Impact of pairing on clusterization of stellar matter

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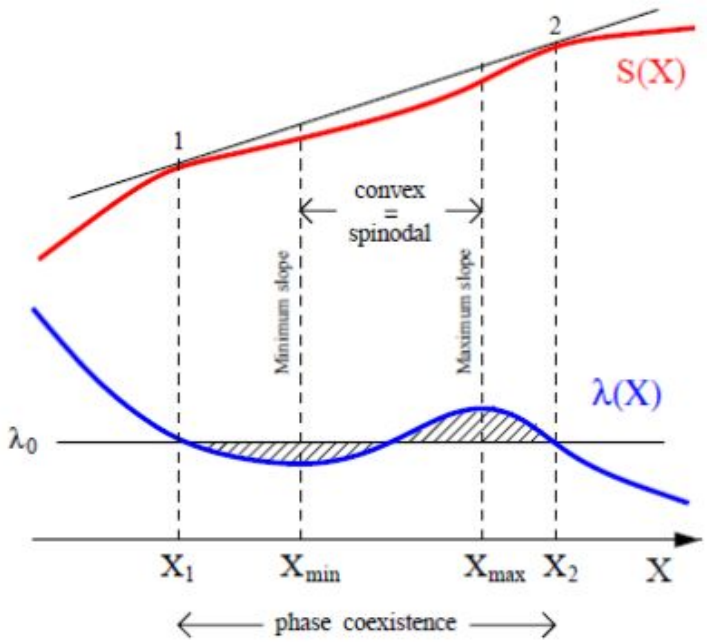
Authors: Burrello S.[1], Colonna M.[1], Matera F.[2]

[1] INFN - LNS, Catania

[2] INFN - Dipartimento di Fisica e Astronomia, Firenze

Liquid-gas phase transition and spinodal instability

- Nuclear matter at $\rho < \rho_0$ and **low T**:
  - **liquid-gas** phase transition
- **Spinodal** (mechanical) instability
  - multifragmentation in heavy-ion collisions
- **Compact-stars** physics:
  - inner crust of neutron stars
  - supernova explosions
- **Pairing** effects:
  - cooling process
  - glitch phenomena



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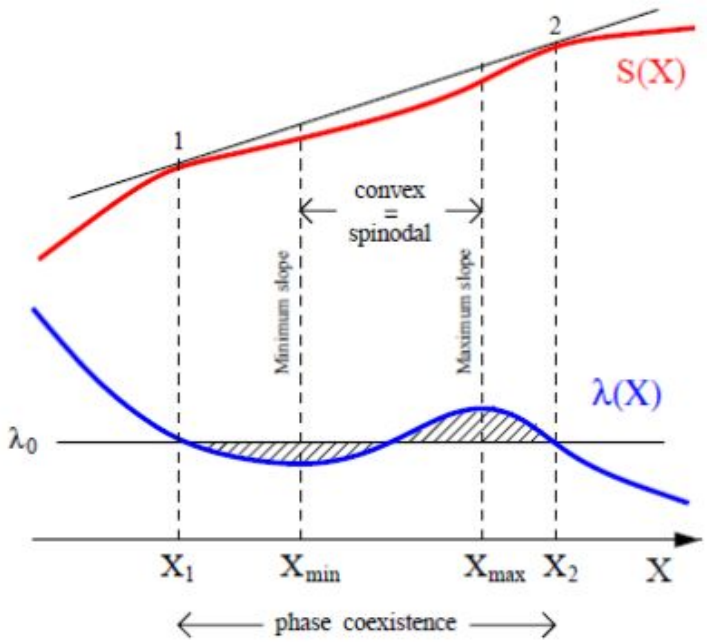

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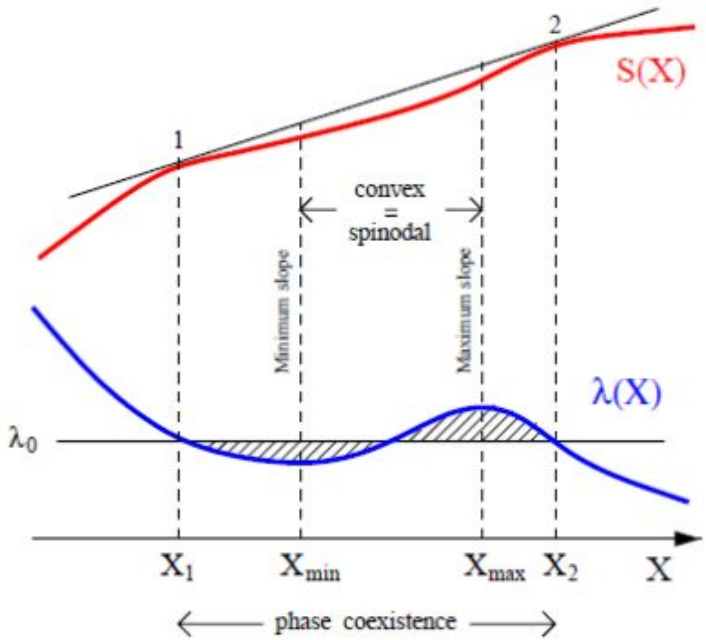

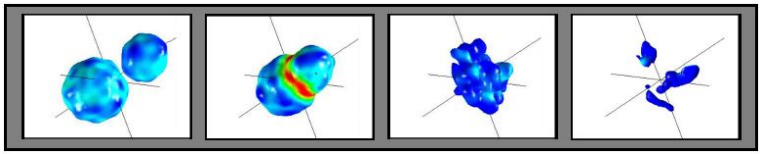

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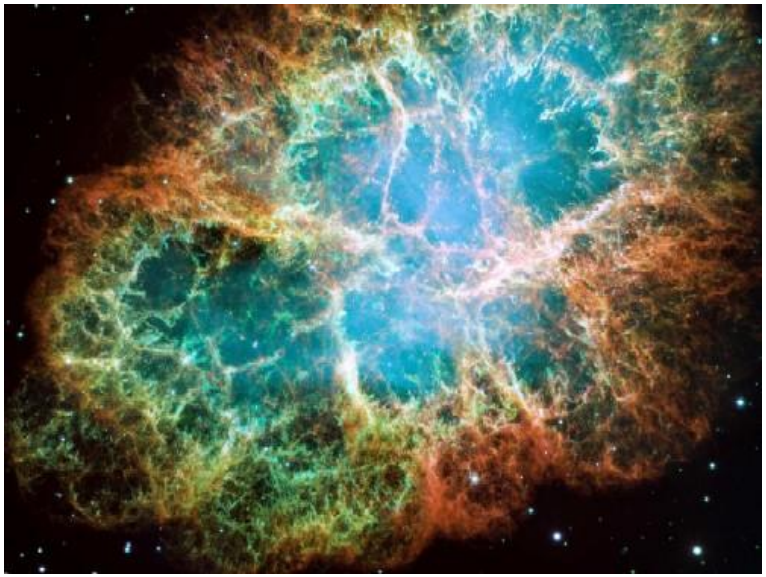

