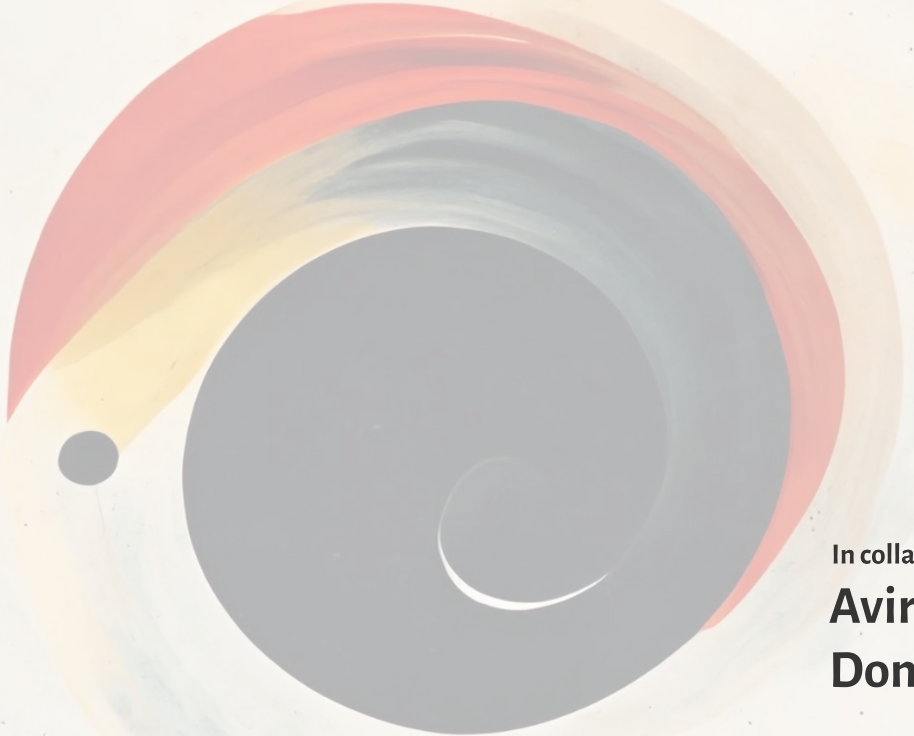
Revealing Phase Transitions with GW Spectroscopy of BNS Mergers

Pedro Luis Espino



In collaboration with:

Aviral Prakash, David Radice, Domenico Logoteta

N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

NSF

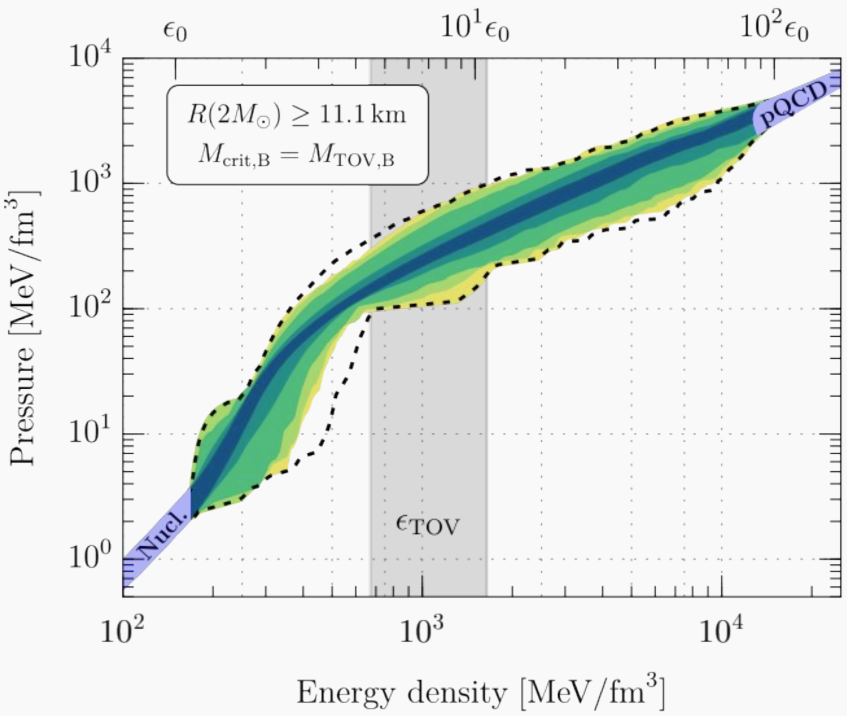
PennState

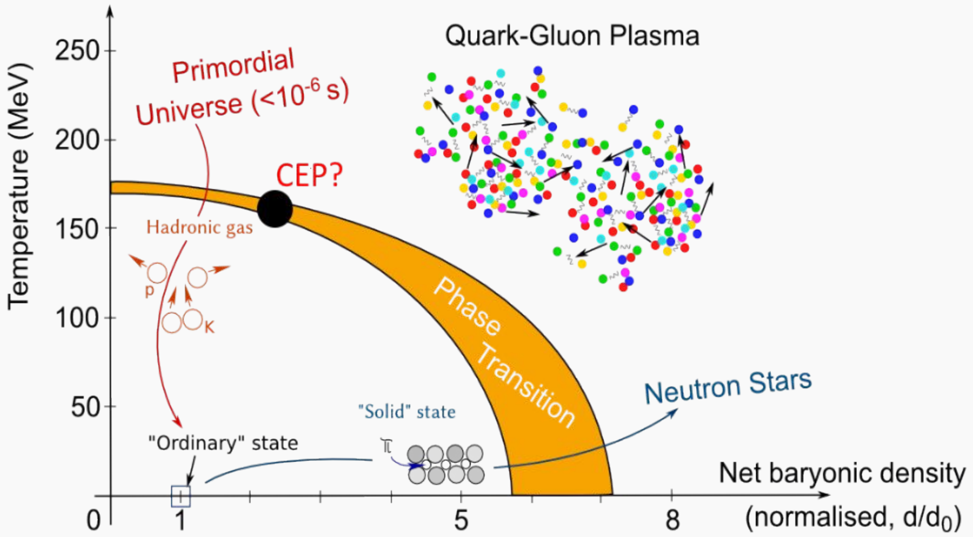
THE UNIVERSITY OF CALIFORNIA 1868 LET THERE BE LIGHT

01 Introduction

- Neutron star equation of state
- Effects of phase transitions in BNS mergers
- One-armed spiral instability

The neutron star equation of state (EOS) remains uncertain – deconfinement phase transitions are astrophysically viable

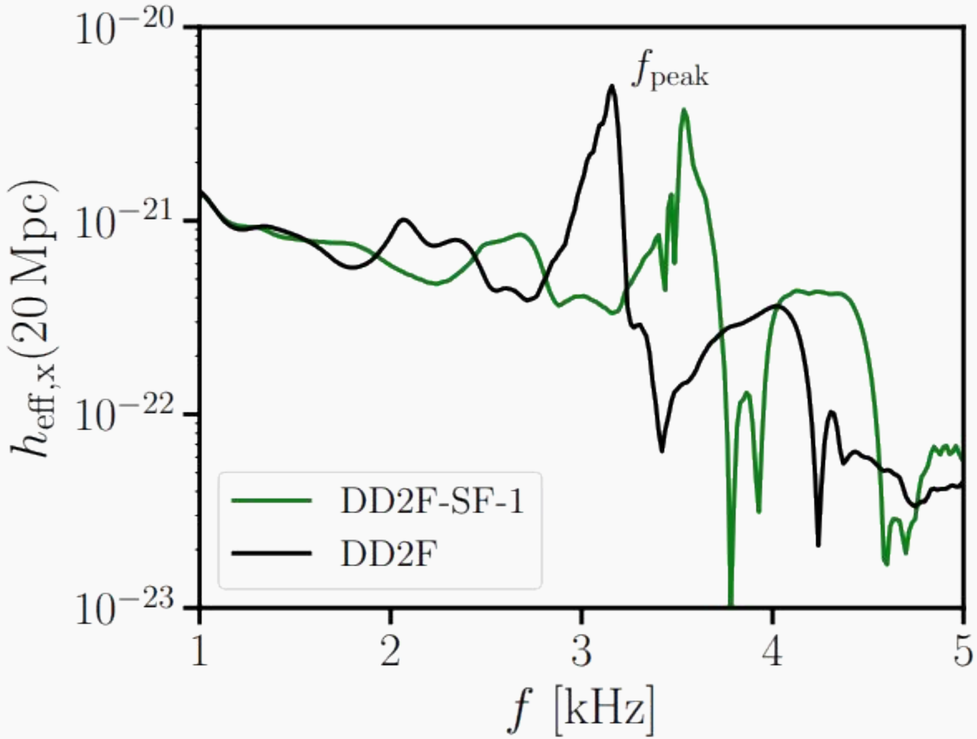




Annala et al., Phys.Rev.X 12 1, 011058 (2022)

