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

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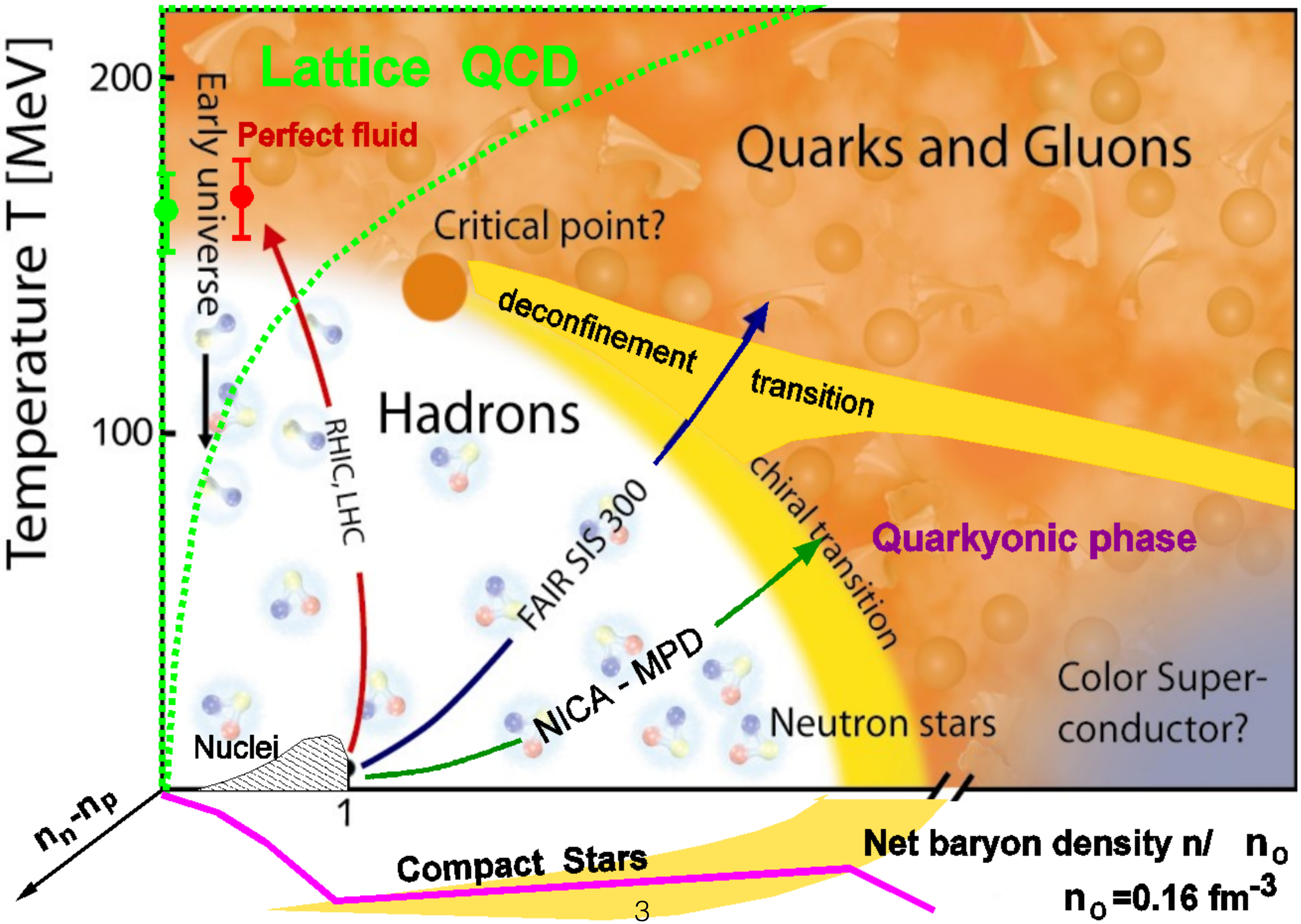
Outline

- First order phase transition and deconfinement in compact stars: neutron star twins.
- Astrophysics measurements of compact stars.
- Bayesian analysis of hybrid stars.
- Astrophysical implications and perspectives.

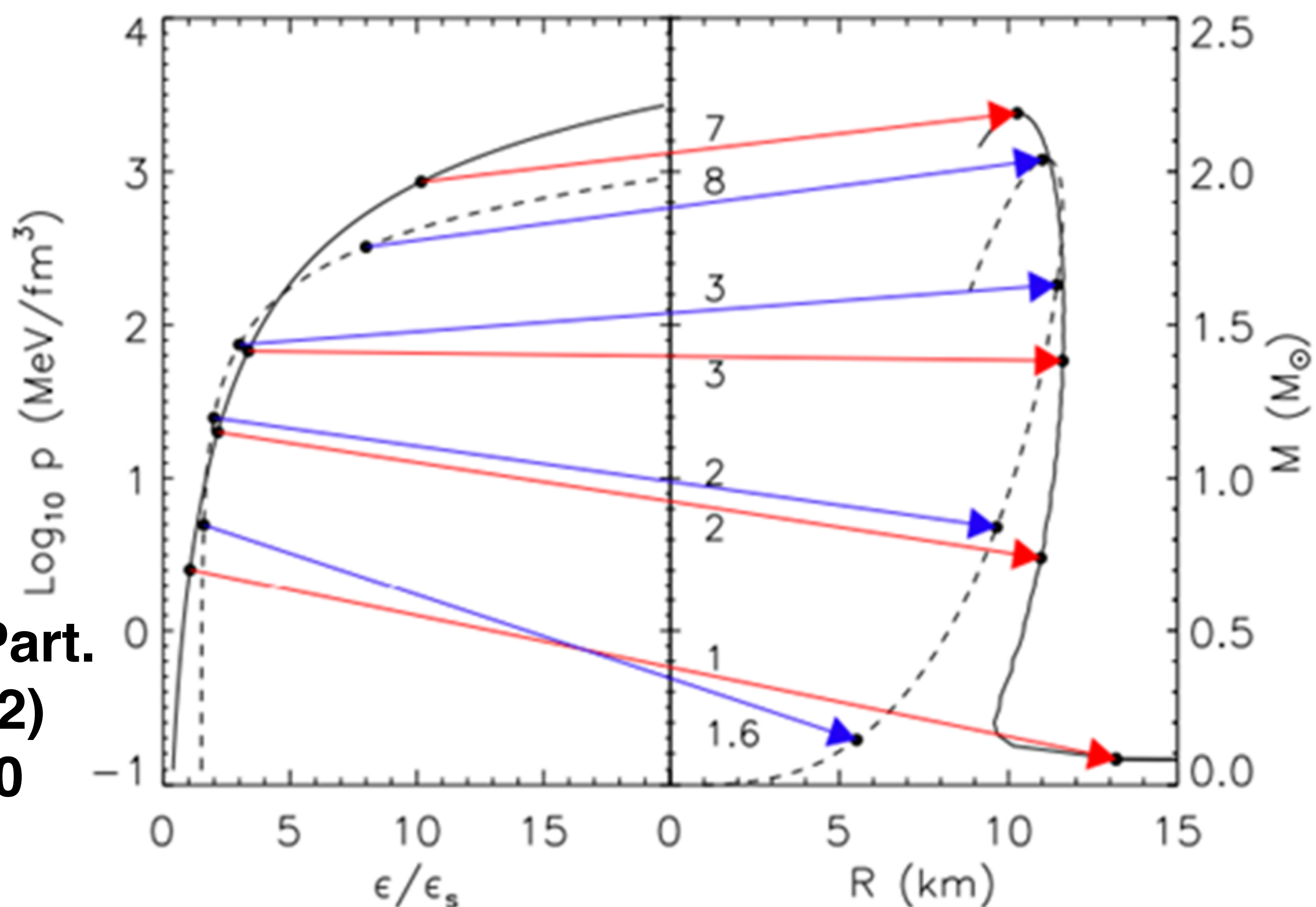
Critical Endpoint in QCD



Key Questions

- 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

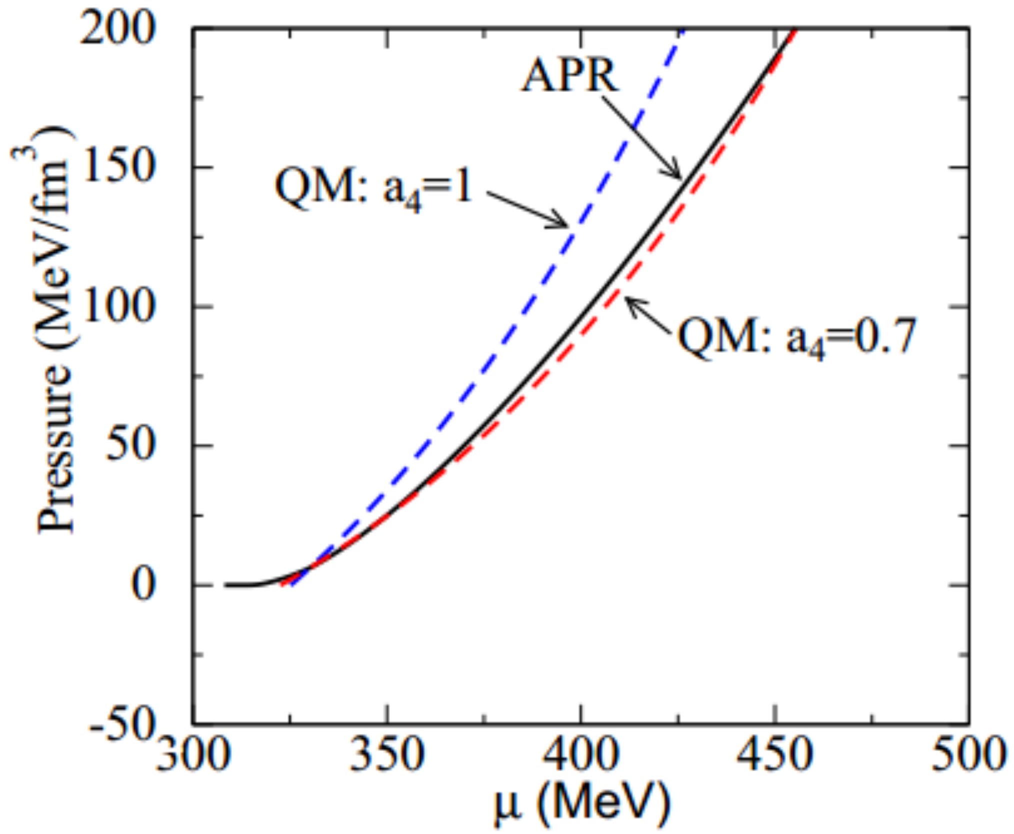
$$\frac{dp}{dr} = -\frac{(\varepsilon + p/c^2)G(m + 4\pi r^3 p/c^2)}{r^2(1 - 2Gm/rc^2)}$$

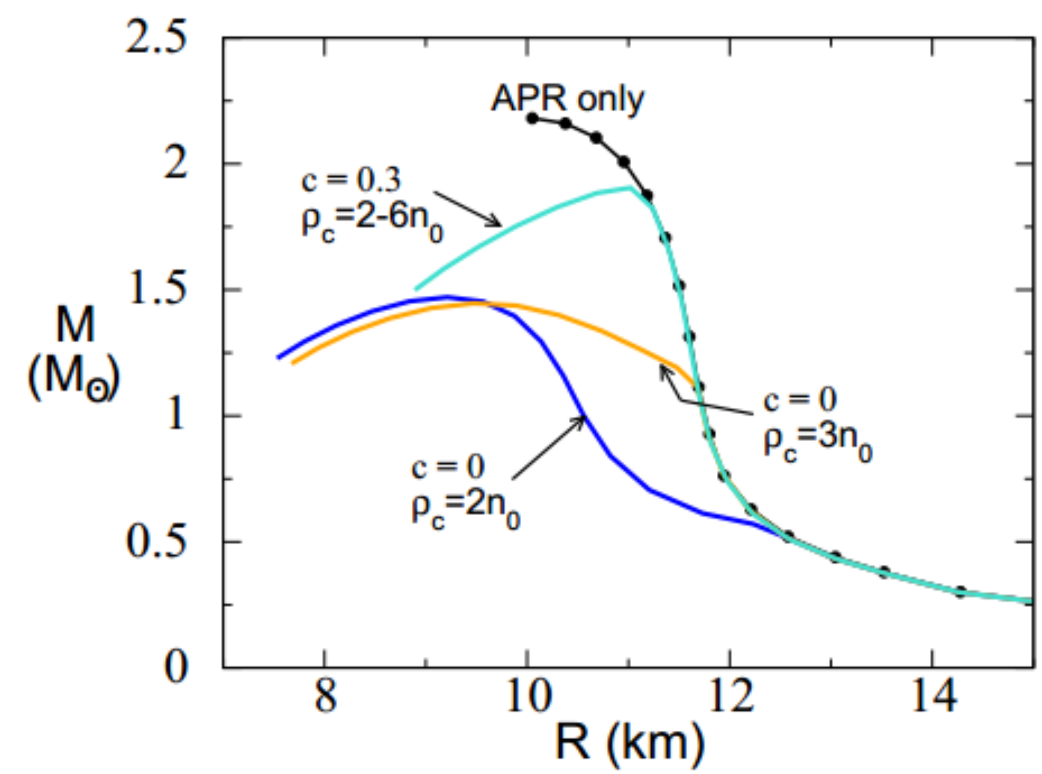
$$\frac{dm}{dr} = 4\pi r^2 \varepsilon$$

