QNP2022 - The international conference on Quarks and Nuclear Physics
5 – 9 September 2022
online

Hot and cold neutron stars in the Quark-Meson-Coupling model

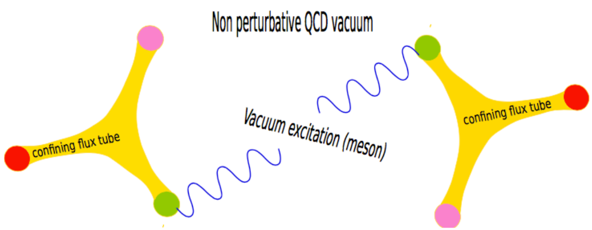
J. R. Stone

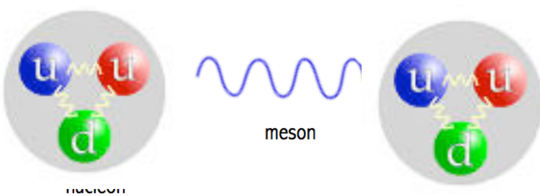
Oxford/Tennessee

jirina.stone@physics.ox.ac.uk

A few remarks about the QMC model:

P.A.M. Guichon, Phys. Letts. B 200, 235 (1988) Saito K and Thomas A. W. *Phys. Lett. B* 327 (1994) Guichon P.A.M. et al, *Nuclear Physics A* 601 (1996) 349. Guichon P.A.M. and Thomas A.W. *Phys.Rev.Lett.* 93 (2004) 132502. Guichon P.A.M, JRS, Thomas A.W. *PPNP* 100 (2018) 262–297





Traditional RMF models ignore internal structure of the nucleon

Basis for quark-meson coupling (lattice QCD)
Bissey et al, Physical Review D 76 (2007) 114512

Assume that quark confinement is produced by relatively thin flux tubes with approximately perturbative vacuum inside. The quarks are attached at the end of the tubes but otherwise move in the non-perturbative QCD vacuum. There, nothing prevents them from feeling the vacuum excitations, which are described by **σ , ω and ρ** meson fields expected to arise in nuclear matter.

QMC: a phenomenological relativistic mean field model for nuclear matter

Guichon, JRS, Thomas: Prog.Part.Nucl.Phys. 100,262(2018)

- **baryons** are represented by MIT bags (only as a source of the confining potential)

- **meson fields**: σ scalar, density dependent, attractive (medium range) component
- of the nuclear force; it modifies dynamics of quarks in baryons – *yields*
- *medium effect on the bare baryon-baryon interaction*
- ω and ρ vector, repulsive (short range), only rescales the energy

$g_{\sigma N}$, $g_{\omega N}$, $g_{\rho N}$, Variable parameters: Nucleon-meson coupling constants in free space, Simply related to quark-meson couplings, fitted to NM at saturation

Effective mass of a baryon immersed in the scalar field

$$M_i(\sigma) = M_i - w_{\sigma i}\, g_{\sigma N}\, \sigma + \frac{d}{2}\tilde{w}_{\sigma i}(g_{\sigma N}\, \sigma)^2,$$

$w_{\sigma i}$ - flavour dependence

d - scalar polarizability

d = 0.0044 + 0.211 R_B − 0.0357 R_B^2.

Total energy of a *classical* system of baryons at zero temperature, modeled as non-overlapping bags coupled to meson fields σ, ω and ρ is expressed as

$$E_{QMC} = \sum_{i=1,\ldots} \sqrt{P_i^2 + M_i^2(\sigma(\vec{R}_i))} + g^i_{\omega N}\omega(\vec{R}_i) + g_{\rho N}\vec{I}_i.\vec{B}(\vec{R}_i) + E_\sigma + E_{\omega,\rho},$$

i –flavour index

Fixed parameters, bag radius (1 fm) and mass of the σ meson (700 MeV) are chosen but not varied

QMC-A model for cold and warm matter including full hyperon octet
(in comparison with the traditional RMF DD2Y model)

Stone et al MNRAS 502,3476 (2021), Typel et al, Physical Review C 81 (2010) 015803
Stone, to appear in Proceedings of the 14th International Conference on
Hypernuclear and Strange Particle Physics, Prague 2022