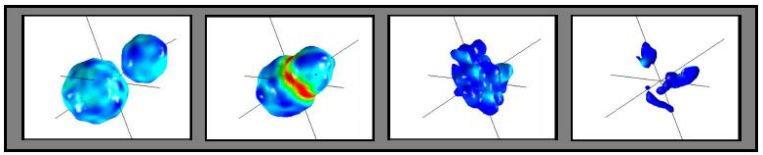

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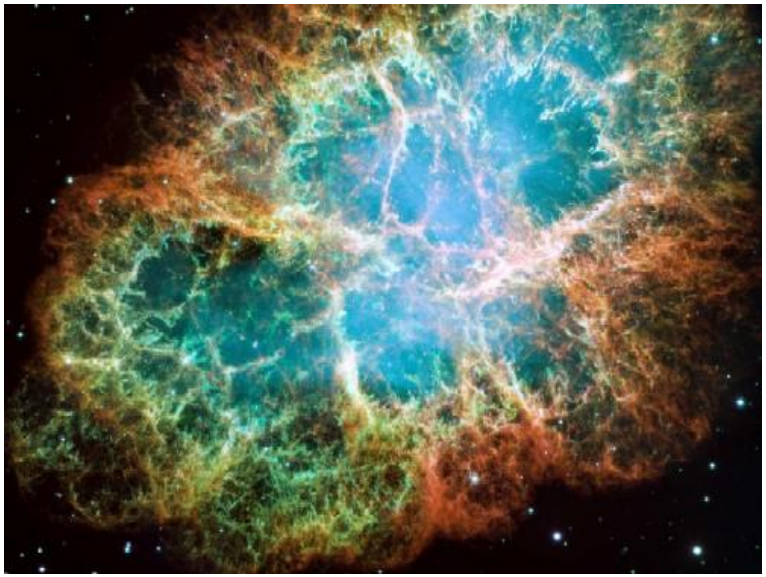

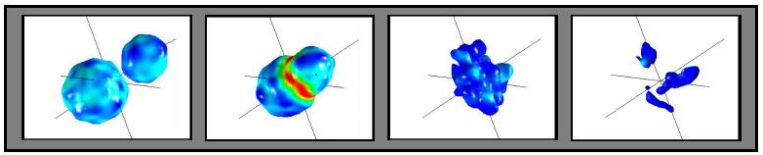

Instabilities of stellar matter: clusterization

- **NMe**: medium of neutrons, protons and electrons (**strict electro-neutrality**)
- **Mean-field** approach: **Skyrme-like** effective interaction
- **Symmetry term**: **SAMi** interactions
  - Free - energy **curvature matrix**

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$$\mathcal{K} = \frac{\hbar^2}{2m}\tau \quad \text{kinetic term}$$

$$\mathcal{H}_0 = C_0\rho^2 + D_0\rho_3^2 \quad \text{density - independent term}$$

$$\mathcal{H}_3 = C_3\rho^{\sigma+2} + D_3\rho^{\sigma}\rho_3^2 \quad \text{density dependent term}$$

$$\mathcal{H}_{eff} = C_{eff}\rho\tau + D_{eff}\rho_3\tau_3 \quad \text{momentum dependent term}$$

$$\mathcal{H}^{\nabla} = C_{nn}^{\nabla}(\nabla\rho_n)^2 + C_{pp}^{\nabla}(\nabla\rho_p)^2 + 2C_{np}^{\nabla}\,\nabla\rho_n\cdot\nabla\rho_p \quad \text{density-gradient term}$$

$\rho = \rho_n + \rho_p \quad \tau = \tau_n + \tau_p$ particle/kinetic isoscalar densities

$\rho_3 = \rho_n - \rho_p \quad \tau_3 = \tau_n\tau_p$ particle/kinetic isovector densities

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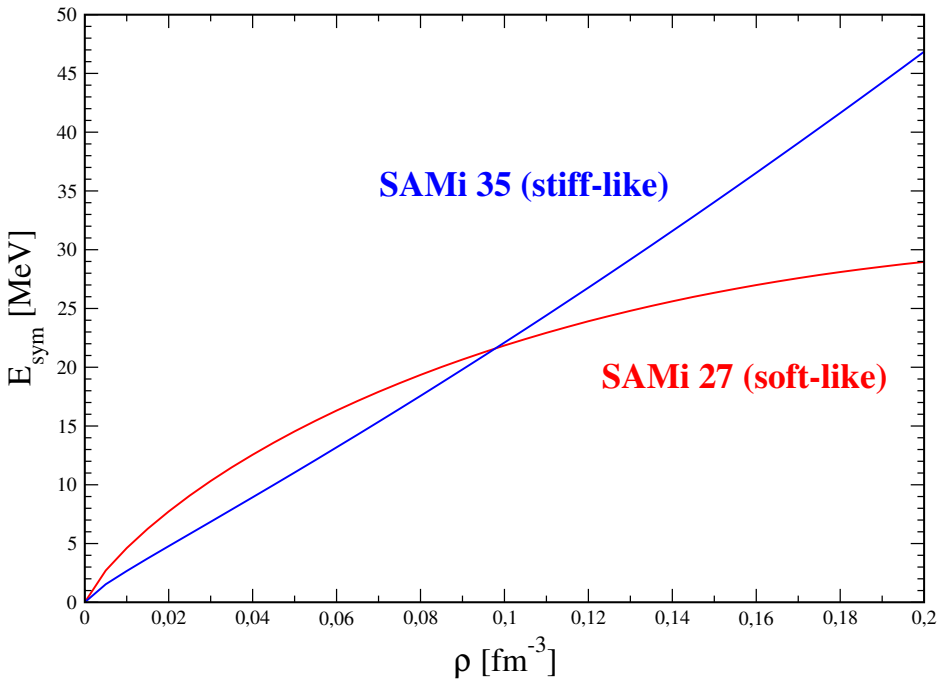

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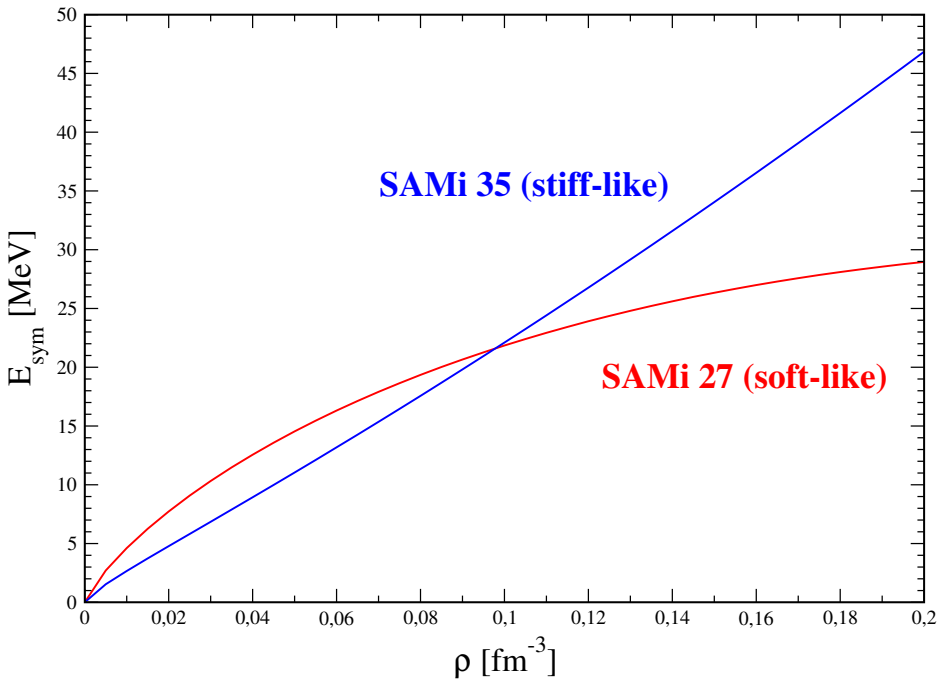

