Impact of neutrino oscillations on ν-process in the core-collapse supernovae and νr-process

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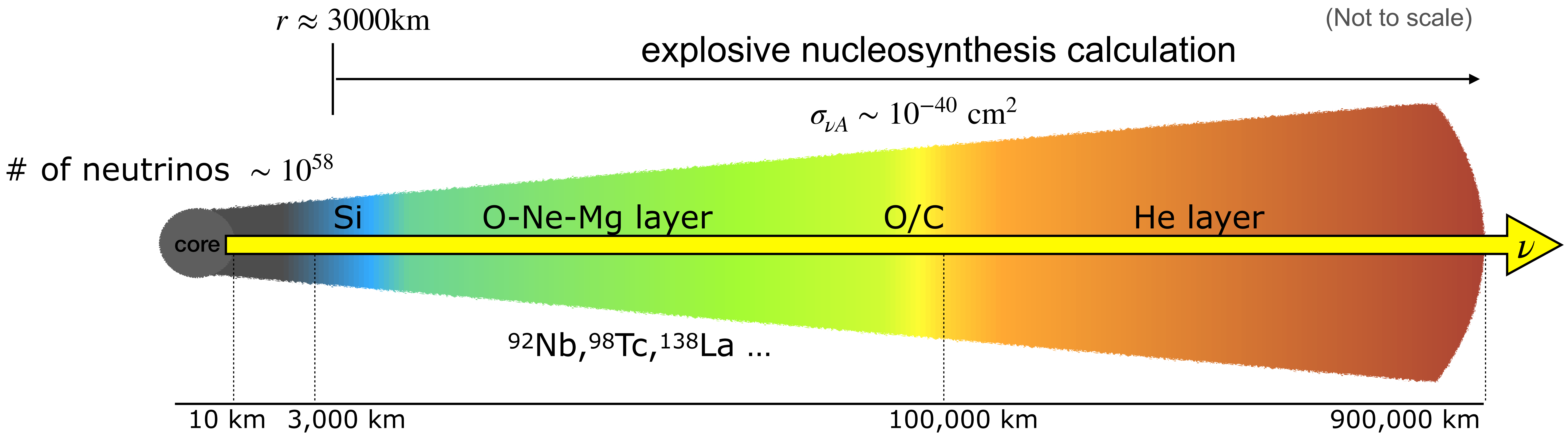
The ν-process

- **Core-collapse supernova**



The ν-process

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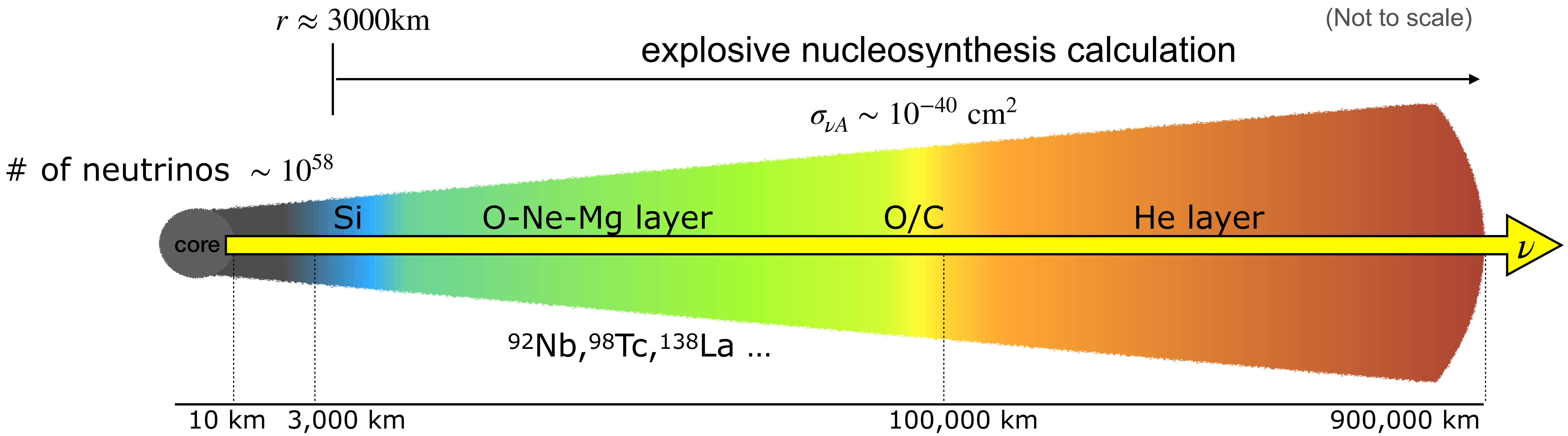
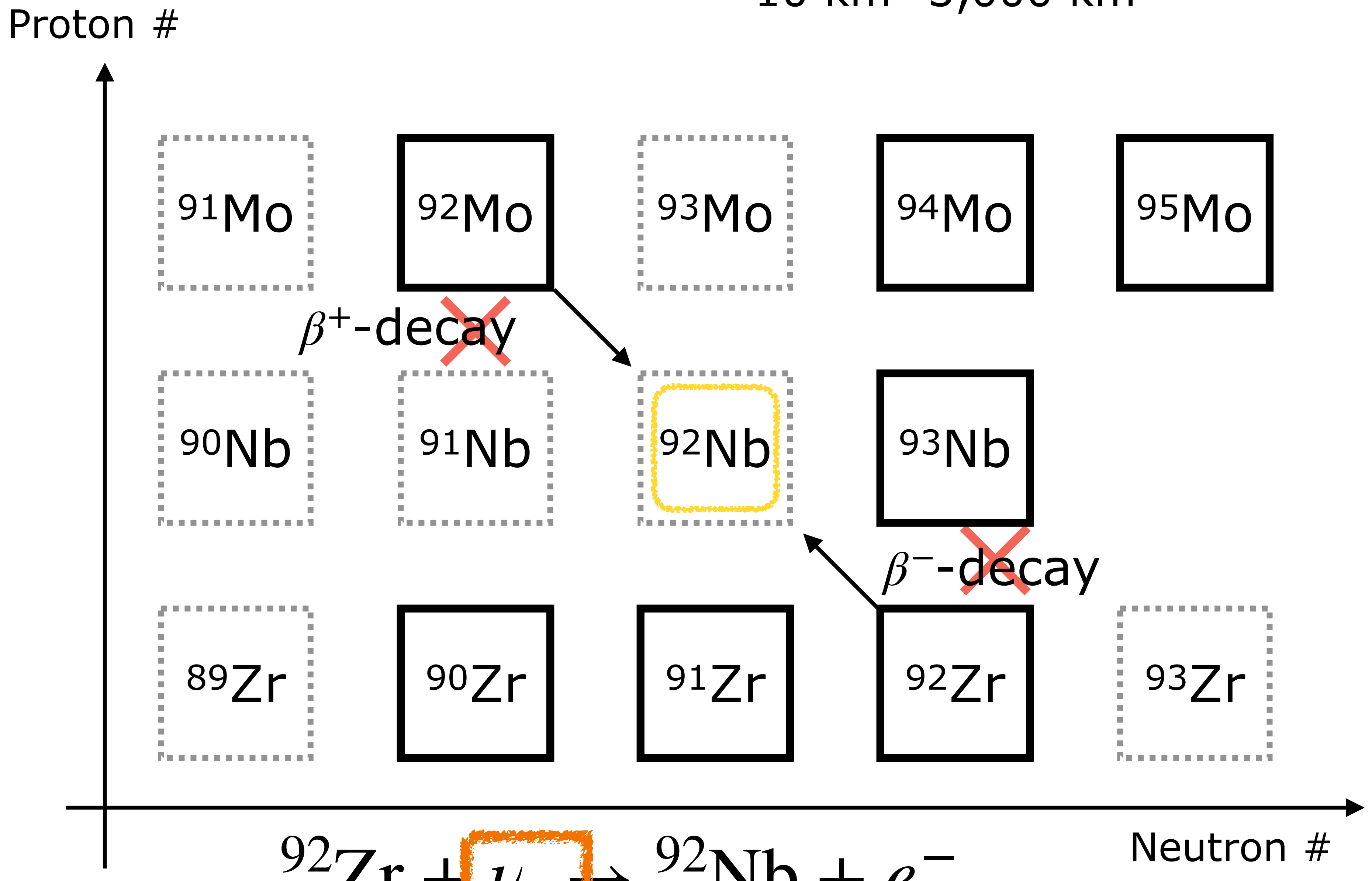




