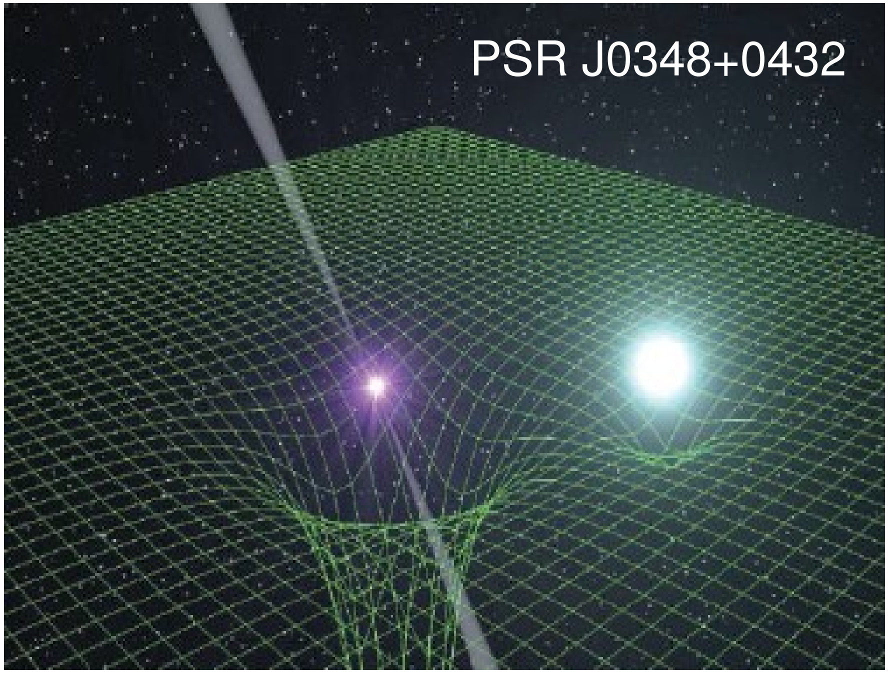
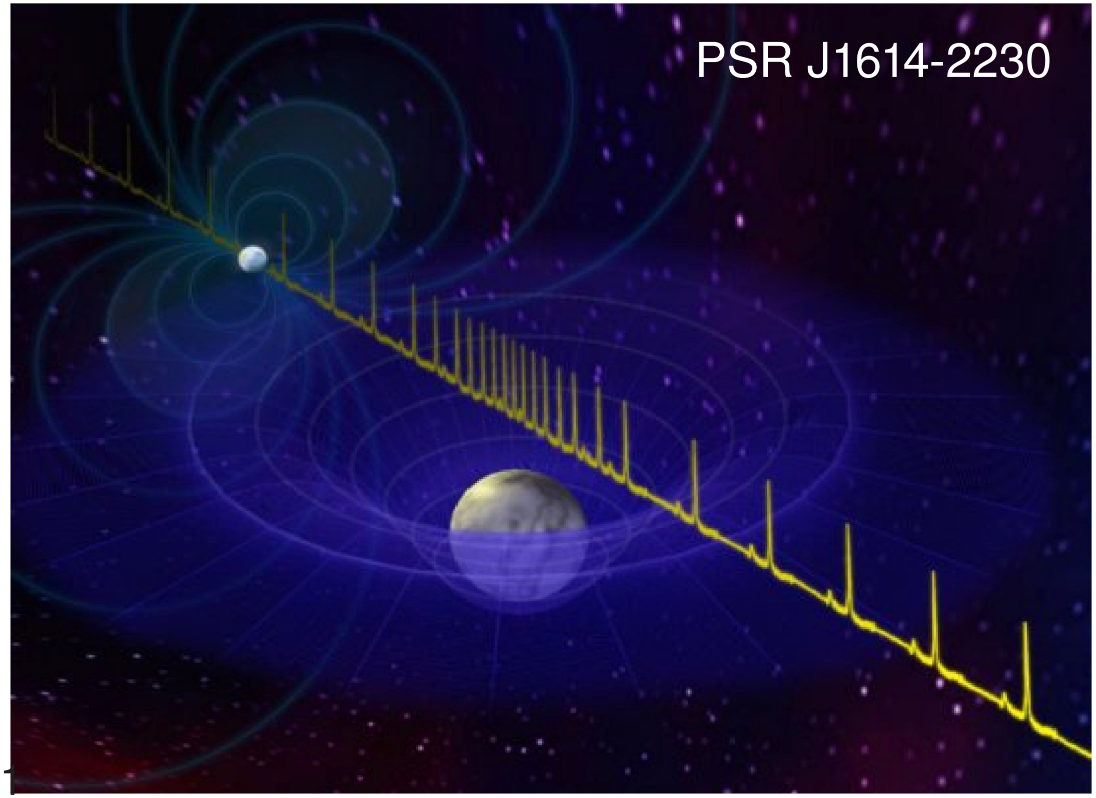
Mass-Radius constraints & QCD Phase Diagram

