CHARGED-CURRENT NEUTRINO OPACITY WITHIN THE RELATIVISTIC HARTREE-FOCK APPROXIMATION

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ACCEPTED PAPER

Charged-current neutrino opacity within the relativistic Hartree-Fock framework for astrophysical simulations of core-collapse supernovae and binary neutron star mergers

Kamil Sokołowski, Anil Kumar, and Tobias Fischer

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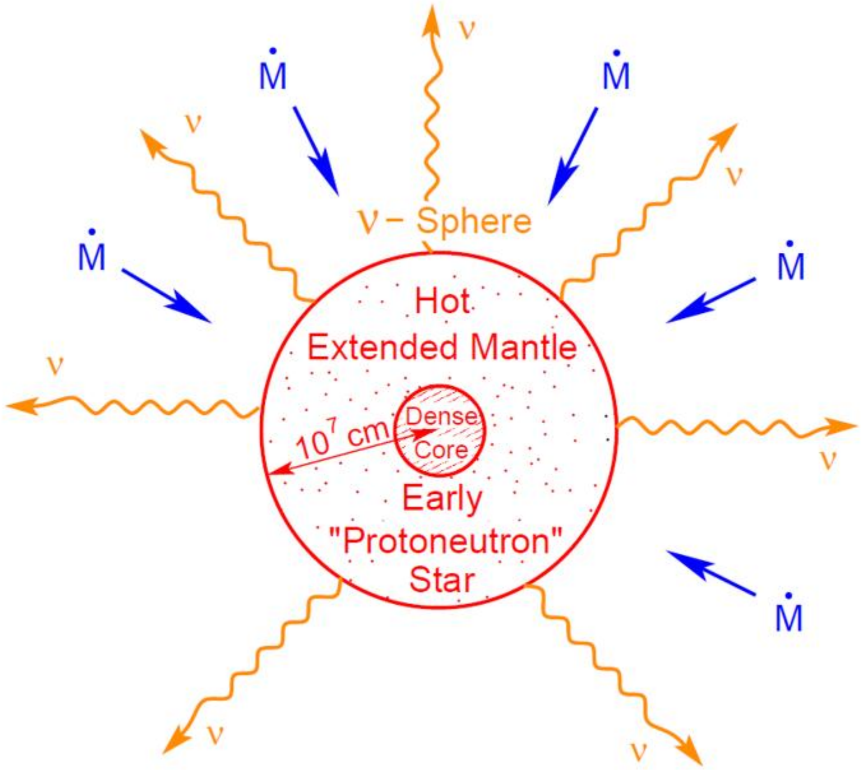
Core-collapse supernova explosions



Janka et al.
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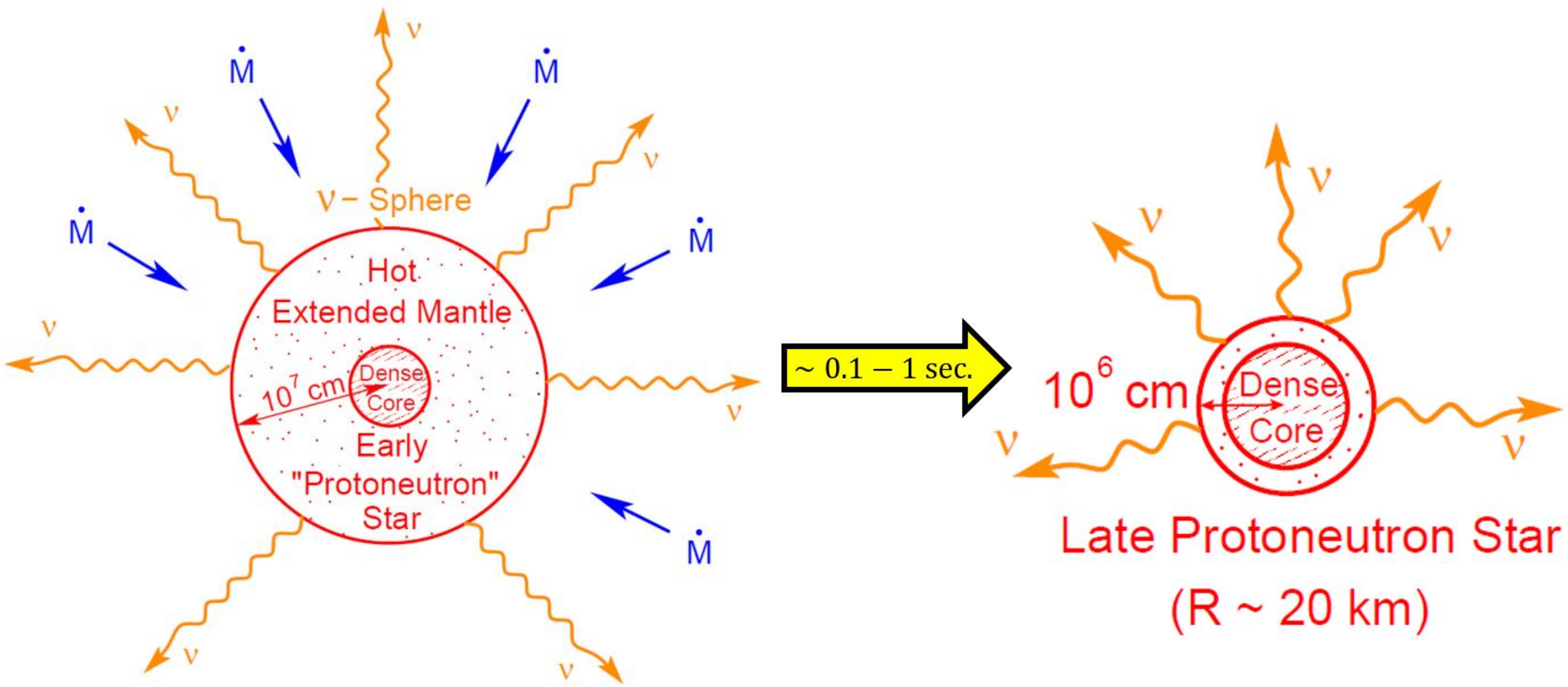

