# The role of hybrid compact stars in the hyperon puzzle

David E. Alvarez Castillo

***Joint Institute for Nuclear Research***

Strange Quark Matter

Dubna - July 2015

# Outline

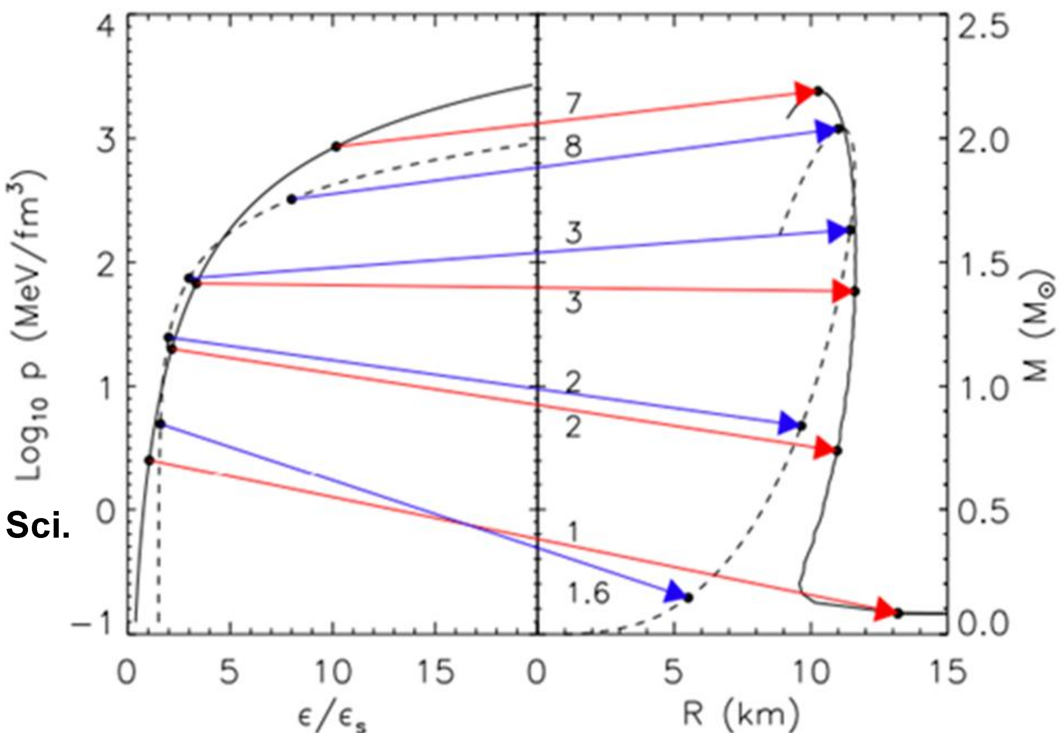
- Introduction to the neutron star equation of state and the hyperon puzzle.
- First order phase transition and deconfinement in compact stars: neutron star twins.
- Astrophysics measurements of compact stars.
- Astrophysical implications and perspectives.

# Key Questions

- Can we resolve the hyperon puzzle in the framework of quark deconfinement in compact stars?
- Can compact star observations provide compelling evidence about a first order phase transition in QCD?
- What are the relevant observables?

# Compact Star Sequences

## (M-R ↔ EoS)




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

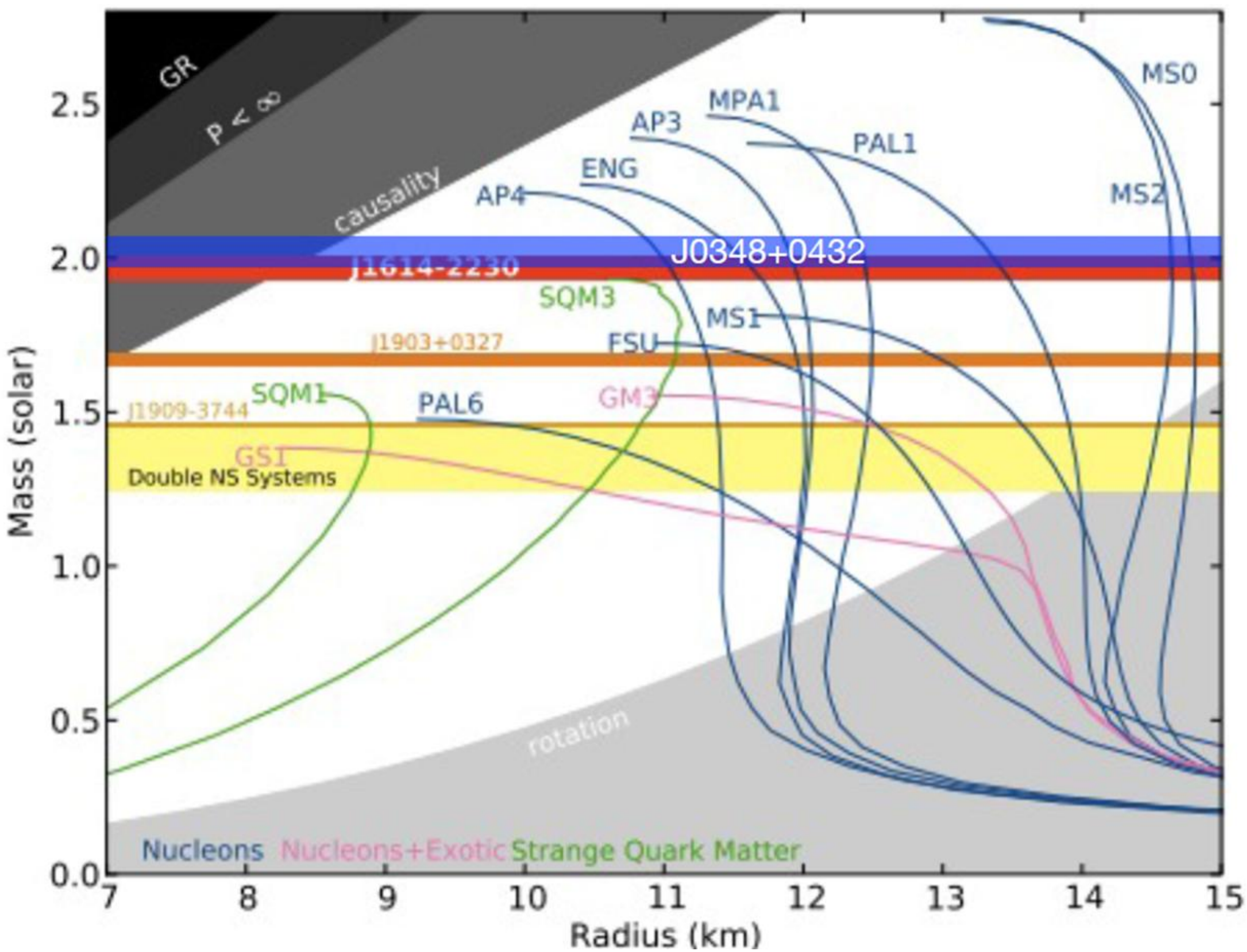
- TOV Equations
- Equation of State (EoS)

