Properties of the HESS J1731-347 Object as a Twin Compact Star

Universe 2025, 11(7), 224

David Álvarez Castillo

Institute of Nuclear Physics PAS
Cracow, Poland
Universidad Autónoma de NL, Mexico

The 4th Einstein Telescope Annual Meeting
the University of Rijeka in Opatija, Croatia
12 of November, 2025

dalvarez@ifj.edu.pl

UANL
UNIVERSIDAD AUTÓNOMA DE NUEVO LEÓN

CREDO
THE QUEST FOR THE UNEXPECTED

ET EINSTEIN TELESCOPE

comp star

Outline

- A brief introduction to the physics of compact stars and their relation to the QCD phase diagram.
- The compact star mass twins scenario: HESS J1731-347.
- Multi-messenger observations of compact stars.
- Outlook and perspectives.

Motivation

- New channels of multi-messenger observations like gravitational radiation from merger events of binary systems of compact stars or radio and X-ray signals from isolated pulsars allow to study their most basic structural properties like mass, radius, compactness, cooling rates and compressibility of their matter.

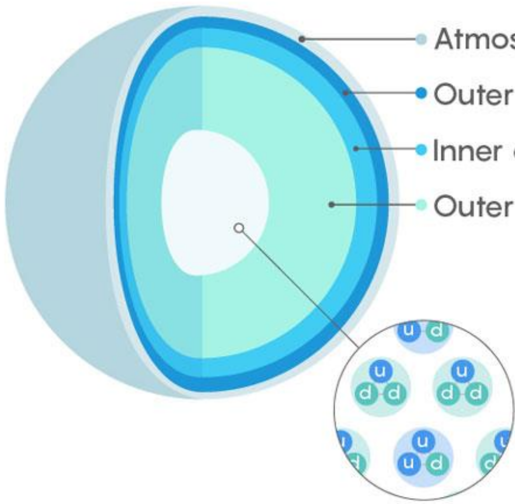
- Nuclear measurement and experiments have narrowed the Equation of State (EoS) uncertainty in the lowest to intermediate density range.

- Violent, transient energetic emissions are associated not only with the strong magnetic fields and extreme gravity in the proximity of NS but with explosive, evolutionary stages often triggered by mass accretion from companion stars. It is expected that are f-modes are excited in many of these astrophysical processes.

The Extraordinary Core of a Neutron Star

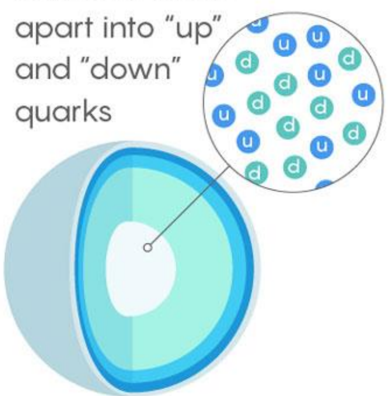
A neutron star's core is so dense that physicists aren't sure what happens inside. Researchers can't recreate the conditions in the lab, and even the theory of nuclear matter is of limited help. Here are some of the main ideas.

TRADITIONAL VIEW OF A NEUTRON STAR



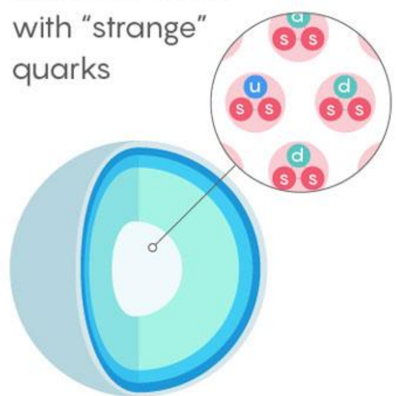
QUARK CORE

Nucleons break apart into "up" and "down" quarks



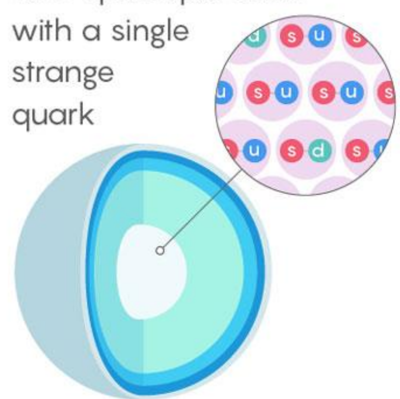
HYPERON CORE

Nucleons made with "strange" quarks

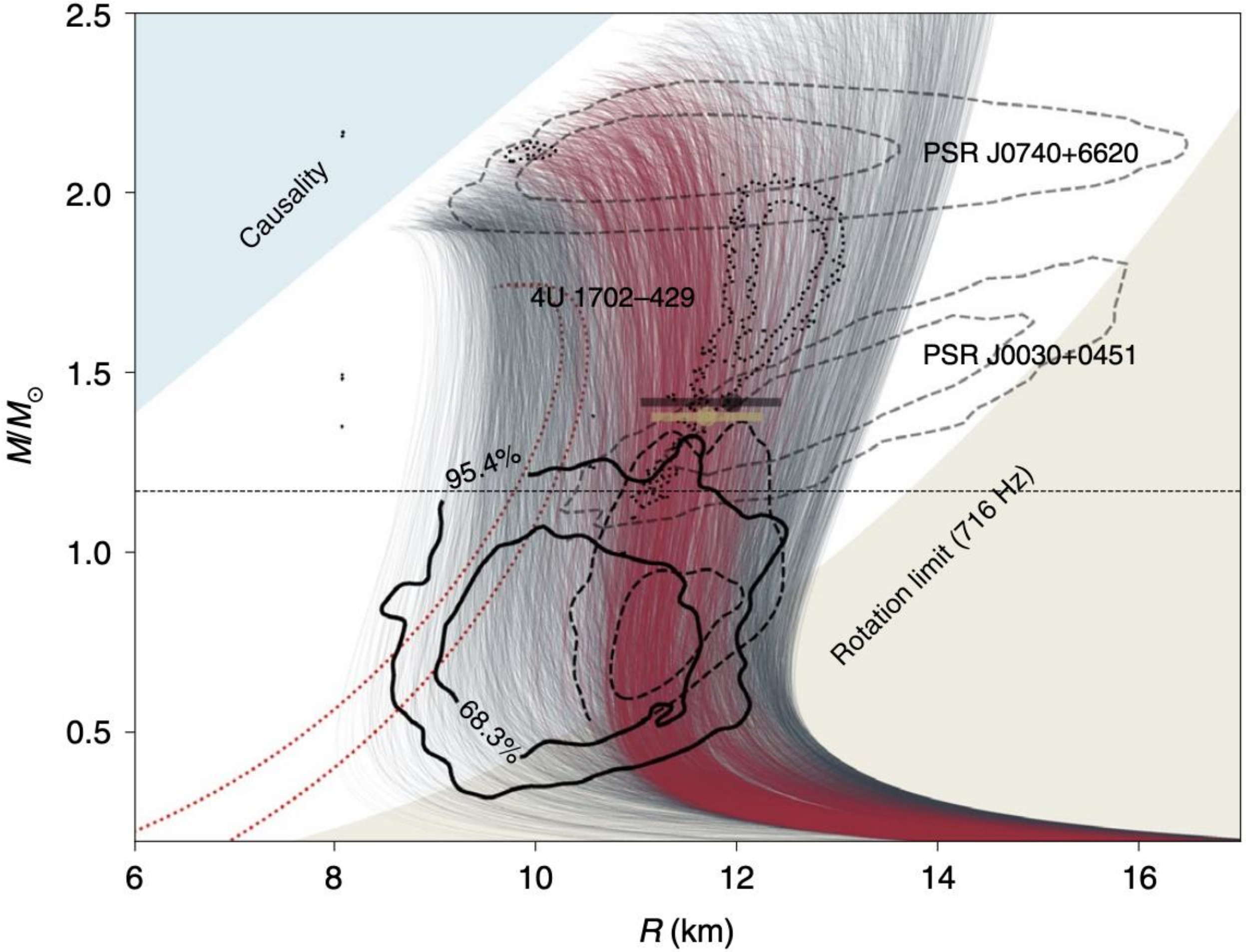


KAON CONDENSATE CORE

Two-quark particles with a single strange quark



HESS J1731-347



HESS J1731-347

Alternatives for description:

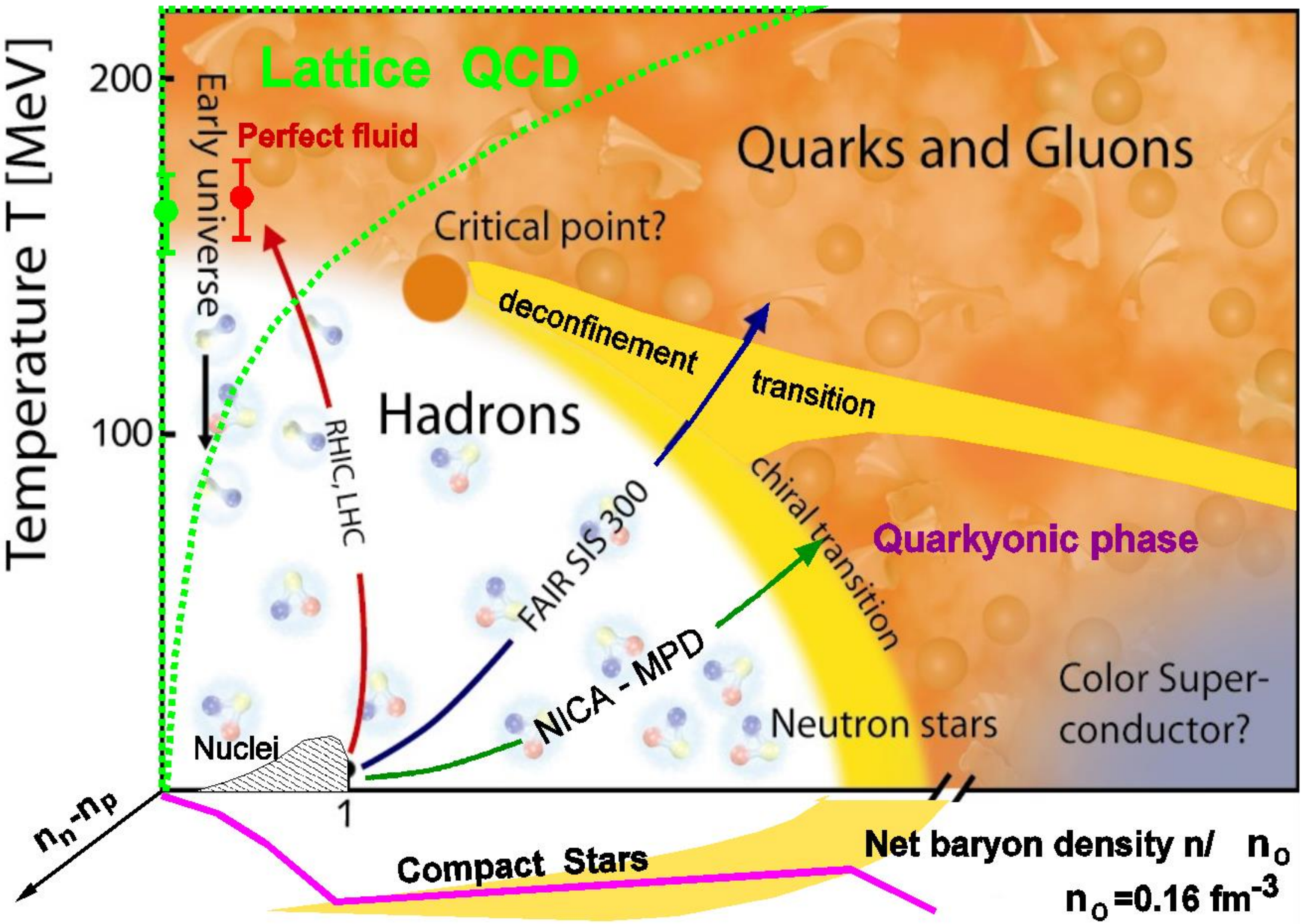
- Pure hadronic compact stars
- Kaon condensation in compact stars
- Strange quark stars
- Hybrid compact stars
- Modifications arising from dark matter content
- Alternative theories of gravity

HESS J1731-347

Alternatives for description:

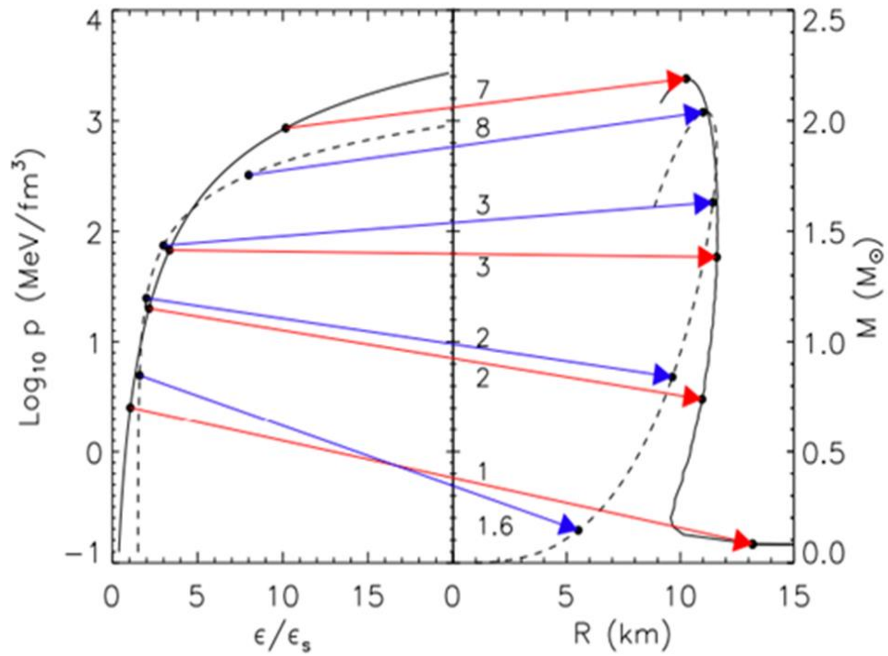
- Pure hadronic compact stars
- Kaon condensation in compact stars
- Strange quark stars
- **Hybrid compact stars**
- Modifications arising from dark matter content
- Alternative theories of gravity

Critical Endpoint in QCD



Compact Star Sequences

(M-R ⇔ EoS)



James Lattimer,
Annu. Rev. Nucl. Part. Sci. 62, 485 (2012), arXiv:1305.3510

- TOV Equations

$$\frac{dp}{dr} = -\frac{(\varepsilon + p/c^2)G(m + 4\pi r^3 p/c^2)}{r^2(1 - 2Gm/rc^2)}$$

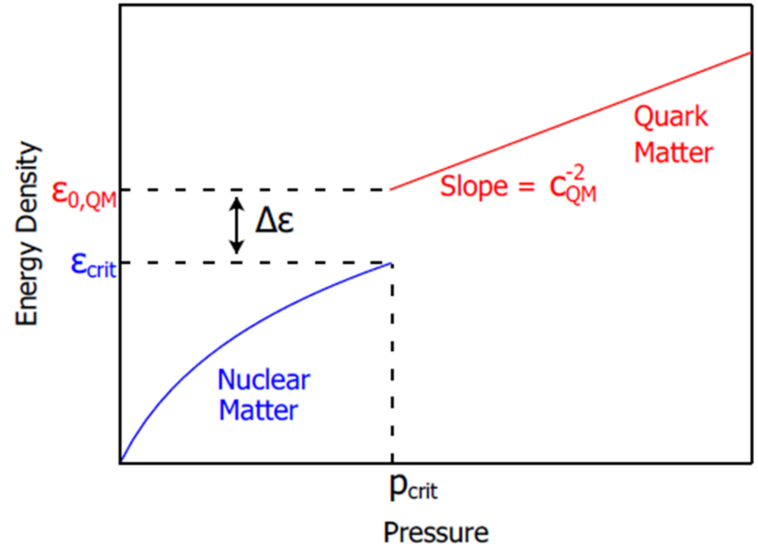
$$\frac{dm}{dr} = 4\pi r^2 \varepsilon \qquad p(\varepsilon)$$

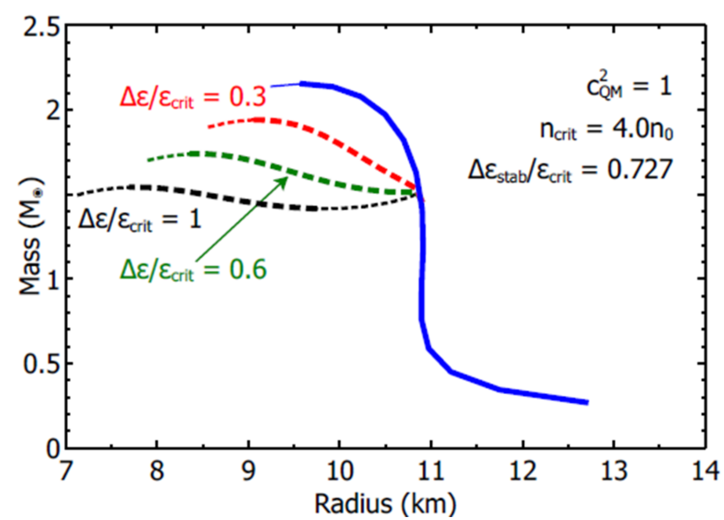
- Equation of State (EoS)

Compact Star Mass Twins and the AHP scheme

- First order PT can lead to a stable branch of hybrid stars with quark matter cores which, depending on the size of the “latent heat” (jump in energy density), can even be disconnected from the hadronic one by an unstable branch → “**third family of CS**”.

- Measuring two **disconnected populations** of compact stars in the M-R diagram would represent **the detection of a first order phase transition** in compact star matter and thus the indirect proof for the existence of a **critical endpoint (CEP) in the QCD phase diagram**!





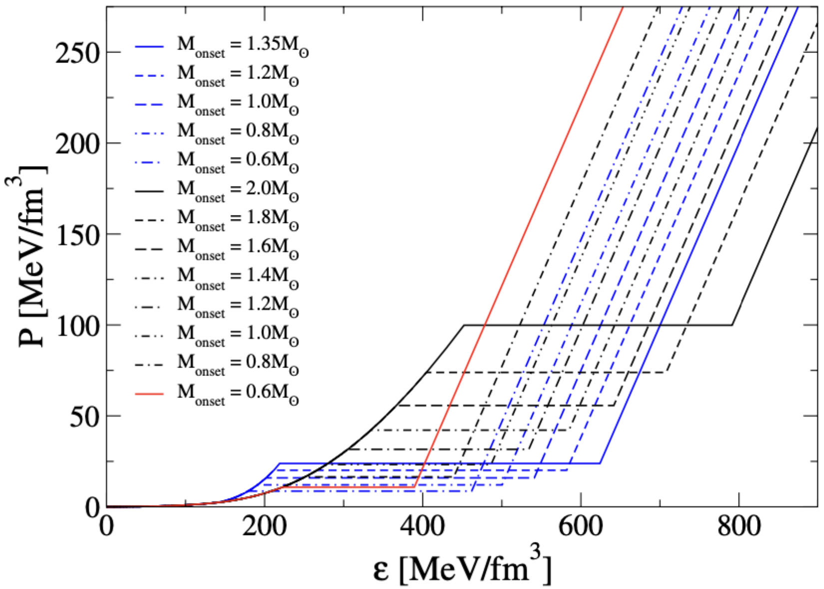
Alford, Han, Prakash,
Phys. Rev. D 88, 083013 (2013)
arxiv:1302.4732

Compact Star Mass Twins

$$\varepsilon(p) = \begin{cases} \varepsilon_{\rm NM}(p) & p < p_{\rm trans} \\ \varepsilon_{\rm NM}(p_{\rm trans}) + \Delta\varepsilon + c_{\rm QM}^{-2}(p - p_{\rm trans}) & p > p_{\rm trans} \end{cases}$$

