Nuclear incompressibility within RHF approaches

Presented by:

Mohamad CHAMSEDDINE

In collaboration with:

Jérôme MARGUERON (PhD advisor)

Guy CHANFRAY (co-PhD advisor)

Hubert HANSEN

Rahul SOMASUNDARAM

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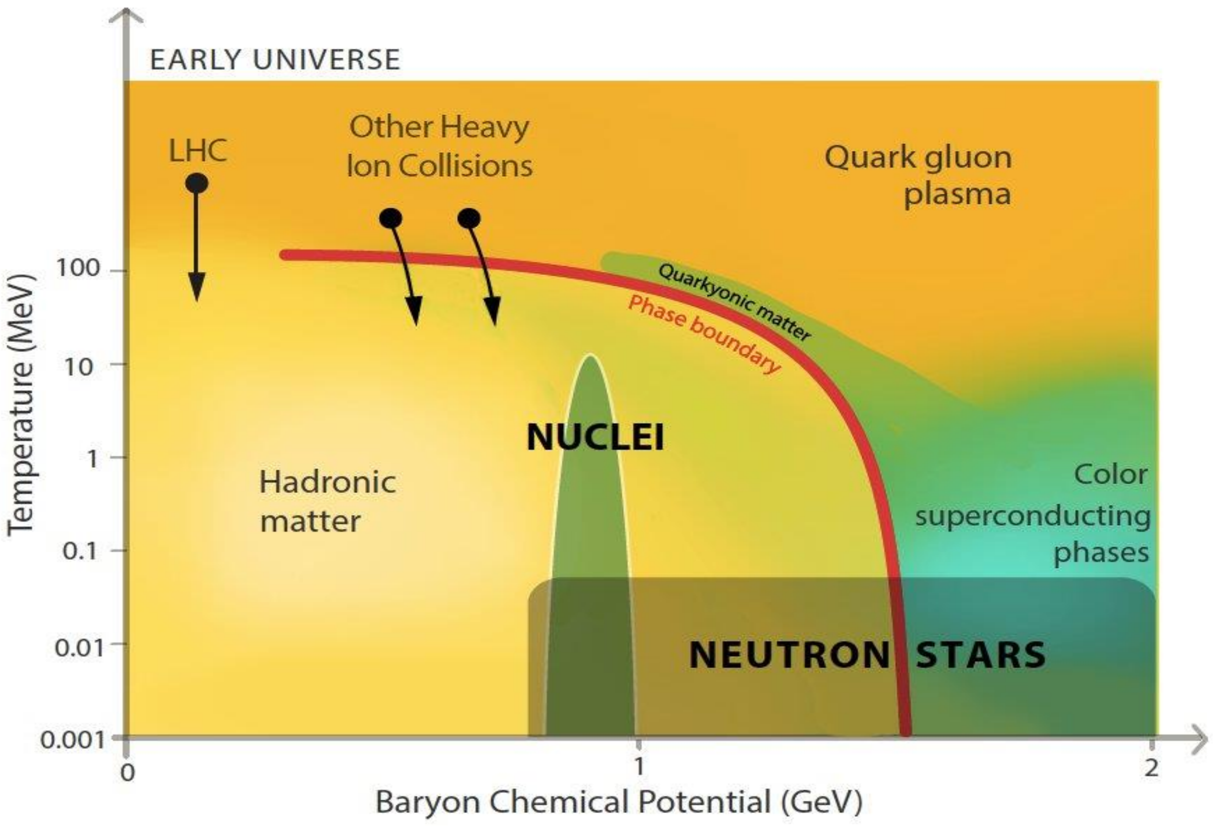
OUTLINE

- Motivation for Relativistic approaches
- RMF with Chiral symmetry and Confinement (RMF-CC)
- Consequences on incompressibility and symmetry energy
- Outlooks

Phase diagram of QCD

Watts et al. '16

- The state of matter at high densities remains a mystery (quark-gluon plasma, hyperons, color superconductivity, …)
- QCD is perturbative but at ~$40 n_{sat}$!!
- No theory applies in the regime of low-T and large densities.



