Studying the effects of the symmetry energy in hybrid stars

David Álvarez Castillo

Institute of Nuclear Physics PAS
Cracow, Poland

The Modern Physics of Compact Stars and Relativistic Gravity 2023
Department of Physics, Yerevan University
September 12, 2023

CREDO THE QUEST FOR THE UNEXPECTED

PHAROS THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS

compstar

Outline

- A brief introduction to the physics of compact stars.
- Measuring the symmetry energy in the laboratory.
- The symmetry energy in the framework of hybrid compact stars.

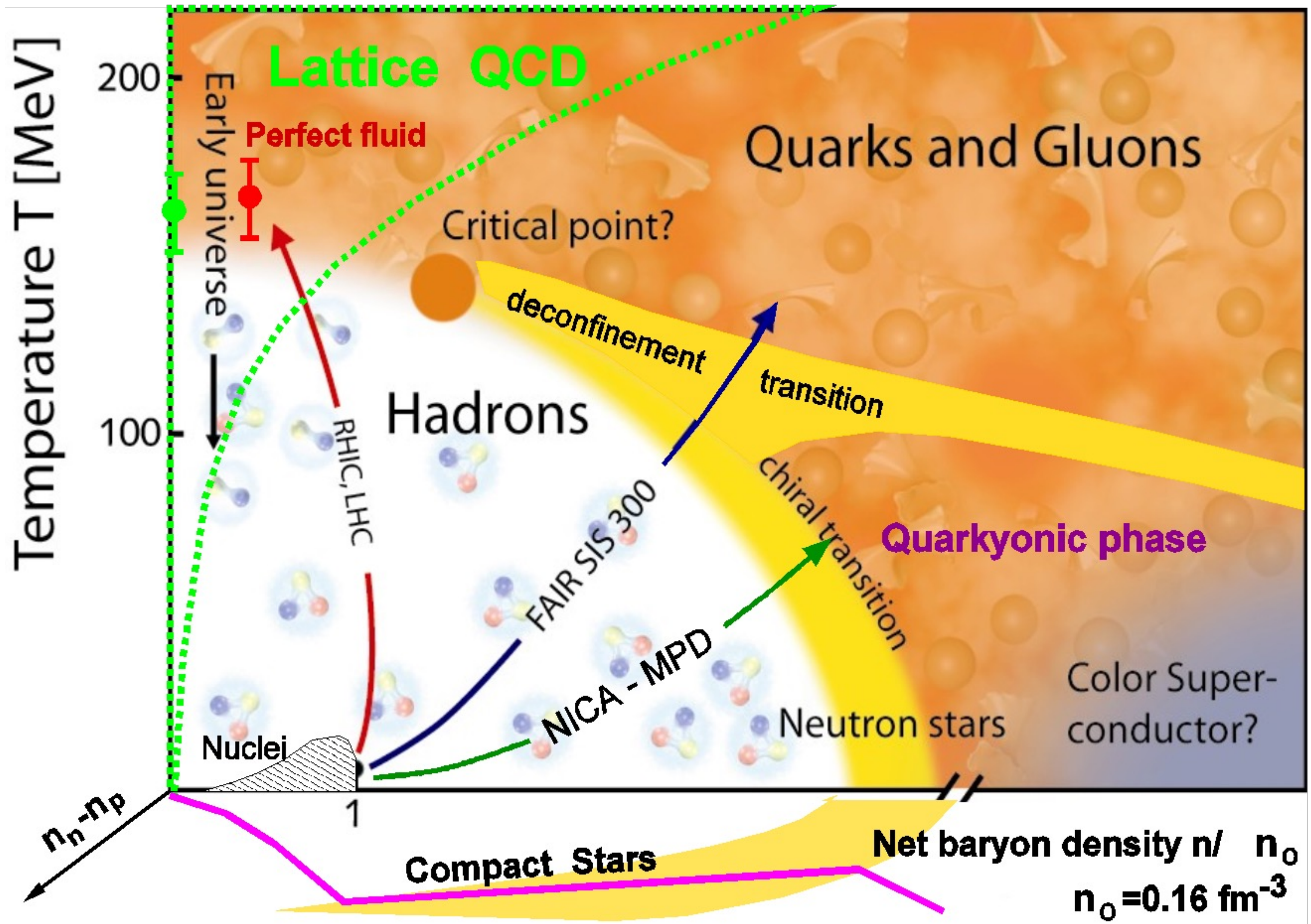
Motivation

- New channels of multi-messenger observations like gravitational radiation from merger events of binary systems of compact stars or radio and X-ray signals from isolated pulsars allow to study their most basic structural properties like mass, radius, compactness, cooling rates and compressibility of their matter.

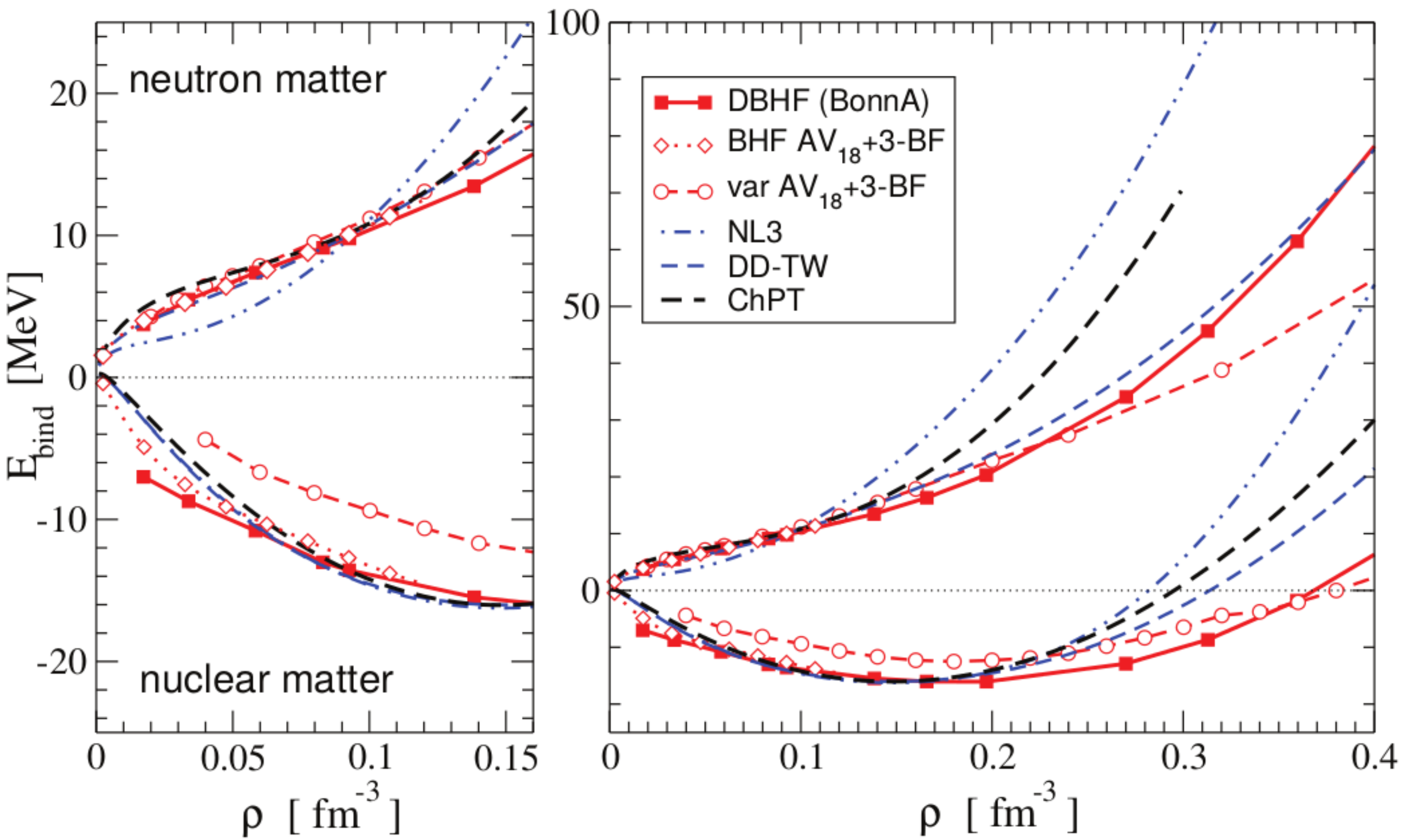
- Nuclear measurement and experiments have narrowed the Equation of State (EoS) uncertainty in the lowest to intermediate density range.

