`Nickel Mass Problem' in the CCSN Explosion Mechanism, and Neutrino-Driven Wind Model as a Solution to it.

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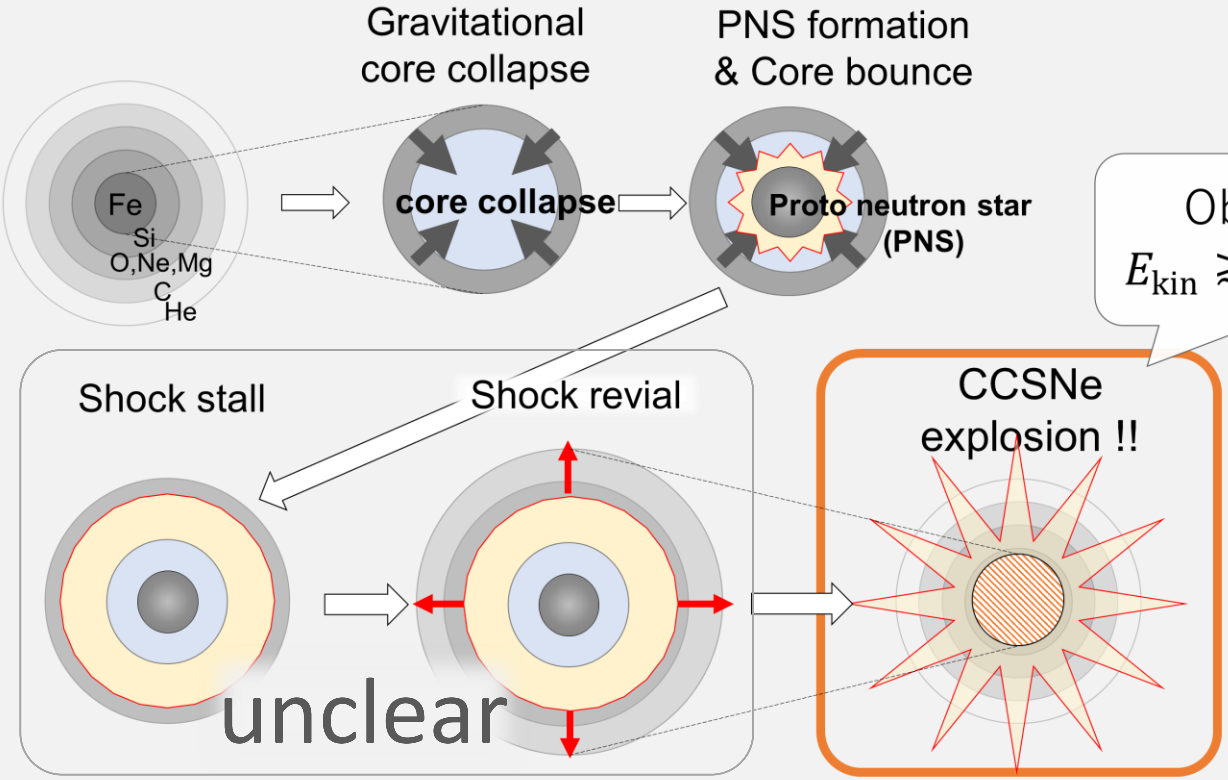
Collaborator：
Yudai Suwa (University of Tokyo & YITP, Kyoto Univ.)
Keiichi Maeda (Kyoto Univ.)

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)

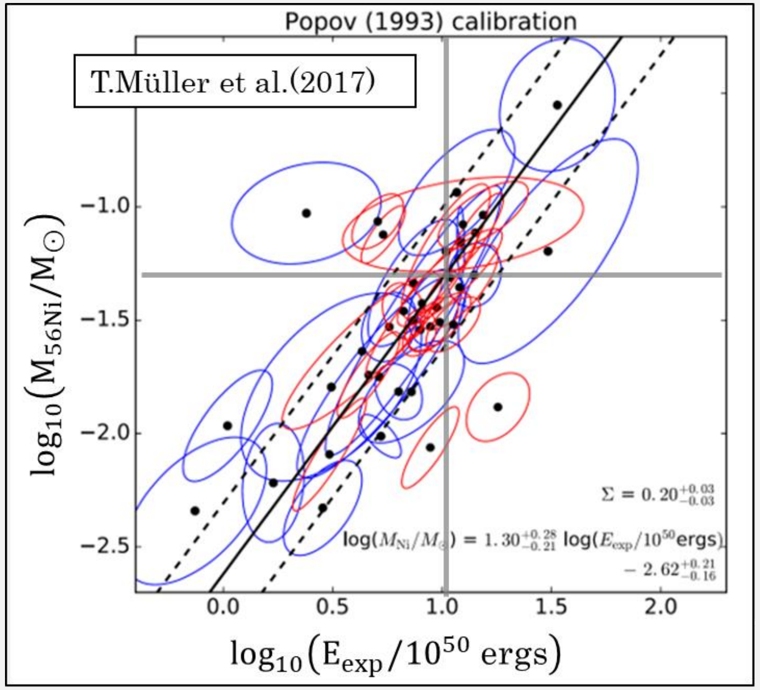
Explosion mechanism of Core-Collapse SNe

- **neutrino-driven explosion**



Observed
$E_{\mathrm{kin}} \gtrsim 10^{51}$ergs

- **observation**



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

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

*unclear：

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

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

my interest

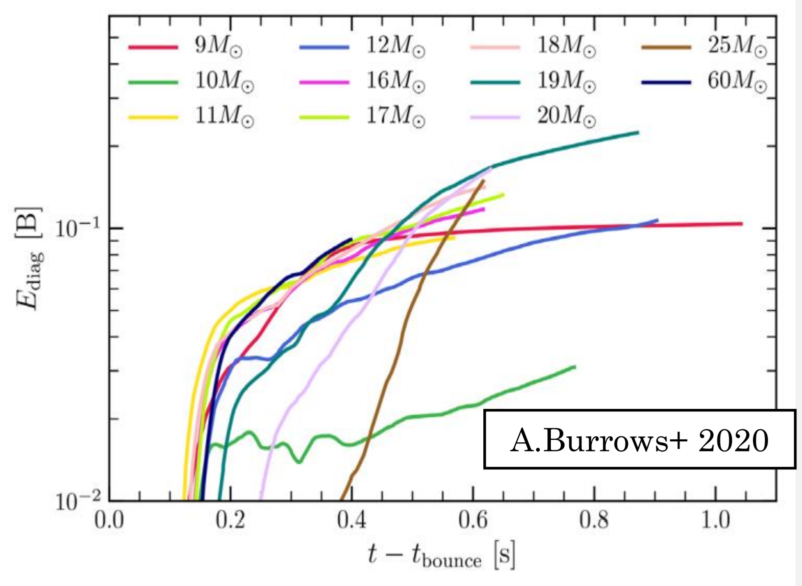
Sawada & Suwa (ApJ, 2021) arxiv. 2010.05615

