Aspherical Explosion of Massive CO Star

- ^{56}Ni production & Hydro-dynamical Effect -

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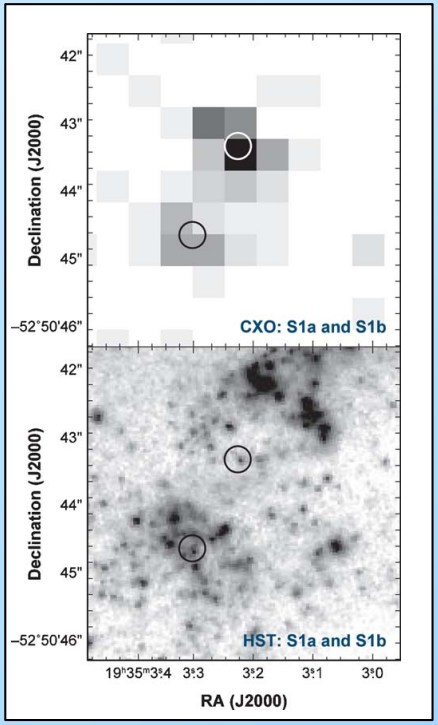
Type Ic Supernova

Type Ic SN

- Absence of H & He Emission Line
- Core-Collapse Explosion of CO Wolf-Rayet Star ?



Woosley & Bloom 2006

Aspherical Nature

Hypernova: E_{ex}~10^{52} erg

SN1998bw

→ aspherical scenario (Maeda&Nomoto 2008)

GRB: Some observational samples associated with SN Ic

Name Burst/SN	z	Peak [mag]	T^{a}_{peak} [day]	SN likeness/ designation	References
GRB 980425/1998bw	0.0085	$M_V = -19.16 \pm 0.05$	17	Ic-BL	b
GRB 030329/2003dh	0.1685	$M_V = -18.8$ to -19.6	10 – 13	Ic-BL	c
GRB 031203/2003lw	0.1005	$M_V = -19.0$ to -19.7	18 – 25	Ibc-BL	d
XRF 020903	0.25	$M_V = -18.6 \pm 0.5$	~15	Ic-BL	e
GRB 011121/2001dk	0.365	$M_V = -18.5$ to -19.6	12 – 14	I (IIn?)	f
GRB 050525a	0.606	$M_V \approx -18.8$	12	I	g
GRB 021211/2002lt	1.00	$M_U = -18.4$ to -19.2	~14	Ic	h
GRB 970228	0.695	$M_V \sim -19.2$	~17	I	i
XRR 041006	0.716	$M_V = -18.8$ to -19.5	16 – 20	I	j
XRR 040924	0.859	$M_V = -17.6$	~11	?	k
GRB 020405	0.695	$M_V \sim -18.7$	~17	I	l

SN2007bi

SN2007bi (Gal-Yum+2009)

- Very Luminous Ic SN
- **Large amount of ^{56}Ni** (>4M_{sun})

  $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$
- Single peak of observed [OI] emission line does **not** suggest asphericity

(Young+2010)

Scenario 1: Pair Instability SN

PISN of ~100M_{sun} He star

○ Can reproduce the yield

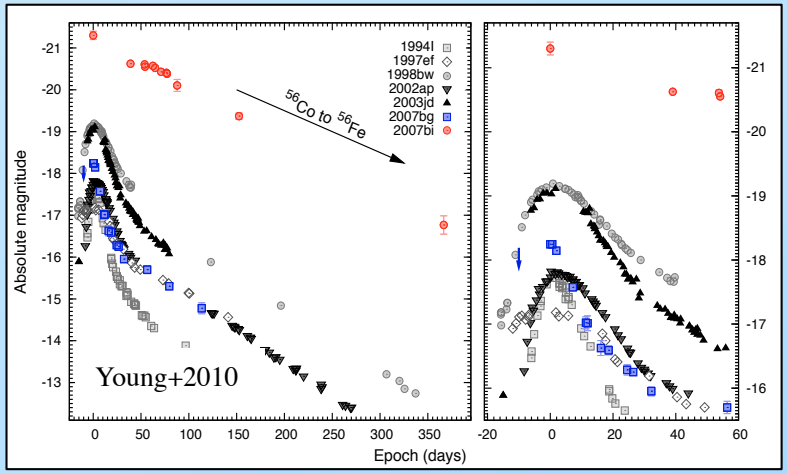
× He envelope remains

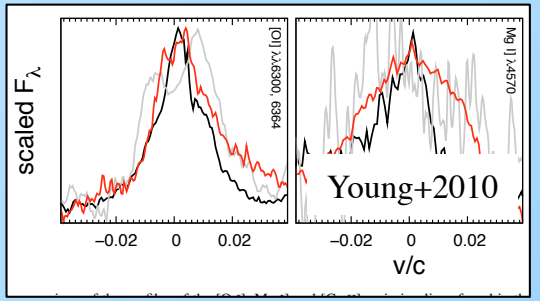
Scenario 2: Core Collapse SN

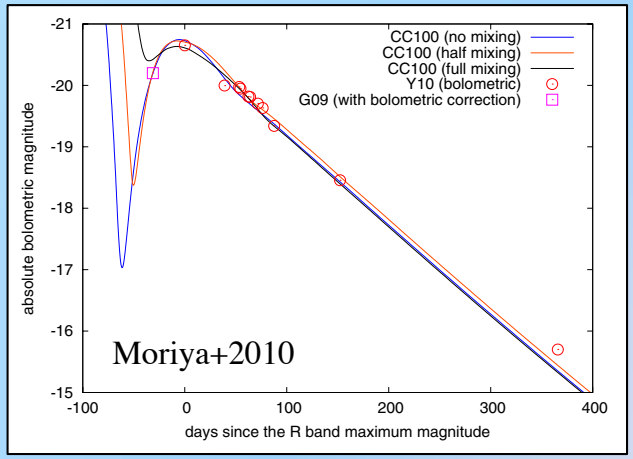
Spherical Explosion of 43M_{sun} CO star

○ ^{56}Ni amount & Light curve evolusion

(Moriya+2010)







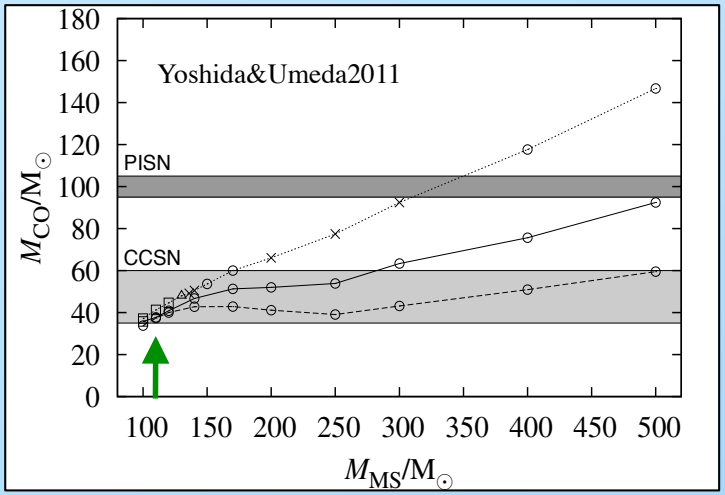
Model & Method 1

Progenitor Model

- M_{MS} = 110$M_{sun,}$ Z=0.004
- Massive CO Wolf-Rayet star deprived of upto He envelope by mass loss wind