- Free - energy **curvature matrix**

$$\mathbf{C}^f_{NMe} = \begin{pmatrix} \partial_{\rho_n}\mu_n & \partial_{\rho_p}\mu_n & 0 \\ \partial_{\rho_n}\mu_p & \partial_{\rho_p}\mu_p & 0 \\ 0 & 0 & \partial_{\rho_e}\mu_e \end{pmatrix}$$

$$+ 2k^2 \begin{pmatrix} C^f_{nn} & C^f_{np} & 0 \\ C^f_{pn} & C^f_{pp} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$+ \frac{4\pi e^2}{k^2} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & -1 \\ 0 & -1 & 1 \end{pmatrix}$$

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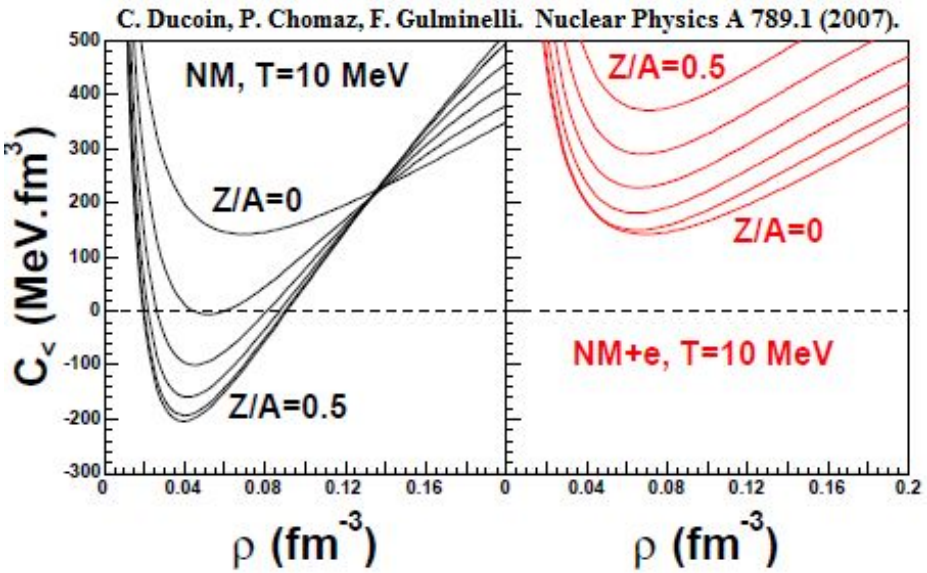

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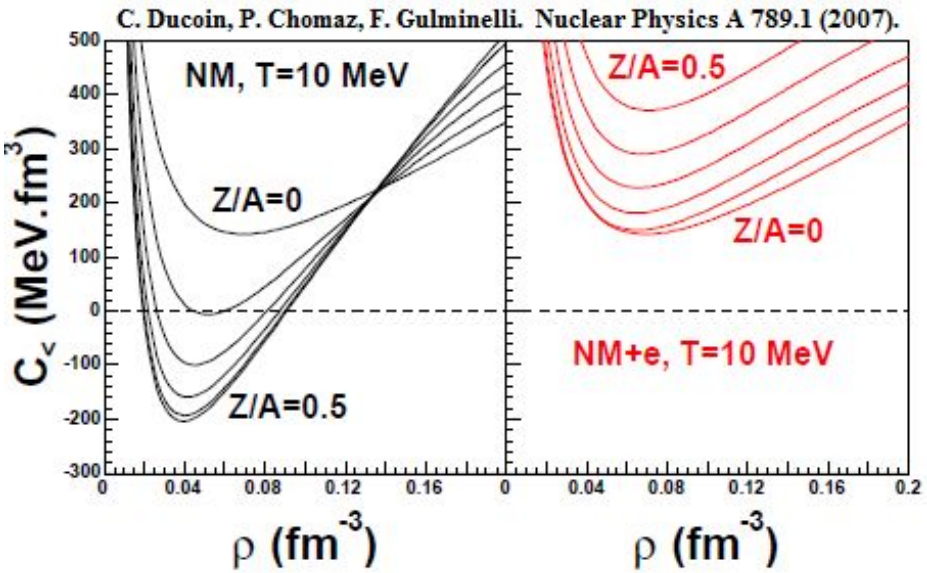

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- **Paired** NMe: effect on **clusterization**

Pairing effective interaction

- **Zero range** pairing effective interaction

$$V_\pi(\mathbf{r}_i, \mathbf{r}_j) = \frac{1}{2}(1-P_\sigma)v_\pi(\rho_q)\delta(\mathbf{r}_{ij}) \qquad q = p, n$$

- **BCS** approx.: density/gap equations

$$\rho_q = \frac{(2m_q^*)^{3/2}}{4\pi^2\hbar^3}\int_0^{\mu_q^*+\epsilon_\Lambda} d\epsilon\sqrt{\epsilon}\left[1-\frac{\xi}{E_\Delta}\tanh\left(\frac{E_\Delta}{2T}\right)\right]$$

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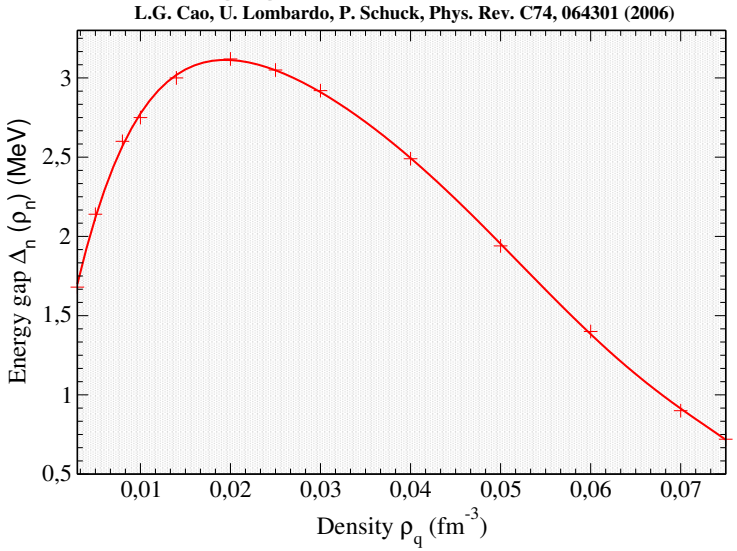
$^1S_0$ pairing gap of neutron matter

L.G. Cao, U. Lombardo, P. Schuck, Phys. Rev. C74, 064301 (2006)



