# RPA correlations & Weak Magnetism in Neutrino-Nucleon interaction in hot dense matter.

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- Neutrino-Nucleon interaction is a key ingredient in SN simulations and NS cooling.
- The success of the SN explosion depends greatly on the neutrino energy deposition in the medium.
- It is necessary to perform calculation of neutrino opacities with an EOS in a consistent way.

- We use the TM1 model for the hadronic matter (n,p) interacting via σ,ω and ρ mesons. $e^-$ are included to provide charge neutrality.

- Finite T, Beta equilibrium:

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

- Neutron-rich matter being probed with typical neutrino energies E~15 MeV

- The neutral current interaction

$$\nu_x + N \rightarrow \nu_x + N$$

- is calculated using the weak vertex:

$$\Gamma^{\mu}(q) = F_1(Q^2)\gamma^{\mu} + iF_2(Q^2)\sigma^{\mu\nu}\frac{q^{\mu}}{2M} - G_A(Q^2)\gamma^{\mu}\gamma^5$$

$$(Q^2 = -q^2 \approx 0)$$

- The <u>weak magnetism</u> terms, $F_2$, provide information from parity violation, Charge Symmetry Breaking .

- The cross section (per nucleon) for these elastic processes

$$\frac{d^2\sigma}{d\Omega' dE'} = -\frac{G_F^2 |k'|}{32\pi^3 nE} \mathrm{Im}\left(L_{\mu\nu}\Pi_{\mu\nu}\right)$$

*polarization:*

$$i\Pi_{\mu\nu} = \int \frac{d^4 p}{(2\pi^4)} Tr\left[G(p+q)\Gamma^\mu G(p)\Gamma^\nu\right]$$

*lepton tensor:*

$$L_{\mu\nu} = 8\left[k'_\mu k_\nu - k.k' g_{\mu\nu} + k'_\nu k_\mu \mp i\varepsilon_{\alpha\mu\nu\beta} k'^\alpha k^\beta\right]$$

- We use finite T in-medium Green function for the nucleons in the dense plasma.
- We compare several approximations:
- <u>Hartree (non-correlated):</u>

$$\Pi_{\mu\nu} \rightarrow \Pi^{Hf}_{\mu\nu}$$

- <u>Random Phase Approx. RPA</u>

$$\Pi_{\mu\nu} \rightarrow \Pi^{Hf}_{\mu\nu} + \Delta\Pi^{RPA}_{\mu\nu}$$

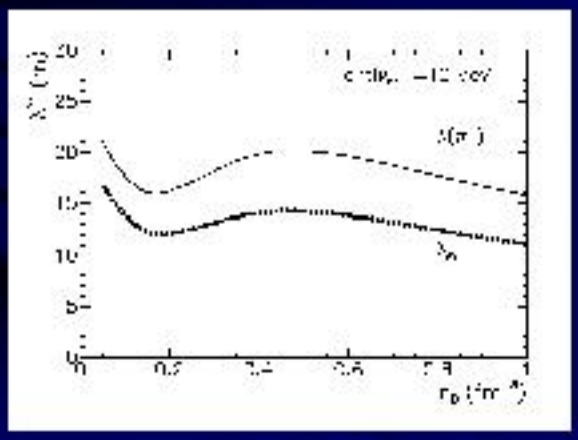
- We include as well:
  - phase-space corrections
  - recoil energy
  - Pauli-Blocking
  - Fermi/Thermal motions of initial nucleons
  - Coulomb interactions

- Mean free paths (MFP): $\lambda(E) = \frac{1}{\sigma'(E)\, n_\pi}$

- Diffussion approx, averaged over E distribution, f(E)~exp(-E/T)

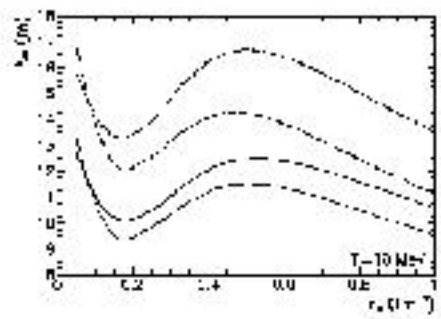
$$\langle \lambda \rangle = \frac{\int \lambda(E)\, E^4 f(E)\, dE}{\int E^4 f(E)\, dE}$$

- The average MFP for (anti-) nu in the plasma differs from that evaluated at <E>.