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

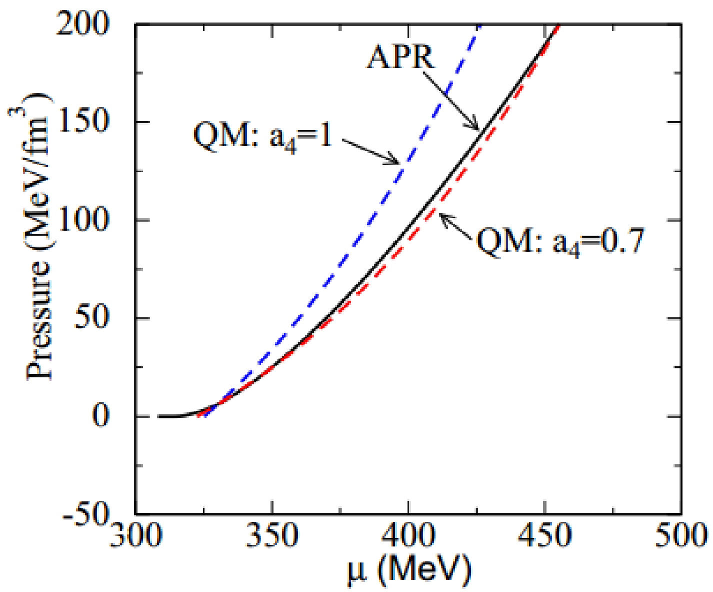
$$\frac{dm}{dr} = 4\pi r^2 \varepsilon$$

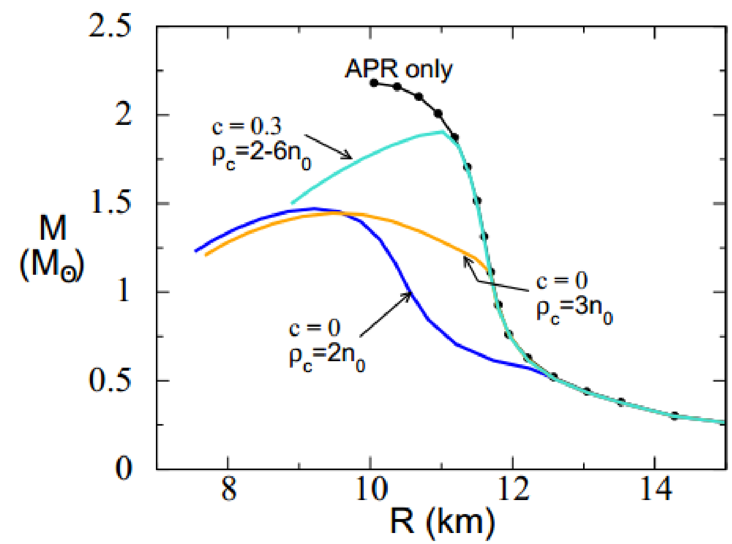
$$p(\varepsilon)$$

# Massive neutron stars



# Masquerades



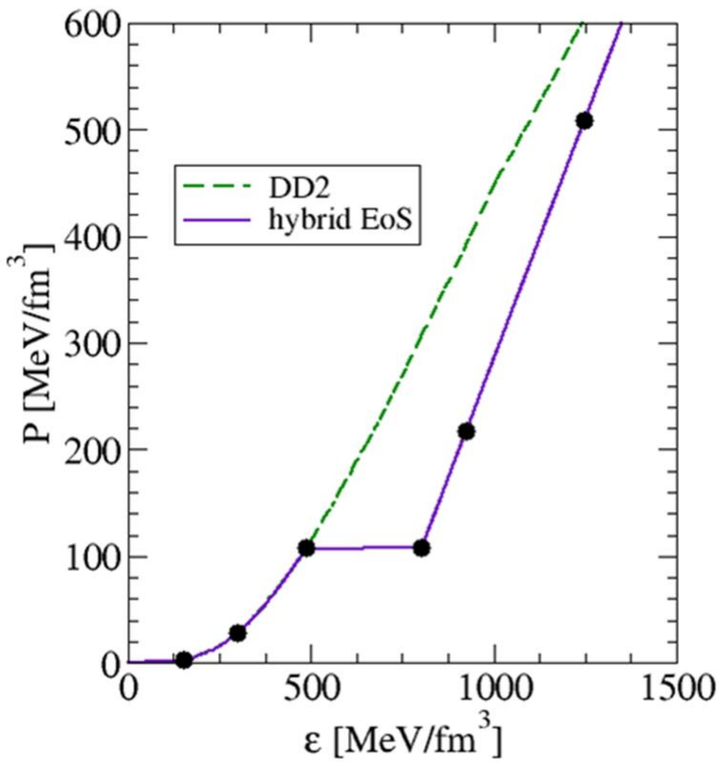

$$\Omega_{\rm QM} = -\frac{3}{4\pi^2}\, a_4\, \mu^4 + \frac{3}{4\pi^2} a_2\, \mu^2 + B_{\rm eff}$$

