Dense Matter in Neutron Stars: Interactions, Composition, and Observables in the QMC Model

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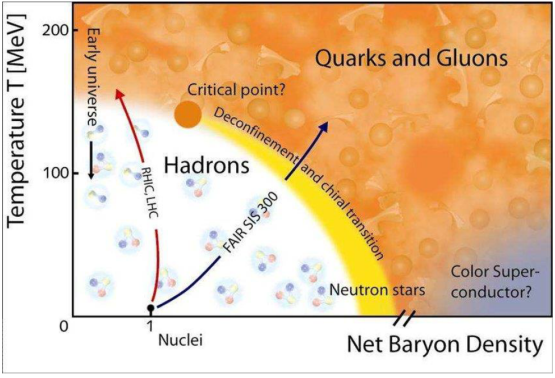
Fundamental Problems in Subatomic Physics
Cairns, 27 September 2026





Outline

1. Motivation
2. The Quark-Meson Coupling model
3. Short-distance repulsion
4. The H-dibaryon
5. Beyond bulk observables
6. Summary



Neutron stars as a laboratory for dense QCD matter

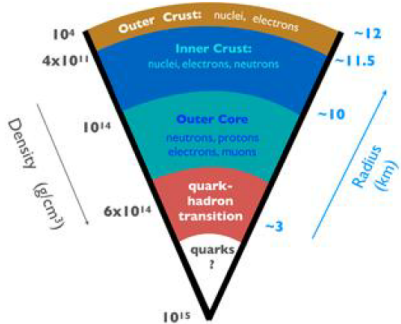
- Mass range $M \sim 1.0$–$2.1\, M_\odot$, radii $R \sim 10$–13 km
- Central densities $n_c \sim 2$–$10\, n_0$, $n_0 = 0.16$ fm^{-3}
- All four fundamental forces

Gravity

Strong interaction

Weak

EM



Equation of State (EoS)

Nuclear model $\longrightarrow$ EoS $p(\epsilon)$ $\longrightarrow$ TOV $\longrightarrow$ M–R

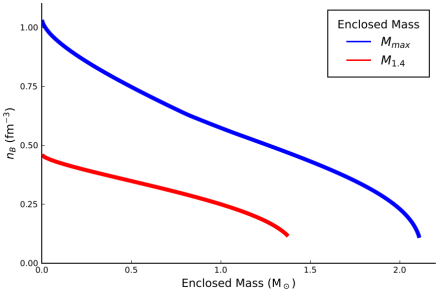
Change the assumptions of the nuclear model, and you predict a different mass and radius.

The tension: stiff core vs. soft crust

- PSR J0740+6620, $M = 2.072^{+0.067}_{-0.066}\, M_\odot$ demand a stiff EoS at high density
- GW170817 and NICER $R_{1.4} < 13.5$ km, and a soft EoS near saturation
- These requirements pull in opposite directions, and are made worse once strangeness enters

The hyperon puzzle: $\mu_i = B_i \mu_n - Q_i \mu_e$

Under β-equilibrium, hyperons ($\Lambda, \Xi^{0,-}$) are energetically favoured once the nucleon Fermi energy is high enough. Their appearance opens new low-momentum states, softening the EoS and *lowering* $M_{\max}$ – in apparent conflict with $2\, M_\odot$ pulsars.



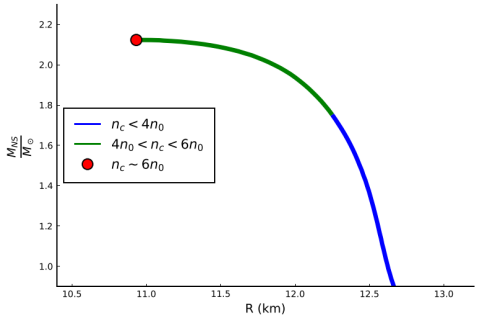
Reaching $M_{\max}$ probes far deeper than $M_{1.4}$

