Cosmological Constant Effects on the Properties of Mass Twin Compact Stars

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AL ZAHRA UNIVERSITY

Key Questions

- What are the effects of a free variation of the cosmological constant on compact stars?
- Are there any special features differentiating classical neutron stars from hybrid compact stars?

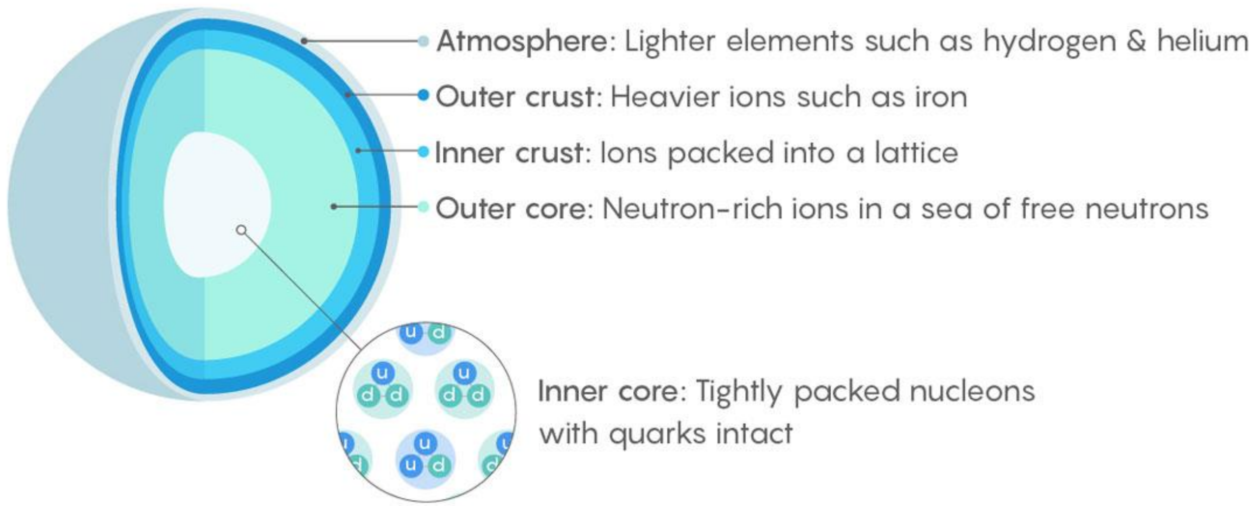
Outline

- Brief introduction to the neutron star equation of state.
- First order phase transition and deconfinement in compact stars: neutron star mass twins.
- Effects of the cosmological constant in compact stars.
- Astrophysical implications and perspectives.

The Extraordinary Core of a Neutron Star

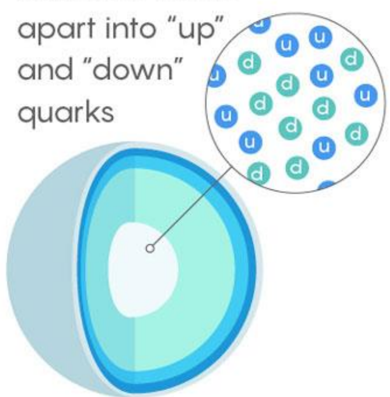
A neutron star's core is so dense that physicists aren't sure what happens inside. Researchers can't recreate the conditions in the lab, and even the theory of nuclear matter is of limited help. Here are some of the main ideas.