- The nuclear symmetry energy plays an important role in the neutron star structure and cooling rates that can be studied.

Critical Endpoint in QCD

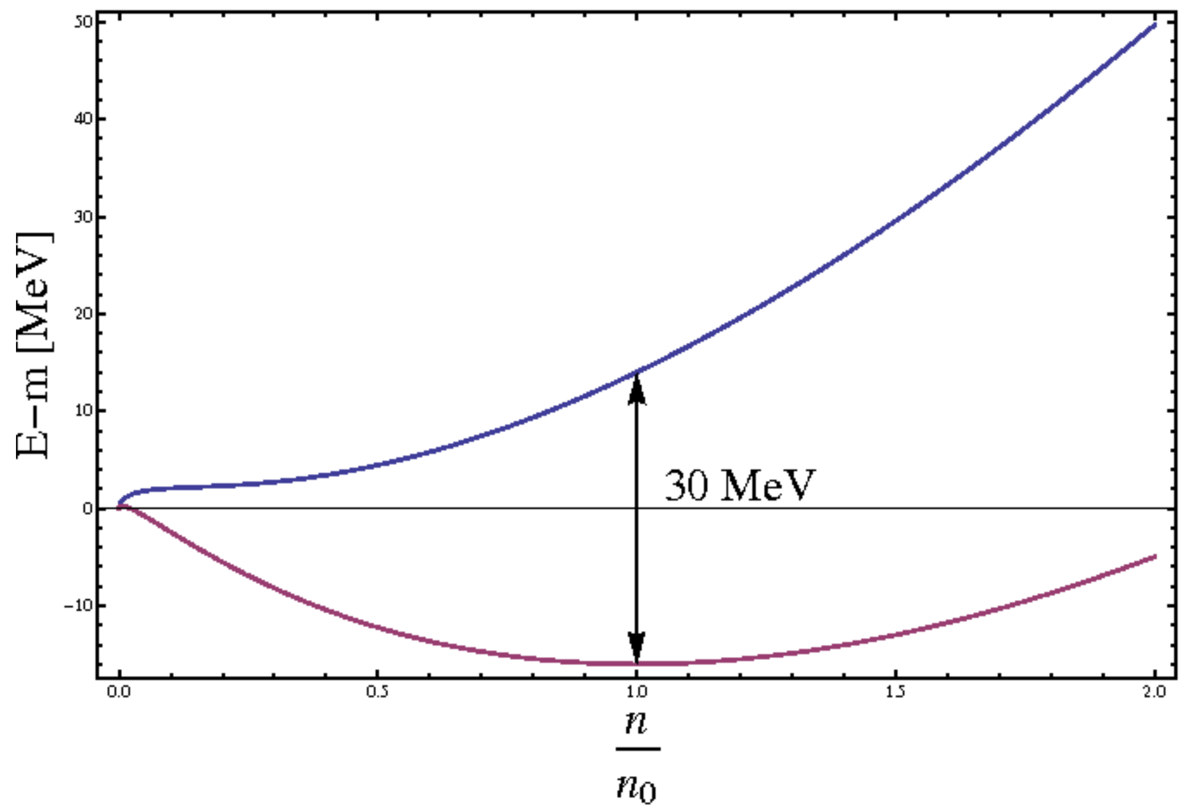


Nuclear Matter



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

Nuclear Symmetry Energy

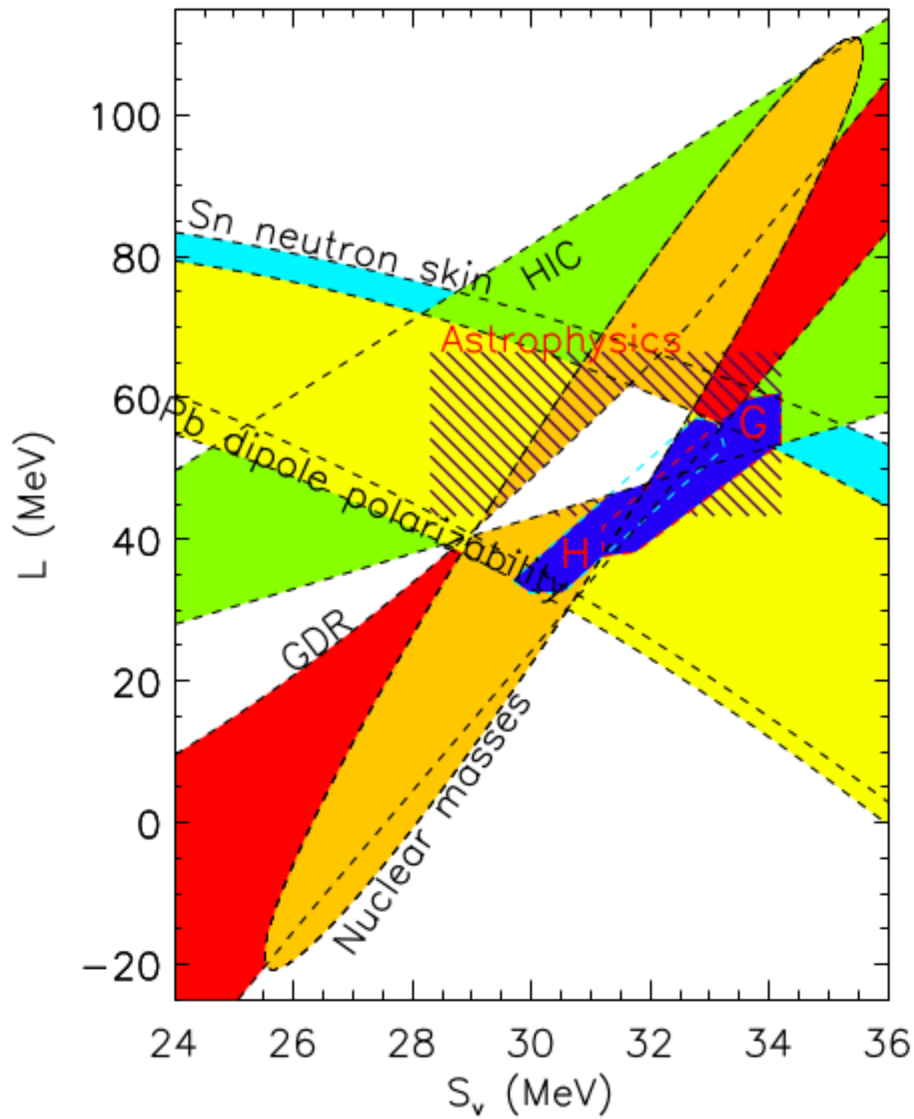


is the difference between symmetric nuclear matter and pure neutron matter:

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

where $\alpha = 1 - 2x$

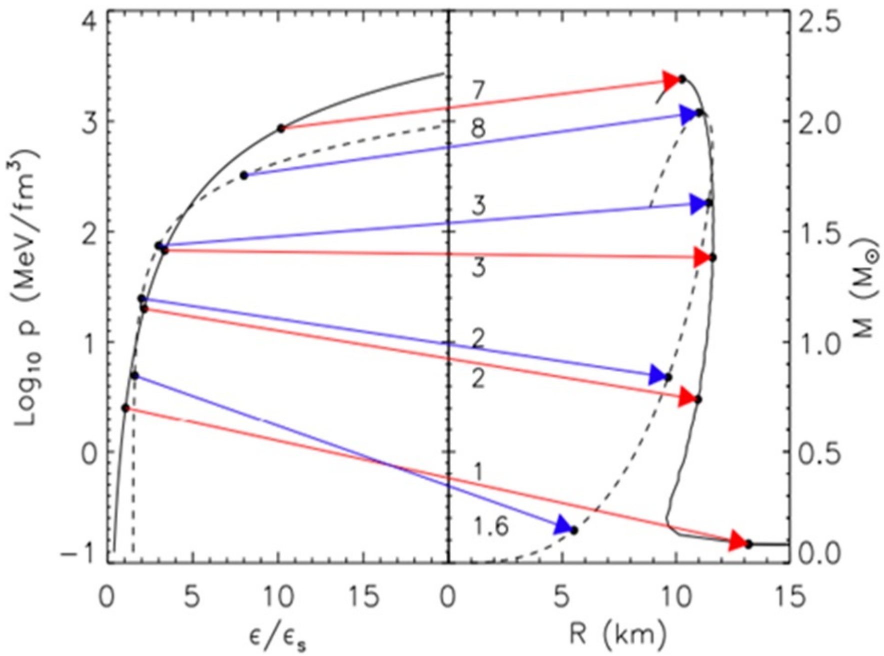
Measuring the symmetry energy



Lattimer and Lim
(2013) ApJ 771 51

Compact Star Sequences

(M-R ⇔ EoS)



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

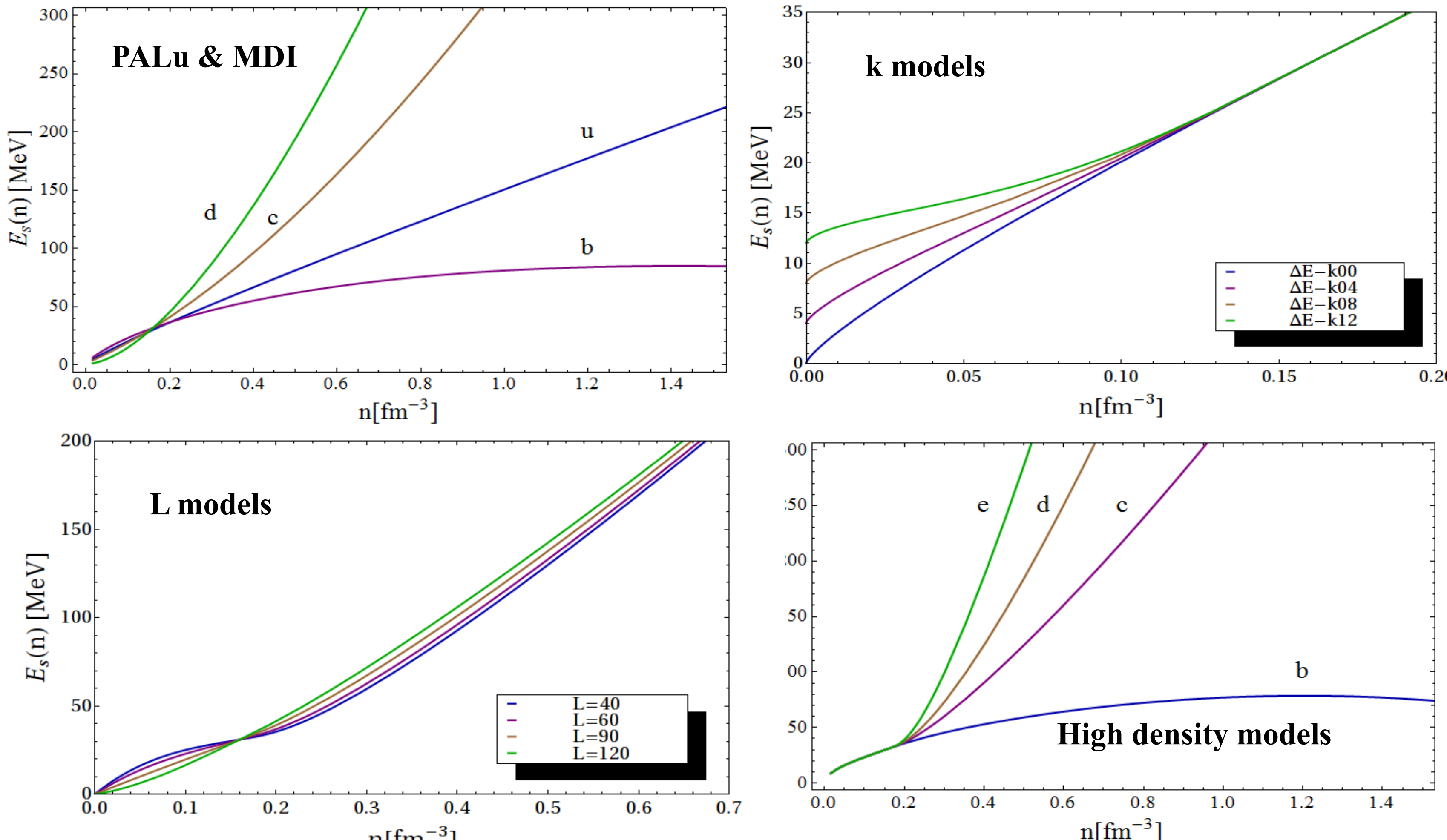
- TOV Equations

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

- Equation of State (EoS)