Effects of deconfinement phase transitions in BNS mergers

Bauswein et al., Phys. Rev. Lett. 122, 061102



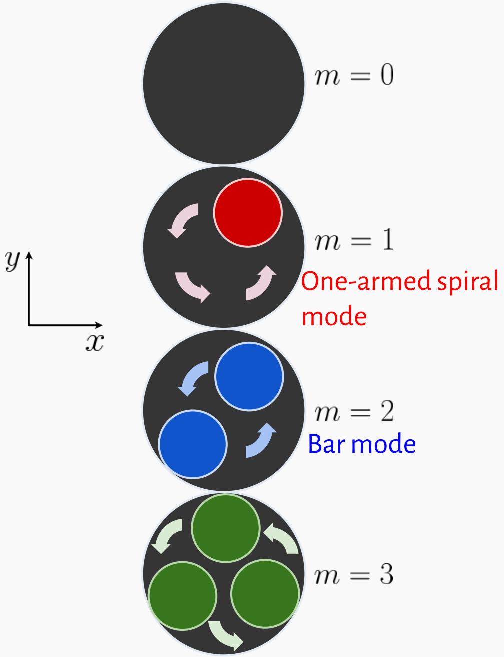
- PTs may lead the characteristic frequency associated with the post-merger signal to shift toward higher values
- This effect is not always seen, and is small

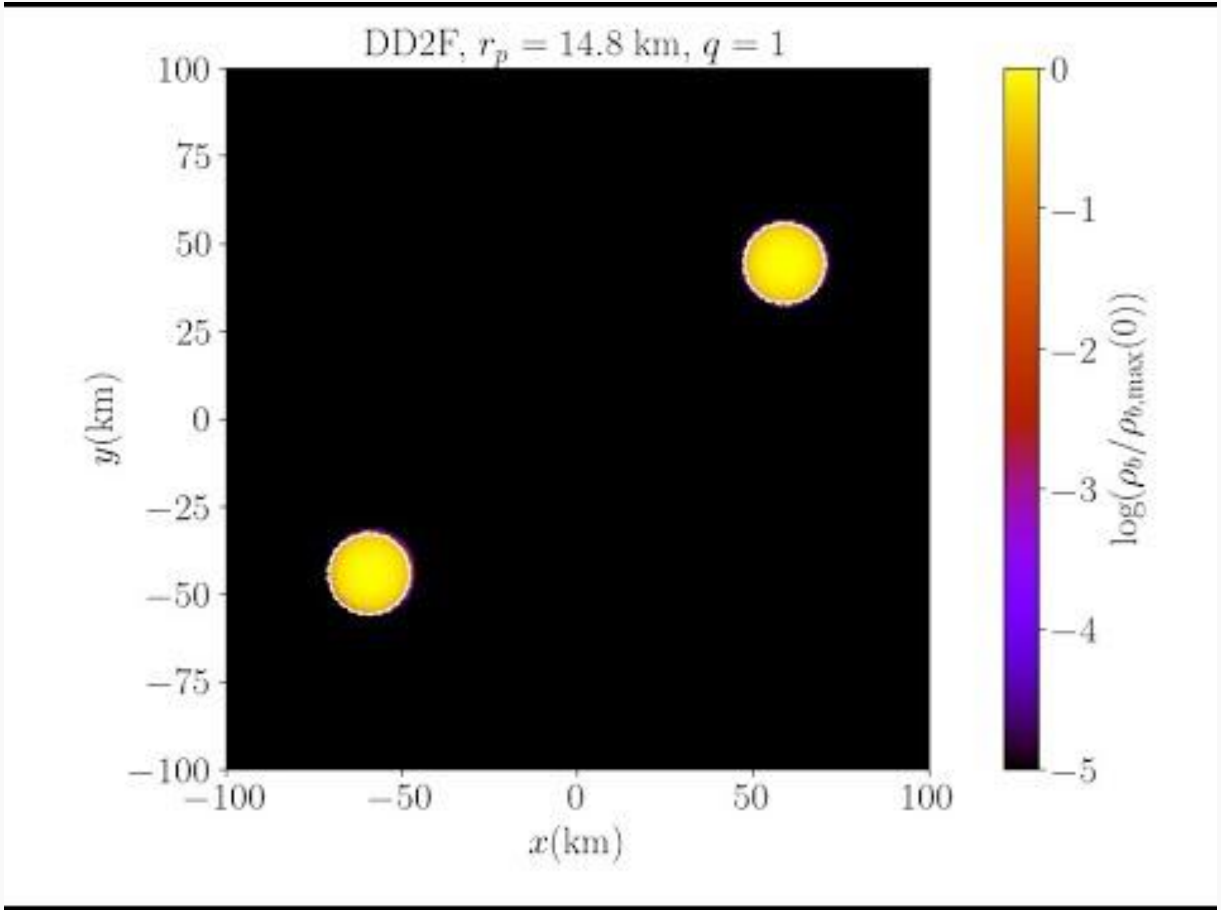
Are there other effects that phase transitions can have on post-merger observables?

The one-armed spiral instability

This is a non-axisymmetric instability which develops in differentially rotating fluids. Small patterns (modes) in the fluid density grow over time and become the dominant fluid pattern, typically at the expense of other patterns.

$$C_m = \int \sqrt{\gamma} W \rho e^{im\phi} \mathrm{d}x\mathrm{d}y$$

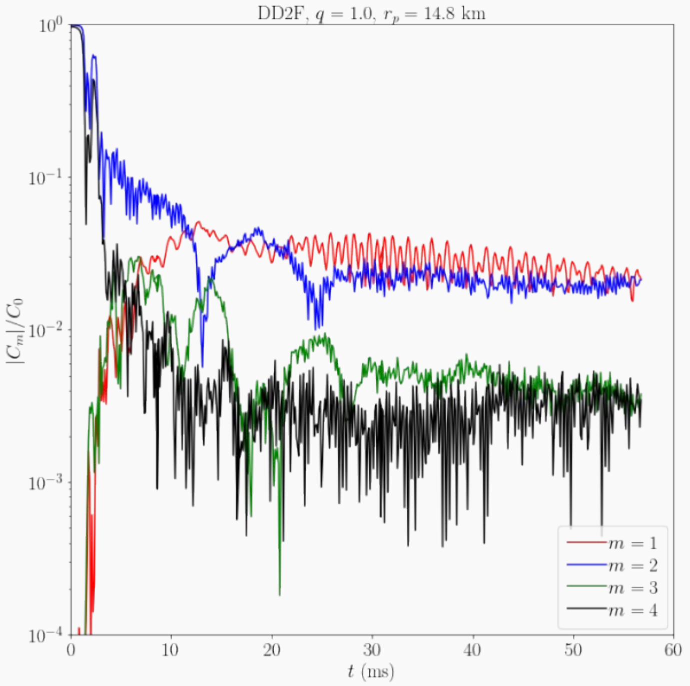


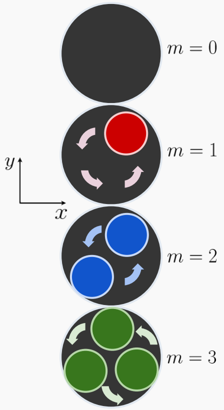


Monitoring the one-armed spiral instability

Density modes: decompose density azimuthally

$$C_m = \int \sqrt{\gamma} W \rho e^{im\phi} \mathrm{d}x\mathrm{d}y$$





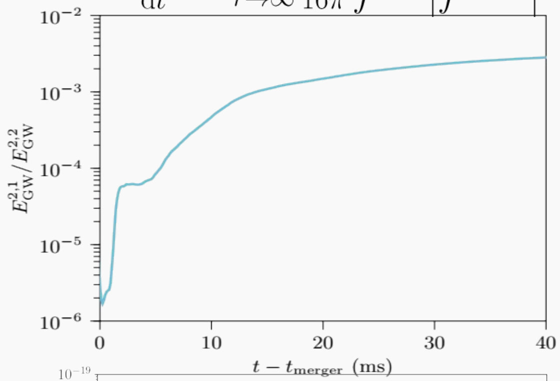
$$f^{2,1}_{\text{peak}} = \frac{f^{2,2}_{\text{peak}}}{2}$$

