Twin stars and the QCD phase diagram

David Blaschke
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Narodowe Centrum Nauki
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Intertwined with Akira Ohnishi

Sunset @ Volga beach in Dubna
Akira Ohnishi and E.M. Ilgenfritz
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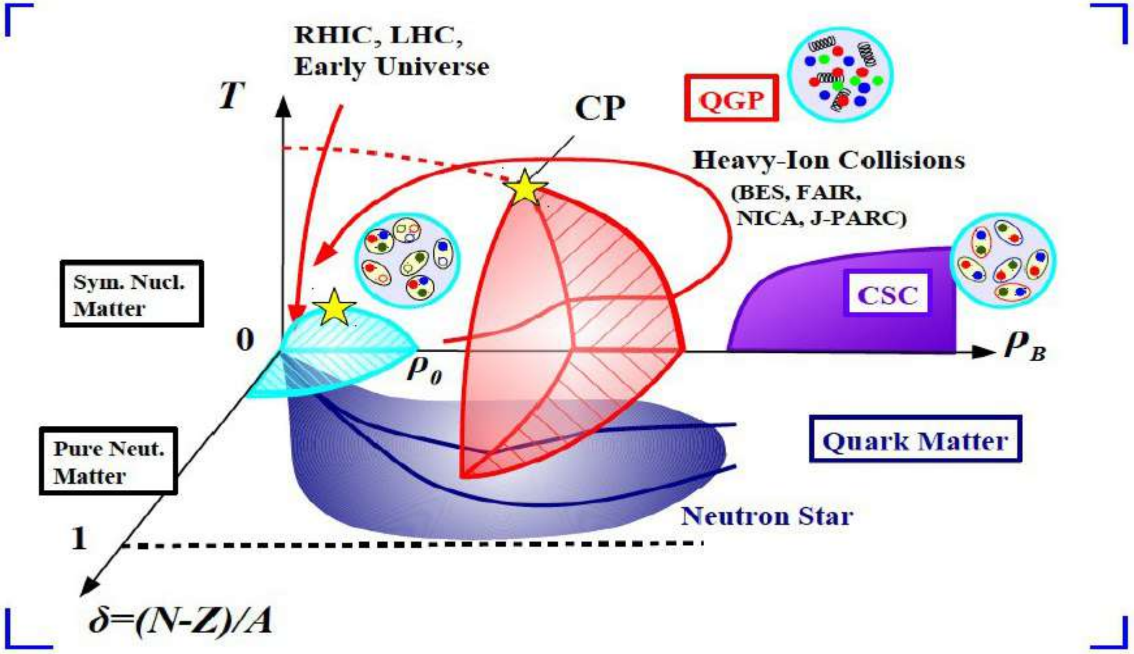
A. Ohnishi @ SQM-2015 in Dubna



Twin stars and the QCD phase diagram

Intertwined with Akira Ohnishi & Critical Point and Onset of Deconfinement

CPOD 2009 @ Brookhaven with Akira Ohnishi & Jorgen Randrup, plays important role for revival of twins @ CPOD 2013 Napa Valley

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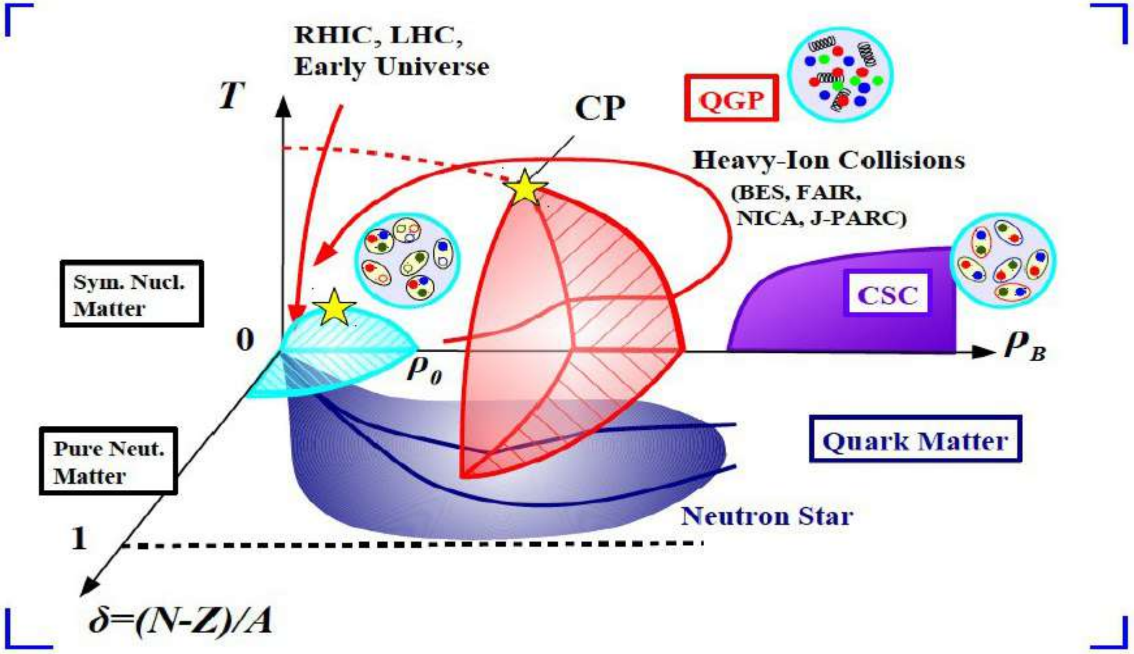

Larry introduces the quarkyonic corner of the QCD phase diagram. Brookhaven (2009)

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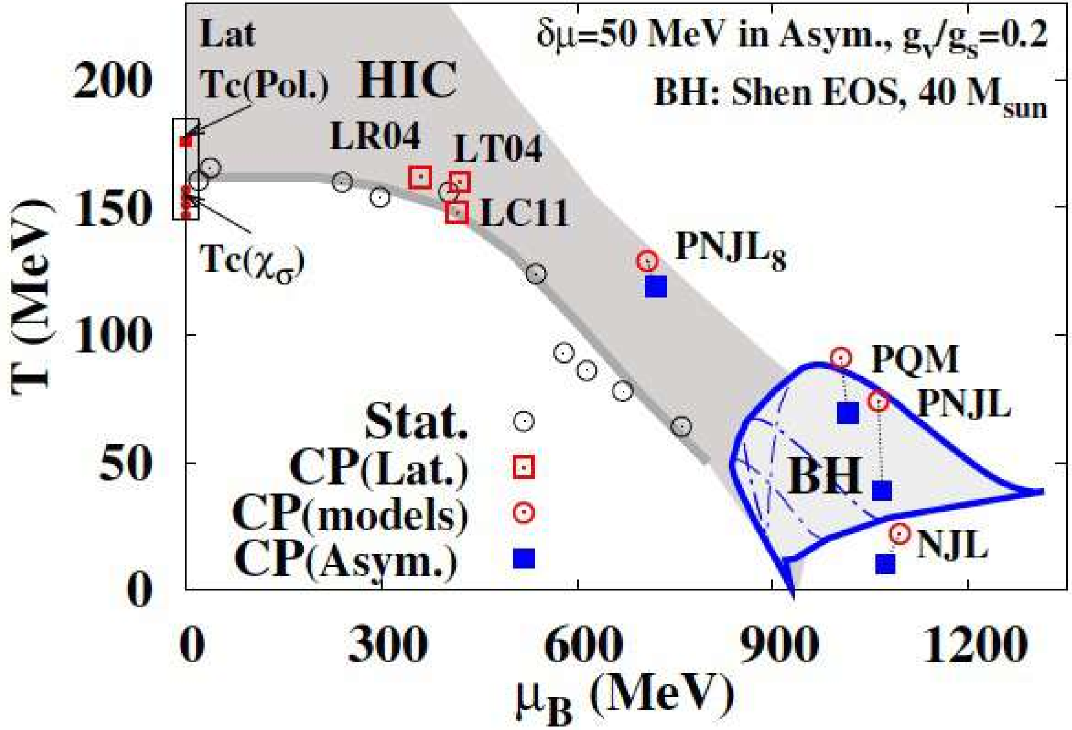
Many predictions for a critical endpoint in the QCD phase diagram: Lattice QCD, NJL models

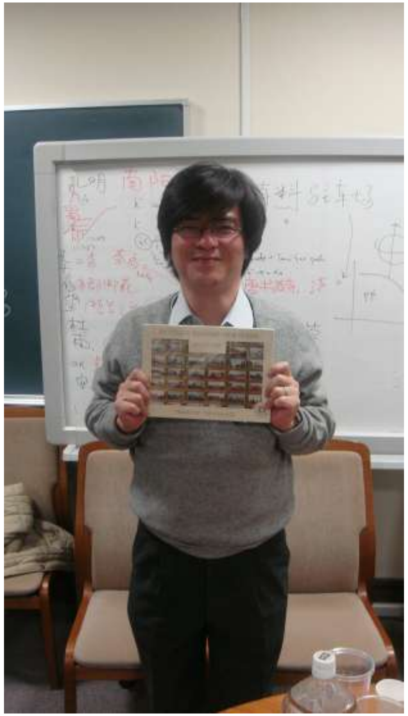
Q: Can astrophysical observations help ?



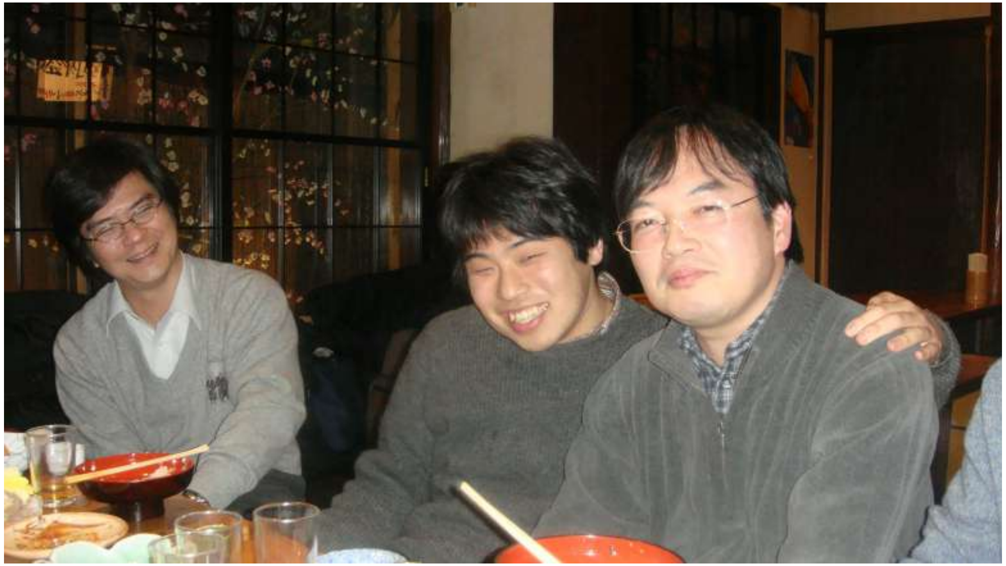
A. Ohnishi et al., APPB PS 5 (2011) 815

Akira Ohnishi opens the neutron star workshop at YITP in January 2010

Akira Ohnishi @ YITP workshop on Neutron Stars, January 2010





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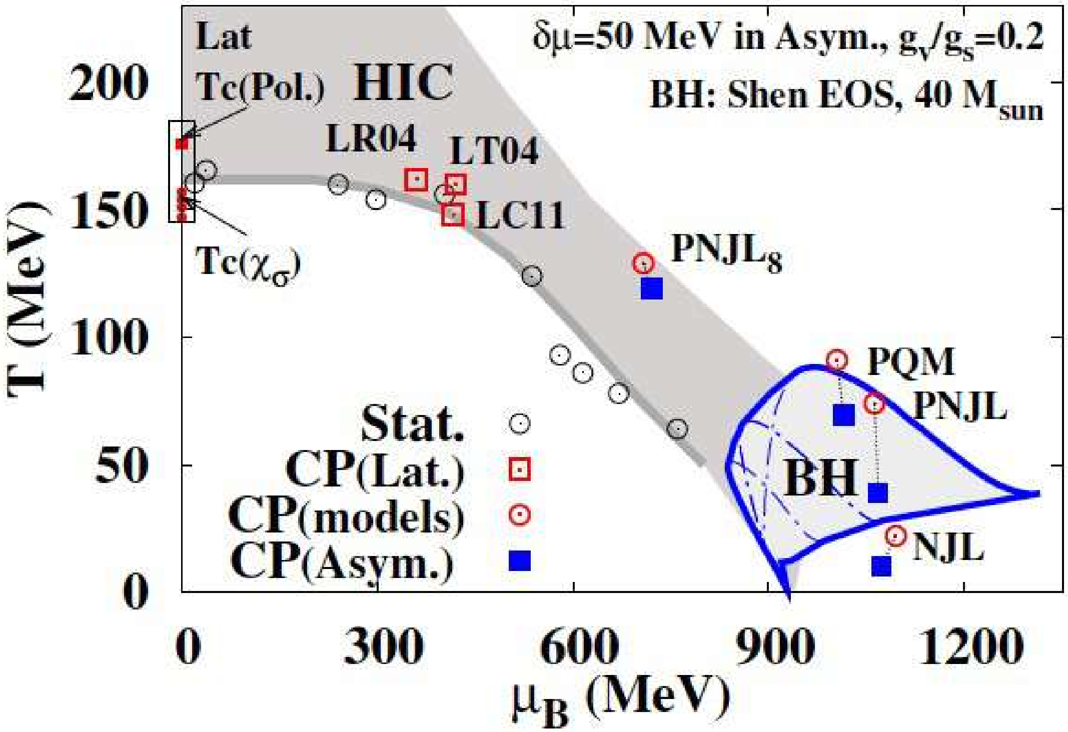
Max Born Symposium, Wroclaw (2011)
„Three Days on Quarkyonic Island“



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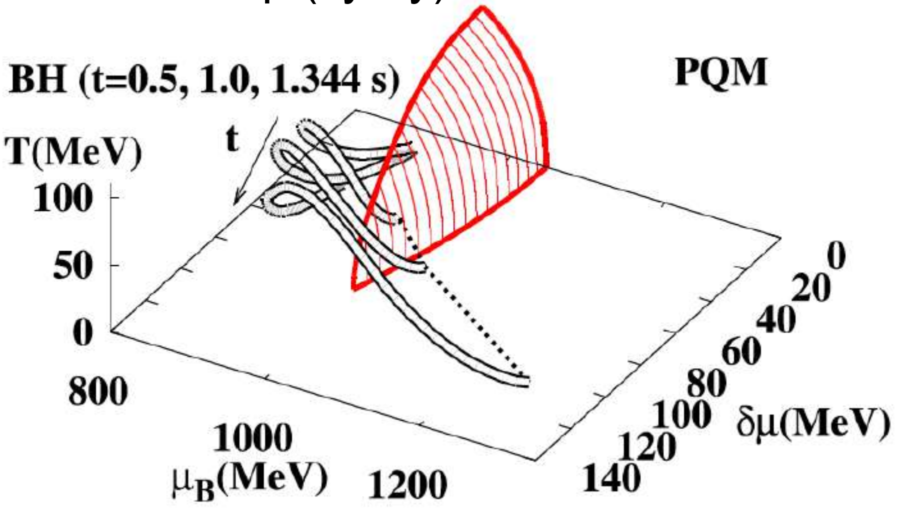
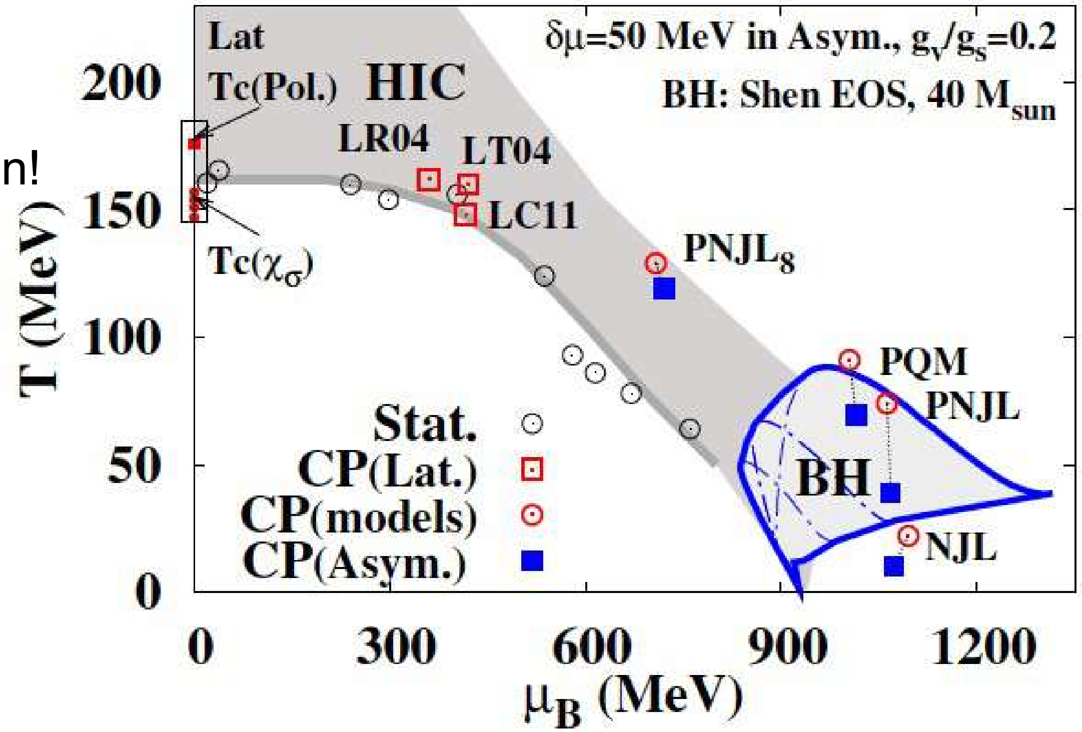
Akira: Sweep (fly-by) in Black Hole formation!