Current results from the ab-initio calculation

many successful examples

of reproducing explosions

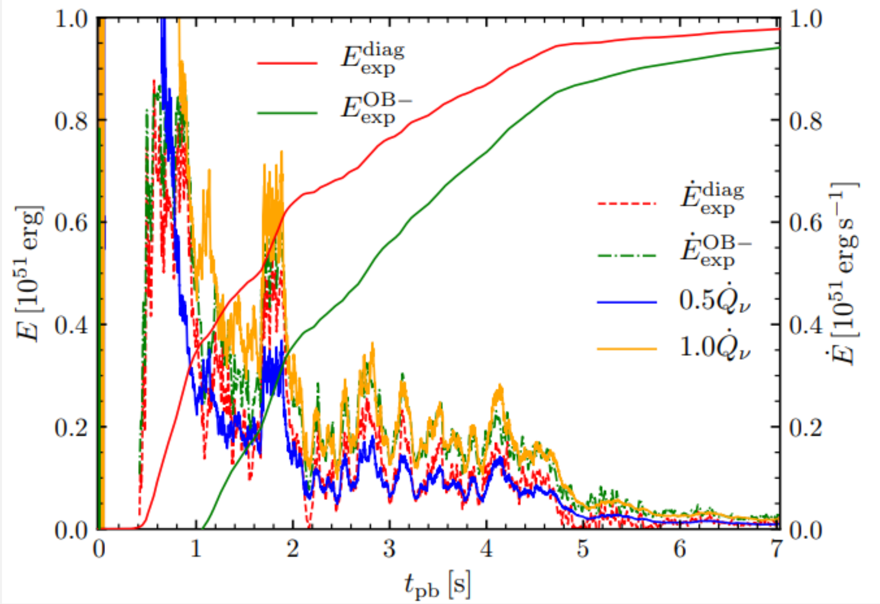
in ab-initio simulations !!



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.

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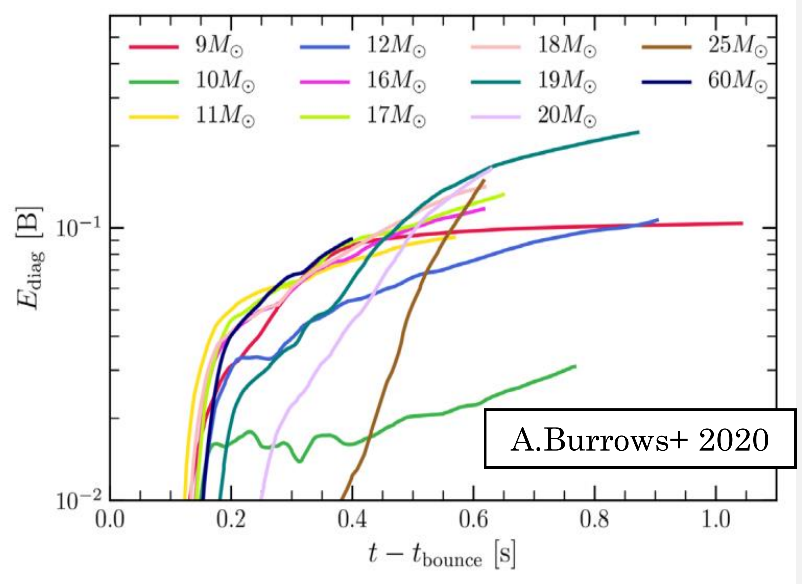

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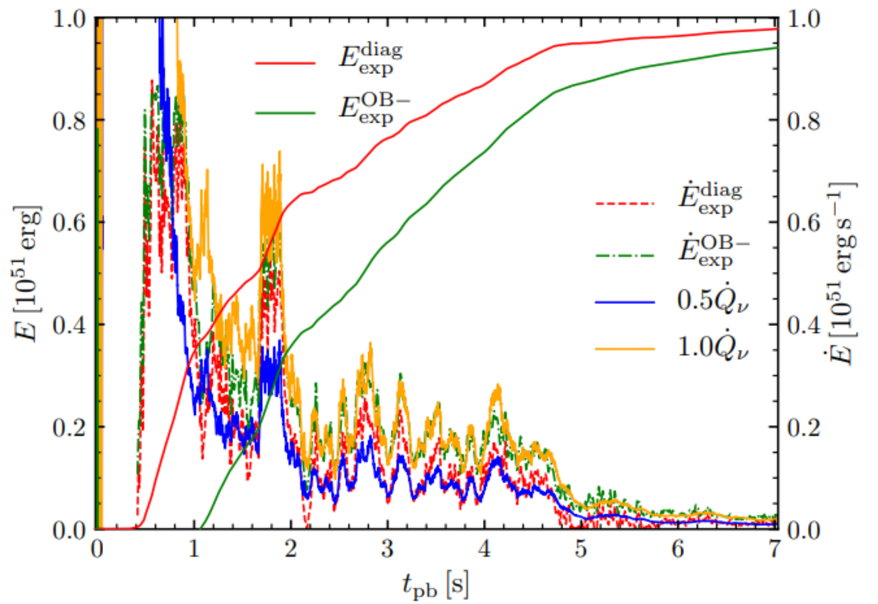

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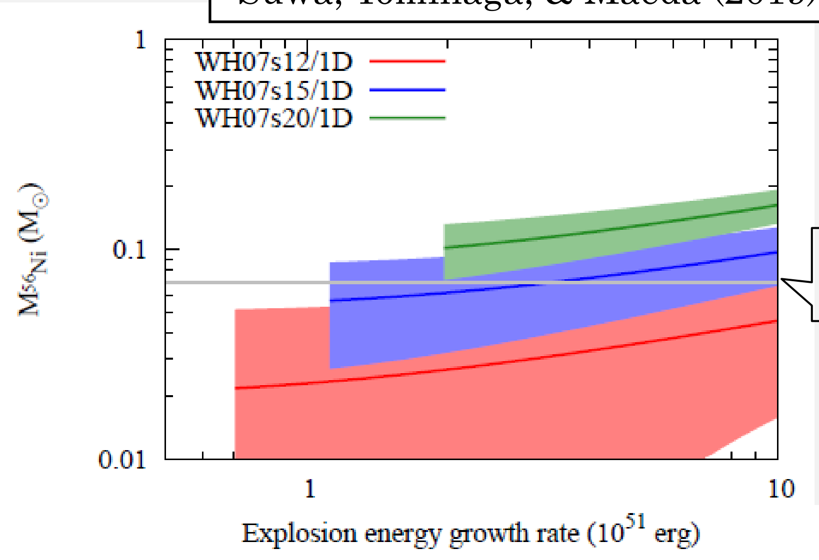
Suwa, Tominaga, & Maeda (2019)



(1D-analytic)

$0.07M_\odot$

- **recent suggestion :**

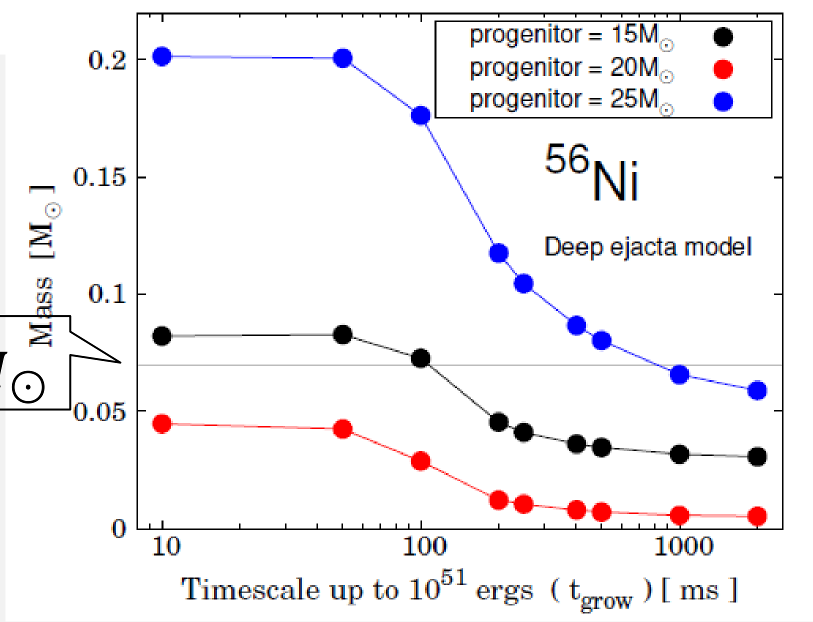
the typical mass $0.07M_\odot$ of 56Ni in CCSNe,

