
Mg: Independent from the mass cut

Observations:
[Mg/Fe]~0.5, almost constant

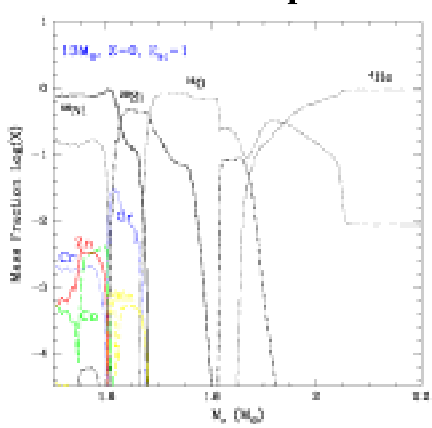


Explosive Nucleosynthesis in SNe

Before the Explosion

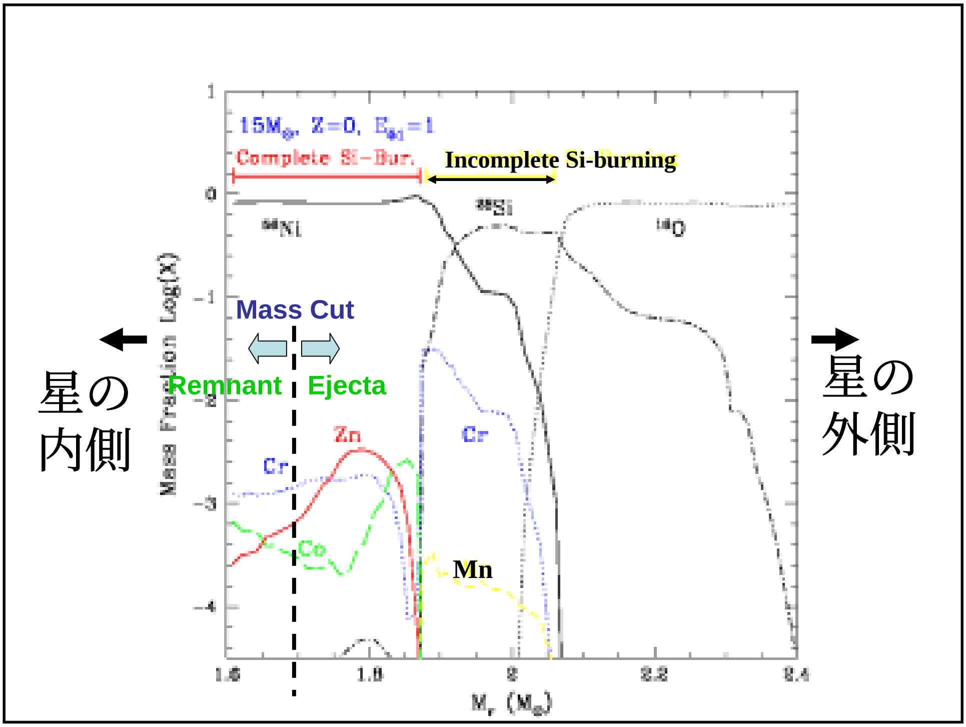


After the Explosion

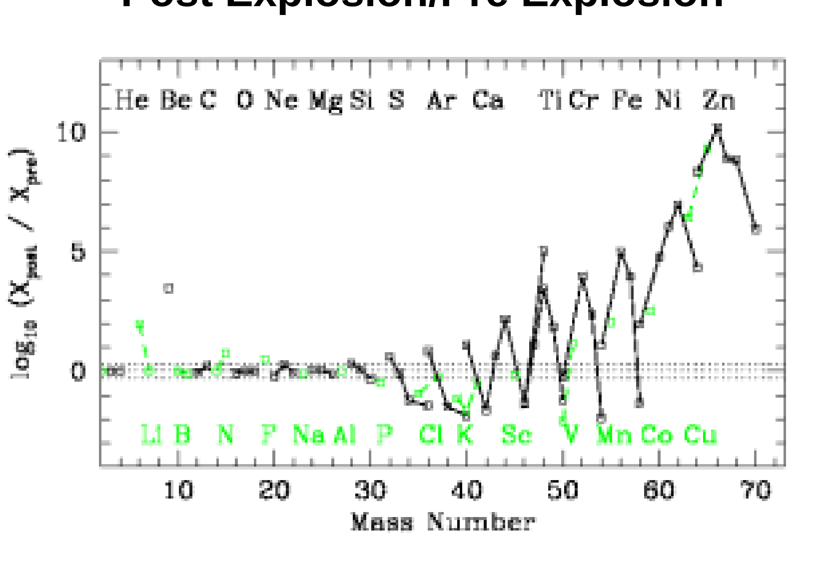


Explosive Nucleosynthesis in SNe

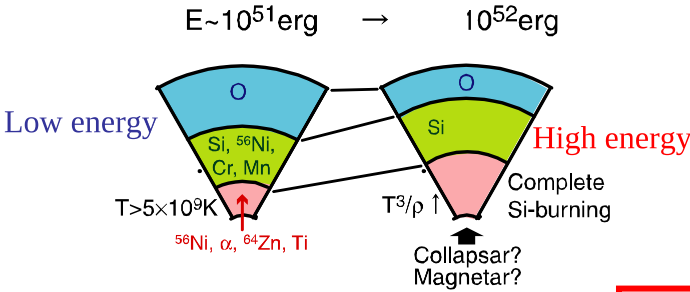
- Explosion ⇒Shock heating⇒Explosive Nucleosynthesis
- T_{peak} (peak temperature after the shock passage)
  - $T_{peak} > 5{\bullet}10^9$K -- Complete Si burning
    - (Products: e.g., ^{56}Ni, Zn, Co)
  - $4{\bullet}10^9\text{K} < T_{peak} < 5{\bullet}10^9$K -- Incomplete Si burning
    - (Products: e.g., ^{56}Ni, Mn, Cr)
- the matter outside the “Mass-Cut” is ejected.
  - The location of Mass-cut is somewhere in the explosive Si-burning region, but uncertain (because of the uncertainty in the explosion mechanism).
  - The location of Mass-cut may be constrained by observations of ^{56}Ni mass and Zn, Co, Mn, Cr abundance.



Abundance Ratio:
Post Explosion/Pre Explosion



Hypernova Nucleosynthesis



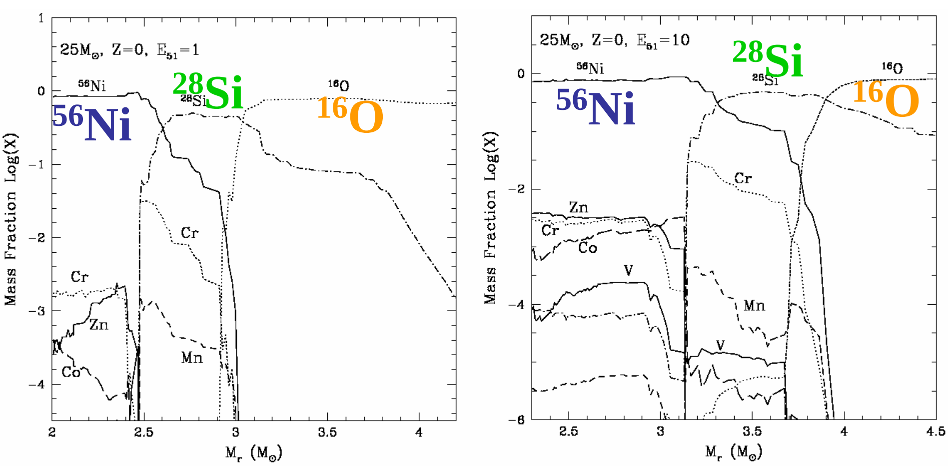
(1) M(Complete Si-burning) ⇗
Zn,Co/Fe ⇗ Mn,Cr/Fe ⇘ Fe/O,Si

(2) more α-rich ← High entropy
Zn/Fe ⇗ ←^{64}Ge Ti/Fe ⇗

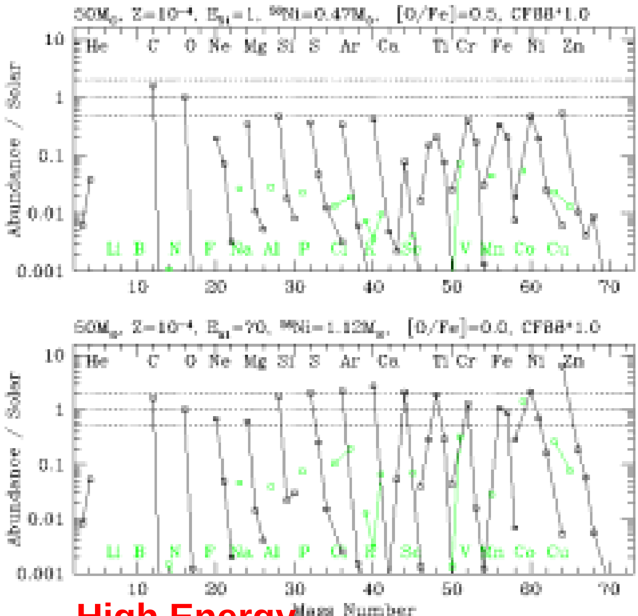
(3) more O burns
Si,S,Ca/O ⇗

For the same Mass-cut, mass fraction of complete Si-burning region becomes larger.

