Neutrino self-interaction and MSW effects on the supernova neutrino-process

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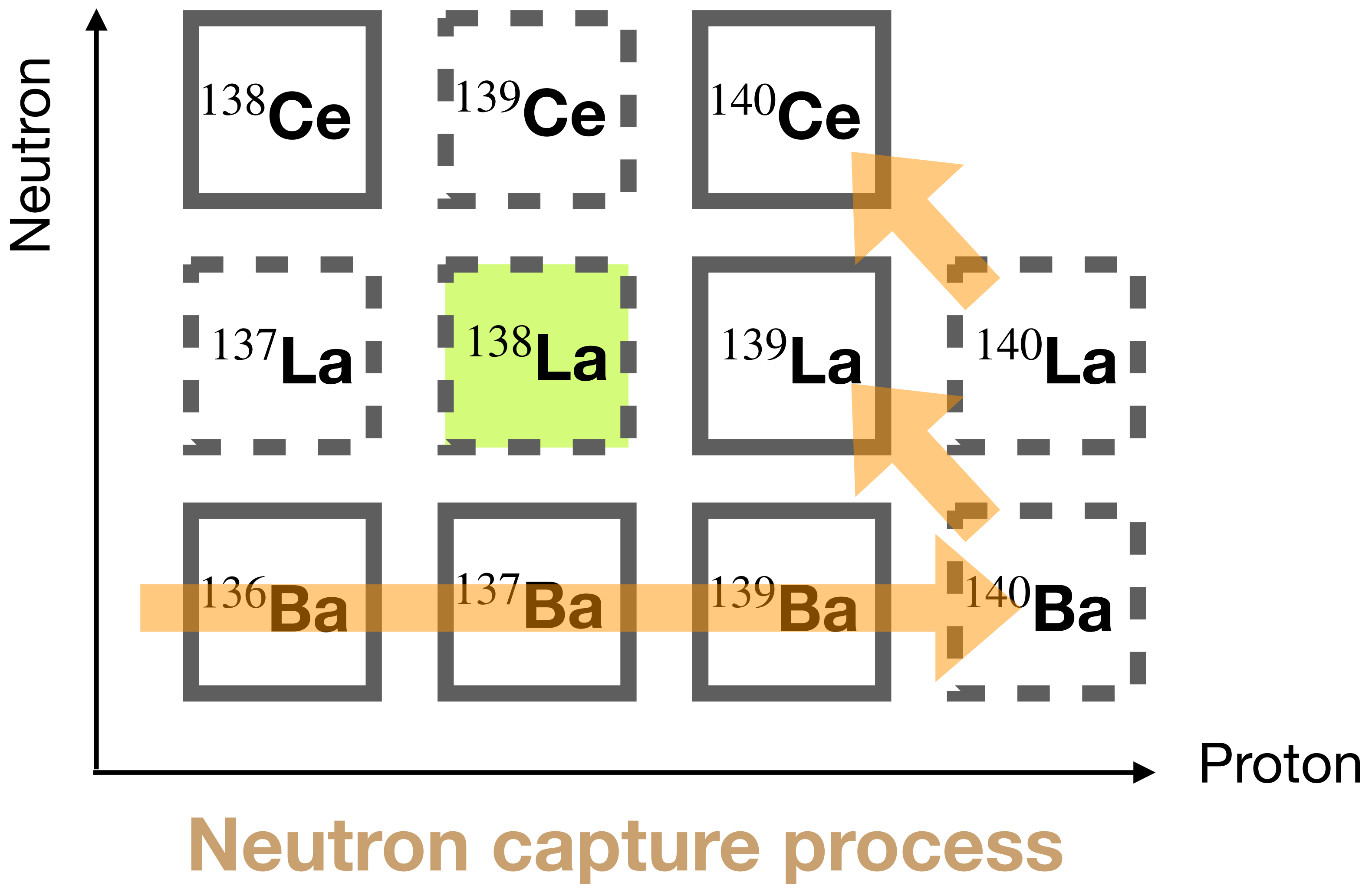
In collaboration with

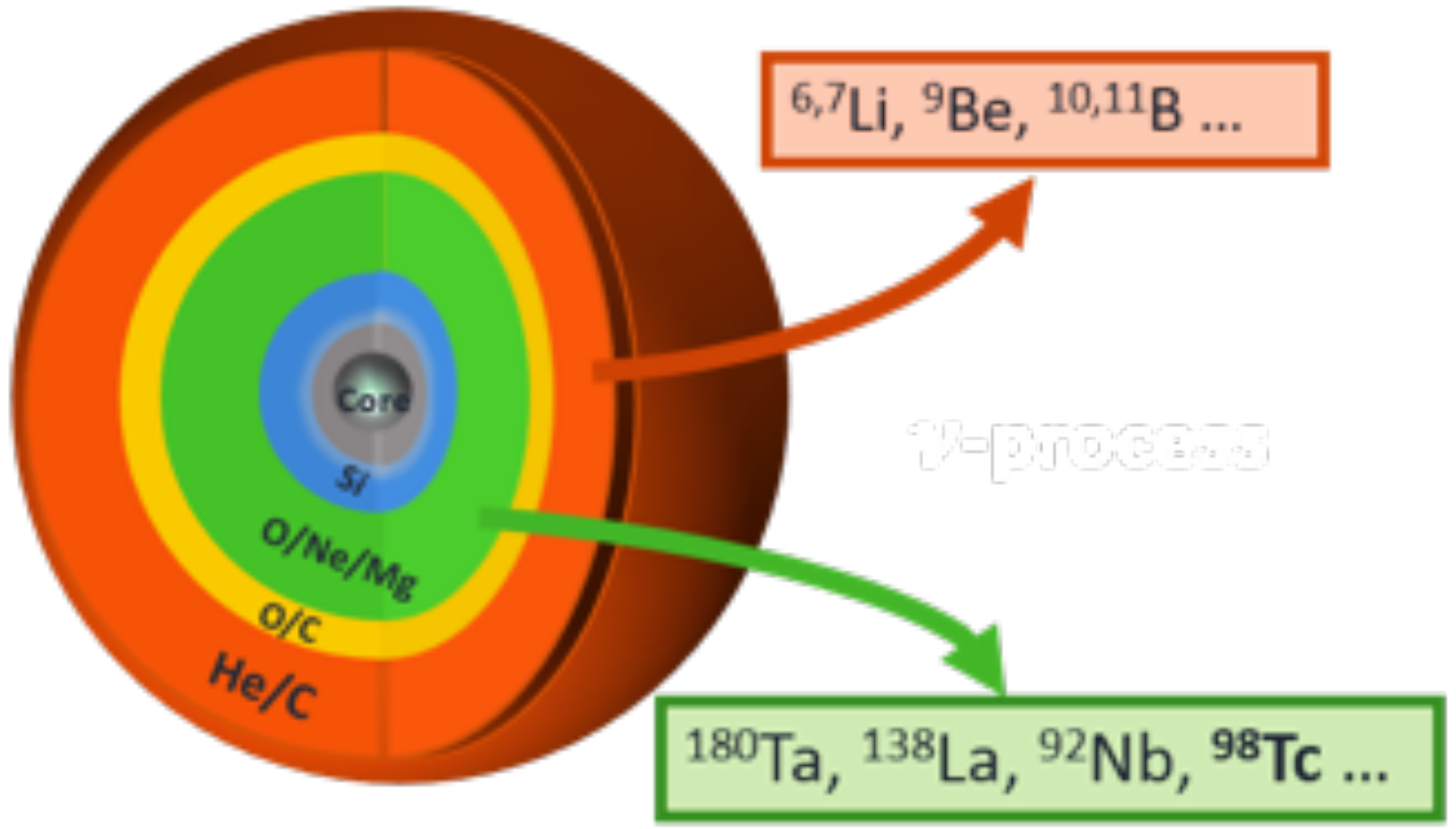
M. -K. Cheoun, E. Ha, M. Kusakabe, T. Hayakawa, H. Sasaki, T. Kajino, M.-a. Hashimoto, M. Ono, M. D. Usang, S. Chiba,K. Nakamura, A. Tolstov, K. Nomoto, T. Kawano, and G. J. Mathews

arXiv:1903.02086 [astro-ph.HE]

1. Neutrino process in core collapse supernova

Neutrino process





M. Kusakabe et al. APJ 872, 164 (2019)
T. Yoshida et al. APJ 686, 448 (2008)
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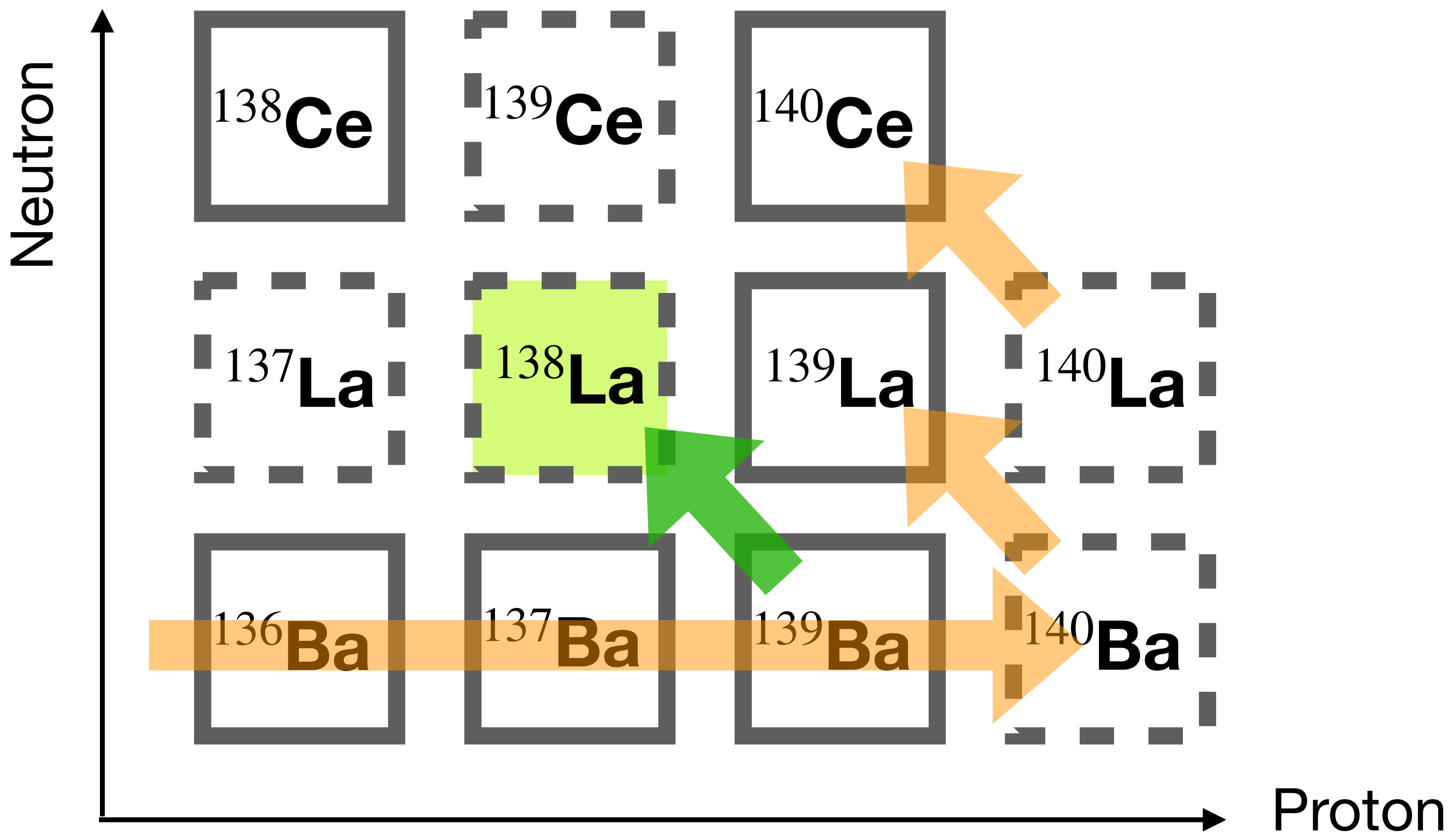
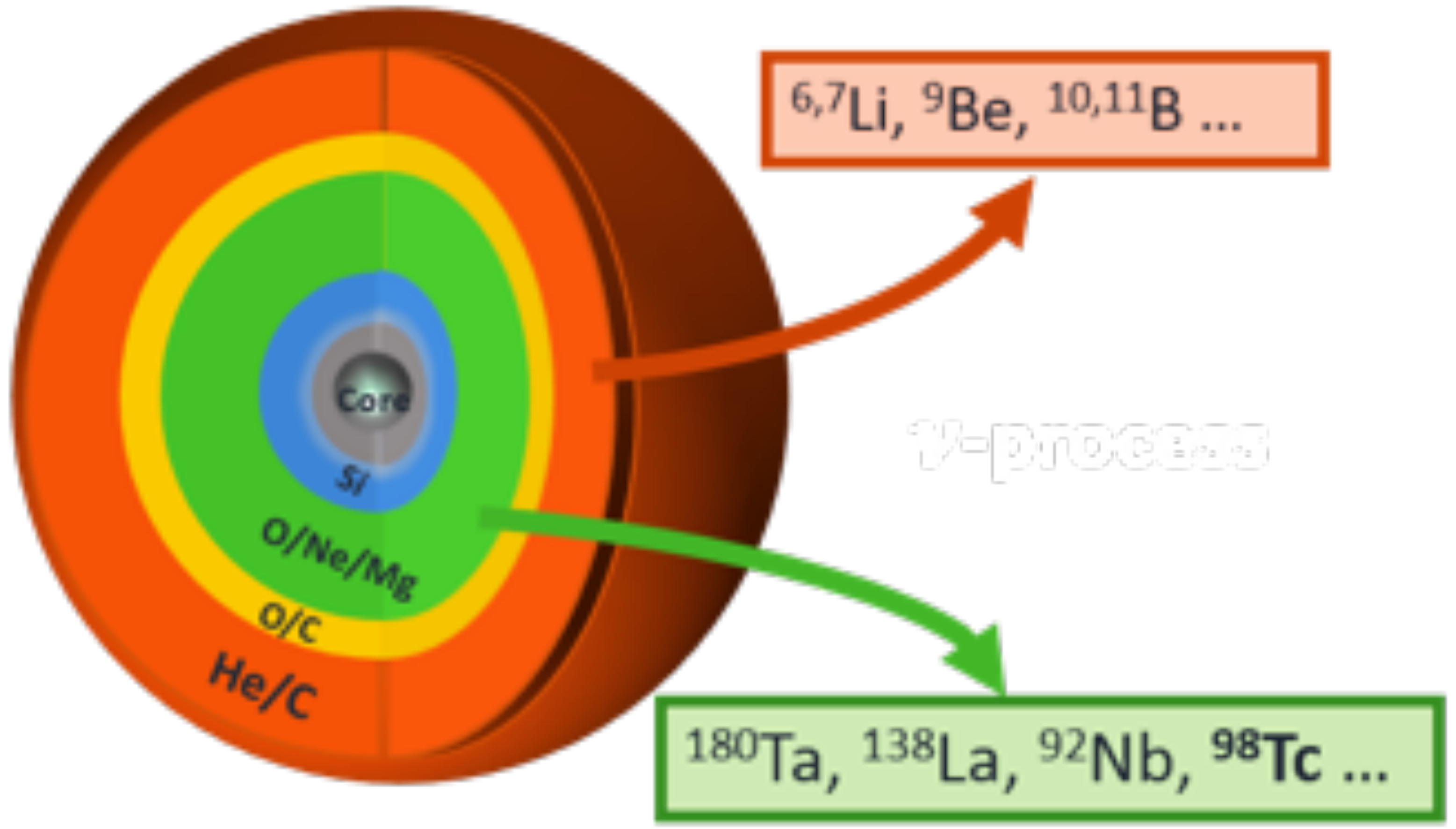


