Rotation and stability of neutrons stars with strong phase transitions

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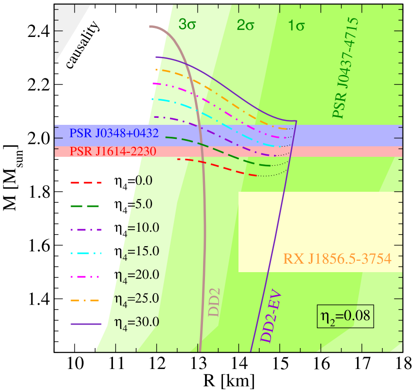
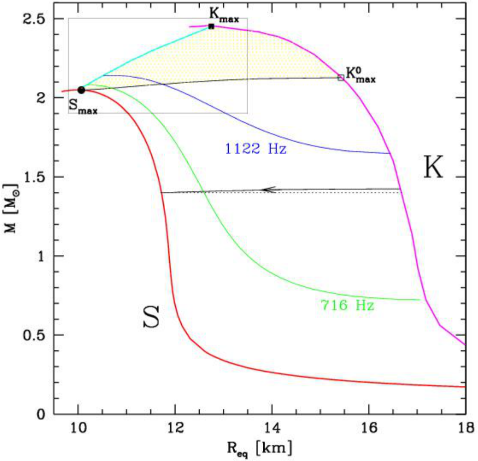
Quark-core twins – rotating configurations and their stability

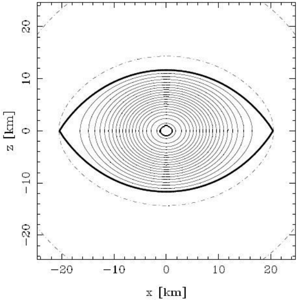


- ⋆ Since PSR J1614-2230 and PSR J0348+0432, the discussion about exotic (beyond *npe*μ) dense matter is really interesting
- ⋆ *„A new quark-hadron hybrid equation of state for astrophysics - I. High-mass twin compact stars"*, Benić et al. (2015) `arXiv:1411.2856`
  - → Exotic quark phase is related to massive NSs.
- ⋆ Here - remarks about the stability of rotating configurations with relation to astrophysics (using DD2-EV $\eta_2 = 0.12$, $\eta_4 = 5$ EOS)
- ⋆ results from `LORENE/rotstar`.

Rotation on the $M(R)$ diagram



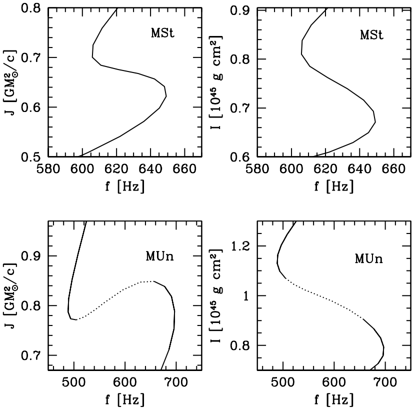
- ⋆ S: static configurations (TOV),
- ⋆ K: "Keplerian" (mass-shedding) configuration - maximally-rotating, rigid stars at a given mass,



- ⋆ in cyan: the instability line (star loses stability w.r.t. axisymmetric oscillations)★

Stability indicators: J and M_b

Sufficient condition for instability (turning-point criterion): Sorkin (1981, 1982), Friedman et al. (1988)★



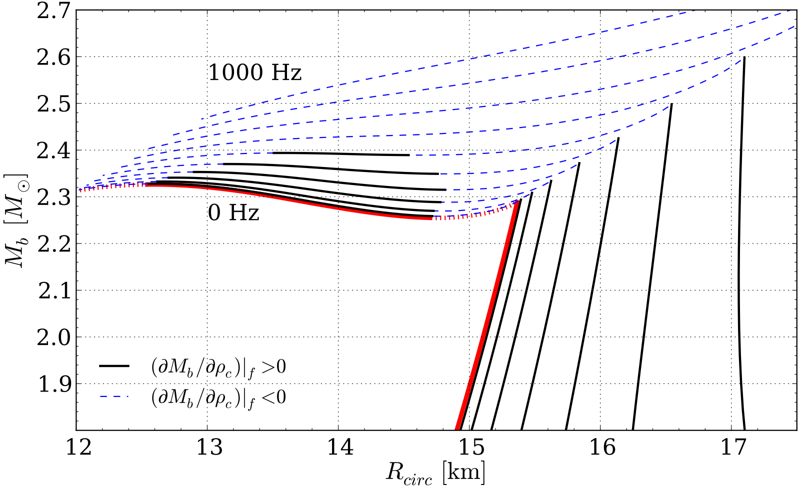
- ⋆ *Change in stability* corresponds to extremum of M or M_b at fixed J, or to extremum of J at fixed either M or M_b:

$$\left(\frac{\partial M_b}{\partial \lambda_c}\right)_J = 0, \quad \left(\frac{\partial J}{\partial \lambda_c}\right)_M = 0,$$

- ⋆ *Back-bending* is related to the existence of a minimum of M_b along $f = const$. sequence,
- ⋆ **Conjecture**: character of stability persists for all rotation rates (A&A **450**, 2006, 747)

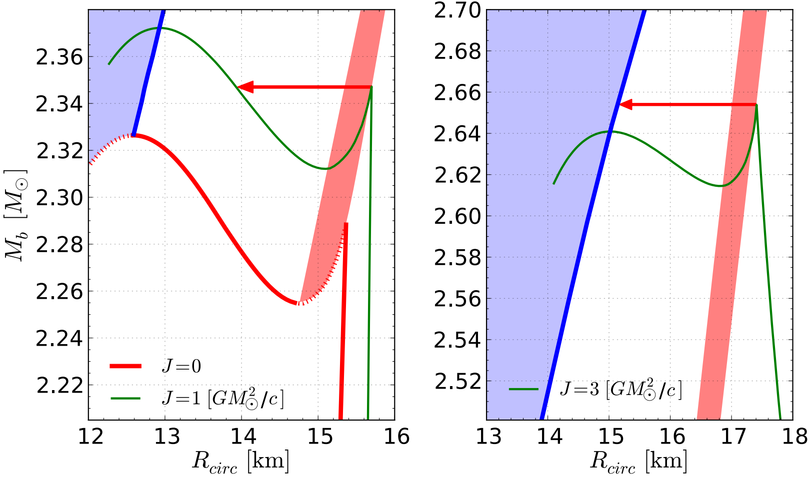
★However, see Takami et al. (2011) for comparison with dynamical calculations

$f = const.$ curves on $M_b(R)$ plane



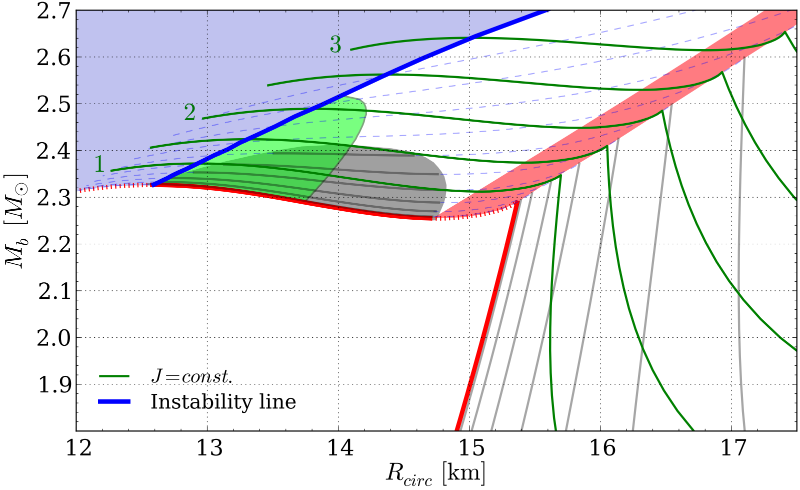
→ Dashed lines - *back-bending* is present (NS spins-up while monotonically losing angular momentum)