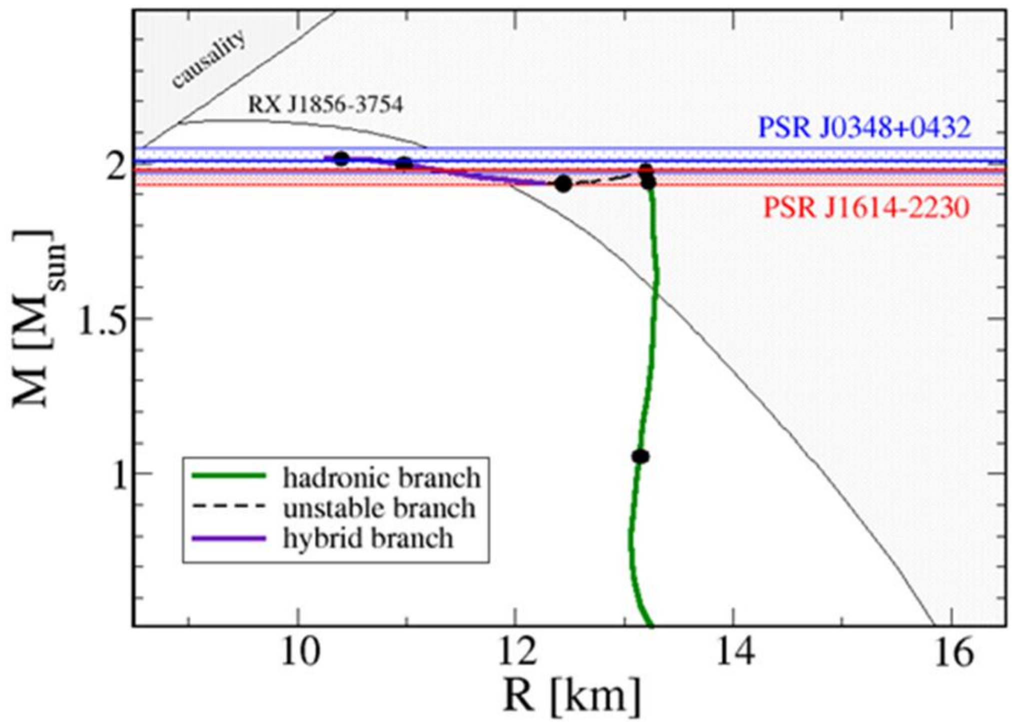
$$a_4 \equiv 1 - c\ ,$$

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

# Compact Star Twins

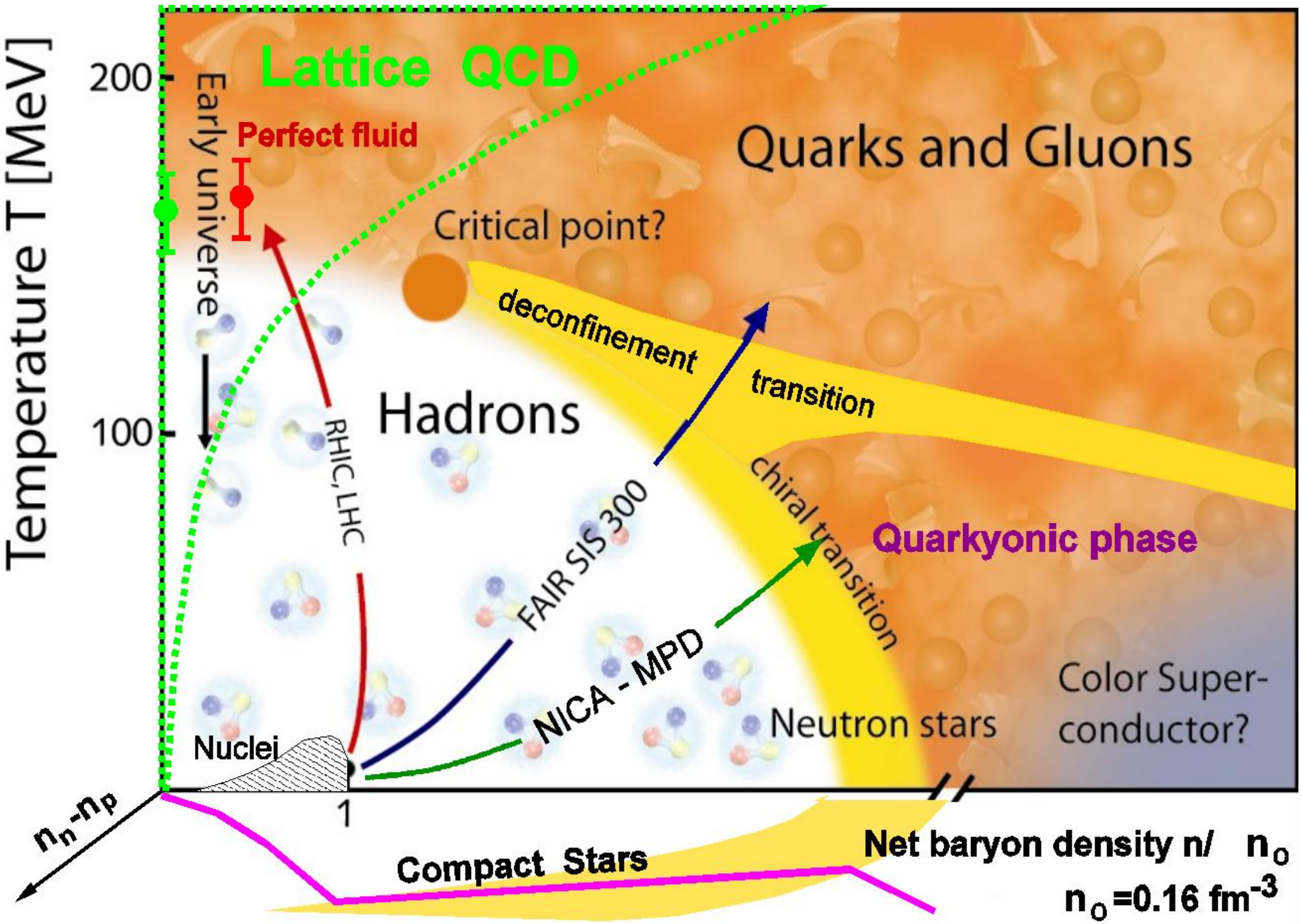
## Third family (disconnected branch)




**Alvarez-Castillo, Blaschke, arXiv: 1304.7758**

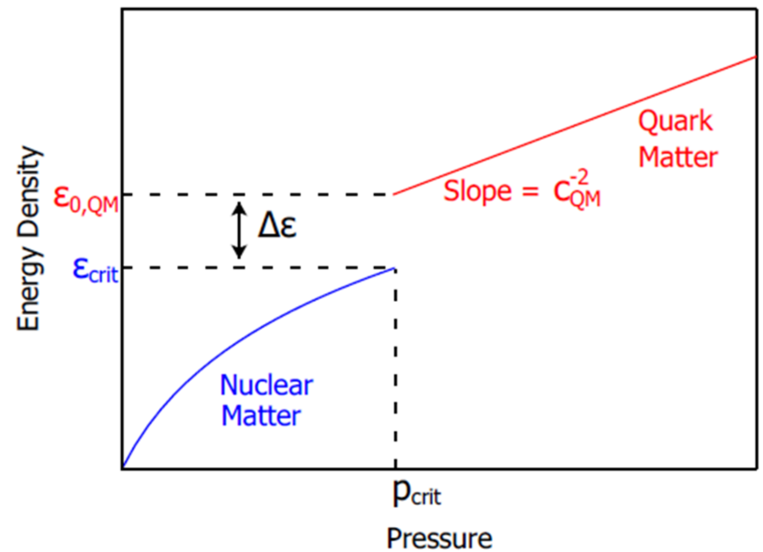
# Critical Endpoint in QCD

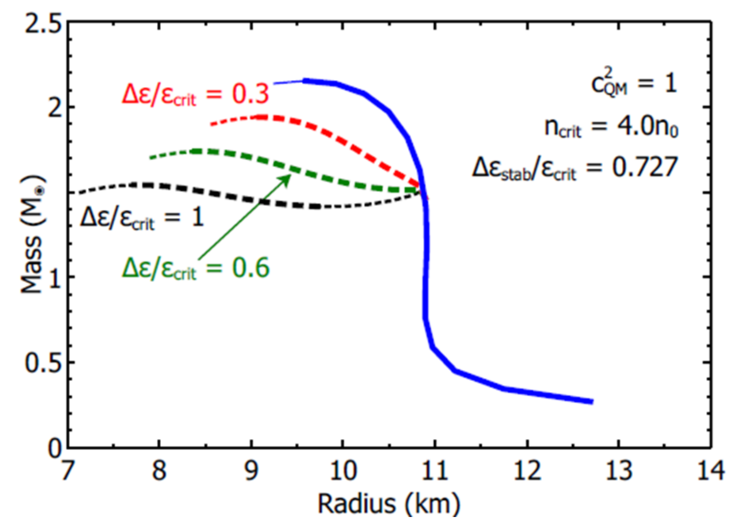


# Neutron Star Twins and the AHP scheme

- 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**!