$$^{92}\text{Zr} + \boxed{\nu_e} \rightarrow {}^{92}\text{Nb} + e^-$$

Short-lived radioactive nuclides

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

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

Long-lived radioactive nuclides

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

Neutrino eigenstates

- **Neutrino flavor basis**

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

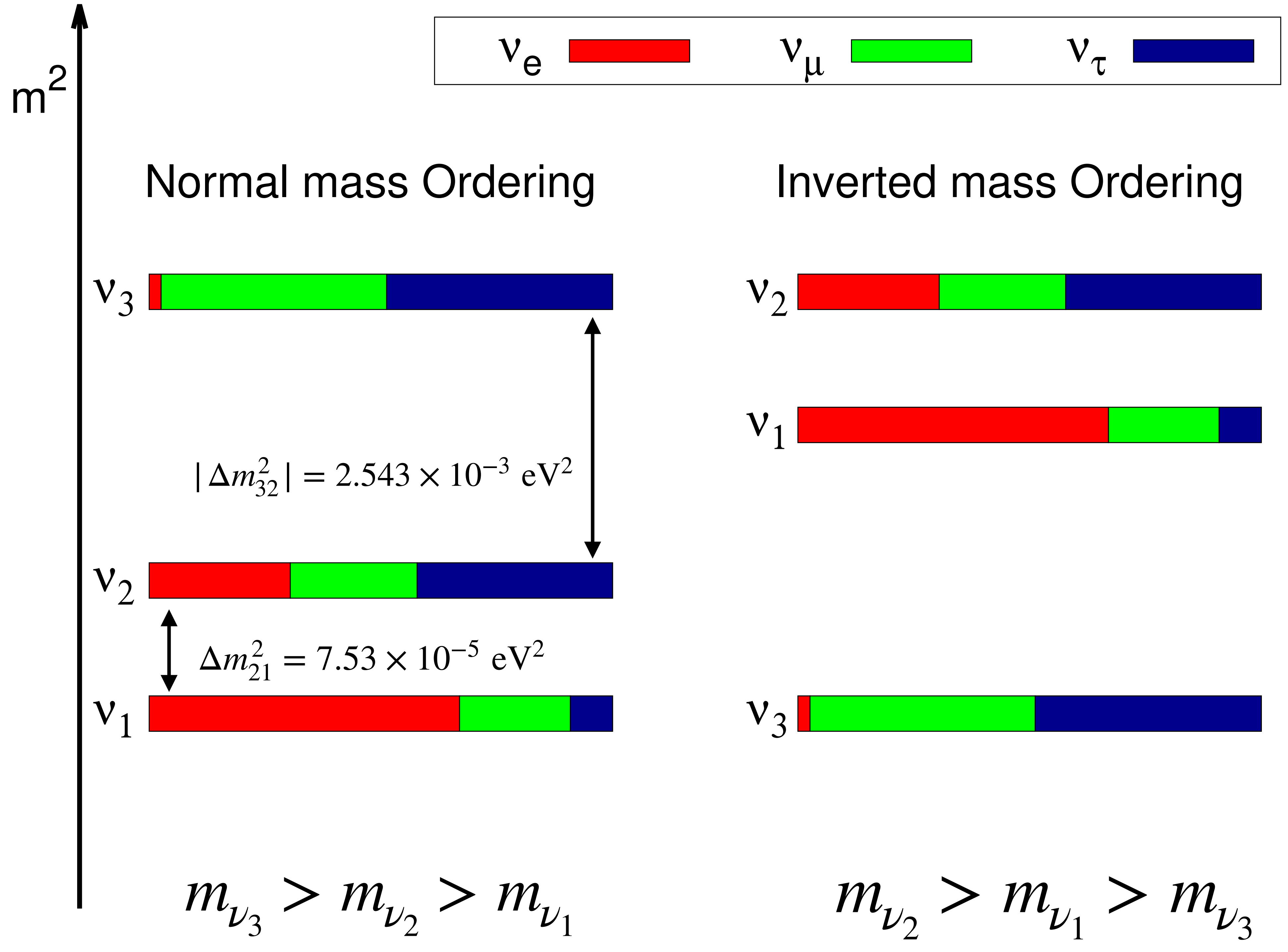
Flavor eigenstate Mass eigenstate

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

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

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

- Mass Ordering (Hierarchy)



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

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

still unsolved

Neutrino oscillation in vacuum

- **Neutrino hamiltonian in vacuum**

$$E_i = \sqrt{p_\nu^2 + m_i^2} \underset{\uparrow}{\approx} E_\nu + \frac{m_i^2}{2E_\nu}$$

Ultrarelativistic

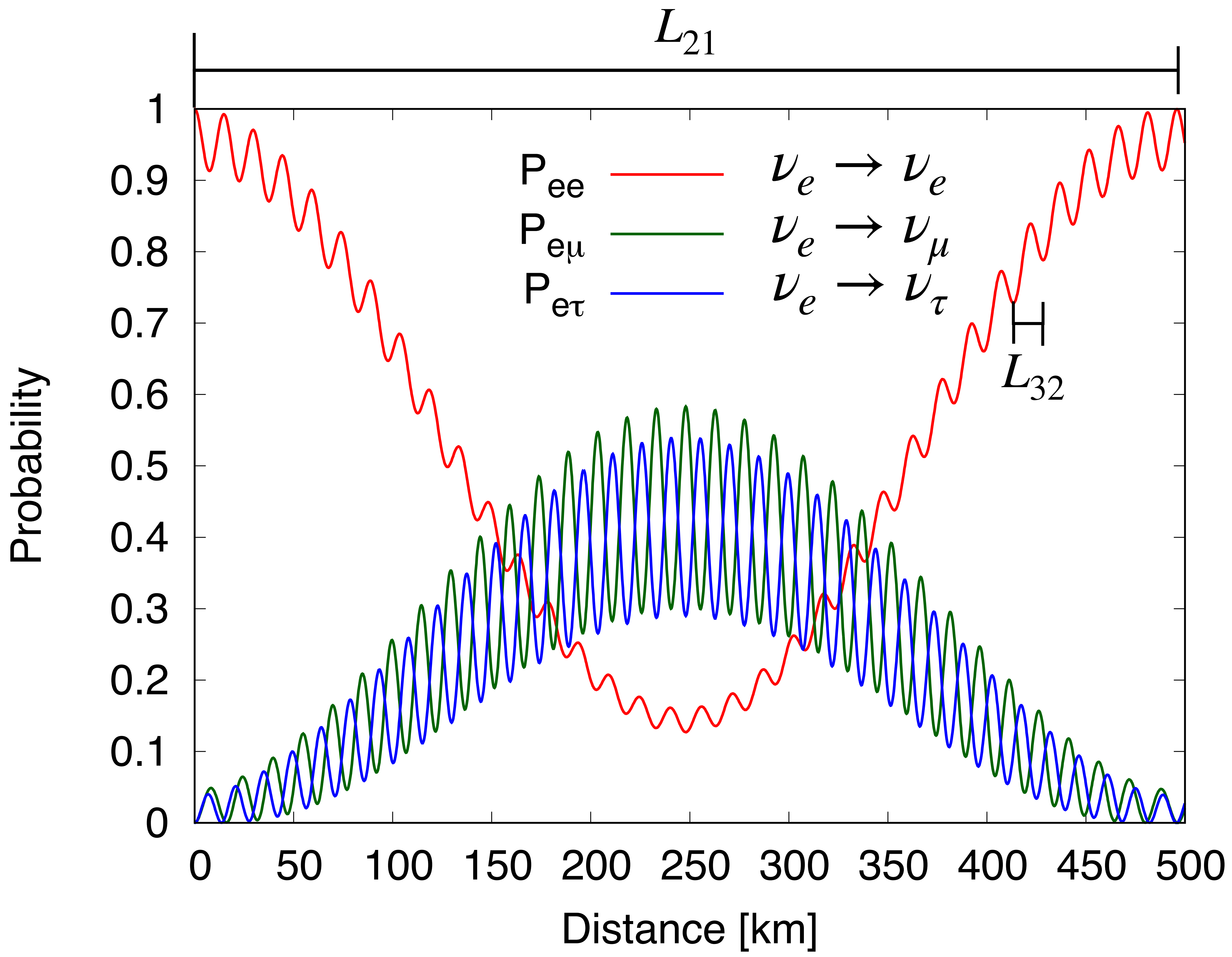
Neutrino equation of motion $\nu_\alpha \rightarrow \nu_\beta$ in flavor basis

