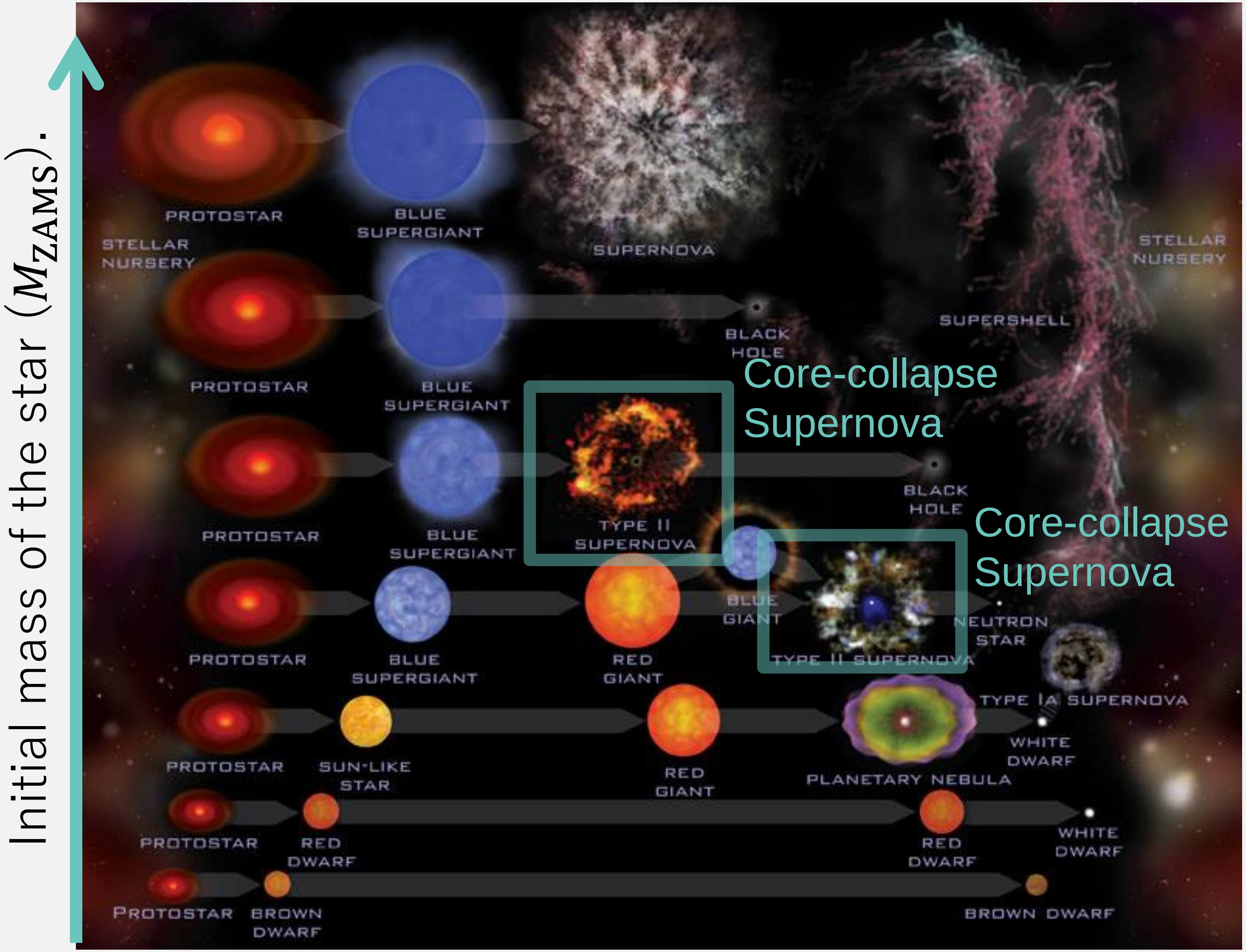
'56Ni problem' in Supernova Explosions

Ryo Sawada The University of Tokyo/ JSPS postdoctoral fellow

Reference：

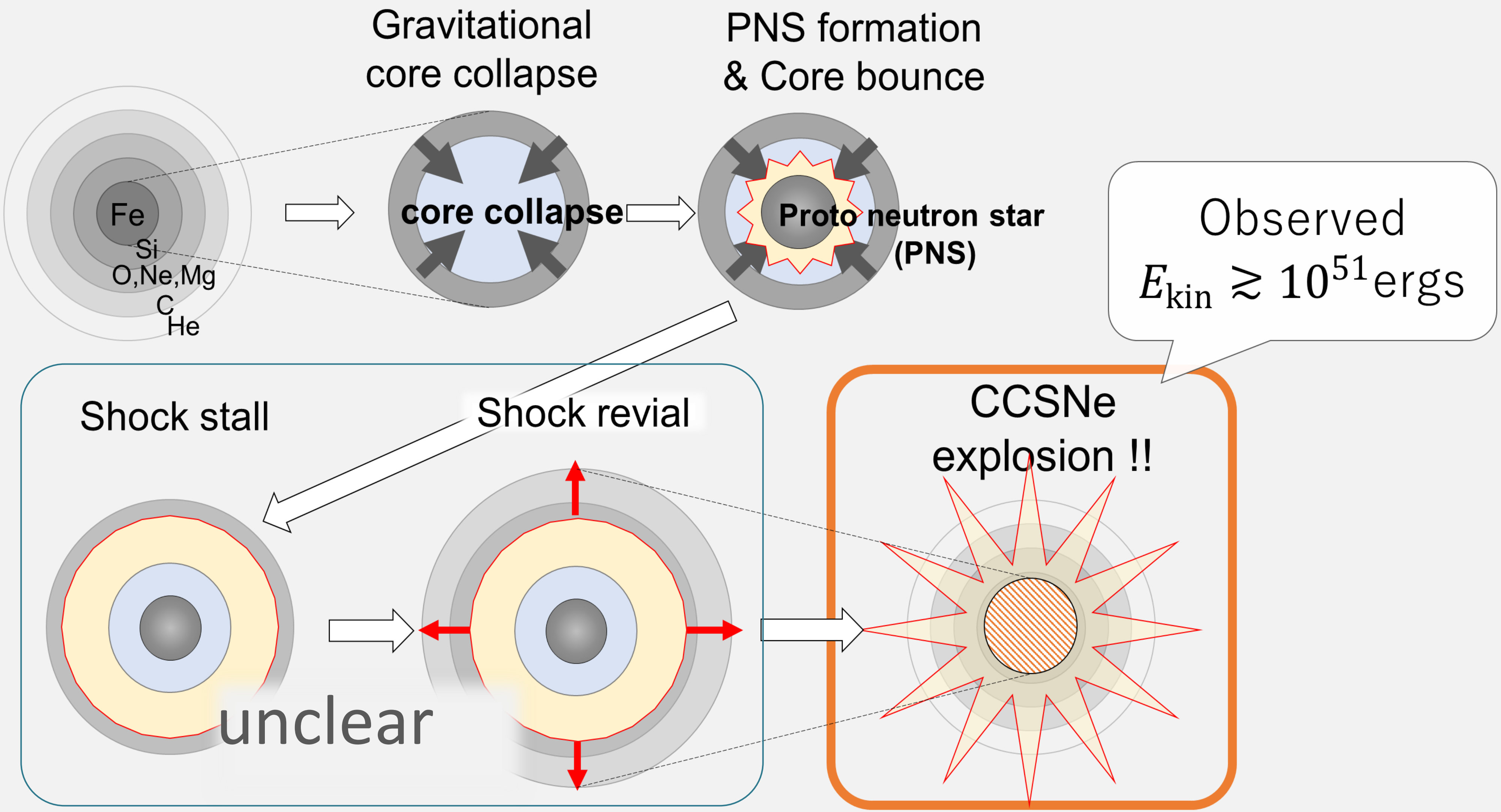
- “Nucleosynthesis Constraints on the Energy Growth Timescale of a Core-collapse Supernova Explosion”
  Sawada & Maeda (2019), ApJ, 886, 47 (arXiv.1910.06972)
- “A Consistent Modeling of Neutrino-driven Wind with Accretion Flow onto a Protoneutron Star and its Implications for 56Ni Production”
  Sawada & Suwa (2021), ApJ, 908, 6 (arXiv.2010.05615)
- “Constraints on the Explosion Timescale of Core-collapse Supernovae Based on Systematic Analysis of Light Curves”
  Saito, Tanaka, Sawada, & Moriya (2022), ApJ 931, 153 (arXiv:2205.00624)
- “Updating the ^{56}Ni Problem in Core-collapse Supernova Explosion”
  Sawada & Suwa (2023) arXiv:2301.03610

What is the core-collapse supernova ?



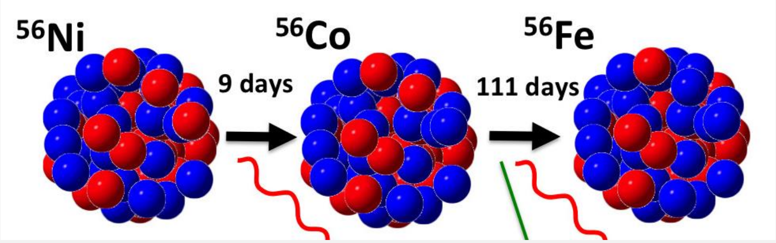
What is the core-collapse supernova ?

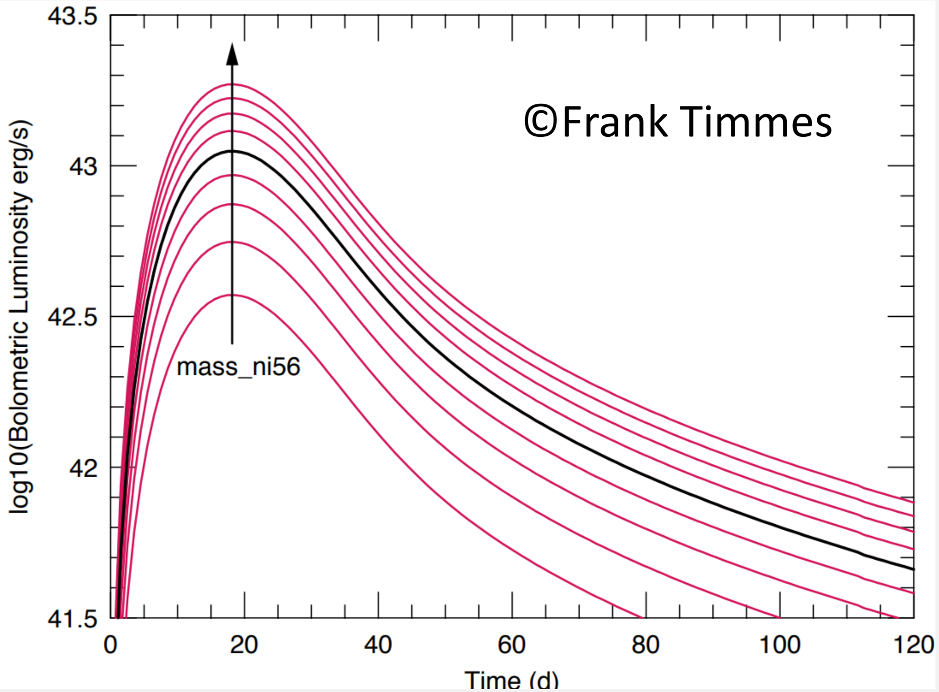
- **Standard scenario : Neutrino-driven model**



Role of isotope 56Ni in supernova explosions

- Radioactive decay heat of 56Ni is the energy source of supernova brightness (hereafter, refer 56Ni as ‘nickel’).





SN1987A; Giordano(ISBN:0534424716)

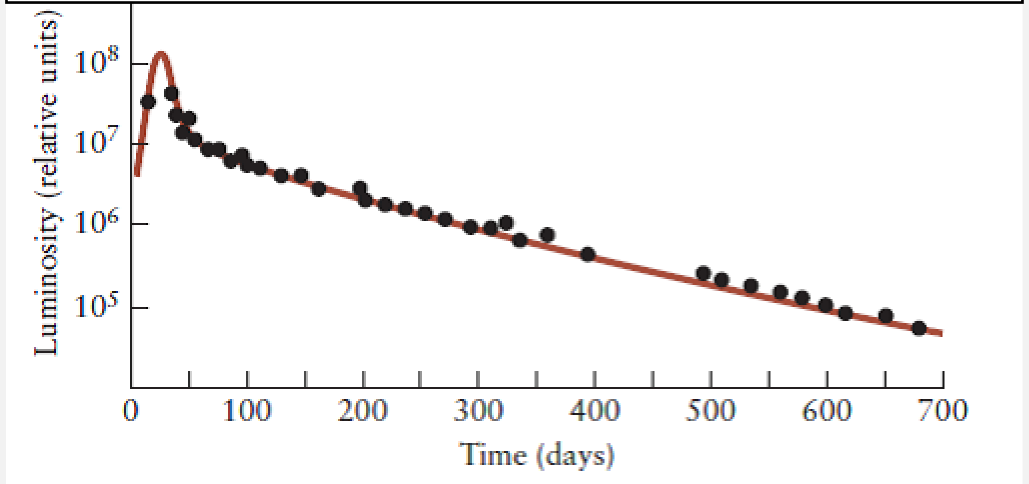
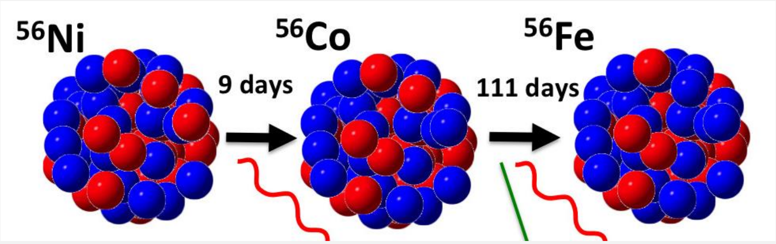


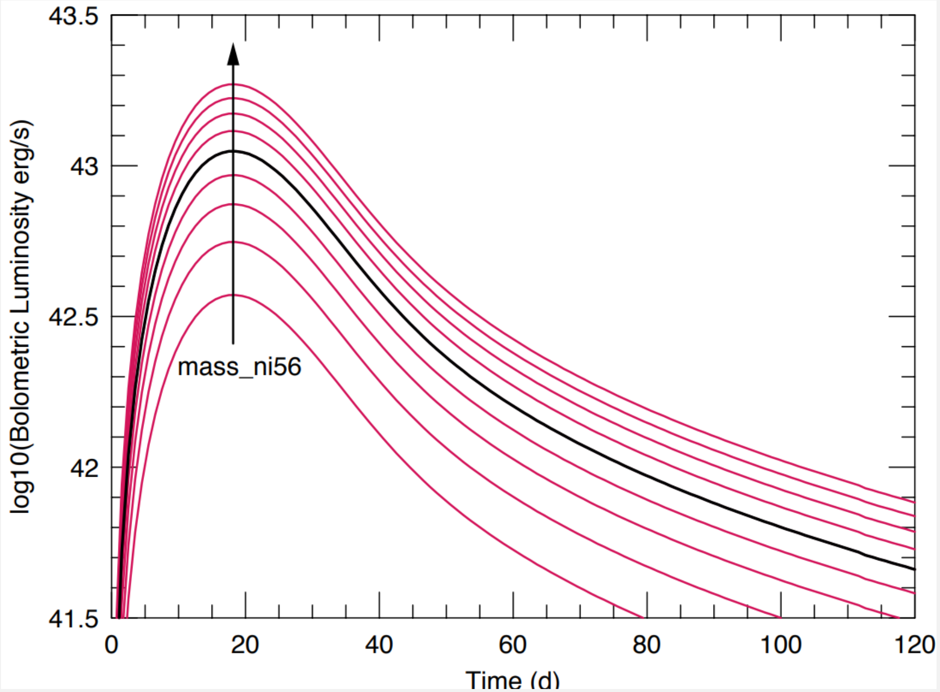
Figure P30.87 The light curve for Supernova 1987A.

- the amount of 56Ni synthesized can be estimated fairly accurately and easily from the SN light curve alone.