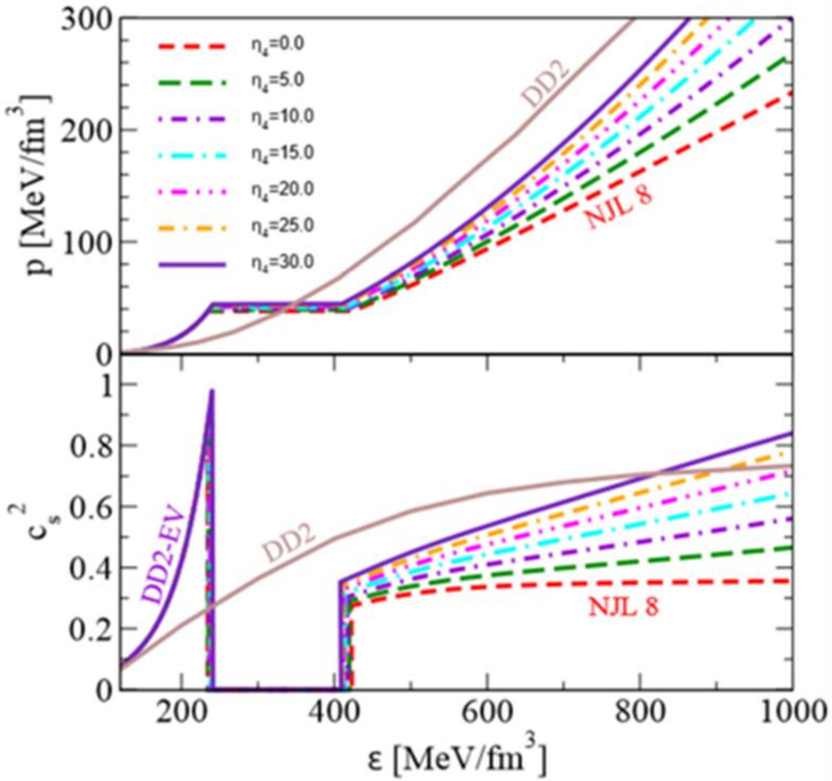


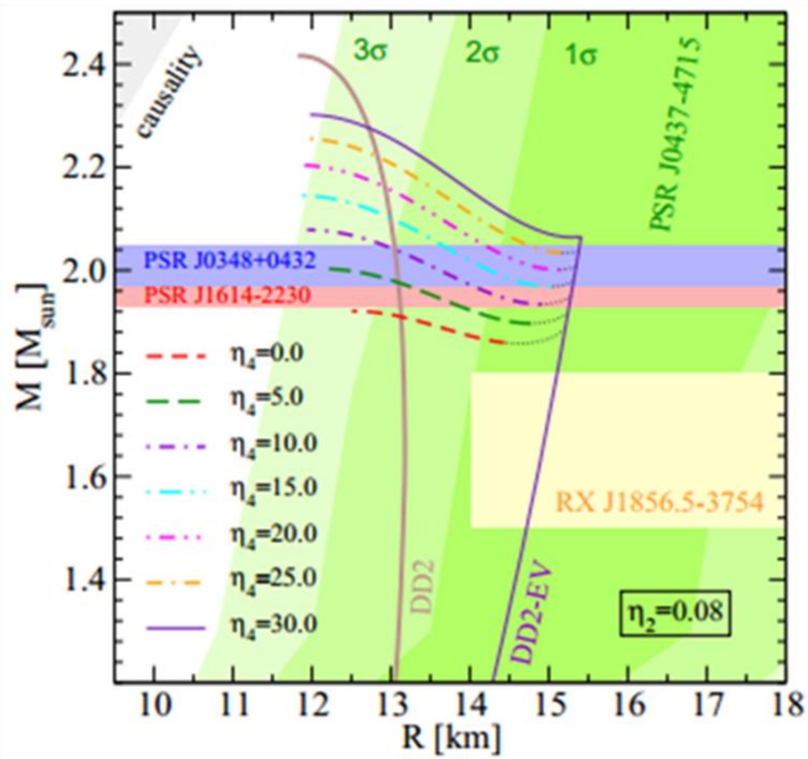

**Alford, Han, Prakash,**
**Phys. Rev. D 88, 083013 (2013)**
**arxiv:1302.4732**

# Neutron Star Twins

## Equation of State




## Mass-Radius Relation




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

# 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 $\mu_n$ and $\mu_p$. 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, Typer, 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**