TRADITIONAL VIEW OF A NEUTRON STAR



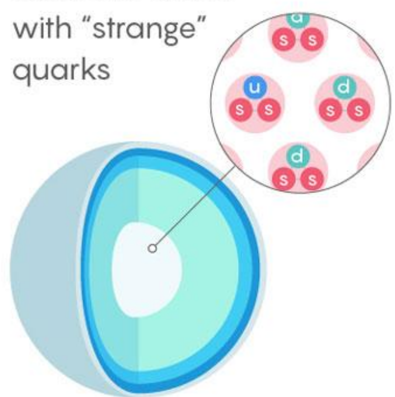
QUARK CORE

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



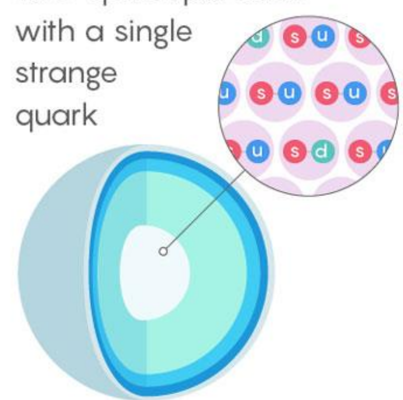
HYPERON CORE

Nucleons made with "strange" quarks

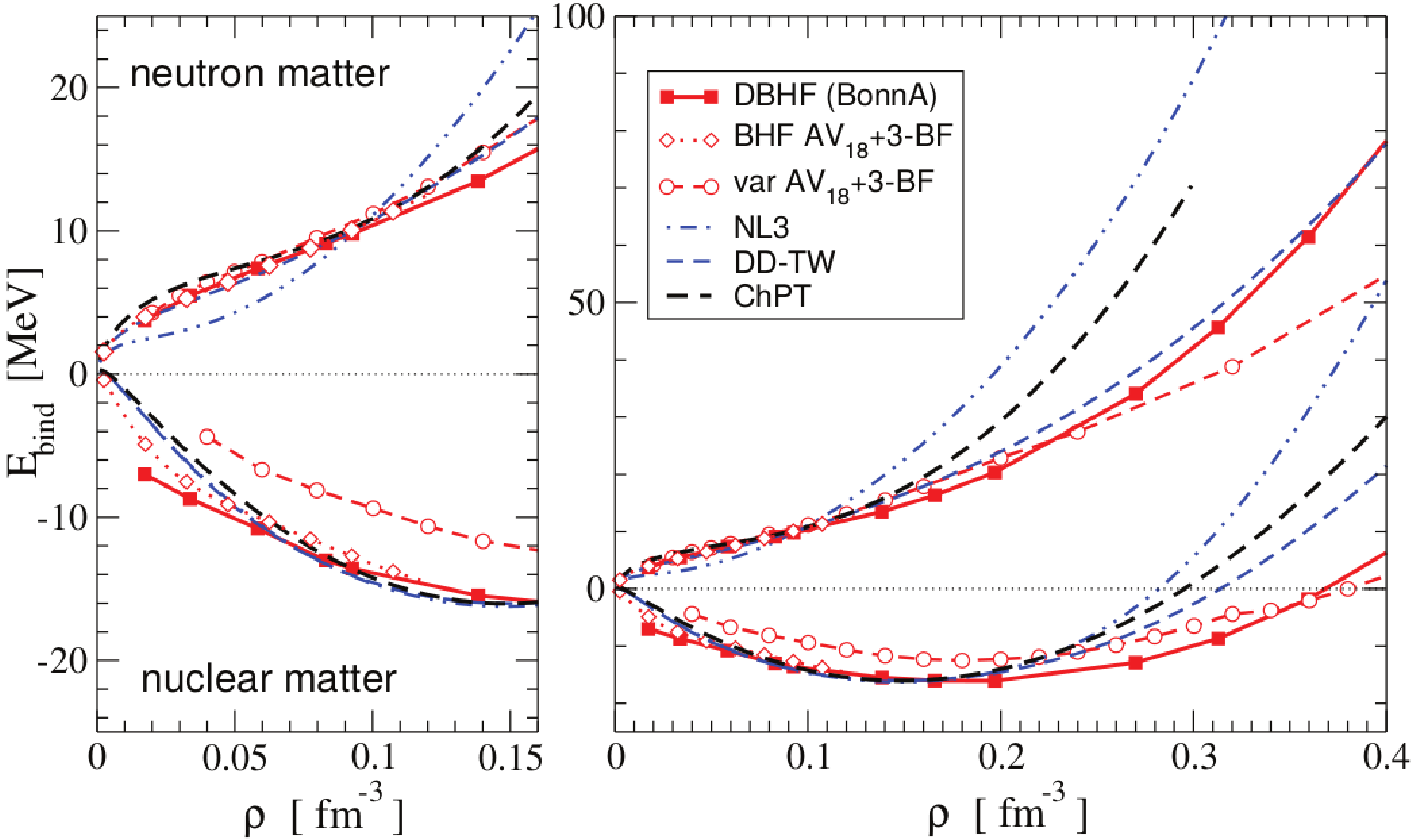


KAON CONDENSATE CORE

Two-quark particles with a single strange quark

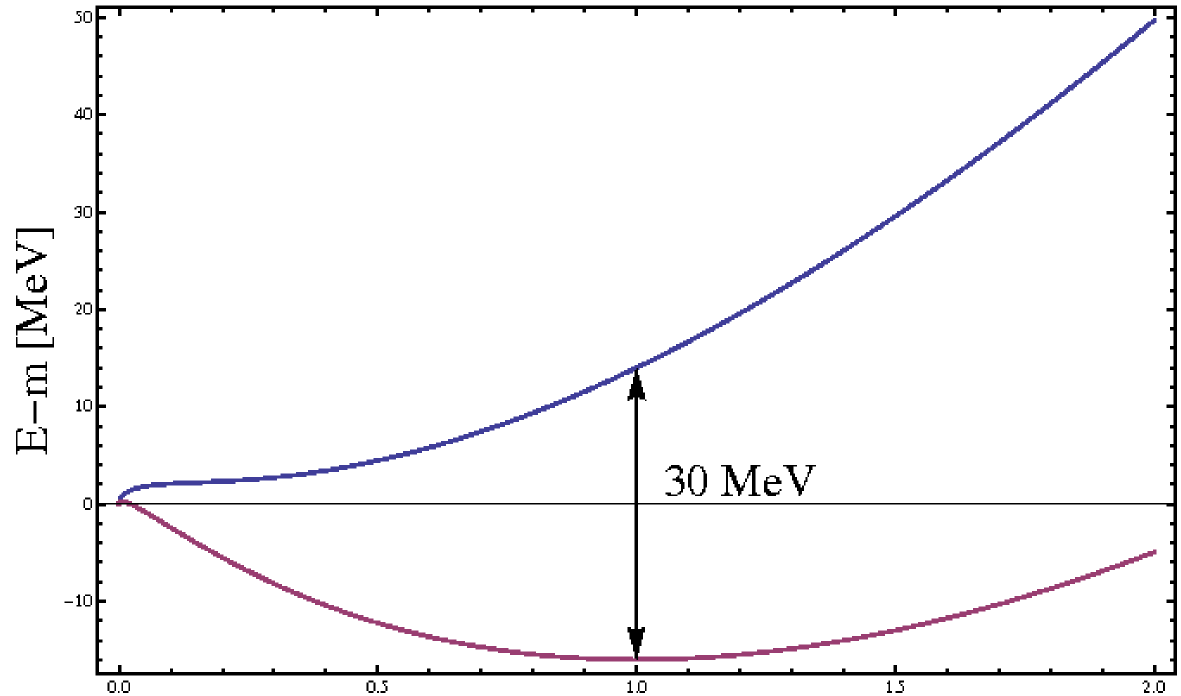


Nuclear Matter



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

Nuclear Symmetry Energy



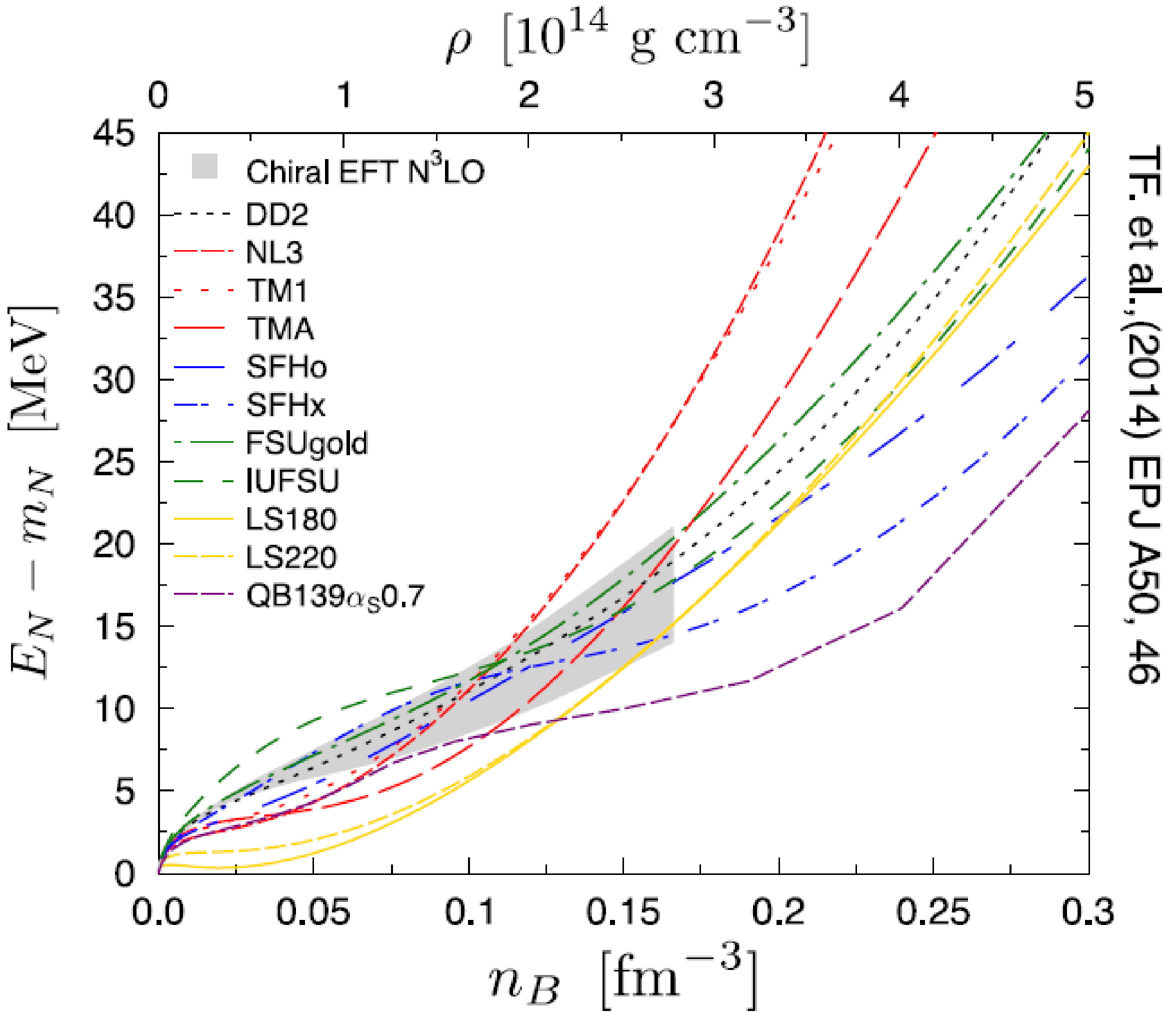
$\frac{n}{n_0}$

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 Equation of State



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)

Neutron Star EoS

