Impact of neutrino oscillation on neutrino-process in the core-collapse supernovae

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In collaboration with

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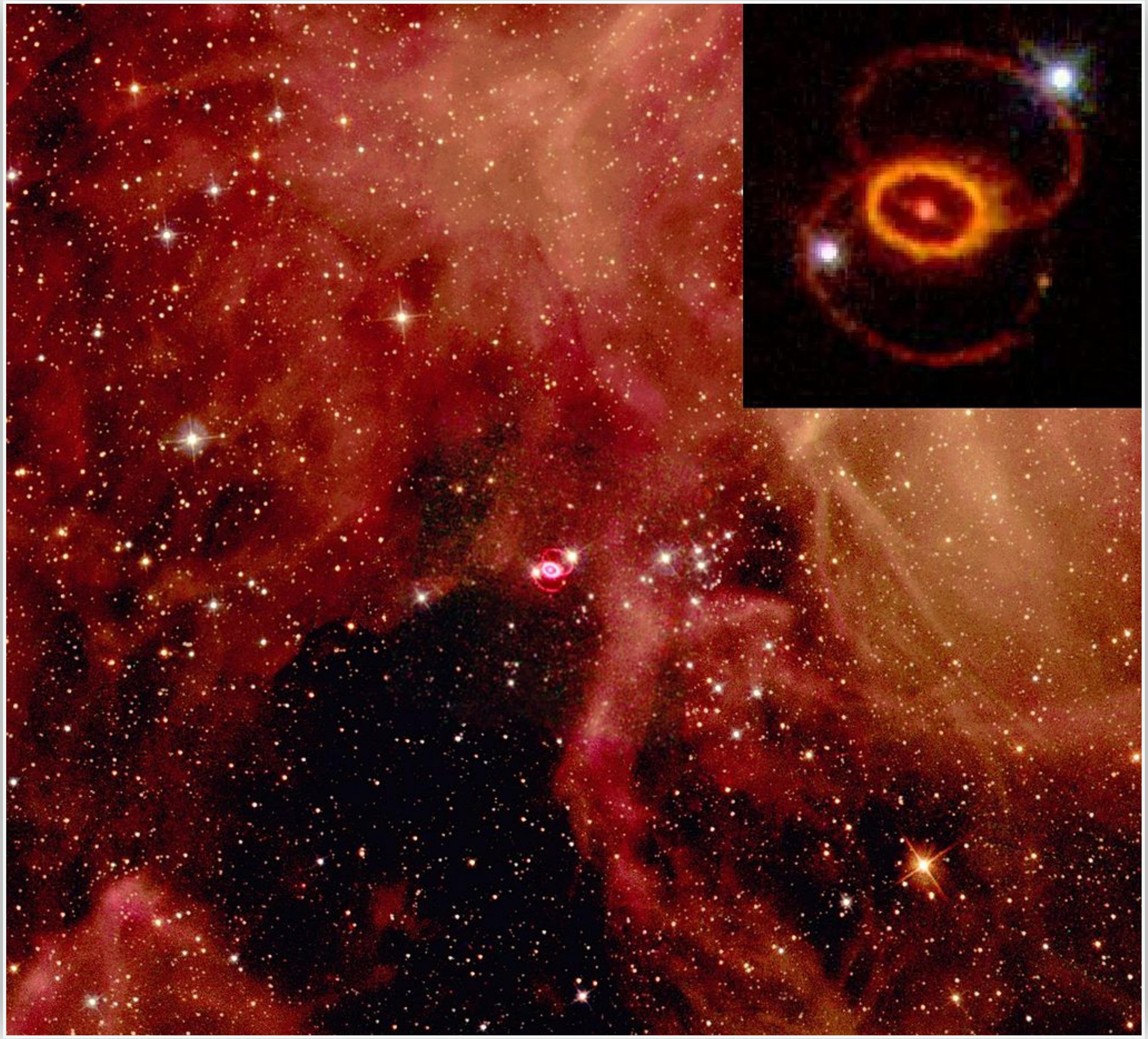
Contents

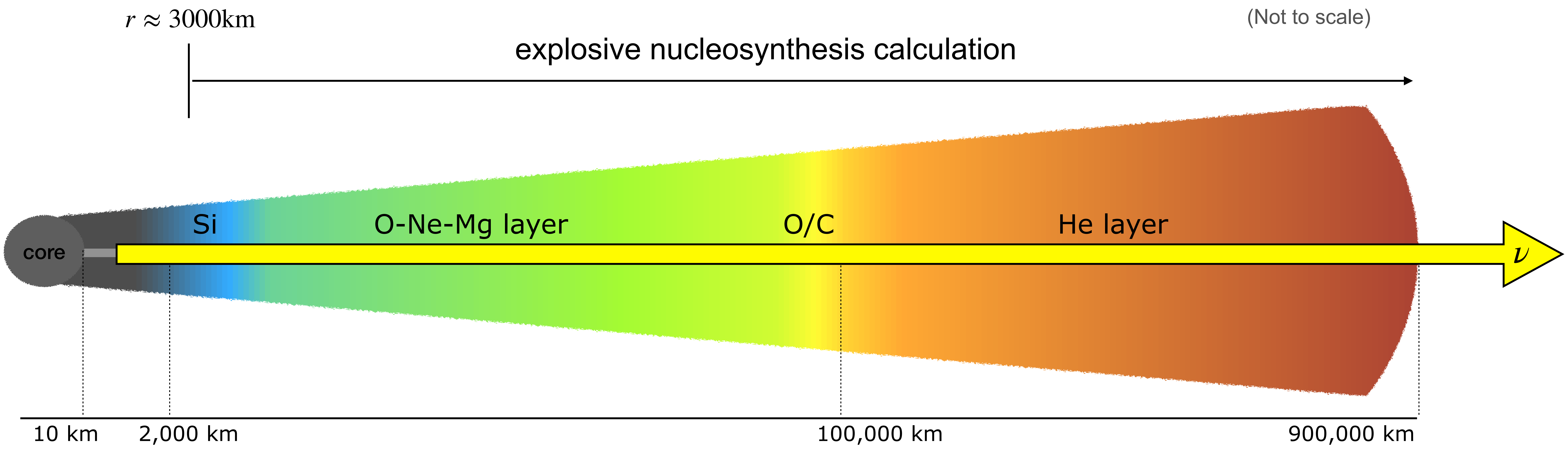
- Introduction
- Neutrino Oscillation
  - In vacuum
  - In electron medium
  - In neutrino gas
- Nucleosynthesis
  - Network calculation
  - Results
- Summary



Supernova 1987A in Large Magellanic Cloud by Hubble Space Telescope

Where do the neutrinos can play an important role?

Core-collapse supernova



Gravitational binding energy

$$\frac{3}{5}\frac{GM_{NS}^2}{R_{NS}} \approx 2\times 10^{59}\ \text{MeV}\left(\frac{M_{NS}}{1.4M_\odot}\right)^2\left(\frac{10\ \text{km}}{R_{NS}}\right)$$

release to neutrino →

If $\langle E_\nu \rangle \sim 10\text{MeV}$,

# of neutrinos $\sim 10^{58}$

↔

ν-nucleus cross section

$\sigma_\nu \sim 10^{-42}\ \text{cm}^2$

Neutrino eigenstates

- **Neutrino flavor basis**

$$|\nu_\alpha\rangle = \sum_k U_{\alpha k} |\nu_k\rangle$$

Flavor eigenstate Mass eigenstate

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

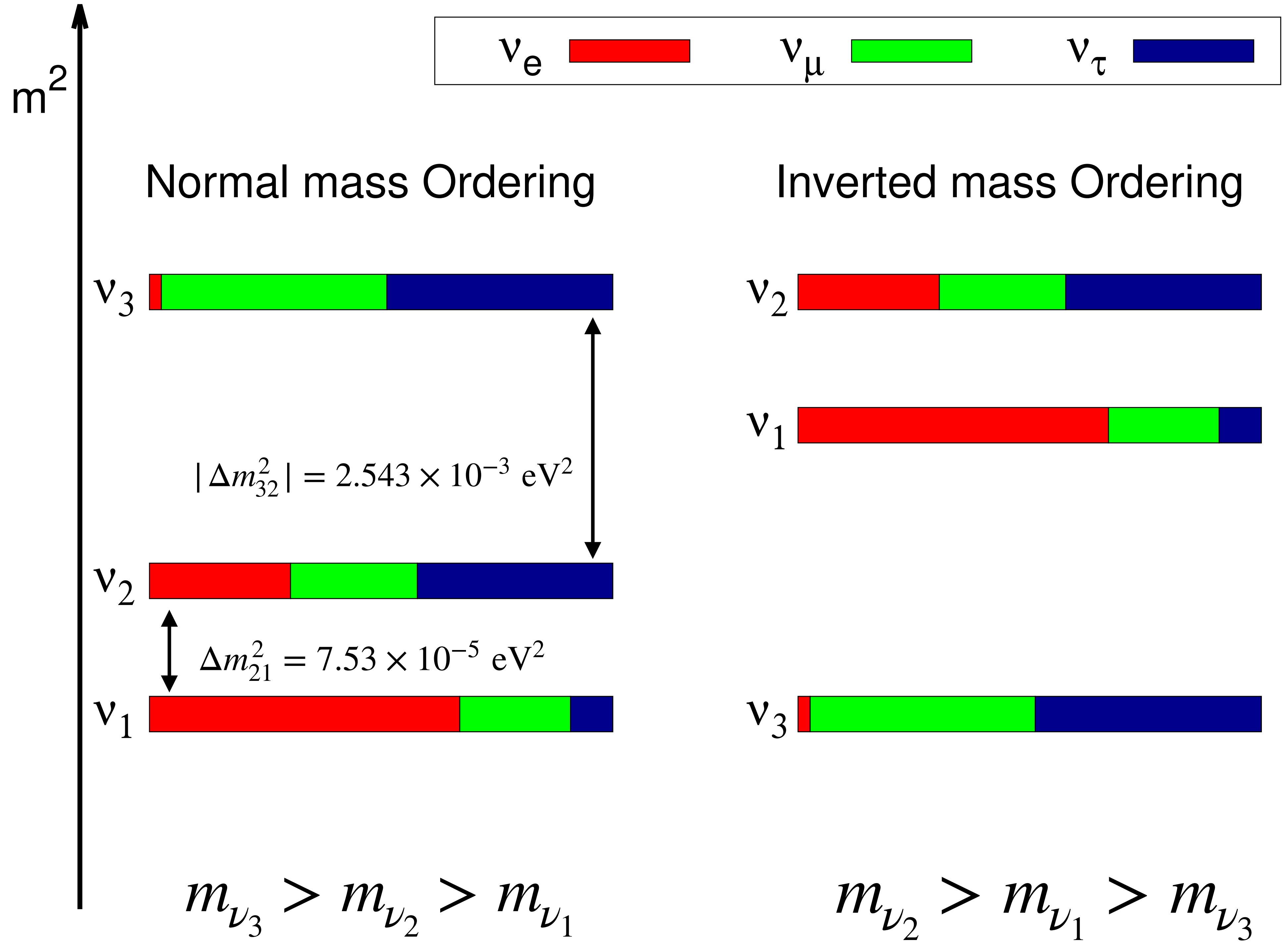
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} \\ 0 & 1 & 0 \\ -\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12}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

$$\delta_{cp} = 0$$

Neutrino mixing parameters

P.A. Zyla et al. (PDG), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

- Mass Ordering (Hierarchy)



still unsolved

Neutrino oscillation in vacuum

- **Neutrino hamiltonian in vacuum**

$$E_i = \sqrt{p_\nu^2 + m_i^2} \approx E_\nu + \frac{m_i^2}{2E_\nu} \quad \& \quad H_{\text{vacuum}} = U\text{diag}\left(0, \frac{\Delta m_{21}^2}{2E_\nu}, \frac{|\Delta m_{31}^2|}{2E_\nu}\right) U^\dagger$$

