The first University in Korea Soongsil University

The neutrino Self-Interaction, MSW and Shock Effects on the Neutrino-Process for Supernovae

Myung-Ki Cheoun
(Soongsil University, **OMEG Institute**, Seoul, Korea)

In collaboration with

Heamin Ko,[1] Myung-Ki Cheoun [a],[1] Eunja Ha,[1] Motohiko Kusakabe,[2] Takehito Hayakawa,[3] Hirokazu Sasaki,[4] Toshitaka Kajino,[2,4] M. Hashimoto,[5] M. Ono,[6] M. D. Usang,[7] S. Chiba,[7] K. Nakamura,[8] A. Tolstov,[9] K. Nomoto,[9] T. Kawano,[10] and G. J. Mathews[11]

OMEG 15, July2-5, Yukawa Inst., Kyoto

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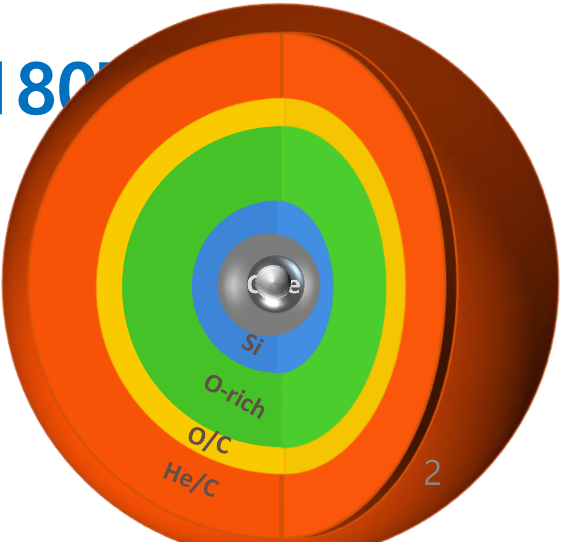
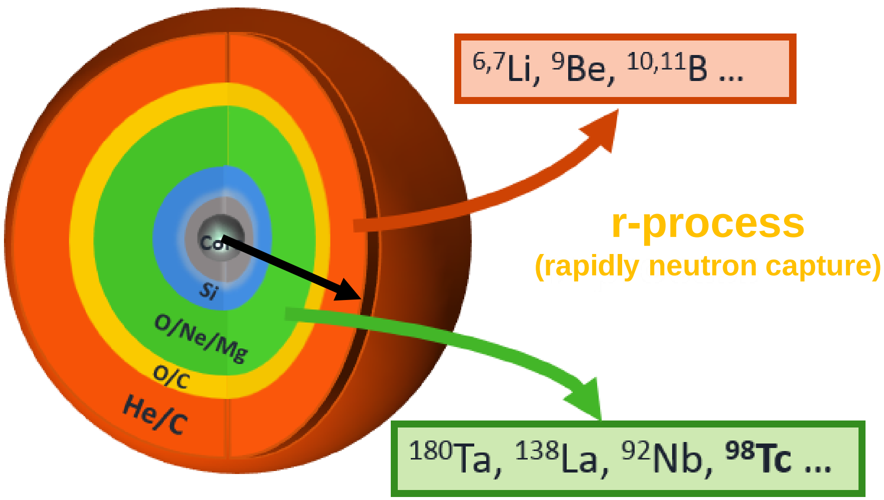
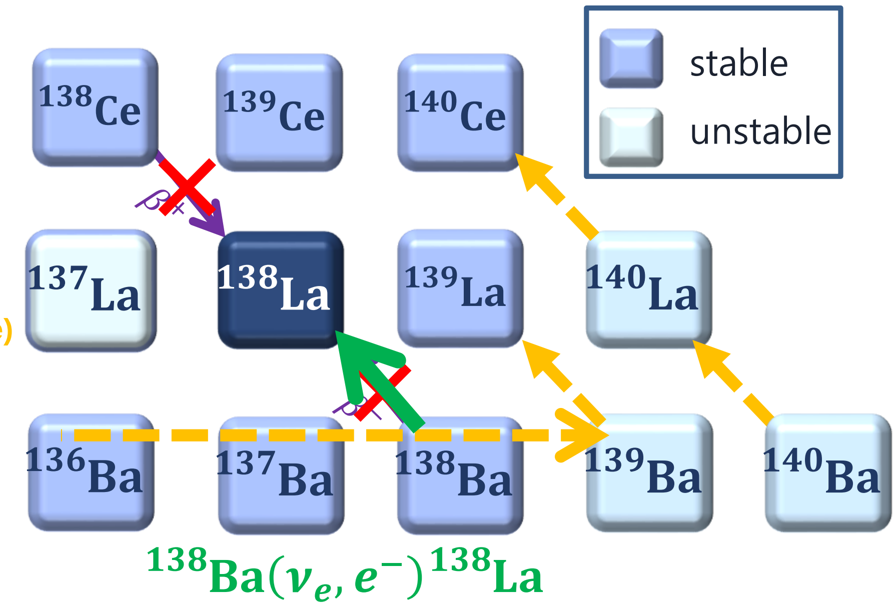
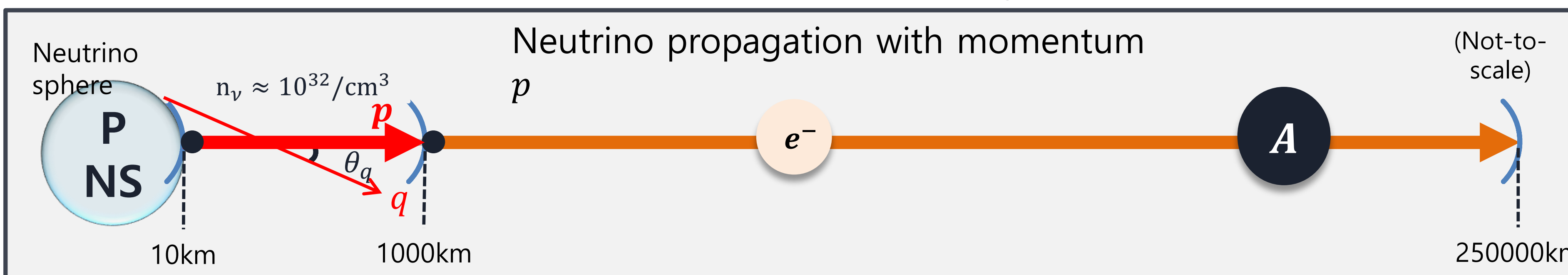


Why neutrino process in SN?





How do neutrino interactions affect the nucleosynthesis in SN environment?



Dominant neutrino interactions depending on the neutrino and electron density.

Total Hamiltonian for neutrino interactions

$$H_{total} = H_{\text{Vacuum}} + V_{\text{matter}} + V_{\text{self}}$$

- Vacuum and matter term

$$H_{\text{Vacuum}} = \frac{1}{2\epsilon_\nu} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^\dagger, \qquad V_{\text{matter}}(r, E, \theta_p) = \begin{pmatrix} \pm\sqrt{2} G_F n_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Unitary mixing PMNS matrix

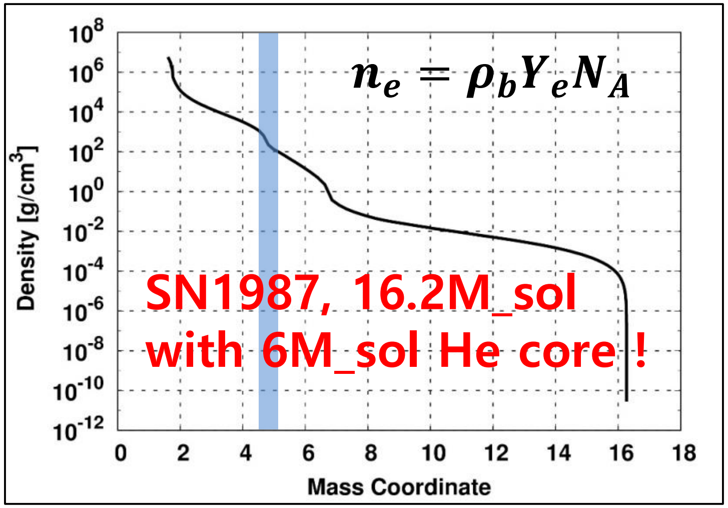
$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13} & -c_{12}s_{23} - s_{12}c_{23}s_{13} & c_{23}c_{13} \end{pmatrix}$$

Neutrino parameters

$$\theta_{12} = 33.8°, \theta_{23} = 45°, \theta_{13} = 9.2°$$

$$\Delta m_{21}^2 = 7.54 \times 10^{-5}\ [\text{eV}^2],\ |\Delta m_{31}^2| \approx 2.4 \times 10^{-3}\ [\text{eV}^2]$$

K. A. Olive, *et al.* [Particle Data Group], Chin. Phys. C 38, 090001 (2014).



A. Tolstov, in private communication (2017)

- Neutrino self-interaction term

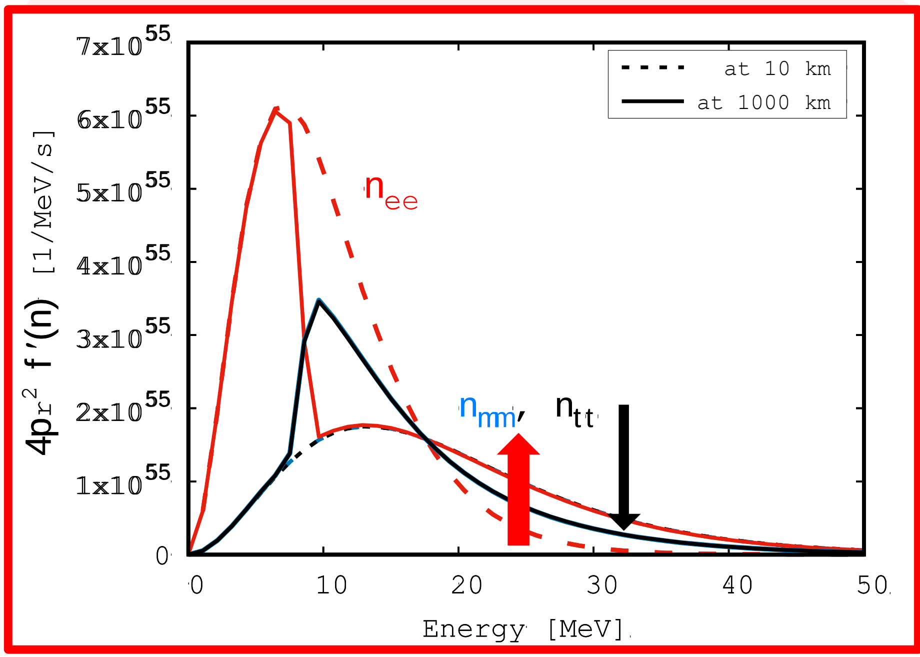
$$V_{\text{self}}(r, E, \theta_p) = \sqrt{2} G_F \sum_\alpha \left[\int (1 - \hat{p}\cdot\hat{q})\, \rho_{\nu_\alpha}(q) dn_{\nu_\alpha} dq - \int (1 - \hat{p}\cdot\hat{q})\, \rho^*_{\bar{\nu}_\alpha}(q) dn_{\bar{\nu}_\alpha} dq \right]$$

$$= \frac{\sqrt{2} G_F}{2\pi R_\nu^2} \sum_\alpha \left[\int dE\, d(\cos\theta_q)(1 - \cos\theta_p \cos\theta_q) \left\{ \frac{L_{\nu_\alpha}}{\langle \epsilon_{\nu_\alpha} \rangle} f_{\nu_\alpha}(E) \rho - \frac{L_{\bar{\nu}_\alpha}}{\langle \epsilon_\nu \rangle} f_{\bar{\nu}_\alpha}(E) \bar{\rho} \right\} \right]$$

H. Sasaki, *et al.*, Phys. Rev. D 96, 043013 (2017)

Self-Interaction effects on the **Neutrino Flux**

$H_{\mathrm{Vacuum}} + V_{\mathrm{matter}} + V_{\mathrm{self}}$



H. Sasaki, *et al.*(NAOJ) in private communication (2018)

Inverted mass hierarchy (IH)

The differential neutrino flux with neutrino flavor α

$$\phi'(t,r;\epsilon_\nu,T_\alpha) \equiv \frac{d}{d\epsilon_\nu}\phi(t,r;\epsilon_\nu,T_\alpha)$$

$$= \frac{L_\nu}{4\pi r^2}\frac{1}{\langle\epsilon_\nu\rangle}\frac{\epsilon_\nu^2}{\exp(\epsilon_\nu/T_\alpha)+1}\langle\rho_{\alpha\alpha}\rangle$$

