Probing the QCD critical end point by multi-messenger observations of compact stars and heavy ion collisions

David E. Álvarez Castillo

Joint Institute for Nuclear Research

Dubna, Russia

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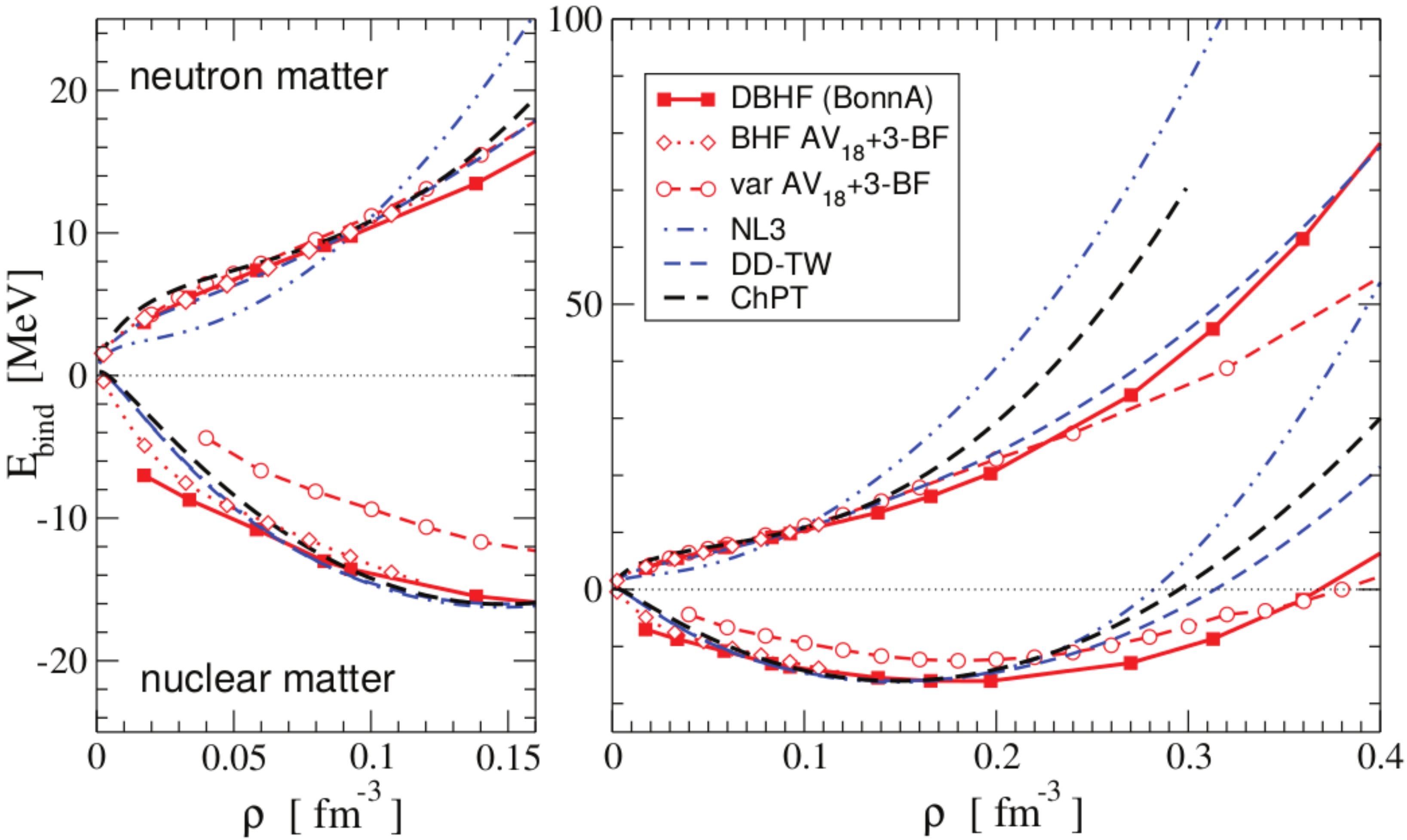
Outline

- A brief introduction to the neutron star equation of state and its location within the QCD phase diagram.
- The compact star mass twins hypothesis.
- Astrophysics measurements of compact stars: multi-messenger astronomy & the GW170817 event.
- Astrophysical implications and perspectives.

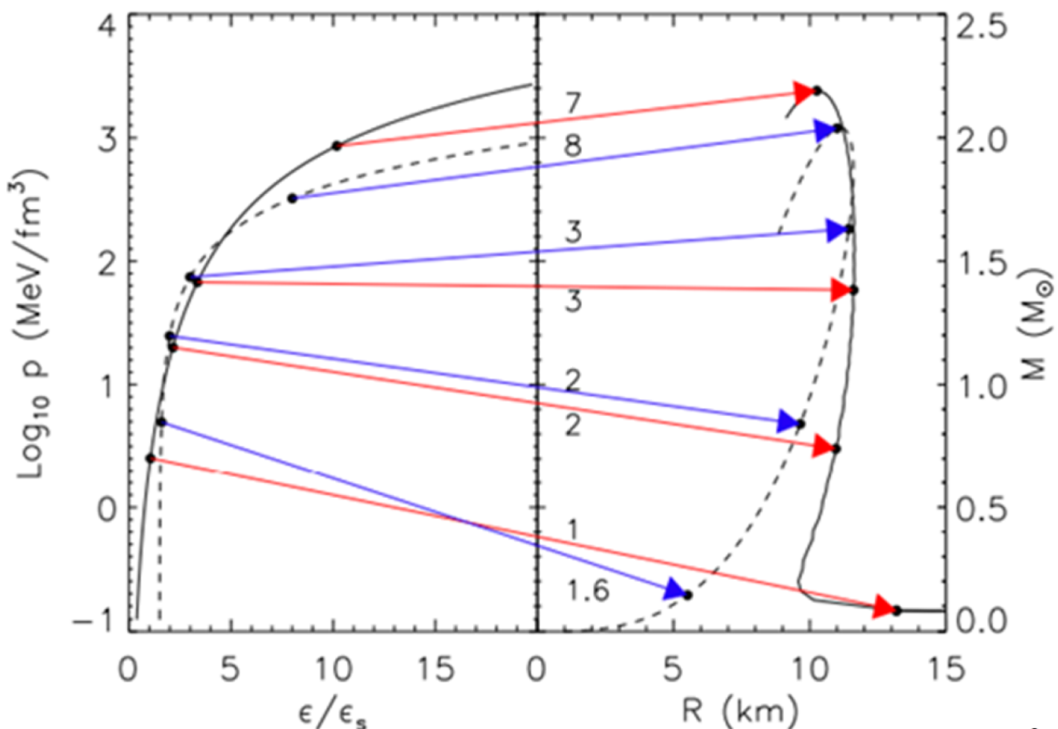
Nuclear Matter



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

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)

$$p(\varepsilon)$$

Flow Constraint

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

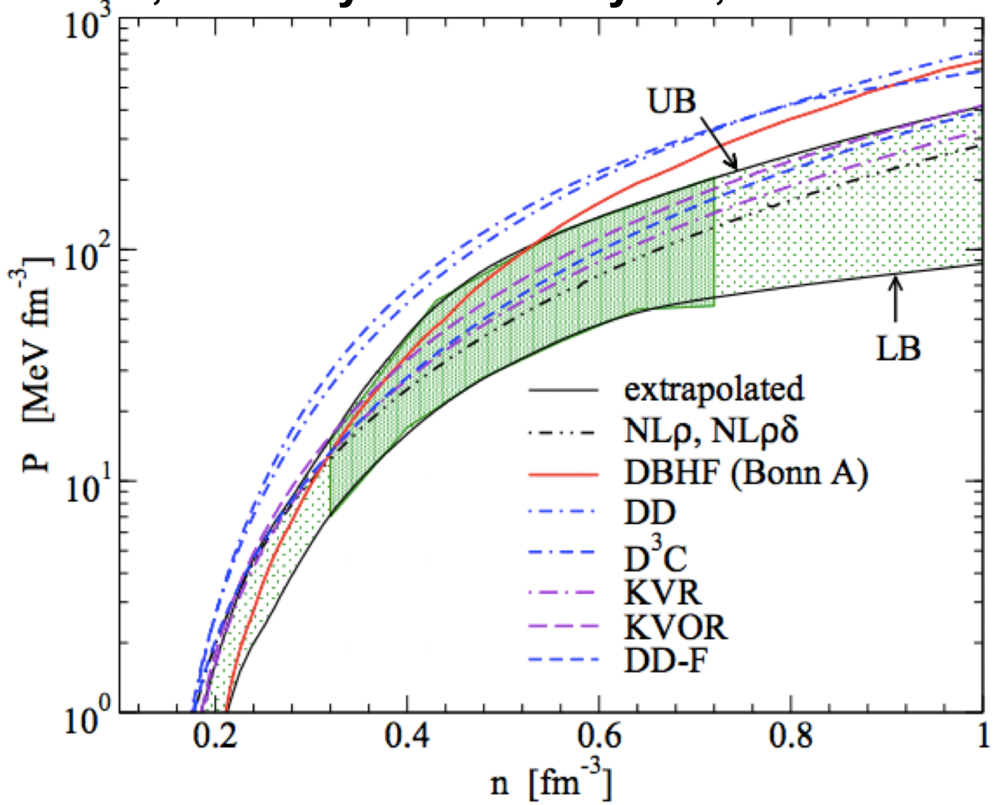
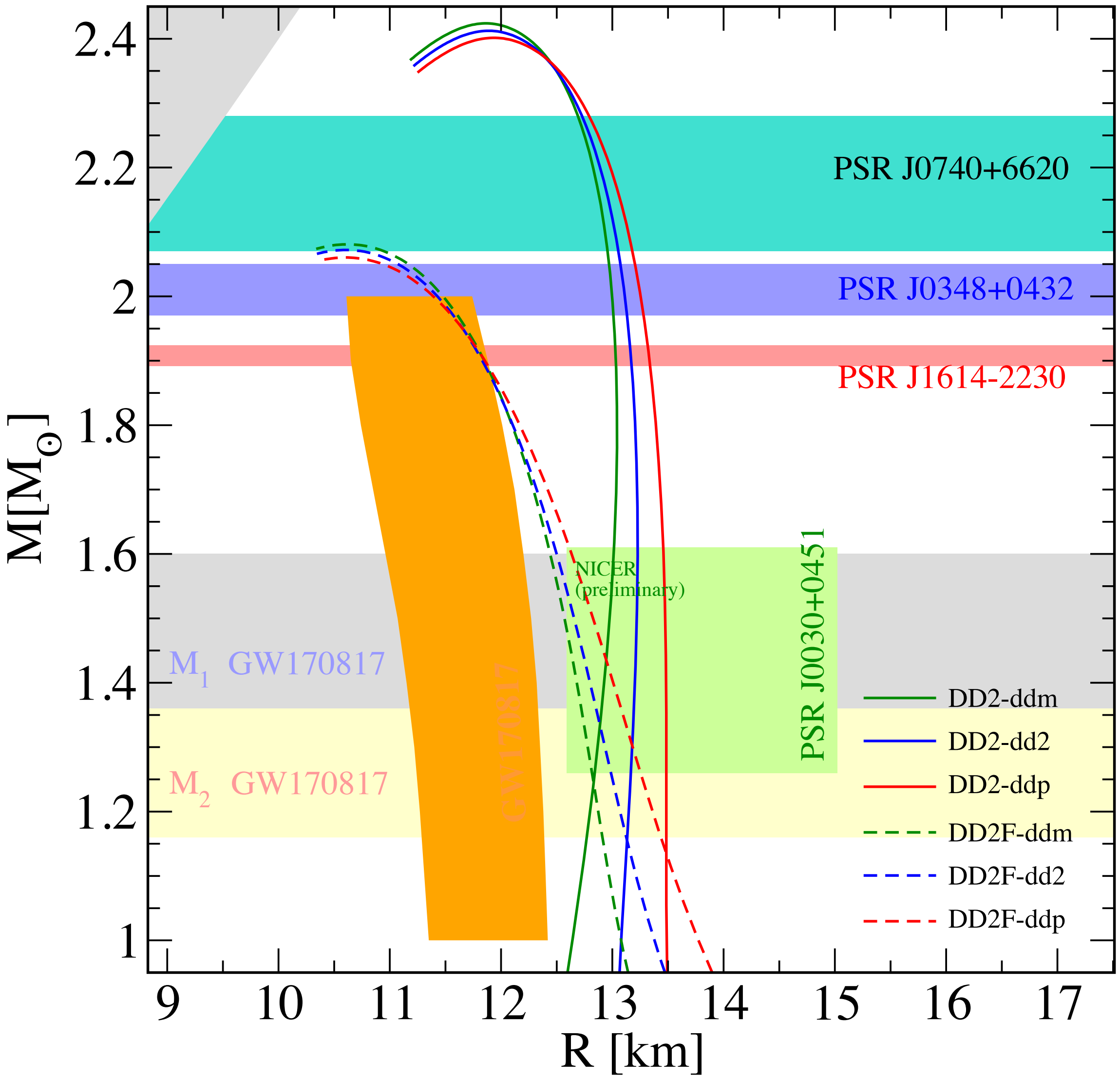


FIG. 6: Pressure region consistent with experimental flow data in SNM (dark shaded region). The light shaded region extrapolates this region to higher densities within an upper (UB) and lower border (LB).

EoS Stiffness



Most massive neutron star ever detected strains the limits of physics

By Ashley Strickland, CNN

Updated 0050 GMT (0850 HKT) September 17, 2019

nature astronomy
LETTERS
https://doi.org/10.1038/s41550-019-0880-2

Relativistic Shapiro delay measurements of an extremely massive millisecond pulsar

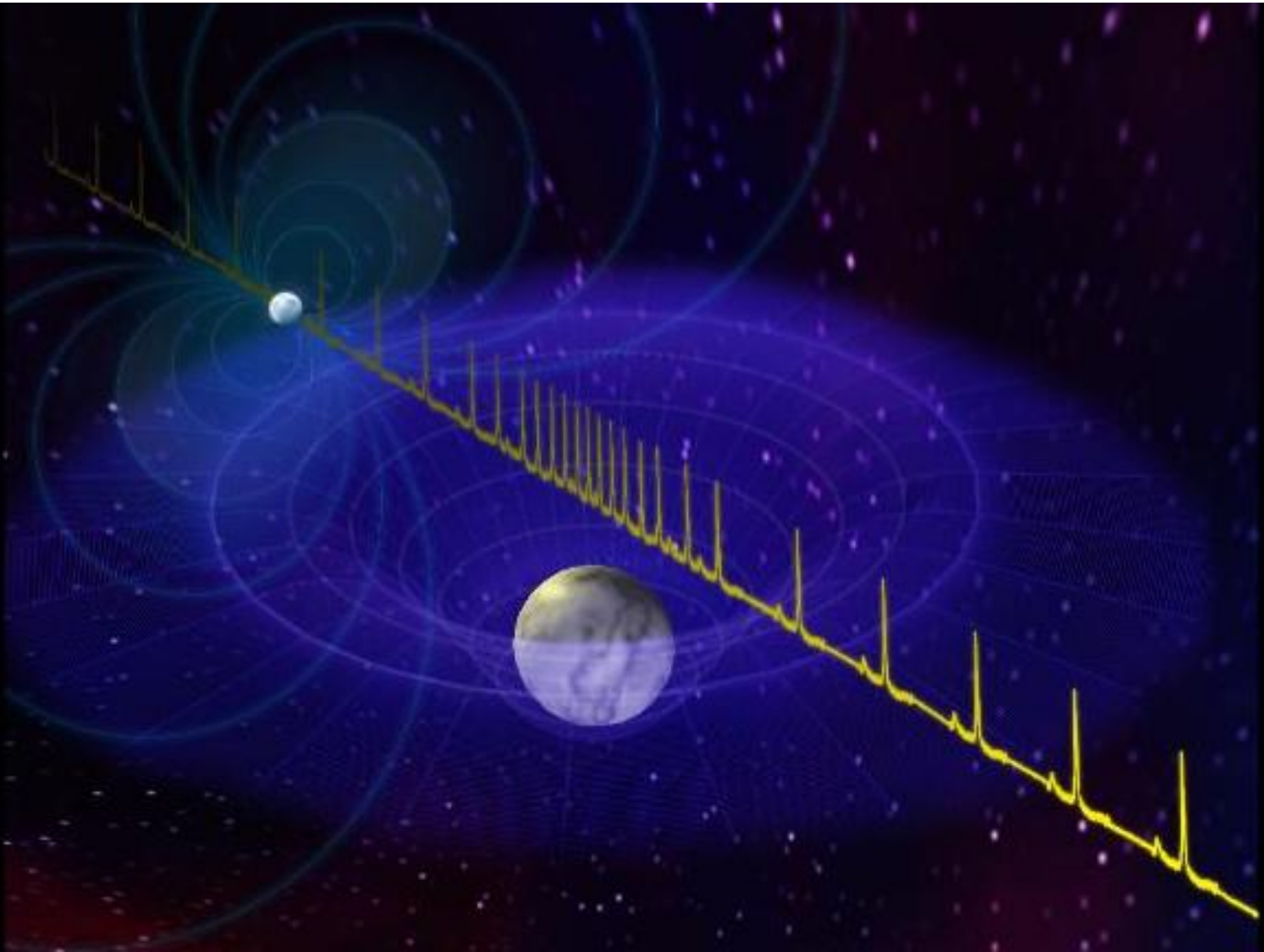
H. T. Cromartie[1*], E. Fonseca[2], S. M. Ransom[3], P. B. Demorest[4], Z. Arzoumanian[5], H. Blumer[6,7], P. R. Brook[6,7], M. E. DeCesar[8], T. Dolch[9], J. A. Ellis[10], R. D. Ferdman[11], E. C. Ferrara[12,13], N. Garver-Daniels[6,7], P. A. Gentile[6,7], M. L. Jones[6,7], M. T. Lam[6,7], D. R. Lorimer[6,7], R. S. Lynch[14], M. A. McLaughlin[6,7], C. Ng[15,16], D. J. Nice[8], T. T. Pennucci[17], R. Spiewak[18], I. H. Stairs[15], K. Stovall[4], J. K. Swiggum[19] and W. W. Zhu[20]

Despite its importance to our understanding of physics at supranuclear densities, the equation of state (EoS) of matter deep within neutron stars remains poorly understood. Millisecond pulsars (MSPs) are among the most useful astrophysical objects in the Universe for testing fundamental physics, and place some of the most stringent constraints on this high-density EoS. Pulsar timing—the process of accounting for every rotation of a pulsar over long time periods—can precisely measure a wide variety of physical phenomena, including those that allow the measurement of the masses of the components of a pulsar binary system[1]. One of these, called relativistic Shapiro delay[2], can yield precise masses for both an MSP and its companion; however, it is only easily observed in a small subset of high-precision, highly inclined (nearly edge-on) binary pulsar systems. By combining data from the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) 12.5-yr data set with recent orbital-phase-specific observations using the Green Bank Telescope, we have measured the mass of the MSP J0740+6620 to be $2.14^{+0.10}_{-0.09}\,M_\odot$ (68.3% credibility interval; the 95.4% credibility interval is $2.14^{+0.20}_{-0.18}\,M_\odot$). It is highly likely to be the most massive neutron star yet observed, and serves as a strong constraint on the neutron star interior EoS.

