The role of Fock terms on nuclear symmetry energy in a relativistic framework

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in collaboration with
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Nuclear symmetry energy

The nuclear symmetry energy is known to be **a important physical quantity** not only in nuclear physics but also in astrophysics.

- neutron skin and the different distributions of neutrons and protons in a nucleus
- isospin-asymmetric nuclear matter in the density region above the saturation density, experimentally performed by the heavy-ion collisions
- some astrophysical observations, for instance the mass-radius relations of neutron stars and the cooling processes of proto-neutron stars, strongly depend on the nuclear symmetry energy.

Theoretical point of view

Many theoretical calculations have been focused on the properties of asymmetric nuclear matter, including the nuclear symmetry energy.

- the phenomenological calculations based on the effective many-body interaction with the Skyrme or Gogny force
- the relativistic mean-field (RMF) models based on Quantum Hadrodynamics (QHD)
- microscopic studies, for examine, the so-called Dirac-Brueckner-Hartree-Fock (DBHF) approach and chiral perturbation theory based on realistic *NN* interactions

However, different results for the high-dense behavior of the nuclear symmetry energy have been reported so far and, in particular,

its density dependence above the saturation density is still unknown.

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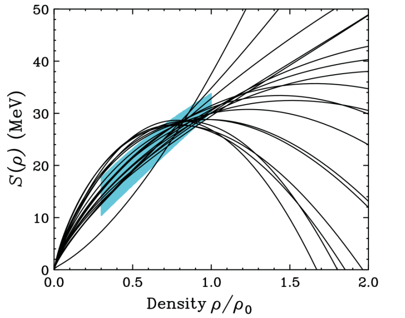

FIG. 1. (Color online) Density dependence of the symmetry energy from the Skyrme interactions used in Ref. [6]. The shaded region is obtained from HIC experiments as described in the text and corresponds to the shaded region in Fig. 2.

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Motivation

We study the Fock contrition to the density dependence of nuclear symmetry energy, E_{sym}, and its slope parameter, L, in relativistic theory.

Relativistic mean-field (RMF) models:

- relativistic Hartree (RH) approximation
- relativistic Hartree-Fock (RHF) approximation

Since only the direct diagram is usually considered in the RH models, interacting mesons are treated within zero momentum transfer.
In contrast, the inclusion of the Fock terms automatically allows us to explore the momentum dependence at meson-nucleon vertices.
In addition, the pion contribution can be taken into account through the exchange contribution.

Model Lagrangian

Lagrangian density for uniform hadronic matter:

$$\mathcal{L} = \sum_{N=p,n} \bar{\psi}_N \left(i\gamma_\mu \partial^\mu - M_N\right) \psi_N + \mathcal{L}_M + \mathcal{L}_{\rm int} - U_{\rm NL}.$$

Interaction Lagrangian density: mesons (σ, ω, $\vec{\pi}$, and $\vec{\rho}$)

$$\mathcal{L}_{\rm int} = \sum_{N=p,n} \left(\mathcal{L}_\sigma + \mathcal{L}_\omega + \mathcal{L}_\pi + \mathcal{L}_\rho\right),$$

$$\underbrace{\mathcal{L}_\sigma = g_{\sigma N}\bar{\psi}_N \sigma \psi_N}_{\text{scalar}}, \quad \underbrace{\mathcal{L}_\omega = -g_{\omega N}\bar{\psi}_N \gamma_\mu \omega^\mu \psi_N}_{\text{vector}}, \quad \underbrace{\mathcal{L}_\pi = -\frac{f_{\pi N}}{m_\pi}\bar{\psi}_N \gamma_5 \gamma_\mu \partial^\mu \vec{\pi} \psi_N \cdot \vec{\tau}_N}_{\text{pseudovector}},$$

$$\mathcal{L}_\rho = \underbrace{-g_{\rho N}\bar{\psi}_N \gamma_\mu \vec{\rho}^{\,\mu} \psi_N \cdot \vec{\tau}_N}_{\text{vector}} + \underbrace{\frac{f_{\rho N}}{2\mathcal{M}}\bar{\psi}_N \sigma_{\mu\nu} \partial^\nu \vec{\rho}^{\,\mu} \psi_N \cdot \vec{\tau}_N}_{\text{tensor}}.$$