- Nuclear interaction:

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

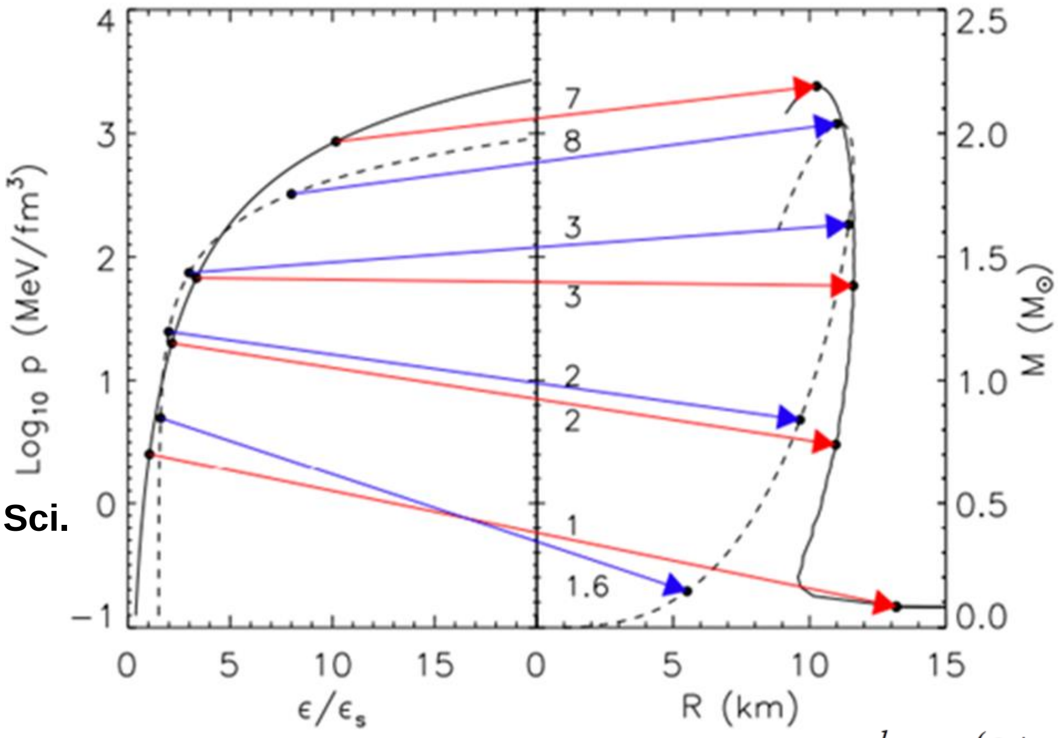
- Beta equilibrium: $\mu_n - \mu_p = \mu_e = \mu_\mu$
- 2 phase construction under Gibbs conditions: $p^I = p^{II}$ $\mu_n^I = \mu_n^{II}$ $\mu_e^I = \mu_e^{II}$
- Charge neutrality: $x_p = x_e$
- TOV equations + Equation of State

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

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

Compact Star Sequences
(M-R ↔ EoS)

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



- TOV Equations

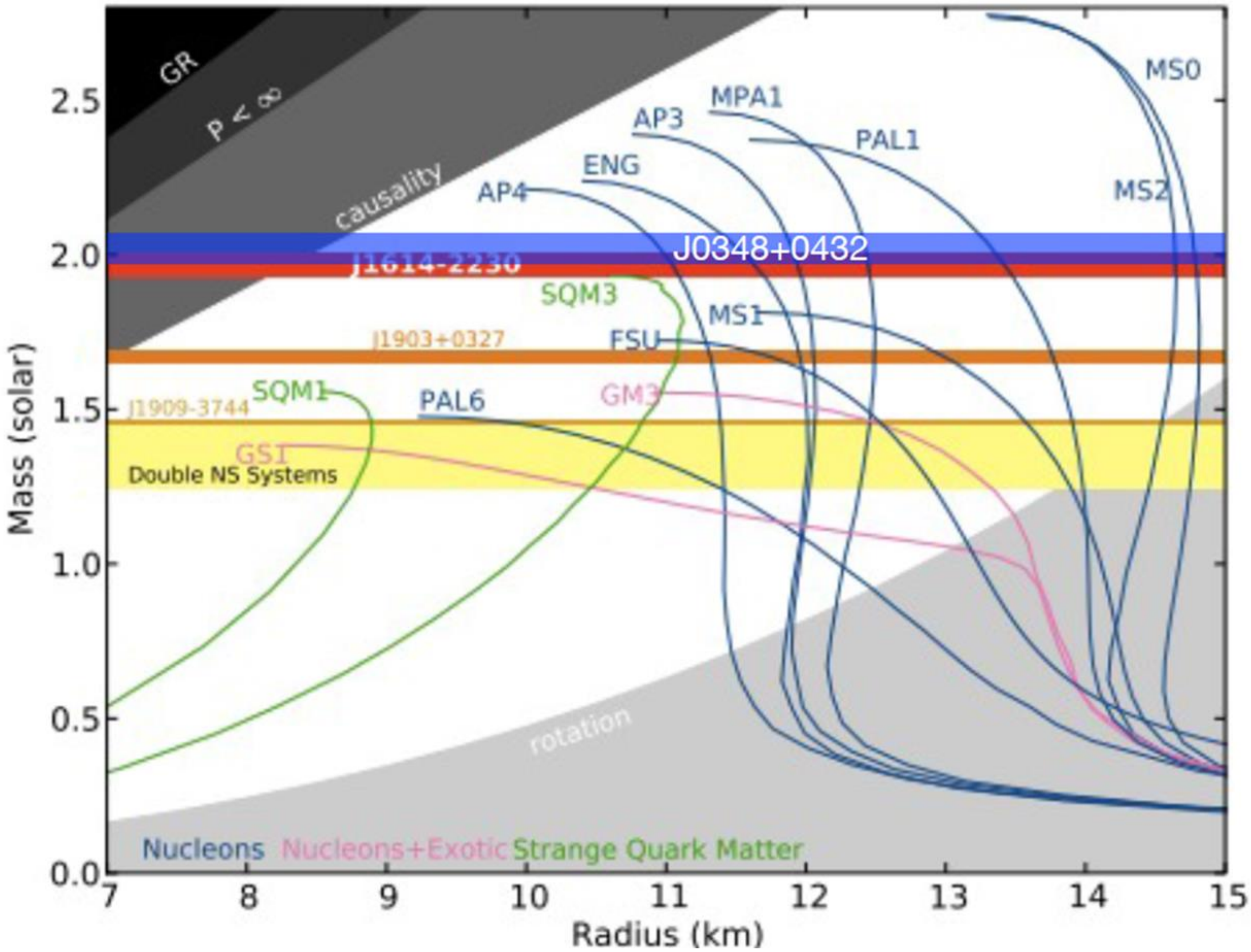
$$\frac{dp}{dr} = -\frac{(\varepsilon + p/c^2)G(m + 4\pi r^3 p/c^2)}{r^2(1 - 2Gm/rc^2)}$$

