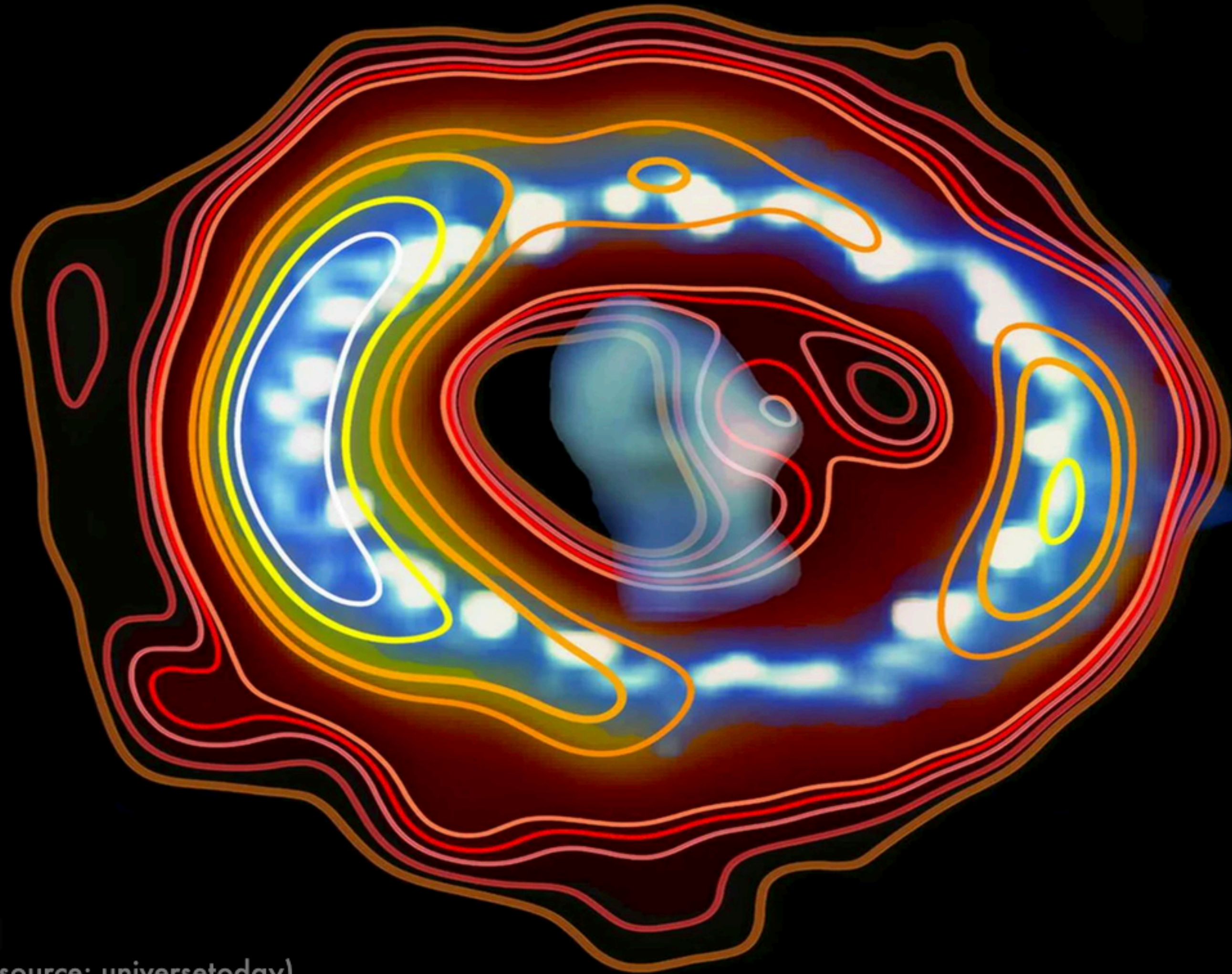


THREE-DAYS OF BRAINSTORMING WORKSHOP - MULTIMESSENGER ASTROPHYSICS WITH CORE-COLLAPSE SUPERNOVAE AND BINARY NEUTRON STAR MERGERS

WROCŁAW UNIVERSITY OF SCIENCE AND TECHNOLOGY, WROCŁAW (POLAND)
9. - 11. SEPTEMBER 2026



SN1987A radio image (source: universetoday)



Brainstorming workshop 2022 to Revolutionize the Core-Collapse Supernova Theory

31 July 2022 to 5 August 2022
Institute of Theoretical Physics, University of Wroclaw
Europe/Warsaw timezone

Wroclaw 2022



Brainstorming workshop: Deciphering the equation of state using gravitational waves from astrophysical sources

5-7 August 2024
Institute of Theoretical Physics, University of Warsaw
Europe/Warsaw timezone

Warsaw 2024

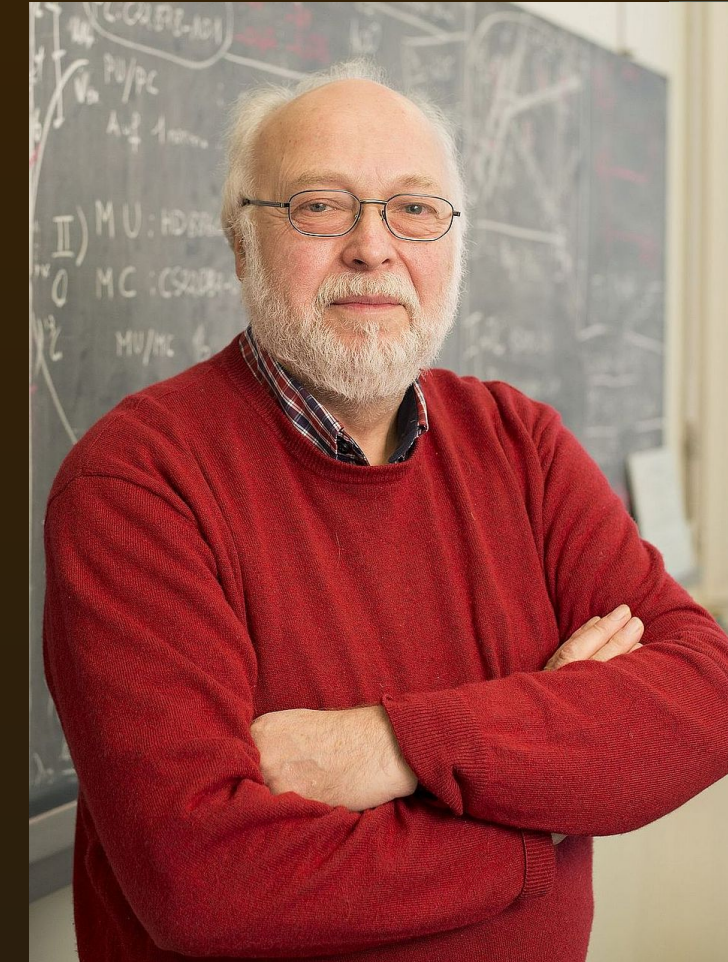
Wroclaw



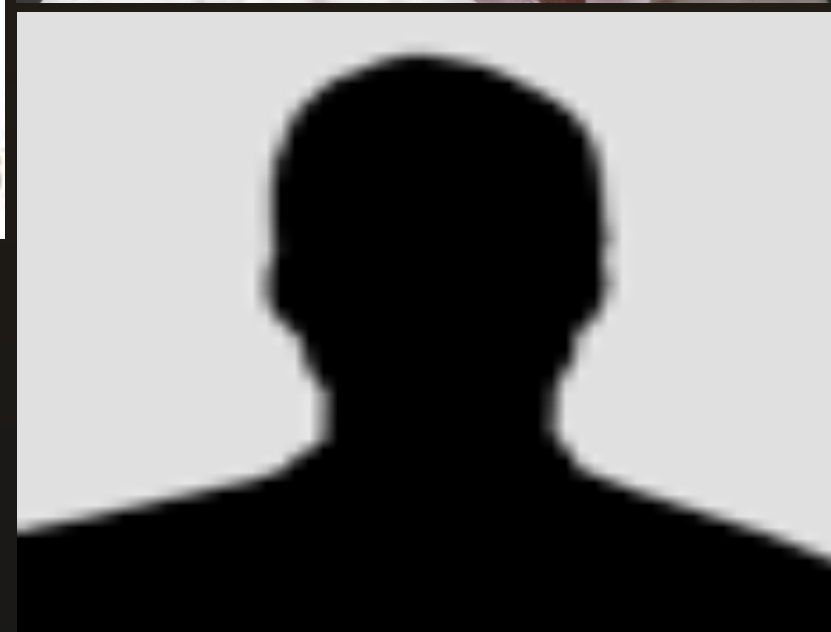
Potsdam



Fukuoka



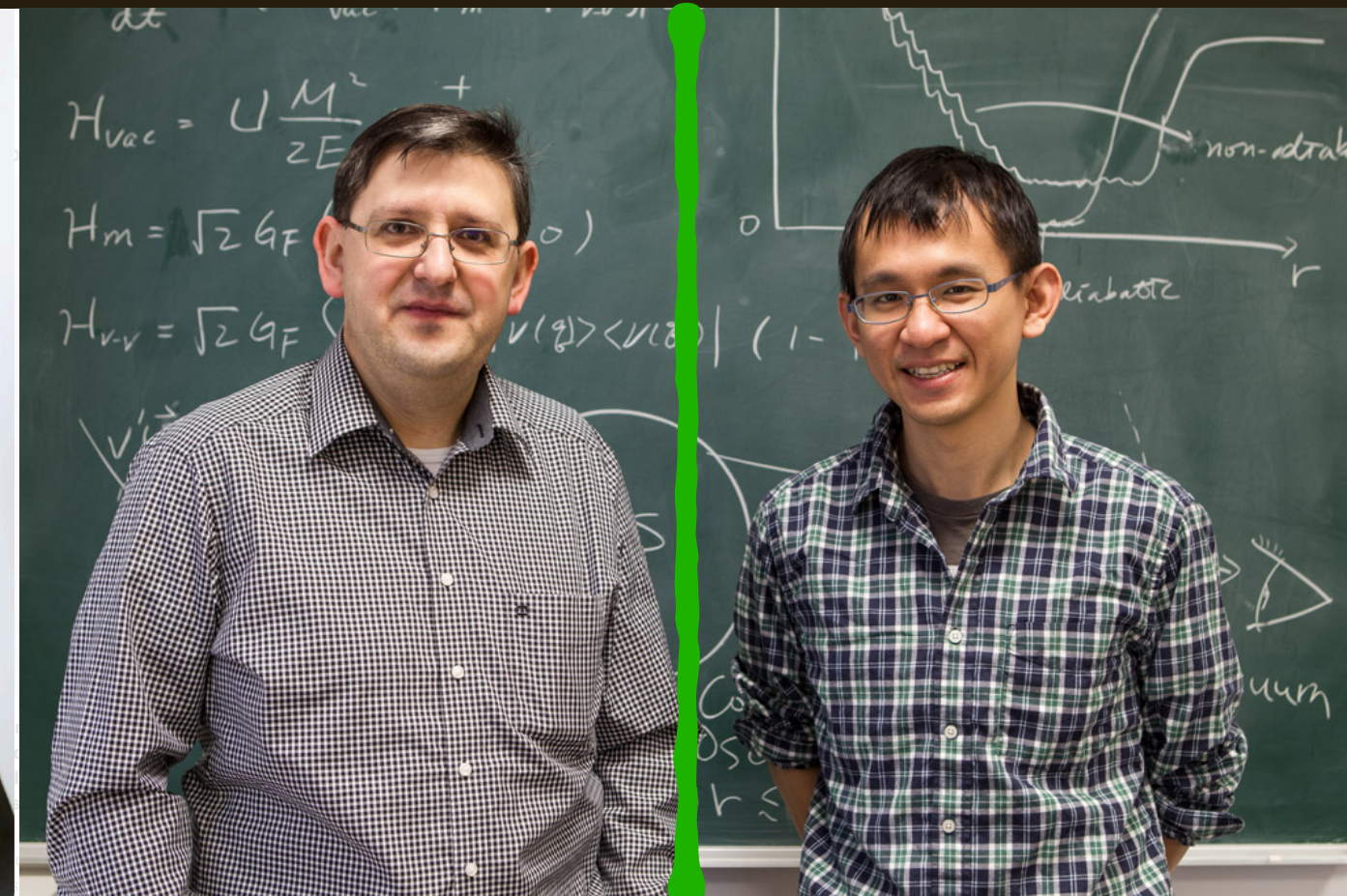
Basel



Warsaw



Darmstadt

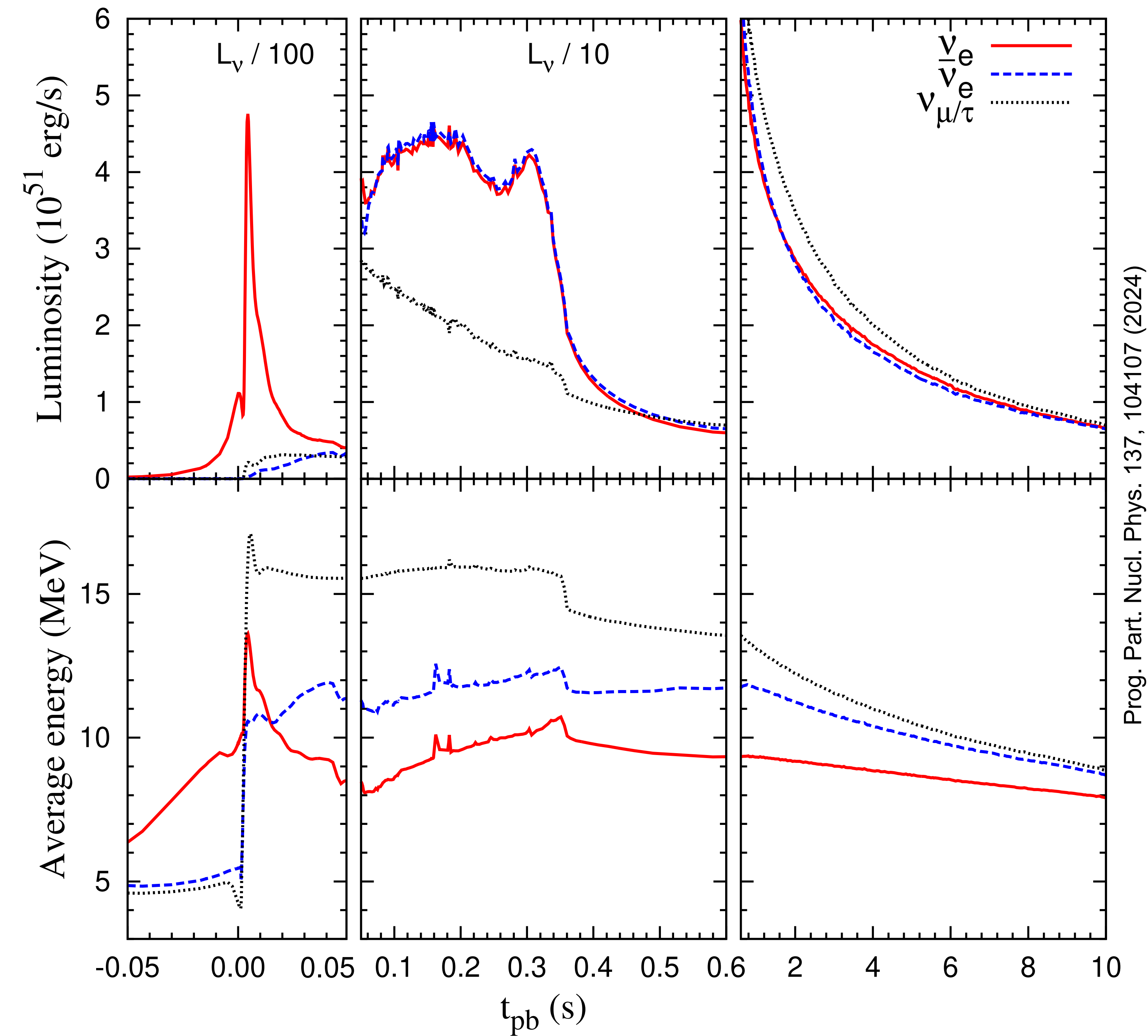


Taipei

Neutrino interaction rates and the
nuclear equation of state

—

mean field approach and beyond



Prog. Part. Nucl. Phys. 137, 104107 (2024)