The following nonlinear term is also introduced in order to reproduce the saturation properties of nuclear matter at the mean-field level:

$$U_{\rm NL} = \frac{1}{3} g_2 \bar{\sigma}^3 + \frac{1}{4} g_3 \bar{\sigma}^4.$$

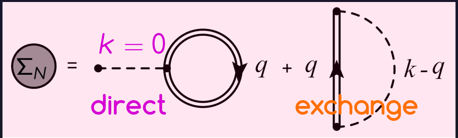
Nucleon self-energy

The nucleon self-energy is given by the Lorentz covariant form with scalar (s), time (0), and space (v) components.

$$\Sigma_N(k) = \Sigma_N^s(k) - \gamma_0 \Sigma_N^0(k) + \left(\vec{\gamma} \cdot \hat{k}\right) \Sigma_N^v, \quad N = n, p.$$

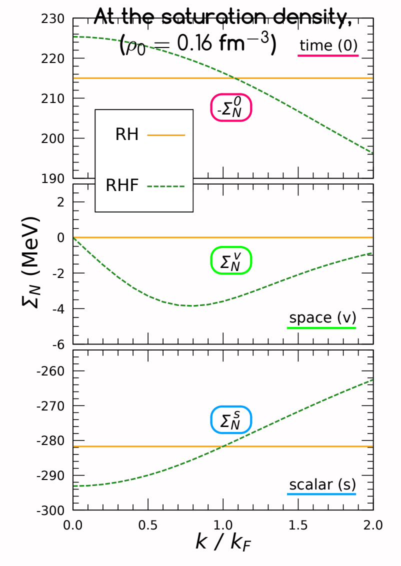
Within the relativistic Hartree-Fock approximation, the Σ_N is composed of the direct and exchange diagrams.

$$\Sigma_N^i(k) = \Sigma_N^{i,\mathrm{dir}} + \Sigma_N^{i,\mathrm{ex}}, \quad i = s, 0, v.$$



Inserting this form into the Dirac equation, we get the effective nucleon mass and momentum in nuclear matter.

$$M_N^*(k) = M_N + \Sigma_N^s(k), \quad k_N^*(k) = \left(k^0 + \Sigma_N^0(k), \vec{k} + \hat{k}\Sigma_N^v(k)\right).$$



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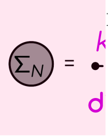
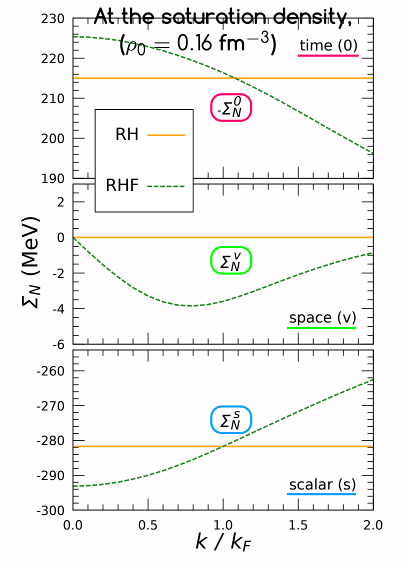


Inserting this form i... nucleon mass and m...

$$M_N^*(k) = M_N + \Sigma_N^s ...$$

		RH			RHF		
		Σ_N^s	$-\Sigma_N^0$	Σ_N^v	Σ_N^s	$-\Sigma_N^0$	Σ_N^v
Direct	σ	−282	0	0	−240	0	0
	ω	0	215	0	0	165	0
Exchange	σ	–	–	–	26	27	−1
	ω	–	–	–	−57	30	−1
	π	–	–	–	−4	−4	−3
	ρ_{VV}	–	–	–	−1	1	0
	ρ_{TT}	–	–	–	−6	−2	0
	ρ_{VT}	–	–	–	0	0	2
Total		−282	215	0	−282	216	−4