Low Energy vs High Energy Explosion



Low Energy



High Energy

(Si, S, Ar, Ca, Ti) /(Mg, O) & Zi/Fe

↓

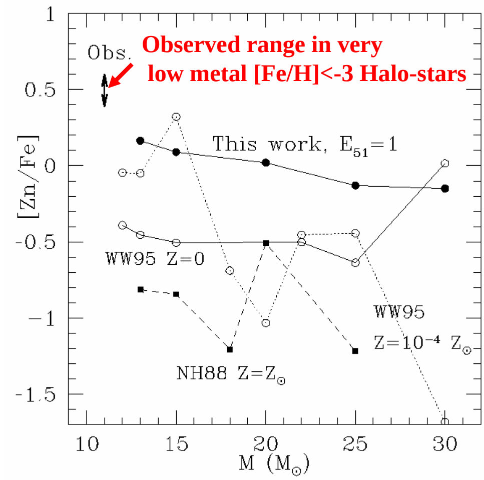
Larger

Hypernova Nuclosynthesis

- M(Complete Si-burning) ⇗
  - Zn,Co/Fe ⇗ Mn,Cr/Fe ⇘ O,Si/Fe ⇘
  - (If Mass-cut is deep enough)
- More α-rich ← High Entropy
  - Zn/Fe ⇗ ← ^{64}Ge Ti/Fe ⇗
- More O burns
  - Si,S,Ca/O ⇗

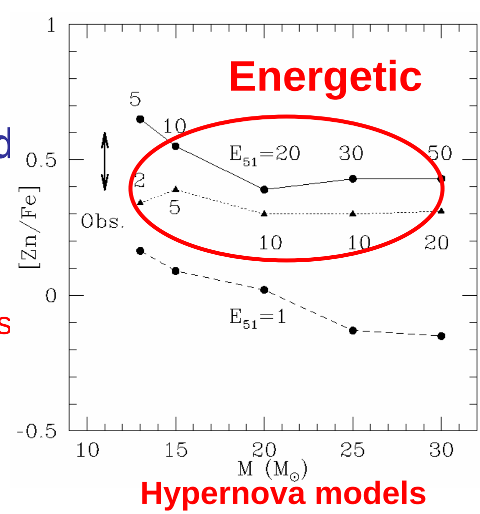
Zn production

- is not successful in the ALL previous models
- is important because, for Damped Lyman-α system abundance, [Zn/Fe]=0 has been often assumed.

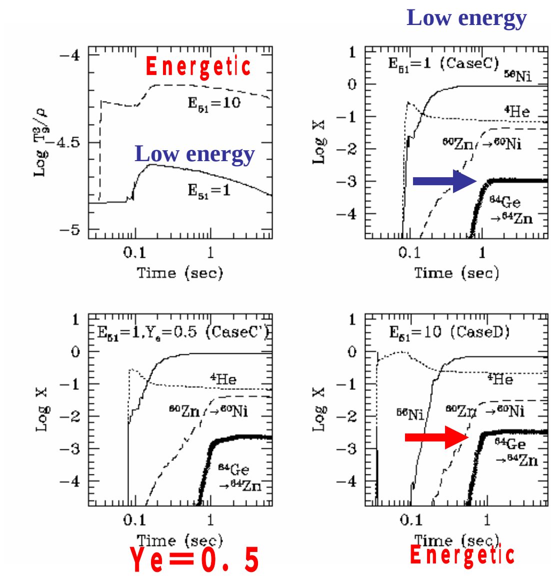


Zn production

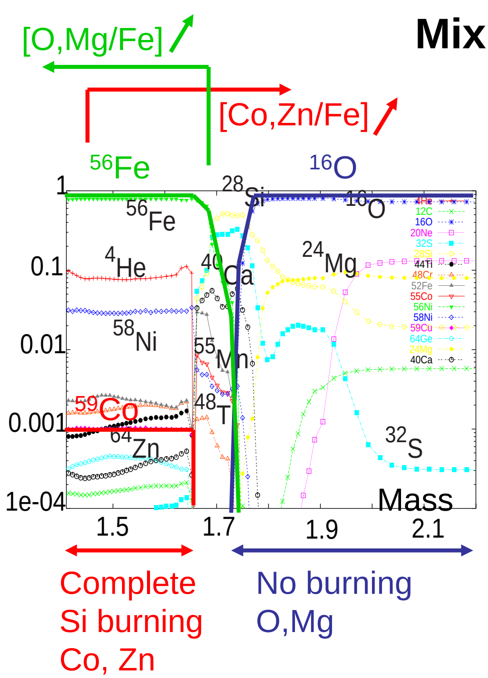
- **Large Explosion Energy is required to get [Zn/Fe]>0.3**
- We claim Zn is mainly produced in Hypernova explosive nucleosynthesis for low [Fe/H]

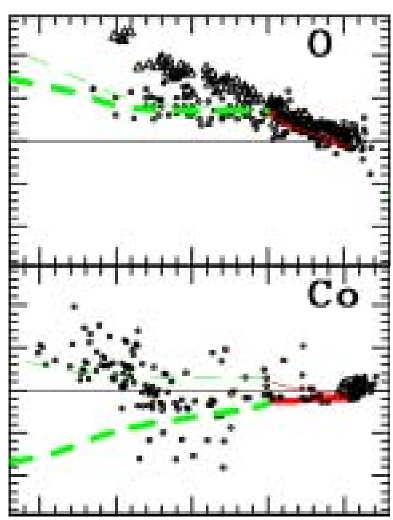


- Larger explosion energy ⇒ Higher entropy (T^3/ρ) ⇒ more α-rich ⇒ more ^{64}Ge ⇒ decay to ^{64}Zn
- Zn abundance is maximum for Ye =0.5 because ^{64}Ge is a symmetric species (Ye: electron mole fraction)

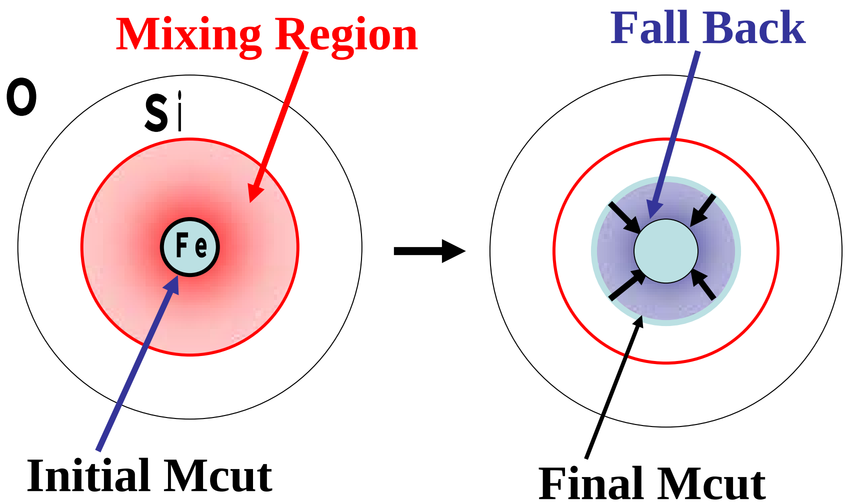


Mixing in SNe?



