Dense nuclear matter in the cores of neutron stars

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Outline

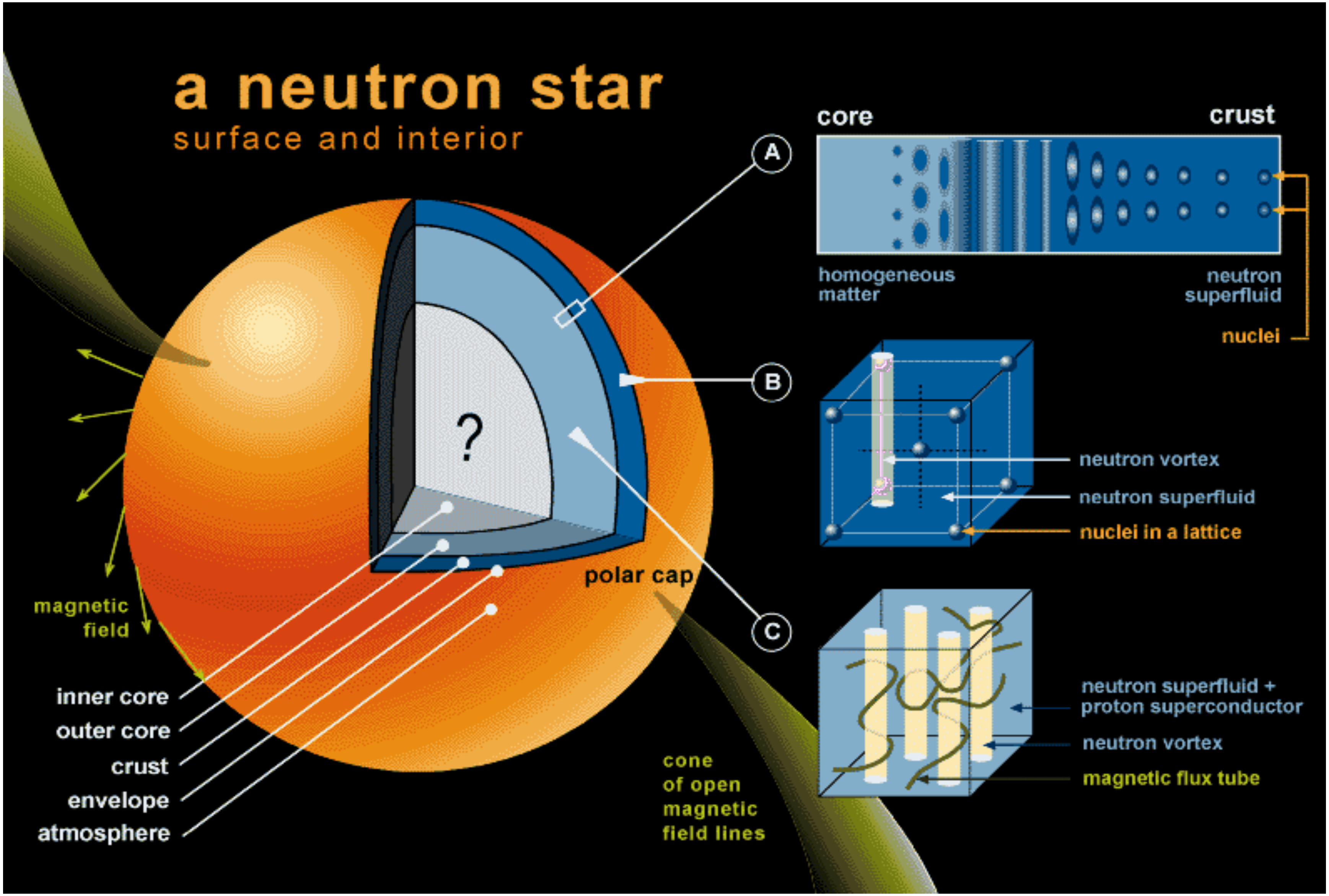
- A brief introduction to the neutron star matter equation of state (EoS) and its relation with the QCD phase diagram.

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

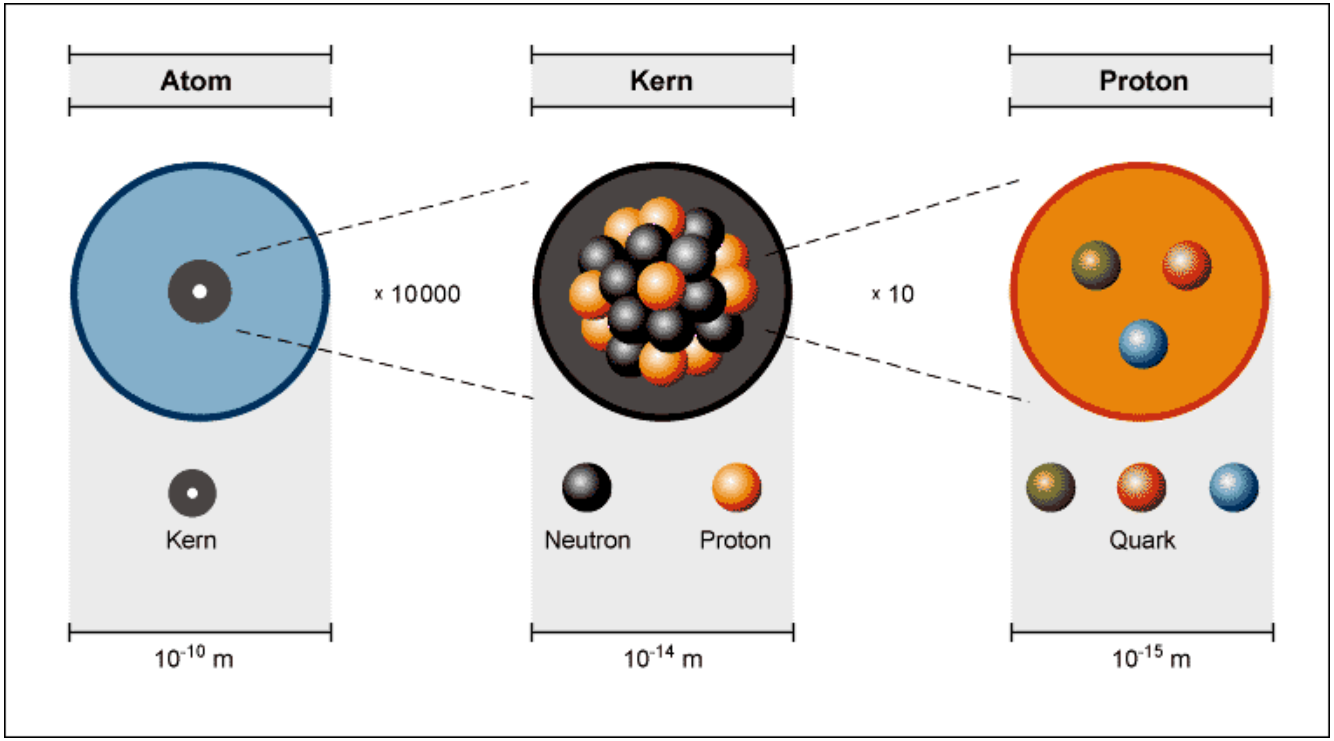
- The mass twins compact stars scenario and the possibility of probing deconfined quark matter.

- Astrophysical implications and perspectives.

Superdense objects – what is inside?



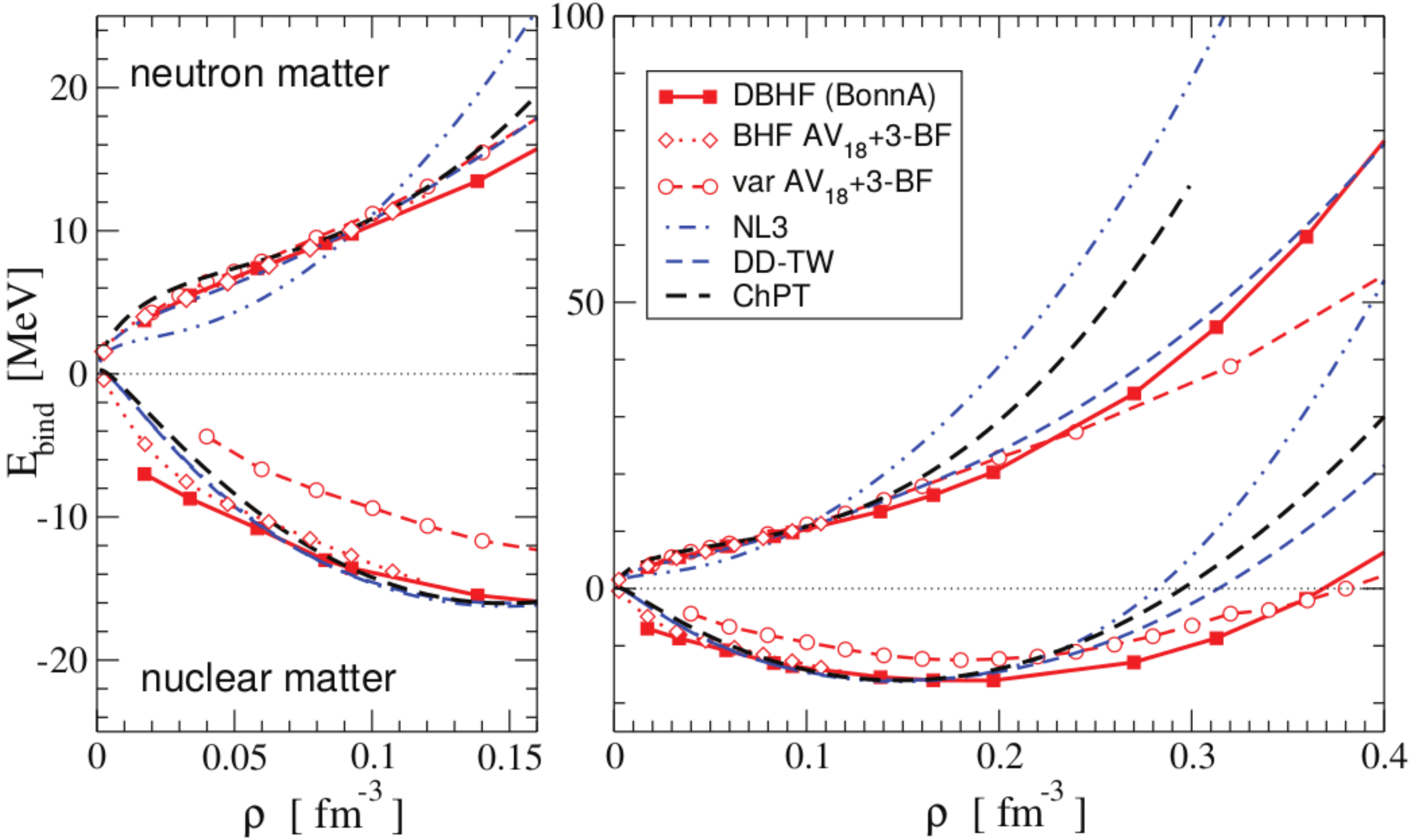
Superdense objects – what is inside?



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)

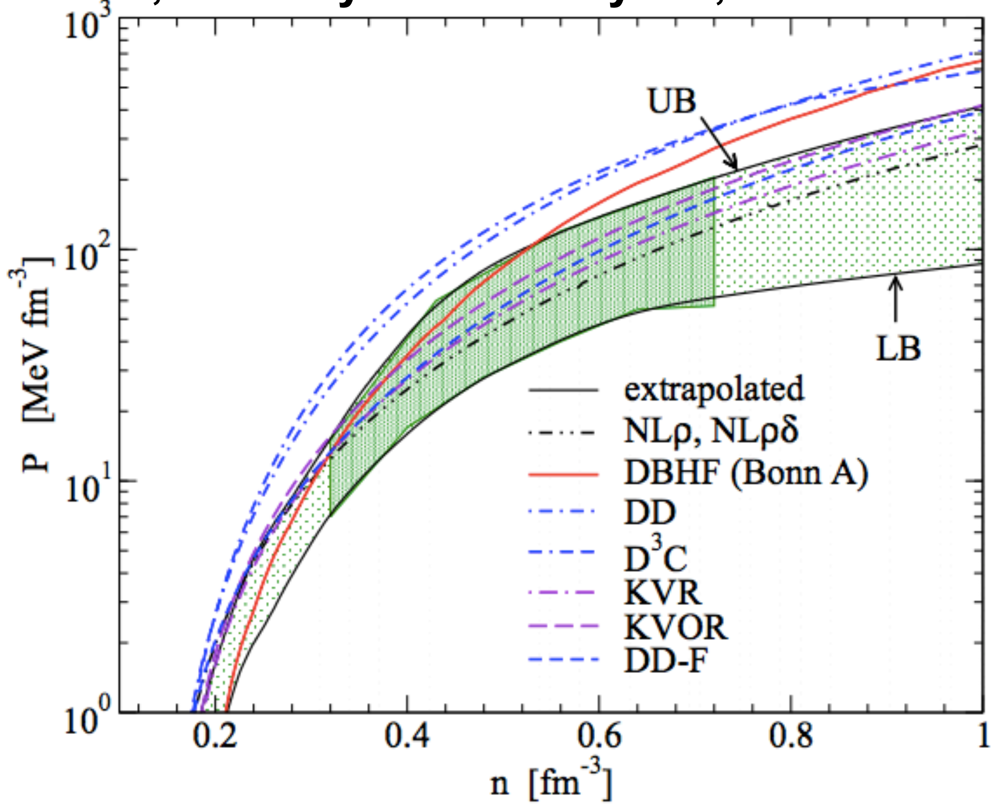
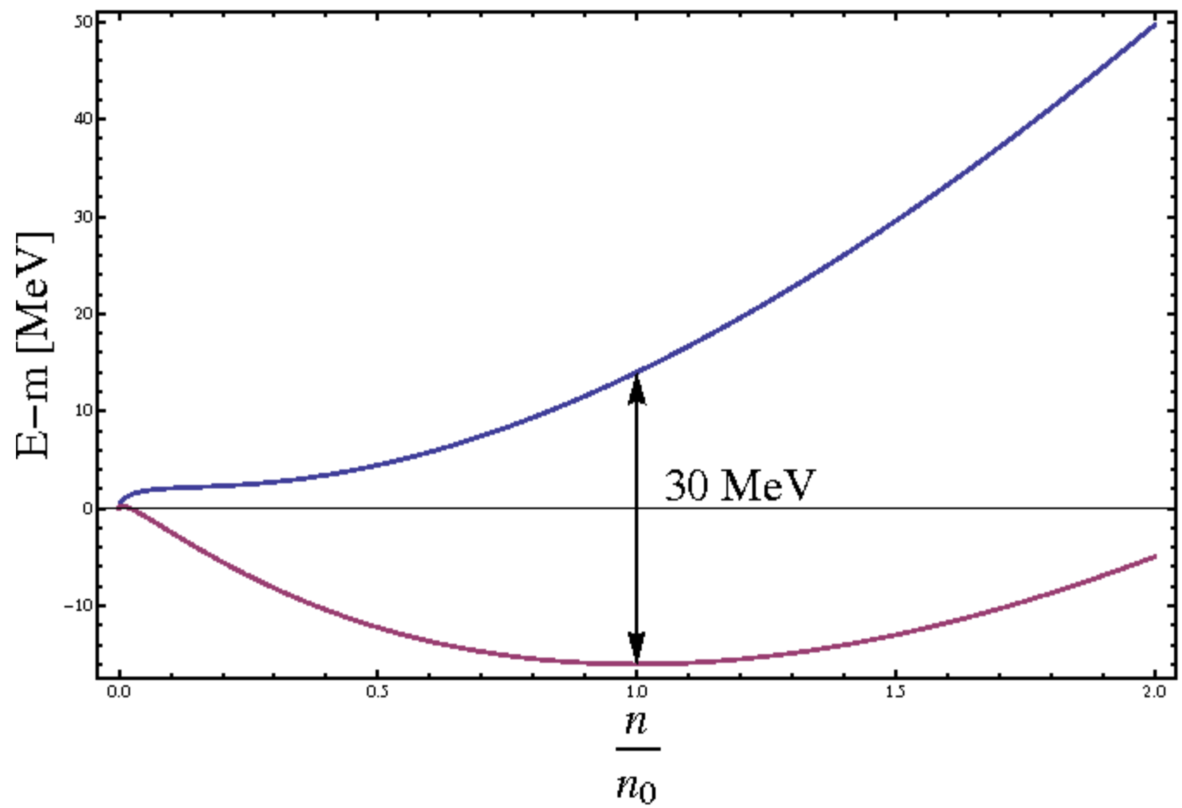


FIG. 6: Pressure region consistent with experimental flow data in SNM (dark shaded region). The light shaded region extrapolates this region to higher densities within an upper (UB) and lower border (LB).