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)

Sawada & Suwa (ApJ, 2021) arxiv. 2010.05615

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 $(r_{\mathrm{shock}} = v_{\mathrm{shock}} \cdot t)$,

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

- ✓ When the explosion is sufficiently instantaneous, then

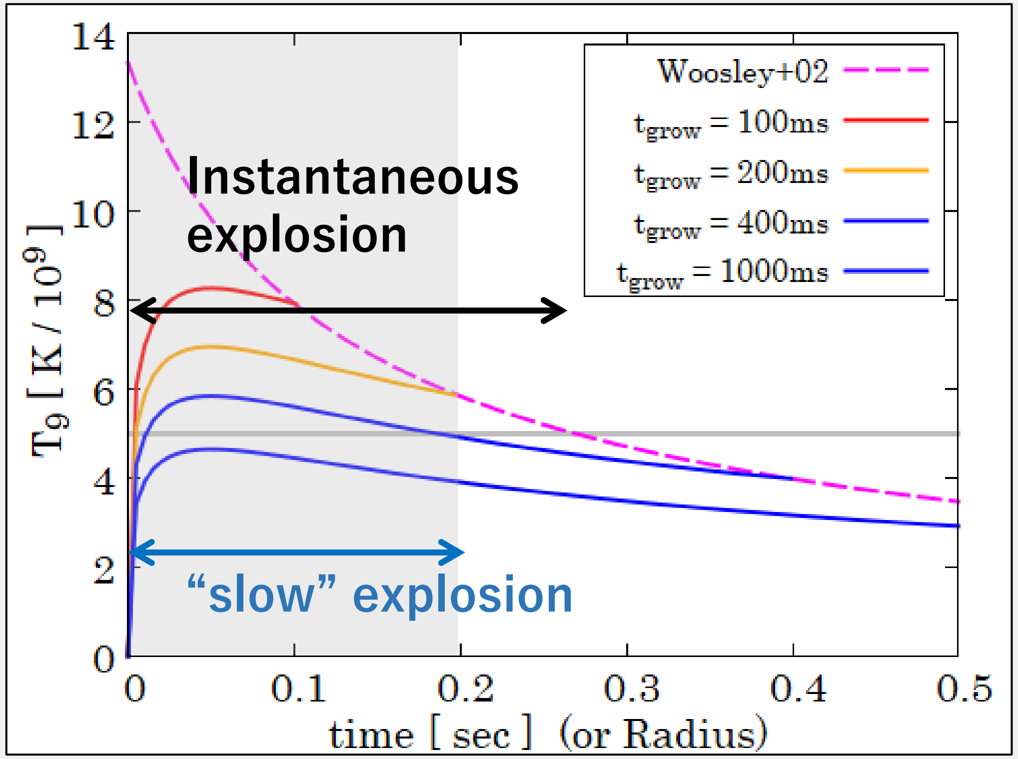
Deposit $E_{\mathrm{exp}} = 10^{51}\mathrm{erg}$ from the initial setup.

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



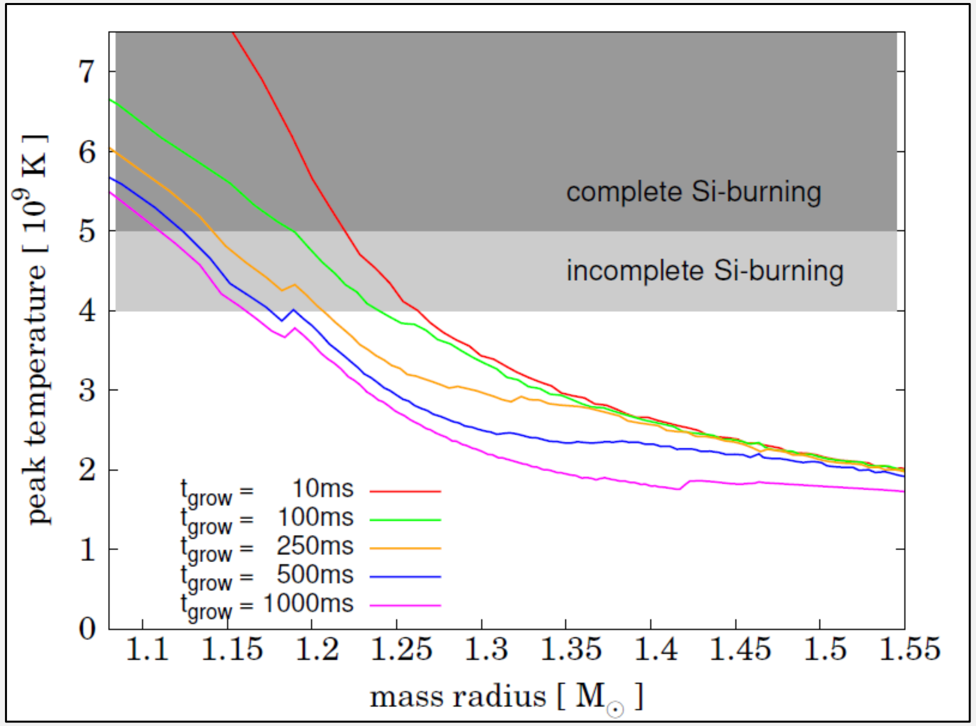
Sawada & Suwa (ApJ, 2021) arxiv. 2010.05615

Can synthesize a sufficient amount of 56Ni ?

Sawada & Maeda (2019)

