A Consistent Modeling of Neutrino-driven Wind with Accretion Flow onto a Proto-Neutron Stars and its Implications for 56 Ni Production

Ryo Sawada (澤田 涼) Univ. of Tokyo / JSPS fellow PD

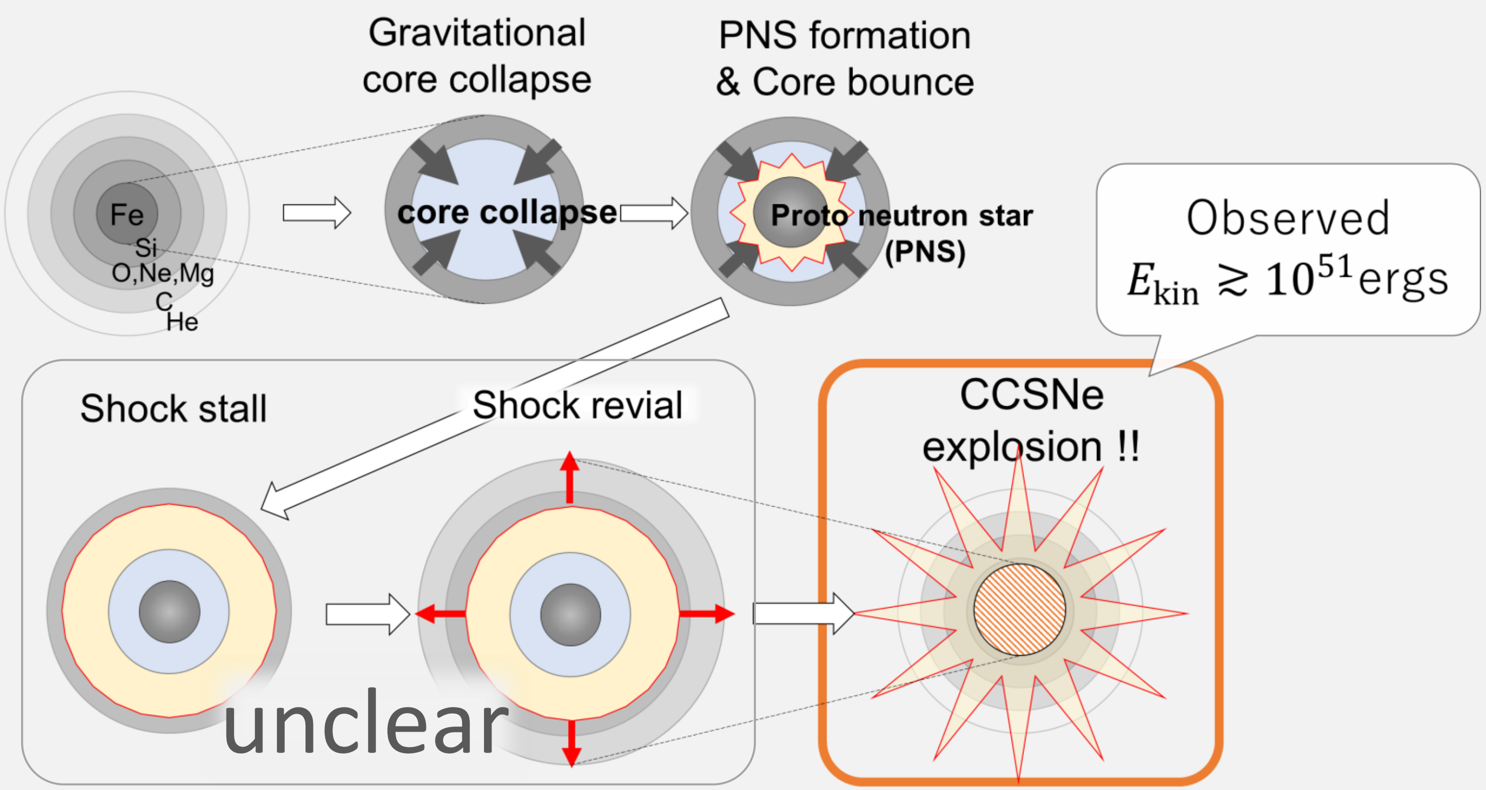
Collaborator：
Yudai Suwa (Univ. of Tokyo & YITP, Kyoto Univ.)
Keiichi Maeda (Kyoto Univ.)

Reference：

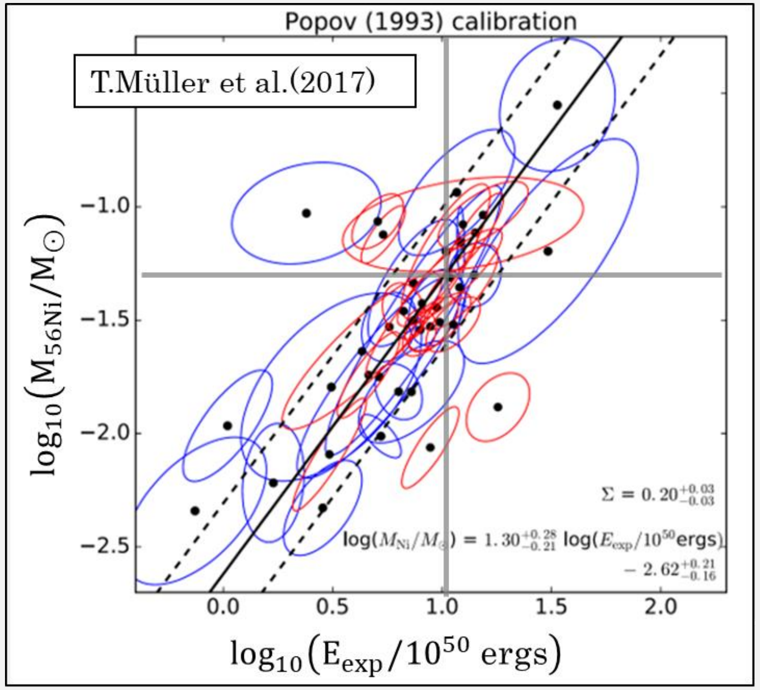
- “A Consistent Modeling of Neutrino-driven Wind with Accretion Flow onto a Protoneutron Star and its Implications for 56Ni Production”
  Sawada & Suwa (2021), ApJ, 908, 6 (arxiv. 2010.05615)
- “Nucleosynthesis Constraints on the Energy Growth Timescale of a Core-collapse Supernova Explosion”
  Sawada & Maeda (2019), ApJ, 886, 47 (arxiv.1910.06972)

Explosion mechanism of Core-Collapse SNe

- **neutrino-driven explosion**



- **observation**



(average property) $E_{kin} \sim 10^{51}$ [erg]

$M_{56ni} \sim 0.07\ [M_\odot]$

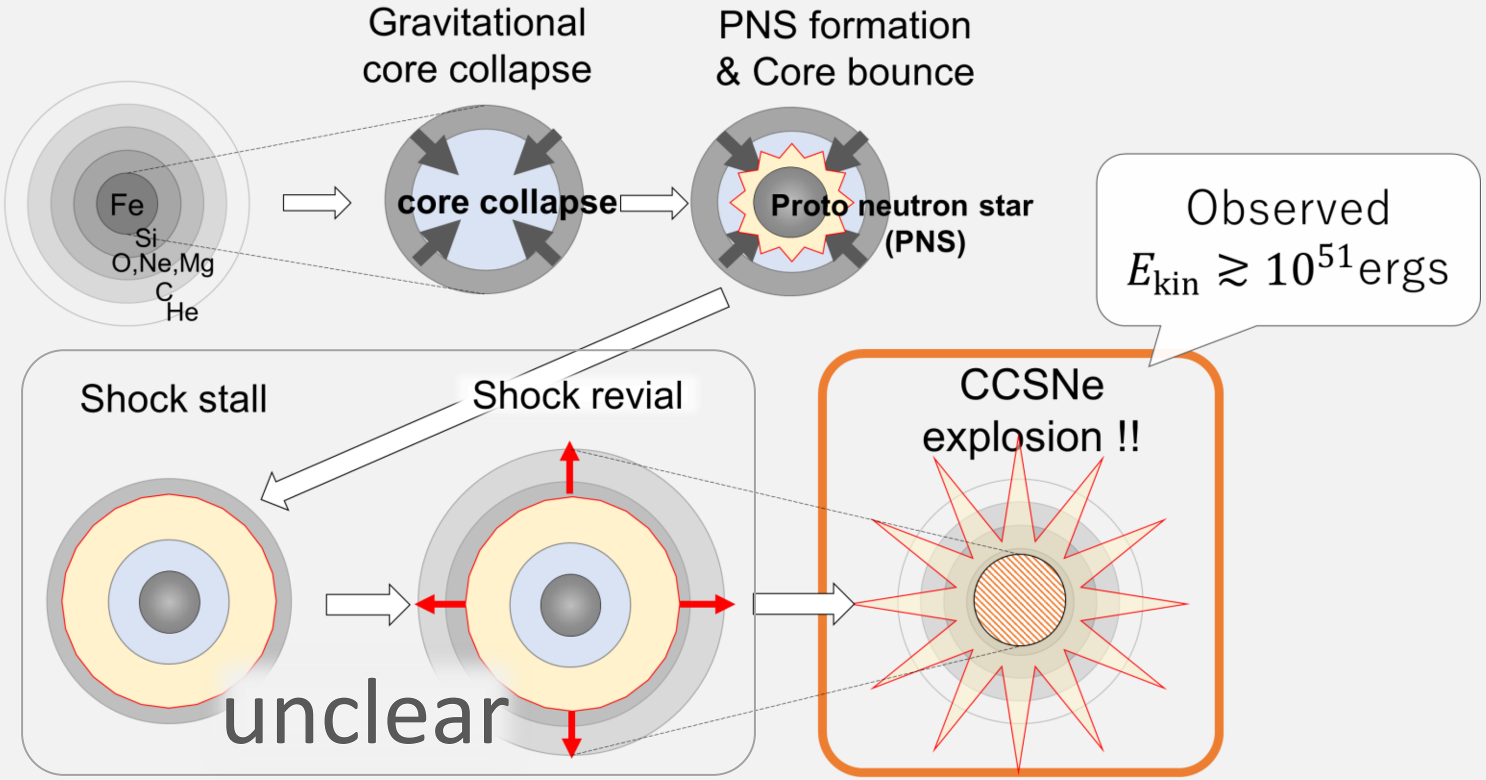
*unclear：

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

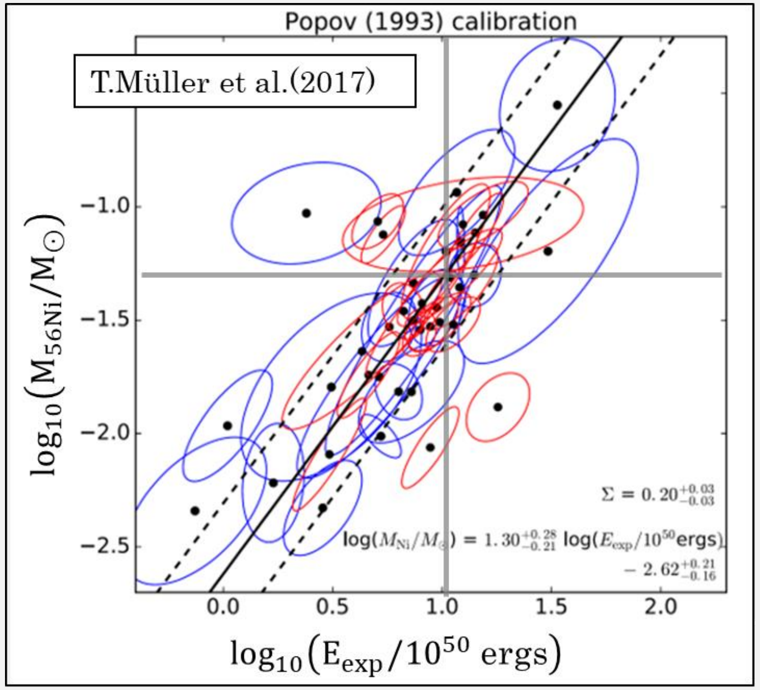
2). Can synthesize a sufficient amount of 56Ni?