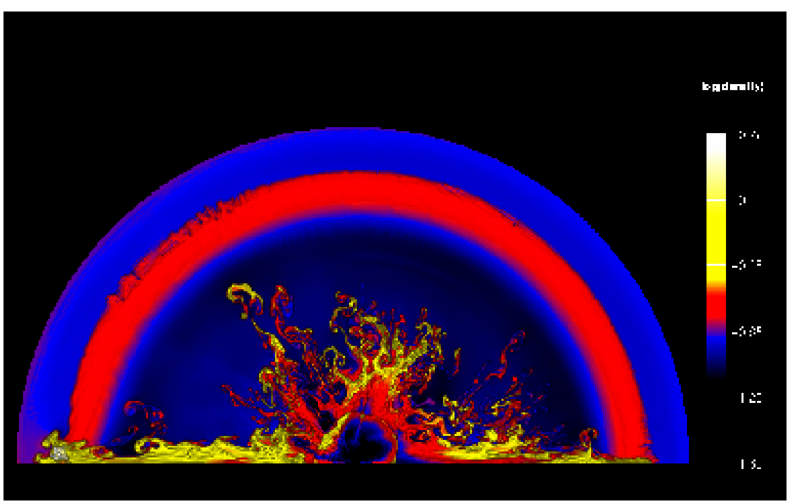


Mixing & Fall-Back Model (1D)

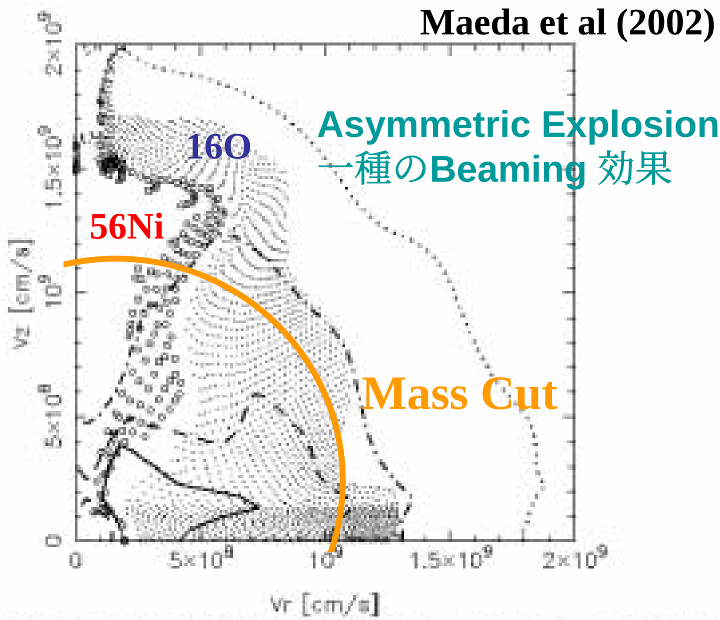


Ejected ^{56}Ni mass can (should) be smaller without changing the Zn,Co/Fe ratio

Matter Mixing by Rayleigh-Taylor Instability



Kifonidis et al. 1999



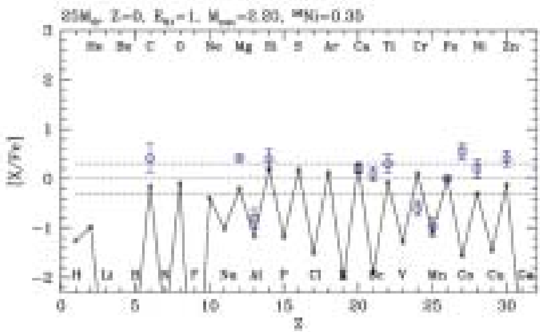
Comparison with Extremely Metal-Poor Stars

Umeda & Nomoto 2002

- Typical (Averaged) Abundance
  (Norris, Ryan, Beers 2001)
  - [Fe/H] ~ -3.7
- C,N rich – Extremely Metal-Poor Stars
  - CS 22949-037
    - [Fe/H]= - 4.0, [C/Fe]=+1.1
  - CS 29498-043
    - [Fe/H]= - 3.8, [C/Fe]=+1.9
  - CS 22957-027
    - [Fe/H]= - 3.1, [C/Fe]=+2.4

Typical (Averaged) Abundance (**NRB01**)

25M$_\odot$, E$_{51}$=1, Mcut=2.20M$_\odot$ (Normal energy model)



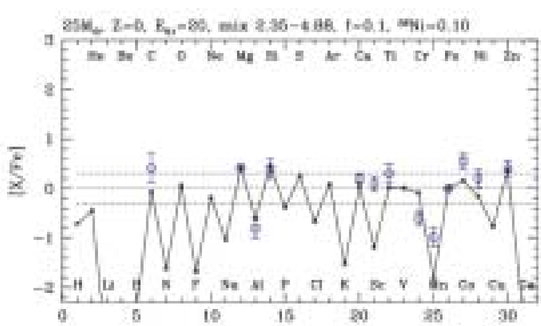
Mg, Al ↗⇒ Mcut ↗
Co, Zn↗⇒ Mcut ↘

Mcut **の違いでは解決しない**
⇒ E **大**

Typical (Averaged) Abundance: **[Fe/H]~ -3.7**

25M$_\odot$, E$_{51}$=20, Mixing =2.35 - 4.88M$_\odot$ (High energy model)

Mcut(I)=2.35, Mcut(f)=4.88, 放出率 f=0.1 --- Mixing & Fallback

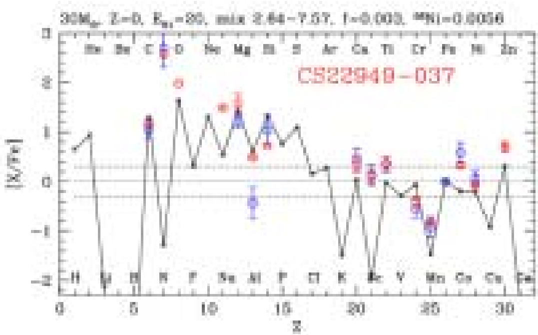


Mg, Al, Zn – O.K. (Large + Mixing Effect)
Sc, Co, Ti – Not enough ⇒ Another Effect (e.g., Jet)?
Mn -- Low energy? Ye?

C,N rich – Extremely Metal-Poor Stars

CS 22949-037, [Fe/H]~ -4.0 **(NRB01; Depagne et al. 2002)**

$30M_\odot$, E_{51}=10, Mixing=2.46 - 6.69$M_\odot$, f= 0.005



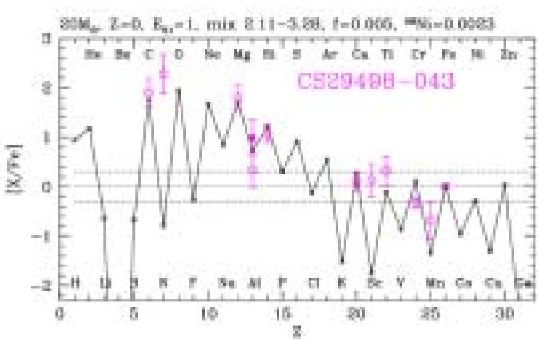
Little Fe (^{56}Ni)
⇒C,N,O/Fe↗

これ以上Eが大きいと
Mg/Si (Si↗)**が合わない**
Ca,Sc,Ti, Co,Zn:
Not enough
⇒Another Effect?

C,N rich – Extremely Metal-Poor Stars

CS 29498-037, [Fe/H]~ -3.8 **(Aoki et al. 2002)**

$25M_\odot$, E_{51}=10, Mixing=2.09 - 4.95$M_\odot$, f= 0.004

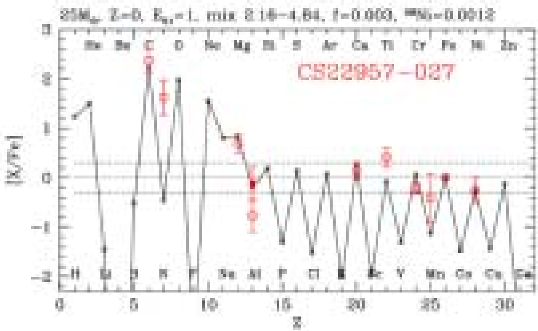


Little Fe (^{56}Ni)
⇒C,N,O/Fe↗

C,N rich – Extremely Metal-Poor Stars

CS 22957-027, [Fe/H]~ -3.1 (Aoki et al. 2002)