Nuclear Symmetry Energy

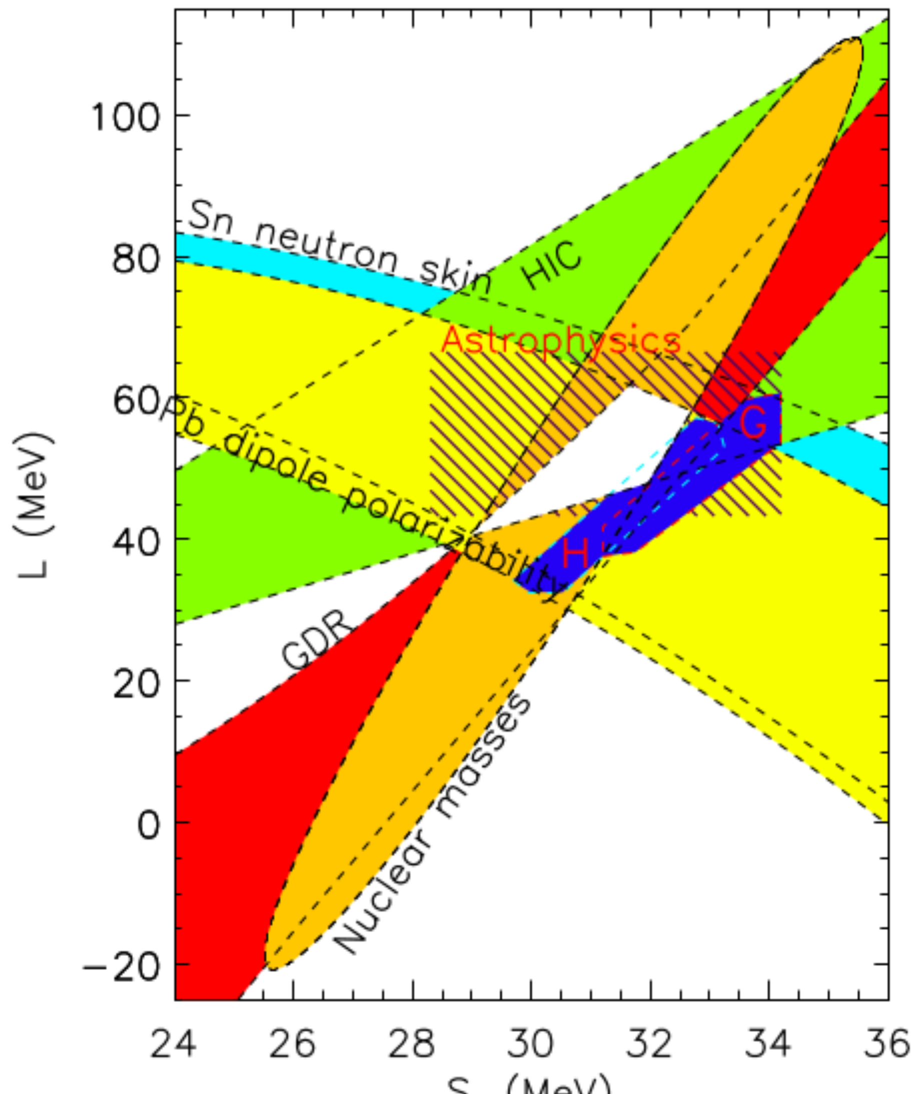


is the difference between symmetric nuclear matter and pure neutron matter:

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

where $\alpha = 1 - 2x$

Measuring the symmetry energy



Lattimer and Lim (2013) ApJ 771 51

Neutron Star Equation of State

The energy per nucleon in neutron star core matter is given by:

$$\begin{aligned} E_{\mathrm{tot}}(n,\{x_i\}) &= E_{\mathrm{b}}(n,x_p) + E_{\mathrm{lep}}(n,x_e,x_\mu)\ , \\ E_{\mathrm{b}}(n,x_p) &= E_0(n) + S(n,x_p) \\ E_{\mathrm{lep}}(n,x_e,x_\mu) &= E_e(n,x_e) + E_\mu(n,x_\mu)\ , \end{aligned}$$

where $n = n_p + n_n$ is the total baryon density and $x_i = n_i/n,\ i = p, e, \mu$ are the fractions of protons, electrons and muons, respectively. The baryonic part is very well described by the parabolic approximation w.r.t. the asymmetry

$$\alpha = \frac{n_n - n_p}{n_n + n_p} = 1 - 2x_p,$$

resulting in $S(n, x_p) = (1 - 2x_p)^2 E_s(n)$. The leptonic contribution is a sum of the Fermi gas expressions for the contributing leptons $l = e, \mu$

$$E_l(n,x_l) = \frac{1}{n}\frac{p_{F,l}^4}{4\pi^2}\left[\sqrt{1+z_l^2}\left(1+\frac{z_l^2}{2}\right) - \frac{z_l^4}{2}\mathrm{Arsinh}\left(\frac{1}{z_l}\right)\right]\ ,$$

where $z_l = m_l/p_{F,l}$. For massless leptons ($z_l \to 0$), this expression goes over to

$$E_l(n,x_l)\big|_{m_l=0} = \frac{1}{n}\frac{p_{F,l}^4}{4\pi^2} = \frac{3}{4}\left(3\pi^2 n\right)^{1/3} x_l^{4/3}\ .$$

Charge neutrality and β-equillibrium

Under neutron star conditions charge neutrality holds,

$$x_p = x_e + x_\mu \ .$$

The $\beta-$ equilibrium with respect to the weak interaction processes $n \to p + e^- + \bar{\nu}_e$ and $p + e^- \to n + \nu_e$ (and similar for muons), for cold neutron stars (temperature T below the neutrino opacity criterion $T < T_\nu \sim 1$ MeV) implies

$$\mu_n - \mu_p = \mu_e = \mu_\mu \ .$$

The chemical potentials are defined as

$$\mu_i = \frac{\partial \varepsilon_i}{\partial n_i} = \frac{\partial}{\partial x_i} E_i(n, \{x_j\}) \ , \quad i, j = n, p, e, \mu \ ,$$

where $\varepsilon_i = n \ E_i(n, \{x_j\})$ is the partial energy density of species i in the system. From the above equations:

$$\mu_e = 4(1 - 2x) E_s(n) \ .$$

Since electrons in neutron star interiors are ultrarelativistic,

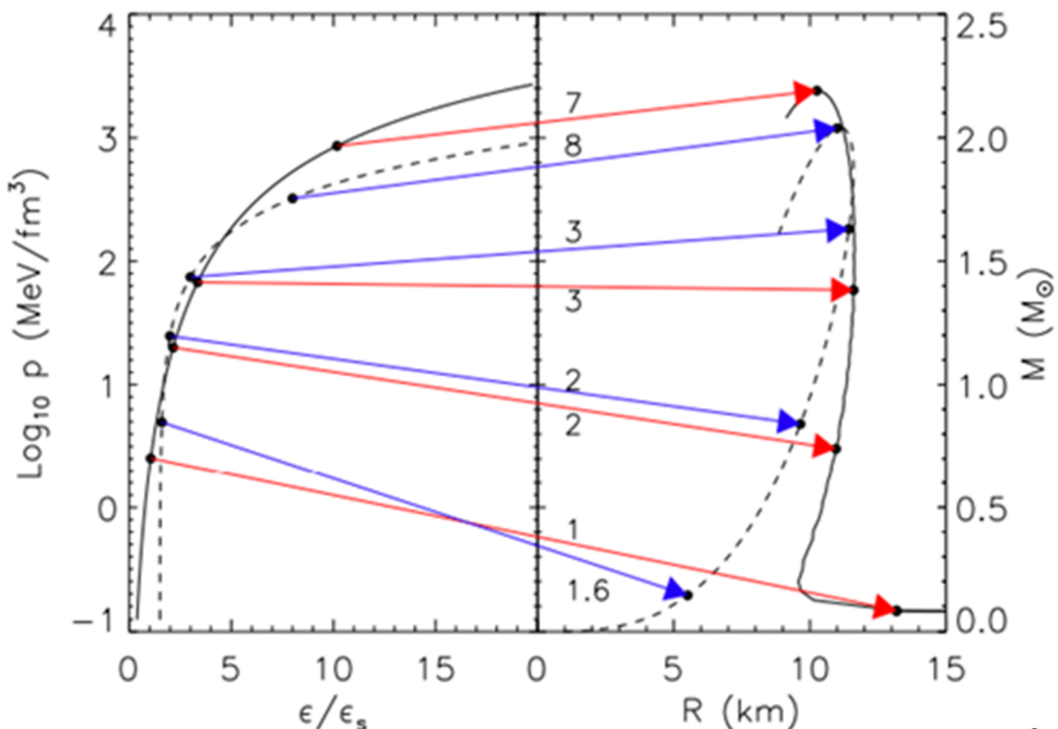
$$\mu_e = \sqrt{p_{F,e}^2 + m_e^2} \approx p_{F,e}, \text{ and } p_{F,e} = (3\pi^2 n_e)^{1/3} = (3\pi^2 n)^{1/3} (x - x_\mu)^{1/3} \ ,$$

$$\frac{x - x_\mu}{(1-2x)^3} = \frac{64 E_s^3(n)}{3\pi^2 n} \ , \qquad (x - x_\mu)^{2/3} - x_\mu^{2/3} = \frac{m_\mu^2}{(3\pi^2 n)^{2/3}} \ .$$

The total pressure is then given as $P(n) = n^2 \left(\frac{\partial E_{\rm tot}}{\partial n} \right)$.

Compact Star Sequences

(M-R ⇔ EoS)



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

- TOV Equations

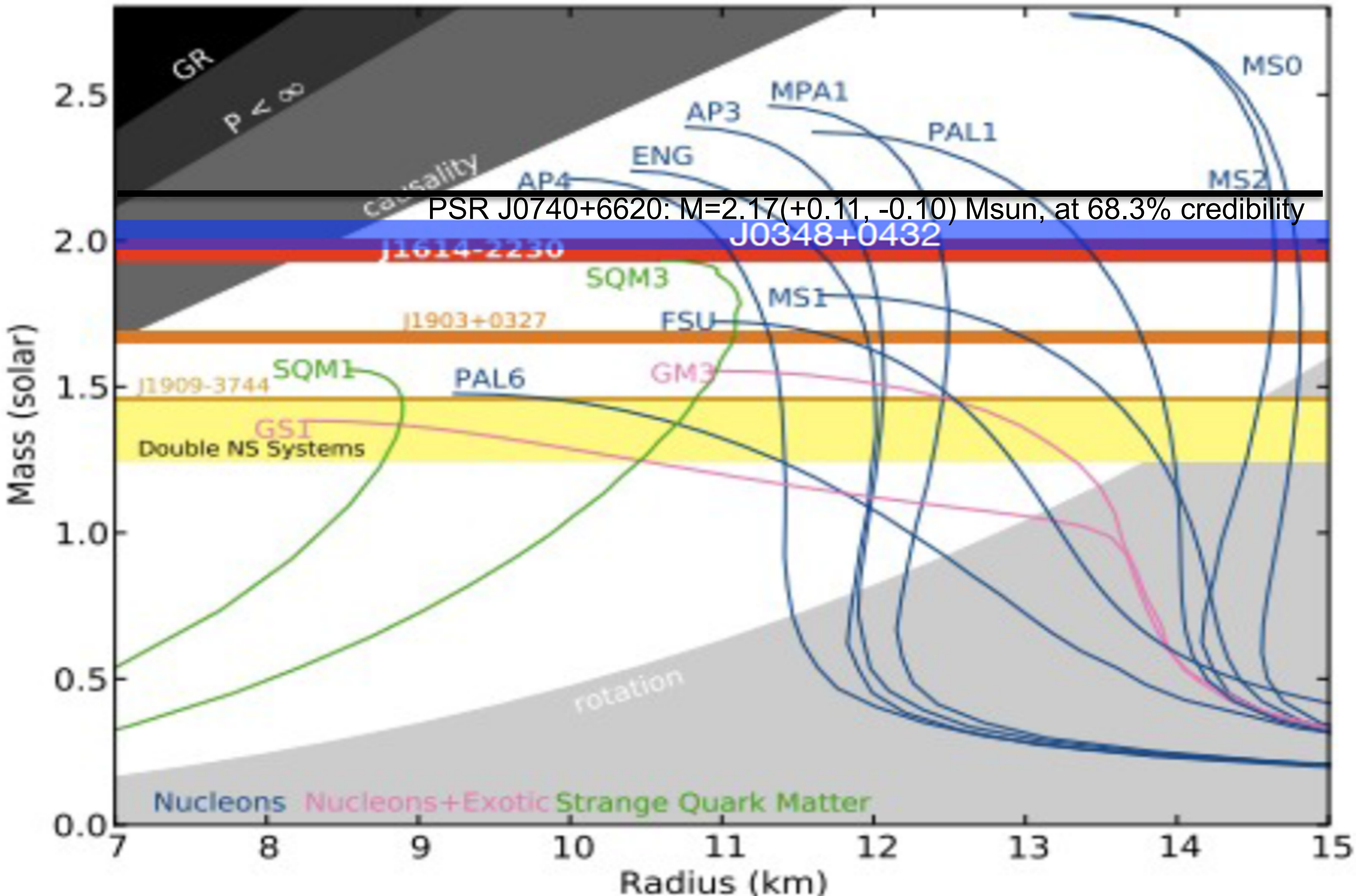
$$\frac{dp}{dr} = -\frac{(\varepsilon + p/c^2)G(m + 4\pi r^3 p/c^2)}{r^2(1-2Gm/rc^2)}$$

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

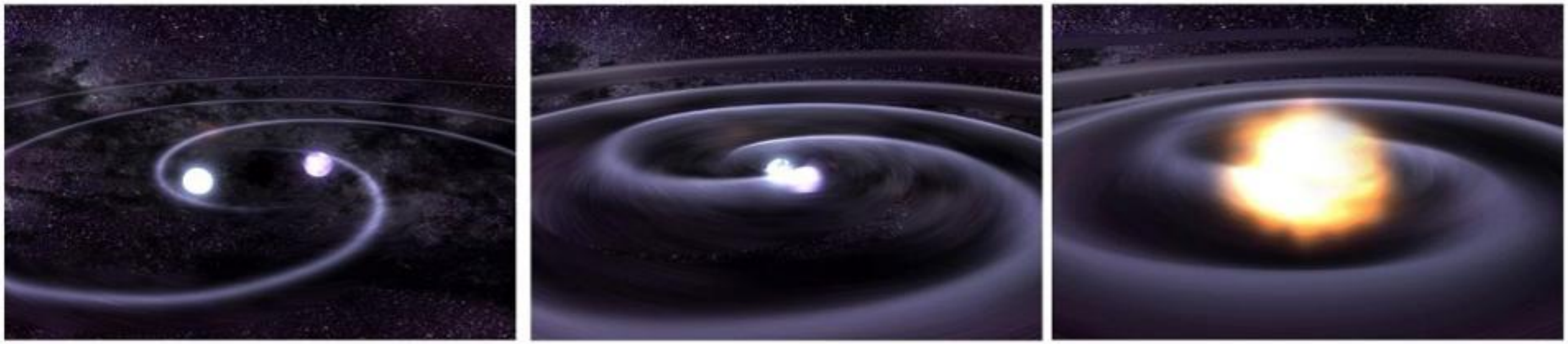
- Equation of State (EoS)

