Models of Nuclear Many-Body Effects in Neutrino-Nucleon Interactions

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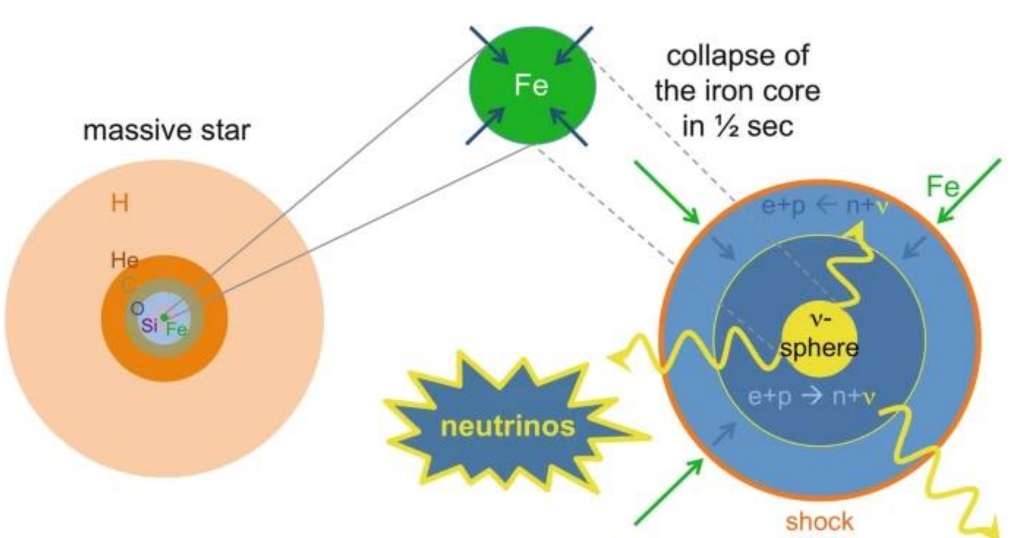
Motivation

Dense nuclear matter is the primary composition of **neutron stars and supernovae cores.** Studying this medium, which is primarily held together by the nuclear force, can help probe these astrophysical phenomena.

In core-collapse supernovae:

- Neutrinos absorbed into the core are released
- Carry **almost all the energy** of the supernovae, ~10 MeV



Janka et. al (2012)

This results in a variety of **neutrino interactions**, including:

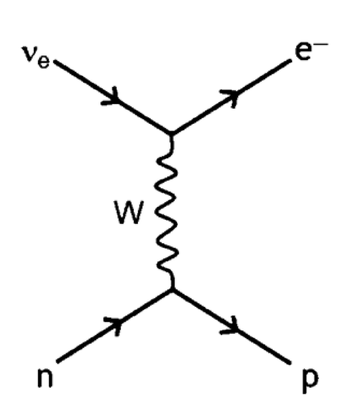
- neutrino scattering
- thermal pair processes
- **beta processes**

We can use these astrophysical phenomena to extract **neutrino properties:**

- neutrino **transport, absorption** rates
- neutrino **opacities** and **cross sections**
- cooling and evolution of the star

We therefore calculate **response functions**:

- Density, Spin
  - T = 0
  - Pure neutron matter



Response Functions

- Quantification of system reaction to **external perturbation**
  - function of **momentum and energy transfer** *(q, ω)*
- Imaginary part: dynamical structure functions
  - from this we can find **neutrino cross sections**
- Zeroth order contribution to neutral current response functions:

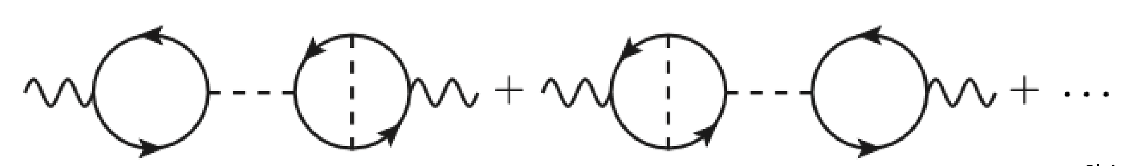
$$\chi_\rho^{(0)}(\vec{q},\omega) = \sum_{s_1 s_2 t_1 t_2} \int \frac{d\vec{k}}{(2\pi)^3} \frac{f_{\vec{k},t_1} - f_{\vec{k}+\vec{q},t_2}}{\omega + e_{\vec{k},t_1} - e_{\vec{k}+\vec{q},t_2} + i\eta} \delta_{s_1,s_2}\delta_{t_1,t_2},$$