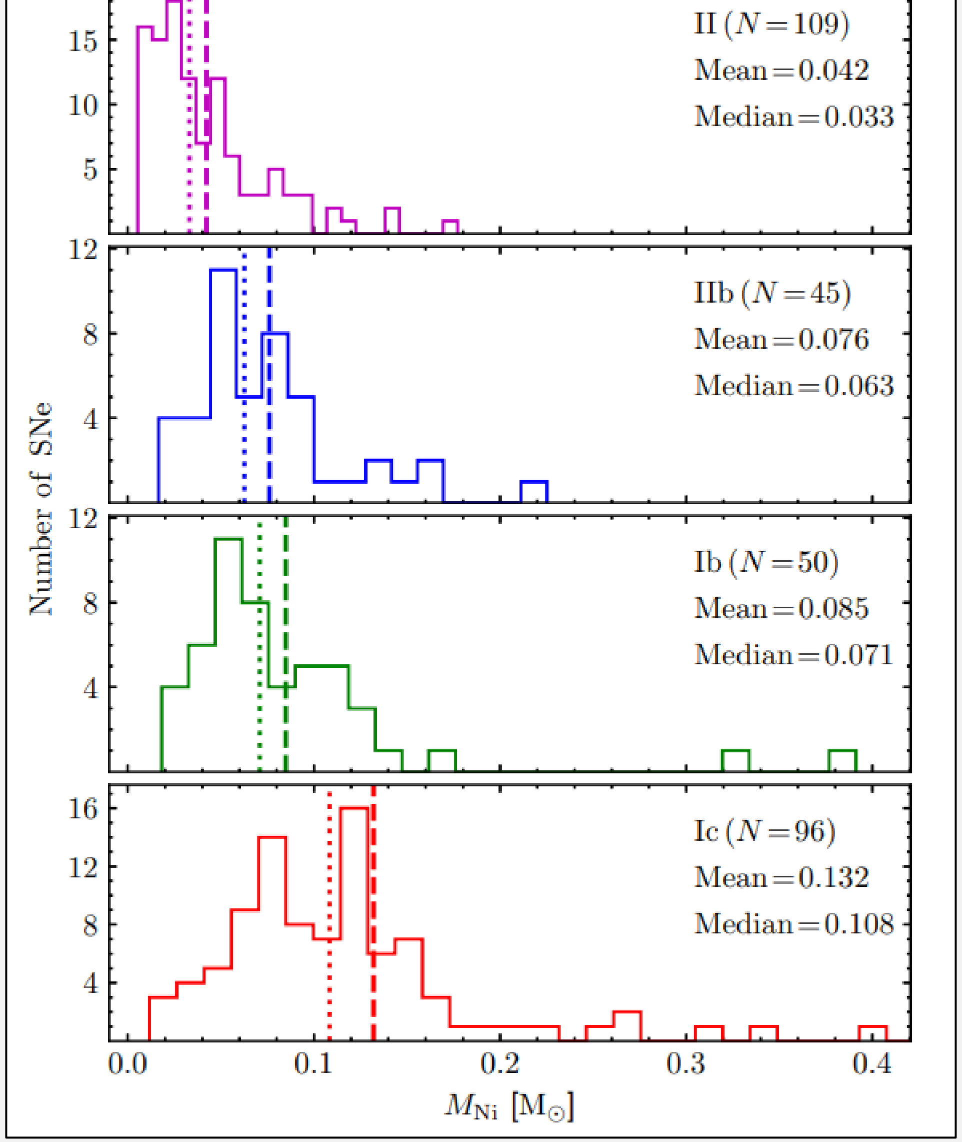
Role of isotope 56Ni in supernova explosions

- Radioactive decay heat of 56Ni is the energy source of supernova brightness (hereafter, refer 56Ni as 'nickel').





Rodríguez et al.(2022)



Role of isotope 56Ni in supernova explosions

- Light-curve calculation：Based on One-zone Arnett model （Arnett 1982）

$$\frac{\partial E_{\rm int}(t)}{\partial t} = -P\frac{\partial V(t)}{\partial t} + \dot{Q}(t) - L(t).$$

$$\frac{\partial E_{\rm kin}(t)}{\partial t} = P\frac{\partial V(t)}{\partial t}.$$

Assuming that the internal energy is dominated by radiation,

$$P\frac{\partial V(t)}{\partial t} = \frac{\epsilon}{3}\cdot 4\pi R_{\rm ej}^2 v_{\rm ej}(t) = \frac{E_{\rm int}(t)}{R_{\rm ej}} v_{\rm ej}(t) = \frac{E_{\rm int}(t)}{t_{\rm dyn}}, \qquad \left[t_{\rm dyn} = \frac{R_{\rm ej}(t)}{v_{\rm ej}(t)}\right]$$

When the luminosity is described by the spherical diffusion equation,

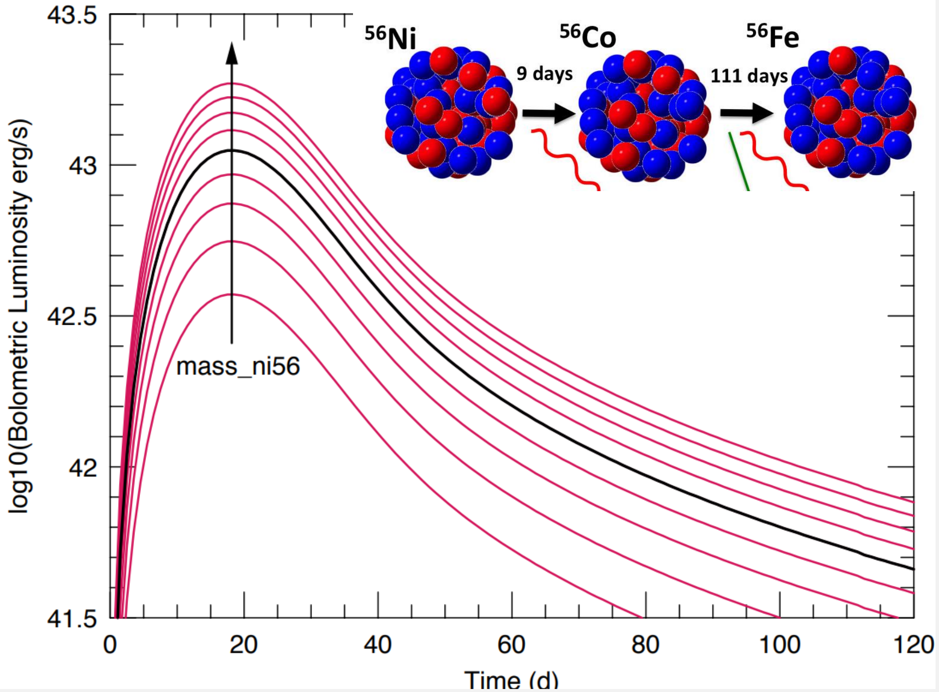
$$L(t) = -4\pi r^2 \frac{c}{3\kappa\rho}\frac{\partial e}{\partial r} = -4\pi r^2 \frac{c}{3\kappa\rho}\frac{\partial}{\partial r}\left(\frac{E_{\rm int}(t)}{V(t)}\cdot\left(\frac{\pi}{3}\frac{\sin(\pi x)}{x}\right)\right)$$

$$= E_{\rm int}\cdot\frac{t_{\rm dyn}}{t_{\rm diff}^2}, \qquad \left[t_{\rm diff} = \frac{3}{4\pi}\frac{\kappa M_{\rm ej}}{c v_{\rm ej}}\frac{1}{\xi}\right]$$

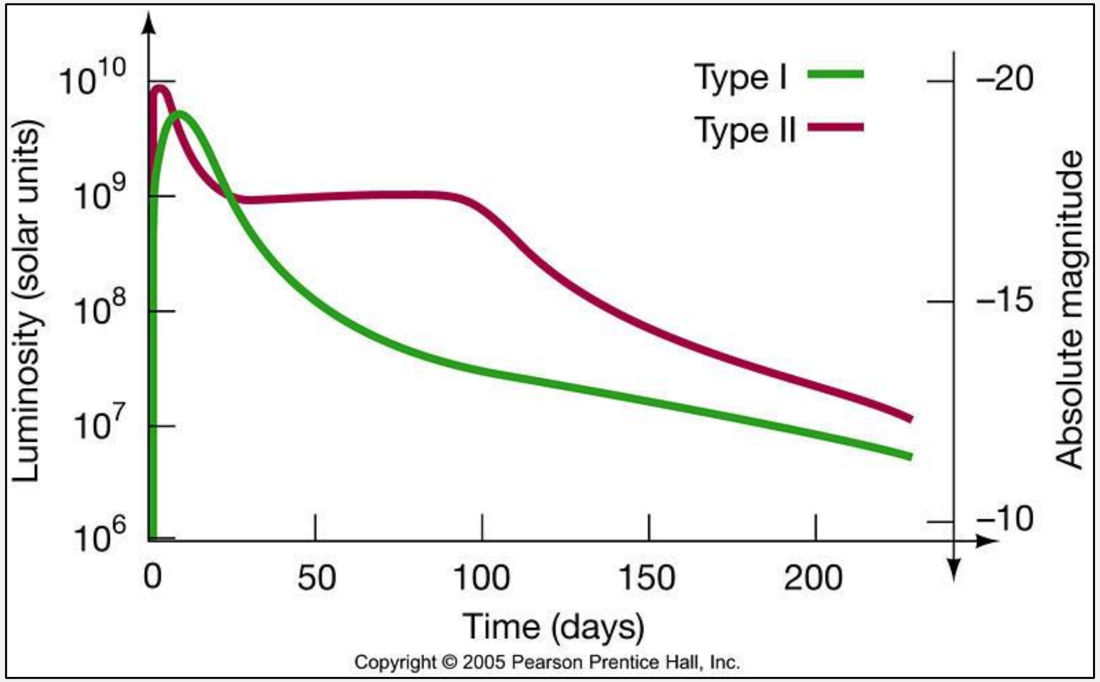
$$\frac{\partial E_{\rm int}(t)}{\partial t} = -\frac{E_{\rm int}(t)}{t_{\rm dyn}} + \dot{Q}(t) - E_{\rm int}\cdot\frac{t_{\rm dyn}}{t_{\rm diff}^2}$$

$$\frac{\partial E_{\rm kin}(t)}{\partial t} = \frac{E_{\rm int}(t)}{t_{\rm dyn}}.$$

$$\dot{Q}(t) = f_{dep}\cdot[M(^{56}{\rm Ni})\cdot q_{\rm Ni}(t)]$$



Role of isotope 56Ni in supernova explosions

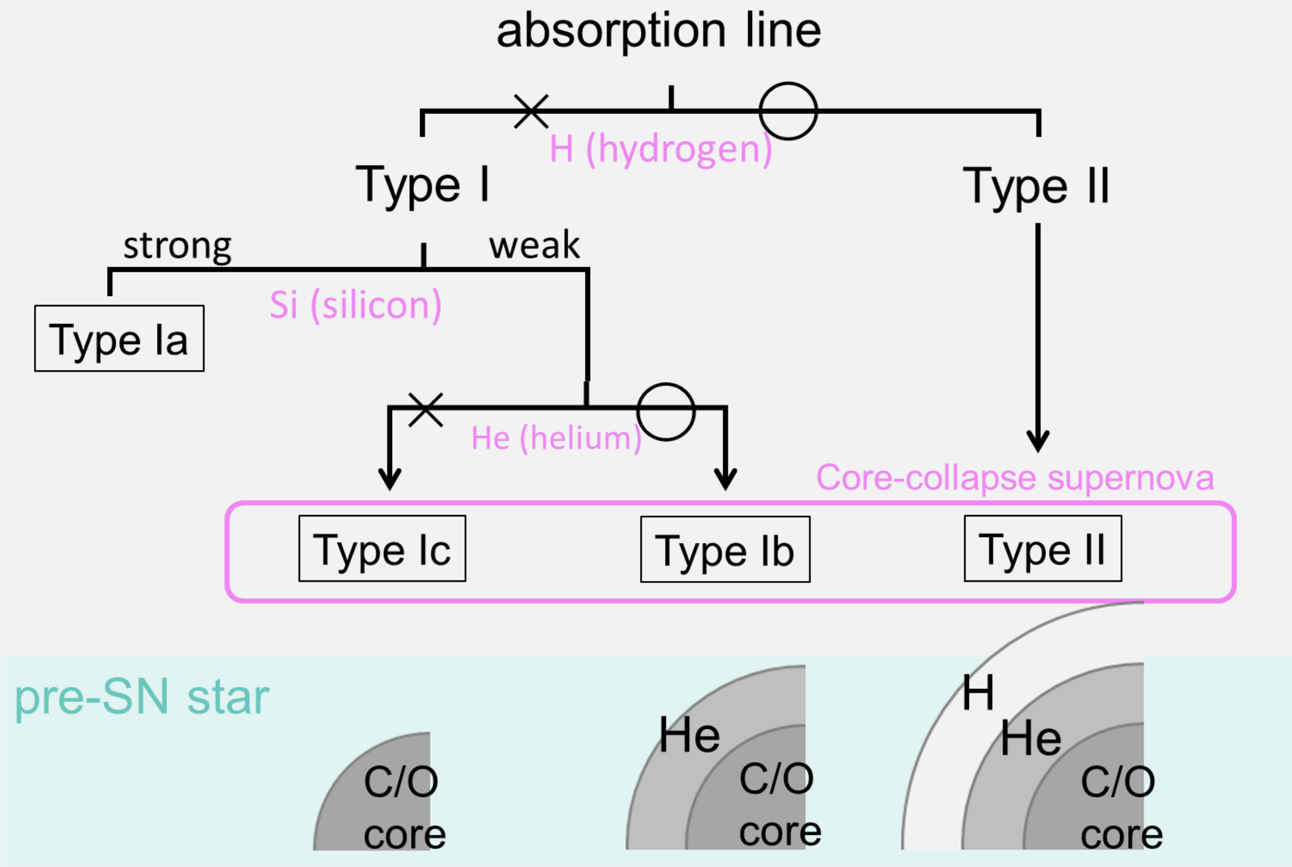


Arnett model : for Type-I Supernova

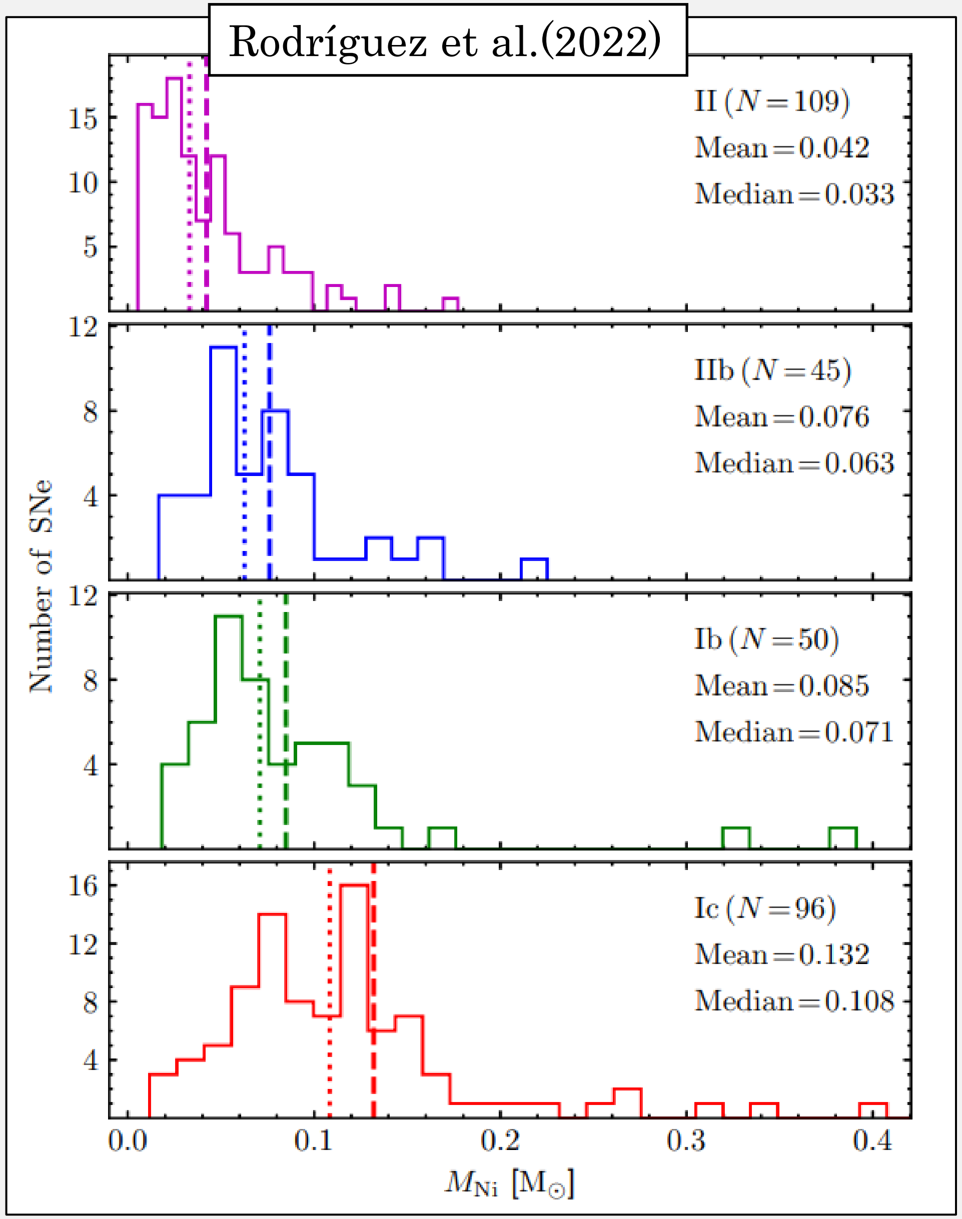
$$\frac{\partial E_{\rm int}(t)}{\partial t} = -\frac{E_{\rm int}(t)}{t_{\rm dyn}} + \dot{Q}(t) - E_{\rm int} \cdot \frac{t_{\rm dyn}}{t_{\rm diff}^2}$$

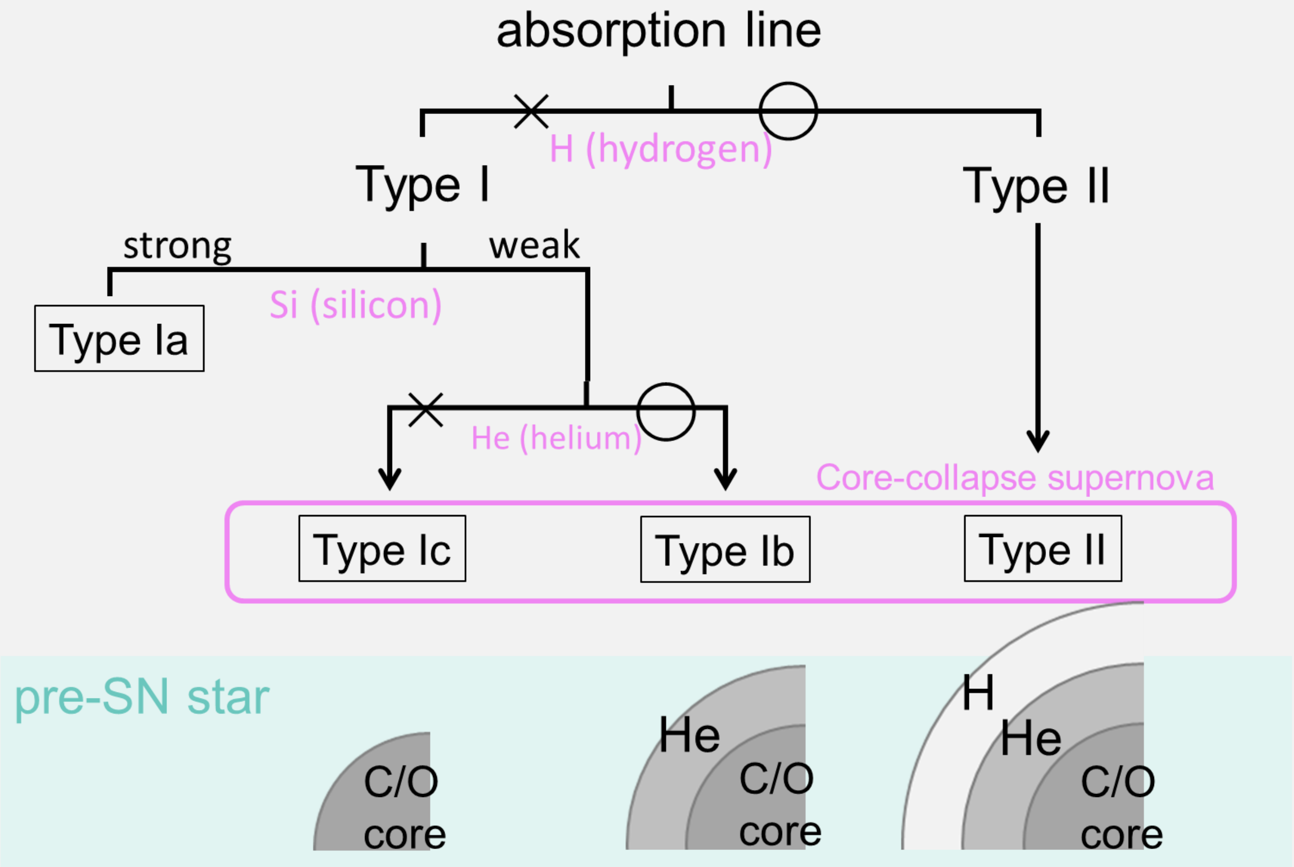
$$\frac{\partial E_{\rm kin}(t)}{\partial t} = \frac{E_{\rm int}(t)}{t_{\rm dyn}}.$$

$$\dot{Q}(t) = f_{\rm dep} \cdot [M(^{56}{\rm Ni}) \cdot q_{\rm Ni}(t)] + Q_{\rm heat}$$



Role of isotope 56Ni in supernova explosions





Where is the synthesized amount of 56Ni determined?