A. Ohnishi et al., Phys. Lett. B 704 (2011) 284



A. Ohnishi et al., APPB PS 5 (2011) 815

Another question:

At CPOD 2013, Jorgen Randrup asks:

„Can astrophysics colleagues find out whether in neutron stars the quark deconfinement transition is first order?“

The idea

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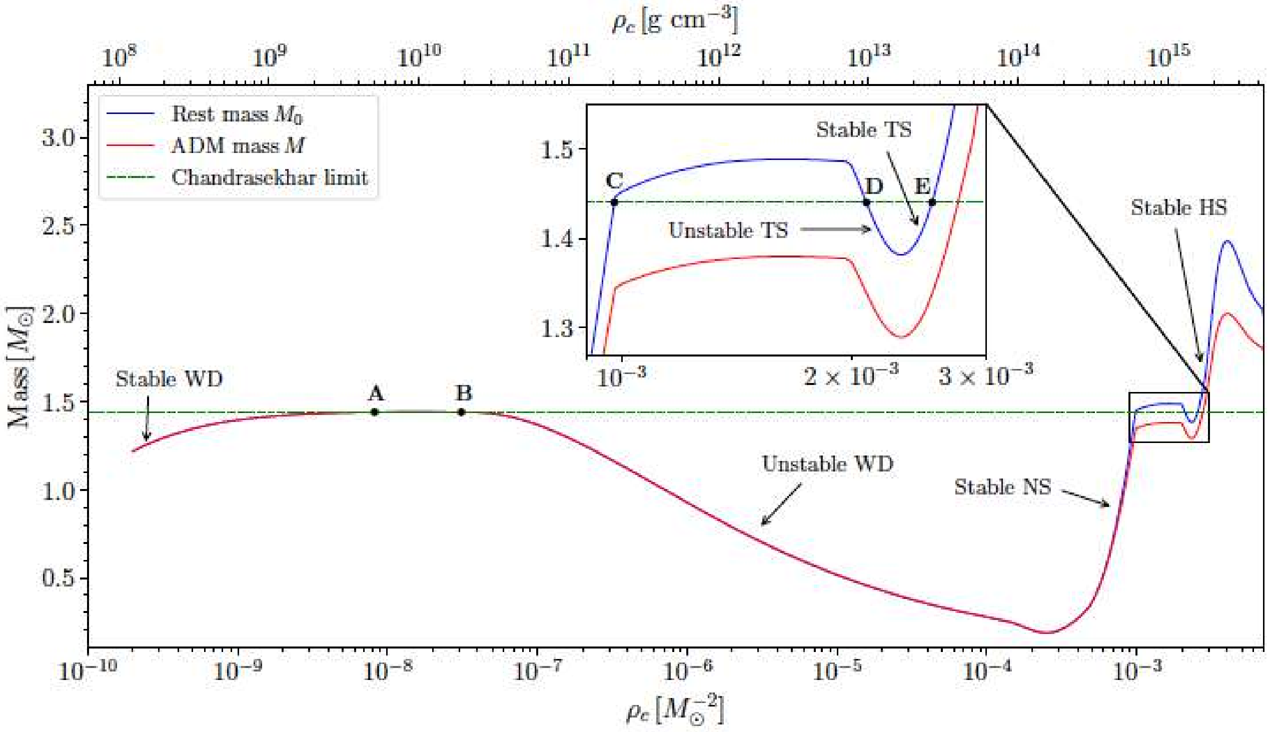
„Can astrophysics colleagues find out whether in neutron stars the quark deconfinement transition is first order?“

David Blaschke answers:
In principle – yes !
If they can find twin compact stars !
PoS CPOD2013 (2013)

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

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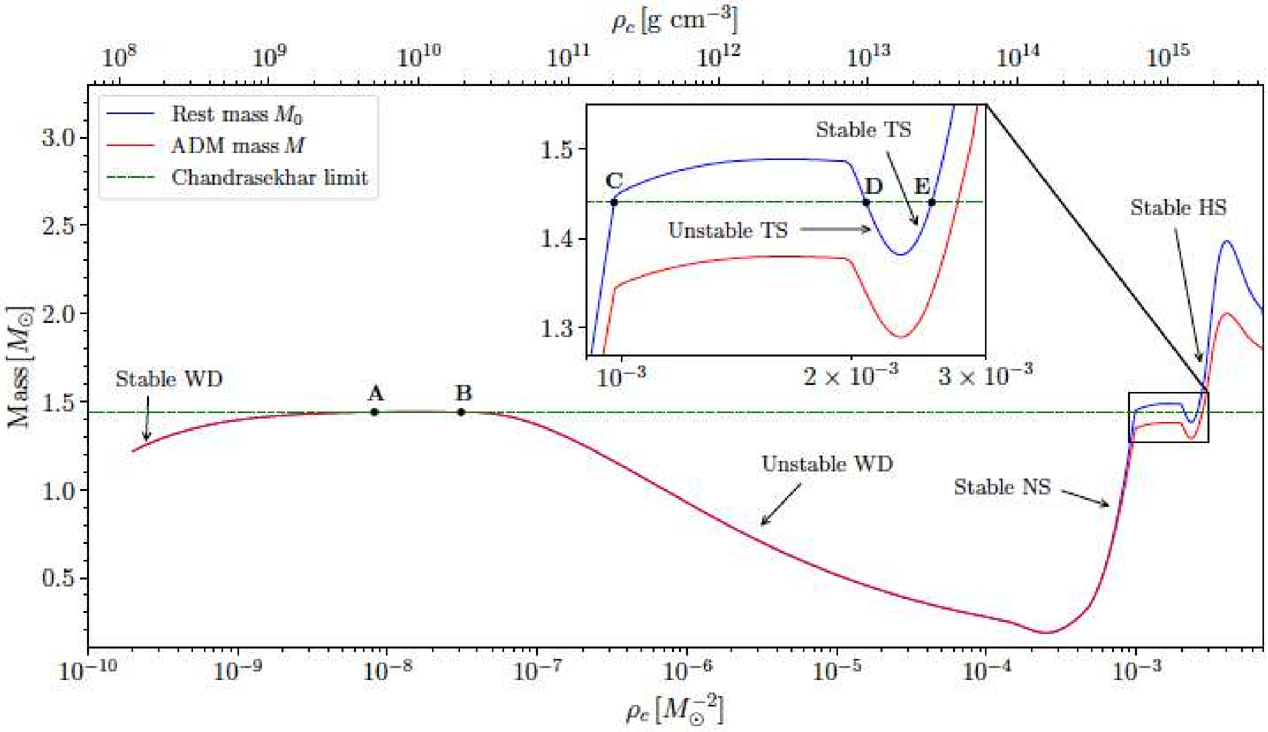

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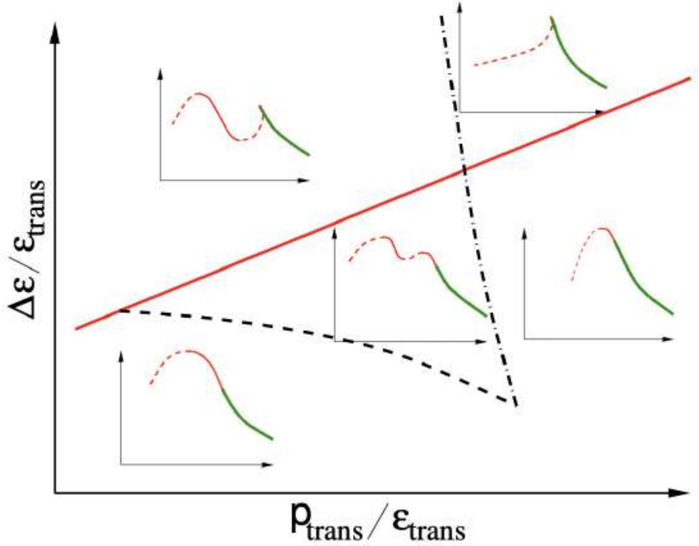
Disconnected HS branch indicates a Strong (1st-order) phase transition



Seidov criterion for gravitational Instability (red line):

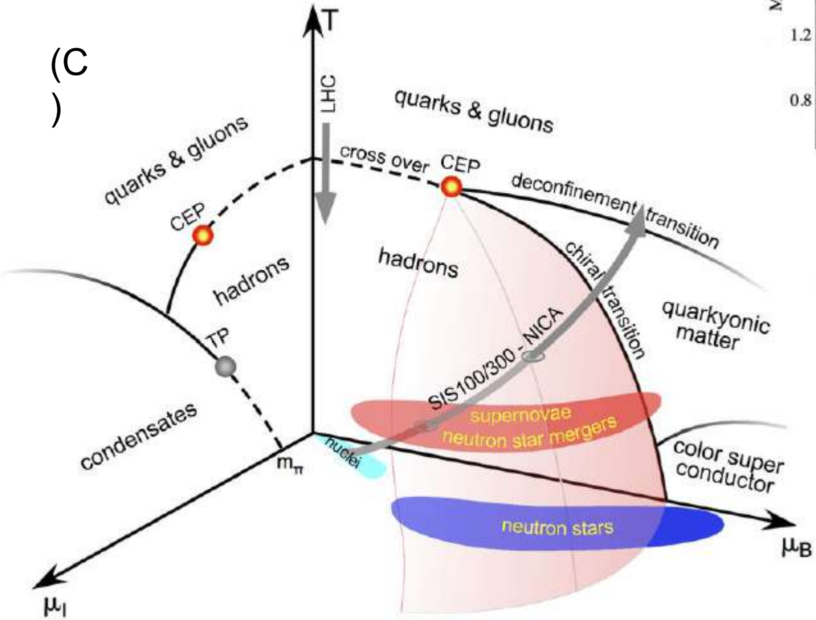
$$\frac{\Delta\varepsilon_{\rm crit}}{\varepsilon_{\rm trans}} = \frac{1}{2} + \frac{3}{2}\frac{p_{\rm trans}}{\varepsilon_{\rm trans}}$$

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

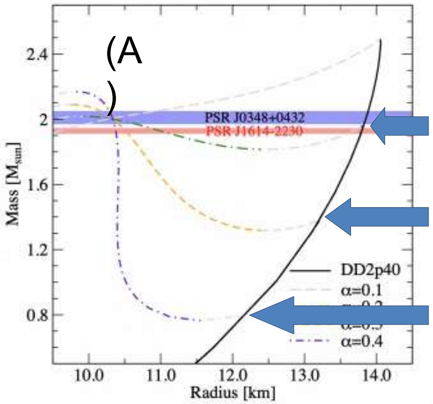
The idea

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

(C
)



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

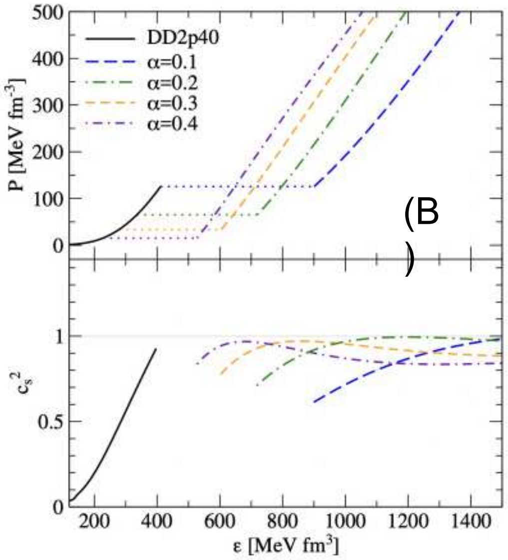


Which Mass?

High?

Typical?

Low?



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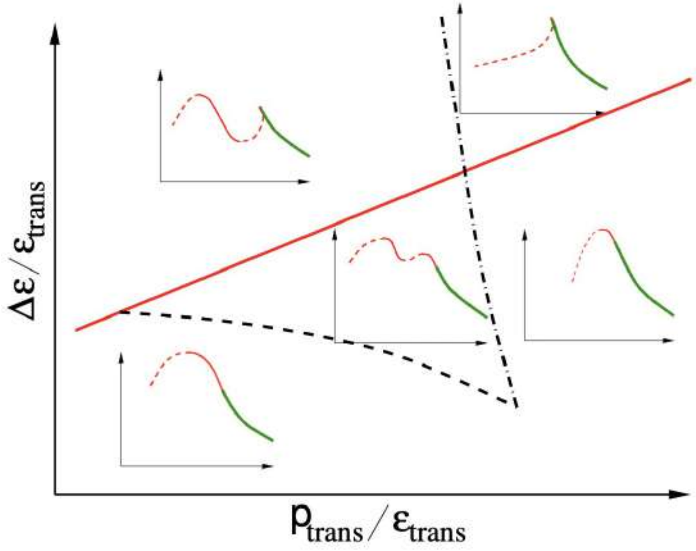

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Thermal and non-thermal twin stars

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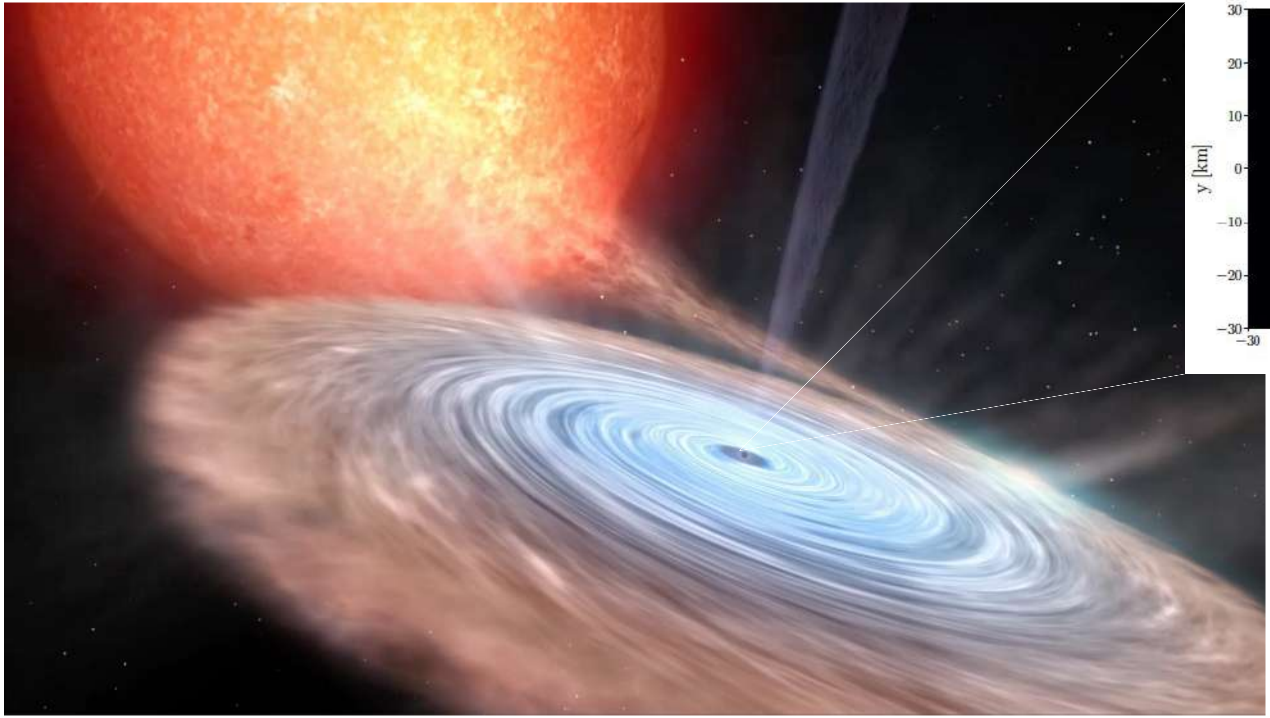