→ M_{CO}= 43.1M_{sun}

Yoshida&Umeda 2011

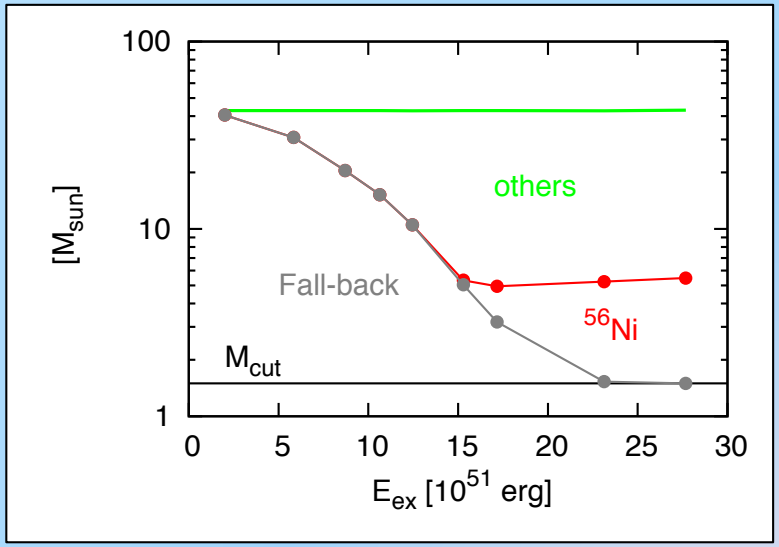


Hydrodynamics

- Code: 2D axis-symmetric
- Explosion Energy: E_{ex}= 30×10^{51} erg

  ^{56}Ni ~ 4M_{sun}
- Inner boundary: absorbing

  Fall-back onto central remnant



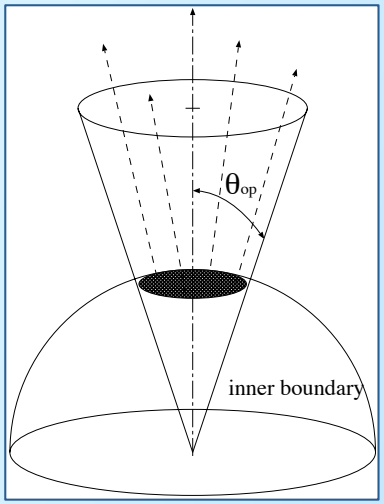
Spherical explosion

^{56}Ni is totally ejected if E_{ex} > 25×10^{51}erg

Method 2

Aspherical Explosion

- Induced by abrupt energy injection in polar direction
- 7 models calculated with various opening angle (θ_{op})



* Explosion energy is injected only around the polar axis as kinetic form

Table 1: Calculated models

Name	OA1	OA2	OA3	OA4	OA5	OA6	OA7
θ_{op}	7.03°	11.3°	22.5°	45.0°	67.5°	78.8°	90.0°
$\theta_{op}/90°$	5/64	1/8	1/4	1/2	3/4	7/8	1

Nucleosynthesis

- Post-process
- Network with 282 isotopes (n,p ~ Br)

Input: Thermodynamical Histories

$$\{\rho_i(t_n), T_i(t_n)\}$$

(for every differential mass)

