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

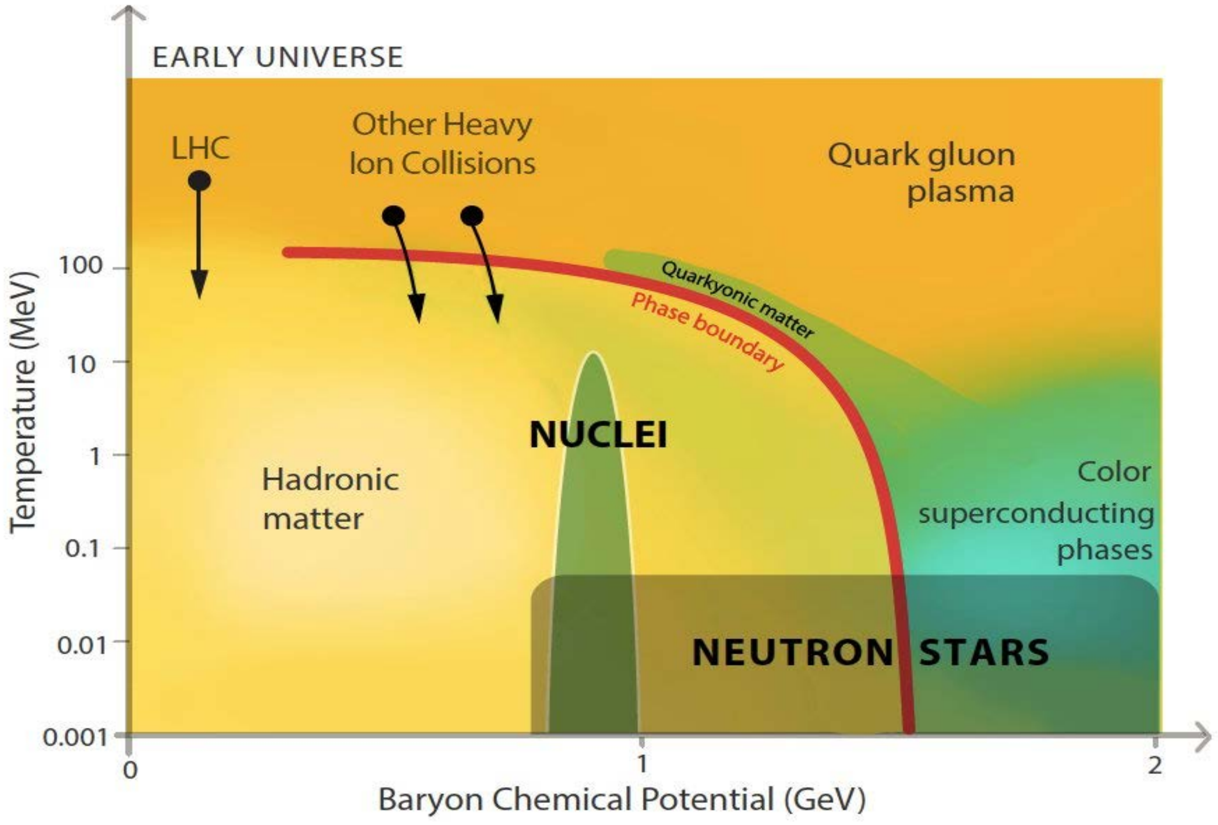
OUTLINE

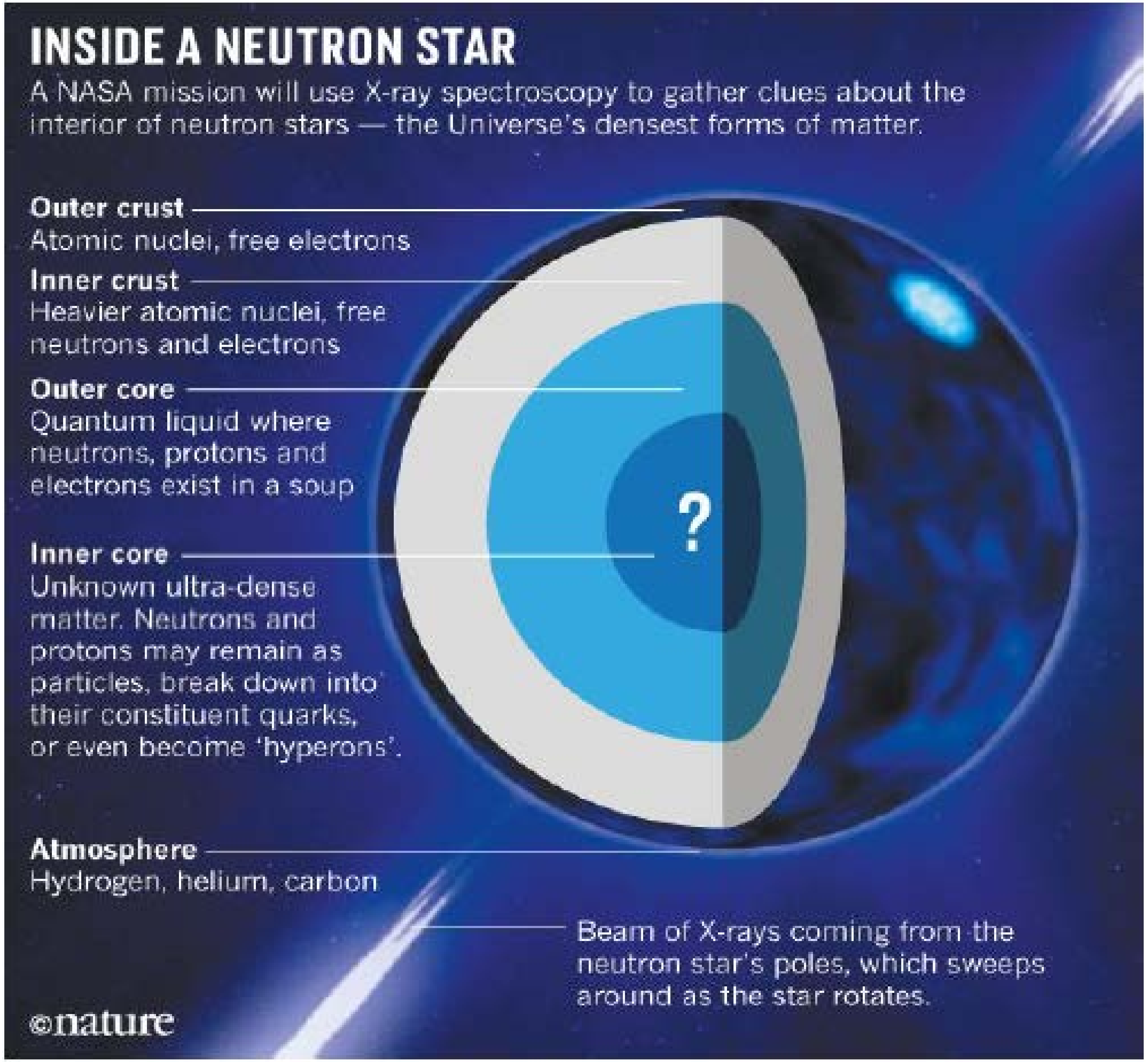
- Motivation for Relativistic approaches
- Neutron stars
- RMF with Chiral symmetry and Confinement (RMF-CC)
- Results
- Conclusions and outlooks

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.