$$e^- + \langle A, Z \rangle \longrightarrow \langle A, Z - 1 \rangle + \nu_e$$

$$\nu + \langle A, Z \rangle \rightleftharpoons \nu' + \langle A, Z \rangle$$

$$l^- + p \rightleftharpoons \nu_l + n$$

$$l^+ + n \rightleftharpoons \bar{\nu}_l + p$$

$$\nu + N \rightleftharpoons \nu' + N$$

$$\nu + l^\pm \rightleftharpoons \nu' + l^\pm$$

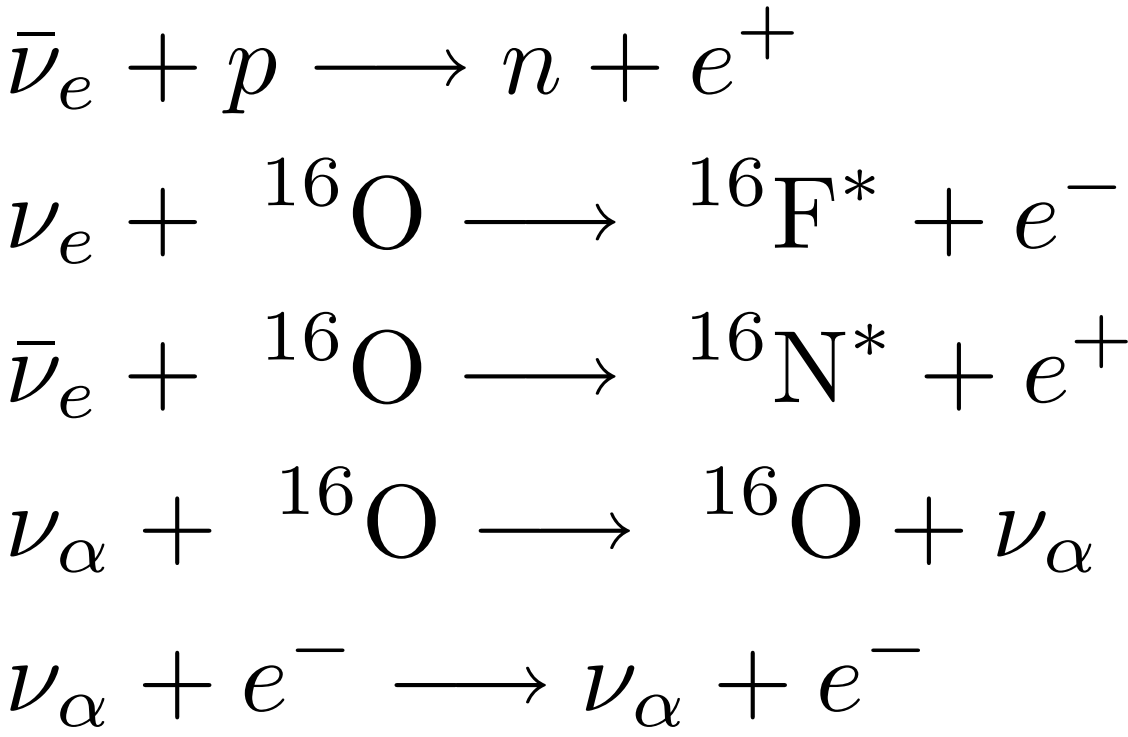
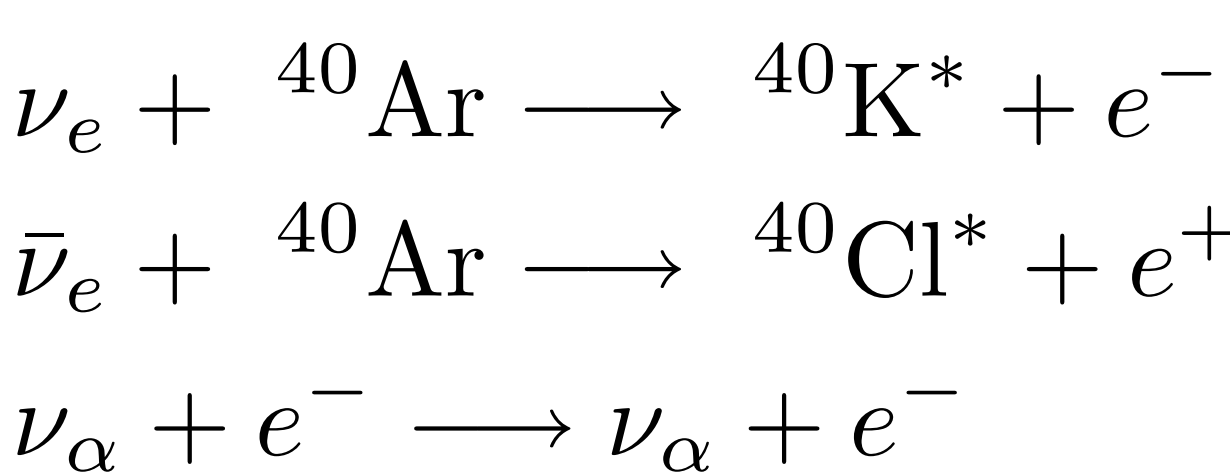
$$e^- + e^+ \rightleftharpoons \nu + \bar{\nu}$$

$$N + N \rightleftharpoons N + N + \nu + \bar{\nu}$$

$$\nu_\alpha + \bar{\nu}_\alpha \rightleftharpoons \nu_\beta + \bar{\nu}_\beta$$

LArTPC (fictive 34 kton liquid argon time projection chamber)

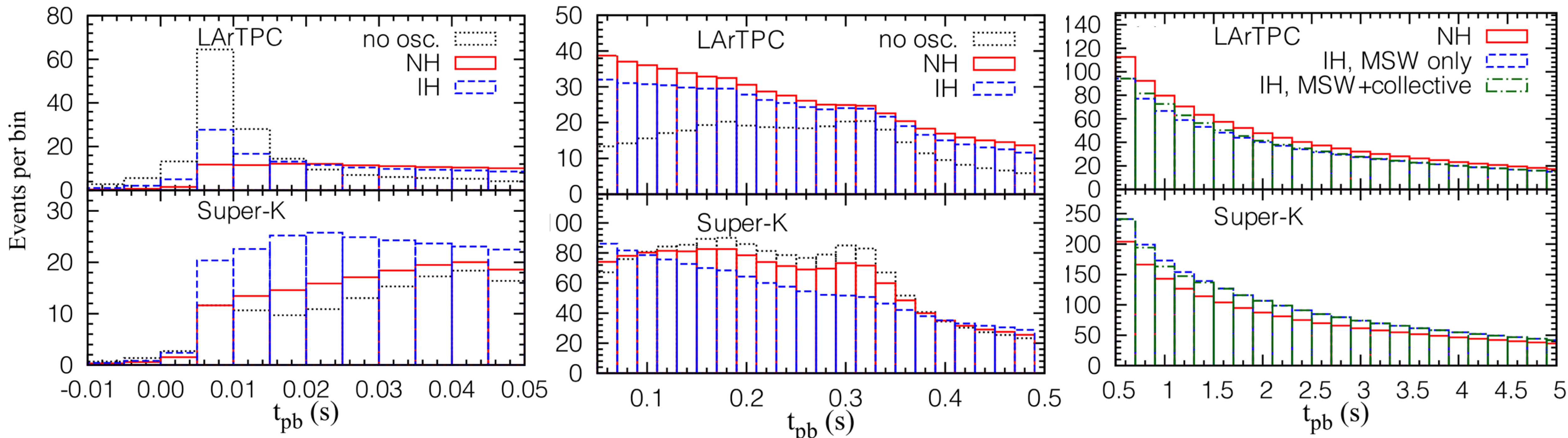
Super-K (50 kton ultra-pure water)



ν_e -burst

accretion phase

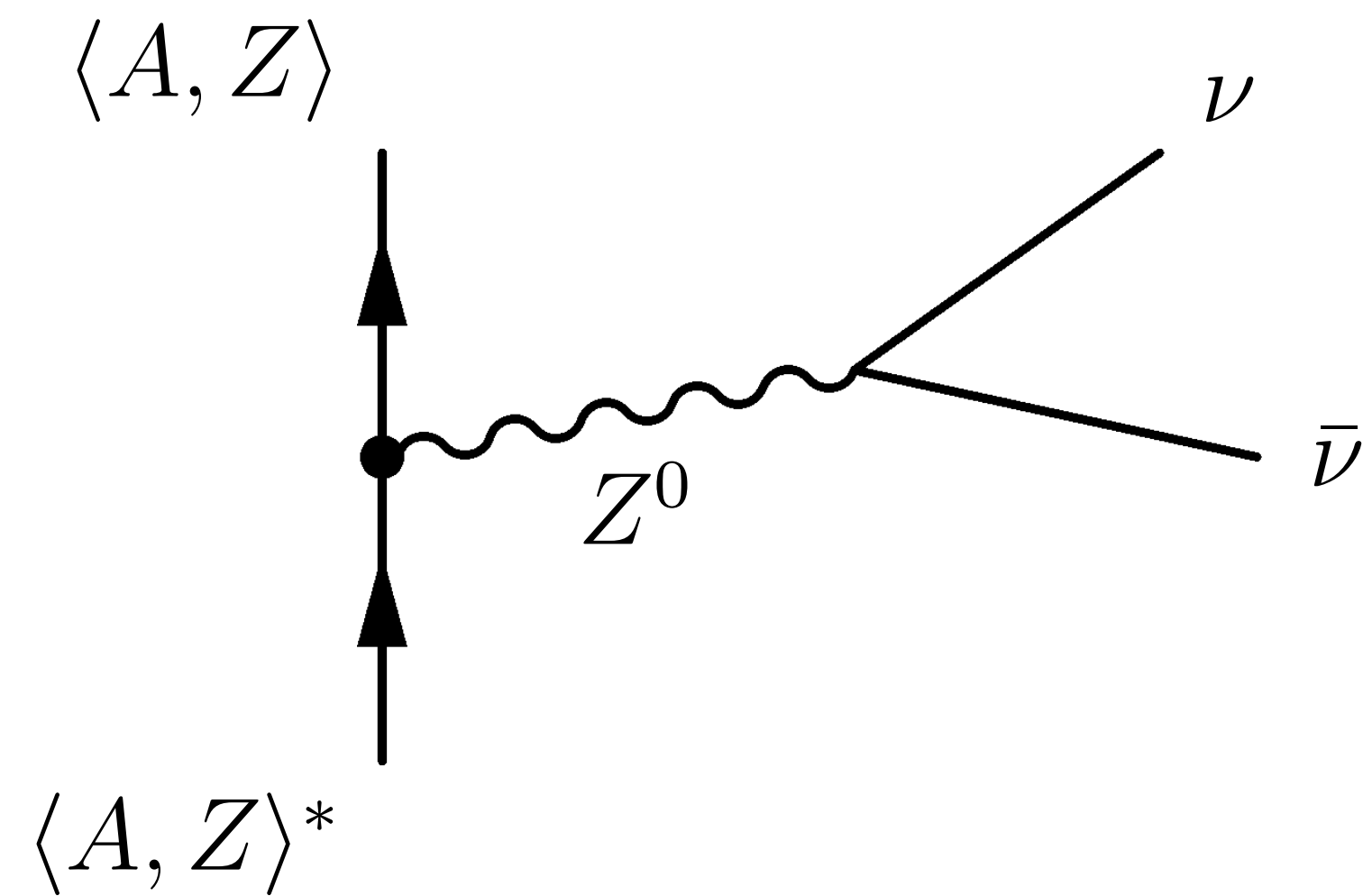
deleptonization



weak rates during stellar core collapse

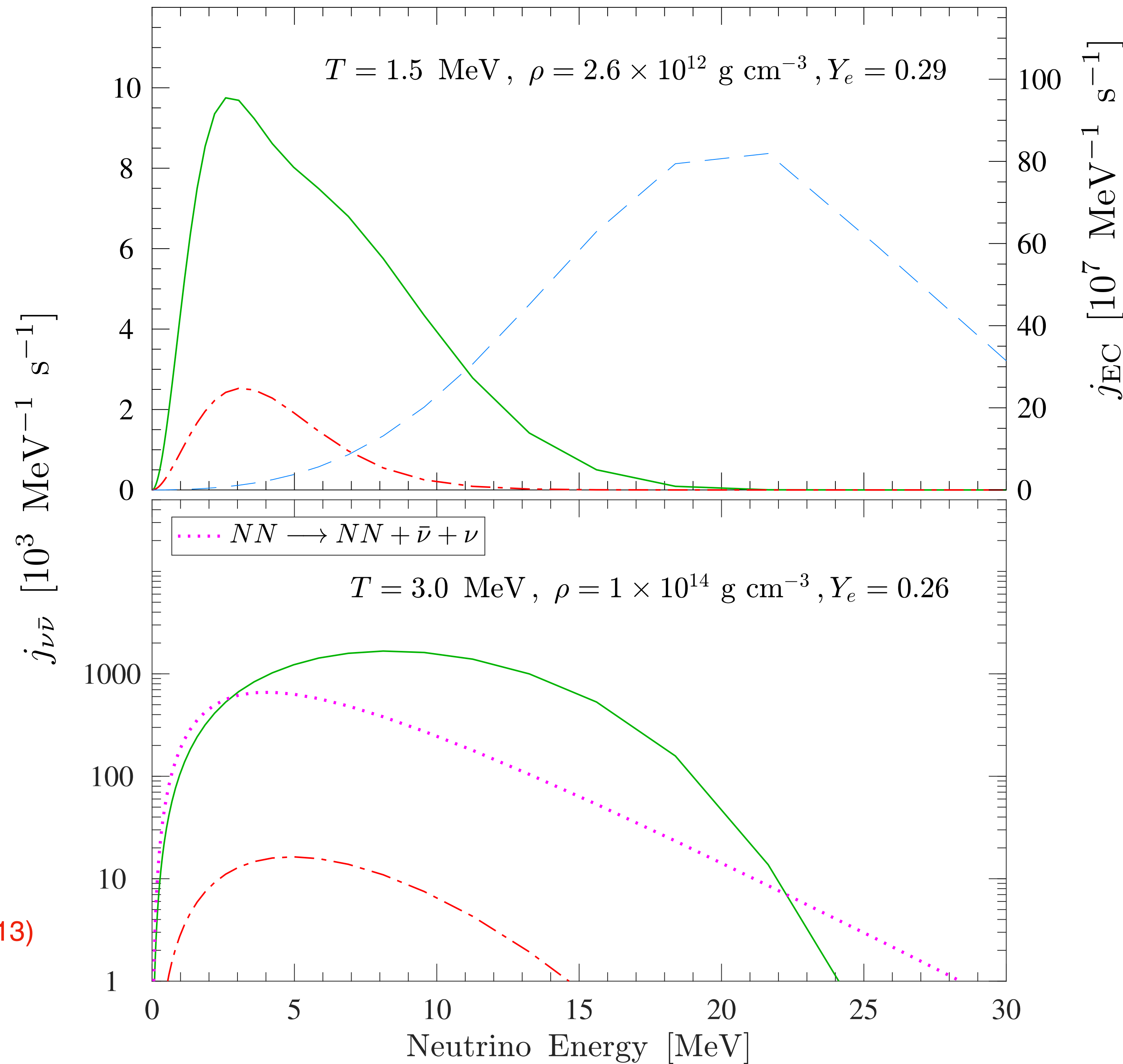
$$e^{-} + \langle A, Z \rangle \rightarrow \nu_e + \langle A, Z - 1 \rangle$$

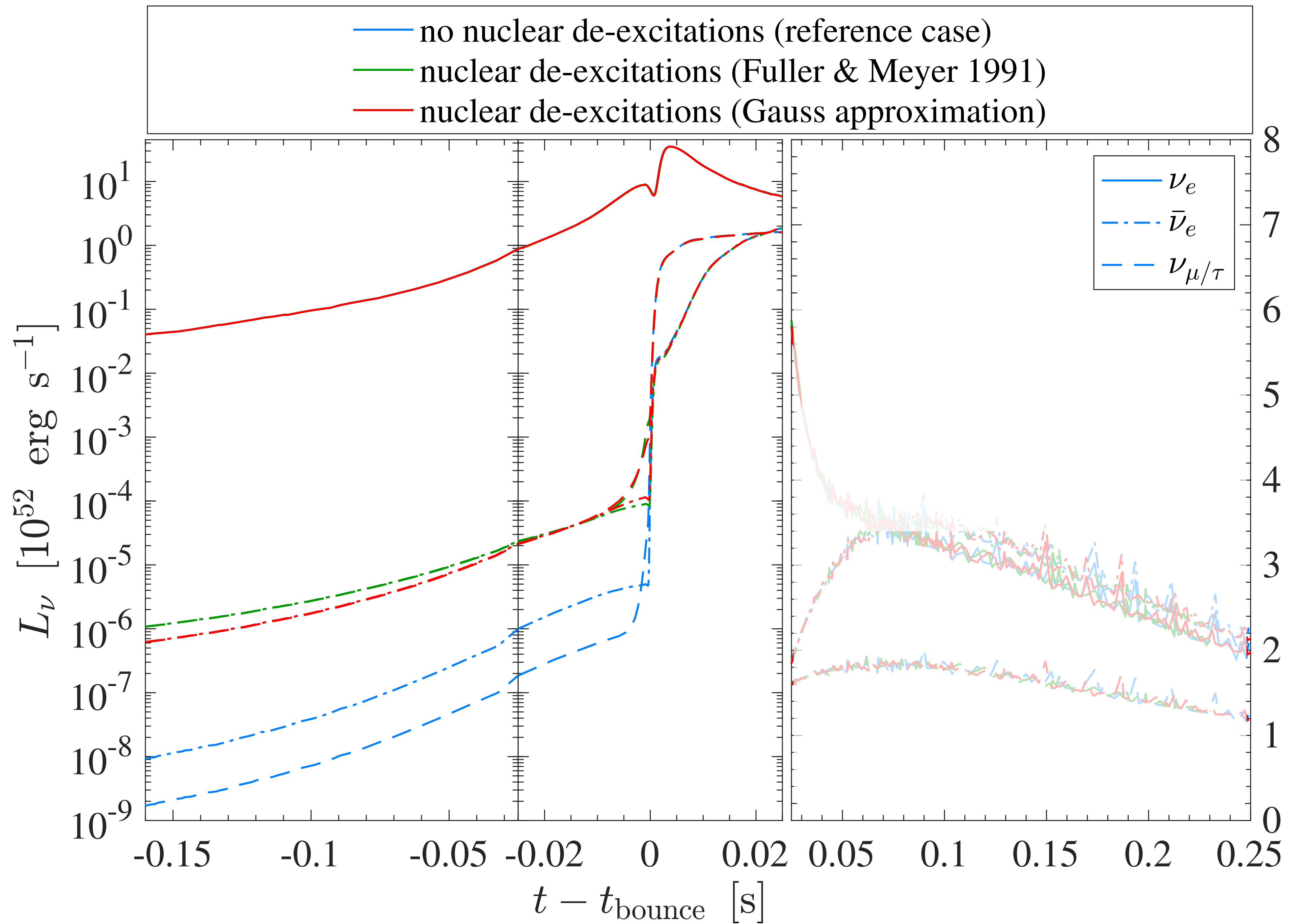
$$\langle \lambda_{\text{EC}} \rangle = \frac{\sum_{A,Z} n_{A,Z} \lambda_{A,Z}}{\sum_{A,Z} n_{A,Z}}$$