$$\chi_\sigma^{(0)}(\vec{q},\omega) = \sum_{s_1 s_2 t_1 t_2} \int \frac{d\vec{k}}{(2\pi)^3} \frac{f_{\vec{k},t_1} - f_{\vec{k}+\vec{q},t_2}}{\omega + e_{\vec{k},t_1} - e_{\vec{k}+\vec{q},t_2} + i\eta} |\langle s_1|\sigma_z|s_2\rangle|^2 \delta_{t_1,t_2}.$$

s,t : spin, isospin projections
$f_{k,t}$: Fermi Dirac distribution functions
$e_{k,t}$: single-particle energy

Random Phase Approximation

- Many-body, conserving approximation:
  - **collective excitations** in interacting system
  - derived from linear response theory
- Builds upon the Hartree-Fock ground state
  - lowest energy state by assuming mean field
  - Includes small oscillations of HF Slater determinant
    - **particle-hole excitations**
    - use of **Chiral EFT** to derive nuclear forces
- Infinite summation of **bubble diagrams**



Shin et. al (2024)

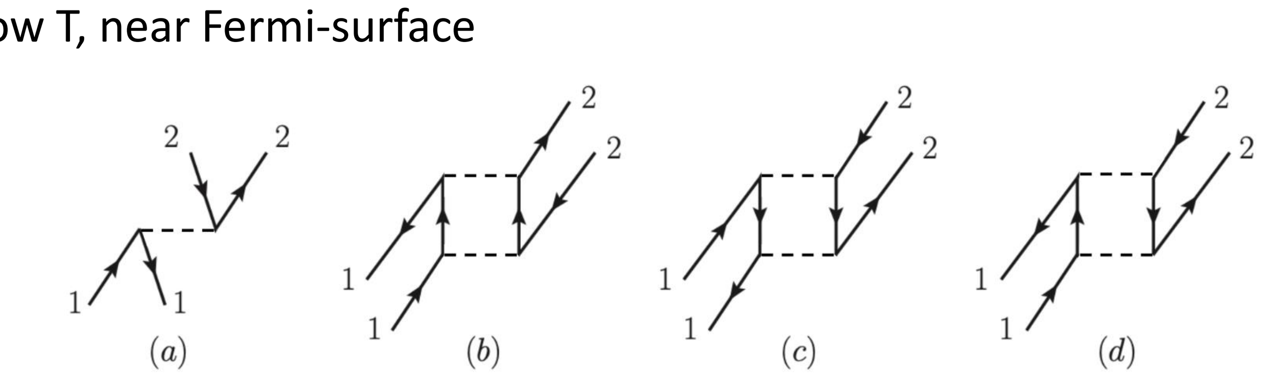
$$\chi^{RPA}(q,\omega) = \chi_0(q,\omega) + v_q[\chi_0(q,\omega)]^2 + v_q^2[\chi_0(q,\omega)] \quad \cdots$$
$$= \frac{\chi_0(q,\omega)}{1 - v_q\chi_0(q,\omega)}.$$