David Blaschke (University of Wroclaw, Poland & JINR Dubna, Russia)





Antoniadis et al., Science 340 (2013) 448

Demorest et al., Nature 467 (2010) 1081

EMMI RRTF “QM in Compact Stars”, Frankfurt, 09.10.2013

CSQCD IV Proposal: Sept. 26-30, 2014

Venue: ``Haus hinter den Dünen'' in Prerow, Baltic Sea (Germany)

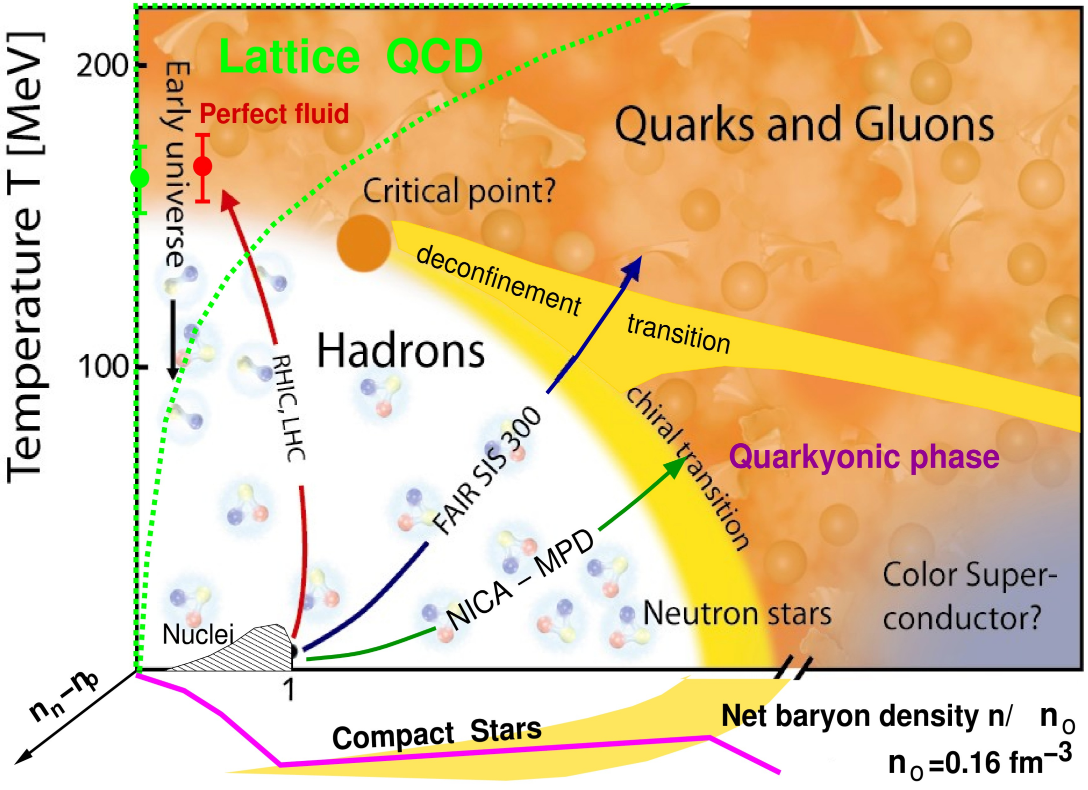
Contact: j.wambach@gsi.de , blaschke@ift.uni.wroc.pl

