Recent results on quark plasma at extreme densities in neutron stars and their mergers

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1. Introduction: Recent relevant multi-messenger observations
2. Hybrid EoS construction and M-R constraints
3. Outlook: Supernovae & Mergers in the QCD phase diagram

NPP 2020 Videoconference, 16. December 2020

JINR DUBNA
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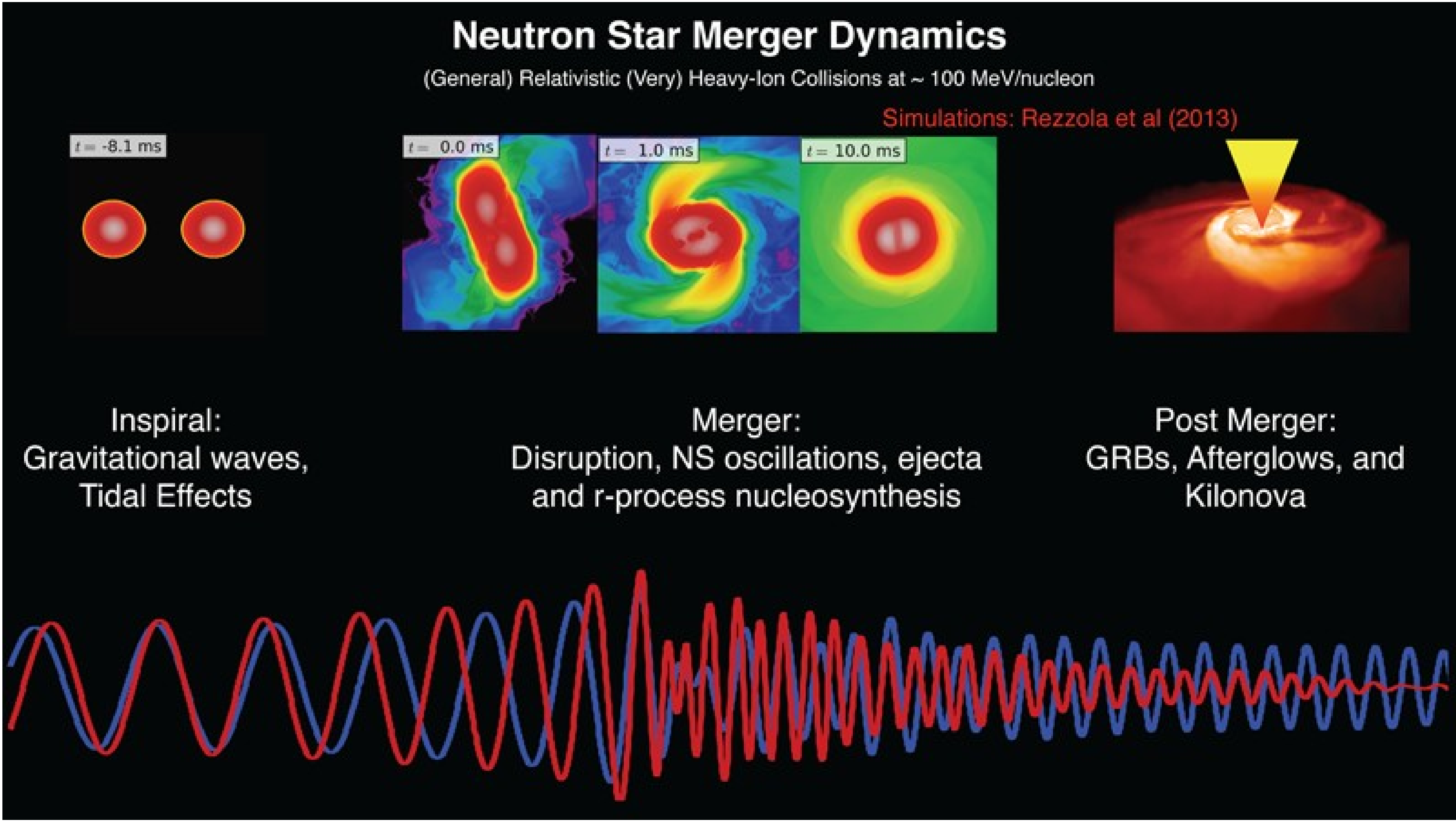
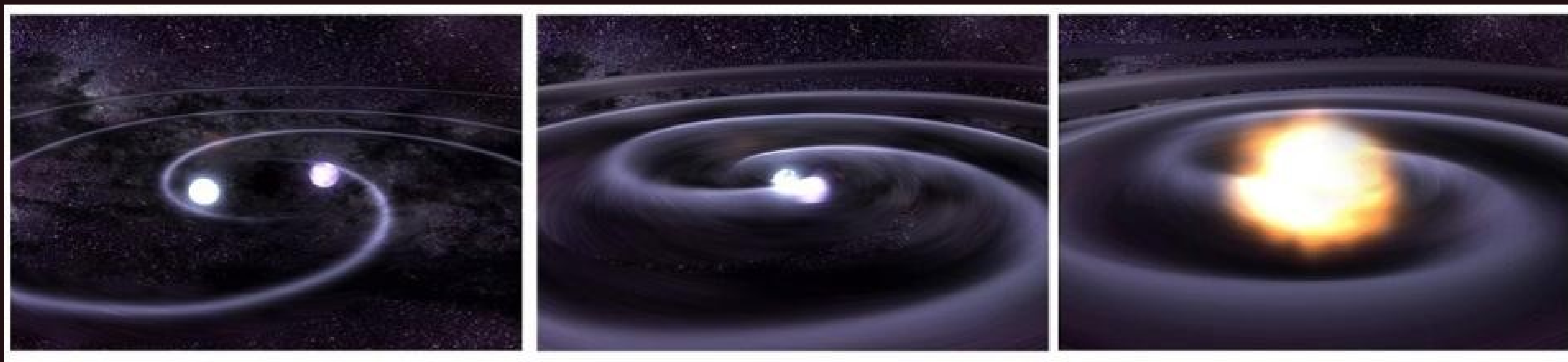
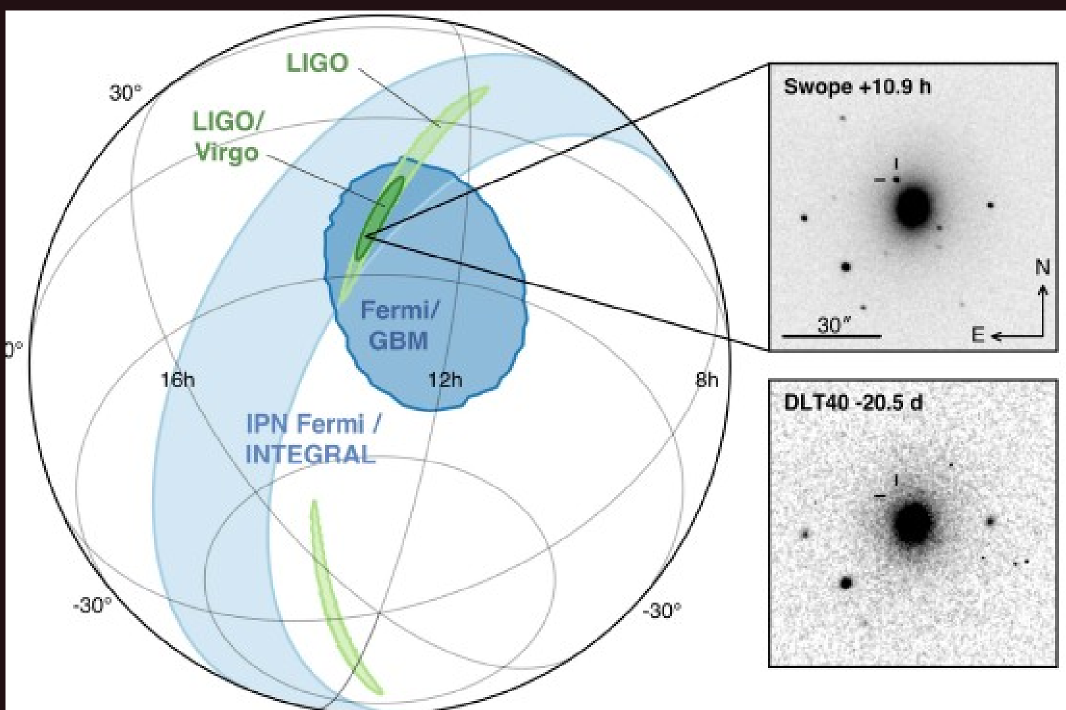
Uniwersytet Wrocławski
RSF Russian Science Foundation
Grant No. 17-12-01427
PHAROS The multi-messenger physics and astrophysics of neutron stars
THOR

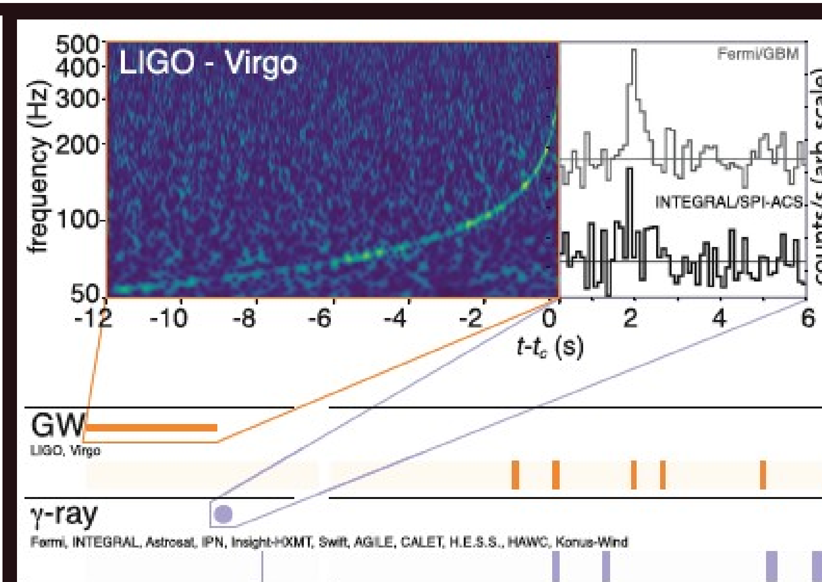
GW170817 – a merger of two compact stars



Discovery: neutron star merger !







GW170817A , announced 16.10.2017 *)

*) B.P. Abbott et al. [LIGO/Virgo Collab.], PRL 119, 161101 (2017); ApJLett 848, L12 (2017)

NS-NS merger !

GW170817A , announced 16.10.2017 *)

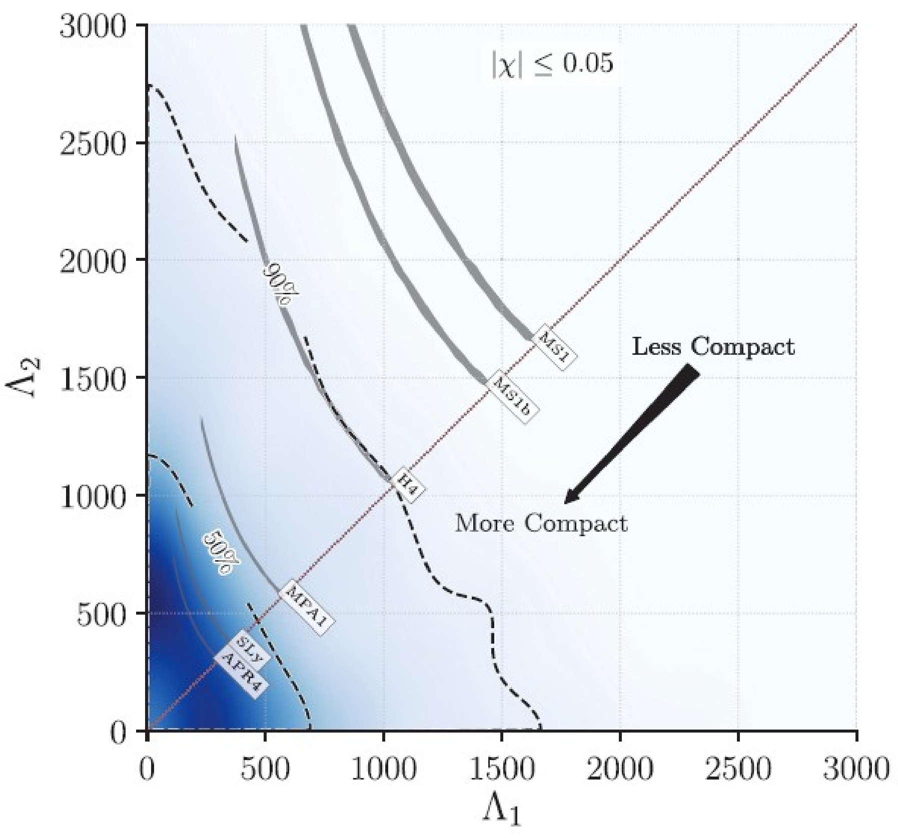
Multi-Messenger Astrophysics !!