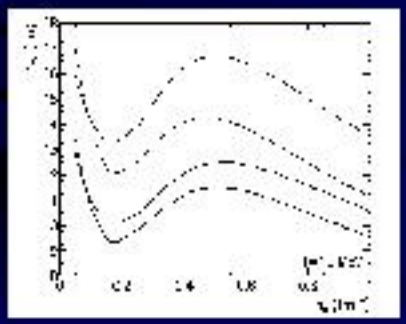


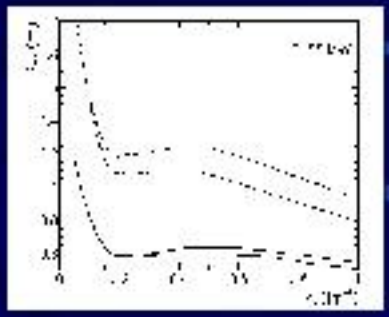

E Hernandez, M.A. Perez, Phys. Rev. C 2001, in press

- Our calculations lead to **smaller** CS for the anti-nu comparing to those for the neutrinos or **larger** mean free paths for anti-nu

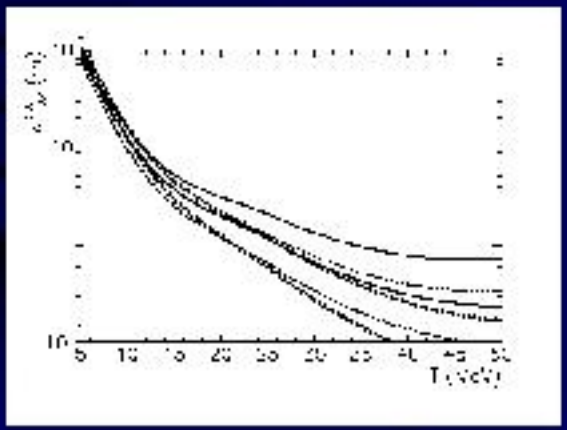


- RPA correlations are smaller as T increases.
- Instability of Correlations to non-uniform matter make RPA mean free paths smaller than Hartree at lower densities.



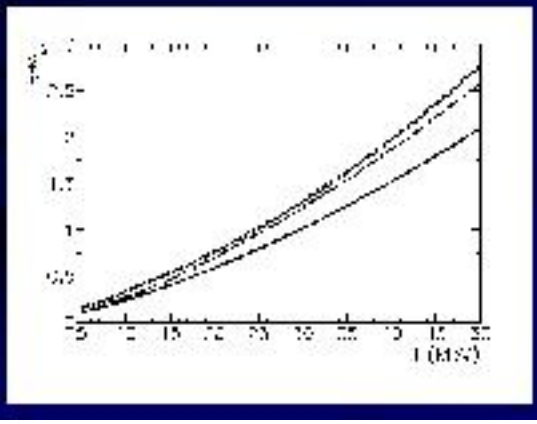


- RPA MFPs have a very rapid decrease with larger T but small dependence with density.



