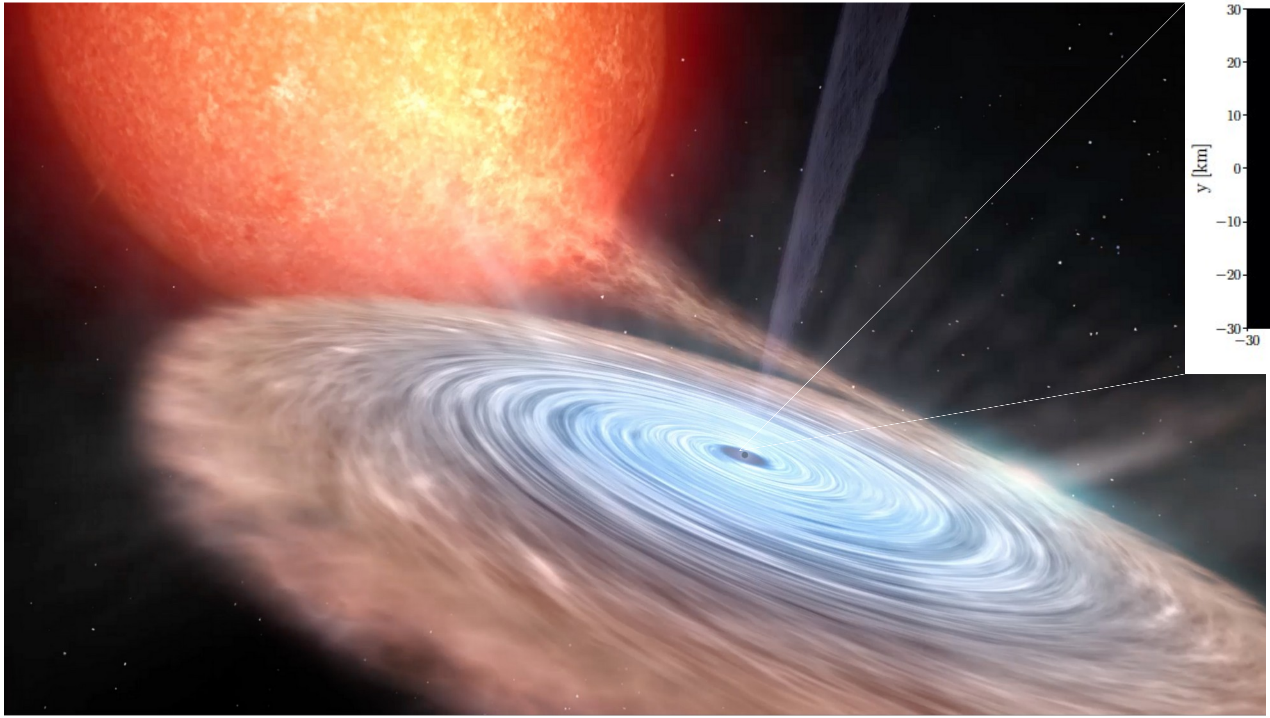
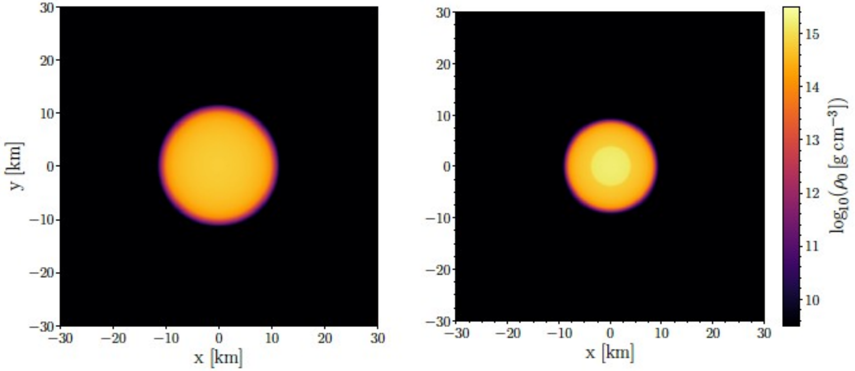
Thermal twin stars

David Blaschke
University of Wroclaw, Poland & HZDR/CASUS Görlitz, Germany





Neutron star (NS) ↔ Hybrid star (HS)

Twin stars:
Stars with the same baryon mass,
but with different composition

Artistic view of a neutron star accreting mass from a companion star in a low-mass X-ray binary (LMXB) system

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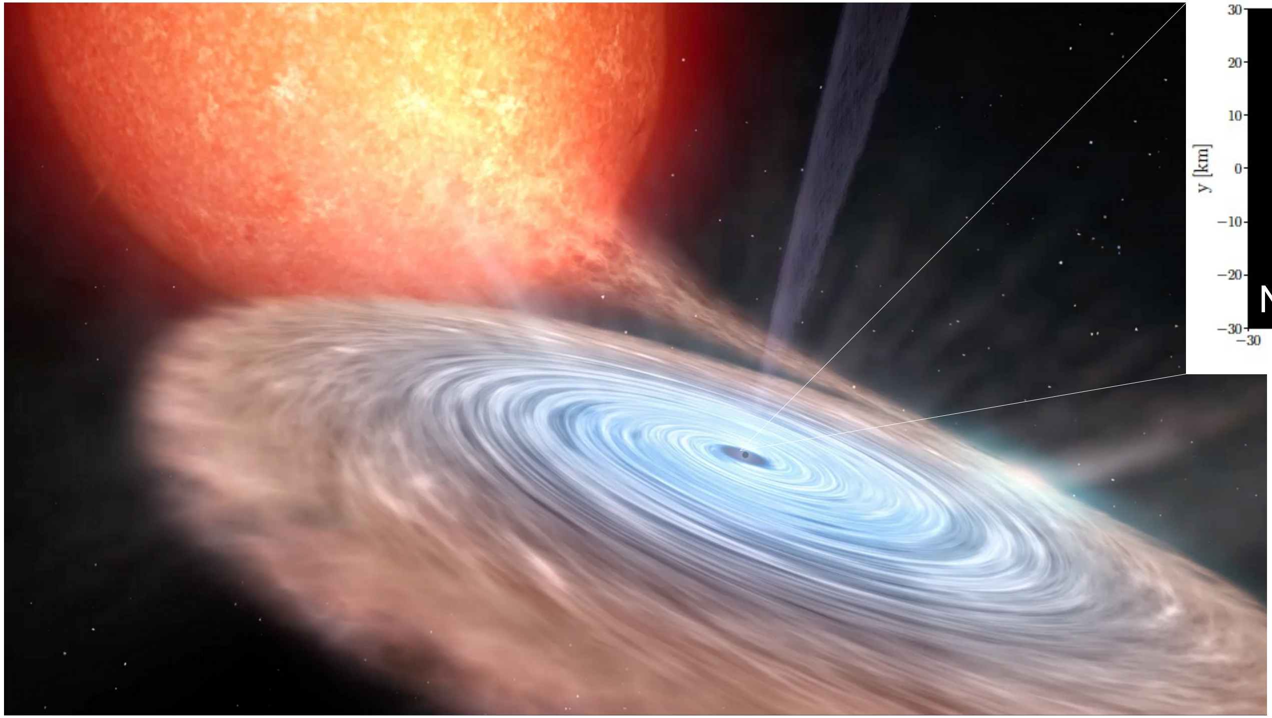
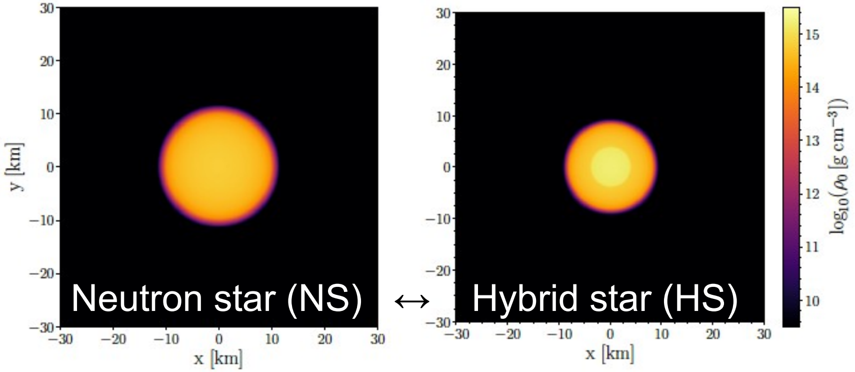


Artistic view of a neutron star accreting mass from a companion star in a low-mass X-ray binary (LMXB) system

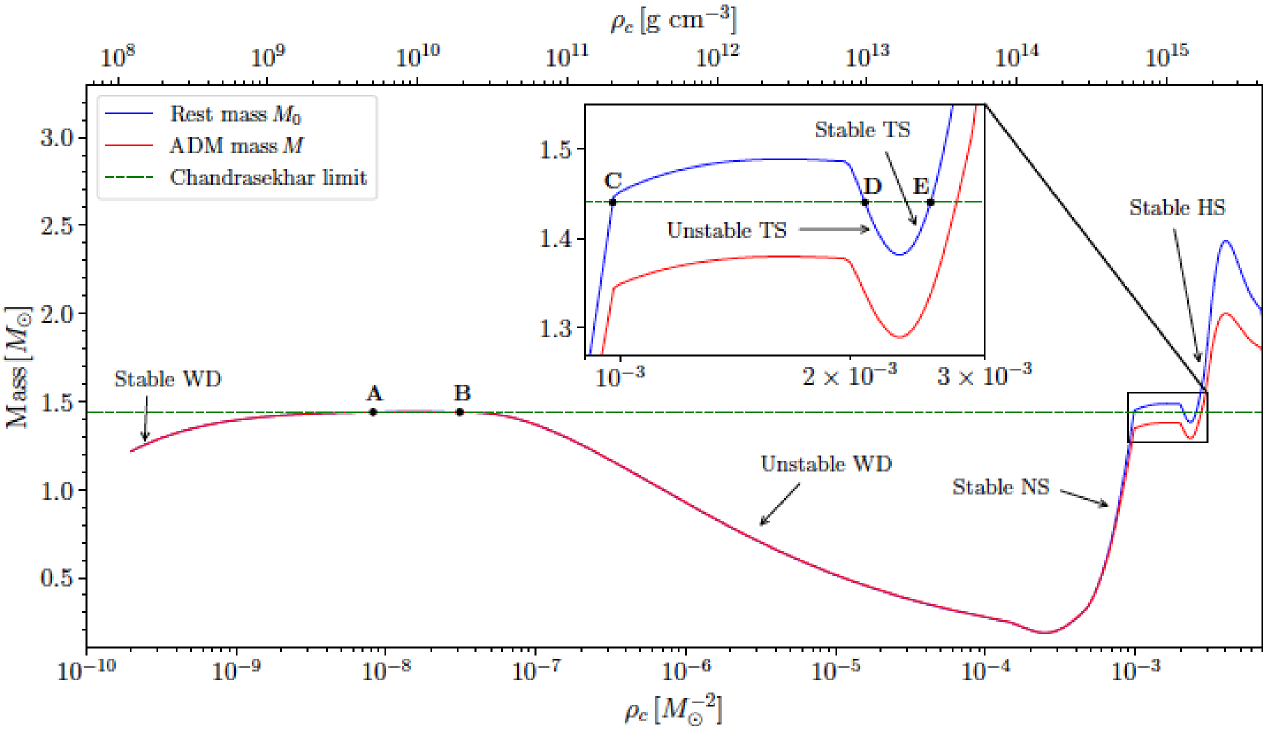


Plan:
1. The idea:
   Twins → 1st Order PT → CEP
2. Twins in LMXB's
   → eccentric and isolated MSP's
3. Thermal twins in CCSNe
   → explodability of massive SG's
4. Discussion

The idea

Three families of stable compact stars, separated by unstable configurations:
1. White Dwarfs (WD), 2. Neutron Stars (NS), 3. Hybrid Stars (HS)