The relativistic mean-field starting point

$$\mathcal{L} = \sum_f \bar{\psi}_f \left[i\gamma^\mu \partial_\mu - M_f^*(\sigma) - g_\omega^f \gamma_\mu \omega^\mu - g_\rho^f \gamma_\mu \boldsymbol{\rho}^\mu \cdot \frac{\boldsymbol{\tau}}{2} \right] \psi_f + \frac{1}{2} \left(\partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2 \right)$$

$$- \frac{1}{4} \Omega_{\mu\nu} \Omega^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu - \frac{1}{4} R_{\mu\nu} \cdot R^{\mu\nu} + \frac{1}{2} m_\rho^2 \boldsymbol{\rho}_\mu \cdot \boldsymbol{\rho}^\mu$$

- $\sigma, \omega, \boldsymbol{\rho}$ meson fields standing in for the underlying QCD dynamics
- Couplings are fixed at saturation density – any stiffening/softening then propagates to *all* densities
- Fixing the hyperon puzzle needs density dependence: density-dependent couplings, non-linear meson self-couplings (σ^3, σ^4; ω^4; ω–ρ cross term), or many-body potentials



Why go to the quark level? $m_q^* = m_q - g_\sigma^q \sigma$

Quarks satisfy the Dirac equation inside a bag of radius R_B,

$$[i\gamma^\mu \partial_\mu - (m_q - g_\sigma^q \sigma)]\, q = 0 \quad (|\mathrm{r}| < R_B), \qquad (1 + i\gamma\cdot\hat{\mathrm{r}})q = 0 \quad (|\mathrm{r}| = R_B)$$

The meson-quark coupling modifies the wavefunction. The rest mass of a free 3-quark bag is

$$M_N = \frac{N_u \Omega_u + N_d \Omega_d - z_0}{R_B} + B V_B + \Delta E_M,$$

- In the quark-meson coupling (QMC) model, the σ, ω, ρ mesons couple directly to the confined u, d quarks (MIT bag), not to the baryon as a whole
- The internal quark wavefunctions respond self-consistently to the medium – this is what conventional RMF cannot capture

Scalar polarisability: the heart of QMC

Coupling the σ field to the quarks (not to the whole baryon) gives an effective mass

$$M_f^*(\sigma) = M_f - w_\sigma^f\, g_\sigma \sigma + \tilde{w}_\sigma^f\, \frac{d}{2}\,(g_\sigma \sigma)^2 ,$$

where d is the scalar polarisability. By the Feynman–Hellmann theorem,

$$g_\sigma^f(\sigma) = -\frac{\partial M_f^*}{\partial \sigma} = n_q\, g_\sigma^q\, S_f(\sigma), \qquad S_f(\sigma) \sim \int_0^{R_B} \left(f^2 - g^2\right) d^3 r,$$

with f, g the upper/lower Dirac components. As σ grows, the lower component grows and $S_f(\sigma)$ *decreases*: the effective coupling weakens with density.

Consequence

This is a genuine three– and many-body force, generated with *no new parameters* – it is what allows QMC to saturate nuclear matter and to predict hyperon couplings.

Nuclear matter energy density

At the mean-field (Hartree) level, the baryon single-particle energy is

$$E_f = \sqrt{k^2 + M_f^{*2}(\bar{\sigma})} + g_\omega^f \bar{\omega} + I_m^f g_\rho \bar{\rho},$$

sourced self-consistently by

$$m_\sigma^2 \bar{\sigma} = \sum_f \left(-\frac{\partial M_f^*}{\partial \sigma} \right) n_f^s, \qquad m_\omega^2 \bar{\omega} = \sum_f g_\omega^f n_f^v, \qquad m_\rho^2 \bar{\rho} = \sum_f g_\rho I_m^f n_f^v.$$

Hyperons ($\Lambda, \Xi^{0,-}$) couple through their light-quark content – QMC predicts their couplings, with no extra fit parameters, and Σ hyperons are excluded because the in-medium hyperfine splitting raises their threshold beyond where they appear.

Where does extra repulsion come from?