Watts et al. '16



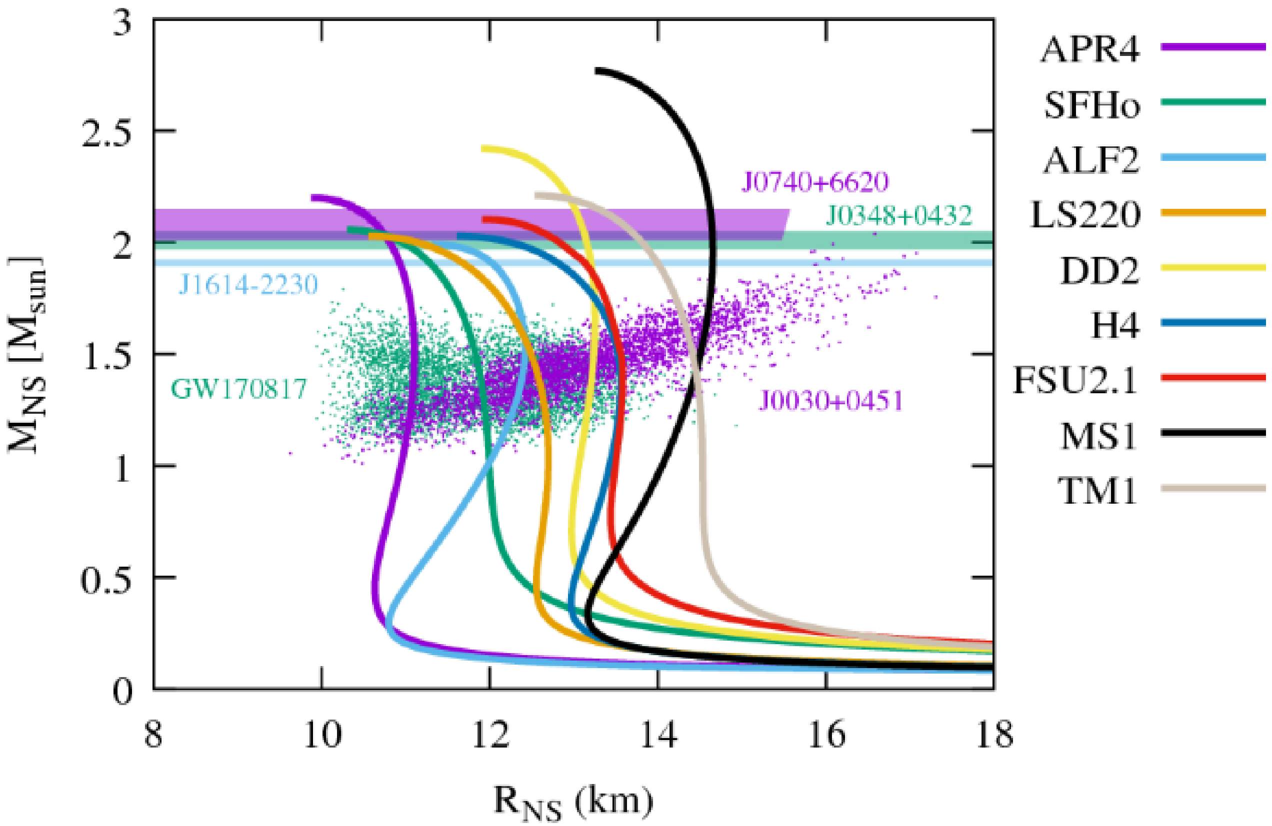


Neutron stars

- 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)



$$\frac{dm(r)}{dr} = 4\pi r^2 \rho(r)$$

$$\frac{d\Phi(r)}{dr} = \frac{Gm(r)}{r^2} \frac{1 + \frac{4\pi r^3 P(r)}{m(r)c^2}}{1 - \frac{2Gm(r)}{rc^2}}$$