Explosion mechanism of Core-Collapse SNe

- **neutrino-driven explosion**



- **observation**



(average property) $E_{kin} \sim 10^{51}$ [erg]

$M_{56ni} \sim 0.07\ [M_\odot]$

*unclear：

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

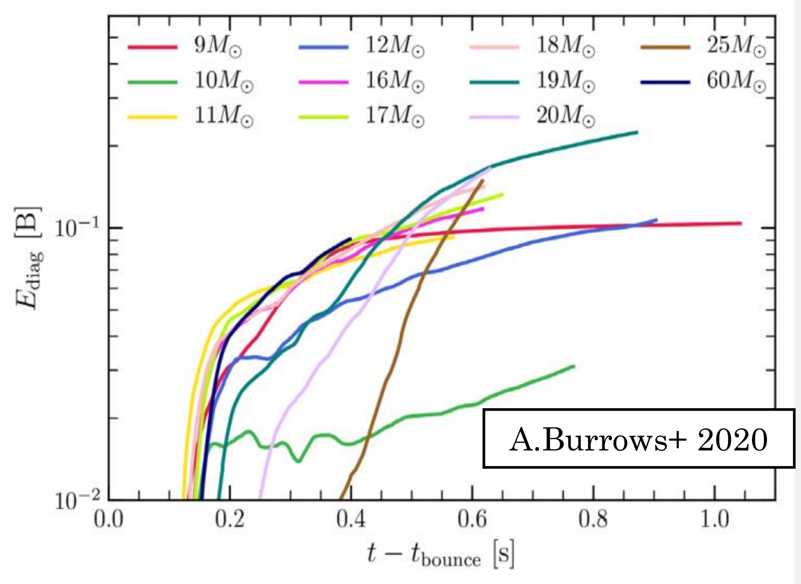
2). Can synthesize a sufficient amount of 56Ni?

Current results from the ab-initio calculation

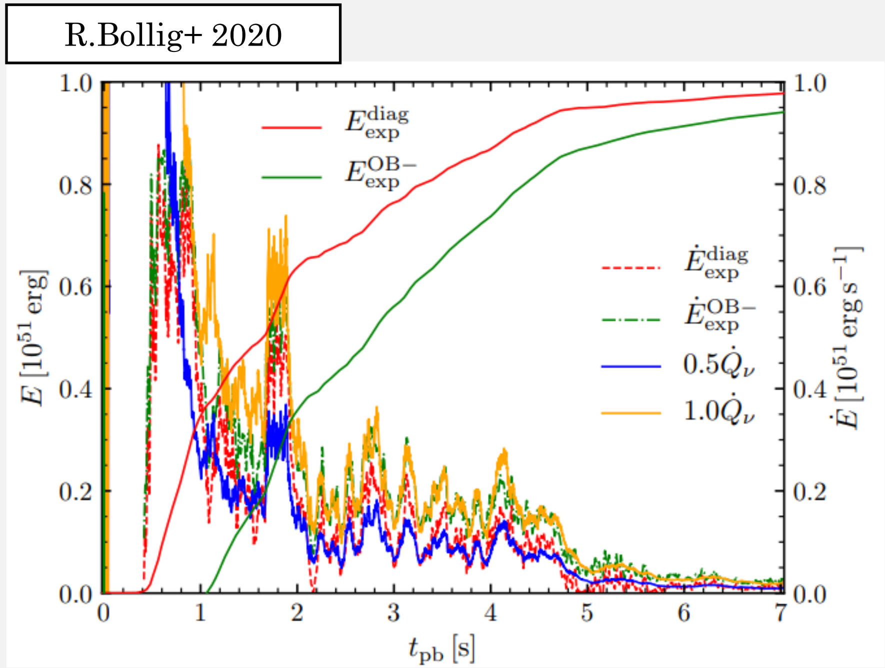
many successful examples

of reproducing explosions

in ab-initio simulations !!



the first example reproducing 10^{51}erg in a 3D ab-initio calculation!



growing rate of the explosion energy

$$\dot{E} \sim \mathcal{O}(0.1)\ [10^{51}\ \mathrm{erg/s}]$$

especially for 3D simulations.

*unclear：

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

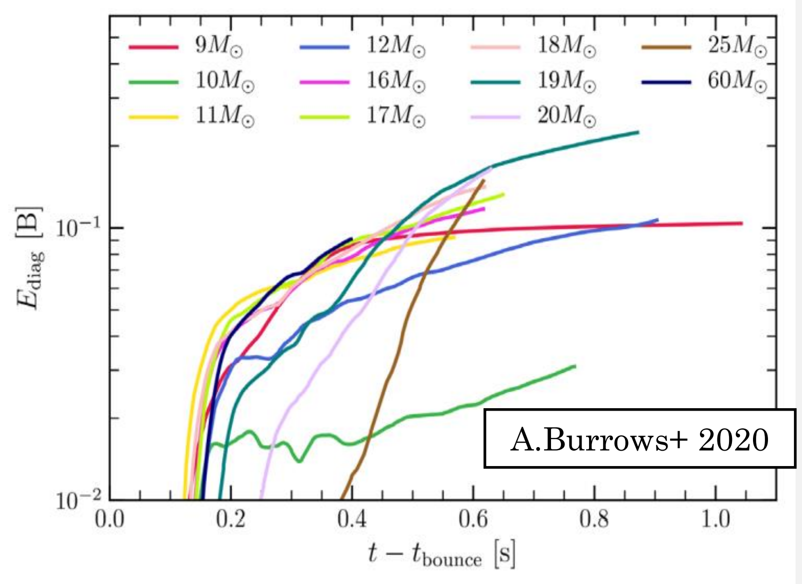
2). Can synthesize a sufficient amount of 56Ni?

Current results from the ab-initio calculation

many successful examples

of reproducing explosions

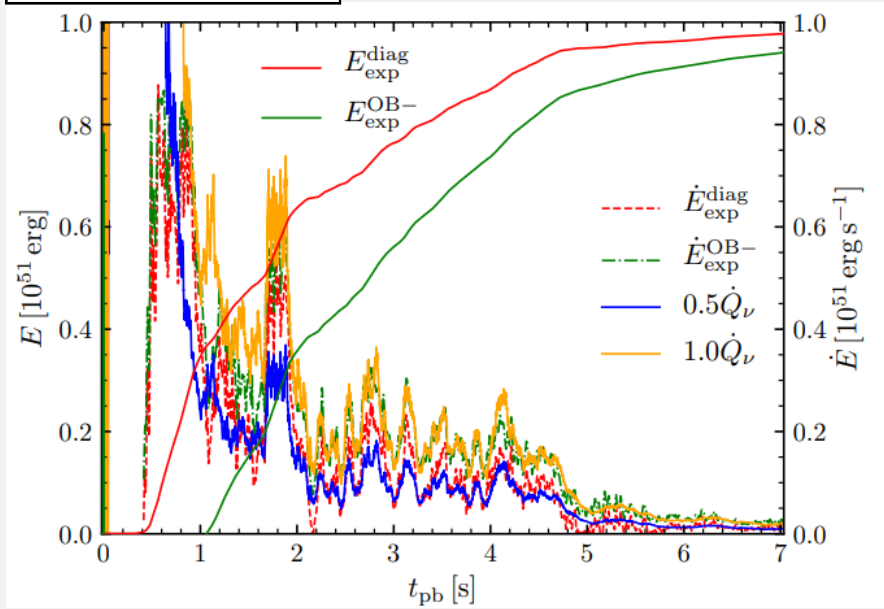
in ab-initio simulations !!



A.Burrows+ 2020

the first example reproducing 10^{51}erg in a 3D ab-initio calculation!

R.Bollig+ 2020



growing rate of the explosion energy

$$\dot{E} \sim \mathcal{O}(0.1)\ [10^{51}\ \mathrm{erg/s}]$$

especially for 3D simulations.

*unclear：

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

2). Can synthesize a sufficient amount of 56Ni?

my interest

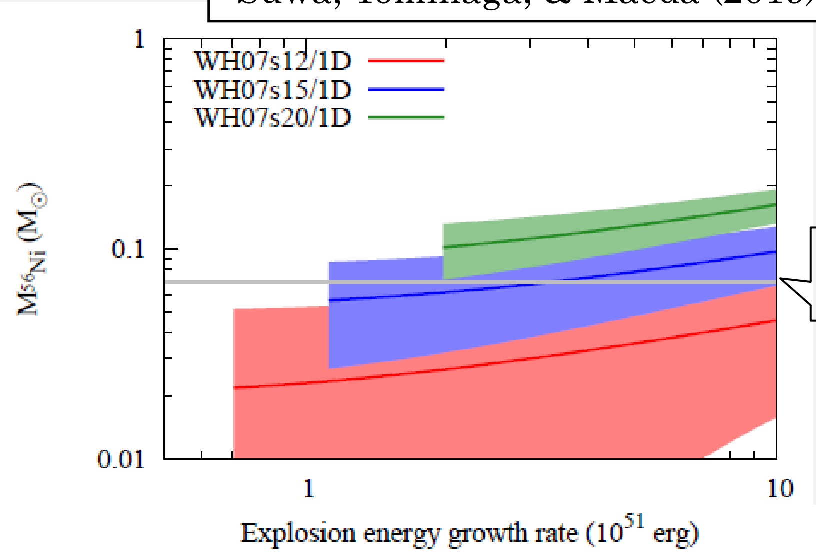
Can synthesize a sufficient amount of 56Ni ?

growing rate of the explosion energy

$\dot{E} \sim \mathcal{O}(0.1)\ [10^{51}\ \mathrm{erg/s}]$

especially for 3D simulations.

