PARTICLE COMPOSITION AND NUCLEAR PAIRING MODELS OF NEUTRON STARS CORES: A STUDY OF TRANSIENTLY ACCRETING STAR MXB 1659-29

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compute canada | calcul canada

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SUMMARY:

Neutron star cooling data can constrain equation of state (EOS) properties, such as particle composition. We study source MXB 1659-29, a transiently accreting star whose temperature is consistent with fast-cooling processes [1], to investigate whether this data can be reproduced with a family of hadronic EOS parametrized by the slope of symmetry energy (L).

WHAT'S MXB 1659-29 MASS?

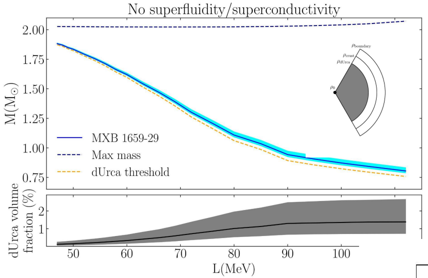


Figure 1: Mass predictions for no nuclear pairing

→ EOS need to have proton fraction large enough to accomodate dUrca processes **(check yours!)**

Different mass ranges for low, intermediate and high L ⟶

(more details in the next slides)

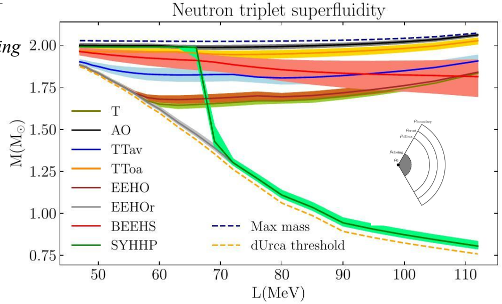


Figure 2: Mass predictions with neutron pairing

Quark-hadron transition density **(2 $\rho_0 \leq \rho$), if $\rho > 5\ \rho_0$, no quark signature detectable⟶**

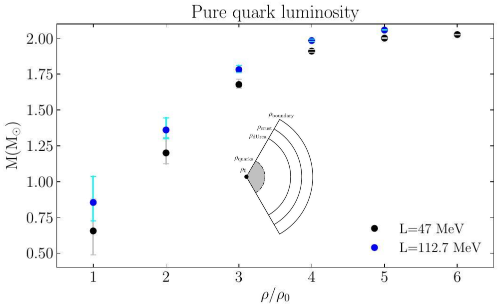


Figure 3: Mass predictions with quarks EOS

TAKE HOME MESSAGES:

- If no quarks in your EOS, you need to have dUrca processes (limits proton fraction)
- If L ≳ 80, strong nuclear pairing is needed (explains fast and slow cooling stars)
- Mass observations for this source will exclude some scenarios

REFERENCES:

[1] Brown, E. et al. Rapid Neutrino Cooling in the Neutron Star MXB 1659-29. Phys. Rev. Lett. 120, 18 (2018), 182701

[2] Mendes, M. et al. Probing dense matter physics with transiently-accreting neutron stars: the case of source MXB 1659-29. Proceedings of XVI Marcel Grossmann Meeting (2021), arXiv:2110.11077 [nucl-th]

NUCLEAR PAIRING:

Proton superconductivity and neutron superfluidity are expected to exist at neutron star core densities. We used models described by [5] and references therein, with critical temperatures: They suppress the direct Urca neutrino emission rate by $\epsilon^{\mathrm{dUrca}} = \epsilon_0^{\mathrm{dUrca}} R$

