Can all the observed neutron stars contain color-superconducting quark cores?

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Credits: **A. Ayriyan & D. Blaschke**

Compact Stars in QCD Phase Diagram 2026

Barcelona, 18 - 22 May 2026

Based on

PHYSICAL REVIEW D **111,** 034004 (2025)

Asymptotically conformal color-flavor-locked quark matter within a nonlocal chiral quark model

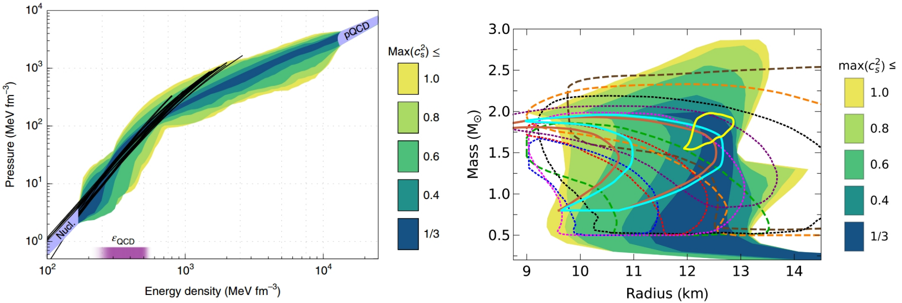
Oleksii Ivanytskyi*

arxiv:2508.02554 [nucl.th], accepted to Physical Review D

Bayesian inference favors quark matter in neutron star interiors

Alexander Ayriyan [1,2,*] Oleksii Ivanytskyi [1,3,4,5,†] and David Blaschke [1,4,5,‡]

Quark matter in neutrons stars? pQCD vs $2M_\odot$



E. Annala, T. Gorda, A. Kurkela, J. Nättilä, A. Vuorinen, Nature Physics 16, 907 (2020)

Existence of parameterization consistent with pQCD and $2M_\odot$

Can NSs accommodate quark cores?

Quark matter in neutrons stars? Supernova explosions

- $2M_\odot$ stars formation? (accretion is too slow)
- Supernovae with progenitor mass $\sim 50\ M_\odot$
- Quark-hadron transition stabilizes collapse

T. Fischer et al., Nature Astronomy 2, 980–986 (2018)

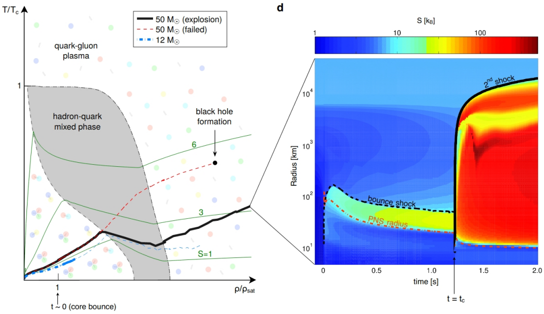


Table 1 | Summary of the supernova simulation results with hadron-quark phase transition

M_{ZAMS} ($M_\odot$)	t_{onset} (s)	$t_{collapse}$ (s)	$\rho\vert_{collapse}$ (ρ_{sat})	$T\vert_{collapse}$ (MeV)	$M_{PNS,collapse}$[a] ($M_\odot$)	t_{final} (s)	$\rho\vert_{final}$ (ρ_{sat})	$T\vert_{final}$ (MeV)	$M_{PNS,final}$[a] ($M_\odot$)	E^*_{expl} (10^{51} erg)
12[12]	3.251	3.489	2.49	28	1.727	3.598	5.5	17	1.732	0.1
18[12]	1.465	1.518	2.53	27	1.958	1.575	5.9	18	1.964	1.6
25[14]	0.905	0.976	2.40	31	2.163	0.983	9.6	19	2.171[b]	-
50[13]	1.110	1.215	2.37	32	2.105	1.224	5.8	31	2.092	2.3

Deconfinement is a supernova engine for blue supergiants

Quark matter in neutrons stars? Hyperons

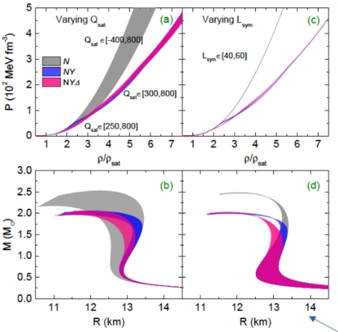


FIG. 4. EoS models and MR relations for N, NY, and $NY\Delta$ compositions of stellar matter. The bands are generated by varying the parameters Q_{sat} [MeV] (a, b) and L_{sym} [MeV] (c, d). The ranges of Q_{sat} and L_{sym} allowed by χEFT and maximum mass constraints are indicated in the figures.