<u>[ESTIMATE]</u> how much explosive 56Ni nucleosynthesis in the CCSN

$M(^{56}\mathrm{Ni}) \approx$ [Mass contained in region:**Tpeak $> 5.0 \times 10^9$ [K]**] $-$ [Central compact object mass]

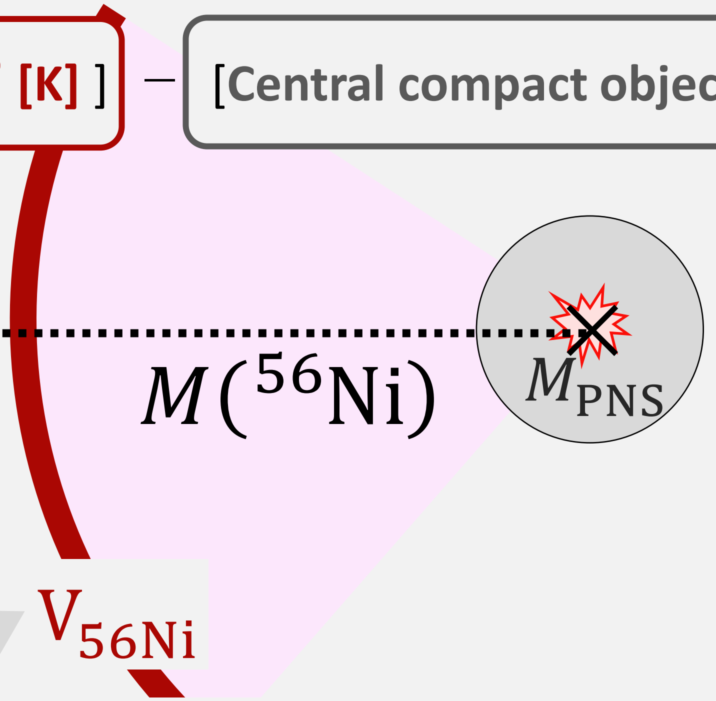


Image of CC-SN explosion

Fire-ball model

(1) radiation dominant,

(2) isothermal @post-shock,

(3) adiabatic expansion.

$$E_{\mathrm{expl.}} = (aT^4) \times \left(\frac{4\pi}{3} r_{\mathrm{shock}}^3\right)$$

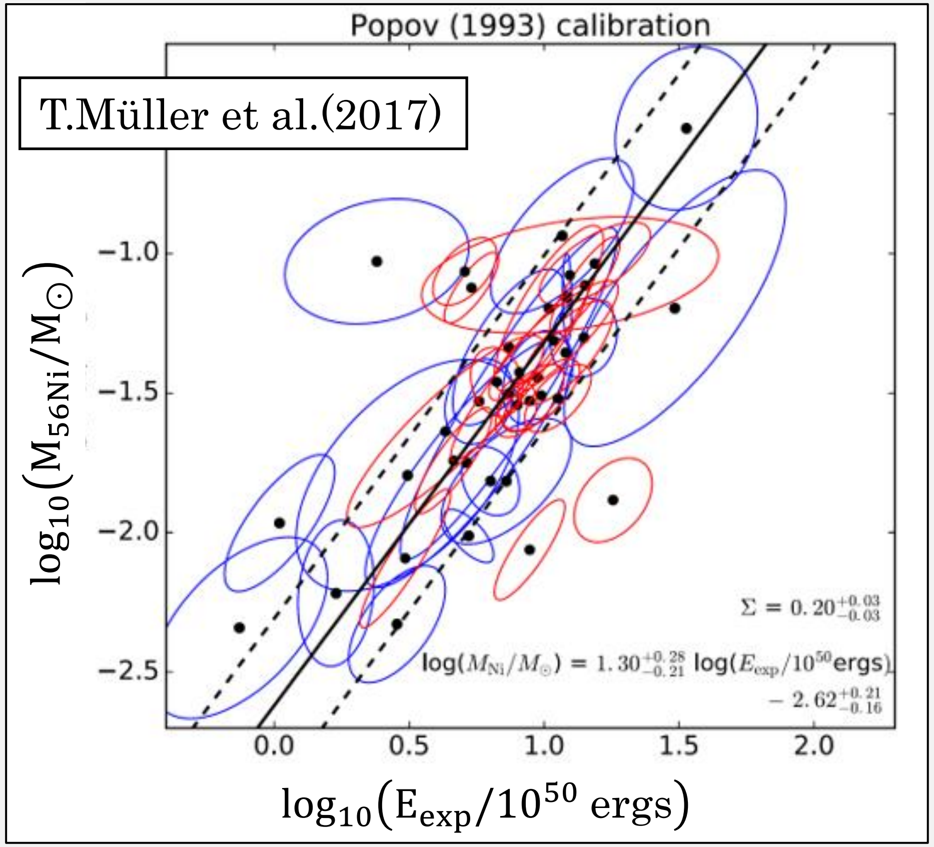
→ **when T= 5.0×10^9 [K], then** $V_{56\mathrm{Ni}} \propto (E_{\mathrm{expl.}}/10^{51})$

$\therefore \quad M(^{56}\mathrm{Ni}) \propto$

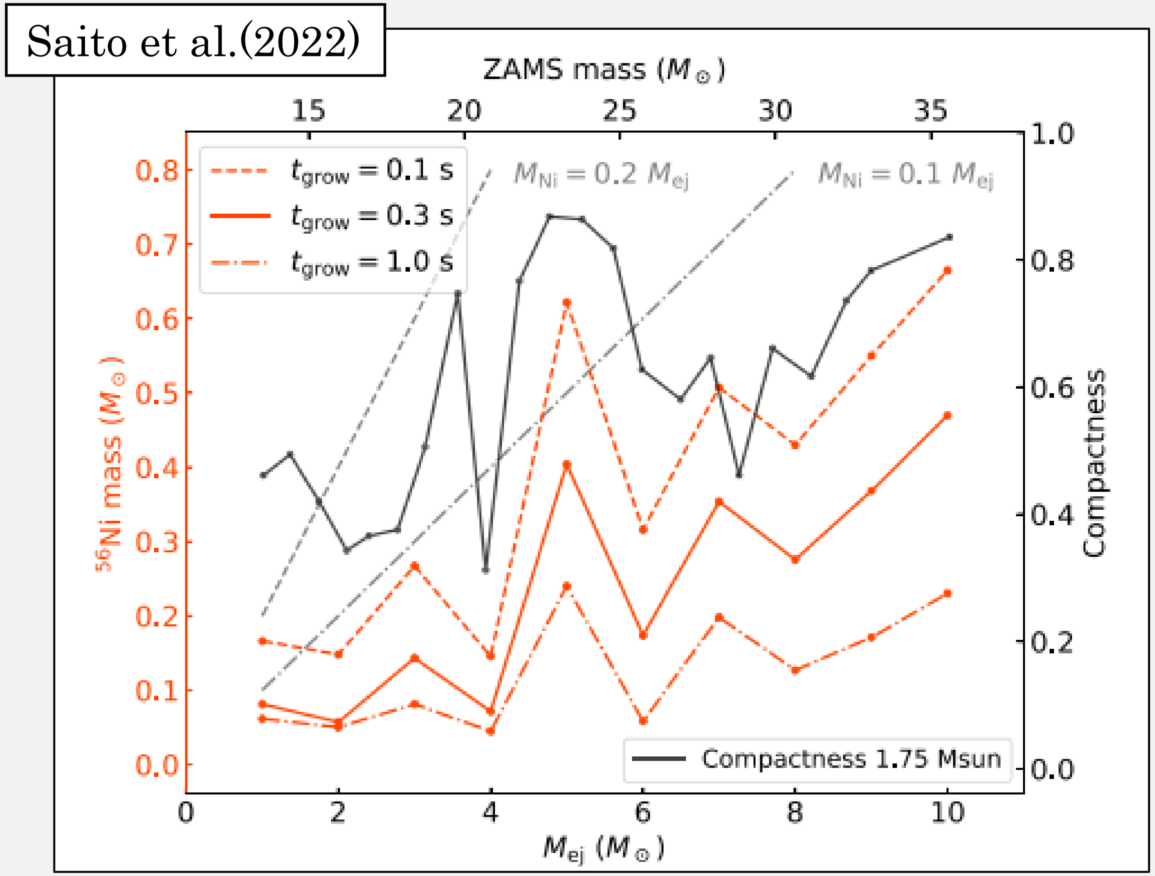
1. **explosion energy.** (How much extends the 56Ni synthesis region?)
2. **compactness.** (How much mass is contained in the 56Ni synthesis region?)

Where is the synthesized amount of 56Ni determined?

- **Observational**



- **Theoretical**



$\therefore \quad M(^{56}\mathrm{Ni}) \propto$

1. **explosion energy.** (How much extends the 56Ni synthesis region?)
2. **compactness.** (How much mass is contained in the 56Ni synthesis region?)

[topic 1] Can modern supernova simulations synthesize sufficient 56Ni?

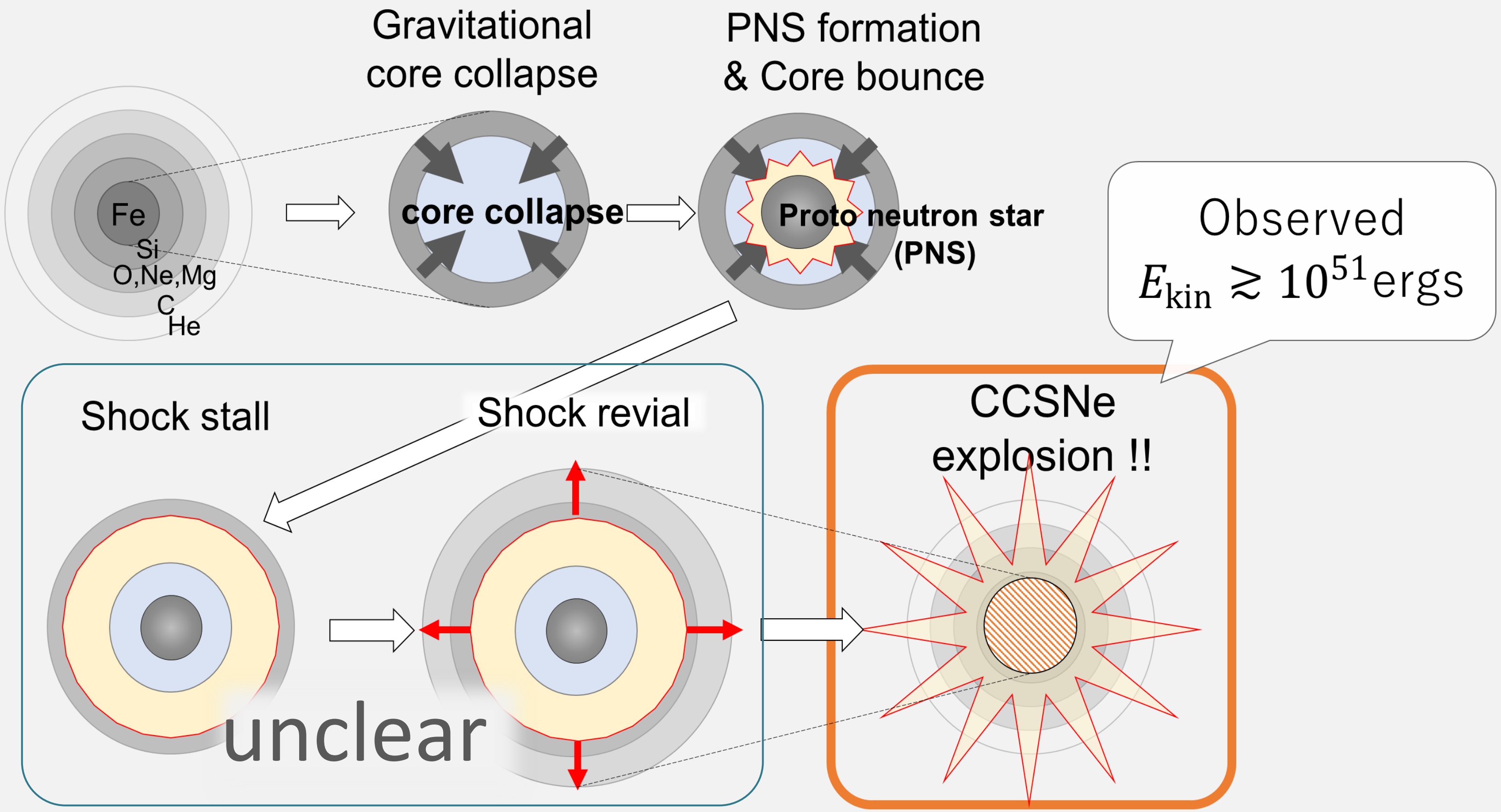
'56Ni problem' in Supernova Explosions

Reference：

- “Nucleosynthesis Constraints on the Energy Growth Timescale of a Core-collapse Supernova Explosion”
  Sawada & Maeda (2019), ApJ, 886, 47 (arXiv.1910.06972)
- “A Consistent Modeling of Neutrino-driven Wind with Accretion Flow onto a Protoneutron Star and its Implications for 56Ni Production”
  Sawada & Suwa (2021), ApJ, 908, 6 (arXiv.2010.05615)
- “Constraints on the Explosion Timescale of Core-collapse Supernovae Based on Systematic Analysis of Light Curves”
  Saito, Tanaka, Sawada, & Moriya (2022), ApJ 931, 153 (arXiv:2205.00624)

[topic 1] Can modern supernova simulations synthesize sufficient 56Ni?