$J = const.$ curves, loss of stability and critical angular momentum J



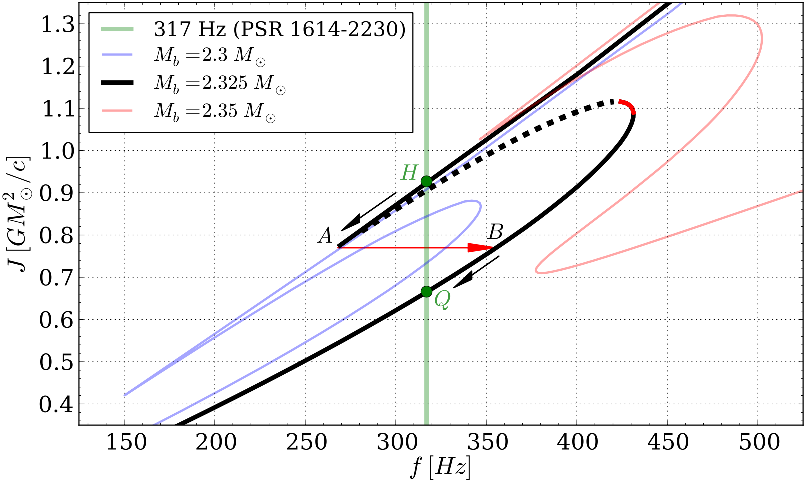
Analysis of $J = const.$ sequences: stars with too much angular momentum (*e.g., spun-up by accretion*) end up in the instability.

$J = const.$ curves on $M_b(R)$ plane



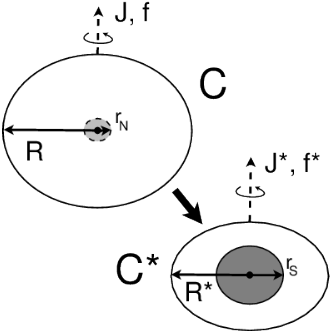
Red region - strong phase-transition instability,
Blue region - unstable w.r.t axisymmetric oscillations,
Grey region - no back-bending,
Green region - stable twin branch reached after the mini-collapse from the tip of $J = const.$ curve, along $M_b = const.$

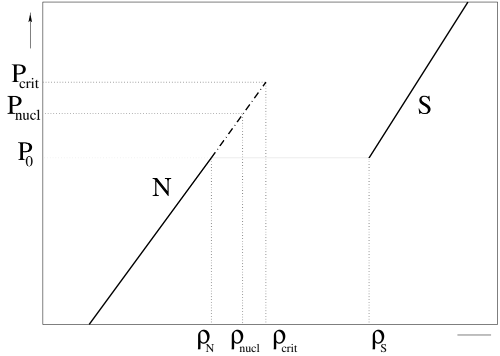
$M_b = const.$ curves on $J(f)$ plane



For NSs with measured gravitational mass M and frequency - possibility to put limits on M_b, J, moment of inertia I, core EOS composition etc.

Energy release (A&A **479**, 2008, 515)