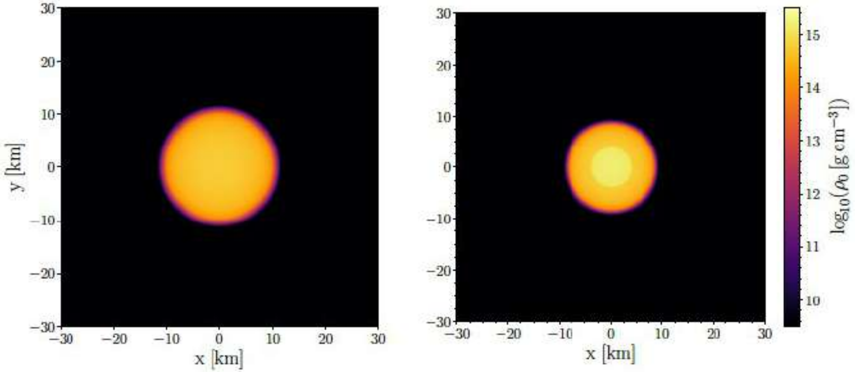

Neutron star (NS) ↔ Hybrid star (HS)

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

Thermal and non-thermal twin stars

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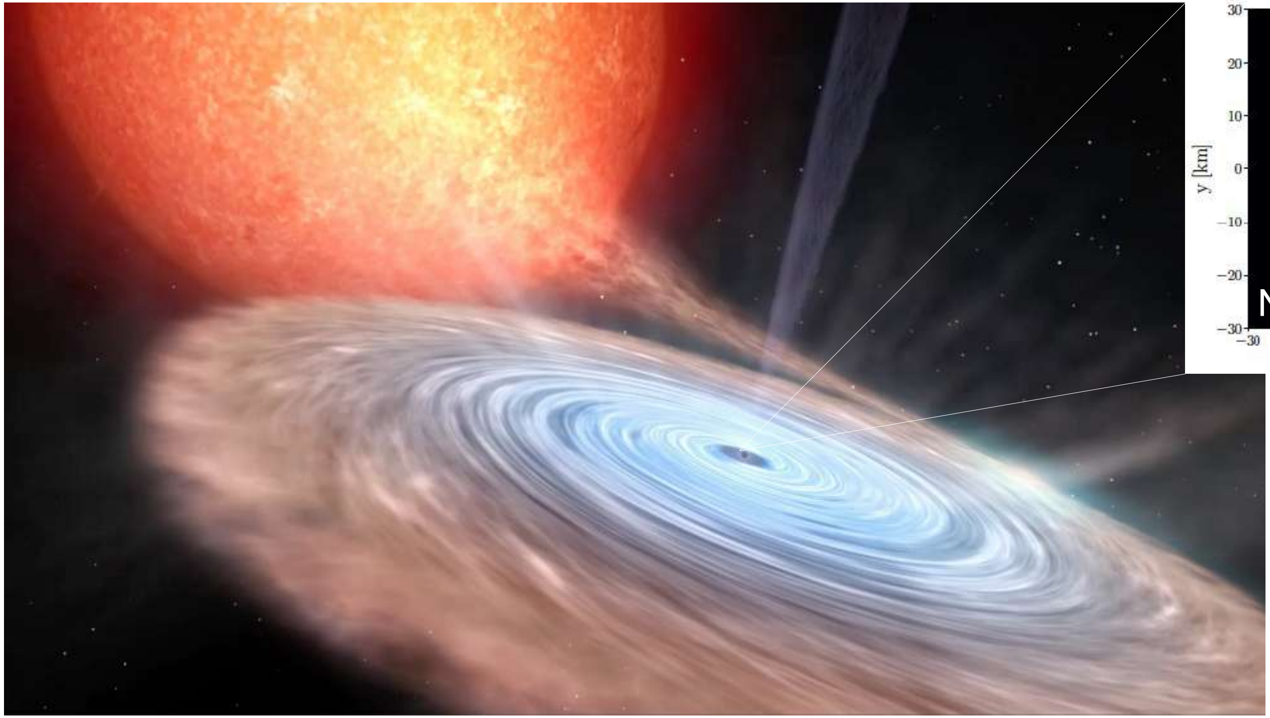
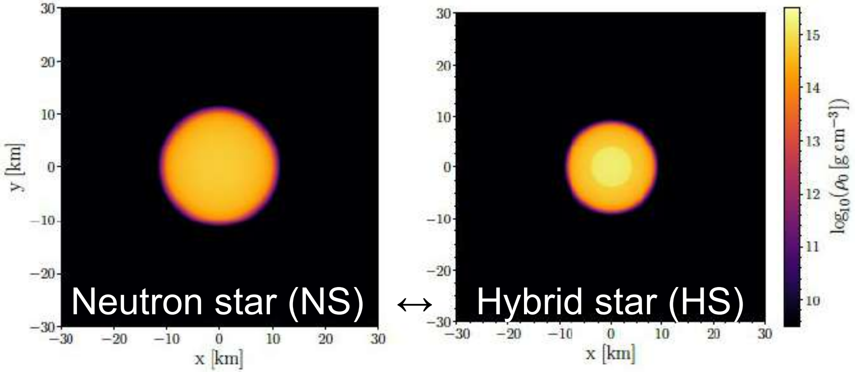
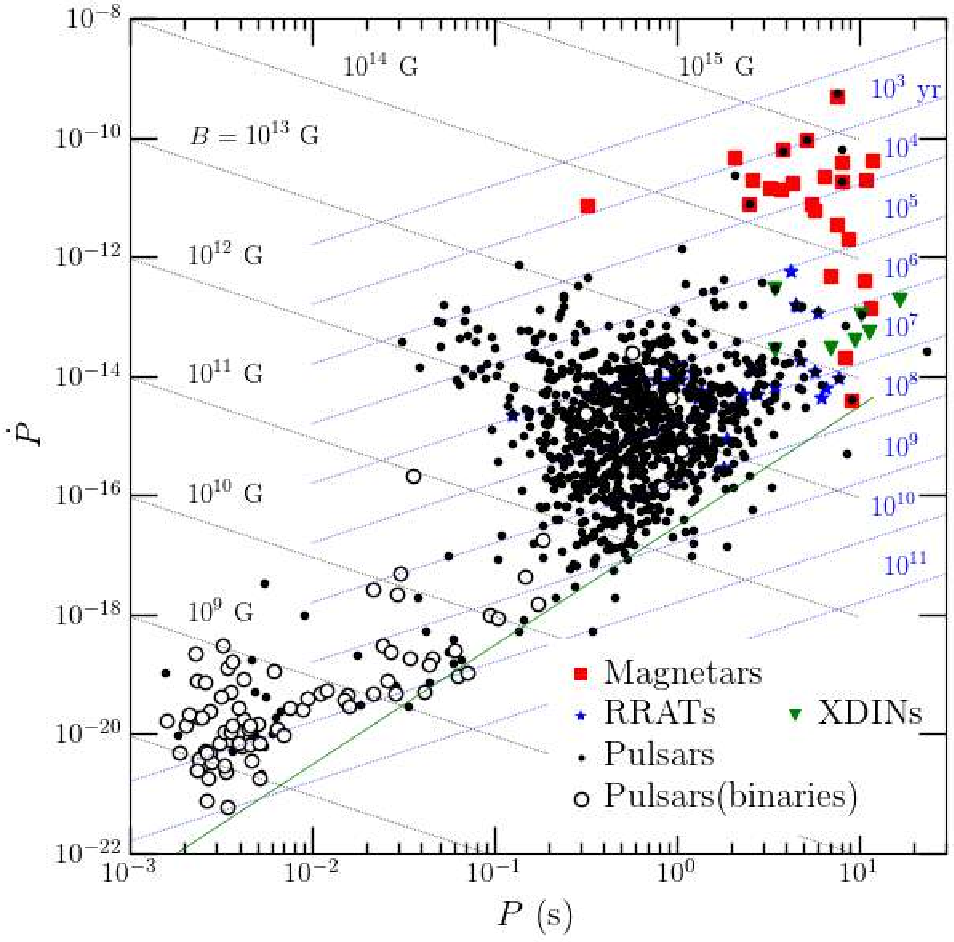


Artistic view of a neutron star accreting mass from a companion star in a low-mass X-ray binary (LMXB) system



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

Introduction: Millisecond Pulsars in the Ṗ-P Diagram



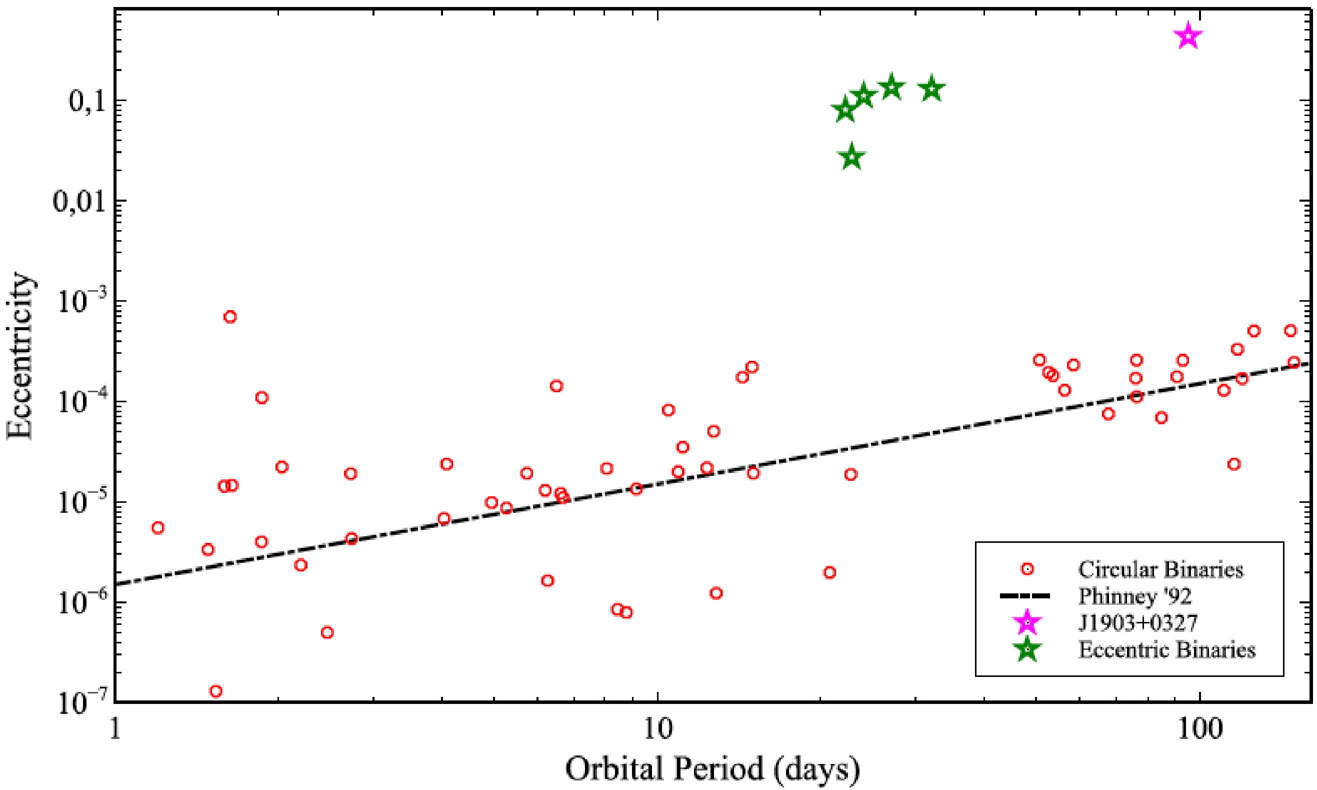
- Pulsars are born with periods P ~ 0.1 – 1.0 seconds and magnetic fields B ~ 10^{12} G

- 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: $e \sim 10^{-6} – 10^{-4}$ → „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 ~ 1

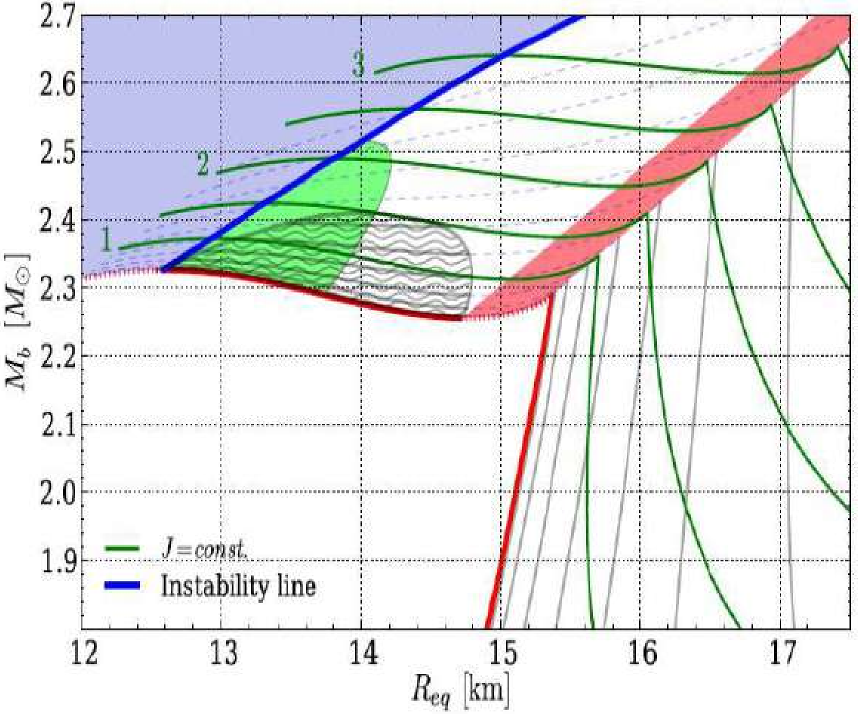
→ Puzzle!

