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

David E. Álvarez Castillo

Joint Institute for Nuclear Research

Hadronic Matter Under Extreme Conditions

JINR Dubna

31.10.2016 - 3.11.2016

3rd of November, 2016

Collaborations

David Blaschke (BLTP, Univ. Wroclaw, MEPhI)
Stefan Typel (GSI Darmstadt)
Sanjin Benic (Univ. Zagreb, Univ. Tokyo)
Hovik Grigorian, Alexander Ayriyan (LIT)
Pawel Haensel, Leszek Zdunik, Michal Bejger (CAMK Warsaw)

Special thanks to our supporters:

Heisenberg-Landau Program (with S. Typel)
Bogoliubov-Infeld Program (with D. Blaschke)
Ter Antonian - Smorodinsky Program (with H. Grigorian)
RSA - JINR Collaboration (visits in SA for Schools and Conference)
COST Action STSM Program (with D. Blaschke & CompStar Conferences)
Narodowe Centrum Nauki (visits in Wroclaw, Poland)

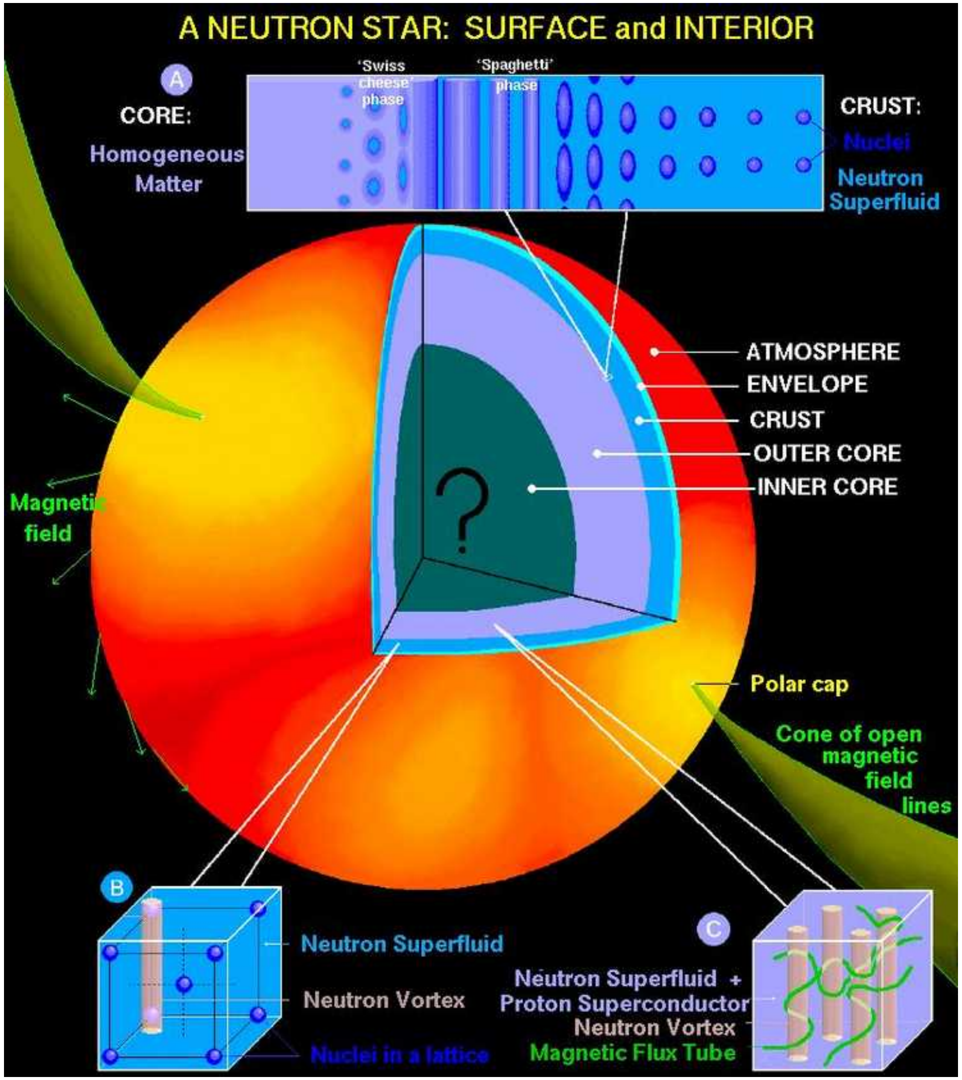
Key Questions

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

Outline

- Introduction to the neutron star equation of state.
- First order phase transition and deconfinement in compact stars: neutron star twins.
- Astrophysics measurements of compact stars.
- Astrophysical implications and perspectives.

Neutron Stars



Credit: Dany Page, UNAM

Neutron Star EoS

- Nuclear interaction:

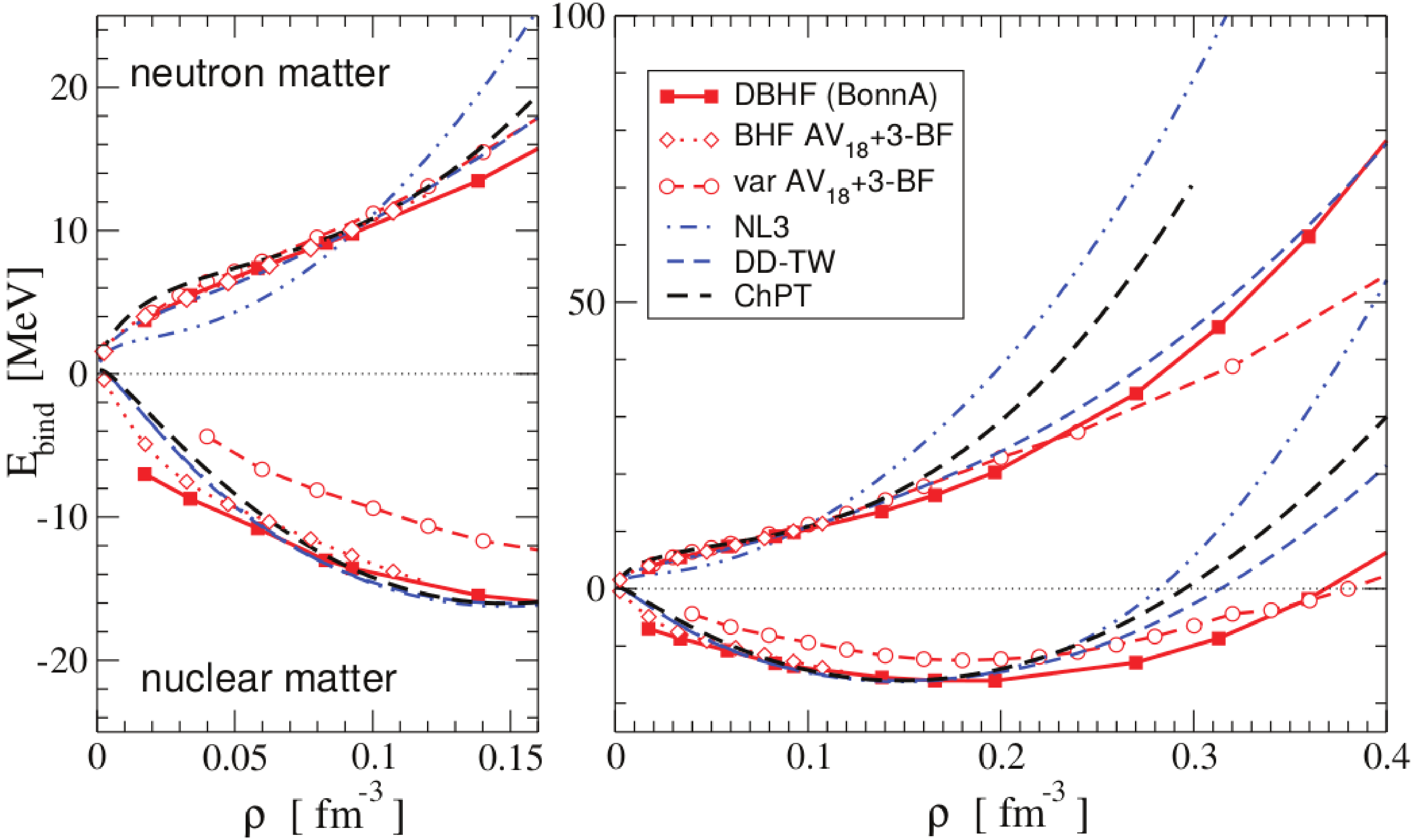
$$E(n,x) = E(n, x = 1/2) + E_s(n) * \alpha^2(x),$$

- Beta equilibrium: $\mu_n - \mu_p = \mu_e = \mu_\mu$
- 2 phase construction under Gibbs conditions: $p^I = p^{II}$ $\mu_n^I = \mu_n^{II}$ $\mu_e^I = \mu_e^{II}$
- Charge neutrality: $x_p = x_e$
- TOV equations + Equation of State

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

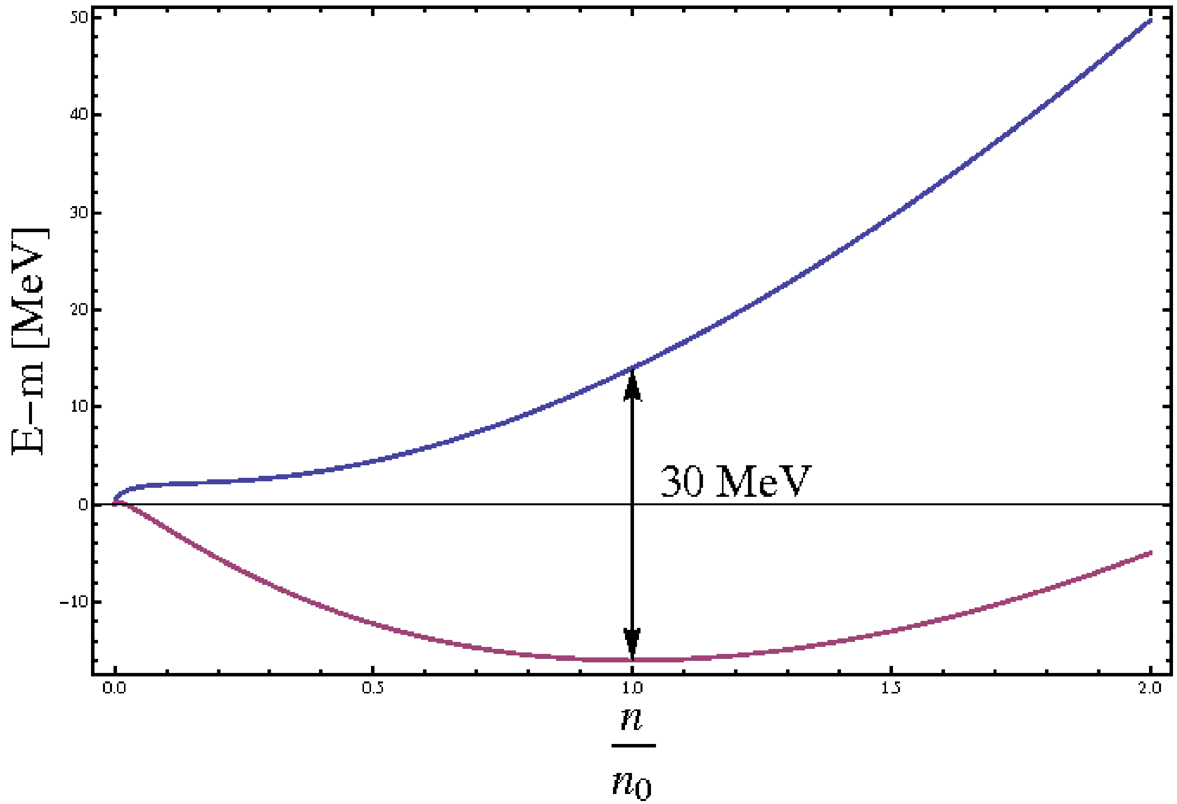
$$\frac{dm}{dr} = 4\pi r^2 \rho$$

Nuclear Matter



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

Nuclear Symmetry Energy

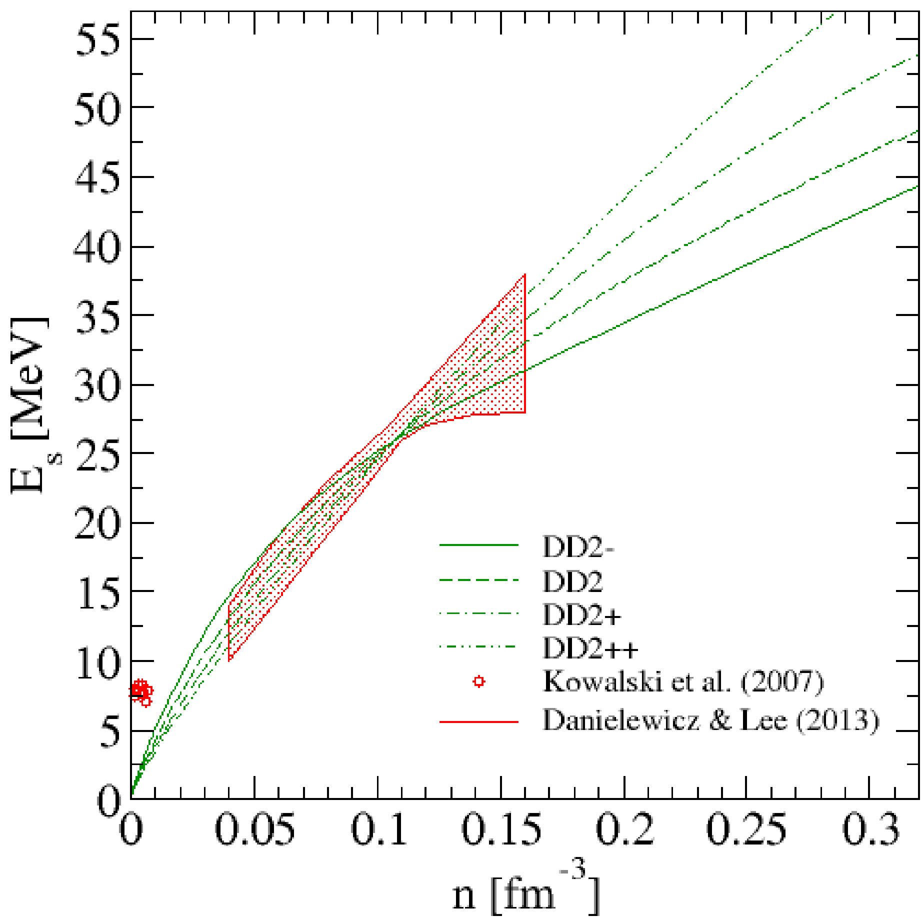


is the difference between symmetric nuclear matter and pure neutron matter:

