Hybrid Nuclear Matter EOS with Color Superconducting Quark Phase: Bayesian Constraints from Observations

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GOAL

Perform a physics-informed Bayesian Analysis (BA) to test hybrid star EOS under modern astrophysical constraints.

HYBRID EOS

The **hybrid EOS** allowing a **first-order phase transition** from hadronic to two-flavor color-superconducting (2SC) quark matter, was constructed with a two-phase approach:

- The hadronic phase is represented by the **DD2 density-dependent relativistic mean-field EOS**.
- The quark matter phase is described by **a nonlocal chiral quark model with 2SC phase**.

NONLOCAL CHIRAL 2SC

The effective Euclidean action for quark matter is given by:

$$S_E = \int d^4x \left\{ \bar{\psi}(x)(-i\not\partial + \hat{m} - \gamma_0\hat{\mu})\psi(x) - \frac{G_S}{2}\left[j_S^f(x) j_S^f(x) + \eta_D \left[j_D^a(x)\right]^\dagger j_D^a(x) - \eta_V j_V^\mu(x)\, j_V^\mu(x) \right] \right\}.$$

with scalar and diquark nonlocal currents:

$$j_S^f(x) = \int d^4z\, g_S(z)\, \bar{\psi}(x+\frac{z}{2})\, \Gamma_f\, \psi(x-\frac{z}{2}),$$

$$j_D^a(x) = \int d^4z\, g_D(z)\, \bar{\psi}_C(x+\frac{z}{2})\, i\gamma_5\tau_2\lambda_a\, \psi(x-\frac{z}{2}),$$

$$j_V^\mu(x) = \int d^4z\, g_V(z)\, \bar{\psi}(x+\frac{z}{2})\, i\gamma^\mu\, \psi(x-\frac{z}{2}),$$

For the nonlocality a **Gaussian ansatz is employed** which after Fourier transformation to the momentum space reads (the vector current is taken local!):

$$g_i(\vec{p}) = \exp(-\vec{p}^2/\Lambda_i^2), \quad i = S, D$$

The quark matter **EOS is parameterized by the dimensionless couplings** ($G_S = 9.92\,\mathrm{GeV}^{-2}$):

$$\eta_V = G_V/G_S \quad \text{and} \quad \eta_D = G_D/G_S$$

BA WITH MULTI-MESS. ASTRO.

A physics-informed Bayesian analysis is then performed to constrain (η_D, η_V) using observational data:

- NICER **mass-radius measurements** (e.g. PSR J0030+0451)
- Gravitational-wave **tidal deformability** from GW170817
- Precise pulsar **mass measurements** (e.g. PSR J0348+0432)
- Additionally: highest mass (PSR J0952−0607 "BW") and highly compact object (low mass-radius) (HESS J1731−347)

RESULTS

The Bayesian posterior favors:

- Low-to-moderate $\eta_V \lesssim 0.6$ → **moderate stiffness**
- High η_D ($\gtrsim 1.1$) → **early deconfinement** at M ≈ 0.5–0.7 $M_\odot$
- Hybrid stars are favored to have: maximum masses up to ≈ 2.2 $M_\odot$ and radii R ≈ 12 km for M ≈ 1.2–2.0 $M_\odot$
- **Large η_V (stiff EOS) are disfavored** due to failure to match tidal deformability constraints.
- **Twin star configurations are allowed** in a narrow region.
- **New NICER M-R favors** even less onset and low mass twins

CONCLUSION

This analysis **supports** the scenario of **early quark deconfinement to 2SC matter** in the cores of neutron stars, consistent with all current astrophysical constraints.