The neutrino temperatures are

$$T_{\nu_e} = 3.2,\ T_{\bar{\nu}_e} = 5 \text{ and } T_{\nu_x} = 6\ [\mathrm{MeV}/k_B]$$

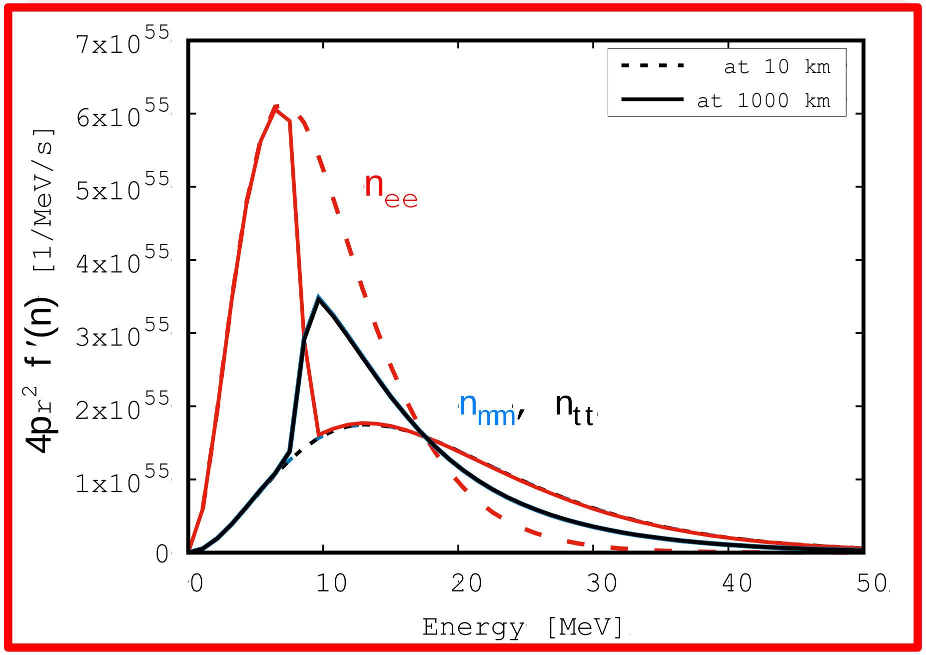
T. Yoshida, *et al.*, Astrophys. J. 686, 448 (2008)

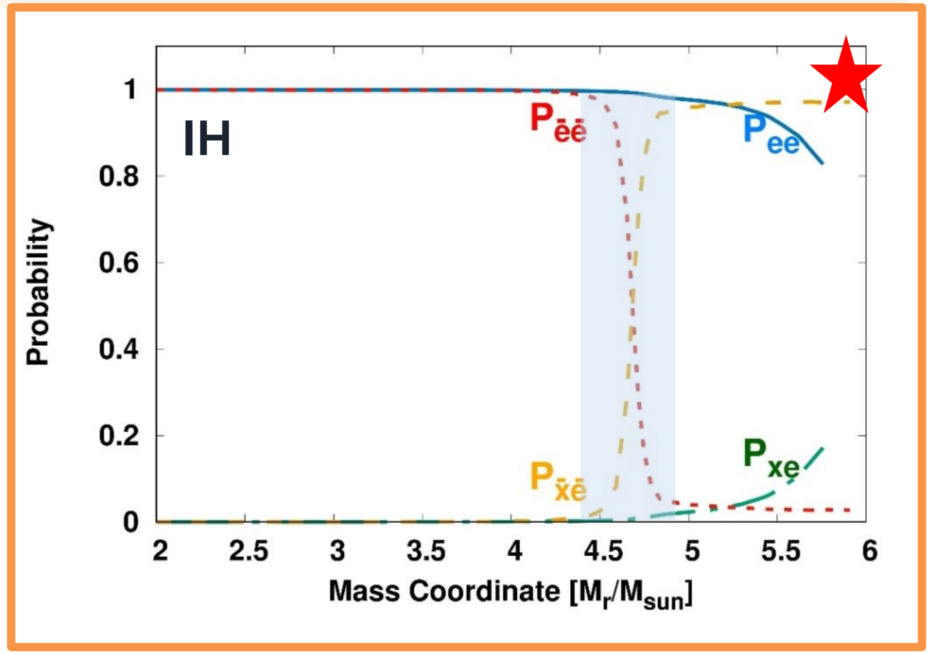
- ✓ In the case of normal mass hierarchy, the SI effect is suppressed.
- ✓ For anti-neutrino, similar effects are found.
- ✓ Initially we assume Fermi-Dirac distribution for neutrino spectra (Case I).
- ✓ We extend it by using other numerical luminosity (Case II).

Neutrino process MSW Effects on the Neutrino Flux (IH)

$H_{\text{Vacuum}} + V_{\text{matter}} + V_{\text{self}}$

$H_{\text{Vacuum}} + V_{\text{matter}}$ (MSW effect)





H. Sasaki, *et al.*(NAOJ) in private communication (2018)

The differential neutrino flux **again** including outer region oscillation

$$\frac{d}{d\epsilon_\nu}\phi_\alpha(t,r;\epsilon_\nu,T_\alpha) = \frac{L_\nu(t)}{4\pi r^2}\frac{1}{\langle\epsilon_\nu\rangle}\frac{\epsilon_\nu^2}{\exp(\epsilon_\nu/T_\alpha)+1}\langle\rho_{\alpha\alpha}(t)\rangle \times P_{\alpha\beta}(\epsilon_\nu)$$

Neutrino Reactions Rates with Nuclei

Network calculation for nucleosynthesis

$$\frac{dN_j}{dt} = N_i\,\lambda_{i,j} - N_j\,\lambda_{j,h} + \ \dots \rightarrow \frac{dY_j}{dt} = \boldsymbol{Y_i\,\lambda_{i,j} - Y_j\,\lambda_{j,h}} + \cdots$$

$$Y_j = \frac{N_j}{\rho\,N_A}$$

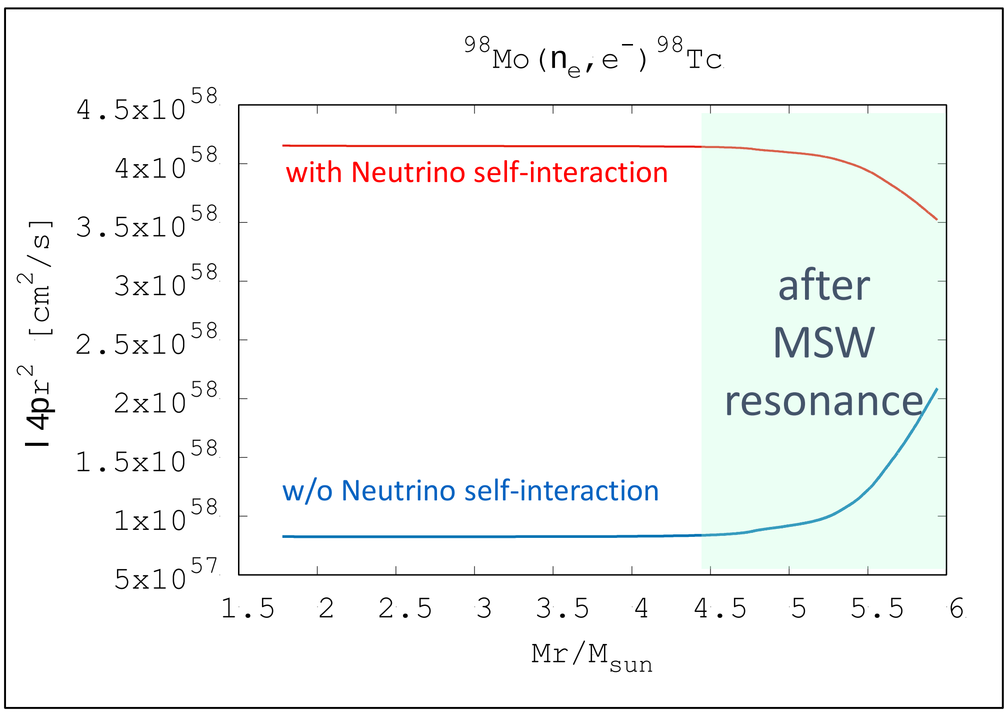
JINA REACLIB & Los Alamos (n,g) Data !

Kyushu-Tokyo Progenitor Model !

Part for neutrino reaction rates

$$\lambda_{\nu_\alpha}(r) = \sigma\,\phi = \int_0^\infty \sum_{\alpha=e,\mu,\tau} \frac{d\phi_{\nu_\alpha}}{d\epsilon_\nu}\, Br(\epsilon)\, \sigma_{\nu_\alpha}(\epsilon_\nu)\, d\epsilon_\nu$$

Example:



Cross section data using QRPA

TABLE I. Averaged cross sections in units of 10^{-42} cm^2 for ^{98}Mo via CC and ^{99}Ru via NC, and ^{92}Zr via CC and ^{93}Nb via NC with particle emission. Neutrino temperatures are taken from [4] and $\langle E_k \rangle$ is calculated from $\langle E_k \rangle / T \sim 3.1514 + 0.1250\alpha$ with $\alpha = 0$ [31,42].

Reactions	$\langle E_k \rangle$ [MeV]	T [MeV]	$\langle \sigma \rangle$
^{98}Mo$(\nu_e, e^-)^{98}$Tc	10.08	3.2	7.77
^{98}Mo$(\nu_e, e^- p)^{97}$Mo	10.08	3.2	1.90
^{98}Mo$(\nu_e, e^- n)^{97}$Tc	10.08	3.2	0.09
^{99}Ru$(\bar\nu_\mu, \bar\nu'_\mu)^{99}$Ru	18.90	6.0	78.5
^{99}Ru$(\bar\nu_\mu, \bar\nu'_\mu n)^{98}$Ru	18.90	6.0	14.6
^{99}Ru$(\bar\nu_\mu, \bar\nu'_\mu p)^{98}$Tc	18.90	6.0	1.70

E-neutrino is increased by SI.
In MSW region, e-neutrino is increased by the e-neutrino resonance w/o SI.

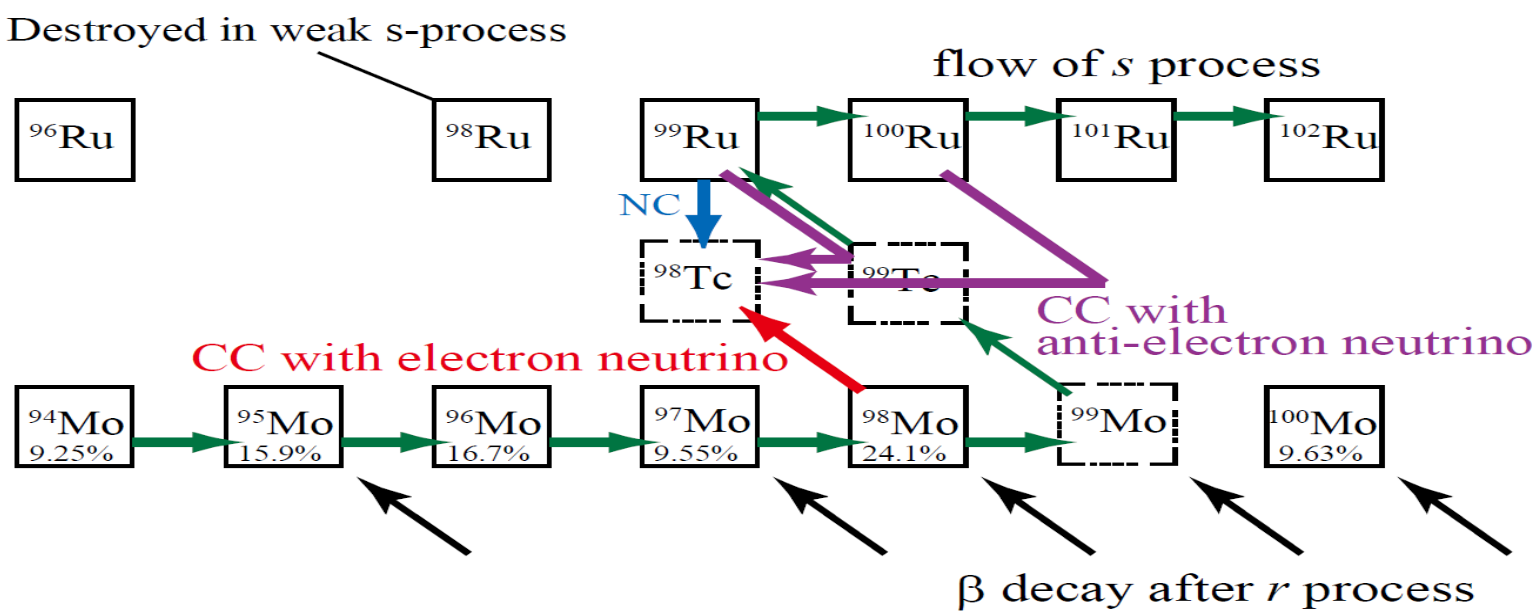
But it is a bit decreased with the decrease of X-neutrino in SI