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

where $\alpha = 1 - 2x$

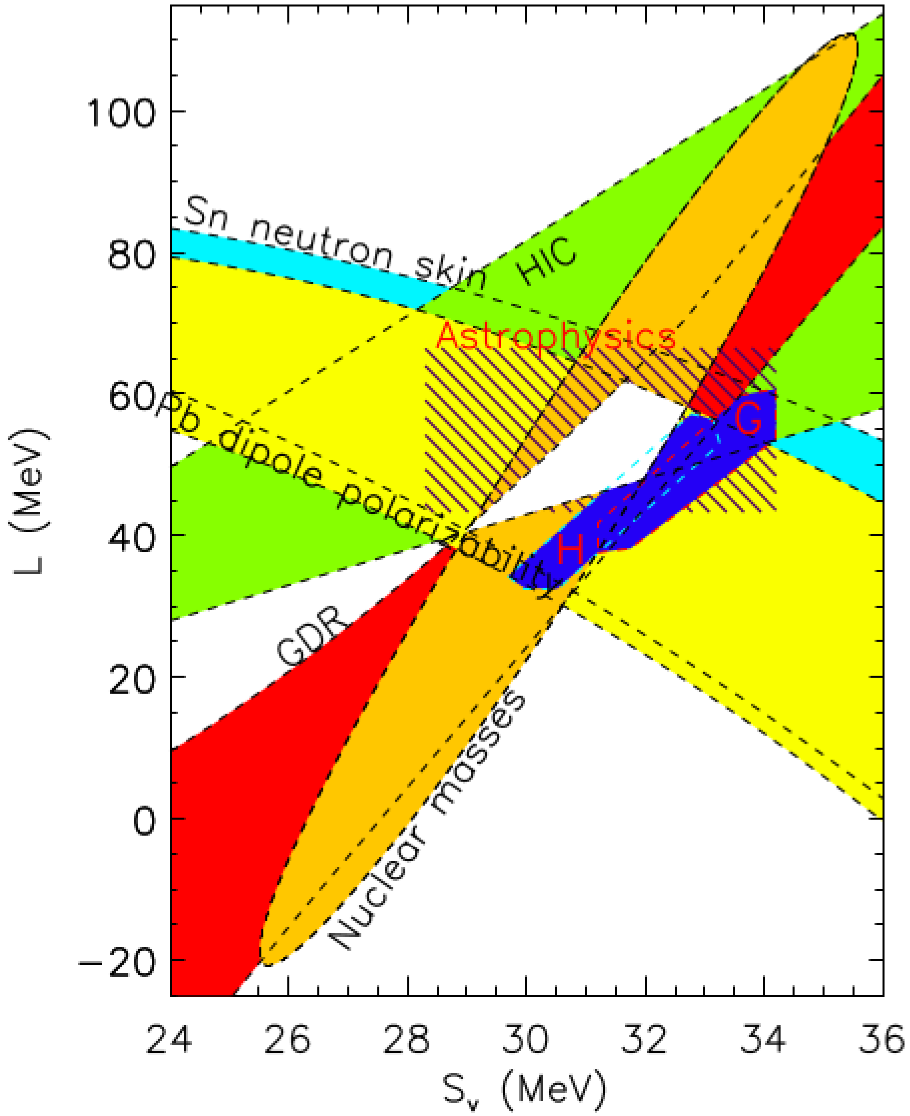
Nuclear Symmetry Energy



$E_s(n)$	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)

Measuring the symmetry energy



Lattimer and Lim - (2013) ApJ 771 51

Charge neutrality and β-equillibrium

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

$$E_{\rm tot}(n,\{x_i\}) = E_{\rm b}(n,x_p) + E_{\rm lep}(n,x_e,x_\mu)\ ,$$
$$E_{\rm b}(n,x_p) = E_0(n) + S(n,x_p)$$
$$E_{\rm lep}(n,x_e,x_\mu) = E_e(n,x_e) + E_\mu(n,x_\mu)\ ,$$

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 $l = e, \mu$

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

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:

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

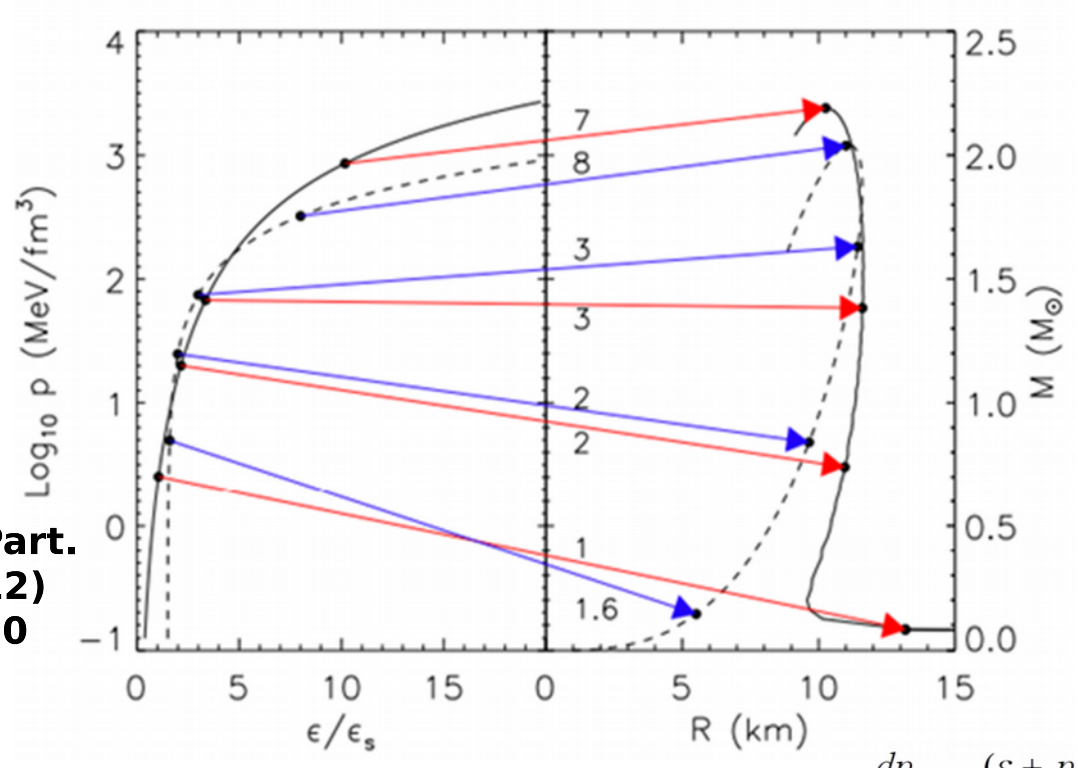
Since electrons in neutron star interiors are ultrarelativistic,

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

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

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

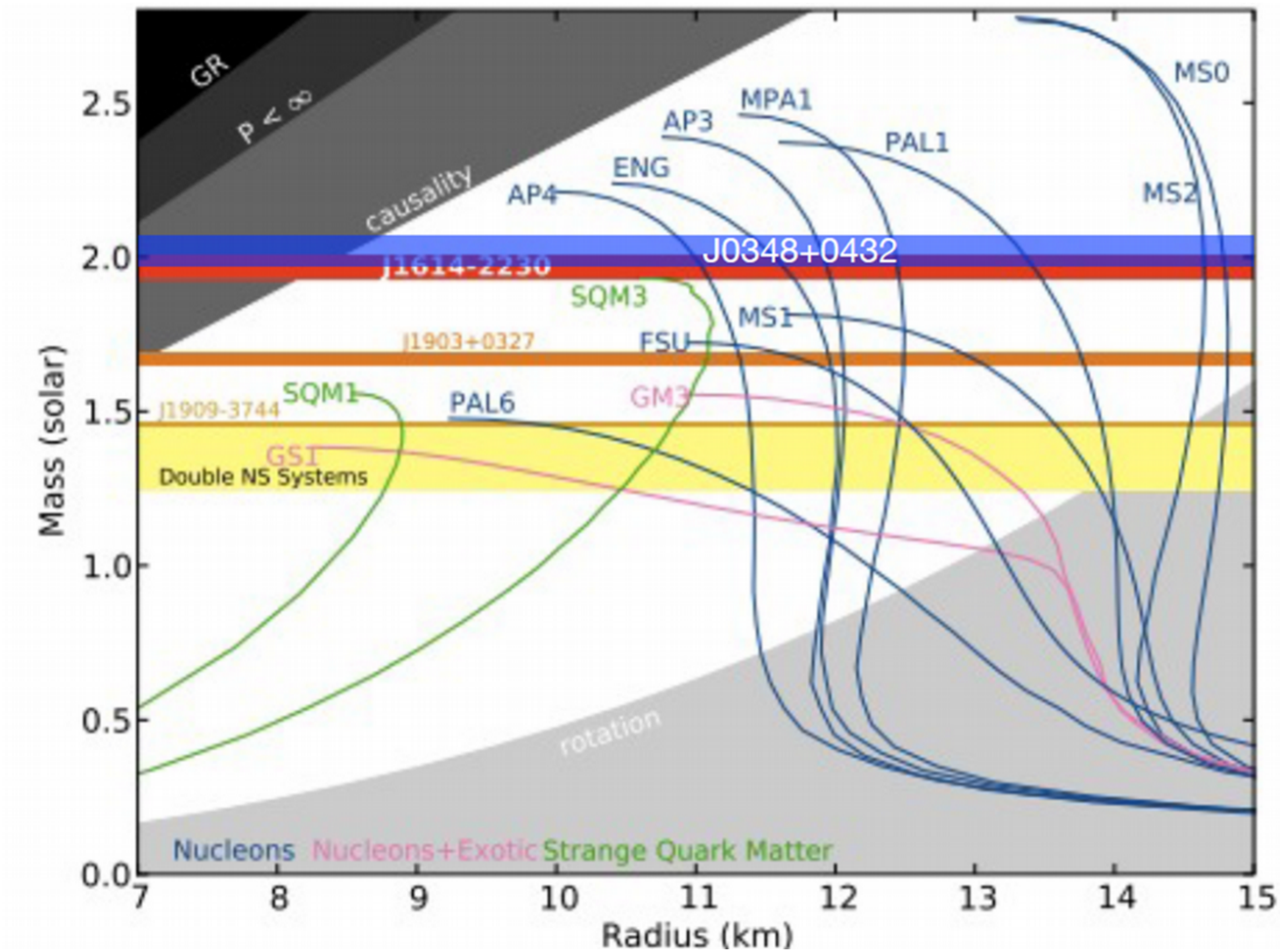
$$\frac{dp}{dr} = -\frac{(\varepsilon + p/c^2)G(m + 4\pi r^3 p/c^2)}{r^2(1 - 2Gm/rc^2)}$$