Ultrarelativistic

Neutrino equation of motion $\nu_\alpha \to \nu_\beta$

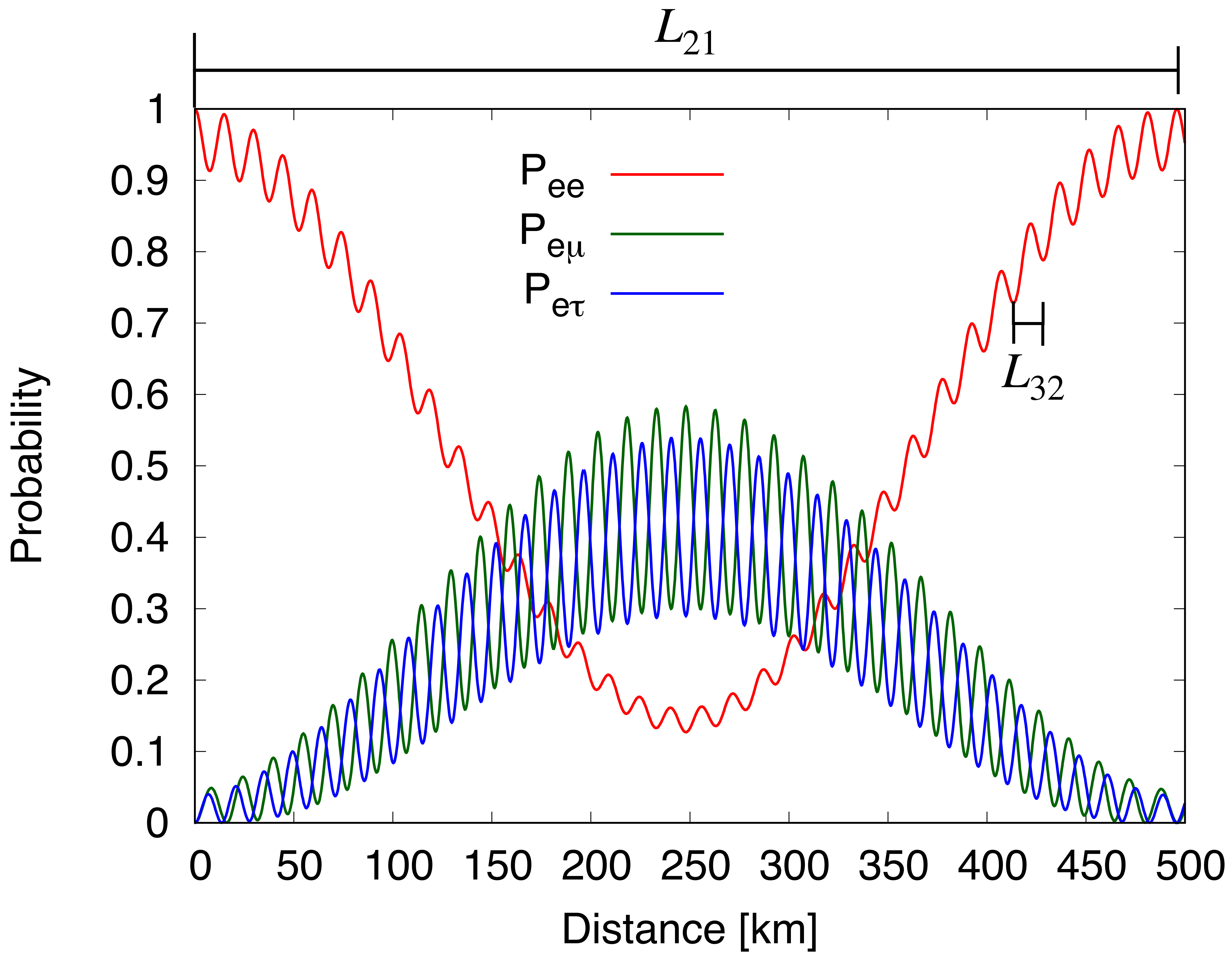
$$i\frac{d}{dt}\psi_{\nu_\alpha \to \nu_\beta} = H_{\text{Vacuum}}\psi_{\nu_\alpha \to \nu_\beta}$$

Neutrino oscillation length

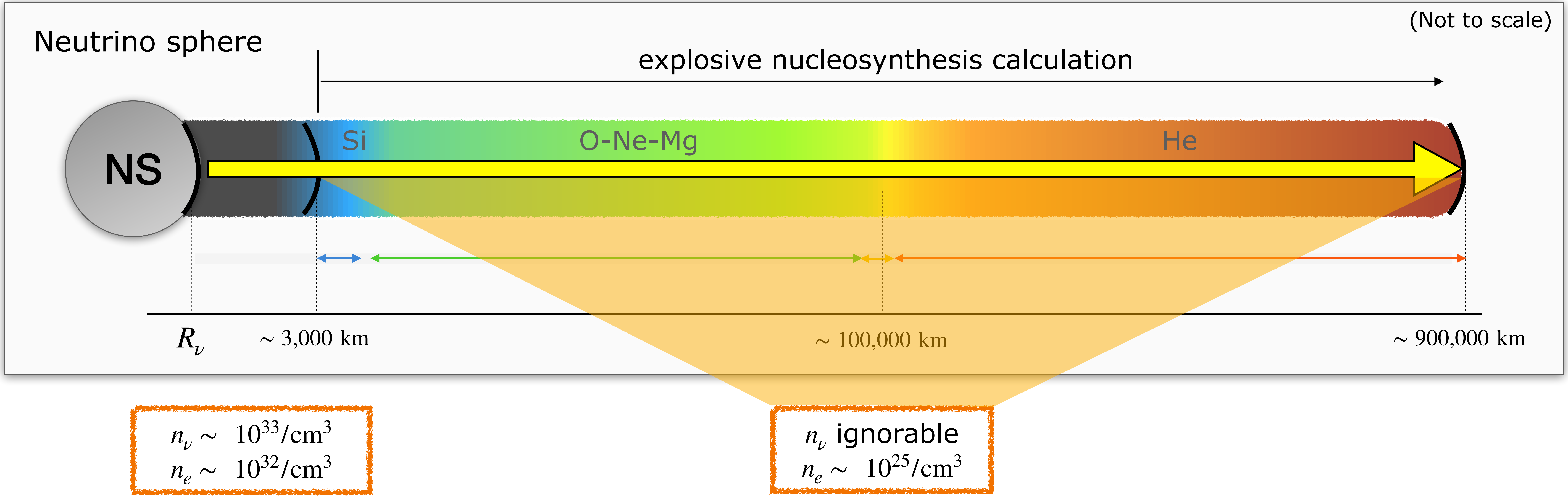
$$L_{osc}(\text{km}) = 7.88\pi \times 10^{-4} \times \left(\frac{E_\nu}{\text{MeV}}\right)\left(\frac{\text{eV}^2}{\Delta m_{ij}^2}\right)$$

$$L_{21} \sim 493 \text{ [km]}$$

$$L_{32} \sim 14.6 \text{ [km]}$$



Neutrino oscillation in star

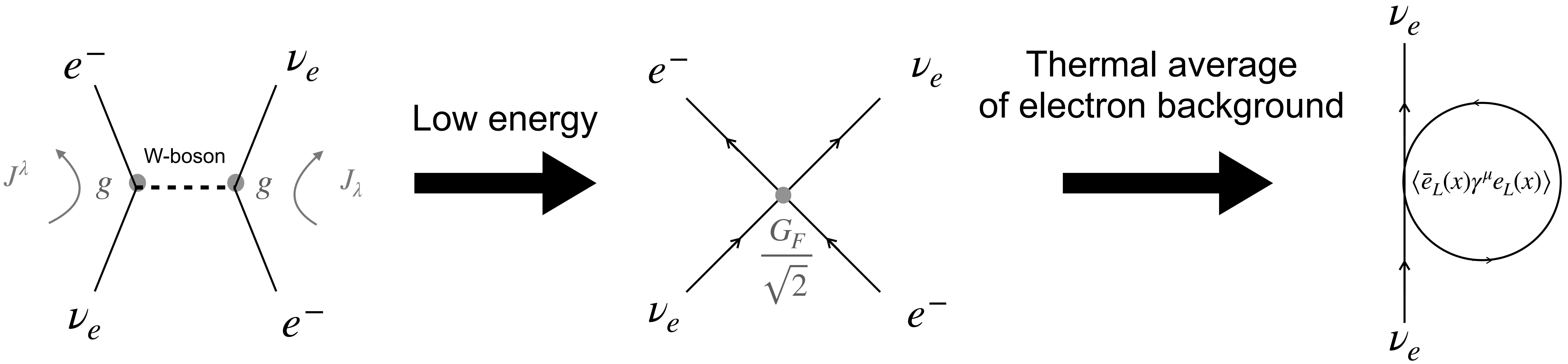


- Neutrino-electron (charged current interaction)
- Neutrino-neutrino (neutral current interaction)
- Neutrino-nucleus (charged and neutral current interaction)