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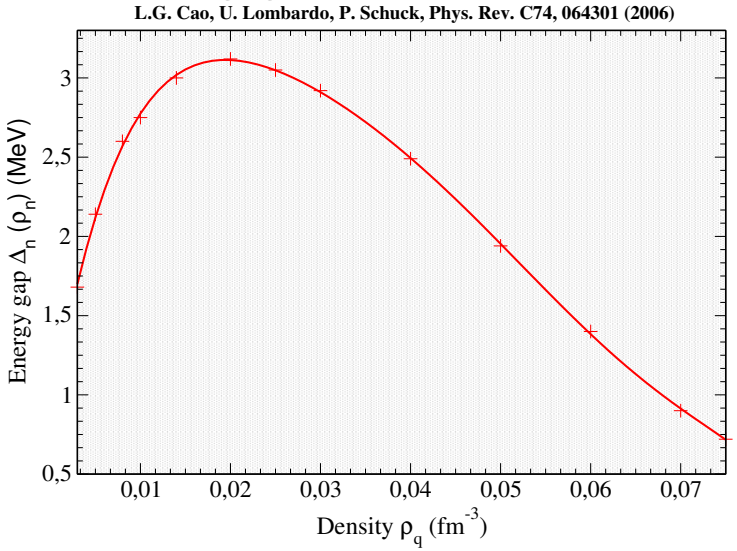

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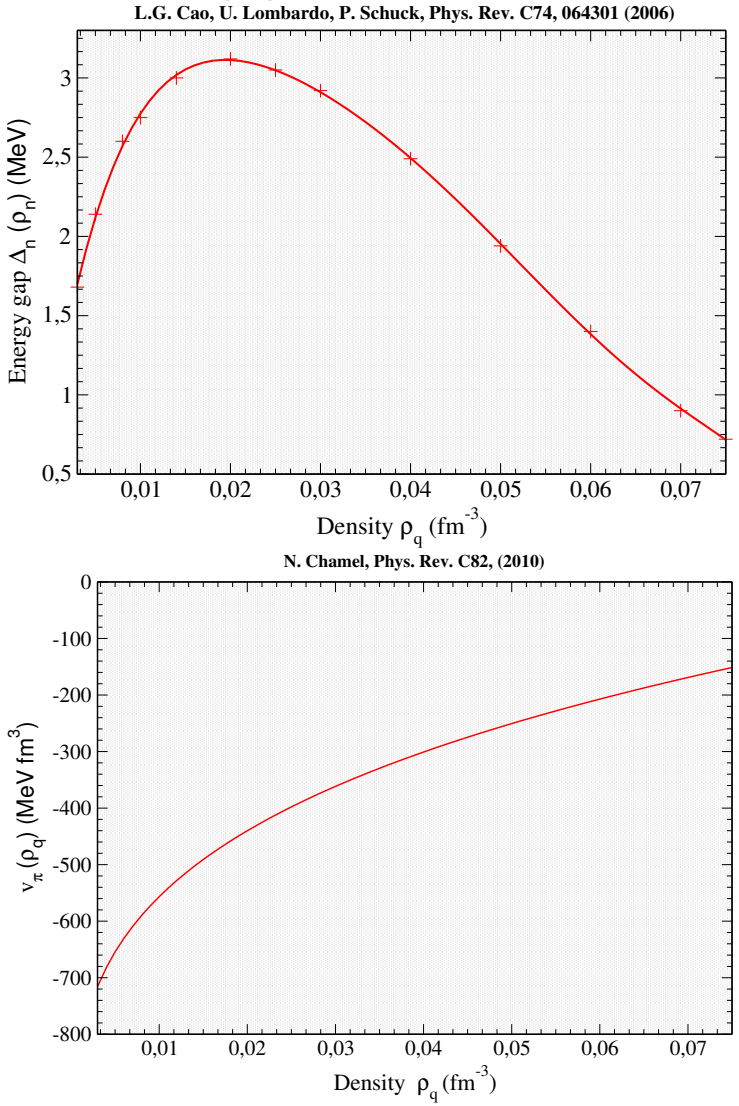

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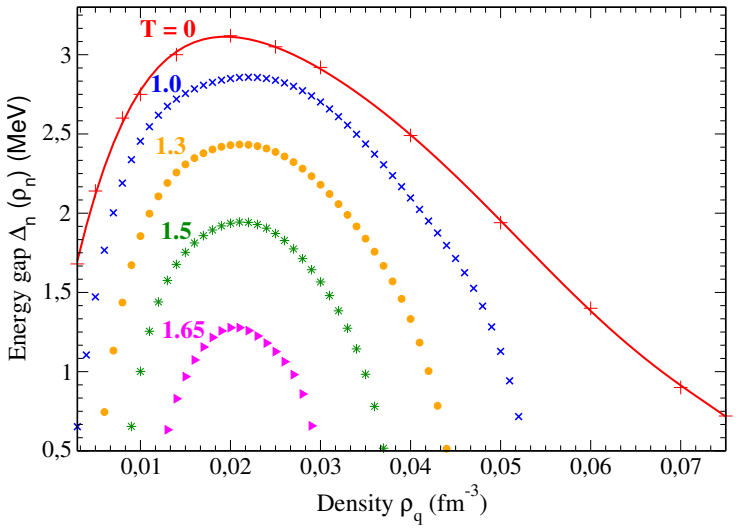

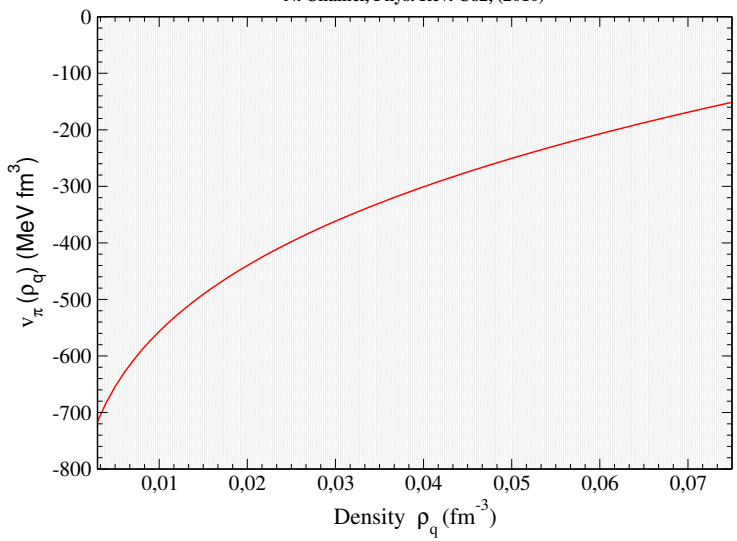

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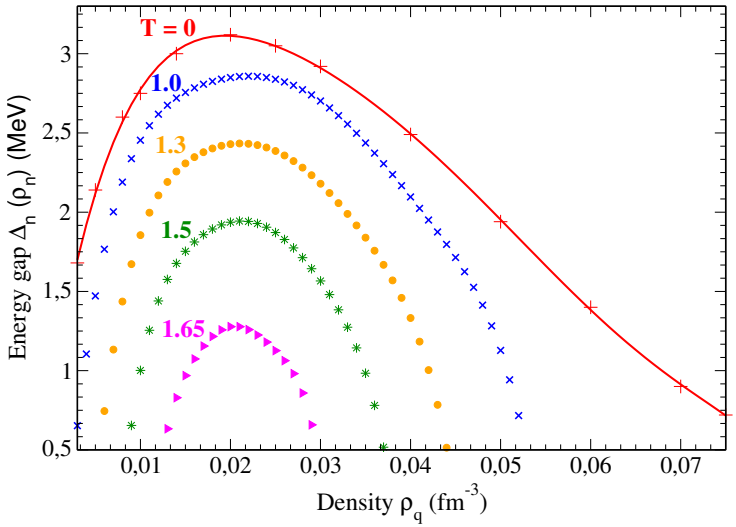

