Dense nuclear matter in the cores of neutron stars

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RagTime 22 Online
October 23, 2020

Outline

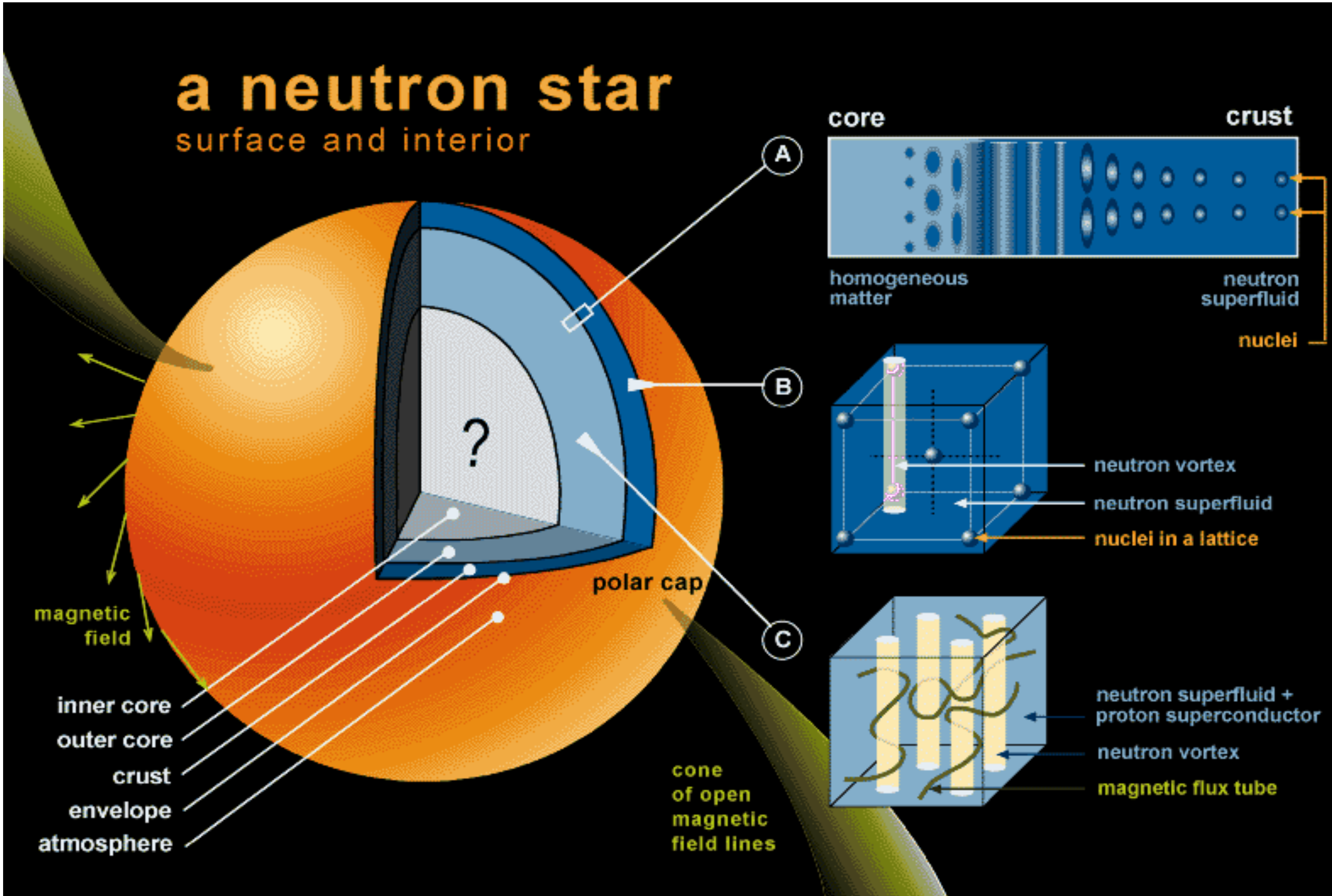
- A brief introduction to the neutron star matter equation of state (EoS) and its location within the QCD phase diagram.

- Compact star model predictions.

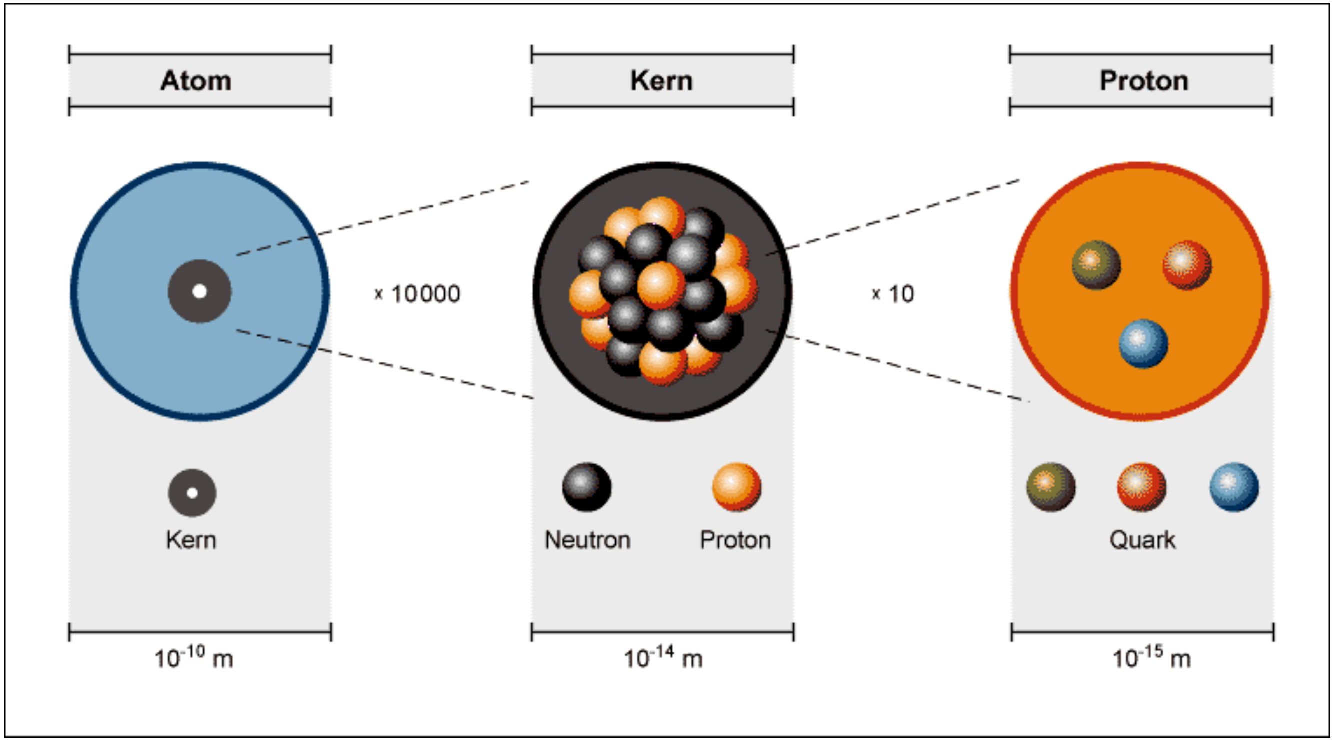
- Astrophysics measurements of compact stars: multi-messenger astronomy: GW170817 event & NICER measurements.

- Astrophysical implications and perspectives.

Superdense objects – what is inside?



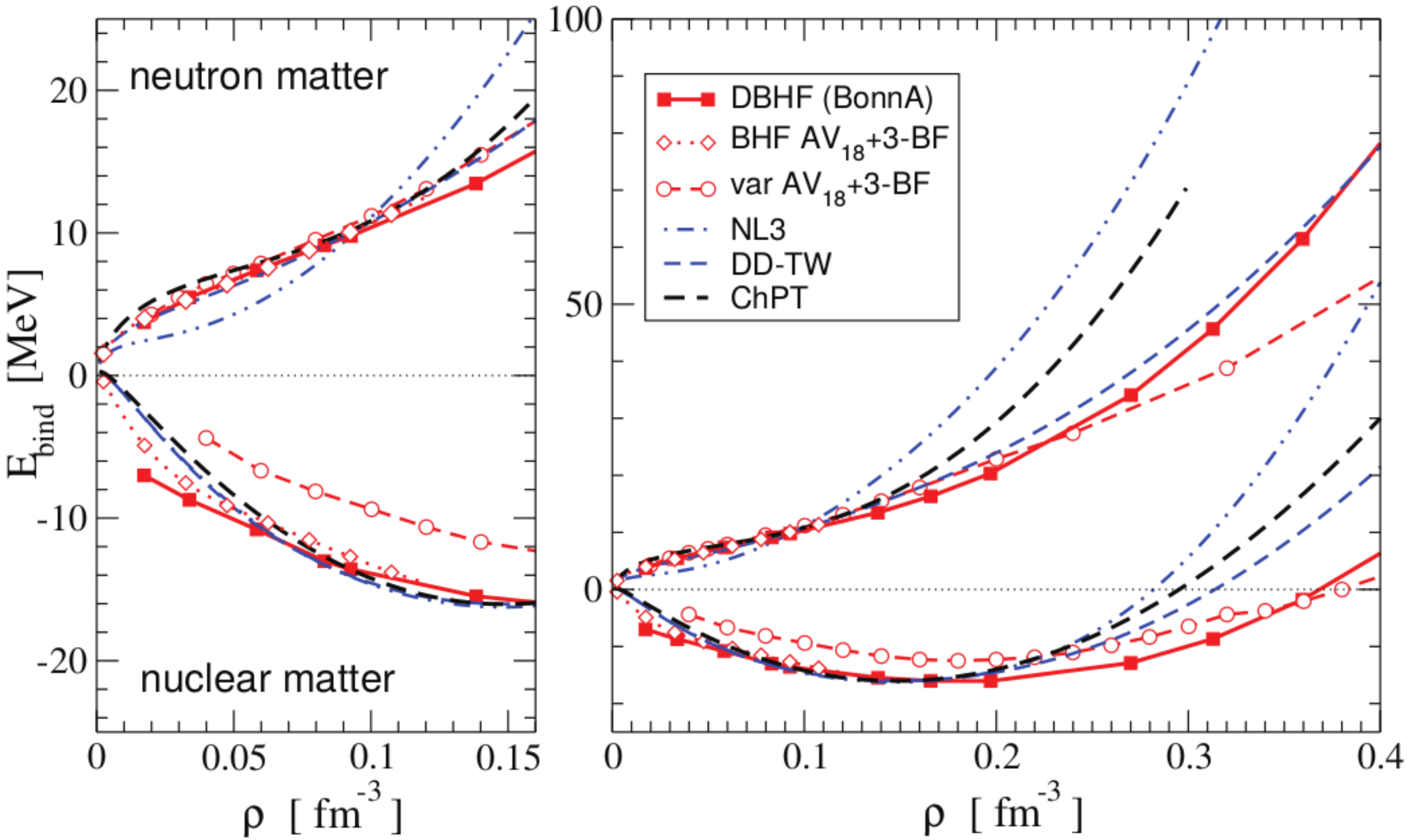
Superdense objects – what is inside?



Nucleus, A nucleons: R_A=1.2 10^{-13} cm $A^{1/3}$; ρ_0=A1.67 10^{-24} g/(4π/3 $R_A{}^3$)= 2.3 10^{14} g/cm^3

Neutron star: R= 10 km; ρ= 2 Mo/(4π/3 R^3) = 4 10^{33} g/(4 10^{18} cm^3)= 10^{15} g/cm^3 = 4 ρ_0

Nuclear Matter



C. Fuchs, H.H. Wolter, EPJA 30(2006)5

Flow Constraint

Klaehn et al. PhysRev C74 (2006)
P. Danielewicz, R. Lacey and W.G. Lynch, Science 298, 1592 (2002)

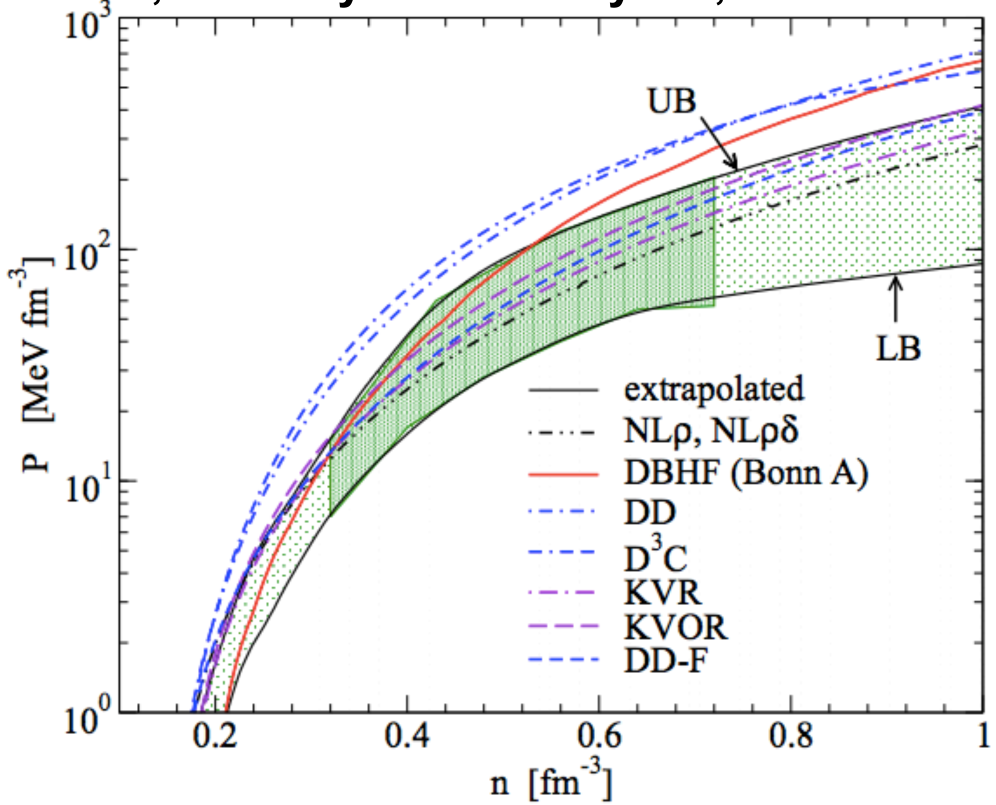
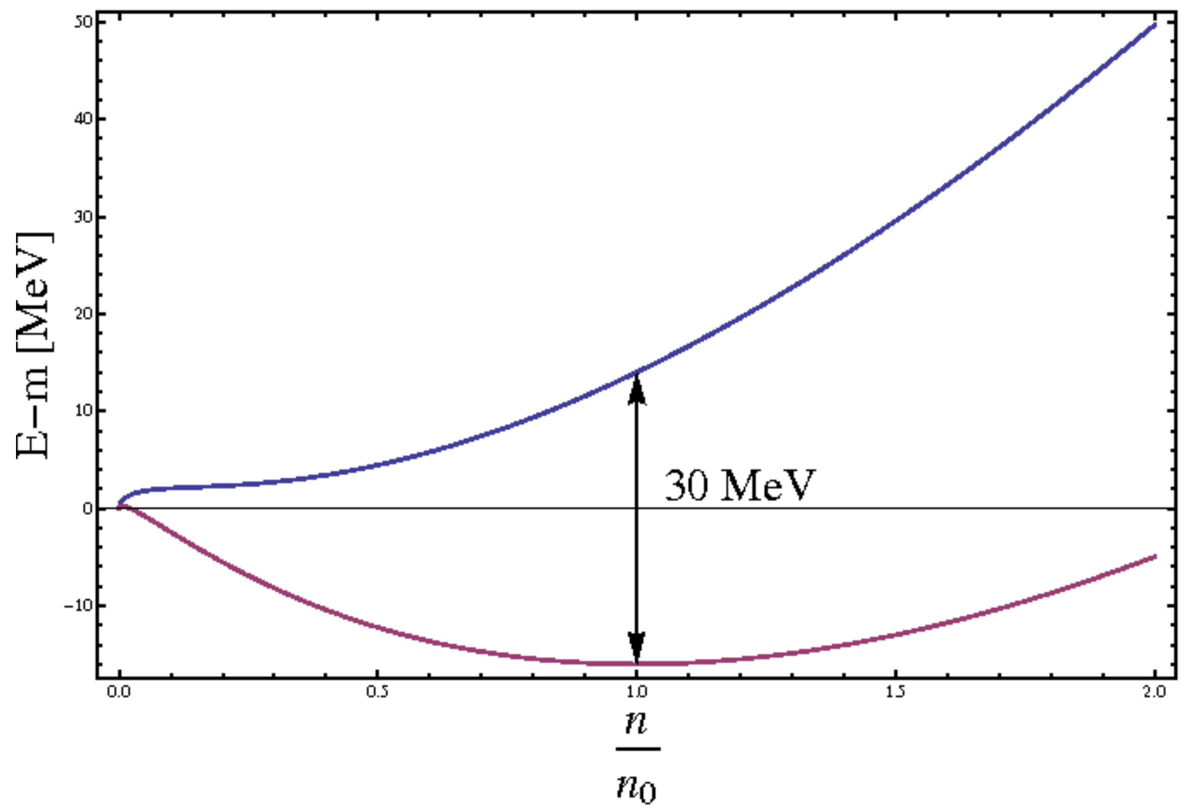


FIG. 6: Pressure region consistent with experimental flow data in SNM (dark shaded region). The light shaded region extrapolates this region to higher densities within an upper (UB) and lower border (LB).