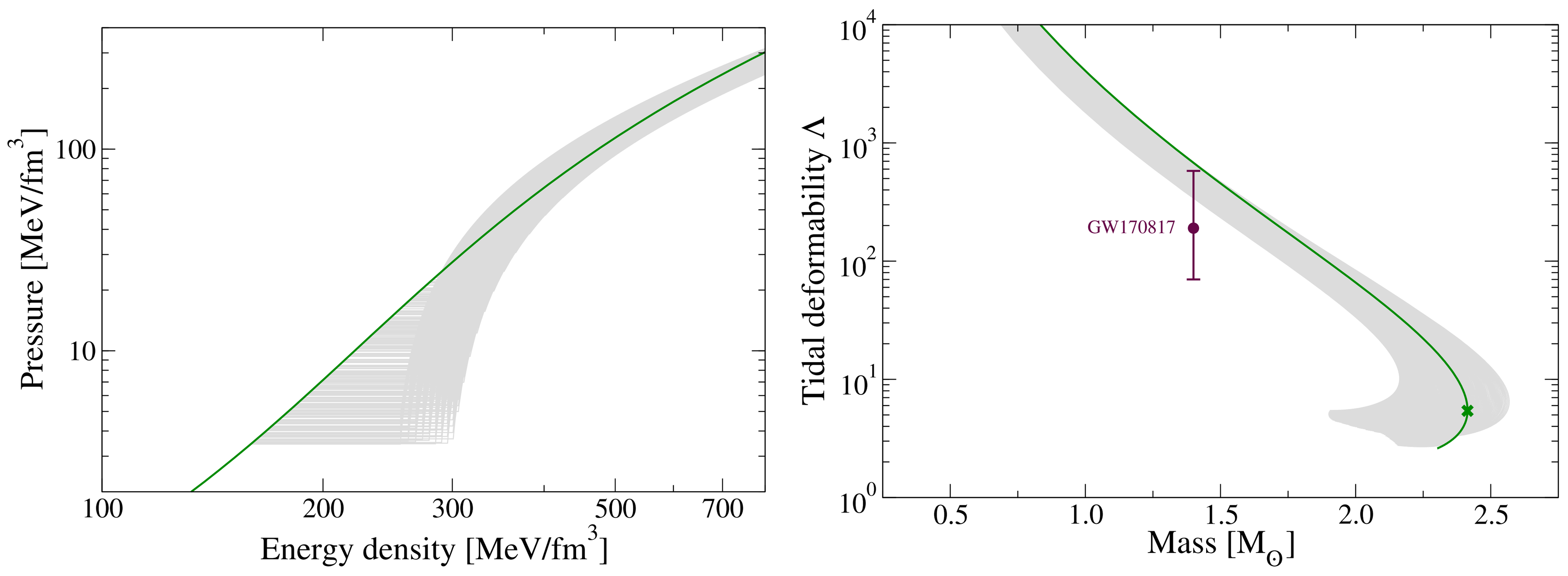


Figure 1: Pressure vs. Energy Density (left) and Tidal Deformability vs. Star Mass (right).