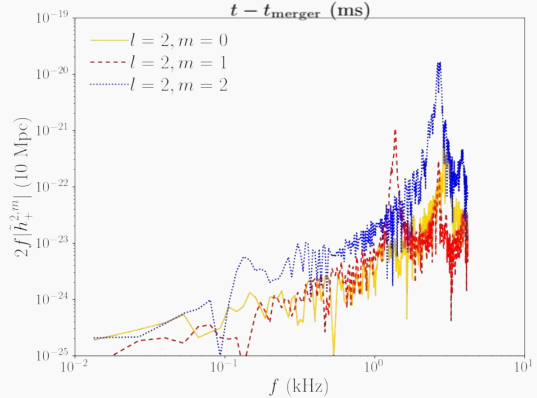
Gravitational waves: decompose gravitational radiation onto (s=-2 spin weighted) sphere (Newman-Penrose formalism)

$$\psi_4 = \ddot{h}_+ - i\ddot{h}_\times$$

$$\psi_4^{l,m} = \int \mathrm{d}\Omega ({}_{-2}Y^{l,m}) \psi_4$$

$$-\frac{\mathrm{d}E_{\text{GW}}}{\mathrm{d}t} = \lim_{r\to\infty} \frac{r^2}{16\pi} \int \mathrm{d}\Omega \left| \int \mathrm{d}t \psi_4 \right|^2$$





02 Methods

- EOS models
- GRHD simulations
- Monitoring the development of fluid instabilities

Methods overview

- We run 3D GRHD simulations of BNS mergers

- We construct initial configurations in two ways:
  - **Quasi-circular**: we build equilibrium BNS initial data (ID) with the `Lorene` code
  - **Eccentric**: we build **approximate** ID by superposing two static TOV solutions and boosting them based on parabolic Newtonian trajectories
- Fluid evolution: `WhiskyTHC` code
- Spacetime evolution: `CTGamma`

- We consider many different binary properties

- We consider **7 EOS models**:
  - 2 EOSs are purely hadronic
  - 5 EOSs contain a hadron-quark PT
- We consider both quasi-circular and highly eccentric inspirals - for a total of **8 simulations**
- We fix mass ratios to q=1
- In some cases we consider M0 neutrino transport and sub-grid viscosity
- Crucially, the **hadron-quark EOSs cover a range of the gap in energy density between the hadronic and quark phases**

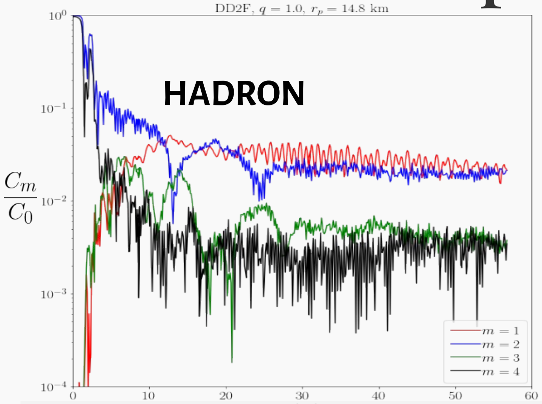
03 Results

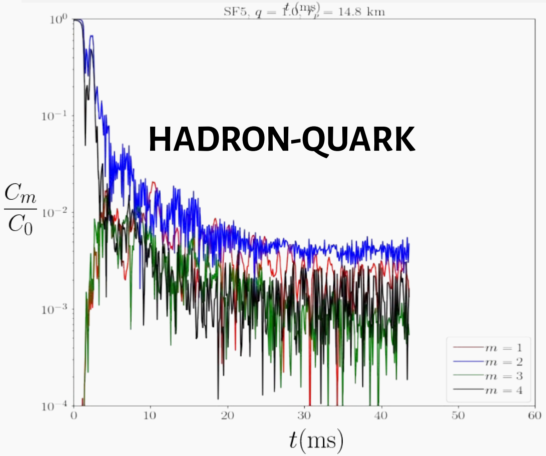
- How is the development of fluid instabilities affected by the presence of quarks in the post-merger remnant?

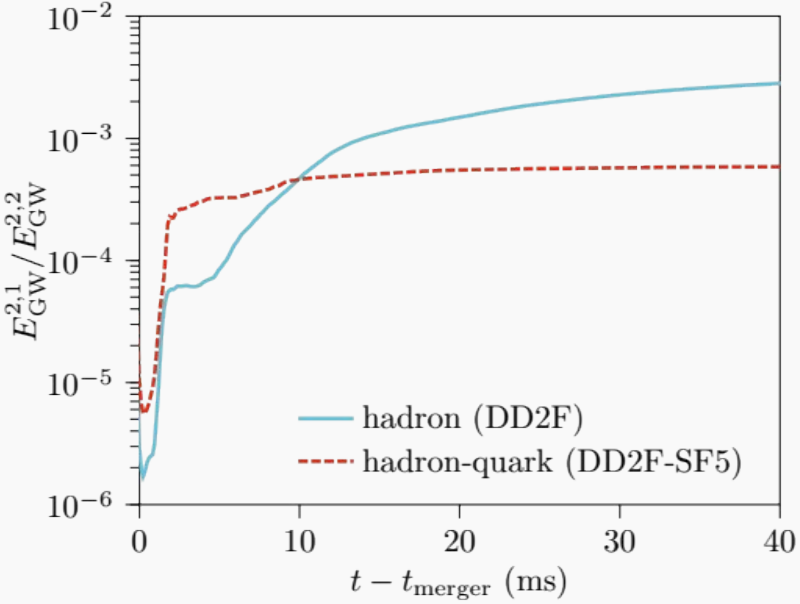
Deconfinement phase transitions suppress the one-armed spiral instability

- Density modes show that one-armed spiral instability does not easily develop in simulations with phase transitions

- GW energy carried in the 2,1 mode is significantly suppressed, and bolsters what is shown in the density modes