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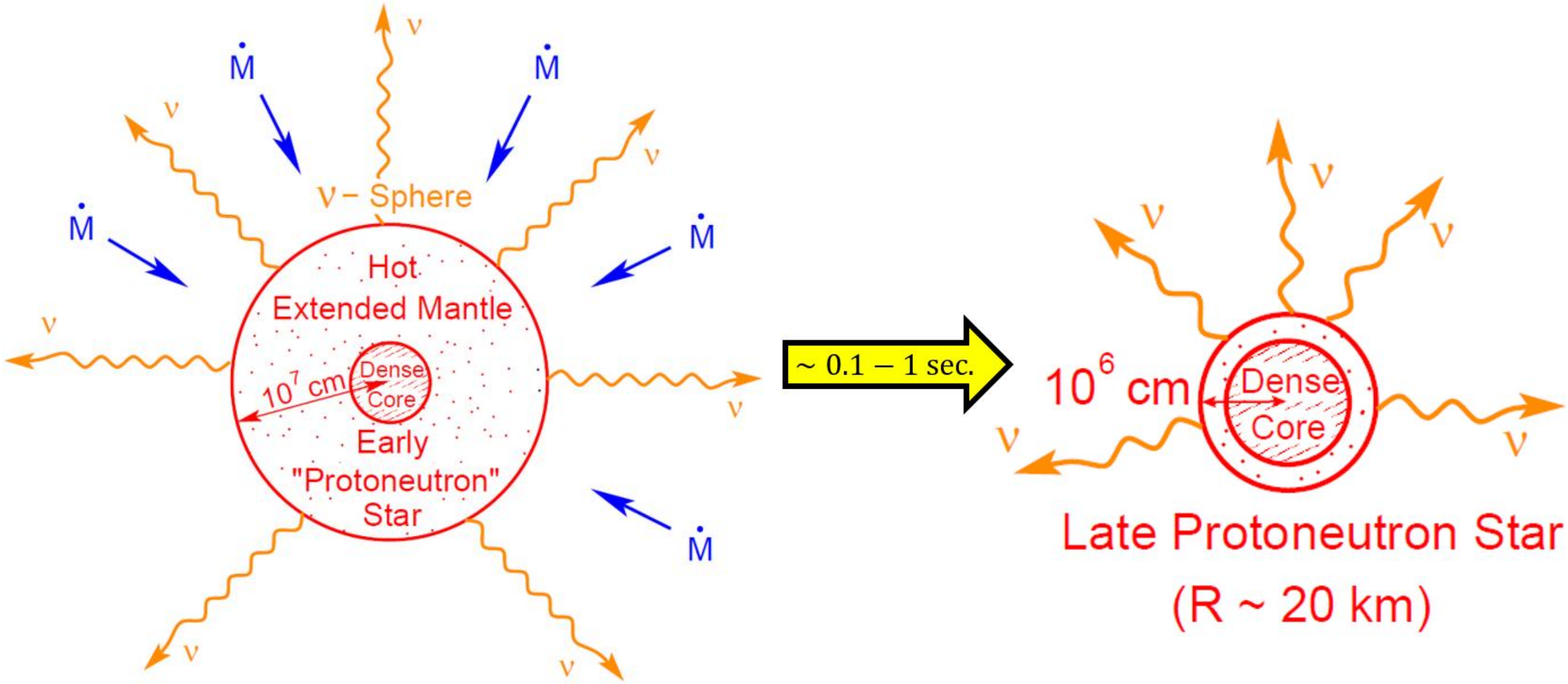

$l = \{e, \mu\}$

Charged-current reactions:

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

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

Neutral-current reactions:

$$\nu + N \rightleftarrows \nu' + N$$

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

Pair creation/annihilation

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

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

$$\nu_e + \bar{\nu}_e \rightleftarrows \nu_{\mu/\tau} + \bar{\nu}_{\mu/\tau}$$

Janka et al.
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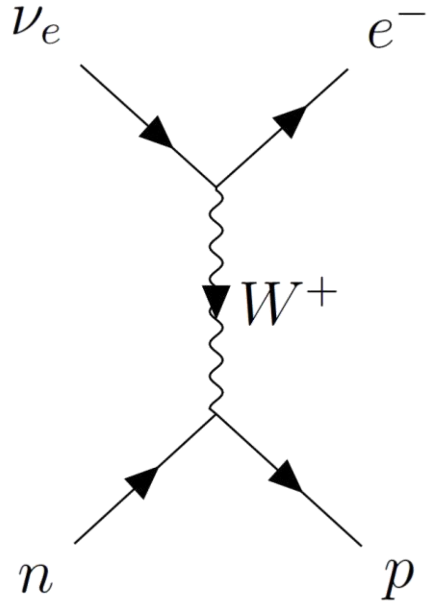
$$\nu_e(p_1) + n(p_2) \to e^-(p_3) + p(p_4)$$



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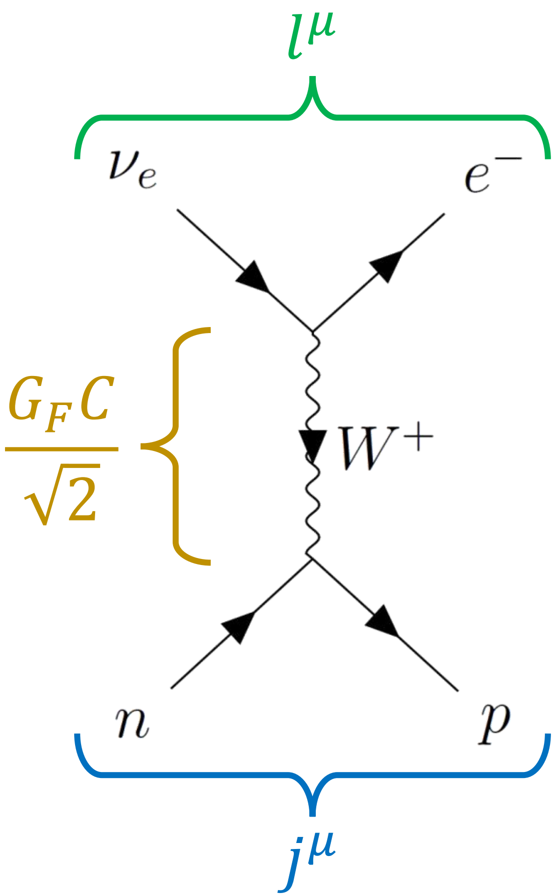