Nuclear Symmetry Energy

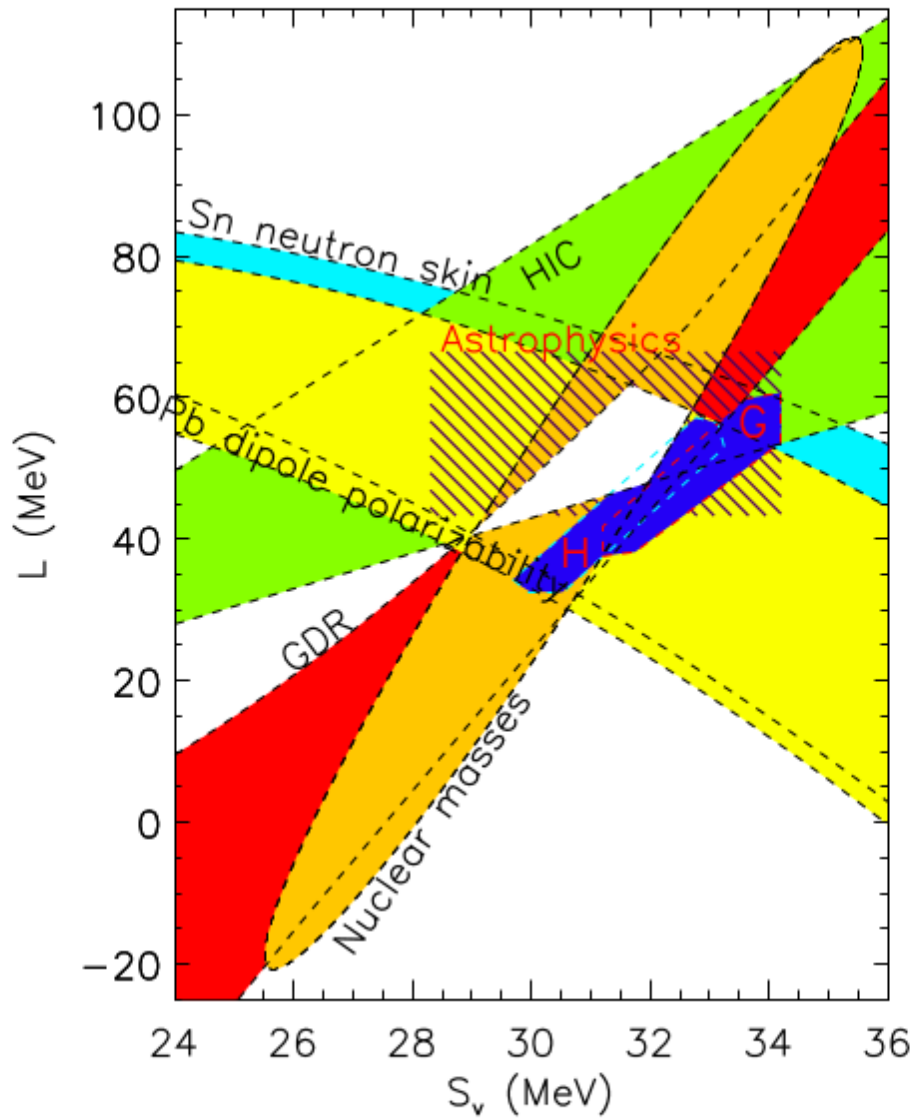


is the difference between symmetric nuclear matter and pure neutron matter:

$$E(n,x) = E(n,x=1/2) + E_s(n) * \alpha^2(x) + E_q(n) * \alpha^4(x) + O(\alpha^6(x))$$

where $\alpha = 1-2x$

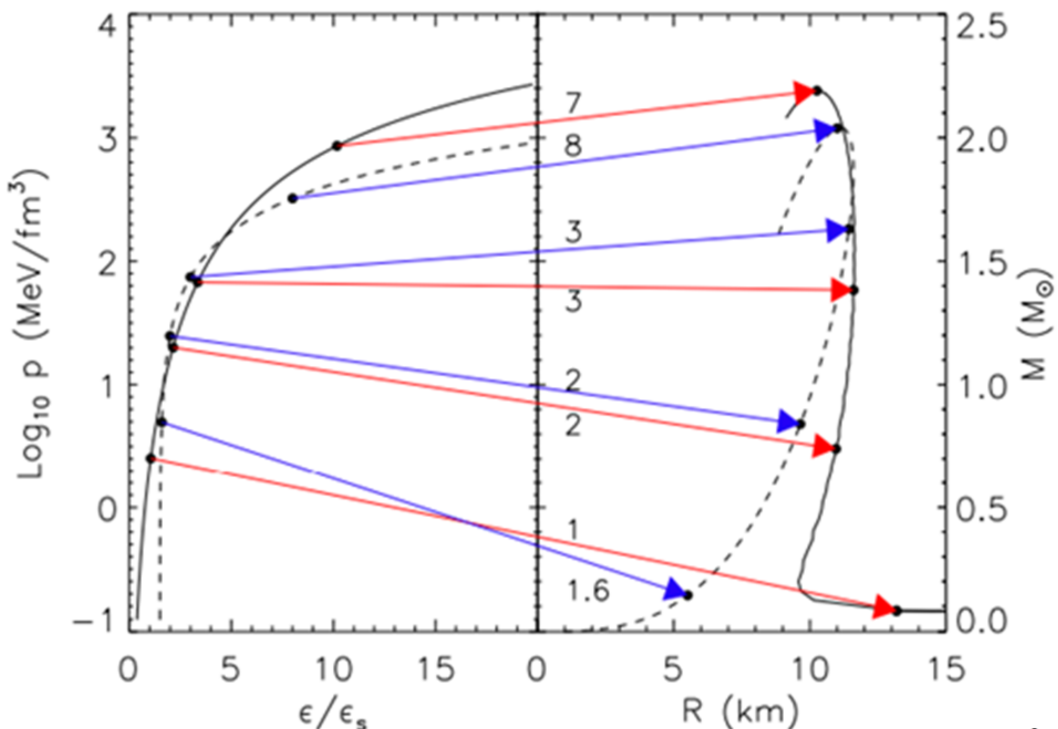
Measuring the symmetry energy



Lattimer and Lim
(2013) ApJ 771 51

Compact Star Sequences

(M-R ⇔ EoS)



Lattimer,
Annu. Rev. Nucl. Part. Sci. 62, 485 (2012)
arXiv: 1305.3510

- TOV Equations

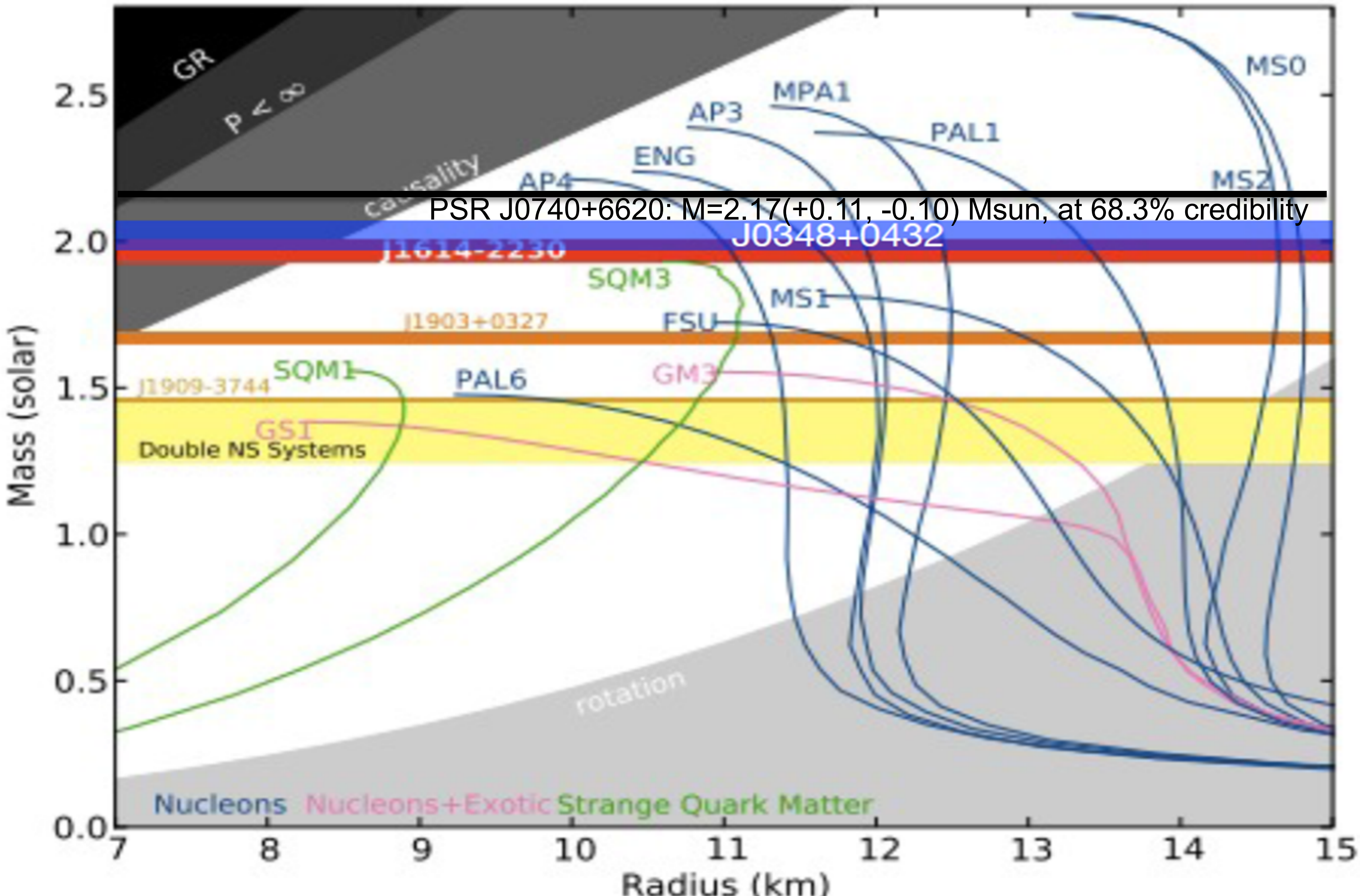
$$\frac{dp}{dr} = -\frac{(\varepsilon + p/c^2)G(m + 4\pi r^3 p/c^2)}{r^2(1 - 2Gm/rc^2)}$$

$$\frac{dm}{dr} = 4\pi r^2 \varepsilon$$

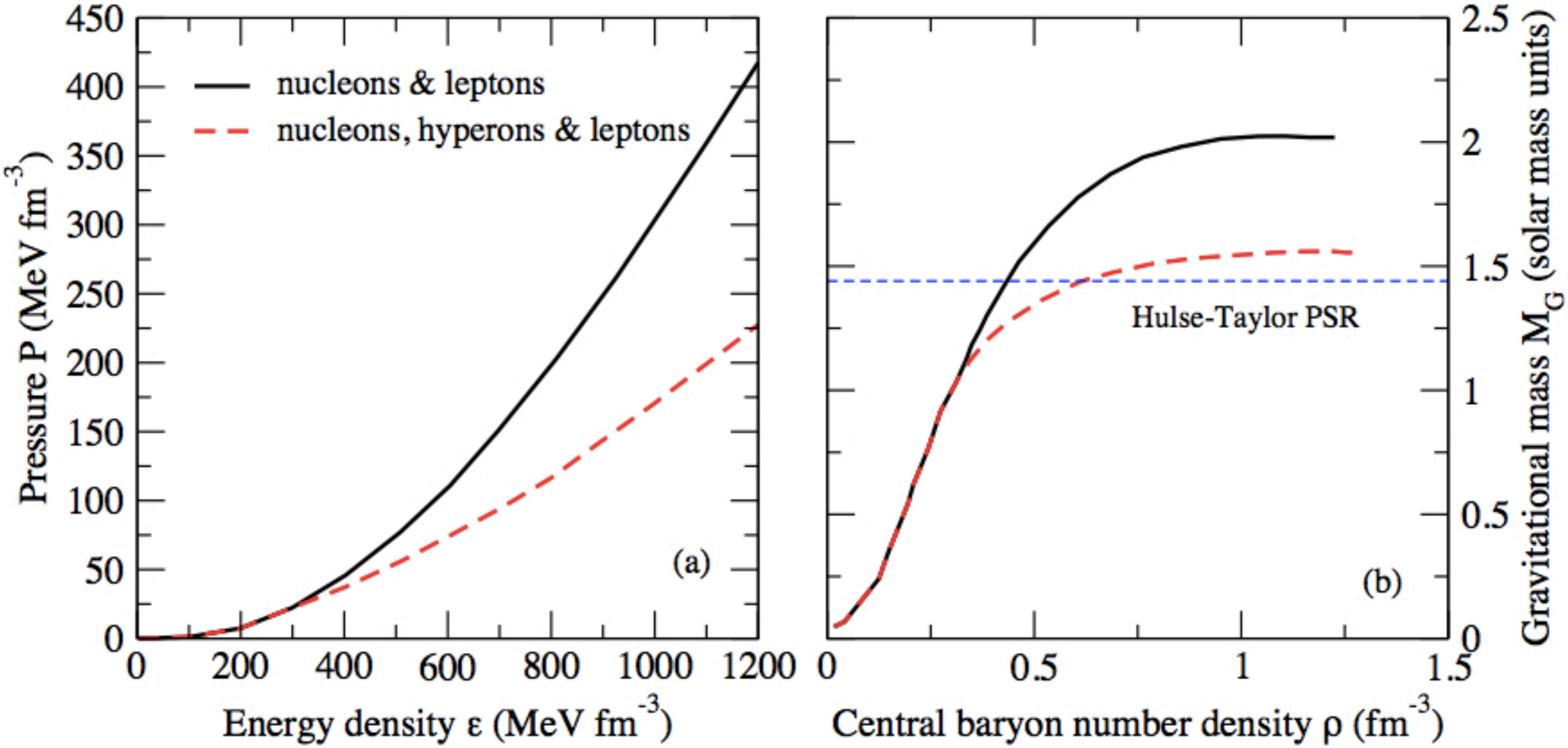
- Equation of State (EoS)

$$p(\varepsilon)$$

Massive Neutron Stars



Hyperon Puzzle



[Hyperon Puzzle Website]

Masquerades

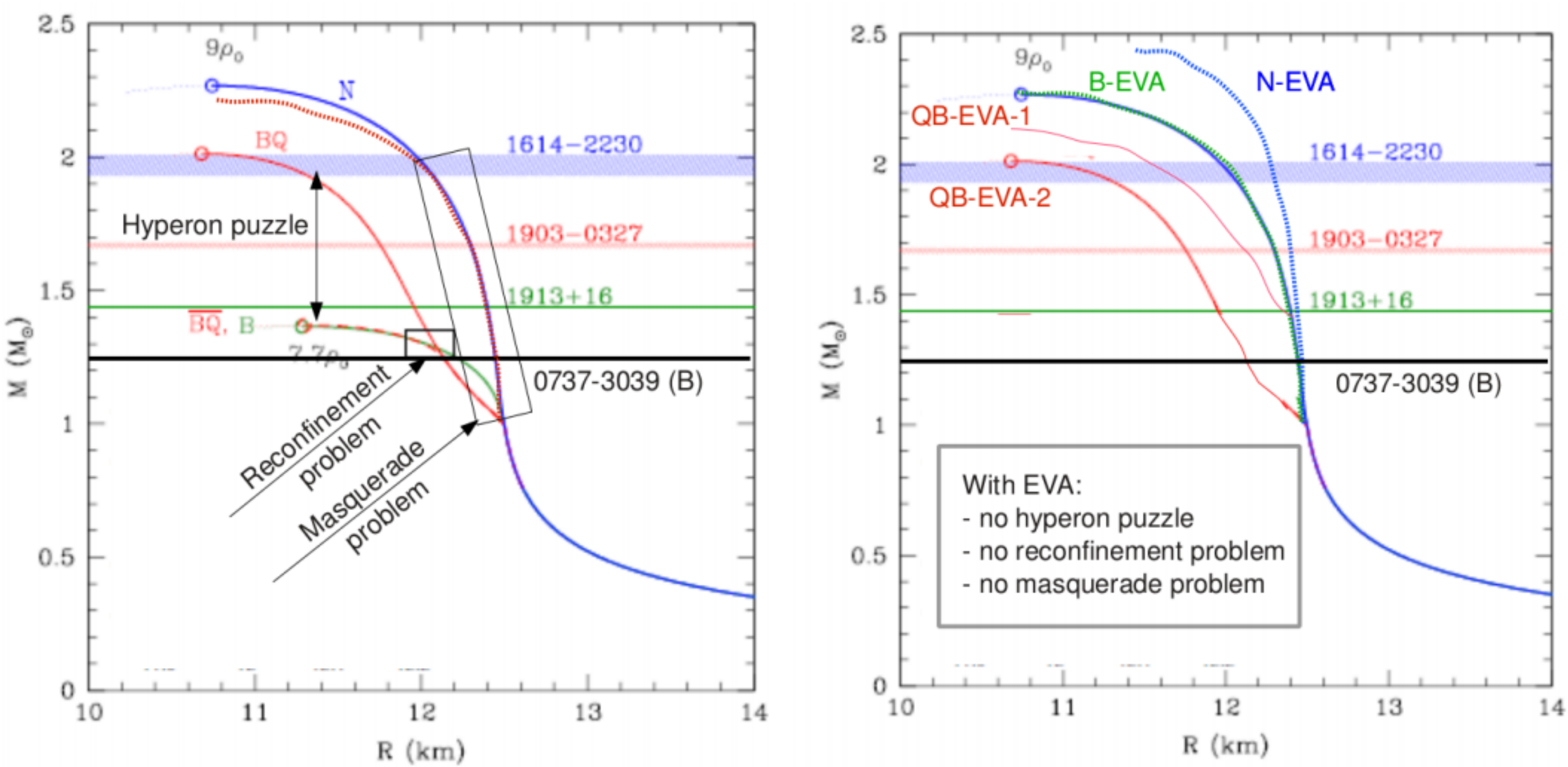
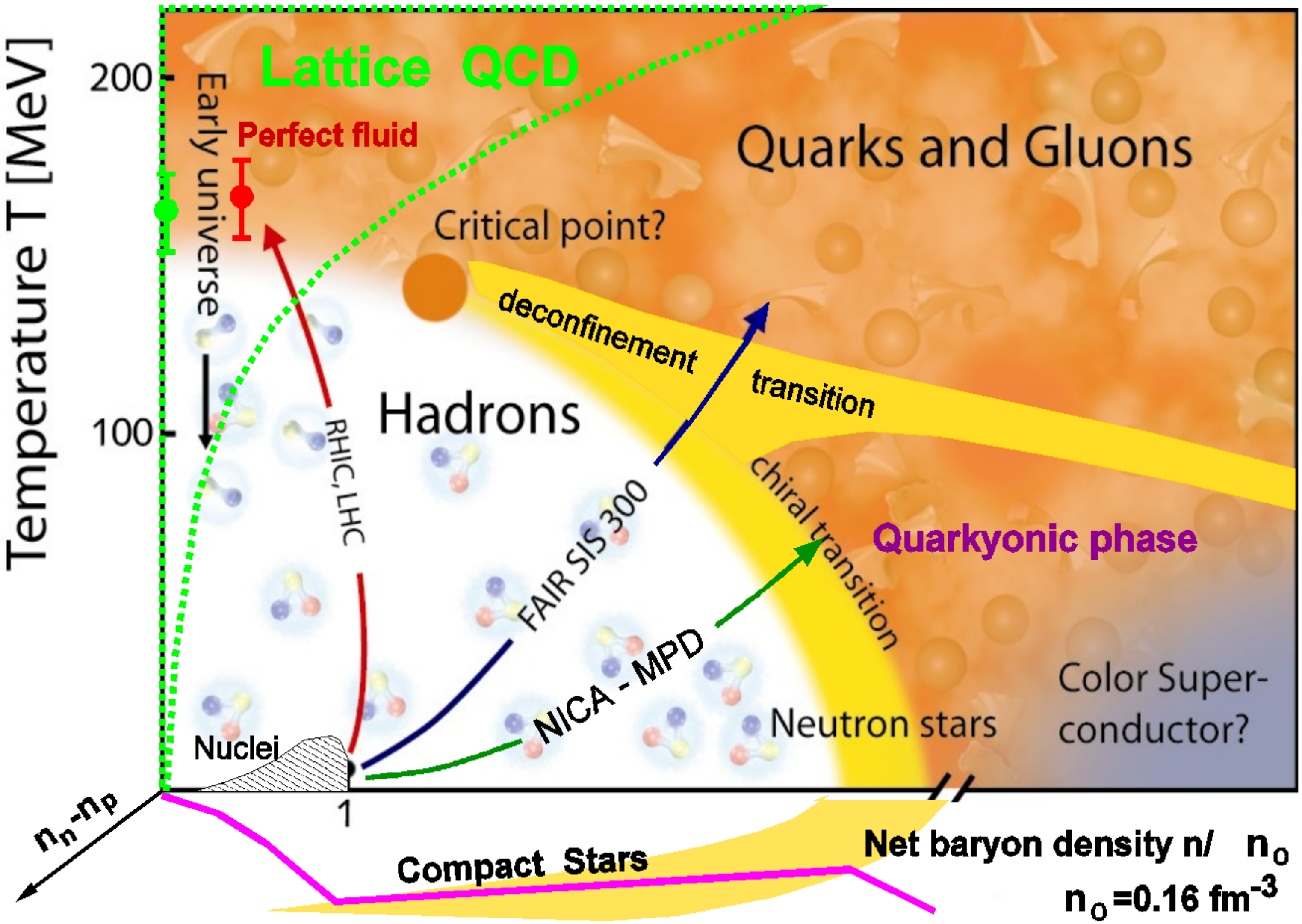