$$^{138}\mathrm{Ba} + \nu_e \rightarrow {}^{138}\mathrm{La} + e^-$$



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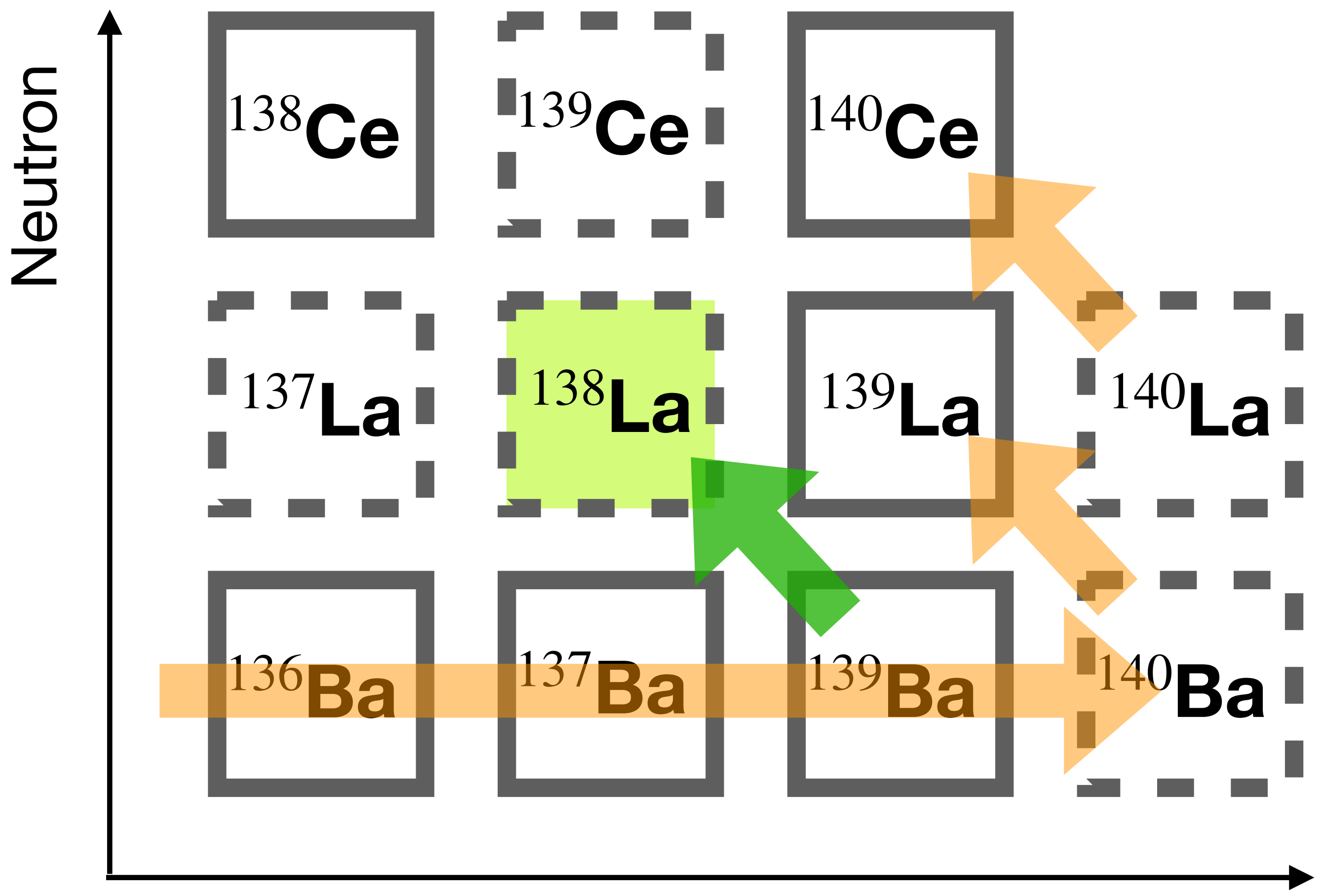

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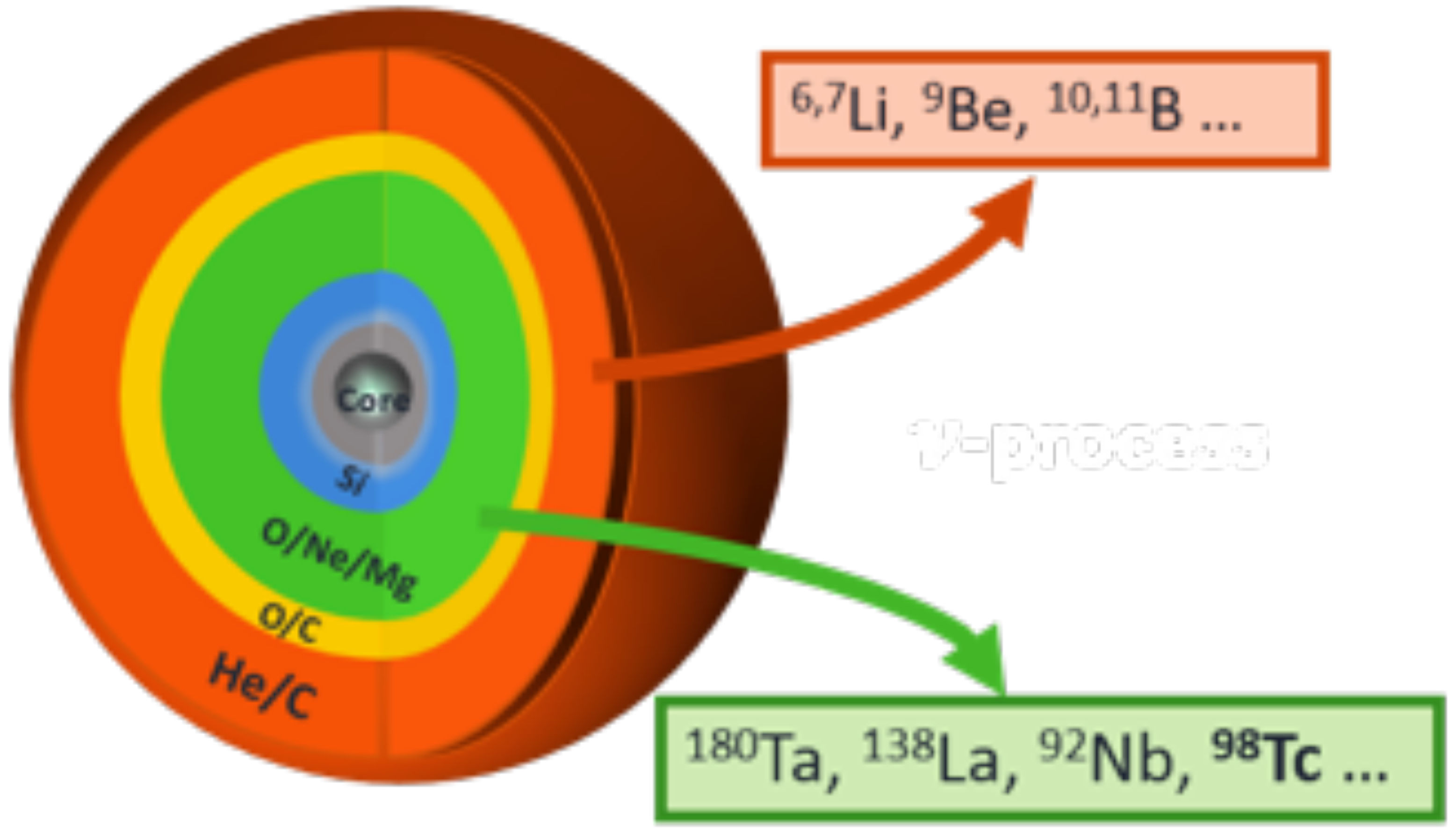

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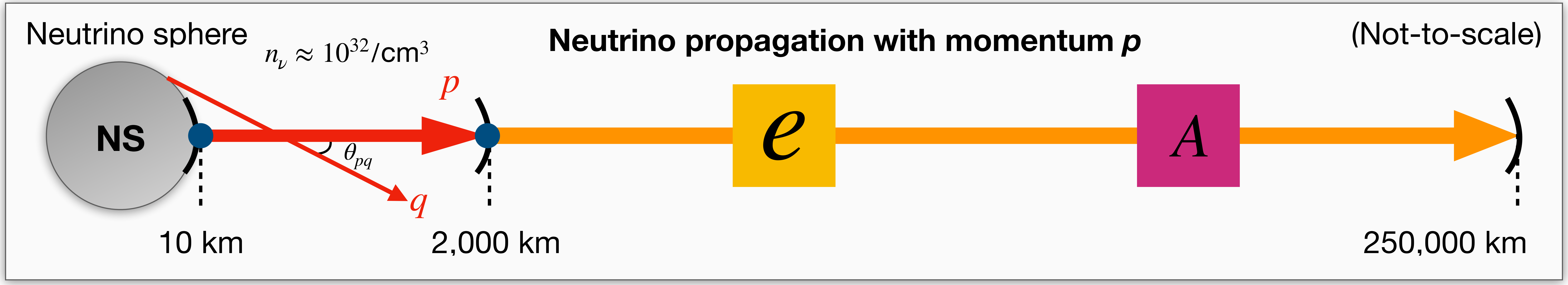


Neutrino interaction depending on the neutrino and electron density

Neutrino self-coupling	Neutrino in matter	Neutrino-nucleus
$\nu\nu$-scattering	$\nu_e e$-scattering	νA-scattering

2.1 Neutrino oscillation

Neutrino in flavor basis

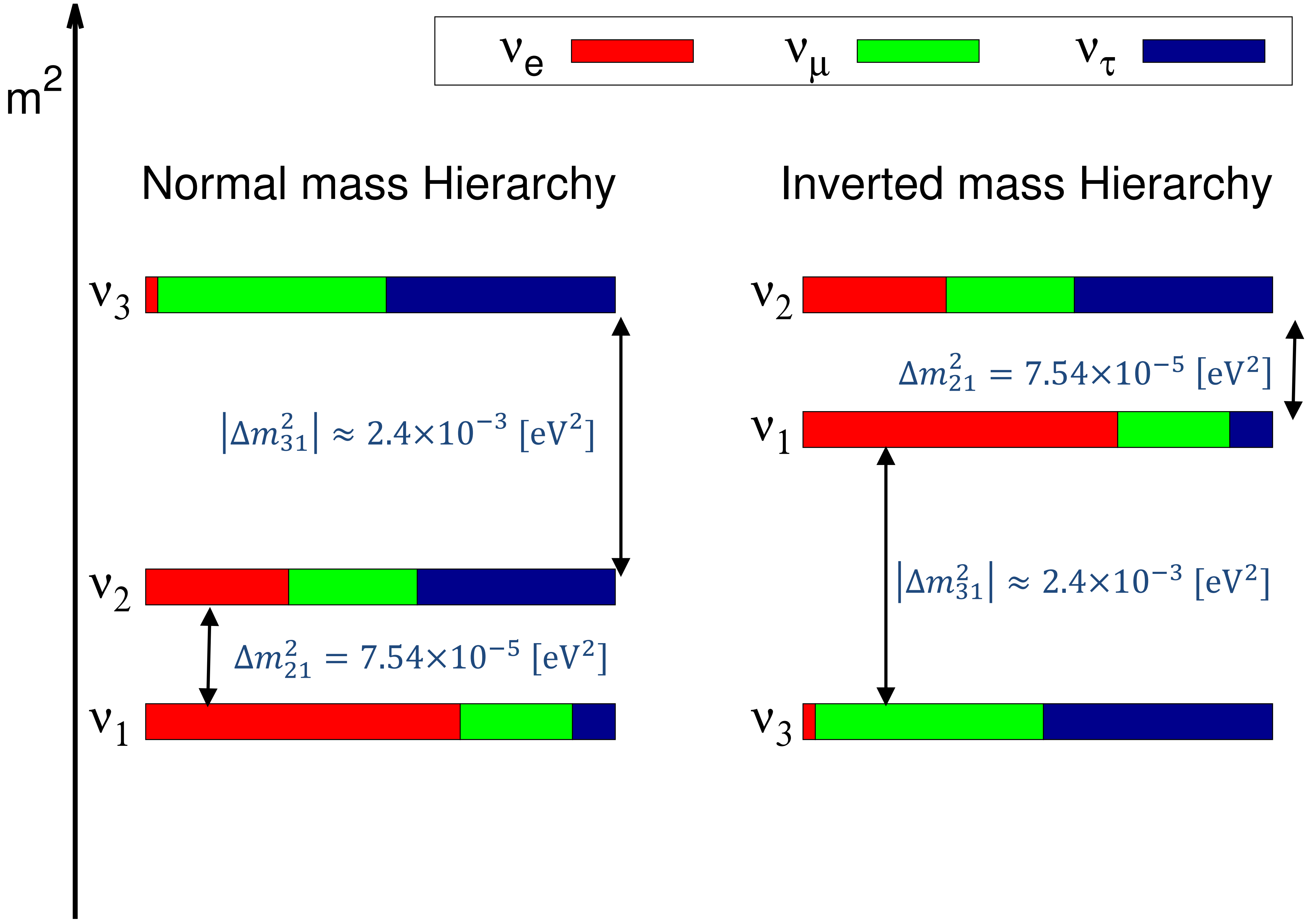
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

where U is the PMNS (Pontecorvo-Maki-Nakagawa-Sakata) mixing matrix

$$U = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}\\ 0 & 1 & 0\\ -\sin\theta_{13} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

$$\boxed{\begin{array}{ccc}\theta_{12} = 33.8^\circ & \theta_{23} = 45^\circ & \theta_{13} = 9.2^\circ\\ \Delta m^2_{21} = 7.5\times10^{-5}\ [\mathrm{eV}^2] & & |\Delta m^2_{31}| = 2.4\times10^{-3}\ [\mathrm{eV}^2]\end{array}}$$