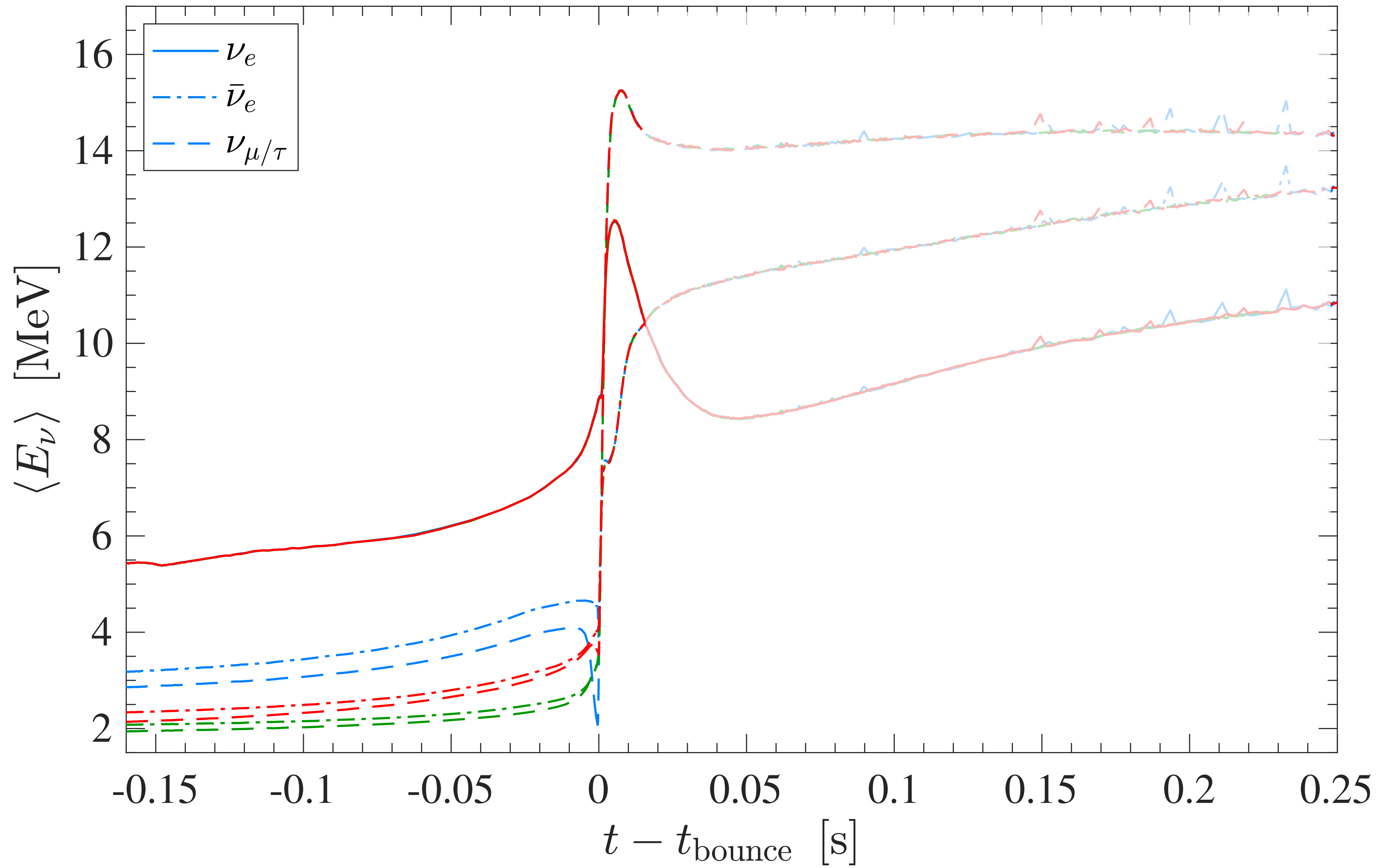


Fuller & Meyer, ApJ 376, 701 (1991)

Fischer, Martinez-Pinedo & Langanke Phys. Rev. C88, 06504 (2013)







Nuclear Statistical Equilibrium

$$n_{A,Z} \propto g_{A,Z}(T) \exp \left\{ \frac{\mu_{A,Z} - M_{A,Z}}{T} \right\}$$

(Rauscher)

$$g(T) = g_0 + \int_0^{E_{\text{max}}} dE \, \rho_{A,Z}(E) \, e^{E/T}$$

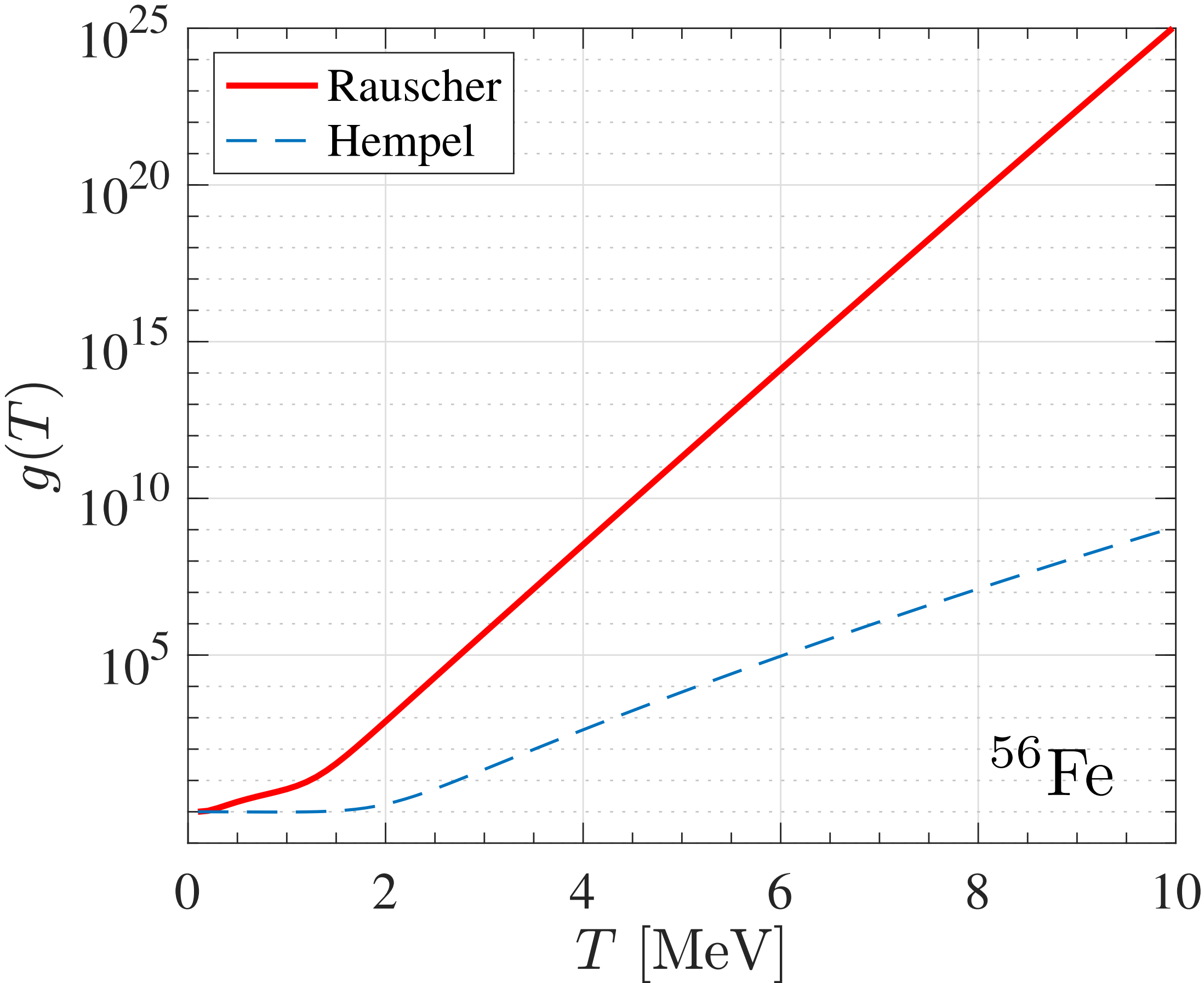
$$E_{\text{max}} = \min(S_n, S_p)$$

(Hempel)

$$g(T) = g_0 + \int_0^{\infty} dE \, \rho_{A,Z}(E) \, e^{E/T} \, \gamma_{A,Z}(E, T)$$

(level density, Bethe formula)

$$\rho \propto \frac{1}{E^{5/4}} \exp \left\{ 2\sqrt{aE} \right\} \qquad (a = A/8 \text{ [MeV}^{-1}\text{)])}$$

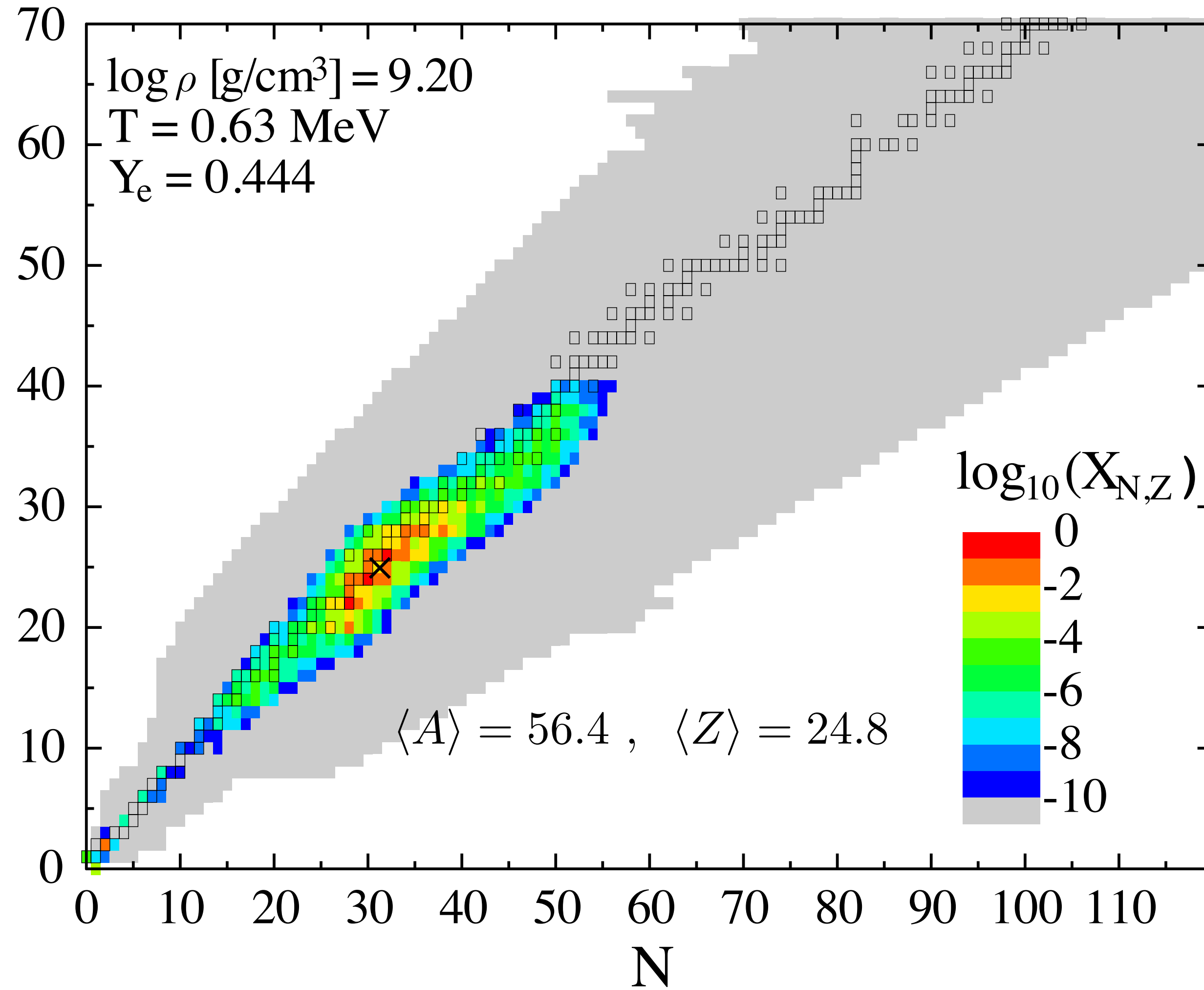


Phys. Rev. C 56, p.1613 (1997)

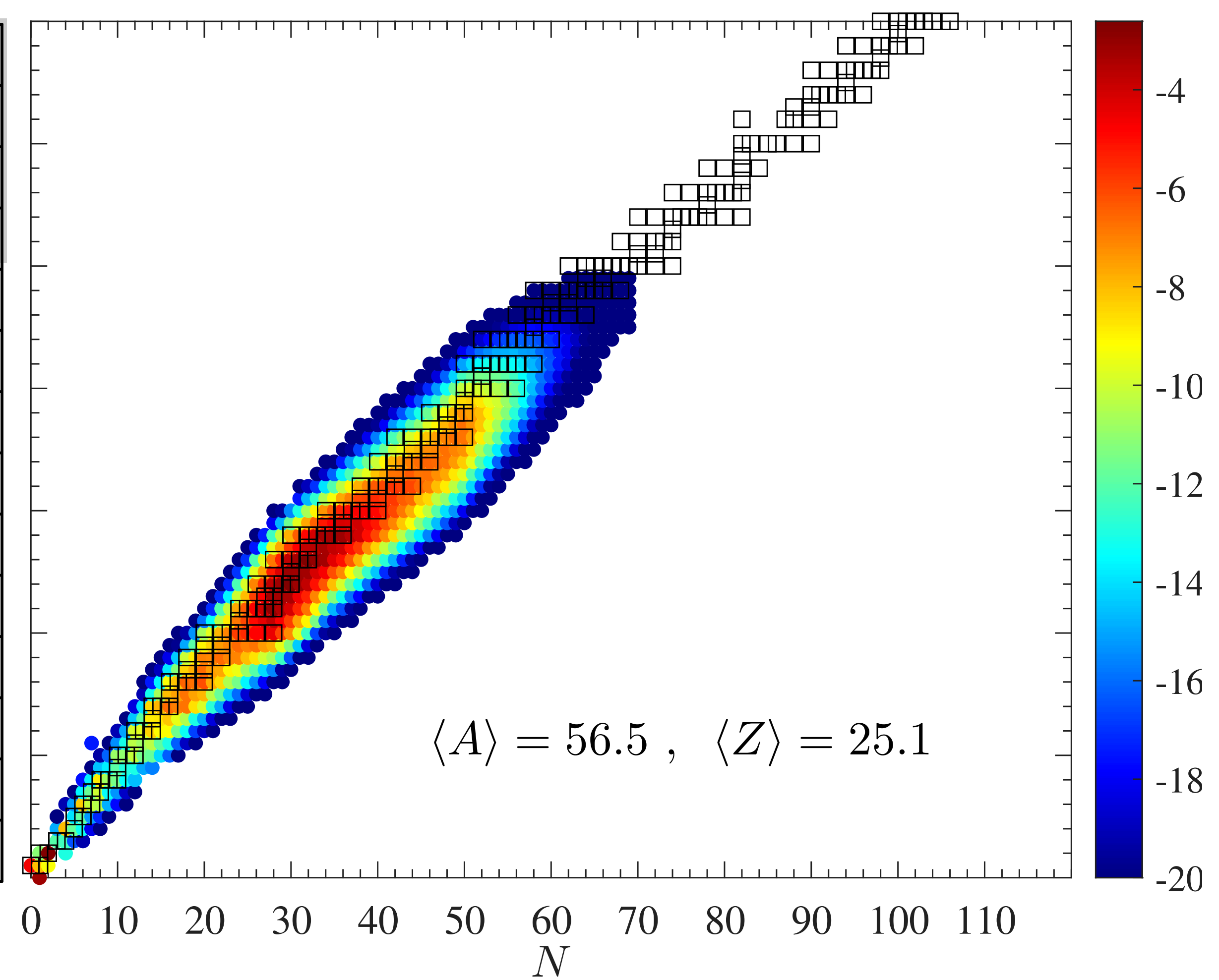
Astrophys. J. Suppl., 147, p. 403 (2003)

