Nucleosynthesis Constraints on the Energy Growth Timescale of Core-Collapse Supernova Explosion

Sawada & Maeda (2019), ApJ, 886, 47 (arxiv.1910.06972)

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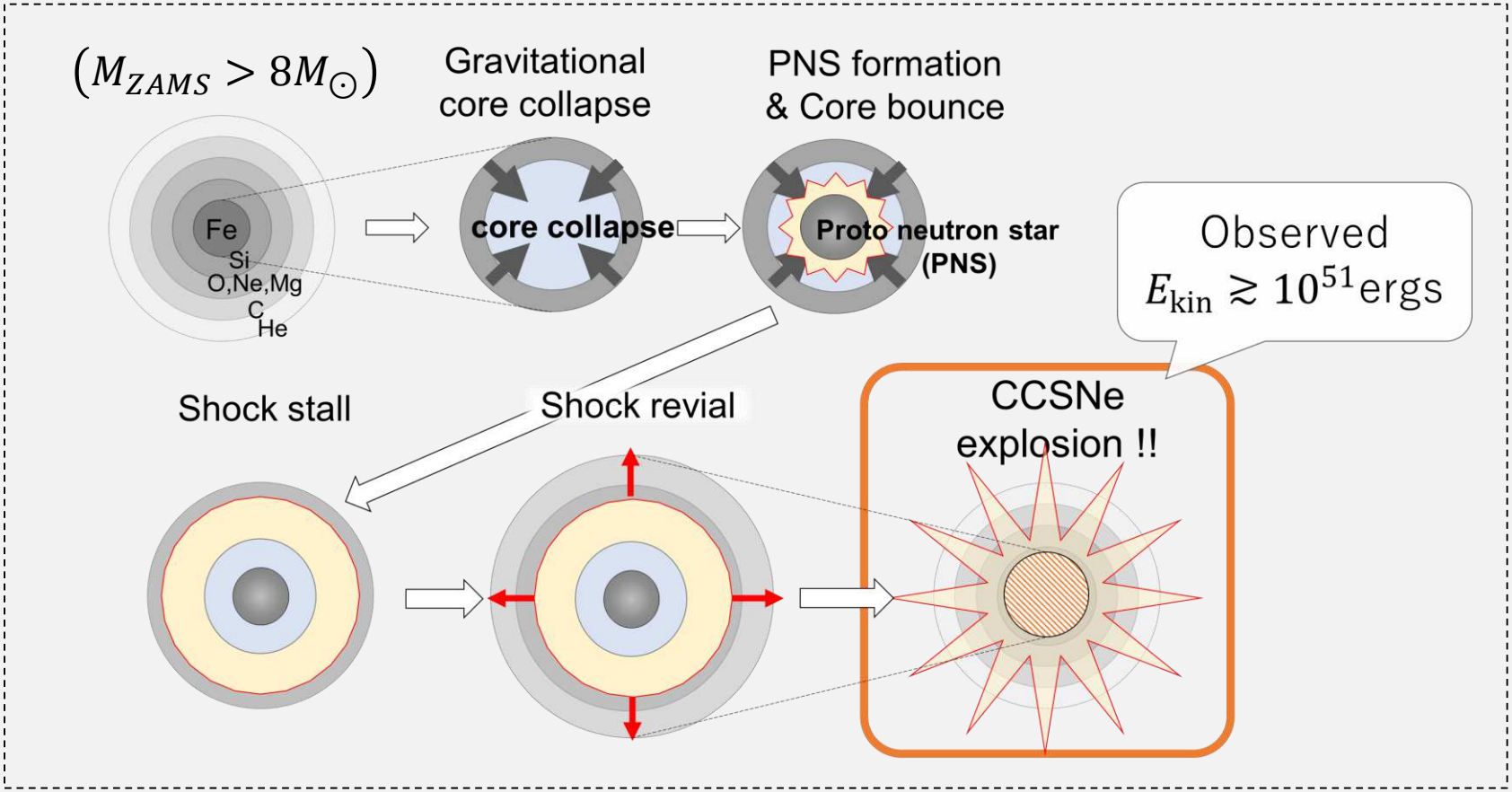
Department of astronomy, Kyoto-University

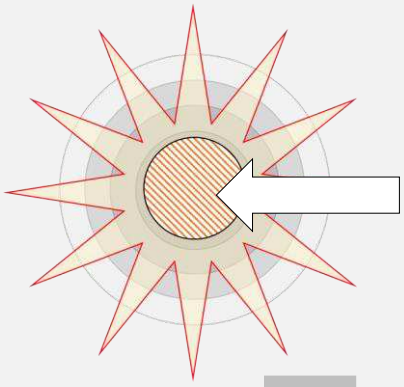
standard scenario : neutrino driven explosion



***unclear : Can reach to 10^{51} [erg] ?**

with the ab-initio simulation (e.g.; Janka 2012)

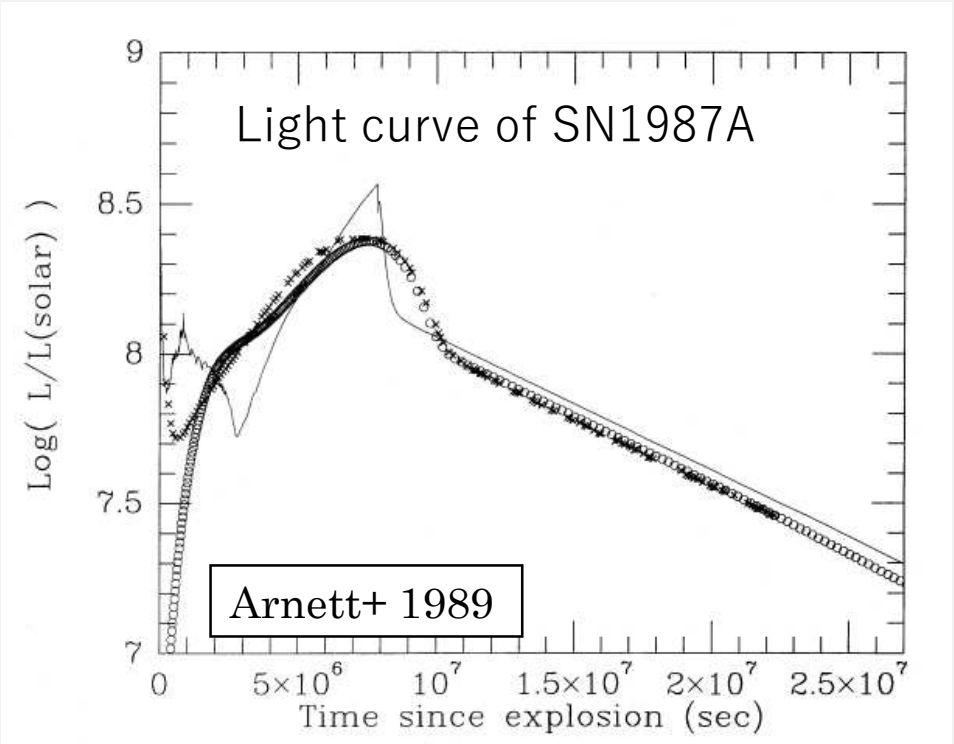
(obs./classic) Explosion model of CCSNe



- calculation model e.g., Woosley+ 1995

deposit (thermal/kinetic)energy:10^{51}erg

Nucleosynthesis / Radiation transfer



assumption

Timescale of
Nucleosynthesis (~ 1 sec)

⋙

Timescale of "up to 10^{51}erg"

Obs. consistent with instantons explosion [~10ms]

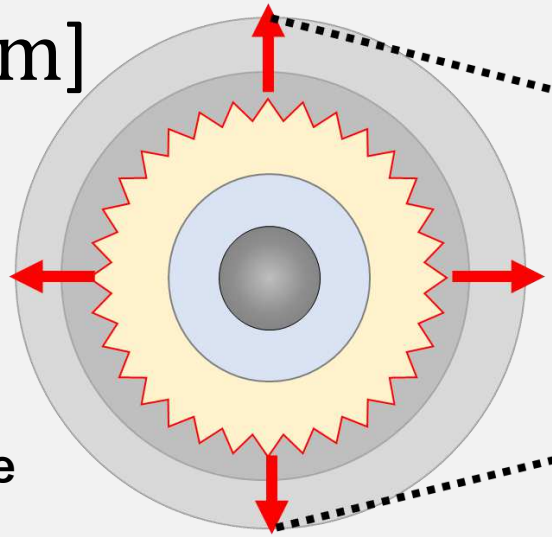
Studies on “neutrino driven explosion"

Can reach to 10^{51} [erg] ?

【AB-*initio* calculation】

(e.g. Takiwaki+ 2014, Nakamura+ 2014)

$[\sim 10^{6}\mathrm{cm}]$



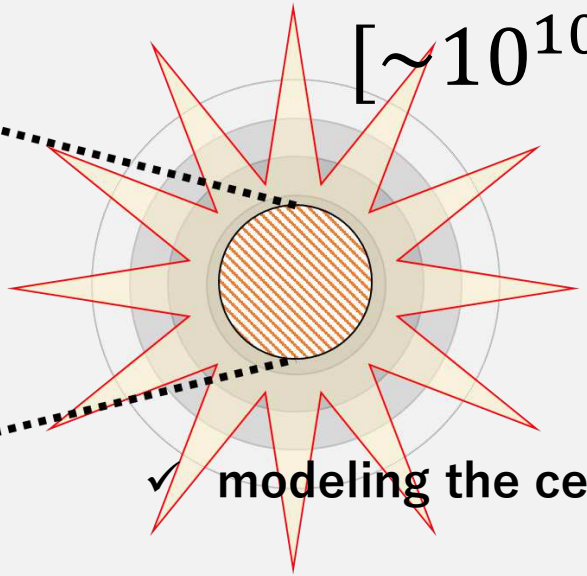
✓ **only Fe-core**

Can reproduce obs. profiles?

【Artificial explosion simulation】

(e.g. Woosley+ 1995)

$[\sim 10^{10-12}\mathrm{cm}]$



✓ **modeling the central engine**

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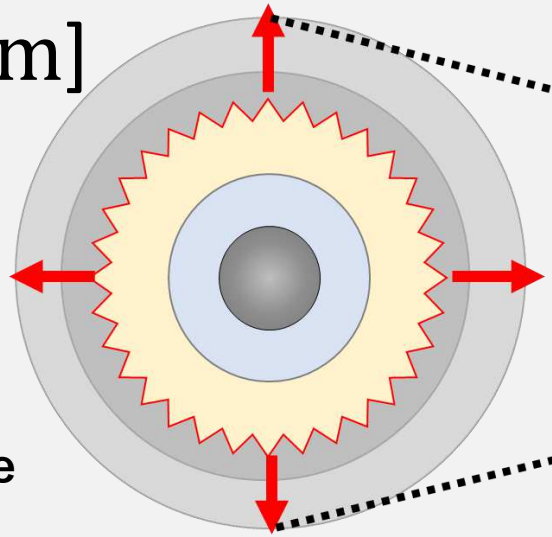

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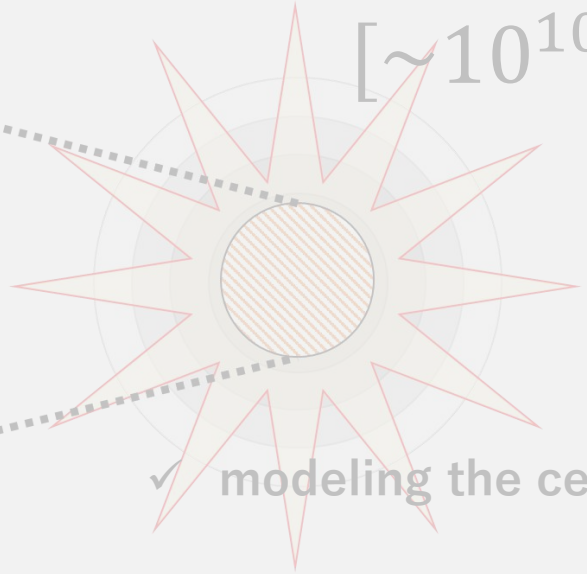
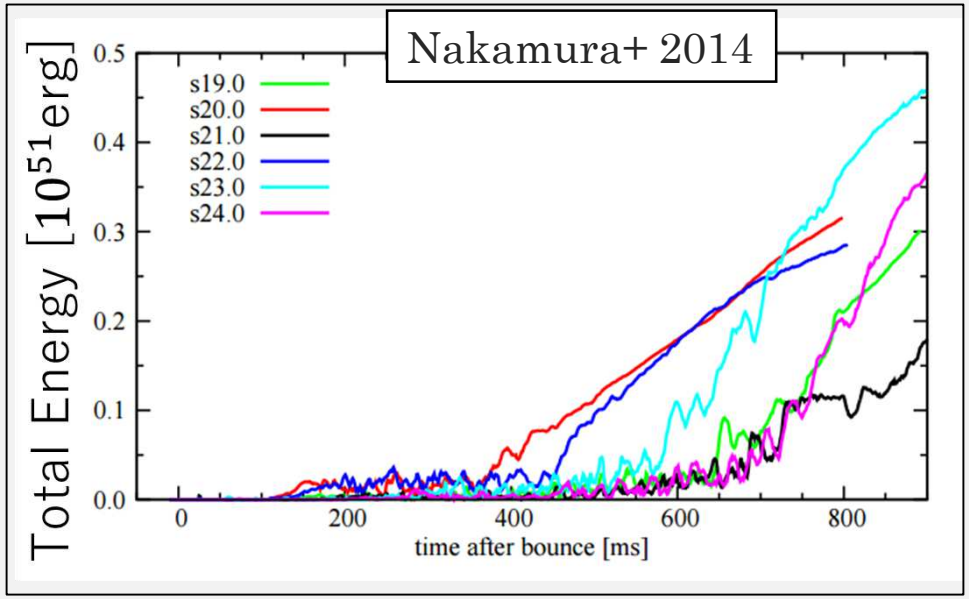
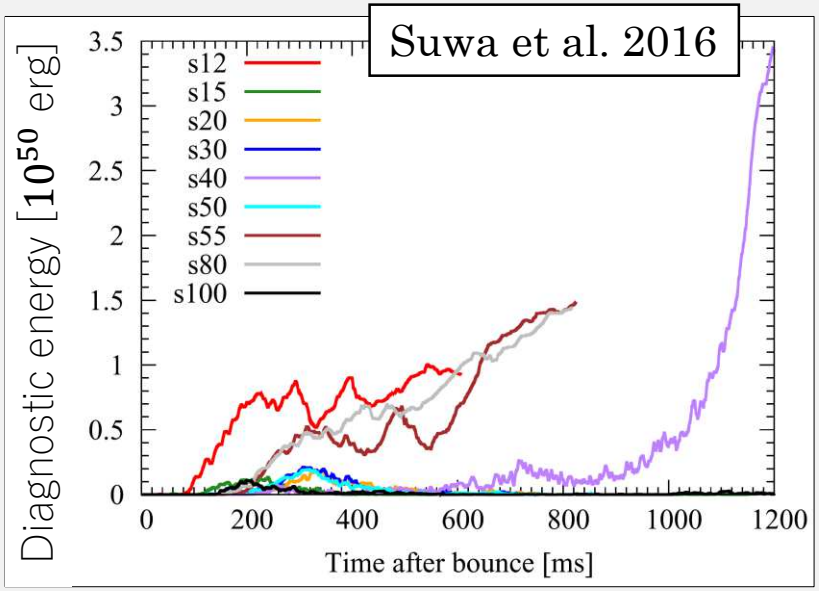


✓ **modeling the central engine**

Recent ab-initio calculation.





- ✓ calculation is set up in Multi-D.
- ✓ detailed treatment of neutrino transport
- ✓ Difficult to reproduce, but can extrapolate up to 10^{51} ergs (?).

