Neutrino-nucleon interactions in dense and hot matter

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Outline

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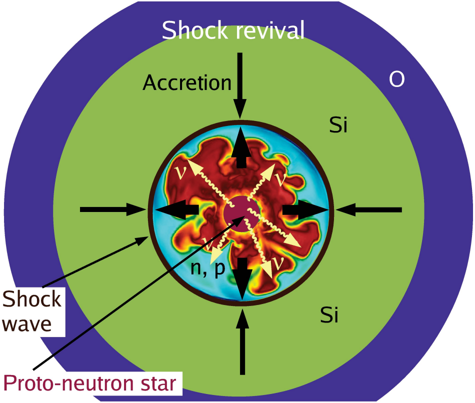
Neutrino interactions

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

Shock revival in a CCSN



[Janka 2012]

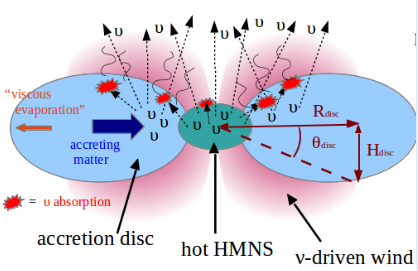
Neutrino interactions

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]

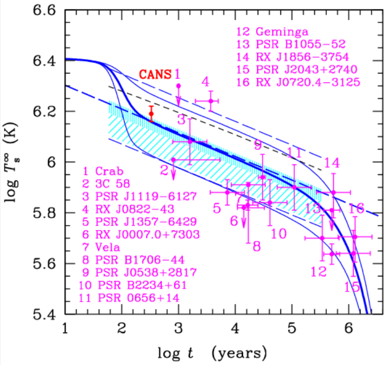
Neutrino interactions

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]

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

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

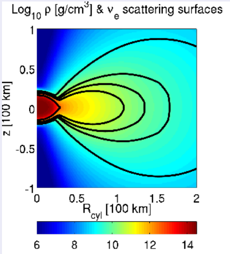
- Here : charged current processes on nucleons
  (for a recent work on reactions on nuclei see e.g. [Pascal 2019])

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 several to tens of MeV
- Neutron star cooling
  - Neutrino emission from the core, typical neutrino energies $\sim T$

BNS merger remnant



[Perego 2014]

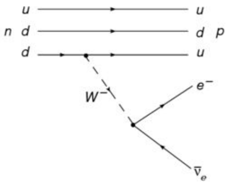
Hot central part	Neutrinosphere	NS cooling
$n_B \gtrsim .1\text{fm}^{-3}$	$10^{-4}\text{fm}^{-3} \lesssim n_B \lesssim .1\text{fm}^{-3}$	$n_B \gtrsim .1\text{fm}^{-3}$
$T \gtrsim 10$ MeV	$5\text{MeV} \lesssim T \lesssim 10$ MeV	$T \lesssim 100$ keV
$Y_e \sim 0.1\text{-}0.3$	$Y_e \sim 0.1\text{-}0.3$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

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

Electron/positron capture

$$p + e^- \leftrightarrow n + \nu_e$$
$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$

Neutron/proton decay

$$n \leftrightarrow p + e^- + \bar{\nu}_e$$
$$p \leftrightarrow n + e^+ + \nu_e$$

- 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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Different approximations

Basic approximation

Elastic approximation [Bruenn 1985]

- Nuclear matrix element

$$\langle N|\bar{q}\gamma_\mu q|N\rangle \to g_V \bar{N}\gamma_\mu N \text{ (vector)}$$

and

$$\langle N|\bar{q}\gamma_\mu\gamma_5 q|N\rangle \to g_A \bar{N}\gamma_\mu\gamma_5 N \text{ (axial)}$$

- $g_V = 1$ and $g_A = 1.26$ from free neutron decay
- Neglect momentum transfer to the nucleons
- Non (special-)relativistic kinematics
- No nuclear interaction :
  $\rightarrow$ free nucleon masses and single particle energies
  $\rightarrow$ energy transferred to the nuclear medium is $E_e - E_\nu = m_n - m_p$

$\rightarrow$ simple analytic expressions for opacities widely used in simulations

Different approximations

Free matrix element and kinematics

Corrections to the nuclear matrix element [Horowitz 2002]