- **Superfluid** $\xleftrightarrow{T=T_c}$ **normal** (2^{nd} order)
- Variation on **energy density**

[Burrello S., Colonna M., Matera F., 2014, PRC 89]

$$\mathcal{H}_\pi = 2\sum_{q=n,p}\int_0^\Lambda \frac{d\mathbf{p}}{h^3} f_q^\pi \frac{p^2}{2m_q^*} + \mathcal{H}_\pi^{pot} + \mathcal{H}^{pot}$$

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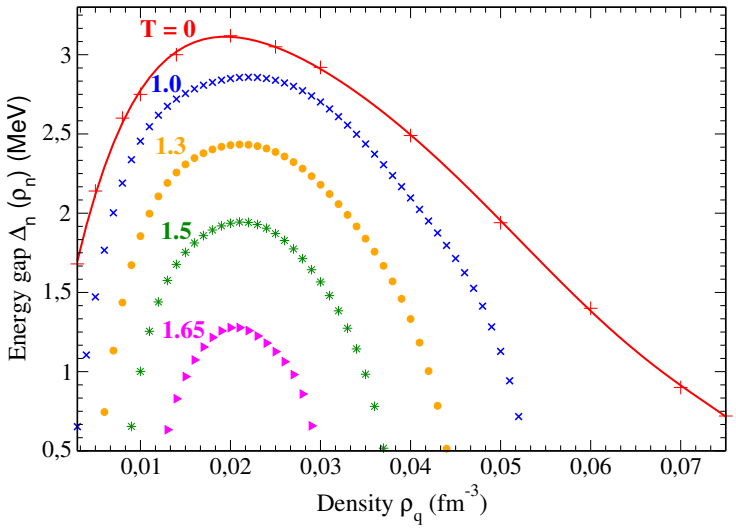

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Chemical potential derivatives in superfluid matter

- **Heat capacity** $\Rightarrow$ **cooling** of neutron stars [see Fortin M. et al., Phys. Rev. C 82, (2010)]
- $\partial_{\rho_i}\mu_j \Leftrightarrow$ isothermal **compressibility**
- **Aim of the work**: application to **core-collapse** in supernova explosions
- Before/Core Bounce (**BB/CB**)

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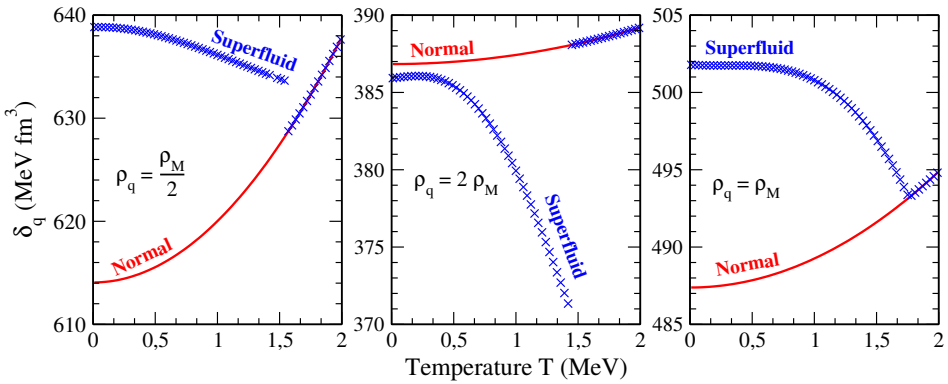

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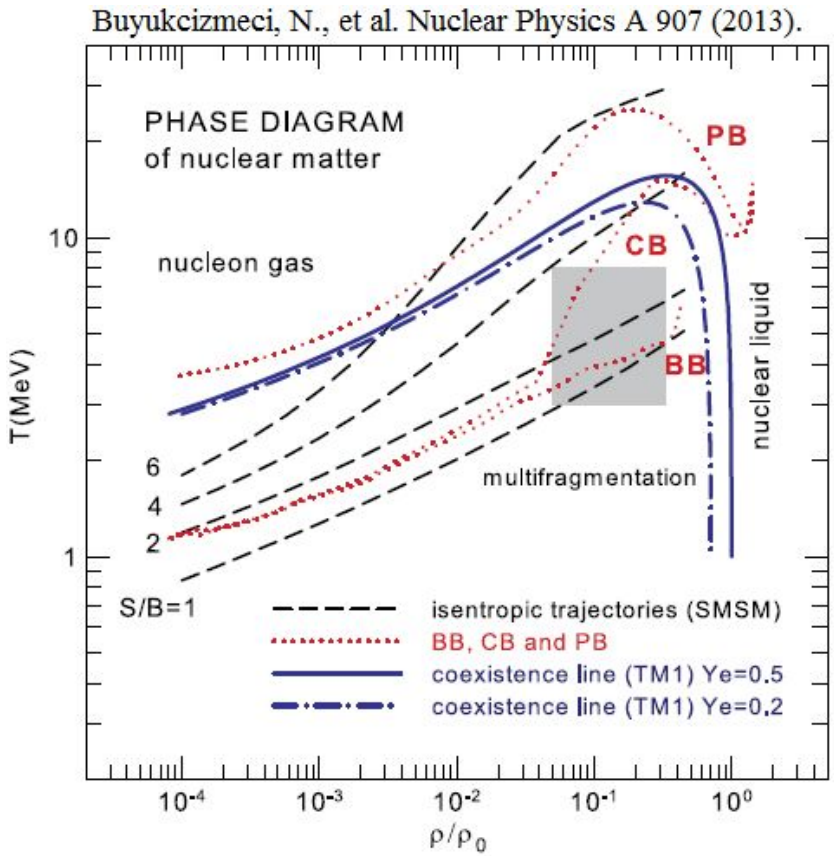