Suwa, Tominaga, & Maeda (2019)



(1D-analytic)

$0.07M_\odot$

- **recent suggestion :**

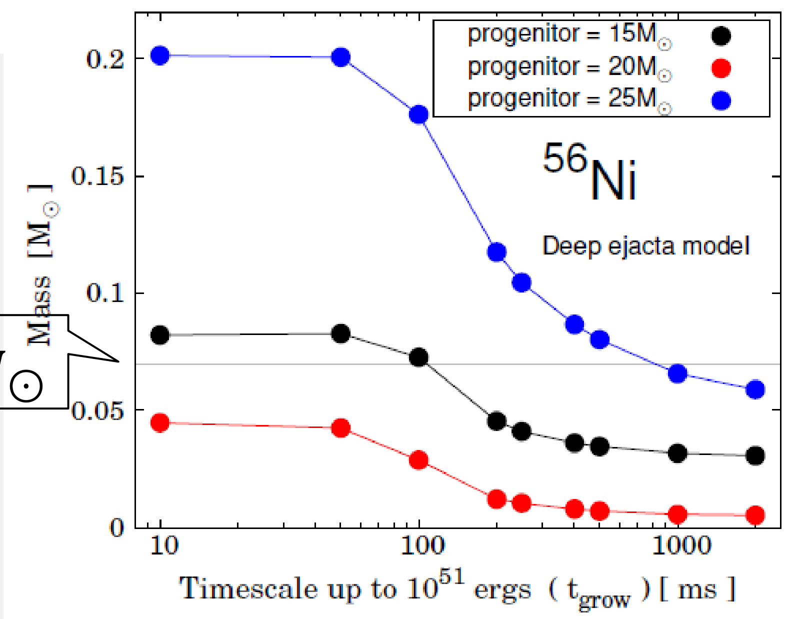
the typical mass $0.07M_\odot$ of 56Ni in CCSNe,

the growth rate of the explosion energy of

$\dot{E} \geq \mathcal{O}(1)\ [10^{51}\ \mathrm{erg/s}]$ is required

(1D-numerical & nucleosynthesis)

Sawada & Maeda (2019)



$0.07M_\odot$

→'nickel mass problem'(Ni problem)

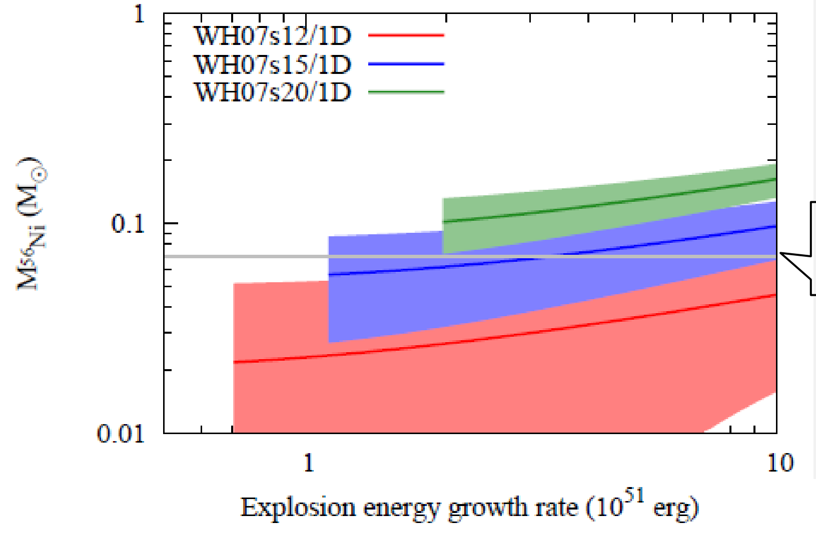
Can synthesize a sufficient amount of 56Ni ?

growing rate of the explosion energy

$\dot{E} \sim \mathcal{O}(0.1)$ $[10^{51}$ erg/s$]$

especially for 3D simulations.

Suwa, Tominaga, & Maeda (2019)



(1D-analytic)

$\mathbf{0.07}\boldsymbol{M_\odot}$

- **recent suggestion :**

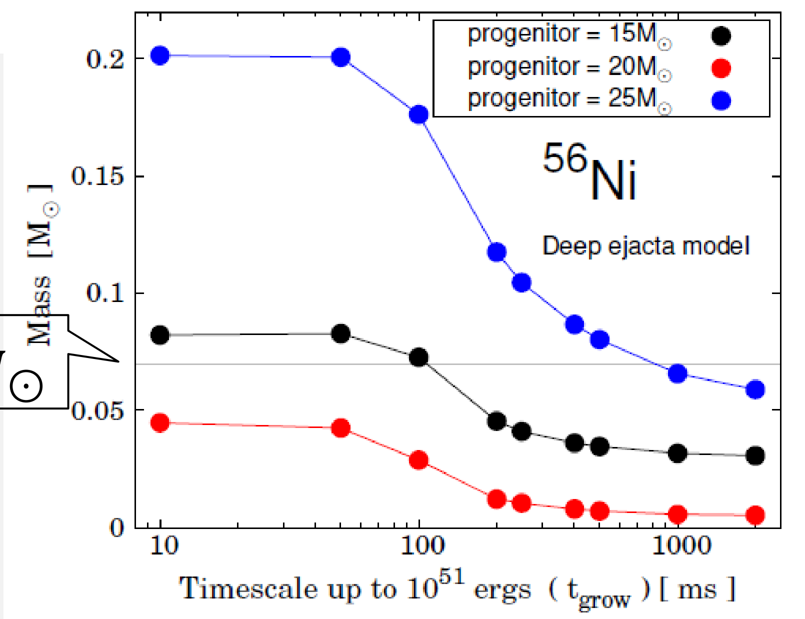
the typical mass $0.07M_\odot$ of 56Ni in CCSNe,

the growth rate of the explosion energy of

$\dot{E} \geq \mathcal{O}(1)$ $[10^{51}$ erg/s$]$ is required

(1D-numerical & nucleosynthesis)

Sawada & Maeda (2019)



$\mathbf{0.07}\boldsymbol{M_\odot}$

→**'nickel mass problem'(Ni problem)**

my interest

Can synthesize a sufficient amount of 56Ni ?

Suwa, Tominaga, & Maeda (2019)

Sawada & Maeda (2019)

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

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

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

✓ When the explosion is sufficiently instantaneous, then

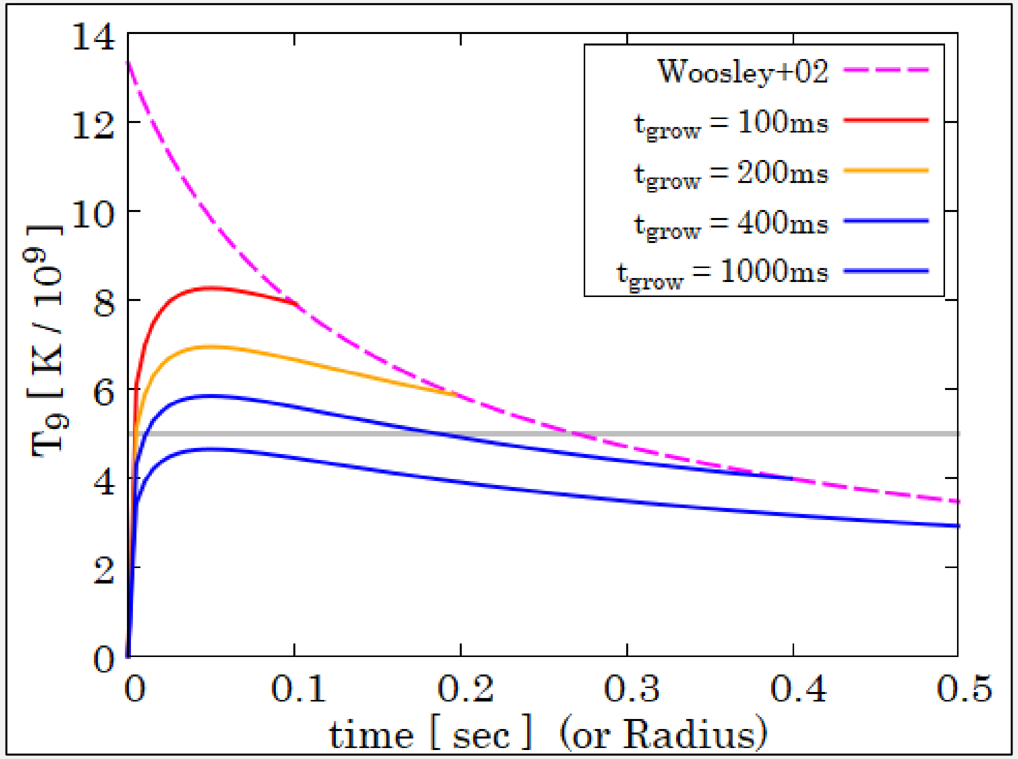
Deposit $E_{\rm exp} = 10^{51}{\rm erg}$ from the initial setup.

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



Can synthesize a sufficient amount of 56Ni ?

