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

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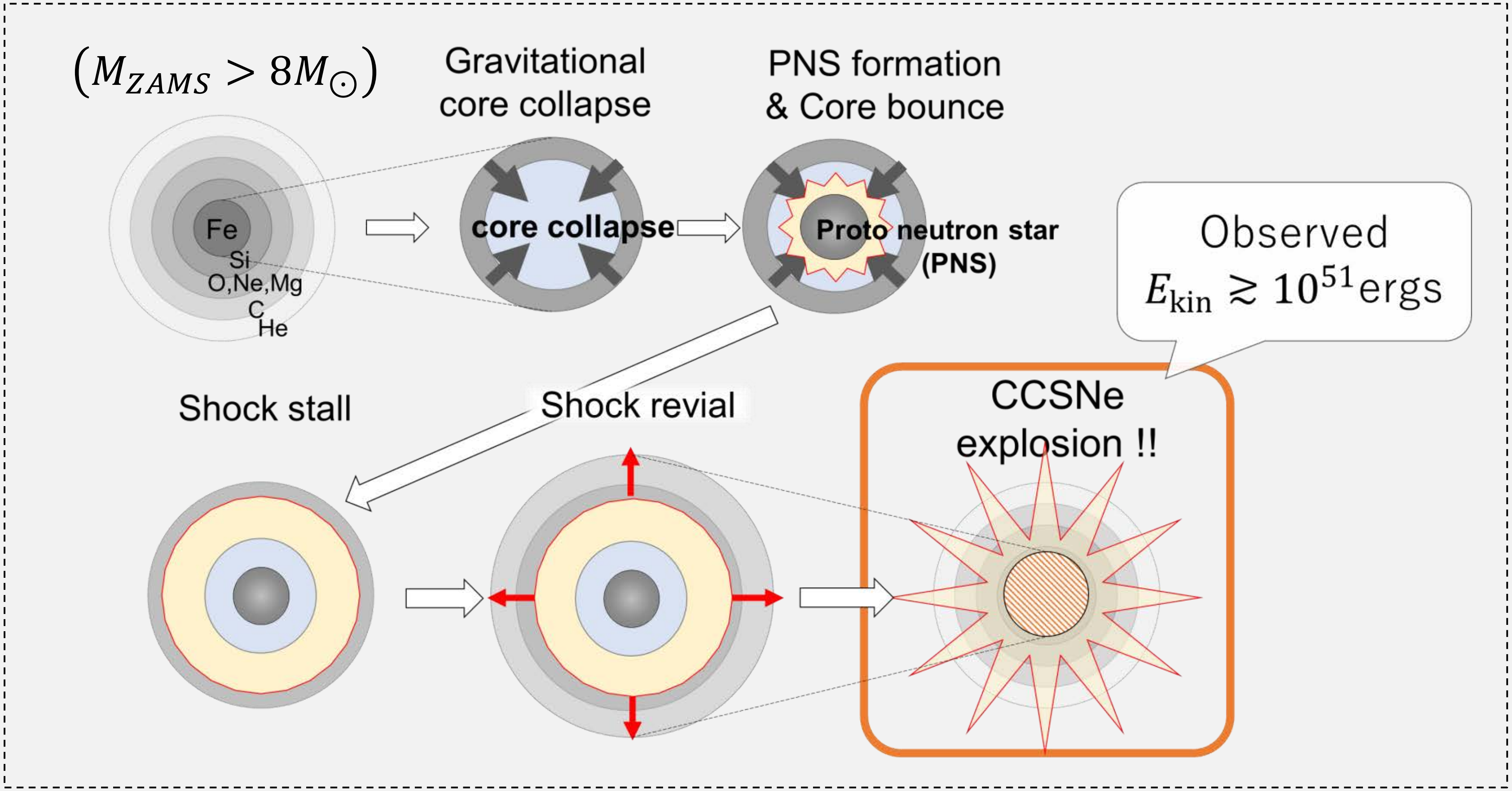
standard scenario : neutrino driven explosion



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

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

Studies on "neutrino driven explosion"

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

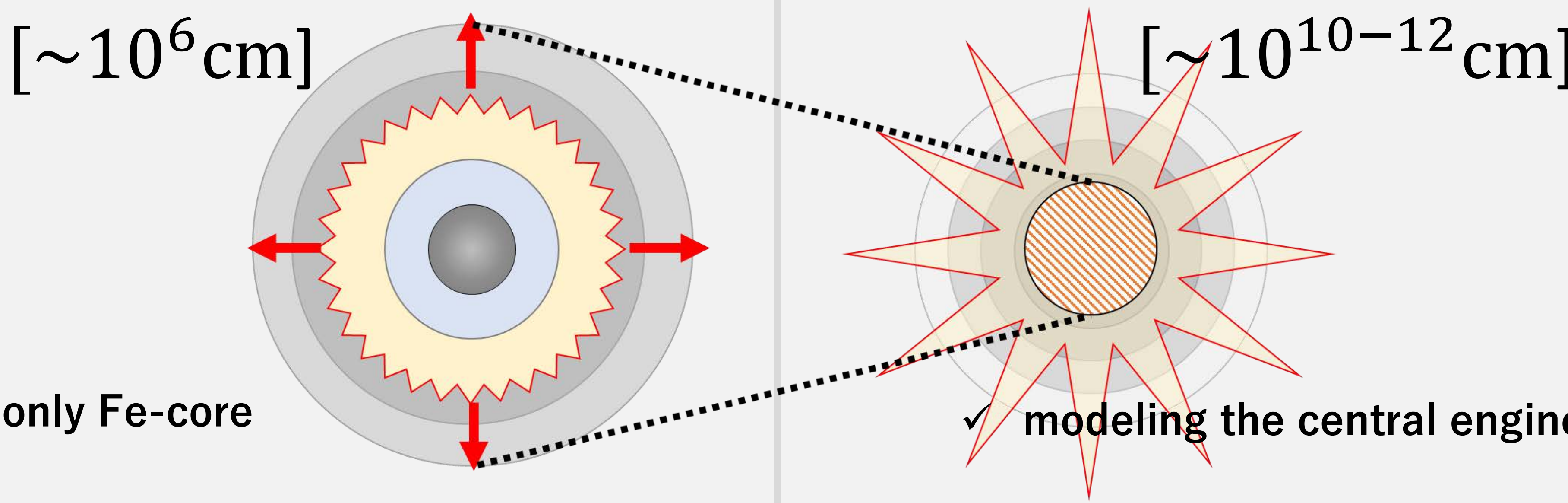
【AB-*initio* calculation】

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

Can reproduce obs. profiles?

【Artificial explosion simulation】

(e.g. Woosley+ 1995)



- ✓ **only Fe-core**
- ✓ **modeling the central engine**

Studies on "neutrino driven explosion"