Twin Stars (TS): subclass of HS for which a NS with same baryon mass exists



From: M. Naser, G. Bozzola, V. Paschalidis, arXiv:2406.15544

The idea

Three families of stable compact stars, separated by unstable configurations:
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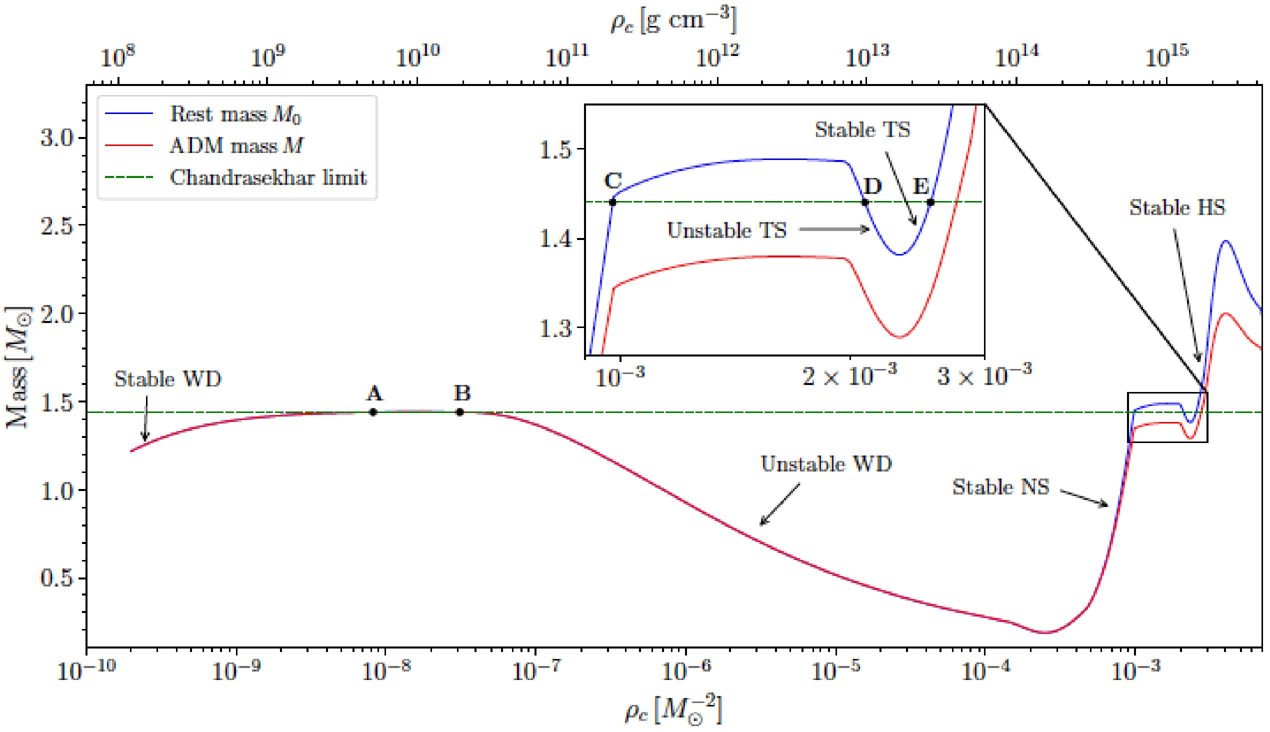
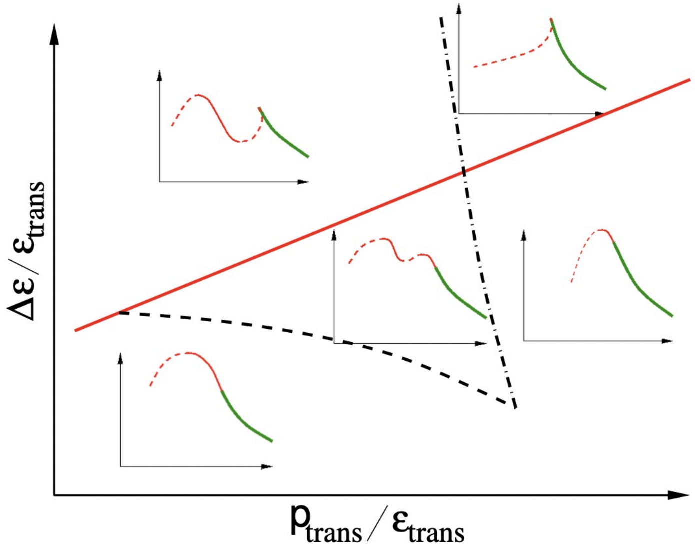


From: M. Naser, G. Bozzola, V. Paschalidis, arXiv:2406.15544

Disconnected HS branch indicates a Strong (1st-order) phase transition



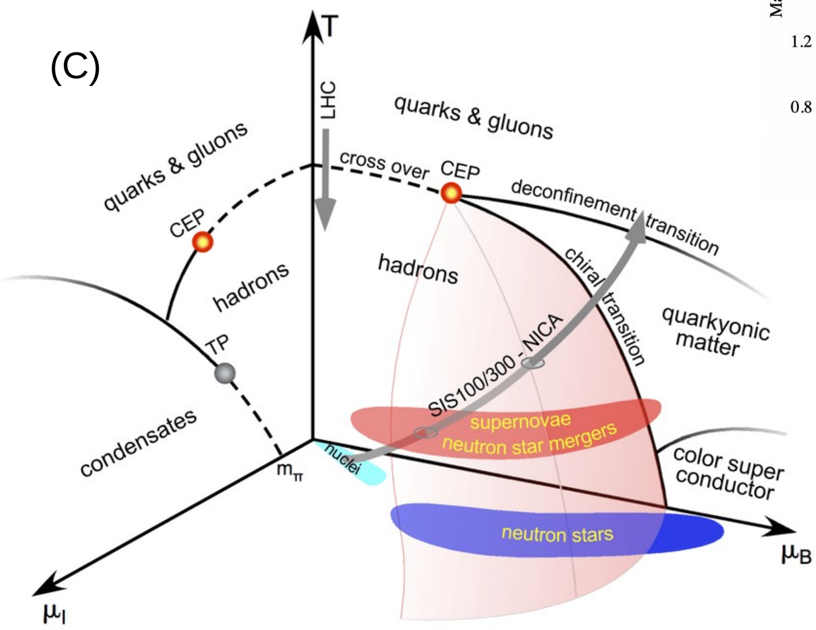
Seidov criterion for gravitational Instability (red line):

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

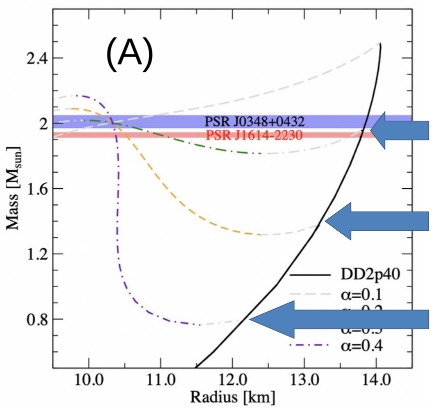
The idea

Twin Stars (A)
→ Strong Phase Transition (B)
→ Existence of CEP in Phase Diagram (C)

(C)



From: M. Kaltenborn, N. Bastian, D.B., PRD 96 (2017) 056024

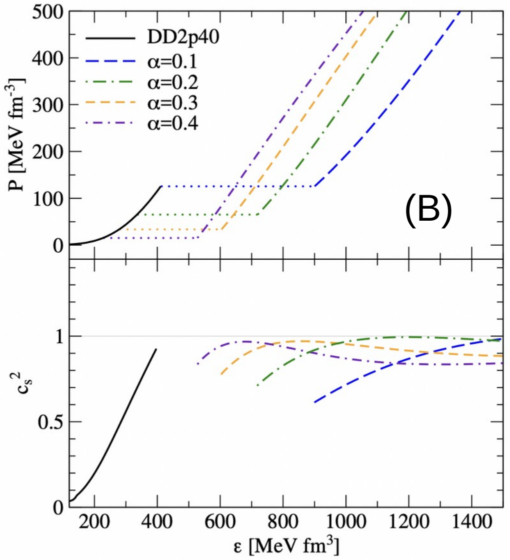


Which Mass?

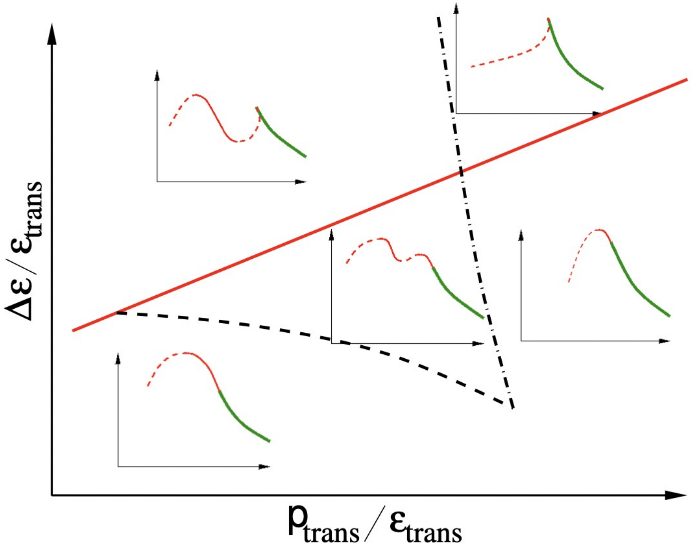
High?

Typical?

Low?



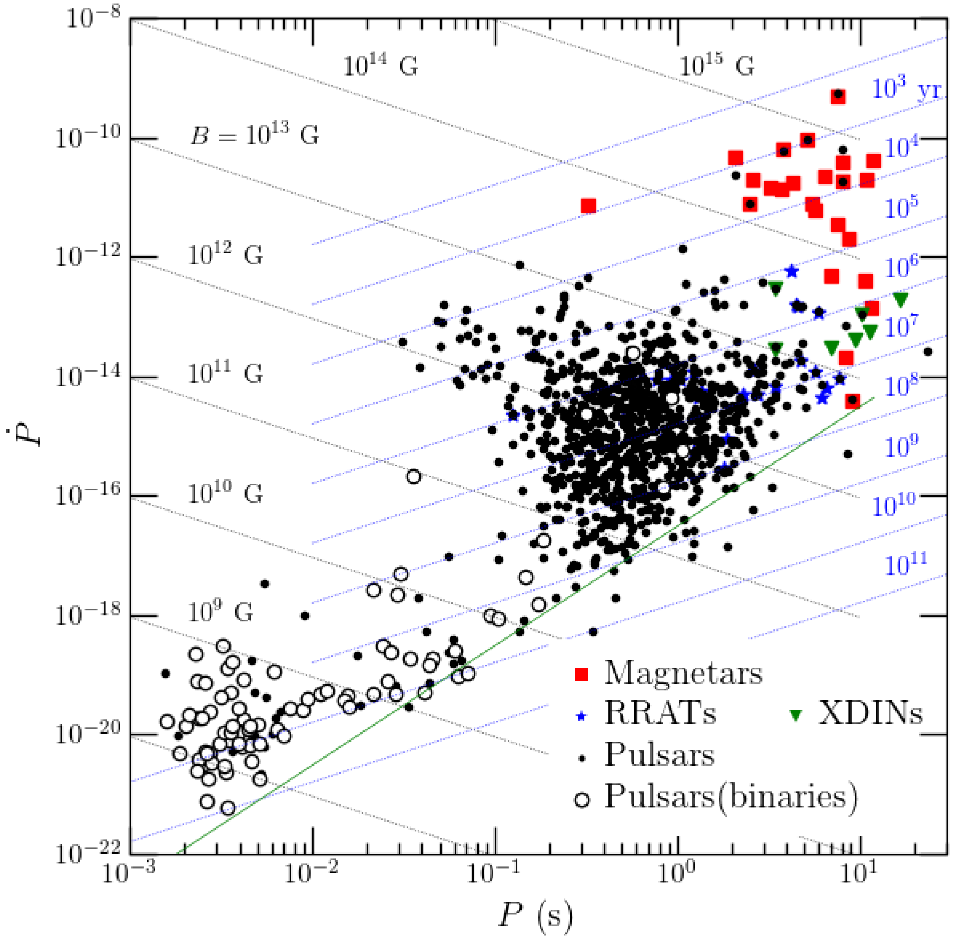
Disconnected HS branch indicates a Strong (1st-order) phase transition