Nucl. Phys. A837, p.210 (2010)

M. Hempel

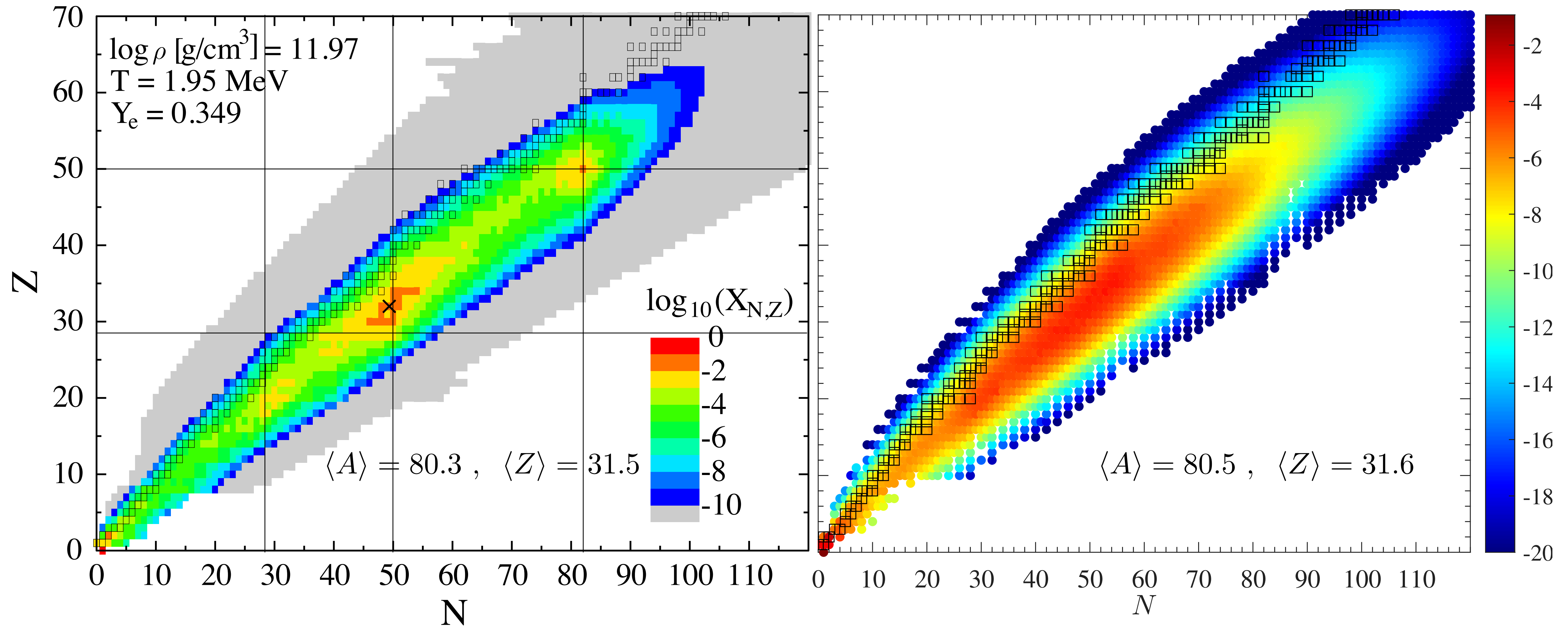


T. Rauscher



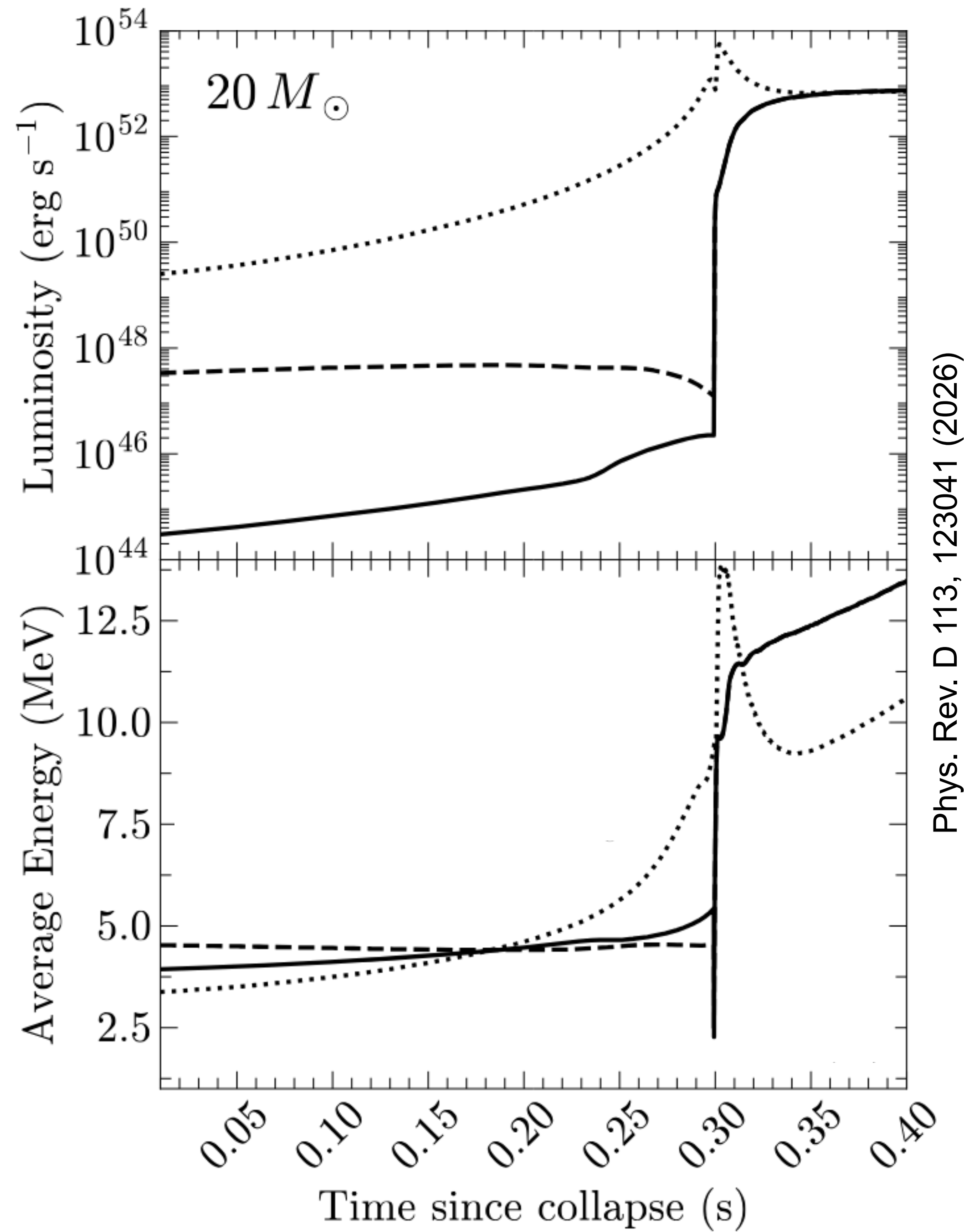
M. Hempel

T. Rauscher



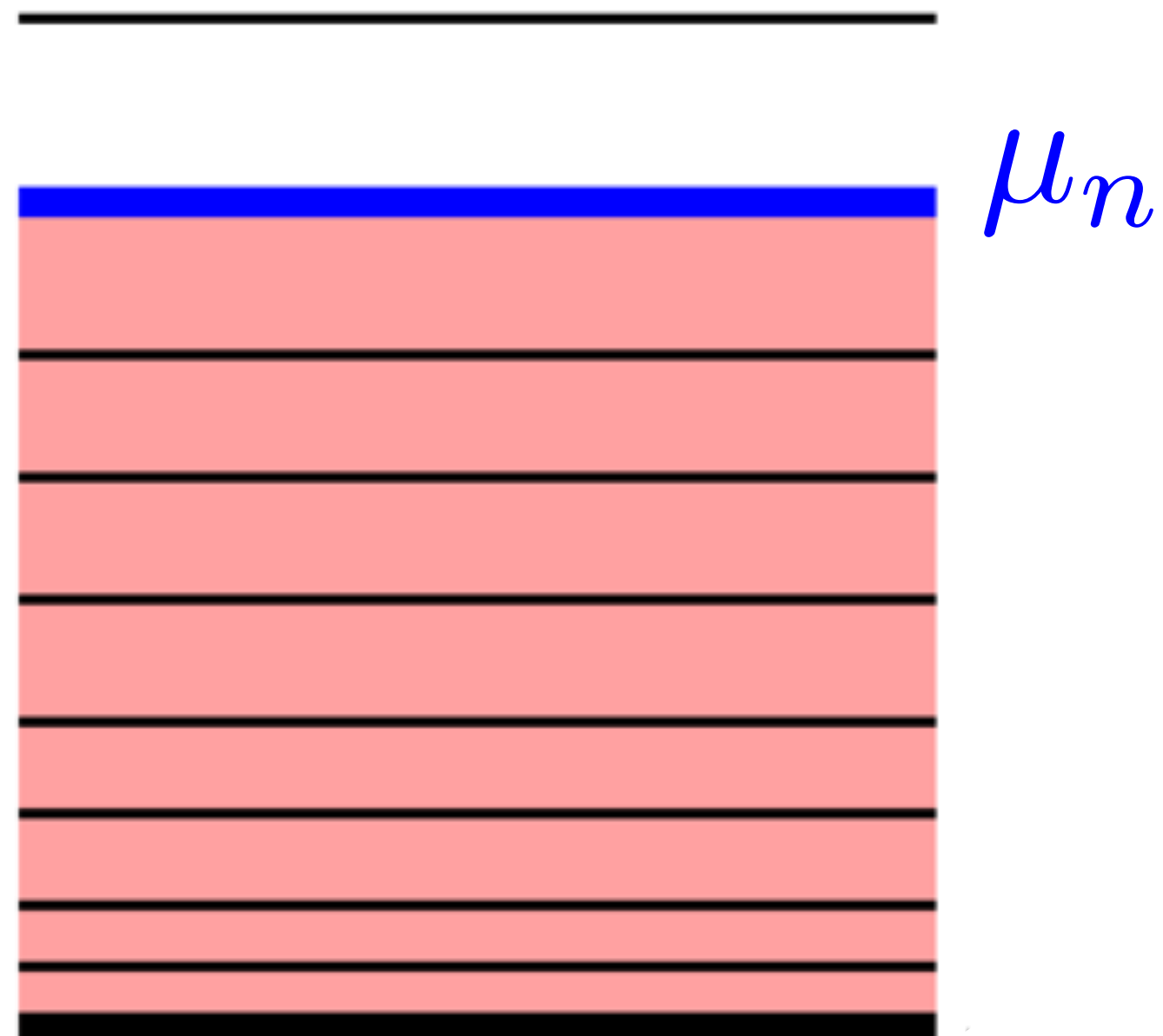
$$\langle A, Z \rangle \longrightarrow \langle A, Z + 1 \rangle + e^- + \bar{\nu}_e$$

- FT-QRPA $\bar{\nu}_e$
- Ref. case
- FT-QRPA ν_e

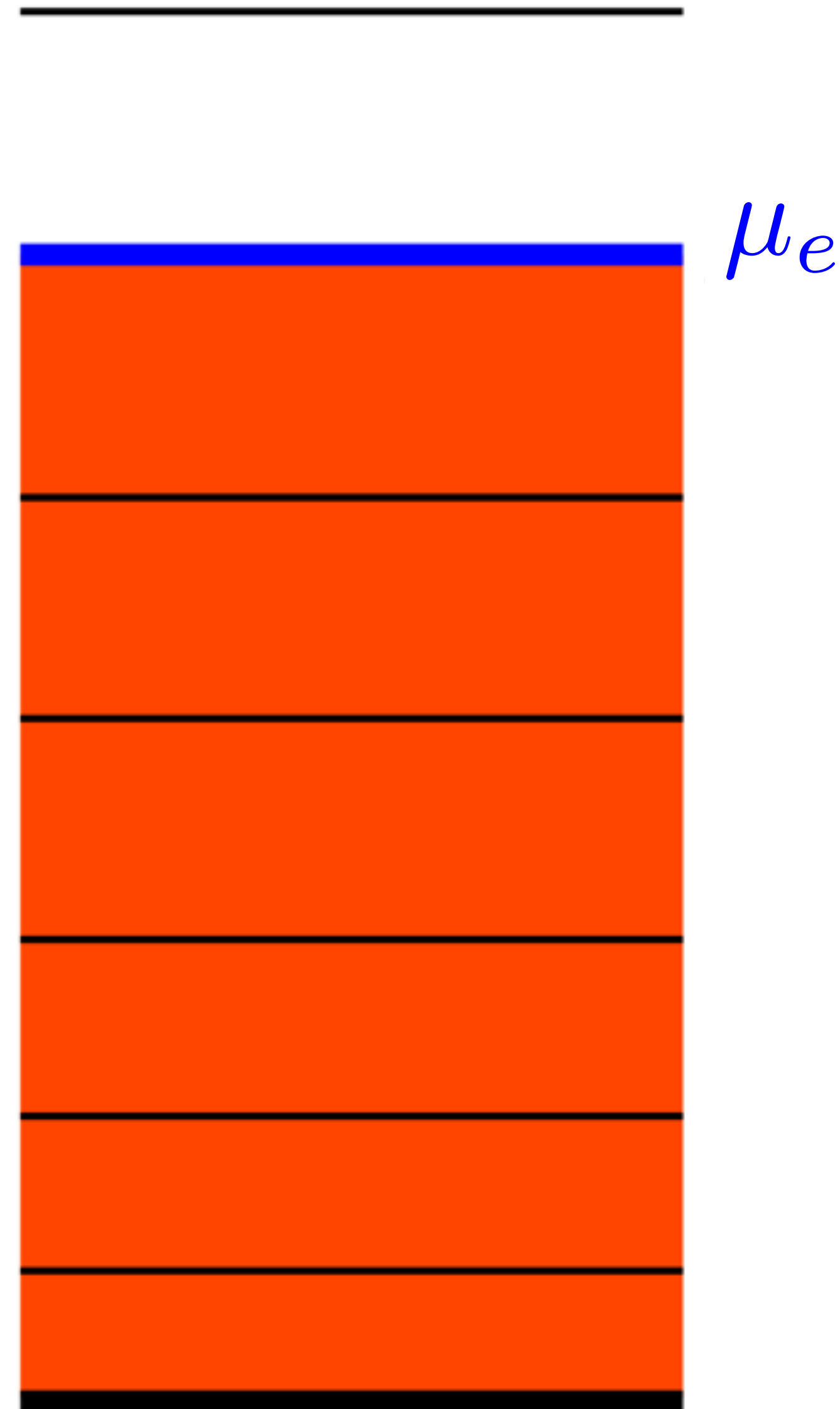
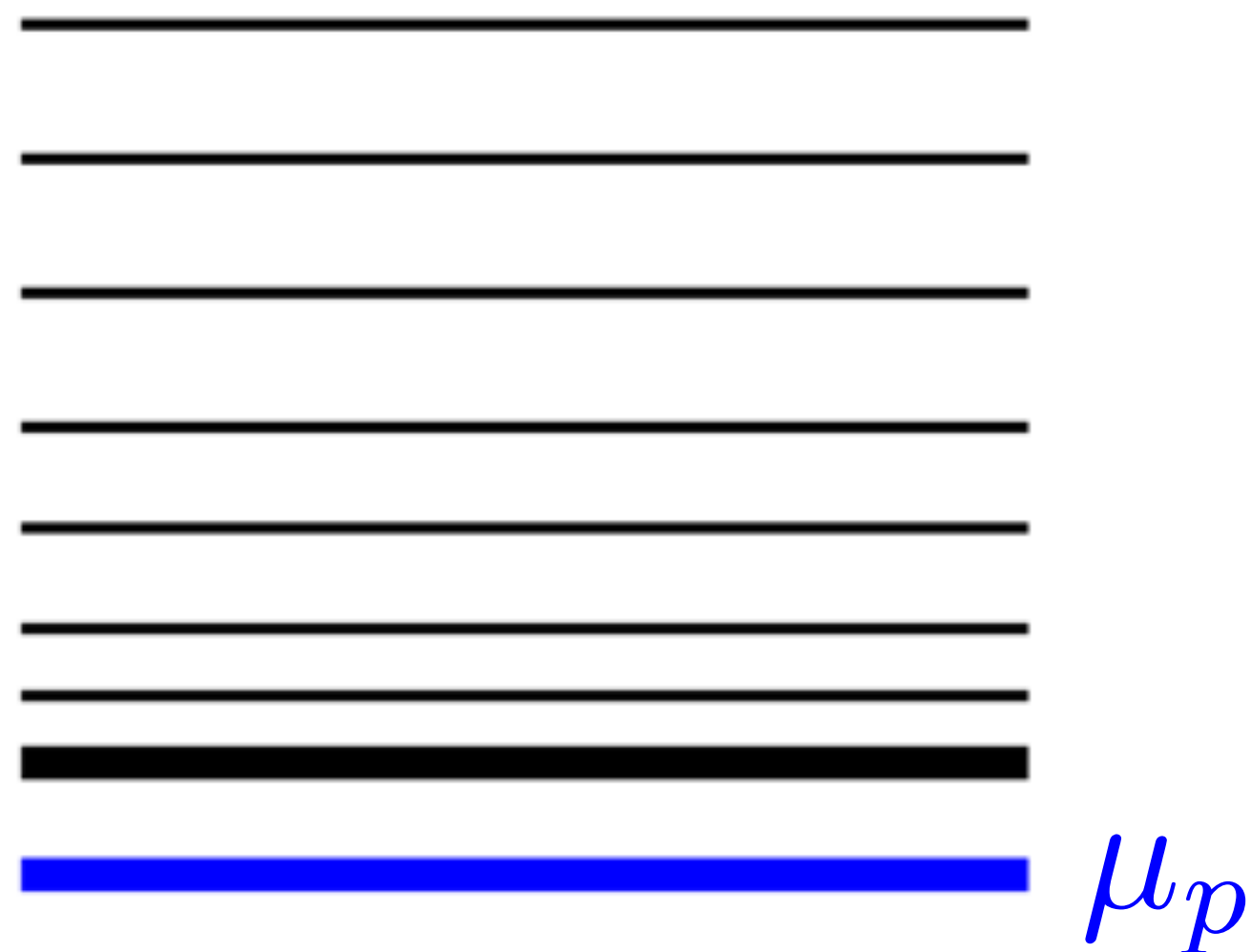
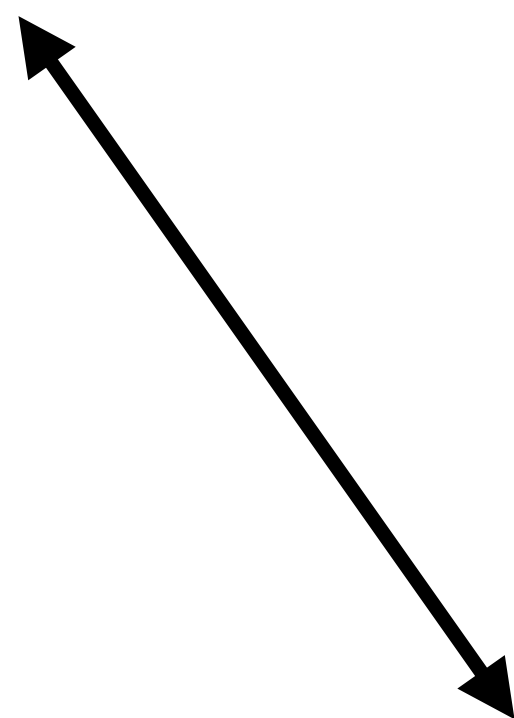


