Observational implications of dense matter phase transitions for the rotational evolution of neutron stars

Michał Bejger

Nicolaus Copernicus Astronomical Center, PAS

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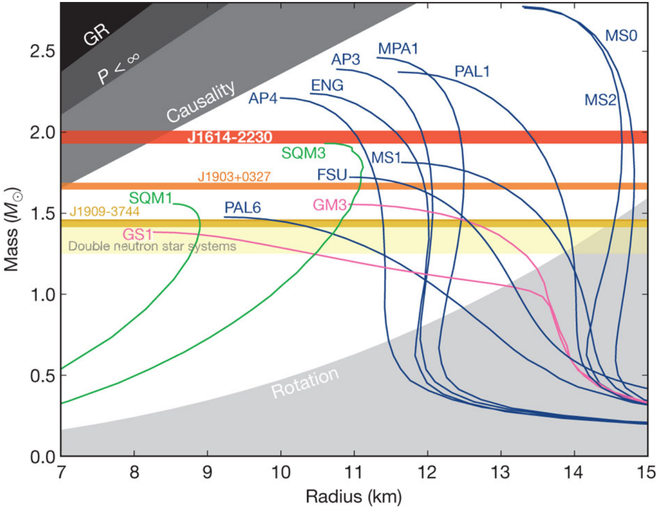
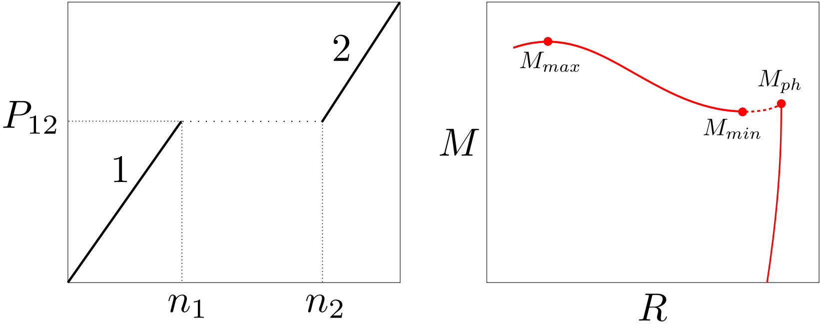


Since PSR J1614-2230 and PSR J0348+0432, the discussion about exotic dense matter (beyond *npe*μ) started to be interesting.

Dense-matter phase transitions and $M(R)$



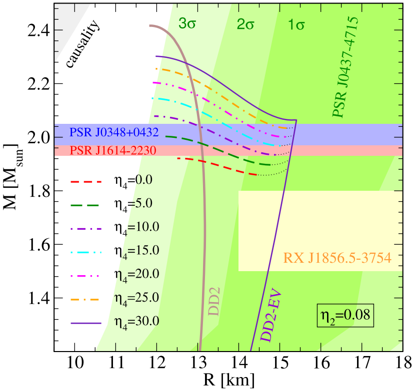
Every softenning in the EOS (e.g., creation of a new phase) leads to lowering the M_{max}. There is a critical softening that leads to an instability (Seidov 1971),

e.g. critical density jump between the phases

$$\lambda_{crit} = \rho_2/\rho_1 > \frac{3}{2}(1 + P_{12}/\rho_1 c^2)$$

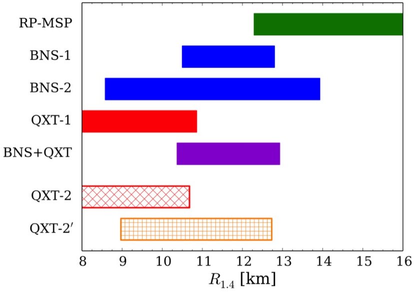
(detached branch forming the third family of NS, twins...)