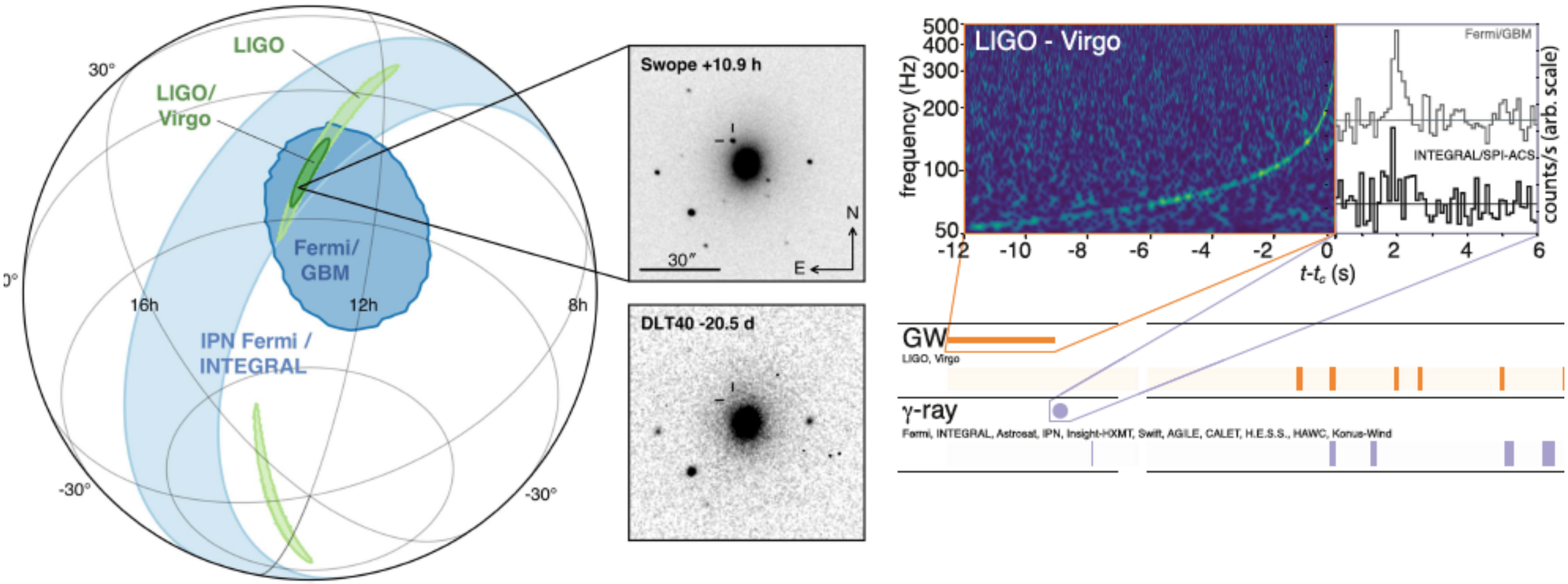
$$p(\varepsilon)$$

Massive Neutron Stars



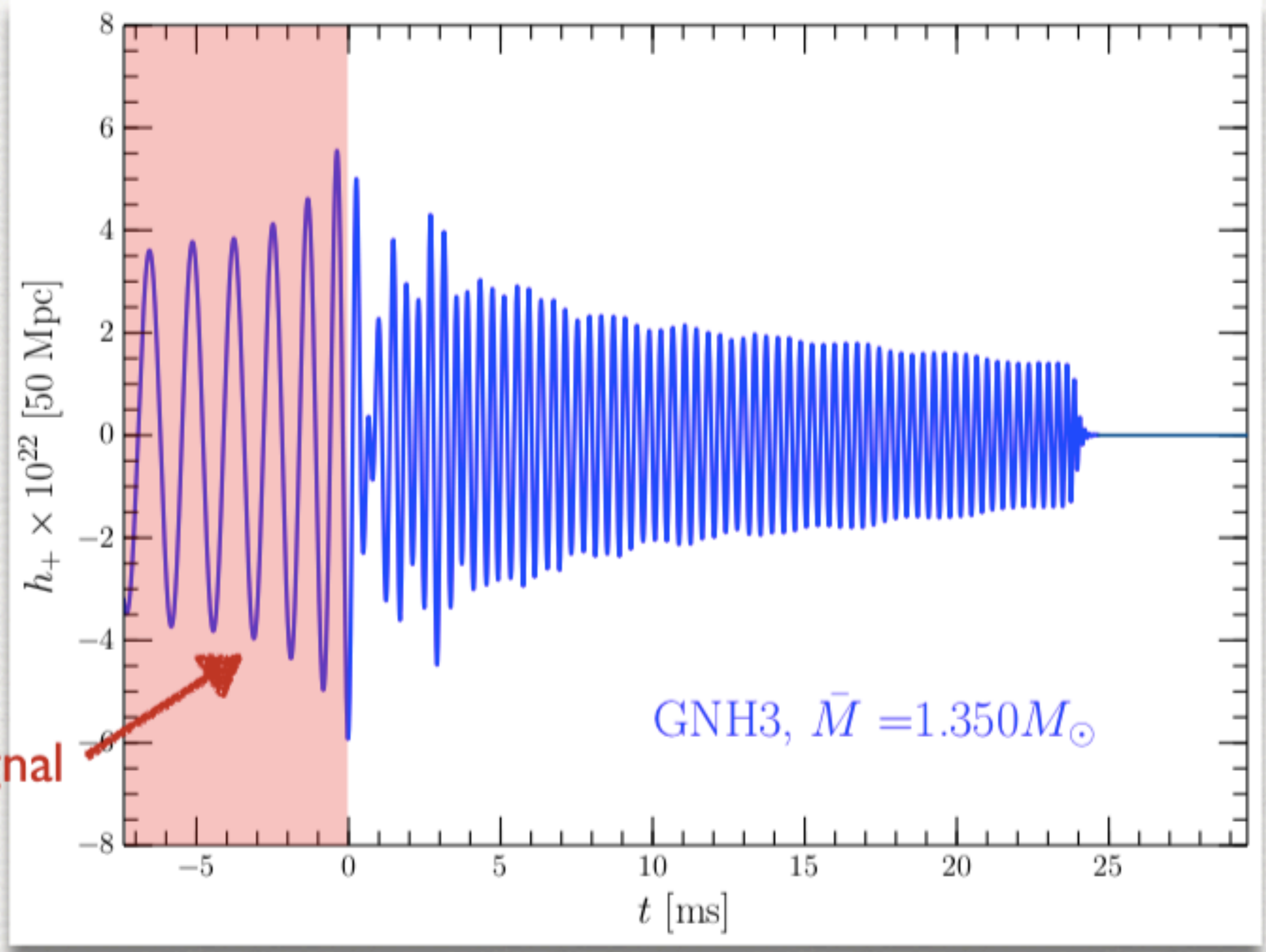
GW170817: Neutron Star Merger





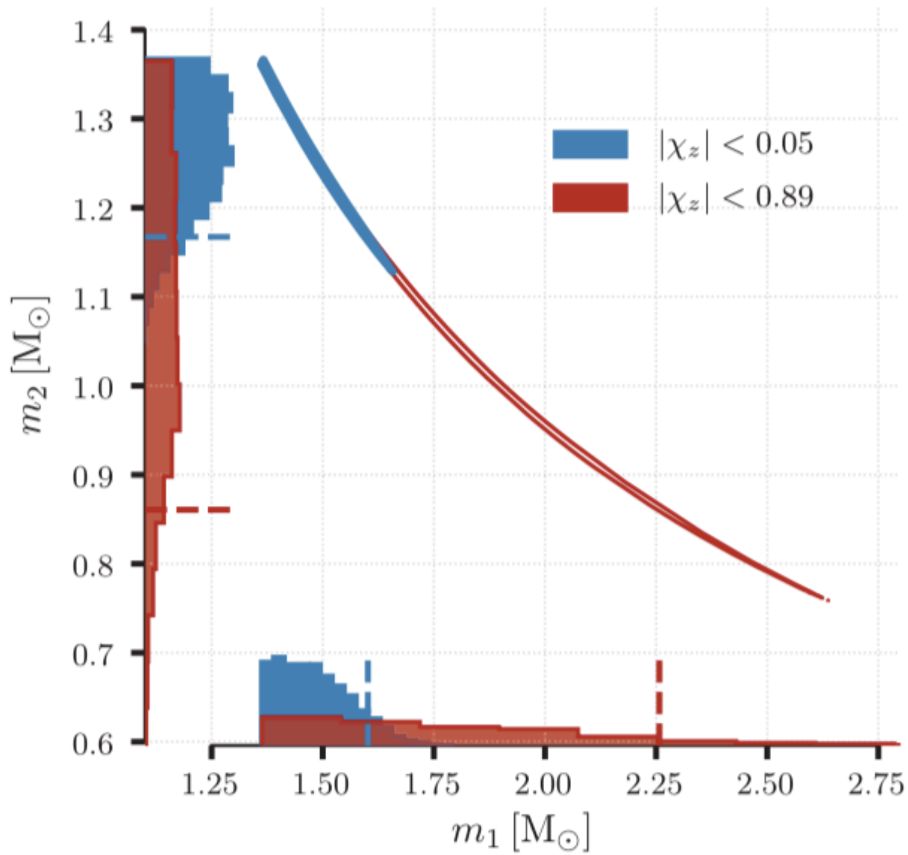
*) B.P. Abbott et al. [LIGO/Virgo Collab.], PRL 119, 161101 (2017); ApJLett 848, L12 (2017)

Anatomy of the GW signal



Chirp 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

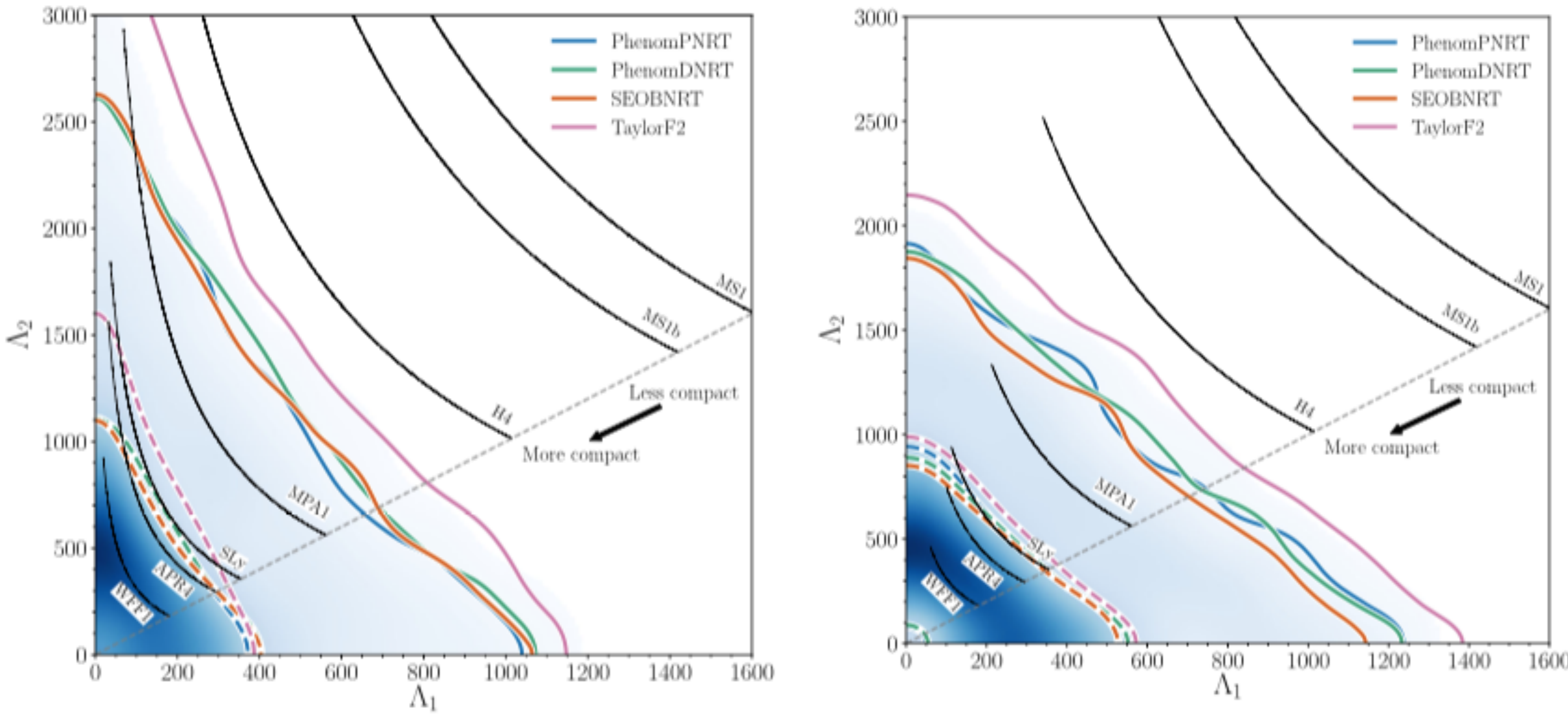
$$y = \frac{R\,\beta(R)}{H(R)}$$

$$\Lambda = \frac{2}{3}\frac{R^5}{M^5}k_2$$

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

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)

Neutron Star Radius

C.J. Horowitz / Annals of Physics 411 (2019) 167992 5

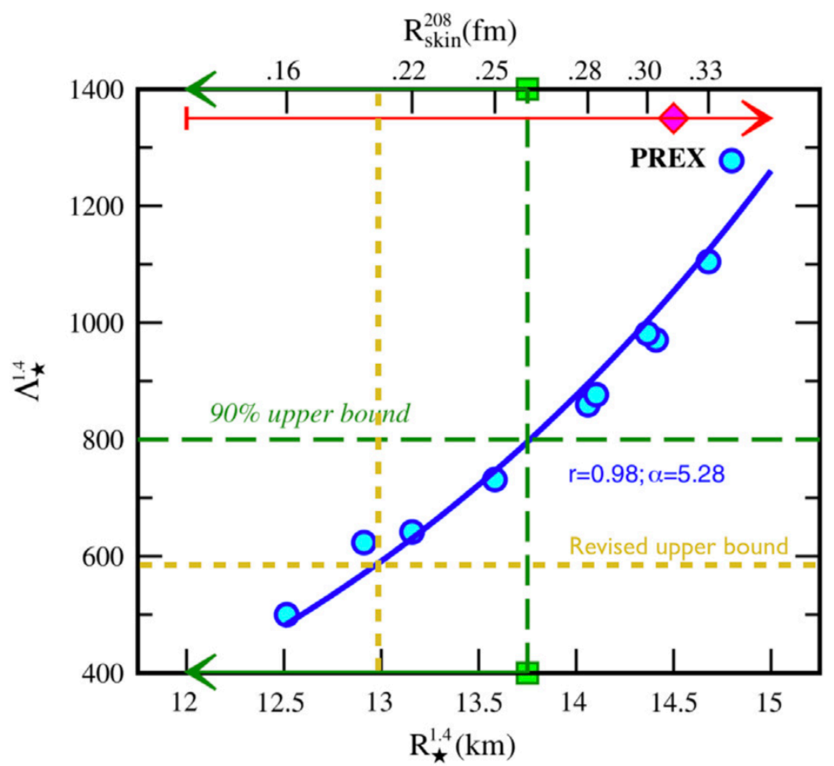
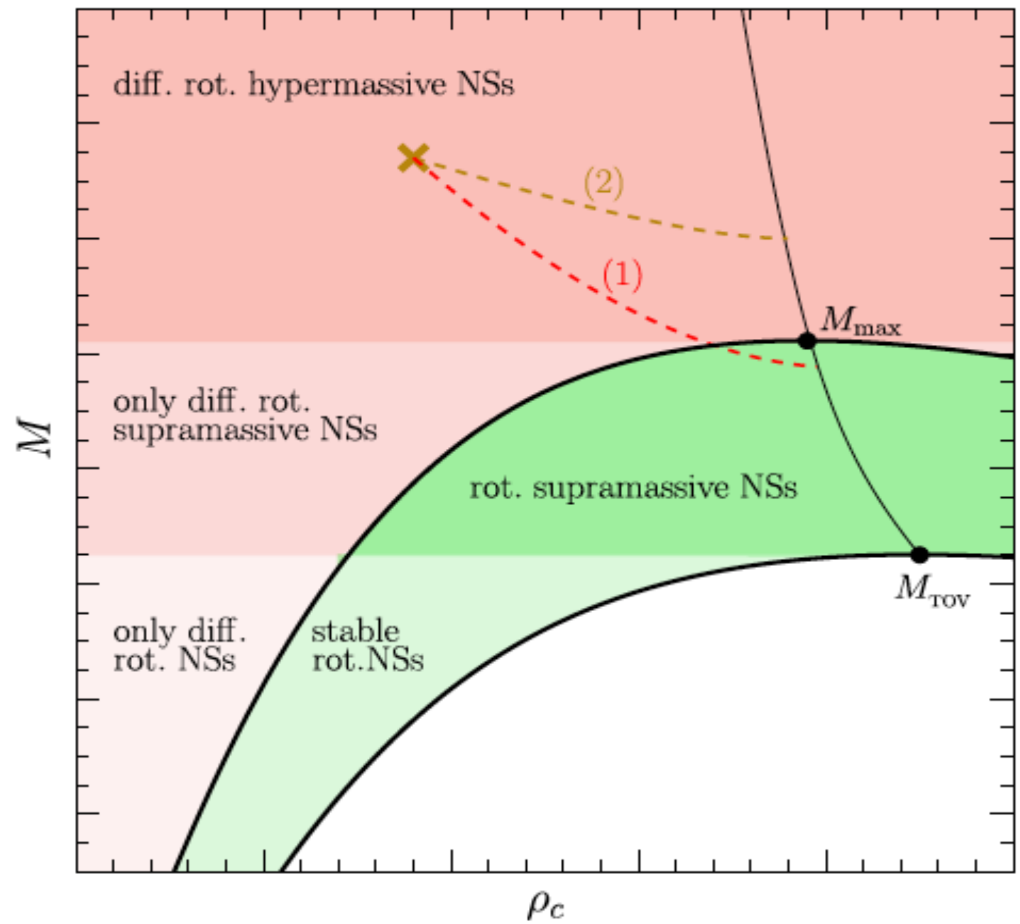


