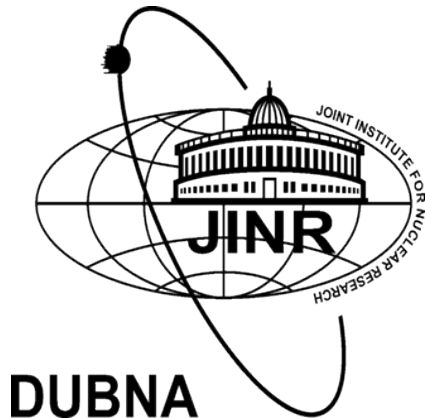# Supporting the existence of the QCD critical point by compact star observations

David E. Álvarez Castillo
Joint Institute for Nuclear Research

RAGtime@Opava
November 25, 2017

Collaborations

David Blaschke (BLTP, Univ. Wroclaw, MEPhI)
Stefan Typel (GSI Darmstadt)
Sanjin Benic (Univ. Zagreb, Univ. Tokyo)
Hovik Grigorian, Alexander Ayriyan (JINR LIT)
Pawel Haensel, Leszek Zdunik, Michal Bejger (CAMK Warsaw)
Gabriela Grunfeld (CONICET) and Valeria Pagura (Valencia)

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?
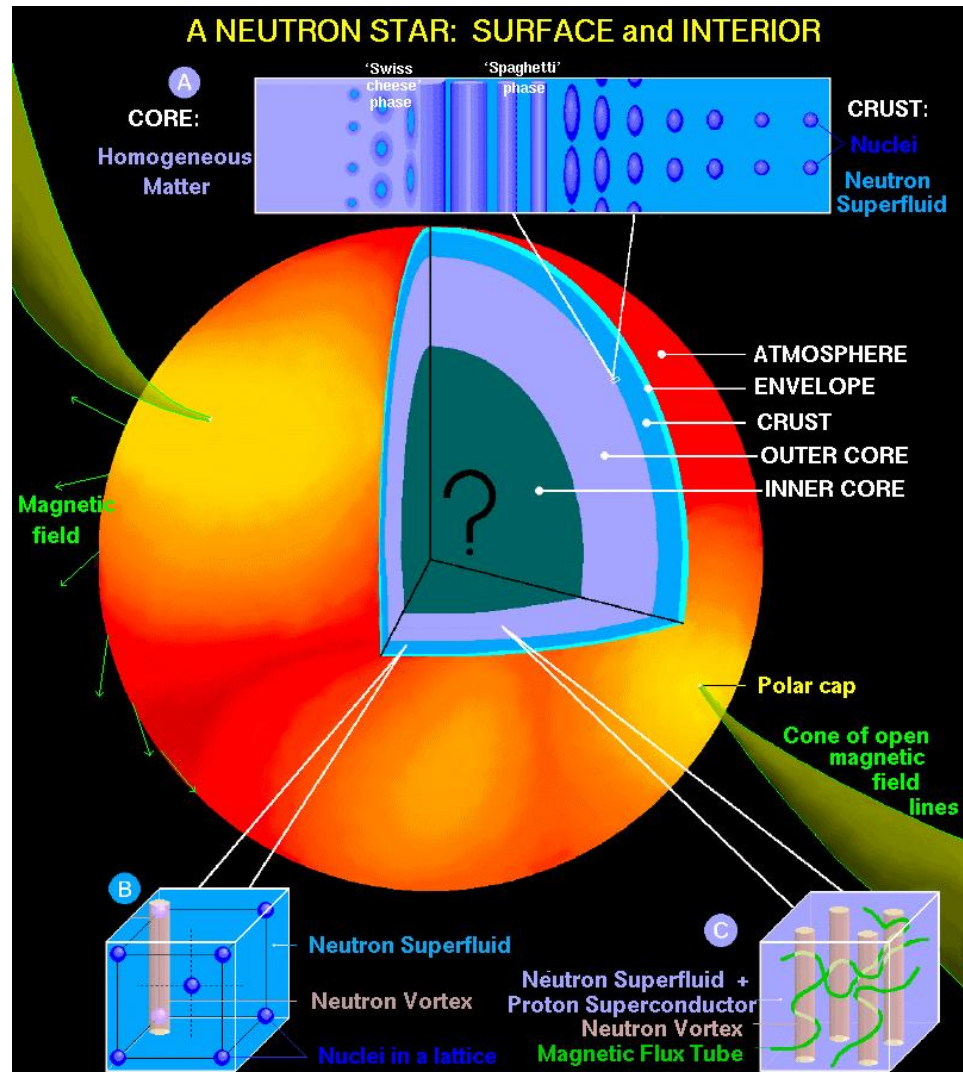
- What are the relevant observables?

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

A NEUTRON STAR: SURFACE and INTERIOR

**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: $\quad \mu_n - \mu_p = \mu_e = \mu_\mu$

- 2 phase construction under Gibbs conditions: $\quad p^I = p^{II} \qquad \mu_n^I = \mu_n^{II} \qquad \mu_e^I = \mu_e^{II}$

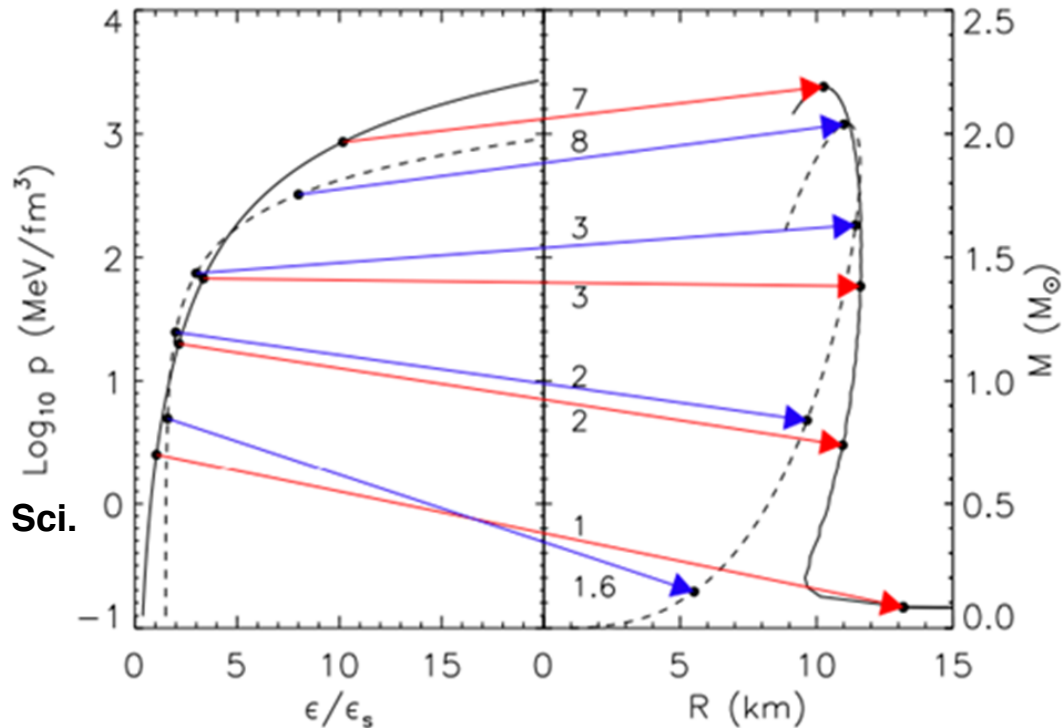- Charge neutrality: $\quad x_p = x_e$

- TOV equations + Equation of State

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

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

Compact Star Sequences
(M-R ↔ EoS)

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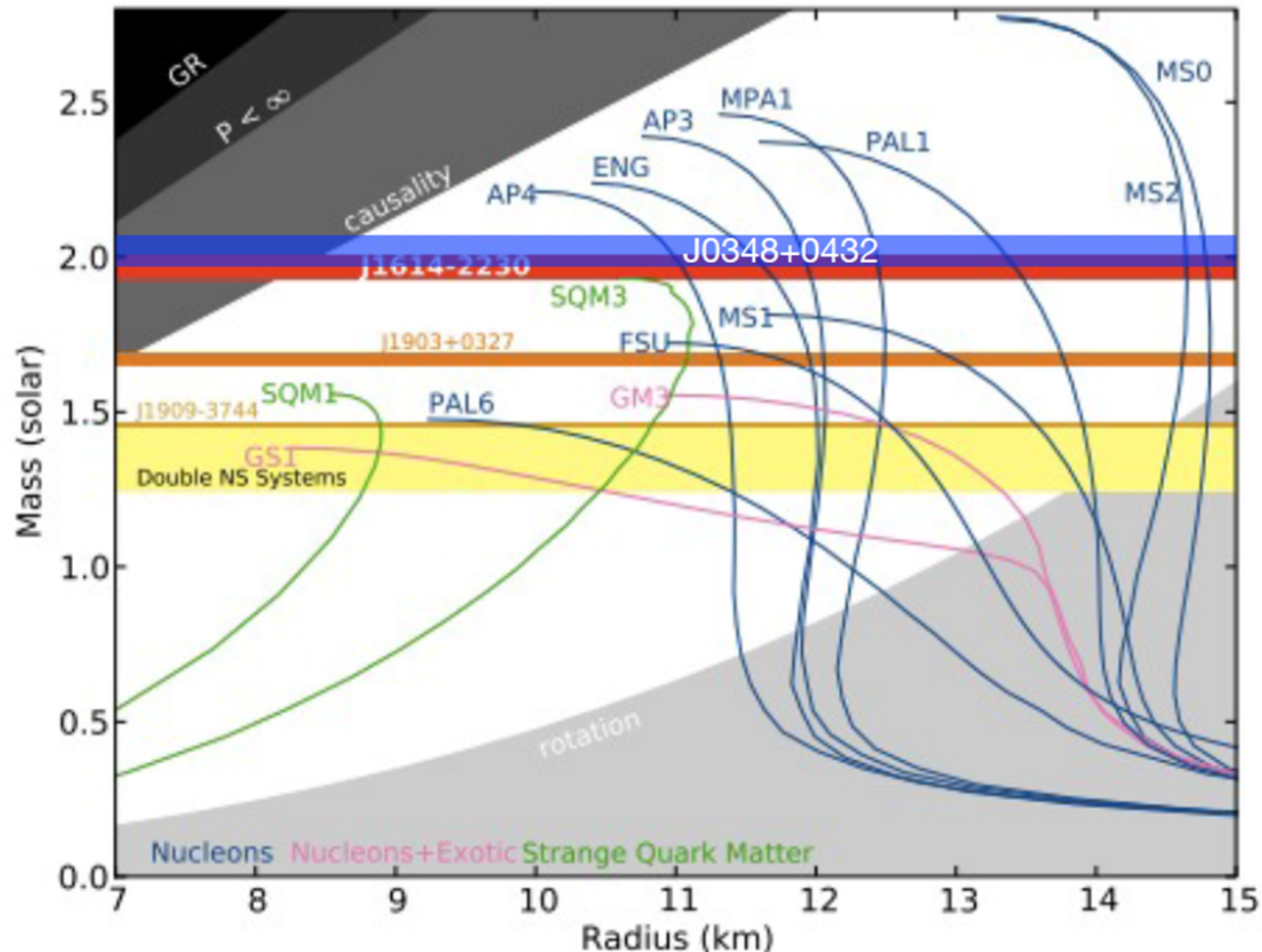arXiv: 1305.3510**

- TOV Equations

- Equation of State (EoS)

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

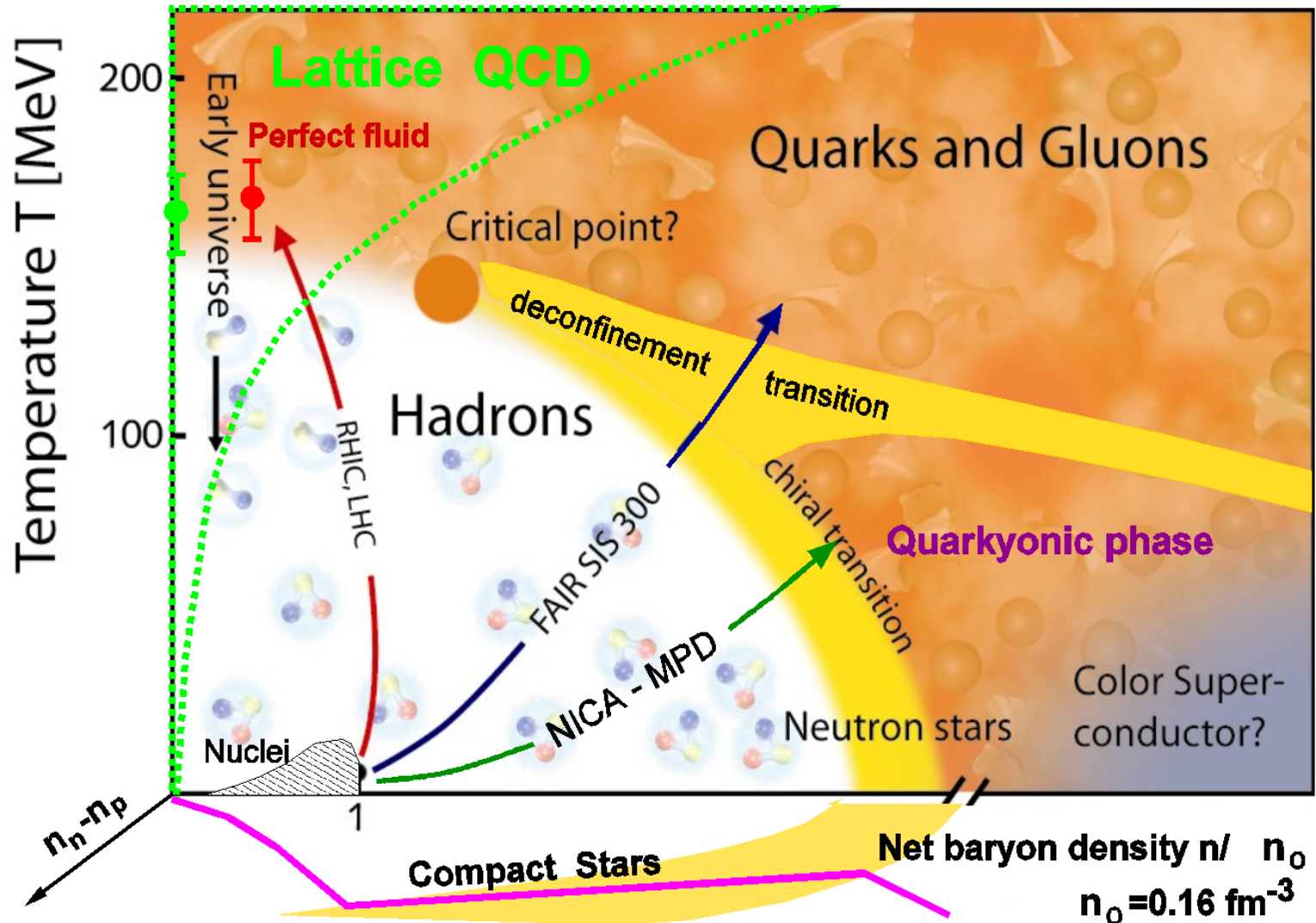$$\frac{dm}{dr} = 4\pi r^2 \varepsilon$$
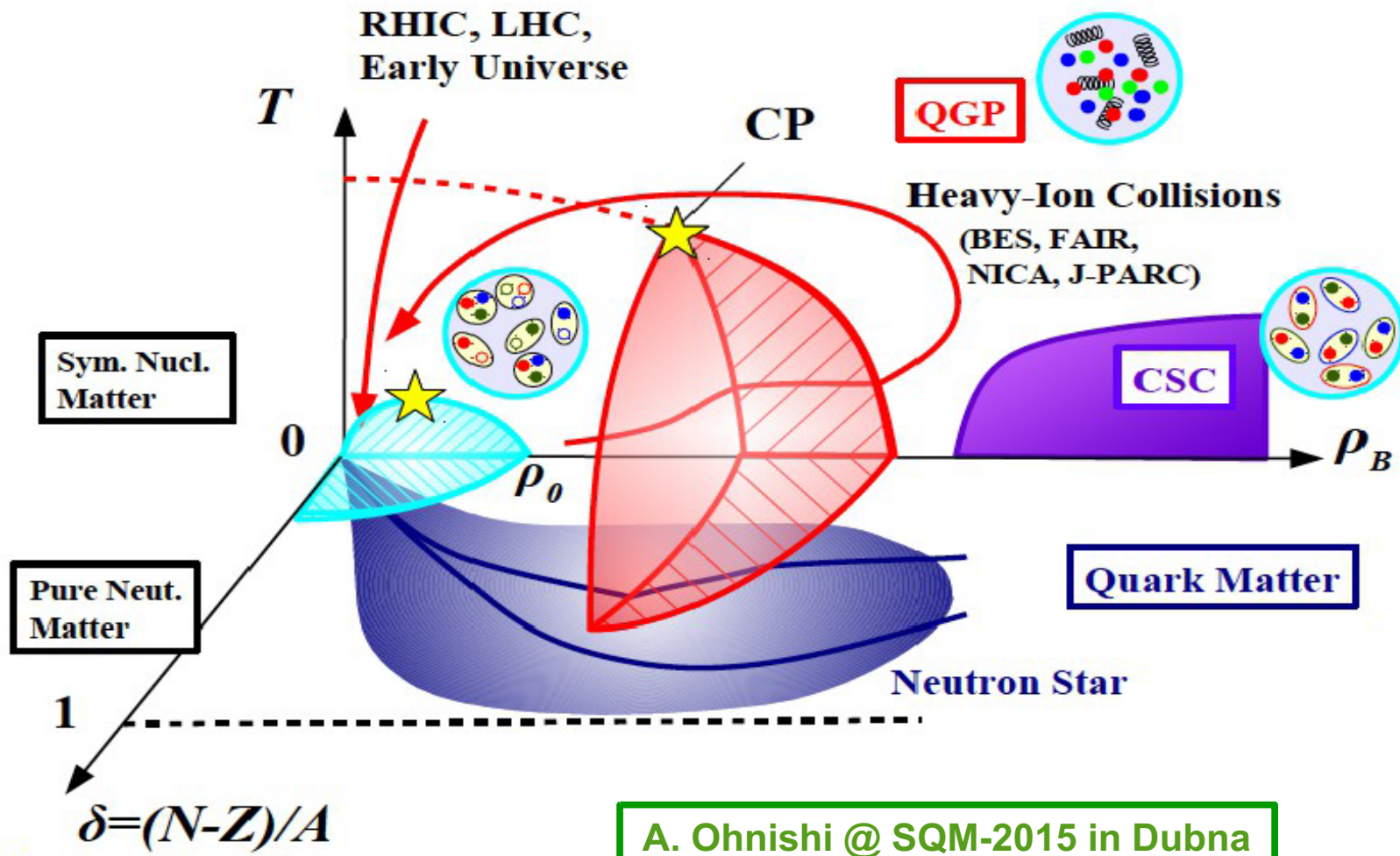
$$p(\varepsilon)$$