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

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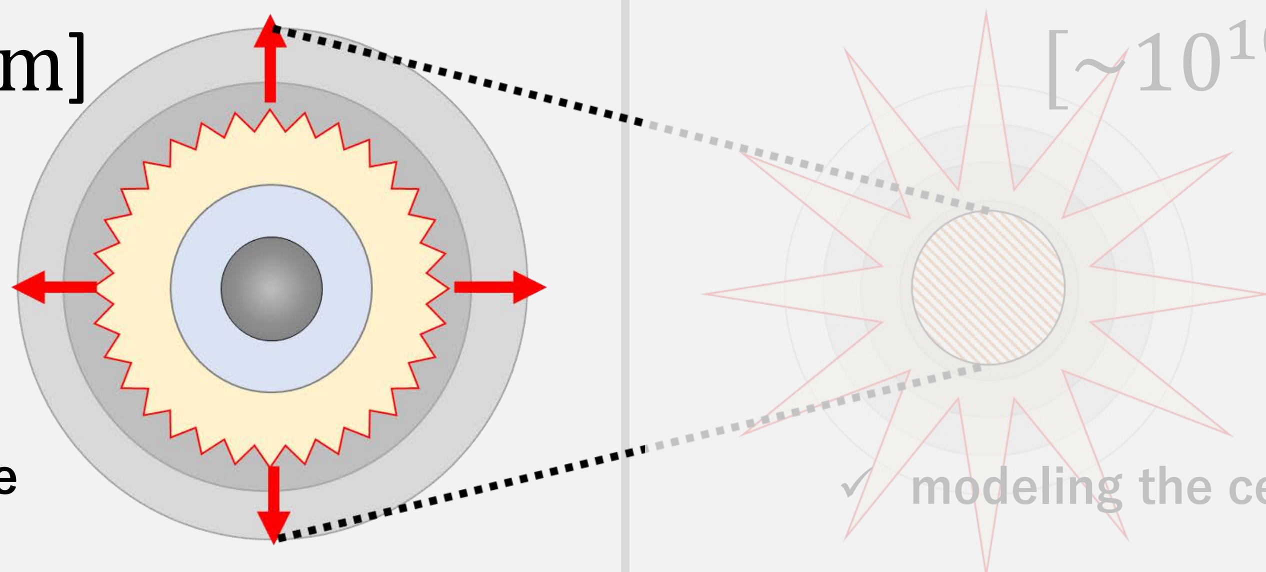
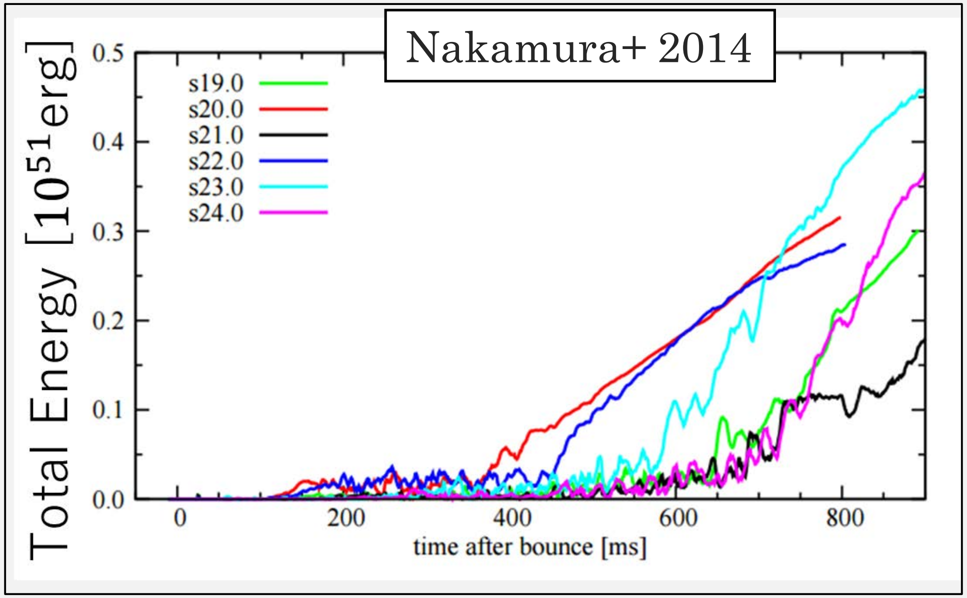
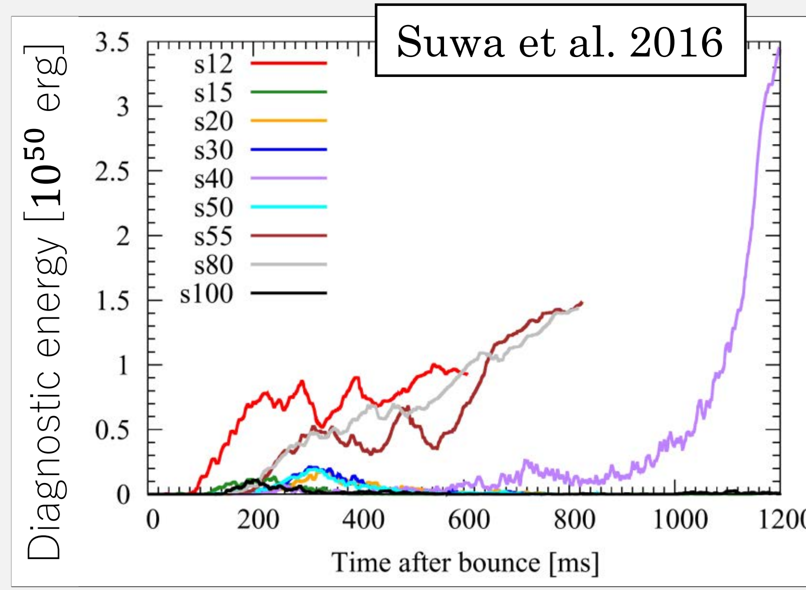
[$\sim 10^{6}$ cm]



✓ **only Fe-core**

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

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

Studies on “neutrino driven explosion"

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

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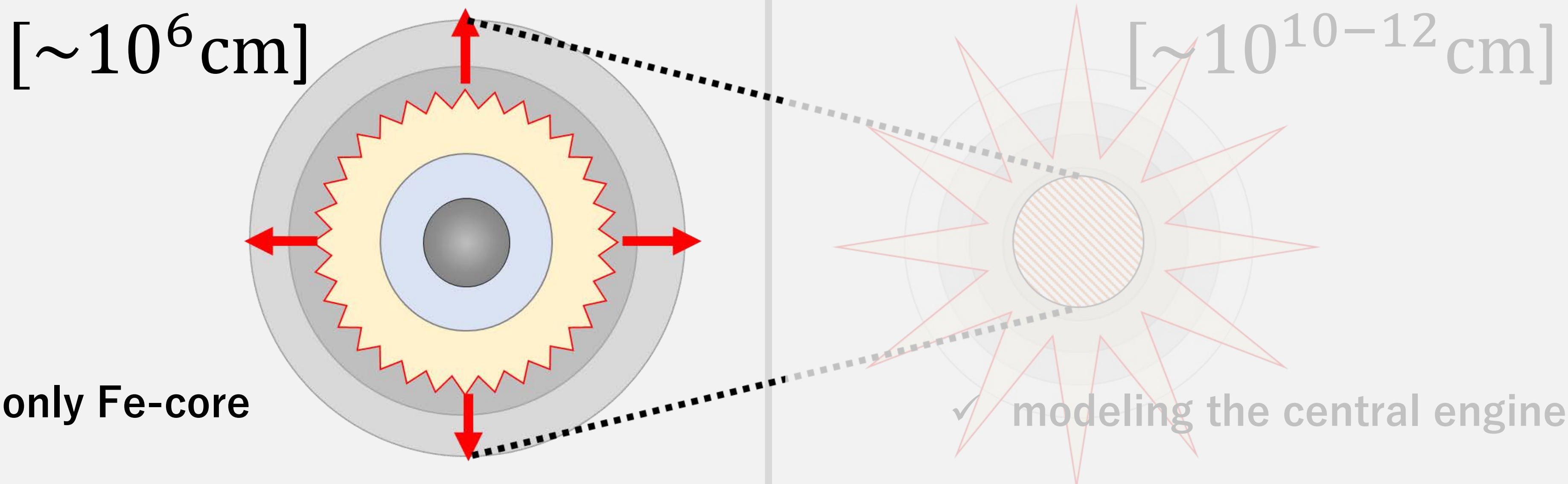


$\boxed{\text{for the growth up to } 10^{51} \text{ ergs,}}$

suggest ‘slow’ explosion

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

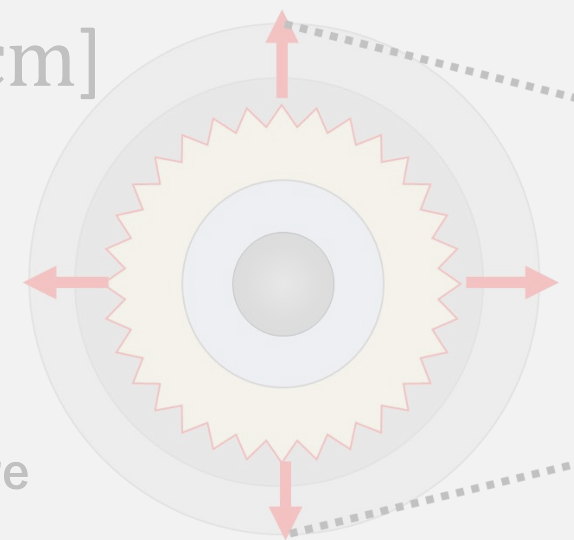
Studies on “neutrino driven explosion"

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

【AB-*initio* calculation】

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

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



✓ **only Fe-core**

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

suggest ‘slow’ explosion

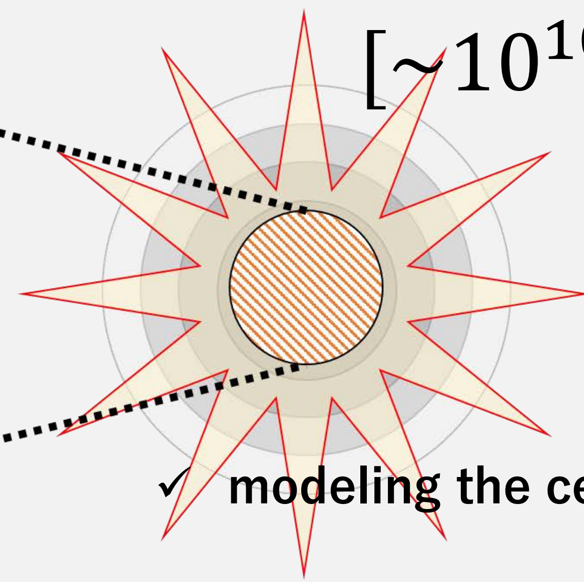
$[t_{\rm grow} \gtrsim 1\mathrm{s}]$

Can reproduce obs. profiles?

【Artificial explosion simulation】

(e.g. Woosley+ 1995)

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

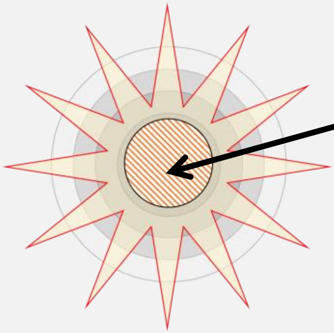


✓ **modeling the central engine**

Classical nucleosynthesis calculation.

