Neutron Star Structure in QMC with Hyperons and High-Density Repulsion

JESPER LEONG, UNIVERSITY OF ADELAIDE

SUPERVISOR: PROFESSOR ANTHONY THOMAS

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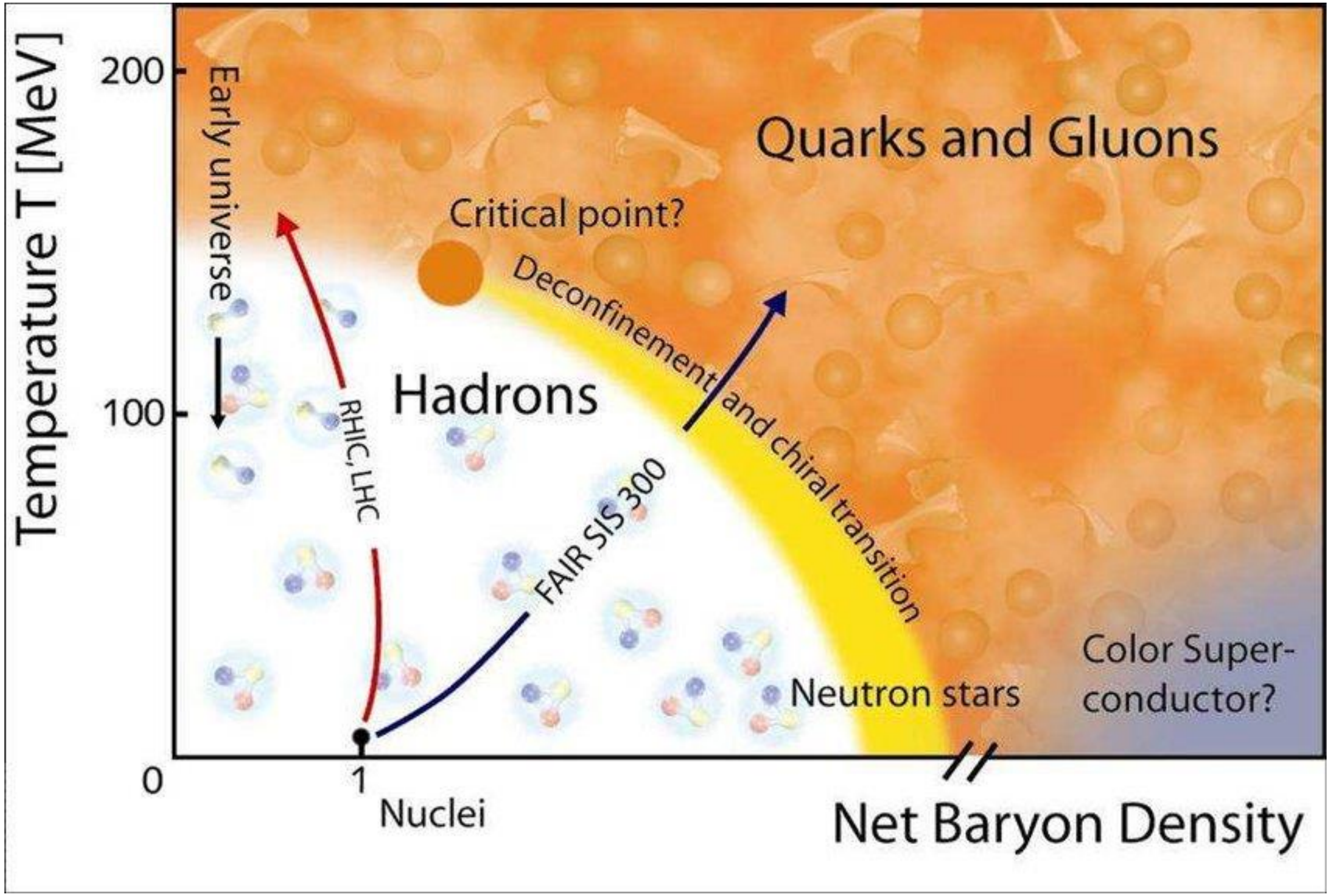
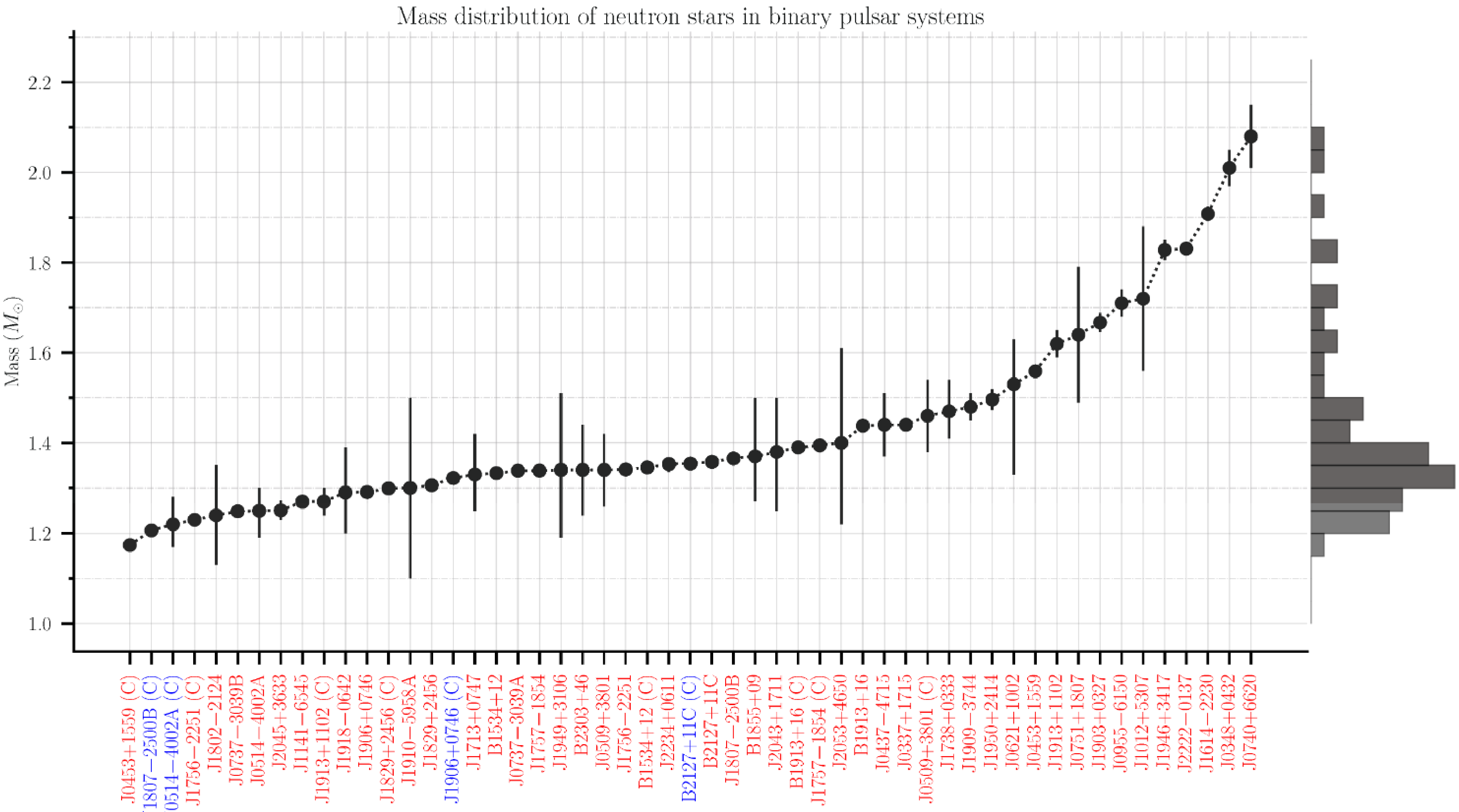
Why Neutron Stars?