- Weak magnetism correction $\propto$ difference of neutron and proton anomalous magnetic moment
  relevant at any density
- Nucleon internal structure corrections : e.g. $g_V \to g_V(Q^2)$
  typical energy scale is 1 GeV $\longrightarrow$ small correction for relevant energies

$\longrightarrow$ (slightly less) simple analytic expressions for opacities

Phase space and recoil [Horowitz 2002, Leinson 2001]

- Take momentum transfer to the nucleon into account and use momentum dependence in phase space
  - To lowest order in E_ν/M $\longrightarrow$ analytic expressions [Horowitz 2002]
  - Full (special relativistic) kinematics $\longrightarrow$ numerical expressions [Leinson 2001]

- We are concerned with a hot and dense asymetric $(n_n \neq n_p)$ matter
  $\longrightarrow$ we need to consider nucleonic correlations

Different approximations

Corrections from nucleon nucleon correlations at high densities

Mean field corrections

[Reddy 1998, Leinson 2001]

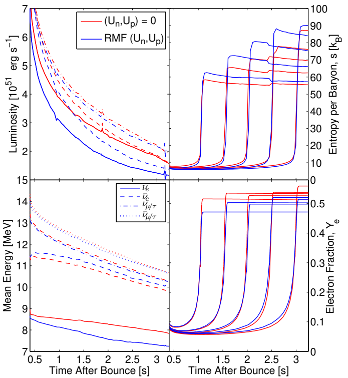
- Nucleonic interactions via mean field potentials $U_{n,p}(T, n_B, Y_e)$ and effective masses (as in many EoS)

  $\rightarrow E_{n,p} = \frac{\vec{p}^{\,2}_{n,p}}{2m^*_{n,p}} + U_{n,p}$ and thus

  $E_\nu - E_e = m_n - m_p + U_n - U_p$
- Energy difference between ν_e and $\bar{\nu}_e$ increased
- Neutron rich ejecta possible in CCSN neutrino driven winds
  $\rightarrow$ consequences for nucleosynthesis

[Roberts 2012, Martinez-Pinedo 2012]

Effect of mean field potentials in a CCSN



[Martinez-Pinedo 2012]

Different approximations

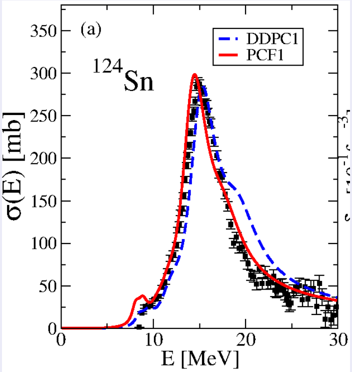
Corrections from nucleon nucleon correlations at high densities

Random phase approximation (RPA)

[Reddy 1999, Burrows 1999, Margueron 2006, Dzhioev 2018, ...]

- Summing up particle-hole excitations of the nuclear medium (long range collective response) $\rightarrow$ collective Fermi (vector) and Gamow-Teller (axial) modes
- Widely used in nuclear physics
- Reduce to mean field at low densities
- Significant suppression of neutrino opacities and energy dependent enhancement/suppression for antineutrinos

IVGDR strength calculated in RPA

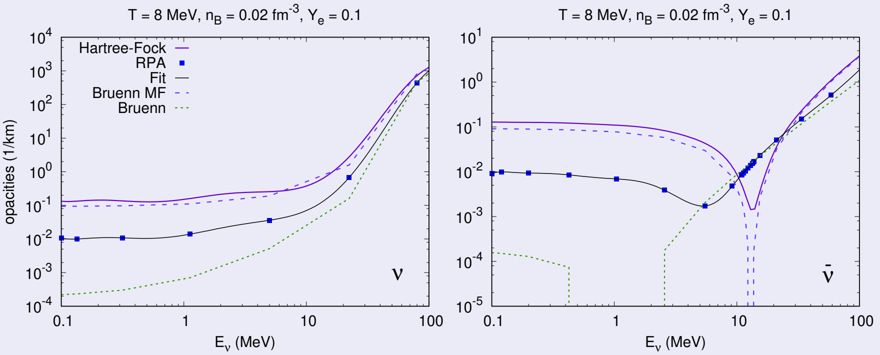


[Daoutidis 2011]