✓ Classical nucleosynthesis

e.g. Woosley+ 1995,

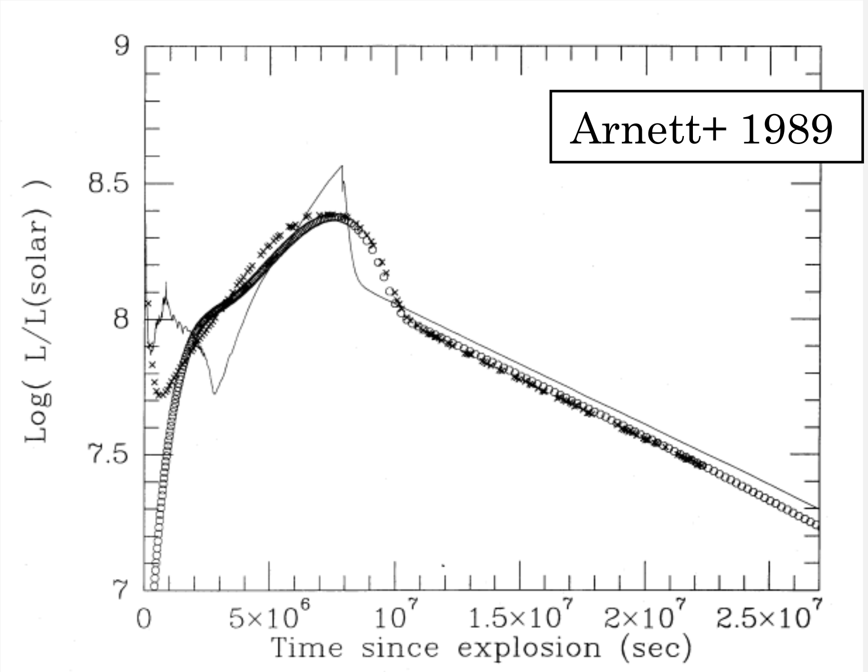


Deposit 10^{51} ergs,
(explosive nuclear burning timescale[~1s]
≫ modeling **instantaneous explosion [~10ms]**)

$\boxed{^{56}\mathrm{Ni}}$ synthesized at central region

$$^{56}\mathrm{Ni} \xrightarrow{\gamma} {}^{56}\mathrm{Co} \xrightarrow{\gamma} {}^{56}\mathrm{Fe}$$

$$L_{\mathrm{peak}} \propto M(^{56}\mathrm{Ni})$$

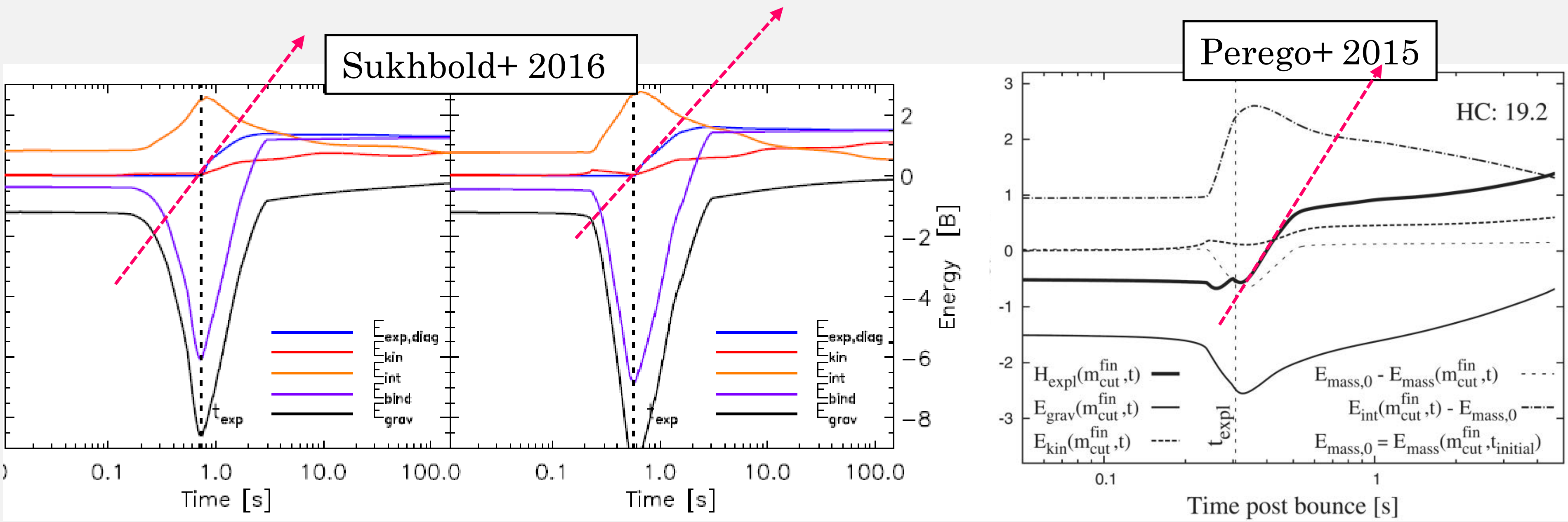


Bolometric light-curve of SN1987A

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.



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

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

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

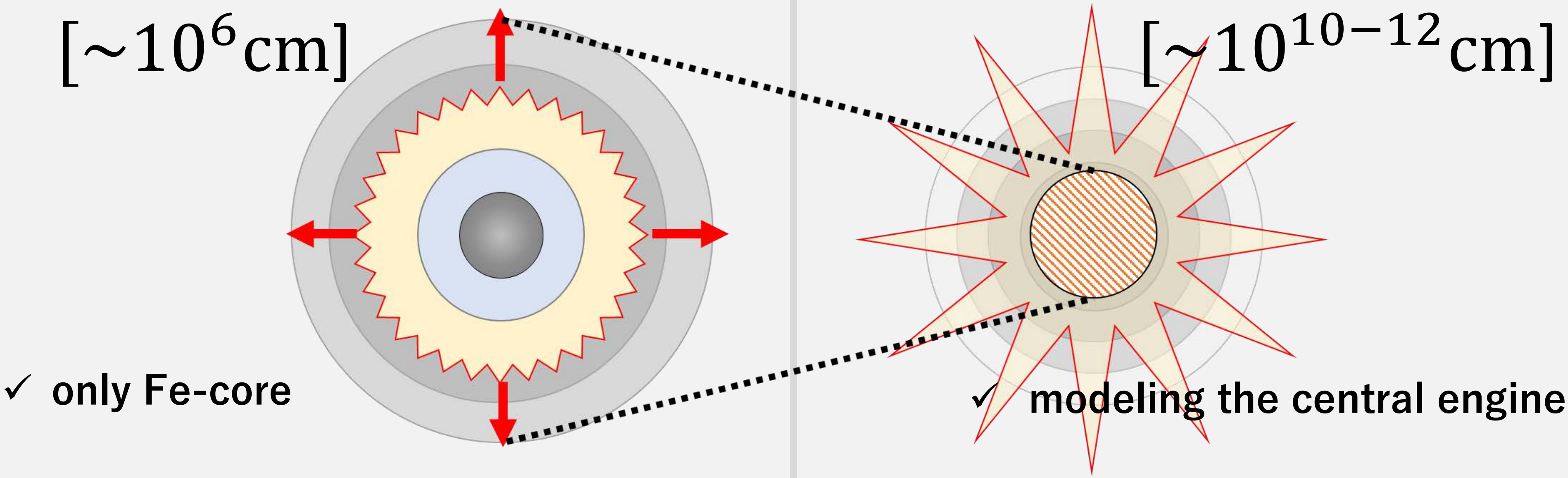
【AB-*initio* calculation】

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

Can reproduce obs.profiles?

【Nucleosynthesis】

(e.g. Woosley+ 1995)



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

suggest ‘slow’ explosion

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

assuming instant explosion

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

This study: Nucleosynthesis from ‘slow’ expl.

motivation

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

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

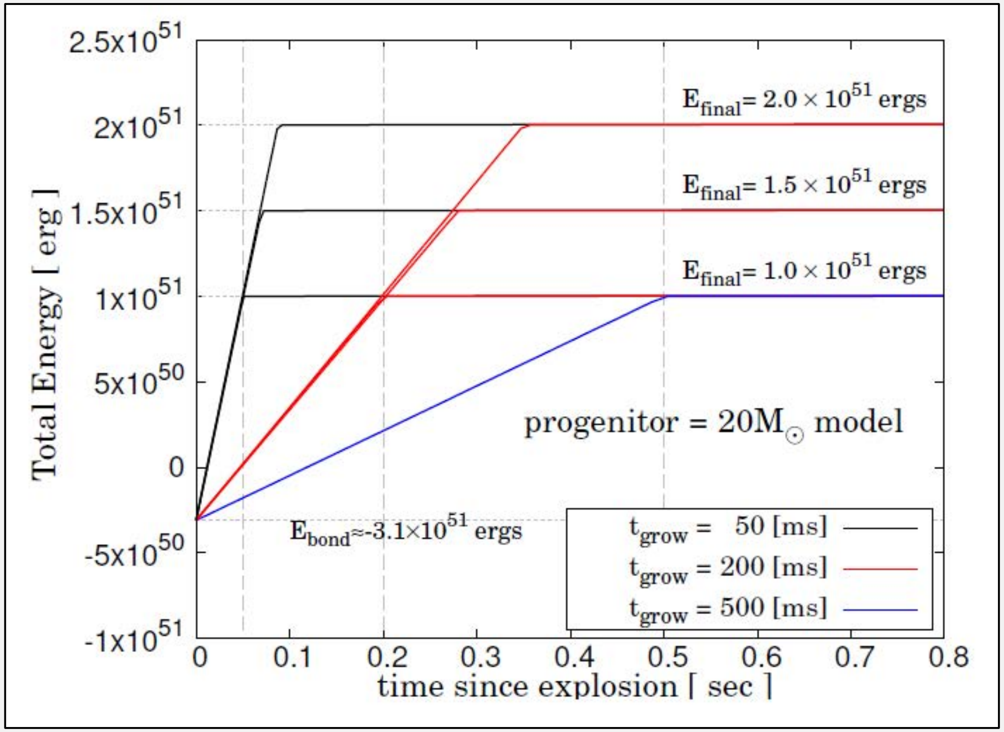
t_{grow} : timescale up to 10^{51}[erg]

