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Gravitational-wave constraints on neutron-star pressure anisotropy via universal relations

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INTRODUCTION

- Typically, equation-of-state (EOS) models for nuclear matter inside neutron stars (NSs) are used to describe a spherically symmetric, isotropic fluid distribution, in which the pressure is the same in the radial and tangential directions;
- However, local pressure anisotropy can arise in NS interiors due to e.g. strong magnetic fields, elasticity etc.;

Fluid: Same stress in all directions
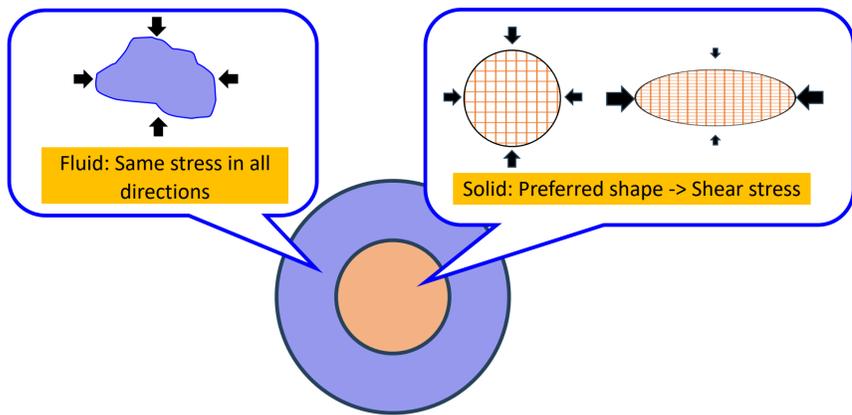
Solid: Preferred shape -> Shear stress

Diagram showing elastic hybrid star with anisotropic stresses (adapted from Shu Yan Lau).

- Pressure anisotropy can affect NS observables (such as tidal deformability and oscillation modes) in a significant way, and can pose alternative interpretations for current and future observations in gravitational waves (GWs);
- In this work, we demonstrate how we can use the anisotropy-dependent but EOS-independent f-Love relation to infer the pressure anisotropy in NSs through GW observations;

METHODS AND RESULTS

- NS pressure anisotropy: $\sigma \equiv p_r - p_t$, where p_r is the radial pressure and p_t is the tangential pressure;
- We use the model [1]: $\sigma = 4\beta p_r m^2/r^2$, β is the amount of anisotropy, r is the radial coordinate, and m is the mass;
- Using perturbation theory in general relativity and our new formulation for anisotropic stars [2], we compute: mass (M), radius (R), tidal deformability (or Love number, $\bar{\Lambda}$), and fundamental quadrupolar oscillation mode (or f-mode, $\omega = 2\pi f + i/\tau$, where f is frequency and τ is damping time);
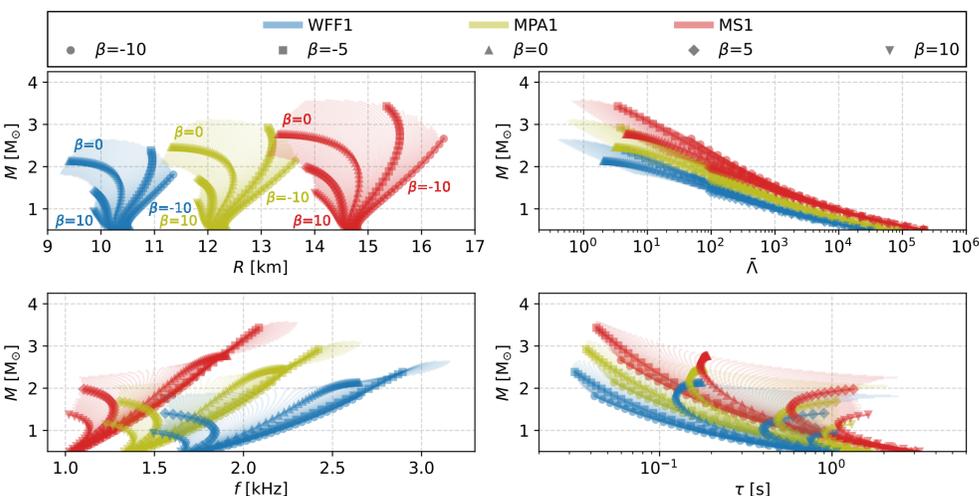
Mass-radius, mass-tidal deformability, mass-frequency, and mass-damping time relations.

