

Thermal and non-thermal twin stars

David Blaschke

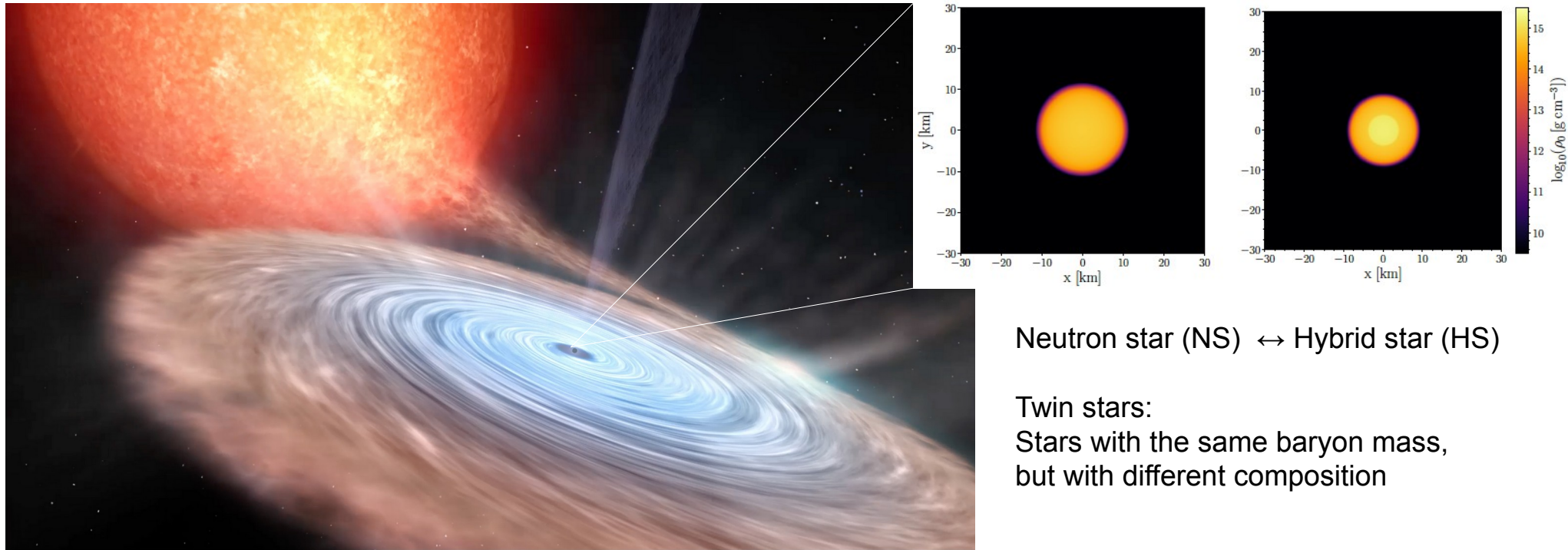
University of Wroclaw, Poland & HZDR/CASUS Görlitz, Germany



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Neutron star (NS) ↔ Hybrid star (HS)

Twin stars:

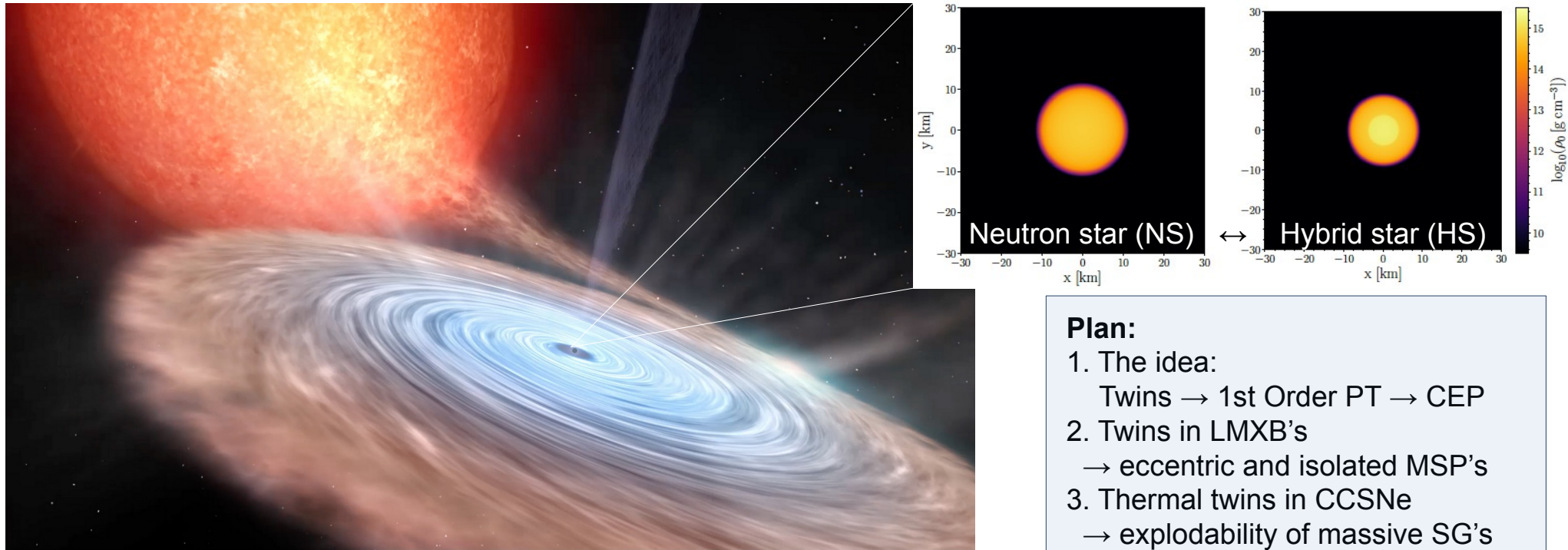
Stars with the same baryon mass,
but with different composition

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:

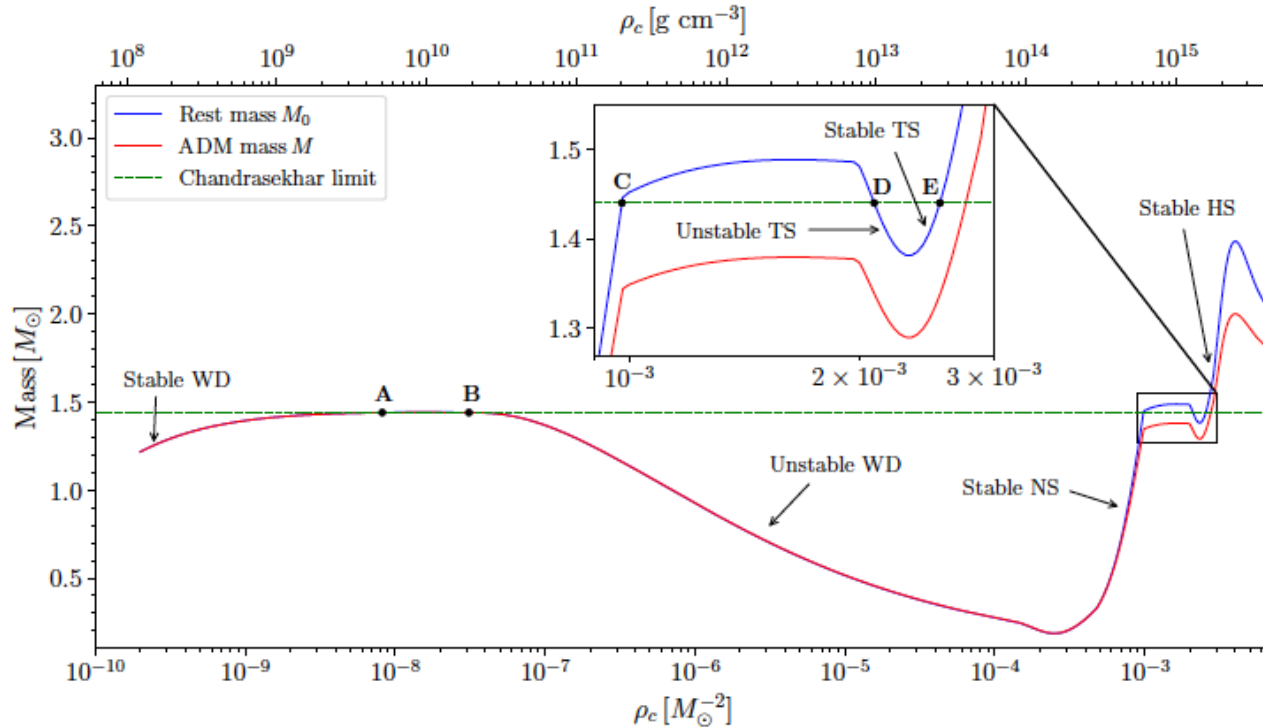
1. The idea:
 - Twins \rightarrow 1st Order PT \rightarrow CEP
2. Twins in LMXB's
 - \rightarrow eccentric and isolated MSP's
3. Thermal twins in CCSNe
 - \rightarrow explodability of massive SG's
4. Discussion

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

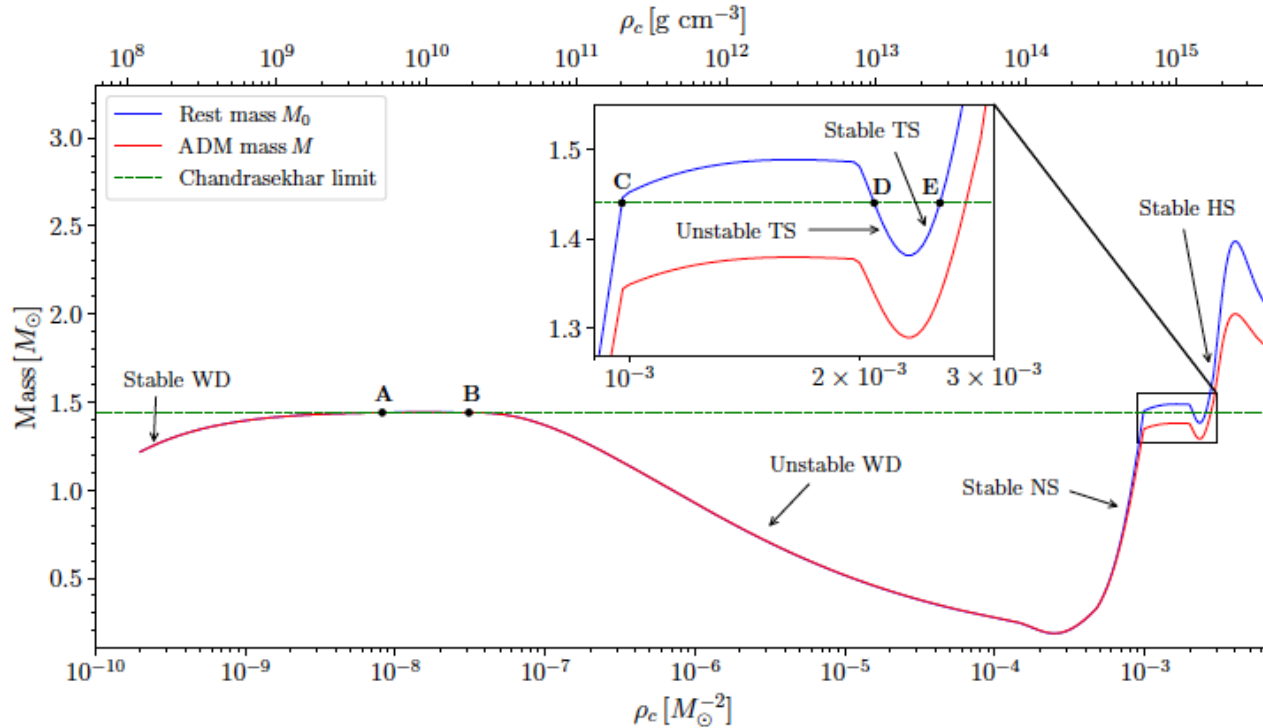


From: M. Naser, G. Bozzola, V. Paschalidis, arXiv:2406.15544

The idea

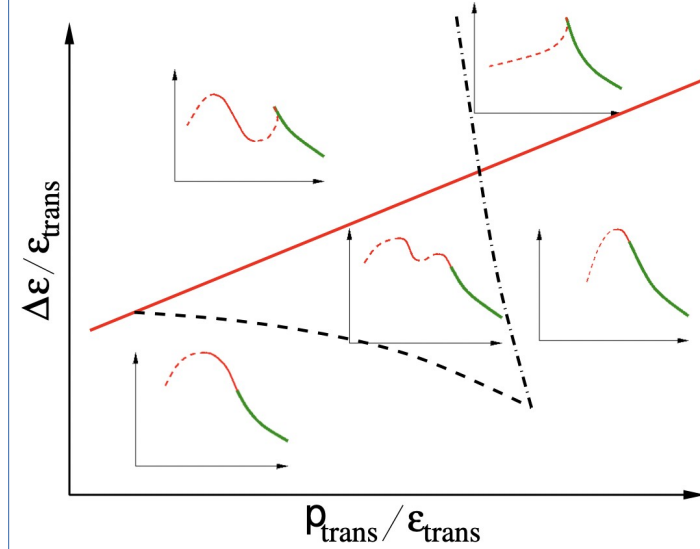
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Disconnected HS branch indicates a Strong (1st-order) phase transition