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

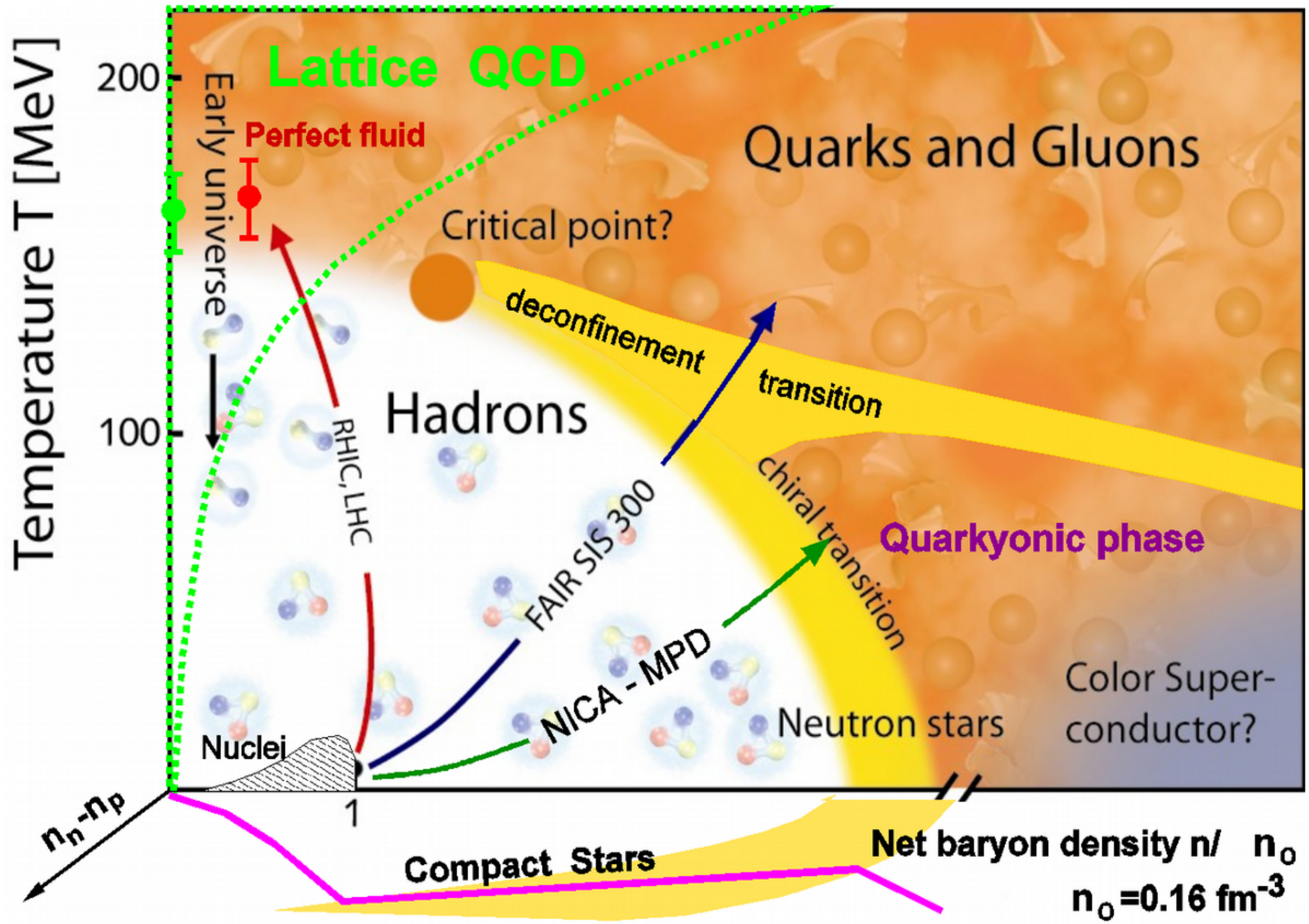
- Equation of State (EoS)

$$p(\varepsilon)$$

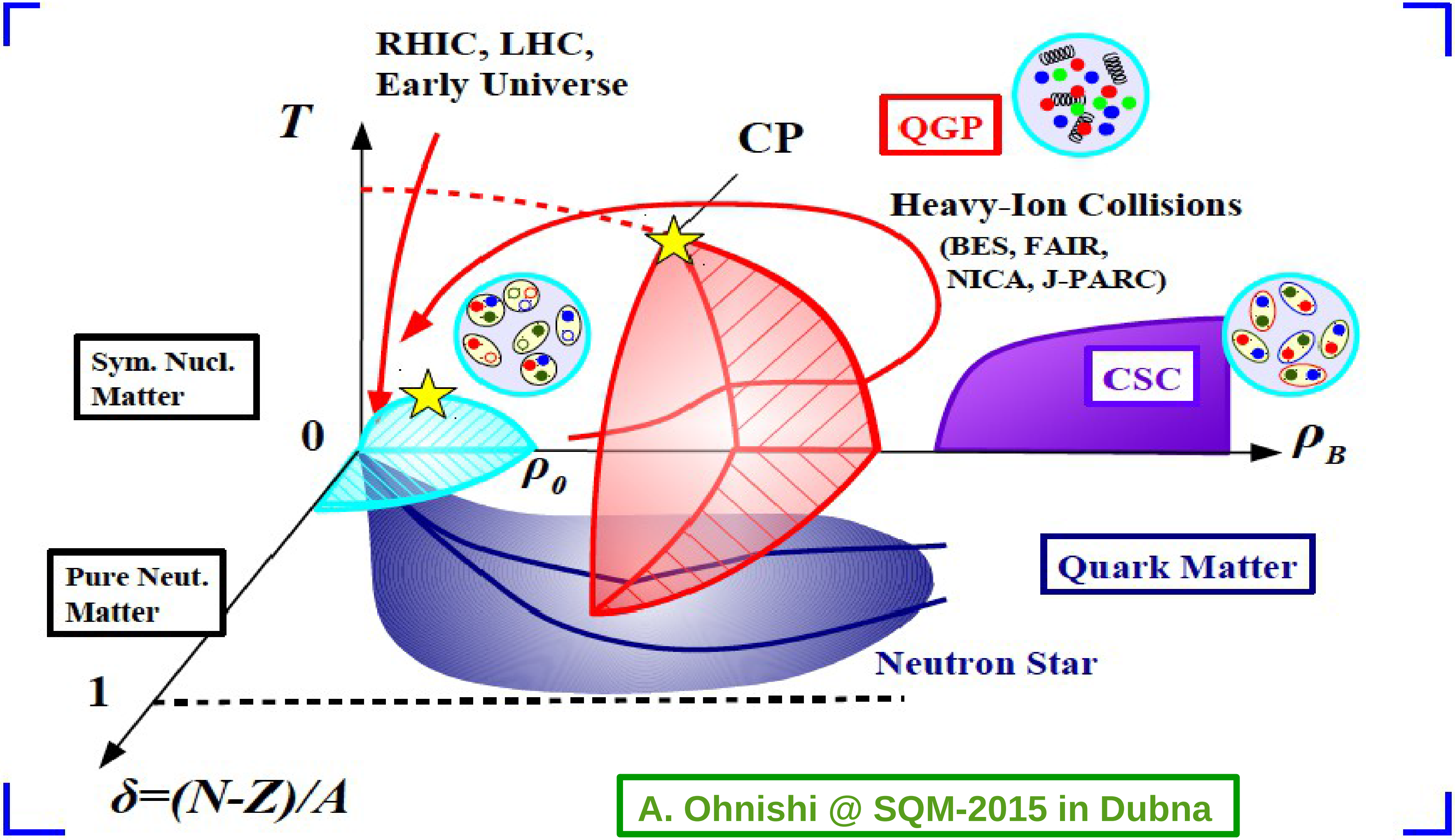
Massive neutron stars



Critical Endpoint in QCD



Support a CEP in QCD phase diagram with Astrophysics?



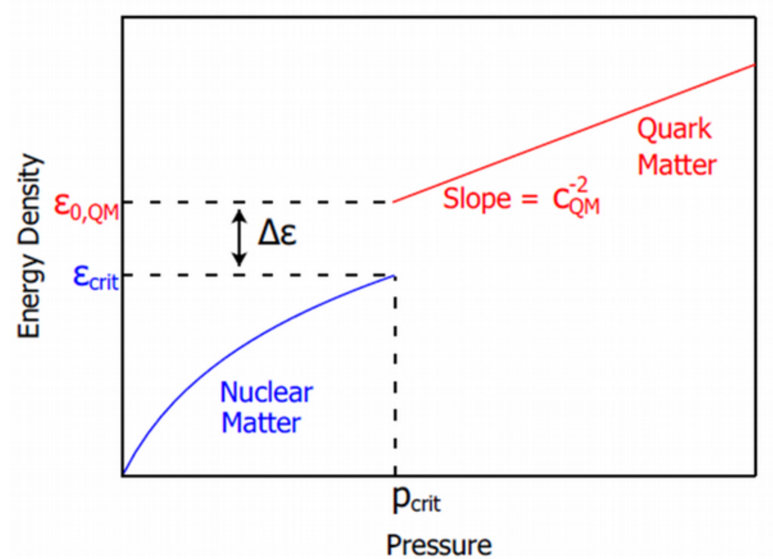
Crossover at finite T (Lattice QCD) + First order at zero T (Astrophysics) = Critical endpoint exists!

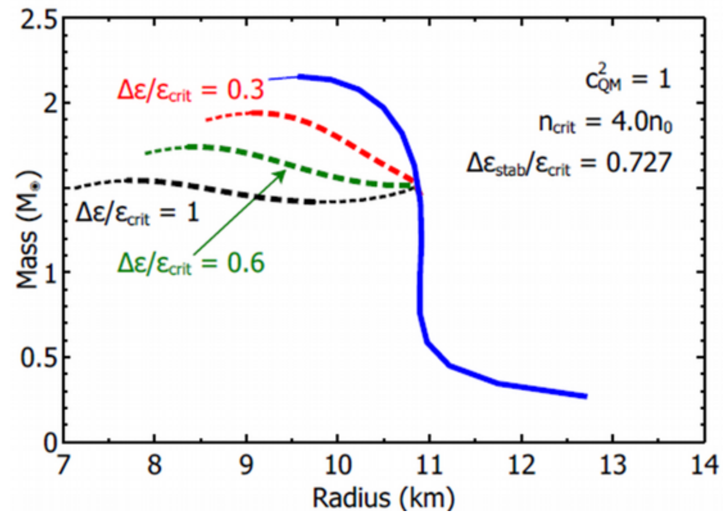
Neutron Star Twins and the AHP scheme

- 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**!

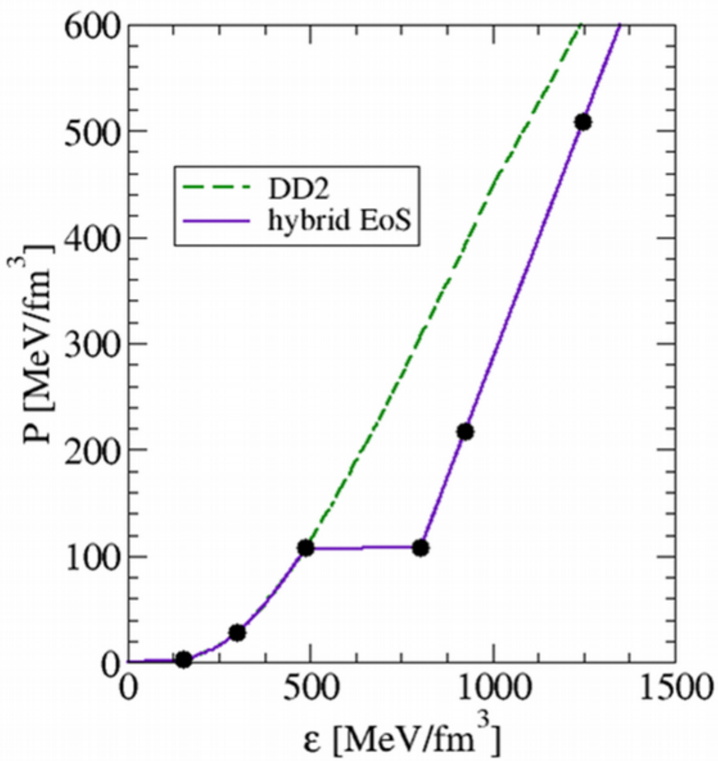
Alford, Han, Prakash,
Phys. Rev. D 88, 083013 (2013)
arxiv:1302.4732