n/p CC weak rates

$$E_n = \sqrt{p^2 + (m_n^*)^2} + U_n$$



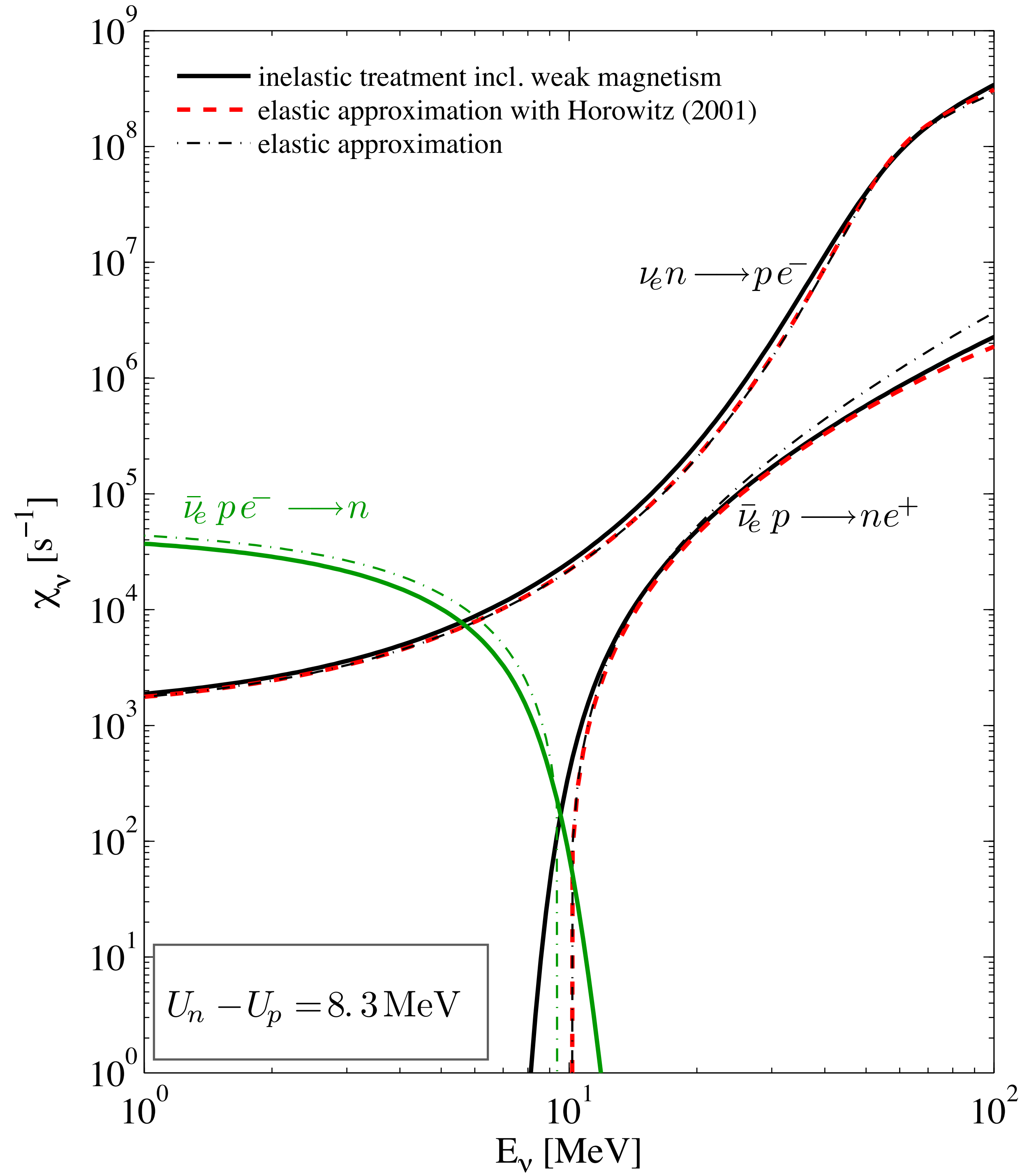
$$E_p = \sqrt{p^2 + (m_p^*)^2} + U_p$$

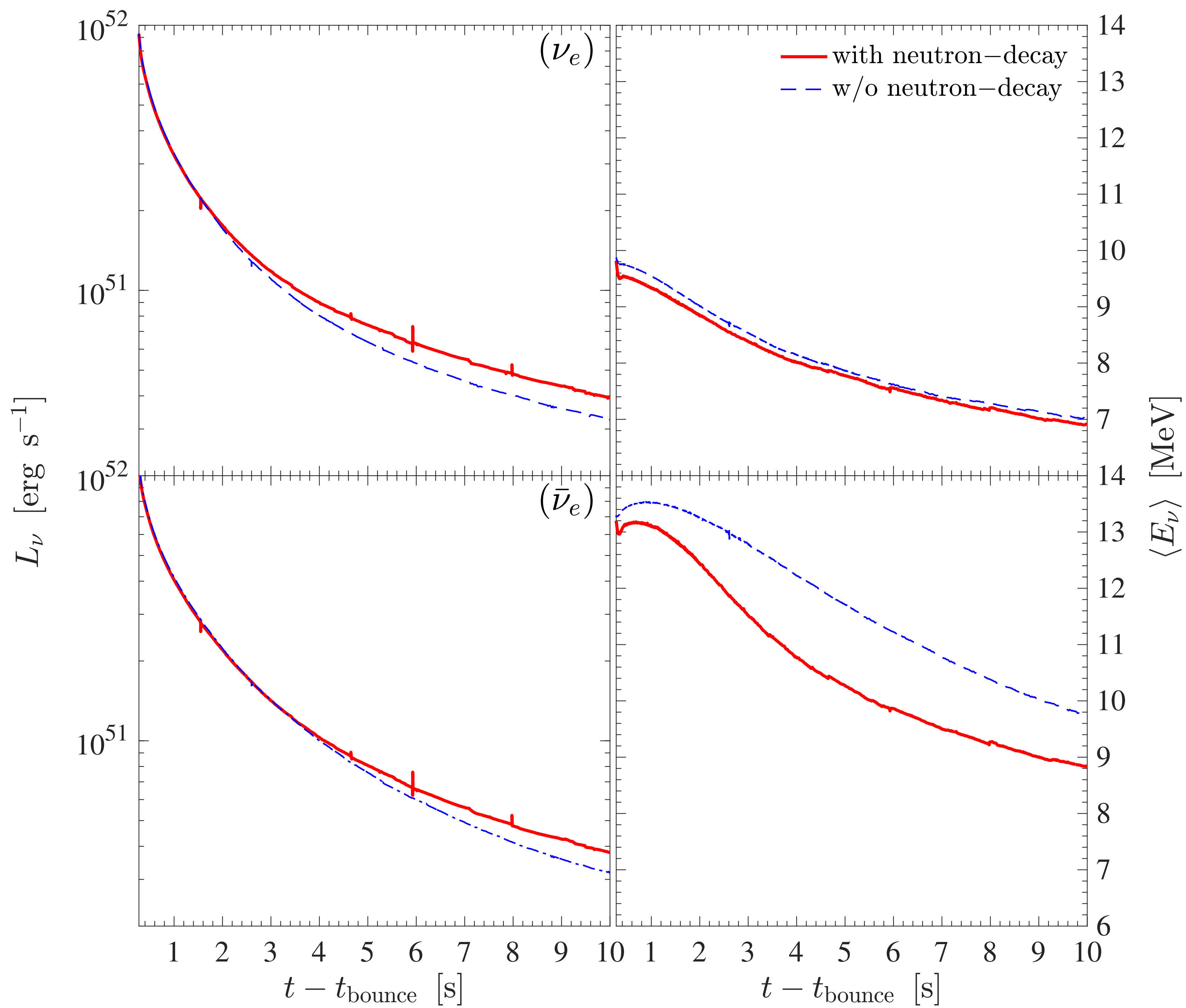


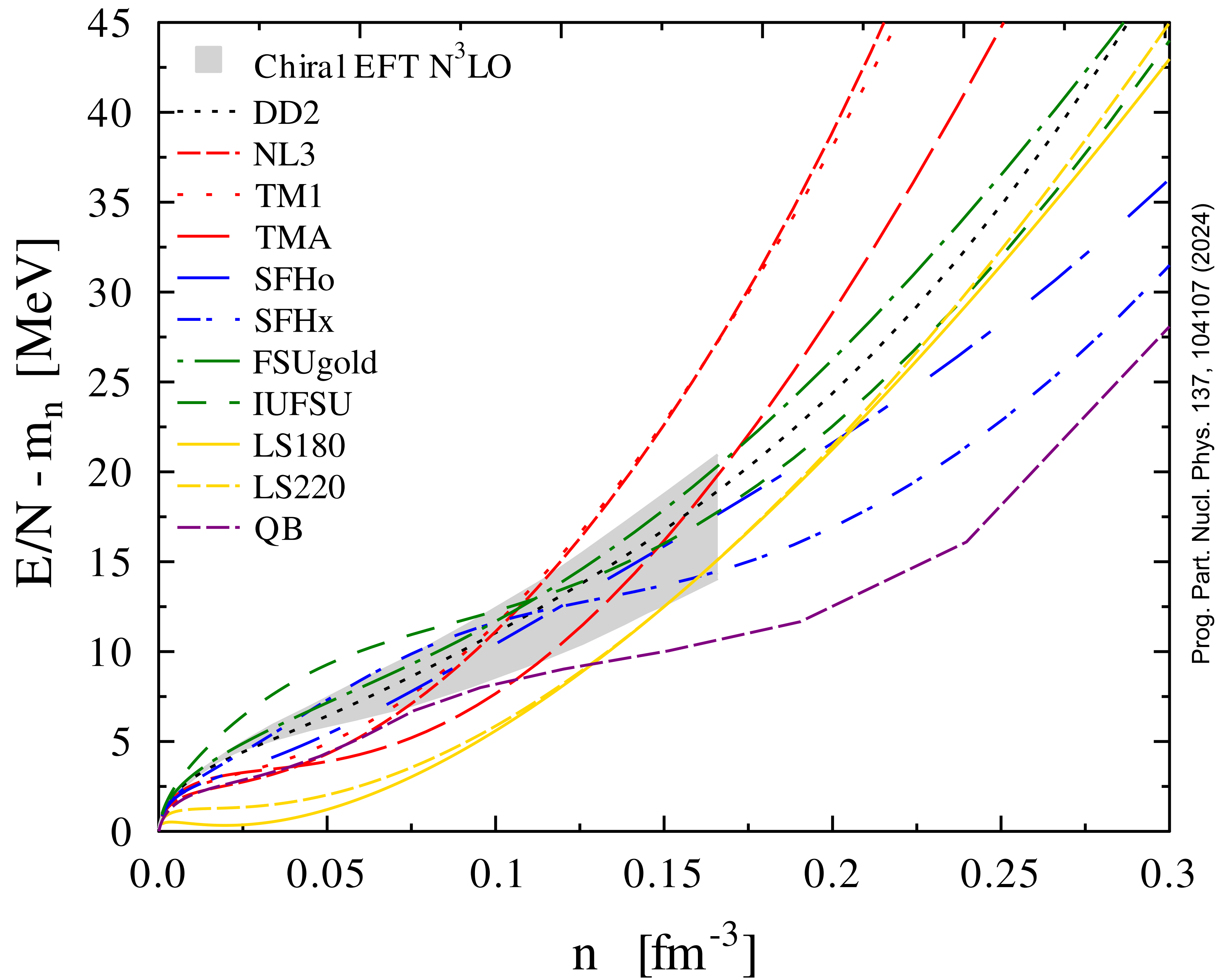
$$\begin{aligned}
T &= 7 \text{ MeV} , \\
Y_p &= 0.1 , \\
\rho &= 2 \times 10^{13} \text{ g cm}^{-3}
\end{aligned}$$

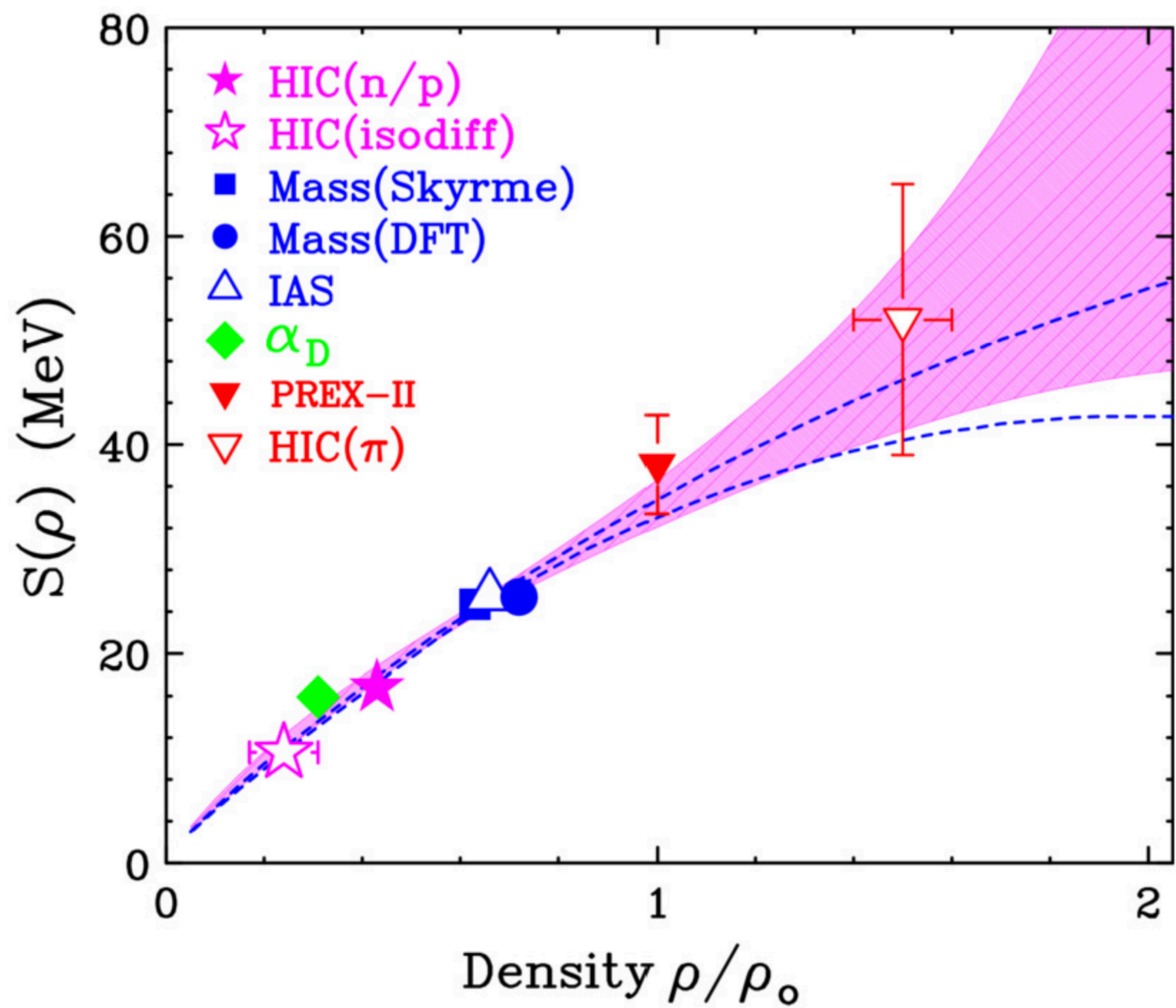
$$\begin{aligned}
E_{e^-} &= E_{\nu_e} + (E_n - E_p) \\
E_{e^+} &= E_{\bar{\nu}_e} - (E_n - E_p) \\
E_{e^-} &= -E_{\bar{\nu}_e} + (E_n - E_p)
\end{aligned}$$