	Low-spin priors ($\|\chi\| \leq 0.05$)
Primary mass m_1	1.36–$1.60\ M_\odot$
Secondary mass m_2	1.17–$1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc

Constraint on neutron star maximum mass

M_{TOV} < 2.17 M_sun

(Margalit & Metzger, arxiv:1710.05938)



Constraint on parameter (Λ<800)

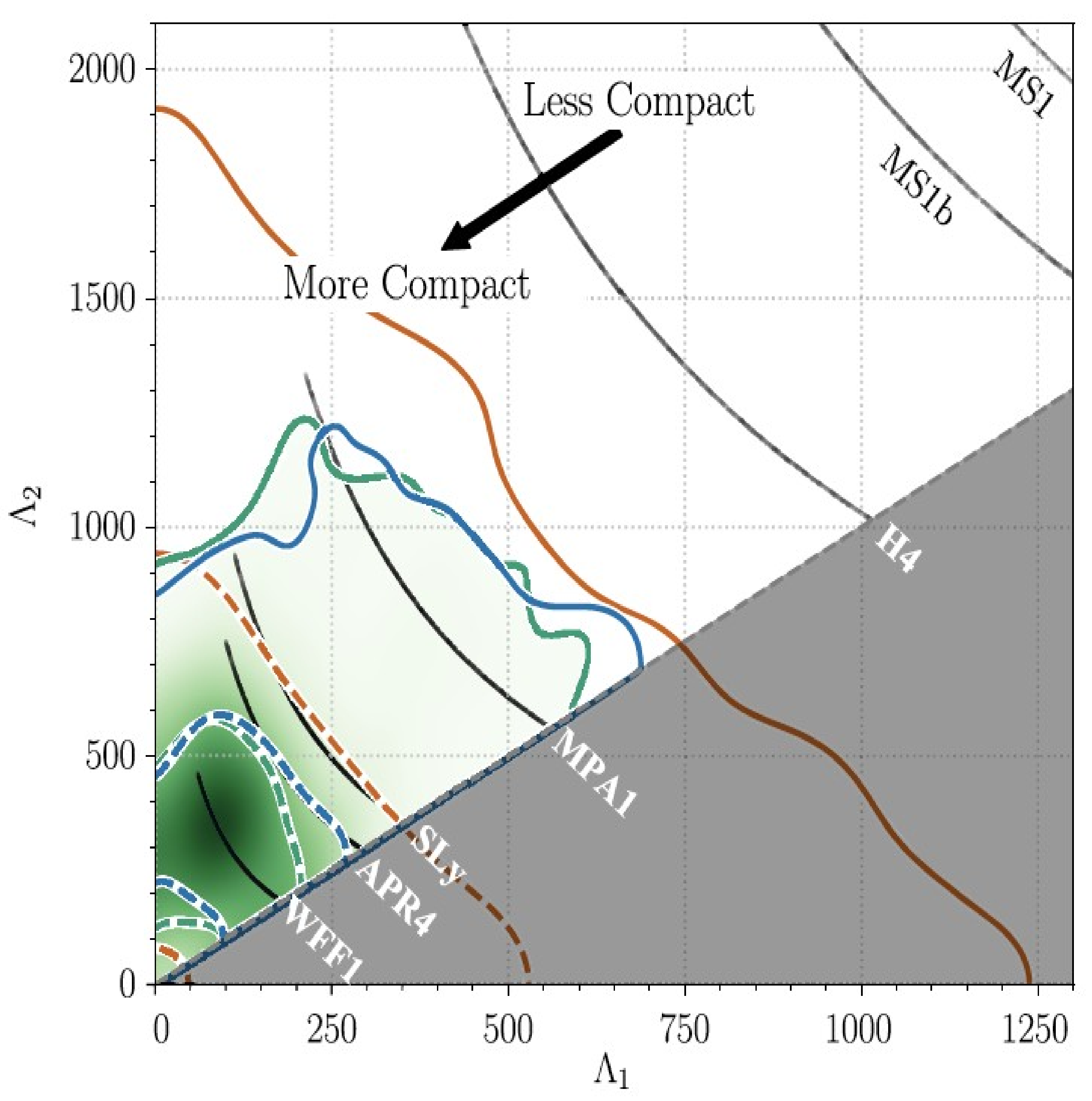
$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}$$

Dimensionless tidal deformability

$$\Lambda = (2/3)k_2[(c^2/G)(R/m)]^5$$

*) B.P. Abbott et al. [LIGO/Virgo Collab.], PRL 119, 161101 (2017); ApJLett 848, L12 (2017)

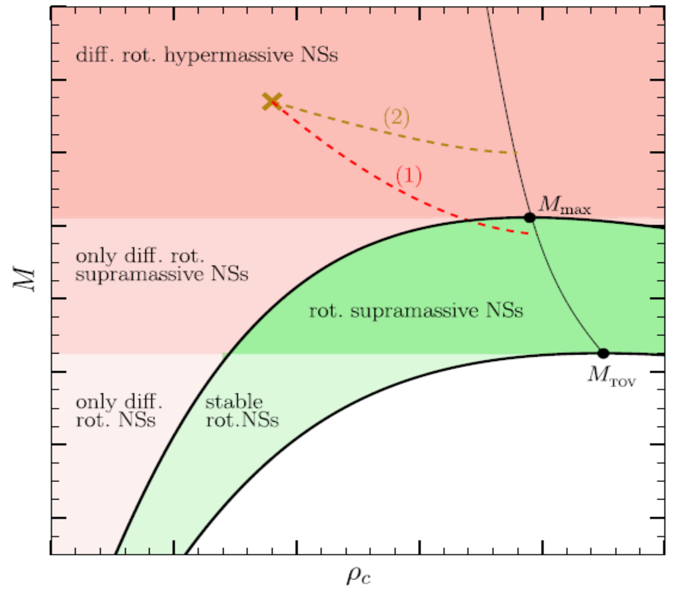
Constraints on NS mass and radii !



Constraint on maximum mass

2.01 < M_{TOV}/M_{O} < 2.16

(Rezzolla et al., arxiv:1710.05938)



LVC radius constraint

GW170817

(Abbott et al., PRL (2018))

GW190425

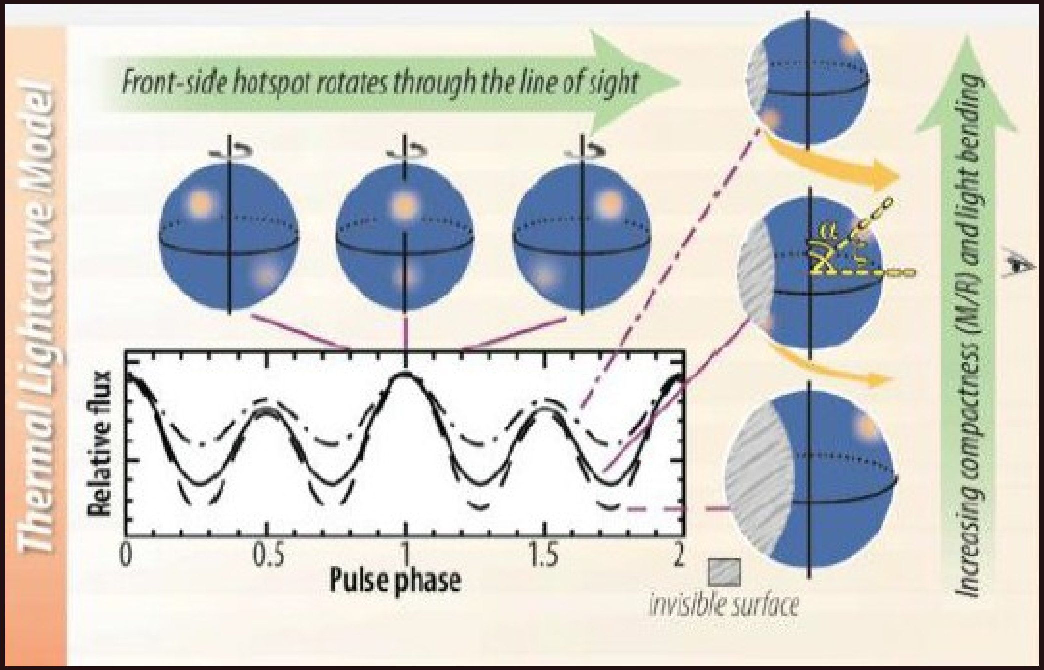
(Abbott et al., arxiv:2001.01761)

NICER mass -radius constraint

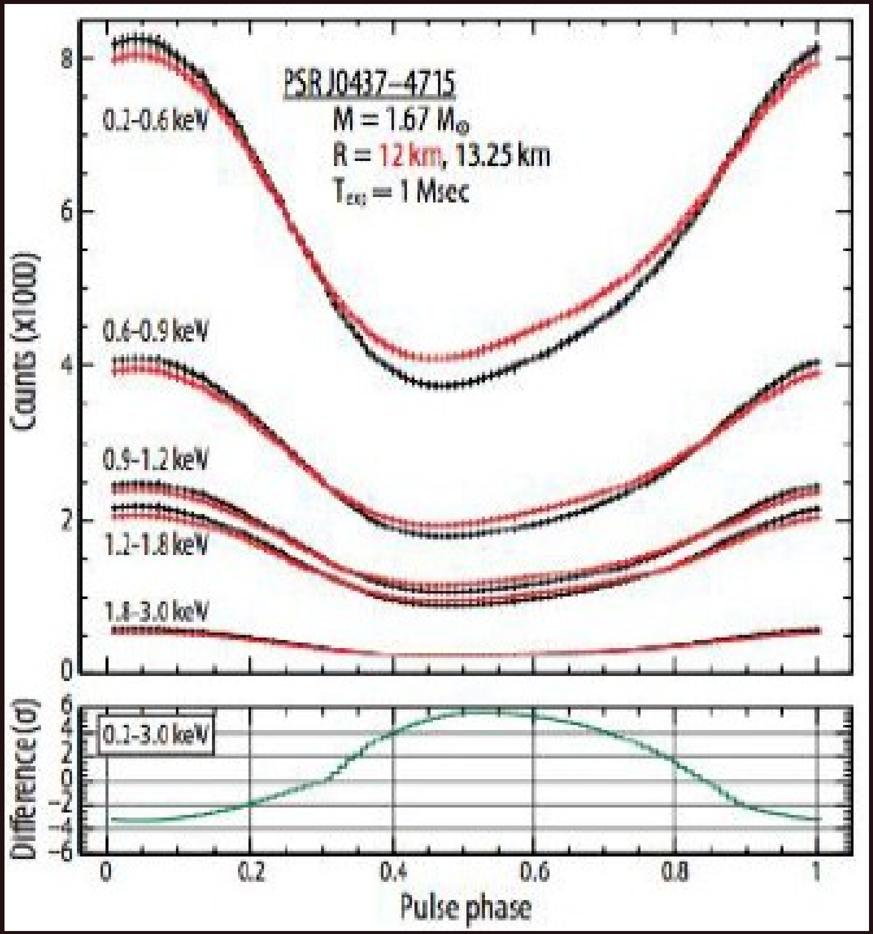
PSR J0030+0451

(Miller et al., ApJLett. (2019))

Measure NS Radii ...