# Avoiding reconfinement

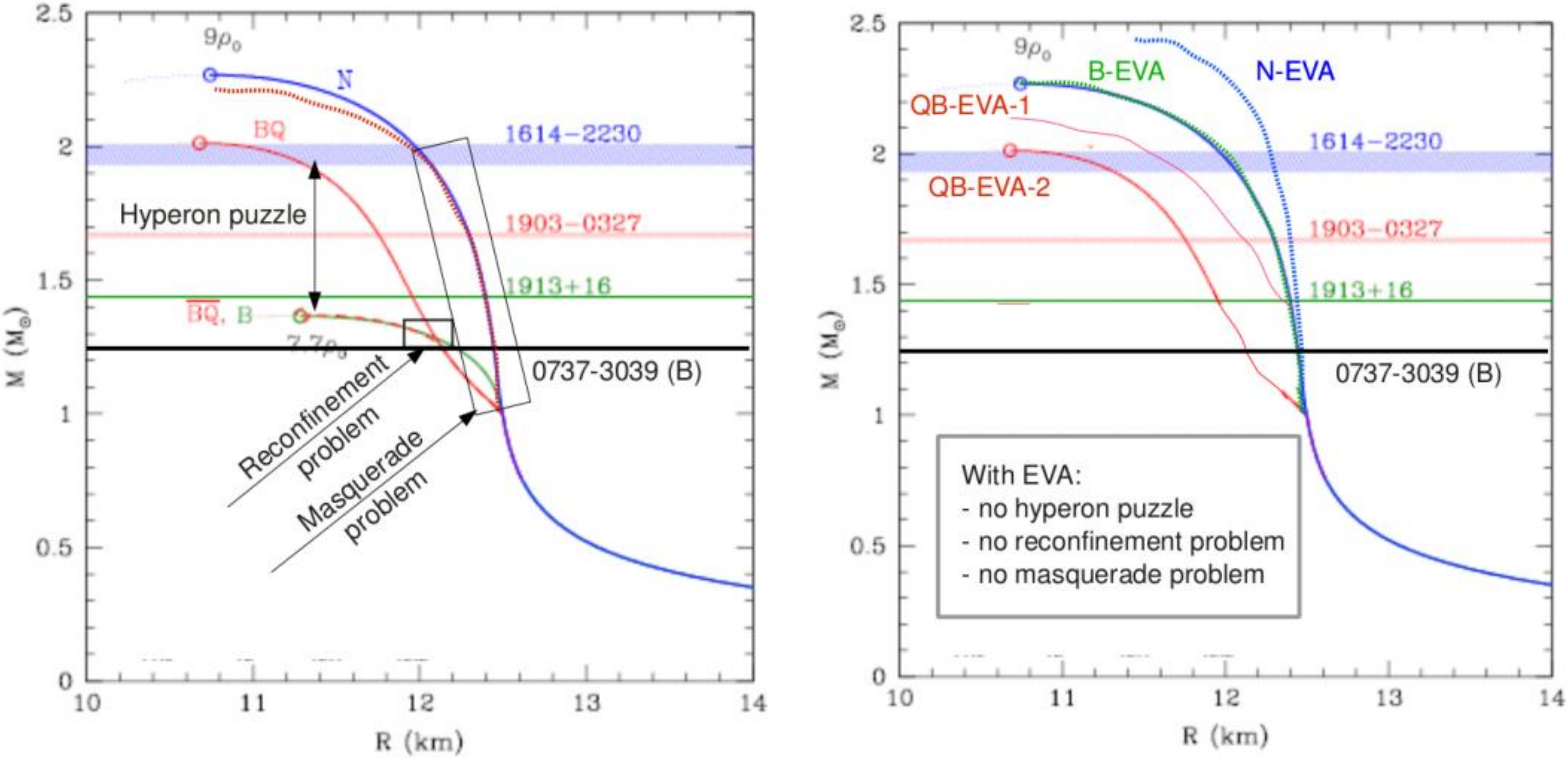
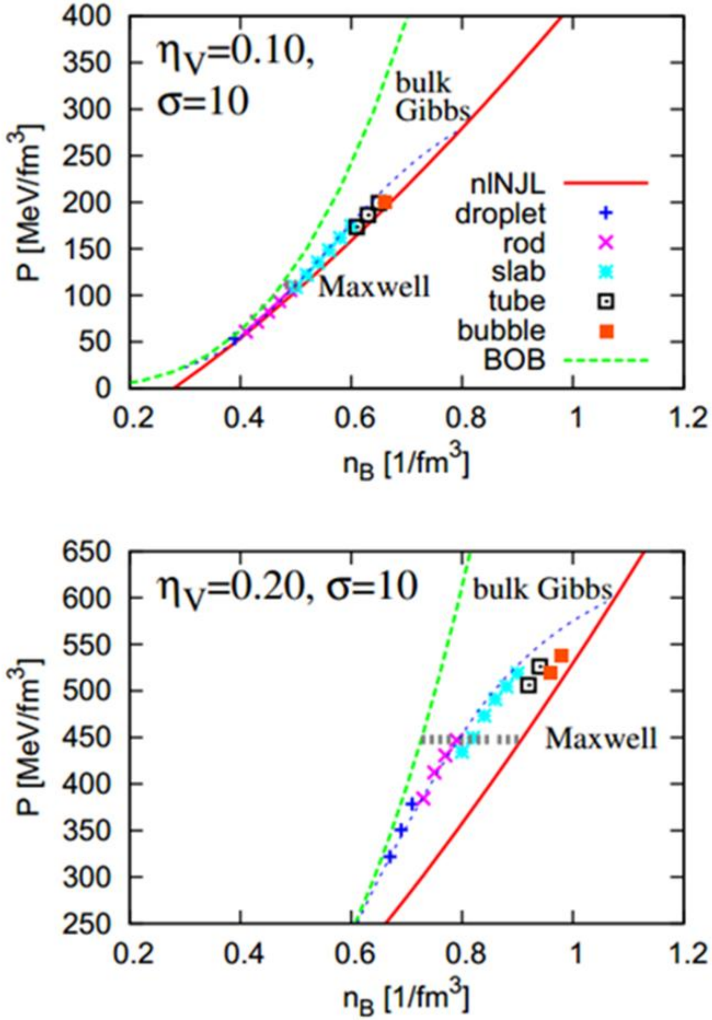
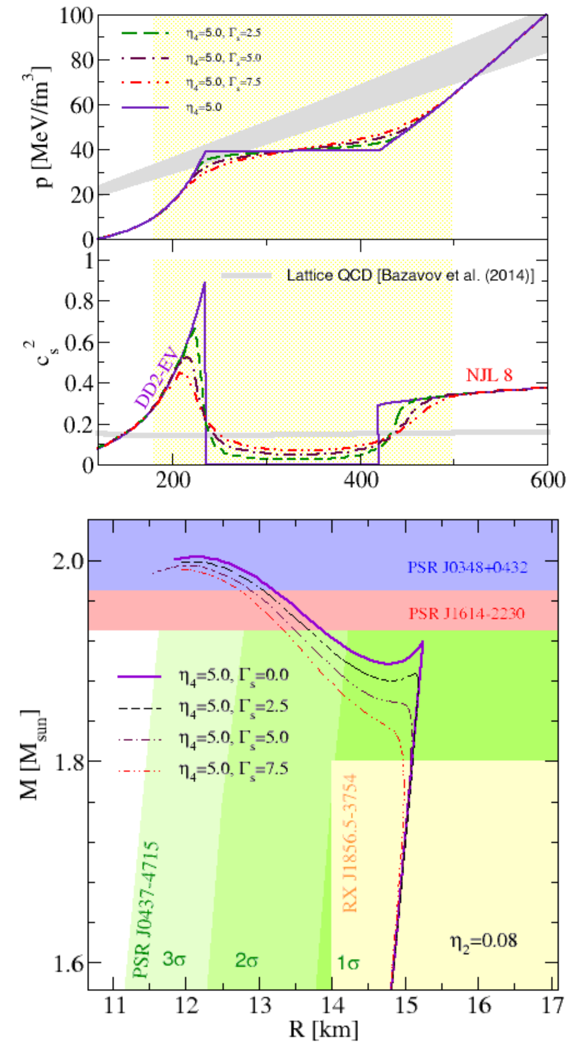



**FIGURE 1.** Mass-radius sequences for different model equations of state (EoS) illustrate how the three major problems in the theory of exotic matter in compact stars (left panel) can be solved (right panel) by taking into account the baryon size effect within a excluded volume approximation (EVA). 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 (2015), arXiv:1503.03834**