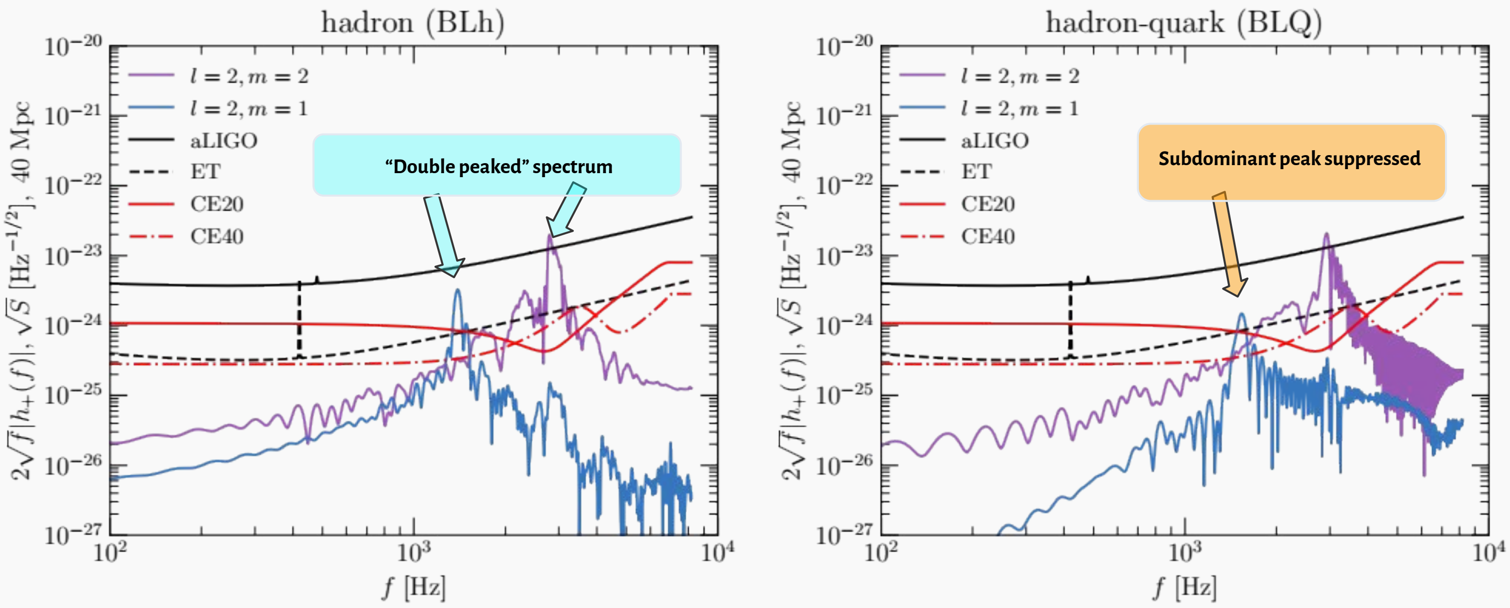


PLE, Prakash, Radice, Logoteta (2301.03619)

The suppression of the one-armed spiral instability affects the post-merger GW spectrum

- The one-armed spiral instability is (in principle) detectable in future generation detectors

- Detection of the one-armed spiral instability (and its ratio to the dominant post-merger signal) can allow us to place constraints on the energy density gap



PLE, Prakash, Radice, Logoteta (2301.03619)

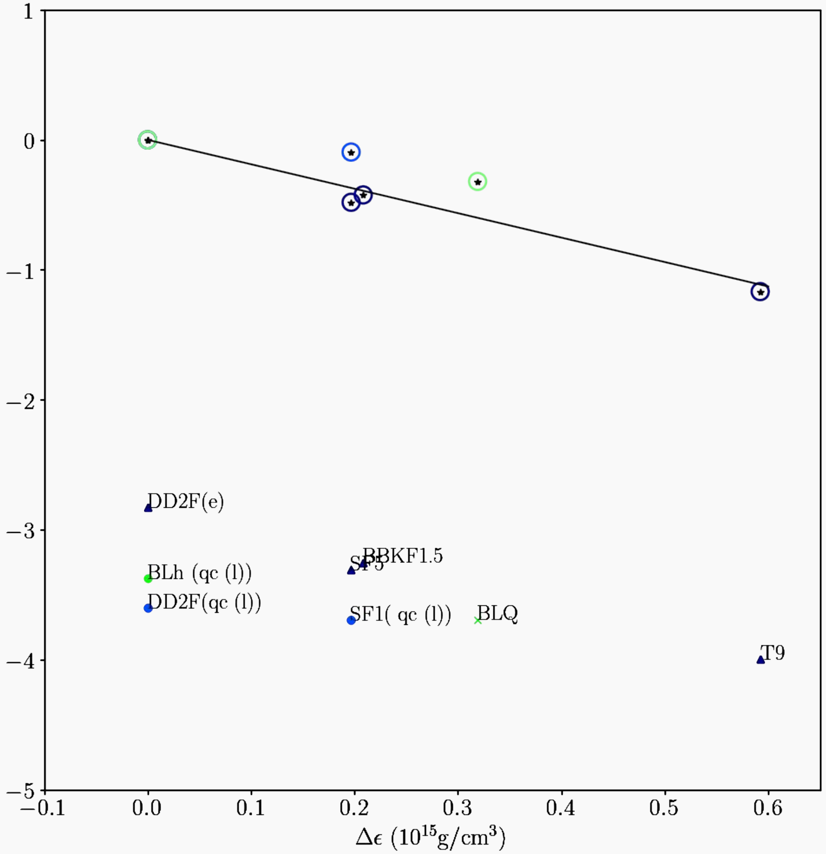
We find an anti-correlation between the 'strength' of the one-arm spiral instability and the 'strength' of the phase transition

- Accounting for uncertainties in the hadronic EOS and disparities in the timescale over which the instability develops, a trend emerges in how much the one-armed spiral instability is suppressed

- The larger the energy density gap between the two phases, the higher the suppression of the instability

- This shows a deep connection between microphysical features of the EOS and potentially observable features of the GW spectrum

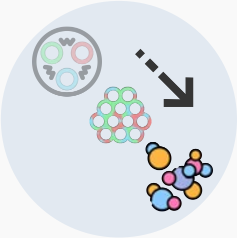
$$\frac{\log_{10}(\langle E_{\rm GW}^{2,1}\rangle)}{\log_{10}(\langle E_{\rm GW}^{2,2}\rangle)} \sim \frac{\mathrm{SNR}(f_{\rm peak}/2)}{\mathrm{SNR}(f_{\rm peak})}$$



PLE, Prakash, Radice, Logoteta (2301.03619)

04 Conclusion

Conclusion



Deconfinement phase transitions suppress fluid instabilities

- One-armed spiral instability suppressed with onset of the PT
- **The ‘stronger’ the PT, the ‘stronger’ the suppression (the ‘weaker’ the instability)**

GW signature of one-armed spiral instability affected by phase transition

- The **unique GW signal associated with the one-armed spiral instability** is affected by the onset of the PT

Effect may be detectable in future generation GW observatories

- Known **observable** effects:
  - Relative dimming of KN
  - Observable shift in post-merger peak frequency
  - **Suppression of one-armed spiral instability**

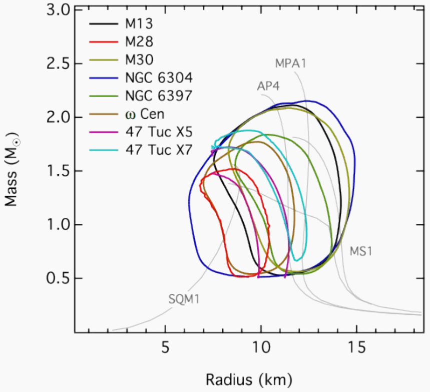
- Combined effects allow us to place constraints on whether PTs happen at densities/temperatures relevant to NS mergers

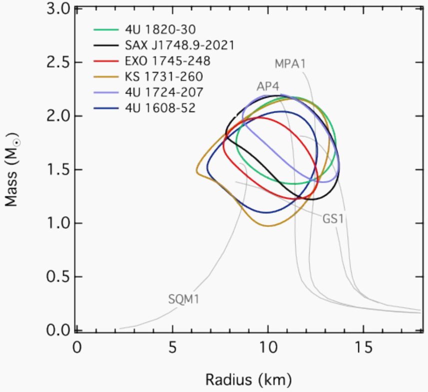
Future work

- Systematic determination of suppression
  - Assume fixed hadronic EOS
  - Change only features of phase transition
  - Consider identical ID across all runs
- Account for other effects (magnetic fields, unequal mass ratio)