$25M_\odot$, E_{51}=1, Mixing=2.16 - 4.84$M_\odot$, f= 0.003

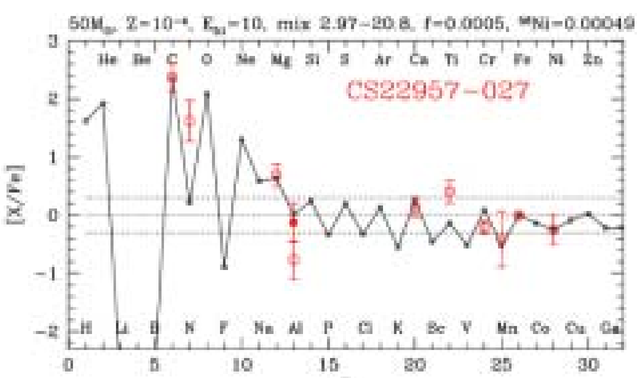


Little Fe (56Ni)
⇒C,N,O/Fe ↗

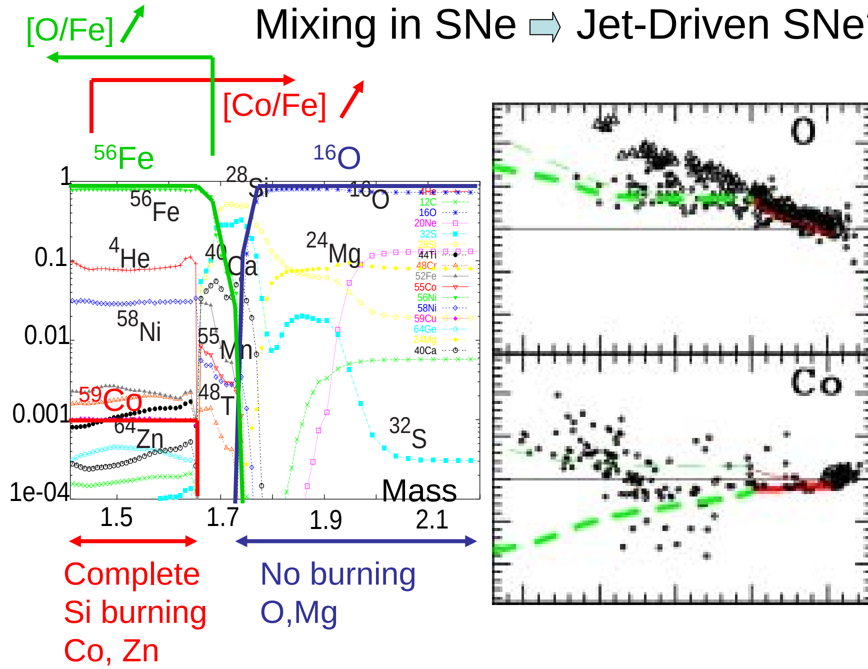
C/Mg↗ ⇒E↘、M_{cut}(f)↗

質量がより大きく、Eも大きいものでも合う

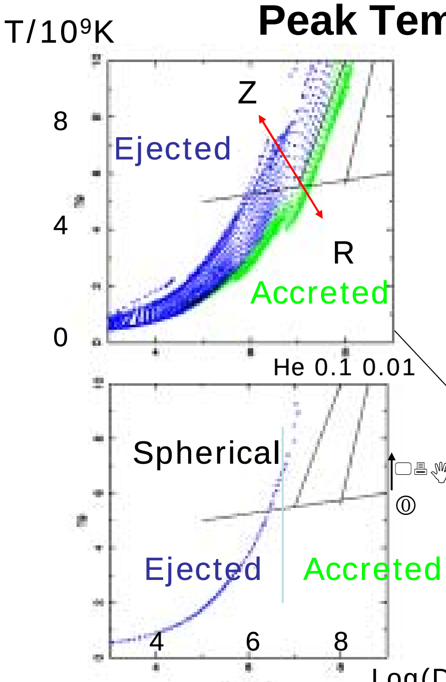
M=$50_\odot$, E_{51}=10

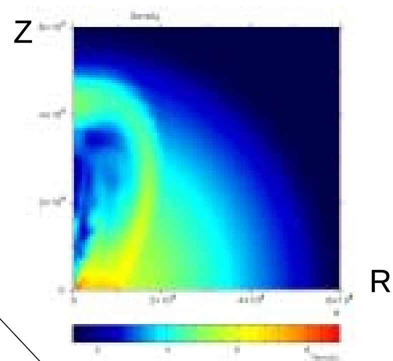


Mixing in SNe ⇨ Jet-Driven SNe?



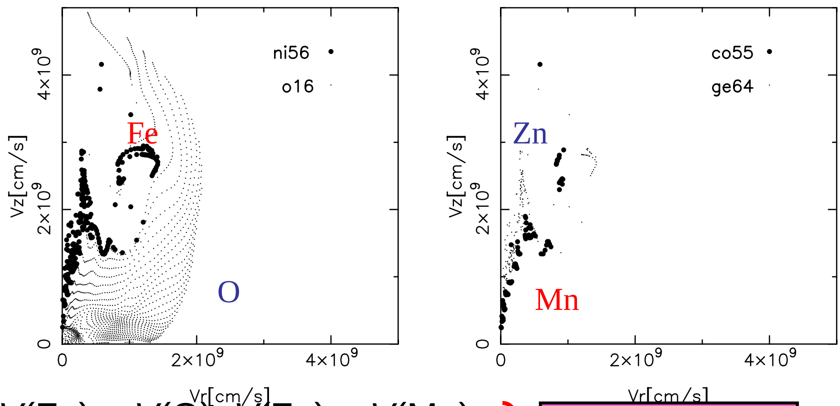
Peak Temperature & Density





- High T + Low ρ Material are preferentially ejected.

Velocity Inversion of isotopes



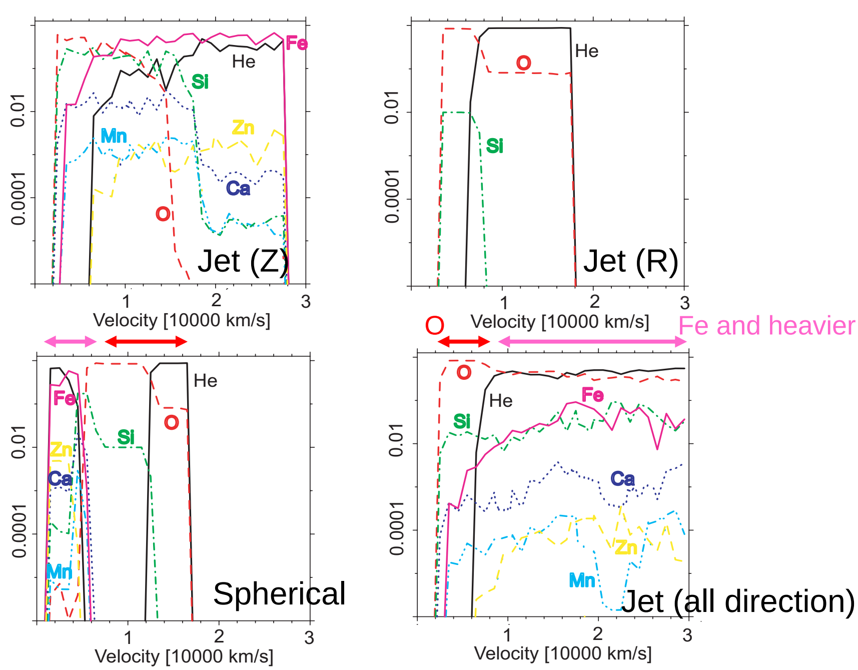
V(Fe) > V(O), V(Zn) > V(Mn)

Spherical; Zn Fe Mn O

T↗, Inner (smaller V)