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“

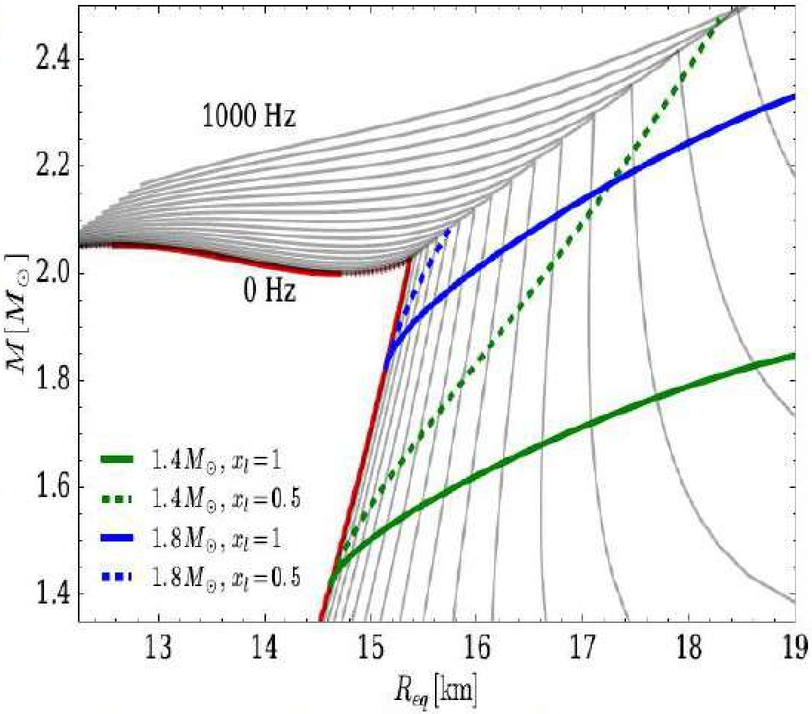
Let us discover the 3rd family of compact stars!

Observation:

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



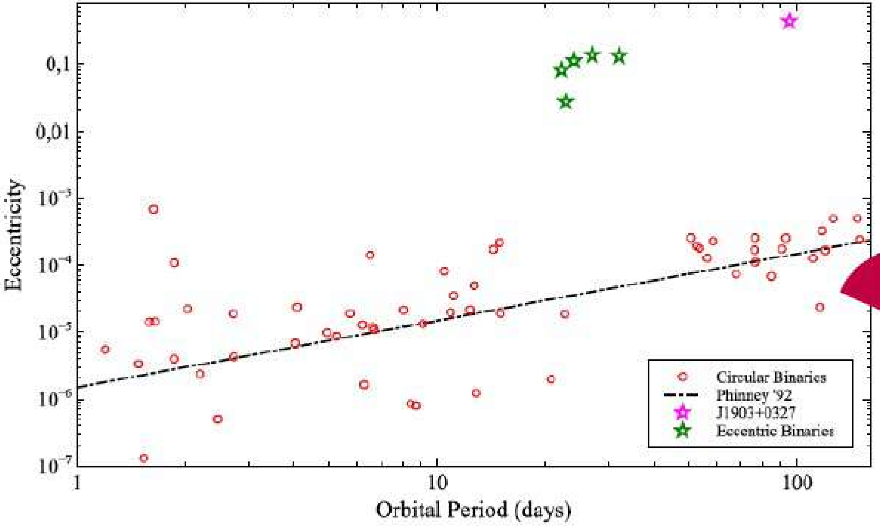
M. Bejger, D.B., et al., A&A 600 (2017) A39



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!

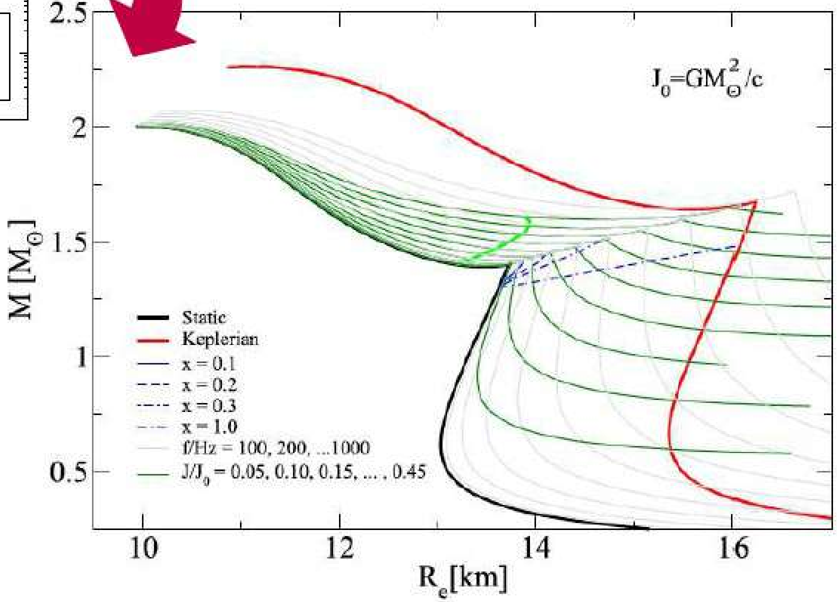
Antoniadis-puzzle



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

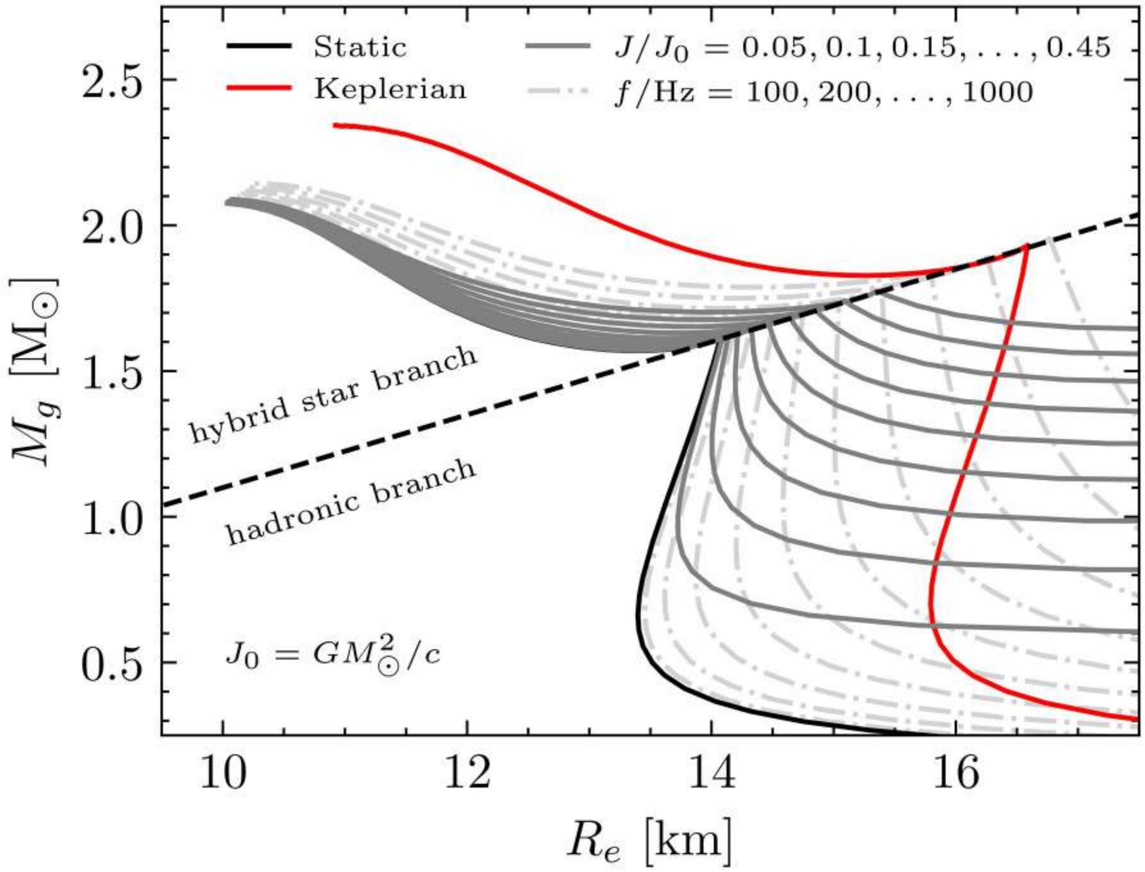
K. Stovall, P.C.C. Freire, J. Antoniadis, ApJ 870(2), 74 (2019)

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“

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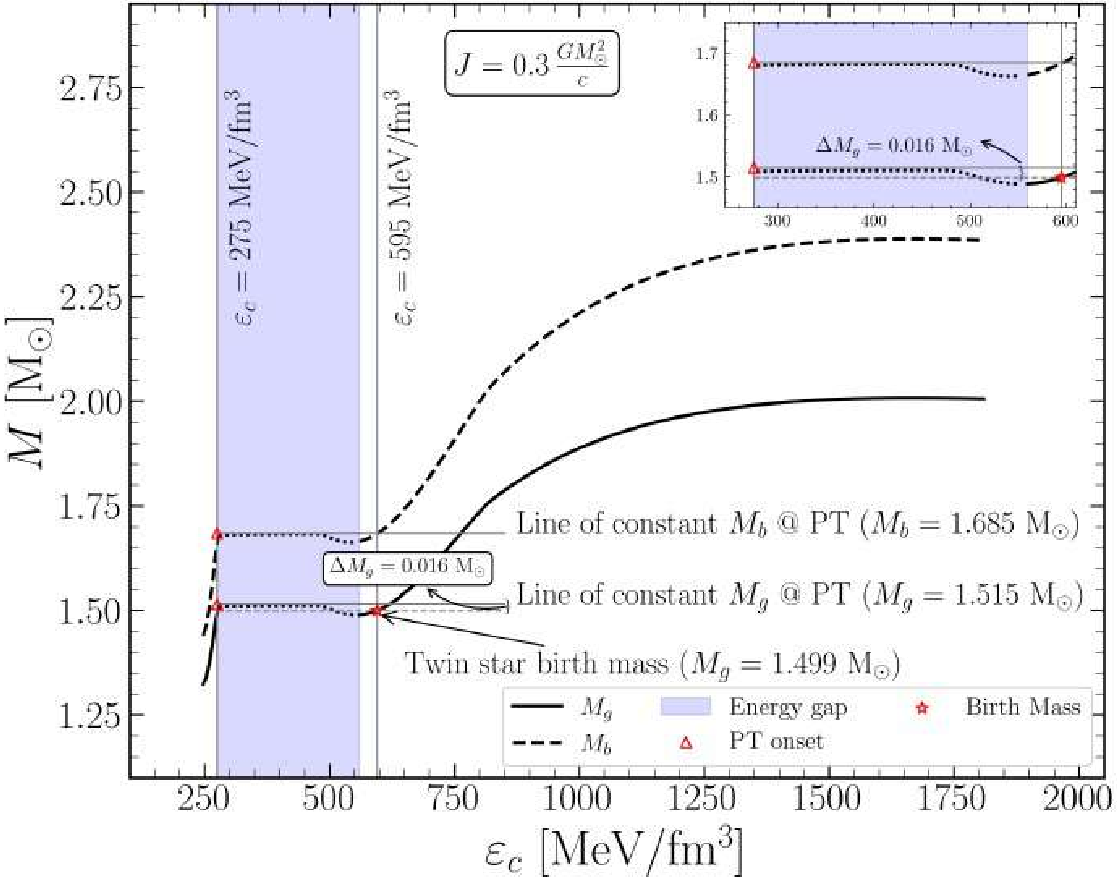


How to calculate the mass defect?

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

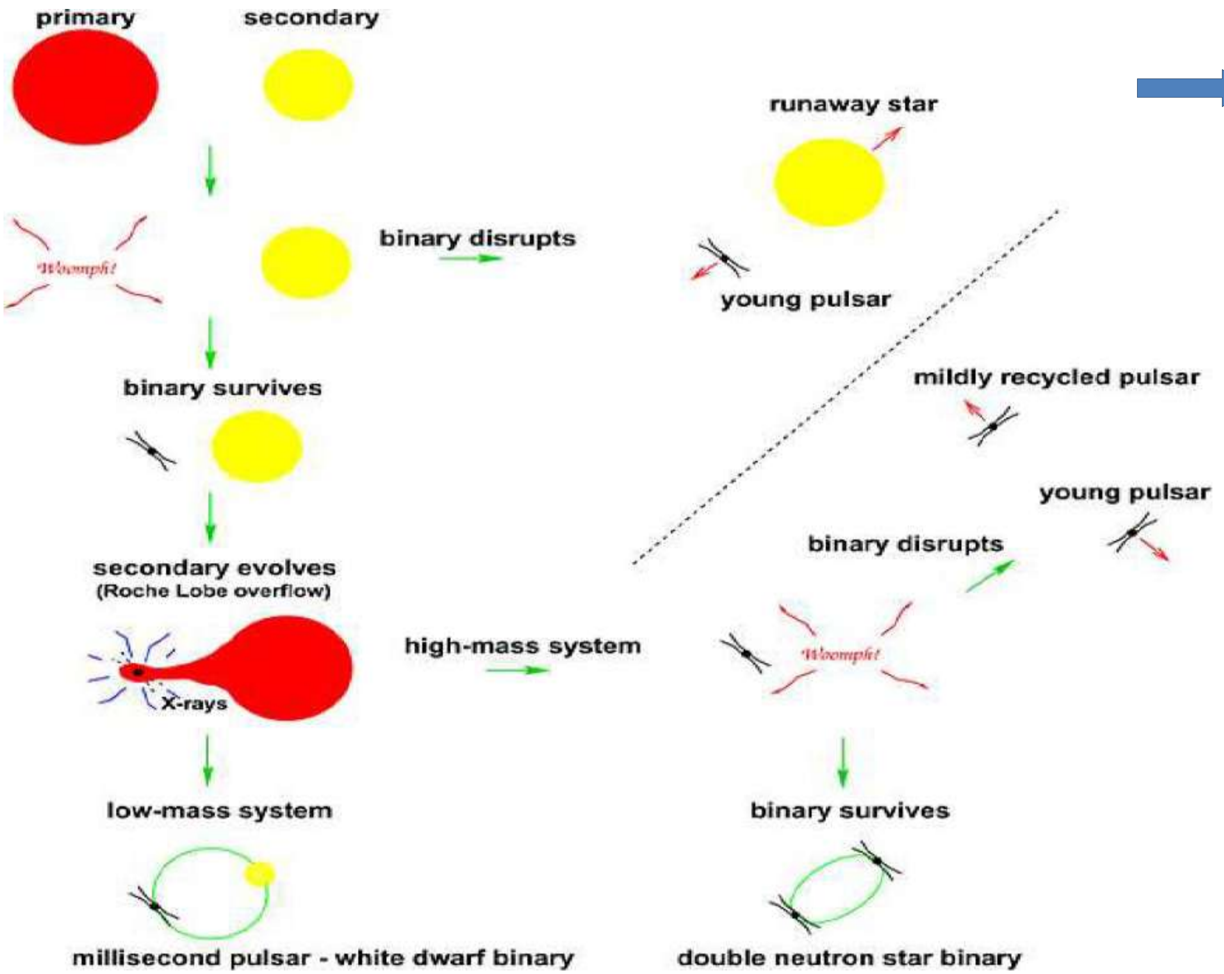
- Consider transition at constant baryon mass N_B and constant angular momentum J

- 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“

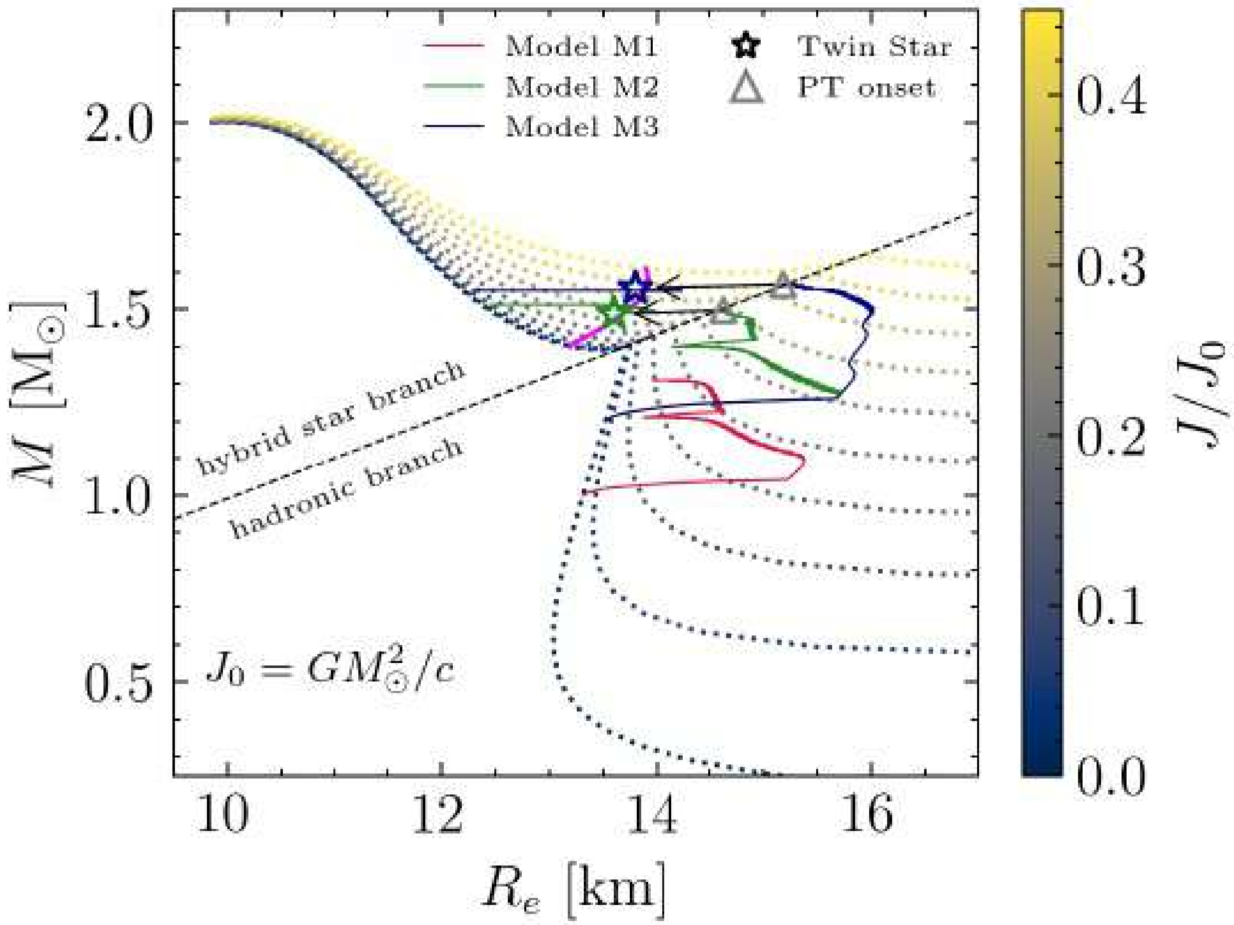
Another kick explanation: Strong QCD phase transition in NS evolution!