Massive neutron stars

Critical Endpoint in QCD

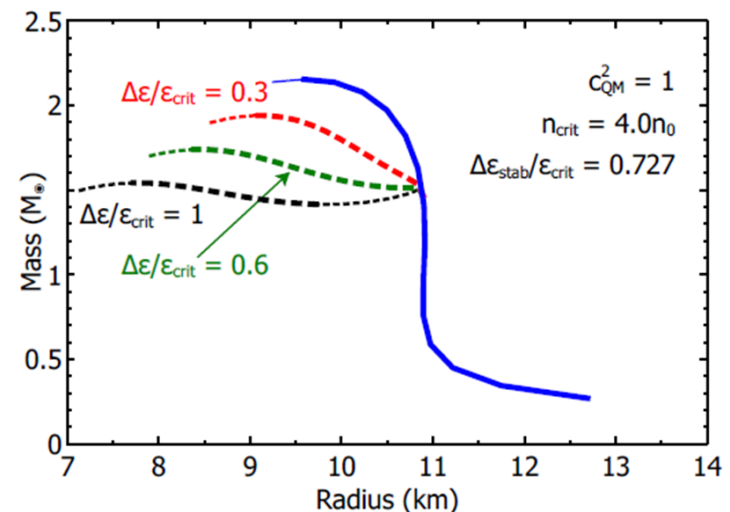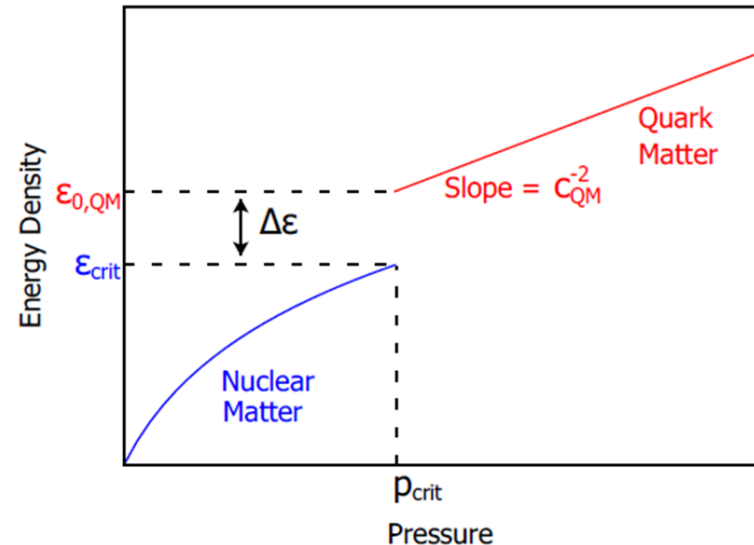# Support a CEP in QCD phase diagram with Astrophysics?

A. Ohnishi @ SQM-2015 in Dubna

Crossover at finite T (Lattice QCD) + First order at zero T (Astrophysics)
=> Critical endpoint exists!
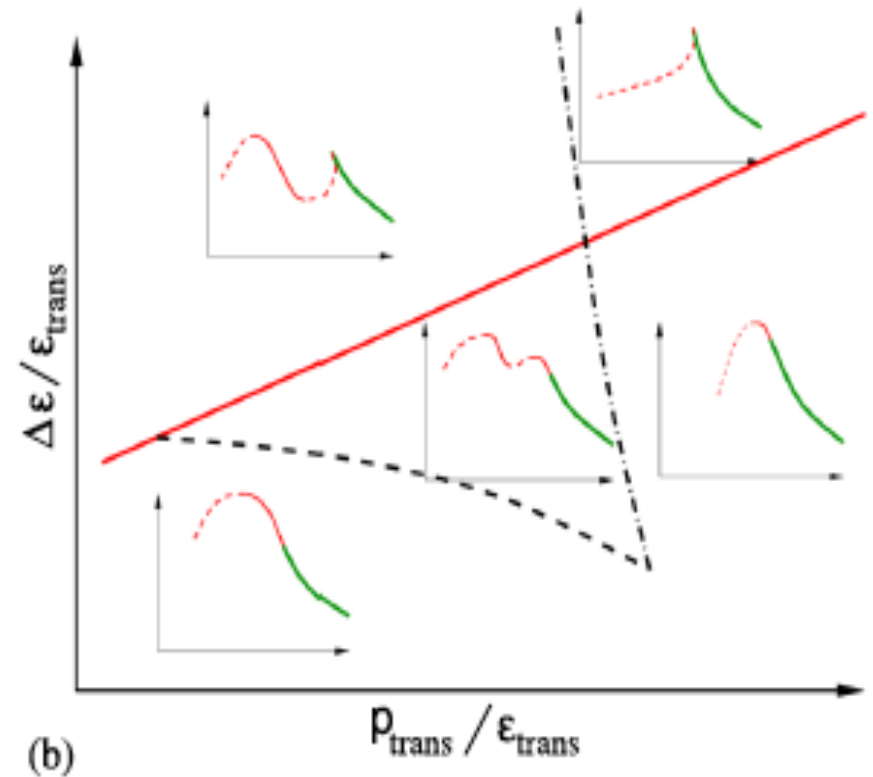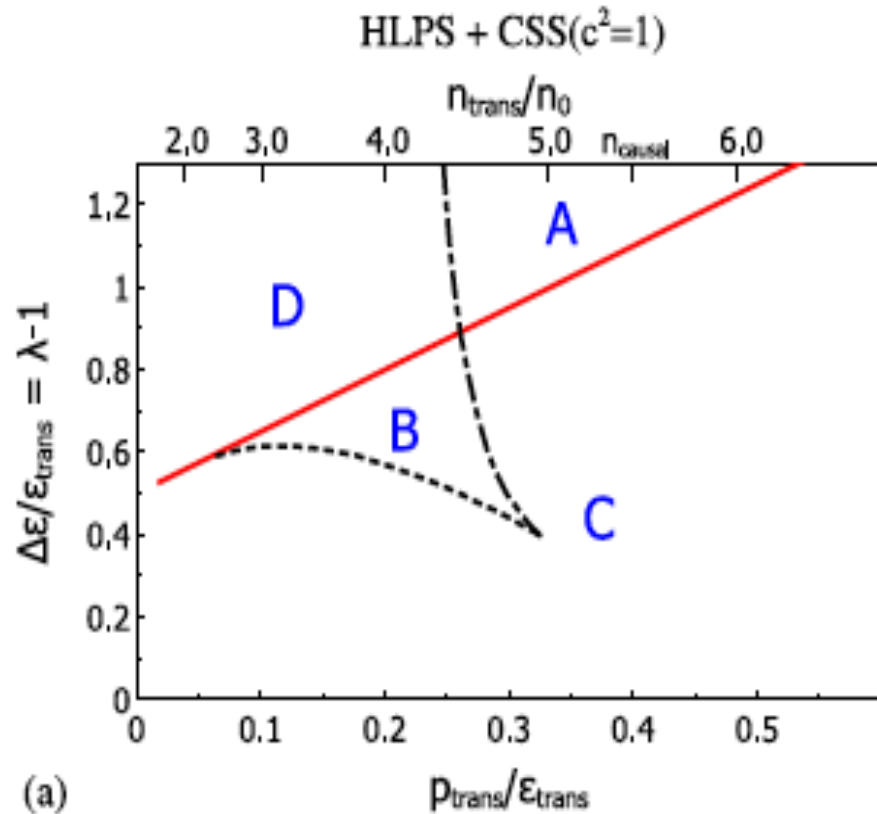
Neutron Star Twins and the AHP scheme

- 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)**

Energy density vs Pressure:
$\varepsilon_{0,QM}$, ε_{crit}, $\Delta\varepsilon$, Slope $= c_{QM}^{-2}$, Quark Matter, Nuclear Matter, p_{crit}

Mass (M☉) vs Radius (km):
$\Delta\varepsilon/\varepsilon_{crit} = 0.3$
$\Delta\varepsilon/\varepsilon_{crit} = 1$
$\Delta\varepsilon/\varepsilon_{crit} = 0.6$
$c_{QM}^2 = 1$
$n_{crit} = 4.0 n_0$
$\Delta\varepsilon_{stab}/\varepsilon_{crit} = 0.727$

Key fact: Mass "twins" ↔ 1st order PT

HLPS + CSS($c^2=1$)

(a)

(b)

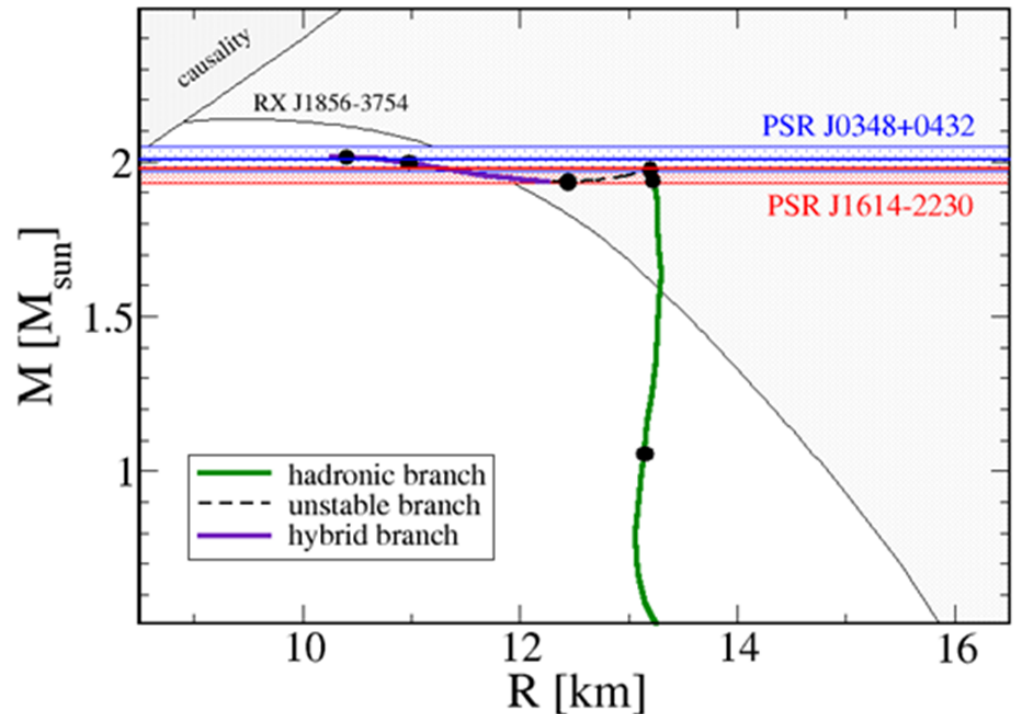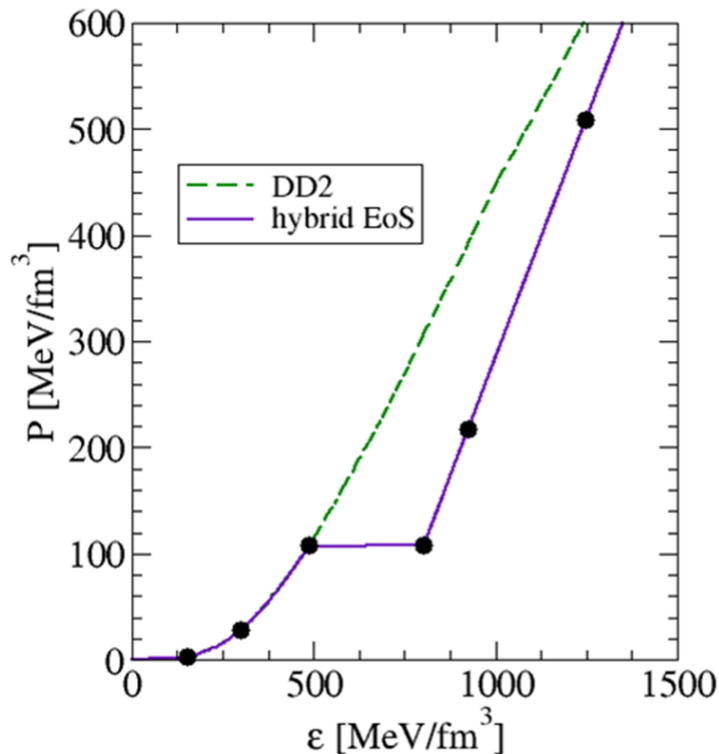**Systematic Classification** [Alford, Han, Prakash: PRD88, 083013 (2013)]

EoS P(ε) <--> Compact star phenomenology M(R)

Most interesting and clear-cut cases: (D)isconnected and (B)oth – high-mass twins!

Compact Star Twins
Third family (disconnected branch)

High Mass Star Twins Based on multipolytrope EoS

Piecewise polytrope EoS – high mass twins?

Hebeler et al., ApJ 773, 11 (2013)

$$P_i(n) = \kappa_i n^{\Gamma_i}$$

$$i = 1 \; : \; n_1 \leq n \leq n_{12}$$

$$i = 2 \; : \; n_{12} \leq n \leq n_{23}$$

$$i = 3 \; : \; n \geq n_{23} \; ,$$
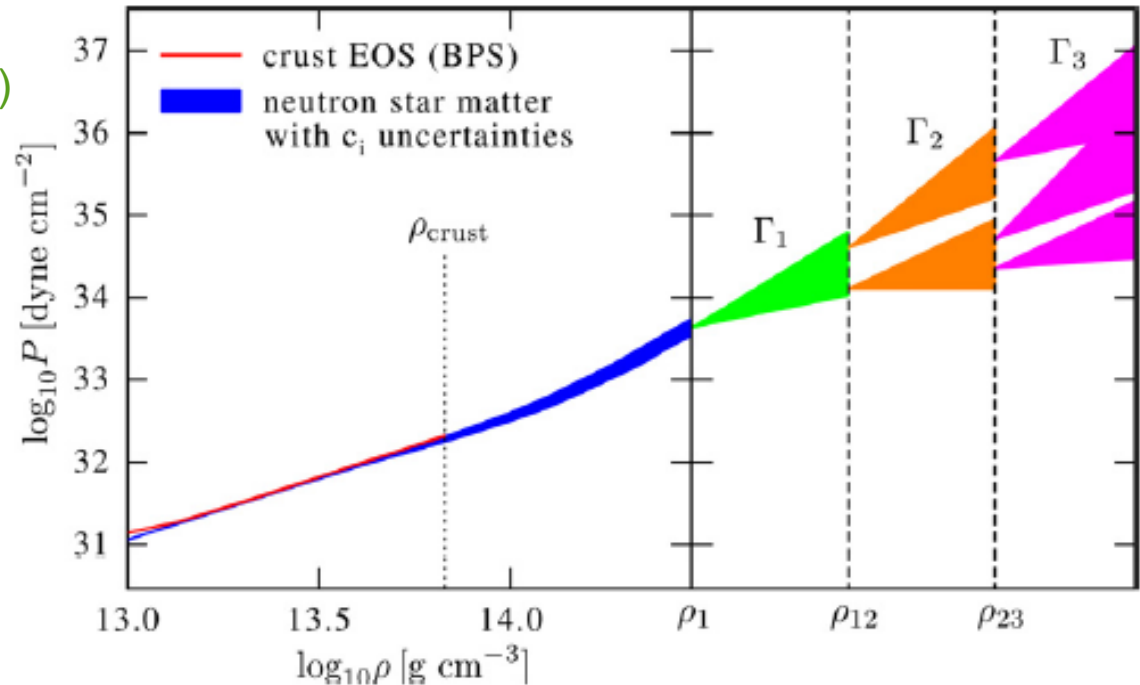

Here, 1st order PT in region 2:

$$\Gamma_2 = 0 \text{ and } P_2 = \kappa_2 = P_{\text{crit}}$$

$$P(n) = n^2 \frac{d(\varepsilon(n)/n)}{dn},$$

$$\varepsilon(n)/n = \int dn \, \frac{P(n)}{n^2} = \int dn \, \kappa n^{\Gamma-2} = \frac{\kappa \, n^{\Gamma-1}}{\Gamma - 1} + C,$$

$$\mu(n) = \frac{P(n) + \varepsilon(n)}{n} = \frac{\kappa \, \Gamma}{\Gamma - 1} n^{\Gamma-1} + m_0,$$

$$n(\mu) = \left[(\mu - m_0)\frac{\Gamma - 1}{\kappa \Gamma} \right]^{1/(\Gamma-1)}$$

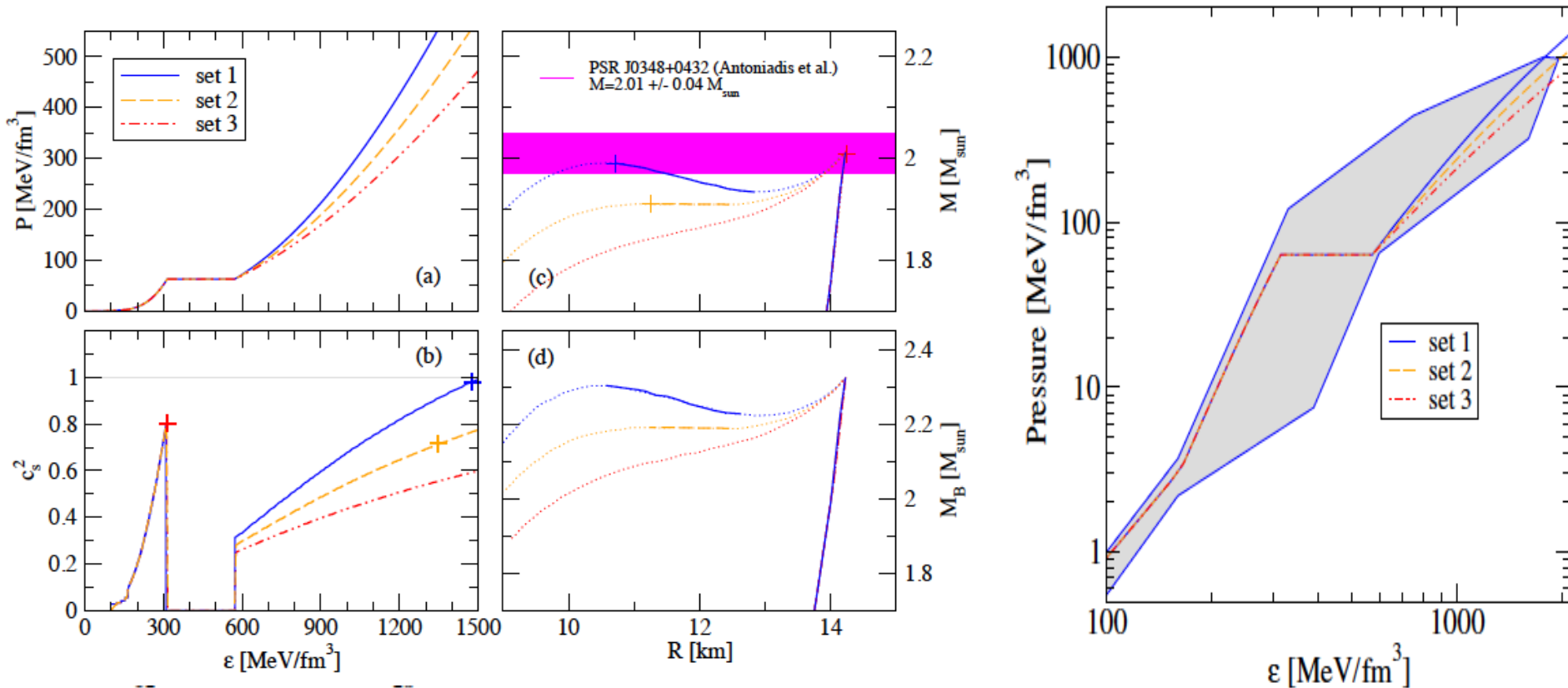$$P(\mu) = \kappa \left[(\mu - m_0)\frac{\Gamma - 1}{\kappa \Gamma} \right]^{\Gamma/(\Gamma-1)}$$

Maxwell construction:

$$P_1(\mu_{\text{crit}}) = P_3(\mu_{\text{crit}}) = P_{\text{crit}}$$

$$\mu_{\text{crit}} = \mu_1(n_{12}) = \mu_3(n_{23})$$

Seidov criterion for instability:

$$\frac{\Delta\varepsilon}{\varepsilon_{\text{crit}}} \geq \frac{1}{2} + \frac{3}{3}\frac{P_{\text{crit}}}{\varepsilon_{\text{crit}}}$$

Piecewise polytrope EoS – high mass twins?