Equation of state

Hyperonic composition of neutron star cores

Mass, radius and central density of neutron stars

Adiabatic index and the speed of sound

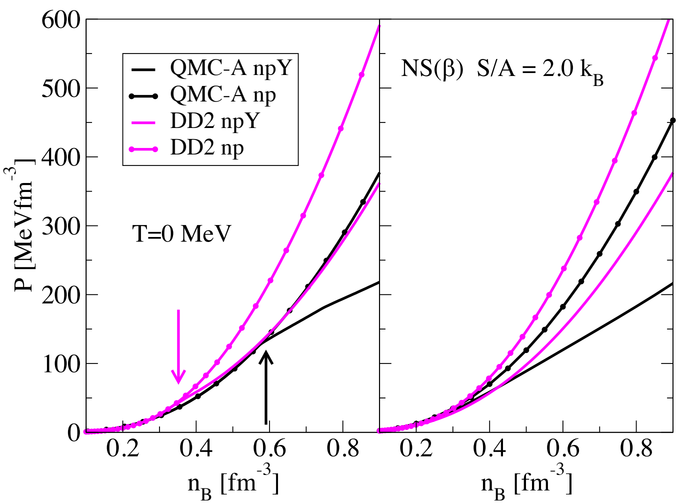
Single-particle hyperon potentials in nuclear matter

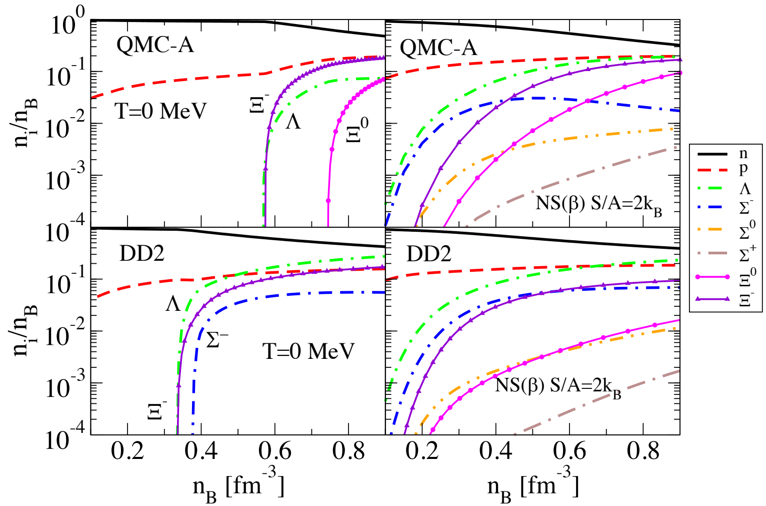
Important physics: hyperon presence decreases pressure – finite temperature
Increases pressure. The interplay of these two effects has important consequences.

QMC-A: quark-meson couplings, 3 variable parameters, the same for nucleons
and hyperons. Single-particle hyperon potentials are calculated within the model

DD2Y: nucleon-meson density dependent couplings, 10 variable independent
parameters + 3 single-particle hyperon potentials

The EoS of cold and β-equilibrated matter with entropy density S/A=2 k_B (T∼ 20 – 50 MeV) in deleptonized proto-neutron stars. Nucleon-only (np) and with full hyperon octet (npY) cases are shown