Seidov criterion for gravitational Instability (red line):

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

Introduction: Millisecond Pulsars in the Ṗ-P Diagram



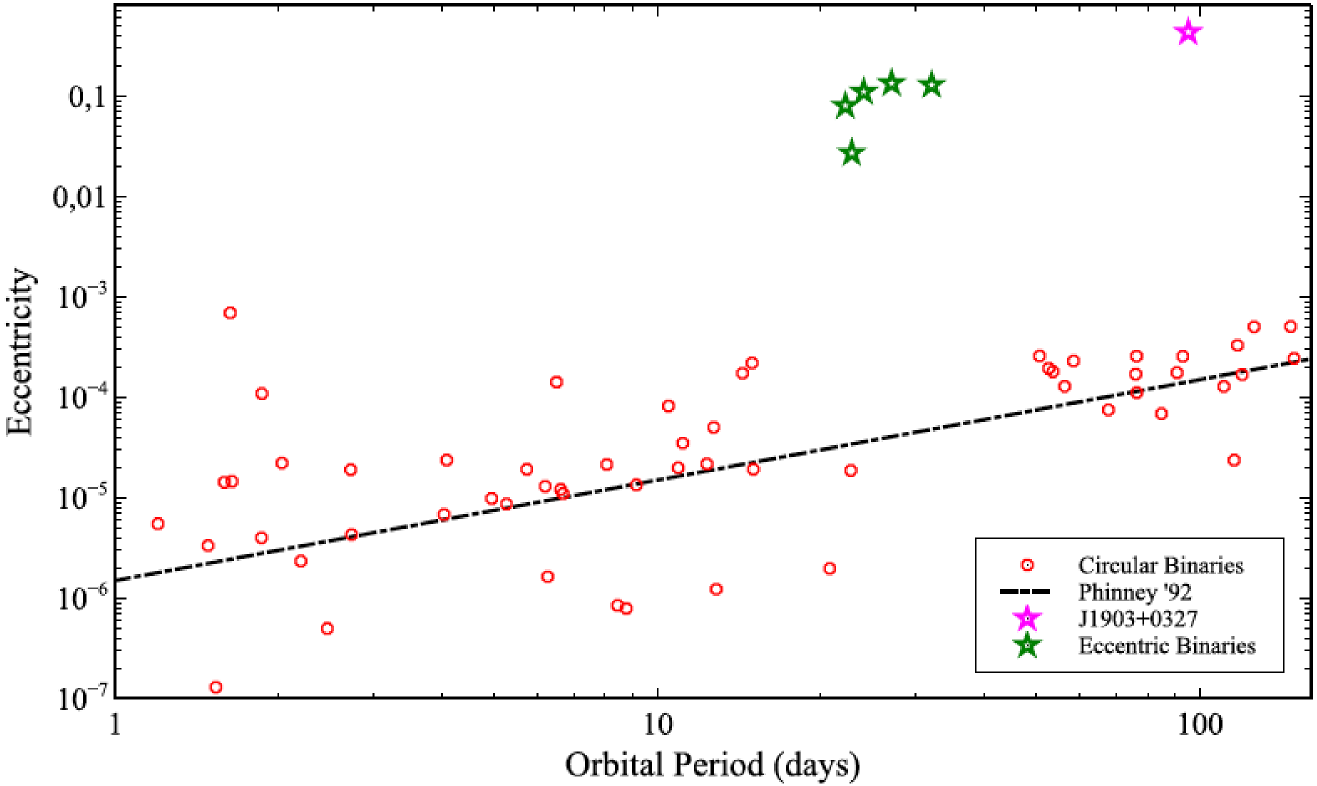
- Pulsars are born with periods P ~ 0.1 – 1.0 seconds and magnetic fields B ~ 10^{12} G

- They spin down for millions of years and cross the „death-line“ (green) to the pulsar graveyard, where their dipole radiation is „switched off“

- Eventually, they accrete matter from a companion star in a binary system and spin-up to periods of milliseconds (MSPs)

- Presently ~ 600 MSPs are known, most of them in binaries (~ 500) but some are isolated (~ 20%) and 5 are a Puzzle!

Introduction: The Puzzle of Eccentric MSPs



- Most MSPs are in binaries with circular orbits: e ~ 10^{-6} – 10^{-4}

- Period gap 20 – 50 d, with 5 eccentric binaries with white dwarfs: e ~ 10^{-1}

- One binary with a main sequence star (J1903+0327) with larger period, 100 d, and e ~ 1

→ Puzzle!

J. Antoniadis, Astrophys. J. 797, L24 (2014): „On the Formation of Eccentric Millisecond Pulsars with He-WD Companions“
D. Alvarez-Castillo, J. Antoniadis, A. Ayriyan, D. Blaschke, V. Danchev et al., Astron. Nachr. 340 (2019) 878, „Accretion-induced collapse to third family compact stars as trigger for eccentric orbits of millisecond pulsars in binaries“

Let us discover the 3rd family of compact stars!

CASUS
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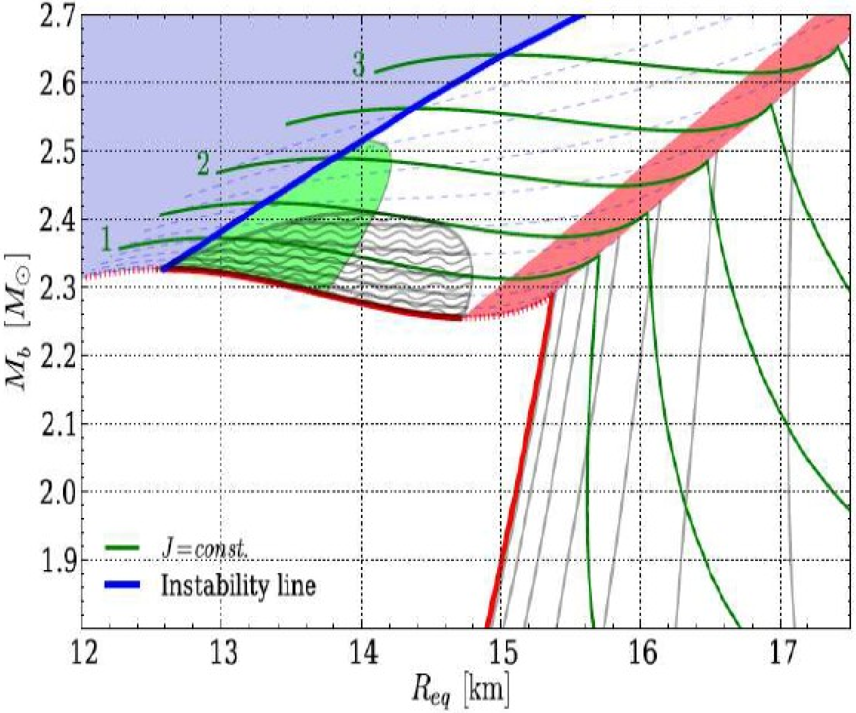
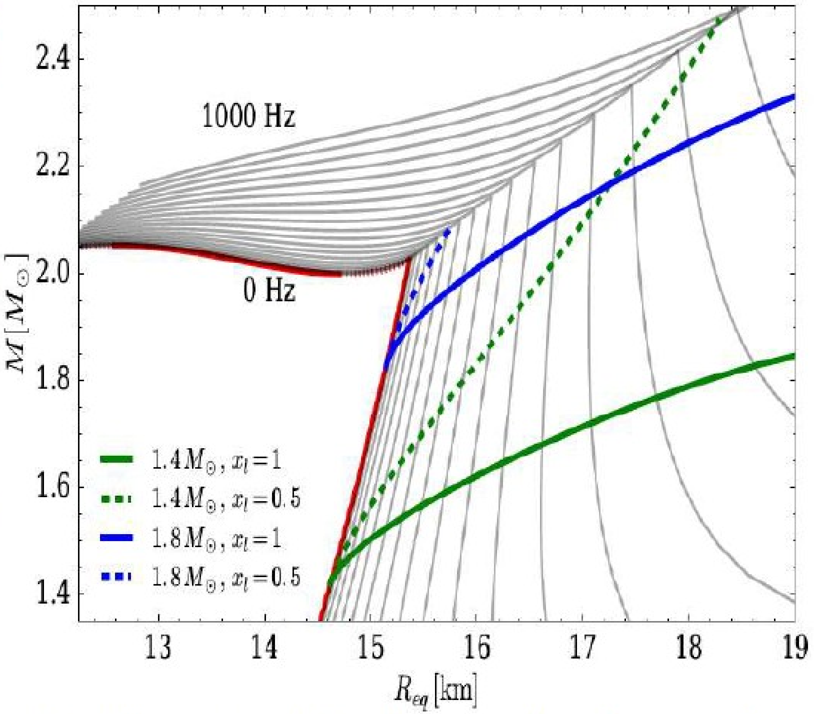
Observation:

With a strong PT (mass twins), a sudden transition NS → HS is possible, Triggered by accretion, under simultaneous conservation of Mb and J



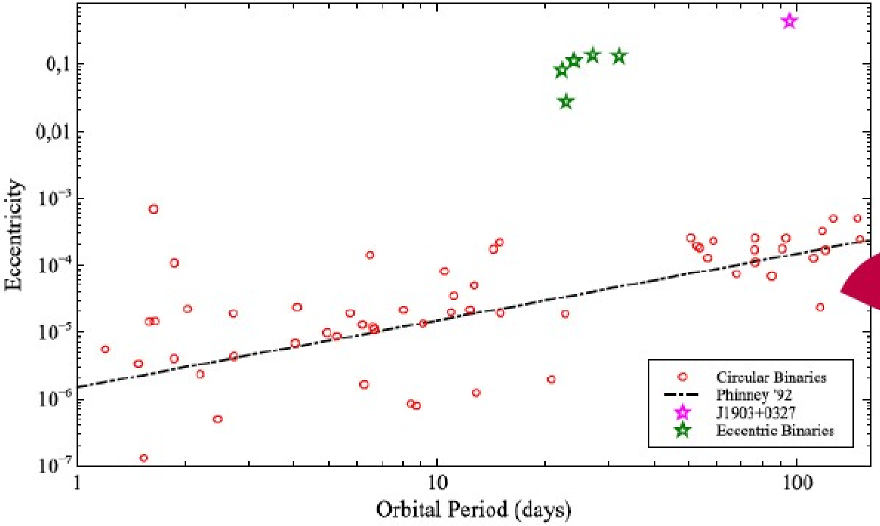
M. Bejger, D.B., et al., A&A 600 (2017) A39



Evolutionary tracks for disc accretion of mass with efficiency xl=1(0.5) of angular momentum transfer

Let us discover the 3rd family of compact stars!