# Pasta phases in hybrid stars

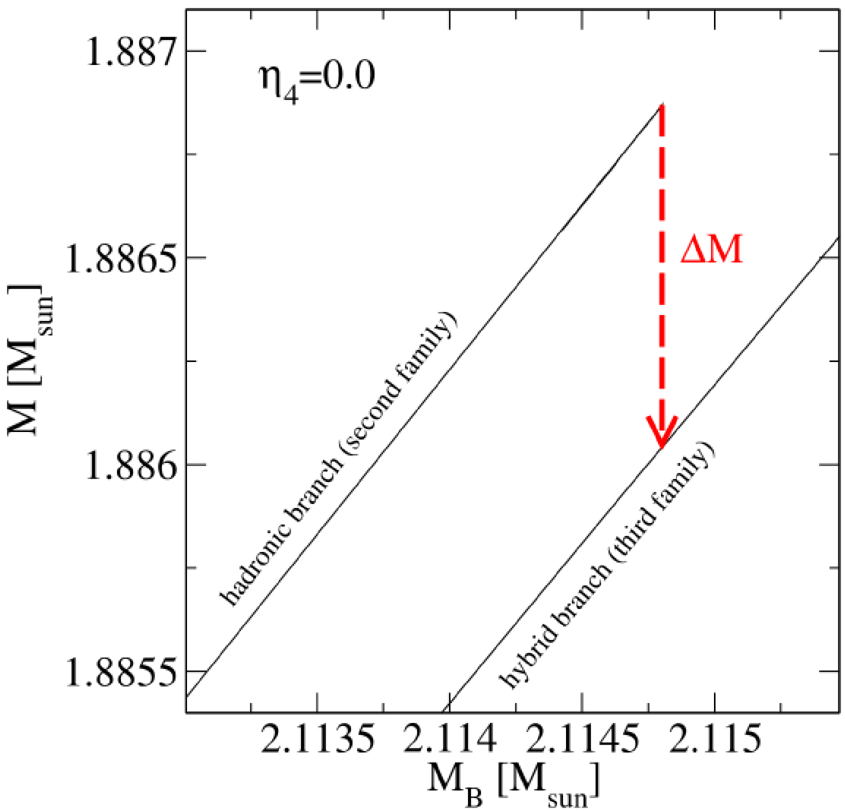


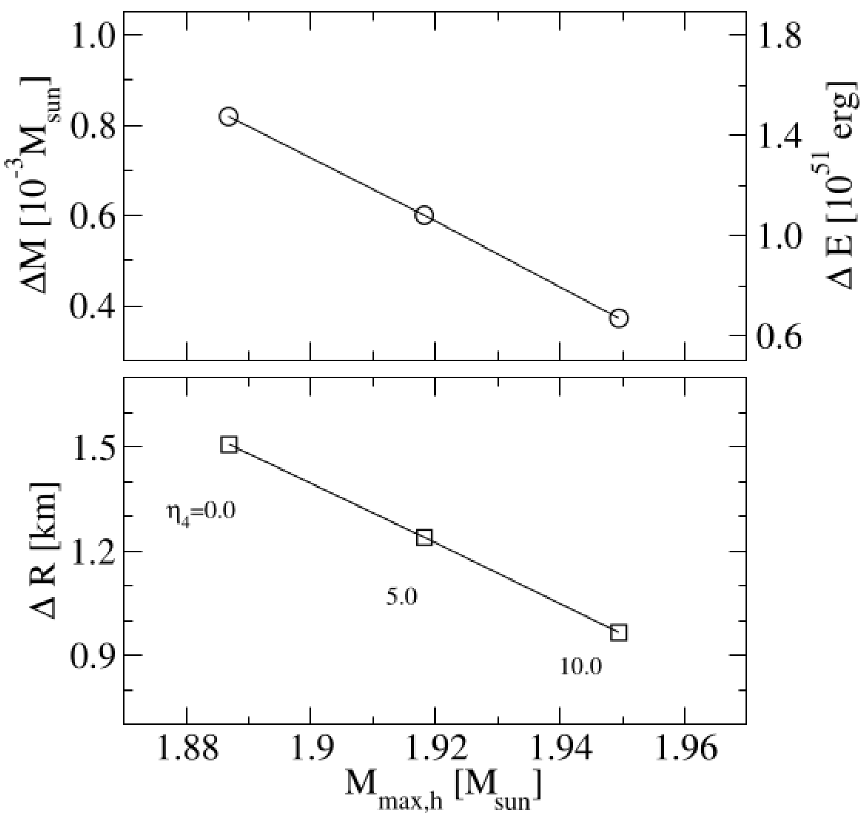




Yasutake et al., Phys. Rev. C 89, 065803 (2014)
arXiv:1403.7492

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

# Energy bursts from deconfinement

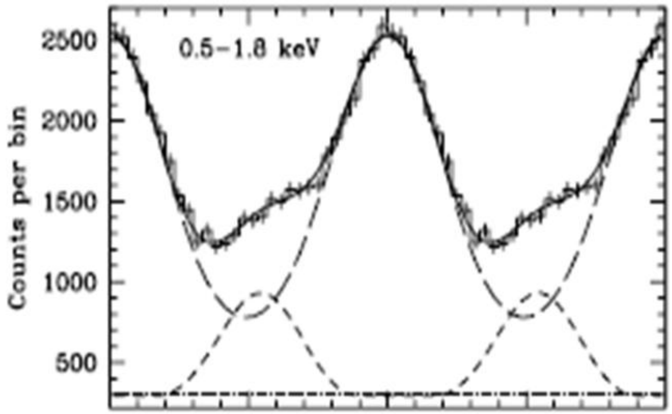


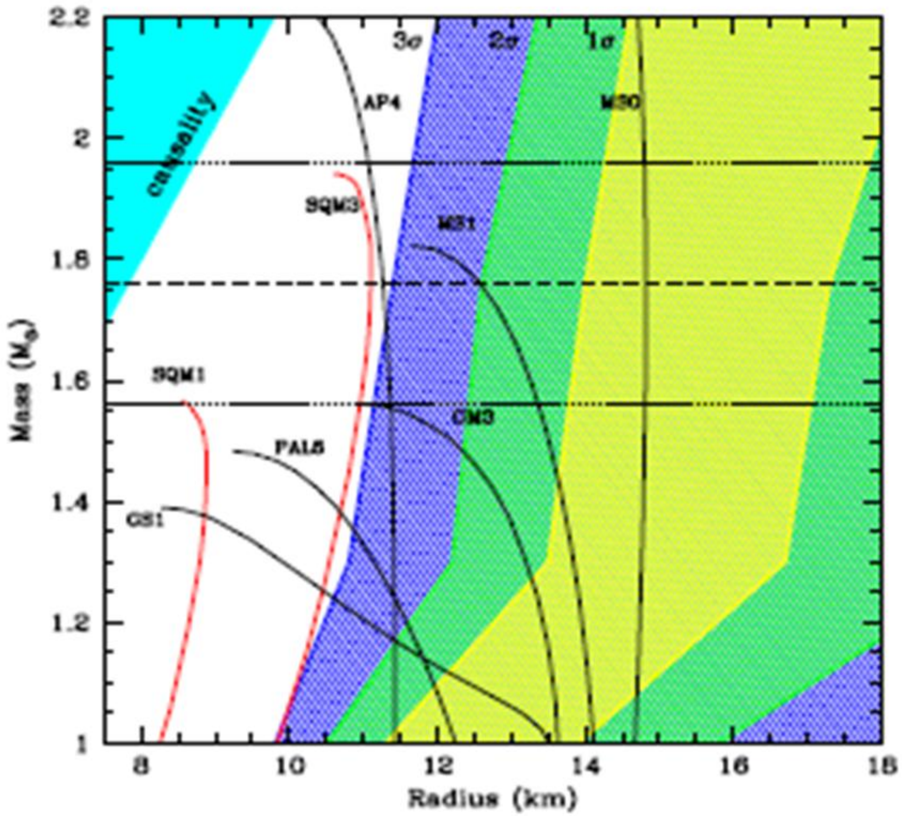




**Alvarez-Castillo, Bejger, Blaschke, Haensel, Zdunik (2015), arXiv:1401.5380**

# Radius measurement

- Nearest millisecond pulsar PSR J0437 – 4715 revisited by XMM Newton
- Distance: d = 156.3 +/- 1.3 pc
- Period: P= 5.76 ms, dot P = $10^{-20}$ s/s,
- Field strength B = $3 \times 10^8$ G