Experimental analyses on $E_{\rm sym}$

The recent experimental analyses on the density dependence of $E_{\rm sym}$ have been performed by using the free Fermi Gas (FFG) model and it is separated into the kinetic and potential terms:

$$E_{\rm sym}(\rho_B) = E_{\rm sym}^{\rm kin}(\rho_B) + E_{\rm sym}^{\rm pot}(\rho_B) \simeq E_{\rm sym}^{\rm kin}(\rho_0)\left(\frac{\rho_B}{\rho_0}\right)^{2/3} + E_{\rm sym}^{\rm pot}(\rho_0)\left(\frac{\rho_B}{\rho_0}\right)^{\gamma},$$

where $\rho_{B(0)}$ is the total number (nuclear saturation) density.

In the theoretical calculations,

$$E_{\rm sym}^{\rm kin} = \frac{1}{6}\frac{k_F^*}{E_F^*}k_F, \qquad E_{\rm sym}^{\rm pot} = \frac{1}{8}\rho_B\left(\frac{M_N^*}{E_F^*}\partial\Sigma_{\rm sym}^{s} - \partial\Sigma_{\rm sym}^{0} + \frac{k_F^*}{E_F^*}\partial\Sigma_{\rm sym}^{v}\right) = E_{\rm sym}^{{\rm pot},s} + E_{\rm sym}^{{\rm pot},0} + E_{\rm sym}^{{\rm pot},v},$$

with $k_F = k_{F_p} = k_{F_n}$, $E_F^* = \sqrt{k_F^{*2} + M_N^{*2}}$, and

$$\partial\Sigma_{\rm sym}^{s(0)[v]} \equiv \left(\frac{\partial}{\partial\rho_p} - \frac{\partial}{\partial\rho_n}\right)\left(\Sigma_p^{s(0)[v]} - \Sigma_n^{s(0)[v]}\right).$$

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Lorentz covariance of nucleon self-energy

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$$E_{\rm sym}^{{\rm pot},s} \to 0, \quad E_{\rm sym}^{{\rm pot},0} \to \frac{1}{2}\frac{g_\rho^2}{m_\rho^2}\rho_B, \quad E_{\rm sym}^{{\rm pot},v} \to 0$$

(in Hartree limit.)

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Symmetry energy and slope parameter at ρ_0

$$E_{\rm sym} = E_{\rm sym}^{\rm kin} + E_{\rm sym}^{\rm pot} = E_{\rm sym}^{\rm kin} + E_{\rm sym}^{\rm pot,s} + E_{\rm sym}^{\rm pot,0} + E_{\rm sym}^{\rm pot,v}$$

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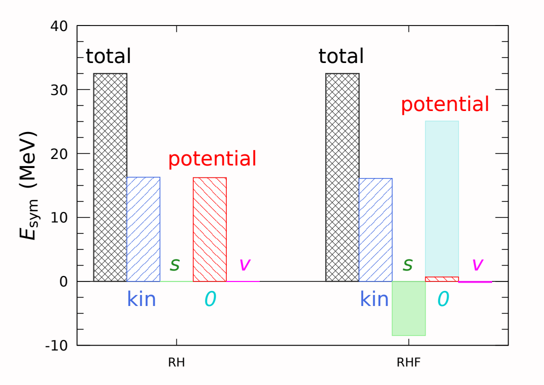

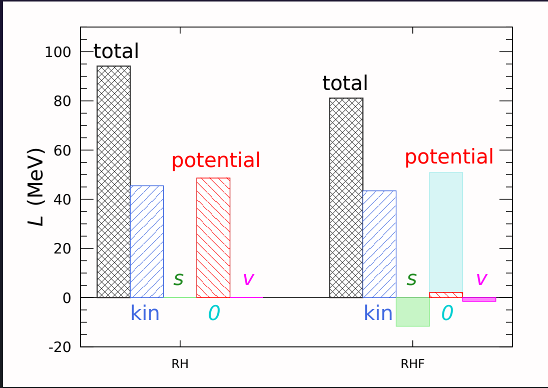

Density dependence of nuclear symmetry energy

Nuclear symmetry energy, E_{sym}

Constraints:

- HIC: heavy ion collision

  M. B. Tsang, et al., Phys. Rev. C **86**, 015803 (2012).

- EDP: electric dipole polarizability in ^{208}Pb experiment

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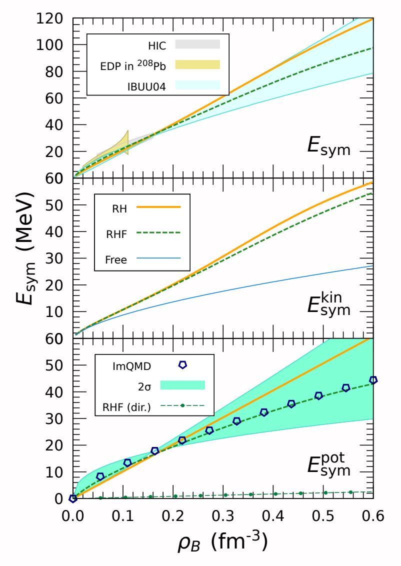

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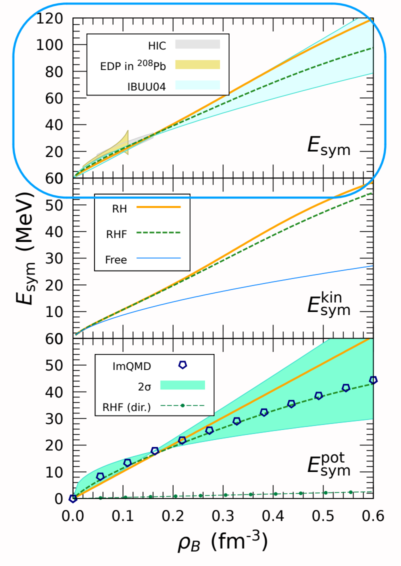

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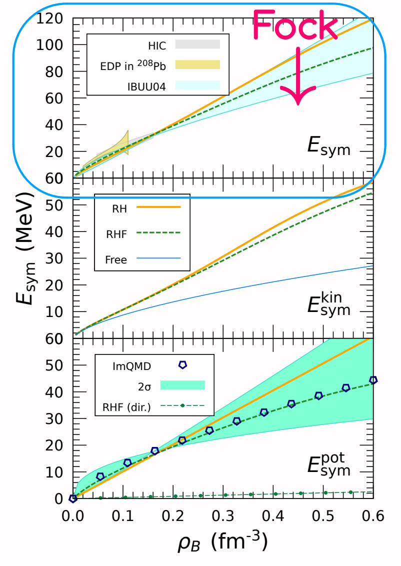

Density dependence of nuclear symmetry energy

Kinetic term, $E_{\rm sym}^{\rm kin}$

- Hartree (RH) approximation

$$\frac{1}{6}\frac{k_F^2}{E_F^*} = \frac{1}{6}\frac{k_F^2}{\sqrt{k_F^2 + M_N^{*2}}}, \quad M_N^* = M_N + \Sigma_N^{s,\rm dir} = M_N - g_{\sigma N}\bar{\sigma}$$

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- Free: interactions are ignored.

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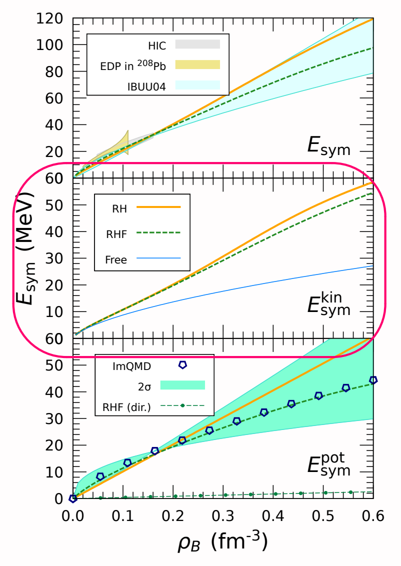

