"Sapienza" Università di Roma
Department of Physics

Neutrino opacity in neutron matter

Andrea Cipollone

&

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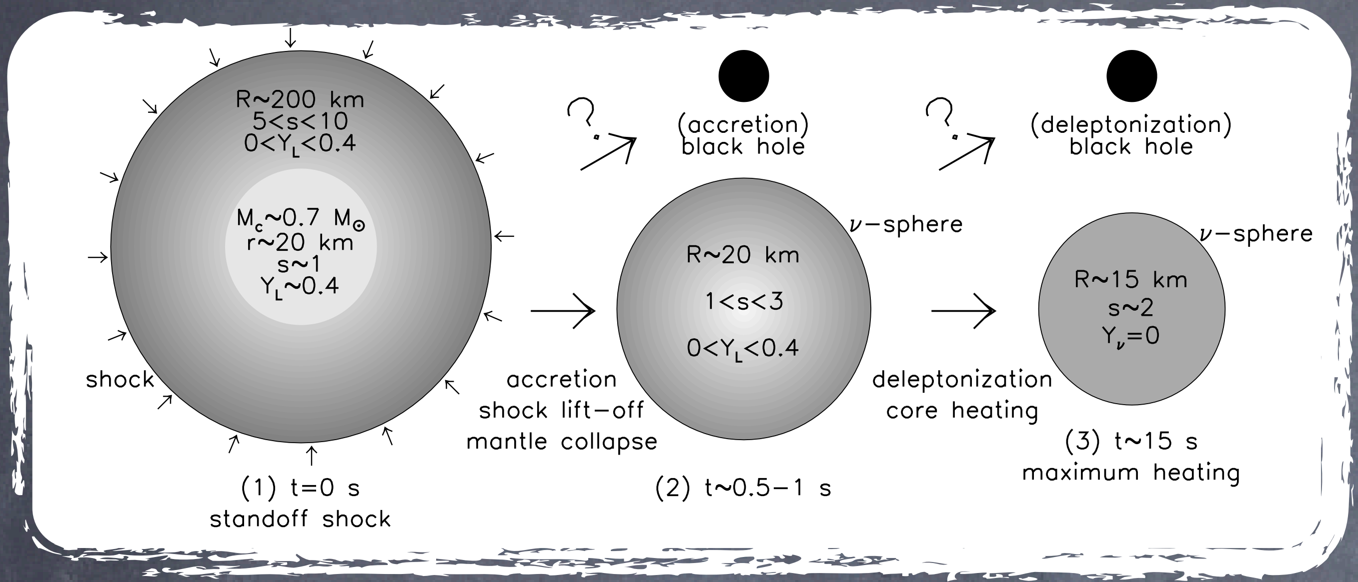
Collaborator: Andrea Loreti

@ECT*, 16 December 2011

Neutrino opacity of N. M.: an astrophysical scenario

✓ From a qualitative point of view...



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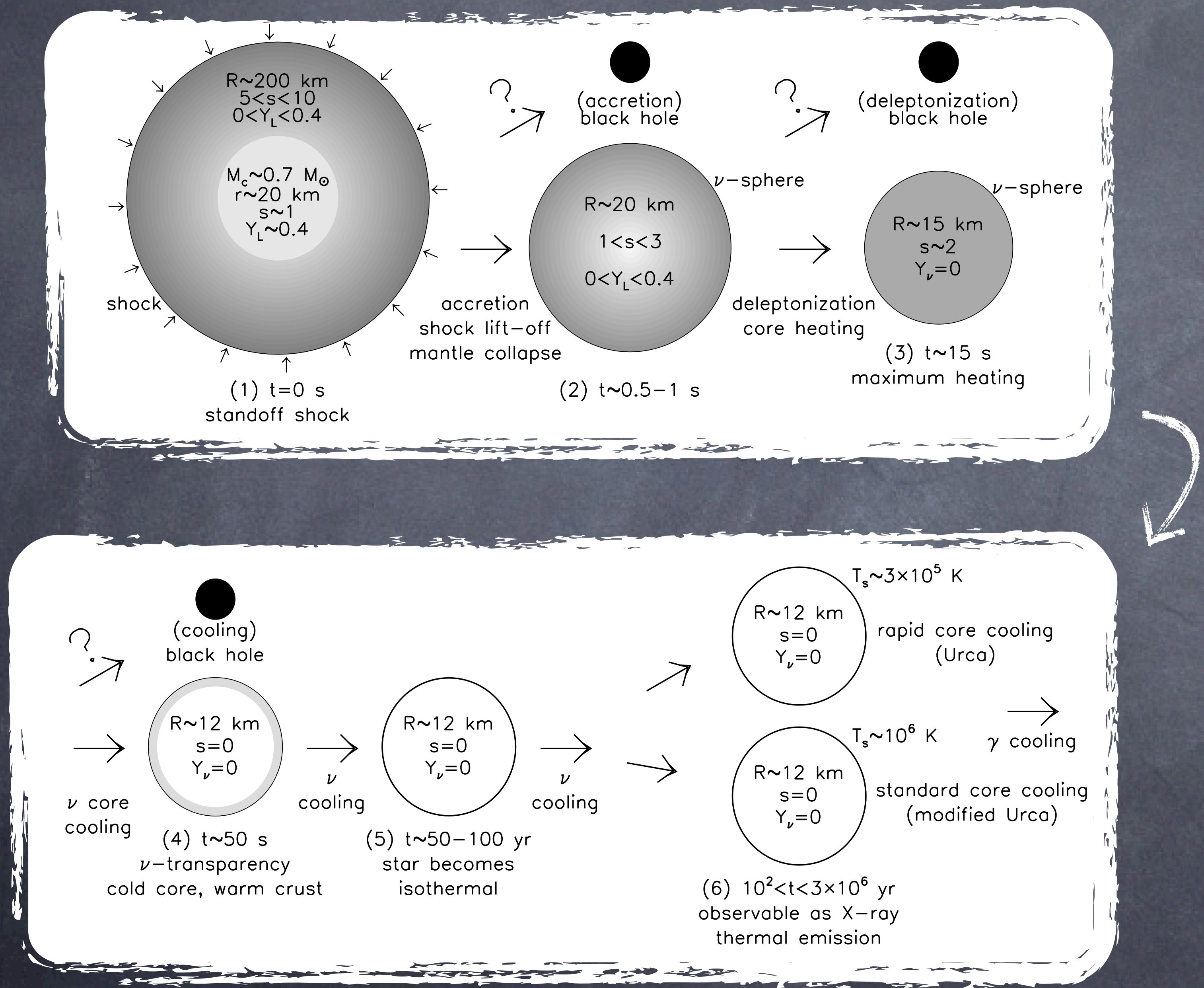

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✓ ...to a quantitative description

Improved models of stellar core collapse and still no explosions: What is missing?

R. Buras, M. Rampp, H.-Th. Janka, and K. Kifonidis[1]

[1] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, D-85741 Garching, Germany*

(Dated: February 2, 2008)

Two-dimensional hydrodynamic simulations of stellar core-collapse with and without rotation are presented which for the first time were performed by solving the Boltzmann equation for the neutrino transport including a state-of-the-art description of neutrino interactions. Although convection develops below the neutrinosphere and in the neutrino-heated region behind the supernova shock, the models do not explode. This suggests missing physics, possibly with respect to the nuclear equation of state and weak interactions in the subnuclear regime. However, it might also indicate a fundamental problem of the neutrino-driven explosion mechanism.

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✓ SN 1987A data*

$$E_{grav} \approx 10^{53}\text{erg} \qquad E_{\nu} \approx 2.7 \times 10^{53}\text{erg}$$

$$E_{rad} \approx 10^{49}\text{erg} \qquad E_{kin} \approx 10^{51}\text{erg}$$

* *K. Laganke*, nuclear physics school "Raimondo Anni", spring 2011 (Otranto)

Looking at microscopic world. . .

✓ Modelling neutrino-matter interaction

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \overbrace{\bar{l}\gamma^\mu(1-\gamma_5)\nu_l}^{l^\mu} (V_\mu - A_\mu)$$

in vacuum

neutral $\quad l^0 V^0 \sim l^0(x) \left[\psi_n^+(x) \psi_n(x) \right]$

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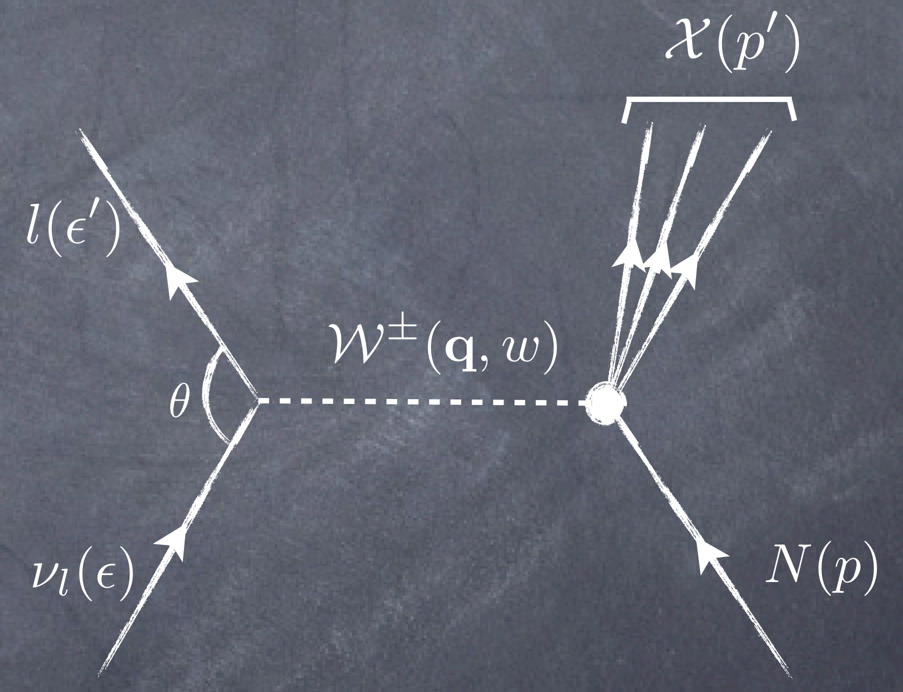
✓ $\nu_l + N \rightarrow l + X$ cross section



$$\frac{\partial^2\sigma}{\partial\epsilon'\partial\Omega} = \frac{G_F^2}{(2\pi)^2}\frac{\epsilon'(1-n_l(\epsilon'))}{8\epsilon} L^{\mu\nu}(\mathbf{q}, w)\, H_{\mu\nu}(\mathbf{q}, w)$$