Seidov criterion for gravitational Instability (red line):

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

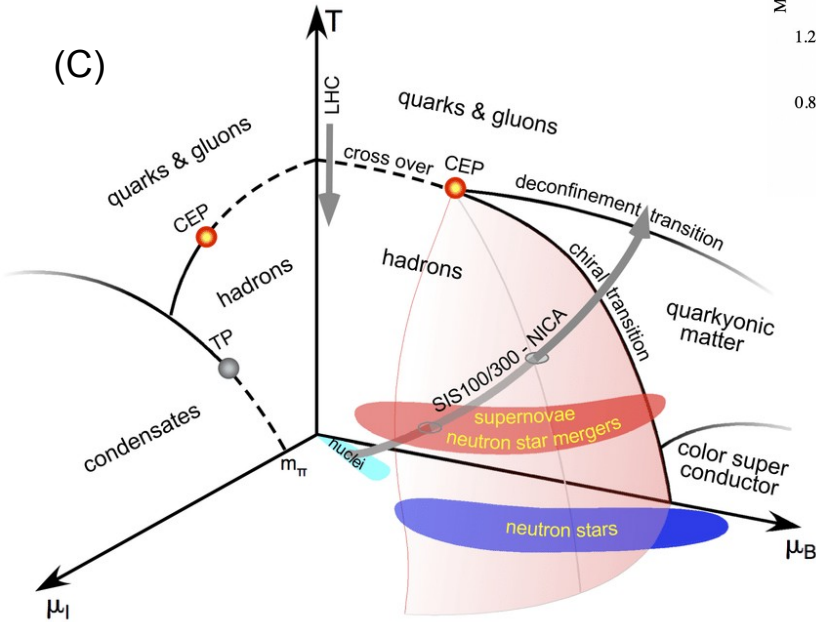
From: M. Alford, S. Han, M. Prakash, PRD (2013):
 „Generic conditions for stable hybrid stars“

The idea

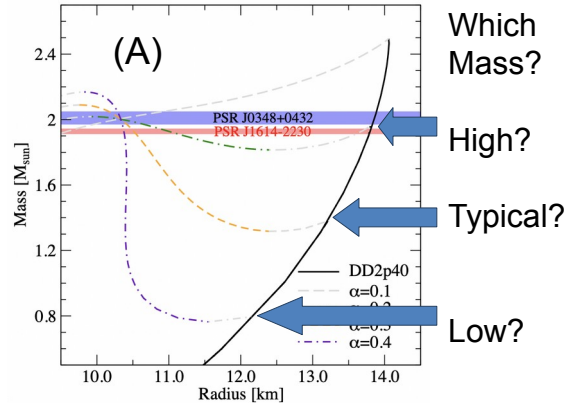
Twin Stars (A)

→ Strong Phase Transition (B)

→ Existence of CEP in Phase Diagram (C)



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

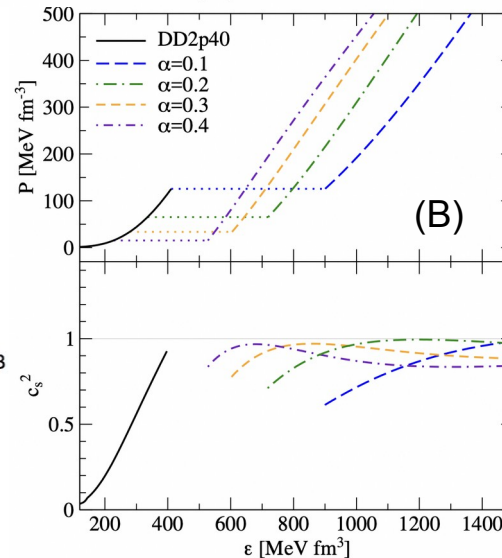


Which Mass?

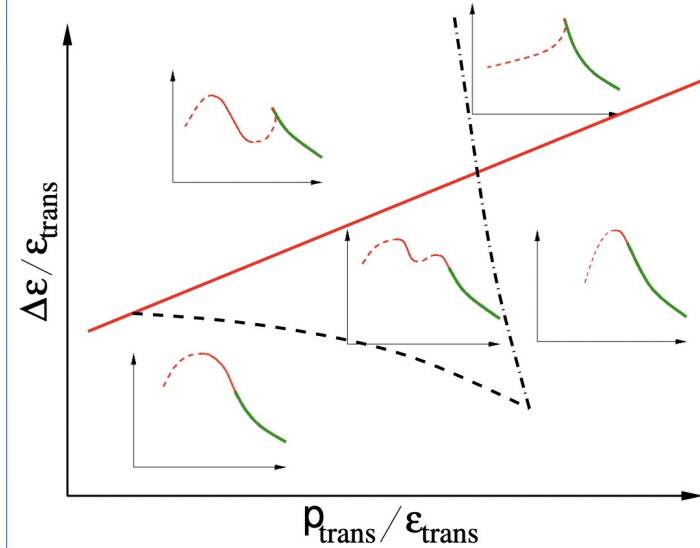
High?

Typical?

Low?



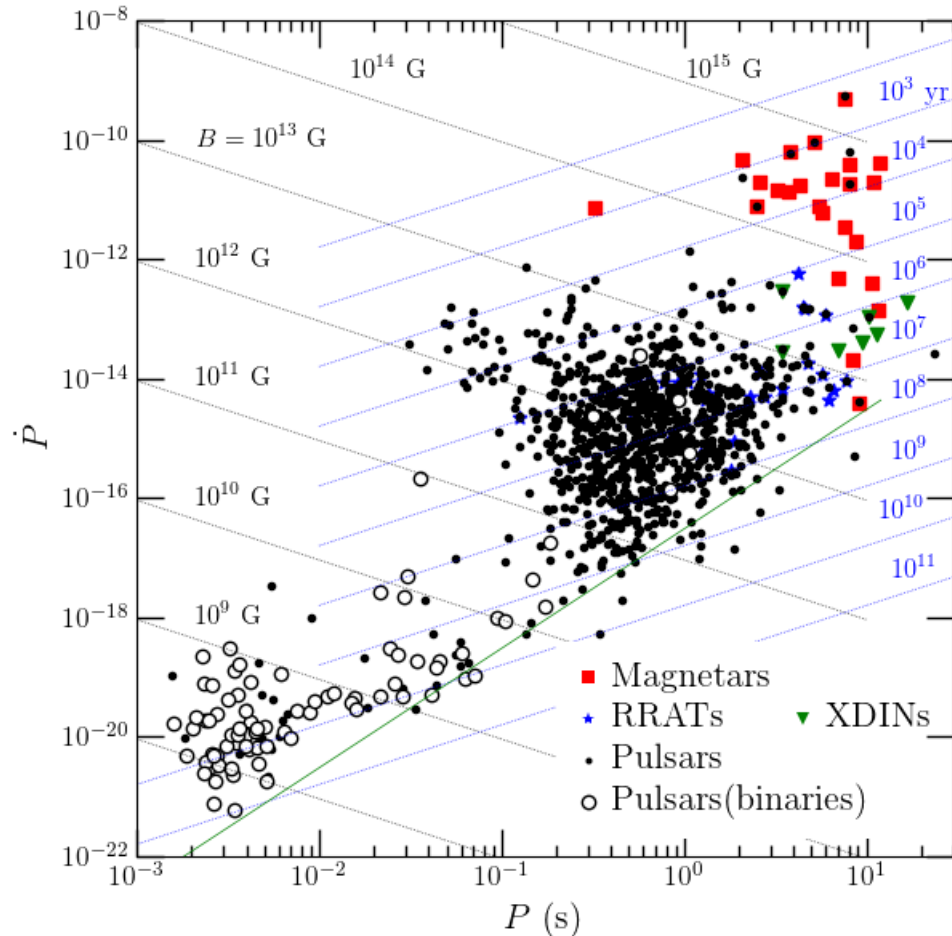
Disconnected HS branch indicates a Strong (1st-order) phase transition



Seidov criterion for gravitational Instability (red line):

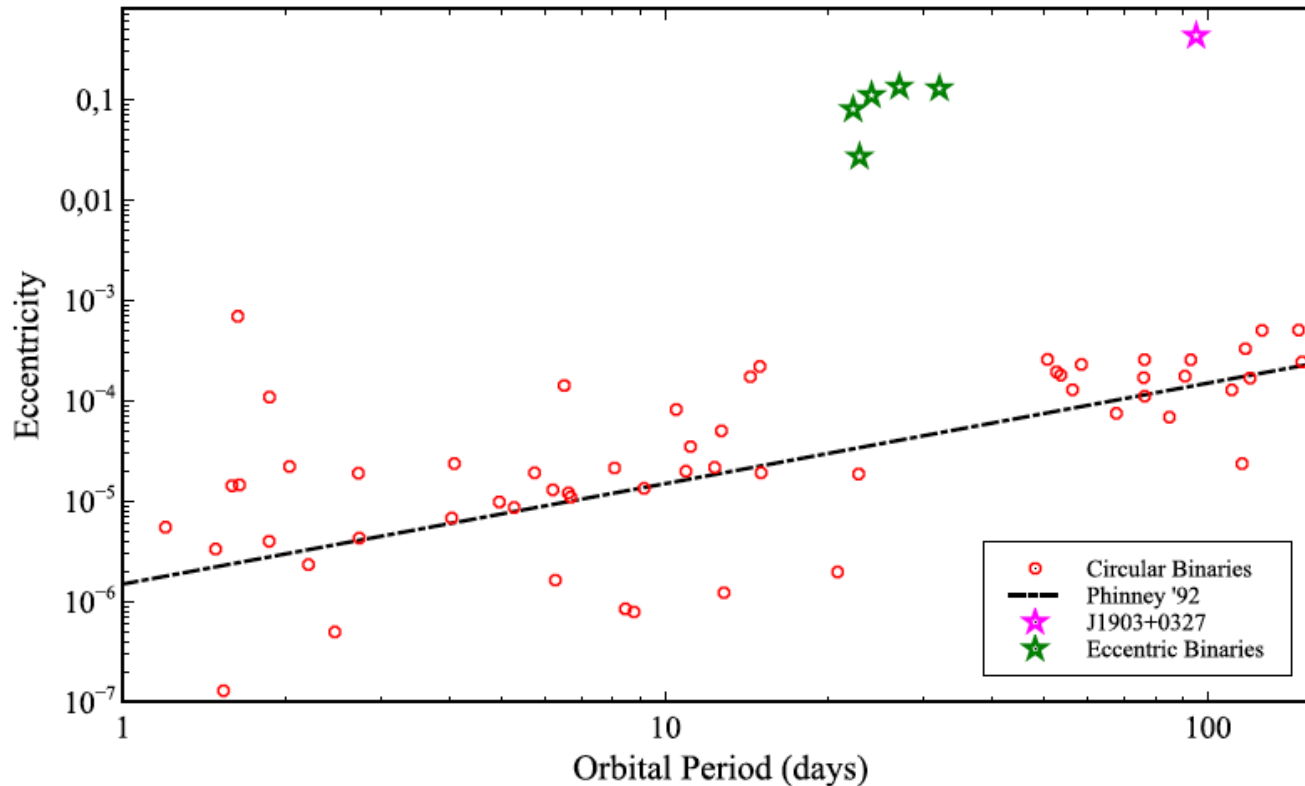
$$\frac{\Delta\epsilon_{\text{crit}}}{\epsilon_{\text{trans}}} = \frac{1}{2} + \frac{3}{2} \frac{p_{\text{trans}}}{\epsilon_{\text{trans}}}$$

Introduction: Millisecond Pulsars in the \dot{P} -P Diagram



- Pulsars are born with periods $P \sim 0.1 - 1.0$ seconds and magnetic fields $B \sim 10^{12}$ 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 ($\sim 20\%$) and 5 are a Puzzle!