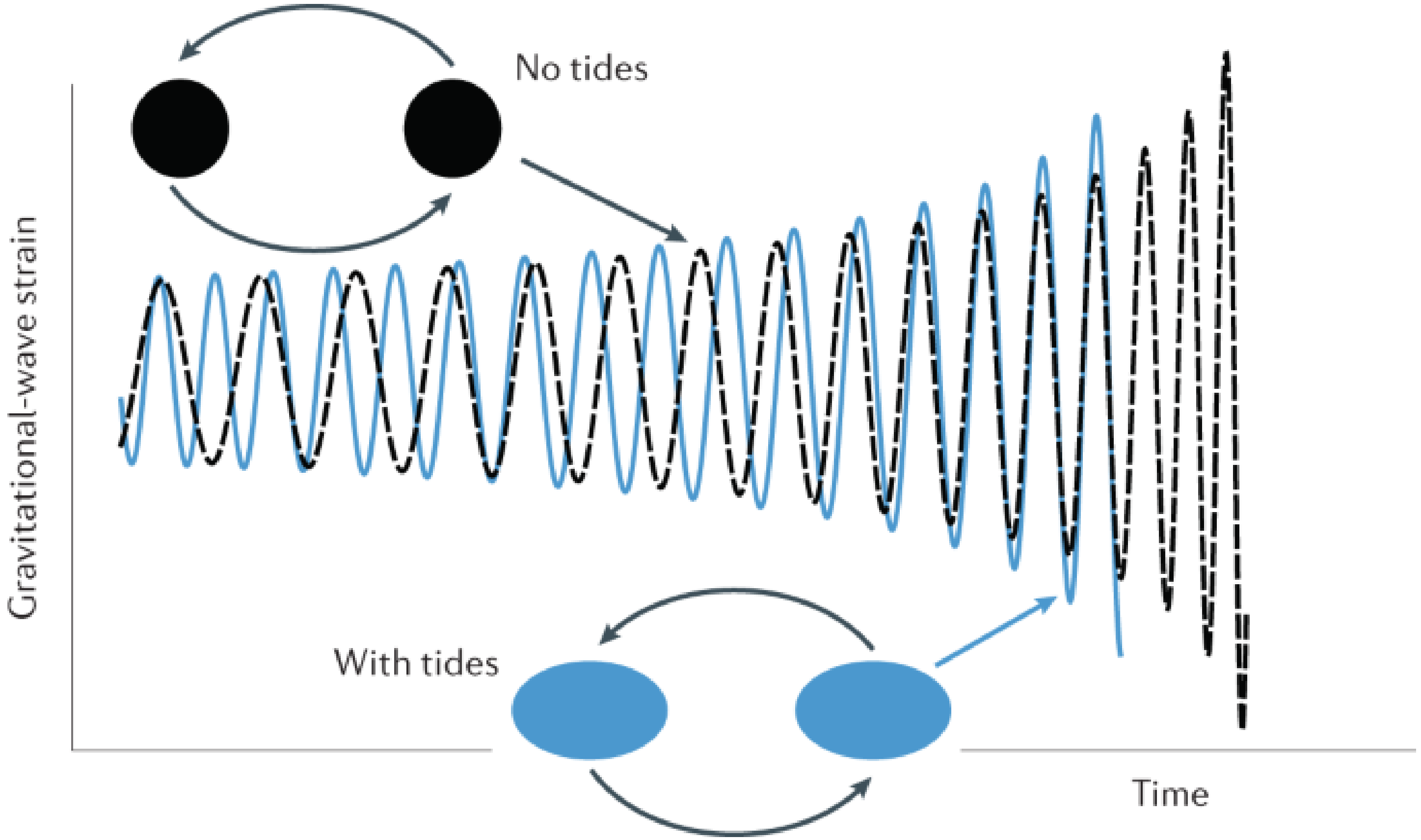
$$\frac{dP(r)}{dr} = -\rho(r)\left(1 + \frac{P(r)}{\rho(r)c^2}\right)\frac{d\Phi(r)}{dr}$$

Tidal deformability

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

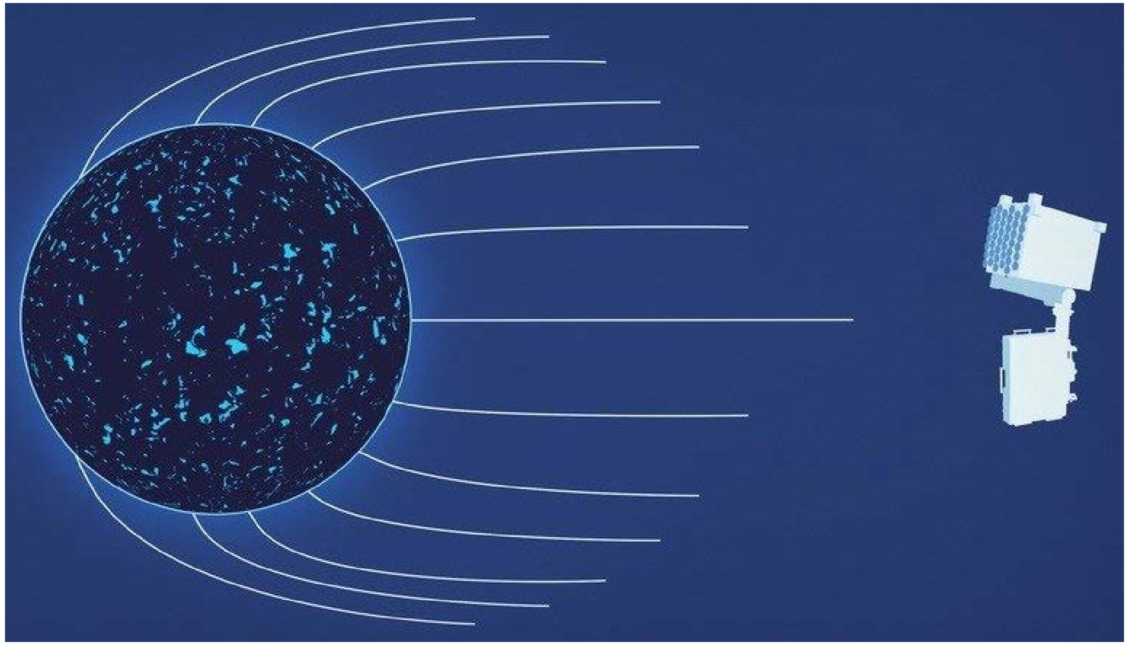
With k_2 the gravitational Love number and C the compactness.