Why Relativistic approaches ?

- Many models for nuclear matter exist, with chiral effective theory being one of them: a perturbative expansion with a hierarchy of leading orders
- Advantages : systematic addition of higher-order contributions, which allows us to know at which density our expansion should stop (χEFT ~ $2n_{sat}$)
- Disadvantages: breaks down at ~ $2n_{sat}$, whereas we need to describe nuclear matter at higher densities

- At high density, we need a relativistic approach since the sound speed in NS cores is expected to be larger than 10% of the light speed. See recent radio observations as well as X-ray observations from NICER of massive NSs.
- Advantages : can go beyond $2n_{sat}$.
- Disadvantages: no simple way to decide where the model breaks down, or to quantify the uncertainties.

What is RMF-CC?

- An effective model describing the nuclear interaction as an exchange of mesons.
- A lagrangian based on chiral symmetries from QCD and confinement of the quarks (anchored to QCD).
- The mesons field will be decomposed as such:

$$\varphi_R = \overline{\varphi_R} + \Delta\varphi_R$$

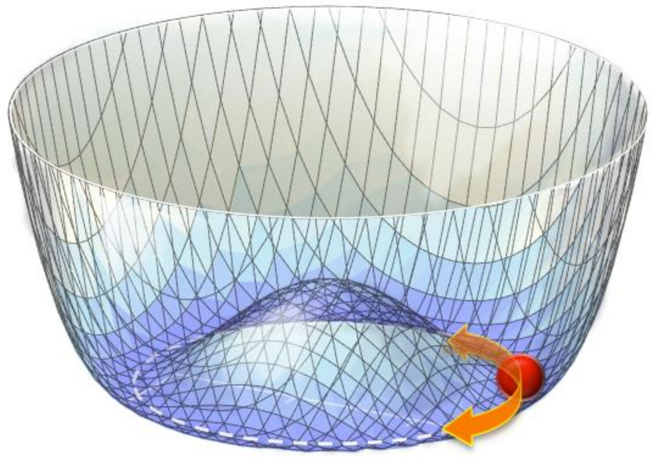
Ground state expectation value, i.e classical value➔ Hartree level

Small fluctuations➔ Fock level

1) Chiral symmetry

- At the limit of zero quark masses (u,d & s), QCD has a chiral symmetry (non-interacting quarks with opposite parity are indistinguishable and do not couple to each other)
- Had the symmetry been realised in nature, we would have observed for each meson, a partner meson with the SAME mass but opposite parity → the symmetry is broken

The radial component corresponds to the σ meson of Walecka, first identified by Chanfray (PRC 63 (2001)), and the phase component corresponds to the massless Goldstone boson, the pion



But since the quarks have a small mass, the symmetry is also explicitly broken and the pion acquires a small mass!

2) Confinement

- It is well established that in QCD, only colour neutral objects can be observed
- Since in our model, the nucleons are considered the "elementary particles", this effect should be taken into consideration
- In Guichon's work (*Guichon, Phys. Lett. B 200 (1988)),* the quarks wave functions get modified by the scalar field → the nucleon mass depends on the surrounding scalar field:
- We parametrize the nucleon mass as:

$$M_N(s) = M_N + g_S\, s + \frac{1}{2}\kappa_{NS}\left(s^2 + \frac{s^3}{3\, f_\pi}\right)$$

Nucleon polarisation

The response parameters, g_S, κ_{NS}, might be given by an underlying quark confining model (confinement mechanism)

The chiral Lagrangian

$$\mathcal{L} = \bar{\Psi} i\gamma^\mu \partial_\mu \Psi + \mathcal{L}_s + \mathcal{L}_\omega + \mathcal{L}_\rho + \mathcal{L}_\delta + \mathcal{L}_\pi$$