$$\mathcal{L} = \frac{G_F C}{\sqrt{2}} l^\mu j_\mu$$

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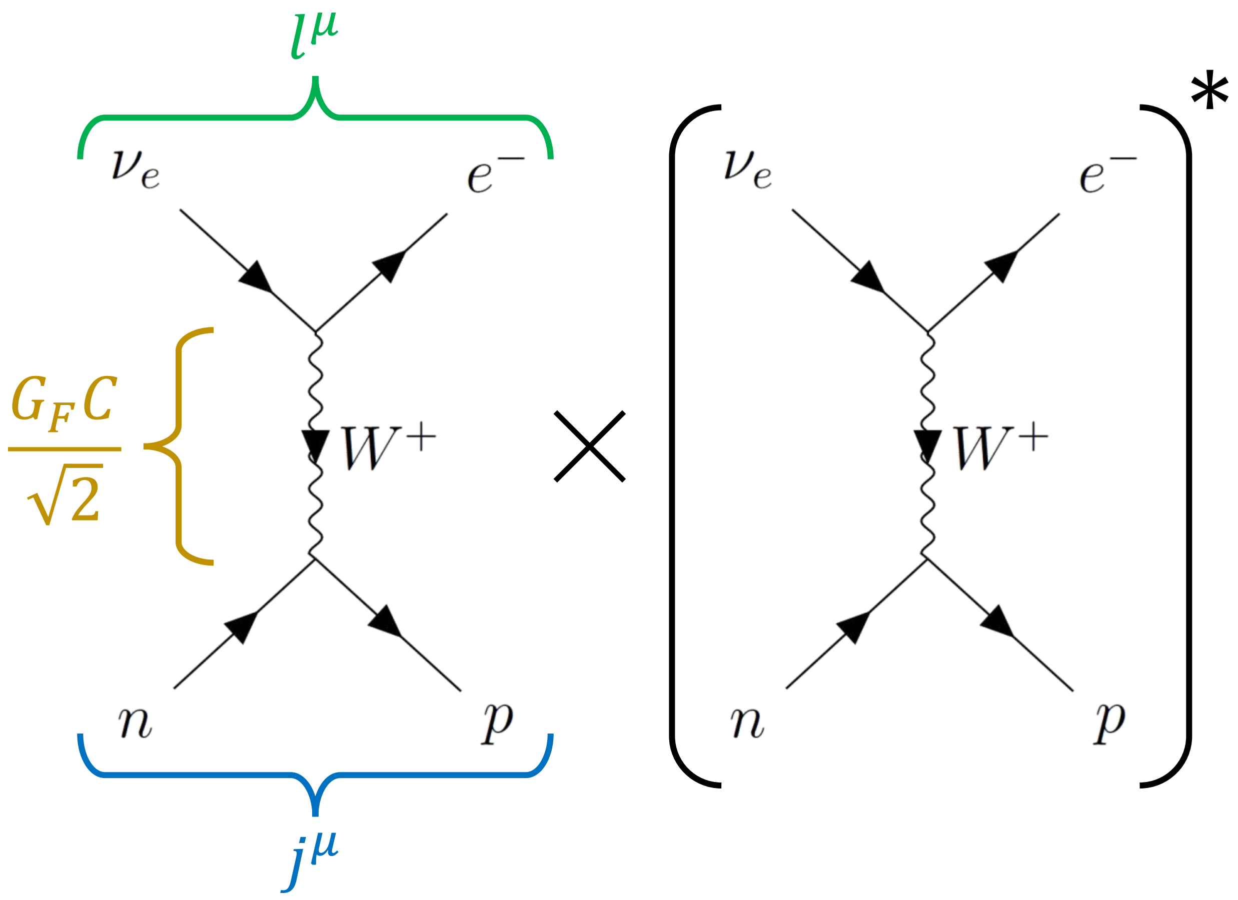

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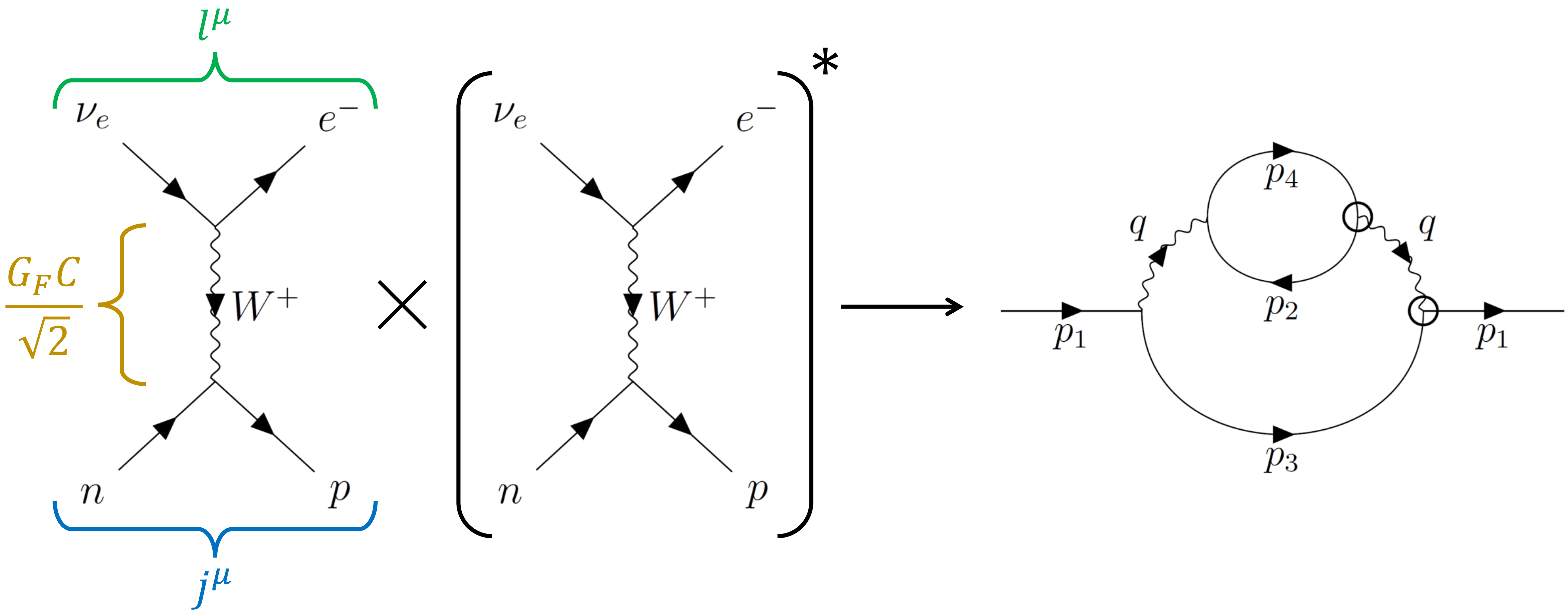