- Equation of State (EoS)

$$p(\varepsilon)$$

Masquerades



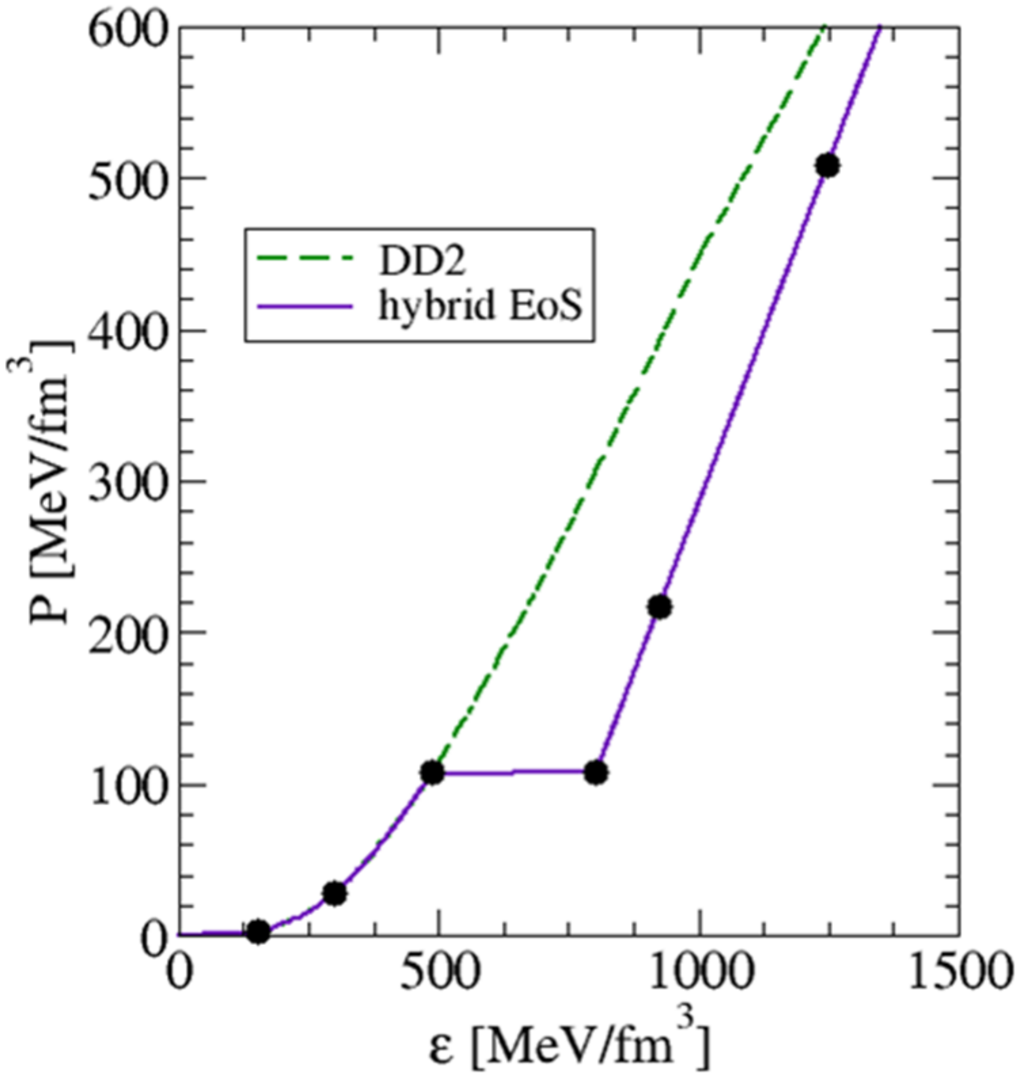


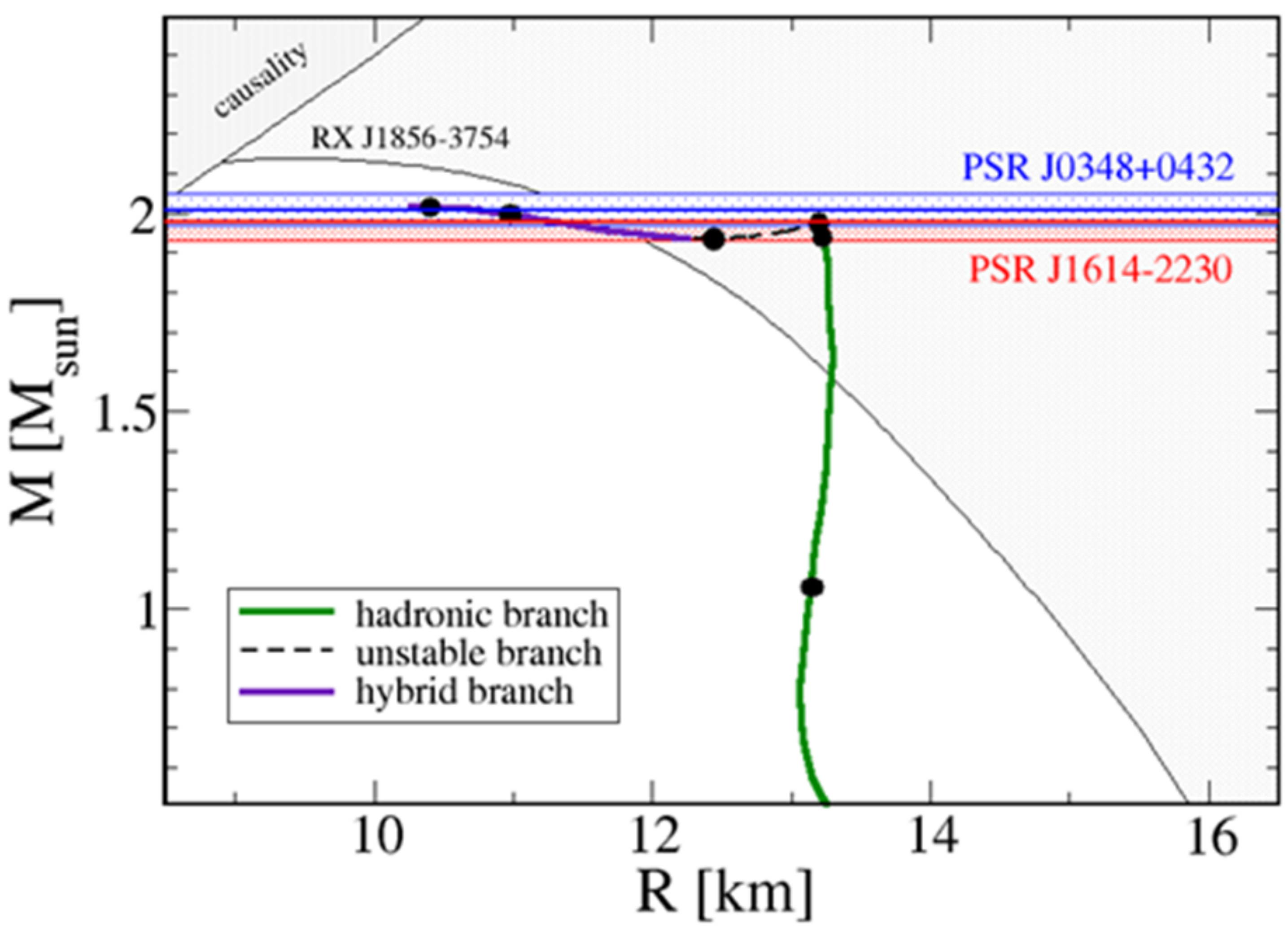
$$\Omega_{\rm QM} = -\frac{3}{4\pi^2}\, a_4\, \mu^4 + \frac{3}{4\pi^2} a_2\, \mu^2 + B_{\rm eff}$$

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

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

Compact Star Twins
Third family (disconnected branch)