Meson	(J^Π, T)	Field	interaction
σ	$(0^+, 0)$	scalar-isoscalar	middlerange attraction
ω	$(1^-, 0)$	vector-isoscalar	shortrange repulsion
ρ	$(1^-, 1)$	vector-isovector	isospin part of nuclear force
δ	$(0^+, 1)$	scalar-isovector	isospin part of nuclear force

$$\mathcal{L}_s = -M_N(s)\Psi\Psi - V(s) + \frac{1}{2}\partial^\mu s \partial_\mu s$$

$$\mathcal{L}_\omega = -g_\omega \omega_\mu \bar{\Psi}\gamma^\mu \Psi + \frac{1}{2} m_\omega^2 \omega^\mu \omega_\mu - \frac{1}{4} F^{\mu v} F_{\mu v}$$

$$\mathcal{L}_\rho = -g_\rho \rho_{a\mu} \bar{\Psi}\gamma^\mu \tau_a \Psi - g_\rho \frac{\kappa_\rho}{2M_N} \partial_v \rho_{a\mu} \Psi \bar{\sigma}^{\mu v} \tau_a \Psi$$
$$+ \frac{1}{2} m_\rho^2 \rho_{a\mu} \rho_a^\mu - \frac{1}{4} G_a^{\mu v} G_{a\mu v}$$

$$\mathcal{L}_\delta = -g_\delta \delta_a \bar{\Psi} \tau_a \Psi - \frac{1}{2} m_\delta^2 \delta^2 + \frac{1}{2}\partial^\mu \delta \partial_\mu \delta$$

$$\mathcal{L}_\pi = \frac{g_A}{2f_\pi} \partial_\mu \varphi_{a\pi} \Psi \gamma^\mu \gamma^5 \tau_a \Psi - \frac{1}{2} m_\pi^2 \varphi_{a\pi}^2 + \frac{1}{2}\partial^\mu \varphi_{a\pi} \partial_\mu \varphi_{a\pi}.$$

with: V(s) a typical “Mexican hat” potential from the linear sigma model

- 4 unknown parameters: m_s, g_s, g_w & C

- C and m_s can be fixed by lattice QCD *(see Somasundaram +, Eur.Phys.J.A 58 (2022) 5, 84)* leaving us with $g_s\ et\ g_w$ to be fitted to nuclear saturation properties($E_{sat} = -15.8\ MeV$, $n_{sat} = 0.155\ fm^{-3}$)

