(Muon-)Neutrino opacities in dense and hot matter

Micaela Oertel

micaela.oertel@astro.unistra.fr

Observatoire astronomique de Strasbourg
CNRS / Université de Strasbourg

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Outline

1. Introduction

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Outline

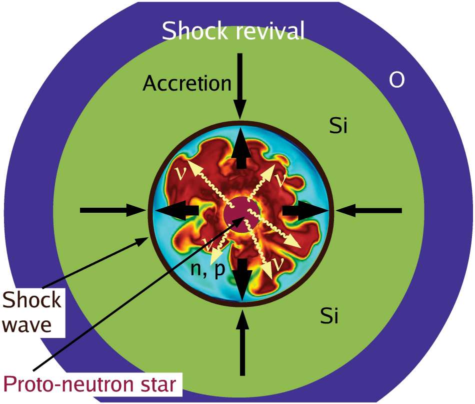
Neutrino interactions

Why are we wondering about ?

1. Core-collapse supernovae

- Neutrino-driven explosion mechanism
- Small changes in interactions rates can push explosions e.g. [Melson 2015]
- Neutrino driven wind and nucleosynthesis
- Proto-neutron star cooling by neutrino emission
- Neutrino emissivities dominant for (P)NS cooling for $\lesssim 10^6$ yrs
- Muons present, but mostly neglected due to low abundance [Bollig 2017]

Shock revival in a CCSN



[Janka 2012]

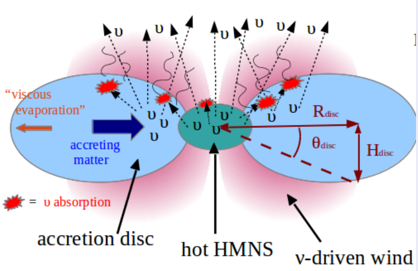
Neutrino interactions

Why are we wondering about ?

2. Binary neutron star mergers

- Neutron rich and hot environment $\rightarrow$ intense neutrino emission
- Determine neutron to proton ratio in the ejecta (conditions for heavy element nucleosynthesis)
- Release energy (cooling effect)
- Energy and momentum exchange with matter
- Muons present, but mostly neglected due to low abundance [Gieg 2024, Loffredo 2023]

Sketch of merger remnant



[Perego 2014]

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Neutrino matter interactions

- Different types of interactions with matter (nucleons, nuclei and charged leptons, photons)
  - scattering (neutral current)
  - absorption/creation processes (charged current)
  - pair creation (neutral current)

Typical reactions

$$
\begin{aligned}
p + l^-(+N) &\leftrightarrow n + \nu_l(+N) \\
n + l^+(+N) &\leftrightarrow p + \bar{\nu}_l(+N) \\
(A,Z) + e^- &\leftrightarrow (A,Z-1) + \nu_e \\
N + N &\rightarrow \nu + \bar{\nu} + N + N \\
\nu + A &\rightarrow \nu + A \\
\nu + N &\rightarrow \nu + N
\end{aligned}
$$

- Will not treat them all here ...

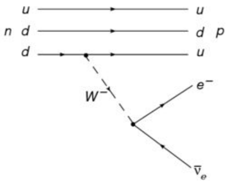
Outline

Neutrino-nucleon charged current reactions

Basic charged current weak interaction [Fermi 1934,...] :

$$G_F V_{ij} \bar{q}_i \gamma_\mu (1-\gamma_5) q_j \, \bar{\psi}_{l_1} \gamma^\mu (1-\gamma_5) \psi_{l_2}$$

Attention : interaction with quarks not nucleons !



- Governs (anti-)neutrino absorption and creation reactions (not all of them are equally relevant)
- Main problem : in medium nuclear response (matrix element + phase space)

General form (here : $p + e^- \to n + \nu_e$)

$$\frac{\partial f_\nu}{\partial t} \propto (1 - f_\nu) \int d_{q_0} \, n_e \int dq \, L^{\lambda\sigma} \, \mathrm{Im}\Pi_{\lambda\sigma}$$

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Direct URCA reactions

- Governs the following reactions (not all of them are equally relevant)

$l^{\pm}$ capture

$$p + l^- \leftrightarrow n + \nu_l$$
$$n + l^+ \leftrightarrow p + \bar{\nu}_l$$

Neutron/proton decay

$$n \leftrightarrow p + l^- + \bar{\nu}_l$$
$$p \leftrightarrow n + l^+ + \nu_l$$