FIGURE 1. Mass-radius sequences for different model equations of state (EoS) illustrate how the three major problems in the theory of exotic matter in compact stars (left panel) can be solved (right panel) by taking into account the baryon size effect within a excluded volume approximation (EVA). Due to the EVA both, the nucleonic (N-EVA) and hyperonic (B-EVA) EoS get sufficiently stiffened to describe high-mass pulsars so that the hyperon puzzle gets solved which implies a removal of the reconfinement problem. Since the EVA does not apply to the quark matter EoS it shall be always sufficiently different from the hadronic one so that the masquerade problem is solved.

Blaschke, Alvarez-Castillo - AIP Conf. Proc. 1701, 020013 (2015) - arXiv:1503.03834

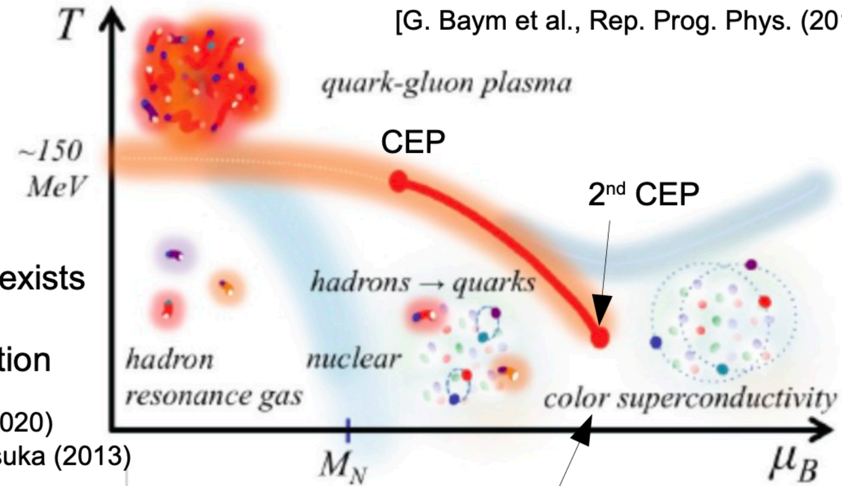
Critical Endpoint in QCD



EoS & Neutron Star Structure

Alternative to the “standard” QCD phase diagram:

[G. Baym et al., Rep. Prog. Phys. (2018)]

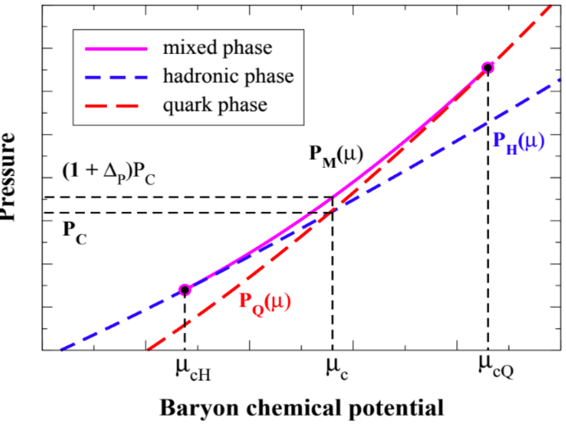


Alternative phase transition constructions:

(a) “normal”

- Maxwell construction exists
- Mixed phase construction
  Mimics “pasta” phases

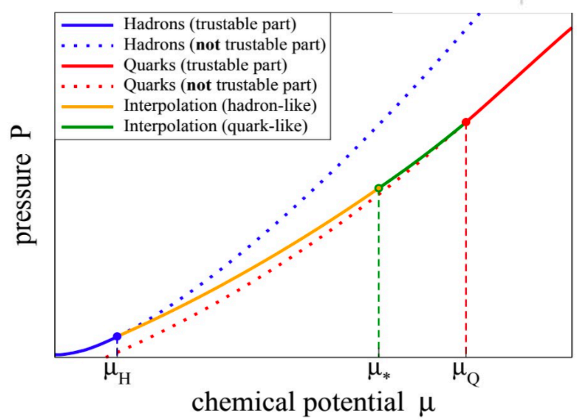
A. Ayriyan et al., PRC 97, 054802 (2018)
K. Maslov et al. PRC 100, 025802 (2019)



(b) “anomalous”

- No Maxwell construction exists
- Interpolation
  Mimics “crossover” transition

A. Ayriyan et al., in preparation (2020)
K. Masuda, T. Hatsuda, T. Takatsuka (2013)



Quark-hadron continuity:

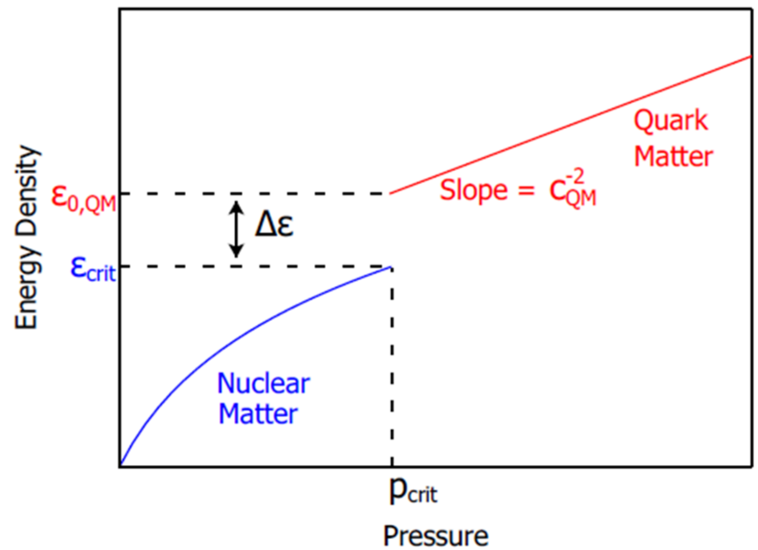
T. Schaefer & F. Wilczek,
Phys. Rev. Lett. 82 (1999) 3956
C. Wetterich,
Phys. Lett. B 462 (1999) 164
T. Hatsuda, M. Tachibana, T. Yamamoto & G. Baym,
Phys. Rev. Lett. 97 (2006) 122001

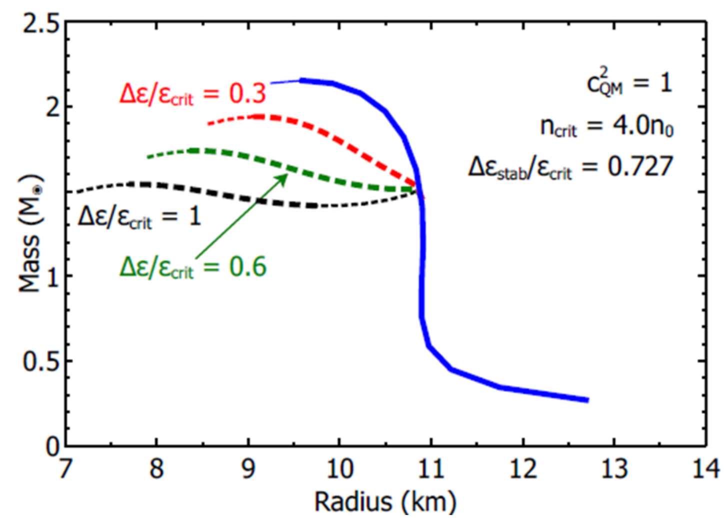
Compact Star Mass Twins and the AHP scheme

- First order PT can lead to a stable branch of hybrid stars with quark matter cores which, depending on the size of the "latent heat" (jump in energy density), can even be disconnected from the hadronic one by an unstable branch → "**third family of CS**".

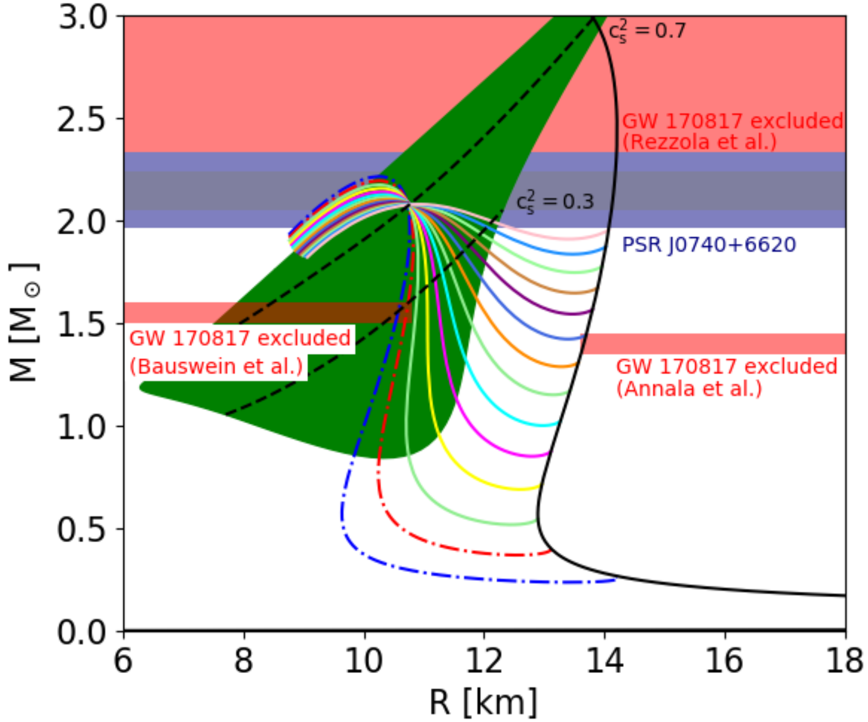
- Measuring two **disconnected populations** of compact stars in the M-R diagram would represent **the detection of a first order phase transition** in compact star matter and thus the indirect proof for the existence of a **critical endpoint (CEP) in the QCD phase diagram**!

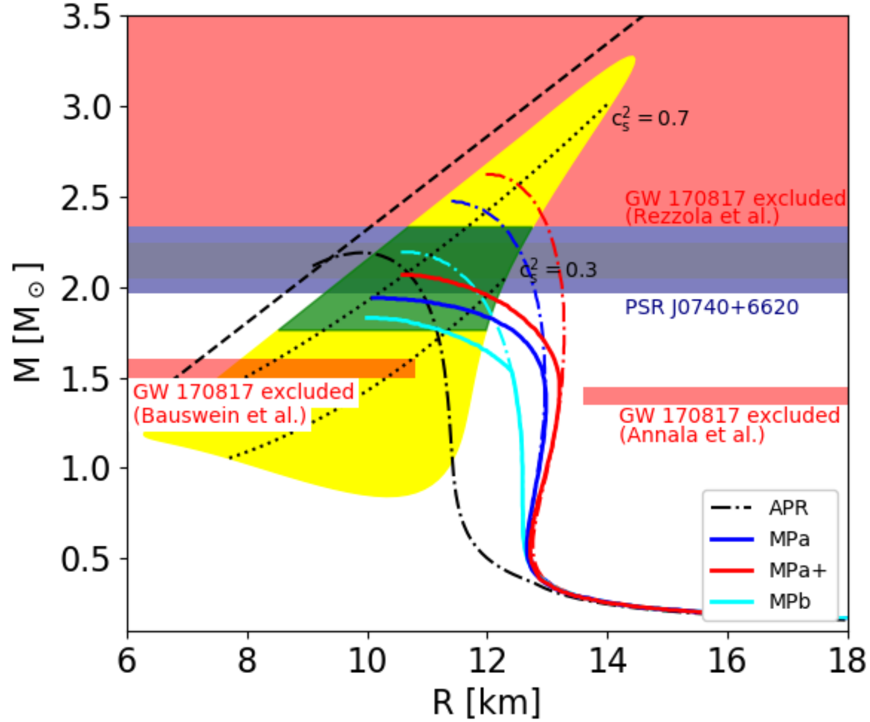
Alford, Han, Prakash,
Phys. Rev. D 88, 083013 (2013)
arxiv:1302.4732





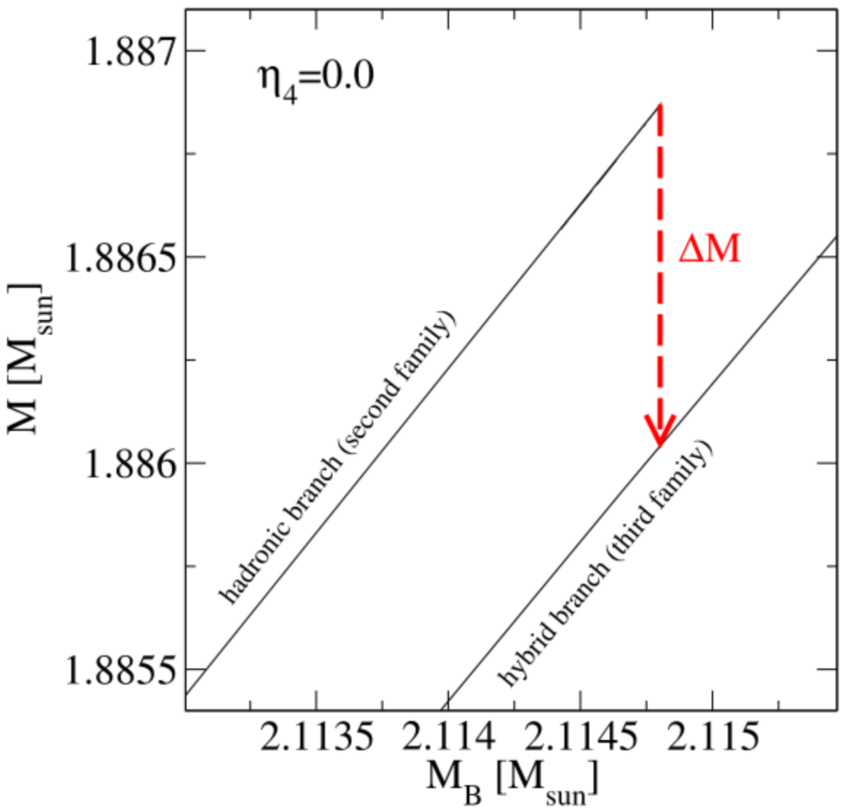
Hybrid star mass–radius diagram

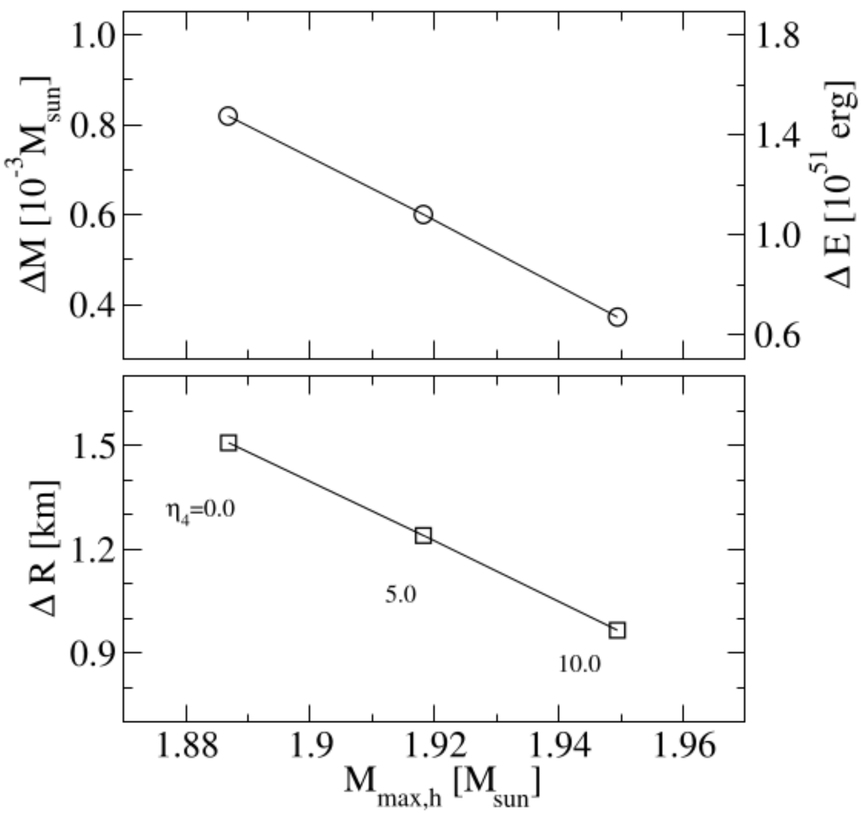




Mateusz Cierniak, David Blaschke, arXiv:2009.12353
Yamamoto, Y., Togashi, H., Tamagawa, T., Furumoto, T., Yasutake, N., &
Rijken, T. A. - Physical Review C, 96(6) (2017)