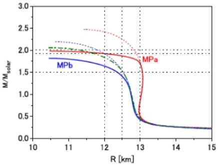


FIG. 7. Neutron-star masses as a function of the radius R. Solid (dashed) curves are with (without) hyperon (Λ and Σ^-) mixing for ESC+MPa and ESC+MPb. The dot-dashed curve for MPb is with Λ mixing only. Also see the caption of Fig. 3.

Yamamoto et al., Phys.Rev.C 96 (2017) 06580; arXiv:1708.06163 [nucl-th]
Yamamoto et al., Eur. Phys. J. A 52 (2016) 19; arXiv:1510.06099 [nucl-th]
Ji & Sedrakian, Phys. Rev. C 100 (2019) 015809; arXiv:1903.06057 [astro-ph.HE]

Examples for realistic hadronic EoS which suggest a Berlin Wall is inferior to the line M = 2.0 M_sun

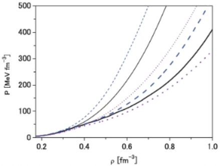


Fig. 8. Pressure P as a function of baryon density ρ. Thick (thin) curves are with (without) hyperon mixing. Solid, dashed and dotted curves are for MPa, MPa$^+$ and MPb.

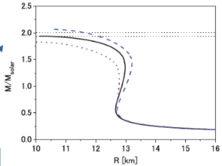


Fig. 9. Neutron-star masses as a function of the radius R. Solid, dashed and dotted curves are for MPa, MPa$^+$ and MPb. Two dotted lines show the observed mass $(1.97 \pm 0.04)M_\odot$ of J1614-2230.

Hyperons soften EoS. Can quarks stiffen it?

Model to probe quark matter neutron stars

- Quark degrees of freedom
- Asymptotically conformal behavior in agreement with pQCD
- Consistency with observational constraints on properties of neutron stars

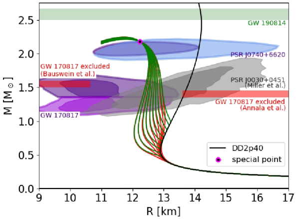
$N_f = 3$ nonlocal NJL model with vector repulsion and diquark pairing

- Realistic hadronic EoS: **DD2npY-T**

  M. Shahrbaf et al., PRD (2022)

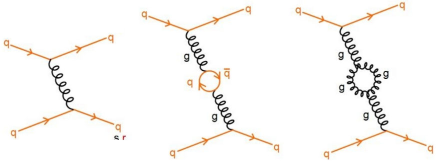
- Phase transition within Maxwell construction (not principal for modeling NSs)

  M. Cierniak, D. Blaschke, Astron.Nachr. 342 (2021)



Nonlocal character of quark interactions

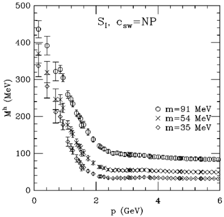
- QCD interactions



- Indications from the lattice

p-dependent renormalization of quark propagator
(*p*-dependent quark mass)
$\Downarrow$
space-time nonlocality of quark interactions

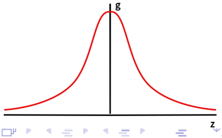
J. Skullerud, D. B. Leinweber, and A. G. Williams, Phys. Rev. D 64 , 074508 (2001)



- Quark interactions in effective approaches (separable approximation)

$$\left(\overline{q}_x\hat{\Gamma}q_x\right)^2 \rightarrow \left(\int dz\ \tilde{g}_z\ \overline{q}_{x+z/2}\hat{\Gamma}q_{x-z/2}\right)^2$$

$\tilde{g}_z$ – space-time dependent fromfactor



Nonlocal NJL model for three-flavor quark matter

- **Lagrangian**

$$\mathcal{L} = \bar{q}(i\partial\!\!\!/ - m + \mu\gamma_0)q + \overbrace{G_S \sum_{a=\overline{0,8}} s_a s_a}^{\text{chiral dynamics}} - \overbrace{G_V j_\mu j^\mu}^{\text{vector repulsion}} + \overbrace{3G_D \sum_{a,b=2,5,7} d^+_{ab} d_{ab}}^{\text{color superconductivity}}$$

$$\int dz\ \tilde{g}(z)\bar{q}\left(x+\frac{z}{2}\right)\hat{\Gamma}\ q\left(x-\frac{z}{2}\right) = \begin{cases} s_a(x),\ \hat{\Gamma} = \tau_a \\ j_\mu(x),\ \hat{\Gamma} = \gamma_\mu \\ d_{ab}(x),\ \hat{\Gamma} = i\gamma_5\tau_a\lambda_b\hat{C} \end{cases}$$