Neutrino-electron interaction

- **Effective charged current hamiltonian**

$$\mathscr{H}^{CC}_{\mathrm{eff}}(x) = J_e^{\lambda} J_{\lambda,\nu}$$



The interaction potential is proportional to electron number density

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

The electron number density is given by SN model

$$n_e = \frac{\rho_b Y_e}{m_u} = N_A \rho_b Y_e \qquad Y_e \sim 0.5$$

Mikheyev–Smirnov–Wolfenstein (MSW) effect

- **Hamiltonian (vacuum+matter)**

$$H_{tot} = H_{\text{vacumm}} + V_{\text{eff}}^{CC}$$

Example for two flavor

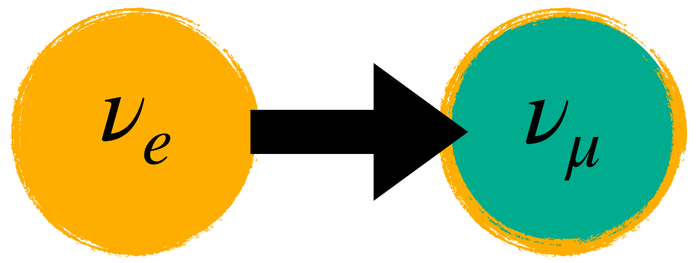
$$H_{tot} = U \begin{pmatrix} \frac{\Delta m^2}{2E_\nu} & 0 \\ 0 & \frac{\Delta m^2}{2E_\nu} \end{pmatrix} U^\dagger + \begin{pmatrix} \sqrt{2} G_F n_e & 0 \\ 0 & 0 \end{pmatrix}$$

Equation of motion - Schrödinger like equation

If $H_{\text{Vacuum}} \approx V_{\text{matter}}$ 0

$$i \frac{d}{dt} \begin{pmatrix} \psi_{\nu_{ee}}(t) \\ \psi_{\nu_{e\mu}}(t) \end{pmatrix} = H_{tot} \begin{pmatrix} \psi_{\nu_{ee}}(t) \\ \psi_{\nu_{e\mu}}(t) \end{pmatrix} = \frac{1}{2} \begin{pmatrix} -\frac{\Delta m_{21}^2}{2E_\nu} \cos 2\theta_{12} + \sqrt{2} G_F n_e & \frac{\Delta m_{21}^2}{2E_\nu} \sin 2\theta_{12} \\ \frac{\Delta m_{21}^2}{2E_\nu} \sin 2\theta_{12} & \frac{\Delta m_{21}^2}{2E_\nu} \cos 2\theta_{12} - \sqrt{2} G_F n_e \end{pmatrix} \begin{pmatrix} \psi_{\nu_{ee}}(t) \\ \psi_{\nu_{e\mu}}(t) \end{pmatrix}$$

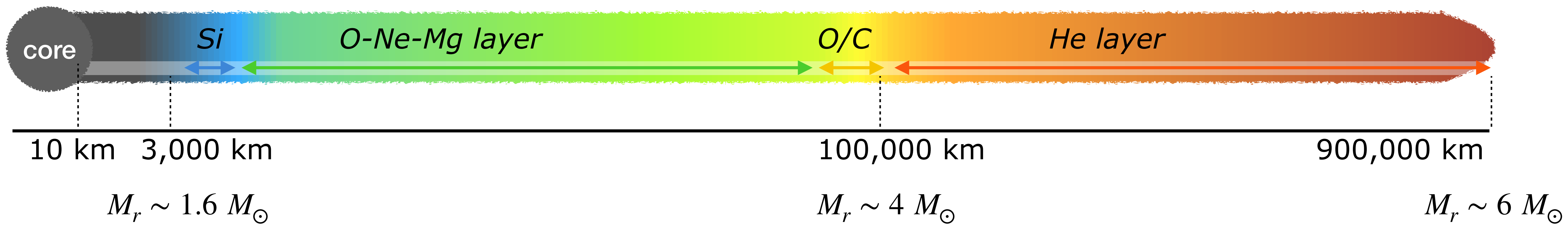
$$i\dot{\Psi}_{\nu_{ee}} = 0\Psi_{\nu_{ee}} + c\Psi_{\nu_{e\mu}}$$



All electron neutrinos are converted into muon neutrinos = **MSW resonance**

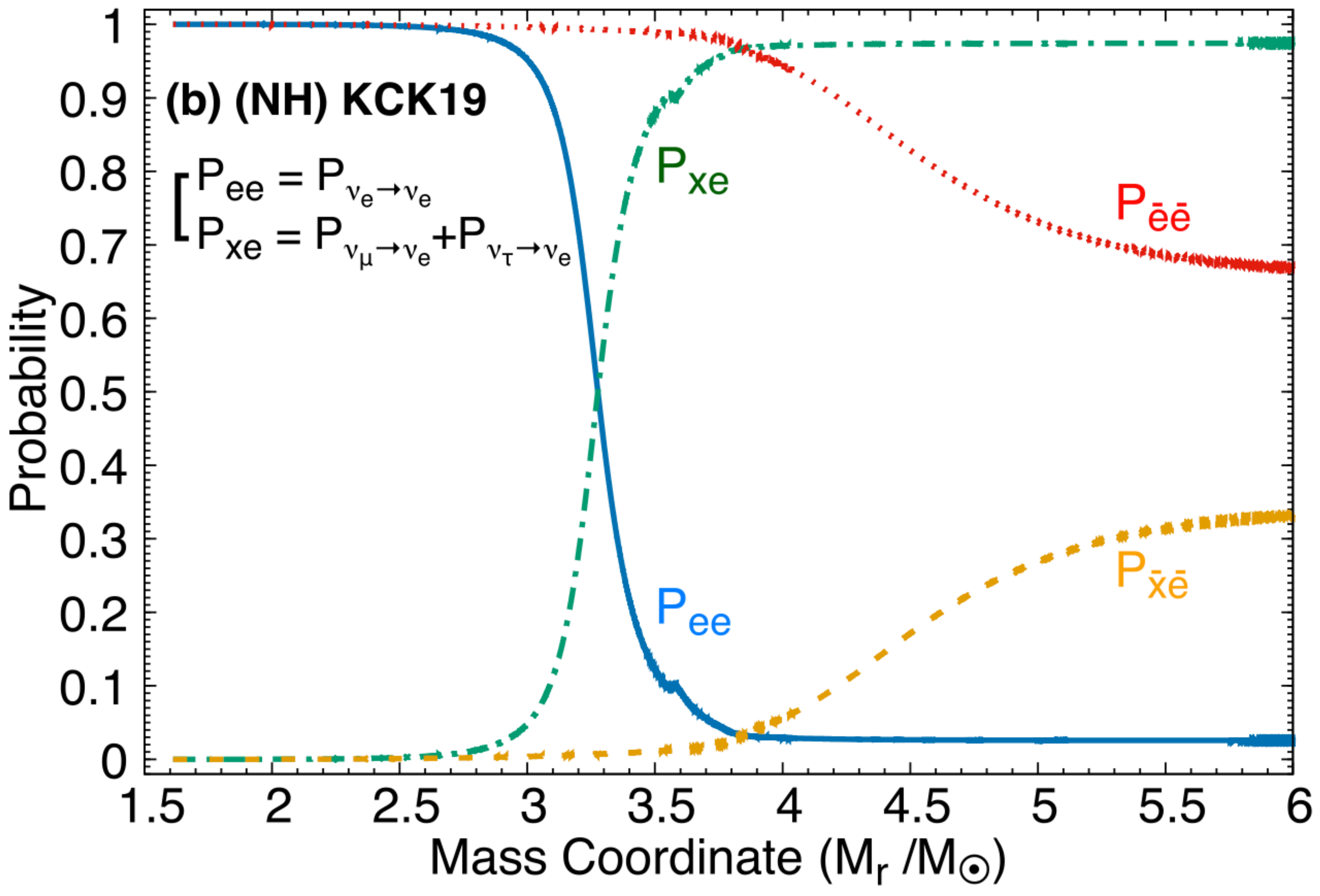
Flavor change probability - Vacuum + electron medium