Strong phase transition if
$\rho_S/\rho_N > \frac{3}{2}(1 + P_0/\rho_N c^2)$

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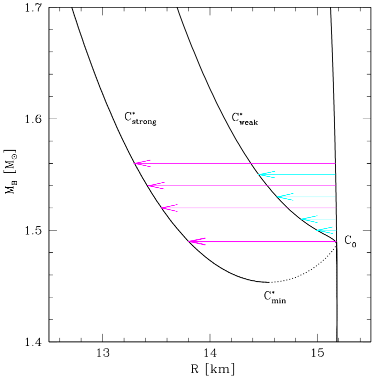
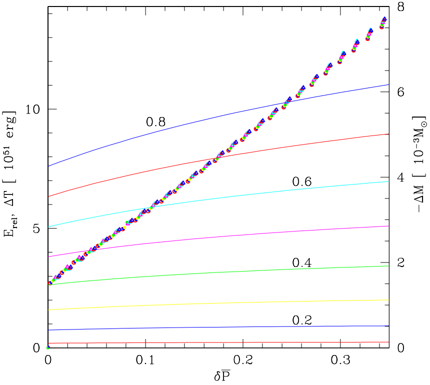
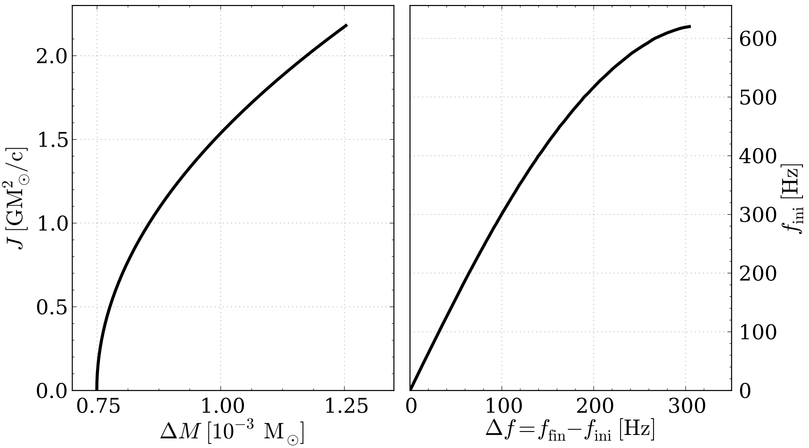




Strong phase transition if
$\rho_S/\rho_N > \frac{3}{2}(1 + P_0/\rho_N c^2)$

Angular momentum
$J = 0.1, \ldots, 0.8 \times GM_\odot^2/c$,
Energy release $E_{rel} = (M - M^\star)c^2$,
Kinetic energy $\Delta T = T^\star - T$.

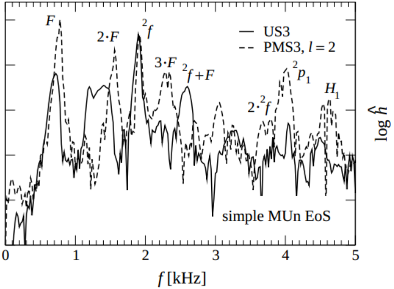
Energy release in case of DD2-EV $\eta_2 = 0.12$, $\eta_4 = 5$ EOS

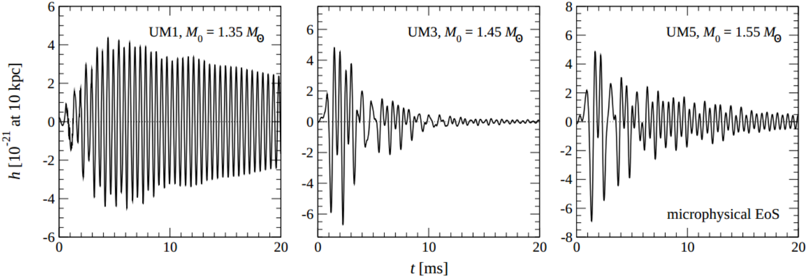


Left panel: energy release (difference in the gravitational mass) vs J of the configuration entering the strong phase-transition instability.
Right panel: spin-up Δf (difference between the final and initial spin frequency) against the spin frequency of the initial configuration.

Burst-like GW emission (MNRAS **502**, 2009, 605)

Time evolution of a dynamical mini-collapse induced by a phase transition (simulations with the `CoCoNuT` code)





Summary/outlook

Instability in the EOS

- ⋆ bypasses back-bending regions,
- ⋆ provides a ”natural” spin frequency cut-off at some moderate (but >716 Hz) frequency,
- ⋆ resembles Fast Radio Burst ’blitzar’ engine (Falcke & Rezzolla 2014):
  - ⋆ catastrophic mini-collapse to the second branch (or to a black hole),
  - ⋆ massive rearrangement of the magnetic field $\rightarrow$ energy emission.

Other astrophysically-interesting questions:

- ⋆ Way to constraint on M_b, J, I, core EOS etc.,
- ⋆ Specific shape of NS-BH mass function (no mass gap?)
- $\rightarrow$ population of massive, low B-field NSs (radio-dead?),
- $\rightarrow$ population of massive, high B-field NSs (collapse enhances the field?),
- ⋆ Characteristic burst-like signature in GW emission during the mini-collapse.