✓ model:

Inject thermal energy

at PNS-surface

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



✓ parameter:

$$t_{\mathrm{grow}} = 10 - 2000 \text{ ms.}$$

$$E_{\mathrm{final}} = 1.0, 1.5, 2.0 \times 10^{51} \text{ ergs}$$

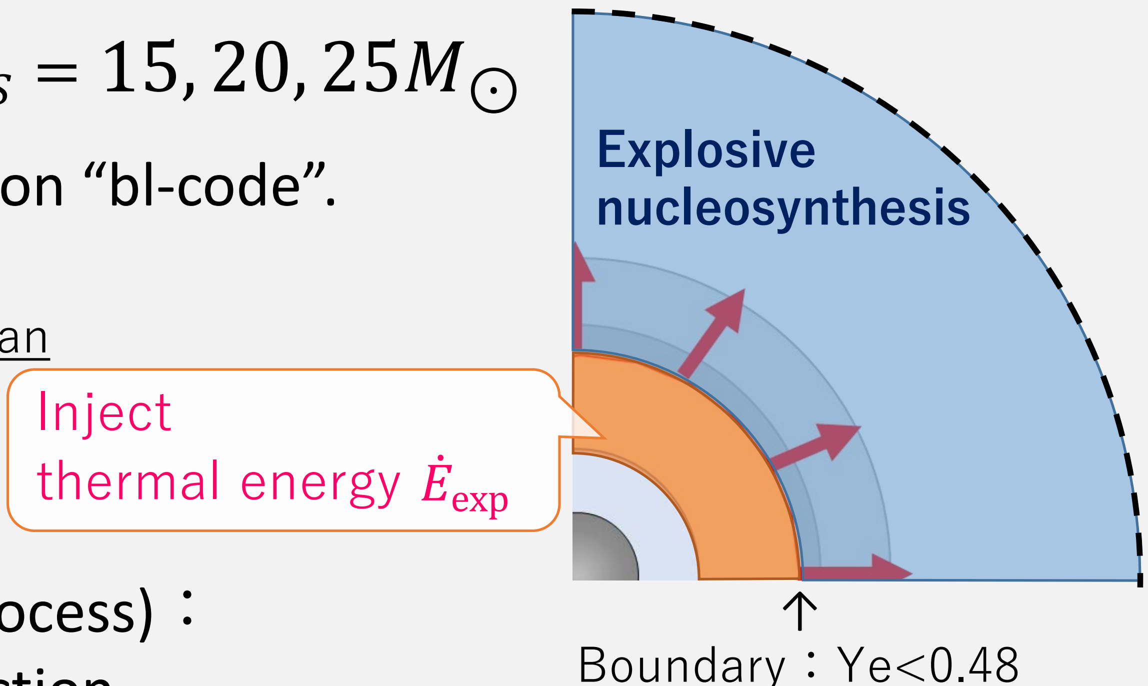
This study: Nucleosynthesis from ‘slow’ expl.

motivation — How the explosive nucleosynthesis products are affected by explosion timescale($t_{\rm grow}$) ?

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

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

- ✓ progenitor mass : $M_{ZAMS} = 15, 20, 25 M_{\odot}$
- ✓ Hydrodynamics : based on “bl-code”.
  - ✓ Hydrodynamics : Newtonian
  - ✓ EoS : Helmholtz
  - ✓ 21-isotope α-reaction
- ✓ Nucleosynthesis (post-process) : 640-isotopes reaction



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

↓

comparing

- ✓ mass of $^{56}\mathrm{Ni}$ @typical-CCSNe.
- ✓ mass of $^{44}\mathrm{Ti}$, $^{57}\mathrm{Ni}$ @SN1987A.
- ✓ abundance patterns @extremely metal-poor(EMP) stars

treatment of mass cut

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

maximum limit!!

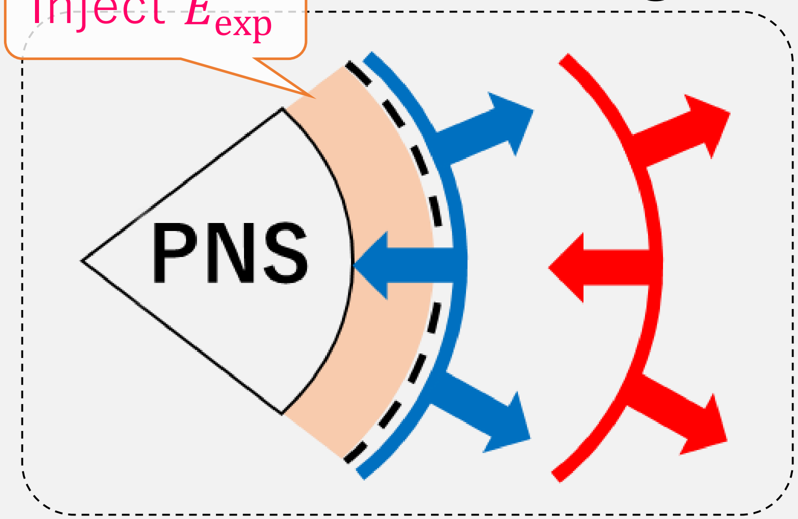
① **Fully ejected above the PNS surface (`deep ejecta model').**

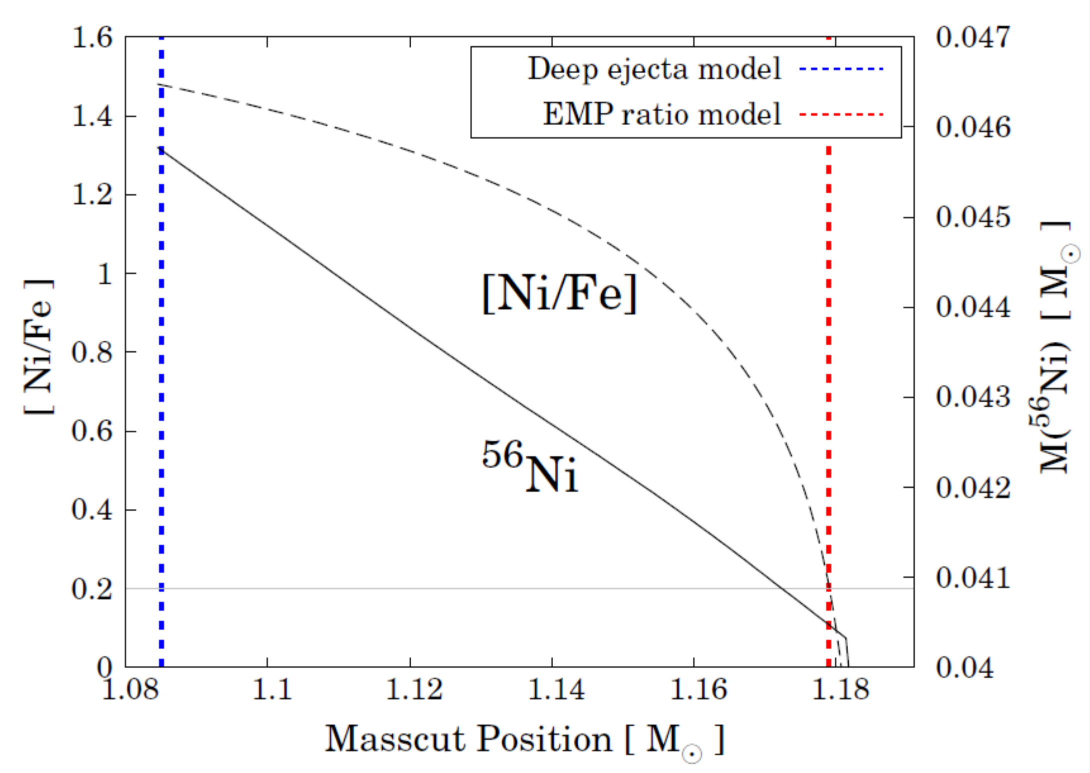
② **To reproduce [Ni/Fe] ratio of EMP stars (`EMP ratio model').**

→ How to decide?