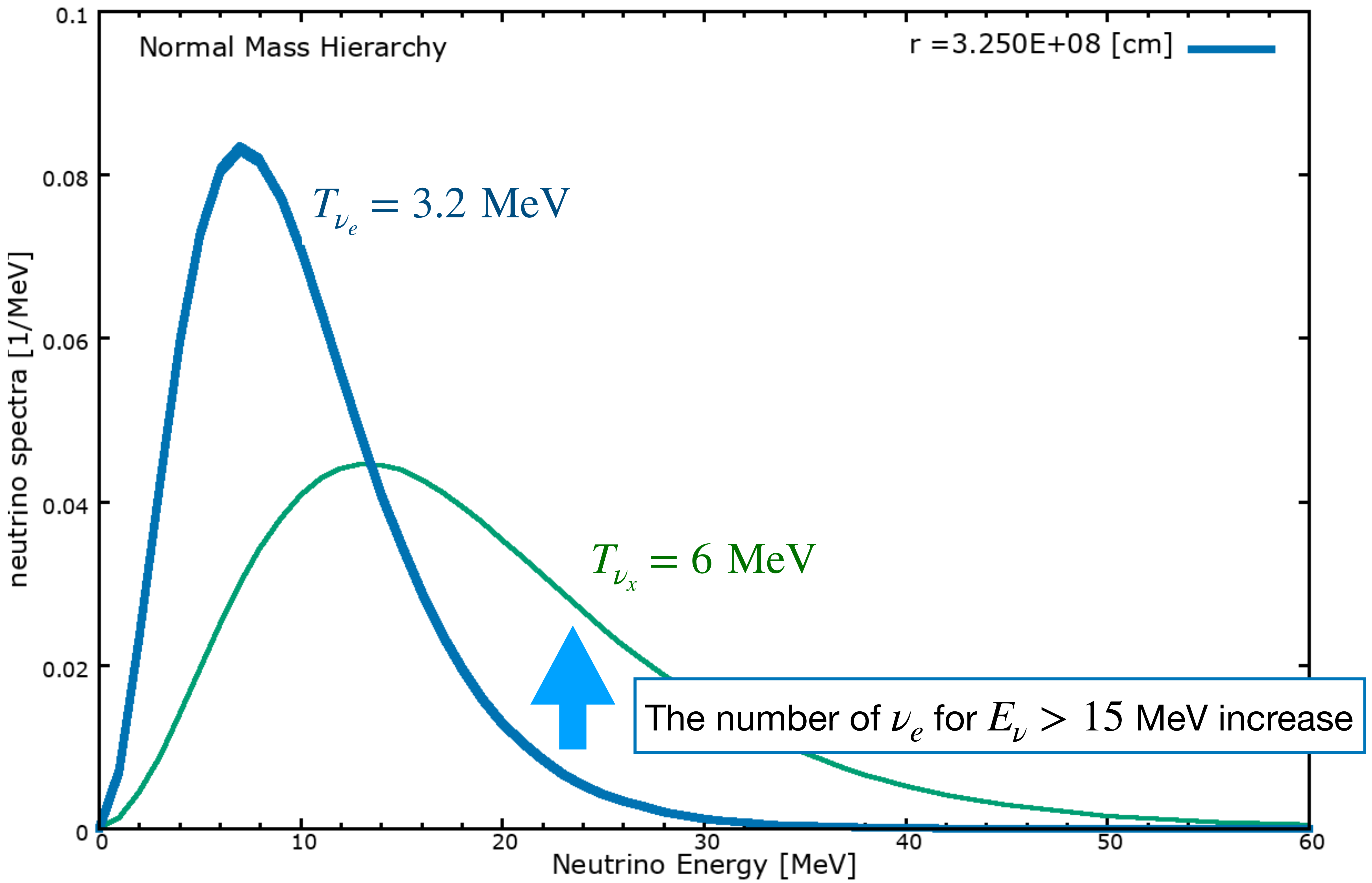
- **MSW effect**



Neutrino energy distribution

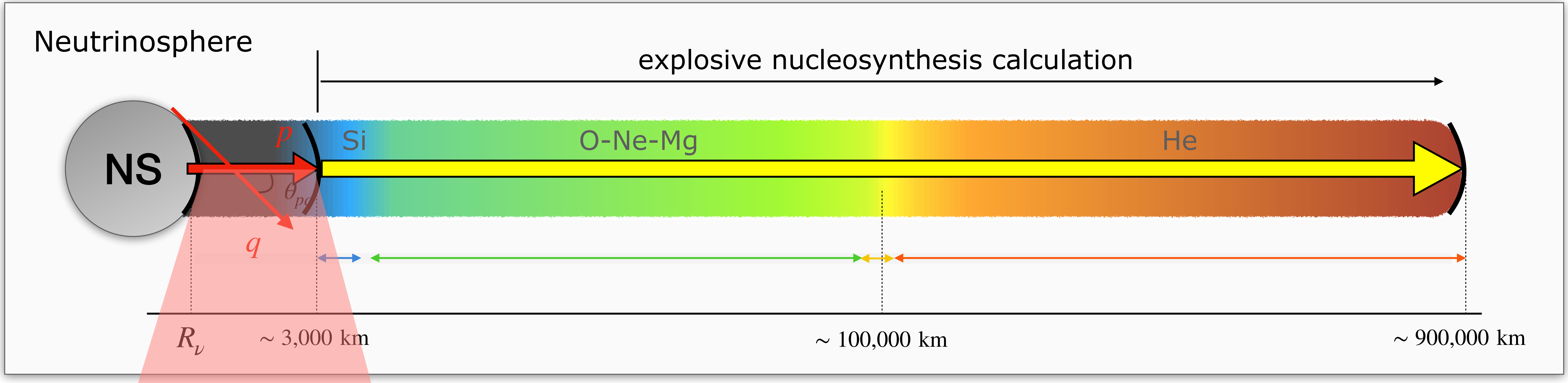
$$f(E,T) = \frac{1}{F_2(0)T_\nu^3} \sum_\beta \frac{E_\nu^2}{\exp(E_\nu/T_{\nu_\beta})+1} P_{\nu_\beta \to \nu_\alpha}(E_\nu, r)$$





$$F_2(0)T_\nu^3 = \int_0^\infty \frac{E_\nu^2}{\exp(E_\nu/T_{\nu_\alpha})+1} dE_\nu$$

Neutrino-neutrino interaction



Neutrino propagation with momentum p

Neutrino-neutrino interaction

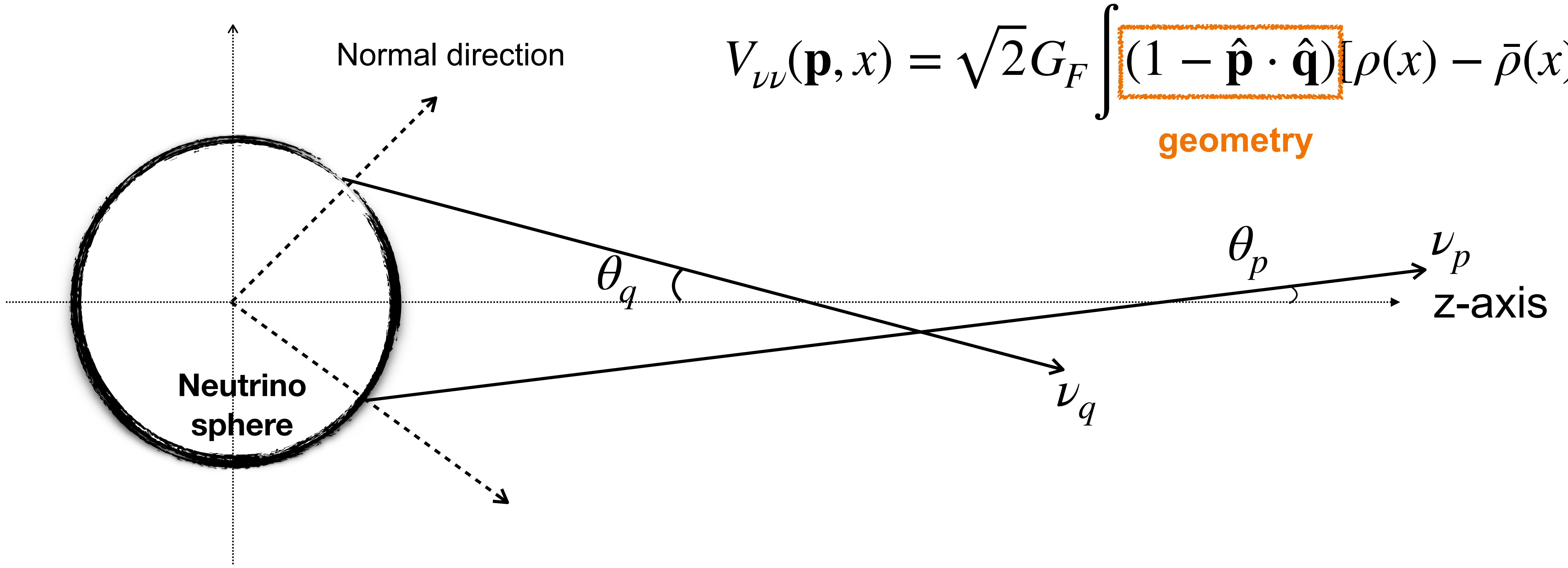
Neutrino-electron interaction

$$H_{tot} = H_{\text{vacumm}} + V_{\text{eff}}^{CC} + V_{\nu\nu}^{NC}$$

Neutrino bulb model *H. Duan et al. PRD 74, 105014 (2006)*

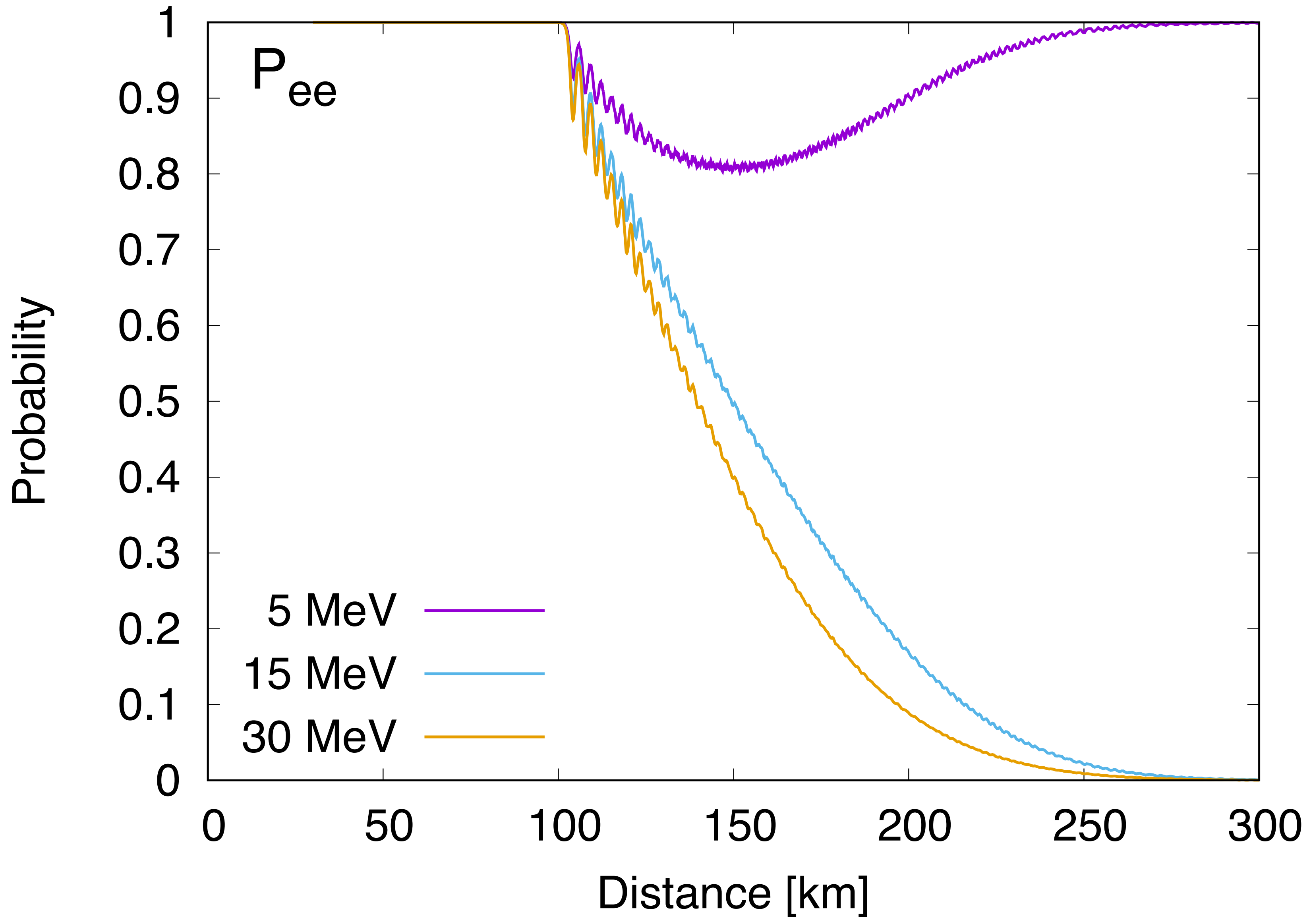
$$V_{\nu\nu}(\mathbf{p}, x) = \sqrt{2} G_F \int (1 - \hat{\mathbf{p}} \cdot \hat{\mathbf{q}}) [\rho(x) - \bar{\rho}(x)] d^3\mathbf{q}$$

