Dense matter within RHF approaches

Presented by:
Mohamad CHAMSEDDINE

In collaboration with:
Jérôme MARGUERON, IP2I Lyon (PhD advisor)
Guy CHANFRAY, IP2I Lyon (co-PhD advisor)
Hubert HANSEN, IP2I Lyon
Rahul SOMASUNDARAM, LANL USA

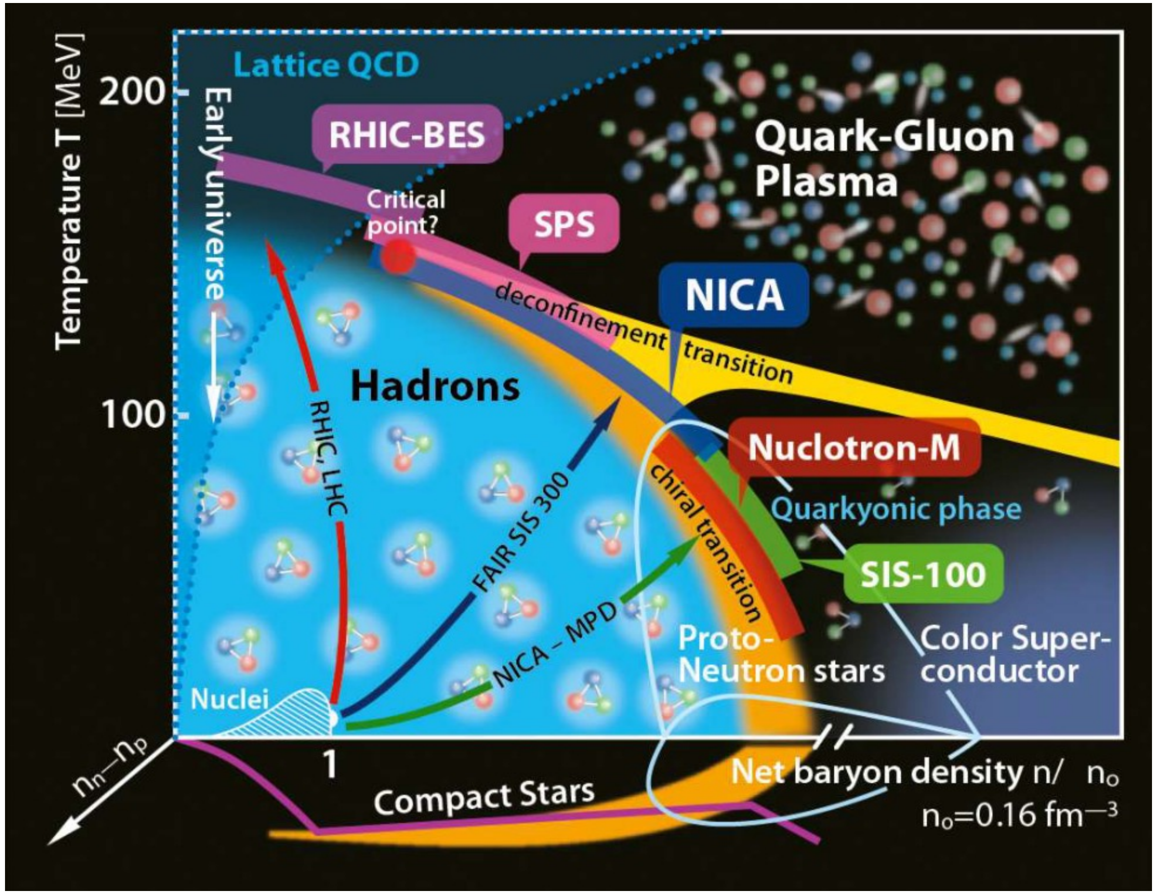
OUTLINE

- Why dense matter?
- Why RMF?
- RMF with Chiral symmetry and Confinement (RMF-CC)
- Results
- Conclusions and outlooks

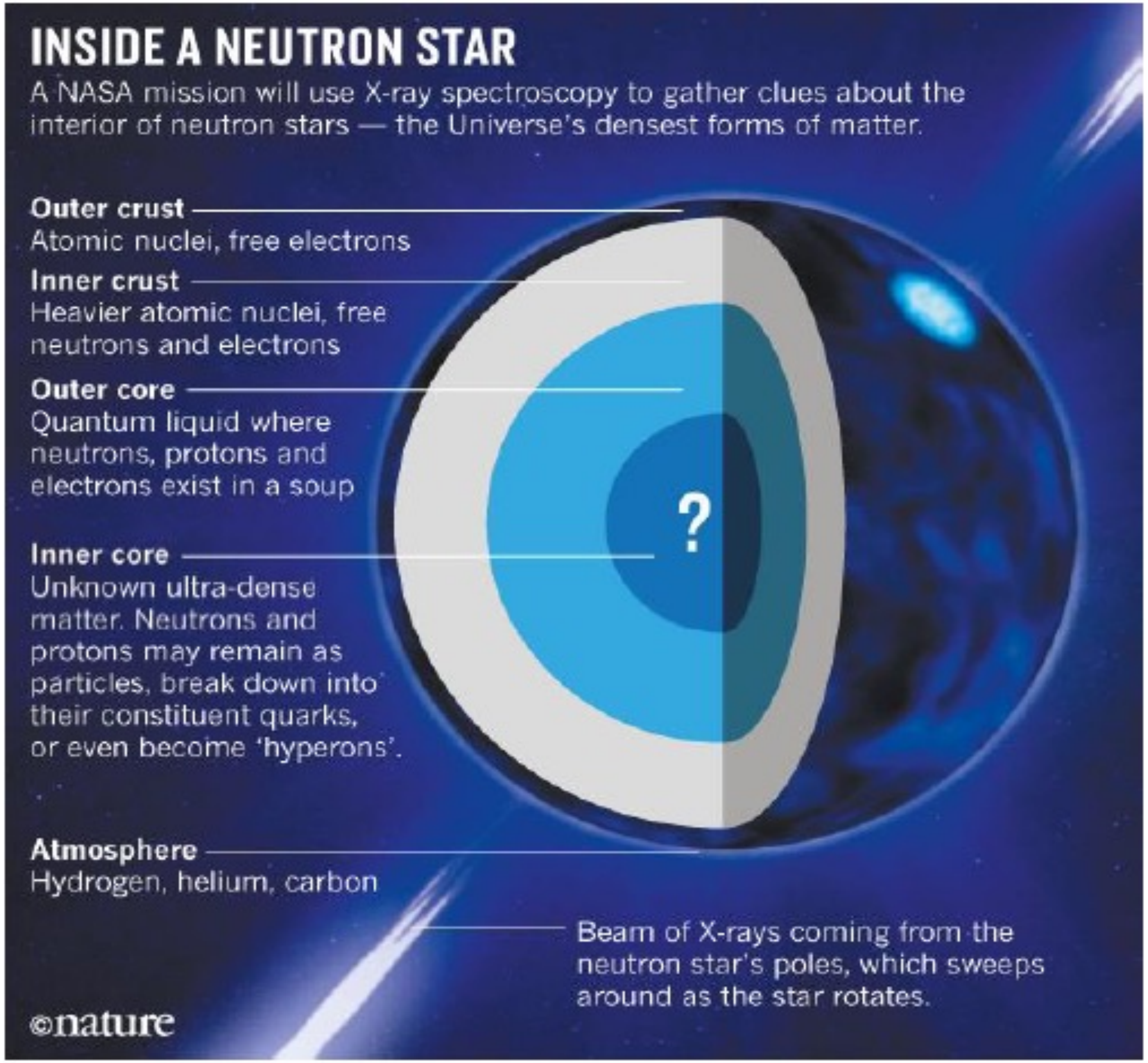
Why dense matter?