Output: Mass Fraction

$$\{X^j{}_i\} \quad (\Sigma_j X^j{}_i = 1)$$

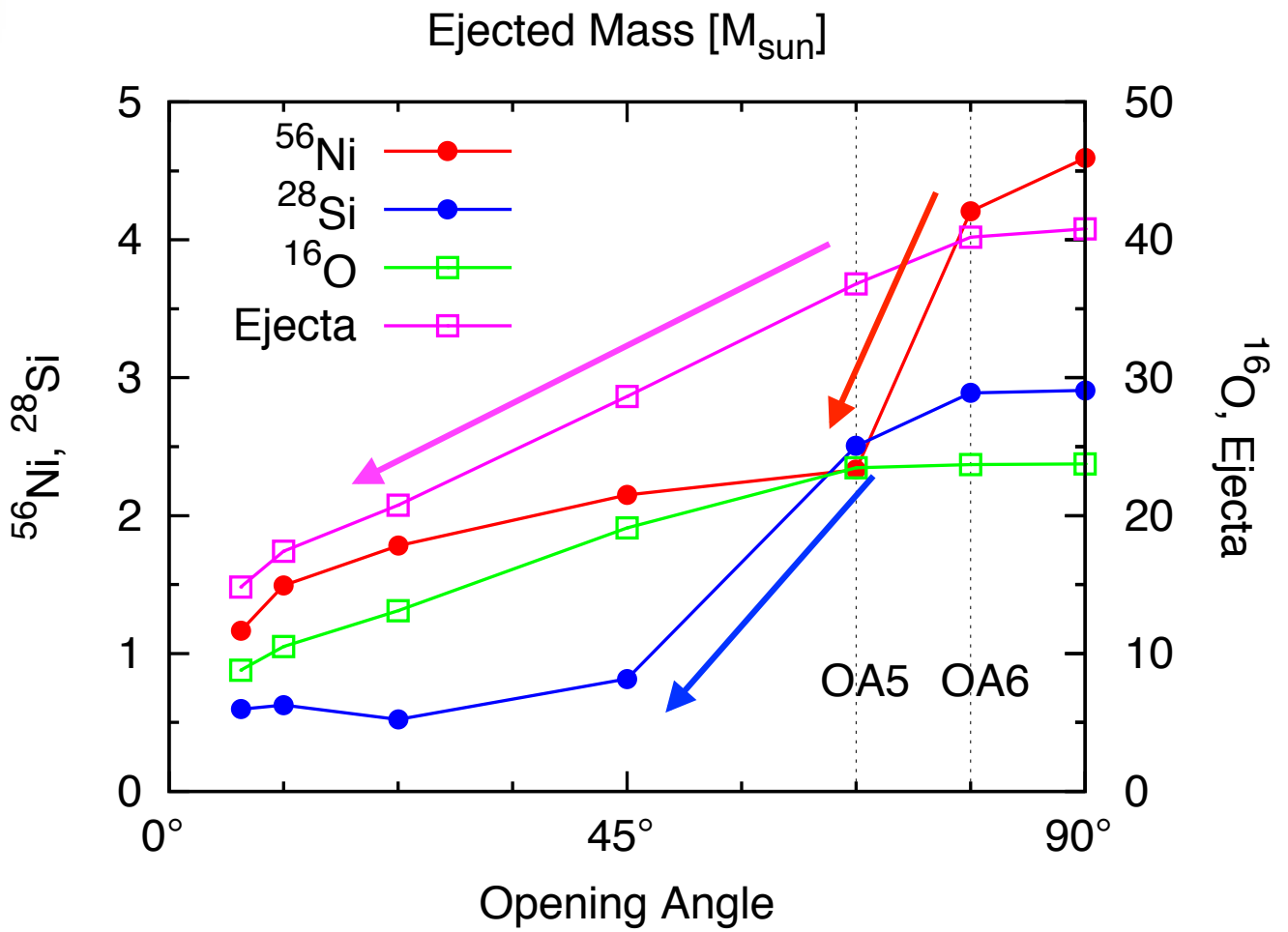
Thermodynamical Histories

Trace Particle Method

- 5200 particles ($\Delta m_i \sim 0.001 M_{sun}$)
- Each particle obtains

$$\{\boldsymbol{r}_i(t_n)\},\ \{\rho_i(t_n), T_i(t_n)\}$$

Ejecta



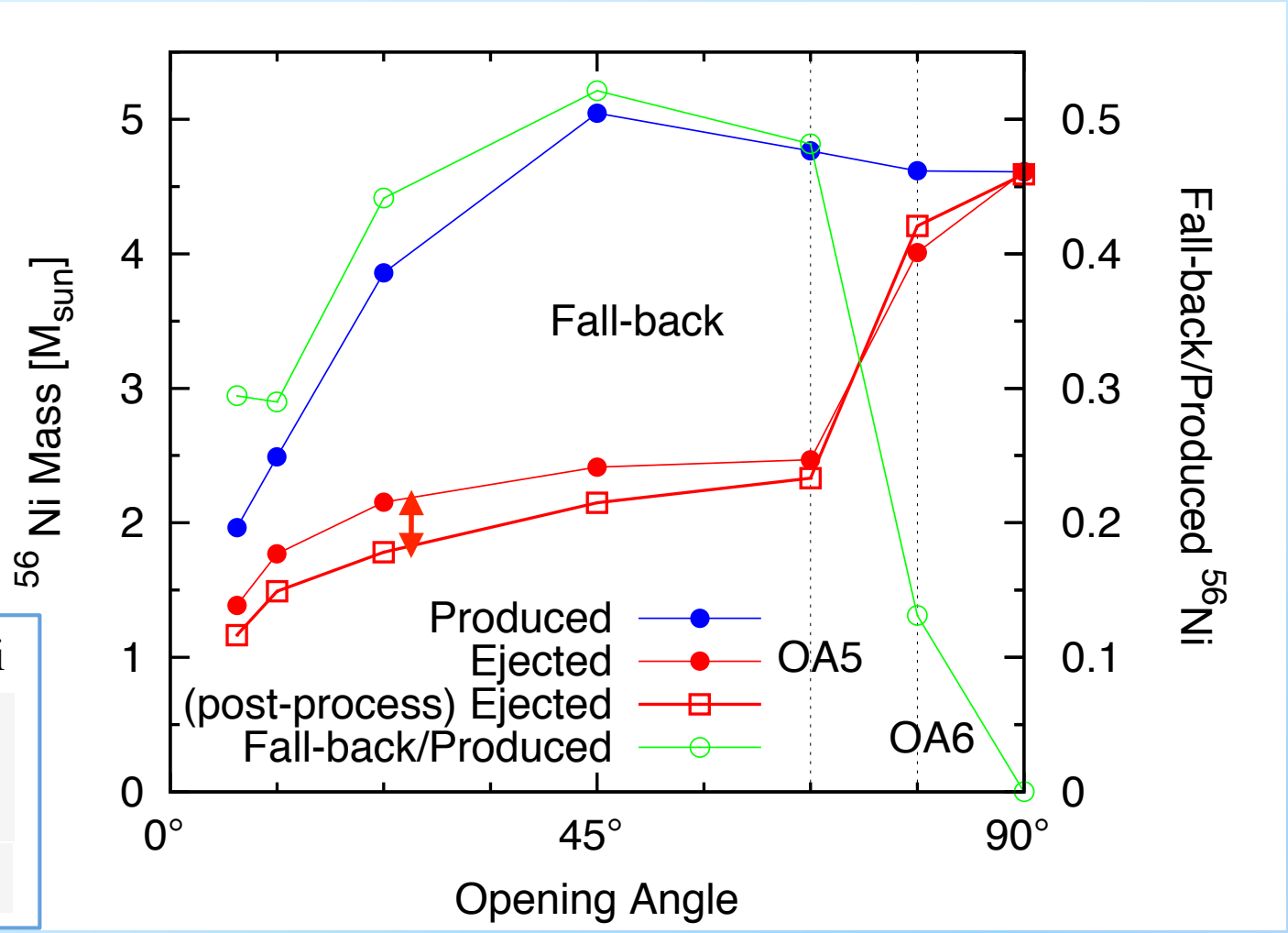
Aspherical feature →

Aspherical explosion induces large amount of fall-back

Ejected ^{56}Ni or ^{28}Si → →

Steep jump in a certain θ_{op} → narrow explosion eject not much ^{56}Ni

^{56}Ni



Simple Evaluation of ^{56}Ni

$$T_i(^{\forall}t_n) < T_{\rm Ni} \rightarrow X^{56{\rm Ni}}{}_i = 0$$
$$T_i(^{\exists}t_n) > T_{\rm Ni} \rightarrow X^{56{\rm Ni}}{}_i = 1$$
$$T_{\rm Ni} = 5 \times 10^9 \ {\rm K}$$