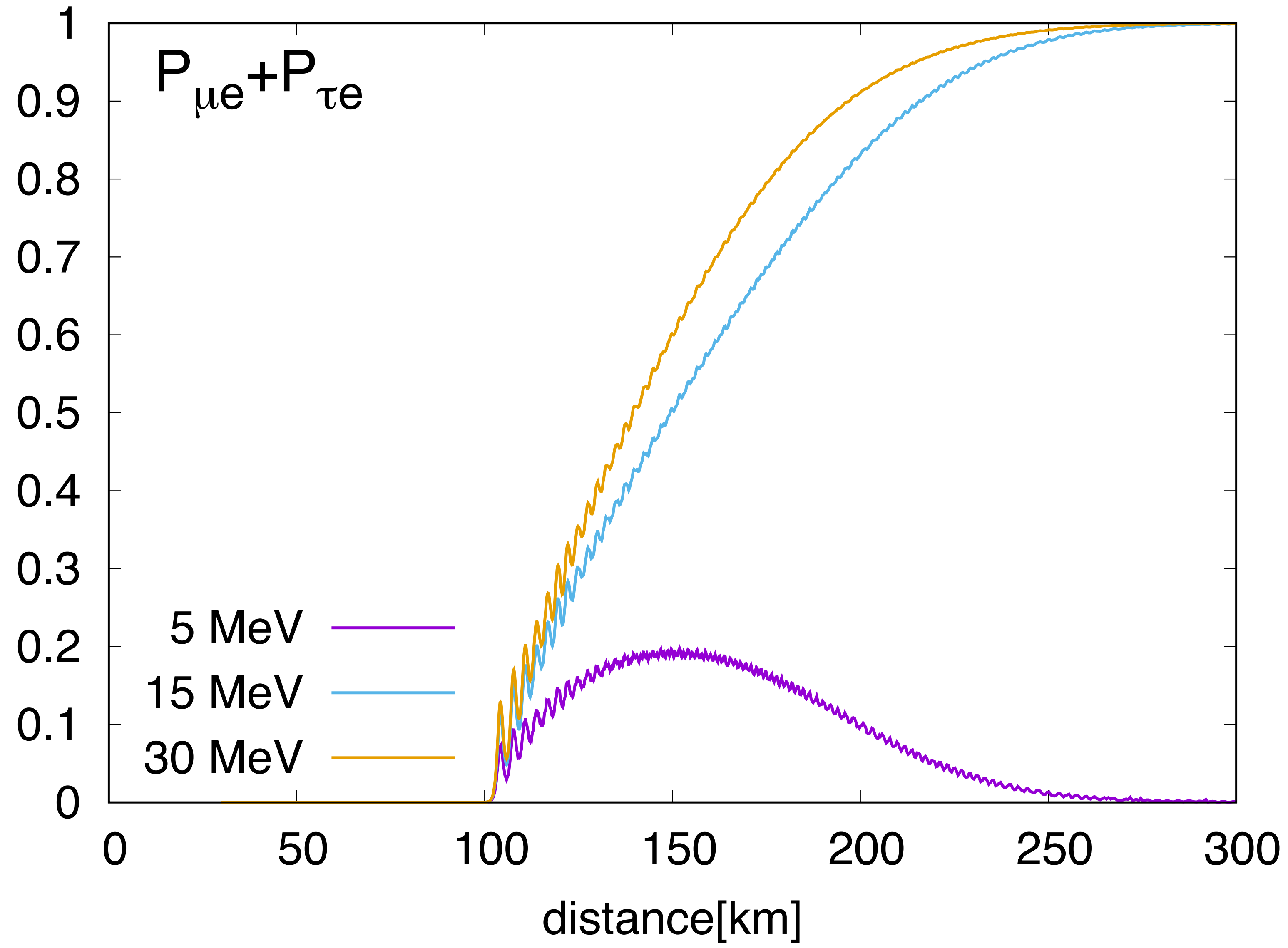
geometry



Flavor change probability - Vacuum + $\nu_e e$ + $\nu\nu$

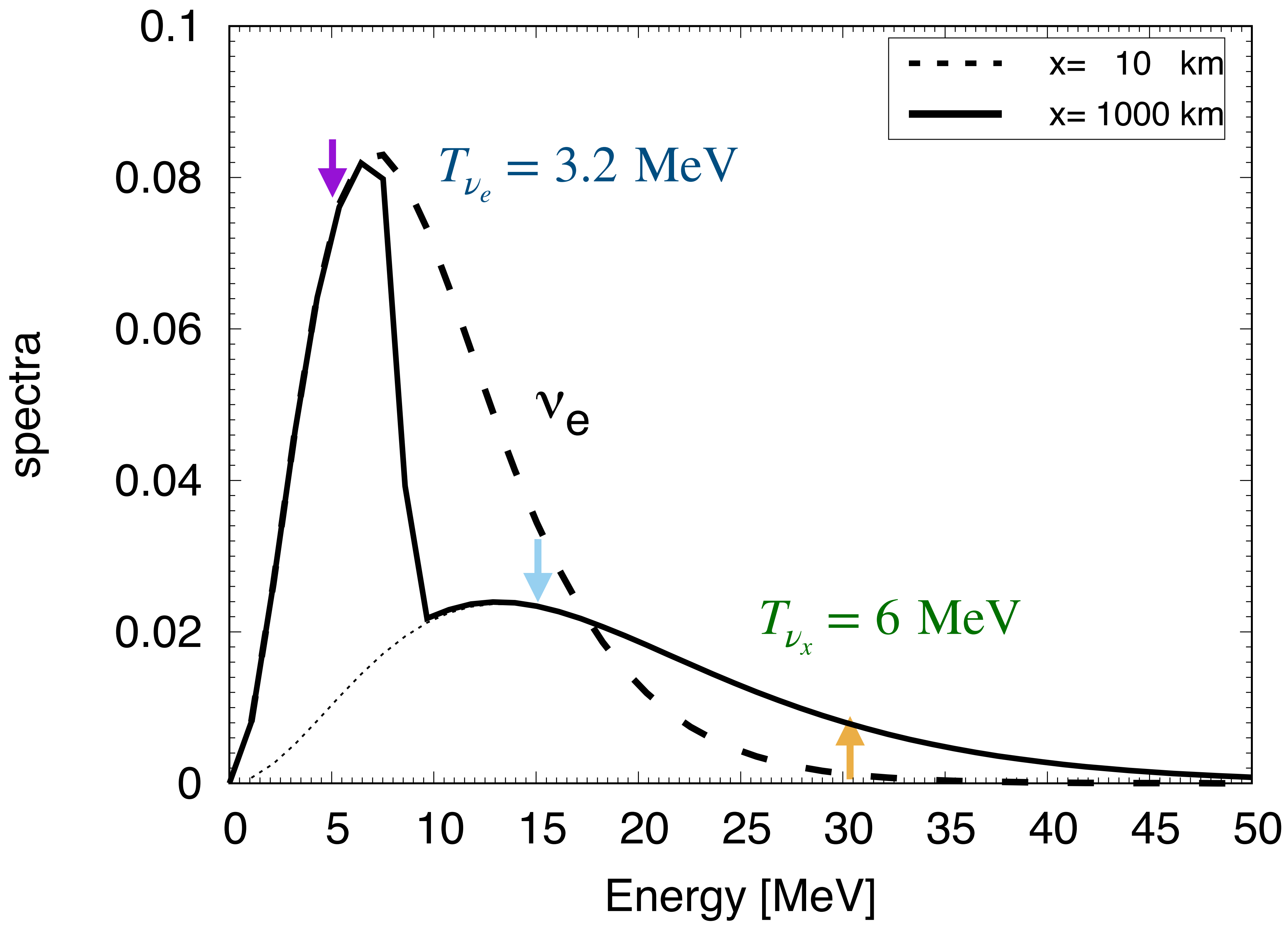
- **Single-angle approximation** ($(1 - \hat{\mathbf{p}} \cdot \hat{\mathbf{q}}) = (1 - \cos\theta_p \cos\theta_q) \approx 1 - \cos\theta_q$)





Neutrino energy distribution

$$f(E,T) = \frac{1}{F_2(0)T_\nu^3} \sum_\beta \frac{E_\nu^2}{\exp(E_\nu/T_{\nu_\beta}) + 1} P_{\nu_\beta \to \nu_\alpha}(E_\nu, r)$$



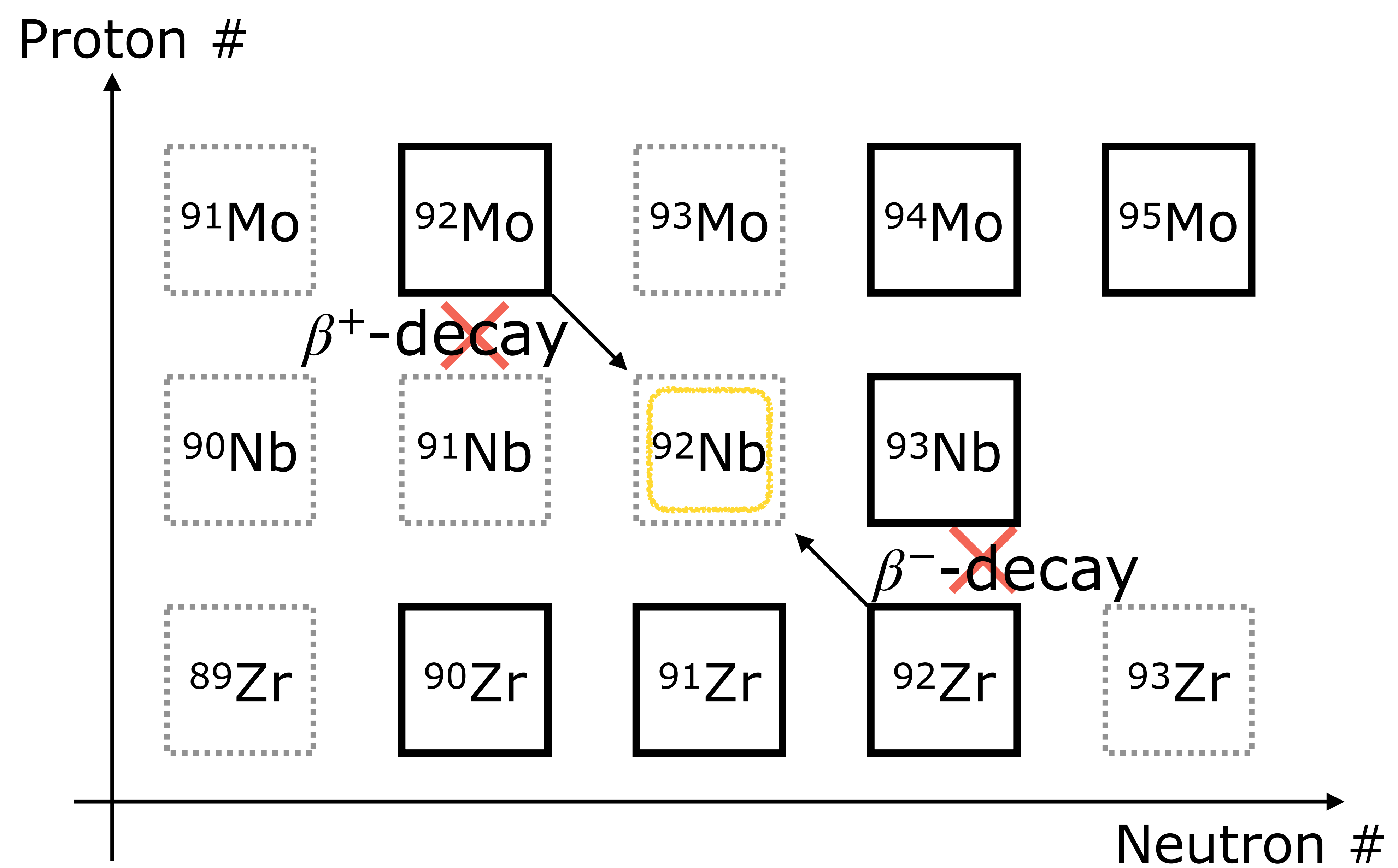
$P_{ee} \to 1$ at $E_\nu < 8$MeV

$P_{ee} \to 0$ at $E_\nu > 10$MeV

Spectral splitting appear by including ν-ν interaction

A role of neutrino oscillation on neutrino-process

- **Why the neutrino flavor change probabilities are important?**



$$^{92}\mathrm{Zr} + \nu_e \rightarrow {}^{92}\mathrm{Nb} + e^-$$

Short-lived radioactive nuclides

$^{92}\mathrm{Nb}$ ($\tau_{1/2} \sim 34.7$ Myr); T. Hayakawa, et al. ApJL (2013)