M. K. Cheoun, *et al.*, Phys. Rev. C 85, 065807 (2012)

Neutrino Reactions for 98Tc by QRPA

Tc-98 neutrino-process memo

T. Hayakawa



There are 4 important reactions:

1) Charged current reactions with electron neutrinos on Mo-98 Q=1.7 MeV

2) Neutral current reactions on Ru-99 Q=7.5 MeV

3) Charged current reactions with anti-electron neutrinos on Ru-99

^{99}Ru($\overline{\nu_e}$, e$^+$n)^{98}Tc Q=9.3 MeV

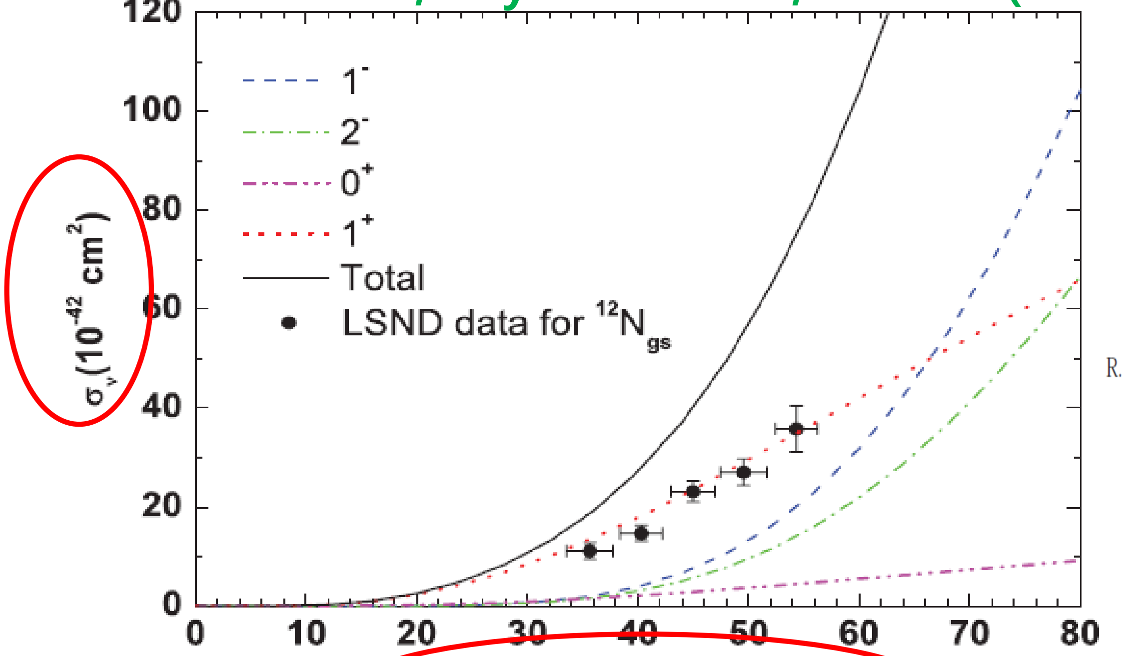
4) Charged current reactions with anti-electron neutrinos on Ru-100

^{100}Ru($\overline{\nu_e}$, e$^+$2n)^{98}Tc Q=19 MeV

Hayakawa, Ko, Cheoun..., ApJL 779, 1 (2013) & PRL 121, 102701, (2018)

Data in Low E. region: KARMEN/LSND/CC and NC

Cheoun, Phys. Rev. C 81, 028501 (2010)



LSND : ν_e ^{12}C -> e- + $^{12}N^*$ **(1^+)**

PHYSICAL REVIEW C, VOLUME 64, 065501

Measurements of charged current reactions of ν_e on ^{12}C

L. B. Auerbach,[8] R. L. Burman,[5] D. O. Caldwell,[3] E. D. Church,[1] J. B. Donahue,[5] A. Fazely,[7] G. T. Garvey,[5] R. M. Gunasingha,[7] R. Imlay,[6] W. C. Louis,[5] R. Majkic,[8] A. Malik,[6] W. Metcalf,[6] G. B. Mills,[5] V. Sandberg,[5] D. Smith,[4] I. Stancu,[1,*] M. Sung,[6] R. Tayloe,[5,†] G. J. VanDalen,[1] W. Vernon,[2] N. Wadia,[6] D. H. White,[5] and S. Yellin[3]

Table 1. Flux-averaged cross sections for neutrinos from π^+ and μ^+ DAR, measured with KARMEN1 (K1) and KARMEN2 (K2).

Reaction	$\langle\sigma\rangle$ in 10^{-42} cm^2	Comment
$^{12}C\,(\nu_e, e^-)\,^{12}N_{g.s.}$	$9.6 \pm 0.3_{(stat)} \pm 0.7_{(syst)}$	846 sequences in K1 and K2
$^{12}C\,(\nu, \nu')\,^{12}C^*$	$10.2 \pm 0.4_{(stat)} \pm 0.8_{(syst)}$	$\nu = \nu_e, \bar{\nu}_\mu$, K1 and K2
$^{12}C\,(\nu, \nu')\,^{12}C^*$	$3.2 \pm 0.5_{(stat)} \pm 0.4_{(syst)}$	$\nu = \nu_\mu$, data from K1 only
$^{12}C\,(\nu_e, e^-)\,^{12}N^*$	$4.8 \pm 0.6_{(stat)}\,^{+0.4}_{-0.5}{}_{(syst)}$	χ^2-fit on energy spectrum of K2
$^{13}C\,(\nu_e, e^-)\,^{13}N$	$50 \pm 25_{(stat)}\,^{+4}_{-6}{}_{(syst)}$	K2 special window evaluation
$^{56}Fe\,(\nu_e, e^-)\,X$	$217 \pm 135_{(stat)}\,^{+27}_{-65}{}_{(syst)}$	χ^2-fit on energy spectrum of K2

JSNS^2 at JPARC ..

2.6. Cross sections

Based on the initial and final nuclear states, the cross section for $\nu(\bar{\nu})$–A reactions through the relevant transition operators in equation (27) is given as [30]

$$\left(\frac{d\sigma_\nu}{d\Omega}\right)_{(\nu/\bar{\nu})} = \frac{G_F^2 \epsilon k}{\pi(2J_i+1)}\Bigg[\sum_{J=0}(1+\vec{\nu}\cdot\vec{\beta})|\langle J_f\|\hat{\mathcal{M}}_J\|J_i\rangle|^2 + (1-\vec{\nu}\cdot\vec{\beta}+2(\hat{\nu}\cdot\hat{q})(\hat{q}\cdot\vec{\beta}))|\langle J_f\|\hat{\mathcal{L}}_J\|J_i\rangle|^2 - \hat{q}\cdot(\hat{\nu}+\vec{\beta})2\,\mathrm{Re}\langle J_f\|\hat{\mathcal{L}}_J\|J_i\rangle\langle J_f\|\hat{\mathcal{M}}_J\|J_i\rangle^* + \sum_{J=1}(1-(\hat{\nu}\cdot\hat{q})(\hat{q}\cdot\vec{\beta}))\left(|\langle J_f\|\hat{\mathcal{T}}_J^{el}\|J_i\rangle|^2 + |\langle J_f\|\hat{\mathcal{T}}_J^{mag}\|J_i\rangle|^2\right) \pm \sum_{J=1}\hat{q}\cdot(\hat{\nu}-\vec{\beta})2\,\mathrm{Re}\left[\langle J_f\|\hat{\mathcal{T}}_J^{mag}\|J_i\rangle\langle J_f\|\hat{\mathcal{T}}_J^{el}\|J_i\rangle^*\right]\Bigg], \quad (30)$$

where ($\pm$) means cases of ν ($\bar{\nu}$). $\vec{\nu}$ and $\vec{k}$ are three-momenta of incident and final leptons, and $\vec{q} = \vec{k} - \vec{\nu}$, $\vec{\beta} = \vec{k}/\epsilon$ with the final lepton's energy ϵ. Of course, the extremely relativistic limit (ERL) may yield more simple formula, but we use the general expression in order to apply for ν_μ–A reactions. For the CC reaction we multiplied the Cabbibo angle $\cos^2\theta_c$ and include the Coulomb distortion of outgoing leptons due to residual nuclei [3, 10].

Phys. Rev. C99 (2019), 064304;
Phys. Rev. C97, (2018), 064322;
Phys. Rev. C97 (2018), 024320;
EPJA 53, (2017), 26 ….
JPG, in press, 2019

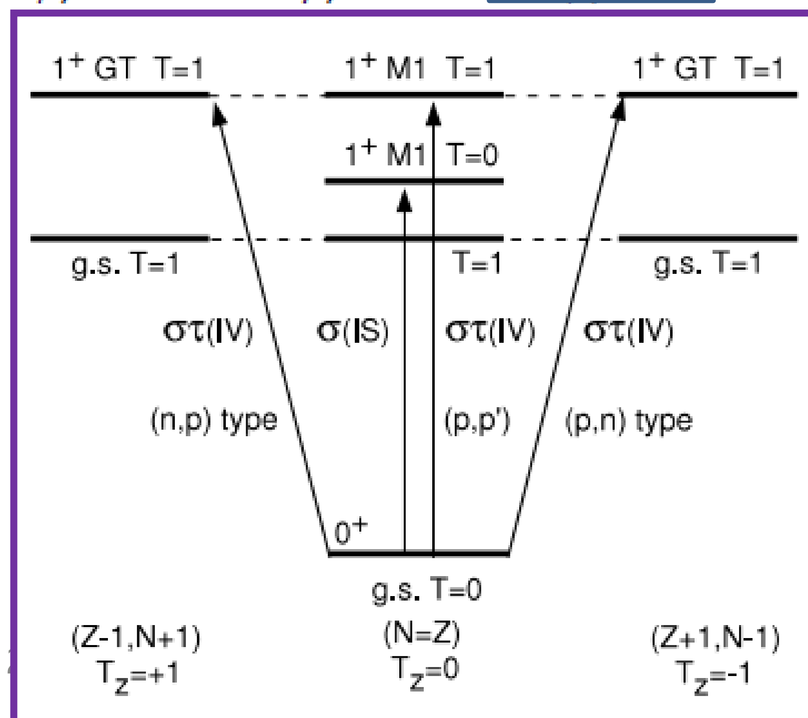
For neutrino-nuclei reactions,

1. We include the transition from 0(+/-) up to 4(+/-) !!!
2. To describe the excitations of compound nuclei, we exploit the (D)QRPA.
3. In the QRPA, the Brueckner G matrix based on the CD Bonn potential and all kinds of pairing interactions in the BCS are included.
4. These (D)QRPA have been successfully tested to reproduce the GT strength distributions.
5. For the excitation spectrum of the compound nuclei,,we exploit a statistical model by S. Chiba in TIT.