[Ni/Fe] ≈ 0.2 at EMP stars

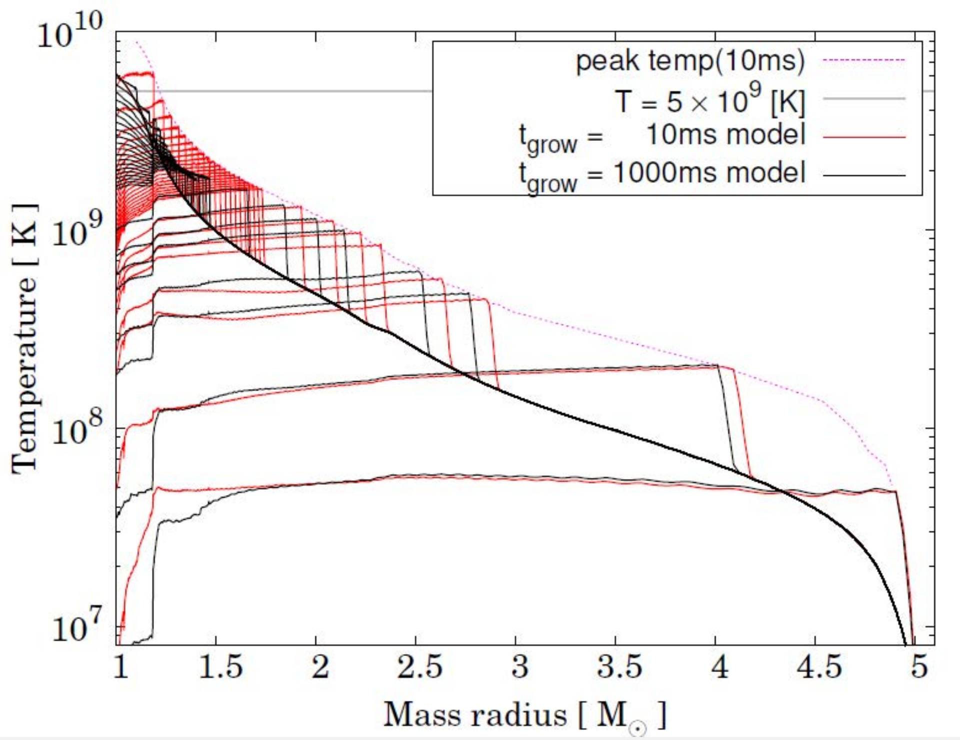
image





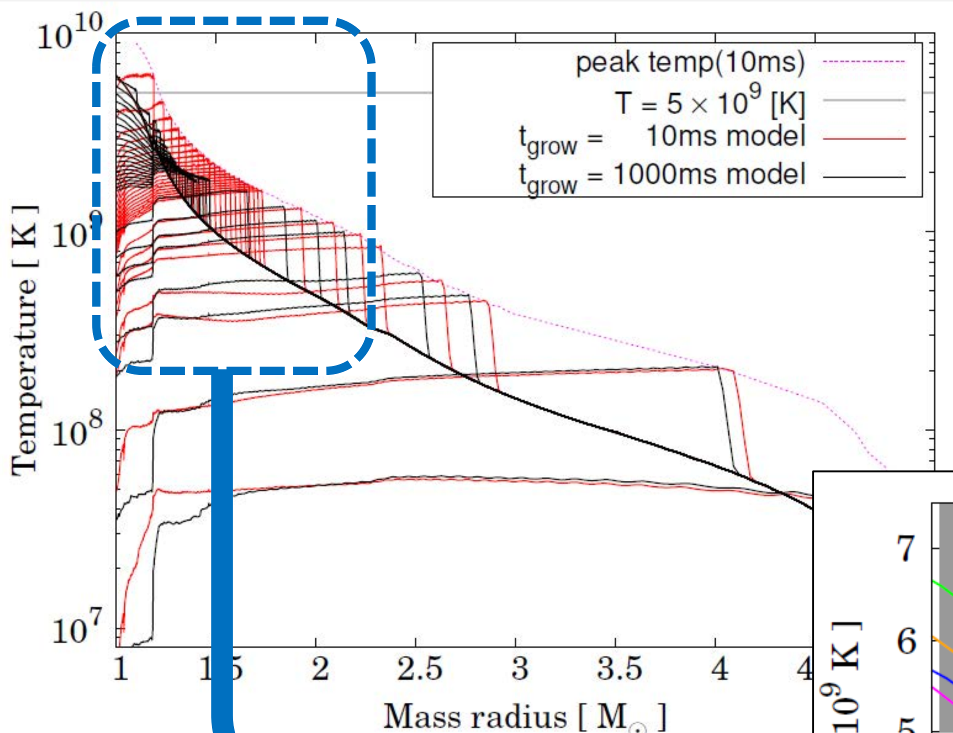
$* \, [\mathrm{Ni/Fe}] = \log_{10}(\mathrm{Ni/Fe}) - \log_{10}(\mathrm{Ni/Fe})_\odot$

Result



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

Result



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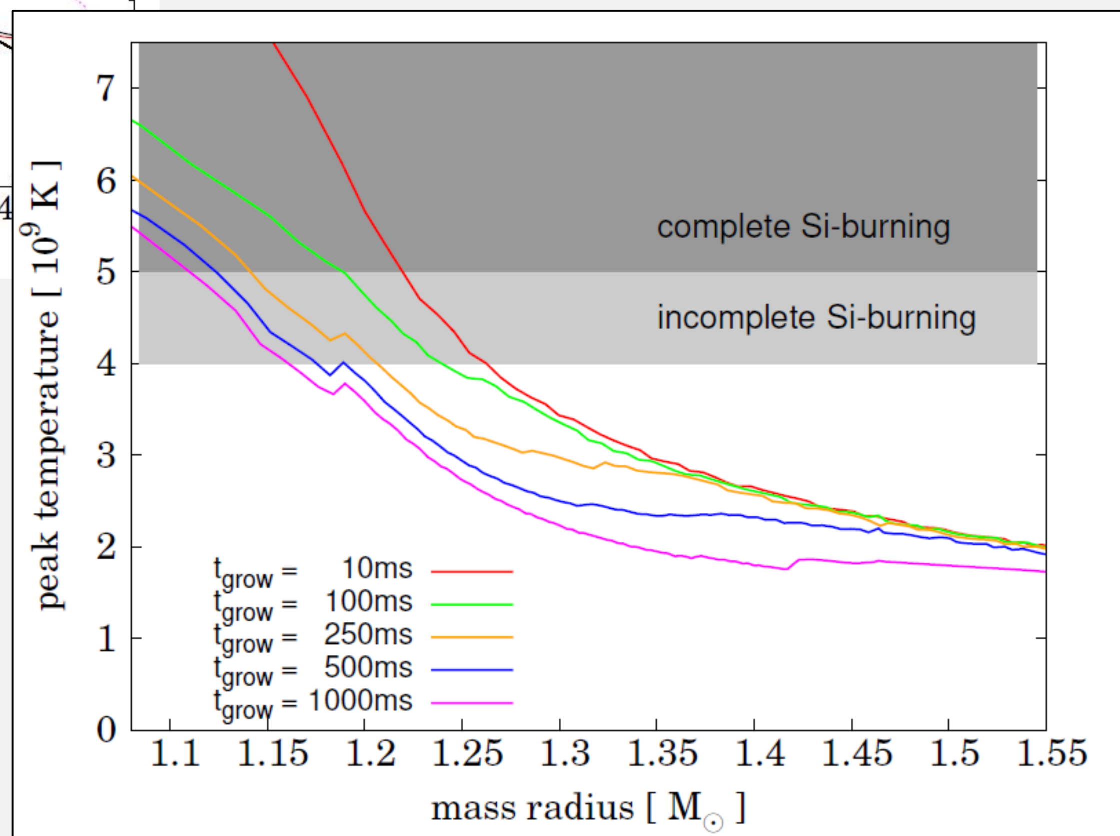
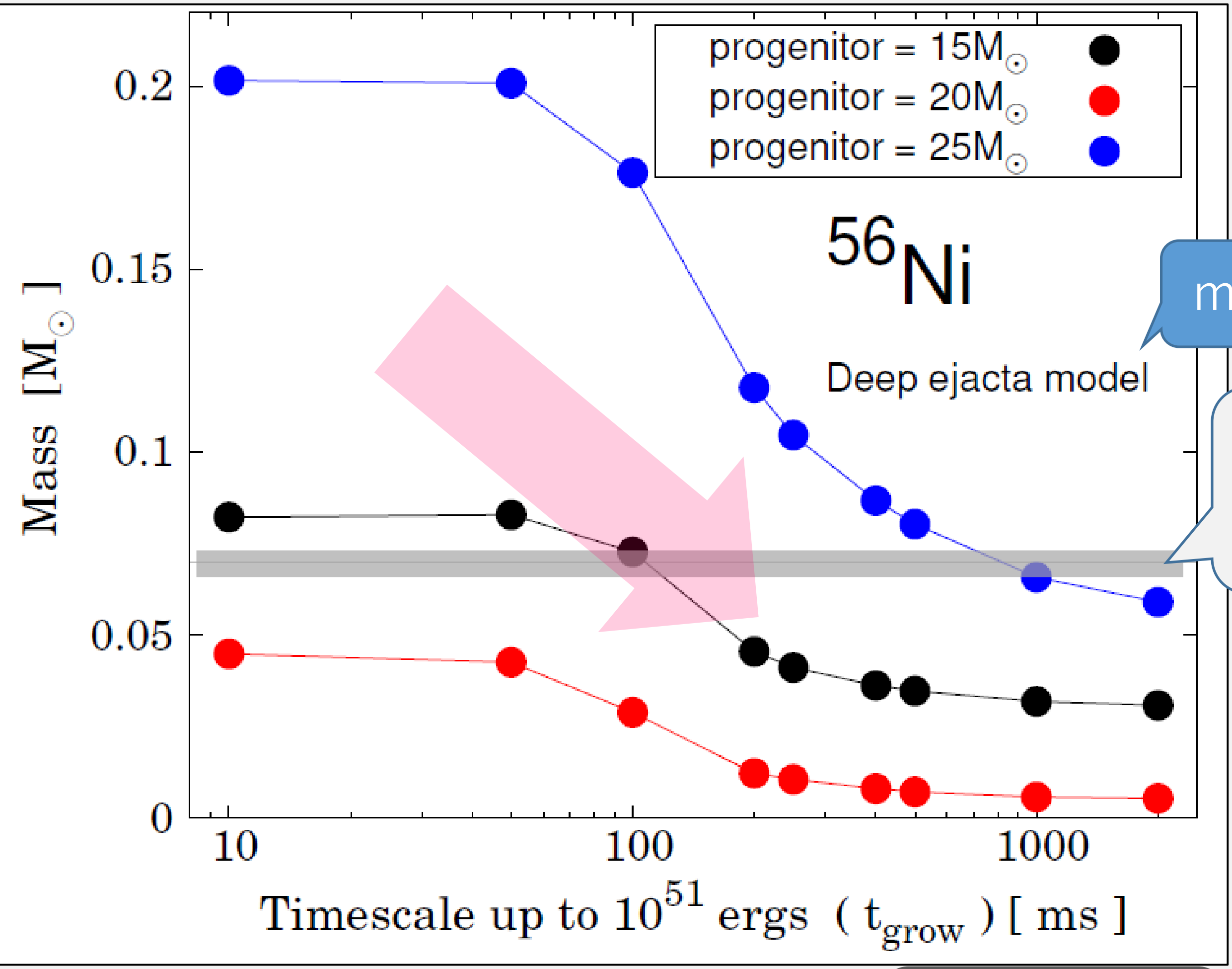