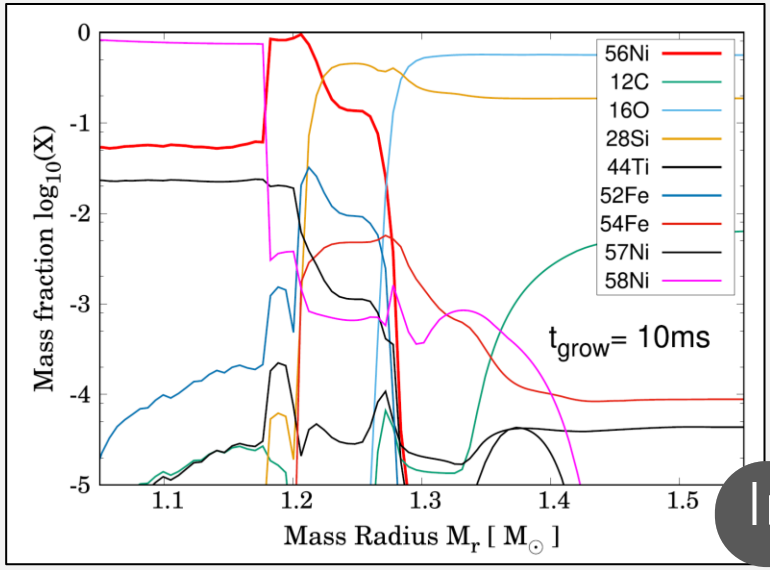
- **Peak tempareture**

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

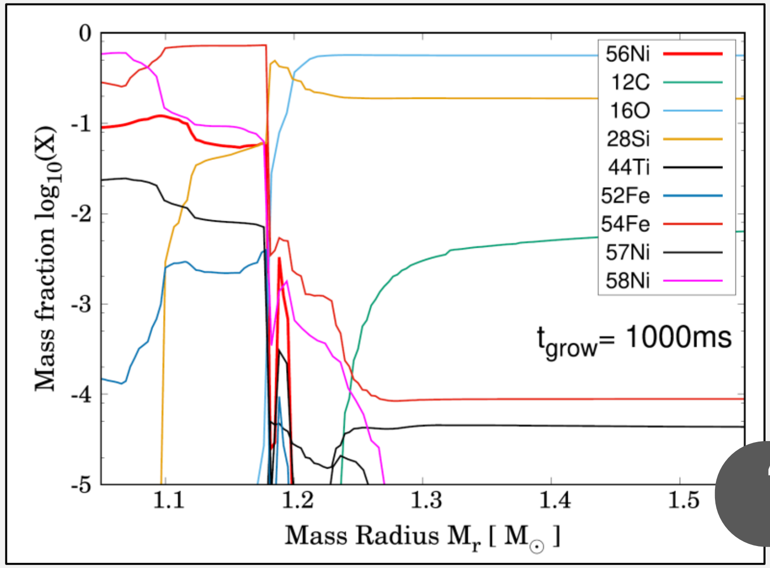


$t_{\mathrm{grow}} = 1000[\mathrm{ms}]$

- **Aboundance**



Instant expl.



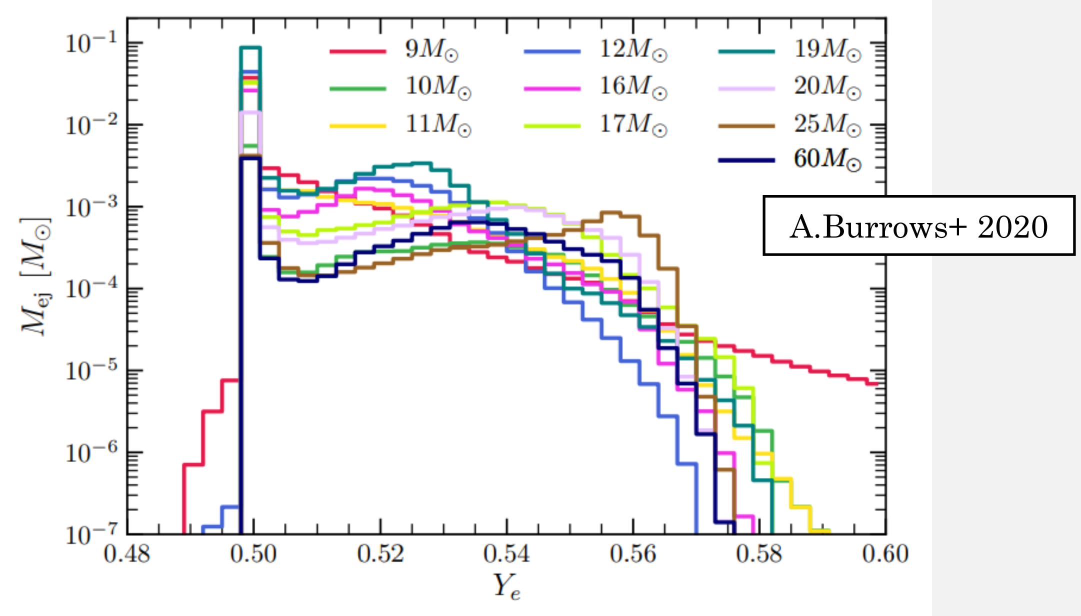
‘slow’ expl.

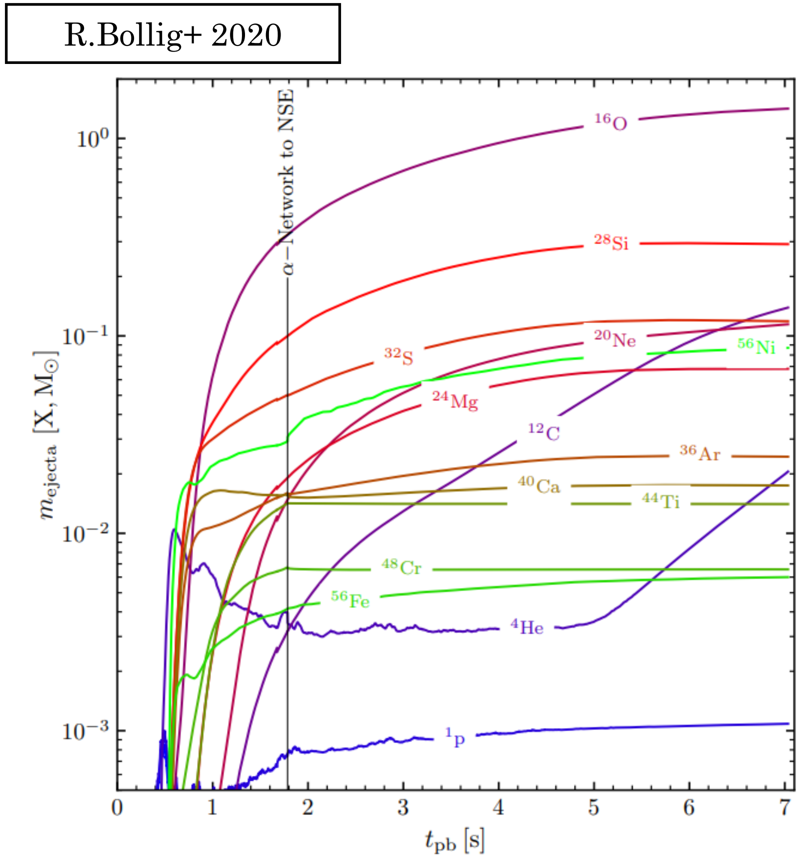
Sawada & Suwa (ApJ, 2021) arxiv. 2010.05615

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,





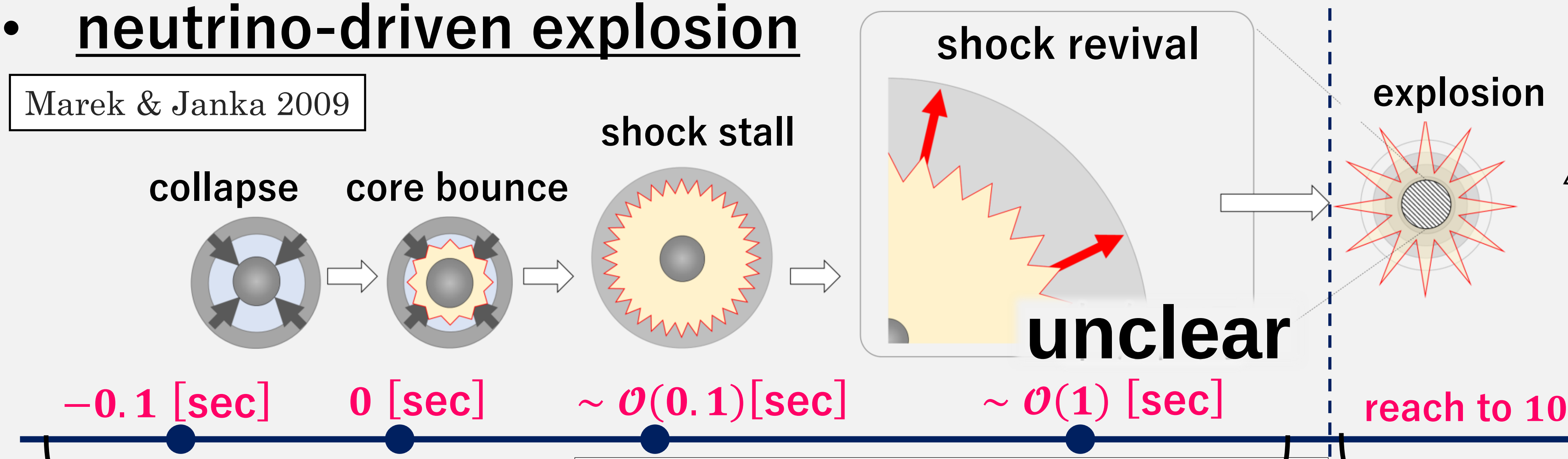
But ‘nickel mass problem’(Ni problem)