Suwa, Tominaga, & Maeda (2019)

Sawada & Maeda (2019)

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

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

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

✓ When the explosion is sufficiently instantaneous, then

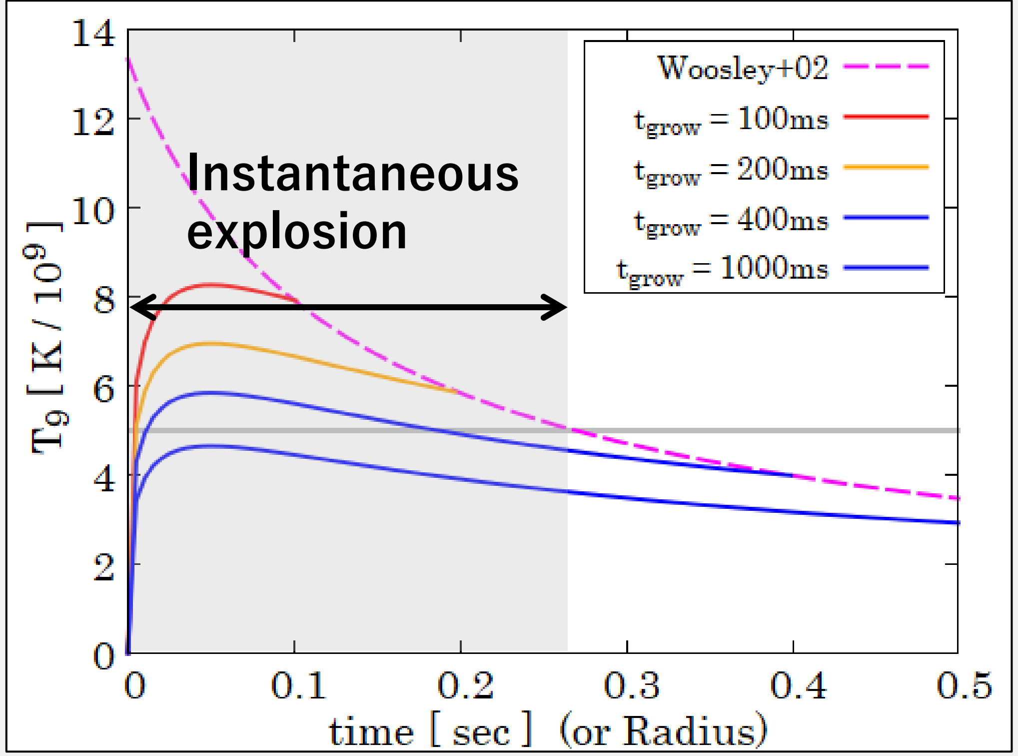
Deposit $E_{\rm exp} = 10^{51}{\rm erg}$ from the initial setup.

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



Can synthesize a sufficient amount of 56Ni ?

Suwa, Tominaga, & Maeda (2019)

Sawada & Maeda (2019)

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

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

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

✓ When the explosion is sufficiently instantaneous, then

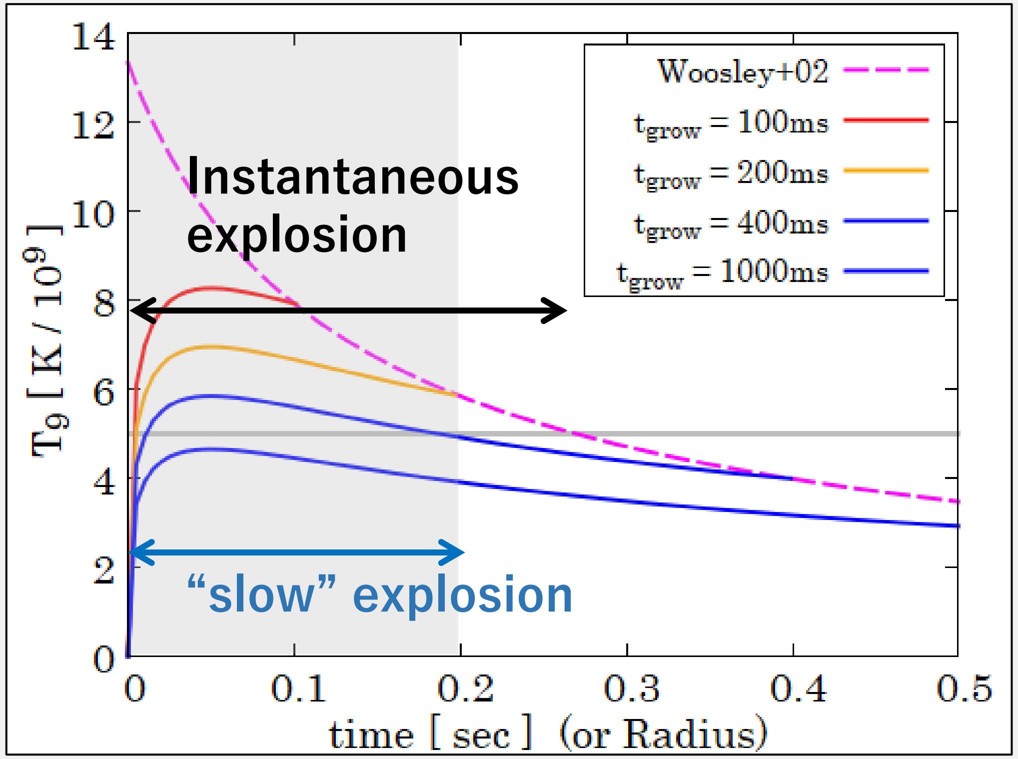
Deposit $E_{\rm exp} = 10^{51}{\rm erg}$ from the initial setup.

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

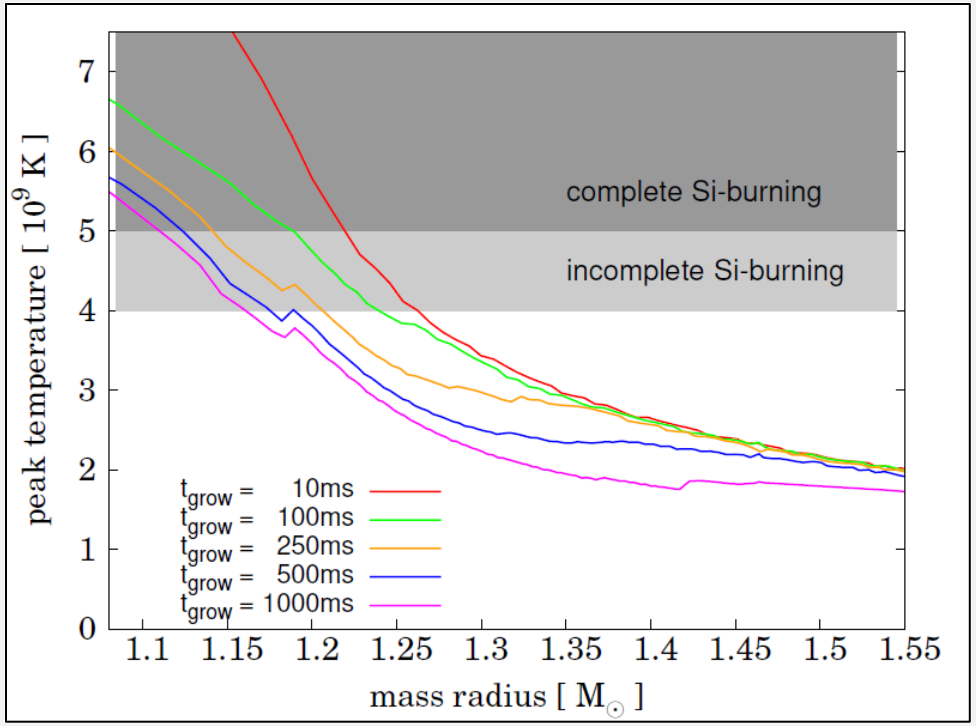


Can synthesize a sufficient amount of 56Ni ?

Sawada & Maeda (2019)

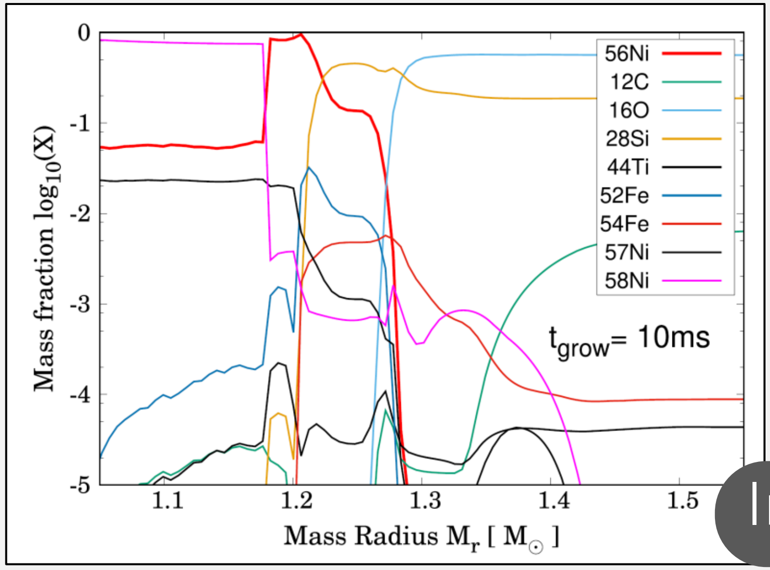
- **Peak tempareture**

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

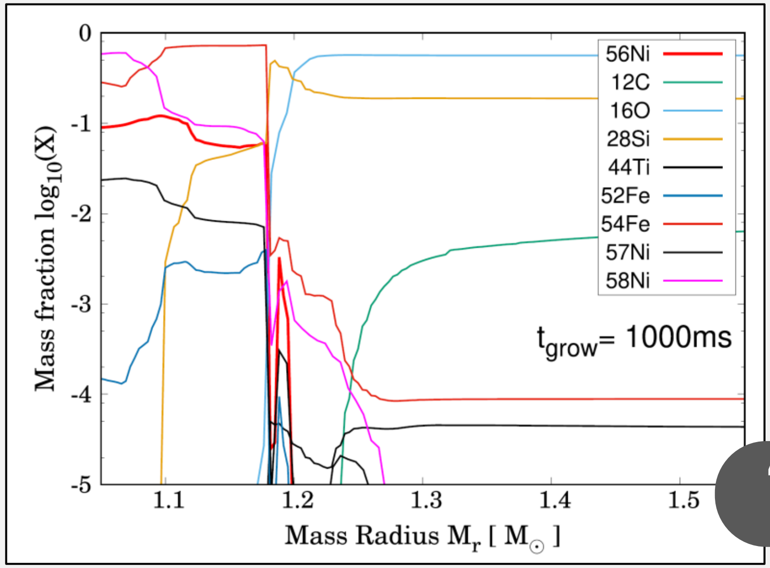


$t_{\text{grow}} = 1000[\text{ms}]$

- **Aboundance**



Instant expl.



