Constraining twin stars with cold neutron star cooling data

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Outline

1. Constraining the core EOS with neutron star luminosities
   - Motivation
   - Research questions
2. EOS we work with
   - Hadronic
   - Hybrid
3. Constraints on hybrid EOS phase transition densities
   - Reproducing sources' luminosities

Based on MM et al, 2024 (submitted to PRD, ArXiv:2408.05287)

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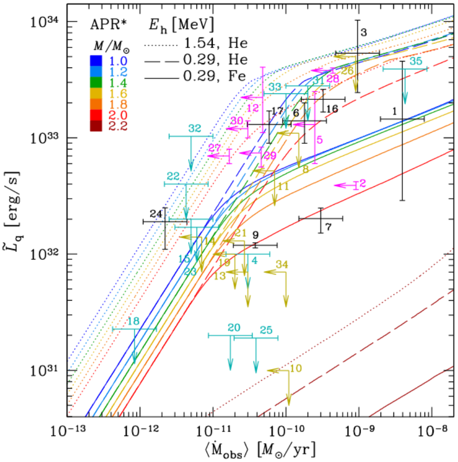
Temperature observations can constrain the core EOS

Transiently-accreting stars provide luminosity as a function of accreted mass

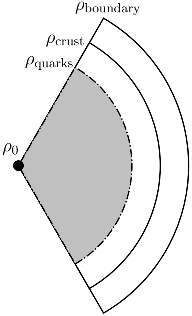
By observing several cycles of accretion, we estimate how fast they cool down

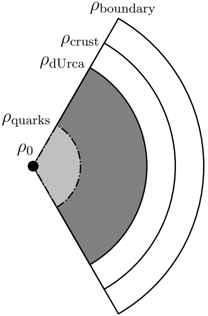


From Potekhin et al, 2023 (MNRAS), ArXiv:[2303.08716]

Research questions

- Are there twin-star EOS that are inconsistent with current luminosity data?
- Can we constrain the quark-hadron phase transition with cooling calculations?





Outline

Realistic hadronic RMF EOS, with e^- and μ^-

Nucleon interactions are modelled by the exchange of mesons, whose interaction strengths are estimated with the relativistic mean field approximation.

The Lagrangian is

$$\mathcal{L}_0 = \bar{\psi}\left(i\gamma^\mu\partial_\mu - m^*\right)\psi + \frac{1}{2}\left(\partial_\mu\phi\partial^\mu\phi - m_{\rm s}^2\phi^2\right) + \frac{1}{2}m_v^2 V_\mu V^\mu - \\ -\frac{1}{4}F_{\mu v}F^{\mu\nu} + \frac{1}{2}m_\rho^2 \boldsymbol{b}_\mu \cdot \boldsymbol{b}^\mu - \frac{1}{4}V_{\mu v}V^{\mu v} - \frac{1}{4}\boldsymbol{b}_{\mu\nu}\cdot\boldsymbol{b}^{\mu\nu}$$

$$\mathcal{L}_{\rm int} = \bar{\psi}\left[g_s\phi - \left(g_{\rm v}V_\mu + \frac{g_\rho}{2}\tau\cdot\boldsymbol{b}_\mu + \frac{e}{2}\left(1+\tau_3\right)A_\mu\right)\gamma^\mu\right]\psi - \frac{\kappa}{3!}\left(g_{\rm s}\phi\right)^3 \\ -\frac{\lambda}{4!}\left(g_{\rm s}\phi\right)^4 + \frac{\zeta}{4!}\left(g_{\rm v}^2 V_\mu V^\mu\right)^2 + \Lambda_{\rm V}\left(g_{\rm v}^2 V_\mu V^\mu\right)\left(g_\rho^2 \boldsymbol{b}_\mu\cdot\boldsymbol{b}^\mu\right)$$