Preliminary results by **nn + pp** + np DQRPA

$$\begin{pmatrix} A^{1111}_{\alpha\beta\gamma\delta}(K) & A^{1122}_{\alpha\beta\gamma\delta}(K) & A^{1112}_{\alpha\beta\gamma\delta}(K) & B^{1111}_{\alpha\beta\gamma\delta}(K) & B^{1122}_{\alpha\beta\gamma\delta}(K) & B^{1112}_{\alpha\beta\gamma\delta}(K) \\ A^{2211}_{\alpha\beta\gamma\delta}(K) & A^{2222}_{\alpha\beta\gamma\delta}(K) & A^{2212}_{\alpha\beta\gamma\delta}(K) & B^{2211}_{\alpha\beta\gamma\delta}(K) & B^{2222}_{\alpha\beta\gamma\delta}(K) & B^{2212}_{\alpha\beta\gamma\delta}(K) \\ A^{1211}_{\alpha\beta\gamma\delta}(K) & A^{1222}_{\alpha\beta\gamma\delta}(K) & A^{1212}_{\alpha\beta\gamma\delta}(K) & B^{1211}_{\alpha\beta\gamma\delta}(K) & B^{1222}_{\alpha\beta\gamma\delta}(K) & B^{1212}_{\alpha\beta\gamma\delta}(K) \\ -B^{1111}_{\alpha\beta\gamma\delta}(K) & -B^{1122}_{\alpha\beta\gamma\delta}(K) & -B^{1112}_{\alpha\beta\gamma\delta}(K) & -A^{1111}_{\alpha\beta\gamma\delta}(K) & -A^{1122}_{\alpha\beta\gamma\delta}(K) & -A^{1112}_{\alpha\beta\gamma\delta}(K) \\ -B^{2211}_{\alpha\beta\gamma\delta}(K) & -B^{2222}_{\alpha\beta\gamma\delta}(K) & -B^{2212}_{\alpha\beta\gamma\delta}(K) & -A^{2211}_{\alpha\beta\gamma\delta}(K) & -A^{2222}_{\alpha\beta\gamma\delta}(K) & -A^{2212}_{\alpha\beta\gamma\delta}(K) \\ -B^{1211}_{\alpha\beta\gamma\delta}(K) & -B^{1222}_{\alpha\beta\gamma\delta}(K) & -B^{1212}_{\alpha\beta\gamma\delta}(K) & -A^{1211}_{\alpha\beta\gamma\delta}(K) & -A^{1222}_{\alpha\beta\gamma\delta}(K) & -A^{1212}_{\alpha\beta\gamma\delta}(K) \end{pmatrix}$$

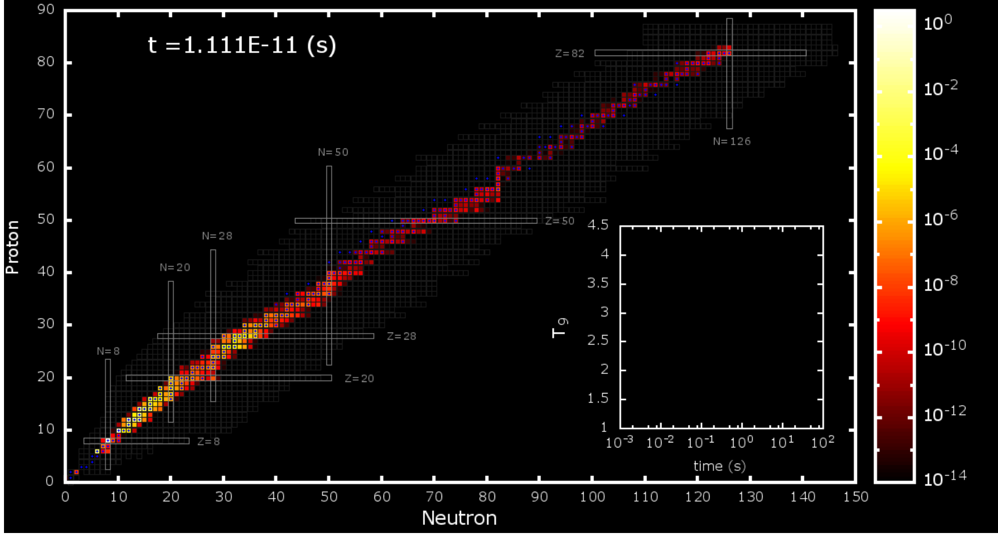
$$\times \begin{bmatrix} \tilde{X}^m_{(\gamma 1 \delta 1)K} \\ \tilde{X}^m_{(\gamma 2 \delta 2)K} \\ \tilde{X}^m_{(\gamma 1 \delta 2)K} \\ \tilde{Y}^m_{(\gamma 1 \delta 1)K} \\ \tilde{Y}^m_{(\gamma 2 \delta 2)K} \\ \tilde{Y}^m_{(\gamma 1 \delta 2)K} \end{bmatrix} = \hbar \Omega^m_K \begin{pmatrix} \tilde{X}^m_{(\alpha 1 \beta 1)K} \\ \tilde{X}^m_{(\alpha 2 \beta 2)K} \\ \tilde{X}^m_{(\alpha 1 \beta 2)K} \\ \tilde{Y}^m_{(\alpha 1 \beta 1)K} \\ \tilde{Y}^m_{(\alpha 2 \beta 2)K} \\ \tilde{Y}^m_{(\alpha 1 \beta 2)K} \end{pmatrix},$$



JINA REALIB

Modified (n,g) Reactions

QRPA & Branching Ratios



Numerical results for elements abundances

1987 SN model

Pre-supernova Model

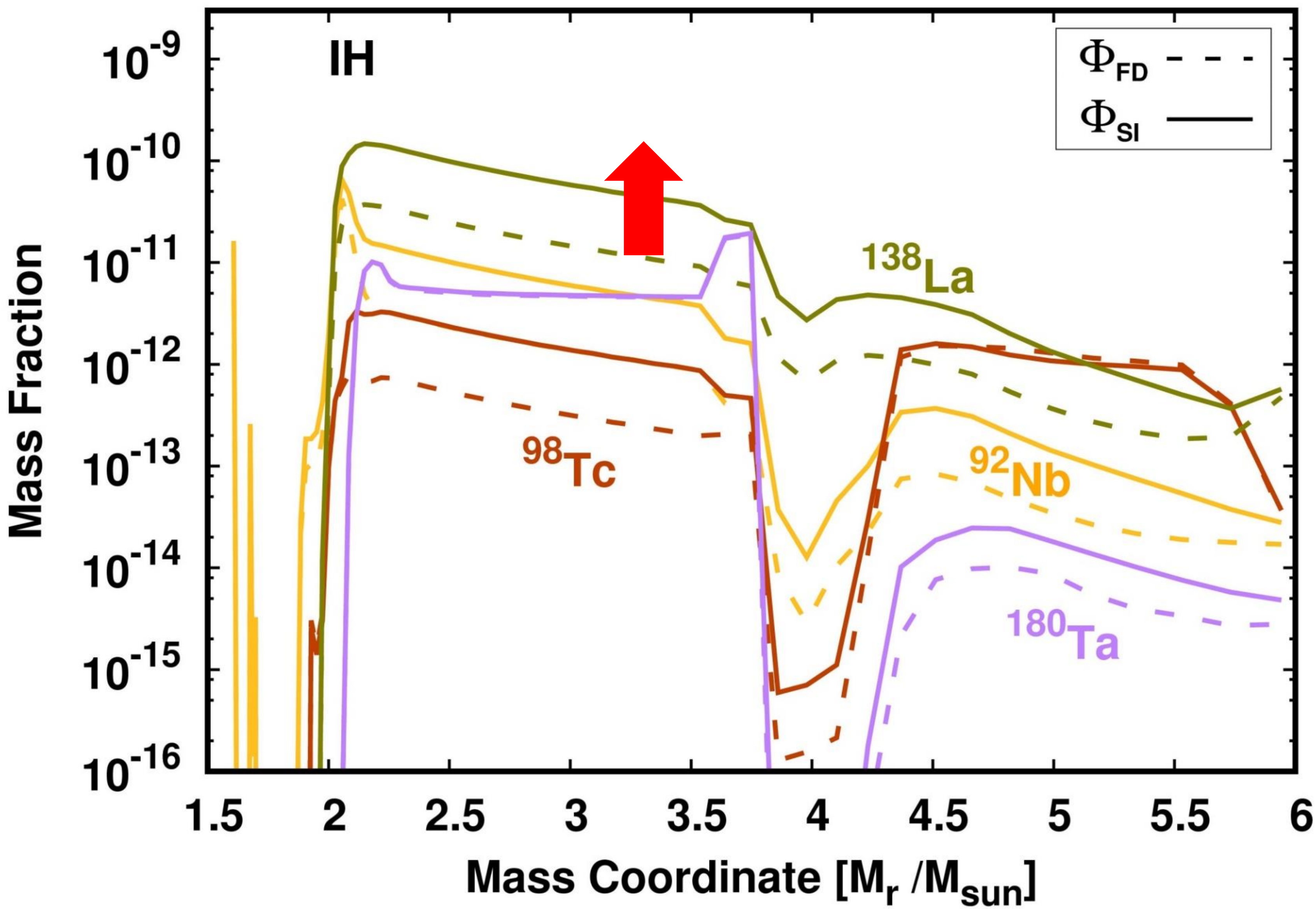
Hydrodynamics Model

Modified Neutrino Flux by Self-interaction

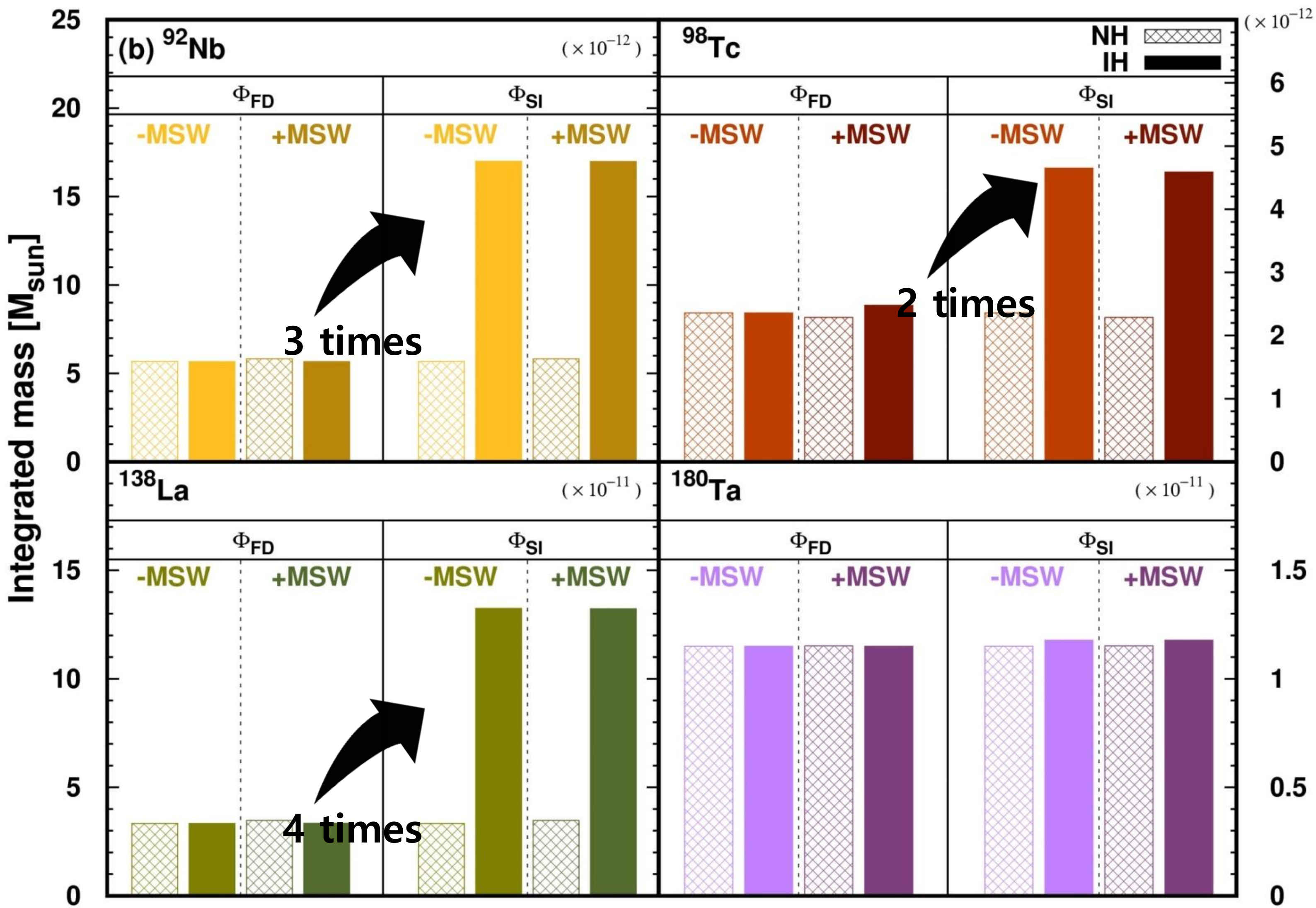
Neutrino Luminosity

Flavor change probability by matter and shock wave

The effect by changed reaction rate



Results for H. Elem. (Total Integrated Masses)