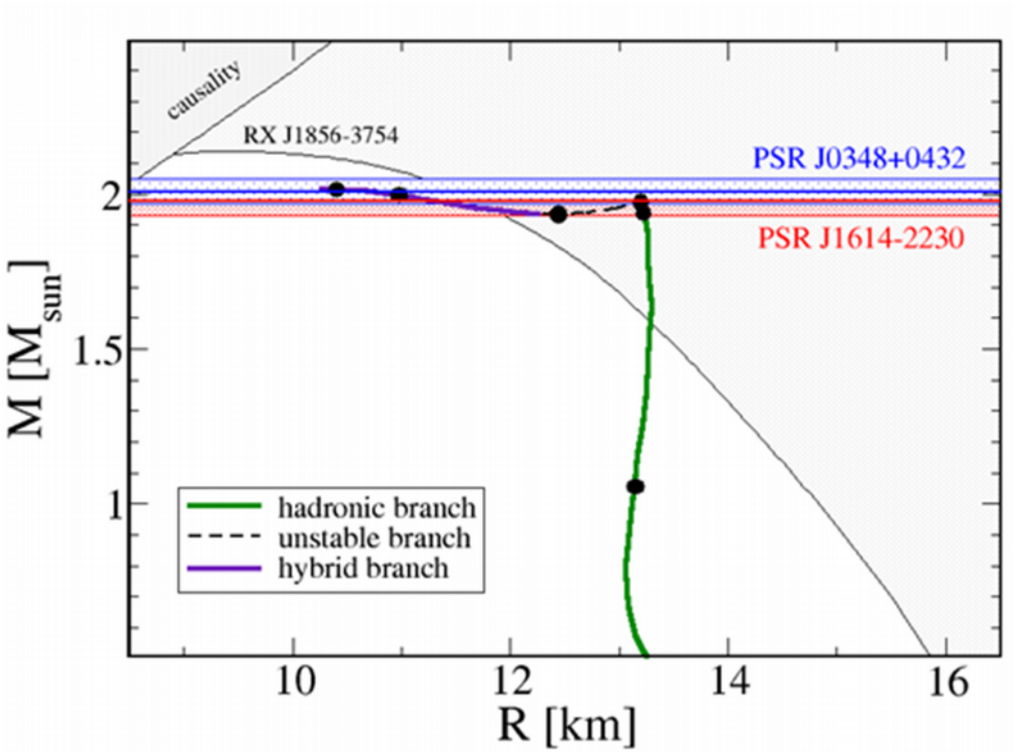




Compact Star Twins

Third family (disconnected branch)





Alvarez-Castillo, Blaschke (2013),
Proceedings of the 17th Conference of Young Scientists and Specialists,
arXiv: 1304.7758

Quark substructure effects in baryonic matter

Excluded volume mechanism in the context of RMF models

Consider nucleons as hard spheres of volume $V_{\rm nuc}$, the available volume V_{av} for the motion of nucleons is only a fraction $\Phi = V_{av}/V$ of the total volume V of the system. We introduce

$$\Phi = 1 - v \sum_{i=n,p} n_i \ ,$$

with nucleon number densities n_i and volume parameter $v = \frac{1}{2}\frac{4\pi}{3}(2r_{\rm nuc})^3 = 4V_{\rm nuc}$ and identical radii $r_{\rm nuc} = r_n = r_p$ of neutrons and protons. The total hadronic pressure and energy density are:

$$p_{\rm tot}(\mu_n, \mu_p) = \frac{1}{\Phi}\sum_{i=n,p} p_i + p_{\rm mes} \ ,$$

$$\varepsilon_{\rm tot}(\mu_n, \mu_p) = -p_{\rm tot} + \sum_{i=n,p} \mu_i n_i \ ,$$

with contributions from nucleons and mesons depending on μ_n and μ_p. The nucleonic pressure

$$p_i = \frac{1}{4}\left(E_i n_i - m_i^* n_i^{(s)}\right) \ ,$$

contains the nucleon number densities, scalar densities and energies:

$$n_i = \frac{\Phi}{3\pi^3}k_i^3, \quad n_i^{(s)} = \frac{\Phi m_i^*}{2\pi^2}\left[E_i k_i - (m_i^*)^2 \ln\frac{k_i + E_i}{m_i^*}\right], \quad E_i = \sqrt{k_i^2 + (m_i^*)^2} = \mu_i - V_i - \frac{v}{\Phi}\sum_{j=p,n} p_j,$$

as well as Fermi momenta k_i and effective masses $m_i^* = m_i - S_i$. The vector V_i and scalar S_i potentials and the mesonic contribution $p_{\rm mes}$ to the total pressure have the usual form of RMF models with density-dependent couplings.

Benic, Blaschke, Alvarez-Castillo, Fischer, Typel, A&A 577, A40 (2015)

NJL model with multiquark interactions

$$\mathcal{L} = \bar{q}(i\partial\!\!\!/ - m)q + \mu_q \bar{q}\gamma^0 q + \mathcal{L}_4 + \mathcal{L}_8\ ,\ \mathcal{L}_4 = \frac{g_{20}}{\Lambda^2}[(\bar{q}q)^2 + (\bar{q}i\gamma_5\tau q)^2] - \frac{g_{02}}{\Lambda^2}(\bar{q}\gamma_\mu q)^2\ ,$$

$$\mathcal{L}_8 = \frac{g_{40}}{\Lambda^8}[(\bar{q}q)^2 + (\bar{q}i\gamma_5\tau q)^2]^2 - \frac{g_{04}}{\Lambda^8}(\bar{q}\gamma_\mu q)^4 - \frac{g_{22}}{\Lambda^8}(\bar{q}\gamma_\mu q)^2[(\bar{q}q)^2 + (\bar{q}i\gamma_5\tau q)^2]$$

Meanfield approximation: $\mathcal{L}_{\rm MF} = \bar{q}(i\partial\!\!\!/ - M)q + \tilde{\mu}_q \bar{q}\gamma^0 q - U\ ,$

$$M = m + 2\frac{g_{20}}{\Lambda^2}\langle\bar{q}q\rangle + 4\frac{g_{40}}{\Lambda^8}\langle\bar{q}q\rangle^3 - 2\frac{g_{22}}{\Lambda^8}\langle\bar{q}q\rangle\langle q^\dagger q\rangle^2\ ,$$

$$\tilde{\mu}_q = \mu_q - 2\frac{g_{02}}{\Lambda^2}\langle q^\dagger q\rangle - 4\frac{g_{04}}{\Lambda^8}\langle q^\dagger q\rangle^3 - 2\frac{g_{22}}{\Lambda^8}\langle\bar{q}q\rangle^2\langle q^\dagger q\rangle\ ,$$

$$U = \frac{g_{20}}{\Lambda^2}\langle\bar{q}q\rangle^2 + 3\frac{g_{40}}{\Lambda^8}\langle\bar{q}q\rangle^4 - 3\frac{g_{22}}{\Lambda^8}\langle\bar{q}q\rangle^2\langle q^\dagger q\rangle^2 - \frac{g_{02}}{\Lambda^2}\langle q^\dagger q\rangle^2 - 3\frac{g_{04}}{\Lambda^8}\langle q^\dagger q\rangle^4\ .$$

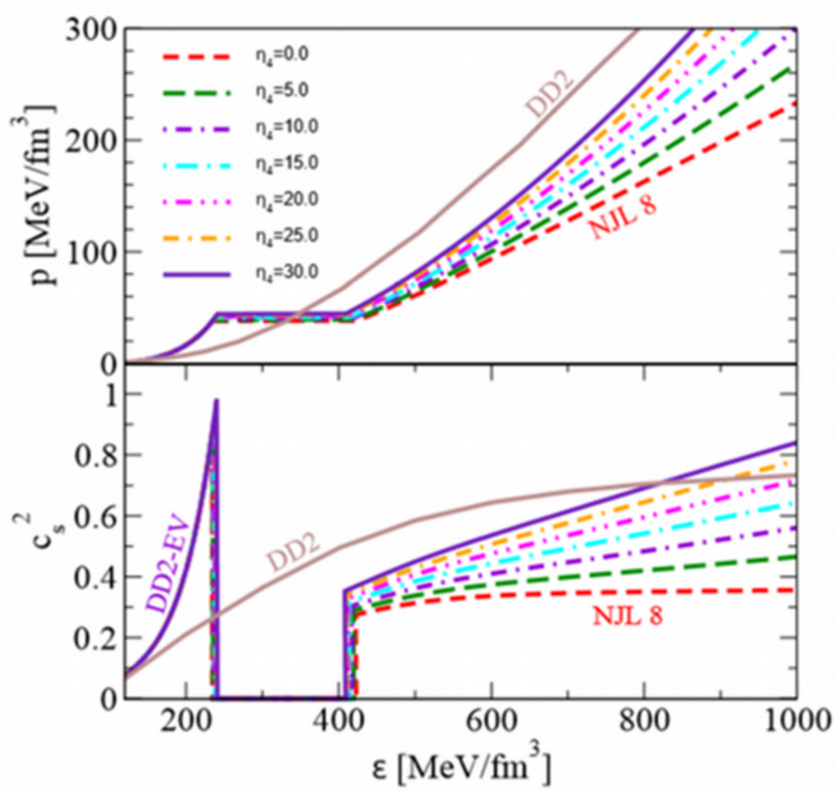
Thermodynamic Potential:

$$\Omega = U - 2N_f N_c \int \frac{d^3p}{(2\pi)^3}\left\{E + T\log[1 + e^{-\beta(E-\tilde{\mu}_q)}] + T\log[1 + e^{-\beta(E+\tilde{\mu}_q)}]\right\} + \Omega_0$$

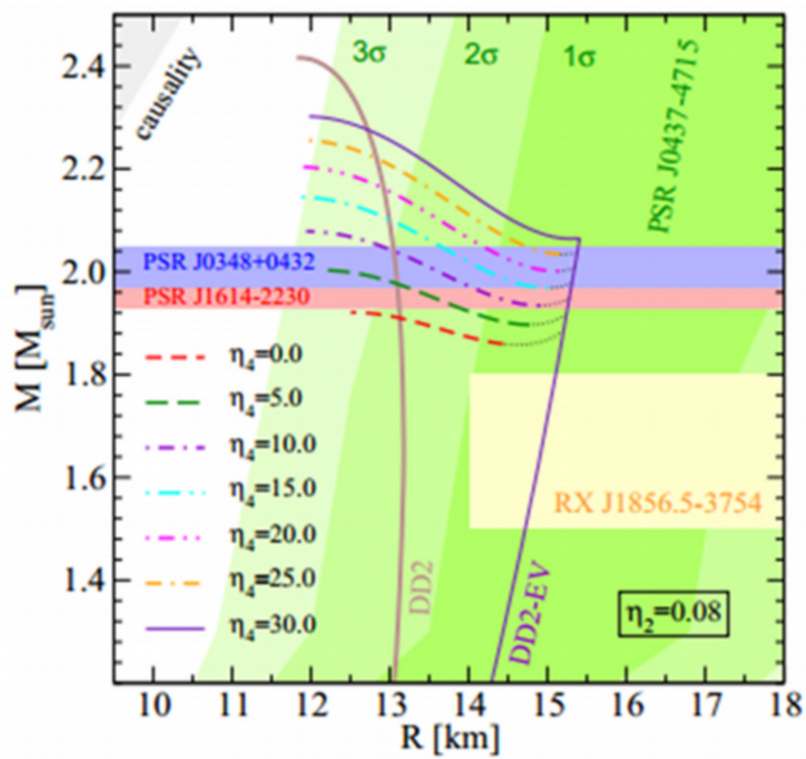
S. Benic - Eur.Phys.J. A50 (2014) 111, arXiv:1401.5380