Example workshop: http://www.mpg.uni-rostock.de/~hic4fair

Proving the CEP with Compact Stars

David Blaschke (University of Wroclaw, Poland & JINR Dubna, Russia)

1. Goal: Find 1st order PT



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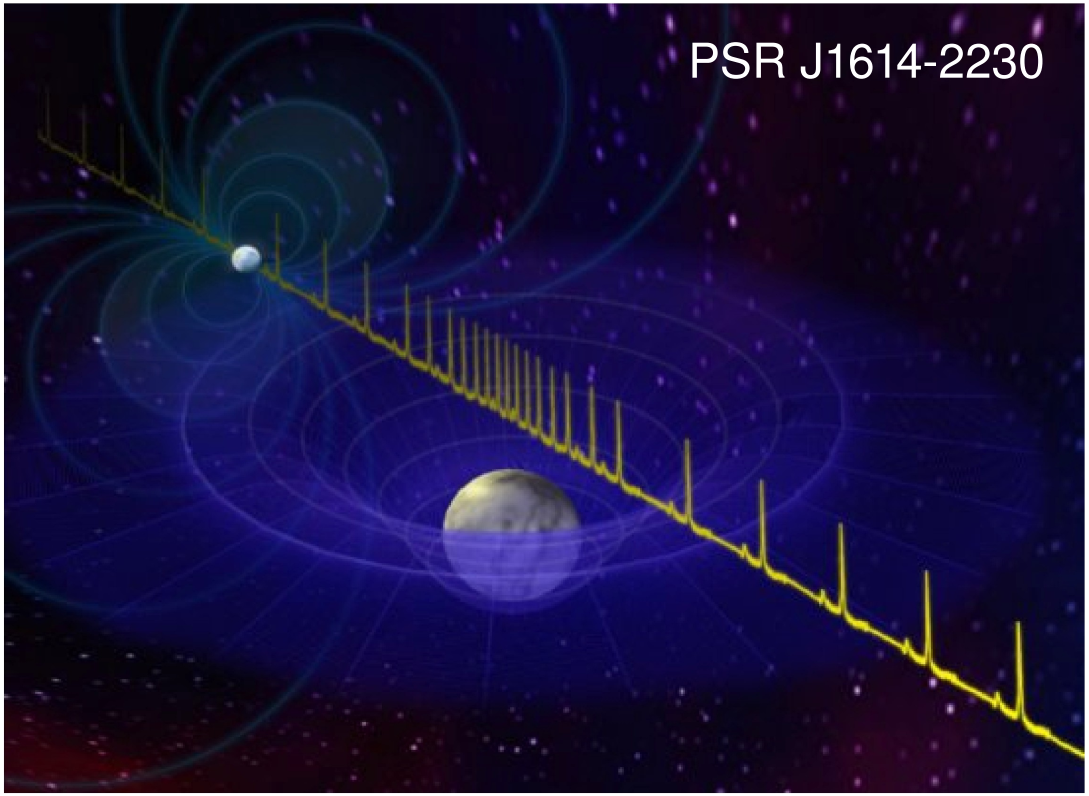