Phase diagram of QCD

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



Adam Mann, 2020



INSIDE A NEUTRON STAR

A NASA mission will use X-ray spectroscopy to gather clues about the interior of neutron stars — the Universe's densest forms of matter.

Outer crust
Atomic nuclei, free electrons

Inner crust
Heavier atomic nuclei, free neutrons and electrons

Outer core
Quantum liquid where neutrons, protons and electrons exist in a soup

Inner core
Unknown ultra-dense matter. Neutrons and protons may remain as particles, break down into their constituent quarks, or even become 'hyperons'.

Atmosphere
Hydrogen, helium, carbon

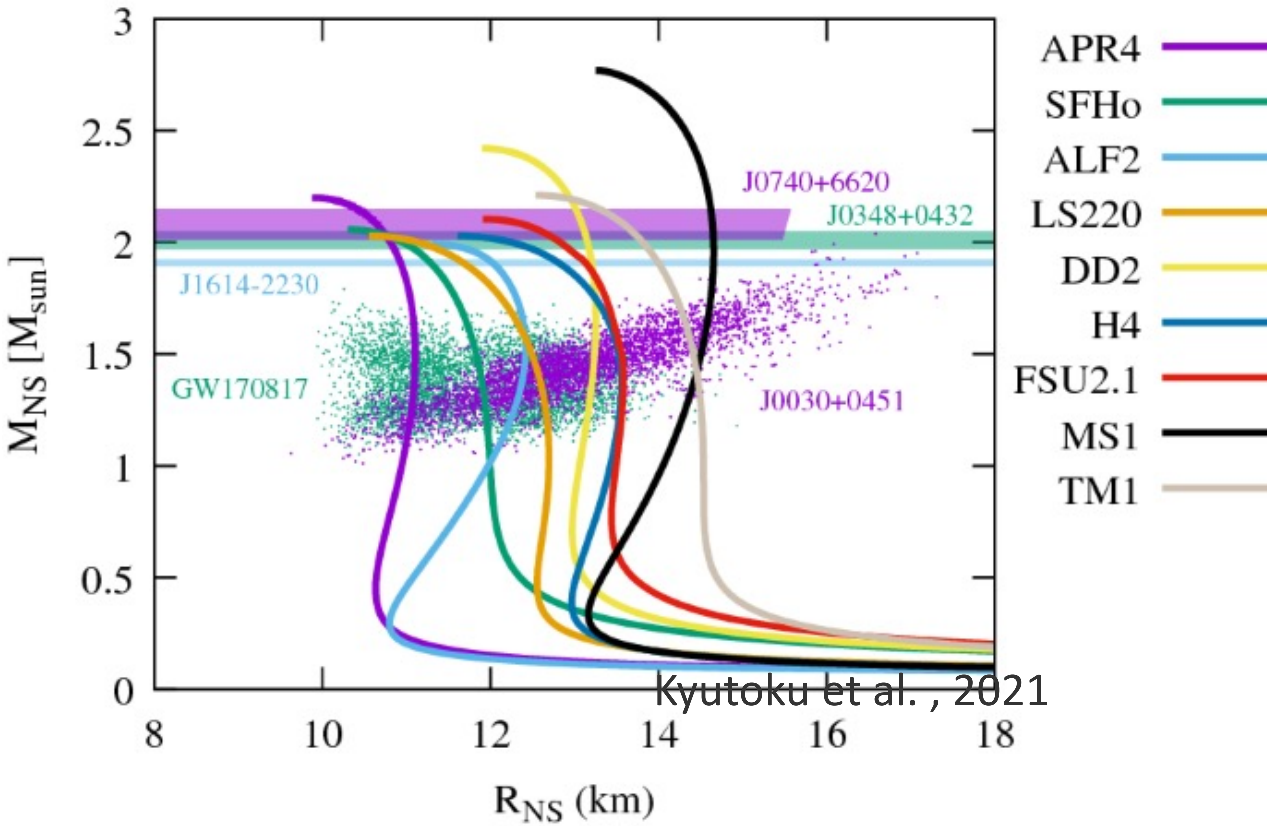
Beam of X-rays coming from the neutron star's poles, which sweeps around as the star rotates.