↓

t_{grow} : timescale up to 10^{51}[erg]

most of all simulation

$t_{\mathrm{grow}} \gtrsim 1$[s]

Studies on “neutrino driven explosion"

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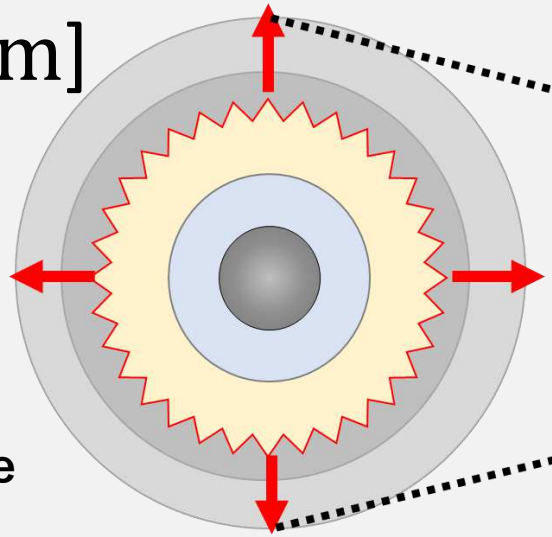

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for the growth up to 10^{51} ergs,

suggest ‘slow’ explosion

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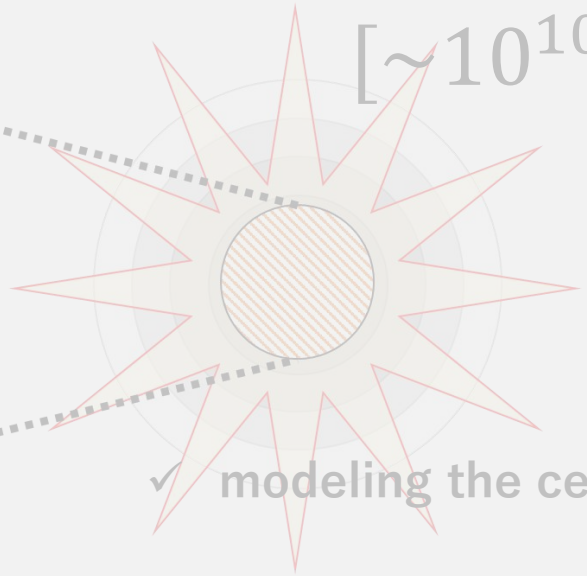

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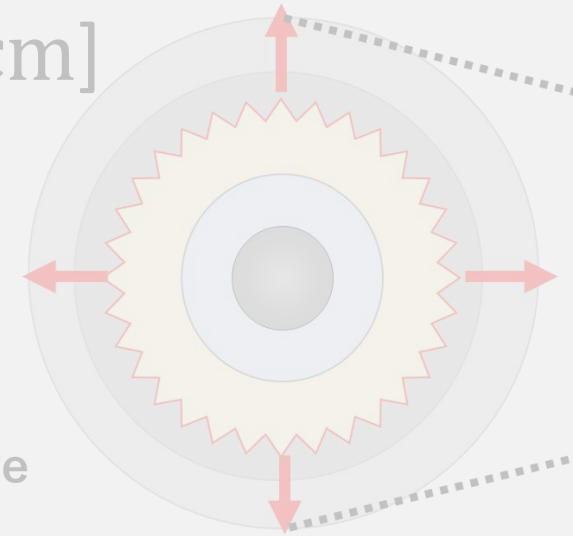

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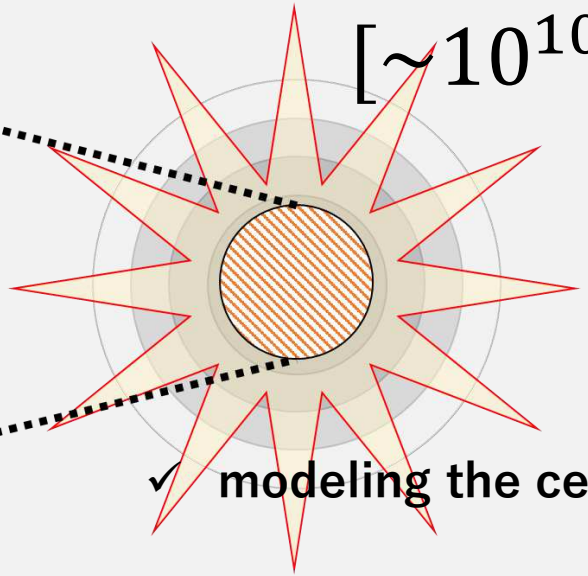


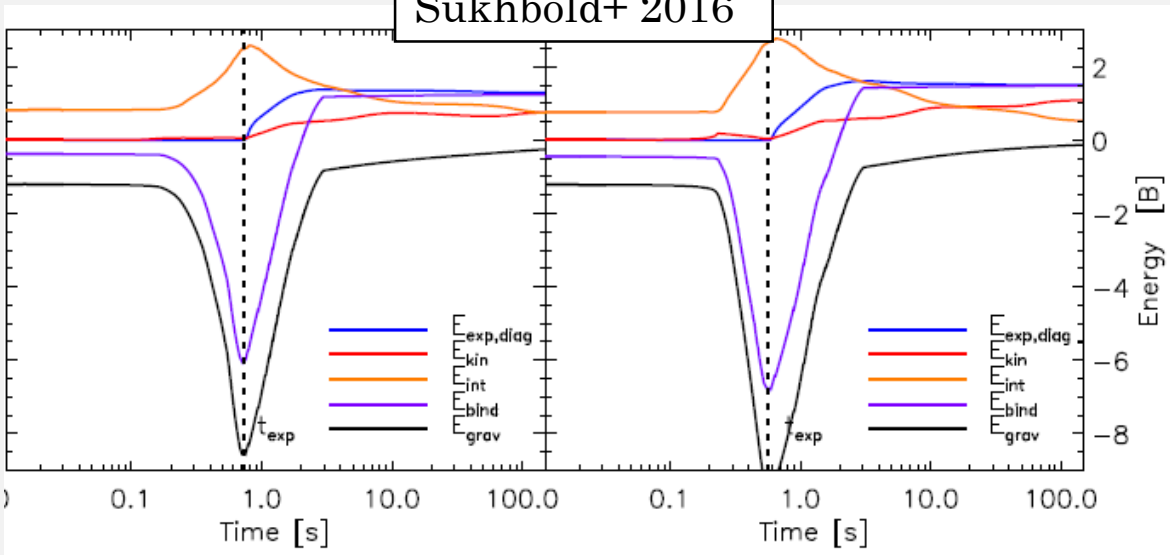
✓ modeling the central engine

Recent intermediate calculation.

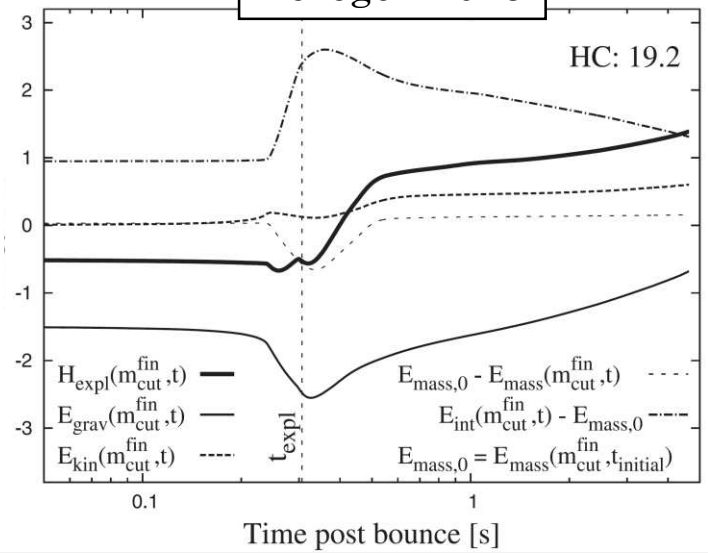
1D artificial explosion model

- ✓ 1D ab-initio simulations do not yield explosions by the neutrino-driven mechanism.
- ✓ In order to explode, calibrate neutrino luminocity.
- ✓ As the result, they success to reproduce obs. prfiles.

Sukhbold+ 2016



Perego+ 2015



These tends to rise exp.energy steeply (especially, at the initiation of explosion.)

$$\dot{E_{exp}} \geq 10\ [\mathrm{Bethe/s}] \Rightarrow t_{grow} \leq 100[\mathrm{ms}]$$

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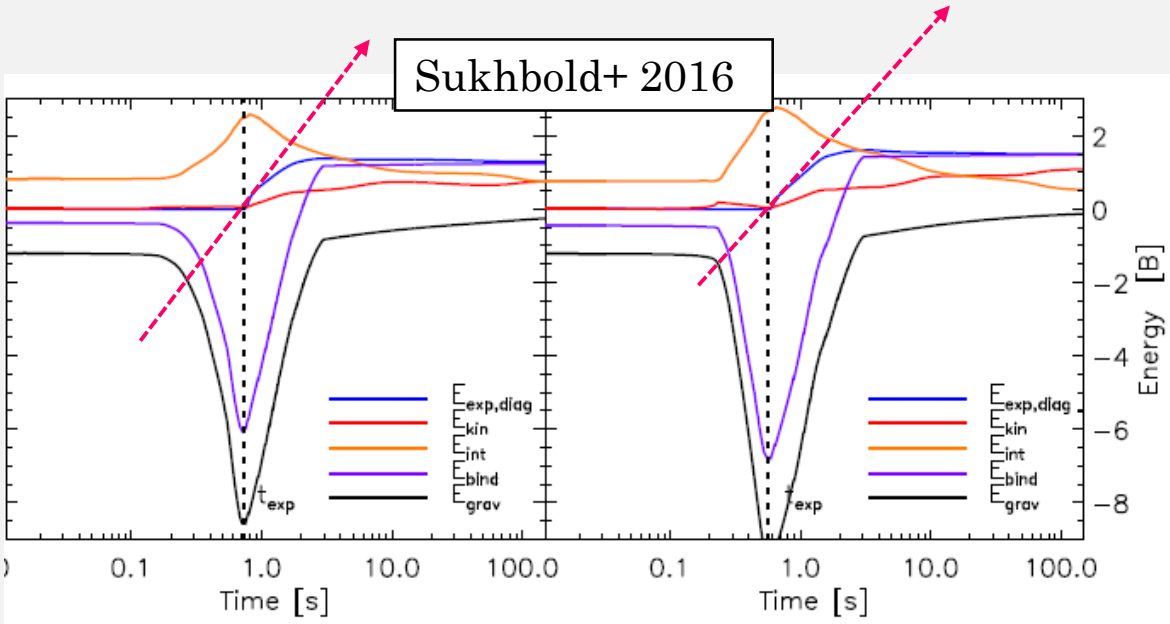

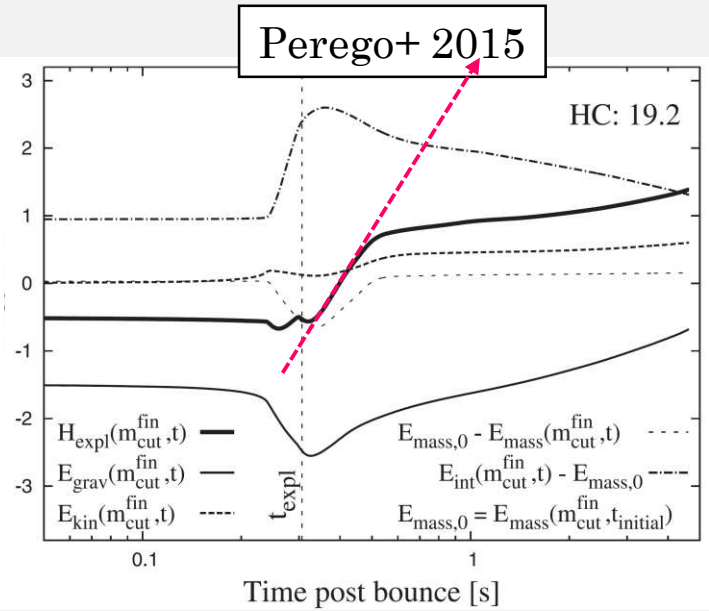

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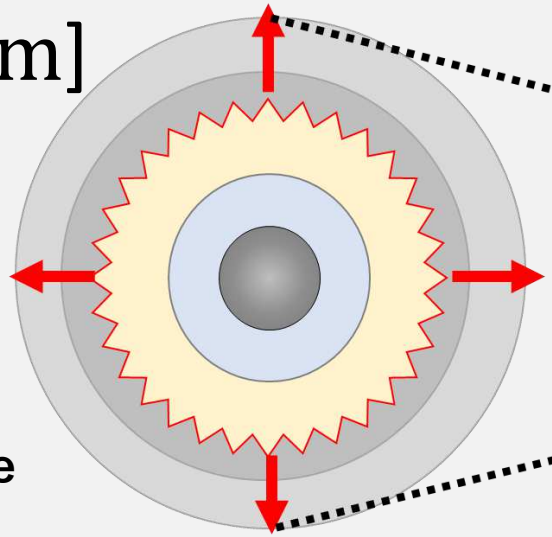

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Can reproduce obs.profiles?

【Nucleosynthesis】

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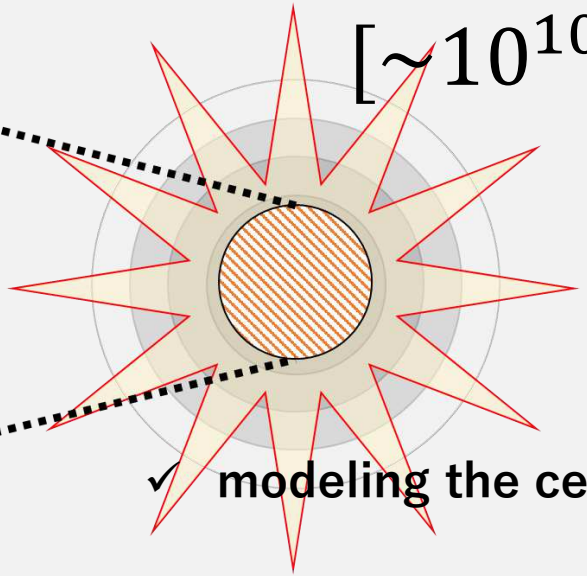


✓ **modeling the central engine**

for the growth up to 10^{51} ergs,

suggest ‘slow’ explosion

$[t_{\mathrm{grow}} \gtrsim 1\mathrm{s}]$

assuming instant explosion

$[t_{\mathrm{grow}} \lesssim 100\mathrm{ms}]$

This study: Nucleosynthesis from 'slow' expl.

motivation → How the explosive nucleosynthesis products are affected by explosion timescale(t_{grow}) ?

simulation → 1D-Simulation w/ explosion timescale as parameter

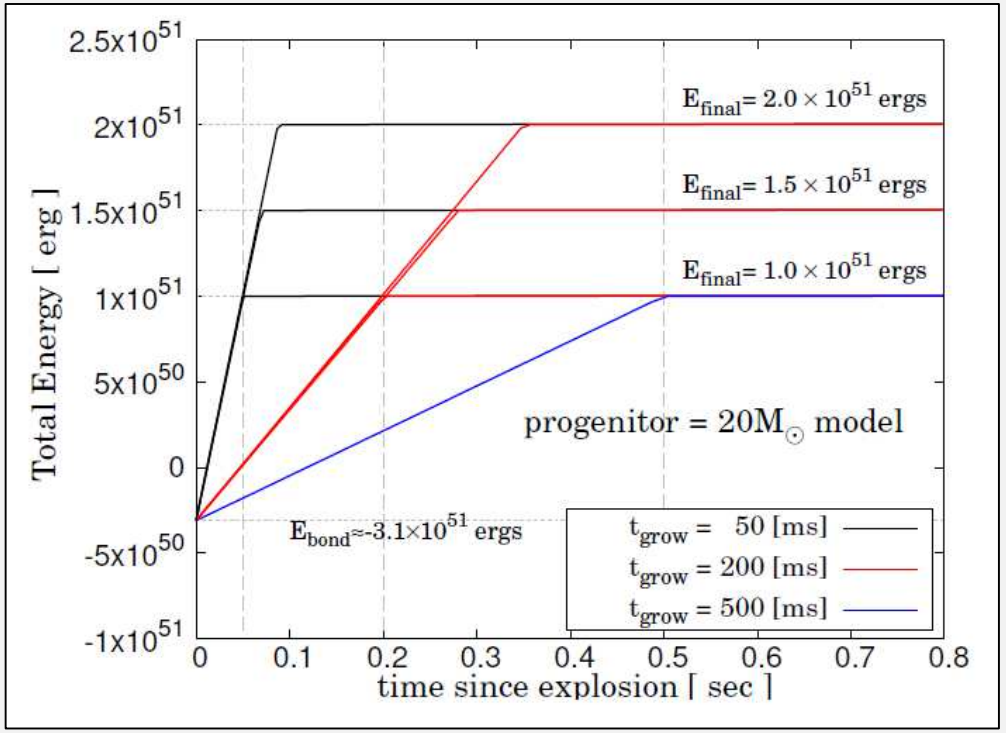
t_{grow} : timescale up to 10^{51}[erg]

✓ model:

Inject thermal energy

at PNS-surface

$$\dot{E}_{in} = \frac{(E_{\mathrm{final}} + |E_{\mathrm{bind}}|)}{t_{\mathrm{grow}}}$$



✓ parameter:

- $t_{\mathrm{grow}} = 10 - 2000$ ms.
- $E_{\mathrm{final}} = 1.0, 1.5, 2.0 \times 10^{51}$ ergs

This study: Nucleosynthesis from 'slow' expl.

motivation

How the explosive nucleosynthesis products are affected by explosion timescale(t_{grow}) ?