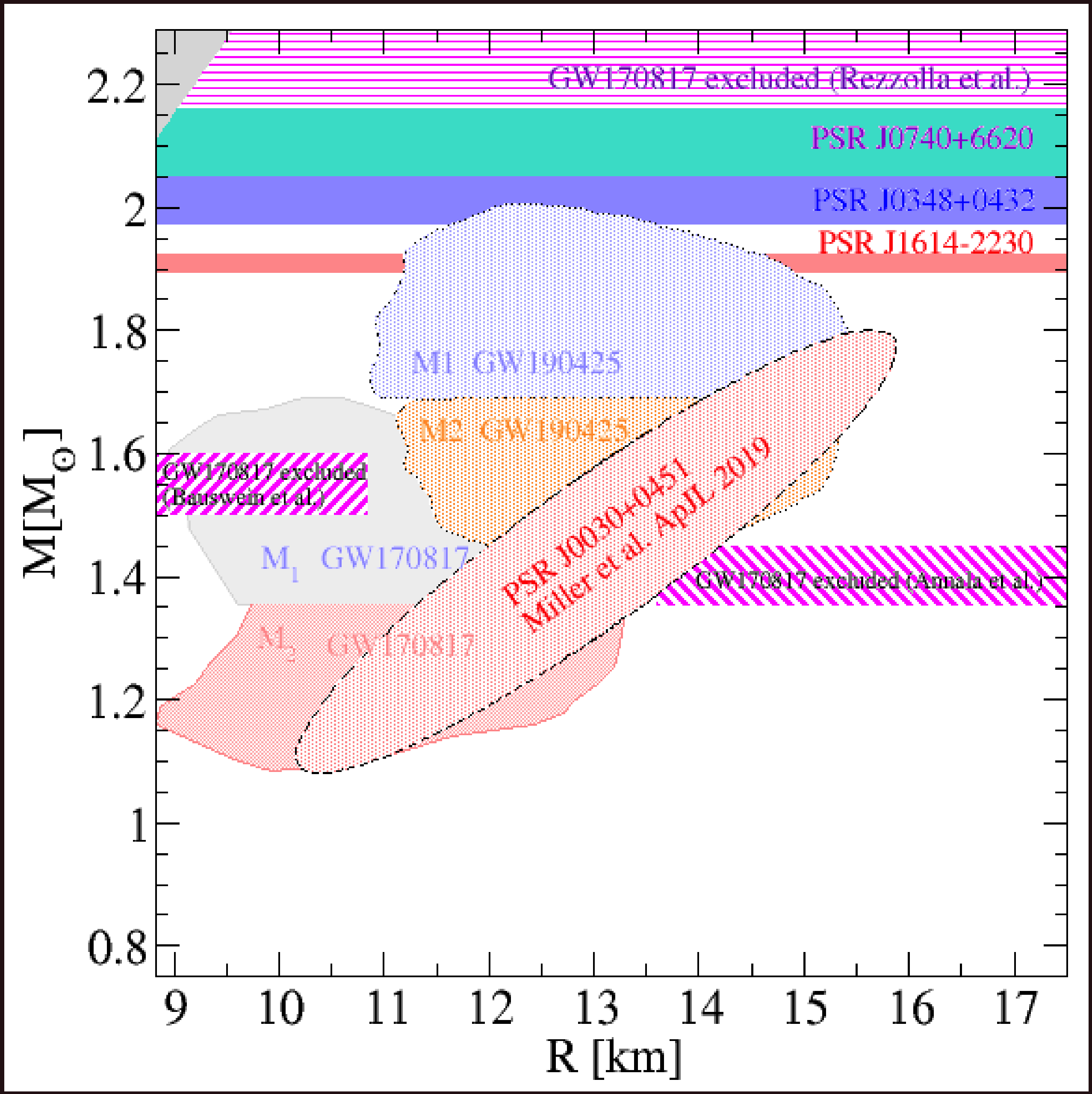


Thermal lightcurves: NS with “hot spots”



K.C. Gendreau et al., Proc. SPIE 8443 (2012) 844313 – first results end of 2019 !!

Constraints on NS mass and radii !



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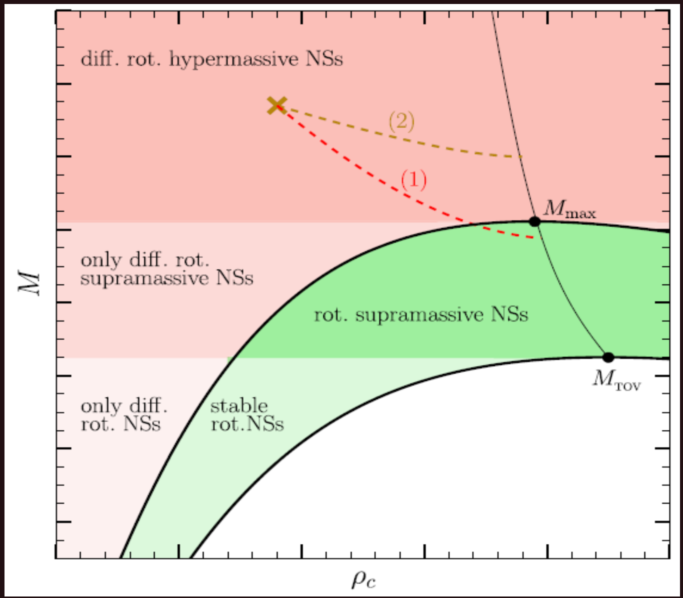

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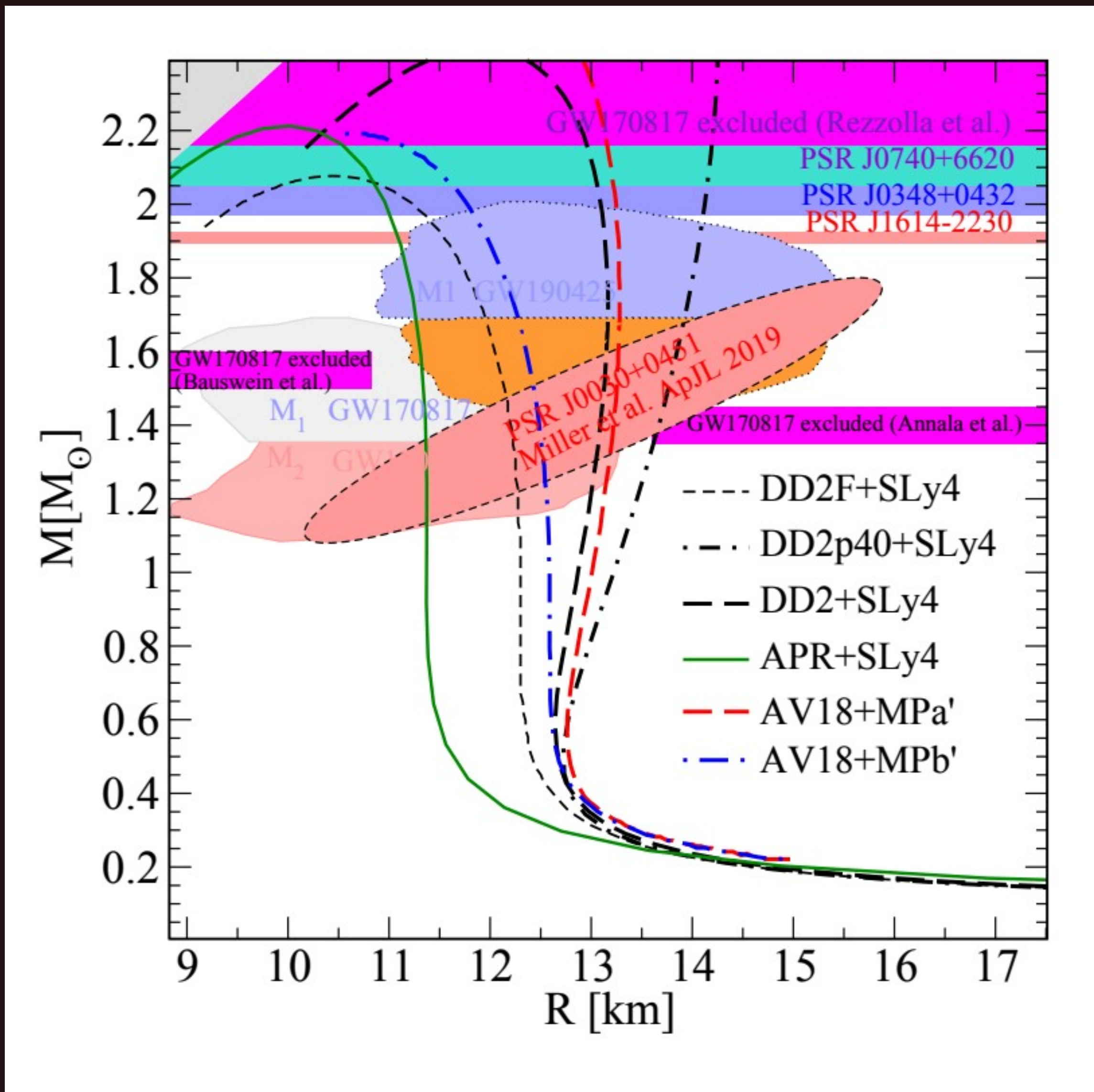
Constraints on NS mass and radii !



AV18*: Yamamoto, Togashi et al., Phys. Rev C 96 (2017) 065804
DD2*: Typel, Röpke, Klähn, et al., Phys. Rev. C 81 (2010) 015803

Constraint on maximum mass
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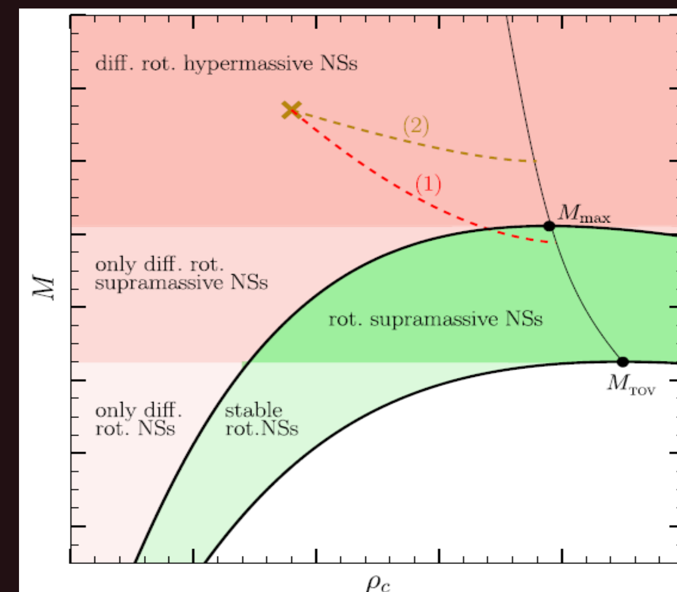