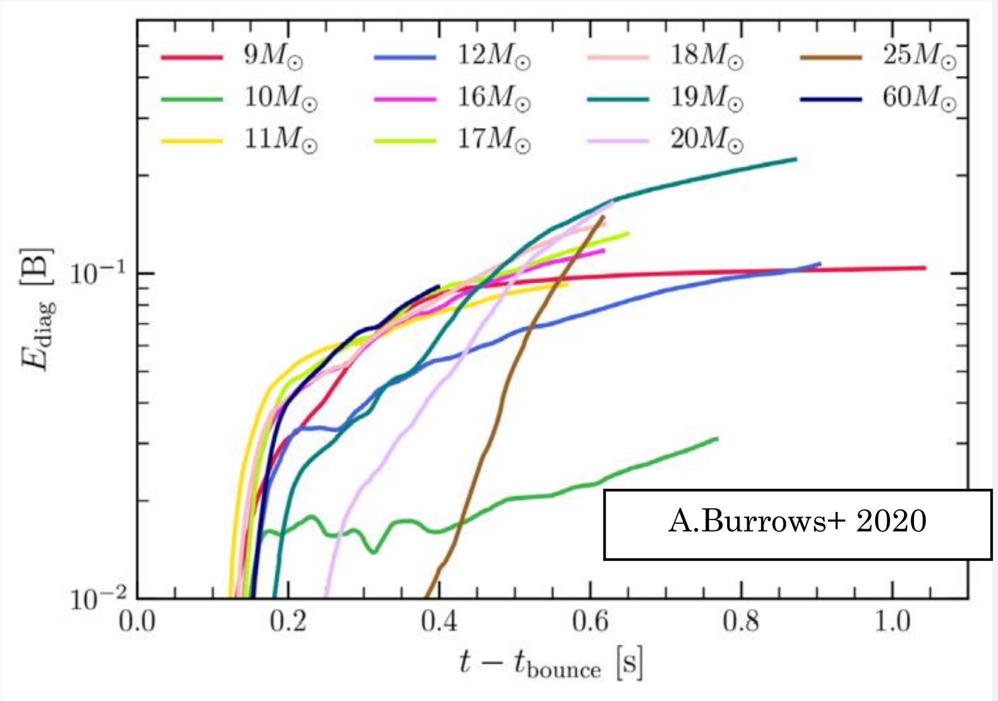
- **Standard scenario : Neutrino-driven model**

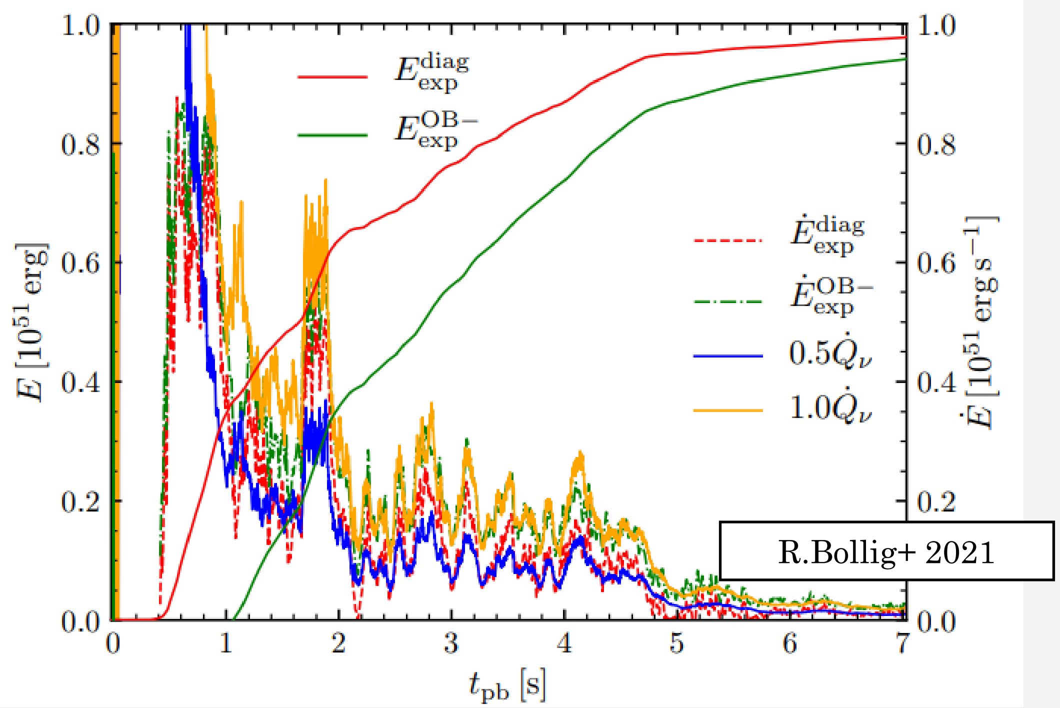


***unclear : Can reach to 10^{51} [erg] ? (see, e.g., Janka 2012, and references therein)**

[topic 1] Can modern supernova simulations synthesize sufficient 56Ni?

- ✓ **<u>The state-of-the-art simulations</u>** employ Multi-D / Full-Boltzmann ν -transport / GR-effect etc.
- ✓ Most, if not all, of these simulations do not reach sufficient explosion energy.
- ✓ those simulations now suggest a "slower" explosion than previously thought.





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

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

[topic 1] Can modern supernova simulations synthesize sufficient 56Ni?

- **Our work**

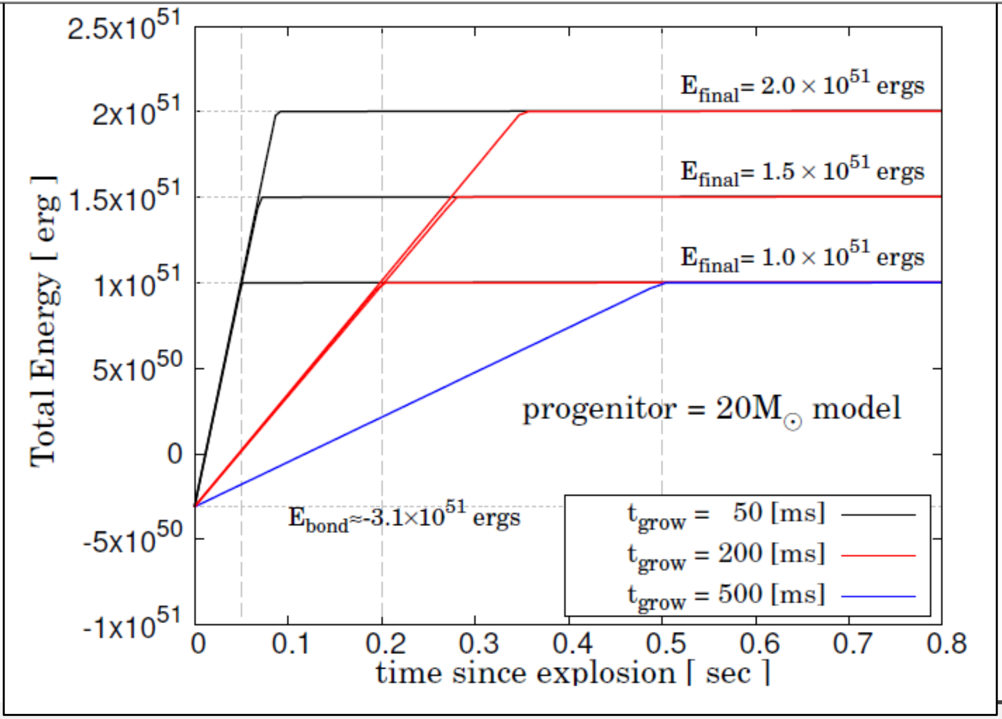
motivation: Does explosion timescale (t_{grow}) affect nucleosynthesis?

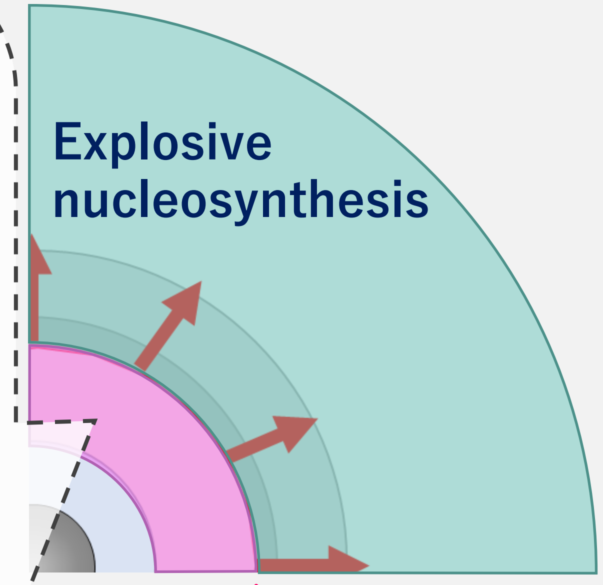
↓

simulation: 1D hydrodynamics and nucleosynthesis with explosion timescale as a parameter

expl. model

Inject thermal energy $\dot{E}_{exp}$ into pre-SN stars





↑ Injection Boundary：Ye<0.48

[topic 1] Can modern supernova simulations synthesize sufficient 56Ni?

- **Our work**

motivation: Does explosion timescale (t_{grow}) affect nucleosynthesis?

↓

simulation: 1D hydrodynamics and nucleosynthesis with explosion timescale as a parameter

✓ model: thermal energy $\dot{E}_{\mathrm{expl.}}$ injected into the surface of proto-neutron stars

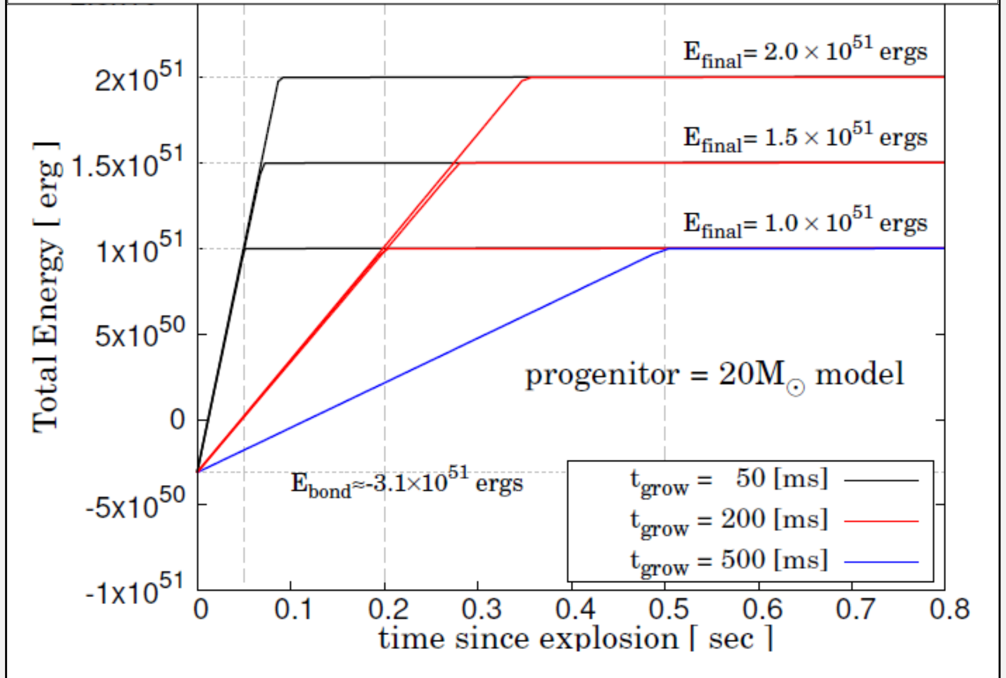
✓ Progenitor : $M_{ZAMS} = 15, 20, 25 M_{\odot}$

✓ hydrodynamics : based on "bl-code".

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

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

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



[topic 1] Can modern supernova simulations synthesize sufficient 56Ni?

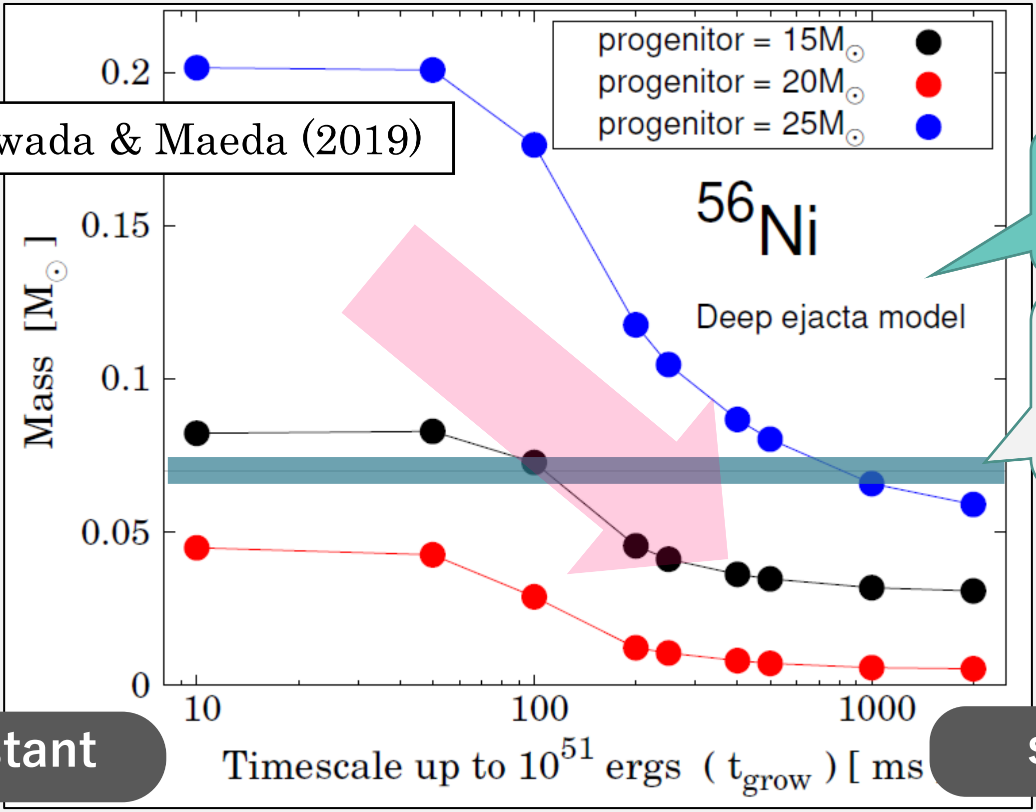
- **Our work**

motivation: Does explosion timescale (t_{grow}) affect nucleosynthesis?

↓

simulation: 1D hydrodynamics and nucleosynthesis with explosion timescale as a parameter

Sawada & Maeda (2019)



instant — slow

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

synthesized amount = maximum value that can be ejected.

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

"Slow" explosions suppress $M(^{56}\mathrm{Ni})$

→unfavorable trend for observation

[topic 1] Can modern supernova simulations synthesize sufficient 56Ni?

Suwa, Tominaga, & Maeda (2019)

Sawada & Maeda (2019)

(1) radiation dominant & isothermal @post-shock region,

(2) adiabatic/constant vel. expansion($r_{\rm shock} = v_{\rm shock} \cdot t$),

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

✓ When the explosion is sufficiently instantaneous, then

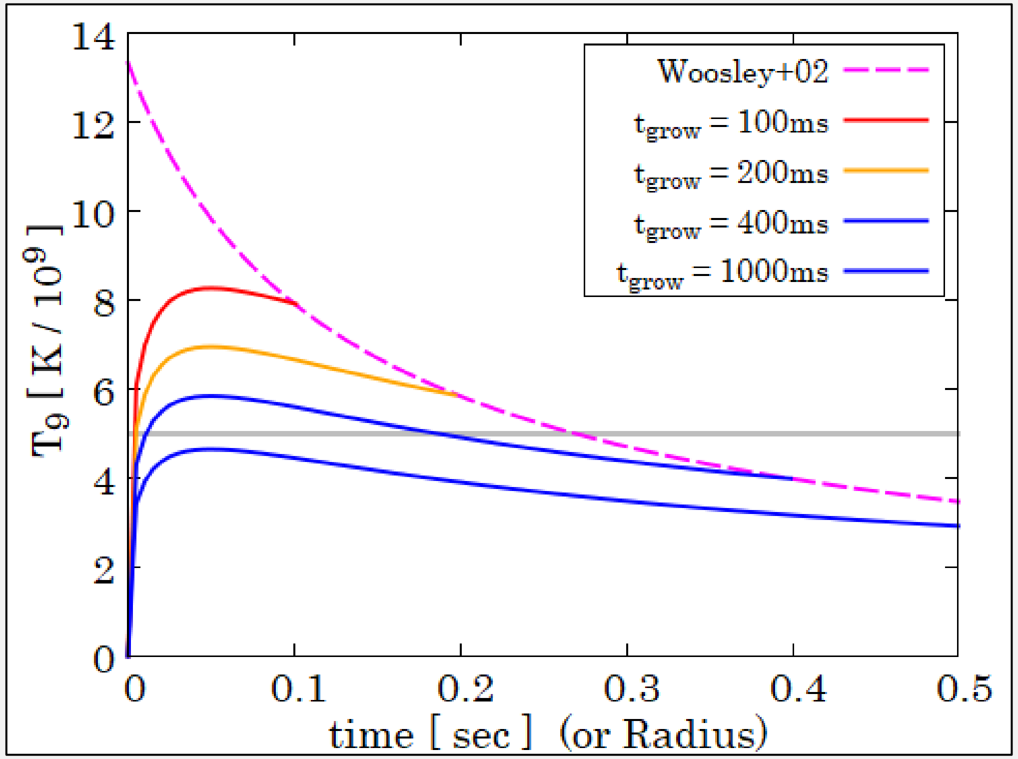
Deposit $E_{\rm exp} = 10^{51}{\rm erg}$ from the initial setup.

e.g., Woosley+ 2002

✓ When taking into account the growth timescale of the explosion energy, then

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

this work



[topic 1] Can modern supernova simulations synthesize sufficient 56Ni?