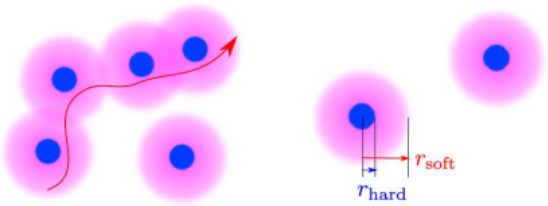


Figure: Representations of high density repulsion

$$\psi \propto e^{-r^2/2b^2}$$

Spatial Component

$$S(\vec{R}) = \int d^3r\, \psi^*(\vec{r})\psi(\vec{r}-\vec{R}) = e^{-R^2/4b^2}$$

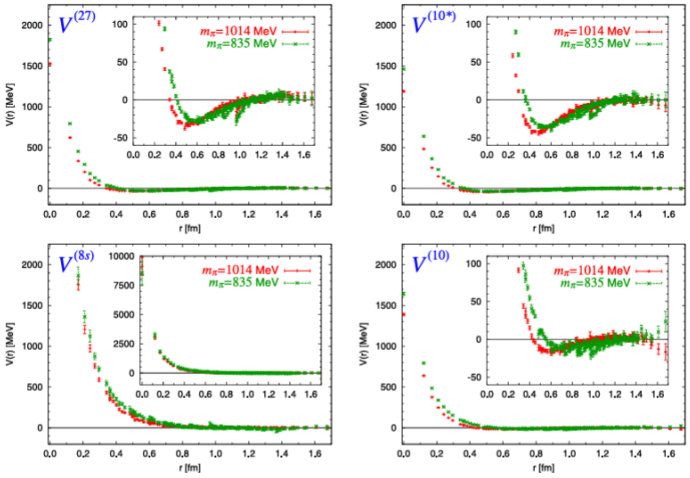
Degree of spatial symmetry

- Quark-model studies (Harvey 1981)

$$|6q\rangle = c_1(R)\,|NN\rangle + c_2(R)\,|\Delta\Delta\rangle + c_3(R)\,|CC\rangle.$$

  configurations make this overlap strongly repulsive
- This physics not probed by low-energy NN scattering and not accounted for by the ω
- $\left[g_\sigma^N,\, g_\omega^N,\, g_\rho^N\right] \rightarrow \left[n_0 = 0.16\,\mathrm{fm}^{-3},\, BE/A = -15.8\,\mathrm{MeV},\, S = 30\,\mathrm{MeV}\right]$

Repulsive hard-core for Y-species



T. Inoue et al. (HAL QCD Collaboration), Prog. Theor. Phys. 124, 591 (2010). arXiv:1007.3559

Mechanism 1: the overlap term

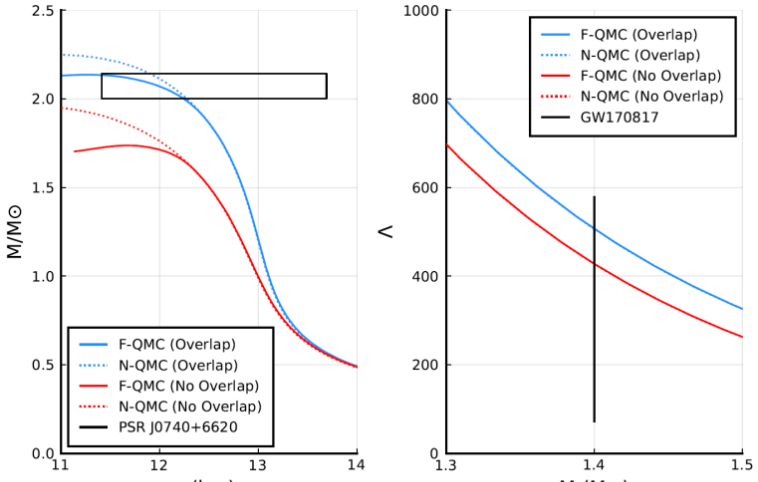
A Gaussian bag-overlap term is added to the energy density,

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

where $n_B^{-1/3}$ is the mean inter-baryon spacing and $b \sim 0.5$ fm is the quark-core size. E_0, b are fixed only by requiring *no change* to nuclear matter at n_0.

- Preferred values: $E_0 = 5500$ MeV, $b = 0.5$ fm
- With the cubic σ^3 self-interaction needed to fit the giant monopole resonance ($\lambda_3 = 0.02\,\mathrm{fm}^{-1}$, $K_\infty \approx 260$ MeV), the bare EoS alone gives $M_{\max} < 2\,M_\odot$
- Adding $\mathcal{H}_O$ restores $M_{\max} > 2.1\,M_\odot$, even with hyperons included, while $R_{1.4}$ sits just under 13 km and c_s^2 reaches ~ 0.5–0.6

Overlap phenomenology: bulk properties with and without hyperons



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

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

Mechanism 2: the excluded volume effect (EVE)