LVC radius constraint
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GW190425
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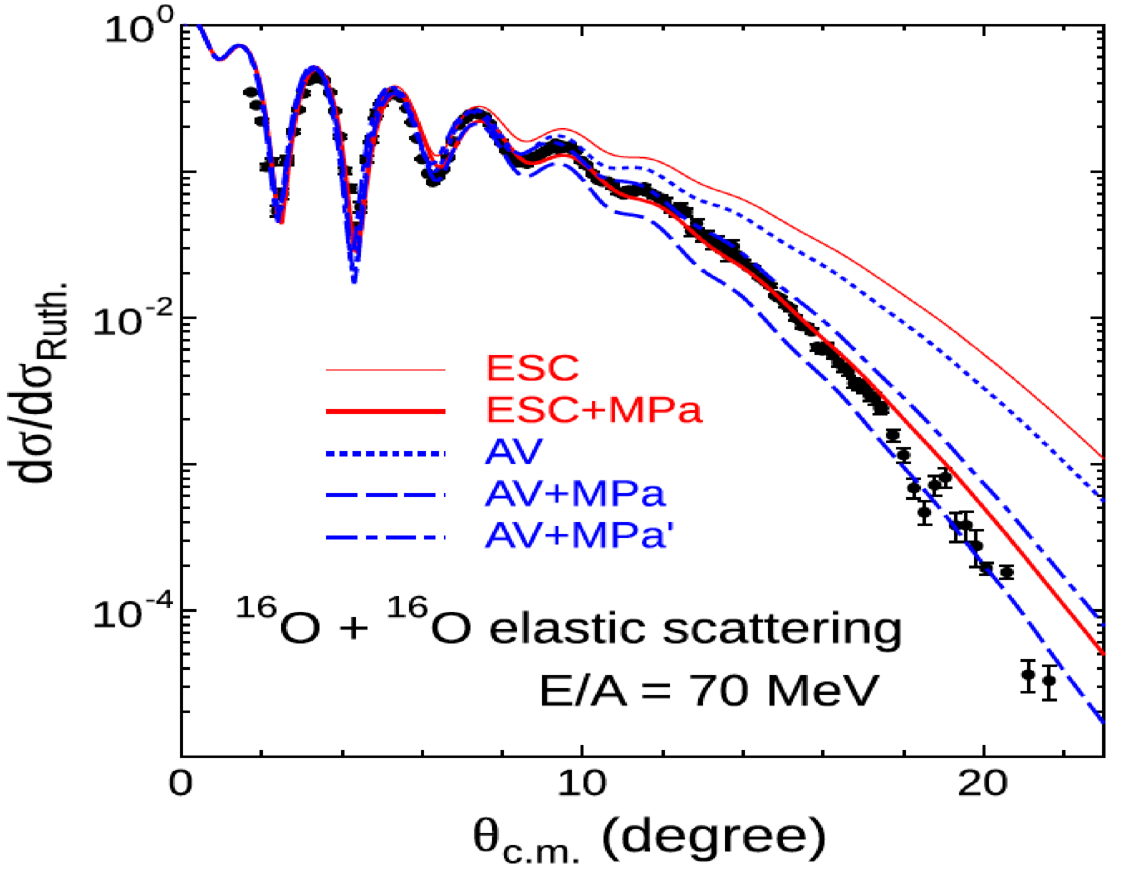
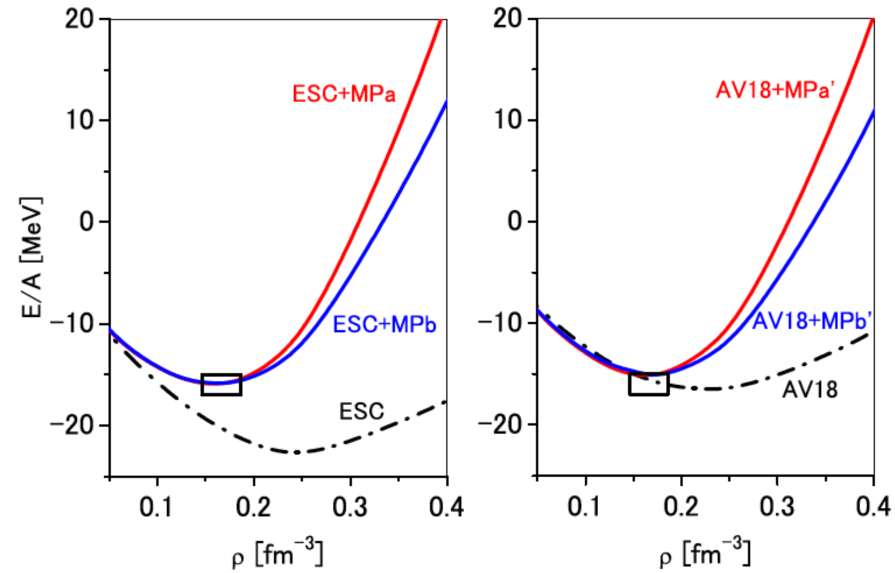
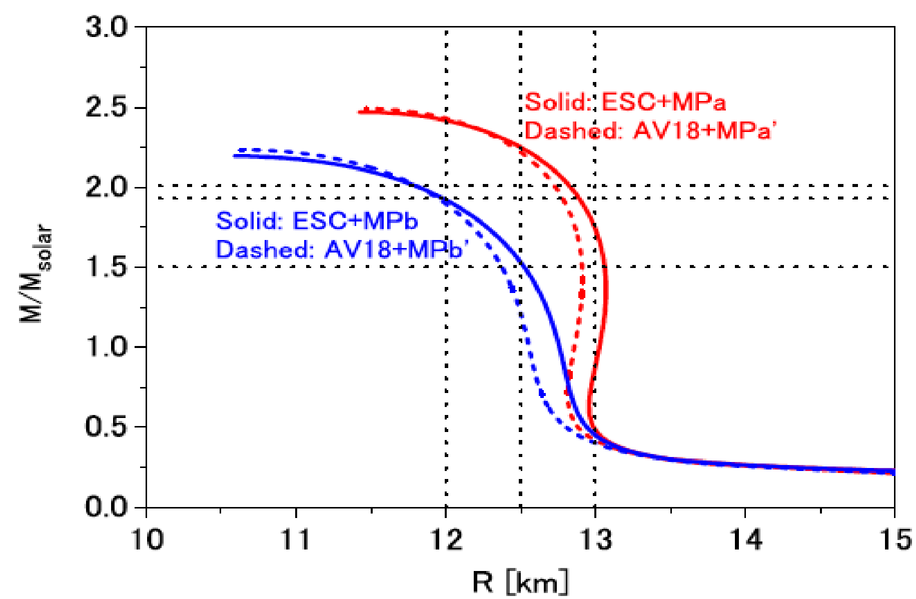
(Miller et al., ApJLett. (2019))

Shall the APR EoS be abandoned?

Y. Yamamoto, H. Togashi, T. Tamagawa, T. Furumoto, N. Yasutake, T. Rijken, PRC 96 (2017)



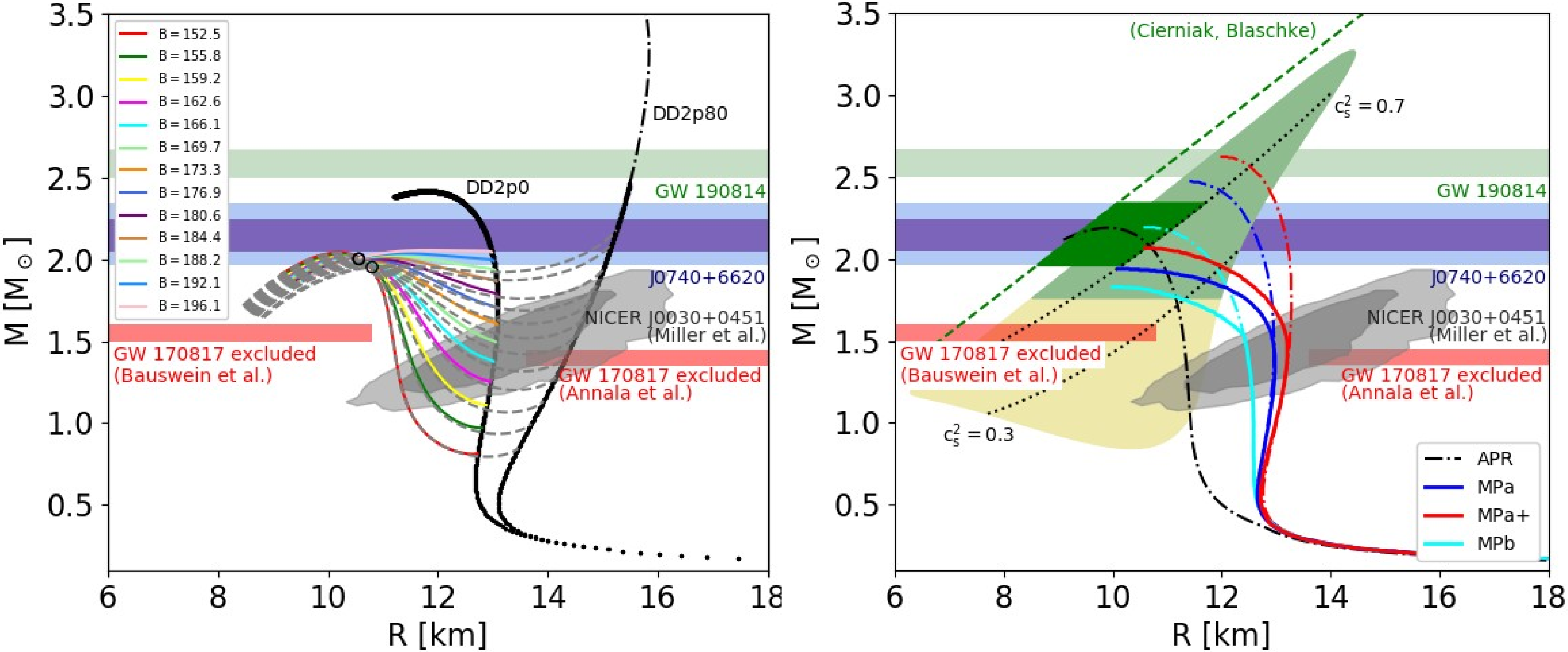




Short-range multipomeron exchange potential (MPP) added to AV18 potential gives significant improvement of large-angle scattering cross section (s.a.) and the Nuclear saturation properties, when compared to APR.
→ Neutron star radii R(M< 2 M_sun) > 12 km !!

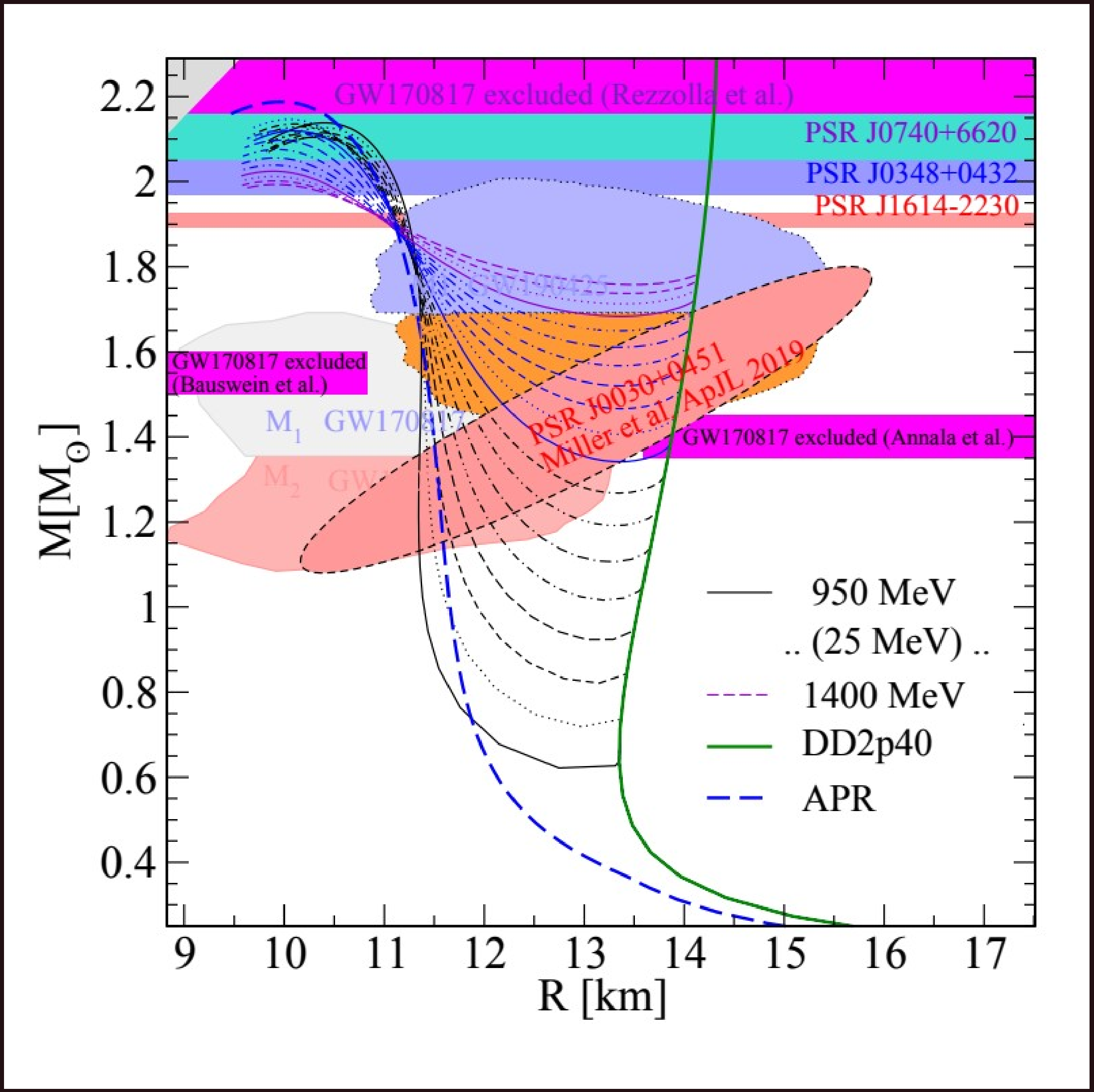
Can NICER prove J0740+6620 to be a hybrid star?

Ongoing work with Mateusz Cierniak et al., see arxiv:2009.12353; EPJ ST 229 (22-23) 3663



If radius of PSR J0740+6620 is measured in the dark-green region then it must harbor a core of superconducting quark matter!

Constraints on NS mass and radii !



