Supporting the existence of the QCD critical point by compact star observations

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Joint Institute for Nuclear Research

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Collaborations

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Vasileios Paschalidis (Arizona), Kent Yagi (Virginia)
and Armen Sedrakian (FIAS)

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Narodowe Centrum Nauki (visits in Wroclaw, Poland)

Key Questions

- Can compact star observations provide compelling evidence about a first order phase transition in QCD?
- What are the relevant observables?

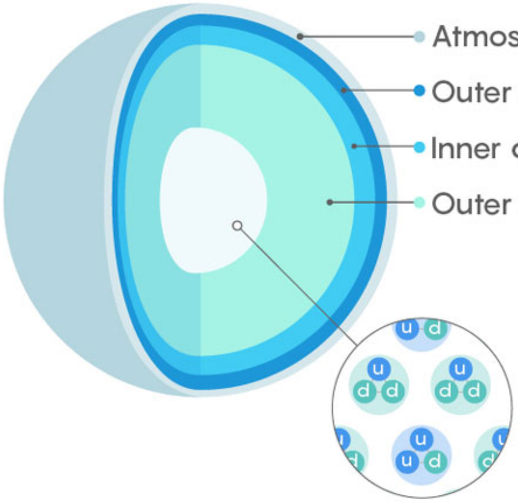
Outline

- Brief introduction to the neutron star equation of state.
- First order phase transition and deconfinement in compact stars: neutron star twins.
- Tidal deformalities of compact stars and the GW170817 event.
- Astrophysical implications and perspectives.

The Extraordinary Core of a Neutron Star

A neutron star's core is so dense that physicists aren't sure what happens inside. Researchers can't recreate the conditions in the lab, and even the theory of nuclear matter is of limited help. Here are some of the main ideas.

TRADITIONAL VIEW OF A NEUTRON STAR



Atmosphere: Lighter elements such as hydrogen & helium

Outer crust: Heavier ions such as iron

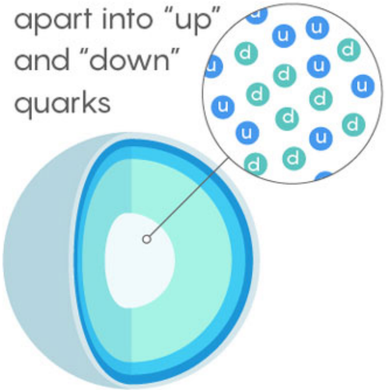
Inner crust: Ions packed into a lattice

Outer core: Neutron-rich ions in a sea of free neutrons

Inner core: Tightly packed nucleons with quarks intact

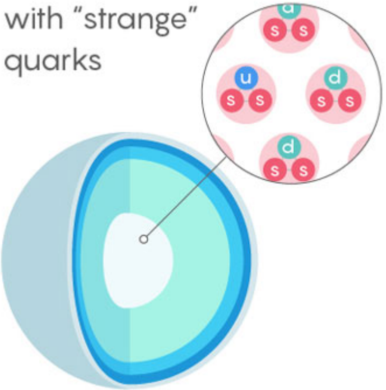
QUARK CORE

Nucleons break apart into "up" and "down" quarks



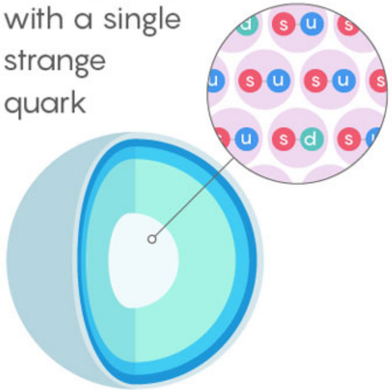
HYPERON CORE

Nucleons made with "strange" quarks

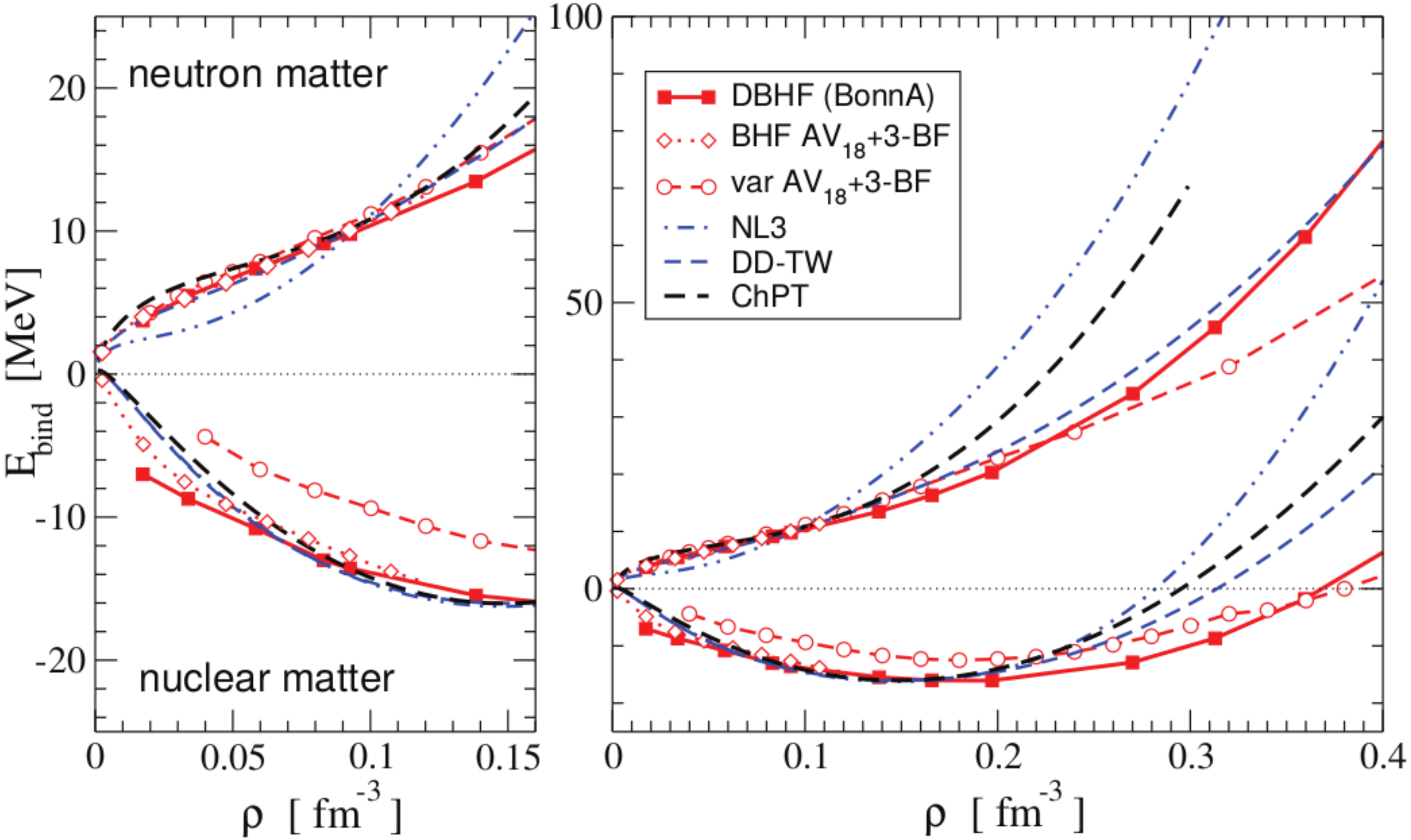


KAON CONDENSATE CORE

Two-quark particles with a single strange quark



Nuclear Matter



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

Flow Constraint

PHYSICAL REVIEW C **74**, 035802 (2006)

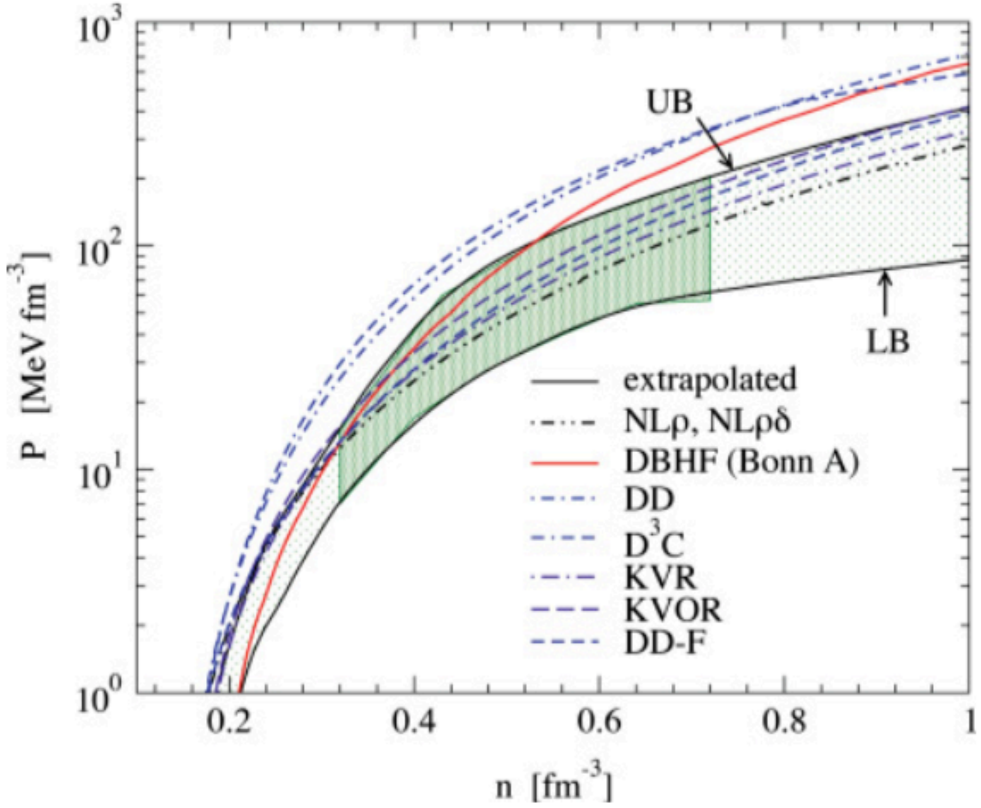
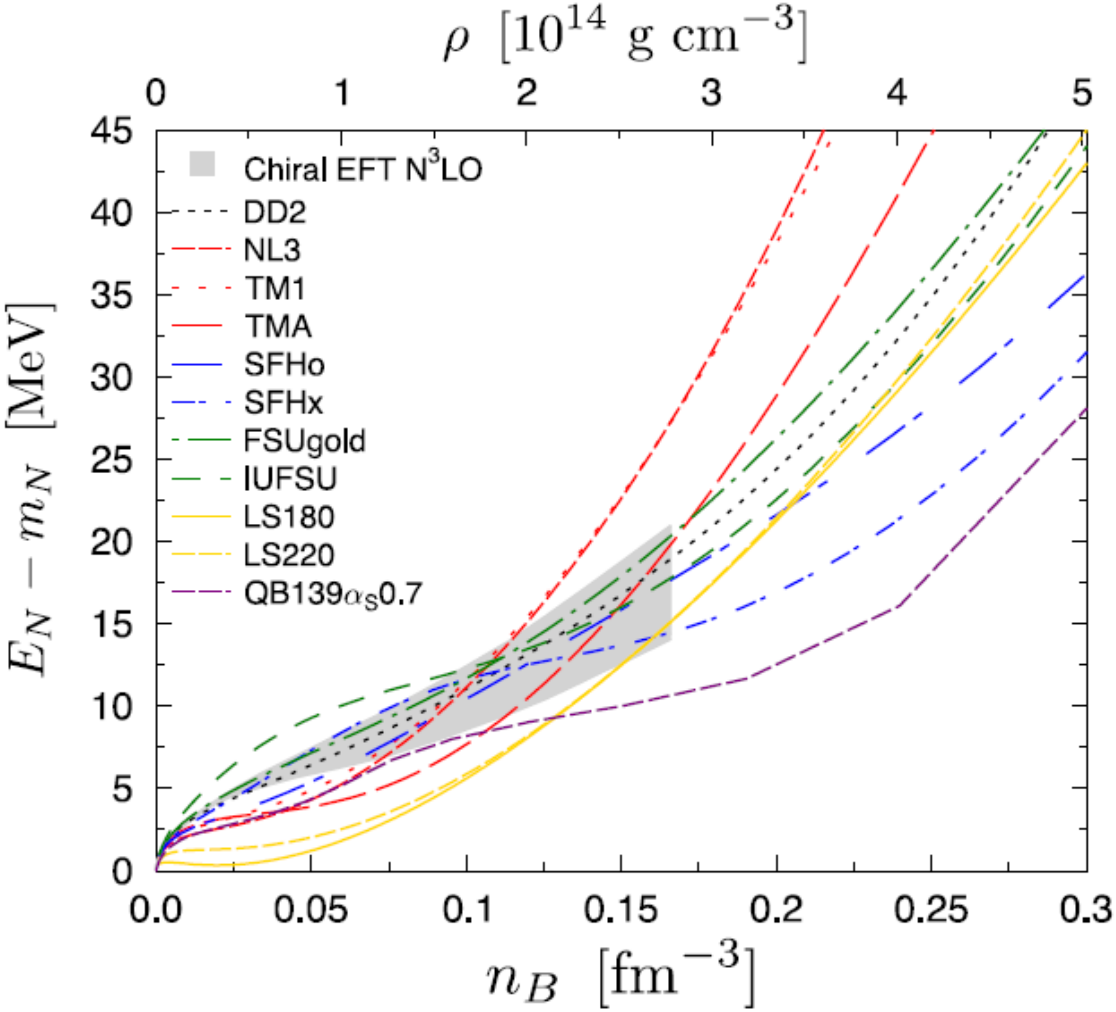


FIG. 6. (Color online) Pressure region consistent with experimental flow data in SNM (dark shaded region). The light shaded region extrapolates this region to higher densities within an upper (UB) and lower border (LB).

Nuclear Equation of State

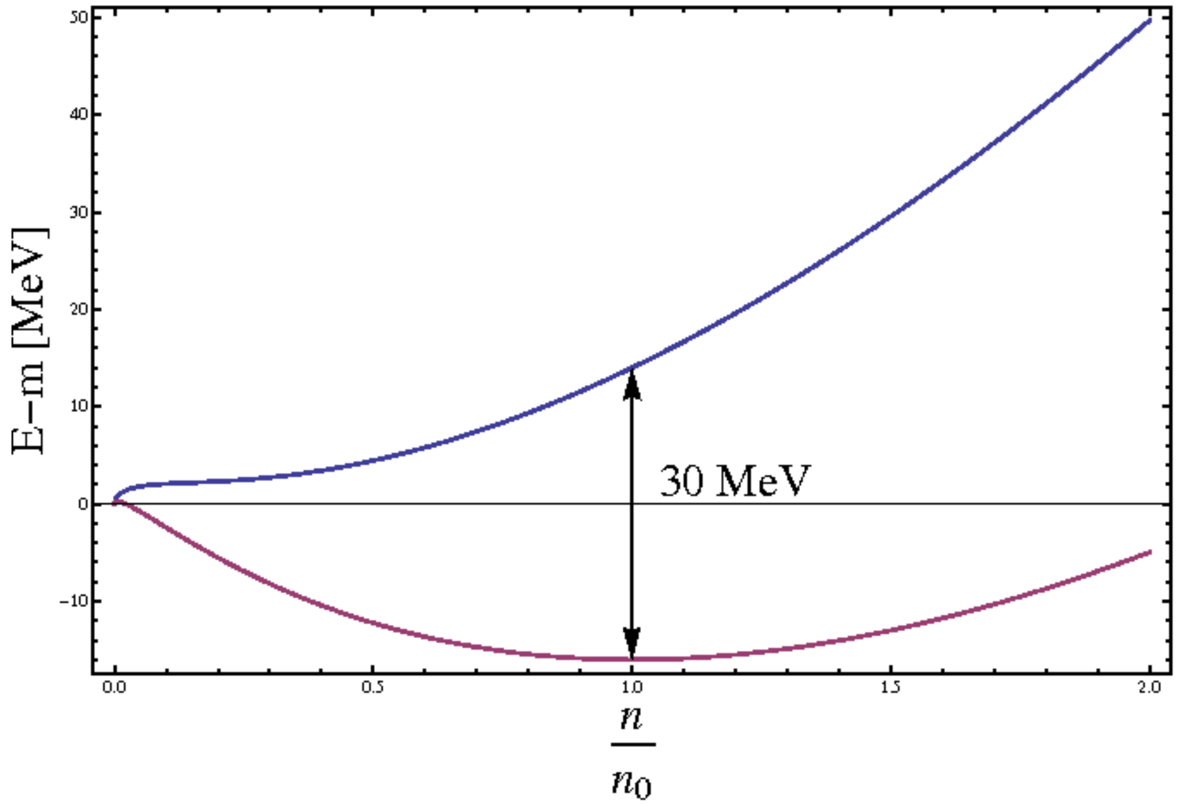


TF. et al.,(2014) EPJ A50, 46

Compilation of Neutron matter Equations of State;
T. Fischer et al., EPJA 50, 46 (2014)

DD2 equation of state (dotted line) [S. Typel et al., Phys. Rev. C 81 (2010)] compares very well with chiral EFT N3LO (grey band)