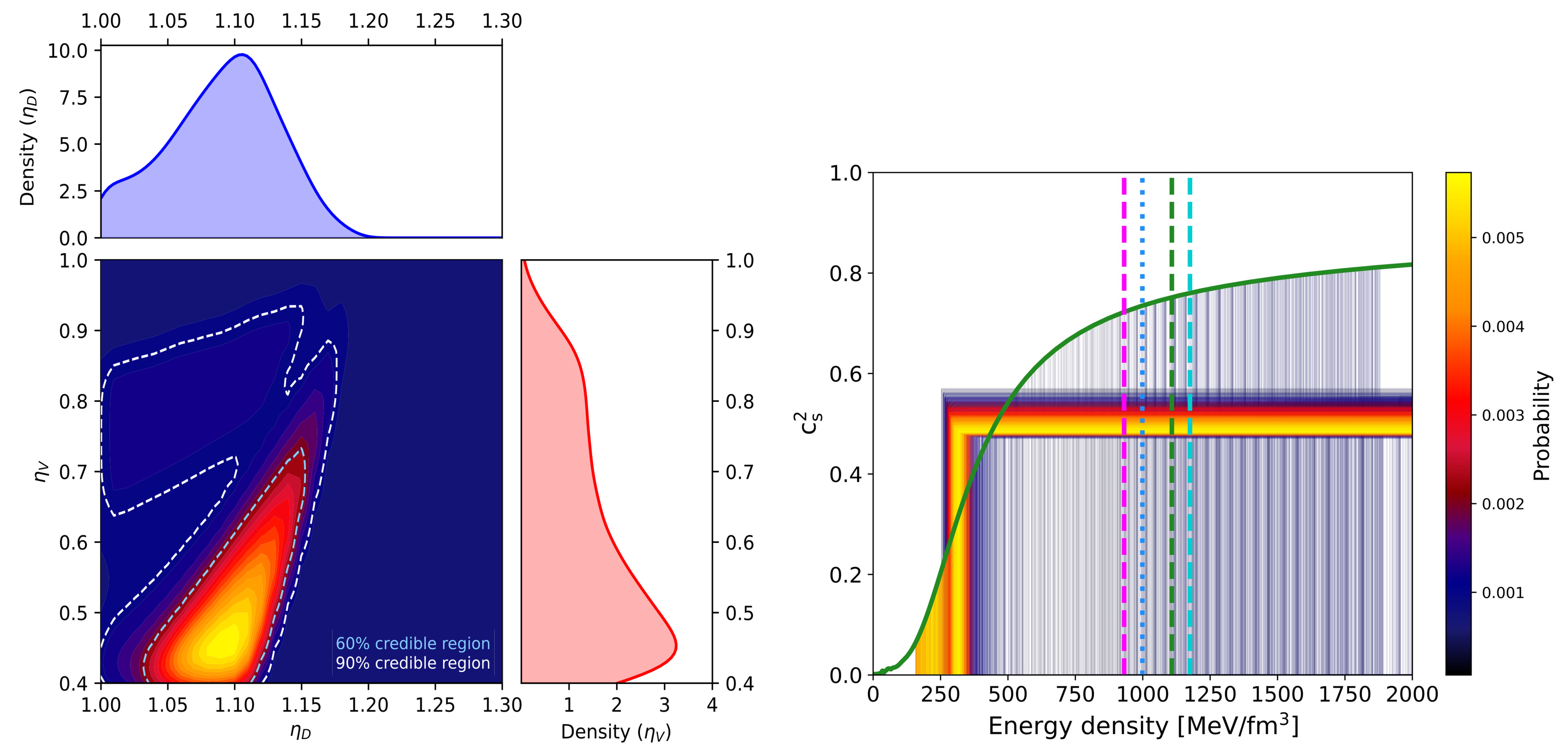


Figure 2: Bayesian Posterior in the (ηV, ηD) Plane (left) and Speed of Sound vs. Energy Density (right).