Neutron Star Twins

Equation of State

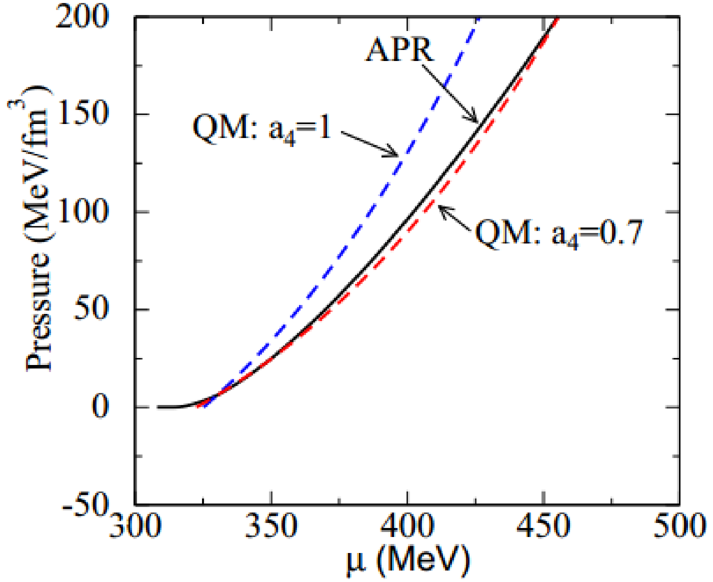


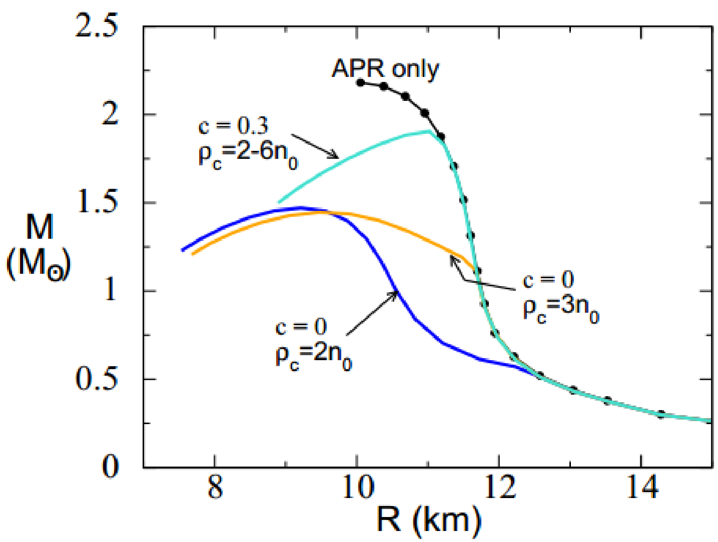
Mass-Radius Relation



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

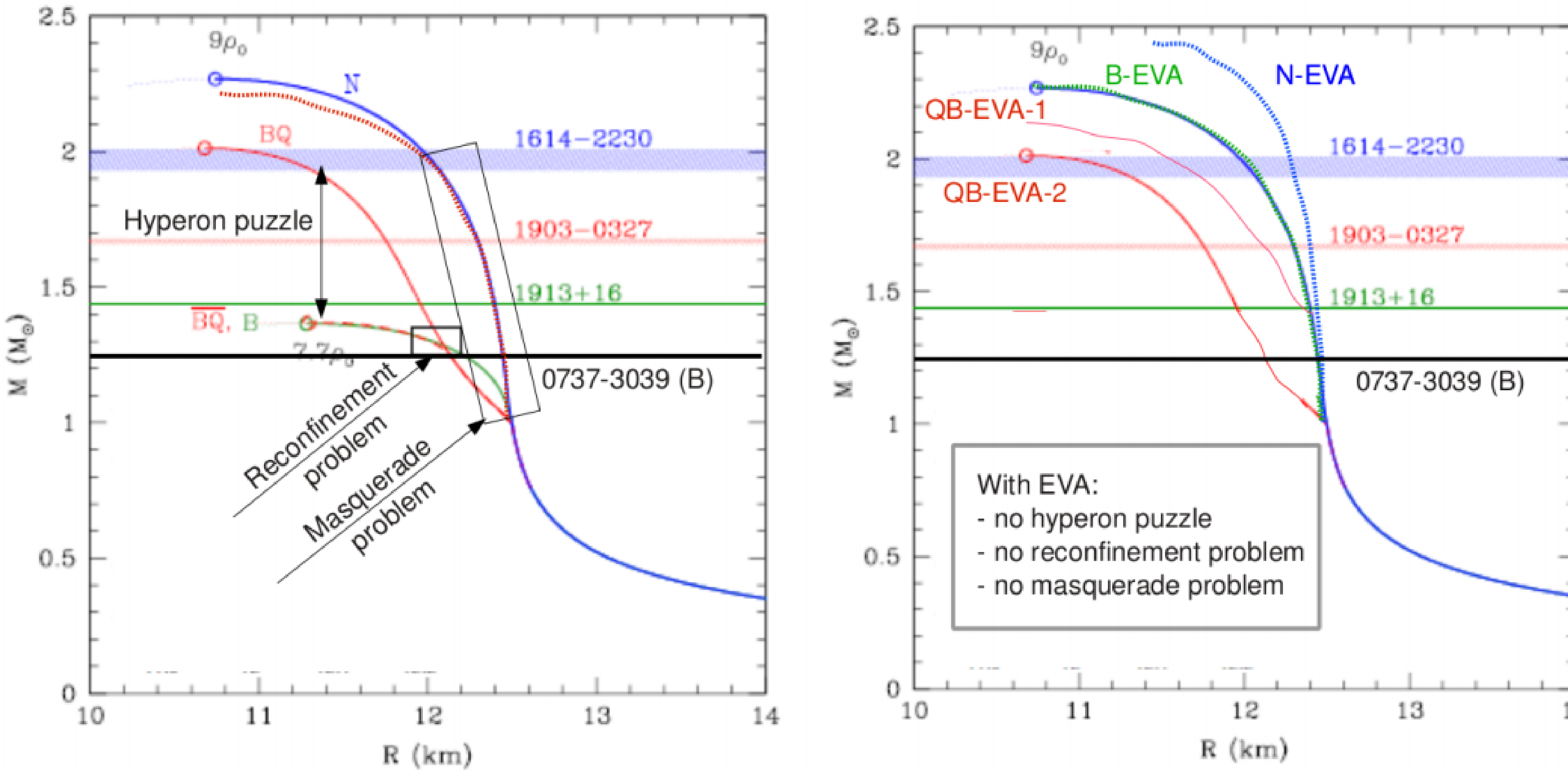
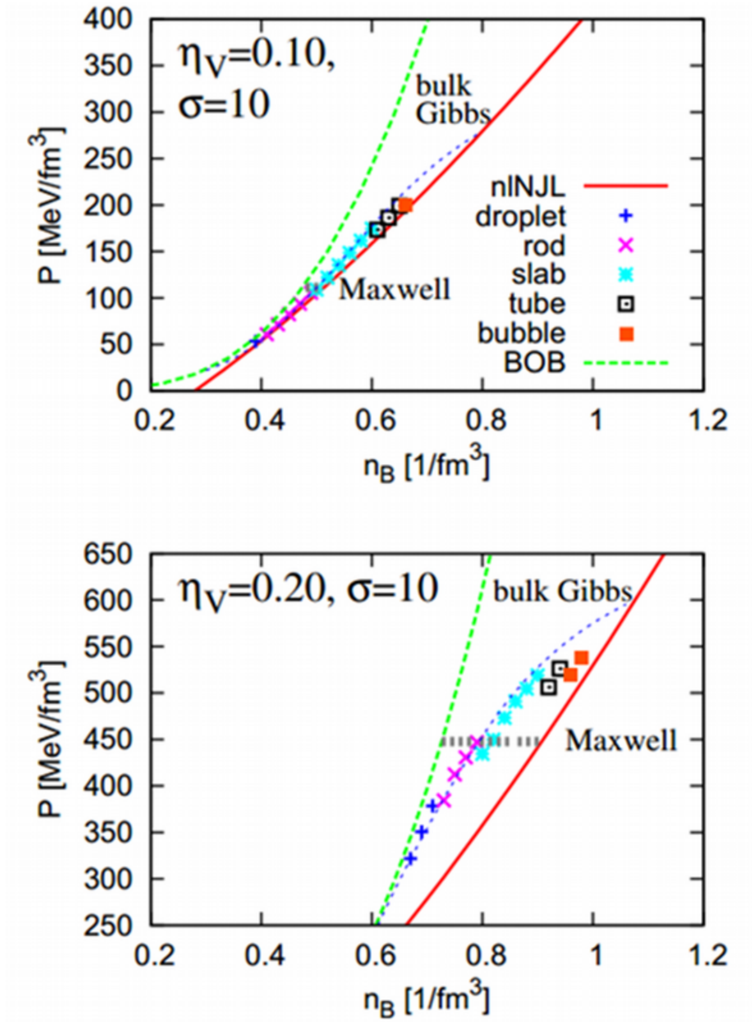


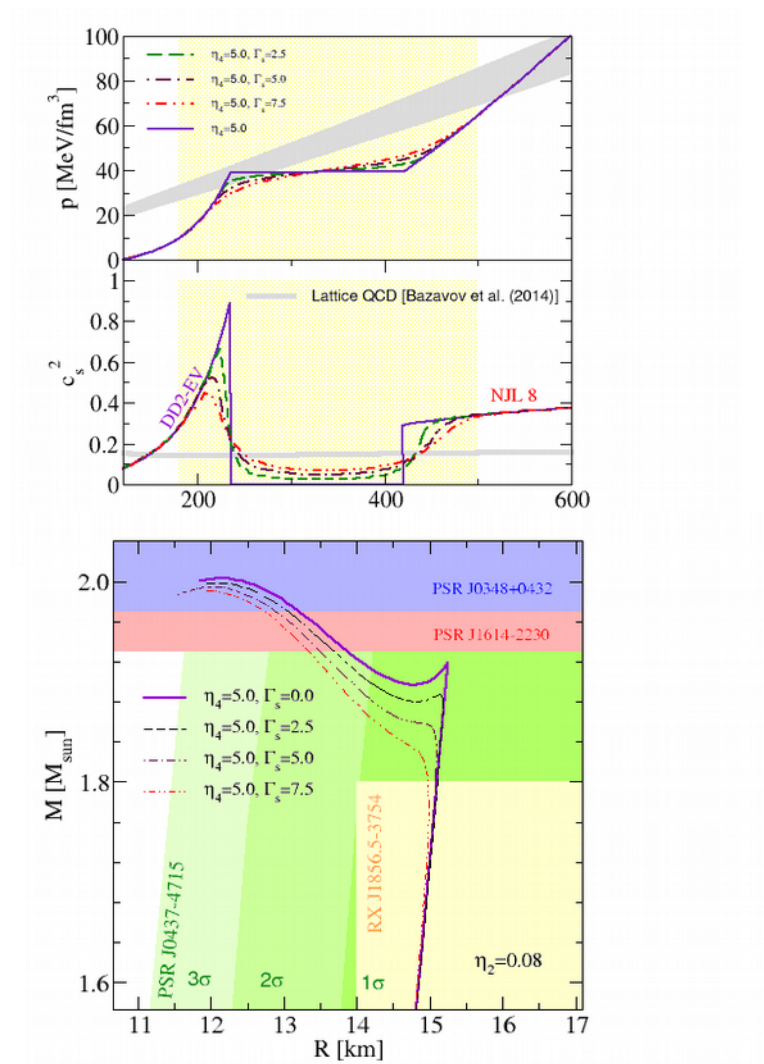
FIGURE 1. Mass-radius sequences for different model equations of state (EoS) illustrate how the three major problems in the theory of exotic matter in compact stars (left panel) can be solved (right panel) by taking into account the baryon size effect within a excluded volume approximation (EVA). Due 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

Pasta phases in hybrid stars

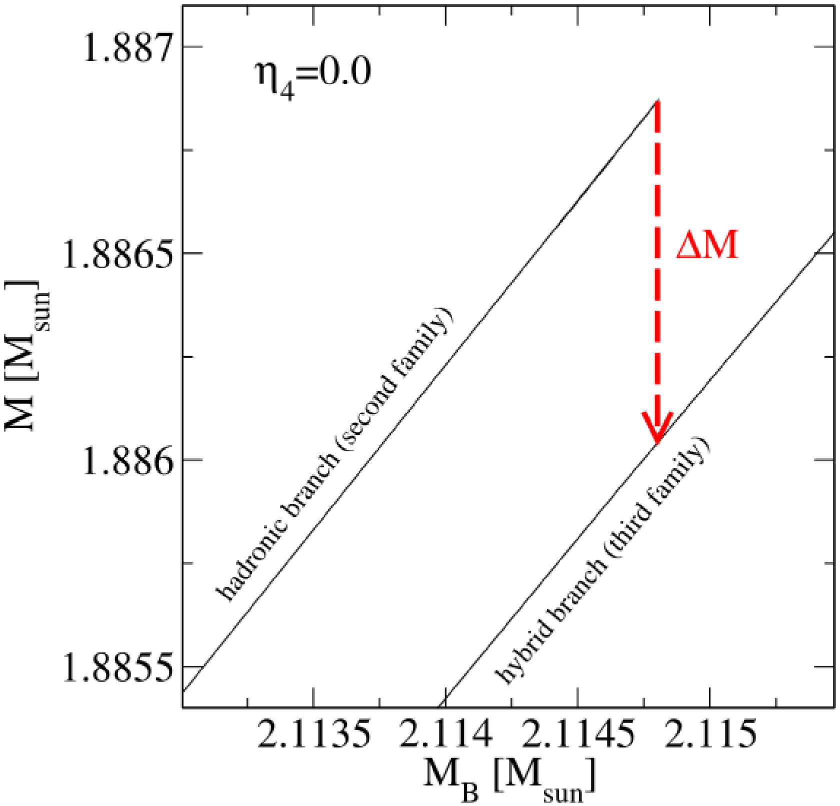


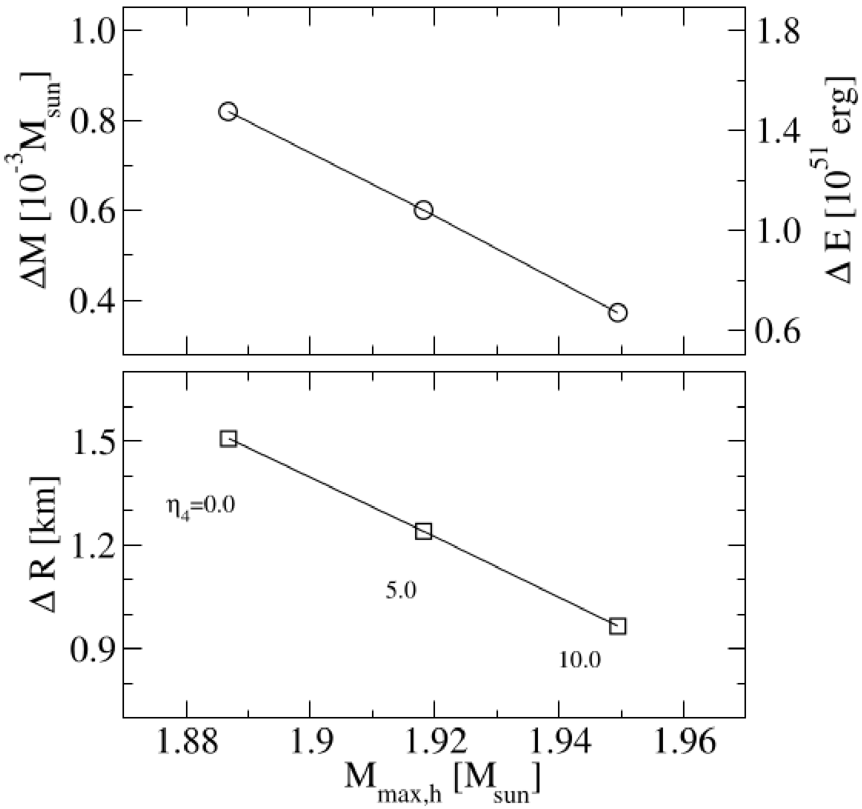
Yasutake et al., Phys. Rev. C 89, 065803 (2014)
arXiv:1403.7492