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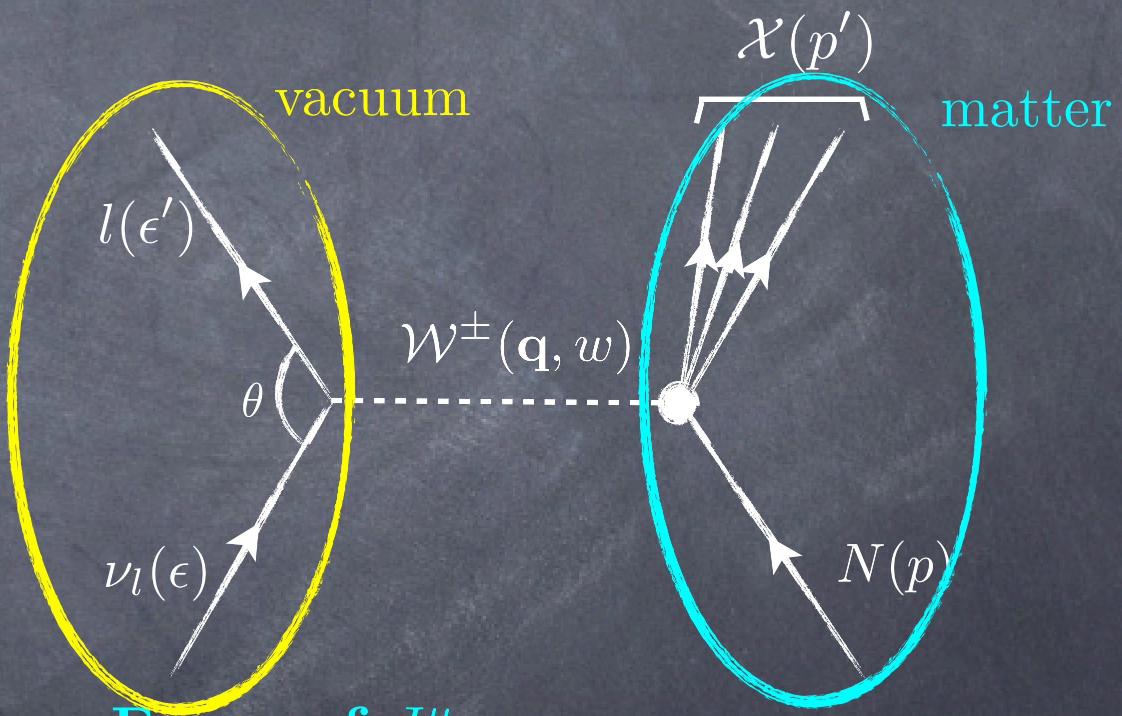

Lepton Trace

Corr. Func. of J^μ

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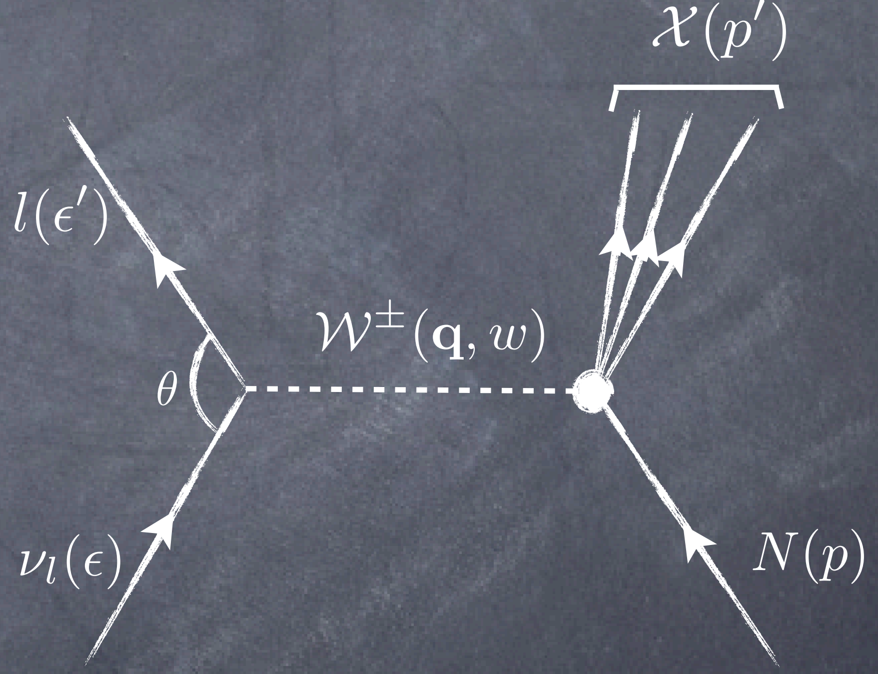

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fluctuation-dissipation theorem

Looking at microscopic world…

- ✓ $p \ll m_N$ $\longrightarrow$ non-rel. nucleons
- ✓ $q \lesssim \mathrm{MeV}$ $\longrightarrow$ ~~e, μ, τ~~, ν (neutral current)

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

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density-density response function   spin-spin response function

where

- $w = |\mathbf{k}| - |\mathbf{k}'|$
- $\mathbf{q} = \mathbf{k} - \mathbf{k}'$

Weak interacting system

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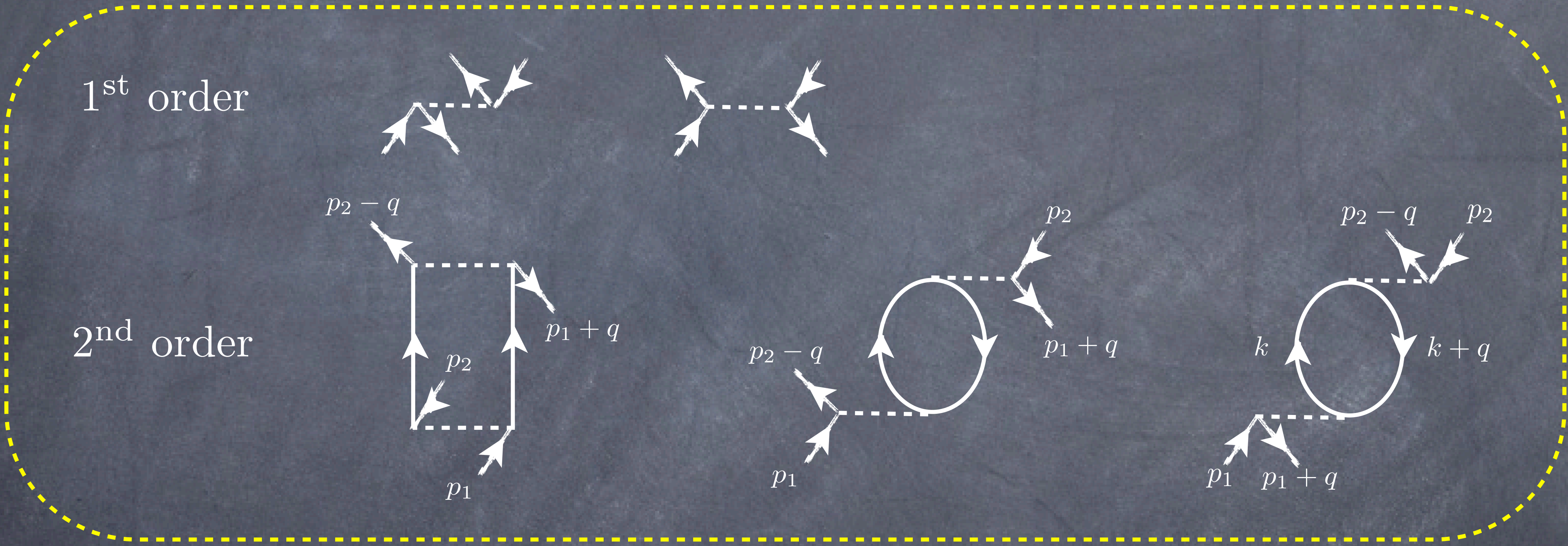
- ✓ Effective interaction between particle and hole