- **Thermodynamic potential**

$$\Omega = -\sum_{j,a=\pm} d_j \int_{\mathbf{k}} \left[\frac{1}{2} - f^a_{j\mathbf{k}}\right]\epsilon^a_{j\mathbf{k}} + \frac{\sigma^2}{4G_S} - \frac{\omega^2}{4G_V} + \frac{\Delta^2}{4G_D}$$

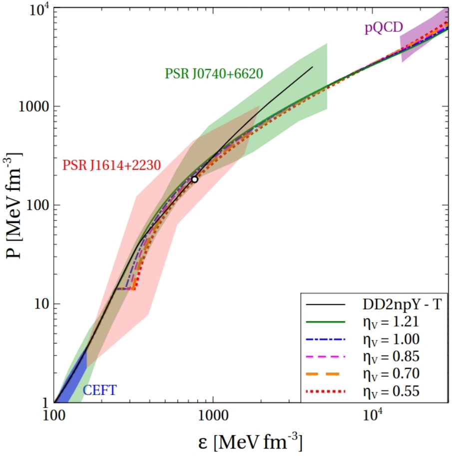
$$\epsilon^a_{j\mathbf{k}} = sign\left(\epsilon^a_{\mathbf{k}}\right)\sqrt{\epsilon^{a2}_{\mathbf{k}} + \Delta^2_{j\mathbf{k}}}, \quad \epsilon^\pm_{\mathbf{k}} = \sqrt{\mathbf{k}^2 + M^2_{\mathbf{k}}} \mp \mu \mp \omega g_{\mathbf{k}}, \quad M_{\mathbf{k}} = m + \sigma g_{\mathbf{k}}$$

$$\frac{\partial\Omega}{\partial\sigma} = \frac{\partial\Omega}{\partial\omega} = \frac{\partial\Omega}{\partial\Delta} = 0$$

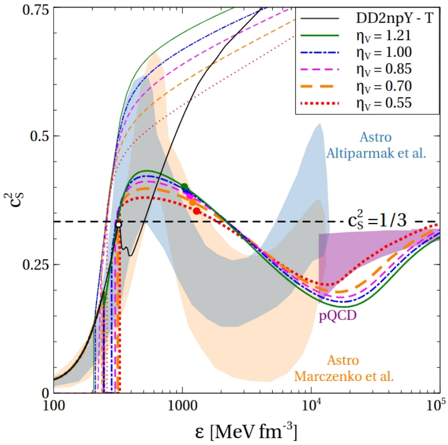
EoS of neutron stars

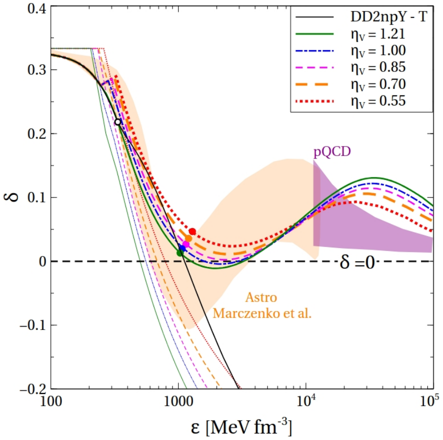
- **Charge neutrality**
- ***β*-equilibrium**
- **Hadron EoS:** DD2npY-T
- **Maxwell construction**

$\mu_{onset} = 1027 \ MeV$



Speed of sound & dimensionless conformality measure



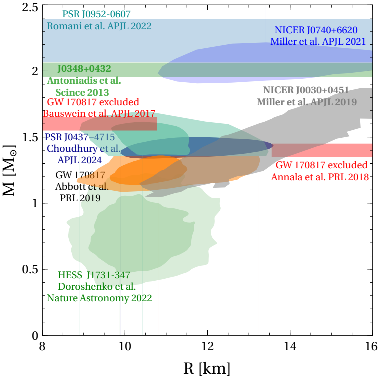


c_S^2 and δ almost simultaneously attain the conformal values

Pseudoconformality at nonperturnative densities (not discussed here)

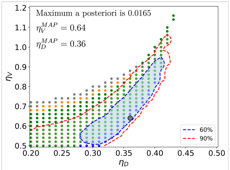
Model-informed Bayesian analysis: data

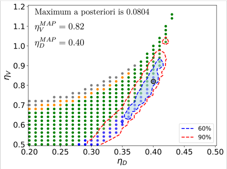
- **Basic constraints**
  1. PSR J0348+0432 by Antoniadis et al.
  2. PSR J0030+0451 by Miller et al.
  3. PSR J0740+6620 by Dittmann et al.
  4. PSR J0437-4715 by Choudhury et al.
  5. GW170817 by Abbott et al.
- **Additional constraints**
  1. PSR J0952-0607 by Romani et al.
  2. HESS J1731-347 by Doroshenko et al.