Different approximations to compute rates

- Elastic approximation (neglect momentum transfer to nucleons and non-interacting nucleons) $\longrightarrow$ simple analytic expressions [Bruenn 1985]
- Include corrections to the nuclear matrix element (weak magnetism ...) $\longrightarrow$ slightly less simple expressions [Horowitz 2002]
- Include full phase space $\longrightarrow$ numerical computation [Roberts& Reddy 2017, Guo+2020,...]
- Include full phase space and nuclear interactions (mean field or RPA) [Reddy+1998, Burrows& Sawyer 1998,Oertel+2020...]
- Holographic approach [Järvinen+2023]

- Analytic results widely used in simulations but crude approximations

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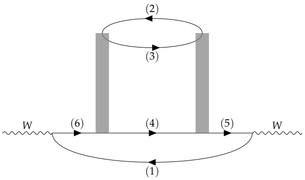
Modified Urca reactions

Example : EC reaction

$p + l^- + N \leftrightarrow n + \nu_l + N$

- Spectator nucleon can lift kinematic restrictions of dUrca reactions
- Considered clearly subdominant to dUrca



Common approximations

- All particles on respective Fermi surface $\longrightarrow$ cold matter [Friman & Maxwell 1979]
- Neglect momentum transfer $\longrightarrow$ low densities [Bacca+2012]
- Intermediate nucleon propagators as $\sim 1/E_e$ or $\sim 1/q_0$
- Only axial part

not adapted to PNS cooling, BNS merger remnant....

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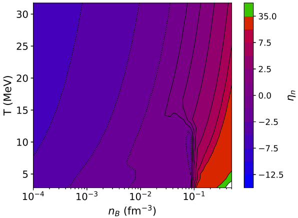
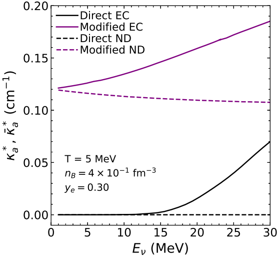
Results for Murca reactions

- Order of magntiude analytic estimate indicates a region in T, n_B where Murca is not necessarily suppressed
  - Low temperatures and high densities : $\frac{I_{mU}}{I_{dU}} \sim 10^{-6}$
  - High temperatures : $\frac{I_{mU}}{I_{dU}} \sim e^{\eta_i}$ $(\eta = (\mu^* - m^*)/T)$
    $\longrightarrow$ mUrca not necessarily suppressed for $\eta \sim 0$!
- Numerical evalulation confirms estimate
  - Full momentum dependence of matrix element and phase space
  - One pion exchange interaction
- Include quasi-particle width in dUrca to mimick Murca [Sedrakian 2024, Pascal+2022, Roberts+2012]





[Suleiman+ 2023]

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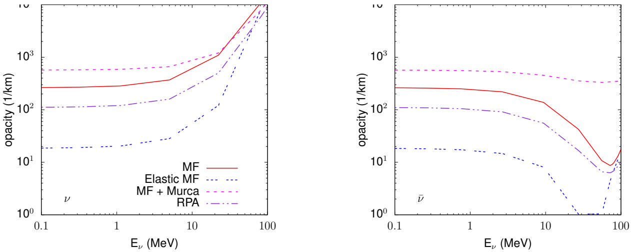
Charged current opacities

Comparing different approximations : electronic reactions

- Rates computed with RG(SLy4) EoS at $T = 16$ MeV, $n_B = 0.15$ fm^{-3}, $Y_e = 0.07$;
  conditions close to neutrinosphere in a PNS [Pascal+2022]
- Murca reactions here as phenomenological finite life-time in Durca reactions

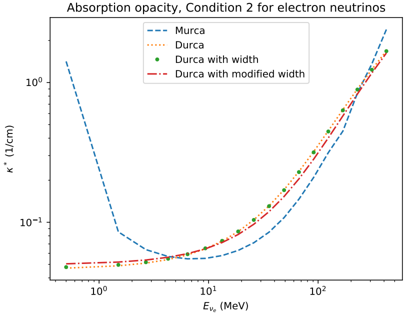


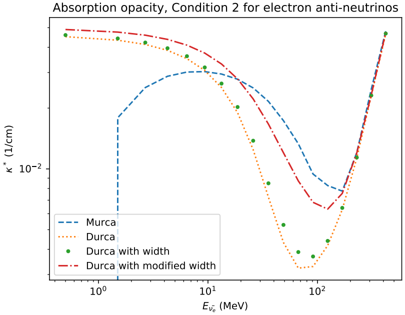
[Pascal+2022]