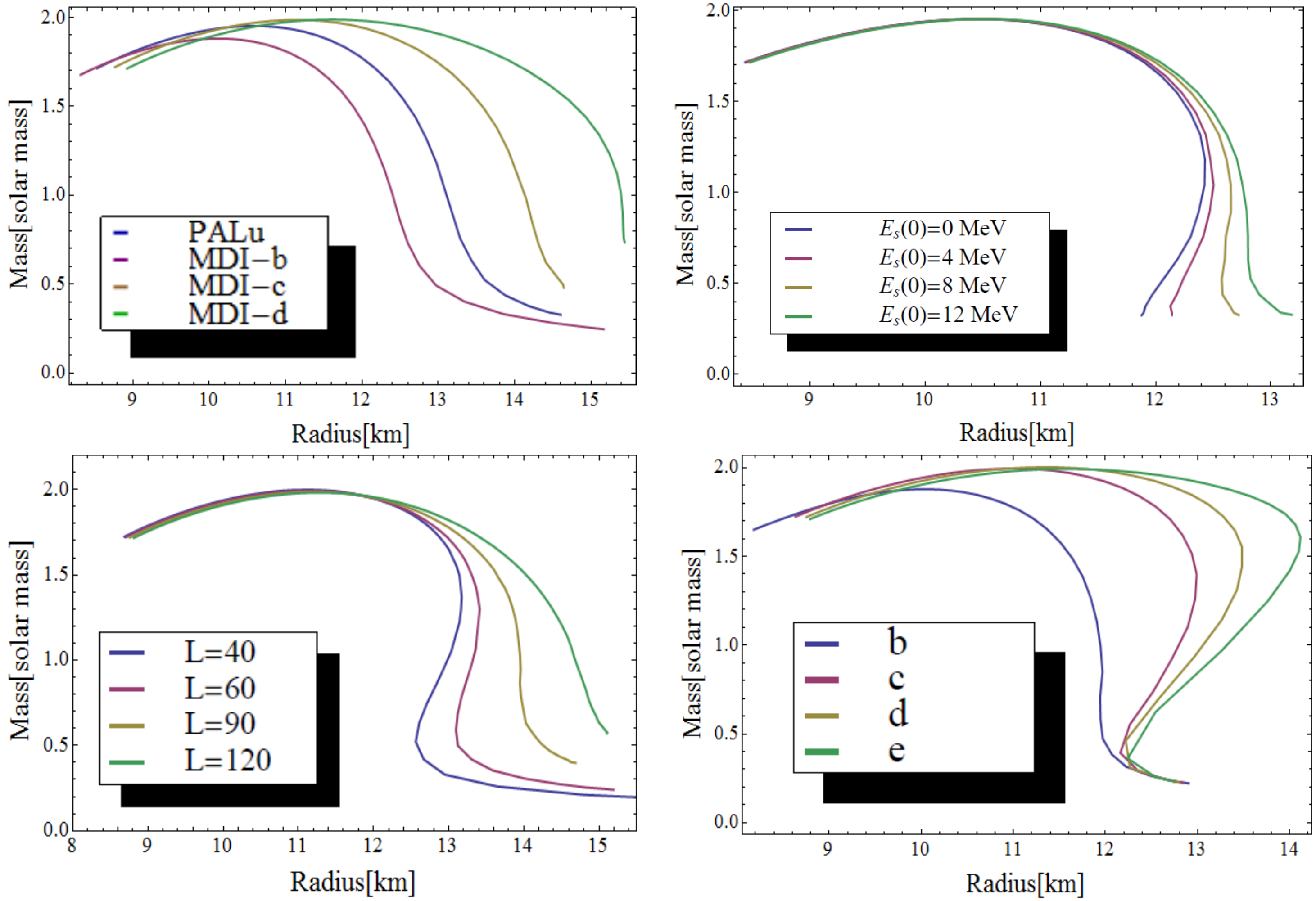
$$\frac{dm}{dr} = 4\pi r^2 \varepsilon \qquad p(\varepsilon)$$

Symmetry energy effects



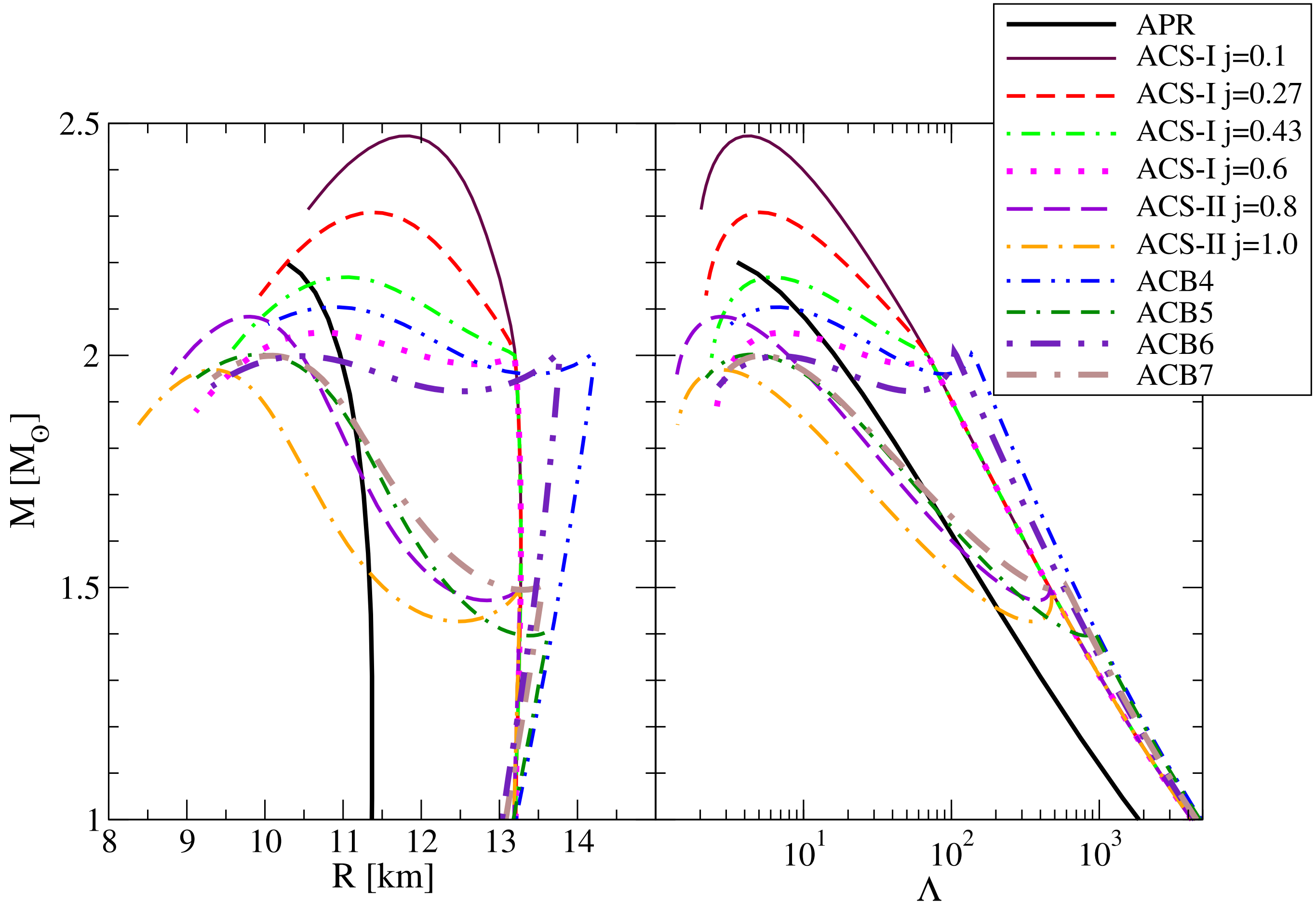
S. Kubis and D. E. Alvarez-Castillo - arXiv:1205.6368