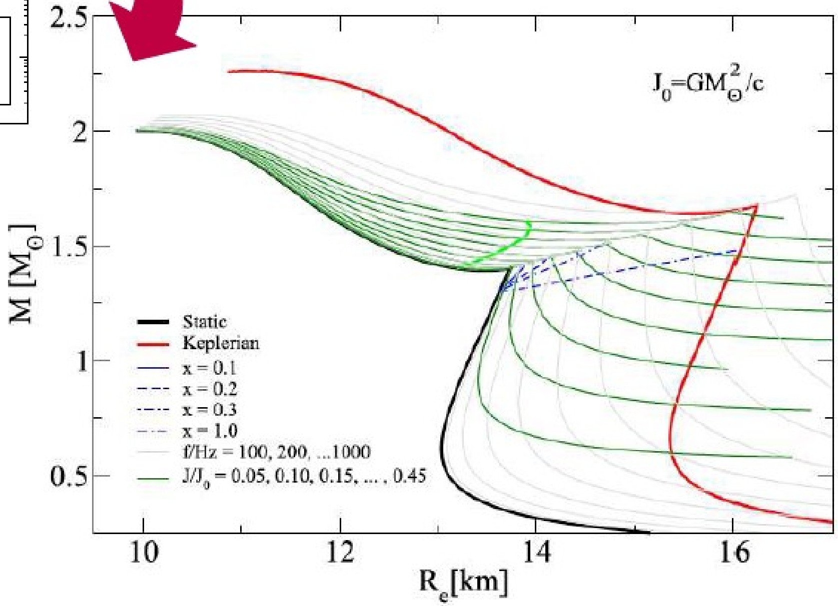
Antoniadis-puzzle



J. Antoniadis, ApJ Lett. 797, L24 (2014)

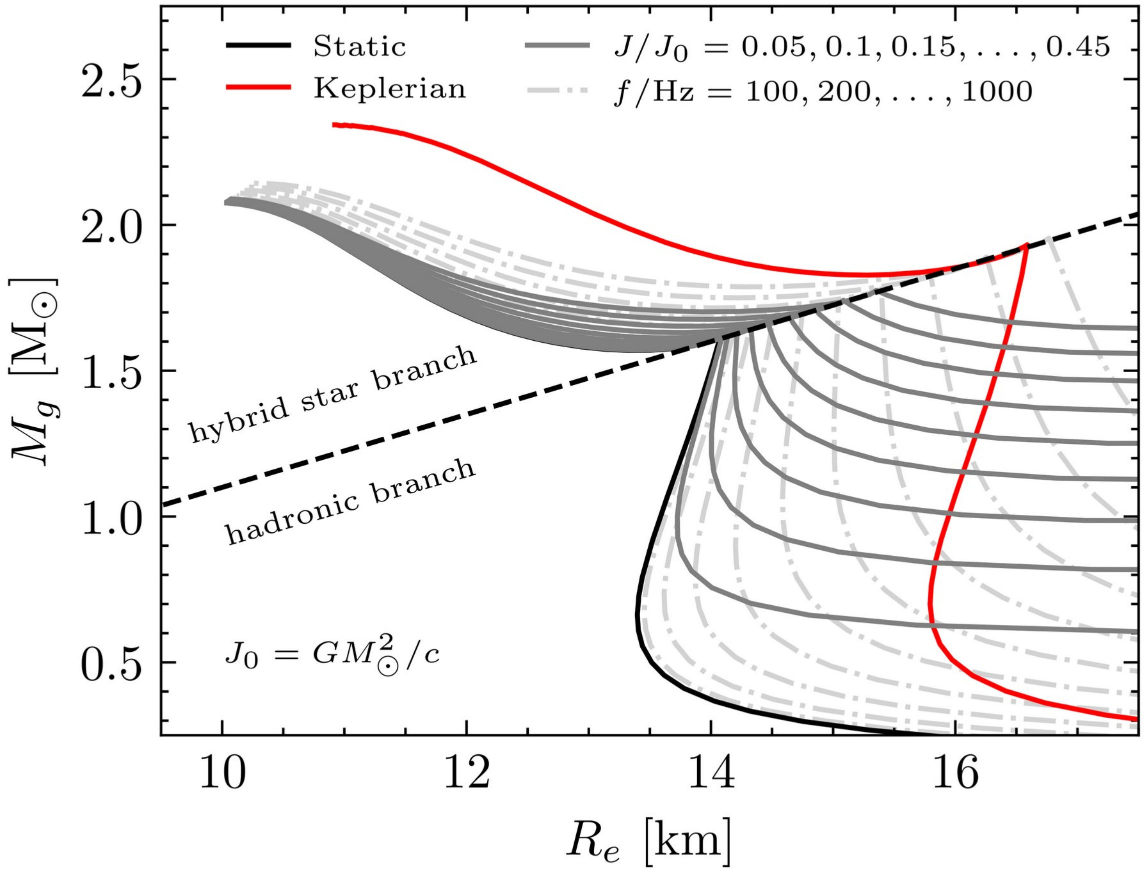
K. Stovall, P.C.C. Freire, J. Antoniadis, ApJ 870(2), 74 (2019)

How to relate this ?



D.E. Alvarez.Castillo, J. Antoniadis, A. Ayriyan, D. Blaschke, V. Danchev, H. Grigorian, N. Khosravi Largani, F. Weber,
Accretion-induced collapse to third family compact stars as trigger for eccentric orbits of Millisecond pulsars in binaries,
Astron. Nachr. 340 (2019) 878;
arXiv:1912.08782 [astro-ph.HE]

Mass Defect



- Multi-polytrope EoS [ACB-5]

$$P(n) = \kappa_i \left(\frac{n}{n_0}\right)^{\Gamma_i}$$

- Seidov criterion forinstability:

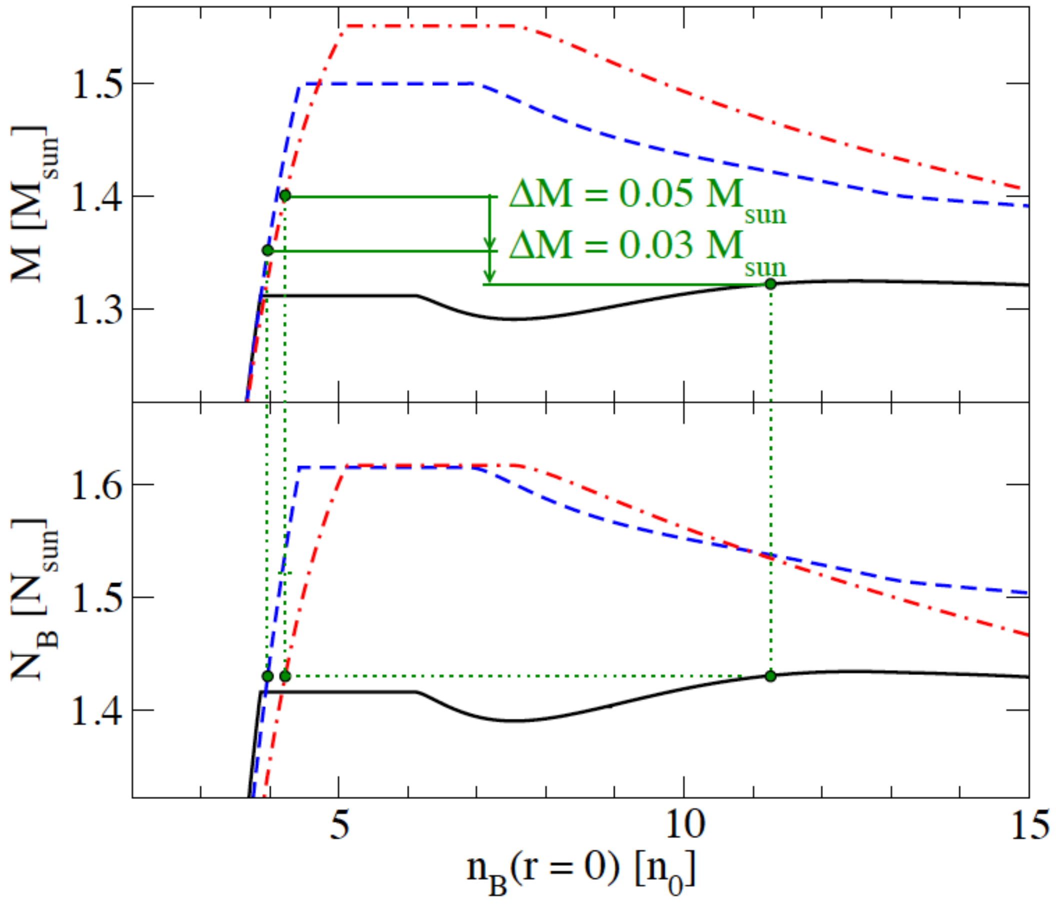
$$\Delta\varepsilon > \frac{\varepsilon_c + 3P_c}{2}$$

- Large jump in energy density (latent heat) → instability → 3rd family of compact stars = mass twin stars

D.E. Alvarez Castillo, D. Blaschke, Phys. Rev. C 96 (2017) 045809 „High-mass twin stars with a multipolytrope equation of state“

V. Paschalidis, K. Yagi, D. Alvarez-Castillo, D. B., A. Sedrakian, Phys. Rev. D 97 (2018) 084038, „Implications from GW170817 and I-Love-Q relations for relativistic hybrid stars“

Mass Defect



How to calculate the mass defect?

- Solve TOV equations for M(n_B(0)) and N_B(n_B(0))

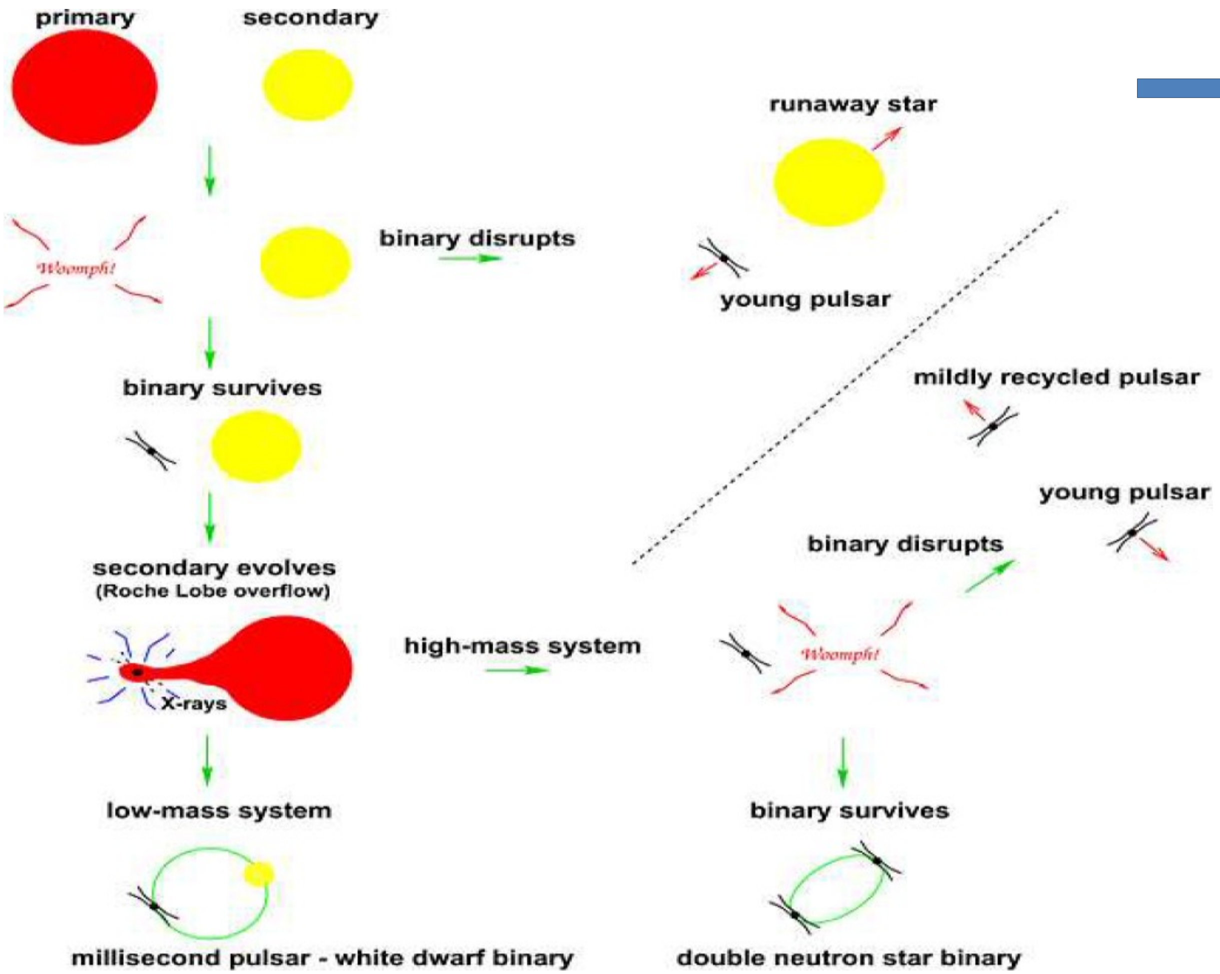
- Consider transition at constant baryon mass N_B and constant angular momentum J