- ✓ <u>The shock weakens rapidly in the slow explosion model!!</u>

56Ni, compare to typical-CCSNe （1）

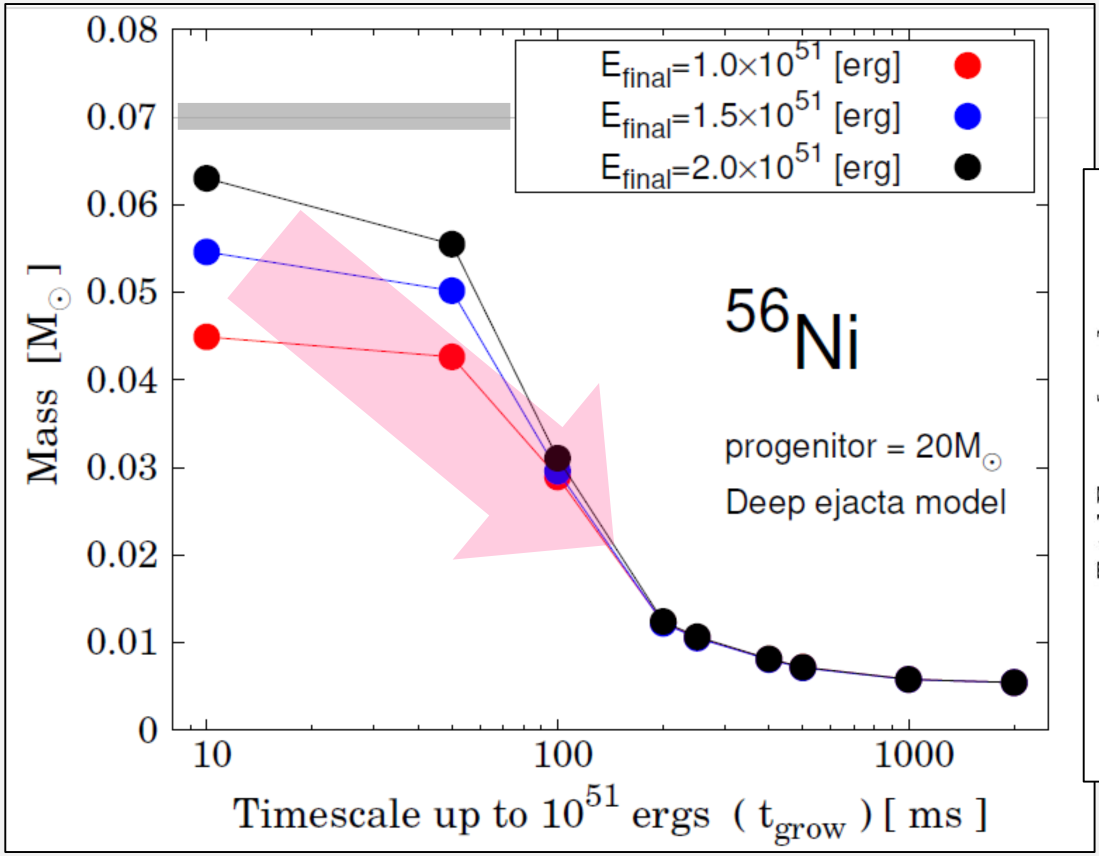


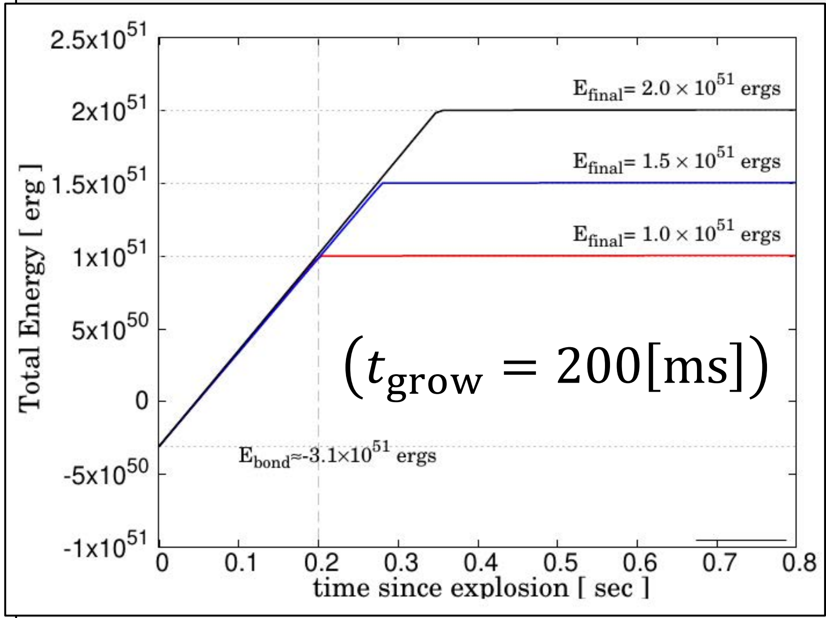
$\mathbf{0.07}\boldsymbol{M_\odot}$; typical CCSNe
(eg., 1987A, 1993J, 2002ap...)

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

Instant explosion → Slow explosion

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





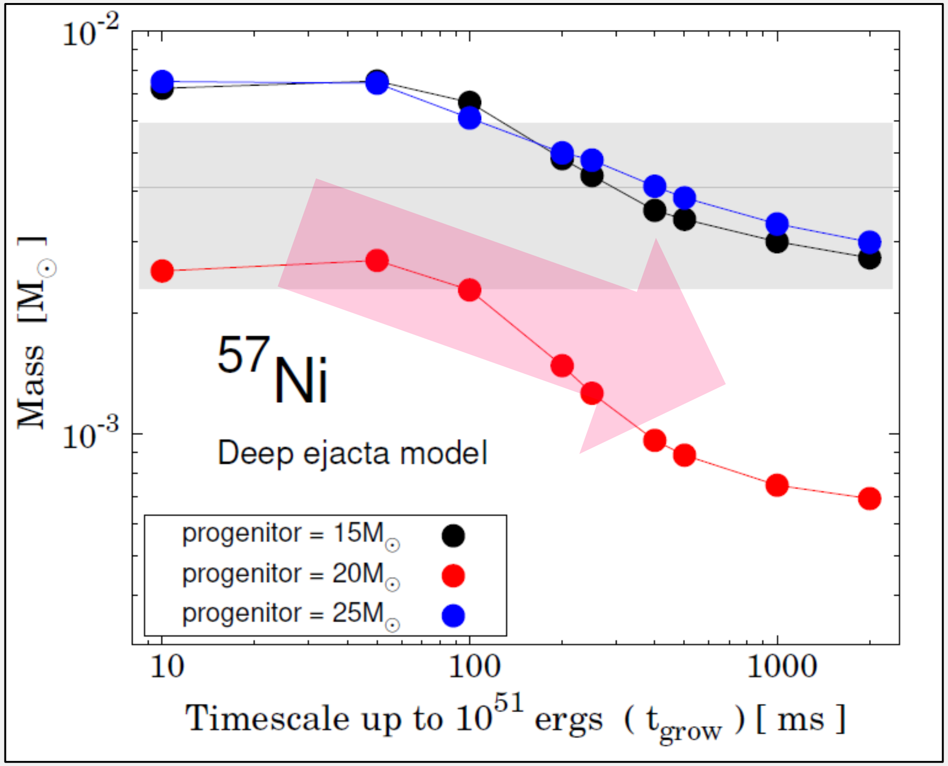
Instant explosion → Slow explosion

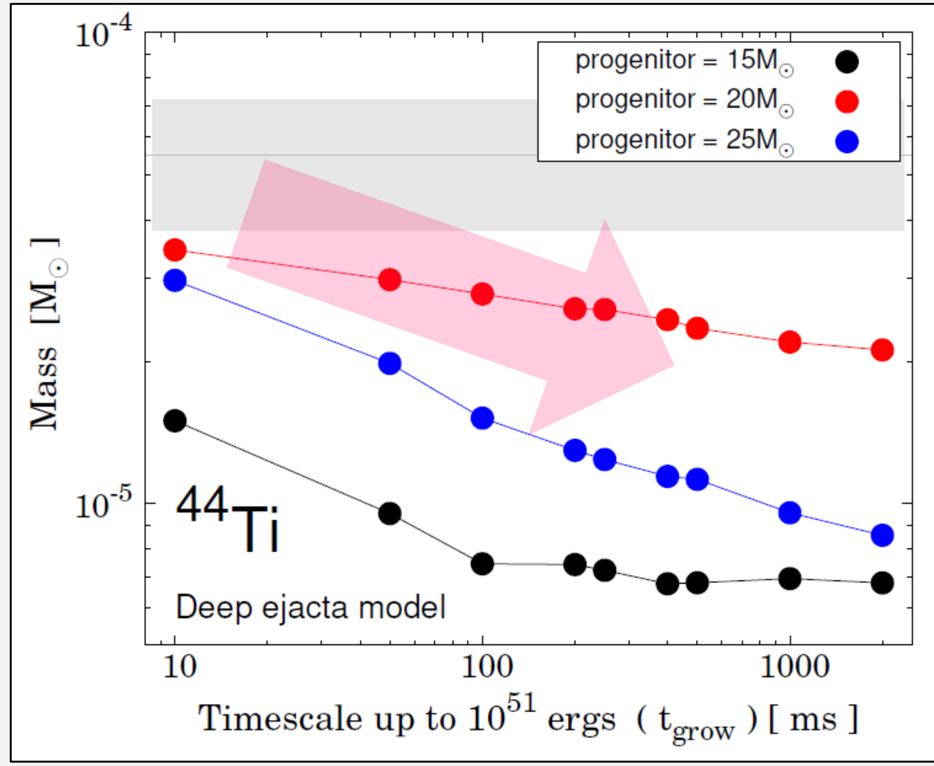
→$M(^{56}\mathrm{Ni})$ is determined by $\dot{E}_{\mathrm{exp}}$