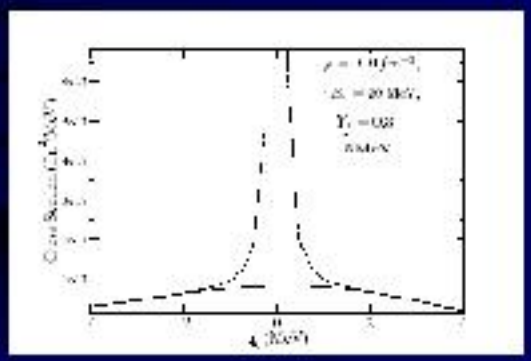
- The fractional difference between nu and anti-nu MFP increases rapidly with T

$$\pi = \frac{\langle \lambda^{-} \rangle - \langle \lambda \rangle}{\langle \lambda \rangle}$$



## Instabilities in non-uniform phase

- Instabilities in RPA arise mostly at non zero Ye and small densities and T, signaling onset of non-homogeneous phase.

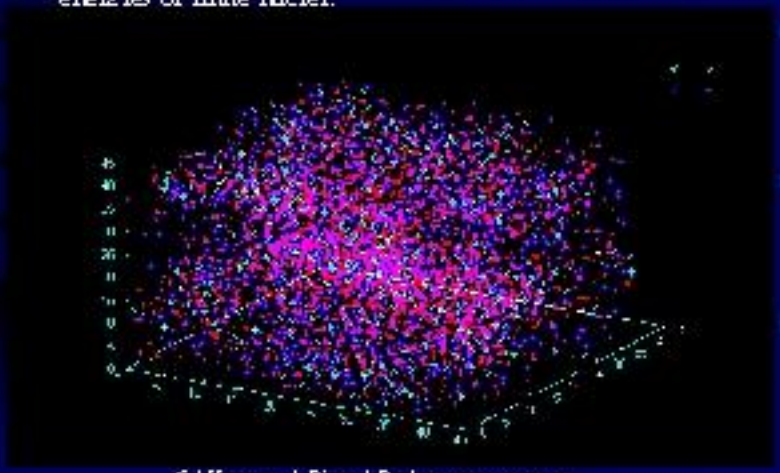


- At densities ranging from $n=0.01$ Fm$^{-3}$ to $n=0.1$ Fm$^{-3}$ and T up to several MeV the PASTA phase is energetically possible in the system.

- In these conditions, likely at the inner crust in dense stars, neutrinos streaming out can excite many oscillation modes and thus big opacities in the medium are expected.

- Using the Metropolis algorithm in a classical Monte Carlo simulation is possible to sample the configurations available to the system.

- MC Simulation with 4000 particles Ye=0.2, n= 0.05 $Fm^{-3}$ ,
- kT=1 MeV. Using gaussian-like potential fitting binding energies of finite nuclei.

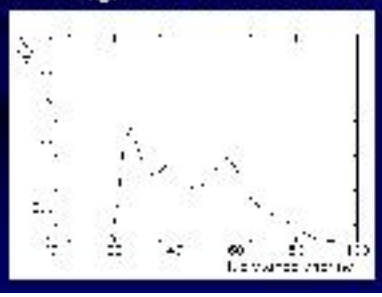


C J Horowitz, A Piekarewicz, J Piekarewicz, in progress

- The cross section for $\nu_\chi$ in the Pasta phase is

$$\frac{d^2\sigma}{d\Omega' dE'} = \frac{d^2\sigma^{NC}{}_0}{d\Omega' dE'} S(q) R_l \propto N^2$$

- $S(q)$ is the static structure factor for n, $R_l$ is the lepton screening. Proportional to n weak charge squared.
- The correlation function, g, shows enhancements at clusters of matter.



# Conclusions

- Weak magnetism allows anti-nu to have larger mean free paths than neutrinos in the medium, as they stream out of the star.
- RPA correlations reduce the opacity compared to the Hartree result. RPA correlation in MFP have weak density dependence and rapidly decrease with Temperature.
- The fractional difference between nu and anti-nu MFP grows with T. At T ~ 10 MeV is 30%. This leads to resolve the degeneracy so $T_{anti\text{-}\nu_x} > T_{\nu_x}$.
- At small densities the RPA response shows instability with respect to density non-uniformities.
- Pasta phase is energetically possible where big enhacement of the neutrino opacities is expected.