Neutrino emission in (proto-)neutron star matter: Urca reactions

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Neutrinos ν and their interaction with matter strongly impact Neutron Star (NS) Physics.

Neutrino's role, from birth to death:

- Dynamics of core-collapse supernovae:
  - stalled shock revival by ν heating,
  - leads to a successful explosion within the ν-driven mechanism.
- Proto and "Mature" NS cooling:
  - ν are the dominant cooling agent $< 10^6$ years.
- NS binary mergers:
  - ν determine the n/p ratio in ejecta,
  - influence heavy element nucleosynthesis.

Core-collapse supernovae, proto NS and mergers require calculation for dense and HOT matter.

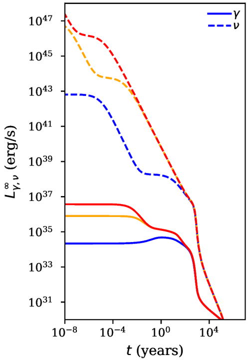

Figure 1: Cooling curve for EoS APR calculated with the NSCool code, for different initial temperatures.

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It is crucial to understand where, and by which processes all neutrinos are emitted/captured.

$$\begin{cases} B_1 \leftrightarrow B_2 + l^{\pm} + \nu_l \ , \\ B_2 + l^{\pm} \leftrightarrow B_1 + \bar{\nu}_l \ , \end{cases}$$

$$\begin{cases} \mathbf{B} + B_1 \leftrightarrow \mathbf{B} + B_2 + l^{\pm} + \nu_l \ , \\ \mathbf{B} + B_2 + l^{\pm} \leftrightarrow \mathbf{B} + B_1 + \bar{\nu}_l \ , \end{cases}$$

$$B + B \leftrightarrow B + B + \nu\bar{\nu} \ ,$$

$$l^{\pm} + C \rightarrow l^{\pm} + C + \nu\bar{\nu}$$

Let's focus on Direct Urca (DUrca), & Modified Urca (MUrca) and compute the emissivity $j(E_\nu)$.

Neutrino emissivity and mean free paths in QTFT

Modified Urca neutrino emission and absorption in *npe* matter

$$N + n \leftrightarrow N + p + e^- + \bar{\nu} \ ,$$
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$$N + n + e^+ \leftrightarrow N + p + \bar{\nu} \ ,$$
$$N + p \leftrightarrow N + n + e^+ + \nu \ .$$

Study of 4 nucleons of momentum p_1, p_2, p_3 and p_4 and described by hadronic polarization function $\Pi^{\alpha\beta}$, and 2 leptons (p_e, p_ν described by lepton tensor $L^{\alpha\beta}$.

Mix of **weak** interaction $W^\pm$ with $Q = (Q_0, \vec{Q})$ and **strong** interaction (we chose the One Pion Exchange).

We want to provide results for finite temperature neutron stars, therefore we use Thermal Quantum Field Theory.

The neutrino emissivity for a modified electron capture gives:

$$j = -\frac{G_F^2 V_{ud}^2}{8} \int \frac{\mathrm{d}^3\vec{p}_e}{(2\pi)^3} \frac{\mathcal{F}_{e^-}(Q)\left(1 + \mathcal{F}_B(Q_0)\right)}{E_e E_\nu} L_{\alpha\beta}(Q) \mathrm{Im}\, \Pi^{\alpha\beta}(Q) \ .$$

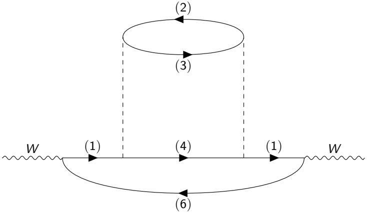
The hardship is with the hadronic polarization function.

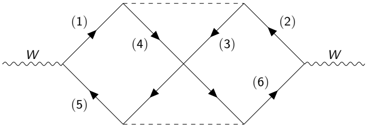
The hadronic polarization function

The hadronic polarization function implies phase space integrals of complicated spin and isospin parts.

$$\Pi^{\alpha\beta}(Q) = \left(\prod_{j=1}^{4} \int \frac{\mathrm{d}^4 p_j}{(2\pi)^4} \right) \sum_X I_X X^{\alpha\beta}_{\mathrm{spin}}(Q) \delta^4(p_1 + p_2 - p_3 - p_4)(2\pi)^4 \,,$$

We use Feynman diagrams to compute the isospin contribution I_X and the isospin contribution $X^{\alpha\beta}_{\mathrm{spin}}$ *i.e.* determine the matrix element of the hadronic part of the reaction which has a vector part ($\alpha = 0, \beta = 0$) and axial part (longitudinal + transverse $\alpha\beta = ij$).





