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

Sawada & Suwa (2020) submitted to ApJ (arxiv. 2010.05615)

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Abstract

What are our interests?

”Ni-problem”: Open issue remaining in the core-collapse supernova(CCSN) explosion mechanism.

- **First-principles simulations** (e.g, **Boling+2020**)
  -> Successful reproduction of a CCSN explosion

However, …

- **Recent suggestion**
  (e.g, **Suwa+2019, Sawada&Maeda 2019**)
  -> the growth rate of explosive energy on the simulation is insufficient to synthesize observed 56Ni mass.

“Neutrino-driven wind”: the most promising candidate to solve the “Ni-problem”, especially **at later phases**.

What is the problem?

a multi-D simulation is computationally too expensive to investigate **upto later phases**.

What we do?

build a consistent model of **'the neutrino-driven wind with an accretion flow onto a PNS’,** and investigate **the potential of the neutrino-driven wind to solve ‘Ni-problem’.**

What is our conclusion?

1. the total ejectable is **determined within ~ 1 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”
by the neutrino-driven wind at the late phase.

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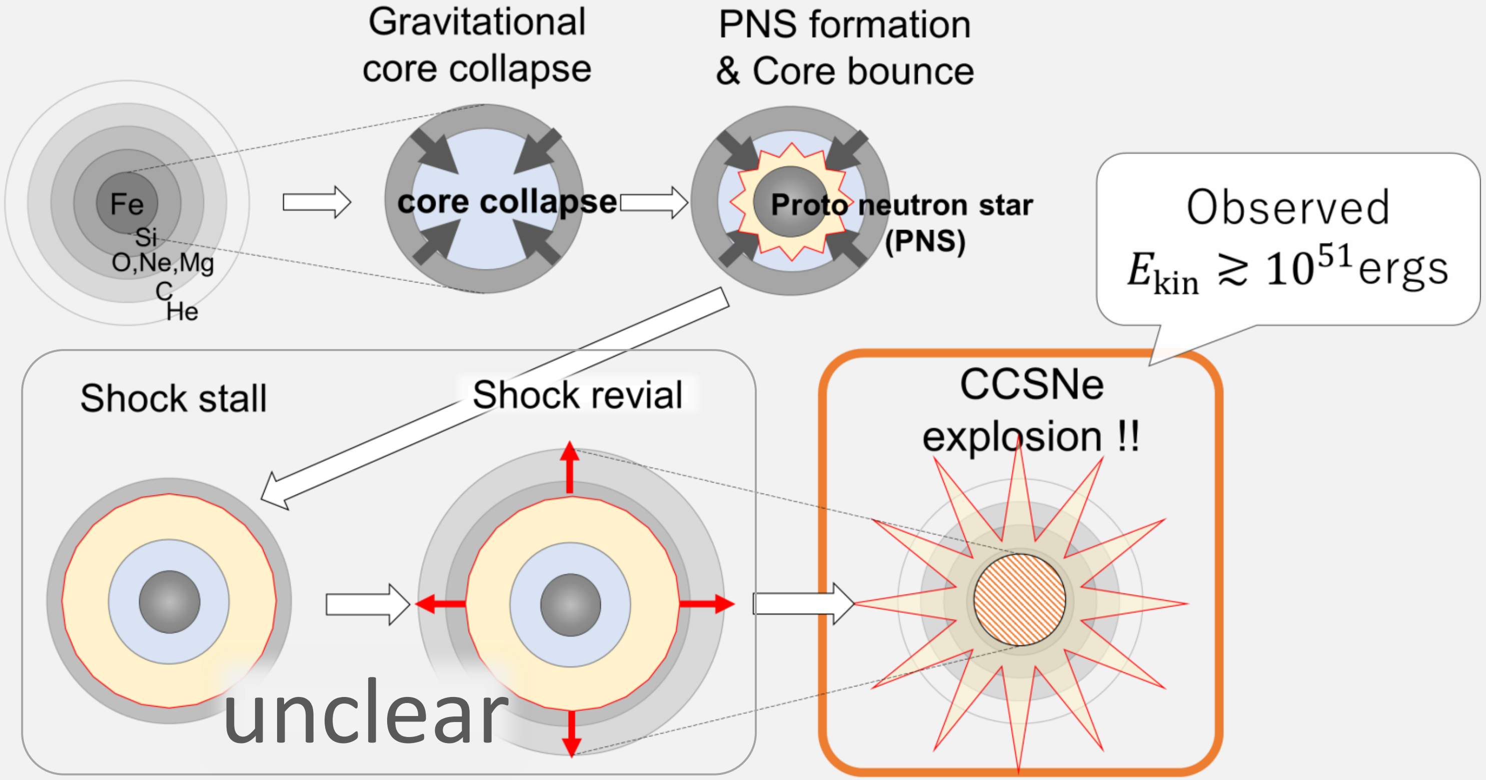
Explosion mechanism of Core-Collapse SNe