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

Explosion mechanism of Core-Collapse SNe

- **neutrino-driven explosion**

Marek & Janka 2009



collapse

core bounce

shock stall

shock revival

unclear

explosion

-0.1 [sec]

0 [sec]

$\sim \mathcal{O}(0.1)$[sec]

$\sim \mathcal{O}(1)$ [sec]

reach to 10^{51} [erg]

observed property

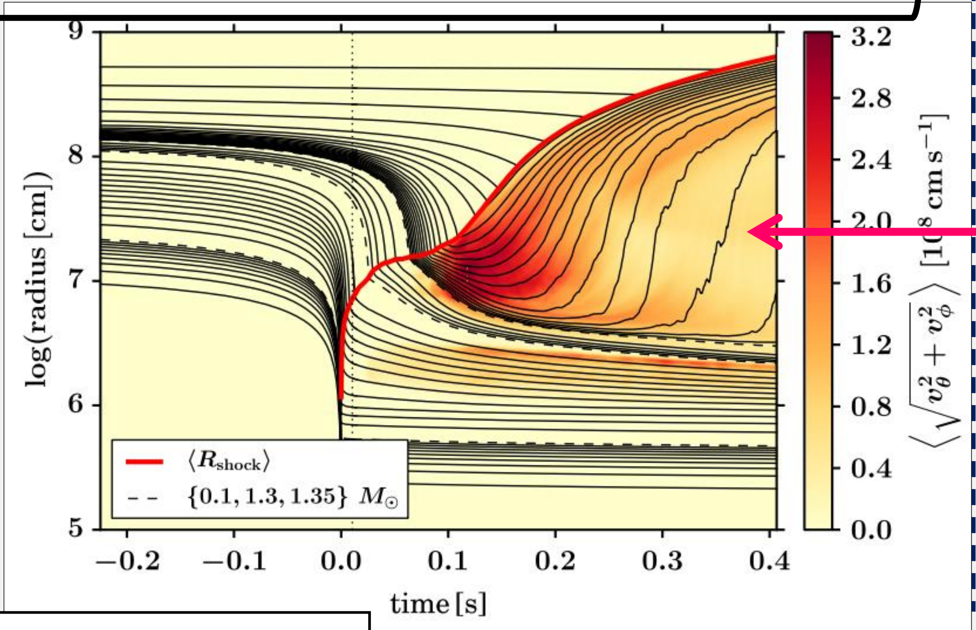
$E_{\rm kin} \sim 10^{51}$ erg

$M_{\rm 56ni} \sim 0.07\ M_{\odot}$

growing rate of the explosion energy

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

especially for 3D simulations.



Melson, Janka & Marek 2015

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

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

Sawada & Suwa (ApJ, 2021) arxiv. 2010.05615

aim and content of our work

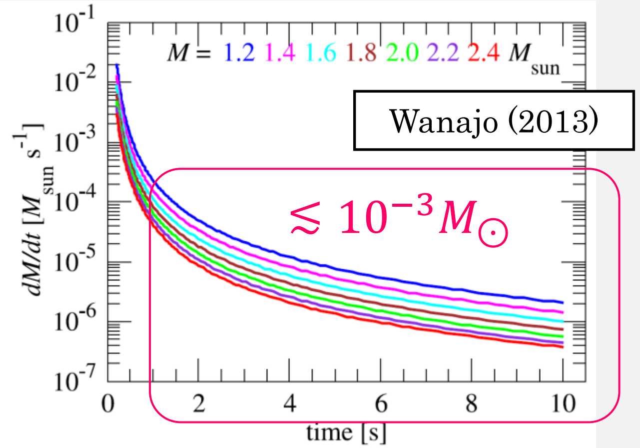
motivation

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

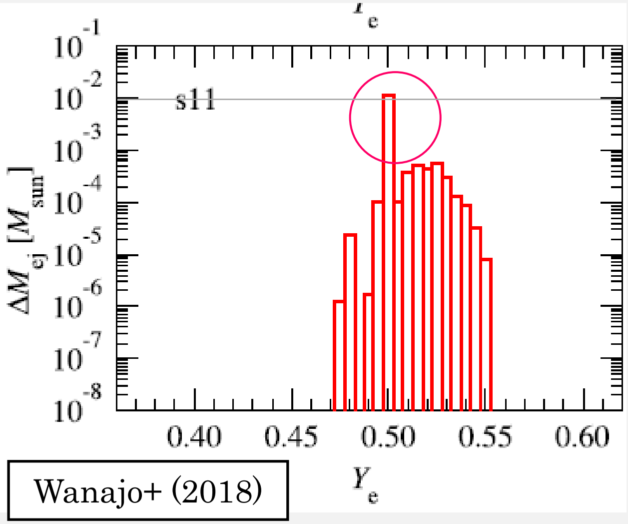
problem

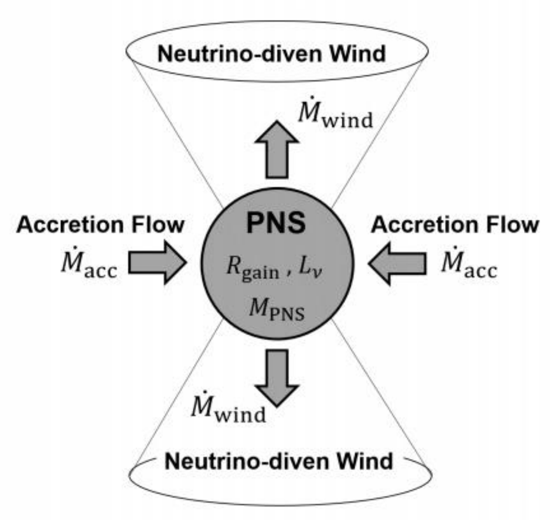
- **1D** (e.g.,Wanajo2013) **:**
  it is already known that 1D wind simulation could not solve Ni problem.
  (→ multi-D, especially energy injection by accretion, is important.)

- **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

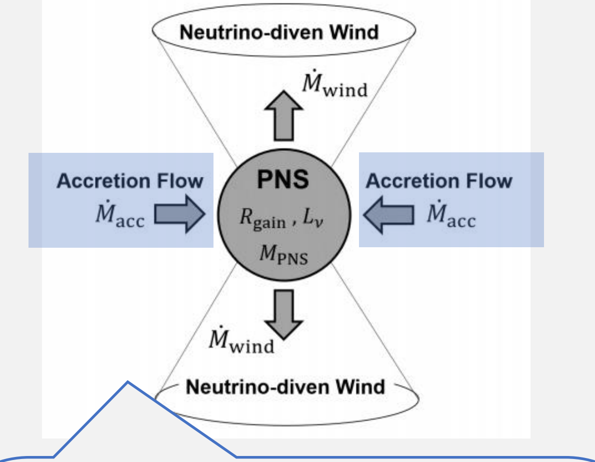
1. Build a consistent model of the neutrino-driven wind with an accretion flow onto a PNS.
2. Investigate the possibility that neutrino-driven wind can solve the "Ni-problem"