Nuclear Symmetry Energy

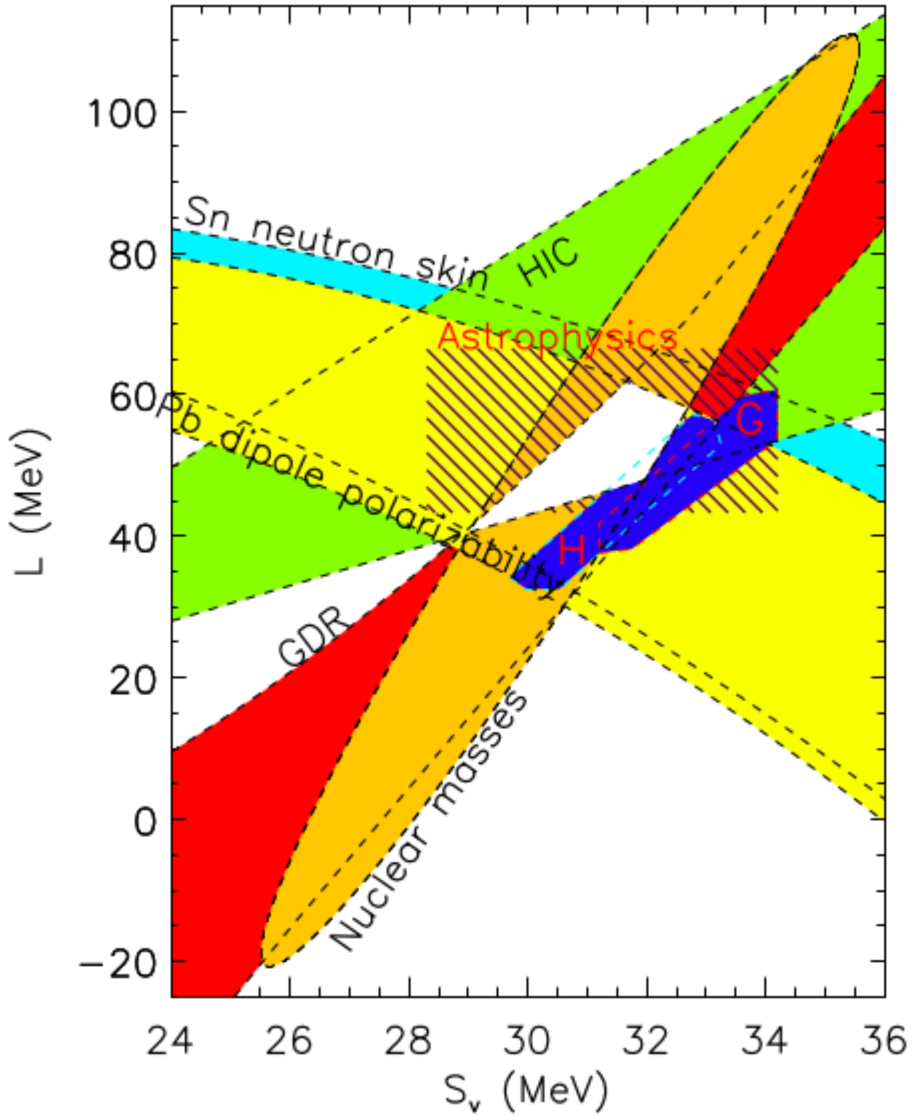


is the difference between symmetric nuclear matter and pure neutron matter:

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

where $\alpha=1-2x$

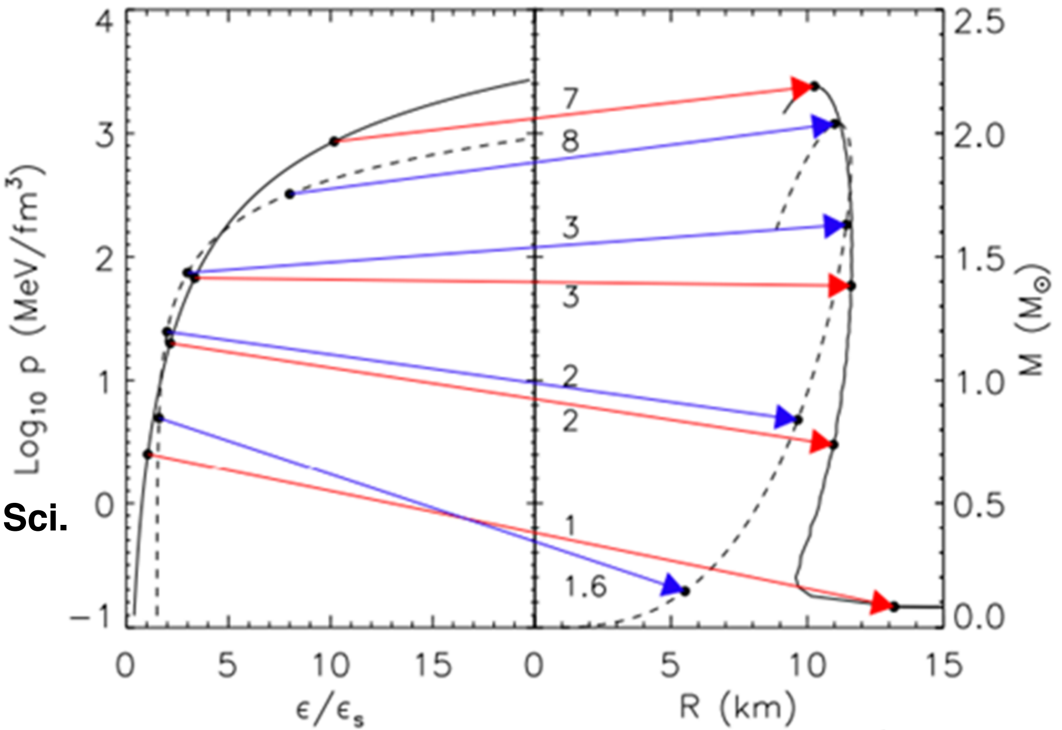
Measuring the symmetry energy



Lattimer and Lim (2013) ApJ 771 51

Compact Star Sequences

(M-R ↔ EoS)



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

- TOV Equations

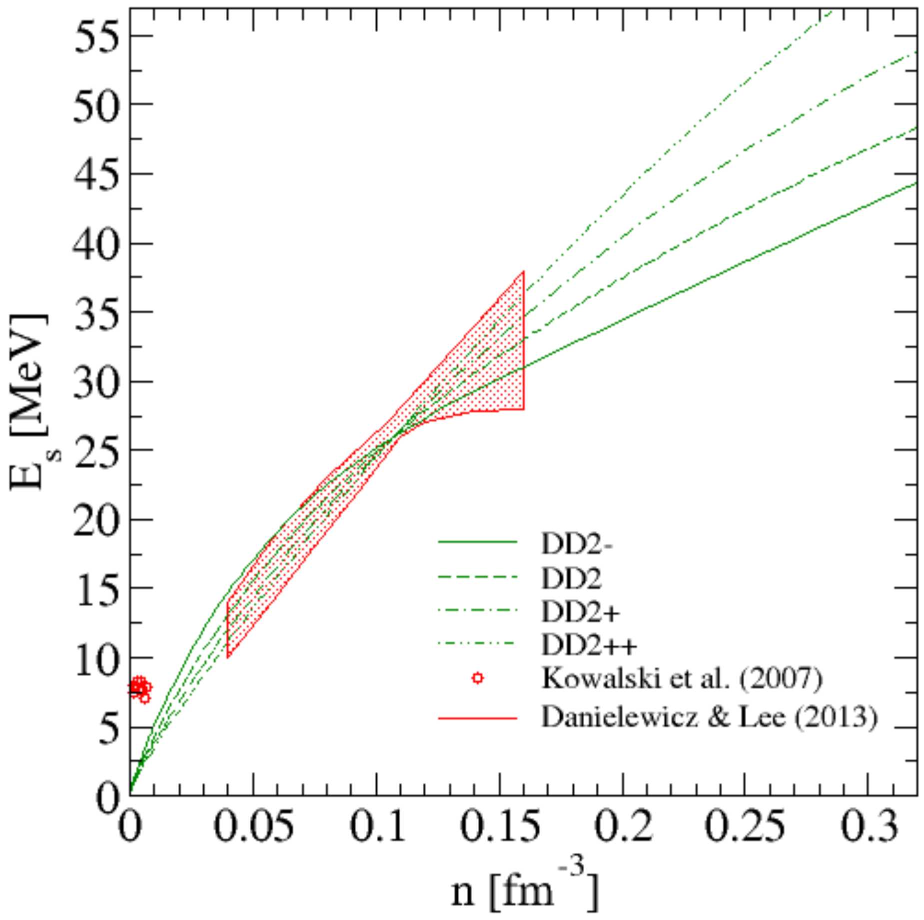
$$\frac{dp}{dr} = -\frac{(\varepsilon + p/c^2)G(m + 4\pi r^3 p/c^2)}{r^2(1 - 2Gm/rc^2)}$$

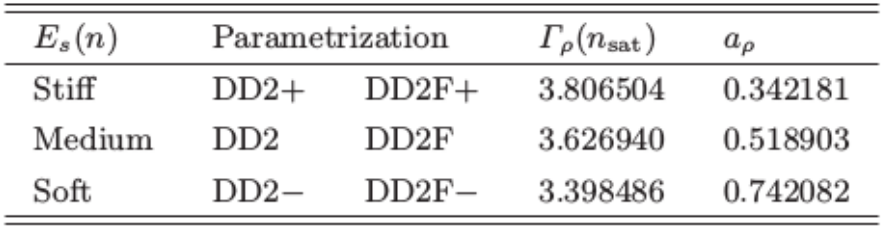
$$\frac{dm}{dr} = 4\pi r^2 \varepsilon$$

- Equation of State (EoS)

$$p(\varepsilon)$$

Nuclear Symmetry Energy

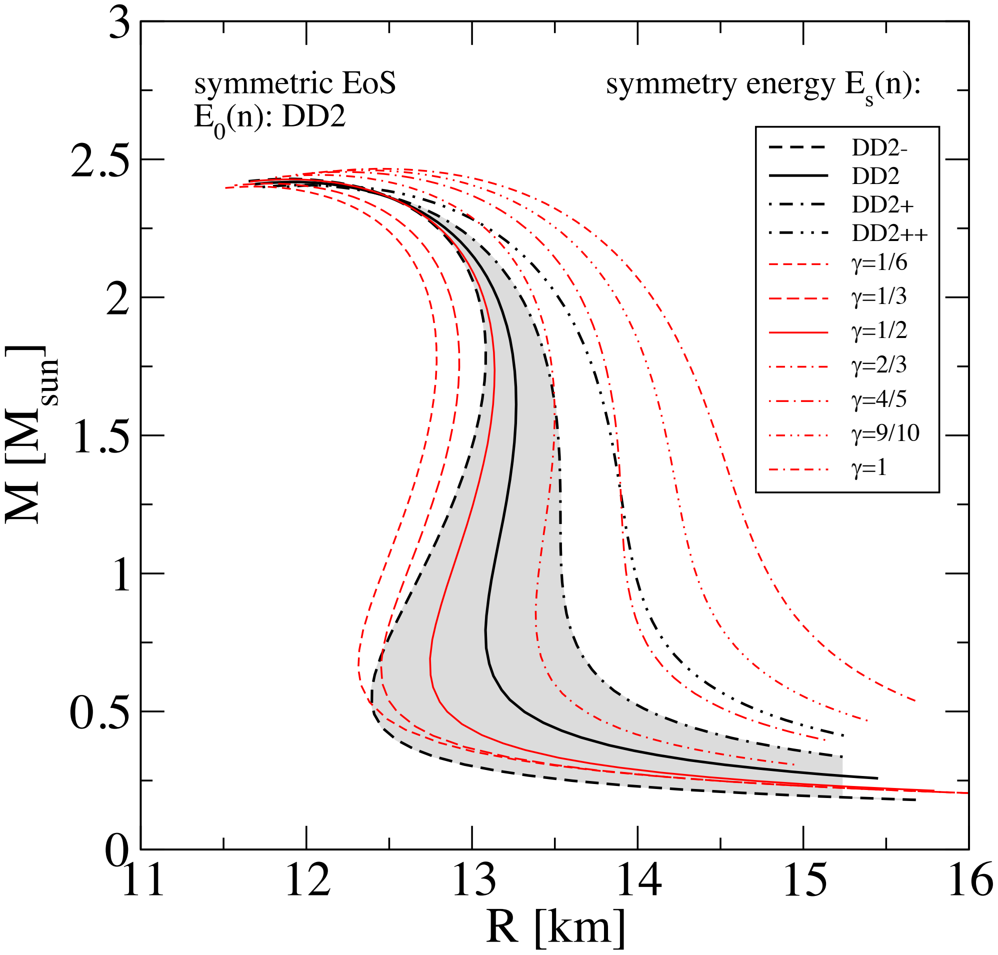




$E_s(n)$	Parametrization		$\Gamma_\rho(n_{\text{sat}})$	a_ρ
Stiff	DD2+	DD2F+	3.806504	0.342181
Medium	DD2	DD2F	3.626940	0.518903
Soft	DD2−	DD2F−	3.398486	0.742082

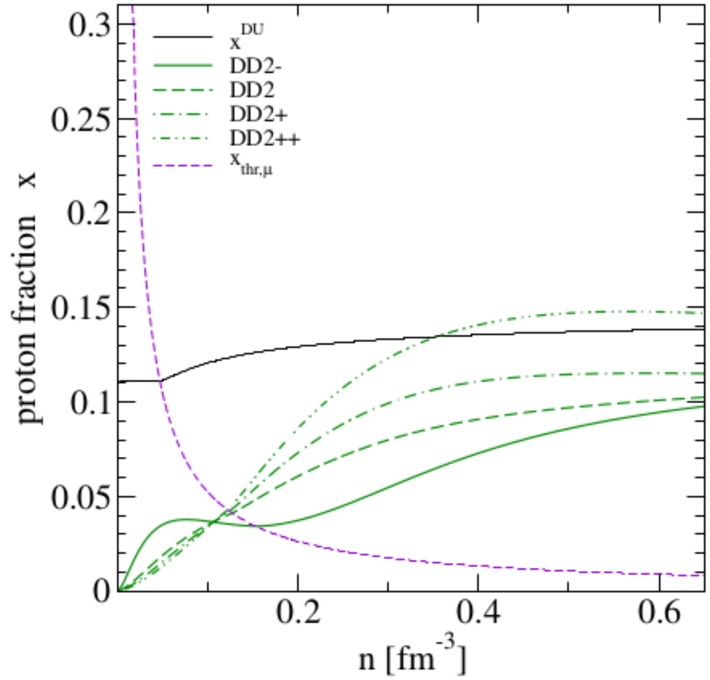
S. Typel, Phys. Rev. C 89, 064321 (2014)

Symmetry energy effects



DUrca Process Constraint

E_s	$n_{\mathrm{DU}}[\mathrm{fm}^{-3}]$	$n_c[\mathrm{fm}^{-3}]$				
		1.25	1.40	1.60	1.80	2.00
DD2-	-	0.331	0.352	0.385	0.423	0.472
DD2	-	0.331	0.354	0.387	0.426	0.478
DD2+	-	0.325	0.349	0.384	0.425	0.479
DD2++	0.354	0.314	0.339	**0.375**	**0.416**	**0.469**



D. E. Alvarez-Castillo, D. Blaschke and T. Klahn. (2016)
arXiv: 1604.08575

Symmetry energy Conjecture

Klaehn et al. PhysRev C74 (2006)

PHYSICAL REVIEW C **74**, 035802 (2006)

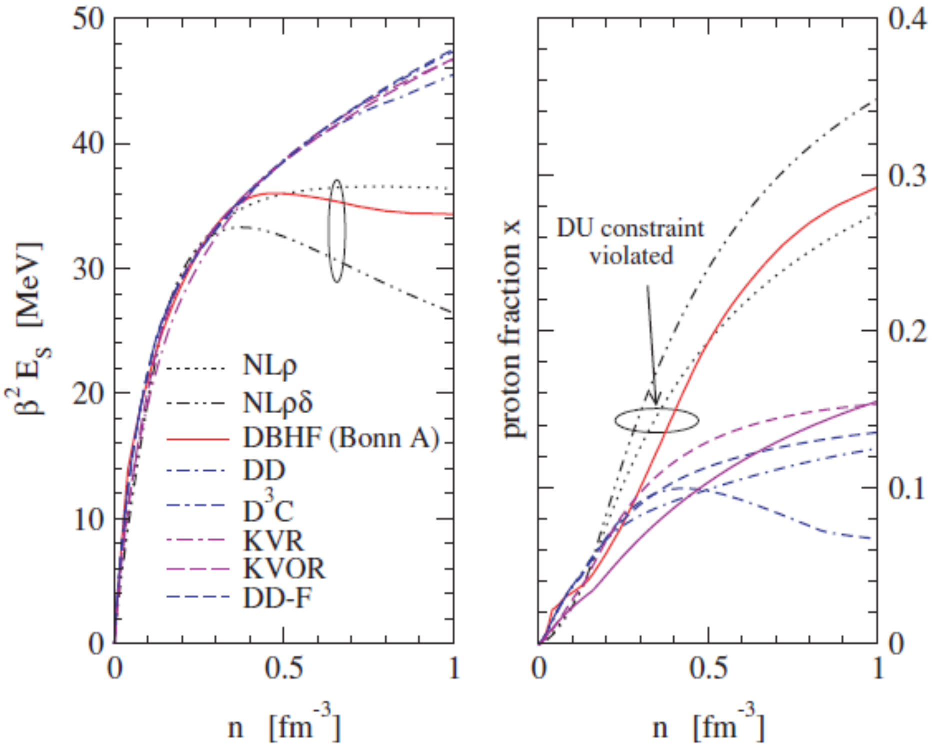
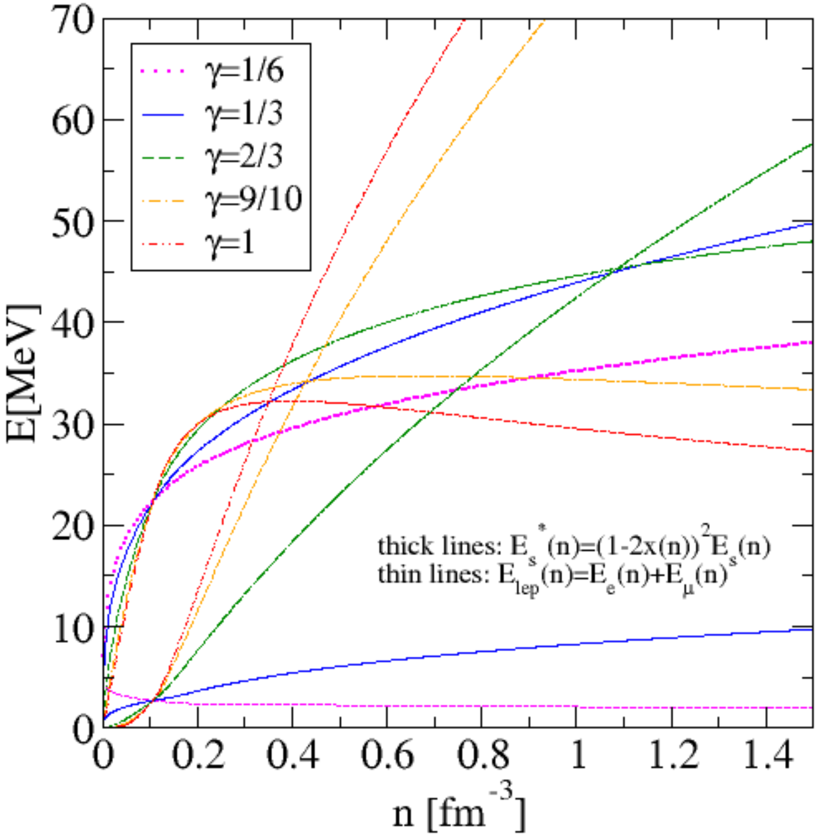