- **neutrino-driven explosion**



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

*unclear：

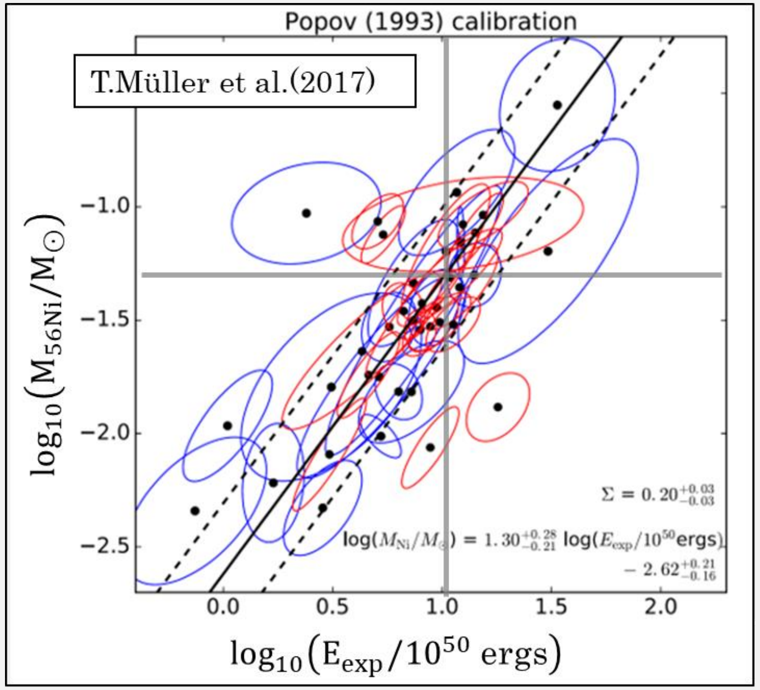
1). Can reach to 10^{51} [erg] ？

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

- **observation**

observed property

$E_{\mathrm{kin}} \sim 10^{51}$ erg
$M_{56\mathrm{ni}} \sim 0.07\ M_{\odot}$



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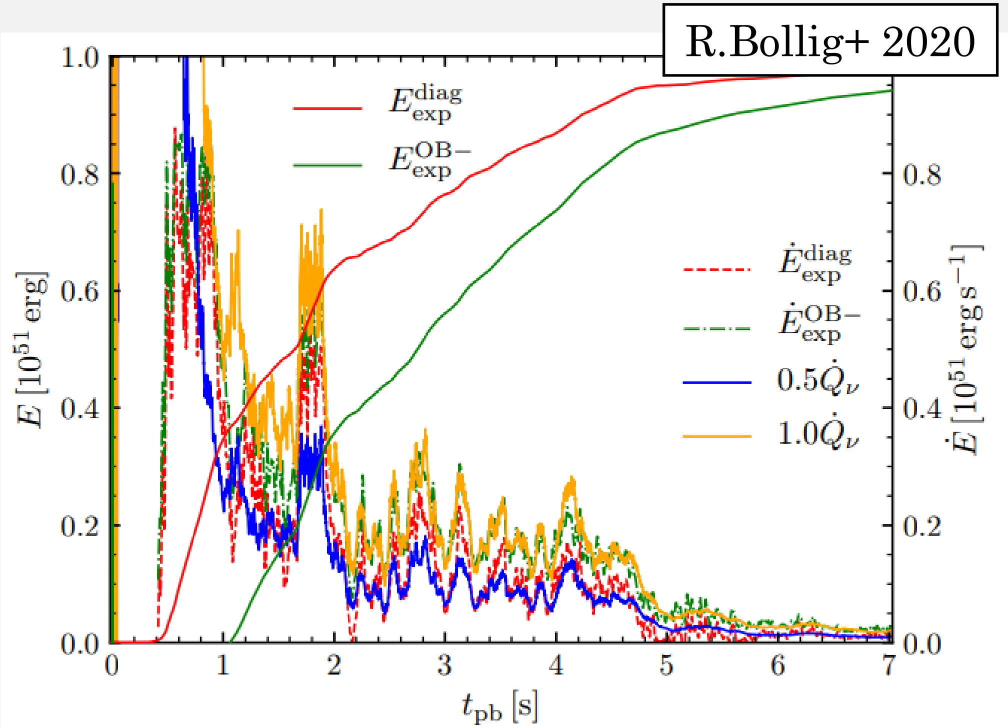
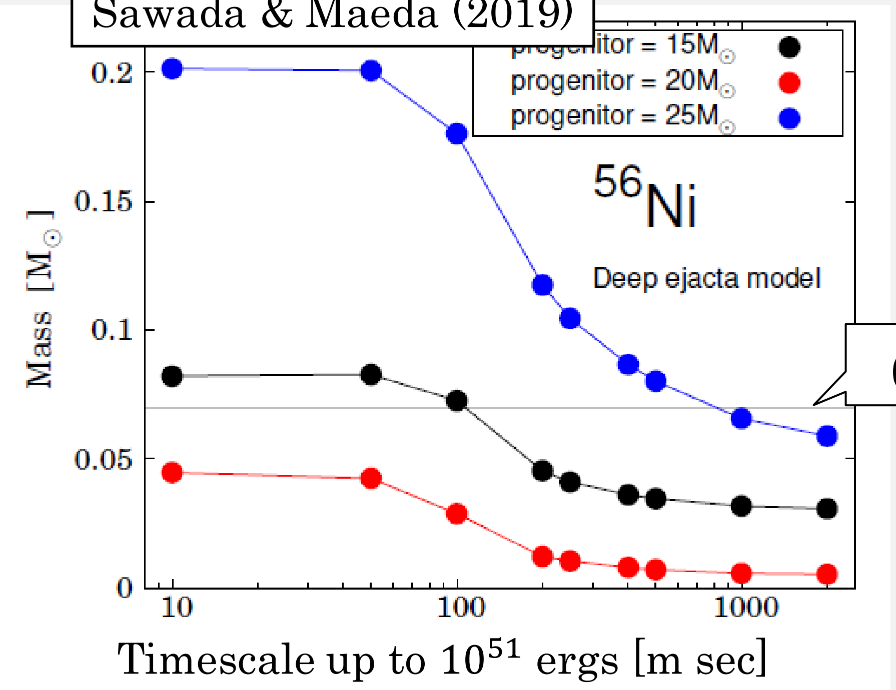
Can synthesize a sufficient amount of 56Ni ?


R.Bollig+ 2020


Sawada & Maeda (2019)

$0.07M_\odot$

- **ab-inito simulation :**

growing rate of the explosion energy

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

especially for 3D simulations.