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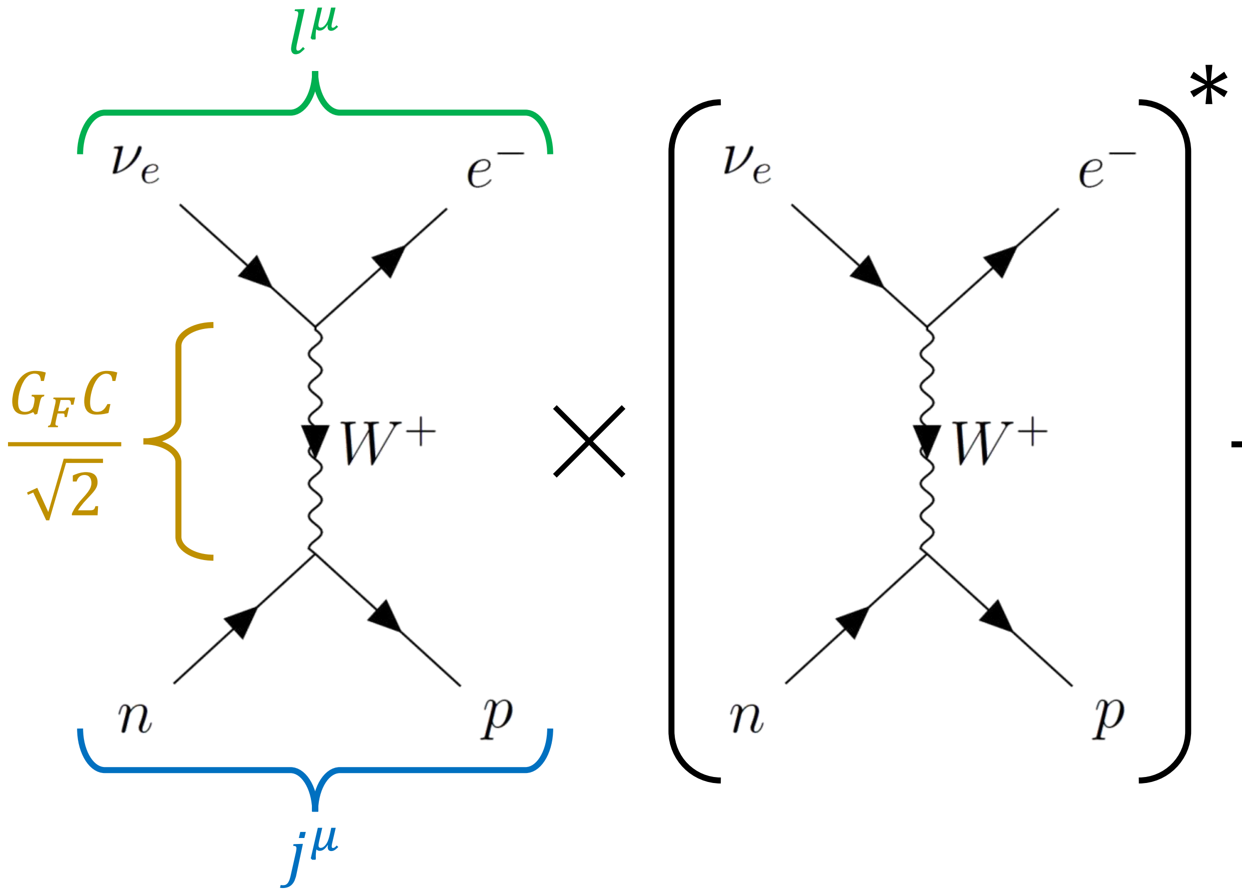

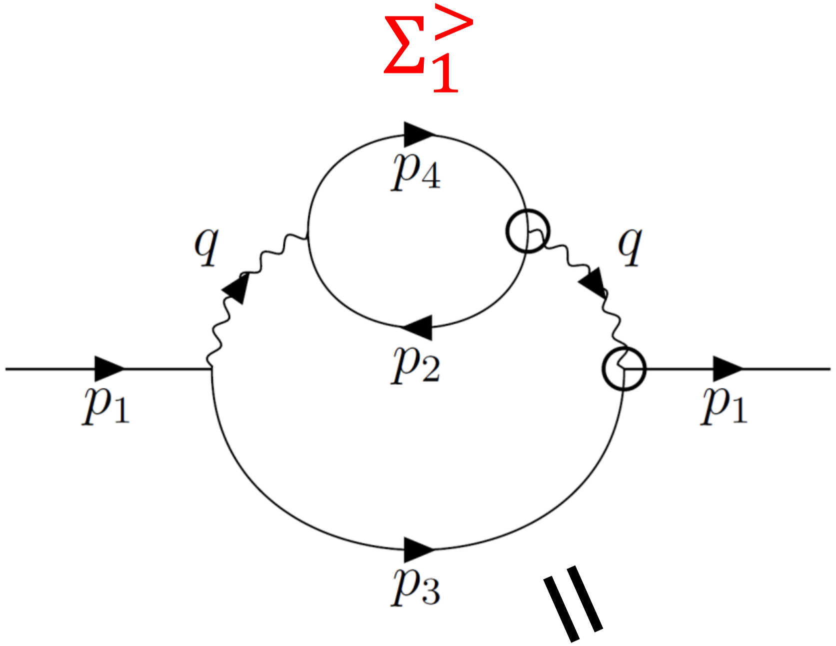

$$\Gamma(E_1) = \frac{1}{2E_1}\mathrm{Tr}\left[\gamma_\mu p_1^\mu \Sigma_1^>\right]$$

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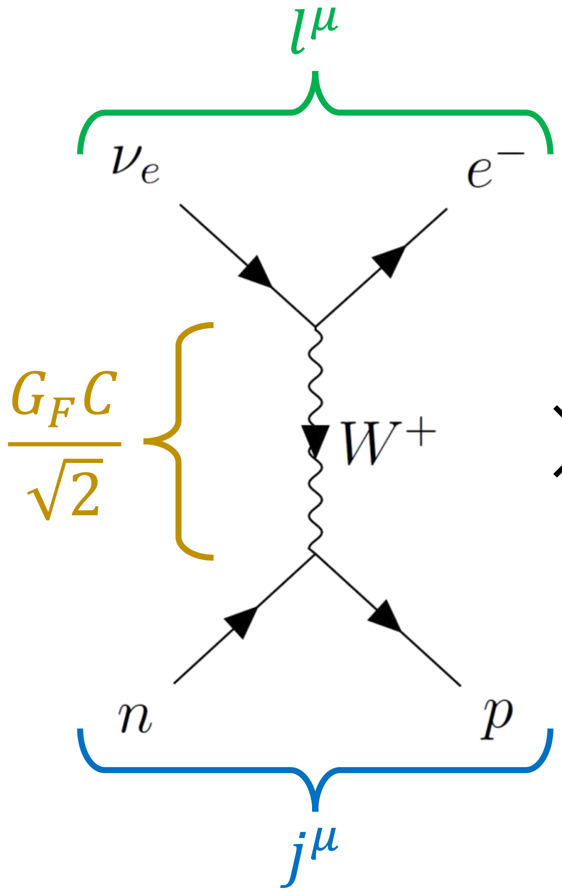