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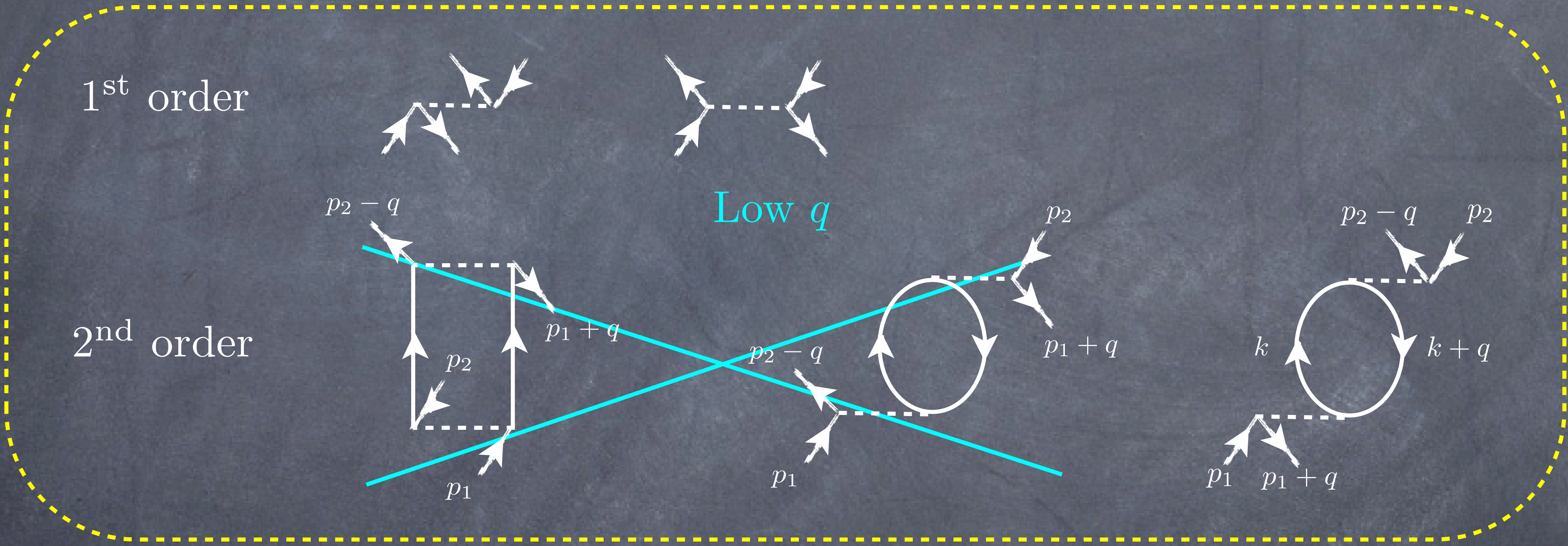
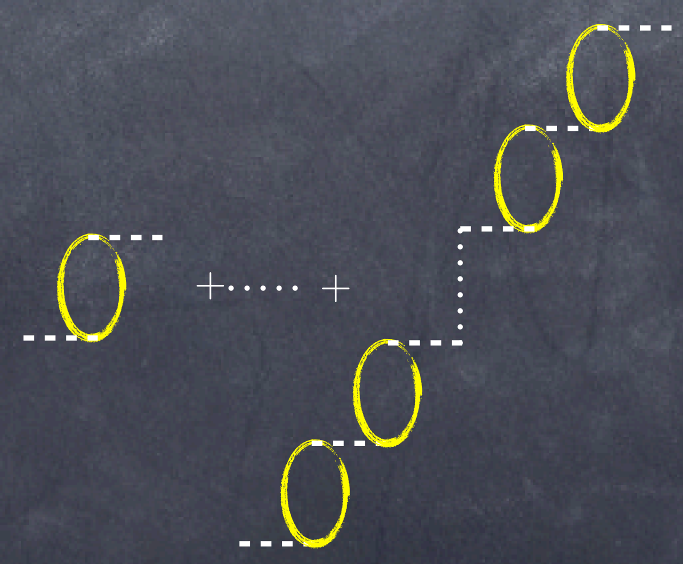


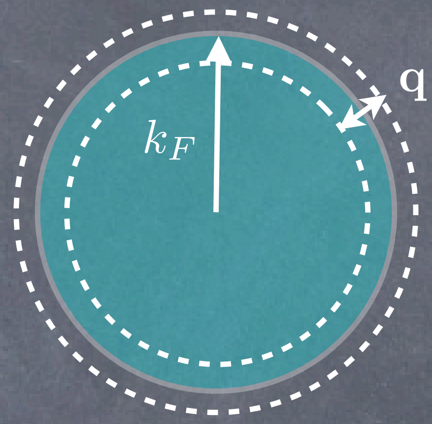
✓ Low-momentum response

Ring approximation (low q)



Interacting Landau Fermi Liquid

✓ Able to treat strong-interacting system but $T \to 0$



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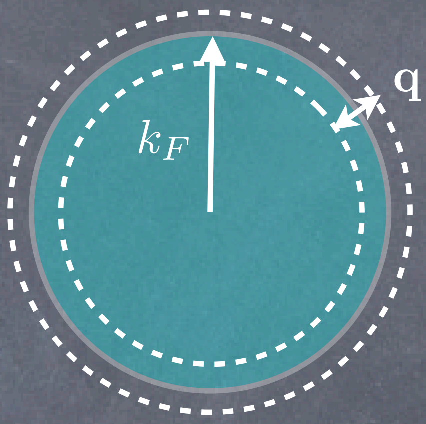

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$$\delta E = E - E^0 = \sum_{\mathbf{k},\sigma} \epsilon^0_\sigma(\mathbf{k}) \delta n_\sigma(\mathbf{k}) + \frac{1}{2} \sum_{\mathbf{k},\mathbf{k}',\sigma,\sigma'} f_{\sigma\sigma'}(\mathbf{k},\mathbf{k}') \delta n_\sigma(\mathbf{k}) \delta n_{\sigma'}(\mathbf{k}')$$

interaction between q-p

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✓ Landau Fermi theory: Dynamic Response (low q)

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

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Landau theory

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

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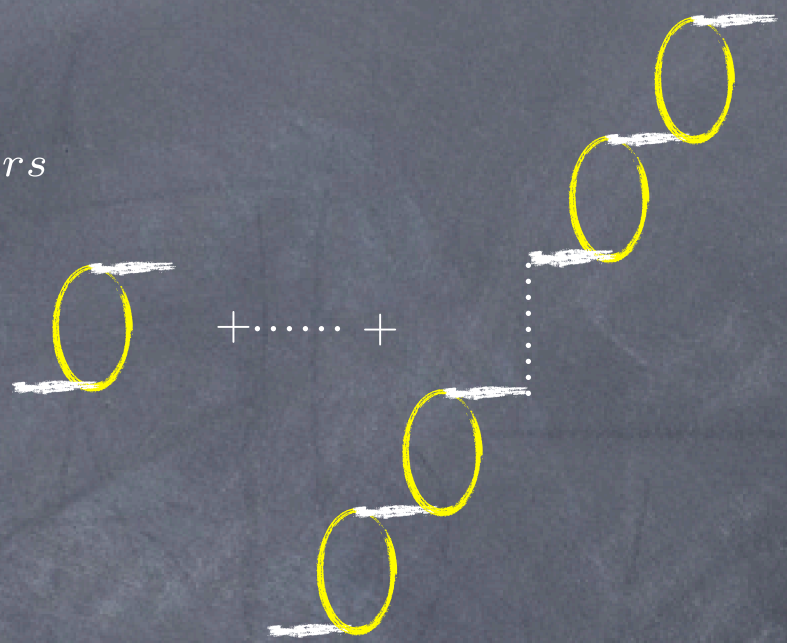

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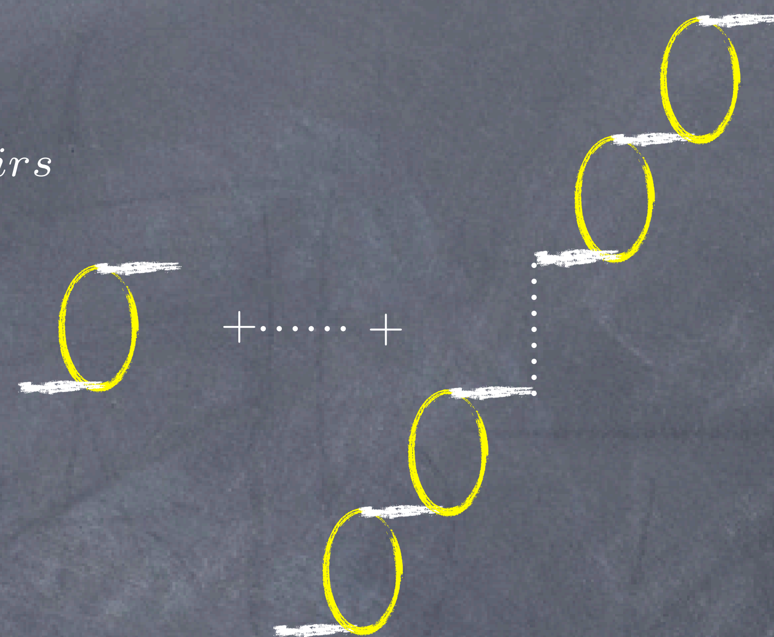
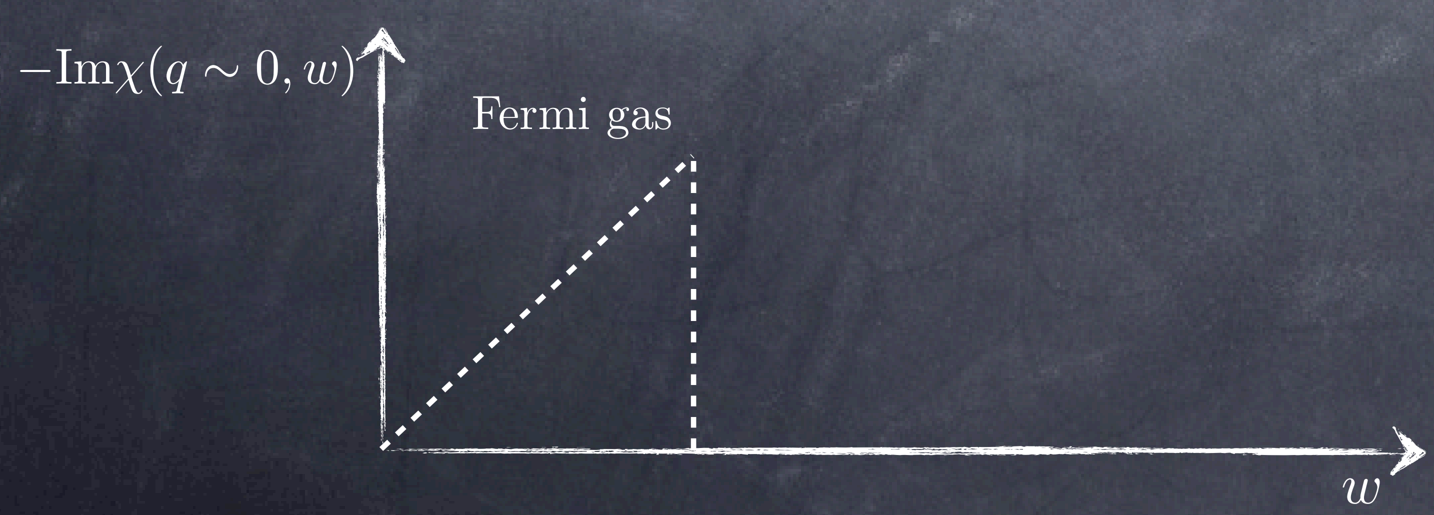
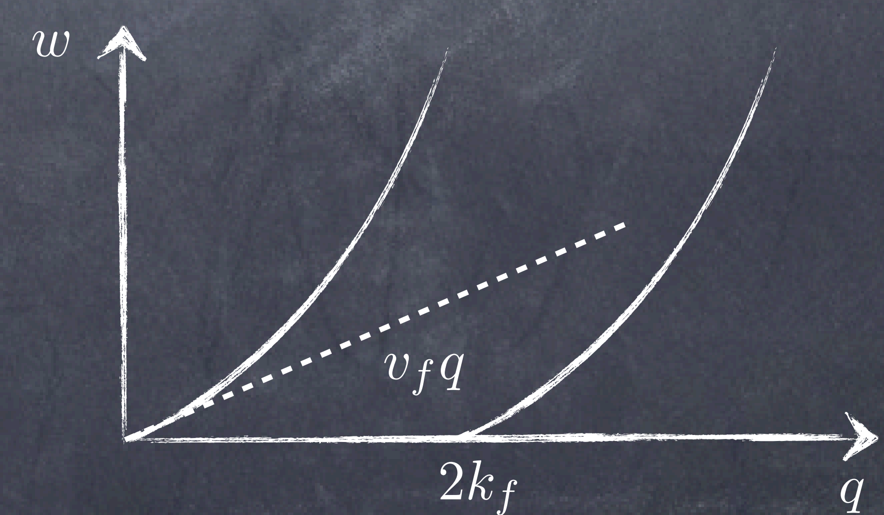