Precise neutron star mass measurements are an effective way to constrain the EoS of the ultradense matter in neutron star interiors. Although radio pulsar timing cannot directly determine neutron star radii, the existence of pulsars with masses exceeding the maximum mass allowed by a given model can straightforwardly rule out that EoS.

In 2010, Demorest et al. reported the discovery of a $2\,M_\odot$ MSP, J1614−2230 (ref. [4]) (though the originally reported mass was $1.97\pm0.04\,M_\odot$, continued timing has led to a more precise mass measurement of $1.928\pm0.017\,M_\odot$ by Fonseca et al.[5]). This Shapiro-delay-enabled measurement disproved the plausibility of some hyperon, boson and free quark models in nuclear-density environments. In 2013, Antoniadis et al. used optical techniques in combination with pulsar timing to yield a mass measurement of $2.01\pm0.04\,M_\odot$ for the pulsar J0348+0432 (ref. [6]). These two observational results (along with others[7]) encouraged a reconsideration of the canonical $1.4\,M_\odot$ neutron star. Gravitational-wave astrophysics has also begun to provide EoS constraints; for example, the Laser Interferometer Gravitational-Wave Observatory (LIGO) detection of a double neutron star merger constrains permissible EoSs, suggesting that the upper limit on neutron star mass is $2.17\,M_\odot$ (90% credibility[8]). Though the existence of extremely massive ($>2.4\,M_\odot$) neutron stars has been suggested through optical spectroscopic

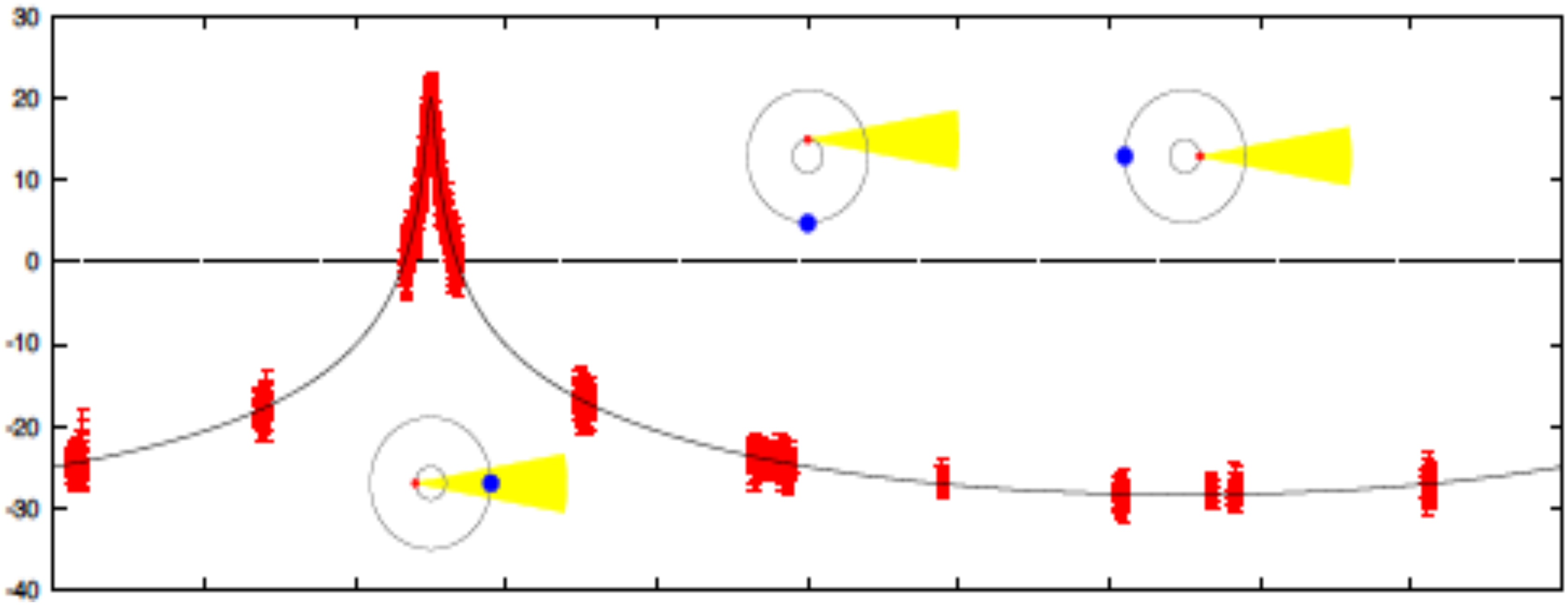
Massive Neutron Stars



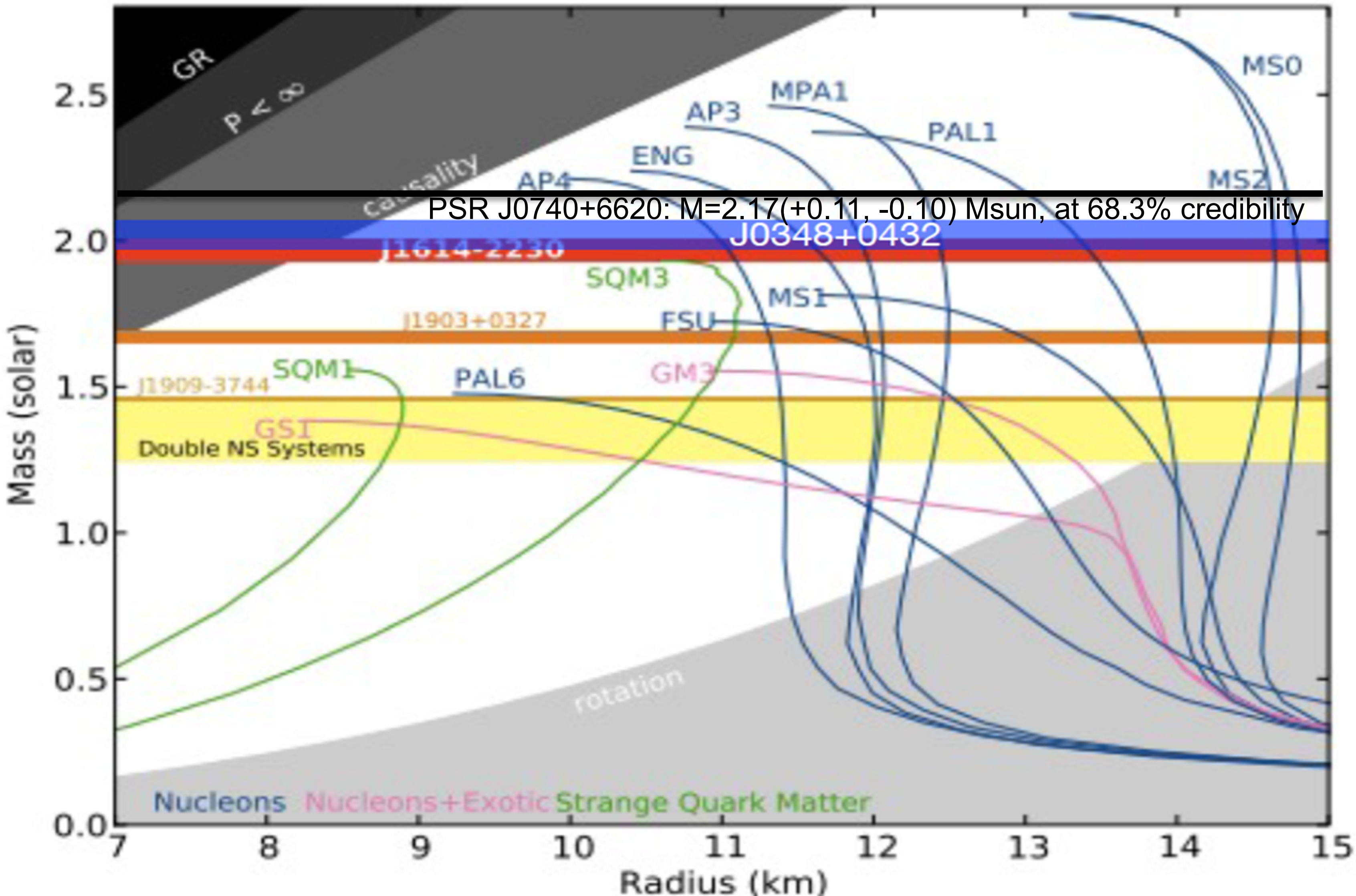
PSR J1614-2230

A precise AND large mass measurement

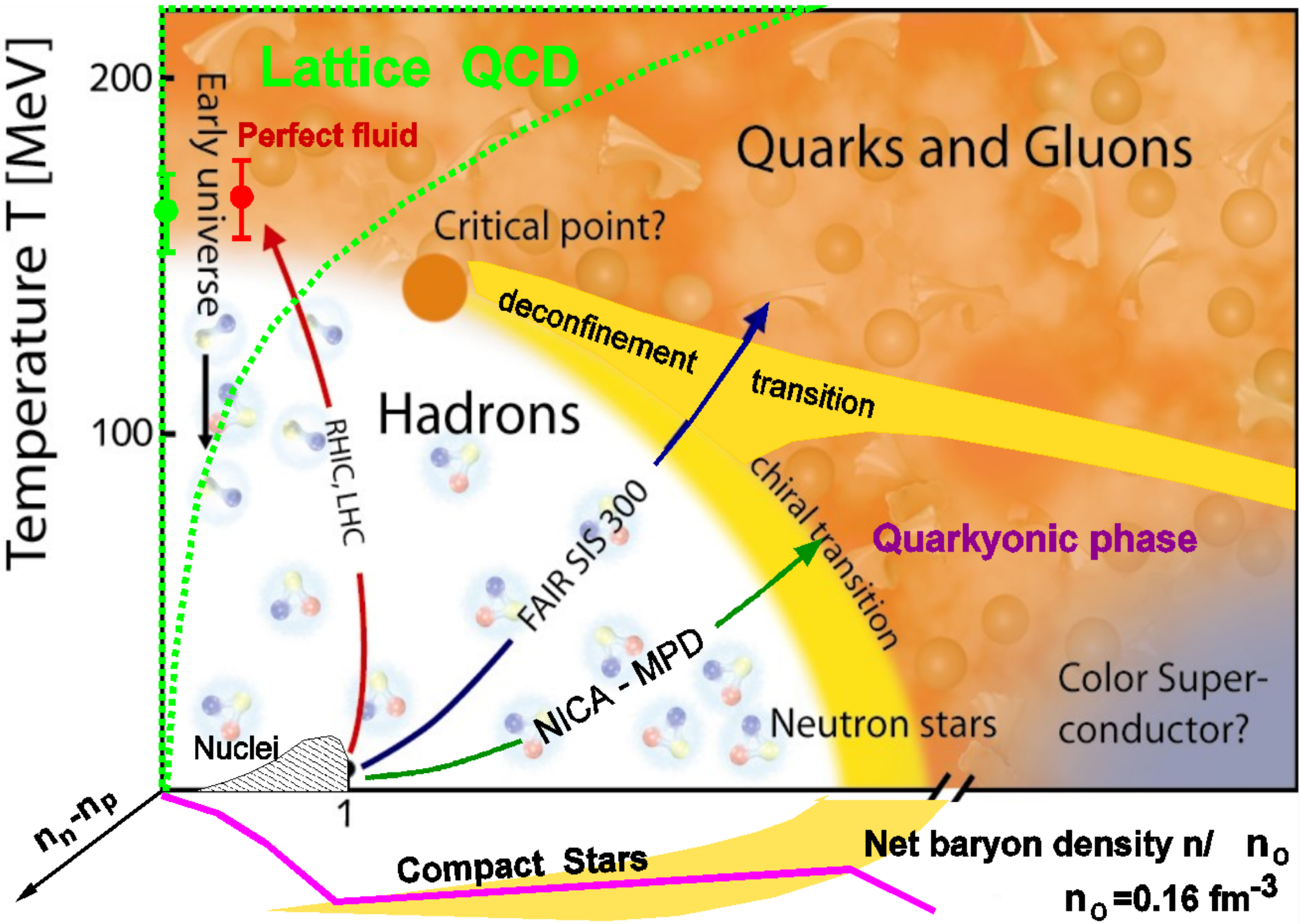
Shapiro delay:



Massive Neutron Stars



Critical Endpoint in QCD

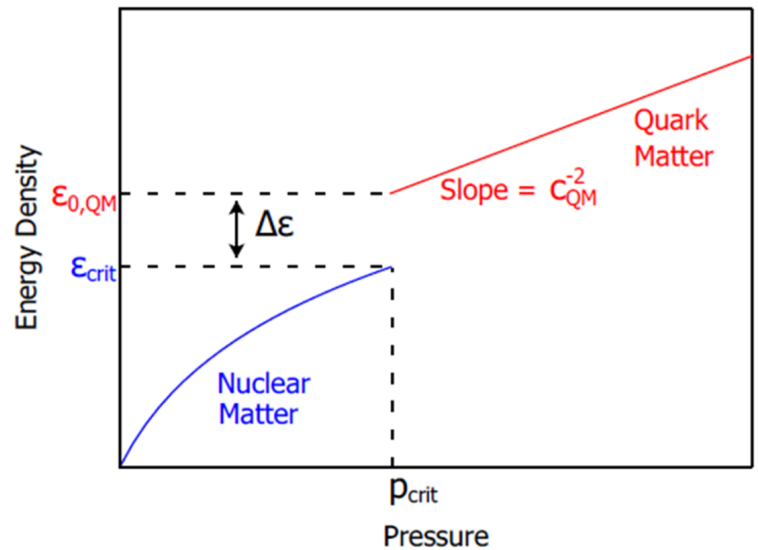


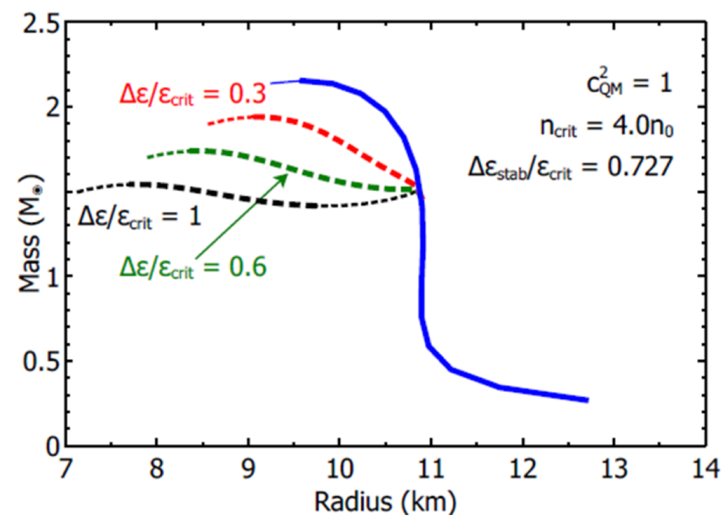
Compact Star Mass Twins and the AHP scheme