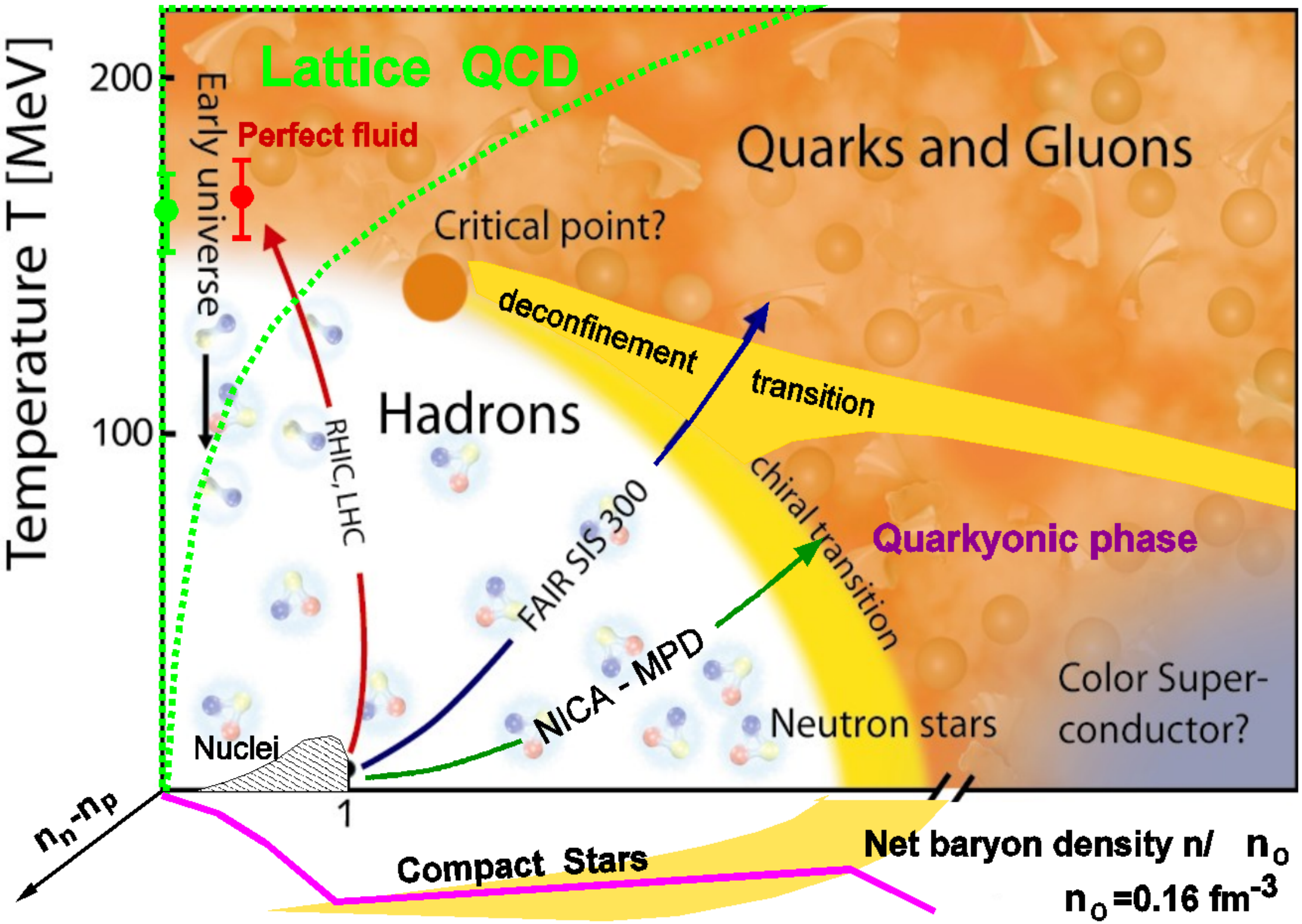
Fig. 2. (Color online) Gravitational deformability $\Lambda_*^{1.4}$ is shown on the Y-axis versus the radius $R_*^{1.4}$ of a $1.4 M_\odot$ NS on the lower X-axis. Also shown is the neutron skin in ^{208}Pb on the upper X-axis. The blue circles are results for a series of model relativistic energy density functionals. The green dashed line shows the original upper bound on Λ from GW170817 data. Finally the dotted yellow line shows a possible more stringent upper bound on Λ from the GW170817 data and assuming the two NS have the same EOS.
Source: Figure adopted from Ref. [10]

Upper limit on the Maximum mass of static compact stars?



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

Critical Endpoint in QCD

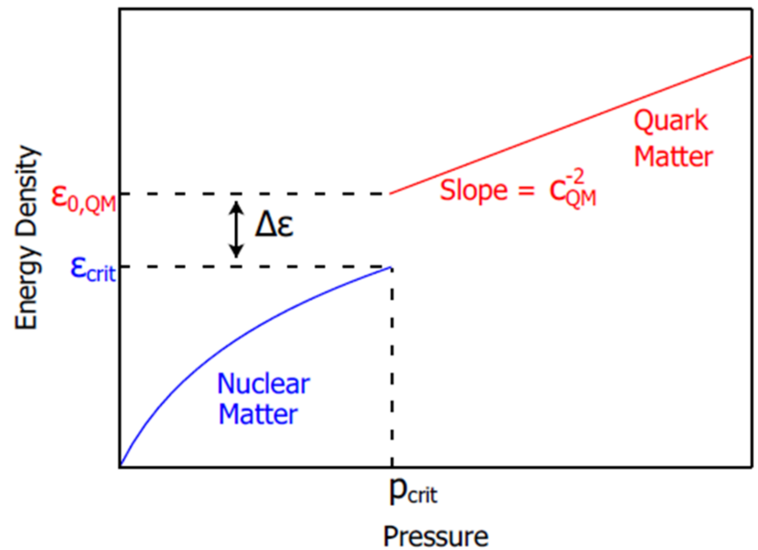


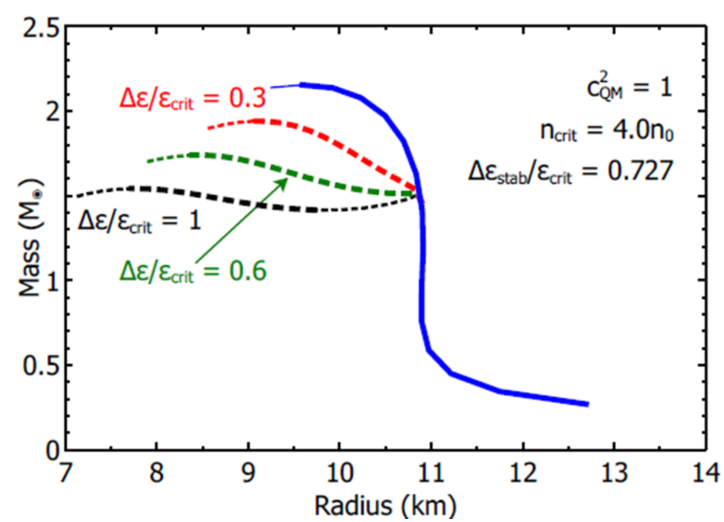
Compact Star Mass Twins and the AHP scheme

- 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

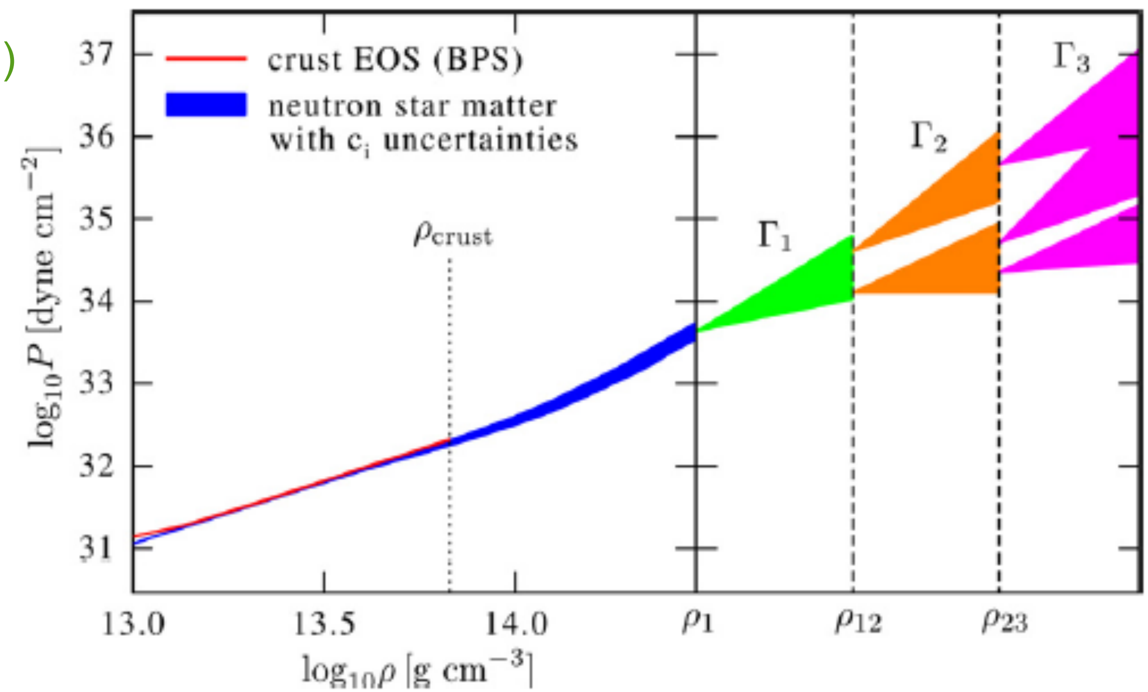
Hebeler et al., ApJ 773, 11 (2013)

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

$$i = 1 \;:\; n_1 \leq n \leq n_{12}$$
$$i = 2 \;:\; n_{12} \leq n \leq n_{23}$$
$$i = 3 \;:\; n \geq n_{23} \;,$$

Here, 1st order PT in region 2:

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



$$P(n) = n^2 \frac{d(\varepsilon(n)/n)}{dn},$$

$$\varepsilon(n)/n = \int dn \, \frac{P(n)}{n^2} = \int dn \, \kappa n^{\Gamma-2} = \frac{\kappa \, n^{\Gamma-1}}{\Gamma - 1} + C,$$

$$\mu(n) = \frac{P(n) + \varepsilon(n)}{n} = \frac{\kappa \, \Gamma}{\Gamma - 1} n^{\Gamma-1} + m_0,$$

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

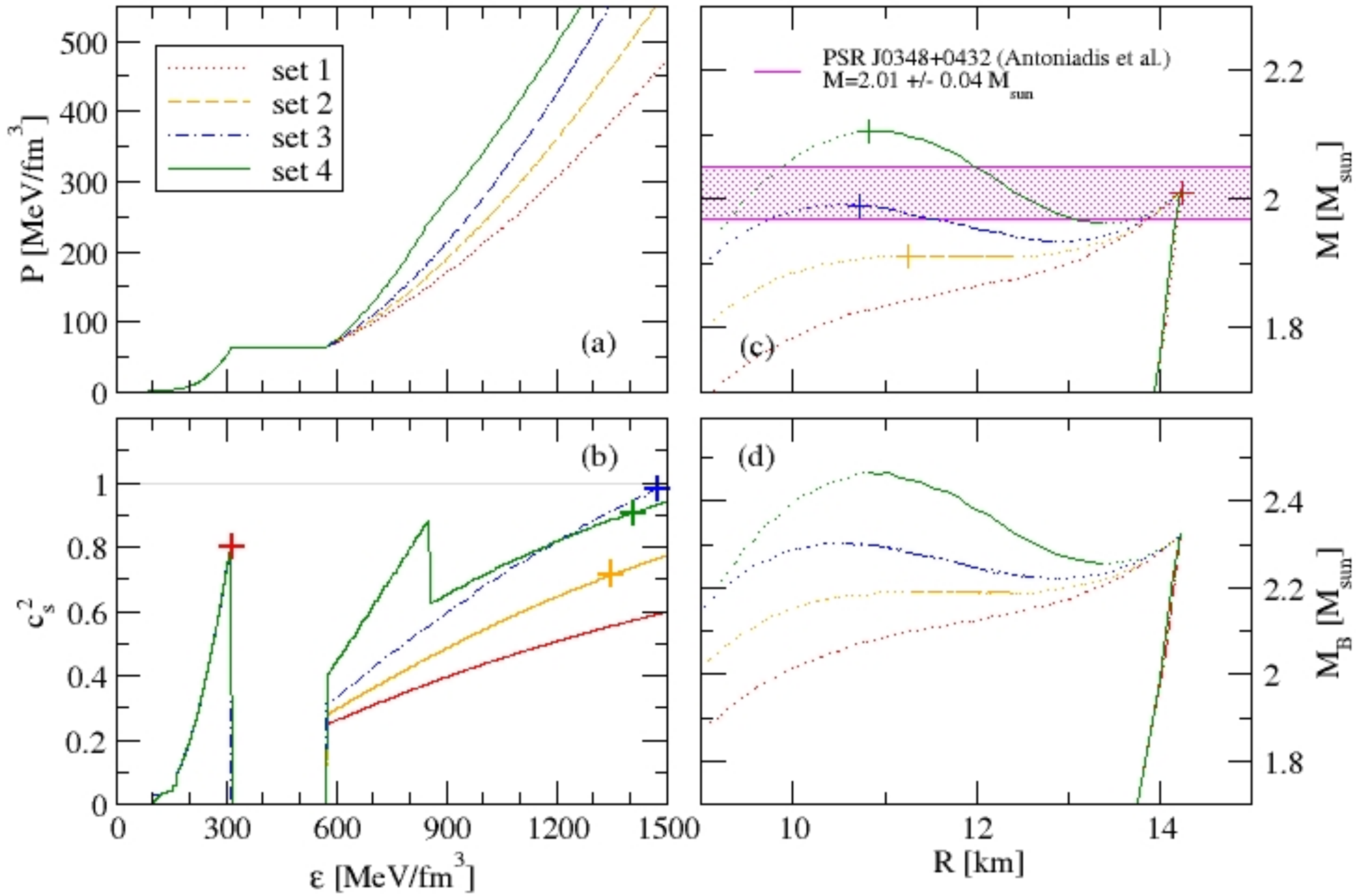
$$P(\mu) = \kappa \left[(\mu - m_0)\frac{\Gamma - 1}{\kappa\Gamma}\right]^{\Gamma/(\Gamma-1)}$$

Maxwell construction:

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

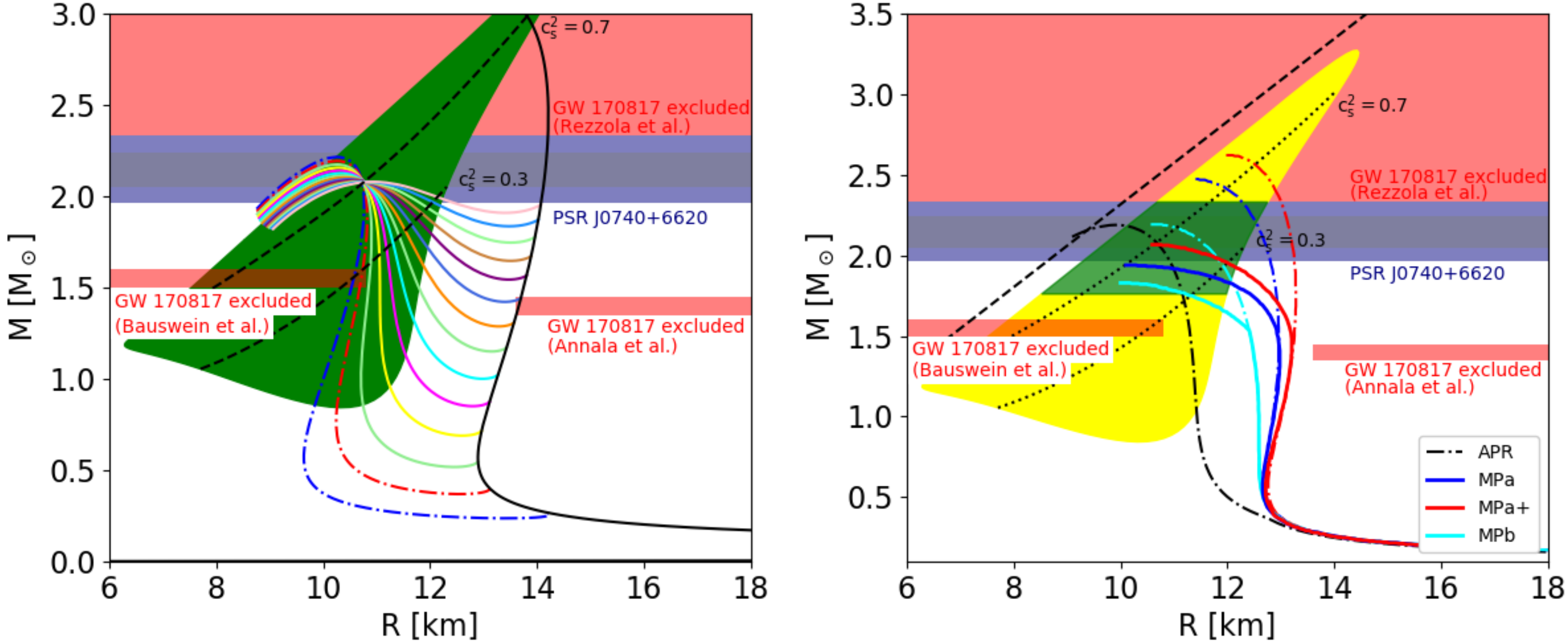
Seidov criterion for instability: $\dfrac{\Delta\varepsilon}{\varepsilon_{\rm crit}} \geq \dfrac{1}{2} + \dfrac{3}{3}\dfrac{P_{\rm crit}}{\varepsilon_{\rm crit}}$