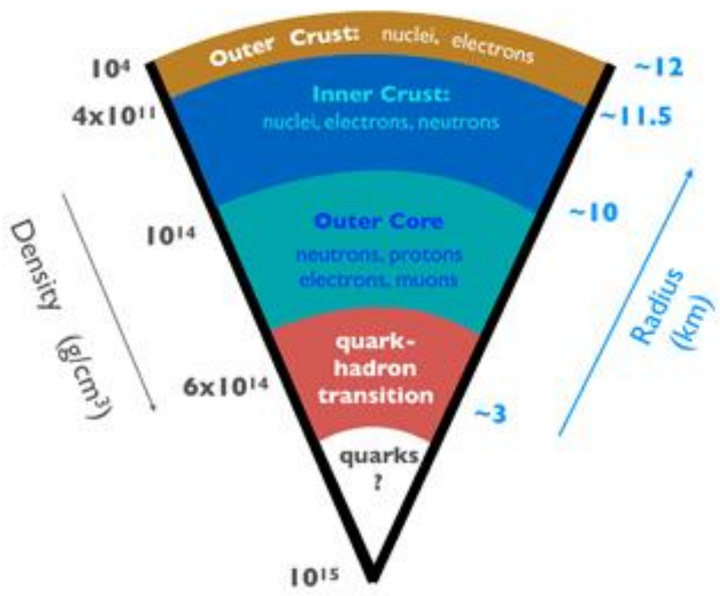


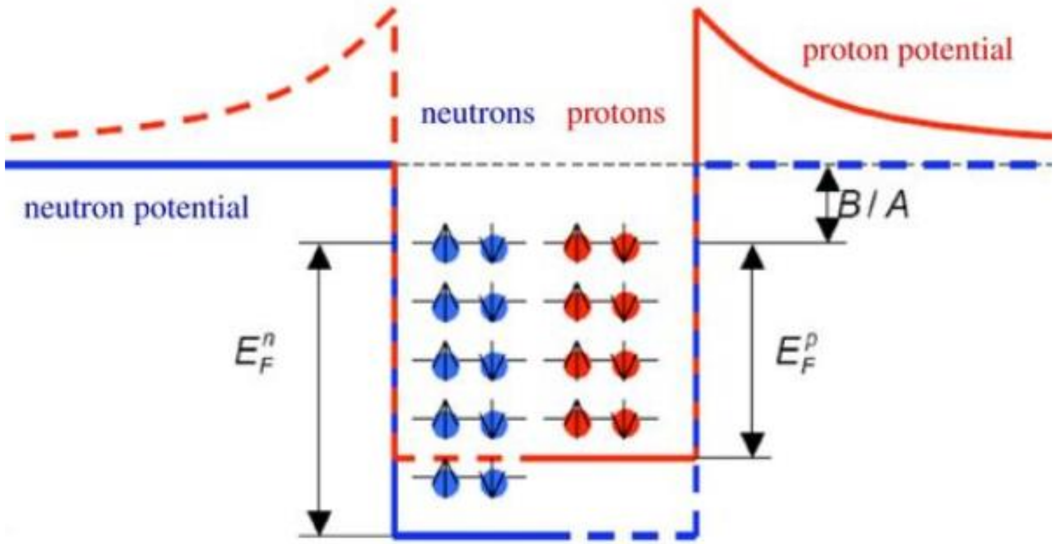
- Liquid Drop Model, shell models, potential models , QMC, …
- Neutron Stars are crucial at constraining the *Equation of State*
- Are NS made of nucleons, hyperons or deconfined quark matter?
- Neutron Stars constrain the EoS