- 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



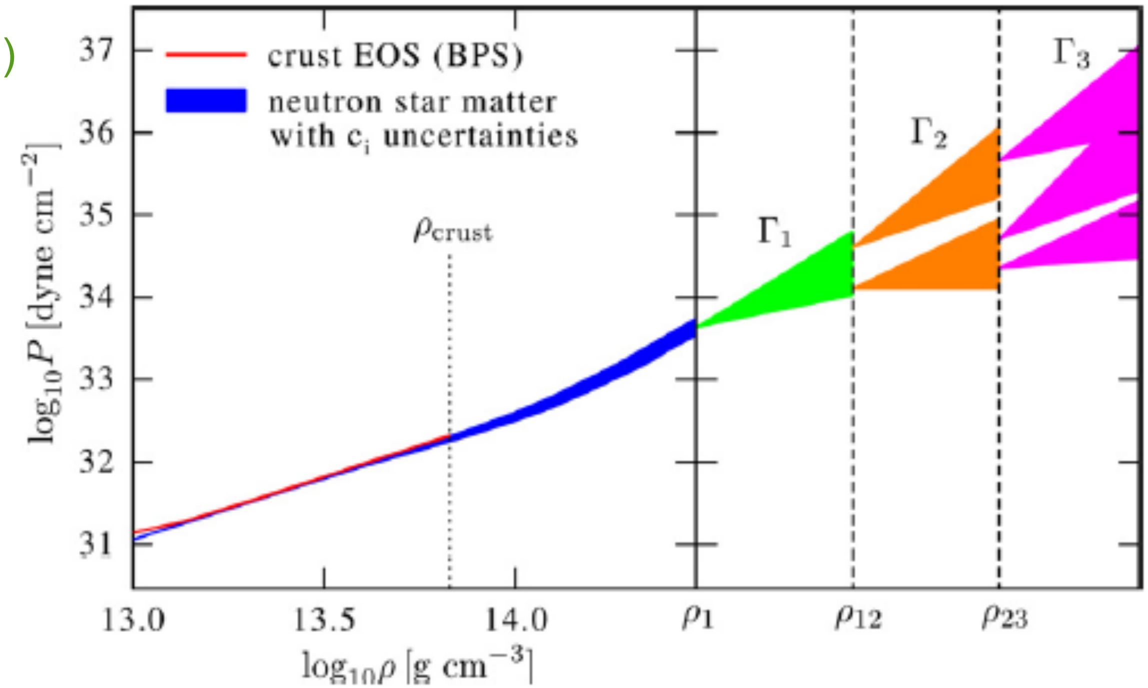


Piecewise polytrope EoS

Hebeler et al., ApJ 773, 11 (2013)

$$P_i(n) = \kappa_i n^{\Gamma_i}$$

$$\begin{aligned} i = 1 &: n_1 \le n \le n_{12} \\ i = 2 &: n_{12} \le n \le n_{23} \\ i = 3 &: n \ge n_{23} \ , \end{aligned}$$



Here, 1st order PT in region 2:

$$\Gamma_2 = 0 \text{ and } P_2 = \kappa_2 = P_{\rm crit}$$

$$\begin{aligned} P(n) &= n^2 \frac{d(\varepsilon(n)/n)}{dn}, \\ \varepsilon(n)/n &= \int dn \, \frac{P(n)}{n^2} = \int dn \, \kappa n^{\Gamma-2} = \frac{\kappa \, n^{\Gamma-1}}{\Gamma-1} + C, \\ \mu(n) &= \frac{P(n)+\varepsilon(n)}{n} = \frac{\kappa \, \Gamma}{\Gamma-1} n^{\Gamma-1} + m_0, \end{aligned}$$

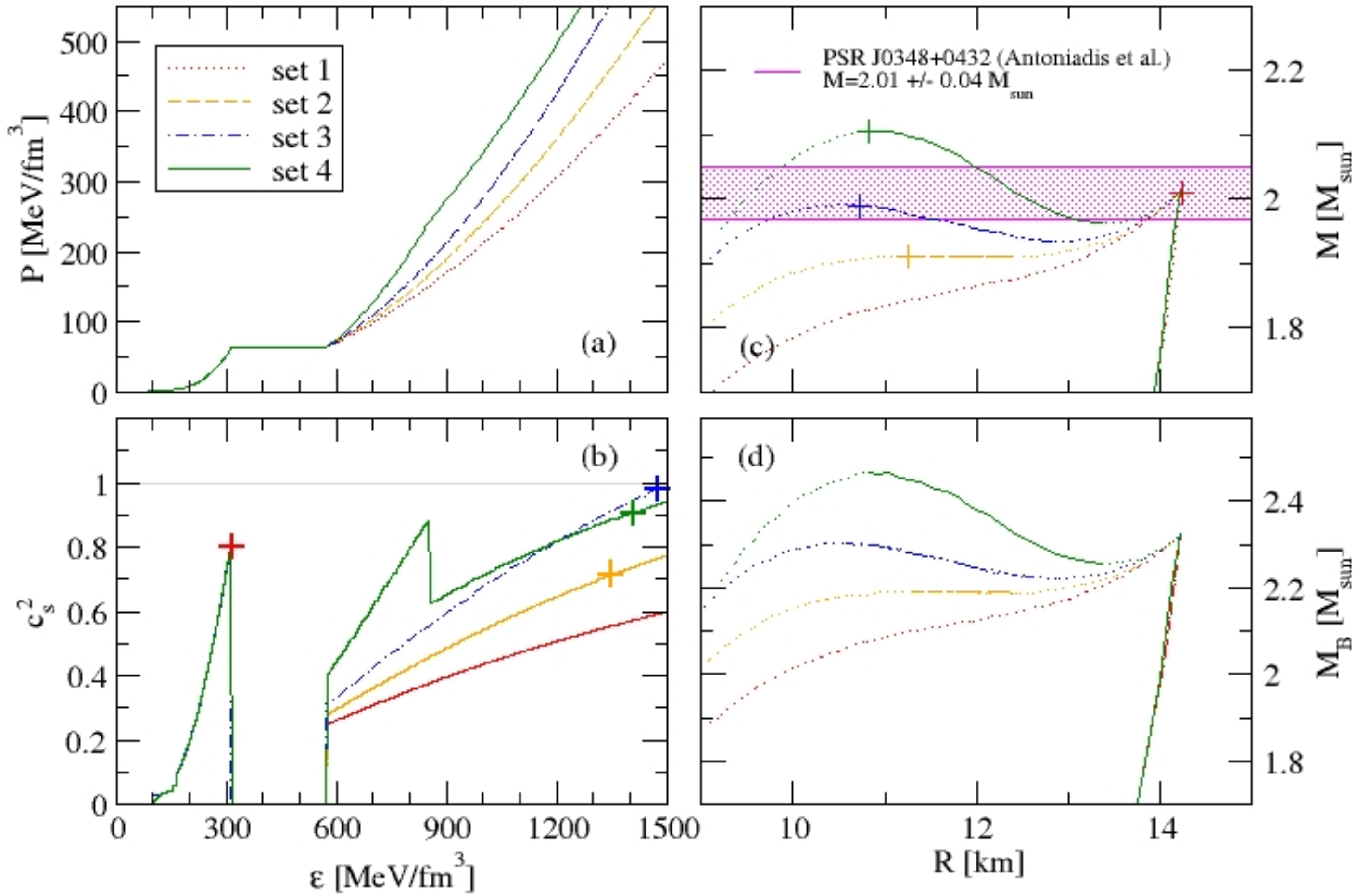
$$\begin{aligned} n(\mu) &= \left[(\mu - m_0) \frac{\Gamma-1}{\kappa\Gamma} \right]^{1/(\Gamma-1)} \\ P(\mu) &= \kappa \left[(\mu - m_0) \frac{\Gamma-1}{\kappa\Gamma} \right]^{\Gamma/(\Gamma-1)} \end{aligned}$$

Maxwell construction:

$$\begin{aligned} P_1(\mu_{\rm crit}) &= P_3(\mu_{\rm crit}) = P_{\rm crit} \\ \mu_{\rm crit} &= \mu_1(n_{12}) = \mu_3(n_{23}) \end{aligned}$$

Seidov criterion for instability: $\frac{\Delta\varepsilon}{\varepsilon_{\rm crit}} \ge \frac{1}{2} + \frac{3}{3} \frac{P_{\rm crit}}{\varepsilon_{\rm crit}}$

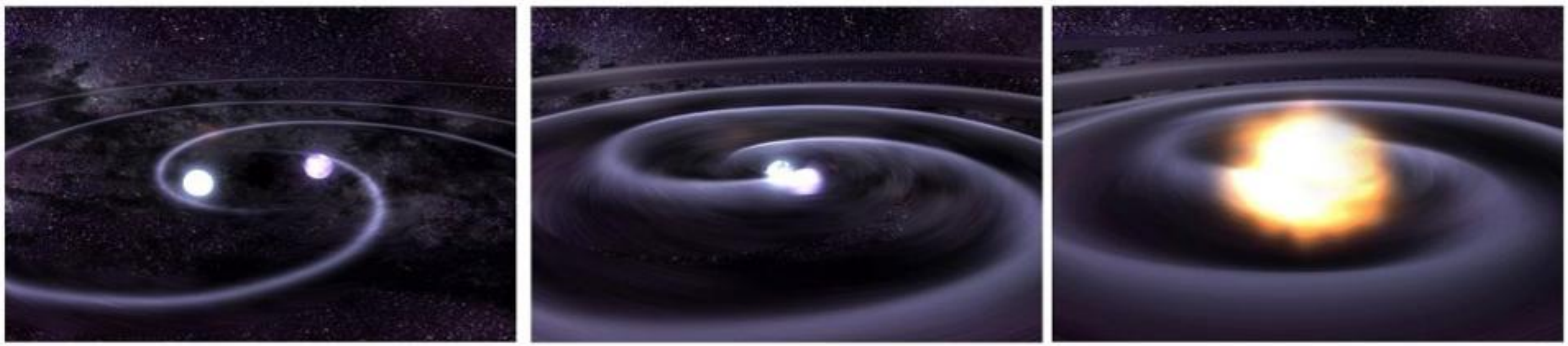
Compact Star Twins

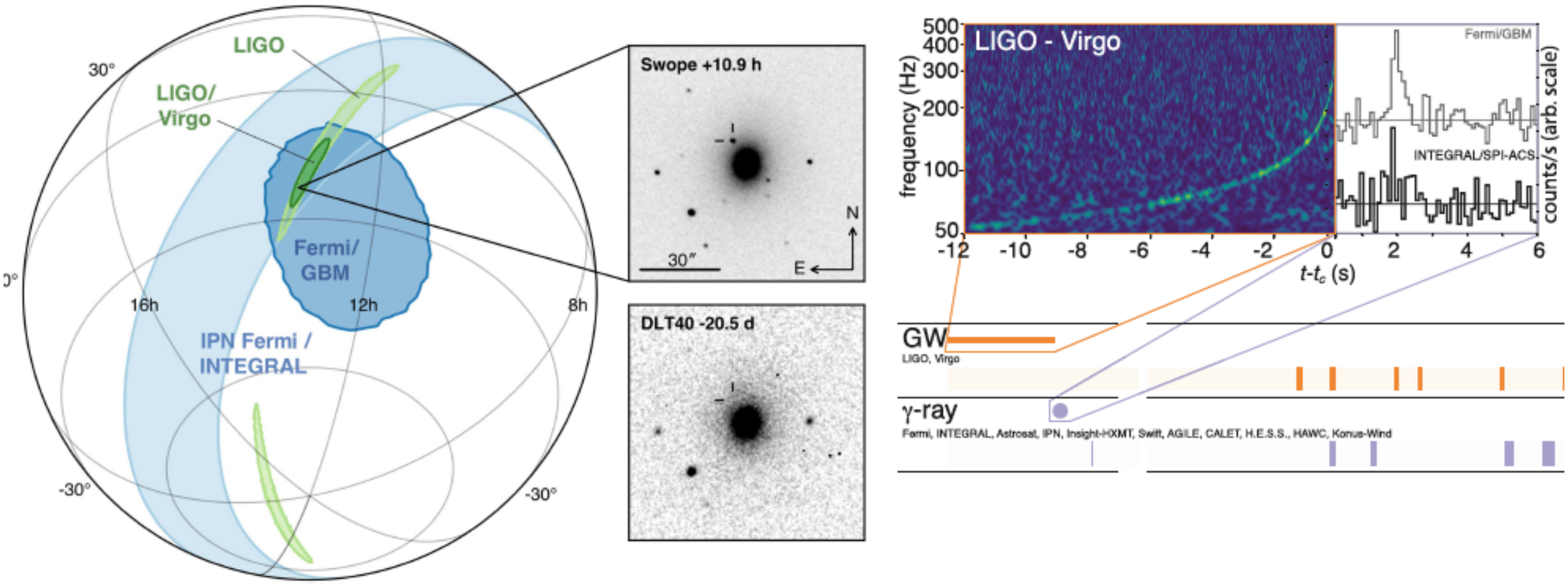


Alvarez-Castillo, Blaschke (2017)
High mass twins from multi-polytrope equations of state
arXiv: 1703.02681v2, Phys. Rev. C 96, 045809 (2017)

Multi-messenger Astronomy

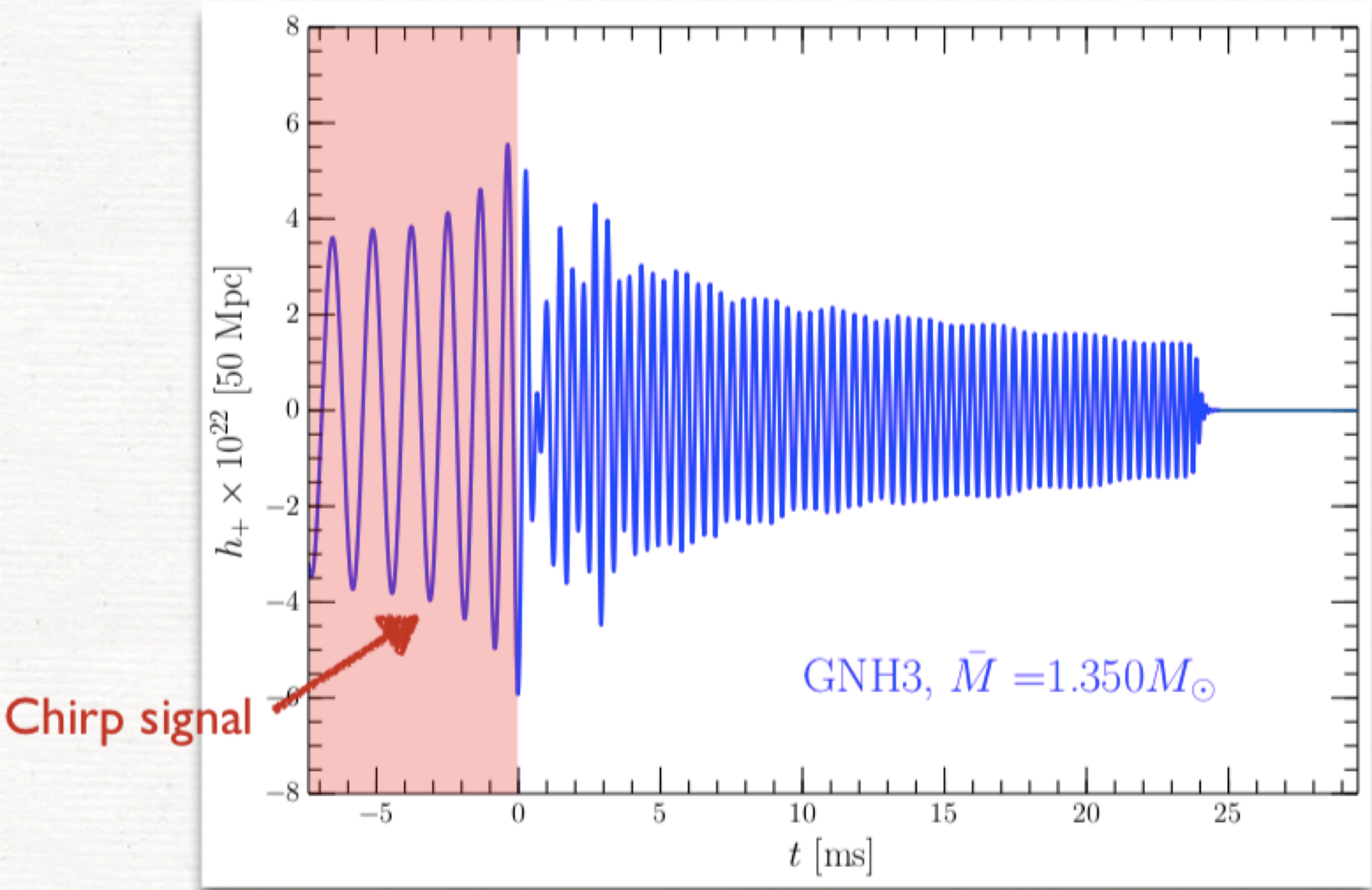
GW170817: Neutron Star Merger



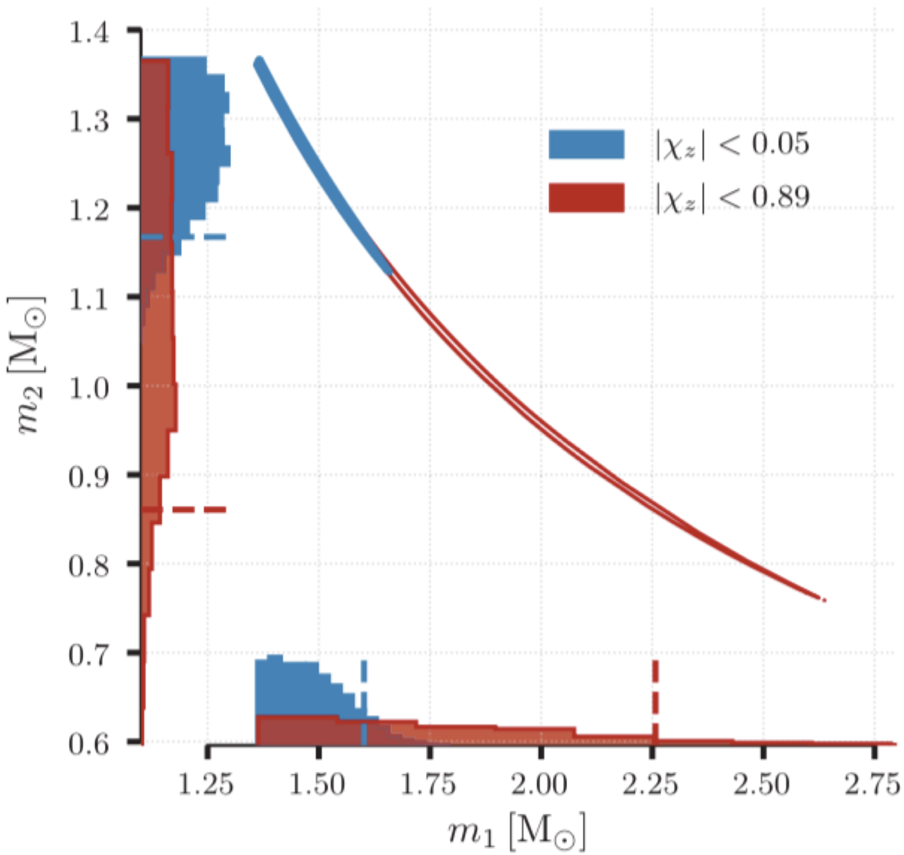


*) B.P. Abbott et al. [LIGO/Virgo Collab.], PRL 119, 161101 (2017); ApJLett 848, L12 (2017)