Model	M_{onset} [$M_\odot$]	n_{trans} [$1/\mathrm{fm}^3$]	ε_{trans} [$\mathrm{MeV/fm}^3$]	p_{trans} [$\mathrm{MeV/fm}^3$]	$\Delta\varepsilon$ [$\mathrm{MeV/fm}^3$]	c_{QM} [c]
DD2p80	0.7	0.193	185.223	10.3131	268.573	0.9

$$\frac{\Delta\varepsilon_{\rm crit}}{\varepsilon_{\rm trans}} = \frac{1}{2} + \frac{3}{2}\frac{p_{\rm trans}}{\varepsilon_{\rm trans}}$$



D. Alvarez-Castillo - Astron. Nachr. 1–6 (2021)

Nonlocal NJL

In this model we introduce a doubly interpolated non-local NJL quark matter EoS as follows:

$$P(\mu) = [f_<(\mu)P(\mu;\eta_<,B) + f_>(\mu)P(\mu;\eta_<,0)]f_\ll(\mu) + f_\gg(\mu)P(\mu;\eta_>,0) \ ,$$

where we have introduced two smooth switch-off functions, one that changes from one to zero at a lower chemical potential $\mu_<$ with a width $\Gamma_<$,

$$f_<(\mu) = \frac{1}{2}\left[1 - \tanh\left(\frac{\mu - \mu_<}{\Gamma_<}\right)\right] ,$$

and one that switches off at a higher chemical potential $\mu_\ll$ with a width $\Gamma_\ll$,

$$f_\ll(\mu) = \frac{1}{2}\left[1 - \tanh\left(\frac{\mu - \mu_\ll}{\Gamma_\ll}\right)\right] ,$$

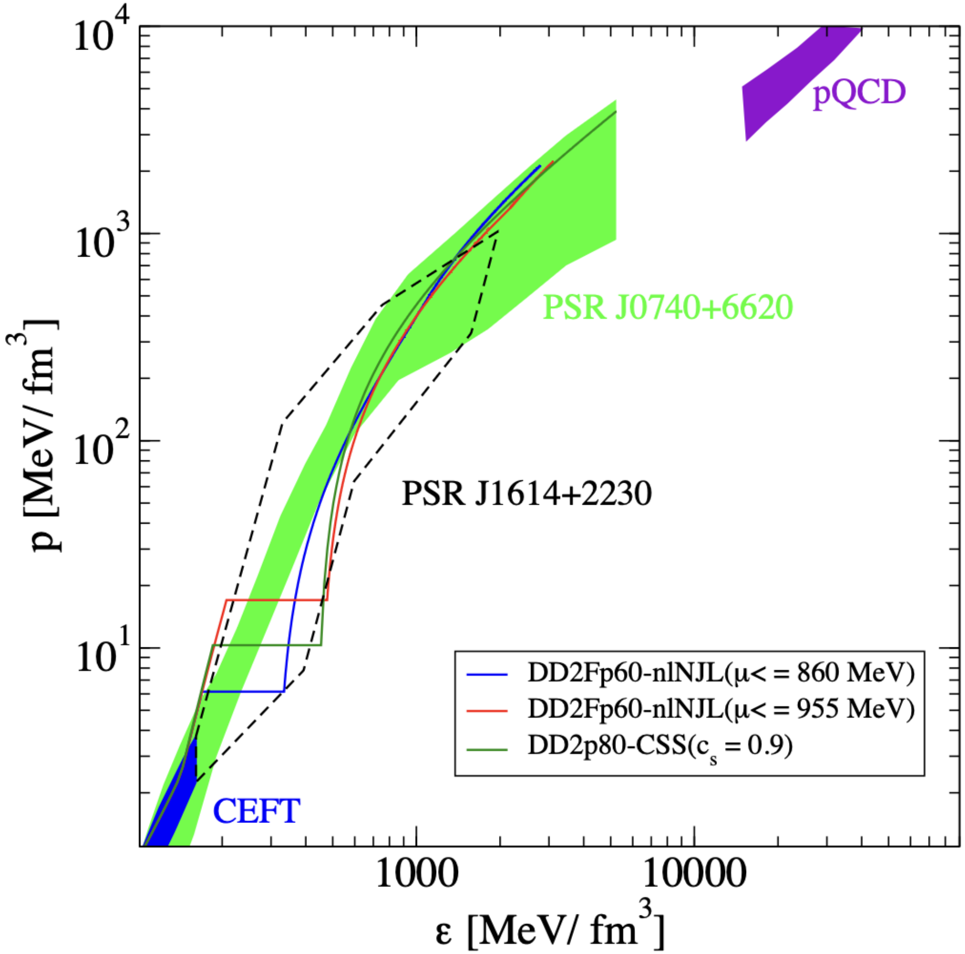
whereby the corresponding switch-on functions are the complementary ones,

$$f_>(\mu) = 1 - f_<(\mu) \ , \quad f_\gg(\mu) = 1 - f_\ll(\mu).$$

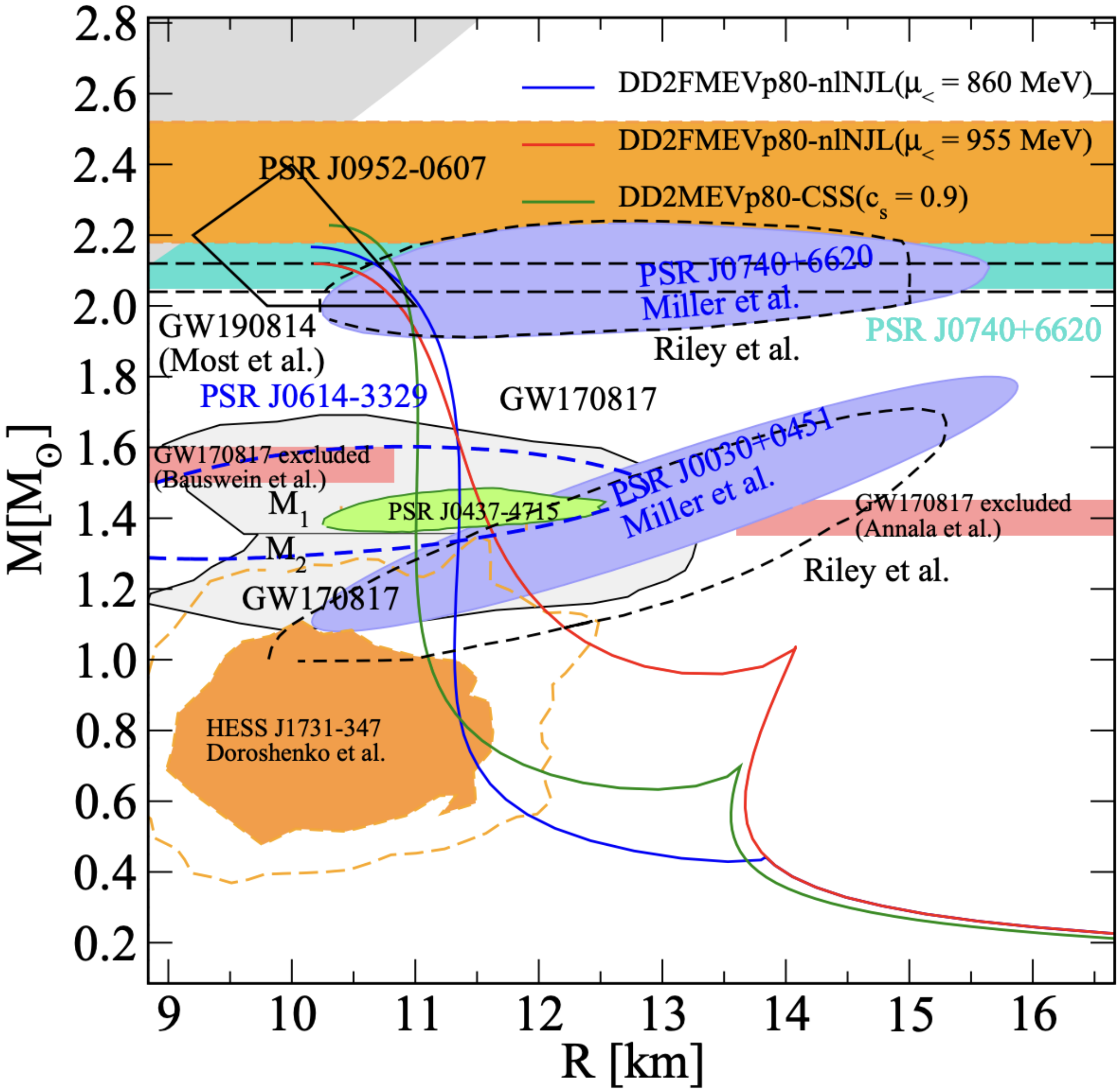
The input EoS differ in their η-values, we have taken for those values at low ($<$) and high ($>$) chemical potentials $\eta_<$ and $\eta_>$. Moreover, B represents a bag constant introduced to enforce confinement effects in the low chemical potential quark EoS.