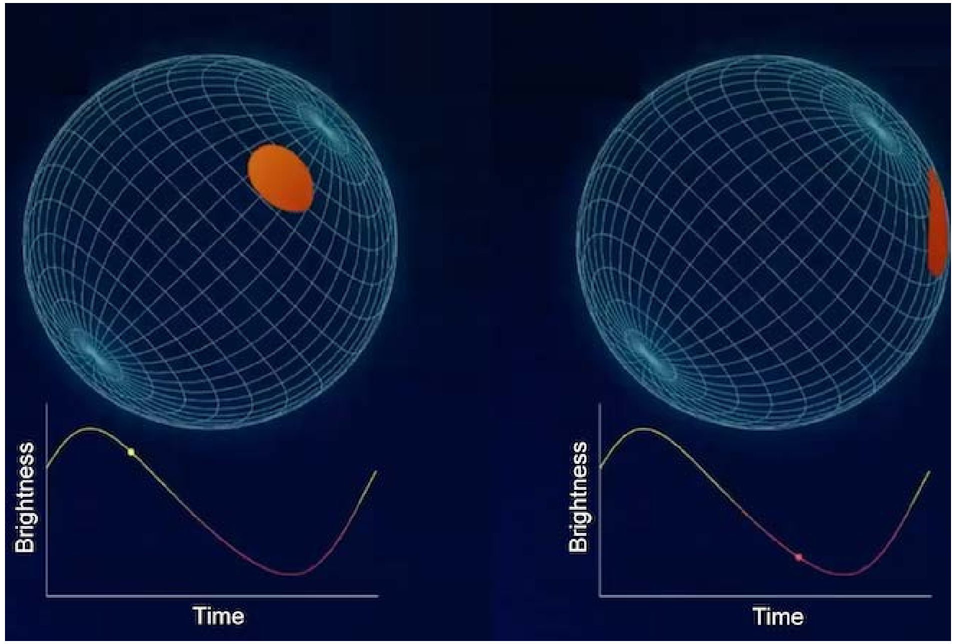
It quantifies how easily the star is deformed when subject to an external tidal field. It shows up as a "dephasing" of the wavefront of the GW signal.



NICER

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





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, 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.

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

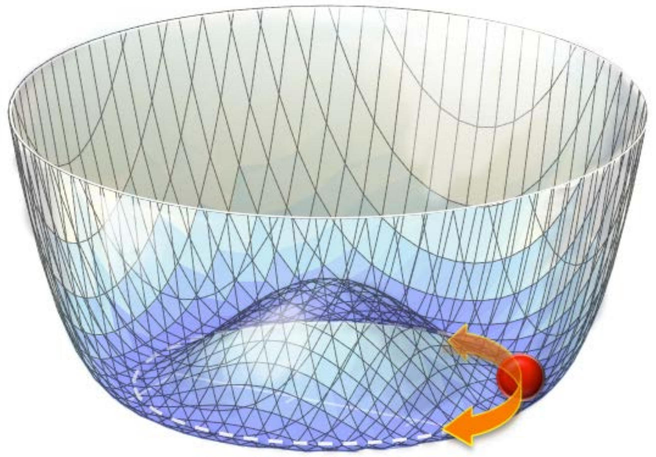
Small fluctuations→ Fock level

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 (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