$^{98}\mathrm{Tc}$ ($\tau_{1/2} \sim 4.2$ Myr); T. Hayakawa, et al., PRL (2018)

Long-lived radioactive nuclides

$^{138}\mathrm{La}$ ($\tau_{1/2} \sim 102$ Gyr); S. E. Woosley et al. APJ (1990)
A. Heger et al. PLB (2005)

Neutrino-induced reactions rate λ_{ν_e} [#/s]

$$\lambda_{\nu_e}(r) \propto \sigma_{\nu_e}\phi_\nu = \int_0^\infty \frac{d\phi}{dE_\nu}\sigma_{\nu_e}(E_\nu)\, dE_\nu$$

Neutrino differential flux

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

Neutrino energy distribution (FD distribution)

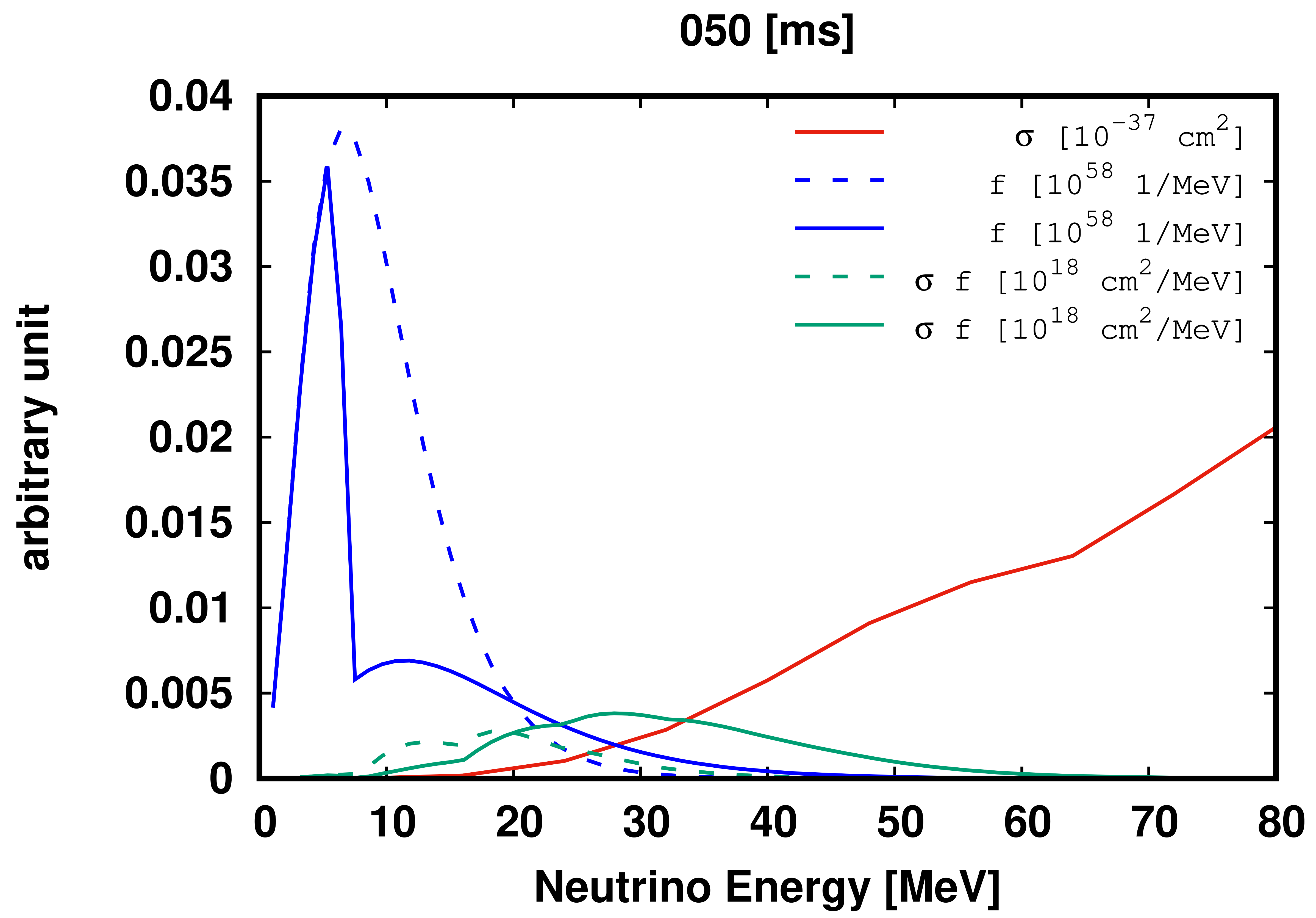
$$f(E_\nu, T_\nu) = P_{\nu_\beta \to \nu_\alpha}(r, E_\nu)\frac{1}{F_2(0)T_\nu^3}\frac{E_\nu^2}{\exp(E_\nu/T_{\nu_\alpha}) + 1}$$

neutrino oscillation

A role of neutrino oscillation on neutrino-process

- **Neutrino reaction rates**

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



Multi-angle/NEQ

Neutrino-induced reactions rate λ_{ν_e}

$$\lambda_{\nu_e}(r) \propto \sigma_{\nu_e}\phi_\nu = \int_0^\infty \frac{d\phi}{dE_\nu}\sigma_{\nu_e}(E_\nu)\, dE_\nu$$

Neutrino differential flux

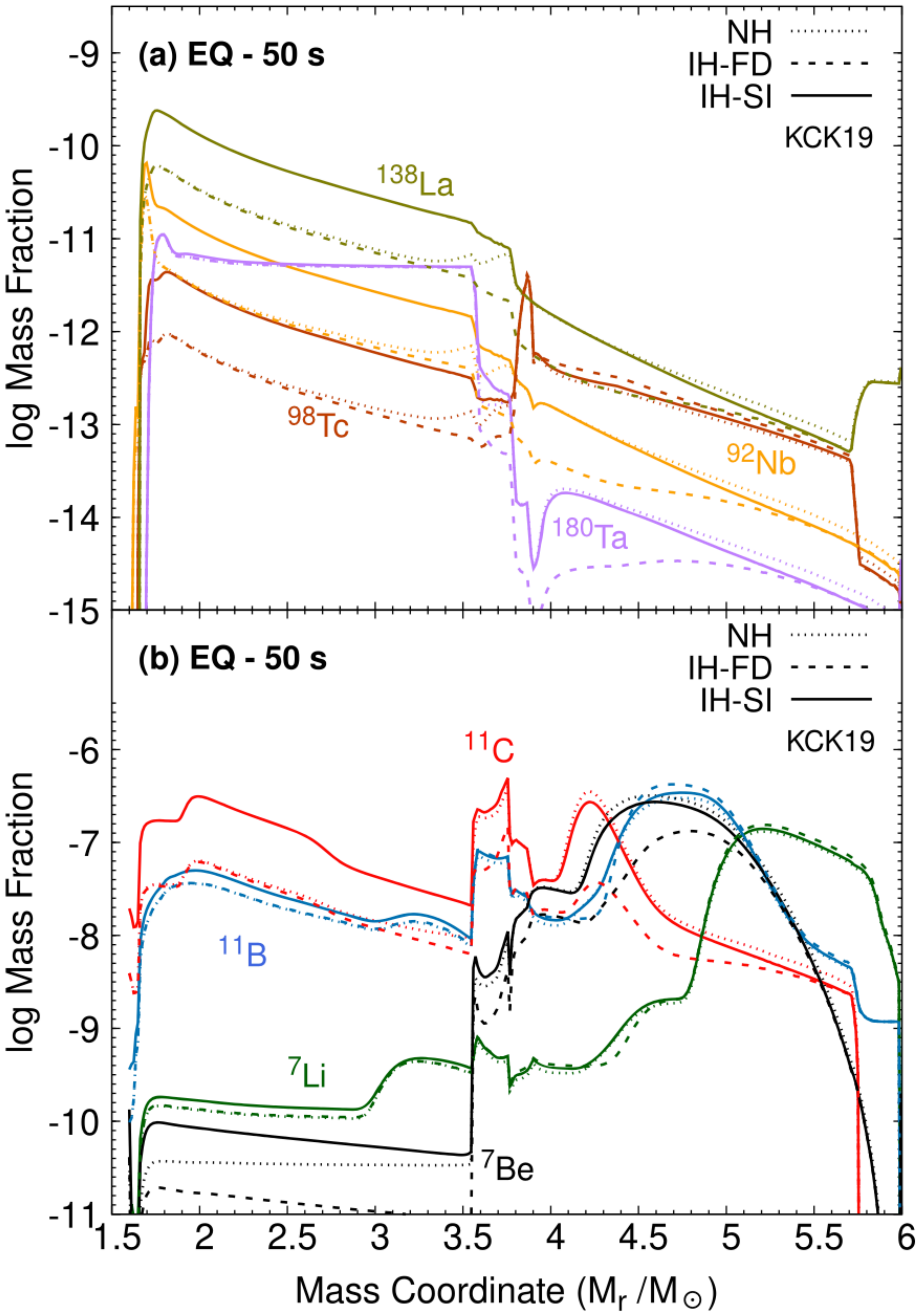
$$\frac{d}{dE_\nu}\phi_{\nu_\alpha}(t, r; E_\nu, T_{\nu_\alpha}) = \frac{1}{4\pi r^2}\frac{L_{\nu_\alpha}(t)}{\langle E_{\nu_\alpha}(t)\rangle} f(E_{\nu_e}, T_{\nu_e}; \langle \lambda_e \rangle)$$