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1D-Simulation w/ explosion timescale as parameter

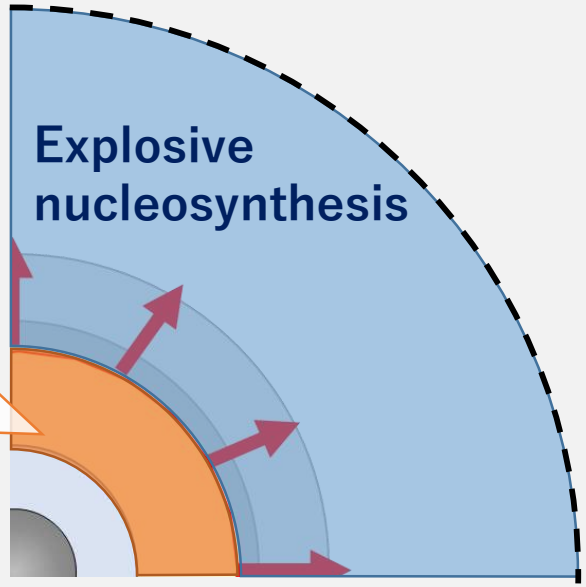
- Energy flux $\dot{E}_{in} = \dfrac{(E_{\mathrm{final}} + |E_{\mathrm{bind}}|)}{t_{\mathrm{grow}}}$ $\left\{ \begin{array}{l} E_{\mathrm{final}} = 1.0, 1.5, 2.0 \times 10^{51}\ \mathrm{ergs} \\ t_{\mathrm{grow}} = 10 - 2000\ \mathrm{ms} \end{array} \right.$

✓ progenitor mass : $M_{ZAMS} = 15, 20, 25 M_{\odot}$

✓ Hydrodynamics : based on "bl-code".

- ✓ Hydrodynamics : Newtonian
- ✓ EoS : Helmholtz
- ✓ 21-isotope α-reaction

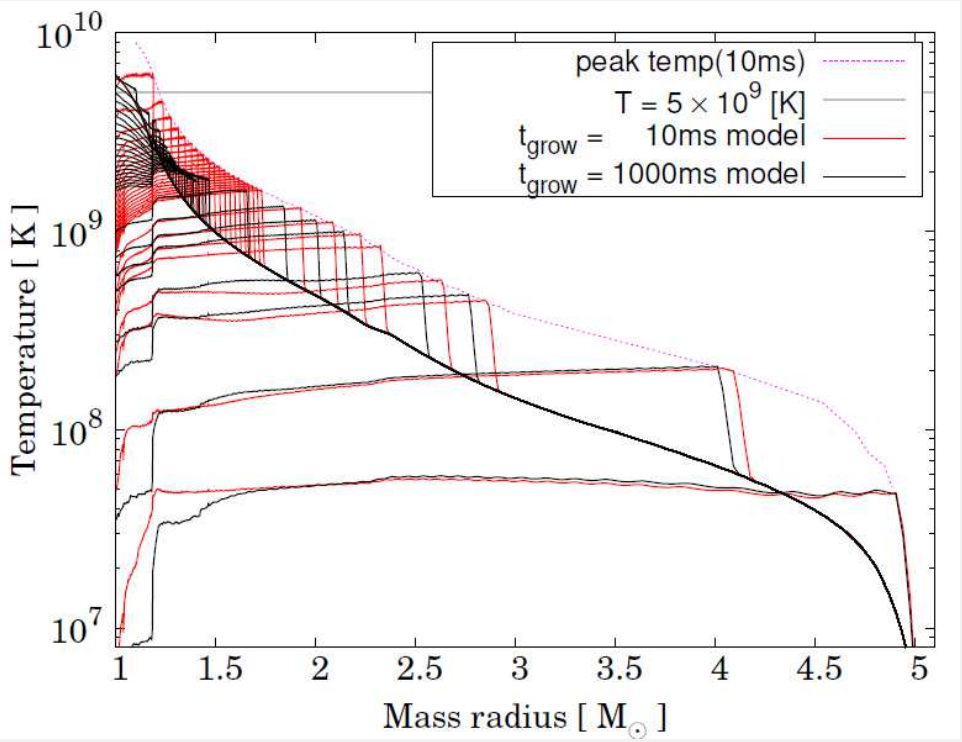
Inject thermal energy $\dot{E}_{\mathrm{exp}}$



↑
Boundary : Ye<0.48

✓ Nucleosynthesis (post-process) :
640-isotopes reaction

Result



- ✓ Both $t_{\mathbf{grow}} = \mathbf{10\&\ 1000\ ms}$ models succeed to explode.
- ✓ The shock loses $t_{\mathbf{grow}}$ information when through O-layer $(3 \gtrsim M_{\odot})$.

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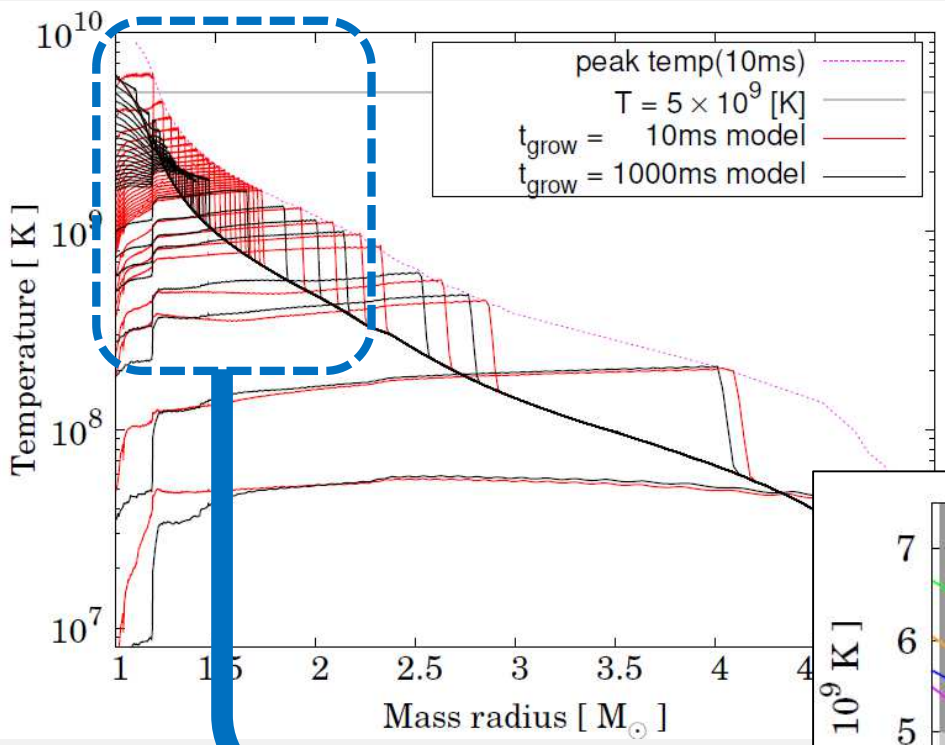

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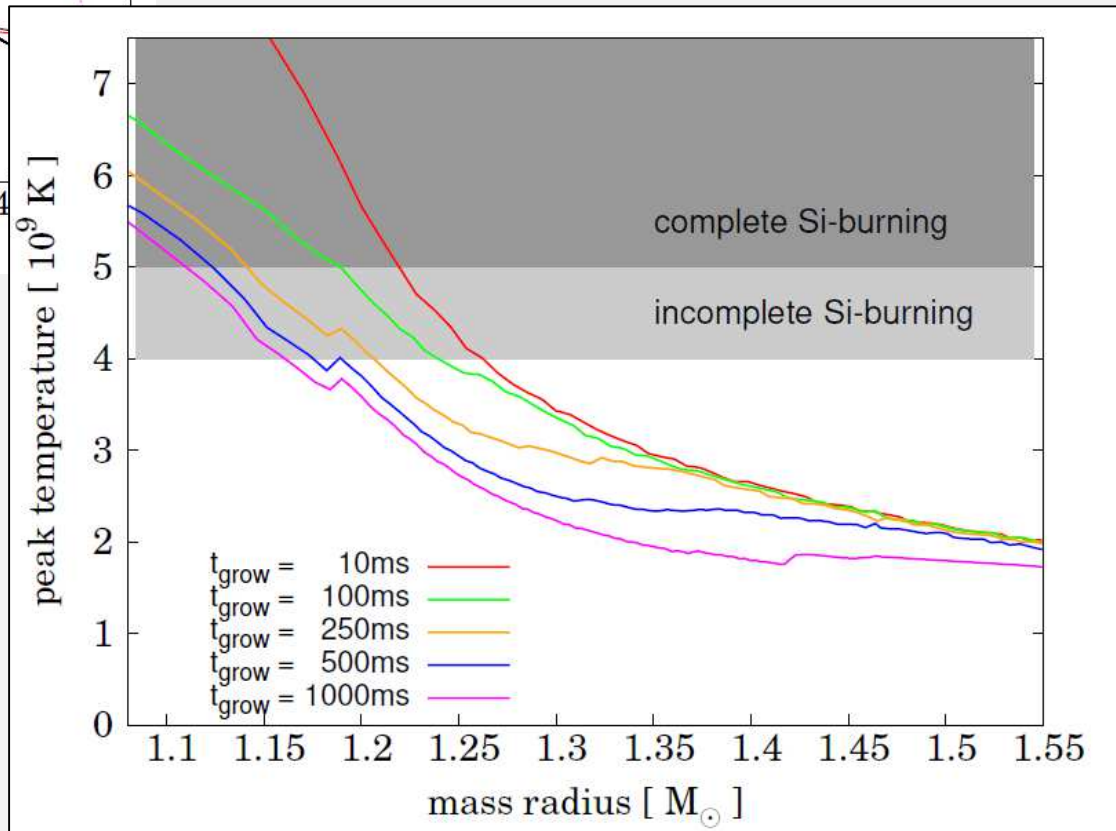


- ✓ <u>The shock weakens rapidly in the slow explosion model!!</u>

Result compared with analytic model

Assume
(1)adiabatic expansion,
(2)post-shock region is radiation dominant($r_{\mathrm{shock}} = v_{\mathrm{shock}} \cdot t$),

$$E_{\mathrm{exp}} = (aT^4) \times \left(\frac{4\pi}{3} r_{\mathrm{shock}}^3\right) \quad , \quad \Rightarrow T_{\mathrm{peak}} \propto t^{-3/4}$$

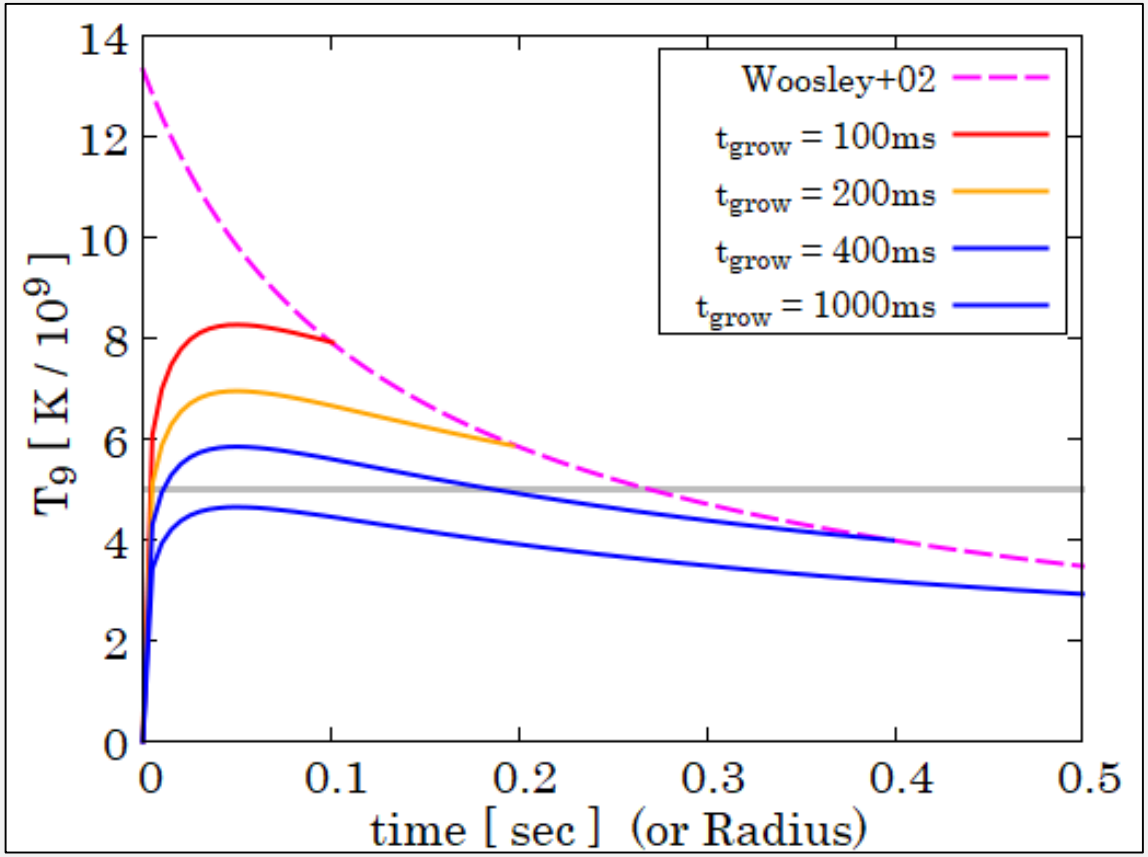
✓ When enough instanious

Woosley+ 2002

$$E_{\mathrm{exp}} = 10^{51}\mathrm{erg}$$

✓ Our model,

$$E_{\mathrm{exp}} = \frac{10^{51}\mathrm{erg}}{t_{\mathrm{grow}}} \cdot t$$



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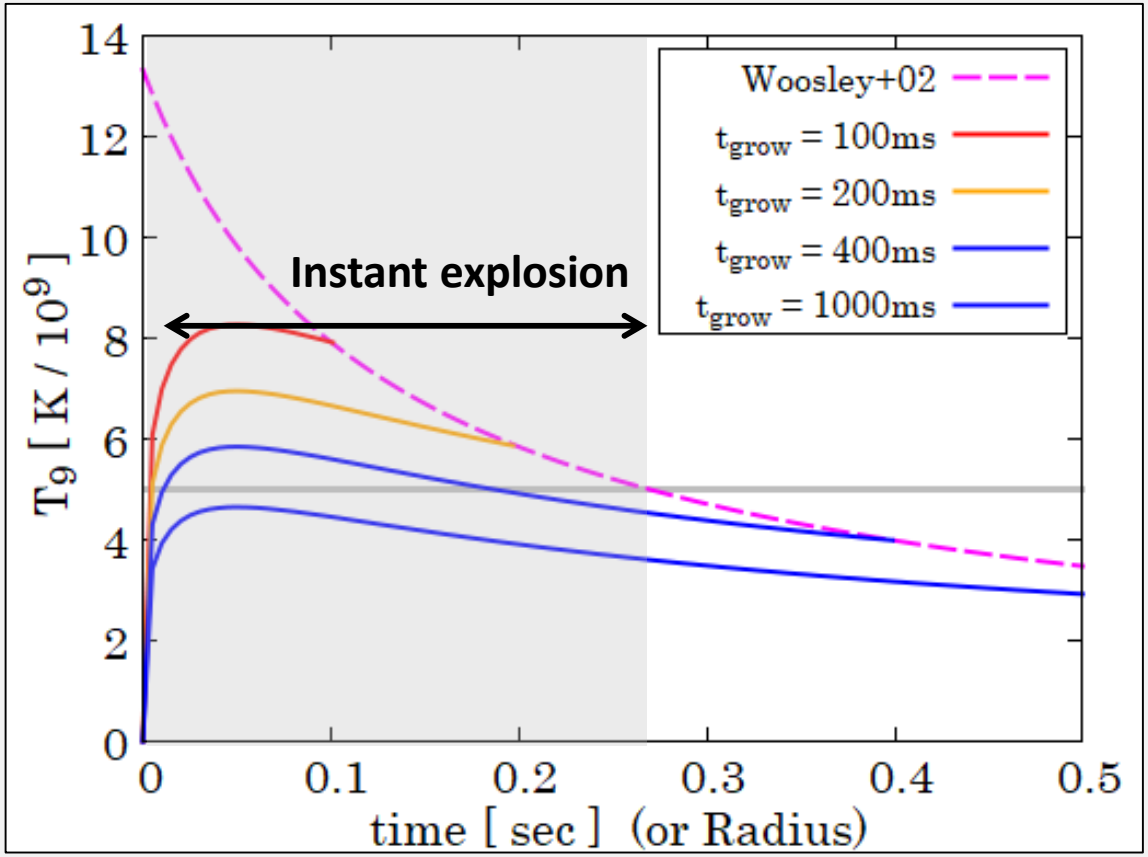