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



Vacuum Hamiltonian

$$E_i = \sqrt{p_\nu^2 + m_i^2} \approx E_\nu + \frac{m_i^2}{2E_\nu} \quad \& \quad H_{vacuum} = U\begin{pmatrix}0 & 0 & 0\\ 0 & \frac{\Delta m^2_{21}}{2E_\nu} & 0\\ 0 & 0 & \frac{|\Delta m^2_{31}|}{2E_\nu}\end{pmatrix}U^\dagger$$

Ultrarelativistic

where $|\Delta m^2_{31}| > 0$, NH and $|\Delta m^2_{31}| < 0$, IH

2.1 Neutrino oscillation in electron matter

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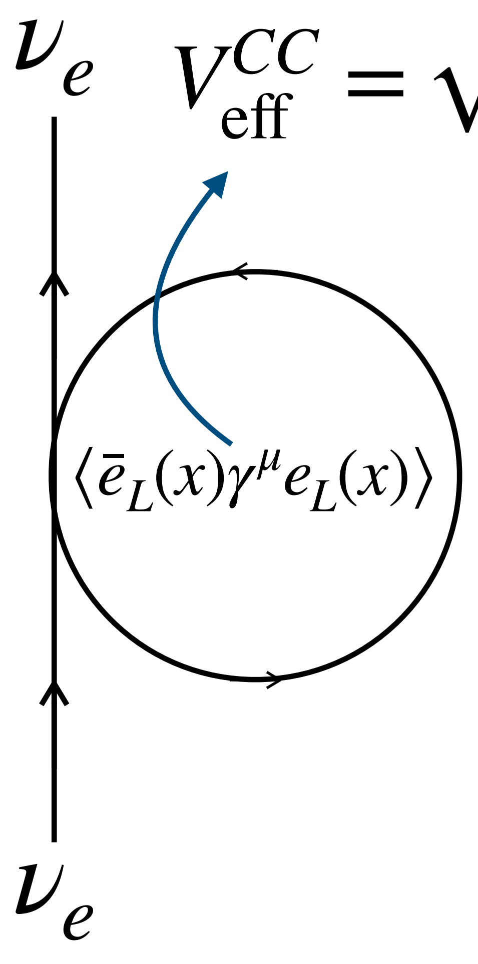
Ultrarelativistic

where $|\Delta m_{31}^2| > 0$, NH and $|\Delta m_{31}^2| < 0$, IH

Matter Hamiltonian - Charged current reaction

$$\mathcal{H}_{\mathrm{eff}}^{CC}(x) = \frac{\sqrt{2}}{2}G_F[\bar\nu_e(x)\gamma^\mu(1-\gamma^5)\nu_e(x)]\ \langle\bar e(x)\gamma_\mu(1-\gamma^5)e(x)\rangle$$

with Fierz transformation and thermal averaged electron matter

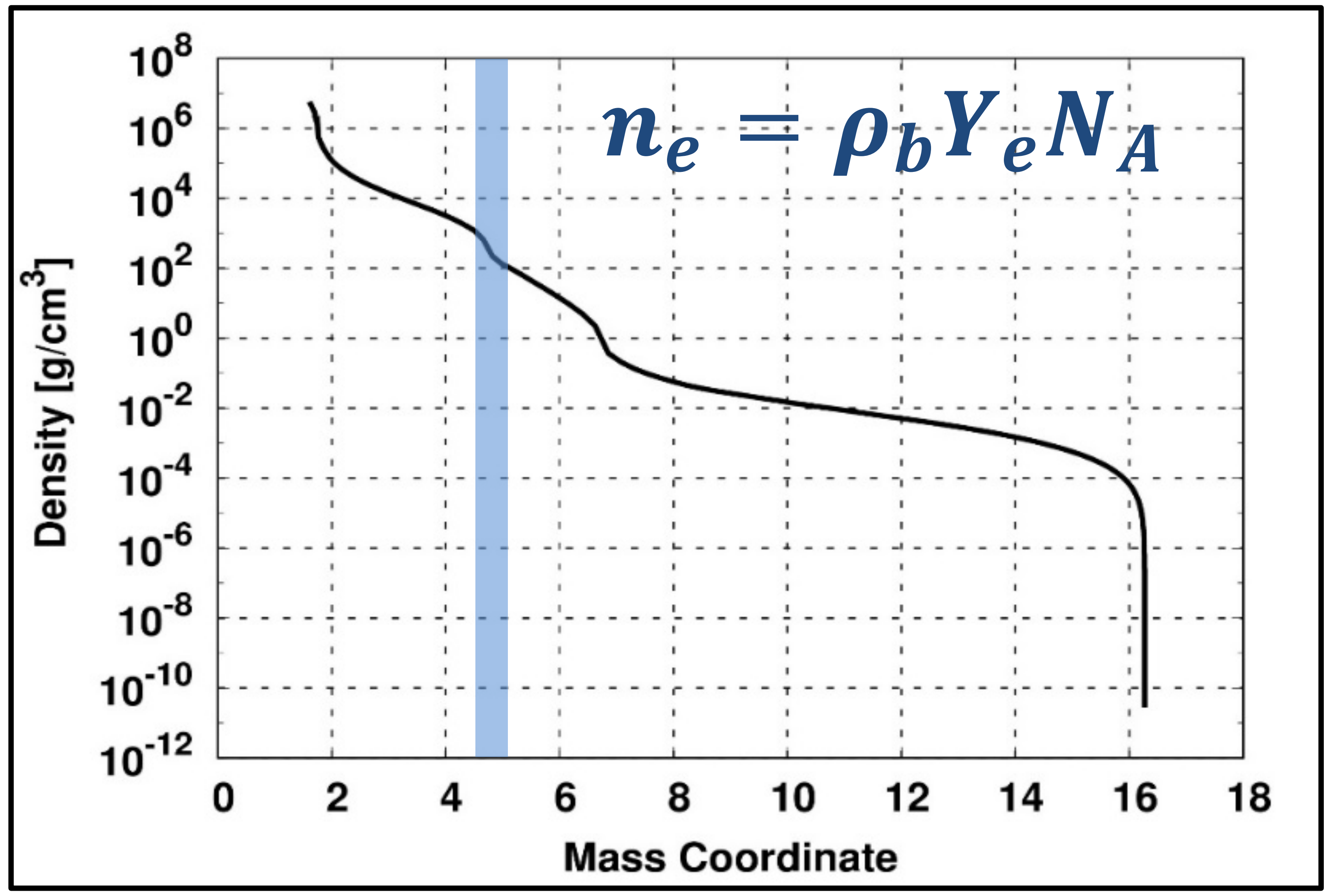


$$V_{\mathrm{eff}}^{CC} = \sqrt{2}G_F n_e$$

$$V_{\nu_e e} = \begin{pmatrix}\sqrt{2}G_F N_A Y_e \rho_b & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}$$

$$Y_e \sim 0.5$$

$$dM(r) = 4\pi r^2 \rho dr$$



Density profile of SN1987A by A. Tolstov

2.1 Neutrino oscillation in electron matter

Total Hamiltonian

$$H_{tot} = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m_{21}^2}{2E_\nu} & 0 \\ 0 & 0 & \frac{\Delta m_{31}^2}{2E_\nu} \end{pmatrix} U^\dagger + \begin{pmatrix} \sqrt{2}G_F n_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Solve the schroedinger like equation

$$i\frac{d}{dt}\begin{pmatrix} \nu_e(t) \\ \nu_\mu(t) \\ \nu_\tau(t) \end{pmatrix} = H_{tot} \begin{pmatrix} \nu_e(t) \\ \nu_\mu(t) \\ \nu_\tau(t) \end{pmatrix}$$

MSW (Mikheyev–Smirnov–Wolfenstein) resonance condition

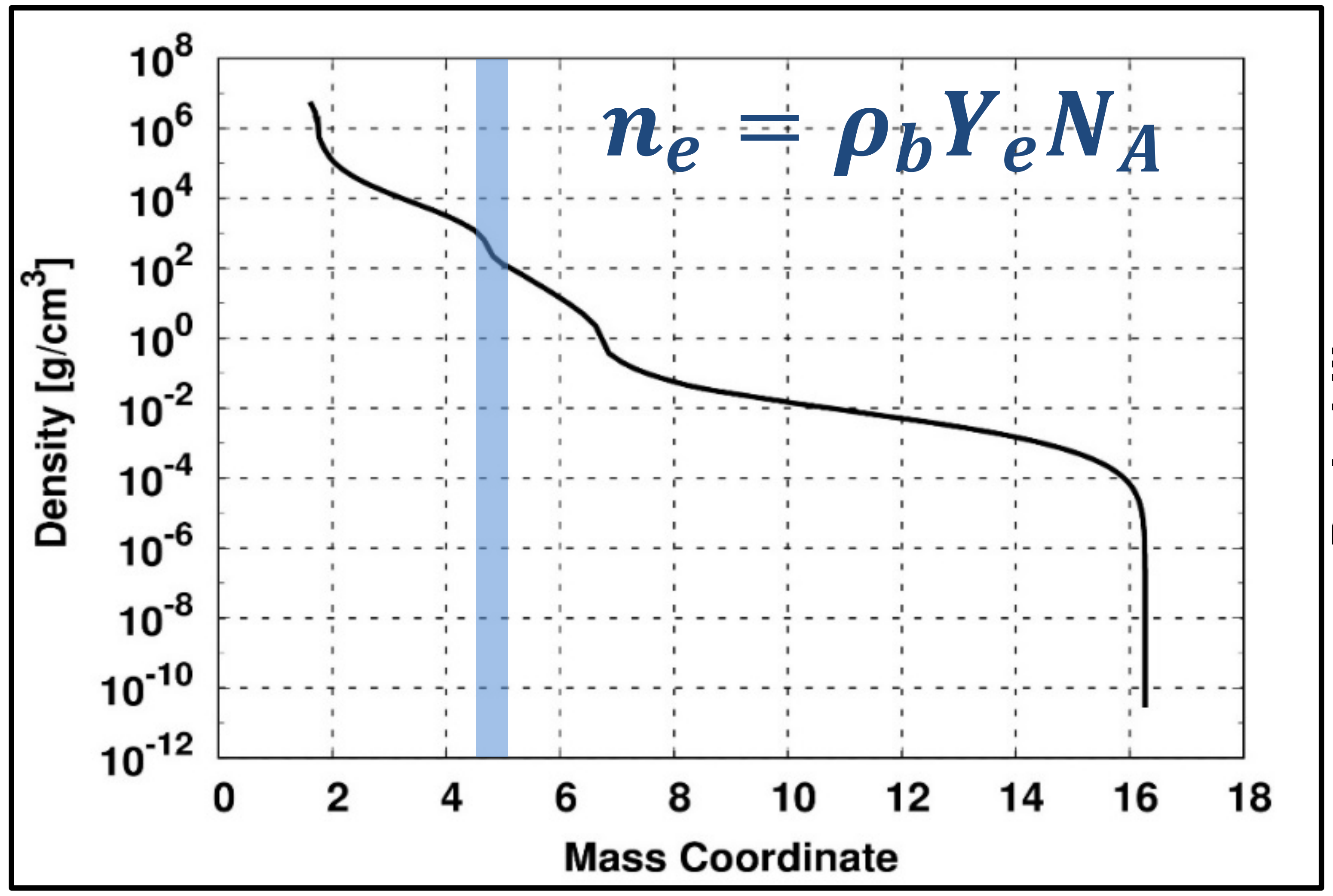
Vacuum term = Matter term

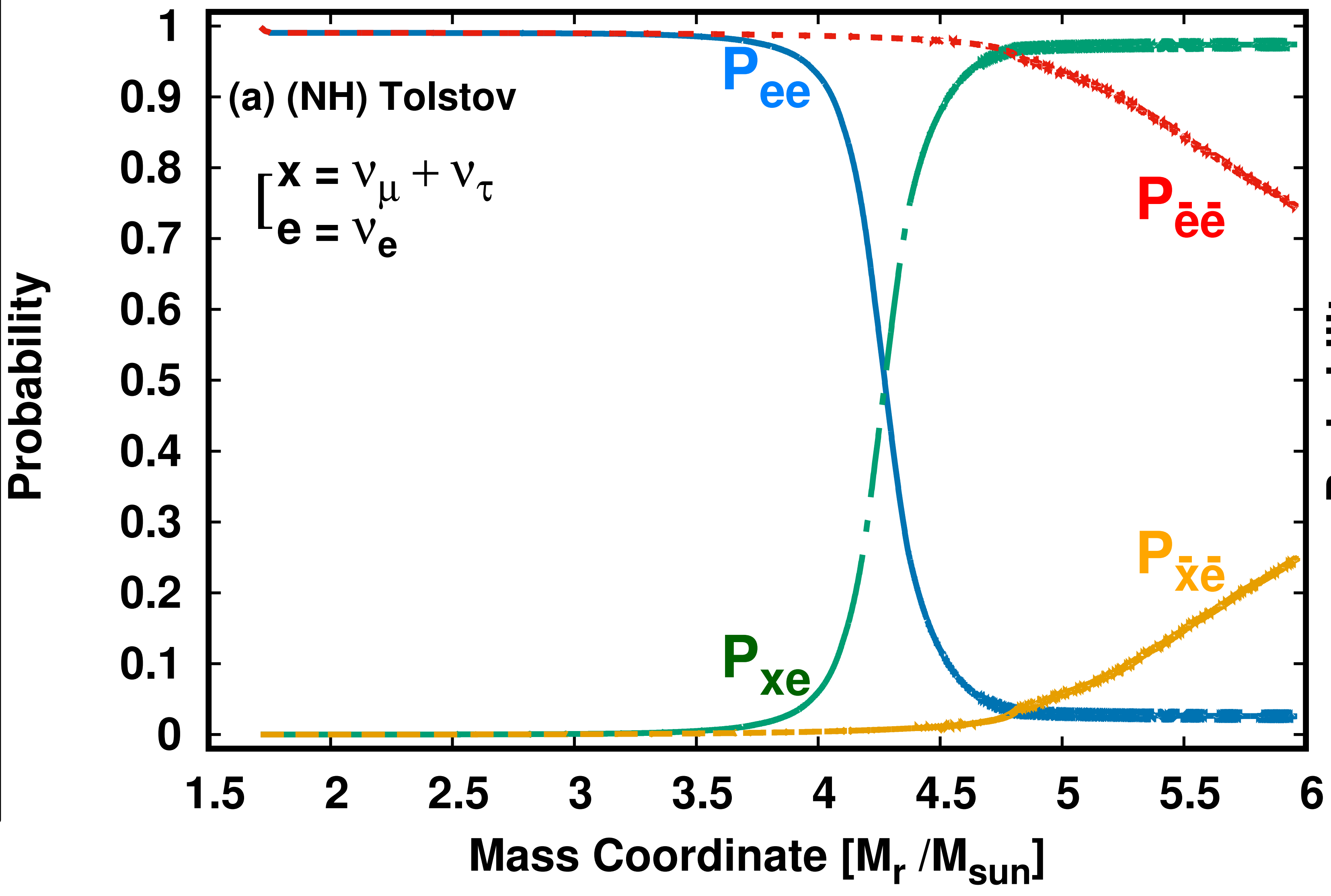
$$\sqrt{2}G_F n_e = \frac{\Delta m_{ji}^2}{2E_\nu}\cos 2\theta_{ij} \Rightarrow \rho_b = \frac{\Delta m_{ji}^2 \cos 2\theta_{ij}}{2\sqrt{2}G_F E_\nu Y_e}$$