D. Alvarez-Castillo, D. Blaschke, G. Grunfeld, V. Pagura
Phys. Rev. D 99, 063010 (2019) - arXiv: 1805.04105

Low Mas Compact Star Twins



[Universe 2025, 11(7), 224](), [arXiv:2504.00240]()



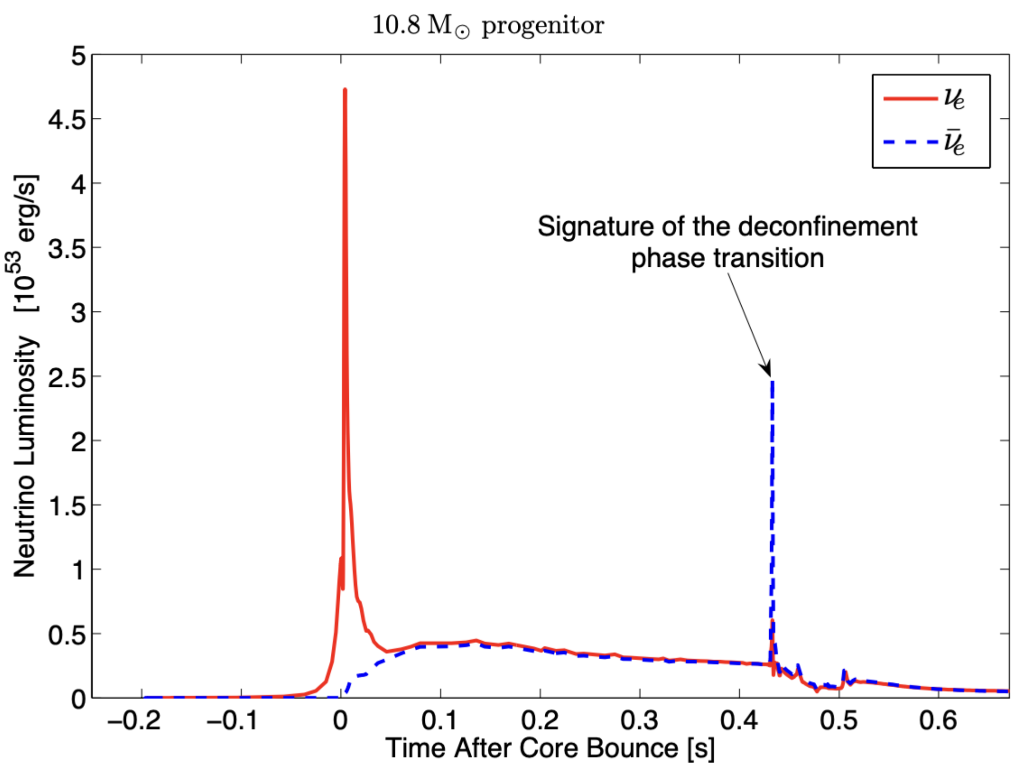
[Universe 2025, 11(7), 224](), [arXiv:2504.00240]()

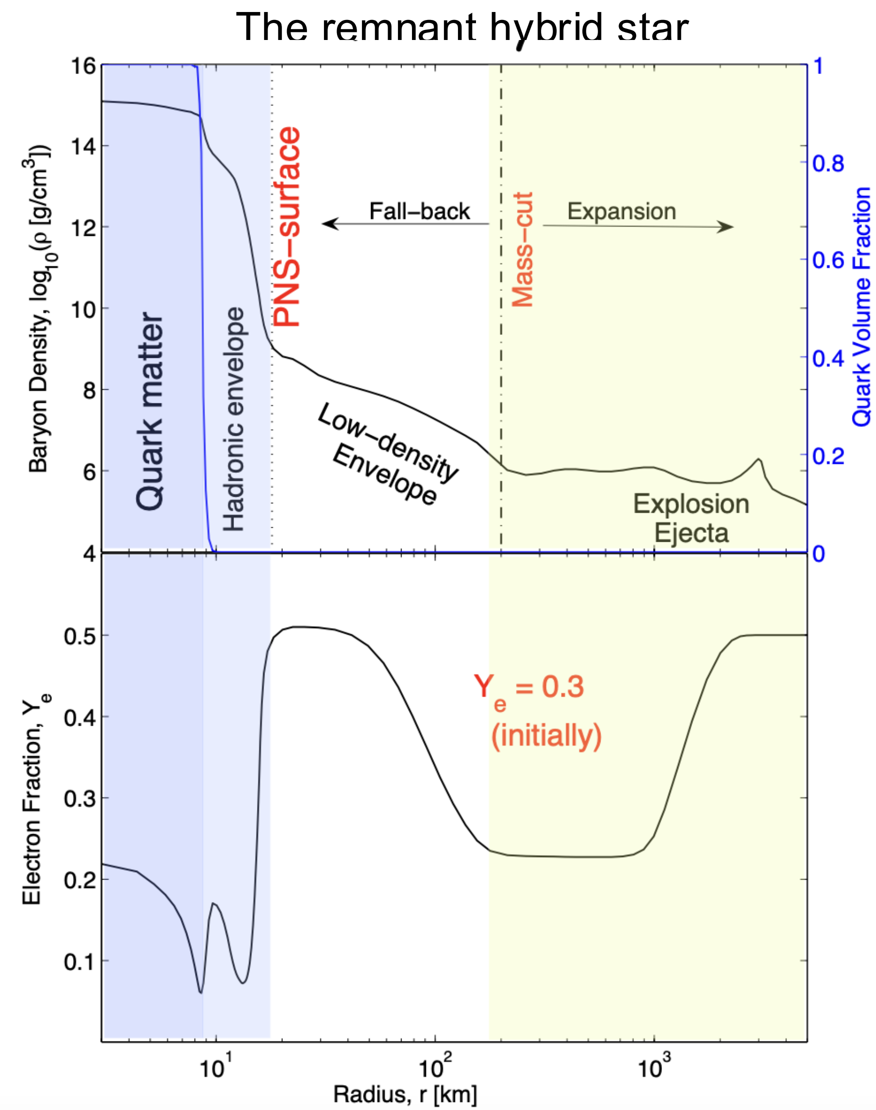
Future Potential Multi-Messenger Observations of Twin Compact Stars

Observables in the quark-hadron phase transition

- Proton neutron star collapse and Shock formation
- Explosion mechanism of massive stars
- Observable in neutrino signal
- Resolvable in (Super-K, Icecube) for a galactic supernova

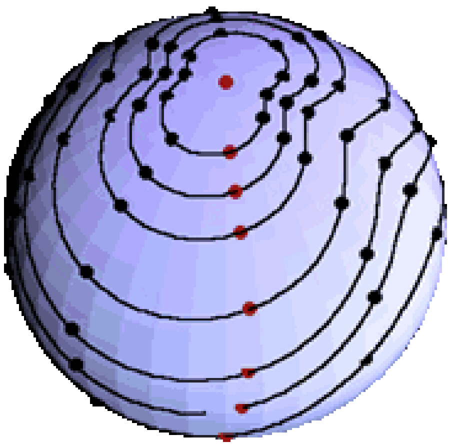
Sagert & T.F. et al. (2009), PRL 102, 081101
Dasgupta & T.F. et al. (2010), PRD 81
T.F. et al. (2011), ApJS 194, 39



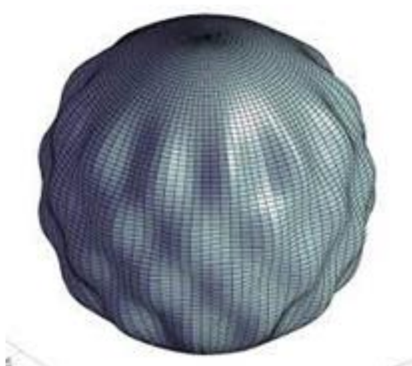


Credit: Tobias Fischer

Gravitational Waves from NS



Credit: C. Hanna and B. Owen

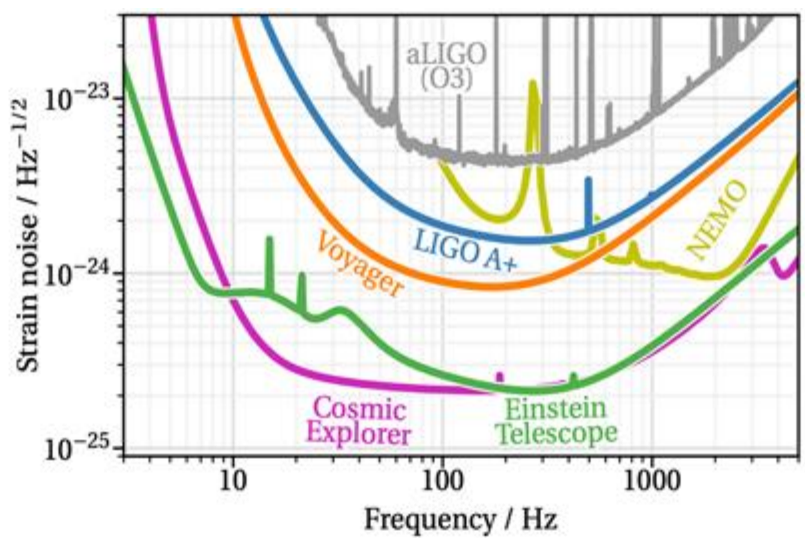


Credit: CERN/Indico

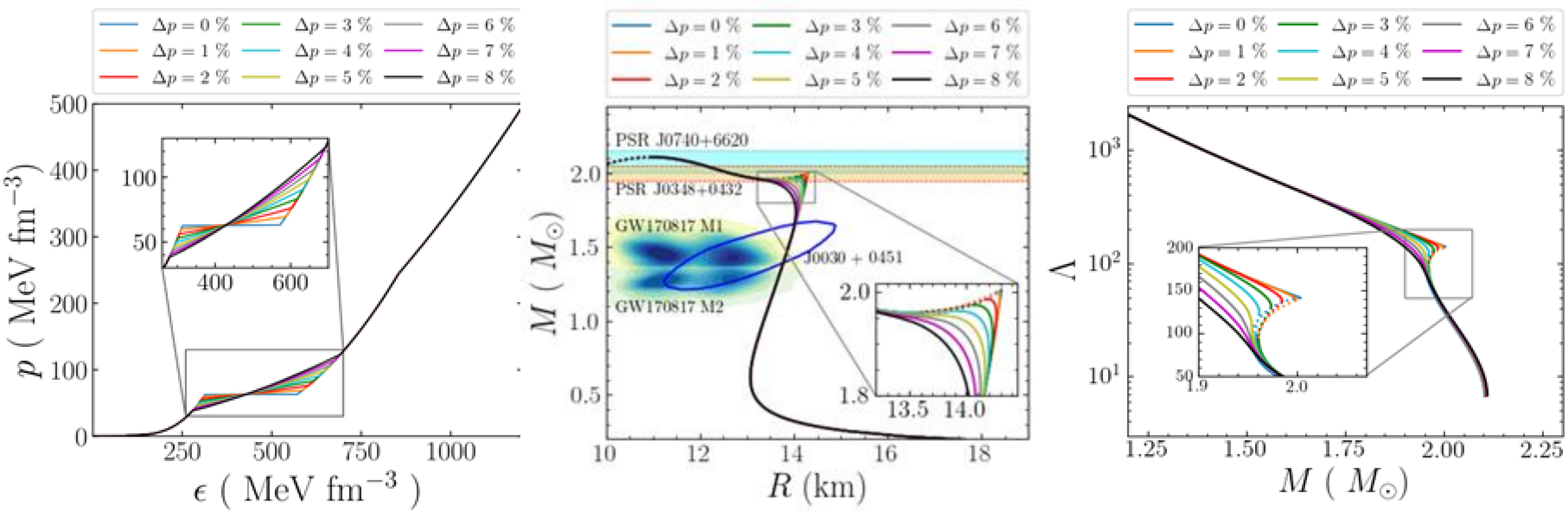
PC: cosmicexplorer.org/sensitivity

- Non-radial QNMs raised from time varying quadrupole deformations are source of GWs.