H. Ko, M. Cheoun..., submitted to PRL, (2018)

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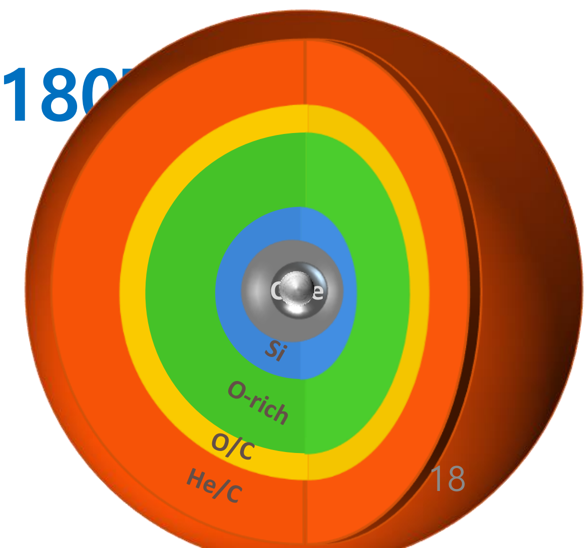
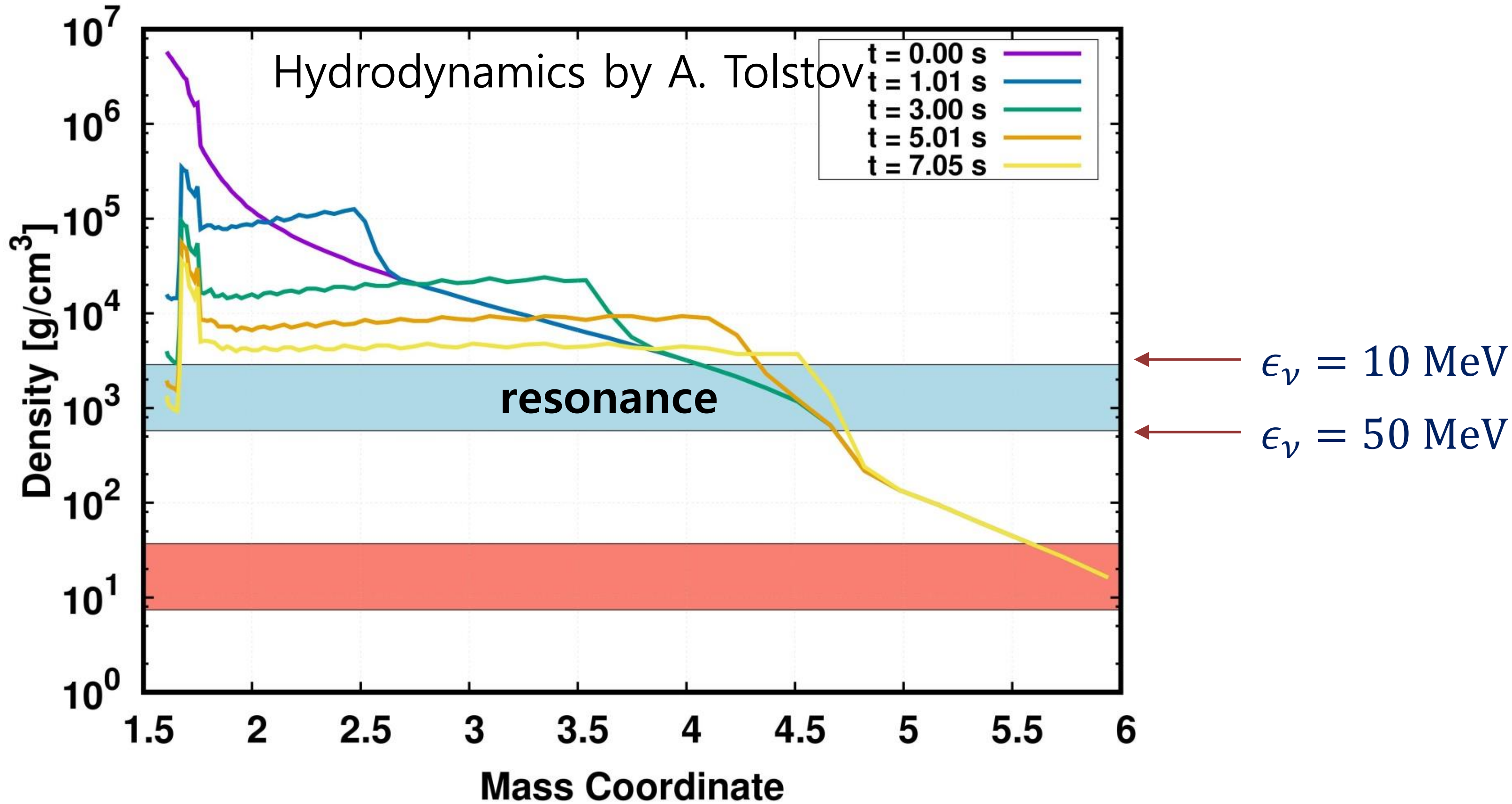


Dependence of the Neutrino Process on the Shock Effects

Flavor change resonance density [Yoshida et. al. APJ (2006)]

$$n_e = \frac{\rho_b Y_e}{m_u}$$

$$\rho_{\rm res} = \frac{m_u \Delta m_{ji}^2 c^4 \cos 2\theta_{ij}}{2\sqrt{2} G_F (\hbar c)^3 \varepsilon_\nu Y_e} = 6.55 \times 10^6 \left(\frac{m_u \Delta m_{ji}^2}{1\ \mathrm{eV}^2}\right)\left(\frac{1\mathrm{MeV}}{\varepsilon_\nu}\right) \cos\theta_{ji}\ [\mathrm{g/cm^3}]$$



that used in Ref. [7]. In this study, the most effective physical quantity is the density profile during the SN explosion given by adopted HD models, for which we use the public **blcode** with the initial density profile in Ref. [9]. This HD result [10] is derived assuming a simple thermal bomb based on a spherical symmetric Lagrangian HD, whose result is shown in Fig. 1 (a).

Landau-Zener crossing formula

$$P = \exp(-\pi\gamma/2)$$

$$\gamma = \frac{\Delta m^2_{ij}}{2E_\nu}\frac{\sin^2 2\theta_{ij}}{\cos 2\theta_{ij}}\frac{n_e}{\mathrm{d}n_e/\mathrm{d}r}$$

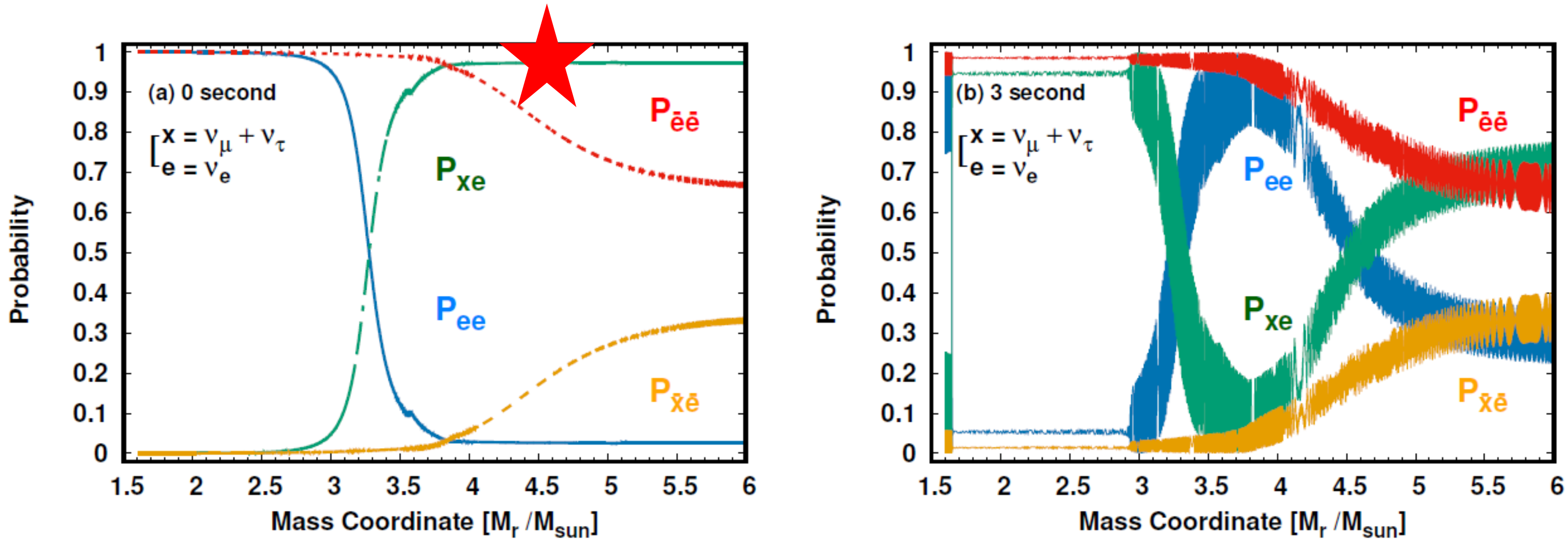
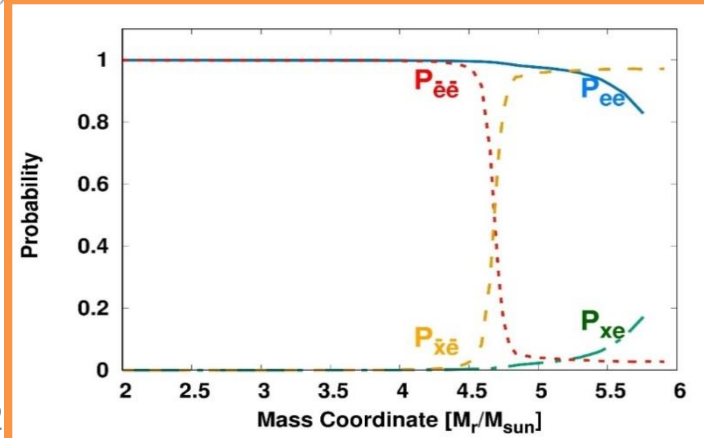


Fig. 2. Flavor transition probabilities at $t = 0$ s (a) and $t = 3$ s after the shock (b), respectively, for $E_\nu = 15$ MeV in the NM hierarchy.



In NH, nu_e has a resonance giving high energy nu_e.
In IH, nu_bar_e has a resonance.

Network calculation for nucleosynthesis

$$\frac{dN_j}{dt} = N_i\,\lambda_{i,j} - N_j\,\lambda_{j,h} + \;\dots \rightarrow \frac{dY_j}{dt} = \boldsymbol{Y_i\,\lambda_{i,j} - Y_j\,\lambda_{j,h}} + \cdots \qquad Y_j = \frac{N_j}{\rho\,N_A}$$

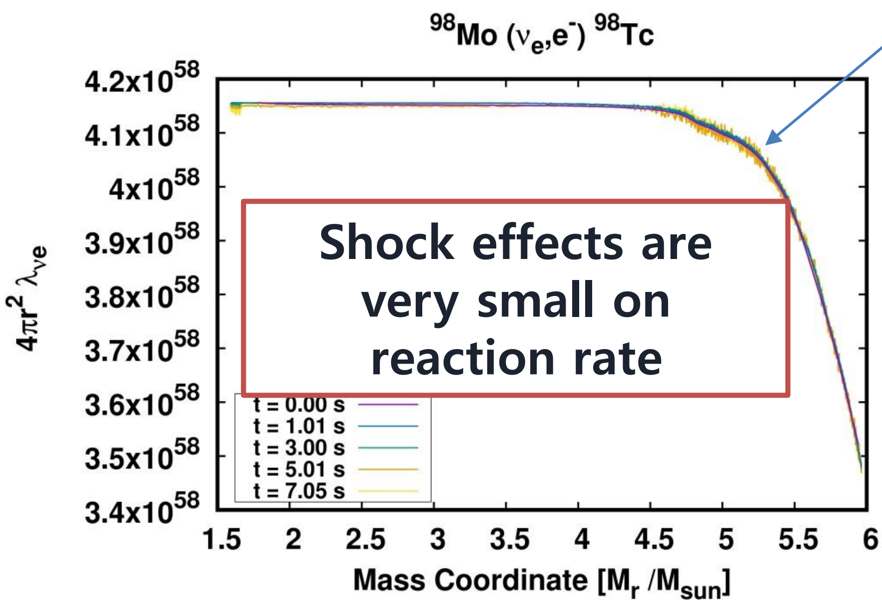
Part for neutrino reaction

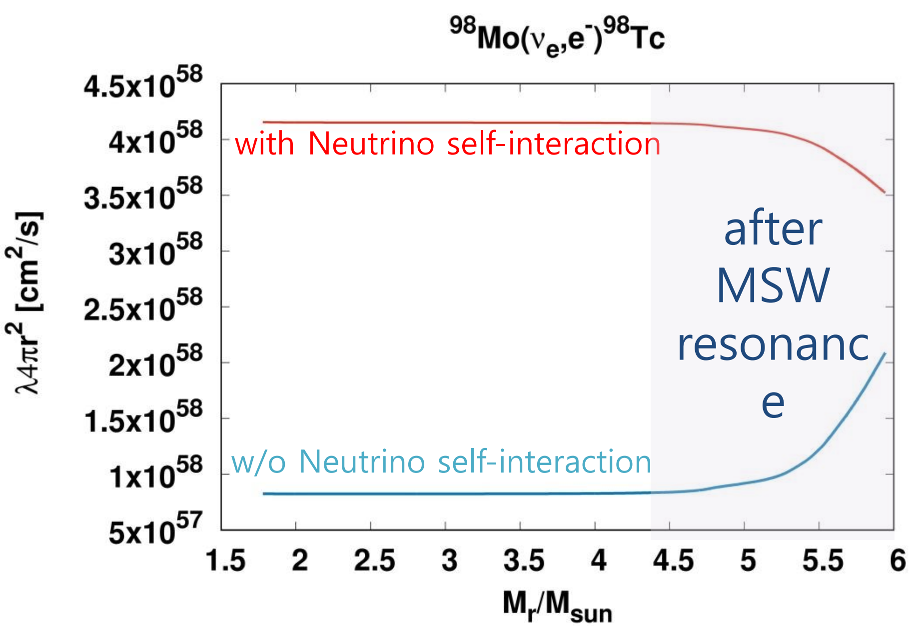
$$P_{\nu_\beta \nu_\alpha}(\epsilon_\nu)$$

$$\lambda_{\nu_\alpha}(r) = \sigma\,\phi = \int_0^\infty \sum_{\alpha=e,\mu,\tau} \frac{d\phi_{\nu_\alpha}}{d\epsilon_\nu} Br(\epsilon)\,\sigma_{\nu_\alpha}(\epsilon_\nu)\,d\epsilon_\nu$$