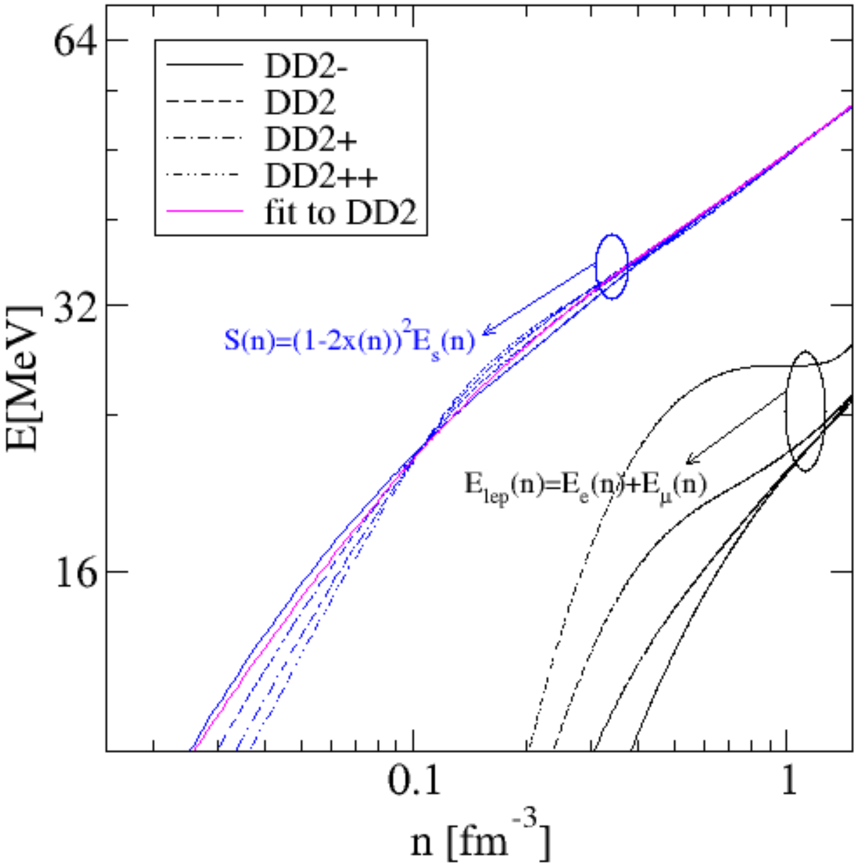
FIG. 7. (Color online) Density dependence of the asymmetry contribution to the energy per particle (left panel) and of the proton fraction (right panel) in NSM. Encircled curves correspond to EoSs that violate the DU-constraint.

Universal symmetry energy contribution



thick lines: $E_s^*(n)=(1-2x(n))^2E_s(n)$
thin lines: $E_{lep}(n)=E_e(n)+E_\mu(n)$

arXiv: 1604.08575

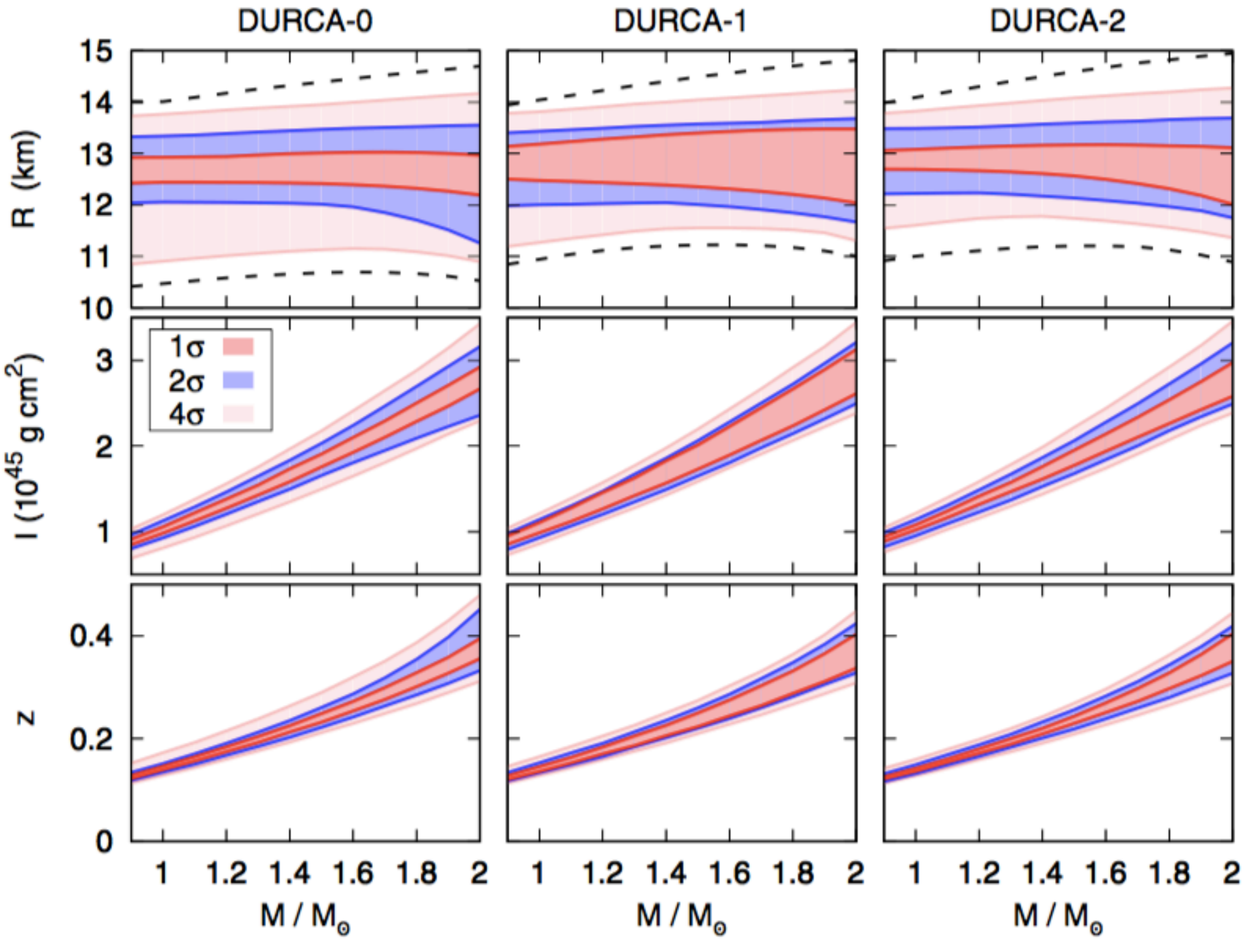


$S(n)=(1-2x(n))^2E_s(n)$

$E_{lep}(n)=E_e(n)+E_\mu(n)$

The symmetry energy contribution to the neutron star EoS behaves universal!

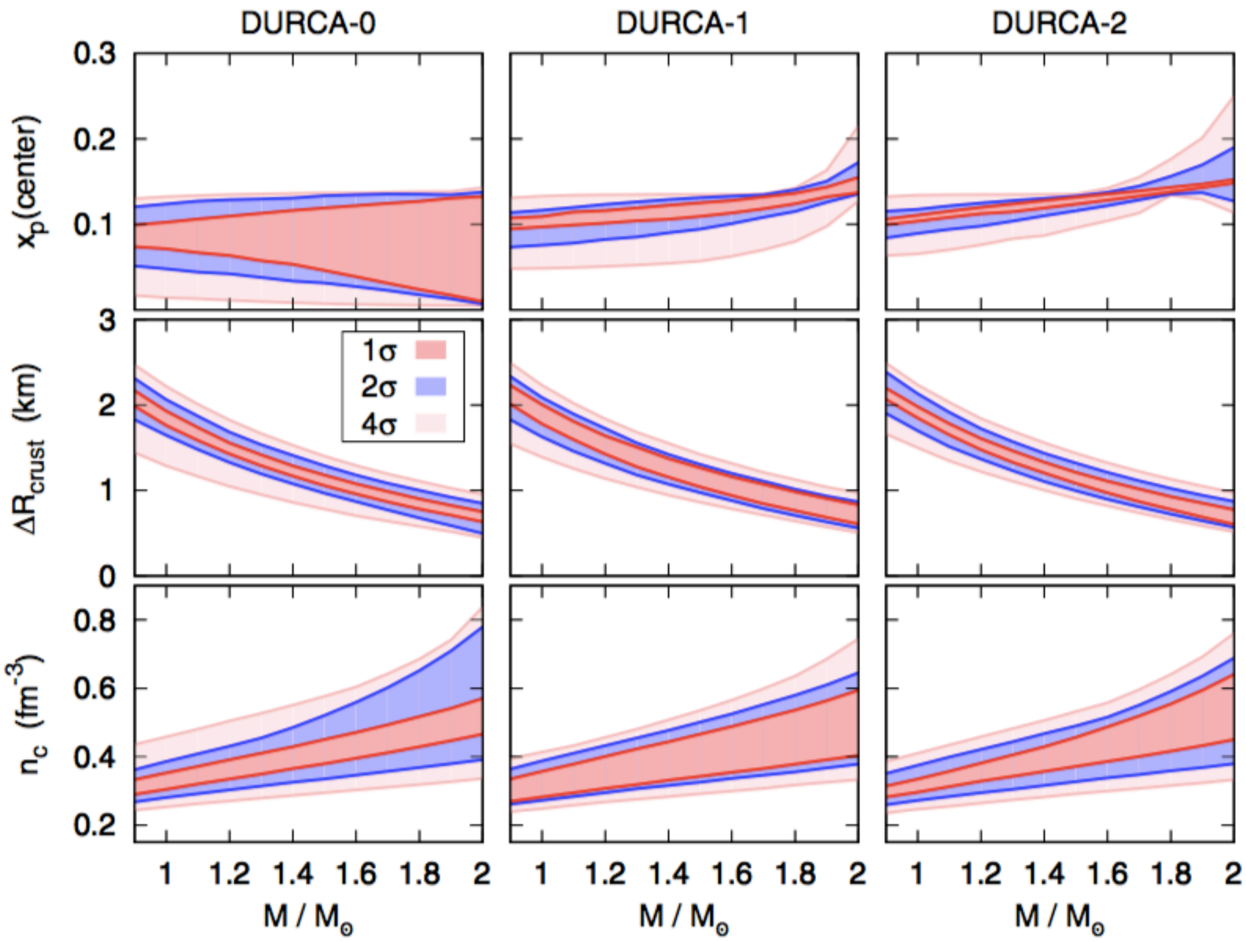
Predictions for neutron stars properties



If composed exclusively of nucleons and leptons, our prediction is that neutron stars have a radius of 12.7 ± 0.4 km for masses between 1 and 2M$_\odot$

J. Margueron, R. Hoffmann Casali, F. Gulminelli - Phys. Rev. C 97, 025806 (2018)

Predictions for neutron stars properties



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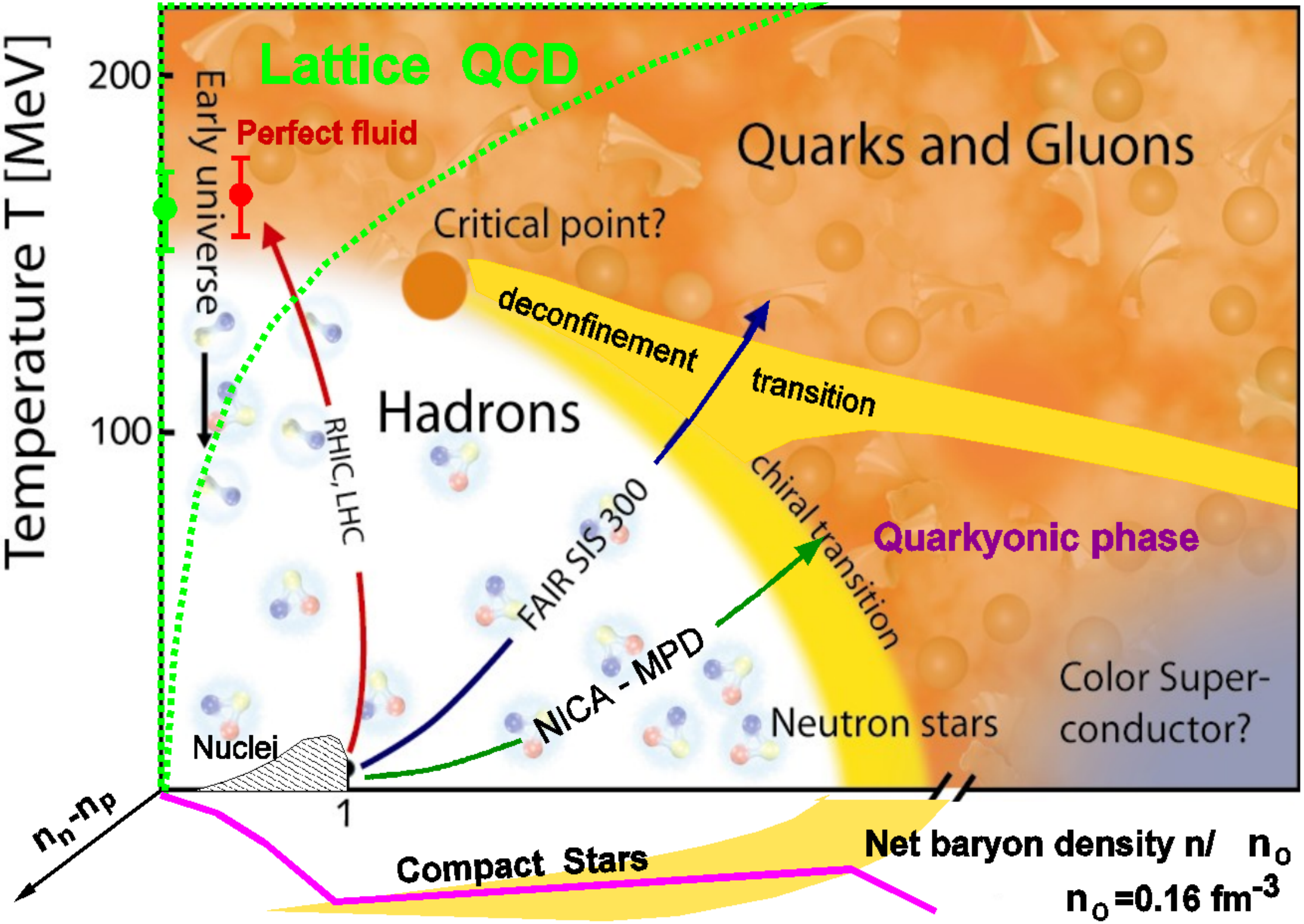
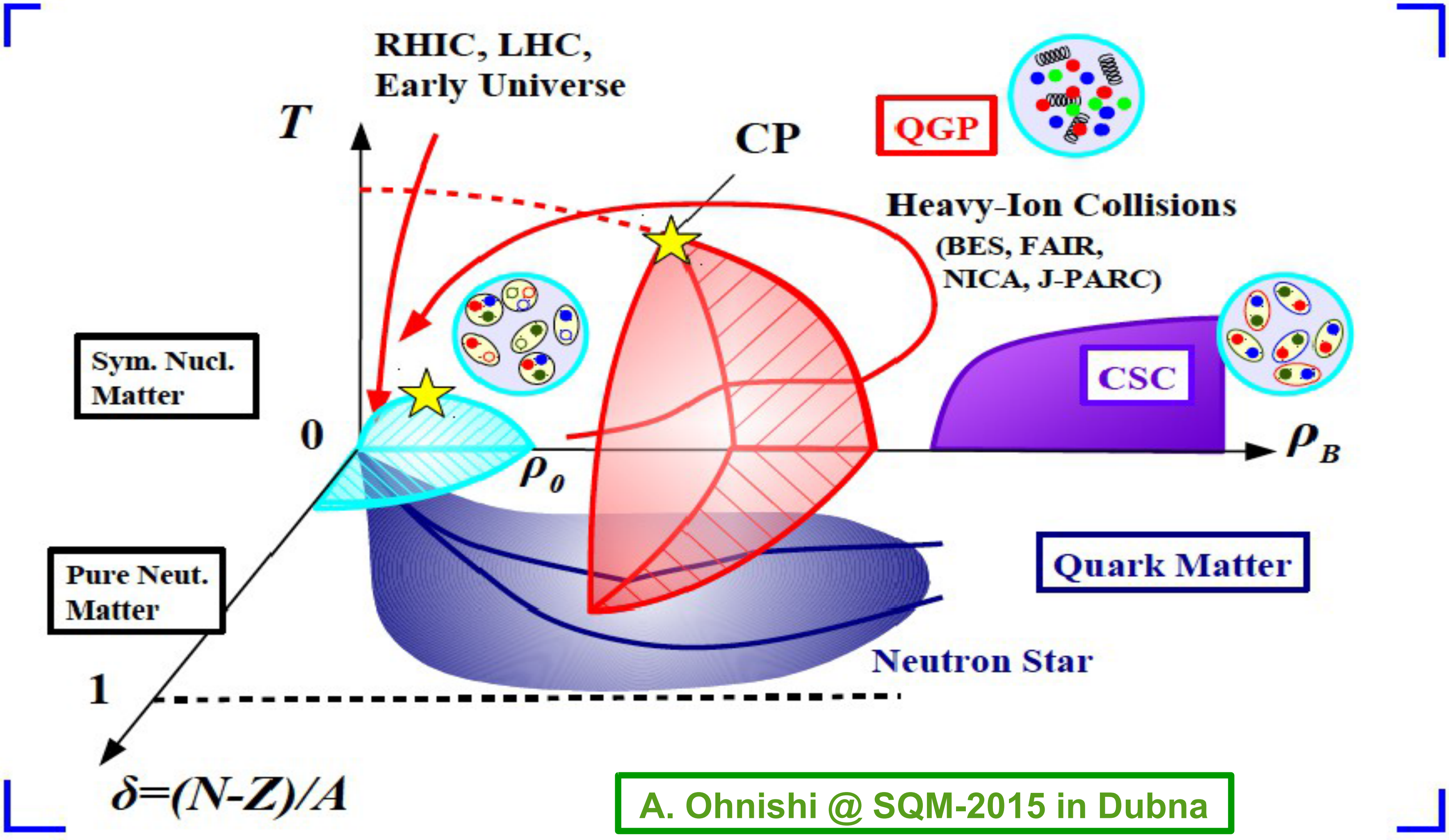
Critical Endpoint in QCD