✓ Response Function



✓ Energy Spectrum



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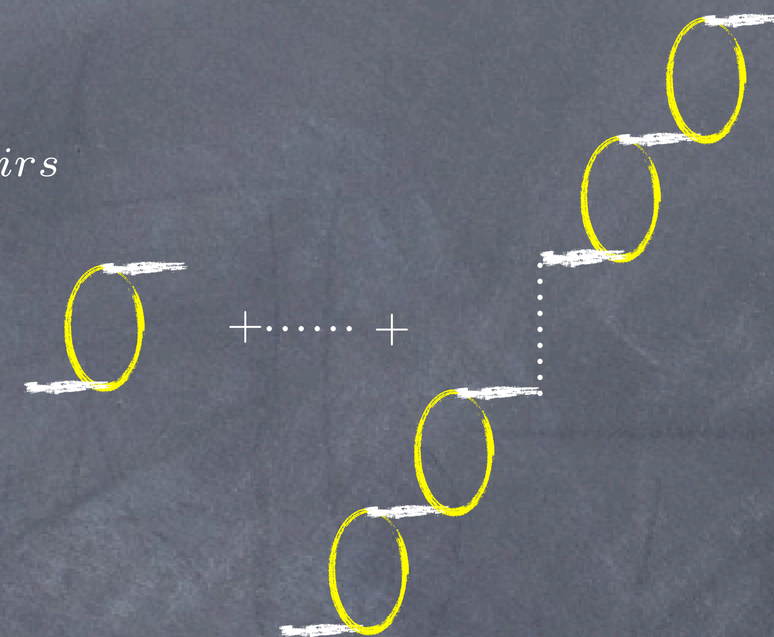

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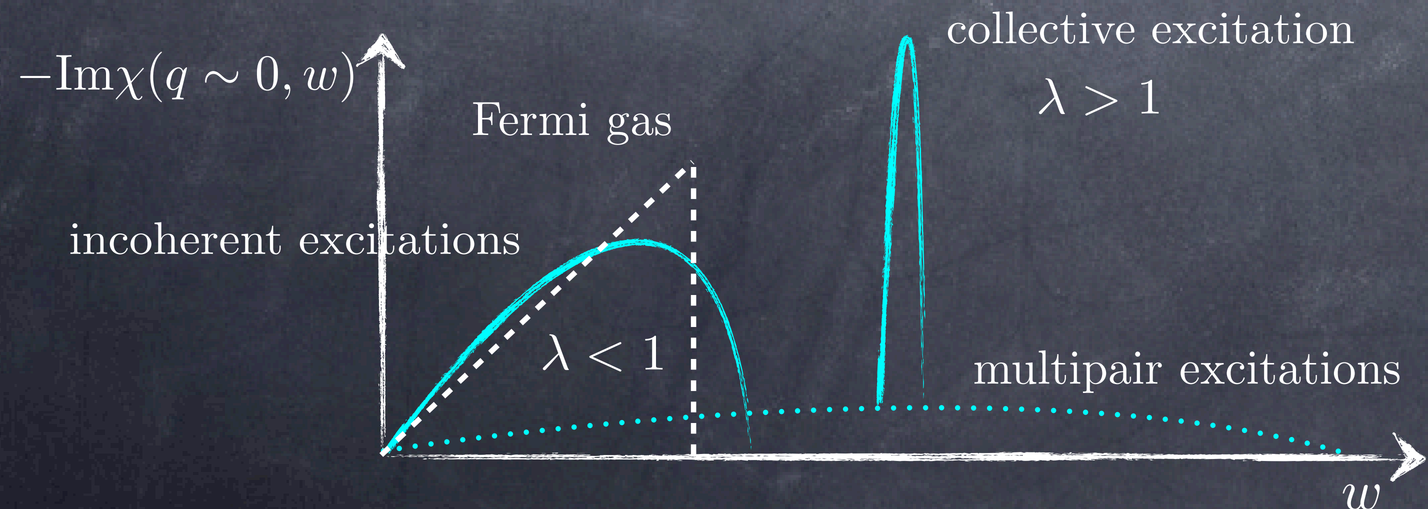

✓ Energy Spectrum

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

How can we get these parameters?

- ✗ No experiments available
- ✓ *Effective* N-N interaction in medium → CBF theory (Correlated Basis Function)

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(Argonne potential)

$$\hat{H} = \hat{T}_0 + \hat{v}_{ij}^{18}$$

Static part $q \to 0$

$$\hat{v}_{12}^{6} = [\,1,\ (\hat{\vec{\sigma}}_1 \cdot \hat{\vec{\sigma}}_2)\,,\ \hat{S}_{12}(\tilde{\mathbf{r}})\,] \otimes [\,1\,,(\hat{\vec{\tau}}_1 \cdot \hat{\vec{\tau}}_2)\,]$$

spin isospin

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spin isospin

$$\Psi \sim \hat{F}(1, \ldots, N) \, \Phi_{FG} = \left[\hat{S} \prod_{i<j}^{N} \hat{f}(\mathbf{r}_{ij}) \right] \Phi_{FG}$$

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Two-body correlation function (non-pert. features)

$$\hat{f}(\mathbf{r}_{ij}) = \sum_{p=1}^{6} f^p(r)\hat{O}^p_{ij}(\tilde{\mathbf{r}})$$

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spin isospin

CBF: looking for the $\hat{f}$

- 2^{nd} order (two-body) cluster approximation

$$\langle \hat{H} \rangle_2 = \sum_{i<j}^{N} \langle \mathrm{FG}, ij | \frac{1}{2} \hat{F}_2 \left[\hat{t}_1 + \hat{t}_2, \hat{F}_2 \right] + \hat{F}_2 \left(\hat{v}_{12}^{6} \right) F_2 | ij, \mathrm{FG} \rangle_a$$

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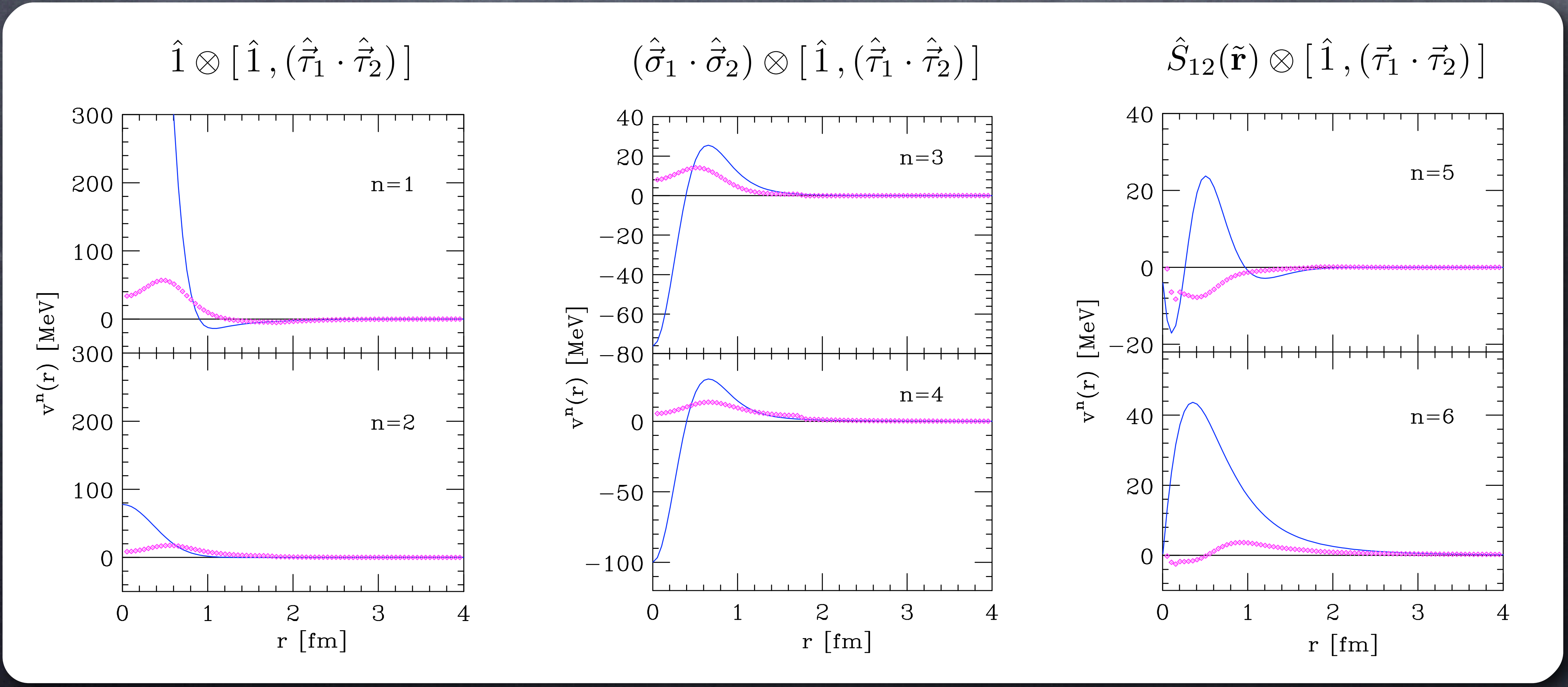
- *quenched* interaction