Introduction: The Puzzle of Eccentric MSPs



- Most MSPs are in binaries with circular orbits: $e \sim 10^{-6} - 10^{-4}$
→ „Phinney line“

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

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

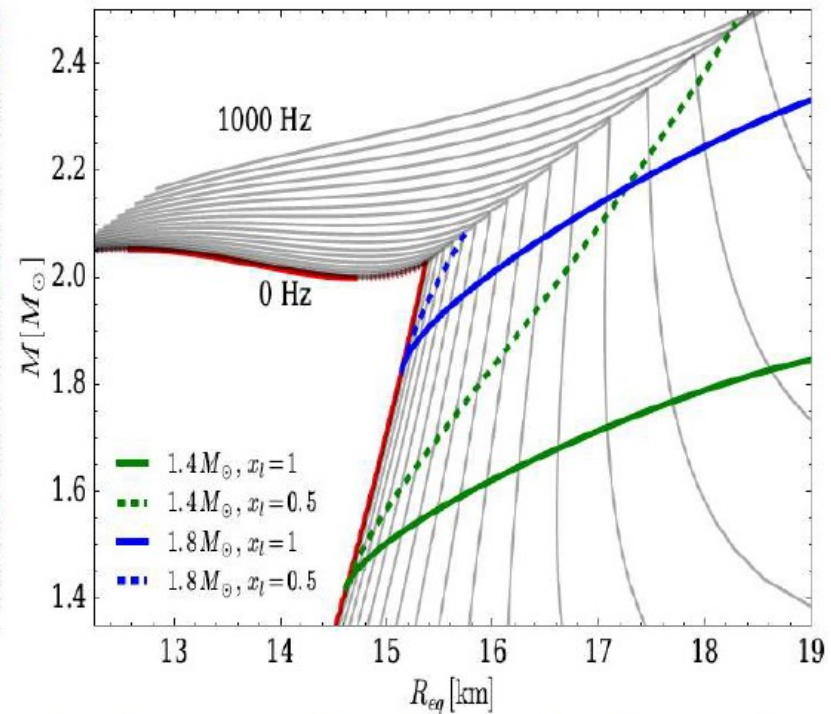
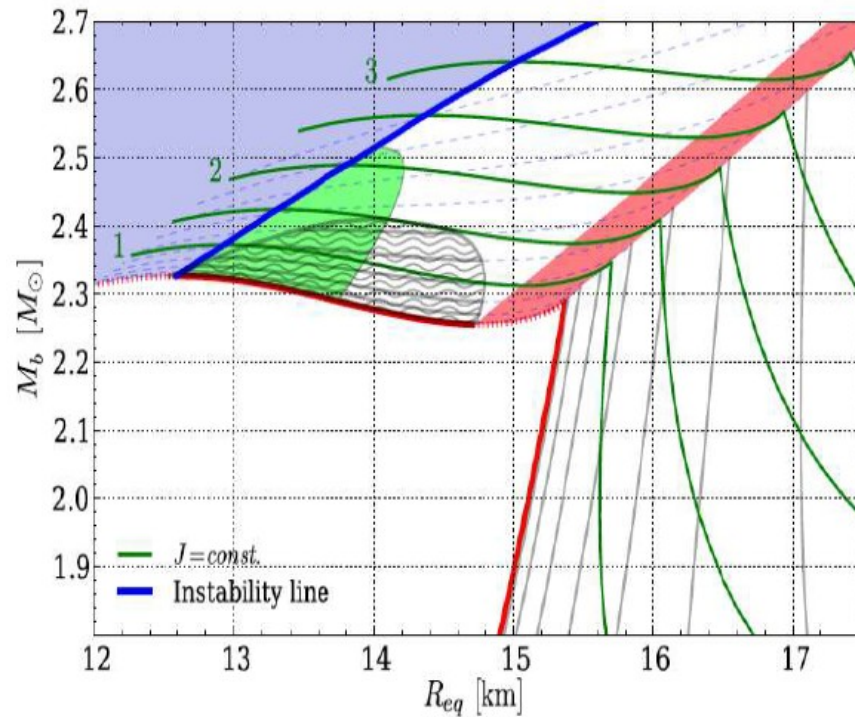
J. Antoniadis, *Astrophys. J.* 797, L24 (2014): „On the Formation of Eccentric Millisecond Pulsars with He-WD Companions“
D. Alvarez-Castillo, J. Antoniadis, A. Ayriyan, D. Blaschke, V. Danchev et al., *Astron. Nachr.* 340 (2019) 878,
„Accretion-induced collapse to third family compact stars as trigger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

→ **Puzzle!**

Let us discover the 3rd family of compact stars!

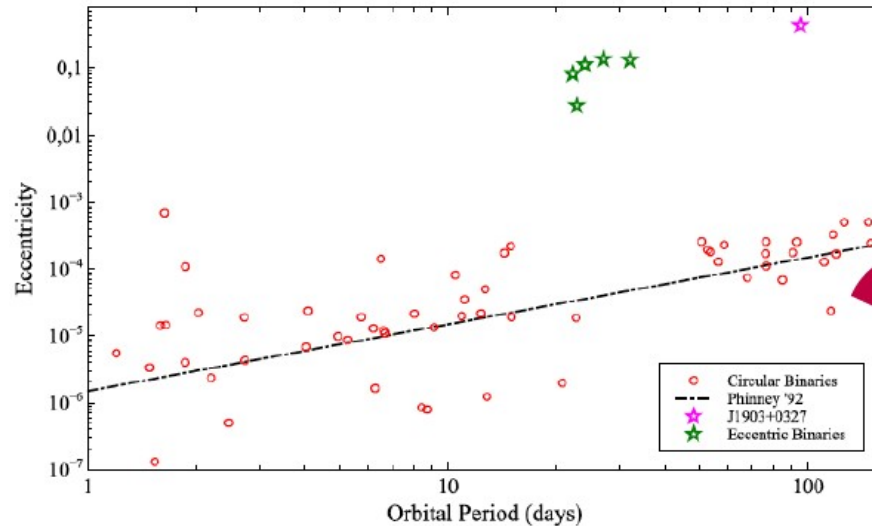
Observation:

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



Let us discover the 3rd family of compact stars!

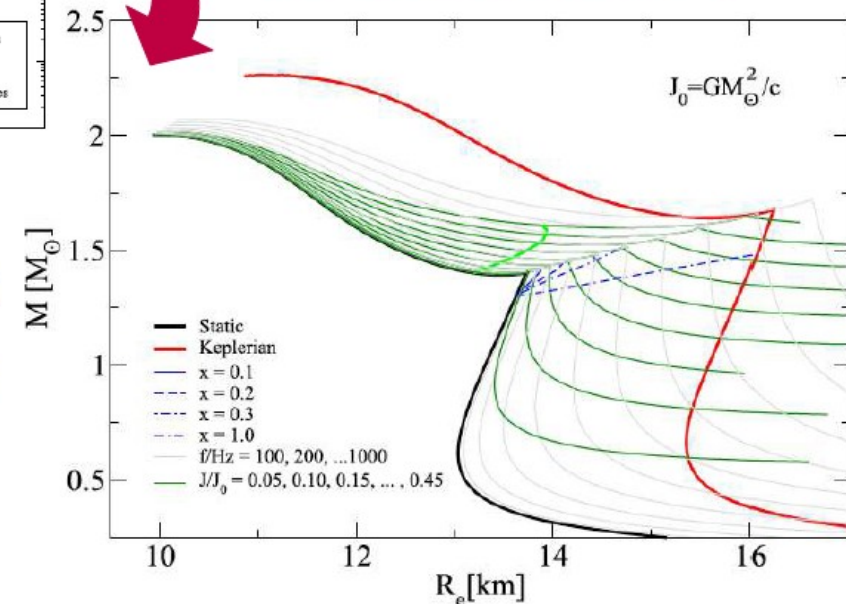
Antoniadis-puzzle



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

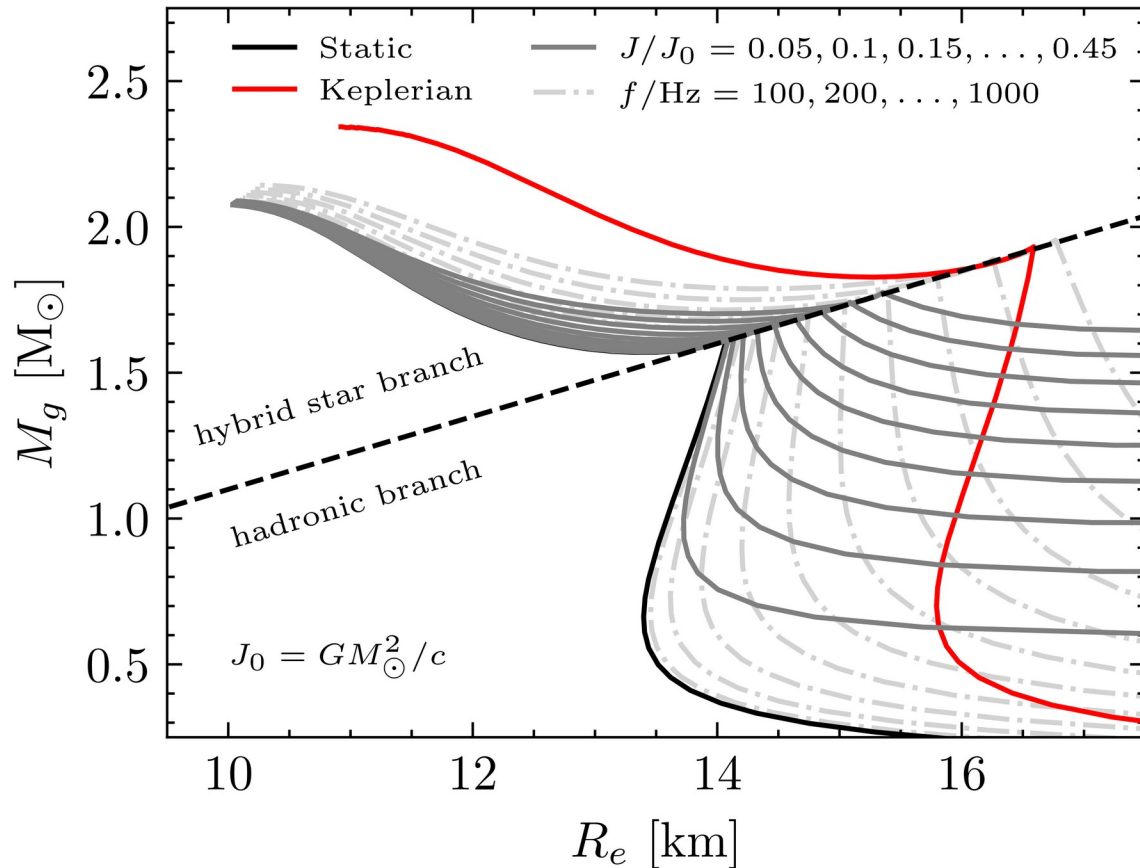
K. Stovall, P.C.C. Freire, J. Antoniadis,
ApJ 870(2), 74 (2019)

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 for instability:

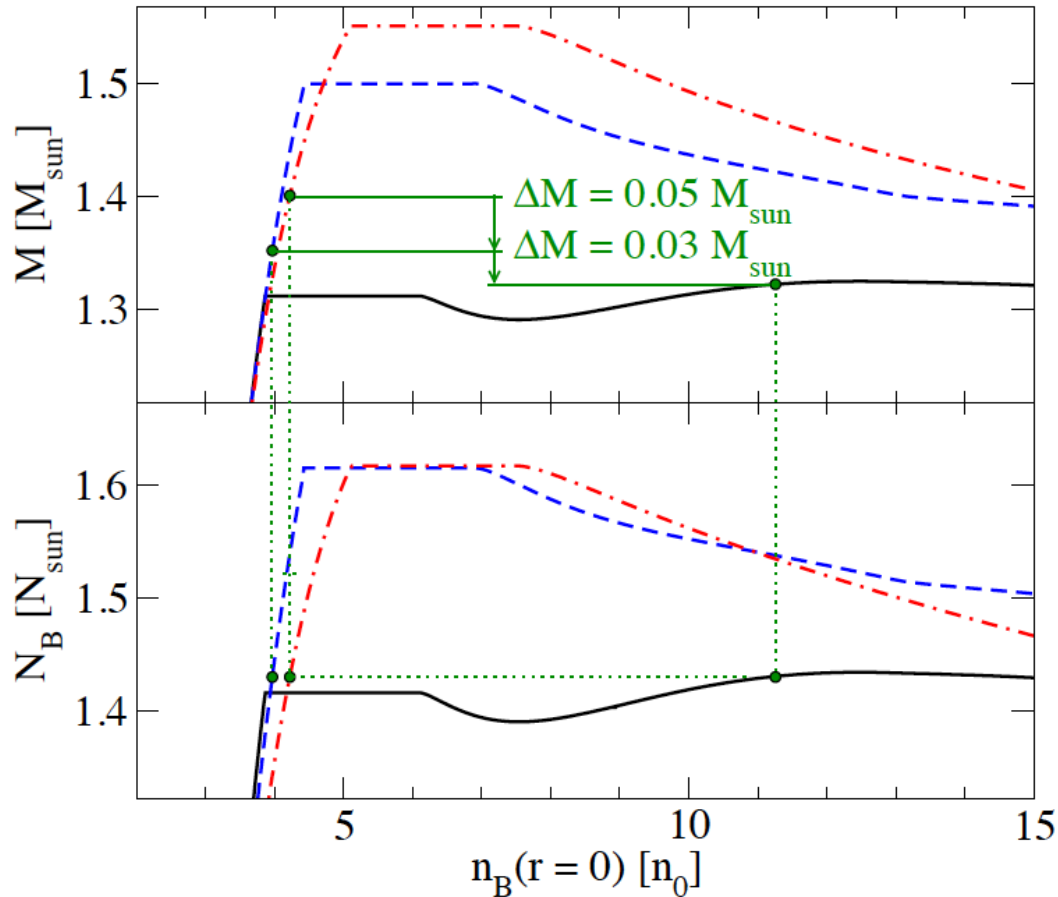
$$\Delta \varepsilon > \frac{\varepsilon_c + 3P_c}{2}$$

- Large jump in energy density (latent heat) \rightarrow instability \rightarrow 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

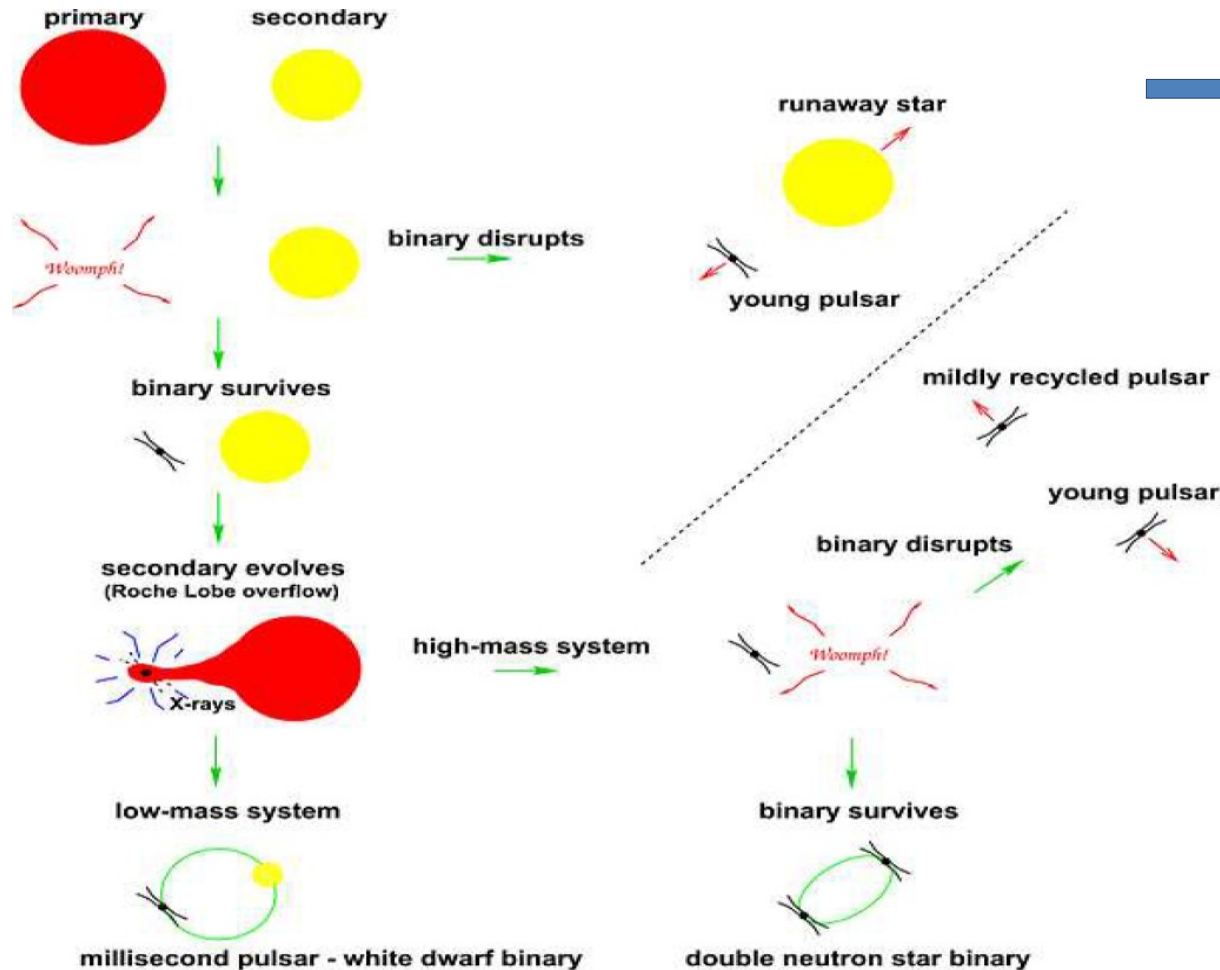


How to calculate the mass defect?

- 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“

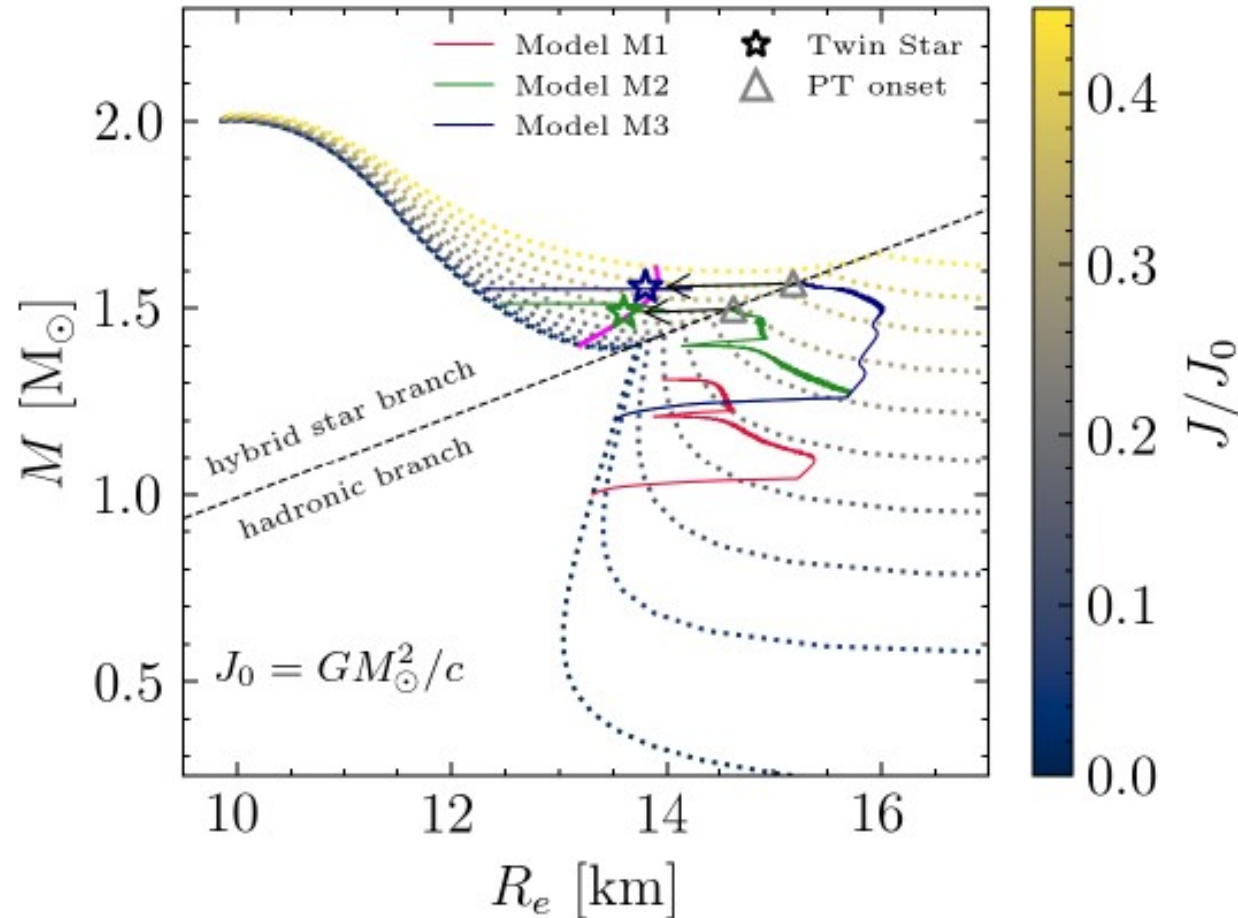
Another kick explanation: Strong QCD phase transition in NS evolution!



Disruption or anomalous eccentricity of a binary system caused by mass defect (grav. binding) in one NS due to a strong phase transition

See also:
 “Catastrophic rearrangement of a compact star ...”
 Mishustin et al.
 hep-ph/0210422 (2002)

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

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

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

w is the magnitude of the kick velocity,
 θ is the kick angle

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

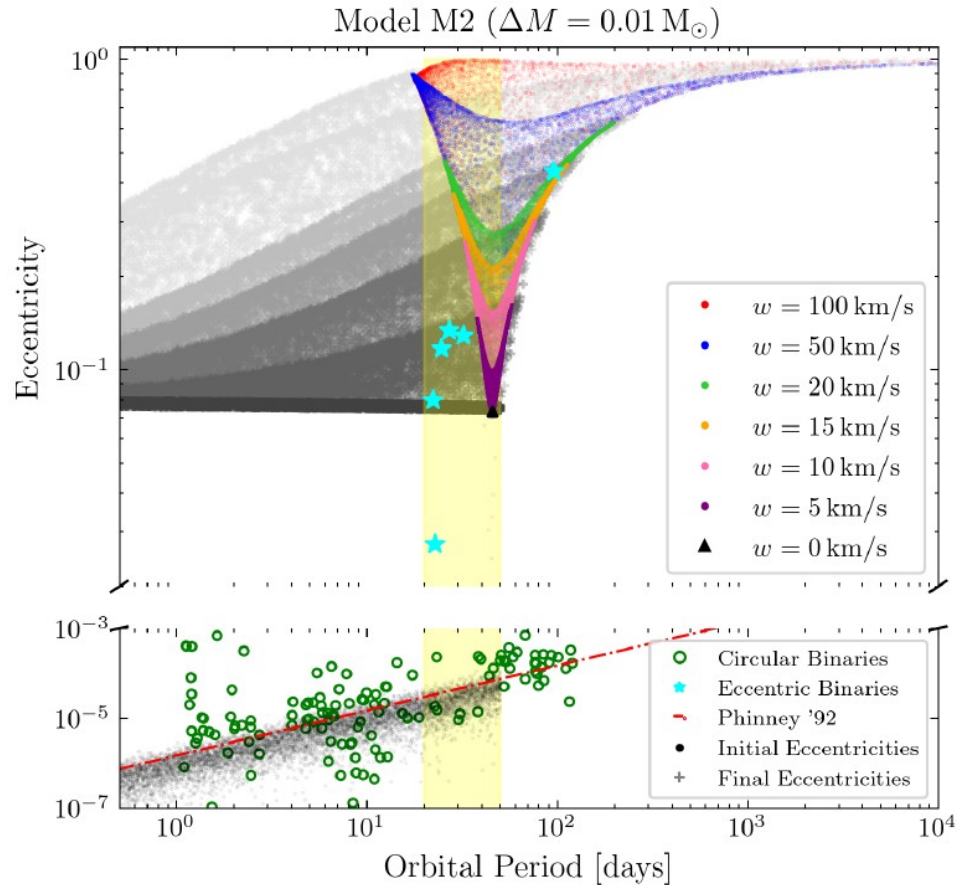
$$e = \sqrt{1 + \frac{2E_{\text{orb},f} L_{\text{orb},f}^2}{\mu_f G^2 M_{f,1}^2 M_{f,2}^2}},$$