Compact Star Twins



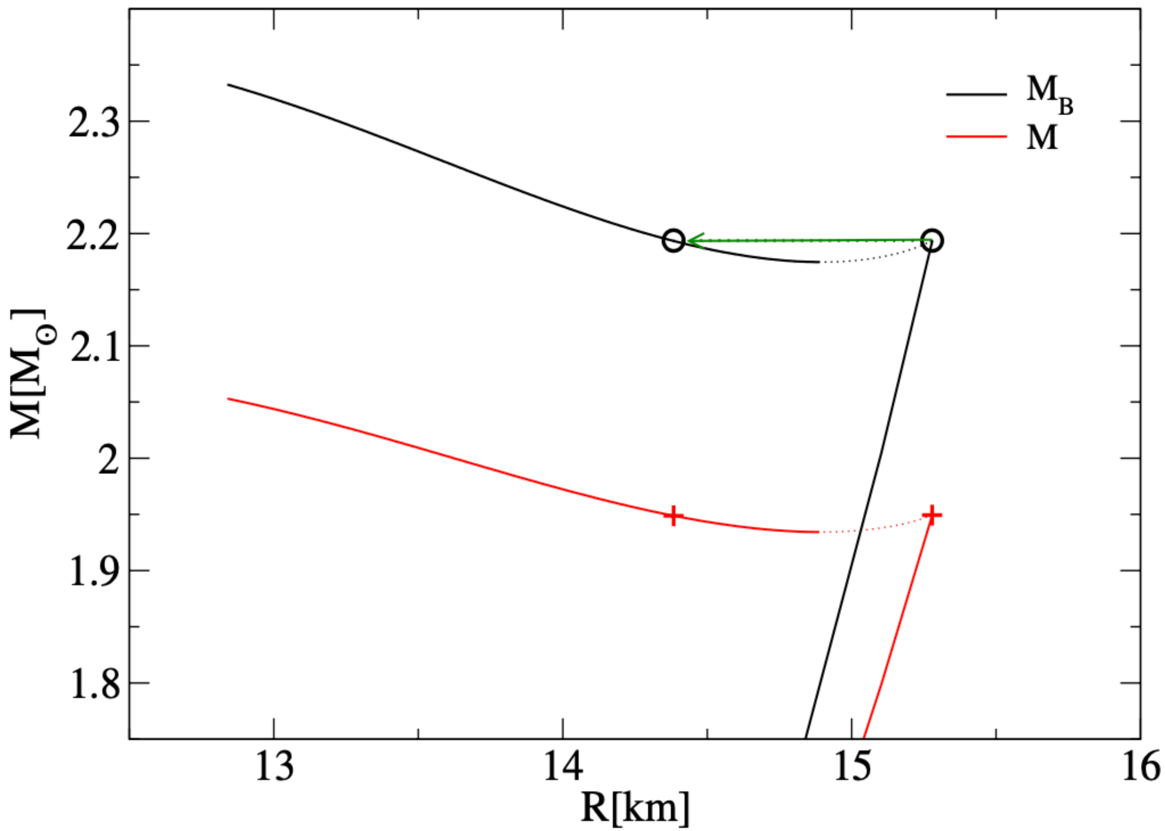
Alvarez-Castillo, Blaschke (2017)
High mass twins from multi-polytrope equations of state
arXiv: 1703.02681v2, Phys. Rev. C 96, 045809 (2017)

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 (2020), arXiv:2011.11145
Alvarez-Castillo, Bejger, Blaschke, Haensel, Zdunik (2015), arXiv:1401.5380

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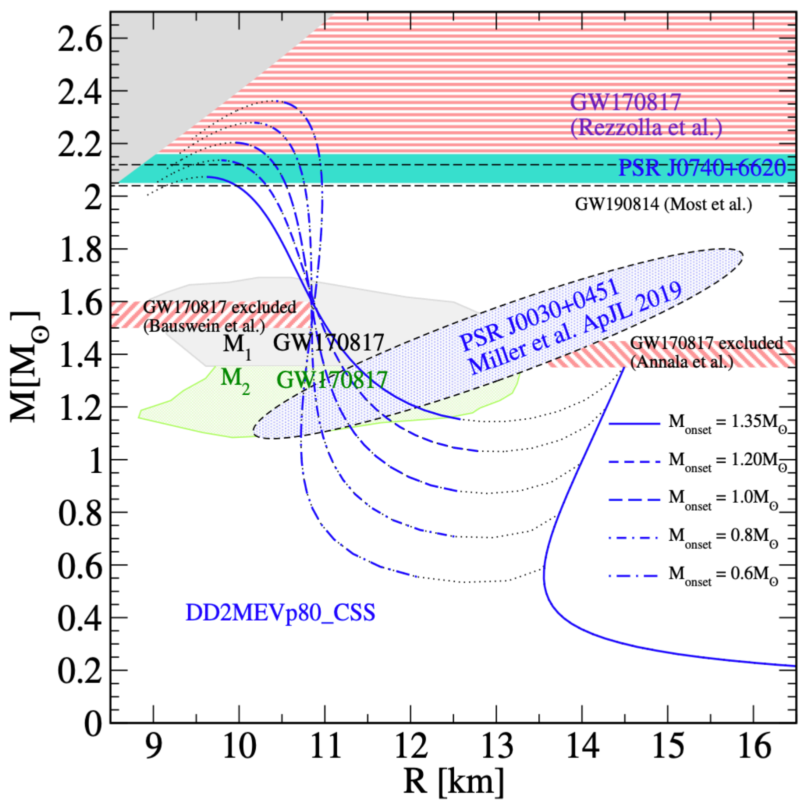
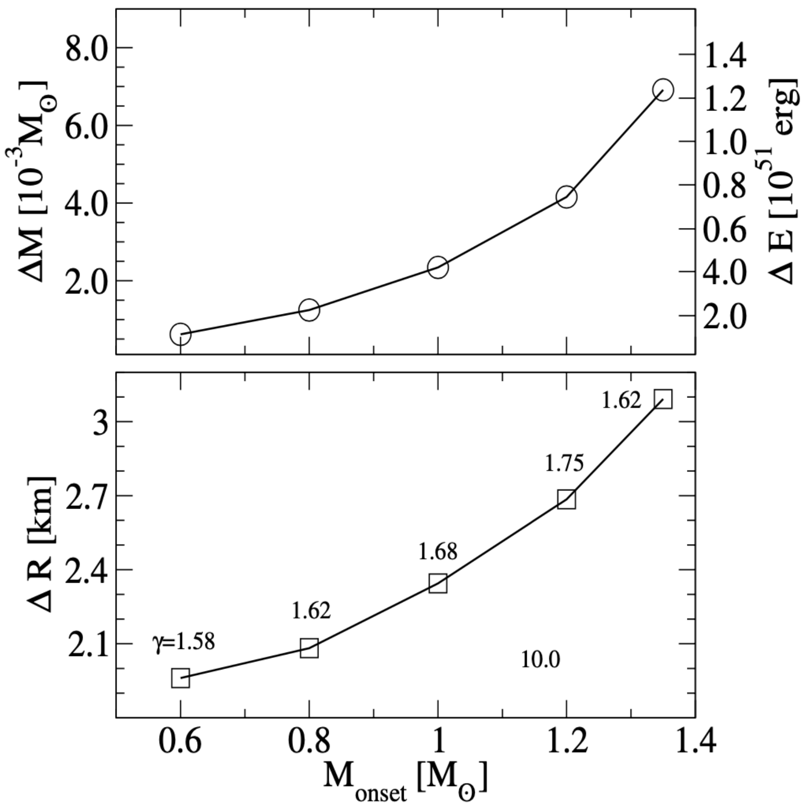




Alvarez-Castillo (2020), arXiv:2011.11145
Alvarez-Castillo, Bejger, Blaschke, Haensel, Zdunik (2015), arXiv:1401.5380

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

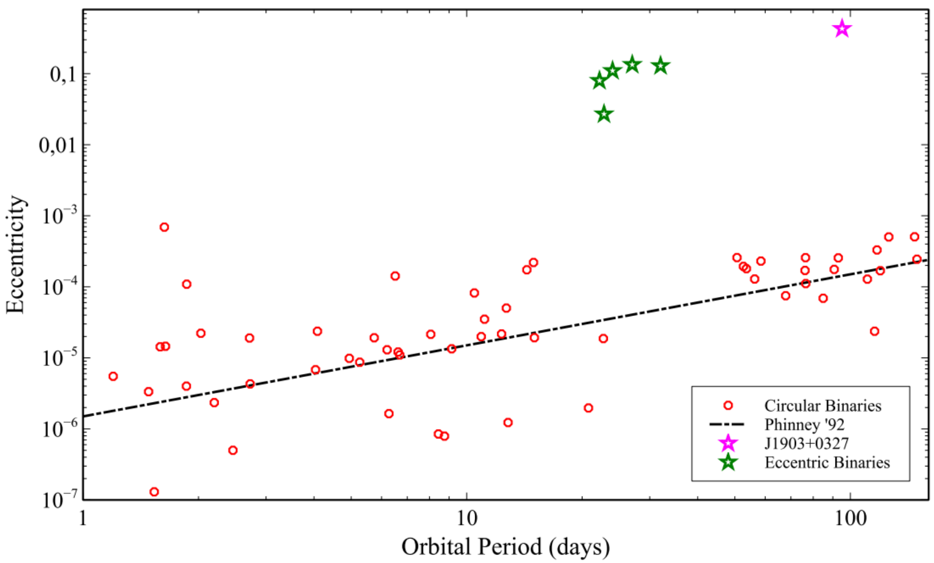
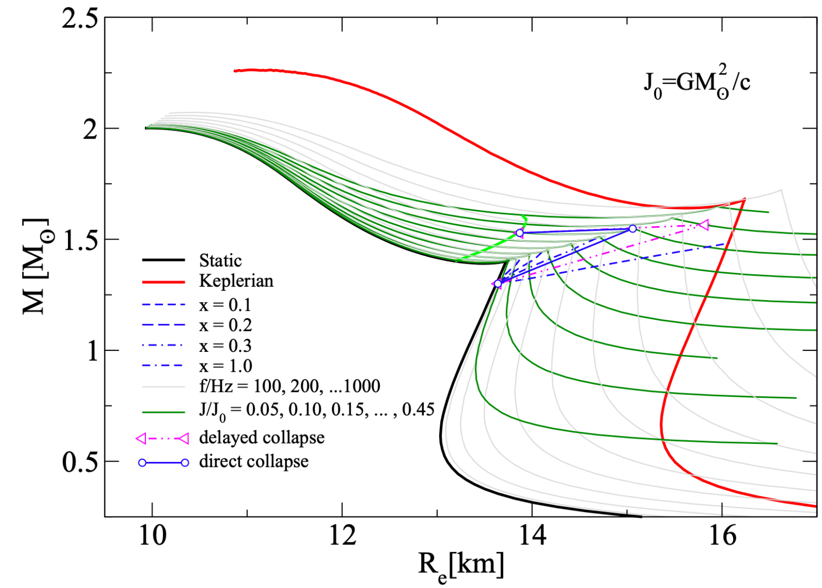


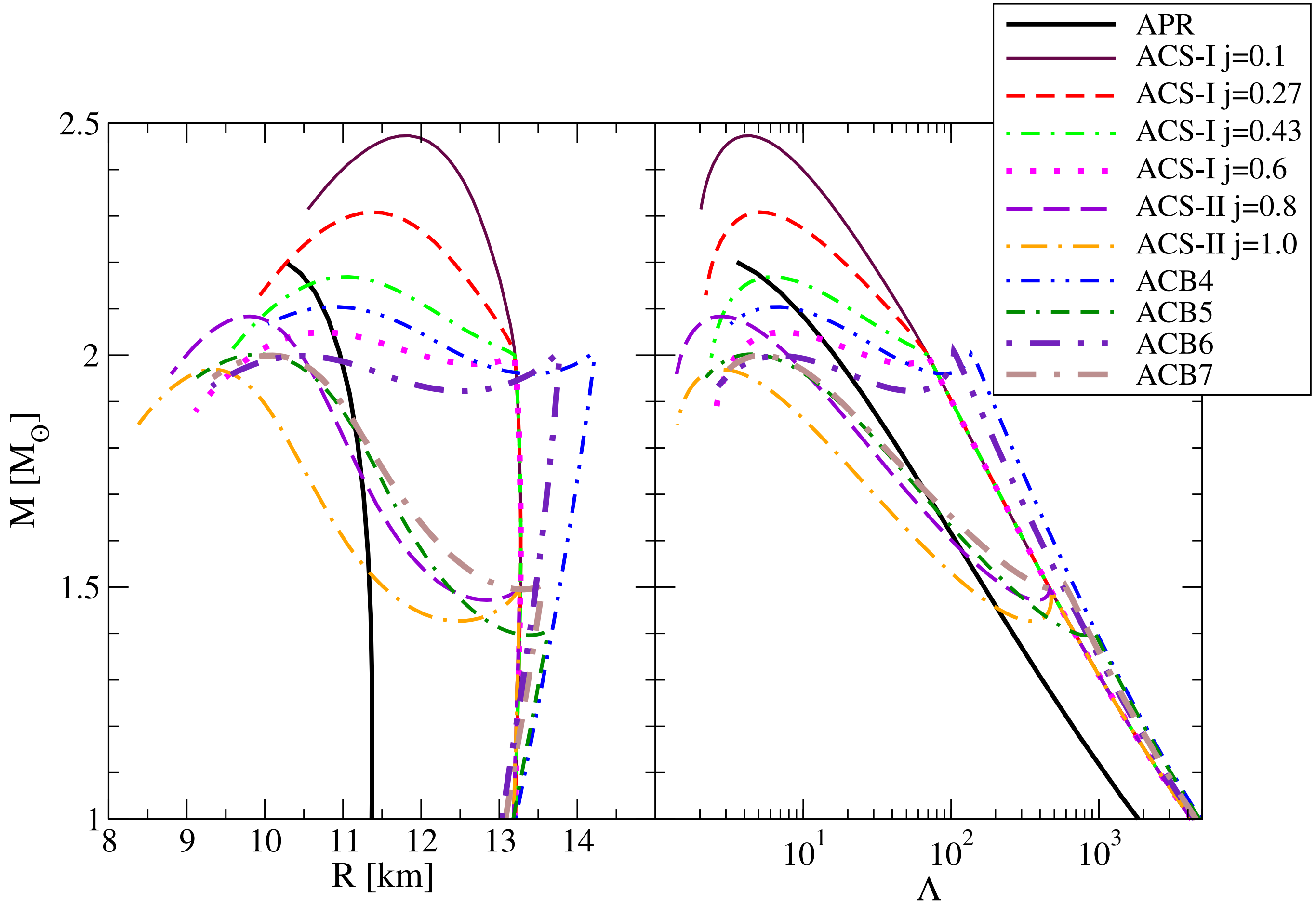
FIGURE 1 Eccentricity vs. orbital period for millisecond pulsars in binaries with white dwarf companions, see (J. Antoniadis, 2014; Stovall, 2019).



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

Implications from GW170817



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

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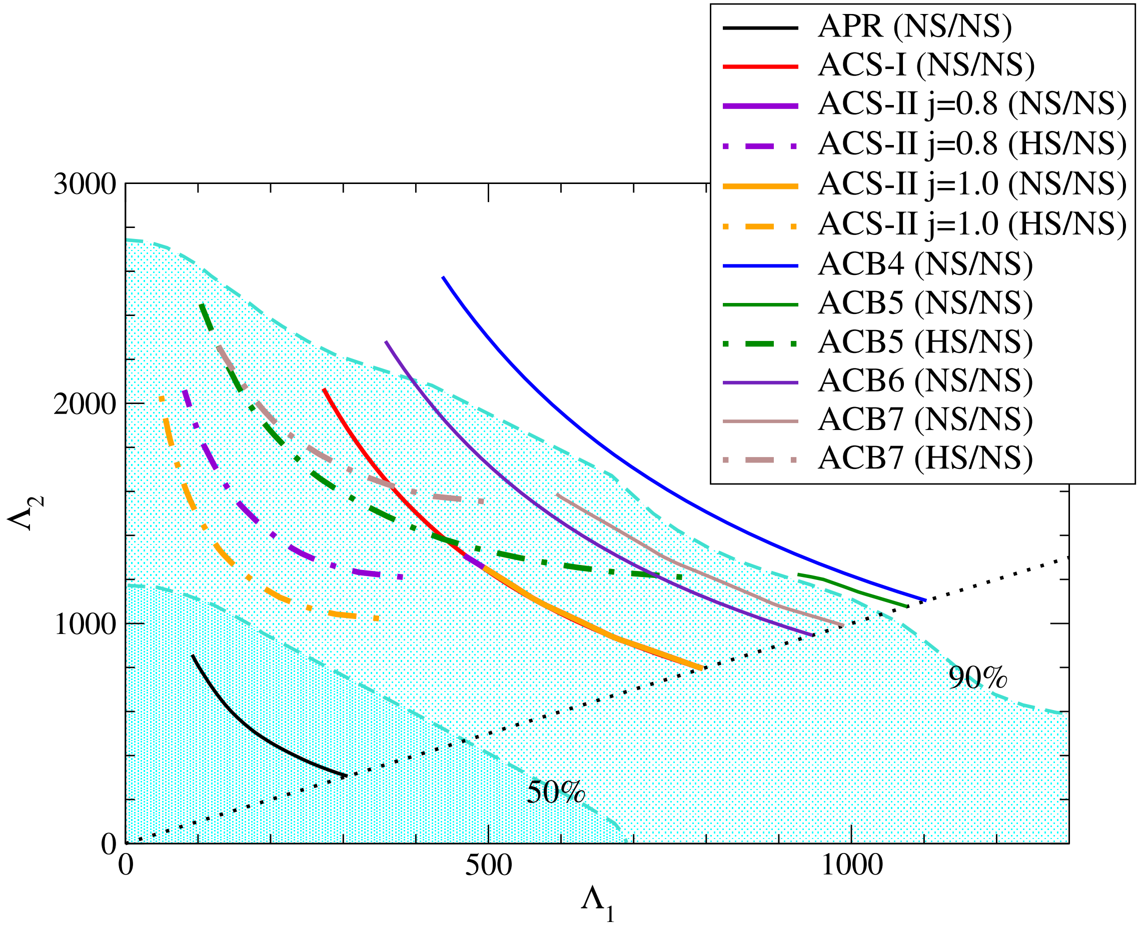