Landau-CBF mixing

✓ Energy per nucleon

$$\frac{E}{N} = \frac{1}{N}\langle T_0 \rangle + \frac{1}{2N}\sum_{k_i,k_j}\sum_{i,I,j,J}\frac{1}{L^3}\Big[\langle \mathrm{FG}, ij|\hat{V}(0) - \hat{V}(\mathbf{k}_i - \mathbf{k}_j)|ij, \mathrm{FG}\rangle\Big] n_{i,I}(\mathbf{k}_i)\, n_{j,J}(\mathbf{k}_j)$$

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$$\sum_{p=1}^{6}\int d^3\mathbf{r}\, w_p^{eff}(r) e^{-i(\mathbf{k}_i - \mathbf{k_j})\cdot\mathbf{r}}\tilde{O}^p(\hat{\mathbf{r}})P_{\sigma\tau}$$

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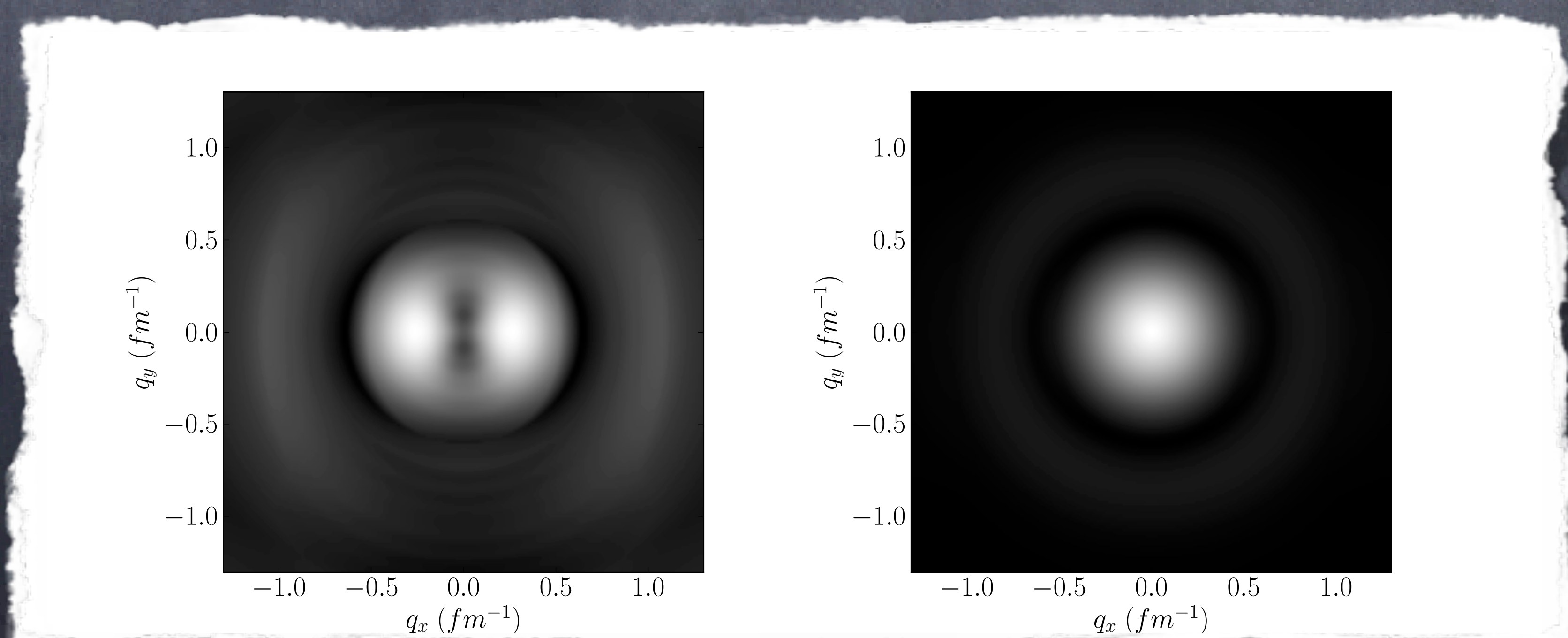
✓ General adimensional Landau parameters

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



$$\mathbf{q} = \mathbf{k} - \mathbf{k}'$$

Landau-CBF mixing

✓ Finally...the Landau parameters

$$F^{s,a}(\cos\xi) = V\, N(0) f^{s,a}(\cos\xi) = \sum_l F_l^{s,a} P_l(\cos\xi) \qquad |\mathbf{q}| = 2k_F \sin(\xi/2)$$

Landau-CBF mixing

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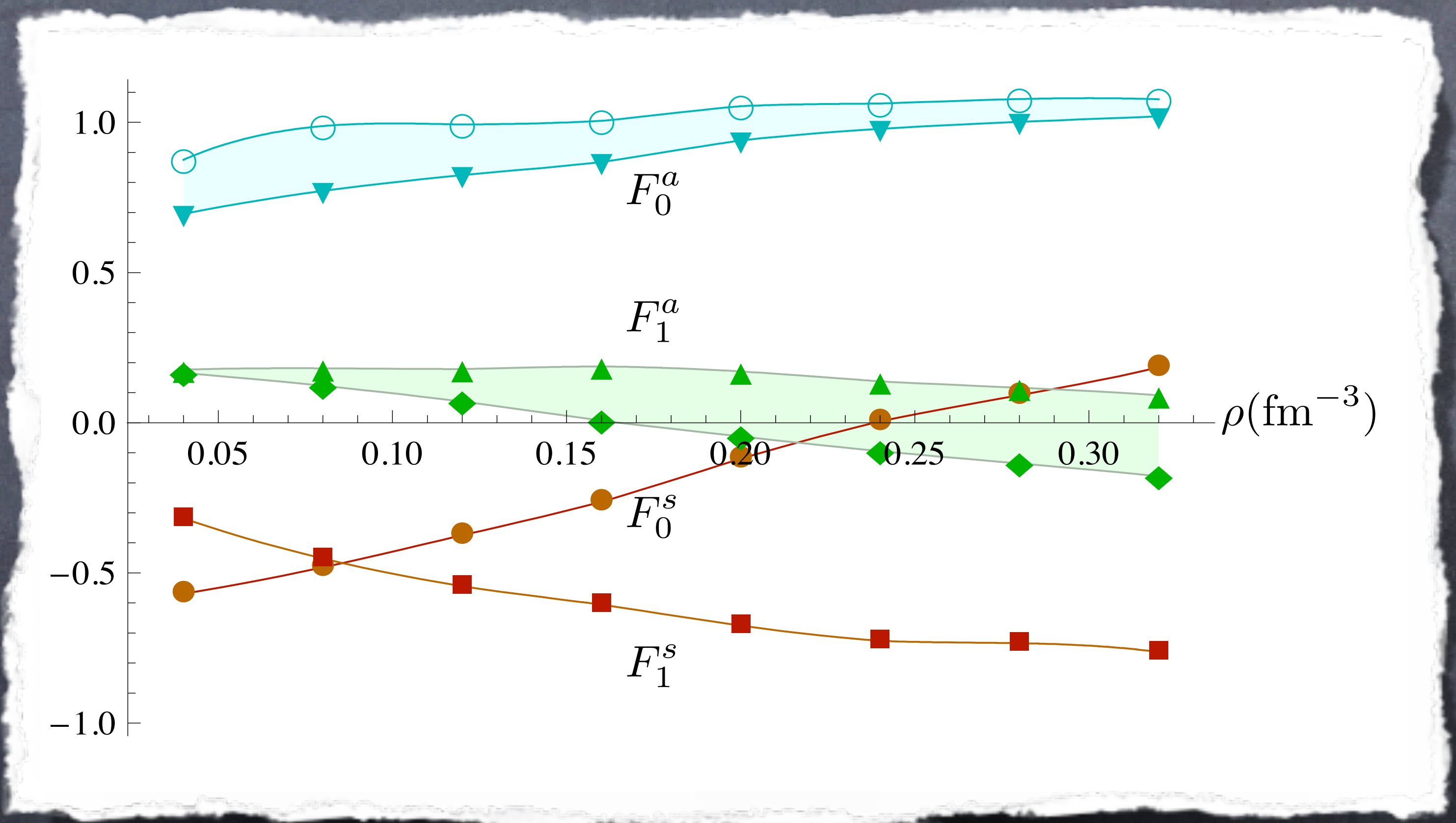

CBF and Landau-CBF...are they comparable?