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

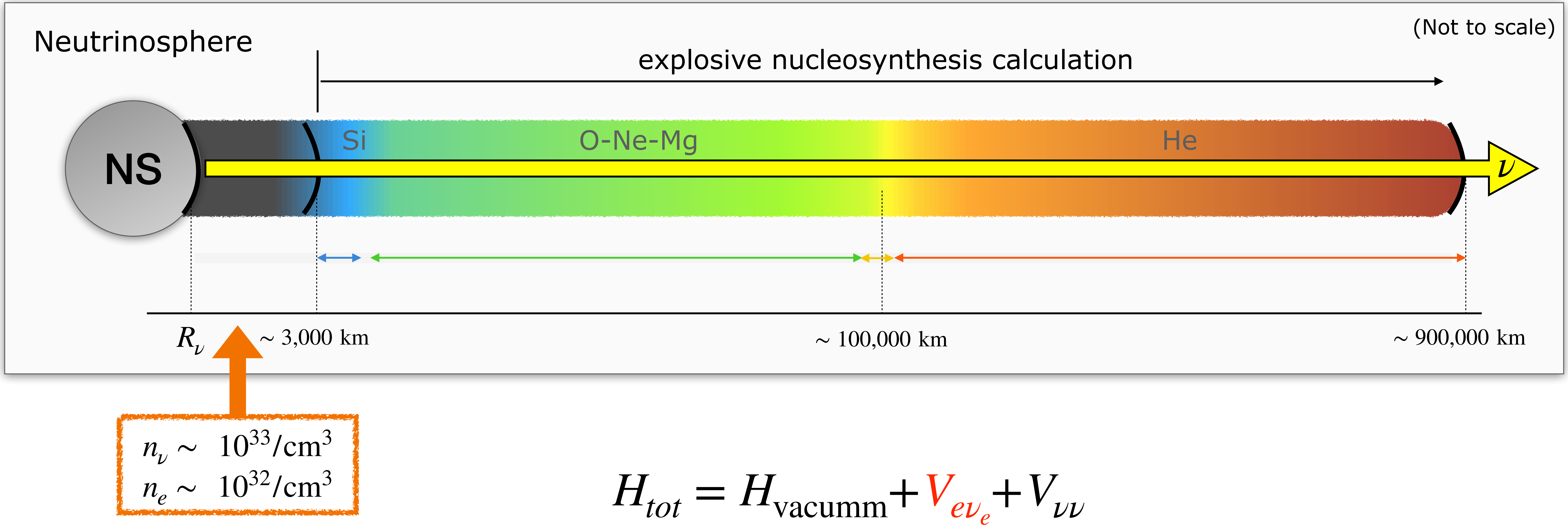
$$H_{\text{vacuum}} = U\text{diag}\left(0, \frac{\Delta m_{21}^2}{2E_\nu}, \frac{|\Delta m_{31}^2|}{2E_\nu}\right)U^\dagger$$

Flavor change probability $\nu_\alpha \rightarrow \nu_\beta$

$$P_{\beta\alpha}(r) = |\psi_{\nu_\alpha\to\nu_\beta}(r)|^2$$



Neutrino oscillation in star



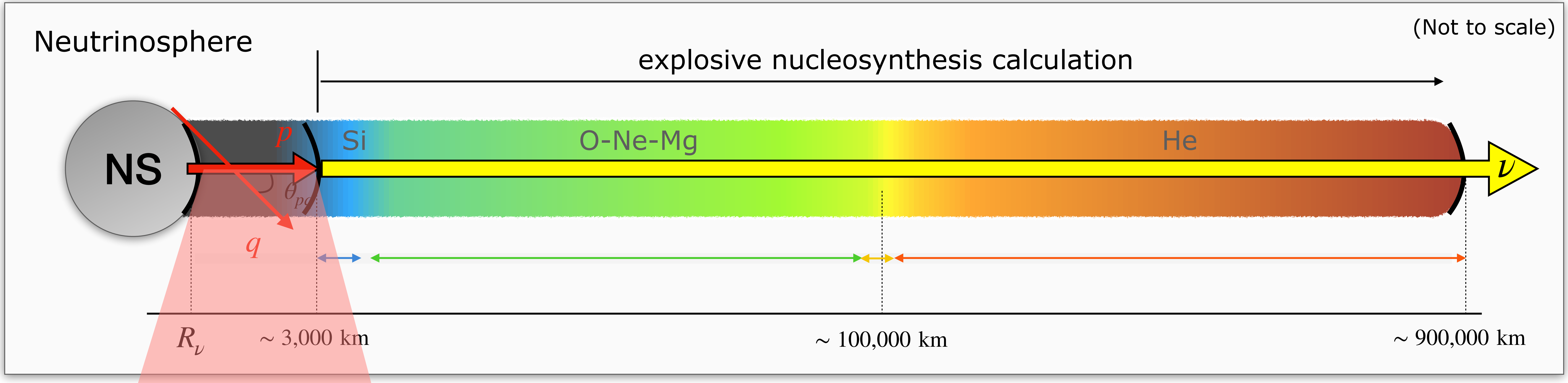
$n_\nu \sim\ 10^{33}/\mathrm{cm}^3$

$n_e \sim\ 10^{32}/\mathrm{cm}^3$

$$H_{tot} = H_{\mathrm{vacumm}} + V_{e\nu_e} + V_{\nu\nu}$$

- Neutrino-electron (charged current interaction); $V_{e\nu_e}(r) = \sqrt{2}G_F n_e(r)\ \mathrm{diag}(1,0,0)$
- Neutrino-neutrino (neutral current interaction)
- Neutrino-nucleus (charged and neutral current interaction)