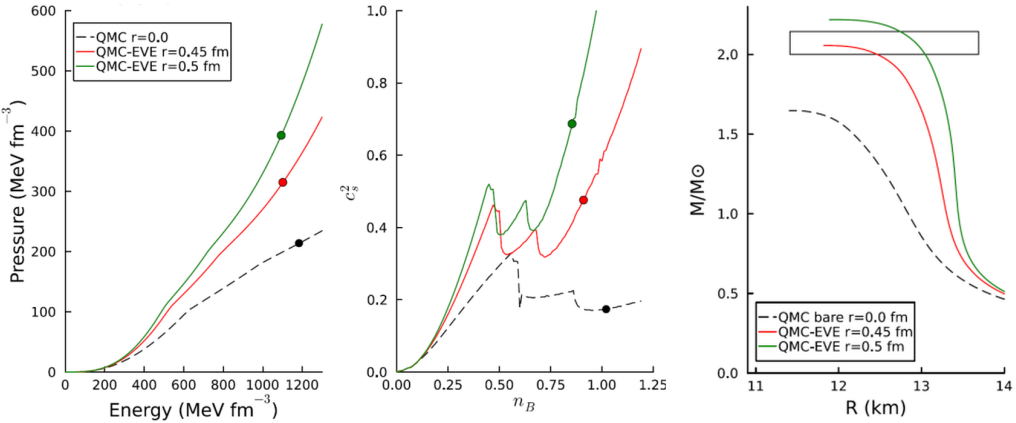
Each baryon excludes a volume $v_0 = \frac{4}{3}\pi r^3$ around itself:

$$\tilde{n}_i = \frac{n_i}{1 - v_0 n_B}, \qquad \tilde{\epsilon}(n_i) = (1 - v_0 n_B)\,\epsilon(\tilde{n}_i), \qquad \tilde{P}(n_i) = P(\tilde{n}_i), \qquad \tilde{\mu}_j = \mu_j(\tilde{n}_i) + v_0 P(\tilde{n}_i).$$

- Couplings refit for each hard-core radius $r = 0, 0.4, 0.45, 0.5$ fm to keep $n_0, E_B/A, S$ fixed
- K_∞ rises mildly (225 $\rightarrow$ 270 MeV); larger r stiffens the EoS and raises $M_{\max}$
- $r = 0.45$ fm: consistent with both PSR J0740+6620 and $\Lambda_{1.4}$ from GW170817
- Largest viable $M_{\max} \approx 2.2\,M_\odot$ at $r = 0.5$ fm, limited by causality ($c_s^2 < 1$)

c.f. Rischke, Gorenstein, Stoecker, Greiner, Excluded volume effect for the nuclear matter equation of state, Z. Phys. C **51**, 485 (1991)

Equation of State and Bulk Stellar Properties



Left/centre: pressure–energy density and $c_s^2(n_B)$ for QMC (bare) vs. QMC-EVE, $r = 0.45, 0.5$ fm.
Right: mass–radius relation with the corresponding constraint band.

Overlap vs. EVE: two views of the same physics

- Phenomenological placeholders for genuine multi-quark dynamics stemming from NN scattering data, Pauli Blocking, Hidden-colour configurations, and lattice QCD.
- Both mechanisms are independent of quark flavour.

Key result

$K_0 \approx 260$ MeV (EVE, $K_0 \approx 225$–270 MeV)
Hyperonic EoS

$$M_{\max} > 2\,M_\odot$$

$$R_{1.4} \lesssim 13.5 \text{ km}$$

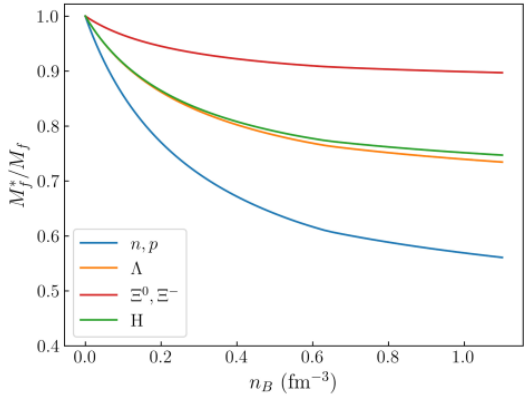
A new exotic candidate: the H-dibaryon

- H: a *uuddss*, spin-0, isospin-0, $B = 2$, $S = -2$ (Jaffe, 1977)
- Recall: the $g_\sigma^H(\sigma)$ and g_ω^H are derived within QMC.