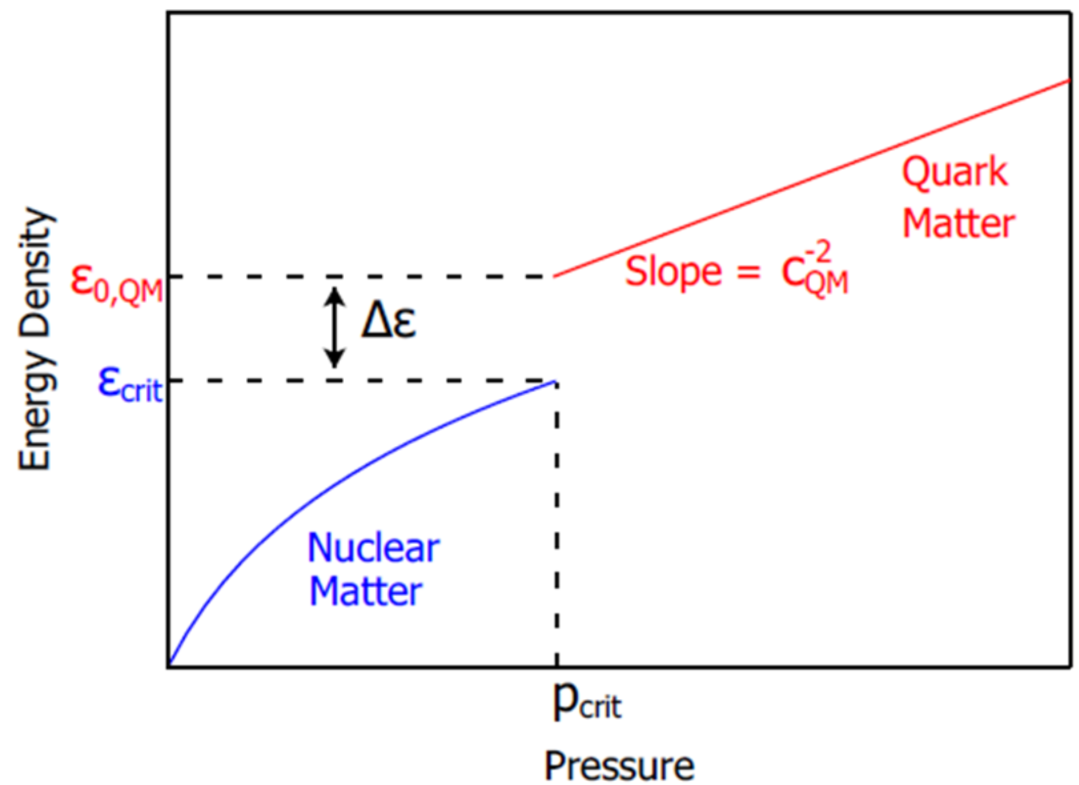




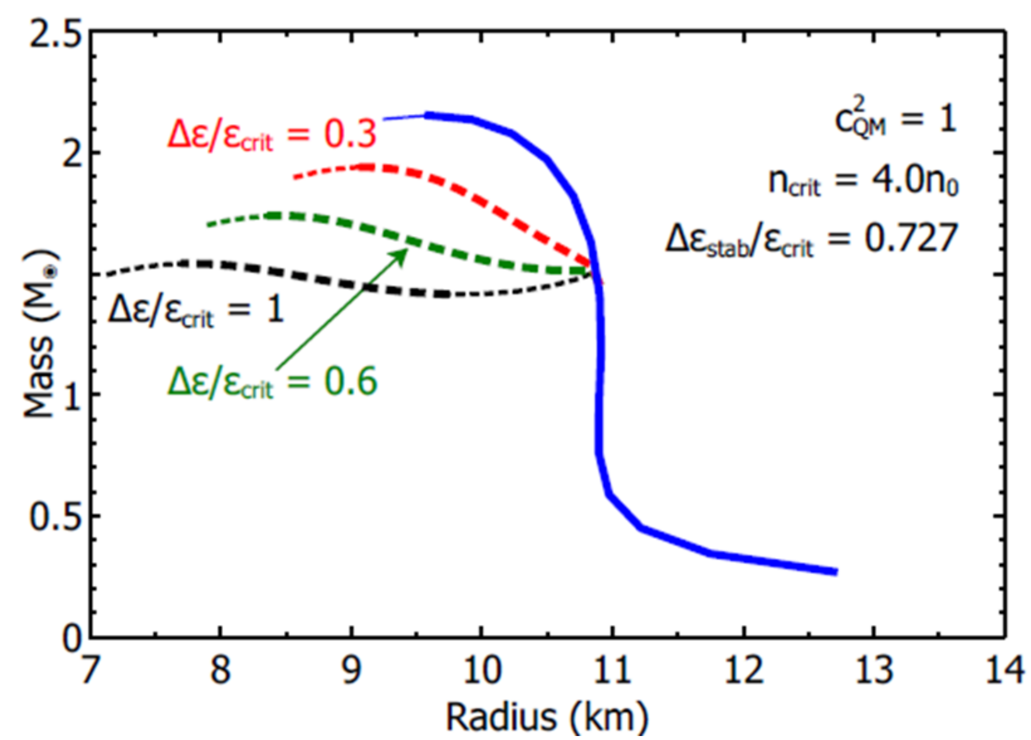
Alvarez-Castillo, Blaschke, arXiv: 1304.7758

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**".



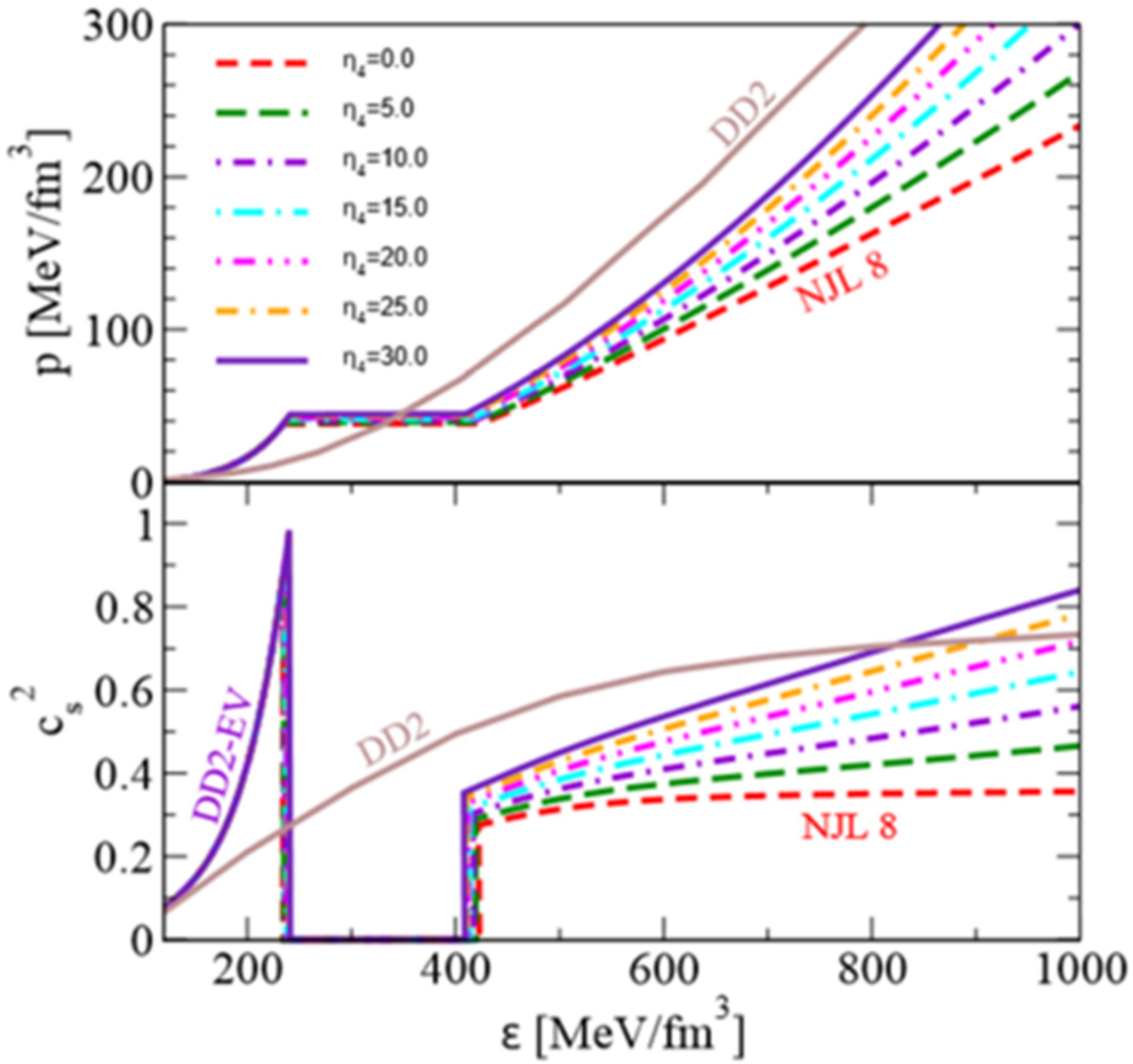
- Measuring two **disconnected populations** of compact stars in the M-R diagram would represent **the detection of a first order phase transition** in compact star matter and thus the indirect proof for the existence of a **critical endpoint (CEP) in the QCD phase diagram**!



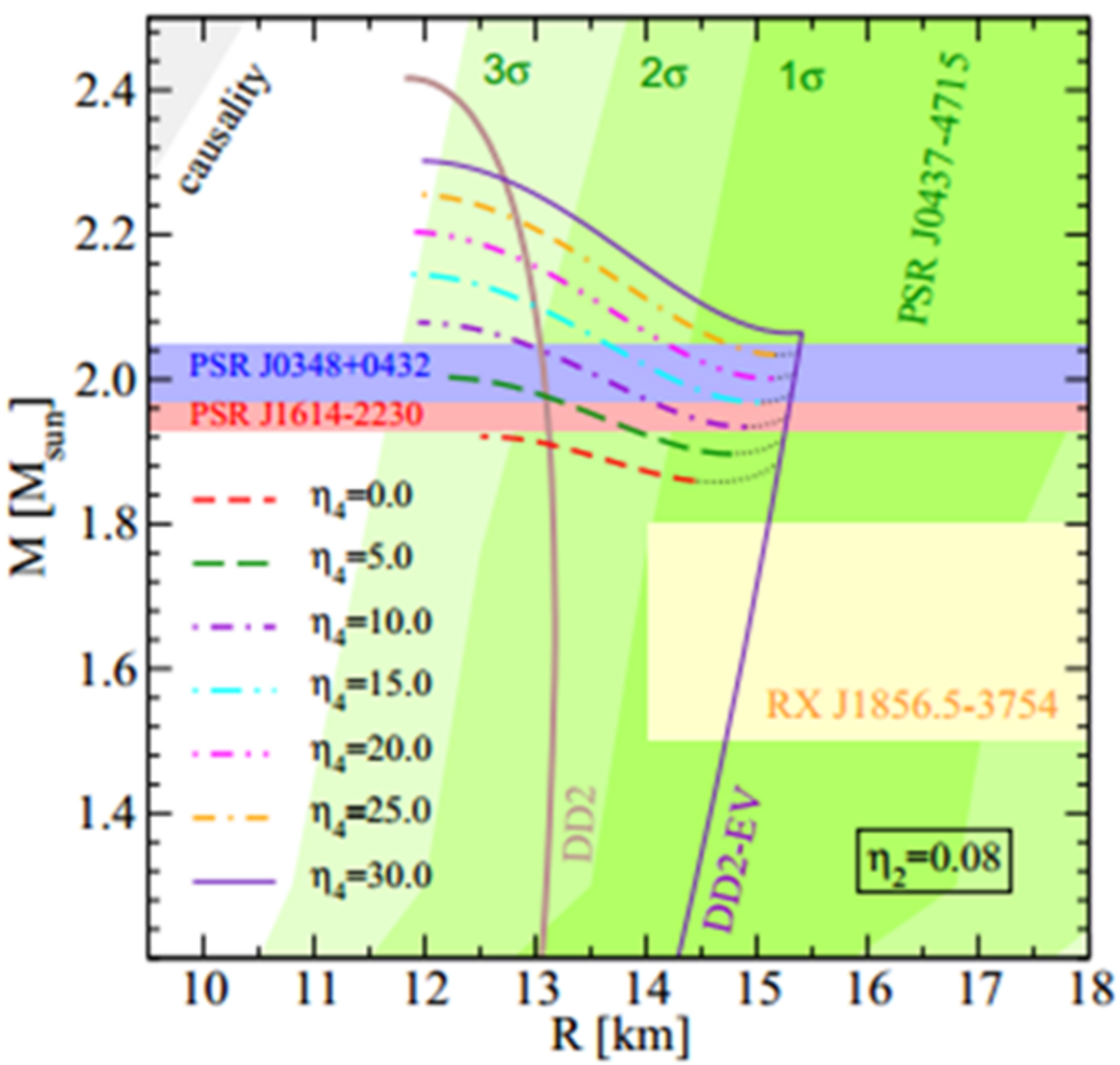
Alford, Han, Prakash,
Phys. Rev. D 88, 083013 (2013)
- arxiv:1302.4732

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

$$\begin{aligned} p_{\rm tot}(\mu_n,\mu_p) &= \frac{1}{\Phi}\sum_{i=n,p} p_i + p_{\rm mes} \ , \\ \varepsilon_{\rm tot}(\mu_n,\mu_p) &= -p_{\rm tot} + \sum_{i=n,p} \mu_i n_i \ , \end{aligned}$$

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.