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“

(arXiv:2409.04755, submitted to A&A)

Simulation of binary evolution

$$\frac{a_{\rm f}}{a_{\rm i}} = \frac{1 - \Delta M/M}{1 - 2\Delta M/M - (w/v_{\rm rel})^2 - 2\cos\theta(w/v_{\rm rel})},$$

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

w is the magnitude of the kick velocity,

θ is the kick angle

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

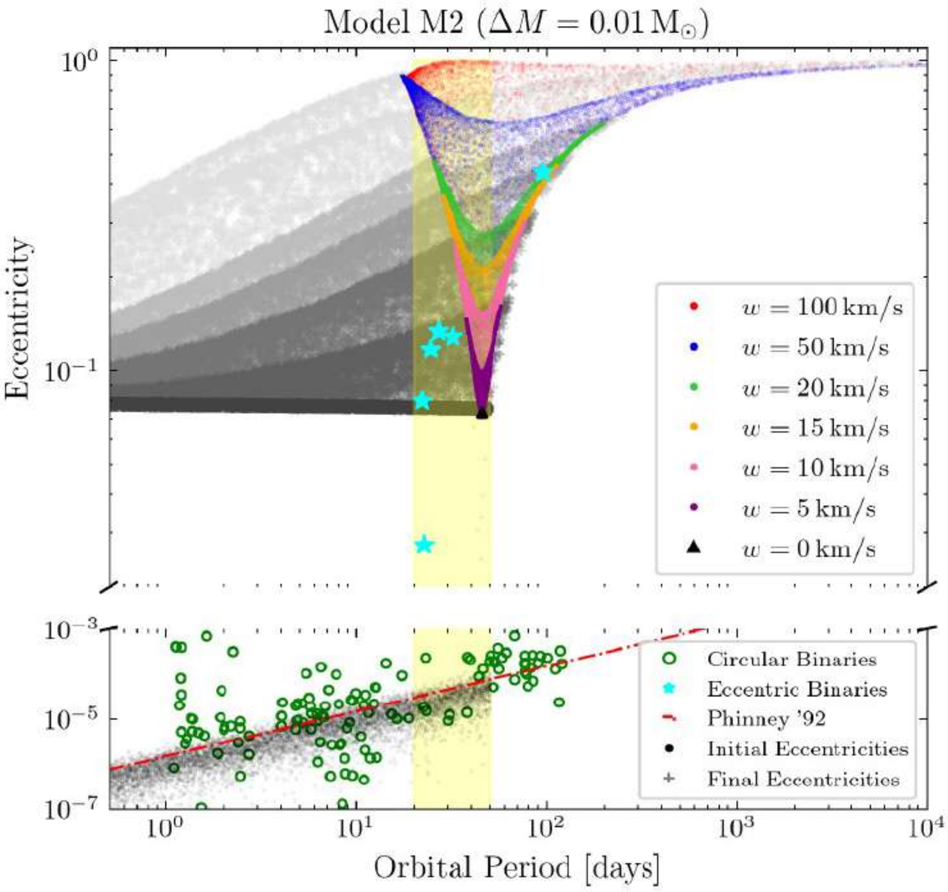
$$e = \sqrt{1 + \frac{2E_{\rm orb,f}L^2_{\rm orb,f}}{\mu_{\rm f}G^2M^2_{\rm f,1}M^2_{\rm f,2}}},$$

$$L_{\rm orb,f} = a_{\rm i}\mu_{\rm f}\sqrt{(v_{\rm rel} + w\cos\theta)^2 + (w\sin\theta\sin\phi)^2}$$

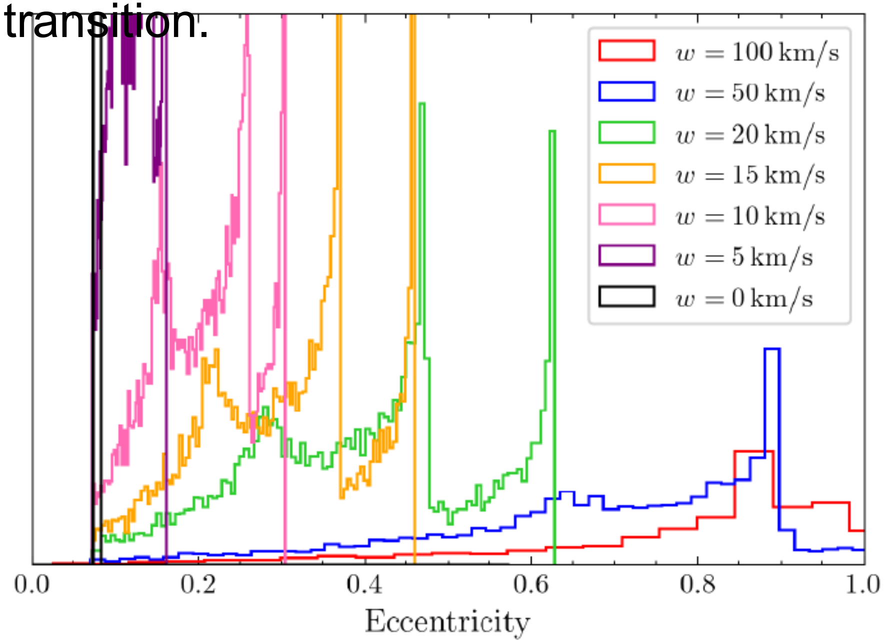
$$E_{\rm orb,f} = -GM_{\rm f,1}M_{\rm f,2}/2a_{\rm f}$$

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

Simulation of binary evolution

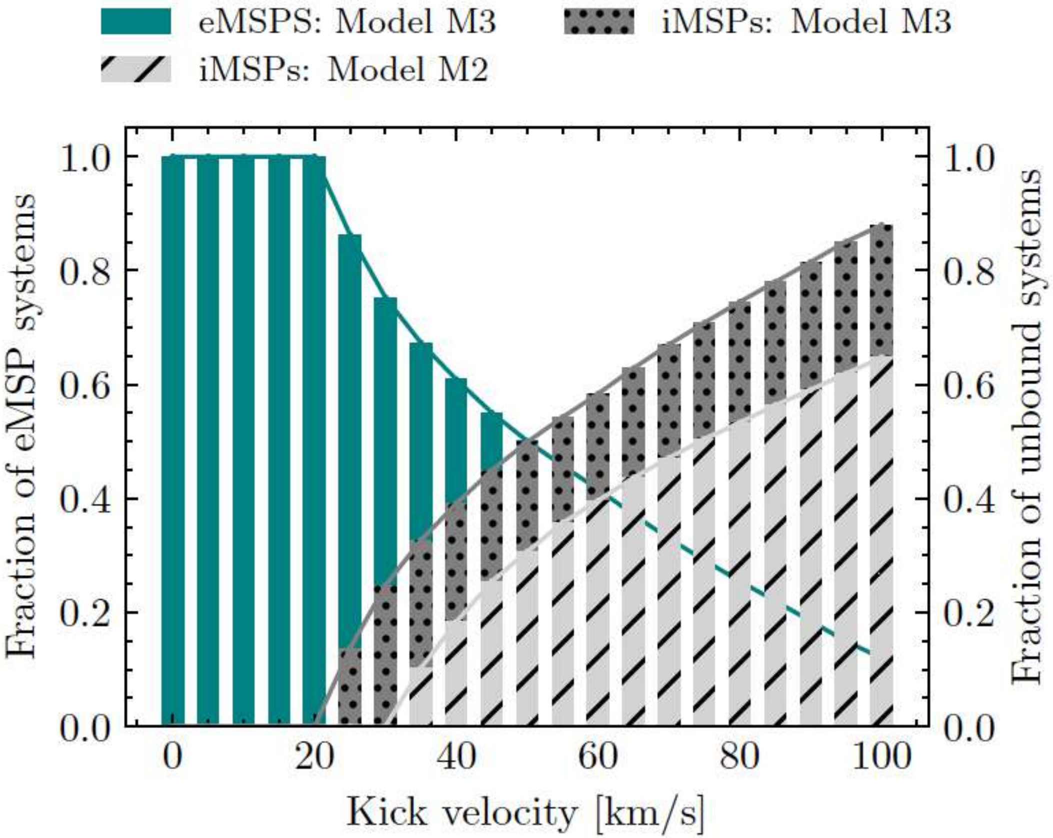


Monte-Carlo simulation of posttransition distribution orbital parameters for a mass defect of 1% solar mass due to the transition.



S. Chanlaridis, D. Ohse, J. Antoniadis, D. Blaschke, D.E. Alvarez-Castillo, V. Danchev, D. Misra and N. Langer: „Formation of twin compact stars in low-mass X-ray binaries“ (arXiv:2409.04755, submitted to 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 compact stars in low-mass X-ray binaries“
(arXiv:2409.04755)

Akira Ohnishi organized another neutron star workshop at YITP in 2016

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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 !!

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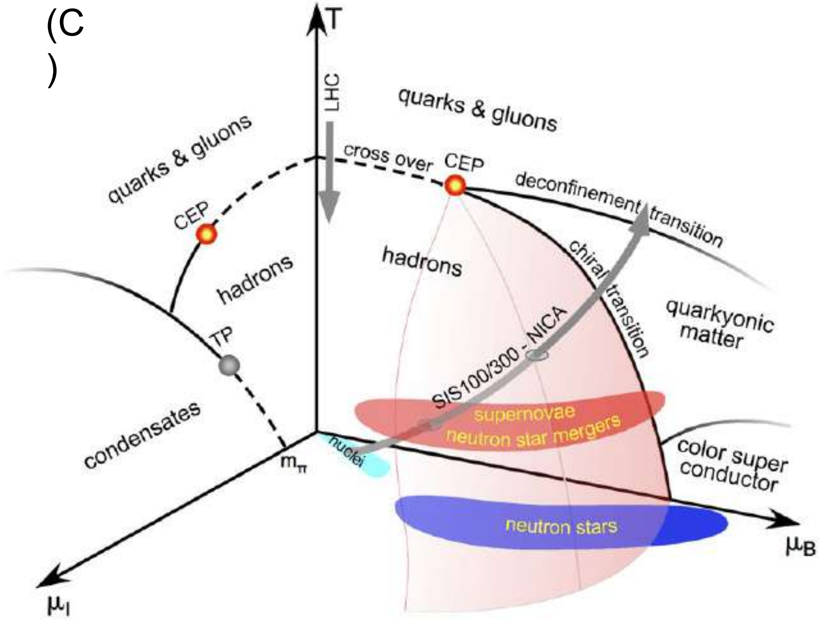
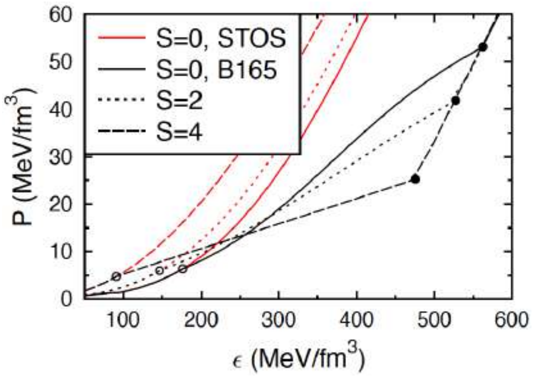
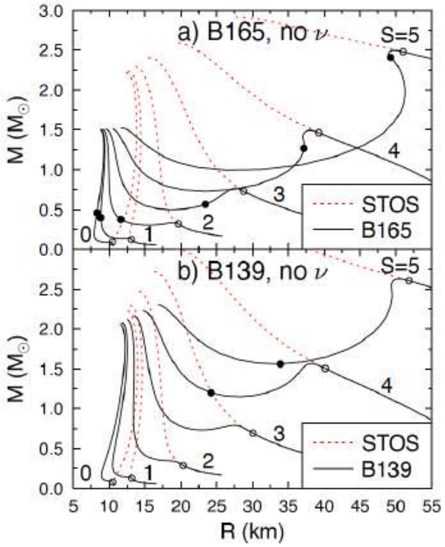
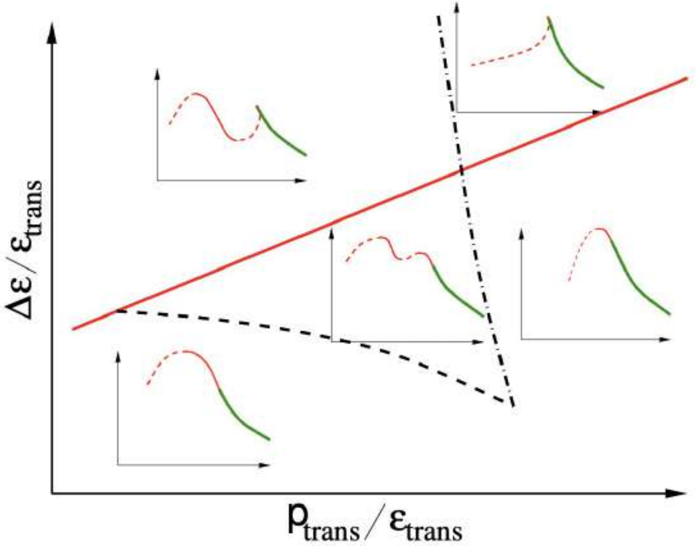