- Compare the gravitational masses after the transition

- Account for neutrino trapping/ untrapping by a finite chemical potential

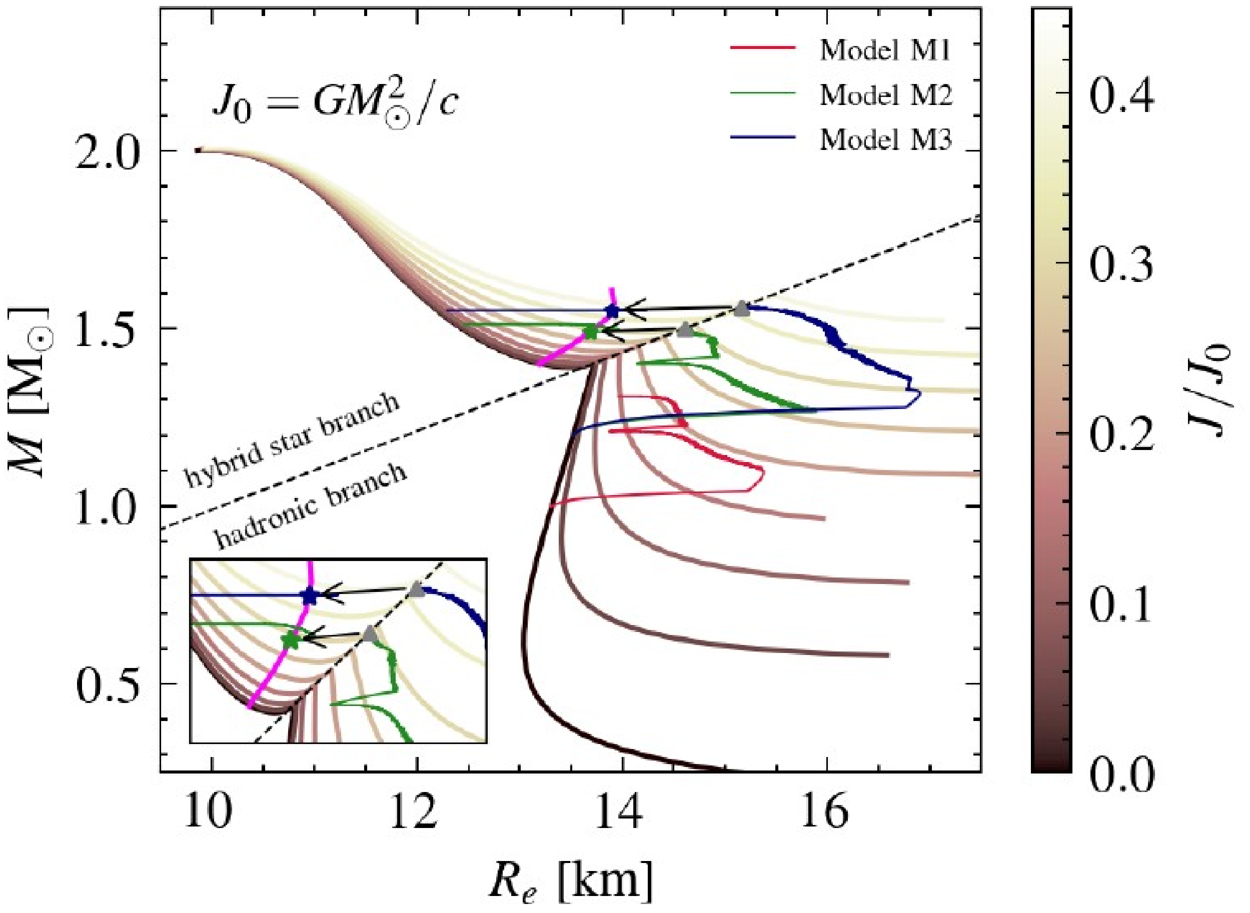
F. Sandin,D. Blaschke, Phys. Rev. D 75 (2007) 125013
„The quark core of protoneutron stars in the phase diagram of quark matter“

Another kick explanation: Strong QCD phase transition in NS evolution!



→ Disruption or anomalous eccentricity of a binary system due to mass defect (grav. binding) in NS catastrophic rearrangement ...

Simulation of binary evolution



S. Chanlaridis, D. Ohse, J. Antoniadis, D. Blaschke, D.E. Alvarez-Castillo, V. Danchev, D. Misra and N. Langer:

„Formation of twin stars in low-mass X-ray binaries“

(in preparation for A&A)

Simulation of binary evolution

$$\frac{a_f}{a_i} = \frac{1 - \Delta M/M}{1 - 2\Delta M/M - (w/v_{rel})^2 - 2\cos\theta(w/v_{rel})},$$

$v_{rel} = \sqrt{GM/a_i}$

w is the magnitude of the kick velocity,

θ is the kick angle

The eccentricity of the post-transition binary system is given by

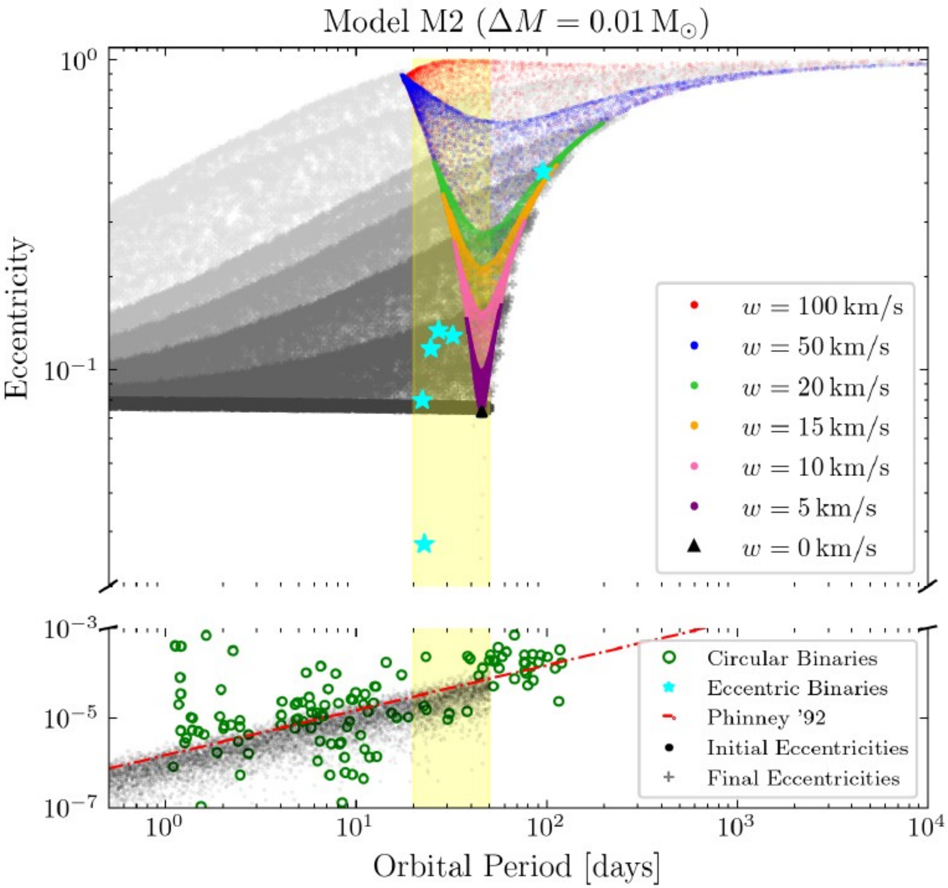
$$e = \sqrt{1 + \frac{2E_{orb,f}L^2_{orb,f}}{\mu_f G^2 M^2_{f,1} M^2_{f,2}}},$$

$$L_{orb,f} = a_i \mu_f \sqrt{(v_{rel} + w\cos\theta)^2 + (w\sin\theta\sin\phi)^2}$$

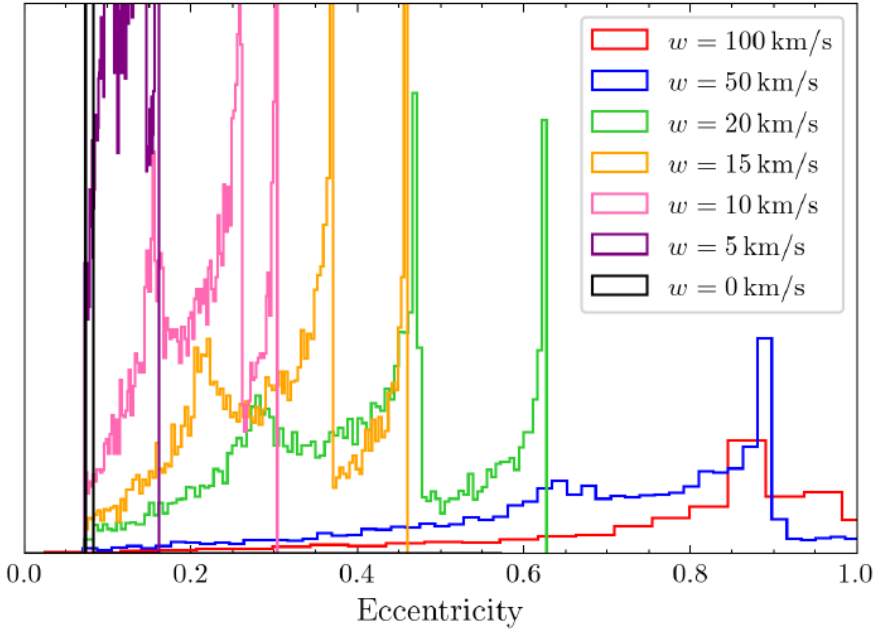
$$E_{orb,f} = -GM_{f,1}M_{f,2}/2a_f$$

Model	M_{don} [$M_\odot$]	M_{ns} [$M_\odot$]	P_{orb} [days]
M1	1.0	1.0	8
M2	1.0	1.2	8
M3	1.0	1.2	22.627

Simulation of binary evolution

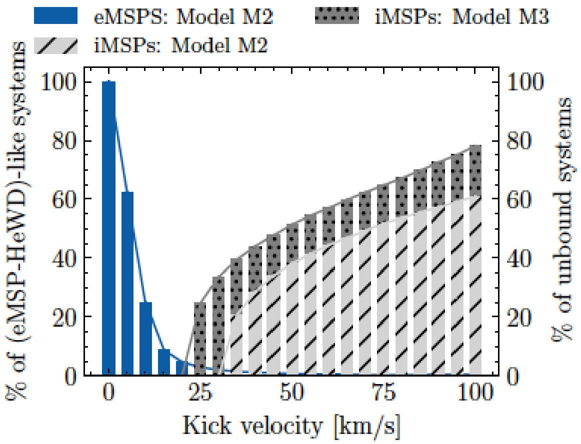


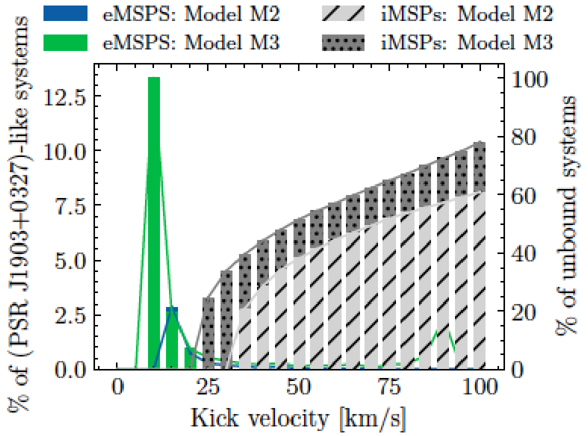
Monte-Carlo simulation of posttransition distribution orbital parameters for a mass defect of 1% solar mass due to the transition.