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

What can we learn from the inspiral II

- Waveforms incl. finite-size effects are described by tidal deformability (how a star reacts on an external tidal field)
- Offer possibility to constrain EoS because tidal deformability depends on EoS

$$\Lambda \equiv \frac{2}{3} k_2 \left(\frac{R}{M} \right)^5$$

- Corresponding to ~10 % error in radius R for nearby events (<100Mpc) (e.g. Read et al. 2013)
- Note: faithful templates to be constructed

R/M compactness (EoS dependent)

k_2 tidal love number (EoS dependent)

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:

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

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

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

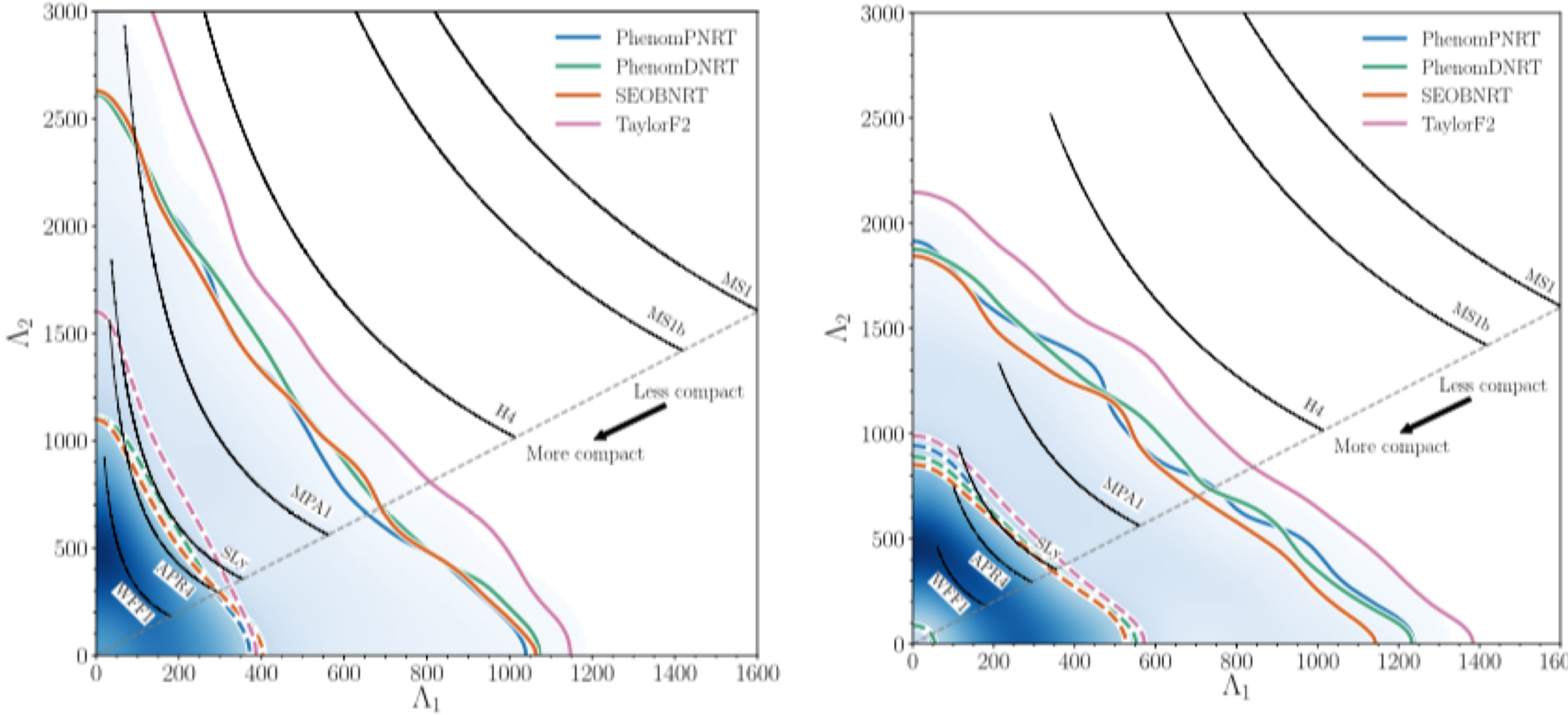
Love number

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

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

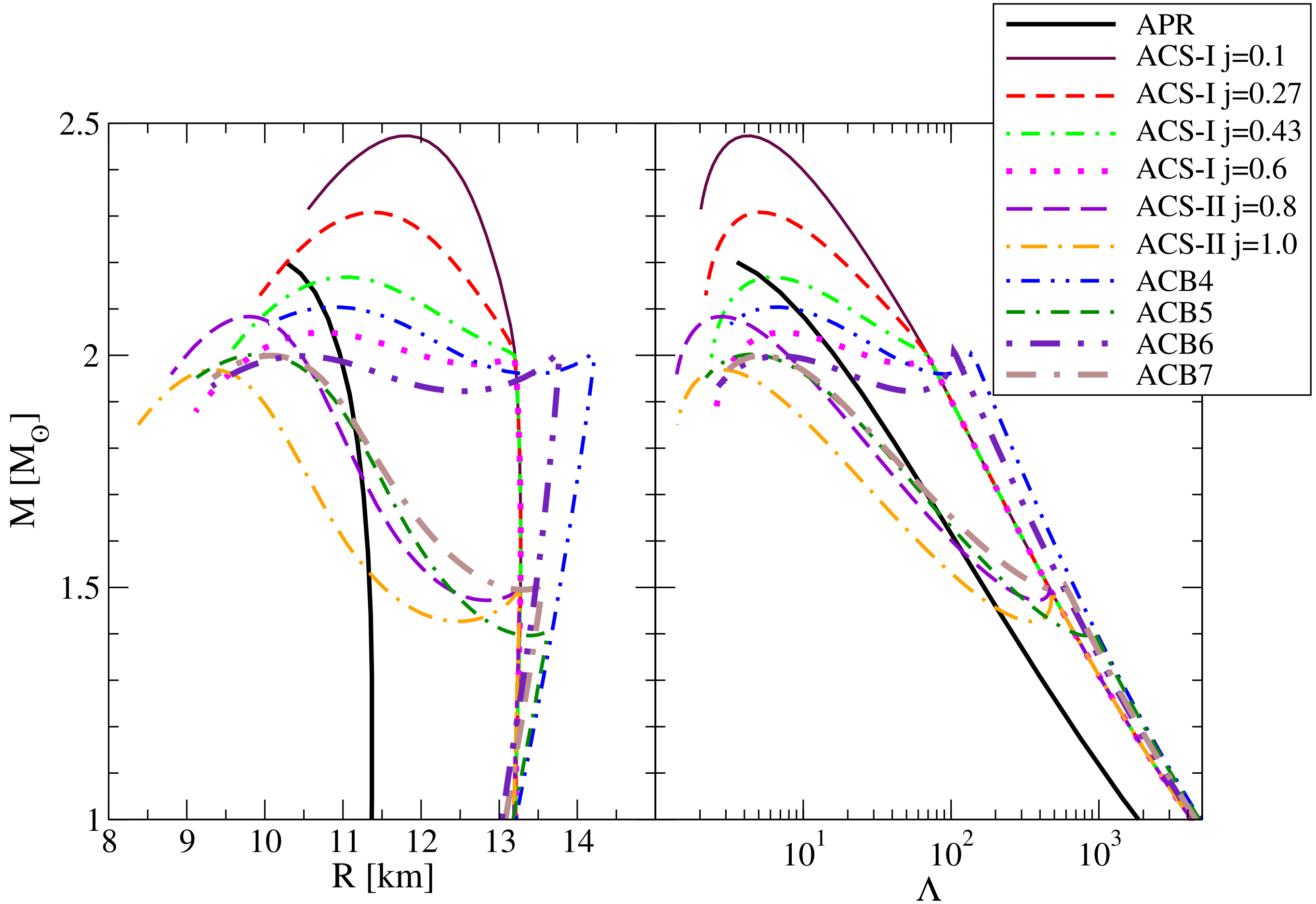
where $C = M/R$ is the compactness of the star.

Implications from GW170817



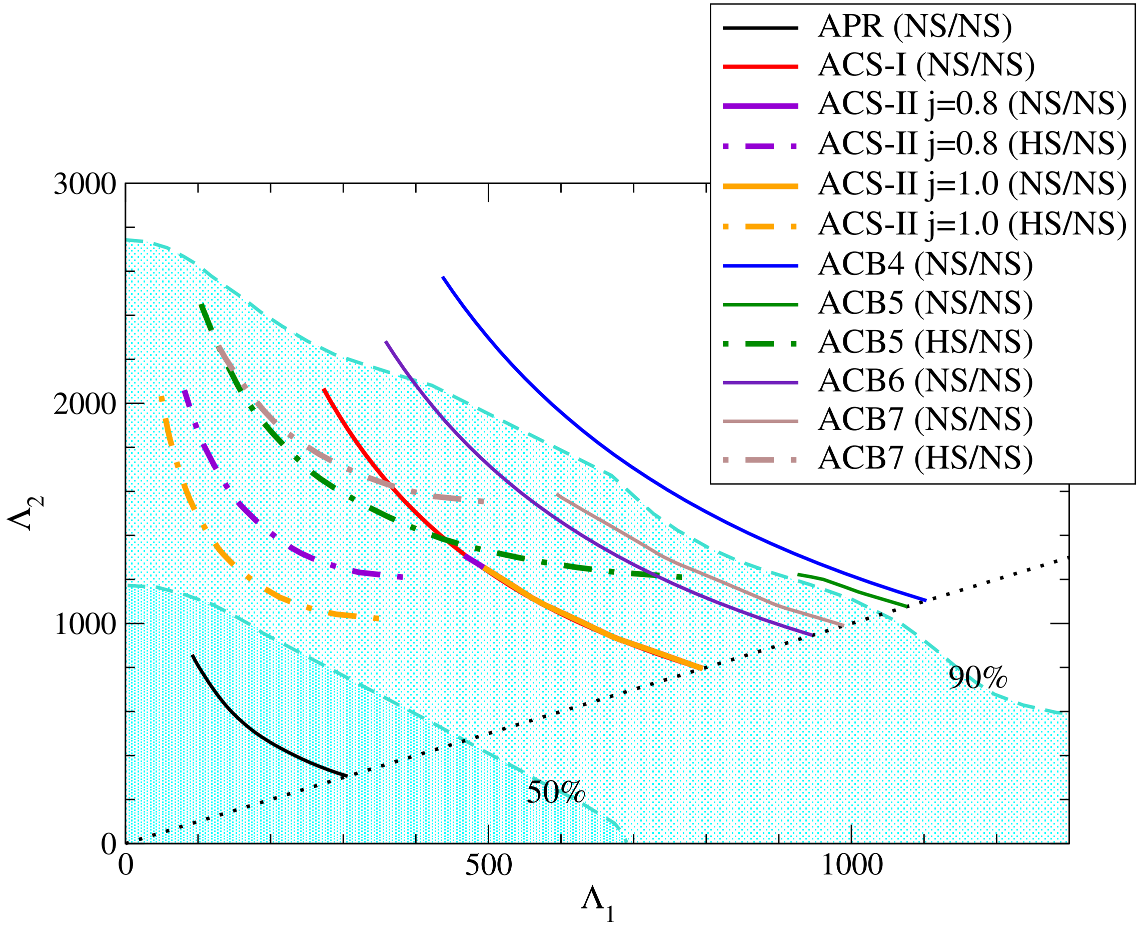
Properties of the Binary Star Merger GW170817
B. P. Abbott et al., Phys. Rev. X 9, 011001 (2019)

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



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Nonlocal NJL

In this model we introduce a doubly interpolated non-local NJL quark matter EoS as follows:

$$P(\mu) = [f_<(\mu)P(\mu;\eta_<,B) + f_>(\mu)P(\mu;\eta_<,0)]f_\ll(\mu) + f_\gg(\mu)P(\mu;\eta_>,0) \ ,$$

where we have introduced two smooth switch-off functions, one that changes from one to zero at a lower chemical potential $\mu_<$ with a width $\Gamma_<$,

$$f_<(\mu) = \frac{1}{2}\left[1 - \tanh\left(\frac{\mu - \mu_<}{\Gamma_<}\right)\right] ,$$

and one that switches off at a higher chemical potential $\mu_\ll$ with a width $\Gamma_\ll$,

$$f_\ll(\mu) = \frac{1}{2}\left[1 - \tanh\left(\frac{\mu - \mu_\ll}{\Gamma_\ll}\right)\right] ,$$

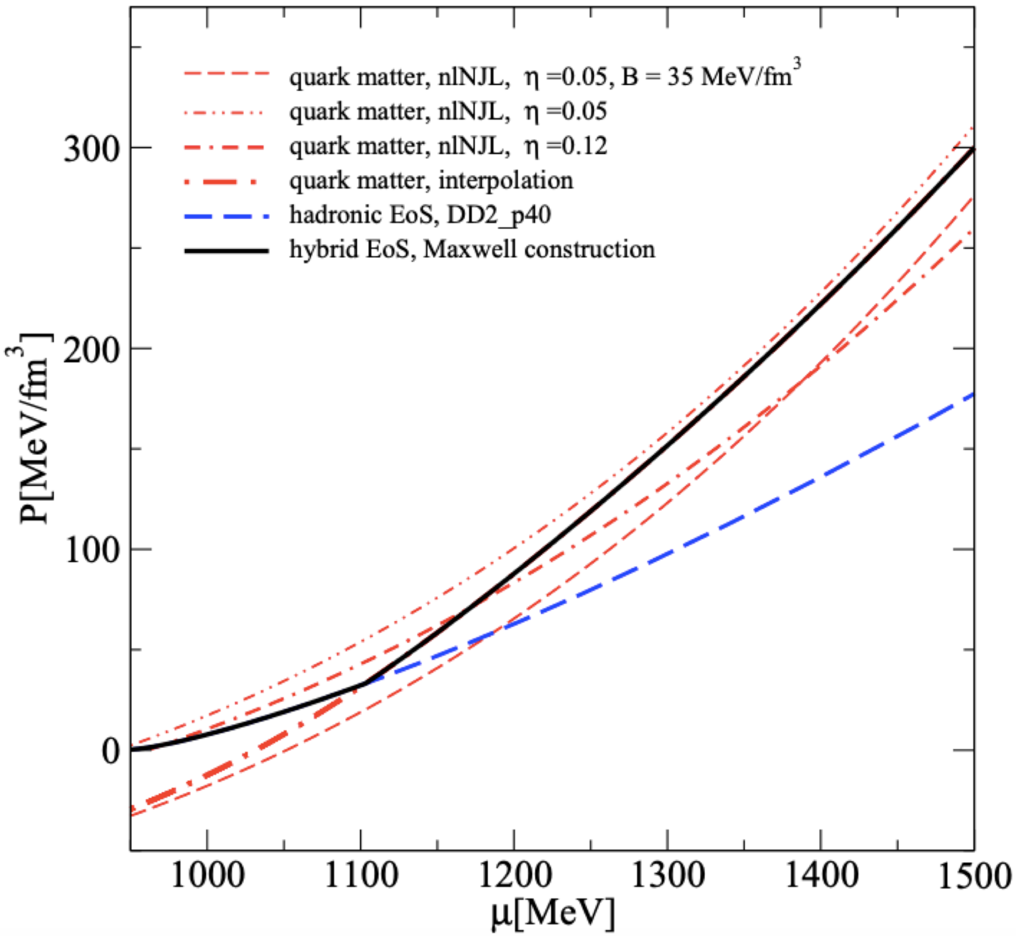
whereby the corresponding switch-on functions are the complementary ones,

$$f_>(\mu) = 1 - f_<(\mu) \ , \quad f_\gg(\mu) = 1 - f_\ll(\mu).$$

The input EoS differ in their η-values, we have taken for those values at low ($<$) and high ($>$) chemical potentials $\eta_<$ and $\eta_>$. Moreover, B represents a bag constant introduced to enforce confinement effects in the low chemical potential quark EoS.