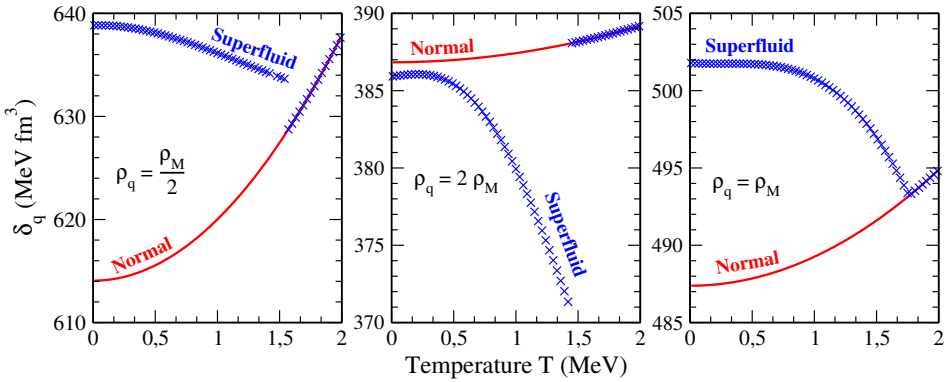

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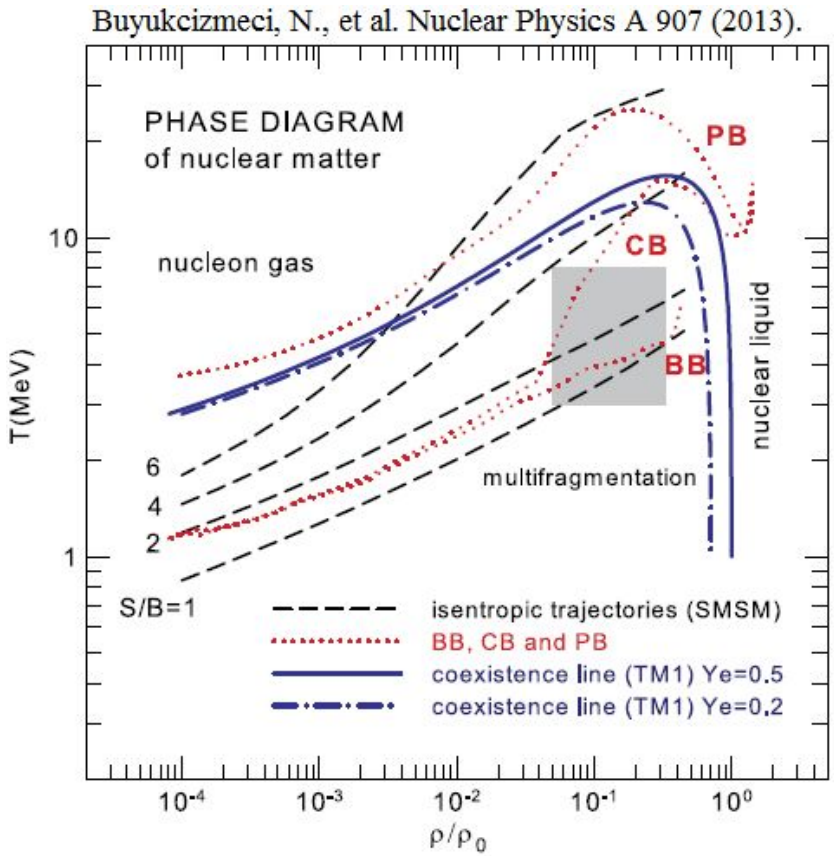

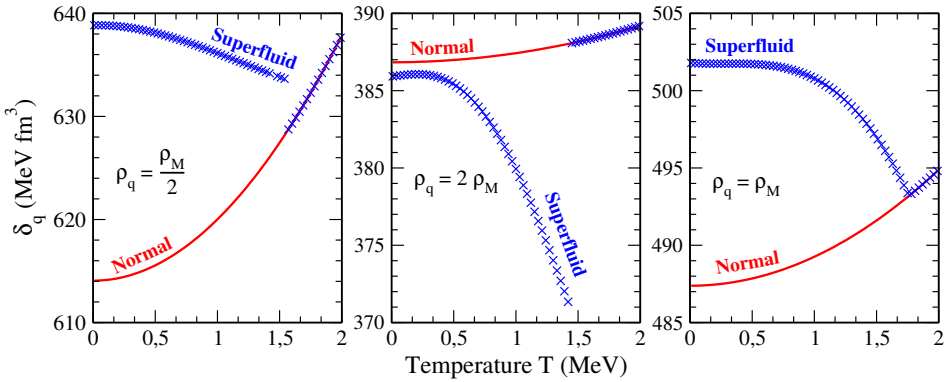

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Pairing effect on isospin distillation mechanism

- θ-direction in (ρ_p, ρ_n) plane for (**unstable**) **isoscalar-like mode**: $\tan\theta = \frac{\delta\rho_n}{\delta\rho_p}$
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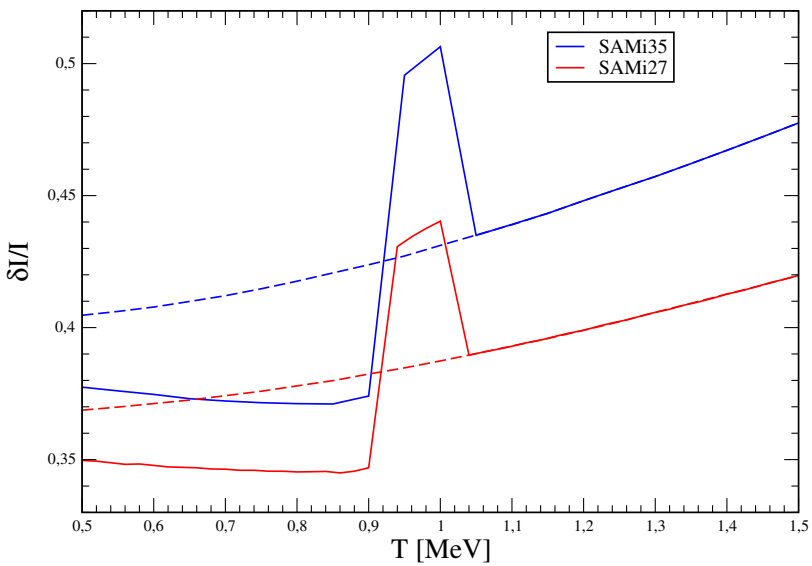
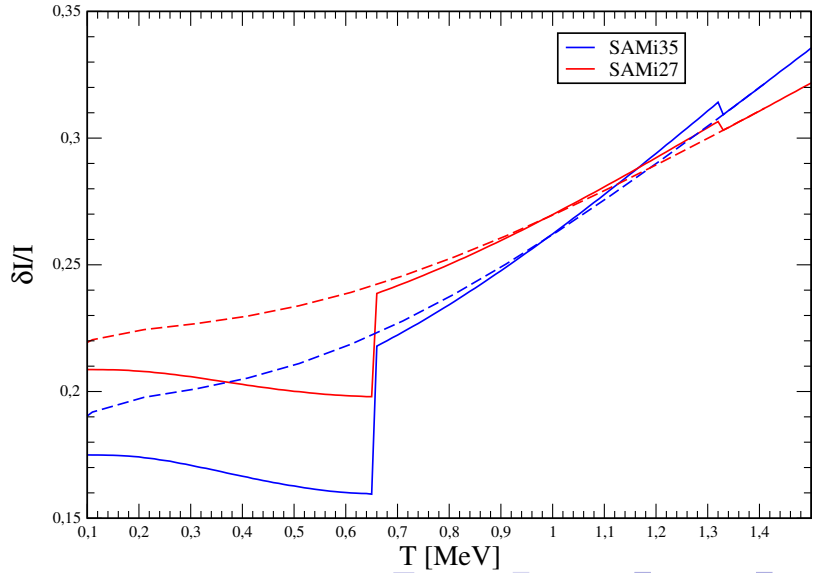
$\rho=\rho_0/20$, I = 0.1, k = 80 MeV/c



$\rho=\rho_0/20$ I = 0.6 k = 80 MeV/c



Cross section of neutrino-nucleon scattering

- **Interaction Lagrangian density** [Fabbri G., Matera F. Physical Review C 54.4 (1996)]

$$\mathcal{L}_I(x) = \frac{G_F}{\sqrt{2}} \hat{j}_\mu(x) \hat{J}^\mu(x)$$

Neutral lepton current:

$$\hat{j}_\mu(x) = \bar{\psi}_l(x)\gamma_\mu(1-\gamma_5)\psi_l(x)$$

Nucleon current:

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- β-**equilibrium** condition: $\mu_n = \mu_p + \mu_e + \mu_\nu \Rightarrow \mu_\nu$
- **Ultra-relativistic** and **degenerate** neutrinos gas: $|\mathbf{k}_\nu| = E_\nu = \frac{3}{4}\mu_\nu$
- **Four-momentum transfer**: $q^\mu = (\omega, \mathbf{q})_\nu = (E - E', \mathbf{k} - \mathbf{k}')_\nu \Rightarrow \sigma(\omega, \mathbf{q})$
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$$\frac{1}{V}\frac{d^3\sigma}{dE' d\phi dq} = \frac{G_F^2}{4\pi}\left(4k_\nu^2 - q^2\right) T \left[\mathscr{C}_V^{(n)2} C_{nn}^{-1}(q) + \mathscr{C}_V^{(p)2} C_{pp}^{-1}(q) + 2\mathscr{C}_V^{(n)}\mathscr{C}_V^{(p)} C_{np}^{-1}(q)\right]$$

$\mathscr{C}_V^{(n)} = -\frac{1}{2}$ $\quad \mathscr{C}_V^{(p)} = \frac{1}{2} - 2\sin^2\theta_W$ $\quad C_{ij}^{-1} \equiv$ **curvature inverse matrix components**

Impact of pairing on neutrino-nucleon scattering

- **Spinodal region** $\lambda_s < 0 \Rightarrow$ temporal **growth** of fluctuations

$$\lambda_s \to |\lambda_s| \frac{1}{\exp(2t/\tau) - 1} \qquad \tau = f(\lambda_s)$$

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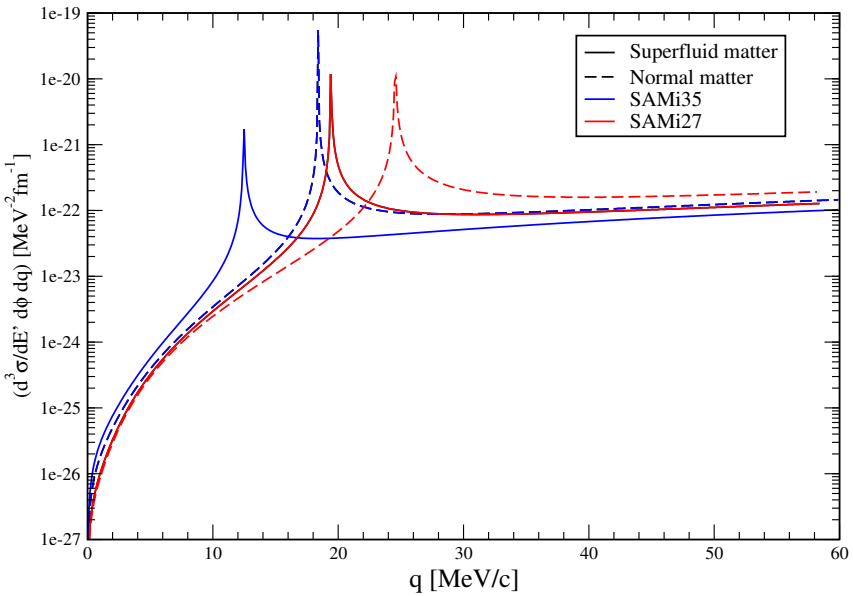

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  [Margueron J., Navarro J., Blottiau P. PRC70 (2004)]
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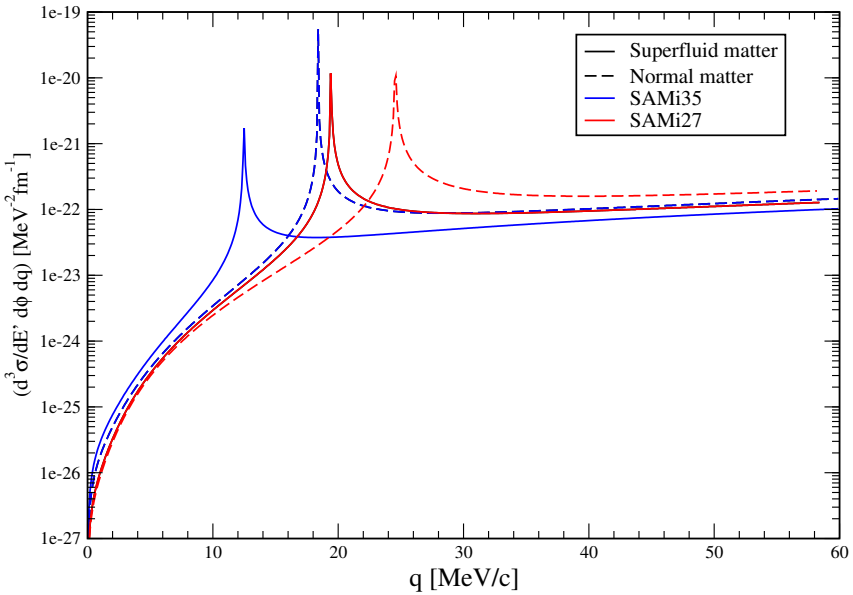

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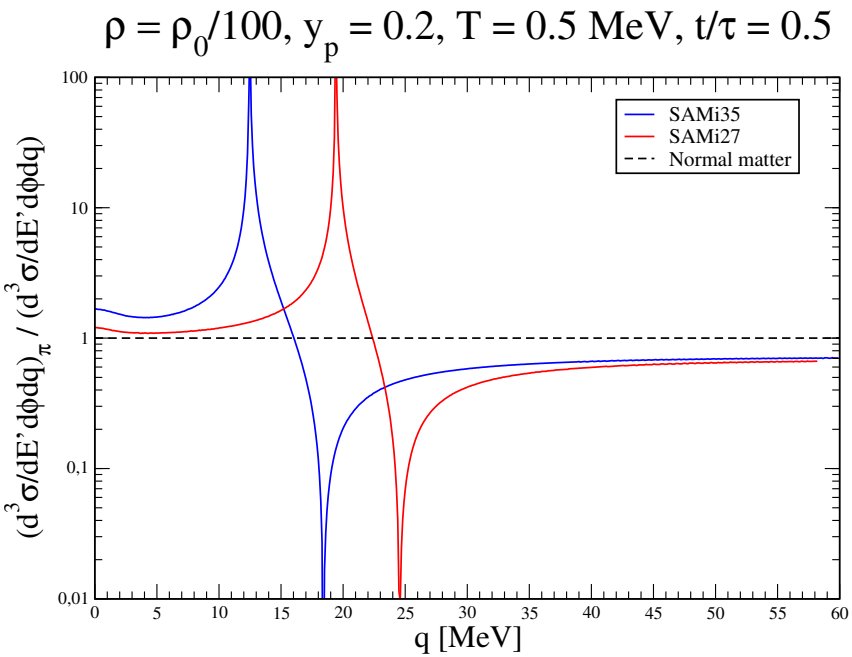