✓ Static properties

$$K^\rho = -V\left(\frac{\partial V}{\partial P}\right)_T \qquad \text{Compressibility} \qquad K^\rho = \frac{1}{\rho^2}\frac{N(0)}{1+F_0^s}$$

$$\chi^\sigma_{\alpha\beta} = \left.\frac{\partial M_\alpha}{\partial H_\beta}\right|_{H=0} \qquad \text{Magnetic susceptibility} \qquad \chi^\sigma = \left(\frac{g\mu_B}{2}\right)^2 \frac{N(0)}{1+F_0^a}$$

$$\frac{1}{m^{eff}} = \frac{1}{p}\left.\frac{de}{dp}\right|_{p_F} \qquad \text{Effective mass} \qquad m^{eff} = m(1+\frac{F_1^s}{3})$$

→ single particle spectrum

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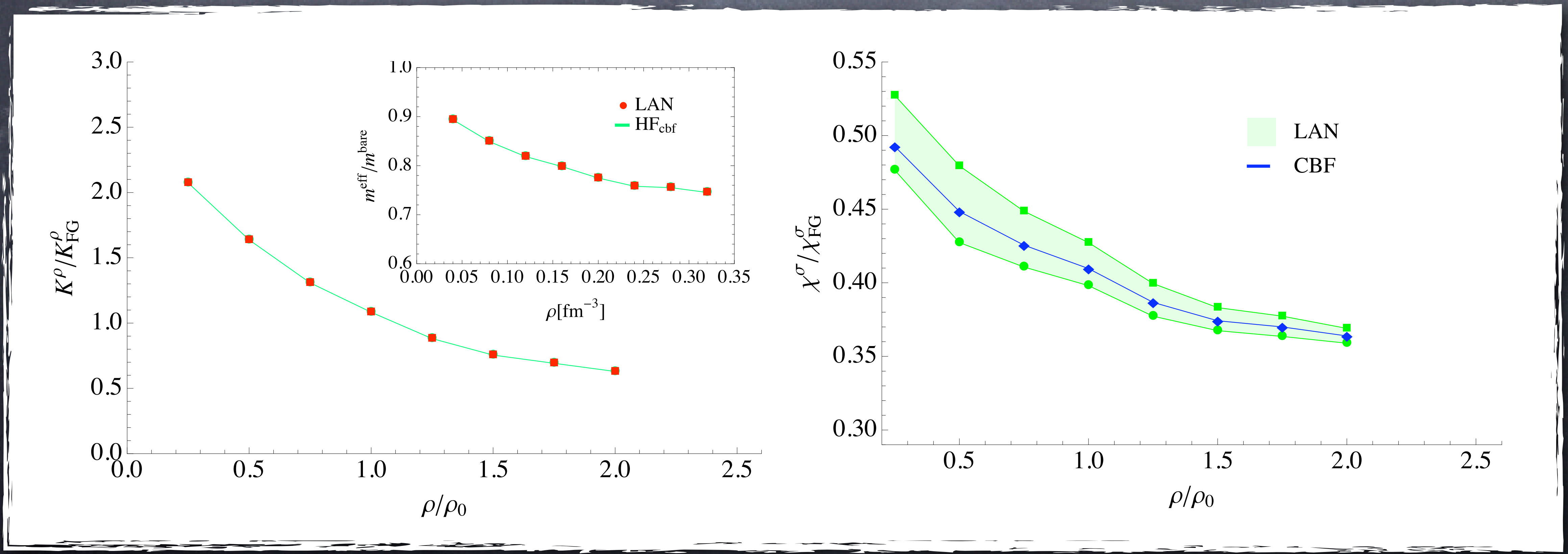
$$K^\rho = -V \left(\frac{\partial V}{\partial P}\right)_T \qquad \text{Compressibility} \qquad K^\rho = \frac{1}{\rho^2}\frac{N(0)}{1+F_0^s}$$

$$\chi^\sigma_{\alpha\beta} = \left.\frac{\partial M_\alpha}{\partial H_\beta}\right|_{H=0} \qquad \text{Magnetic susceptibility} \qquad \chi^\sigma = \left(\frac{g\mu_B}{2}\right)^2 \frac{N(0)}{1+F_0^a}$$

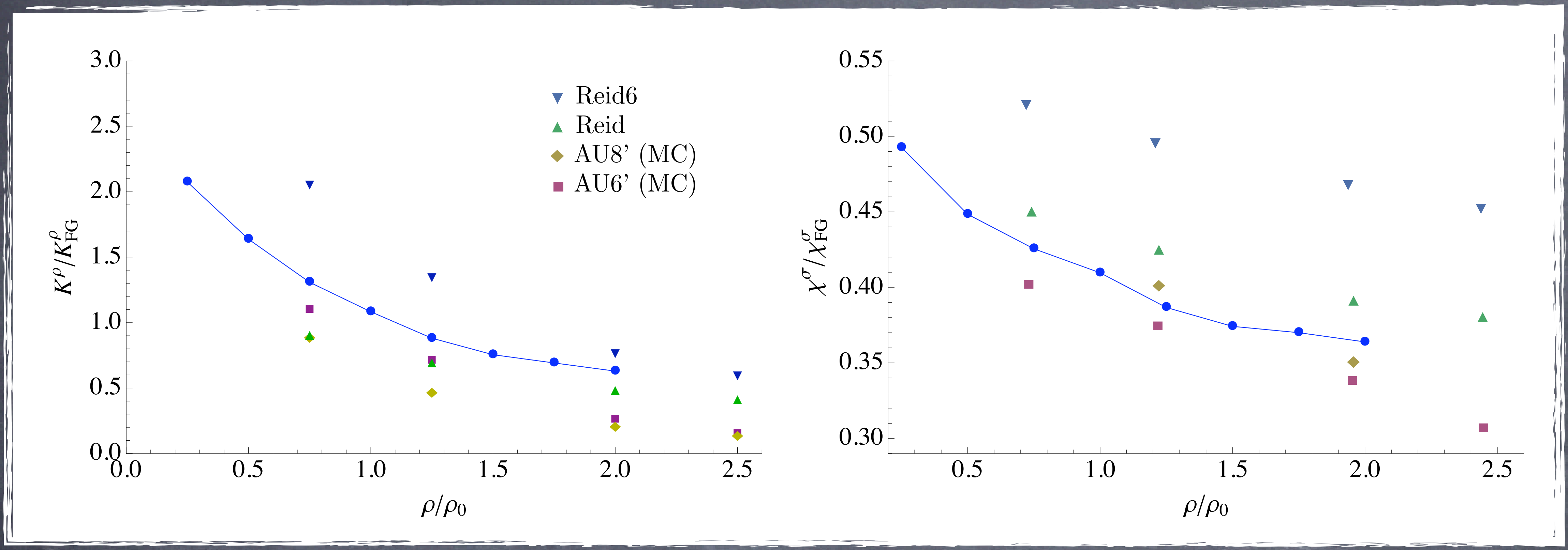
$$\frac{1}{m^{eff}} = \frac{1}{p}\left.\frac{de}{dp}\right|_{p_F} \qquad \text{Effective mass} \qquad m^{eff} = m\left(1+\frac{F_1^s}{3}\right)$$

→ single particle spectrum



Static properties of matter

✓ Static properties



Data from: S. Fantoni, A. Sarsa and K.E. Schmidt, Phys Rev Lett 87, 181101 (2001)

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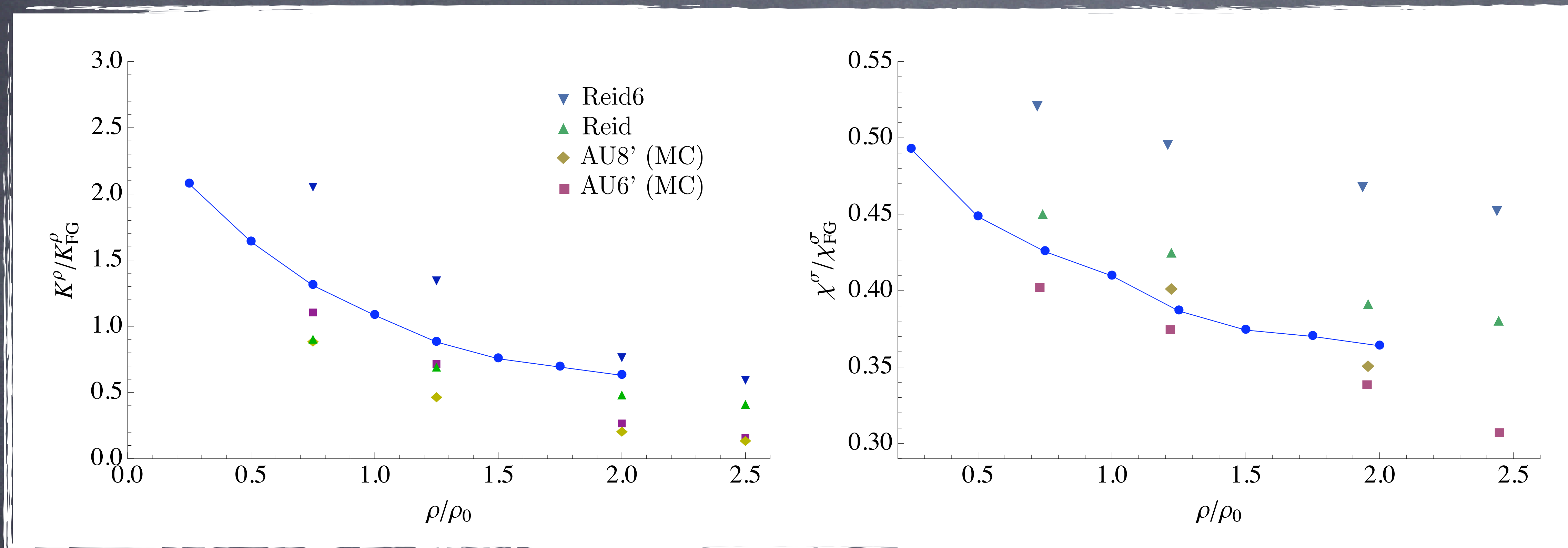
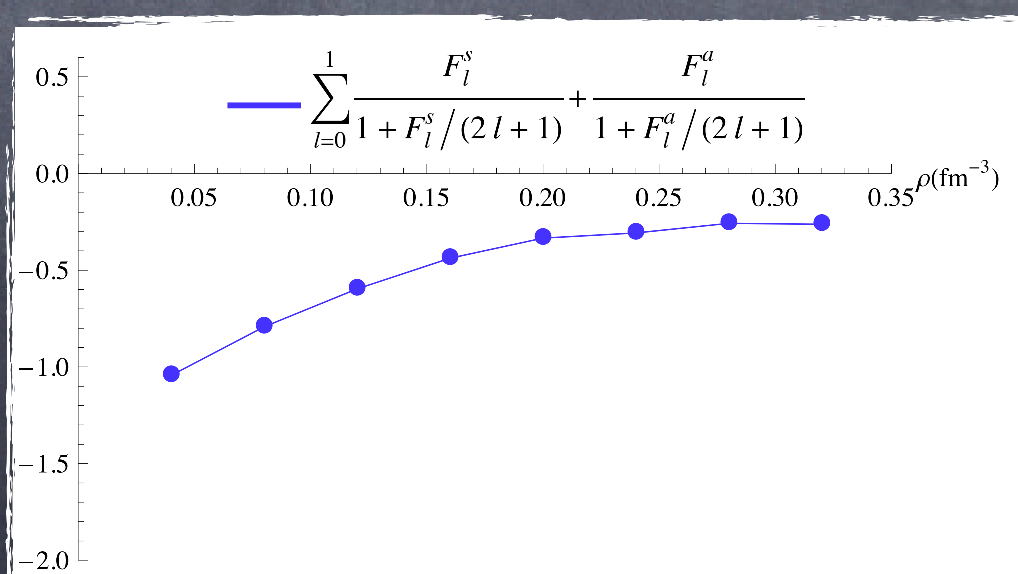