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

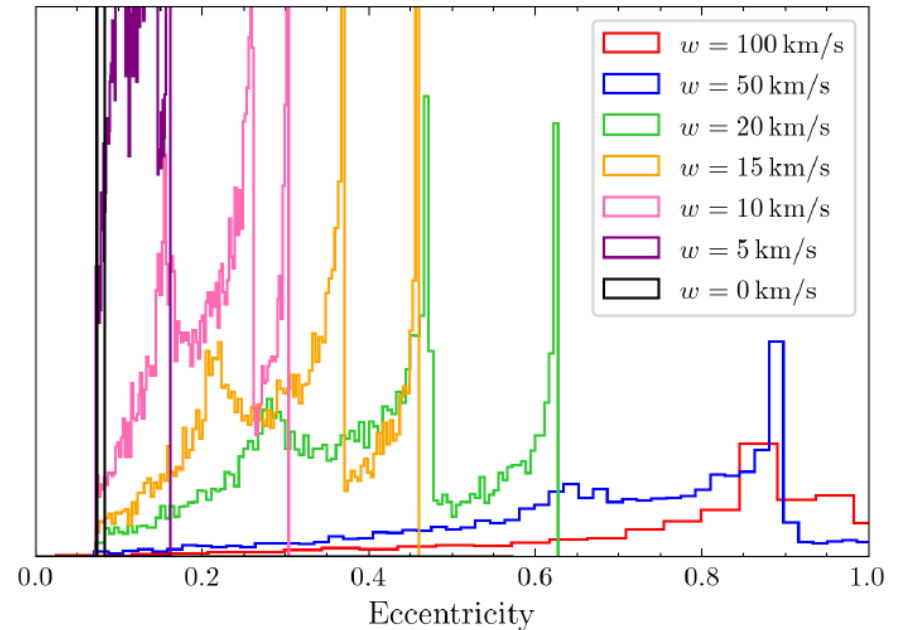
$$E_{\text{orb},f} = -GM_{f,1} M_{f,2} / 2a_f$$

Model	$M_{\text{don}} [M_{\odot}]$	$M_{\text{ns}} [M_{\odot}]$	$P_{\text{orb}} [\text{days}]$
m1	1.0	1.0	8
m2	1.0	1.2	8
m3	1.0	1.2	22.627

Simulation of binary evolution

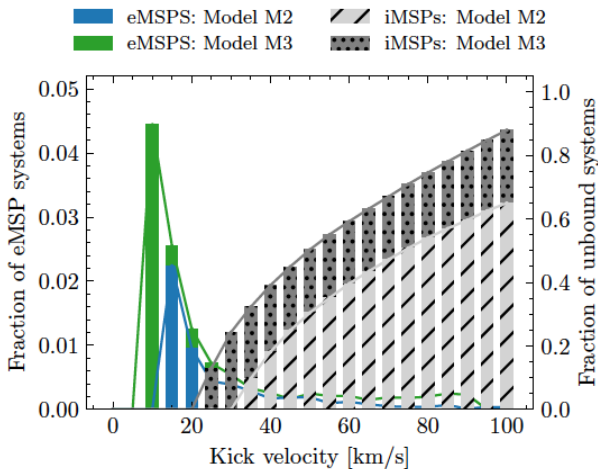
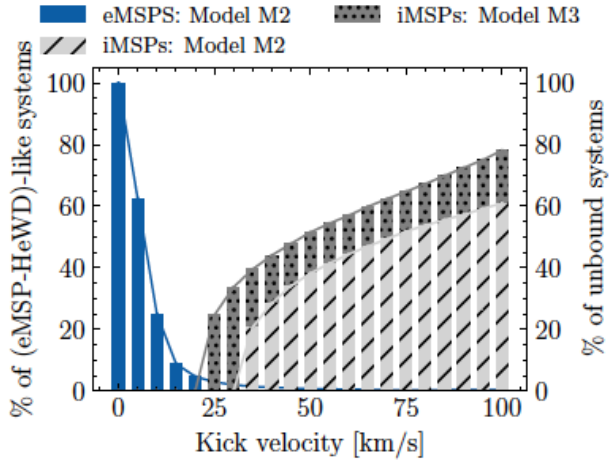


Monte-Carlo simulation of posttransition distribution orbital parameters for a mass defect of 1% solar mass due to the transition.



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



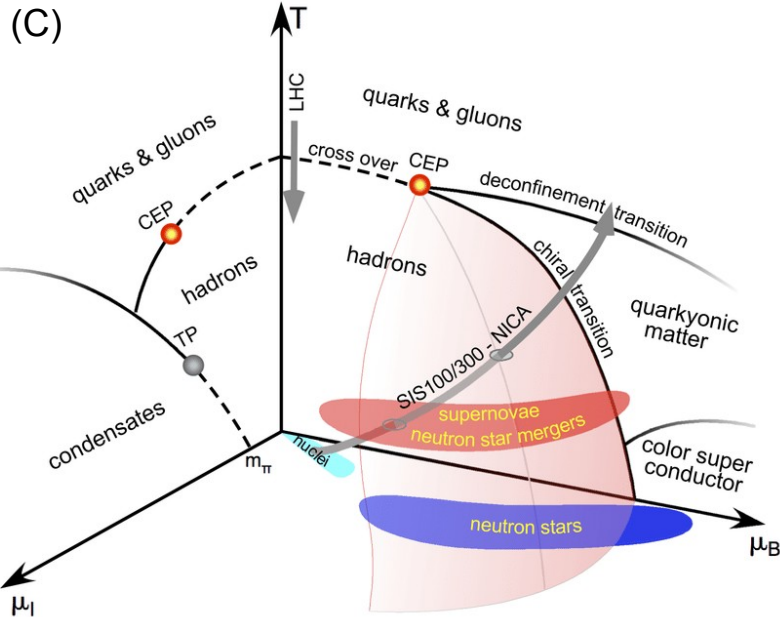
- First results are promising:
- Period gap 20 – 50 d, with $e \sim 10^{-1}$ can be addressed
- One binary with a main sequence star (J1903+0327) with larger period, 100 d, and $e \sim 1$ can also be met
- Appearance of unbound systems → isolated MSPs

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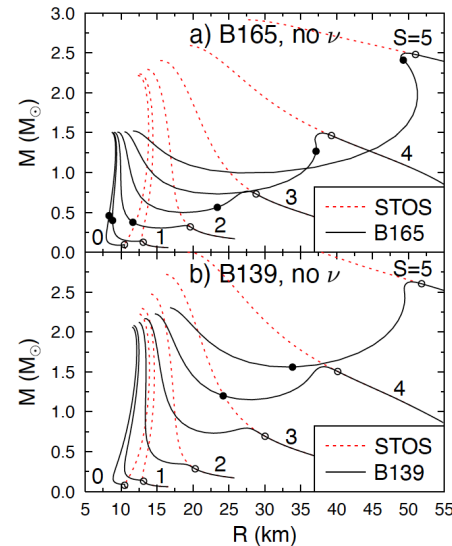
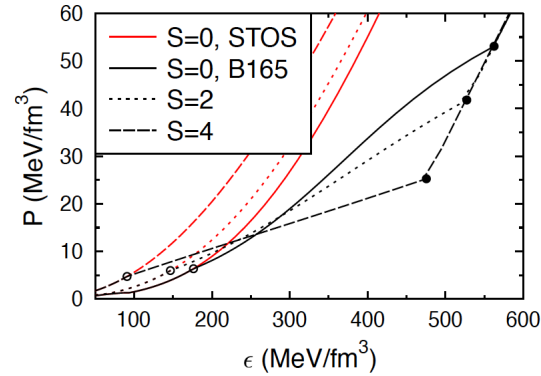
Thermal twin stars

Observation*:

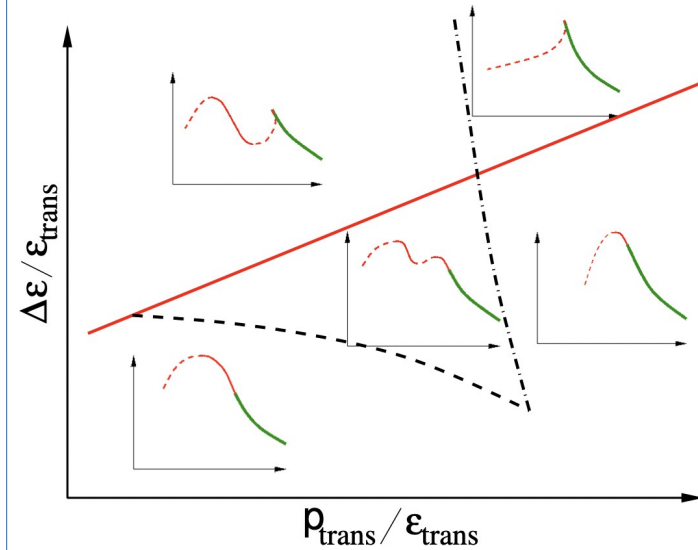
When the transition at $T=0$ is weak, with a connected hybrid star branch, At finite T ($s/n > 0$) a third family (thermal twin stars) can emerge !!



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



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

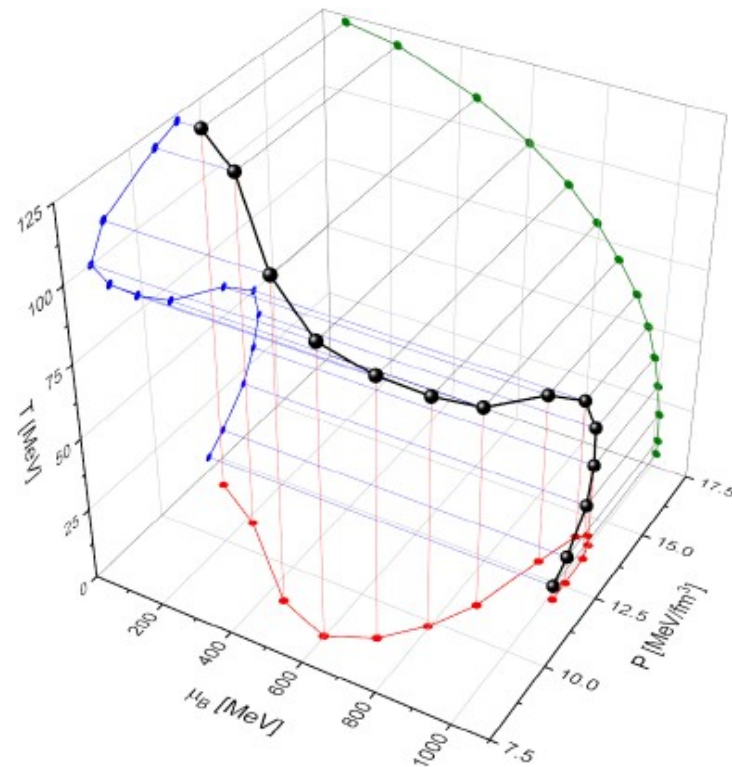
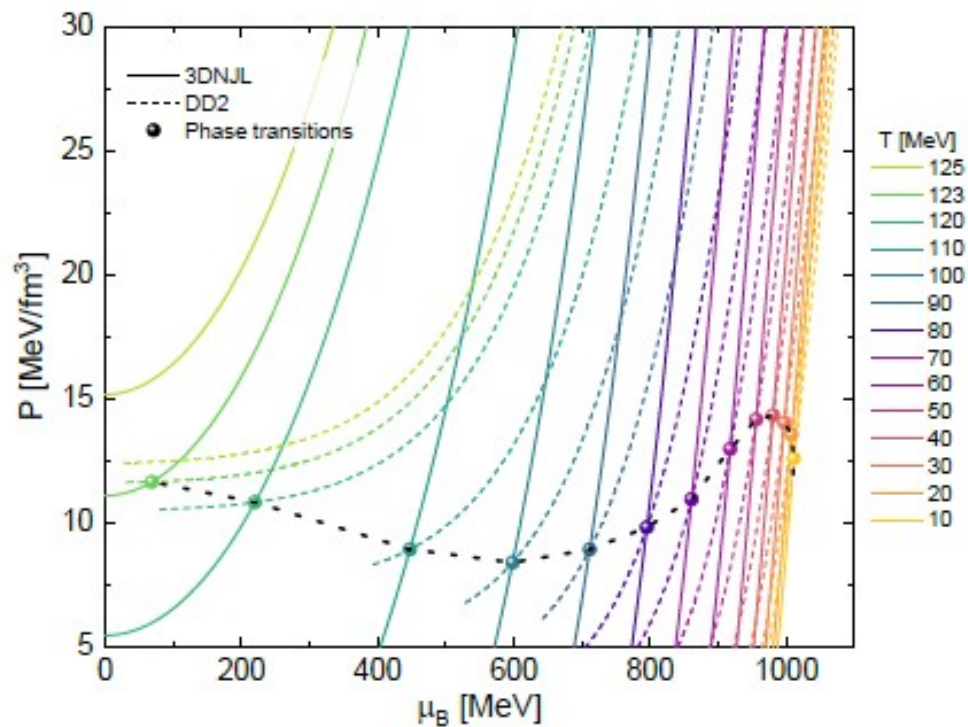