Energy bursts from deconfinement





Alvarez-Castillo, Bejger, Blaschke, Haensel, Zdunik (2015), arXiv:1401.5380

Accretion-induced collapse to third family compact stars as trigger for eccentric orbits of millisecond pulsars in binaries

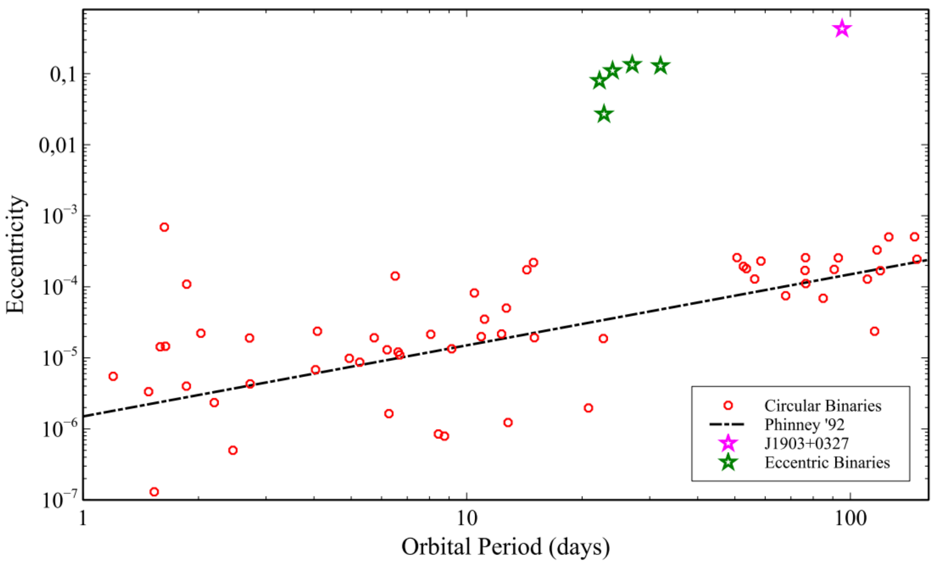
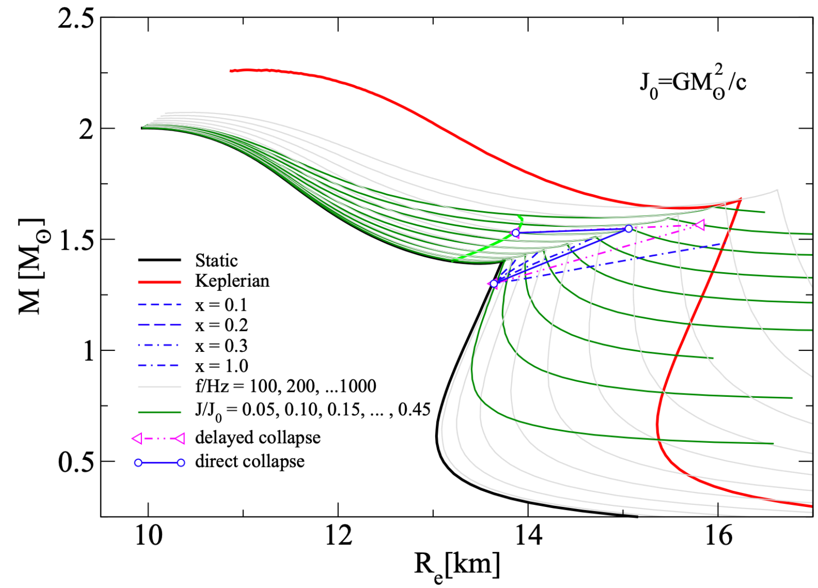


FIGURE 1 Eccentricity vs. orbital period for millisecond pulsars in binaries with white dwarf companions, see (J. Antoniadis, 2014; Stovall, 2019).



David Edwin Alvarez-Castillo, John Antoniadis, Alexander Ayriyan, David Blaschke, Victor Danchev, Hovik Grigorian, Noshad Khosravi Largani, Fridolin Weber.

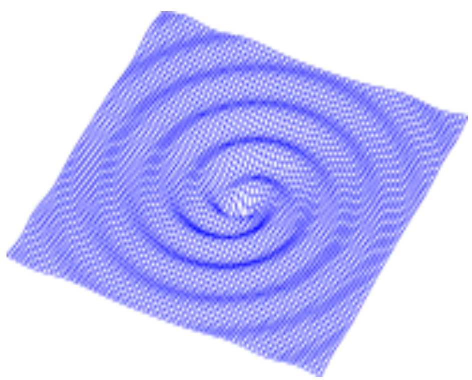
Astron. Nachr. 2019;340:878-884. Eprint: arXiv: 1912.08782

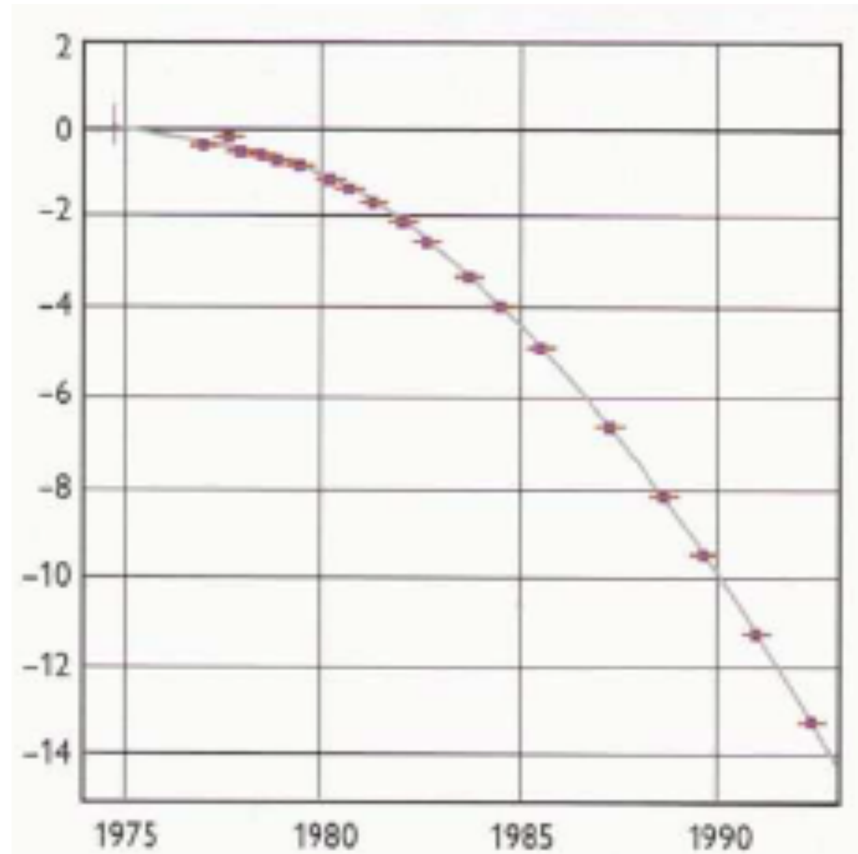
Multi-messenger Astronomy

Hulse-Taylor pulsar – binary system

PSR B1913+16 (now J1915+1606)

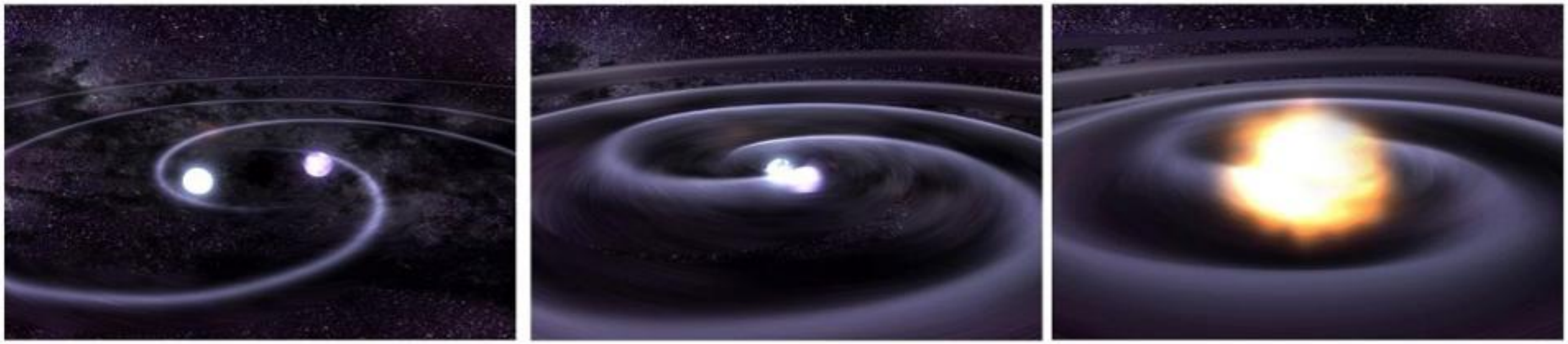
Nobel Prize for Hulse and Taylor (1993)

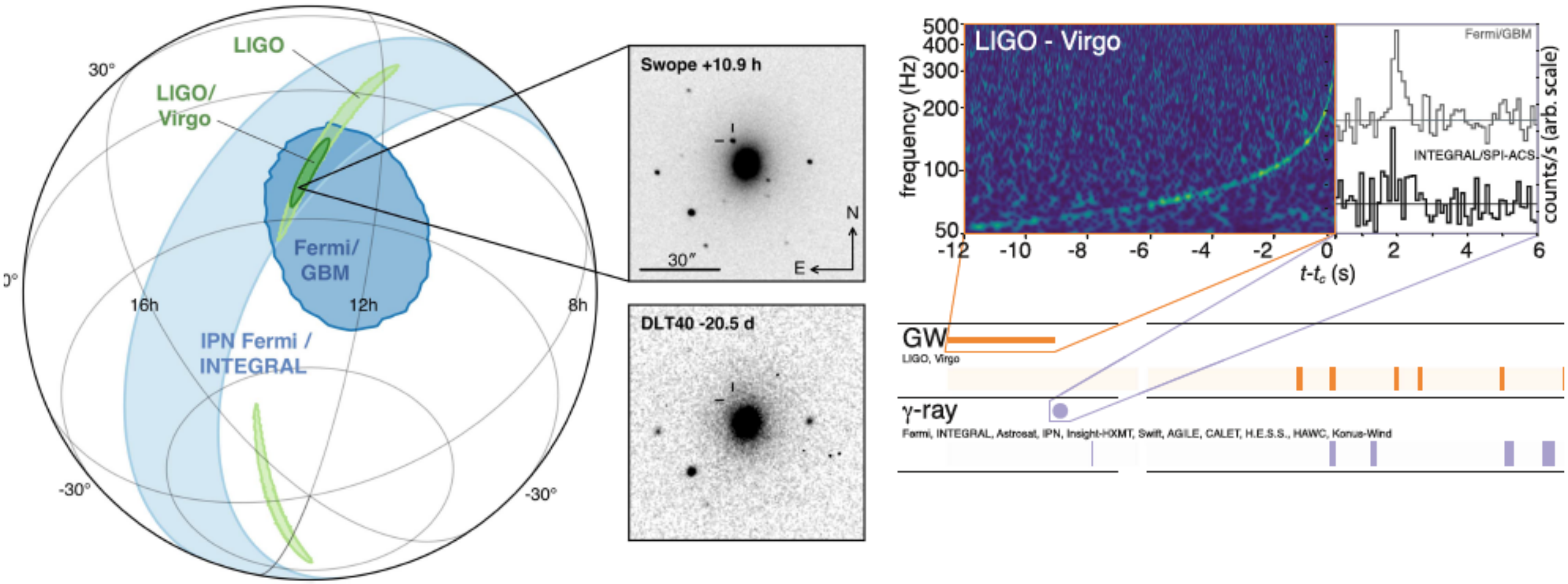




Excellent confirmation of Einstein theory of GW emission by observation of period decay

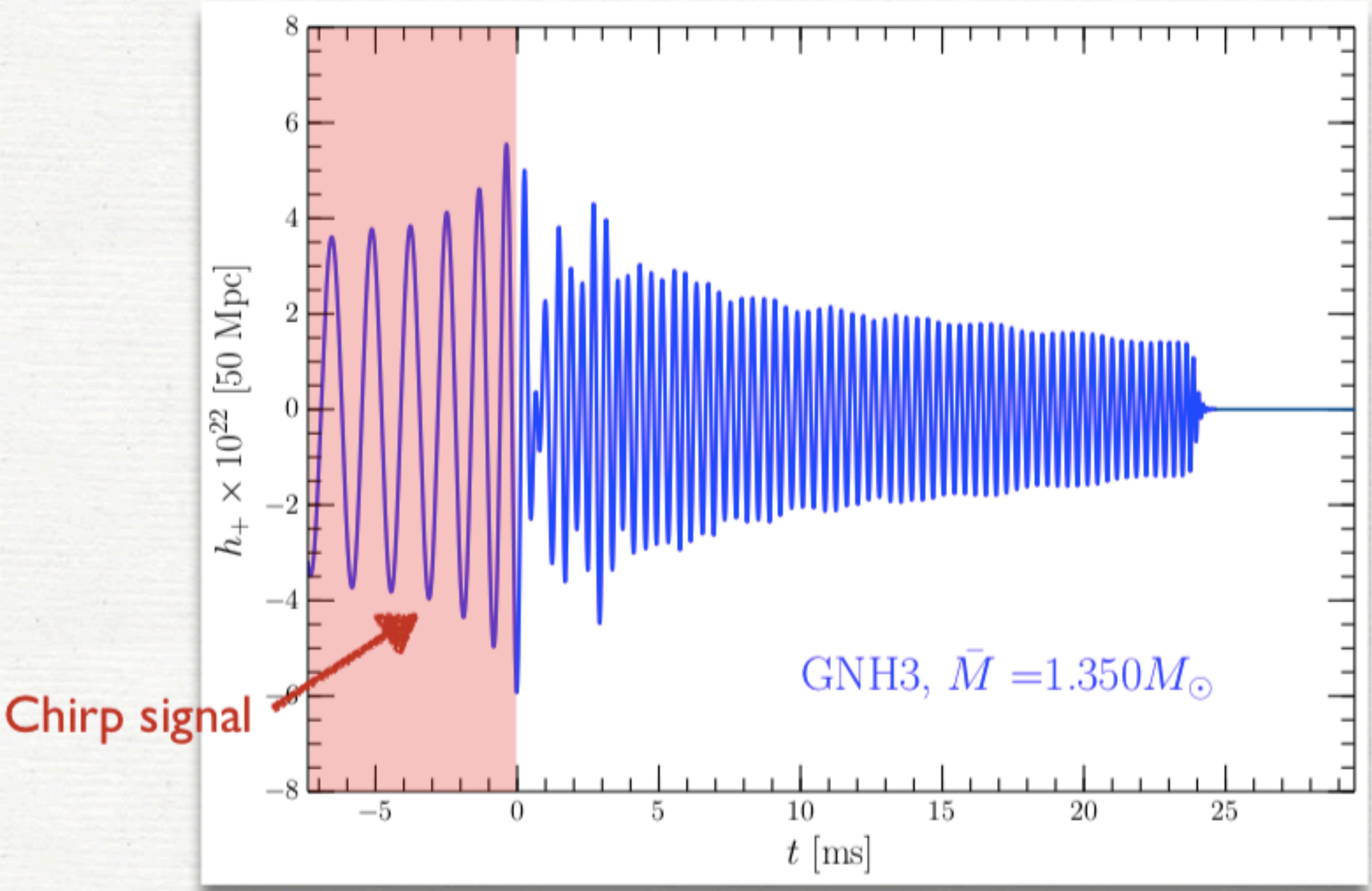
GW170817: Neutron Star Merger



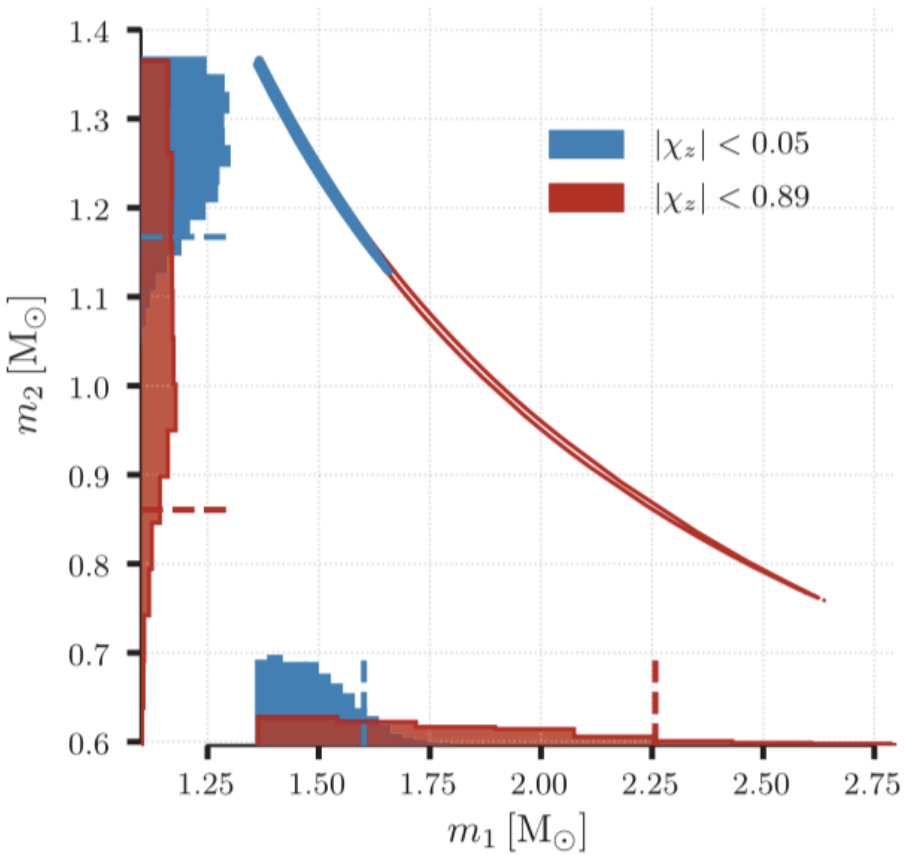


*) B.P. Abbott et al. [LIGO/Virgo Collab.], PRL 119, 161101 (2017); ApJLett 848, L12 (2017)