- **recent suggestion :**

the typical mass $0.07M_\odot$ of 56Ni in CCSNe, the growth rate of the explosion energy of $\dot{E}_{\rm expl.} \geq \mathcal{O}(1)$ [10^{51} erg/s] is required

→‘nickel mass problem’(Ni problem)

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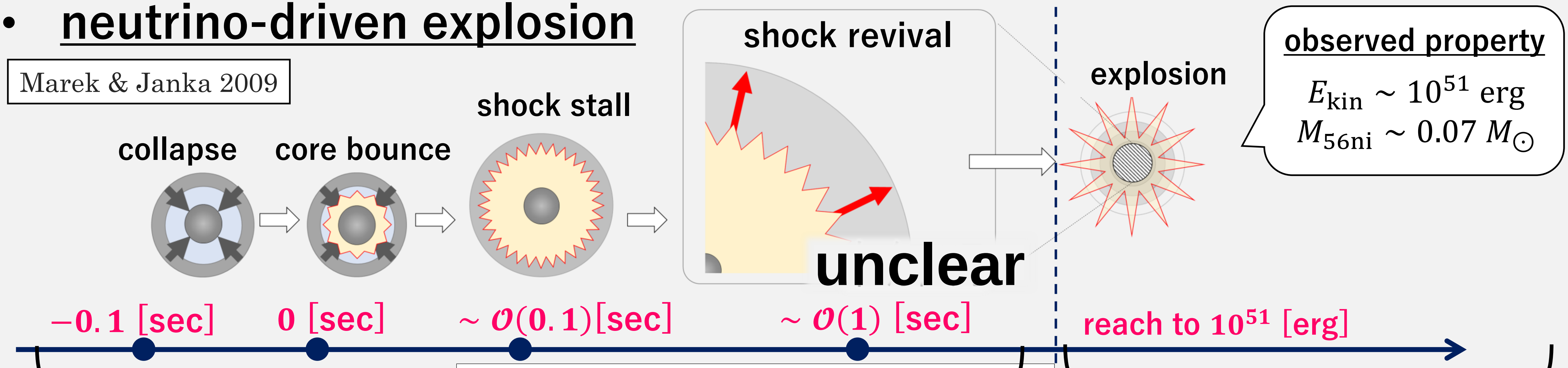
Explosion mechanism of Core-Collapse SNe

- **neutrino-driven explosion**

Marek & Janka 2009



observed property

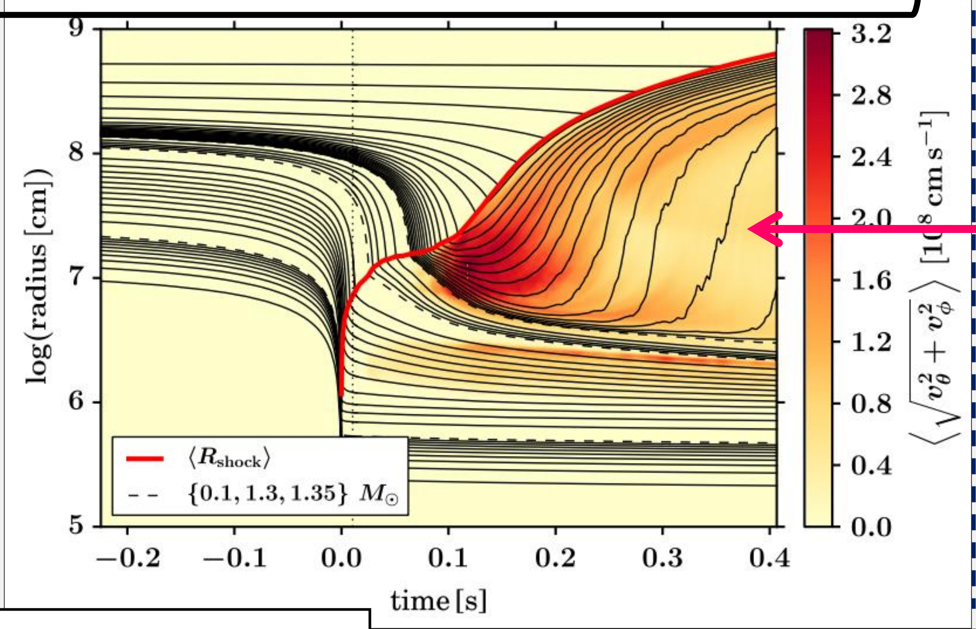
$E_{\rm kin} \sim 10^{51}$ erg

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

growing rate of the explosion energy

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

especially for 3D simulations.



Melson, Janka & Marek 2015

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

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

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aim and content of our work

motivation

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

problem

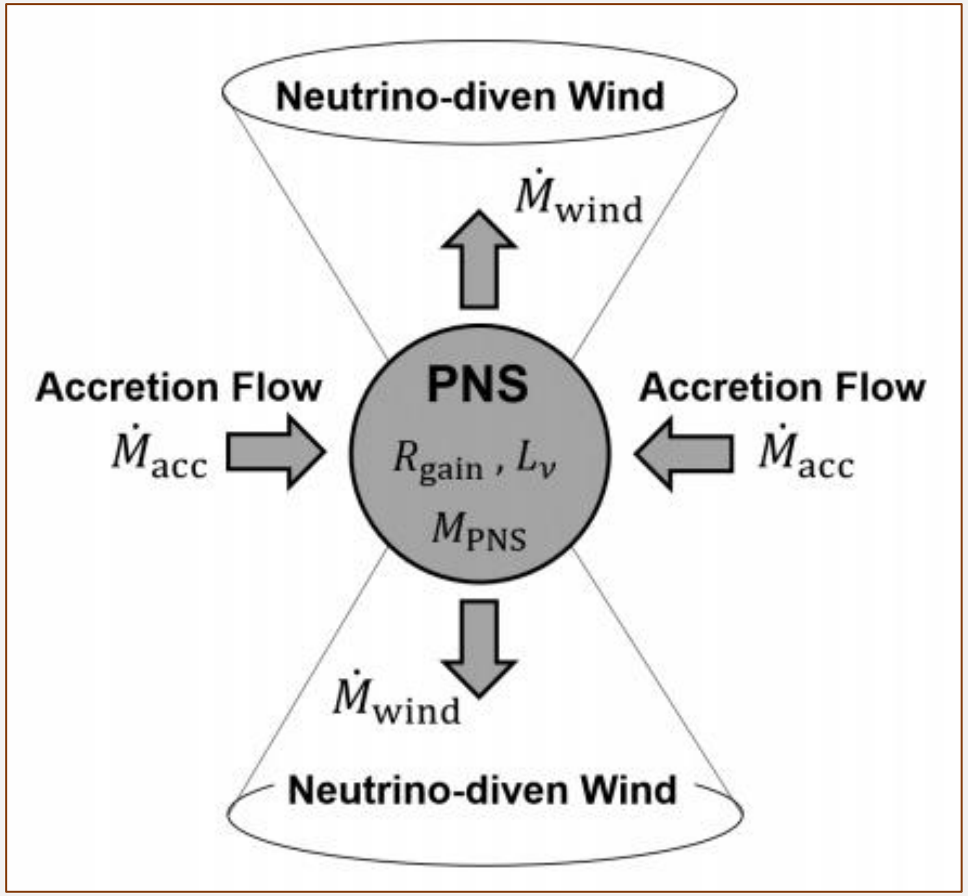
- However, it is difficult to simulate **up to late phases** in multi-D