S. Chanlaridis, D. Ohse, J. Antoniadis, D. Blaschke, D.E. Alvarez-Castillo, V. Danchev, D. Misra and N. Langer: „Formation of twin stars in low-mass X-ray binaries“ (in preparation for A&A)

Results for T=0 twin signals in LMXB’s





- First results are promising:

- Period gap 20 – 50 d, with e ~ 10^{-1} can be addressed

- One binary with a main sequence star (J1903+0327) with larger period, 100 d, and e ~ 1 can also be met

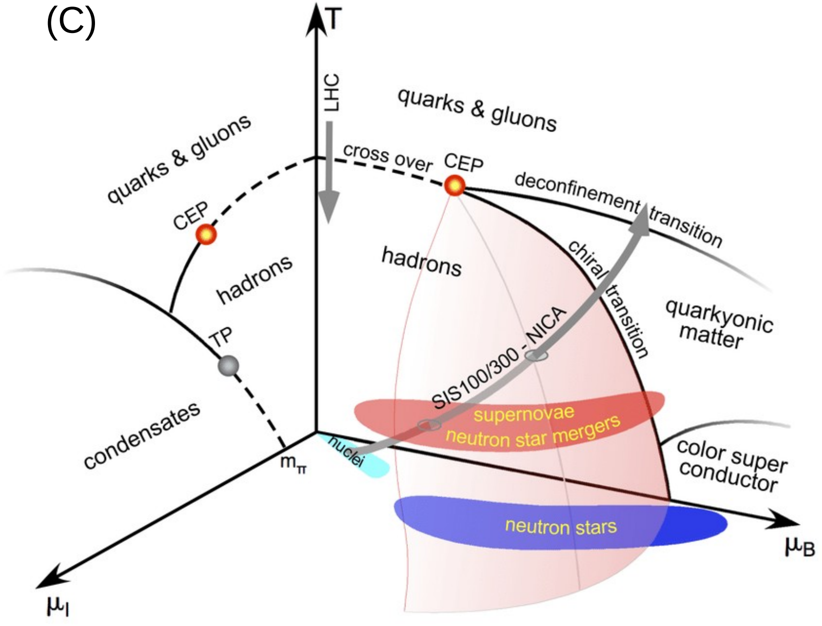
- Appearance of unbound systems → isolated MSPs

S. Chanlaridis, D. Ohse, J. Antoniadis, D. Blaschke, D.E. Alvarez-Castillo, V. Danchev, D. Misra, N. Langer: „Formation of twin stars in low-mass X-ray binaries“ (in preparation for A&A)

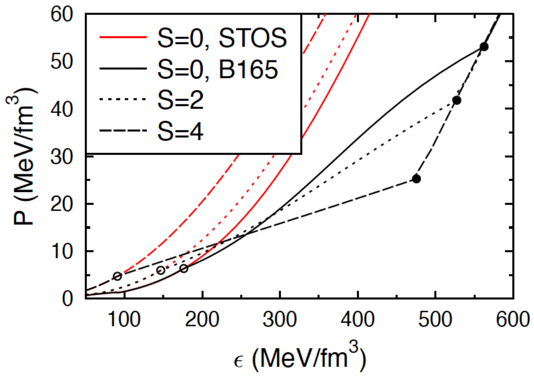
Thermal twin stars

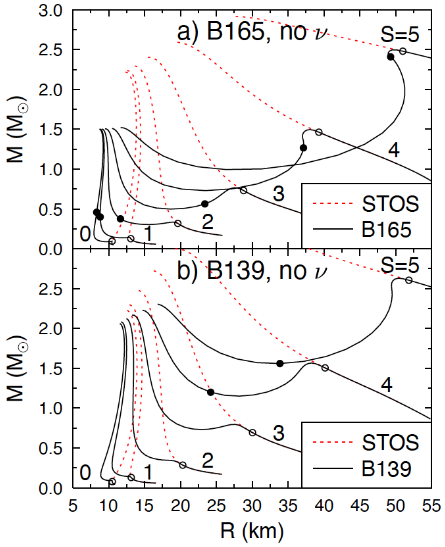
Observation*:
When the transition at T=0 is weak,
with a connected hybrid star branch,
At finite T (s/n>0) a third family (thermal
twin stars) can emerge !!

(C)



*) M. Hempel et al., PRD 94 (2016) 103001





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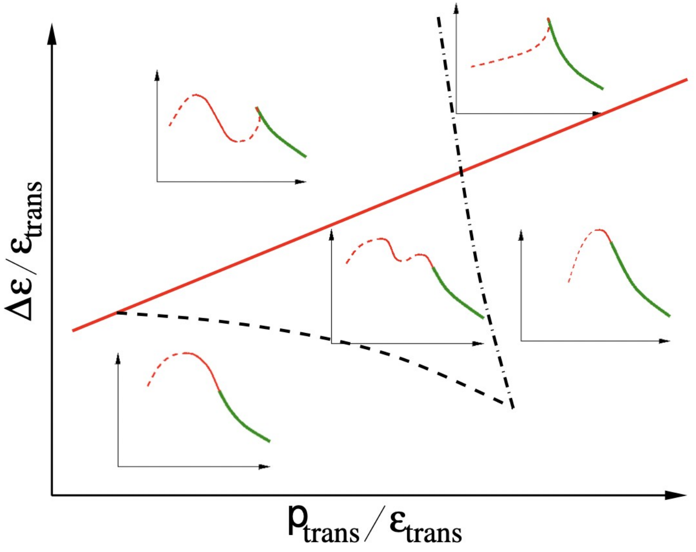

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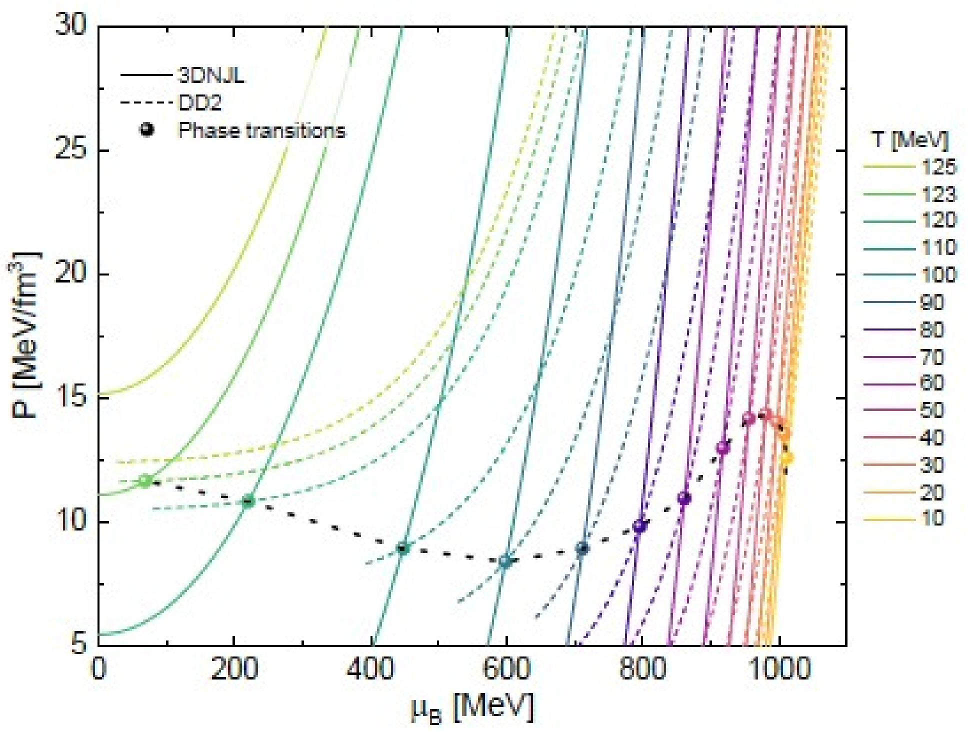
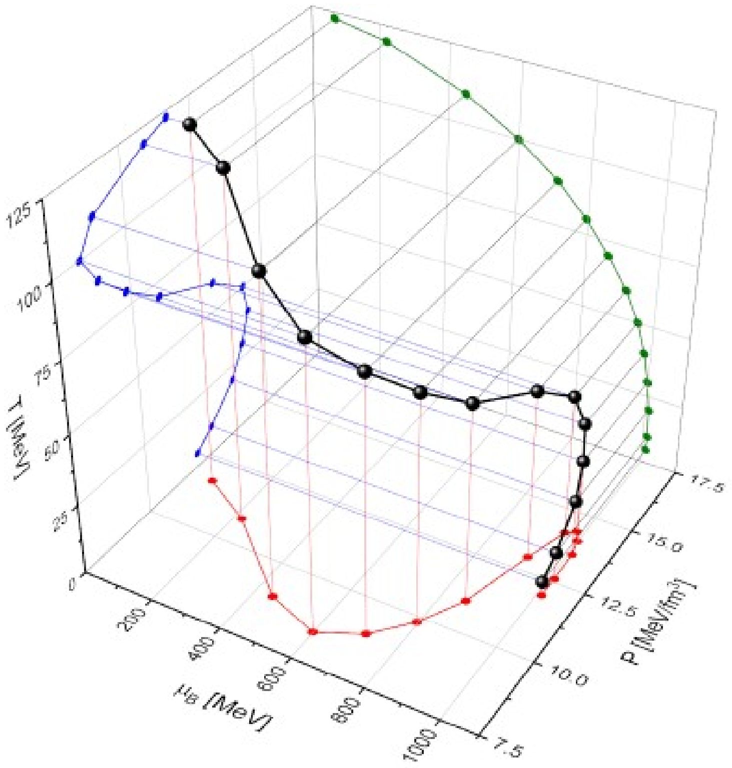
Thermal twin stars

Investigation within a color superconducting, nonlocal chiral quark model*:





*) G. Contrera, D.B., J.P. Carlomagno, A.G. Grunfeld, PRC 105 (2022) 045808
J.P. Carlomagno, G. Contrera, A.G. Grunfeld, D.B., PRD 109 (2024) 043050; arXiv:2406.17193

Thermal twin stars

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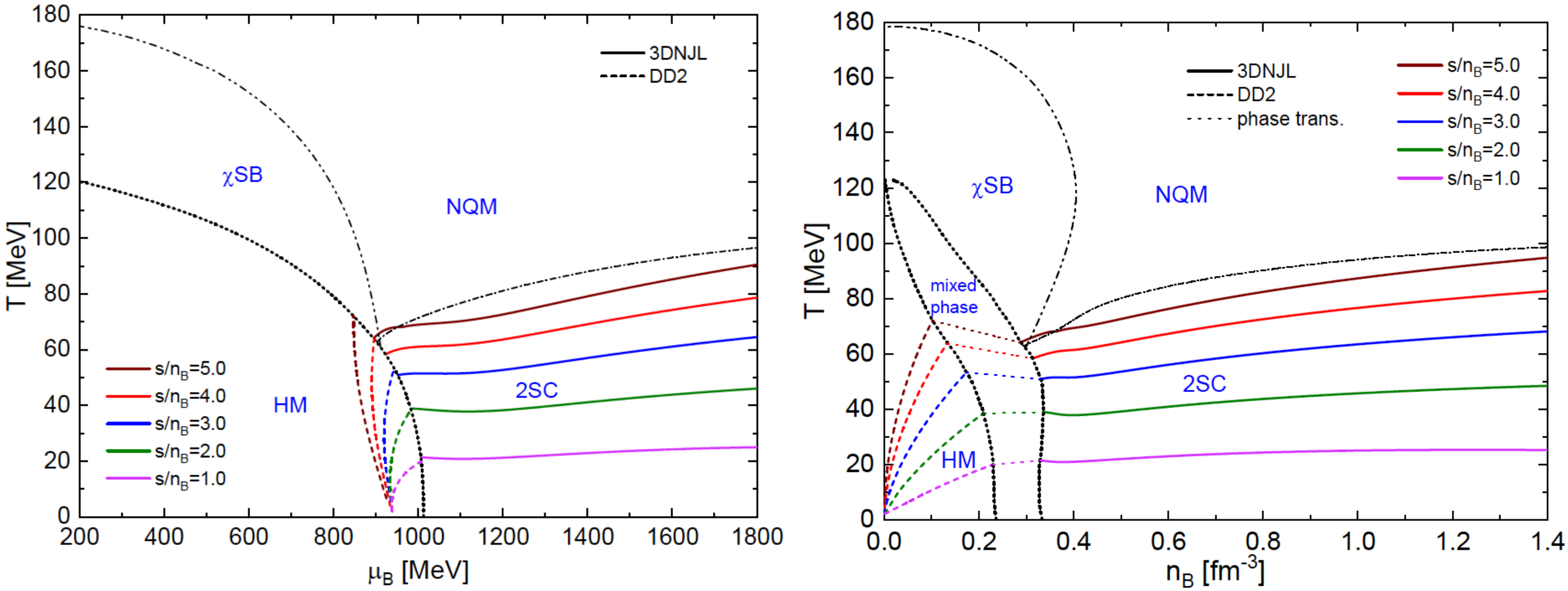