High-mass quark-core twins

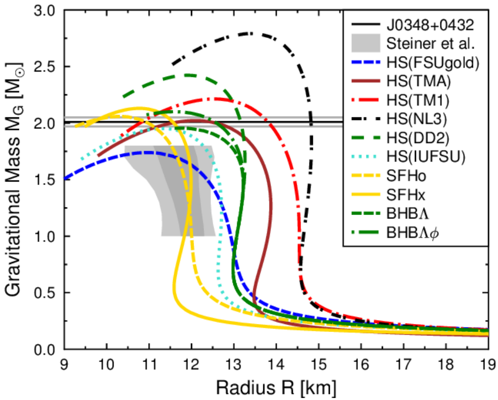


- ⋆ Exotic quark phase is related to massive NSs.
- ⋆ *„A new quark-hadron hybrid equation of state for astrophysics - I. High-mass twin compact stars"*, Benić et al. (2015) `arXiv:1411.2856`
  - ⋆ RMF model with density-dependent coupling constants and excluded volume corrections for the hadronic phase,
  - ⋆ Nambu–Jona-Lasinio with higher order repulsive vector corrections for the quark phase.
- ⋆ Topic of this talk - if we accept that such EOS is possible, what should we expect from astrophysical observations? (details in `arXiv:1608.07049`)

Current NS radii measurements

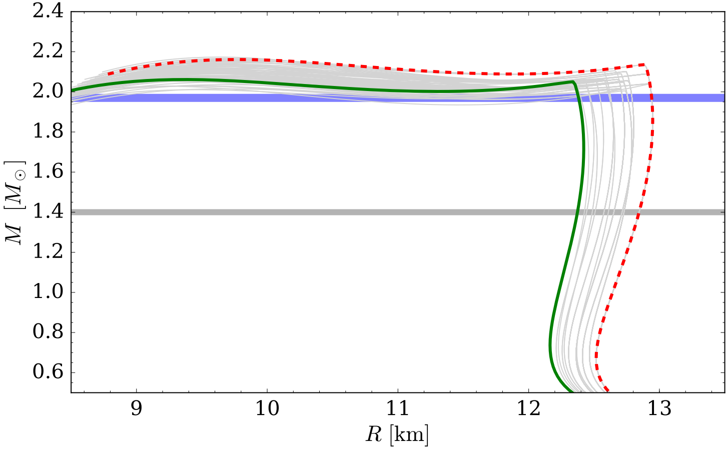


Haensel et al. (2016) `arXiv:1601.05368`: Constraints from pulse profiles from rotation-powered MSP (RP-MSP), bursting NS (BNS), quiestent X-ray transients (QXT).



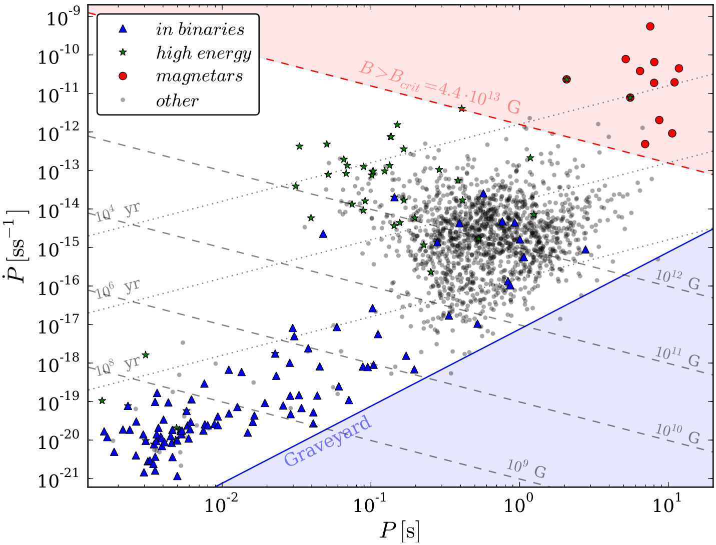
(Matthias Hempel website)

Searching for limits: parametric EOSs with phase transitions



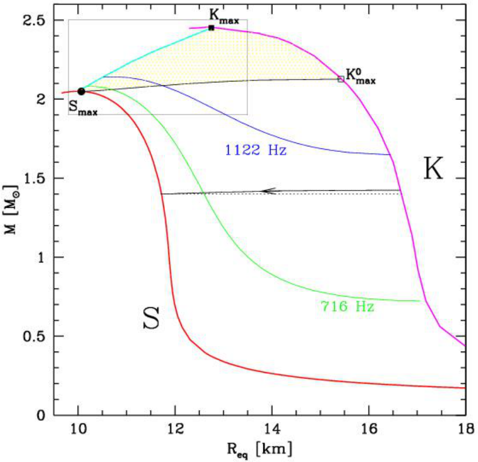
Turczański et al. (2016, in preparation): Realistic crust + piecewise polytropes with density jumps, causal, $M_{max} > 2\ M_\odot$.