  - fundamental (f) mode,
    - no node, probe for mean density,(1 kHz < f < 3kHz)
  - pressure (p) mode,
    - Sound speed, (5 kHz < f < 10kHz)
  - gravity (g) mode,
    - (50 Hz < f < 500 Hz)
- R-mode, for rotating stars only.
  - Viscosity, (0.5 kHz < f < 2kHz)
- Space-time (w) mode.
  - 5 kHz< f



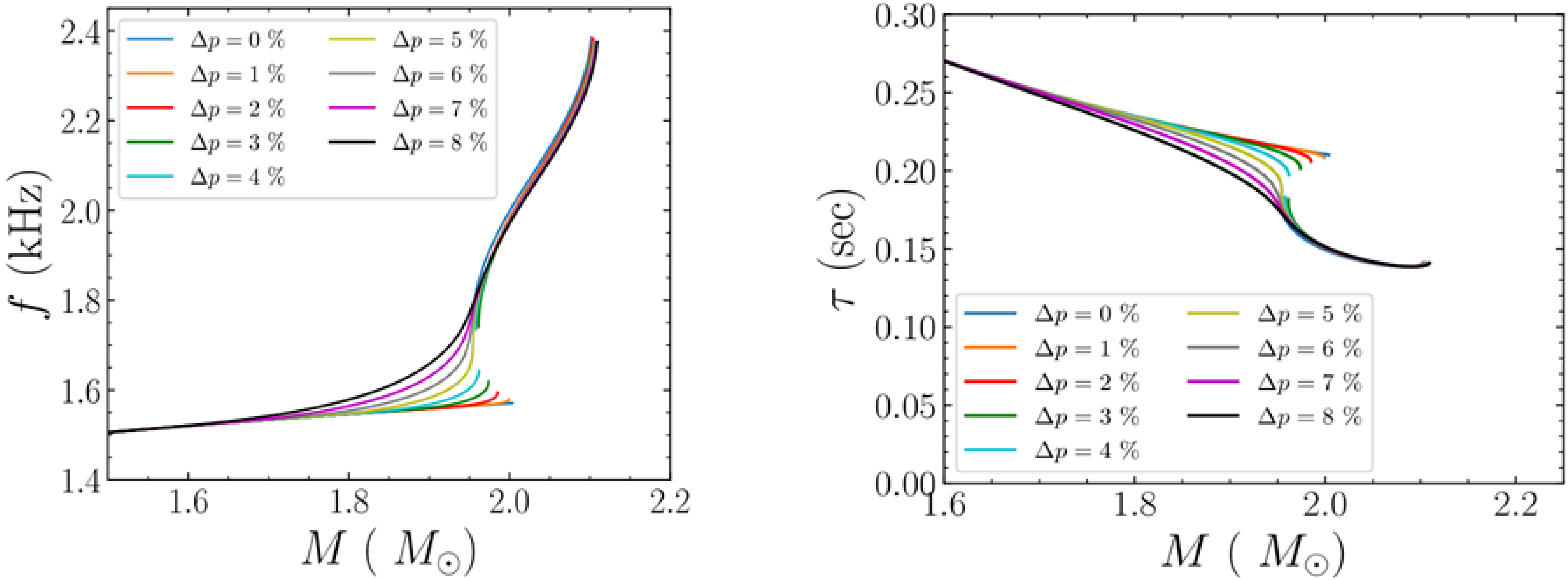
Stellar Properties



- ❖ The second and third family merge to form a single branch for Δp > 4% .
- ❖ Precise measurement of *M-R* required for detection of twin star.
- ❖ The jump ΔΛ (if any) can be measured ~15 % (< 90% CI) with next-generation GW detectors (P. Landry & K. Chakravarti , arXiv:2212.09733 ,2022).

David Alvarez-Castillo, Bikram Keshari Pradhan, Debarati Chatterjee – arXiv:2309.08775
Monthly Notices of the Royal Astronomical Society, Vol 531, Issue 4, Pag 4640–4655 (2024)

f-mode characteristics



- f-mode characteristics are obtained within ***General relativistic*** formalism.
- Sudden increase (decrease) in the frequency (damping time) observed with appearance of twin star.
- Detections of f-mode GWs from compact stars with known mass may reveal the presence of twin stars.
- Simultaneous measurement of *M-f* (from binary system) can be used to reveal twin stars.

David Alvarez-Castillo, Bikram Keshari Pradhan, Debarati Chatterjee – arXiv:2309.08775
Monthly Notices of the Royal Astronomical Society, Vol 531, Issue 4, Pag 4640–4655 (2024)

Asteroseismology and Universal Relations

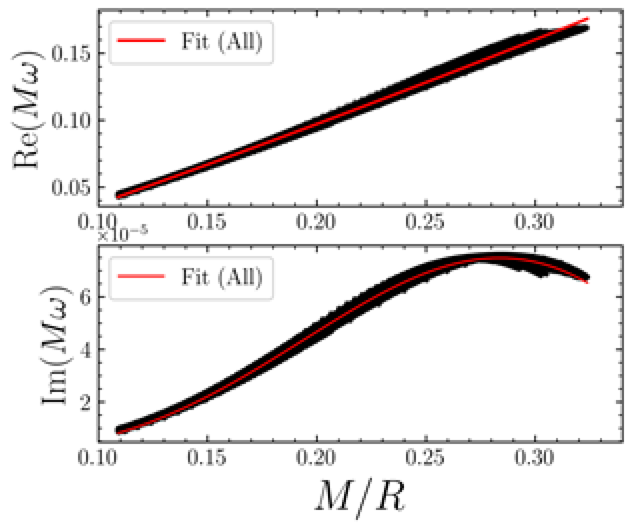
- URs among f-mode characteristics (f, τ_f or $\omega=2\pi f+1/\tau_f$) and NS observables.

$$f(\mathrm{kHz}) = a_r + b_r\sqrt{\frac{M}{R^3}}$$

Empirical relations (EOS dependent)

$$\mathrm{Re}(M\omega) = a_0 + a_1\left(\frac{M}{R}\right) + a_2\left(\frac{M}{R}\right)^2$$

$$\mathrm{Im}(M\omega) = b_0\left(\frac{M}{R}\right)^4 + b_1\left(\frac{M}{R}\right)^5 + b_2\left(\frac{M}{R}\right)^6$$



	Re(Mω)		Im(Mω)
a_0	$-0.027\pm9\times10^{-5}$	b_0	$(9.81\pm0.004)\times10^{-2}$
a_1	0.610 ± 0.0015	b_1	$(-4.444\pm0.003)\times10^{-1}$
a_2	0.049 ± 0.002	b_2	$(4.91\pm0.0045)\times10^{-1}$

- Scaled Universal relations are more useful.
- The URs can be used for EoS inference.
- URs involving tidal deformability have also been examined.

David Alvarez-Castillo, Bikram Keshari Pradhan, Debarati Chatterjee – [arXiv:2309.08775]
[Monthly Notices of the Royal Astronomical Society, Vol 531, Issue 4, Pag 4640–4655 (2024)]

Inclusion of Observational Uncertainties

- F-mode being excited during pulsar glitches. All the energy radiated through GW.
- The burst waveform is modelled as an exponentially damped oscillation.

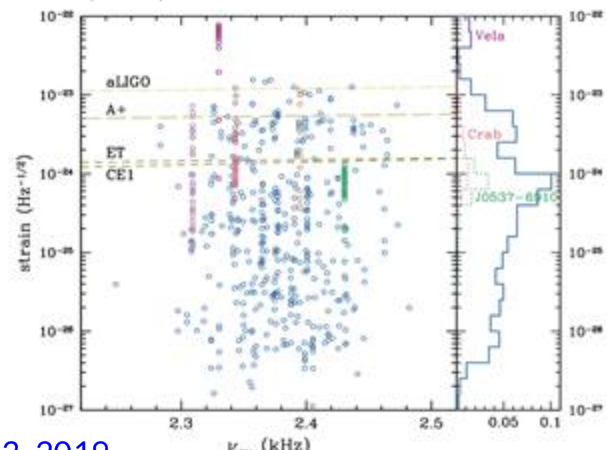
$$h(t) = h_0 \exp(-t/\tau_f) \sin(2\pi\nu_f t), \;\; t > 0$$

(B.J. Owen,2010, Ho et al. 2020)