For neutron triplet

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

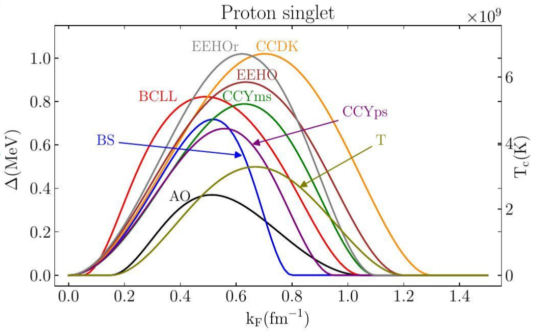
$$R_{\mathrm{L}} = \left[0.2546 + \sqrt{(0.7454)^2 + (0.1284\, v_{\mathrm{T}})^2}\right]^5 \exp\left(2.701 - \sqrt{(2.701)^2 + v_{\mathrm{T}}^2}\right)$$

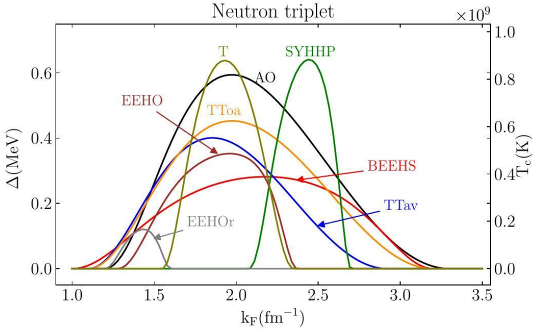
For proton singlet

$$v_{\mathrm{S}} = \sqrt{1-\tau}\left(1.456 - \frac{0.157}{\sqrt{\tau}} + \frac{1.764}{\tau}\right)$$

$$R_{\mathrm{L}} = \left[0.2312 + \sqrt{(0.7688)^2 + (0.1438\, v_{\mathrm{S}})^2}\right]^{5.5} \exp\left(3.427 - \sqrt{(3.427)^2 + v_{\mathrm{S}}^2}\right)$$

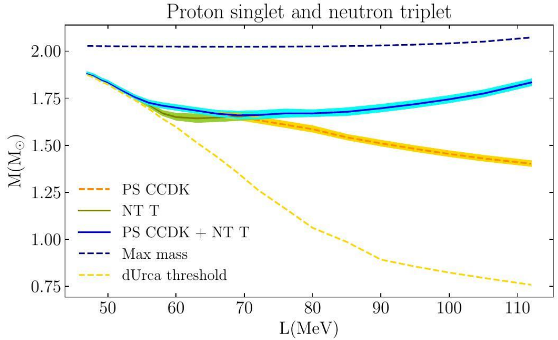
$$\tau = T/T_c$$

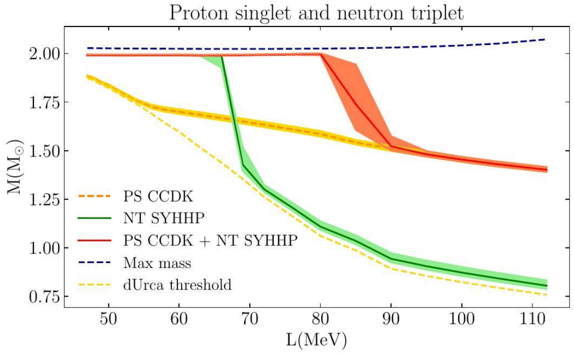




The inferred temperature of the source is 2.5 x 10^7 K, very low compared to the amplitudes of the models, thus, **opening and closing densities are more important factors** in finding dUrca suppression

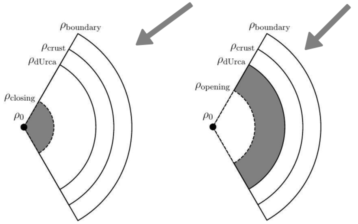
GAP MODELS COMBINATIONS:





Proton and neutron pairing are simultaneously present in the core of neutron stars, but usually neutron superfluidity dominates (Figure 2, slide 1). When it doesn't, **superconductivity can change the results significantly**

