Neutrino-nucleon interactions in dense and hot matter

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Quantum Many-Body Correlations in memory of Peter Schuck,
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Collaborators: A. Pascal, L. Suleiman, M. Mancini, J. Novak

Peter Schuck and nuclear astrophysics

- Peter has been involved in
  - Nuclear pairing in dense matter
  - Nuclear density functional theory
  - Quartetting and the Hoyle state and ...
- See many talks at this workshop

2007 SNNS meeting Orsay

- The SNNS meetings at Orsay in the early 2000's : collaboration between the nuclear physics and the numerical relativity/astrophysics community on neutron star physics
- Peter Schuck and Brandon Carter were leaders in bringing together relativity and nuclear physicists

Outline

Outline

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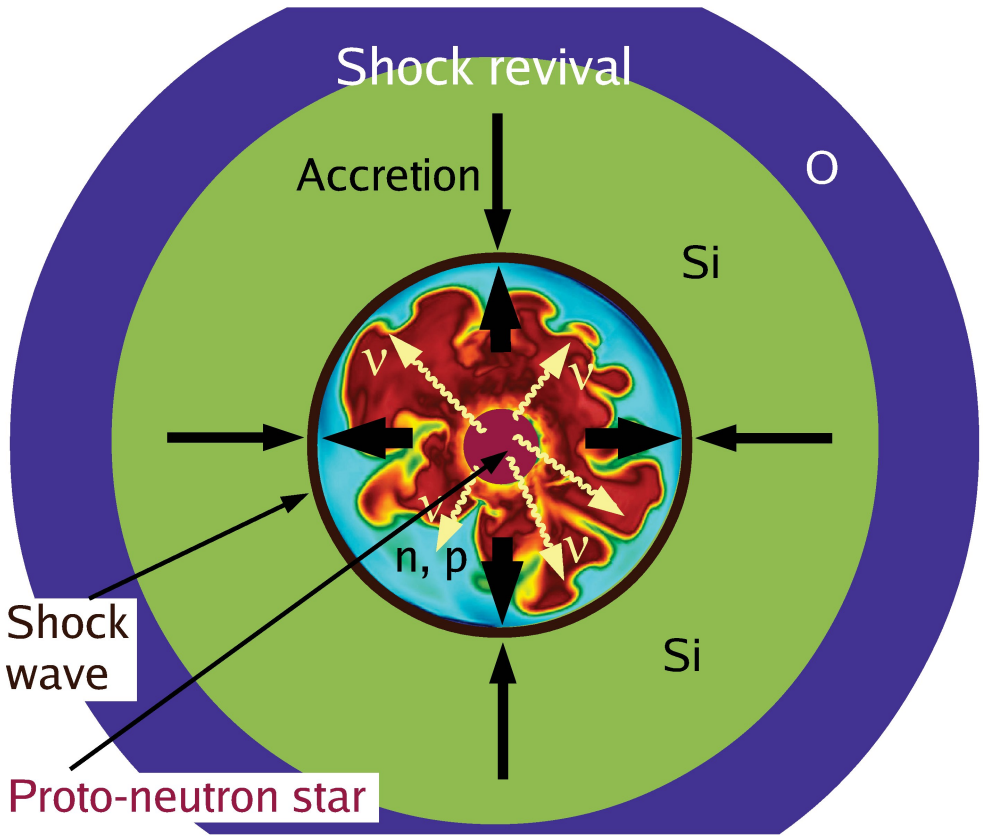
Neutrino interactions

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
   - Neutrino emissivities dominant for (P)NS cooling for about 10^6 yrs

Shock revival in a CCSN



[Janka 2012]