Anatomy of the GW signal



Implications from GW170817



GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral
B. P. Abbott et al. arXiv:1712.00451

Computing the love number/tidal deformability

Extension of a standard TOV solver (i.e. numerically an integration of coupled ODEs):

Ansatz for the metric including a l=2 perturbation

$$
\begin{aligned}
ds^2 &= -e^{2\Phi(r)}\left[1 + H(r)Y_{20}(\theta,\varphi)\right]dt^2 \\
&\quad + e^{2\Lambda(r)}\left[1 - H(r)Y_{20}(\theta,\varphi)\right]dr^2 \\
&\quad + r^2\left[1 - K(r)Y_{20}(\theta,\varphi)\right]\left(d\theta^2 + \sin^2\theta d\varphi^2\right)
\end{aligned}
$$

Following Hinderer et al. 2010

Integrate standard TOV system:

$$
\begin{aligned}
e^{2\Lambda} &= \left(1 - \frac{2m_r}{r}\right)^{-1}, \\
\frac{d\Phi}{dr} &= -\frac{1}{\epsilon + p}\frac{dp}{dr}, \\
\frac{dp}{dr} &= -(\epsilon + p)\frac{m_r + 4\pi r^3 p}{r(r - 2m_r)}, \\
\frac{dm_r}{dr} &= 4\pi r^2 \epsilon.
\end{aligned}
$$

EoS to be provided ε(p)

And additional eqs. for perturbations:

$$
\begin{aligned}
\frac{dH}{dr} &= \beta \qquad (11) \\
\frac{d\beta}{dr} &= 2\left(1 - 2\frac{m_r}{r}\right)^{-1} H \left\{-2\pi\left[5\epsilon + 9p + f(\epsilon + p)\right]\right. \\
&\quad \left. + \frac{3}{r^2} + 2\left(1 - 2\frac{m_r}{r}\right)^{-1}\left(\frac{m_r}{r^2} + 4\pi r p\right)^2\right\} \\
&\quad + \frac{2\beta}{r}\left(1 - 2\frac{m_r}{r}\right)^{-1}\left\{-1 + \frac{m_r}{r} + 2\pi r^2(\epsilon - p)\right\}.
\end{aligned}
$$

(K(r) given by H(r))

Note: Although multidimensional problem – computation in 1D since absorbed in Y20

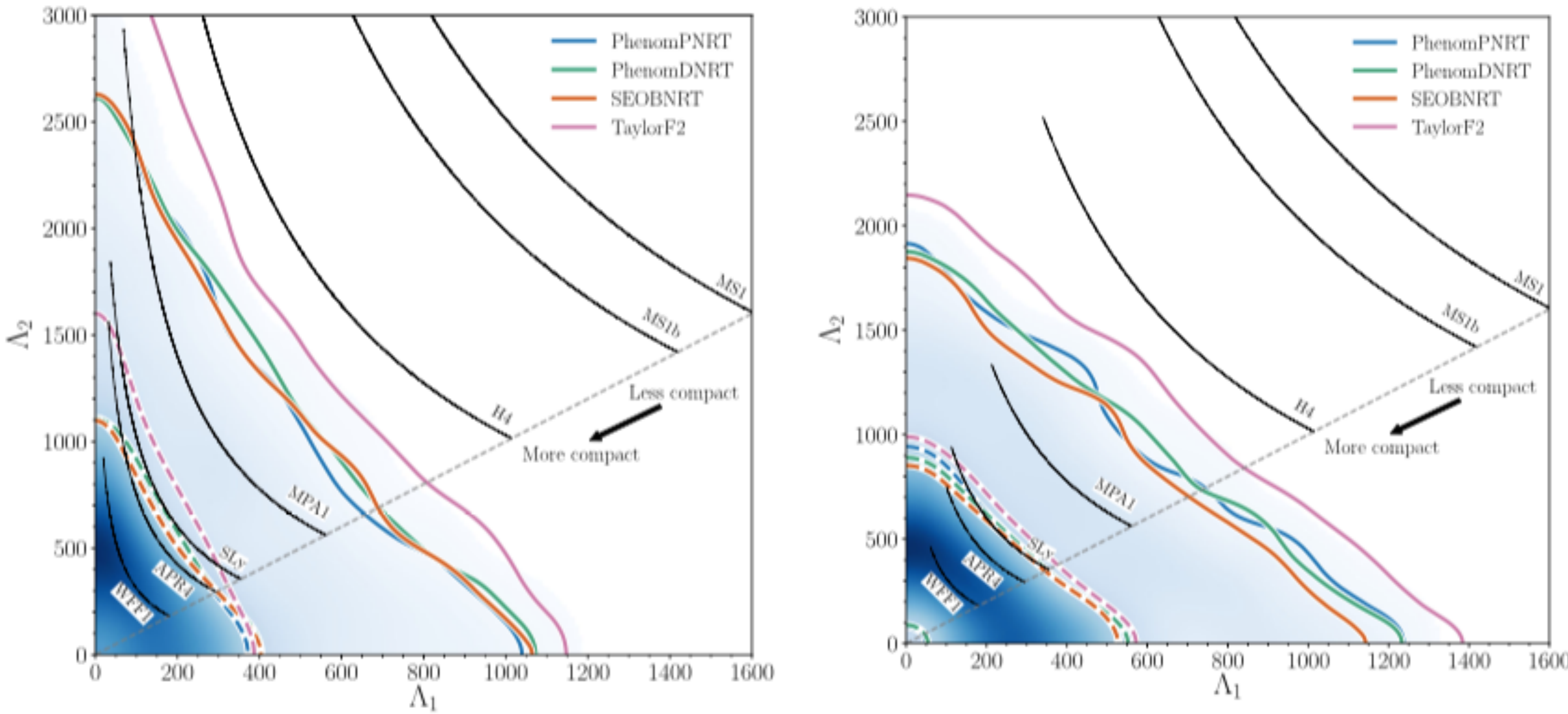
Love number

$$y = \frac{R\,\beta(R)}{H(R)}$$

$$\begin{aligned} k_2 \;=\; & \frac{8C^5}{5}(1-2C)^2[2+2C(y-1)-y] \\ & \times\Big\{2C[6-3y+3C(5y-8)] \\ & \quad +4C^3[13-11y+C(3y-2)+2C^2(1+y)] \\ & \quad +3(1-2C)^2[2-y+2C(y-1)]\ln(1-2C)\Big\}^{-1} \end{aligned}$$

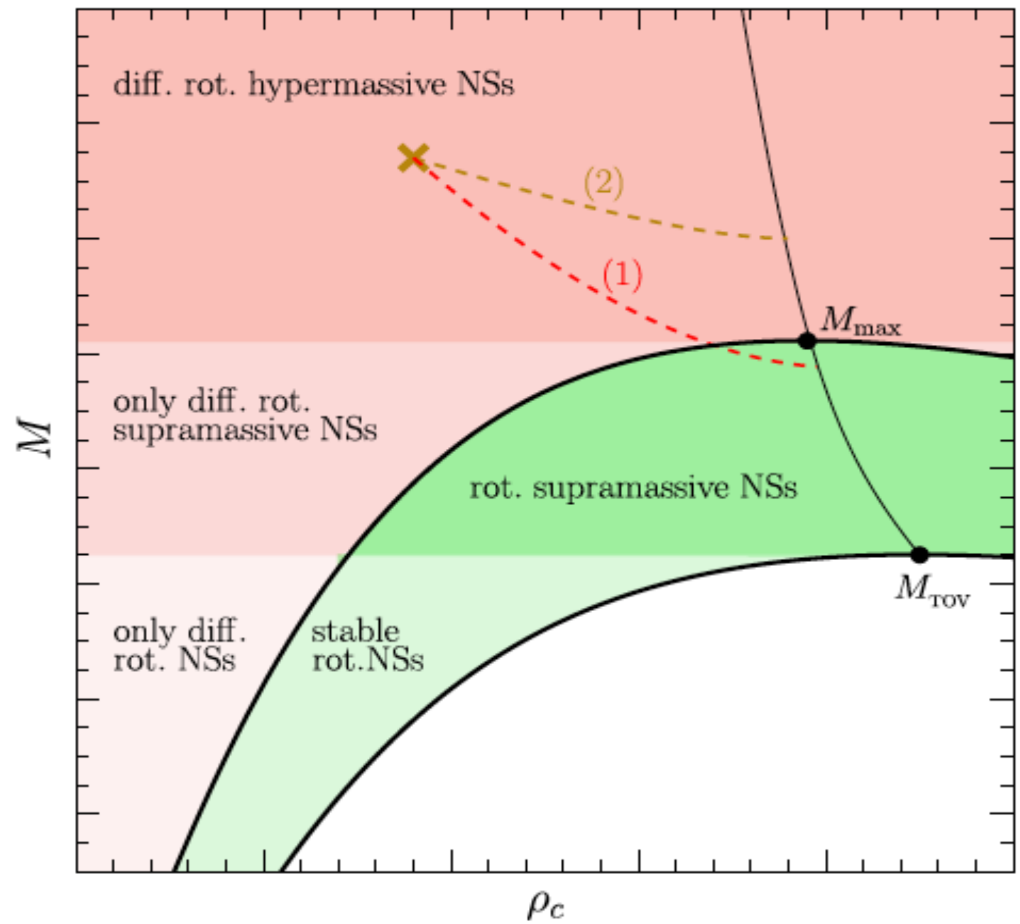
where $C = M/R$ is the compactness of the star.

Implications from GW170817



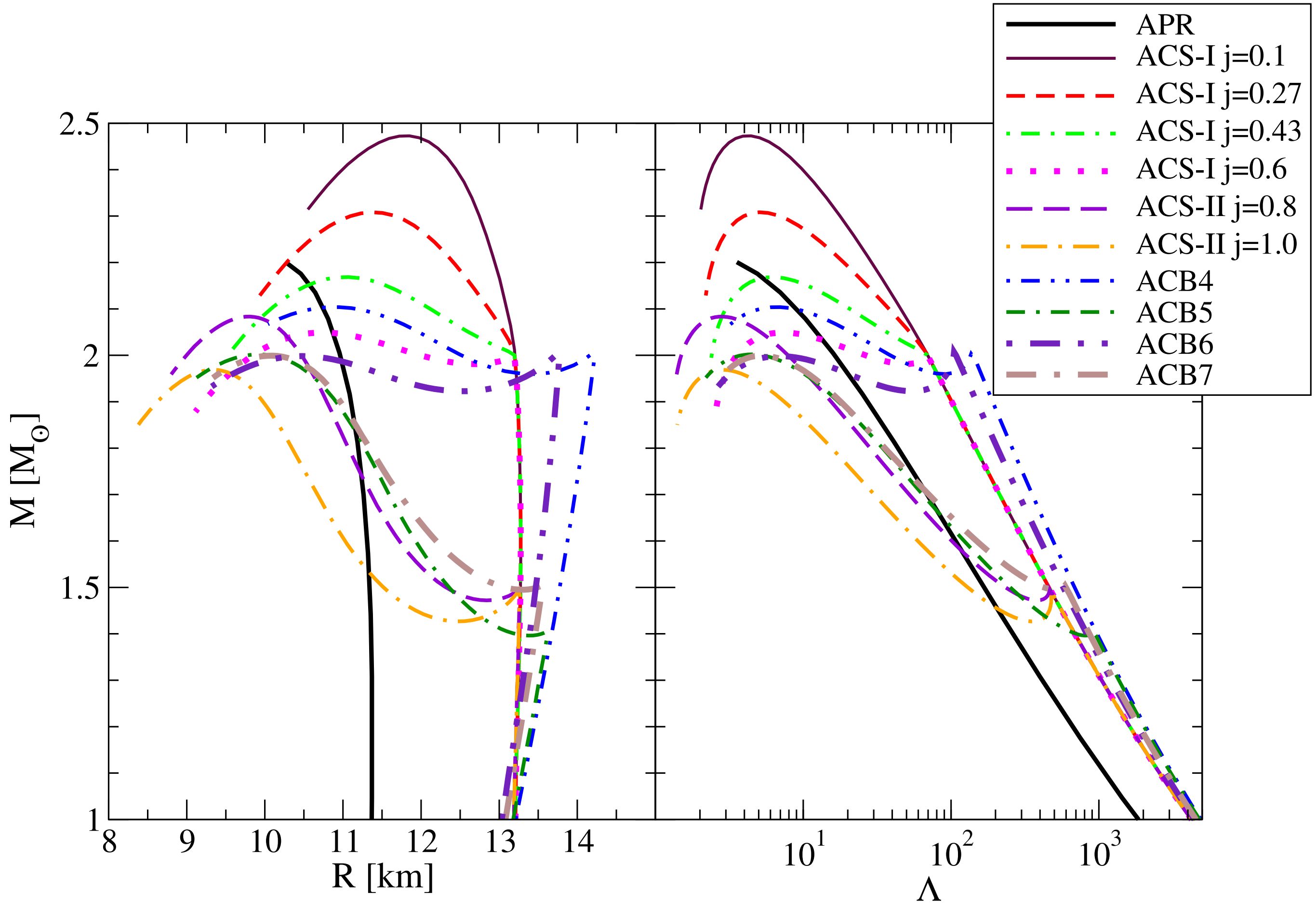
Properties of the Binary Star Merger GW170817
B. P. Abbott et al., Phys. Rev. X 9, 011001 (2019)

Upper limit on the Maximum mass of static compact stars?



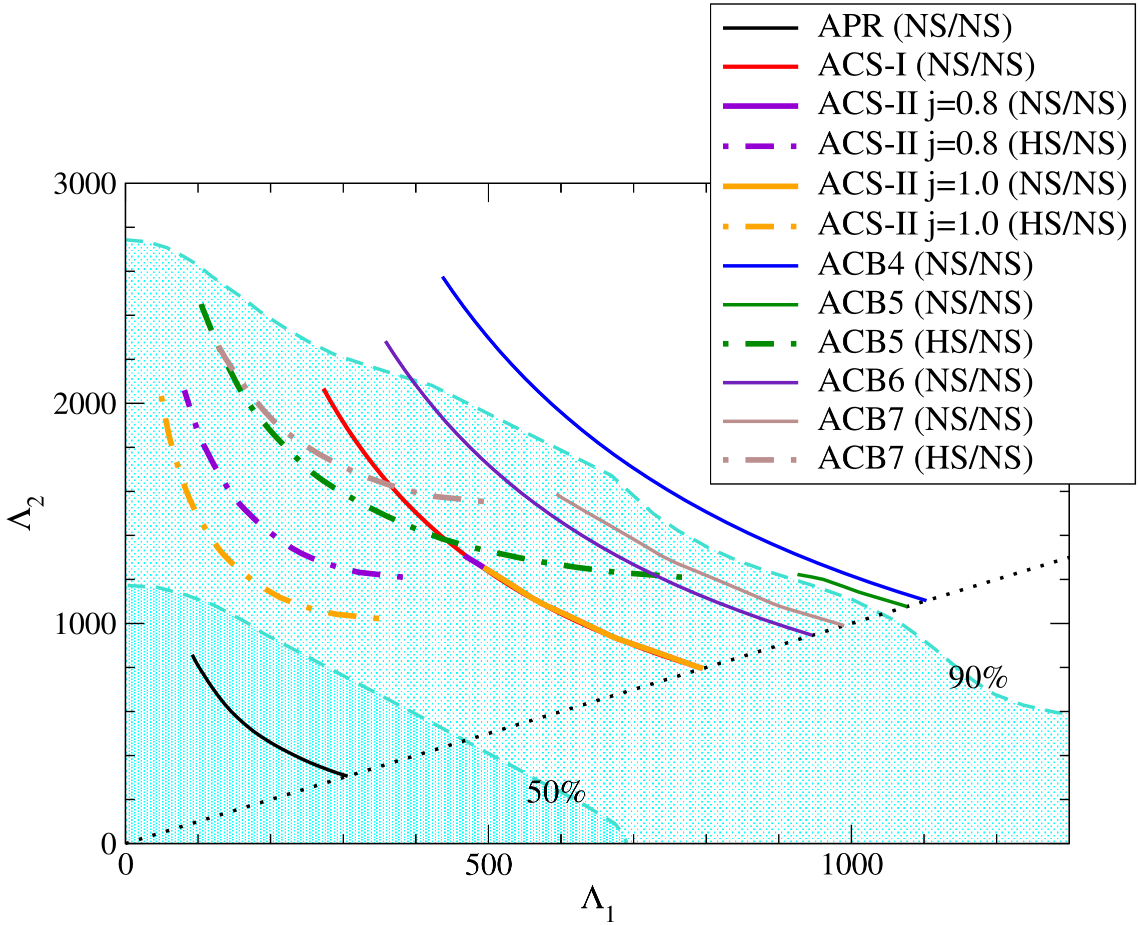
Rezzolla et al., ApJ Lett 852 (2018) L25

Implications from GW170817



Vasileios Paschalidis, Kent Yagi, David Alvarez-Castillo,
David B. Blaschke, Armen Sedrakian
Phys. Rev. D 97, 084038 (2018), arXiv:1712.00451

Implications from GW170817



Vasileios Paschalidis, Kent Yagi, David Alvarez-Castillo, David B. Blaschke, Armen Sedrakian
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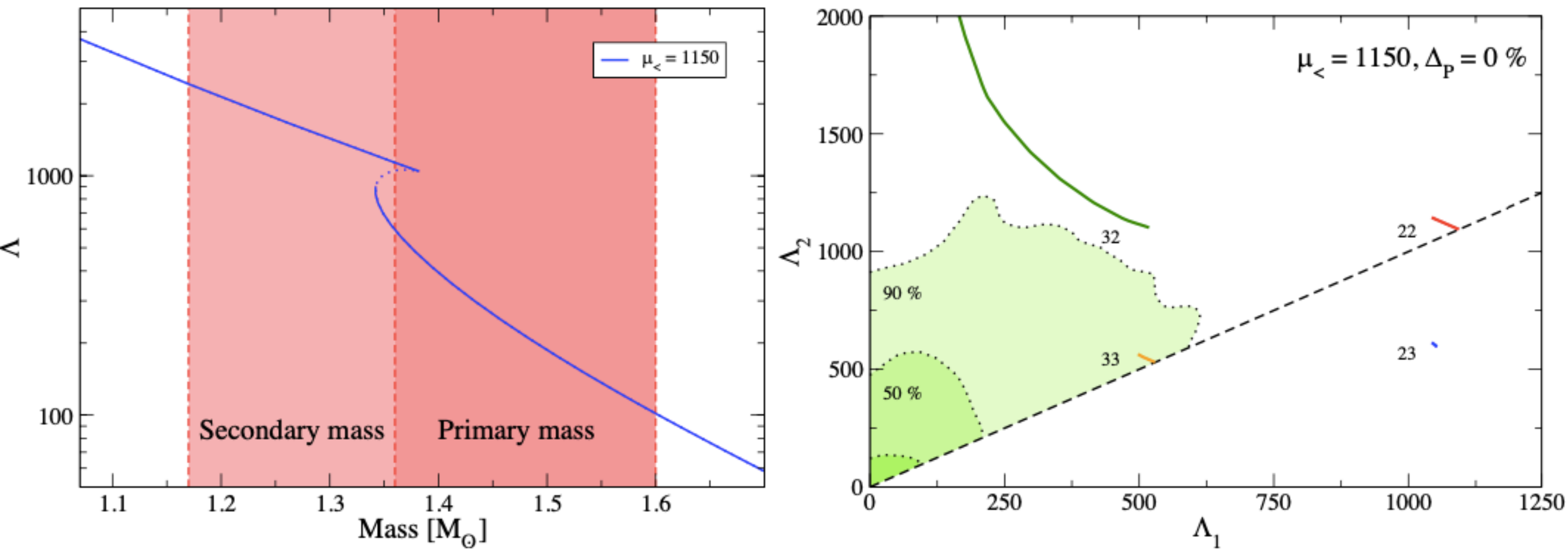
Was GW170817 a canonical neutron star merger?