Disconnected HS branch indicates a Strong (1st-order) phase transition



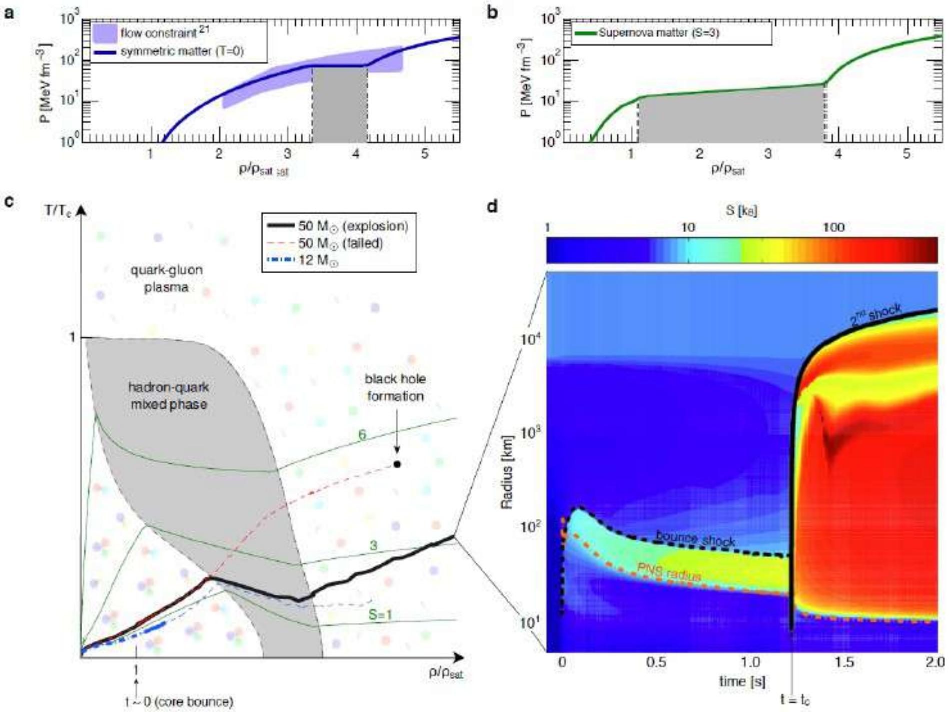
Seidov criterion for gravitational Instability (red line):

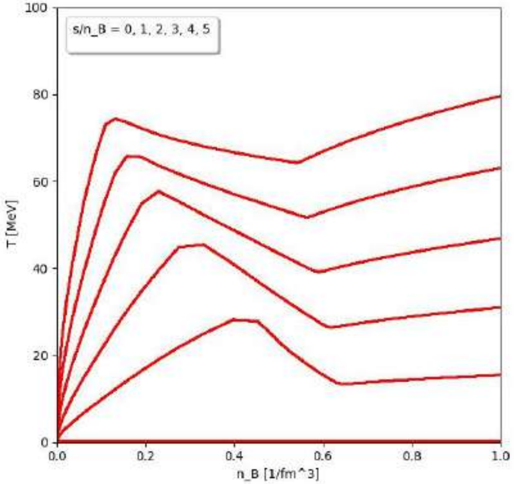
$$\frac{\Delta\varepsilon_{\rm crit}}{\varepsilon_{\rm trans}} = \frac{1}{2} + \frac{3}{2}\frac{p_{\rm trans}}{\varepsilon_{\rm trans}}$$

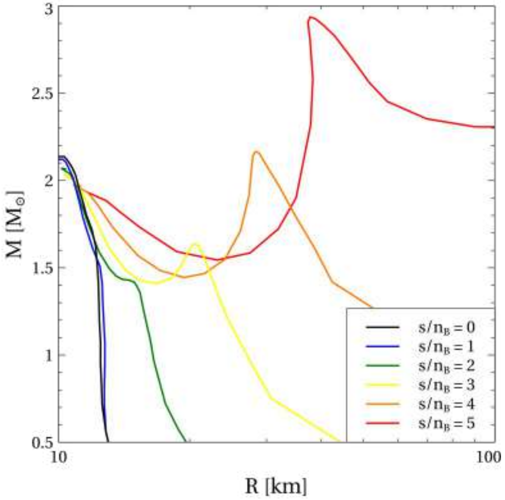
*) M. Hempel et al., PRD 94 (2016) 103001

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:
$M = 50\ M_O$

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

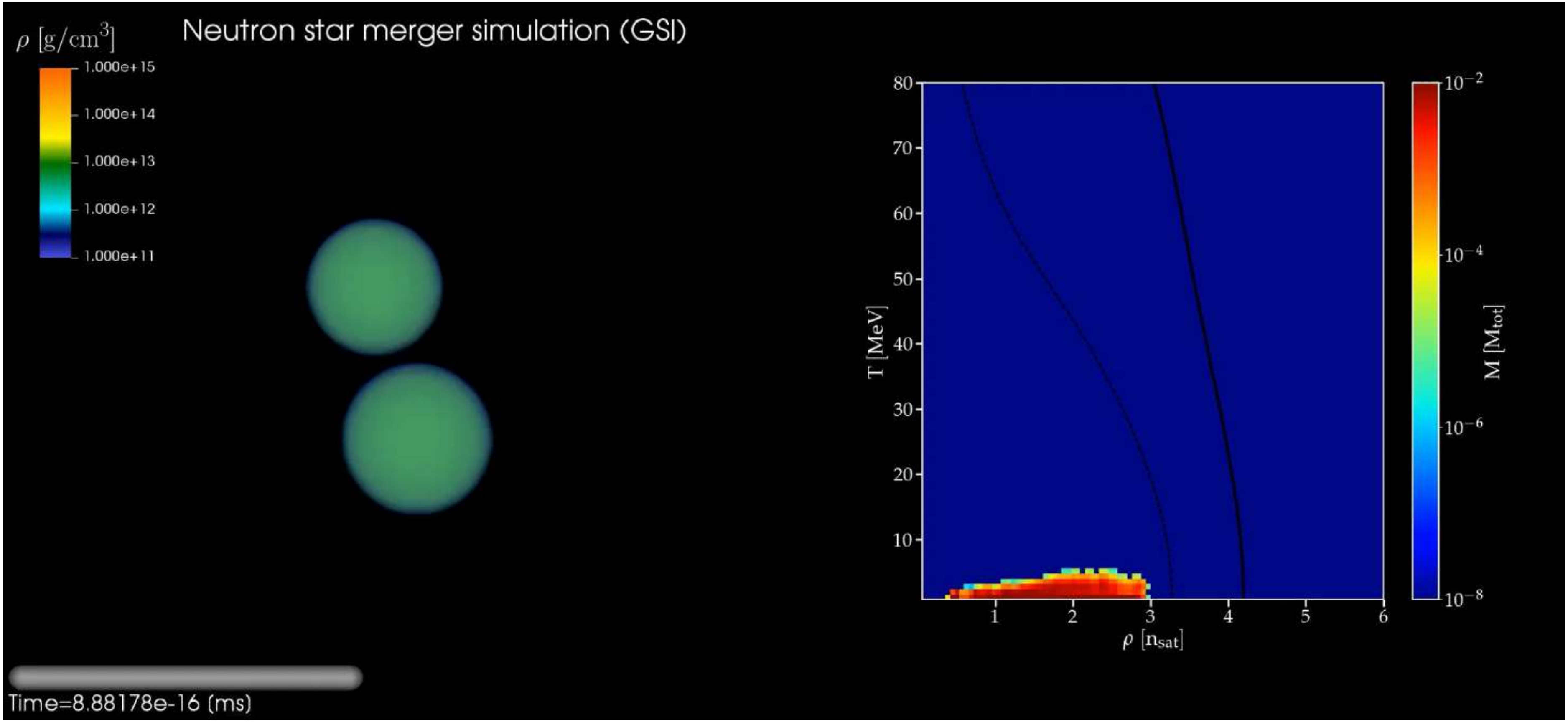
→ supports the fulfillment of the Seidov criterion (mass twins)

→ deconfinement is reached faster (explodability)

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

Quark Matter in a Binary NS merger ?

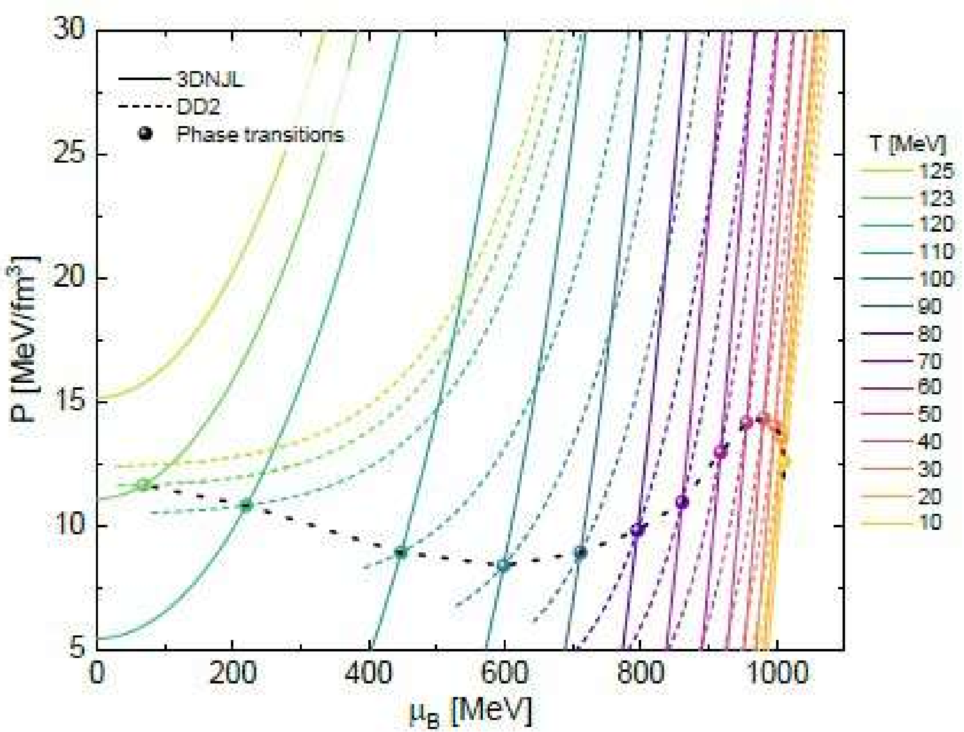
Population of the QCD Phase Diagram – Quark Matter and Mixed Phase Simulation of a BNS merger 1.35+1.35 solar masses
S. Blacker, A. Bauswein et al., Phys. Rev. D 102 (2020) 123023

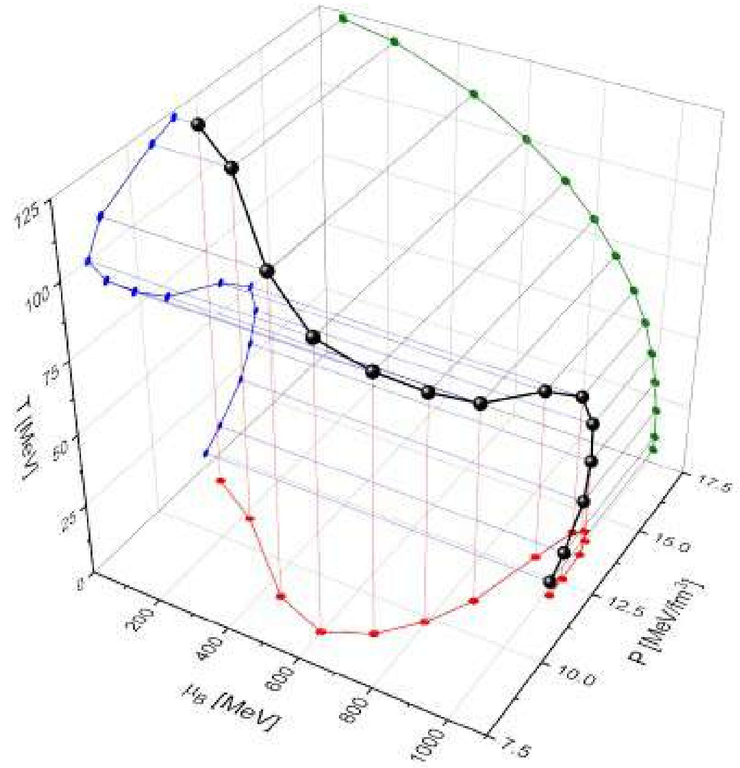


Video available at: http://www.ift.uni.wroc.pl/~blaschke/RhoMovieMed.mp4

Thermal twin stars

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

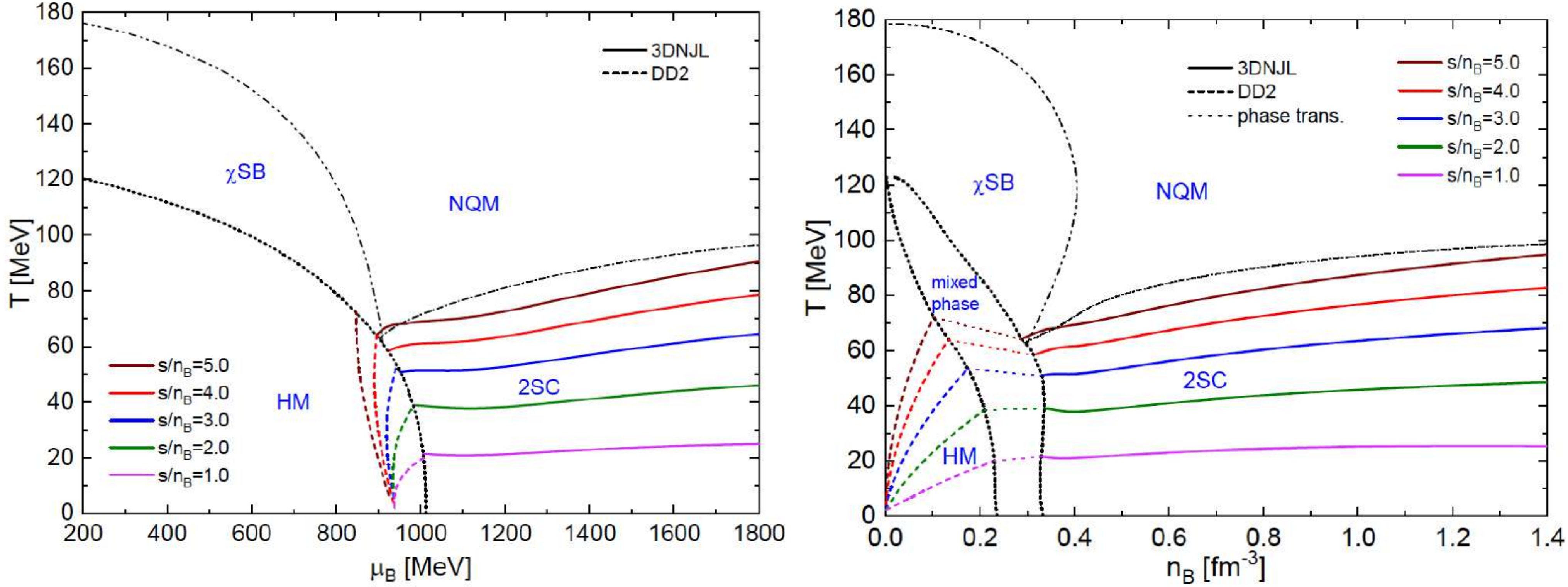




*) G. Contrera, D.B., J.P. Carlomagno, A.G. Grunfeld, PRC 105 (2022) 045808
J.P. Carlomagno, G. Contrera, A.G. Grunfeld, D.B., PRD 109 (2024) 043050;
arXiv:2406.17193