"Known physical ideas which are ignored when studying finite nuclei need to be incorporated when describing neutron stars because of the extreme conditions nuclear matter is now in"



https://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html



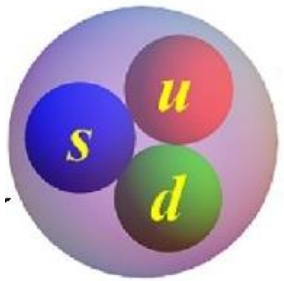


Heavy NS and the Hyperon Crisis

- PSR J0348+0432: $M = 2.01^{+0.04}_{-0.04}\ M_\odot$
  PSR J0740+6620: $M = 2.072^{+0.067}_{-0.066}\ M_\odot$
  PSR J0952-0607: $M = 2.35^{+0.17}_{-0.17}\ M_\odot$
- NS have core densities of 4-10 n_0
- β-equilibrium: Hyperons appear $> 3\ n_0$ (QMC)
- Hyperons: Low momentum
  Little Pressure
  Soften EoS
  Low Mass Stars

Quark-Meson-Coupling

$$M_f^* = M_f - w_\sigma^f g_\sigma \sigma - \tilde{w}_\sigma^f \frac{d}{2}(g_\sigma \sigma)^2 \qquad E_f = \sqrt{M_f^{*2} + \vec{k}^2} + g_\omega^f \omega + g_\rho^f I_m^f \rho$$



QMC is a hadronic theory of the strong interaction.

Meson couple directly to the quarks inside of the proton and neutron.

- Dynamics change the internal structure.
- 3-body forces arise from the scalar polarizability d (NNN, NNY, NYY, YYY)
- σ, ω, and ρ mesons
- Even with hyperons, only 5 parameters needed.
- Applicable in neutron star research

P. A. M. Guichon, J. R. Stone, and A. W. Thomas, *Quark-Meson-Coupling model for finite nuclei, nuclear matter, and beyond,*Prog. Part. Nucl. Phys. 100, 262 (2018)

Note: The isoscalar-scalar δ-interaction has recently been explored by Motta et al., 2019

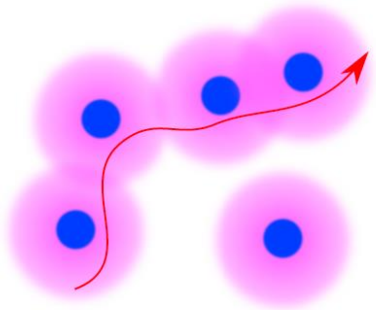
Review: QMC and Neutron Stars

$\boldsymbol{n_0}$	$0.15 - 0.17\ fm^{-3}$
BE/A	$-15.8\ MeV$
$\boldsymbol{S}$	$28 - 32\ MeV$
$\boldsymbol{K}$	$200 - 300\ MeV$
$\boldsymbol{L}$	$40 - 80\ MeV$

$$G_\sigma = \frac{g_\sigma^2}{m_\sigma^2}, \quad G_\omega = \frac{g_\omega^2}{m_\omega^2}, \quad G_\rho = \frac{g_\rho^2}{m_\rho^2}$$

The couplings are often fitted to reproduce the saturation density (n_0), binding energy (BE/A) and symmetry energy (S).

- Stone *et al.* (2007) found $M_{max} = 1.9 - 2.1\ M_\odot$ but $K > 300$ MeV.
- Incompressibility, K, is related to the Giant Monopole Resonance.
- Cubic term in the σ-potential with coefficient λ_3
- $\lambda_3 = 0.02 - 0.05\ fm^{-1}$ required to $\downarrow K$, to satisfy GMR prediction.
- $\downarrow K \rightarrow$ softens the EoS $\rightarrow$ $\downarrow$ Neutron Star Mass



High Density Repulsion Baryon Overlap

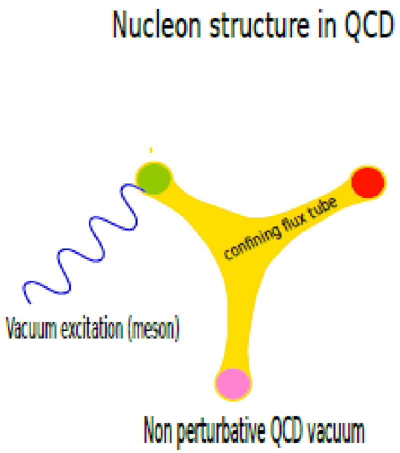
Heavy NS may have a core density between $4 - 10\ n_0$

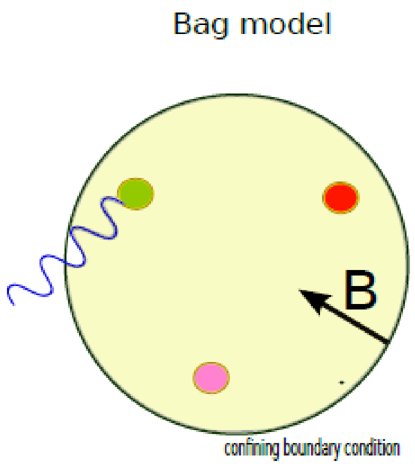
Repulsion in QMC is generated by the ω with the strength set at saturation density.

Motivation: repulsion at short distances

- Pauli Exclusion Principle
- Hidden colour configurations
- Suppression of the wave function at short distances
- New physics?