Sawada & Suwa (ApJ, 2021) arxiv. 2010.05615

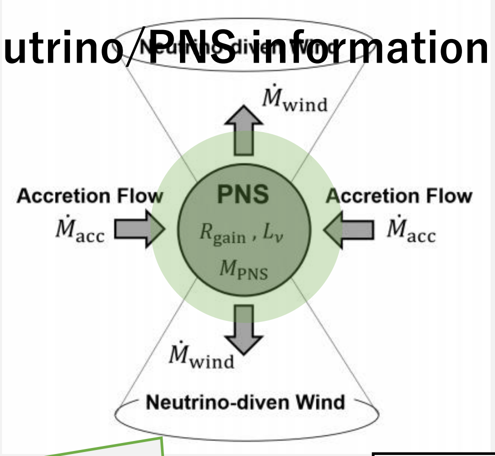
aim and content of our work

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

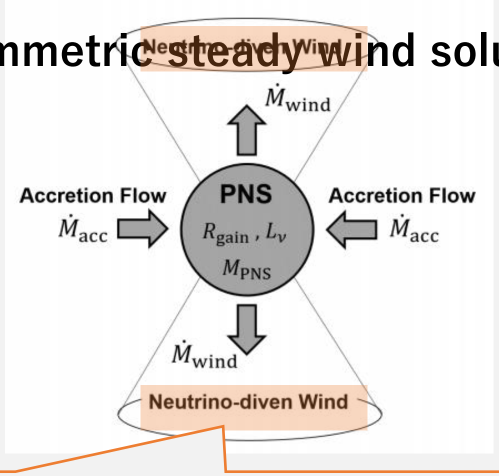
① assume free-fall fallback onto PNS



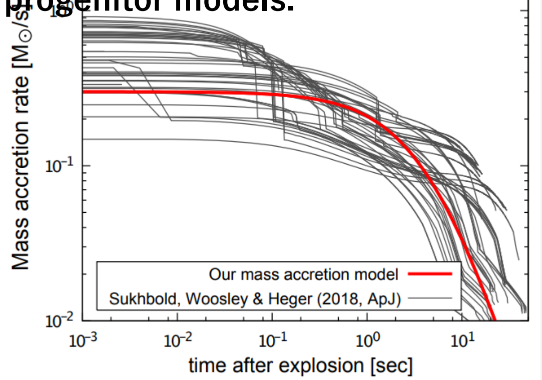
② Converting accretion flow into neutrino/PNS information



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



Approximating phenomenological accretion from progenitor models.



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

Müller +2016

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

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

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

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

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

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

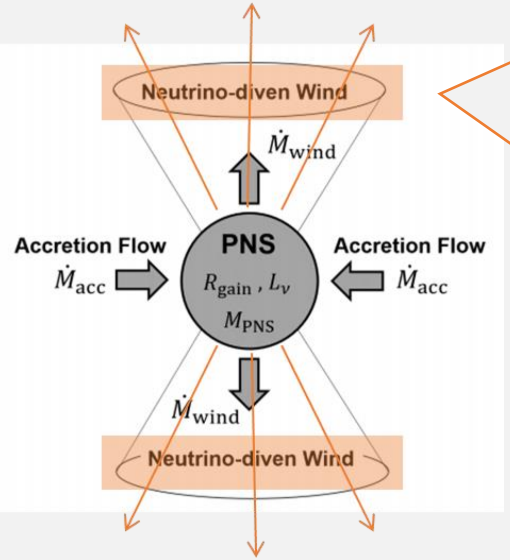
$$\dot{M}_{\rm wind} = f_\Omega \dot{M}_{\rm wind,iso}, \qquad (9)$$

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

④ connect them w/ geometric factor

Sawada & Suwa (ApJ, 2021) arxiv. 2010.05615

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



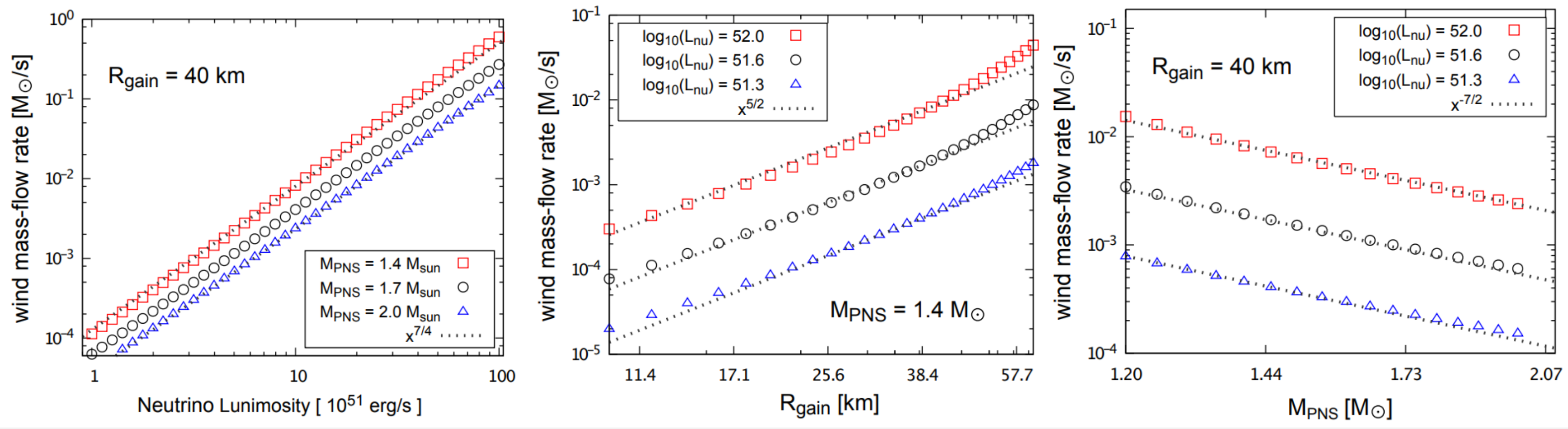
Assume a neutrino-driven wind blowing in the "radial direction" through the low-density region swept by the non-spherically symmetric shock wave

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

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

- $$\dot{M} = 4\pi r^2 \rho v \ , \qquad (1)$$
- $$v\frac{dv}{dr} = -\frac{1+(v/c)^2-(2GM/c^2 r)}{\rho(1+\epsilon/c^2)+P/c^2}\frac{dP}{dr} - \frac{GM_{\rm PNS}}{r^2} \ , \qquad (2)$$
- $$\dot{Q} = v\left(\frac{d\epsilon}{dr} - \frac{P}{\rho^2}\frac{d\rho}{dr}\right) \ , \qquad (3)$$
- 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)
- $$Y_e = \left[1 + \frac{L^n_{\bar{\nu}_e}\langle\sigma_{\bar{\nu}_e p}\rangle}{L^n_{\nu_e}\langle\sigma_{\nu_e n}\rangle}\right]^{-1} = 0.5, \qquad (4)$$
  (e.g., Bliss+ 2018).