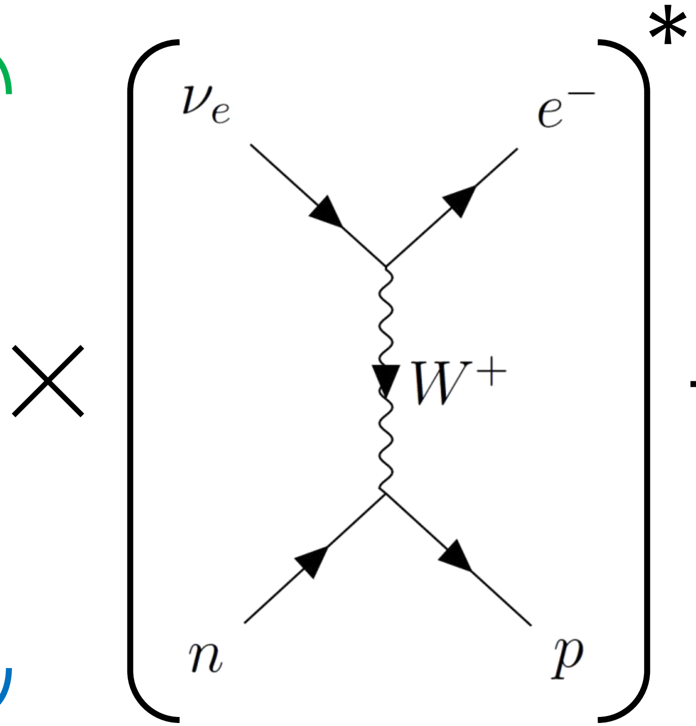

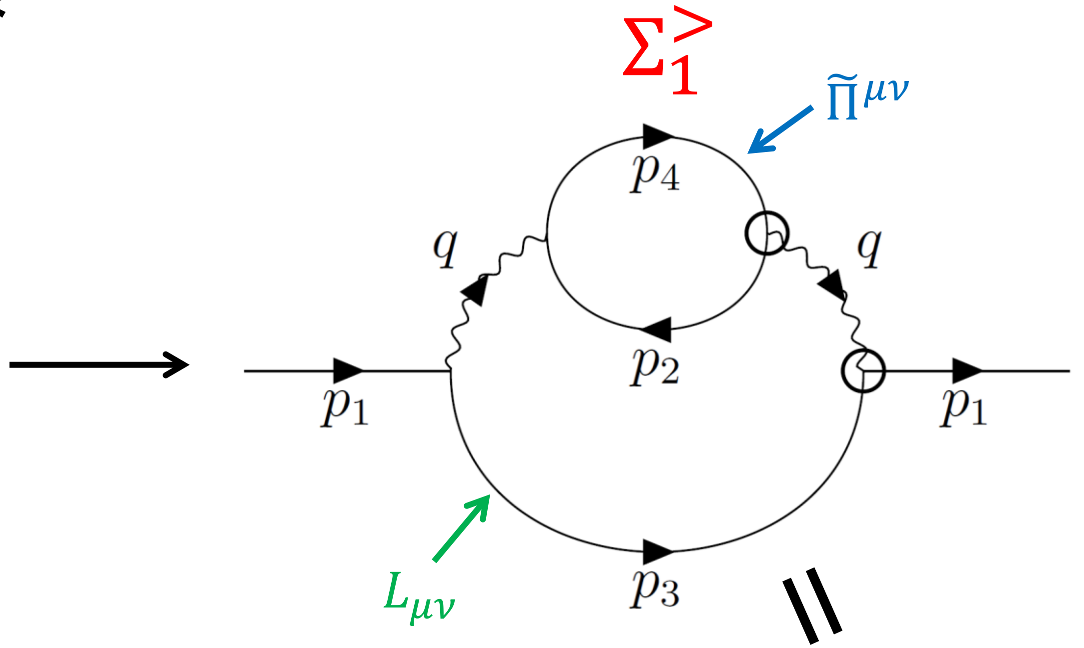

$$\Gamma(E_1) = \frac{1}{2E_1} \mathrm{Tr}\left[\gamma_\mu p_1^\mu \Sigma_1^>\right]$$

DIFFERENTIAL ABSORPTION RATE

$$\mathcal{L} = \frac{G_F C}{\sqrt{2}} l^\mu j_\mu$$

$$\boxed{\frac{d\Gamma(E_1)}{dE_3 d\Omega_{13}} = \frac{G_F^2 C^2}{32\pi^3} \frac{p_3}{E_1} \left(1 - f_3\,(E_3)\right) \int \frac{d^3 p_2}{(2\pi)^3} L_{\mu\nu} \mathrm{Im}\, \widetilde{\Pi}^{\mu\nu}}$$

lepton & hadron tensor

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Hadron tensor $(1 + 2 \to 3 + 4)$

$$\begin{cases} \mathrm{Im}\,\widetilde{\Pi}^{\mu\nu} = -\pi \dfrac{f_2(E_2) - f_4(E_4)}{4E_2E_4} \Lambda^{\mu\nu} \delta(q_0 + E_2 - E_4) \\ \Lambda^{\mu\nu} = \mathrm{Tr}\left[\left(\gamma_\mu p_2^\mu + m_2\right)\bar{\Gamma}^\mu \left(\gamma_\mu p_4^\mu + m_4\right)\Gamma^\nu\right] \\ \Gamma^\mu = \gamma^\mu (g_V - \gamma_5 g_A) + F_2 \dfrac{i\sigma^{\mu\alpha} q_\alpha}{2M_N} - \dfrac{G_P}{M_N}\gamma_5 q^\mu \end{cases}$$

Guo et al., *PRD* **102** (2020)
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\end{aligned}\right.$$

EFFECTIVE QUANTITIES $\boxed{E_i \to E_i^*, \qquad m_i \to m_i^*, \qquad p_i \to p_i^*}$

Guo et al., *PRD* **102** (2020)
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Infinite nuclear matter / effective models

$$\mathcal{L} = \mathcal{L}_{Dirac} + \mathcal{L}_{\sigma} + \mathcal{L}_{\omega} + \mathcal{L}_{\rho} + \mathcal{L}_{\pi} + \mathcal{L}_{int}$$

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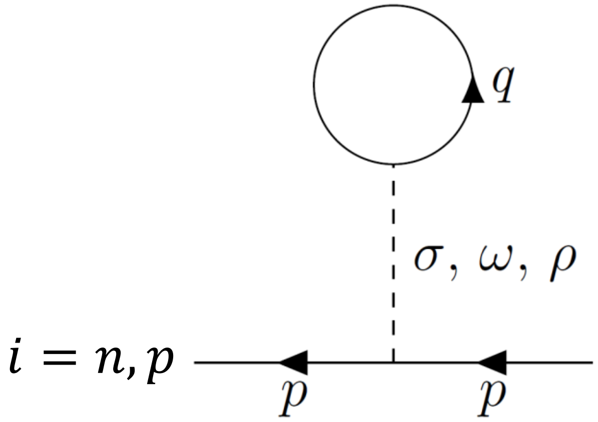