Blaschke, Ayriyan, Alvarez-Castillo et al., Universe 6 (2020) 81

Constraint on maximum mass

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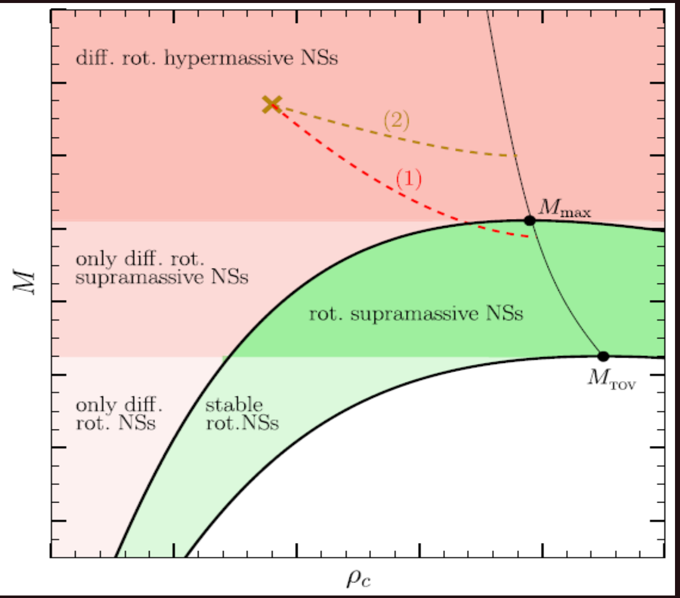
(Rezzolla et al., arxiv:1710.05938)



LVC radius constraint

GW170817

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NICER mass -radius constraint

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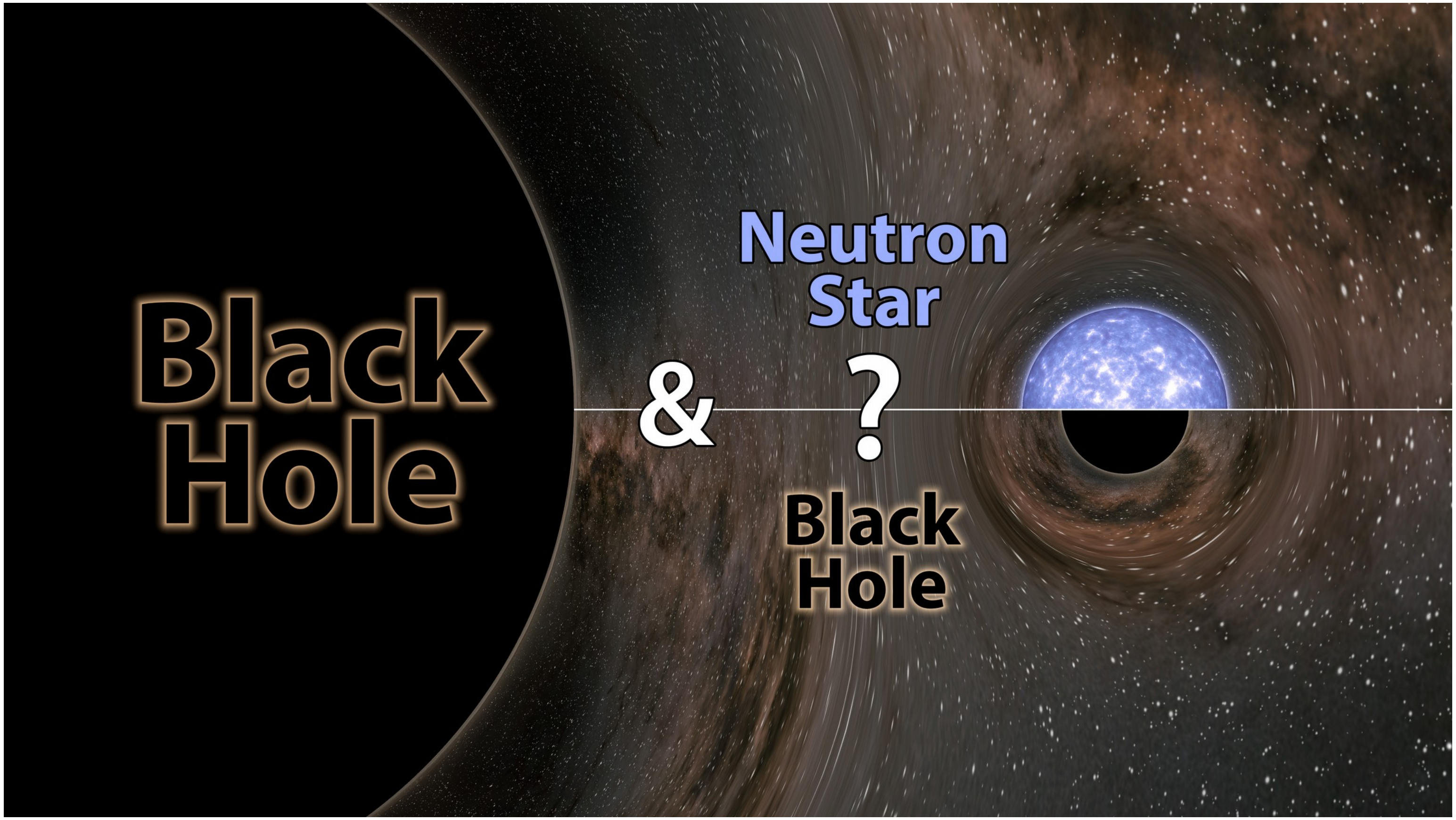
(Miller et al., ApJLett. (2019))

Limits of Neutron Star Physics

GW190814



What is the limiting
Mass of a neutron
Star?

Was GW190814 a
Merger of a 23-M_sun
Black hole with the

Lightest Black hole

Or

Heaviest Neutron star

at 2.6 M_sun ??

Maybe not only NS but even Hybrid star ?

Work with Mateusz Cierniak, see arxiv: 2012.15785 & 2009.12353; EPJ ST 229, 3663 (2020)

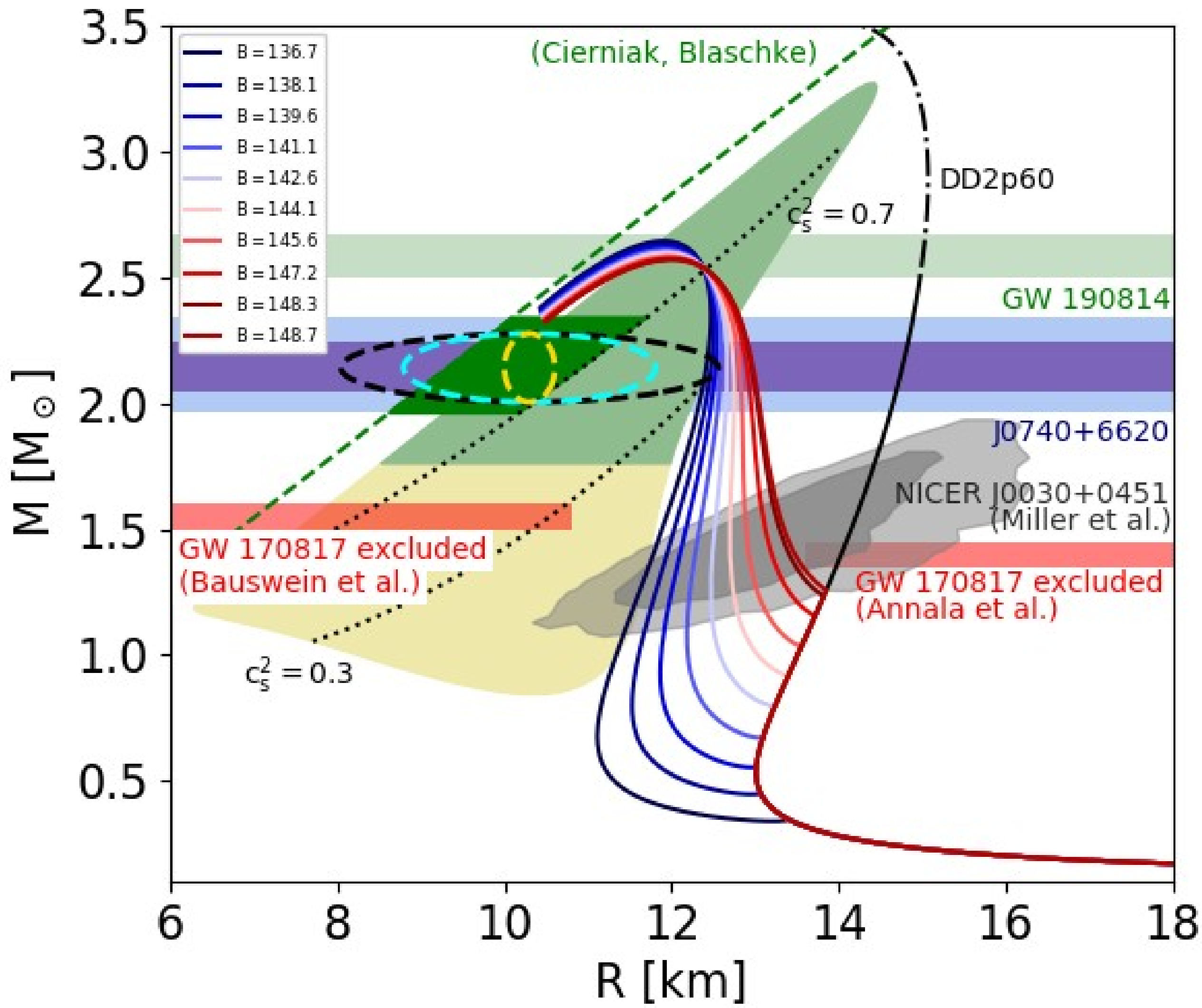
Dense quark plasma
(color supercond. phase):

Constant-speed-of-sound (CSS)
Equation of state (EoS)

$$p(\mu) = A(\mu/\mu_0)^{1+c_s^{-2}} - B,$$

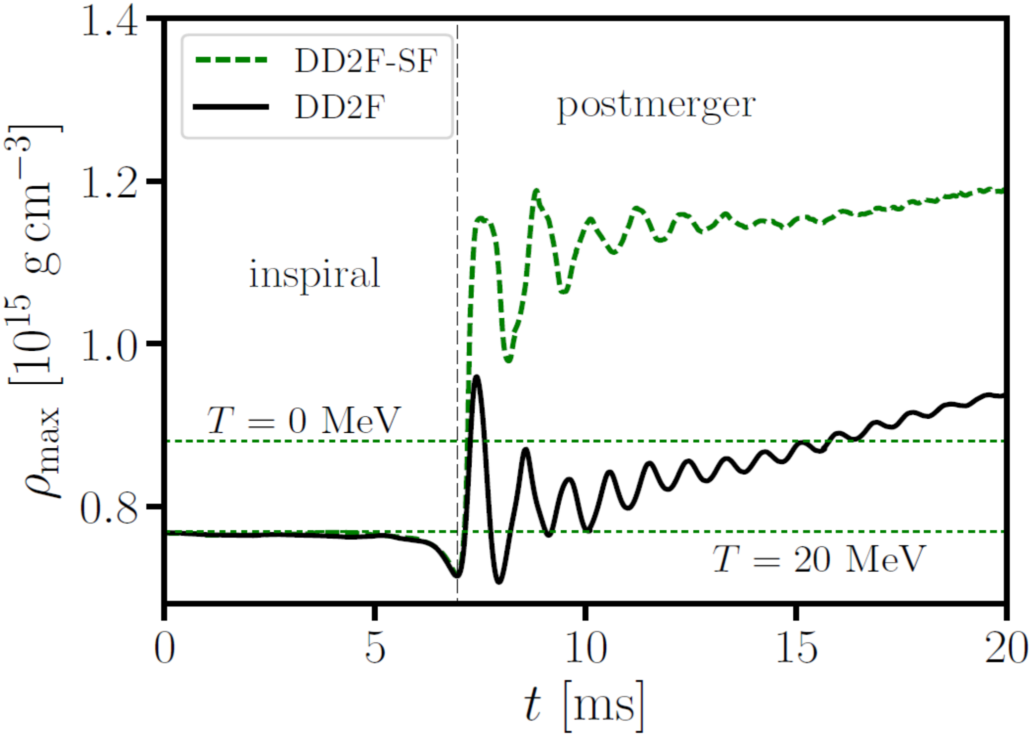
$$p = c_s^2 \varepsilon - (1 + c_s^2)B$$

Maxwell construction with
(1st order phase transition)
Relativistic Density Functional
EoS “DD2pxy” by S. Typel
With density-dependent coupling
And excluded volume v=x.y fm^3