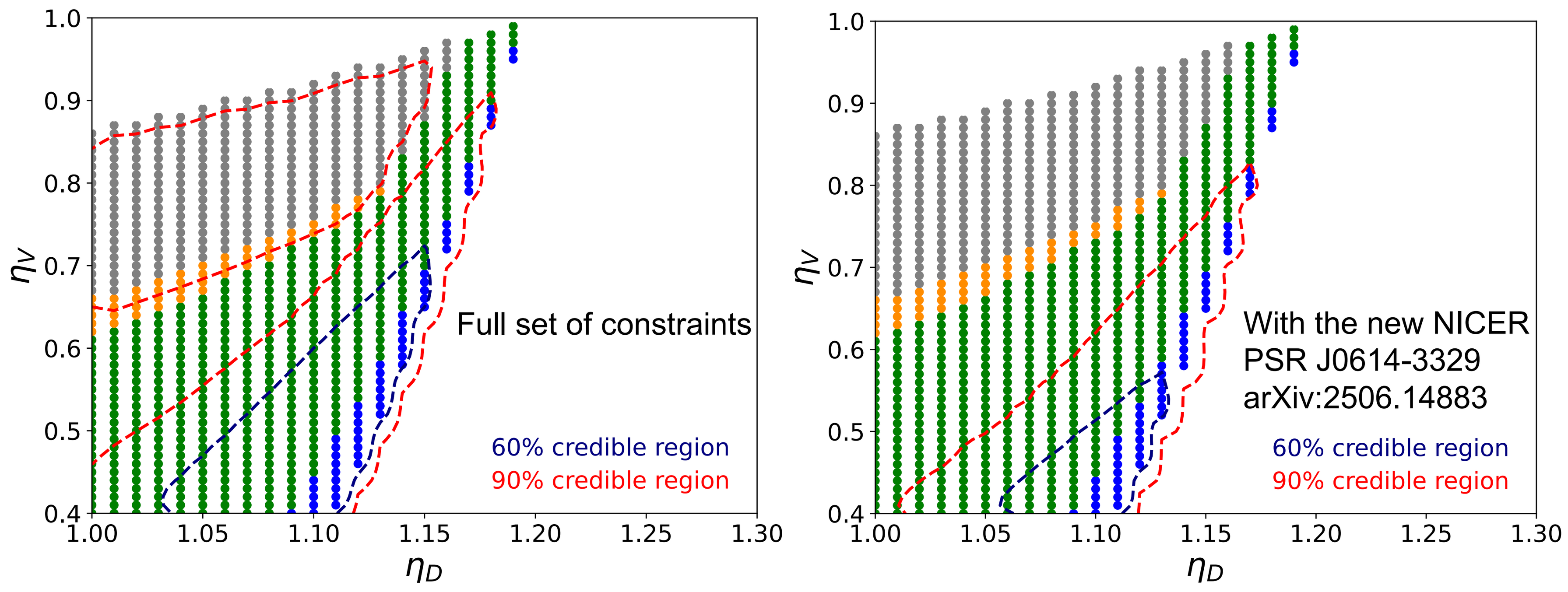


Figure 3: Phase Transition Classification. Color-coded regions in the (ηV, ηD) plane show: no hybrid stars (grey and orange), stable hybrid stars (green and blue), blue color indicates twin stars. Overlaid with 60% and 90% credibility contours.