Support a CEP in QCD phase diagram with Astrophysics?



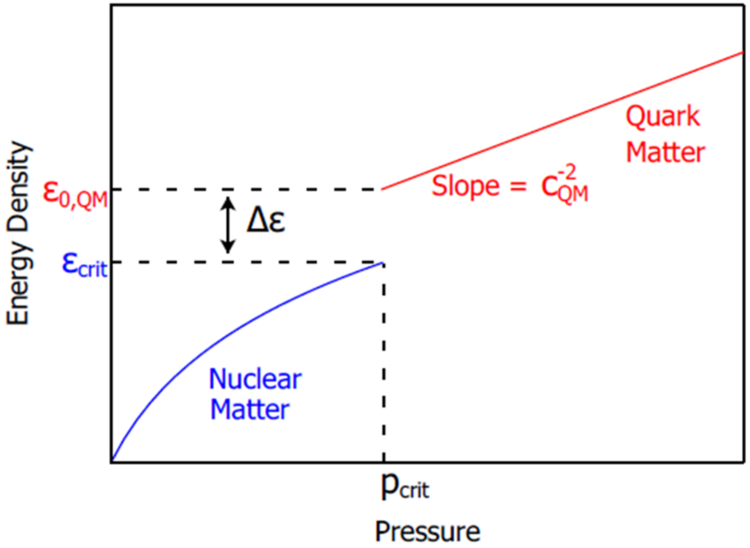
A. Ohnishi @ SQM-2015 in Dubna

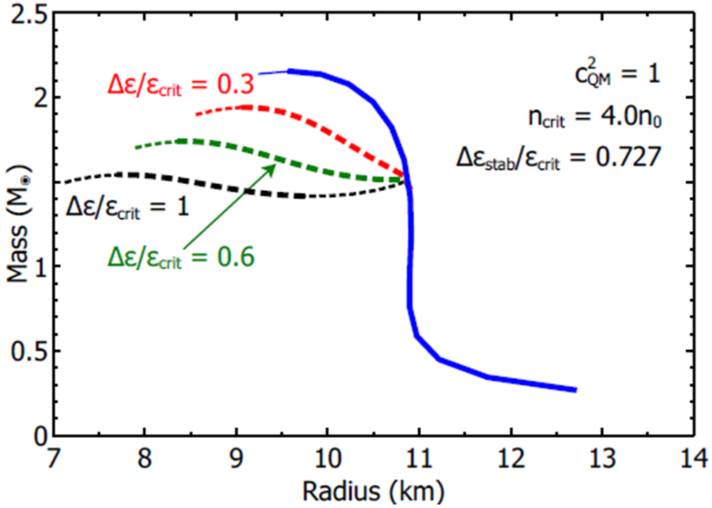
Crossover at finite T (Lattice QCD) + First order at zero T (Astrophysics)
=> Critical endpoint exists!

Neutron Star 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**”.

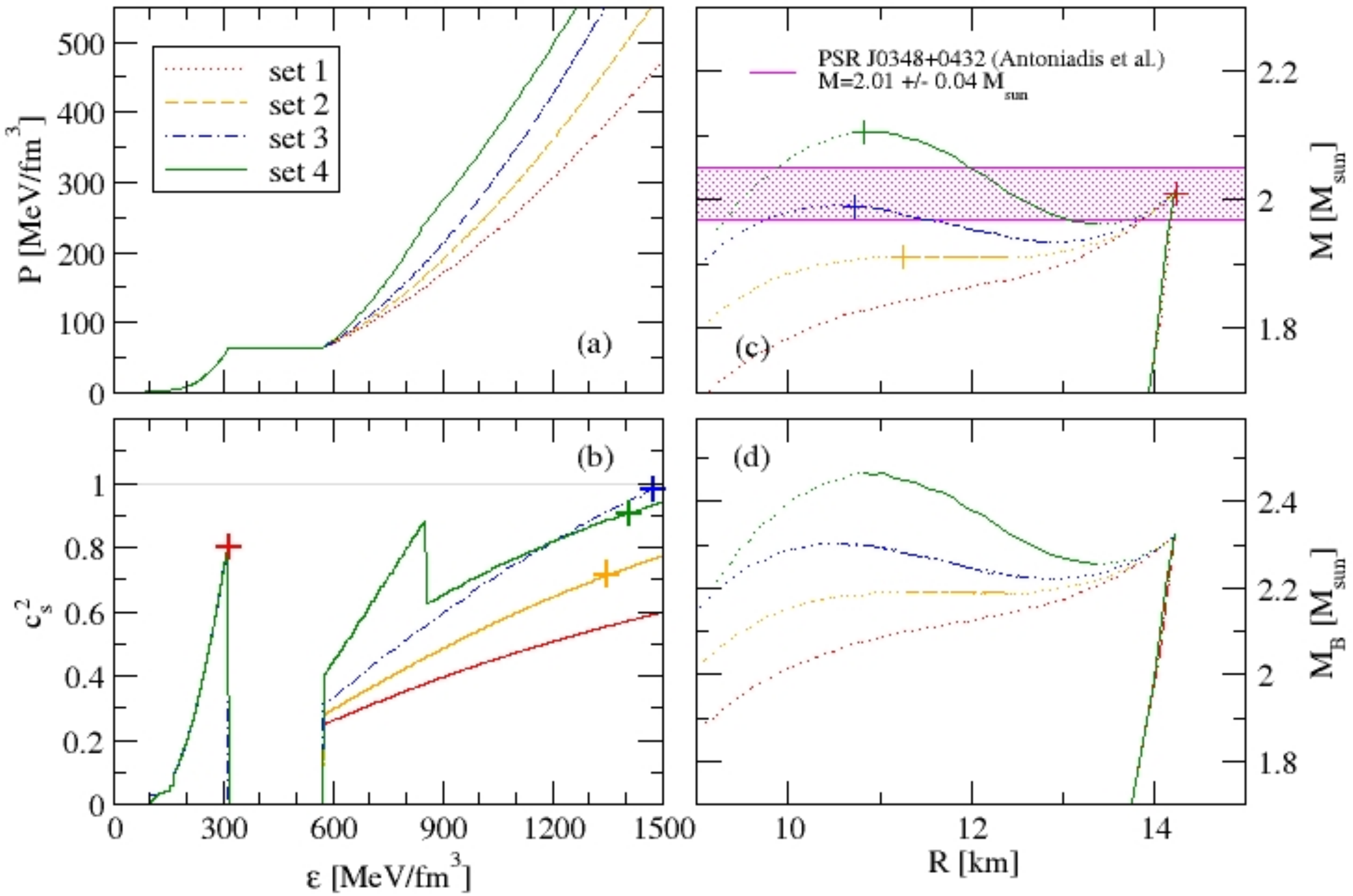
- Measuring two **disconnected populations** of compact stars in the M-R diagram would represent **the detection of a first order phase transition** in compact star matter and thus the indirect proof for the existence of a **critical endpoint (CEP) in the QCD phase diagram**!





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

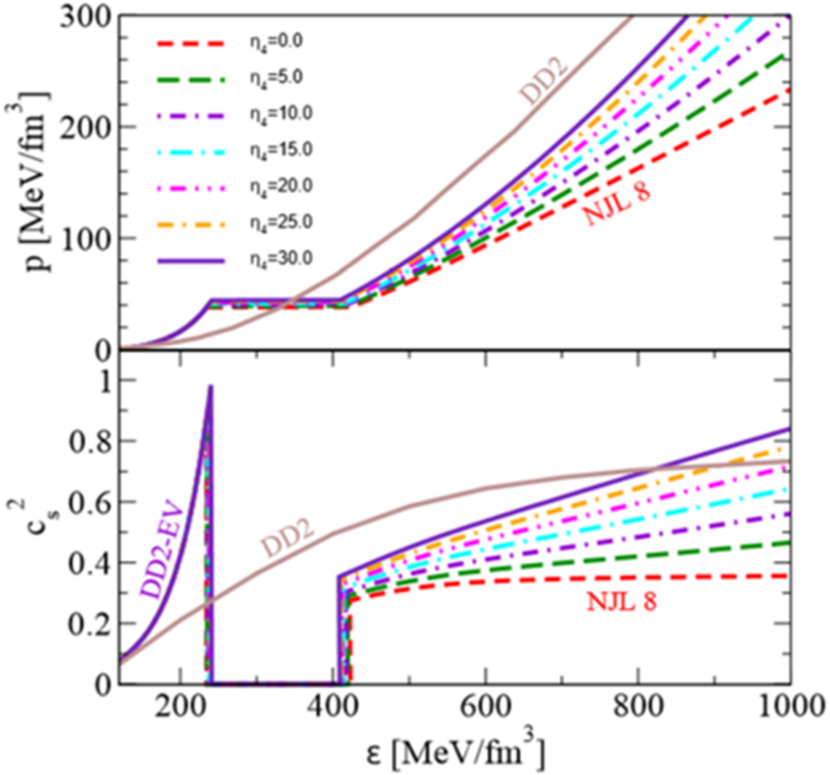
Compact Star Twins



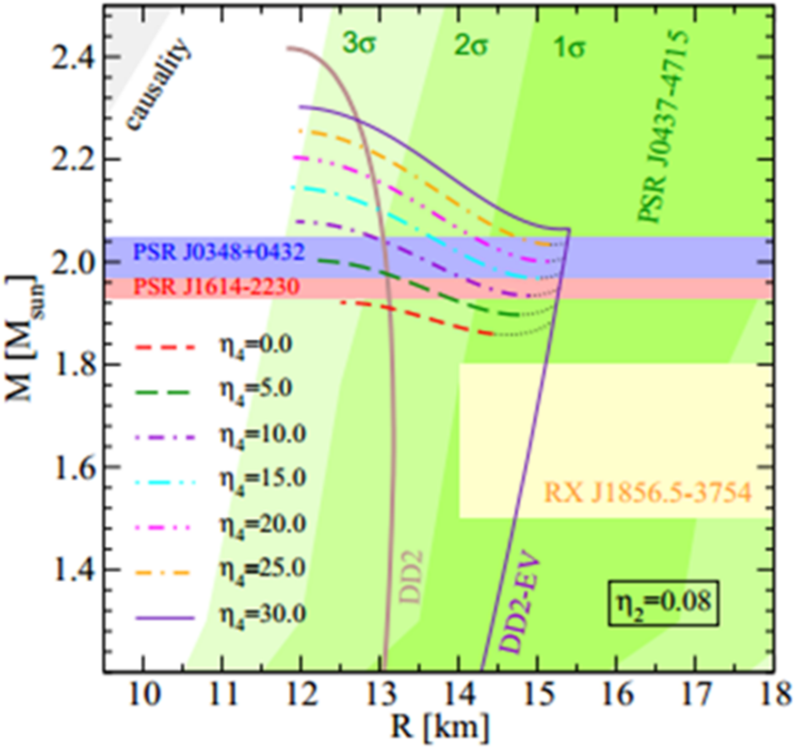
Alvarez-Castillo, Blaschke (2017)
High mass twins from multi-polytrope equations of state
arXiv: 1703.02681v2, Phys. Rev. C 96, 045809 (2017)

Neutron Star Twins

Equation of State

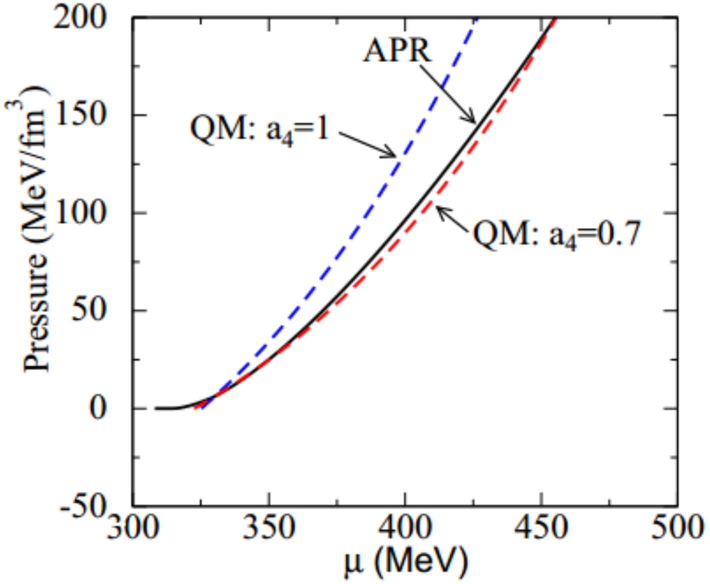


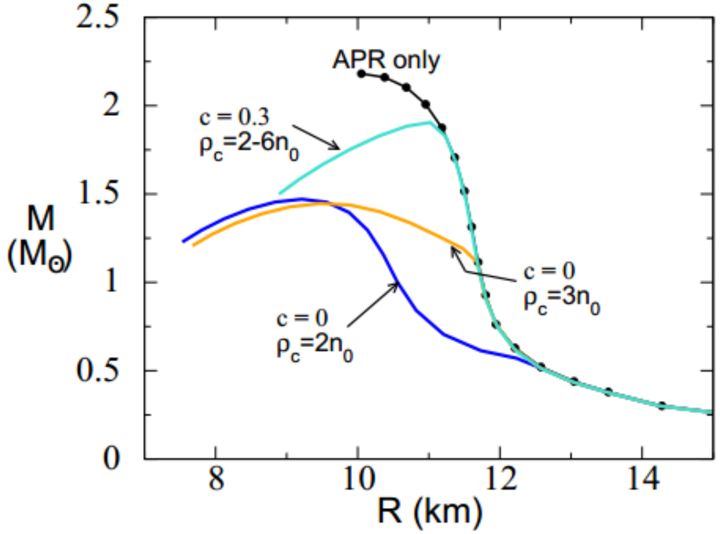
Mass-Radius Relation



Benic, Blaschke, Alvarez-Castillo, Fischer, Typel:
A&A 577, A40 (2015) - arXiv:1411.2856 (2014)

