Neutrino-nucleon interactions in dense and hot matter

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TUG 2023 Workshop,
October 10 - 12, 2023

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Outline

1. Introduction

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2. Charged current neutrino nucleon reactions
   - Direct Urca reactions
   - Modified Urca reactions

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2. Charged current neutrino nucleon reactions
   - Direct Urca reactions
   - Modified Urca reactions
3. Some results on proto-neutron star evolution

Outline

Motivation : compact star physics

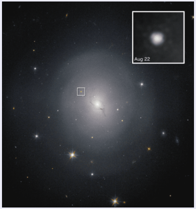
Core-collapse supernovae

[CFHT]

Neutron stars

[Chandra]

NGC 4993 and GRB170817



[ESA]

- Modeling following astrophysical phenomena
  - Core-Collapse supernovae and subsequent neutron star/black hole formation
  - Neutron stars
  - Binary neutron star mergers (inspiral and post-merger)
- Numerical modeling needs input from microphysics
  - Equation of State (EoS)
  - Reaction rates and transport coefficients

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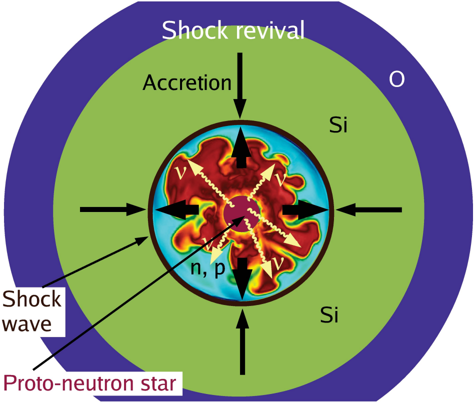
Neutrino interactions

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 about 10^6 yrs

Shock revival in a CCSN



[Janka 2012]

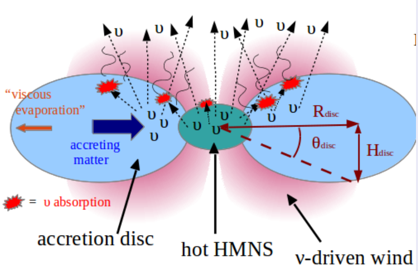
Neutrino interactions

Why are we wondering about ?

2. Binary neutron star mergers

- Neutron rich and hot environment → 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

Sketch of merger remnant



[Perego 2014]

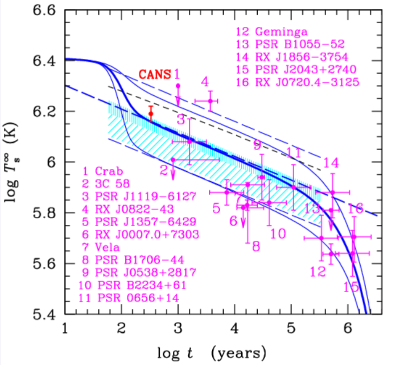
Neutrino interactions

Why are we wondering about ?

3. Neutron star cooling

- Energy loss by surface photon and neutrino emission
- Theory predicts essentially three cooling stages
  - Crust thermalisation ($\sim$ 10-50 yrs)
  - Neutrino cooling ($\sim 10^5 - 10^6$ yrs)
  - Photon cooling ($t \gtrsim 10^6$ yrs)
- Neutrino emissivities dominant for about 10^6 yrs

NS cooling



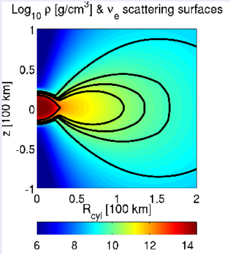
[Yakovlev 2011]

Thermodynamic conditions

Relevant for neutrino-matter interactions

- CCSN and BNS merger remnants
  - Emission from dense and hot central part
  - Neutrino opacities close to the neutrinosphere determine p/n ratio of ejecta and efficiency of neutrino heating mechanism
  - Matter more neutron rich for BNS mergers
  - Typical neutrino energies from a few to tens of MeV
- Neutron star cooling
  - Neutrino emission from the core, typical neutrino energies $\sim T$

BNS merger remnant



[Perego 2014]

Hot central part	Neutrinosphere	NS cooling
$n_B \gtrsim .1\text{fm}^{-3}$	$10^{-4}\text{fm}^{-3} \lesssim n_B \lesssim .1\text{fm}^{-3}$	$n_B \gtrsim .1\text{fm}^{-3}$
$T \gtrsim 10$ MeV	$5\text{MeV} \lesssim T \lesssim 10$ MeV	$T \lesssim 100$ keV
$Y_e \sim 0.1$-0.3	$Y_e \sim 0.1$-0.3	$Y_e \sim 0.1$

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)

Some typical reactions

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

- Here : charged current (CC) processes on nucleons

Direct URCA reactions

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

Electron/positron 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

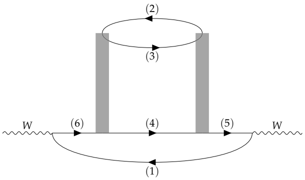
  [Reddy+1998, Burrows& Sawyer 1998,...], see also [Järvinnen+2023]

