Università di Roma "Sapienza", XXV ciclo

Neutrino Interactions in Neutron Star Matter

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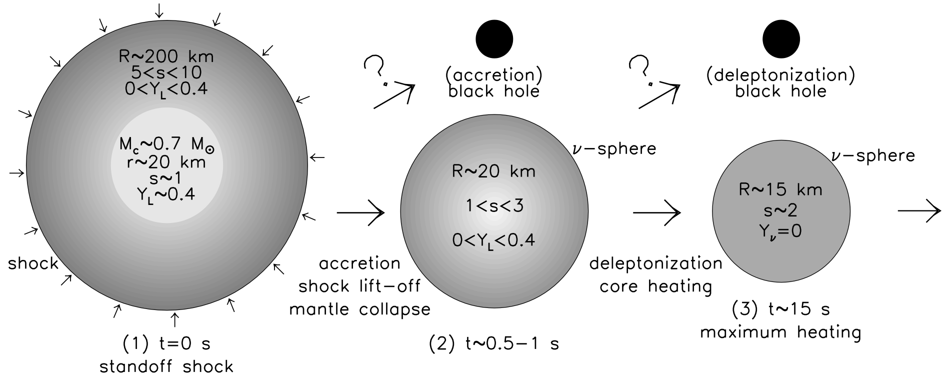
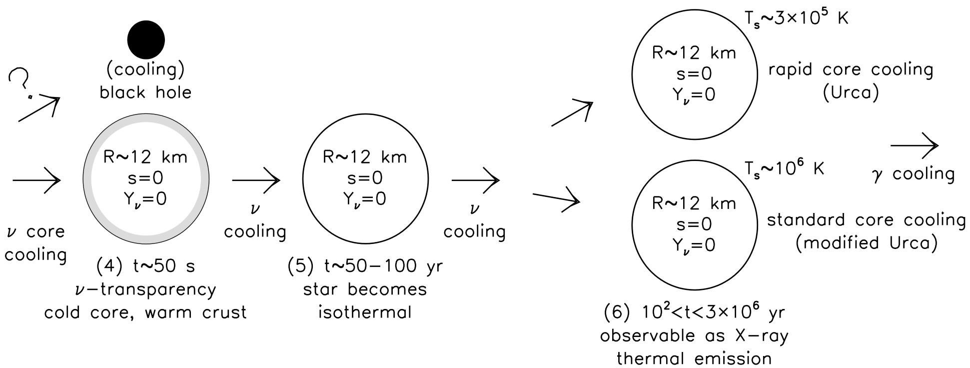
The birth of a neutron star

→ Core Collapse

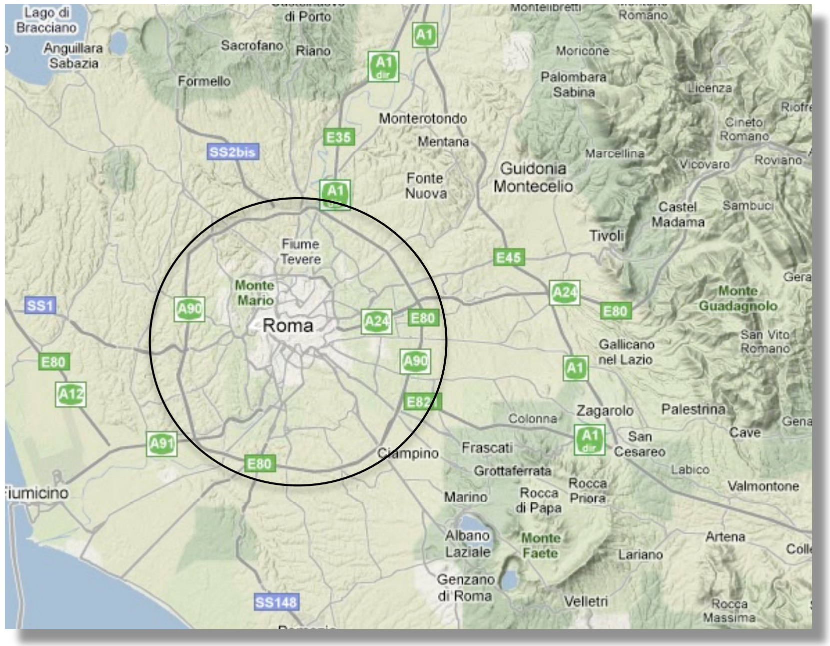
↓

Birth of a neutron star





→ Is it big as... a star?