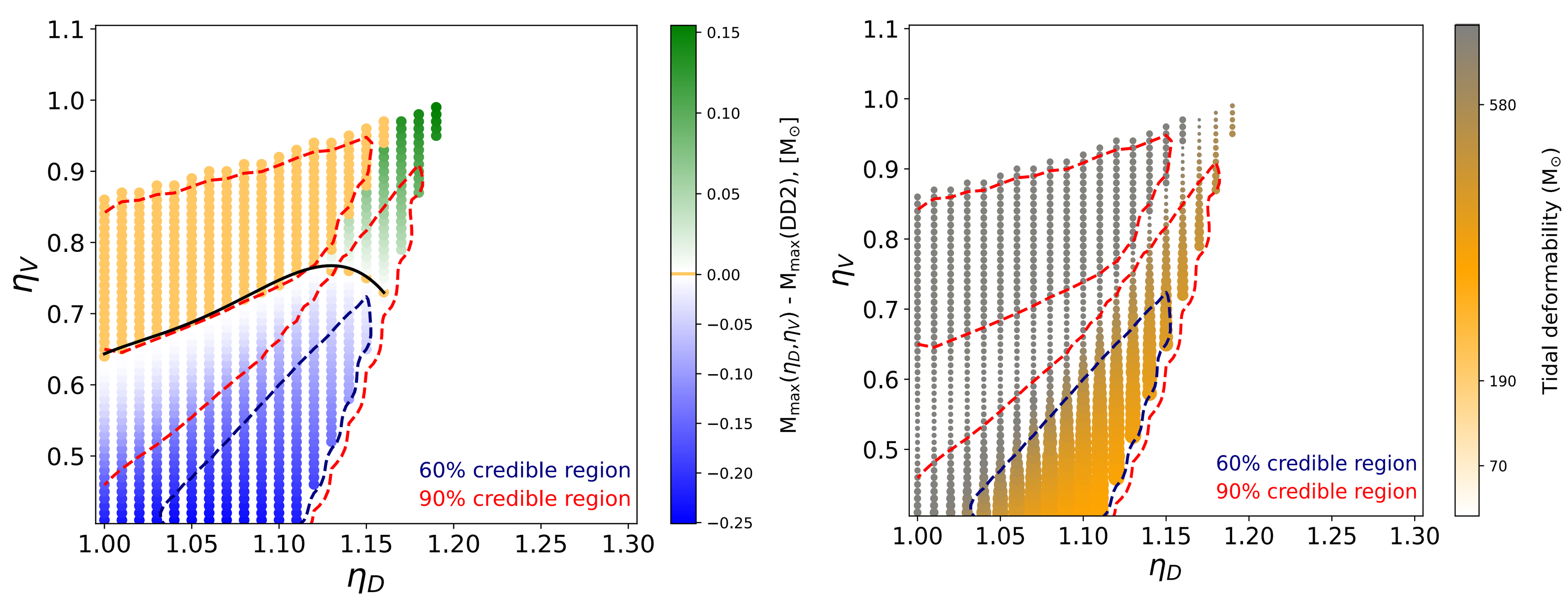
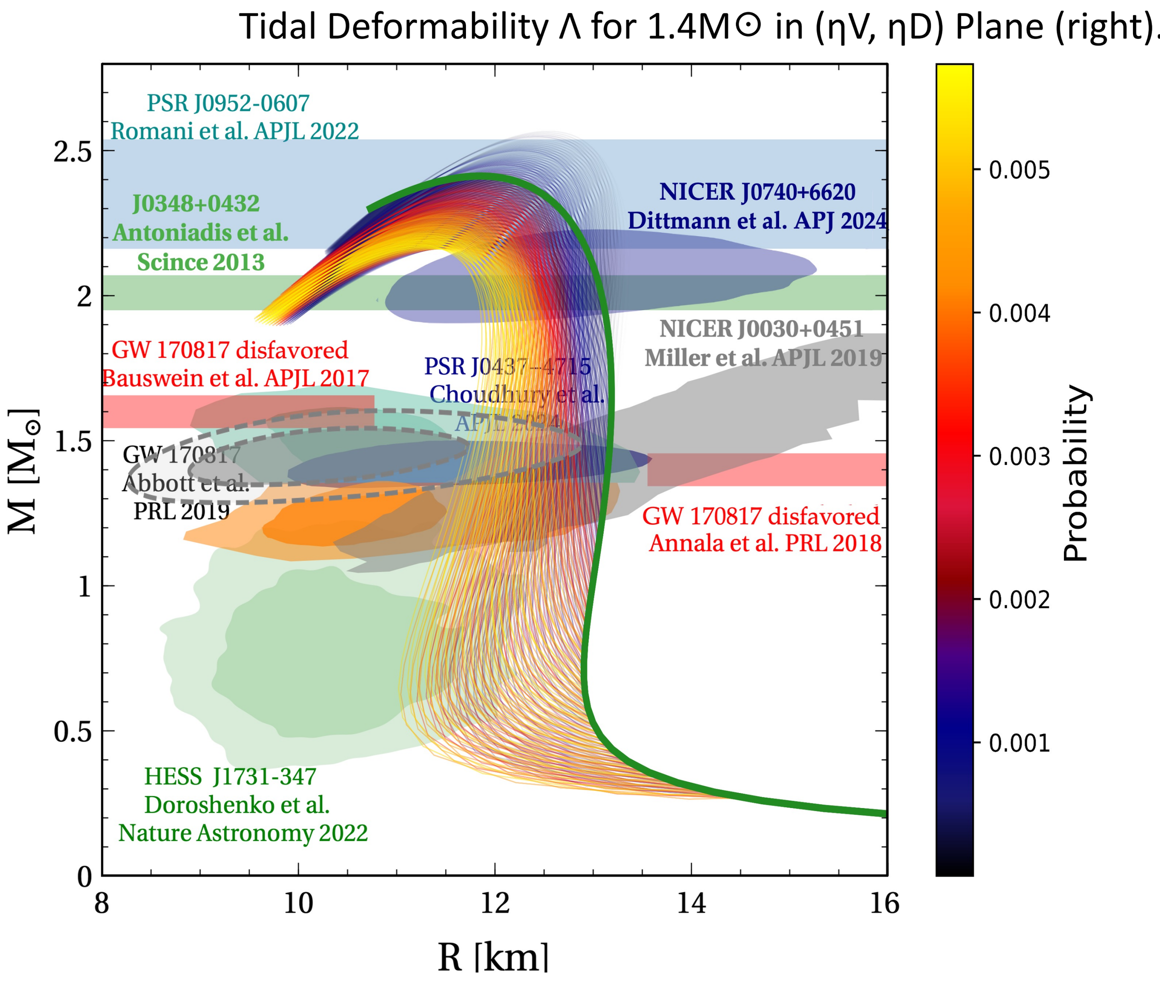


Figure 4: Maximum Mass Difference from Maximum Mass of Hadronic Star (left) and Tidal Deformability Λ for 1.4M⊙ in (ηV, ηD) Plane (right).

Figure 5: Mass-Radius Diagram. Hybrid EOS sequences in M-R space, color-coded by Bayesian posterior probability. Overlaid with the most selective observational constraints. The grey dashed regions is newly reported NICER M-R constraints for PSR J0614-3329



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