Avoiding Masquerades



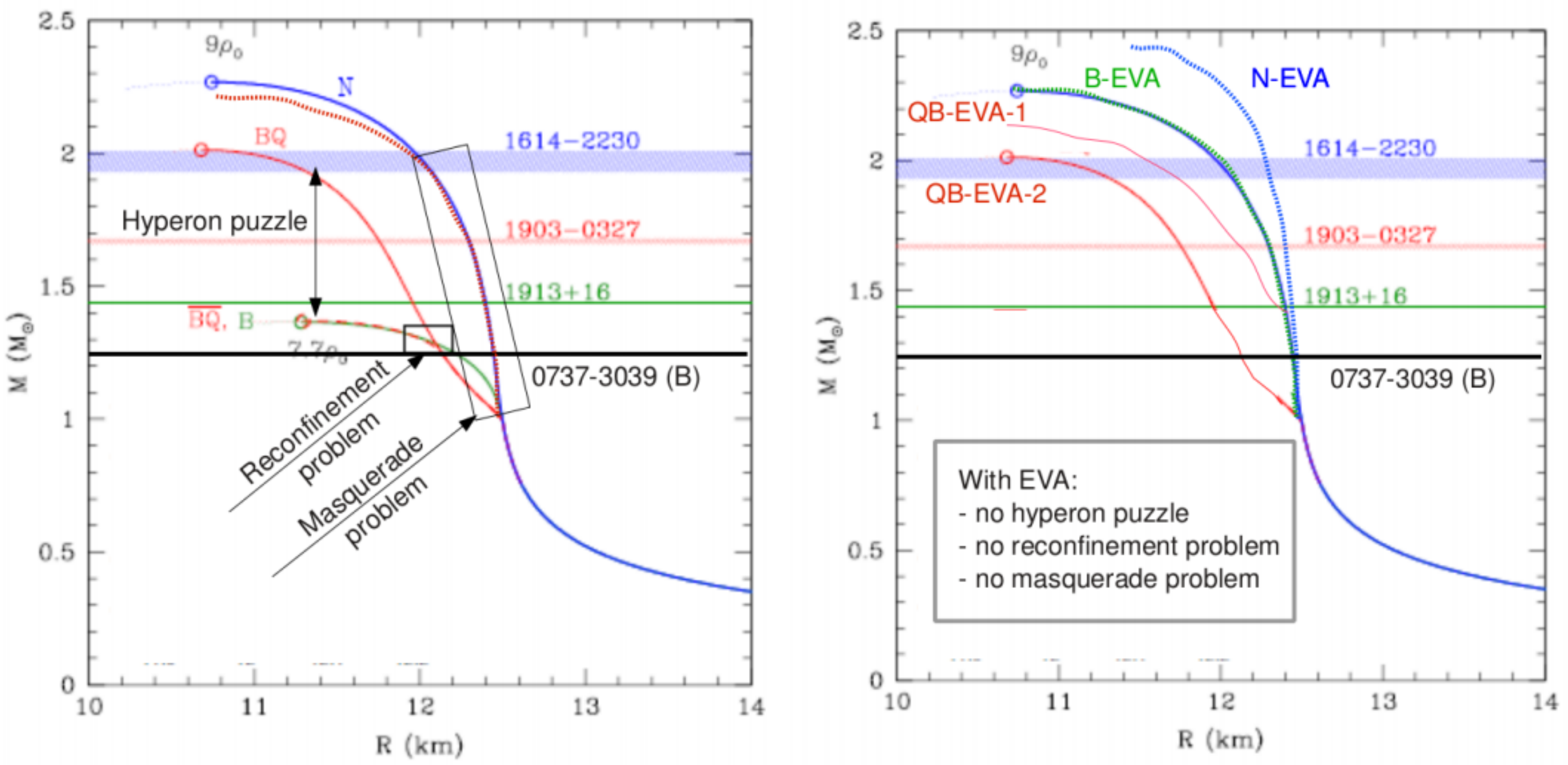


$$\Omega_{\rm QM} = -\frac{3}{4\pi^2}\, a_4\, \mu^4 + \frac{3}{4\pi^2} a_2\, \mu^2 + B_{\rm eff}$$

$$a_4 \equiv 1 - c\,,$$

Alford et al. - Astrophys.J.629:969-978, 2005 - arXiv:nucl-th/0411016

Avoiding reconfinement

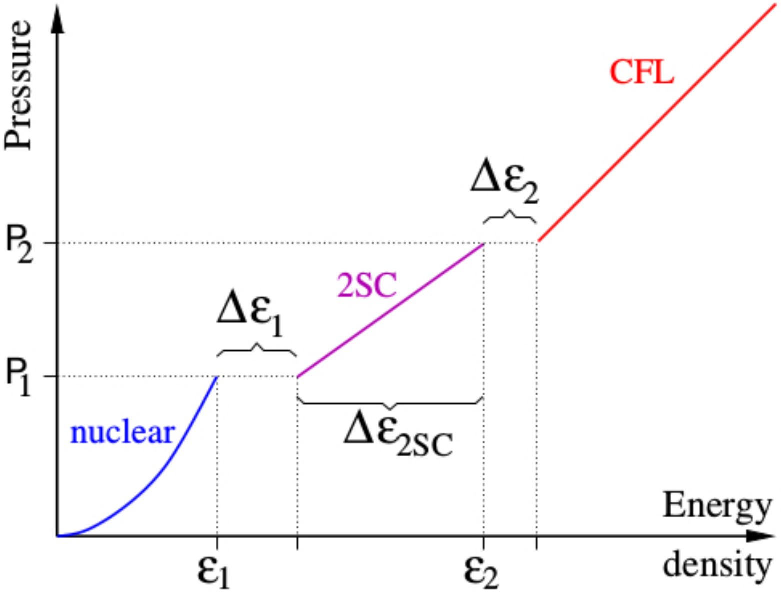


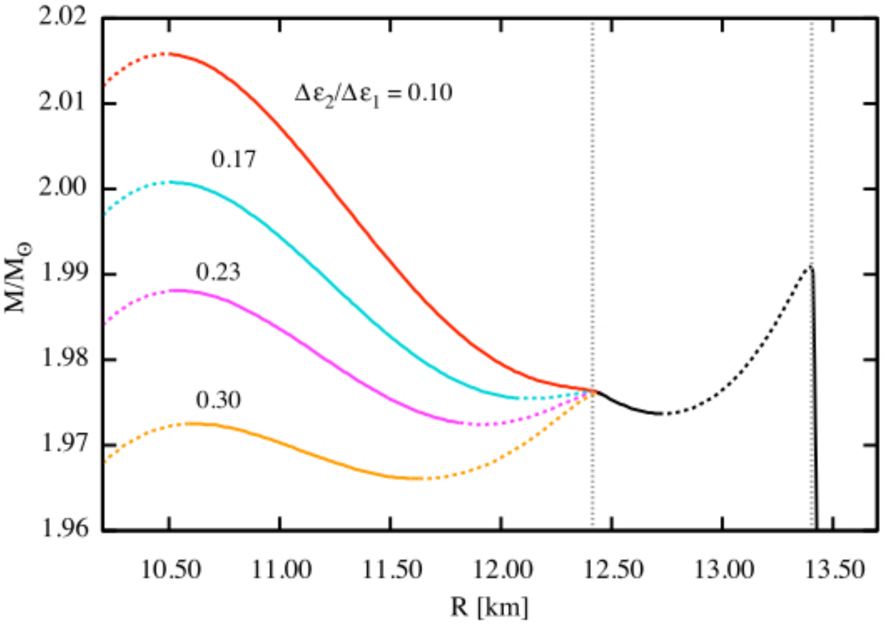
With EVA:
- no hyperon puzzle
- no reconfinement problem
- no masquerade problem

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

Compact Stars with Sequential QCD Phase Transitions





Sedrakian and M. Alford
Phys. Rev. Lett. 119, 161104 (2017) - arXiv:1706.01592

GW170817
and
Tidal deformability

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

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

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)

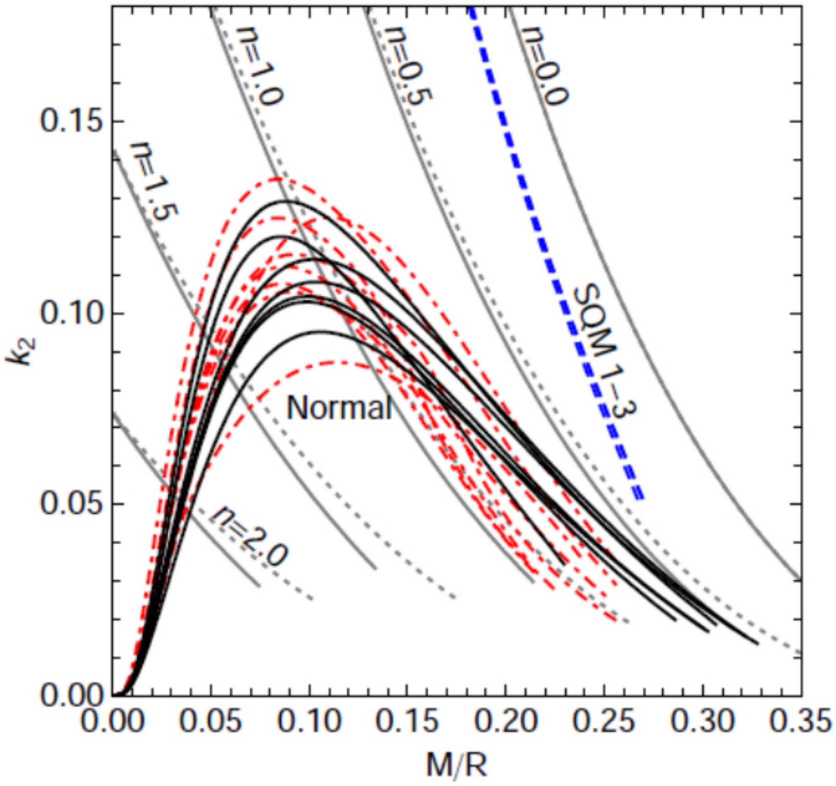
And additional eqs. for perturbations:

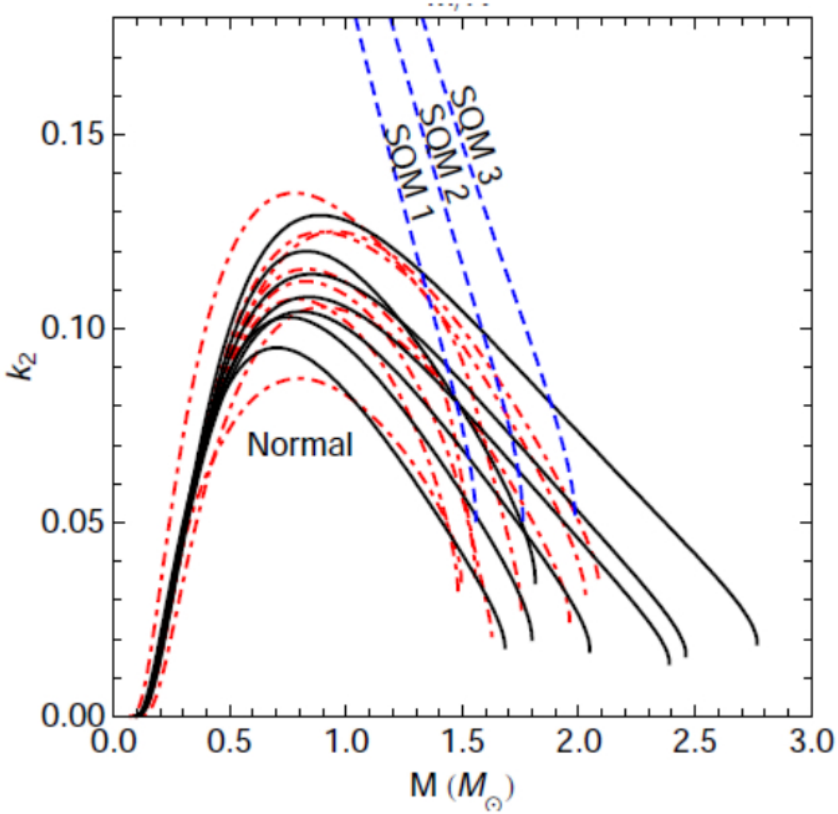
$$\begin{aligned} \frac{dH}{dr} \;=\; & \beta \qquad (11) \\ \frac{d\beta}{dr} \;=\; & 2\left(1 - 2\frac{m_r}{r}\right)^{-1} H \left\{-2\pi\left[5\epsilon + 9p + f(\epsilon + p)\right]\right. \\ & \left. + \frac{3}{r^2} + 2\left(1 - 2\frac{m_r}{r}\right)^{-1}\left(\frac{m_r}{r^2} + 4\pi r p\right)^2\right\}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

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

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

Love number

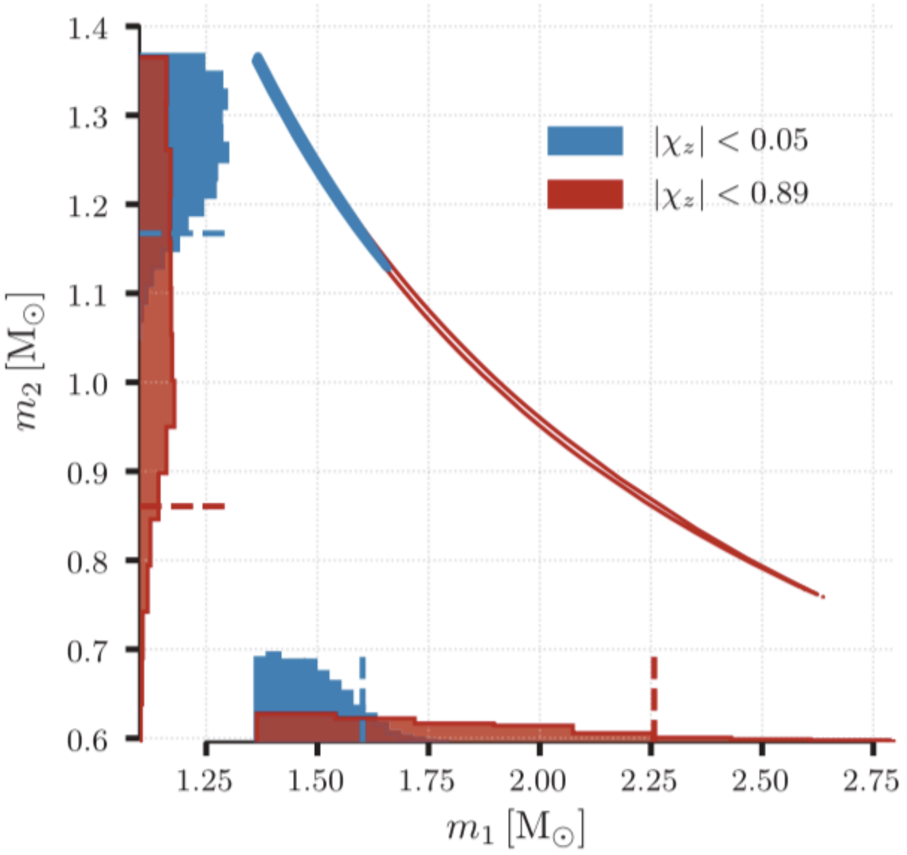




For fixed compactness k_2 depends on EoS => tidal deformability is not a unique function of compactness for different EoSs