Neutrino oscillation in star



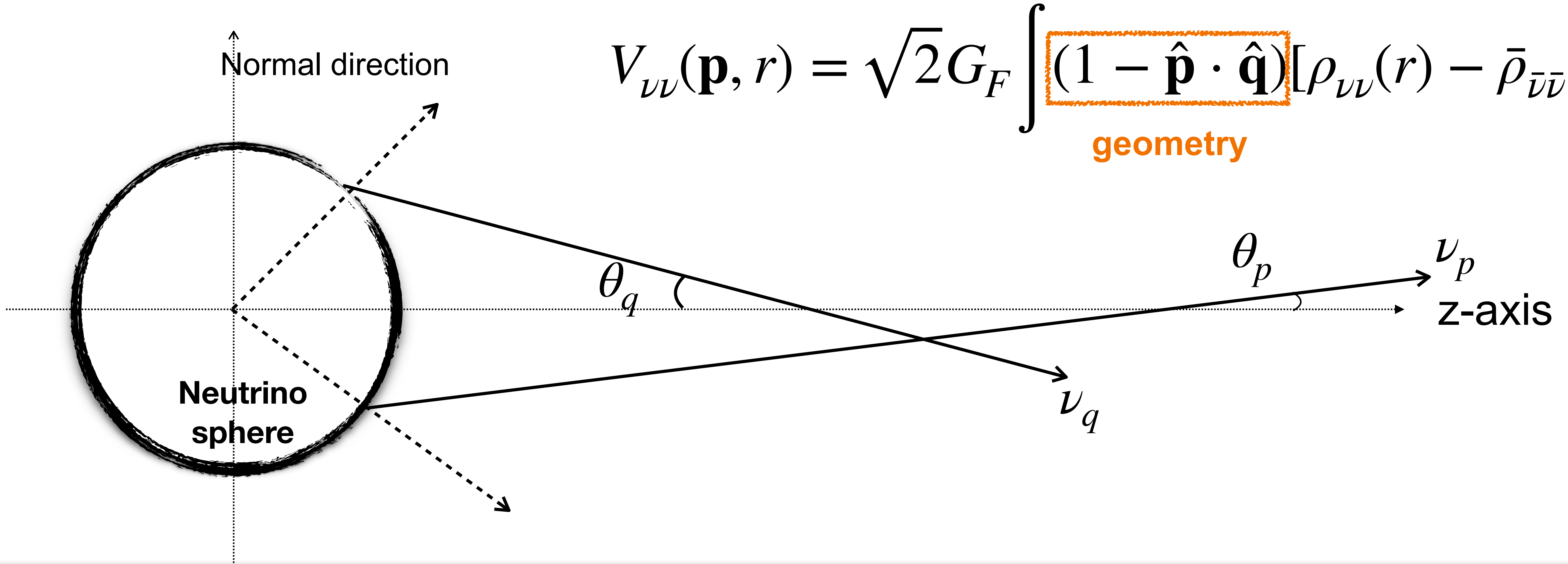
Neutrino propagation with momentum *p*

Neutrino-neutrino interaction

$$H_{tot} = H_{\text{vacumm}} + V_{e\nu_e} + V_{\nu\nu}$$

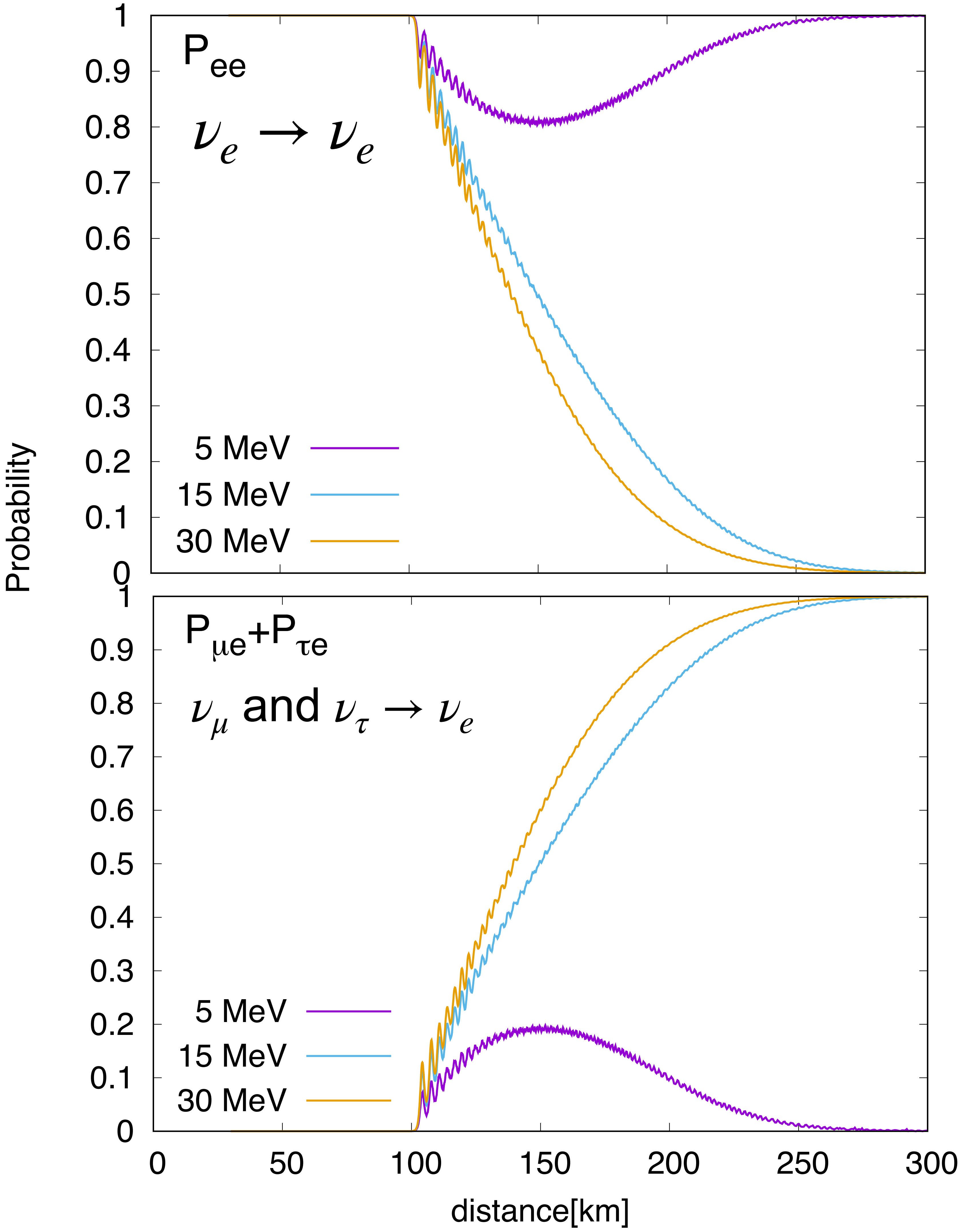
Neutrino bulb model *H. Duan et al. PRD 74, 105014 (2006)*

$$V_{\nu\nu}(\mathbf{p}, r) = \sqrt{2} G_F \int \underbrace{\boxed{(1 - \hat{\mathbf{p}} \cdot \hat{\mathbf{q}})}}_{\text{geometry}} [\rho_{\nu\nu}(r) - \bar{\rho}_{\bar{\nu}\bar{\nu}}(r)] d^3\mathbf{q}$$



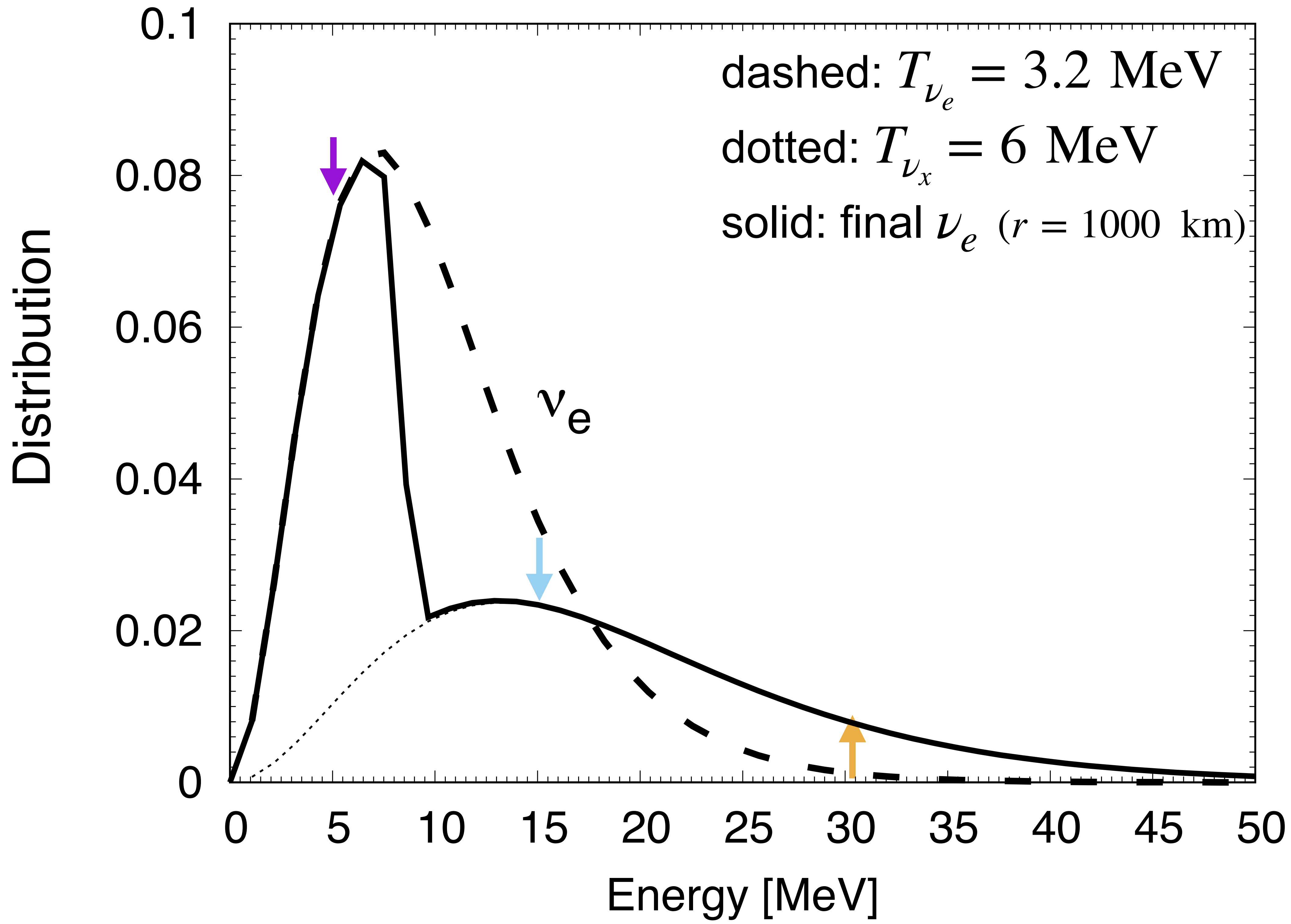
Flavor change probability - Vacuum + $\nu_e e$ + $\nu\nu$

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



Neutrino energy distribution (Fermi-Dirac)