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

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

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

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

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

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

The chiral Lagrangian

- 4 unknown 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)*

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

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

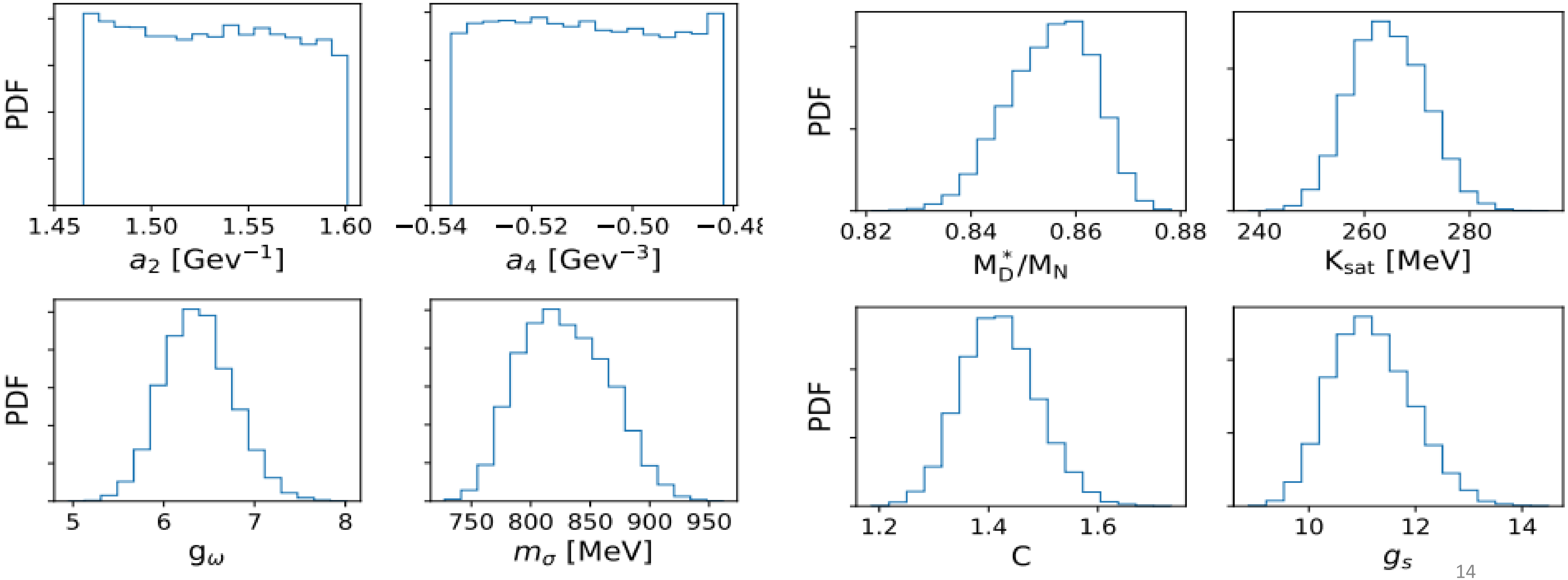
$$a_2 = \frac{g_s f_\pi}{m_\sigma^2} \qquad a_4 = -\frac{f_\pi g_s}{2m_\sigma^4}\left(3 - 2C\frac{M_N}{f_\pi g_s}\right)$$

- 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)*.

Results

1) Hartree level (no pion)

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



Short-Range-Correlation (SRC)

- The model being an effective one, doesn’t have a good resolution at short ranges, 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 the Jastrow function approach: the mesons’ propagators are convoluted with a correlation function forbidding the presence of 2 nucleons at the same point