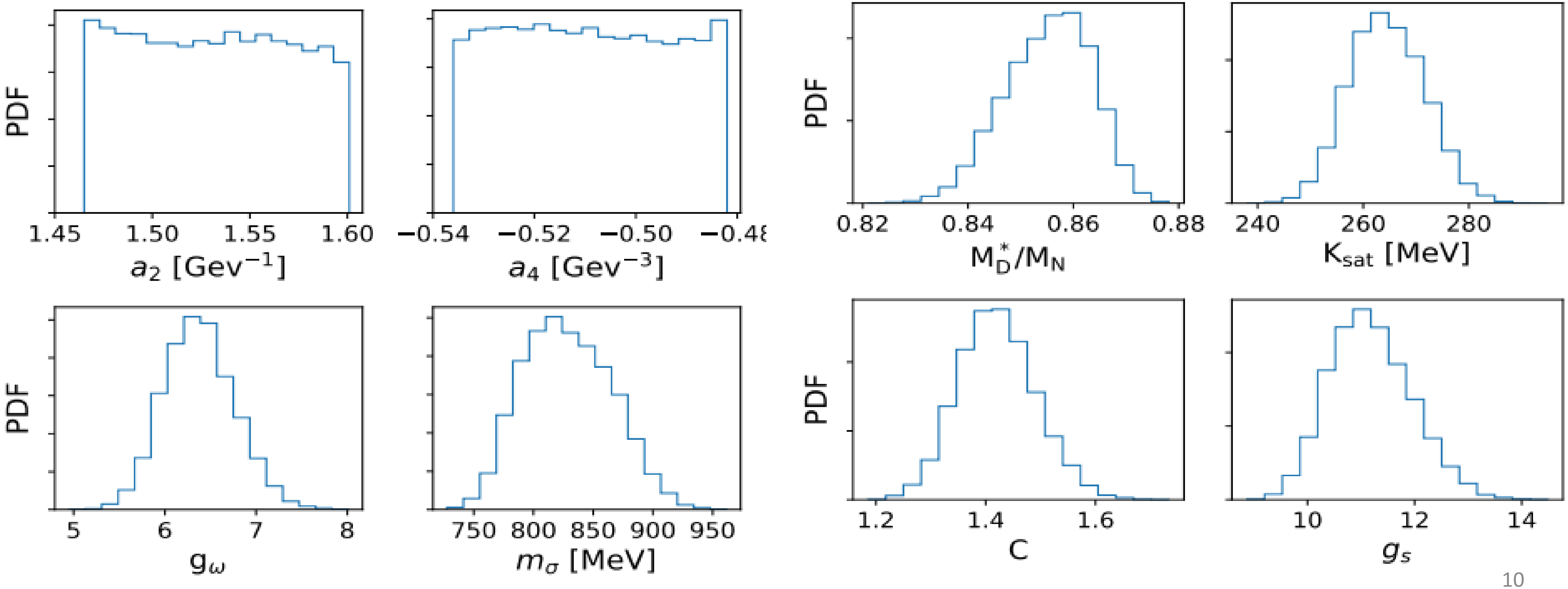
$$a_2 = \frac{g_s f_\pi}{m_\sigma^2};\qquad\qquad a_4 = -\frac{f_\pi g_s}{2m_\sigma^4}\left(3 - 2C\frac{M_N}{f_\pi g_s}\right)$$

- κ_ρ is not well-known: The pure vector dominance model (VDM) implies the identification of κ_ρ with the anomalous part of the isovector magnetic moment of the nucleon (i.e., κ_ρ = 3.7, weak ρ scenario). However, pion-nucleon scattering data suggest κ_ρ = 6.6 (strong ρ scenario*) (G. Hohler and E. Pietarinen, Nucl. Phys. B95, 210 (1975)). We also consider the case where* κ_ρ = 0.0 for reference.