Symmetry energy effects



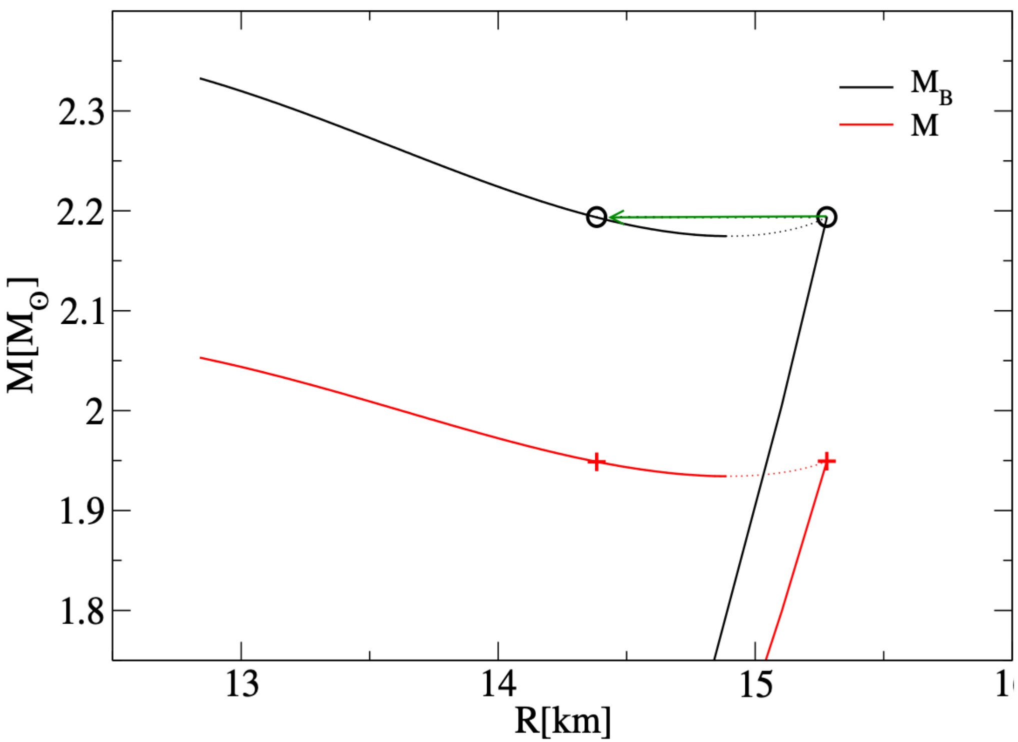
S. Kubis and D. E. Alvarez-Castillo - arXiv:1205.6368