* Cross section data are taken from M. K. Cheoun, *et al.*, Phys. Rev. C 85, 065807 (2012)

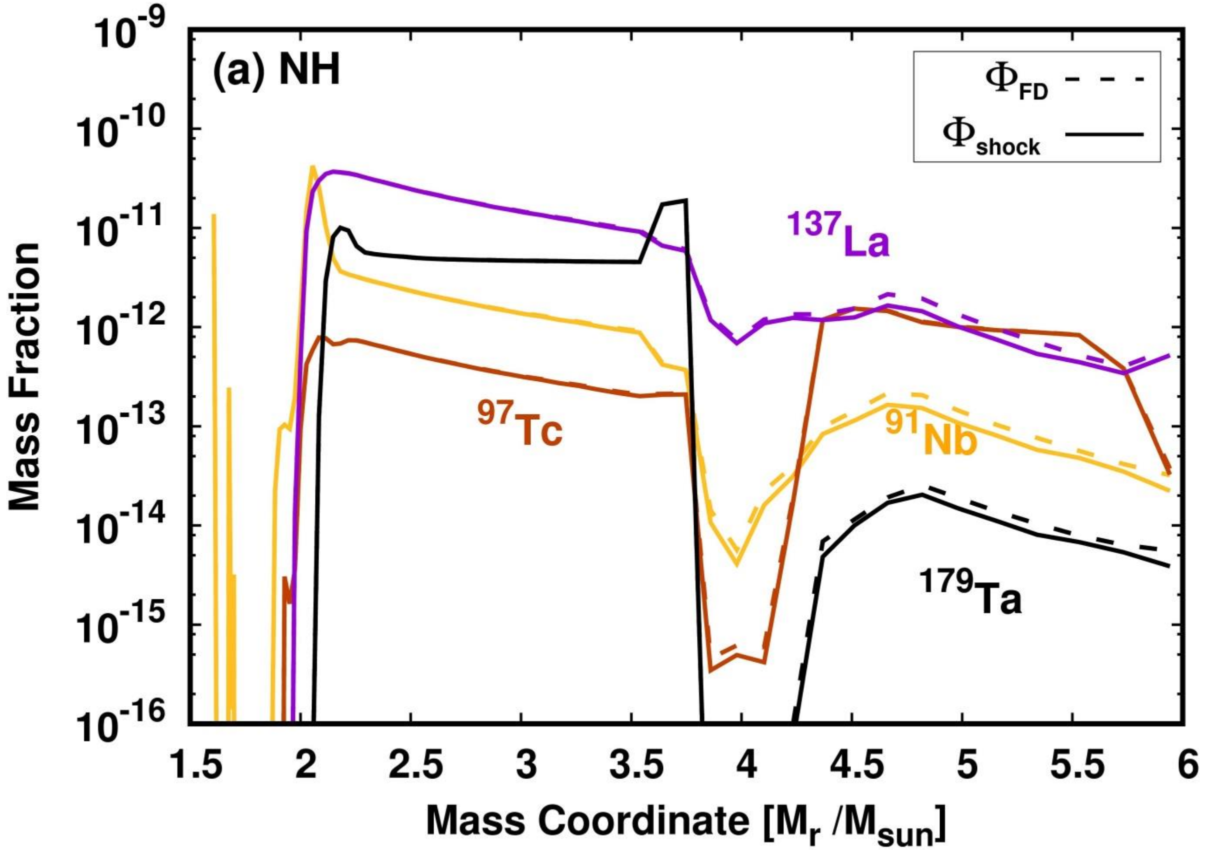
The neutrino reaction rate by Self-interaction and MSW effects





The effect by shock – testing results

Evolution time		MSW effects density profile
~0.5 sec.	→	0 sec.
0.5~1 sec.	→	1 sec.
1~3 sec.	→	3 sec.
3~5 sec.	→	5 sec.
5~7 sec.	→	7 sec.



In the case of NH the shock effects are almost negligible.

Dependence of the SI effects in Neutrino Process on the Luminosity

<From the Fogli's FD Luminosity to numerical Luminosity by neutrino transport calculation>

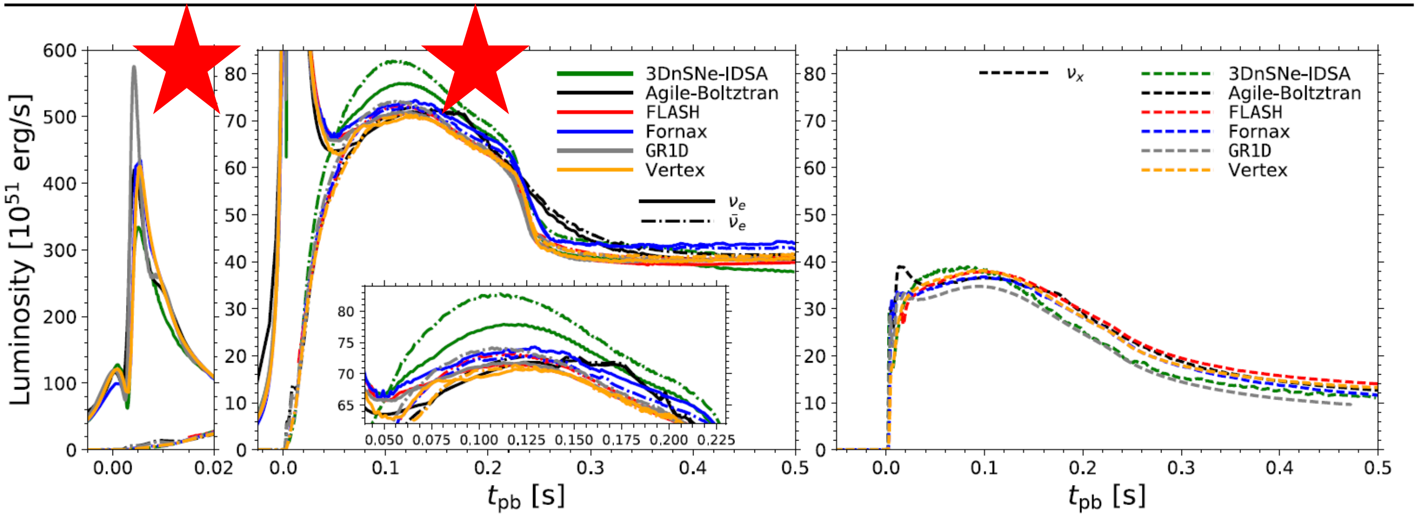


Figure 3. Neutrino luminosities as a function of postbounce time. In the left panels we show electron-type neutrino luminosities (solid lines show electron neutrinos while dashed–dotted lines show electron antineutrinos) and in the right panel we show the characteristic heavy-lepton neutrino luminosity (dashed line). For clarity, we show an inset to highlight the early accretion epoch for the electron-type neutrinos and a panel to show the neutronization burst. Some curves have been smoothed with neighboring zones to remove noise and improve clarity.

3.1. 3DnSNe-IDSA

Contributors: *Tomoya Takiwaki, Kei Kotake*

3.2. AGILE-BOLTZTRAN

Contributors: *Tobias Fischer, Eric Lentz, Matthias Liebendörfer, Bronson Messer, Anthony Mezzacappa*The radiation-hydrodynamics module AGILE is based on the spherically-sym-

3.3. FLASH-M1

Contributors: *Evan O'Connor, Sean Couch*

3.4. FORNAX

Contributors: *Adam Burrows, David Vartanyan*

3.5. GR1D

Contributors: *Evan O'Connor*

3.6. PROMETHEUS-VERTEX

Contributors: *Robert Bollig, Hans-Thomas Janka*

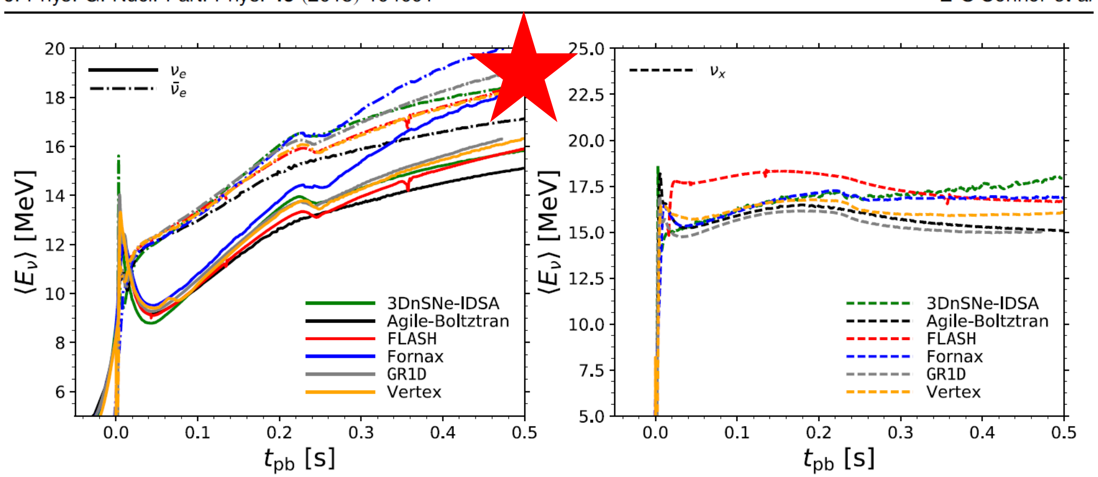
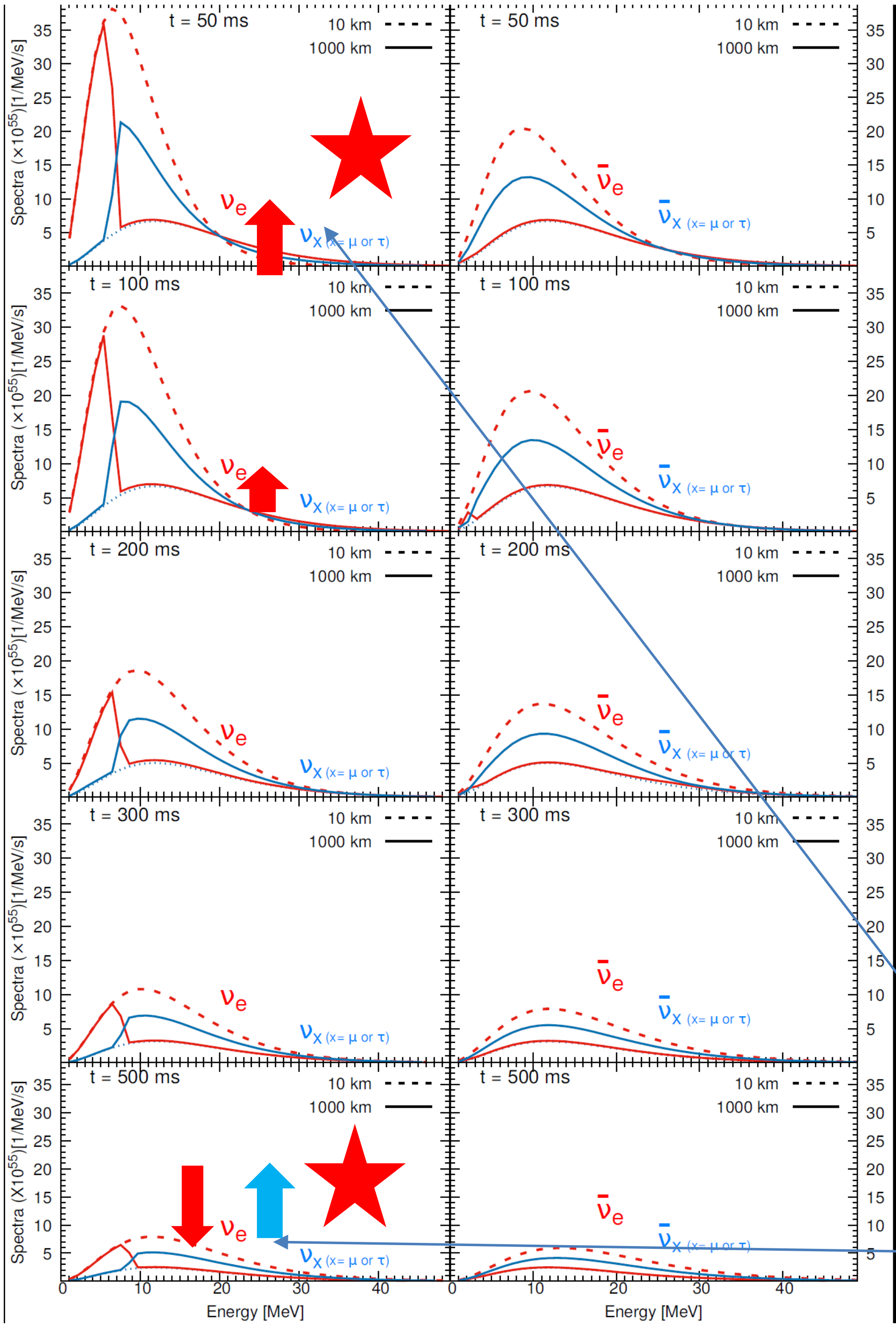
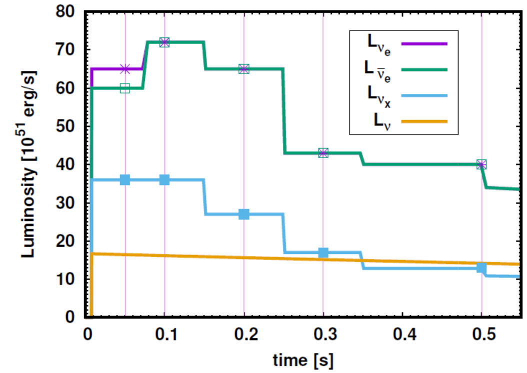