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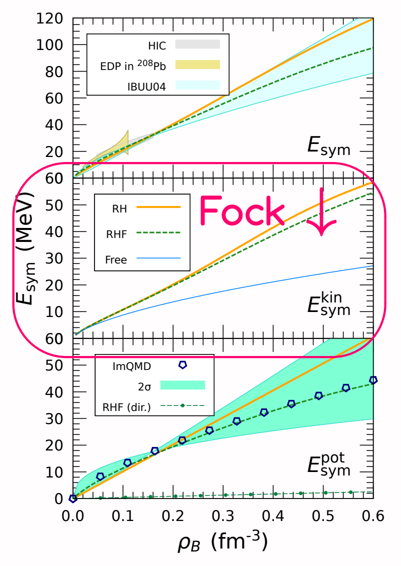

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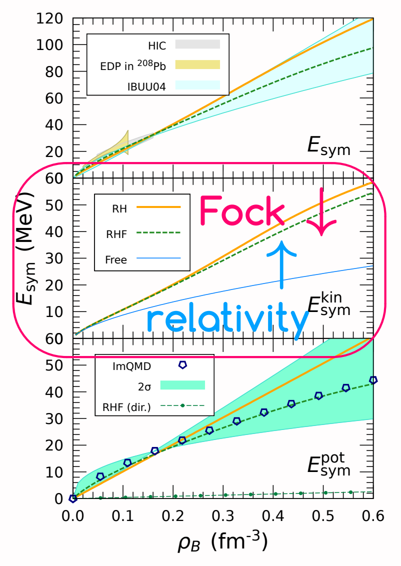

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$$= \frac{1}{2}\frac{g_\rho^2}{m_\rho^2}\rho_B + E_{\rm sym}^{\rm pot,ex}$$

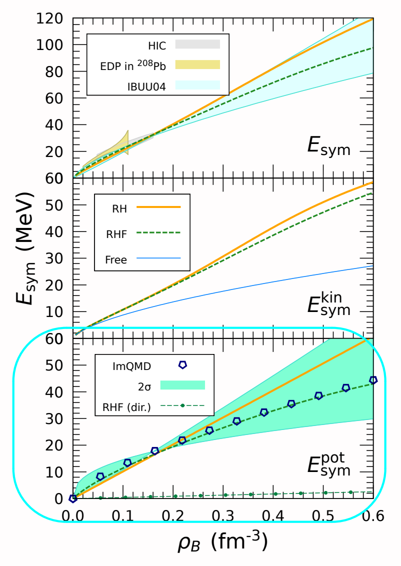
Constraints:

- ImQMD: Improved quantum molecular dynamics transport model

  M. B. Tsang, et al., Phys. Rev. Lett. **102**, 122701 (2009).

$$E_{\rm sym}^{\rm pot}(\rho_0)\left(\frac{\rho_B}{\rho_0}\right)^\gamma \text{ with } \gamma = 0.7^{+0.35}_{-0.3} \text{ (FFG model),}$$

- Hartree (RH) approximation: $\gamma = 1.00$
- Hartree-Fock (RHF) approximation: $\gamma = 0.74$



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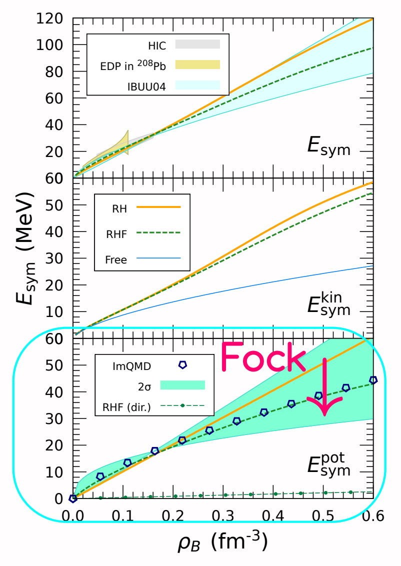