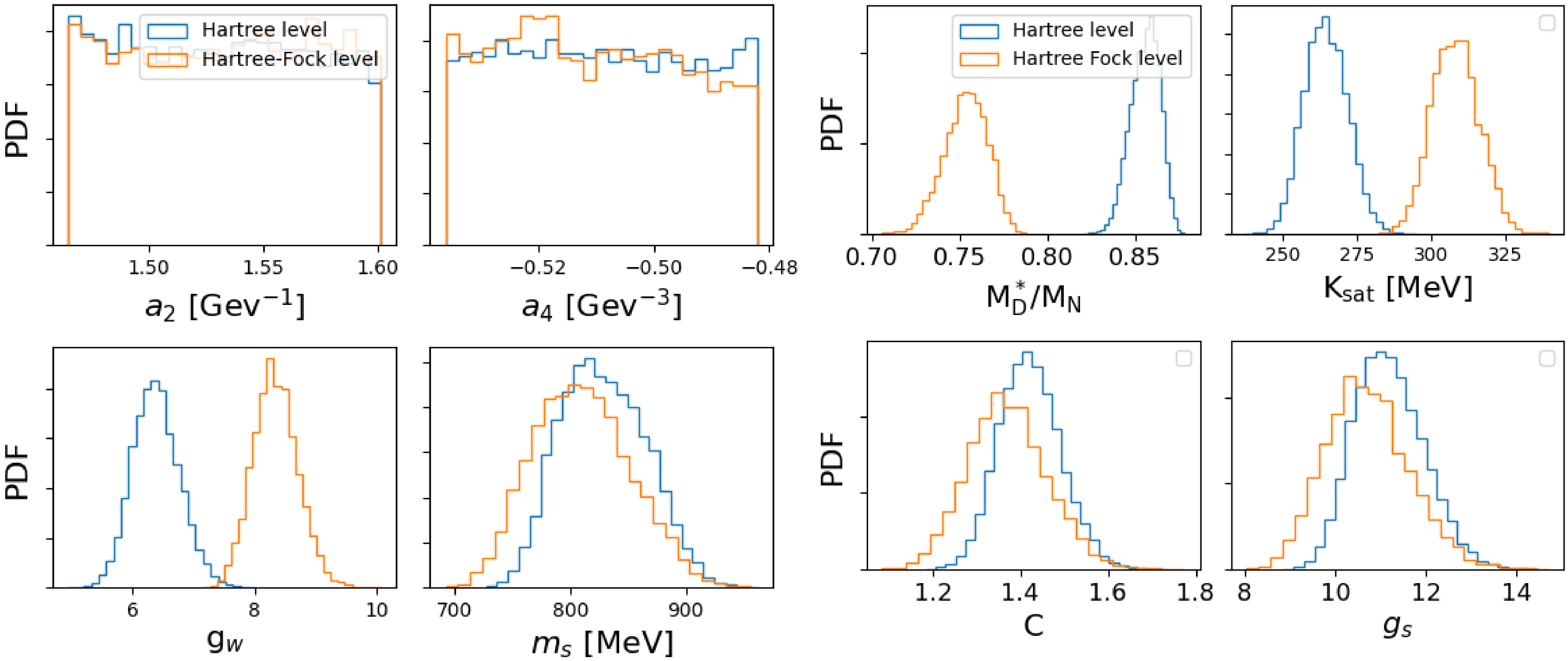
Results

1) Hartree level (no pion)

(Somasundaram +, Eur.Phys.J.A 58 (2022) 5, 84)