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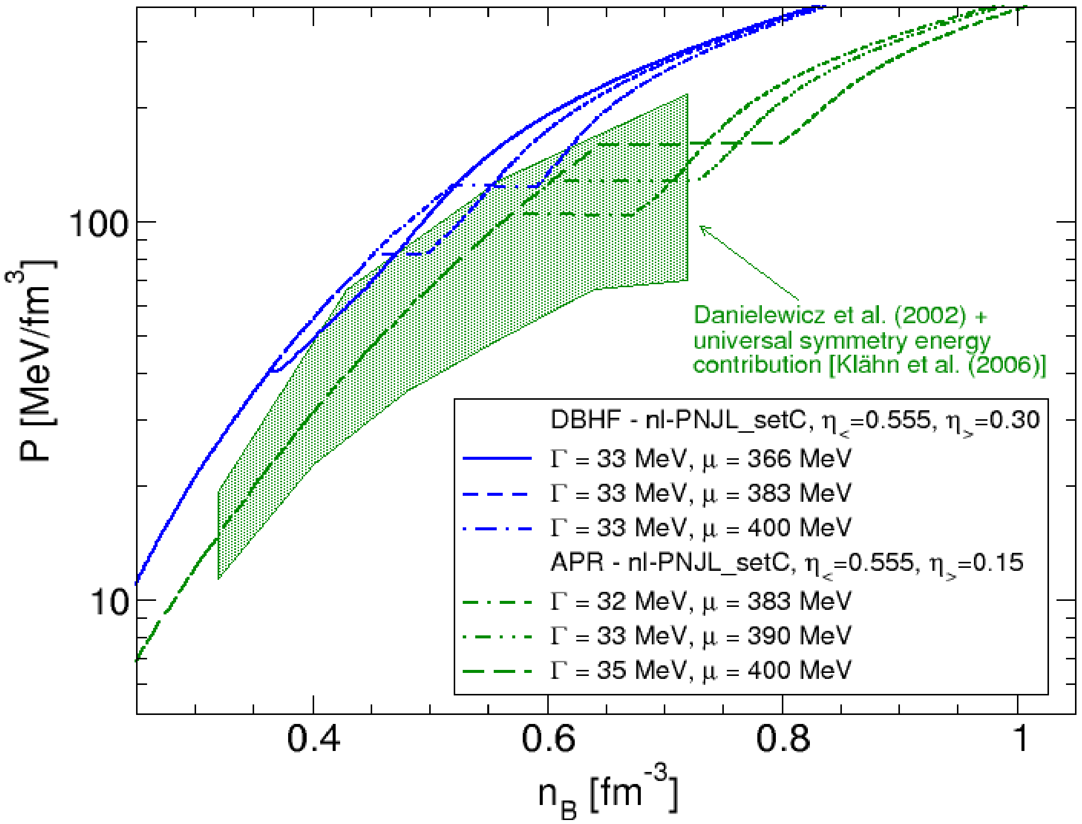
3. Theory: QCD based EoS