Simple Evaluation

Large θ_{op}: Valid by ~5%

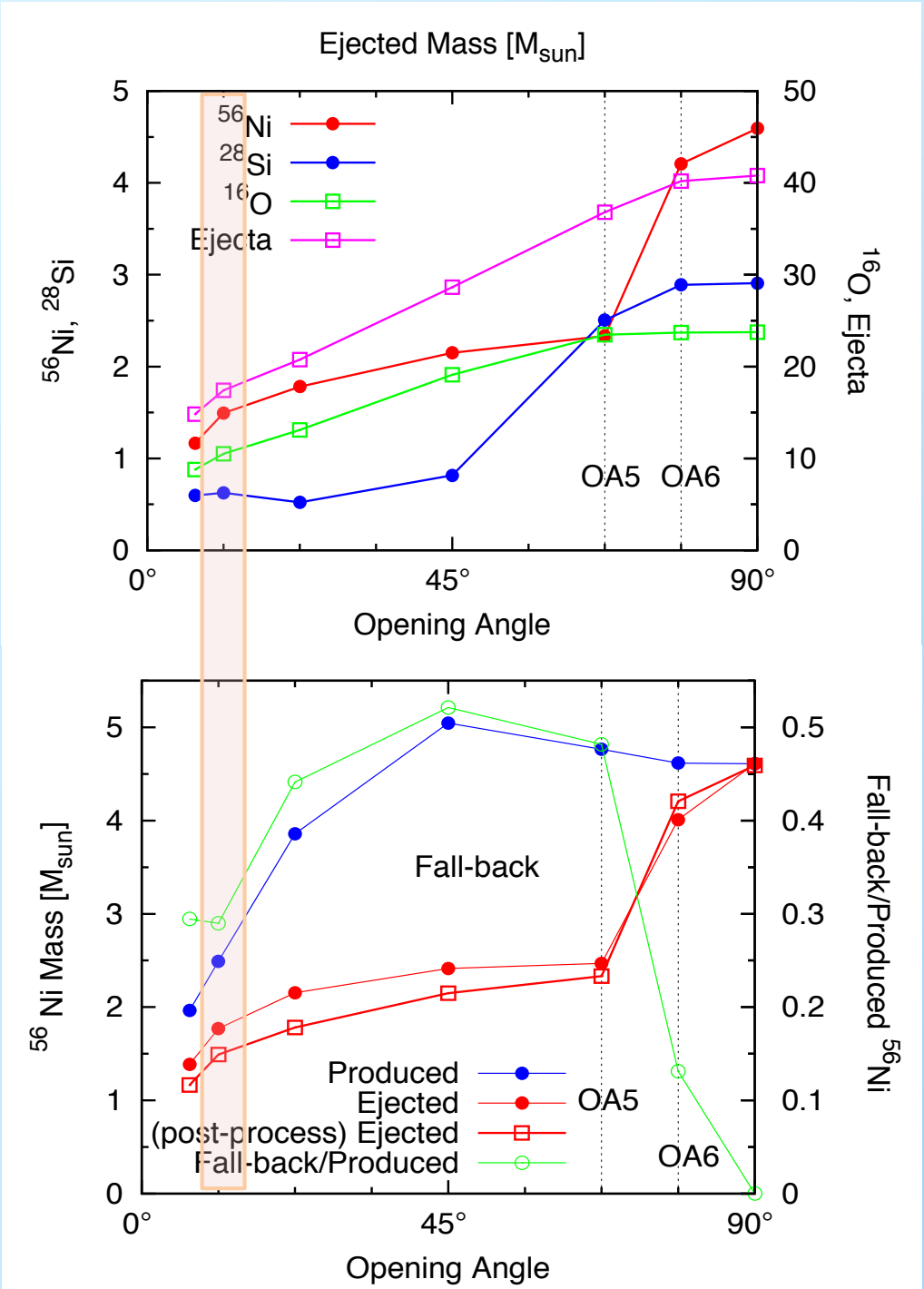
Small θ_{op} : Photo-dissociation

^{56}Ni → 14^{4}He

Fall-back

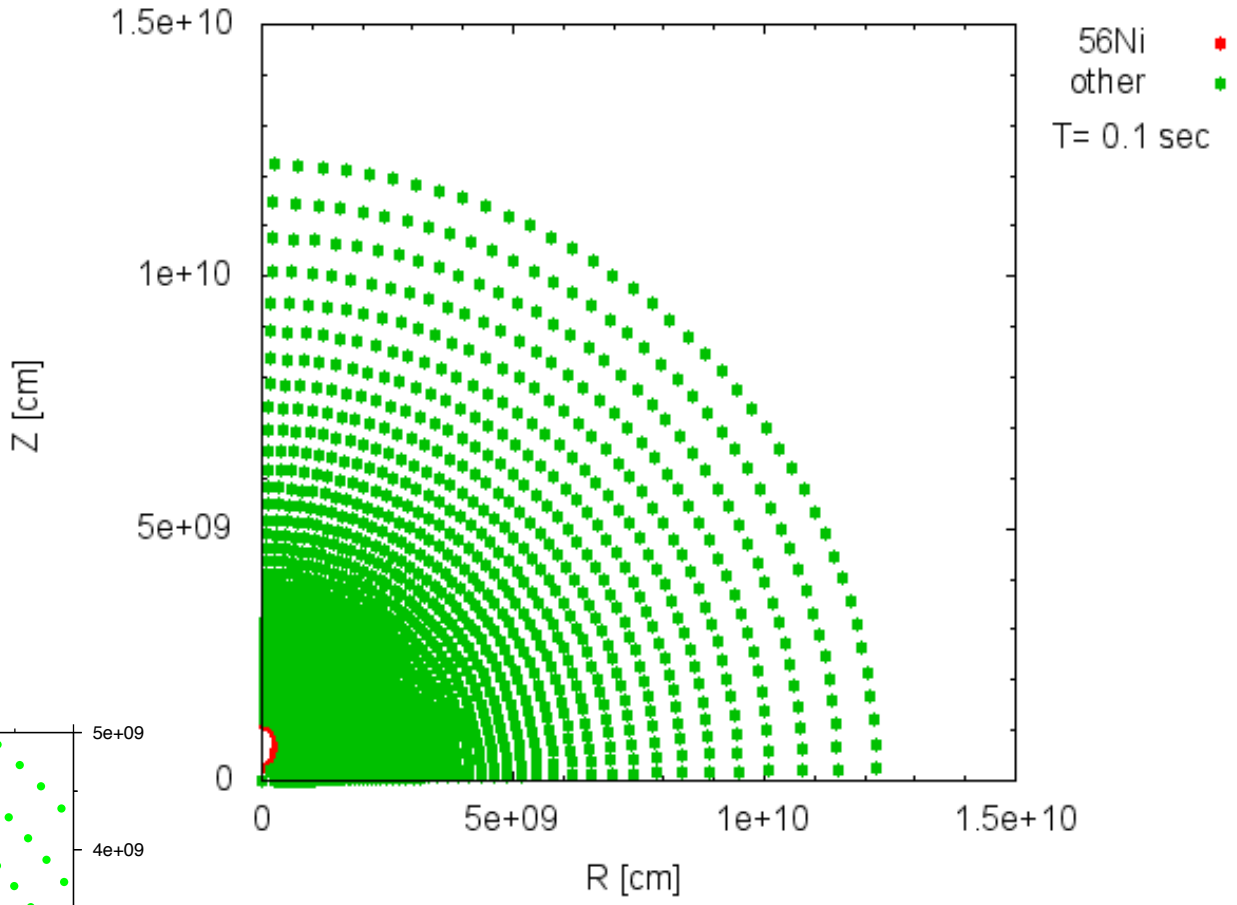
^{56}Ni (isotopes produced around the center):

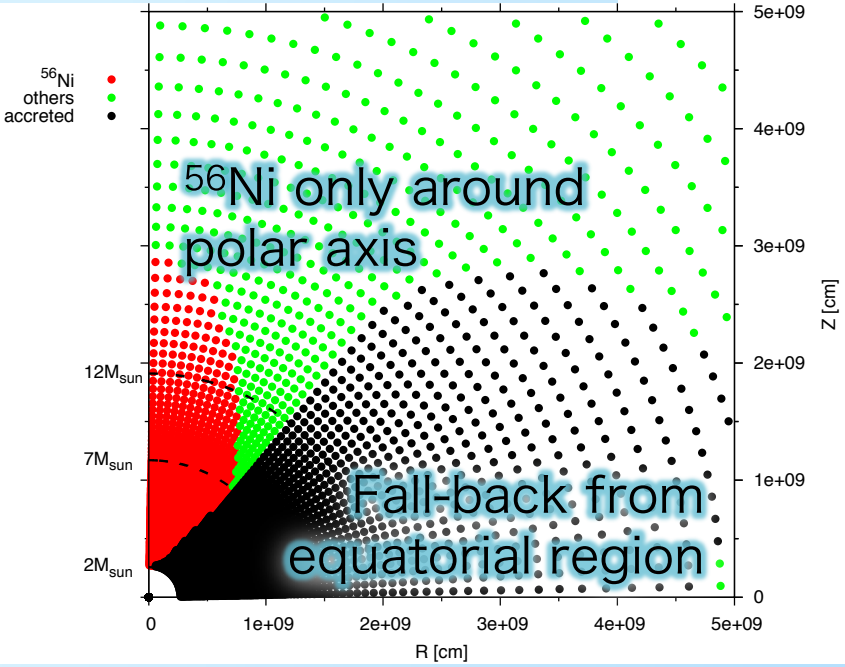
strongly affected by fall-back

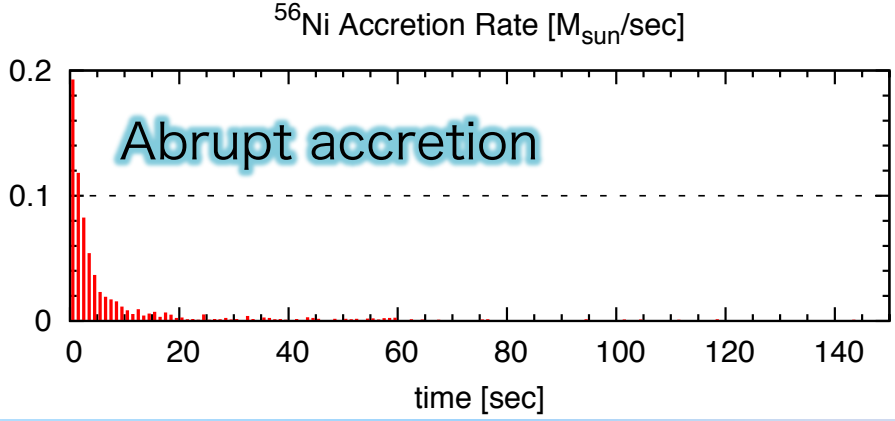

Ejected Mass [M_sun]
56Ni
28Si
16O
Ejecta
OA5
OA6
56Ni, 28Si
16O, Ejecta
Opening Angle
0°
45°
90°
Fall-back
Produced
Ejected
(post-process) Ejected
Fall-back/Produced
56 Ni Mass [M_sun]
Fall-back/Produced 56Ni