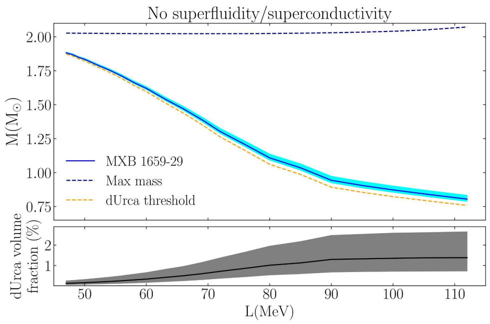
Superconductivity can also determine whether most of the luminosity comes from the innermost or outermost core



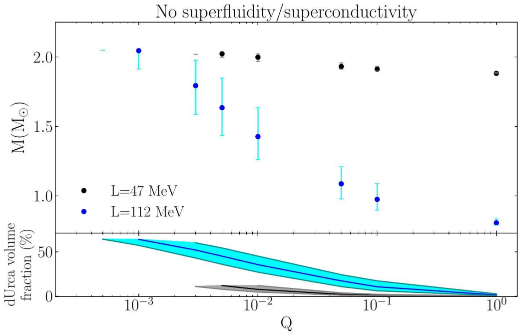
VARYING PRE-FACTOR:

Multiplying the direct Urca emissivities by a pre-factor Q, we model less efficient direct Urca processes with same threshold, or differences on nucleons effective masses.

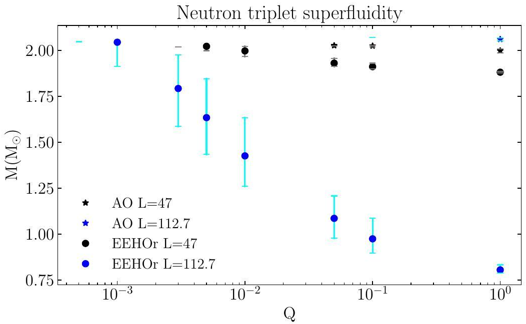
For comparison, the Q=1 case:



All EOS lie between the blue (highest L) and black (lowest L) curves:

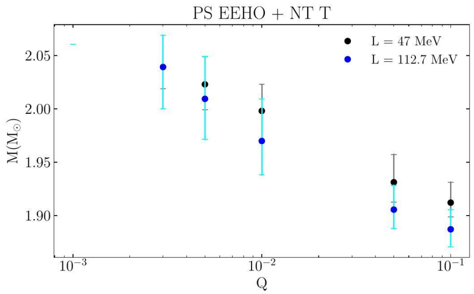


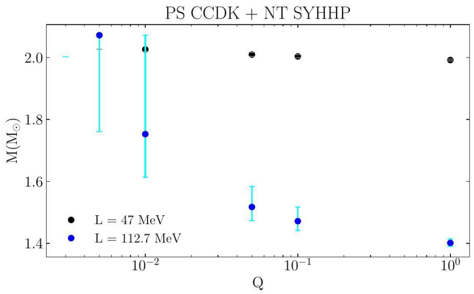
All neutron gap models are between the less suppressive one (EEHOr) and the most suppressive one (AO):



Note how, for Q < 1, the direct Urca volume fraction increases significantly, that is, more of the star's core is actively emitting neutrinos

Similar trends with both nuclear pairings active:





Another EOS can't have $M_{\mathrm{eff\,n}}\, M_{\mathrm{eff\,p}}$ < 0.001-0.005 $M_{\mathrm{eff\,n}}\, M_{\mathrm{eff\,p}}$ (our EOS) for all densities, T=0 **(check yours!)**

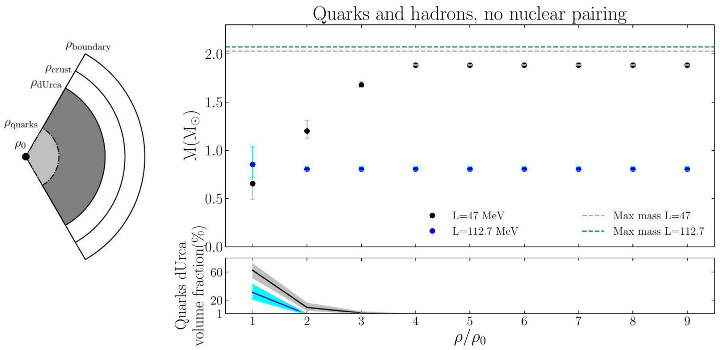
Other fast cooling processes could explain this data, but only if their emissivities > 0.001-0.005 direct Urca emissivity (maybe quarks? let's check!)