A. Ayriyan, D.Alvarez-Castillo, D. Blaschke and H. Grigorian,
Universe 6, 81 (2020)

D. Alvarez-Castillo, D. Blaschke, G. Grunfeld, V. Pagura
Phys. Rev. D 99, 063010 (2019) - arXiv: 1805.04105

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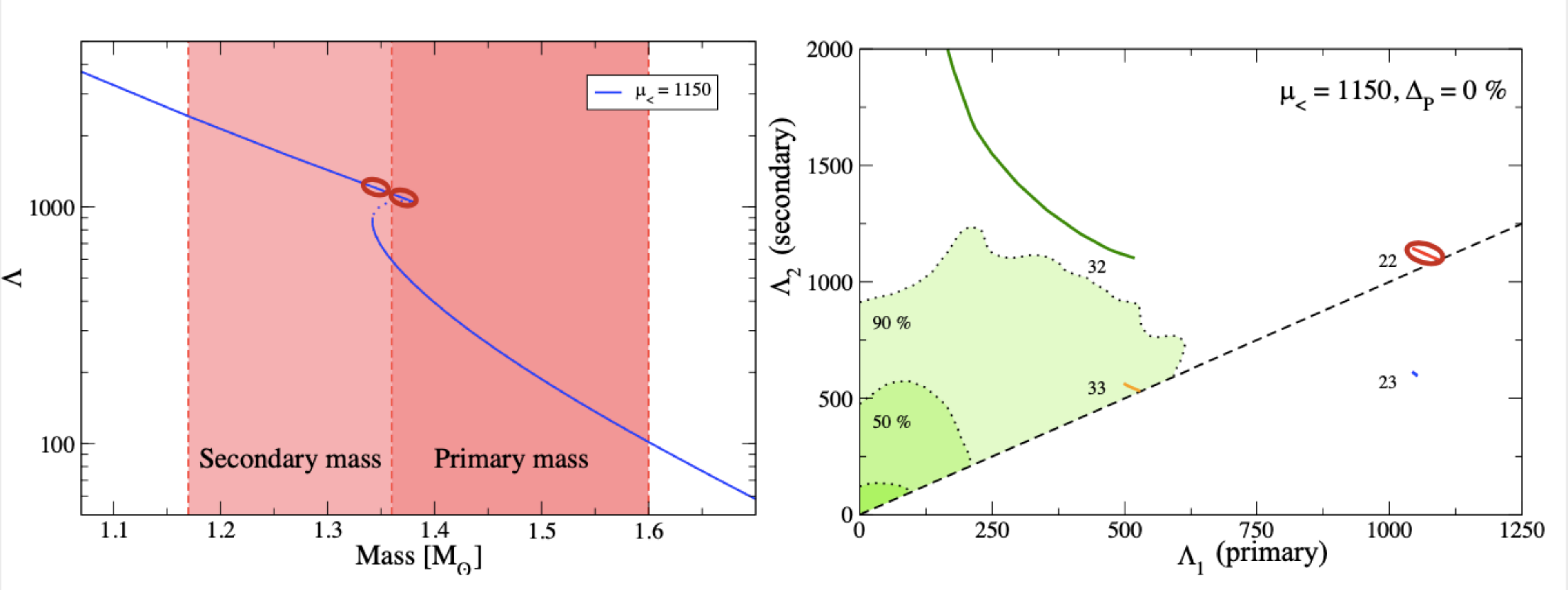

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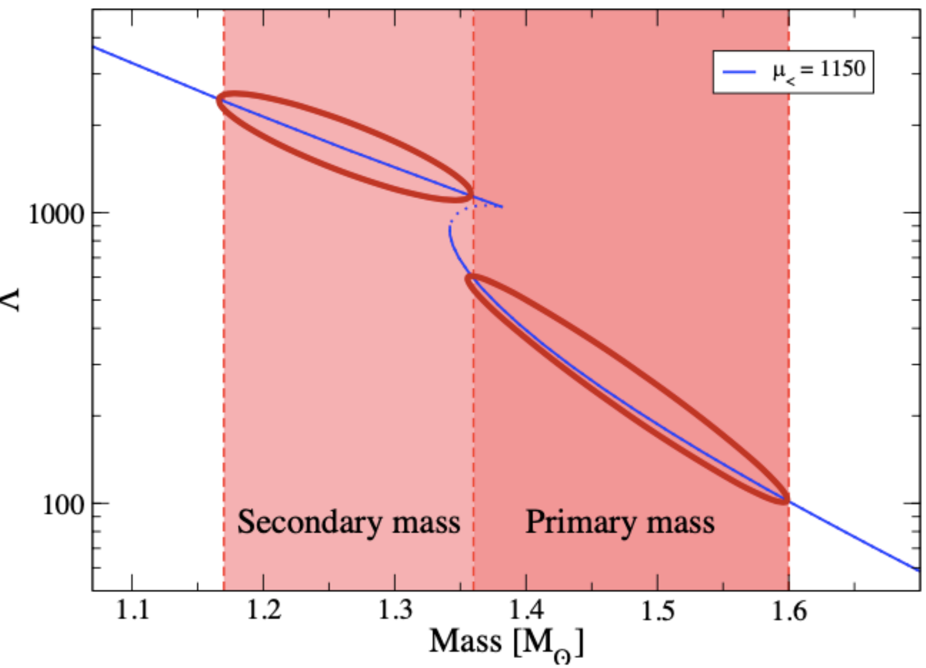

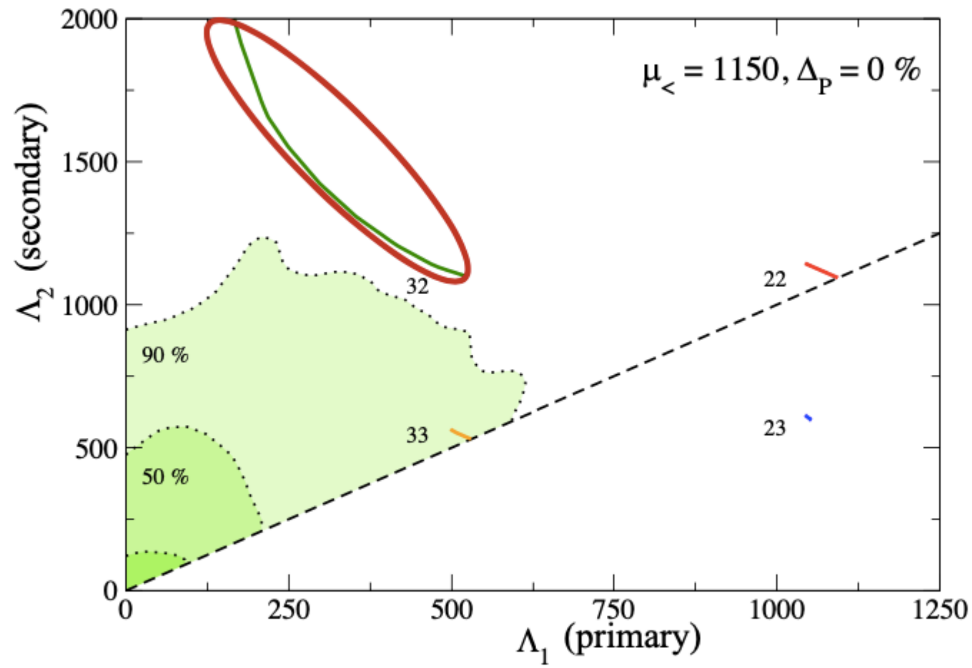

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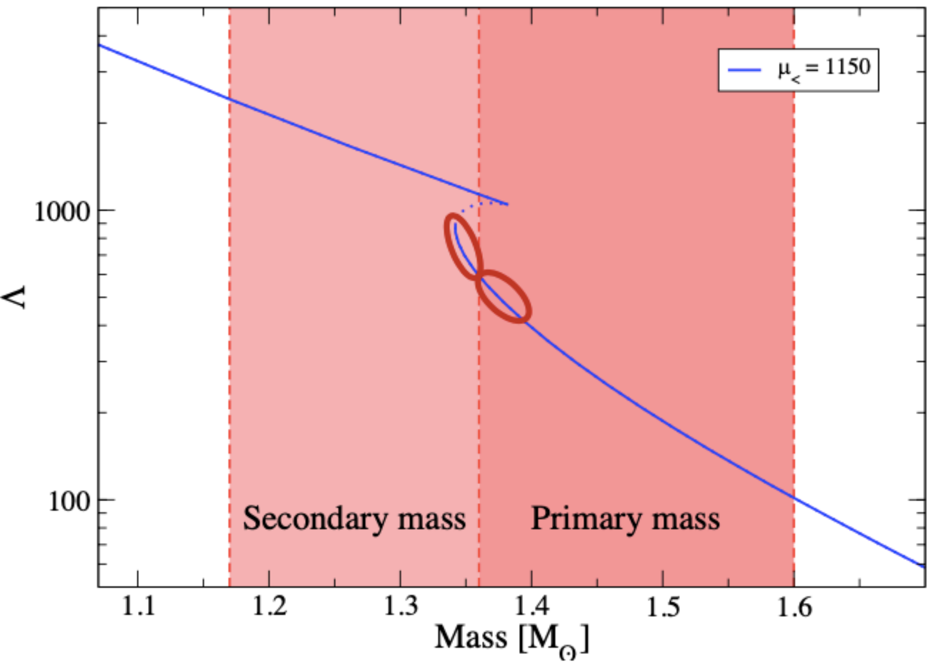

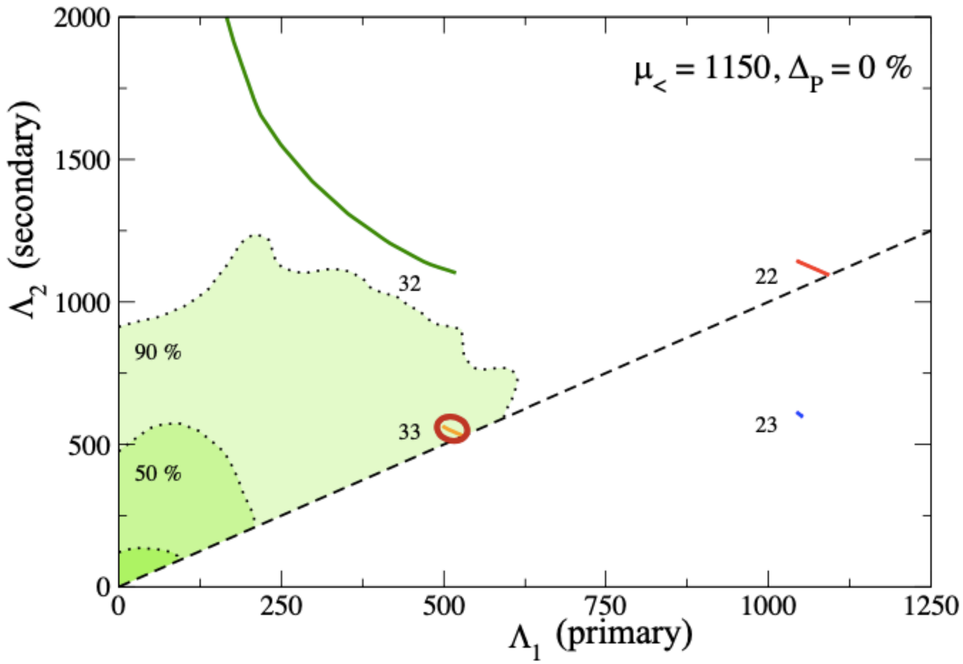

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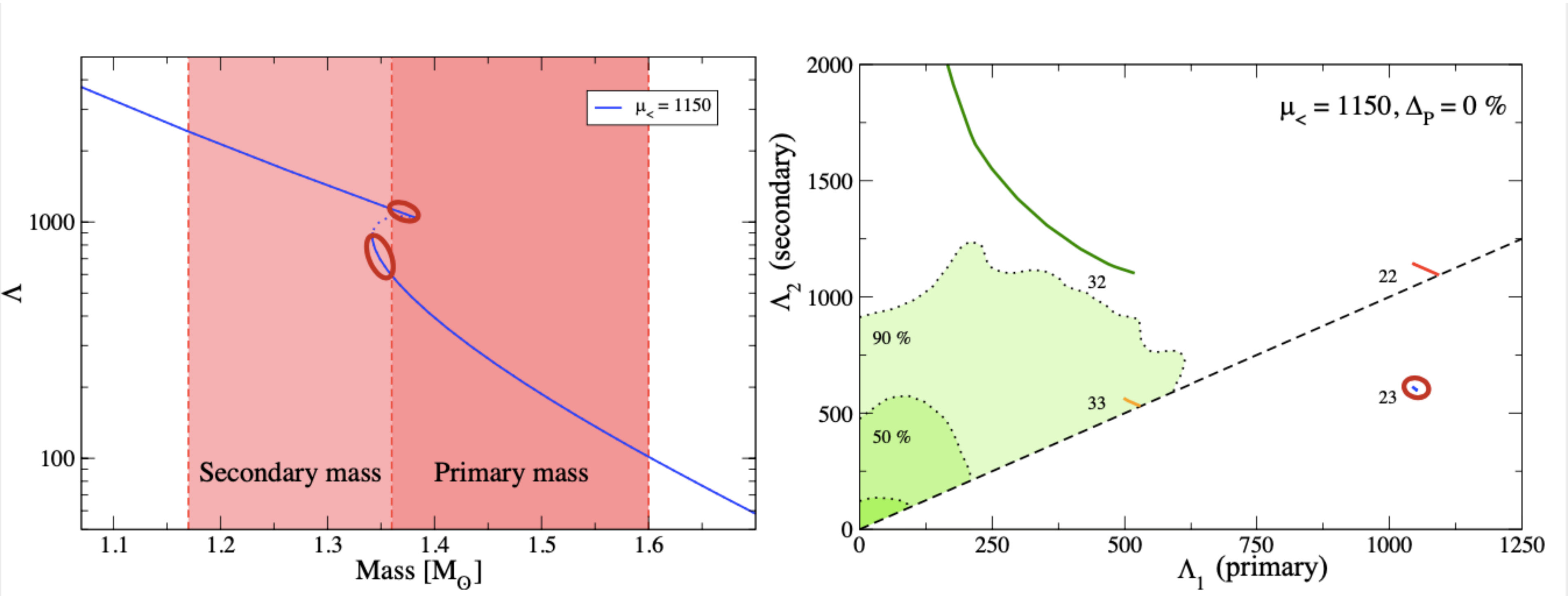

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Universe 6, 81 (2020)

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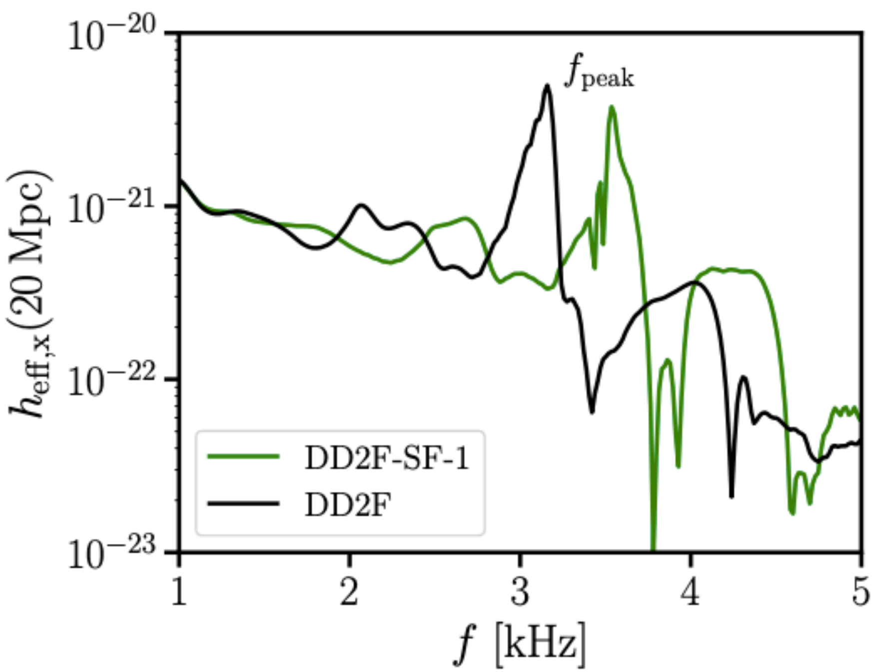
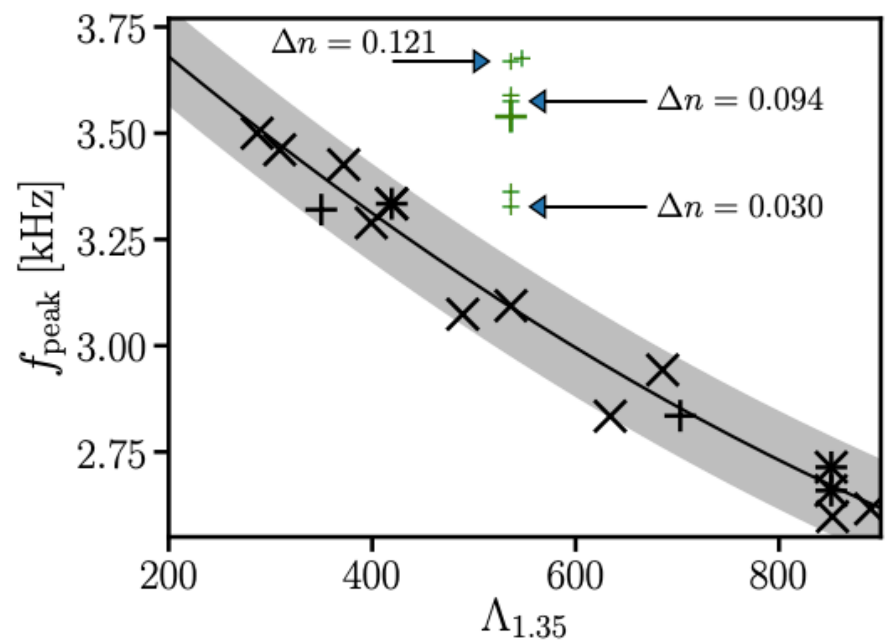
Phys. Rev. D 99, 063010 (2019) - arXiv: 1805.04105

