A Data-Derived Structural Ceiling for Neutron Star Compactness and Tidal Deformability from GW170817

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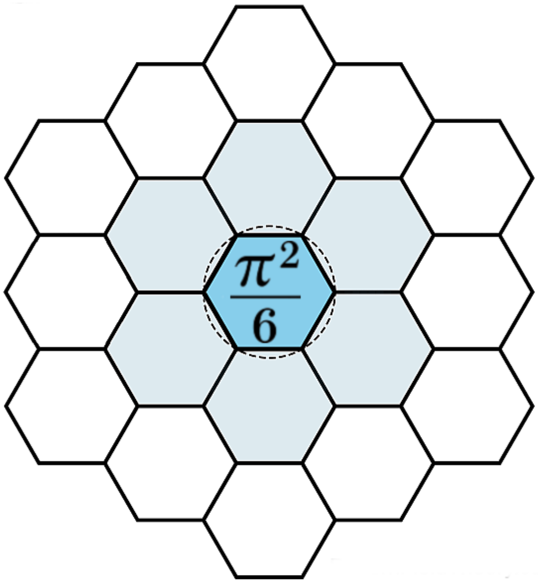

Abstract

We define a monotone scalar envelope functional that compresses neutron star compactness and tidal deformability posterior samples into a single dimensionless load variable

$$L = C + \frac{k}{\sqrt{\Lambda}},$$

where $C = GM/(Rc^2)$ is compactness and Λ is the dimensionless tidal deformability. Using public GW170817 equation-of-state inference posteriors, we compute high-quantile envelope statistics of L and demonstrate the existence of a sharp, thin-tailed upper boundary. In posteriors constrained by threshold-mass and maximum-mass stability conditions, the envelope location is stable and prior-robust under fixed normalization, yielding

$$L_{\max}(q = 0.995) \approx 0.446 \pm 0.004.$$

This result establishes the existence of a compact admissible region in compactness–tidal space defined directly by data. The statistic is fully reproducible and suitable for tracking structural bounds across future binary neutron star events.

Problem Statement

Current neutron star inference pipelines produce multi-dimensional posterior distributions over masses, radii, and tidal deformabilities. While such representations are information-rich, they do not directly expose whether the physically admissible region is merely observationally truncated or intrinsically compact.

This work addresses the following question:

> Does the GW170817-constrained neutron star state space exhibit a sharp, data-defined structural upper boundary when projected onto a suitable monotone scalar?

We answer this question empirically by defining a scalar envelope functional and extracting its high-quantile boundary across multiple public posterior sets.

Data Sources

We use the public posterior samples from the `gw170817-eft-eos` dataset in the following categories:

- Mass priors: `dns_mass_prior`, `uniform_mass_prior`
- Constraint sets: `posterior`, `posterior_mthresh`, `posterior_mthresh_maxmass`

Each posterior sample contains component masses m_1, m_2, radii R_1, R_2, and tidal deformabilities Λ_1, Λ_2.

We define per-sample averages:

$$C = \frac{1}{2}\left(\frac{Gm_1}{R_1c^2} + \frac{Gm_2}{R_2c^2}\right), \qquad \Lambda = \frac{1}{2}(\Lambda_1 + \Lambda_2).$$

Definition of the Envelope Functional

Definition 1 (Load Functional)**.** *We define the dimensionless load functional*

$$L(C, \Lambda) = C + \frac{k}{\sqrt{\Lambda}},$$

where $k > 0$ is a normalization constant.

Remark 1. *The functional is monotone increasing in compactness and monotone decreasing in tidal deformability. It therefore assigns larger values to configurations that are simultaneously more compact and less deformable.*

Two normalization schemes are used:

- Per-file normalization: $k = \mathrm{median}(C)\sqrt{\mathrm{median}(\Lambda)}$
- Fixed normalization: $k = 2.9802987367$, taken from the `dns_mass_prior/posterior_mthresh_maxmass` dataset

For each posterior, we define the envelope statistic:

$$L_{\mathrm{edge}}(q) = \mathrm{quantile}_q(L), \qquad q \in \{0.99, 0.995, 0.999\}.$$

Results

The full scan across six posterior files yields the following results for the stability-constrained sets under fixed normalization:

$$L_{\text{edge}}(0.995) \in [0.442, 0.450].$$

We therefore define the data-derived structural ceiling:

$$L_{\max}(D_{\text{ref}}) = 0.446 \pm 0.004.$$

Across quantiles from 0.99 to 0.999, the envelope shifts by less than 0.02, indicating a thin-tailed, sharply bounded distribution.

Unconstrained posteriors produce significantly higher envelope values, demonstrating that the ceiling is not an artifact of the functional form but of the physical stability constraints.

Interpretation

The existence of a sharp upper envelope in a monotone scalar projection implies that the GW170817-constrained neutron star state space occupies a compact admissible region rather than a diffuse or weakly truncated domain.

This statement is purely empirical and independent of any particular microscopic equation of state.

The scalar envelope statistic provides a reproducible method for:

- Tracking structural bounds across events
- Comparing inference pipelines
- Testing convergence toward a universal ceiling

Conclusion

We have demonstrated the existence of a data-defined structural ceiling in compactness–tidal space using GW170817 EOS-inference posteriors. The ceiling is sharp, stable, and prior-robust under fixed normalization, with

$$L_{\max}(q = 0.995) \approx 0.446 \pm 0.004.$$

This establishes a falsifiable, event-testable structural bound derived directly from data.

Glossary

- C - Compactness $GM/(Rc^2)$
- Λ - Dimensionless tidal deformability
- L - Scalar load functional
- L_{edge} - High-quantile envelope statistic
- L_{max} - Data-derived structural ceiling

References

LIGO Scientific Collaboration and Virgo Collaboration, Phys. Rev. Lett. 119, 161101 (2017).

Document Timestamp and Provenance

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