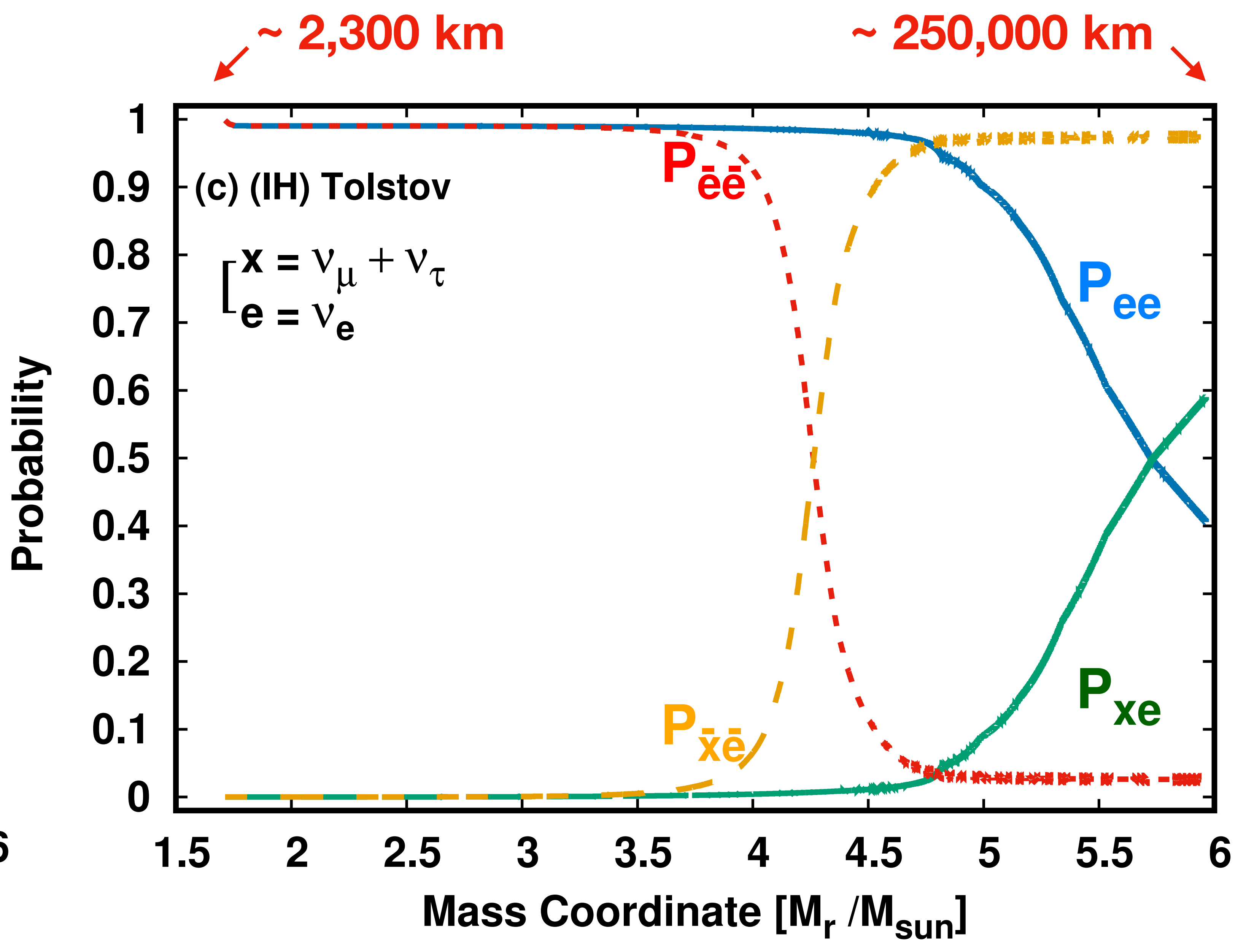
$(E_\nu = 15\ \text{MeV})$

- $j = 2$ and $i = 1 \rightarrow \rho_b \sim 12.3$ [g/cm^3]
- $j = 3$ and $i = 1 \rightarrow \rho_b \sim 994$ [g/cm^3]

Flavor change probability and MSW effect







2.2 Neutrino oscillation in neutrino gas

Neutrino self-interaction Hamiltonian - by taking ensemble average

From 10 km to 2000 km

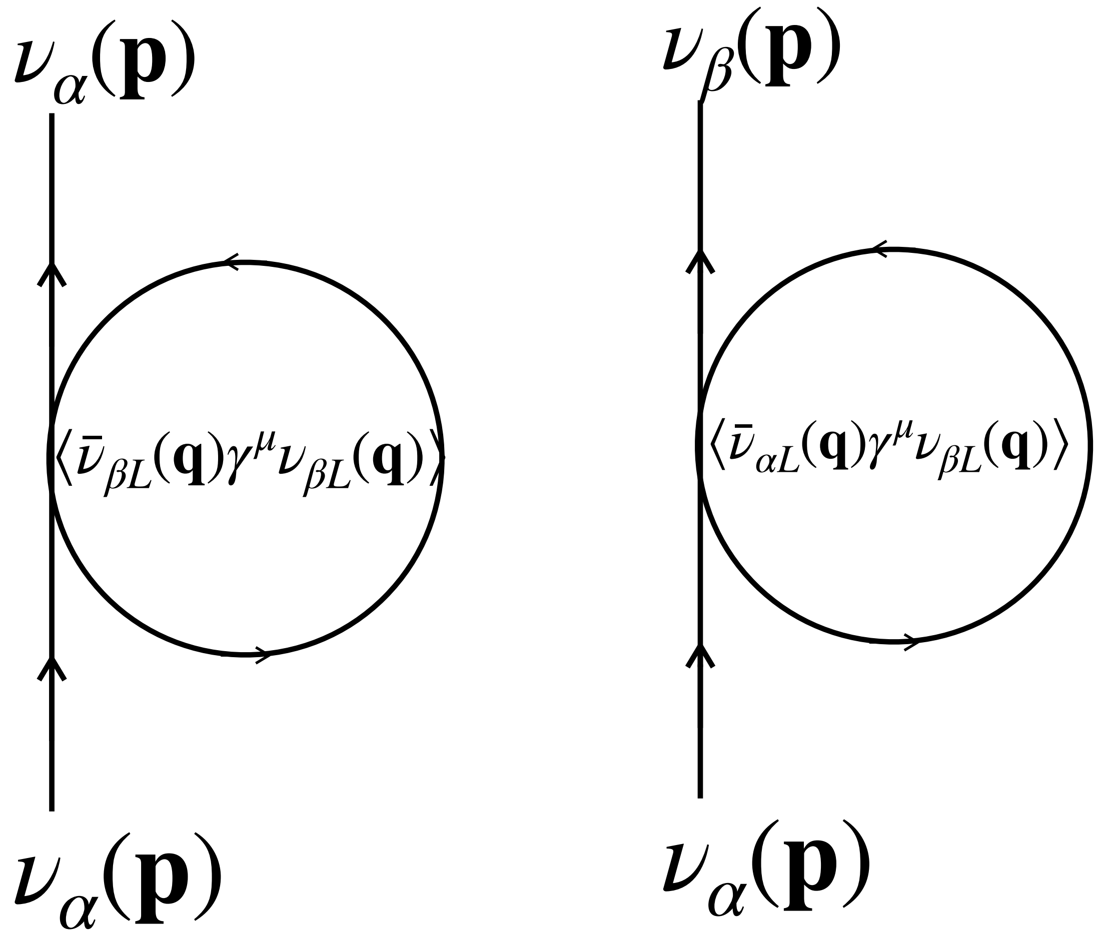
$$\mathscr{H}^{\mathrm{NC}}_{\nu\nu}(x) = \frac{\sqrt{2}}{2}G_F[\bar{\nu}_\alpha(x)\gamma^\mu(1-\gamma^5)\nu_\alpha(x)]\underbrace{\langle\bar{\nu}_\beta(x)\gamma^\mu(1-\gamma^5)\nu_\beta(x)\rangle}_{\text{(a)}}$$

$$+\frac{\sqrt{2}}{2}G_F[\bar{\nu}_\beta(x)\gamma^\mu(1-\gamma^5)\nu_\alpha(x)]\underbrace{\langle\bar{\nu}_\alpha(x)\gamma^\mu(1-\gamma^5)\nu_\beta(x)\rangle}_{\text{(b)}}$$

Potential term

$$V_{\text{diagonal}}(x) = \sqrt{2}G_F\int(1-\hat{\mathbf{p}}\cdot\hat{\mathbf{q}})\ [\rho(x)-\bar{\rho}(x)]_{\beta\beta}d^3\mathbf{q}$$

$$V_{\text{exchange}}(x) = \sqrt{2}G_F\int(1-\hat{\mathbf{p}}\cdot\hat{\mathbf{q}})\ [\rho(x)-\bar{\rho}(x)]_{\alpha\beta}d^3\mathbf{q}$$



(a) Diagonal **(b) Exchange**

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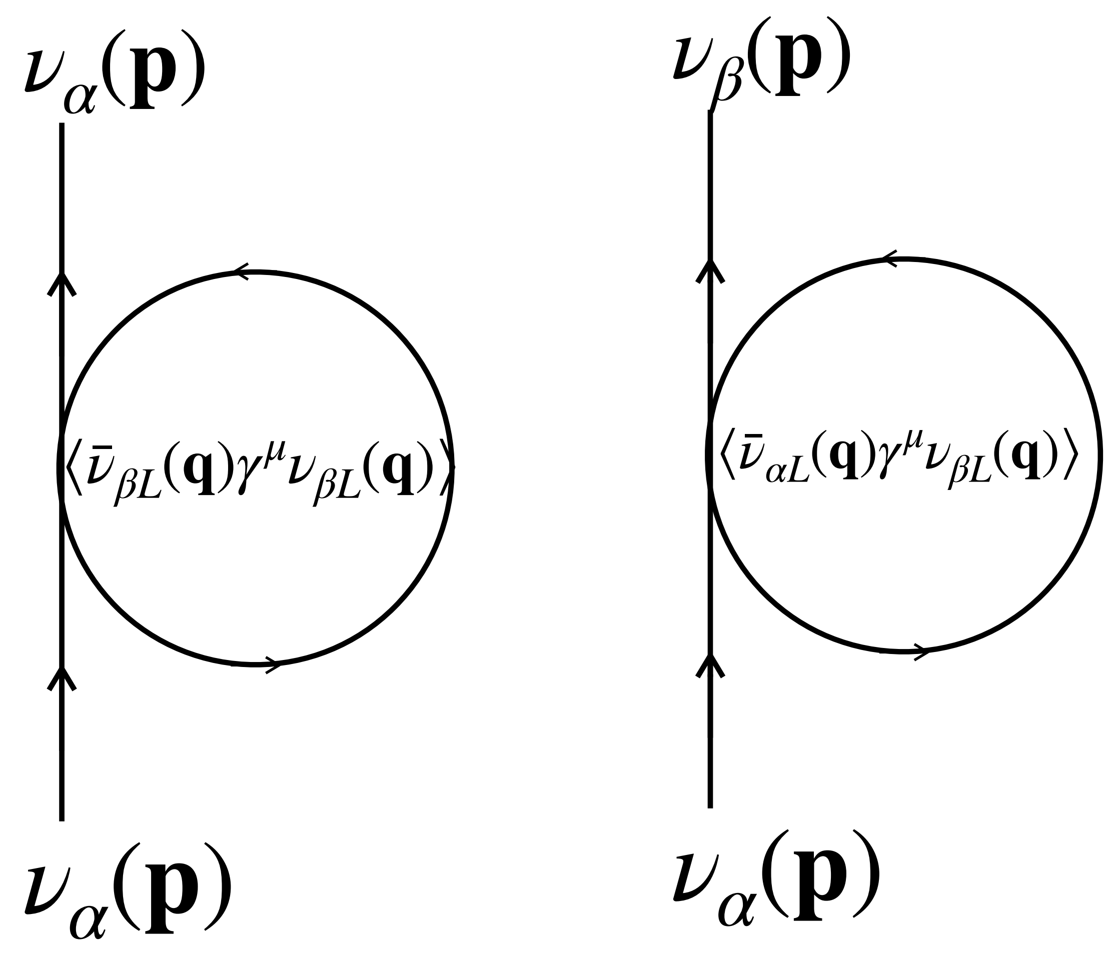
Potential term