Neutron stars

- The remnant of massive dead stars
- Densest matter in the universe: 6-8 times saturation density !
- Excellent laboratory to study dense matter
- Their core remains a mystery

NS observables

- We solve the hydrostatic equations in GR for spherical and nonrotating stars (TOV equations).
- The family of solutions with unique mass M and radii R are generated by varying the central density ρc, BUT THIS REQUIRES AN EQUATION OF STATE !
- We can extract tidal deformabilities from gravitational waves (LIGO/VIRGO) or compactness from X-ray measurements (e.g NICER)



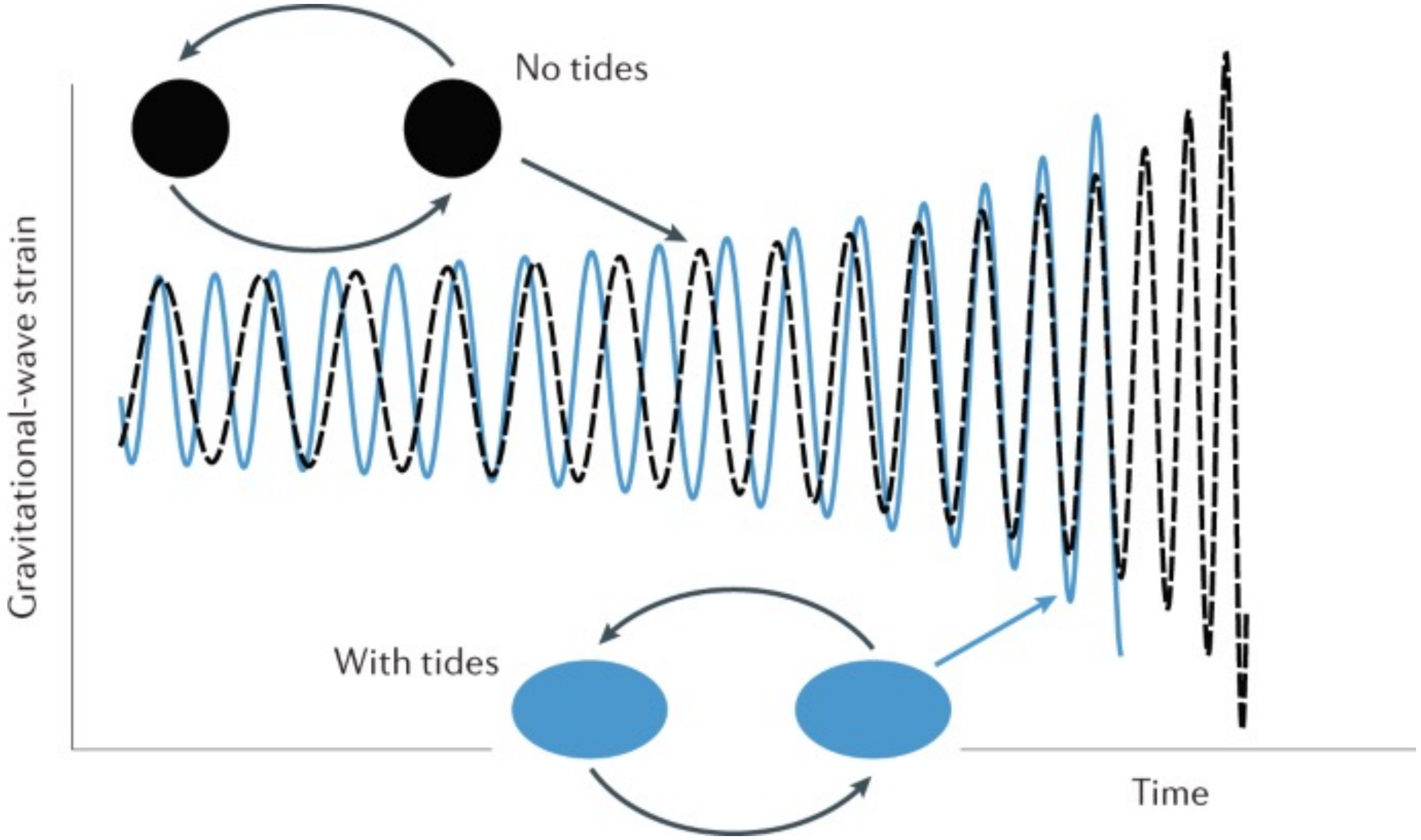
Kyutoku et al. , 2021

Tidal deformability

$$\Lambda \equiv \frac{\lambda}{m^5} = \frac{2}{3} k_2 \frac{R^5}{m^5} = \frac{2}{3} k_2 C^{-5}$$

With k_2 the gravitational Love number and C the compactness.

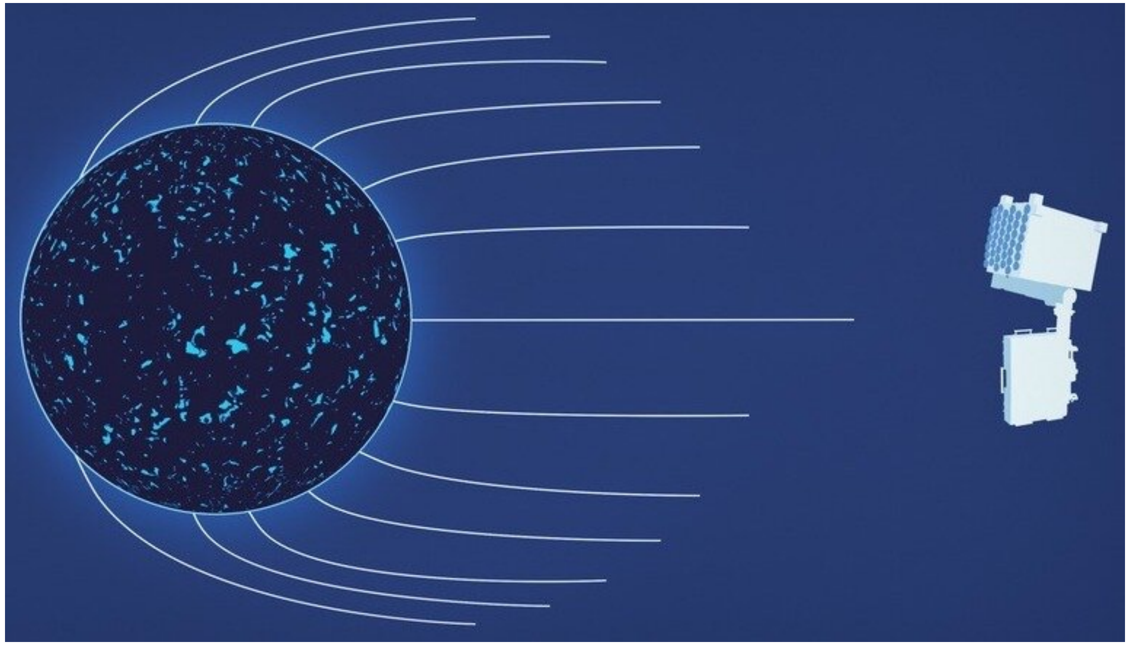
It quantifies how easily the star is deformed when subject to an external tidal field. It shows up as a "dephasing" of the wavefront of the GW signal.