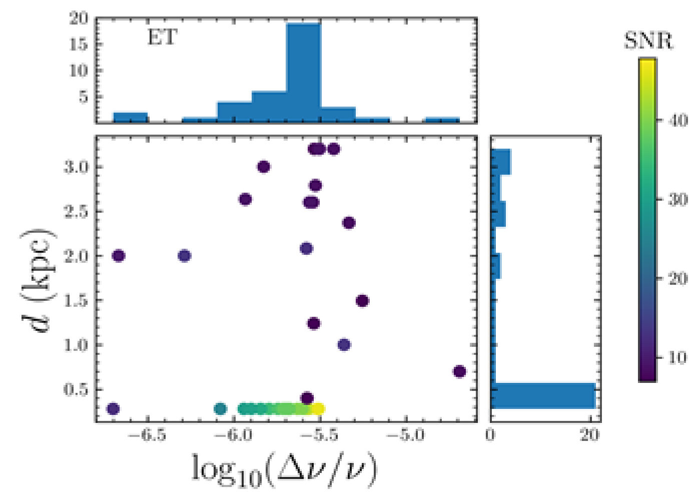
$$h_0 = 4.85\times10^{-17}\sqrt{\frac{E_{\rm gw}}{M_\odot c^2}}\sqrt{\frac{0.1{\rm sec}}{\tau_f}}\frac{1{\rm kpc}}{d}\left(\frac{1{\rm kHz}}{\nu_f}\right)$$

f-modes GW

$$E_{\rm gw} = E_{\rm glitch} = 4\pi^2 I\nu^2(\frac{\Delta\nu}{\nu})$$



Ho et al ,PRD 101, 103009 (2020)



B. K. Pradhan, D. Pathak, and D. Chatterjee, *ApJ* **956** 38, (2023)

- B. Abbott et al.,LVC, *ApJ* **874** 163, 2019.
- R. Abbott et al.,LVK, PhRvD, 104, 122004, 2021.
- R. Abbott, et al., LVK, arXiv:2210.10931, 2022.
- R. Abbott, et al., LVK, arXiv:2203.12038, 2022.
- D. Lopez et al., PhRvD, 106, 103037, 2022

David Alvarez-Castillo, Bikram Keshari Pradhan, Debarati Chatterjee – arXiv:2309.08775
Monthly Notices of the Royal Astronomical Society, Vol 531, Issue 4, Pag 4640–4655 (2024)

The Crust of Twin Compact Stars

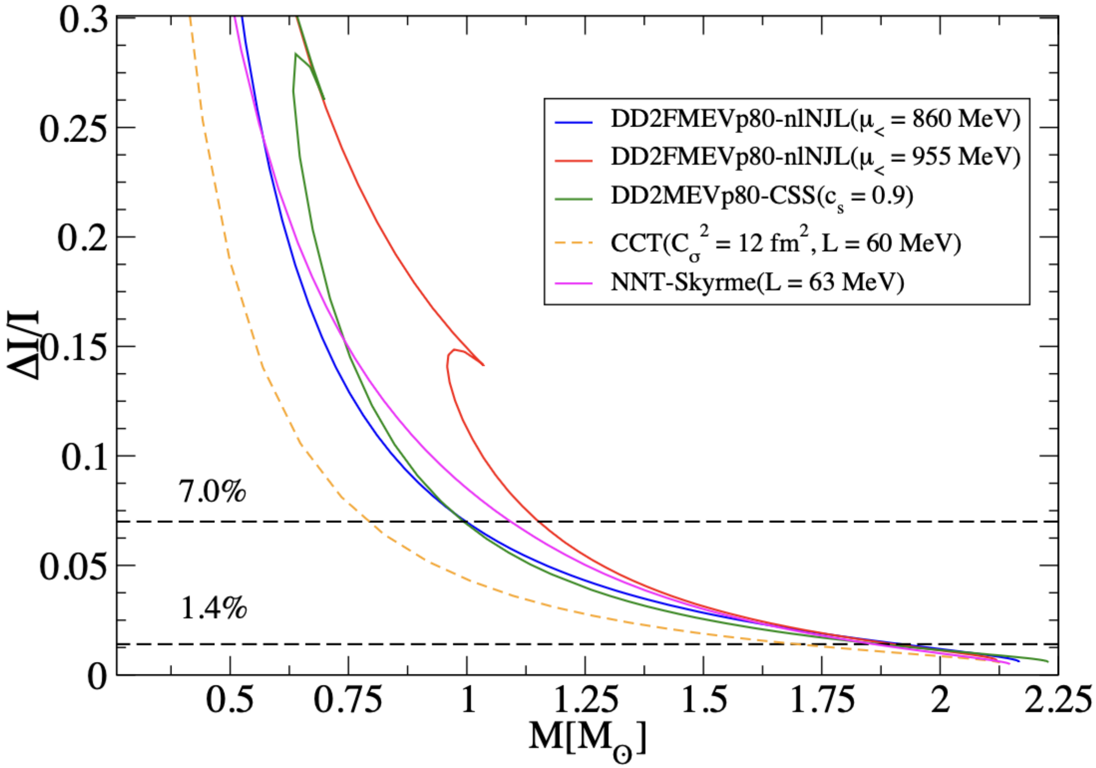
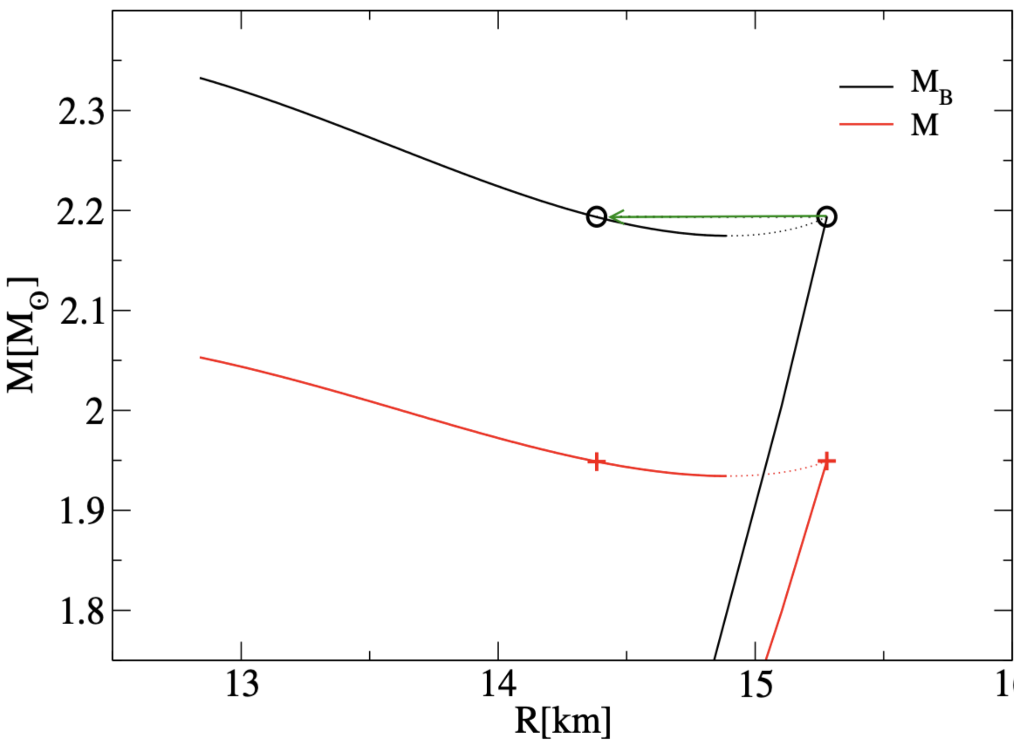
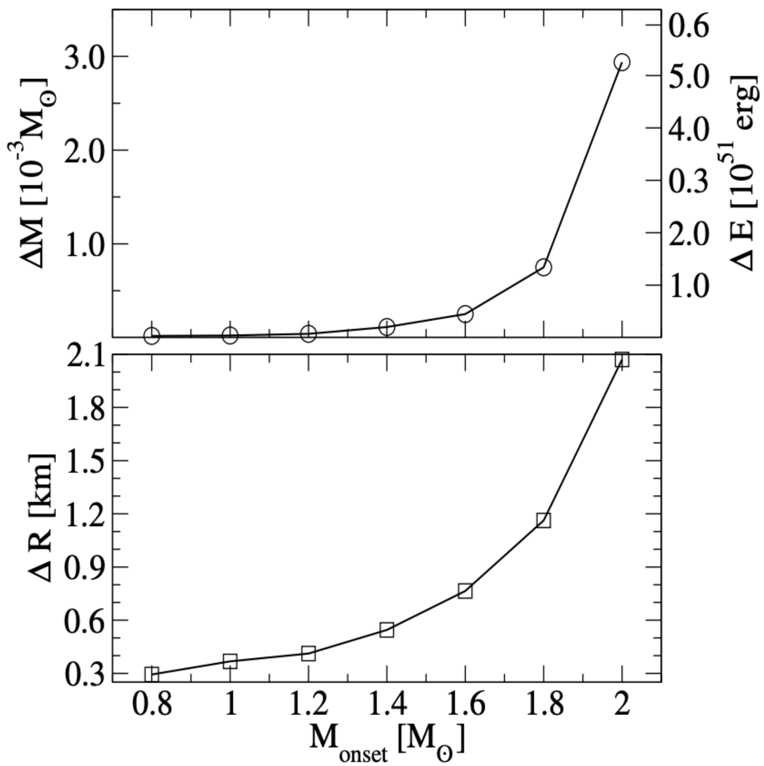


Figure 14. Fraction of the stellar Moment of Inertia carried by the crust together with pulsar glitch constraints for the compact star mass M of a glitcher derived by the Vela pulsar ($\Delta I/I > 1.4\%$), and from consideration of entrainment of superfluid neutrons in the crust ($\Delta I/I > 7.0\%$).