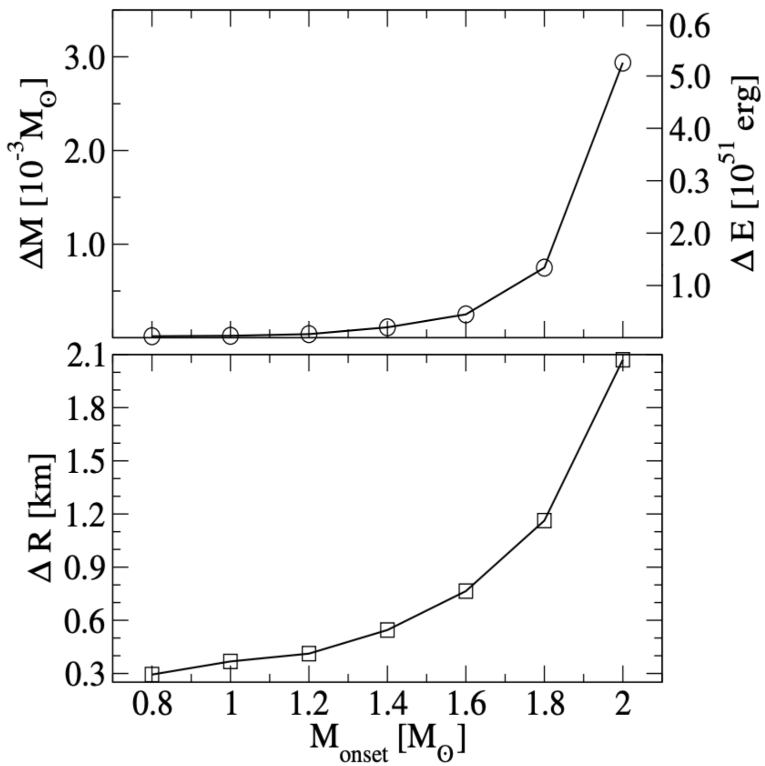
Implications from GW170817



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

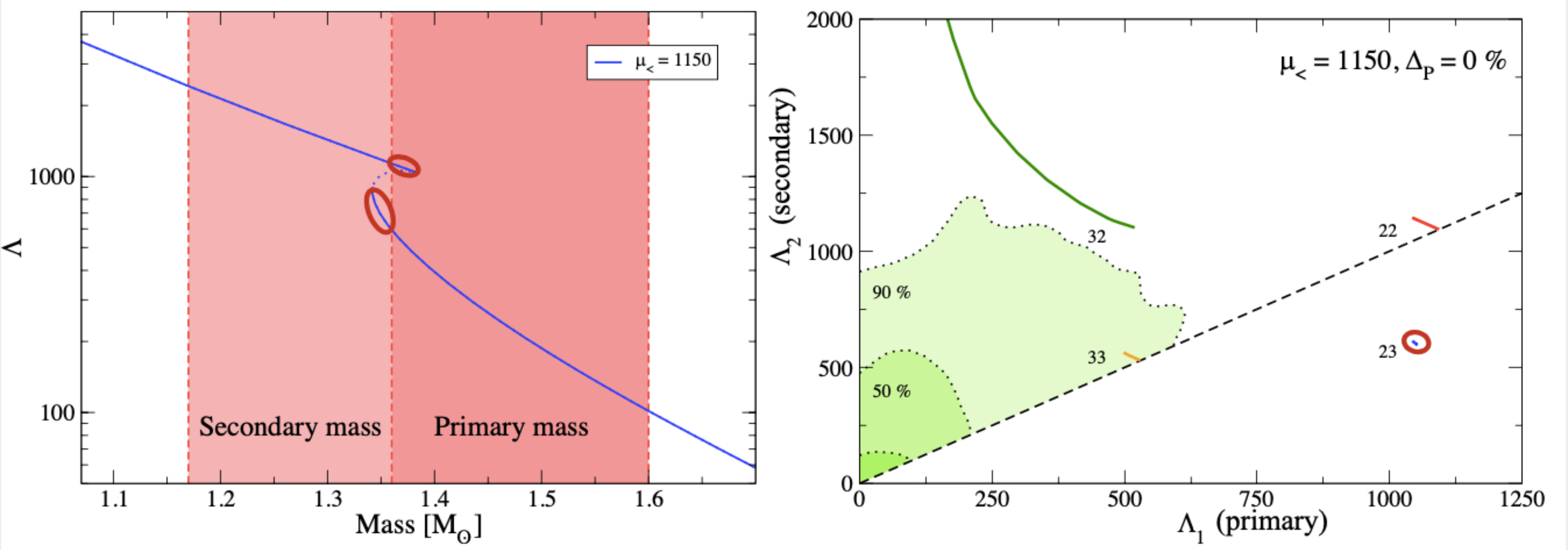
Mass Twins – Energy Released





DD2MEV-CSS EoS, D. A-C, Astronomischen Nachrichten (2021) 1–6, arXiv: 2011.11145

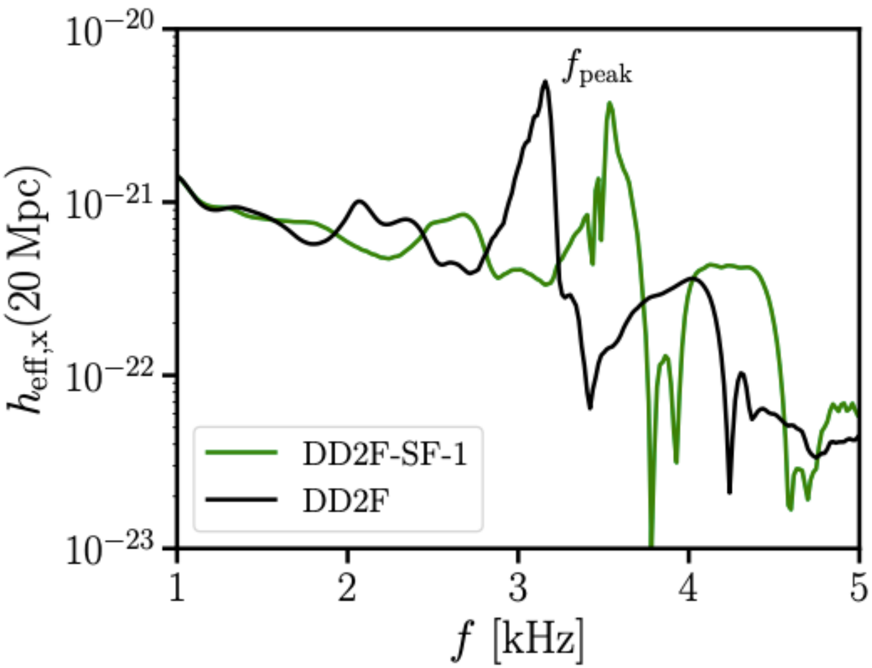
Was GW170817 a canonical neutron star merger?

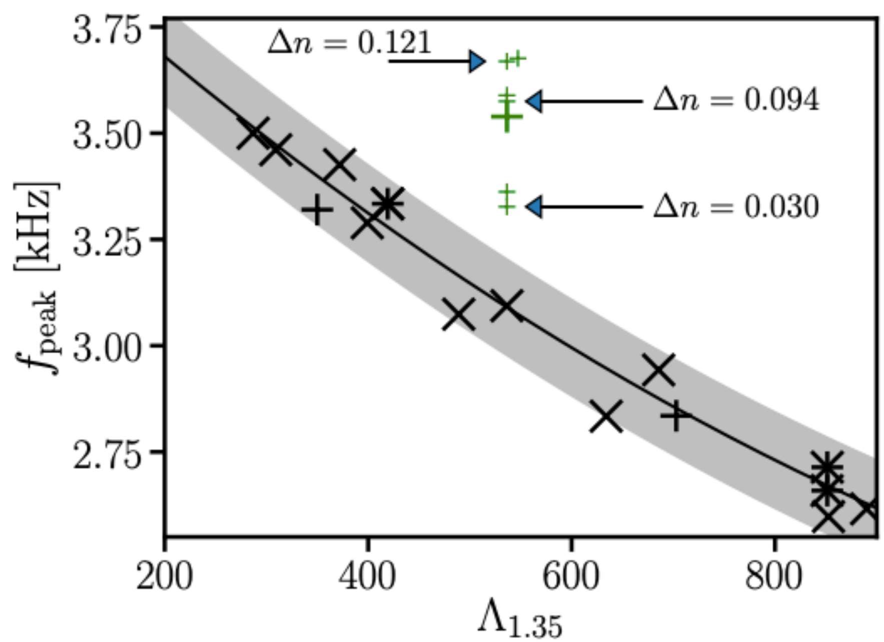


A. Ayriyan, D.Alvarez-Castillo, D. Blaschke and H. Grigorian,
Universe 6, 81 (2020)

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

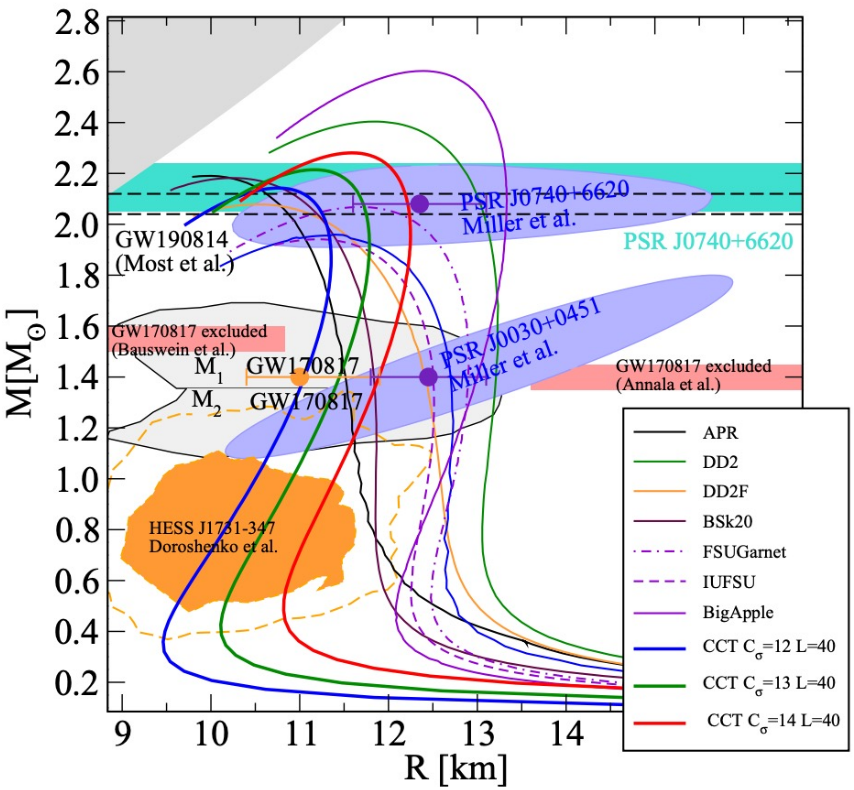
Gravitational Wave Signals
First Order Phase Transitions