Geometry

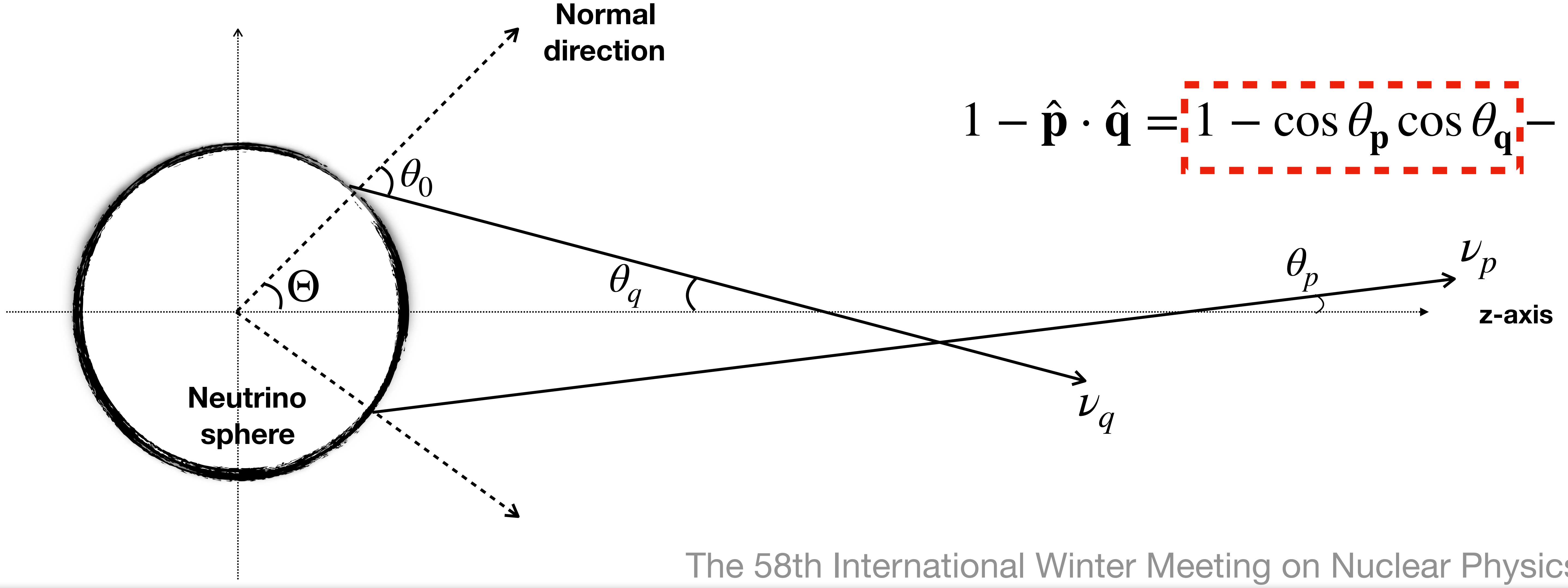
$$V_{\rm diagonal}(x) = \sqrt{2}G_F\int \boxed{(1-\hat{\mathbf{p}}\cdot\hat{\mathbf{q}})}[\rho(x)-\bar{\rho}(x)]_{\beta\beta}d^3\mathbf{q}$$

$$V_{\rm exchange}(x) = \sqrt{2}G_F\int \boxed{(1-\hat{\mathbf{p}}\cdot\hat{\mathbf{q}})}[\rho(x)-\bar{\rho}(x)]_{\alpha\beta}d^3\mathbf{q}$$



(a) Diagonal **(b) Exchange**

Neutrino bulb model



$$1-\hat{\mathbf{p}}\cdot\hat{\mathbf{q}} = \boxed{1-\cos\theta_{\mathbf{p}}\cos\theta_{\mathbf{q}}} - \underline{\sin\theta_{\mathbf{p}}\sin\theta_{\mathbf{q}}(\cos\phi_{\mathbf{p}}\cos\phi_{\mathbf{q}}+\sin\phi_{\mathbf{p}}\sin\phi_{\mathbf{q}})}$$

0 by z-axis symmetry

H. Duan et al. PRD 74, 105014 (2006)
G. Fuller et al. PRD 73. 023004 (2006)

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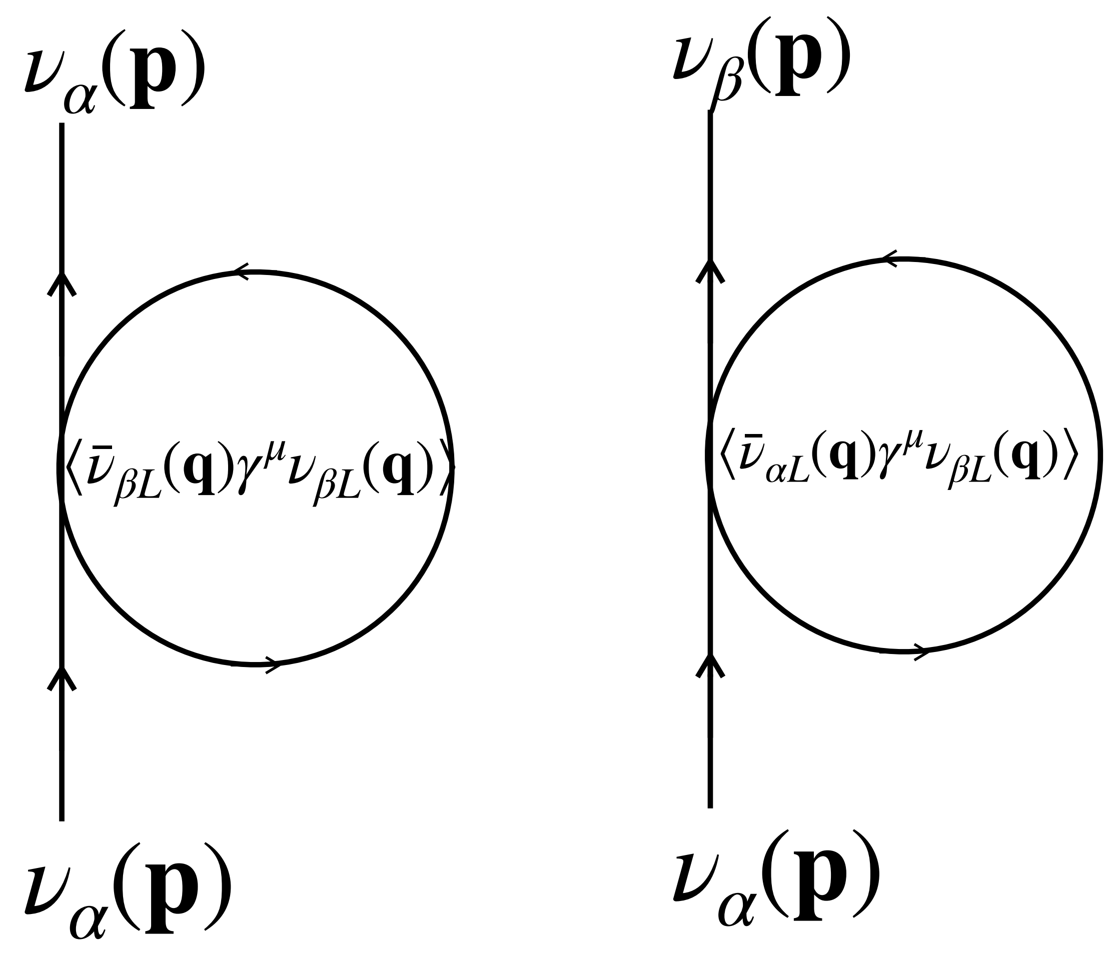

(a) Diagonal **(b) Exchange**

where density operator for mixed ensemble of neutrino states

$$\hat{\rho}(t,\mathbf{q})d^3\mathbf{q} \equiv \sum_\alpha dn_{\nu_\alpha}|\nu_\alpha(t,\mathbf{q})\rangle\langle\nu_\alpha(t,\mathbf{q})|$$
$$\hat{\bar{\rho}}(t,\mathbf{q})d^3\mathbf{q} \equiv \sum_\alpha dn_{\bar{\nu}_\alpha}|\bar{\nu}_\alpha(t,\mathbf{q})\rangle\langle\bar{\nu}_\alpha(t,\mathbf{q})|$$

$$[\rho(x)]_{ee} \equiv \sum_\alpha dn_{\nu_\alpha}\langle\nu_e|\nu_\alpha(t,\mathbf{q})\rangle\langle\nu_\alpha(t,\mathbf{q})|\nu_e\rangle$$

Y.-Z. QIan et al. PRD 51.1479 (1995)

Differential neutrino number density

$$dn_{\nu_\alpha} = \frac{1}{V}f_{dist}d^3\mathbf{q} = \frac{1}{\pi R_\nu^2}\boxed{\frac{L_{\nu_\alpha}(t)}{\langle E_{\nu_\alpha}(t)\rangle}}\frac{1}{1.803T^3_{\nu_\alpha}}\frac{\mathbf{q}}{\exp(\mathbf{q}/T_{\nu_\alpha})+1}d\mathbf{q}\left(\frac{d\Omega}{4\pi}\right)$$

$t_{pb} = 50,\ 100,\ 200,\ 300$ and 500 ms

$t_{pb} > 500$ ms $\to L(500$ ms$) \times$ exp$[-(t-r/c)/\tau]$

E. O'Connor et al. J. Phys. G: Nucl. Part. Phys. 45 104001 (2018)

2.2 Neutrino oscillation in neutrino gas

Neutrino self-interaction Hamiltonian - by taking ensemble average

From 10 km to 2000 km

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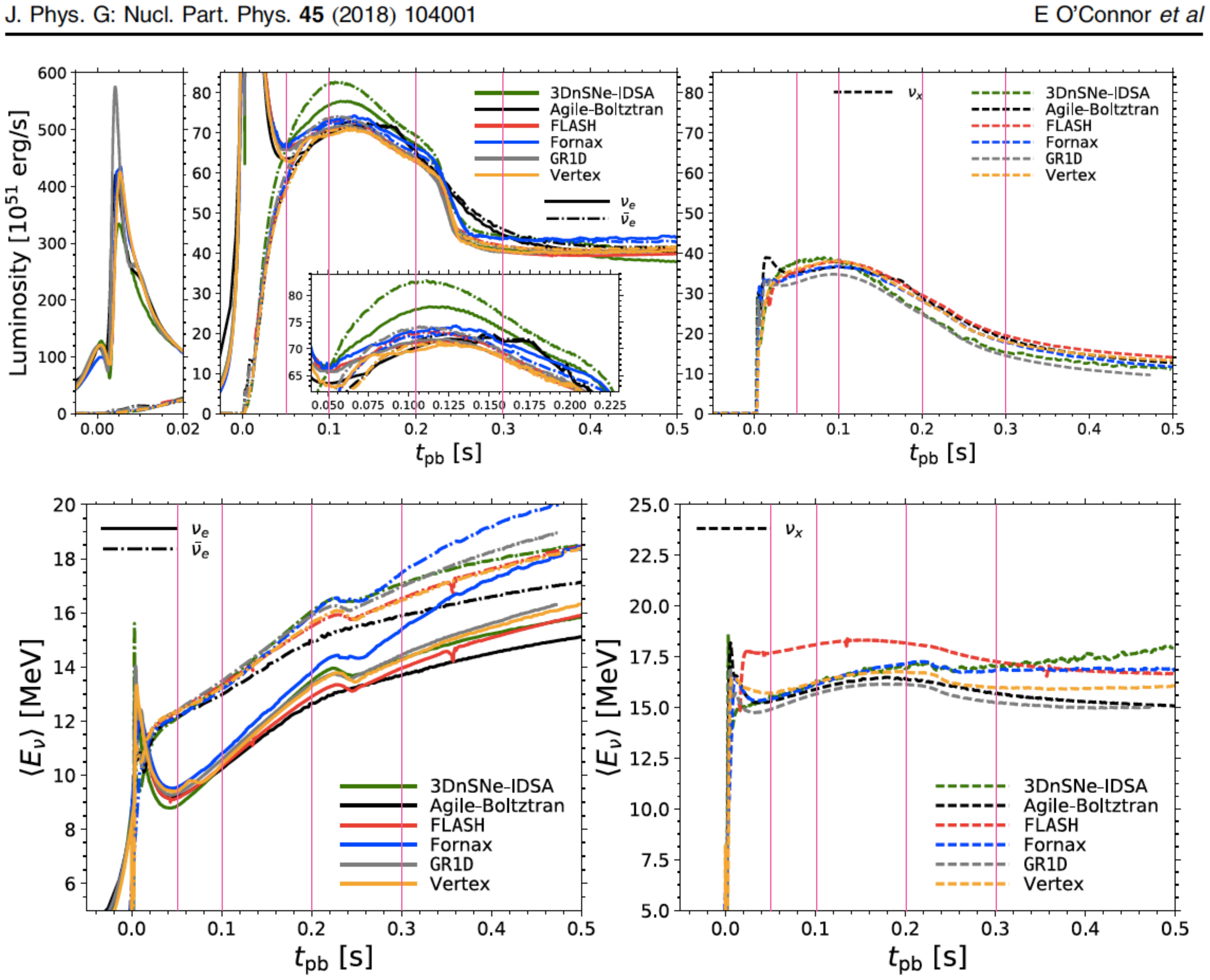

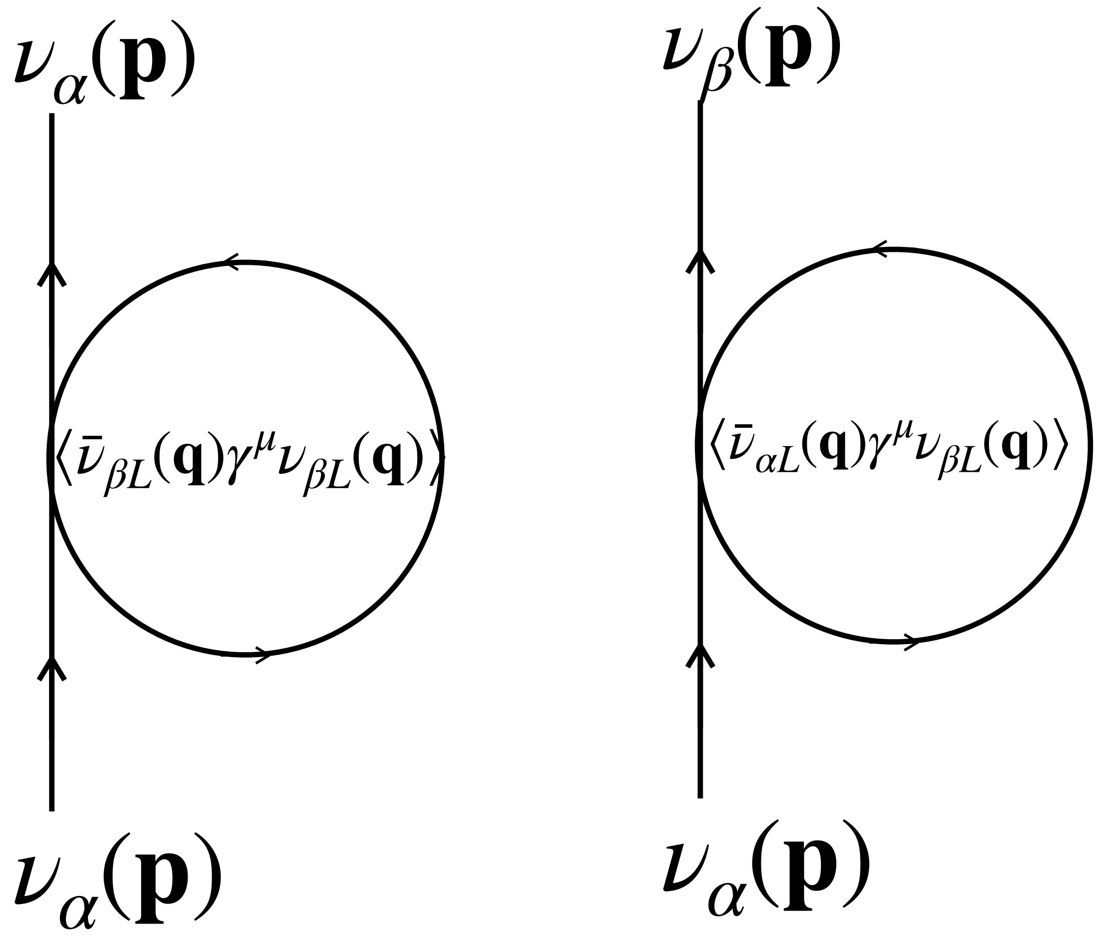

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E. O'Connor et al. J. Phys. G: Nucl. Part. Phys. 45 104001 (2018)