our work

- build a consistent model of **'the neutrino-driven wind with an accretion flow onto a PNS’,**

and

- investigate **the potential of the neutrino-driven wind to solve ‘Ni-problem’.**



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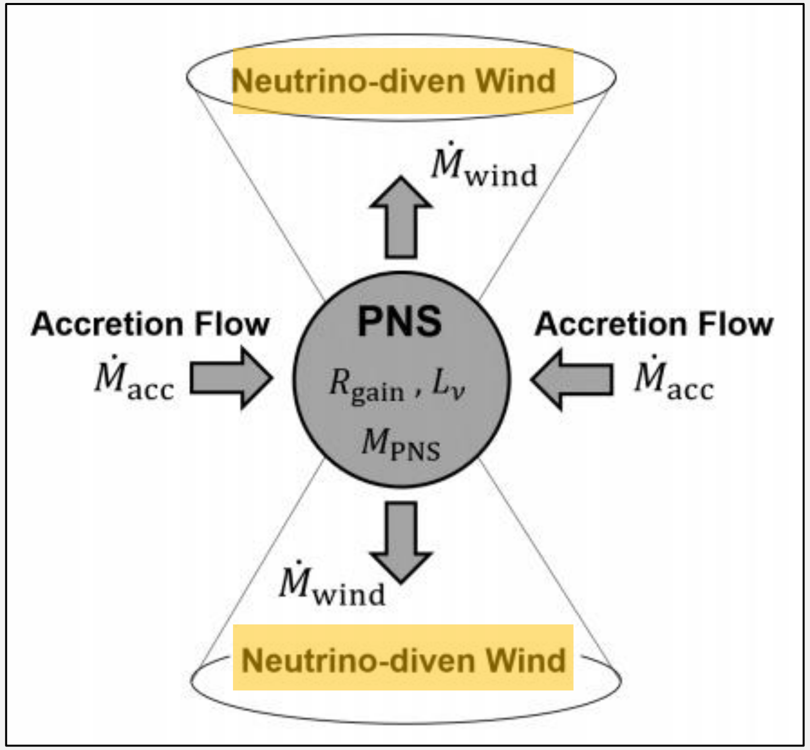
semi-analytic wind model (e.g., Otsuki et al. 2000).

Basic equations

- $$\dot{M} = 4\pi r^2 \rho v \ , \qquad (1)$$
- $$v\frac{dv}{dr} = -\frac{1+(v/c)^2-(2GM/c^2r)}{\rho(1+\epsilon/c^2)+P/c^2}\frac{dP}{dr} - \frac{GM_{\rm PNS}}{r^2} \ , \qquad (2)$$
- $$\dot{Q} = v\left(\frac{d\epsilon}{dr} - \frac{P}{\rho^2}\frac{d\rho}{dr}\right) \ , \qquad (3)$$

- electron/positron capture: $\nu_e + n \rightleftarrows p + e^-$ and $\overline{\nu_e} + p \rightleftarrows n + e^+$,
- neutrino scattering on electrons and positrons
- pair annihilation: $\nu + \bar{\nu} \rightarrow e^- + e^+$

(for more details, see Eqs. (8) – (16) in Otsuki et al. 2000).



- 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 et al. 2015) → T_0, v_0
- $$Y_e = \left[1 + \frac{L^n_{\overline{\nu}_e}\langle\sigma_{\overline{\nu}_e p}\rangle}{L^n_{\nu_e}\langle\sigma_{\nu_e n}\rangle}\right]^{-1} = 0.5, \qquad (4)$$ (e.g., Bliss et al. 2018).

given: $(L_\nu, R_{\rm gain}, M_{\rm PNS})$

⇩

$\dot{M}_{\rm wind}$ as a solution exists

(maximum : transonic)