- In general, we have $M(\rho_0, \beta) < M(\rho_0, \beta = 0)$ for positive β and vice-versa for negative β, where ρ_0 is the central density;
- We see similar trends for $\bar{\Lambda}$, f, and τ;

- f-Love relation: relation between $\bar{\omega} = 2\pi Mf + iM/\tau$ and $\bar{\Lambda}$;
- This relation is known to be EOS-independent for isotropic stars, and we find the same for anisotropic stars;
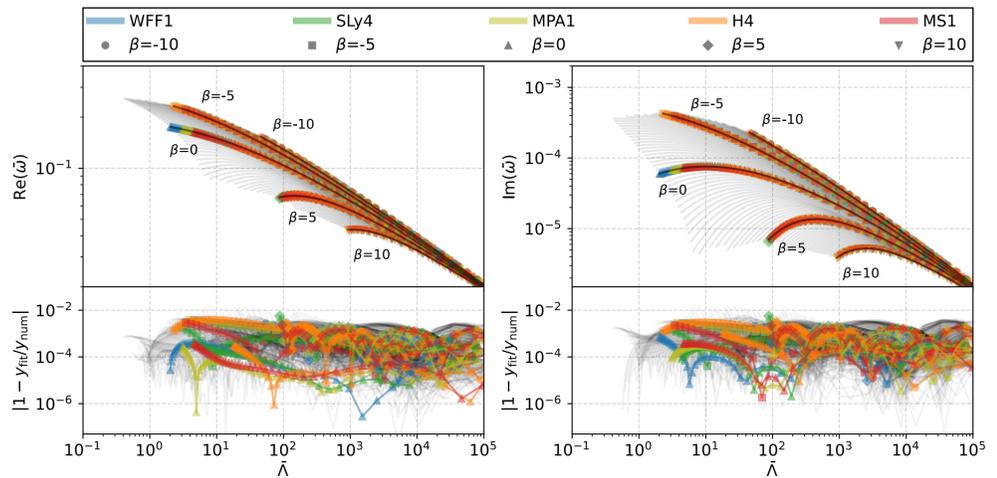
The f-Love relation for anisotropic stars.

- However, we find that the f-Love relation depends sensitively on the anisotropy parameter β, although it remains universal for fixed β with respect to the choice of EOS (p_r vs. ρ relation);
- We obtain bounds on β with GW inference of $\bar{\Omega} = \text{Re}(\bar{\omega})$ and $\bar{\Lambda}$ using current and future (simulated) data;
- Below, in the left panels, we show: contours for the GW inferences for the two NSs in GW170817 from [3] (top) and for NSs in GW170817-like event detected by a future CE/ET network from [4] (bottom);
- In the right panels, we show the 90% upper bounds on the anisotropy (β_{90}) from the posteriors $P(\beta\,|\,\{x,y\})$, for $x = \log_{10}\bar{\Lambda}$ and $y = \log_{10}\bar{\Omega}$;
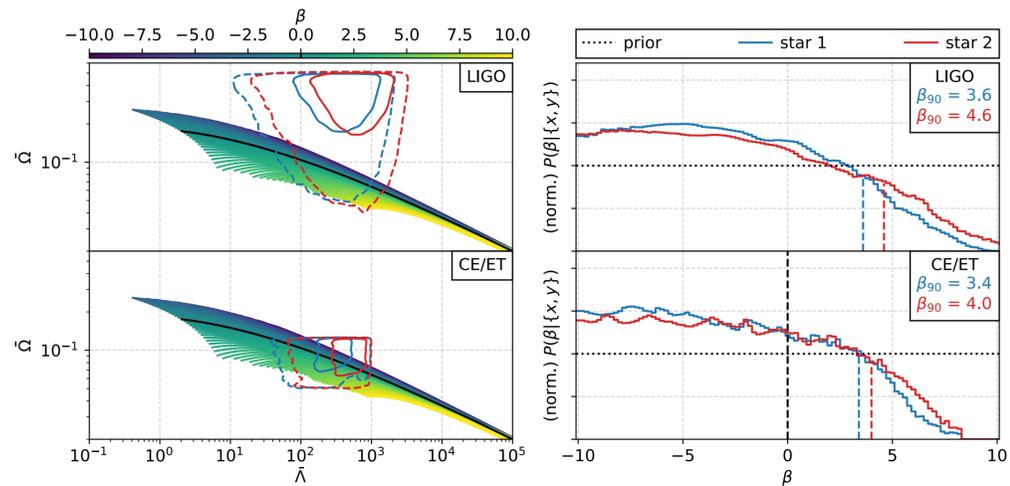
Constraints on anisotropy using GW170817 data from LIGO and simulated GW170817-like data for future CE/ET network.

CONCLUSION

- We computed anisotropic star observables, including tidal deformability and f-mode, following our new formulation [2];
- We found the f-Love relation to be dependent on the p_r vs. ρ relation, but highly dependent on the anisotropy β;
- We obtained the first bounds on NS anisotropy using these new f-Love relations.

REFERENCES

[1] Horvat et al., Class.Quant.Grav. 28, 025009 (2011)
[2] Lau et al., Phys.Rev.D 110, 083020 (2024)
[3] Pratten et al., Nat.Commun. 11, 2553 (2020)
[4] Williams et al., Phys.Rev.D 105, 123032 (2022)