Realistic hadronic RMF EOS, with e^- and μ^-

The EOS can be expanded as

$$E(n, \alpha) = E(n, 0) + E_{\mathrm{sym}}(n)\alpha^2 + \cdots \tag{1}$$

with $\alpha = 1 - 2y$ being the asymmetry parameter with $y = n_P/(n_N + n_P)$

$$E(n, 0) = \epsilon_0 + \frac{1}{2}Kx^2 + \cdots \,, \tag{2}$$

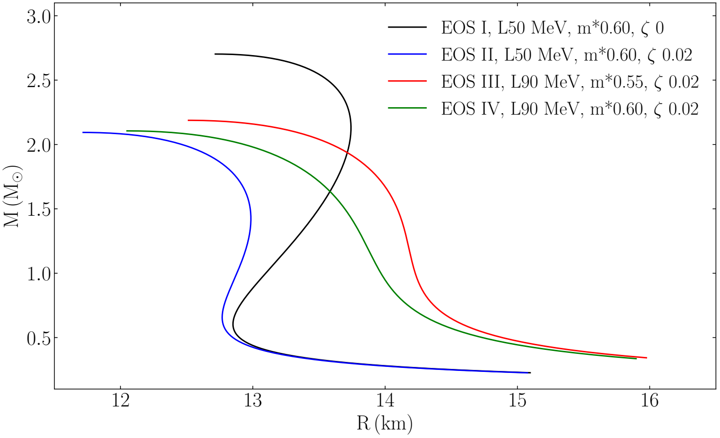
and

$$E_{\mathrm{sym}}(n) = J + Lx + \frac{1}{2}K_{\mathrm{sym}}x^2 + \cdots \,, \tag{3}$$

where $x = (n - n_{\mathrm{sat}})/3$

Hadronic RMF EOS, with e^- and μ^-

We work with EOS with different values of L, Dirac m^* and ζ



Nucleonic direct Urca (dUrca) cooling

Reactions like $n \to p + l + \bar{\nu}_l, \quad p + l \to n + \nu_l$

for NS in beta-equilibrium, can only happen when energy and momentum are conserved, that is, for electrons only:

$$P_{Fn} \leq P_{Fp} + P_{Fe} \Rightarrow \quad Y_p \geq \left[(Y_n)^{1/3} - (Y_e)^{1/3} \right]^3$$

such that neutrino dUrca emissivity

$$Q_0^{dUrca} = \frac{457\pi}{10080} G_{\mathrm{F}}^2 \cos^2 \theta_{\mathrm{C}} \left(1 + 3{g_{\mathrm{A}}^*}^2\right) \frac{m_n^* m_p^* m_e}{h^{10} c^3} (k_{\mathrm{B}} T)^6 \, \Theta_{npe}$$

with $g_A^* \simeq g_A \left(1 - \frac{n}{4.15(n_{sat} + n)}\right)$.

Quark EOS

First-order Maxwell construction, quark phase analytically given by:

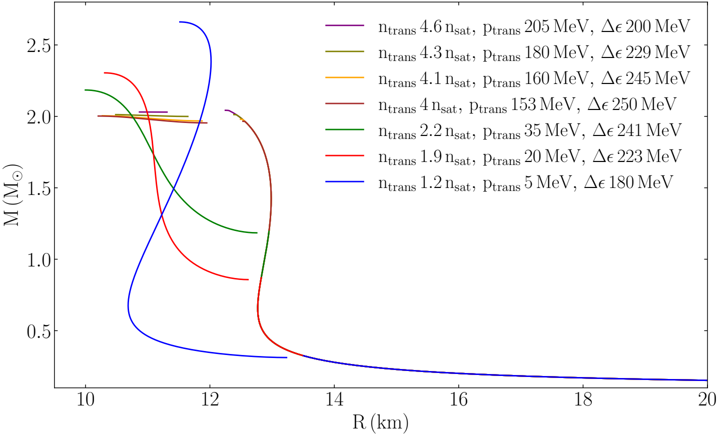
$$\epsilon(p) = \epsilon_{\text{hadronic}}(p), p < p_{\text{trans}}$$
$$\epsilon(p) = \epsilon_{\text{hadronic}}(p_{\text{trans}}) + \Delta\epsilon + c_{QM}^{-2}(p - p_{\text{trans}}), p \geq p_{\text{trans}}$$

$$n = n_{\text{hadronic}}, n < n_{\text{trans}}$$
$$n = \frac{(p_{\text{trans}} + \epsilon_{\text{hadronic}}(p_{\text{trans}}) + \Delta\epsilon) n_{\text{hadronic}}(p_{\text{trans}})}{p_{\text{trans}} + \epsilon_{\text{hadronic}}(p_{\text{trans}})} \sqrt{\frac{\epsilon + p}{\epsilon_{\text{hadronic}}(p_{\text{trans}}) + p_{\text{trans}}}}$$

we choose $c_{QM} = 1$ to maximize the phase space

Quark-hadron hybrid (twin) stars

Hybrid stars with two mass-radius branches, consistent with observations
Phase transition density arbitrarily chosen