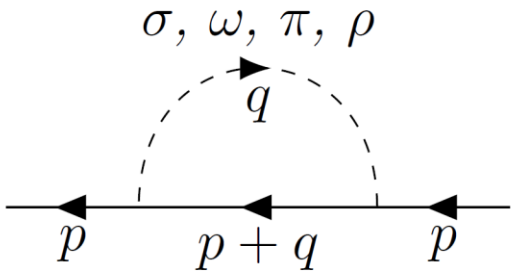

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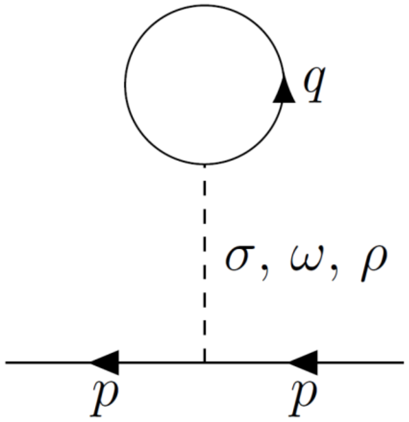
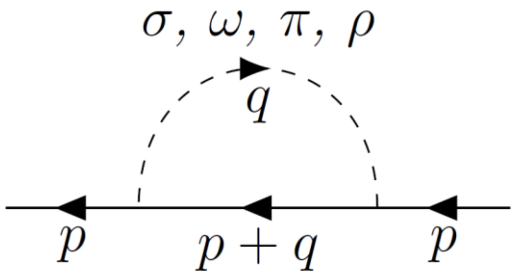
HARTREE

e.g. DD2

Typel et al., *PRC* **81**, 015803 (2010)
Kumar et al., *Mon. Not. Roy. Astron. Soc.* **530**, 501 (2024)

$i = n, p$





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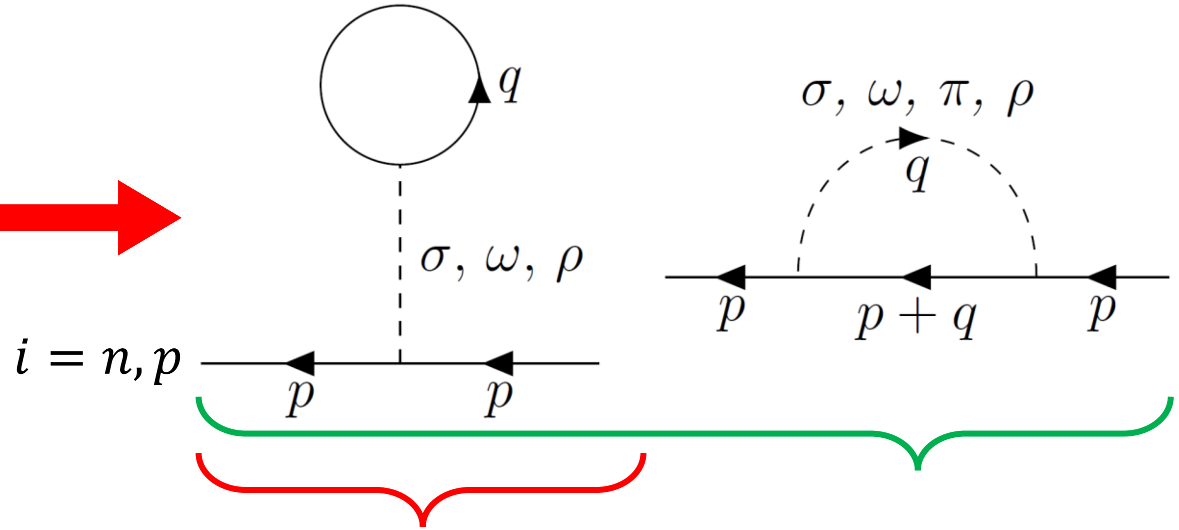

HARTREE-FOCK

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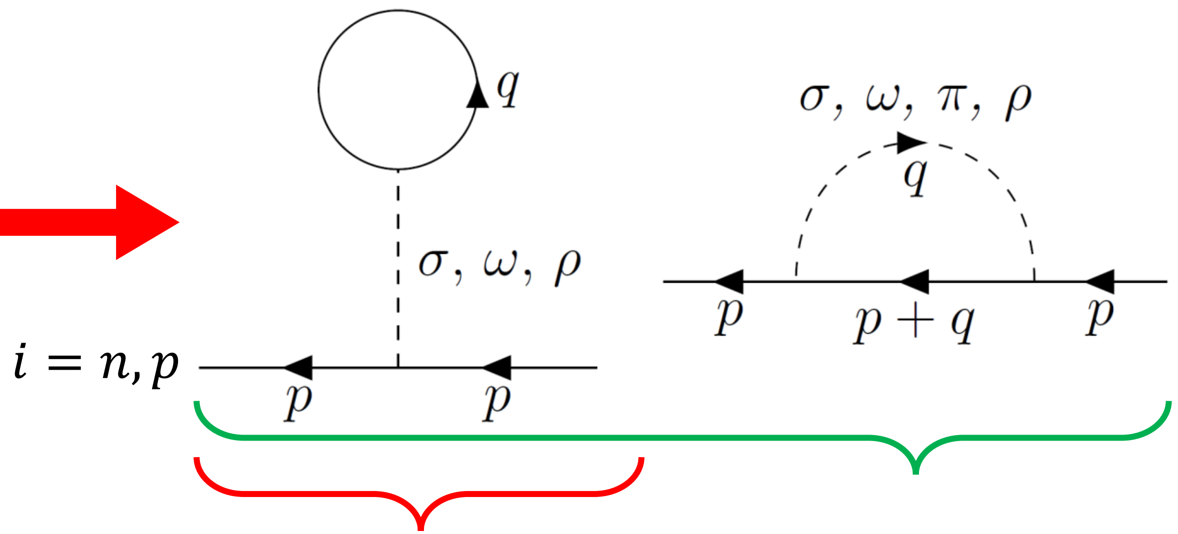

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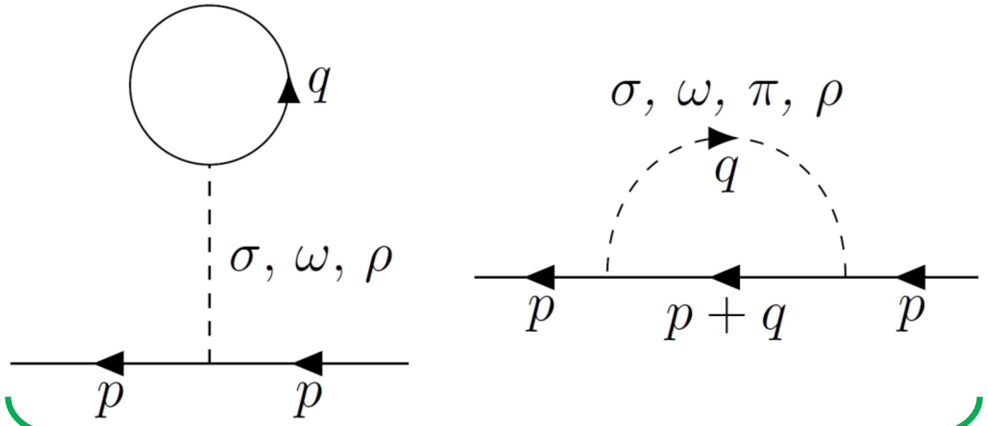