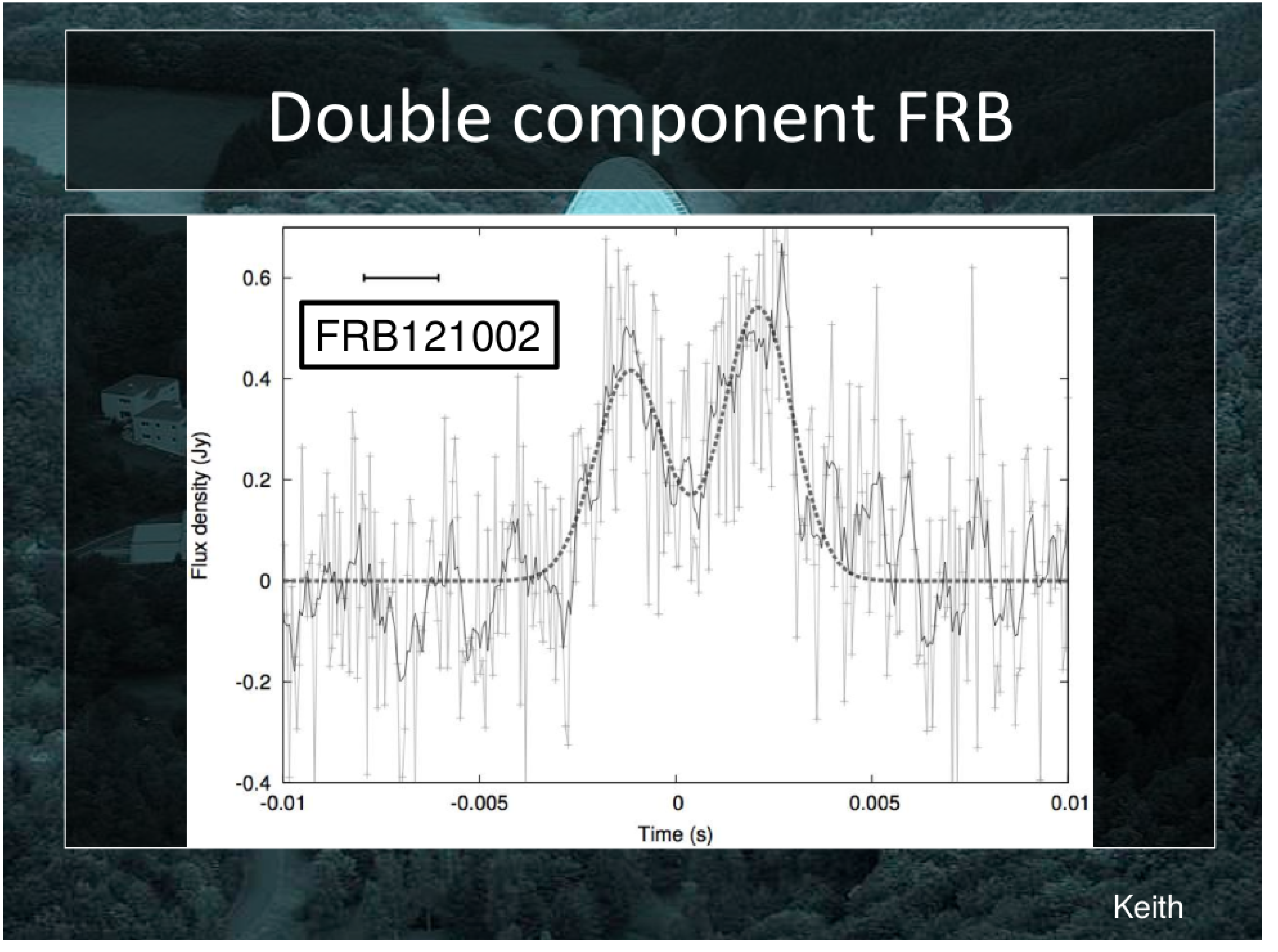
Alvarez Castillo, Blaschke, Phys. Part. Nucl. 46 (2015)
arXiv:1412.8463

Energy bursts from deconfinement





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



Champion, D., 2015, talk at seventh Bonn Work-shop on "Formation and Evolution of Neutron Stars", May 18, 2015 & arXiv: 1511.07746

Bayesian Analysis

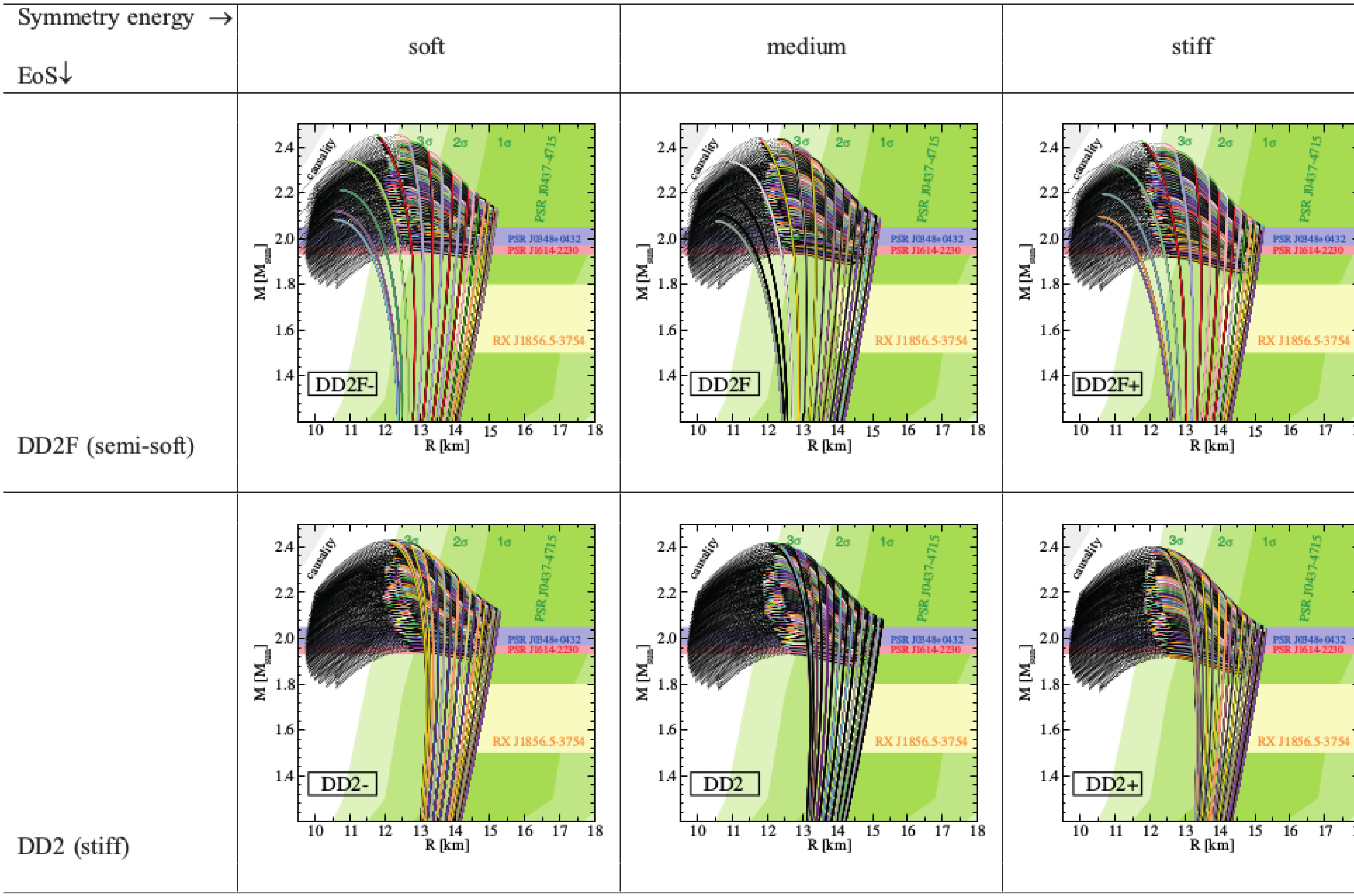
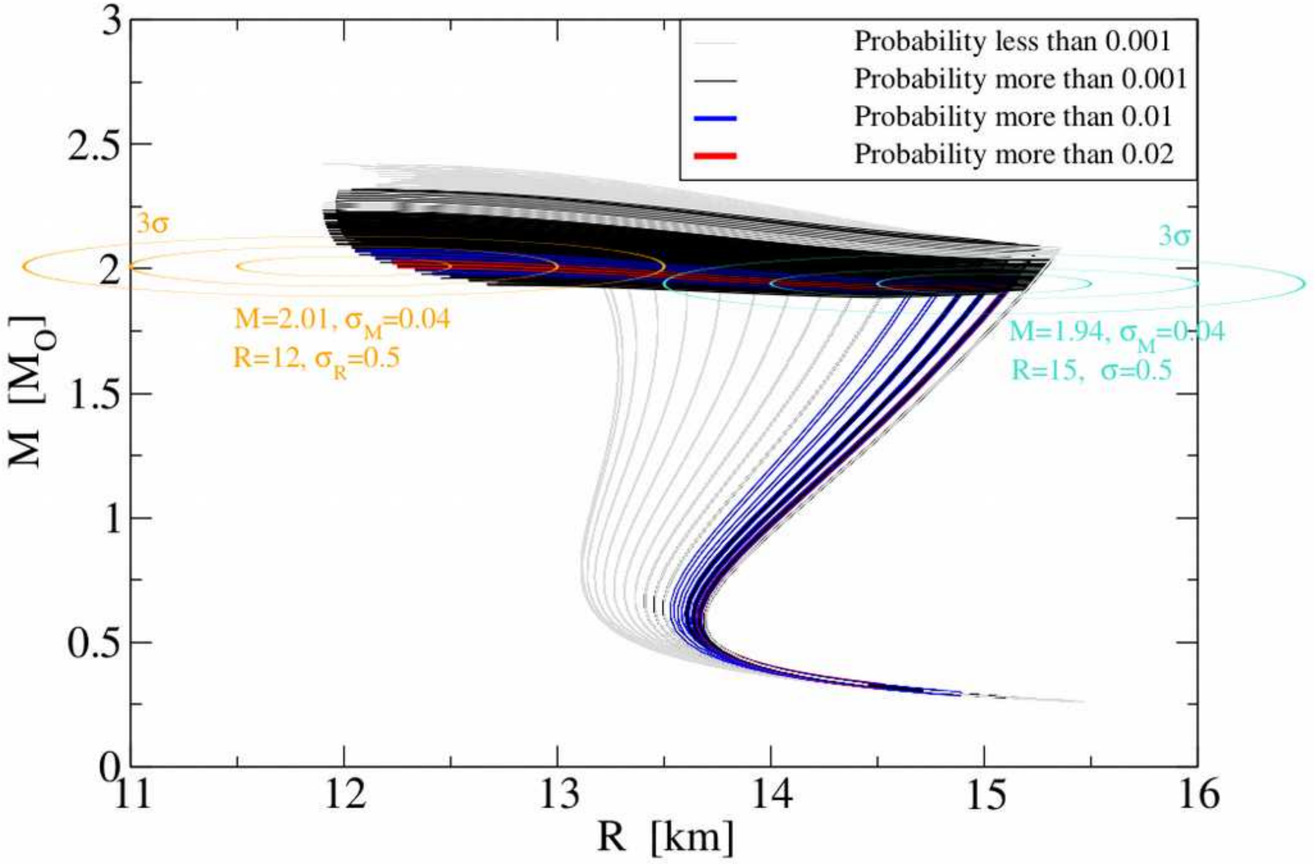


Fig. 2. Mass radius relations for the six hybrid EoS classes constructed from the hNJL quark matter EoS and the six hadronic RMF EoS by a Maxwell construction.