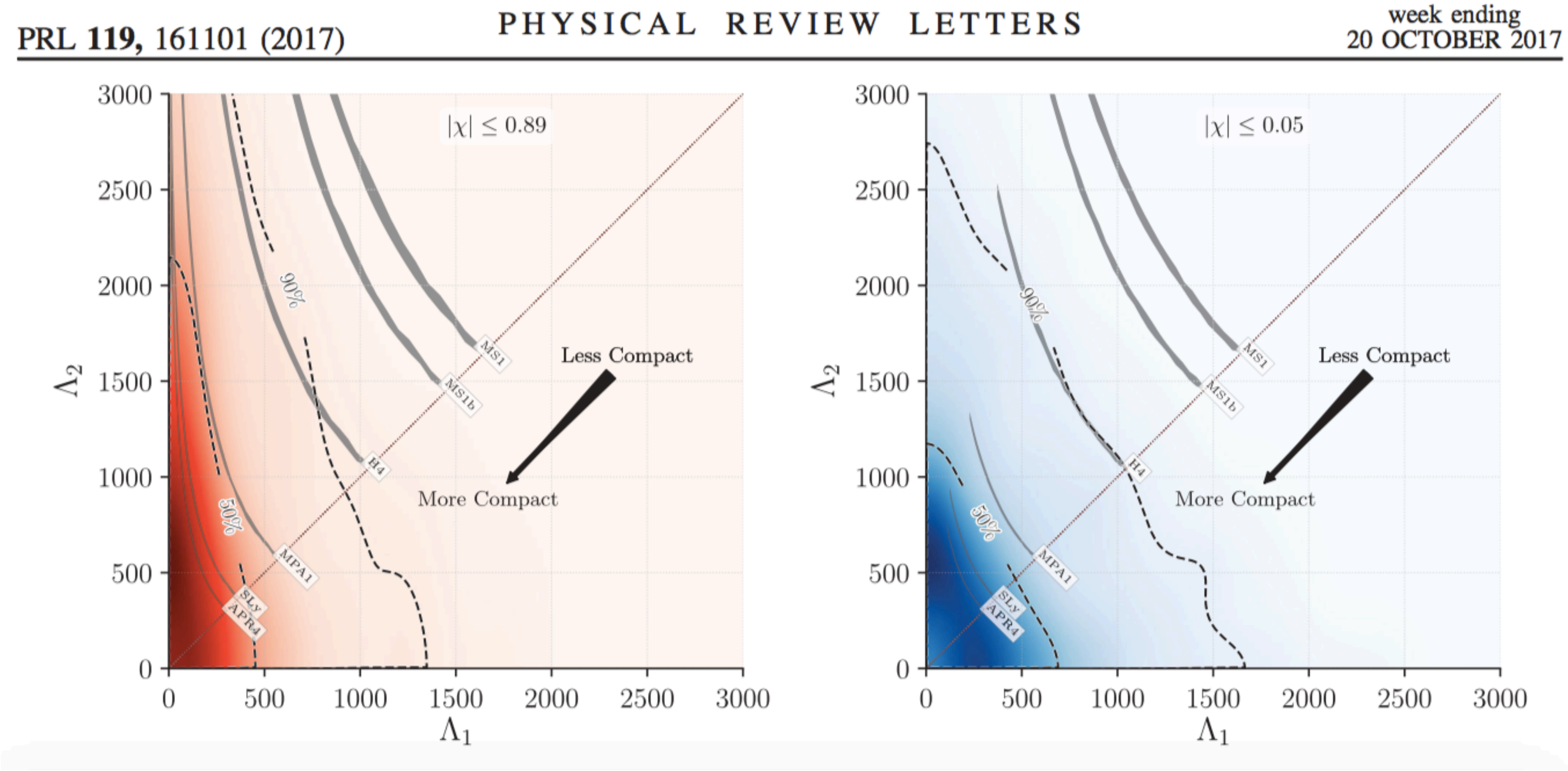
Hinderer et al. 2010

Implications from GW170817



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

Implications from GW170817



PRL 119, 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

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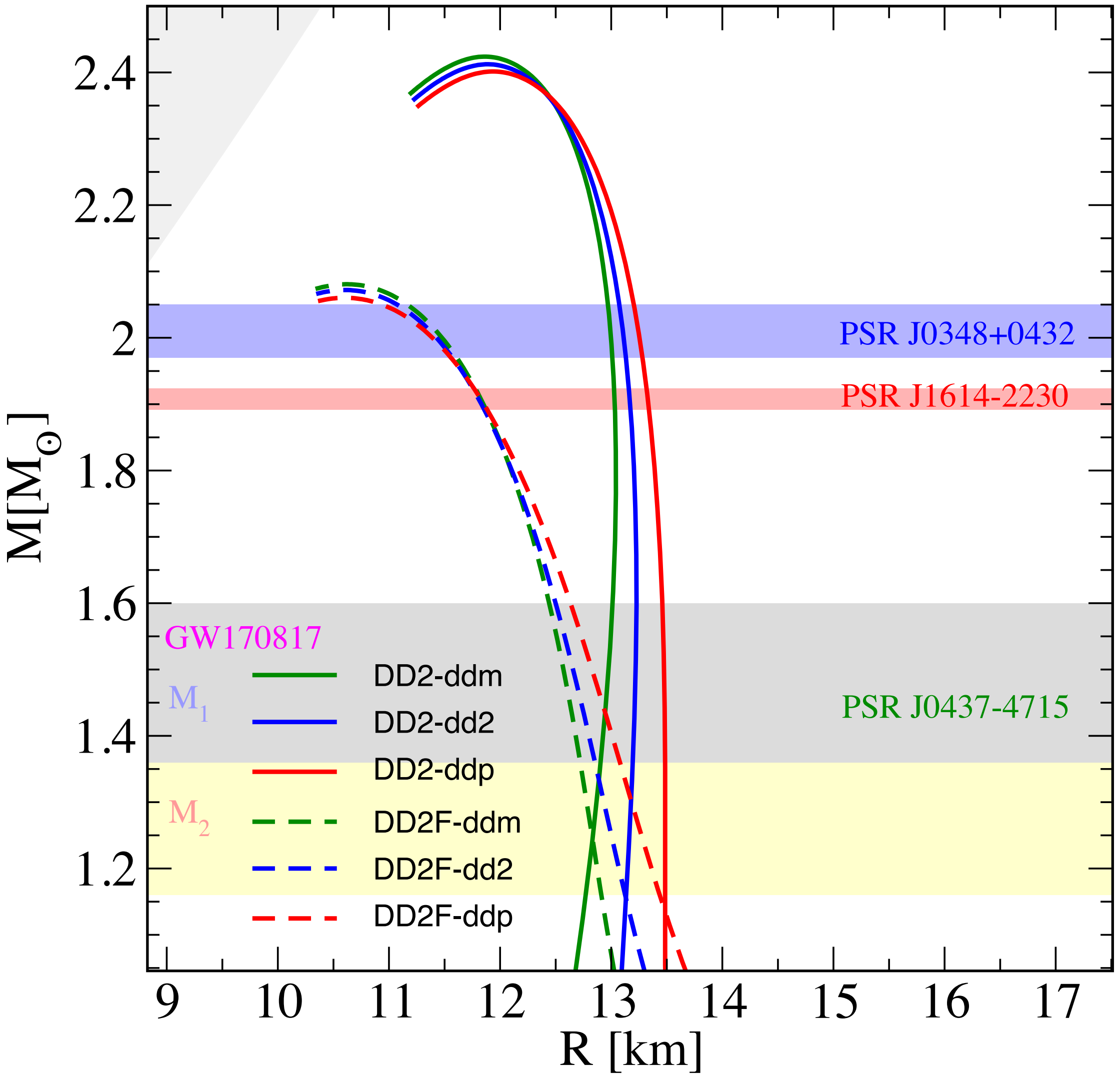
Implications from GW170817



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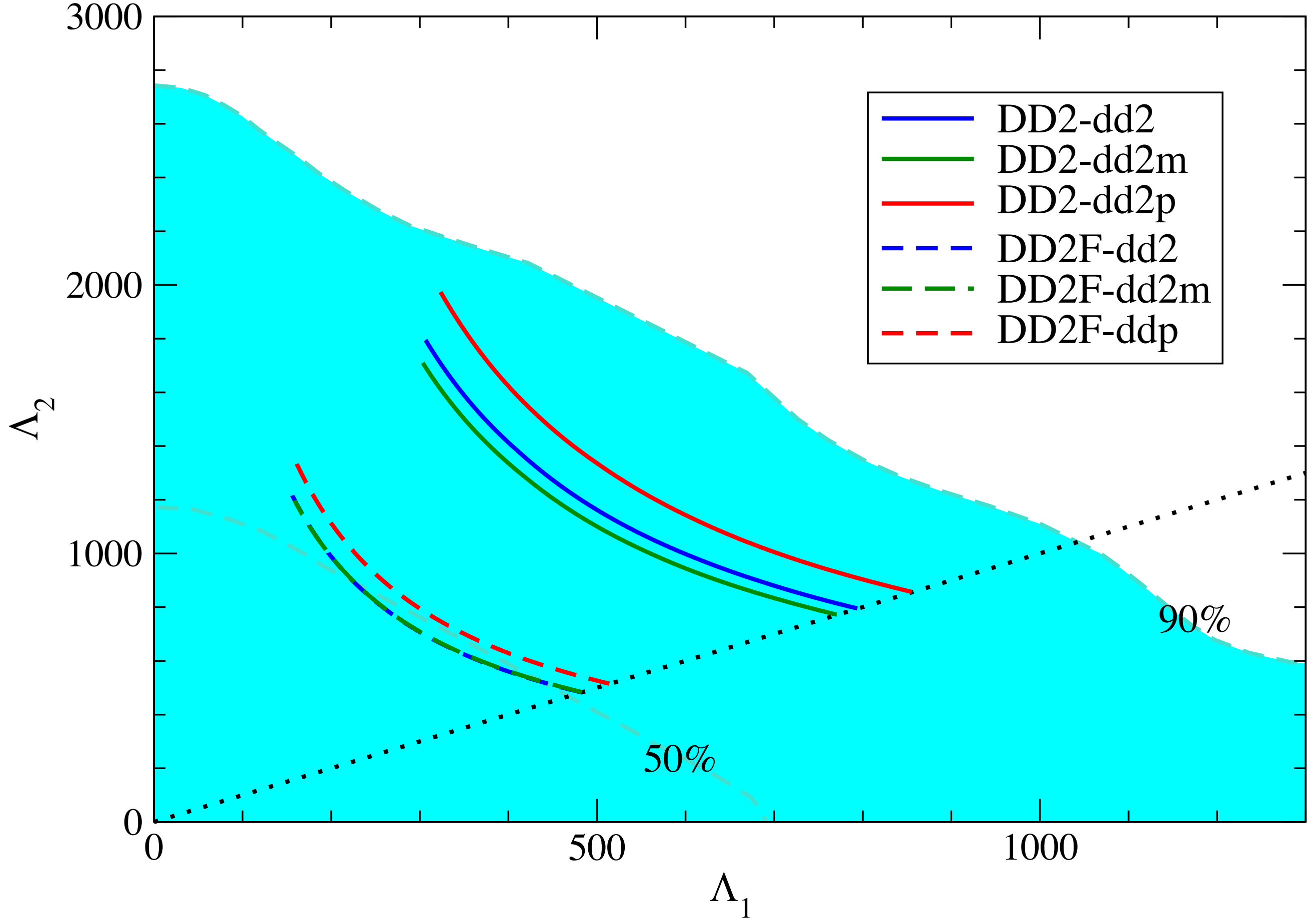

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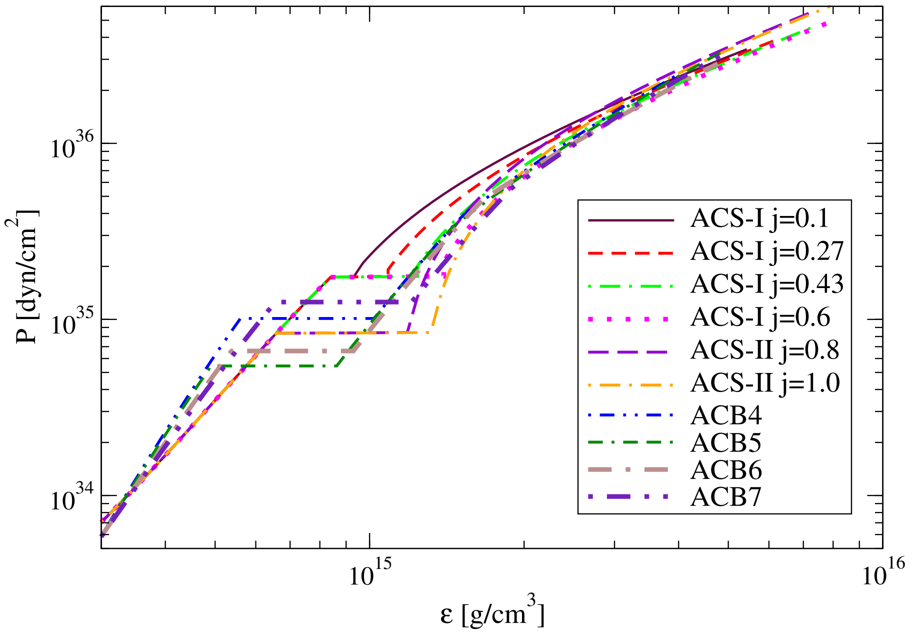
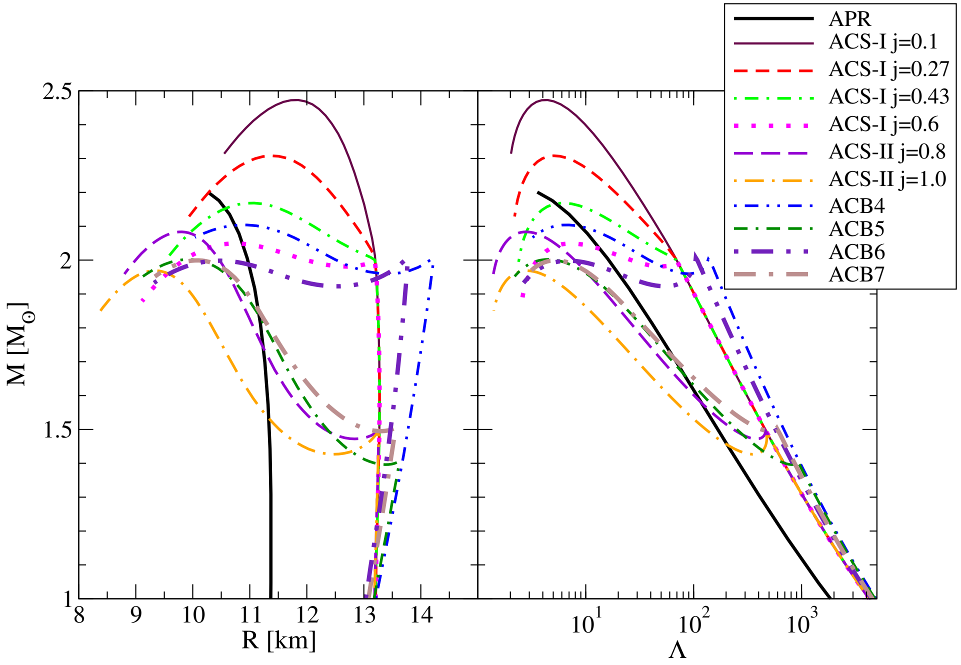
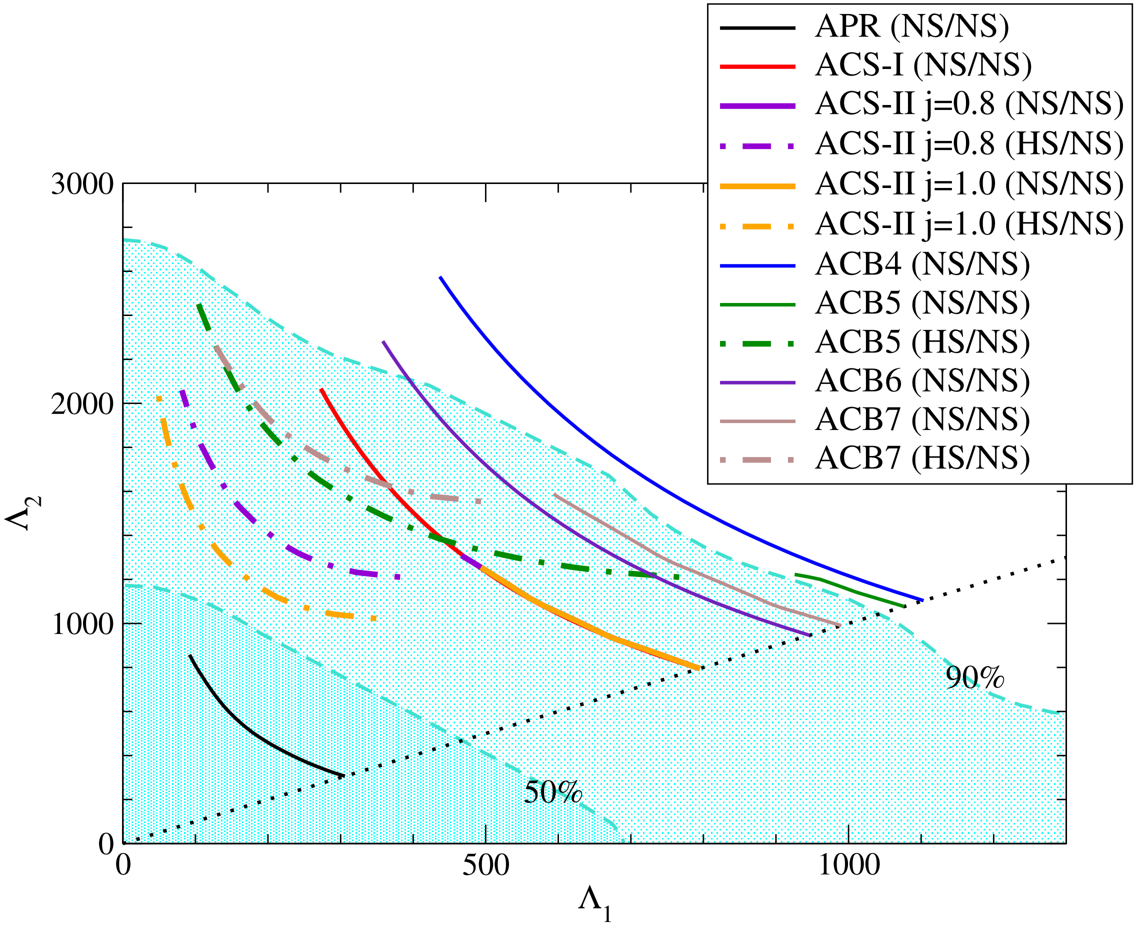




Vasileios Paschalidis, Kent Yagi, David Alvarez-Castillo,
David B. Blaschke, Armen Sedrakian
PRD accepted, arXiv:1712.00451