Fermi Liquid Theory

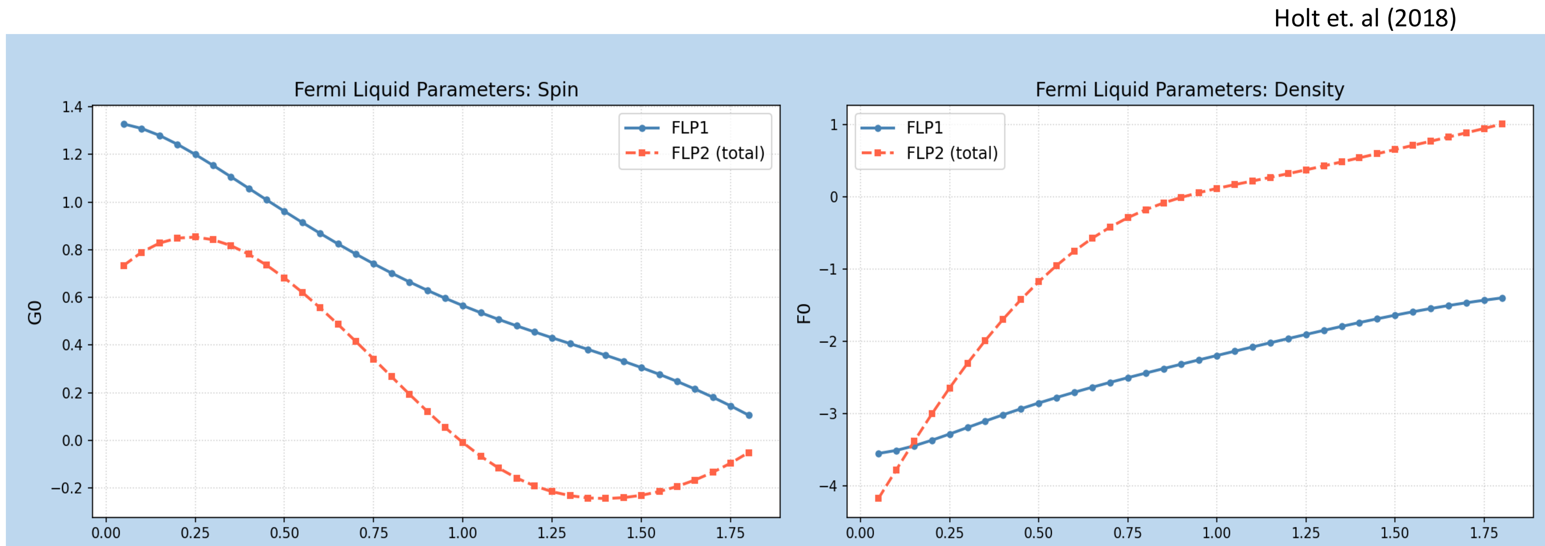
- Estimates fermions as **quasiparticles: weakly-interacting, collective excitations** with **modified properties** of:
  - Effective mass
  - Interaction strength (Landau parameters)

$$\chi_\sigma(\vec{k},\omega) = \frac{N(0)}{V} \frac{g(\lambda)}{1 + [F_0^a + \lambda^2 F_1^a/(1 + \frac{1}{3}F_1^a)]g(\lambda)}$$

- Can help us probe **beyond RPA:** higher order perturbations in interactions between n, p
  - Low T, near Fermi-surface