D. Alvarez-Castillo, A. Ayriyan, S. Benic, D. Blaschke, H. Grigorian, S. Typel
EPJA Topical Issue on "Exotic Matter in Neutron Stars", 2016 - arXiv:1603.03457

Bayesian Analysis



Alvarez-Castillo, Ayriyan, Blaschke, Grigorian, arXiv:1506.07755, arXiv:1402.0478, arXiv:1408.4449

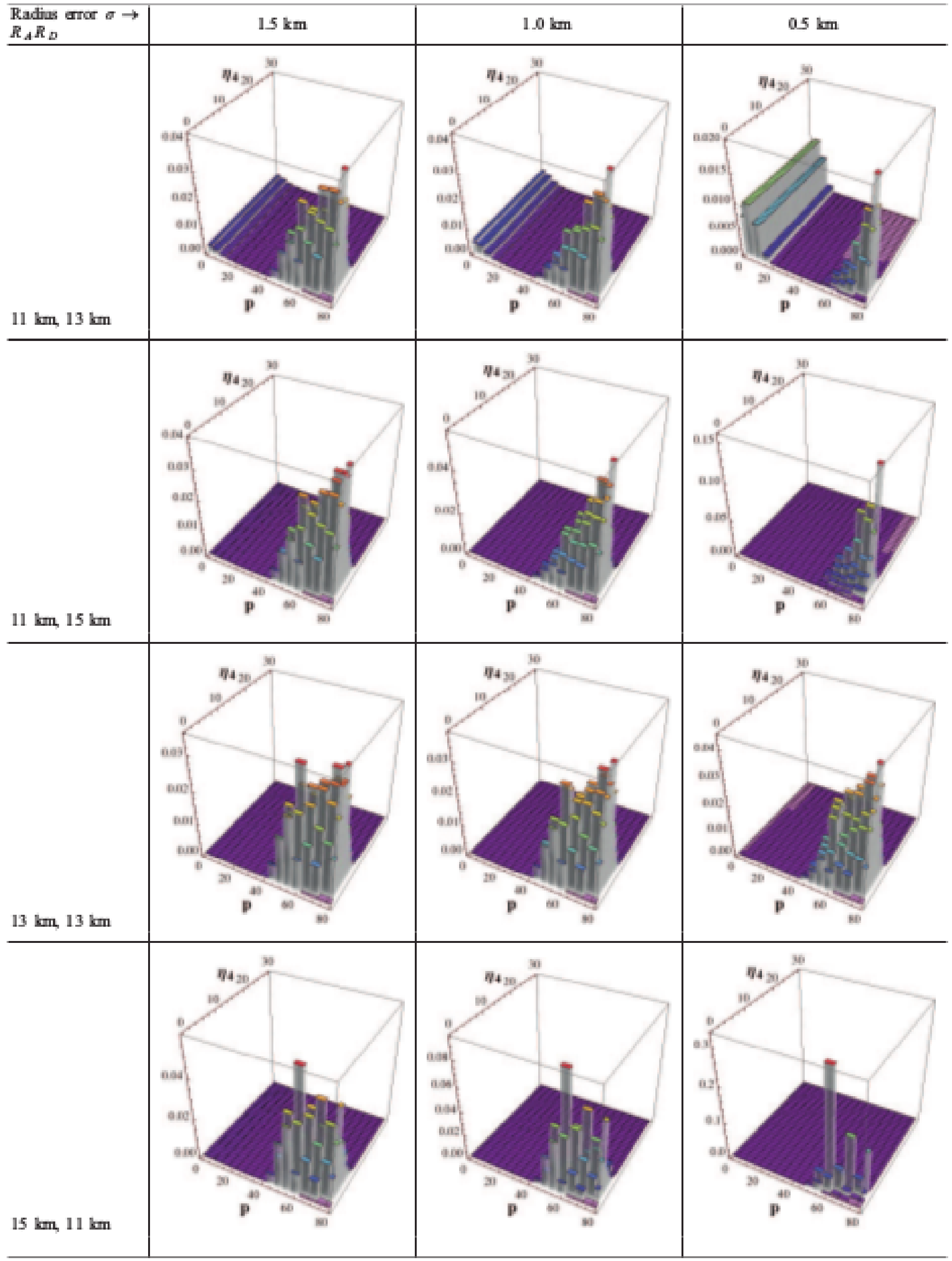
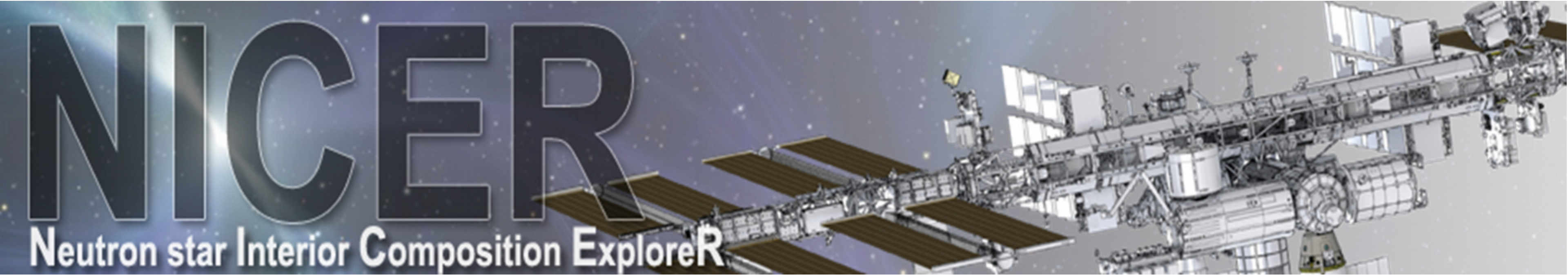
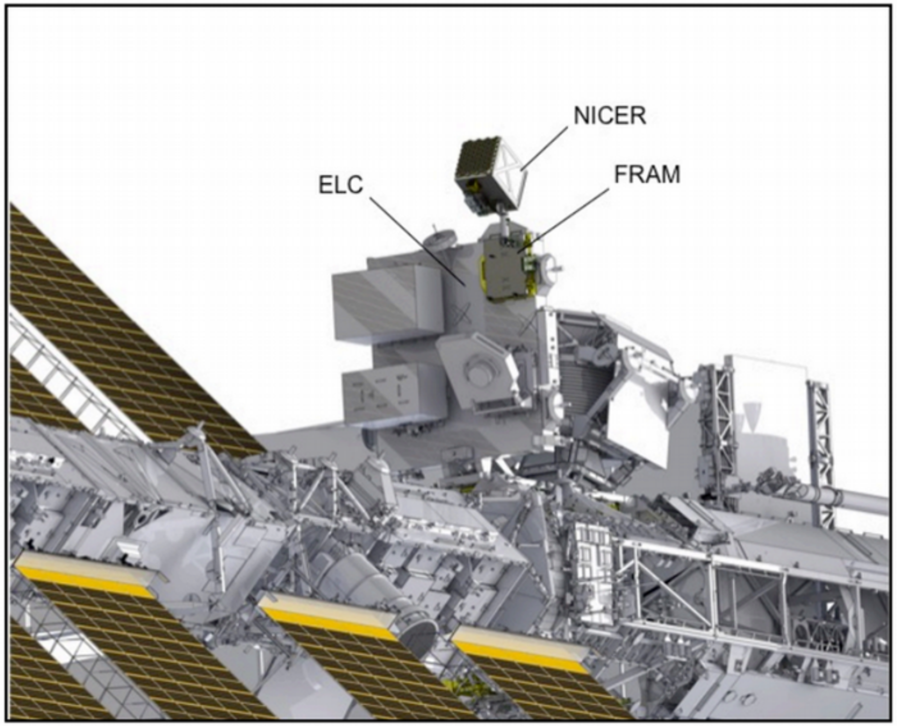
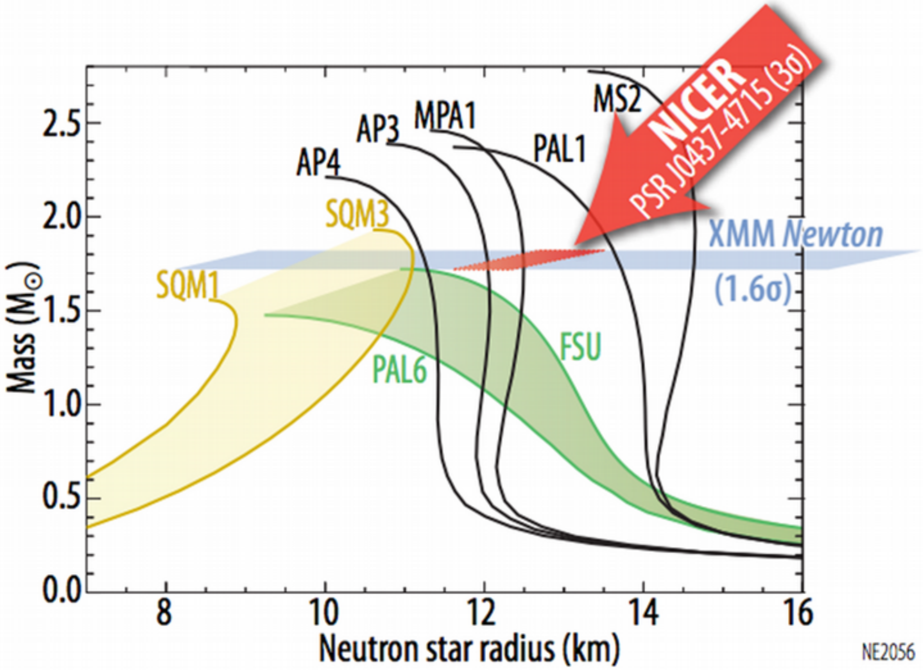


Fig. 6. *Probabilities for an extra fictitious radius measurement.* R_A and R_D denote NS with masses corresponding to the ones measured by Antoniadis *et al.* and by Demorest *et al.*, respectively.