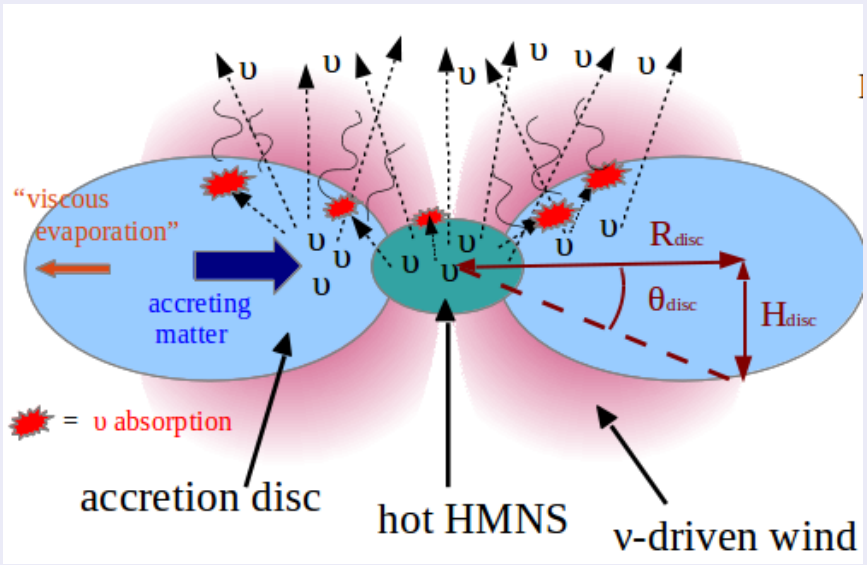
Neutrino interactions

Why are we wondering about ?

2. Binary neutron star mergers

- Neutron rich and hot environment $\longrightarrow$ 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



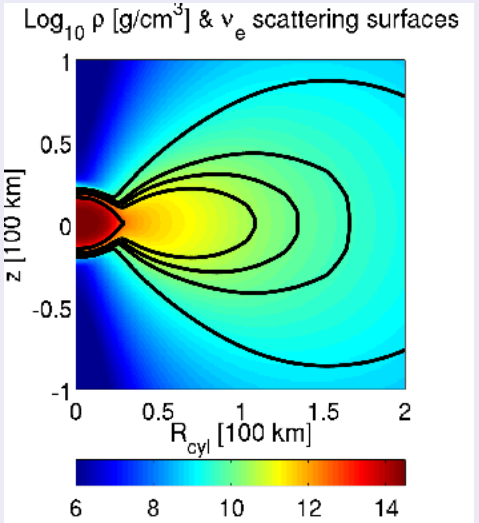
[Perego 2014]

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

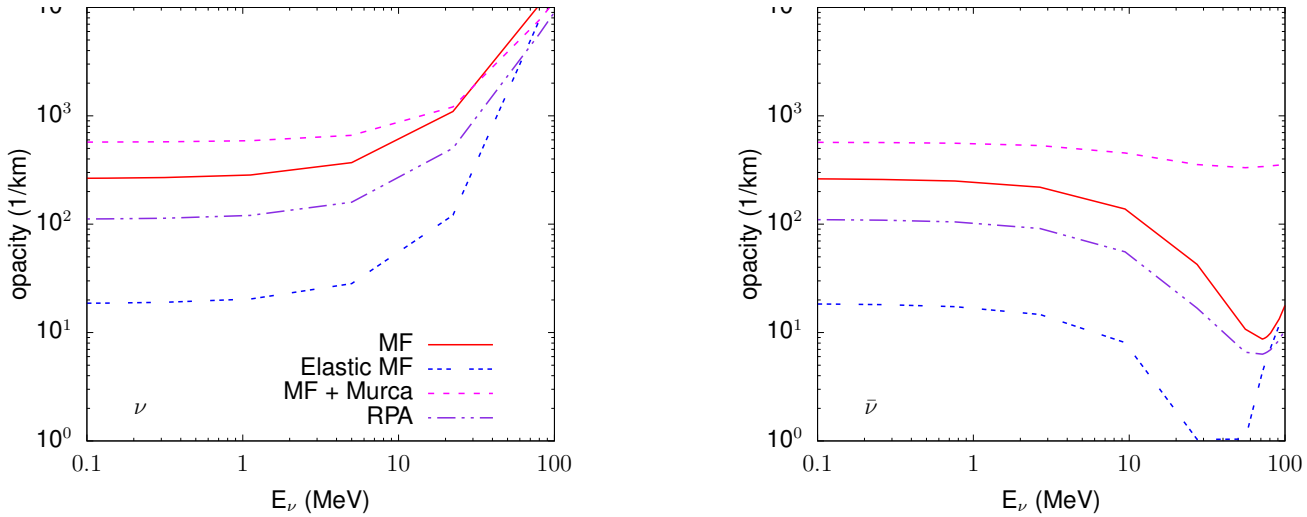
$$
\begin{aligned}
p + e^-(+N) &\leftrightarrow n + \nu_e(+N) \\
n + e^+(+N) &\leftrightarrow p + \bar{\nu}_e(+N) \\
(A, Z) + e^- &\leftrightarrow (A, Z-1) + \nu_e \\
N + N &\rightarrow \nu + \bar{\nu} + N + N \\
\nu + A &\rightarrow \nu + A \\
\nu + N &\rightarrow \nu + N
\end{aligned}
$$