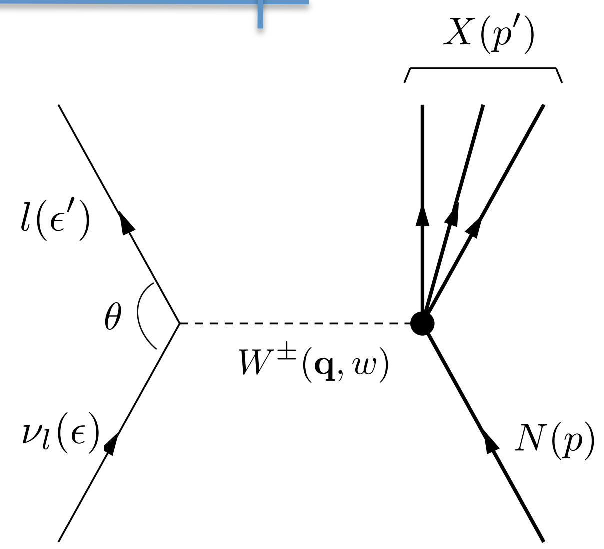


M. Prakash et al., arXiv:astro-ph/0012136v1

Neutrino cross section at nuclear density

- Low energy process ($w \ll M_W$), similar to

$$\nu_l + N \rightarrow l + X$$



Lepton Trace

$$\frac{\partial^2\sigma}{\partial\epsilon'\partial\Omega} = \frac{G_F^2}{(2\pi)^2}\frac{\epsilon'(1-f_l(\epsilon'))}{8\epsilon}L^{\mu\nu}(\mathbf{q},w)\left(-\frac{2}{1-e^{-\beta w}}\mathrm{Im}[\tilde{\mathcal{W}}_{\mu\nu}]\right)$$

Correlation Functional of hadronic current

fluctuaction-dissipation theorem

- Non-relativistic limit $p \ll m_N$, for neutral current:

$$L^{\mu\nu}\mathrm{Im}\left[\tilde{\mathcal{W}}_{\mu\nu}\right] \rightarrow 8\,\epsilon'\epsilon\left[\mathrm{Im}[\chi^{\rho\rho}(\mathbf{q},w)](1+\cos\theta) + \mathrm{Im}[\chi^{\sigma\sigma}(\mathbf{q},w)](3-\cos\theta)\right]$$

density response

spin-density response

Landau Theory: Dynamic Response

Supposing a scalar probe $\delta\rho(\mathbf{q}, w) = \chi(\mathbf{q}, w)\, U_{ex}(\mathbf{q}, w)$

$$\chi(q,w) = \sum_{n\neq 0}{}' |(\rho_q^+)_{n0}|^2 \frac{2w_{n0}}{(w+i\eta)^2 - w_{n0}^2} + \chi_{multipairs}$$

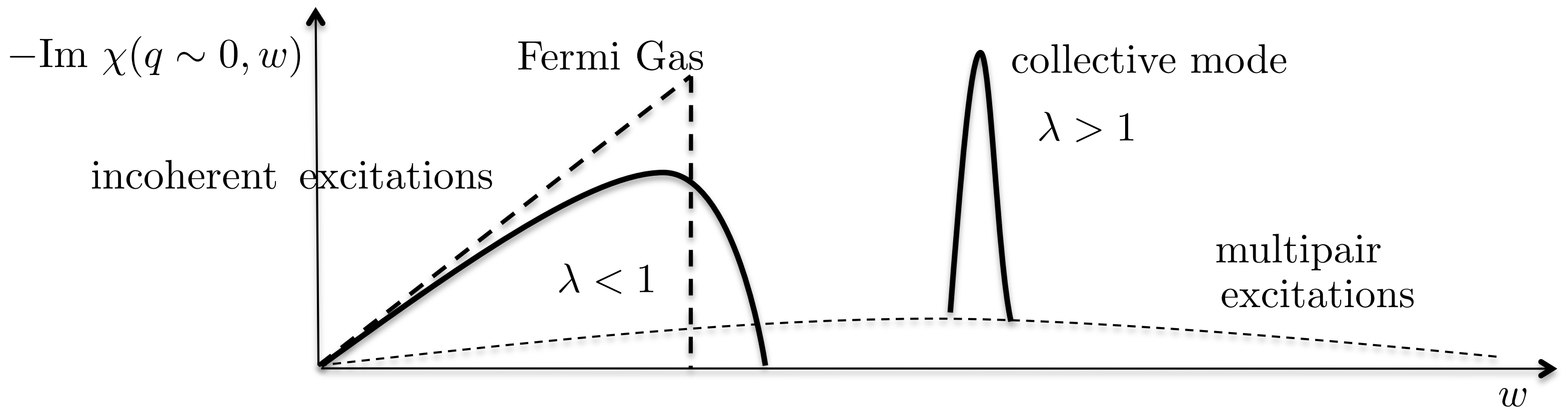
Microscopic theory

Sum on single p-h states (non-int. hamiltonian)

$$\chi_{Landau} \simeq \frac{N(0)}{V} \frac{\Omega_{00}(\lambda)}{1 + \left[F_0^s + \frac{\lambda^2 F_1^s}{1+F_1^s/3}\right]\Omega_{00}(\lambda)}$$