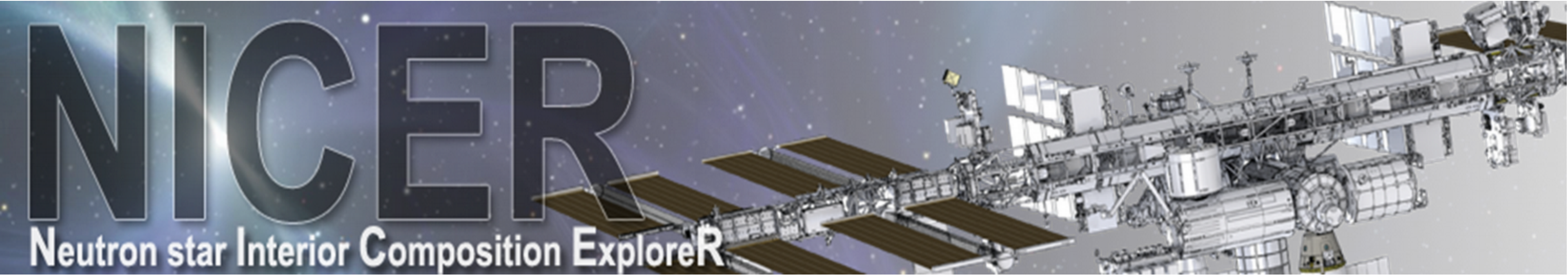


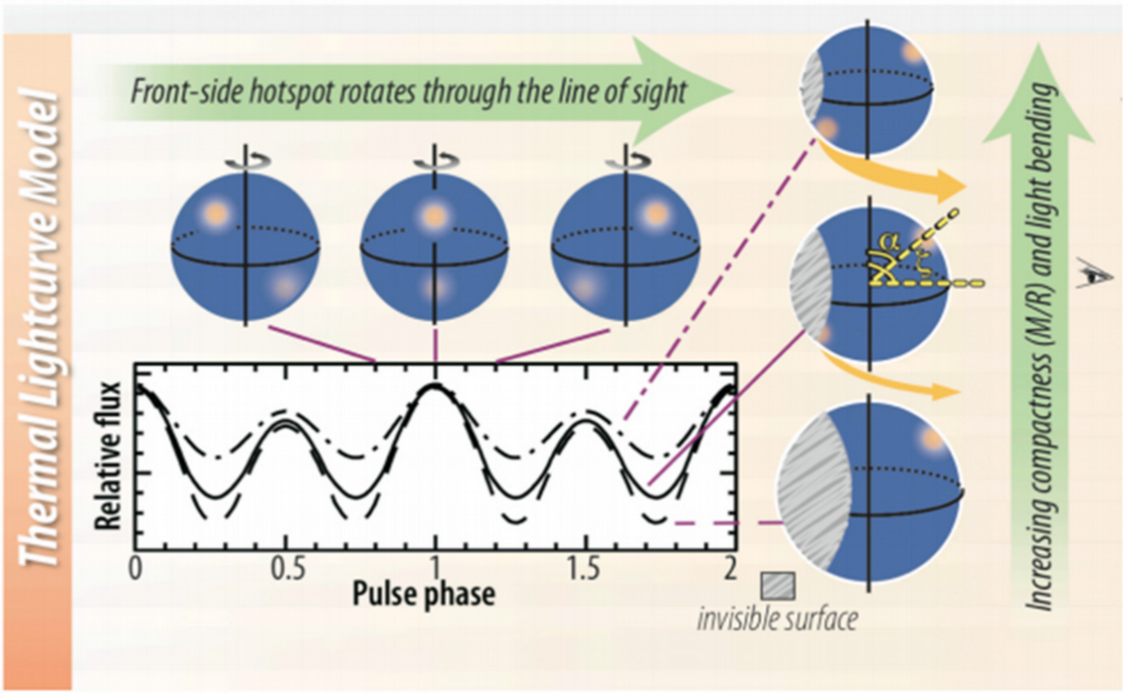


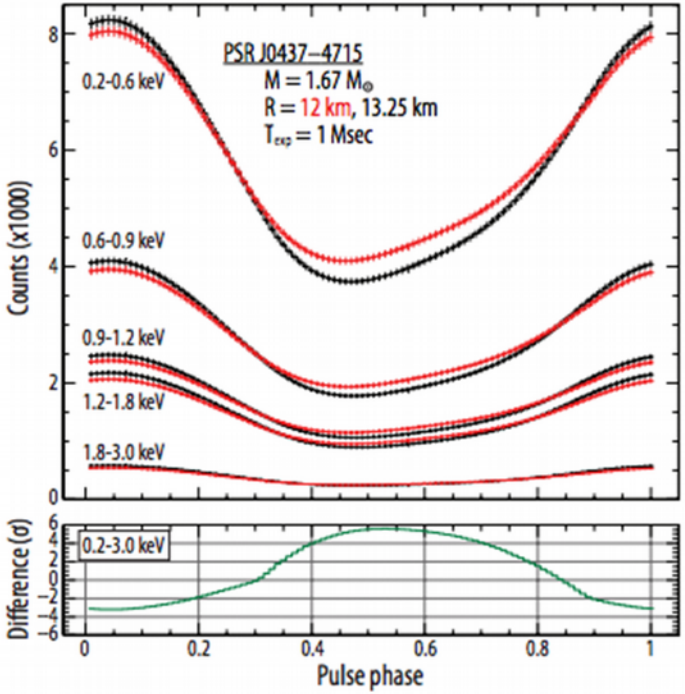


NICER 2017

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
Relative flux
Pulse phase
0
0.5
1
1.5
2
invisible surface
α
ξ

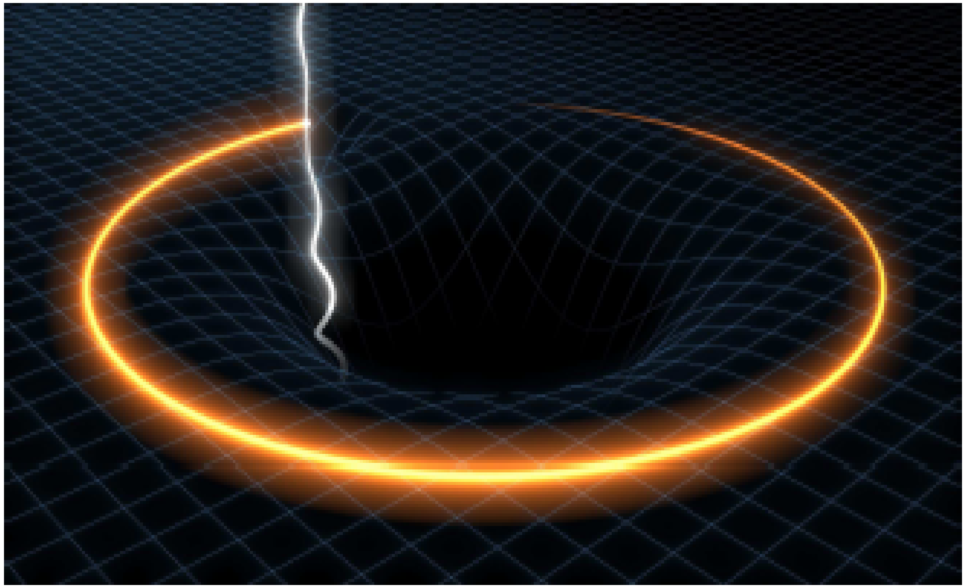

PSR J0437−4715
M = 1.67 M⊙
R = 12 km, 13.25 km
T_exp = 1 Msec
0.2-0.6 keV
0.6-0.9 keV
0.9-1.2 keV
1.2-1.8 keV
1.8-3.0 keV
Counts (x1000)
0.2-3.0 keV
Difference (σ)
Pulse phase
0
0.2
0.4
0.6
0.8
1

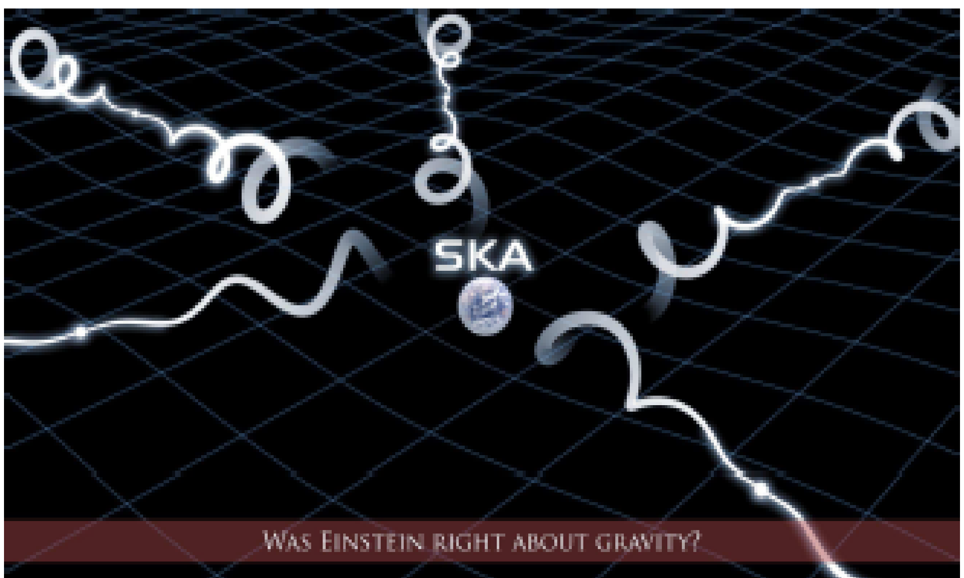
Hot Spots

Perspectives for new Instruments?

THE FUTURE: SKA - SQUARE KILOMETER ARRAY

The Future: SKA - Square Kilometer Array





SKA Facts:

- The dishes of the SKA will produce 10 times the global internet traffic
- The data collected by the SKA in a single day would take nearly two million years to playback on an ipod
- The SKA will be so sensitive that it will be able to detect an airport radar on a planet 50 light years away

Discovery Potential:

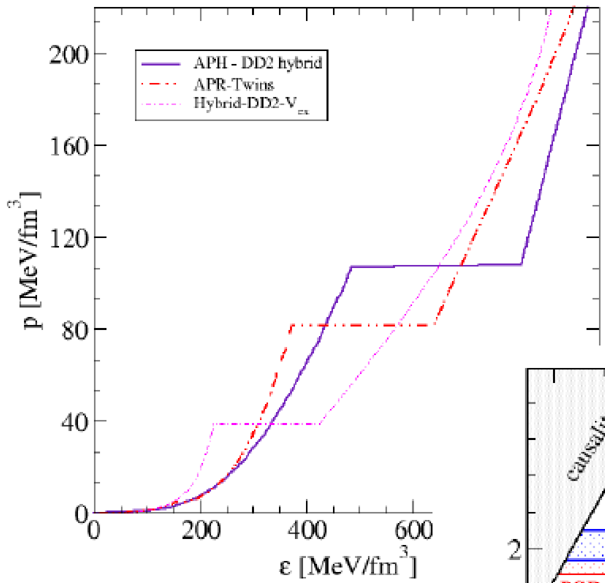
- Find a Pulsar - Black Hole Binary
- Constrain Einstein Gravity
- Gravitational waves

NICA White Paper – selected topics ...

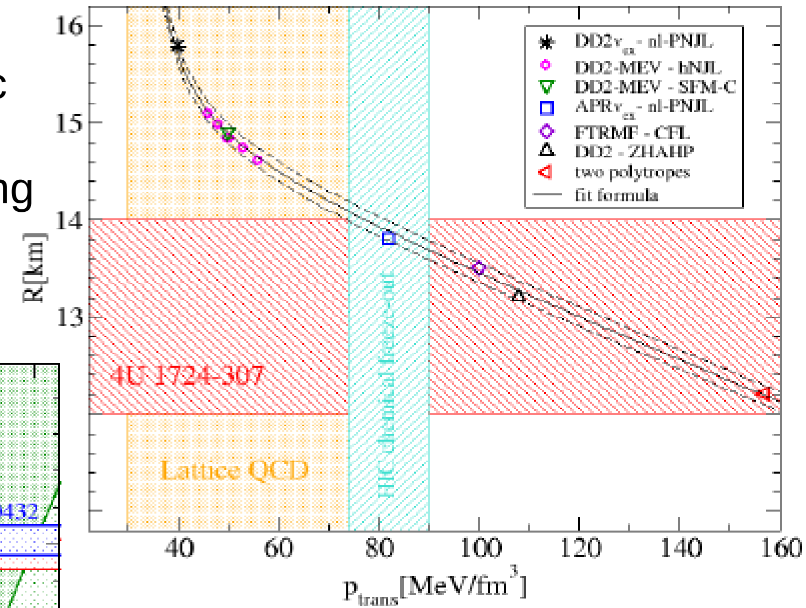
Many cross-relations with astrophysics of compact stars! High-mass twin stars prove CEP !

Neutron star mass limit at $2M_\odot$ supports the existence of a CEP

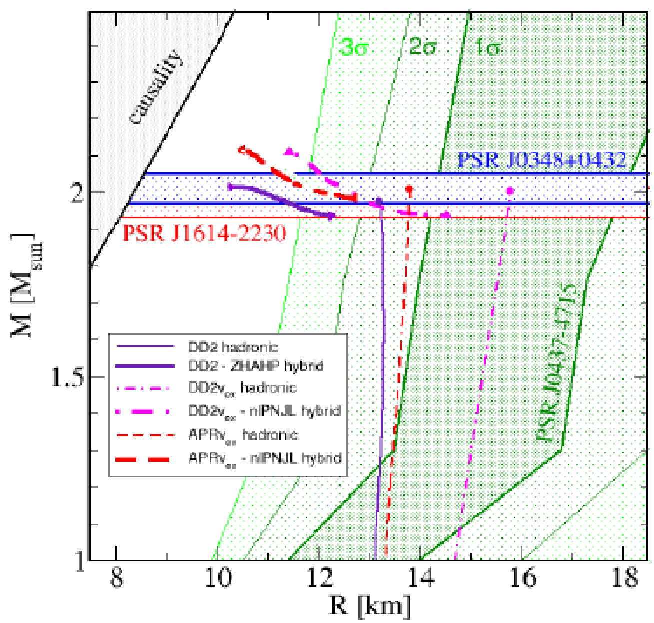
D. Alvarez-Castillo[1,a], S. Benic[2,b], D. Blaschke[1,3,4], Sophia Han[5,6], and S. Typel[7]



Endpoint of hadronic
Neutron star config.
At 2Msun, then strong
Phase transition



Strong phase trans.



High-mass twin stars

Universal transition pressure ?

Petran & Rafelski, PRC 88, 021901

P_{trans} = 82 +/- 8 MeV/fm^3

Conclusions

- Three of the fundamental puzzles of compact star structure, the hyperon puzzle, the masquerade problem and the reconfinement problem may likely be all solved by accounting for the compositeness of baryons (by excluded volume and/or quark Pauli blocking) on the hadronic side and by introducing stiffening effects on the quark matter side of the EoS.
- 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

- Excluded volume effects (quark Pauli blocking) stiffen high-density nuclear matter and trigger an early deconfinement transition, thus play an important role for the M-R relations and cooling properties of compact stars.
- High mass neutron star twins robust against the appearance of pasta phases in the quark-hadron inteface.
- Energy bursts via deconfinement feasible for the twins.
- Possible universal phase transition pressure

Gracias