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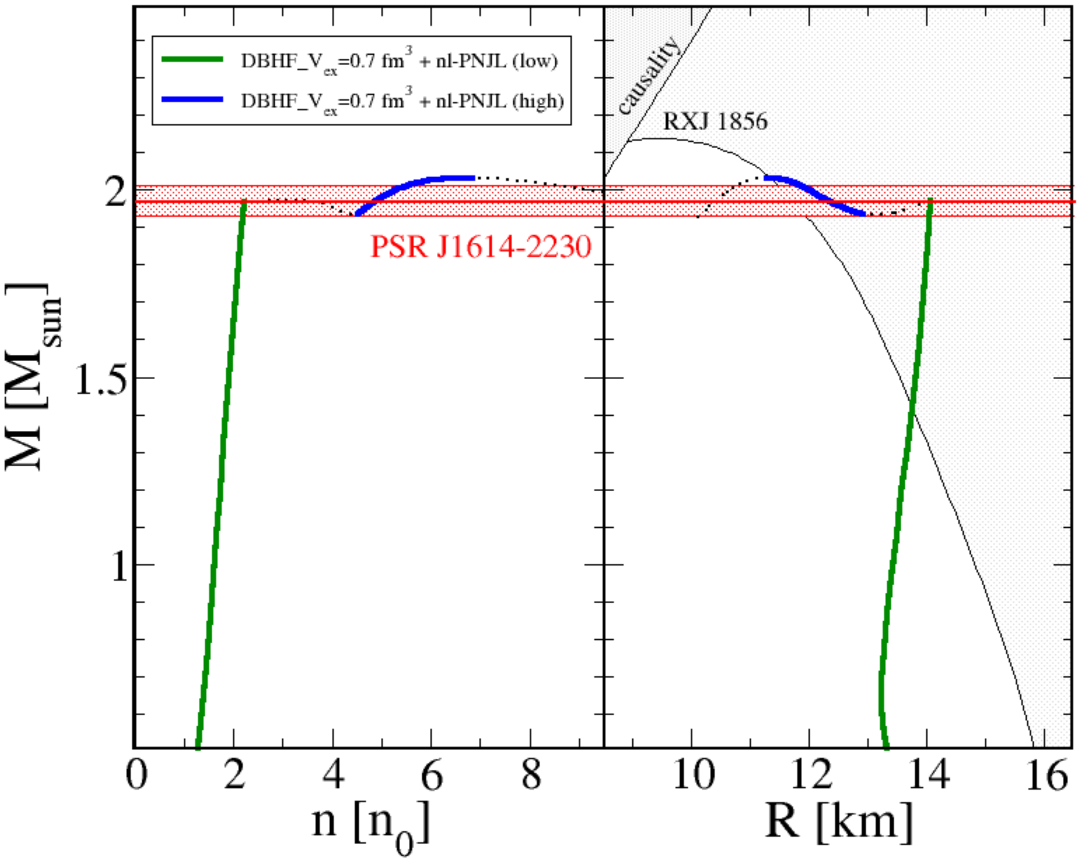

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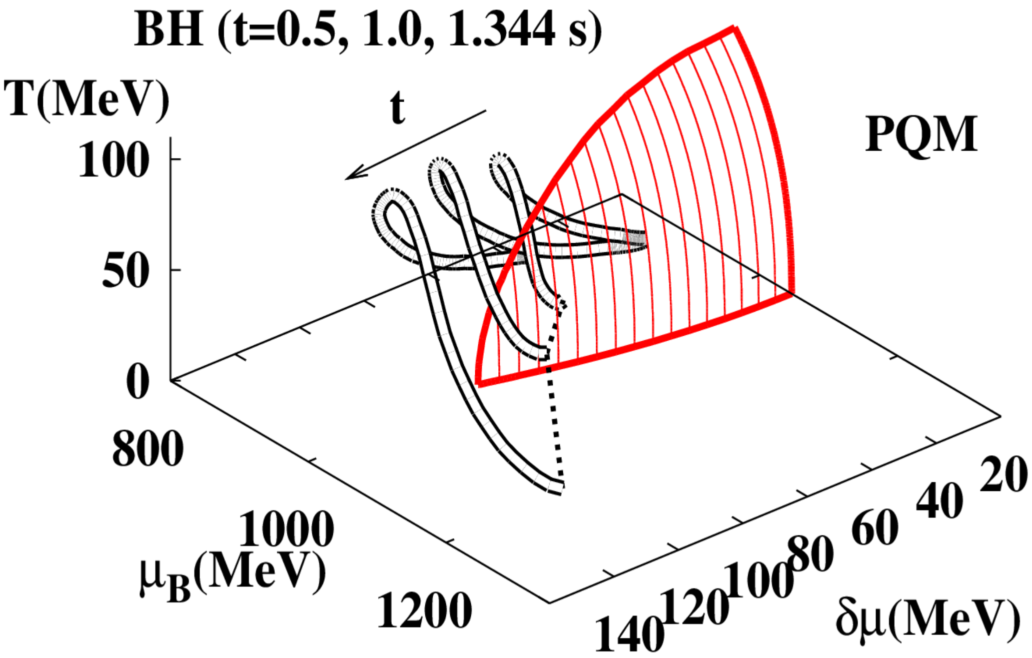