Boltzmann-Landau equation

$$\lambda = \frac{w}{q\, v_F}$$



Landau Theory: Landau parameters

→ Simply related to macroscopic observables (like specific heat, suscept. ecc) so

they can be taken
- from experiments (as for ^{3}He)...
- once an interacting hamiltonian is introduced (Neutron Matter)

→ We need a *realistic*, low-energy, interaction potential instead of QCD

$$H = \tilde{T}_0 + \sum_{i<j=1}^{N} \tilde{v}_{ij}^{18} = \tilde{T}_0 + \sum_{i<j=1}^{N} \left(\sum_{n=1}^{18} f^n(r) \tilde{O}^n(\hat{\mathbf{r}}) \right)$$

fits with $\chi^2/N_{dat} \sim 1$
elastic $N-N$ scattering
(Nijmegen data)

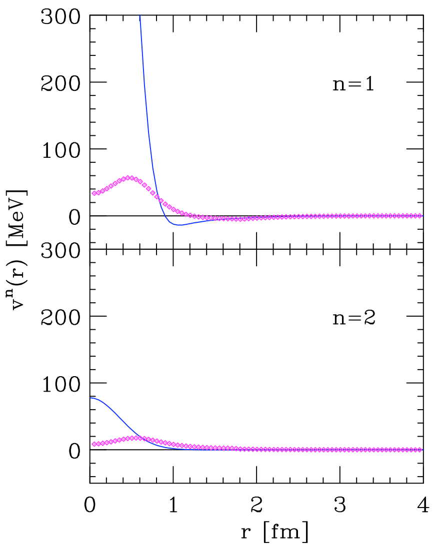
Argonne potential

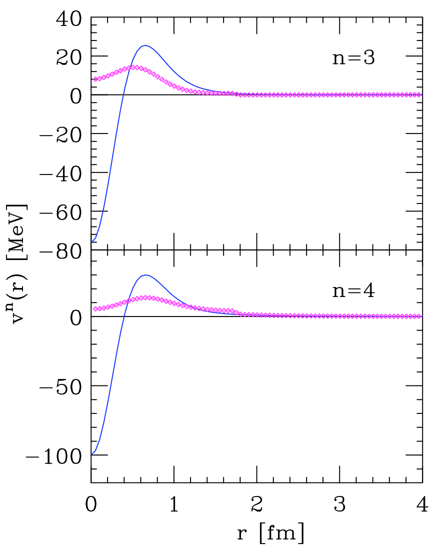
in $q \to 0$, only the *static* part : $\tilde{v}_6 \longrightarrow [\,1,\, (\vec{\sigma}_1 \cdot \vec{\sigma}_2)\,,\, S_{12}(\hat{\mathbf{r}})\,] \otimes [\,1\,,(\vec{\tau}_1 \cdot \vec{\tau}_2)\,]$

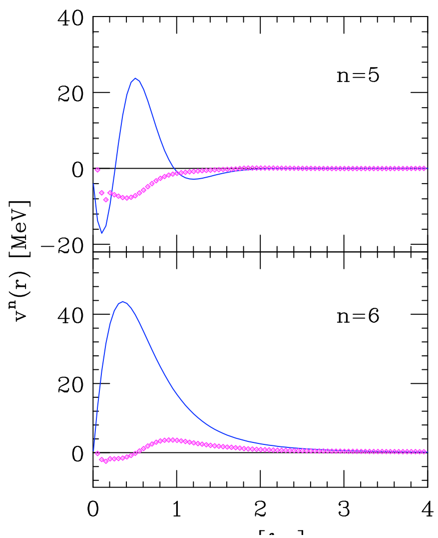
CBF: effective two-body potential

➡ Effective potential (pink) ***Vs*** *Bare* one (Blue)

$S_{12}(\hat{\mathbf{r}})$ channel

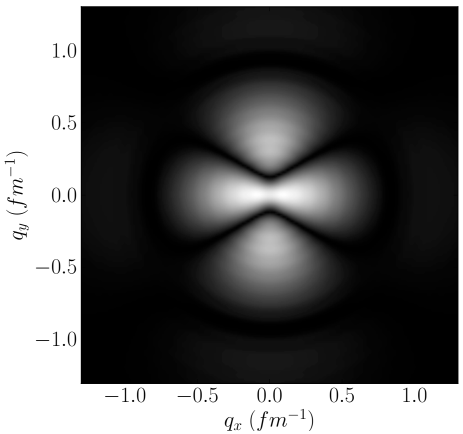






➡ Energy per nucleon

$$\mathcal{E} = \frac{1}{N}\langle T_0 \rangle + \frac{1}{2NL^3} \sum_{k_i,k_j} \sum_{i,j} \left[\langle ij|\tilde{V}(0) - \tilde{V}(\mathbf{k}_i - \mathbf{k}_j)|ij\rangle \right] n_i(\mathbf{k}_i)\, n_j(\mathbf{k}_j)$$