Quark direct Urca cooling

Similarly, reactions like $d \to u + e^- + \bar{\nu}_e, \quad u + e^- \to d + \nu_e$

result in quark dUrca emissivity

$$Q^{\mathrm{q\,dUrca}} = \frac{914}{315} \frac{G_{\mathrm{F}}^2 \cos^2\theta_{\mathrm{C}}}{\hbar^{10} c^6} (3 Y_e)^{1/3} \alpha \pi^2 \hbar^3 n \, (k_{\mathrm{B}} T)^6,$$

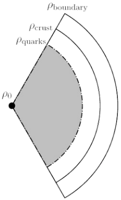
if quark masses neglected and $n_q^i = n_q^j$, $n_e = n_\mu = 0$

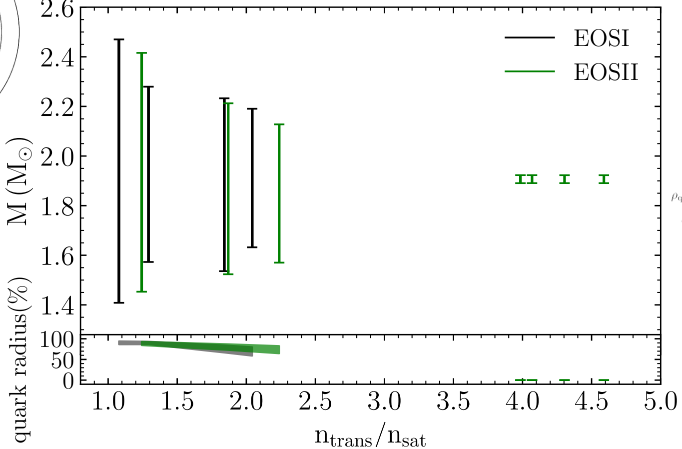
(We assume $\alpha = 0.1$ and $Y_e = 10^{-5}$)

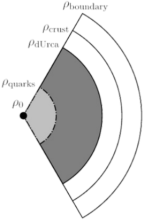
Outline

Can we reproduce MXB 1659-29's inferred luminosity?

Yes but a large quark core is needed







Superfluidity suppresses the dUrca emissivity

When superfluidity or superconductivity are considered, $Q^{dUrca} = Q_0^{dUrca} R$ where, for neutron triplets ($P_2^3, m = 0$),

$$\tau = T/T_c$$

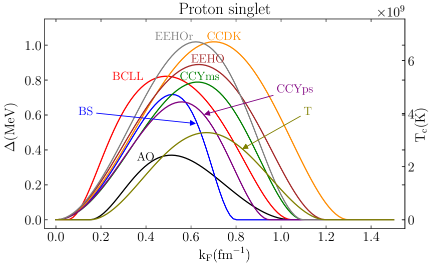
$$v_{\mathrm{T}} = \sqrt{1-\tau}\left(0.7893 + \frac{1.188}{\tau}\right)$$

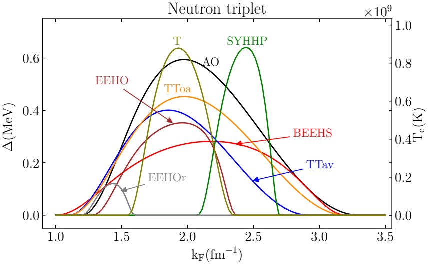
$$R_{\mathrm{L}} = \left[0.2546 + \sqrt{(0.7454)^2 + (0.1284\, v_{\mathrm{T}})^2}\right]^5 \exp\left(2.701 - \sqrt{(2.701)^2 + v_{\mathrm{T}}^2}\right)$$