Baryon Overlap: Overlap energy (E_0) and the range parameter (b), which corresponding to distance when overlap becomes appreciable.





$$\frac{\langle \mathcal{H}_O \rangle}{V} = E_0 n_B \exp\left\{ - \left(\frac{n_B^{-1/3}}{b} \right)^2 \right\}$$

Parameters and Infinite Symmetric Nuclear Matter Properties at Saturation

The hypothesis is that the overlap interaction is only detectable at high densities

Therefore should not change the nuclear properties at ordinary densities (see table)

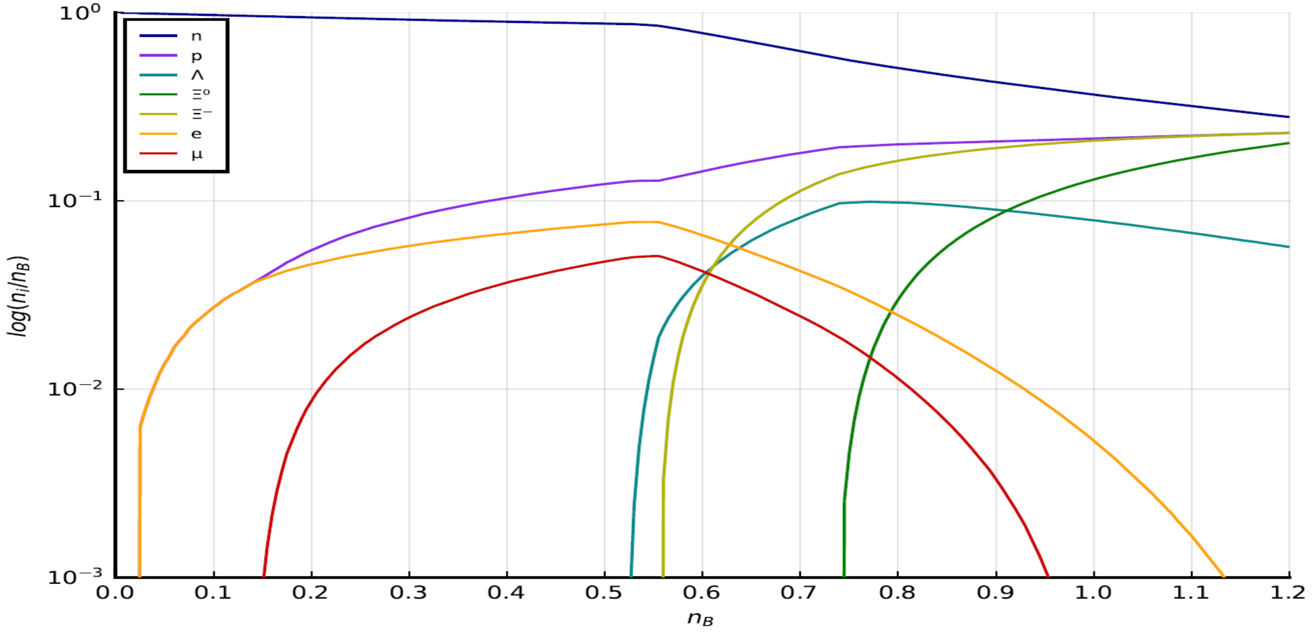
F-QMC	n_0 (fm^{-3})	BE (MEV)	S (MeV)	K (MeV)	L (MeV)
No Overlap	0.16	-15.8	30	260	62
Overlap	0.16	-15.8	30	264	62

- Couplings were fitted without overlap interaction and are then held fixed when overlap is introduced.

Preferred Overlap parameters: $E_0 = 5500$ MeV
$b = 0.5\ fm$
These did not change the incompressibility (K).

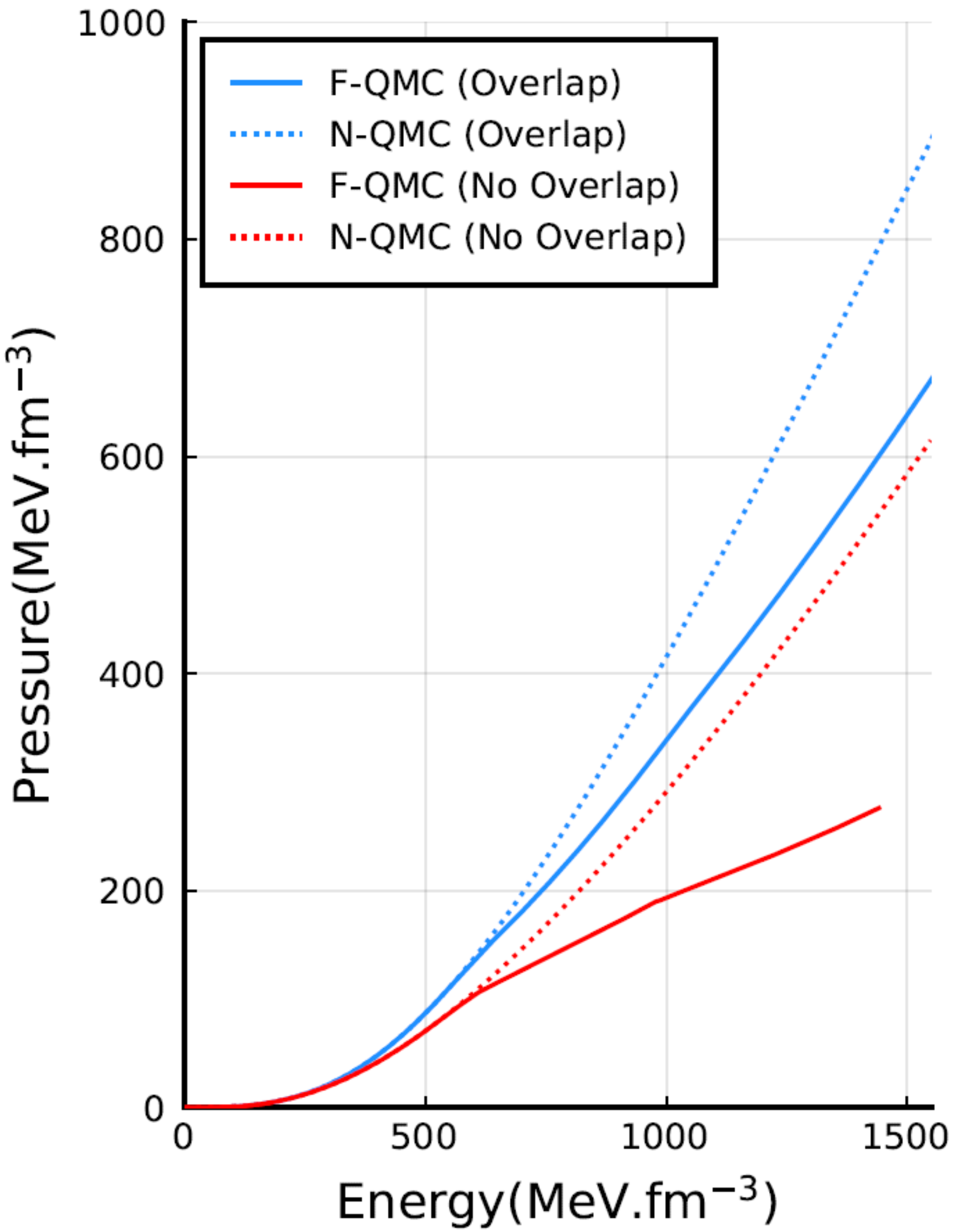
- 4 version of QMC: QMC with and without hyperons
  QMC with and without overlap