(especially, at the initiation of explosion)

44Ti, 57Ni compare to SN1987A

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





Instant → Slow

Instant → Slow

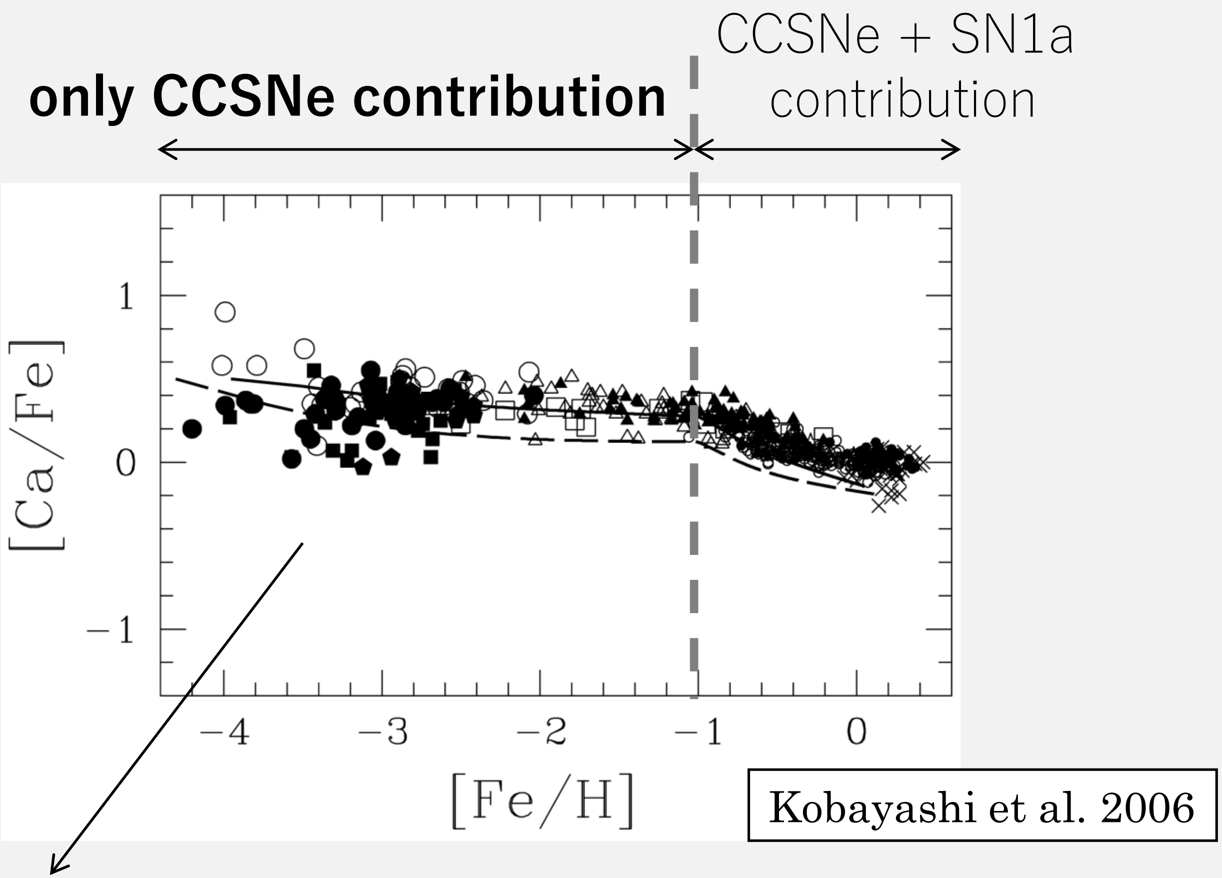
Note: Multi-D effect may enhance M(44Ti)
(Nagataki et al. 1998; Maeda & Nomoto 2003).

→ 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

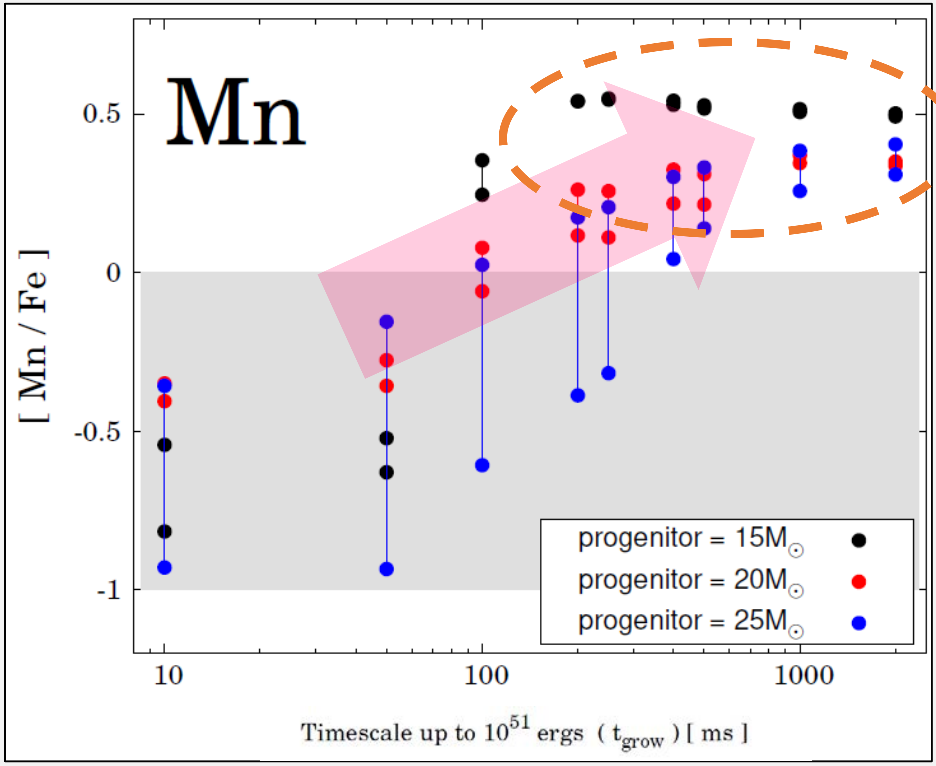
✓ From Galaxy-chemical evolution…

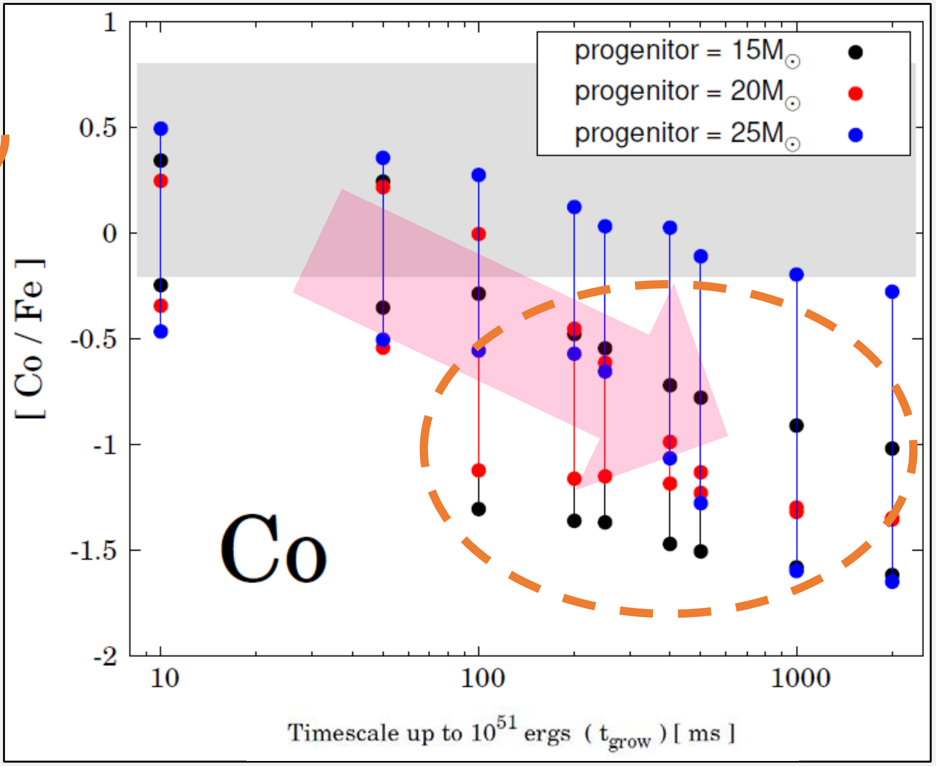


✓ typical-CCSNe **should** reproduce **abundance patterns** of EMP-stars.