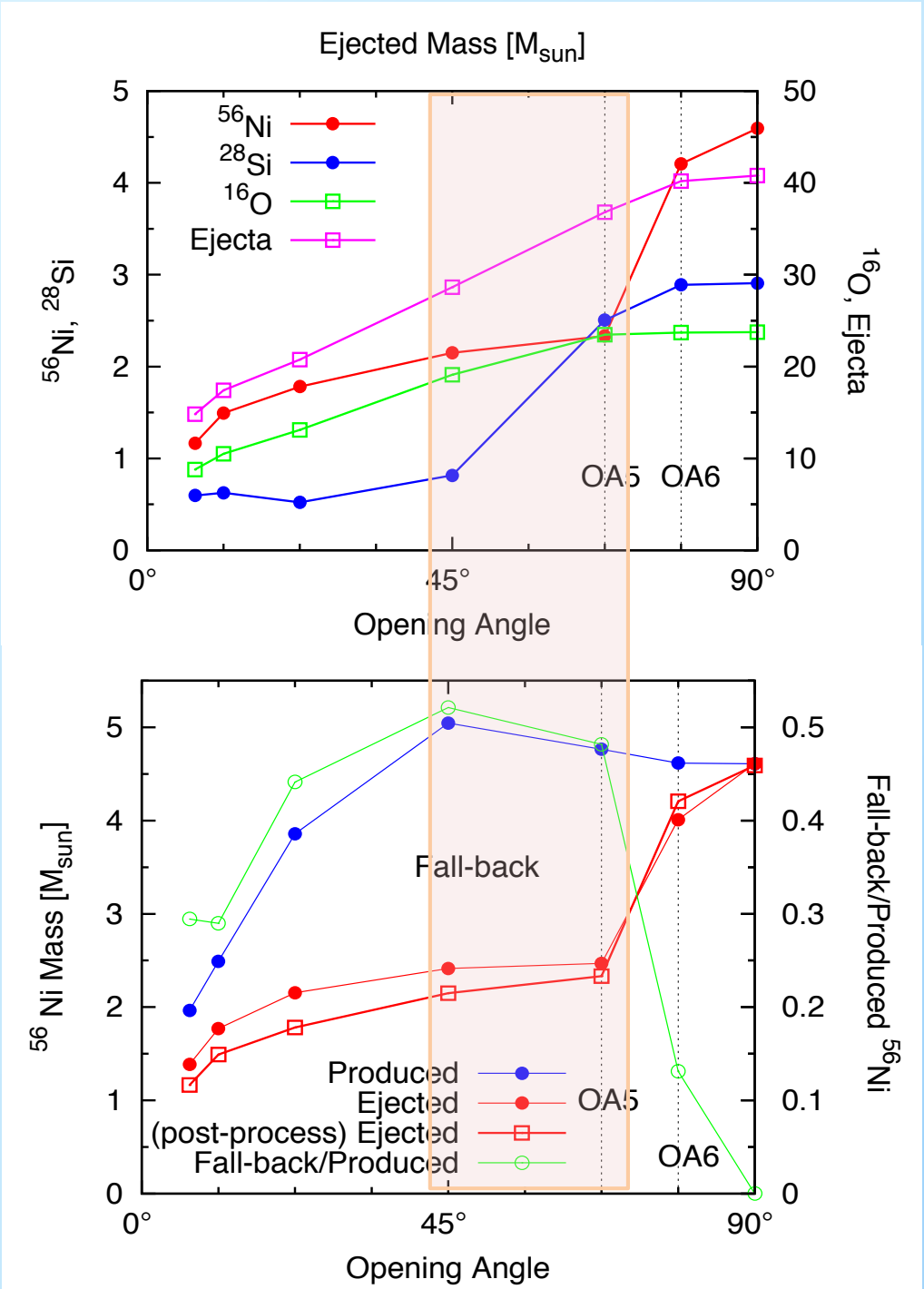
OA2 (θ_{op}=1/8*90°)

M(ejec) = 17.4 M_{sun}
M(^{56}Ni) = 1.77 M_{sun}



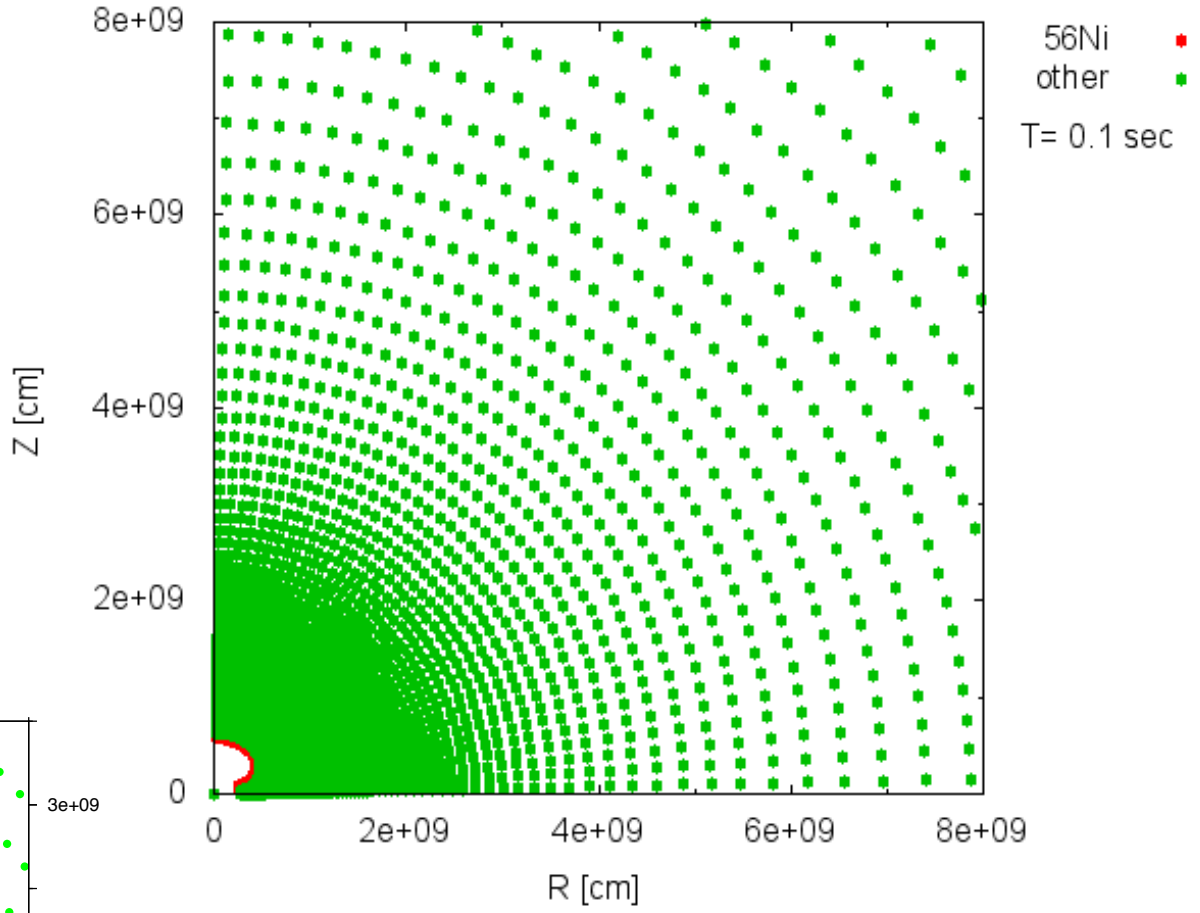


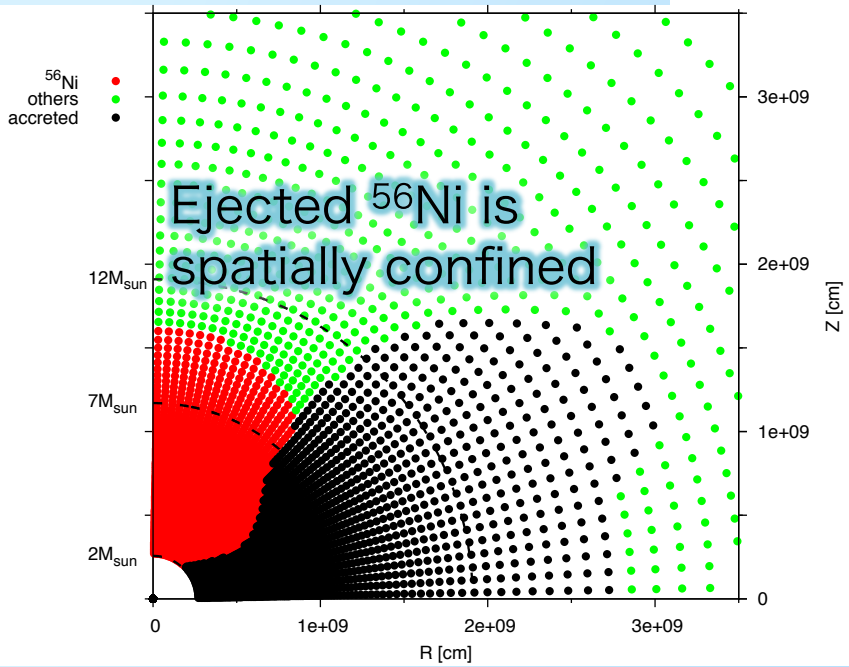



Ejected Mass [M_sun]
56Ni
28Si
16O
Ejecta
OA5
OA6
56Ni, 28Si
16O, Ejecta
Opening Angle
Fall-back
Produced
Ejected
(post-process) Ejected
Fall-back/Produced
OA5
OA6
56 Ni Mass [M_sun]
Fall-back/Produced 56Ni
Opening Angle