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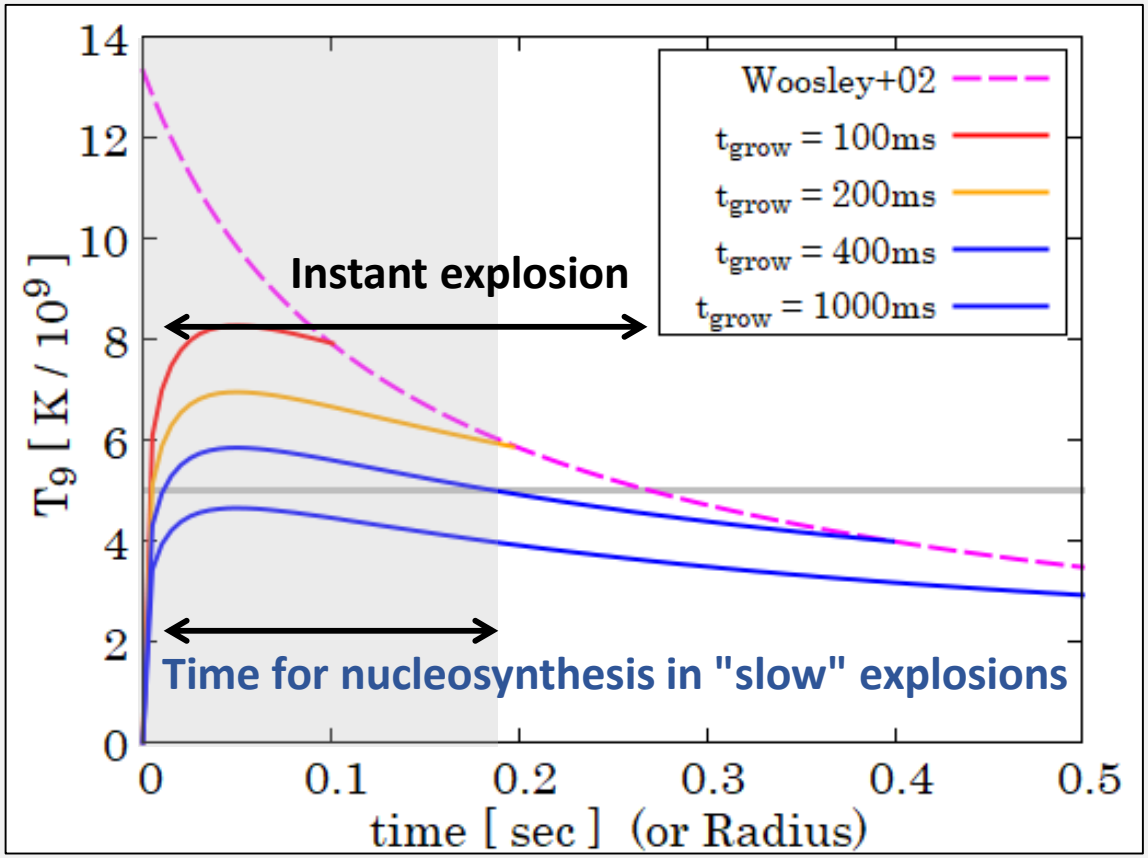
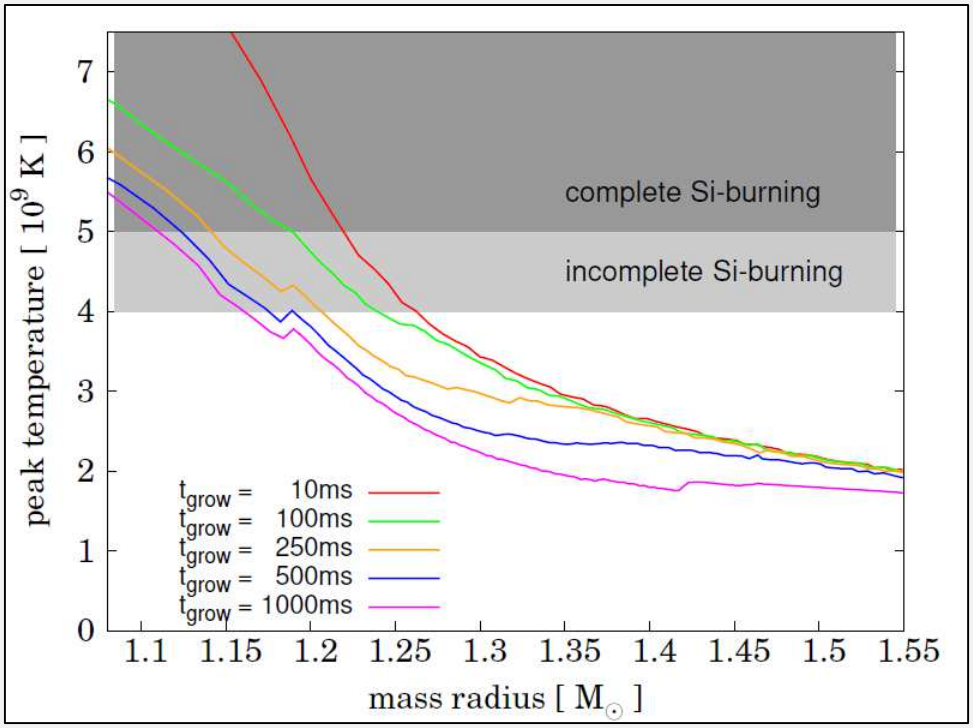


Result ：affect to nucleosynthesis

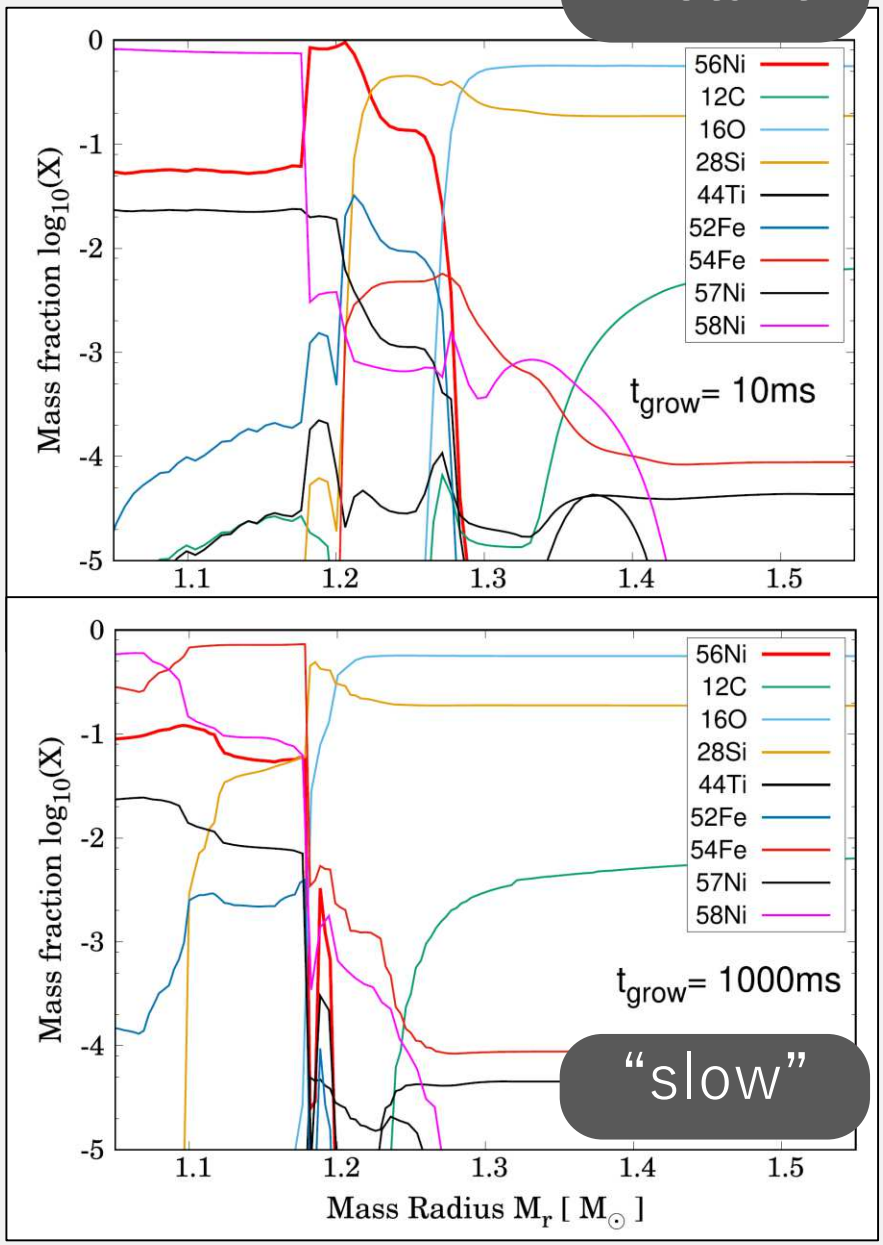
$t_{\mathrm{grow}} = 10[\mathrm{ms}]$

- **Peak temperature**



$t_{\mathrm{grow}} = 1000[\mathrm{ms}]$

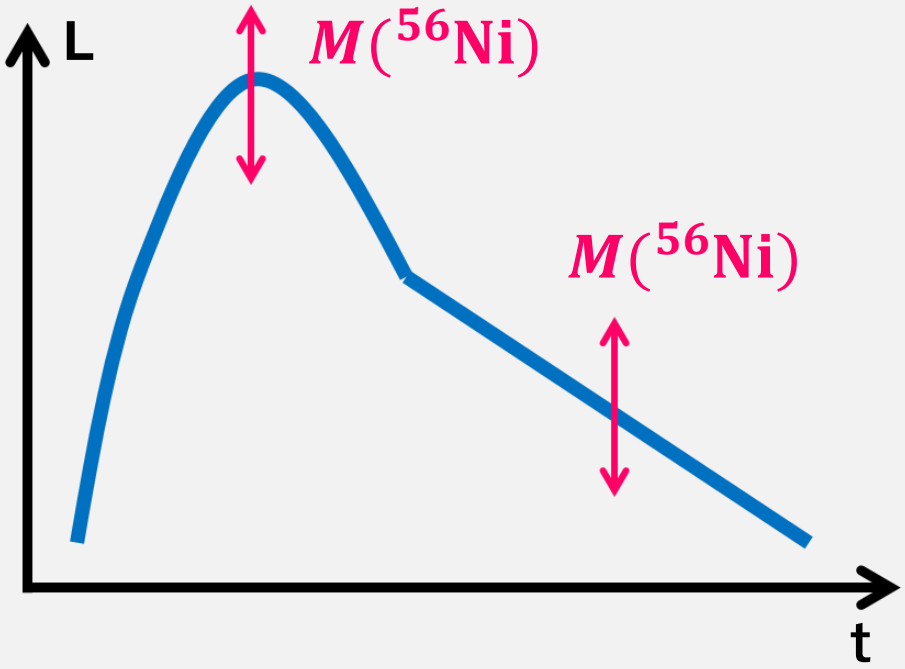
instant



"slow"

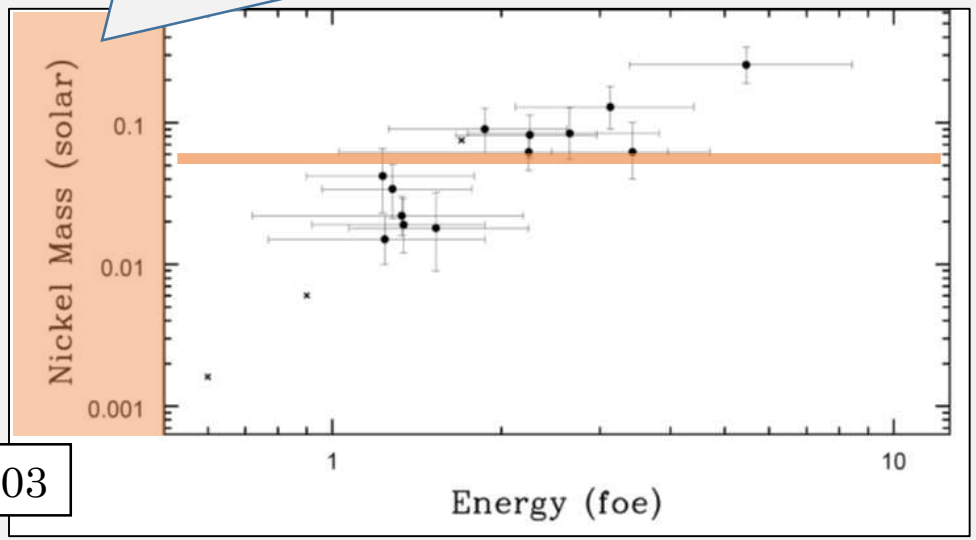
56Ni, compare to typical-CCSNe

1. **^{56}Ni：relate to the light curve of SNe**
2. ^{44}Ti , ^{57}Ni：relate to the late phase light curve of SNe
3. [element/Fe]：abundance of the EMP stars



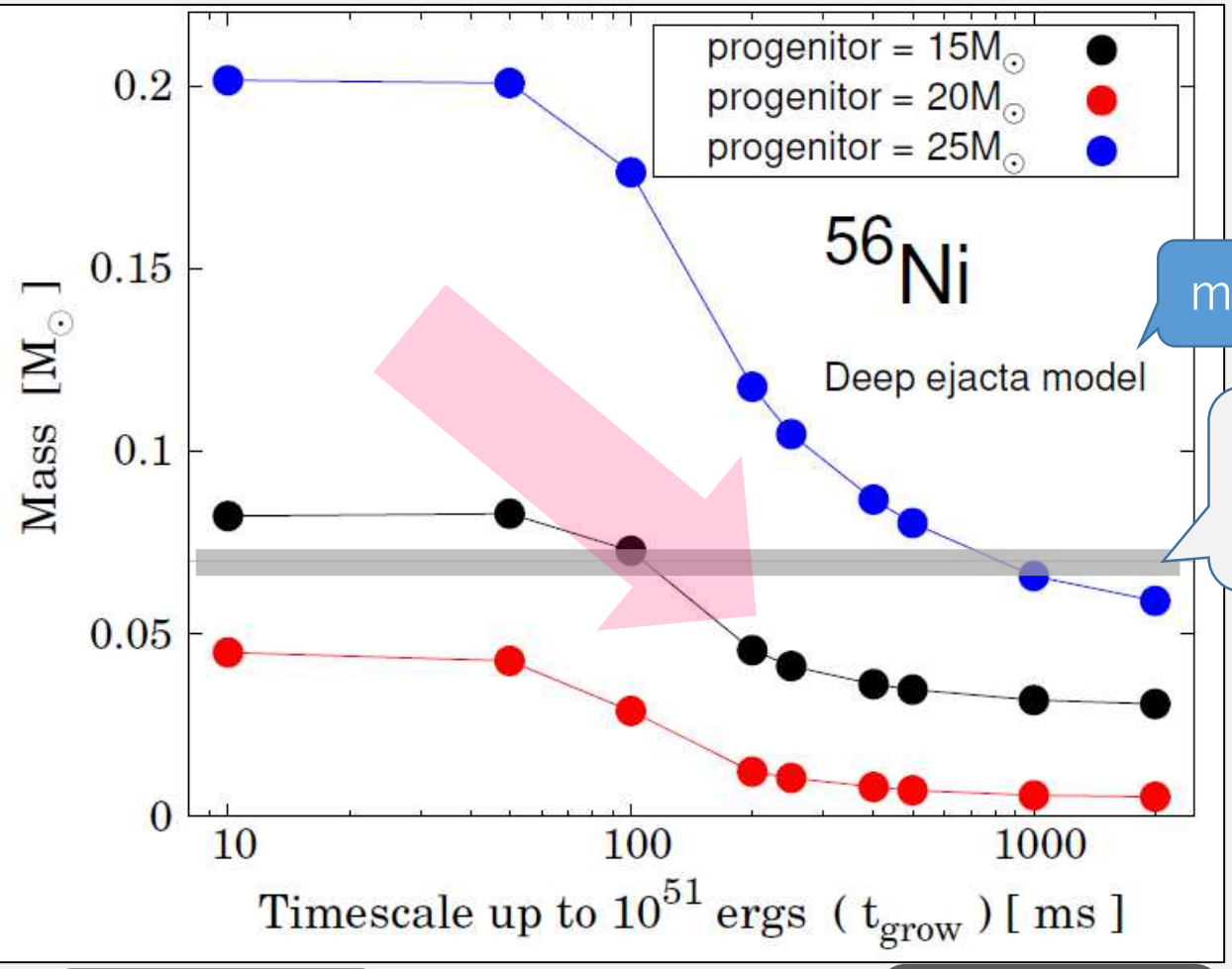
^{56}Ni→ ^{56}Co → ^{56}Fe

$0.07M_{\odot}$; typical CCSNe
(eg., 1987A, 1993J, 2002ap…)



Hamuy 2003

56Ni, compare to typical-CCSNe （1）



maximum limit!!