✓ this calculation considers a typical-CCSN ($M_{ZAMS} = 15M_{\odot}$,$E_{exp} = 10^{51}$erg).

[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.

summary.

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

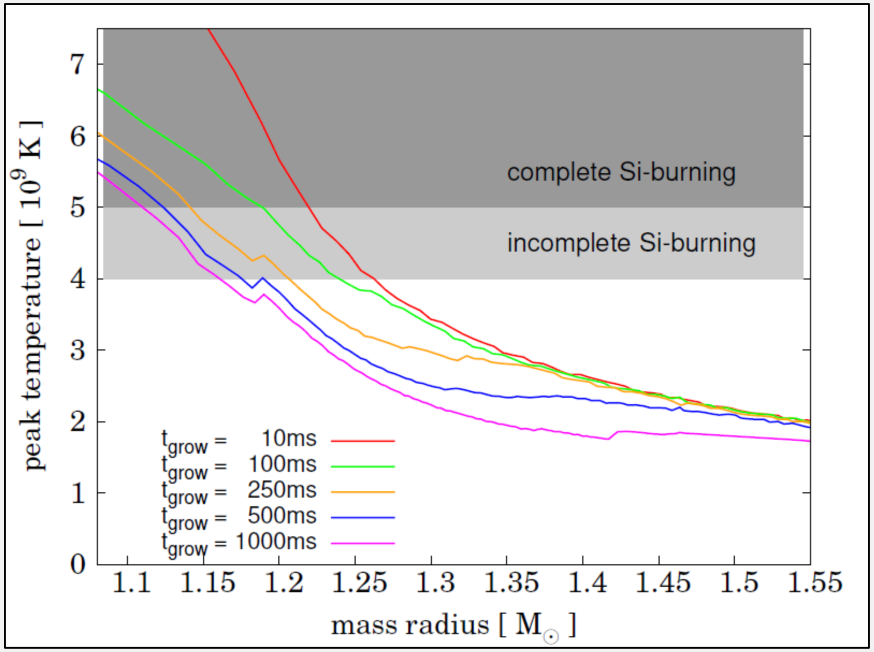
t_{grow} : timescale up to $10^{51}[\mathrm{erg}]$

- **this work:** 1D-hydrodynamic and nucleosynthesis.

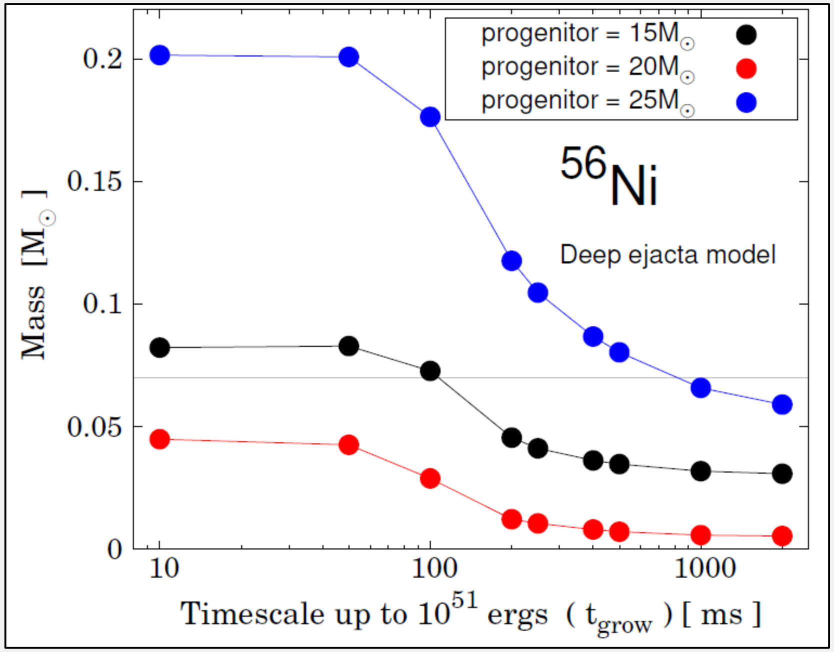
✓ mass of $^{56}\mathrm{Ni}$ @typical-CCSNe.
✓ mass of $^{44}\mathrm{Ti}$, $^{57}\mathrm{Ni}$ @SN1987A.
✓ abundance patterns @extremely metal-poor(EMP) stars

- **conclusion:** $t_{\mathrm{grow}} \gtrsim 1000[\mathrm{ms}]$ is inconsistent with CCSN observation.

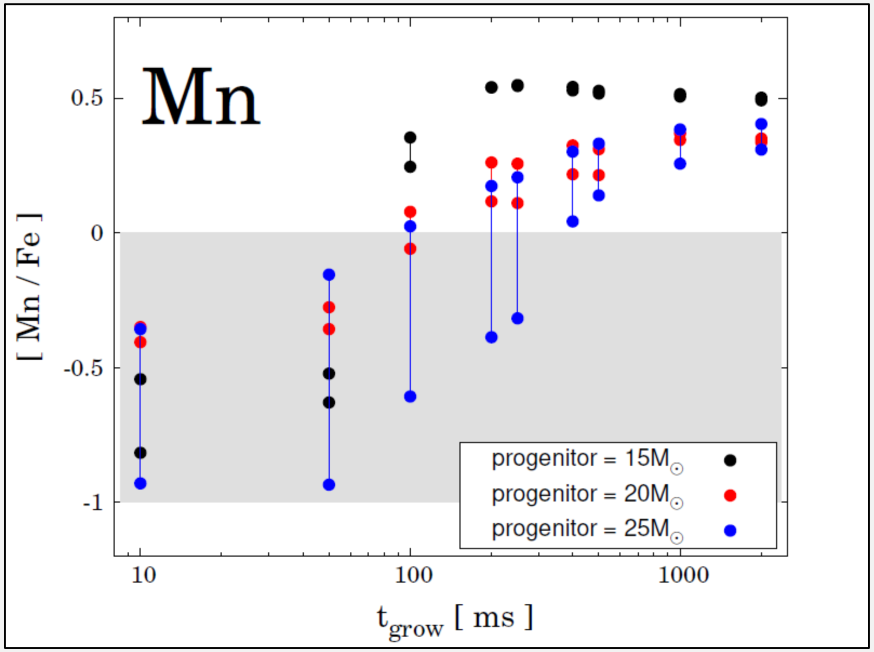
summary.



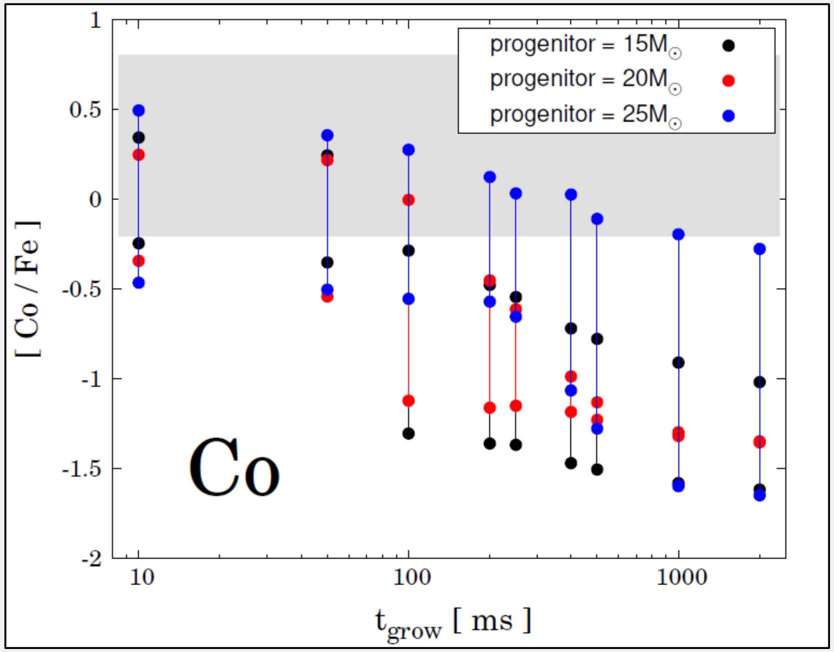
complete Si-burning
incomplete Si-burning
peak temperature [10^9 K]
mass radius [$M_\odot$]
t_{grow} = 10ms
t_{grow} = 100ms
t_{grow} = 250ms
t_{grow} = 500ms
t_{grow} = 1000ms
0 1 2 3 4 5 6 7
1.1 1.15 1.2 1.25 1.3 1.35 1.4 1.45 1.5 1.55



progenitor = 15$M_\odot$
progenitor = 20$M_\odot$
progenitor = 25$M_\odot$
^{56}Ni
Deep ejacta model
Mass [$M_\odot$]
Timescale up to 10^{51} ergs (t_{grow}) [ms]
0 0.05 0.1 0.15 0.2
10 100 1000



Mn
[Mn / Fe]
t_{grow} [ms]
progenitor = 15$M_\odot$
progenitor = 20$M_\odot$
progenitor = 25$M_\odot$
0.5 0 -0.5 -1
10 100 1000



Co
[Co / Fe]
t_{grow} [ms]
progenitor = 15$M_\odot$
progenitor = 20$M_\odot$
progenitor = 25$M_\odot$
1 0.5 0 -0.5 -1 -1.5 -2
10 100 1000