	Γ_3	κ_3 [MeV fm$^{3(\Gamma_3-1)}$]	$m_{0,3}$ [MeV]	M_{max}^{NS} [M$_\odot$]	M_{max}^{HS} [M$_\odot$]	M_{min}^{HS} [M$_\odot$]
set 1	3.12	447.16	1014.87	2.01	1.991	1.934
set 2	2.80	365.12	1004.88	2.01	1.910	1.909
set 3	2.50	302.56	991.75	2.01	-	-

Set with same onset of Phase transition:
P_crit = 68.18 MeV/fm^3
eps_crit = 318.26 MeV/fm^3
Δeps = 253.89 MeV/fm^3
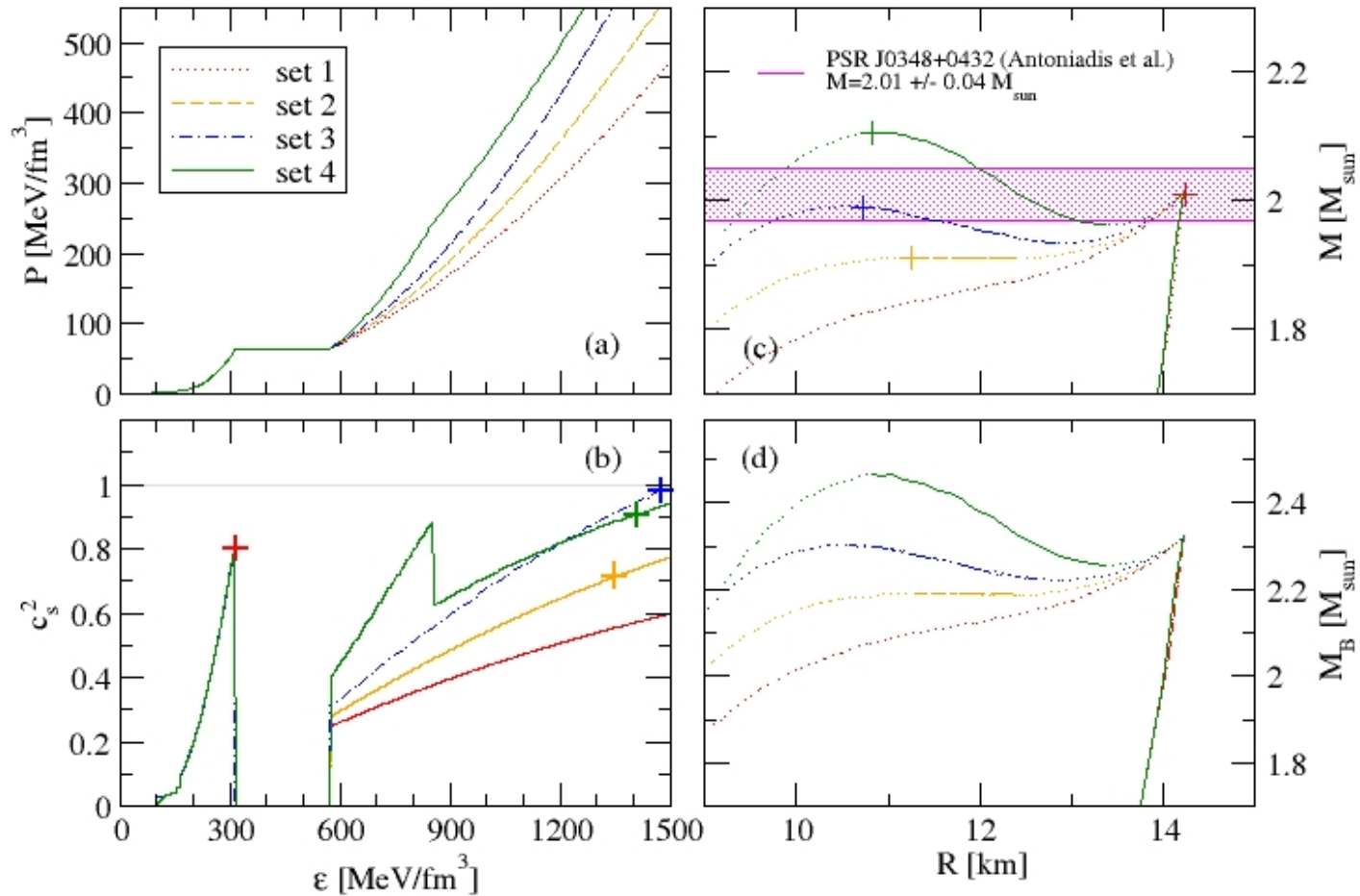n_12 = 0.32 fm^-3 ; n_23 = 0.53 fm^-3

Third family solutions in the 2M_sun mass range (HMT) exist !!

[D. Alvarez-Castillo & D.B. arxiv:1703.02681]
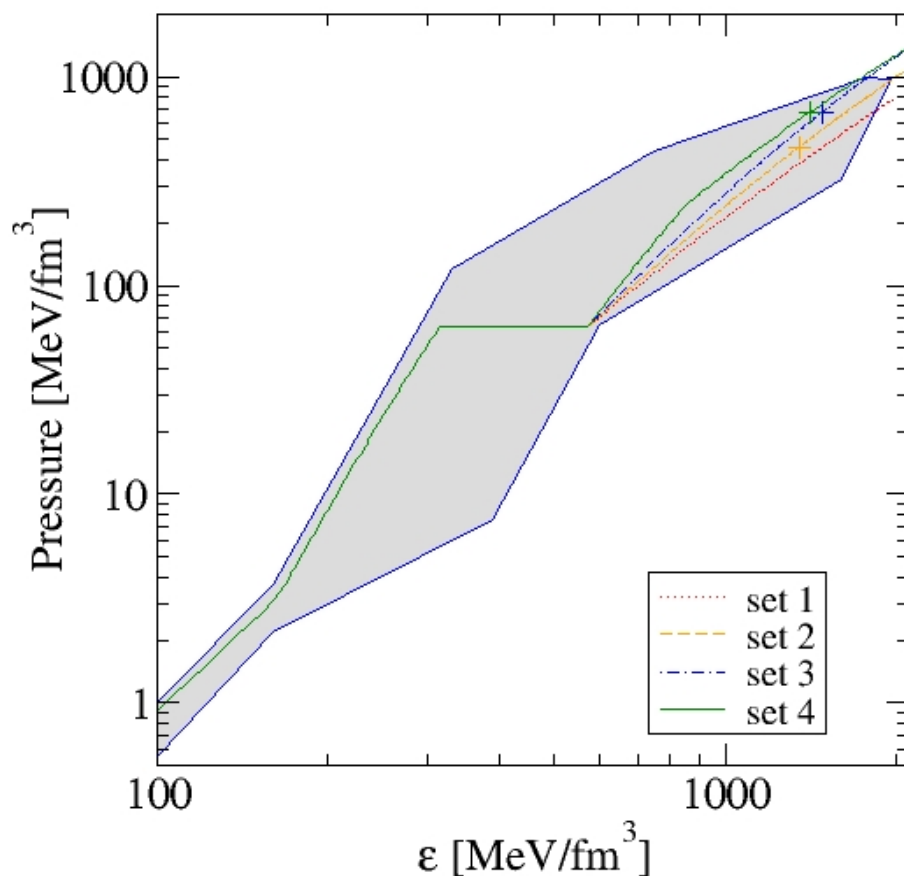
Compact Star Twins

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

Compact Star Twins

Gray region:
K. Hebeler, J. M. Lattimer, C. J. Pethick and A. Schwenk,
Astrophys. J. **773**, 11 (2013).

Lines:
Four-polytrope model;
D.E. Alvarez-Castillo and D. Blaschke,
High mass twins from multi-polytrope equations of state,
arXiv: 1703.02681v2, to appear

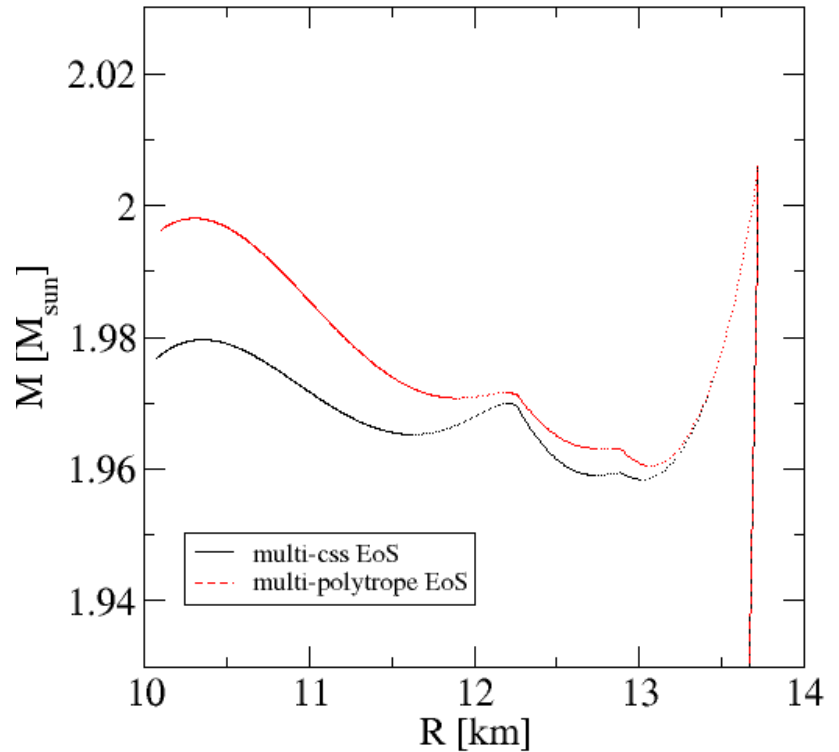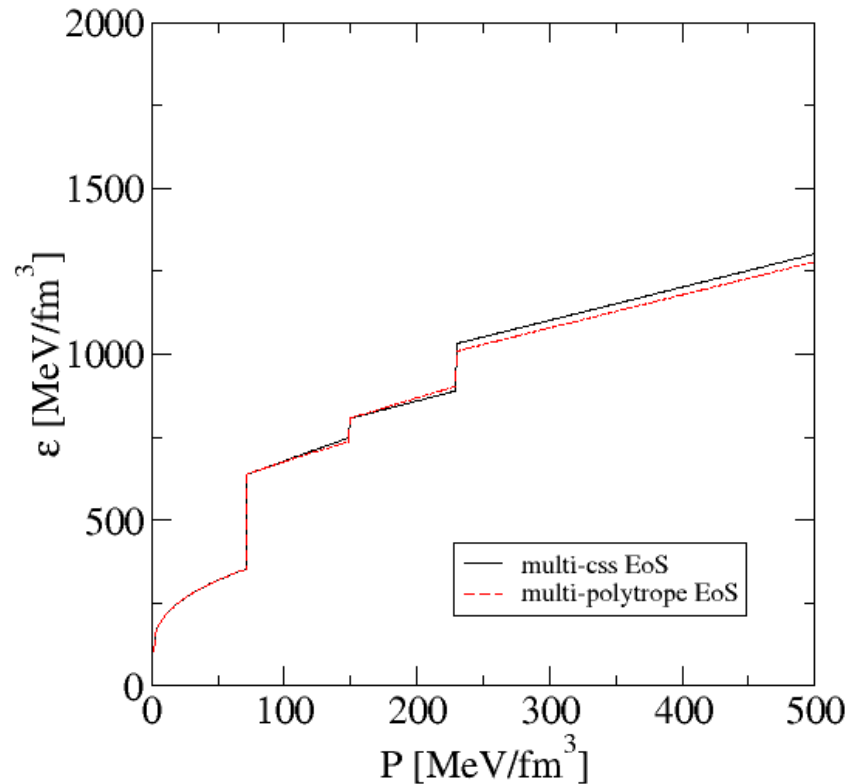|	Γ_3	κ_3	$m_{0,3}$	$M_{\max}^{NS}$	$M_{\max}^{HS}$	$M_{\min}^{HS}$
		[MeV fm$^{3(\Gamma_3-1)}$]	[MeV]	[M$_\odot$]	[M$_\odot$]	[M$_\odot$]
set 1	2.50	302.56	991.75	2.01	-	-
set 2	2.80	365.12	1004.88	2.01	1.910	1.909
set 3	3.12	447.16	1014.87	2.01	1.991	1.934
set 4a	4.00	774.375	1031.815			
set 4b	2.80	548.309	958.553	2.01	2.106	1.961

Compact Stars with Sequential QCD Phase Transitions
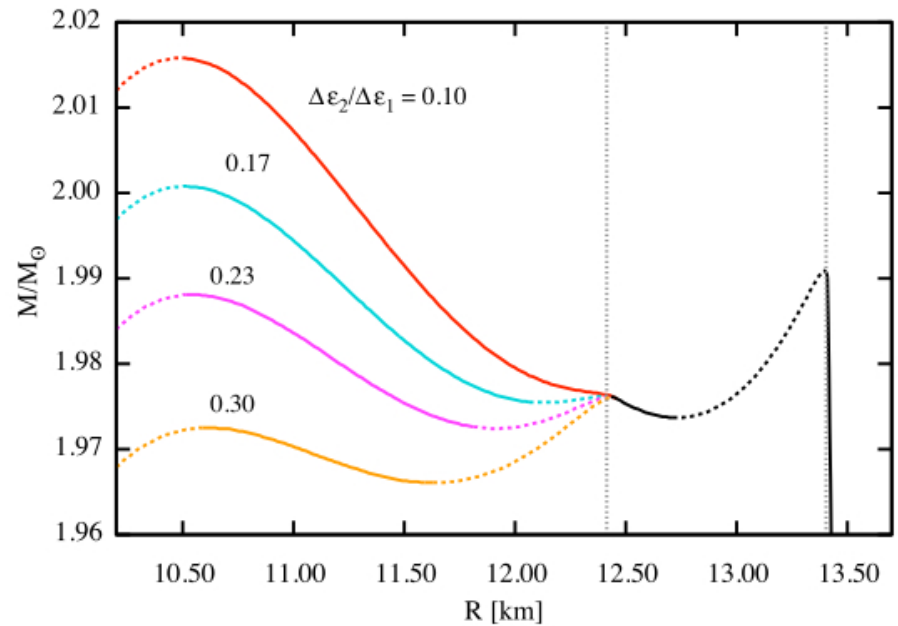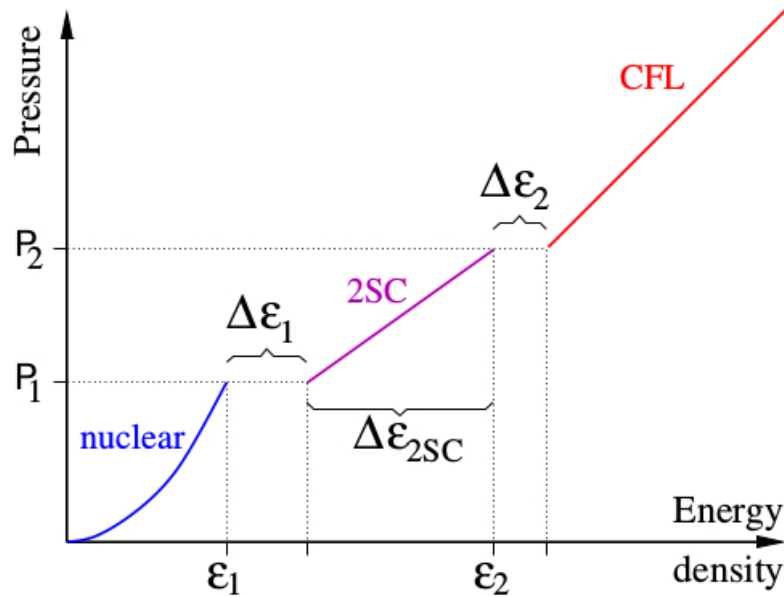
A. Sedrakian and M. Alford - 2017 - arXiv:1706.01592

A fifth family of compact stars at high mass

D. E. Alvarez-Castillo, D. B. Blaschke and H. Grigorian, i*n preparation*.

Quark substructure effects in baryonic matter

Excluded volume mechanism in the context of RMF models

Consider nucleons as hard spheres of volume V_{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 $v = \frac{1}{2}\frac{4\pi}{3}(2r_{\text{nuc}})^3 = 4V_{\text{nuc}}$ and identical radii $r_{\text{nuc}} = r_n = r_p$ of neutrons and protons. The total hadronic pressure and energy density are:

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

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

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_{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