$$M_H^* = M_H - 2\left[0.6672 + 0.04638 R_H - 0.0022 R_H^2\right] g_\sigma \sigma + 2\left[0.00146 + 0.0691 R_H - 0.00862 R_H^2\right] (g_\sigma \sigma)^2,$$

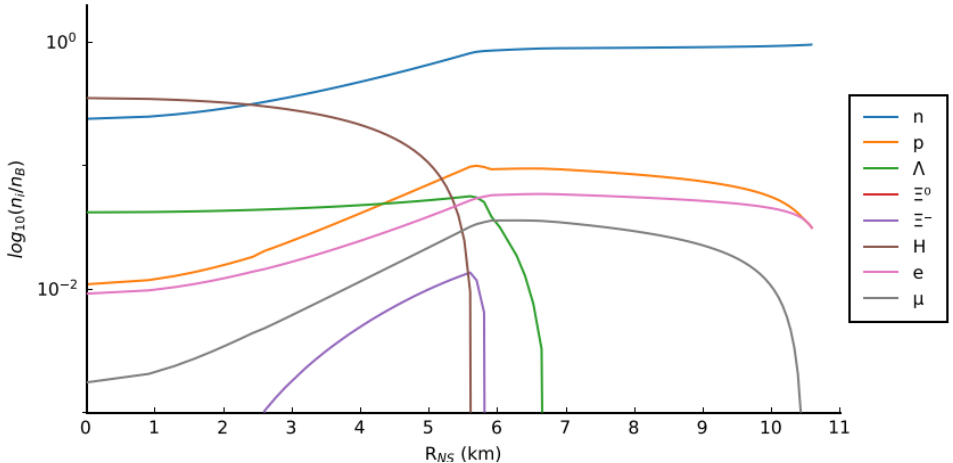
- Nagara event (H. Takahashi et al., Phys. Rev. Lett. 87, 212502 (2001))
  $M_H > 2M_\Lambda - B_{\Lambda\Lambda} = 2224\,\mathrm{MeV}$ ($^{6}_{\Lambda\Lambda}$He)
- Lattice QCD (HAL, NPLQCD) plus chiral extrapolation (Shanahan, Thomas, Young) suggest it is unbound by $\sim 26 \pm 11$ MeV relative to the $\Lambda\Lambda$ threshold, i.e. $M_H \approx$ 2247–2269 MeV
- As a boson, the H forms a zero-momentum condensate: $n_H = 2M_H^*\, H^* H$, $\varepsilon_H = M_H^* n_H$.
- no direct pressure contribution.

$\Lambda(uds)$, $H(uuddss)$



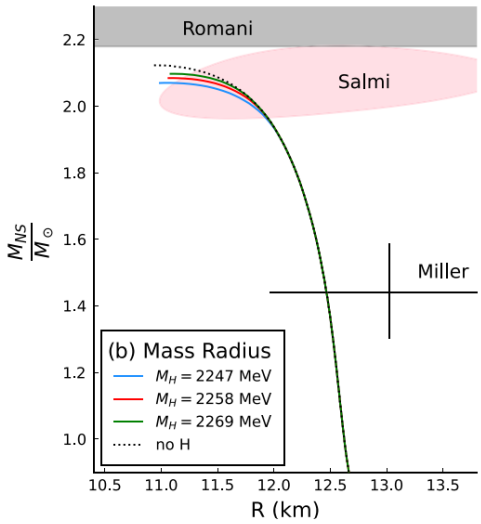
The H couples to σ through twice as many light quarks as the Λ. The small difference comes from the larger 6-quark bag, R_H (Mulders & Thomas, 1983).