Seidov criterion for gravitational Instability (red line):

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

Thermal twin stars

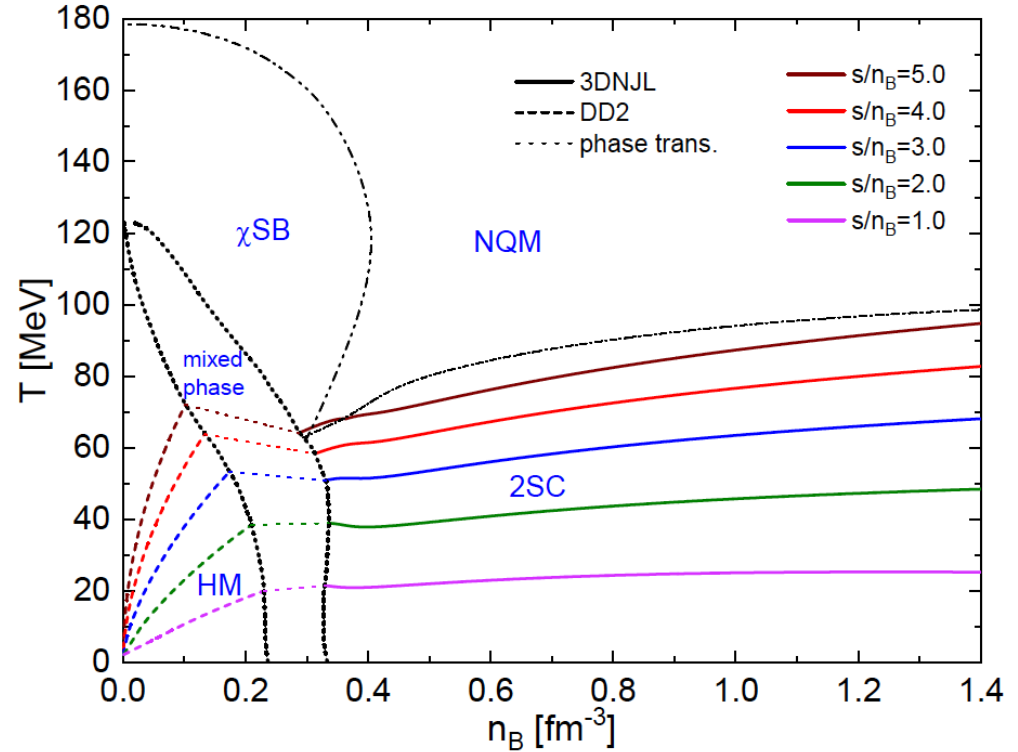
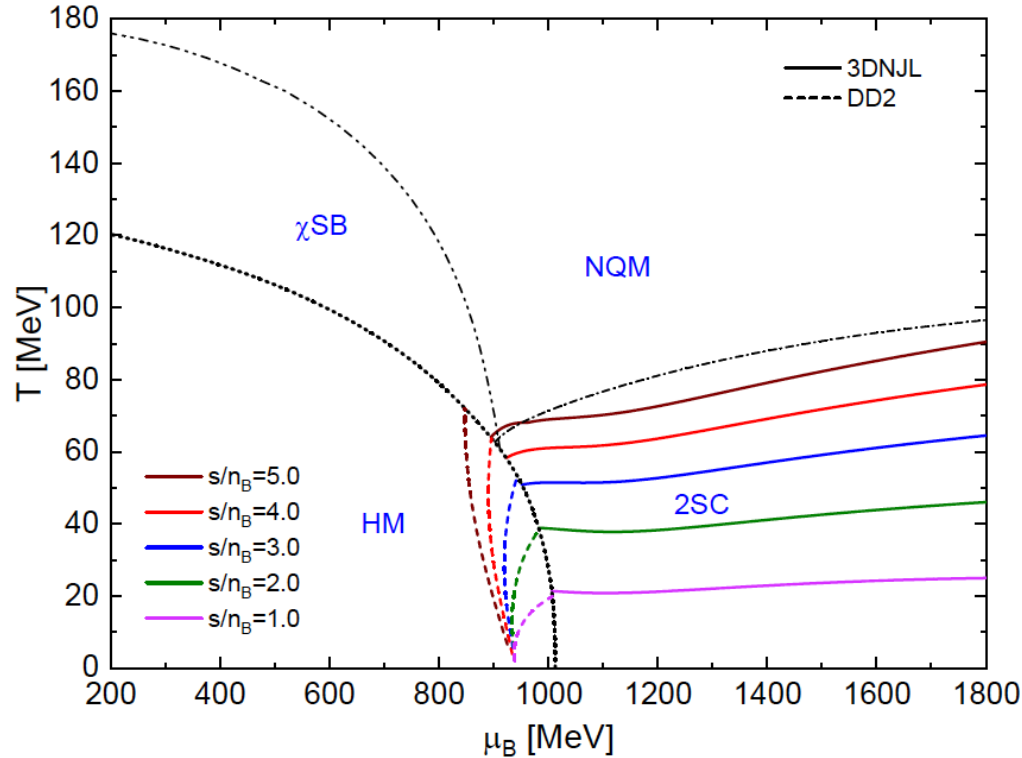
Investigation within a color superconducting, nonlocal chiral quark model*:



*) 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

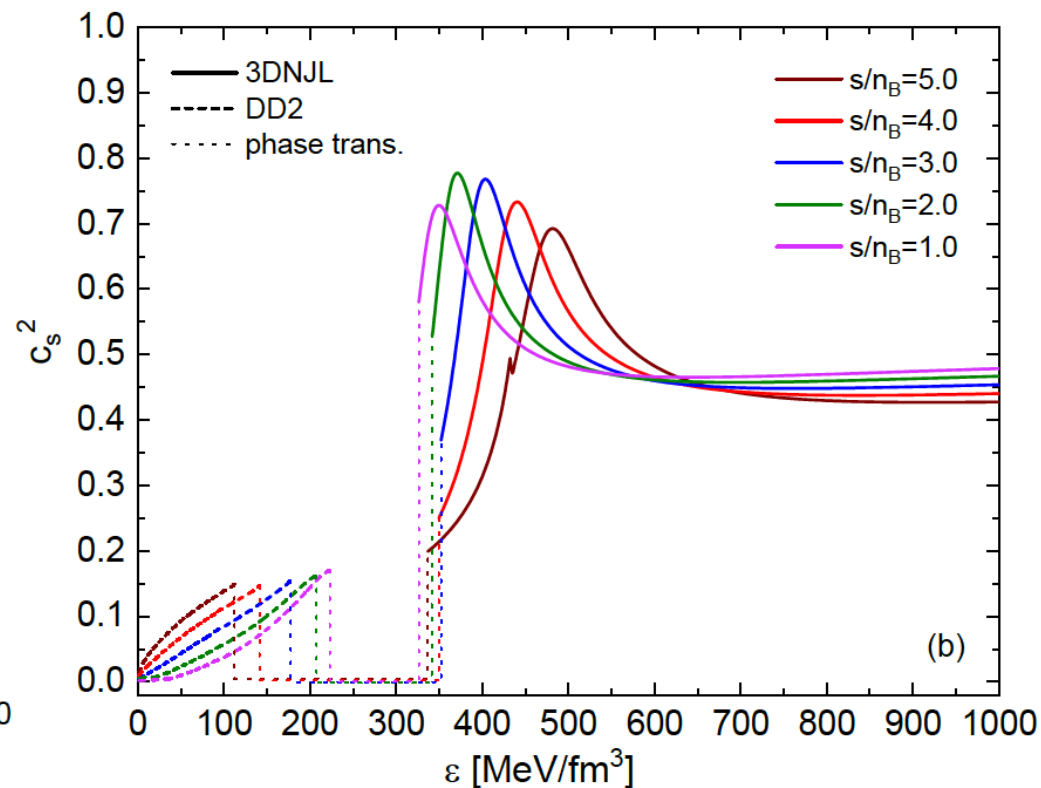
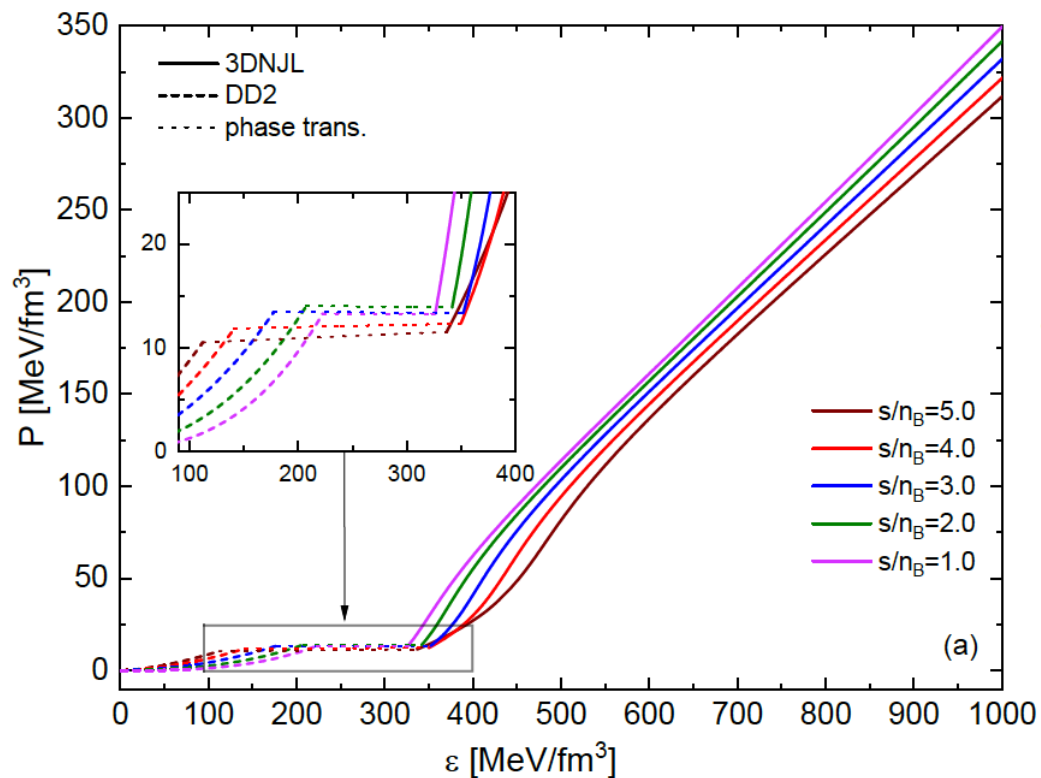
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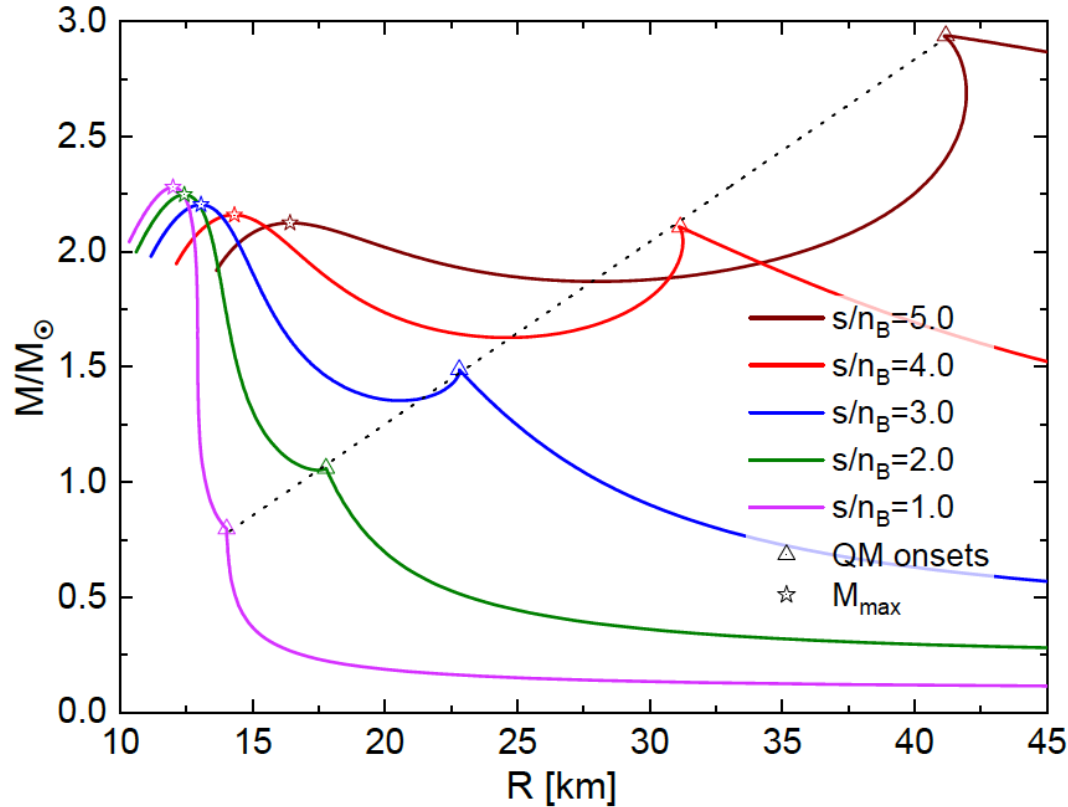
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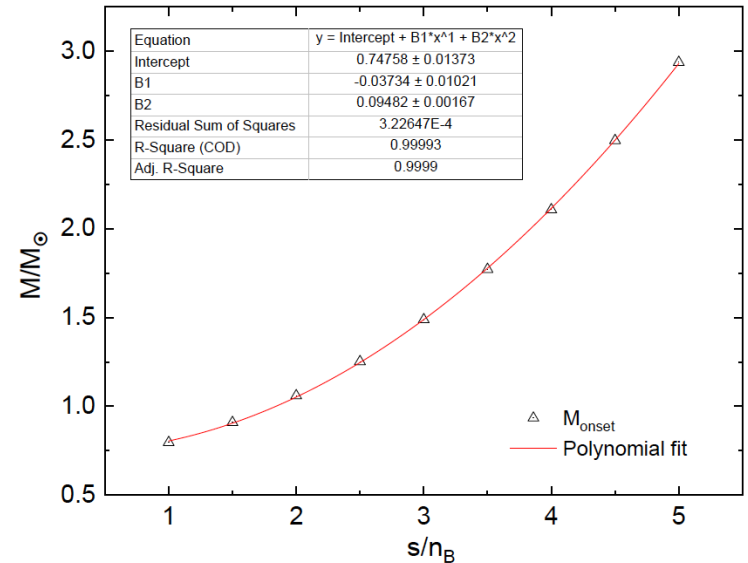
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Thermal twin stars