Thermal twin stars

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



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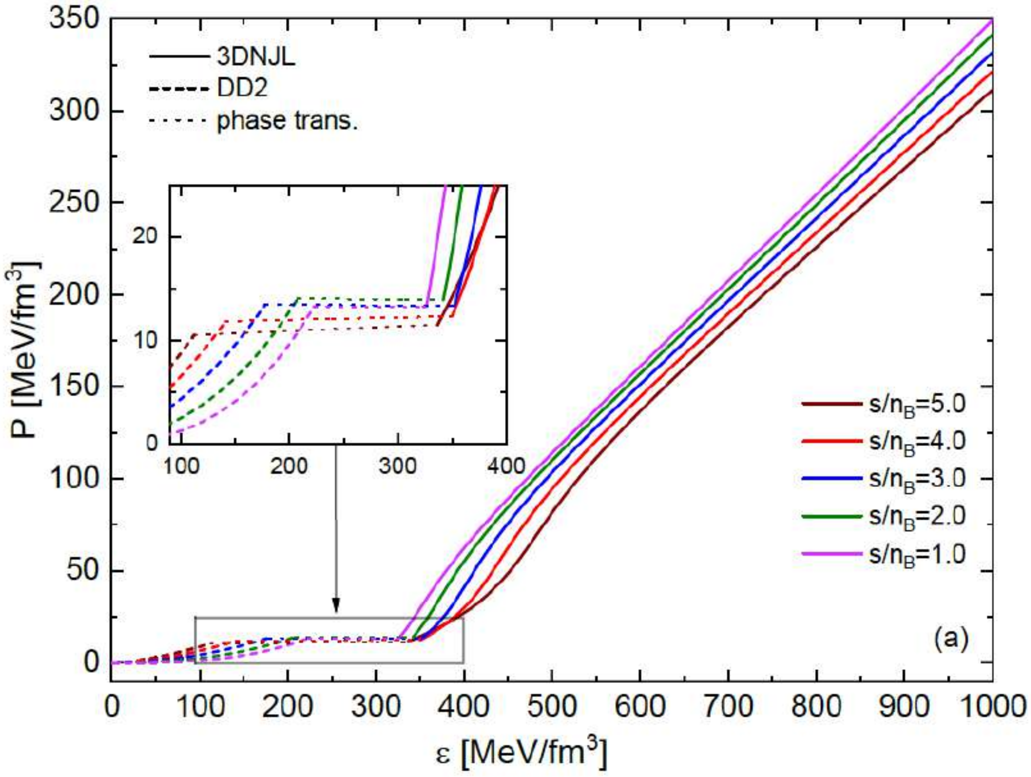

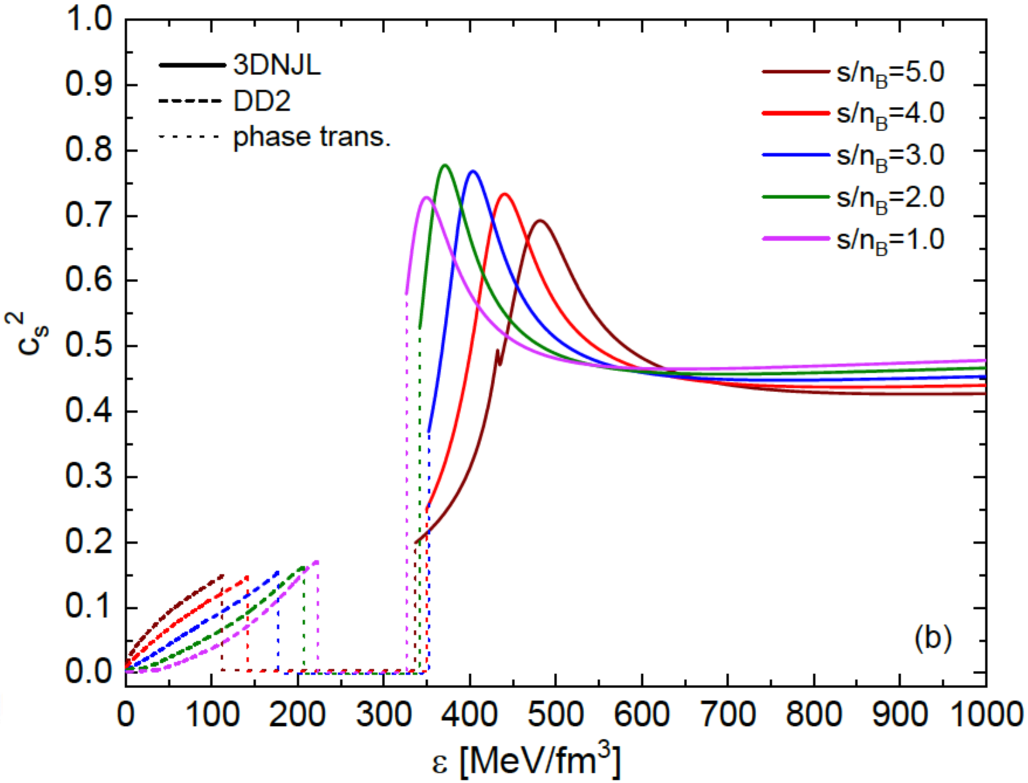

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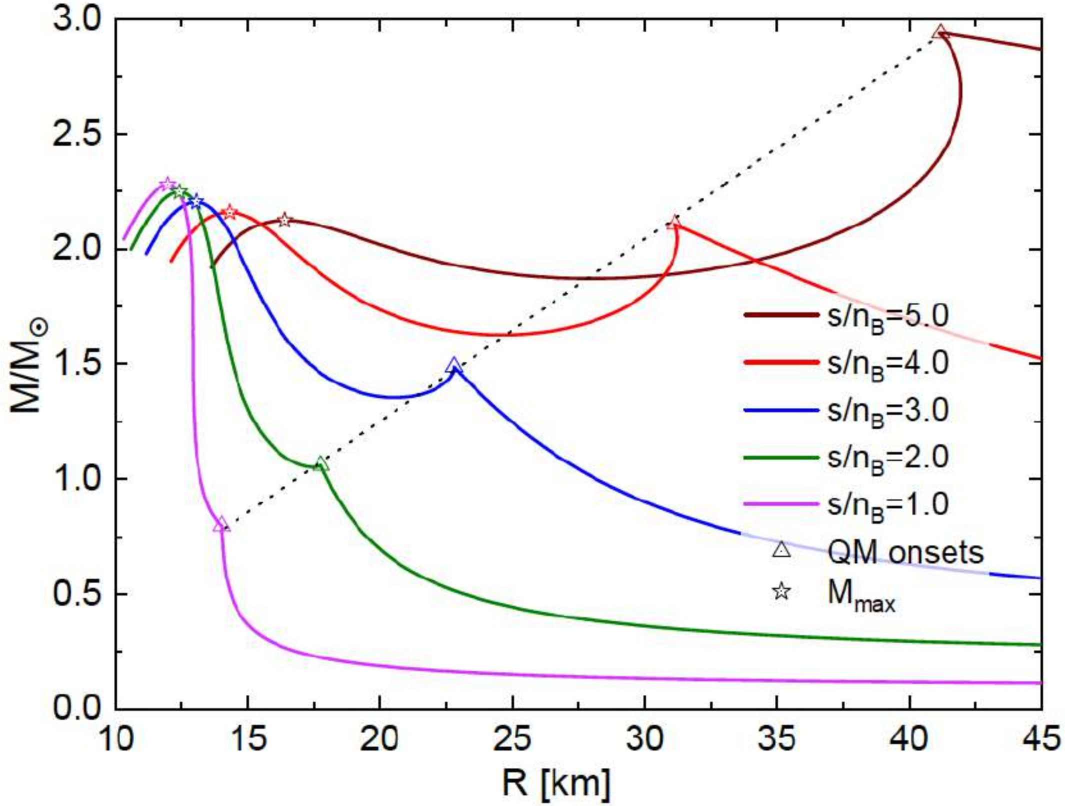
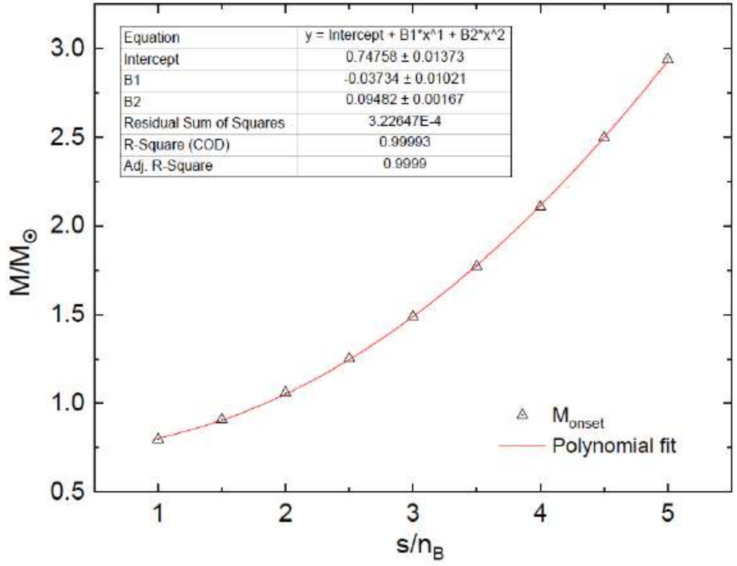


Systematics for the onset: $M = C(R - R_0)\,,$

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

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

is the critical compactness of the star



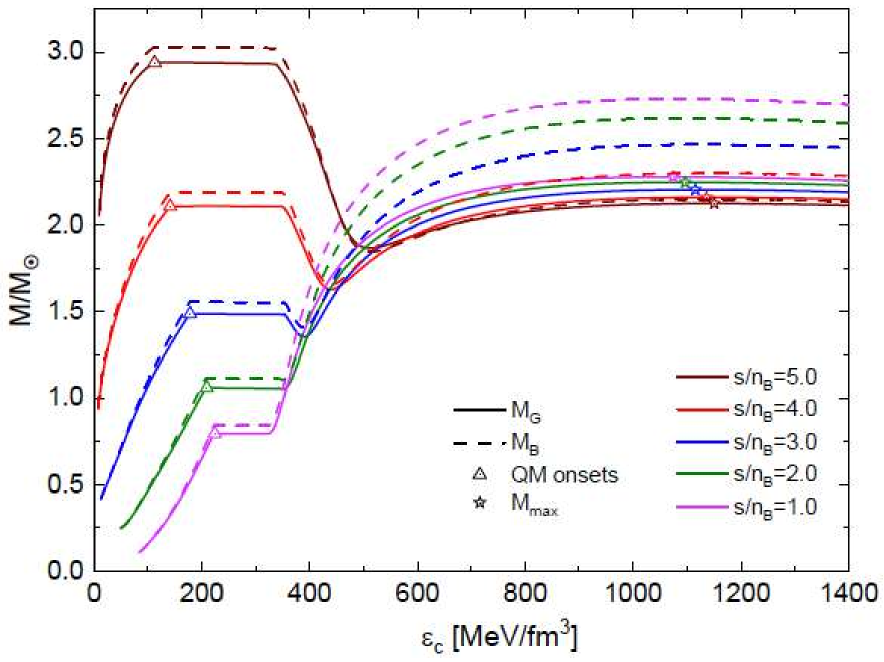
$$\frac{M_{\rm onset}}{M_\odot} = 0.747 - 0.0373\frac{s}{n_B} + 0.0948\left(\frac{s}{n_B}\right)^2$$

*) 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

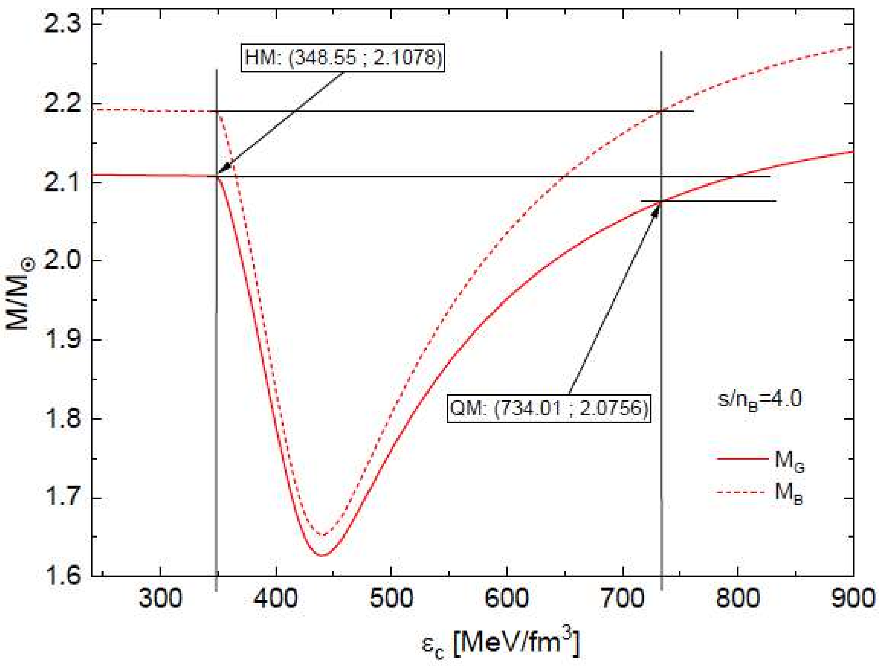
Thermal twin stars

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

Gravitational mass (solid) and baryon mass (dashed)



Extraction of the mass defect (energy release)

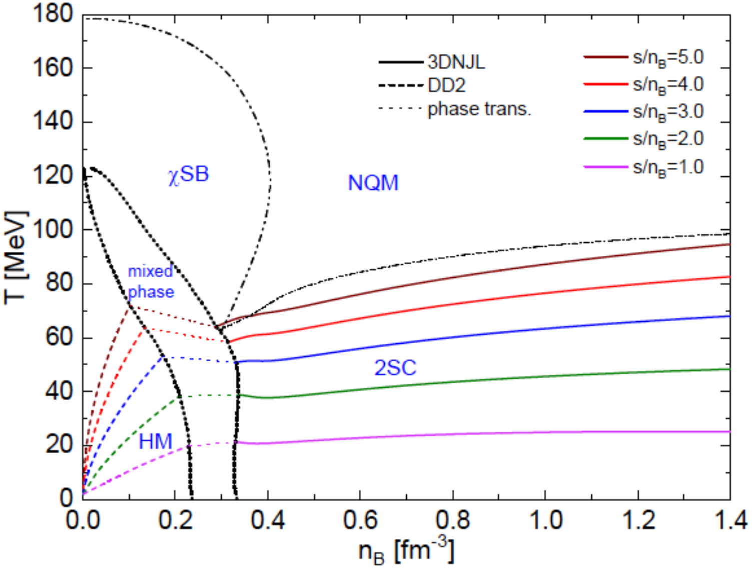


*) G. Contrera, D.B., J.P. Carlomagno, A.G. Grunfeld, PRC 105 (2022) 045808
J.P. Carlomagno, G. Contrera, A.G. Grunfeld, D.B., PRD 109 (2024) 043050;
arXiv:2406.17193

Thermal twin stars

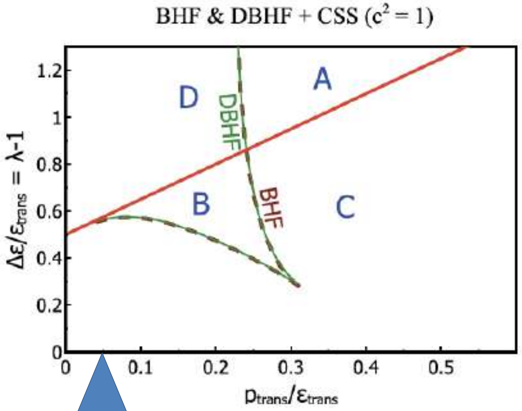
Characterization of the accretion-induced transition to the thermal twin star*

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

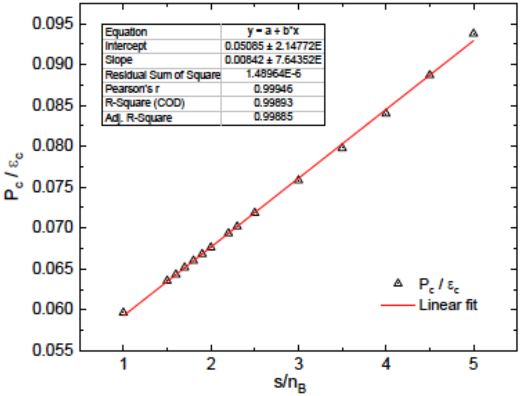


*) J.P. Carlomagno, G. Contrera, A.G. Grunfeld, D.B., arXiv:2406.17193

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



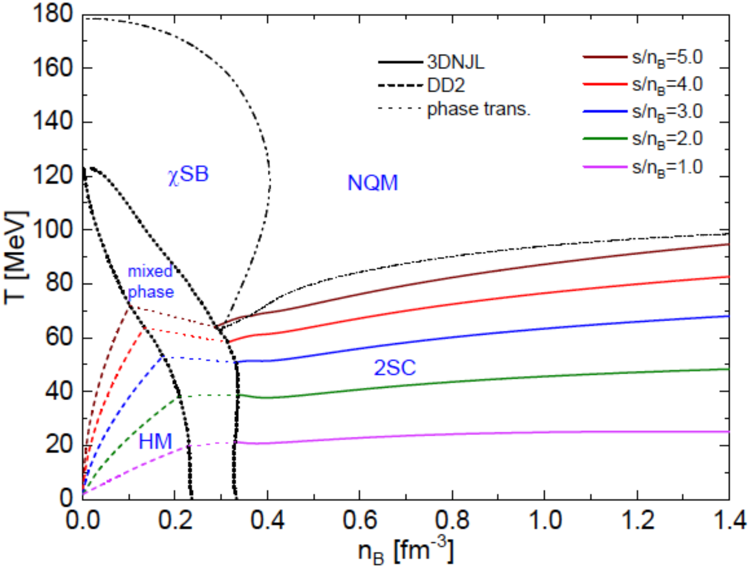
Alford & Han, Eur. Phys. J. A 52, 62 (2016)