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

Nonlocal NJL



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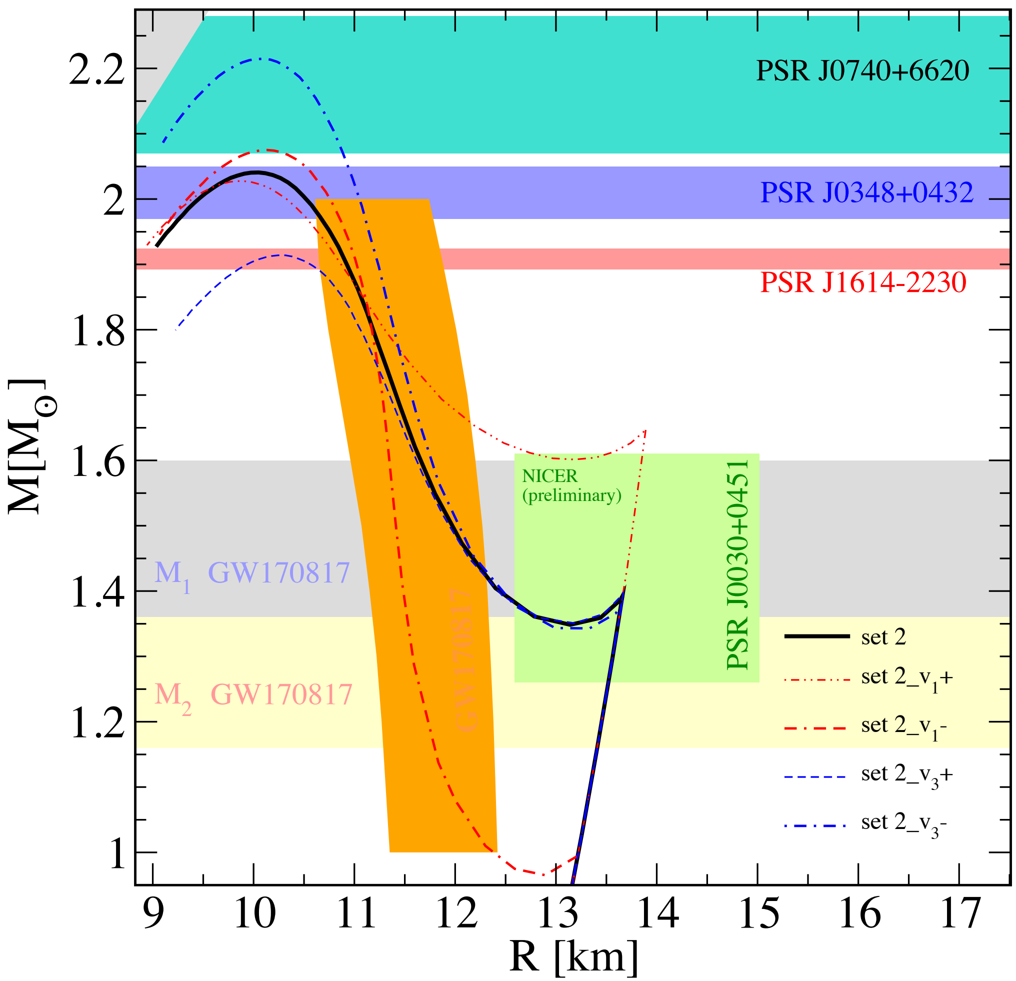
Implications from GW170817
Nonlocal NJL



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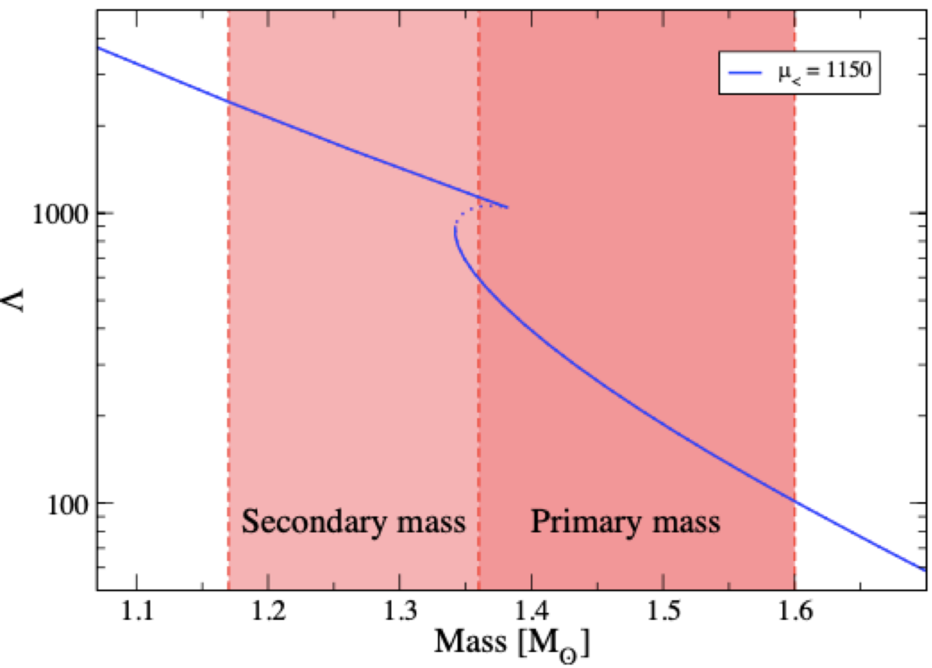
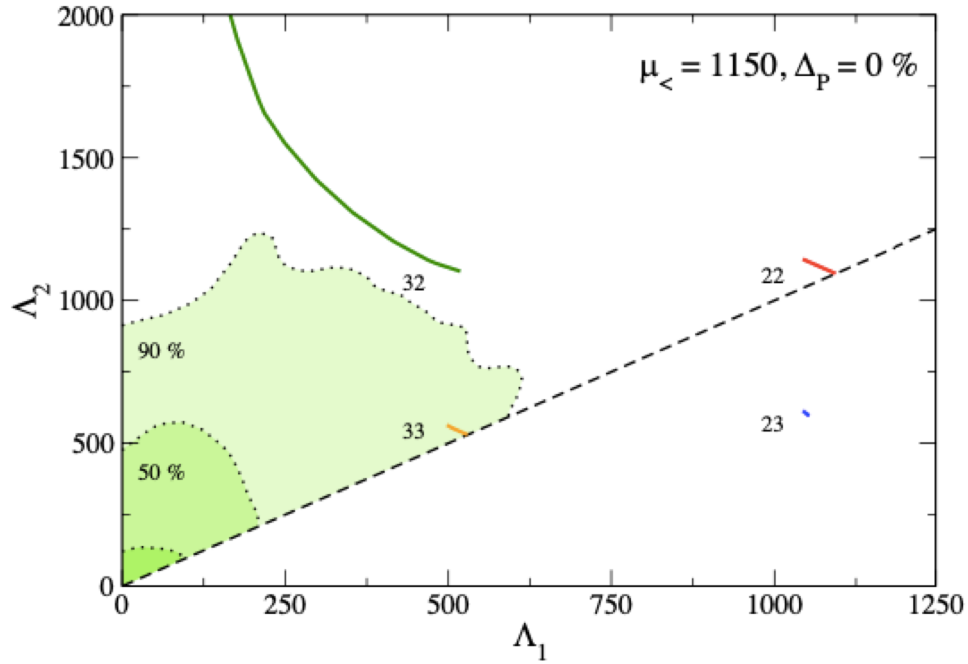
GW170817 - Nonlocal NJL





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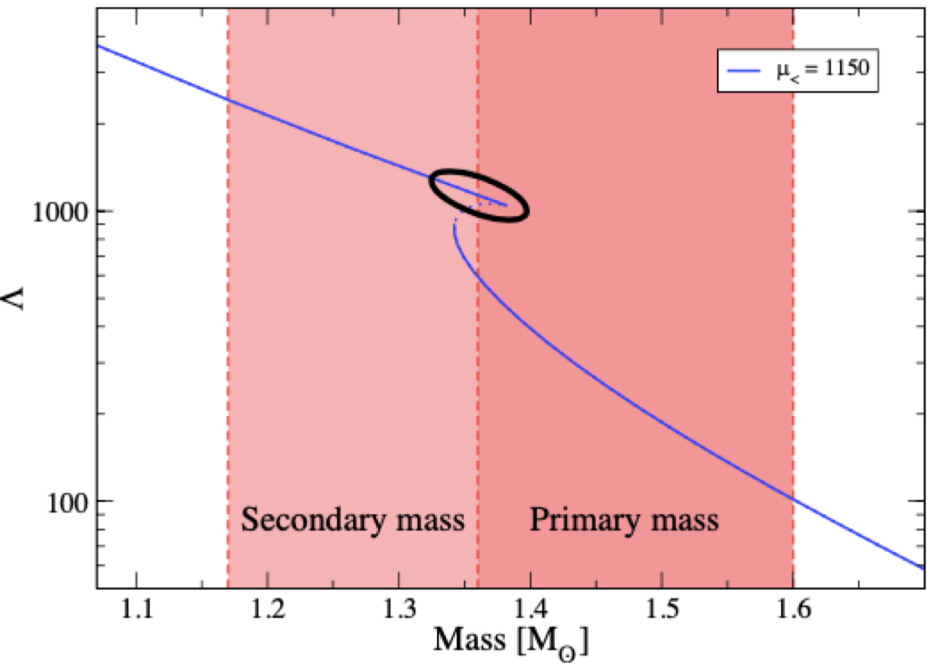

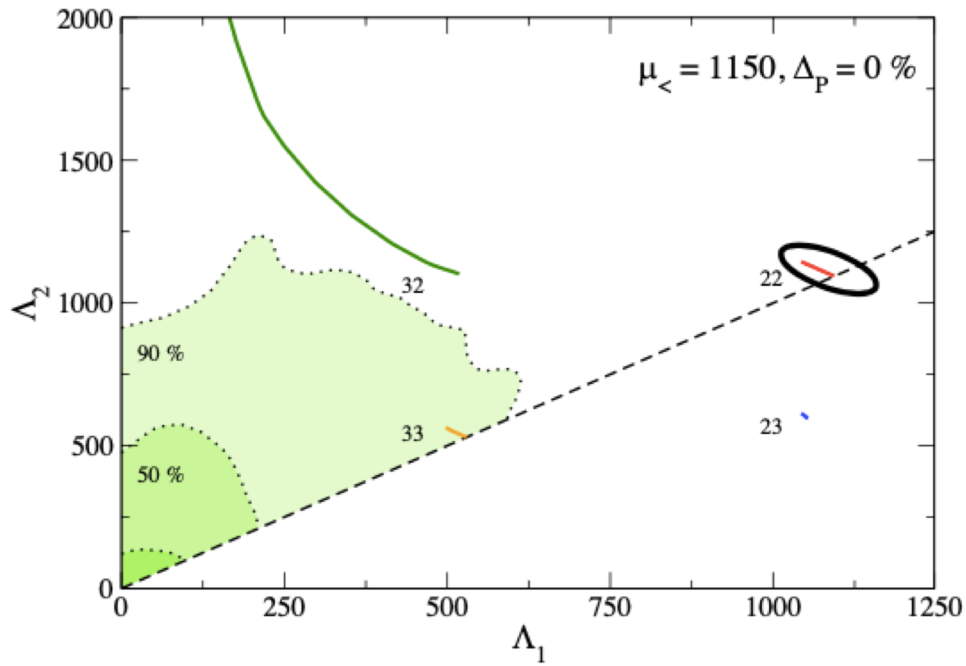

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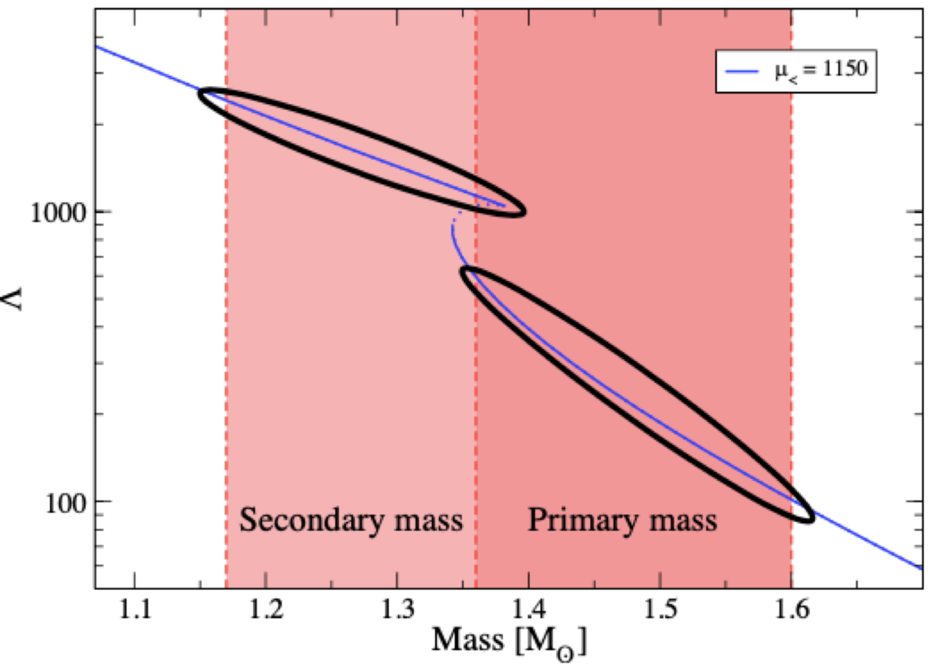

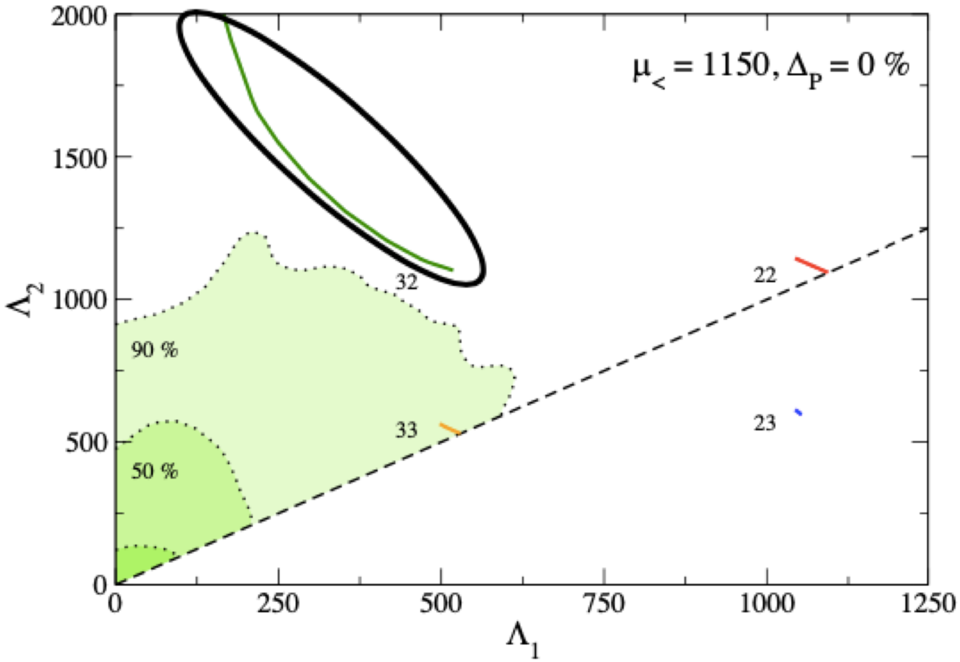

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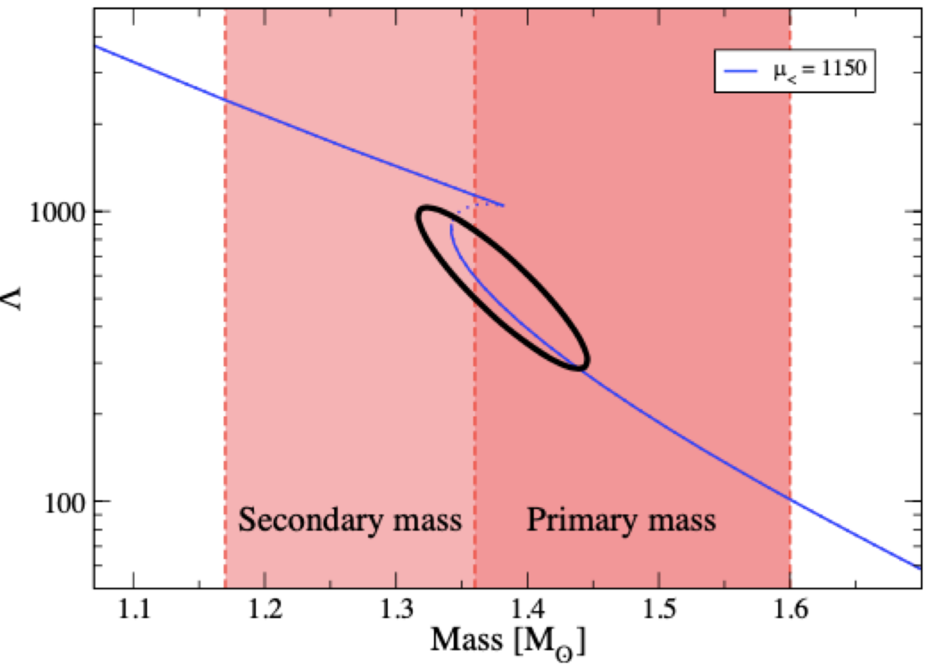