- **result**



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

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

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result

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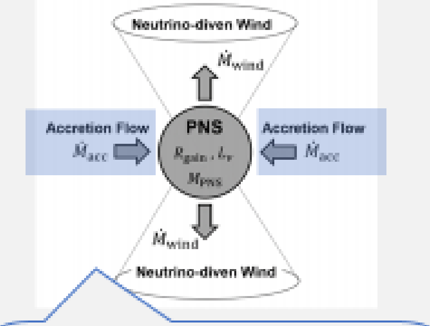

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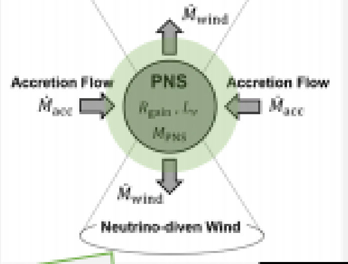

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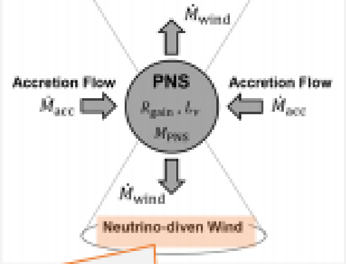

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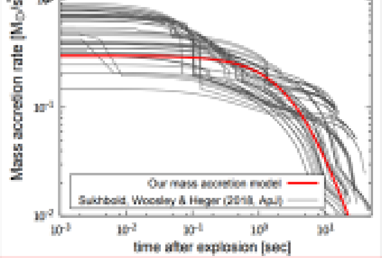

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$$\dot{M}_{\rm wind} \approx 1.3\times10^{-2}\ M_\odot{\rm s}^{-1} \times f_\Omega\left(\frac{(1-f_\Omega)\dot{M}_{\rm acc,iso}}{0.1M_\odot{\rm s}^{-1}}\right)^{\frac{2\alpha+\beta}{3}}\left(\frac{M_{\rm PNS}}{1.4M_\odot}\right)^{2\alpha-\beta+\gamma},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

- **wind model w/ accretion flow**

Sawada & Suwa (ApJ, 2021) arxiv. 2010.05615

Can synthesize a sufficient amount of 56Ni ?

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 $< 0.7 M_\odot$

- total ejected mass of the wind…

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

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

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

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

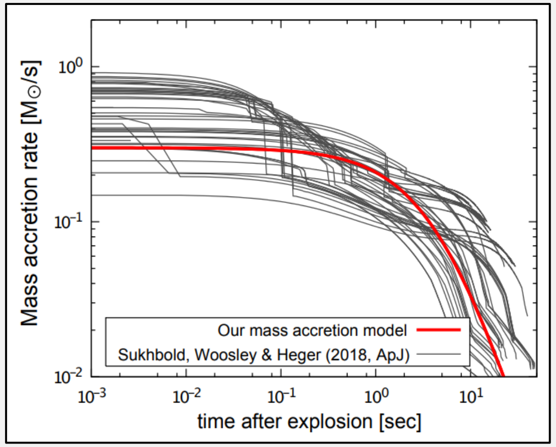
$$\approx 6.4 \times 10^{-4} M_\odot \left[1 - \left(\frac{t_0}{t_0 + t_e}\right)^3\right] \times \left(\frac{t_0}{1s}\right) \left(\frac{\dot{M}_{\mathrm{acc},0}}{0.1 M_\odot s^{-1}}\right)^2 \left(\frac{M_{\mathrm{PNS},0}}{1.4 M_\odot}\right)^{-5/2}$$

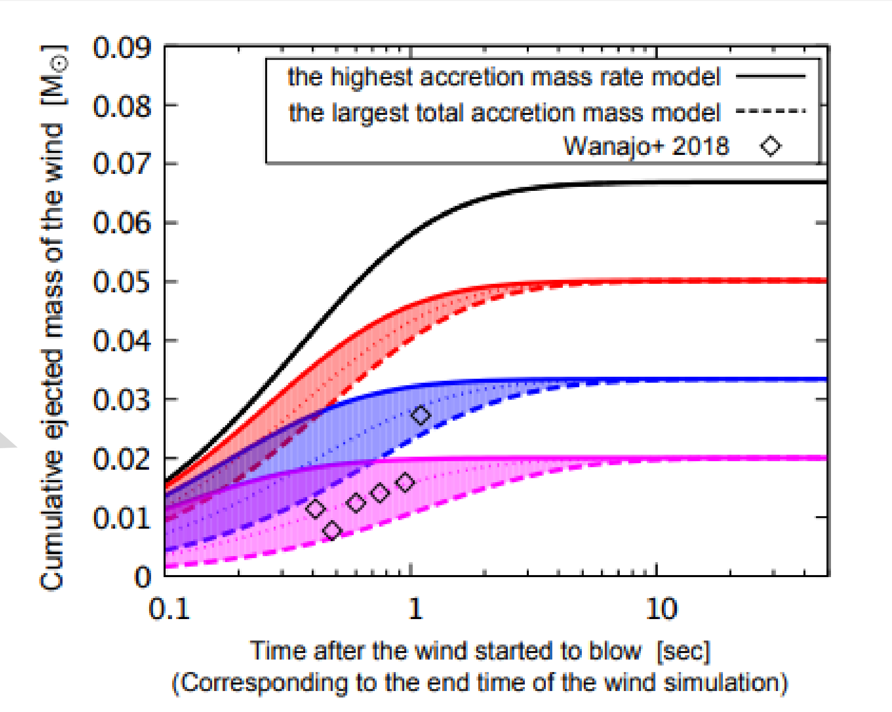
- Conclusion.

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.