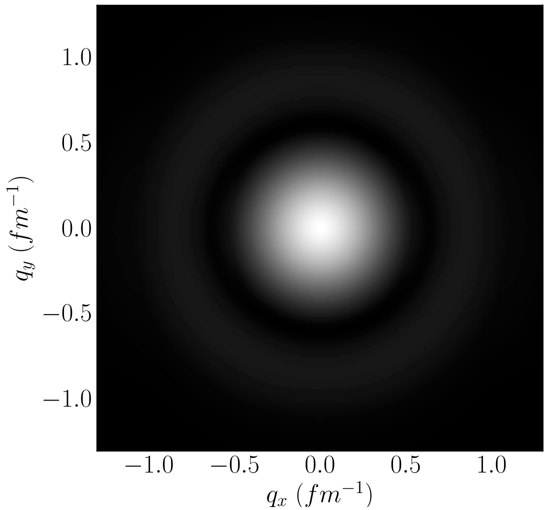


Landau Parameter for Neutron Star matter

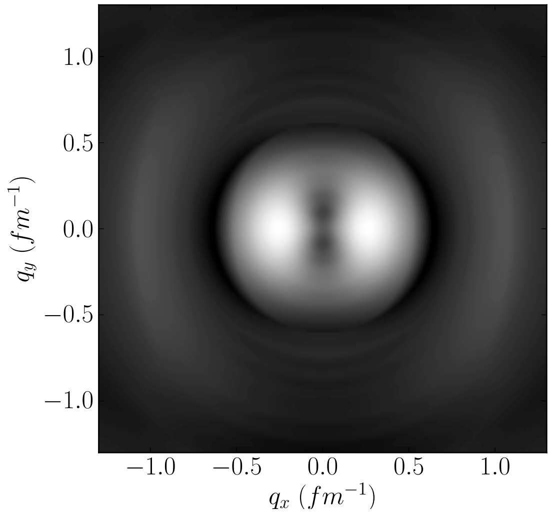
- The *effective* q-p interactions is defined:

$$f_{ij} = \frac{\delta^2 \mathcal{E}}{\delta n_i \delta n_j} = \frac{1}{L^3} \langle ij | \tilde{V}(0) - \tilde{V}(\mathbf{q}) | ij \rangle \qquad \mathbf{q} = \mathbf{k}_i - \mathbf{k}_j$$

$$F^s(\mathbf{q}) = (F_{\uparrow\uparrow} + F_{\uparrow\downarrow})/2$$



$$F^a(\mathbf{q}) = (F_{\uparrow\uparrow} - F_{\uparrow\downarrow})/2$$



*

- Non-central interaction on Fermi surface

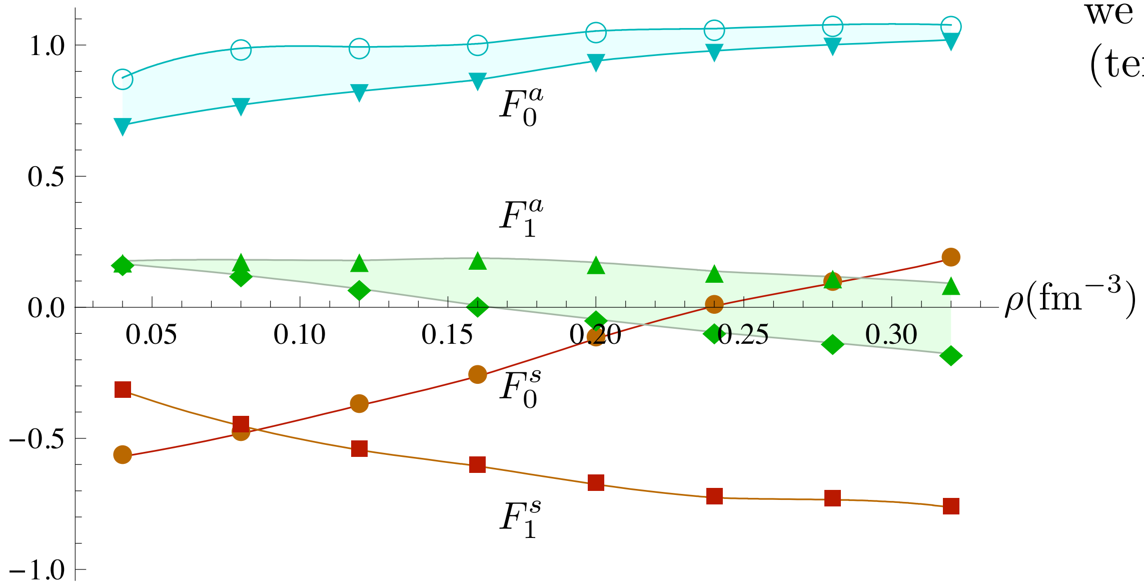
$$\tilde{V}_{S_{12}}(\mathbf{q}) = g(q) \left(\frac{3\hat{\mathbf{q}}_z^2 - 1}{2} \right) \left[3\, \sigma_1^z\, \sigma_2^z - \vec{\sigma}_1 \cdot \vec{\sigma}_2 \right]$$