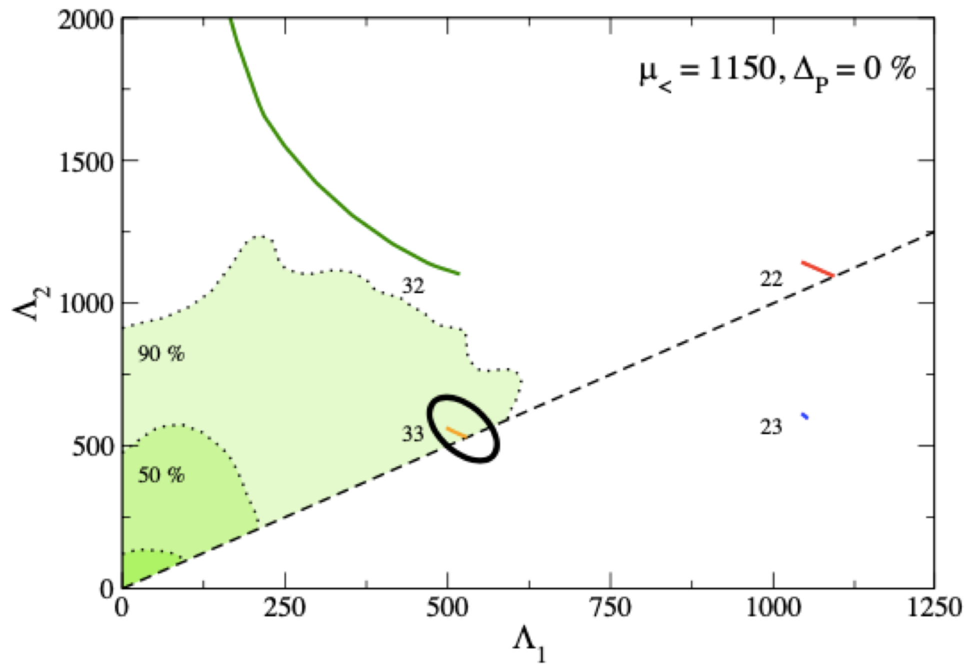

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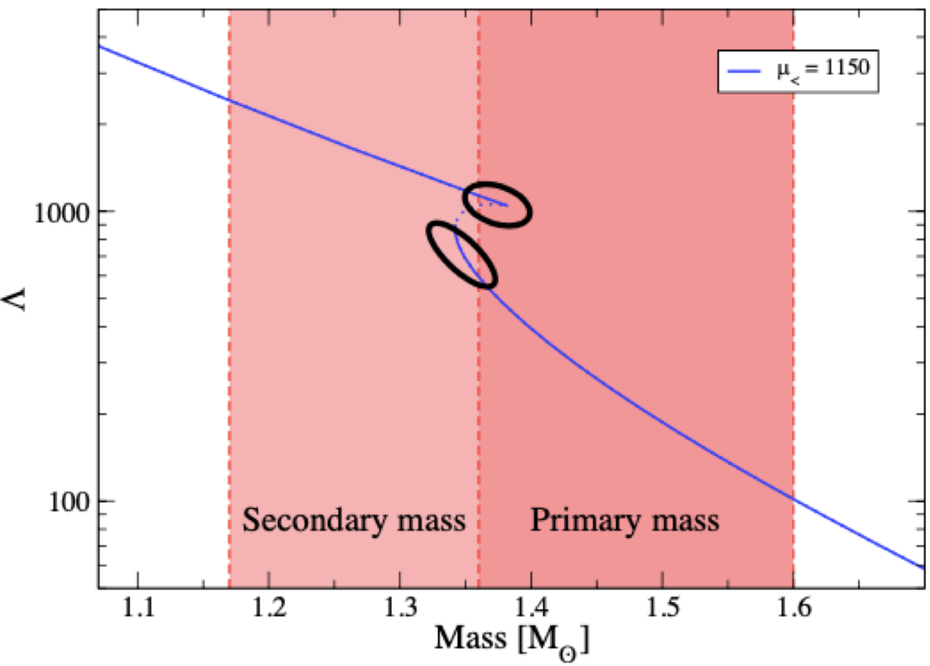

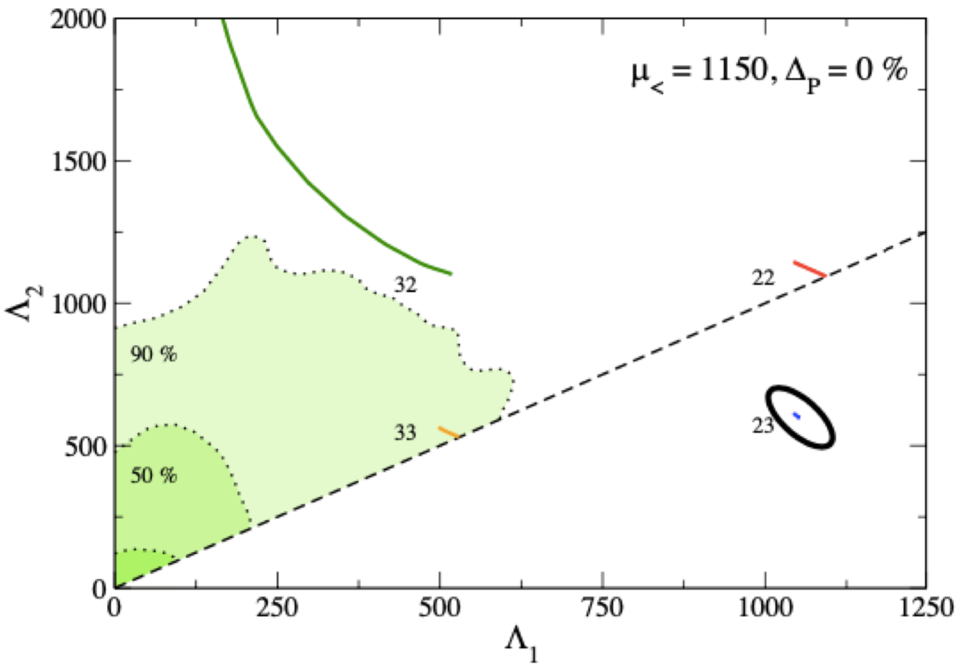

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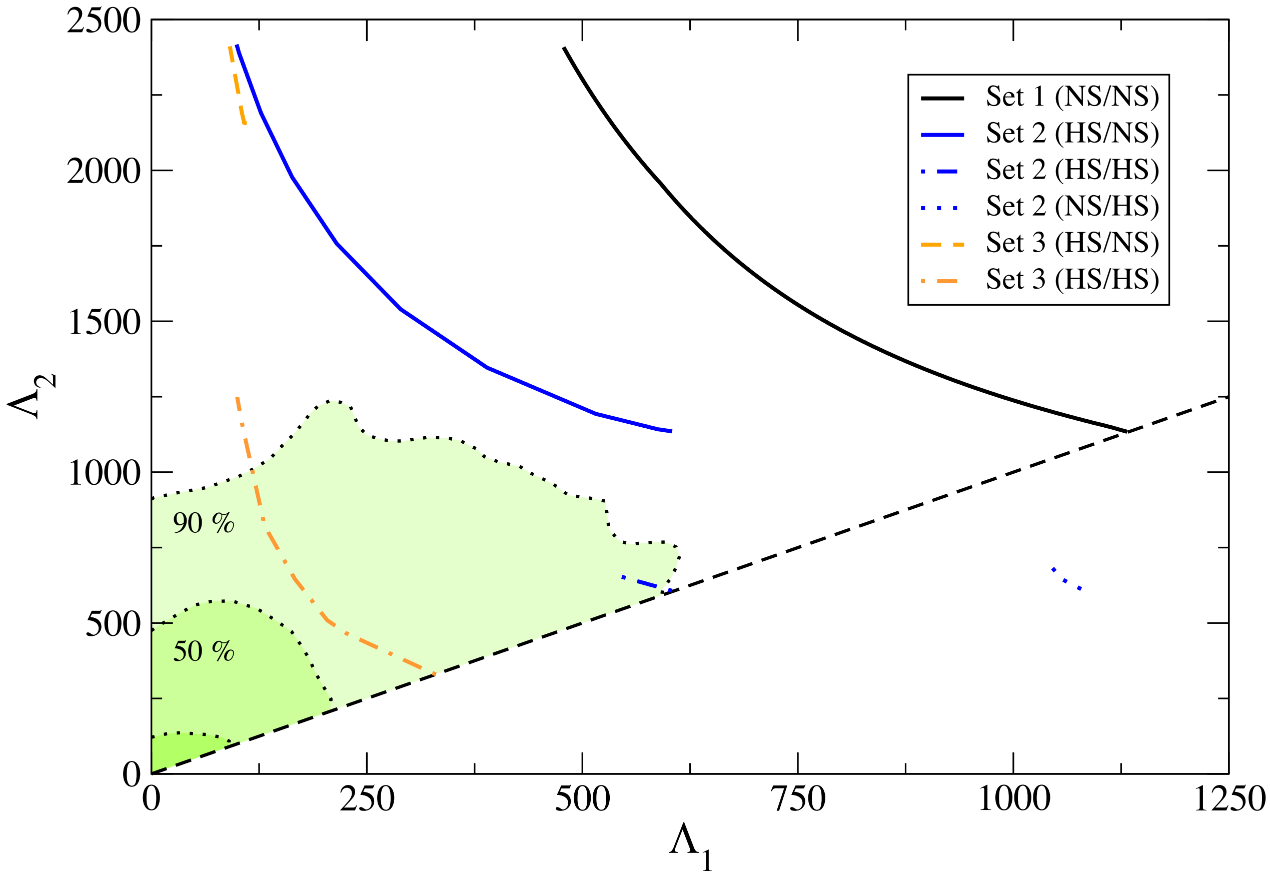

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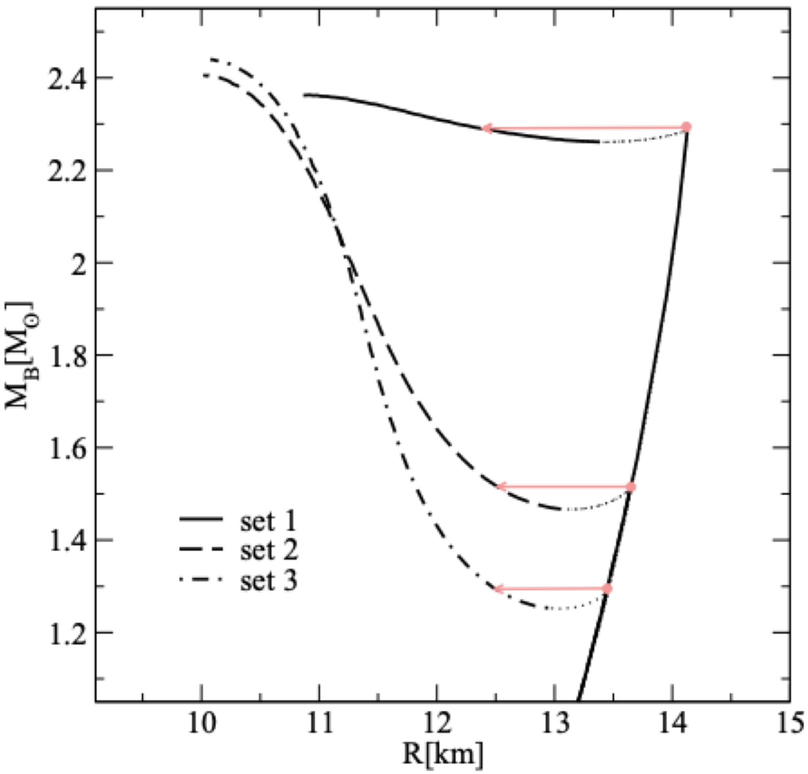

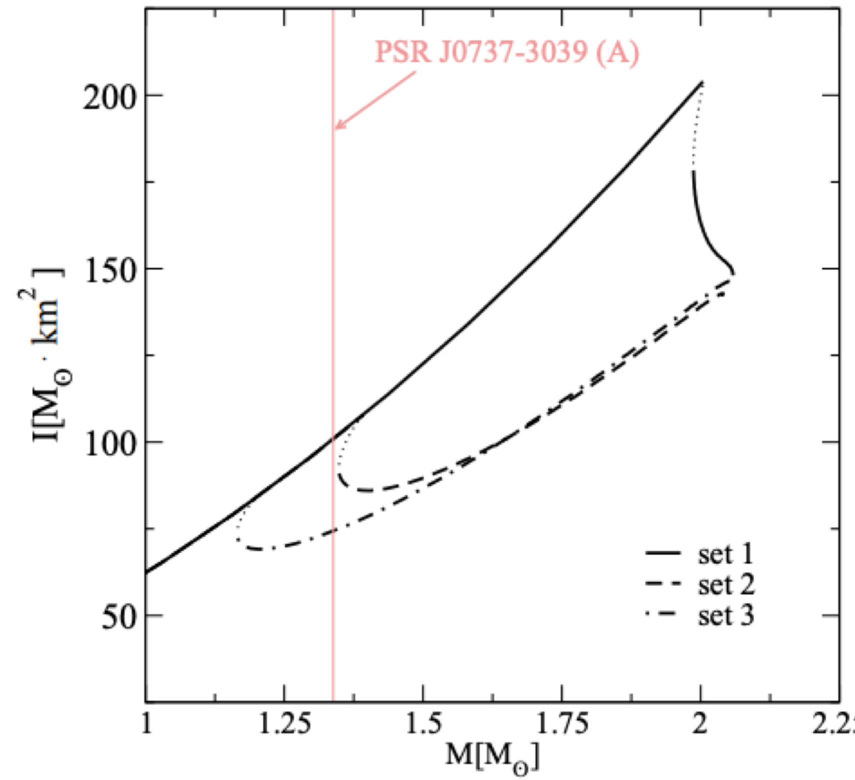

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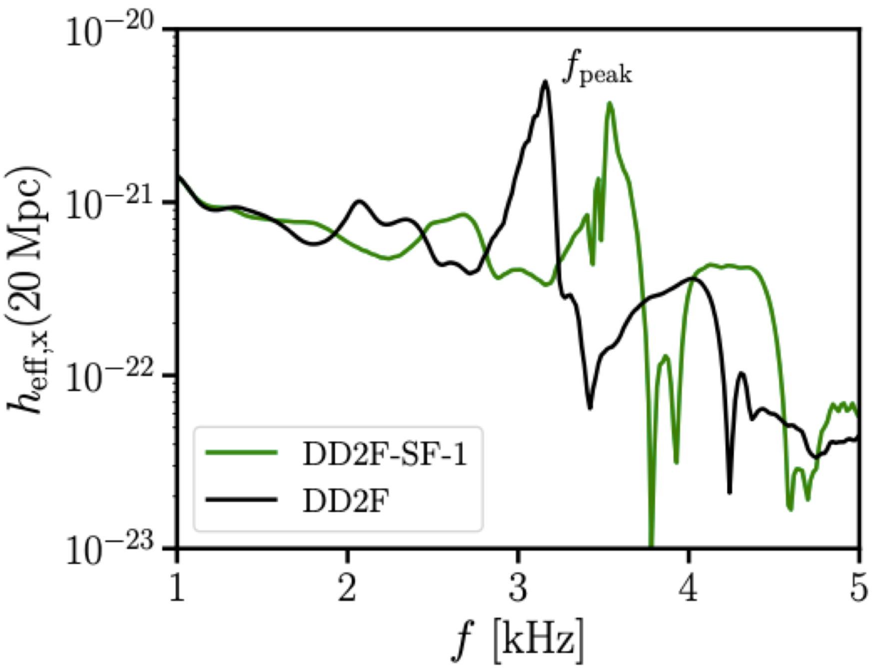
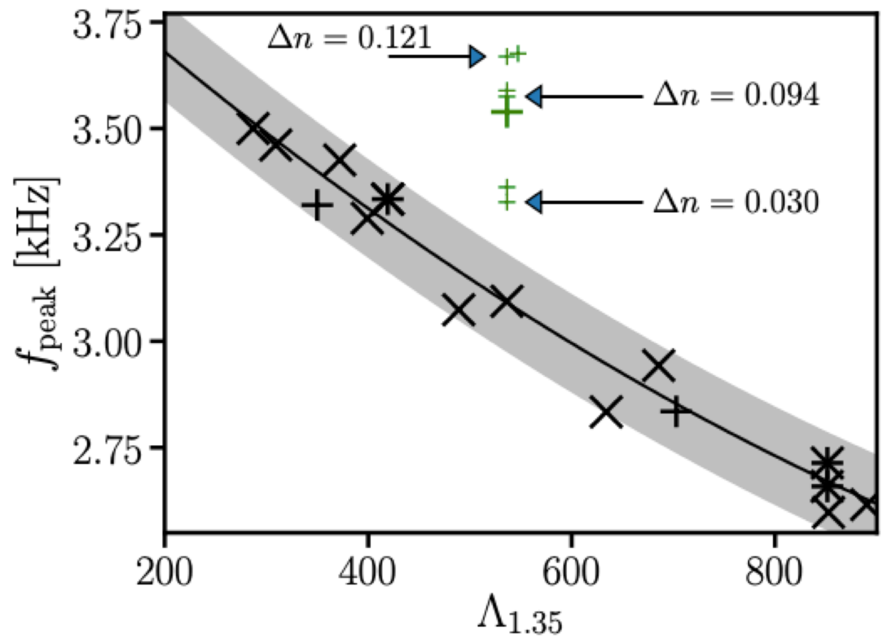
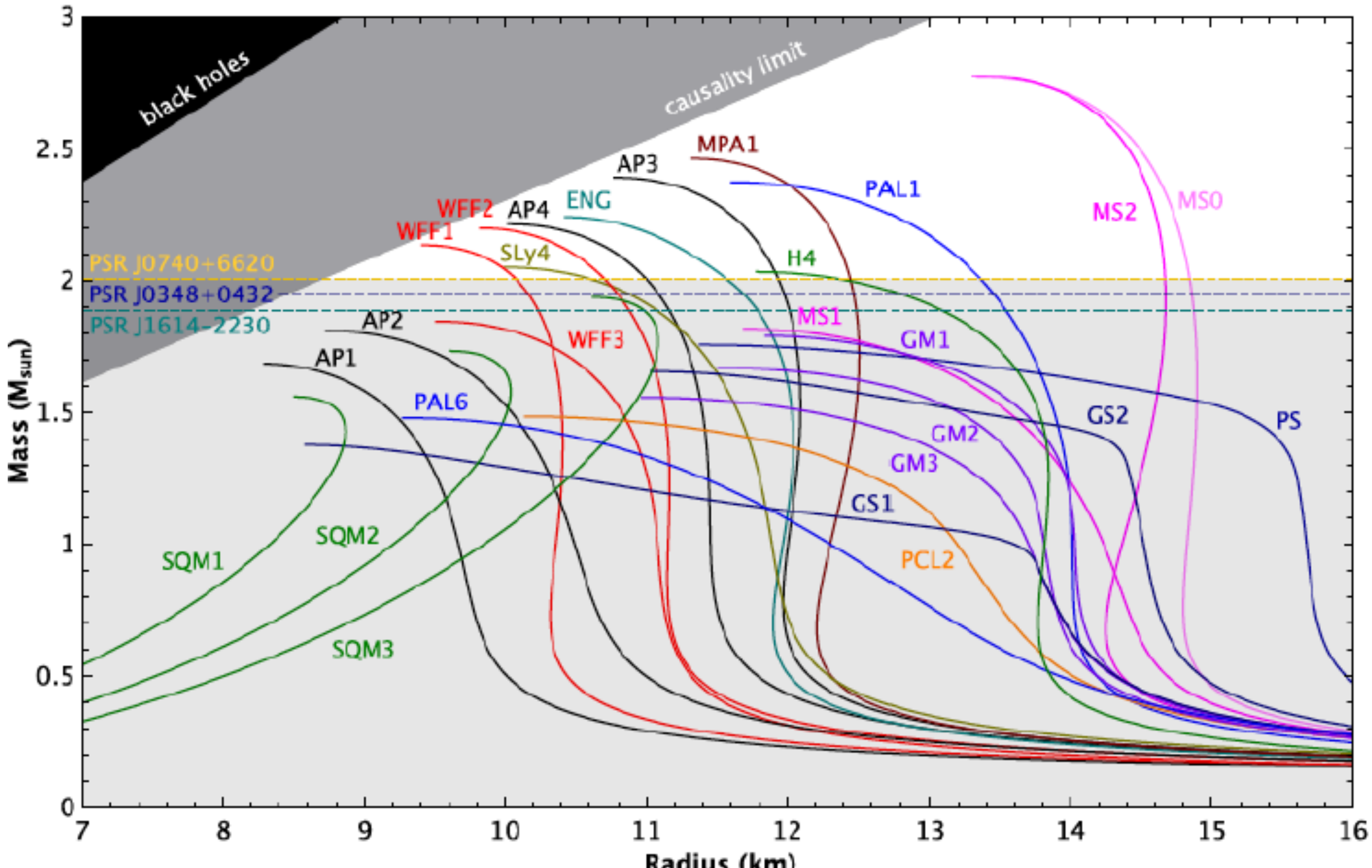
Gravitational Wave Signals
First Order Phase Transitions