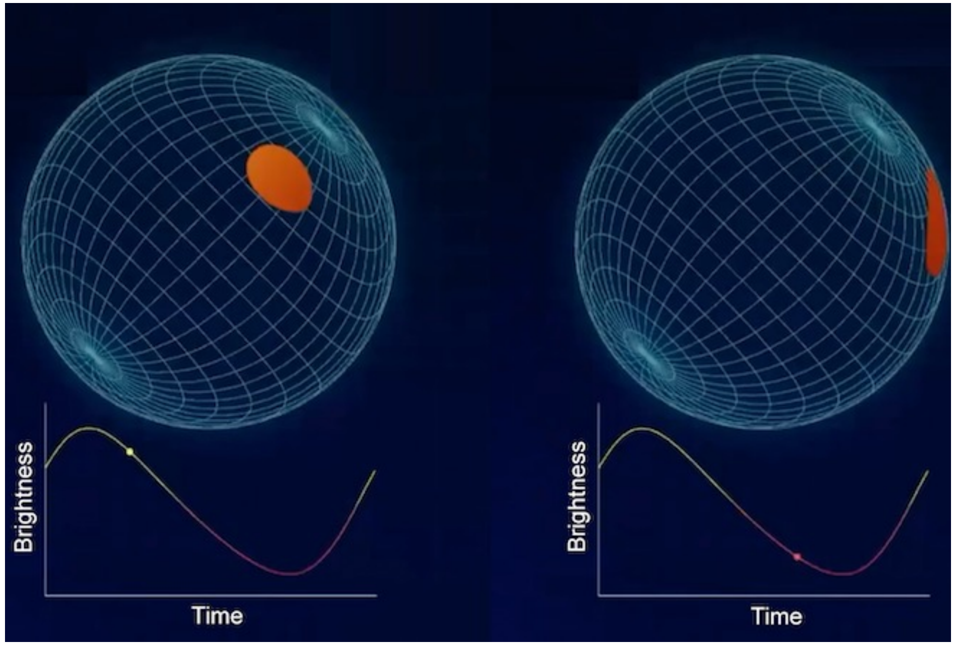


Yunes et al. , 2022

NICER

- Installed on the ISS in 2017
- Can detect X-ray emissions from NS





Jorge Piekarewicz, 2022

Why RMF?

Why relativistic mean field models ?

- 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, as revealed by analyses of recent radio 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.

RMF with Chiral symmetry and Confinement (RMF-CC)

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 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

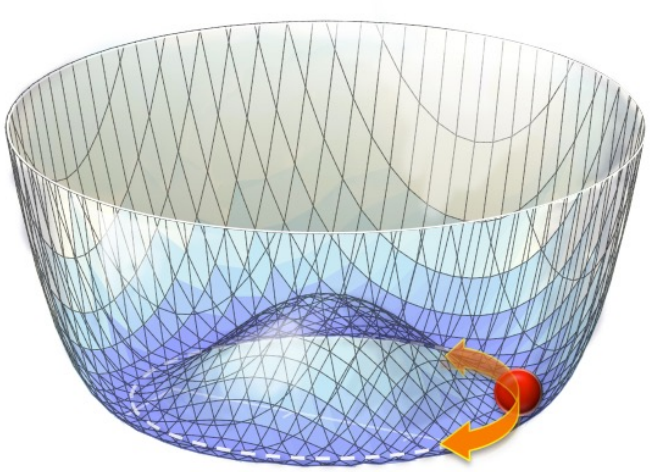
What is RMF-CC?

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!



What is RMF-CC?

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:

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

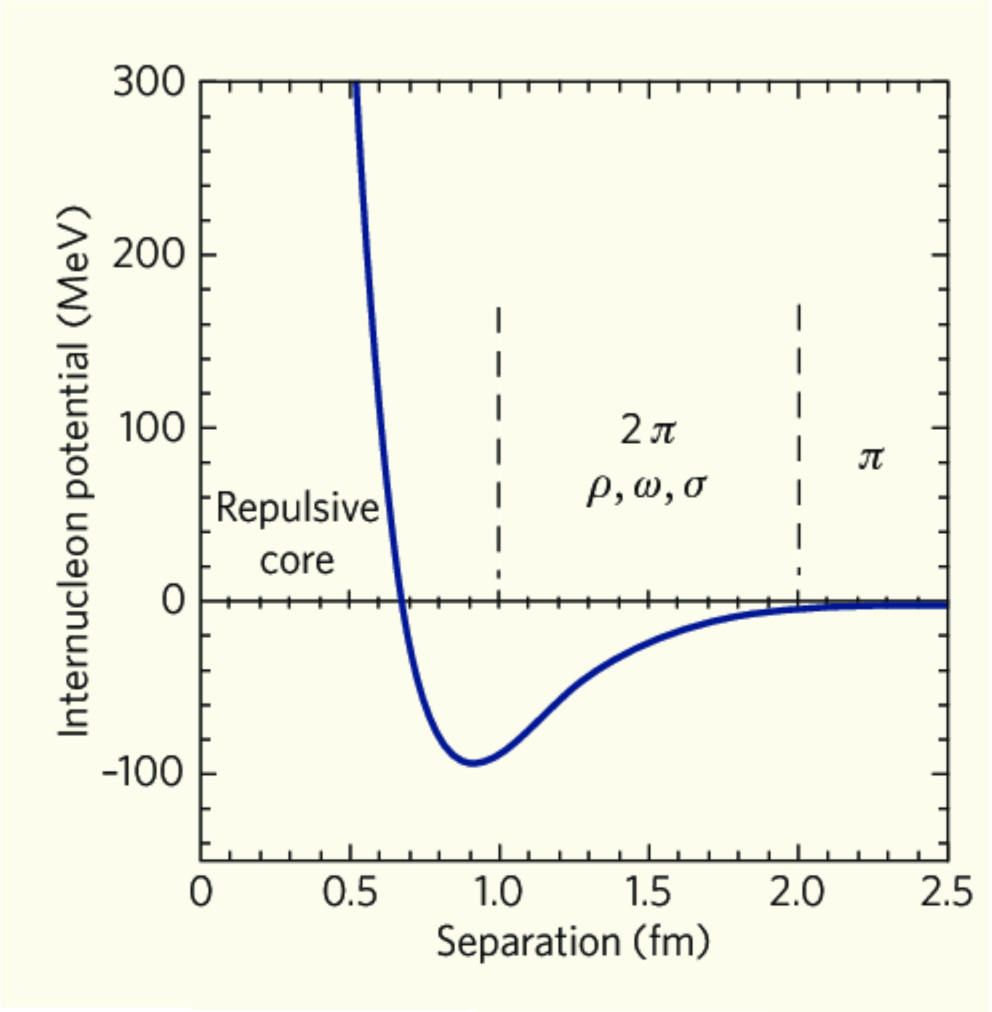
Nucleon polarisation

The response parameters, g_S, κ_{NS}, might be given by an underlying quark confining model like NJL (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