$\mu_H = 2\mu_n$



Neutron star composition with the H-dibaryon condensate. The threshold of the H depends on the free mass, M_H

Mechanism 1: the overlap term — H-dibaryon



The phenomenological overlap term is species-blind, depending only on total baryon density:

$$\varepsilon_{\text{overlap}}(n_B) \;=\; E_0\, n_B\, \exp\left[-\left(\frac{n_B^{-1/3}}{b}\right)^2\right],$$

$$n_B \;=\; \sum_f n_f \;+\; 2\, n_H.$$

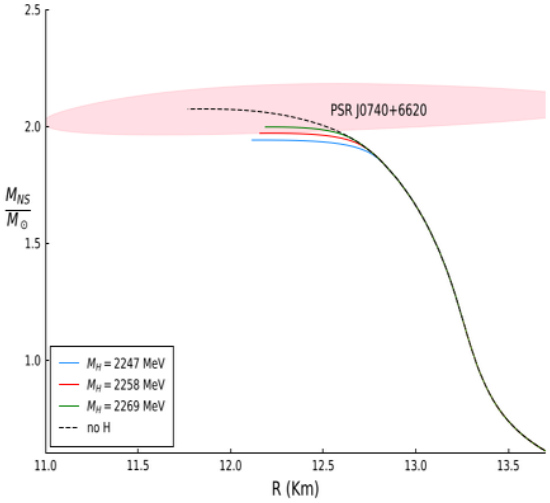
"The H particle has a direct influence on the pressure at high densities through the short-distance repulsion phenomenological term."

Mechanism 2: the excluded volume effect — H-dibaryon

$$n_B = \sum_f n_f + 2\,n_H,$$

$$\tilde{n}_f = \frac{n_f}{1 - v_0\,n_B}, \qquad \tilde{n}_H = \frac{n_H}{1 - v_0\,n_B}.$$

Since the H carries baryon number 2, it already contributes $2n_H$ to n_B — so it excludes twice the volume of an octet baryon *without* needing a separate $v_{0,H}$.



H-dibaryon results: a bosonic core

- $M_{\max}$: 2.12 $\to$ 2.07–2.10 $M_\odot$ (depends on M_H) — still $> 2\,M_\odot$
- H appears just after Λ and *suppresses* $\Xi^{0,-}$
- Heaviest stars: H dominant out to $r \approx 5.7$ km
- $\Lambda_{1.4}$ unaffected — no H in 1.4 $M_\odot$ stars

Interpretation

Pauli blocking of $H \to \Lambda\Lambda$ keeps it stable at high density.

If it exists, the H forms a bosonic condensate in the cores of the most massive neutron stars, without spoiling any bulk observational constraint.

Caveat: a mean-field, leading-order treatment — no lattice guidance is available at finite density.

A degeneracy problem and multimessenger probes

The issue

Nucleon-only, nucleon+hyperon, and nucleon+hyperon+H equations of state can all produce very similar mass–radius curves and tidal deformabilities. Bulk observables alone cannot tell these compositions apart.

This motivates two further probes of the microscopic composition:

- Neutrino transport (mean free path) – relevant to merger and supernova dynamics
- Fundamental (f-mode) oscillations – a future gravitational-wave observable

Neutrino mean free path (NMFP)

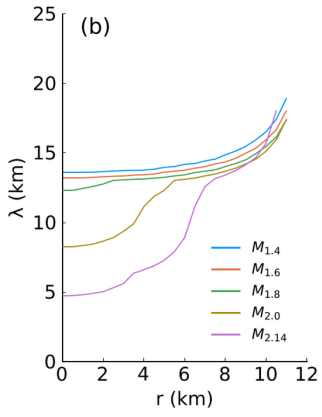
Neutral-current neutrino–baryon scattering, via

$$\mathcal{L}_{\rm NC} = \frac{G_F}{\sqrt{2}} \left[\bar{\nu}_e \gamma^\mu (1-\gamma_5) \nu_e\right] \sum_{B,Y} \bar{\psi}_{B,Y}\, \Gamma^{NC}_{[B,Y],\mu}\, \psi_{B,Y},$$

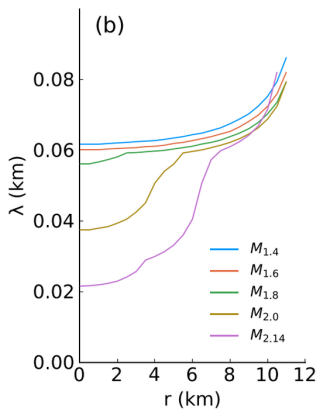
with $\Gamma^{NC}_{\mu} = \gamma_\mu (C_V - C_A \gamma_5)$, using the effective masses and couplings computed self-consistently within QMC.