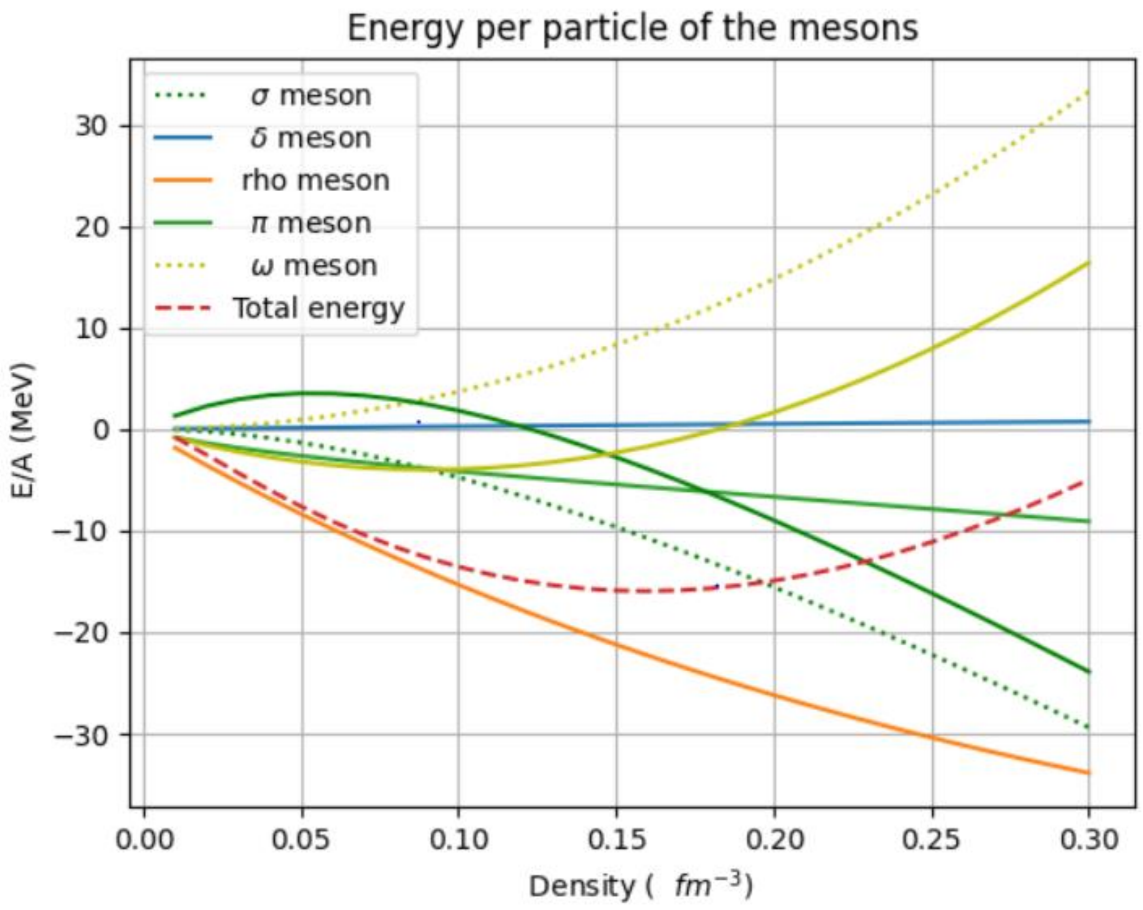


2) Hartree-Fock level (preliminary results including pions)