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

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

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

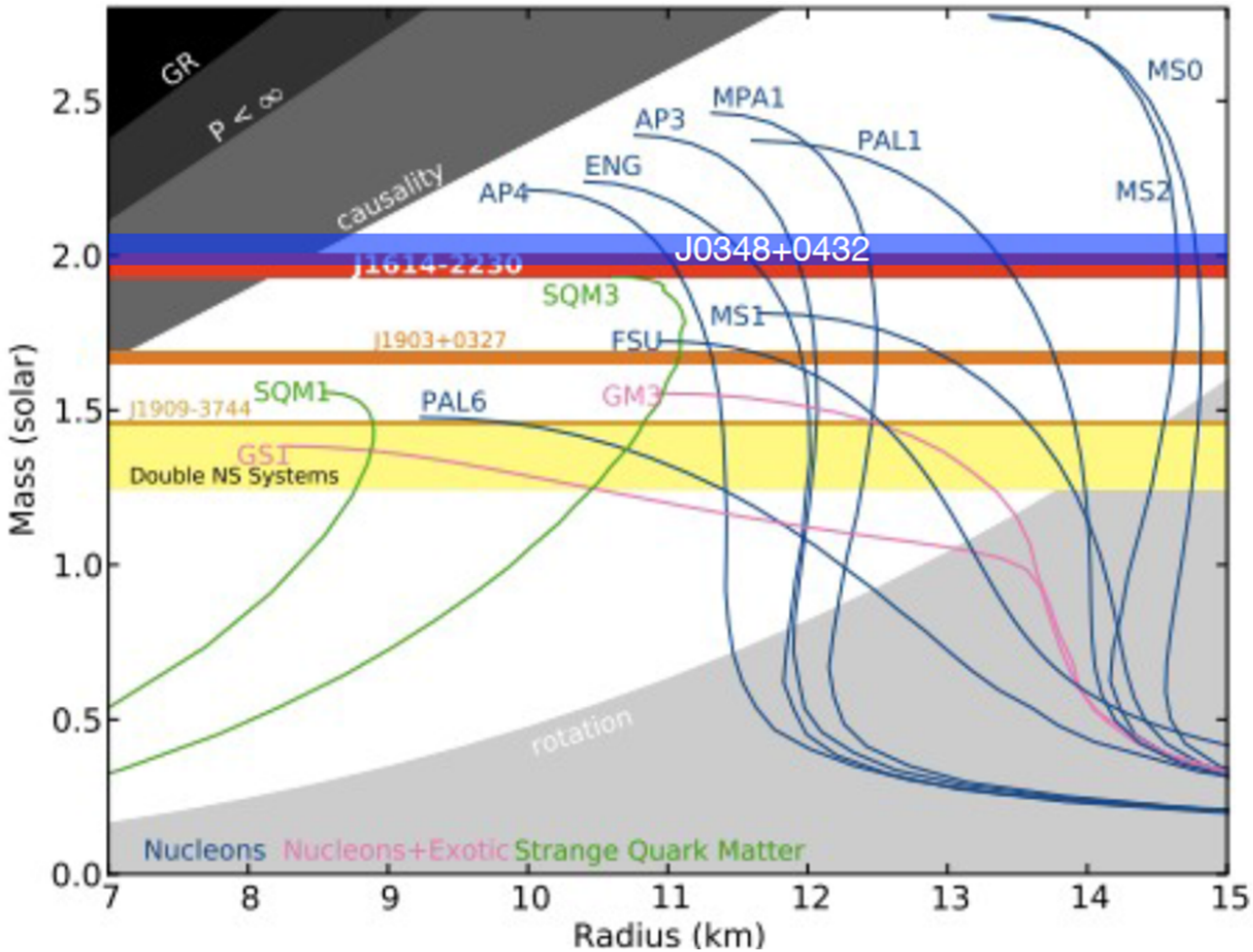
$$U = \frac{g_{20}}{\Lambda^2}\langle\bar{q}q\rangle^2 + 3\frac{g_{40}}{\Lambda^8}\langle\bar{q}q\rangle^4 - 3\frac{g_{22}}{\Lambda^8}\langle\bar{q}q\rangle^2\langle q^\dagger q\rangle^2 - \frac{g_{02}}{\Lambda^2}\langle q^\dagger q\rangle^2 - 3\frac{g_{04}}{\Lambda^8}\langle q^\dagger q\rangle^4\ .$$

Thermodynamic Potential:

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

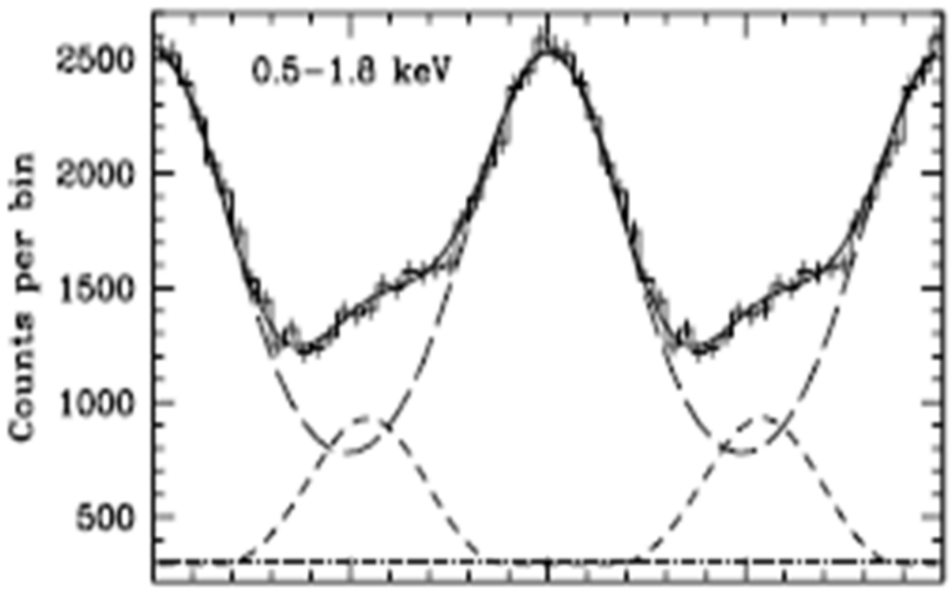
S. Benic - Eur.Phys.J. A50 (2014) 111, arXiv:1401.5380

Mass measurements

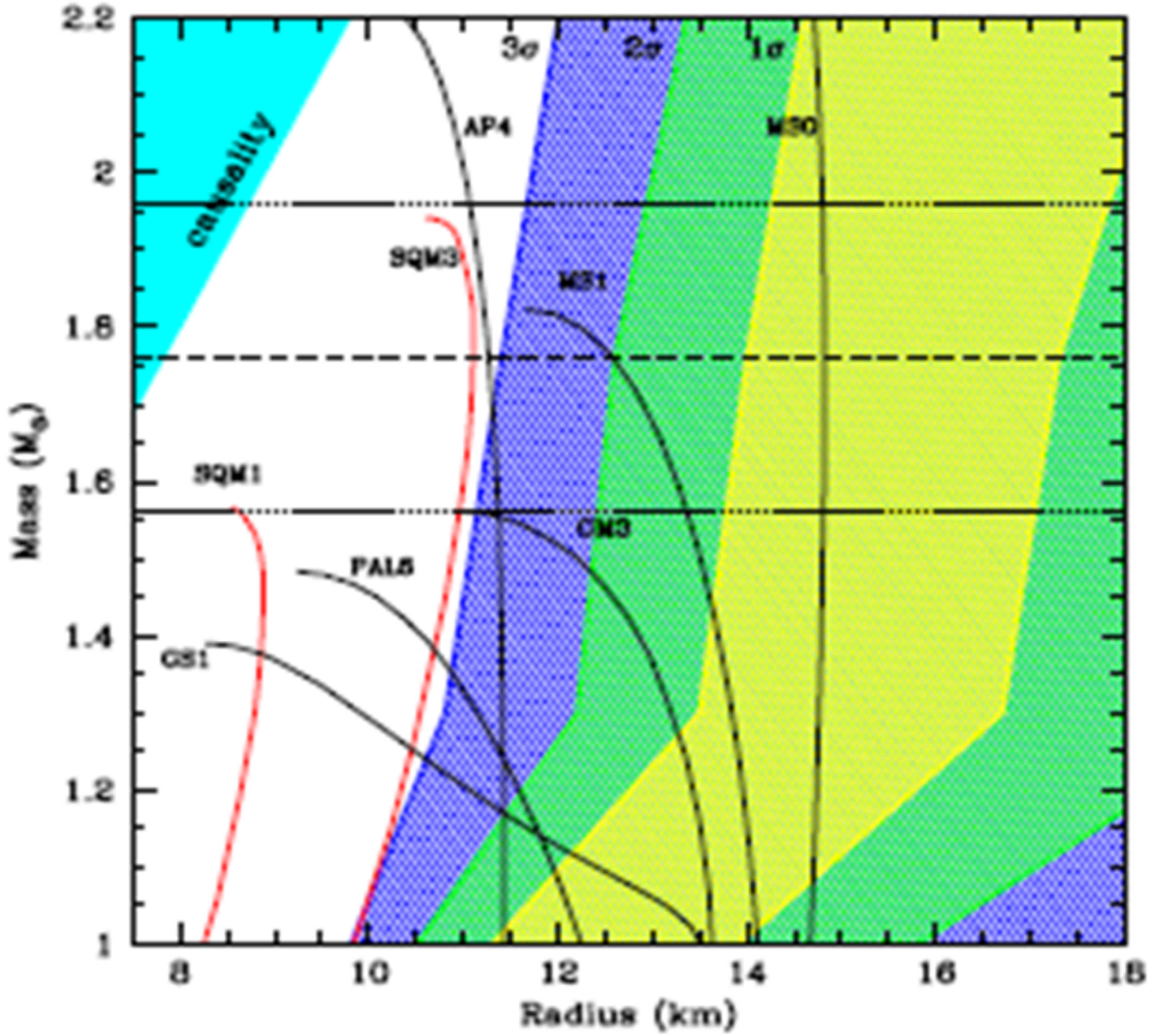


Radius measurement

- 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 = 3×10^{8} G



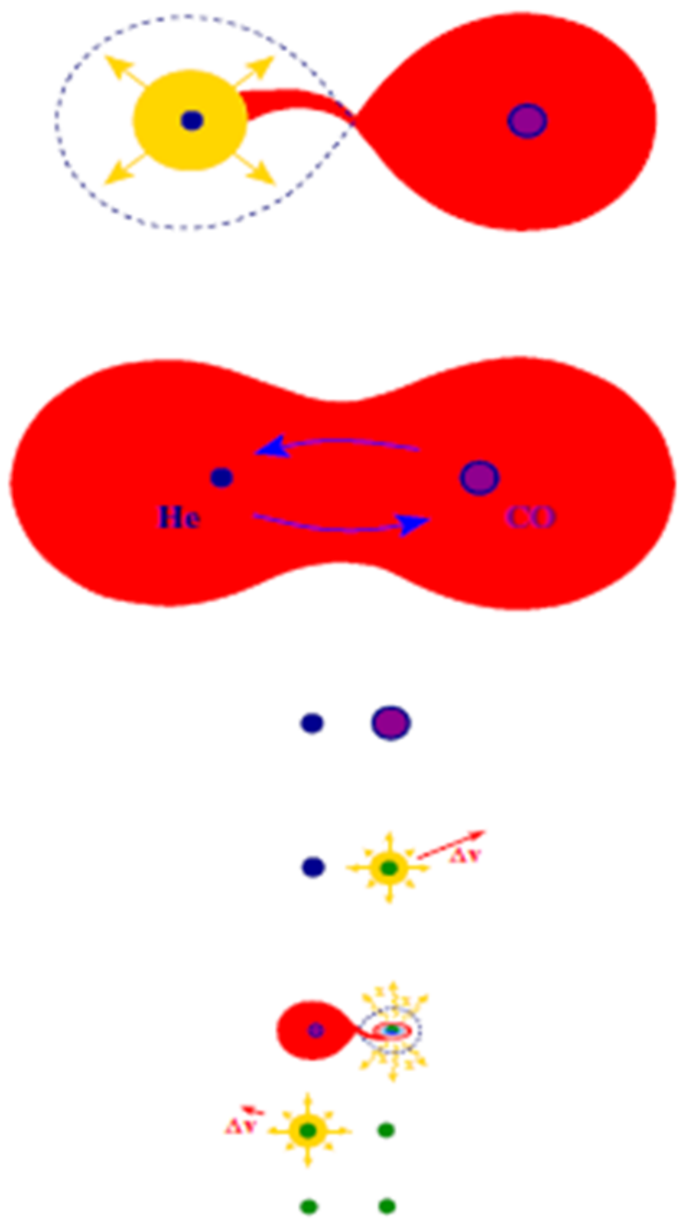
- Three thermal component fit: R > 11.1 km (at 3 sigma level), M = 1.76 M_{SUN}