Implications from GW170817



Vasileios Paschalidis, Kent Yagi, David Alvarez-Castillo, David B. Blaschke, Armen Sedrakian
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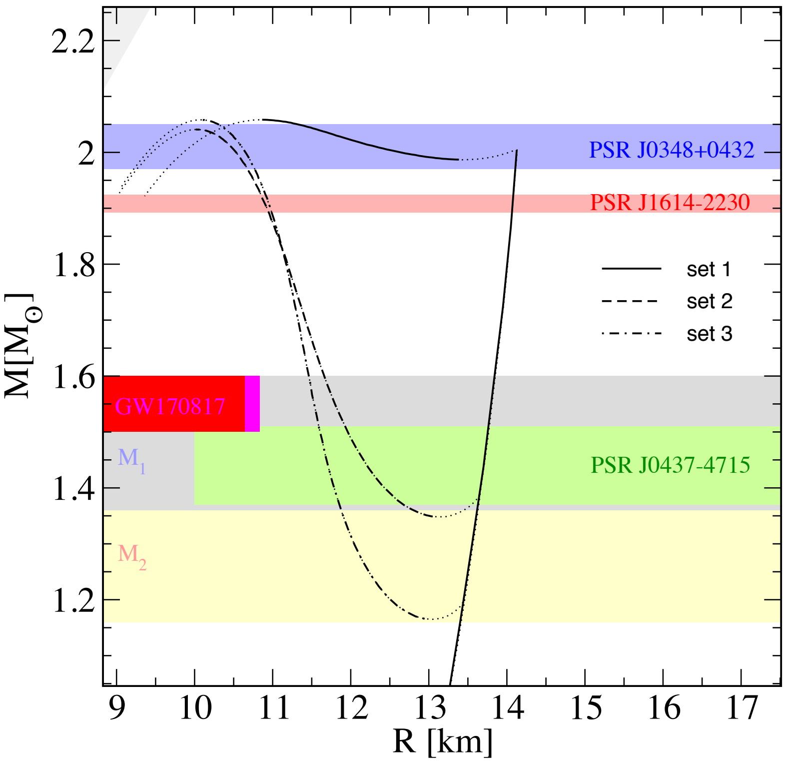
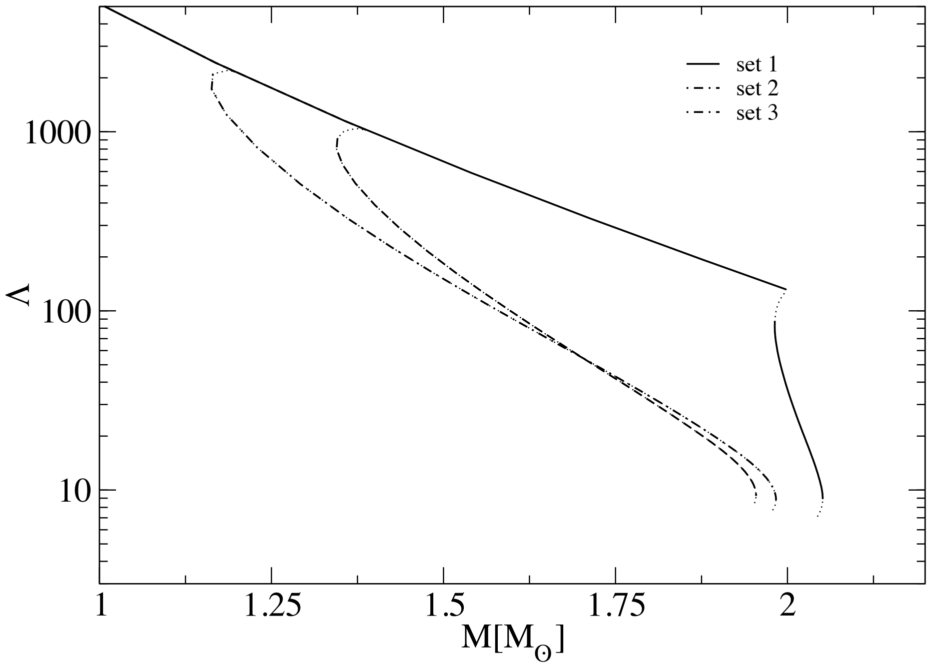
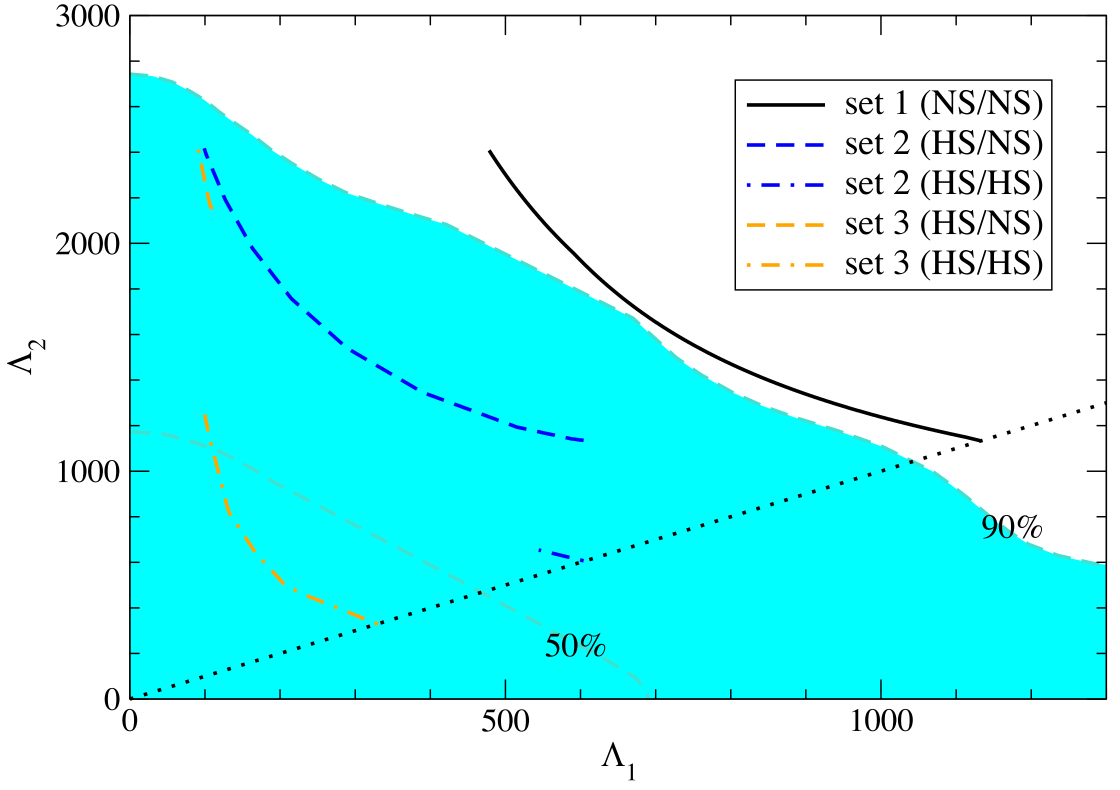




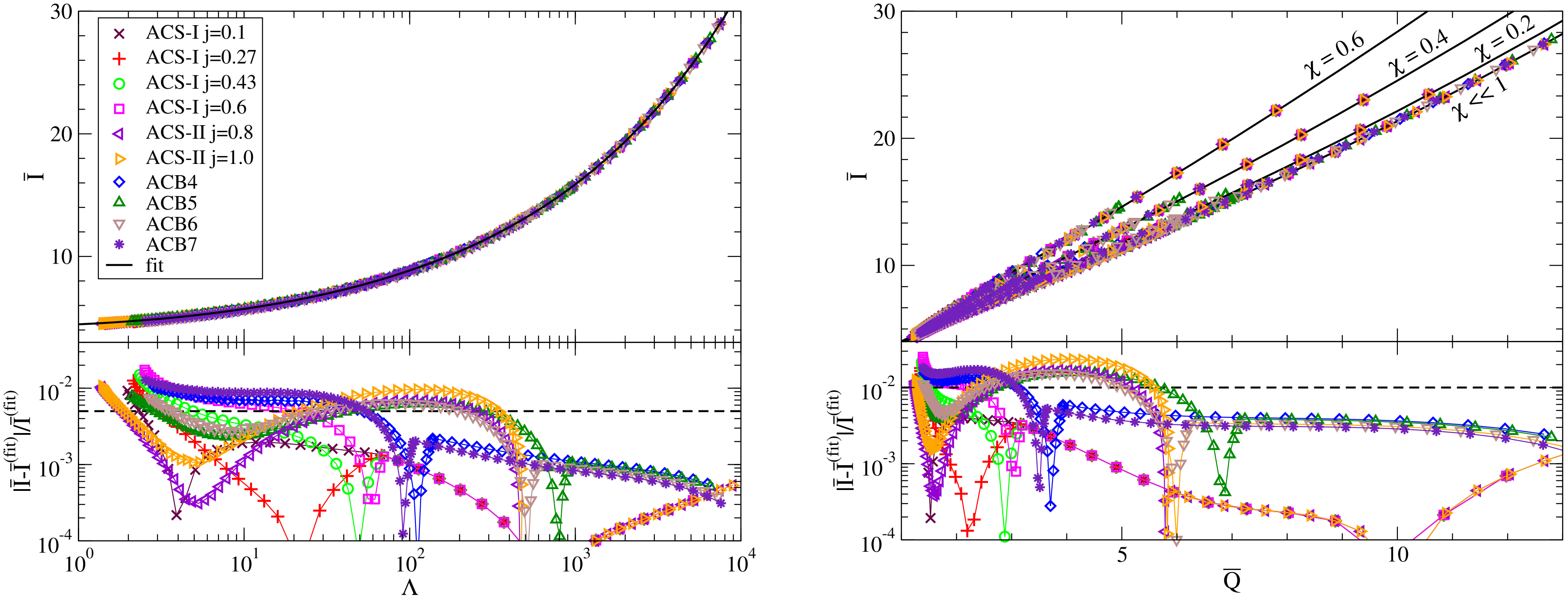
D. Alvarez-Castillo, D. Blaschke, G. Grunfeld, V. Pagura
In preparation

Implications from GW170817



D. Alvarez-Castillo, D. Blaschke, G. Grunfeld, V. Pagura
In preparation

Implications from GW170817 and I-Love-Q relations



Vasileios Paschalidis, Kent Yagi, David Alvarez-Castillo,
David B. Blaschke, Armen Sedrakian
PRD accepted, arXiv:1712.00451

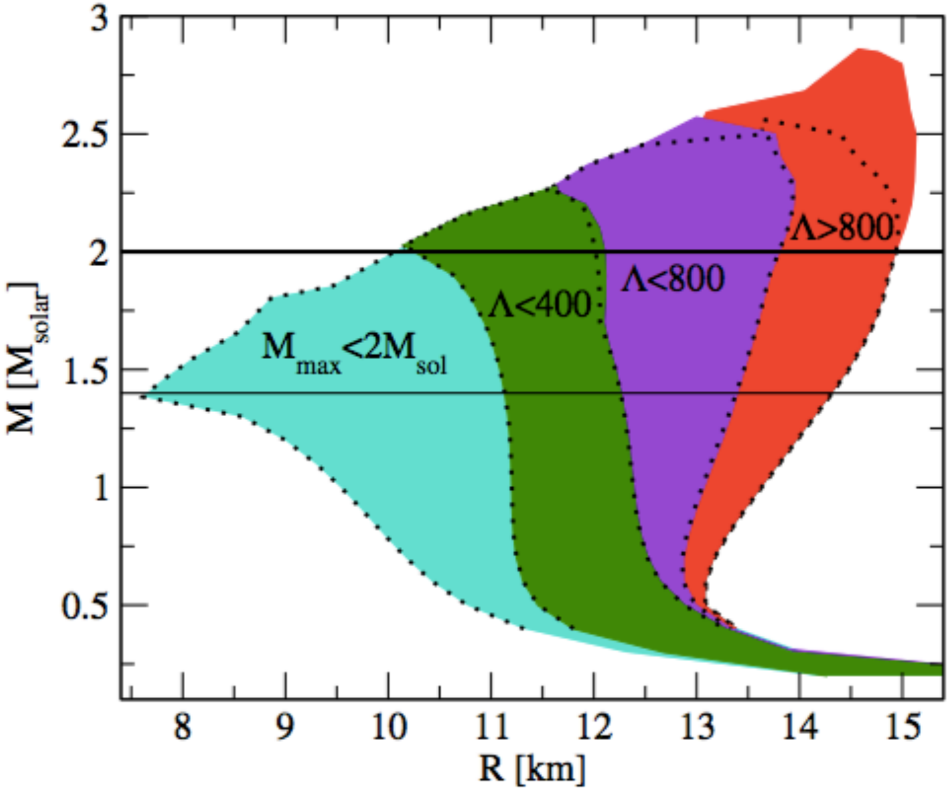


FIG. 1: The mass-radius clouds corresponding to our EoSs. The cyan area corresponds to EoSs that cannot support a $2M_\odot$ star, while the rest denote EoSs that fulfill this requirement and in addition have $\Lambda(1.4M_\odot) < 400$ (green), $400 < \Lambda(1.4M_\odot) < 800$ (violet), or $\Lambda(1.4M_\odot) > 800$ (red), so that the red region is excluded by the LIGO/Virgo measurement at 90% credence. This color coding is used in all of our figures. The dotted black lines denote the result that would have been obtained with bitropic interpolation only.

E. Annala et al. arXiv:1711.02644

Perspectives

NEUTRON-STAR RADIUS CONSTRAINTS FROM GW170817 AND FUTURE DETECTIONS

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ABSTRACT

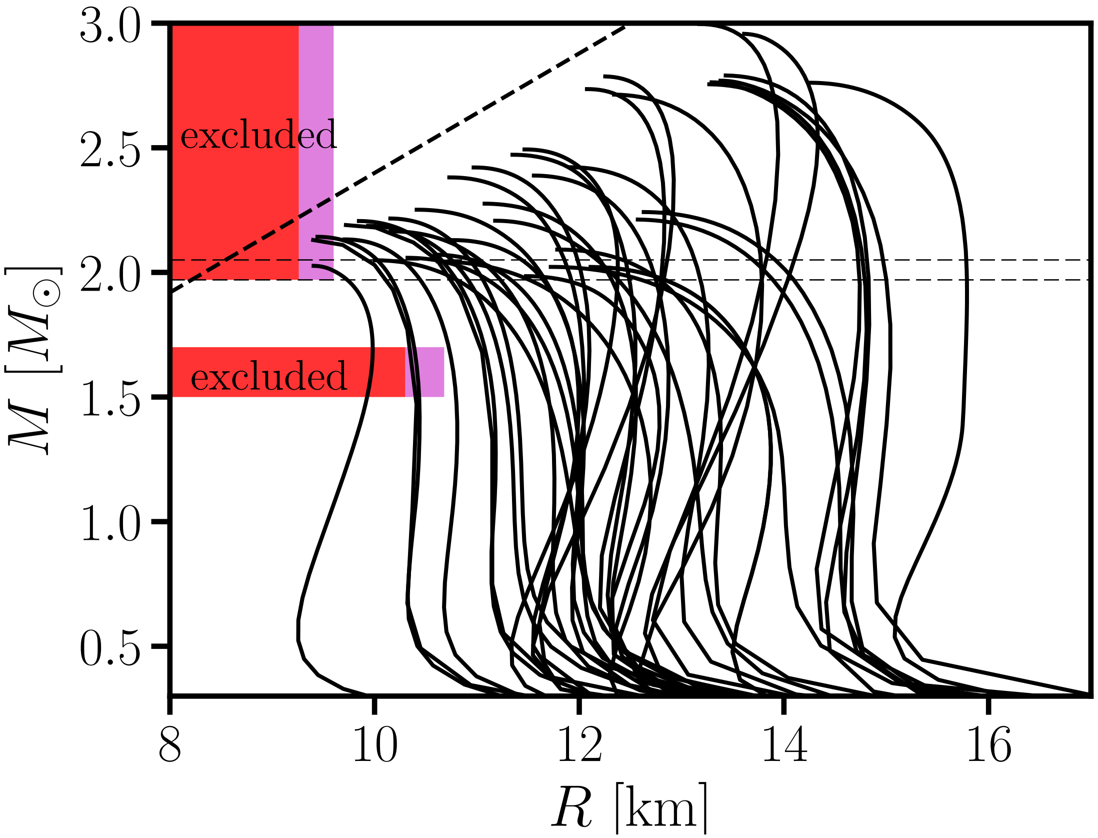
We introduce a new, powerful method to constrain properties of neutron stars (NSs). We show that the total mass of GW170817 provides a reliable constraint on the stellar radius if the merger did not result in a prompt collapse as suggested by the interpretation of associated electromagnetic emission. The radius $R_{1.6}$ of nonrotating NSs with a mass of 1.6 $M_\odot$ can be constrained to be larger than $10.68^{+0.15}_{-0.04}$ km, and the radius $R_{\rm max}$ of the nonrotating maximum mass configuration must be larger than $9.60^{+0.14}_{-0.03}$ km. We point out that detections of future events will further improve these constraints. Moreover, we show that a future event with a signature of a prompt collapse of the merger remnant will establish even stronger constraints on the NS radius from above and the maximum mass $M_{\rm max}$ of NSs from above. These constraints are particularly robust because they only require a measurement of the chirp mass and a distinction between prompt and delayed collapse of the merger remnant, which may be inferred from the electromagnetic signal or even from the presence/absence of a ringdown gravitational-wave (GW) signal. This prospect strengthens the case of our novel method of constraining NS properties, which is directly applicable to future GW events with accompanying electromagnetic counterpart observations. We emphasize that this procedure is a new way of constraining NS radii from GW detections independent of existing efforts to infer radius information from the late inspiral phase or postmerger oscillations, and it does not require particularly loud GW events.

$$M_{\rm thres} > M_{\rm tot}^{\rm GW170817} = 2.74^{+0.04}_{-0.01}\ M_\odot,$$

$$M_{\rm thres} = \left(-3.606\frac{GM_{\rm max}}{c^2 R_{1.6}} + 2.38\right)\cdot M_{\rm max}$$