Gravitational Wave Signals

First Order Phase Transitions





A. Bauswein et al. - arXiv: 1904.01306, PRL 122 (2019) 061102

A lower bound on the maximum mass if the secondary in GW190814 was once a rapidly spinning neutron star

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[2]School of Mathematics, Trinity College, Dublin 2, Ireland
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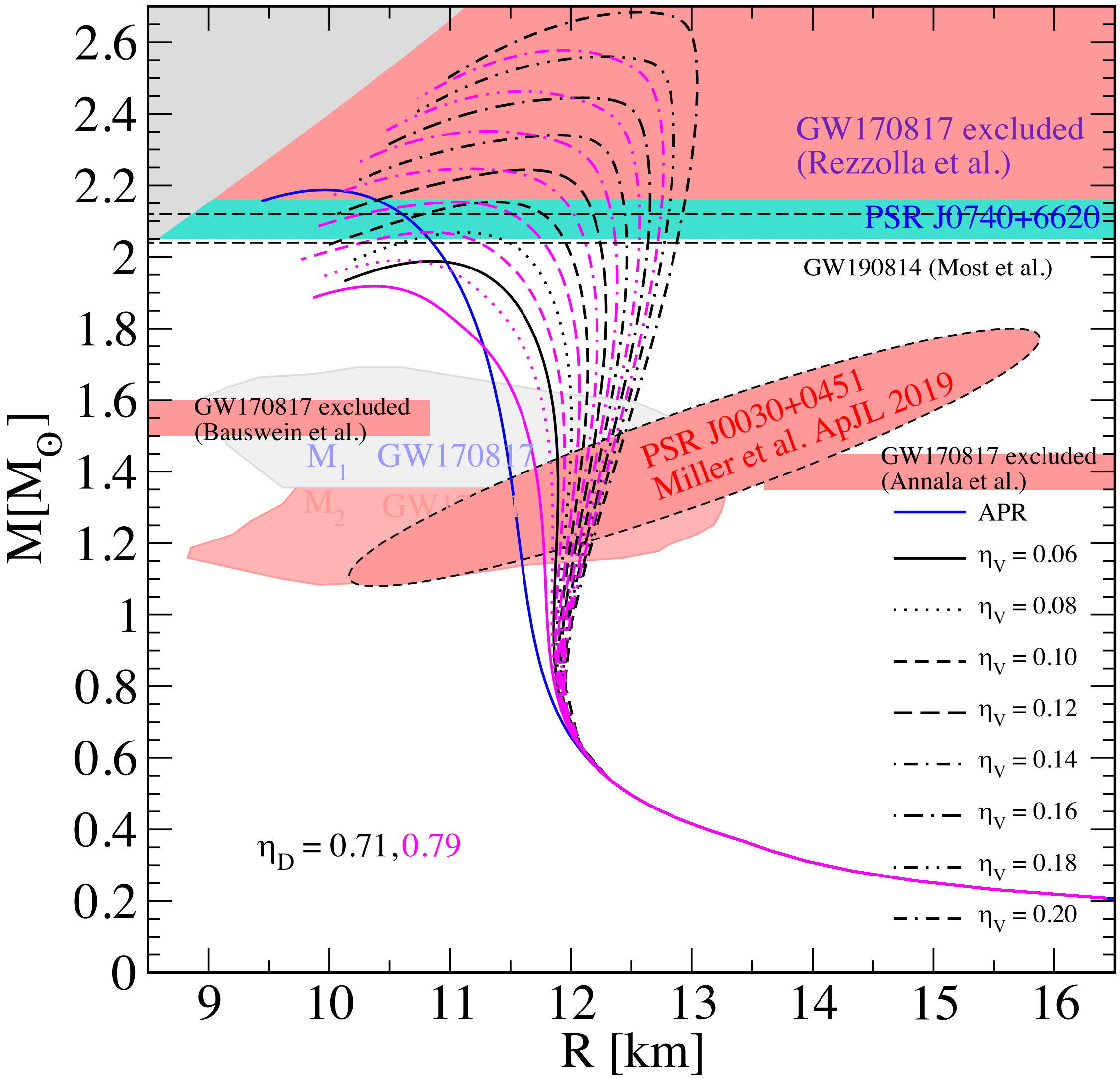
ABSTRACT

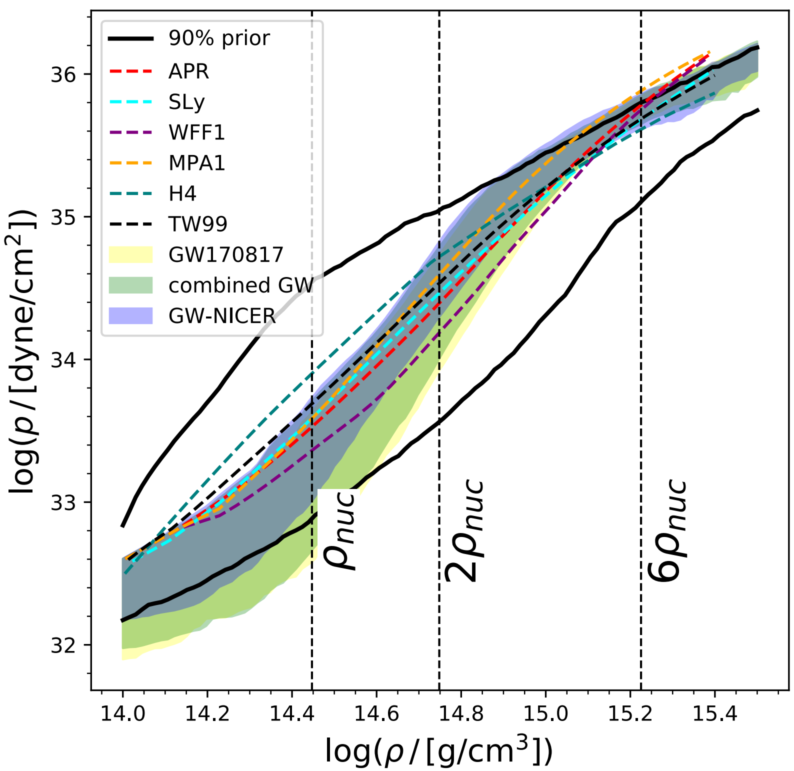
The recent detection of GW190814 featured the merger of a binary with a primary having a mass of $\sim 23\,M_\odot$ and a secondary with a mass of $\sim 2.6\,M_\odot$. While the primary was most likely a black hole, the secondary could be interpreted as either the lightest black hole or the most massive neutron star ever observed, but also as the indication of a novel class of exotic compact objects. We here argue that the secondary in GW190814 needs not be an ab-initio black hole nor an exotic object; rather, based on our current understanding of the nuclear-matter equation of state, it can be a rapidly rotating neutron star that collapsed to a rotating black hole at some point before merger. Using universal relations connecting the masses and spins of uniformly rotating neutron stars, we estimate the spin, $0.49 \lesssim \chi \lesssim 0.68$, of the secondary – a quantity not constrained so far by the detection – and a novel strict lower bound on the maximum mass, $M_{\rm TOV} > 2.08^{+0.04}_{-0.04}\,M_\odot$, of nonrotating neutron stars, consistent with recent observations of a very massive pulsar. The new lower bound also remains valid even in the less likely scenario in which the secondary neutron star never collapsed to a black hole.

Keywords: transients: black hole - neutron star mergers — gravitational waves —stars: neutron

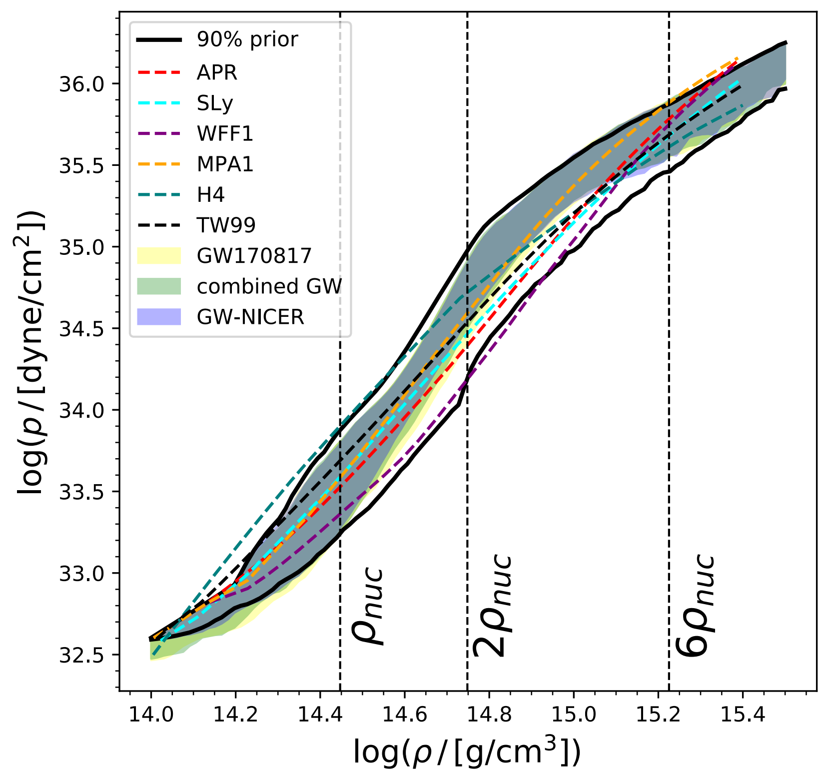
New Constraints!



Hint of a tension between Nuclear physics and Astrophysical observations



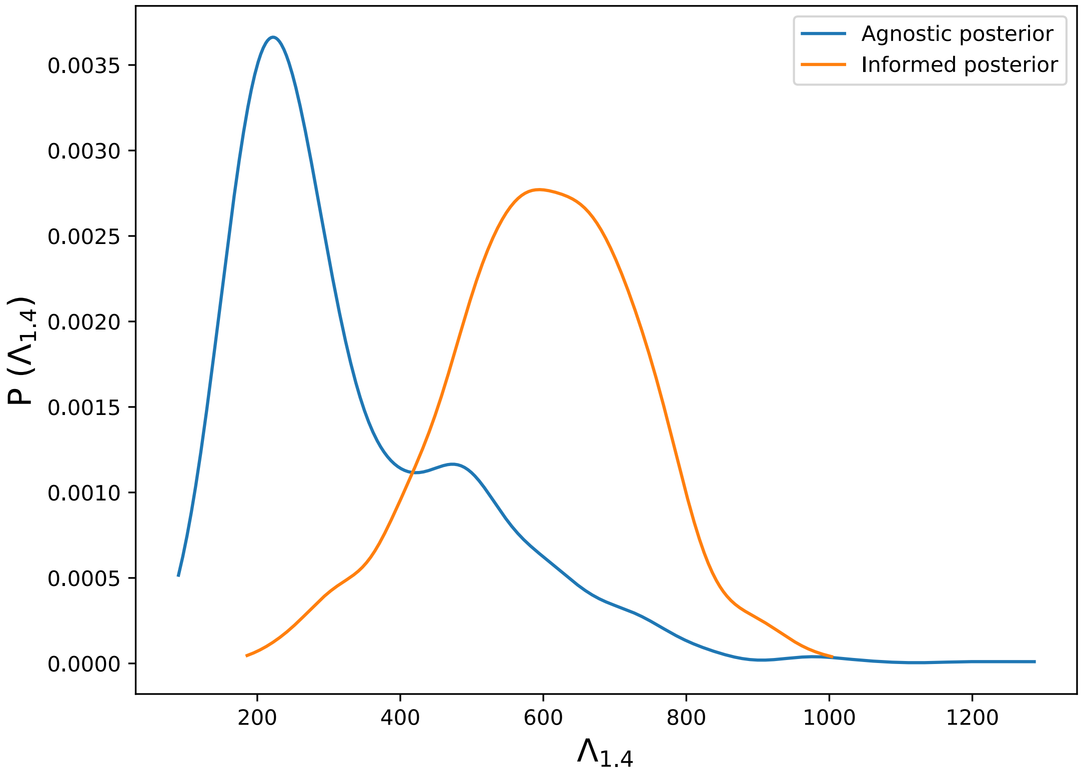
nuclear-physics agnostic priors



nuclear-physics priors

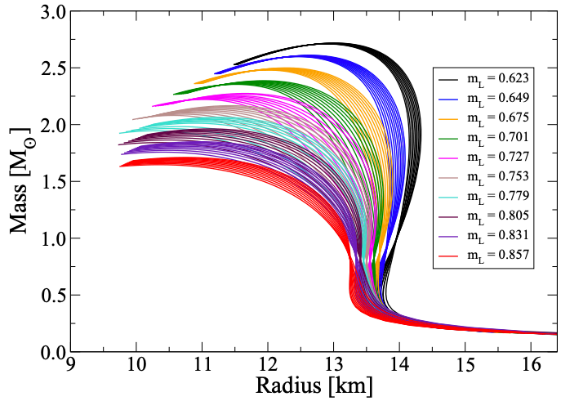
Bhaskar Biswas, Prasanta Char, Rana Nandi, Sukanta Bose, arXiv:2008.01582

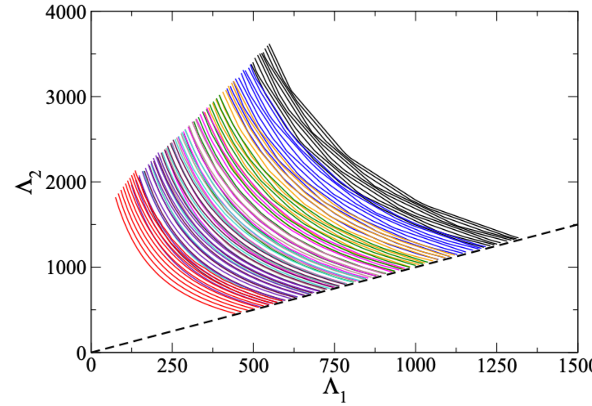
Hint of a tension between Nuclear physics and Astrophysical observations

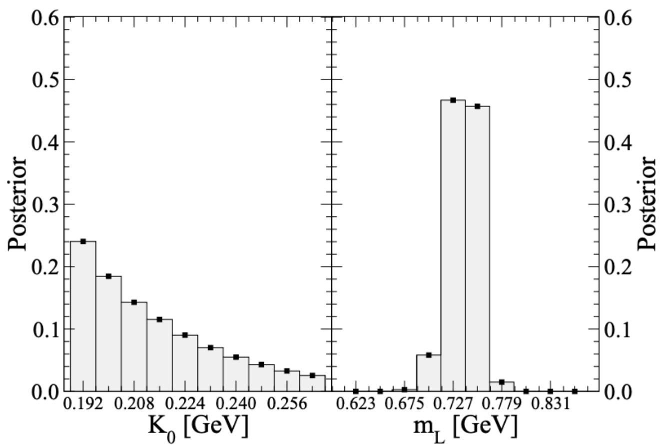


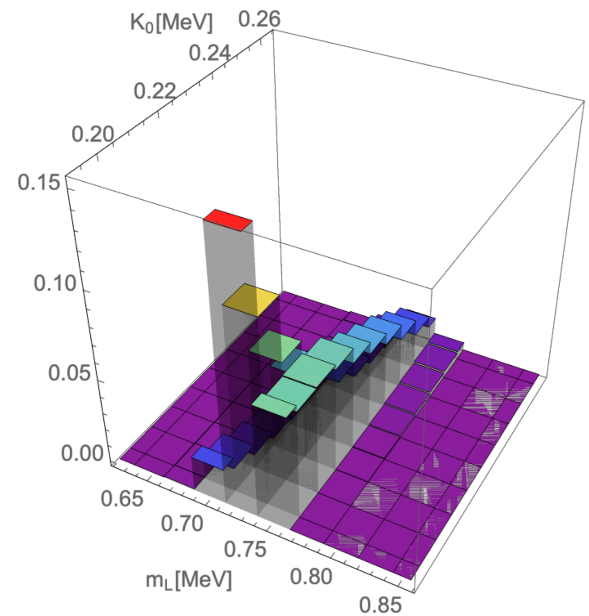
Bhaskar Biswas, Prasanta Char, Rana Nandi, Sukanta Bose, arXiv:2008.01582

σ-ω model for neutron star matter







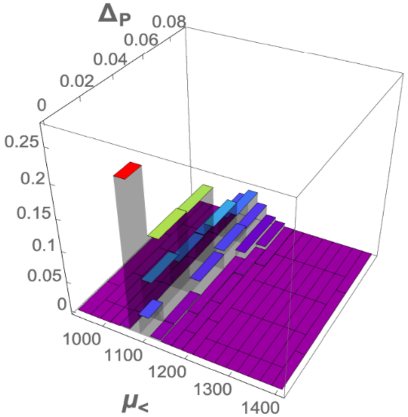


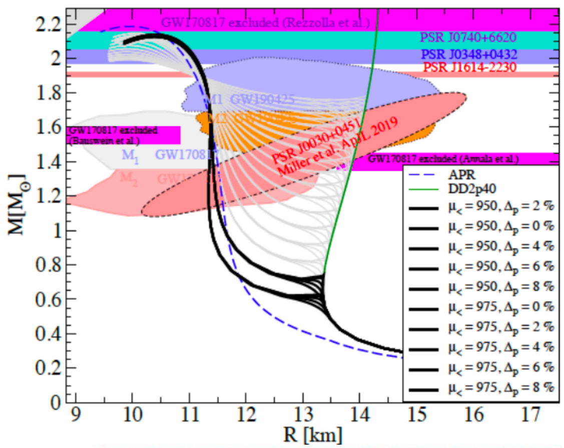
D. A-C., A. Ayriyan, G. G. Barnaföldi, H. Grigorian, P. Pósfay, arXiv:2006.03676