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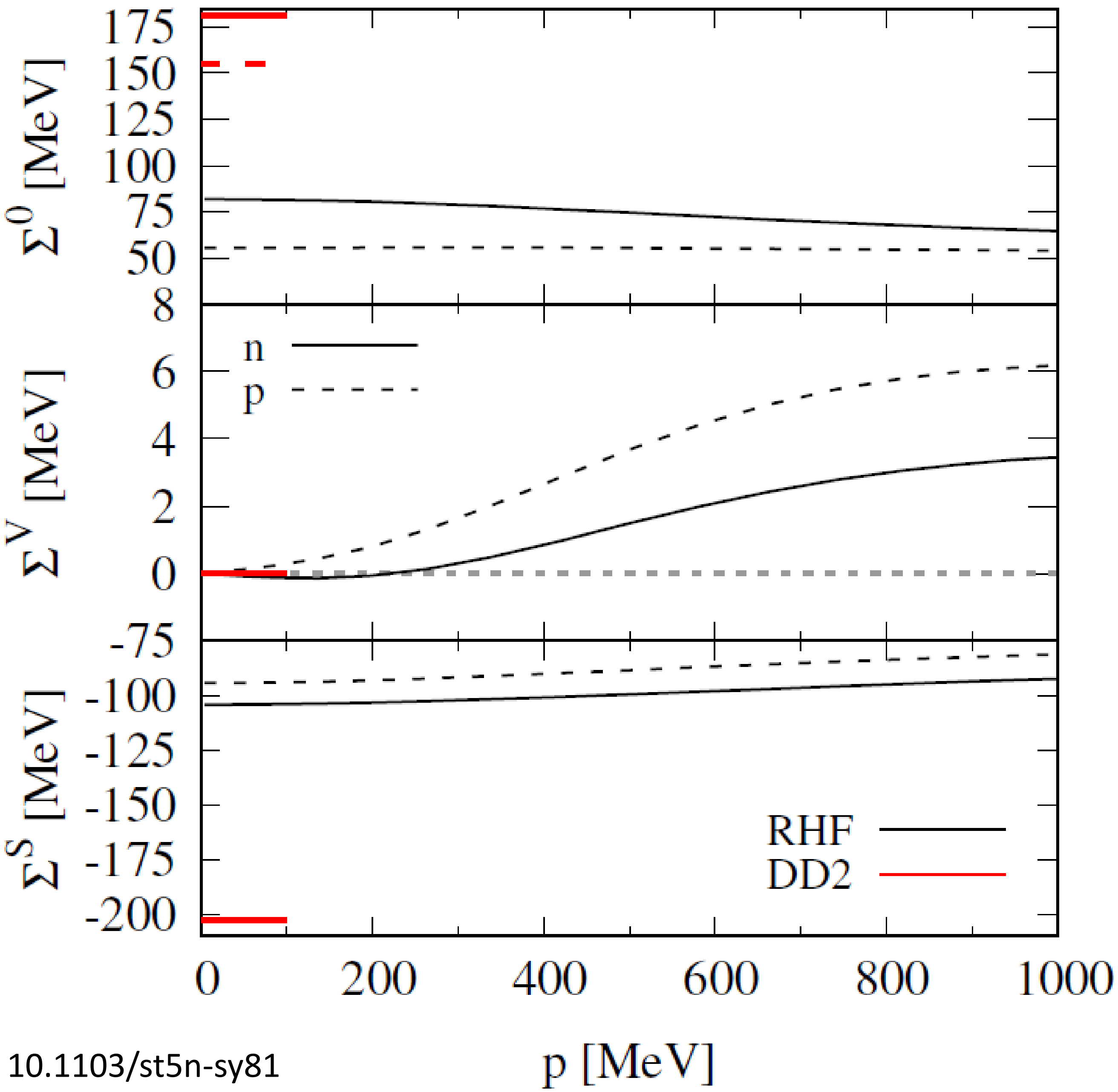
Nucleon self-energy



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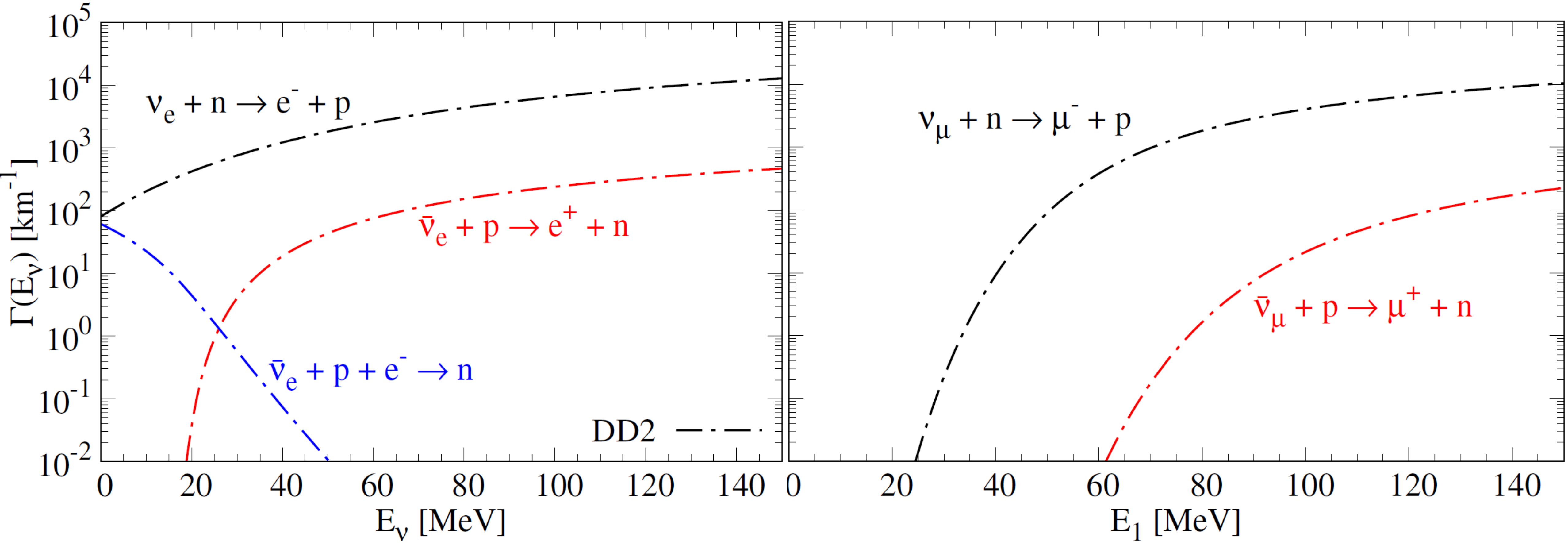
Neutrino opacity vs E_ν