Suwa, Tominaga, & Maeda (2019)

Sawada & Maeda (2019)

(1) radiation dominant & isothermal @post-shock region,

(2) adiabatic/constant vel. expansion($r_{\mathrm{shock}} = v_{\mathrm{shock}} \cdot t$),

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

✓ When the explosion is sufficiently instantaneous, then

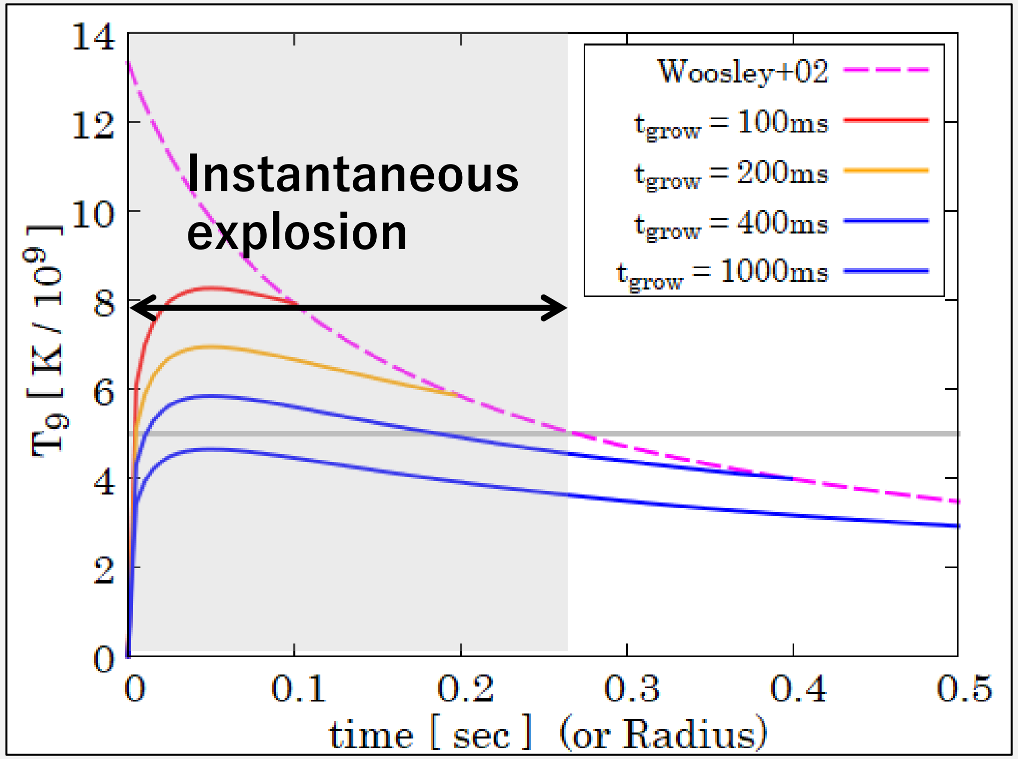
Deposit $E_{\mathrm{exp}} = 10^{51}\mathrm{erg}$ from the initial setup.

e.g., Woosley+ 2002

✓ When taking into account the growth timescale of the explosion energy, then

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

this work



[topic 1] Can modern supernova simulations synthesize sufficient 56Ni?

Suwa, Tominaga, & Maeda (2019)

Sawada & Maeda (2019)

(1) radiation dominant & isothermal @post-shock region,

(2) adiabatic/constant vel. expansion($r_{\mathrm{shock}} = v_{\mathrm{shock}} \cdot t$),

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

✓ When the explosion is sufficiently instantaneous, then

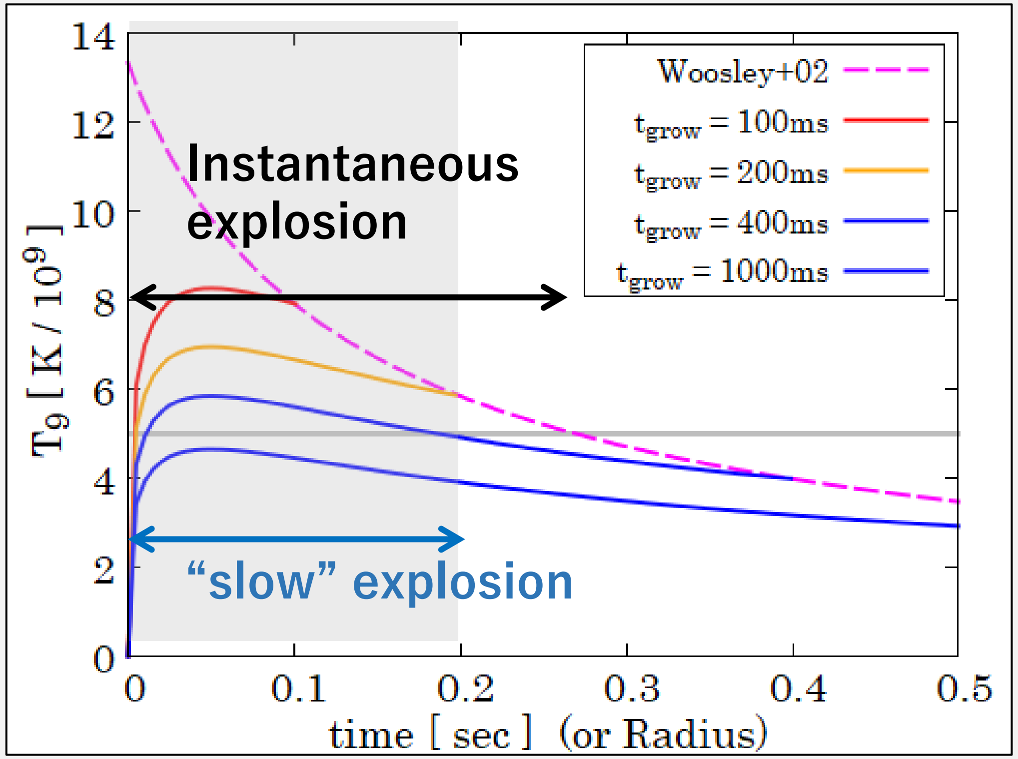
Deposit $E_{\mathrm{exp}} = 10^{51}\mathrm{erg}$ from the initial setup.

e.g., Woosley+ 2002

✓ When taking into account the growth timescale of the explosion energy, then

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

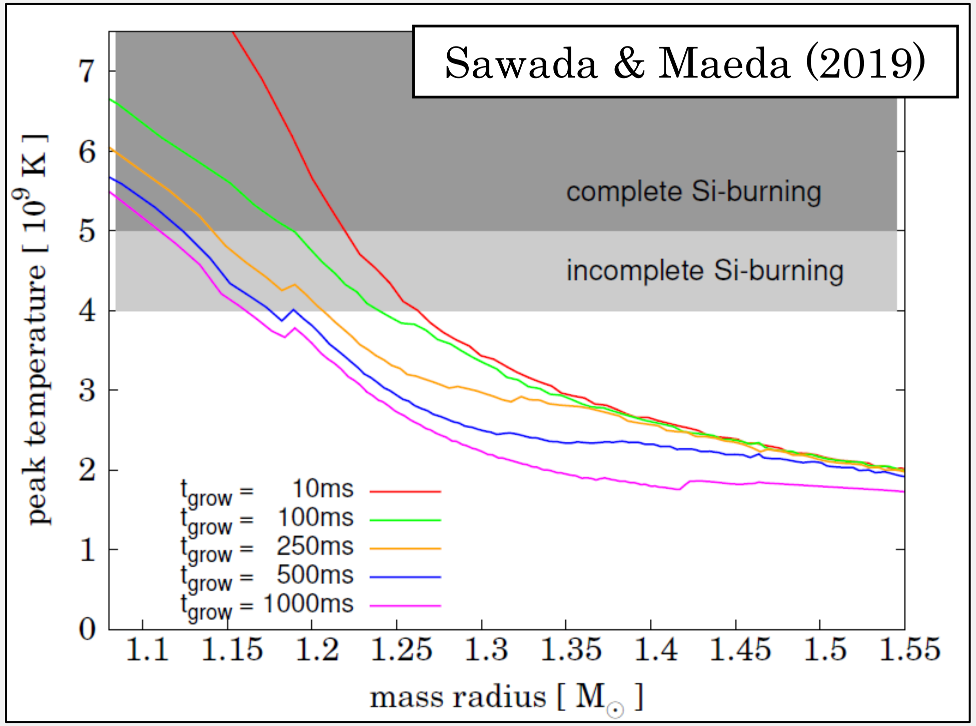
this work

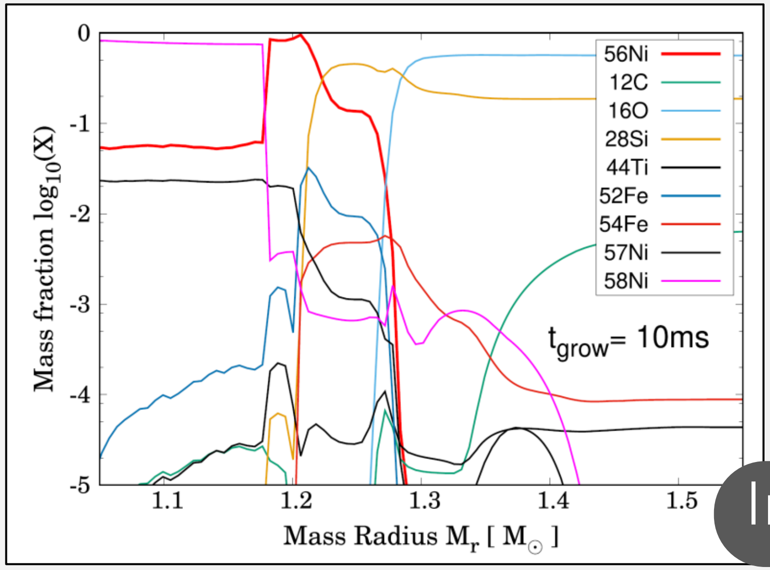


[topic 1] Can modern supernova simulations synthesize sufficient 56Ni?

- **Peak tempareture**

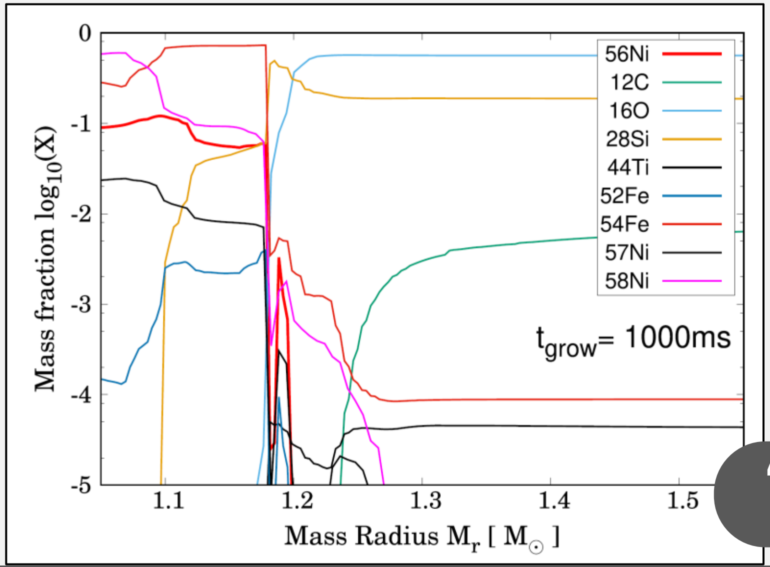
$t_{grow} = 10[ms]$





Instant expl.

$t_{grow} = 1000[ms]$



‘slow’ expl.

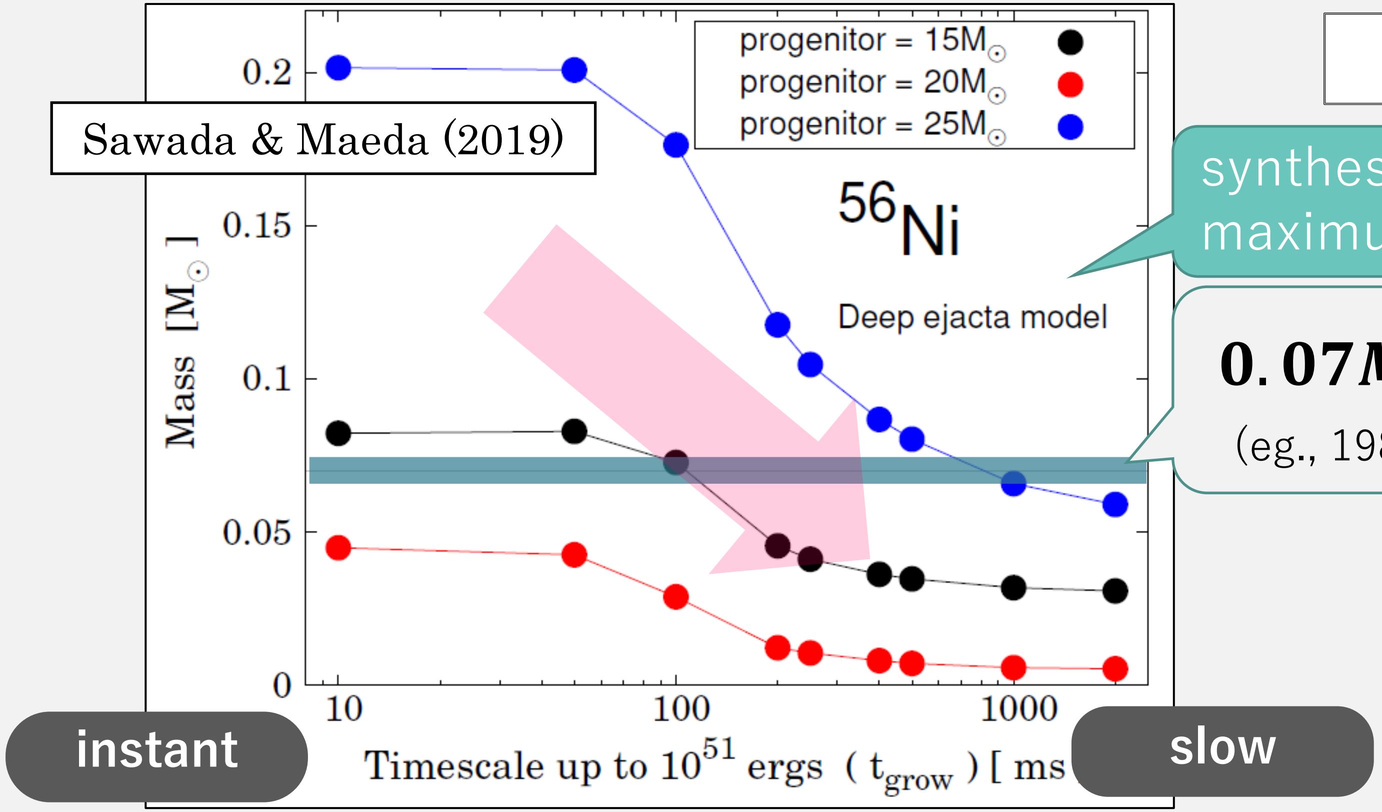
[topic 1] Can modern supernova simulations synthesize sufficient 56Ni?

- **Our work**

motivation: Does explosion timescale (t_{grow}) affect nucleosynthesis?

↓

simulation: 1D hydrodynamics and nucleosynthesis with explosion timescale as a parameter



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

synthesized amount = maximum value that can be ejected.

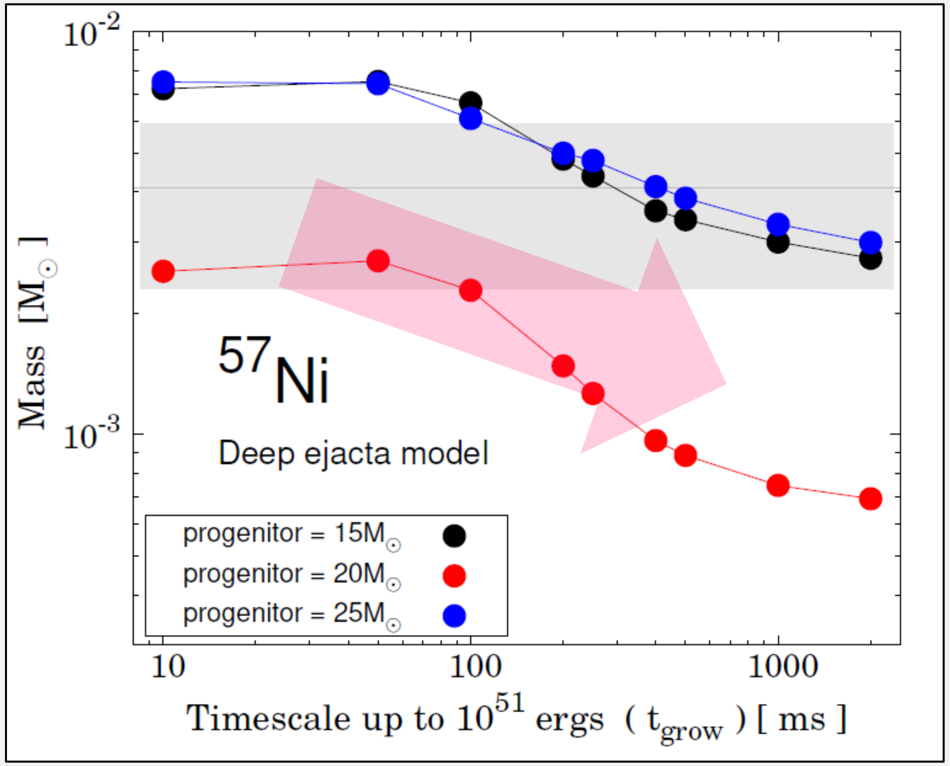
$\mathbf{0.07}M_{\odot}$; typical value (eg., 1987A, 1993J, 2002ap...)

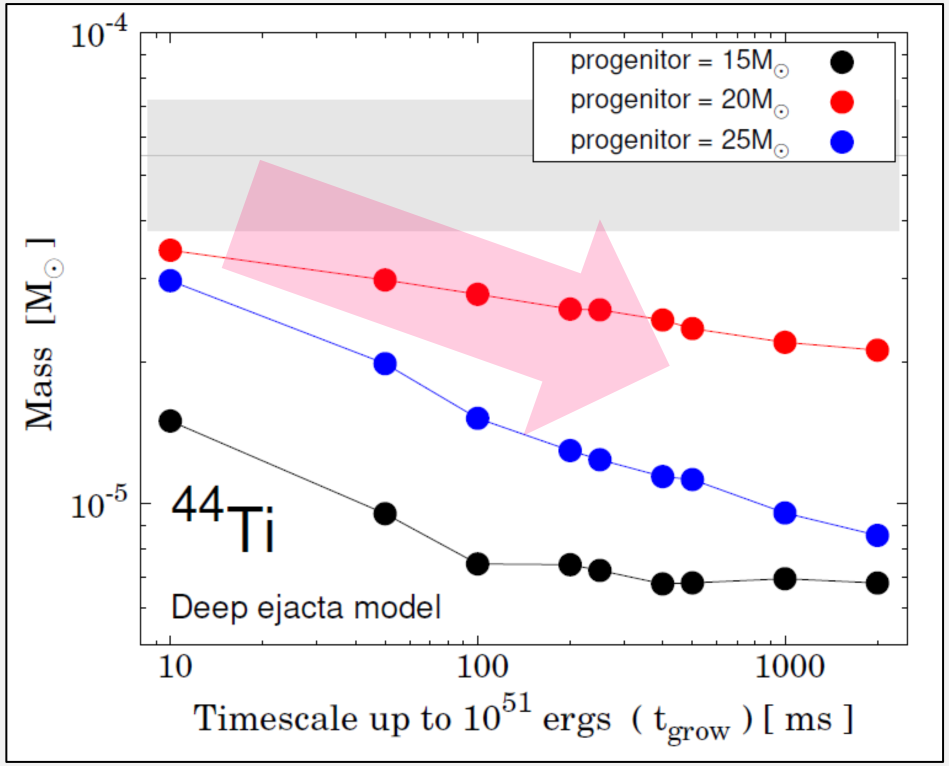
"Slow" explosions suppress $M(^{56}\mathrm{Ni})$

→unfavorable trend for observation

[topic 1] Can modern supernova simulations synthesize sufficient 56Ni?