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

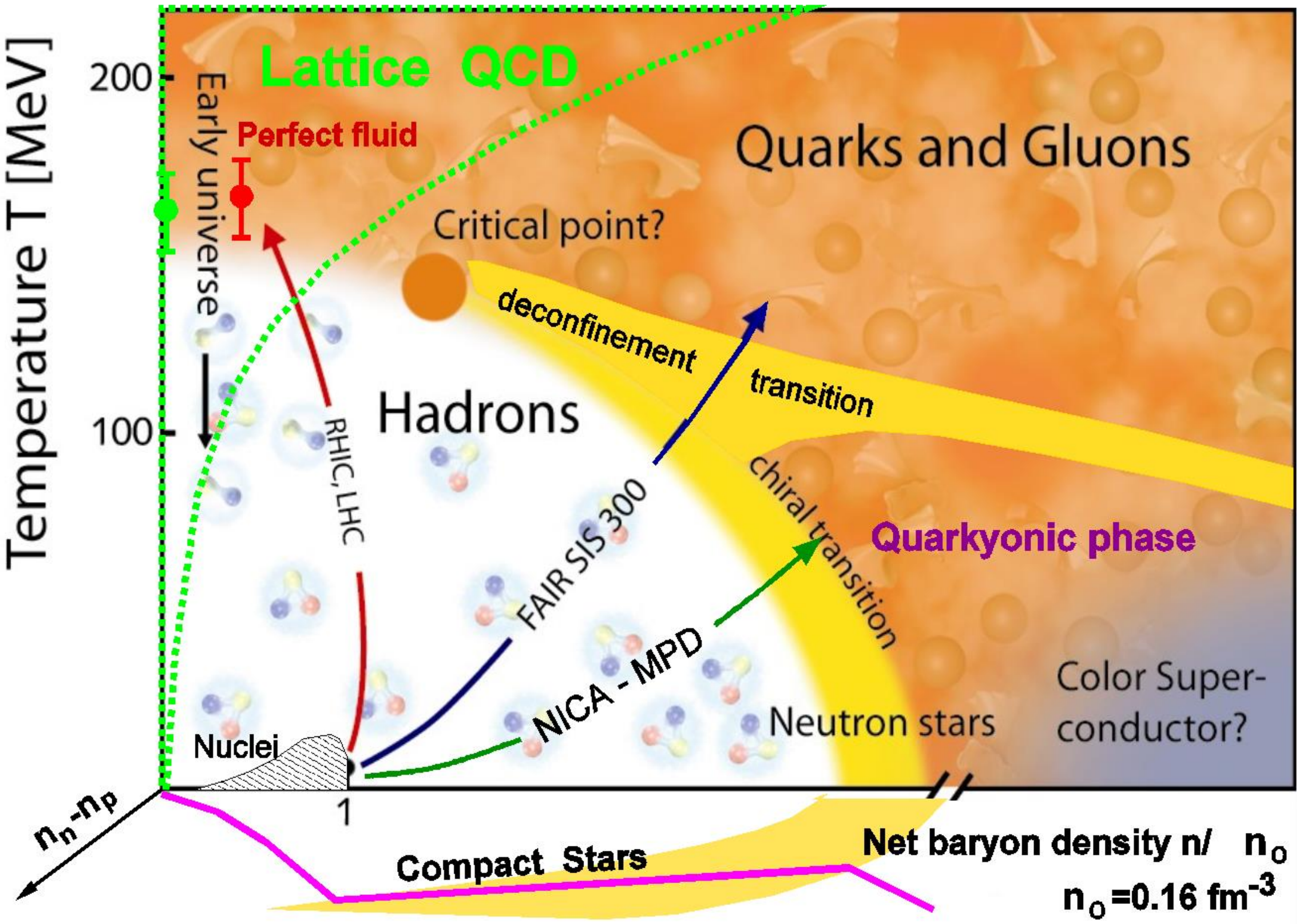
- Equation of State (EoS)