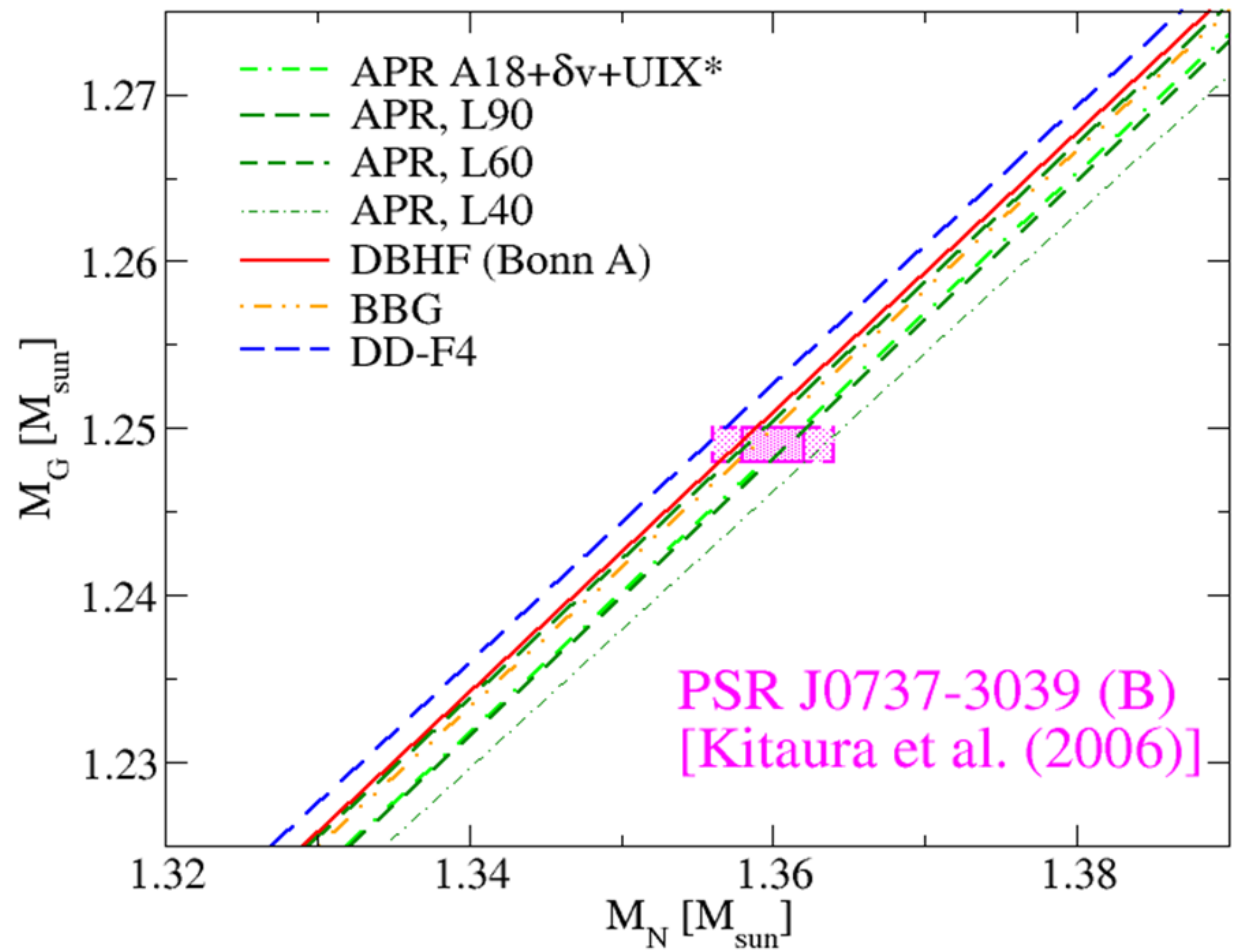
S. Bogdanov, 2013 ApJ 762 96
arxiv:1211.6113

Baryonic Mass

Double core scenario:



Dewi et al., MNRAS (2006)

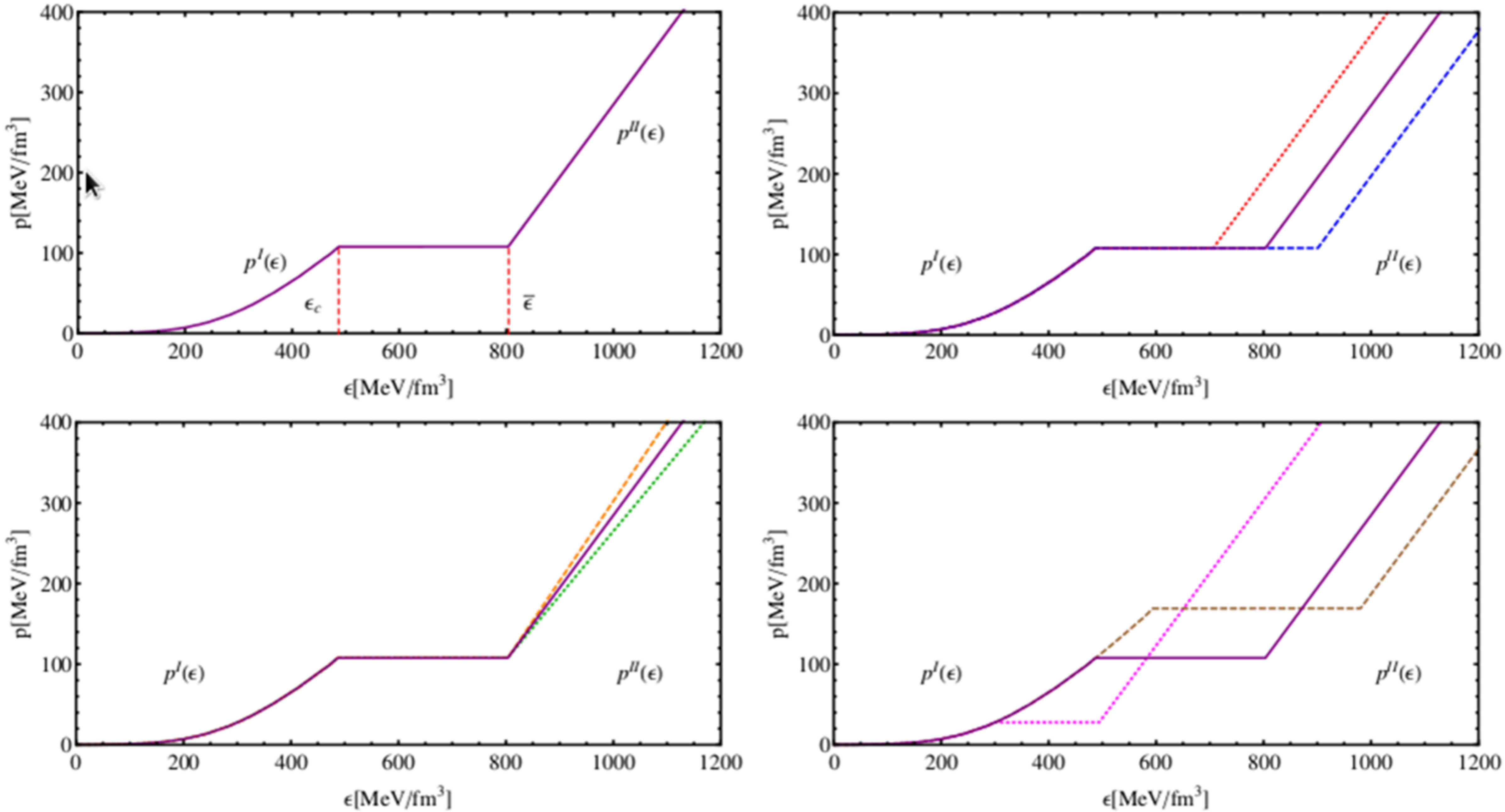


$$\frac{dn_B(r)}{dr} = 4\pi r^2 m_N \frac{n_B(r)}{\sqrt{1 - 2Gm(r)/r}}$$

Podsiadlowski et al., MNRAS 361 (2005) 1243

Kitaura, Janka. Hillebrandt, A&A (2006); arXiv: astro-ph/0512065

EoS parameterization in the AHP scheme



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

Bayesian Analysis

We define the vector of free parameters π_i defining the hybrid EoS

$$\pi_i = \vec{\pi}\left(\varepsilon_k, \gamma_l, c^2_{q_m}\right)$$

with $i = 0 \ldots N-1$ $(N = N_1 \times N_2 \times N_3)$ as $i = N_1 \times N_2 \times k + N_2 \times l + m$ and $k = 0 \ldots N_1 - 1$, $l = 0 \ldots N_2 - 1$, $m = 0 \ldots N_3 - 1$, where N_1, N_2 and N_3 denote the number of parameters for ε_k, γ_l and c^2_{qm}, respectively. Solving the TOV equations with varying boundary conditions for $\varepsilon(r = 0)$ generates a sequence of $M(R)$ curves characteristic for each of these N EoS. Subsequently, different neutron star observations with their error margins can be used to assign a probability to each choice in from the set of EoS parameters.

We consider these independent measurements for this analysis and compute the complete conditional probability of an event E that a compact star object characterized by π_i fulfills all constraints:

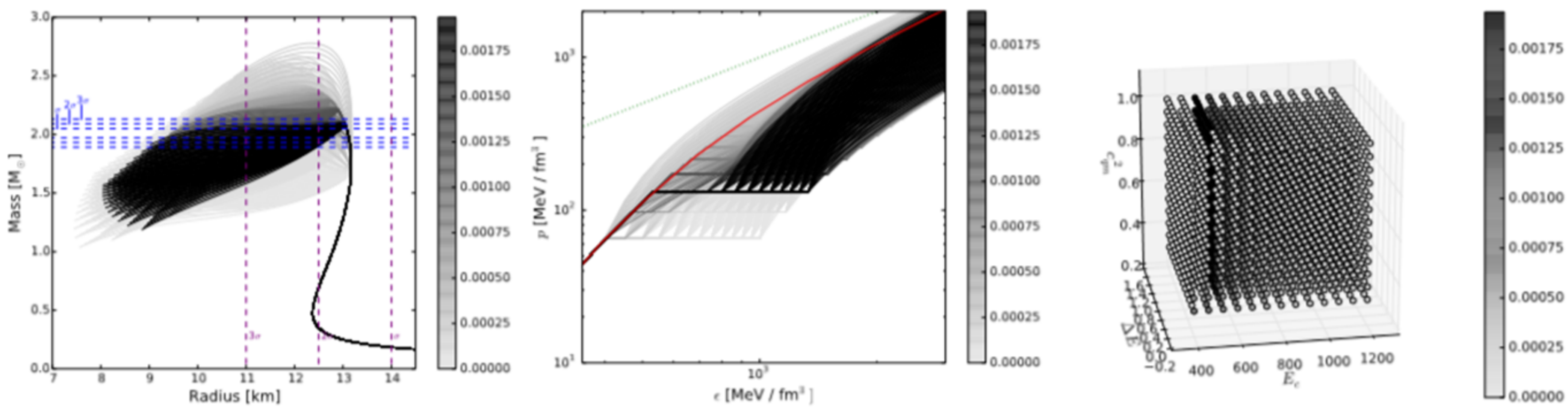
$$\mathrm{P}(E\,|\pi_i) = P\left(E_A\,|\pi_i\right) \times P\left(E_B\,|\pi_i\right) \times P\left(E_K\,|\pi_i\right)$$

Then we can calculate the probability of π using Bayes' theorem:

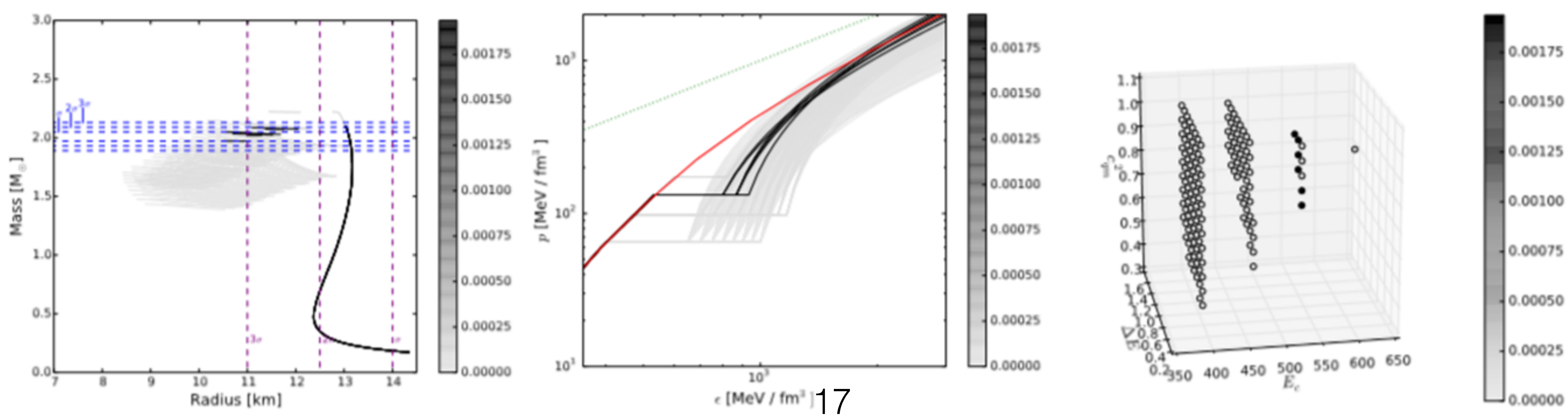
$$\mathrm{P}(\pi_i\,|E) = \frac{P(E|\pi_i)P(\pi_i)}{\sum\limits_{j=0}^{N-1} P(E|\pi_j)P(\pi_j)}$$