INCLUDING QUARKS:

Setting the transition density by hand, assuming no mixed phase, $\alpha = 0.1$, $Y_e = 0.01$ (as model independent as possible), we find:

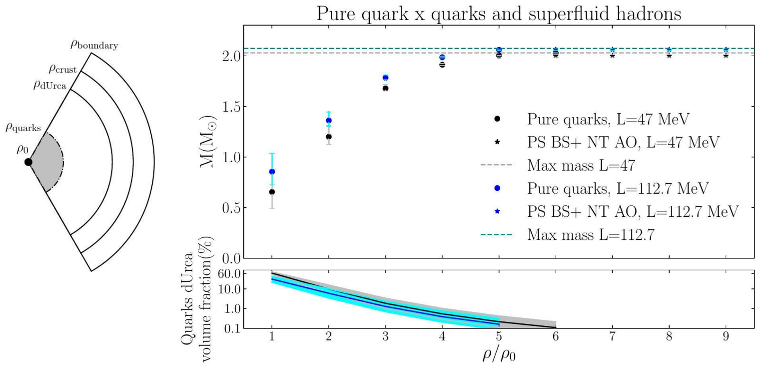
When the star is not superfluid at all (PS BS+NT EEHOr, for example)

Hadronic direct Urca dominates, thus, quark presence is masked unless
-small transition density AND small/intermediate L EOS



When the star is strongly superfluid (PS BS+NT AO, for example), simulated by the pure quarks case

Hadronic direct Urca dominates, thus, **quark presence is masked for transition density larger than ~ 5/6 ρ_0**



The realistic case is something in between, either way, **transition at ρ_0 is disfavored** because it creates too small stars

Detailed equations on the next slide

EXTRA REFERENCES:

[*] Mendes, M. et al. Probing the dense matter physics of neutron star cores with source MXB 1659-29. In preparation :)

[3] Chen, W.-C., Piekarewicz, J. Building relativistic mean field models for finite nuclei and neutron stars. Phys. Rev. C: Nucl. Phys. 90,4 (2014), 044305

[4] Fattoyev, F.F., Piekarewicz, J. Relativistic models of neutron-star matter equation of state. Phys. Rev. C.: Nucl. Phys. 82, 2 (2010), 025805

[5] Ho, W. C. G. et al. Tests of the nuclear equation of state and superfluid and superconducting gaps using the Cassiopeia A neutron star. Phys. Rev. C: Nucl. Phys. 91,1 (2015), 015806

EQUATION OF STATE:

We used relativistic mean field EOS derived from the FSUGold family [3], consistent with experimental low-energy nuclear physics data (binding energy, charge radii and giant monopole resonance of nuclei) and astronomical observations (maximum mass, radius of 1.4 M_{sun} ($M_{\odot}$) stars) [4]

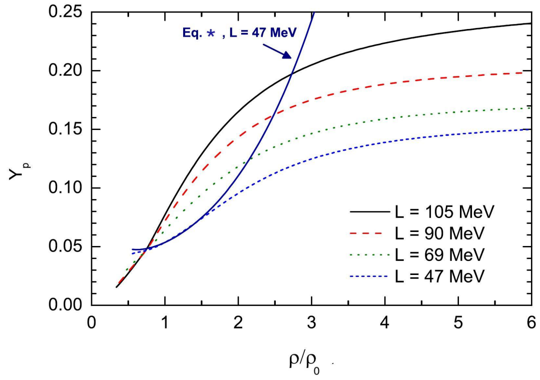
$$E(\rho,\delta) = E_0(\rho) + E_{sym}(\rho)\cdot\delta^2 + \mathcal{O}(\delta^4) \qquad \delta = \frac{(\rho_n-\rho_p)}{\rho}$$