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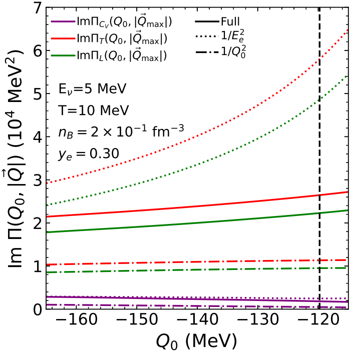
Approximations to obtain an analytical expression:

- Fermi surface and β-equilibrium,
- Neglecting $\vec{Q}$ in the matrix element → neglected vector contribution in $\mathrm{Im}\,\Pi^{\alpha\beta}$,
- Simplified denominator of the matrix element: either use $1/E_e^2$ or $1/Q_0^2$ when it should be a function of p_j, μ_j^*, m_j^* (effective quantitiess) and Q_0.



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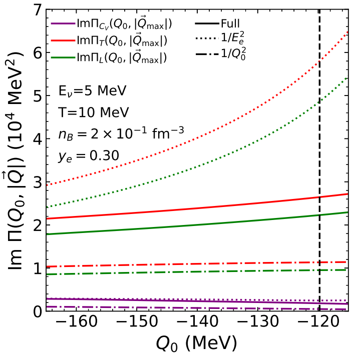
BUT there is no need for any of those approximations with a numerical approach !
Our "Full" approach operates the phase space integrals numerically with an importance sampling Monte-Carlo technique.

We can compute neutrino emission and capture in condition relevant for all stages of the neutron star life, without taking any of the usual approximations.



Estimation of the ratio between MUrca and DUrca neutrino emissivity:

- Treating zero temperature NS: [Yakovlev et al.(2001)]

$$\frac{I^{\mathrm{Mu}}}{I^{\mathrm{Du}}} = 10^{-6} \ ,$$

- Treatment in the high temperature regime: approximation for the nucleon distribution

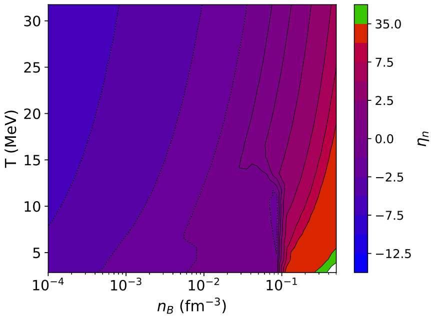
$$n_i \to e^{-\beta \epsilon_i} e^{\eta_i} \ , \qquad \frac{I^{\mathrm{Mu}}}{I^{\mathrm{Du}}} \propto e^{\eta_i} \ .$$

Reveals **different regimes of temperature and density**:

- around $\eta = 0 \to \frac{I^{\mathrm{Mu}}}{I^{\mathrm{Du}}} \sim 1$,
- for $\eta \leq 0$, then $\frac{I^{\mathrm{Mu}}}{I^{\mathrm{Du}}} \ll 1$.

Our calculations apply to proto-NS, mergers, core-collapse supernovae.

$$\eta_i = \frac{\mu_i^* - m_i^*}{T} \ .$$



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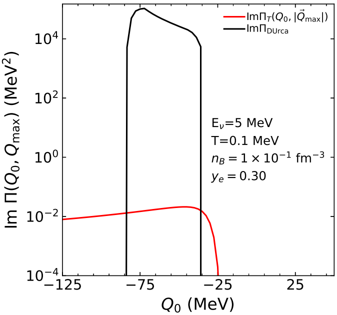

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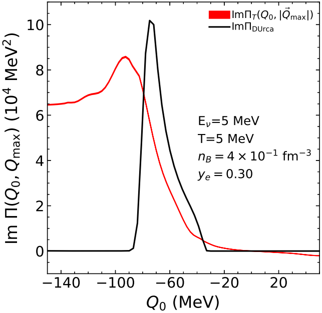

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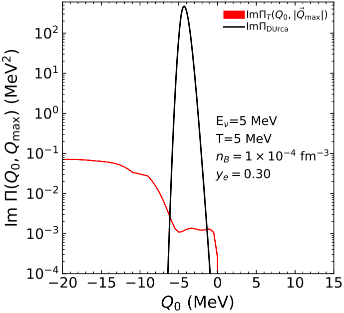

Conclusion

MUrca neutrino emission at finite temperature:

- Neutrinos play an important role in Neutron Star's Physics, at various stages in the star's life.
- We have provided results for MUrca neutrino emission at finite temperature without drastic approximations usually taken.
- A simple approximation for the distribution of nucleons revealed temperature and density regimes in which MUrca is not necessarily suppressed with respect to DUrca; results were confirmed numerically.
- *Long term improvements: calculating properly the nucleon self-energy (tricky...), consider relativistic particles, going beyond OPE, and discussion on β-equilibrium...*
- *Big challenge: provide tables of DUrca and MUrca results for simulations (computationally time consuming). What is the impact of considering MUrca in the same order of magnitude as DUrca in supernovae and merger calculations ?*

Thank you for your attention ! Questions ?