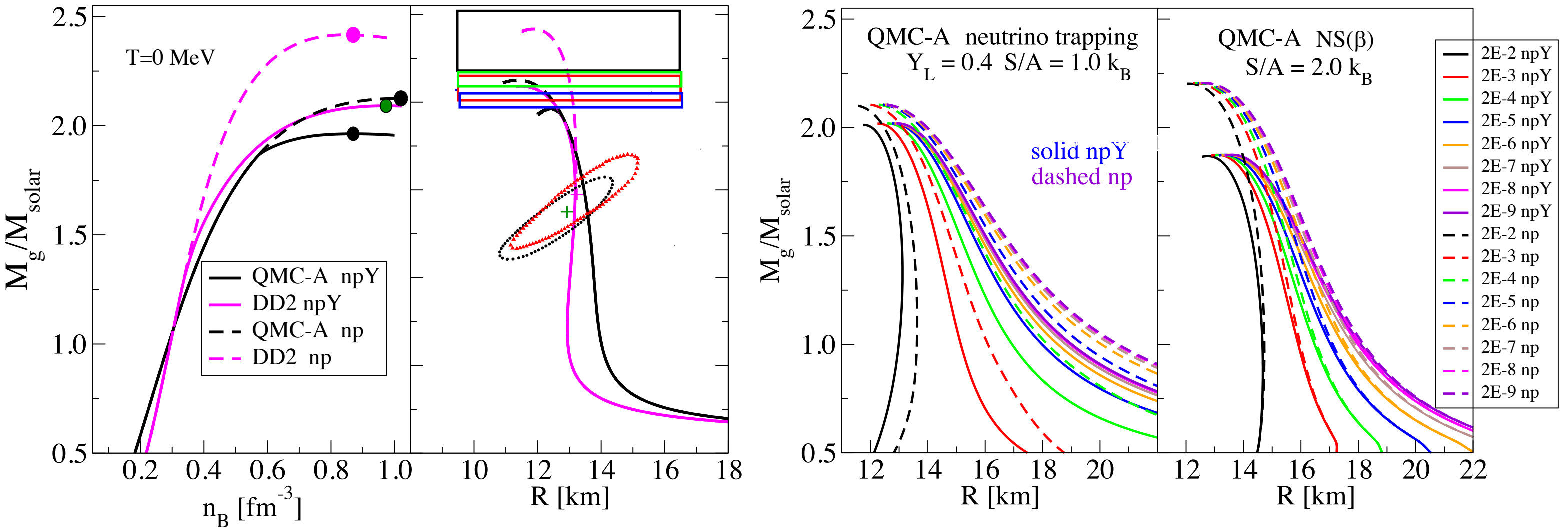




- T=0 : **there is a density threshold** for appearance of hyperons
- onset of hyperons softens the EoS (black arrow QMC-A, magenta arrow DD2)
- T≠ 0 : **There is NO threshold**; hyperons are present at all densities
- Hyperon and temperature effects compensate
- **Model dependence in all predictions**

M-R and M-central n_B curves for T=0 MeV (left). QMC-A M-R curves for two cases of warm matter in proto-neutron stars (right). Observation data on maximum mass are taken from

Romani et al, ApJL 934, L17 (2022) 2.35±0.17, Romani et al, ApJL908, L46 (2021) 2.13±0.04, Fonseca et al, ApJL915, L12 (2021) 2.08±0.07, Antoniadis et al, Science 340 (2013) 2.01±0.03 and on radius of 1.4 M_{solar} star from Miller et al, ApJL887, L24 (2019) and Riley ApJL 887, L21 (2019) .



T=0: maximum mass and radius within observational limits

T≠ 0: surface not well defined – search for minimum pressure needed

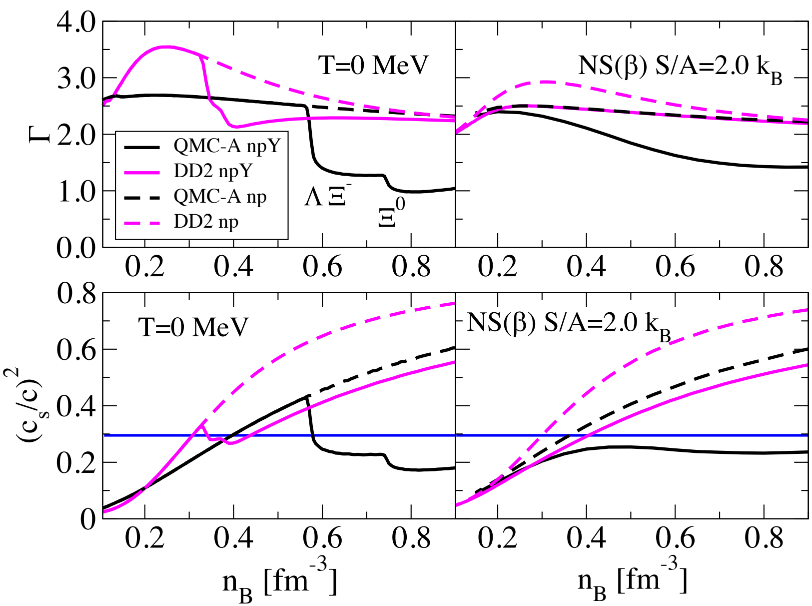
NO HYPERON PUZZLE DETECTED IN EITHER MODEL

Adiabatic index and the speed of sound - pulsation of neutron star cores:

Haensel et al, 2002, A&A, 394, 213

Polytropic EoS: $P=K\rho^{\Gamma}$ $\quad \Gamma = \frac{d\log P}{d\log n_B} = \frac{n_B}{P}\frac{dP}{dn_B}.$ $\quad \Gamma = \frac{n+1}{n}$ $\quad$ Γ adiabatic index, n polytropic index

https://sites.astro.caltech.edu/~jlc/ay101_fall2015/ay101_polytropes_fall2015.pdf



Speed of sound $c_s^2 = \frac{dP}{d\epsilon},$

Conformal limit $(c_s/c)^2 = 1/3$.