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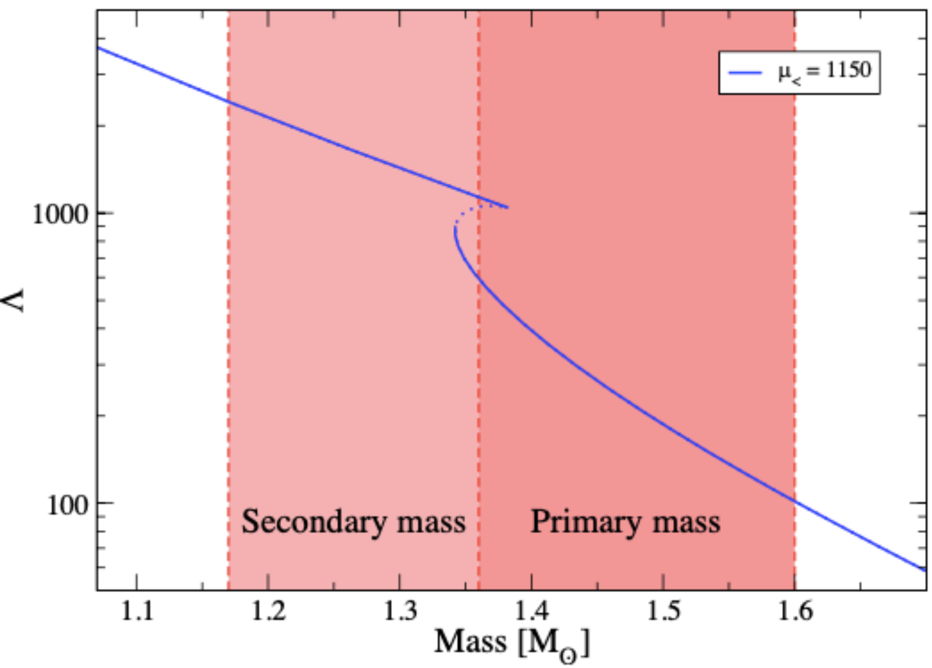
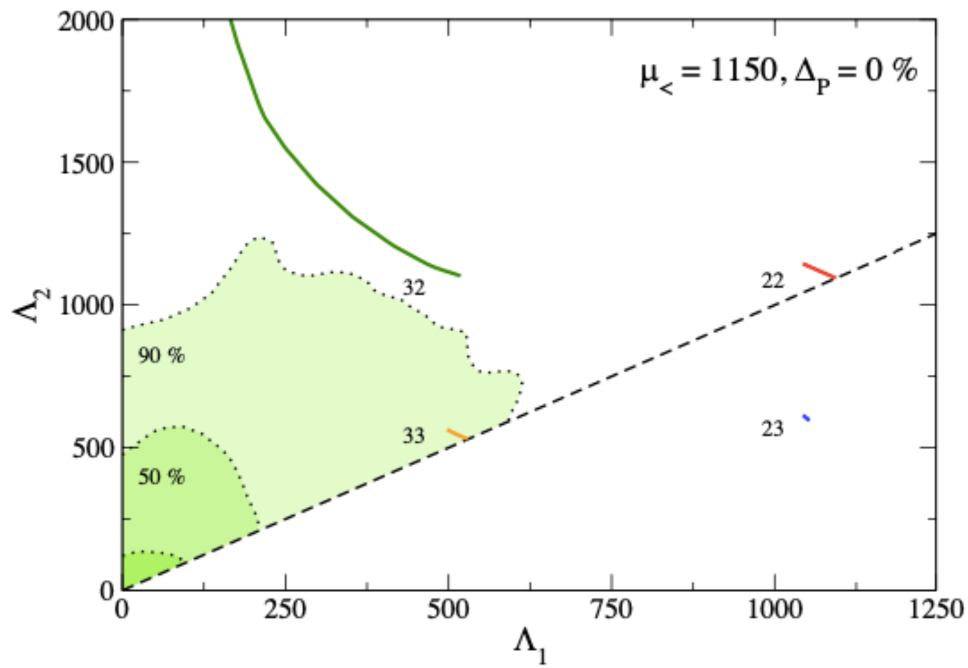
Was GW170817 a canonical neutron star merger?





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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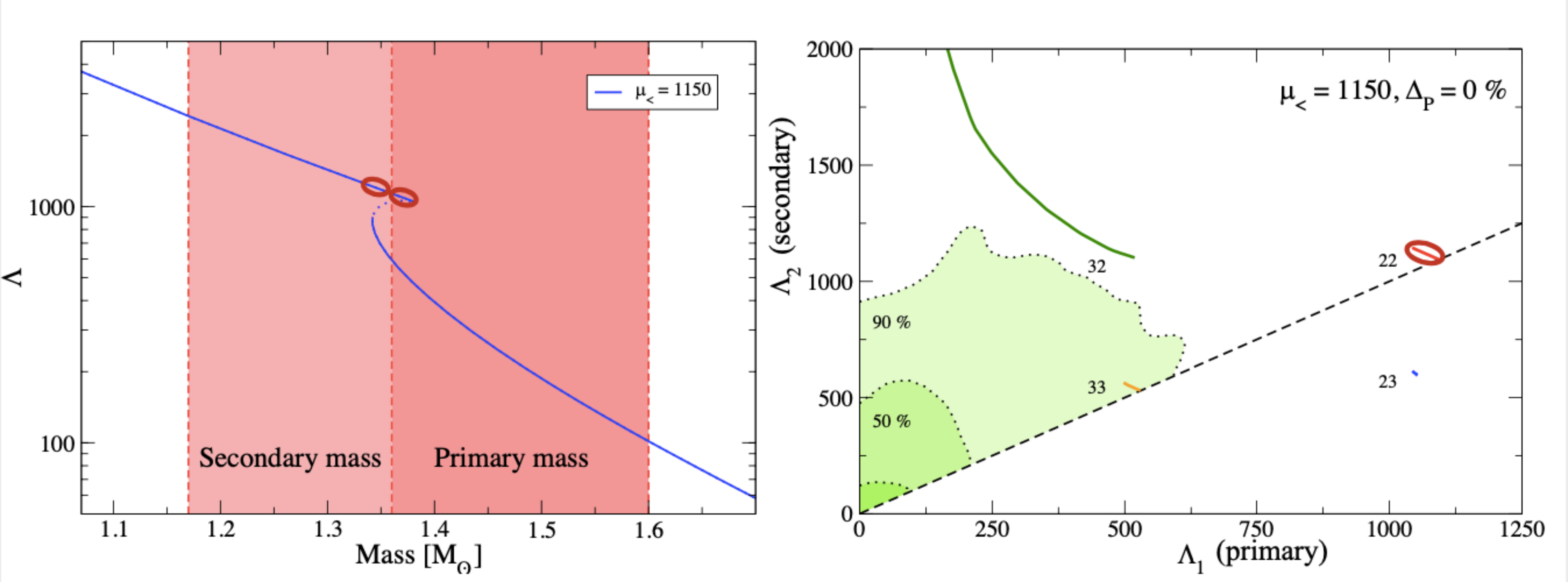

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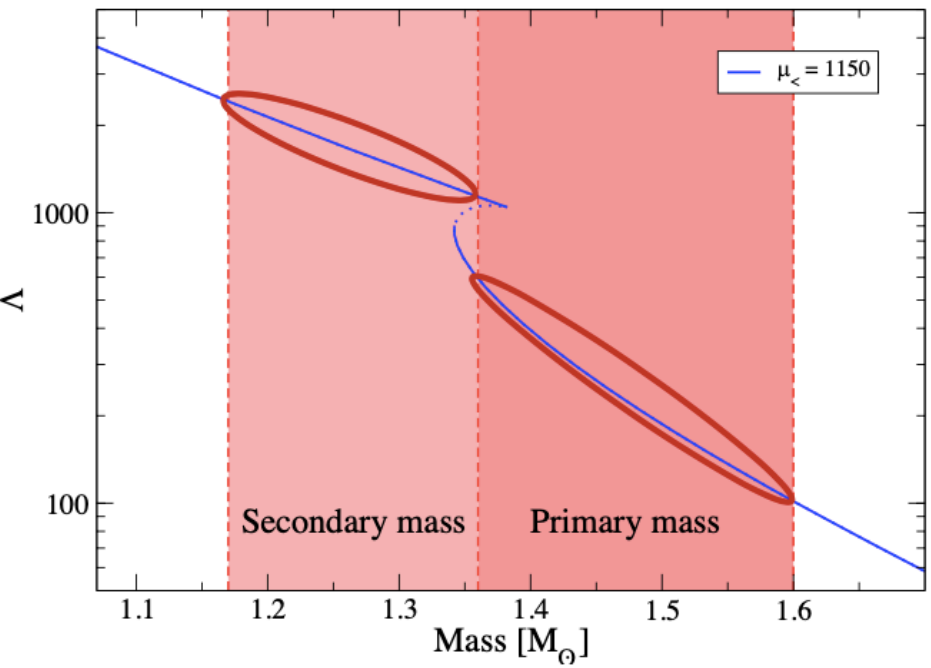

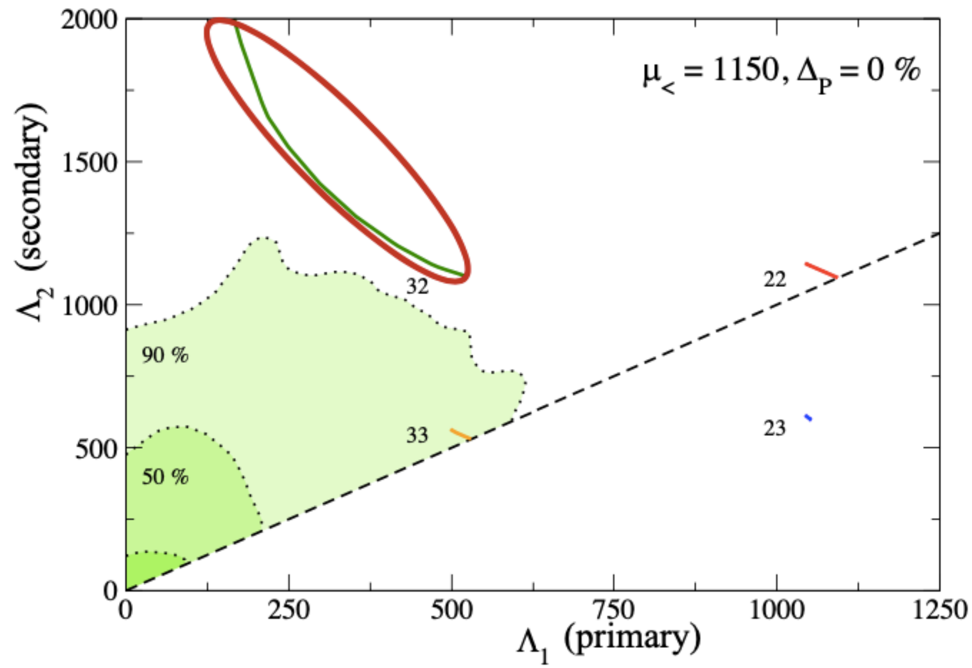

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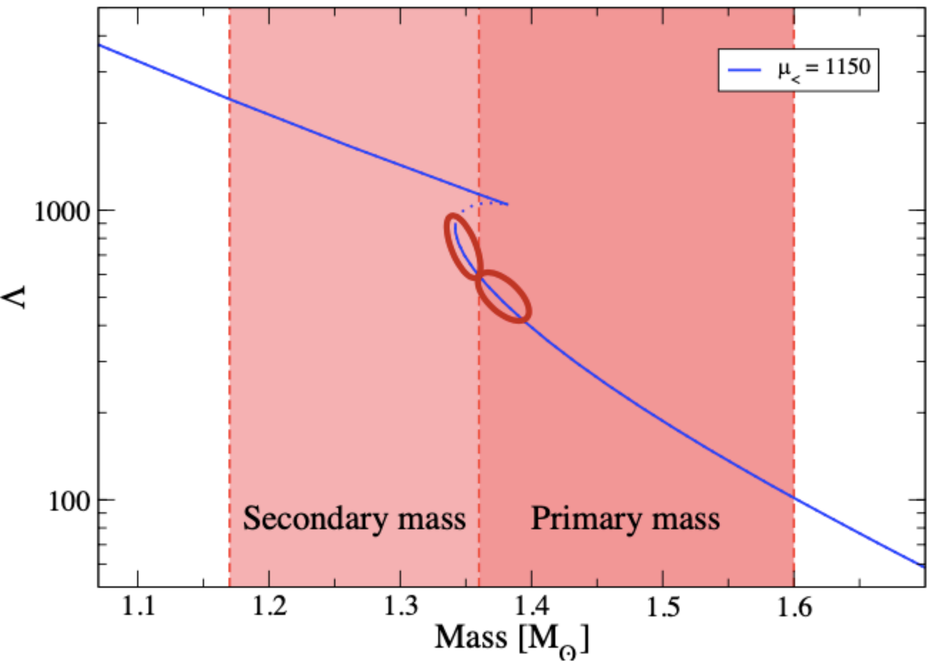

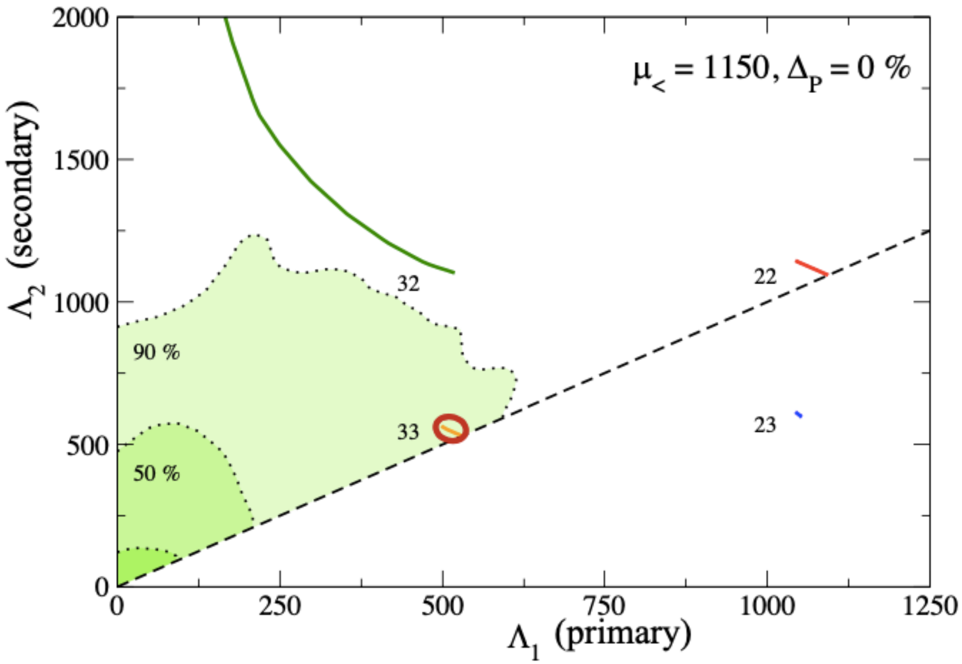

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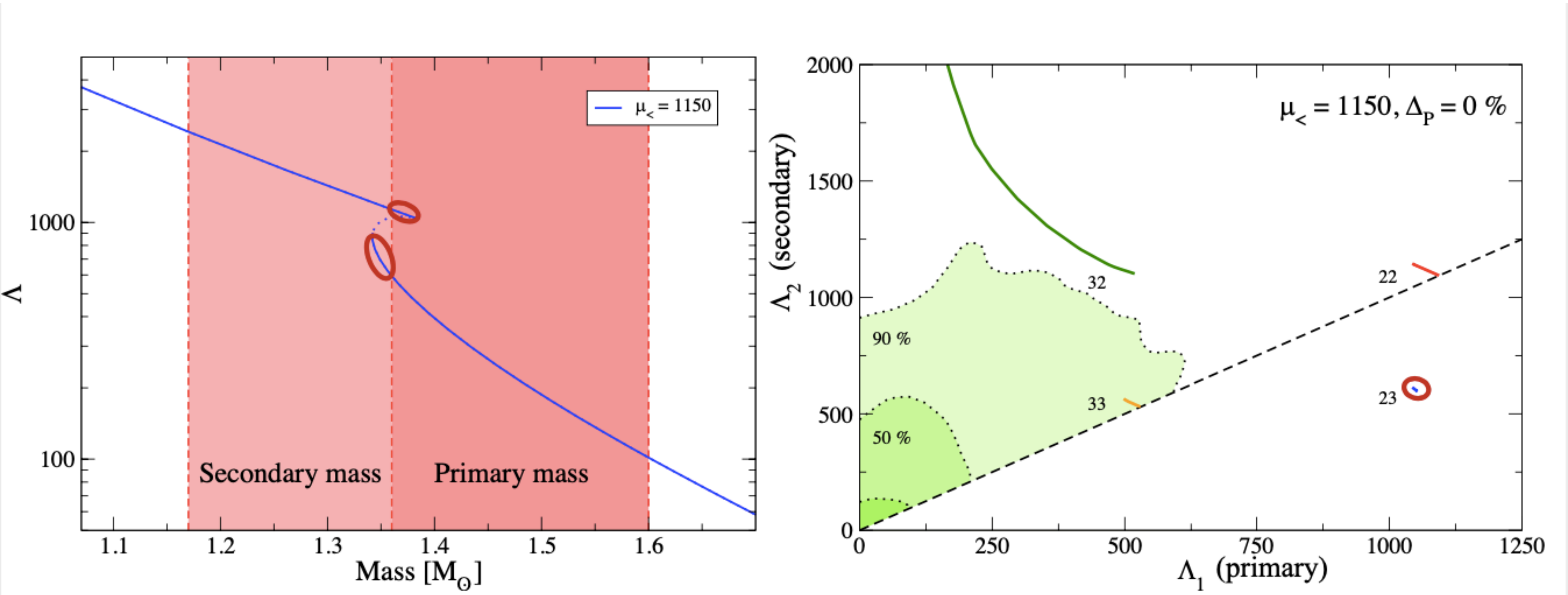
Phys. Rev. D 99, 063010 (2019) - arXiv: 1805.04105