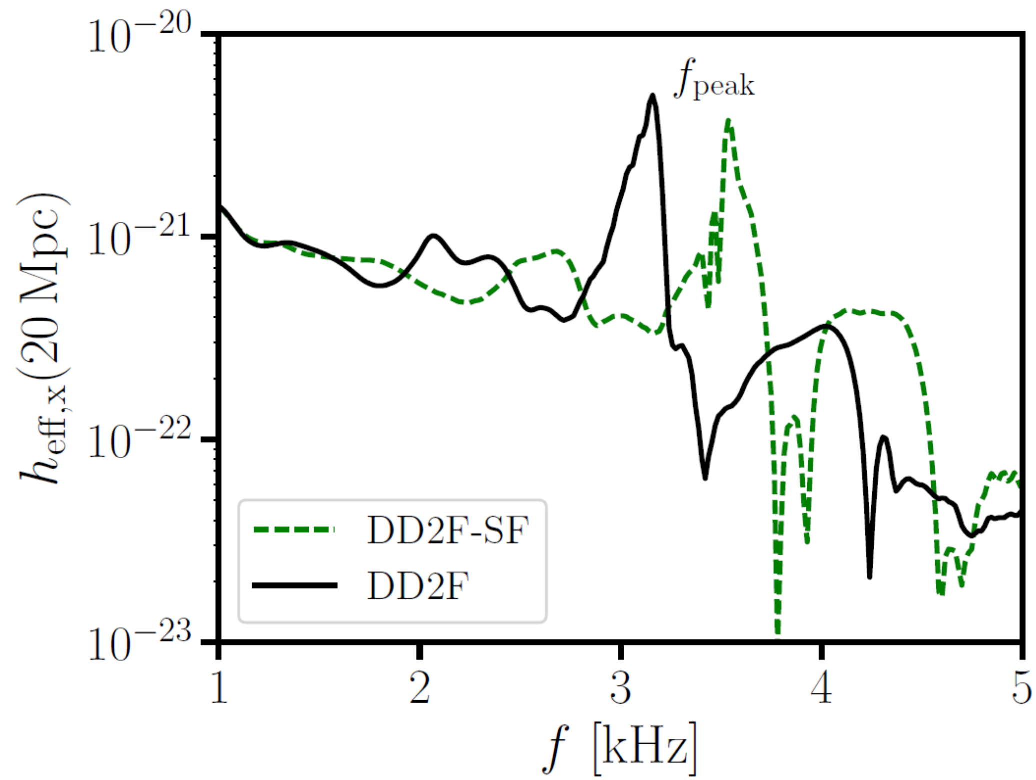


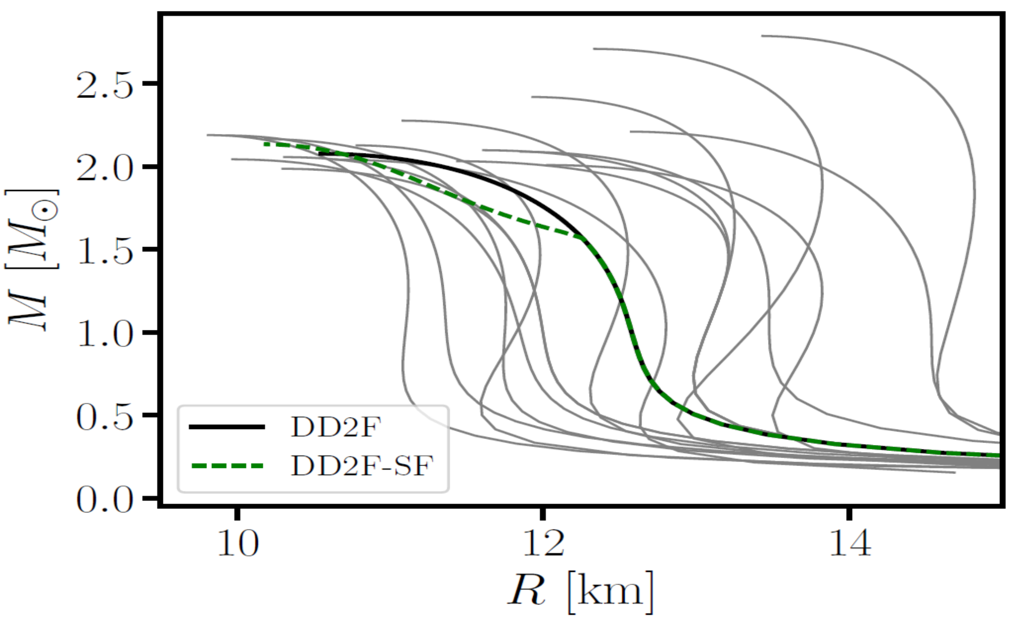
2.6 M_sun object can by a hybrid neutron star! With early onset of deconfinement and twins!

Hybrid star formation in postmerger phase



Strong phase transition in postmerger GW,
A. Bauswein et al. arxiv:1809.01116



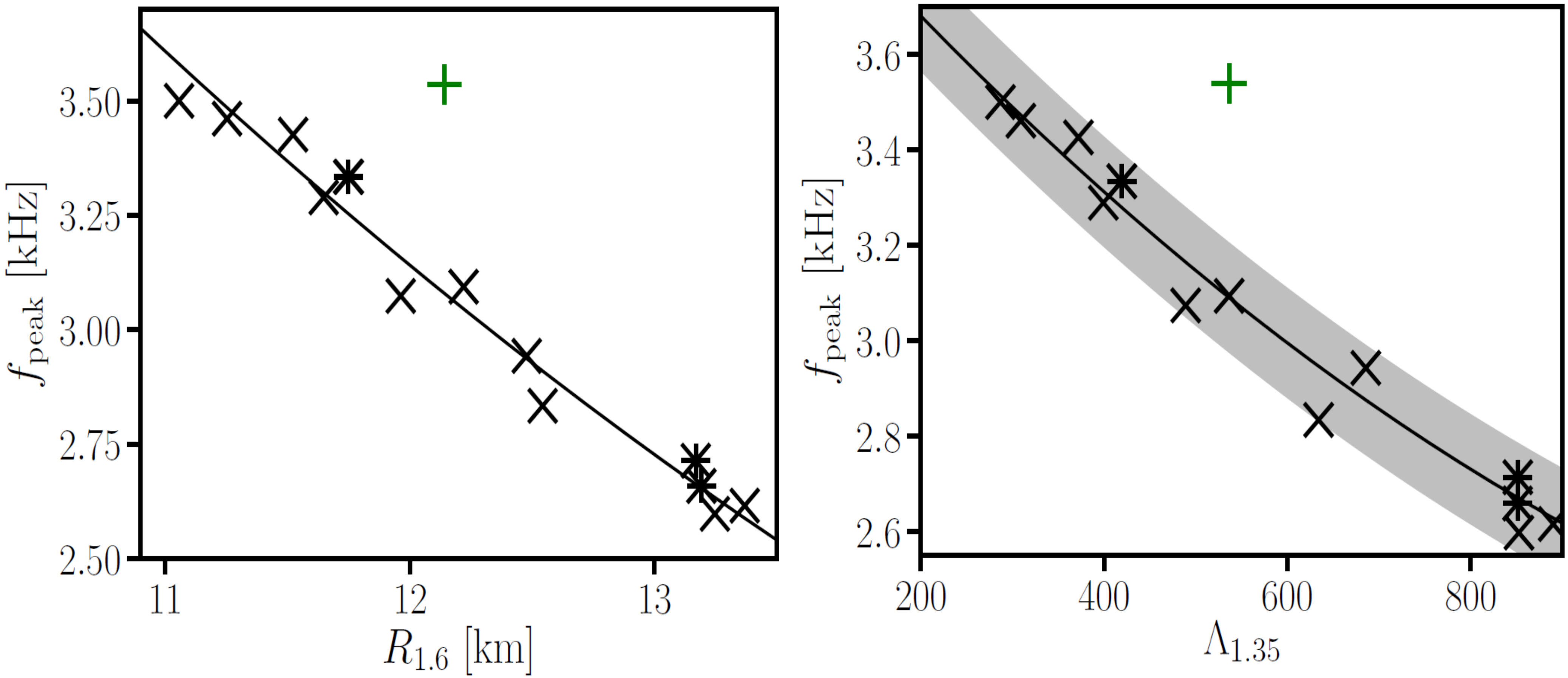


Hybrid star formation during NS merger
→ higher densities and compacter star
→ higher peak frequency of the GW

A. Bauswein et al., PRL 122 (2019) 061102

Hybrid star formation in postmerger phase

Strong phase transition in postmerger GW signal,
A. Bauswein et al., PRL 122 (2019) 061102; [arxiv:1809.01116]

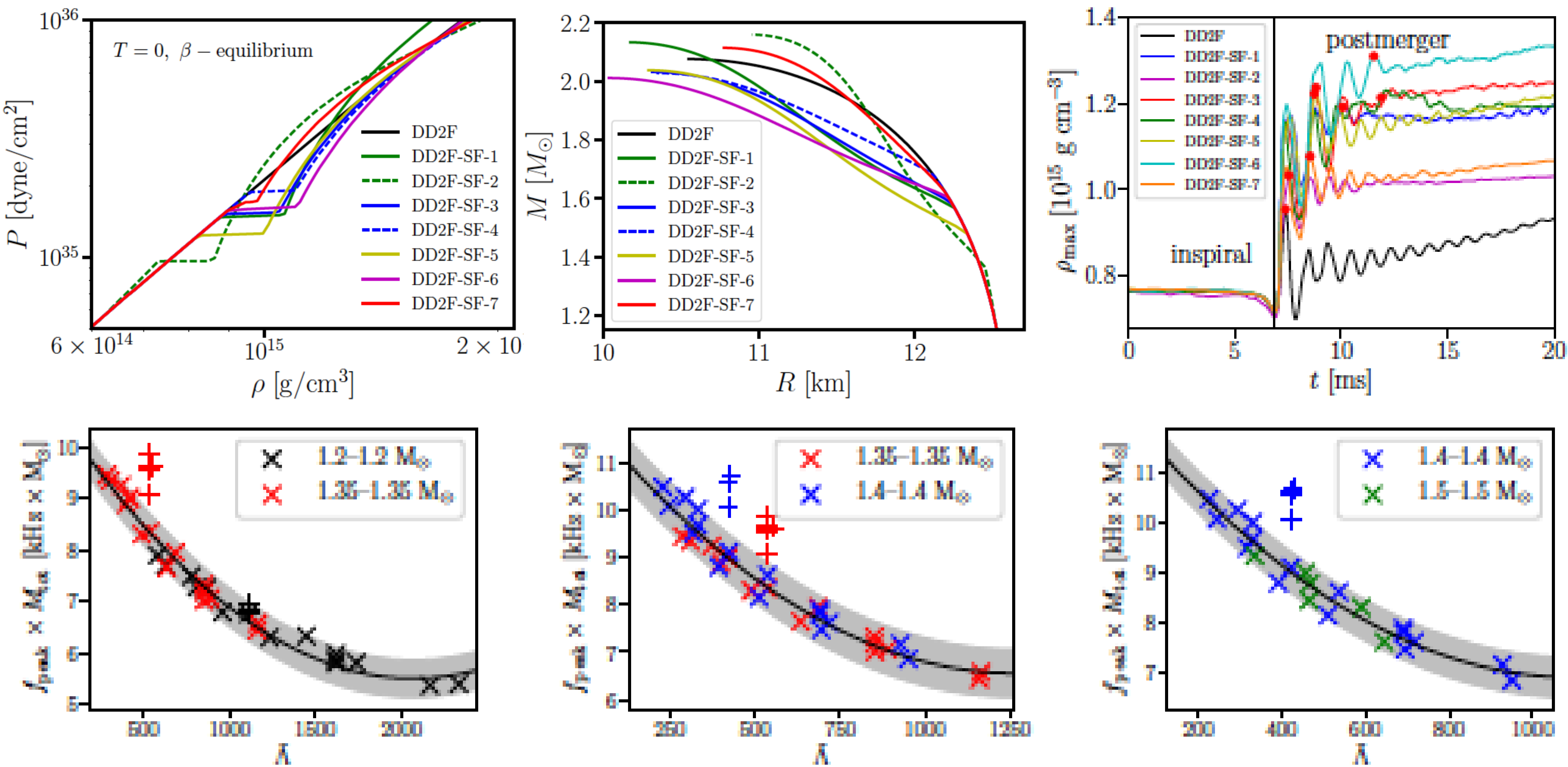


Strong deviation from **f_{peak} – $R_{1.6}$** relation signals **strong phase transition in** NS merger**!**

Complementarity of **f_{peak}** from postmerger with tidal deformability **$\Lambda_{1.35}$** from inspiral phase.