※ 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).

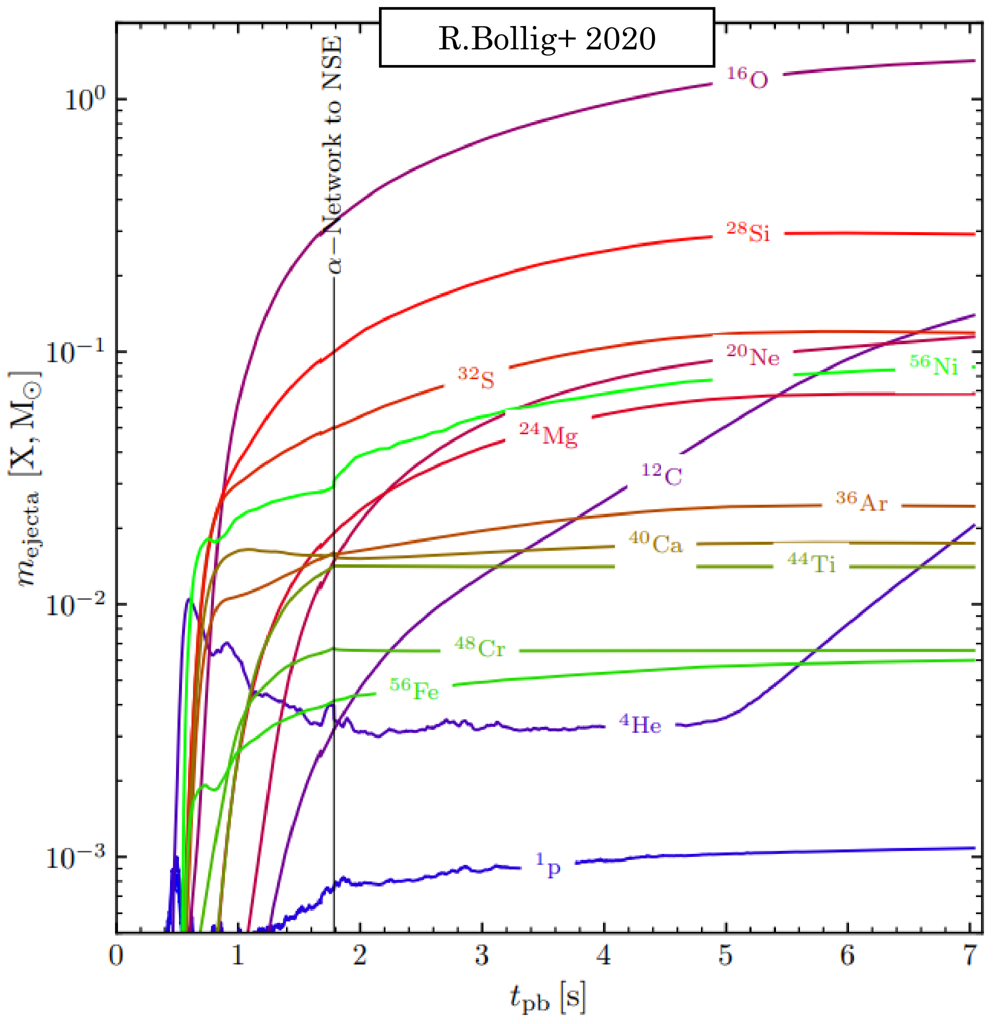
[topic 1] Can modern supernova simulations synthesize sufficient 56Ni?

- **NOTE (1): all models ?**

  some models in the state-of-the-art simulations have succeeded in producing the typical mass $0.07M_{\odot}$ of 56Ni in CCSNe,

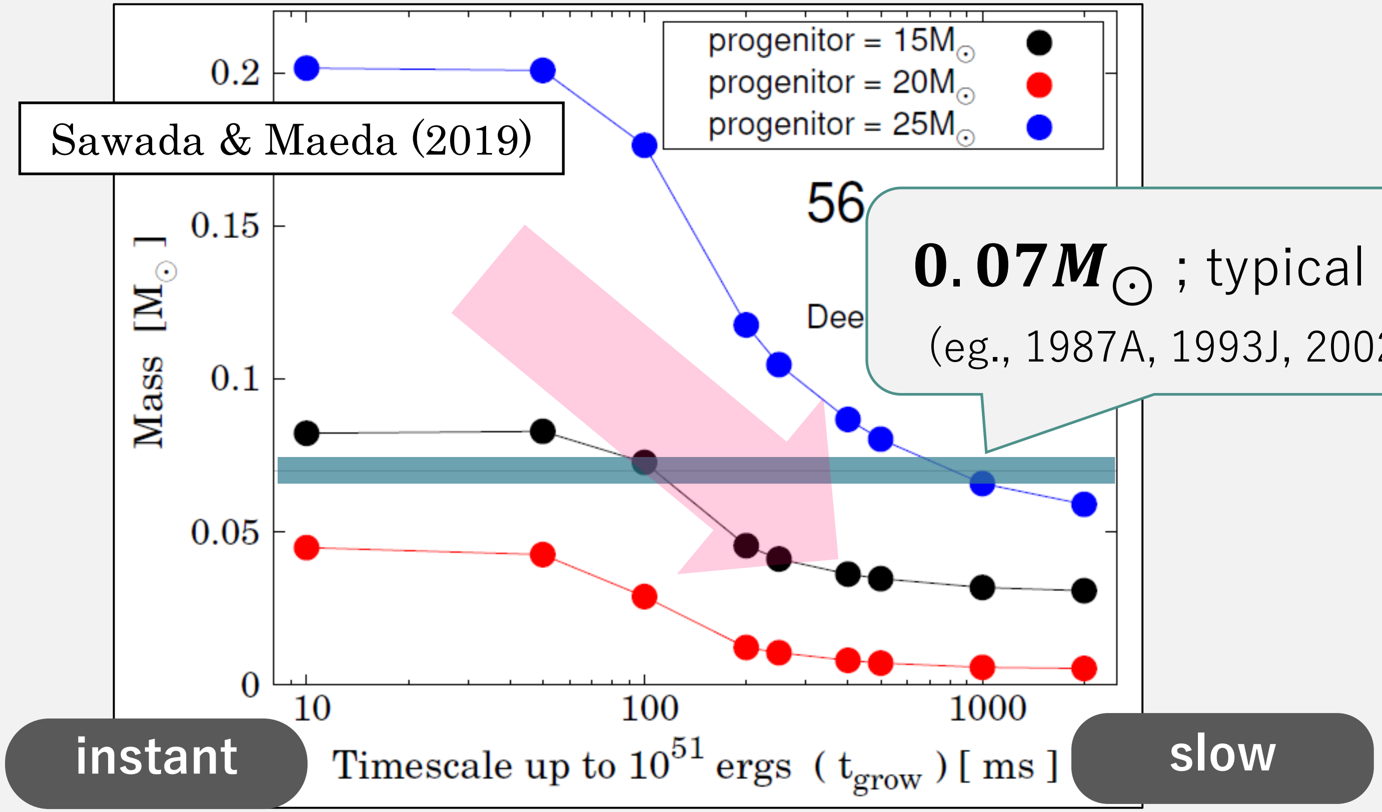
But 'nickel mass problem'(Ni problem)

→ unclear whether we can reproduce sufficient 56Ni amount **as a canonical nature.**

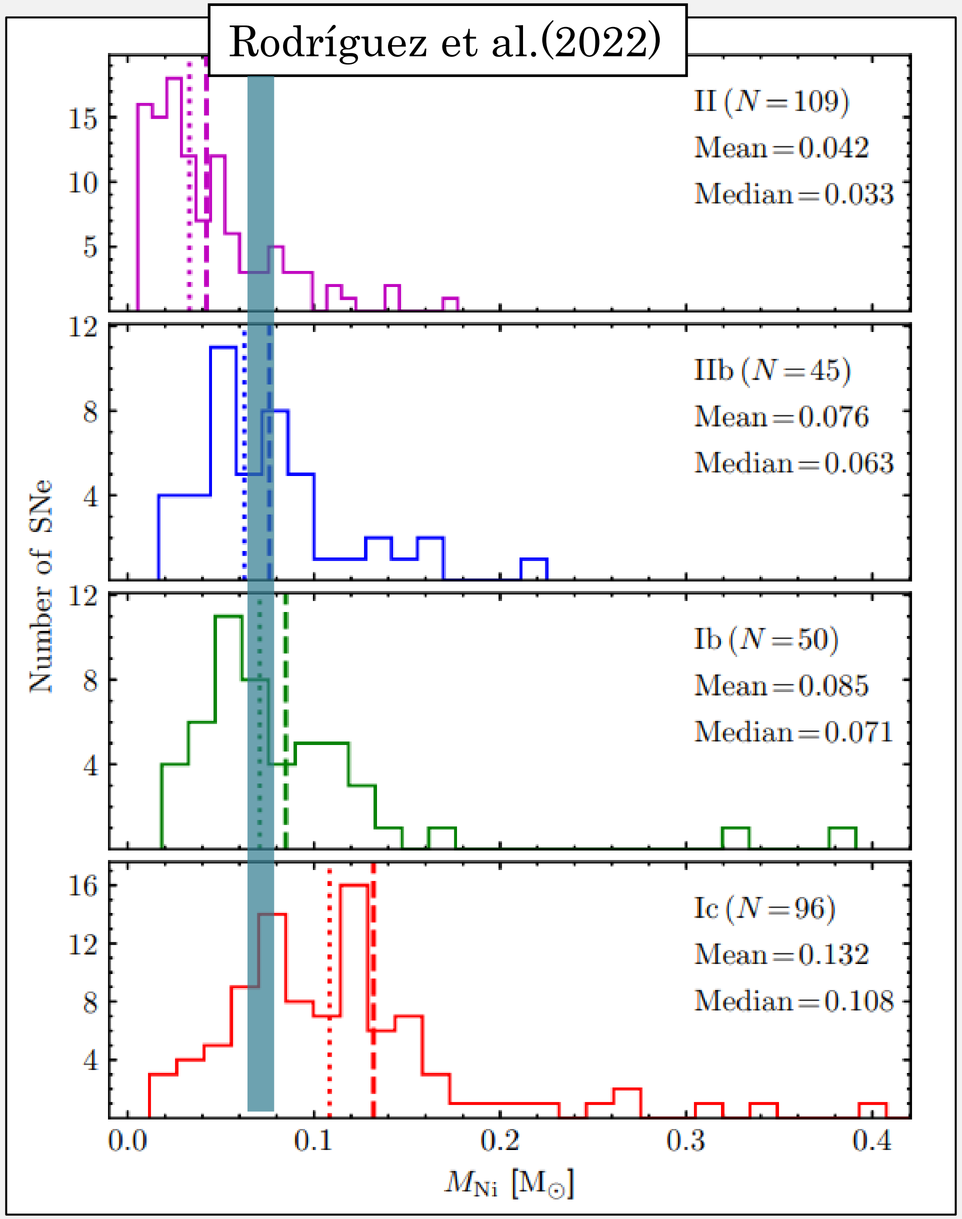


[topic 1] Can modern supernova simulations synthesize sufficient 56Ni?

- **NOTE (2): choice of typical value?**

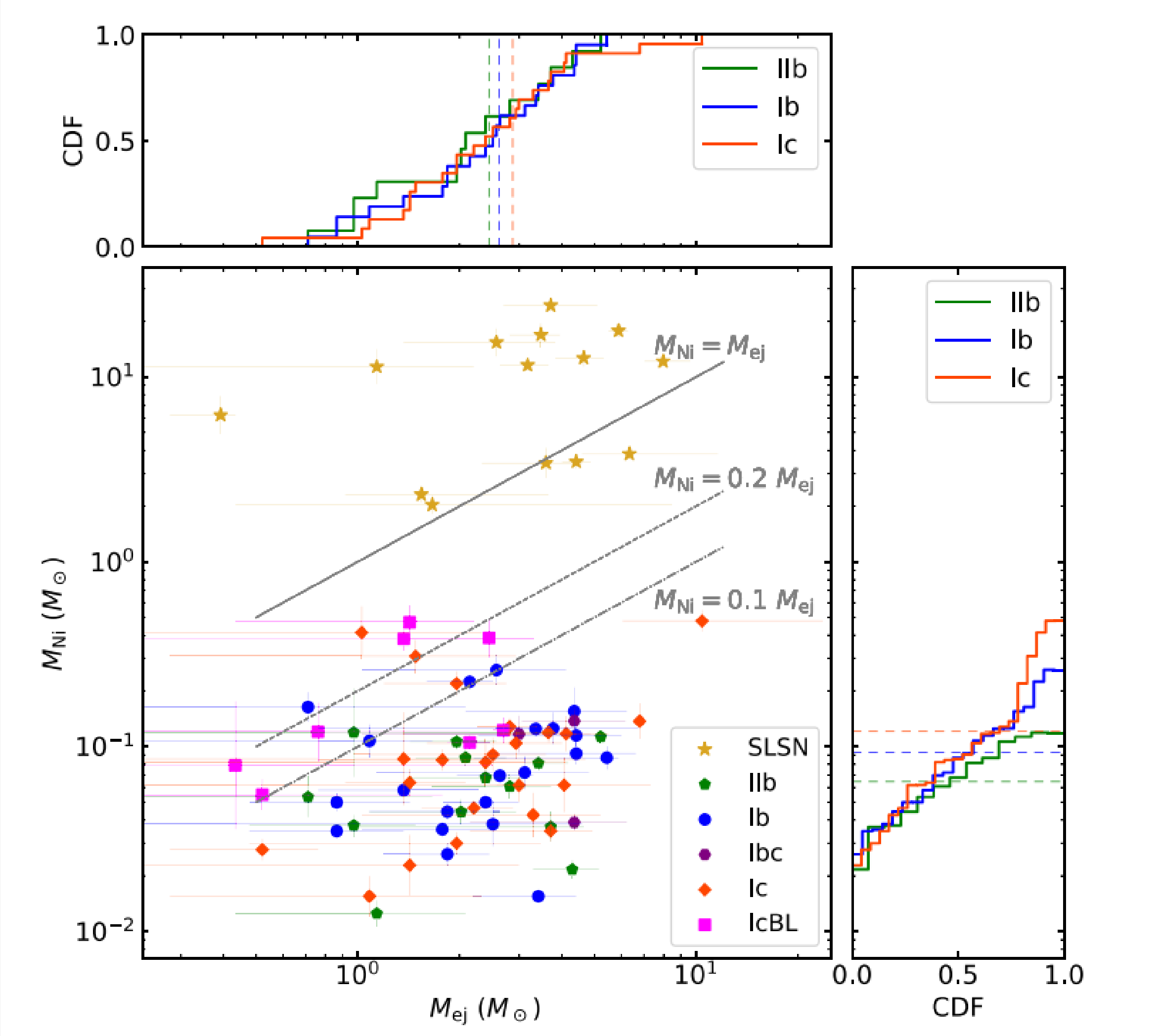


$0.07M_\odot$; typical value
(eg., 1987A, 1993J, 2002ap...)

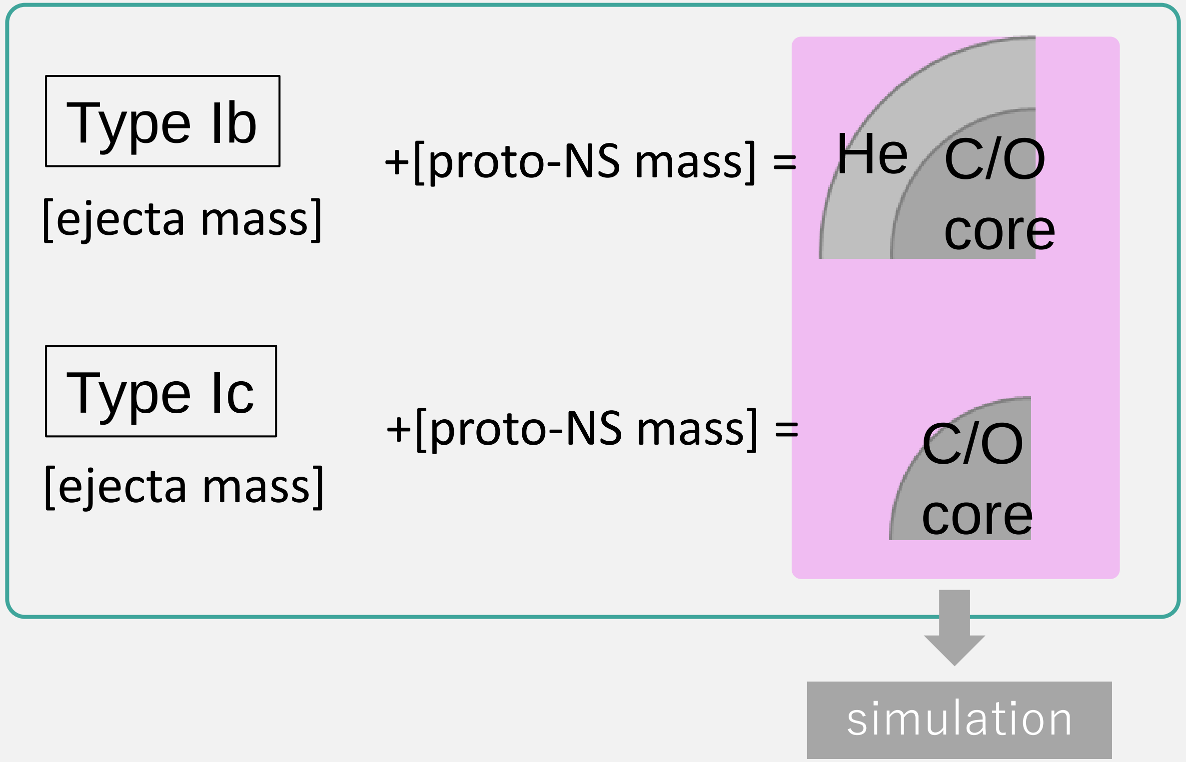


[topic 1] Can modern supernova simulations synthesize sufficient 56Ni?