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



P$_{ee} \rightarrow 1$ at $E_\nu < 8$MeV

P$_{ee} \rightarrow 0$ at $E_\nu > 10$MeV

P$_{\mu e}$ + P$_{\tau e} \rightarrow 1$ at $E_\nu > 10$MeV

Spectral splitting appear by including ν-ν interaction

The role of neutrino oscillations on the ν-process

- **Neutrino reaction rates**

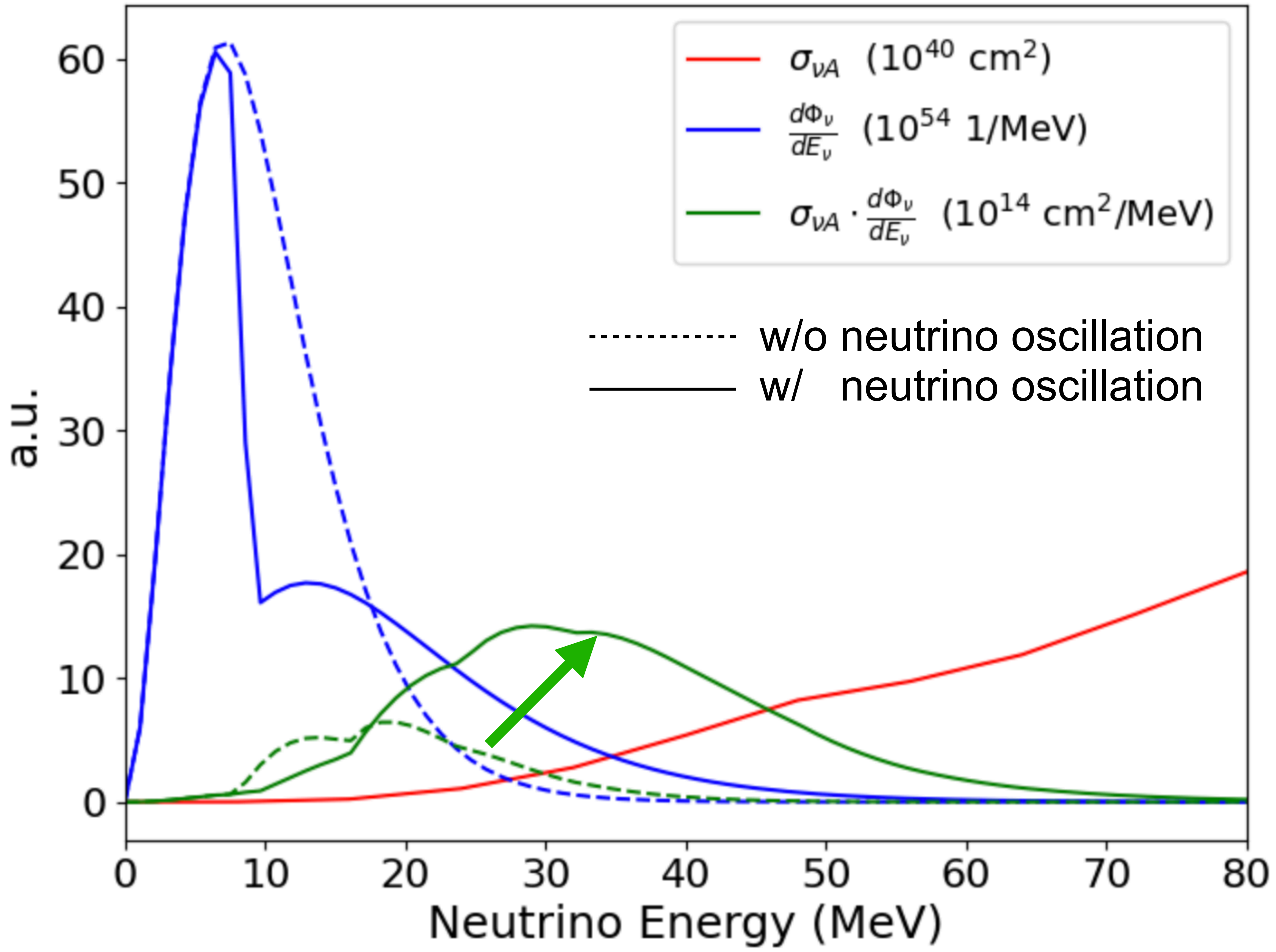
Neutrino-induced reactions rate λ_{ν_e}

$$\lambda_{\nu_e}(r) = n_{\nu_e}\langle\sigma_{\nu_e A}c\rangle = \int_0^\infty \boxed{\frac{d\phi_{\nu_e}}{dE_\nu}\sigma_{\nu_e A}(E_\nu)} dE_\nu$$

Neutrino differential flux

$$\frac{d}{dE_\nu}\phi_{\nu_e}(t, r; E_\nu, T_{\nu_e}) \propto \sum_{\beta=e,\mu,\tau} \underset{\substack{\downarrow \\ \text{by } \nu\text{-oscillation}}}{P_{\nu_\beta\to\nu_e}(r, E_\nu)} f^\beta_{FD}(E_\nu, T_{\nu_\beta})$$

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



- Multi-angle approximation $(1 - \hat{\mathbf{p}}\cdot\hat{\mathbf{q}}) \approx (1 - \cos\theta_p\cos\theta_q)$
- Inverted mass hierarchy

Result - Abundance at 50 s

- **SN1987A**

Initial progenitor mass : ~ 20 $M_\odot$

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

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

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

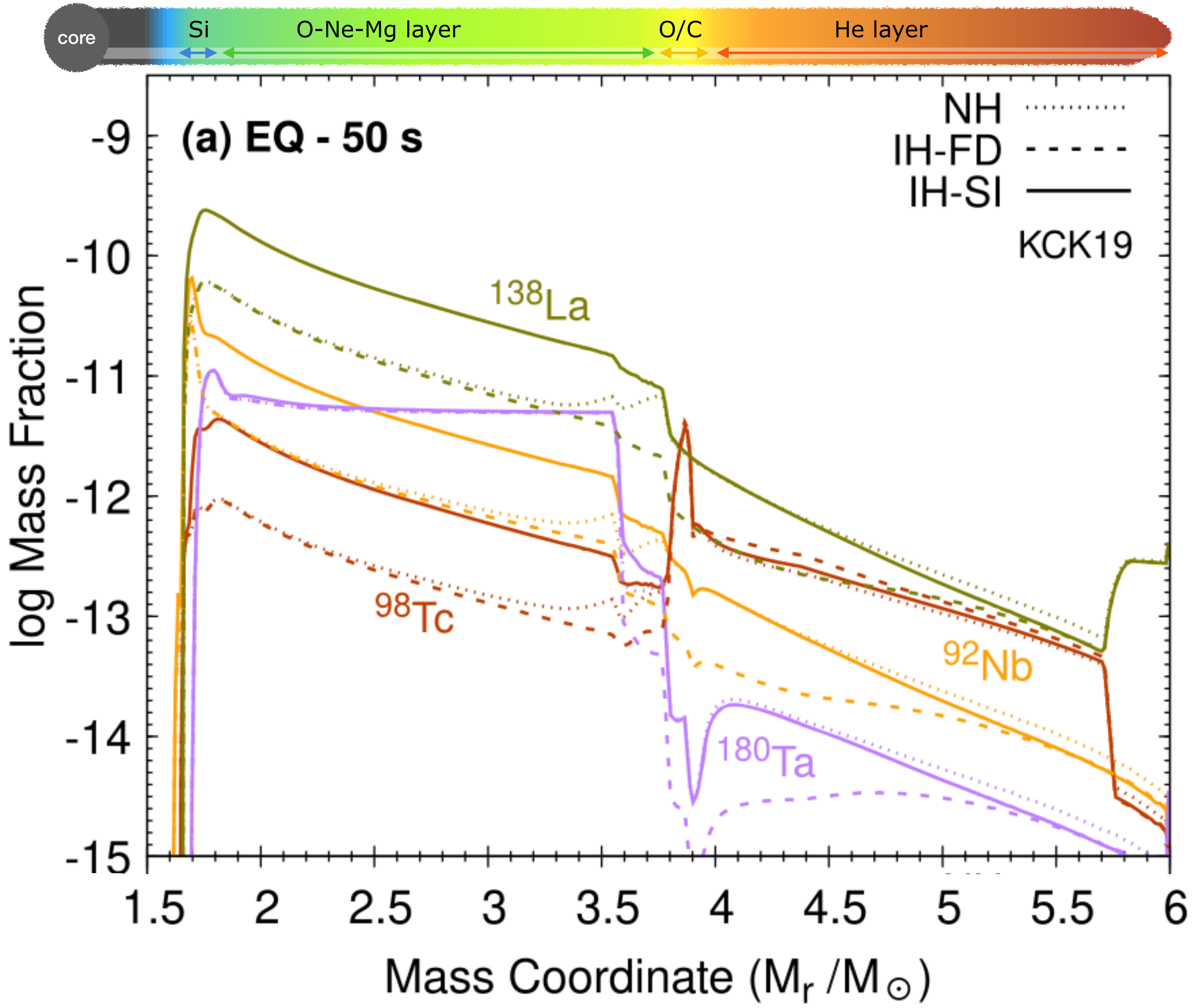
NH

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

IH

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

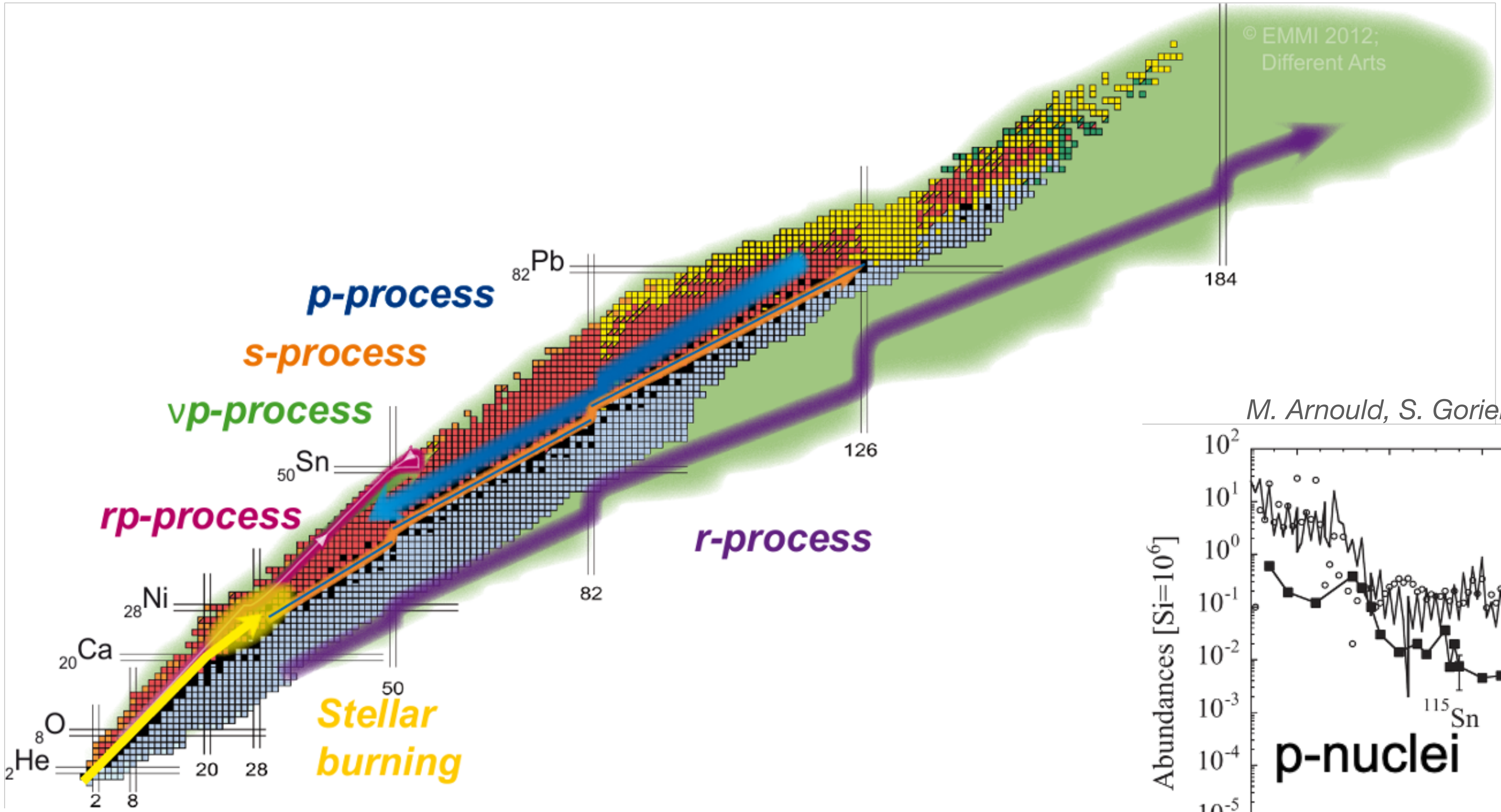
H. Ko et al. APJ 937, 116 (2022)