$$\boxed{\Gamma(E_\nu) = \frac{1}{\lambda_\nu}}$$



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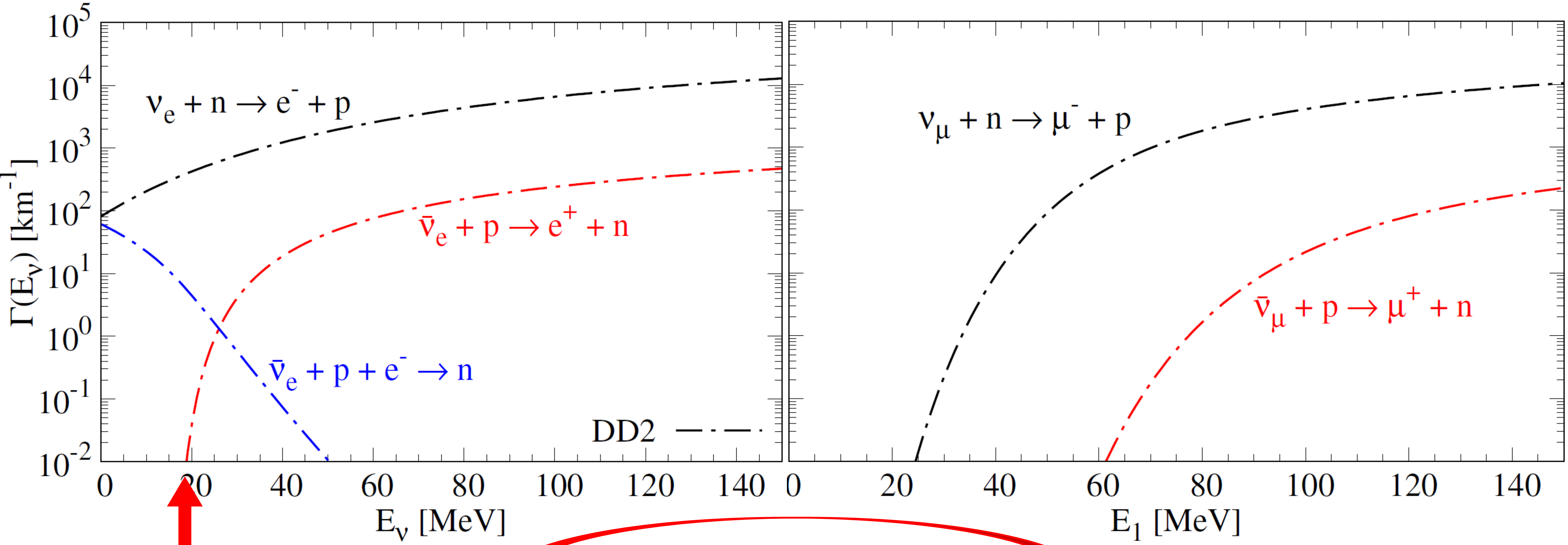

$$Q^* = (m_n - m_p) + (\Sigma_n^S - \Sigma_p^S) + (\Sigma_n^0 - \Sigma_p^0)$$

In H approx.
$\Sigma_n^S = \Sigma_p^S$

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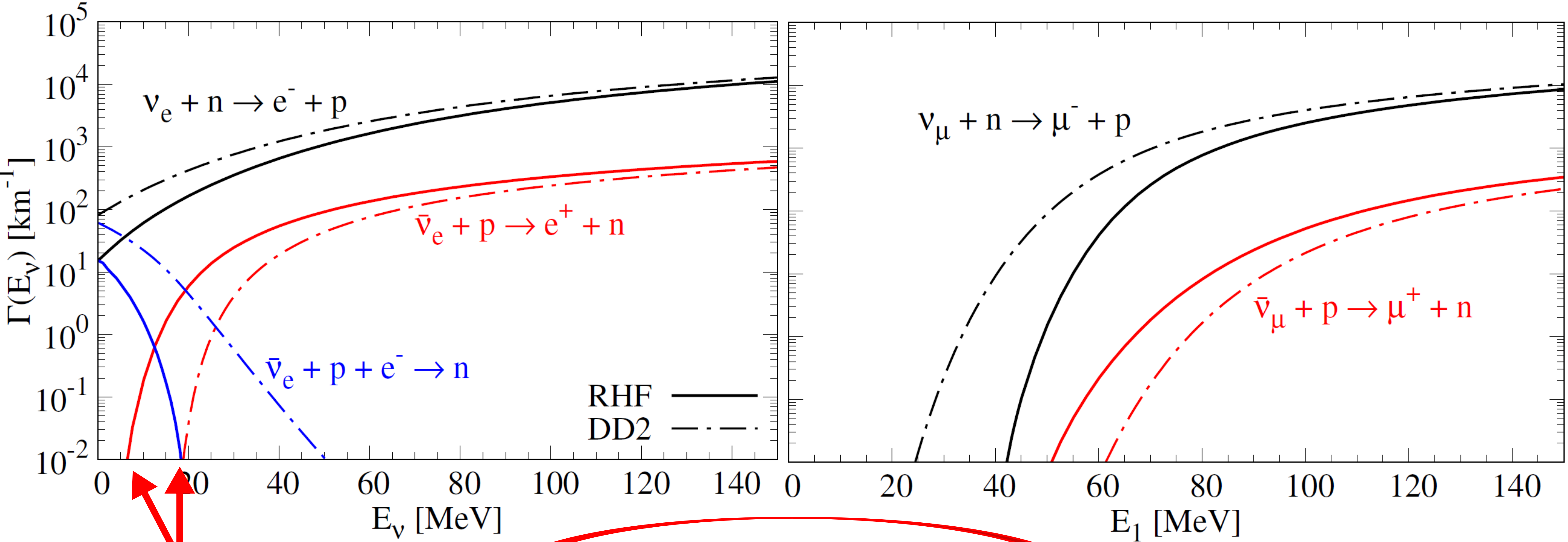

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- Hartree-Fock reduces medium modifications of weak rates
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- Impact on nucleosynthesis in neutrino-driven wind ?

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$$Y_e \approx \frac{\Gamma_{\nu_e n}}{\Gamma_{\nu_e n} + \Gamma_{\overline{\nu}_e p}} \approx \left(1 + \frac{L_{\overline{\nu}_e}}{L_{\nu_e}} \frac{E_{\overline{\nu}_e} - 2\Delta + 1.2\Delta^2/E_{\overline{\nu}_e}}{E_{\nu_e} + 2\Delta + 1.2\Delta^2/E_{\nu_e}}\right)^{-1} = \begin{cases} < \mathbf{0.5} & \text{if } E_{\nu_e} - E_{\overline{\nu}_e} > 5 \text{ MeV} \\ > \mathbf{0.5} & \text{else} \end{cases}$$

$$\Delta = m_n - m_p$$

Qian et al., *ApJ* **471**, 331 (1996)

Thank you for your attention