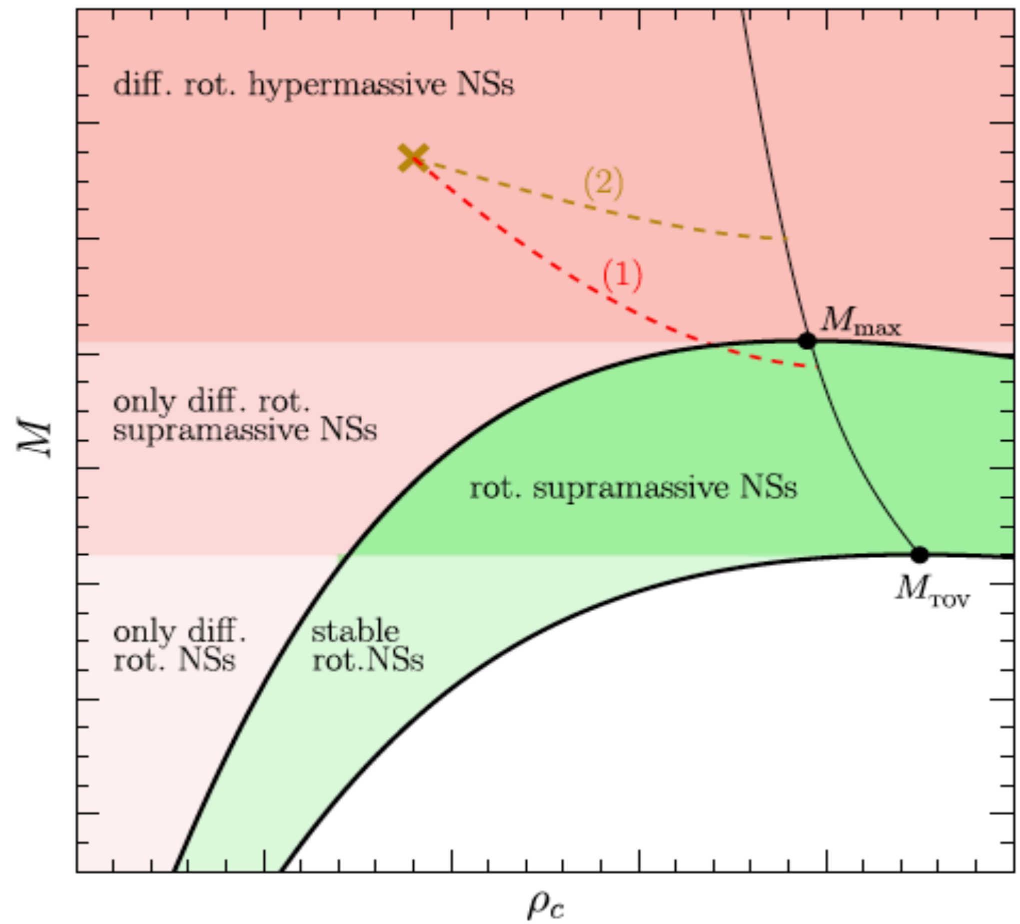
A. Bauswein et al. - arXiv: 1904.01306, PRL 122 (2019) 061102

Massive Neutron Stars: Is there a concrete limit for the maximum mass?



www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html

Upper limit on the Maximum mass of static compact stars?

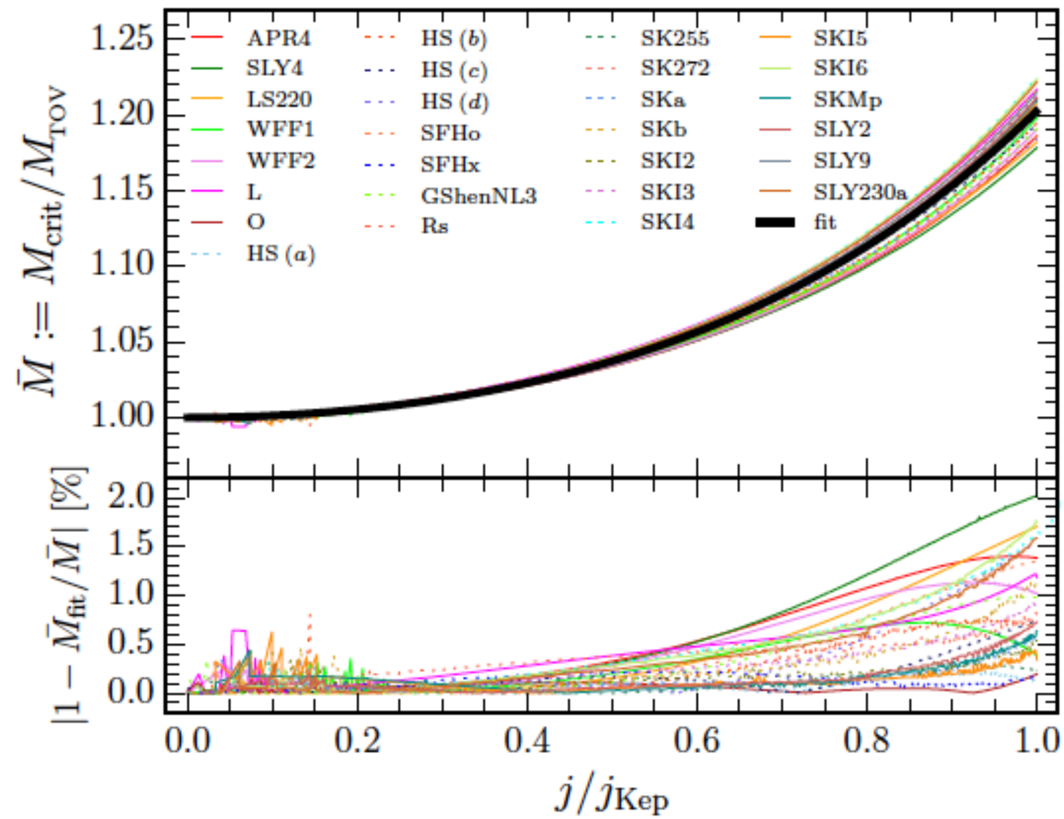


Rezzolla et al., ApJ Lett 852 (2018) L25

Universal relation for maximum mass increase upon rigid rotation

$$\frac{M_{\rm crit}}{M_{\rm TOV}} = 1 + a_2\left(\frac{j}{j_{\rm Kep}}\right)^2 + a_4\left(\frac{j}{j_{\rm Kep}}\right)^4$$

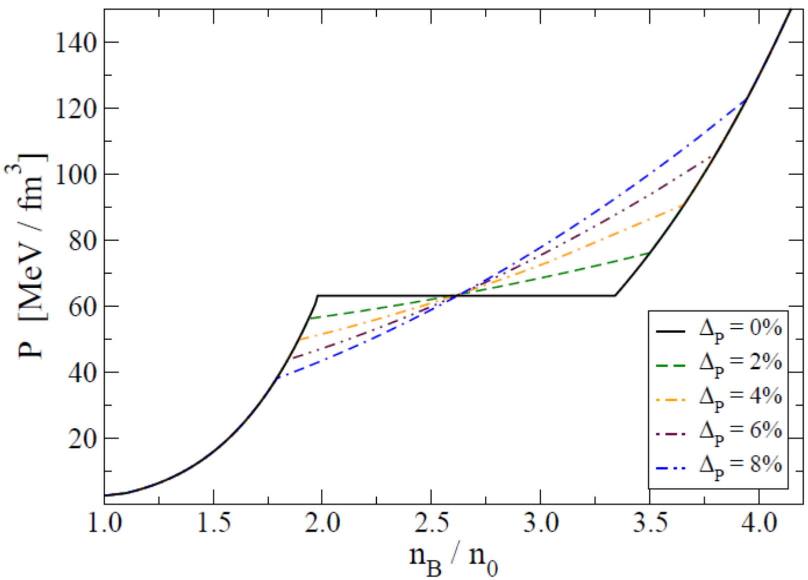
$$M_{\rm max} := M_{\rm crit}(j = j_{\rm Kep}) = (1 + a_2 + a_4)\,M_{\rm TOV}$$
$$\simeq (1.203 \pm 0.022)\,M_{\rm TOV}$$



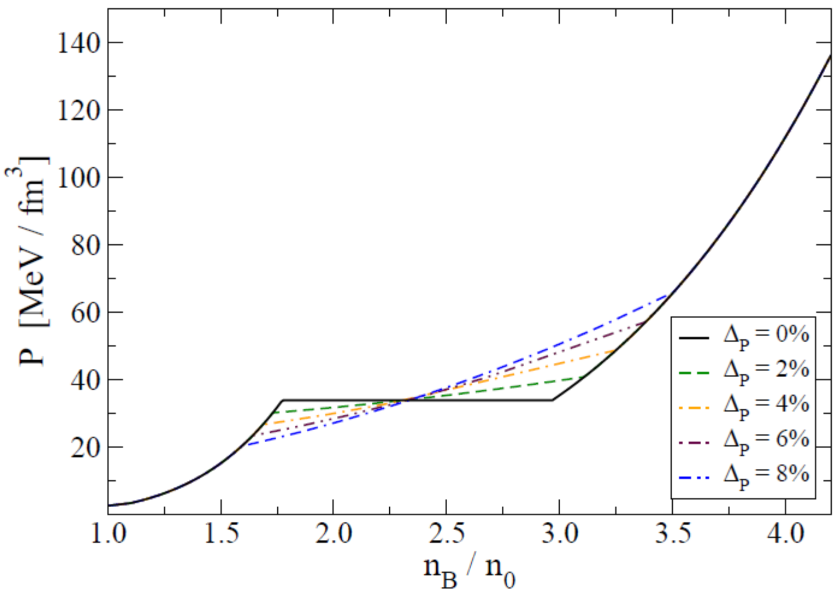
"Universal" increase of maximum mass by 20% due to rigid rotation at maximum (critical) angular momentum

Breu & Rezzolla et al., MNRAS (2016)

Mixed phase effects (pasta phases)

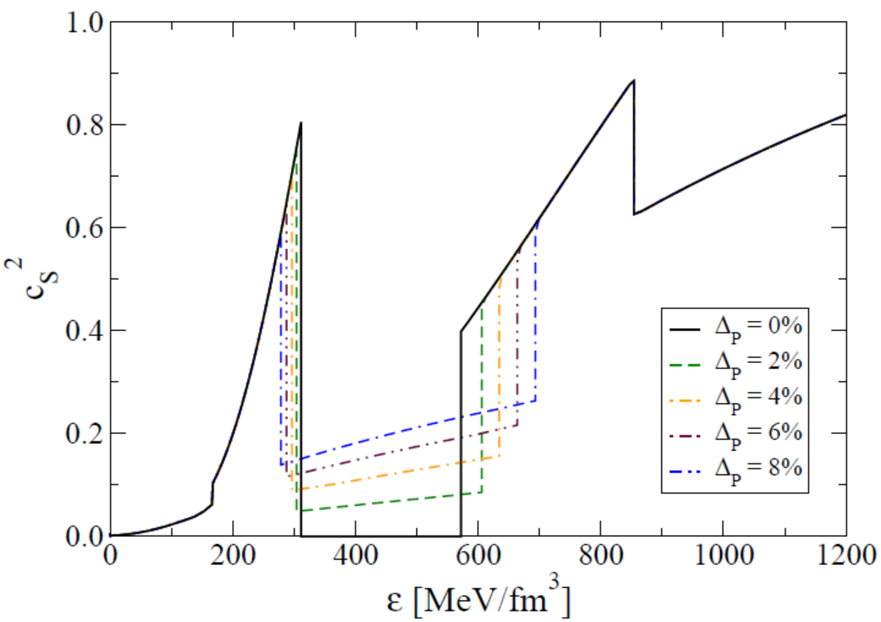


High mass twin stars
(ACB4)

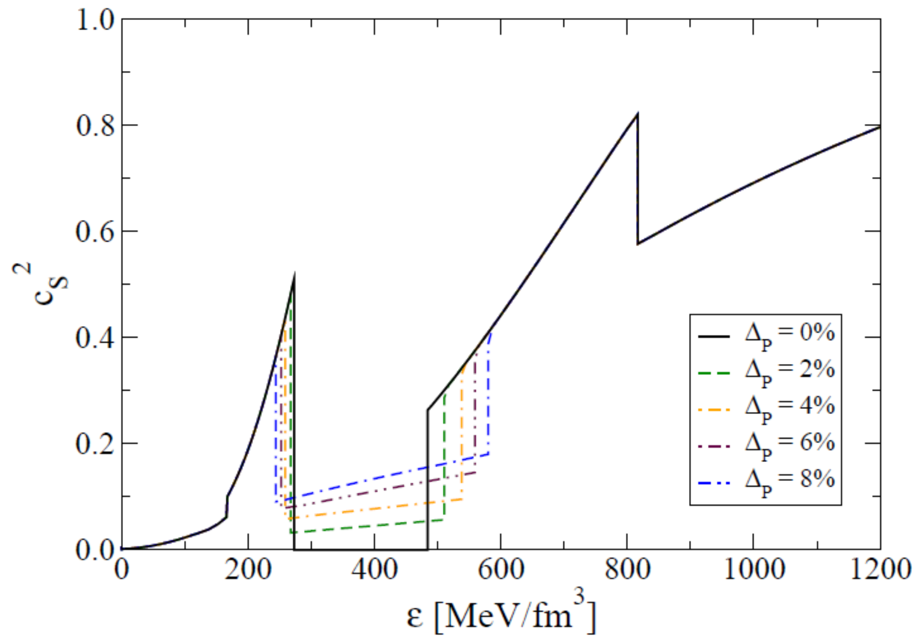


Low mass twin stars
(ACB5)

Speed of sound and causality

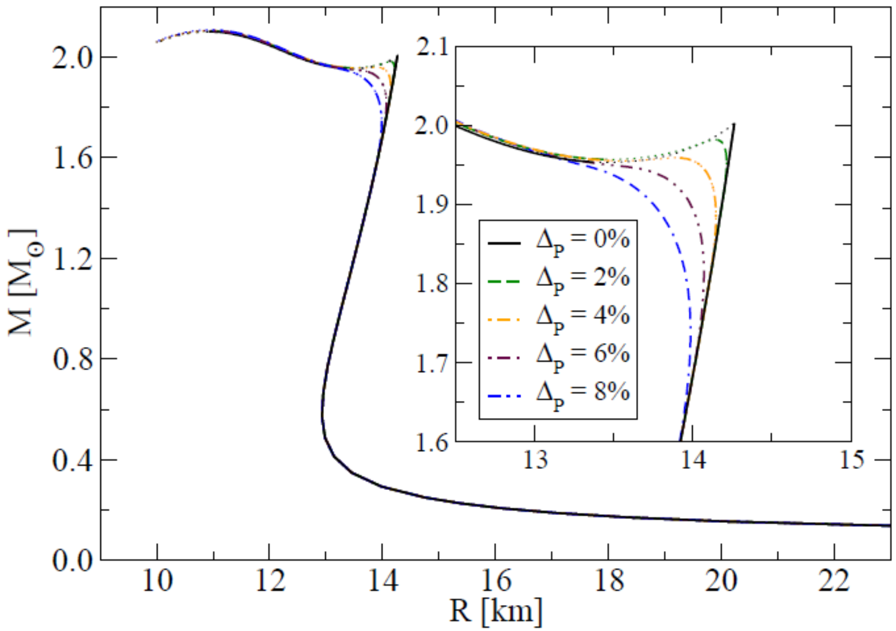


High mass twin stars
(ACB4)