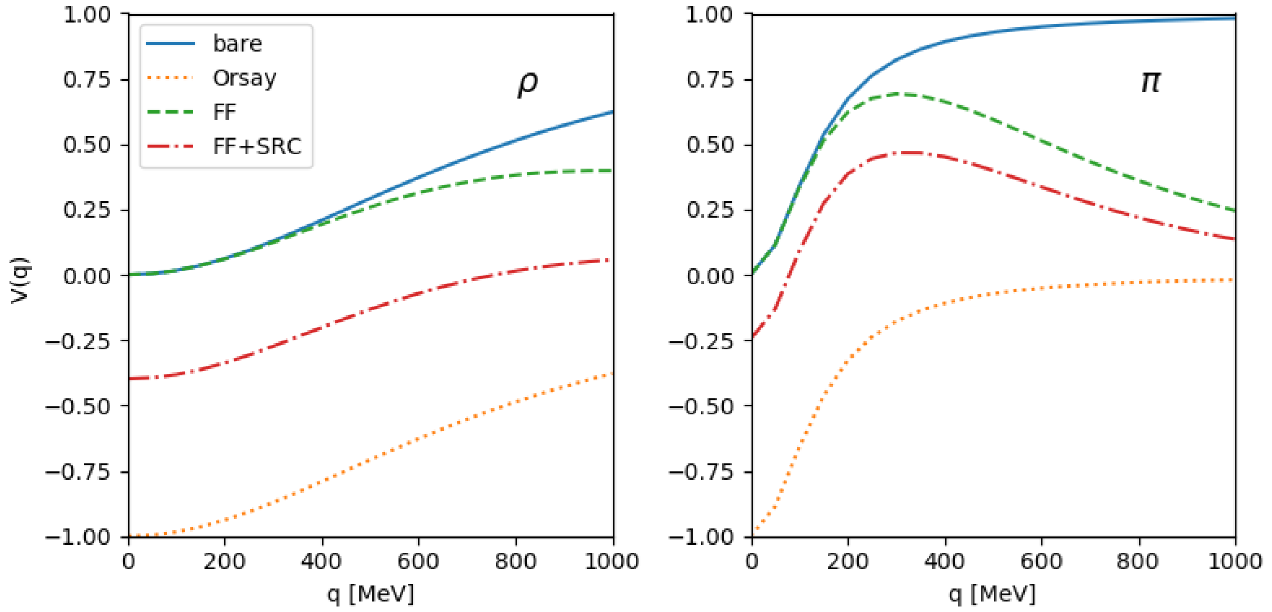
Short-Range-Correlation (SRC)

- They can be mainly seen for the pion and tensor ρ channels
- Experiments show that the pion term should be repulsive at short ranges, the scale at which we don't have a good resolution

$$V(q) = \frac{q^2}{q^2+m^2} = 1 - \frac{m^2}{q^2+m^2}$$

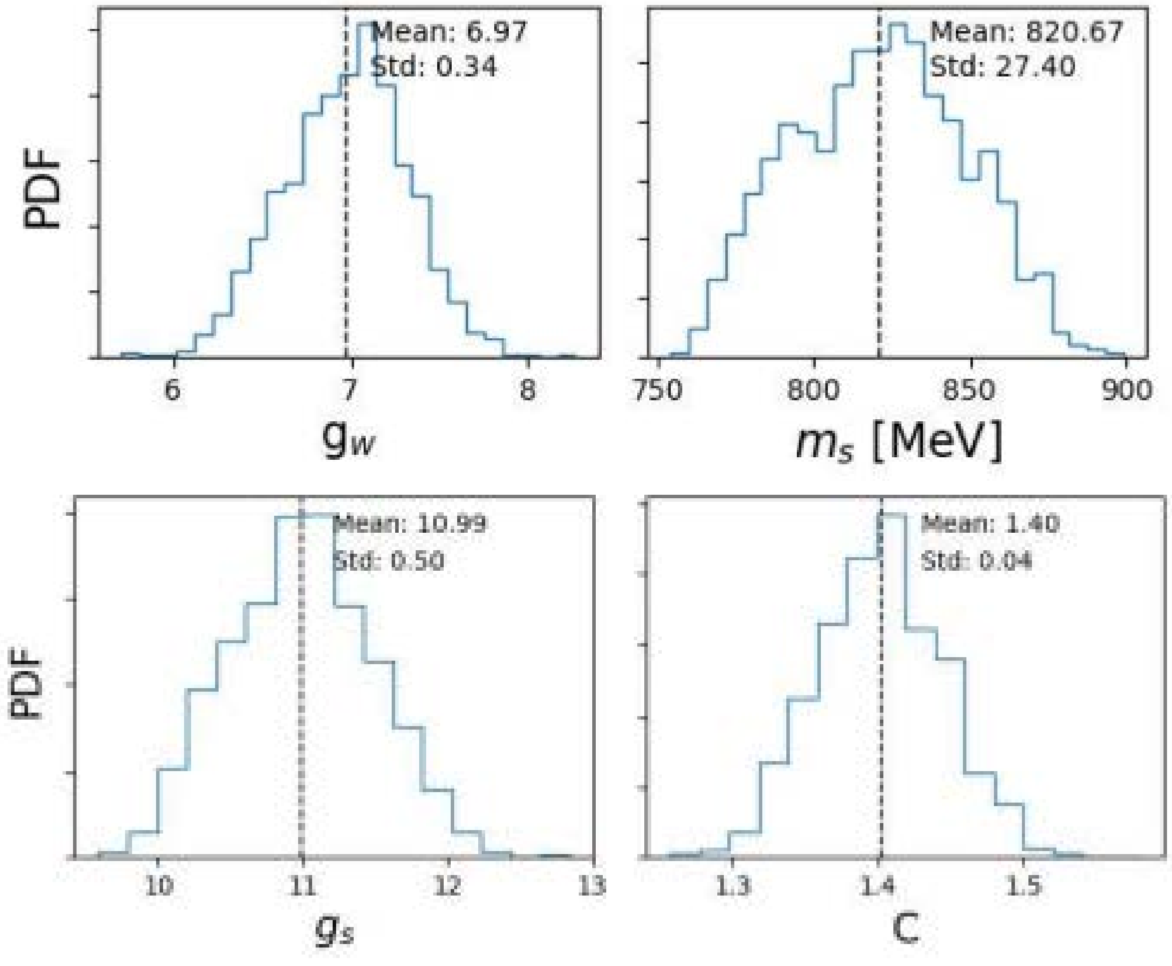
Contact term ➔ should be suppressed by SRC