*thanks to E. Cammarota

Landau Parameter for Neutron Star matter

On Fermi surface, with $|\mathbf{k}| \sim |\mathbf{k}'| \sim k_F$ and $q = 2k_F \sin(\xi/2))$ we can be defined:

$$f_{s,a}(\cos\xi) = \sum_l f_l^{s,a} P_l(\cos\xi) \qquad F_l^{s,a} = V D(\epsilon_F) f_l^{s,a}$$

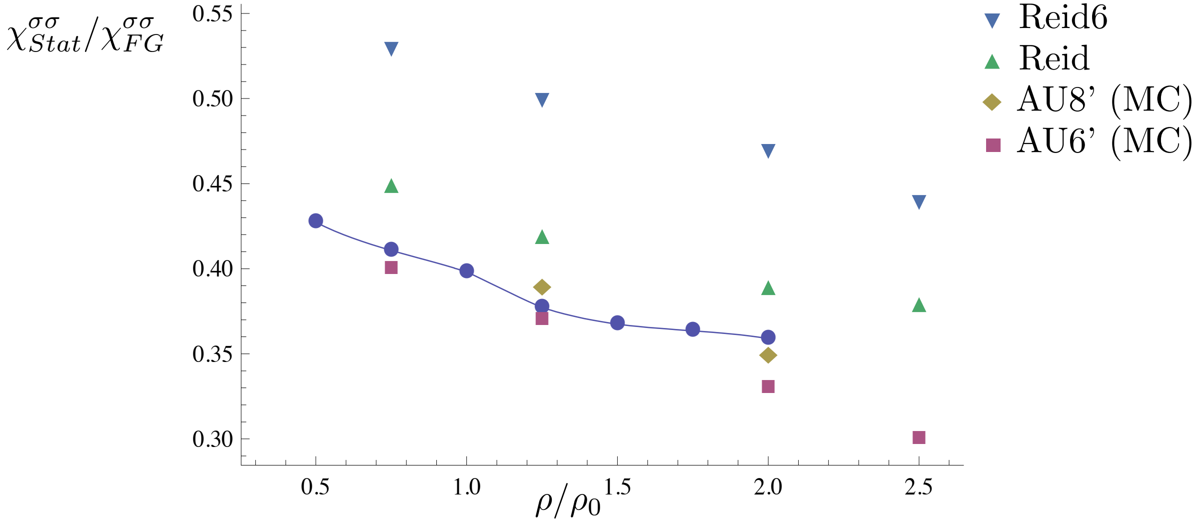


we have another degree of freedom (tensor term)

dependence on $\hat{\mathbf{q}}$

Results

Susceptibility



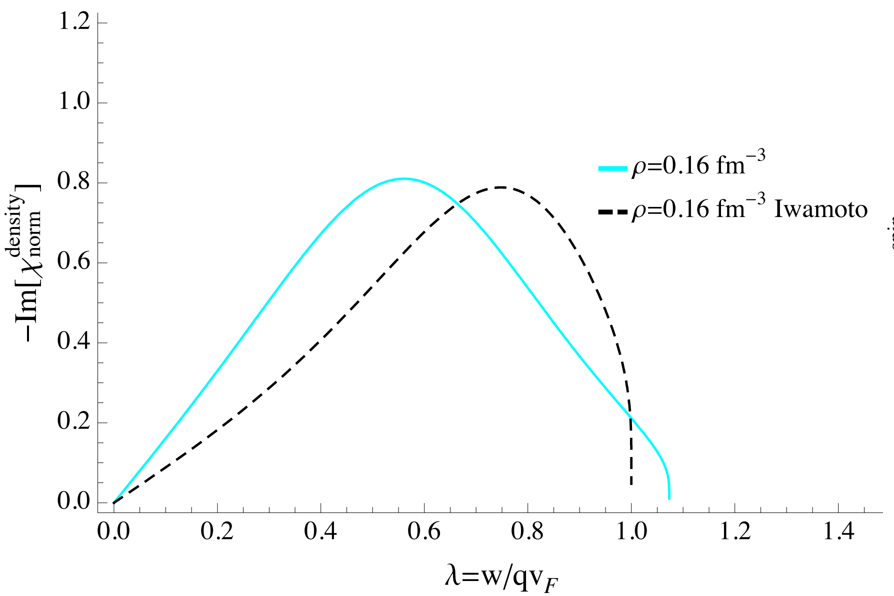
Iwamoto et al., Phys. Rev. D 25, 313 (1982)