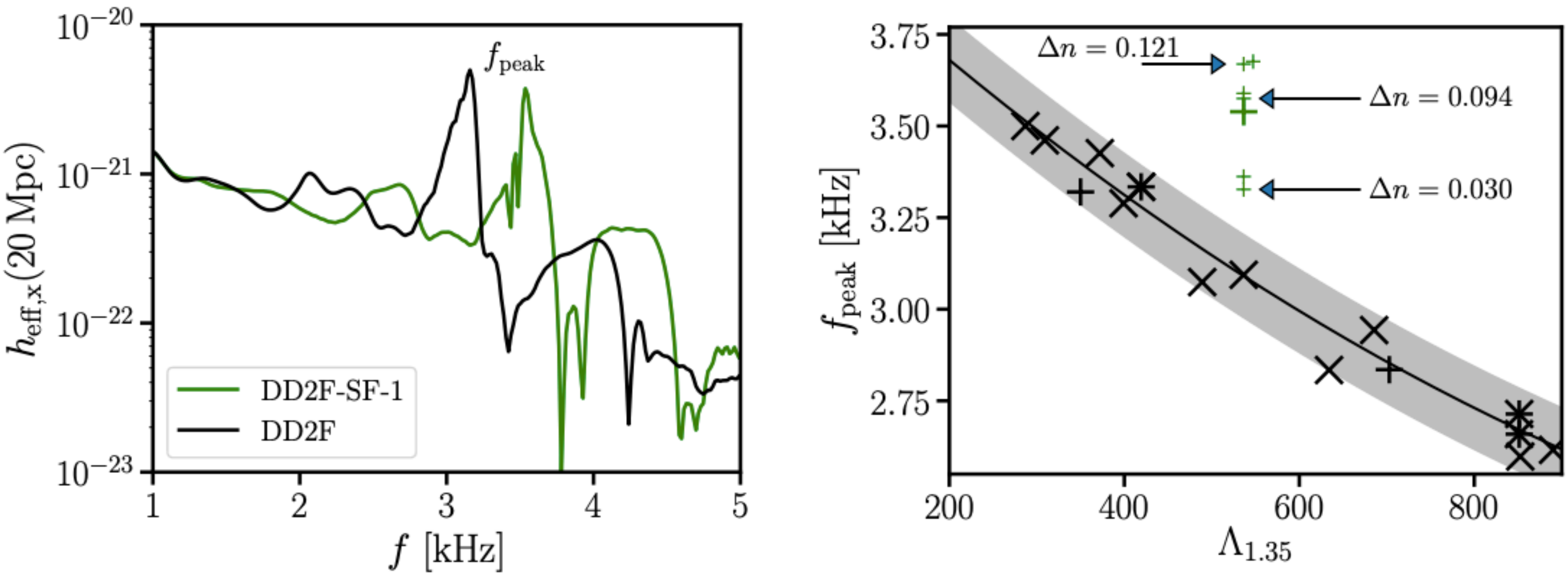
Was GW170817 a canonical neutron star merger?



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

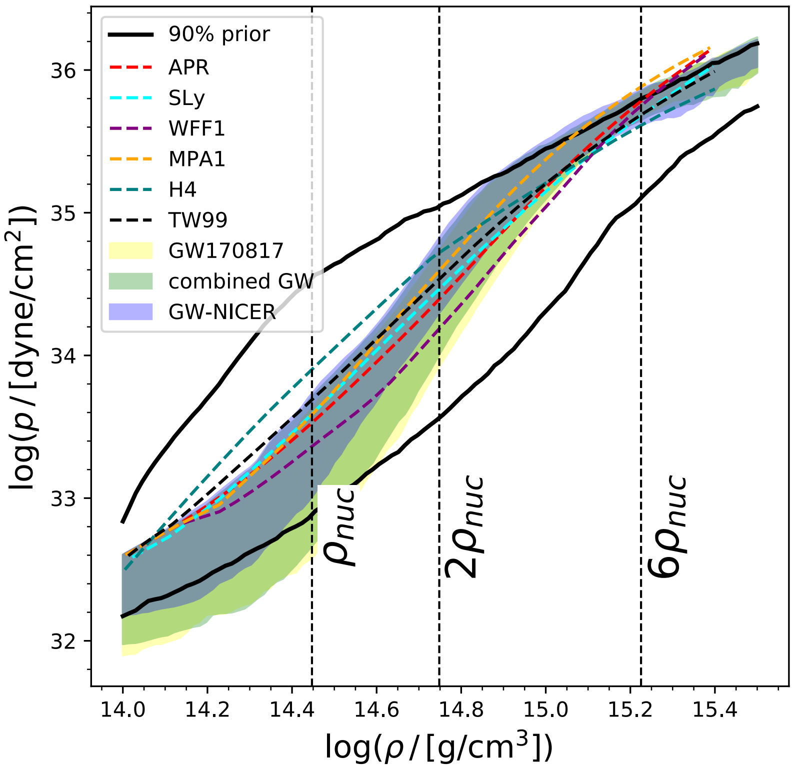
D. Alvarez-Castillo, D. Blaschke, G. Grunfeld, V. Pagura
Phys. Rev. D 99, 063010 (2019) - arXiv: 1805.04105

Gravitational Wave Signals
First Order Phase Transitions

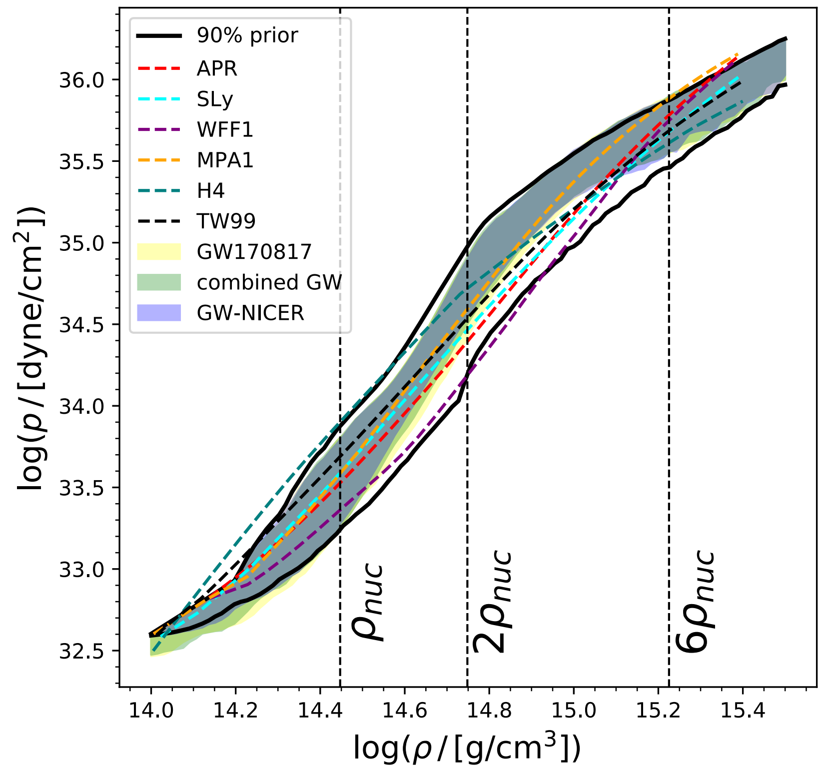


A. Bauswein et al. - arXiv: 1904.01306, PRL 122 (2019) 061102

Hint of a tension between Nuclear physics and Astrophysical observations



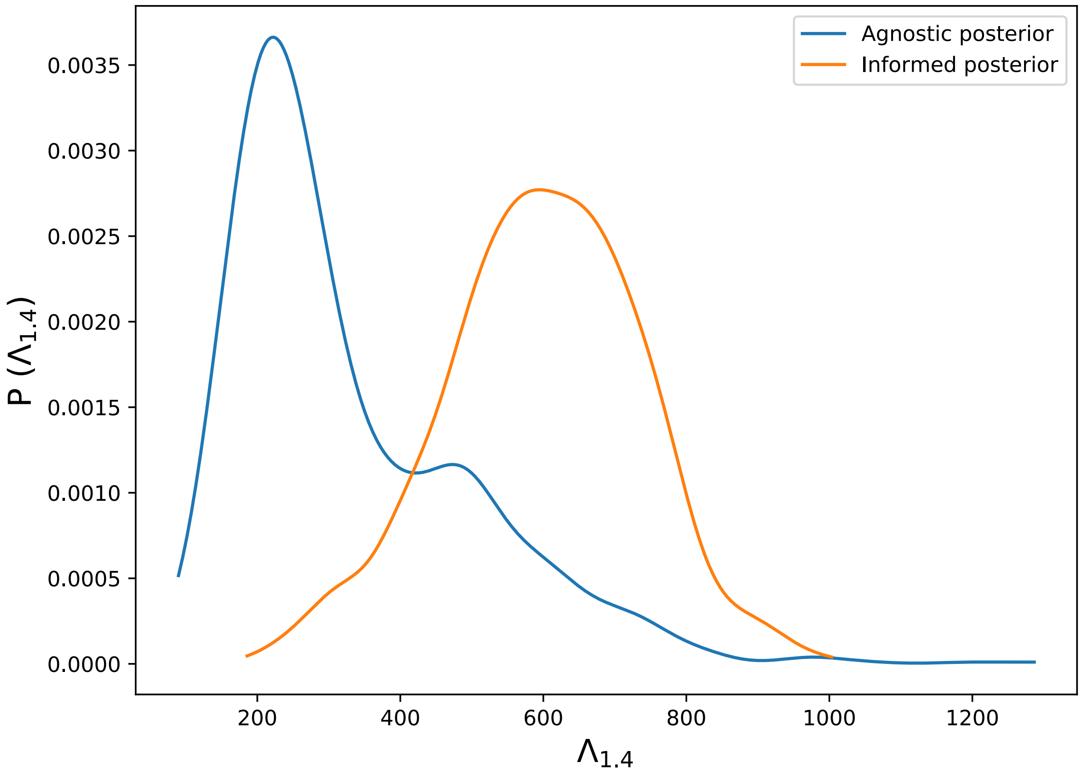
nuclear-physics agnostic priors



nuclear-physics priors

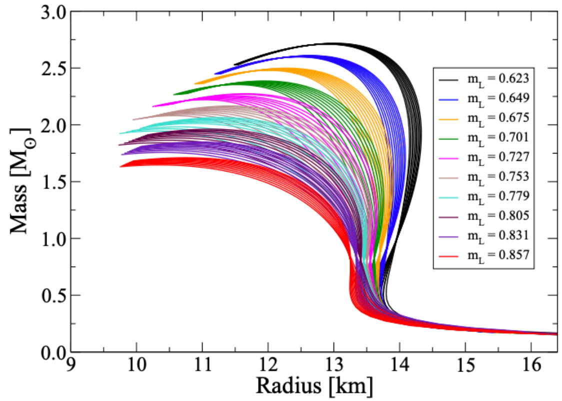
Bhaskar Biswas, Prasanta Char, Rana Nandi, Sukanta Bose, arXiv:2008.01582

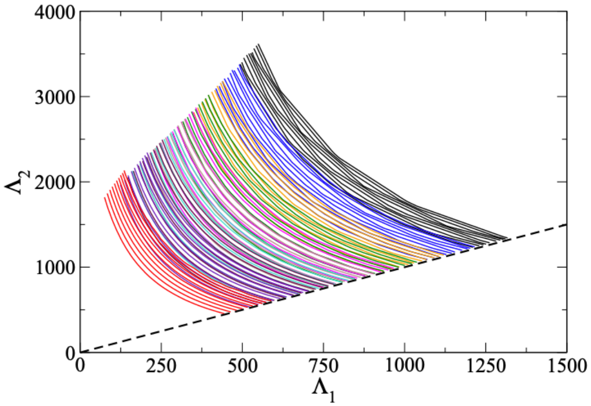
Hint of a tension between Nuclear physics and Astrophysical observations

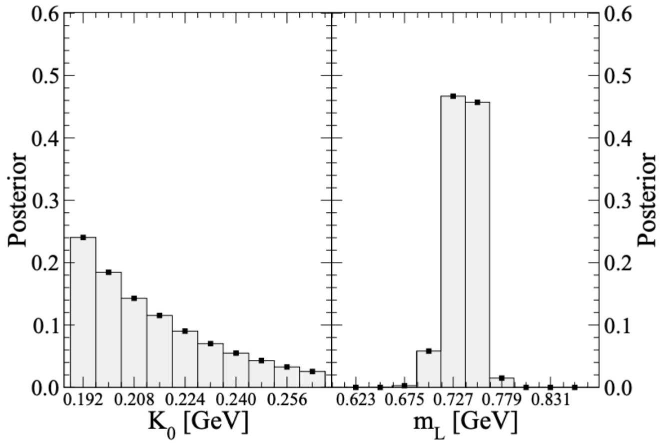


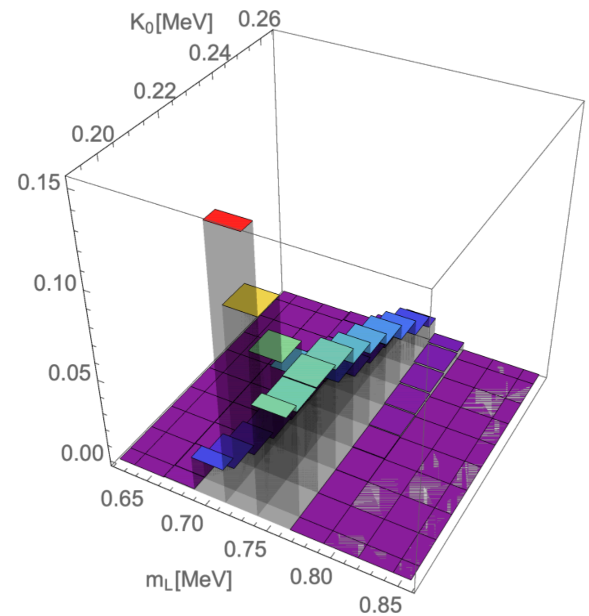
Bhaskar Biswas, Prasanta Char, Rana Nandi, Sukanta Bose,
arXiv:2008.01582

σ-ω model for neutron star matter





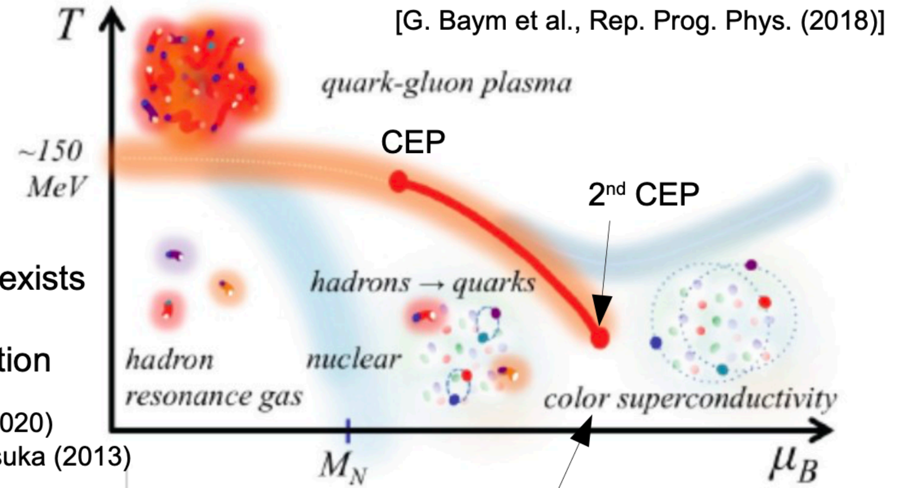




D. A-C., A. Ayriyan, G. G. Barnaföldi, H. Grigorian, P. Pósfay, arXiv:2006.03676

EoS & Neutron Star Structure

Alternative to the "standard" QCD phase diagram:

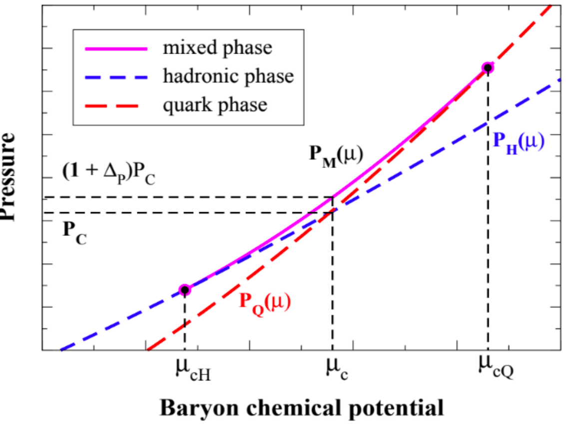


Alternative phase transition constructions:

(a) "normal"

- Maxwell construction exists
- Mixed phase construction
  Mimics "pasta" phases

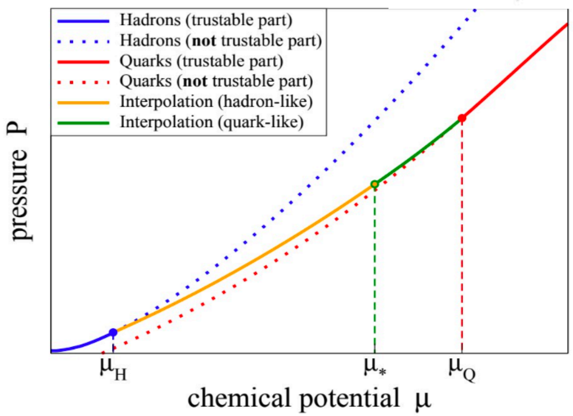
A. Ayriyan et al., PRC 97, 054802 (2018)
K. Maslov et al. PRC 100, 025802 (2019)



(b) "anomalous"

- No Maxwell construction exists
- Interpolation
  Mimics "crossover" transition

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



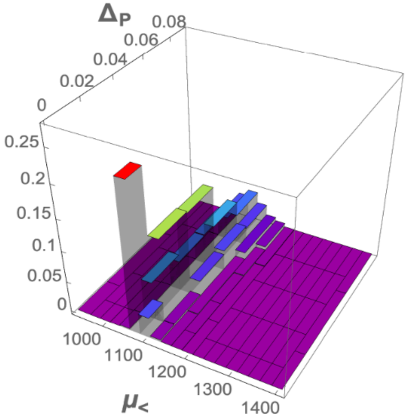
Quark-hadron continuity:

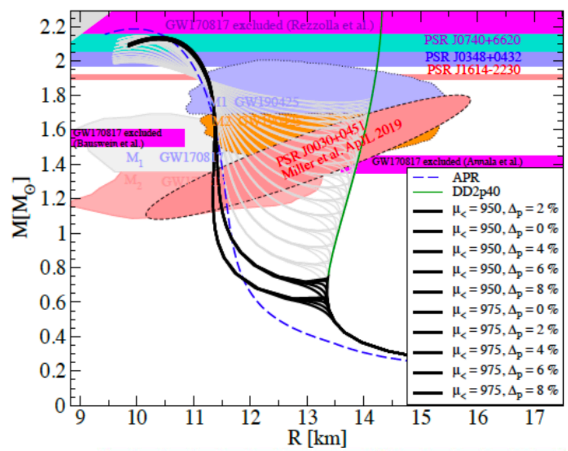
T. Schaefer & F. Wilczek,
Phys. Rev. Lett. 82 (1999) 3956
C. Wetterich,
Phys. Lett. B 462 (1999) 164
T. Hatsuda, M. Tachibana, T. Yamamoto & G. Baym,
Phys. Rev. Lett. 97 (2006) 122001

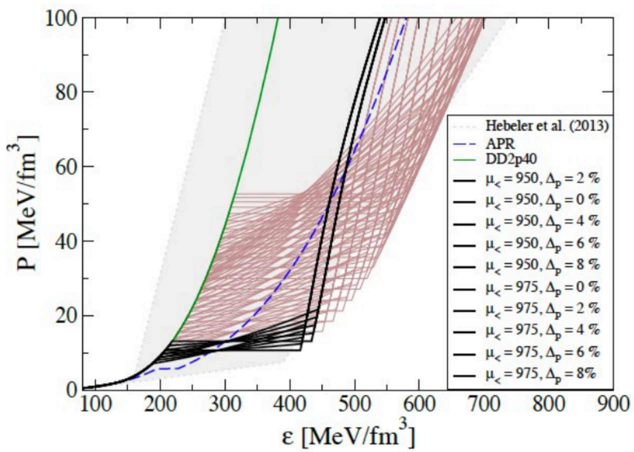
Bayesian inference for (normal) hybrid EoS Models

M-R from NICER:

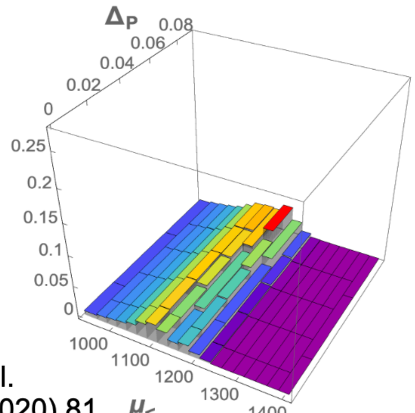
Present Variance →

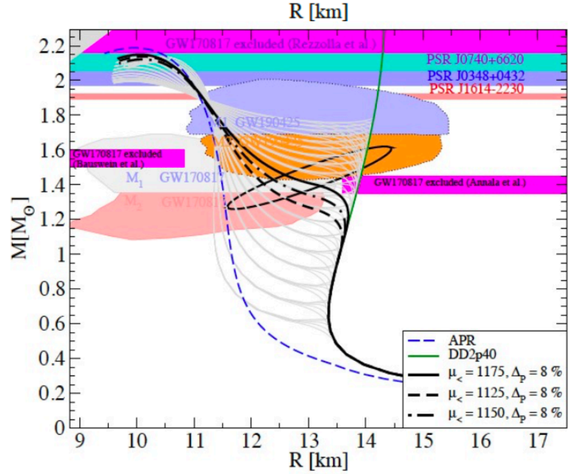


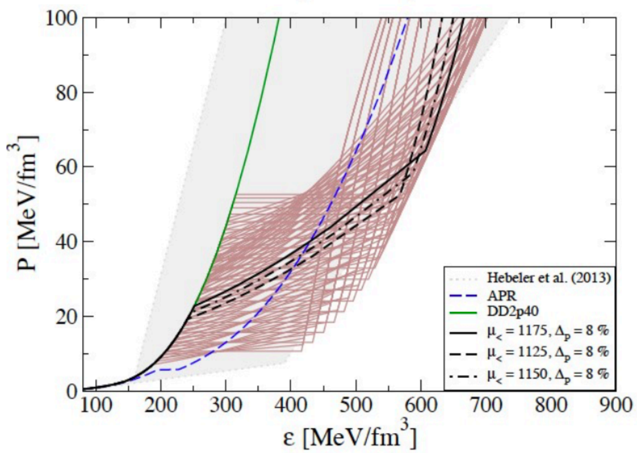




Fictitious Reduced Variance →



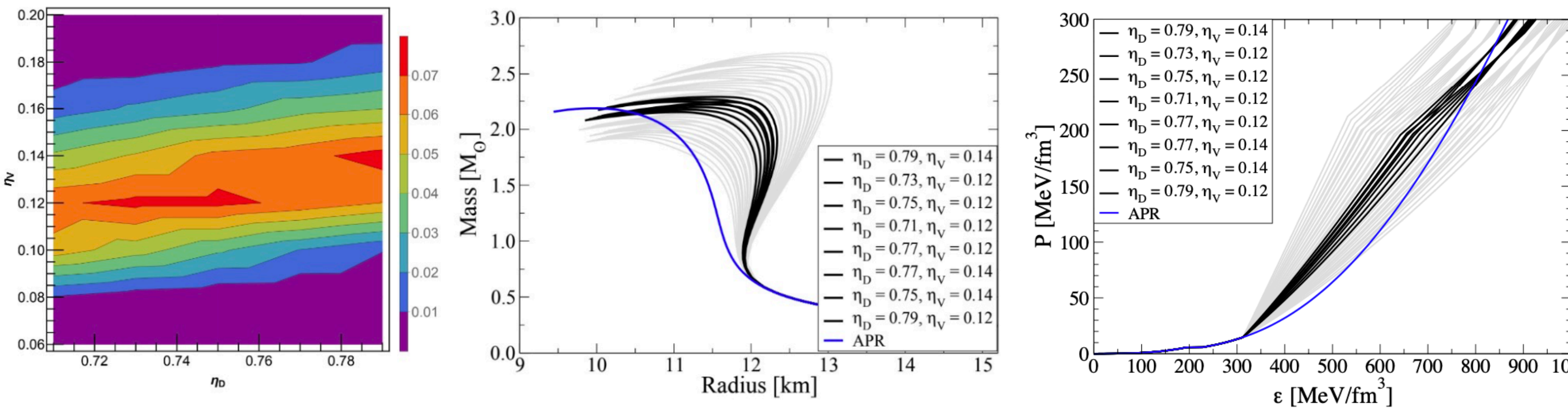




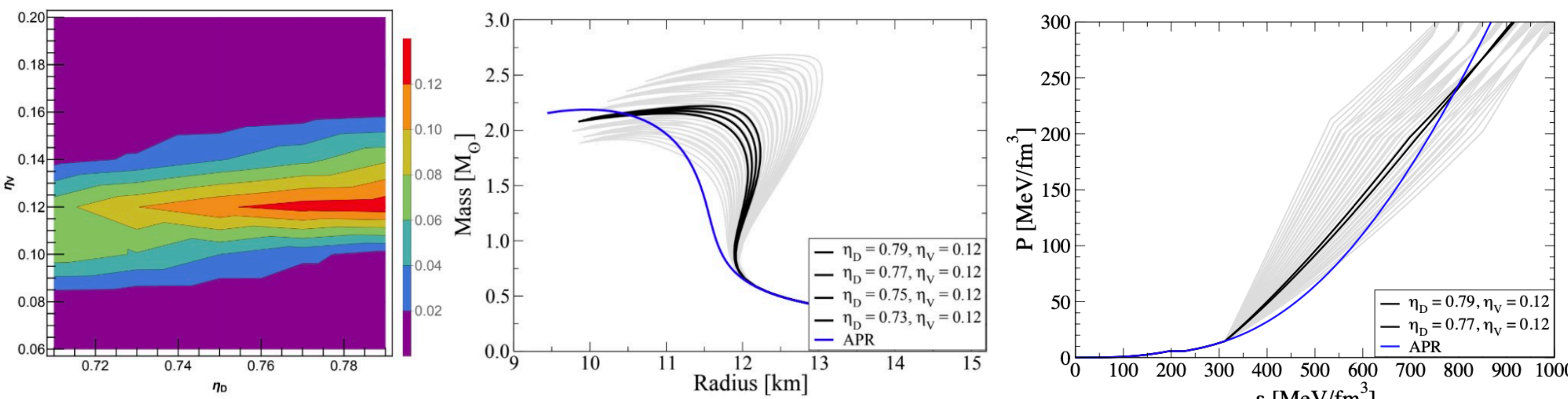
Blaschke et al. Universe 6 (2020) 81

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

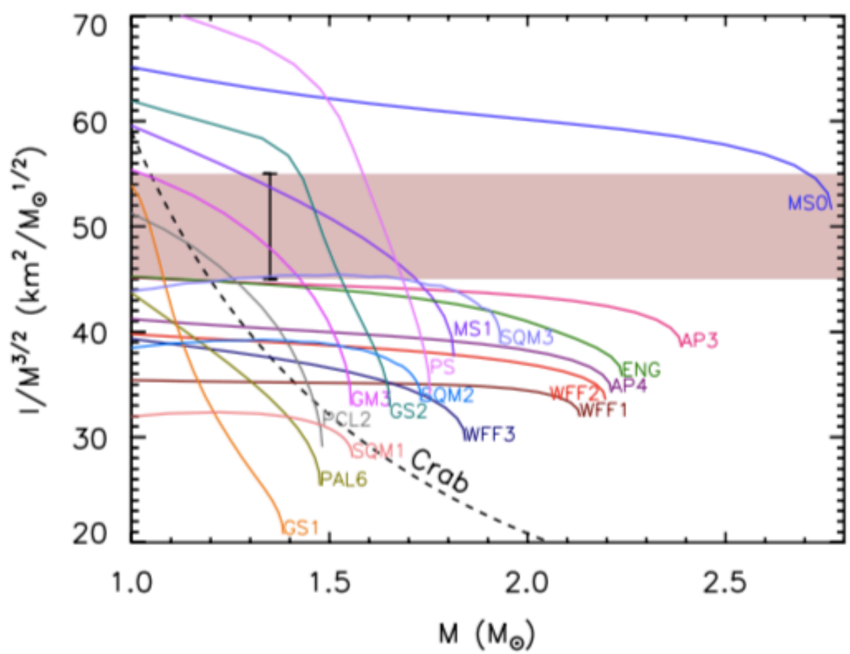
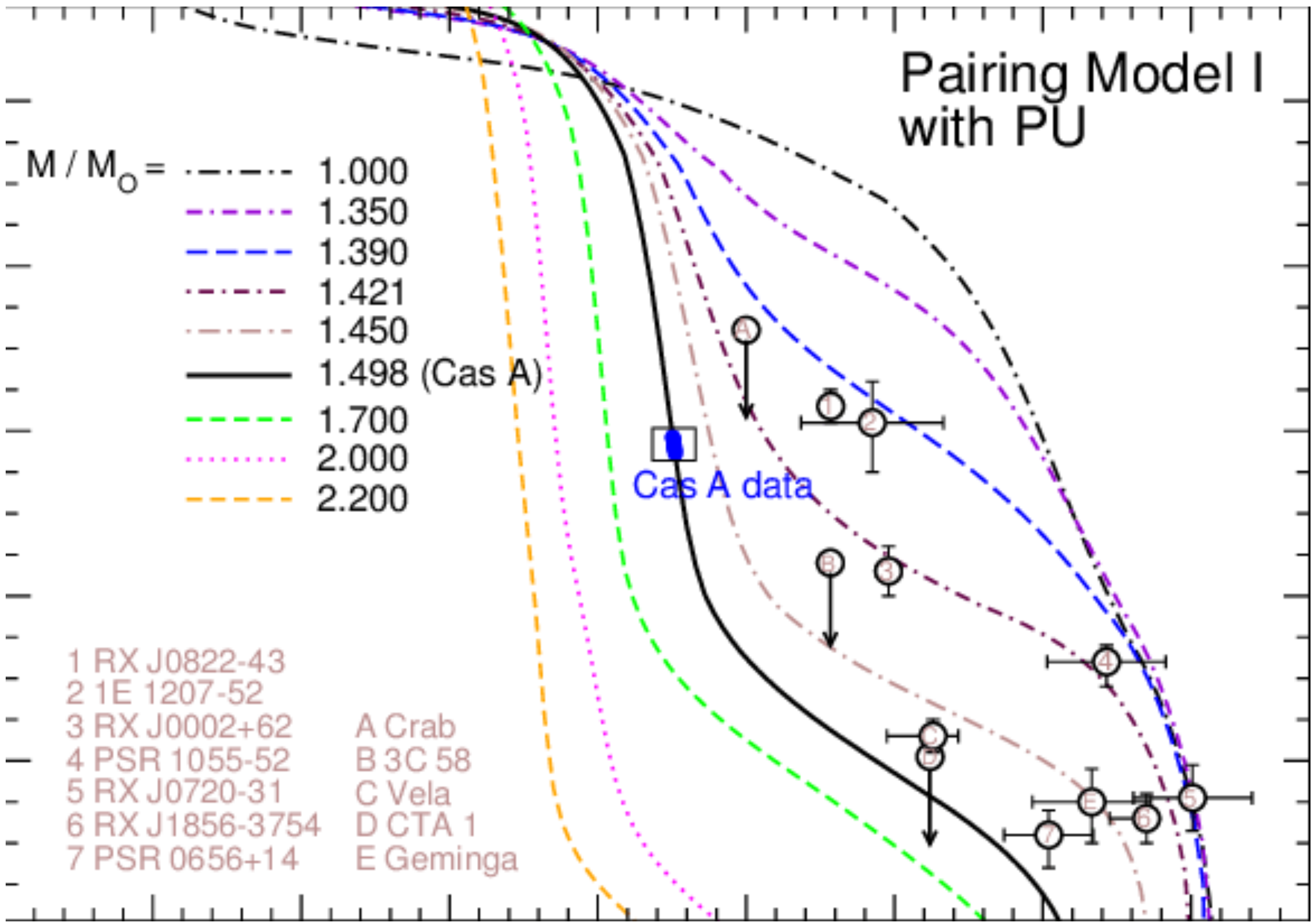


Fig. 9. The moment of inertia scaled by $M^{3/2}$ as a function of stellar mass M for EOSs described in [6]. The shaded band illustrates a $\pm 10\%$ error on a hypothetical $I/M^{3/2}$ measurement with centroid $50\,\mathrm{km}^2\,\mathrm{M}_\odot^{-1/2}$; the error bar shows the specific case in which 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.

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

Compact Stars Cooling



Conclusions

- NICER radius measurement of massive PSR J0740+6620 of much less than 12 km supports the existence of a quark matter core in neutron stars
- Radius measurements of about 1.2 solar mass compact stars can probe the stiffness of nuclear matter around 1 to 2 times saturation density therefore probing the low mass twins hypothesis.
- Bayesian analysis analysis favors low mass twins over high mass twins.
- Detection of signals from dynamical scenarios like star transitional evolution from second to third family may serve as a smoking gun for mass twins.
- The non-existence of compact star twins does not rule out the possibility of a CEP in the QCD phase diagram.
- How to determine the matter content in compact stars without ambiguity, avoiding masquerades? Bayesian inference!

Gracias