$$p(\varepsilon)$$

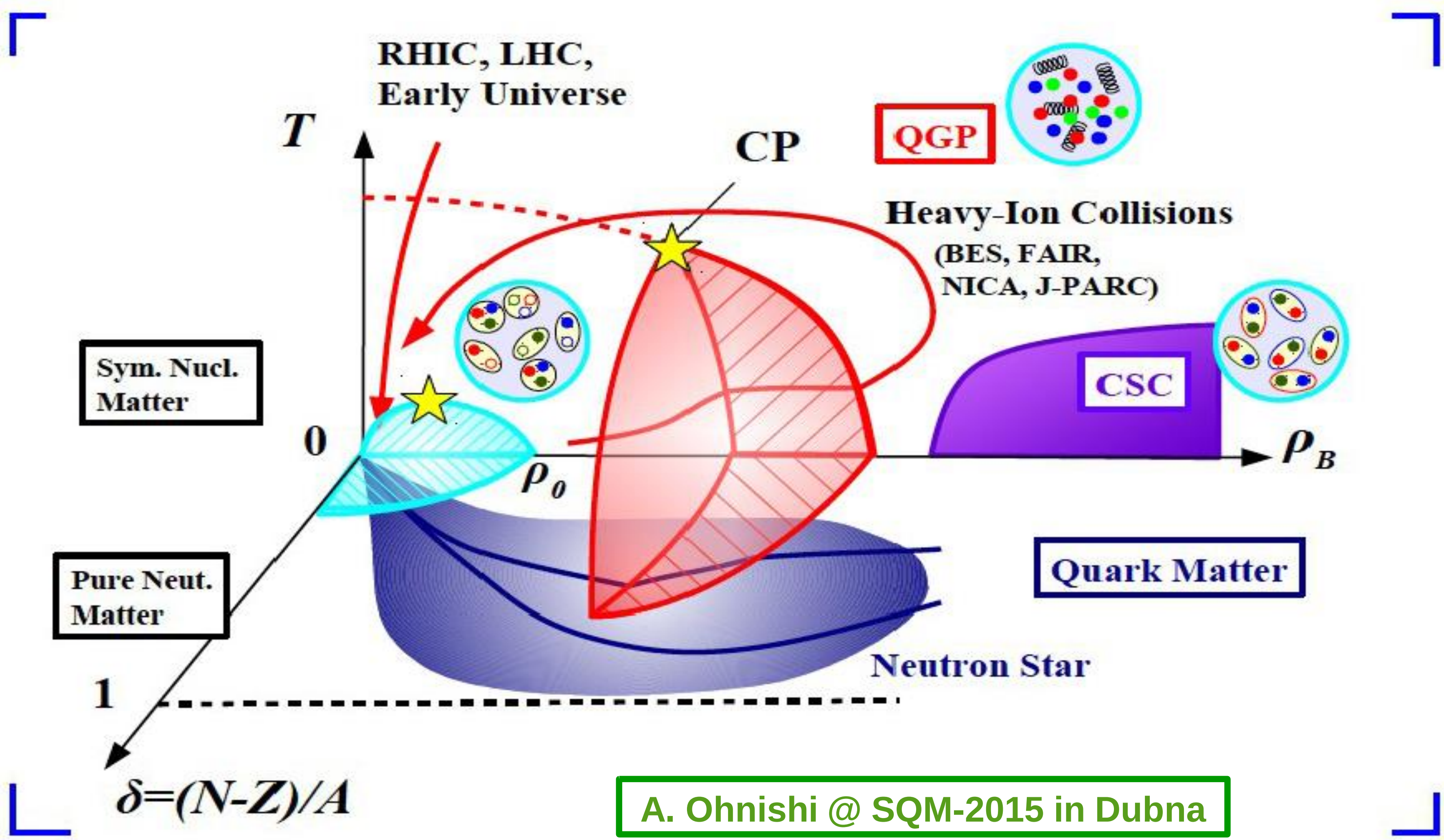
Massive neutron stars



Critical Endpoint in QCD



Support a CEP in QCD phase diagram with Astrophysics?

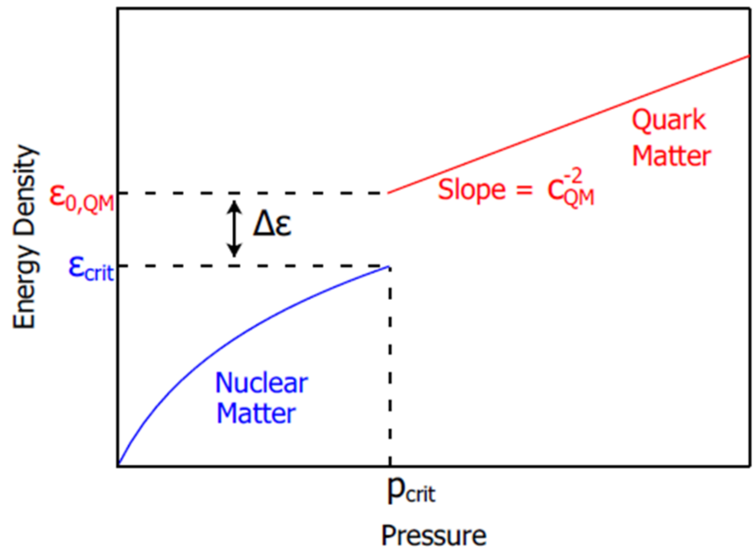


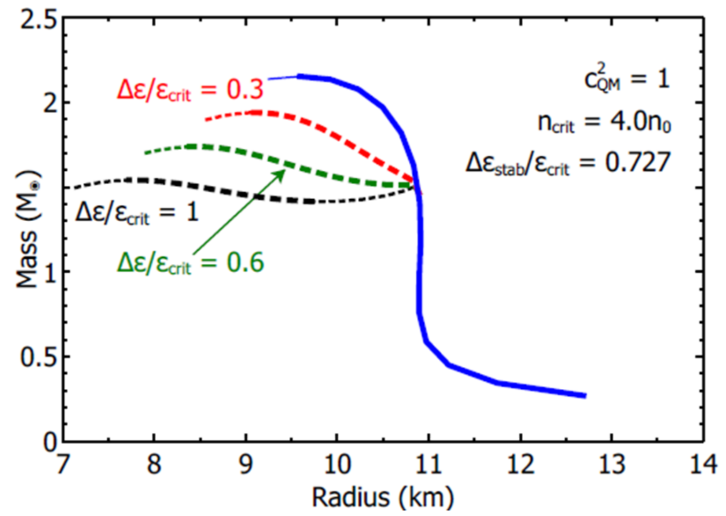
Crossover at finite T (Lattice QCD) + First order at zero T (Astrophysics)
=> Critical endpoint exists!

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**”.