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

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

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

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

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

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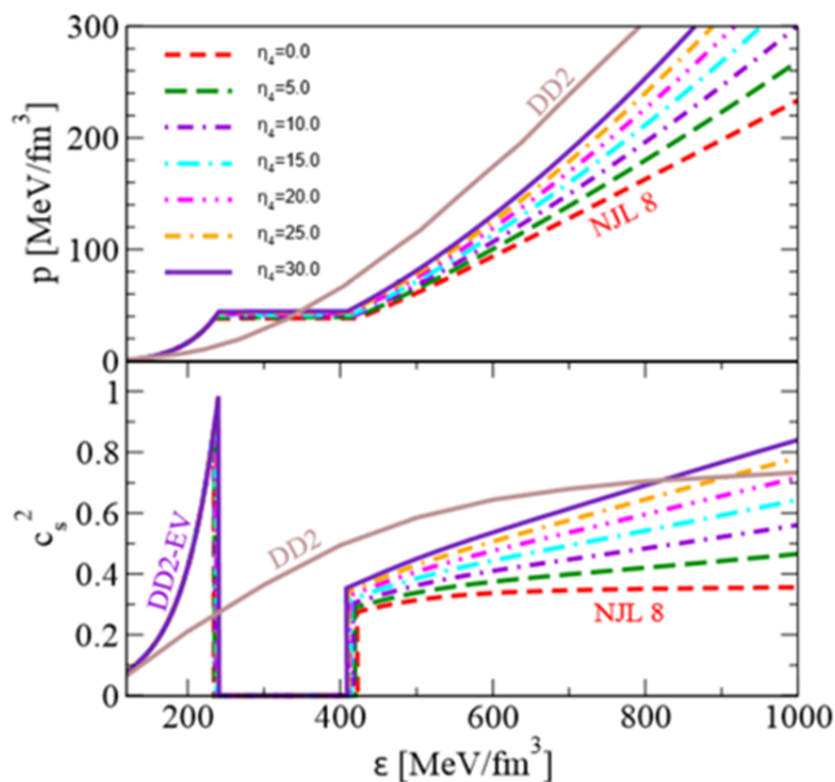
Thermodynamic Potential:

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

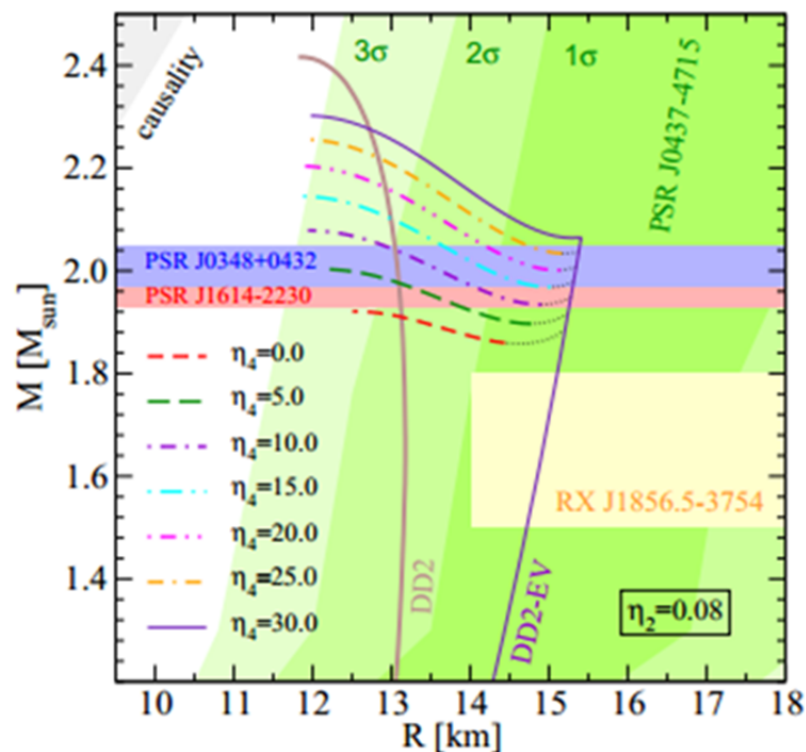# Neutron Star Twins

Equation of State

Mass-Radius Relation
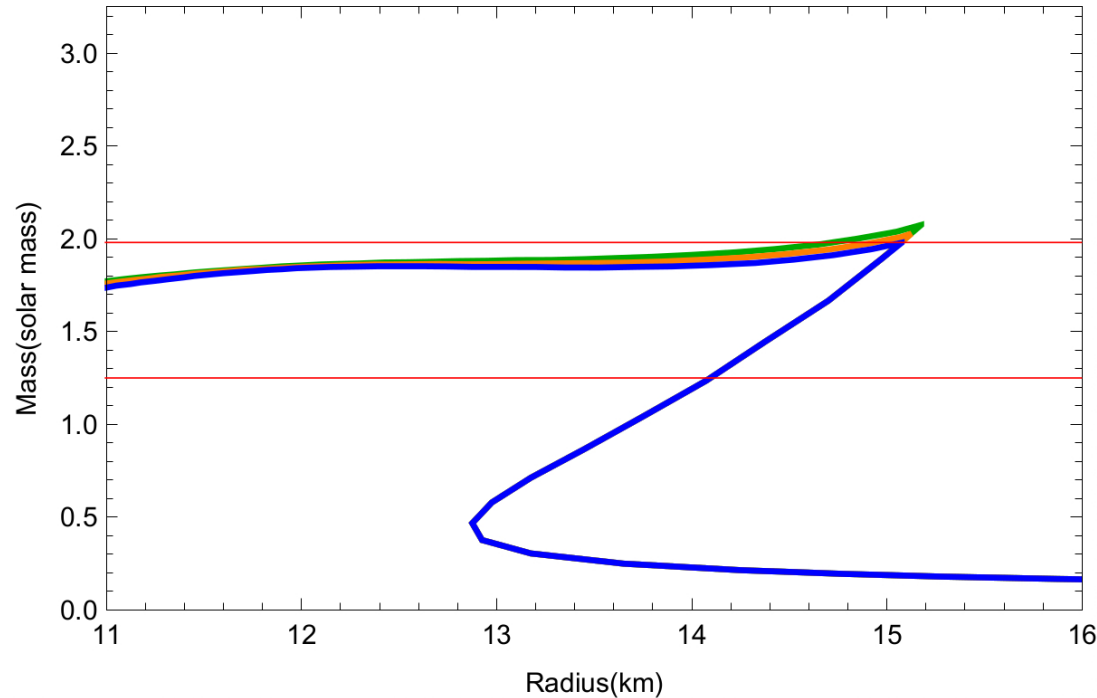

**Benic, Blaschke, Alvarez-Castillo, Fischer, Typel:
A&A 577, A40 (2015) - arXiv:1411.2856 (2014)**

Neutron Star Twins

Nonlocal NJL models

$$S_E = \int d^4x \ \left\{ \bar{\psi}(x) \left(-i\slashed{\partial} + m_c \right) \psi(x) - \frac{G_S}{2} j_S^f(x) j_S^f(x) - \frac{H}{2} \left[j_D^a(x) \right]^\dagger j_D^a(x) \right\}$$

$$j_S^f(x) = \int d^4z \ g(z) \ \bar{\psi}\left(x + \frac{z}{2}\right) \Gamma_f \ \psi\left(x - \frac{z}{2}\right), \ j_D^a(x) = \int d^4z \ g(z) \ \bar{\psi}_C\left(x + \frac{z}{2}\right) i\gamma_5 \tau_2 \lambda_a \ \psi\left(x - \frac{z}{2}\right)$$

Grunfeld, Alvarez-Castillo, Blaschke, Pagura
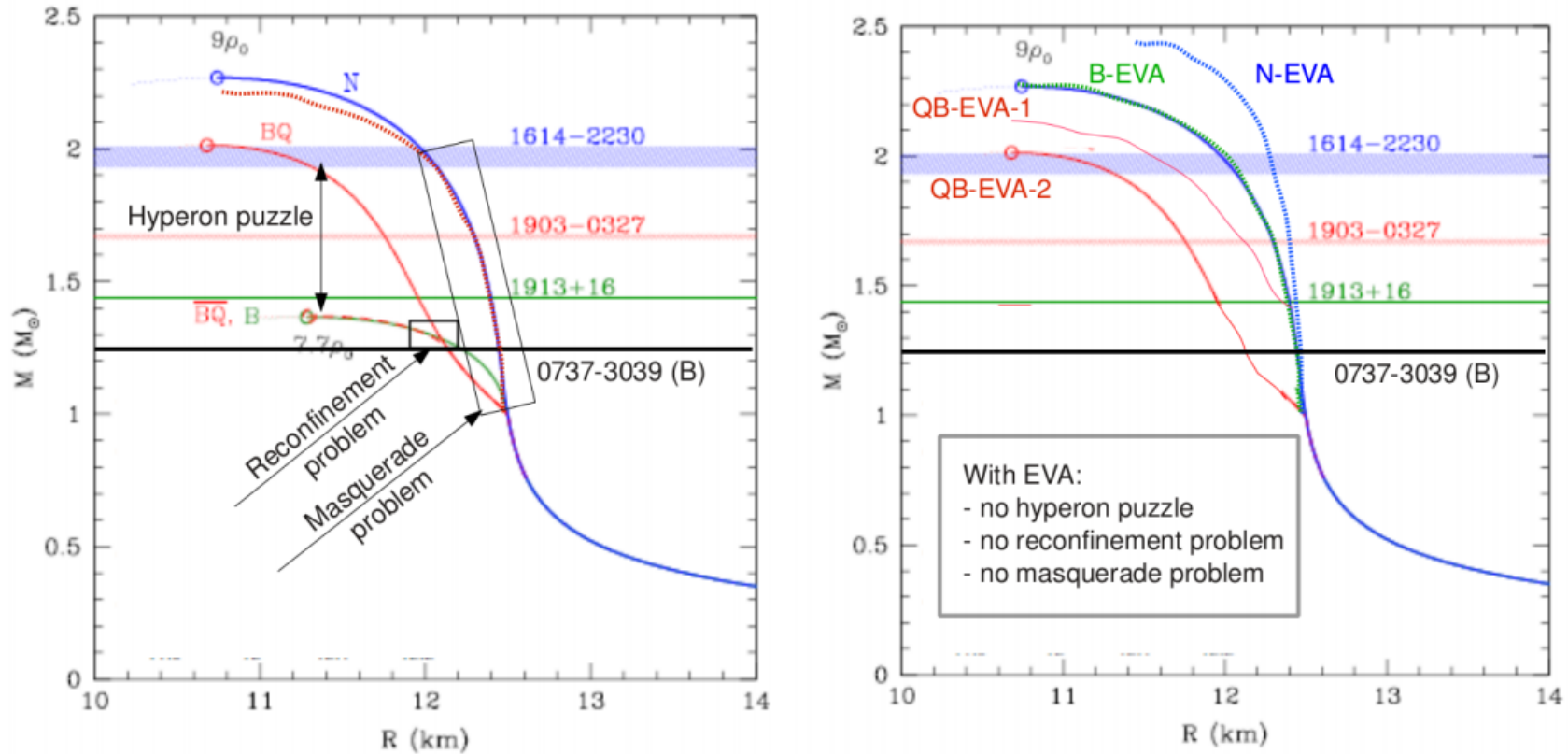***Work in Progress***

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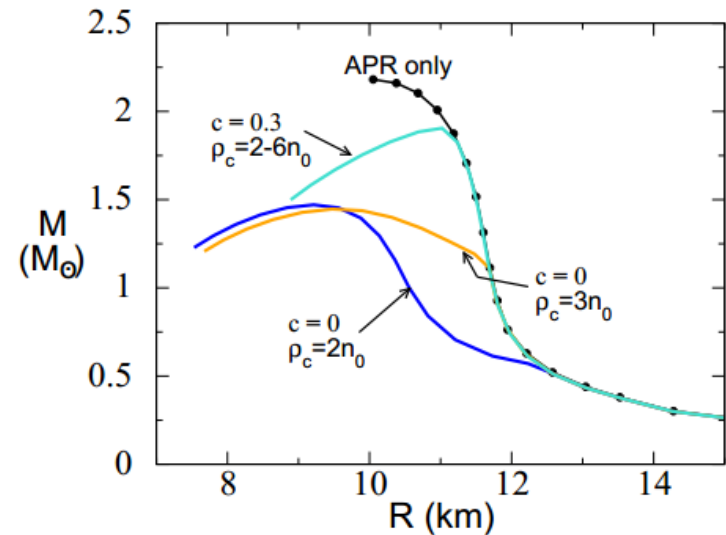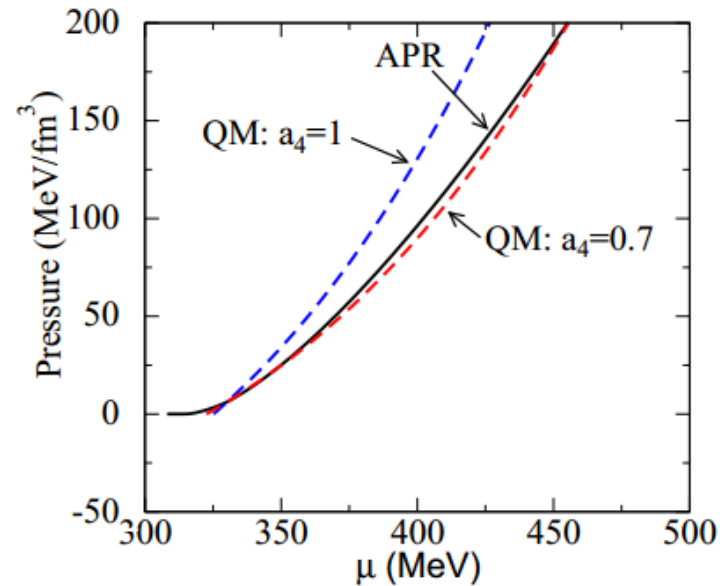
$$\Omega_{QM} = -\frac{3}{4\pi^2}\, a_4\, \mu^4 + \frac{3}{4\pi^2} a_2\, \mu^2 + B_{eff}$$

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

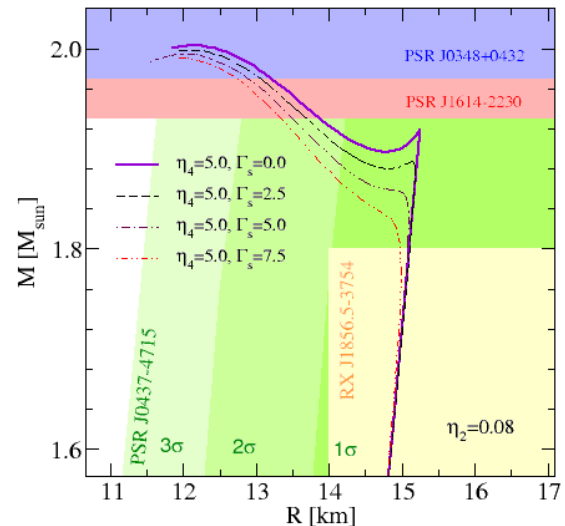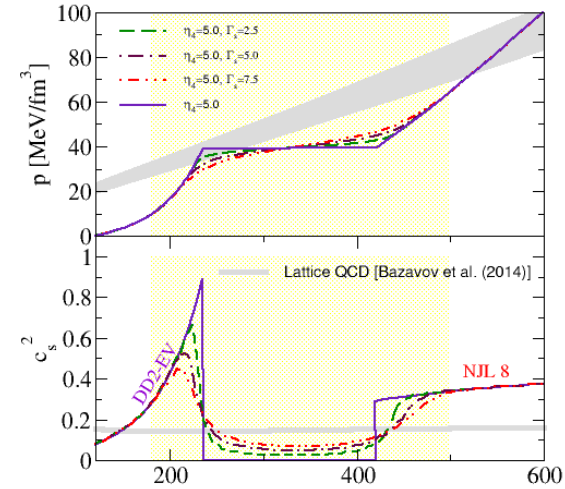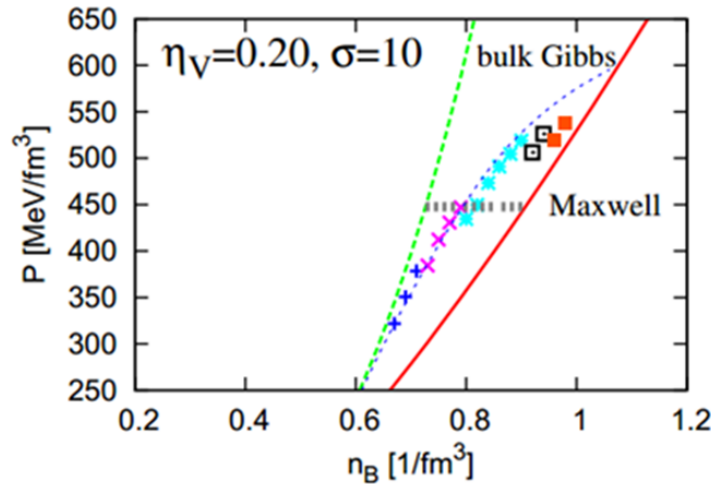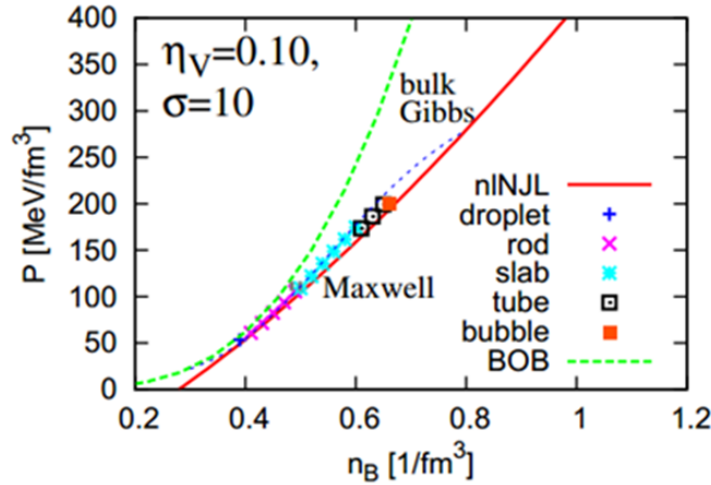**Alford et al. - Astrophys.J.629:969-978, 2005 - arXiv:nucl-th/0411016**