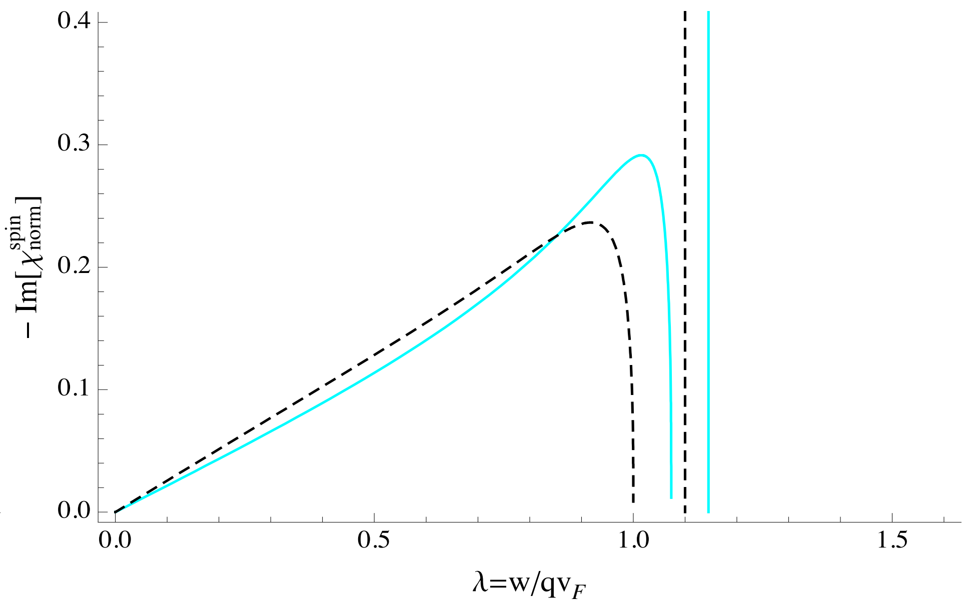
Results

Dynamic Response

$$L^{\mu\nu}\mathrm{Im}\left[\tilde{\mathcal{W}}_{\mu\nu}\right] \rightarrow 8\,\epsilon'\epsilon\left[\mathrm{Im}[\chi^{\rho\rho}(\mathbf{q},w)](1+\cos\theta)+\mathrm{Im}[\chi^{\sigma\sigma}(\mathbf{q},w)](3-\cos\theta)\right]$$

density response — spin-density response





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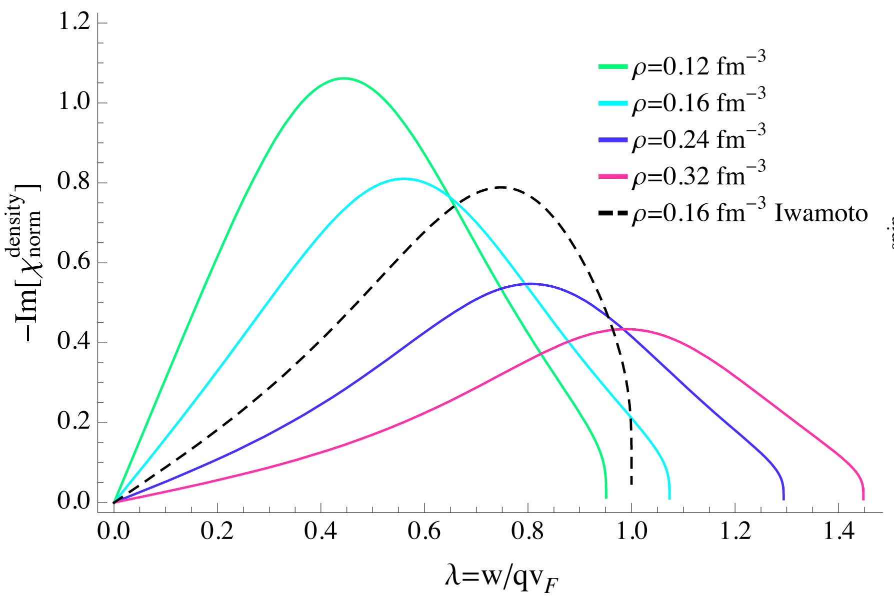
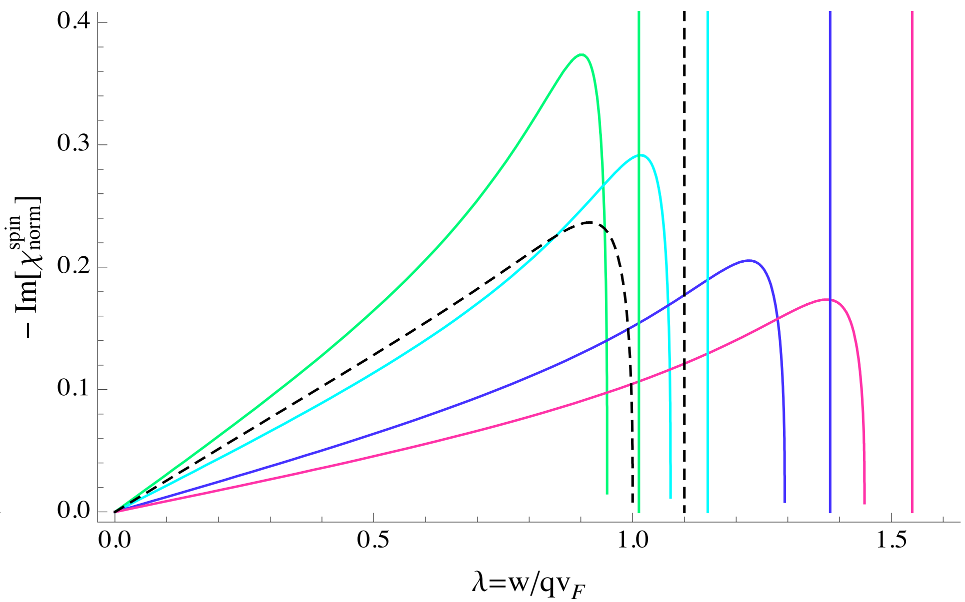
Results