Figure 4. Neutrino average energy as a function of postbounce time. In the left panel we show electron-type neutrino average energies (solid lines show electron neutrinos while dashed–dotted lines show electron antineutrinos) and in the right panel we show





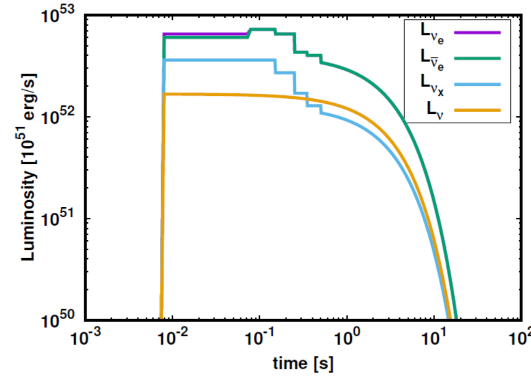
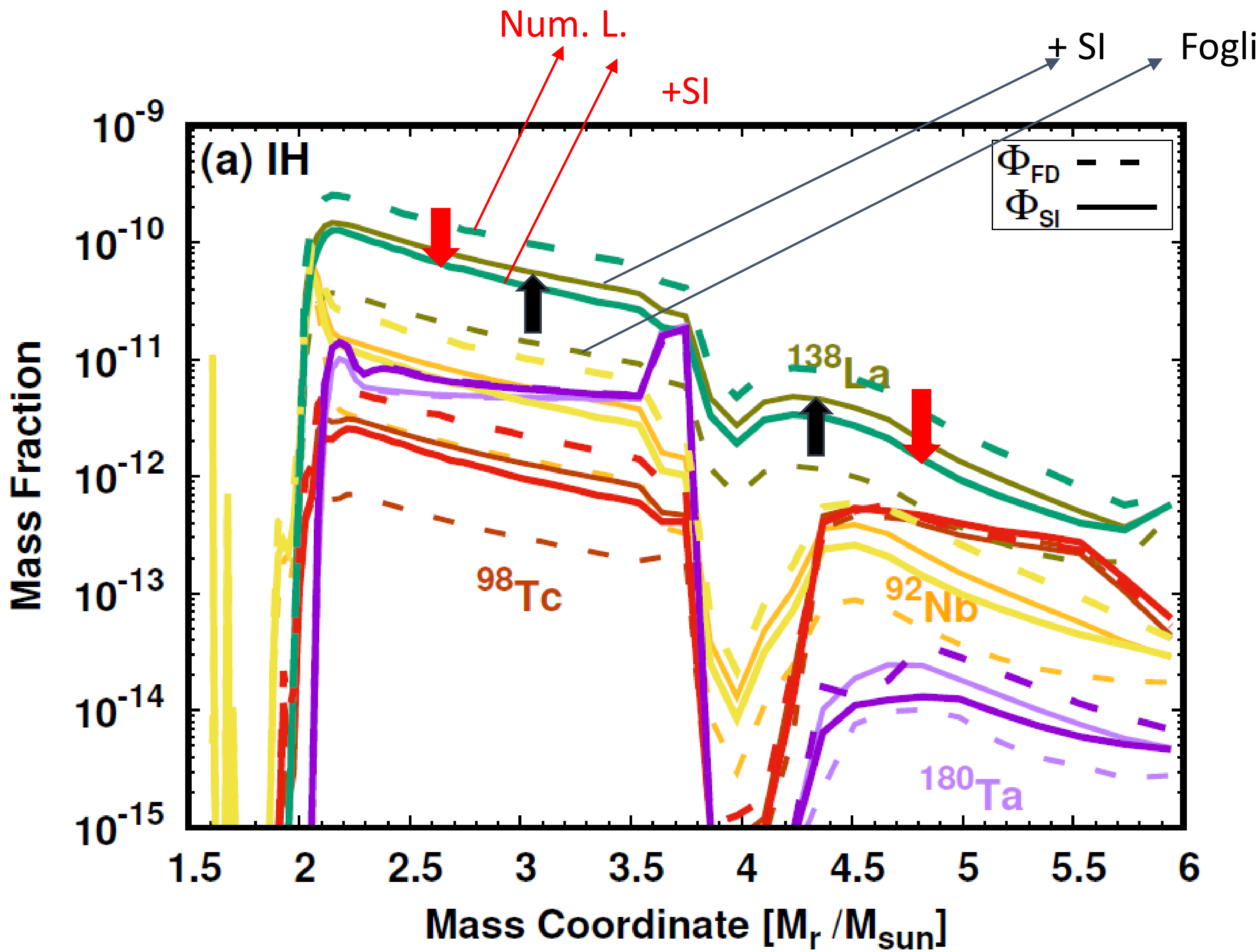


FIG. 2: Neutrino luminosity for each flavor ν_e, $\bar{\nu}_e$ and $\nu_x (= \nu_\mu, \nu_\tau, \bar{\nu}_\mu$ and $\bar{\nu}_\tau)$ in the region $M_r = 1.6 M_\odot (\approx 2300 km)$ after t=0.008 postbounce from [20]. The yellow line is from Refs. [4, 19]. We will take one of Fig. 2 and Table 1.

TABLE I: The luminosity and averaged energy at each time from Ref.[20]. The

time	L_{ν_e}	$L_{\bar{\nu}_e}$	L_{ν_x}	$\langle E_{\nu_e} \rangle$	$\langle E_{\bar{\nu}_e} \rangle$	$\langle E_{\nu_x} \rangle$
[s]	$[10^{52}$ erg/s]			[MeV]		
0.05	6.5 (4.1)	6.0 (3.8)	3.6 (2.3)	9.3	12.2	16.5
0.1	7.2 (4.5)	7.2 (4.5)	3.6 (2.3)	10.5	13.3	16.5
0.2	6.5 (4.1)	6.5 (4.1)	2.7 (1.7)	13.3	15.5	16.5
0.3	4.3 (2.7)	4.3 (2.7)	1.7 (1.1)	14.2	16.6	16.5
0.5	4.0 (2.5)	4.0 (2.5)	1.3 (0.8)	16.0	18.5	16.5



Num. L.
+SI
+ SI
Fogli
(a) IH
Φ_{FD}
Φ_{SI}
138La
98Tc
92Nb
180Ta
Mass Fraction
Mass Coordinate [Mr /Msun]

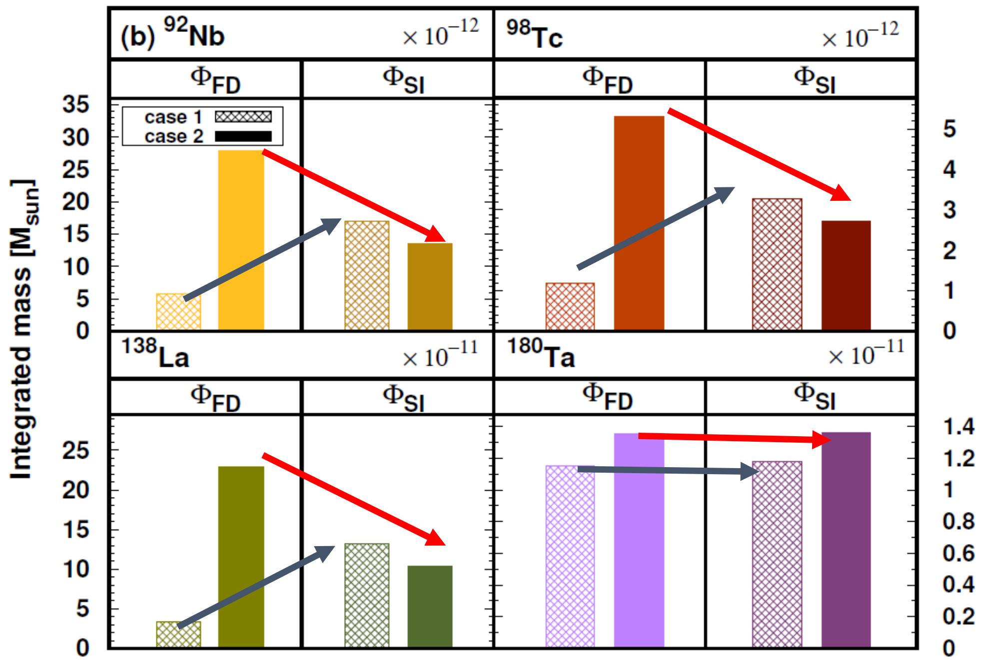


FIG. 3: Abundances (a) of ^{92}Nb, ^{98}Tc, ^{138}La and ^{180}Ta in the IH scheme and (b) their integrated masses. Solid and dashed lines are the results with and without the ν-SI, respectively.(a) shows four different cases for each nucleus, FD1(Previous, thin dashed), thick dashed FD2(New, thick dashed), IS1(Previous, thin solid) and IS2(New, thick solid). (b) is to be changed. Please delete NH case and add FD2 and FD2 + SI results !