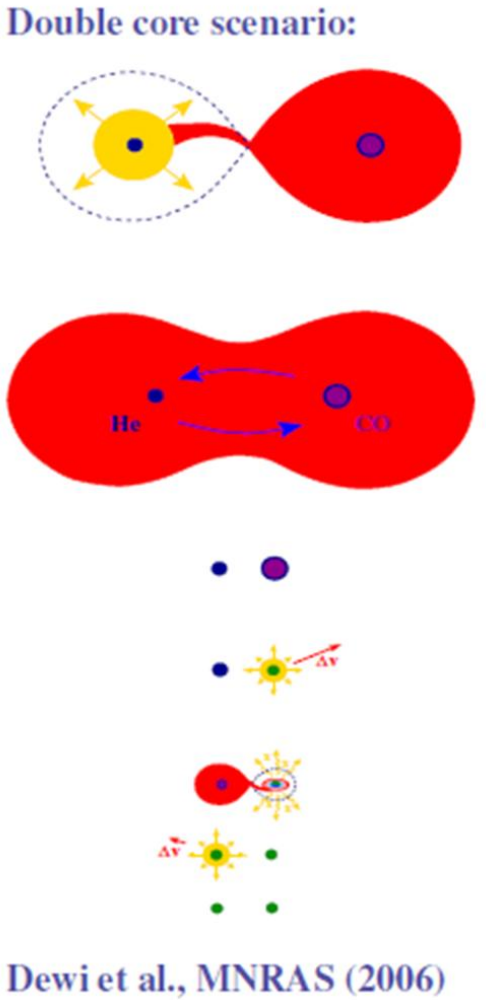


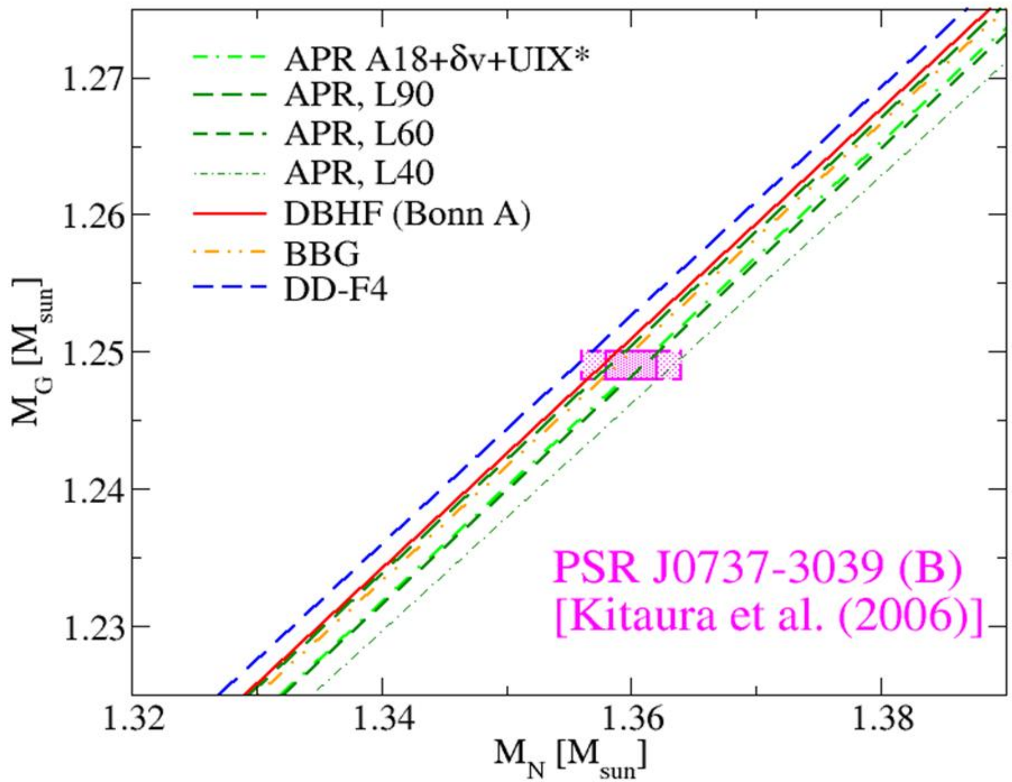




- Three thermal component fit: R > 11.1 km (at 3 sigma level), M = 1.76 $M_{SUN}$