→ Dynamic Response

$$L^{\mu\nu}\mathrm{Im}\left[\tilde{\mathcal{W}}_{\mu\nu}\right] \to 8\,\epsilon'\epsilon\left[\underbrace{\mathrm{Im}[\chi^{\rho\rho}(\mathbf{q},w)]}_{\text{density response}}(1+\cos\theta)+\underbrace{\mathrm{Im}[\chi^{\sigma\sigma}(\mathbf{q},w)]}_{\text{spin-density response}}(3-\cos\theta)\right]$$





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Results

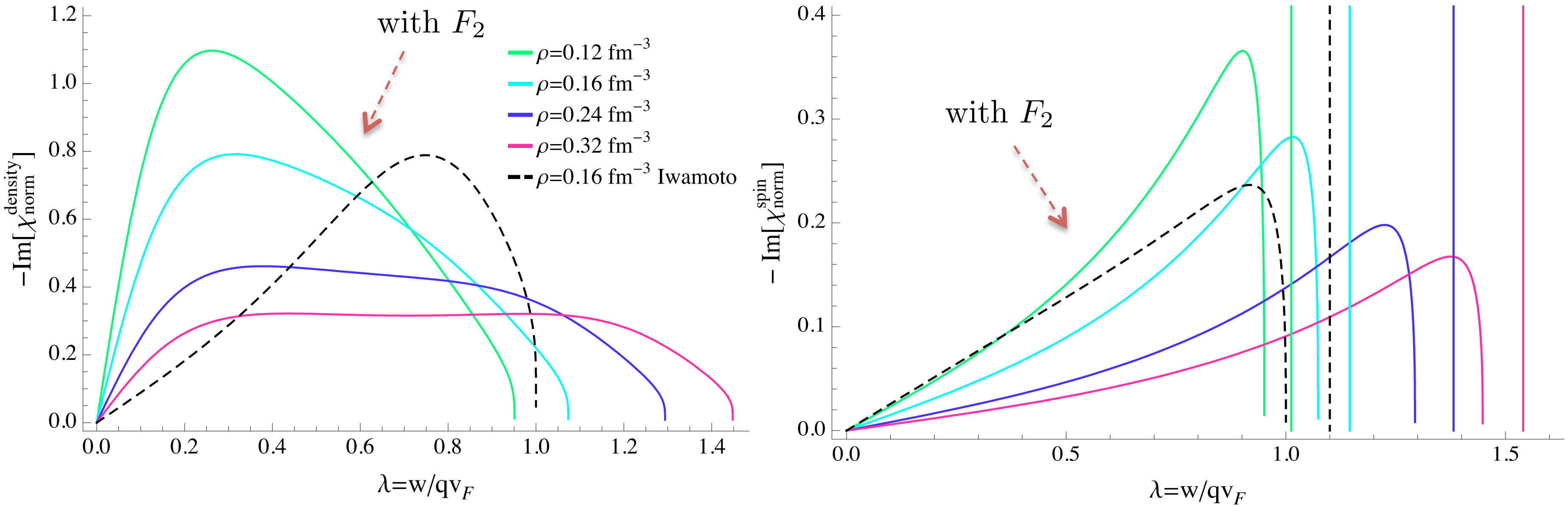
Dynamic Response

$$L^{\mu\nu}\mathrm{Im}\left[\tilde{\mathcal{W}}_{\mu\nu}\right] \to 8\,\epsilon'\epsilon\left[\mathrm{Im}[\chi^{\rho\rho}(\mathbf{q},w)](1+\cos\theta) + \mathrm{Im}[\chi^{\sigma\sigma}(\mathbf{q},w)](3-\cos\theta)\right]$$