05 BONUS!

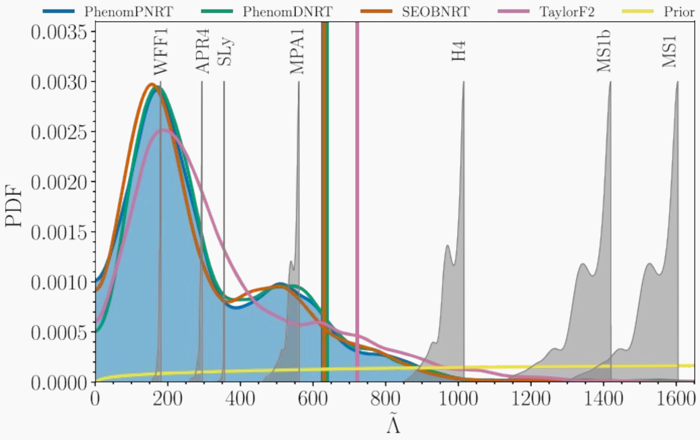
The neutron star equation of state (EOS) remains uncertain - deconfinement phase transitions are astrophysically viable

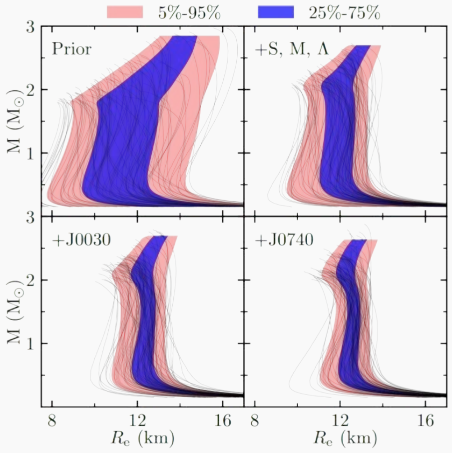


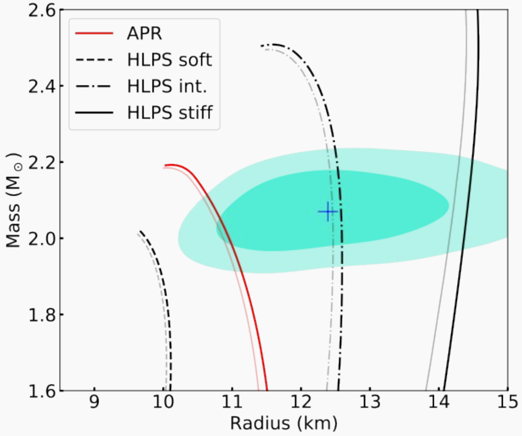


constraints:

- X-ray probes of NS Mass and Radius – **Ozel & Freire,** Ann.Rev.Astron.Astrophys. 54 (2016)
- Multimessenger constraints from GW170817 – **LVC**, Phys.Rev.X 9 1, 011001 (2019)
  - **smaller radii (R<13.6 km) favored**
- X-ray observation of NS hotspots (NICER)
  - PSR J0030+0451 – **Miller et al.**, Astrophys.J.Lett. 887 1, L24 (2019)
    M ~ 1.44 M⊙ R ~ 13.02 km
  - PSR J0030+0451 – **Riley et al.**, Astrophys.J.Lett. 887 1, L21 (2019)
    M ~ 1.34 M⊙ R ~ 12.71 km
  - PSR J0740+6620 – **Riley et al.**, Astrophys.J.Lett. 918 2, L27 (2021)
    M ~ 2 M⊙ R ~ 12.4 km (right plot)
  - PSR J0740+6620 – **Miller et al.**, Astrophys.J.Lett. 918 2, L28 (2021)
    M ~ 2 M⊙ R ~ 13.7 km (left plot)