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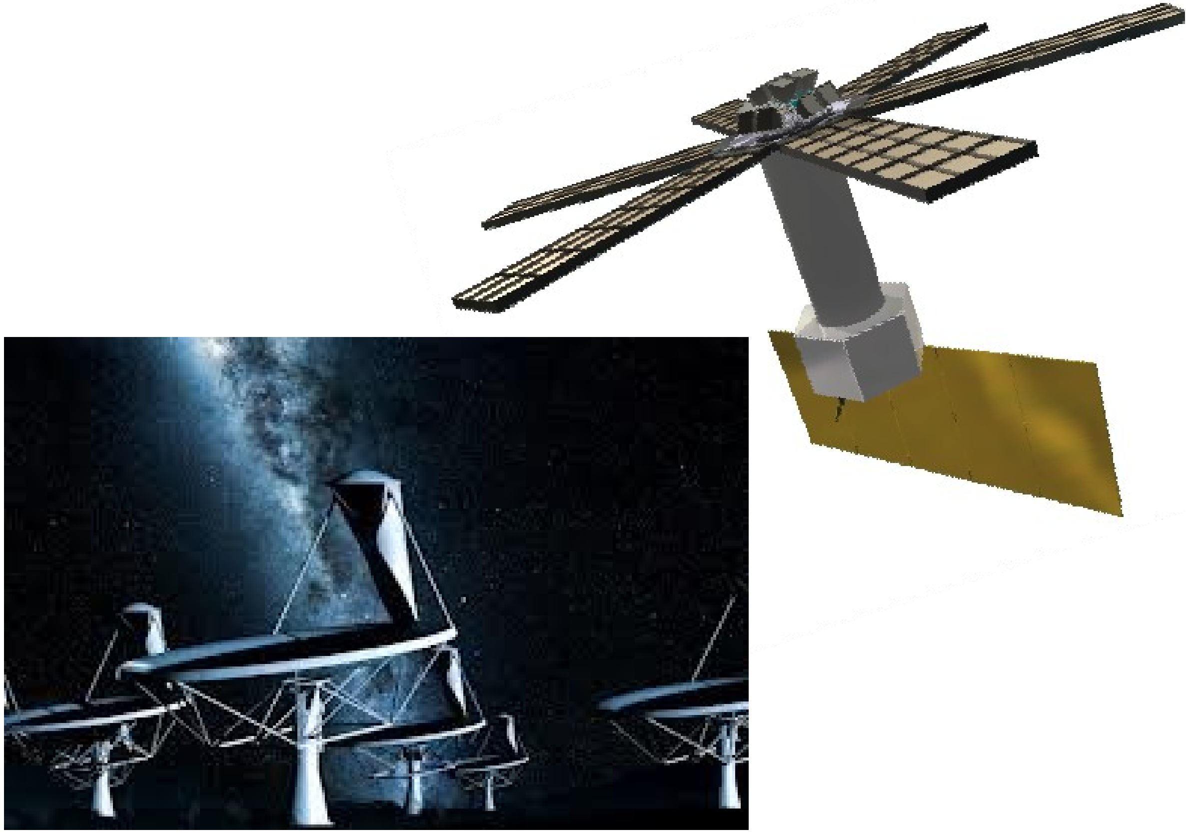
Proving the CEP with Compact Stars

David Blaschke (University of Wroclaw, Poland & JINR Dubna, Russia)

1. Goal: Find 1st order PT
2. Observation: M & R
3. Theory: QCD based EoS
4. Holy Grail: Twins !
5. Hot: BH formation
6. Future: LOFT, SKA, ...



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Goal 1: Measure the cold EoS !