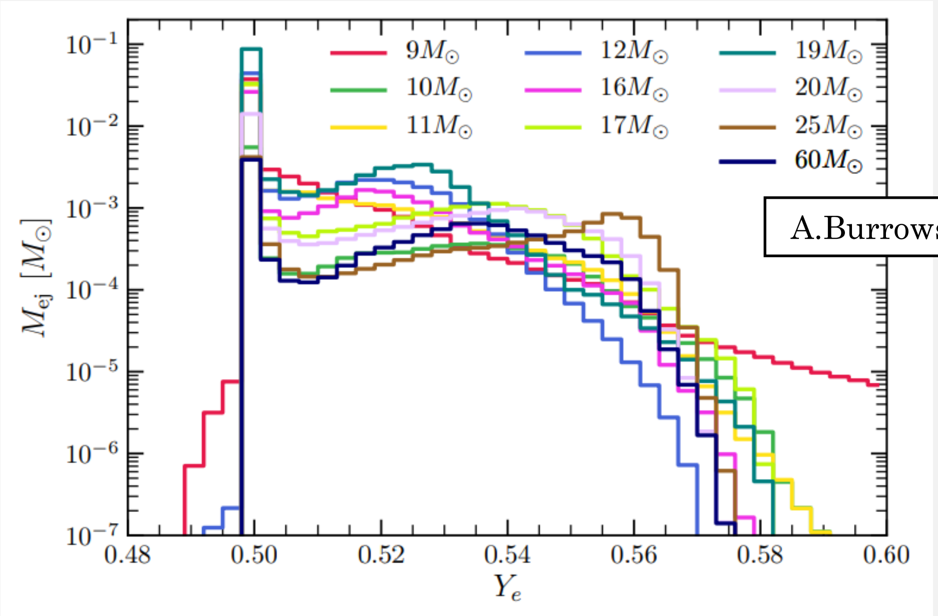
‘slow’ expl.

Can synthesize a sufficient amount of 56Ni ?

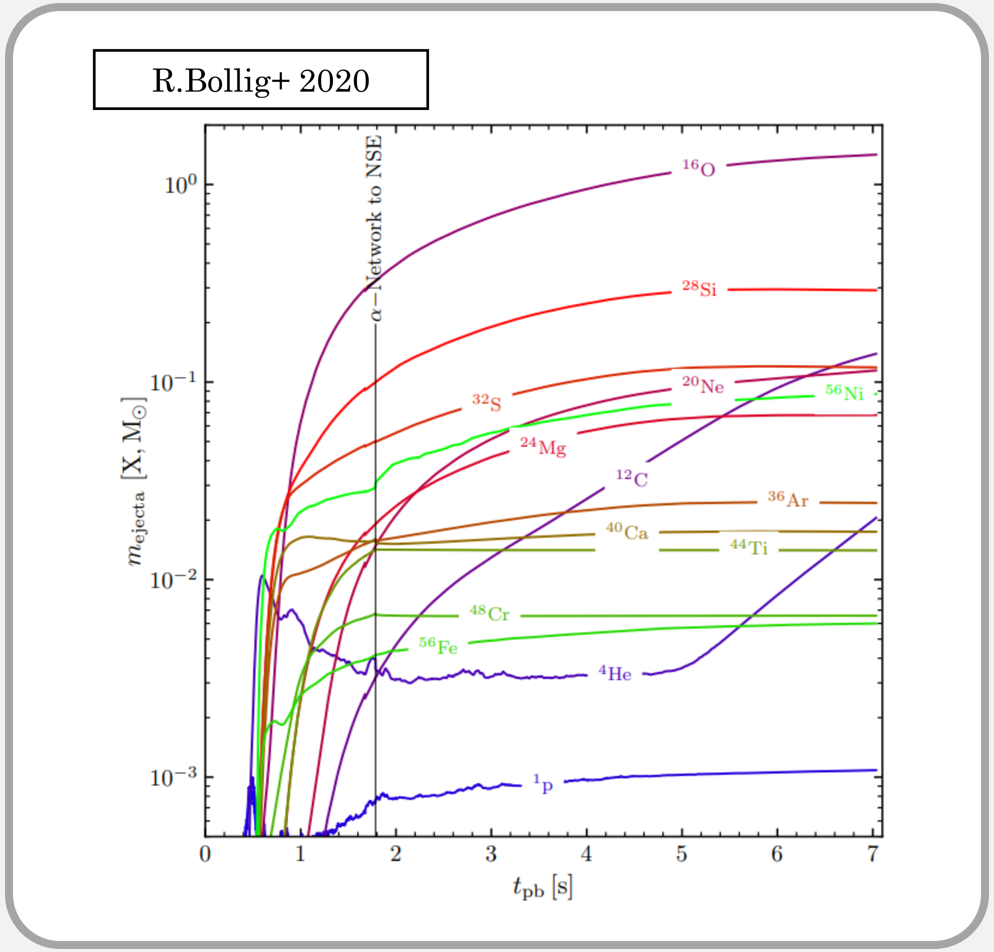
- **NOTE :**

some models in ab-initio simulations have succeeded

in producing the typical mass $0.07M_{\odot}$ of 56Ni in CCSNe,



A.Burrows+ 2020



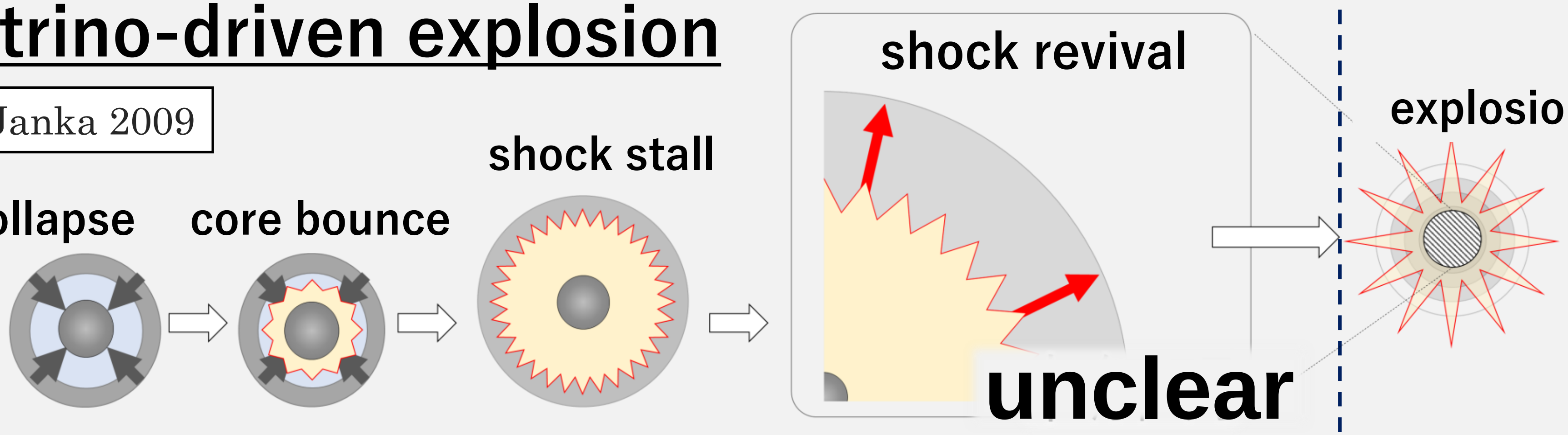
But ‘nickel mass problem’(Ni problem)

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

Explosion mechanism of Core-Collapse SNe

- **neutrino-driven explosion**

Marek & Janka 2009



observed property

$E_{\mathrm{kin}} \sim 10^{51}$ erg

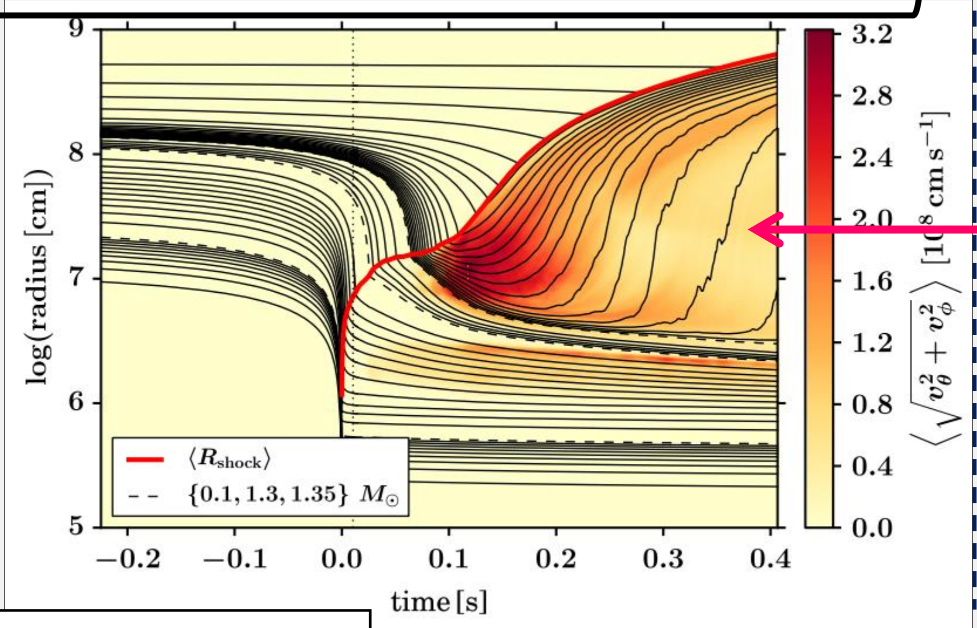
$M_{56\mathrm{ni}} \sim 0.07\, M_{\odot}$

-0.1 [sec] $\quad$ 0 [sec] $\quad \sim \mathcal{O}(0.1)$[sec] $\quad \sim \mathcal{O}(1)$ [sec] $\quad$ reach to 10^{51} [erg]

growing rate of the explosion energy

$\dot{E}_{\mathrm{expl.}} \sim \mathcal{O}(0.1)\ [10^{51}\ \mathrm{erg/s}]$

especially for 3D simulations.



Melson, Janka & Marek 2015

"Neutrino-driven wind" continues about 1-20 sec.

→ contributing to 56Ni(??) especially **at later phases.**

aim and content of our work

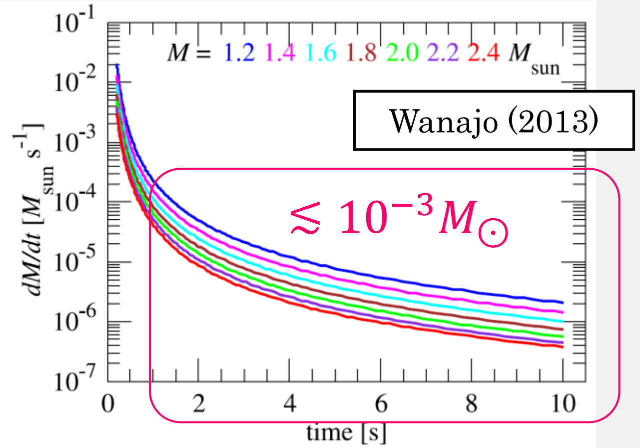
motivation

- investigate the potential of the neutrino-driven wind to solve 'Ni problem', especially **at later phases.**

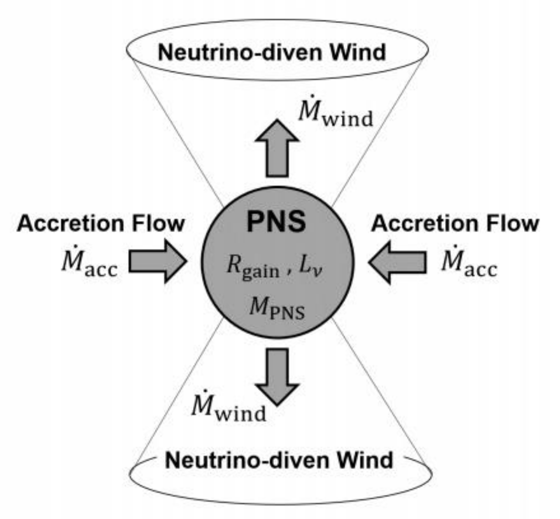
problem

- **1D** (e.g.,Wanajo2013) :
  it is already known that 1D wind simulation could not solve Ni problem.
  (→ multi-D, especially energy injection by accretion, is important.)