When proton and neutron pairing are simultaneously present, $R_L \sim \min\left(R_{L\,\mathrm{singlet}}, R_{L\,\mathrm{triplet}}\right)$

Varied nuclear pairing gap models

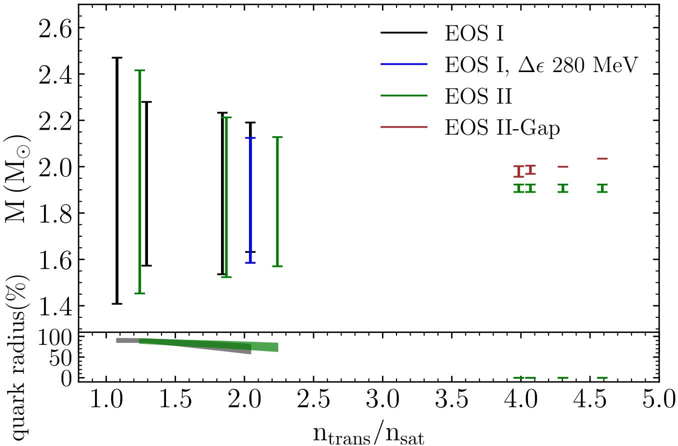
Many possible parametrizations, Ho et al, 2015 (PRC) [ArXiv:1412.7759]





With nuclear superfluidity

Including nuclear pairing doesn't improve the situation necessarily



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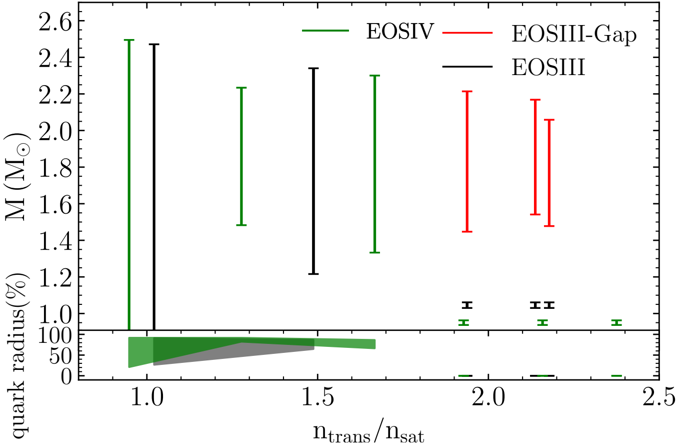
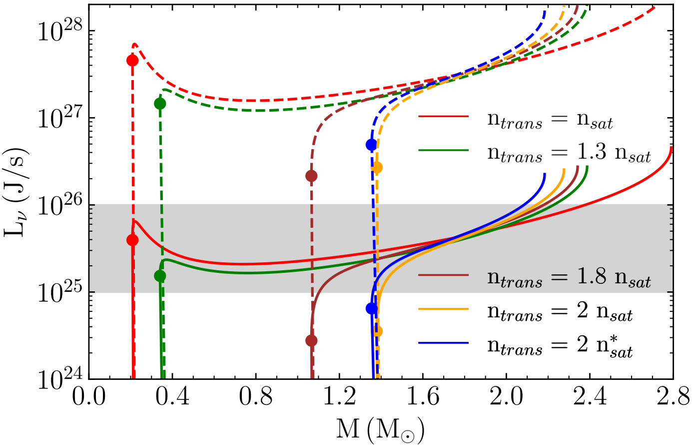


Can we reproduce SAX 1808.4-3625's inferred luminosity?