Rotating NS

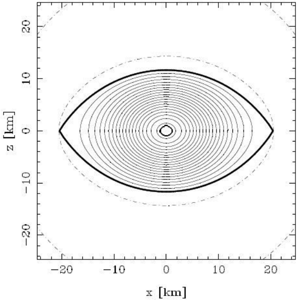


in binaries
high energy
magnetars
other
B > B_crit = 4.4·10^13 G
10^4 yr
10^6 yr
10^8 yr
10^12 G
10^11 G
10^10 G
10^9 G
Graveyard
$\dot{P}$ [ss^-1]
P [s]
10^-9
10^-10
10^-11
10^-12
10^-13
10^-14
10^-15
10^-16
10^-17
10^-18
10^-19
10^-20
10^-21
10^-2
10^-1
10^0
10^1

Rotation on the $M(R)$ diagram

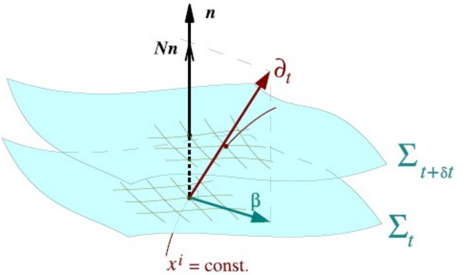


- ⋆ S: static configurations (TOV),
- ⋆ K: ”Keplerian” (mass-shedding) configuration - maximally-rotating, rigid stars at a given mass,



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

3+1 formalism of general relativity (LORENE, www.lorene.obspm.fr)



Hypersurfaces of constant time Σ_t, each with its own coordinate system. 3-metric induced on Σ_t: $\mathbf{h} = \mathbf{g} + \mathbf{n} \otimes \mathbf{n}$, where **n** in normal to Σ_t.

Evolution is described by auxiliary parameters:

- ⋆ Time "lapse" N, $\mathbf{n} = N \nabla t$,
- ⋆ space "shift" $\beta = -\mathbf{h} \cdot \xi$

General metric:

$$g_{\mu\nu} dx^\mu dx^\nu = -(N^2 - \beta_i \beta^i) dt^2 - 2\beta_i dt\, dx^i + h_{ij} dx^i\, dx^j$$

Conformally flat metric $\mathbf{h} = \Psi \eta$, where η is flat 3-metric. With a particular choice of the conformal factors A and B:

$$g_{\alpha\beta} dx^\alpha dx^\beta = -N^2 dt^2 + A^4 B^2 r^2 \sin^2\theta (d\phi + N^\phi dt)^2 + \frac{A^4}{B^2}(dr^2 + r^2 d\theta^2)$$

Global quantities (LORENE/rotstar)

Using the property of asymptotic flatness:

⋆ **Total mass-energy** (gravitational potential $\nu(r,\ \theta)|_{r\to+\infty} \to 0$, leading term $\nu(r,\ \theta) \sim -M/r$):

$$M := \int_{\Sigma_t} (2T_{\mu\nu} - Tg_{\mu\nu}) n^{\mu} \xi^{\nu} \sqrt{h} dx^3 = \int \frac{NA^6}{B} \left(E + S^i_i + \frac{2}{N} N^{\phi} p_{\phi} \right) r^2 \sin\theta dr d\theta d\phi$$

⋆ **Number of particles inside the star:**

$$A_{\rm B} := -\int_{\Sigma_t} \mathbf{n u} n_{\rm b} \sqrt{h} dx^3 = \int \frac{A^6}{B} \Gamma n_{\rm b} r^2 \sin\theta dr d\theta d\phi$$

⋆ **Total angular momentum:** Leading term in frame-dragging $N^{\phi}(r,\ \theta)|_{r\to+\infty} \sim -2J/r^3$):