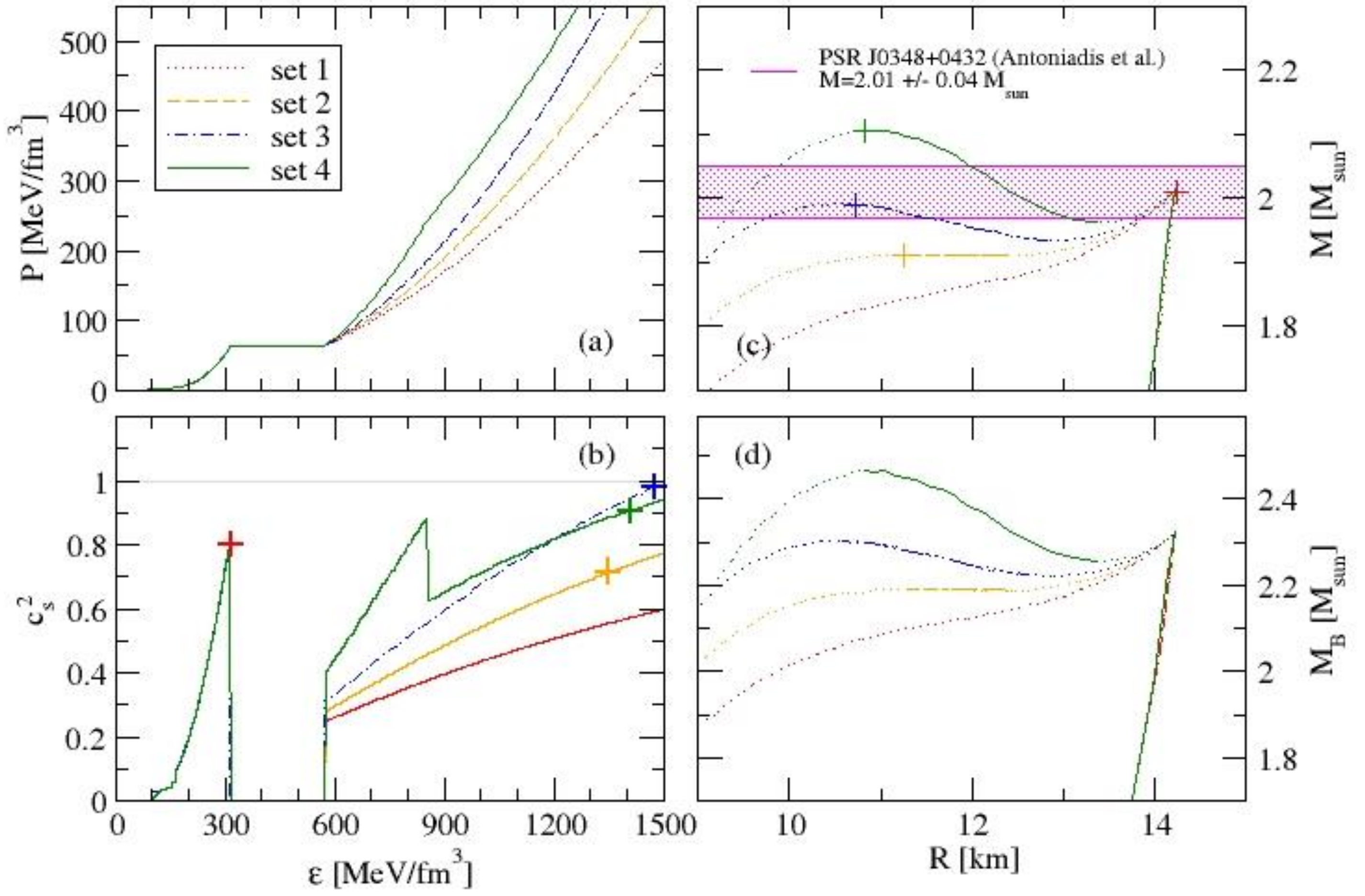
- Measuring two **disconnected populations** of compact stars in the M-R diagram would represent **the detection of a first order phase transition** in compact star matter and thus the indirect proof for the existence of a **critical endpoint (CEP) in the QCD phase diagram**!





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

Compact Star Twins

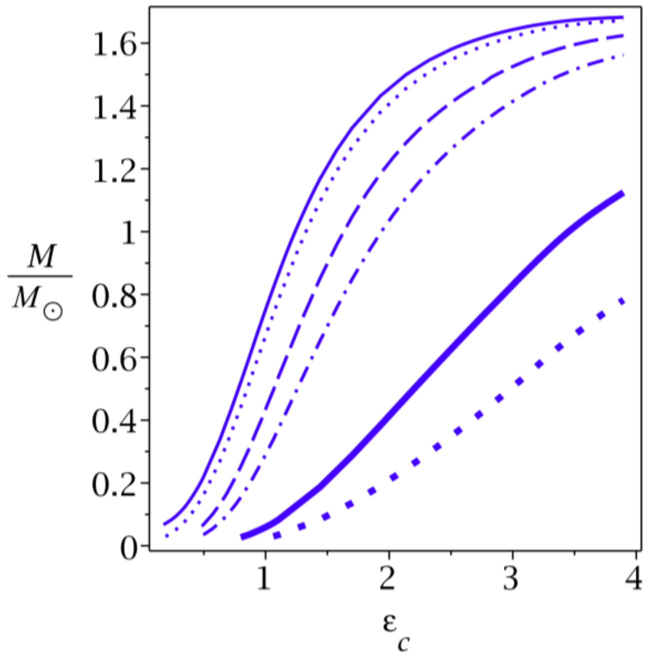


Alvarez-Castillo, Blaschke (2017)
High mass twins from multi-polytrope equations of state
arXiv: 1703.02681v2, Phys. Rev. C 96, 045809 (2017)

TOV with Λ

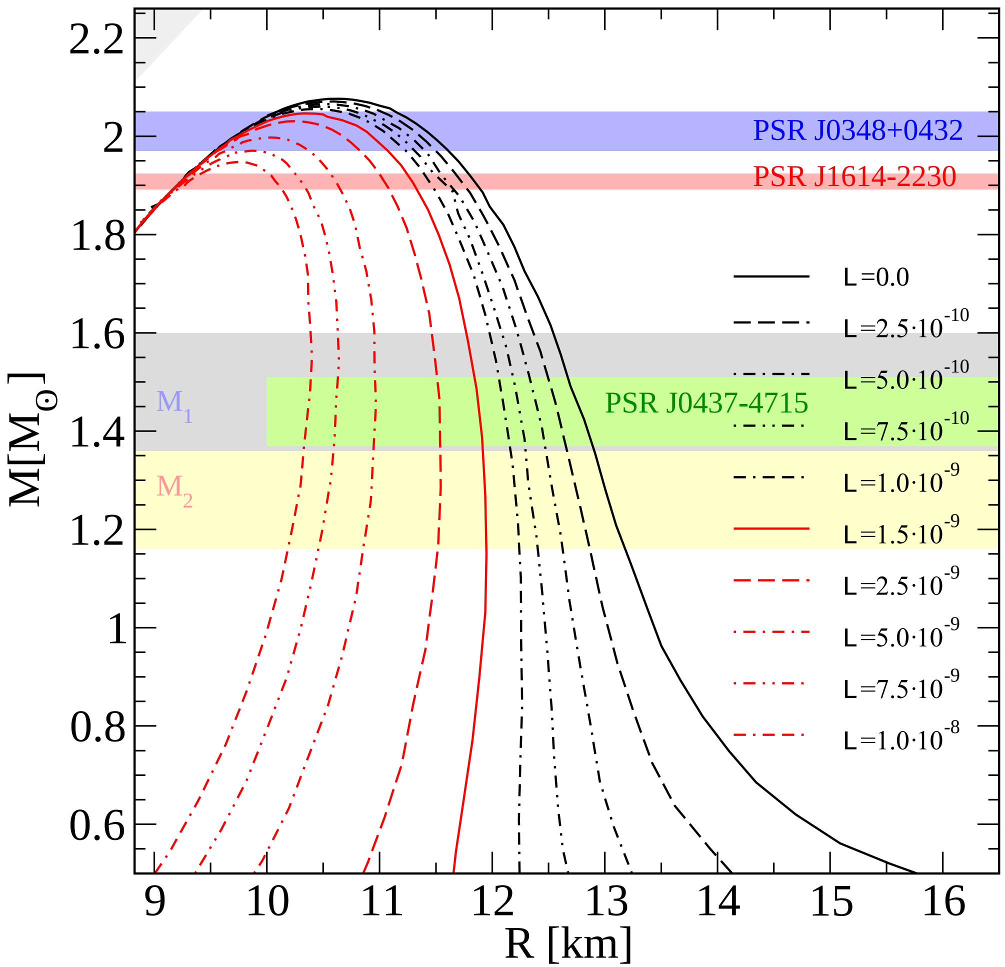
$$\frac{dp}{dr} = \frac{3c^2Gm + r^3(\Lambda c^4 + 12\pi Gp)}{c^2r[6Gm - c^2r(\Lambda r^2 + 3)]}(c^2\epsilon + p)$$