Bayesian probabilities for phase transitions

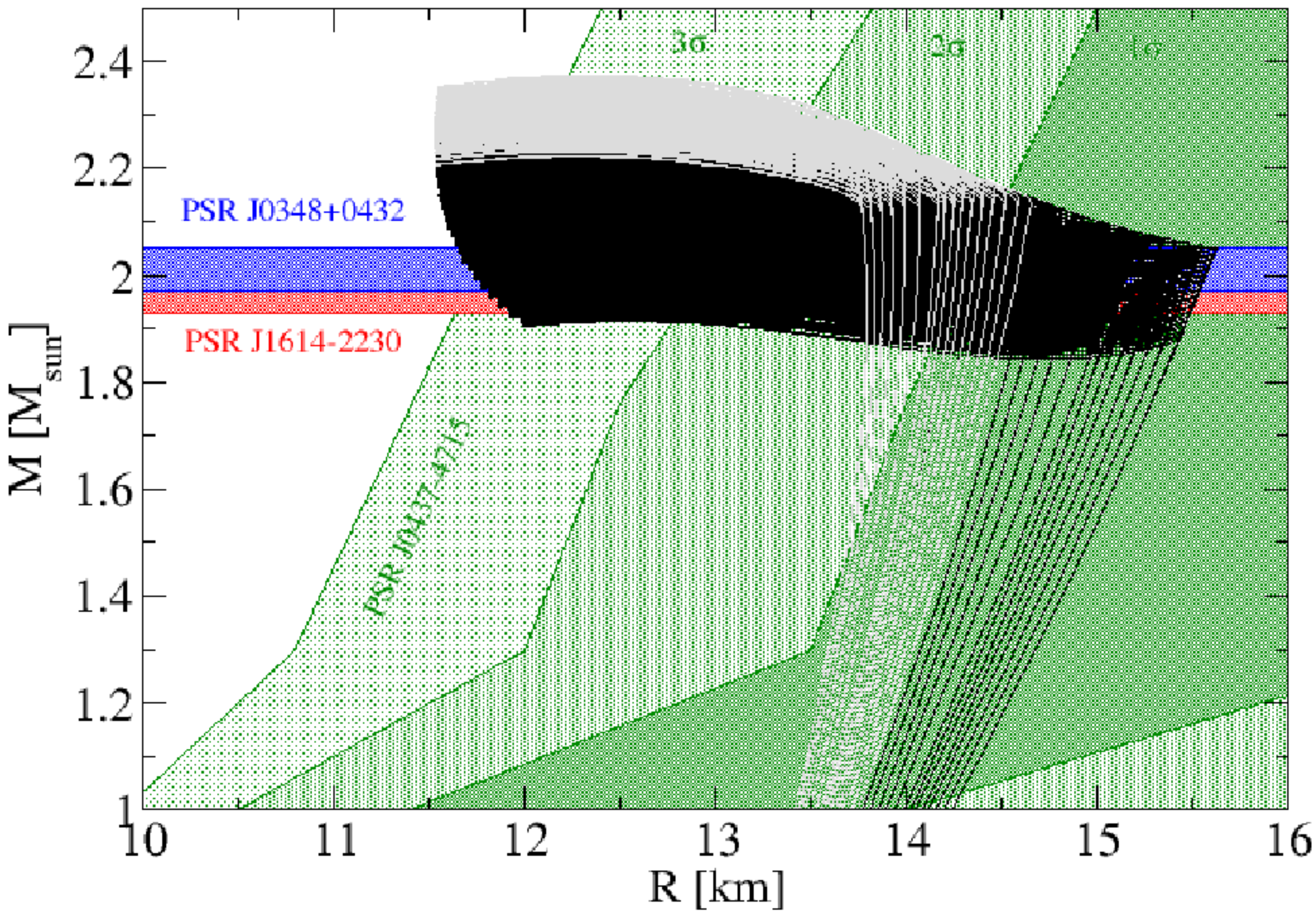
- Full set of configurations based on DD2 EoS



- High Mass Twin Configurations on DD2 EoS

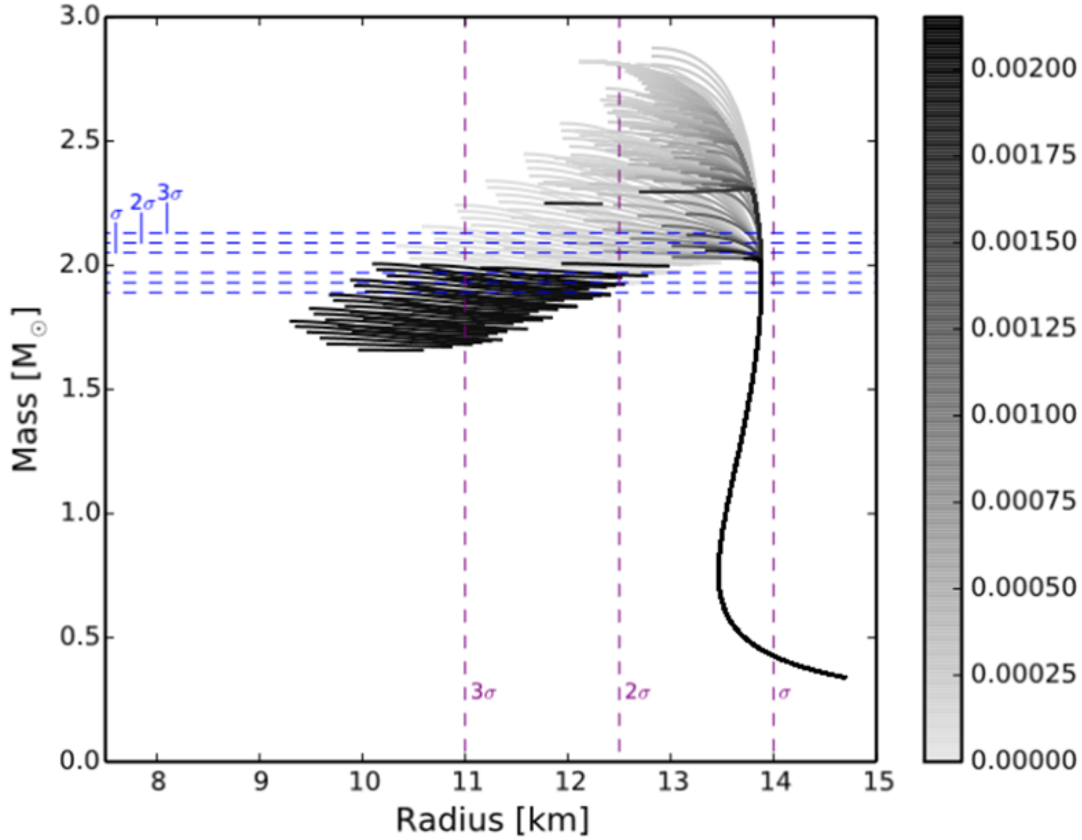


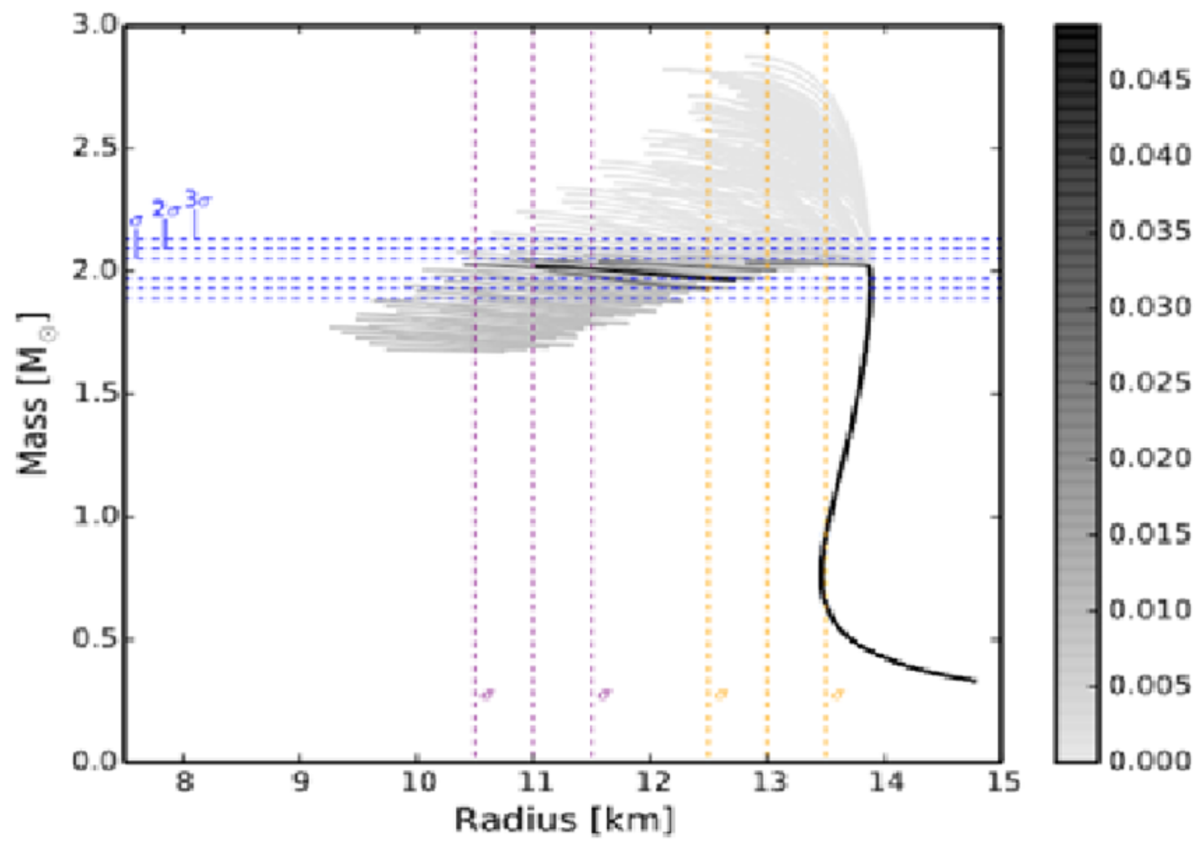
Two dimensional Bayes



Alvarez-Castillo, Ayriyan, Blaschke, Grigorian, CSQCD (2015)

Fictitious Radius Measurement





Without twin mass measurement

With twin mass measurement

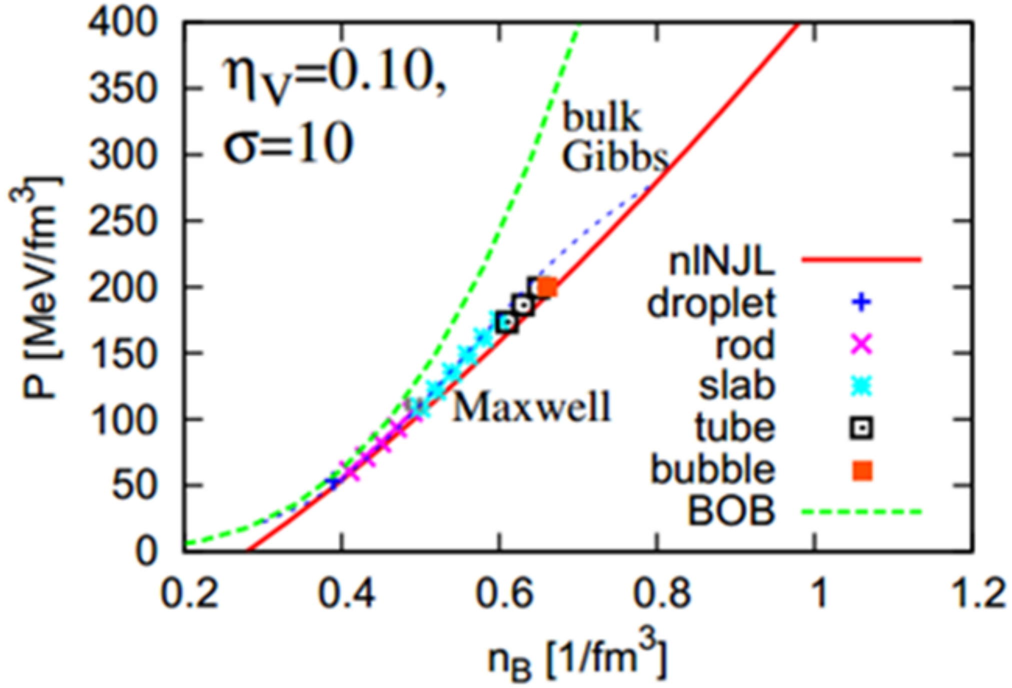
$M_1 = 2.01 \pm 0.04\ M_{SUN}$
$R_1 = 11$ km