2.3 Neutrino spectra

The equation of motion, $t \sim x$

$$i\frac{d}{dx}\rho(x,\mathbf{p},\theta_{\mathbf{p}}) = [H_{vacuum} + V_{\nu_e e}(x) + V_{\nu\nu}(x), \rho(x,\mathbf{p},\theta_{\mathbf{p}})]$$

$$V_{\nu_e e}(x) = \sqrt{2}G_F \mathrm{diag}[n_e,0,0]$$

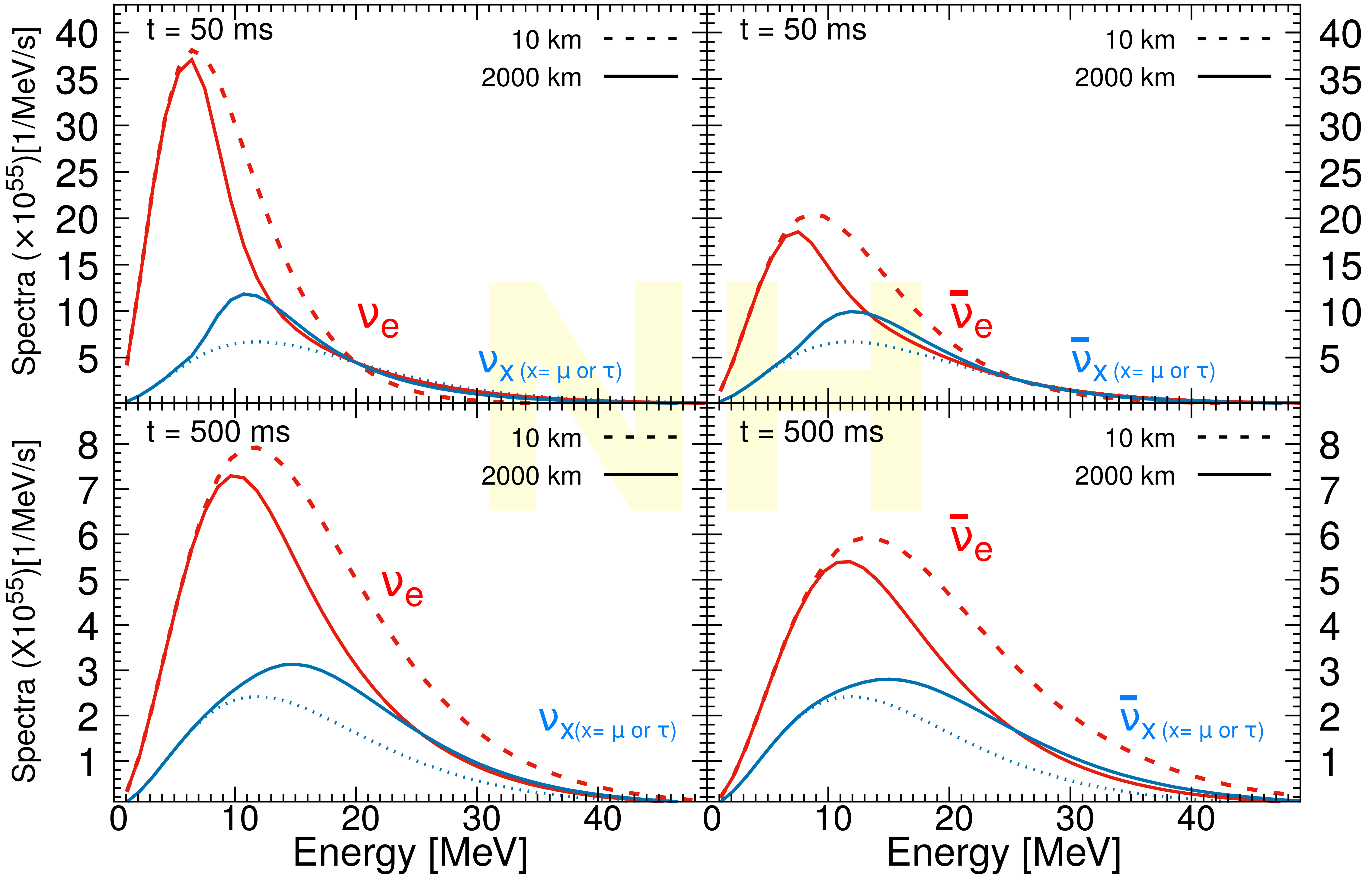
G.L. Fogli et al. PRD 68, 033005 (2003)

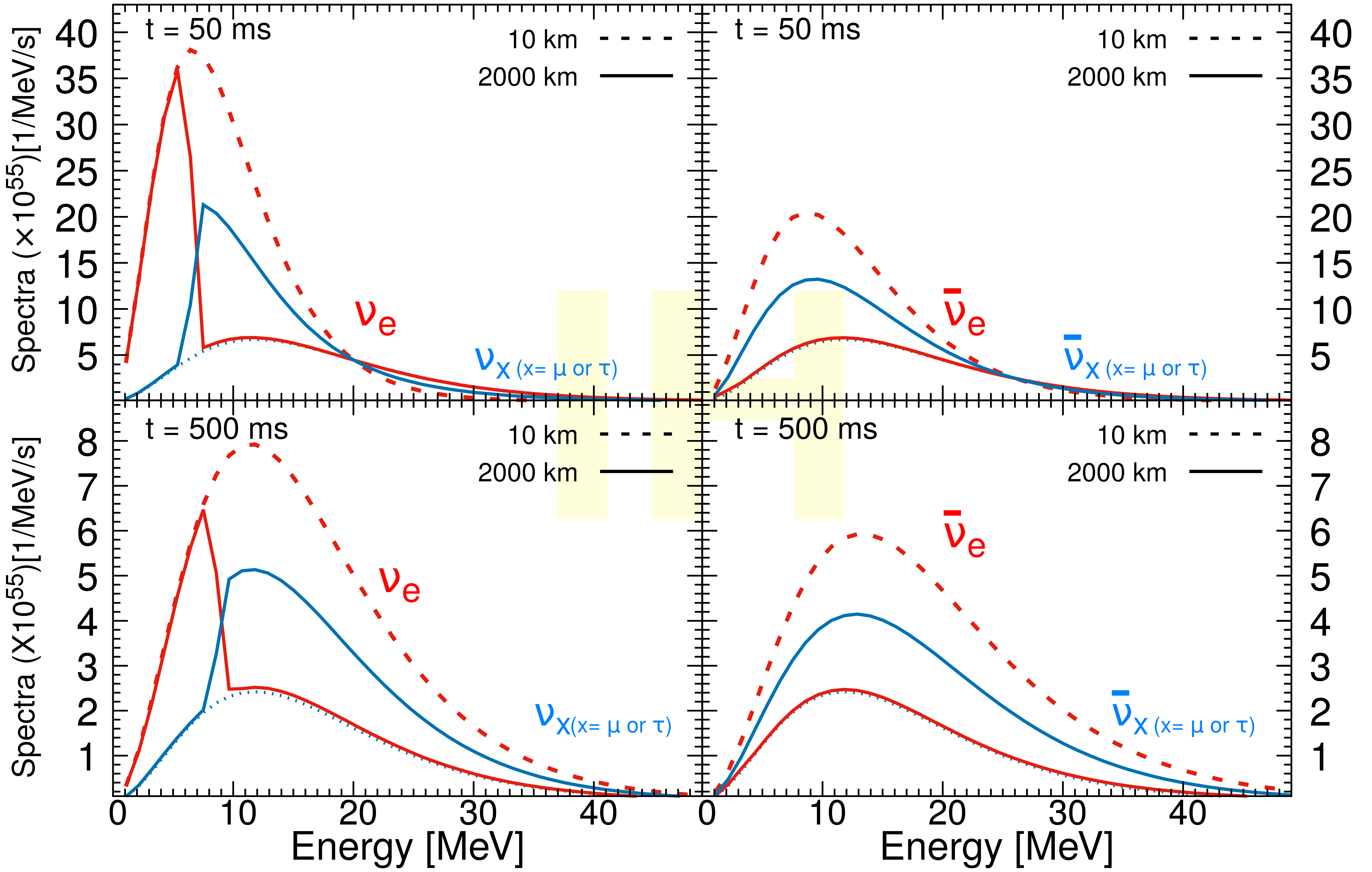
$$V_{\nu\nu}(x) = \sqrt{2}G_F \int (1-\cos\theta_{\mathbf{p}}\cos\theta_{\mathbf{q}})\ [\rho(x)-\bar{\rho}(x)]d^3\mathbf{q}$$

Differential neutrino flux (Neutrino spectra)

$$\frac{d}{dE_\nu}\phi_{\nu_\alpha}(t,r;E_\nu,T_{\nu_\alpha}) = \frac{1}{4\pi r^2}\frac{L_{\nu_\alpha}(t)}{\langle E_{\nu_\alpha}(t)\rangle} f_{dist}(E_\nu,T_{\nu_\alpha})\langle\rho_{\alpha\alpha}\rangle$$

same method in *H. Sasaki et al. PRD 96, 043013 (2017)*





3. Supernova nucleosynthesis

Network Calculation

$$Y_j = \frac{N_j}{\rho_b N_A}$$

$$\frac{dY_j}{dt} = +Y_i\lambda_{i,j} - Y_j\lambda_{j,h}$$ … decay rates

$$+Y_k Y_l \rho_b N_A \langle\sigma v\rangle_{kl,j} - Y_j Y_m \rho_b N_A \langle\sigma v\rangle_{jm,n}$$ … two body reactions

$$\vdots$$ … 3 and4 body reactions

JINA data base; Cyburt et al. ApJS, 189, 240 (2010)
A~100 neutron capture (n,γ) in Kawano et al. J. Nucl. Sci. Technol. 47, 462 (2010)

Neutrino reaction rate

$$\lambda_{\nu_\alpha}(r) \propto \sigma_{\nu_\alpha}\phi_\nu = \int_0^\infty \frac{d\phi}{dE_\nu}\mathrm{Br}(E_\nu)\sigma_{\nu_\alpha}(E_\nu)dE_\nu$$

$$\frac{d}{dE_\nu}\phi_{\nu_\alpha}(t,r;E_\nu,T_{\nu_\alpha}) = \frac{1}{4\pi r^2}\frac{L_{\nu_\alpha}(t)}{\langle E_{\nu_\alpha}(t)\rangle}f_{dist}(E_\nu,T_{\nu_\alpha})\langle\rho_{\alpha\alpha}\rangle P_{x\alpha}(r)$$

Neutrino-nucleus cross sections (Theoretical calculation)

- ^{4}He and ^{12}C : *T. Yoshida et al. APJ 686, 448 (2008)*
- ^{13}C to ^{80}Kr: *D. H. Hartmann and S. E. Woosley et al. (1995)*
- Nb, Tc, La and Ta: *Cheoun et al. PRC 82, 035504 (2010), PRC 85, 065807 (2012)*