The chiral Lagrangian

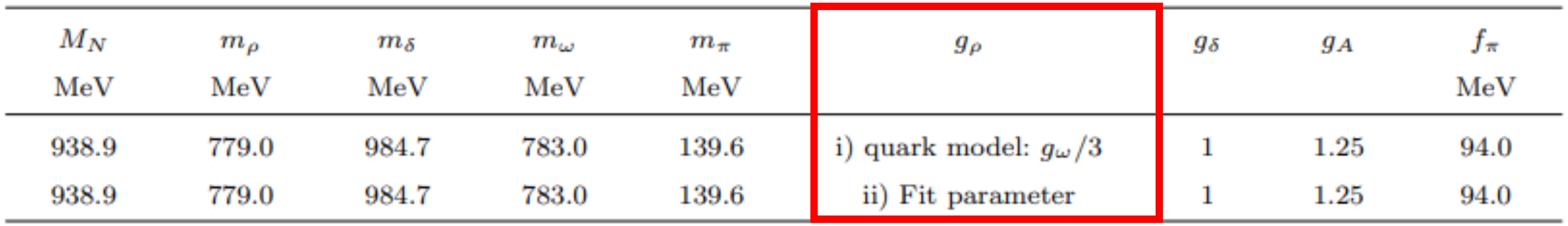
- 4 uknown parameters : m_s, g_s, g_w & C
  They can be fixed by :
  - Lattice QCD *(see Somasundaram +, Eur.Phys.J.A 58 (2022) 5, 84)*

$$M_N\left(m_\pi^2\right) = a_0 + a_2\, m_\pi^2 + a_4\, m_\pi^4 + \Sigma_\pi(m_\pi, \Lambda).$$

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

  - Nuclear saturation properties ($E_{sat} = -15.8\ MeV, n_{sat} = 0.155\ fm^{-3}$)

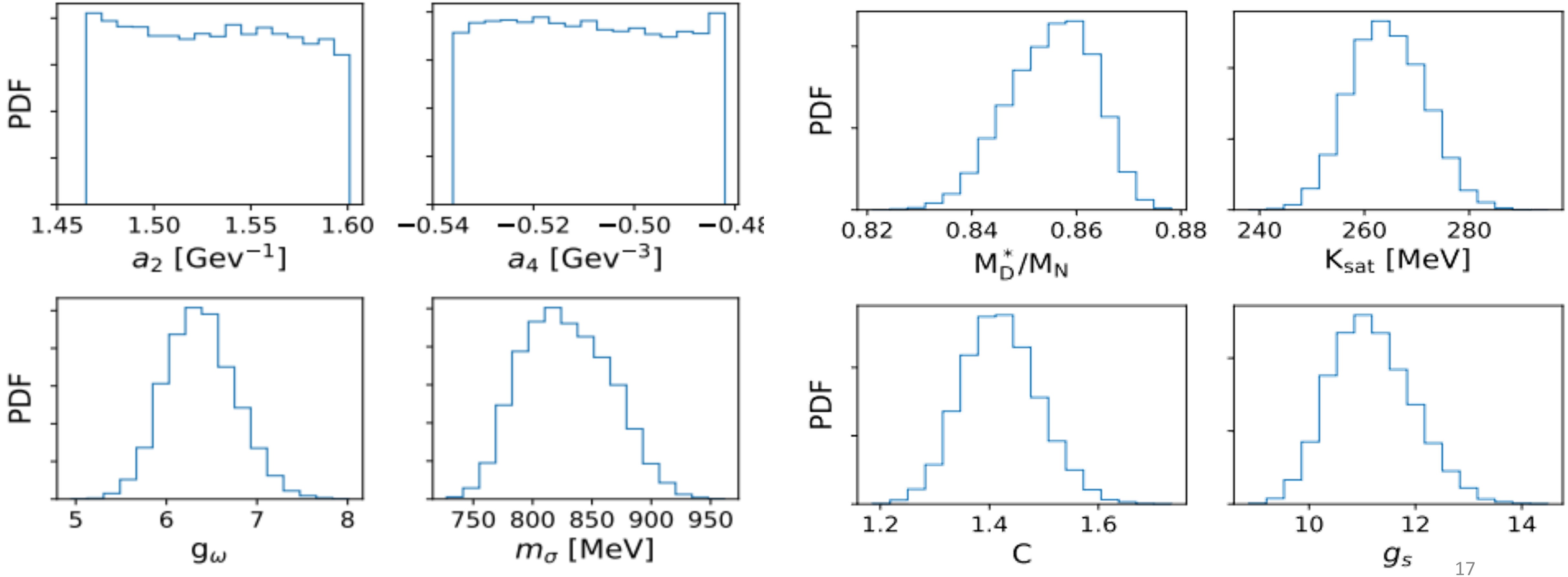
- κ_ρ is not well-known : the pure vector dominance model (VDM) implies the identification of κ_ρ with the anomalous part of the isovector magnetic moment of the nucleon ($\kappa_\rho = 3.7$, weak ρ scenario). However, pion-nucleon scattering data suggest $\kappa_\rho = 6.6$ (strong ρ scenario) (*G. Hohler and E.Pietarinen, Nucl. Phys. B95, 210 (1975)).*



M_N MeV	m_ρ MeV	m_δ MeV	m_ω MeV	m_π MeV	g_ρ	g_δ	g_A	f_π MeV
938.9	779.0	984.7	783.0	139.6	i) quark model: $g_\omega/3$	1	1.25	94.0
938.9	779.0	984.7	783.0	139.6	ii) Fit parameter	1	1.25	94.0

A first attempt: Hartree level (no pion)

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



Short-Range-Correlations (SRC)