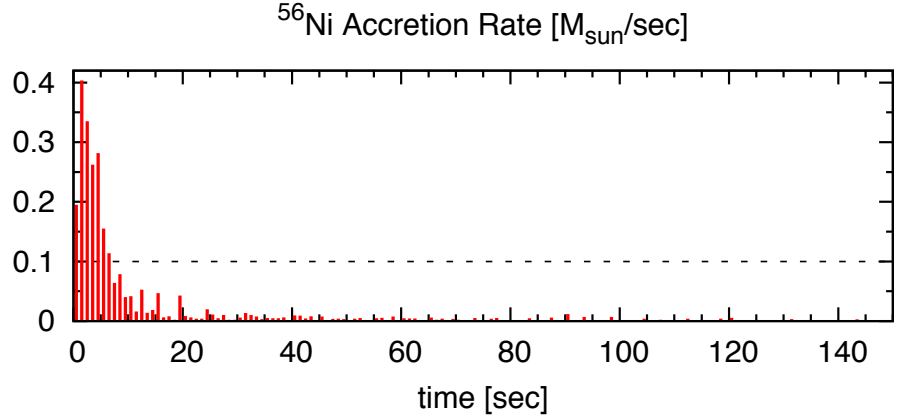
OA4
(θ_{op}=1/2*90°)

M(ejec) = 28.7 M_{sun}
M(^{56}Ni) = 2.42 M_{sun}



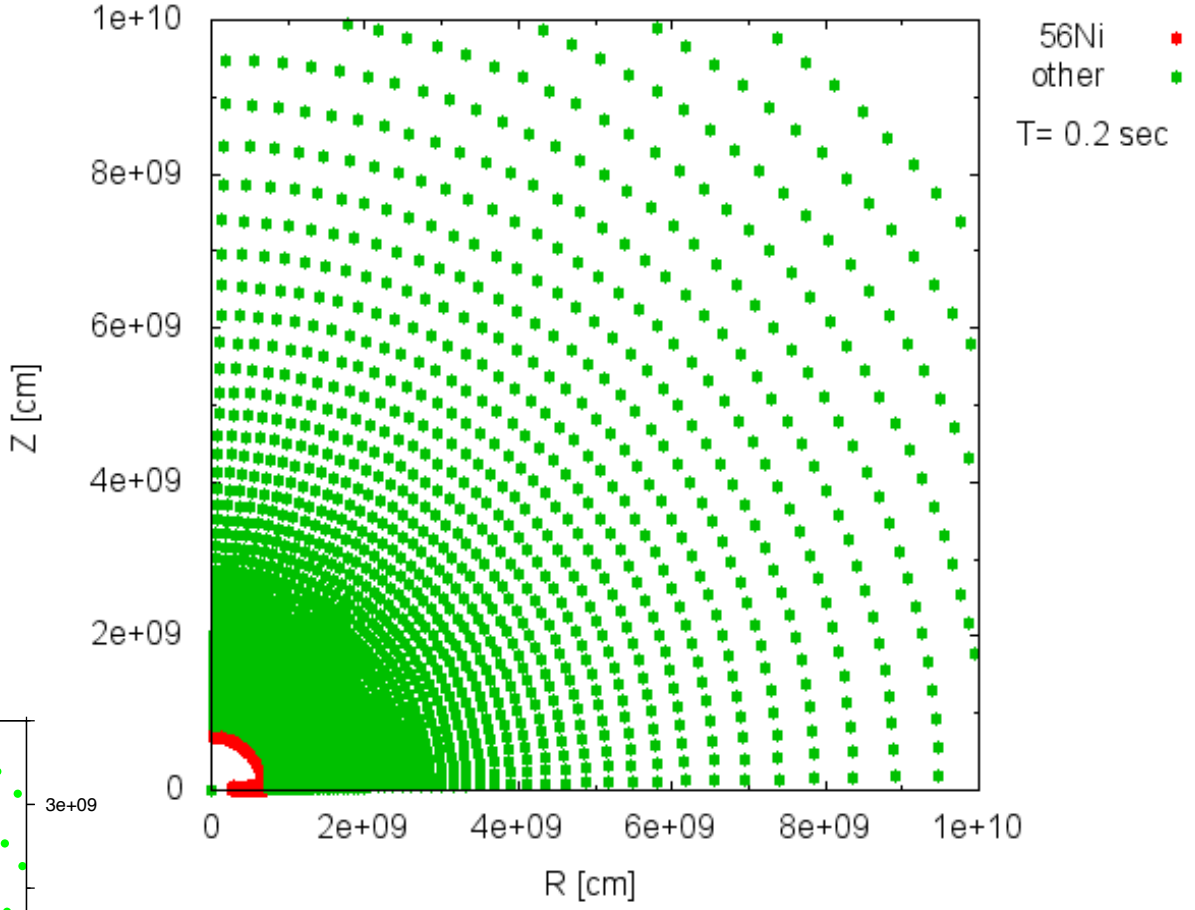


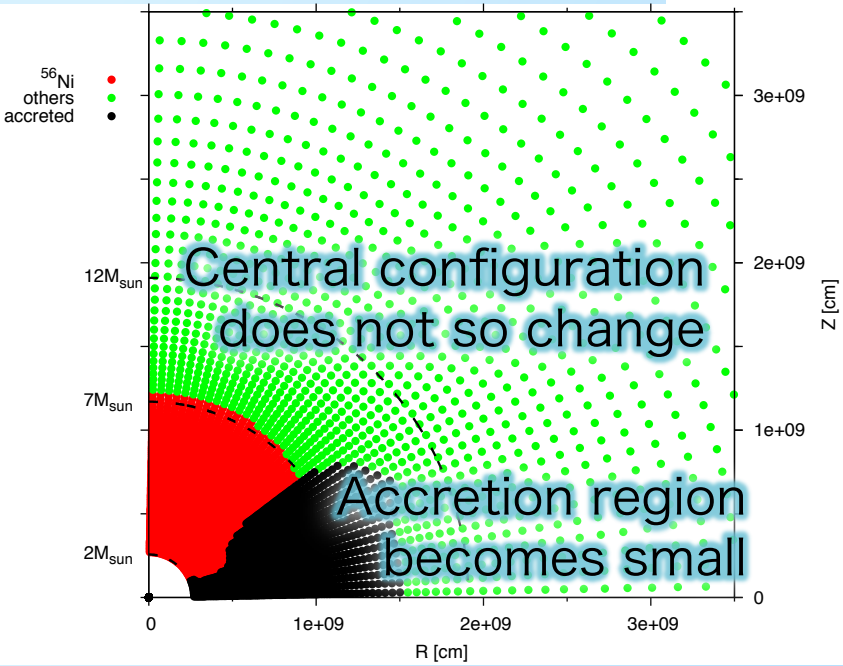
Ejected ^{56}Ni is spatially confined



OA5 (θ_{op}=3/4*90°)

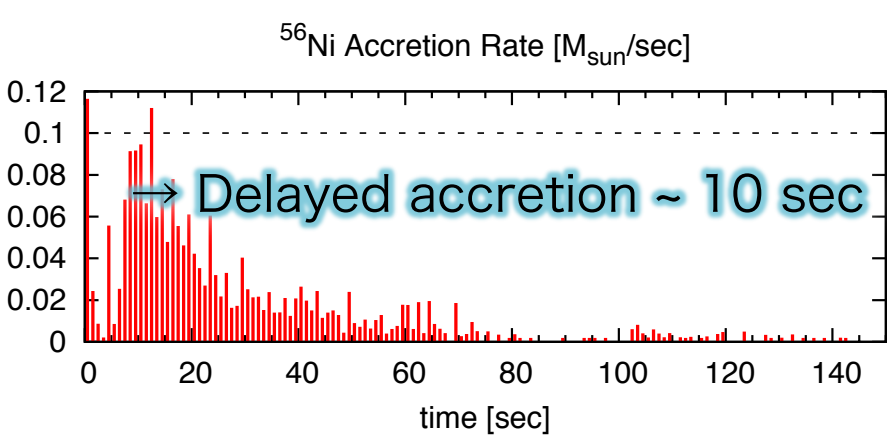
M(ejec) = 36.8 M_{sun}
M(^{56}Ni) = 2.47 M_{sun}