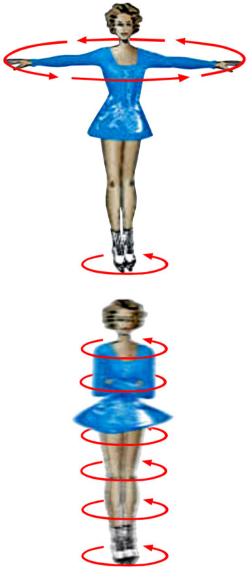
$$J := -\int_{\Sigma_t} T_{\mu\nu} n^{\mu} \chi^{\nu} \sqrt{h} dx^3 = \int \frac{A^6}{B} p_{\phi} r^2 \sin\theta dr d\theta d\phi$$

⋆ **Circumferential radius:**

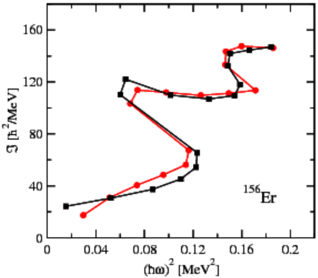
$$R_{\rm eq} = A^2(r_{\rm eq},\ \pi/2) B(r_{\rm eq},\ \pi/2) r_{\rm eq}$$

Accuracy check: projection of Einstein equations on $\Sigma_{\phi} \to$ 2-dimensional virial identity (Bonazzola & Gourgoulhon 1994).

The back-bending phenomenon



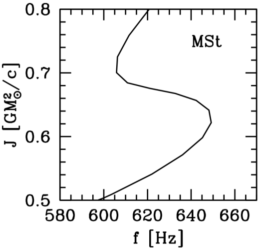
Originally, the idea comes from nuclear physics:

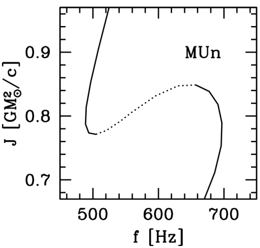


For NS, back-bending is the temporary spin-up of the star while it loses the angular momentum due to the change of its internal structure (e.g., the phase transition).

Stability indicators: J and M_b (not I and f)

Sufficient condition for instability in rotating stars: Sorkin (1981, 1982), Friedman et al. (1988)





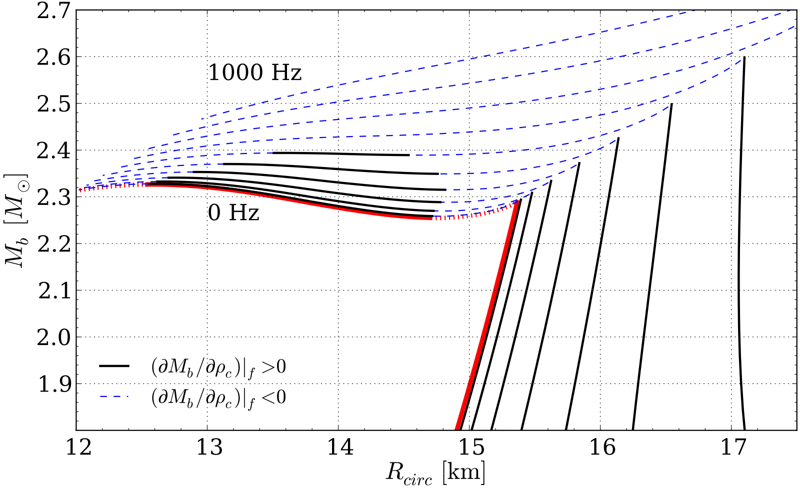
- ⋆ *Change in stability* corresponds to extremum of M or M_b at fixed J, or to extremum of J at fixed either M or M_b:

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

- ⋆ **Conjecture**: character of stability persists for all rotation rates (A&A **450**, 2006, 747)