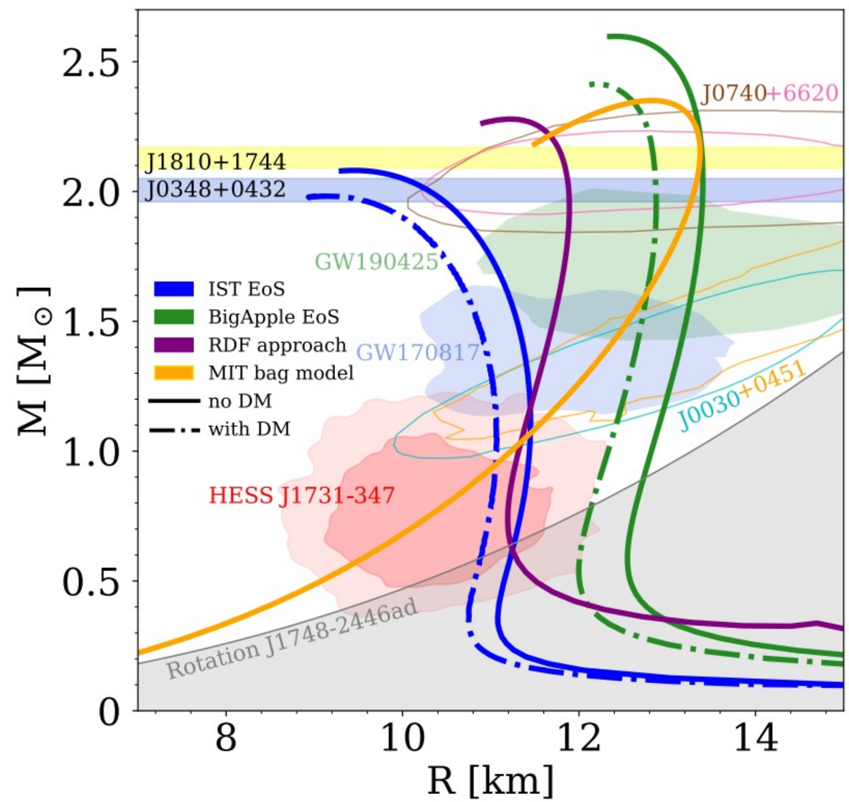


A. Bauswein et al. - arXiv: 1904.01306, PRL 122 (2019) 061102

HESS J1731-347



Relativistic mean field model for ultra-compact low mass neutron star of HESS J1731-347
Kubis et al. arXiv:2307.02979



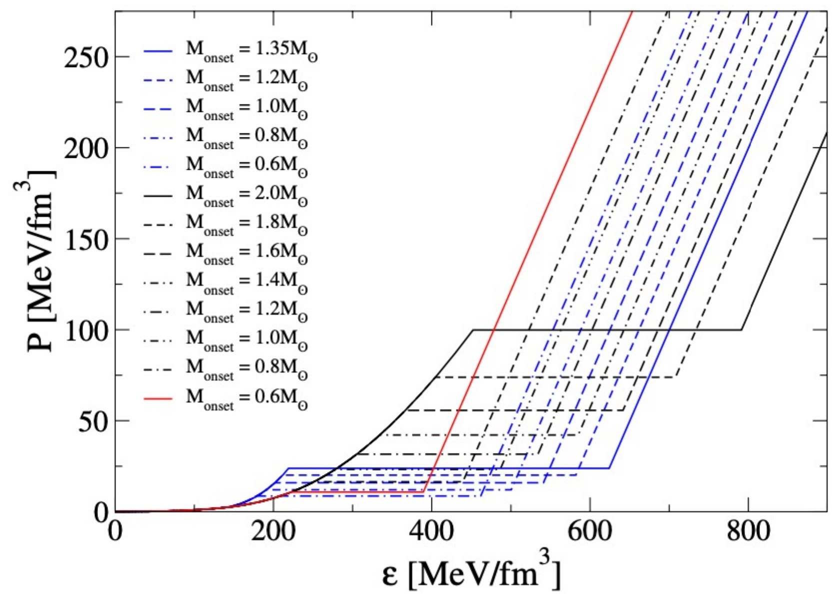
What is the nature of the HESS J1731-347 compact object?
Sagun et al. arXiv:2306.12326

Compact Star Mass Twins

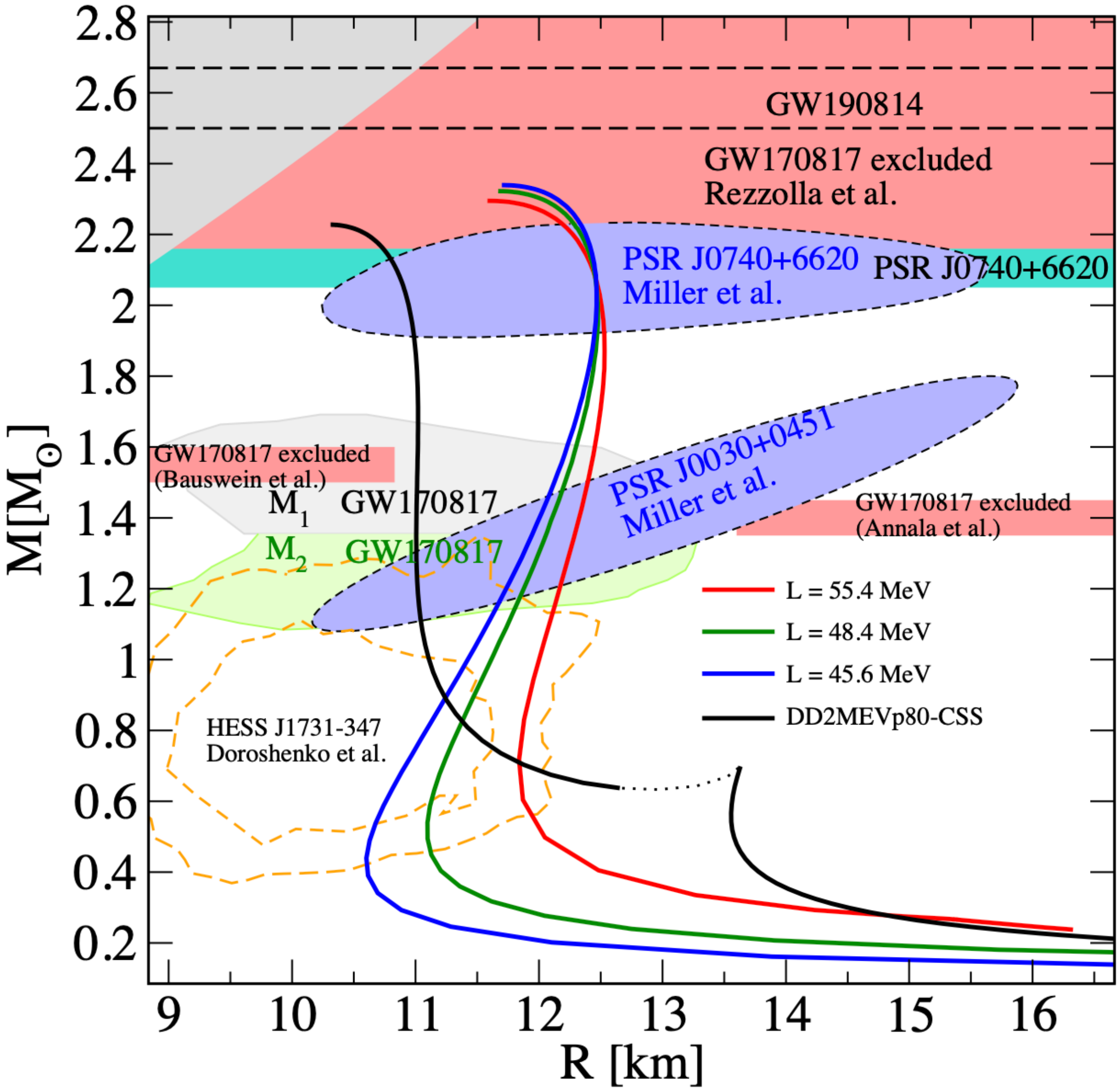
$$\varepsilon(p) = \begin{cases} \varepsilon_{\rm NM}(p) & p < p_{\rm trans} \\ \varepsilon_{\rm NM}(p_{\rm trans}) + \Delta\varepsilon + c_{\rm QM}^{-2}(p - p_{\rm trans}) & p > p_{\rm trans} \end{cases}$$