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Cons

exchange contribution mainly affects $E_{\rm sym}^{\rm pot}$

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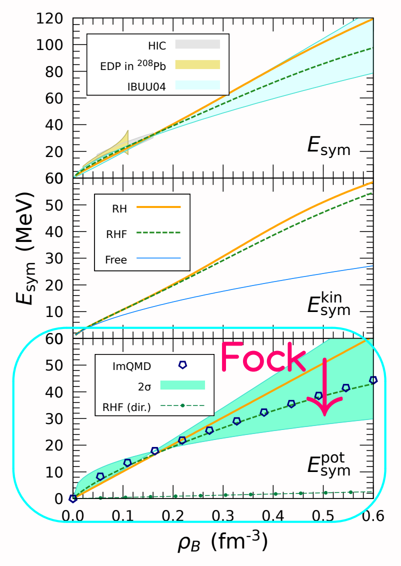


Lorentz decomposition and meson contributions

- Hartree (RH) approximation: only ρ meson

$$E_{\rm sym}^{\rm pot} = E_{\rm sym}^{\rm pot,dir} = \frac{1}{2}\frac{g_\rho^2}{m_\rho^2}\rho_B$$

- Hartree-Fock (RHF) approximation:

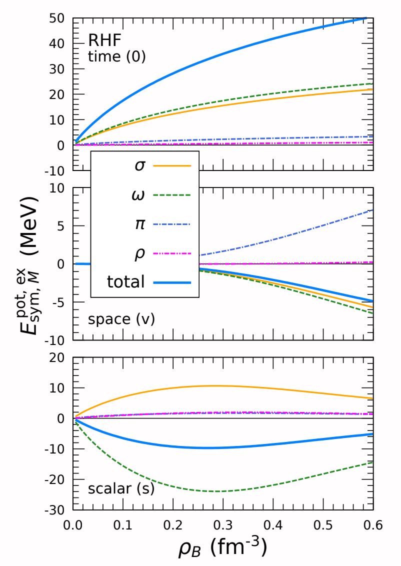
$$E_{\rm sym}^{\rm pot} = E_{\rm sym}^{\rm pot,dir} + E_{\rm sym}^{\rm pot,ex}$$

$$= \frac{1}{2}\frac{g_\rho^2}{m_\rho^2}\rho_B + \sum_{i=s,0,v}\left(\sum_{M=\sigma,\omega,\rho,\pi} E_{{\rm sym},M}^{\rm pot,ex}\right)^i$$

Not only ρ meson but also σ, ω, and π mesons influence $E_{\rm sym}^{\rm pot,ex}$.

The σ and ω mesons play a important role in $E_{\rm sym}^{\rm pot,ex}$.

The contributions due to ρ and π mesons are extremely small even at high densities.



Density dependence of slope parameter

$$L = L^{\rm kin} + L^{\rm pot}$$

with

$$L^{\rm kin} = \frac{1}{6}k_F \left[\frac{k_F^*}{E_F^*} + \frac{k_F}{E_F^*}\left(\frac{M_N^*}{E_F^*}\right)^2 + \frac{2k_F^2}{\pi^2}\frac{k_F}{E_F^*}\frac{M_N^*}{E_F^*}\left(\frac{M_N^*}{E_F^*}\frac{\partial \Sigma_N^v}{\partial \rho_B} - \frac{k_F^*}{E_F^*}\frac{\partial \Sigma_N^s}{\partial \rho_B}\right)\right],$$

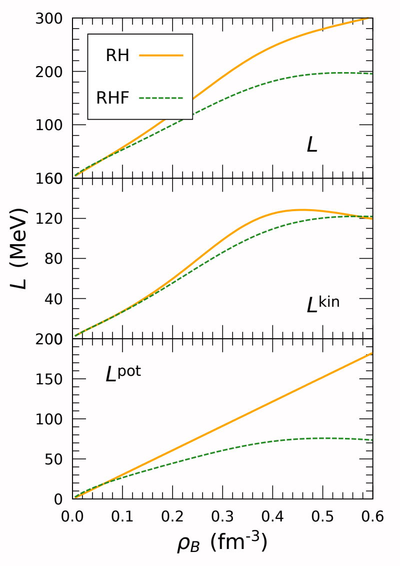
$$L^{\rm pot} = 3E_{\rm sym}^{\rm pot} + \frac{3}{8}\rho_B \frac{\partial}{\partial \rho_B}\left(\frac{M_N^*}{E_F^*}\partial\Sigma_{\rm sym}^s - \partial\Sigma_{\rm sym}^0 + \frac{k_F^*}{E_F^*}\partial\Sigma_{\rm sym}^v\right).$$