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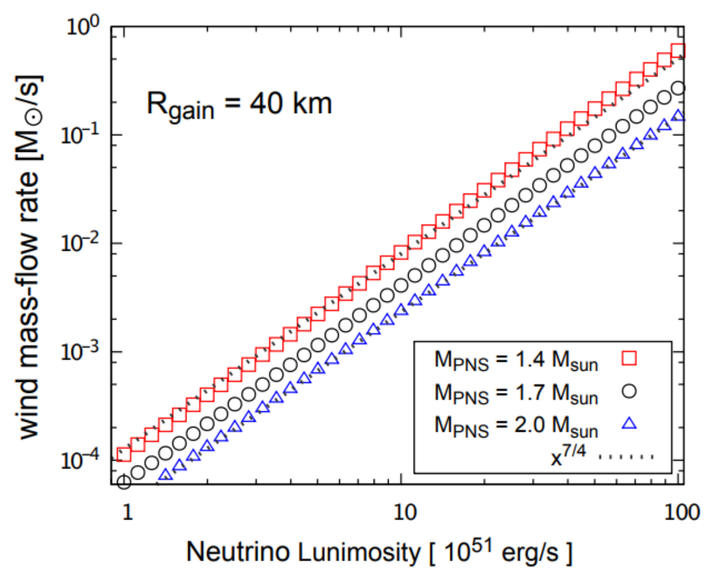
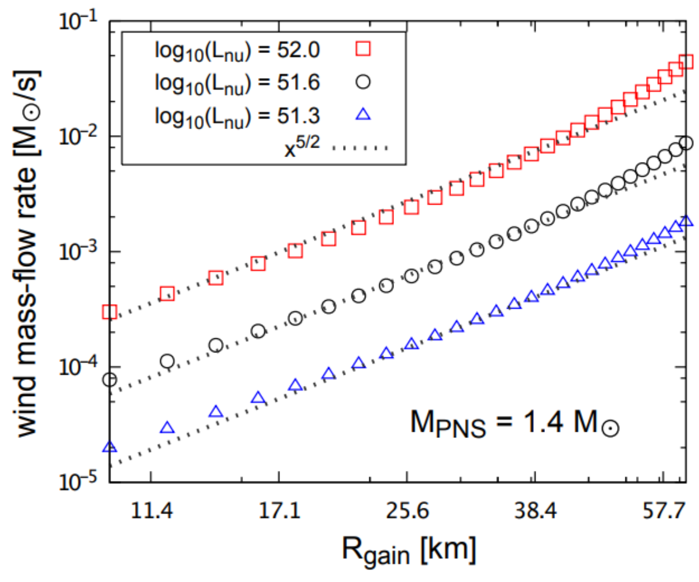
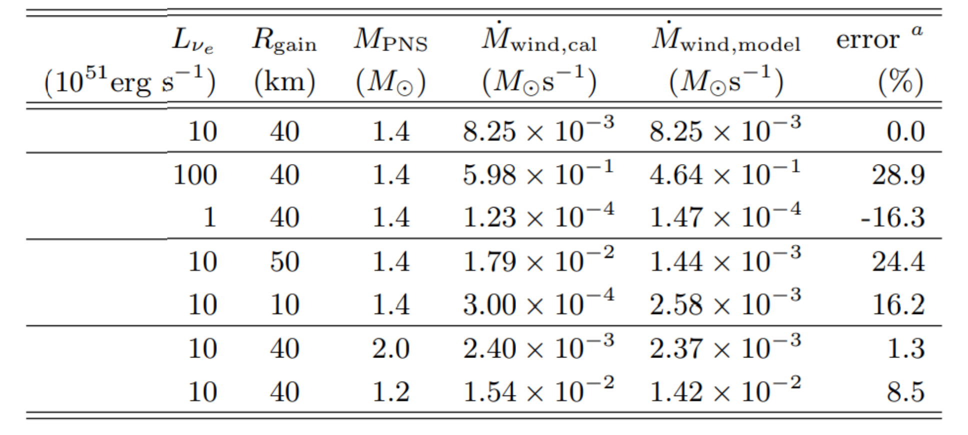
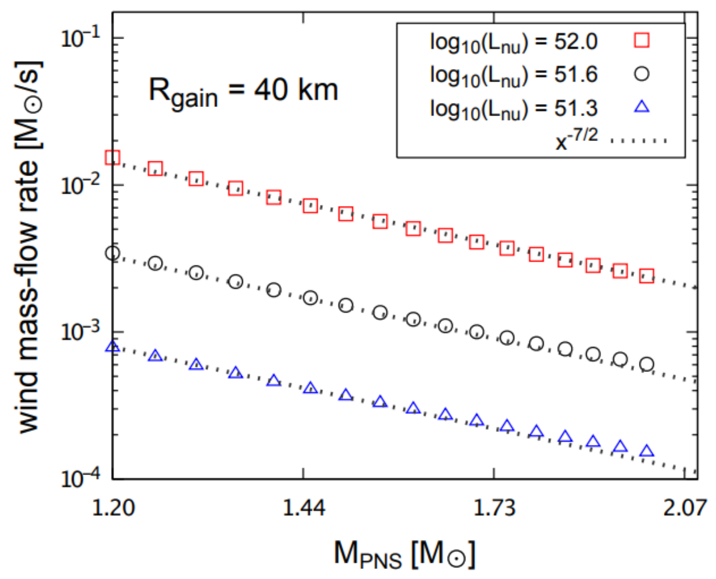
semi-analytic wind model (e.g., Otsuki et al. 2000).







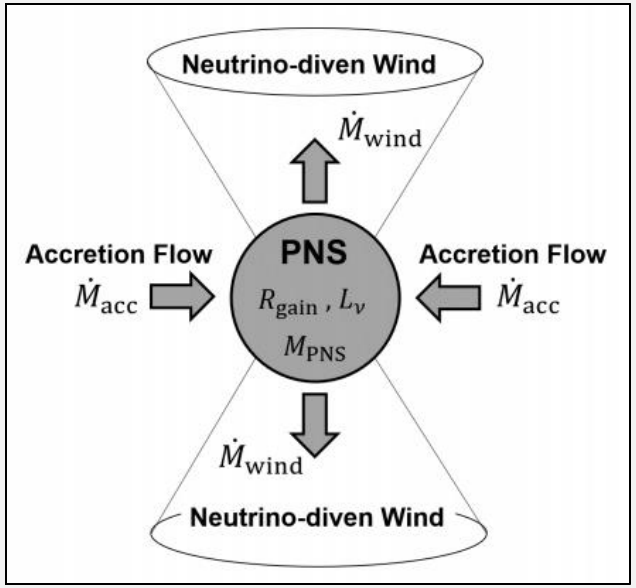
L_{ν_e} (10^{51}erg s^{-1})	$R_{\rm gain}$ (km)	$M_{\rm PNS}$ ($M_\odot$)	$\dot{M}_{\rm wind,cal}$ ($M_\odot$s^{-1})	$\dot{M}_{\rm wind,model}$ ($M_\odot$s^{-1})	error ^{a} (%)
10	40	1.4	8.25×10^{-3}	8.25×10^{-3}	0.0
100	40	1.4	5.98×10^{-1}	4.64×10^{-1}	28.9
1	40	1.4	1.23×10^{-4}	1.47×10^{-4}	-16.3
10	50	1.4	1.79×10^{-2}	1.44×10^{-3}	24.4
10	10	1.4	3.00×10^{-4}	2.58×10^{-3}	16.2
10	40	2.0	2.40×10^{-3}	2.37×10^{-3}	1.3
10	40	1.2	1.54×10^{-2}	1.42×10^{-2}	8.5