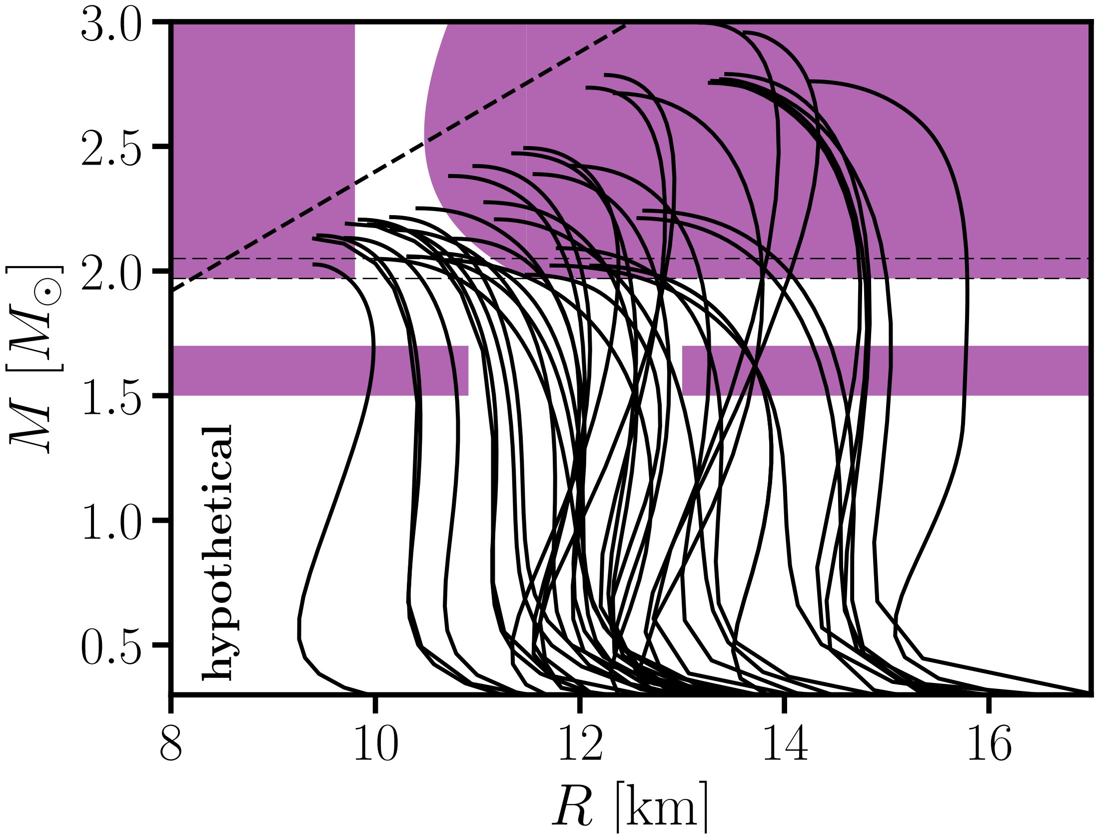
$$M_{\rm thres} = \left(-3.38\frac{GM_{\rm max}}{c^2 R_{\rm max}} + 2.43\right)\cdot M_{\rm max}$$

GW170817 Radius Constraints



Andreas Bauswein, Oliver Just, Hans-Thomas Janka and Nikolaos Stergioulas
arXiv: 1710.06843

Fictitious GW constraints



Andreas Bauswein, Oliver Just, Hans-Thomas Janka and Nikolaos Stergioulas
arXiv: 1710.06843

Moments of Inertia

J.M. Lattimer, M. Prakash / Physics Reports 442 (2007) 109–165 135

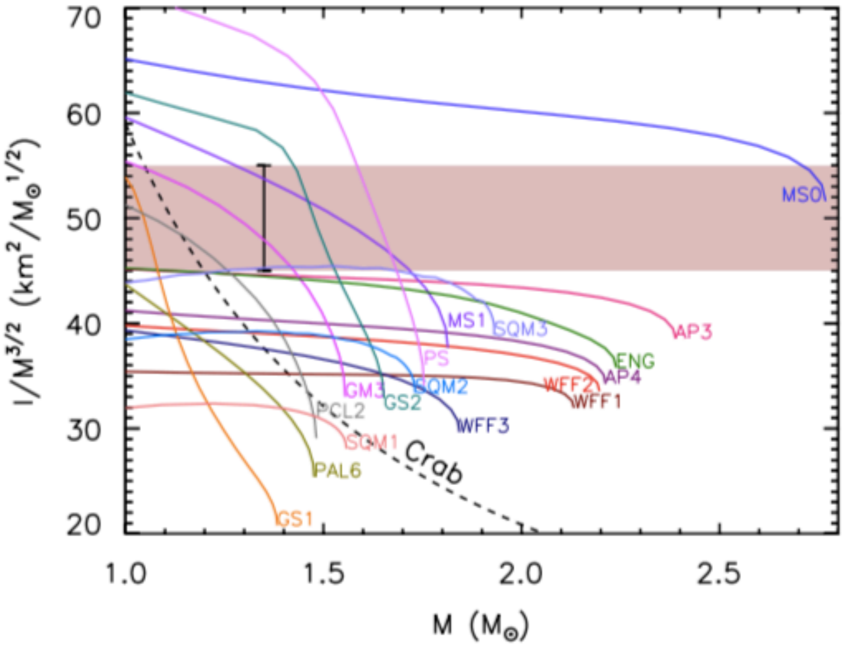
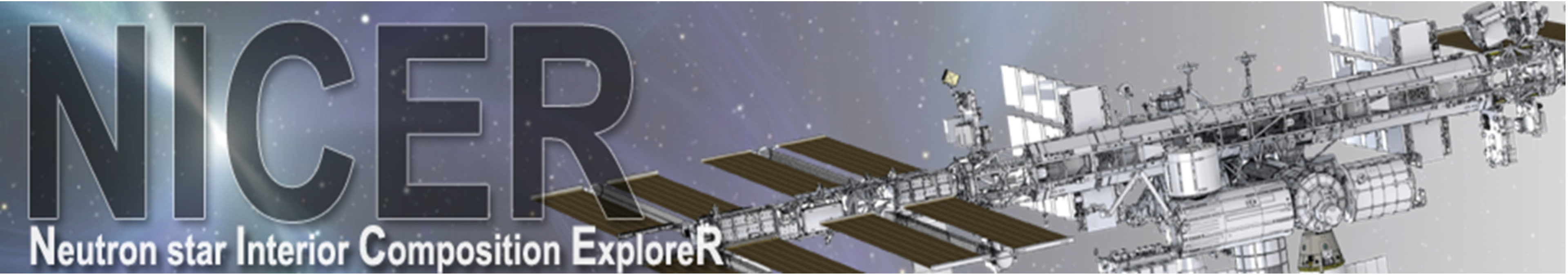


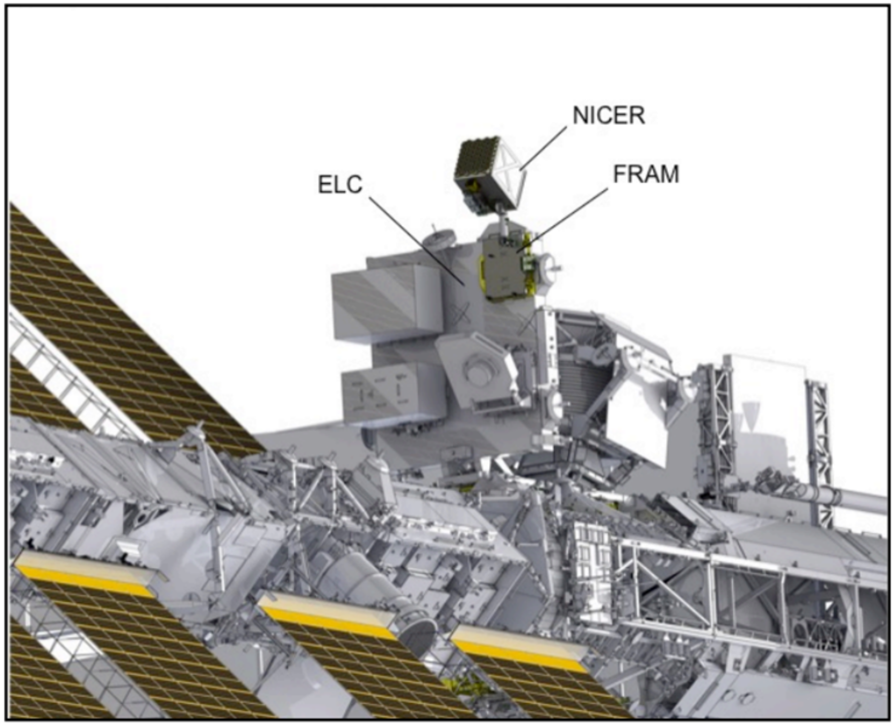
Fig. 9. The moment of inertia scaled by $M^{3/2}$ as a function of stellar mass M for EOSs described in [6]. The shaded band illustrates a ±10% error on a hypothetical $I/M^{3/2}$ measurement with centroid 50 km^2 M$_\odot^{-1/2}$; the error bar shows the specific case in which the mass is 1.34 M$_\odot$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

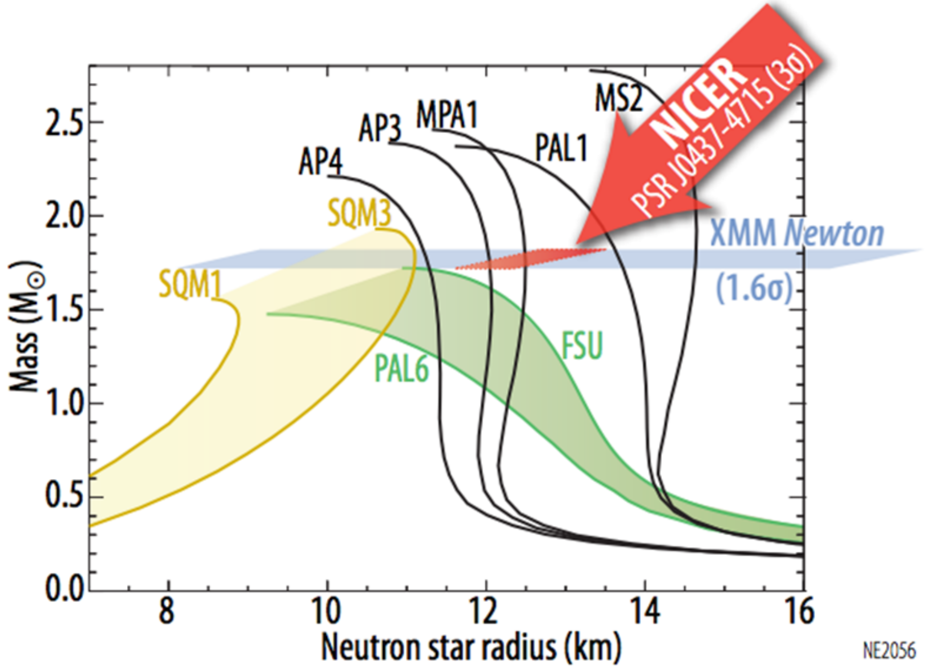
$$I \simeq \frac{J}{1+2GJ/R^3c^2}, \quad J = \frac{8\pi}{3}\int_0^R r^4\left(\rho+\frac{p}{c^2}\right)\Lambda dr, \quad \Lambda = \frac{1}{1-2Gm/rc^2}$$

Perspectives for new Instruments?

THE FUTURE: SKA - SQUARE KILOMETER ARRAY

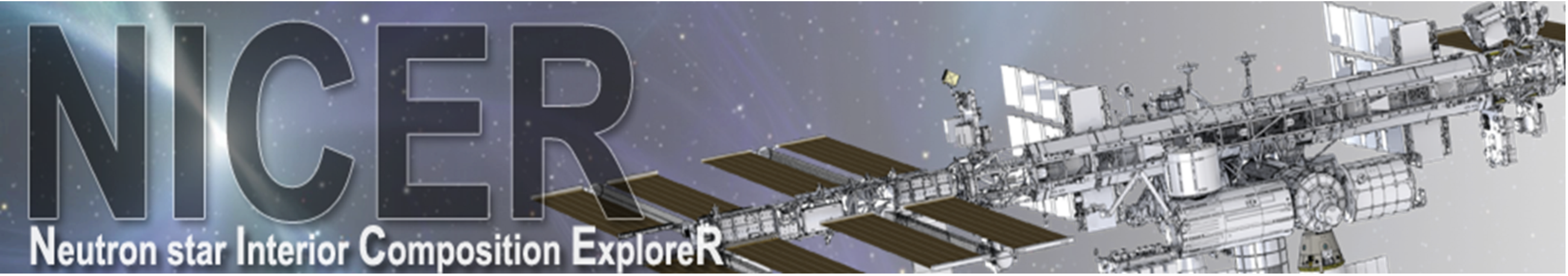


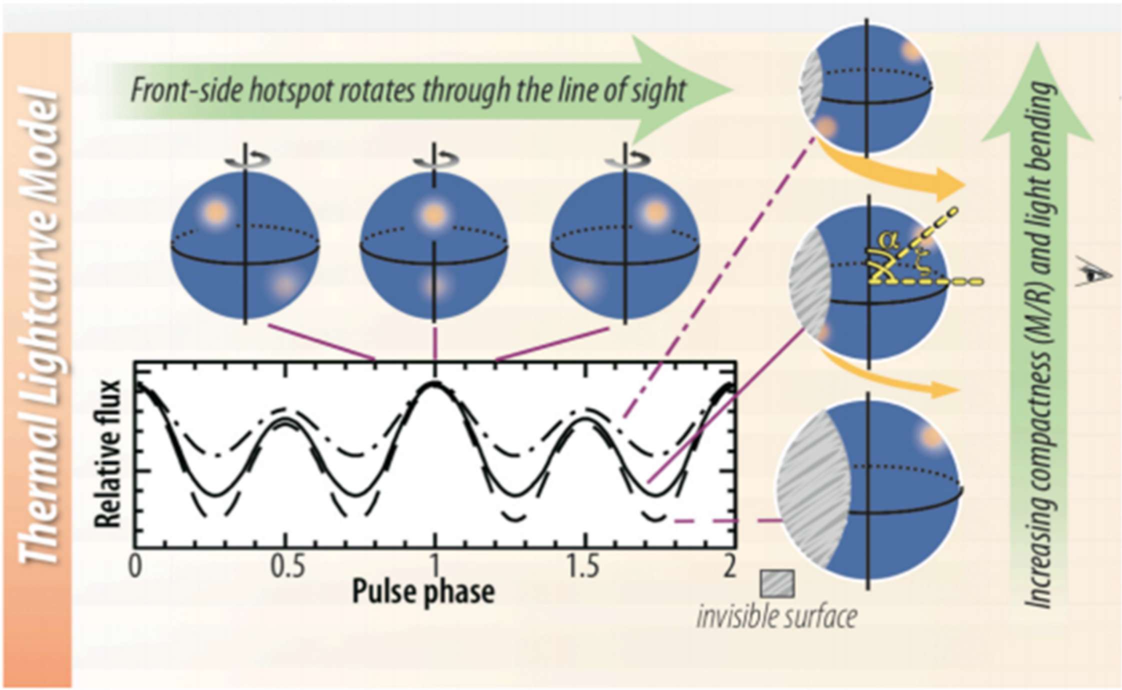


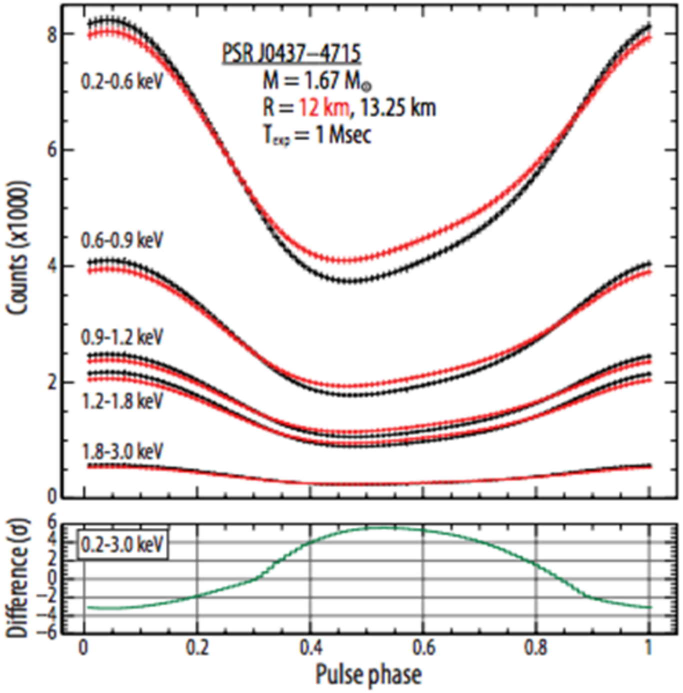


NICER 2017

Gendreau, K. C., Arzoumanian, Z., & Okajima, T. 2012, Proc. SPIE, 8443, 844313


NICER
Neutron star Interior Composition ExploreR


Thermal Lightcurve Model
Front-side hotspot rotates through the line of sight
Increasing compactness (M/R) and light bending
α
ξ
Relative flux
Pulse phase
0
0.5
1
1.5
2
invisible surface


PSR J0437−4715
M = 1.67 M⊙
R = 12 km, 13.25 km
T_exp = 1 Msec
0.2-0.6 keV
0.6-0.9 keV
0.9-1.2 keV
1.2-1.8 keV
1.8-3.0 keV
Counts (x1000)
0
2
4
6
8
0.2-3.0 keV
Difference (σ)
6
4
2
0
−2
−4
−6
0
0.2
0.4
0.6
0.8
1
Pulse phase

Hot Spots

Conclusions

- The symmetry energy strongly determines the NS radius.
- USEC conjecture has been corroborated and E_s related quantities found to be correlated with the NS radius.
- Given the knowledge from lattice QCD that at zero baryon density the QCD phase transition proceeds as a crossover, twins would then support the existence of a CEP in the QCD phase diagram.

Conclusions

- Three of the fundamental puzzles of compact star structure, the hyperon puzzle, the masquerade problem and the reconfinement problem may be all solved by accounting for quark Pauli blocking on the hadronic side and by introducing stiffening effects on the quark matter side of the EoS.

- GW170817 favours softer hadronic EoS and together with the Durca constraint DD2F-like EoS are favoured.

- Hybrid stars also favoured by GW170817.

- Future GW observations, NICER and SKA will soon result into stronger NS EoS constraints.

Gracias