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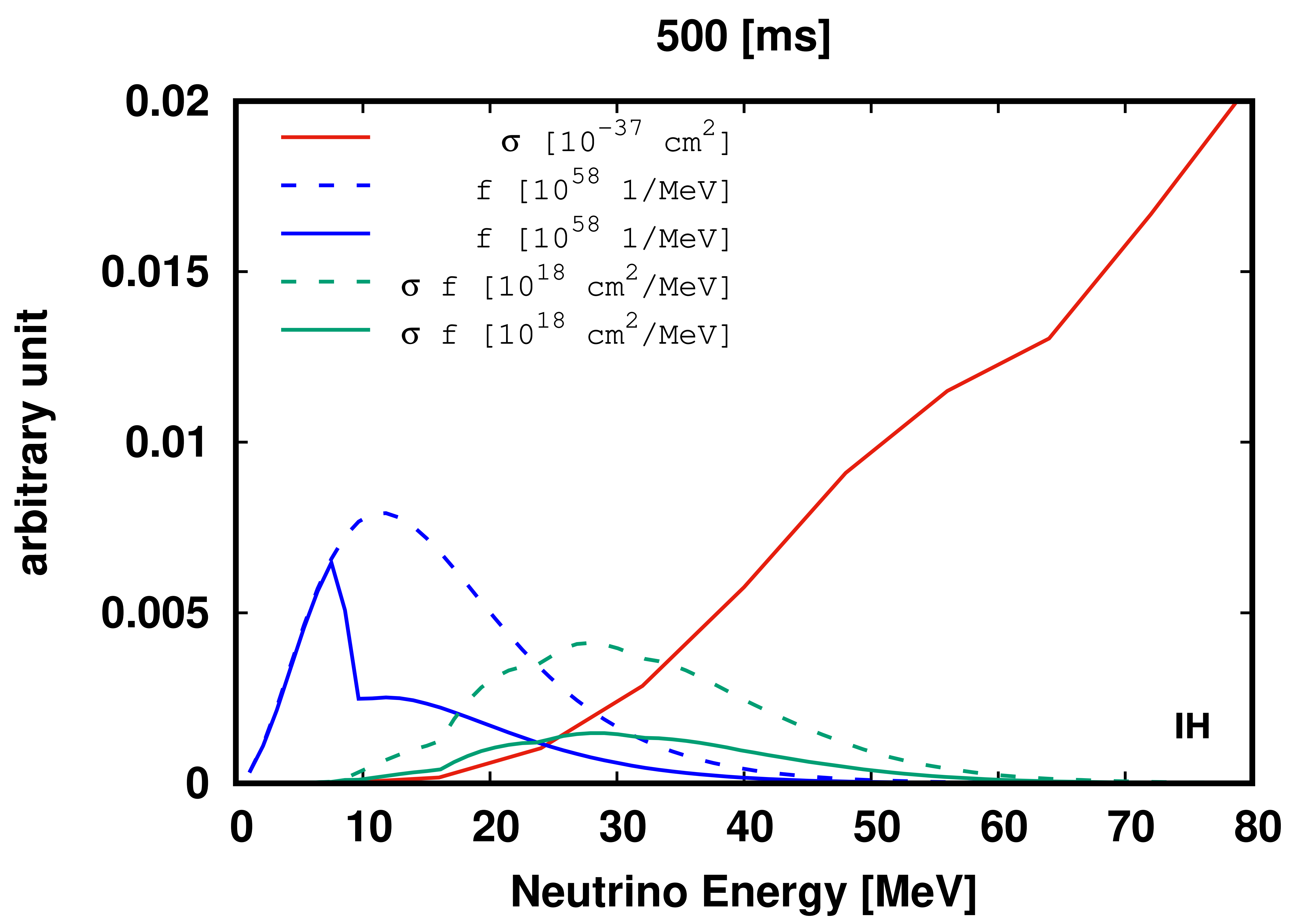
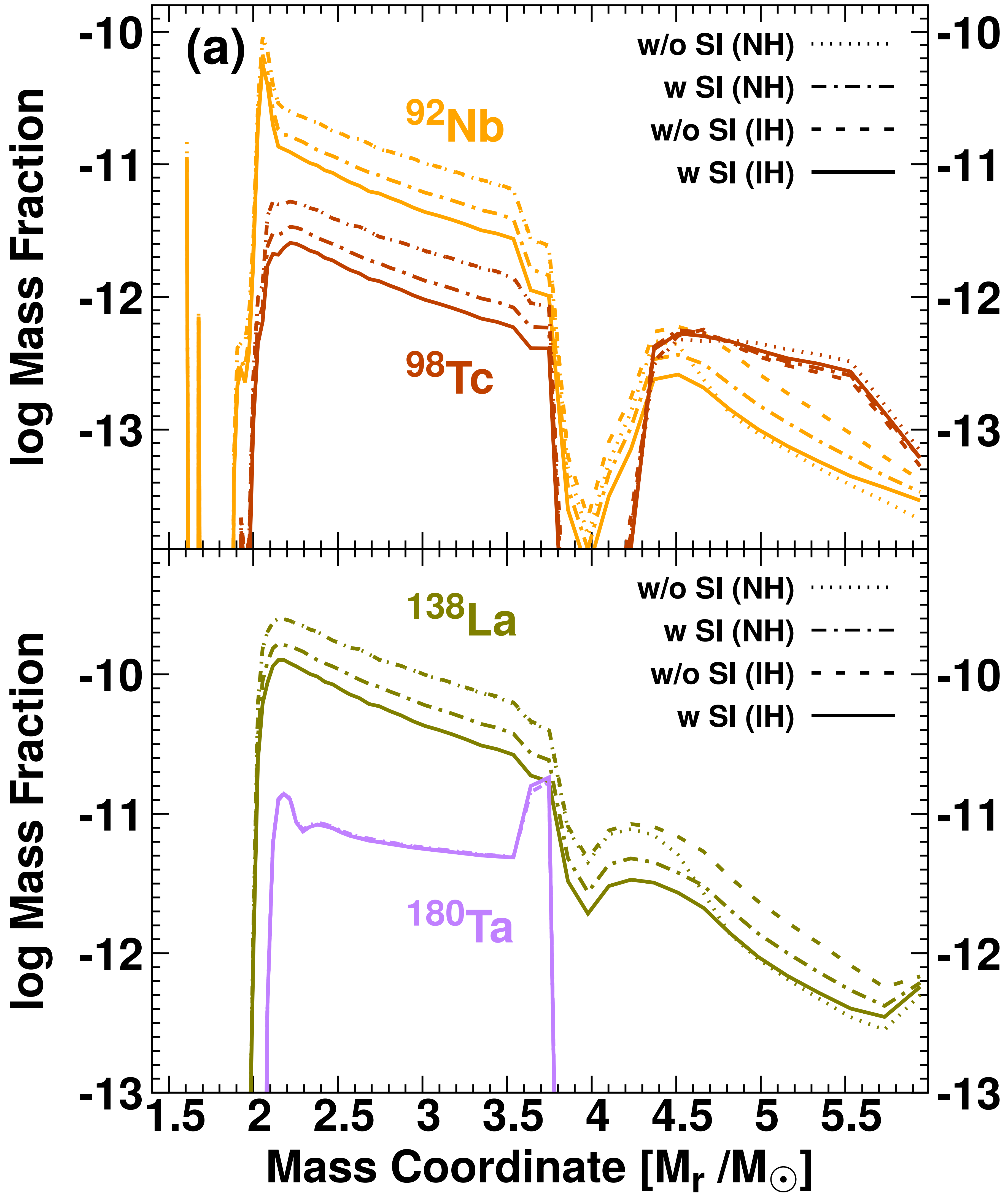
Neutrino window

$$^{98}\mathrm{Mo} + \nu_e \rightarrow {}^{98}\mathrm{Tc} + e^-$$



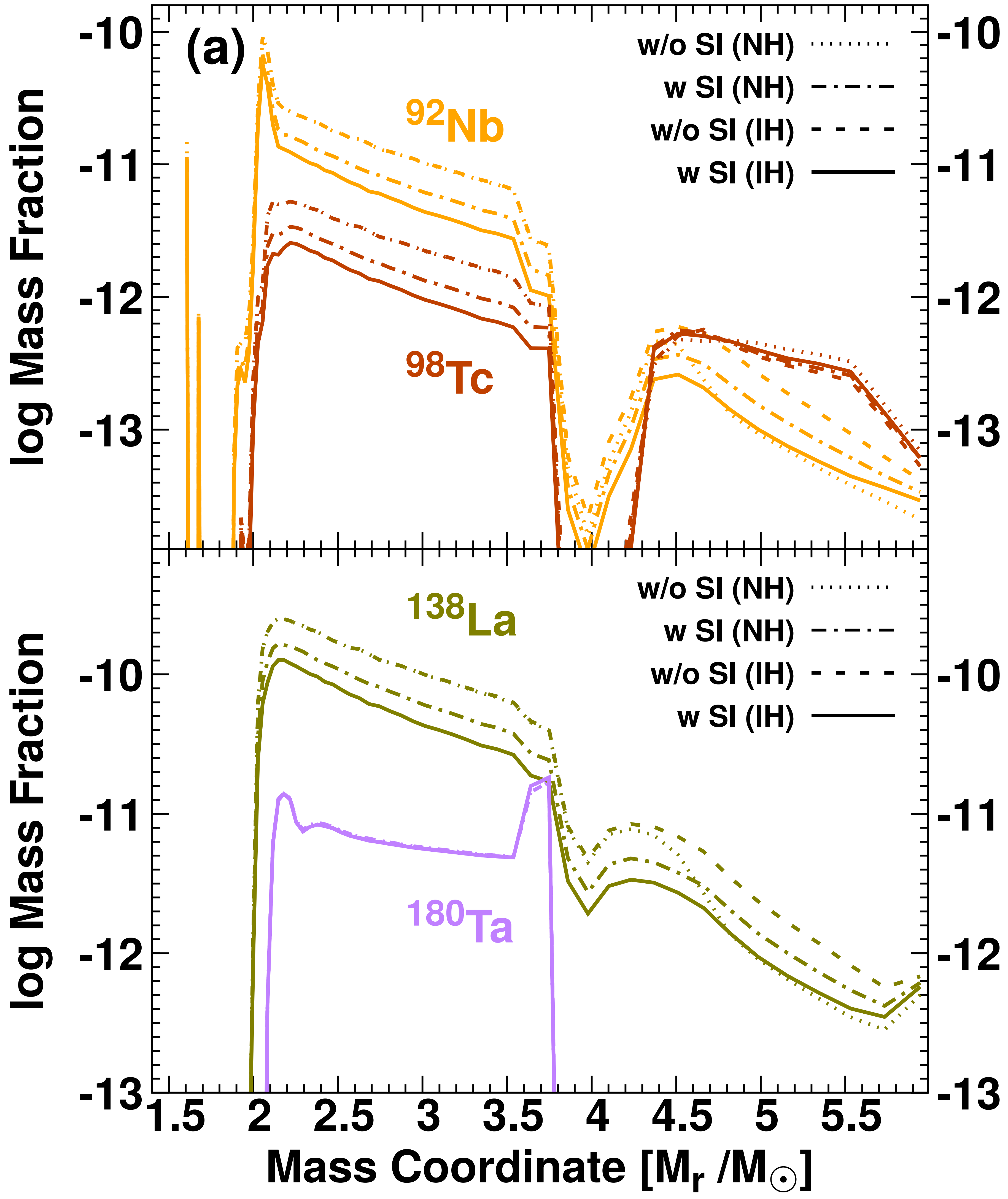
4. Results - ^{92}Nb, ^{98}Tc, ^{138}La and ^{180}Ta



- The elements are produced mostly inside the $M_r < 4M_\odot$.
- The valley around the $M_r \sim 4M_\odot$ is due to the strong neutron capture reaction(n, γ).
- The elements are produced through the charged current reaction with electron neutrinos (ν_e, e^-). The anti-electron neutrinos has 20% contribution to produce ^{98}Tc.

  T. Hayakawa et al. PRL 121, 102701,(2018)
- In case of without neutrino self-interaction, mass hierarchy has negligible effect on the synthesis. Because most of them are produced inside $M_r < 4M_\odot$, where this region is before the MSW resonance.

4. Results - ^{92}Nb, ^{98}Tc, ^{138}La and ^{180}Ta



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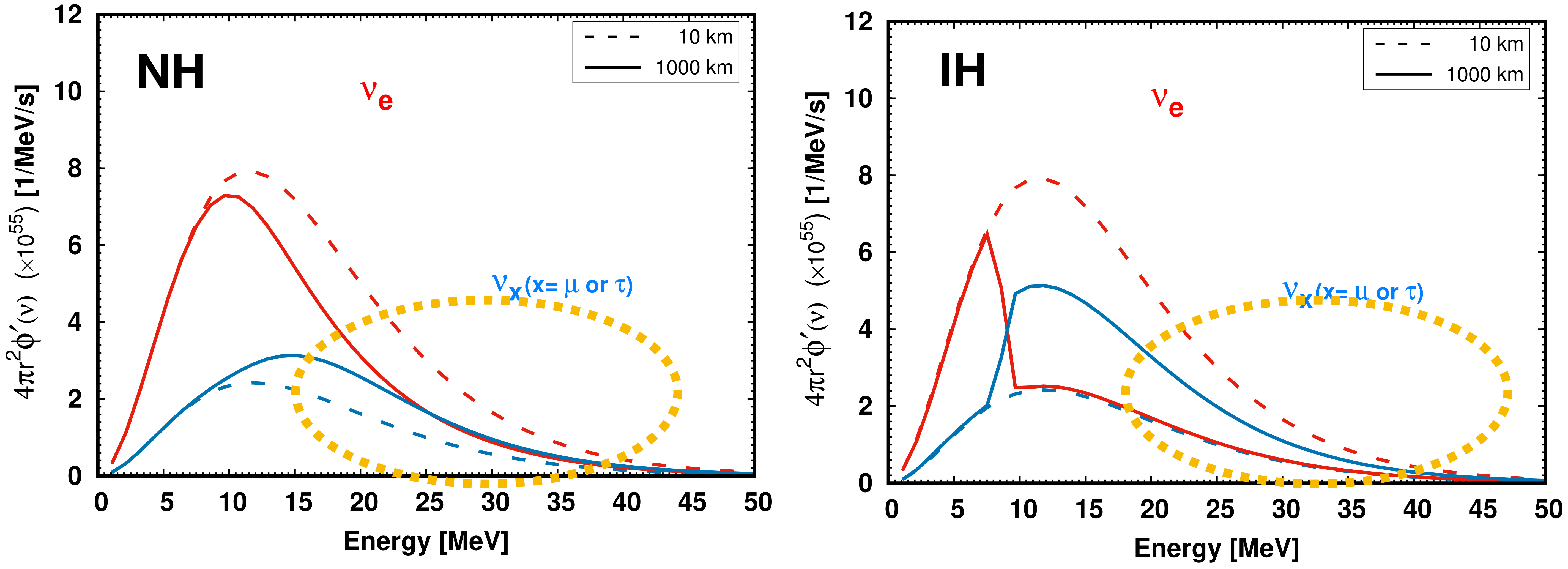


- (With neutrino self-interaction) After 500 ms, NH case has more higher electron neutrino energy distribution than IH case. So the final abundances are larger in NH case.

Summary

- Neutrinos during the supernova explosion play a key role to produce some elements which exist in our solar system

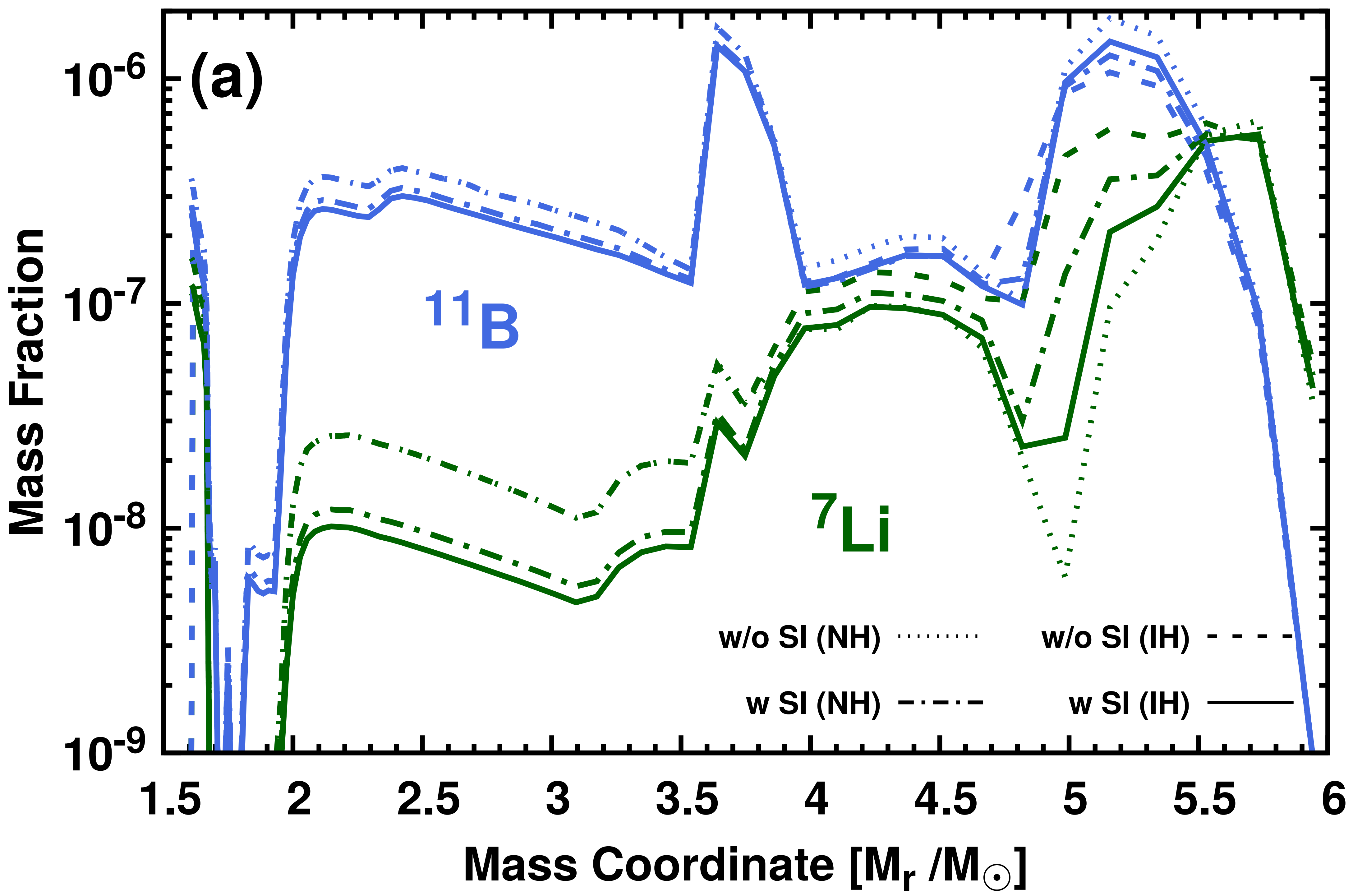
- Inside the supernova, neutrino self-interaction can change the neutrino spectra and it depends on the supernova model and neutrino mass hierarchy