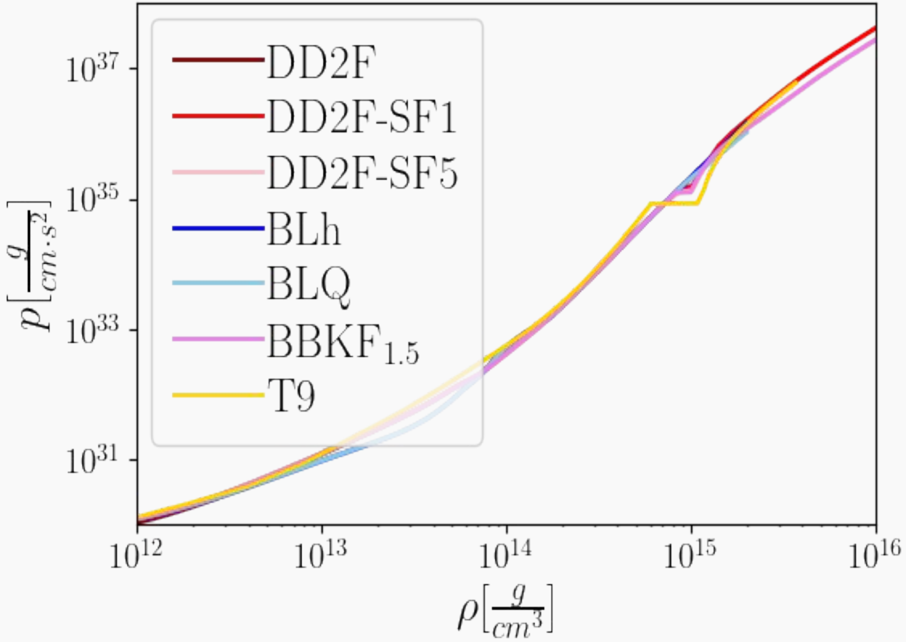


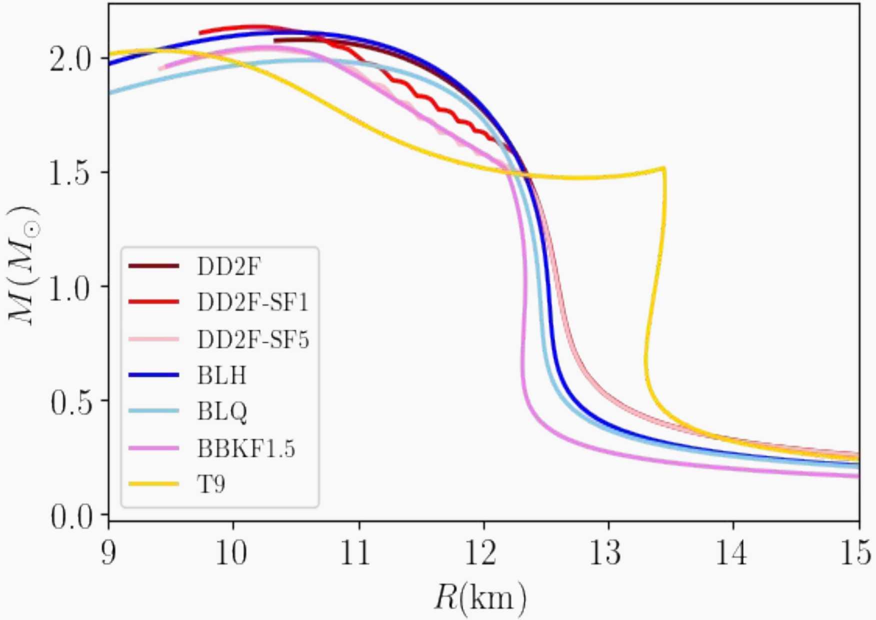




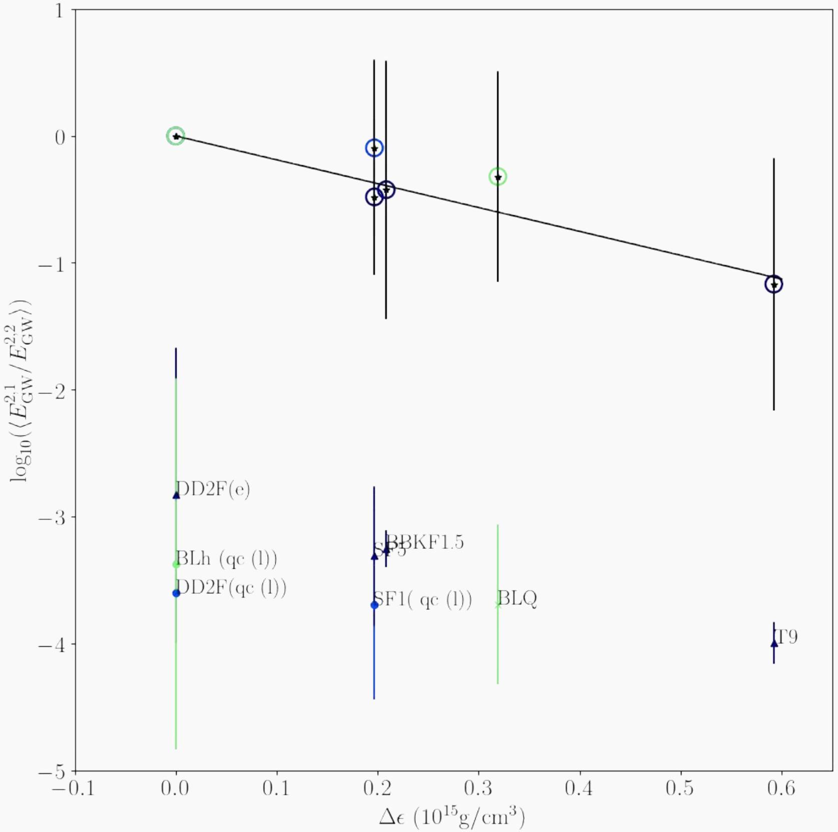
Annala et al., Phys.Rev.X 12 1, 011058 (2022)

Pressure-density and Mass-radius relations

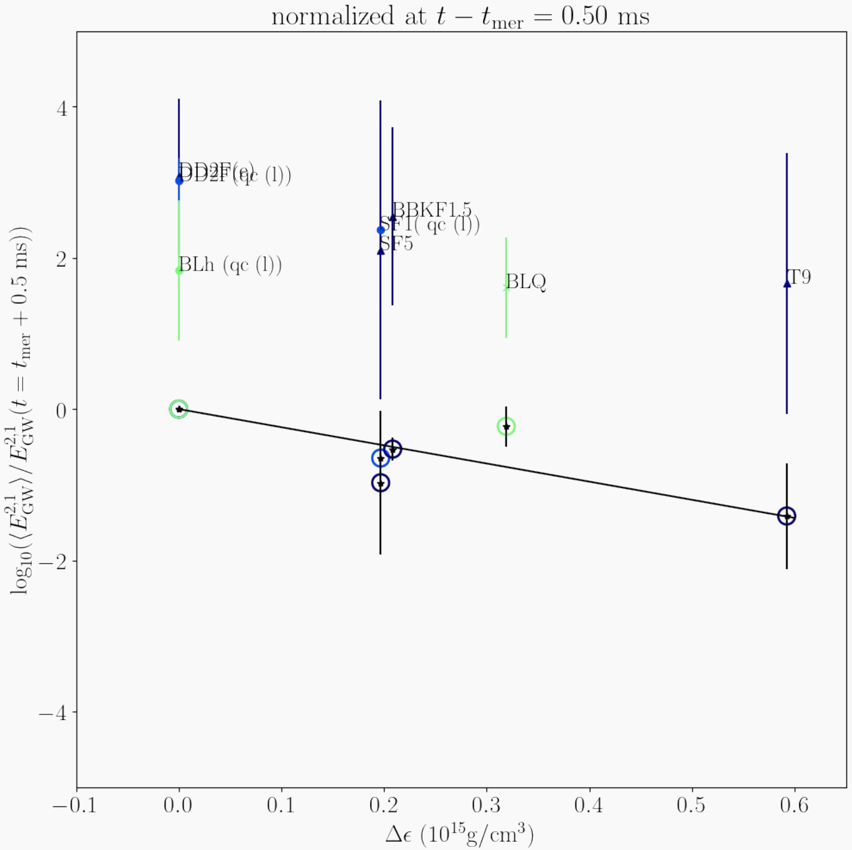




Error bars

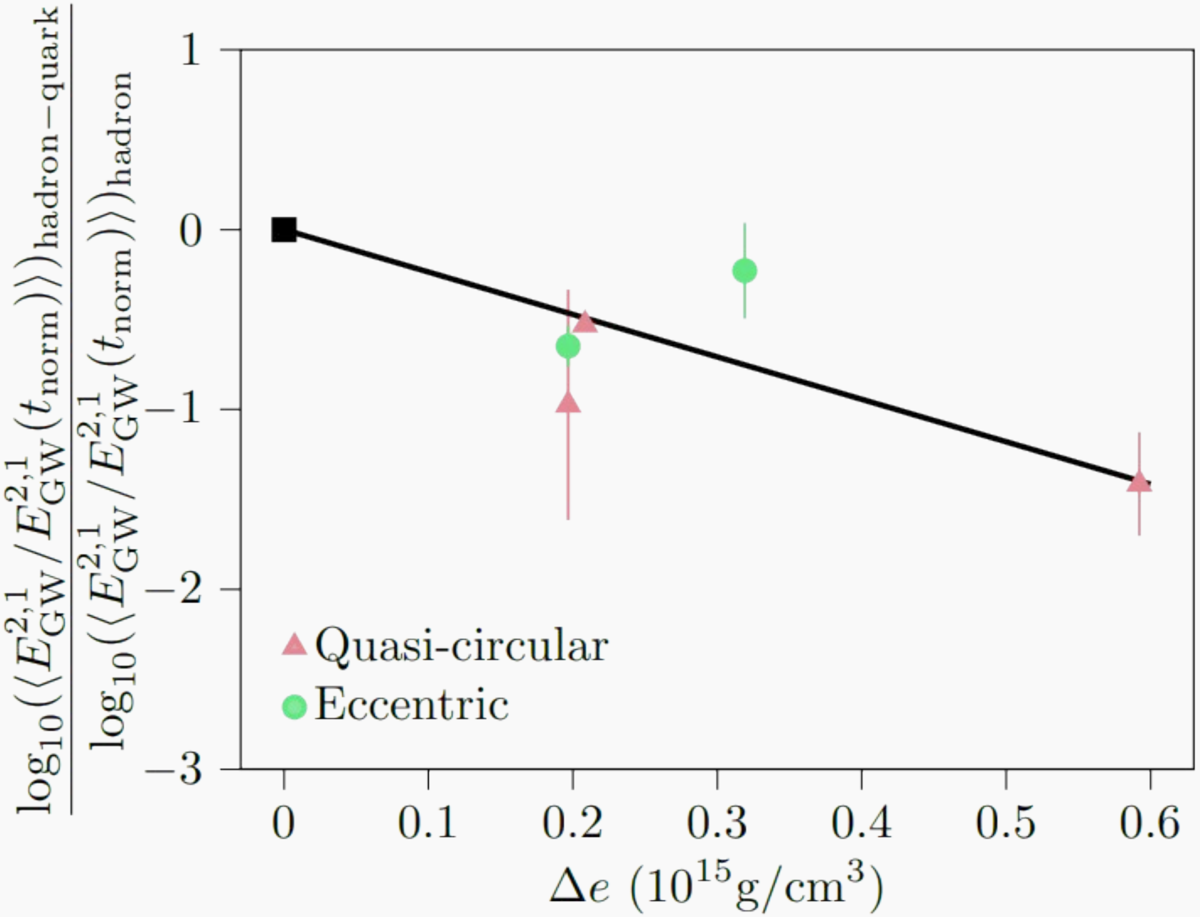


$\log_{10}(\langle E^{2,1}_{\rm GW}/E^{2,2}_{\rm GW}\rangle)$
$\Delta\epsilon\ (10^{15}{\rm g/cm^3})$
DD2F(e)
BLh (qc (l))
DD2F(qc (l))
SF5
BBKF1.5
SF1(qc (l))
BLQ
T9



normalized at $t - t_{\rm mer} = 0.50$ ms
$\log_{10}(\langle E^{2,1}_{\rm GW}\rangle/E^{2,1}_{\rm GW}(t = t_{\rm mer} + 0.5\ {\rm ms}))$
$\Delta\epsilon\ (10^{15}{\rm g/cm^3})$
DD2F(e)
DD2F(qc (l))
BBKF1.5
SF1(qc (l))
SF5
BLh (qc (l))
BLQ
T9