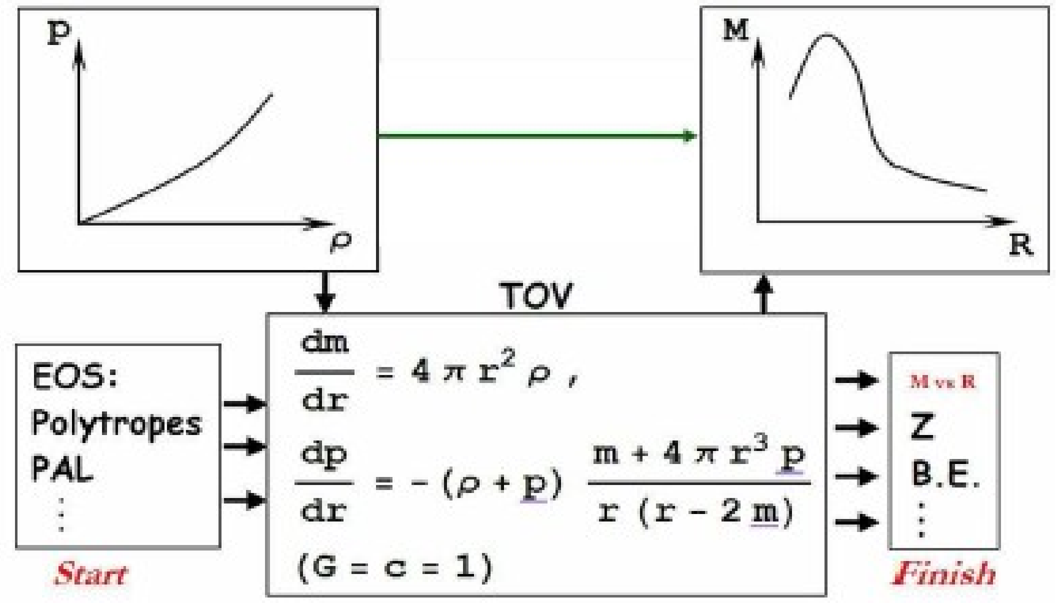
Direct approach:

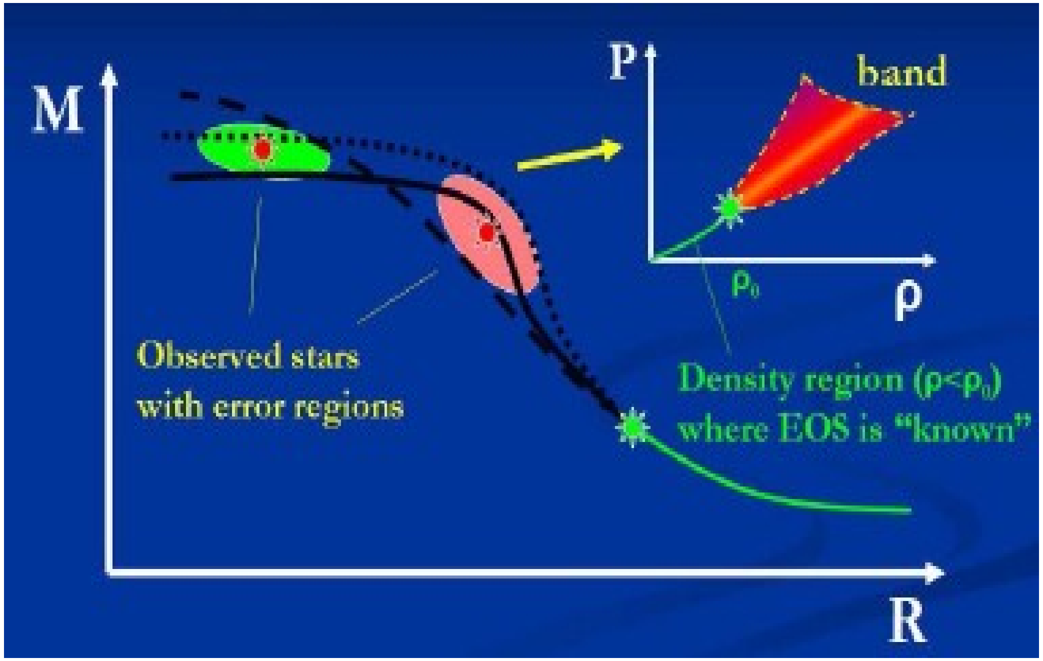
EoS is given as P(ρ)
→ solve the TOV Equation
to find M(R)