- Here : charged current (CC) processes on nucleons

CC REACTIONS IN DENSE AND HOT MATTER

- Different approximations to compute charged current neutrino-nucleon rates
  - Elastic approximation (neglect momentum transfer to nucleons and non-interacting nucleons) $\longrightarrow$ simple analytic expressions [Bruenn 1985]
  - Include full phase space $\longrightarrow$ numerical computation
  - Include full phase space and nuclear interactions (mean field or RPA)

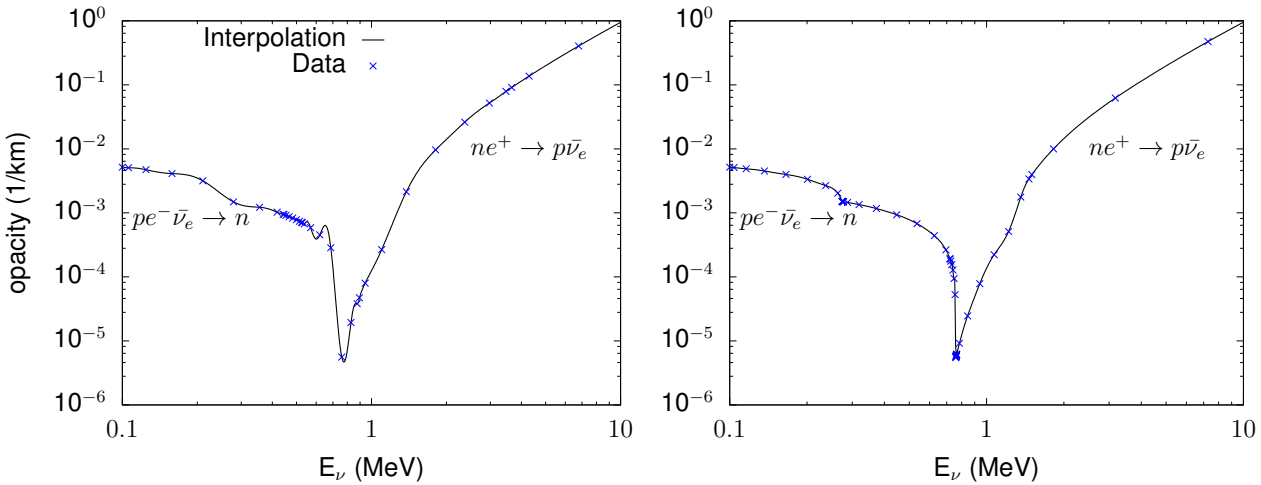
    [Reddy+1998, Burrows& Sawyer 1998,...]
  - Murca reactions here as phenomenological finite life-time in Durca reactions
- Analytic results widely used in simulations but crude approximations



[Pascal+2022]