✓ Sum Rule



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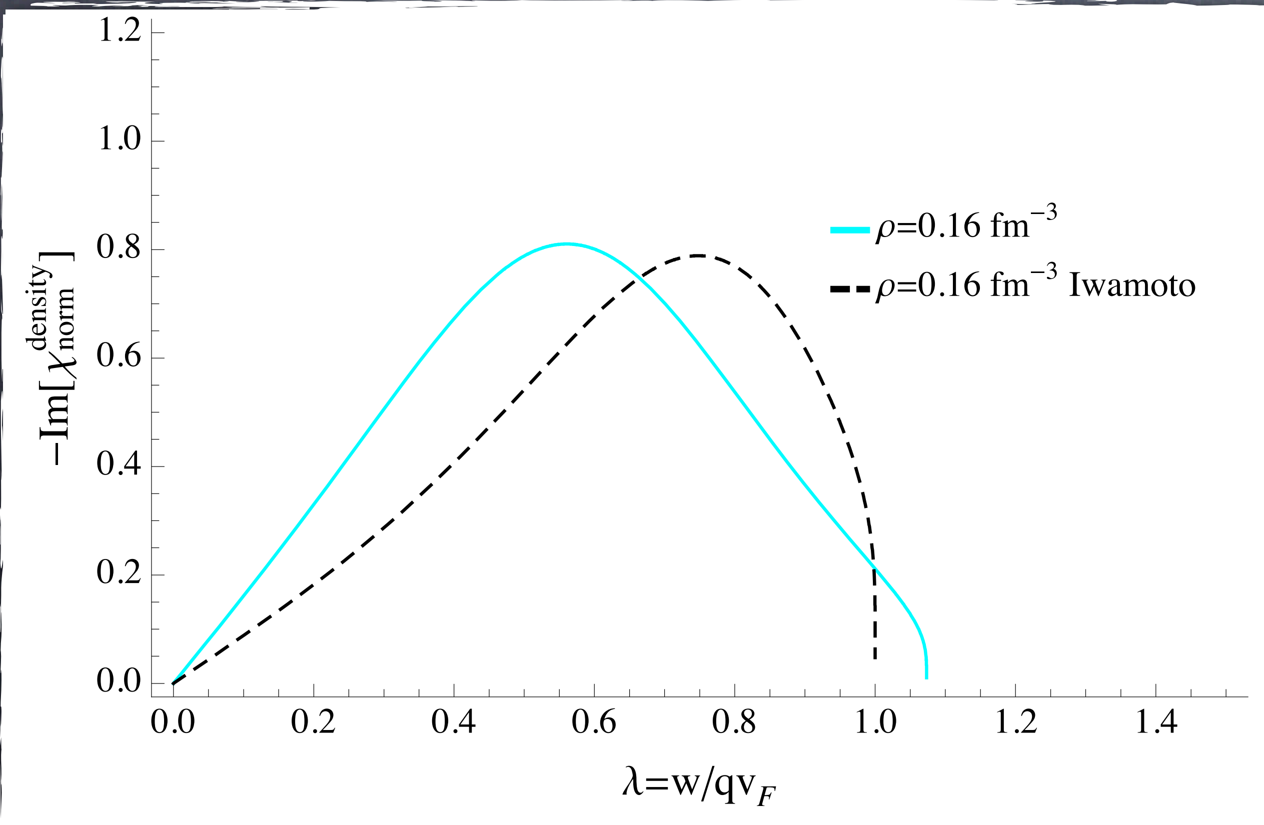
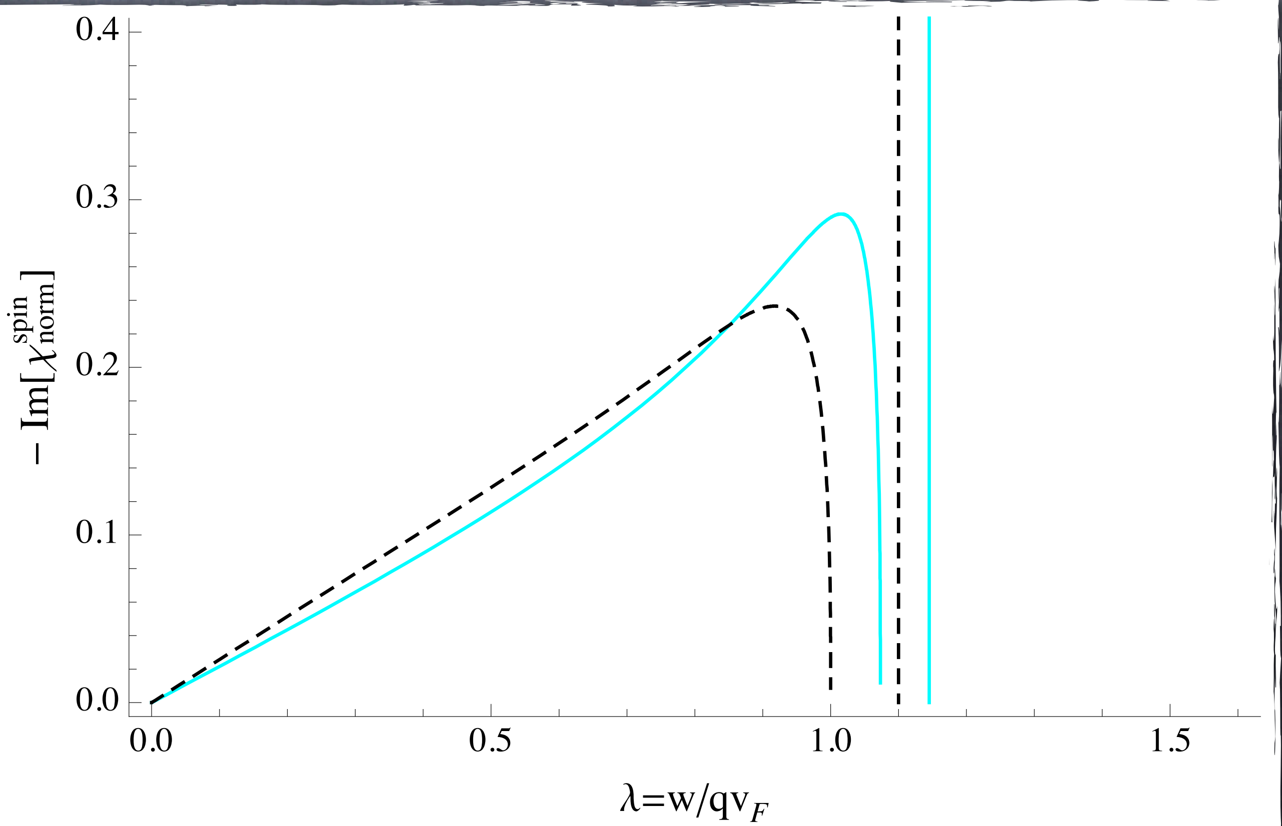
Dynamic Response of neutron matter

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

density-density response function

spin-spin response function





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

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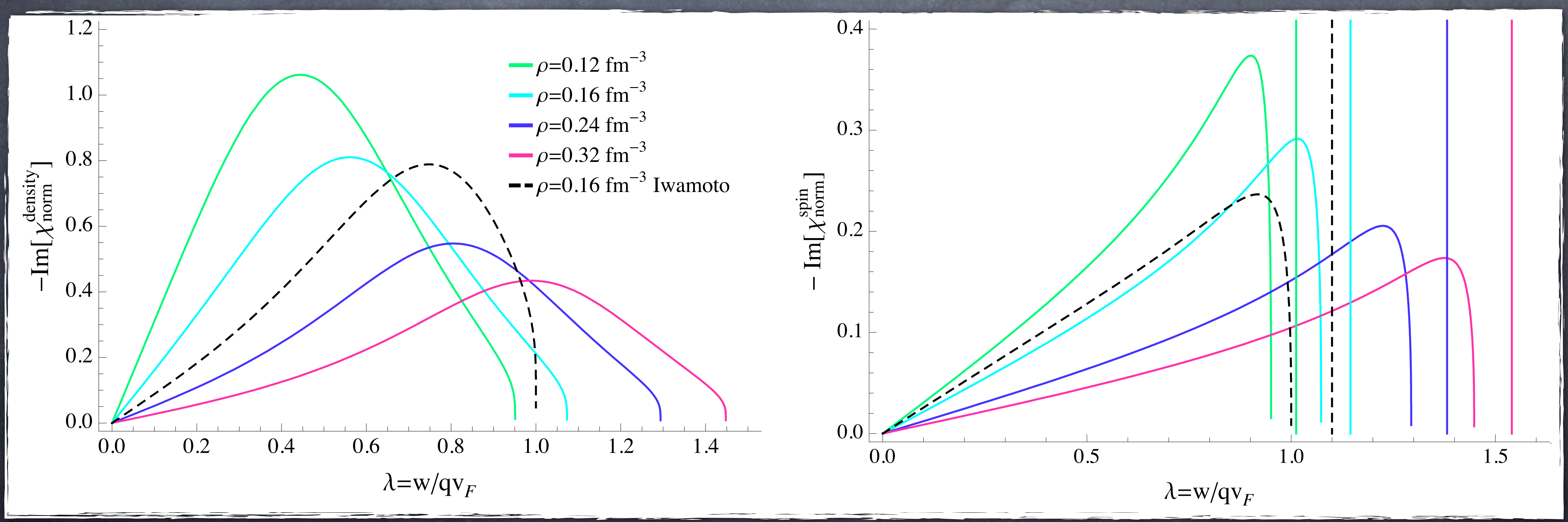