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.
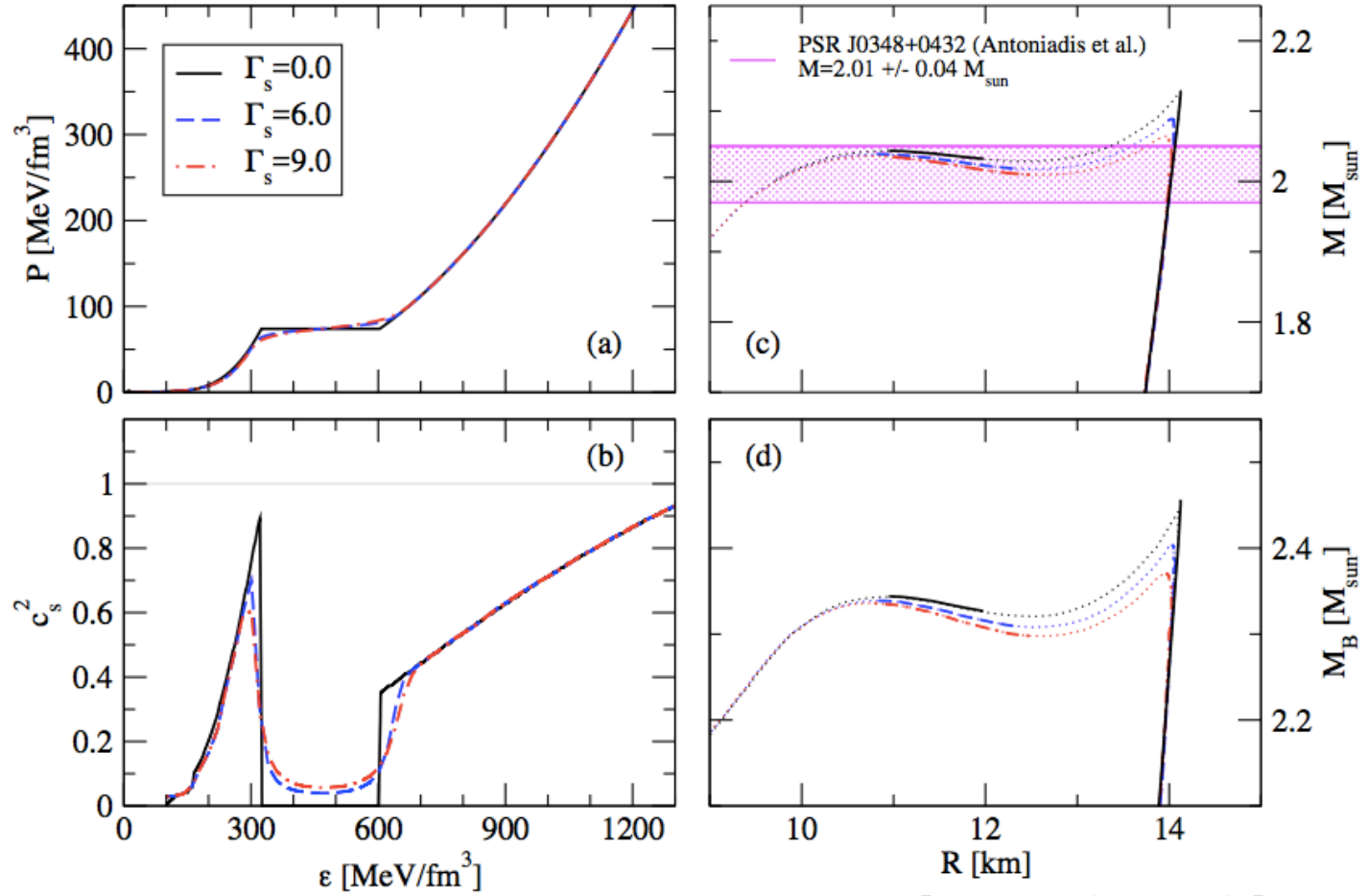
Pasta phases in hybrid stars

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

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

Pasta phases in hybrid stars

$$\varepsilon(p) = \varepsilon_h(p)f_<(p) + \varepsilon_q(p)f_>(p)$$

$$f_{\lessgtr}(p) = \frac{1}{2}\left[1 + \tanh\left(\mp\frac{p - p_c}{\Gamma_s}\right)\right]$$

D. Alvarez Castillo, D. Blaschke, S. Typel

Astrophysical Applications

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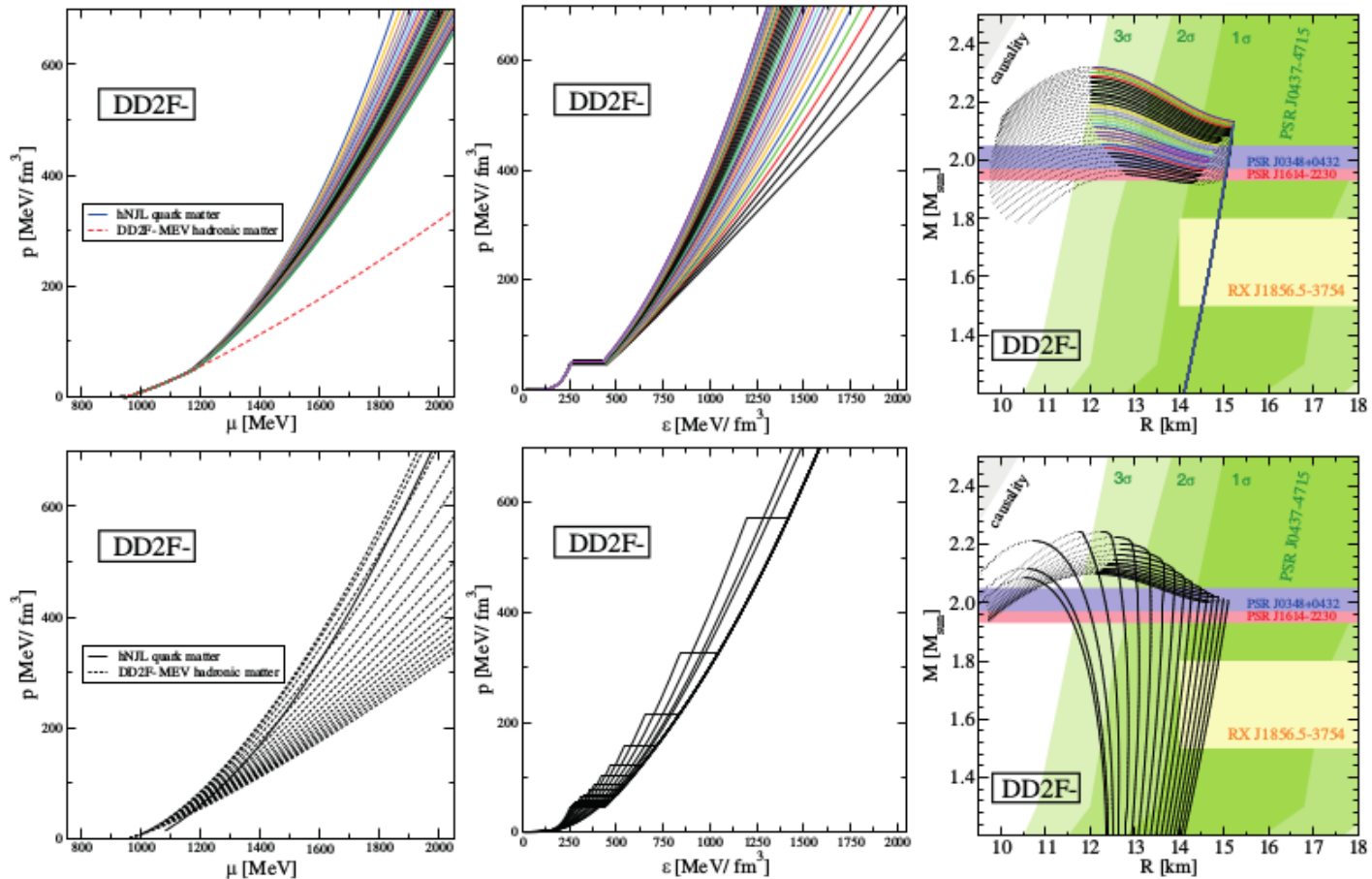
Fig. 1. Variations of the hybrid EoS for the DD2F⁻ model. Upper row. The hadronic EoS is kept fixed while the quark EoS is allowed to vary for the parameters $\eta_4 = 0, 1, 2, \ldots, 30$. Lower row. The quark EoS is fixed whereas the hadronic EoS takes the values $p = 0, 5, 10, \ldots, 80$. For all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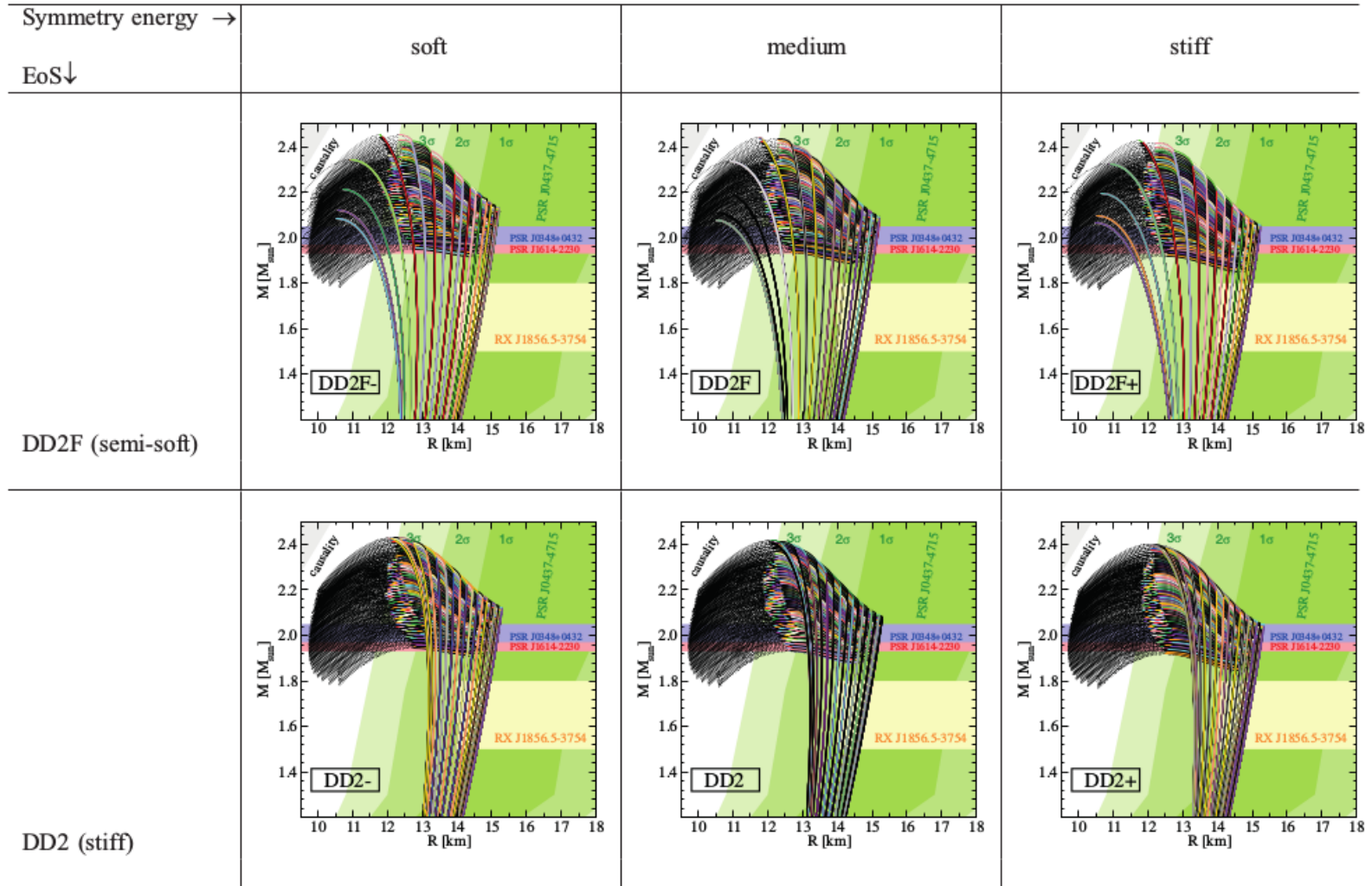
Bayesian Analysis

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
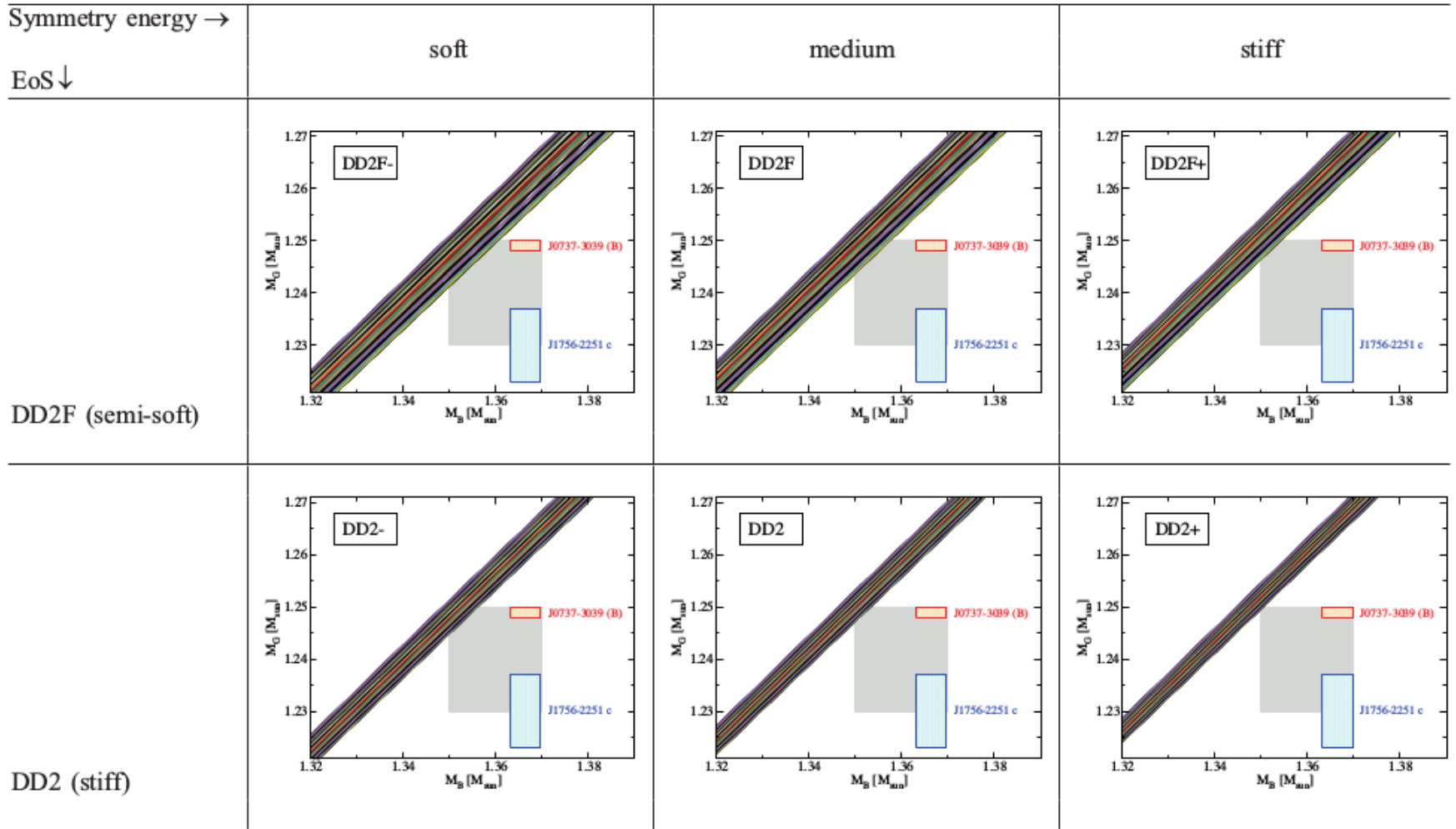
Bayesian Analysis

Fig. 3. Gravitational mass *vs.* baryonic mass for the six classes of new hybrid EoS. For the explanation of the boxes, see text.
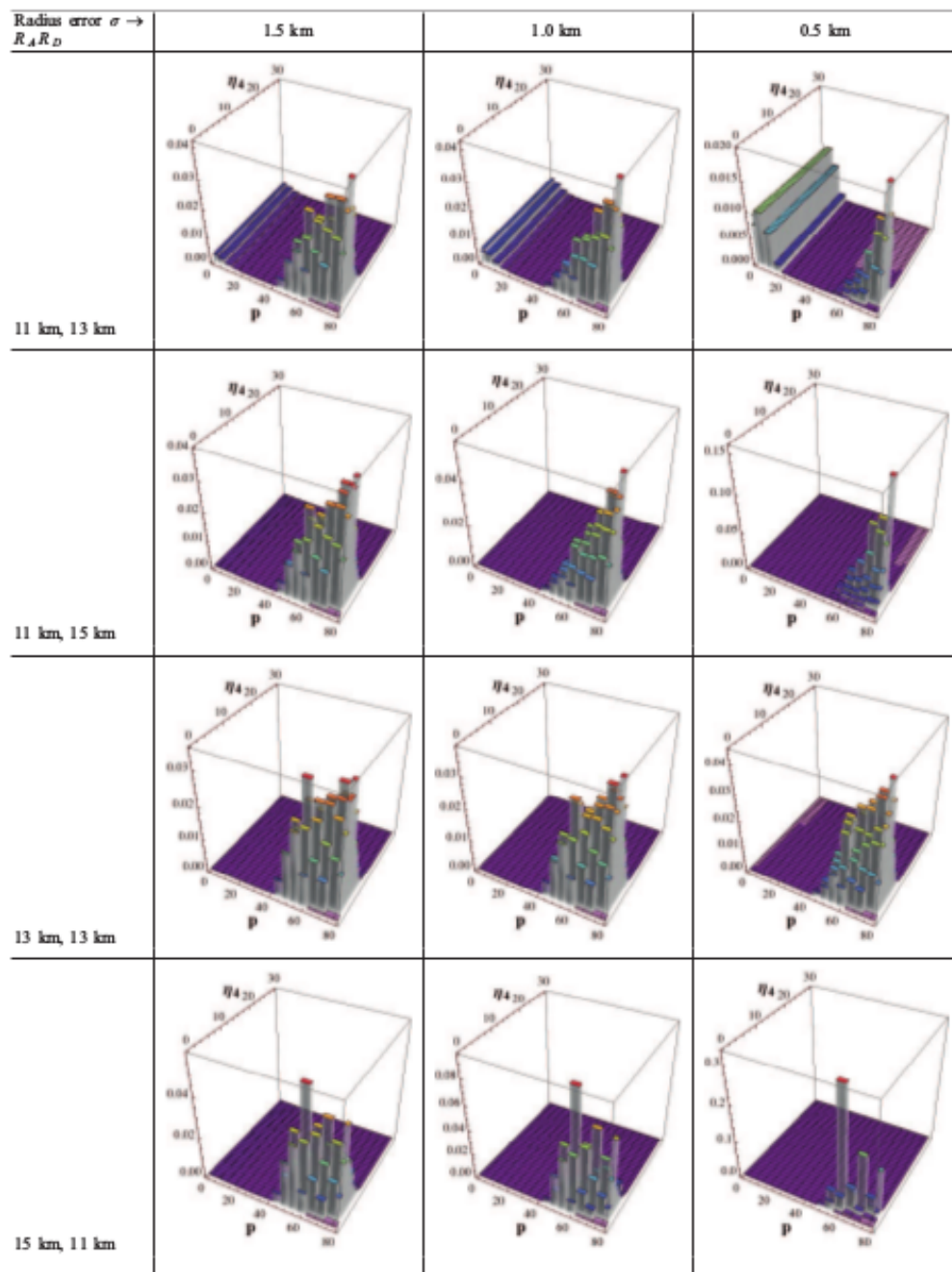
D. Alvarez-Castillo, A. Ayriyan, S. Benic, D. Blaschke, H. Grigorian, S. Typel
EPJA Topical Issue on "Exotic Matter in Neutron Stars", 2016 - arXiv:1603.03457