**S. Bogdanov, 2013 ApJ 762 96**
**arxiv:1211.6113**

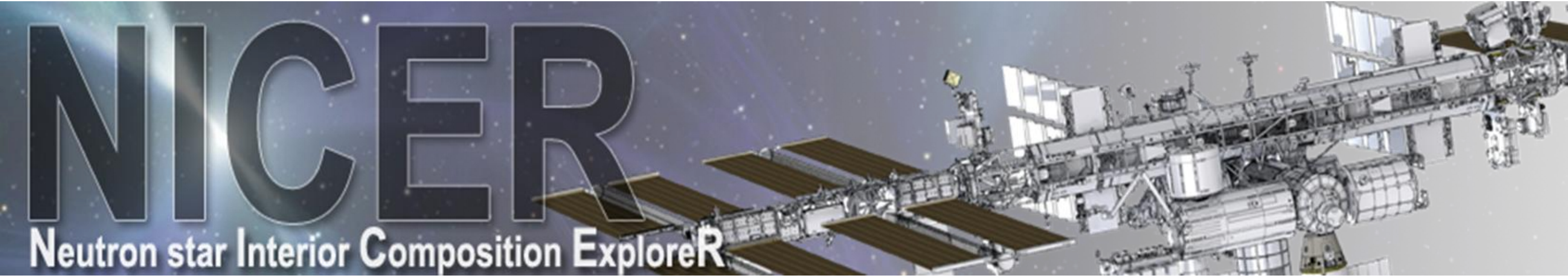
# Baryonic Mass

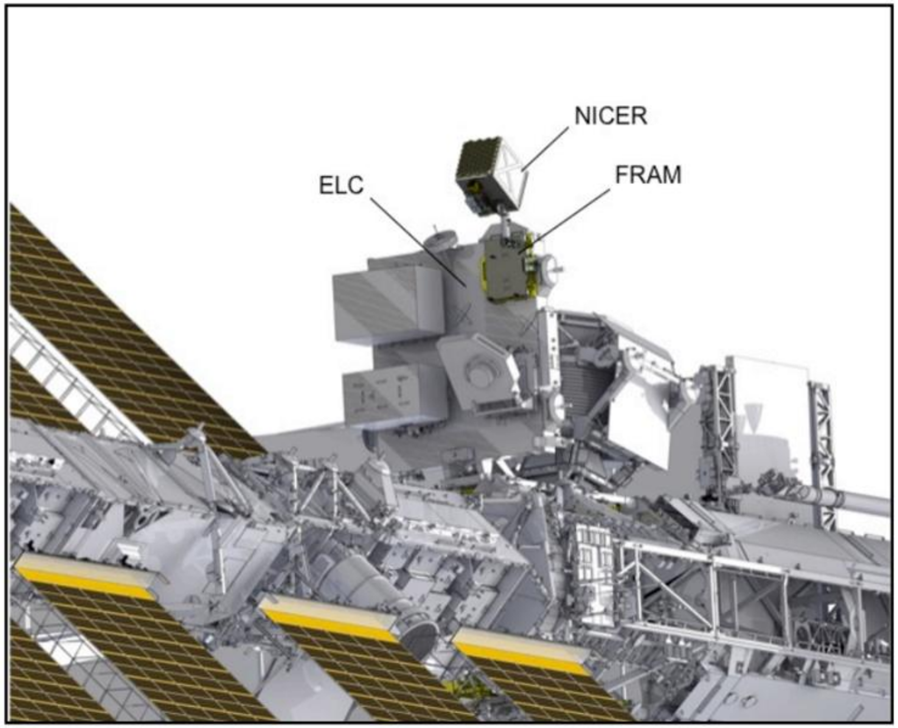


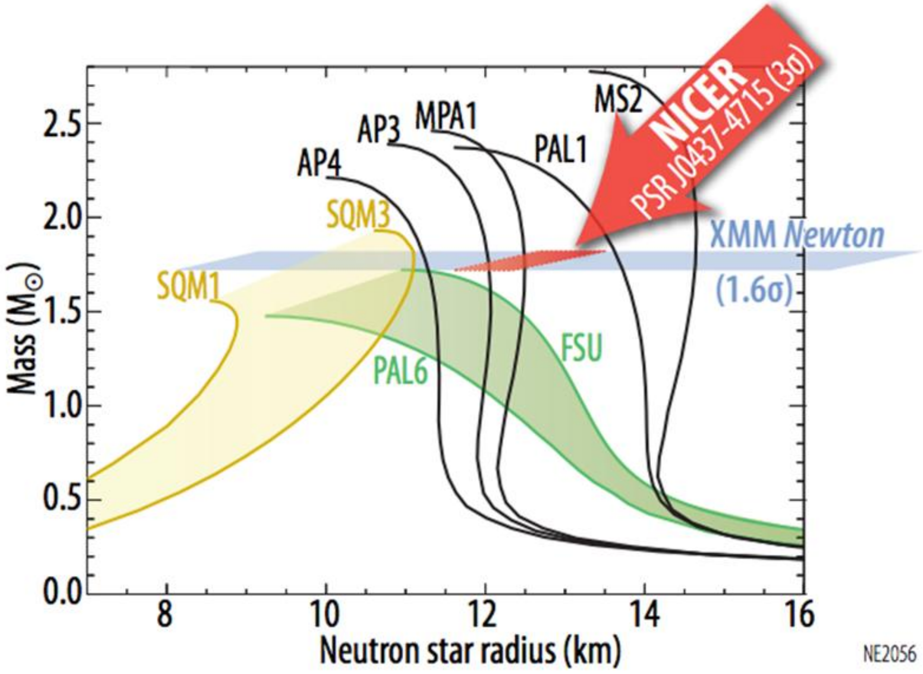




$$\frac{dn_B(r)}{dr} = 4\pi r^2 m_N \frac{n_B(r)}{\sqrt{1 - 2Gm(r)/r}}$$

**Podsiadlowski et al., MNRAS 361 (2005) 1243**
**Kitaura, Janka. Hillebrandt, A&A (2006); arXiv: astro-ph/0512065**

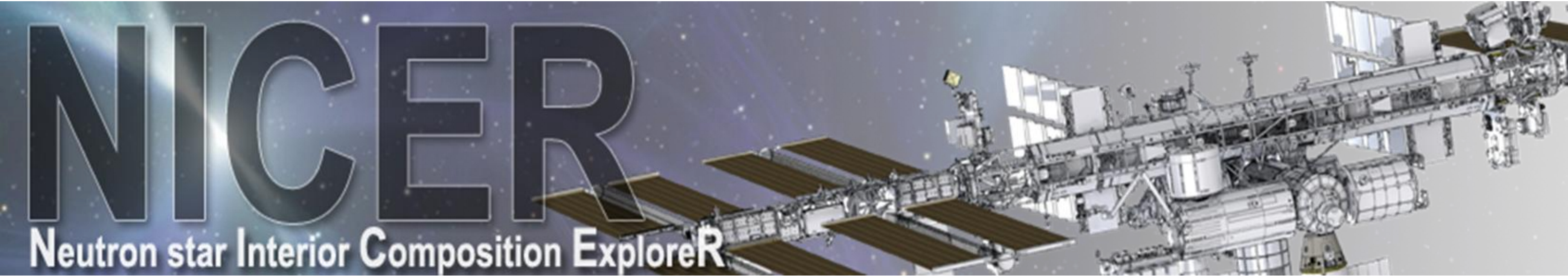


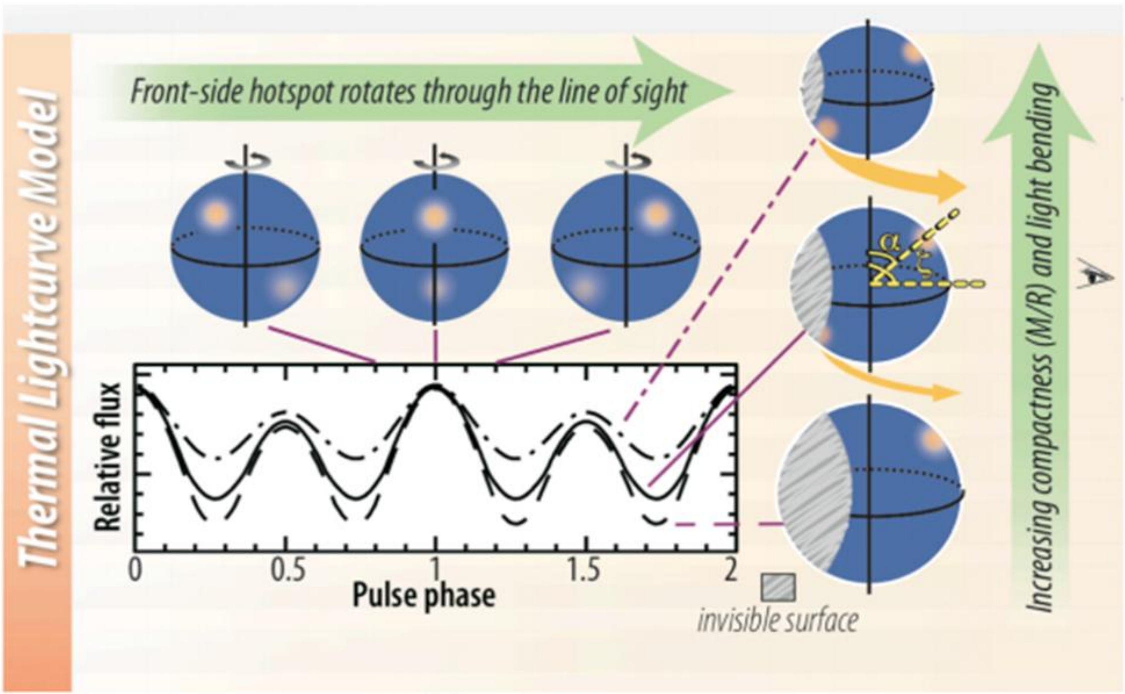



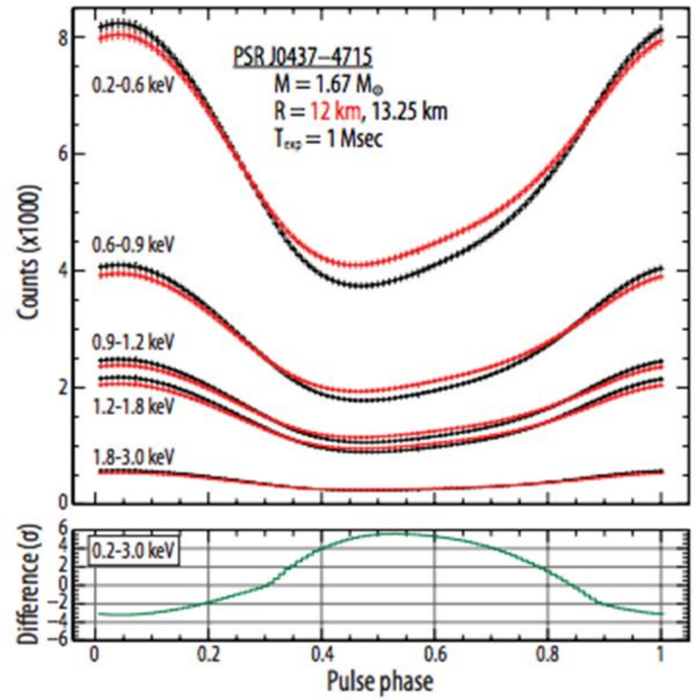




**NICER 2017**

**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
Relative flux
0
0.5
1
1.5
2
Pulse phase
α
ξ
invisible surface
Increasing compactness (M/R) and light bending


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)
Difference (σ)
0.2-3.0 keV
Pulse phase

# Hot Spots

# 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.

Gracias