- Analytic results widely used in simulations but crude approximations

Modified Urca reactions

Example : EC reaction

$p + e^- + N \leftrightarrow n + \nu_e + N$



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

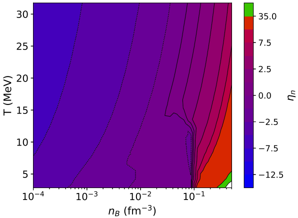
Common approximations

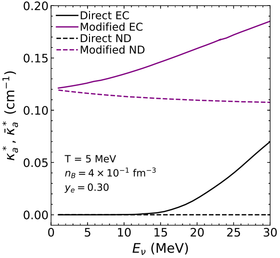
- All particles on respective Fermi surface $\longrightarrow$ cold matter [Friman & Maxwell 1979]
- Neglect momentum transfer $\longrightarrow$ low densities [Bacca+2012]
- Intermediate nucleon propagators as $\sim 1/E_e$ or $\sim 1/q_0$
- Only axial part

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

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 : $\frac{I_{mU}}{I_{dU}} \sim e^{\eta_i}$
    $(\eta = (\mu^* - m^*)/T)$
    $\rightarrow$ mUrca not necessarily suppressed for $\eta \sim 0$!
- Numerical evalulation computed with
  - Full momentum dependence of matrix element and phase space
  - One pion exchange interaction
- Results confirm estimate

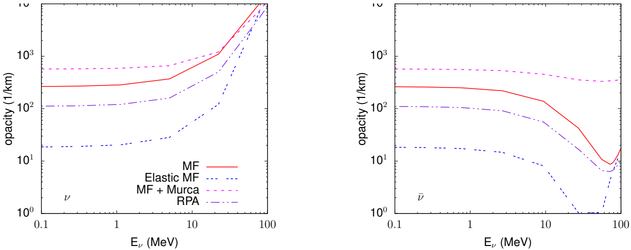




[Suleiman+ 2023]

Comparing different approximations

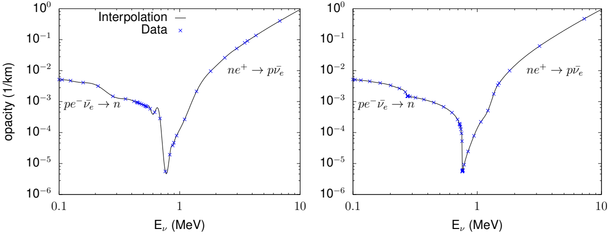
- Rates computed with RG(SLy4) EoS at $T = 16$ MeV, $n_B = 0.15$ fm^{-3}, $Y_e = 0.07$
- Murca reactions here as phenomenological finite life-time in Durca reactions



[Pascal+2022]

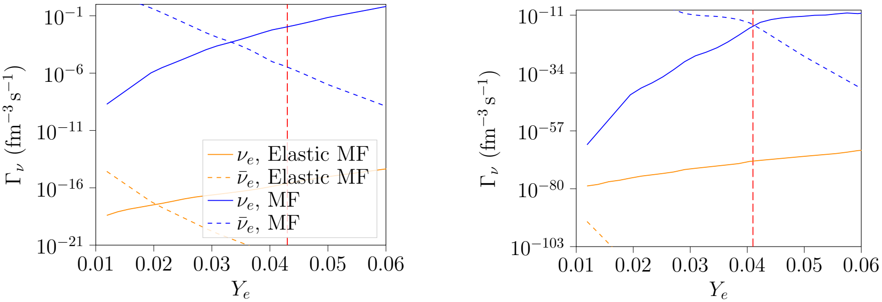
Neutrino tool kit

- Aim : provide numerically computed rates for use in simulations
  - Consistent with the underlying equation of state (EoS) model
  - Different levels of approximation : kinematics and nuclear interactions
  - Corrections are energy dependent (difficult to cast into a "gray" correction)
  - Polynomial fit (neutrino energy) to the opacities [Oertel+2020,Pascal+2022], see the data base https://compose.obspm.fr
  - Application to core-collapse supernova simulations (shift in position of neutrinosphere) [Oertel+2020] and proto-neutron star evolution [Pascal+2022]



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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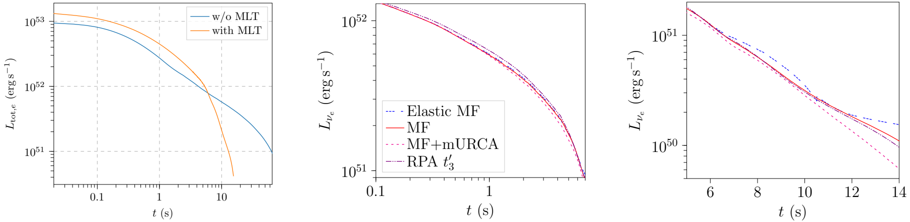
Influence of nuclear interactions



- Prevalent role of convection for dynamical proto-neutron star evolution, nuclear interactions in the opacities is subdominant effect
- Murca processes start to become important for late time evolution $\longrightarrow$ better calculation needed

Summary and outlook

Summary

- Neutrino nucleon interactions important ingredient in compact star astrophysics
- Collective effects important in dense matter $\longrightarrow$ considerably modified neutrino opacities
- Provide up to date opacities/rates for simulations of compact star astrophysics (dynamics, nucleosynthesis, ...)
- Murca not necessarily suppressed with respect to dUrca reactions $\longrightarrow$ need to care about Murca type reactions
- Prediction of PNS neutrino signal not only needs detailed microphysics but also convection

Outlook

- Conditions for β-equilibrium $\longrightarrow$ conditions for nucleosynthesis
- Include other types of reactions (scattering...) for consistent treatment