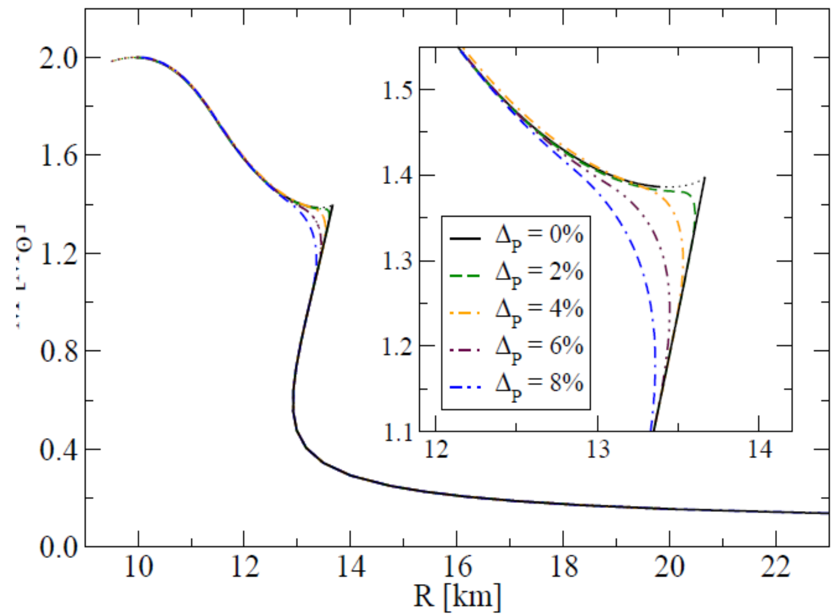


Low mass twin stars
(ACB5)

Mass Radius Relations



ACB4

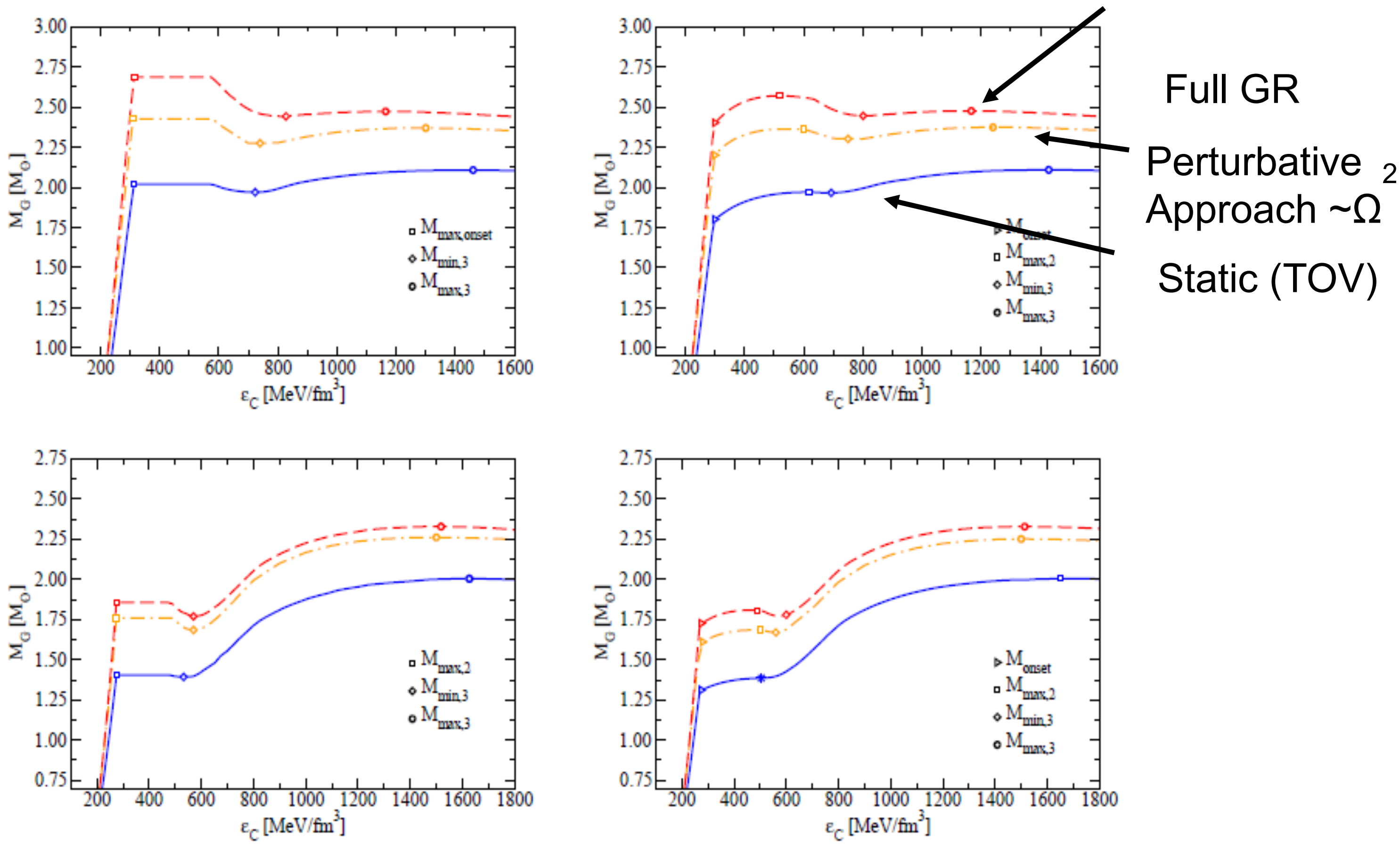


ACB5

Effect of Rotation and Mixed Phase

ACB4

ACB5



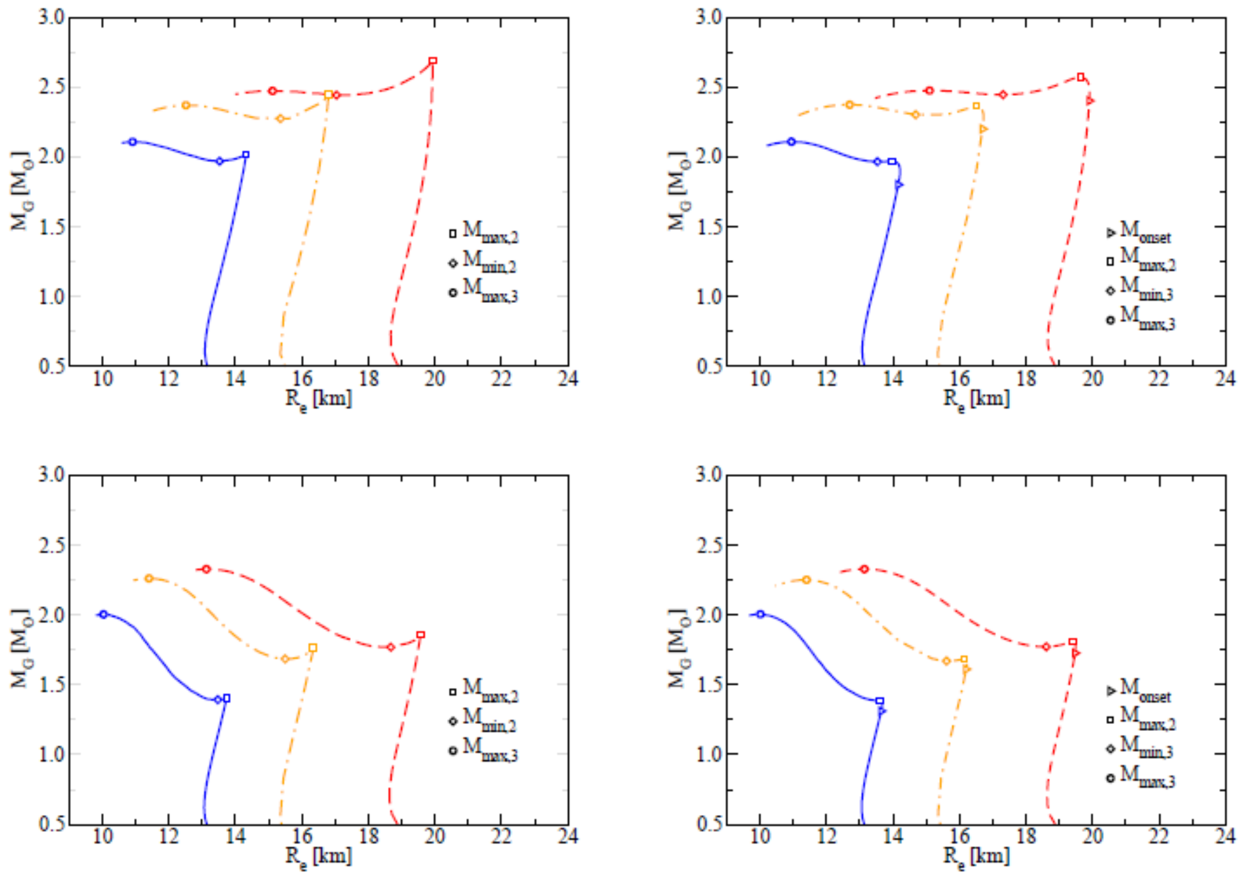
Maxwell construction

Critical value of Mixed-phase parameter

Effect of Rotation and Mixed Phase

ACB4

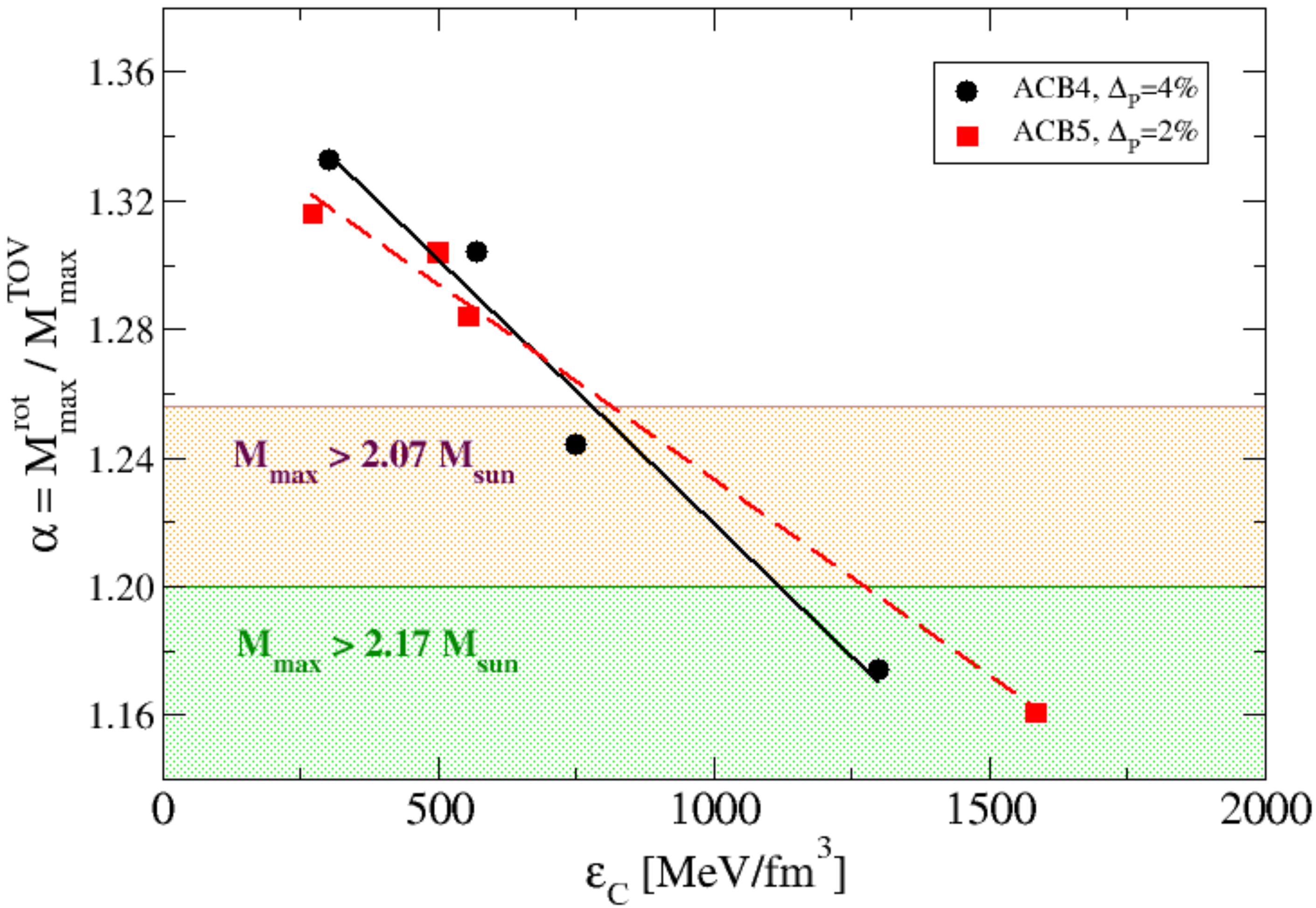
ACB5



Maxwell construction

Critical value of Mixed-phase parameter

Universal Relationship for Rotating Compact Stars



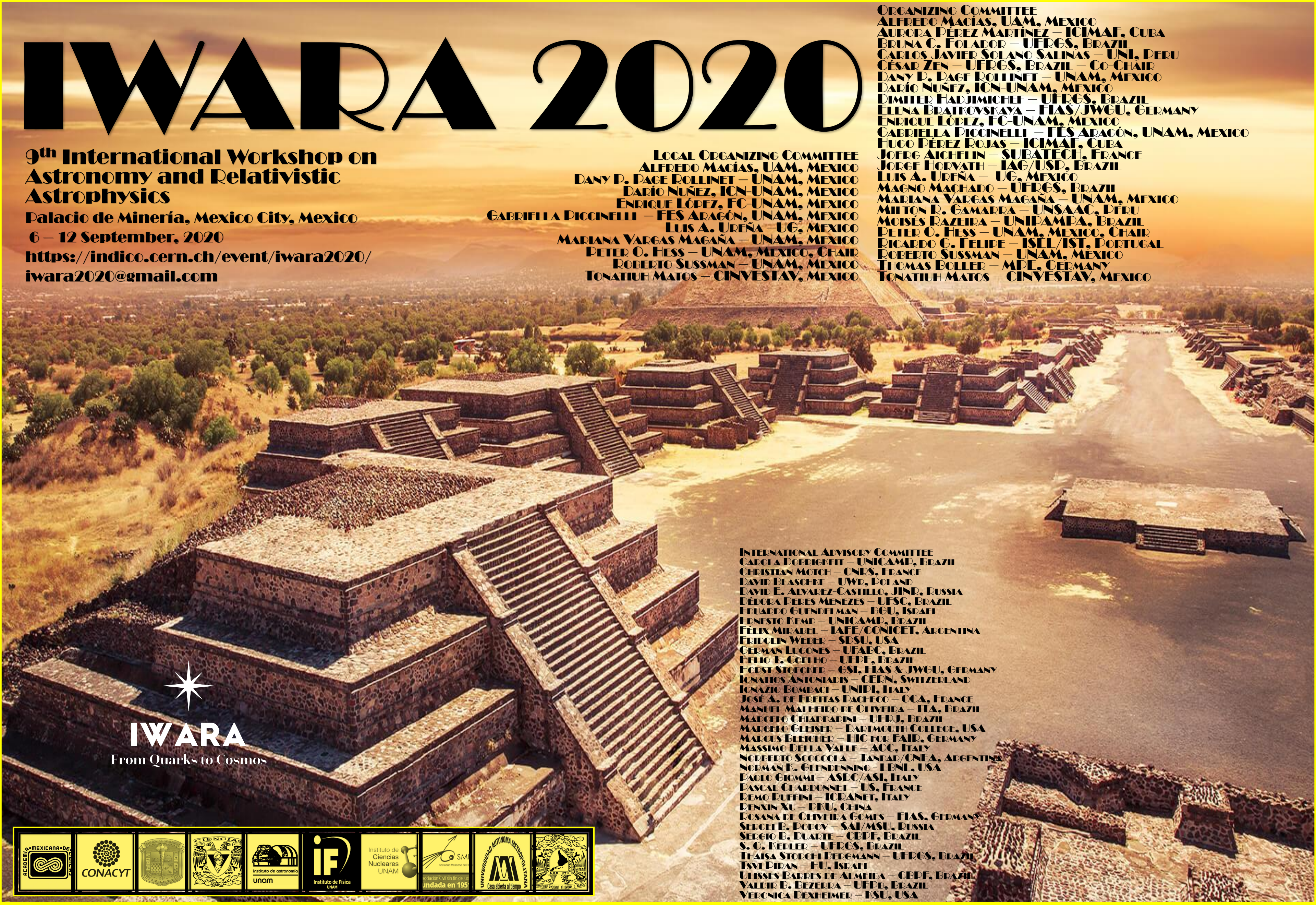
Conclusions

- GW170817 favours softer EoS but also hybrid stars with strong phase order transitions.
- Future GW observations, NICER and SKA will soon result into stronger NS EoS constraints probing the mass twins hypothesis.
- Many possible astrophysical scenarios for mass twins could be confirmed implying a CEP in QCD.
- The mixed phase construction mimics the pasta phase in accordance with a full pasta calculation. This construction makes the approach more realistic and has advantages for numerical treatment of hybrid stars in general relativity.

Conclusions

- The conjecture of an upper limit on the maximum mass of nonrotating compact stars derived from GW170817 has been revisited. We find a criterion for the minimal central energy density in the maximum mass configuration that would correspond to the core of GW170817. The equation of state at high densities must be effectively soft, either as a relatively soft hadronic one or a hybrid one with a strong phase transition. The NICER radius measurement could be decisive

Gracias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