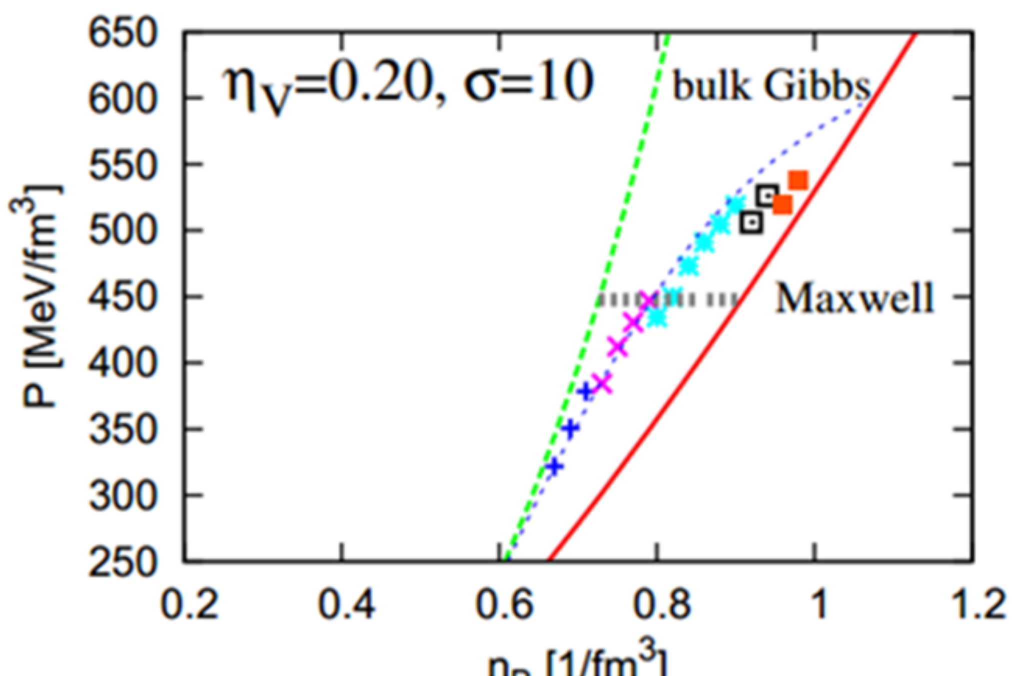
$M_2 = 1.93 \pm 0.04\ M_{SUN}$
$R_2 = 13$ km

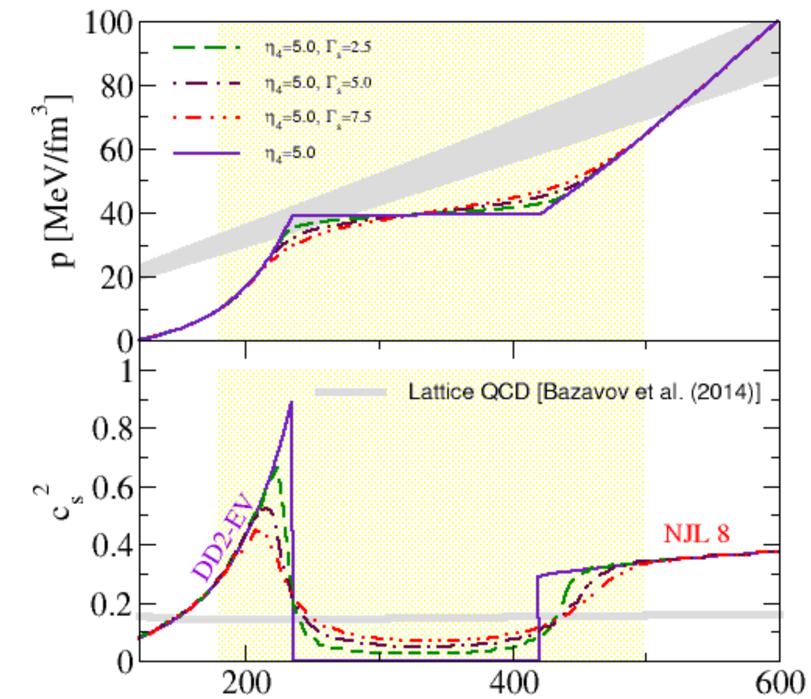
with $\sigma_{1,2} = 0.5$ km

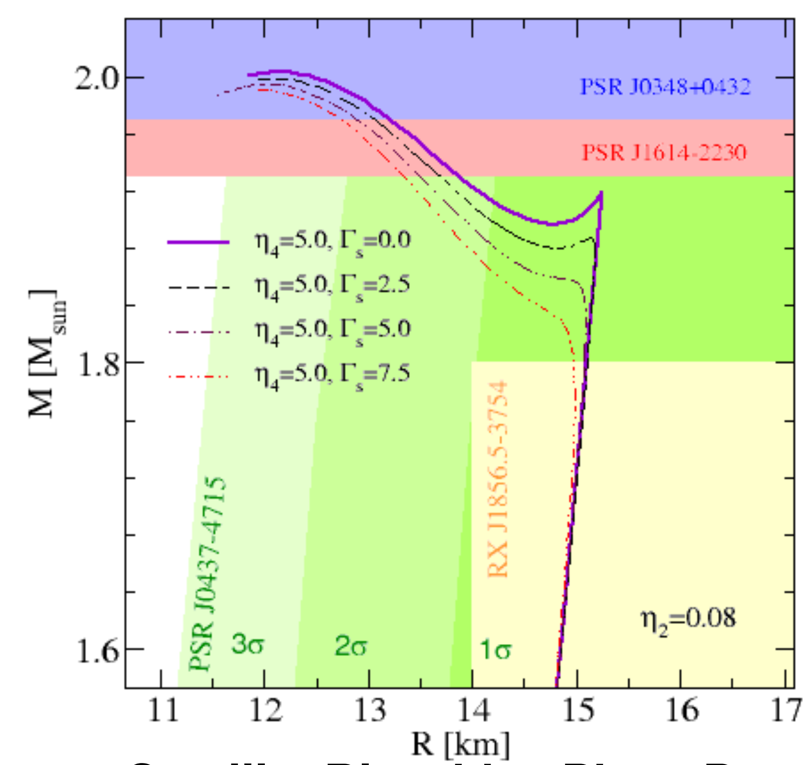
Alvarez-Castillo, Ayriyan, Blaschke, Grigorian, Sokolowski, Phys. Part. Nucl. 46 (2015) - arXiv:1412.8226