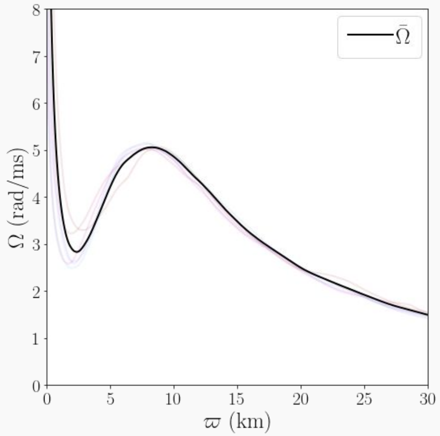
Error bars



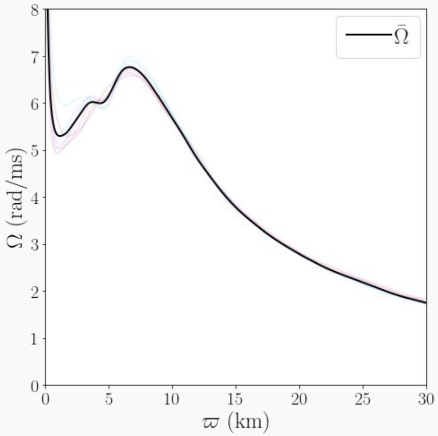
$\frac{\log_{10}(\langle E^{2,1}_{GW}/E^{2,1}_{GW}(t_{norm})\rangle)_{hadron-quark}}{\log_{10}(\langle E^{2,1}_{GW}/E^{2,1}_{GW}(t_{norm})\rangle)_{hadron}}$
1
0
−1
−2
−3
0
0.1
0.2
0.3
0.4
0.5
0.6
Δe (10^{15}g/cm^3)
Quasi-circular
Eccentric

Potential mechanisms for instability suppression

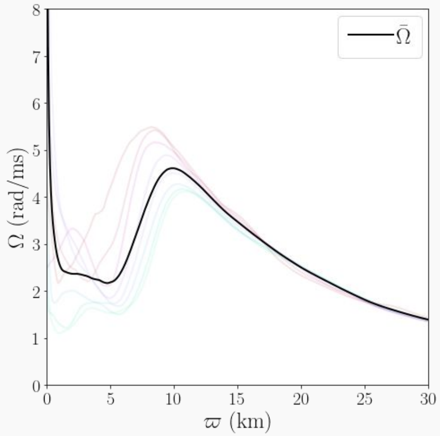
DD2F (hadron)



DD2F-SF5 (hybrid)



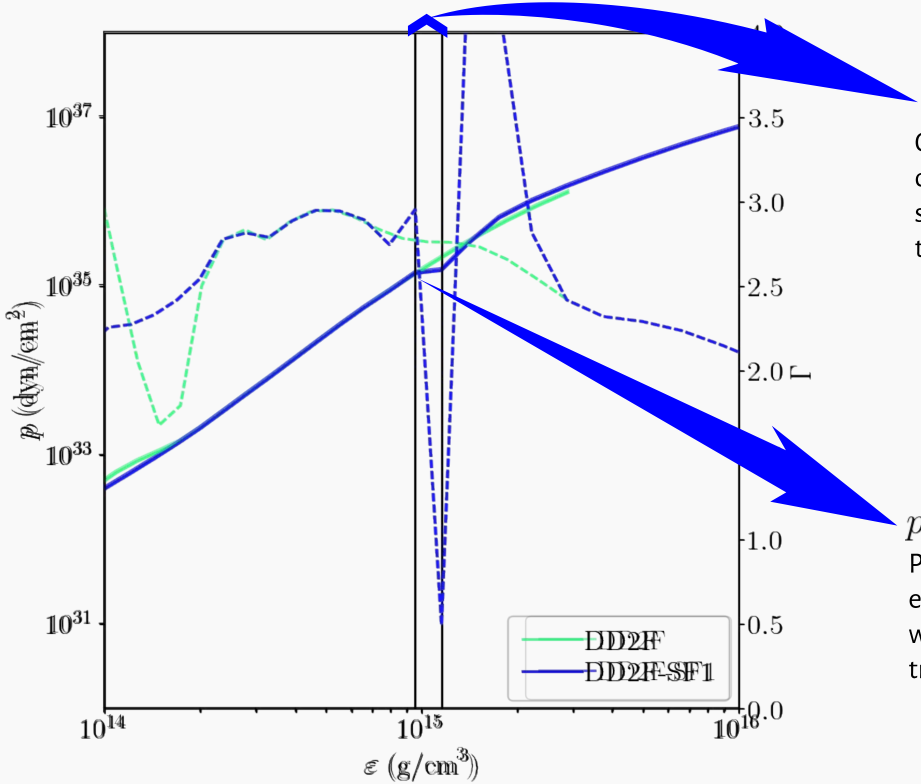
T9 (hybrid)



- Differential rotation is crucial for the development of one-armed spiral instability
  - Calculation of approximate angular velocity profiles show “two-core” structure in simulations with significantly large quark regions near the core, with higher angular velocity than in hadronic cases. Do angular velocity profiles play a role?

- Hybrid star remnants tend to be more compact than purely hadronic NS remnants. Differentially rotating fluids with larger extent are more conducive to development of instability
  - Does the compactness of HS remnant make it a less conducive environment for instability to grow?

EOS models

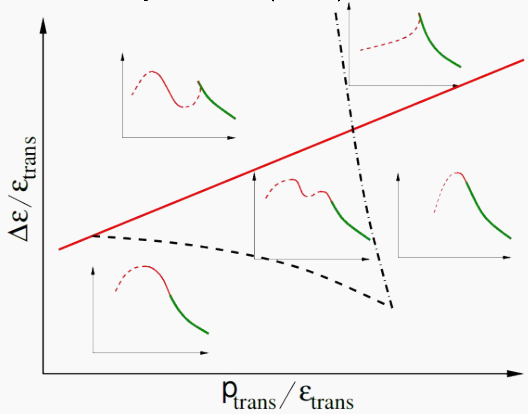


$$\Gamma = \frac{d(\log p)}{d(\log \rho)}$$

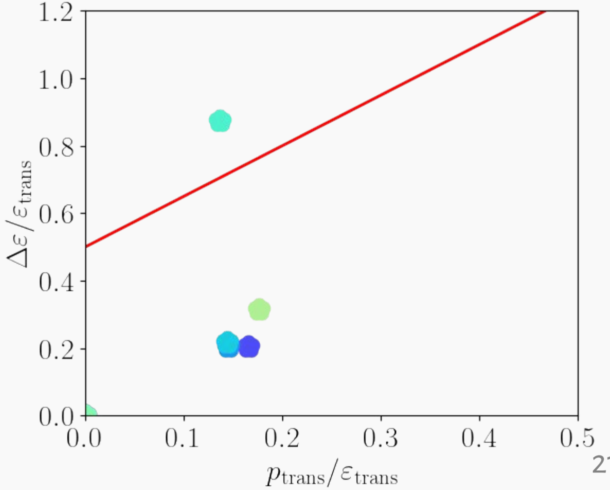
$\Delta\varepsilon$
Gap in energy density separating the two phases

$p_{\mathrm{trans}}, \varepsilon_{\mathrm{trans}}$
Pressure and energy density at which phase transition occurs