Not always, especially for low density quark-hadron phase transitions



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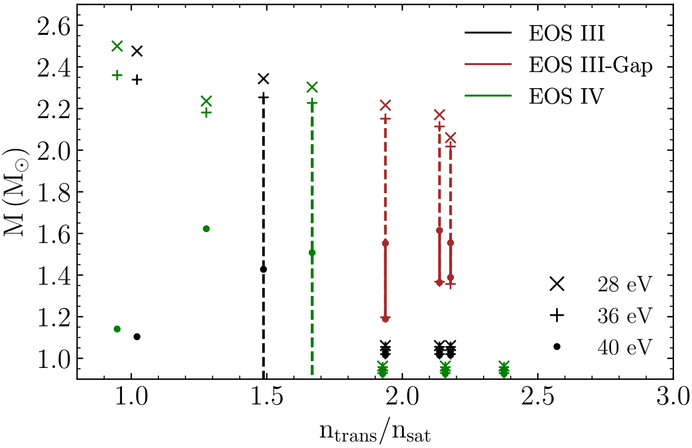
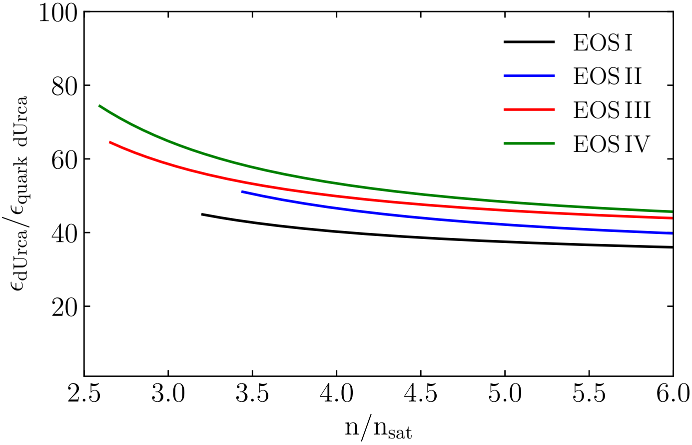


Results sensitive to efficiency rates of the cooling processes



Summary

- It's challenging to build twin stars that respect mass-radius, tidal deformability and luminosity constraints
- Low density phase transitions (below 1.7 n_{sat}) fail to reproduce cold neutron stars
- Further investigating the sensitivity of these results would be interesting

Thank you!

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Outline

4 Extra slides

Transiently-accreting NS

Crust reactions release

$$Q_{\text{nuc}} \approx 1 - 2\text{MeV}/m_{\text{u}},$$

per accreted nucleon. Hence the luminosity entering the core can be estimated

$$L_v(\tilde{T}) + L_\gamma(\tilde{T}) \approx \langle \dot{M} \rangle Q_{\text{nuc}}$$

But don't forget that

$$\tilde{T} = 7.0 \times 10^7 \text{ K} \left(\frac{T_{\text{eff}}^{\infty}}{63.1\text{eV}} \right)^{1.82} \quad \text{(Fe envelope)}$$

$$\tilde{T} = 3.1 \times 10^7 \text{ K} \left(\frac{T_{\text{eff}}^{\infty}}{63.1\text{eV}} \right)^{1.65} \quad \text{(He envelope)}$$

Heat capacity

The total heat capacity is a combination of specific volumetric heat capacities,

$$C_v = \int_0^R \frac{4\pi r^2 \sum c_x}{\left(1 - (2Gm(r)/c^2 r)\right)^{1/2}} dr,$$

where $c_x = \frac{2k_B^2 T}{(2\pi\hbar)^3} \int d\mathbf{k}_x \, (\epsilon_x - \mu_x) \, \frac{df_x}{dT}$.

If strongly degenerate, $c_x = \frac{m_x^* k_{F\ x} k_B^2 T}{3\hbar^3}$

If superfluid/superconducting, $c_x^{paired} = c_x R$, where R is a function of T/T_c and depends on nuclear pairing channel

Heat capacity calculation details

Given the individual heat capacities of each species C_x, we find the total heat capacity by

$$C_{\rm total}^{\rm core} = \int_0^{R_{\rm core}} \frac{4\pi r^2 \sum C_x}{\left(1 - (2Gm(r)/c^2 r)\right)^{1/2}} dr$$

where $C_x = \frac{m_x^* p_{{\rm F},x}}{3\hbar^3} k_B^2 T$. With superfluidity, it gets reduced such that $C_x^{pairing} = C_x R$. For neutron triplets,

$$\tau = T/T_c$$
$$u_{\rm T} = \sqrt{1-\tau}(5.596 + 8.424/\tau)$$
$$R_C = \left[0.6893 + \sqrt{(0.790)^2 + (0.03983\, u_{\rm T})^2}\right]^2 \exp\left(1.934 - \sqrt{(1.934)^2 + \frac{u_{\rm T}^2}{16\pi}}\right),$$