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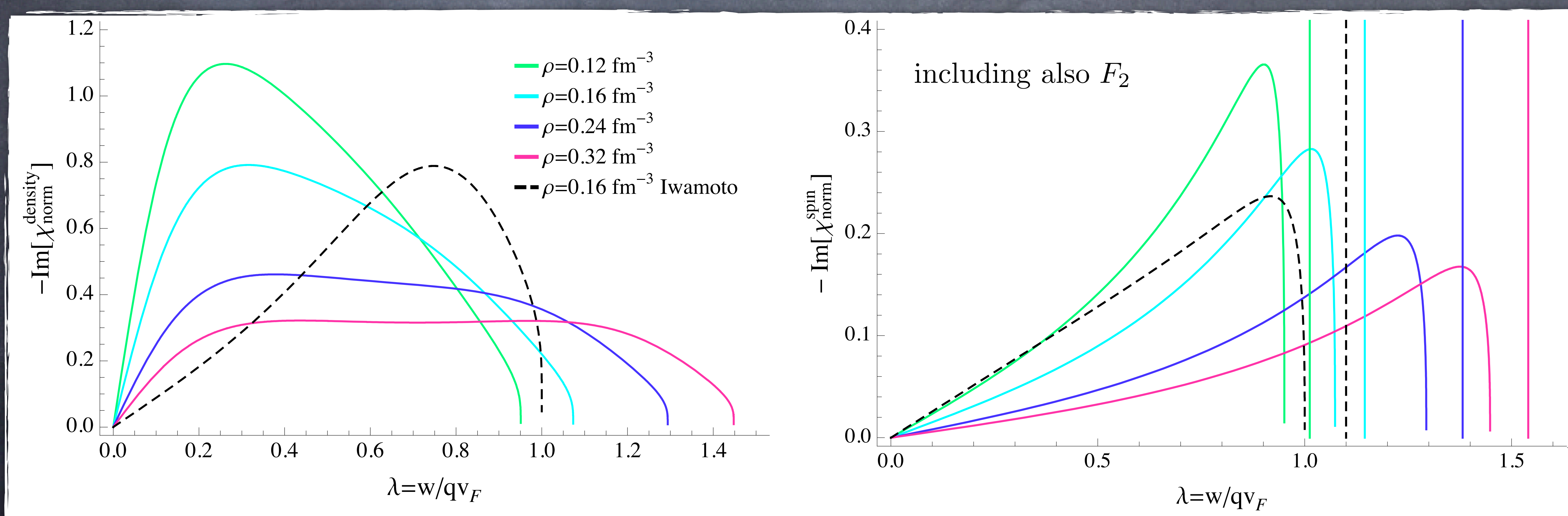

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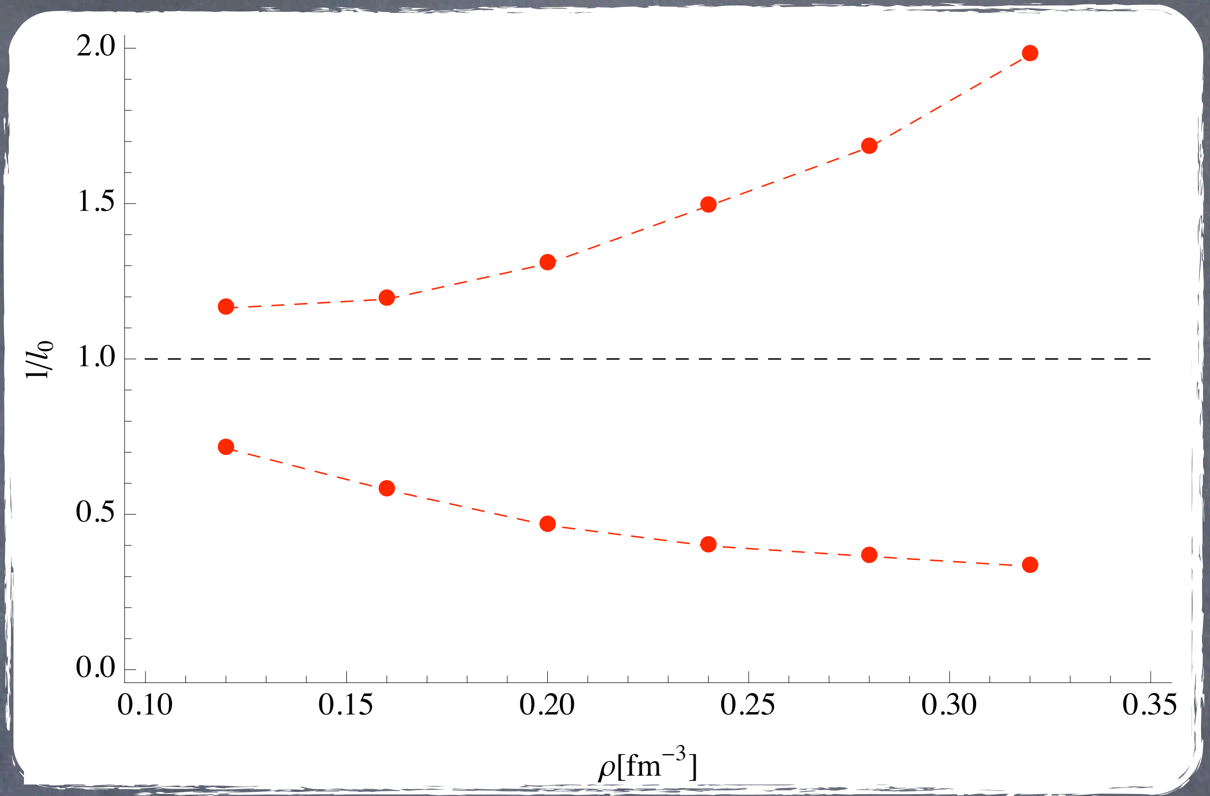
An hint of result ...

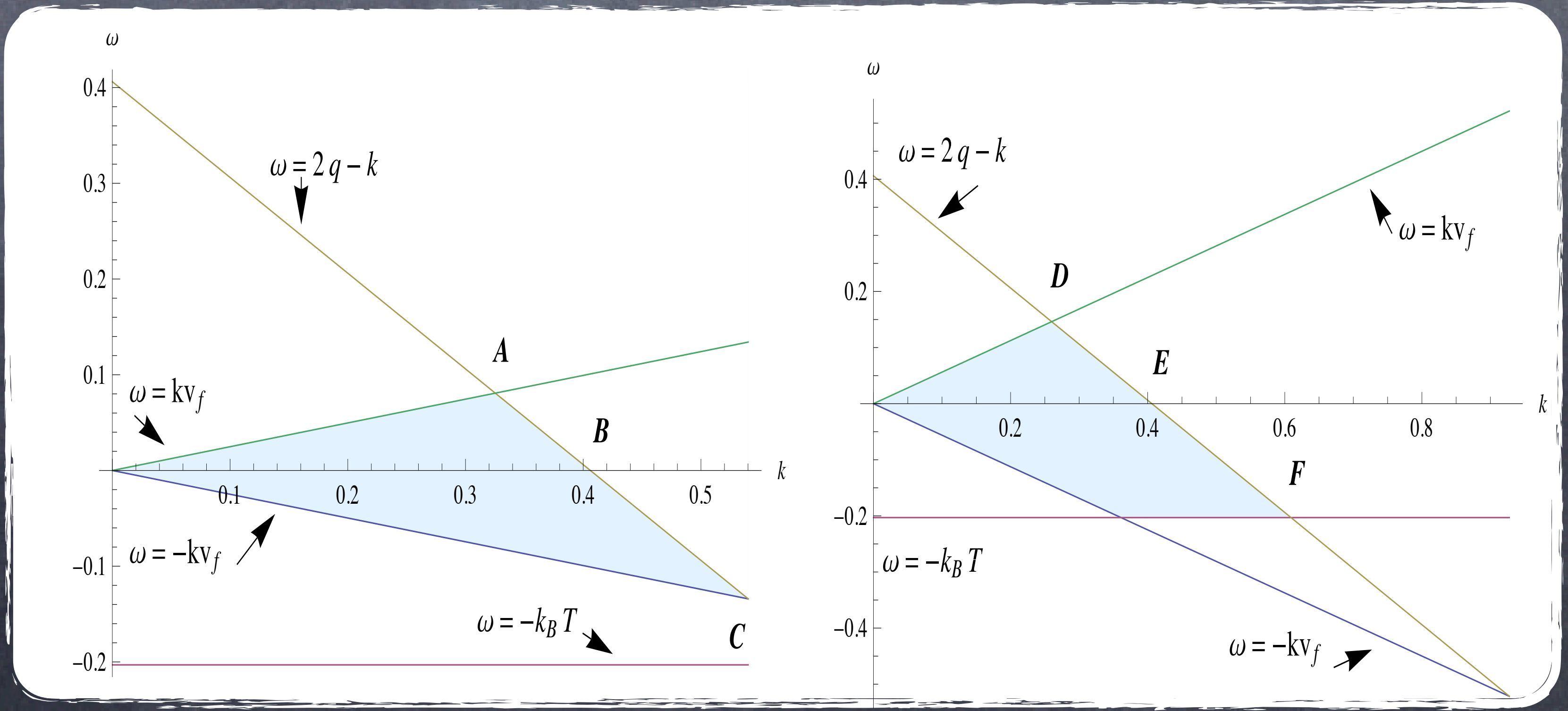
✓ Neutrino mean free path



$kT \ll qv_F$

$kT \gg qv_F$

✓ Phase space



Summary and perspective

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- ✓ Evaluation of Landau parameters: No discrepancy within the *static* properties
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- ✓ Evaluation of Landau parameters: No discrepancy within the *static* properties
- ✓ Landau dynamical response
- Neutrino mean free path and finite-temperature effects
- Extension to asymmetric nuclear matter in β-equilibrium