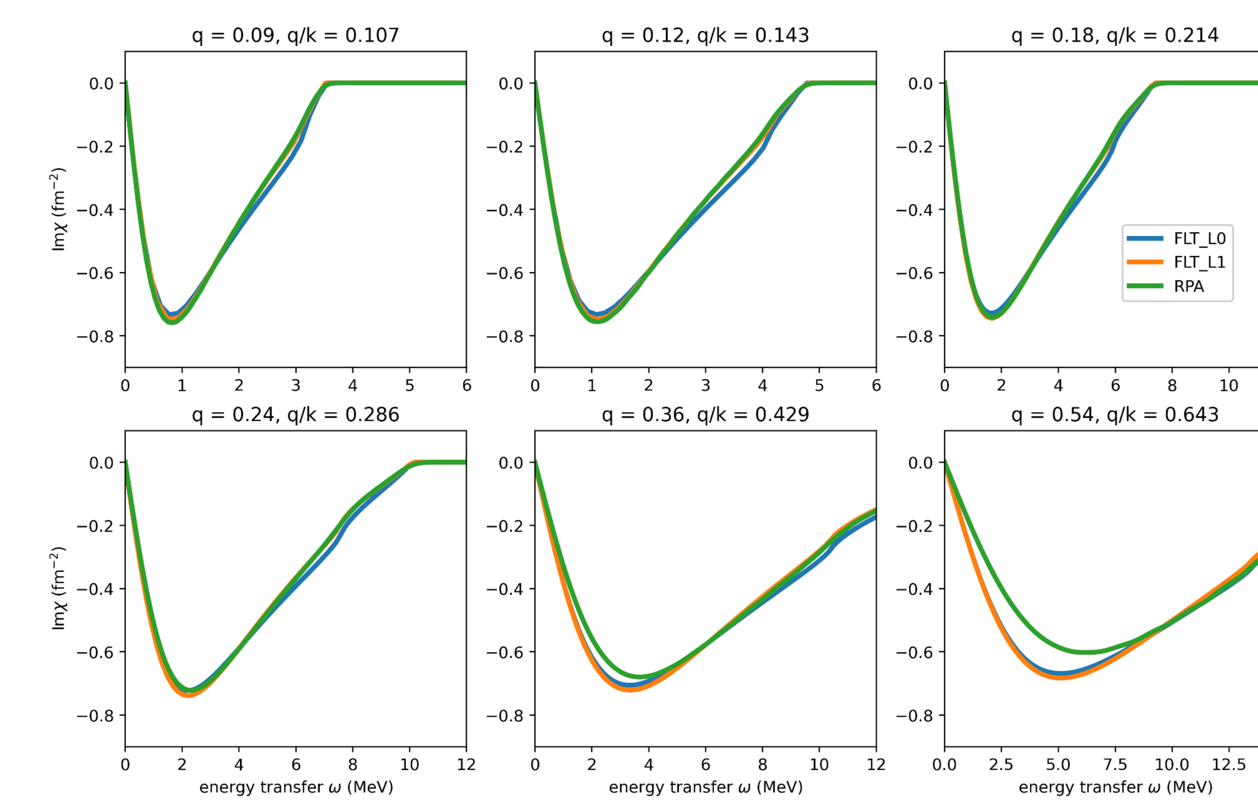


Holt et. al (2018)



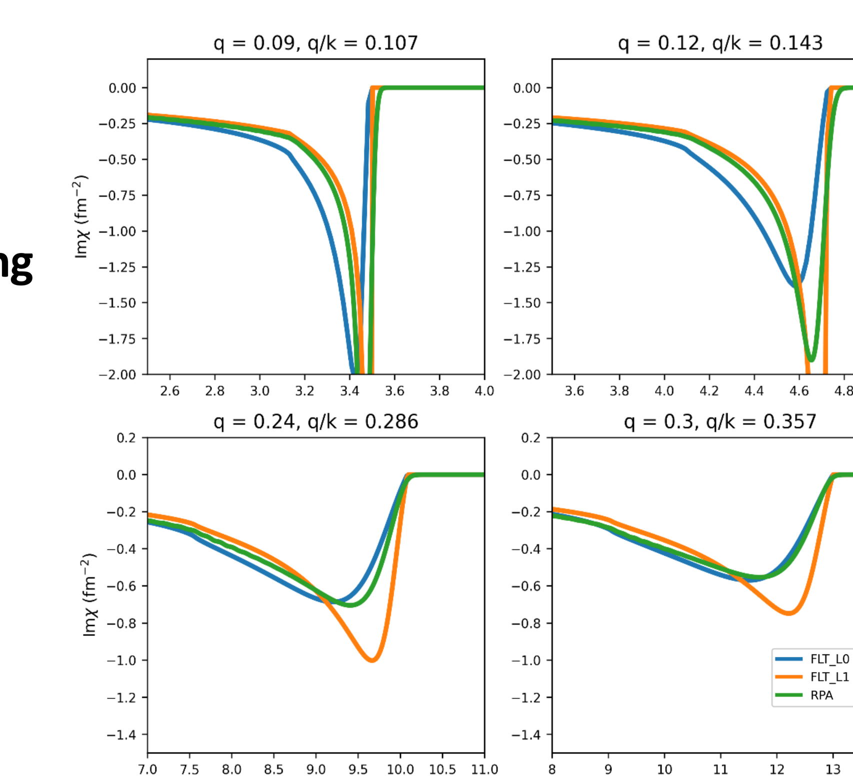
Results

0[th]-order Landau parameters obtained for first-order diagram of the quasiparticle interaction (FLP1) and for second-order diagrams (FLP2) for both density and spin show significant disparity both in value and trend.



(Above) The imaginary part of density response functions, generated from RPA and FLT techniques, **demonstrate strong agreement** up to momentum transfer of about 0.3 Fm[-1]

(Right) For spin response functions, the curves diverge earlier, only agreeing for **very low momentum and energy transfer.**



Conclusion and Next Steps

- FLT is valid, correlating with RPA, in regimes of lower momenta transfer and low energy transfer. In these boundaries it can offer a more comprehensive measurement of neutrino cross sections and opacities.
- **Future plans:**
  - Comparison with symmetric nuclear matter. finite T
  - Incorporation of second-order FLT diagrams, and extracting modified neutrino properties.

References

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