QMC Equation of State

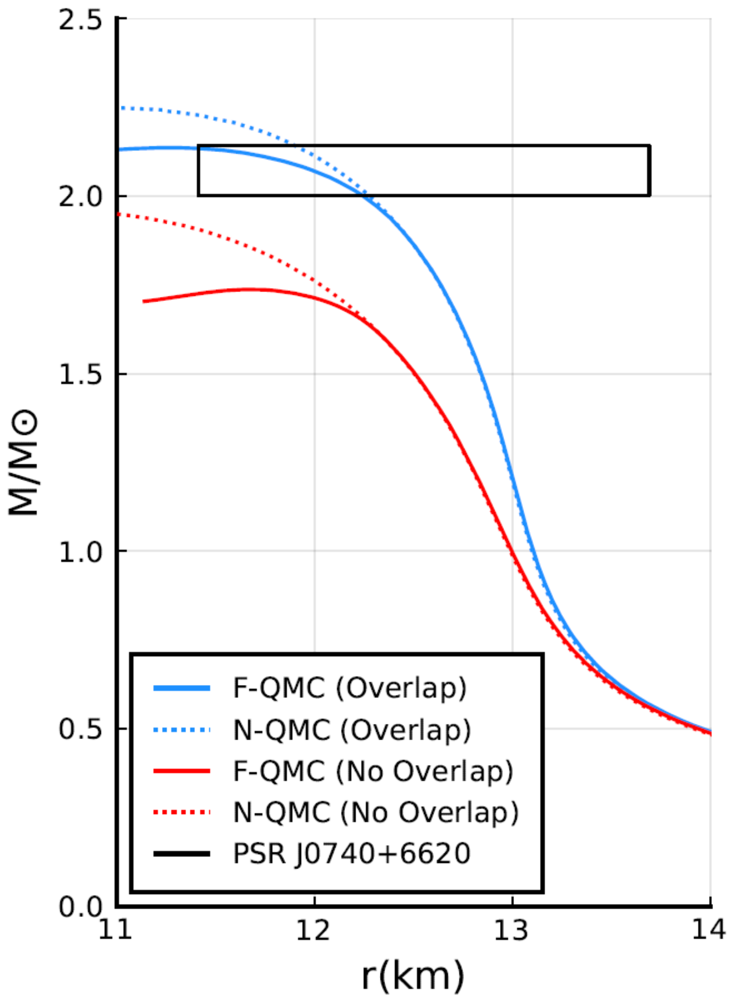


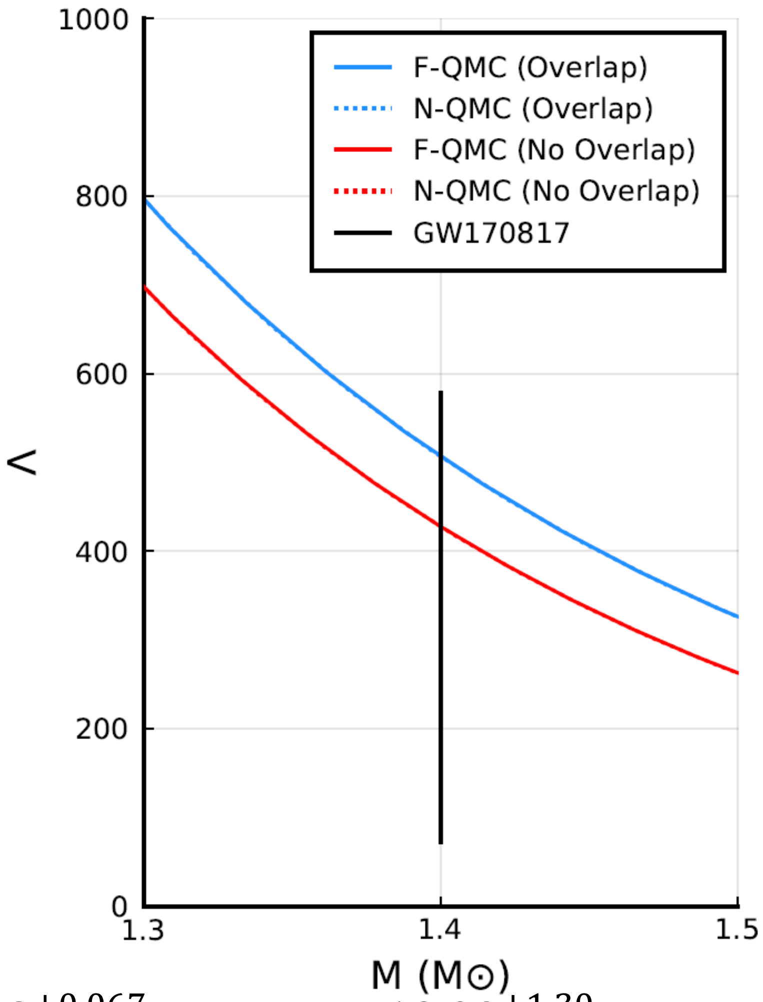
Hyperons only appear in stars which have a core density greater than 3 times saturation density (above).