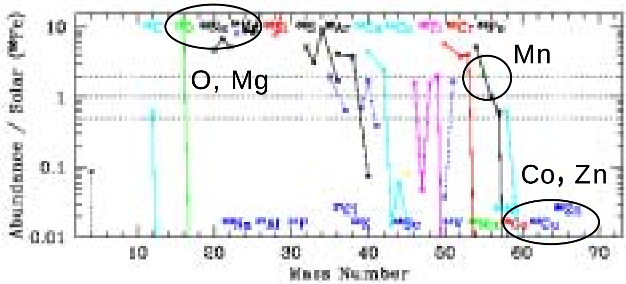
Prediction

Ejection of heavier isotopes with higher V

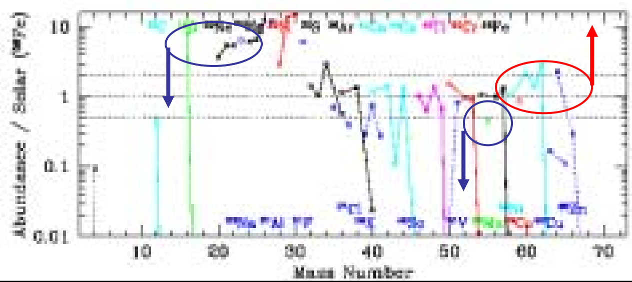


Abundances in the whole ejecta

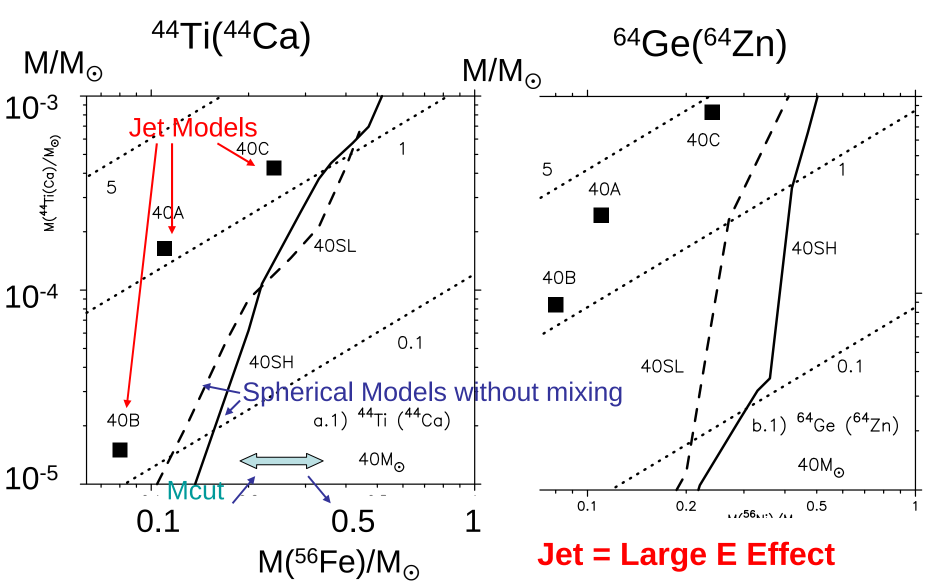
Spherical, 10^{52}ergs, 0.1M Ni



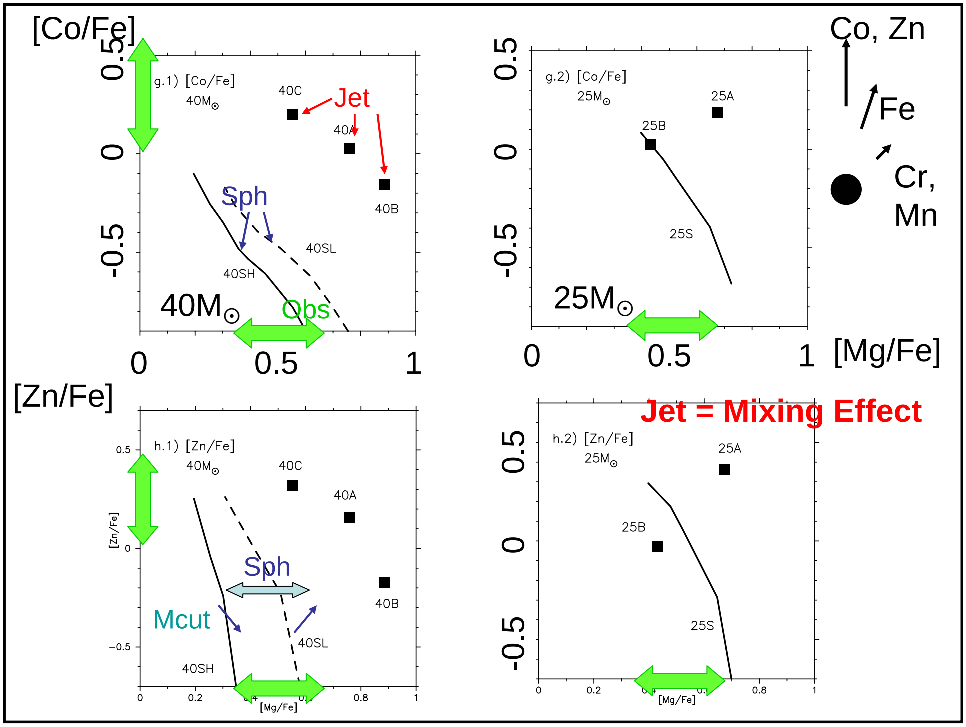
Jet-Driven, 10^{52}ergs, 0.1M Ni

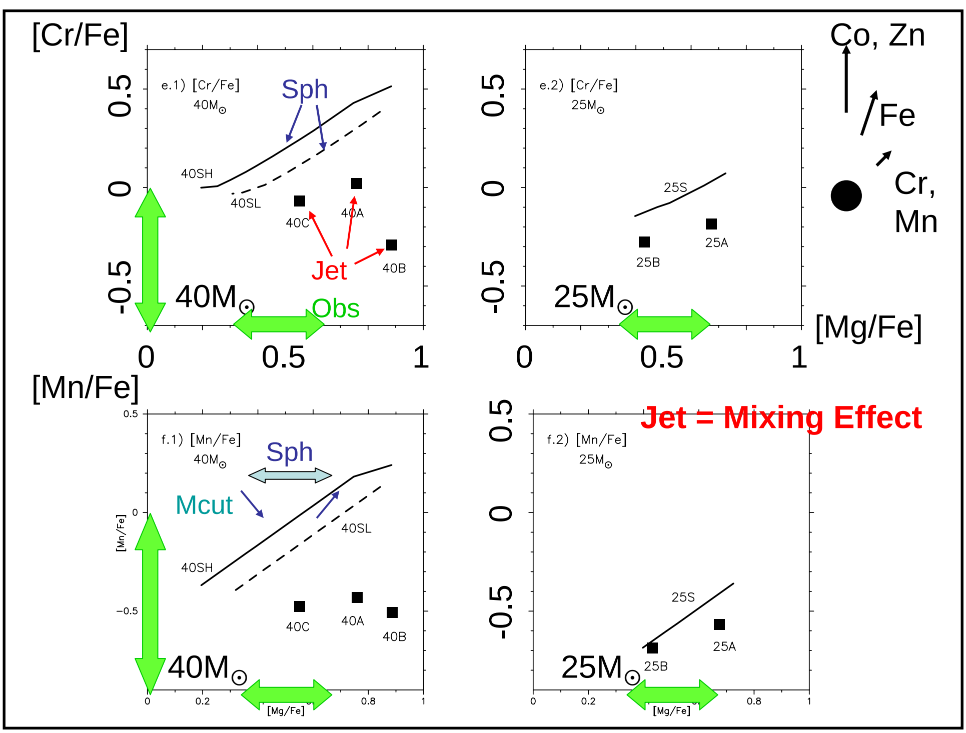


Fe-Peak Elements



Jet = Large E Effect

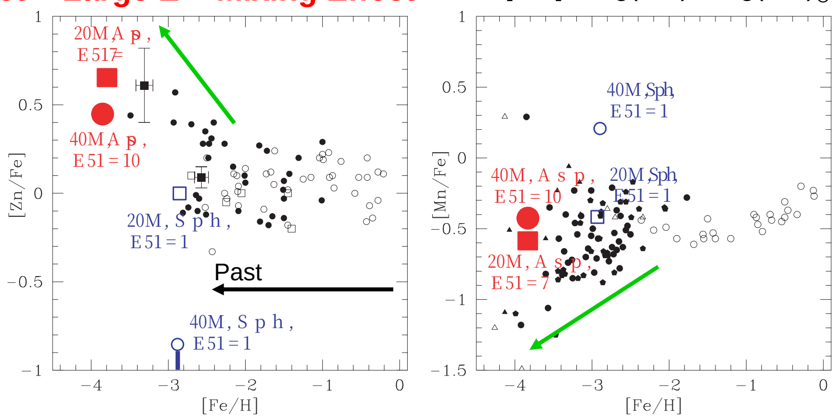

[Co/Fe]
g.1) [Co/Fe]
40M⊙
40C
Jet
40A
40B
Sph
40SL
40SH
40M⊙
Obs
g.2) [Co/Fe]
25M⊙
25A
25B
25S
25M⊙
Co, Zn
Fe
Cr,
Mn
[Mg/Fe]
[Zn/Fe]
h.1) [Zn/Fe]
40M⊙
Sph
Mcut
40SL
40SH
Jet = Mixing Effect
h.2) [Zn/Fe]
25M⊙


[Cr/Fe]
e.1) [Cr/Fe]
40M⊙
Sph
40SH
40SL
40C
40A
Jet
40B
40M⊙
Obs
e.2) [Cr/Fe]
25M⊙
25S
25B
25A
25M⊙
Co, Zn
Fe
Cr,
Mn
[Mg/Fe]
[Mn/Fe]
f.1) [Mn/Fe]
40M⊙
Sph
Mcut
40SL
40SH
Jet = Mixing Effect
f.2) [Mn/Fe]
25M⊙