- **spherical wind relation**

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

$$\left(\alpha = \frac{7}{4}, \quad \beta = \frac{5}{2}, \quad \gamma = -\frac{7}{2}\right)$$



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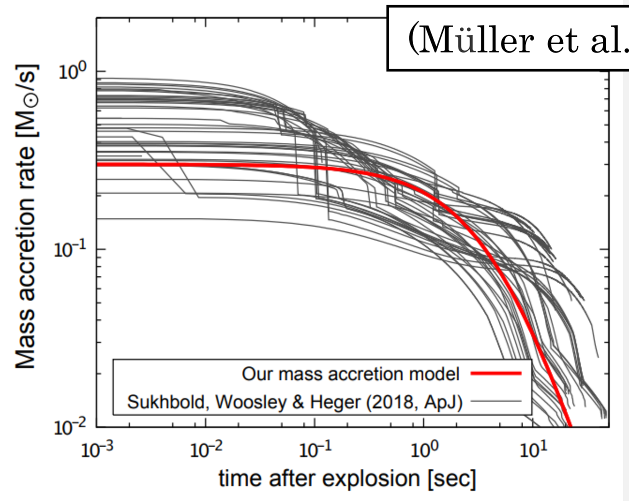
connecting wind model with accretion flow onto a PNS

- spherical semi-analytic wind model

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

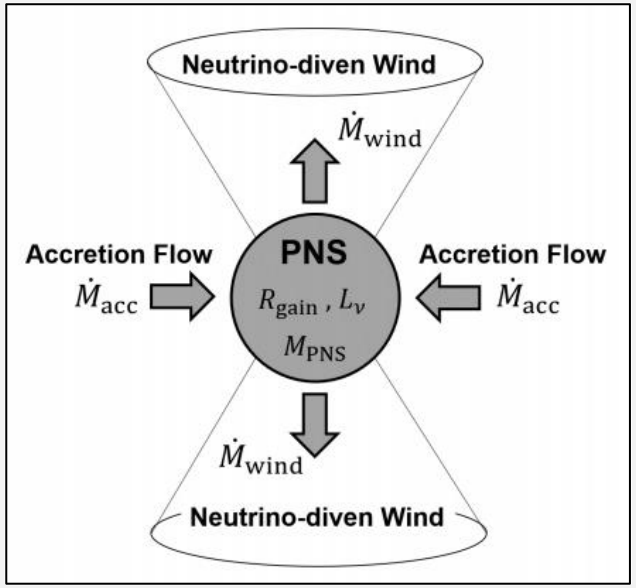
$+$

- phenomenological mass accretion model



(Müller et al. 2016)

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



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

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

$+$

- Analytic CCSN-explosion modeling

(Müller et al. 2016)

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

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

$$\dot{M}_{\rm wind} \approx 1.3\times 10^{-2}\ M_\odot {\rm s}^{-1} \times f_\Omega \left(\frac{(1-f_\Omega)\dot{M}_{\rm acc,iso}}{0.1M_\odot {\rm s}^{-1}}\right)^{\frac{2\alpha+\beta}{3}} \left(\frac{M_{\rm PNS}}{1.4M_\odot}\right)^{2\alpha-\beta+\gamma}, \qquad (13)$$

- **wind model w/ accretion flow**

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whether the wind can eject 0.07M of 56Ni or not?

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

$$\approx 1.3 \times 10^{-2} M_\odot s^{-1} f_\Omega (1 - f_\Omega)^2 \left(\frac{\dot{M}_{\mathrm{acc},0}}{0.1 M_\odot s^{-1}}\right)^2 \left(\frac{M_{\mathrm{PNS},0}}{1.4 M_\odot}\right)^{-\frac{5}{2}} \int_0^\infty dt \left(\frac{t}{t_0} + 1\right)^{-4}$$

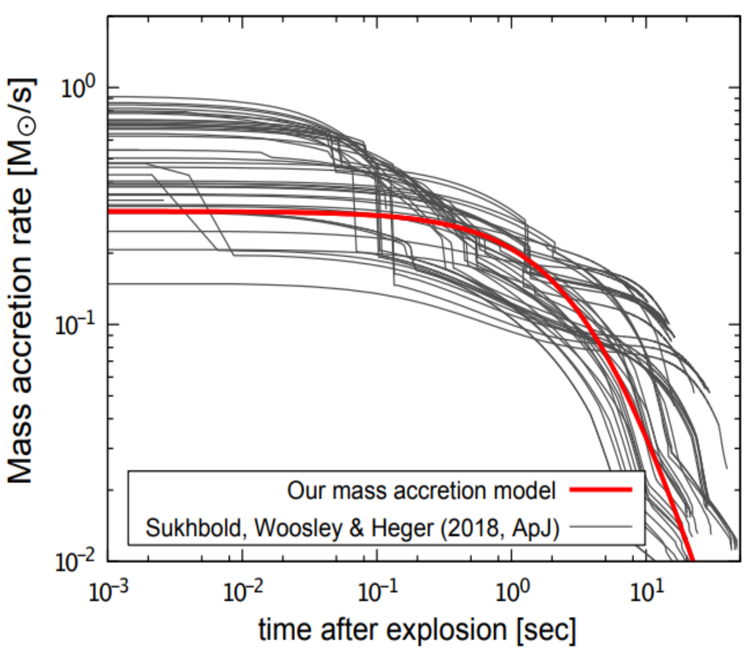
(when $f_\Omega = \frac{1}{3}$, which geometric effect term $f_\Omega(1 - f_\Omega)^2$ maximum)

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

total ejectable amount
of the neutrino-driven wind is roughly…

$$M_{\mathrm{ej},\infty} \leq 0.067 M_\odot$$

If most of the wind is added at late phase,
this value is sufficient to solve the Ni problem.