Thermal twin stars

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

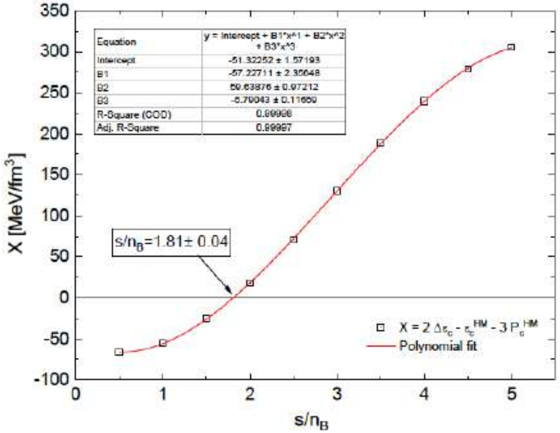
s/n_B	$R(M^{max}_{HYB})$	$M_{B,tr}$	$M_{G,HM}$	$M_{G,QM}$	ΔM	$T(0)_{HM}$	$T(0)_{QM}$	$\Delta T(0)$	character
2.0	12.41	1.114	1.0582	1.0582	0.0000	38.36	38.87	0.51	enthalpic
2.5	12.61	1.311	1.2490	1.2487	0.0003	46.33	45.57	-0.76	entropic
3.0	13.06	1.557	1.4878	1.4853	0.0025	53.16	50.84	-2.32	entropic
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

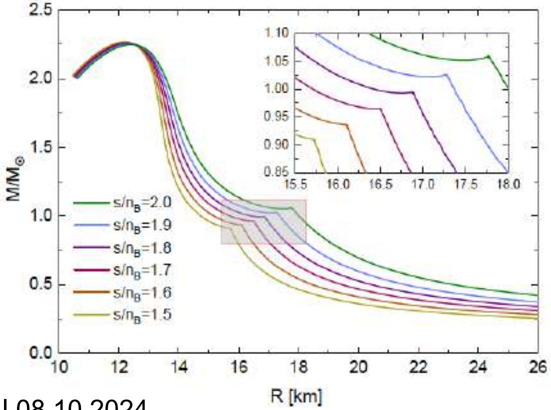


*) J.P. Carlomagno, G. Contrera, A.G. Grunfeld, D.B., arXiv:2406.17193

Seidov criterion for instability:

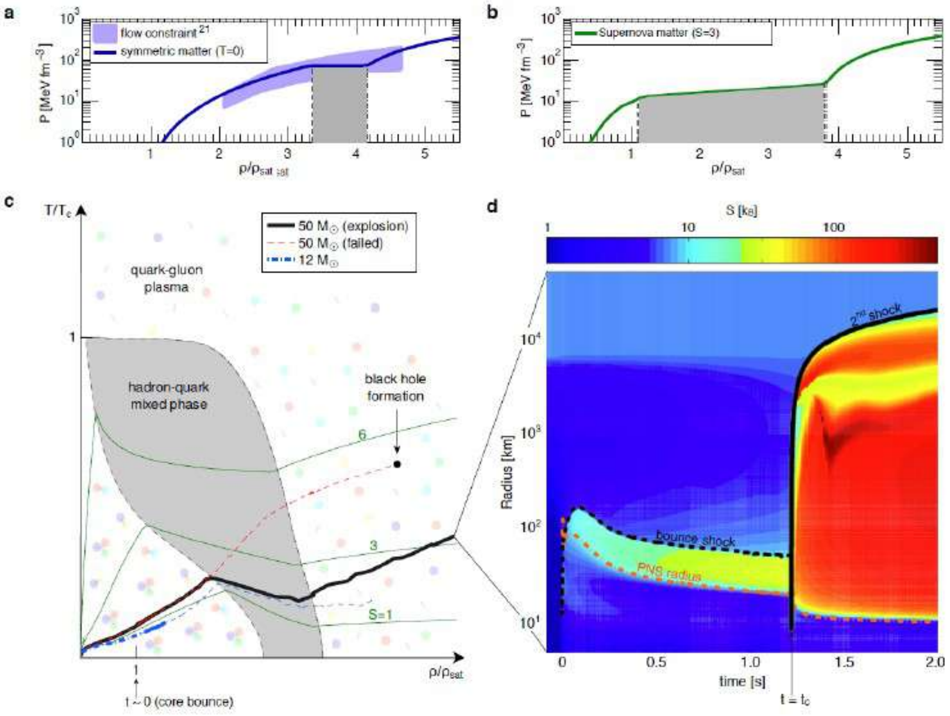
$$X = 2\Delta\varepsilon - \varepsilon_c^{HM} - 3P_c^{HM} > 0$$

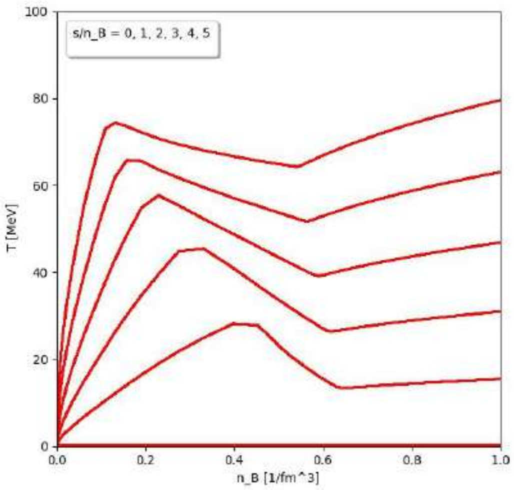


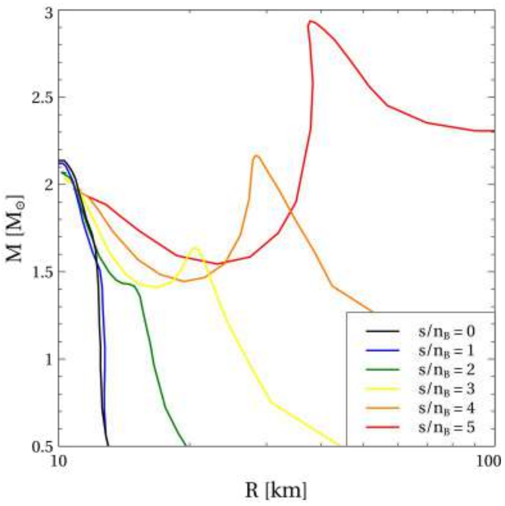


Thermal twin stars – Indicators of CCSN explodability ?

Successful application of hybrid EoS with entropic first-order transition (thermal twin stars) as an explosion mechanism for massive blue supergiant stars*:







Courtesy: Oleksii Ivanytskyi

Progenitor:
$M = 50\ M_O$

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

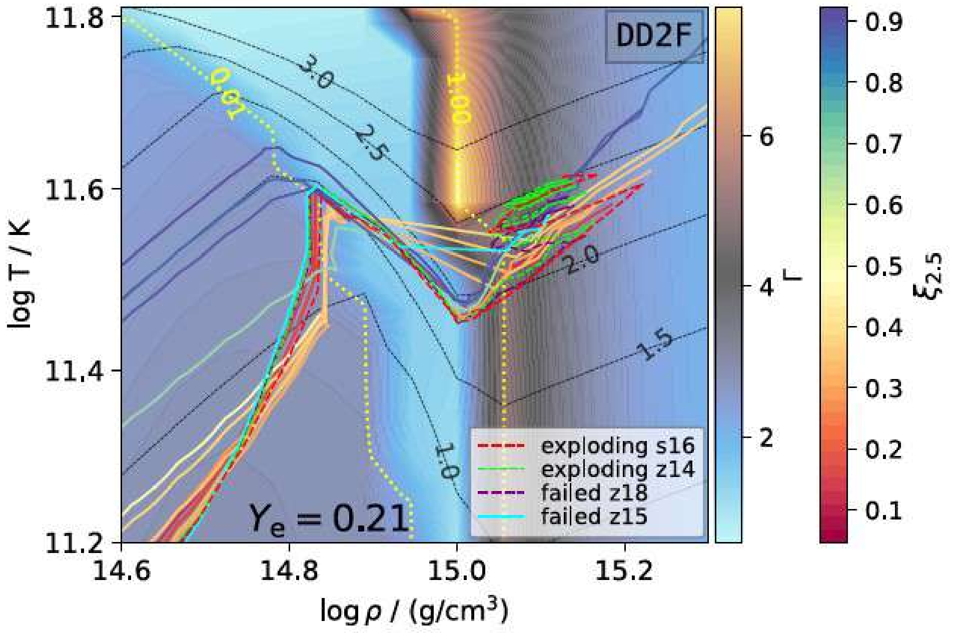
→ supports the fulfillment of the Seidov criterion (mass twins)

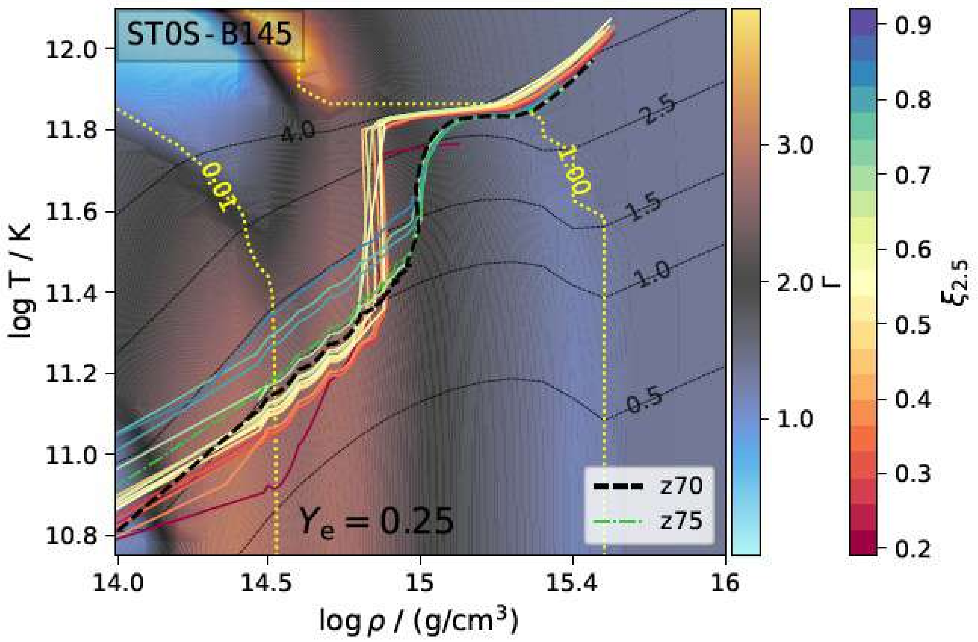
→ deconfinement is reached faster (explodability)

*) T. Fischer et al., Nature Astronomy 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:

David E. Alvarez-Castillo (IFJ PAN Cracow, Poland & Incubator CSSF Wroclaw, Poland)
Alexander Ayriyan (A. Alikhanyan National Science Lab, Armenia & University of Wroclaw, Poland)

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:

Juan Pablo Carlomagno, Gustavo Contrera (CONICET, Univ. La Plata, Argentina),
Gabriela Grunfeld (CONICET & CNEA Buenos Aires, Argentina),
Oleksii Ivanytskyi (University of Wroclaw, Poland & Incubator CSSF Wroclaw, Poland)

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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 Wroclaw

May-June 2016

Critical Point & Onset of Deconfinement (CPOD)

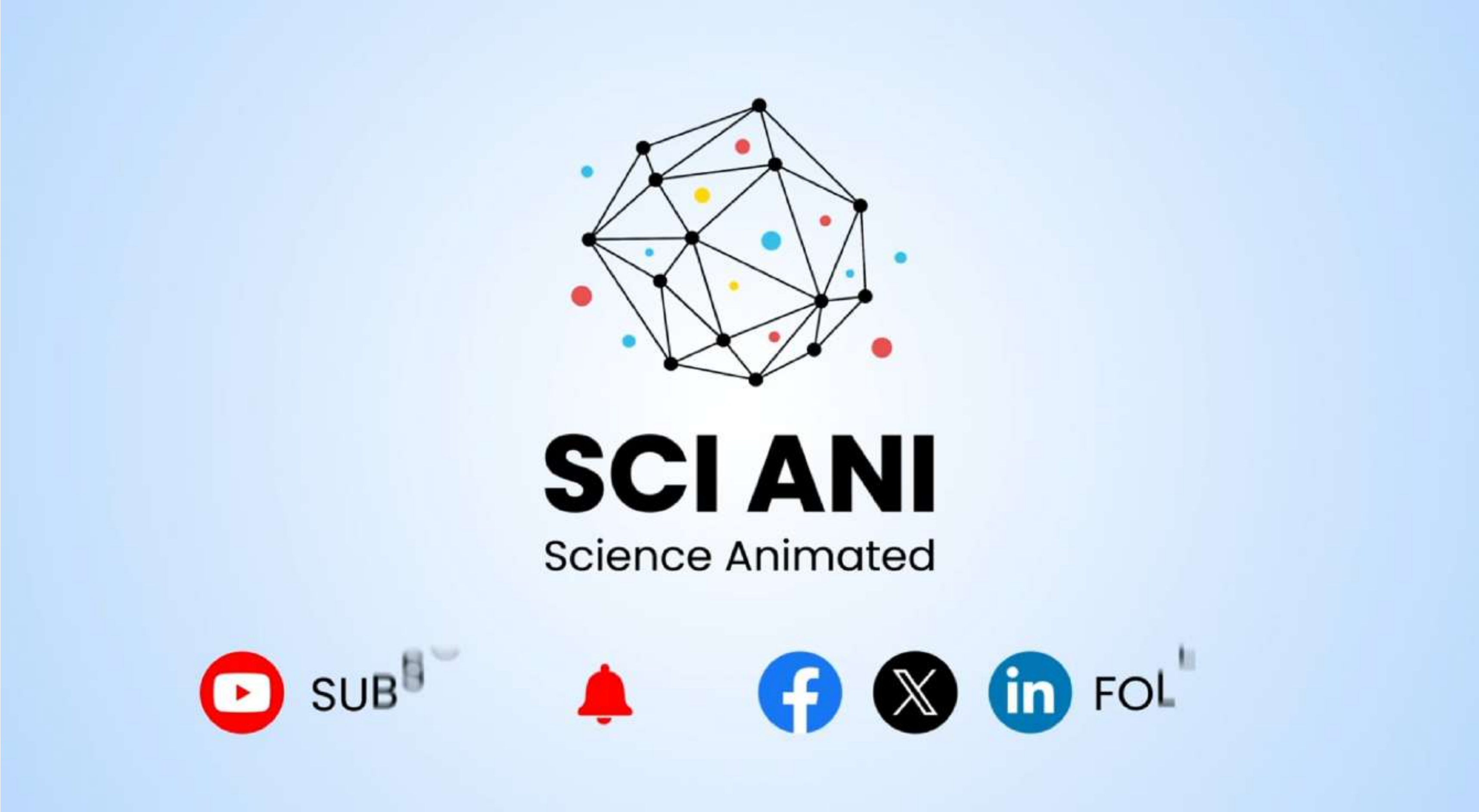
„Oratorium Marianum“
University of Wroclaw

May-June 2016

Akira Ohnishi

with
David & Ani Blaschke
(born 6. May 2016)

Massive hybrid compact stars born in supernova explosions



Video available at: http://www.youtube.com/watch?v=IYHqZHgz2UA