Model	M_{onset} [$M_\odot$]	n_{trans} [$1/\mathrm{fm}^3$]	ε_{trans} [$\mathrm{MeV/fm}^3$]	p_{trans} [$\mathrm{MeV/fm}^3$]	$\Delta\varepsilon$ [$\mathrm{MeV/fm}^3$]	c_{QM} [c]
DD2p80	0.7	0.193	185.223	10.3131	268.573	0.9

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



D. Alvarez-Castillo - Astron. Nachr. 1–6 (2021)



dalvarez@ifj.edu.pl

CRUST-CORE Transition

The shear modulus in the crust is given by

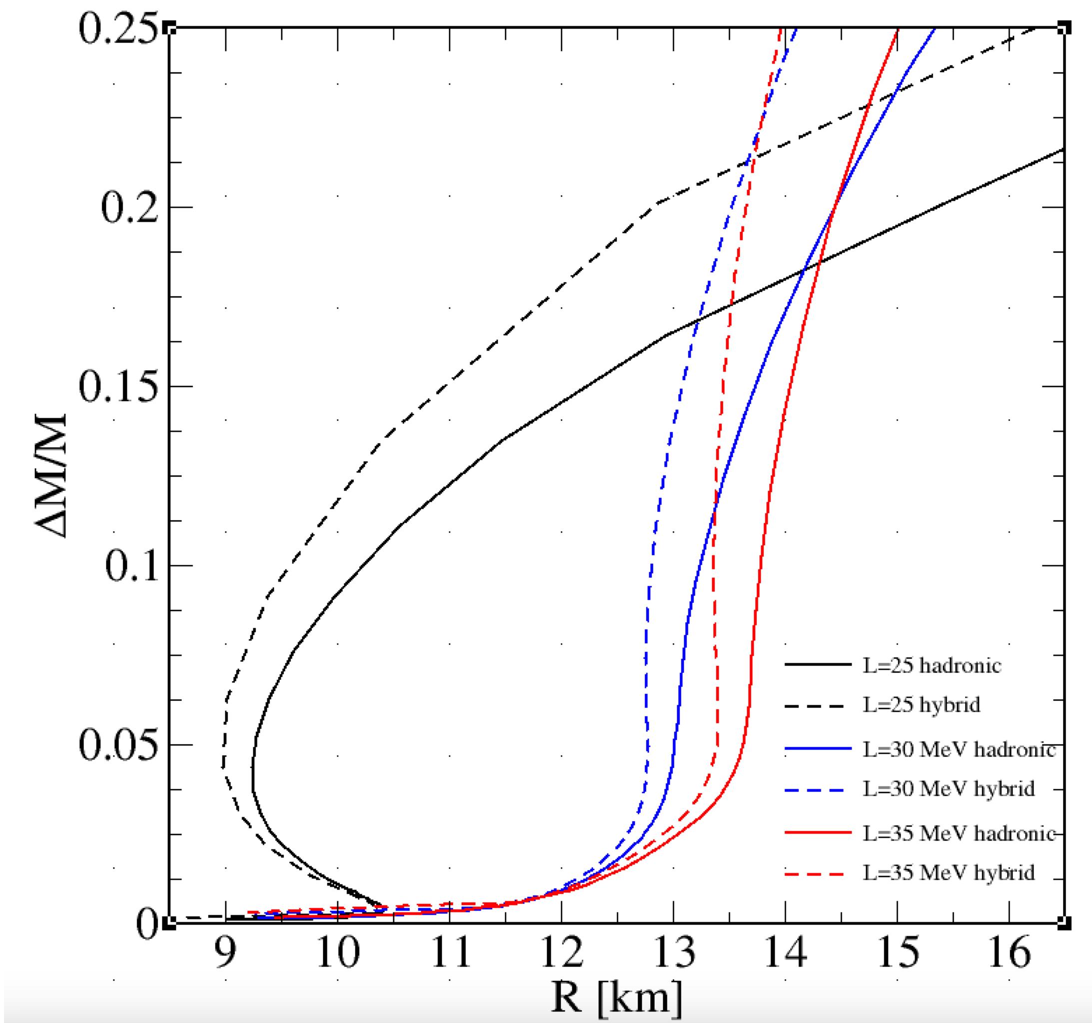
$$\mu = \frac{0.1106}{1 + 17810\left(\frac{ak_bT}{(Ze)^2}\right)^2}\frac{n_i\,(Ze)^2}{a}, \tag{5}$$

where T is the temperature, n_i is the ion density, Z is the proton number of the nuclei, and

$$a = \left(\frac{3}{4\pi n_i}\right)^{\frac{1}{3}}. \tag{6}$$

Resonant Shattering Flares as Multimessenger Probes of the Nuclear Symmetry Energy
Duncan Neill, William G. Newton, David Tsang, MNRAS Volume 504, Issue 1 (2021)
arXiv: 2012.10322

Mass of the CS CRUST



*Hybrid stars within the CSS model with $c_s=1$

Outlook

- Multi-messenger astronomy and collider experiments will continue probing the properties of dense matter.
- Studying the crust of neutron stars may reveal whether neutron stars are hybrid or not.
- Bayesian Analysis and Machine Learning methods are useful for estimation of unknown physical parameters.
- Probing the usage of the universal I-Love-Q relations to study CS crusts.
- Studying finite temperature effects relevant for CS mergers.