Charged current opacities

Electronic reactions

- Rates computed with HS(SFHo) EoS at $T = 44$ MeV, $n_B = 0.32$ fm^{-3}, $Y_p = 0.07$;
  conditions at hot interface of a BNS merger simulation [Gieg+ 2024]
- Murca : full calculation [Suleiman+2023] vs quasi-particle width [Sedrakian 2024]





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Charged current opacities

Muonic reactions

- Rates computed with HS(SFHo) EoS at $T = 44$ MeV, $n_B = 0.32$ fm^{-3}, $Y_p = 0.07$;
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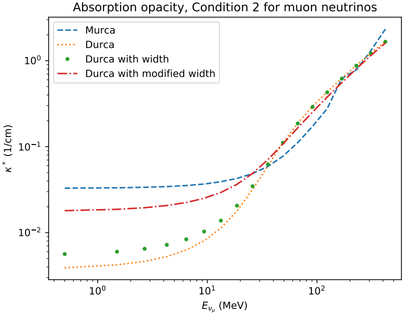

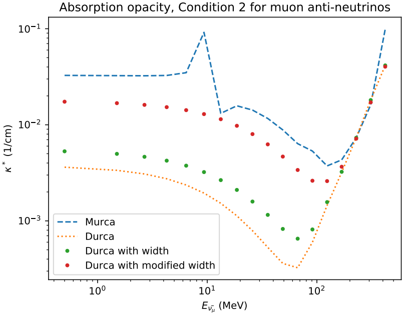

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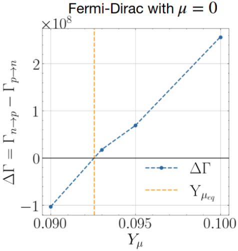
Chemical equilibrium

- Neutrinos not in thermal equilibrium $\rightarrow$chemical equilibrium : $\Gamma_{n\rightarrow p} = \Gamma_{p\rightarrow n}$
  Γ : integrated reaction rate $\Gamma \propto d^3p_\nu(j(1-f_\nu) - \kappa f_\nu)$

Mature NS

- $T = 0$
- Neutrinos freely leave the system $\rightarrow f_\nu = 0$.
- Only l^- capture and neutron decay relevant

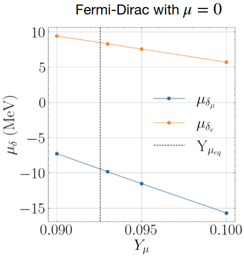
$\rightarrow \mu_e + \mu_p = \mu_n$ and $\mu_\mu + \mu_p = \mu_n$



Hot proto-NS/merger remnant

- Neutrinos partly trapped at the center
- Neutrinos not necessarily in thermal/chemical equilibrium $\rightarrow f_\nu = f_{FD}(\mu = 0)$ [Ruffert+1996]
- All reactions contribute

$\rightarrow \mu_l + \mu_p = \mu_n + \mu_{\nu_l}^{eq}$



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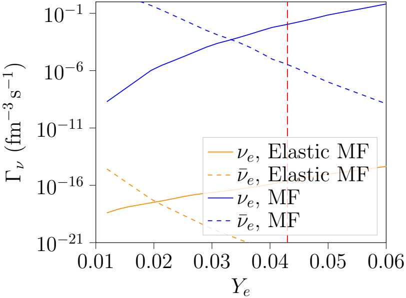
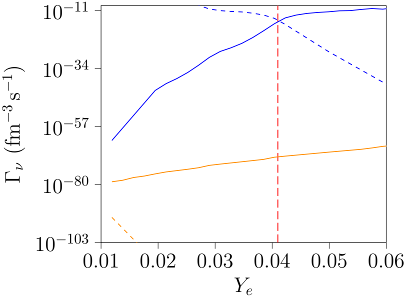
Weak equilibrium during PNS evolution

- Simulation of PNS evolution with quasi-static GR hydrodynamics + neutrino transport [Pascal+2022]





- β-equilibrium not correctly obtained $\rightarrow$ breakdown of the elastic approximation at high densities, need for numerical (pre-)computation of opacities

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Summary and outlook

Summary

- Neutrino nucleon interactions important in compact star astrophysics
- In-medium effects $\longrightarrow$ considerably modified neutrino opacities
- Microphysics effort since many years, here :
  - Need to care about Murca type reactions at intermediate densities/temperatures
  - Muonic reactions equally sensitive to Murca in this range
  - Murca reactions "fill" the dip due to thresholds
  - Muonic reactions important for p/n ratio

Outlook

- How to implement numerically computed rates with ongoing efforts in the nuclear physics community ? (Provided polynomial representations for CC rates)
- Do we need this for all applications ? Crude approximations might be good for some temperatures/densities