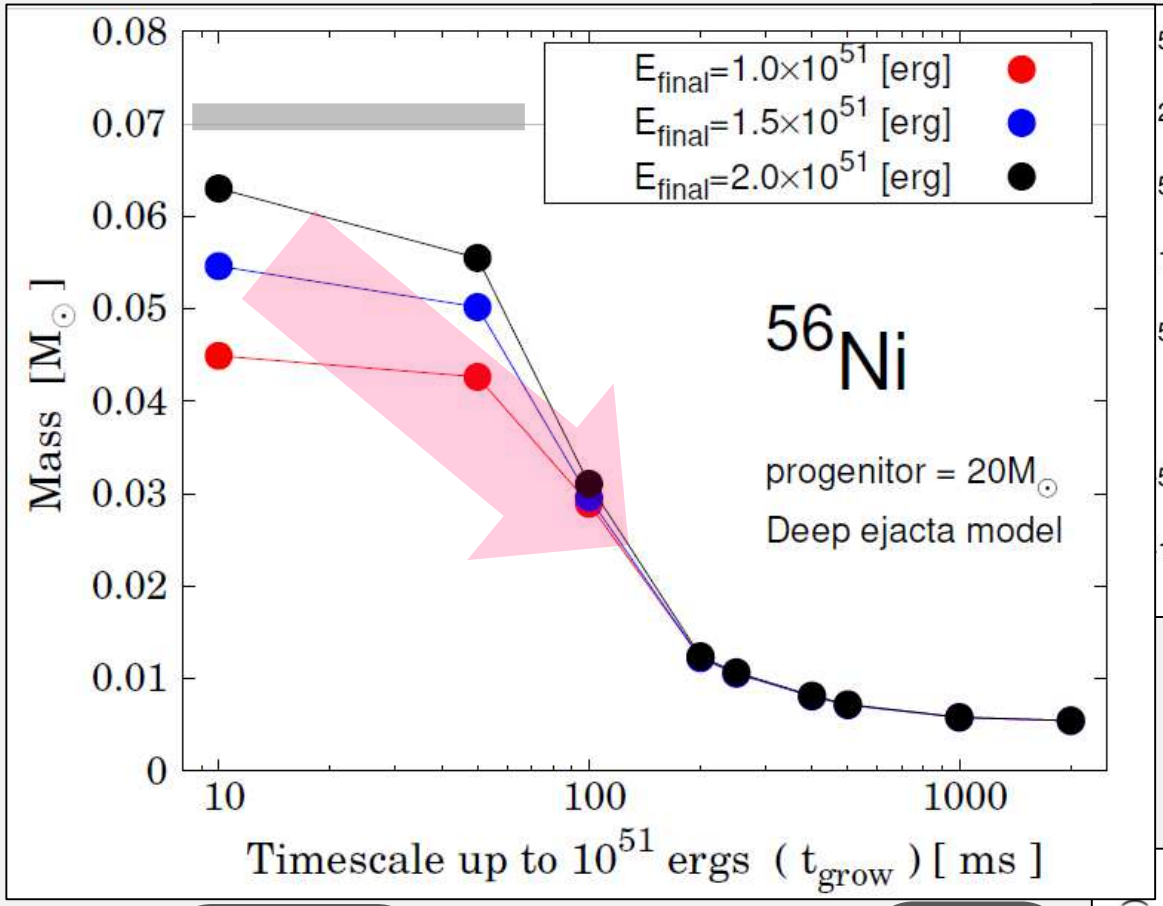
$\mathbf{0.07}\boldsymbol{M}_{\odot}$; typical CCSNe
(eg., 1987A, 1993J, 2002ap…)

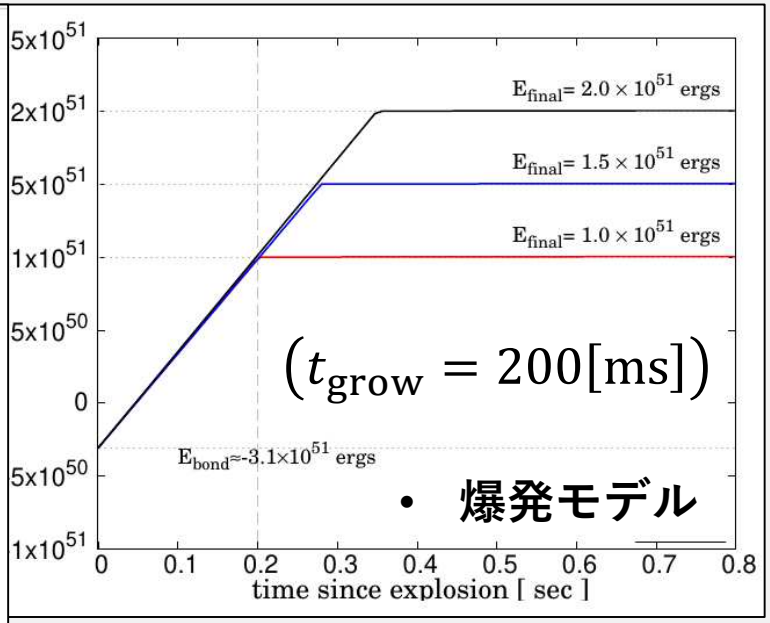
$t_{\mathrm{grow}} \gtrsim 1000[\mathrm{ms}]$
is inconsistent with
typical-CCSNe

Instant explosion → Slow explosion

→ $M(^{56}\mathrm{Ni})$ decrease for “**slow**” exp.model

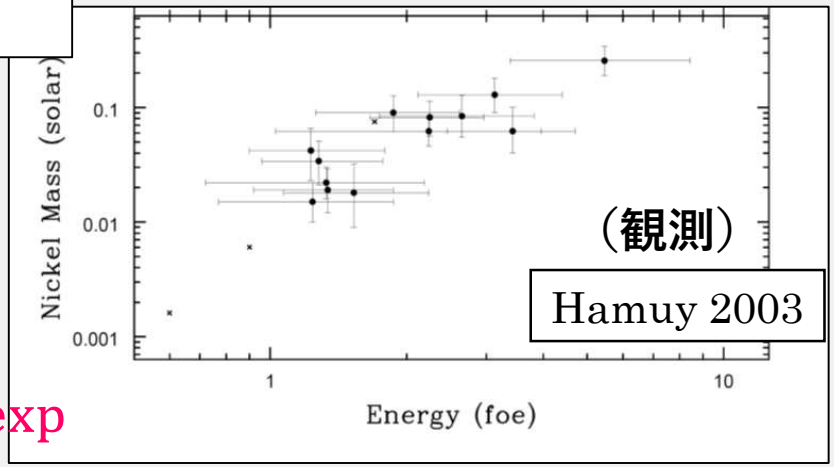
56Ni, compare to typical-CCSNe （2）





瞬間爆発 → “遅い”

エネルギーと生成量に相関性



“**slow**” exp.model lose the relation between $M(^{56}\mathrm{Ni})$ and E_{exp}

44Ti, 57Ni compare to SN1987A

1. ^{56}Ni：relate to the light curve of SNe
2. **^{44}Ti , ^{57}Ni：relate to the late phase light curve of SNe**
3. [element/Fe]：abundance of the EMP stars

late phase LC of SN1987A

Seitenzahl+ 2014

$$^{56}\mathrm{Ni} \xrightarrow{t_{1/2}=6.08d} {}^{56}\mathrm{Co} \xrightarrow{t_{1/2}=77.2d} {}^{56}\mathrm{Fe} \quad (1)$$

$$^{57}\mathrm{Ni} \xrightarrow{t_{1/2}=35.60h} {}^{57}\mathrm{Co} \xrightarrow{t_{1/2}=271.79d} {}^{57}\mathrm{Fe} \quad (2)$$

$$^{55}\mathrm{Co} \xrightarrow{t_{1/2}=17.53h} {}^{55}\mathrm{Fe} \xrightarrow{t_{1/2}=999.67d} {}^{55}\mathrm{Mn} \quad (3)$$

$$^{44}\mathrm{Ti} \xrightarrow{t_{1/2}=58.9y} {}^{44}\mathrm{Sc} \xrightarrow{t_{1/2}=3.97h} {}^{44}\mathrm{Ca} \quad (4)$$

$$^{60}\mathrm{Co} \xrightarrow{t_{1/2}=5.27y} {}^{60}\mathrm{Ni}. \quad (5)$$

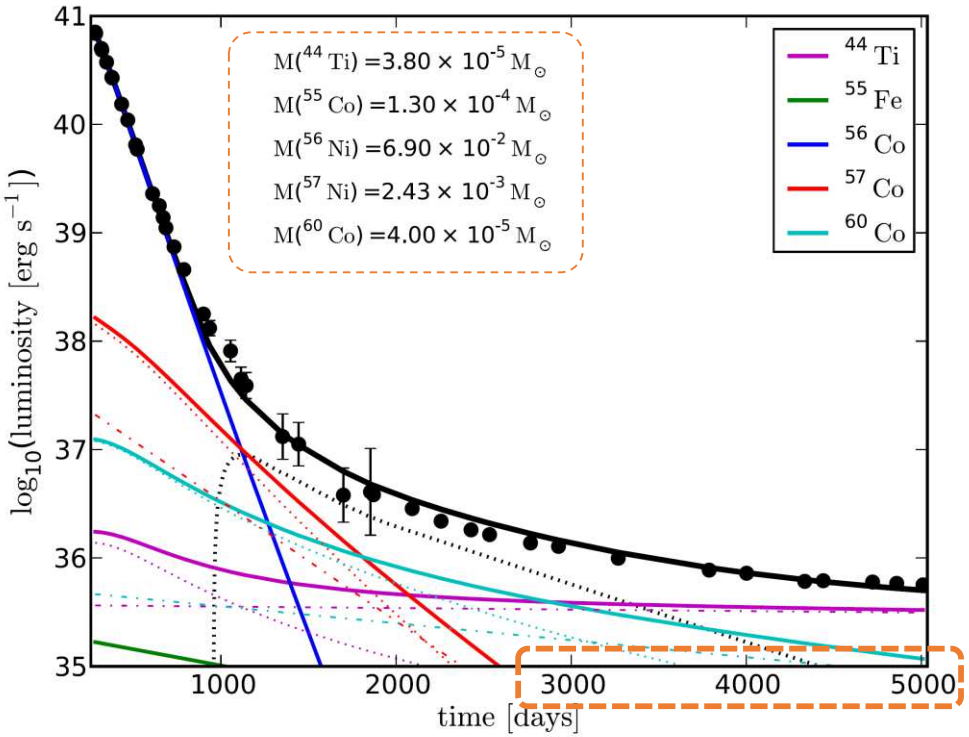
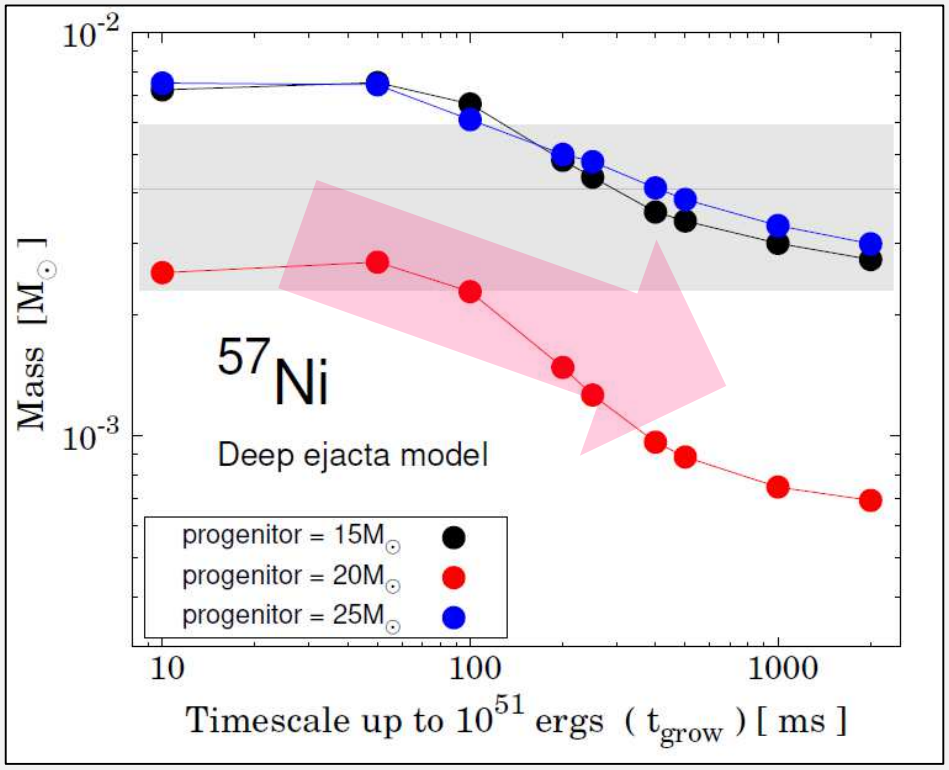


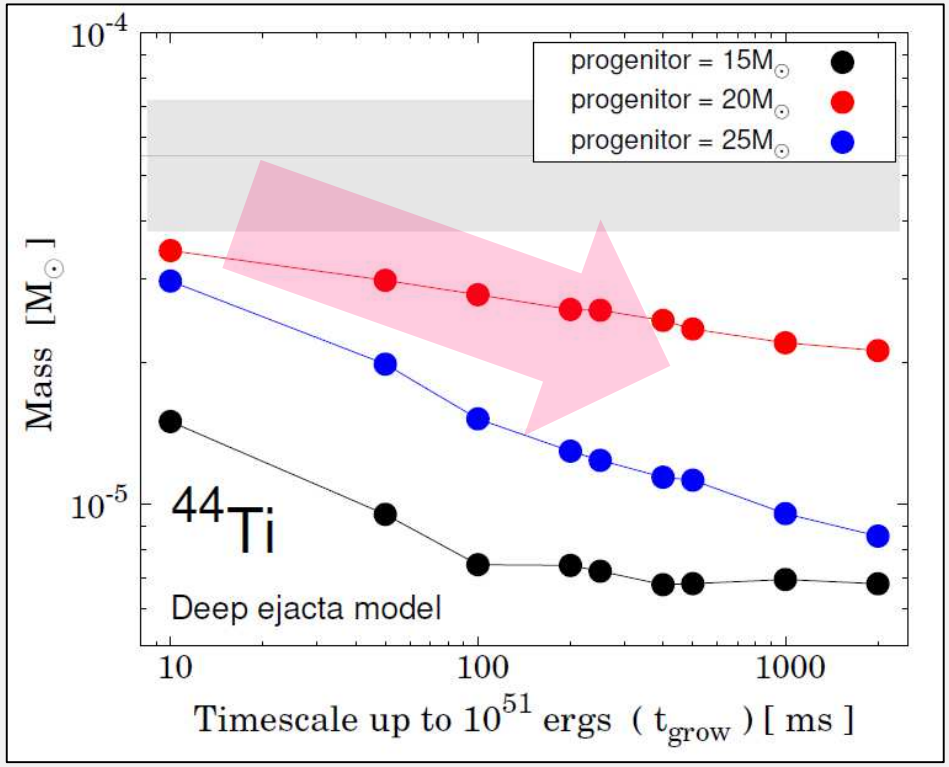
Figure 6. Model light curve (thick black line) including our time-dependent freeze-out correction (dashed black line) for a choice of initial masses that results in a good fit to the data. For ^{44}Ti, ^{57}Co, and ^{60}Co, gamma-ray (thin dotted lines) and leptonic (thin dash-dotted lines) partial light curves are shown separately as in Figures 3 and 4.