- Hyperons (solid lines) soften the EoS
- QMC without overlap is indicated in red
- Overlap is repulsive and stiffer (blue) the EoS



Bulk Properties of NS





- Without overlap, the λ_3 term reduces the mass at maximum to 1.74 $M_\odot$
- With overlap, $M_{max} = 2.14\ M_\odot$
- Overlap increases the radii at low mass values but is reduced at maximum
- All cases conform to tidal deformability. Low mass star are composed of nucleons only.
- Hyperons only appear in the heaviest of NS.

PSR J0740+6620: $M = 2.072^{+0.067}_{-0.066}\ M_\circ$, $R = 12.39^{+1.30}_{-0.98}$

GW170817: $\Lambda_{1.4} = 190^{+390}_{-120}$ or $\Lambda_{1.4} < 800$

Excluded Volume Effect (EVE)

All baryons adopt a finite size, $v_0 = \frac{4}{3}\pi r^3$, regardless of flavour. No baryon is permitted to enter the space occupied by other baryons.

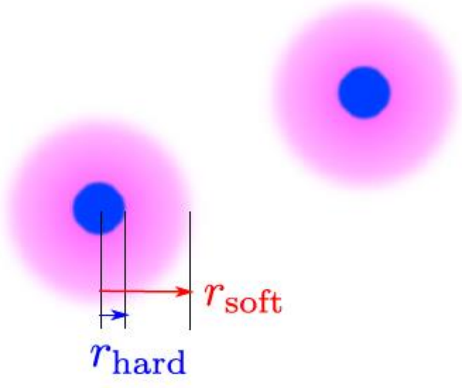
r (fm)	K (MeV)	L (MeV)
0	225	58
0.45	257	61
0.5	270	62

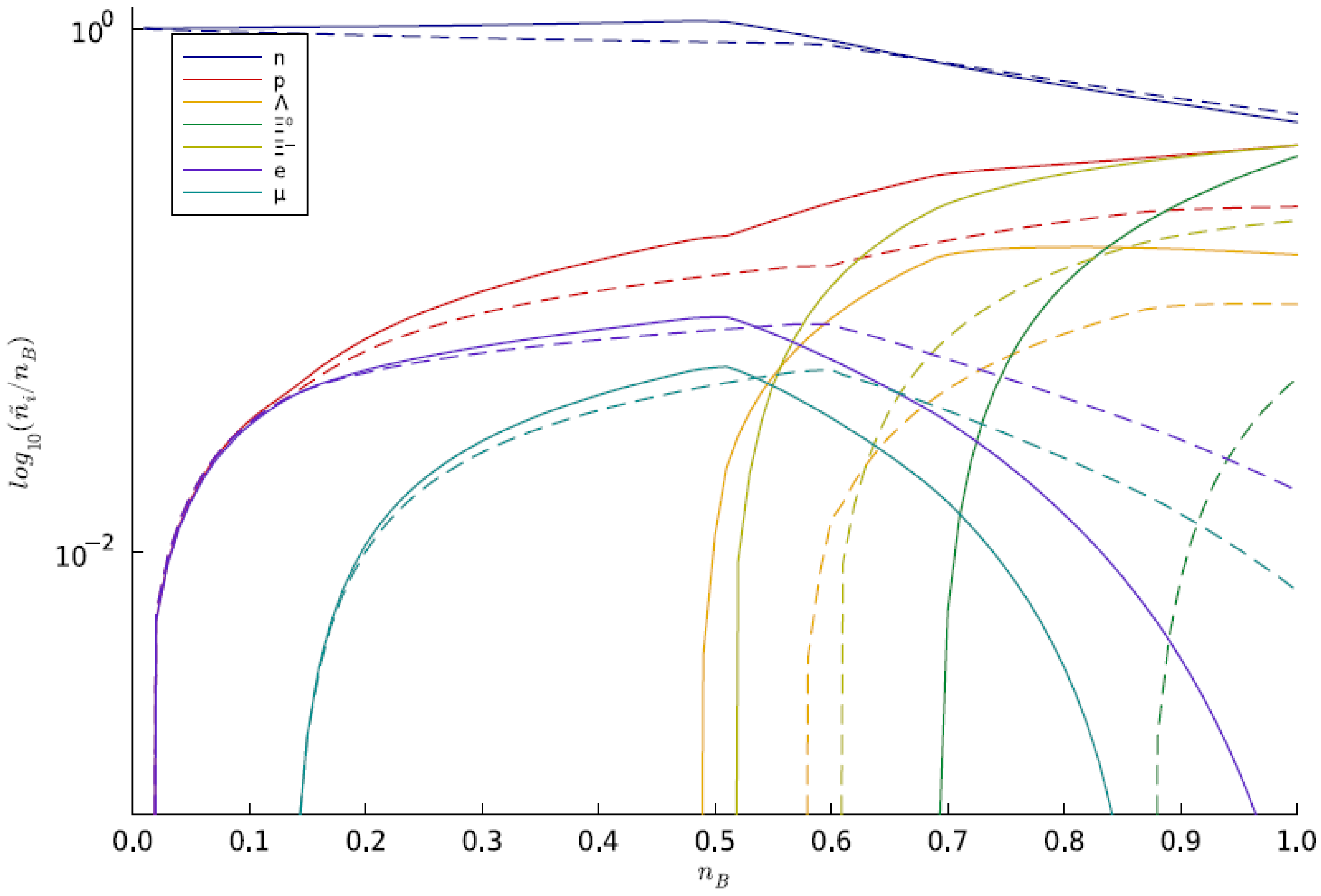
$$\tilde{n}_i = \frac{n_i}{1 - v_0 n_B},$$