- The model being an effective one, doesn’t have a good resolution at short ranges ($q \sim M_N$), where we expect it to start to break
- Short range effects should be treated by hand, but maintaining as much as possible a connection with underlying microscopic descriptions
- We use form factors (FF) for nucleon finite size, and the Jastrow function approach for SRC: the mesons’ propagators are convoluted with a correlation function forbidding the presence of 2 nucleons at the same point

Short-Range-Correlations (SRC)

- They can be mainly seen for the pion and tensor ρ channels
- The pion term and rho tensor have a derivative coupling which induces a UV divergence:

$$V(q) = \frac{q^2}{q^2+m^2} = \underset{\swarrow\ \text{Contact term} \rightarrow \text{ should be suppressed by SRC}}{1} - \underbrace{\frac{m^2}{q^2+m^2}}_{\text{Normal Yukawa potential(attractive)}}$$

Treatment of the contact term

$$V_A = 1 - \frac{m^2}{q^2 + m^2}$$

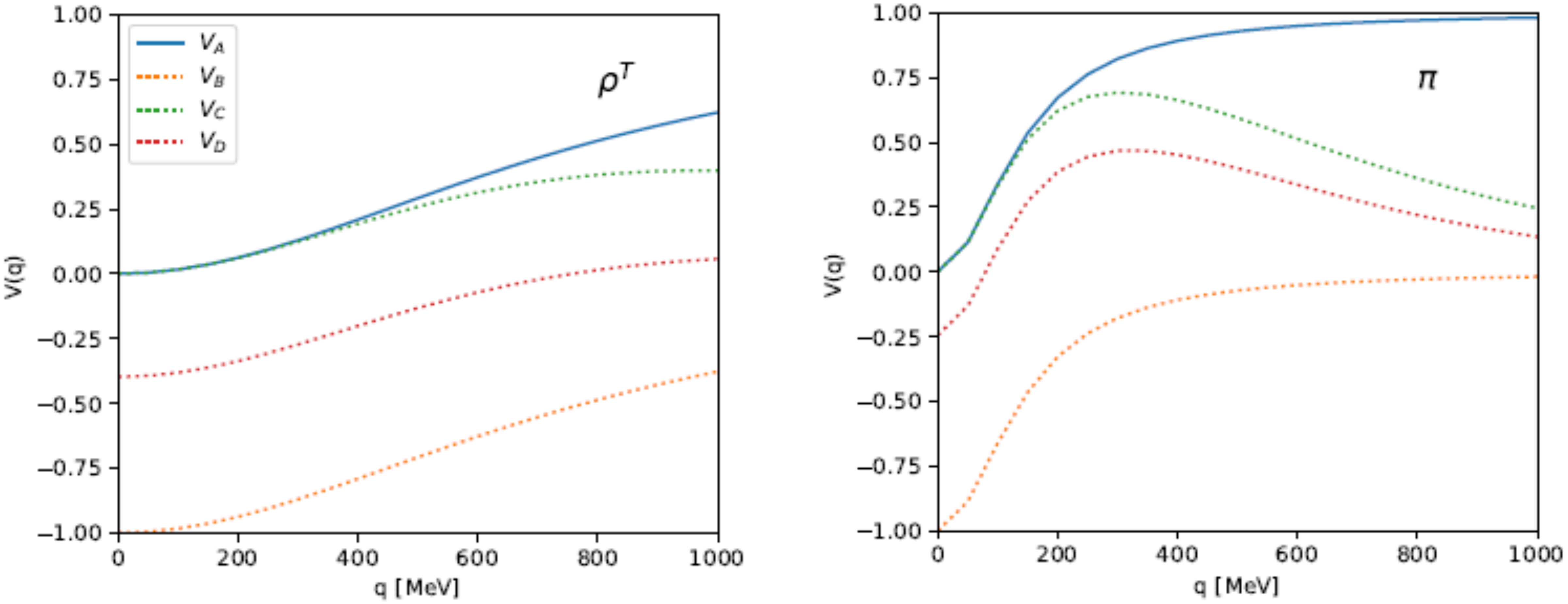
can be treated in different ways:

a) Orsay prescription: just substract the contact term

$$V_A \to V_B = -\frac{m^2}{q^2 + m^2}$$

b) Form factors: $V_A \to V_C = V_A F^2(q) = V_A(q) \left(\frac{\Lambda^2}{\Lambda^2 + q^2}\right)^2$ where Λ is some cut-off

c) FF + Jastrow ansatz: $V_A \to V_D = V_C(q) - V_C(q^2 \to q^2 + q_c^2)$
with q_c a parameter controlling the shape of the correlation function