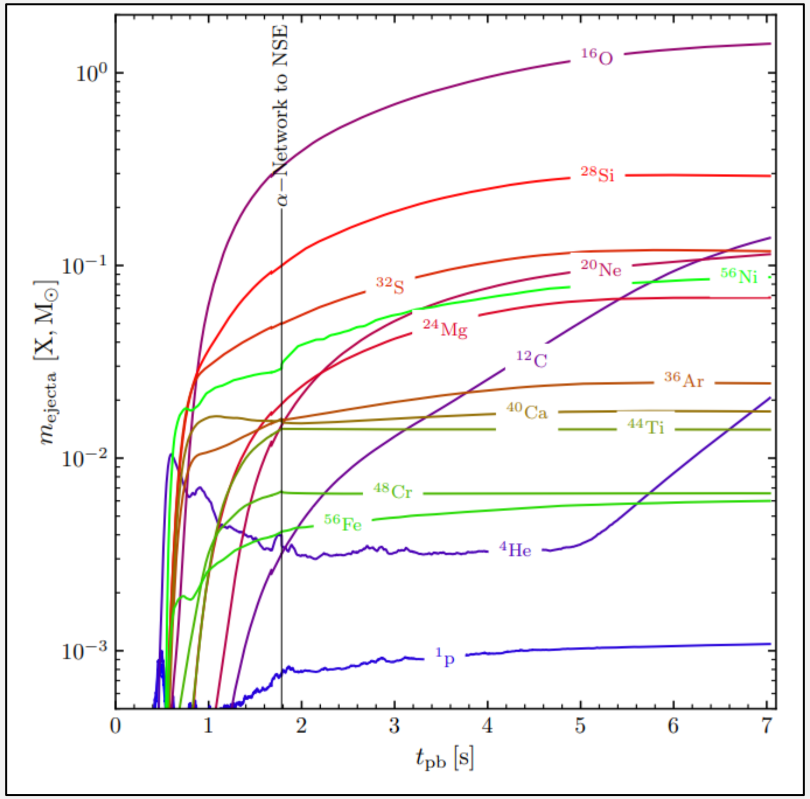


Sawada & Suwa (ApJ, 2021) arxiv. 2010.05615

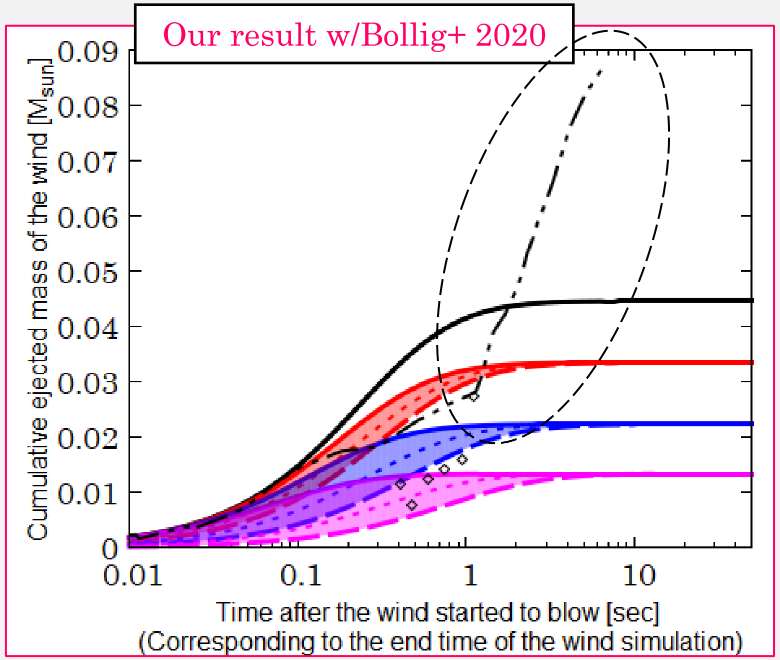
Can synthesize a sufficient amount of 56Ni ?

- **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.”

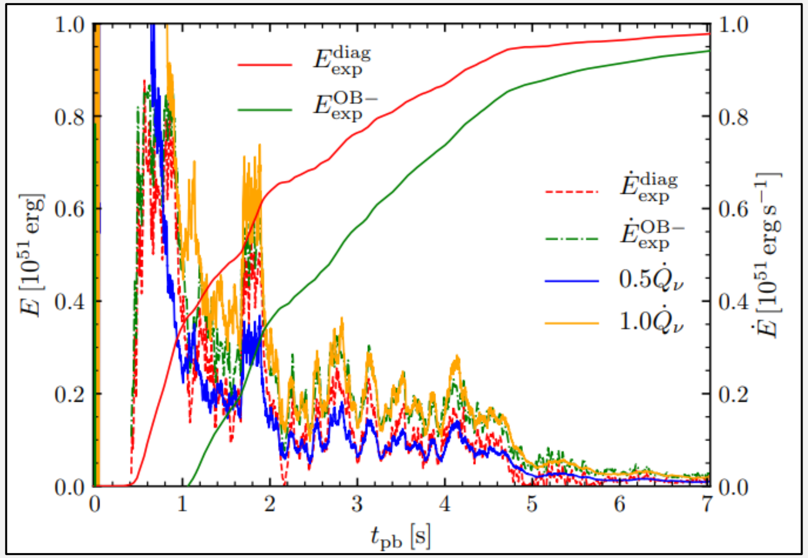


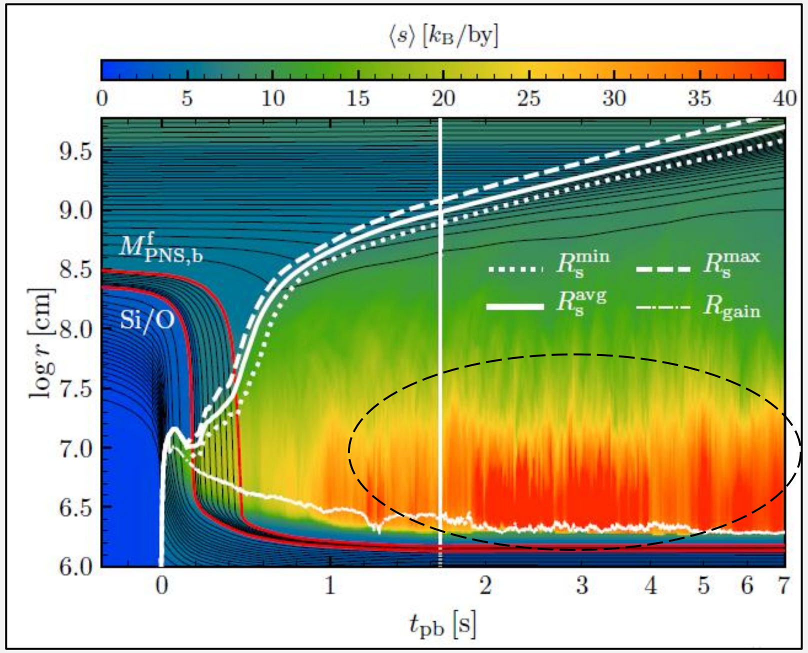
Our result w/Bollig+ 2020



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

Our work





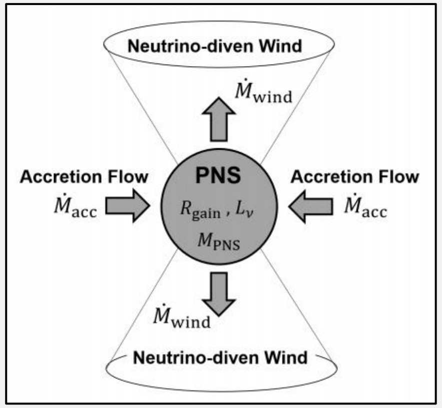
Sawada & Suwa (ApJ, 2021) arxiv. 2010.05615

Summary

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

- **spherical wind**

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



- **wind model w/ accretion flow**

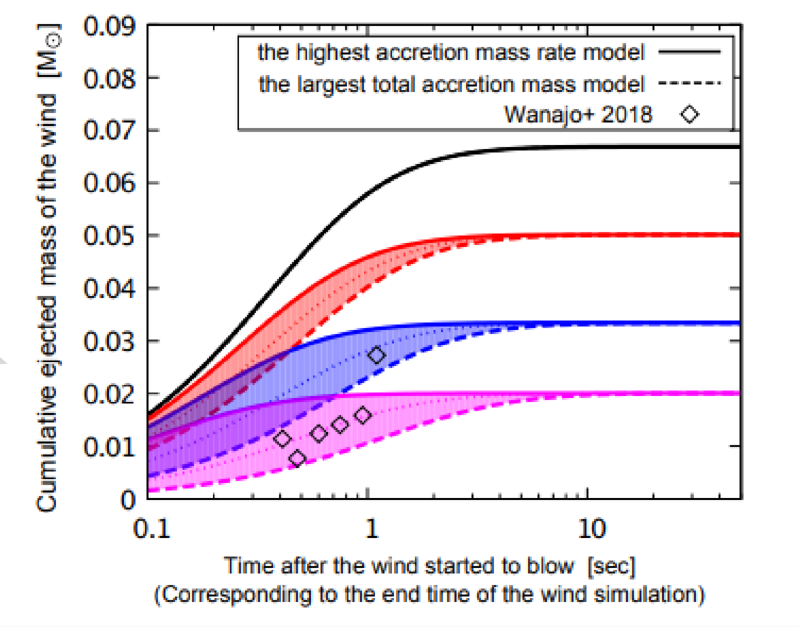
$$\dot{M}_{\rm wind} \approx 1.3\times10^{-2}\ M_\odot {\rm s}^{-1} \times f_\Omega \left(\frac{(1-f_\Omega)\dot{M}_{\rm acc,iso}}{0.1M_\odot {\rm s}^{-1}}\right)^{2} \left(\frac{M_{\rm PNS,0}}{1.4M_\odot}\right)^{-5/2}. \quad (23)$$

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 $M_{\rm ej} < 0.01M_\odot$**.

→ difficult to solve the Ni problem

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



Sawada & Suwa (ApJ, 2021) arxiv. 2010.05615