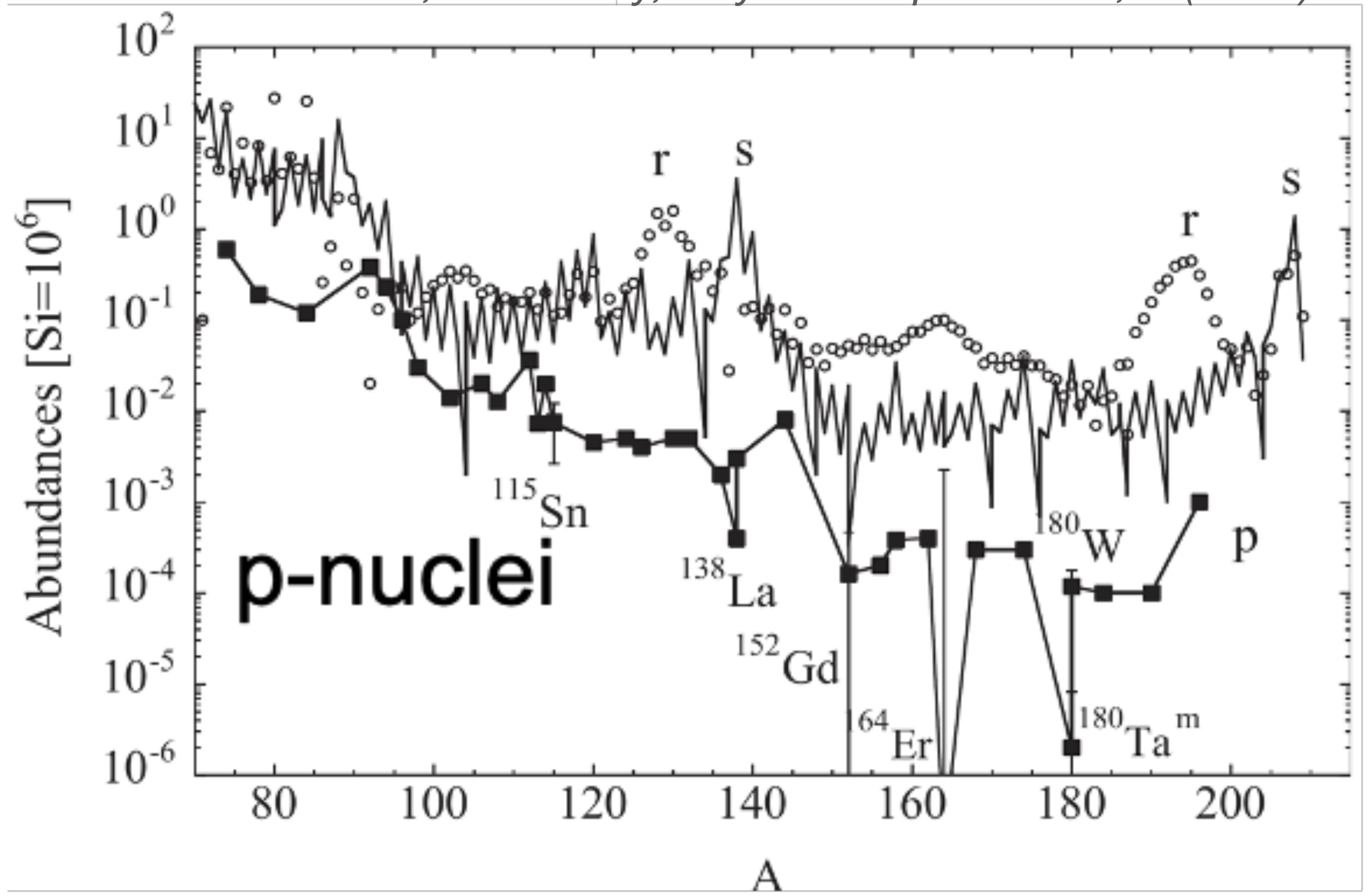
Neutrino oscillation → change in neutrino reaction rates → abundance change

Another environment to produce ^{92}Nb and also p-nuclei

- **Several processes contribute to the nucleosynthesis beyond Iron: s-process, r-process and p-process (γ-process)**



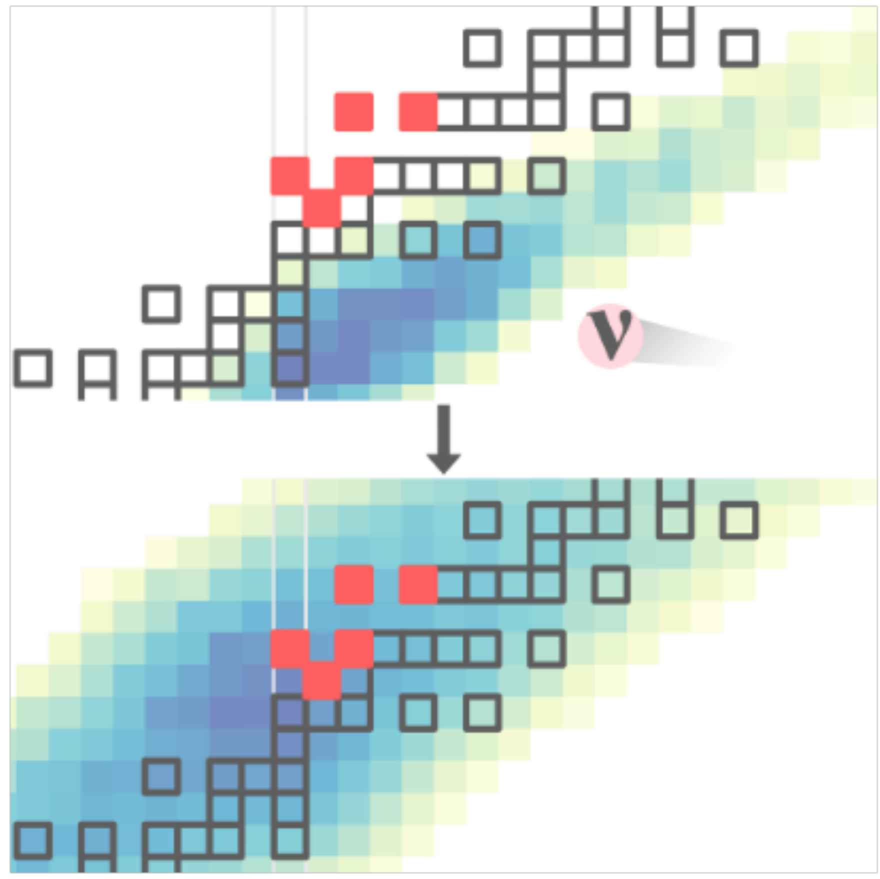
M. Arnould, S. Goriely, Physics Reports 384, 1 (2003)



- Origin p-nuclei unclear
- Can neutrino-nucleus reactions help producing p-nuclei?