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

from figure
Given maximum parameter sets

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

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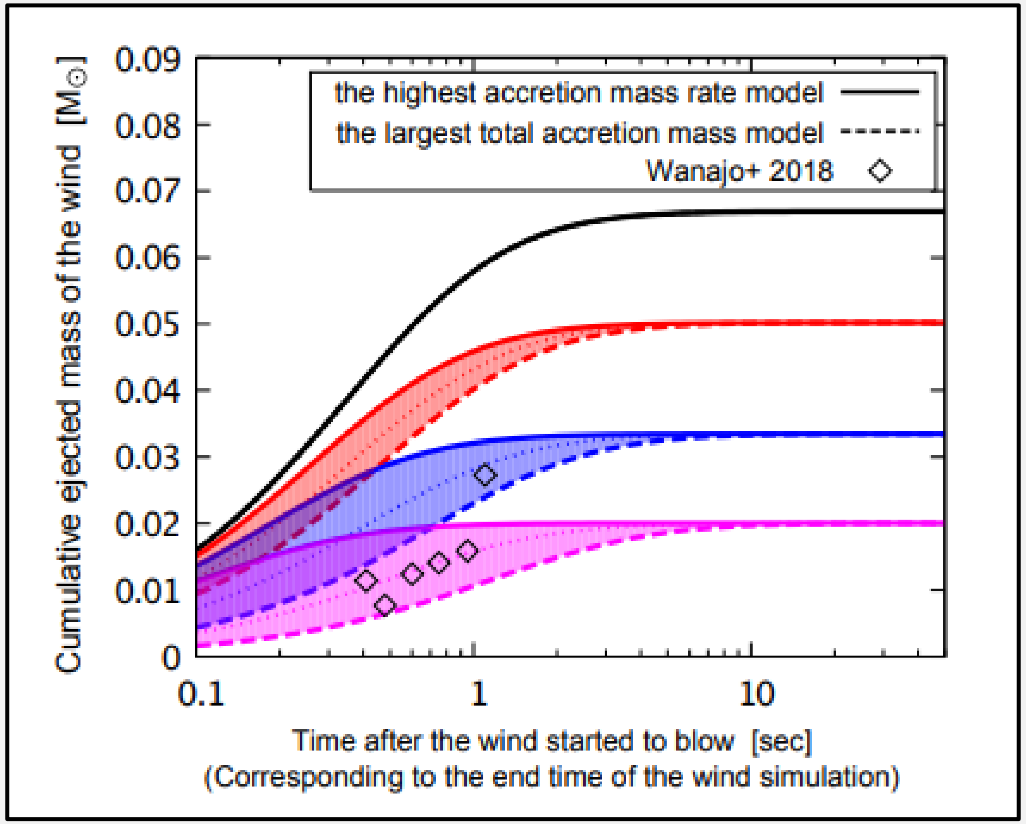
Possible Contribution to the ‘Ni problem’

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

$$M_{\rm ej}(t_e) = \int_0^{t_e} dt\,\dot{M}_{\rm wind} \approx 6.4\times10^{-4}M_\odot\left[1-\left(\frac{t_0}{t_0+t_e}\right)^3\right]\times\left(\frac{t_0}{1s}\right)\left(\frac{\dot{M}_{\rm acc,0}}{0.1M_\odot s^{-1}}\right)^2\left(\frac{M_{\rm PNS,0}}{1.4M_\odot}\right)^{-5/2}$$



conclusion

- the total ejectable is **determined within ~ 1 sec** from the onset of the explosion.

- 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.

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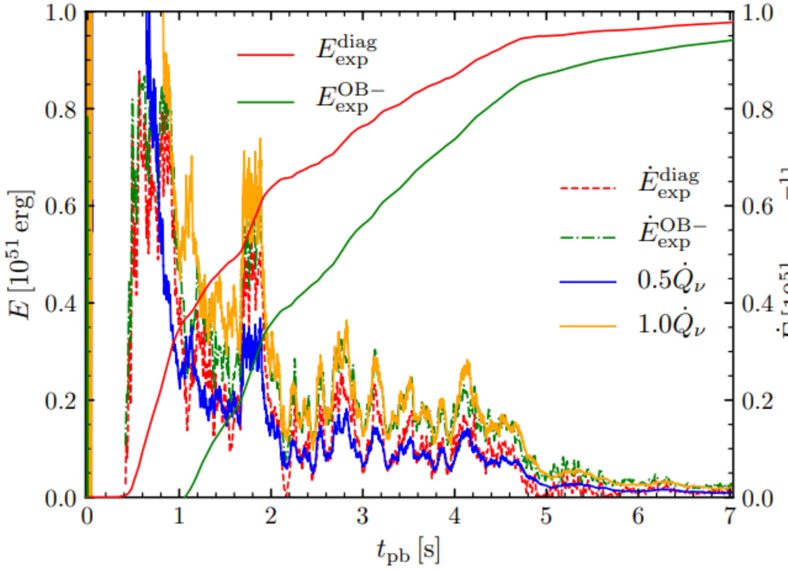
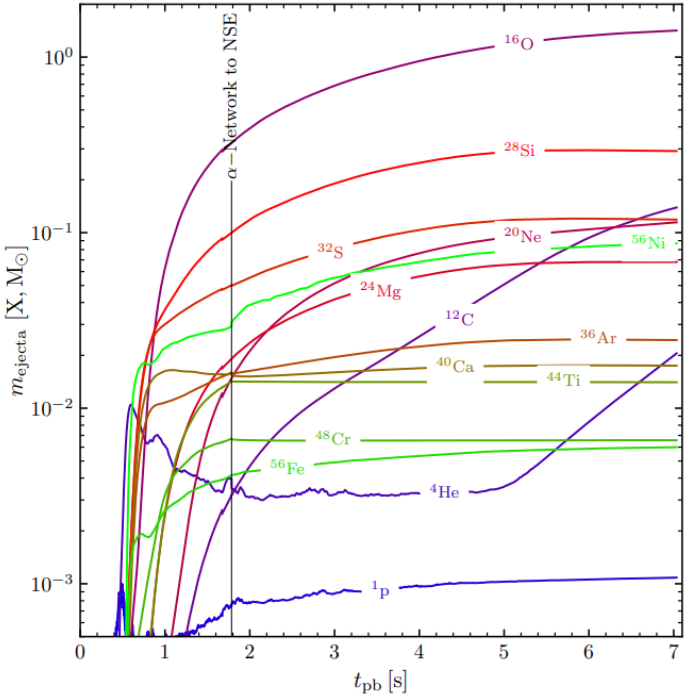
Can synthesize a sufficient amount of 56Ni ?