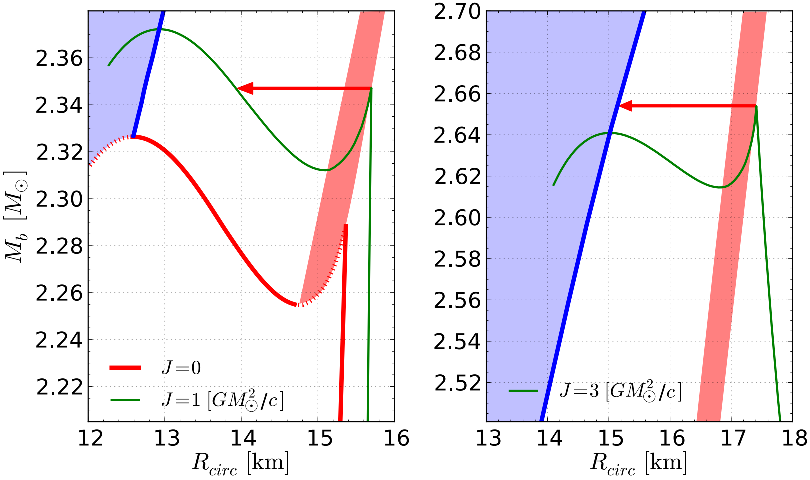
- ⋆ *Back-bending* is related to the existence of a minimum of M_b along $f = const.$ sequence and **does not** indicate the instability.

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



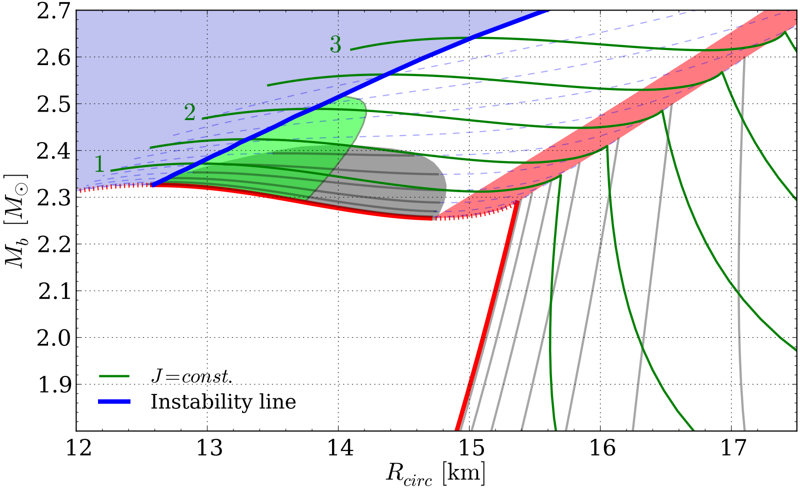
→ Dashed lines - *back-bending* is present (NS spins-up while monotonically losing angular momentum)

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



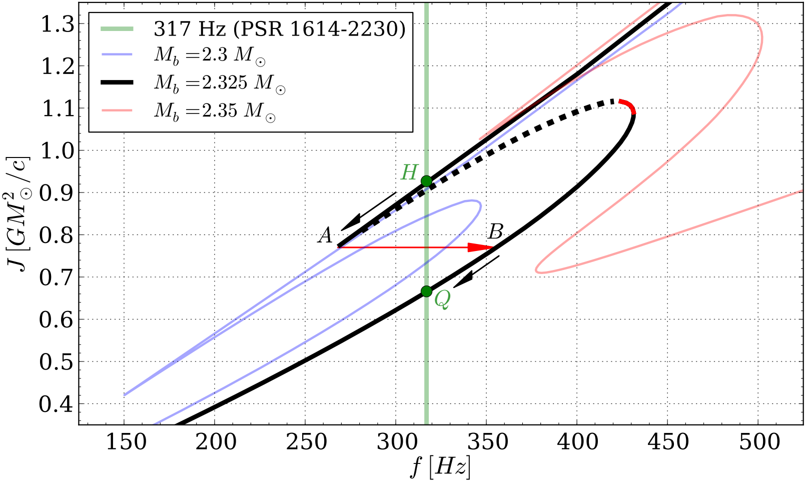
Analysis of $J = const.$ sequences: stars with too much angular momentum (*e.g., spun-up by accretion*) end up in the instability.