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



G.H. Bordbar, S.H. Hendi1 and B. Eslam Panah
Eur. Phys. J. Plus (2016) 131: 315

TOV with Λ (DD2F hadronic EoS)



Excluded Volume effects

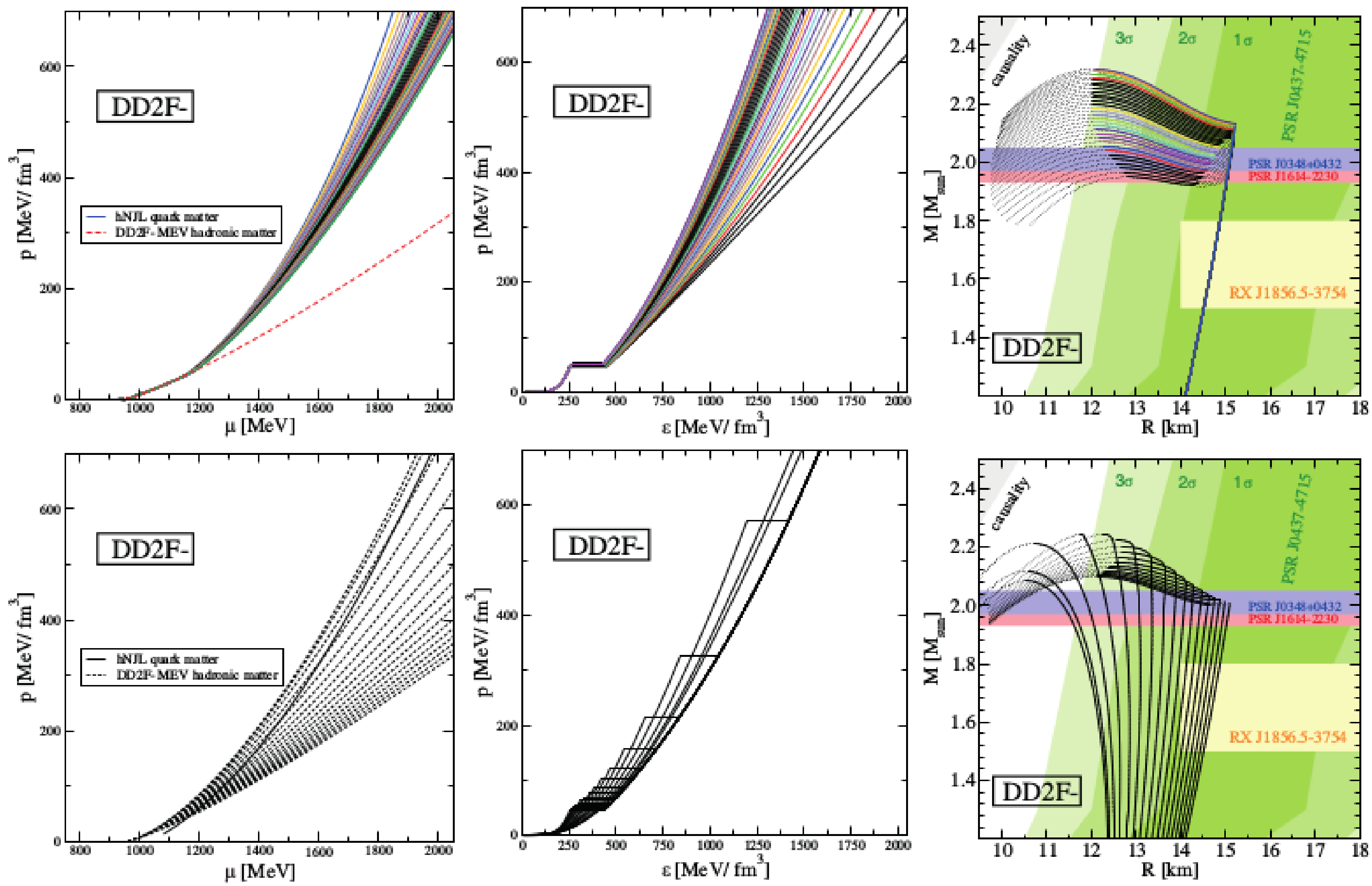
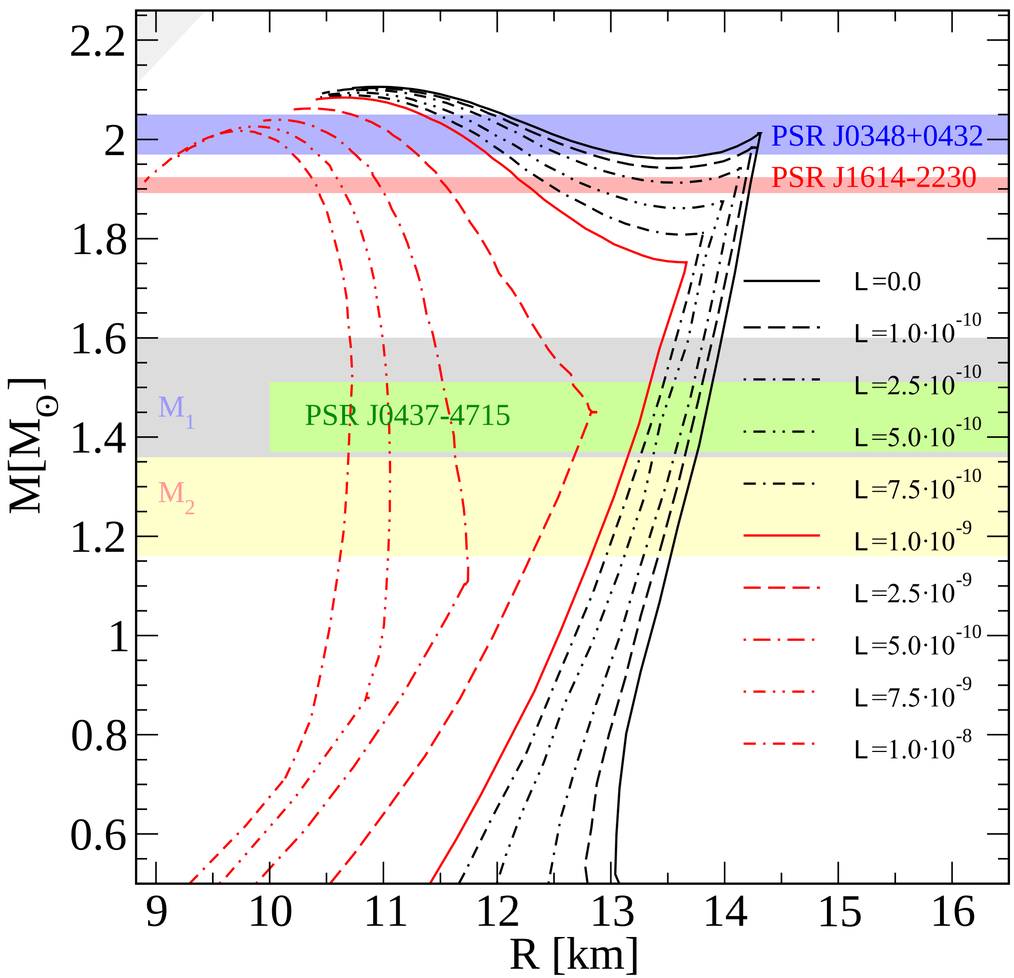