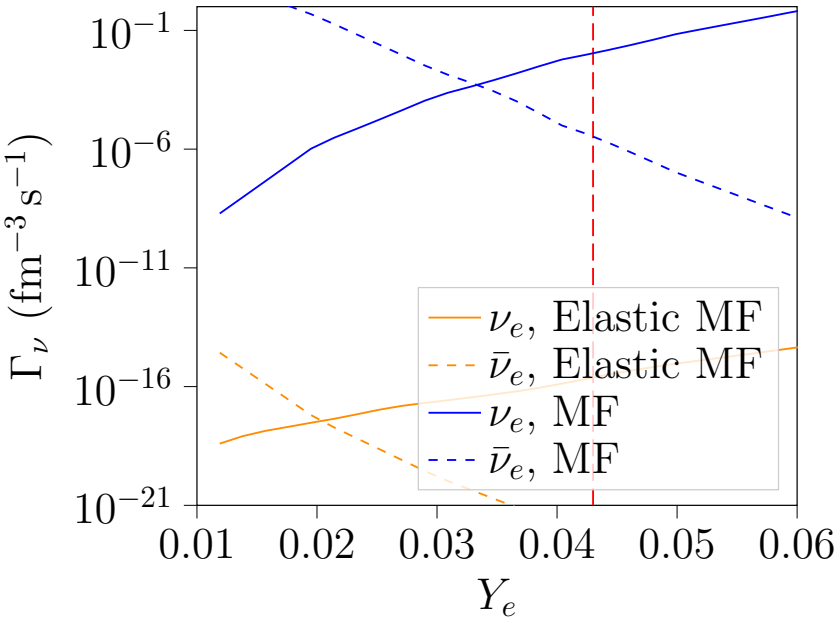
Neutrino tool kit

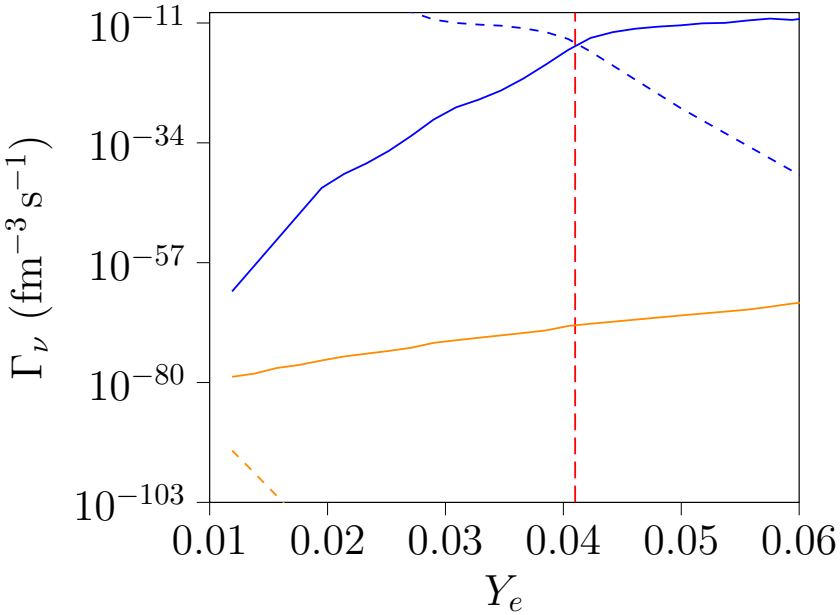
- Aim : provide numerically computed rates for use in simulations
  - Consistent with the underlying equation of state (EoS) model
  - Different levels of approximation : kinematics and nuclear interactions
  - Corrections are energy dependent (difficult to cast into a "gray" correction)
  - Polynomial 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

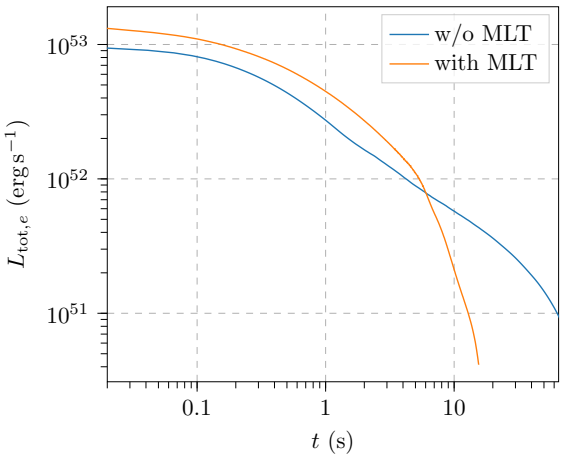
- Simulation of PNS evolution with quasi-static GR hydrodynamics + neutrino transport [Pascal+2022]

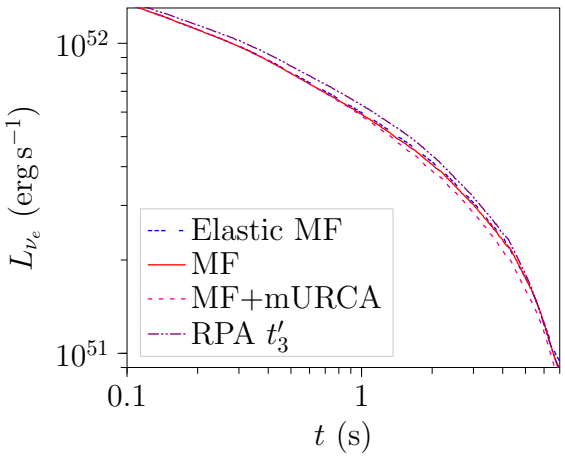


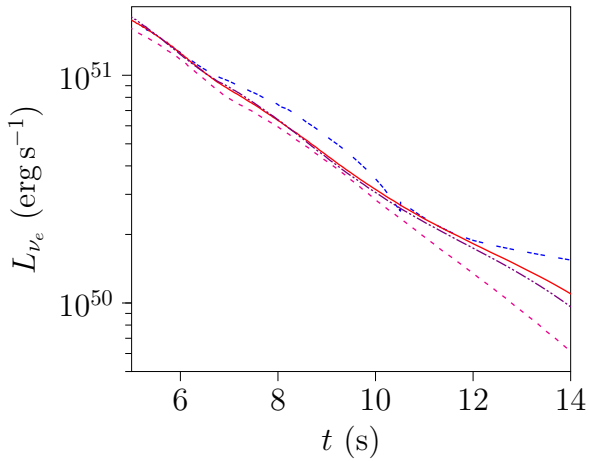


- β-equilibrium not correctly obtained $\rightarrow$ breakdown of the elastic approximation at high densities, need for numerical (pre-)computation of opacities