Robert & Reddy, Phys. Rev. C95, 045807 (2017)
Fischer et al., Phys. Rev. C101, 025804 (2020)
Gu et al., Phys. Rev. C102, 023037 (2020)





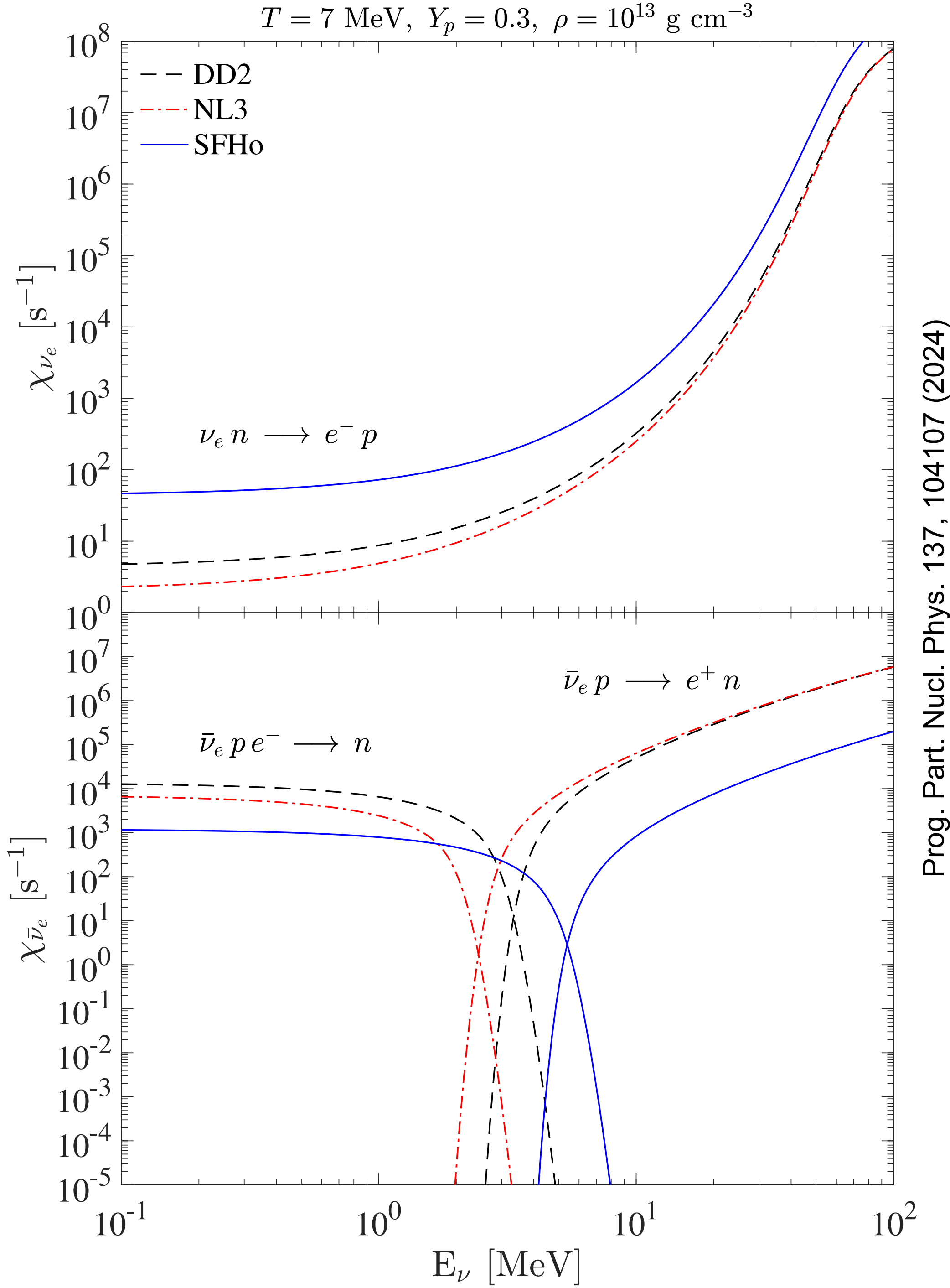




$$G_V(q^2) - \gamma^5 G_A(q^2)$$

$$+ \frac{iF_2(q^2)}{2M_N} \sigma^{\mu\nu} q_\nu^*$$

$$- \frac{2M_N}{m_\pi^2 - q^2} \gamma^5 G_A(q^2) q^{*\mu}$$



What's missing?

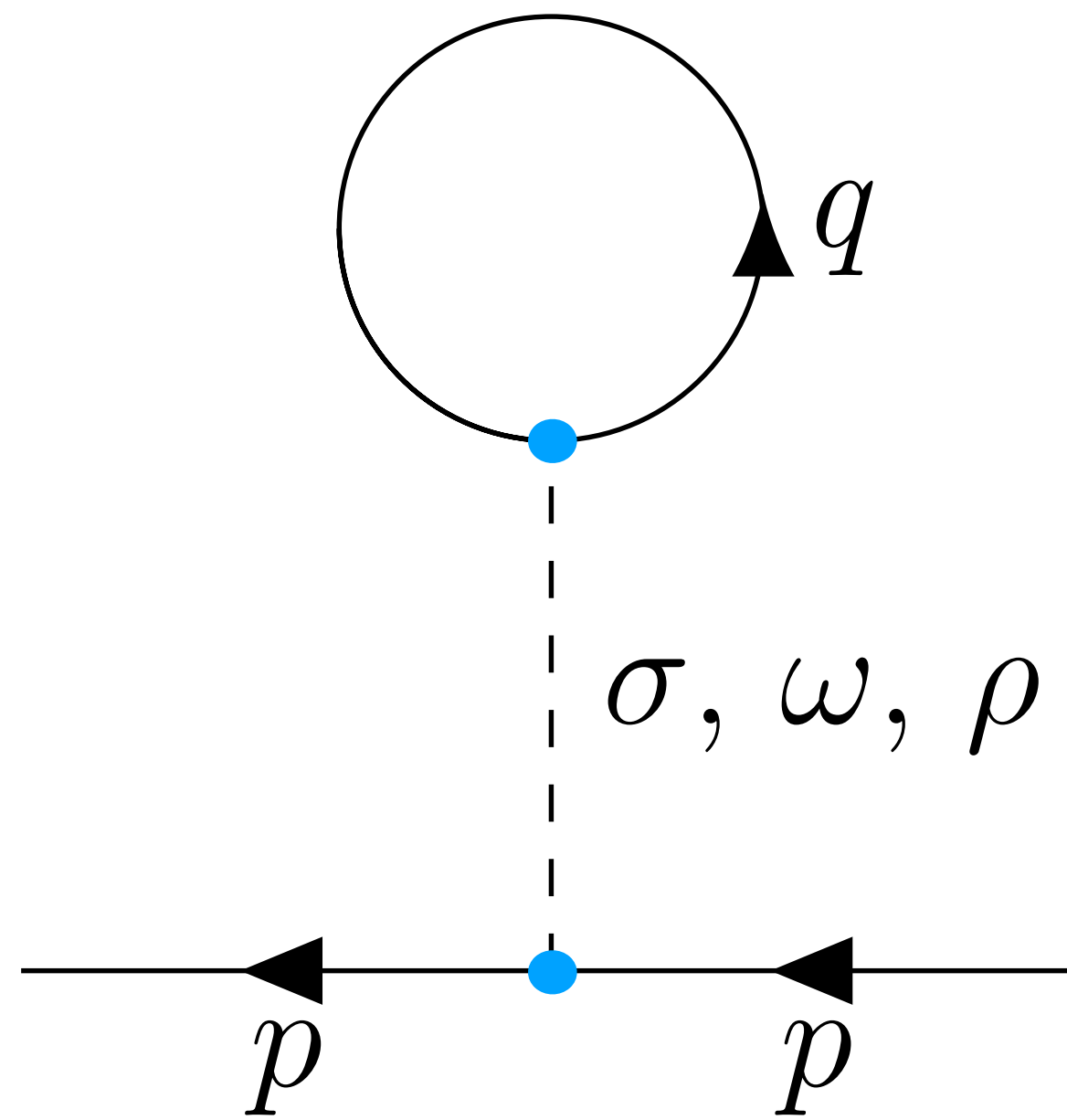
$$a=\{n,p\} \quad : \quad \Sigma_a(p_a) = \Sigma_a^S(p_a) + \gamma^0 \Sigma_a^0(p_a) + \boldsymbol{\gamma} \cdot \hat{\boldsymbol{p}}_a \Sigma_a^V(p_a)$$

$$m_a^*(p_a) \quad = \quad m_a + \Sigma_a^S(p_a)$$

$$\boldsymbol{p}_a^*(p_a) \quad = \quad \boldsymbol{p}_a + \hat{\boldsymbol{p}}_a \Sigma_a^V(p_a)$$

$$E_a^*(p_a) \quad = \quad E_a(p_a) - \Sigma_a^0(p_a)$$

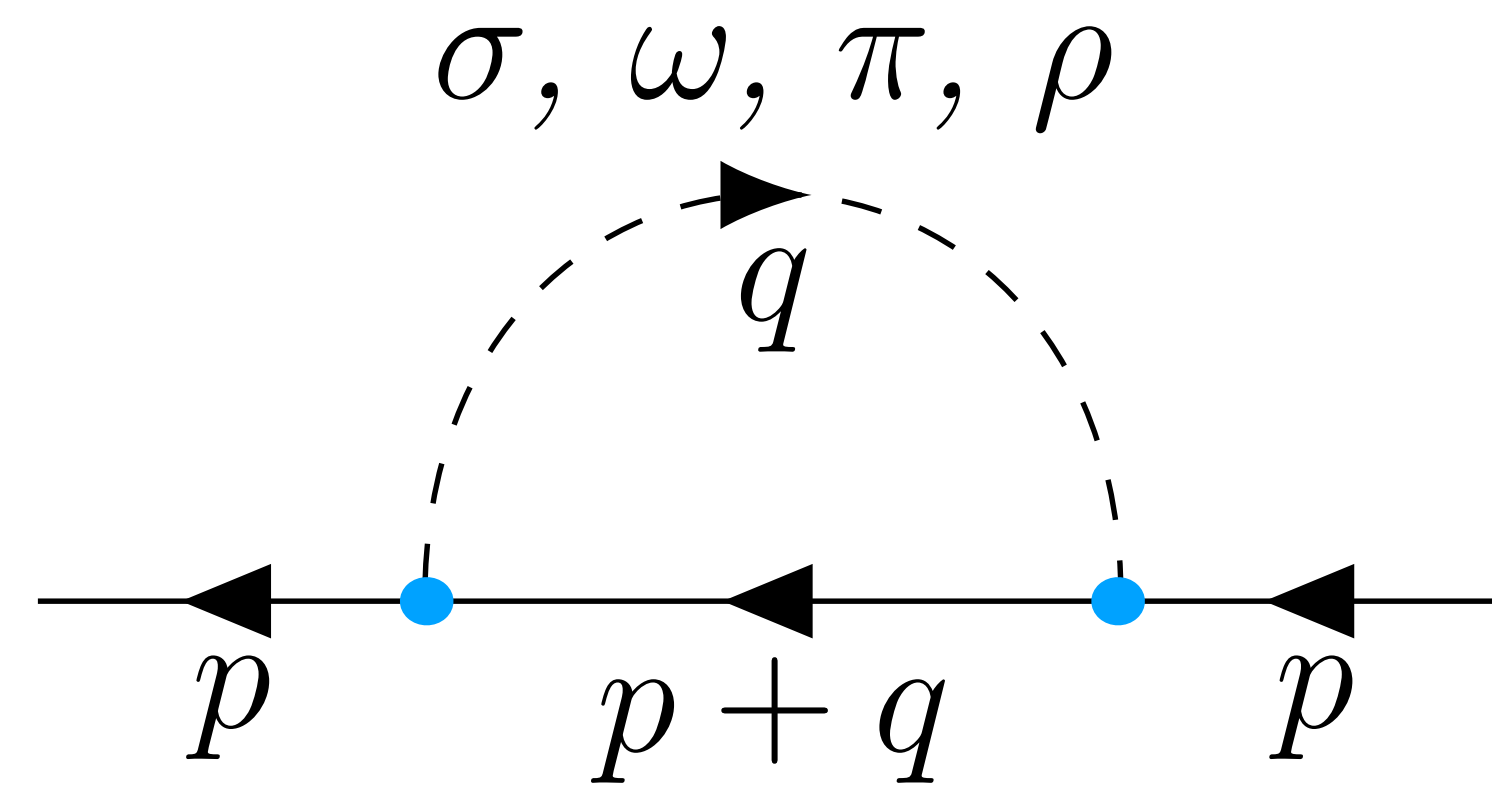
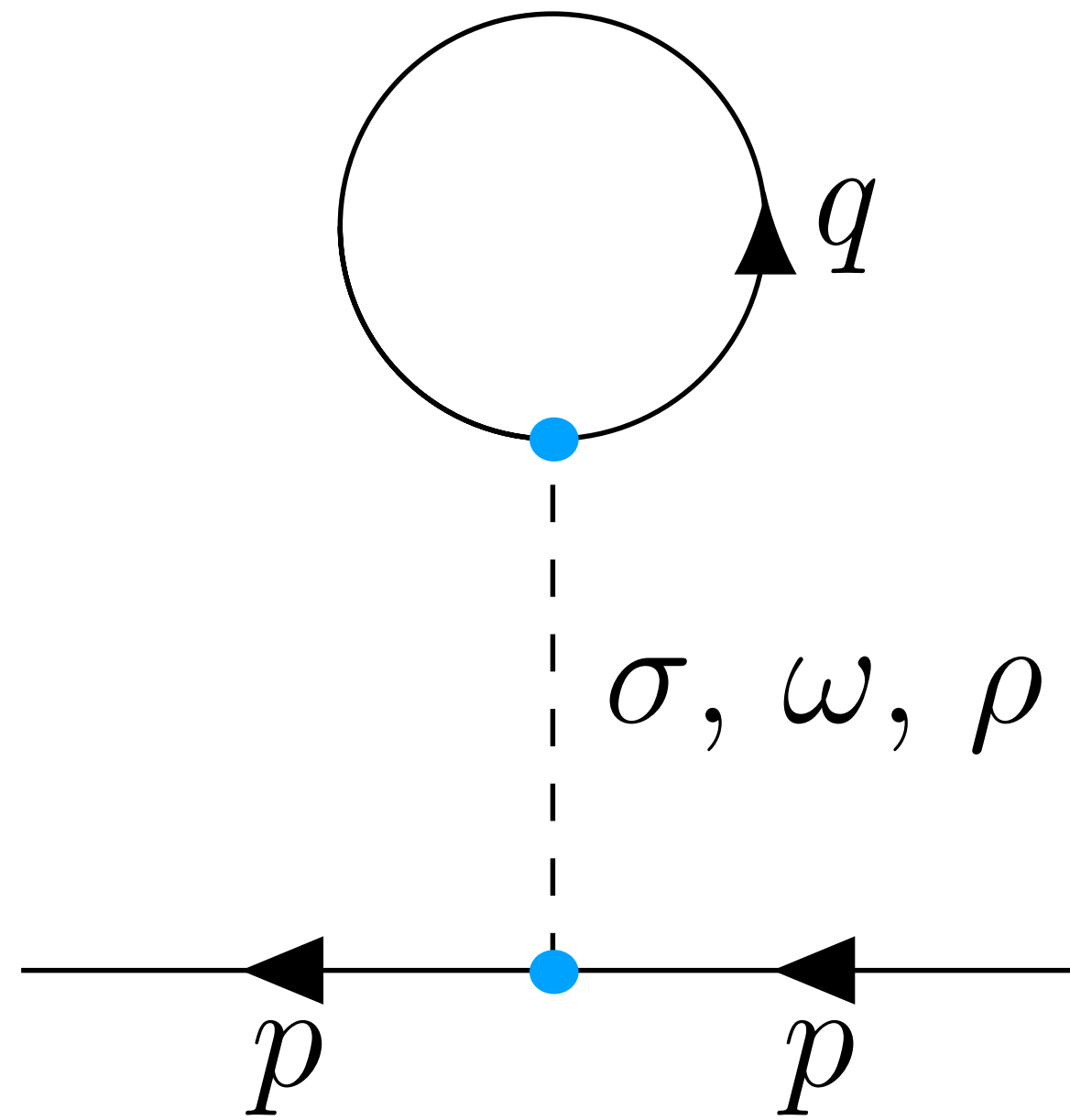
$$\cancel{\Sigma_a(p_a)} = \cancel{\Sigma_a^S(p_a)} + \gamma^0 \cancel{\Sigma_a^0(p_a)} + \cancel{\gamma \cdot \hat{\mathbf{p}}_a \Sigma_a^V(p_a)}$$