Neutrino opacities from absorption/creation

Preliminary results for different thermodynamic conditions

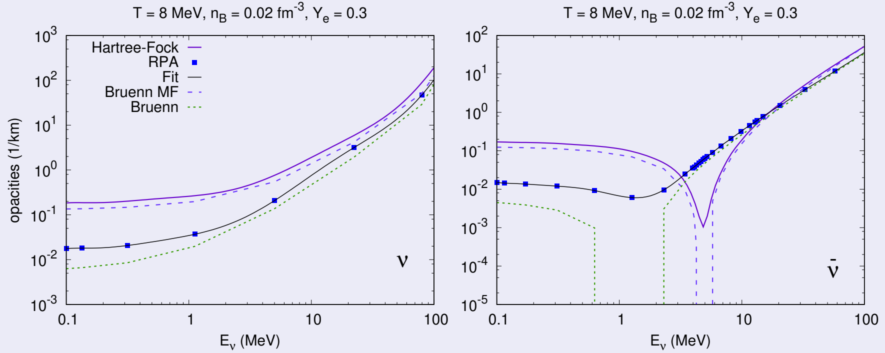
Equation of state : SLy4 model [Gulminelli 2015]



- Antineutrinos : shift of reaction threshold due to $U_n - U_p$, collective RPA response reduces effect
- Collective effects less important for high (anti-)neutrino energies

Neutrino opacities from absorption/creation

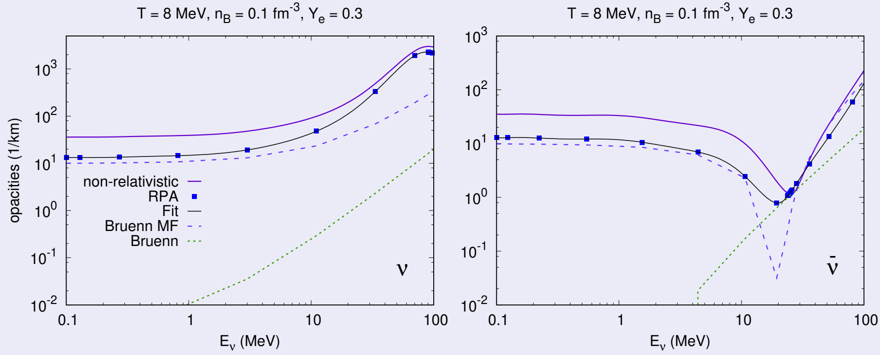
Preliminary results for different thermodynamic conditions



- Antineutrinos : shift of reaction threshold less pronounced for less neutron rich matter (neutron/proton potential difference smaller)
- Qualitative agreement with [Dzhioev 2018] (different EoS)

Neutrino opacities from absorption/creation

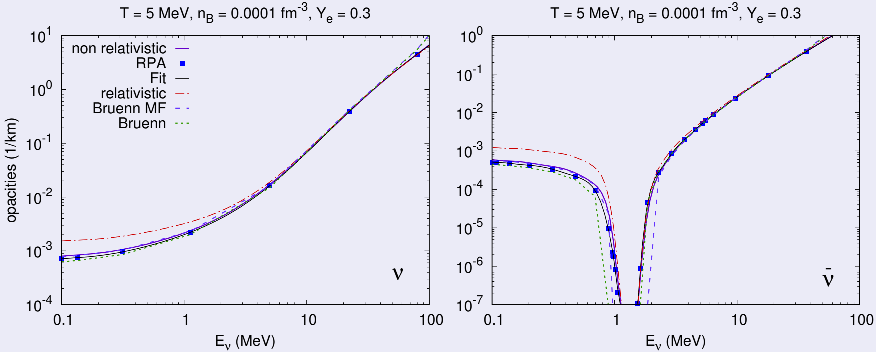
Preliminary results for different thermodynamic conditions



- Very strong (special) relativistic effects have to be checked (in agreement with [Leinson 2001])