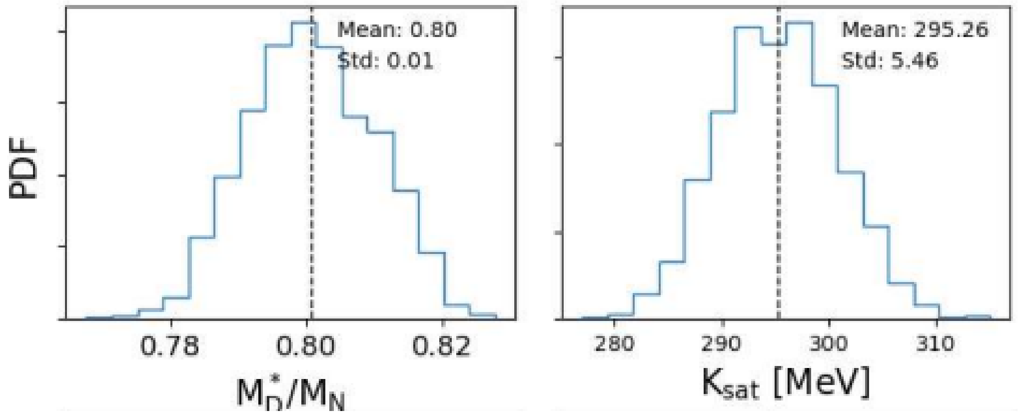
Normal Yukawa potential(attractive)

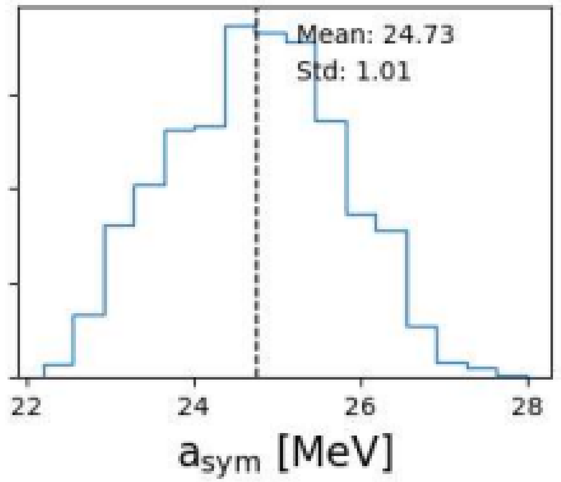


Results

2) Hartree Fock level + SRC







Results

M. Chamseddine, et al., in progress

κ_ρ = 6.6	Hartree level	Hartree-Fock level	Hartree-Fock with SRC	Experimental values
C	1.40	1.66	1.40	
g_s	11	13.53	10.99	
m_s	820	911	821	
g_w	6.5	5.84	6.97	
E_{sym}	18	19.36	24.73	32 ± 2
K_{sat}	265	306	295	230 ± 20

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

THANK YOU