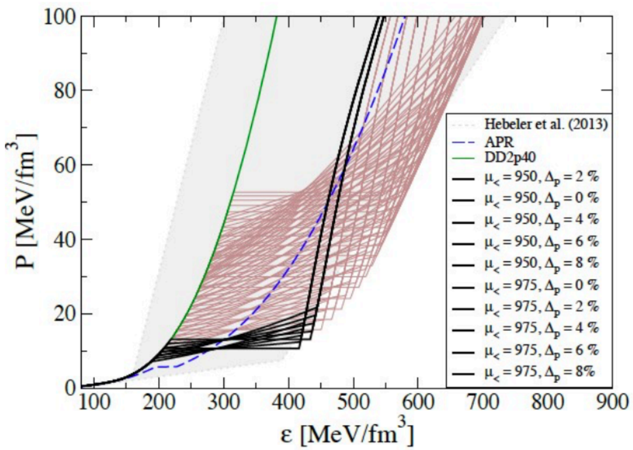
Bayesian inference for (normal) hybrid EoS Models

M-R from NICER:

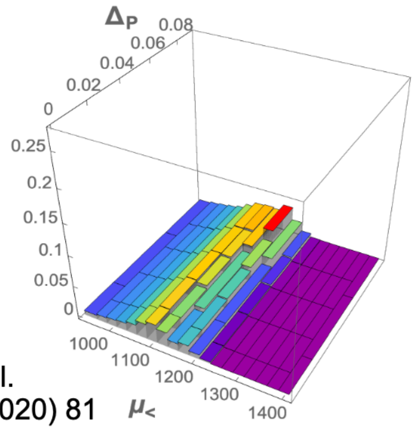
Present Variance →

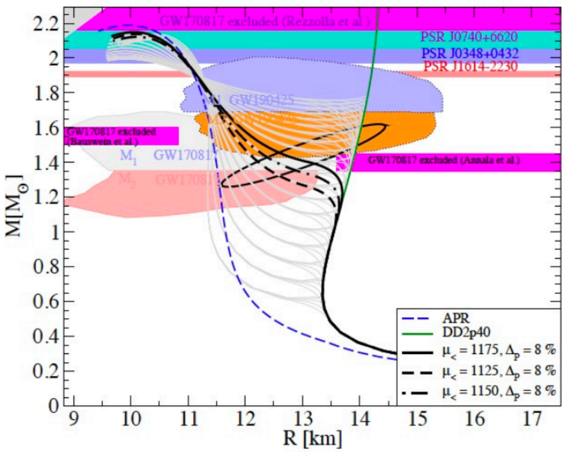


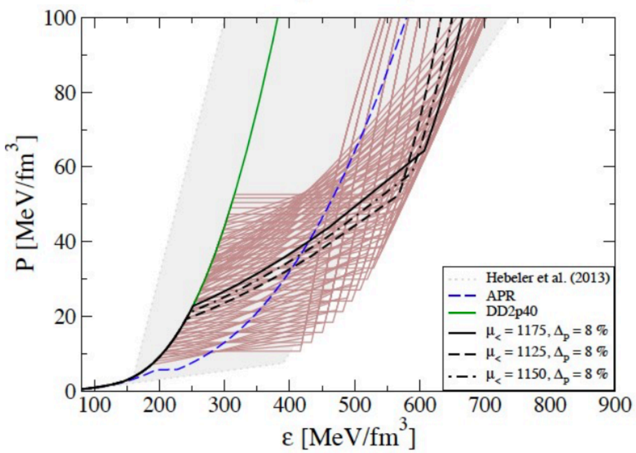




Fictitious Reduced Variance →







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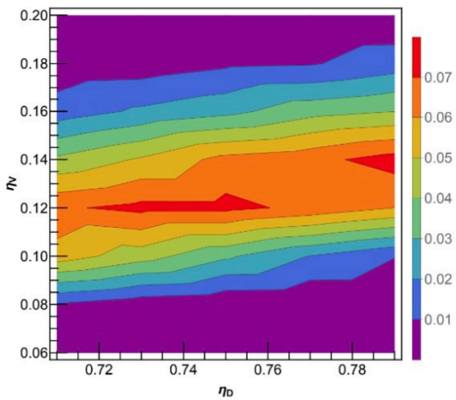
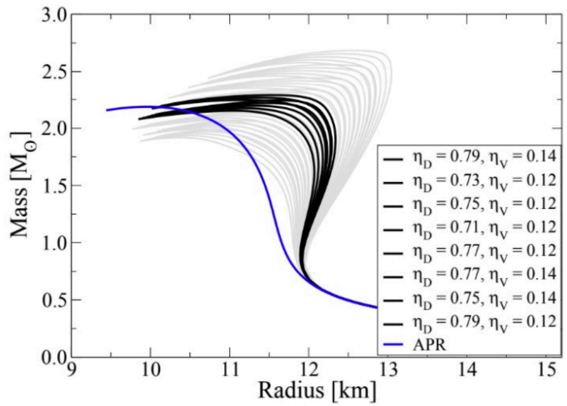
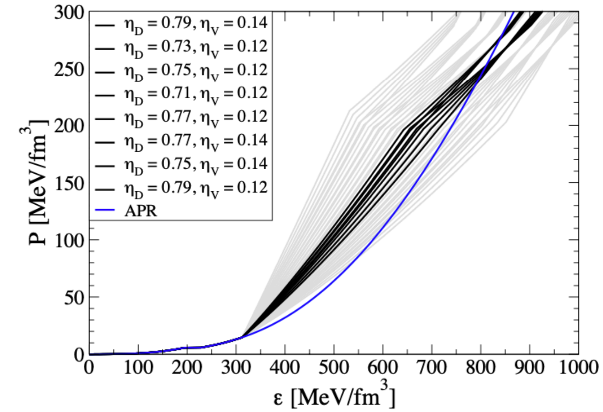
Bayesian inference for (anomalous) hybrid EoS Models

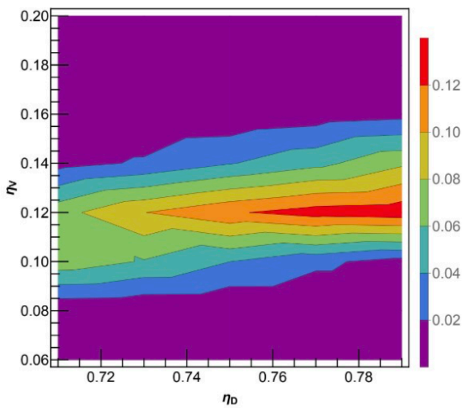
Present Constraints →

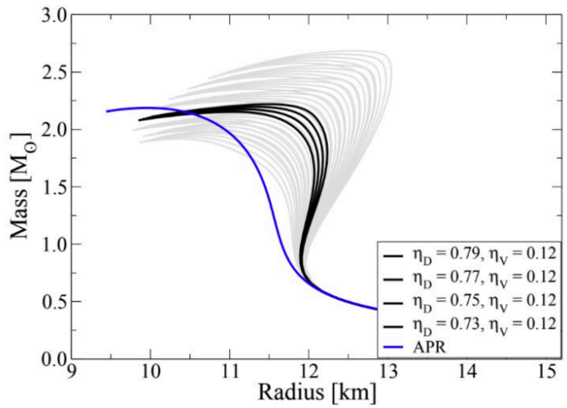


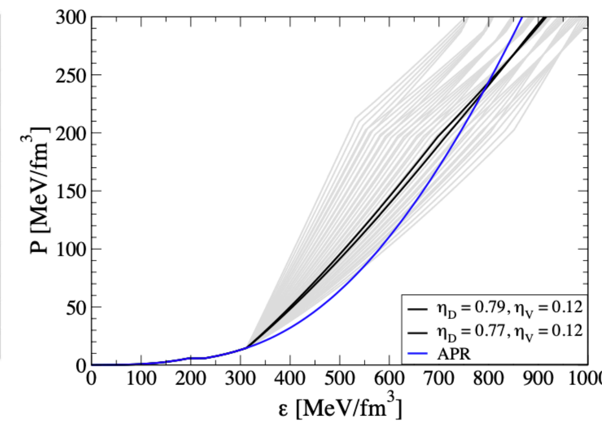




NICER Fictitious R=11 km For PSR J0740+6620 →







Ayriyan et al. EPJA (2020) in prep.

Moments of Inertia

J.M. Lattimer, M. Prakash / Physics Reports 442 (2007) 109–165

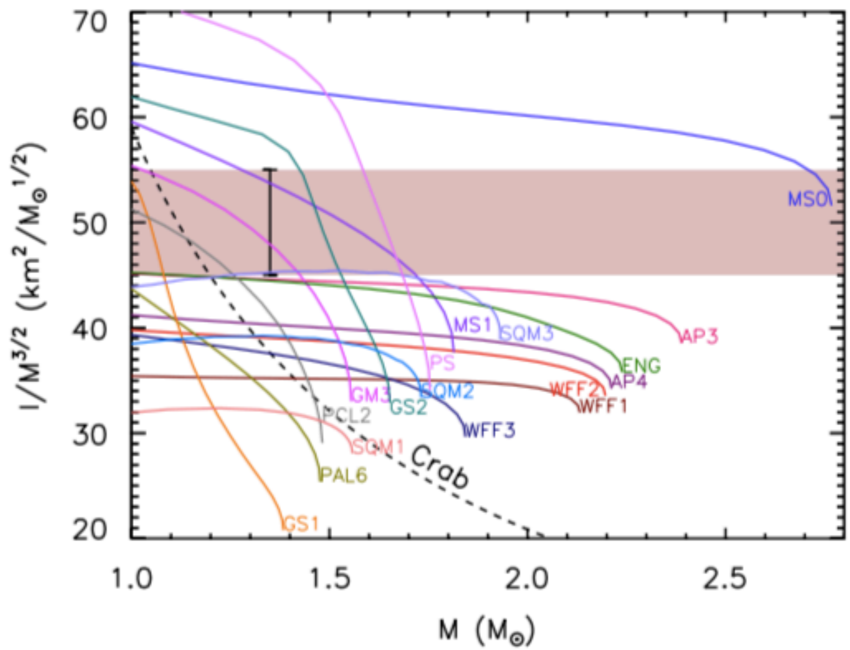
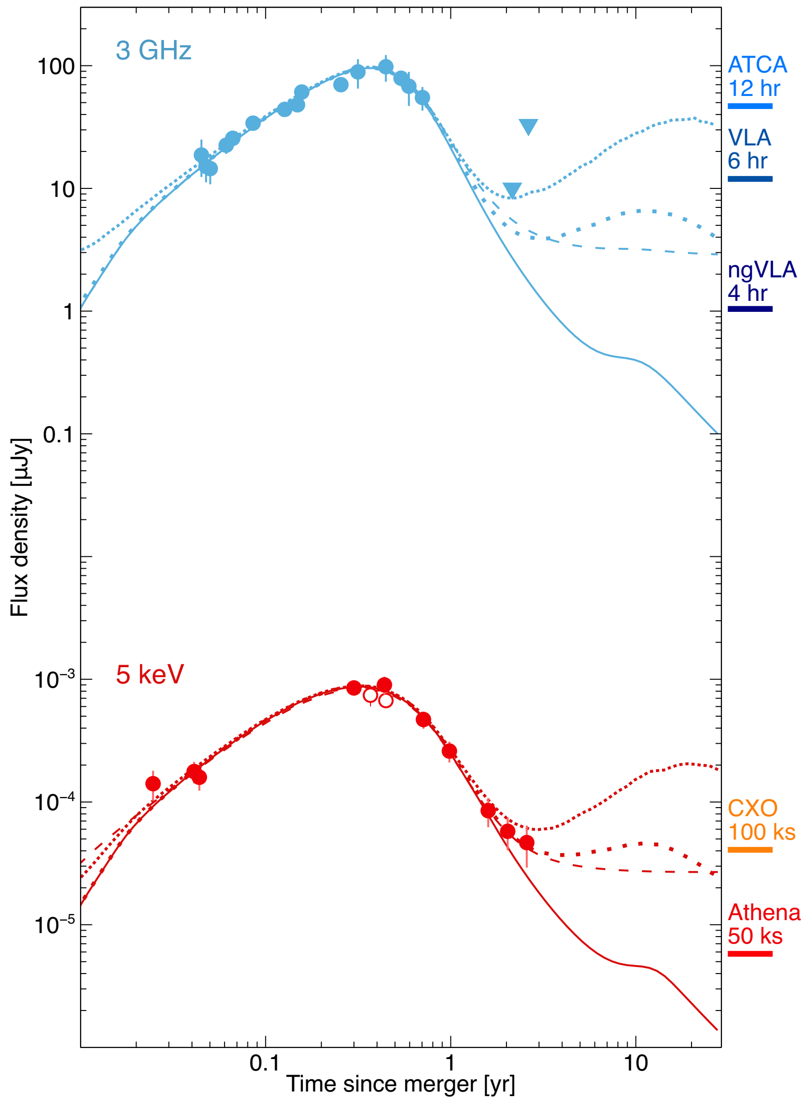


Fig. 9. The moment of inertia scaled by $M^{3/2}$ as a function of stellar mass M for EOSs described in [6]. The shaded band illustrates a $\pm 10\%$ error on a hypothetical $I/M^{3/2}$ measurement with centroid $50\,\mathrm{km}^2\,\mathrm{M}_\odot^{-1/2}$; the error bar shows the specific case in which the mass is $1.34\,\mathrm{M}_\odot$ with essentially no error. The dashed curve labelled "Crab" is the lower limit derived by [123] for the Crab pulsar.

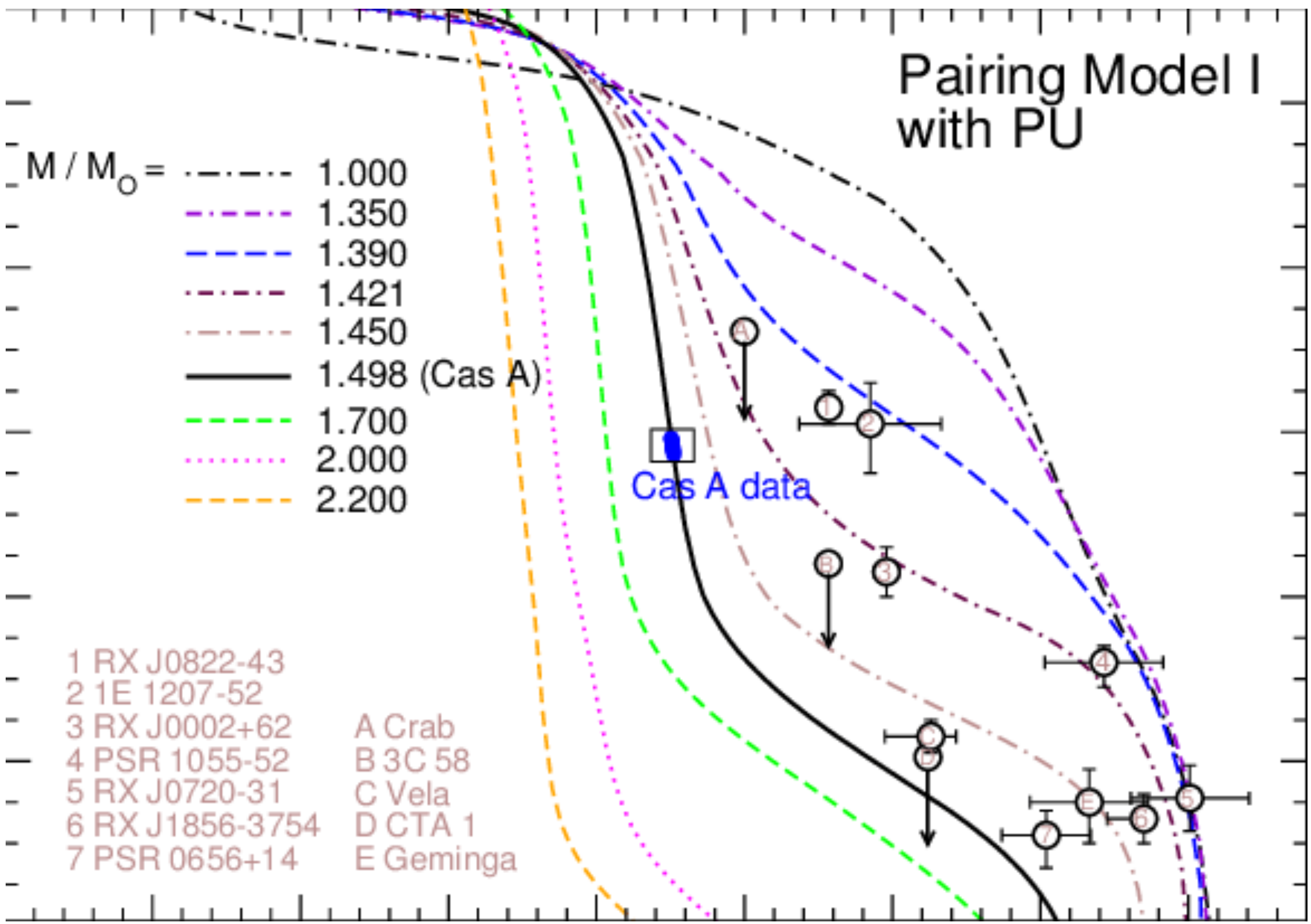
$$I \simeq \frac{J}{1+2GJ/R^3c^2}, \quad J = \frac{8\pi}{3}\int_0^R r^4\left(\rho + \frac{p}{c^2}\right)\Lambda dr, \quad \Lambda = \frac{1}{1-2Gm/rc^2}$$

Continued X-ray emission from GW170817



A thousand days after the merger- continued X-ray emission from GW170817 - E. Troja, et al. - MNRAS Vol. 498, Issue 4, (2020)

Compact Stars Cooling



Conclusions

- Astrophysical constraints indicate that the EoS at high densities must be effectively soft, either as a relatively soft hadronic one or a hybrid one with a strong phase transition. However, there seems to be tension with nuclear empirical data

- GW, NICER and future SKA observations will result into stronger NS EoS constraints probing compact star EoS.

- How to determine the matter content in compact stars without ambiguity, avoiding masquerades? Bayesian inference not enough at the moment.

- Many possible astrophysical scenarios for mass twins could be confirmed implying a CEP in QCD.

Gracias