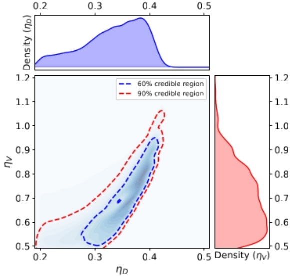
Model-informed Bayesian analysis: results

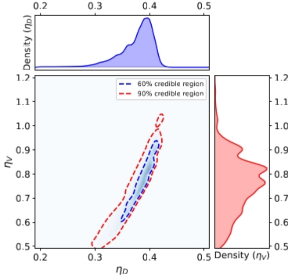
- $\eta_V = [0.5, 1.5]$, $\eta_D = [0.2, 0.5]$
- $51 \times 31 = 1581$ quark EoSs
- 259 hybrid EoSs



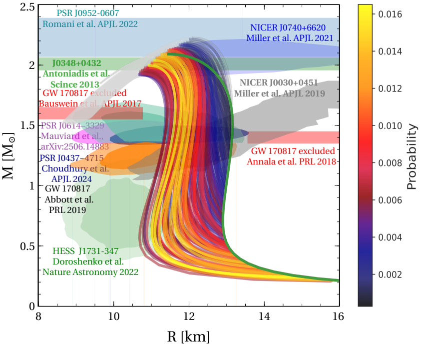


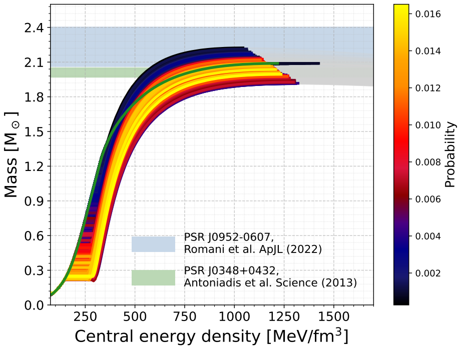
- $\eta_V \times \eta_D$ – s space





Neutron stars with CFL cores



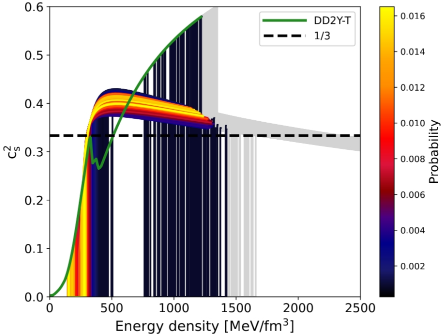


A. Ayriyan, O. Ivanytskyi, D. Blaschke, 2509.02554 [nucl-th], accepted to PRD

Onset of quark matter below $\varepsilon \simeq 300$ MeV/fm^3 and $1M_\odot$

All the observed neutron stars have quark cores

Speed of sound of the neutron star matter



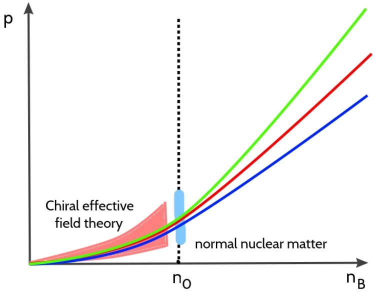
A. Ayriyan, O. Ivanytskyi, D. Blaschke, 2509.02554 [nucl-th], accepted to PRD

Speed of sound peaks at $\varepsilon \simeq 500$ MeV/fm^3 and $c_s^2 \simeq 1/3$

Neutron star matter is far from conformality

Th role of hadronic EoS

- **Constraints**
  1. Chiral effectibve field theory
  2. Normal nuclear matter
  3. Symmetry energy from PREX
  4. ...



All realistic nuclear EoSs should be very similar at $1 - 2\ n_0$.
Thus, make no difference if $n^{onset} < 2n_0$

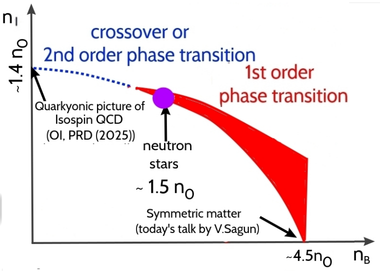
Conclusions

- **Hybrid stars are 1-2 o.o.m. more preferred over the hadronic stars**
- **Most probable onset of quark matter**

$$n_{onset} \lesssim 2n_0, \quad M \lesssim 1M_\odot$$

All neutron stars have quark cores

- **My proposal of phase diagram**



Quark matter should be included to simulations of supernovae, NS cooling and mergers