- **NOTE (2): choice of typical value?**



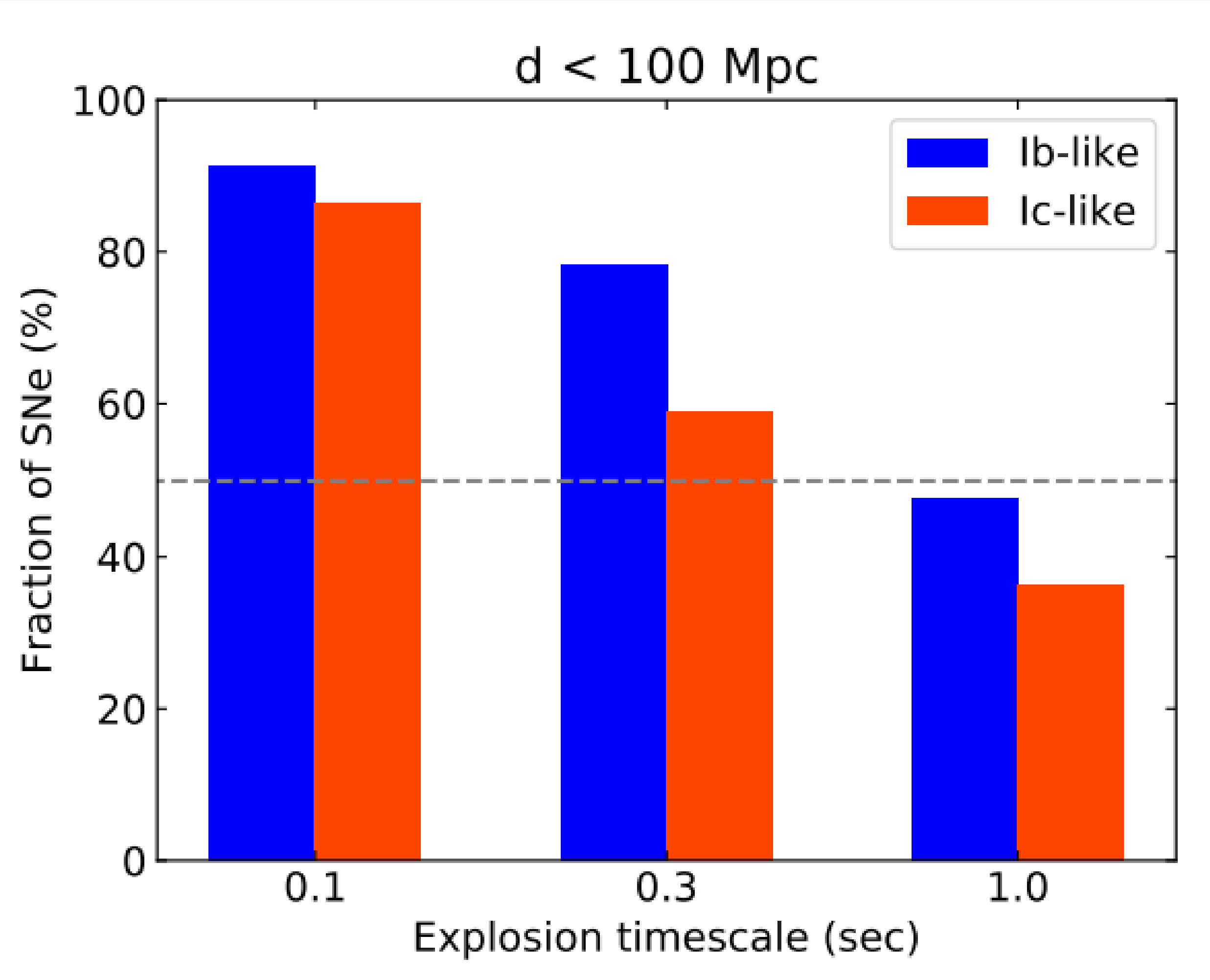
How to estimate the progenitor structure before the explosion



1D hydrodynamics and nucleosynthesis
with explosion timescale as a parameter

[topic 1] Can modern supernova simulations synthesize sufficient 56Ni?

- **NOTE (2): choice of typical value?**



A few tens of percent of observations can be explained by the *non-standard supernova explosions*,

But, the timescales that reproduce less than 50% are difficult to adopt as standard explosion models.

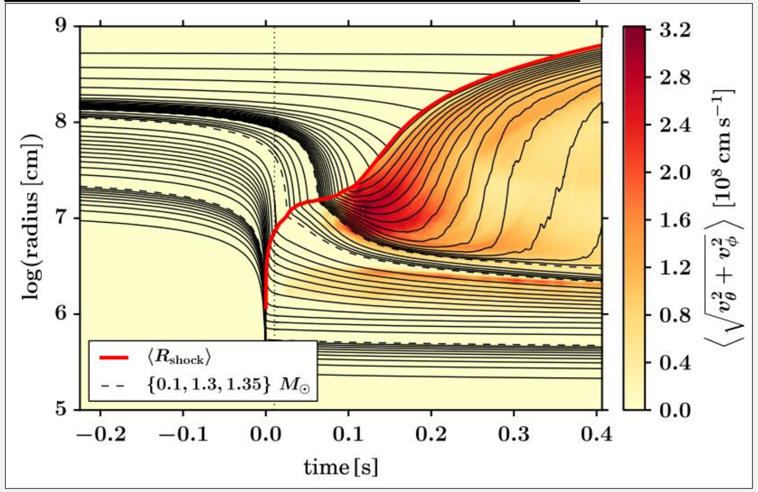
"Constraints on the Explosion Timescale of Core-collapse Supernovae Based on Systematic Analysis of Light Curves"
Saito, Tanaka, Sawada, & Moriya (2022), ApJ 931, 153 (arXiv:2205.00624)

[topic 1] Can modern supernova simulations synthesize sufficient 56Ni?

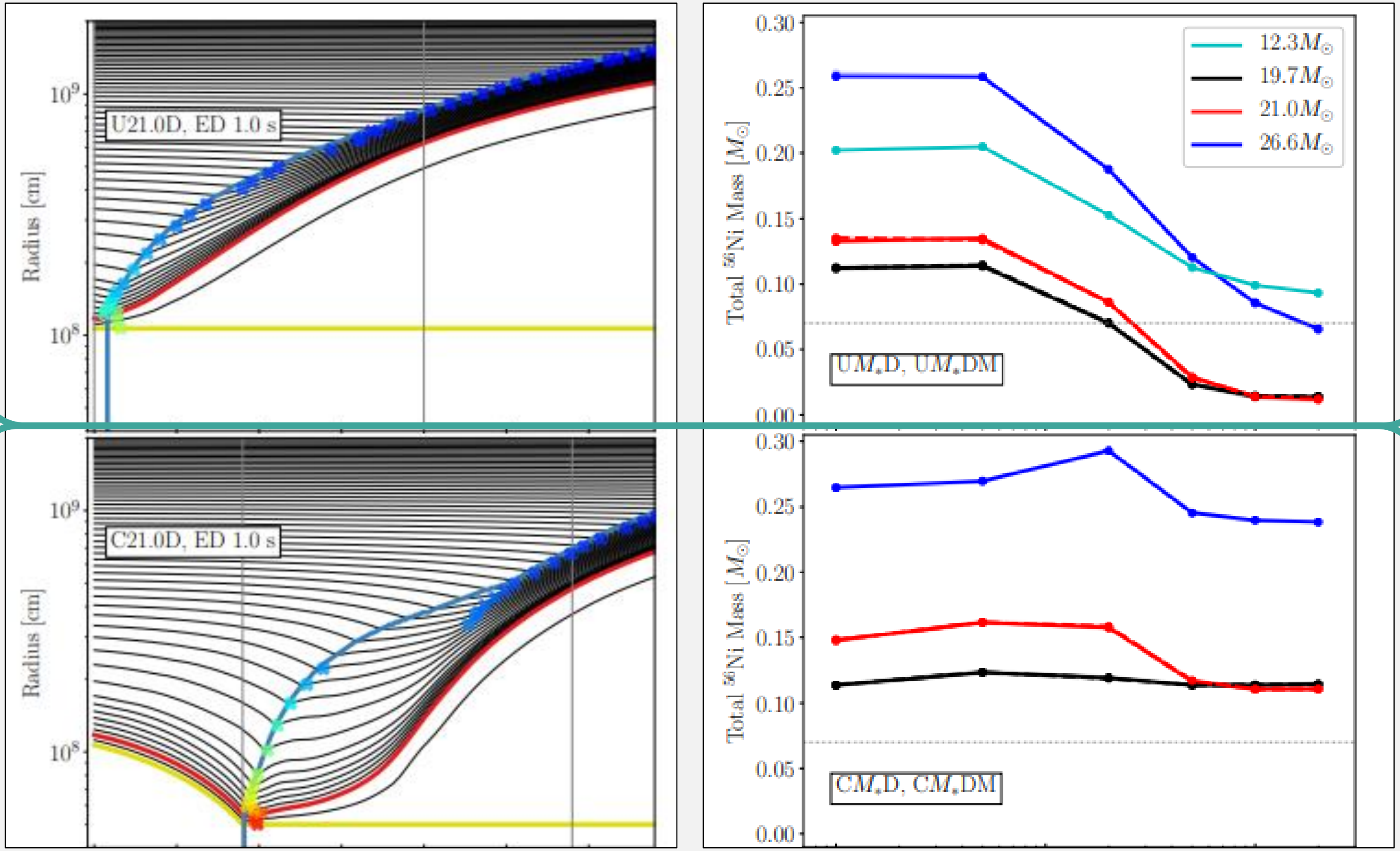
- **<u>NOTE (3): Opposition to this study</u>** (Imasheva + 2022)

They pointed out that
**"This results may comes from
the explosion model assumed
in our calculations is too simple?"**

Melson, Janka & Marek 2015



Imasheva + 2022



[topic 1] Can modern supernova simulations synthesize sufficient 56Ni?

- **Our work** 1D hydrodynamics and nucleosynthesis

simulation

with more realistic explosion calculations /with lightbulb approximation
(not detailed, but mimics neutrino-driven explosions to some extent)

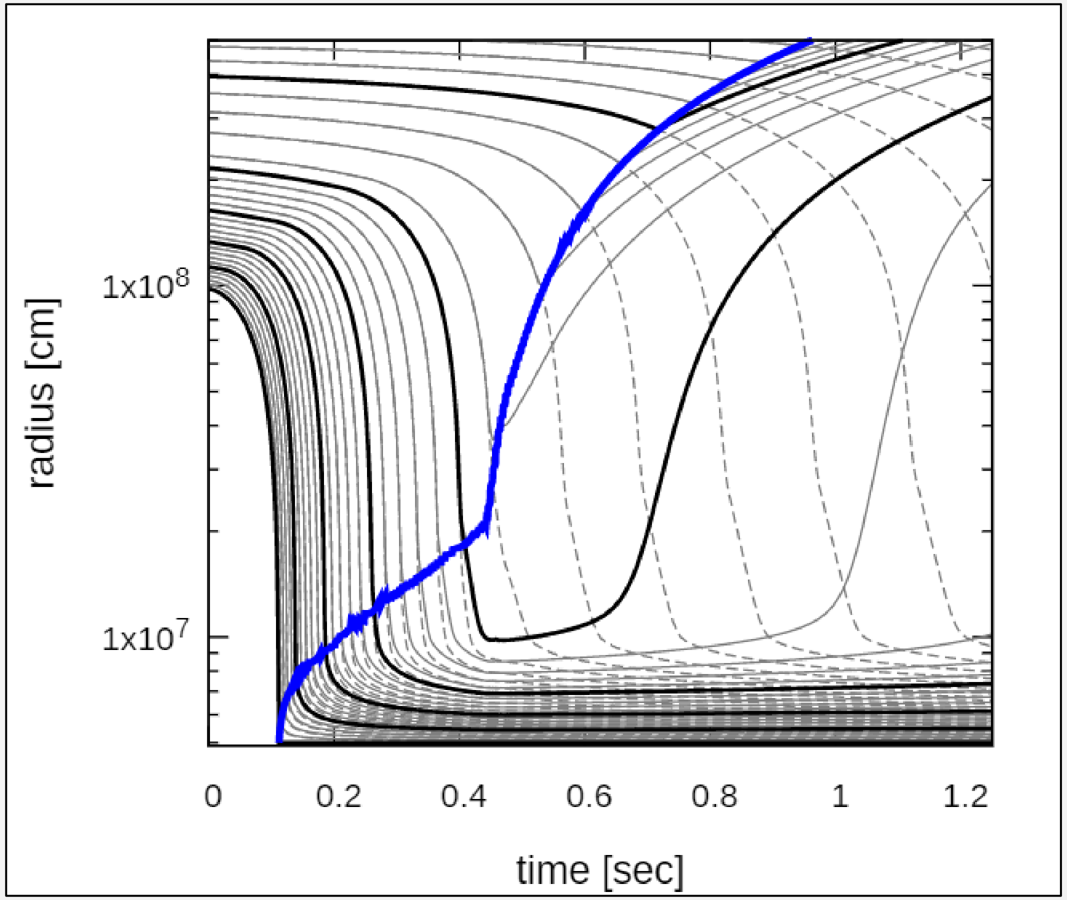
$$\frac{\partial r}{\partial M_r} = \frac{1}{4\pi r^2 \rho}, \quad (5)$$

$$\frac{Dv}{Dt} = -\frac{GM_r}{r^2} - 4\pi r^2 \frac{\partial P}{\partial M_r}, \quad (6)$$

$$\frac{D\epsilon}{Dt} = -P\frac{D}{Dt}\left(\frac{1}{\rho}\right) + \mathcal{H} - \mathcal{C}, \quad (7)$$

$$\mathcal{H} = 1.544 \times 10^{20} \text{ erg g}^{-1} \text{ s}^{-1} \times \left(\frac{L_{\nu_e}}{10^{52}\text{MeV}}\right)\left(\frac{r_{\nu_e}}{100\text{km}}\right)^{-2}\left(\frac{T_{\nu_e}}{4.0\text{MeV}}\right)^2,$$

$$\mathcal{C} = 1.399 \times 10^{20} \text{ erg g}^{-1} \text{ s}^{-1} \times \left(\frac{T}{2.0\text{MeV}}\right)^6.$$