- **multi-D** (e.g.,Wanajo+2018) :
  it may solve the Ni problem .
  → However, calculation time is limited.
  Can it be solved if we follow it to the late explosion stage?

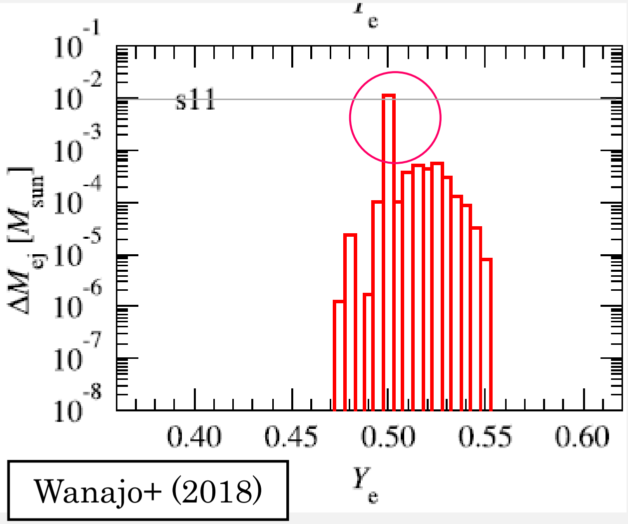


$\gtrsim 0.01 M_\odot$ ejection is required for Ni problem



our work

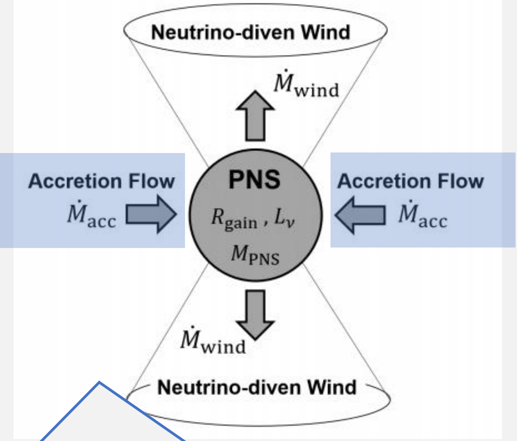
1. Build a consistent model of the neutrino-driven wind with an accretion flow onto a PNS.
2. Investigate the possibility that neutrino-driven wind can solve the "Ni-problem"



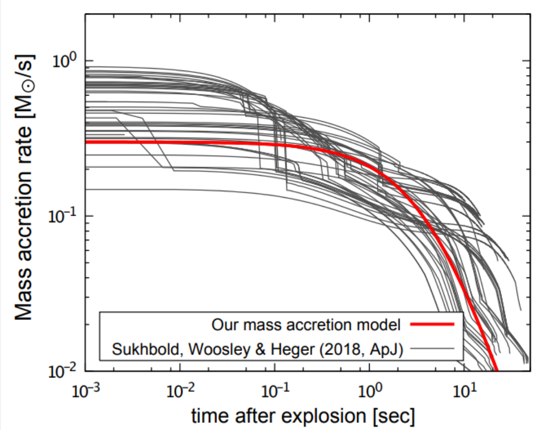
aim and content of our work

our work: the neutrino-driven wind with an accretion flow onto a PNS.

① assume free-fall fallback onto PNS

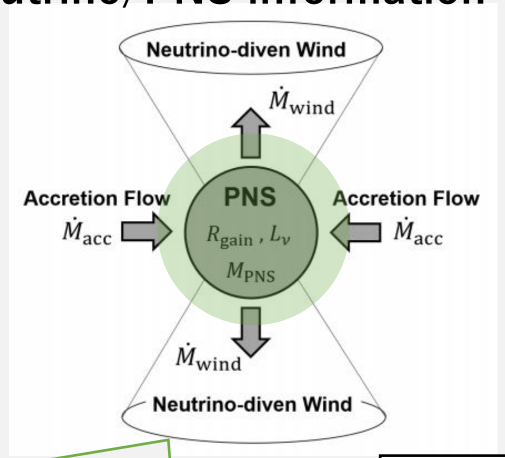


Approximating phenomenological accretion from progenitor models.



$$\dot{M}_{acc,iso}(t) = \dot{M}_{acc,0}\left(\frac{t}{t_0}+1\right)^{-2}, \qquad (8)$$

② Converting accretion flow into neutrino/PNS information



Müller +2016

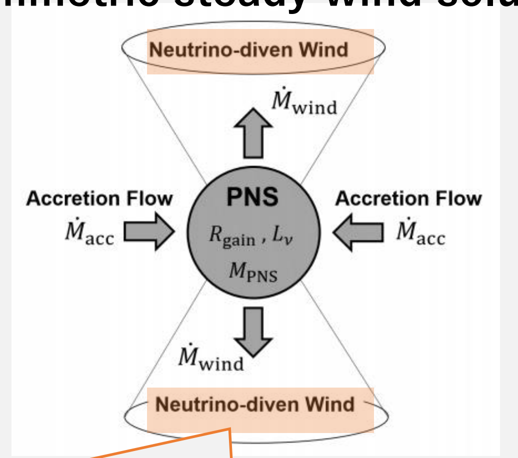
Neutrino luminosity
= η × (gravitational release energy of accretion flow)

$$L_{\nu_e} \approx L_{\nu,acc} = \eta \frac{G M_{PNS} \dot{M}_{acc}}{R_{PNS}}, \qquad (12)$$

Initial radius of Wind (gain radius): approximation from first-principles calculations

$$R_{gain} \approx 40\,\mathrm{km}\left(\frac{\dot{M}_{acc}}{0.1 M_\odot \mathrm{s}^{-1}}\right)^{1/3}\left(\frac{M_{PNS}}{1.4 M_\odot}\right)^{-1}. \qquad (11)$$

③Derive $\dot{M}_{wind}$ from the spherically symmetric steady wind solution



3 parameter$(L_\nu, R_{gain}, M_{PNS}) \Rightarrow \dot{M}_{wind,iso}$

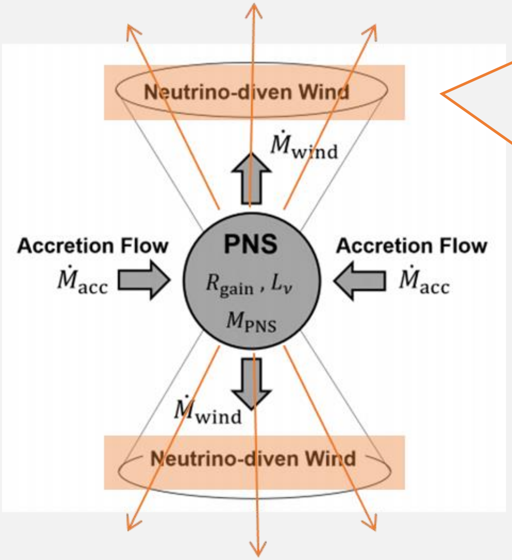
$$\dot{M}_{wind,iso} \approx 8.3\times 10^{-3} M_\odot \mathrm{s}^{-1} \times \left(\frac{L_{\nu_e}}{10^{52}\mathrm{erg\ s}^{-1}}\right)^{7/4}\left(\frac{R_{gain}}{4\times 10^{6}\mathrm{cm}}\right)^{5/2}\left(\frac{M_{PNS}}{1.4 M_\odot}\right)^{-7/2}. \qquad (22)$$

④ connect them w/ geometric factor

$$\dot{M}_{wind} = f_\Omega \dot{M}_{wind,iso}, \qquad (9)$$

$$\dot{M}_{acc} = (1-f_\Omega)\dot{M}_{acc,iso}. \qquad (10)$$

semi-analytic wind model (e.g., Otsuki et al. 2000).



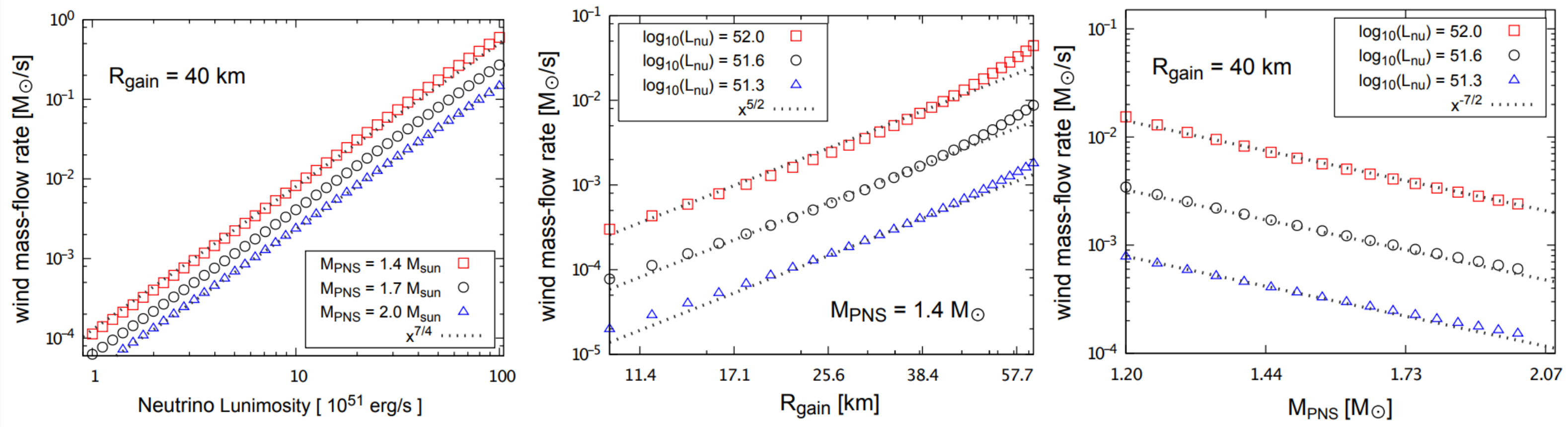
Assume a neutrino-driven wind blowing in the "radial direction" through the low-density region swept by the non-spherically symmetric shock wave

spherically symmetric steady-state wind solution(e.g., Otsuki et al. 2000).