νr-process: another environment to produce ^{92}Nb and also p-nuclei

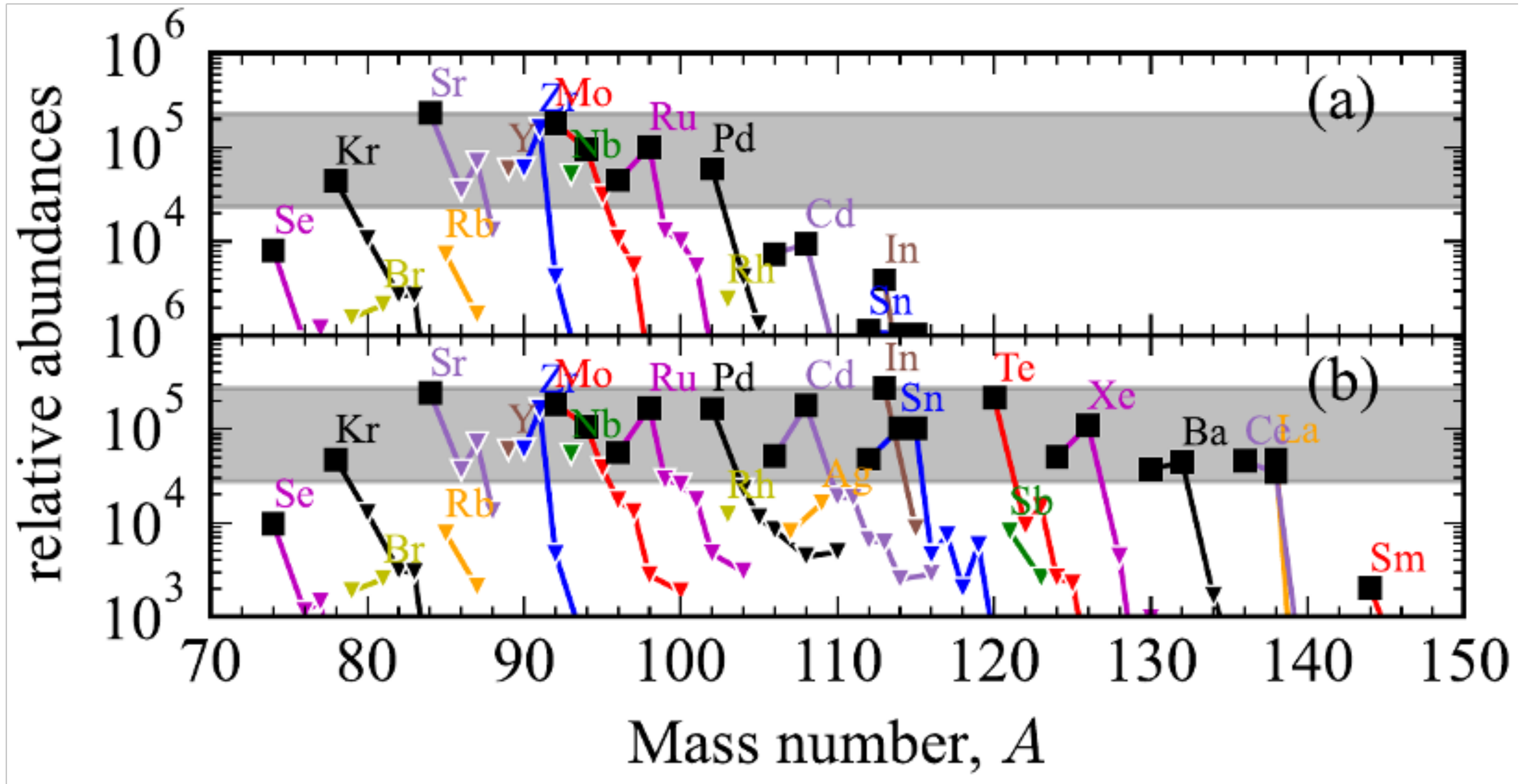
- **p-nuclei from neutron-rich outflows**
  - Novel nucleosynthesis process that operates under strong neutrino fluxes
  - Sequence of neutron captures and charged-current neutrino-nucleus reactions
  - Co-production of p-nuclei from A=88-138
  - May require high magnetic fields as found in magnetars (see arXiv:2402.06003)
  - Experimental constraints to neutrino-nucleus cross sections are necessary



In neutron-rich condition ($Y_e \approx 0.4 - 0.5$)

ν_e-nucleus reactions drive material towards and across stability

→ Production of p-nuclei from neutron-rich nuclei.



Z.Xiong, G. Martínez-Pinedo, O. Just and A. Sieverding, PRL 132.192701 (2024)

νr-process: another environment to produce ^{92}Nb and also p-nuclei

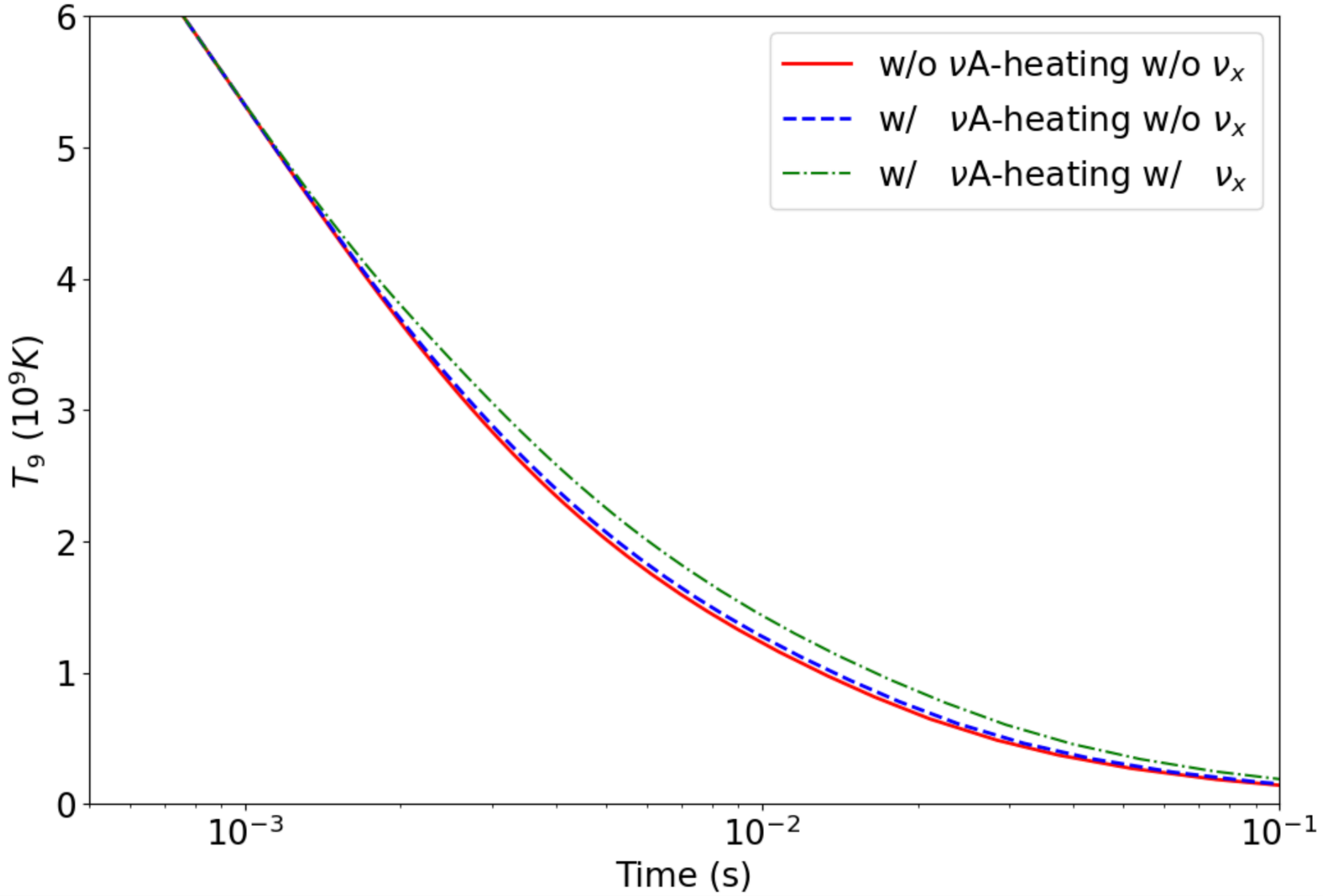
- **The role of neutrino in nucleosynthesis**

Neutrino changes the thermal energy by heating and cooling

$$T\Delta s + \sum_i \mu_i \Delta Y_i = (\dot{\varepsilon}_{\nu A} - \dot{\varepsilon}_{\beta\nu})\Delta t$$

By the neutrino-nucleus interaction

$$\langle \dot{\varepsilon}_{\nu A} \rangle_{\mathrm{total}} = \sum_i \langle \dot{\varepsilon}_{\nu A_i} \rangle Y_i$$
$$= n_\nu c \sum_i Y_i \frac{\int_0^\infty f_{FD}(E_\nu, T_\nu)\sigma_{\nu A_i}(E_\nu) E_\nu dE_\nu}{\int_0^\infty f_{FD}(E_\nu, T_\nu) dE_\nu}$$