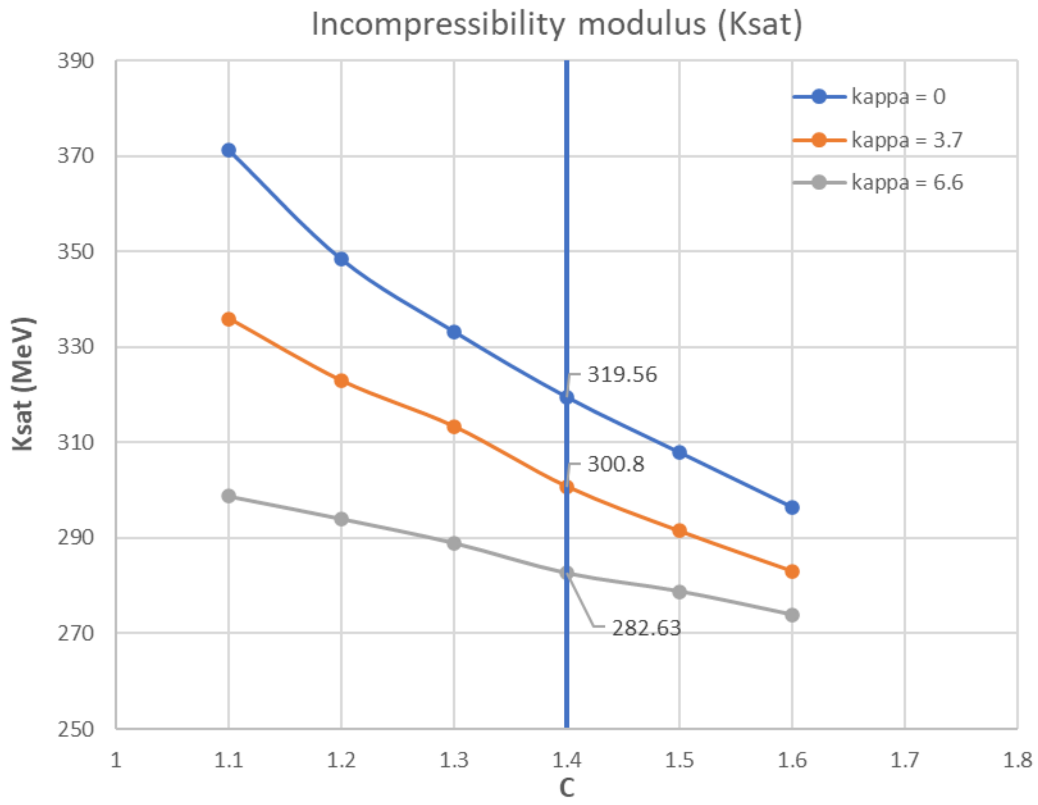


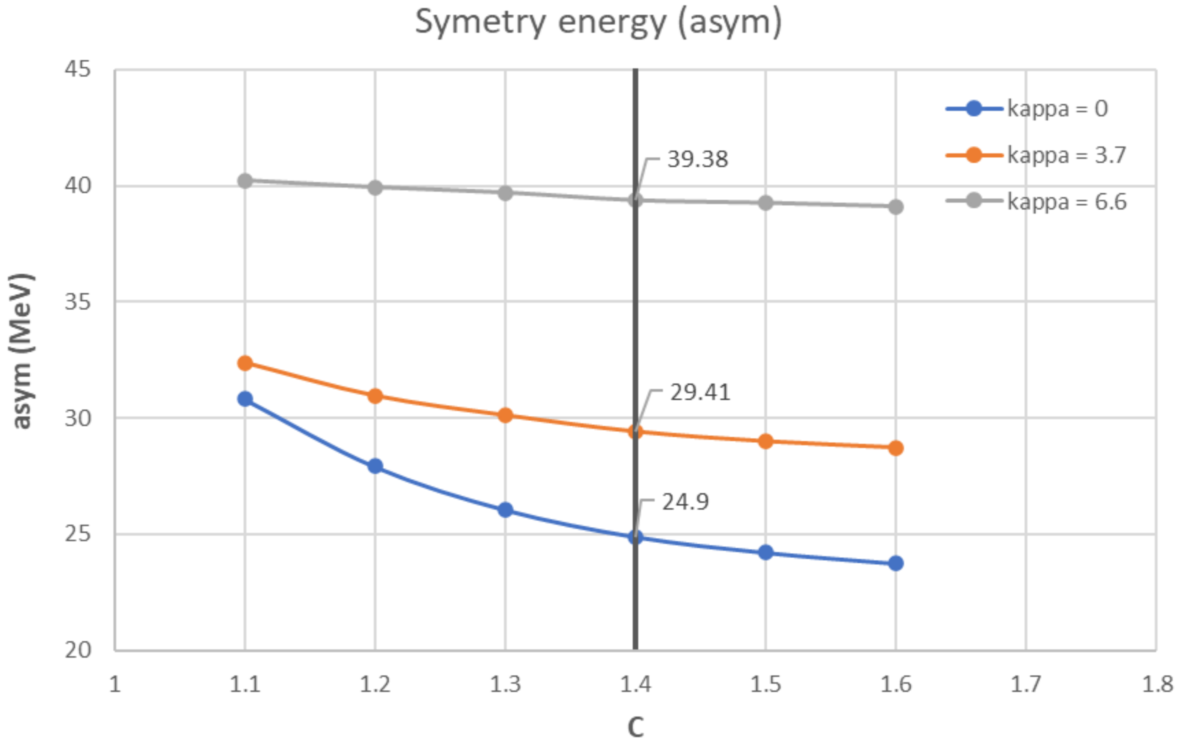
Hartree versus Hartree-Fock

κ_ρ = 3.7	Hartree level	Hartree Fock	Experimental value
C	1.4	1.37	
g_s	11	10.7	
g_w	6.5	8.34	
E_{sat}	-15.8	-15.8	-15.8 $\pm$0.3
n_{sat}	0.155	0.155	0.155 $\pm$ 0.005
E_{sym}	19	29.86	32$\pm$2
K_{sat}	265	308	240$\pm$10



Impact of κ_ρ on incompressibility and symmetry energy





Outlooks

Conclusions:

- HF improves the results from Hartree only: the value for a_{sym} is in better agreement with experimental data, but K_{sat} is pushed to values too high.

Outlooks:

- The inclusion of higher order correction in the pion channel, also known as the « pion cloud » which could decrease K_{sat} closer to its experimental value and also lower the value of the coupling constants which is also a desired effect in models

- Checking the effect of incorporating short range correlations (Jastrow functions, form factors)