- $(R_{\rm gain}, L_\nu, M_{\rm PNS})$
  ⇒ tran-sonic solution $v_{\rm tran}$ ⇔ **maximum $\dot{M}_{\rm wind}$**

- $\dot{M} = 4\pi r^2 \rho v\ ,$ (1)
- $v\dfrac{dv}{dr} = -\dfrac{1+(v/c)^2-(2GM/c^2r)}{\rho(1+\epsilon/c^2)+P/c^2}\dfrac{dP}{dr} - \dfrac{GM_{\rm PNS}}{r^2}\ ,$ (2)
- $\dot{Q} = v\left(\dfrac{d\epsilon}{dr} - \dfrac{P}{\rho^2}\dfrac{d\rho}{dr}\right)\ ,$ (3)
- Helmholtz EoS (Timmes & Swesty 2000),
- Boundary condition:
  $r = R_{\rm gain}\ (\dot{Q} \approx 0)$
  Given: $\rho_0 = 10^{10}{\rm g\,cm^{-3}} \cdot L_{\nu,51}^{1/2}$, (Fujibayashi+ 2015)
- $Y_e = \left[1 + \dfrac{L_{\bar{\nu}_e}^n \langle\sigma_{\bar{\nu}_e p}\rangle}{L_{\nu_e}^n \langle\sigma_{\nu_e n}\rangle}\right]^{-1} = 0.5,$ (4)
  (e.g., Bliss+ 2018).

- **result**

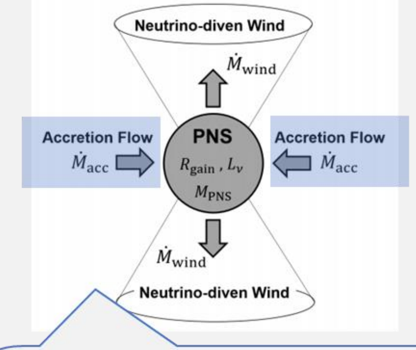


- **spherical wind $\dot{M}_{\rm wind,iso}$**

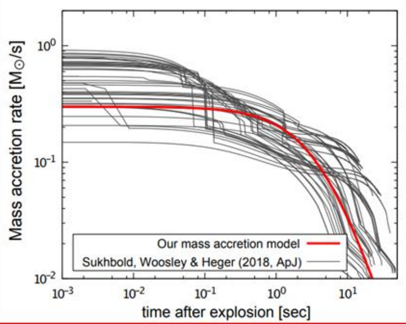
$$\dot{M}_{\rm wind,iso} \approx 8.3\times10^{-3} M_\odot {\rm s}^{-1} \left(\frac{L_{\nu_e}}{10^{52}{\rm erg\ s^{-1}}}\right)^\alpha \left(\frac{R_{\rm gain}}{4\times10^6{\rm cm}}\right)^\beta \left(\frac{M_{\rm PNS}}{1.4M_\odot}\right)^\gamma, \quad (5)$$

our work

① assume free-fall fallback onto PNS

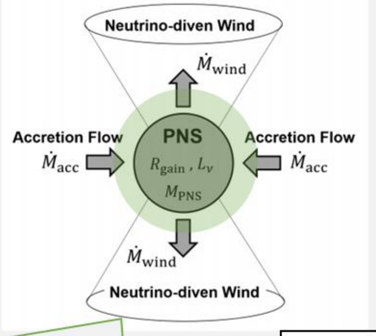


Approximating phenomenological accretion from progenitor models.



$$\dot{M}_{\rm acc,iso}(t) = \dot{M}_{\rm acc,0}\left(\frac{t}{t_0}+1\right)^{-2}, \quad (8)$$

② Converting accretion flow into neutrino/PNS information



Müller +2016

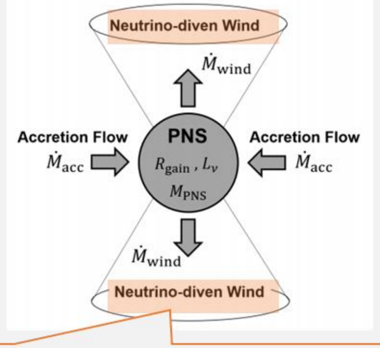
Neutrino luminosity
$= \eta\ \times$ (gravitational release energy of accretion flow)

$$L_{\nu_e} \approx L_{\nu,\rm acc} = \eta\frac{GM_{\rm PNS}\dot{M}_{\rm acc}}{R_{\rm PNS}}, \quad (12)$$

Initial radius of Wind (gain radius): approximation from first-principles calculations

$$R_{\rm gain} \approx 40\,{\rm km}\left(\frac{\dot{M}_{\rm acc}}{0.1M_\odot {\rm s}^{-1}}\right)^{1/3}\left(\frac{M_{\rm PNS}}{1.4M_\odot}\right)^{-1}. \quad (11)$$

③Derive $\dot{M}_{\rm wind}$ from the spherically symmetric steady wind solution



3 parameter$(L_\nu, R_{\rm gain}, M_{\rm PNS}) \Rightarrow \dot{M}_{\rm wind,iso}$

$$\dot{M}_{\rm wind,iso} \approx 8.3\times10^{-3}M_\odot{\rm s}^{-1} \times\left(\frac{L_{\nu_e}}{10^{52}{\rm erg\ s^{-1}}}\right)^{7/4}\left(\frac{R_{\rm gain}}{4\times10^6{\rm cm}}\right)^{5/2}\left(\frac{M_{\rm PNS}}{1.4M_\odot}\right)^{-7/2}. \quad (22)$$

④ connect them w/ geometric factor

$$\dot{M}_{\rm wind} = f_\Omega \dot{M}_{\rm wind,iso}, \quad (9)$$
$$\dot{M}_{\rm acc} = (1-f_\Omega)\dot{M}_{\rm acc,iso}. \quad (10)$$

$$\dot{M}_{\rm wind} \approx 1.3\times10^{-2}\ M_\odot{\rm s}^{-1} \times f_\Omega\left(\frac{(1-f_\Omega)\dot{M}_{\rm acc,iso}}{0.1M_\odot{\rm s}^{-1}}\right)^{\frac{2\alpha+\beta}{3}}\left(\frac{M_{\rm PNS}}{1.4M_\odot}\right)^{2\alpha-\beta+\gamma}, \quad (13)$$

- wind model w/ accretion flow

Can synthesize a sufficient amount of 56Ni ?

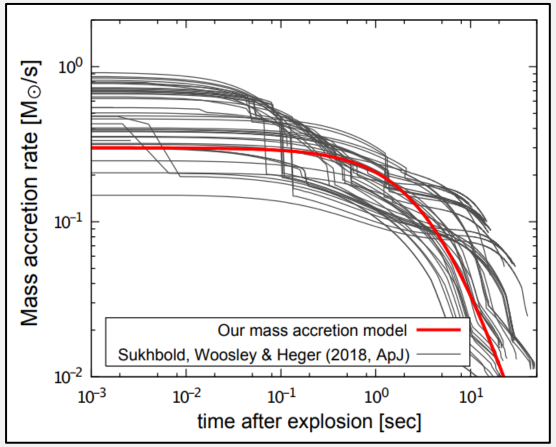
- total ejected mass of the wind…

$$M_{\mathrm{ej},\infty} = \int_0^\infty dt\, \dot{M}_{\mathrm{wind}}$$

$$\approx 4.3 \times 10^{-3} M_\odot s^{-1} f_\Omega (1 - f_\Omega)^2 \left(\frac{\dot{M}_{\mathrm{acc},0}}{0.1 M_\odot s^{-1}}\right)^2 \left(\frac{M_{\mathrm{PNS},0}}{1.4 M_\odot}\right)^{-\frac{5}{2}} \leq 0.067 M_\odot$$

maximum parameter sets

- $M_{\mathrm{PNS},0} \geqq 1.4 M_\odot$,
- $\dot{M}_{\mathrm{acc},0} < 1.0 M_\odot s^{-1}$
- Total accretion mass $< 0.7 M_\odot$



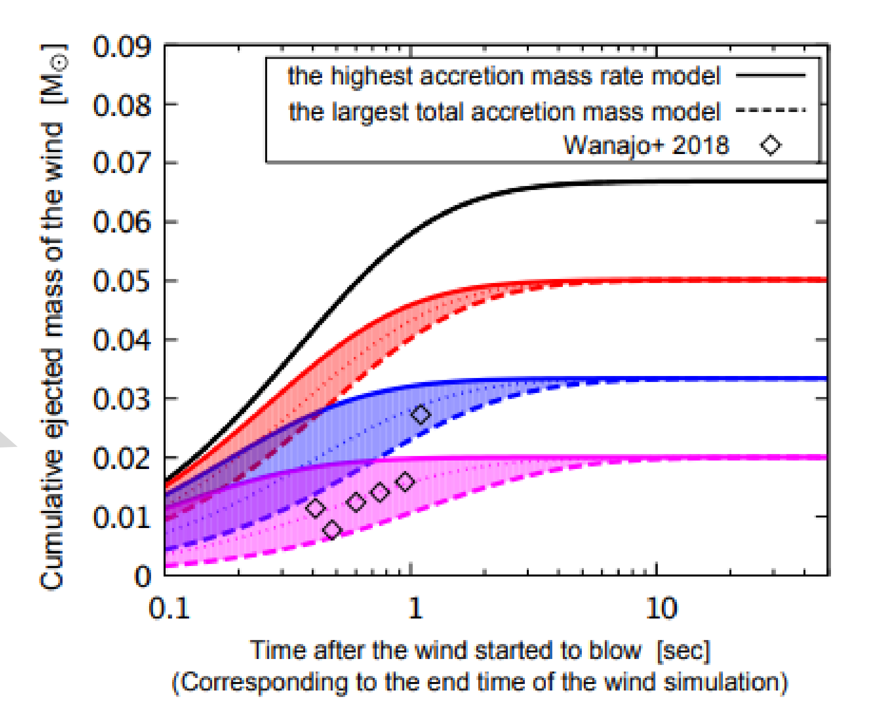
- the time evolution of the cumulative ejected mass of the wind…

$$M_{\mathrm{ej}}(t_e) = \int_0^{t_e} dt\, \dot{M}_{\mathrm{wind}}$$

$$\approx 6.4 \times 10^{-4} M_\odot \left[1 - \left(\frac{t_0}{t_0 + t_e}\right)^3\right] \times \left(\frac{t_0}{1s}\right) \left(\frac{\dot{M}_{\mathrm{acc},0}}{0.1 M_\odot s^{-1}}\right)^2 \left(\frac{M_{\mathrm{PNS},0}}{1.4 M_\odot}\right)^{-5/2}$$

- Conclusion.