44Ti, 57Ni compare to SN1987A

※ note : This model is not a fine-turned model to SN1987A



Instant → Slow



Instant → Slow

Note: Multi-D effect may enhance M(44Ti)
(Nagataki et al. 1998; Maeda & Nomoto 2003).

→ not only $M(^{56}\mathrm{Ni})$,

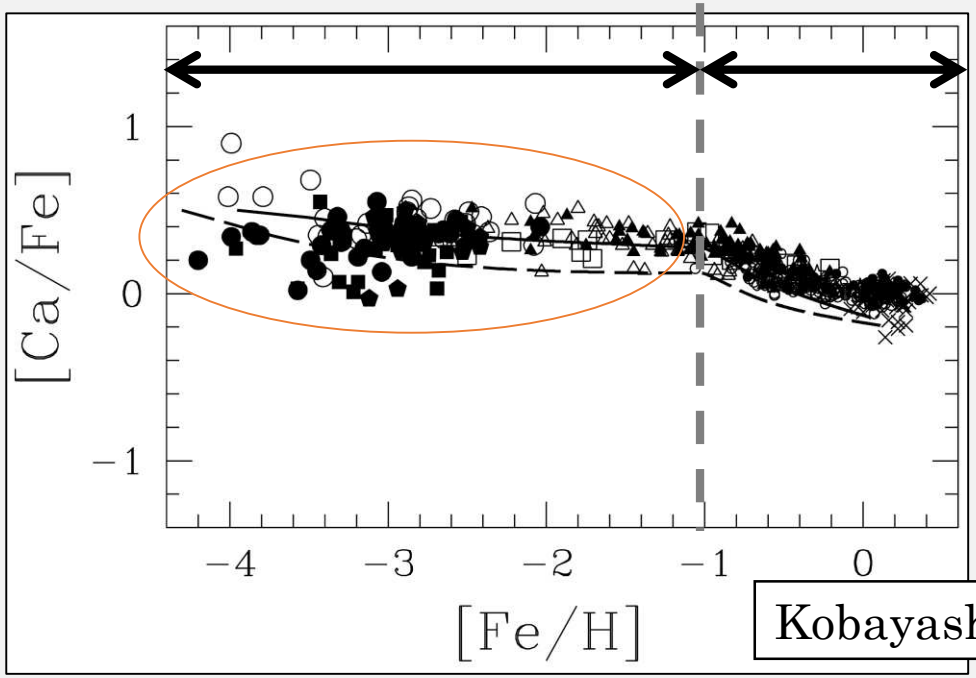
$M(^{44}\mathrm{Ti})$ & $M(^{57}\mathrm{Ni})$ also decrease for "**slow**" exp.model

[element/Fe] compare to EMP-stars

1. ^{56}Ni : relate to the light curve of SNe
2. ^{44}Ti , ^{57}Ni : relate to the late phase light curve of SNe
3. **[element/Fe] : abundance of the EMP stars**

✓ From Galaxy-chemical evolution…

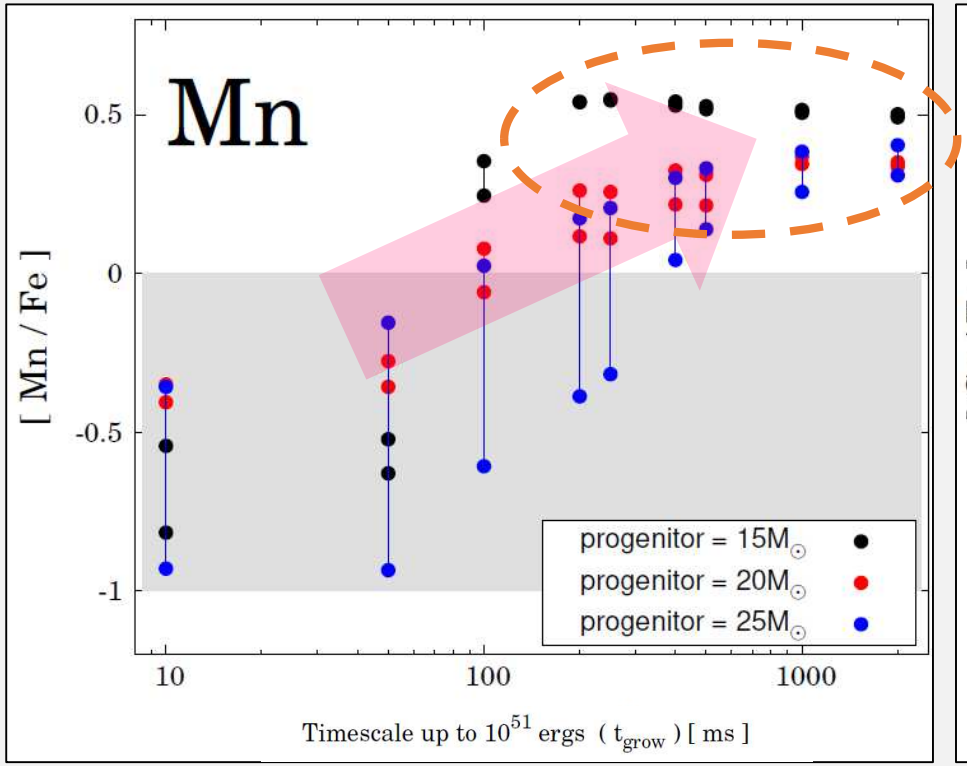
only CCSNe contribution | CCSNe + SN1a contribution

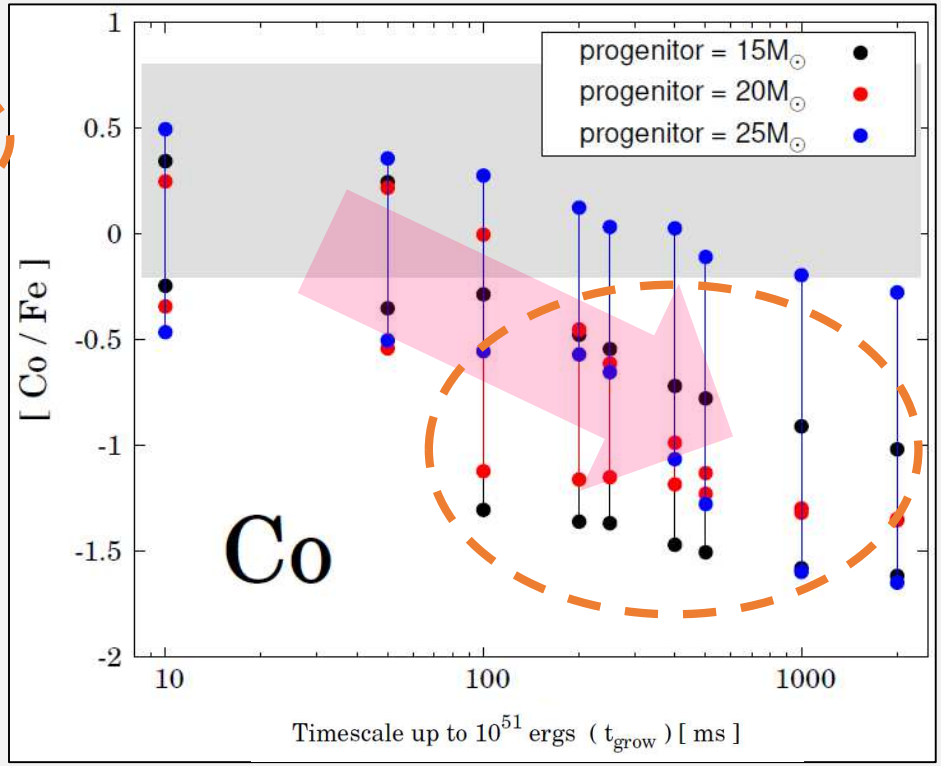


Kobayashi + 2006

✓ typical-CCSNe **should** reproduce **abundance patterns** of EMP-stars.

[element/Fe] compare to EMP-stars





※ note : This model is using a solar metallicity progenitor, but

- ✓ $\mathrm{Mn/Fe} \approx {}^{55}\mathrm{Co}/{}^{56}\mathrm{Ni}$
- ✓ $\mathrm{Co/Fe} \approx {}^{59}\mathrm{Cu}/{}^{56}\mathrm{Ni}$

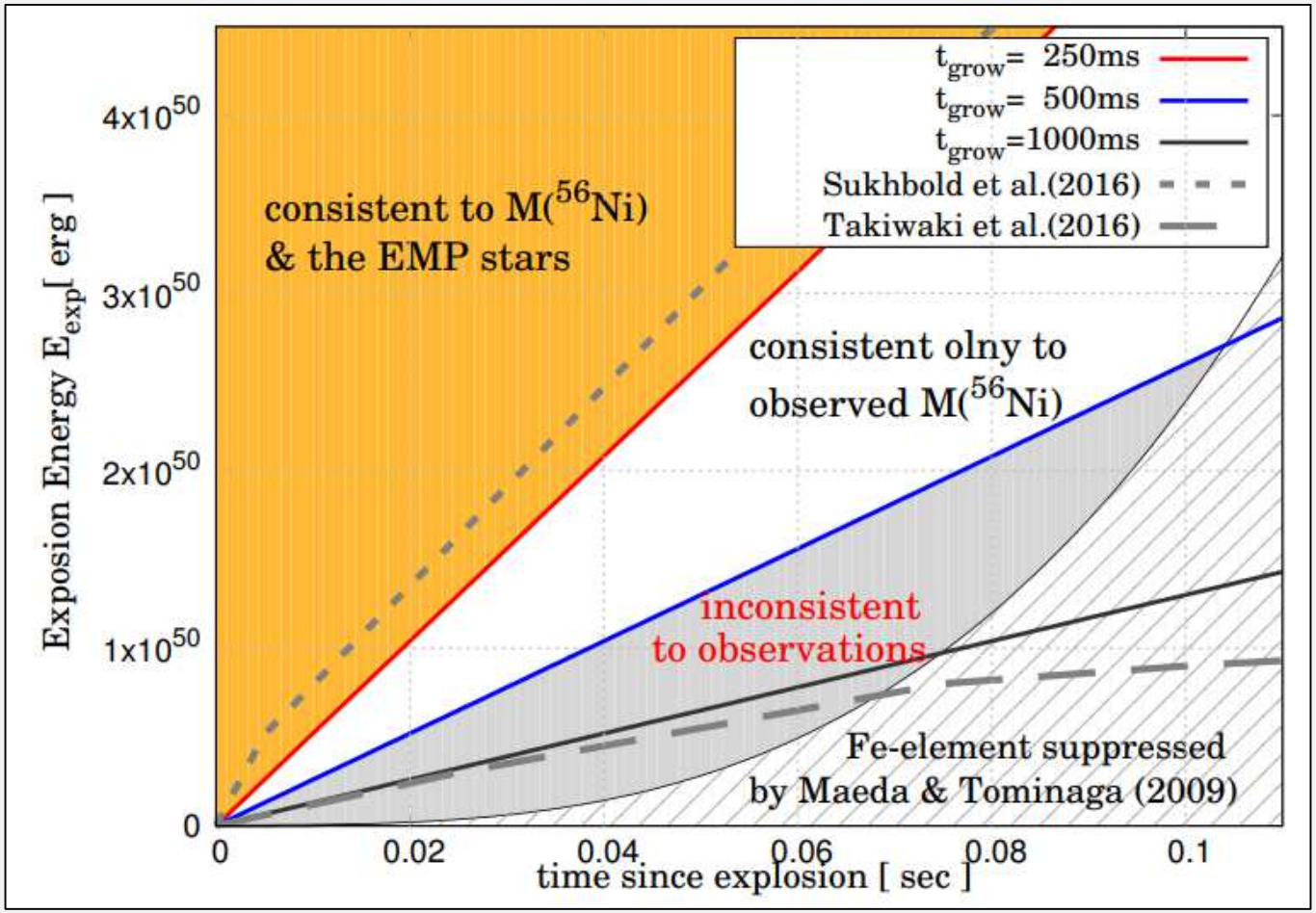
, both of $^{55}\mathrm{Co}$ and $^{59}\mathrm{Cu}$ are neutron excess,

→ [Mn/Fe] and [Co/Fe] tend to be smaller for large Ye.

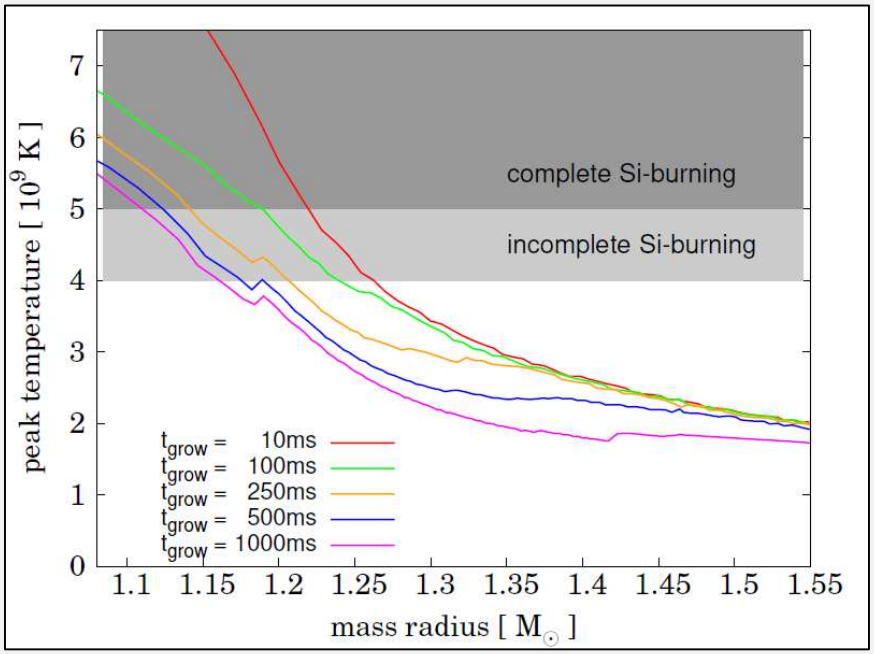
→ a better match to both ratios by changing Ye would never be obtained.