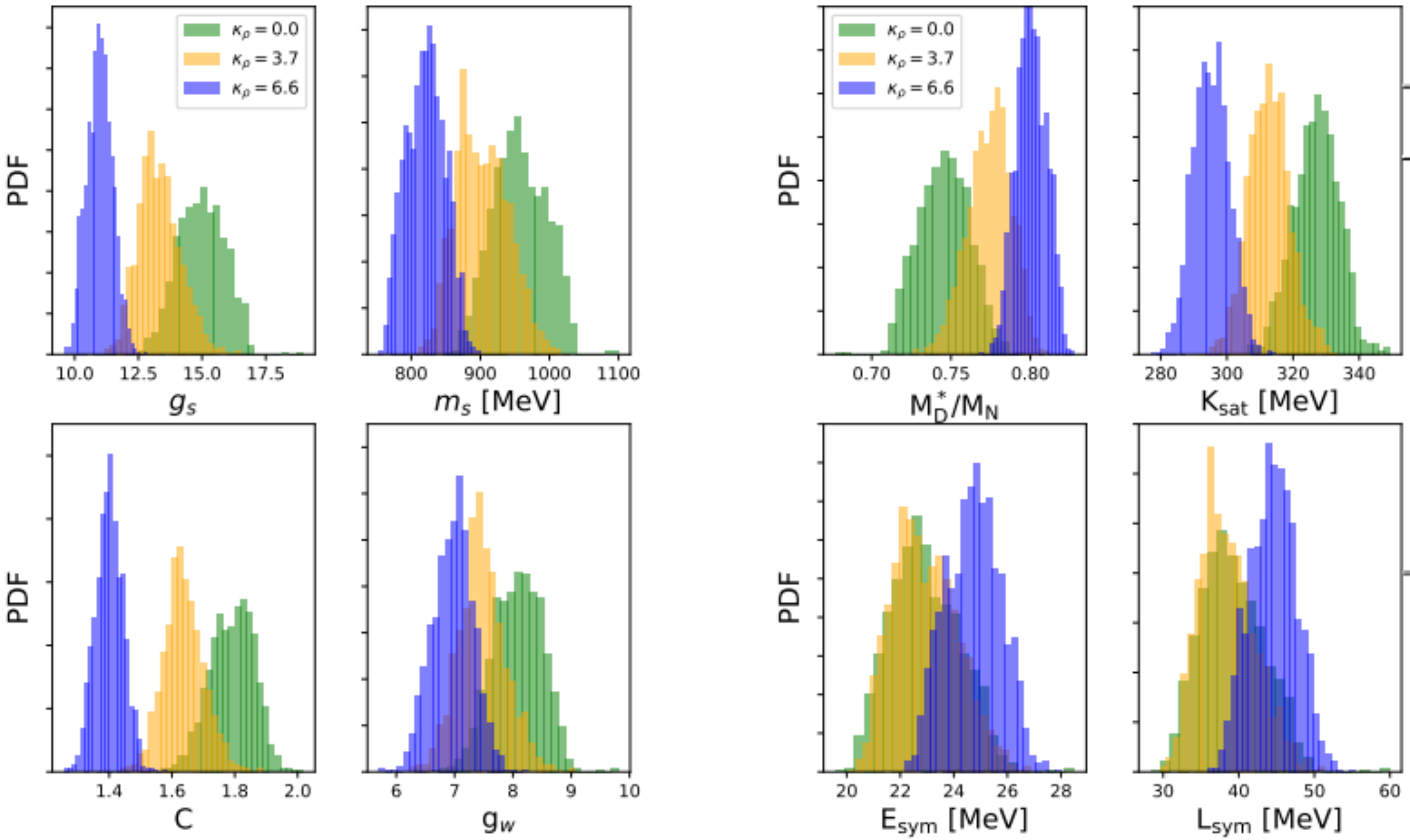


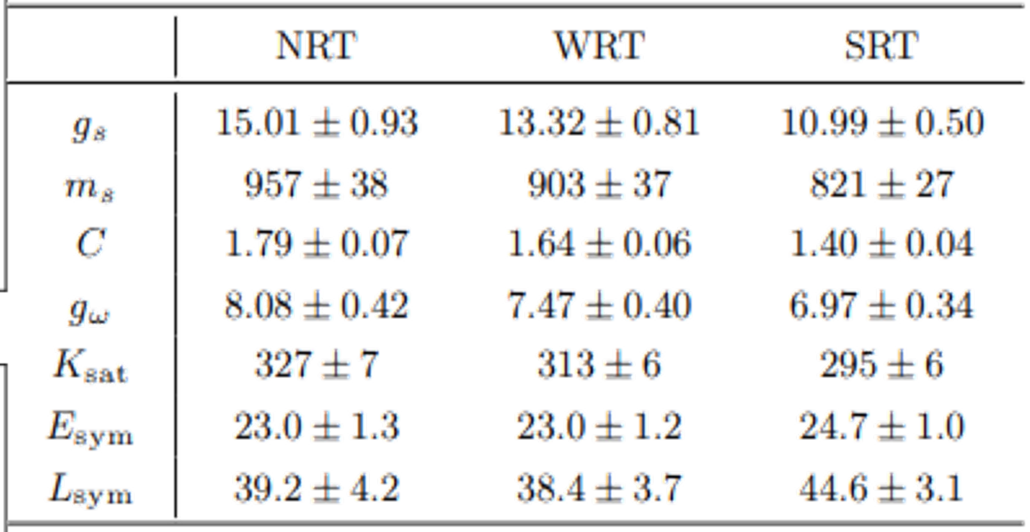
M. Chamseddine, et al., arXiv:2304.01817