Pasta phases in hybrid stars



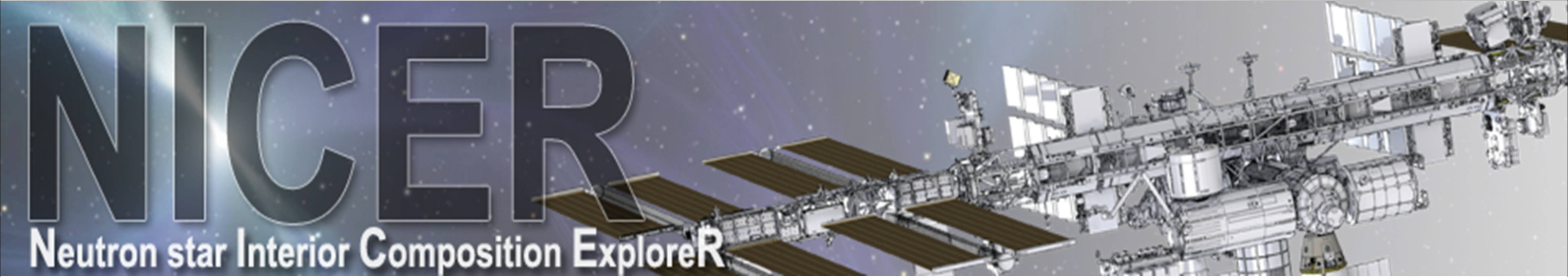


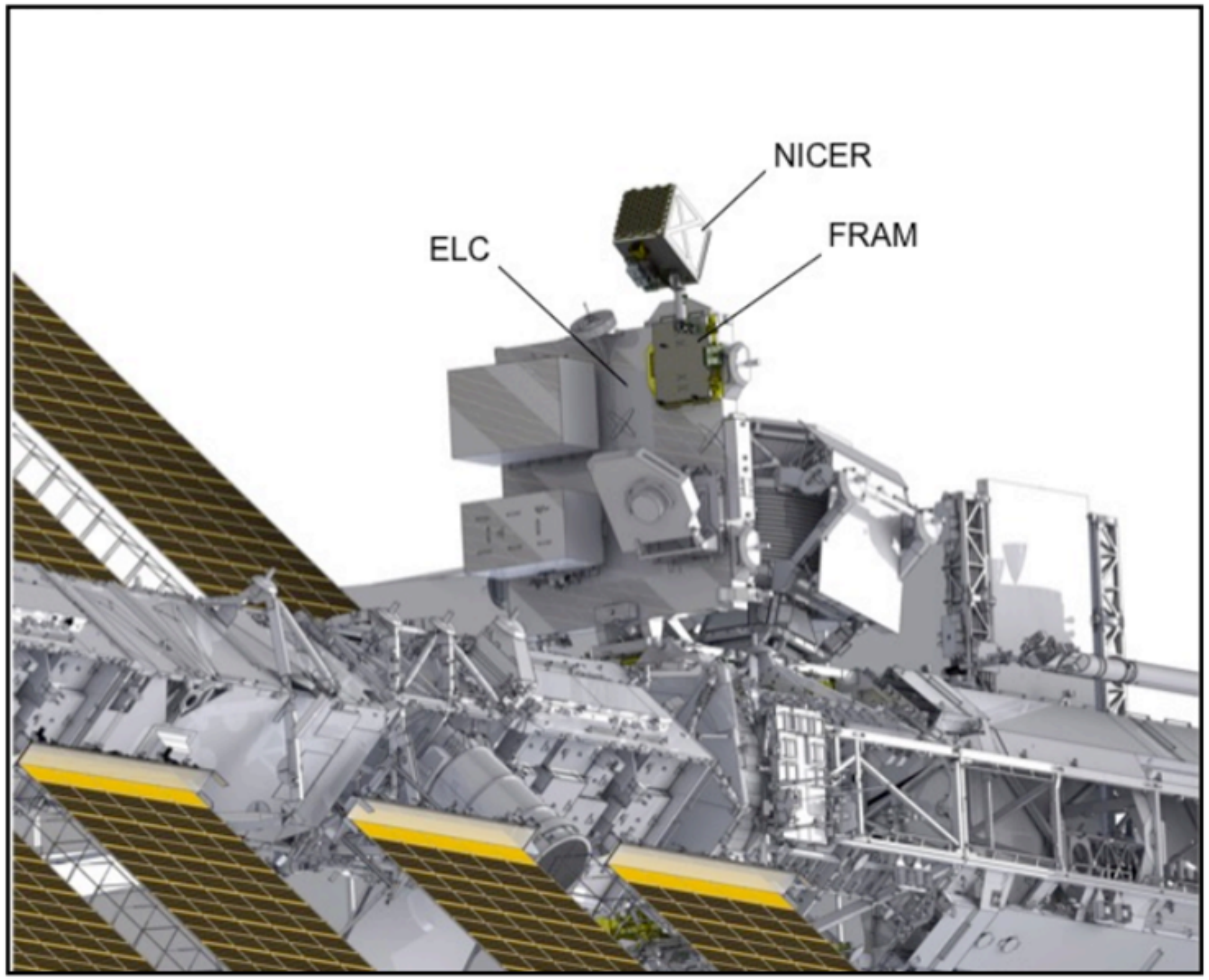


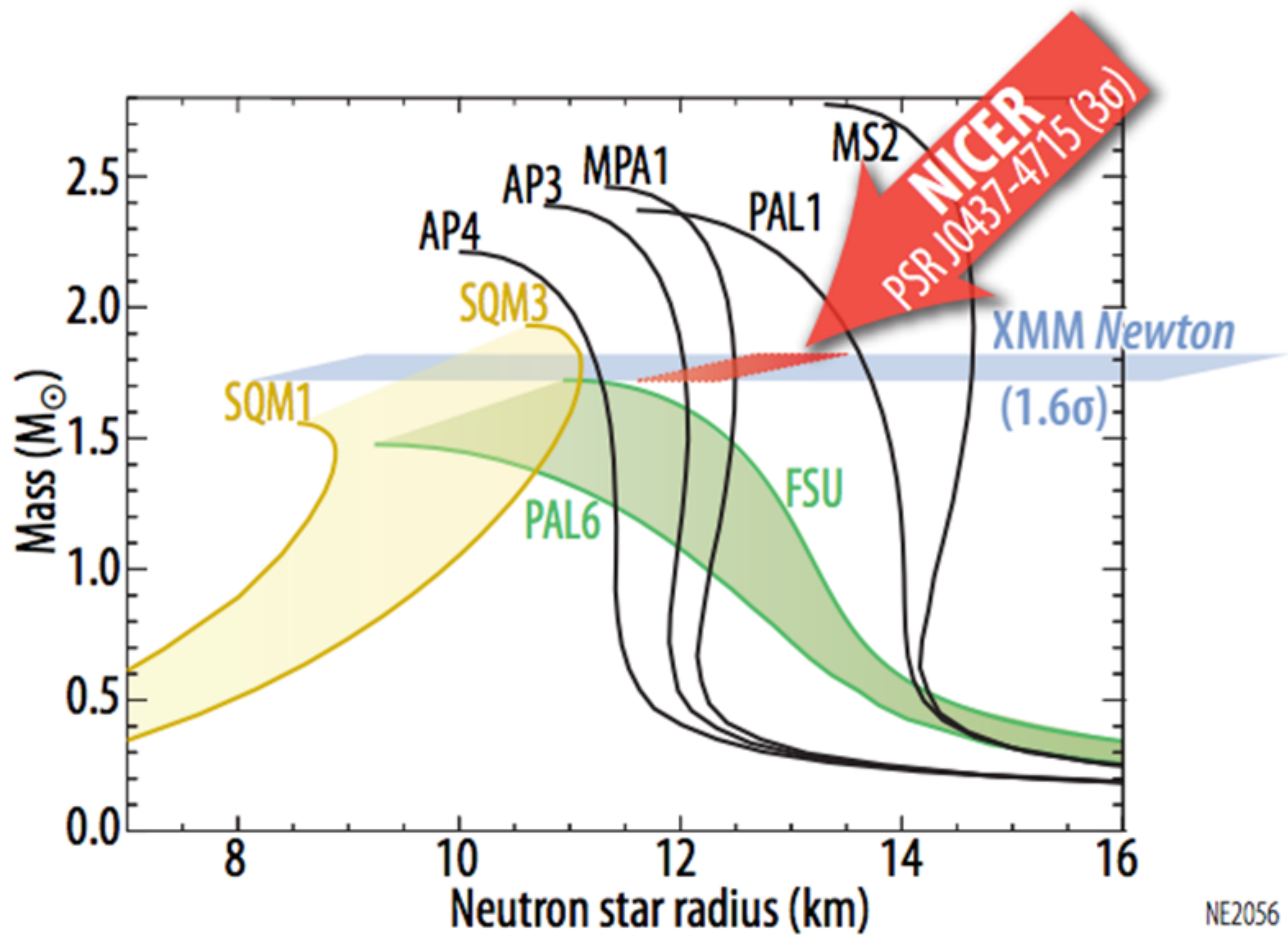


Yasutake et al., Phys. Rev. C 89, 065803 (2014)
arXiv:1403.7492

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

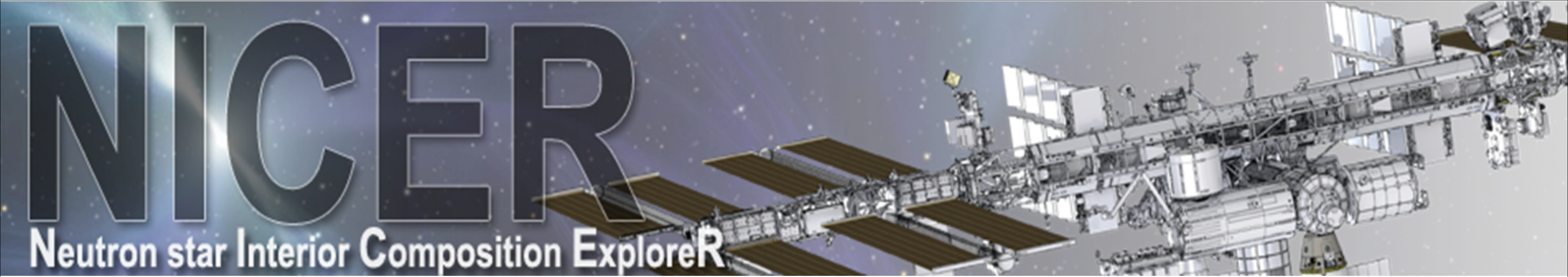


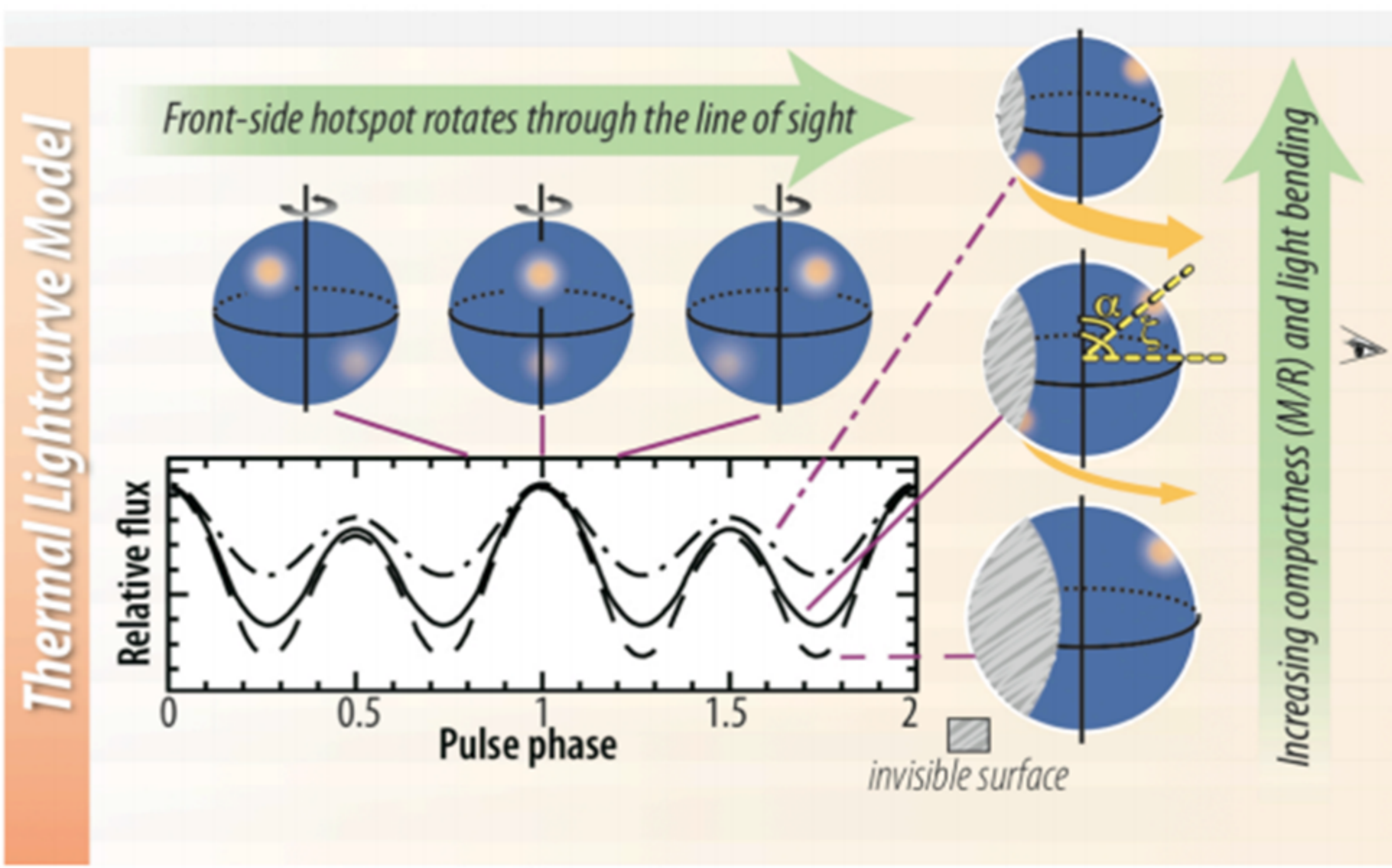


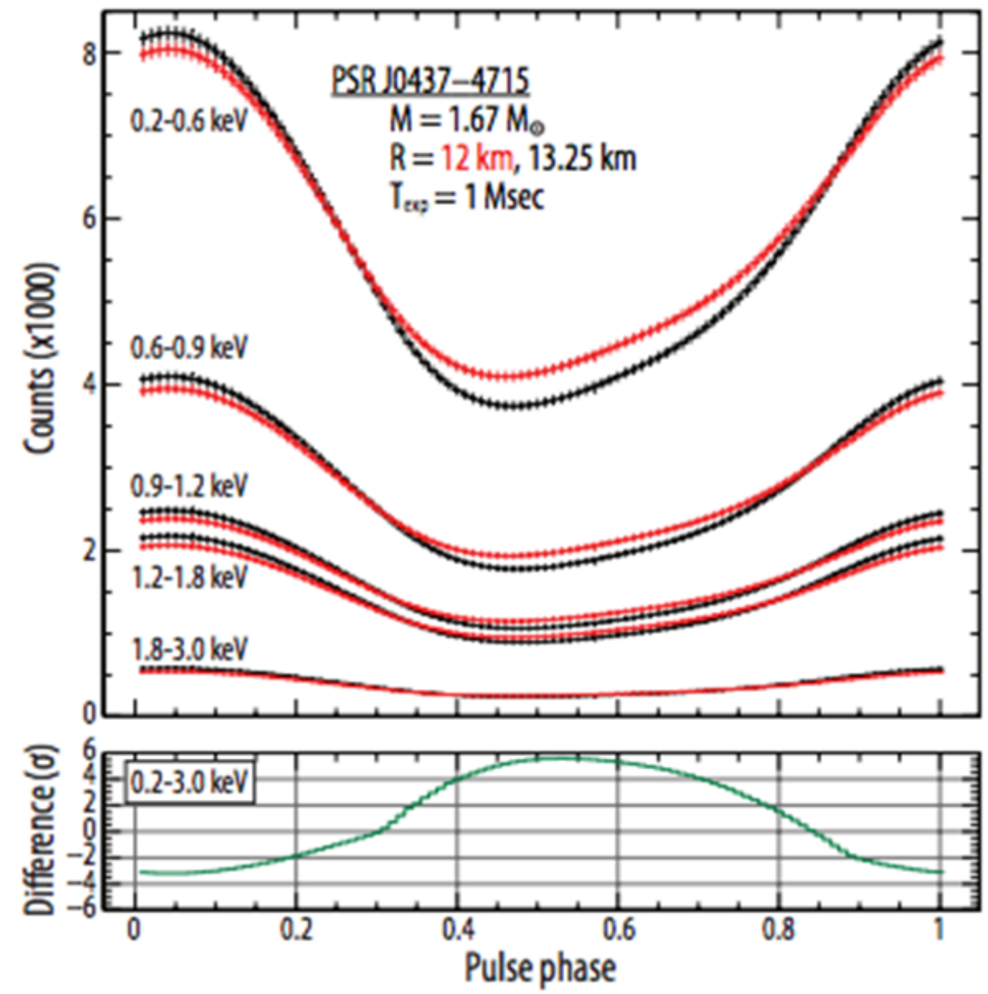


NICER 2017

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







Hot Spots

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

Conclusions

- 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.

- Modeling compact star twins is possible via a microscopic approach based on a QCD motivated hNJL models fulfilling astronomical observations and offers a solution to the hyperon puzzle and the masquerade stars ambiguity.

- Bayesian Analysis on hybrid compact star EoS has the power to provide the corresponding probabilities for radius measurements in order to identify mass twins.

Gracias