Mass Twins – Energy Released





DD2MEV-CSS EoS, Astron. Nachr. 1–6 (2021), arXiv: 2011.11145

Dynamical interaction of a binary with a circumbinary disc

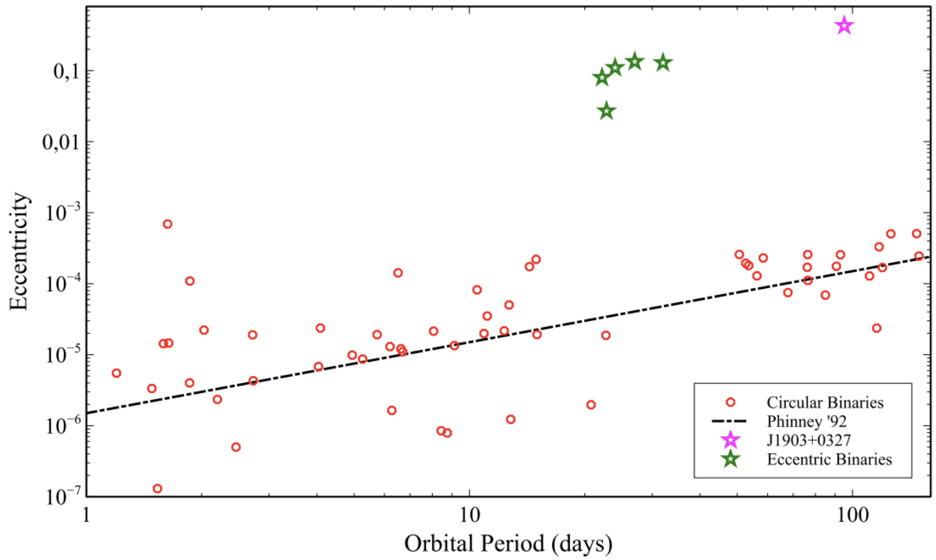
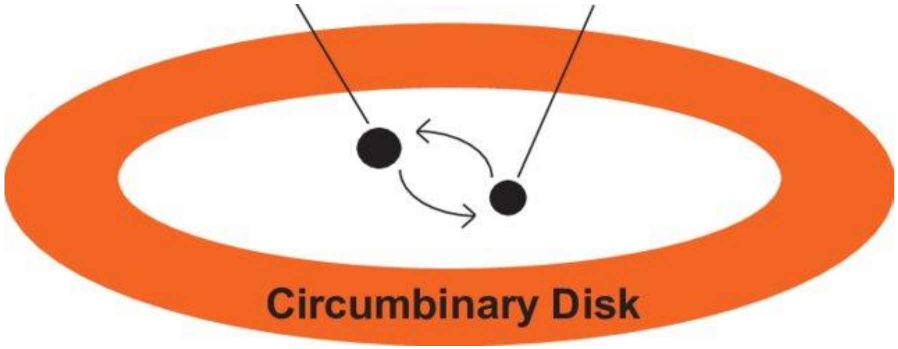


FIGURE 1 Eccentricity vs. orbital period for millisecond pulsars in binaries with white dwarf companions, see (J. Antoniadis, 2014; Stovall, 2019).



David Edwin Alvarez-Castillo, John Antoniadis, Alexander Ayriyan, David Blaschke, Victor Danchev, Hovik Grigorian, Noshad Khosravi Largani, Fridolin Weber.

Astron. Nachr. 2019;340:878-884, Eprint: arXiv: 1912.08782

Implications on eccentric and isolated millisecond pulsar populations

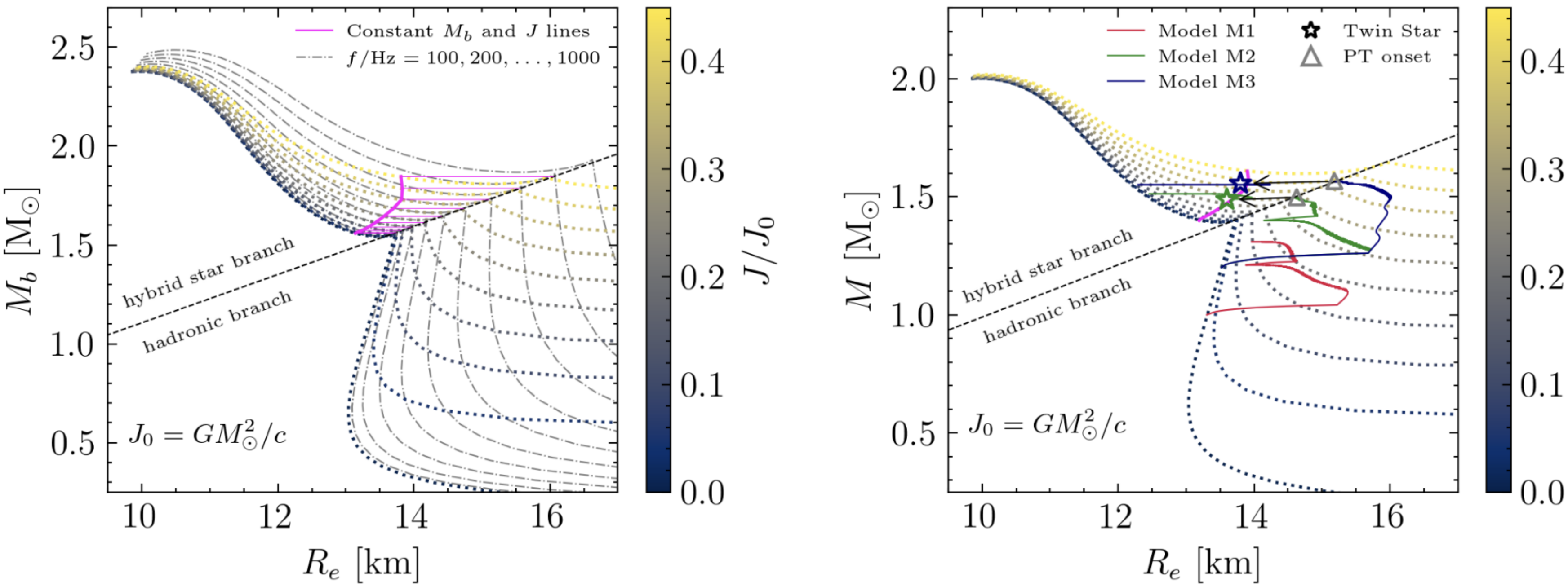


Fig. 1: *Left Panel*: Baryonic mass vs. equatorial radius. Dotted and dot-dashed curves indicate lines of constant angular momentum and constant frequency respectively. The black dashed line highlights the points of maximum stability in the hadronic branches, signaling the onset of a phase transition (PT). Thin, horizontal magenta lines show trajectories where angular momentum (J) and baryonic mass (M_b) are conserved. The thick magenta curve connects points on the hybrid star branches that can be reached through a collapse conserving both J and M_b. *Right Panel*: Similar to the left panel, but with the y-axis representing gravitational mass. Star markers denote the endpoint trajectories for direct (M2) and delayed (M3) collapse models. Here, the arrows are inclined because gravitational mass, unlike baryonic mass, is not conserved during the PT.

S. Chanlaridis et al. - [A&A 695, A16 (2025)](), [arXiv:2409.04755]()

Implications on eccentric and isolated millisecond pulsar populations

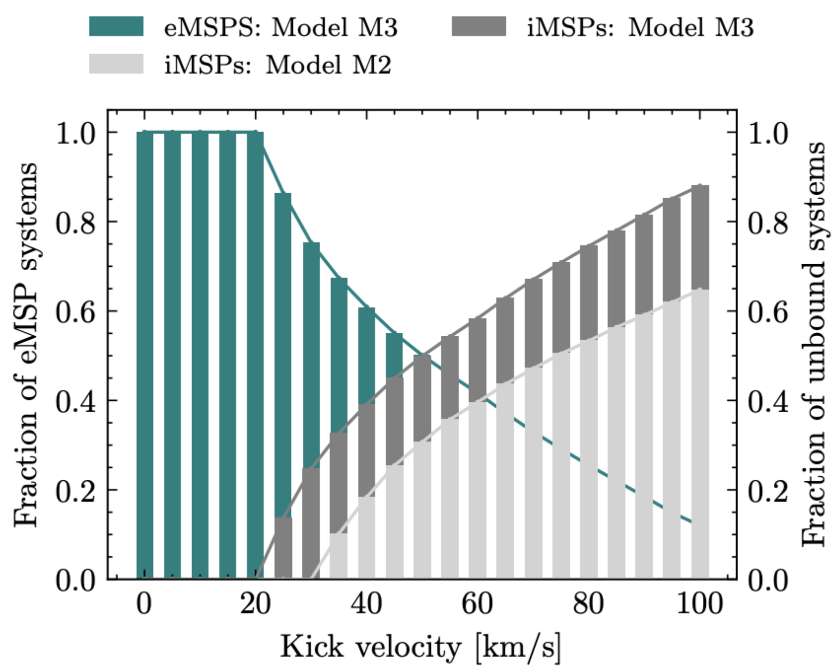
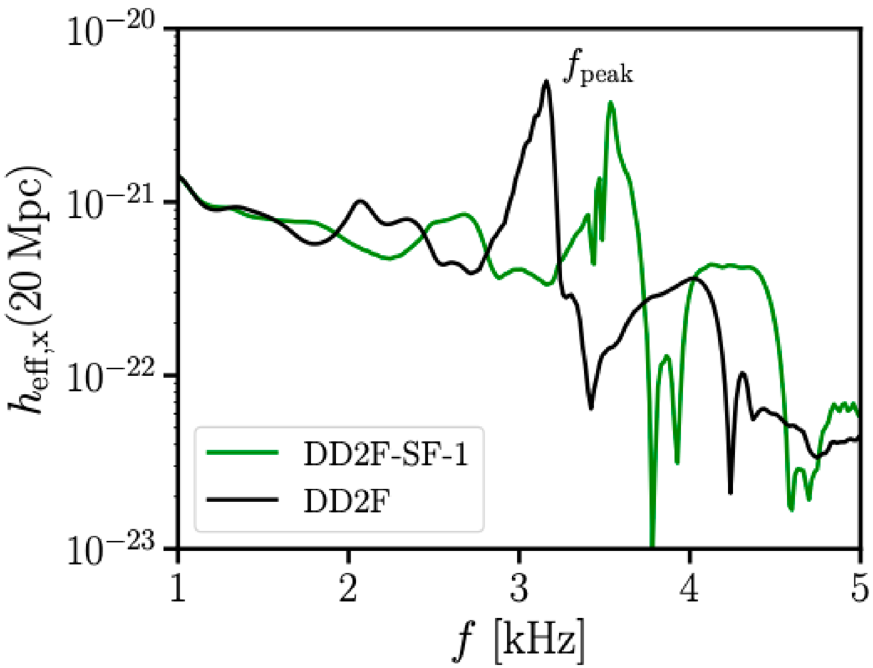
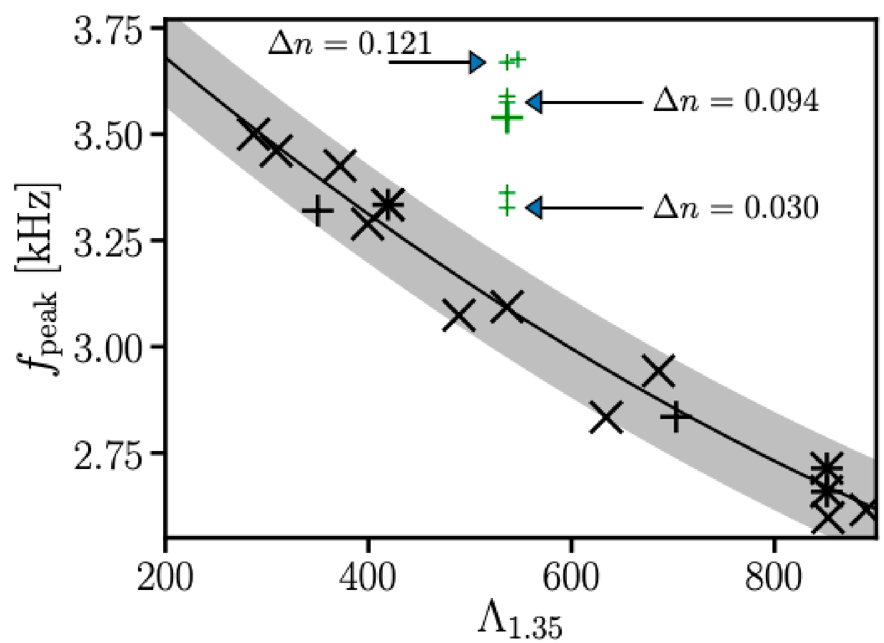