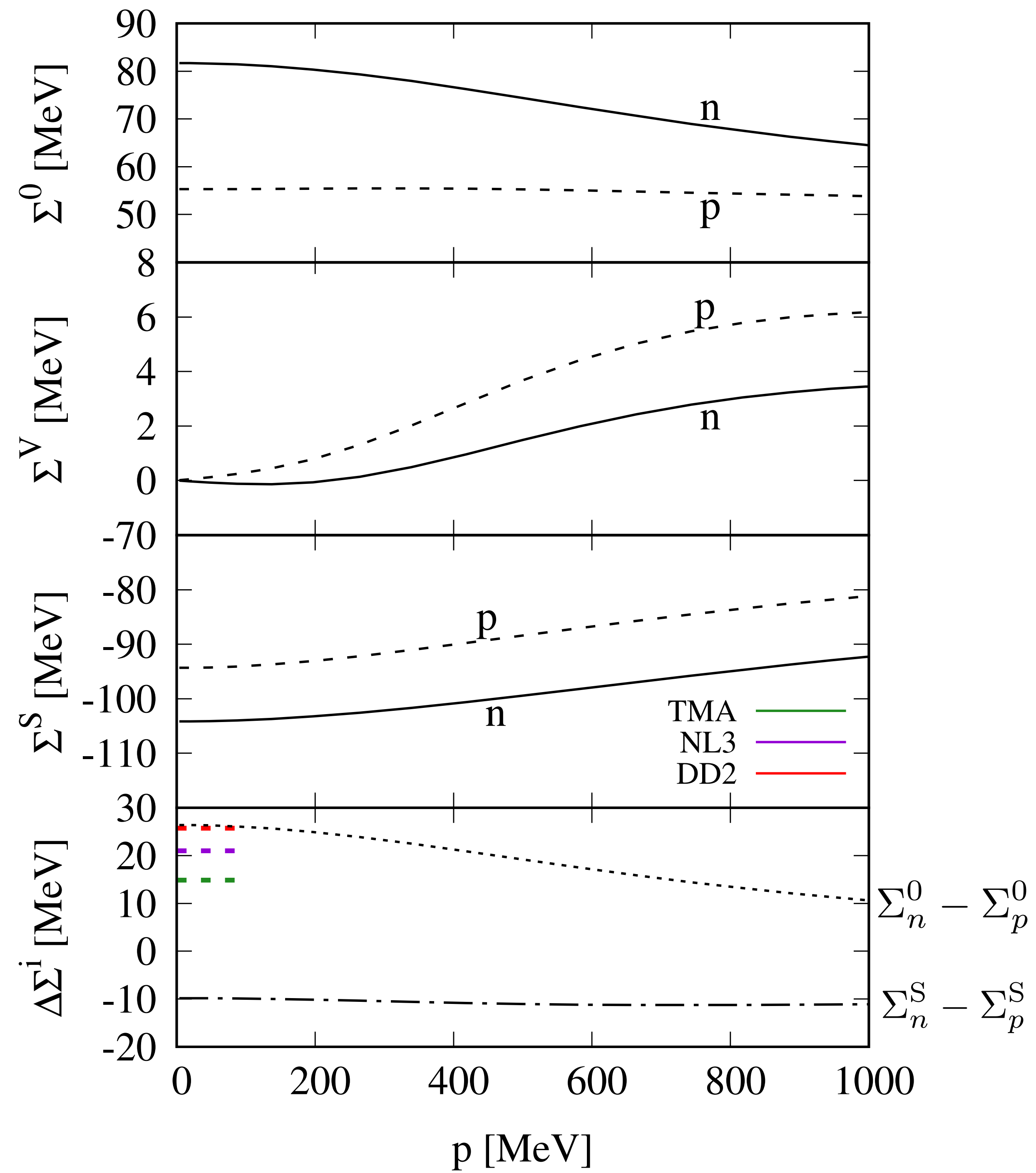




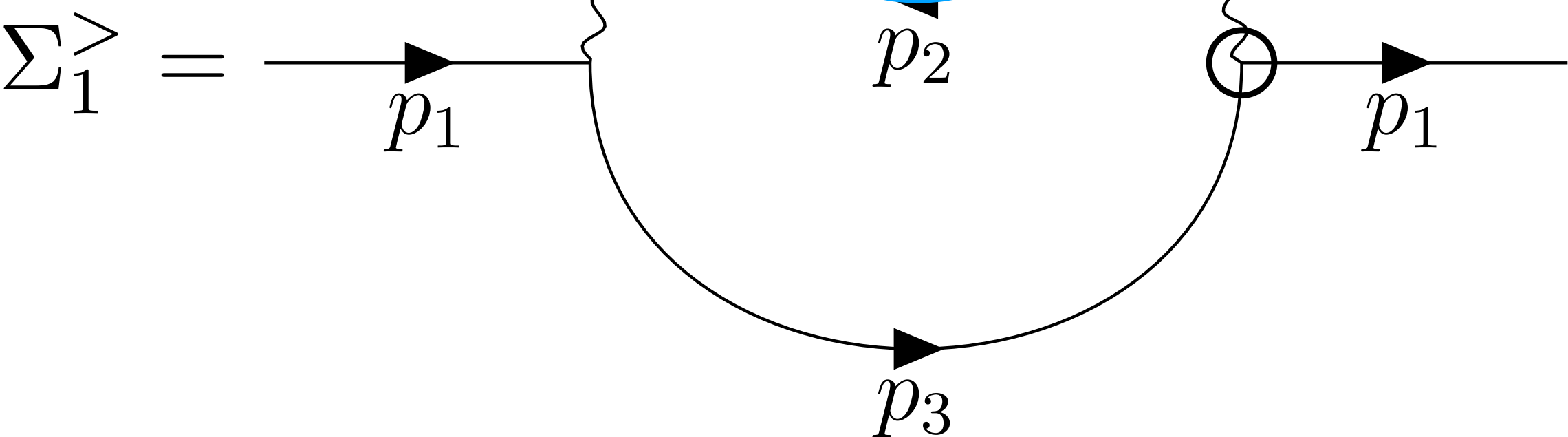
Kamil Sokolowski

$$\Sigma_a(p_a) = \Sigma_a^S(p_a) + \gamma^0 \Sigma_a^0(p_a) + \boldsymbol{\gamma} \cdot \hat{\mathbf{p}}_a \Sigma_a^V(p_a)$$





$$\nu_1(p_1) + N_2(p_2) \longrightarrow l_3(p_3) + N_4(p_4) :$$



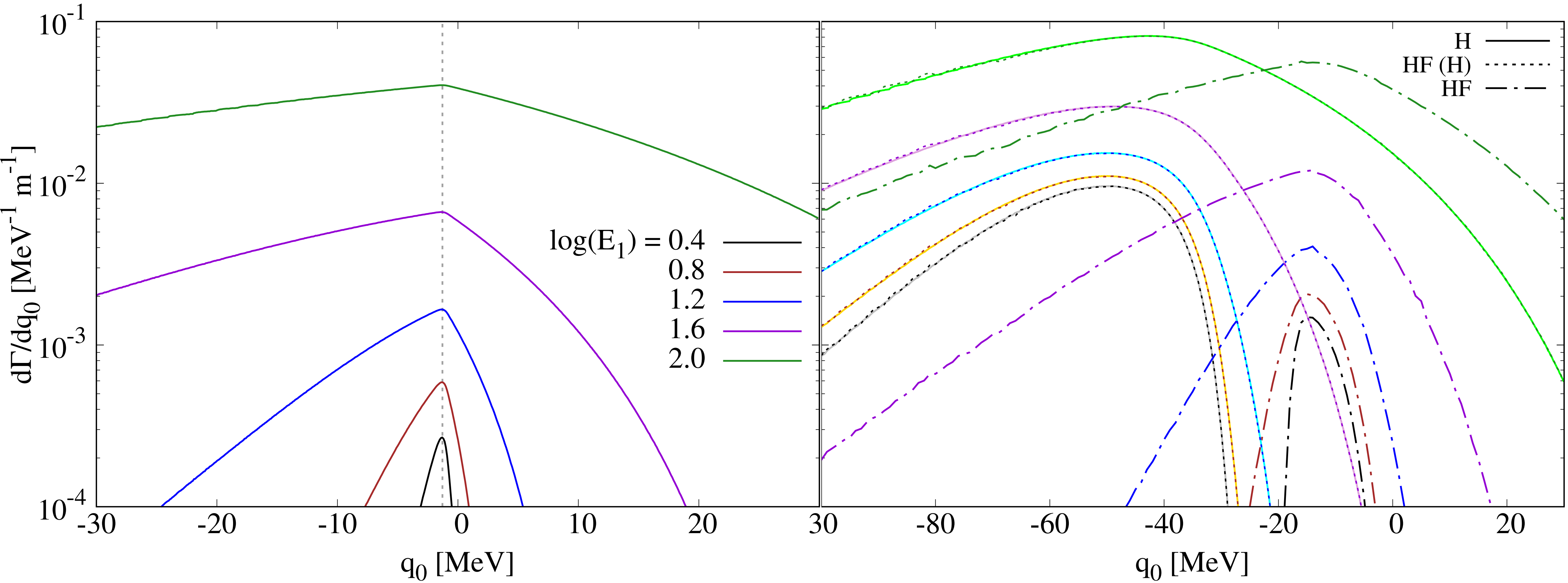
$$\Gamma(E_1) = \frac{1}{2E_1} \text{Tr} \left\{ \not{p}_1 \Sigma_1^>(E_1, \mathbf{p}_1) \right\}$$

$$\Sigma_1^>(E_1, \mathbf{p}_1) = -2(1 + f_1(E_1)) \text{Im} \Sigma_1(E_1, \mathbf{p}_1)$$

$$= \frac{G_F^2 C^2}{2} \int \frac{d^4 p_2}{(2\pi)^4} \int \frac{d^4 p_3}{(2\pi)^4} \bar{\Gamma}_L^\mu G_3^>(p_3) \Gamma_L^\nu \text{Tr} \left\{ G_2^<(p_2) \bar{\Gamma}_\mu^H G_4^>(p_4) \Gamma_\nu^H \right\}$$

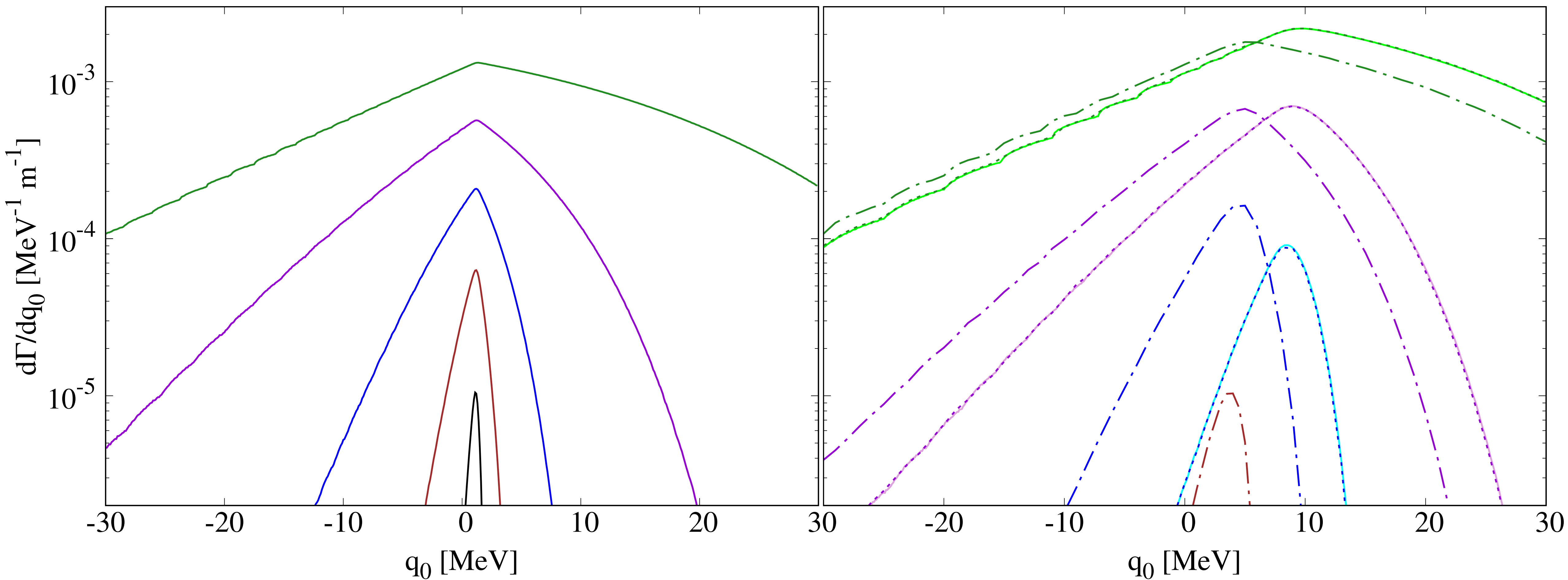
$$\longrightarrow \Gamma(E_1) = \frac{G_F^2 C^2}{4\pi^2} \int \frac{d^3 p_3}{(2\pi)^3} \frac{1}{E_1 E_3} T \sum_n \int \frac{d^3 p_2}{(2\pi)^3} \frac{[1 - f_3(E_3)]}{[1 - \exp(-(q^0 + \Delta\mu)/kT)]} L_{\mu\nu} \text{Im} \tilde{\Pi}^{\mu\nu}$$

$$\nu_e + n \longrightarrow e^- + p$$

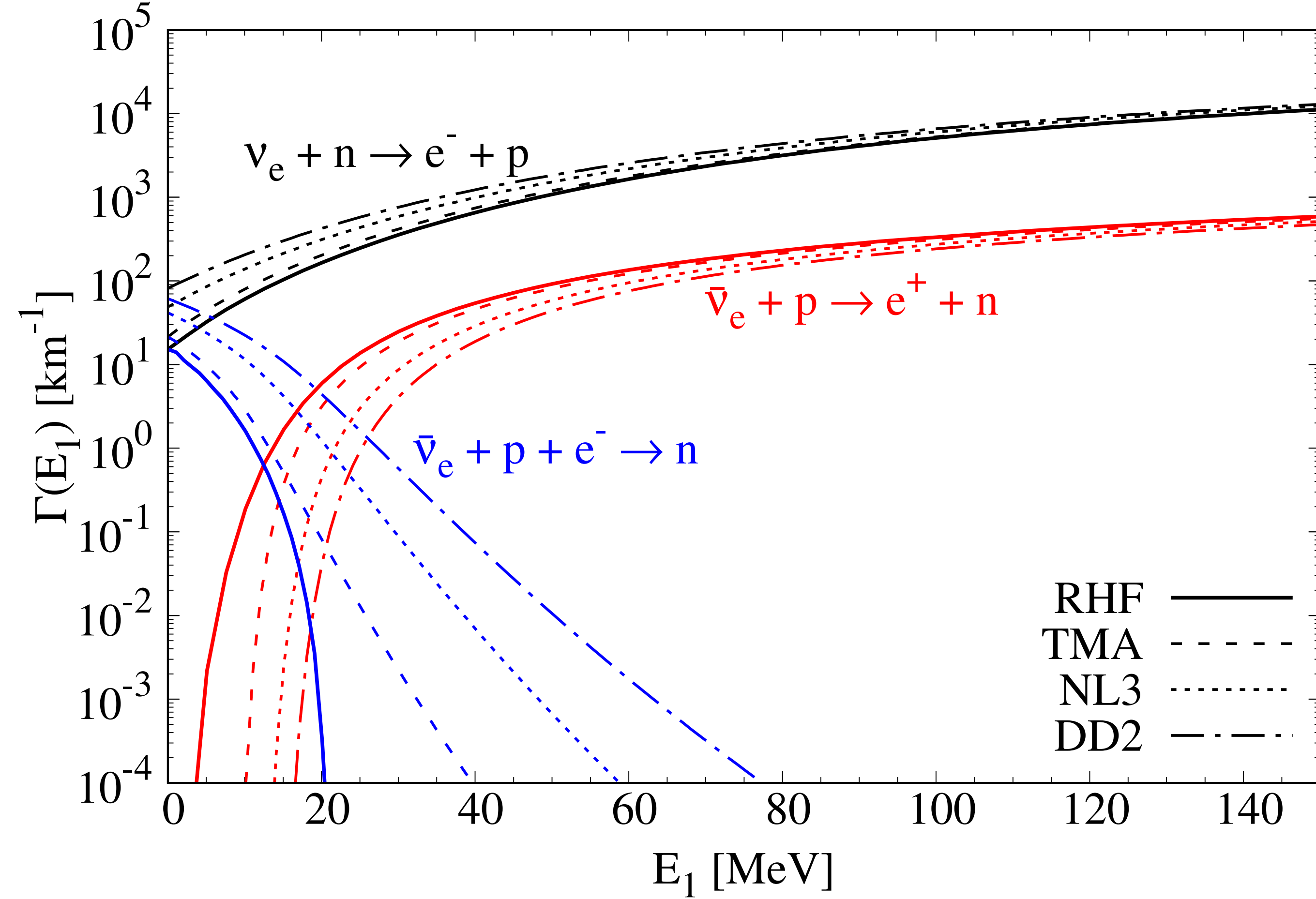


$$E_{\nu_e} - E_e \equiv q_0 \propto -(m_n - m_p) - \boxed{(\Sigma_n^S - \Sigma_p^S)} - (\Sigma_n^0 - \Sigma_p^0)$$