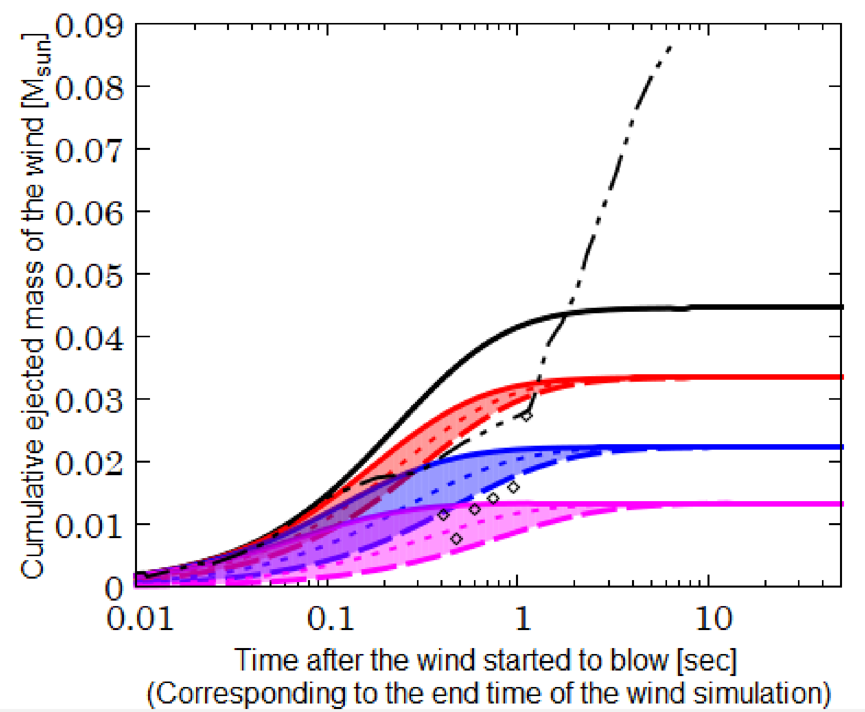
- **NOTE :**

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.**"







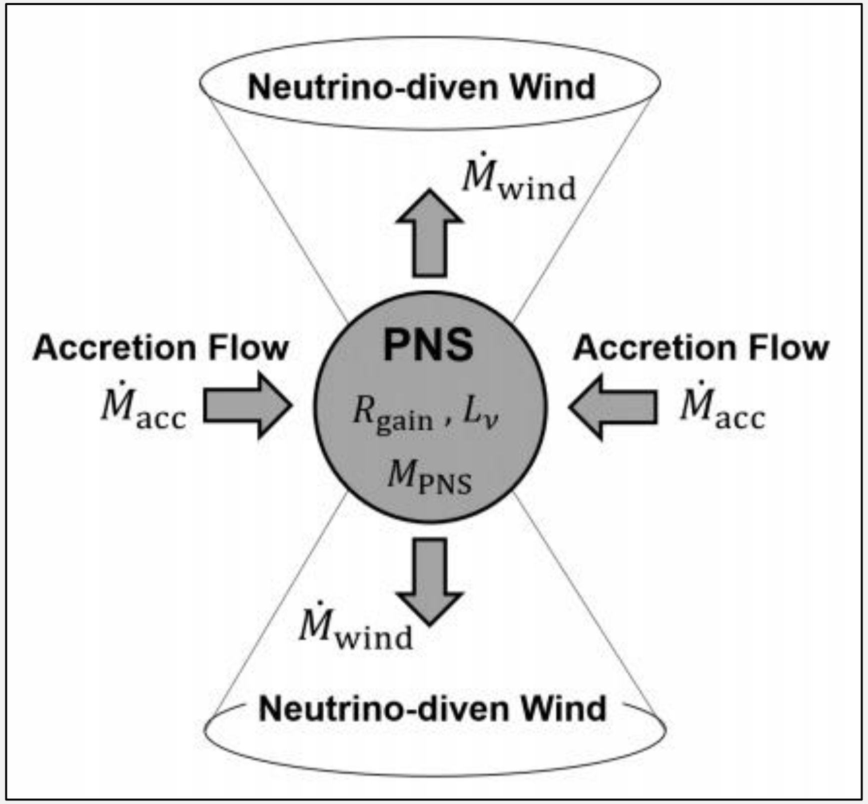
Summary

- **spherical wind relation**

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

- **wind model w/ accretion flow**

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



- the total ejectable is **determined within** ~ **1 sec** from the onset of the explosion.

- 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.

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