Fig. 6: Expected fraction of eMSPs (left y-axis) and iMSPs (hatched gray-colored bars, right y-axis) as a function of kick velocity, assuming a mass defect of $\Delta M = 0.016\,M_\odot$. For iMSPs, we consider those systems with eccentricities greater than unity. Model M2 cannot create eccentric systems due to rapid re-circularization of the orbit.

S. Chanlaridis et al. - A&A 695, A16 (2025), arXiv:2409.04755

Gravitational Wave Signals
First Order Phase Transitions





A. Bauswein et al. - PRL 122 (2019) 061102, arXiv: 1904.01306

LA-UR-25-22199, INT-PUI

Interface modes in inspiralling neutron stars: A gravitational-wave probe of first-order phase transitions

A. R. Counsell,[1,*] F. Gittins,[2,3,†] N. Andersson,[1] and I. Tews[4]

[1] *Mathematical Sciences and STAG Research Centre, University of Southampton, Southampton SO17 1BJ, United Kingdom*

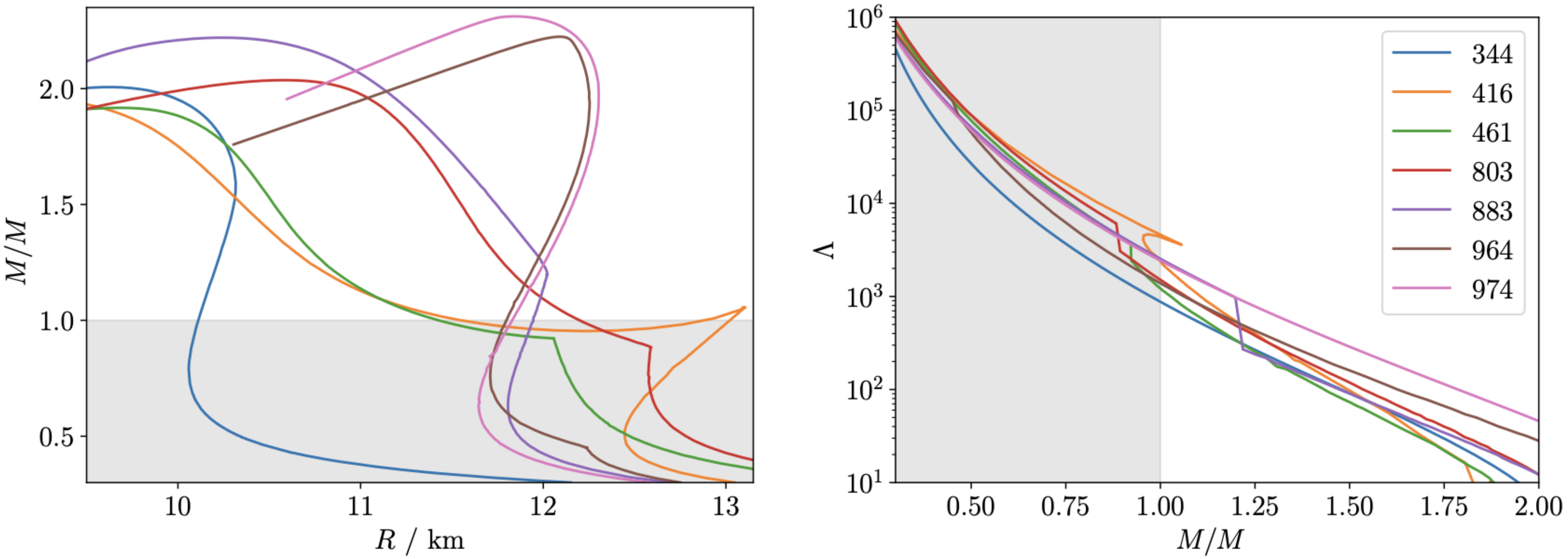
[2] *Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University, Princetonplein 1, 3584 CC Utrecht, Netherlands*

[3] *Nikhef, Science Park 105, 1098 XG Amsterdam, Netherlands*

[4] *Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, United States*

(Dated: April 9, 2025)

At the extreme densities in neutron stars, a phase transition to deconfined quark matter is anticipated. Yet masses, radii and tidal deformabilities offer only indirect measures of a first-order phase transition, requiring many detections to resolve or being ineffective observables if the discontinuity exists at lower densities. We report on a *smoking-gun* gravitational-wave signature of a first-order transition: the resonant tidal excitation of an interface mode. Using relativistic perturbation theory with an equation-of-state family informed by chiral effective field theory, we show that such a resonance may be detectable with next-generation interferometers and possibly already with LIGO A+ for sufficiently loud events.



A. R. Counsell et al. - [Phys. Rev. Lett. 135, 081402 (2025)], [arxiv: 2504.06181]

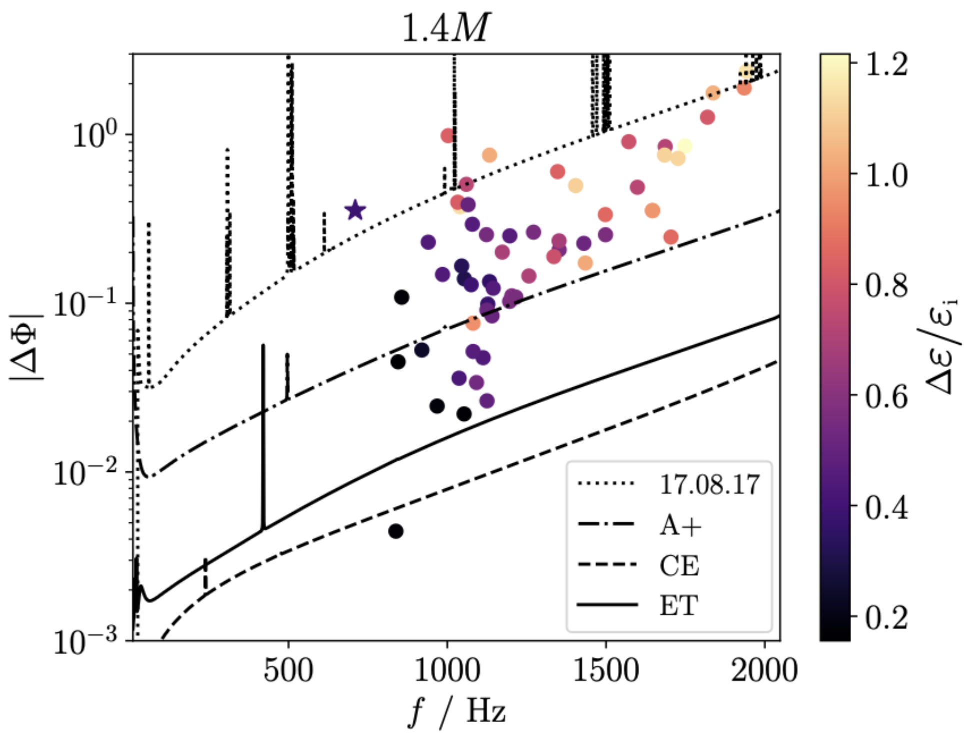


FIG. 2. Estimated shift in orbital phase $|\Delta\Phi|$ against gravitational-wave frequency f for an equal-mass $M = 1.4M_\odot$ binary. Each marker corresponds to an $l = 2$ i-mode resonance computed from a different EOS in the ensemble, coloured by the relative jump in energy density $\Delta\varepsilon/\varepsilon_{\rm i}$. We indicate with a star the interface mode associated with model 964 in Fig. 1. Also inlaid are the sensitivity curves for LIGO Livingston during the GW170817 event, LIGO A+ (dot-dashed), Cosmic Explorer (CE, dashed) and the Einstein Telescope (ET, solid), assuming the binary is at a luminosity distance of 40 Mpc from the instrument.

Outlook

- Multi-messenger astronomy and collider experiments will continue probing the properties of dense matter.
- Bayesian Analysis and Machine Learning methods are useful for estimation of unknown physical parameters.
- f-mode oscillation of hybrid stars and twin stars involving the “pasta phase” has been investigated, future GW interferometers will be able to corroborate.
- Re-examination of the asteroseismology problem considering the twin stars.
- Compact star crusts studies and measurements are promising, work in progress.
- Further signatures for twins may come from secondary neutrinos from supernova explosions, cooling rates, extremal rotation, thermal twins, etc.

Gracias