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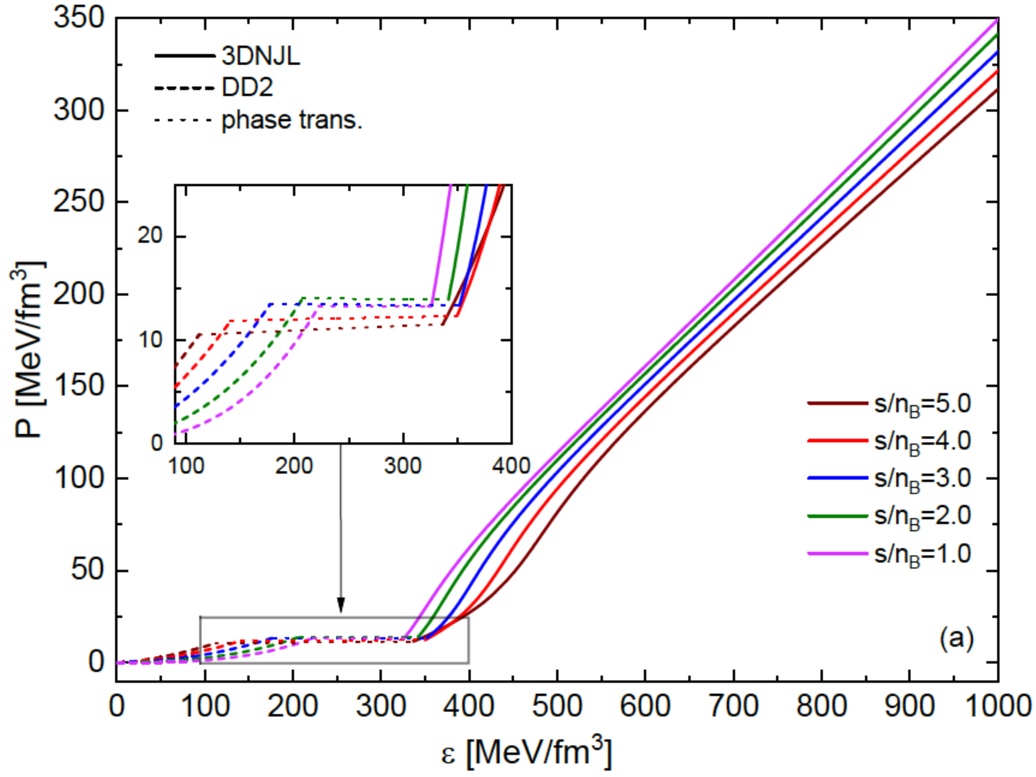

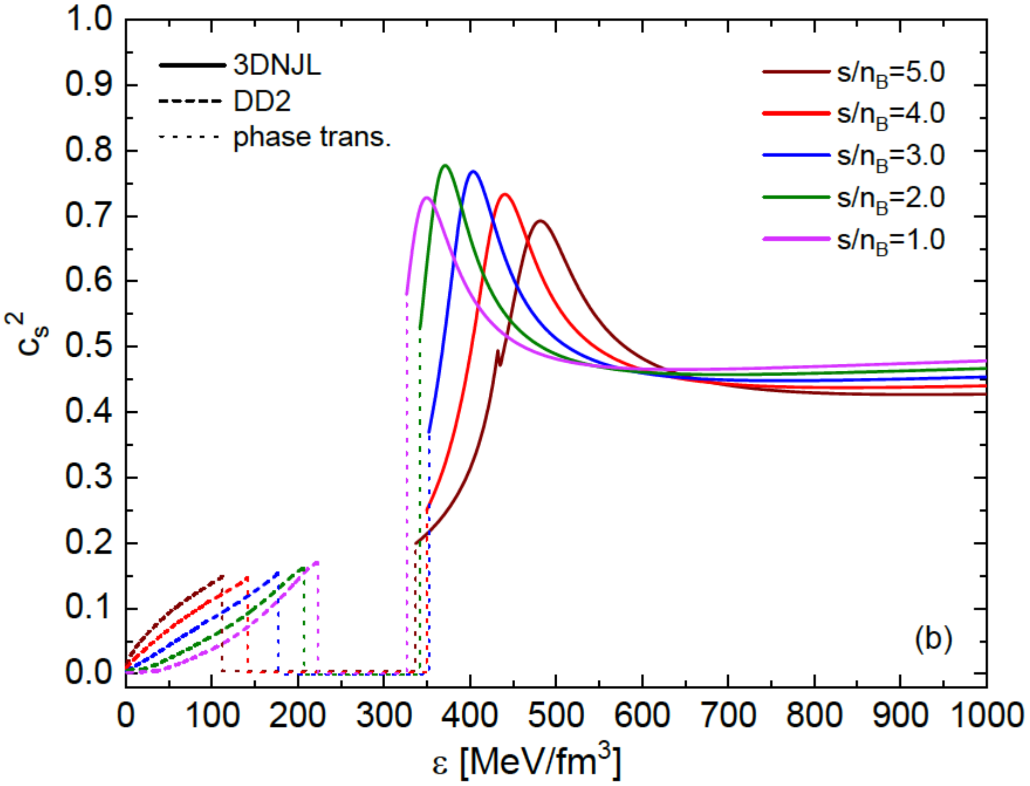

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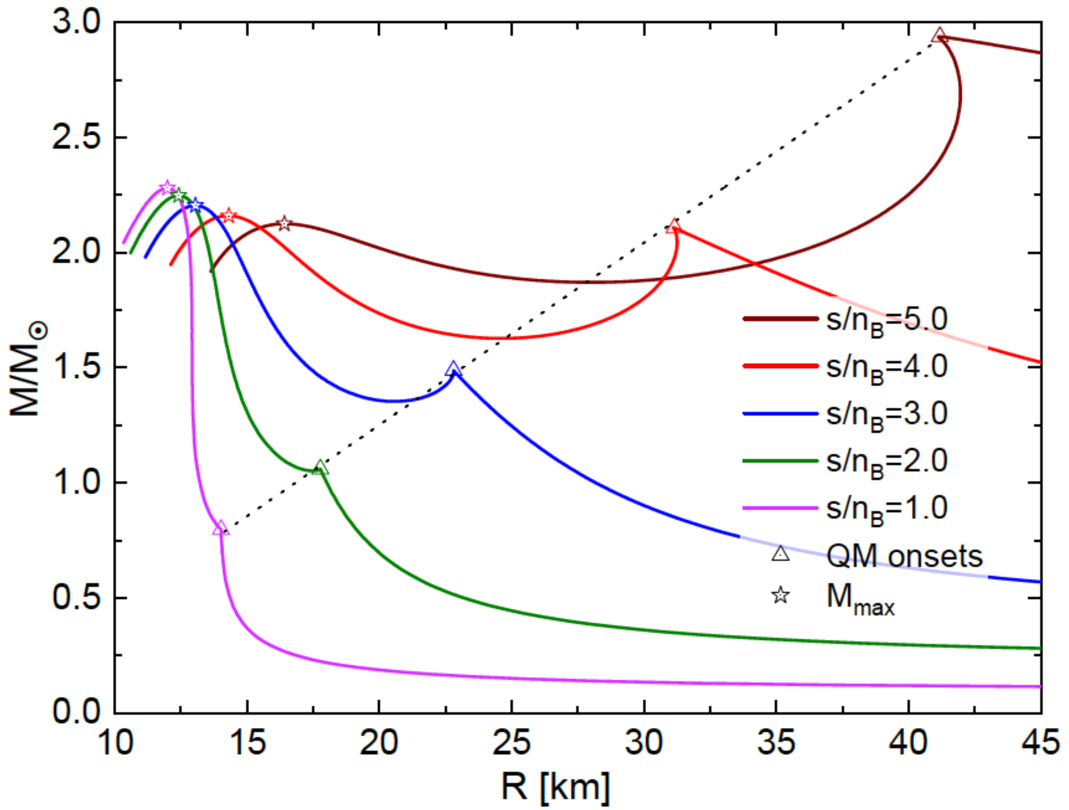
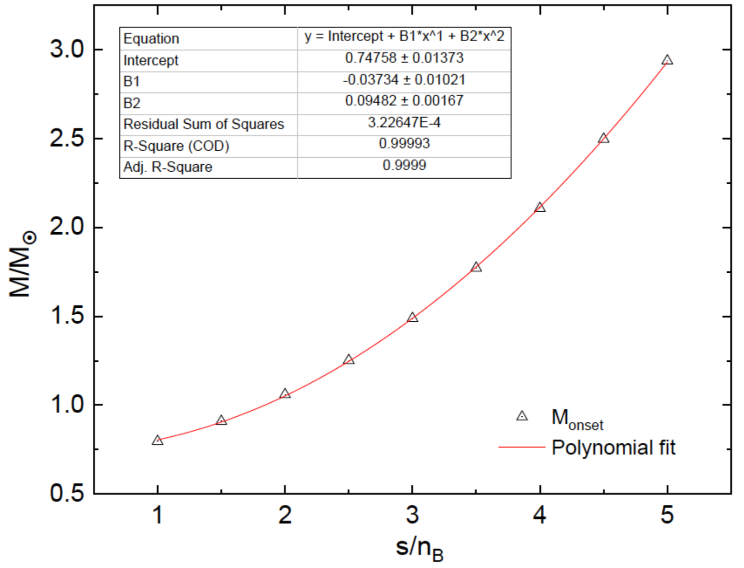


Systematics for the onset: $M = C(R - R_0)$,

where $R_0 = 4.20 \pm 0.35$ km is the radius offset

and $C = dM_{\rm onset}/dR = 0.0792 \pm 0.0009\ M_\odot/\mathrm{km}$

is the critical compactness of the star



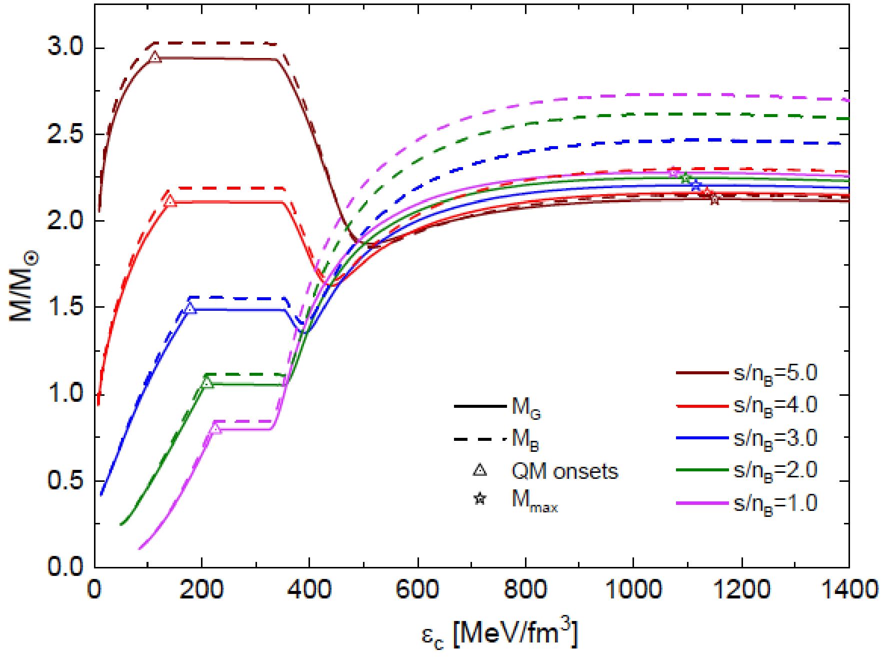
$$\frac{M_{\rm onset}}{M_\odot} = 0.747 - 0.0373\frac{s}{n_B} + 0.0948\left(\frac{s}{n_B}\right)^2$$