Neutrino energy distribution (FD distribution)

$$f(E_\nu, T_\nu) = P_{\nu_\beta \rightarrow \nu_\alpha}(r, E_\nu)\frac{1}{F_2(0)T_\nu^3}\frac{E_\nu^2}{\exp(E_\nu/T_{\nu_\alpha}) + 1}$$

Neutrino oscillation -> different neutrino reaction rates -> abundance change

Abundance at 50 s



Main production reactions

Heavy element

- $^{138}\mathrm{Ba} + \nu_e \rightarrow {}^{138}\mathrm{La} + e^-$
- $^{98}\mathrm{Mo} + \nu_e \rightarrow {}^{98}\mathrm{Tc} + e^-$
- $^{92}\mathrm{Zr} + \nu_e \rightarrow {}^{92}\mathrm{Nb} + e^-$

Light element (He-layer; $M_r > 4M_\odot$)

- $^4\mathrm{He}(\nu, \nu' n)^3\mathrm{He}(\alpha, \gamma)^7\mathrm{Be}$
- $^4\mathrm{He}(\nu_e, e^- p)^3\mathrm{He}(\alpha, \gamma)^7\mathrm{Be}$

- $^4\mathrm{He}(\nu, \nu' p)^3\mathrm{H}(\alpha, \gamma)^7\mathrm{Li}$
- $^4\mathrm{He}(\bar{\nu}_e, e^+ n)^3\mathrm{H}(\alpha, \gamma)^7\mathrm{Li}$

NH

$m_{\nu_3} > m_{\nu_2} > m_{\nu_1}$

IH

$m_{\nu_2} > m_{\nu_1} > m_{\nu_3}$

Results and conclusion

Table 4. integrated masses of nuclei after 50 s in the rage $M_r = 1.6$–6 ($M_\odot$)

	Mass Hierarchy	^{7}Li	^{7}Be	^{11}B	^{11}C	^{92}Nb	^{98}Tc	^{138}La	^{180}Ta	Yield ratio	PF ratio
		(10^{-7} $M_\odot$)				(10^{-12} $M_\odot$)		(10^{-11} $M_\odot$)		N(^{7}Li)/N(^{11}B)	^{138}La/^{11}B
FD EQ (KCK19)	NH	0.979	2.568	2.580	2.207	4.591	1.203	3.806	1.017	1.165	0.2299
	IH	1.166	0.973	3.269	0.893	4.256	1.245	3.471	1.012	0.808	0.2412
FD EQ Shock (KCK19)	NH	0.983	1.951	2.669	1.847	5.262	1.348	4.441	1.019	1.021	0.2844
	IH	1.080	1.083	3.074	0.948	4.293	1.237	3.508	1.013	0.845	0.2522
SI EQ[a] (KCK19)	NH	0.979	2.568	2.580	2.207	4.591	1.203	3.806	1.017	1.165	0.2299
	IH	1.054	2.162	2.971	3.945	15.19	3.303	13.71	1.053	0.731	0.5732
SI NEQ (KCK19)	NH	1.164	1.620	4.256	4.848	16.42	3.548	15.05	1.294	0.481	0.4780
	IH	1.298	1.217	4.607	4.212	12.31	2.855	11.21	1.281	0.448	0.3676
FD NEQ (KCK19)	NH	1.526	0.847	5.393	5.174	25.25	5.321	22.81	1.322	0.353	0.6242
	IH	0.986	2.339	3.923	6.483	25.93	5.250	23.59	1.330	0.502	0.6555

$$\frac{^7\mathrm{Li}_\nu}{^{11}\mathrm{B}_\nu} < 0.53 \ (2\sigma\ 95\,\%\,\mathrm{C.L.})$$

Meteorite data analysis

G. J. Mathews et al., Phys. Rev. D 85,105023 (2012)

$$R_{exp}\left(\frac{^{138}\mathrm{La}}{^{11}\mathrm{B}}\right) = 0.41^{+0.21}_{-0.42}$$

Expectation ratio

Summary

- The neutrino during the supernova explosion plays a key role to produce the elements (^{92}Nb, ^{98}Tc, and ^{138}La).

- Neutrino oscillates in the star interacting with electron and neutrinos. As a result, the each neutrino energy distribution are change.

- The neutrino oscillation calculation has a dependency not only on <u>neutrino mass hierarchy</u> but also on the SN condition ($n_e, L_\nu,$ and $\langle E_\nu \rangle$).

- The elements today presented are produced by <u>$\nu-$process and sensitive to the ν_e flux</u> due to the charged current reaction.

- We compare the <u>meteorite data ^{7}Li/^{11}B</u> and <u>expected ratio of ^{138}La/^{11}B</u> in our solar system to our model.

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Comprehensive Analysis of the Neutrino Process in Core-collapsing Supernovae

Heamin Ko[1], Dukjae Jang[2], Myung-Ki Cheoun[1,3,4], Motohiko Kusakabe[3,4], Hirokazu Sasaki[4,5,6], Xingqun Yao[3], Toshitaka Kajino[3,4,5], Takehito Hayakawa[7,8], Masaomi Ono[9], Toshihiko Kawano[6], and Grant J. Mathews[3,4,10]

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Thank You

BACK UP

Expectation ratio of 138La/11B

$$R_{\text{expect}} = f_{\text{metal}} \frac{f_{^{138}\text{La}}}{f_{^{11}\text{B}}} \longleftarrow \quad f_{\text{metal}} = \frac{1}{4} \; (\because Z = Z_\odot/4) \;\; \& \;\; f_{^{138}\text{La}} = 1$$

The contributed fraction of ^{11}B by SN to solar abundance

$$\left(\frac{^{11}\text{B}}{^{10}\text{B}}\right)_\odot = \left(\frac{^{11}\text{B}_{SN} + {}^{11}\text{B}_{CR}}{^{10}\text{B}_{SN} + {}^{10}\text{B}_{CR}}\right) \quad \& \quad {}^{10}\text{B}_{SN} \approx 0 \quad \Rightarrow \quad {}^{10}\text{B}_\odot \approx {}^{10}\text{B}_{CR}$$

$$1 = \frac{\left(\frac{^{11}\text{B}_{SN}}{^{10}\text{B}_{CR}}\right)}{\left(\frac{^{11}\text{B}}{^{10}\text{B}}\right)_\odot} + \frac{\left(\frac{^{11}\text{B}_{CR}}{^{10}\text{B}_{CR}}\right)}{\left(\frac{^{11}\text{B}}{^{10}\text{B}}\right)_\odot} = \frac{^{11}\text{B}_{SN}}{^{11}\text{B}_\odot} + \frac{\left(\frac{^{11}\text{B}_{CR}}{^{10}\text{B}_{CR}}\right)}{\left(\frac{^{11}\text{B}}{^{10}\text{B}}\right)_\odot} = f^{SN}_{^{11}\text{B}} + \frac{\left(\frac{^{11}\text{B}_{CR}}{^{10}\text{B}_{CR}}\right)}{\left(\frac{^{11}\text{B}}{^{10}\text{B}}\right)_\odot} \longleftarrow$$

Silberberg & Tsao 1990

$$\left(\frac{^{11}\text{B}}{^{10}\text{B}}\right)_{\text{CR}} / \left(\frac{^{11}\text{B}}{^{10}\text{B}}\right)_\odot = \frac{2.33^{+4}_{+1.5}}{3.98}$$

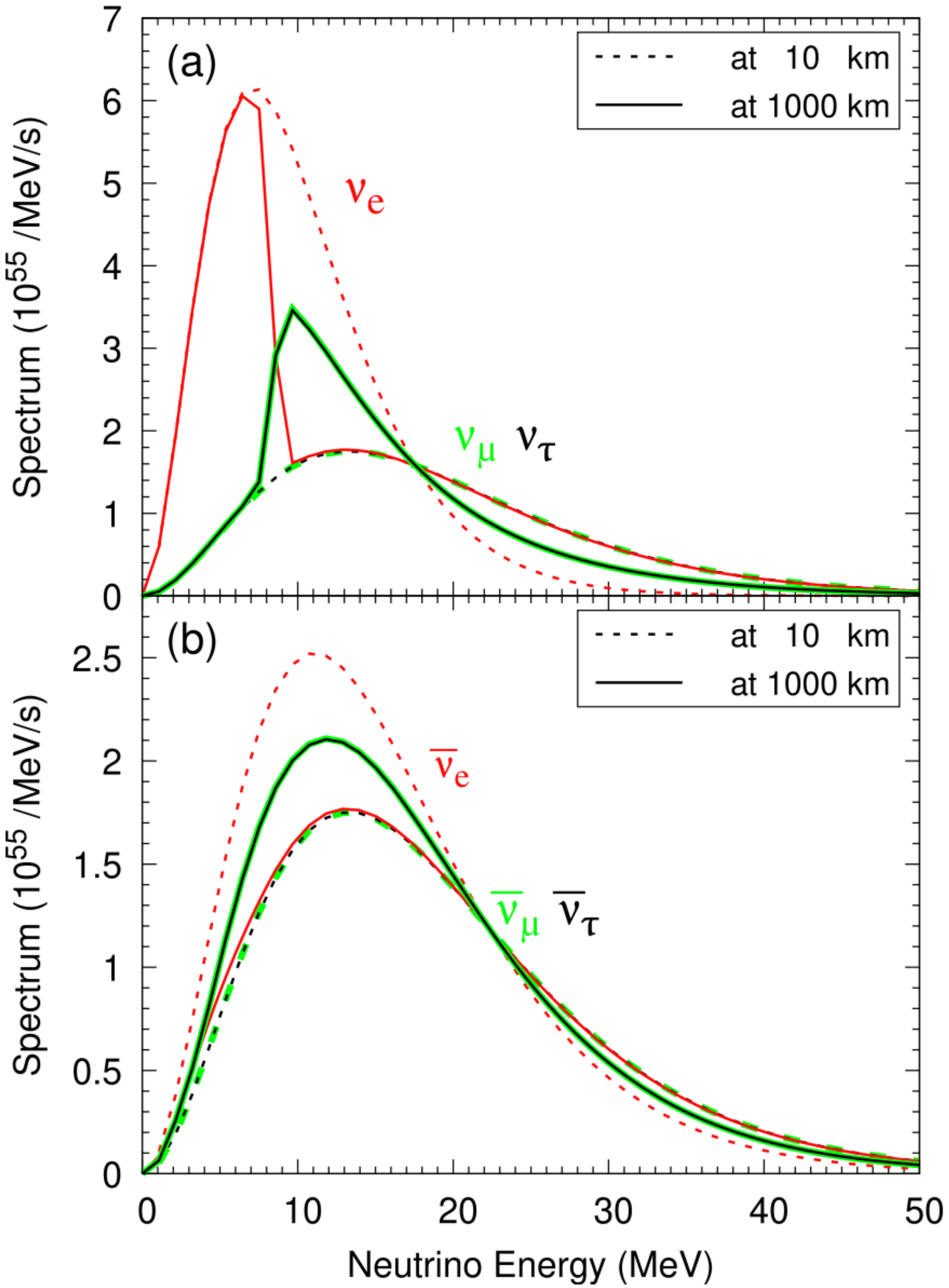
Liu et al. (2010)