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



Systematics for the onset: $M = C(R - R_0)$,
 where $R_0 = 4.20 \pm 0.35$ km is the radius offset
 and $C = dM_{\text{onset}}/dR = 0.0792 \pm 0.0009 M_{\odot}/\text{km}$
 is the critical compactness of the star



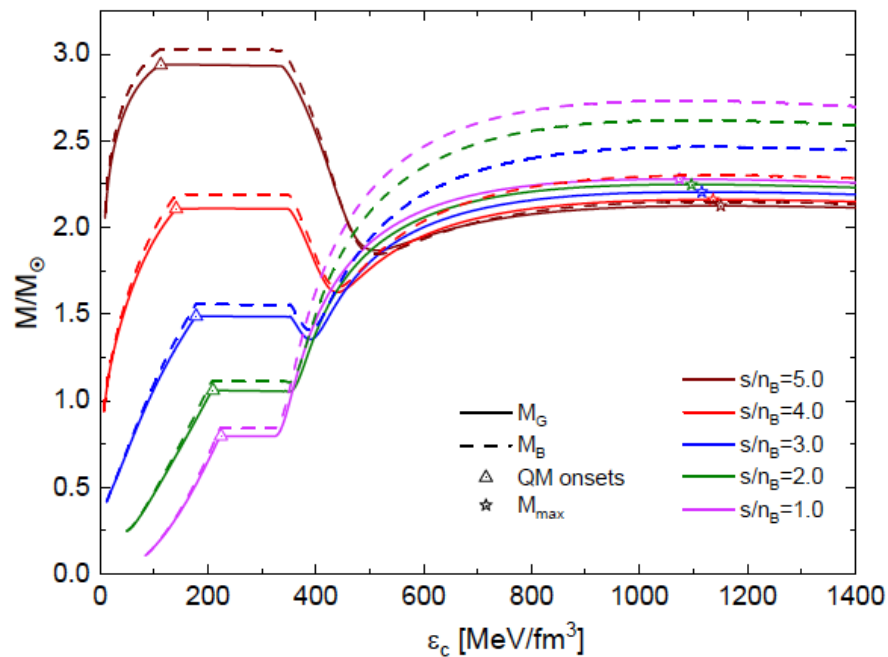
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$$\frac{M_{\text{onset}}}{M_{\odot}} = 0.747 - 0.0373 \frac{s}{n_B} + 0.0948 \left(\frac{s}{n_B} \right)^2$$

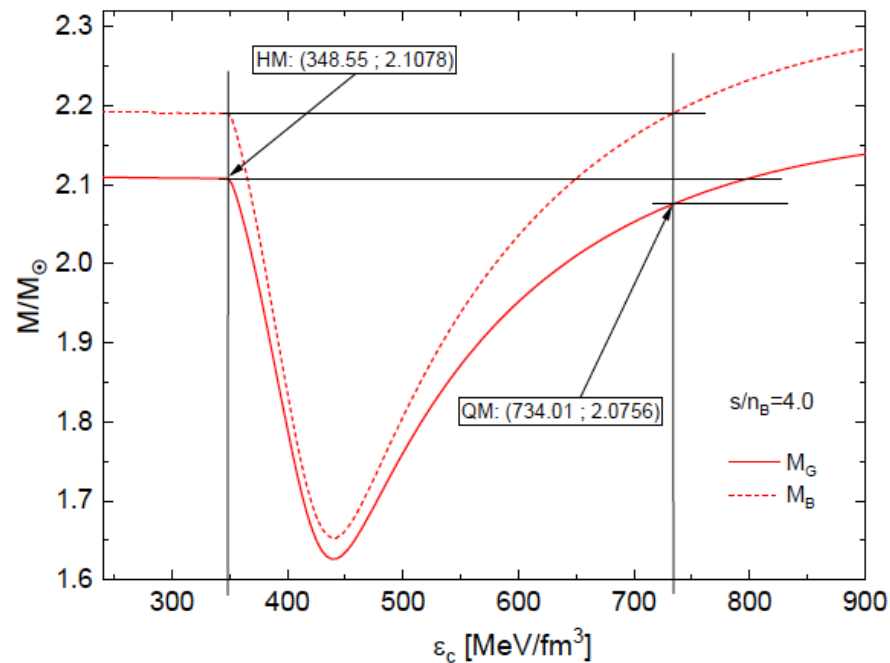
Thermal twin stars

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

Gravitational mass (solid) and baryon mass (dashed)



Extraction of the mass defect (energy release)

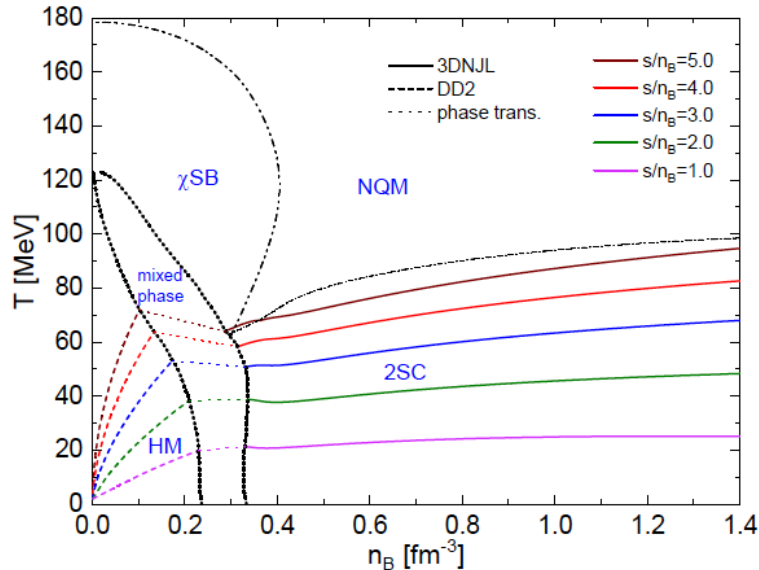


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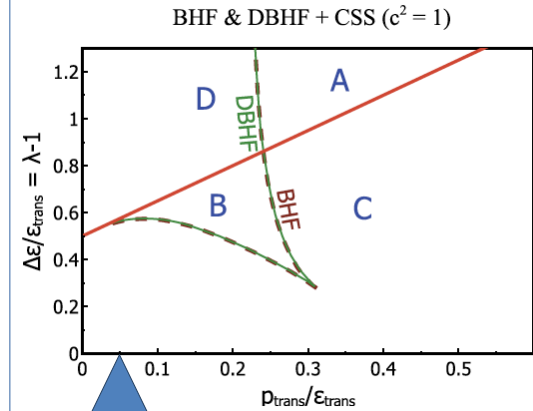
Thermal twin stars

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

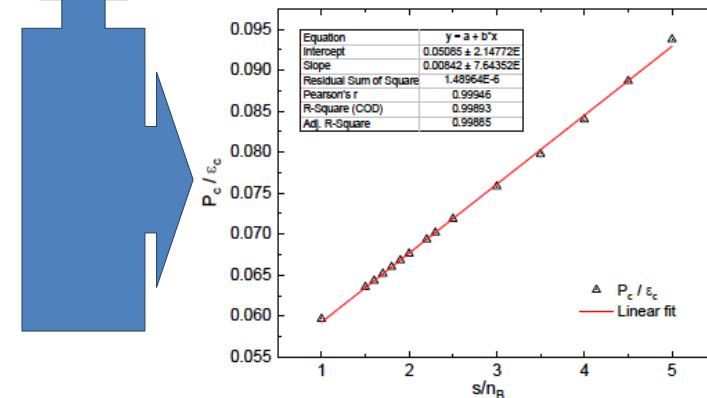
s/n_B	$M_{B,tr}$	$M_{G,HM}$	$M_{G,QM}$	ΔM	$T(0)_{HM}$	$T(0)_{QM}$	$\Delta T(0)$	character
2.0	1.114	1.0582	1.0582	0.0000	38.36	38.87	0.51	enthalpic
2.5	1.311	1.2490	1.2487	0.0003	46.33	45.57	-0.76	entropic
3.0	1.557	1.4878	1.4853	0.0025	53.16	50.84	-2.32	entropic
3.5	1.849	1.7726	1.7621	0.0105	58.89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