QMC-A :	Astro	complied
	Conform limit	complied
DD2:	Astro	complied
	Conform limit	violated

Cherman, Cohen & Nellore 2009

Bedaque and Steiner, PRL 114, 031103 (2015)

Tews *et al* *ApJ* **860** 149 (2018)

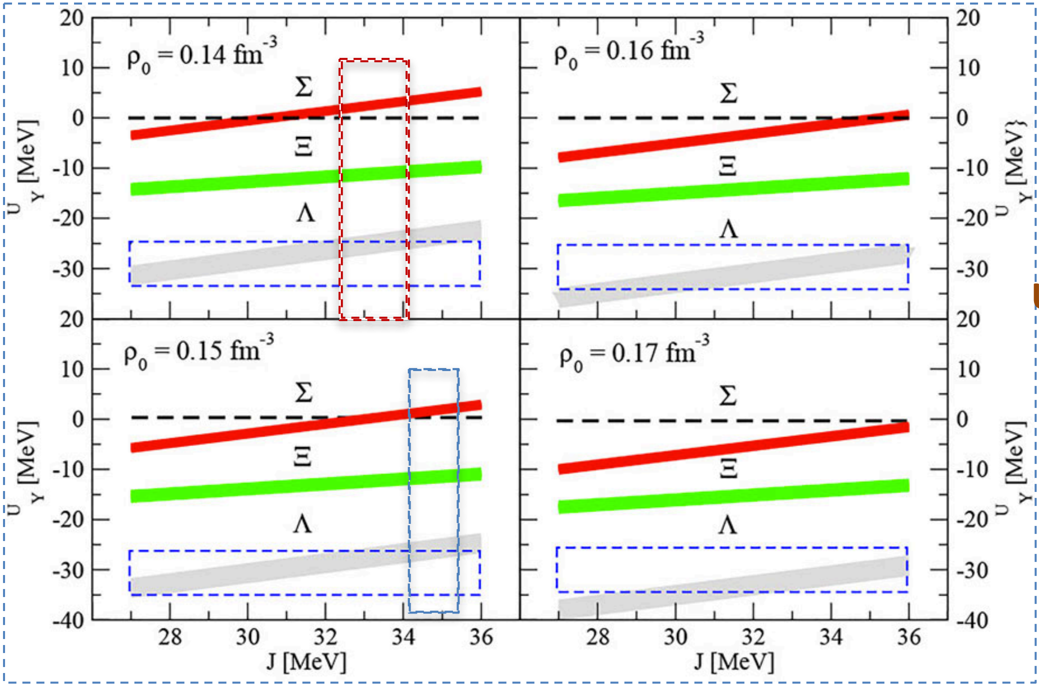
Traversi et al, A&A, A62 (2022)

Brandes et al, arXiv 2208.03026 (2022)

Γ is ratio of the heat capacity at constant pressure (C_P) to heat capacity at constant volume (C_V)

Constraining nuclear matter parameters at saturation with hyperon single particle potentials in nuclear matter calculated in QMC-A at T=0 MeV

Stone et al, Frontiers in Astronomy and Space Sciences 9 (2022)



ρ_0	0.14 – 0.17 fm^{-3}
E_0/A	-15 – -18 MeV
J	27 – 36 MeV

U_Y *calculated* in QMC-A
free parameters in RMF

- Λ reasonably known
- Σ positive or negative?
- Ξ ?

More data needed

Summary

Neutron stars with nucleon only and with full hyperon octet cores were shown at zero and finite temperatures in QMC-A and RMF DD2 models.

The QMC-A model with the minimal number of variable parameters yields predictions comparable with the DD2 model, albeit interesting differences exist.

The threshold densities for the onset of hyperons at T=0 MeV and the hyperon content in the NS core are strongly model dependent. There is no threshold at finite T and hyperons are present at all densities. The interplay between hyperonic and temperature effects significantly NS properties.

The maximum mass of cold and hot hyperonic stars in both models satisfies observational limits - no "hyperon puzzle" is predicted.

The QMC-A model, satisfies the conformal limit on the speed of sound AND astrophysical constrains on NS properties.
The DD2 model satisfies astrophysical data on NS but NOT the conformal limits.