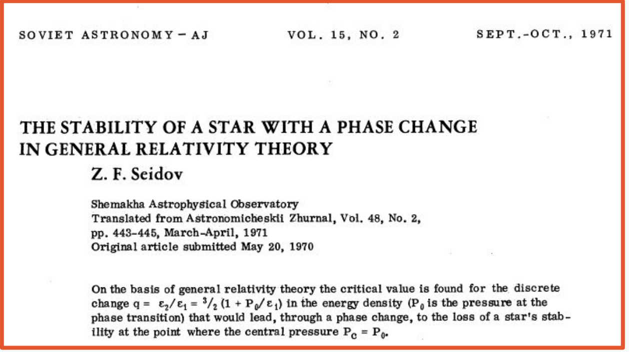
Alford, Han, *Eur.Phys.J.A* 52 (2016) 3, 62



OUR MODELS:



Properties of hybrid stars



SOVIET ASTRONOMY – AJ VOL. 15, NO. 2 SEPT.-OCT., 1971

THE STABILITY OF A STAR WITH A PHASE CHANGE IN GENERAL RELATIVITY THEORY

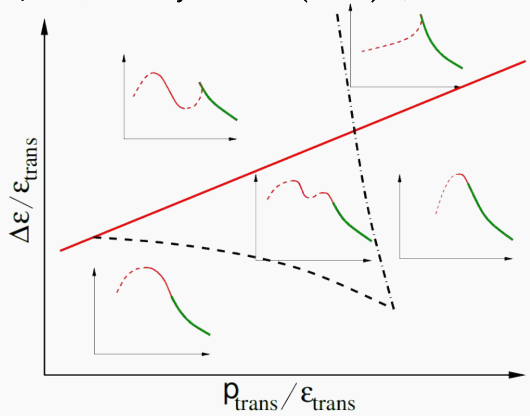
Z. F. Seidov

Shemakha Astrophysical Observatory
Translated from Astronomicheskii Zhurnal, Vol. 48, No. 2, pp. 443-445, March-April, 1971
Original article submitted May 20, 1970

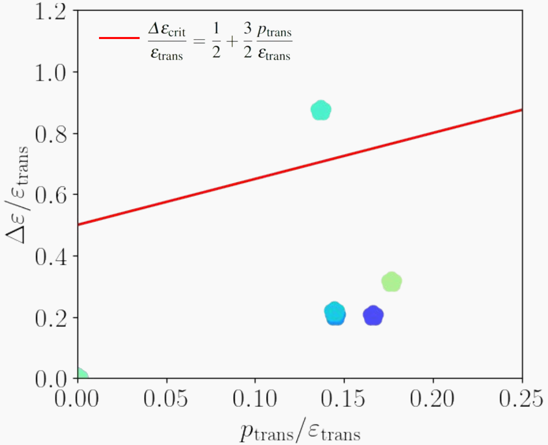
On the basis of general relativity theory the critical value is found for the discrete change $q = \varepsilon_2/\varepsilon_1 = {}^3/_2\,(1 + P_0/\varepsilon_1)$ in the energy density (P_0 is the pressure at the phase transition) that would lead, through a phase change, to the loss of a star's stability at the point where the central pressure $P_c = P_0$.

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

Alford, Han, *Eur.Phys.J.A* 52 (2016) 3, 62



OUR MODELS:

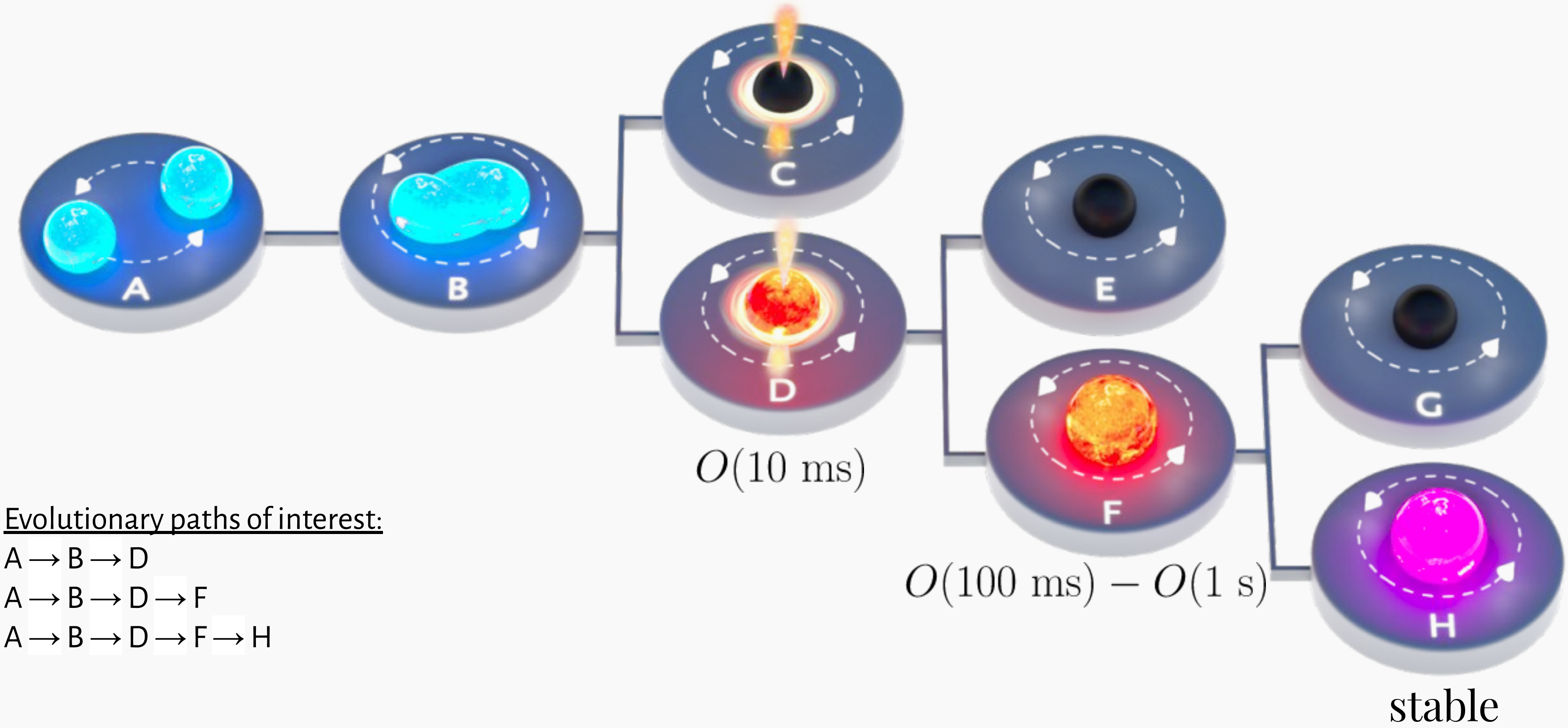


Hybrid stars with $p_c > p_{trans}$ will remain stable only if energy density gap is not too large. So, EOSs with energy density gap larger than the critical produce branches of unstable hybrid stars (though some may still produce stable hybrid stars)

See also:

- **R. Schaeffer, L. Zdunik, and P. Haensel**, Phase transitions in stellar cores. I - Equilibrium configurations, Astron. Astrophys. 126 (Sept., 1983) 121–145
- **L. Lindblom**, Phase transitions and the mass radius curves of relativistic stars, Phys.Rev. D58 (1998) 024008
- **Z. F. Seidov**, The Stability of a Star with a Phase Change in General Relativity Theory, Sov. Astron. 15 (Oct., 1971) 347
- **PLE and V. Paschalidis**, Fate of twin stars on the unstable branch: Implications for the formation of twin stars, Phys.Rev.D 105 (2022) 4, 043014

The post-merger environment can reveal much about the NS EOS



<u>Evolutionary paths of interest:</u>

A $\longrightarrow$ B $\longrightarrow$ D

A $\longrightarrow$ B $\longrightarrow$ D $\longrightarrow$ F

A $\longrightarrow$ B $\longrightarrow$ D $\longrightarrow$ F $\longrightarrow$ H

Sarin and Lasky, Gen.Rel.Grav. 53 (2021) 6, 59