Seidov criterion:
$$\frac{\Delta \varepsilon_{\text{crit}}}{\varepsilon_{\text{trans}}} = \frac{1}{2} + \frac{3 p_{\text{trans}}}{2 \varepsilon_{\text{trans}}}$$



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

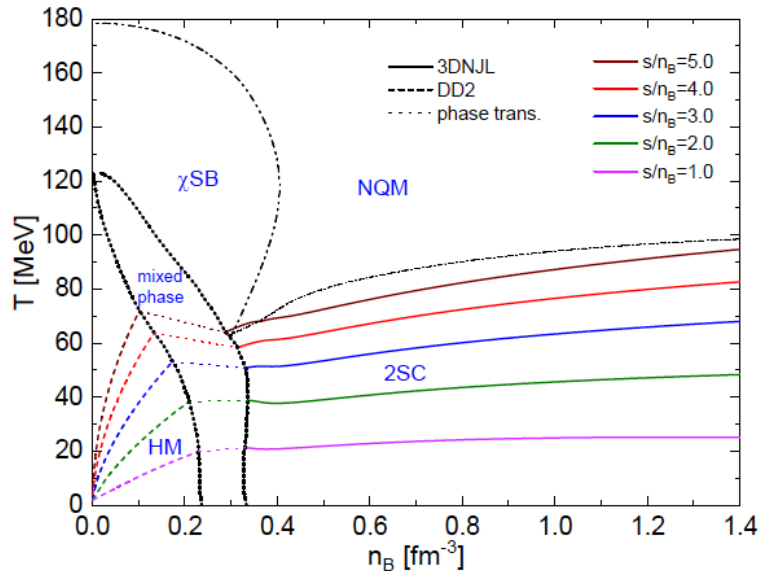


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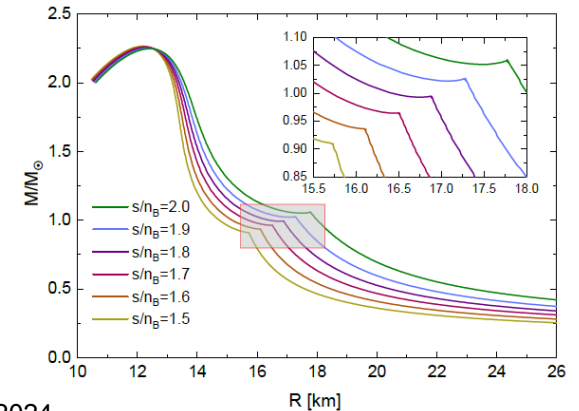
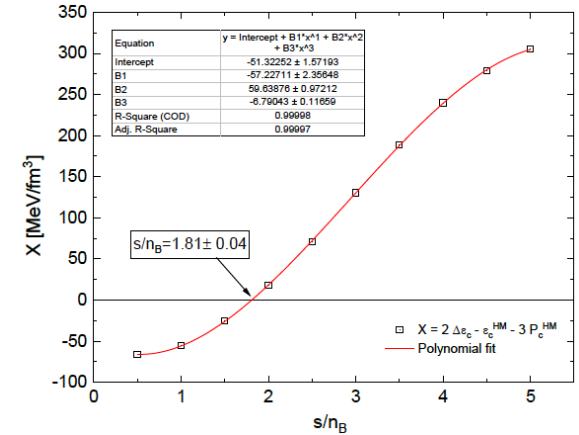
s/n_B	$R(M_{HYB}^{max})$	M_{BJT}	$M_{G,HM}$	$M_{G,QM}$	ΔM	$T(0)_{HM}$	$T(0)_{QM}$	$\Delta T(0)$	character
2.0	12.41	1.114	1.0582	1.0582	0.0000	38.36	38.87	0.51	enthalpic
2.5	12.61	1.311	1.2490	1.2487	0.0003	46.33	45.57	-0.76	entropic
3.0	13.06	1.557	1.4878	1.4853	0.0025	53.16	50.84	-2.32	entropic
3.5	13.58	1.849	1.7726	1.7621	0.0105	58.89	55.01	-3.88	entropic
4.0	14.29	2.190	2.1078	2.0756	0.0322	63.74	58.28	-5.46	entropic



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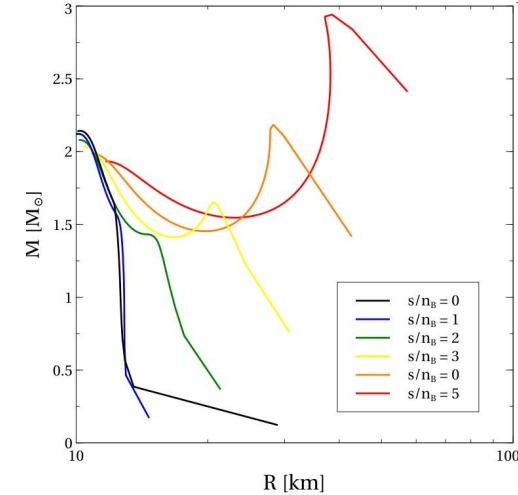
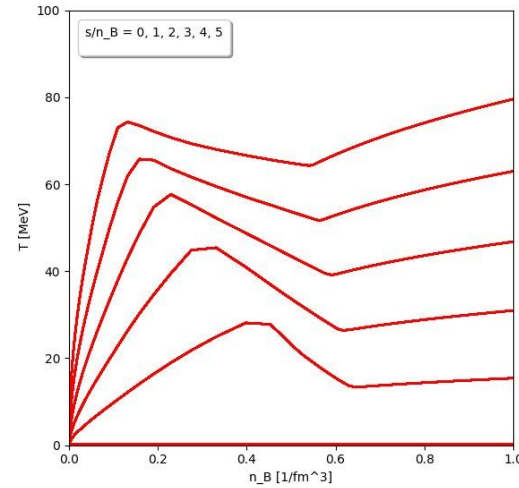
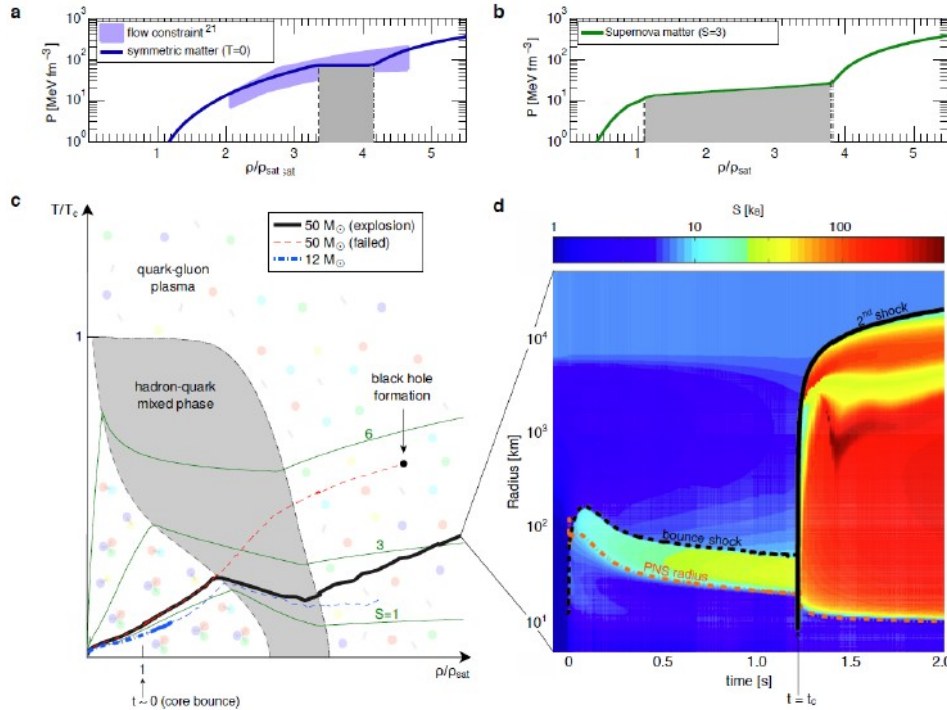
Seidov criterion for instability:

$$X = 2\Delta\epsilon - \epsilon_c^{HM} - 3P_c^{HM} > 0$$



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*:



Courtesy: Oleksii Ivanytskyi

Progenitor:
 $M = 50 M_{\odot}$

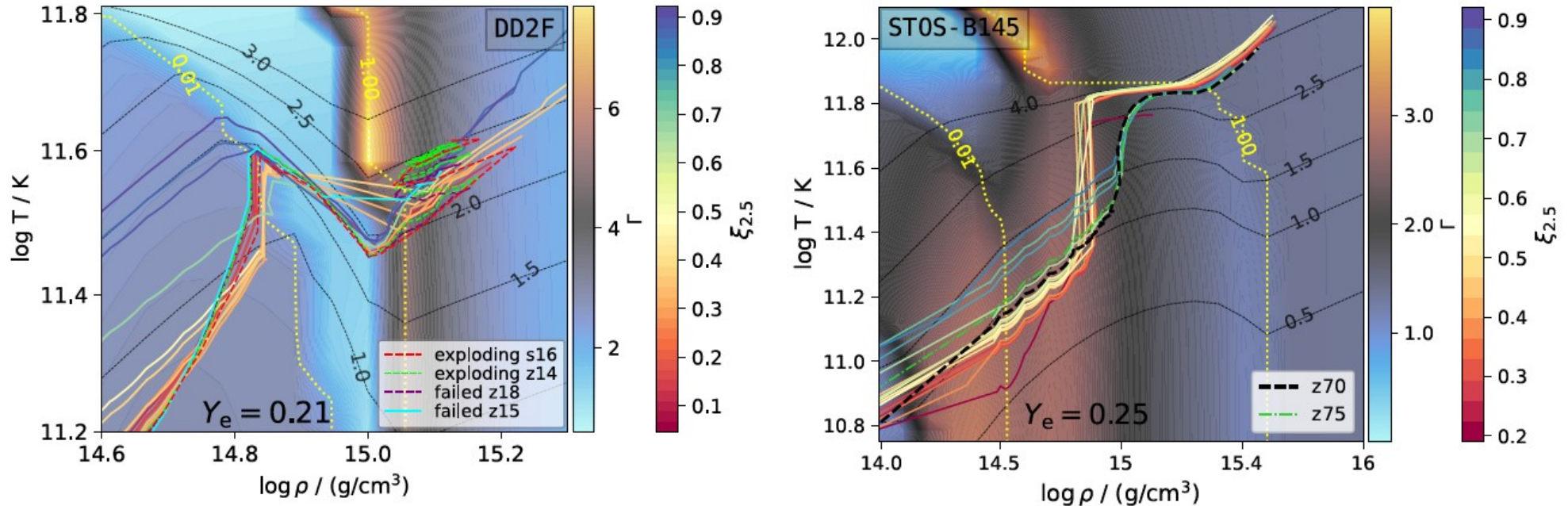
Increase of s/n_B lowers the onset density for deconfinement:

- supports the fulfillment of the Seidov criterion (mass twins)
- deconfinement is reached faster (explodability)

*) T. Fischer et al., Nature Astron. 2, 980 (2018)

Thermal twin stars – Indicators of CCSN explodability ?

Successful explosion of massive progenitor stars* for hybrid EoS with entropic first-order transition (thermal twin stars)



Important for explodability: Postbounce mass accretion rate (metallicity) vs. Time to reach the onset of deconfinement**)

*) Pia Jakobus et al., MNRAS 516, 2554 (2022); arxiv:2204.10397 [astro-ph.HE]

***) Noshad Khosravi Largani et al., Astrophys. J. 964, 143 (2024); arxiv:2304.12316 [astro-ph.HE]

Thanks to collaborators

On non-thermal twin stars:

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On eccentric MSPs in low-mass X-ray binaries:

Savvas Chanlaridis, John Antoniadis (FORTH Heraklion, Greece), David Ohse (MPIfR Bonn, Germany)

On the color-superconducting quark matter EOS, QCD phase diagram and thermal twin stars:

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Oleksii Ivanytskyi (University of Wroclaw, Poland & Incubator CSSF Wroclaw, Poland)

Acknowledgement of funding



NATIONAL SCIENCE CENTRE
POLAND

2019/33/B/ST9/03059: Neutron stars: birth, structure and mergers

2021/43/P/ST2/03319: Bayesian analysis of the dense matter equation of state



Critical Point & Onset of
Deconfinement (CPOD)

„Oratorium Marianum“
University of Wrocław

May-June 2016