Fe-Peak Elements in the Jet Model compared with Metal-Poor Stars

Jet = Large E + Mixing Effect

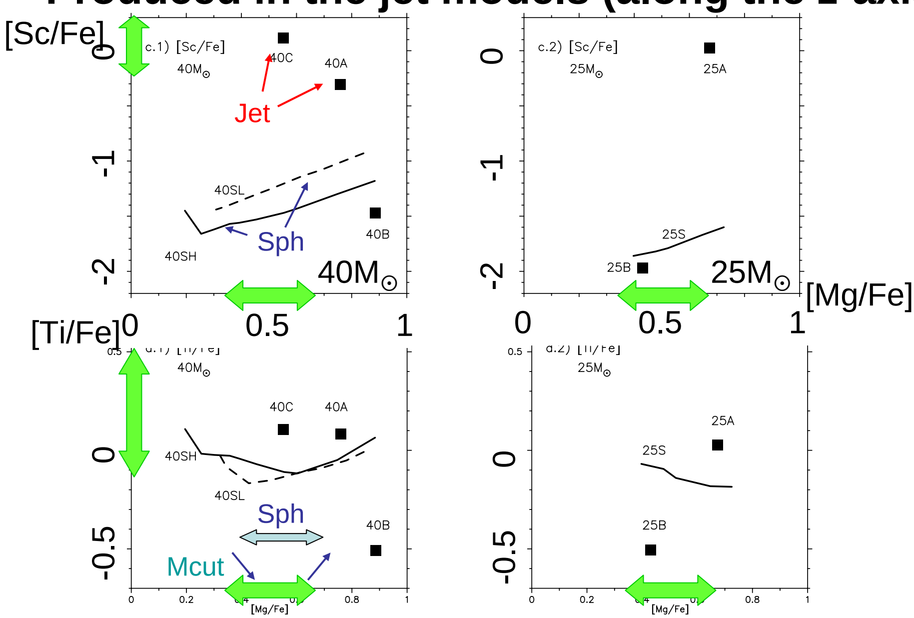
$[X/Y] = \log(X/Y) - \log(X/Y)_{\odot}$

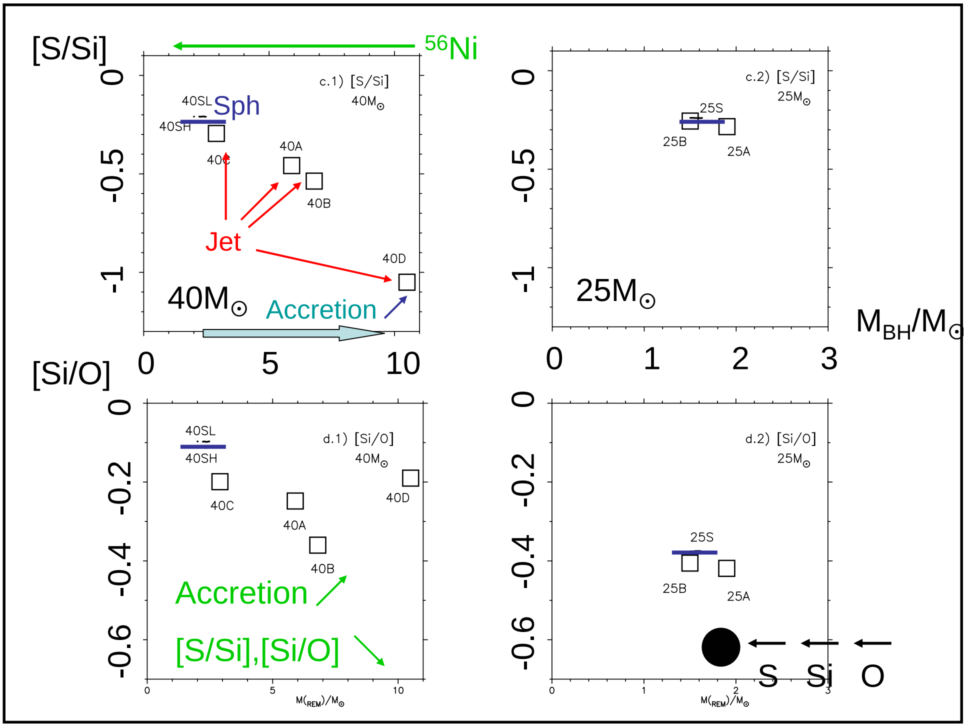


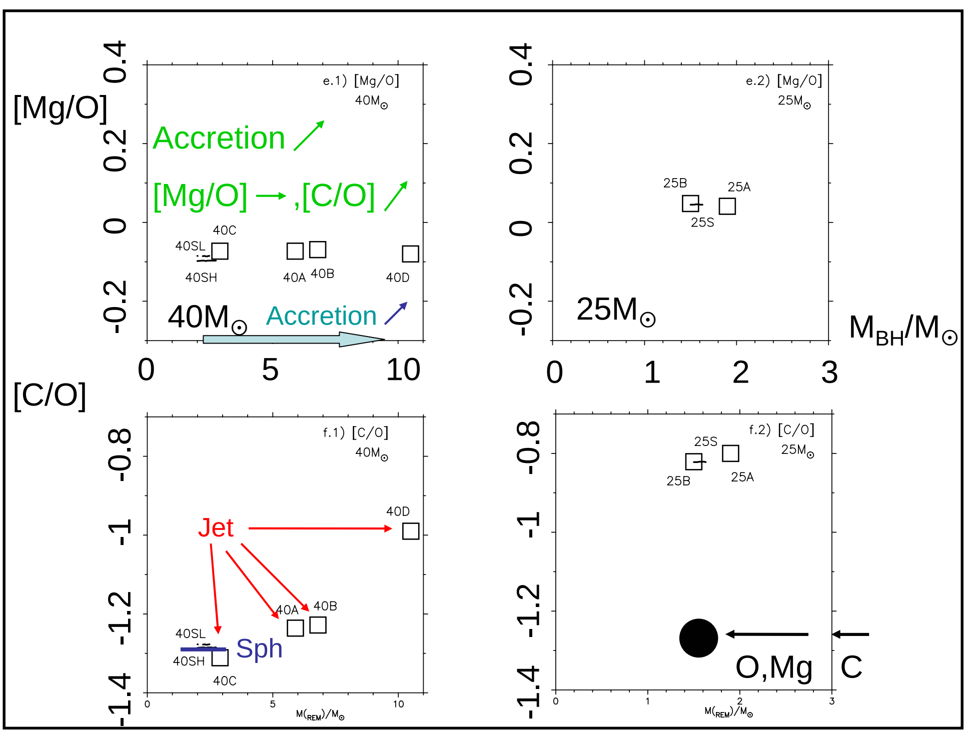
Jet model: [Zn/Fe] ↗, [Mn/Fe] ↘

Agrees with the abundances in old stars.

Sc & Ti: Failed in Sph. Models Produced in the jet models (along the z-axis)



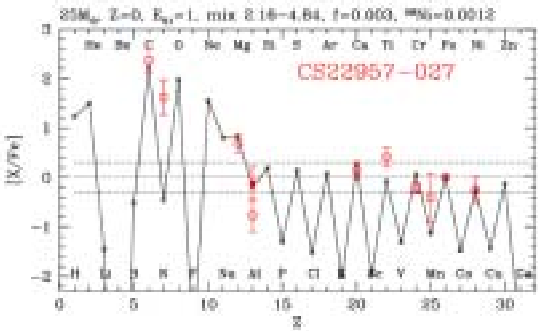

[S/Si]
56Ni
c.1) [S/Si]
40M⊙
40SL
Sph
40SH
40C
40A
40B
Jet
40D
40M⊙
Accretion
c.2) [S/Si]
25M⊙
25S
25B
25A
25M⊙
MBH/M⊙
[Si/O]
d.1) [Si/O]
40M⊙
40SL
40SH
40C
40A
40B
40D
Accretion
[S/Si],[Si/O]
M(REM)/M⊙
d.2) [Si/O]
25M⊙
25S
25B
25A
S
Si
O
M(REM)/M⊙


[Mg/O]
e.1) [Mg/O]
40M⊙
Accretion
[Mg/O] →,[C/O]
40C
40SL
40SH
40A
40B
40D
40M⊙
Accretion
e.2) [Mg/O]
25M⊙
25B
25A
25S
25M⊙
MBH/M⊙
[C/O]
f.1) [C/O]
40M⊙
40D
Jet
40A
40B
40SL
Sph
40SH
40C
M(REM)/M⊙
f.2) [C/O]
25M⊙
25S
25B
25A
O,Mg
C
M(REM)/M⊙

C,N rich – Extremely Metal-Poor Stars

CS 22957-027, [Fe/H]~ -3.1 **(Aoki et al. 2002)**

$25M_\odot$, E_{51}=1, Mixing=2.16 - $4.84M_\odot$, f= 0.003

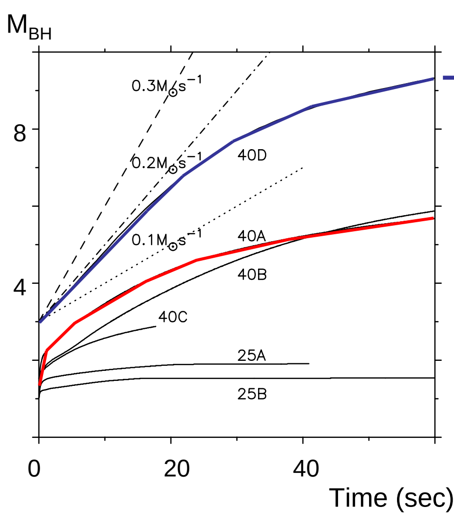


Little Fe (^{56}Ni)

⇒C,N,O/Fe ↗

C/Mg↗ ⇒E↘, M_{cut}(f)↗

Fe-deficient Hypernovae?