$$\tilde{\epsilon}(n_1, n_2, ..., n_i) = (1 - v_0 n_B)\epsilon(\tilde{n}_1, \tilde{n}_2, .., \tilde{n}_i),$$

$$\tilde{P}(n_1, n_2, ..., n_i) = P(\tilde{n}_1, \tilde{n}_2, .., \tilde{n}_i),$$

$$\tilde{\mu}_j(n_1, n_2, ..., n_i) = \mu_j(\tilde{n}_1, \tilde{n}_2, ..., \tilde{n}_i) + v_0 P(\tilde{n}_1, \tilde{n}_2, ..., \tilde{n}_i)$$





β-equilibrium

Hyperons: Λ Ξ^- Ξ^0

EVE lowers the threshold of hyperon appearance

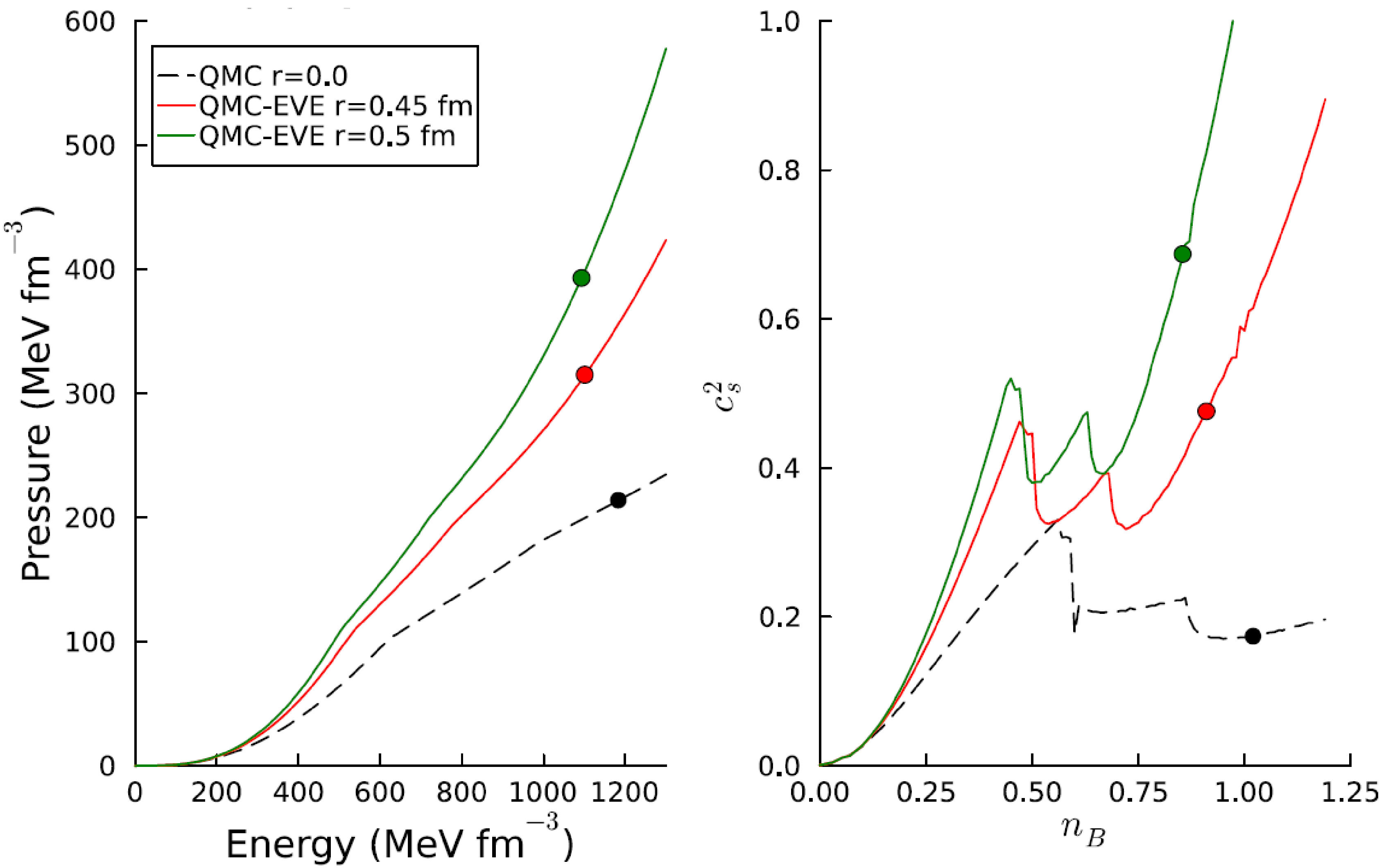
Causality

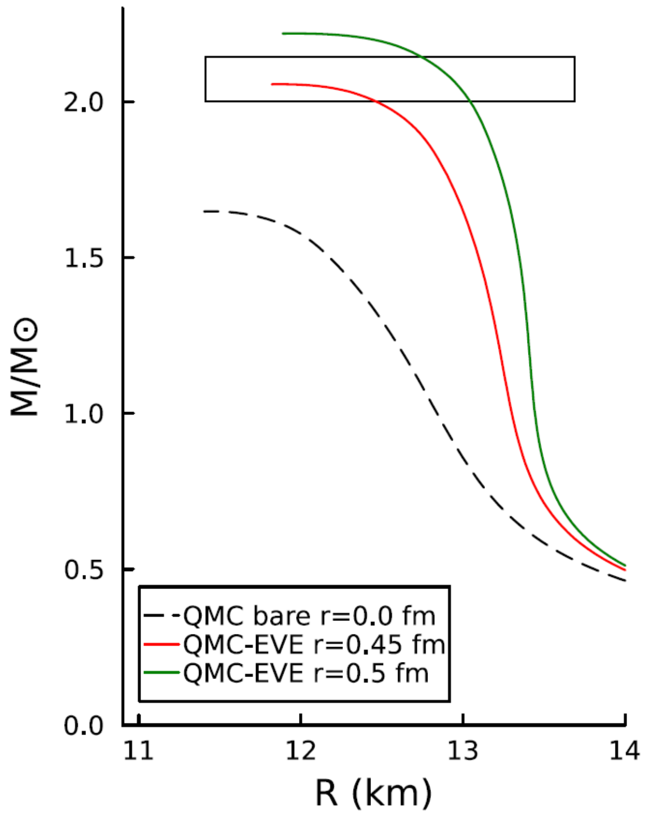
EVE is known to violate Special Relativity

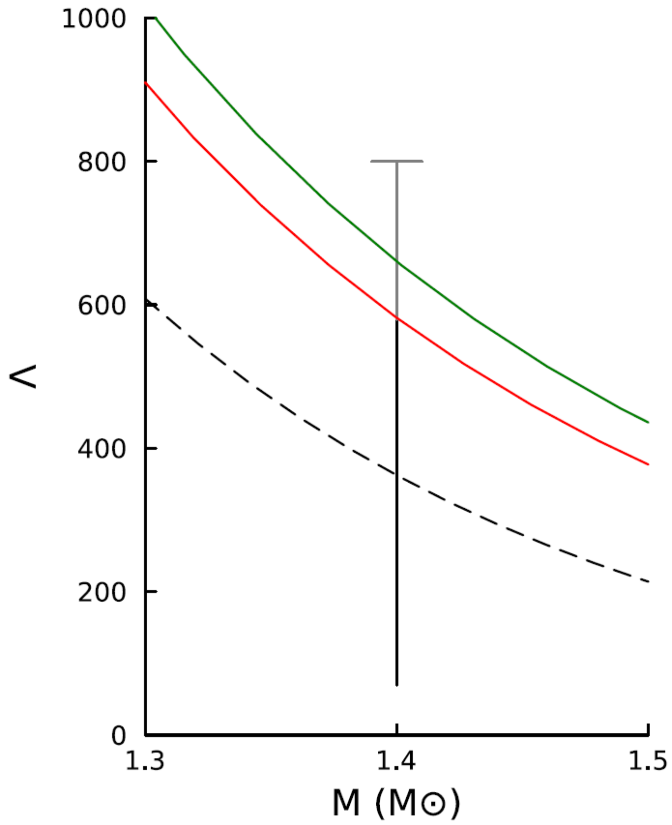
Causality requires $c_s^2 < 1$

Markers indicate central density at maximum

The core density of the physical star does not violate causal for r<0.5 fm







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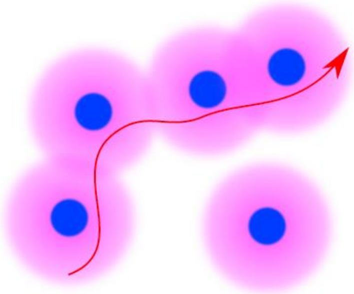
MR curve and Tidal Deformation

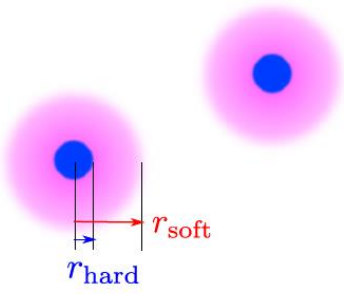
Hardcore radius, r, increases the maximum mass and the radii at all mass values.

- $r = 0.45\ fm \rightarrow 2.06\ M_\odot$
- $r = 0.5\ fm \rightarrow 2.22\ M_\odot$

Tidal deformation but for $r = 0.5\ fm$ only if $\Lambda_{1.4} < 800$



Summary: Overlap and EVE



- The combination of the **Pauli Exclusion Principle, hidden colour configurations and suppression of the wavefunction at short distances** is expected to contribution additional repulsion within neutron stars.
- The **ω-meson strength is set at saturation density** and is not strong enough to generate high density repulsion.
- Overlap or EVE correction is adopted to compensate for this and **increases the star's maximum mass and the radii** at all masses.
- QMC with overlap or EVE is compatible with heavy NS observations and tidal deformability, even when hyperons are included.

References

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arXiv: 2208.09331

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