$$E_0(\rho) = B + \frac{1}{18}K\delta^2 + \cdots \qquad E_{sym}(\rho) = E_{sym}(\rho_0) + \frac{L}{3\rho_0}(\rho-\rho_0) + \frac{K_{sym}}{18\rho_0^2}(\rho-\rho_0)^2 + \cdots \qquad L = 3\rho_0 \frac{\partial S(\rho)}{\partial\rho}\Big|_{\rho=\rho_0} \text{ and } K_{sym} = 9\rho_0^2 \frac{\partial^2 S(\rho)}{\partial\rho^2}\Big|_{\rho}$$

All EOS have B = -16.26 MeV, K = 237.7 MeV and ρ_0=0.1504 fm^{-3} with varying $E_{sym}(\rho_0)$, L and K_{sym}

Larger L is correlated with larger proton fractions (Yp). For low densities, the following equation (*) describes it well:

$$Y_p \simeq \frac{64}{3\pi^2\rho_0(\delta+1)}\left(\frac{E_{sym}(\rho_0)+3L\delta+\frac{1}{18}K_{sym}\delta^2}{\hbar c}\right)^3$$



DIRECT URCA COOLING:

The most effective cooling process within neutron stars are direct Urca reactions. For purely hadronic EOS, they are

$$n \to p + e^- + \bar{\nu}_e, \quad p + e^- \to n + \nu_e \qquad n \to p + \mu^- + \bar{\nu}_{\mu^-}, \quad p + \mu^- \to n + \nu_{\mu^-}$$

These processes can only happen when energy and momentum are conserved, that is, without muons, $k_{Fn} \le k_{Fp} + k_{Fe}$ $\quad Y_p \ge Y_{p\,\mathrm{dUrca}} = \frac{\left[(3\pi^2\hbar^3\rho Y_n)^{1/3} - (3\pi^2\hbar^3\rho_e)^{1/3}\right]^3}{3\pi^2\hbar^3\rho}$

The emissivities are given by $\begin{cases} \epsilon_0^{\mathrm{dUrca}\ e^-} = \dfrac{457\pi}{10080} G_F^2 \cos^2\theta_C \left(1+3g_A^2\right) \dfrac{m_n^* m_p^* m_e^*}{\hbar^{10}c^3}(k_B T)^6\,\Theta_{npe} \\ \epsilon_0^{\mathrm{dUrca}\ \mu^-} = \epsilon_0^{\mathrm{dUrca}\ e^-} \end{cases}$ and the total direct Urca neutrino luminosity is $L_{\nu_{\mathrm{dUrca}}} = \int_0^{R_{\mathrm{core}}} \frac{4\pi r^2 \epsilon_0^{\mathrm{dUrca\ total}}}{\left(1-(2Gm(r)/c^2 r)\right)^{1/2}} dr$

For purely quark EOS, there are similar reactions with up and down quarks, where the emissivity is given by $\epsilon_{QB} = \frac{914}{315}\frac{G_F^2\cos^2\theta_C}{\hbar^{10}c^6}\alpha_c\, k_{Fd}\, k_{Fu}\, k_{Fe}\, (k_B T)^6$

For a model-independent estimate of those rates, we assume α = 0.1, Y_e =0.01 and $\begin{cases} k_{Fq} = 235\,(\epsilon/\epsilon_0)^{1/3}\ \mathrm{MeV}/c \\ k_{Fe} = k_{Fq}(3Y_e)^{1/3} \end{cases}$

We work with a quark-hadron transition without mixed phase, so for each density there is only hadronic or quark neutrino emission, if at all
(I can show you the mixed phase results, ask me Friday!)