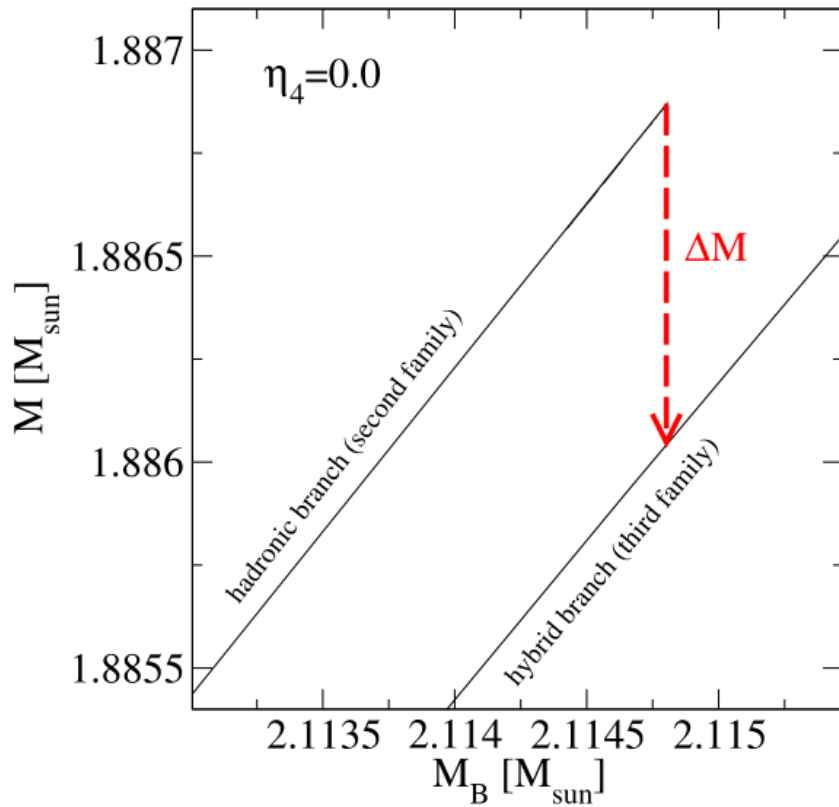| Radius error $\sigma \rightarrow$ $R_A R_D$	1.5 km	1.0 km	0.5 km
11 km, 13 km			
11 km, 15 km			
13 km, 13 km			
15 km, 11 km			

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.
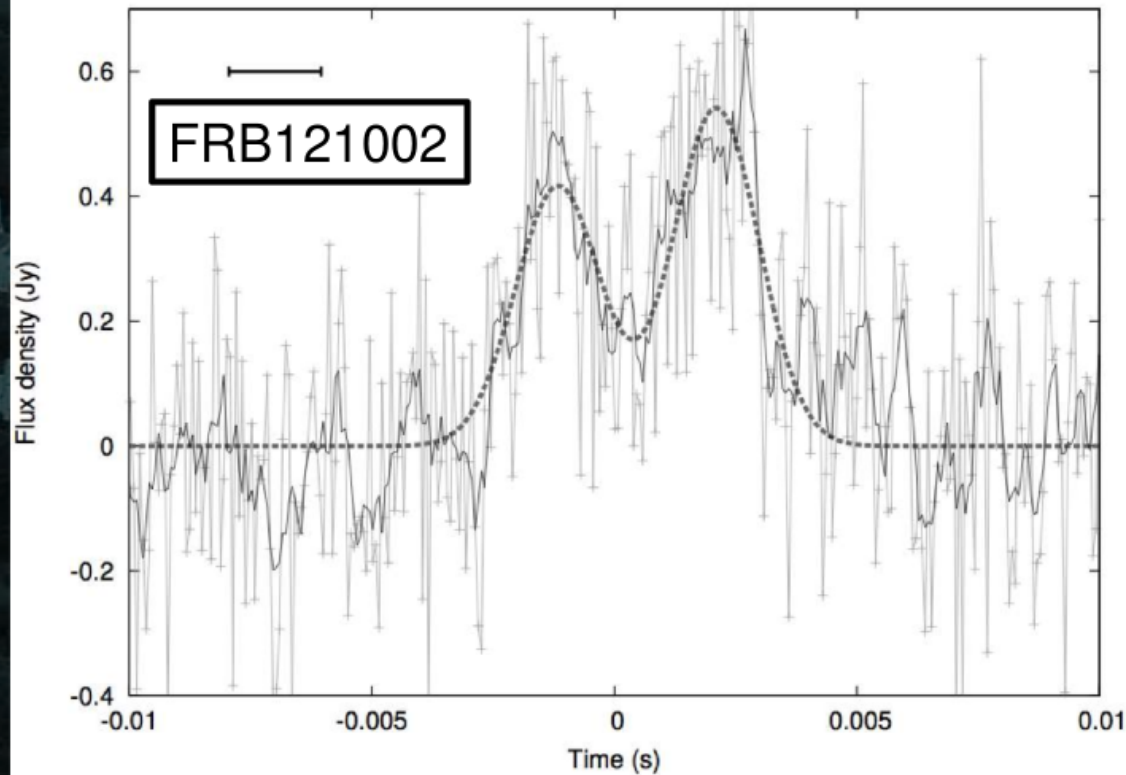
Energy bursts from deconfinement

(Problem: no neutrino trapping yet)
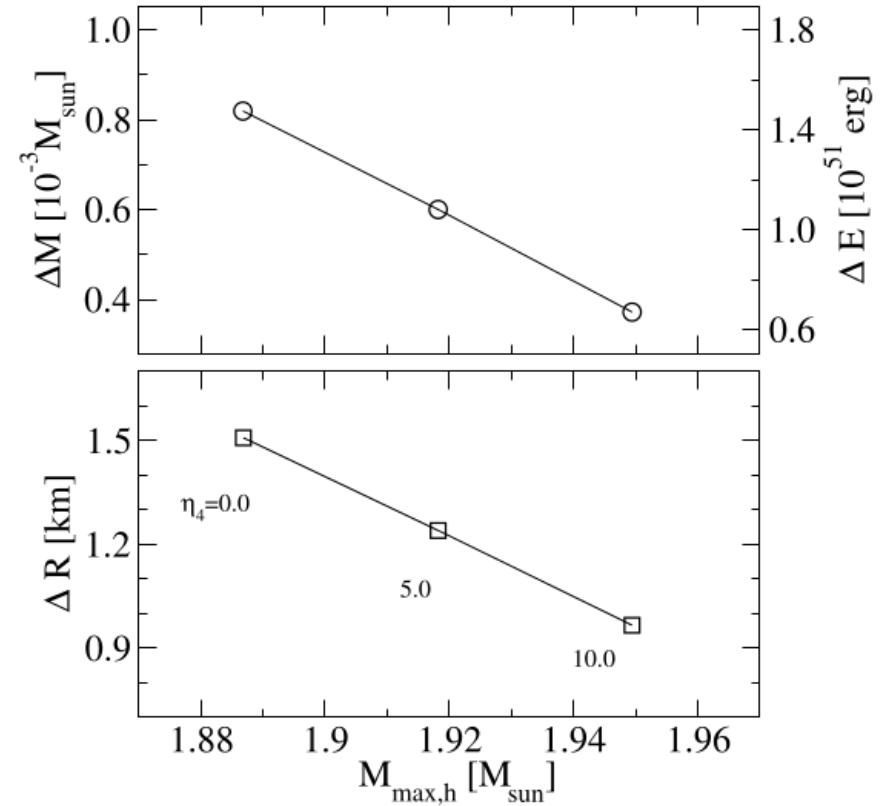
Alvarez-Castillo, Bejger, Blaschke, Haensel, Zdunik (2015), arXiv:1401.5380

Double component FRB

FRB121002

Champion, D., 2015, talk at seventh Bonn Workshop on "Formation and Evolution of Neutron Stars", May 18, 2015 & arXiv: 1511.07746
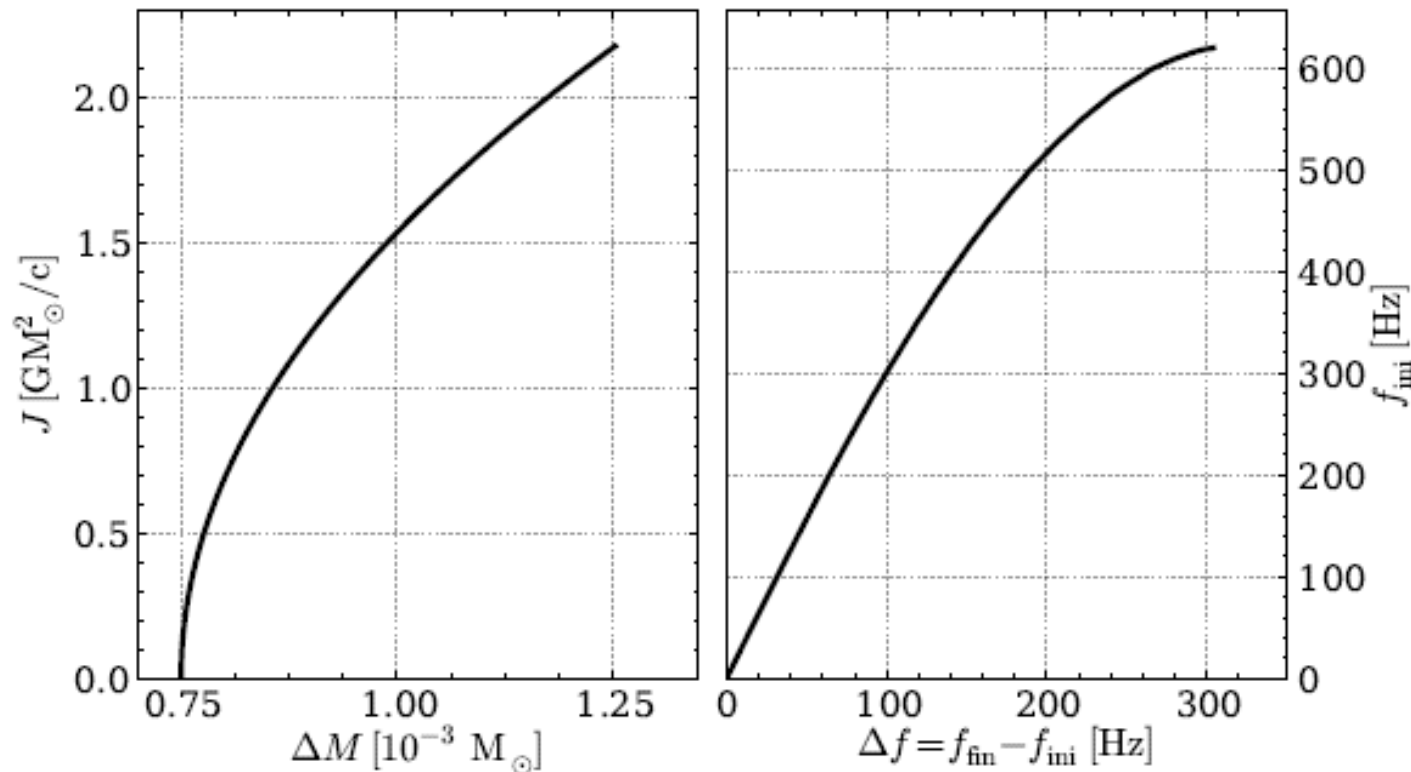
Energy bursts from deconfinement

(case with rotation)

$$\Delta E^{\text{rot}} = E^{\text{rot}}_{\text{fin}} - E^{\text{rot}}_{\text{ini}} = \frac{1}{2} J \left(\Omega_{\text{fin}} - \Omega_{\text{ini}} \right)$$

**For J=2 GM_sun/c frequency changes by
240 Hz and Delta E^rot ~ 2x10^52 erg ...**

Bejger, Blaschke, Haensel, Zdunik, Fortin, A&A 600 (2017) A39, arXiv:1608.07049

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

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

Following Hinderer et al. 2010

Integrate standard TOV system:

$$e^{2\Lambda} = \left(1 - \frac{2m_r}{r}\right)^{-1},$$

$$\frac{d\Phi}{dr} = -\frac{1}{\epsilon+p}\frac{dp}{dr},$$

$$\frac{dp}{dr} = -(\epsilon+p)\frac{m_r + 4\pi r^3 p}{r(r-2m_r)},$$

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

EoS to be provided ε(p)

And additional eqs. for perturbations:

$$\frac{dH}{dr} = \beta \tag{11}$$

$$\frac{d\beta}{dr} = 2\left(1 - 2\frac{m_r}{r}\right)^{-1} H \left\{-2\pi\left[5\epsilon + 9p + f(\epsilon+p)\right]\right.$$

$$+\frac{3}{r^2} + 2\left(1 - 2\frac{m_r}{r}\right)^{-1}\left(\frac{m_r}{r^2} + 4\pi rp\right)^2\right\}$$

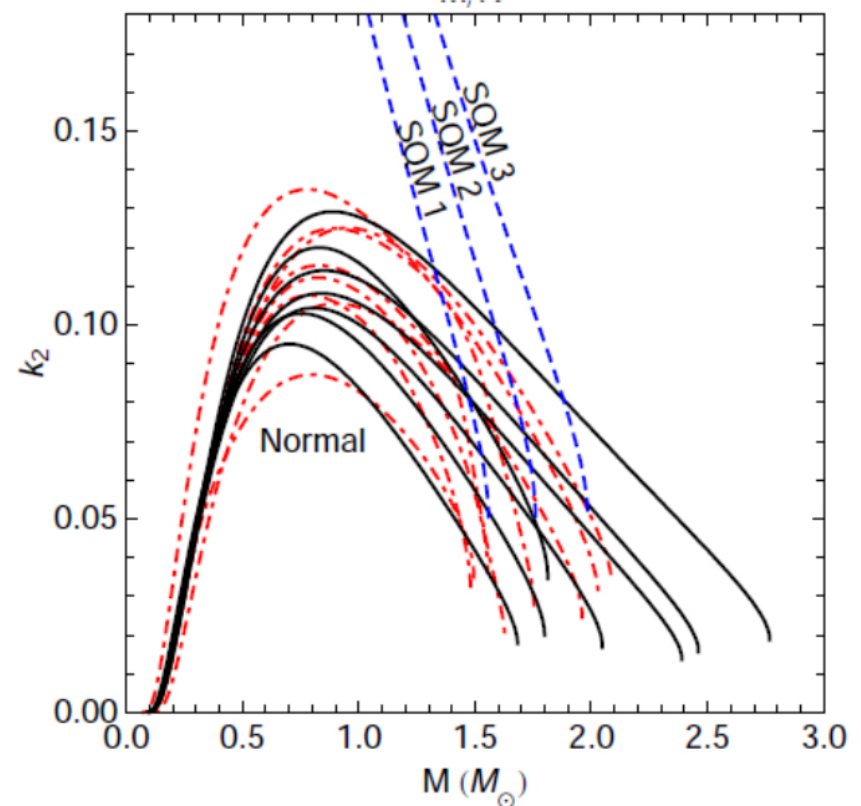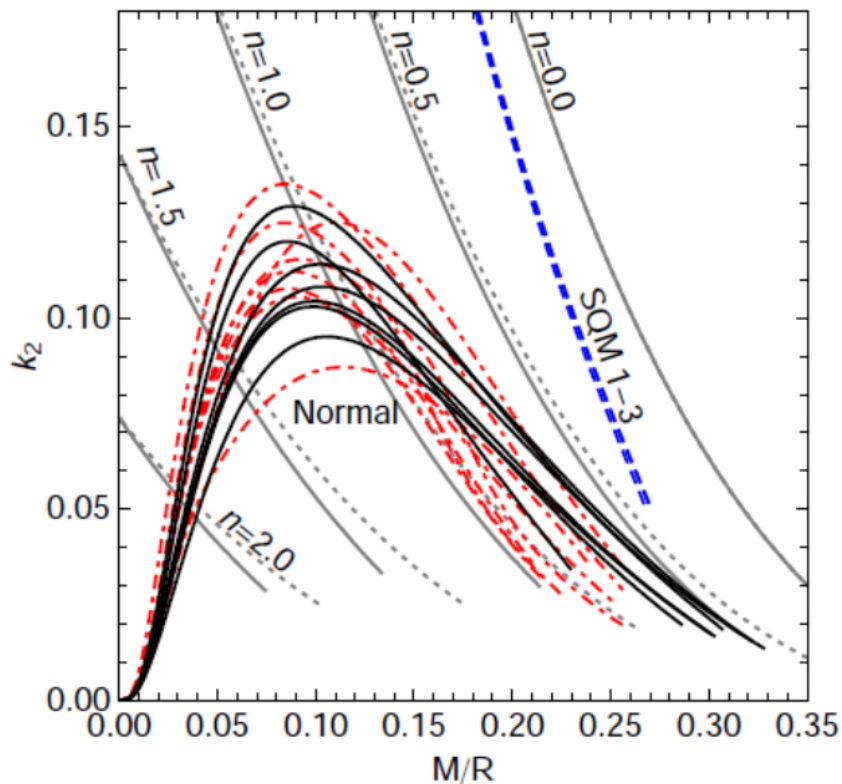$$+\frac{2\beta}{r}\left(1 - 2\frac{m_r}{r}\right)^{-1}\left\{-1 + \frac{m_r}{r} + 2\pi r^2(\epsilon - p)\right\}.$$