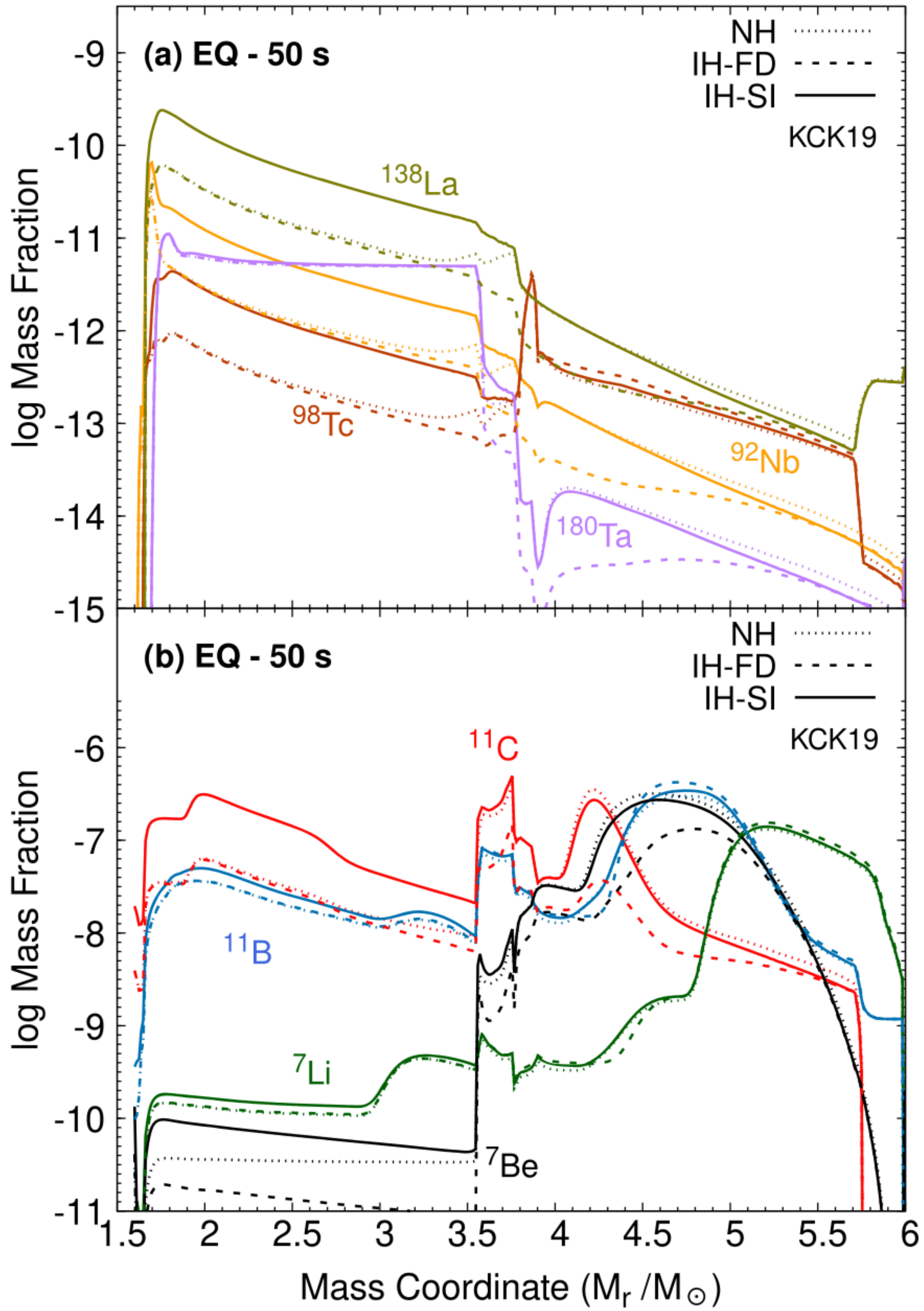
$$R_{exp}\left(\frac{^{138}\text{La}}{^{11}\text{B}}\right) = 0.41^{+0.21}_{-0.42}$$

Our calculation result

	MH	^{7}Li	^{7}Be $(10^{-7} M_\odot)$	^{11}B	^{11}C	^{92}Nb $(10^{-12} M_\odot)$	^{98}Tc	^{138}La $(10^{-11} M_\odot)$	^{180}Ta	Yield Ratio N(^{7}Li)/N(^{11}B)	PF Ratio ^{138}La/^{11}B
SI NEQ (KCK19)	NH	1.132	1.601	4.276	4.920	16.44	3.559	15.19	1.295	0.467	0.4776
	IH	1.261	1.206	4.623	4.283	12.29	2.854	11.31	1.281	0.435	0.3672
FD NEQ (KCK19)	NH	1.483	0.841	5.407	5.258	25.44	5.367	23.14	1.323	0.342	0.6274
	IH	0.959	2.303	3.946	6.566	26.15	5.302	23.94	1.331	0.488	0.6585

Abundance at 50 s





Presupernova

- SN1987A

  Initial progenitor mass : ~ 20 $M_\odot$

  Metallicity: $Z = Z_\odot/4$ in Large Magellanic cloud

  Explosive nucleosynthesis for He-core $6M_\odot$

- Network calculation

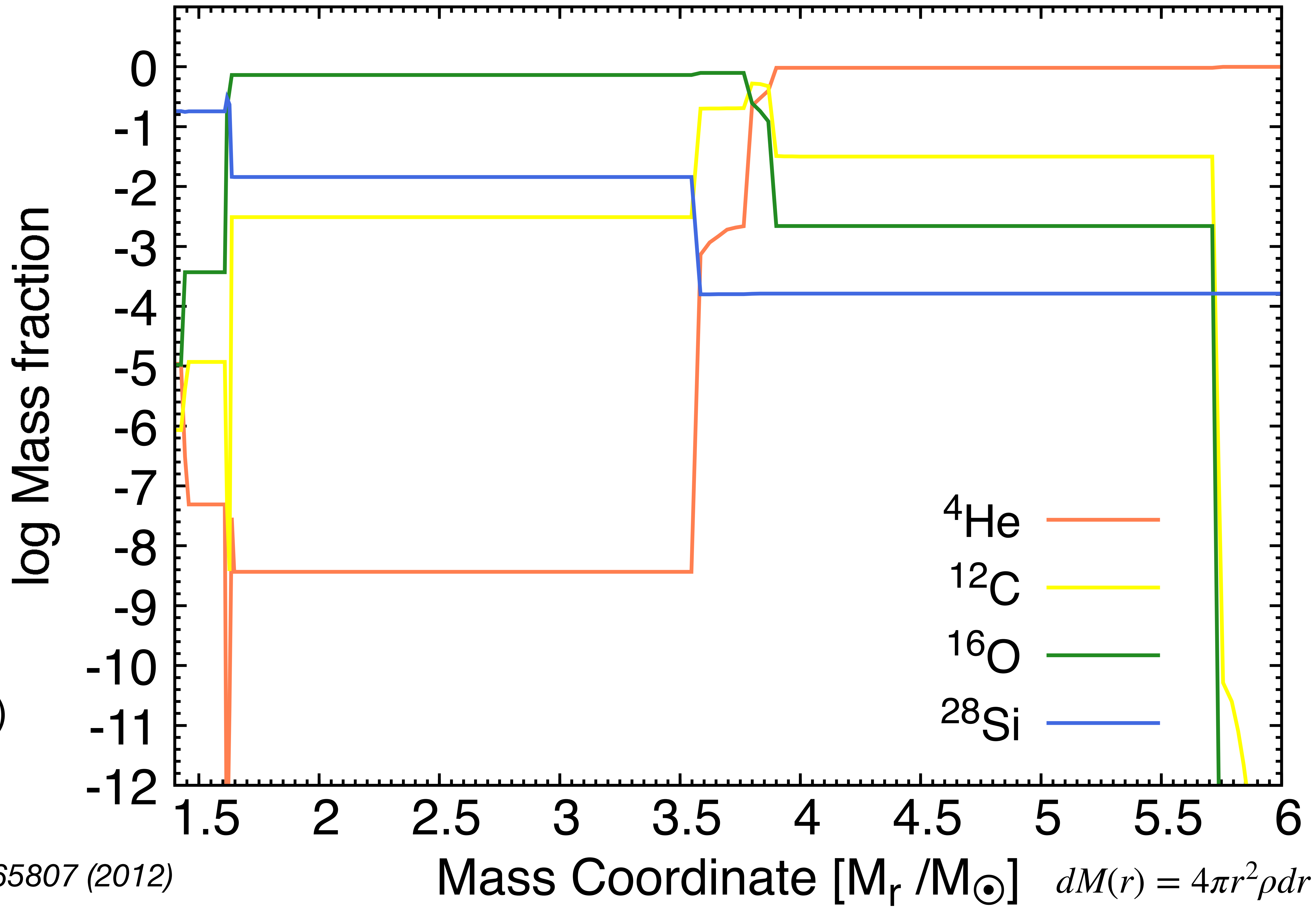
  Nuclides: 3080 *Cyburt et al. ApJS, 189, 240 (2010)*

  \# of thermonuclear reactions: 38198 JINA database

  \# of neutrino-induced reactions: about 4300

  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)*



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

Presupernova

- SN1987A

  Initial progenitor mass : ~ 20 $M_\odot$

  Metallicity: $Z = Z_\odot/4$ in Large Magellanic cloud

  Explosive nucleosynthesis for He-core $6M_\odot$

- Network calculation

  Nuclides: 3080

  Cyburt et al. ApJS, 189, 240 (2010)

  # of thermonuclear reactions: 38198 JINA database

  # of neutrino-induced reactions: about 4300

^{92}Nb ($\tau_{1/2} \sim 34.7$ Myr)
^{98}Tc ($\tau_{1/2} \sim 4.2$ Myr)
^{138}La ($\tau_{1/2} \sim 1.02 \times 10^{11}$yr)
^{180}Ta^m ($\tau_{1/2} \sim 7.15 \times 10^{15}$ yr)