Hybrid star formation in postmerger phase

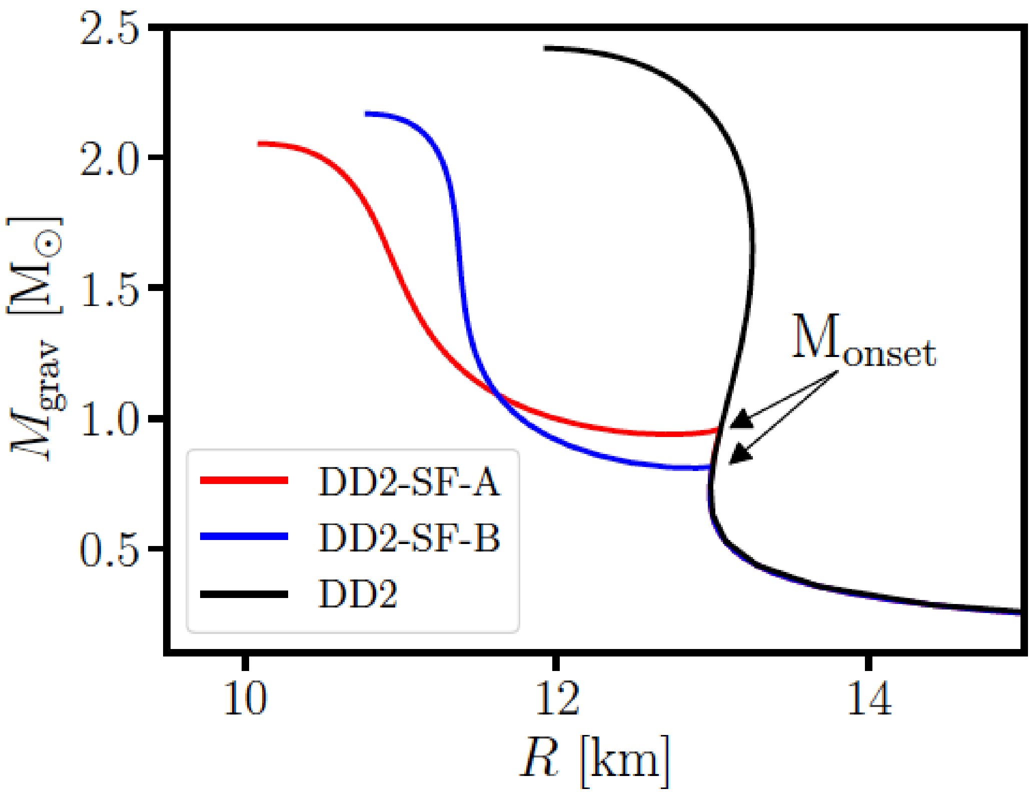
Strong phase transition in postmerger GW signal, S. Blacker et al., arxiv:2006.03789

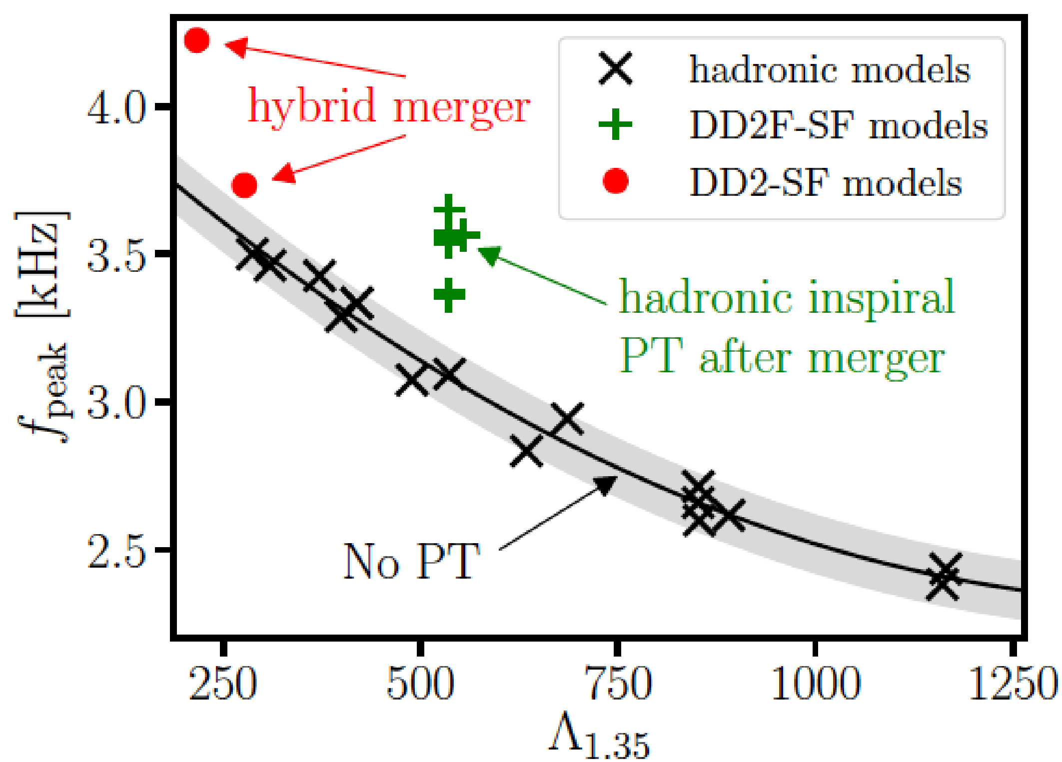


Dominant postmerger frequency f_{peak} vs. tidal deformability $\Lambda_{1.35}$ from inspiral phase:
Results from hybrid models appear as **outliers** of the grey band (maximal deviation of purely hadronic models from a least squares fit) = signalling a **strong phase transition in** NS **!**

GW signal of deconfinement in merger of hybrid stars

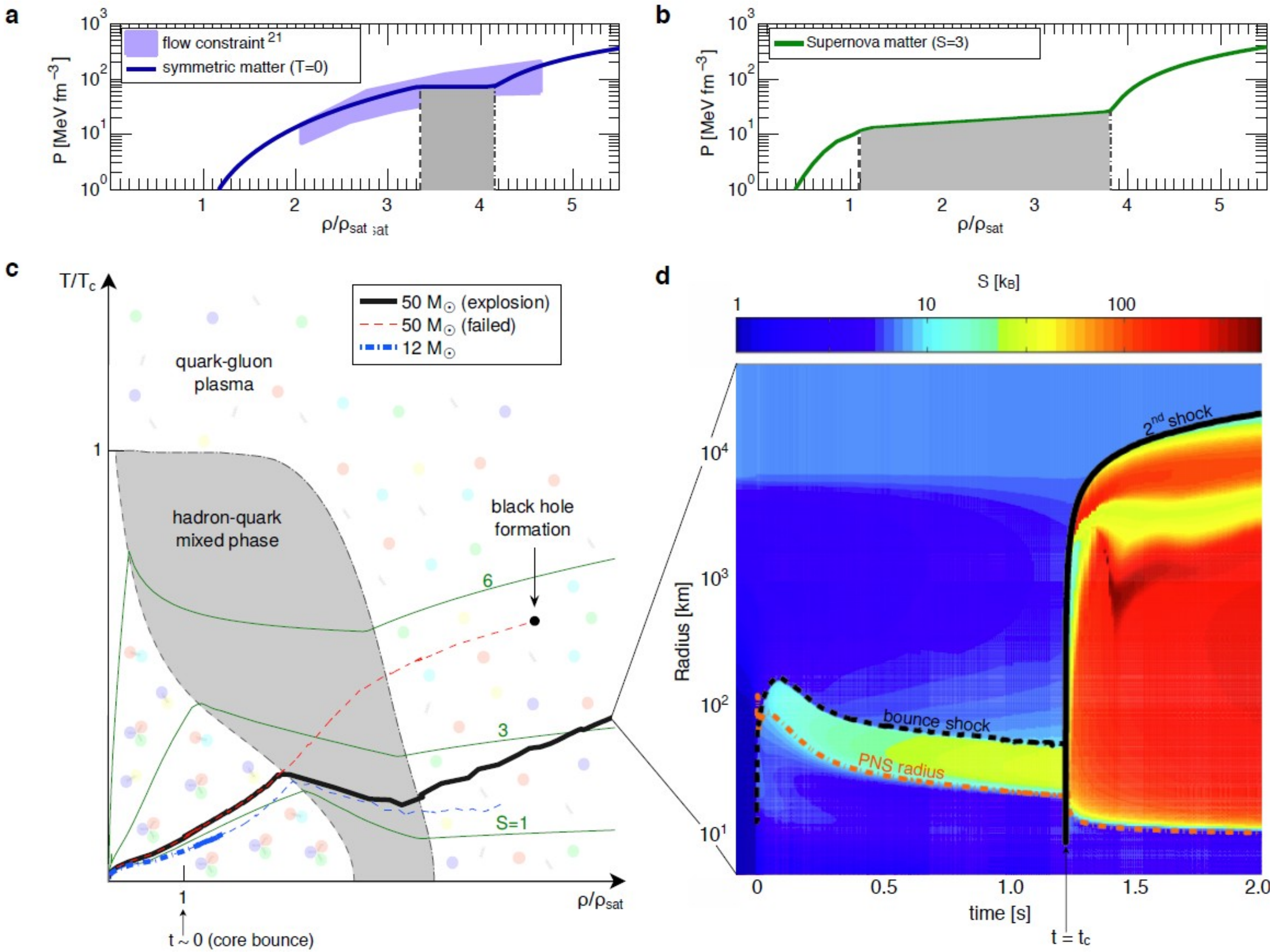
Merger of hybrid stars with early phase transition: Bauswein & Blacker, EPJ ST 229 (2020)





The combination of stiff hadronic EoS (DD2) and string-flip (SF) model allows for early onset of deconfinement in low-mass neutron stars and even third-family solutions (mass twins). For these cases, the event GW170817 could have been a **merger of two hybrid stars**! Also in these cases (red dots in above figure) a **significant deviation** from the grey band of Purely hadronic star mergers without a phase transition is obtained!

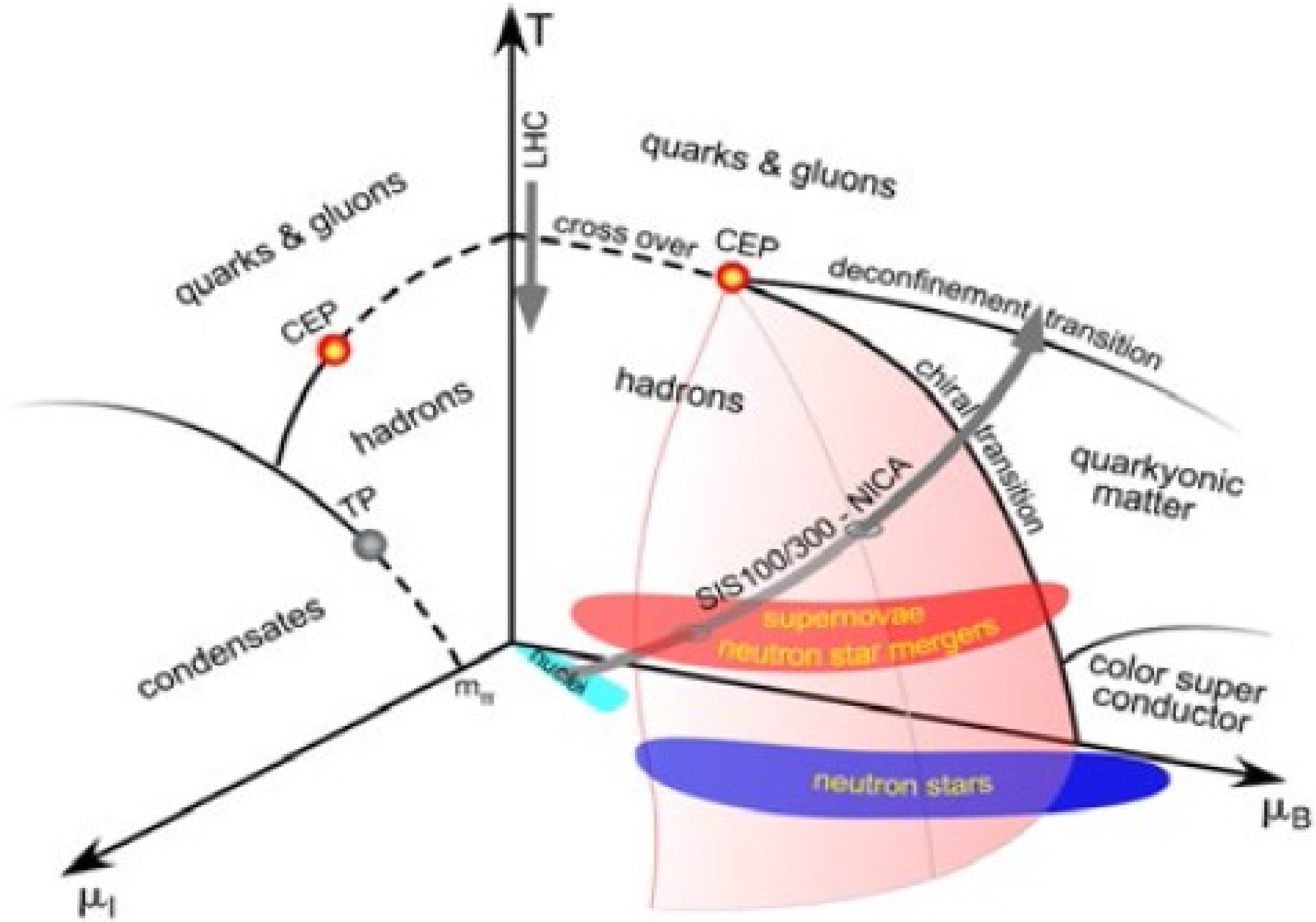
Deconfinement transition as SN explosion mechanism