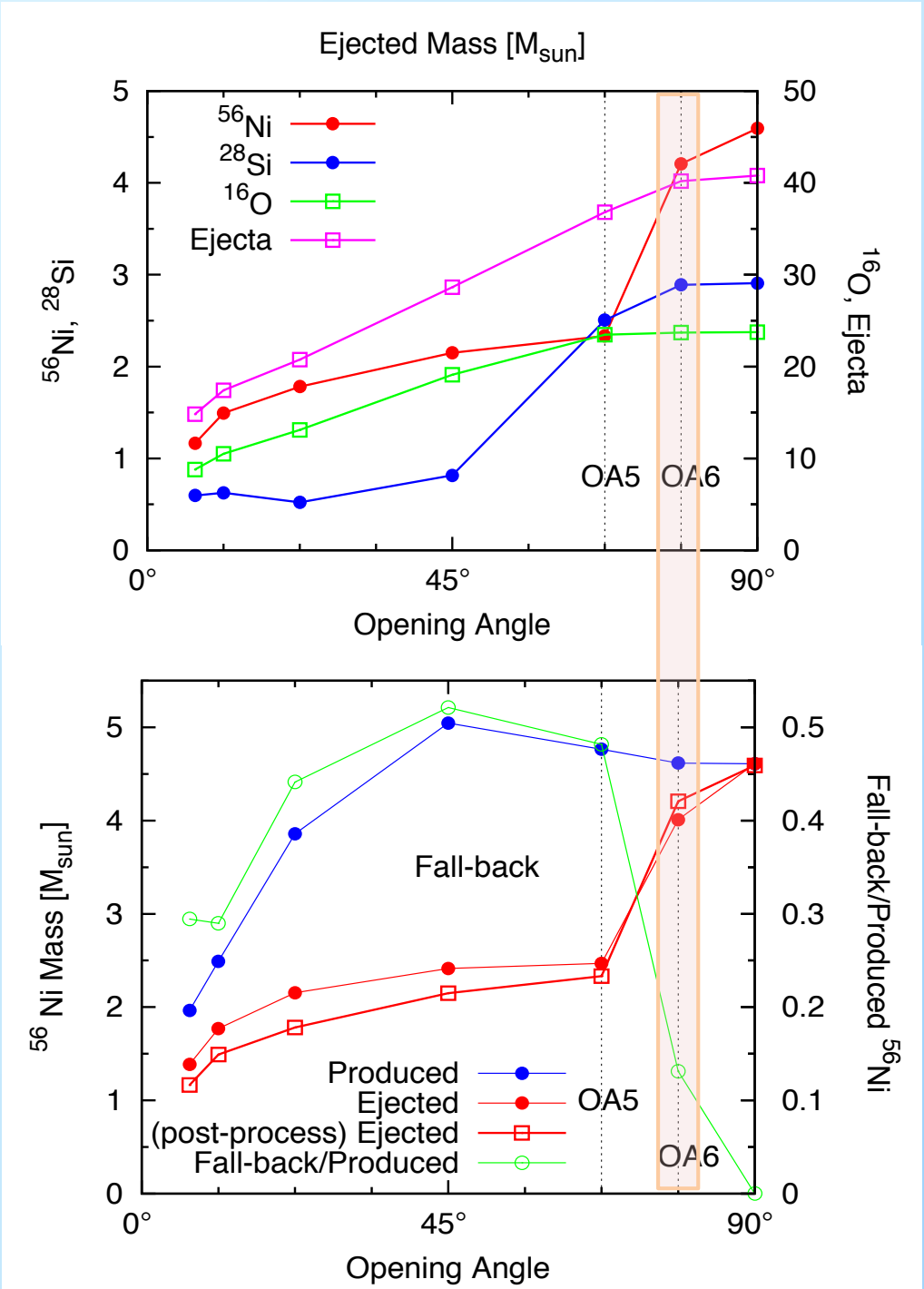


Central configuration does not so change

Accretion region becomes small



→ Delayed accretion ~ 10 sec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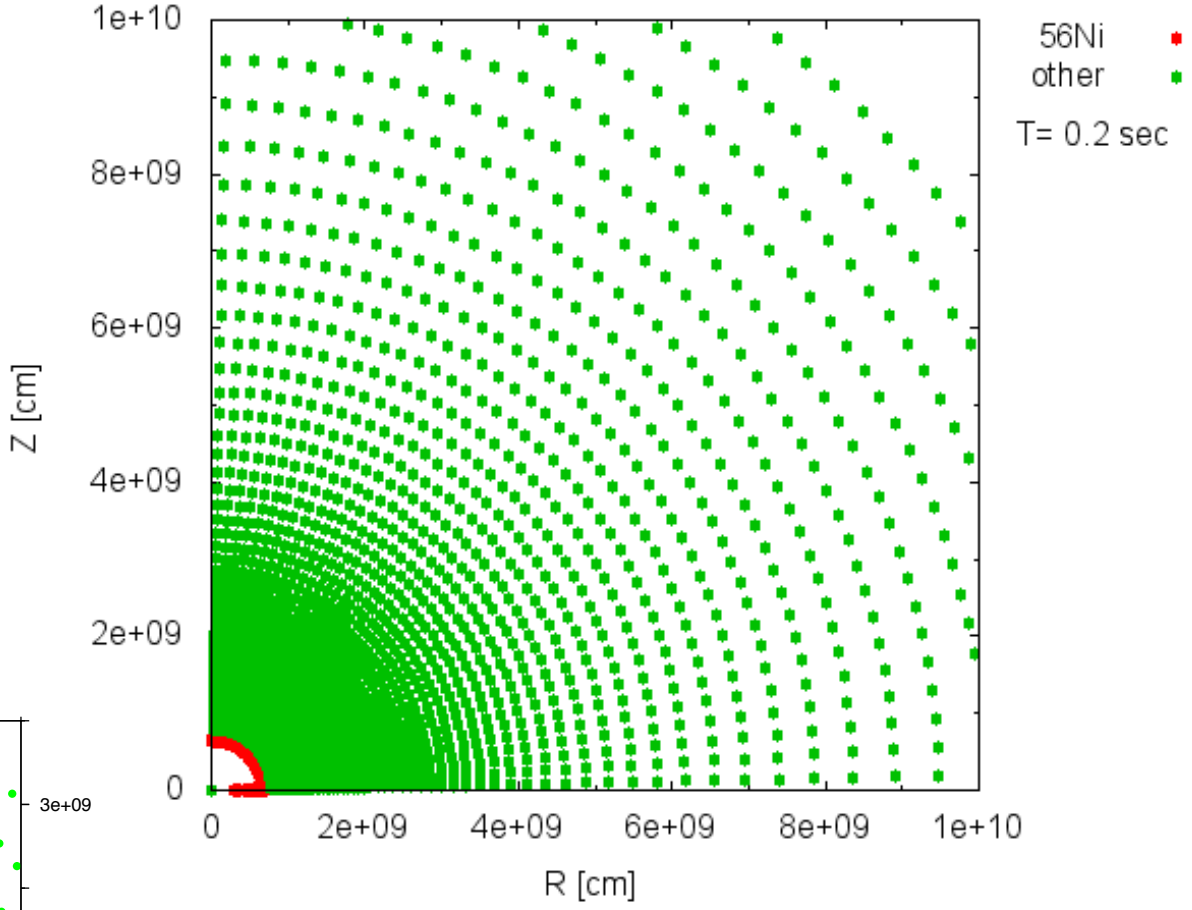
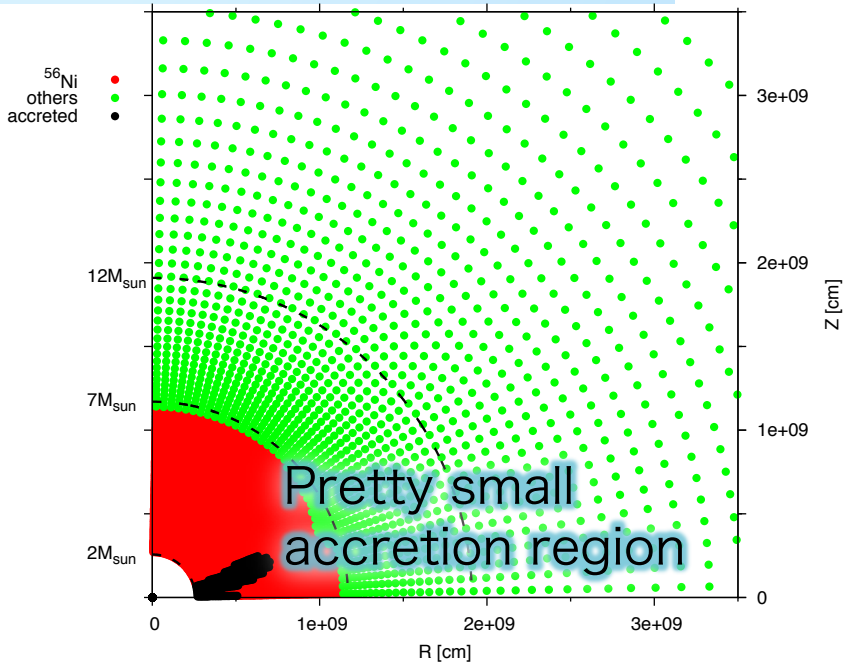
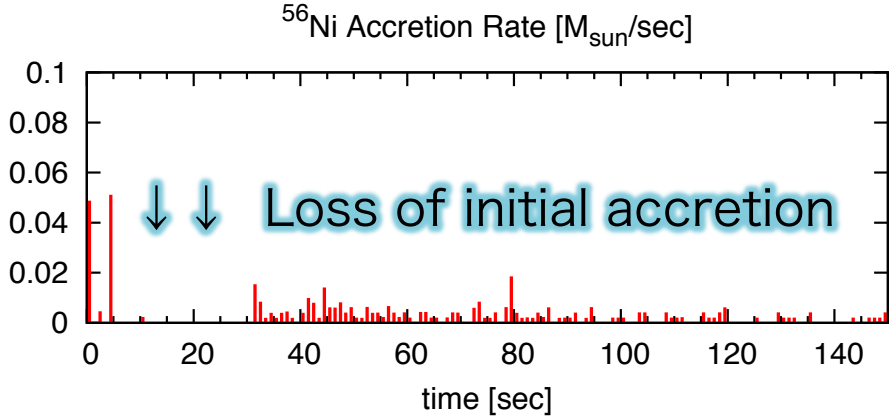
Opening Angle
0°
45°
90°
Fall-back
Produced
Ejected
(post-process) Ejected
Fall-back/Produced
56 Ni Mass [M_sun]
Fall-back/Produced 56Ni