- **Number density** n_B — sets the Fermi momentum p_F of each species (more scatterers $\rightarrow$ shorter λ)
- **Flavoured couplings** C_V, C_A — so equal abundances still give unequal opacity
- **Effective mass** $M_f^*(\sigma)$ — density-dependent via QMC; enters the axial/spin response (and sets the kinematic peak $q_0^{\max} \approx |\vec{q}|/\sqrt{(M_f^*/p_F)^2 + 1}$)
- **Neutrino energy** E_ν — cross section scales as $\lambda^{-1} \propto G_F^2 E_\nu^3$, so 5 $\rightarrow$ 30 MeV drops λ by $\sim 216\times$

Neutrino Mean Free Path: Trapping vs. Stellar Mass



$E_\nu = 5$ MeV



$E_\nu = 30$ MeV

$\lambda(r)$ for neutron stars of mass $M = 1.4$–$2.14\,M_\odot$, at two neutrino energies.

Key result

Cold NS: $\lambda \sim 5$–19 km — free-streaming.

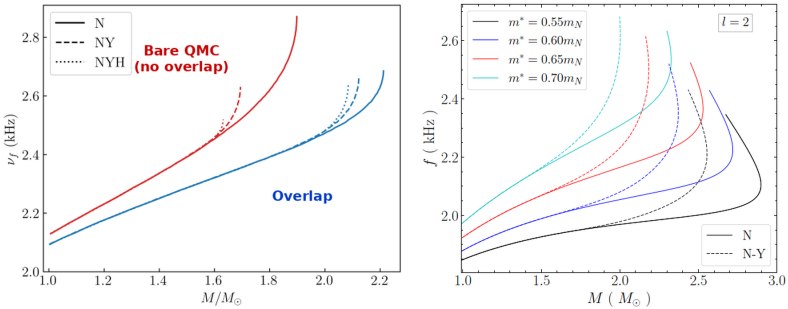
Hot/proto-NS: λ collapses to tens of metres, more strongly for massive stars.

Finite T: $n_Y \sim e^{-(E_Y-\mu_Y)/T}$ — thermal hyperons, shorter λ.

f-mode oscillations

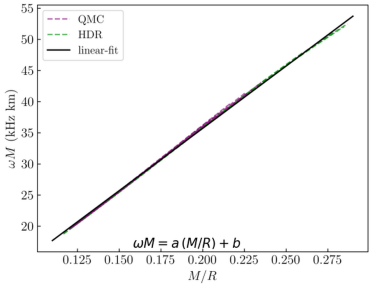
- Fundamental quadrupole ($l = 2$) oscillations, computed here for the first time within QMC, in the relativistic Cowling approximation
- Frequencies span $\nu_f \sim 1.97$–2.13 kHz at low mass to ~ 2.40–2.66 kHz at $M_{\max}$ – within reach of next-generation detectors (Einstein Telescope, Cosmic Explorer)
- Differences between nucleon-only, hyperonic, and H-bearing EoS are small: $|\Delta\nu_f/\nu_f| \lesssim 3.4\%$ at the maximum mass of each parametrisation
- Softer EoS $\rightarrow$ higher ν_f at fixed mass; the H competes with Ξ^0, and this competition – not the H itself directly – is what shifts ν_f
- QMC shows the *opposite* trend to some other RMF models: non-nucleonic degrees of freedom *lower* ν_f at $M_{\max}$ here, rather than raising it

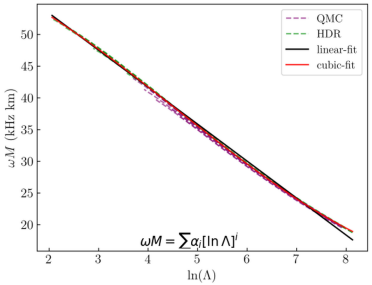
f-modes: A Muted Signature Compared to Other Models

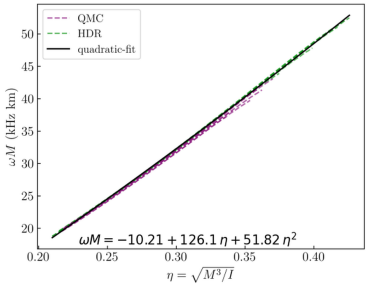


QMC: including H shifts $\nu_f^{\max}$ by only $|\Delta\nu_f/\nu_f| \lesssim 3.4\%$. RMF (Pradhan & Chatterjee, arXiv:2011.02204): hyperons robustly *raise* $\nu_f^{\max}$ — a clean discriminator.