$$\bar{\nu}_e + p \longrightarrow e^+ + n$$

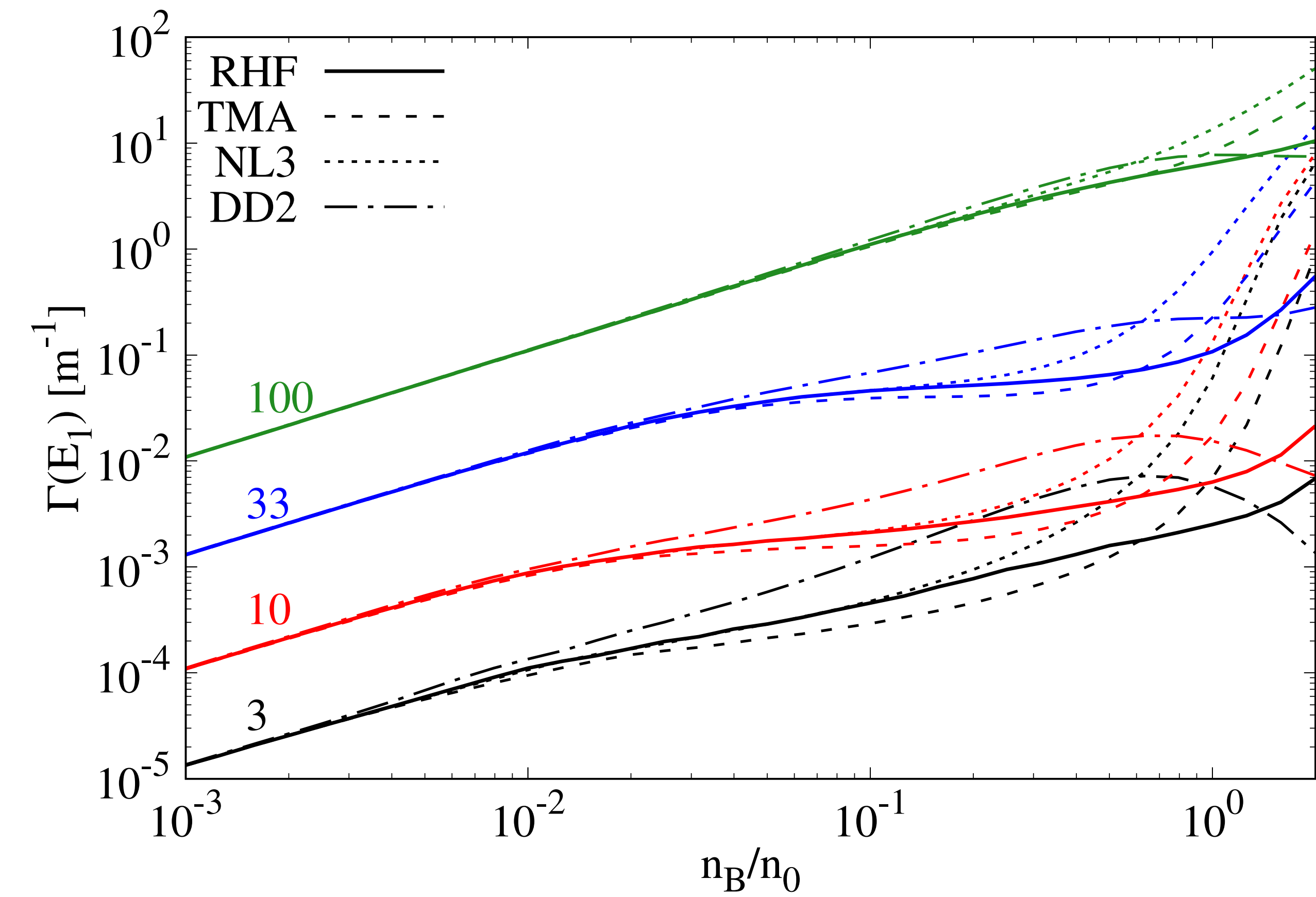


$$E_{\bar{\nu}_e} - E_e \equiv q_0 \propto (m_n - m_p) + \boxed{(\Sigma_n^S - \Sigma_p^S)} + (\Sigma_n^0 - \Sigma_p^0)$$

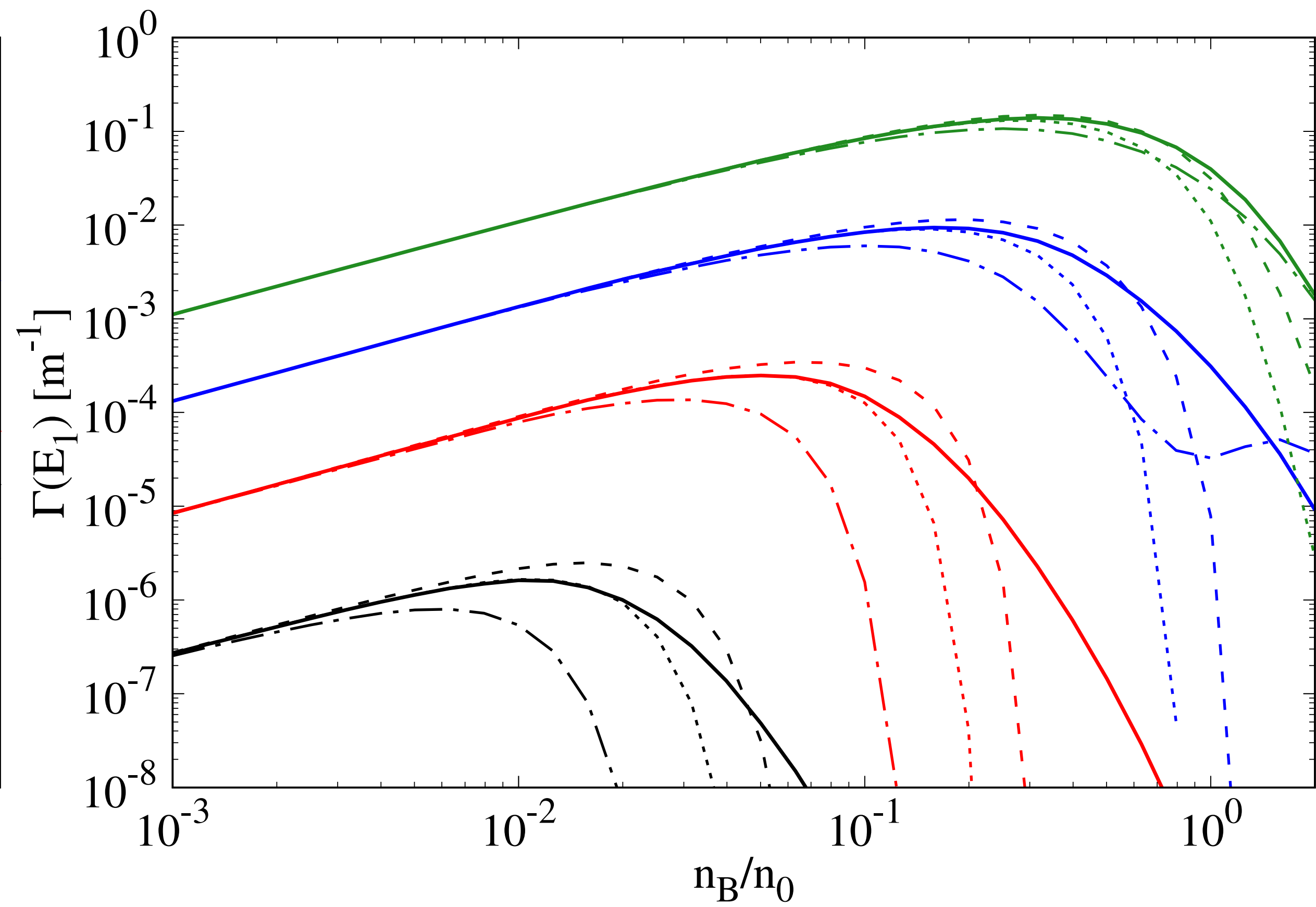


Model	n_0 [fm^{-3}]	E_B [MeV]	m^*/M_N	K [MeV]	E_{sym} [MeV]	L [MeV]
RHF	0.148	-15.77	0.76	252	29.6	63.5
TMA	0.147	-16.03	0.64	317	30.6	90.0
TMA δ	0.147	-16.03	0.64	317	30.6	113.7
NL3	0.148	-16.24	0.60	272	37.4	118.6
DD2	0.149	-16.02	0.63	243	32.7	57.9

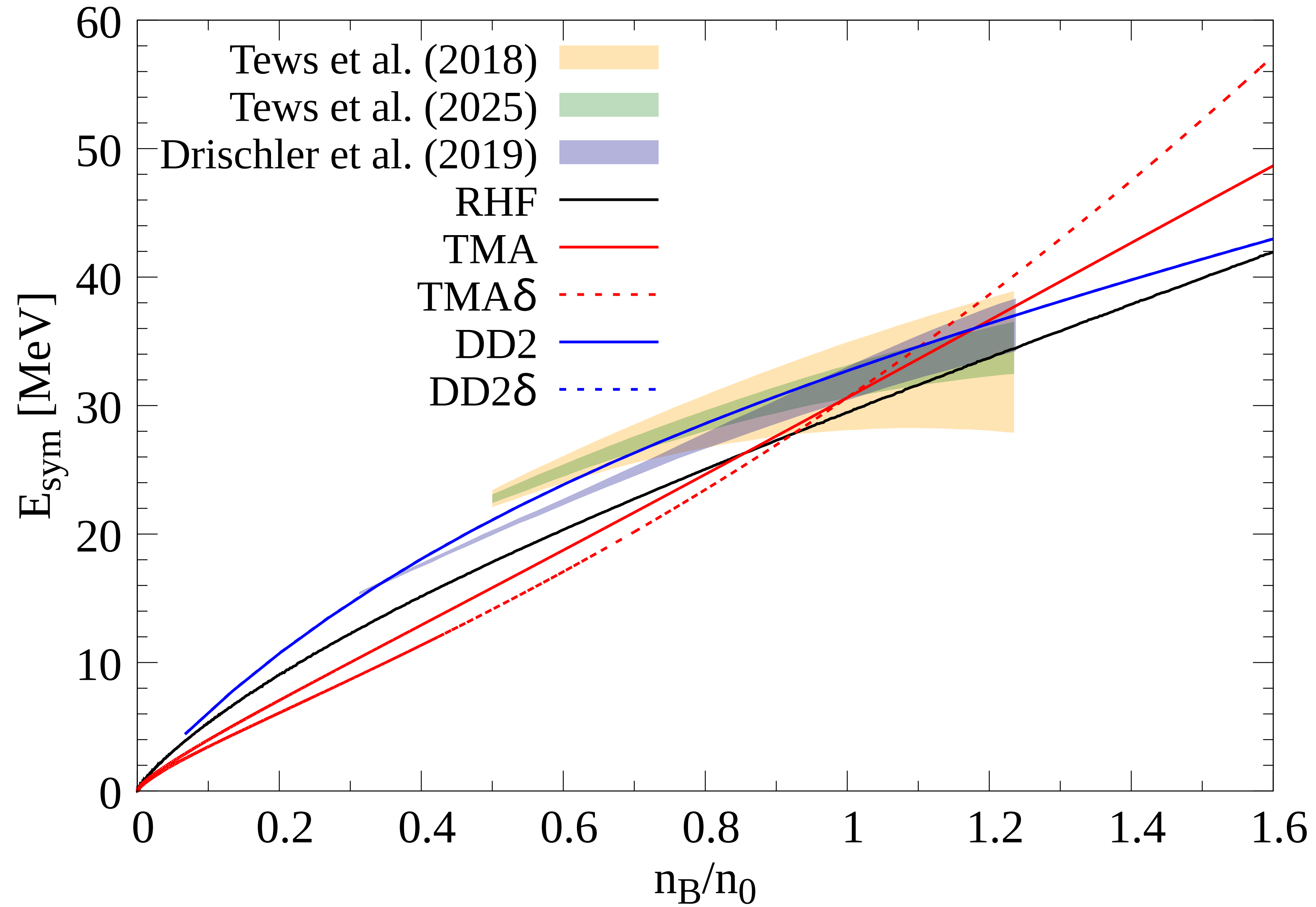
$$\nu_e + n \longrightarrow e^- + p$$

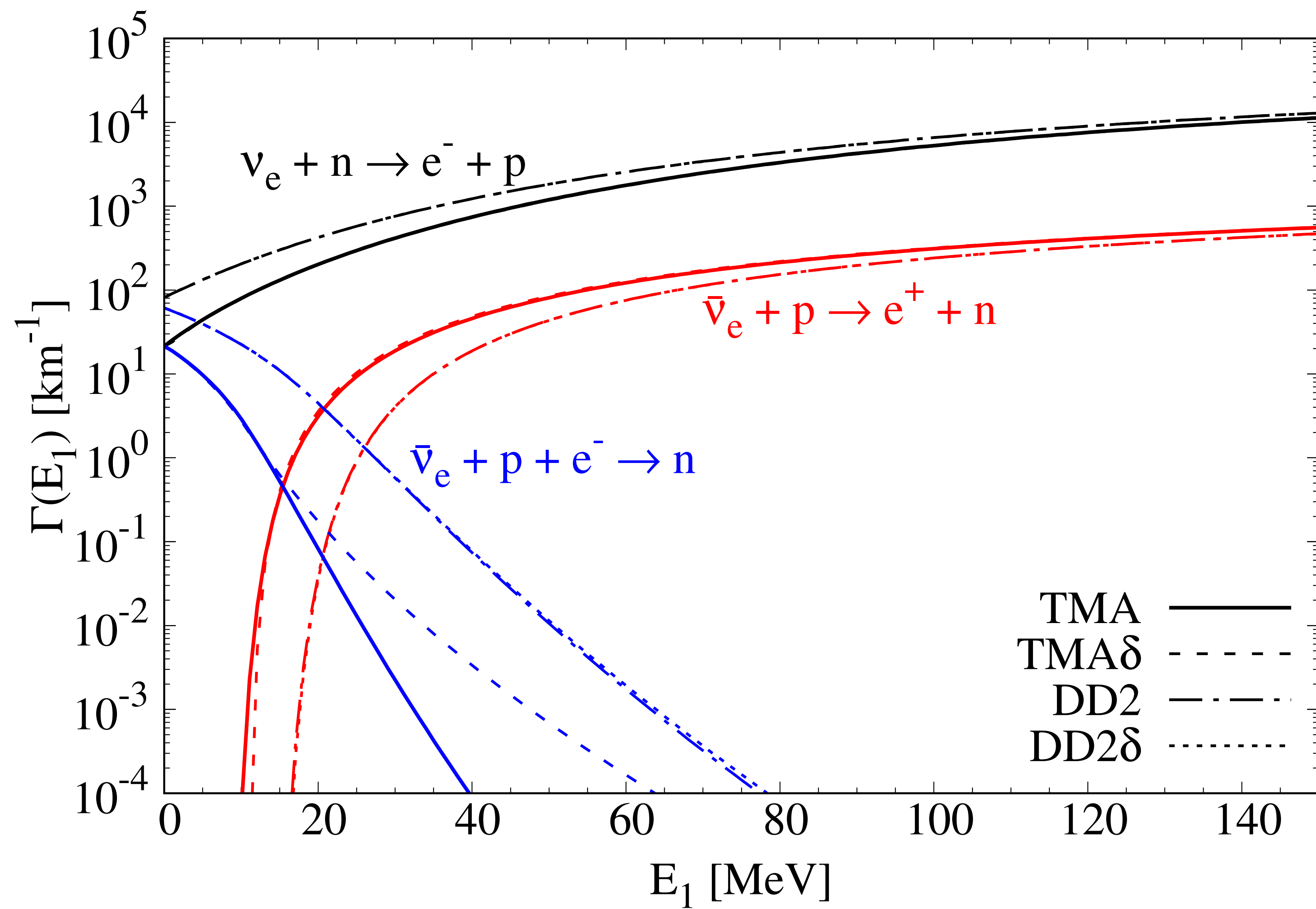


$$\bar{\nu}_e + p \longrightarrow e^+ + n$$



$$E_{\nu_e} - E_e \equiv q_0 \propto -(m_n - m_p) - \boxed{(\Sigma_n^S - \Sigma_p^S)} - (\Sigma_n^0 - \Sigma_p^0)$$





Thanks for your attention