OA6
(θ_{op}=7/8*90°)

M(ejec) = 40.2 M_{sun}
M(^{56}Ni) = 4.01 M_{sun}

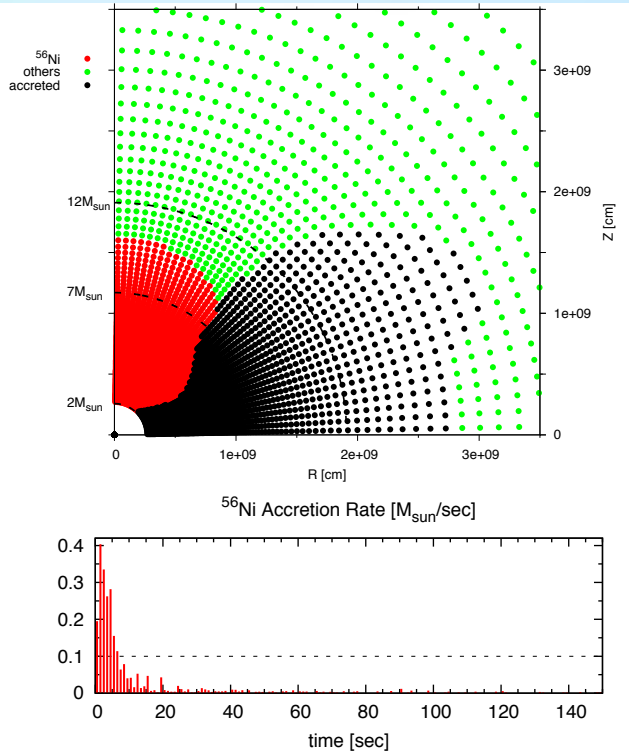






Hydro-dynamical Effect

OA4



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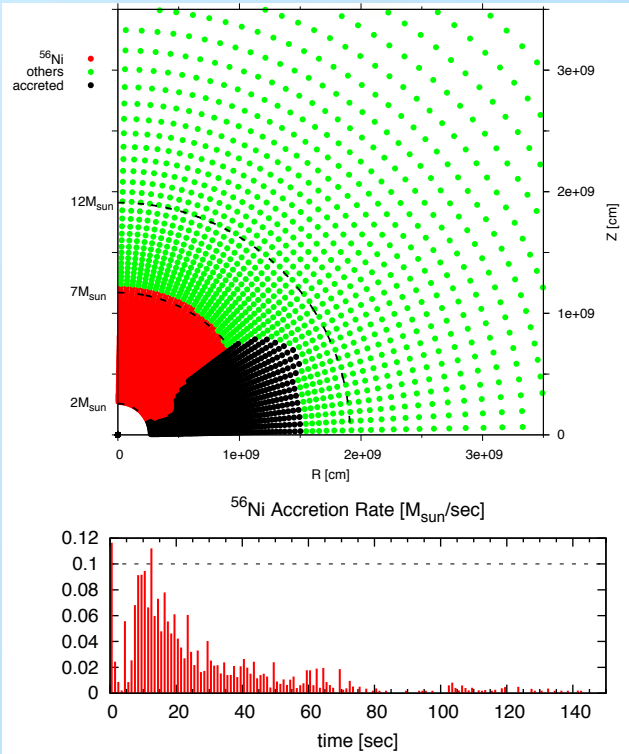
OA5



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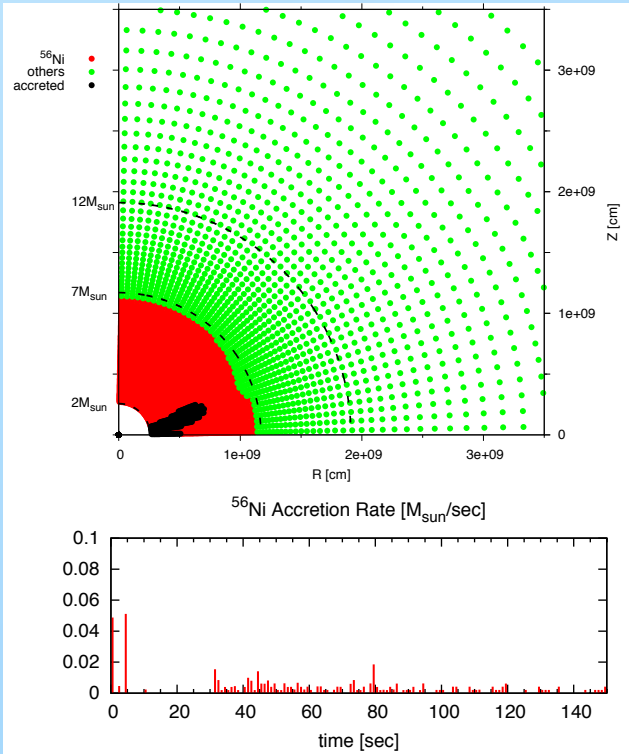
OA6



M(ejec) = 40.2 M_{sun}
M(^{56}Ni) = 4.01 M_{sun}

Summary

Chemical Abundance Ejected by Aspherical Explosion of Massive CO Star

- **Aspherical Effect**: Ejecta decreases toward small θ_{op}
- Isotopes produced around the center suffer from **Fall-back** or **Hydro-dynamical Effect** according to θ_{op}
- ^{56}Ni is ejected more than $4M_{sun}$ if $\theta_{op}/90° \geq 7/8$

→ Observed sphericity of SN2007bi is not accidental