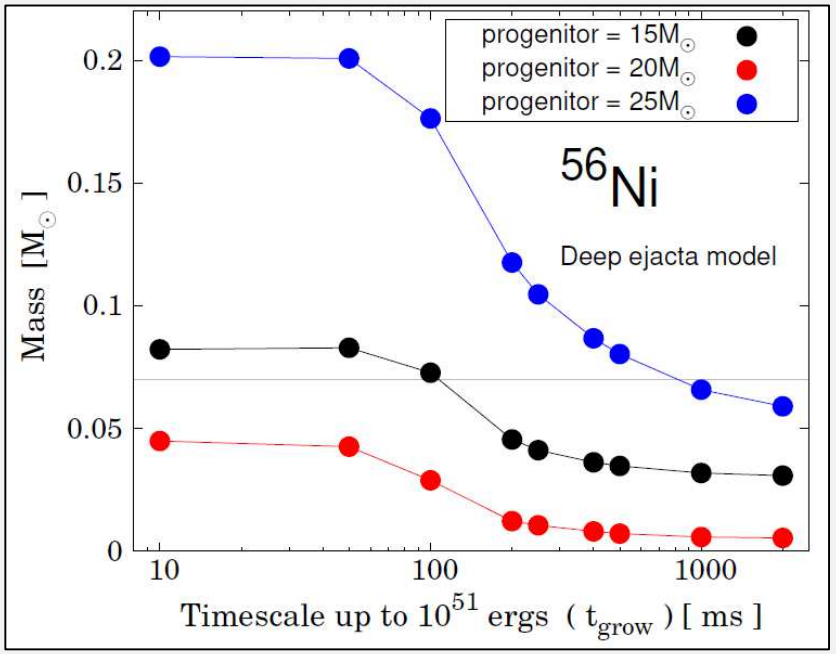
- **motivation:** How the explosive nucleosynthesis products are affected by t_{grow} ?

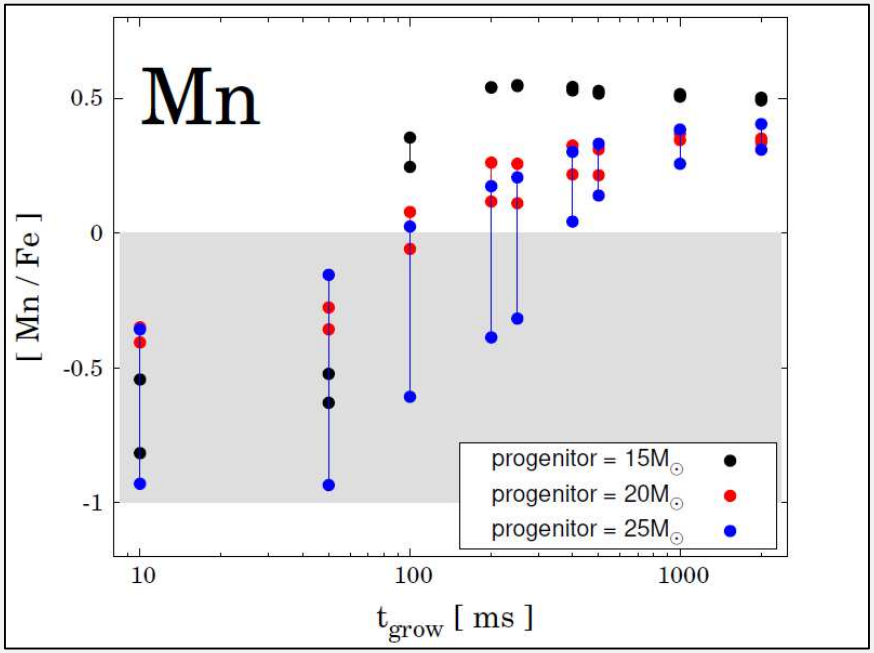
t_{grow} : timescale up to 10^{51}[erg]

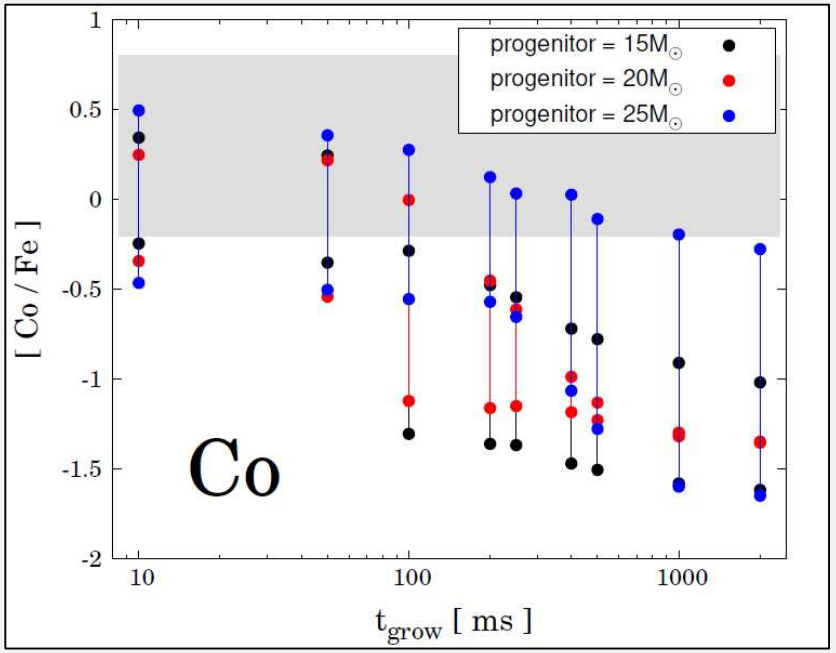


Please check arxiv.1910.06972









treatment of mass cut

◆ **fall back effect**; a part of the ejecta falls into the central object.

maximum limit!!

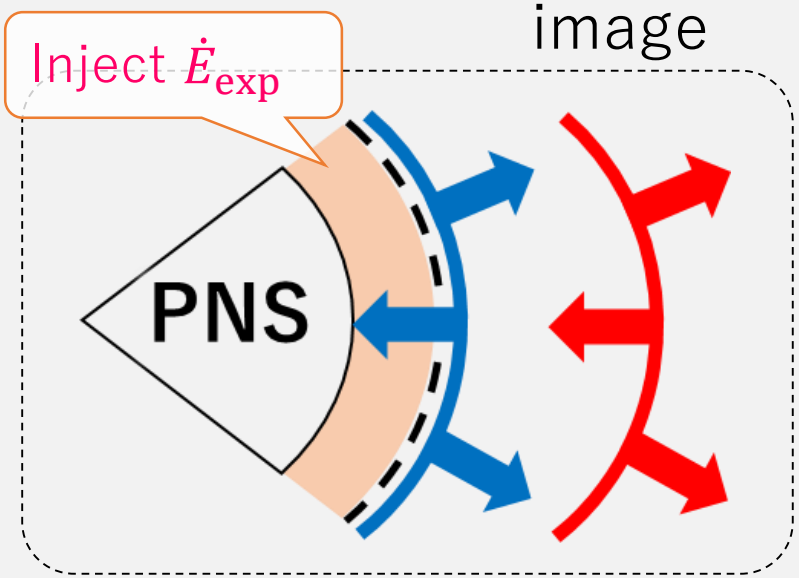
① **Fully ejected above the PNS surface (`deep ejecta model').**

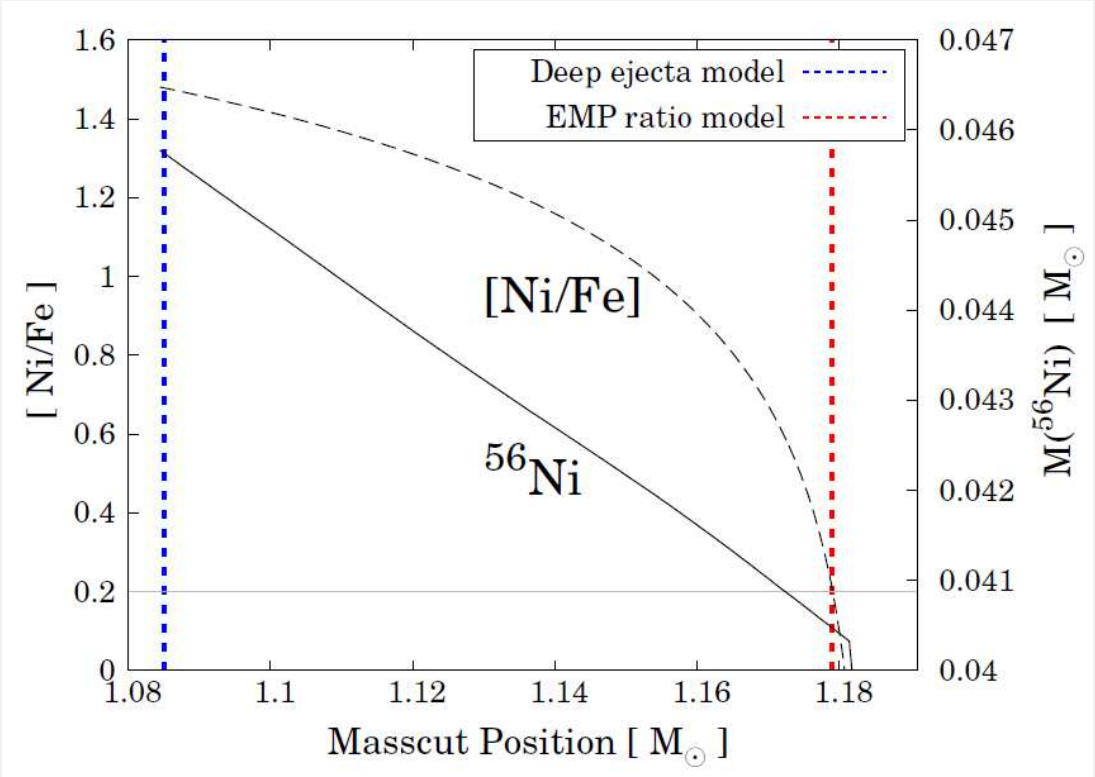
② **To reproduce [Ni/Fe] ratio of EMP stars (`EMP ratio model').**

→ How to decide?

[Ni/Fe] ≈ 0.2 at EMP stars

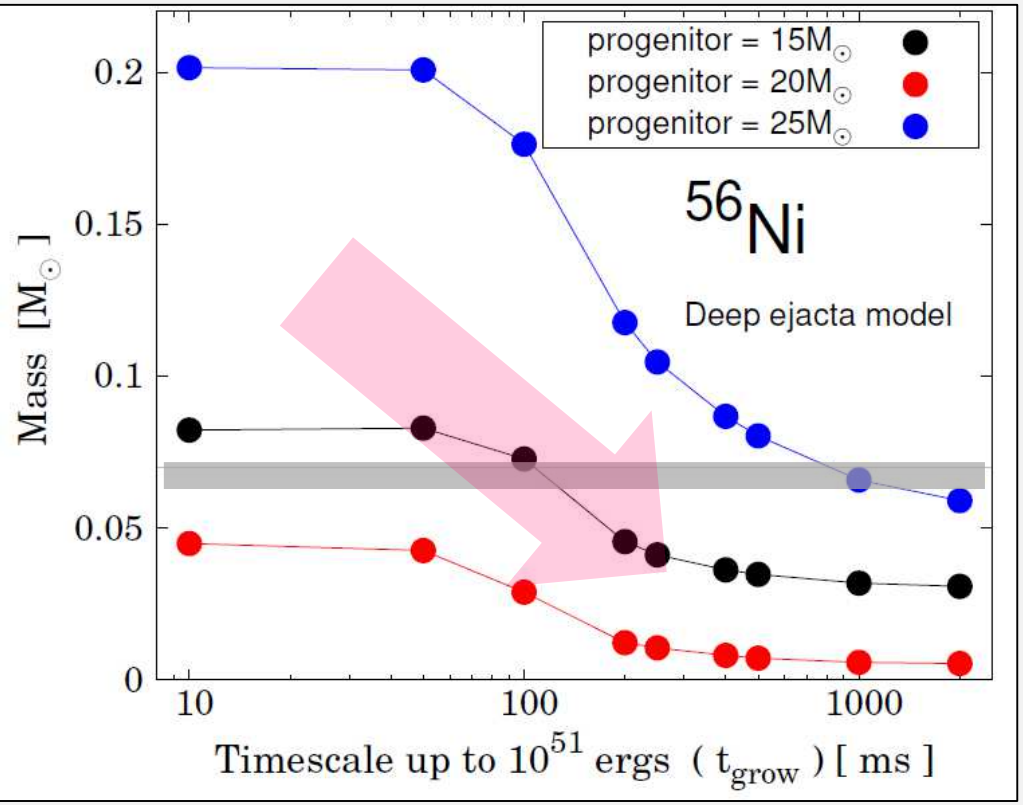
image

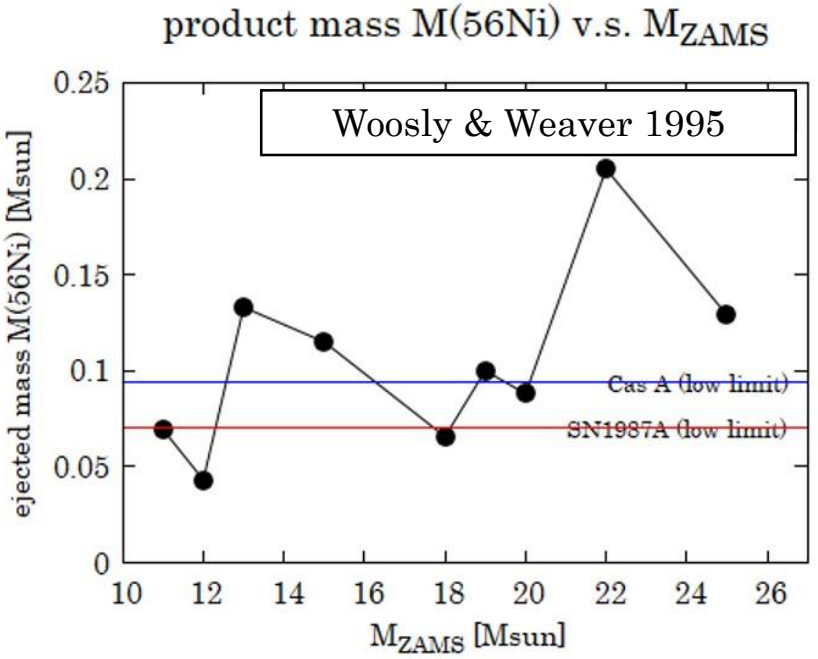




$* \ [\mathrm{Ni/Fe}] = \log_{10}(\mathrm{Ni/Fe}) - \log_{10}(\mathrm{Ni/Fe})_\odot$