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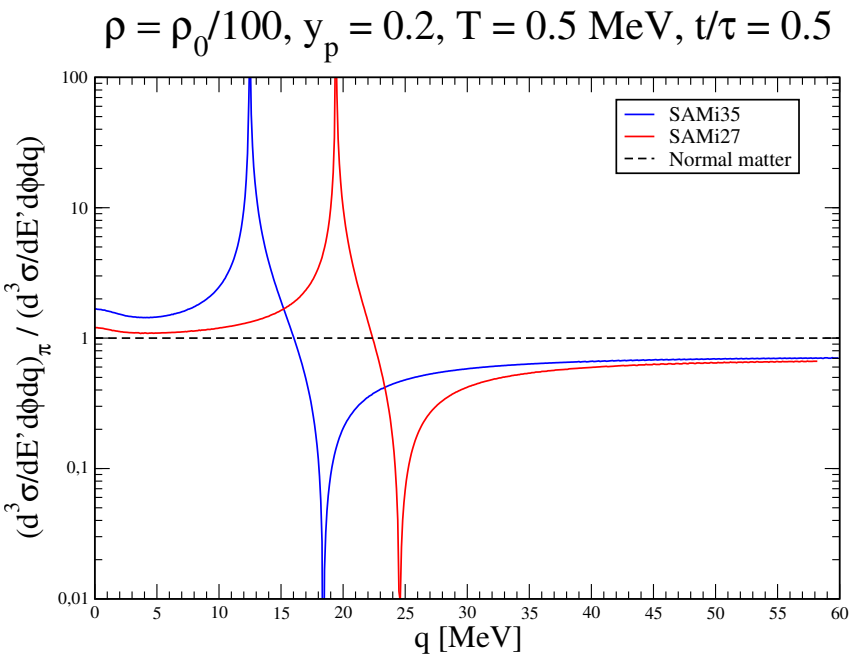

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title

"Work is **SALT** of our life" (Polish saying)

THANK YOU FOR YOU KIND ATTENTION!

Further insights

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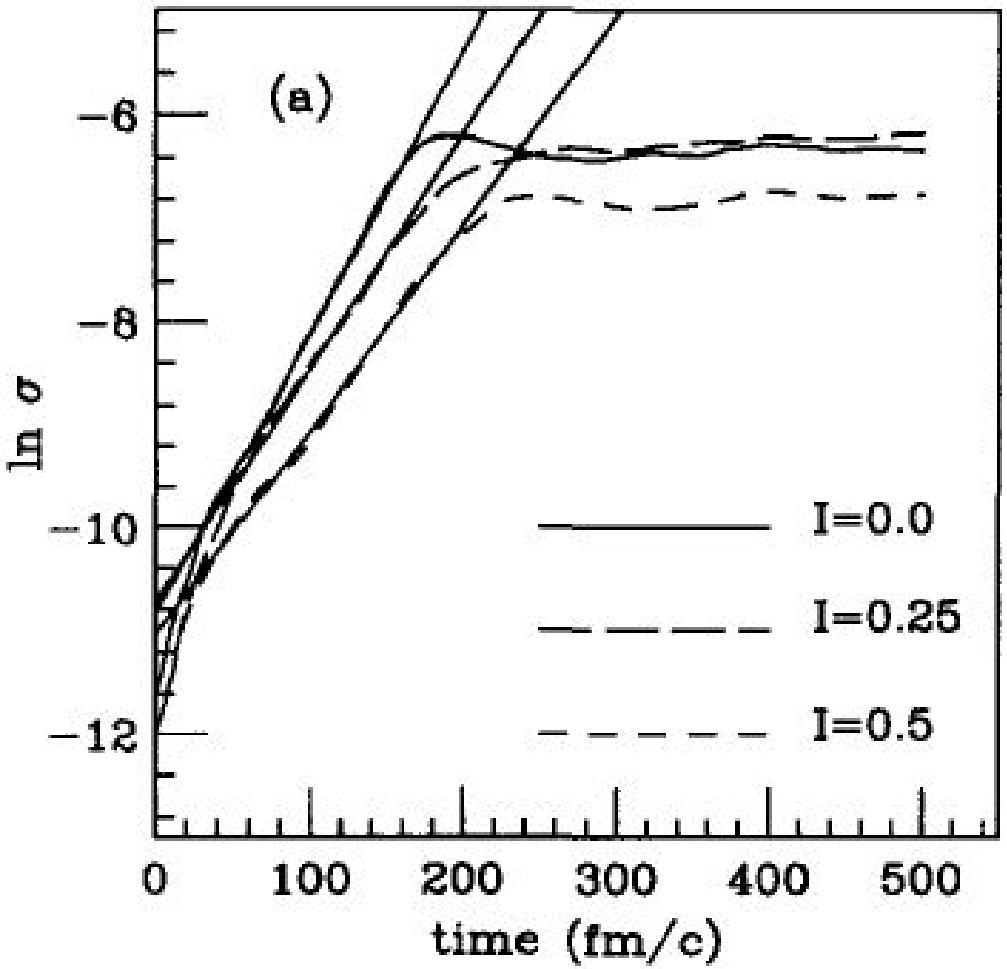

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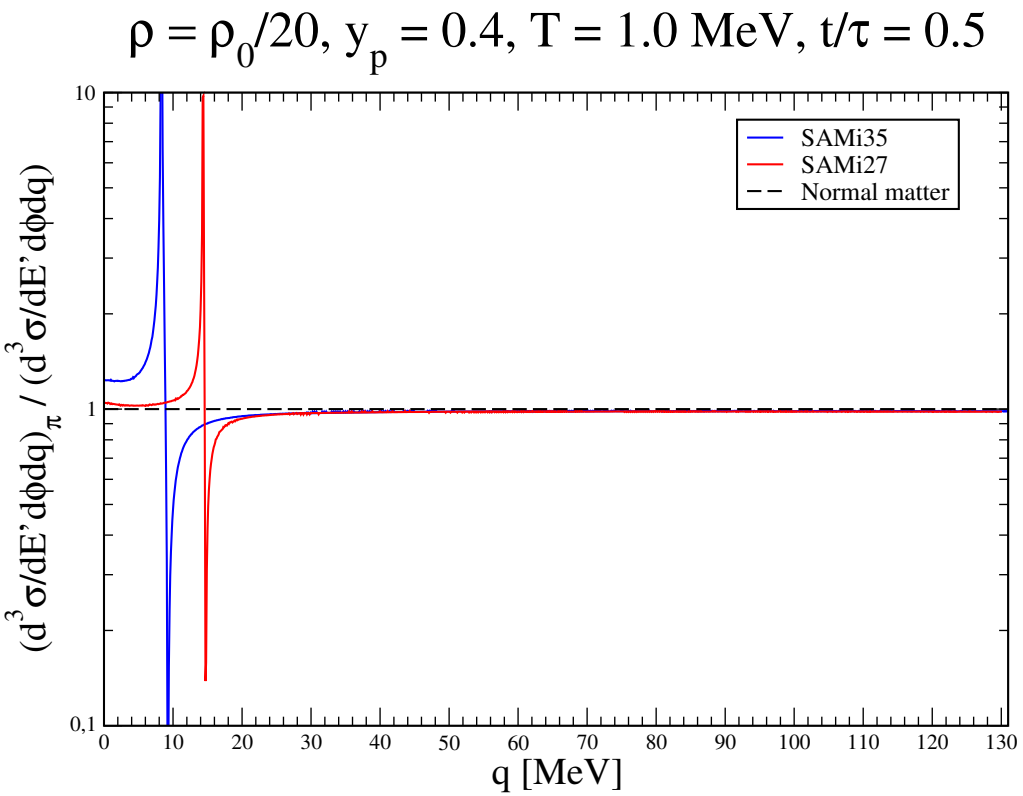

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