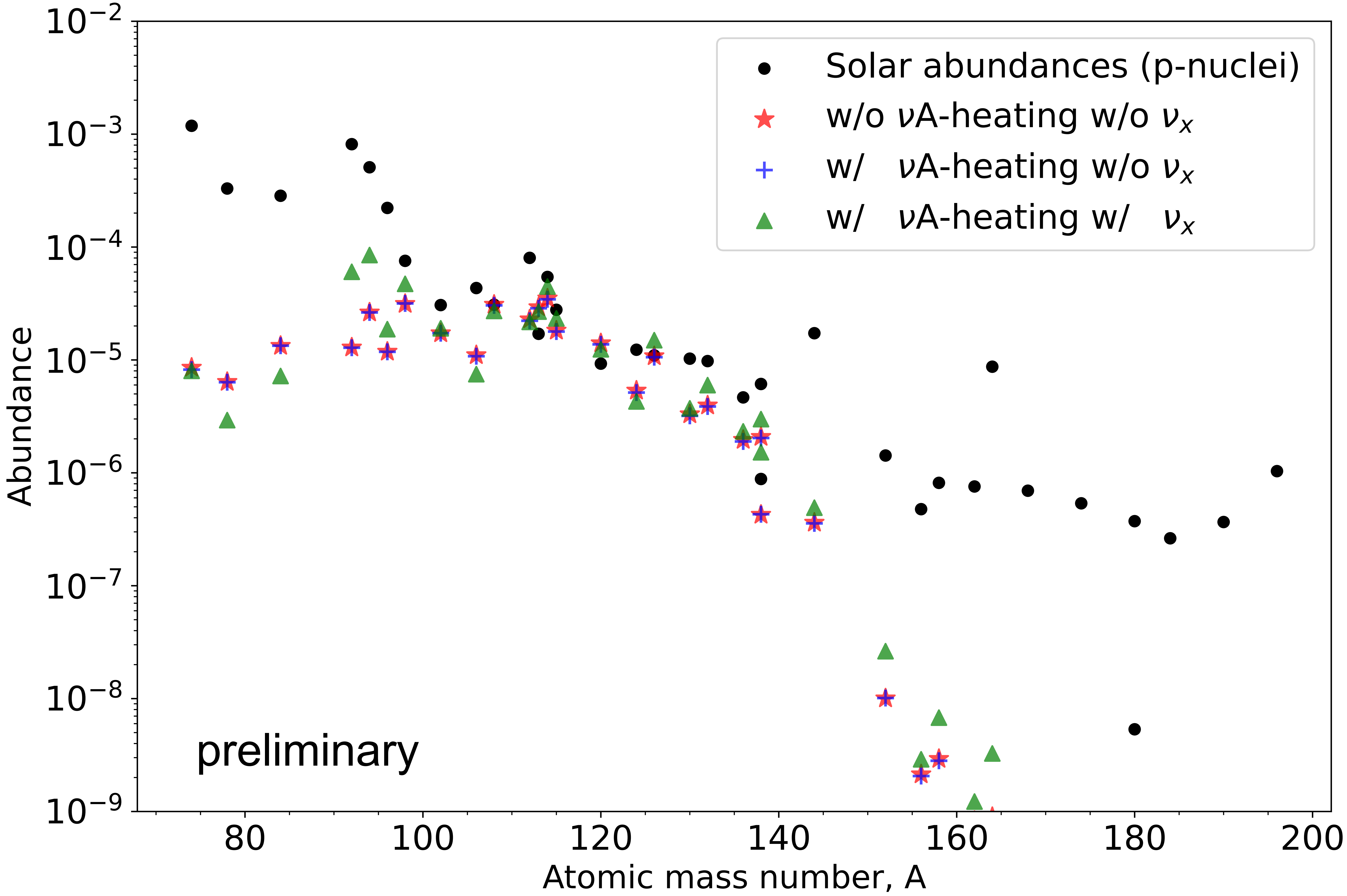


Parameters

- n_ν: neutrino number density
- T_ν: neutrino temperature
- $\sigma_{\nu A}$: *A. Severing et al. APJ. 865, 143 (2018).*
  ν_e and $\bar{\nu}_e$ → Charged current
  $\nu_{e,\mu,\tau}$ and $\bar{\nu}_{e,\mu,\tau}$ → Neutral current

νr-process: another environment to produce ^{92}Nb and also p-nuclei

- **The p-nuclei production**
  - Temperature changes caused by neutrino heating are less effective.
  - The heavy neutrinos interact with nucleus through the NC reactions and change the abundance.
  - The dependence of neutrino parameters (n_{ν_x}, T_{ν_x}) needs to be studied.



Summary

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

- Neutrinos interact with electron and neutrinos in the star. As a result, the each neutrino energy distribution are change.

- The neutrino oscillation calculation has a dependency on neutrino mass hierarchy.

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

- νr-process can produce not only the ^{92}Nb, but also the p-nuclei.

- The ν-nucleus interactions can also increase the temperature, but the effect of changing the abundances is small.

- Further sensitivity studies on heavy neutrinos are needed.

Thank You

BACK UP

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

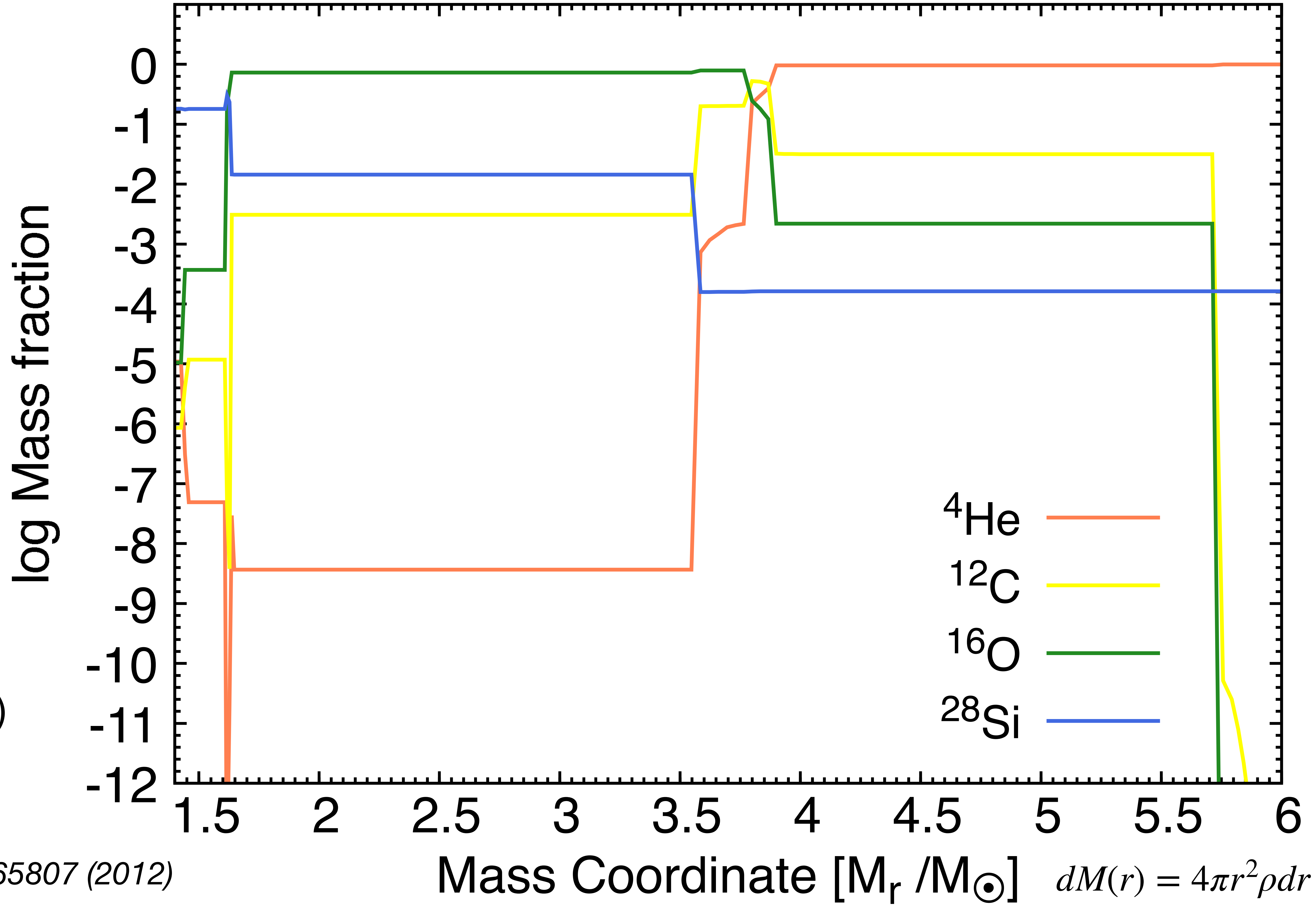
  Cyburt et al. ApJS, 189, 240 (2010)

  # 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)*



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

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$^{98}\mathrm{Tc}$ ($\tau_{1/2} \sim 4.2$ Myr)

$^{138}\mathrm{La}$ ($\tau_{1/2} \sim 1.02 \times 10^{11}$yr)

$^{180}\mathrm{Ta}^m$ ($\tau_{1/2} \sim 7.15 \times 10^{15}$ yr)