Progenitor:
M = 50 M_O

T. Fischer, N.-U. Bastian et al., Quark deconfinement as supernova engine of massive blue Supergiant star explosions, Nature Astronomy 2 (2018) 980-986; arxiv:1712.08788

CEP in the QCD phase diagram: HIC vs. Astrophysics

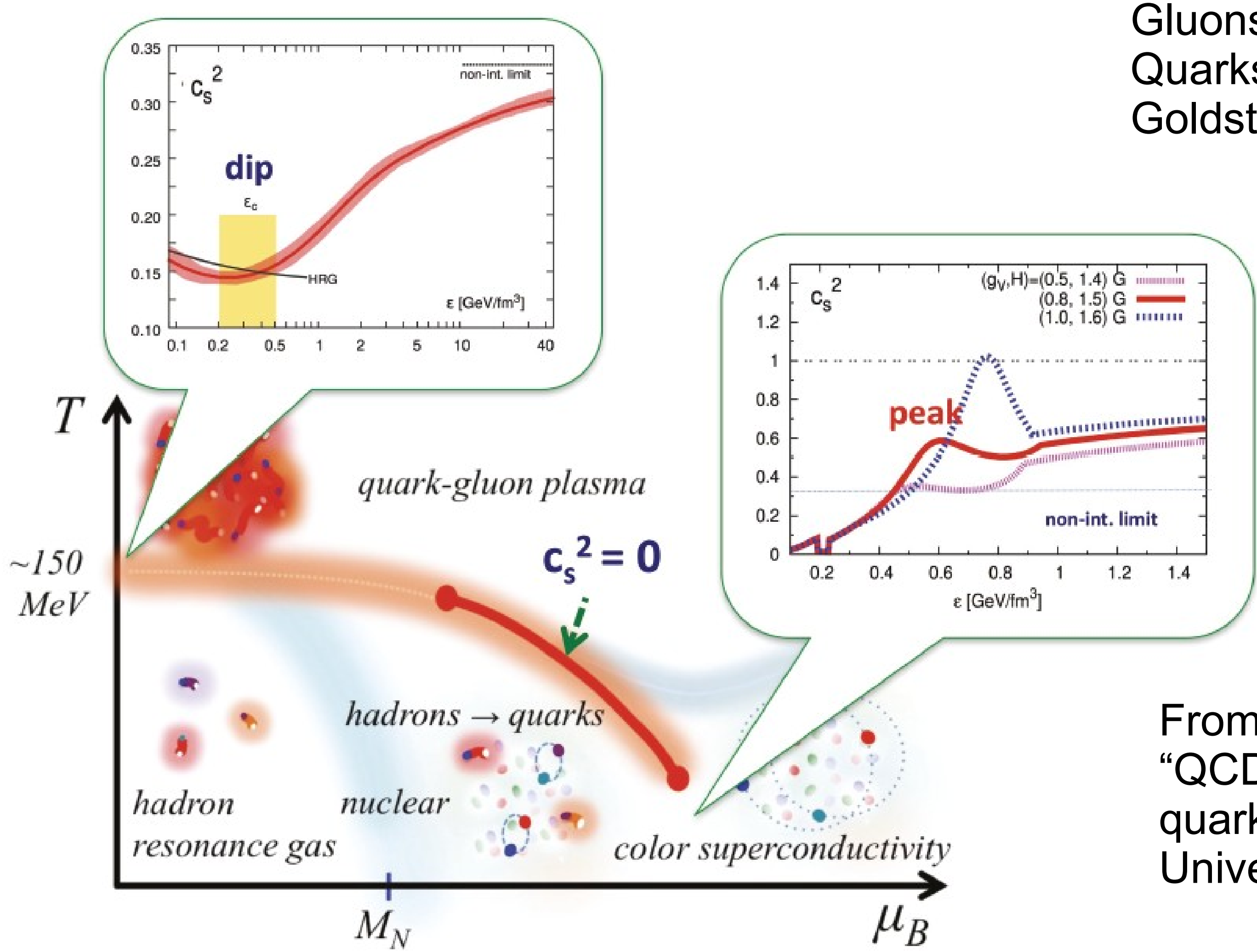


NuPECC Long Range Plan 2017; http://www.nupecc.org

A. Andronic, D. Blaschke, et al., “Hadron production ...”, Nucl. Phys. A 837 (2010) 65 - 86

2^{nd} CEP in QCD phase diagram: Quark-Hadron Continuity?

Gluons ↔ Vector mesons
Quarks ↔ Baryons
Goldstones ↔ Pseudoscalar mesons



From: T. Kojo,
“QCD equations of state in quark-hadron continuity”,
Universe 4 (2018) 42

T. Schaefer & F. Wilczek, Phys. Rev. Lett. 82 (1999) 3956
C. Wetterich, Phys. Lett. B 462 (1999) 164
T. Hatsuda, M. Tachibana, T. Yamamoto & G. Baym, Phys. Rev. Lett. 97 (2006) 122001

Conclusions

- First observations of binary mergers open new possibilities to constrain properties of the Quark-gluon plasma at low temperatures and high baryon densities. A hybrid EoS is presented that allows to estimate quark plasma parameters in those compact stars

- GW170817: narrow window of small radii at 1.4 M_sun (Capano et al.: 10.4 km < R_1.4 < 11.9) strongly suggests an early onset of deconfinement with a critical density n_c < 2 n_0 and an onset mass M_onset < 1.0 M_sun [Blaschke & Cierniak: 2012.15785]

- GW190814: the lighter object in the extemely asymmetric merger with its 2.6 M_sun can be either the heaviest neutron star or the lightest black hole. The central baryon density in such high-mass hybrid stars reaches 5.3 n_0. Our EoS allows it to be a hybrid star, even on a third family branch (mass twin stars), disproving Christian & Schaffner-Bielich [arxiv:2011.01001]

- 2MASS J05215658+4359220 is a rapidly rotating giant star in a binary with an unseen massive Companion of 3.3 +2.8 –0.7 M_sun that can be a low-mass black hole or a massive NS [T.A. Thompson et al., Science 366, 637-640 (2019)]

- PSR J0740+6620 must have a deconfined quark matter core if the NICER radius measurement gives a value significantly below 11 km at its mass of 2.14 +0.1 – 0.09 M_sun. Such a result would disprove the "two families" scenario of Drago & Pagliara, PRD 102 (2020) For the baryon density at the center of a star with 2.1 M_sun we find 7.5 n_0, n_0=0.15 1/fm^3.

D. Blaschke & M. Cierniak, "Studying the onset of deconfinement ...", arxiv:2012.15785; Astron. Nachr. (2021)

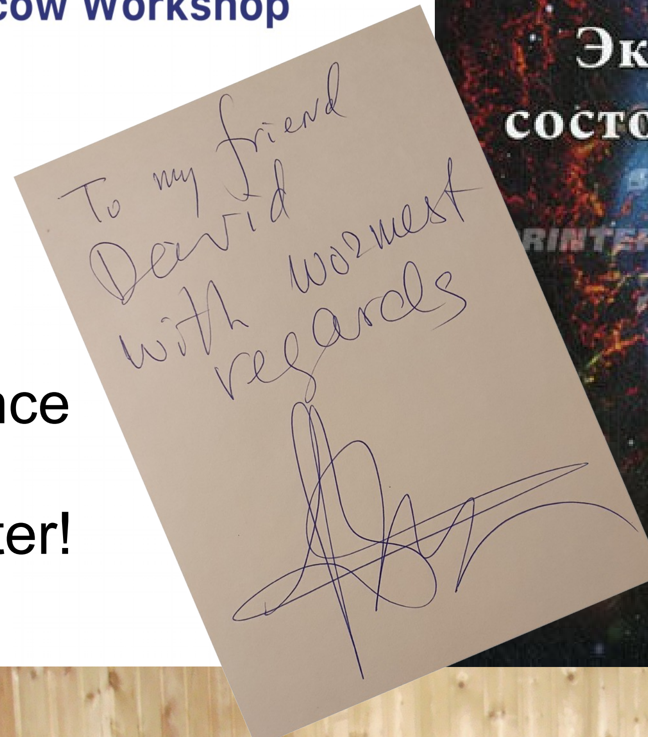
NPP 2020

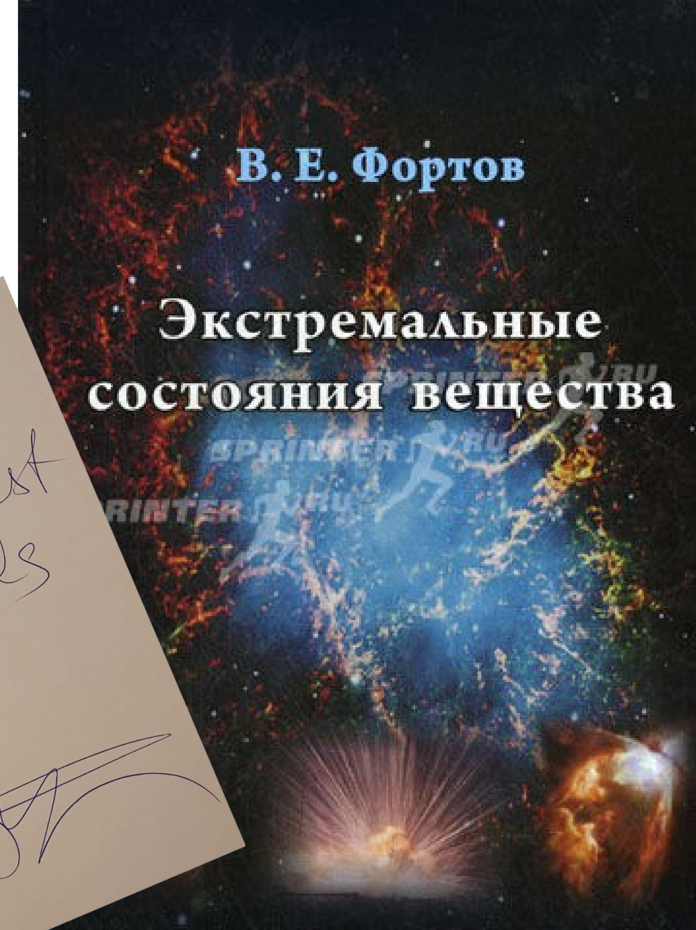
NON-IDEAL PLASMA PHYSICS

Annual Moscow Workshop

Thank you, Vladimir!

For sharing your experience with extreme states of matter!





57th Karpacz Winter School of Theoretical Physics and PHAROS COST Action CA16214 Training School COMING !!! #

Karpacz: March 07 - 13, 2021

Equation of State of dense matter and multimessenger astronomy

Directors: David Blaschke

Organizers: David Blaschke, Sebastiano Bermuzzi, Tobias Fischer, Armen Sedrakian, Laura Tolos, Ludwik Turko

https://events.ift.uni.wroc.pl/event/68

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