Neutrino process Results for Light Elements II

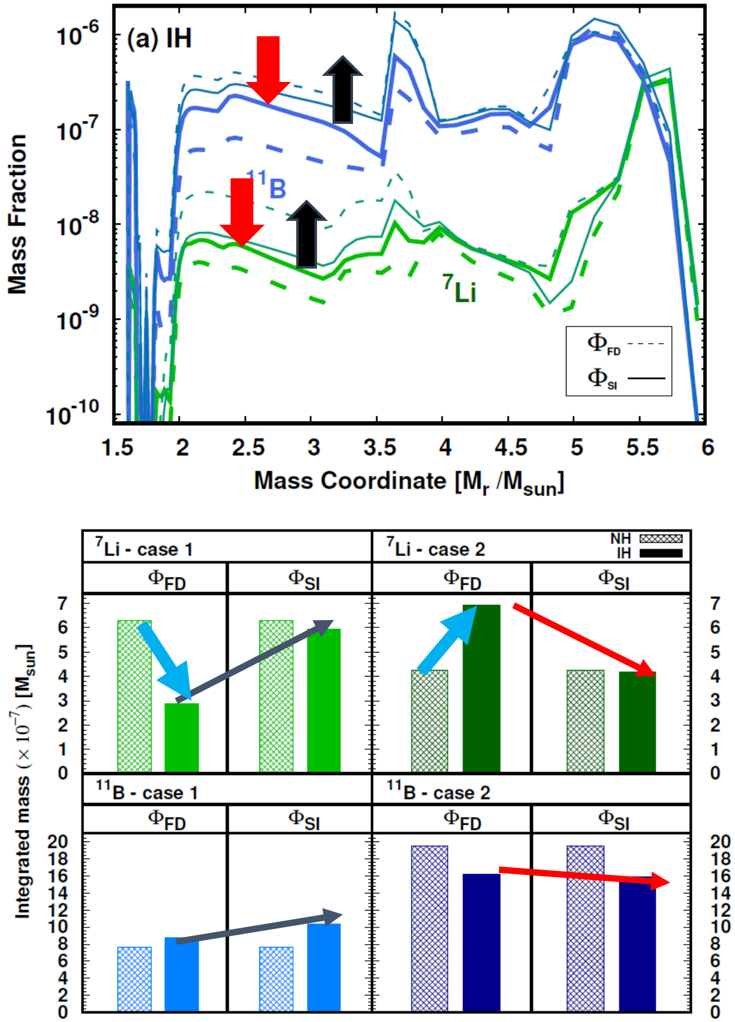
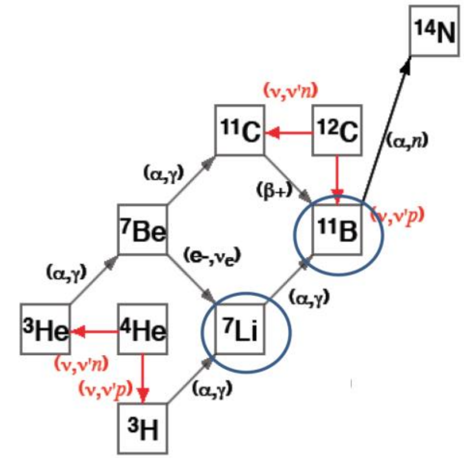


FIG. 4: Same as Fig. 3, but for ^{7}Li and ^{11}B. Abundances are plotted at 1 yr after the SN explosion. All results (a) included the MSW effect. Please change panel (b).

For 7Li, the main CC reaction is e-neutrino producing 3He and 7Be from 4He.



In case1, NH has a e-neutrino **MSW resonance** which increases 7Be and 7Li.
But, IH, the **MSW resonance** occurs for anti-e-neutrino, Which decreases the ratio.

In case2, the e-neutrino MSW resonance comes from the x-neutrino, which is smaller than the case 1.

As for SI interaction, for case 1,
high energy e-neutrino appears due to **the swapping, which increases the ratio**.

But, for case 2, **no swapping** occurs.

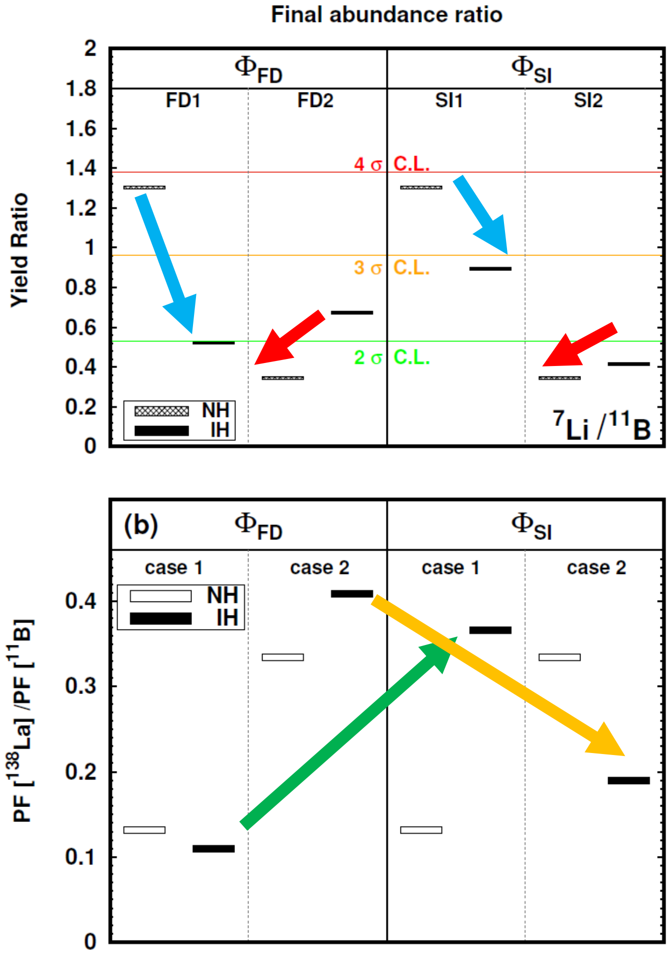


FIG. 5: Ratios of the abundance of ^{7}Li to ^{11}B (a) and the production factor of PF(^{138}La) to PF(^{11}B) (b) defined as PF[A] = [A]/[$A_\odot$] for various cases of the MSW, ν-SI and the MH scheme. The width of each band represents a presumed few percent uncertainty from the mixing angle. Data from the Bayesian analysis of the related ratio data ^{7}Li/^{11}B are given at the 1 σ and 2 σ upper limits [10]. Please change these results for FD1, FD2, FD1+SI, FD2+SI. (This results is after 1 yr SN explosion, when all ^{11}C decay to ^{11}B.)

G. J. Mathews, T. Kajino, W. Aoki, W. Fujiya and J. B. Pitts, Phys. Rev. D **85**, 105023 (2012)

In case I, ratio of 7Li/11B is decreased in IH scheme within 2 sigma level. But with the SI, it goes around 3 sigma level.

In case II, ratio of 7Li/11B is decreased in the NH scheme within 2 sigma level. With the SI, it goes within 1.4 sigma level.

As for the ratio 138La/11B, NH does not show any SI effects. But IH scheme illustrates the increase for the case I, and the decrease for the case II by the SI.

Therefore, the ratio turns out to be sensitive to the MH and the SI effects.

Neutrino Process and Sterile Neutrino

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = \hat{H}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix}, \qquad (1)$$

vhere we used unit of $\hbar = c \equiv 1$. For the non-interacting sterile neutrino, we can compose he total Hamiltonian as vacuum ($\hat{H}_{\mathrm{vacuum}}$) and matter ($\hat{H}_{\mathrm{matter}}$) terms,

$$\hat{H}_{\mathrm{vacuum}} = U\mathrm{diag}(0, \frac{\Delta m^2_{21}}{2E_\nu}, \frac{\Delta m^2_{31}}{2E_\nu}, \frac{\Delta m^2_{41}}{2E_\nu})U^\dagger, \qquad (2)$$

$$\hat{H}_{\mathrm{matter}} = \mathrm{diag}(V_{\mathrm{CC}} + V_{\mathrm{NC}}, V_{\mathrm{NC}}, V_{\mathrm{NC}}, 0),$$

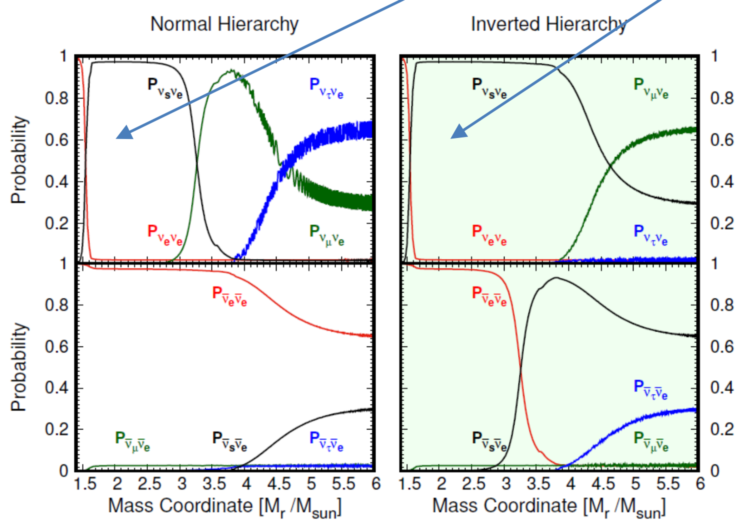


FIG. 1. Survival probability of ν_e with E_ν =15 MeV as a function of mass coordinate. $P_{\nu_\alpha\nu_\beta}$ denotes the flavor change probability from α to β flavors. Left and right panels show results for the normal and inverted mass hierarchy, respectively. Upper and lower panels, respectively, describe the flavor change probabilities for neutrinos and anti-neutrinos.

We found that there is a resonance for e-neutrino around 1.6 M_sol.

This provides the energetic e-neutrino which may affect the neutrino reaction Rate.

But it depends on the scenario of sterile neutrino.

The 1st scenario is zero luminosity of Sterile neutrino only with mixing.

The 2nd is equivalent luminosity with the mixing. But the s-neutrino may decouple by the s-neutrino interactions with electrons.

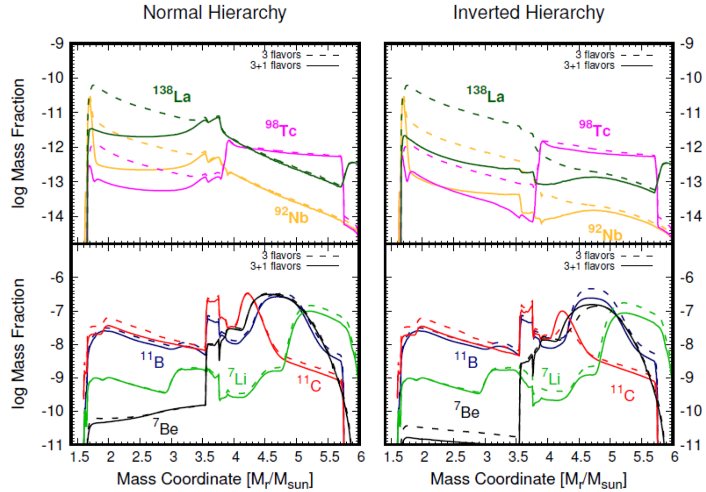


FIG. 2. Mass fractions of ^{7}Li, ^{7}Be, ^{11}B, ^{11}C, ^{92}Nb, ^{98}Tc and ^{138}La as a function of the mass coordinate after 50 seconds from SN explosion. Left and right panels, respectively, correspond to the NH and IH cases. Dashed and solid lines denote the results in the standard model and the 3+1 neutrino scenario, respectively.

1st scenario (zero luminosity) but with the mixing

Yield ratio [^{7}Li/^{11}B]

ν model	NH	IH	Observation [35]
3 flavors	1.22	0.80	< 0.53 (2σ 95% C.L.)
3+1 flavors	1.27	1.04	< 0.95 (3σ 99.7% C.L.)

TABLE I. Abundance ratio of ^{7}Li and ^{11}B produced within the whole mass coordinate region and observations from analysis of SiC X grains.

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2nd scenario (equi-luminosity) with the mixing

Yield ratio [^{7}Li/^{11}B] in the 3+1 model

Neutrino Mass Hierarchy	Temperature of ν_s 7 MeV	8 MeV	9 MeV	10 MeV
normal	0.89	0.85	0.81	0.79
inverted	0.92	1.05	1.11	1.20

O.K.

????

TABLE II. Total abundance ratio of ^{7}Li and ^{11}B in the 3+1 flavor neutrino model with an equivalent luminosity of all flavors.

Neutrino process Summary

- Neutrino spectra are largely changed by the neutrino self-interaction for inverted mass hierarchy case.
- Although there is shock propagation, MSW effect impacts rarely on heavy elements.
  (But with other hydrodynamics model it can affect them.)

- Heavy elements, $^{92}\mathrm{Nb}$, $^{138}\mathrm{La}$ $^{98}\mathrm{Tc}$ and $^{180}\mathrm{Ta}$, are mainly produced in inner region below O-Ne-Mg layer, and increased about 3 or 4 times larger by the neutrino self-interaction. But, $^{180}\mathrm{Ta}$ abundance depends on the pre-supernova model.
- But it depends on the luminosity. For example, if we take some numerical luminosities from the simulation of the neutrino transportation, results show that the situation is reversed.
- Light elements, which are produced in outer region, turn out to be mainly sensitive on the MSW effects.
- Mass hierarchy can be determined by more accurate data of 7Li/11Be ratio in the astronomy.
- Ratio of 138La/11B could be an interesting quantity for SI and MSW effects.
- Sterile neutrinos are allowed in the equivalent luminosity scenario with NH scheme.

Thanks for your attention !