Influence of nuclear interactions





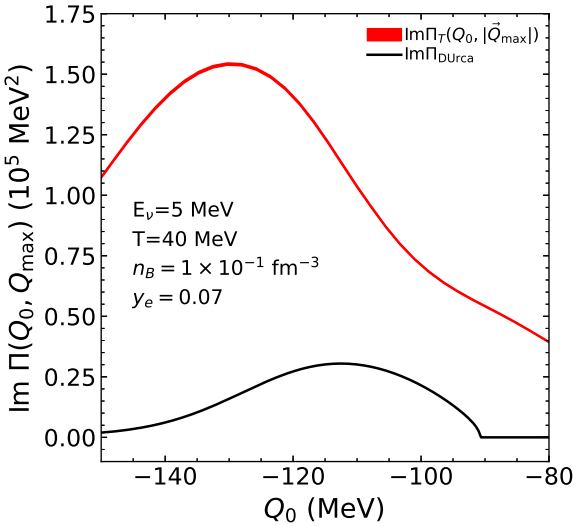


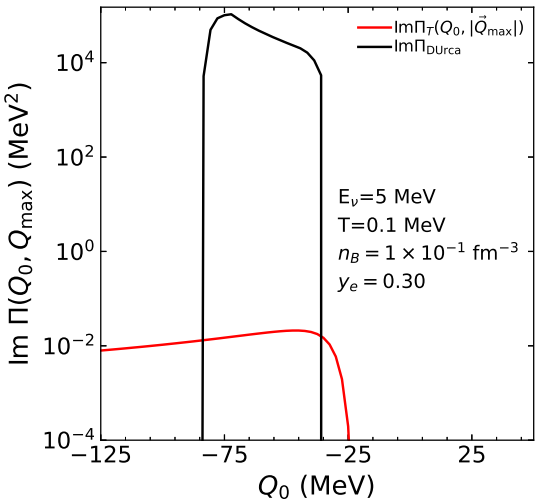
- Prevalent role of convection for dynamical proto-neutron star evolution, nuclear interactions in the opacities is subdominant effect
- Murca processes start to become important for late time evolution $\longrightarrow$ better calculation needed

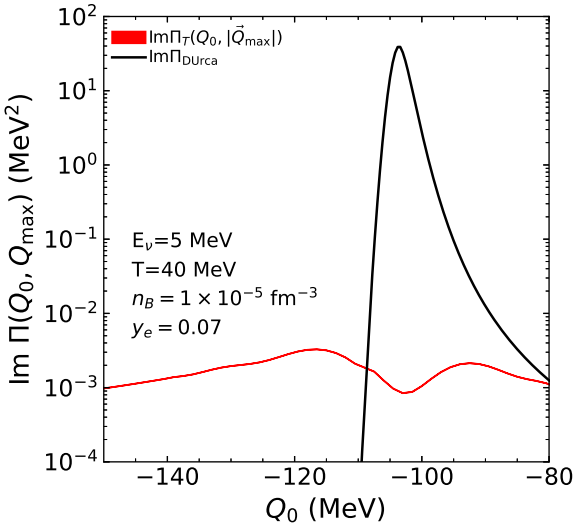
Preliminiary results for Murca reactions

- Common approximations
  - All particles on respective Fermi surface
    $\rightarrow$ cold matter
  - Neglect momentum transfer $\rightarrow$ low densities

  not adapted to PNS cooling, BNS merger remnant....
- Preliminary results indicate that Murca not necessarily suppressed
  $\rightarrow$ need to care about Murca [Suleiman+ in prep]







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 polynomial representations for rates (`https://compose.obspm.fr`)
- Prediction of PNS neutrino signal not only needs detailed microphysics but also convection

Outlook

- Need to care about Murca type reactions
- More complete description of convection for PNS evolution
- PNS evolution code does not yet reach the conditions for crust formation $\longrightarrow$ should be extended