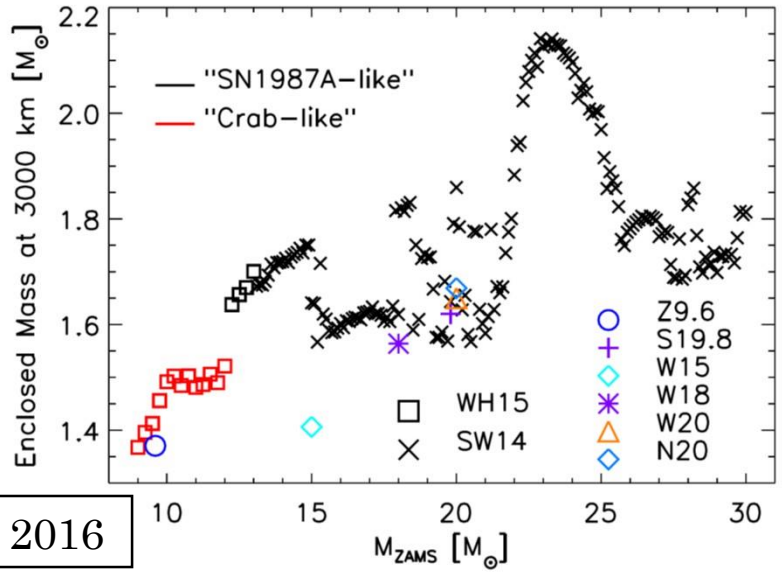
56Ni, compare to typical-CCSNe





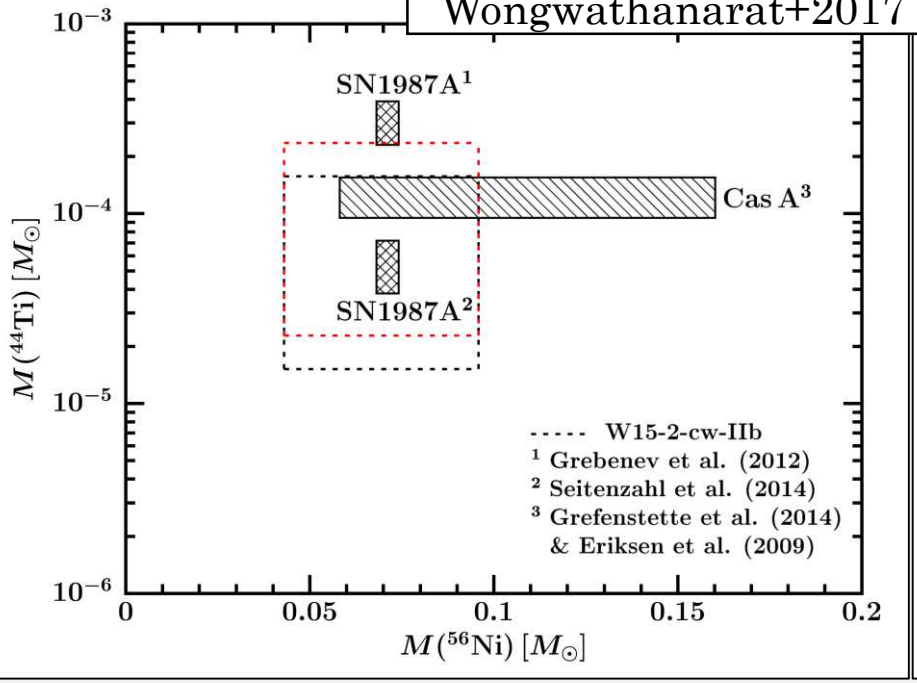
Fire-ball model

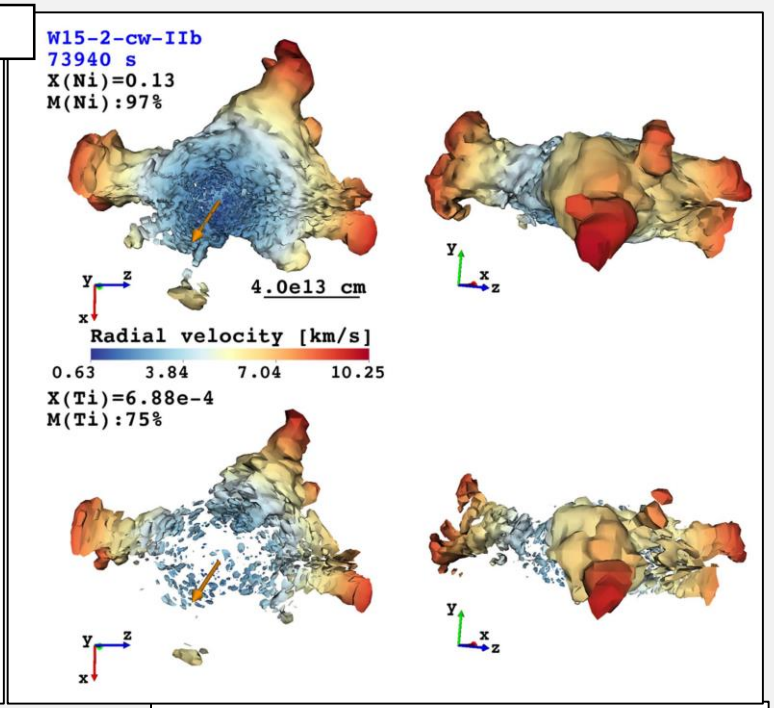
$$r_{\mathrm{shock}} = 3.7 \times 10^{9}\ \mathrm{cm} \left(\frac{T}{5 \times 10^{9}\ \mathrm{K}}\right)^{-4/3} \left(\frac{E_{\mathrm{exp}}}{10^{51}\mathrm{erg}}\right)^{1/3}$$



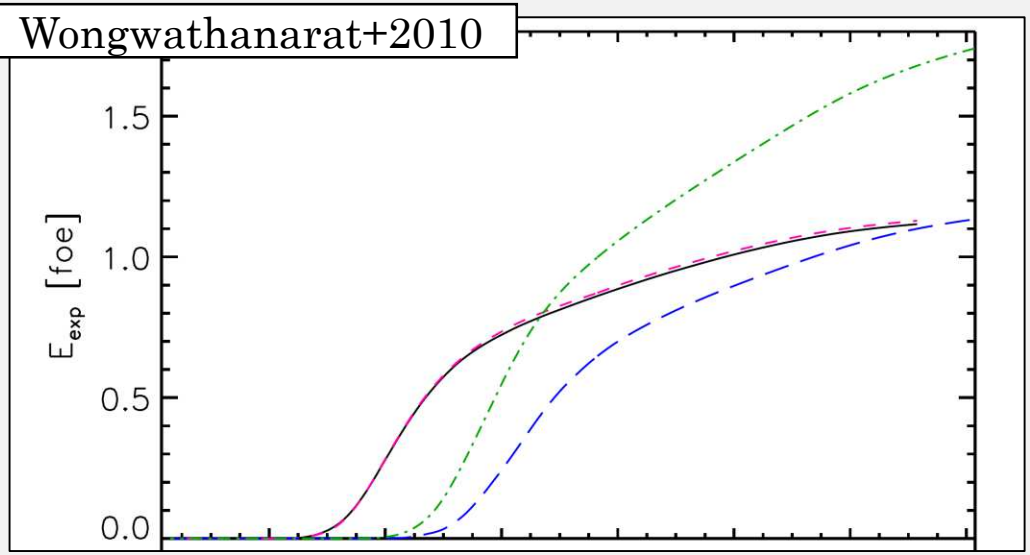
Sukhbold + 2016

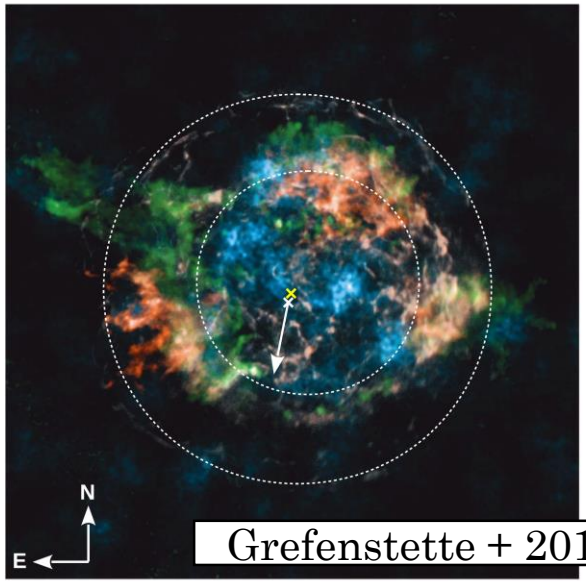
Wongwathanarat+2017



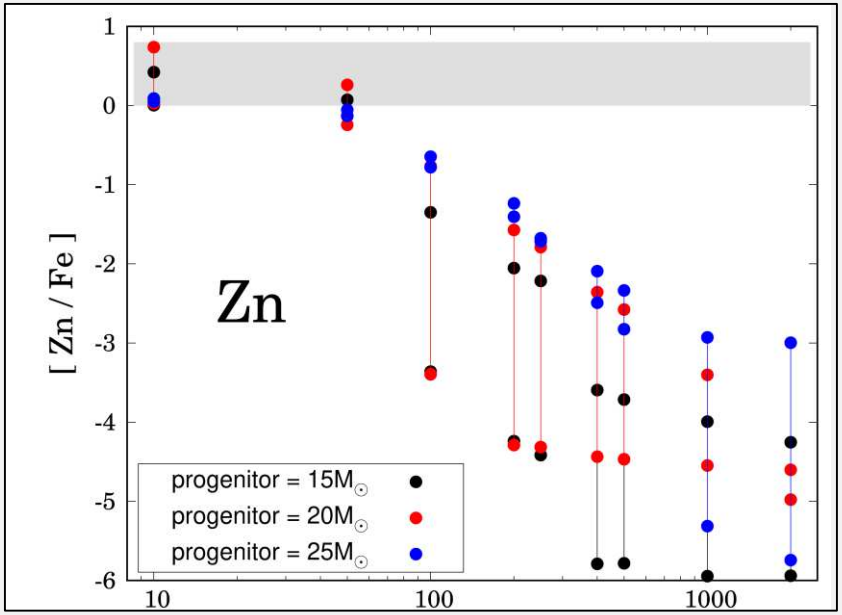


Wongwathanarat+2010



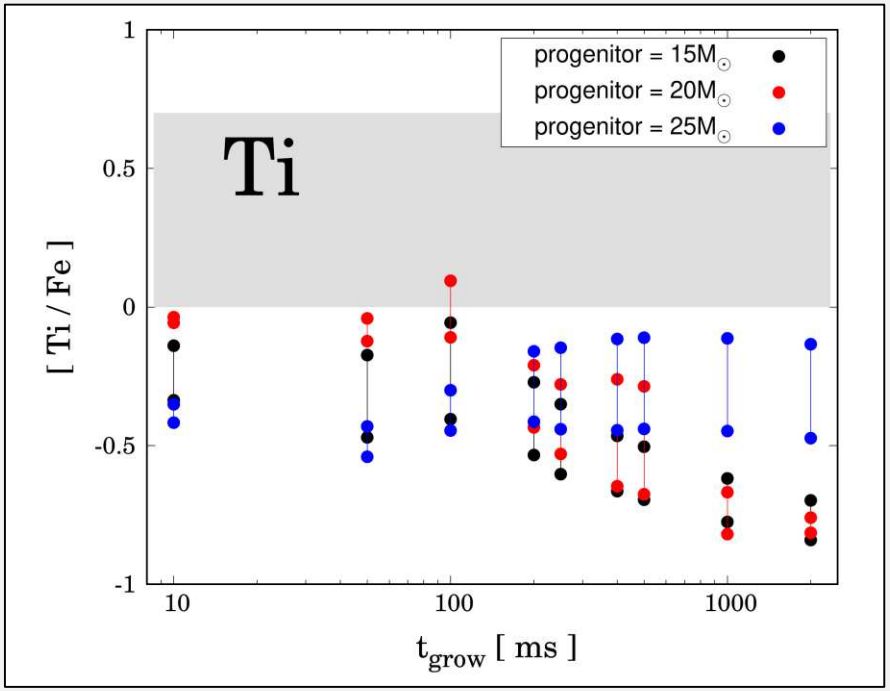


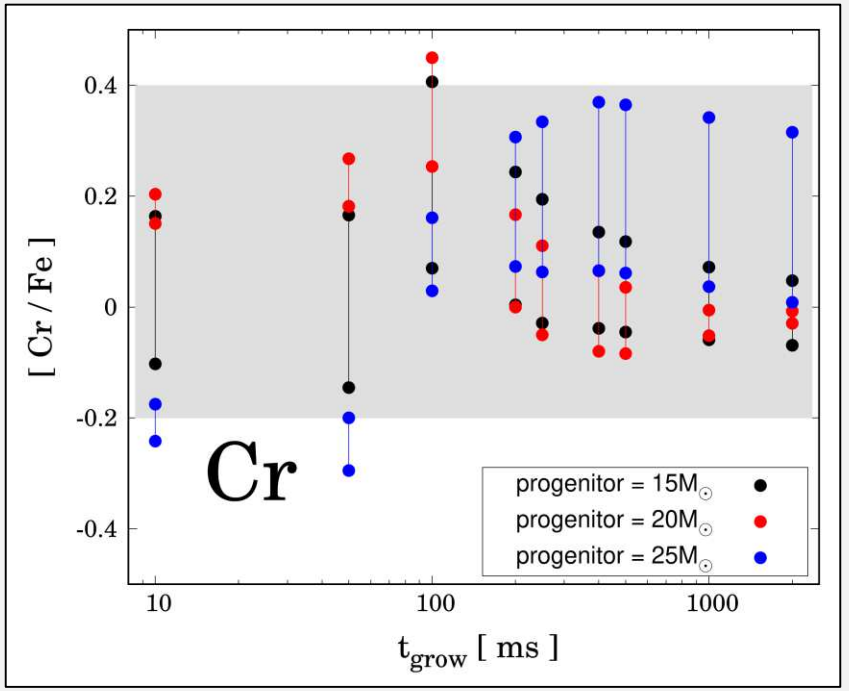
Grefenstette + 2014

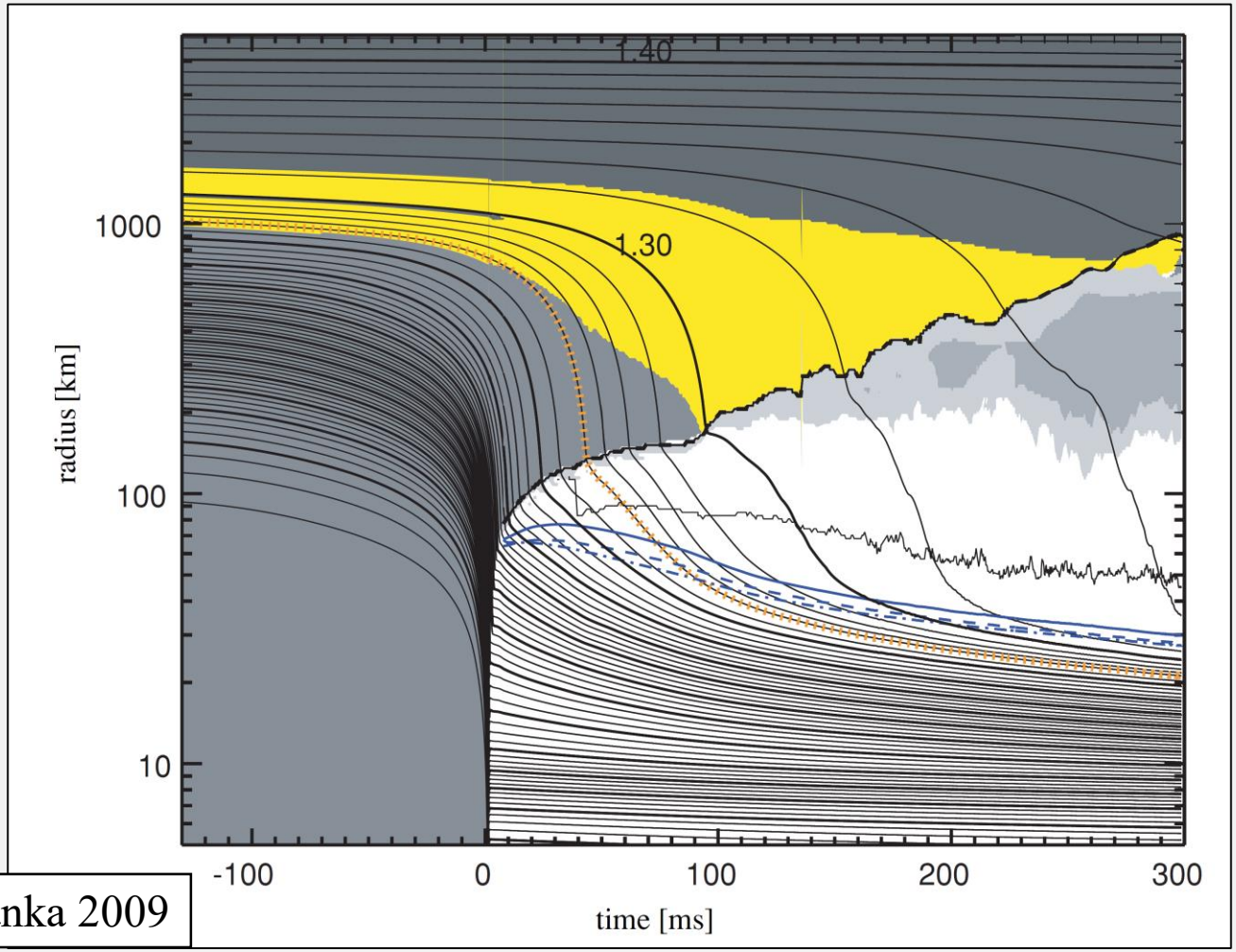


※　note：今回の親星モデル
＝太陽金属量の親星モデル

$$[\mathrm{X/Fe}] \equiv \log\left(\frac{M(\mathrm{X})_{T_{\mathrm{peak}}>1.0\times10^9\ \mathrm{K}}}{M(\mathrm{Fe})_{T_{\mathrm{peak}}>1.0\times10^9\ \mathrm{K}}}\right) - \log\left(\frac{\mathrm{X}}{\mathrm{Fe}}\right)_{\odot},$$







Marek & Janka 2009