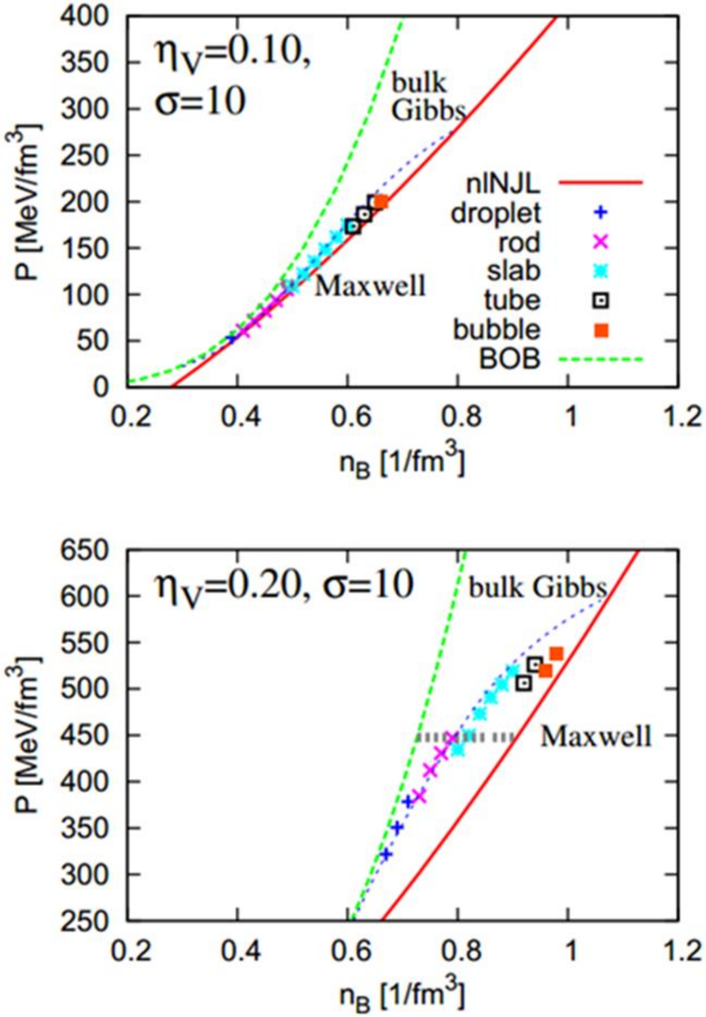
Fig. 1. Variations of the hybrid EoS for the DD2F$^-$ model. Upper row. The hadronic EoS is kept fixed while the quark EoS is allowed to vary for the parameters $\eta_4 = 0, 1, 2, \ldots, 30$. Lower row. The quark EoS is fixed whereas the hadronic EoS takes the values $p = 0, 5, 10, \ldots, 80$. For all these models the EoS is shown on the left and central plots while the resulting mass radius diagrams are shown on the right side.

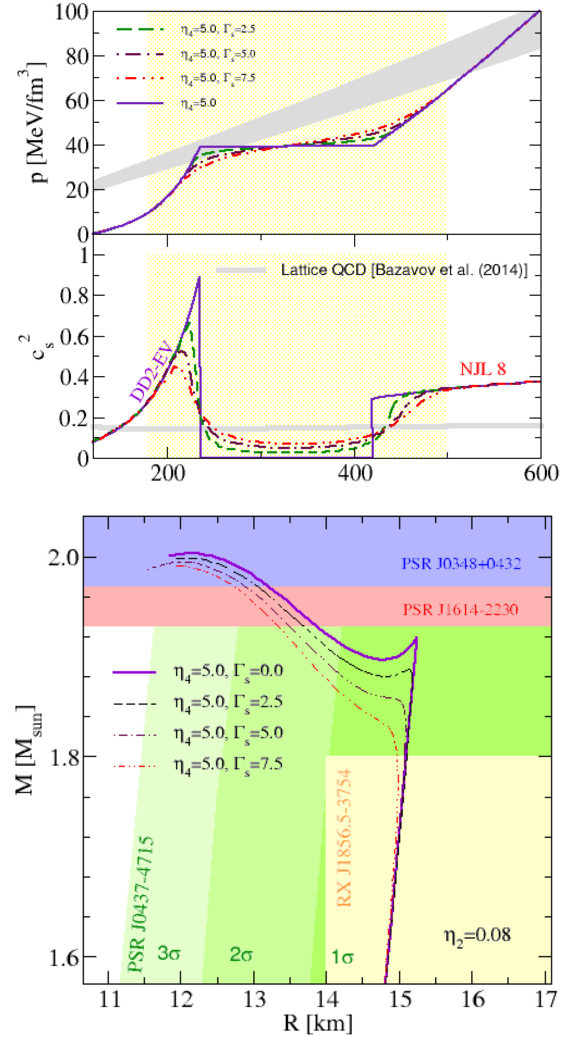
D. Alvarez-Castillo, A. Ayriyan, S. Benic, D. Blaschke, H. Grigorian, S. Typel
EPJA Topical Issue on "Exotic Matter in Neutron Stars", 2016 - arXiv:1603.03457

TOV with Λ
(HMTs hadron-quark EoS)



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

Conclusions

- The cosmological constant affects the topology of the compact star mass-radius relation for values around 10^{-9} m^{-2}.
- The higher the cosmological constant the more compact the resulting star becomes. This is in contrast to the inverse effect from excluded volume microscopic approaches that stiffen the equation of state.
- Hadronic stars masquerade as quark stars for the highest cosmological constant values.
- Mass twins compact stars are robust against cosmological constant effects for the lowest cosmological constant values. This case can be clearly distinguished from the appearance of pasta phases at the hadron-quark transition.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