Results

Hartree-Fock with FF+SRC

*M. Chamseddine, et al., arXiv:*2304.01817

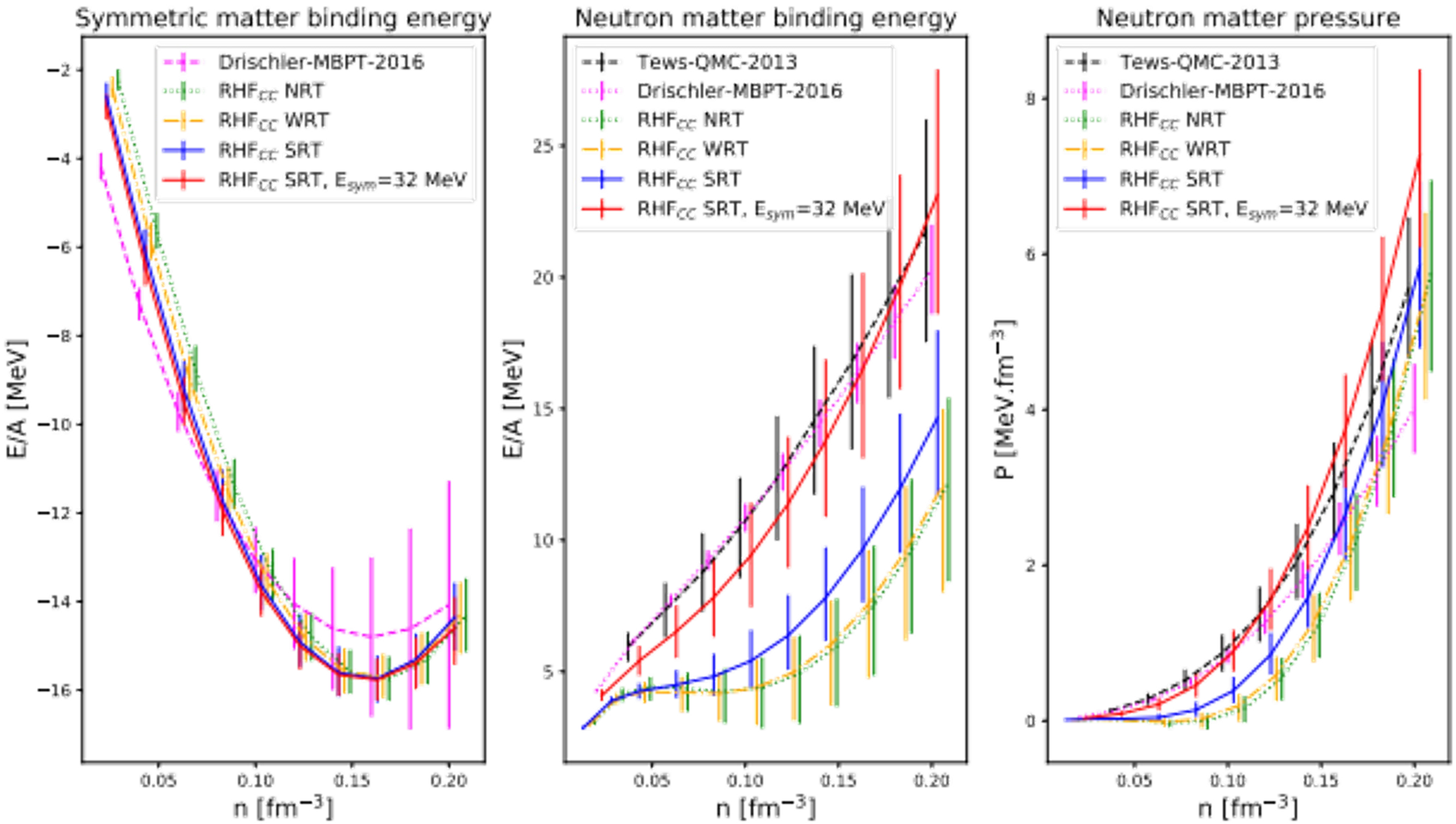




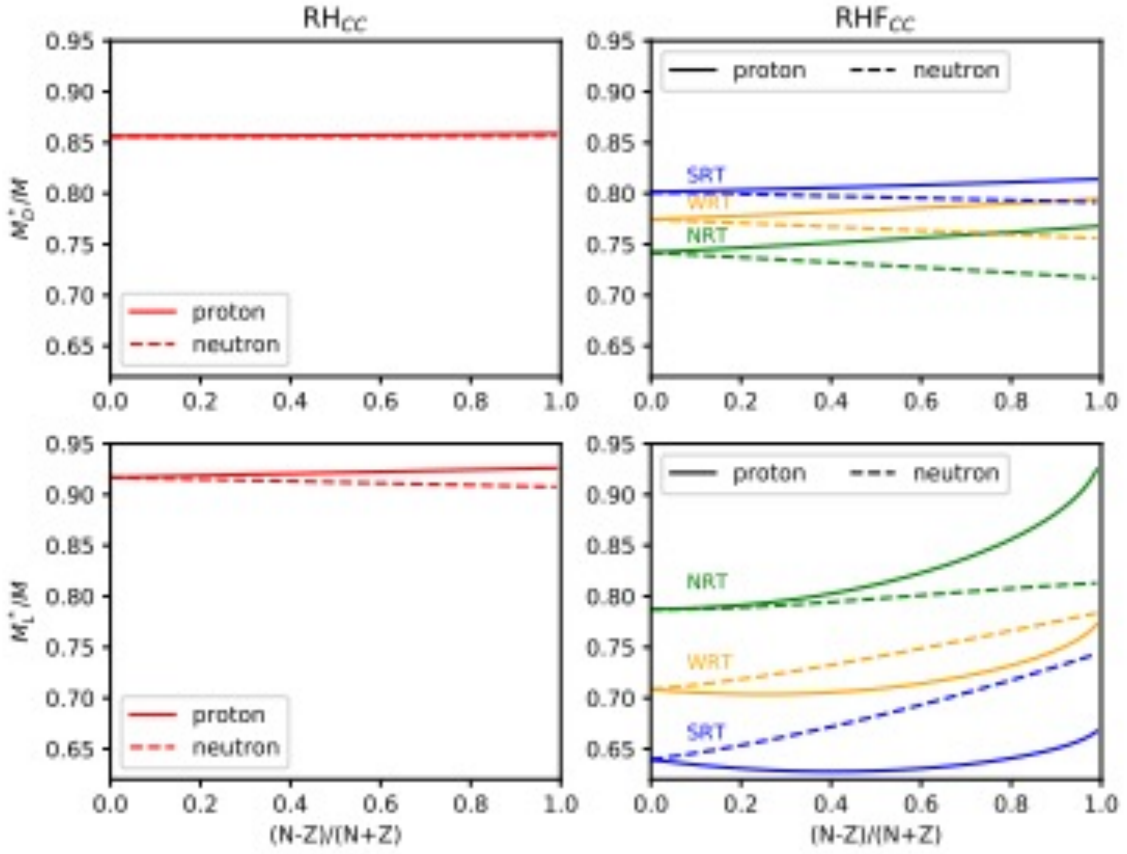
	NRT	WRT	SRT
g_s	15.01 ± 0.93	13.32 ± 0.81	10.99 ± 0.50
m_s	957 ± 38	903 ± 37	821 ± 27
C	1.79 ± 0.07	1.64 ± 0.06	1.40 ± 0.04
g_ω	8.08 ± 0.42	7.47 ± 0.40	6.97 ± 0.34
$K_{\rm sat}$	327 ± 7	313 ± 6	295 ± 6
$E_{\rm sym}$	23.0 ± 1.3	23.0 ± 1.2	24.7 ± 1.0
$L_{\rm sym}$	39.2 ± 4.2	38.4 ± 3.7	44.6 ± 3.1

Low density EoS

*M. Chamseddine, et al., arXiv:*2304.01817



Dirac vs Landau Mass



$$(\boldsymbol{\gamma}\cdot\mathbf{k}^* + M_D^*)\psi = \gamma_0 E^*\psi$$

$$k^{*2} + M_D^{*2} = E^{*2}$$

Non-relativistic rewriting

$$\frac{\mathrm{k}^2}{2M_N} + V_{\mathrm{eq}} = \frac{E^2 - M_N^2}{2M_N}$$

$$v_g^* = \frac{\mathrm{k}}{M_L^*} \equiv \frac{d\epsilon}{d\mathrm{k}}$$

*M. Chamseddine, et al., arXiv:*2304.01817

Conclusions and outlooks

Conclusions

- HF+SRC seems to be heading towards the right direction vis-à-vis the experimental data
- The model at its current state is not ready yet to be extrapolated to higher densities for applications to neutrons stars

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
- A more microscopic treatment of SRC using the UCOM method
- A more microscopic treatment of the chiral potential from an underlying NJL model

THANK YOU