density response

spin-density response

F_3 is negligible



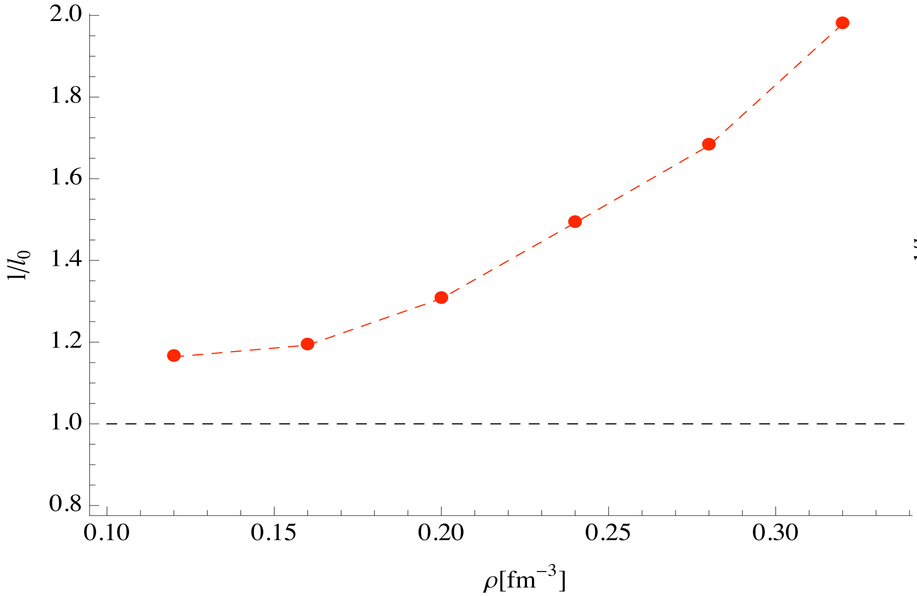
Iwamoto et al., Phys. Rev. D 25, 313 (1982)

Results

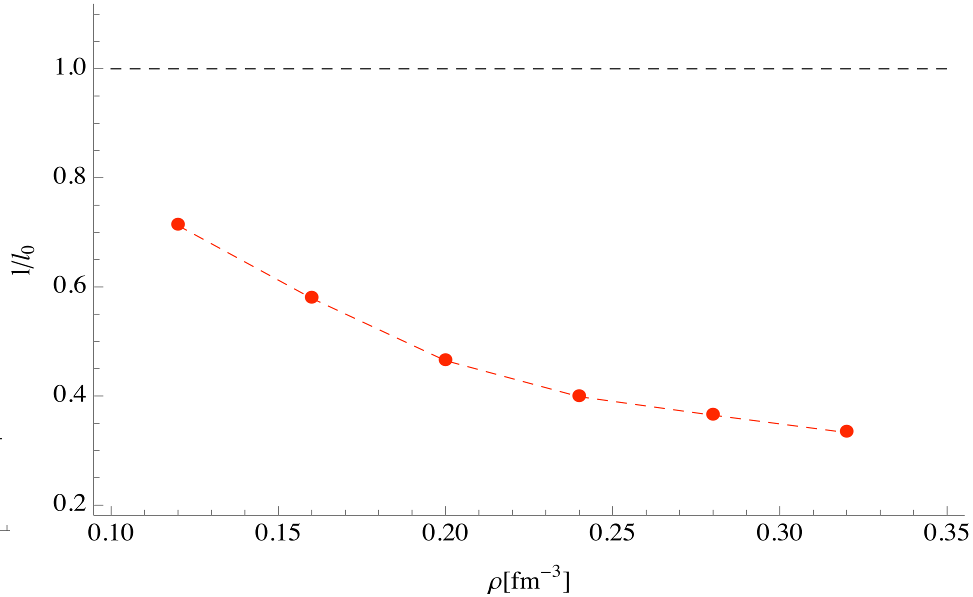
NEW

Evaluation of Mean Free Path

$k_B T \ll q v_F$



$k_B T \gg q v_F$



Summary and Perspective

- We use a nuclear many-body theory (CBF) to model "low-energy" hamiltonian H_{int} in dense matter

- Dynamic response is evaluated within Landau framework for different channel:

  ↓

  neutron Landau parameters

→ Neutrino mean free path and finite-temperature effects

→ Extension to asymmetric nuclear matter in β-equilibrium