M(Fe) = 1.6E-4$M_\odot$

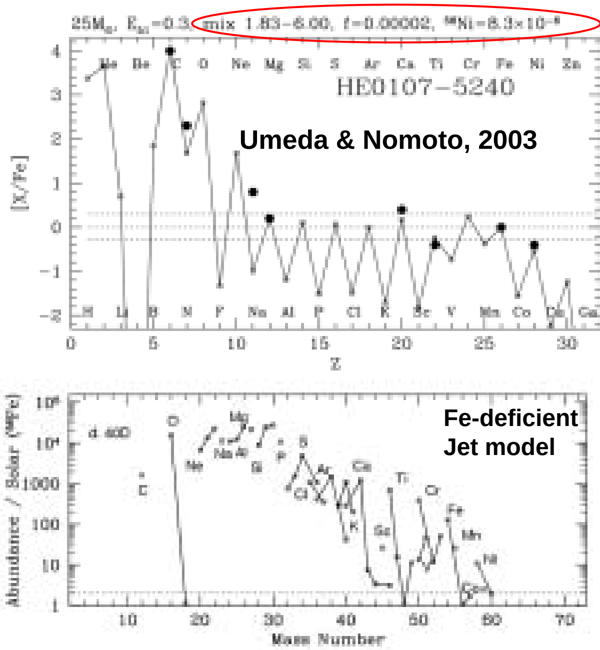
E_{51}= 8.5

M_{BH}=10.5M⊙

Prediction:

[S/Si], [O/C] ↘

Most Fe-deficient Star



How to satisfy this extreme condition?

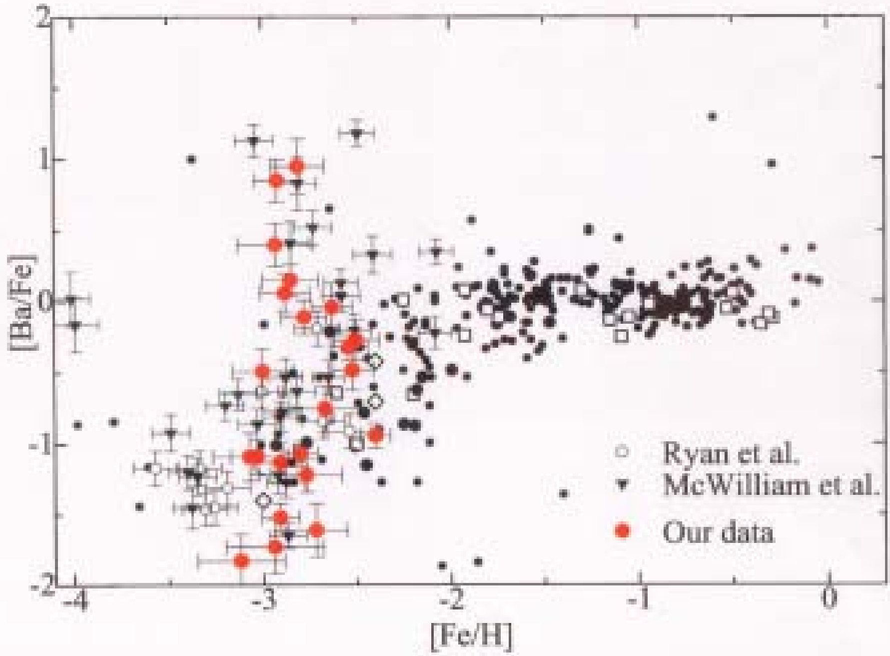
Summary (1)

- The studies on hypernovae indicate;
  - Velocity inversion of Fe and O
  - Dense core
  - Black hole formation
- Jet-induced explosions satisfy the above condition!
  - Blow up heavy isotopes (e.g., Fe, Zn) to the surface.
  - A black hole grows, with an energetic explosion
  - M_{BH} $\Leftrightarrow$ efficiency of the jets (e.g., rotation?)
  - M_{BH} $\nearrow$ ($\Leftarrow$inefficient Jets) $\Leftrightarrow$ L_{Opt} $\searrow$
  - M_{BH} $\Leftrightarrow$ Abundances (e.g., M_{BH} $\nearrow$ $\Leftrightarrow$ [S/Si], [O/C] $\searrow$)

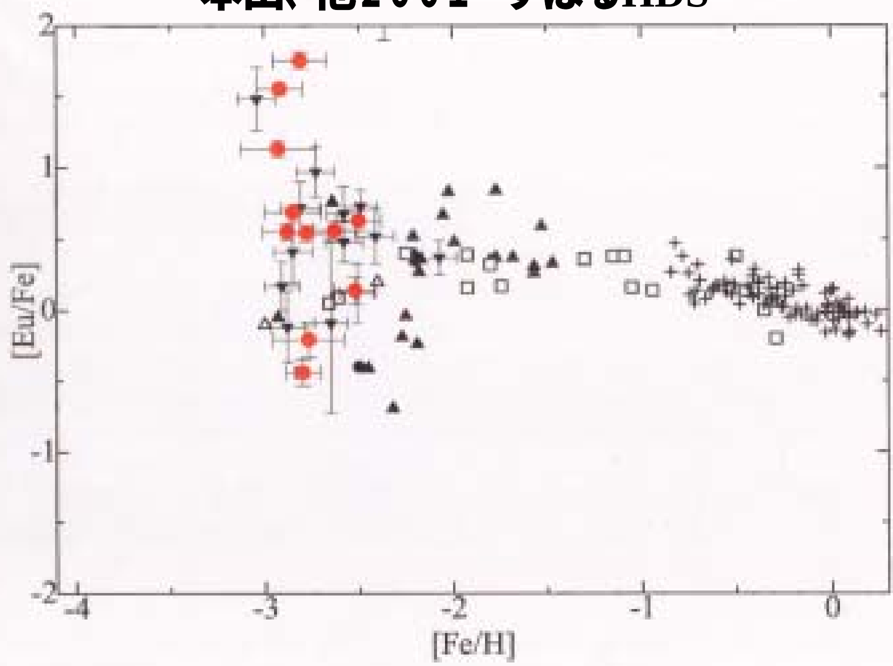
Summary (2)

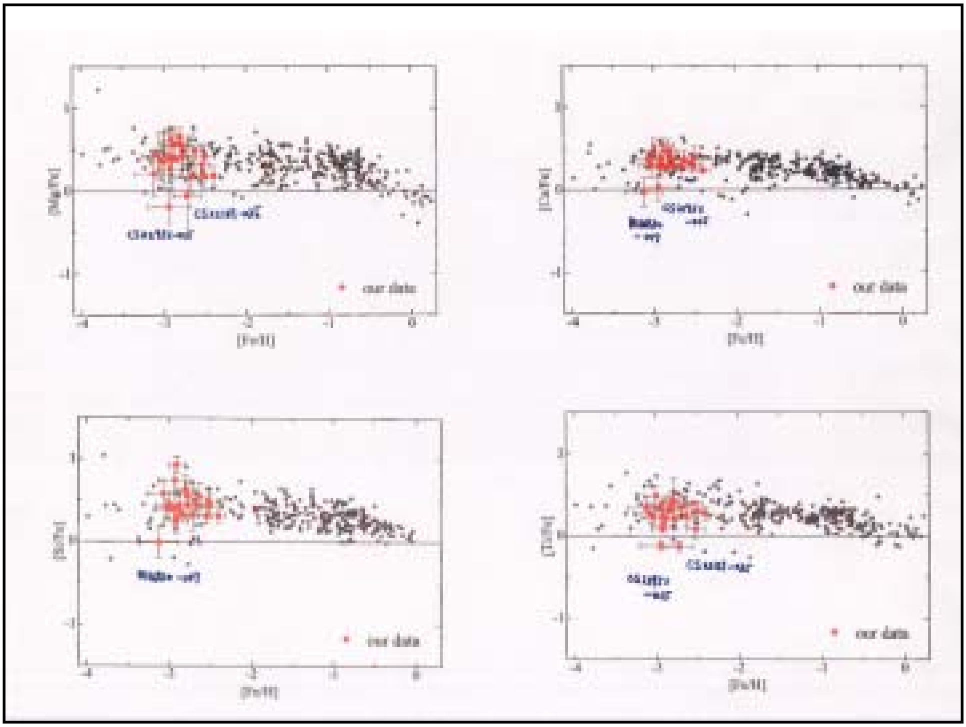
- Extremely Metal-Poor Stars
  - Large [Zn,Co/Fe]
    - Large E and/or Jet
  - Small [Mg, O, Mn, Cr/Fe]
    - Mixing and Fallback Effect
  - Trends in Fe-peak Elements
    - More massive star for lower [Fe/H]
  - Most-Fe deficient Star
    - Very small Fe ejected (~$10^{-5} M_{\odot}$), significant mixing
- Effect of Jet
  - Large [Zn, Co/Fe] (high T along the jet axis)
  - Similar effect to mixing and fallback: [Zn,Co,Mg,O/Fe]
  - Large [Sc, Ti/Fe]