*) G. Contrera, D.B., J.P. Carlomagno, A.G. Grunfeld, PRC 105 (2022) 045808
J.P. Carlomagno, G. Contrera, A.G. Grunfeld, D.B., PRD 109 (2024) 043050; arXiv:2406.17193

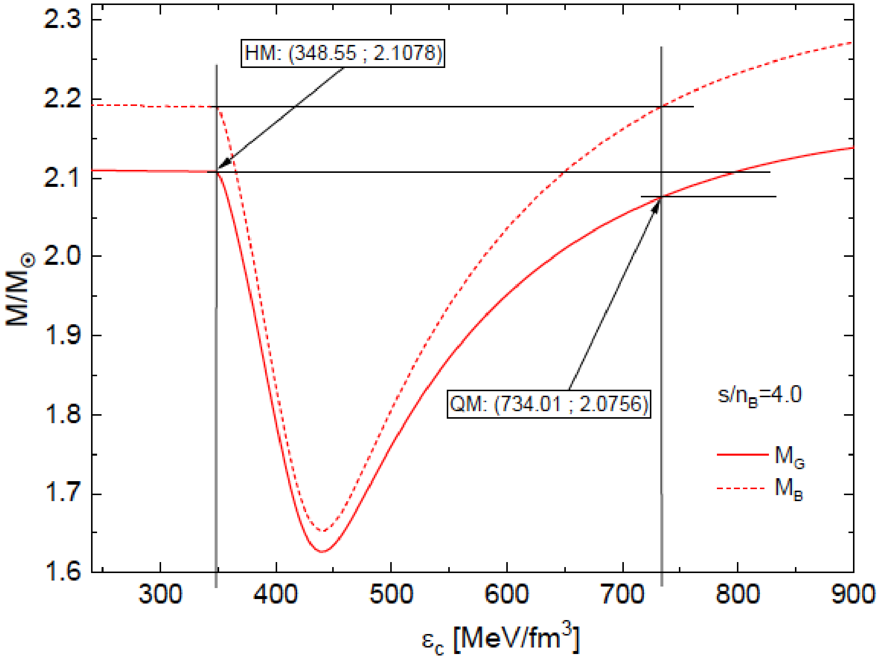
Thermal twin stars

Investigation within a color superconducting, nonlocal chiral quark model*:

Gravitational mass (solid) and baryon mass (dashed)



Extraction of the mass defect (energy release)

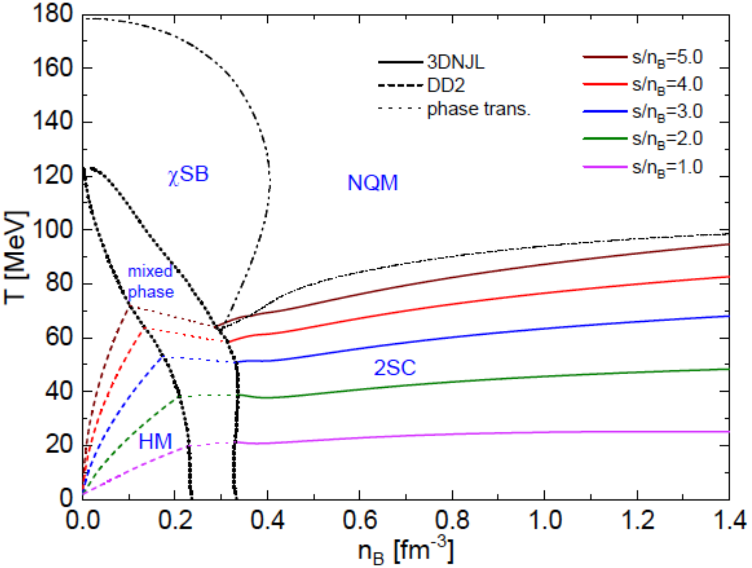


*) G. Contrera, D.B., J.P. Carlomagno, A.G. Grunfeld, PRC 105 (2022) 045808
J.P. Carlomagno, G. Contrera, A.G. Grunfeld, D.B., PRD 109 (2024) 043050; arXiv:2406.17193

Thermal twin stars

Characterization of the accretion-induced transition to the thermal twin star*

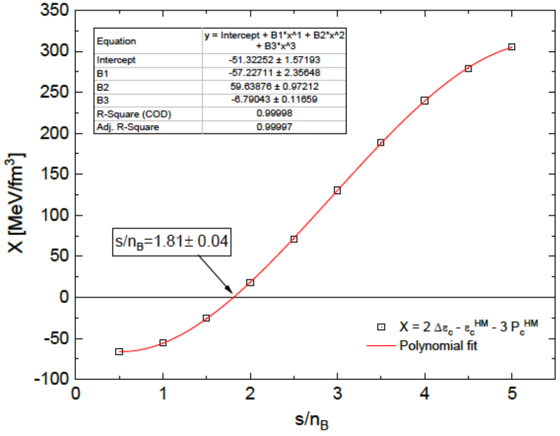
s/n_B	$M_{B,tr}$	$M_{G,HM}$	$M_{G,QM}$	ΔM	$T(0)_{HM}$	$T(0)_{QM}$	$\Delta T(0)$	character
2.0	1.114	1.0582	1.0582	0.0000	38.36	38.87	0.51	enthalpic
2.5	1.311	1.2490	1.2487	0.0003	46.33	45.57	-0.76	entropic
3.0	1.557	1.4878	1.4853	0.0025	53.16	50.84	-2.32	entropic
3.5	1.849	1.7726	1.7621	0.0105	58.89	55.01	-3.88	entropic
4.0	2.190	2.1078	2.0756	0.0322	63.74	58.28	-5.46	entropic

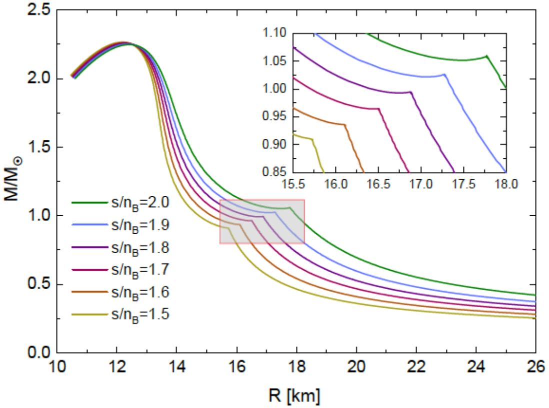


*) J.P. Carlomagno, G. Contrera, A.G. Grunfeld, D.B., arXiv:2406.17193

Seidov criterion for instability:

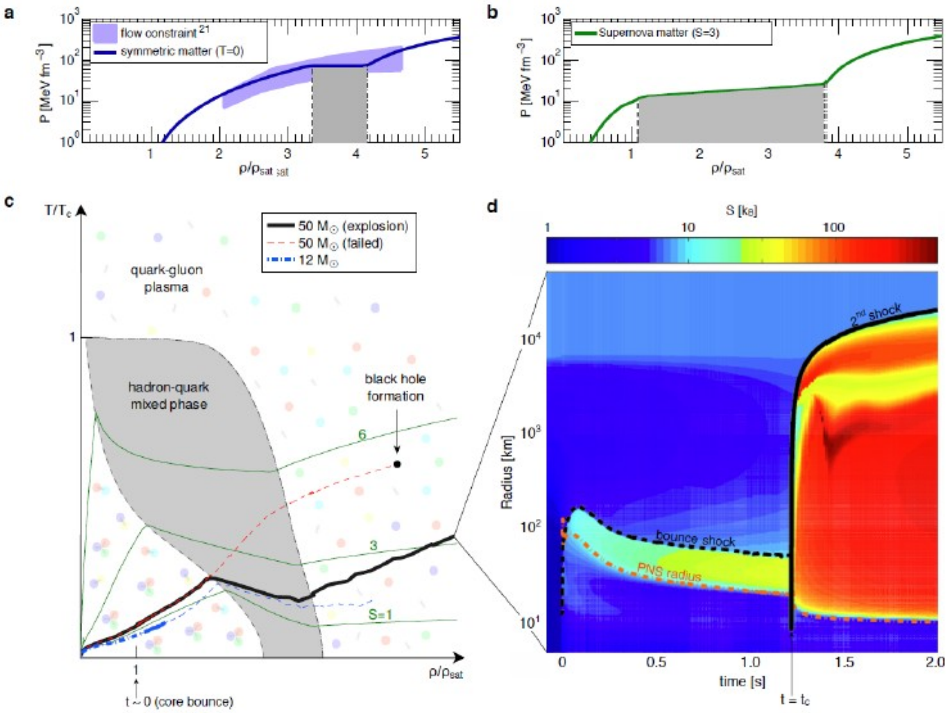
$$X = 2\Delta\varepsilon - \varepsilon_c^{HM} - 3P_c^{HM} > 0$$



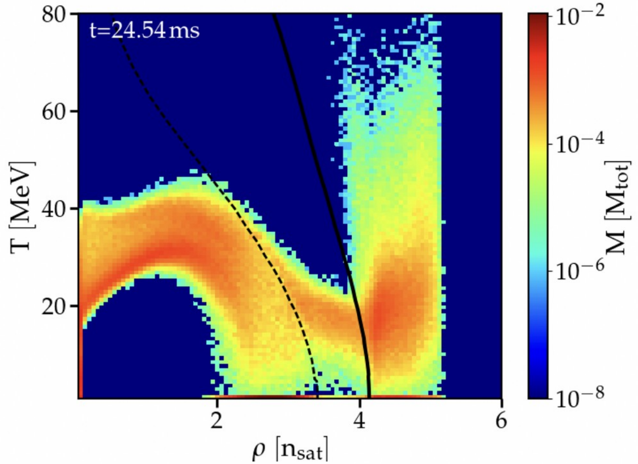


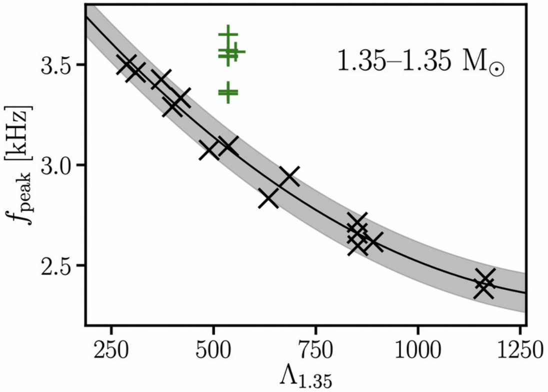
Thermal twin stars – Indicators of CCSN explodability ?

Successful application of hybrid EoS with entropic first-order transition (thermal twin stars) as an explosion mechanism for massive blue supergiant stars* and for a GW signal from binary neutron star mergers**:



Progenitor:
M = 50 M_O





*) T. Fischer et al., Nature Astron. (2018)
**) A. Bauswein et al., PRL (2019)