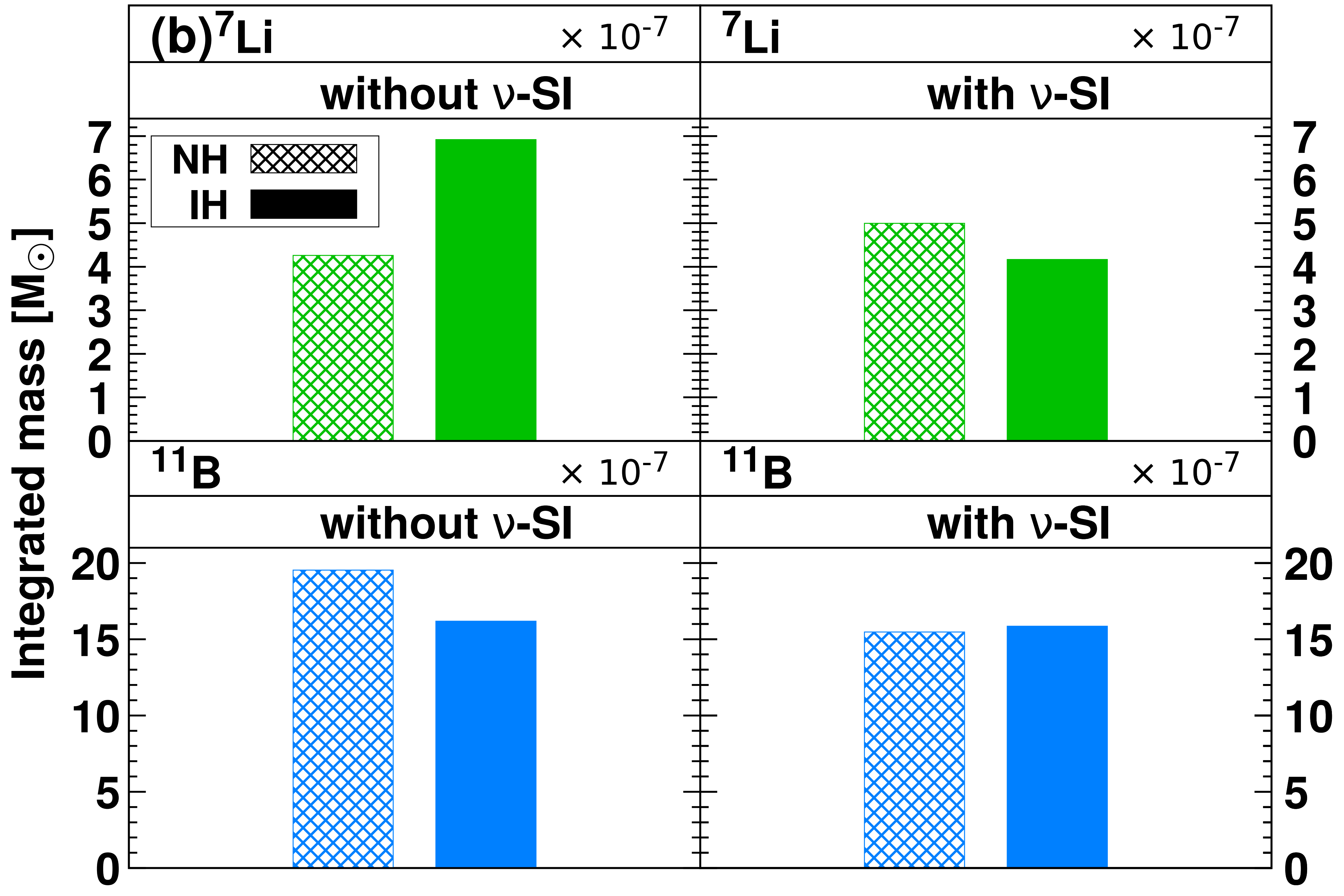
- The elements, which are produced from neutrino-induced reactions, can be understood by the reduction of the ν_e flux by the neutrino self-interaction.

Thank you for your attention

Back up

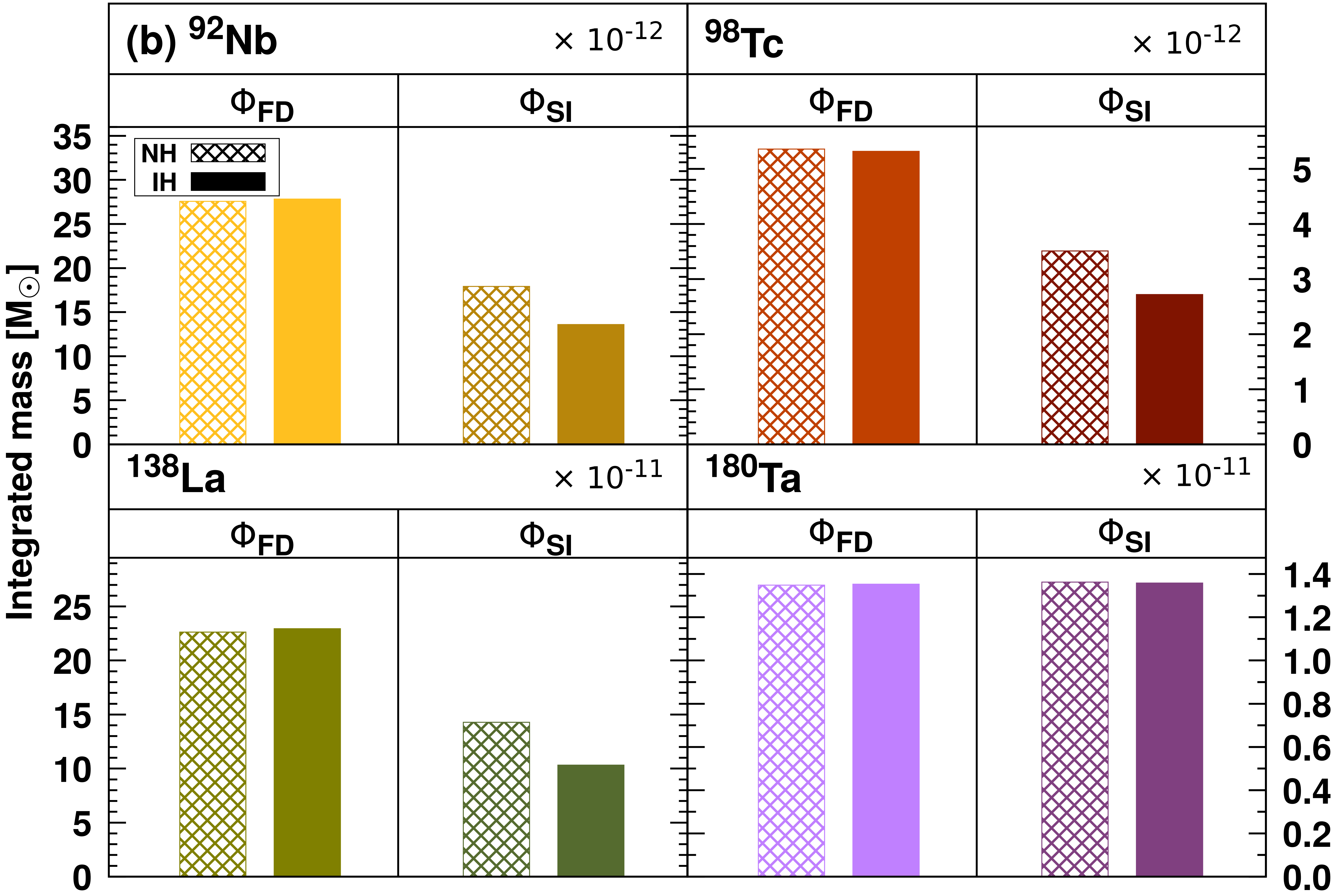
Light element abundances





4. Results - ^{92}Nb, ^{98}Tc, ^{138}La and ^{180}Ta

Integrated mass over whole region



Neutrino self-interaction potential

$$
\begin{aligned}
\mathcal{V}_{\rm eff}^{NC} &= \mathcal{V}_{\rm diagonal}^{NC} + \mathcal{V}_{\rm exchange}^{NC} \\
&= \sqrt{2} G_F \sum_\eta \int (1-\cos\theta_{\mathbf p}\cos\theta_{\mathbf q}) \left[\begin{pmatrix} \langle\nu_e|\nu_\eta(t)\rangle\langle\nu_\eta(t)|\nu_e\rangle & \langle\nu_e|\nu_\eta(t)\rangle\langle\nu_\eta(t)|\nu_\mu\rangle & \langle\nu_e|\nu_\eta(t)\rangle\langle\nu_\eta(t)|\nu_\tau\rangle \\ \langle\nu_\mu|\nu_\eta(t)\rangle\langle\nu_\eta(t)|\nu_e\rangle & \langle\nu_\mu|\nu_\eta(t)\rangle\langle\nu_\eta(t)|\nu_\mu\rangle & \langle\nu_\mu|\nu_\eta(t)\rangle\langle\nu_\eta(t)|\nu_\tau\rangle \\ \langle\nu_\tau|\nu_\eta(t)\rangle\langle\nu_\eta(t)|\nu_e\rangle & \langle\nu_\tau|\nu_\eta(t)\rangle\langle\nu_\eta(t)|\nu_\mu\rangle & \langle\nu_\tau|\nu_\eta(t)\rangle\langle\nu_\eta(t)|\nu_\tau\rangle \end{pmatrix} dn_{\nu_\eta} \right. \\
&\qquad \left. - \begin{pmatrix} \langle\bar\nu_e|\bar\nu_\eta(t)\rangle\langle\bar\nu_\eta(t)|\bar\nu_e\rangle & \langle\bar\nu_e|\bar\nu_\eta(t)\rangle\langle\bar\nu_\eta(t)|\bar\nu_\mu\rangle & \langle\bar\nu_e|\bar\nu_\eta(t)\rangle\langle\bar\nu_\eta(t)|\bar\nu_\tau\rangle \\ \langle\bar\nu_\mu|\bar\nu_\eta(t)\rangle\langle\bar\nu_\eta(t)|\bar\nu_e\rangle & \langle\bar\nu_\mu|\bar\nu_\eta(t)\rangle\langle\bar\nu_\eta(t)|\bar\nu_\mu\rangle & \langle\bar\nu_\mu|\bar\nu_\eta(t)\rangle\langle\bar\nu_\eta(t)|\bar\nu_\tau\rangle \\ \langle\bar\nu_\tau|\bar\nu_\eta(t)\rangle\langle\bar\nu_\eta(t)|\bar\nu_e\rangle & \langle\bar\nu_\tau|\bar\nu_\eta(t)\rangle\langle\bar\nu_\eta(t)|\bar\nu_\mu\rangle & \langle\bar\nu_\tau|\bar\nu_\eta(t)\rangle\langle\bar\nu_\eta(t)|\bar\nu_\tau\rangle \end{pmatrix} dn_{\bar\nu_\eta} \right] \\
&\equiv \sqrt{2} G_F \sum_\eta \int \left[\frac{L_{\nu_\eta}}{2\pi R_\nu^2} \frac{1}{\langle E_{\nu_\eta}\rangle} \frac{1}{(T_{\nu_\eta})^3 F_2(0)} \frac{E_\nu^2}{\exp(E_\nu/T_{\nu_\eta})+1} \rho(\mathbf q) \right. \\
&\qquad \left. - \frac{L_{\bar\nu_\eta}}{2\pi R_\nu^2} \frac{1}{\langle E_{\bar\nu_\eta}\rangle} \frac{1}{(T_{\bar\nu_\eta})^3 F_2(0)} \frac{E_\nu^2}{\exp(E_\nu/T_{\bar\nu_\eta})+1} \bar\rho(\mathbf q) \right] (1-\cos\theta_{\mathbf p}\cos\theta_{\mathbf q}) dE_\nu d(\cos\theta_{\mathbf q}) \\
&= \sqrt{2} G_F \sum_\eta \left[\int (1-\cos\theta_{\mathbf p}\cos\theta_{\mathbf q}) |\nu_\eta(t)\rangle\langle\nu_\eta(t)| dn_{\nu_\eta} - \int (1-\cos\theta_{\mathbf p}\cos\theta_{\mathbf q}) |\bar\nu_\eta(t)\rangle\langle\bar\nu_\eta(t)| dn_{\bar\nu_\eta} \right]. \qquad \text{(B27)}
\end{aligned}
$$

The luminosity values

time	$\mathcal{L}_{\nu_e}$	$\mathcal{L}_{\bar{\nu}_e}$	$\mathcal{L}_{\nu_x}$	$\langle E_{\nu_e} \rangle$	$\langle E_{\bar{\nu}_e} \rangle$	$\langle E_{\nu_x} \rangle$
[ms]	[10^{52} erg/s]			[MeV]		
50	6.5	6.0	3.6	9.3	12.2	16.5
100	7.2	7.2	3.6	10.5	13.3	16.5
200	6.5	6.5	2.7	13.3	15.5	16.5
300	4.3	4.3	1.7	14.2	16.6	16.5
500	4.0	4.0	1.3	16.0	18.5	16.5

Simulation data - Neutrino luminosity and averaged energy