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

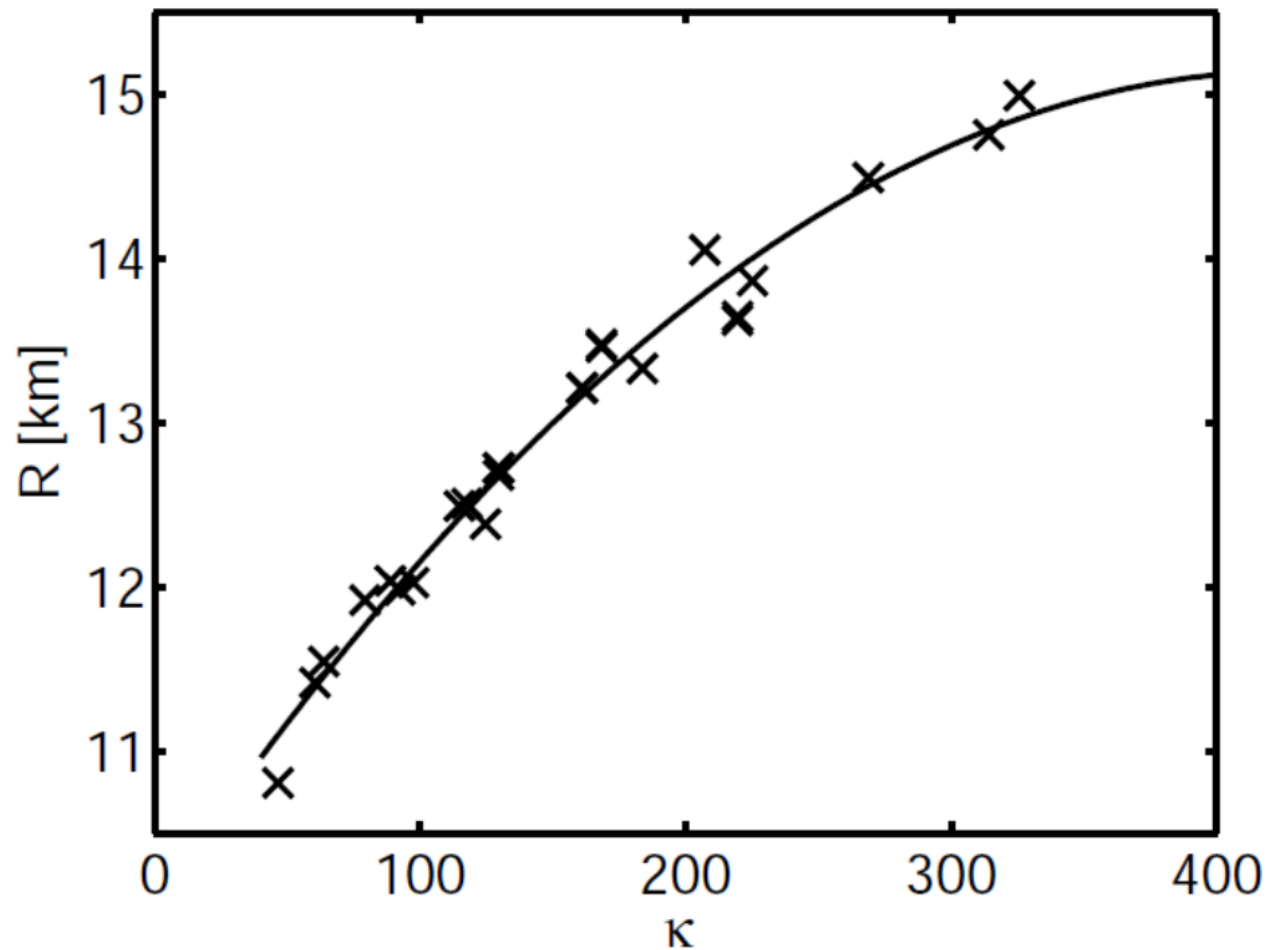Note: Although multidimensional problem – computation in 1D since absorbed in Y20

Love number

For fixed compactness k_2 depends on EoS => tidal deformability is not a unique function of compactness for different EoSs
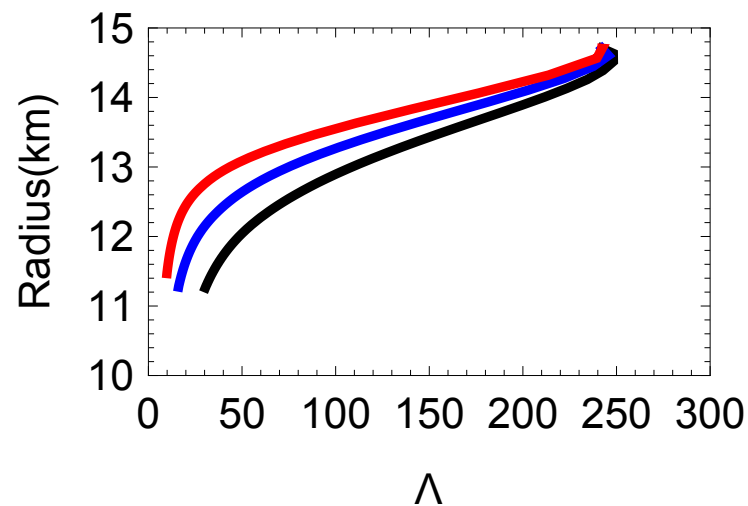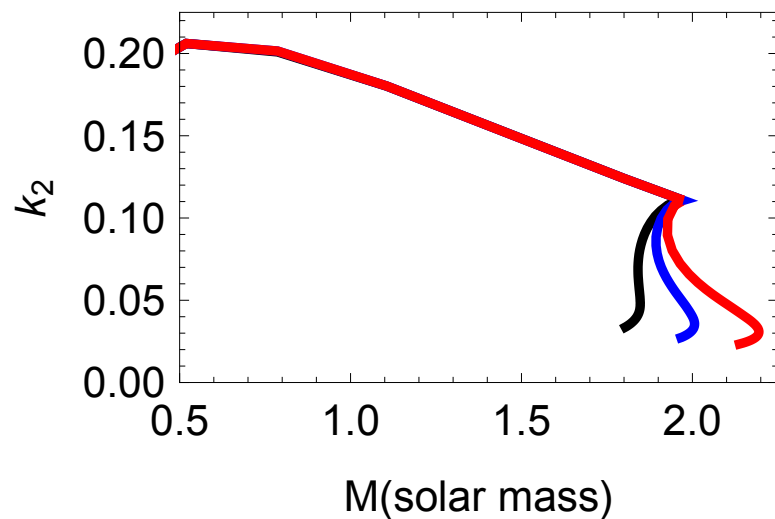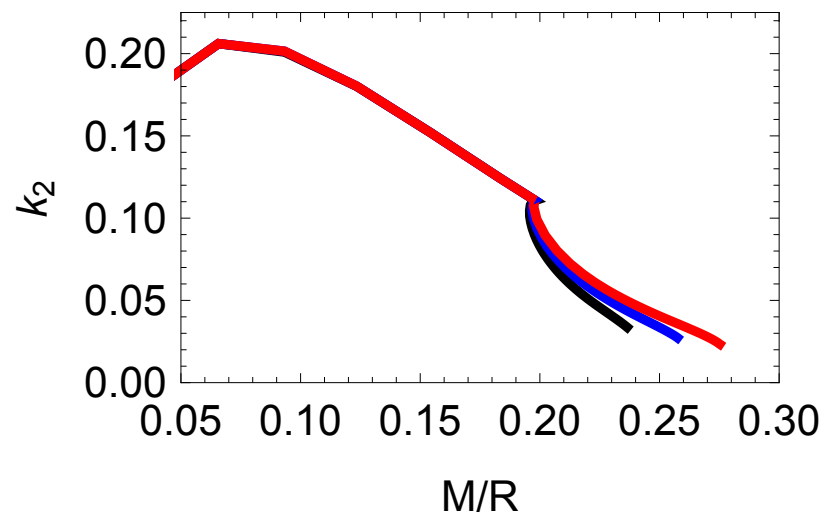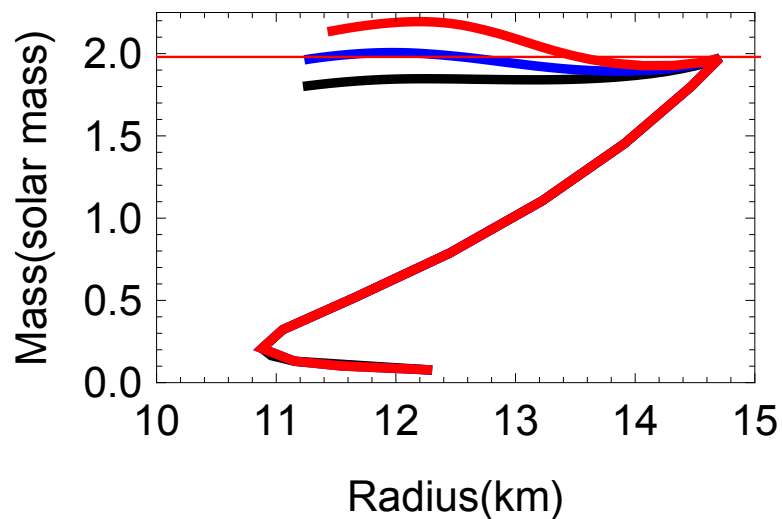
Hinderer et al. 2010

Tidal deformability vs radius

1.35 Msun stars with many different EoS, Bauswein 2015 unpublished, max dev. 314 meters

Neutron Star Twins
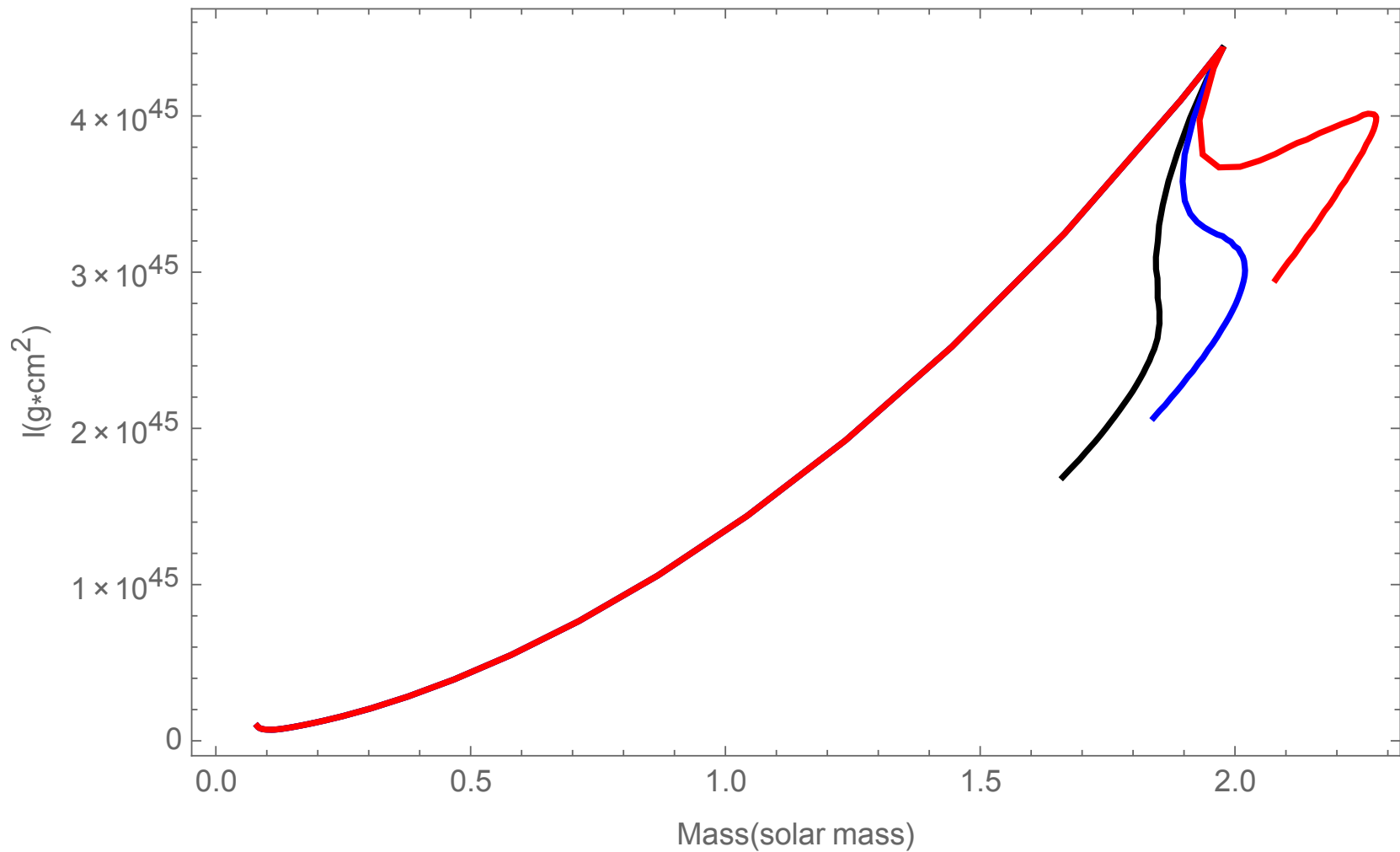
Neutron Star Twins

NEUTRON-STAR RADIUS CONSTRAINTS FROM GW170817 AND FUTURE DETECTIONS

Andreas Bauswein,[1] Oliver Just,[2] Hans-Thomas Janka,[3] and Nikolaos Stergioulas[4]

[1] *Heidelberger Institut für Theoretische Studien, Schloss-Wolfsbrunnenweg 35, D-69118 Heidelberg, Germany*
[2] *Astrophysical Big Bang Laboratory, RIKEN, Saitama 351-0198, Japan*
[3] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, D-85748 Garching, Germany*
[4] *Department of Physics, Aristotle University of Thessaloniki, GR-54124 Thessaloniki, Greece*

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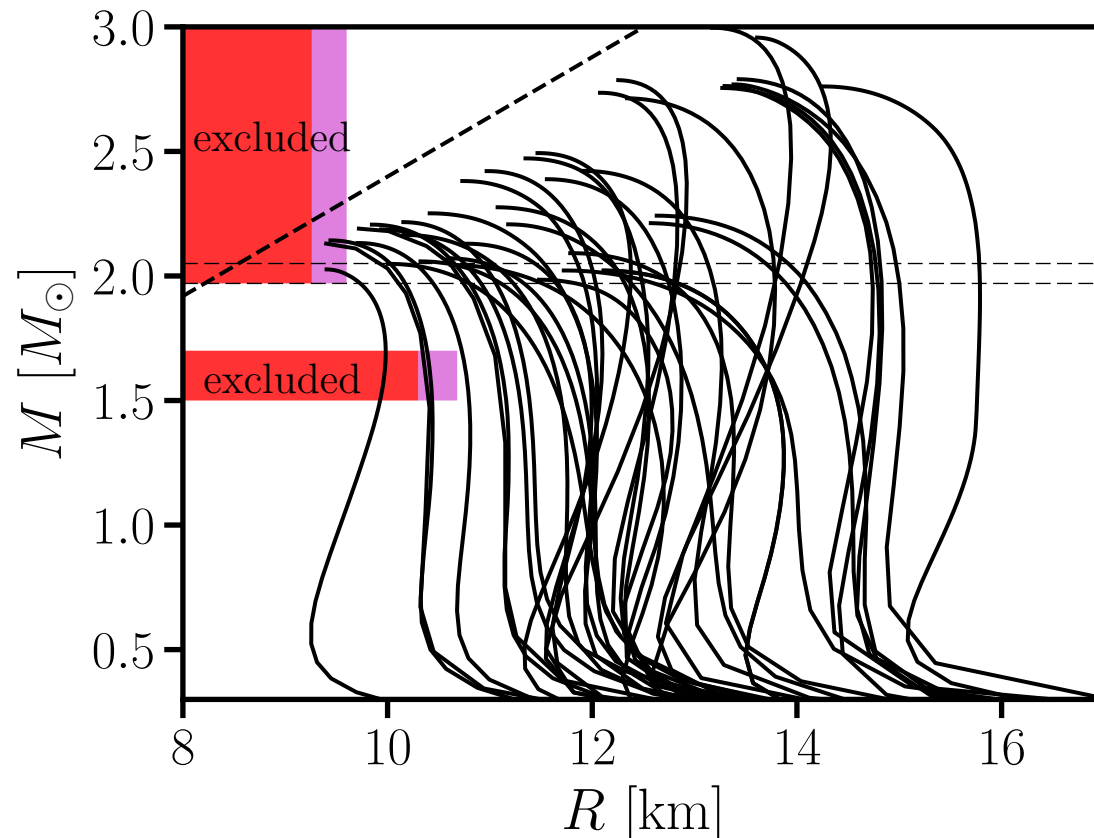
$$M_{\rm thres} > M_{\rm tot}^{\rm GW170817} = 2.74^{+0.04}_{-0.01} \ M_\odot,$$

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

$$M_{\rm thres} = \left(-3.38 \frac{G M_{\max}}{c^2 R_{\max}} + 2.43 \right) \cdot M_{\max}$$
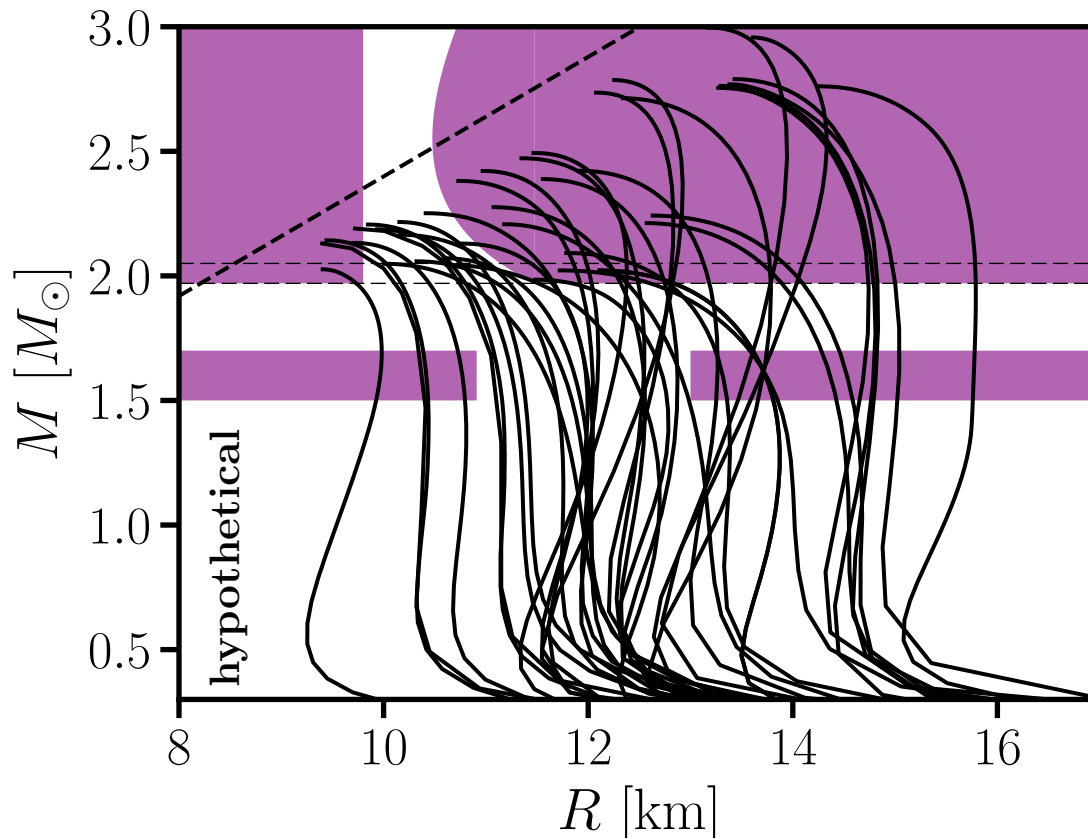
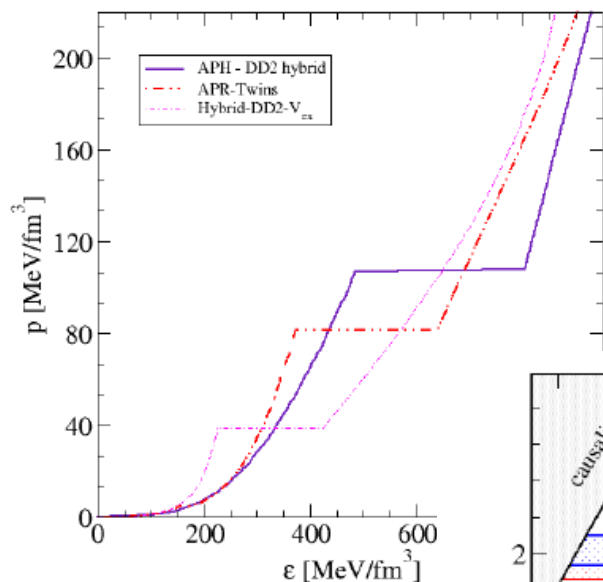# GW170817 Radius Constraints

Fictitious GW constraints

NICA White Paper – selected topics ...