1. the total ejectable is determined within ~2 sec from the onset of the explosion.
2. the supplementable amount **at a late phase ($t > 1$ sec) remains $M_{\mathrm{ej}} < 0.01 M_\odot$**.



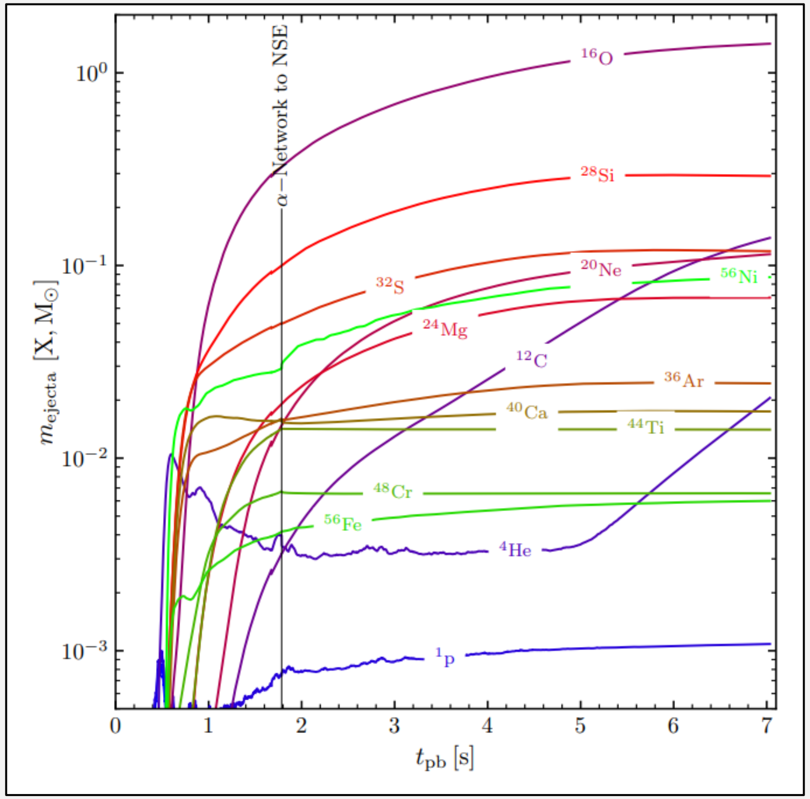
→ difficult to solve the Ni problem

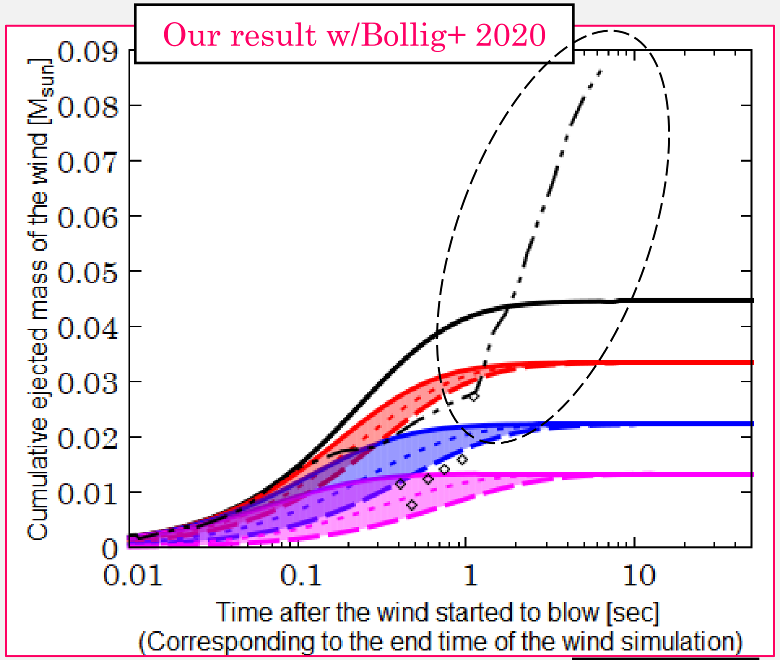
at the late phase of the explosion by the neutrino-driven wind.

Can synthesize a sufficient amount of 56Ni ?

- **NOTE :** R.Bollig+ 2020

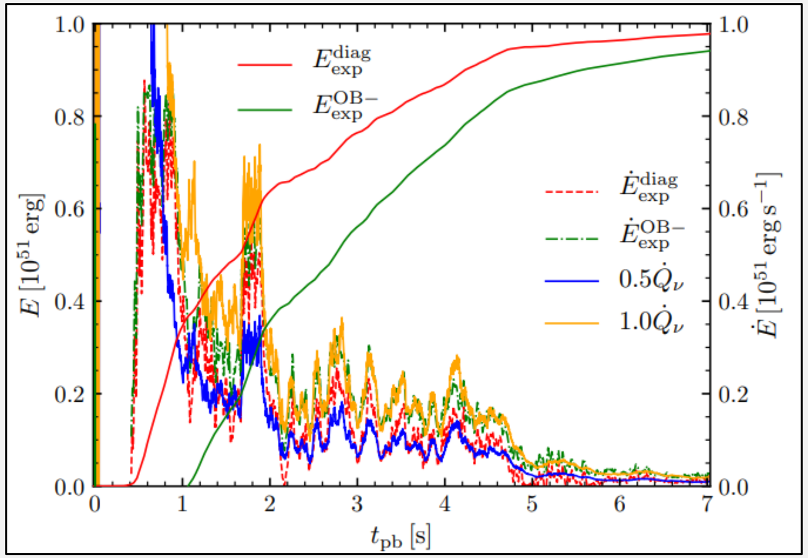
"The converged value of the explosion energy at infinity (with overburden subtracted) is roughly 1B and the ejected 56Ni mass **up to 0.087** solar masses"
"Our final 56Ni mass is therefore an upper limit, and we expect the actual mass to be around **0.05 M.** Nevertheless, it demonstrates that 56Ni masses in the ballpark of those of typical CCSNe can be ejected in 3D neutrino-driven explosions."

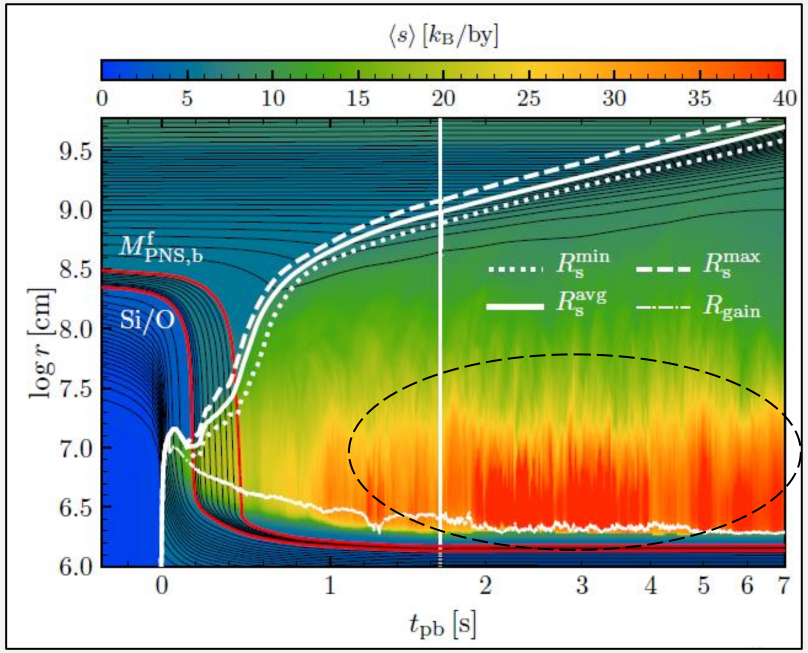




Our work

$$\dot{M}_{\rm wind} \approx 1.3 \times 10^{-2}\ M_\odot {\rm s}^{-1} \times f_\Omega \left(\frac{(1 - f_\Omega)\dot{M}_{\rm acc,iso}}{0.1 M_\odot {\rm s}^{-1}} \right)^2 \left(\frac{M_{\rm PNS,0}}{1.4 M_\odot} \right)^{-5/2} . \quad (23)$$



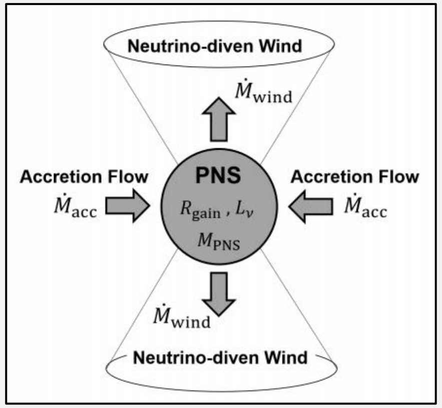


Summary

1. a model of the neutrino-driven wind with an accretion flow onto a PNS.

• spherical wind

$$\dot{M}_{\rm wind,iso} \approx 8.3 \times 10^{-3} M_\odot {\rm s}^{-1} \times \left(\frac{L_{\nu_e}}{10^{52}{\rm erg\ s^{-1}}}\right)^{7/4} \left(\frac{R_{\rm gain}}{4\times 10^6 {\rm cm}}\right)^{5/2} \left(\frac{M_{\rm PNS}}{1.4 M_\odot}\right)^{-7/2}. \quad (22)$$



• wind model w/ accretion flow

$$\dot{M}_{\rm wind} \approx 1.3 \times 10^{-2}\ M_\odot {\rm s}^{-1} \times f_\Omega \left(\frac{(1-f_\Omega)\dot{M}_{\rm acc,iso}}{0.1 M_\odot {\rm s}^{-1}}\right)^2 \left(\frac{M_{\rm PNS,0}}{1.4 M_\odot}\right)^{-5/2}. \quad (23)$$

2. the possibility that neutrino-driven wind can solve the "Ni-problem“

1. the total ejectable is determined within ~2 sec from the onset of the explosion.
2. the supplementable amount **at a late phase ($t > 1$ sec) remains $M_{\rm ej} < 0.01 M_\odot$.**

→ difficult to solve the Ni problem

at the late phase of the explosion by the neutrino-driven wind.