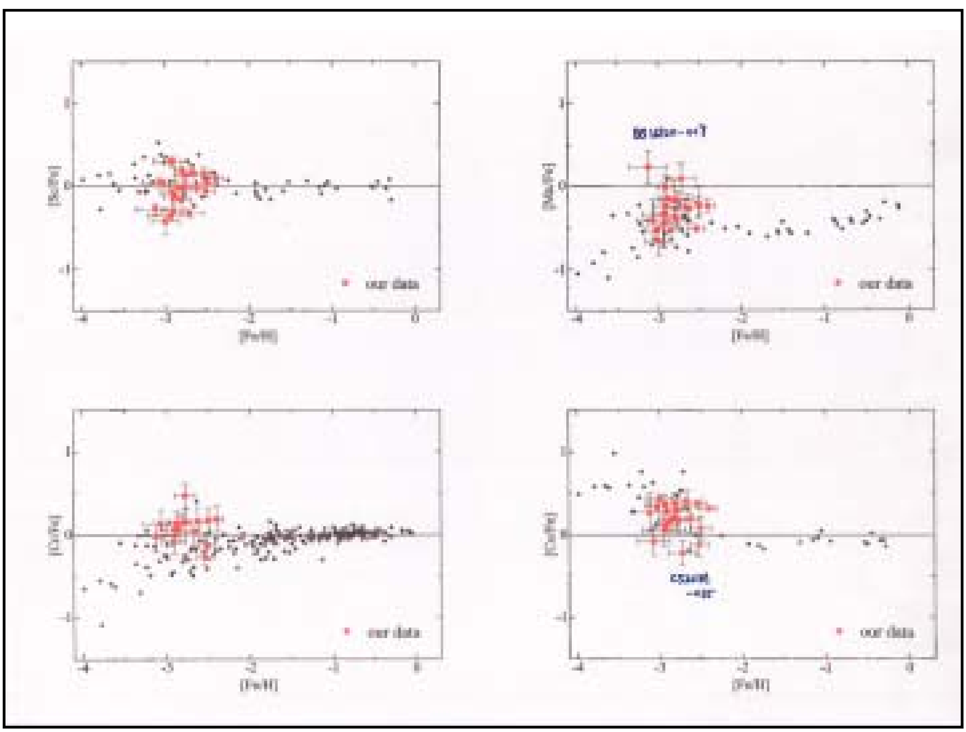
本田、他２００１　すばるHDS、preliminary



本田、他２００１　すばるHDS




[Mg/Fe]
[Ca/Fe]
[Si/Fe]
[Ti/Fe]
[Fe/H]
our data

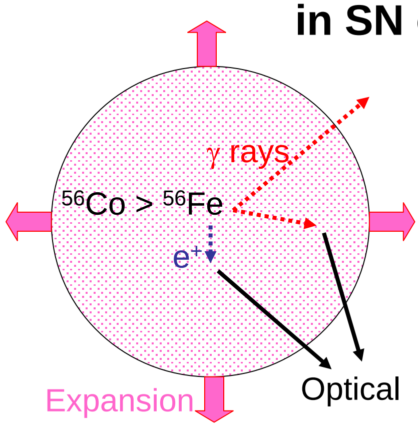

[Sc/Fe]
[Mn/Fe]
[Cr/Fe]
[Co/Fe]
[Fe/H]
our data

2) Light Curves of Hypernovae

Radioactivities in SN ejecta

Decay	τ	Ee^+ (keV)	%	$E\gamma$ (keV)	%
$^{56}Ni > ^{56}Co$	8.8 days	---	---	158 750 812	99 50 87
$^{56}Co > ^{56}Fe$	111.3 days	660	19	847 1238 2598	100 68 17
$^{57}Co > ^{57}Fe$	391.0 Days	---	---	14 122 136	89 89 11
$^{44}Ti > ^{44}Ca$	69.2 years	597	94	68 78 1156	100 100 100

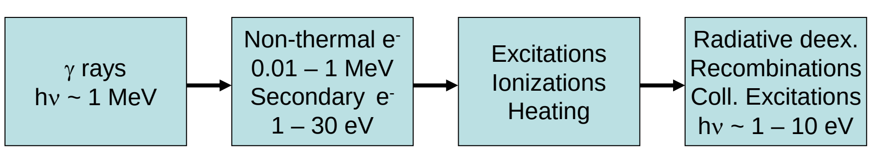
Optical output as a result of γ ray transfer in SN ejecta



$$L_{optical} \sim L_\gamma (1-\exp(-\tau_\gamma)) + L_{e+}$$

$$\tau_\gamma = \kappa_\gamma \rho R = \tau_0 (t/1\mathrm{day})^{-2}$$

$$\tau_0 \propto M^2/E$$



Optical Light Curves of ‘Original’ models

Spherical Hydro

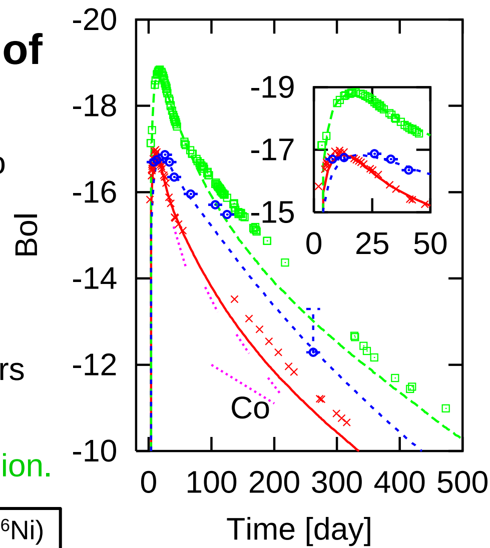
Model curves fainter than observed after ~ 50 days.

Needs to increase $\tau_\gamma = \kappa_\gamma \rho R$.

But must not in the outer layers (V>10000km/s).

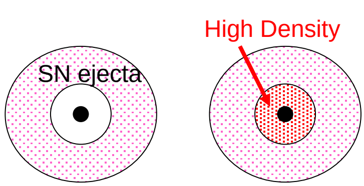
⇨ Larger ρ in the central region.

SN	M_{ej}	E_{51}	M (^{56}Ni)
1997ef	9.5	21	0.11
1998bw	10.2	45	0.5
2002ap	2.4	5.4	0.07



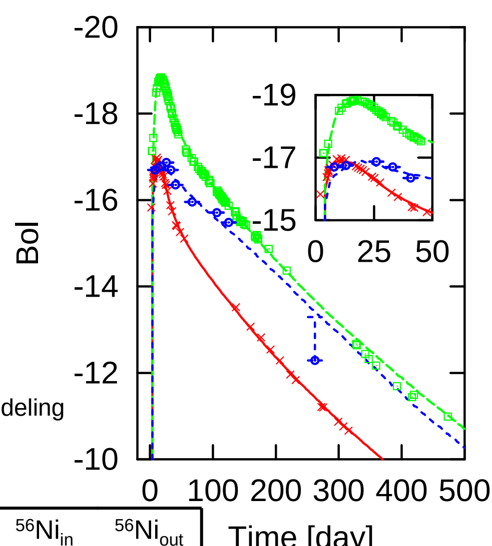
Models with Inner Dense Cores

Observations fitted well!!



Spherical Hydro | Required in L.C Modeling

K. Maeda, in preparation



SN	V_{in} (km/s)	M_{in}	$^{56}Ni_{in}$	$^{56}Ni_{out}$
1997ef	3500	5.0	0.084	0.050
1998bw	5000	3.9	0.12	0.44
2002ap	3000	1.1	0.014	0.065