Universal Relations: One Measurement, Three Structural Handles







Why this matters

The Claim is *given any two measurements of M, R, ν_f, Λ, or I; we extract the other quantities from URs in a model independent way.*

Summary

- Quark-level short-distance repulsion (overlap or EVE) resolves the hyperon puzzle within QMC: $M_{\max} \sim 2.1$–$2.2\,M_\odot$ with hyperons, $K_0 \approx 260$ MeV, $R_{1.4} \lesssim 13.5$ km – with no new free parameters beyond the two repulsion parameters
- The H-dibaryon can be incorporated the same way: it forms a sizeable ($\sim$5–6 km) bosonic condensate in the heaviest stars, with only a small reduction in $M_{\max}$
- Bulk mass–radius observables cannot distinguish nucleonic, hyperonic, and H-bearing compositions – a genuine degeneracy
- Neutrino transport and f-modes offer complementary, though currently modest, discriminating power

Thank you

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In collaboration with: A. W. Thomas, P. A. M. Guichon, T. F. Motta, P. T. P. Hutauruk, R. Maiti, D. Chatterjee

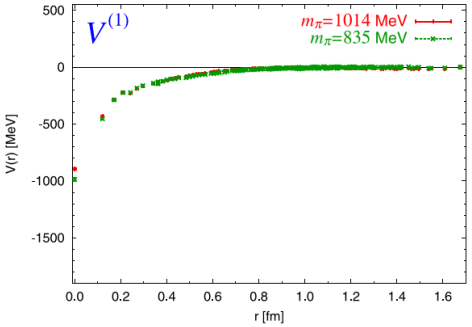




Publications

1. J. Leong, T. F. Motta, A. W. Thomas, P. A. M. Guichon, *Dense nuclear matter with phenomenological short distance repulsion*, Phys. Rev. C **108**, 015804 (2023).
2. J. Leong, A. W. Thomas, P. A. M. Guichon, *Excluded volume effects on cold neutron star phenomenology*, Nucl. Phys. A **1050**, 122928 (2024).
3. J. Leong, P. A. M. Guichon, A. W. Thomas, *Heavy neutron star phenomenology with an H dibaryon*, Phys. Rev. C **113**, 015809 (2026).
4. J. Leong, A. W. Thomas, P. A. M. Guichon, *Are neutron stars rich in H-dibaryons?*, PoS QCHSC24, 250 (2025).
5. J. Leong, P. T. P. Hutauruk, A. W. Thomas, *Neutrino mean free path in neutron stars in the presence of hyperons*, Phys. Rev. C **110**, 025503 (2024).
6. R. Maiti, J. Leong, D. Chatterjee, A. W. Thomas, *f-mode oscillations for hyperons and H-dibaryons in neutron stars*, Phys. Rev. D **113**, 063064 (2026).

The flavour-singlet channel: where the H lives



HAL QCD, Inoue et al., PTP **124**, 591 (2010)

$$8 \otimes 8 = 27 \oplus 8_s \oplus 1 \oplus \overline{10} \oplus 10 \oplus 8_a$$

$$|1\rangle = -\sqrt{\tfrac{1}{8}}\,|\Lambda\Lambda\rangle + \sqrt{\tfrac{3}{8}}\,|\Sigma\Sigma\rangle + \sqrt{\tfrac{4}{8}}\,|N\Xi\rangle$$

$$J^P = 0^+, \quad I = 0, \quad S = -2, \quad B = 2 \quad (uuddss)$$

- No core: attractive at all r (Jaffe, 1977)
- SU(3) limit: bound; physical point: $\gtrsim 2M_\Lambda$

In QMC

$$M_H^* = M_H - 2\,w_\Lambda(R_H)\,g_\sigma\sigma + 2\,\tilde{w}_\Lambda(R_H)\,\frac{d}{2}\,(g_\sigma\sigma)^2$$

- Free-space binding $\rightarrow M_H$ (scanned)
- In-medium response + hyperfine $\rightarrow \Lambda$ weights