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

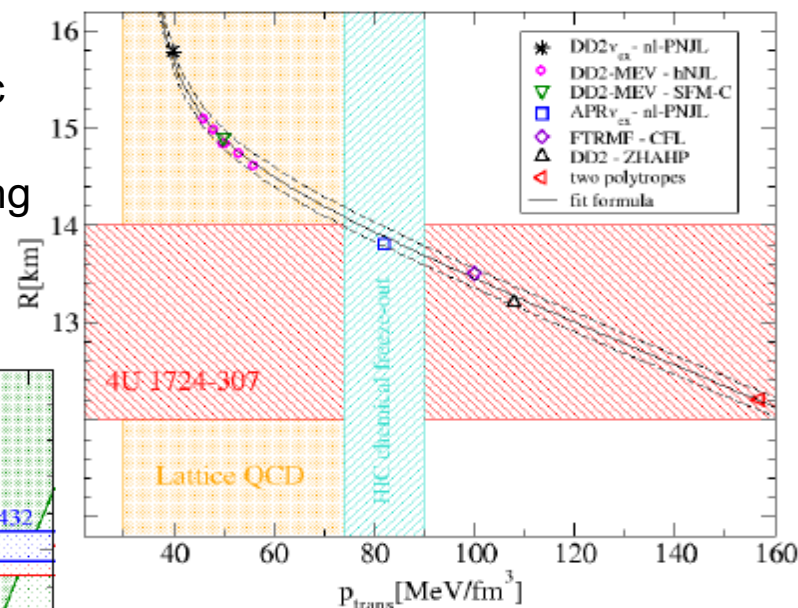## Neutron star mass limit at $2M_\odot$ supports the existence of a CEP
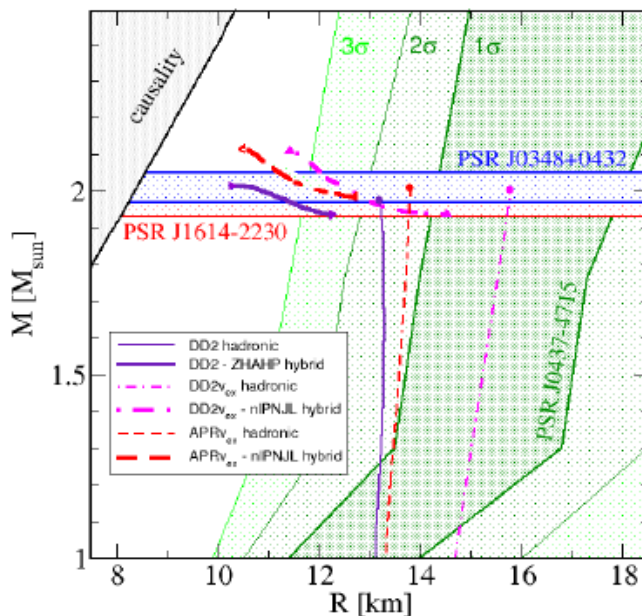
D. Alvarez-Castillo[1,a], S. Benic[2,b], D. Blaschke[1,3,4], Sophia Han[5,6], and S. Typel[7]

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

Strong phase
transition

High-mass twin stars

Universal transition pressure ?

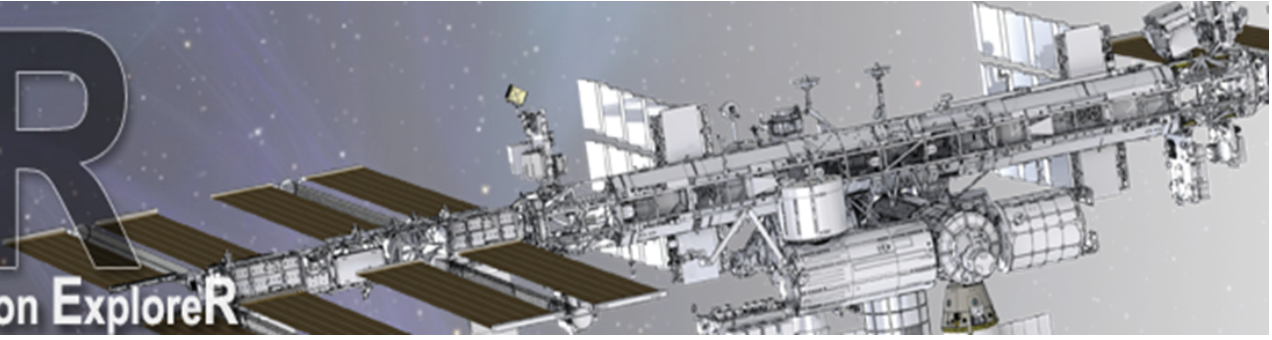Petran & Rafelski, PRC 88, 021901

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

Perspectives and future work

- Extension of the EoS to finite T: applications to supernovae and heavy ion collisions

- Gravitational wave signal estimation

- Moments of inertia: I love Q relations

- Radio emission description and dynamical collapse for the twins

- Pasta phases inclusion into the Bayesian Analysis for detection assessment
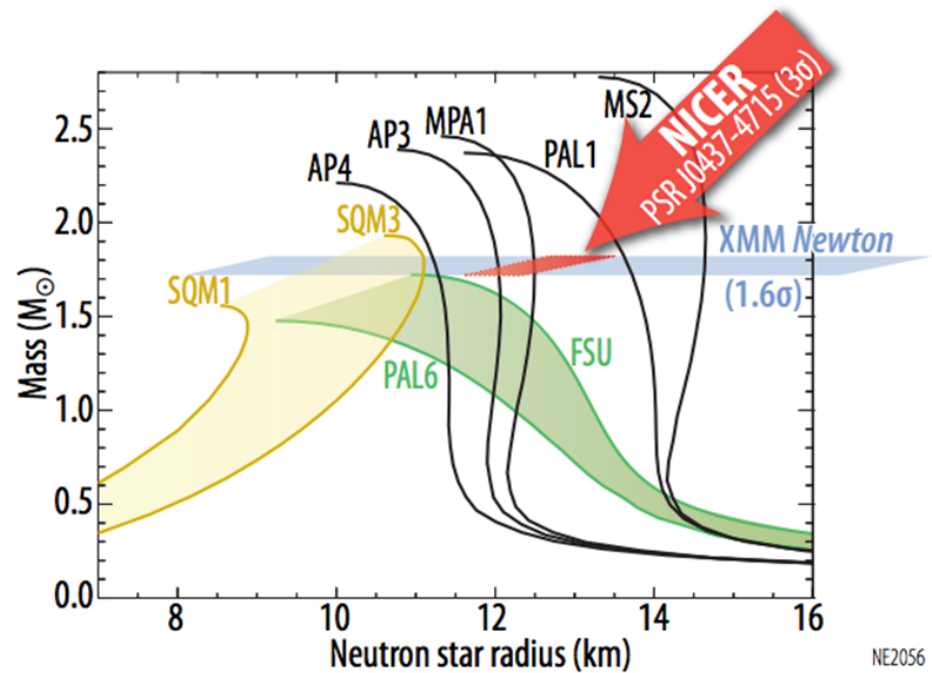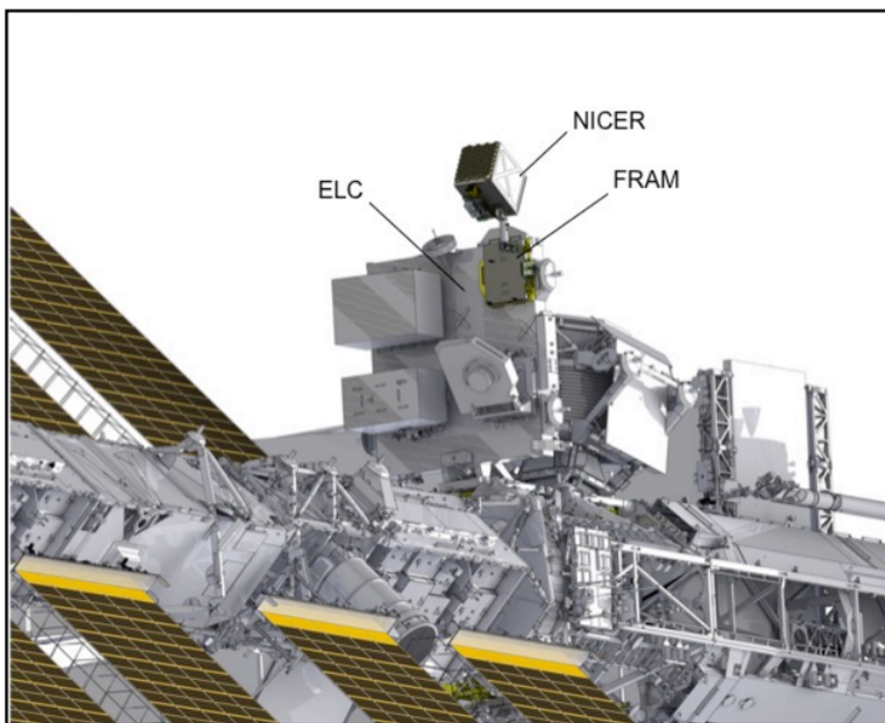
NICER 2017

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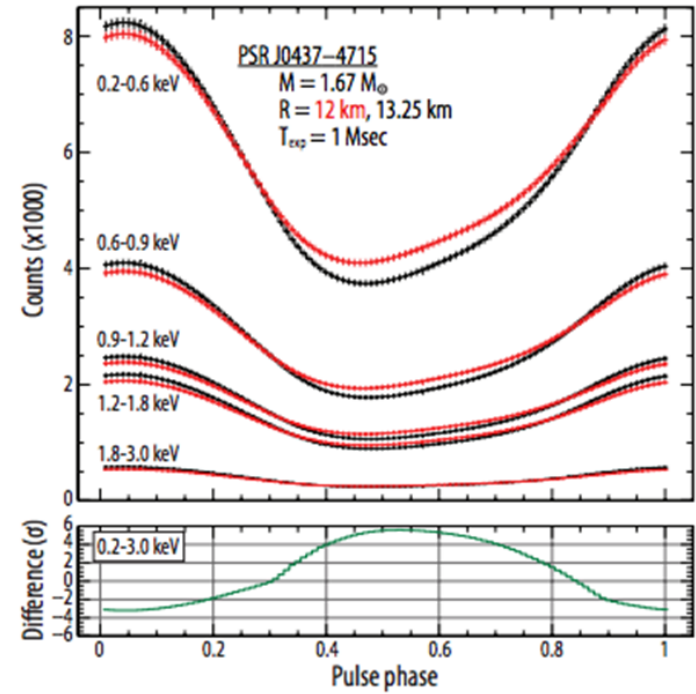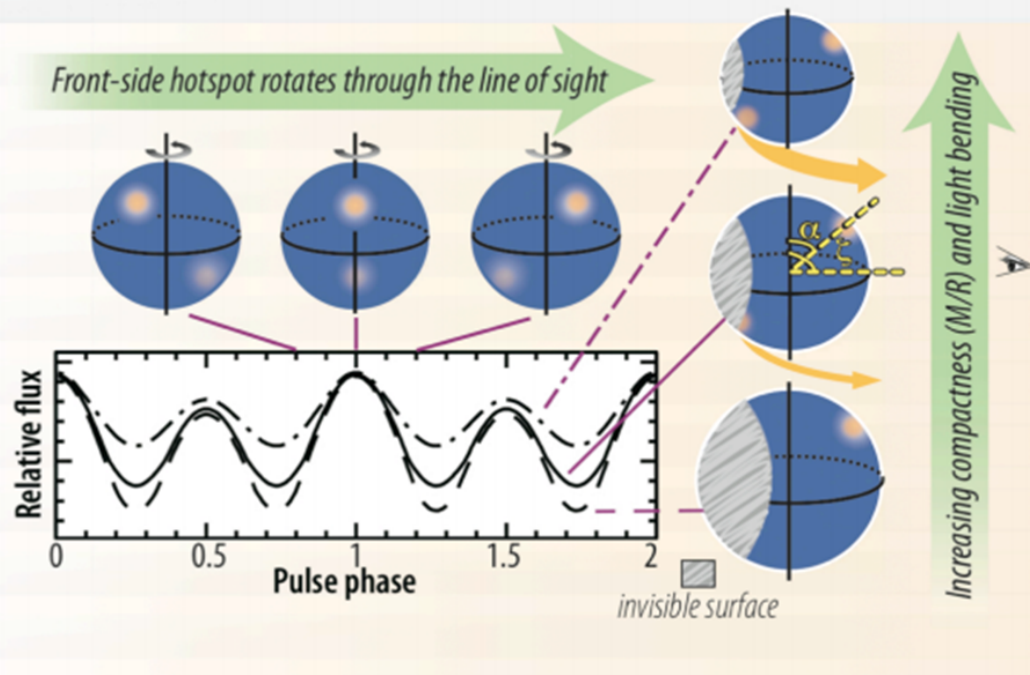
Hot Spots

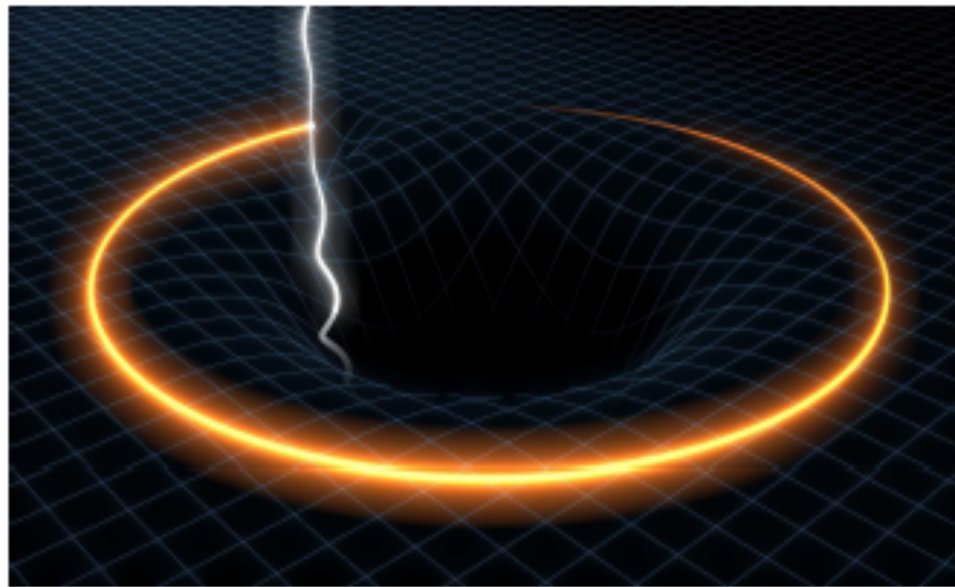# Perspectives for new Instruments?

THE FUTURE: SKA - SQUARE KILOMETER ARRAY

THE FUTURE: SKA - SQUARE KILOMETER ARRAY

WAS EINSTEIN RIGHT ABOUT GRAVITY?

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
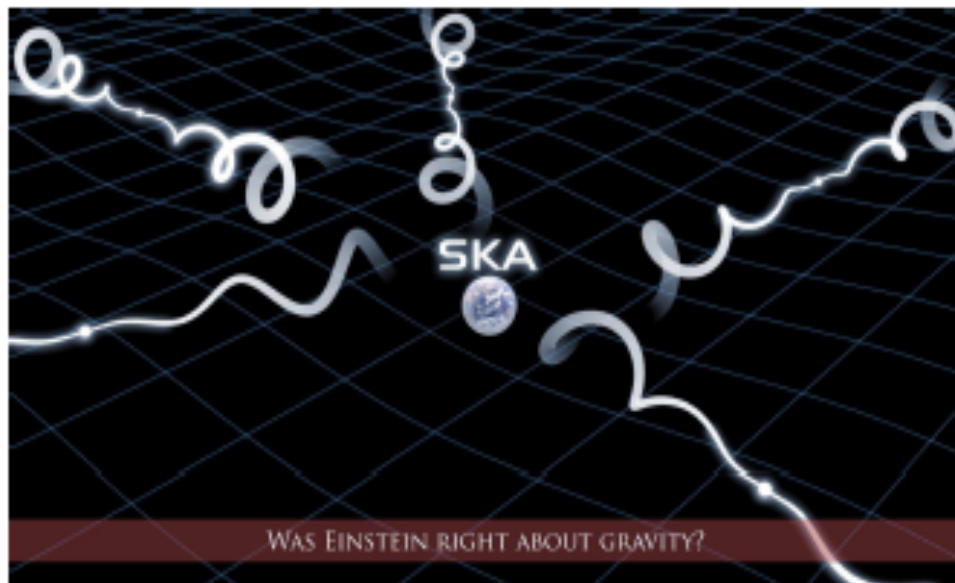
Discovery Potential:

- Find a Pulsar - Black Hole Binary

- Constrain Einstein Gravity

- Gravitational waves

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 interface.

- Energy bursts via deconfinement feasible for the twins.

- Possible universal phase transition pressure.

Gracias

©NASA

Announcement of the 11th BONN workshop on

– Formation and Evolution of Neutron stars –

- December 11+12, 2017
- MPIfR/AIfA University of Bonn, Auf dem Hügel 69–71, 53121 Bonn

- **Programme**:
  Start: 11:00 Monday, Dec. 11, 2017
  End: 16:00 Tuesday, Dec. 12, 2017

  Dinner Monday night is optional (at your own expense – @19:00 at a local restaurant)

- The topic for this 11th meeting is: *Neutron Stars in Future Research*
  There will be a total of six sessions over two days:
  – Highlights and General News on Neutron Stars (New Research Results)
  – Accreting Neutron Stars
  – Millisecond Pulsars and their Applications I.
  – Millisecond Pulsars and their Applications II.
  – Supernovae, Young Neutron Stars and the Equation-of-state
  – Neutron Stars as Gravitational Wave Sources