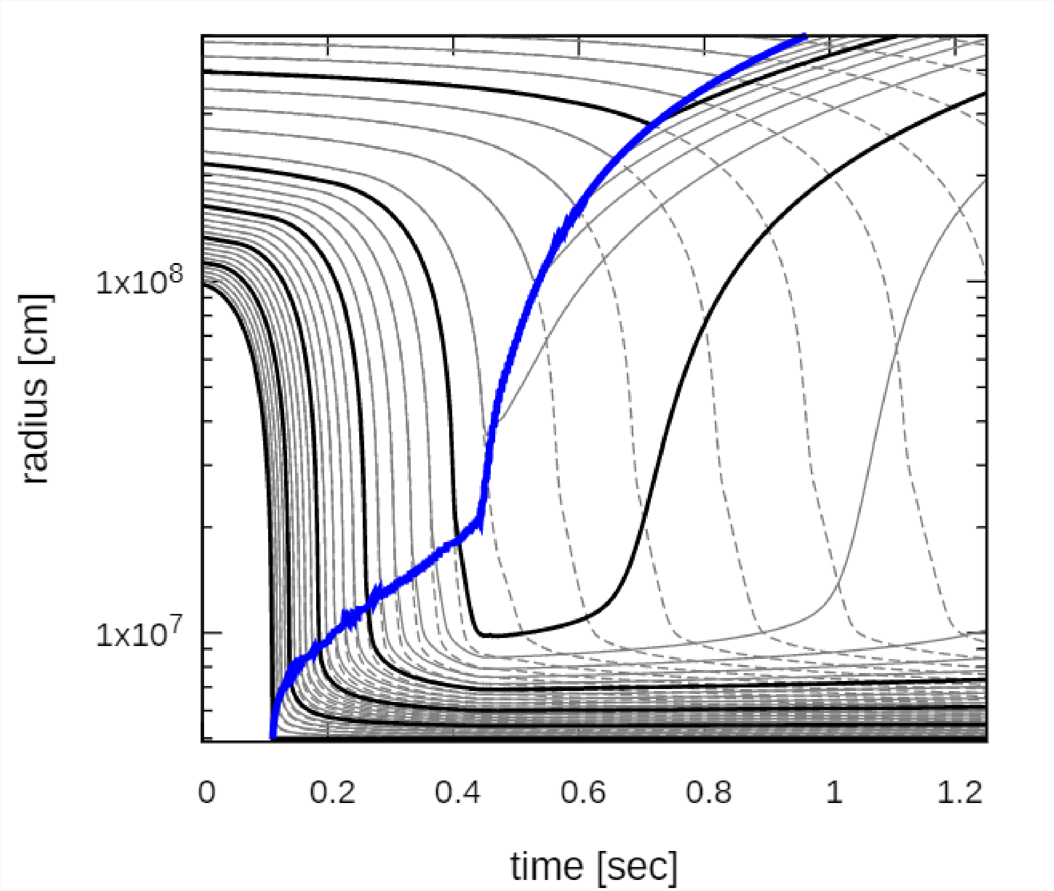


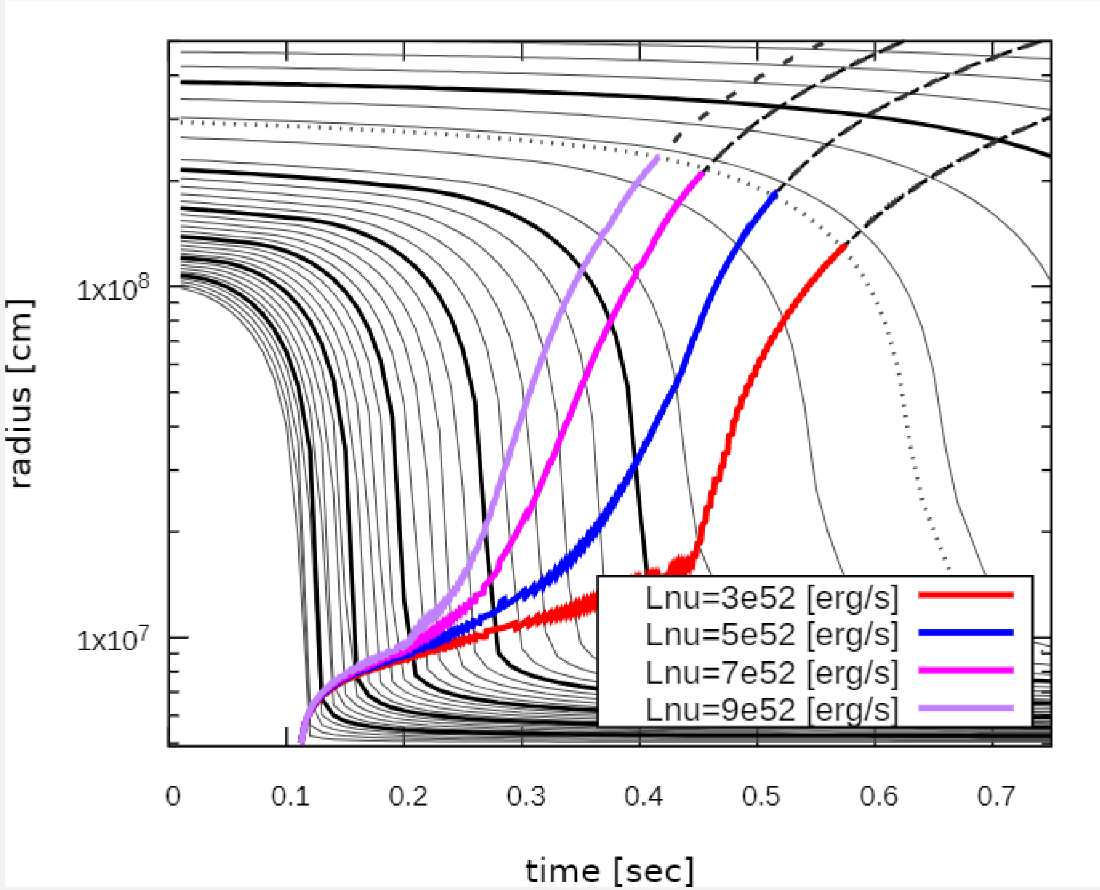
[topic 1] Can modern supernova simulations synthesize sufficient 56Ni?

- **Our work** 1D hydrodynamics and nucleosynthesis

simulation

with more realistic explosion calculations /with lightbulb approximation
(not detailed, but mimics neutrino-driven explosions to some extent)



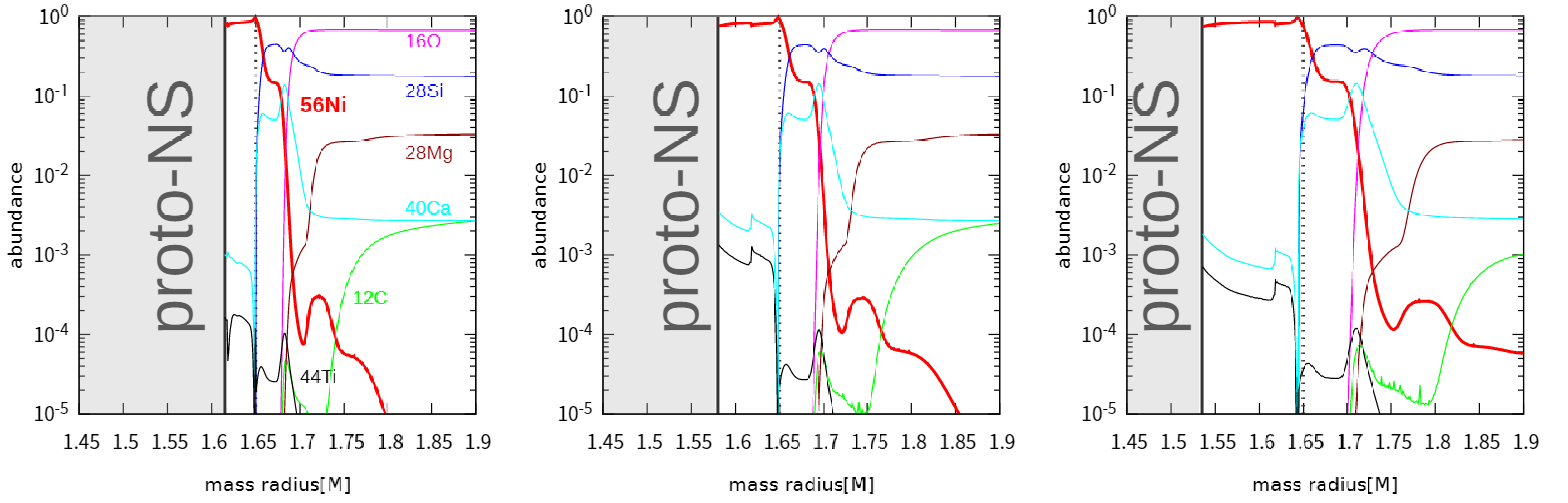


[topic 1] Can modern supernova simulations synthesize sufficient 56Ni?

- **Our work**

simulation

1D hydrodynamics and nucleosynthesis
with more realistic explosion calculations /with lightbulb approximation
(not detailed, but mimics neutrino-driven explosions to some extent)

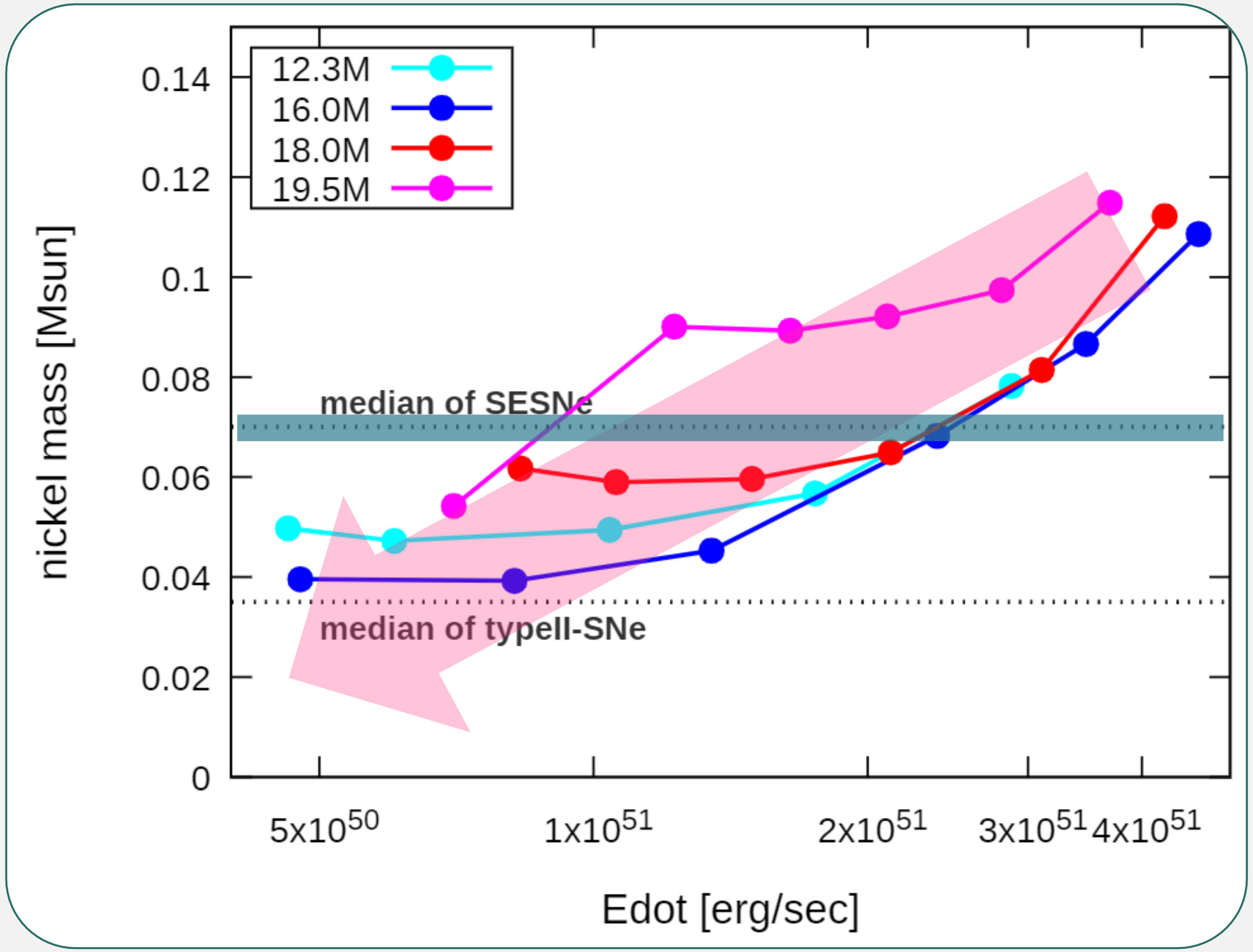


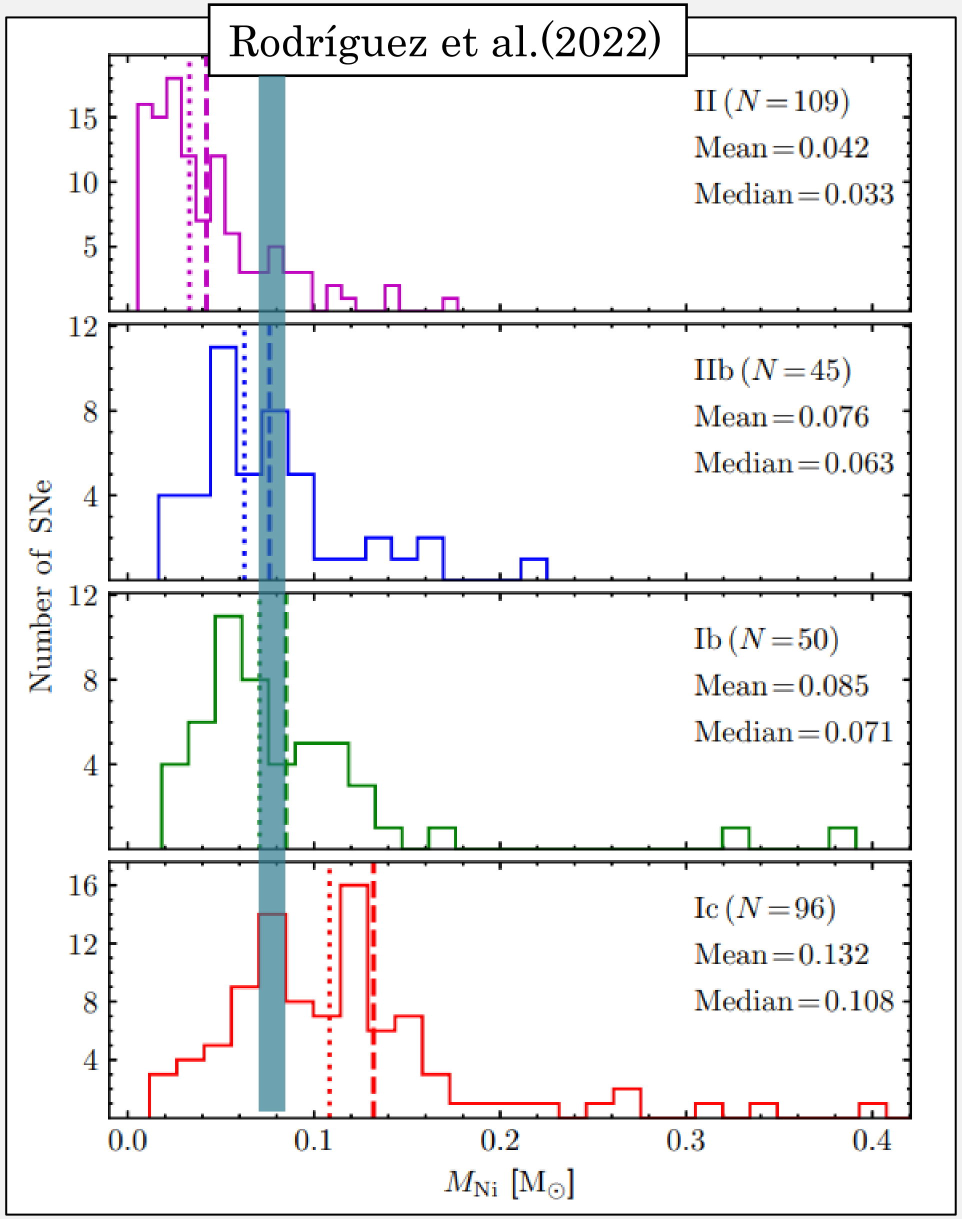
(a) (b) (c)

[topic 1] Can modern supernova simulations synthesize sufficient 56Ni?

- **NOTE (3): Opposition to this study** (Imasheva + 2022)

->Using more realistic explosion calculations /with lightbulb approximation (not detailed, but mimics neutrino-driven explosions to some extent)

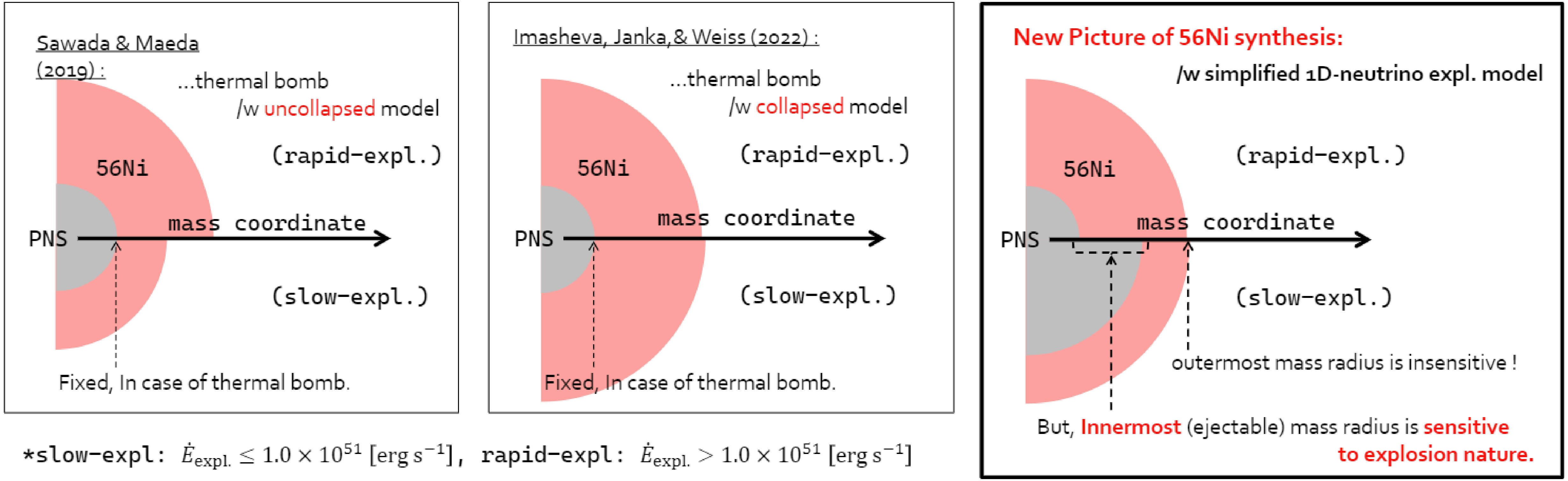




[topic 1] Can modern supernova simulations synthesize sufficient 56Ni?

- **<u>NOTE (3): Opposition to this study</u>** (Imasheva + 2022)

->Using more realistic explosion calculations /with lightbulb approximation
(not detailed, but mimics neutrino-driven explosions to some extent)



*slow-expl: $\dot{E}_{\rm expl.} \leq 1.0 \times 10^{51}$ [erg s^{-1}], rapid-expl: $\dot{E}_{\rm expl.} > 1.0 \times 10^{51}$ [erg s^{-1}]

Figure 11. Schematic picture of core-collapse supernova.