In RH approximation:

$$L^{\rm kin,dir} = \frac{1}{3}\frac{k_F^2}{\sqrt{k_F^2 + M_N^{*2}}}\left[1 - \frac{k_F^2}{2\left(k_F^2 + M_N^{*2}\right)}\left(1 + \frac{2M_N^* k_F}{\pi^2}\frac{\partial M_N^*}{\partial \rho_B}\right)\right],$$

$$L^{\rm pot,dir} = \frac{3}{2}\frac{g_\rho^2}{m_\rho^2}\rho_B.$$

The exchange contribution prevents the slope parameter from increasing monotonically at high densities.



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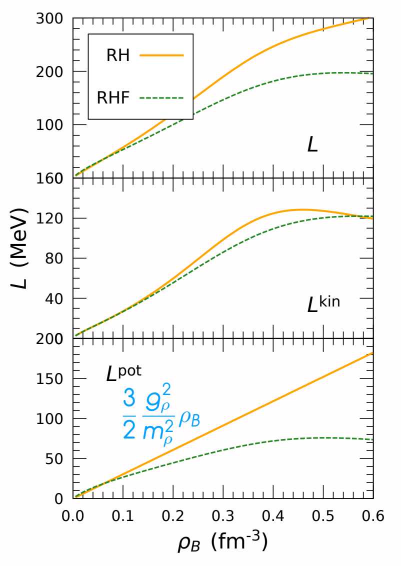

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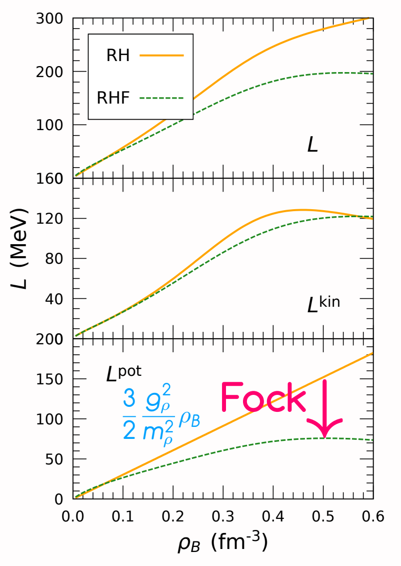

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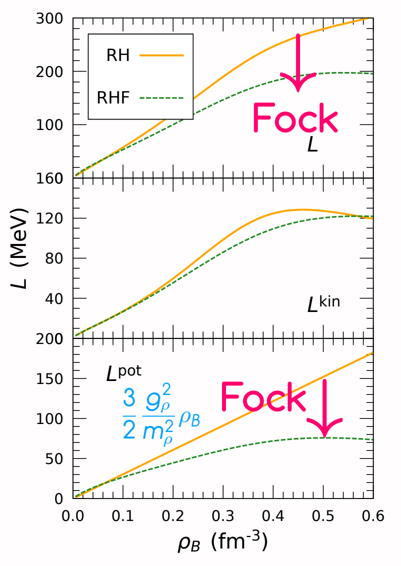

Summary

Motivation:

- Using the relativistic Hartree-Fock (RHF) approximation, we study the effect of the Fock terms on the nuclear properties not only around the saturation density but also at higher densities.

- In particular, by taking into account the Lorentz-covariant decomposition of the nucleon self-energy, we investigate how the momentum dependence due to the exchange contribution affects the nuclear symmetry energy, $E_{\rm sym}$, and its slope parameter, L.

Summary

Results:

- We find that the Fock contribution suppresses the nuclear symmetry energy, E_{sym}, at the densities around and above the saturation density.
- Not only the isovector-vector (ρ) meson but also the isoscalar-scalar (σ) and isoscalar-vector (ω) mesons and pion make significant influence on the potential term of E_{sym} through the exchange diagram.
- The exchange contribution prevents the slope parameter, L, from increasing monotonically at high densities.

Thank You for Your Attention.