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



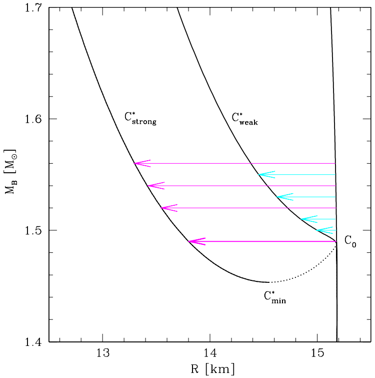
Red region - strong phase-transition instability,
Blue region - unstable w.r.t axisymmetric oscillations,
Grey region - no back-bending,
Green region - stable twin branch reached after the mini-collapse from the tip of $J = const.$ curve, along $M_b = const.$

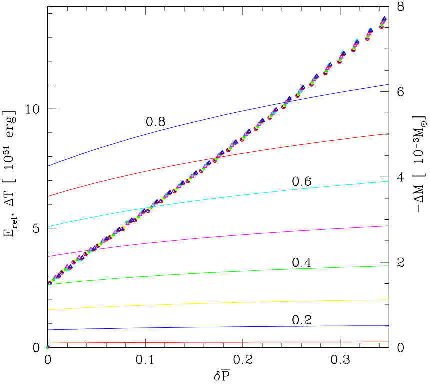
$M_b = const.$ curves on $J(f)$ plane



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)

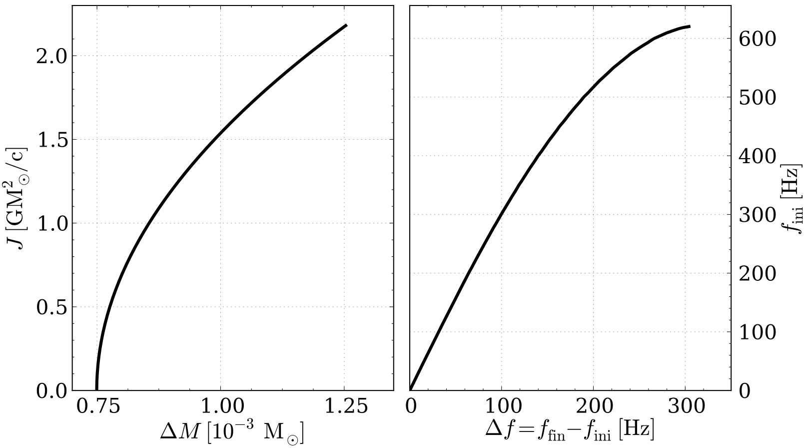




Strong phase transition if
$\rho_S/\rho_N > \frac{3}{2}(1 + P_0/\rho_N c^2)$

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

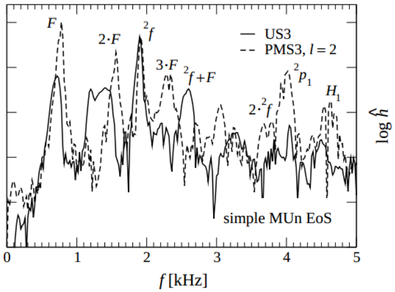
Energy release in case of DD2-EV $\eta_2 = 0.12$, $\eta_4 = 5$ EOS

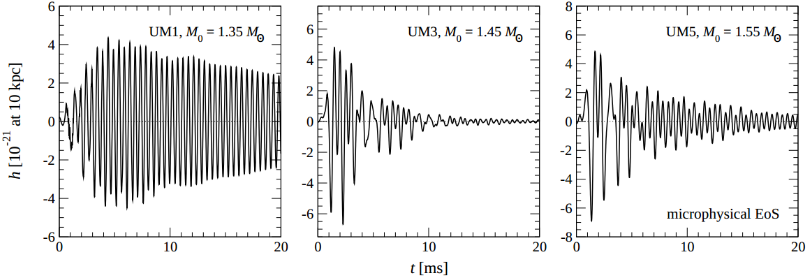


Left panel: energy release (difference in the gravitational mass) vs J of the configuration entering the strong phase-transition instability.
Right panel: spin-up Δf (difference between the final and initial spin frequency) against the spin frequency of the initial configuration.

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

Strong phase-transition instability in the EOS

- ⋆ bypasses the majority of 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.