Neutrino opacities from absorption/creation

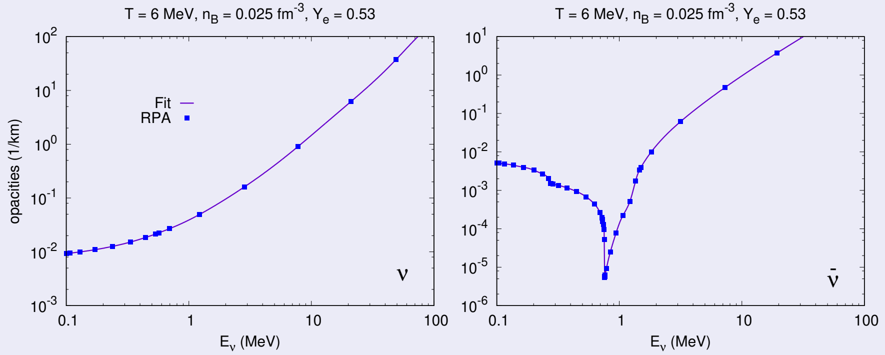
Preliminary results for different thermodynamic conditions



- At low densities and temperatures different approximations agree except for very small (anti-)neutrino energies

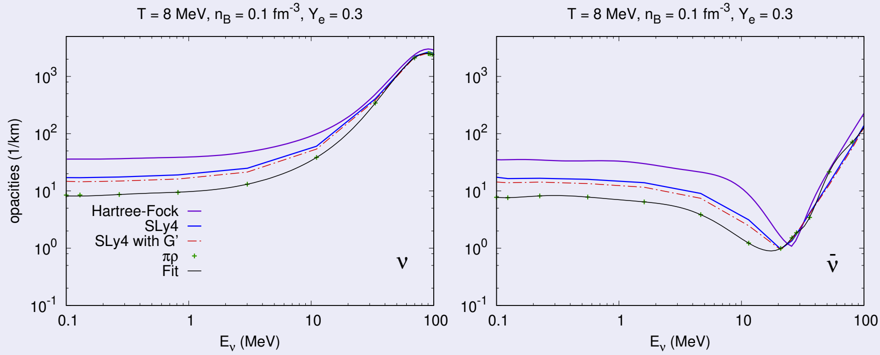
Polyonomial fit to the opacities

- Analytic approximations can be used in simulations "on the run", but improved calculations too time consuming
  $\rightarrow$ provide opacities in tabular form on a large (T, n_B, Y_e) grid (same as underlying EoS, $\sim 10^6$ grid points) to be used in simulations
- Give coefficients of polyonmial fit (logarithmic scale) to opacities with domains in energy chosen from thresholds



A remark on RPA

- Many Skyrme forces show an instability in the spin-isospin channel at high densities/temperatures [Pastore 2014]
- Two proposed remedies (this channel anyway poorly constrained) :
  - Microscopically motivated residual interaction ($\pi\rho$) model [Reddy 1999]
  - Add additional repulsive term in this channel (coherent with EoS) [Margueron 2009]

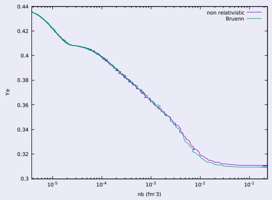


Neutrino tool kit

- Neutrino opacities in dense and hot matter sensitive to nuclear interaction
- Aim : provide results ready for use in simulations
  - Consistent with the underlying EoS model
  - Charged current reactions with full isospin breaking corrections ($m_n \neq m_p$!)
  - Different levels of approximation : full (non)-relativistic kinematics, RPA correlations with EoS dependent residual interaction
  - Corrections are energy dependent (difficult to cast into a "gray" correction factor)
  - Polynomial fit to the results on the same (T, n_B, Y_e) grid as EoS

- First CCSN results consistent
  - CoCoNuT code
  - FMT neutrino treatment [Müller 2015]
  - 15 solar mass progenitor, HS(DD2) EoS
  - spherical symmetry

Electron fraction during infall



Summary and outlook

1. Summary

- Neutrino nucleon interactions important ingredient in
  - Core-collapse supernovae and (proto)-neutron star cooling
  - Binary neutron star mergers
- Collective effects important in dense matter $\rightarrow$ considerably modified neutrino opacities !
- Provide polynomial representations for rates including collective effects coherent with EoS within the Compose data base `https://compose.obspm.fr`

2. Outlook

- Implement additional contributions to CC reactions (weak magnetism) and effects (e.g. magnetic field)
- Full "neutrino tool kit" : extent the calculations to neutral current reactions, reactions on nuclei and leptons
- Any comments are welcome !