Idea: Invert the approach

Given M(R) → find the EoS

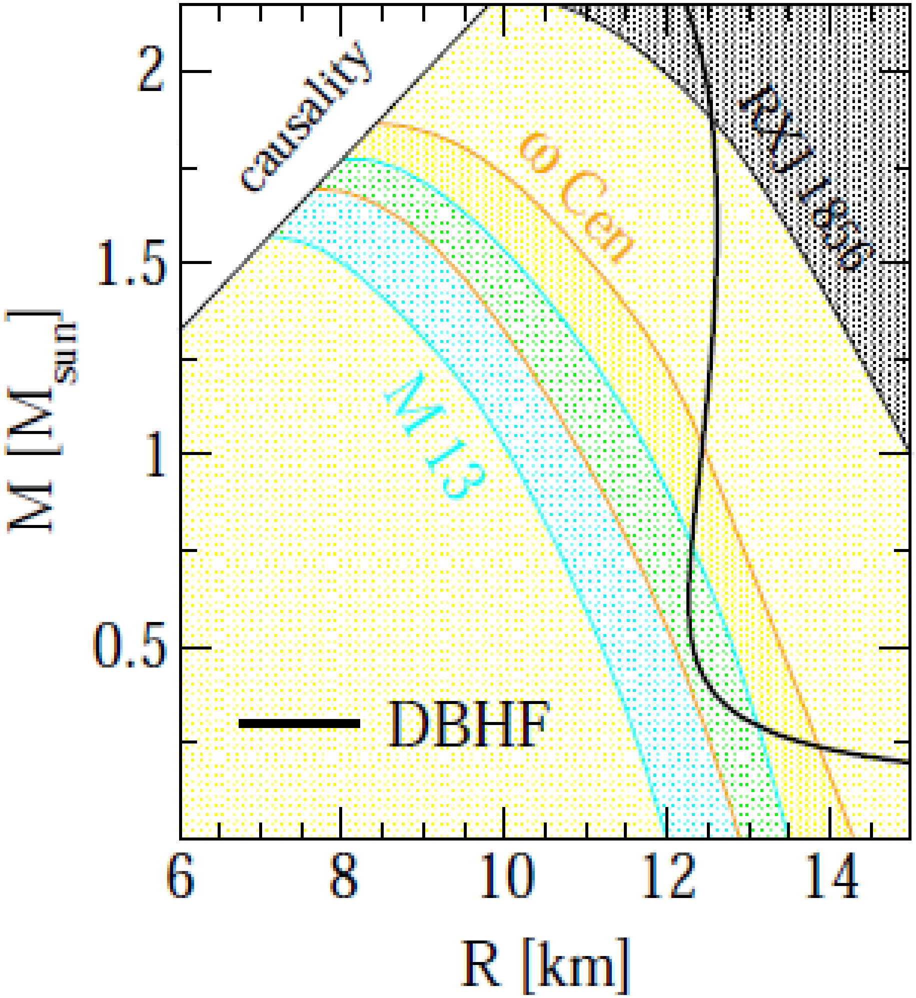
Bayesian analysis





Plots: M. Prakash, Talk Hirschegg 2009

Measure masses and radii of CS!



- Distance measured
- Spectrum measured (ROSAT, XMM, Chandra)
- Luminosity measured

→ effective temperature T_∞

→ photospheric radius

$$R_\infty = R/\sqrt{1 - R/R_S}\,, \quad R_S = 2GM/R$$

Object	R_∞ [km]	Reference
RXJ 1856	16.8	Trümper et al. (2004)
ωCen	13.6 ±0.3	Gendre et al. (2003)
M13	12.8 ±0.4	Gendre et al. (2004)

Lower limit from RXJ 1856 incompatible with ω Cen and M13 ?

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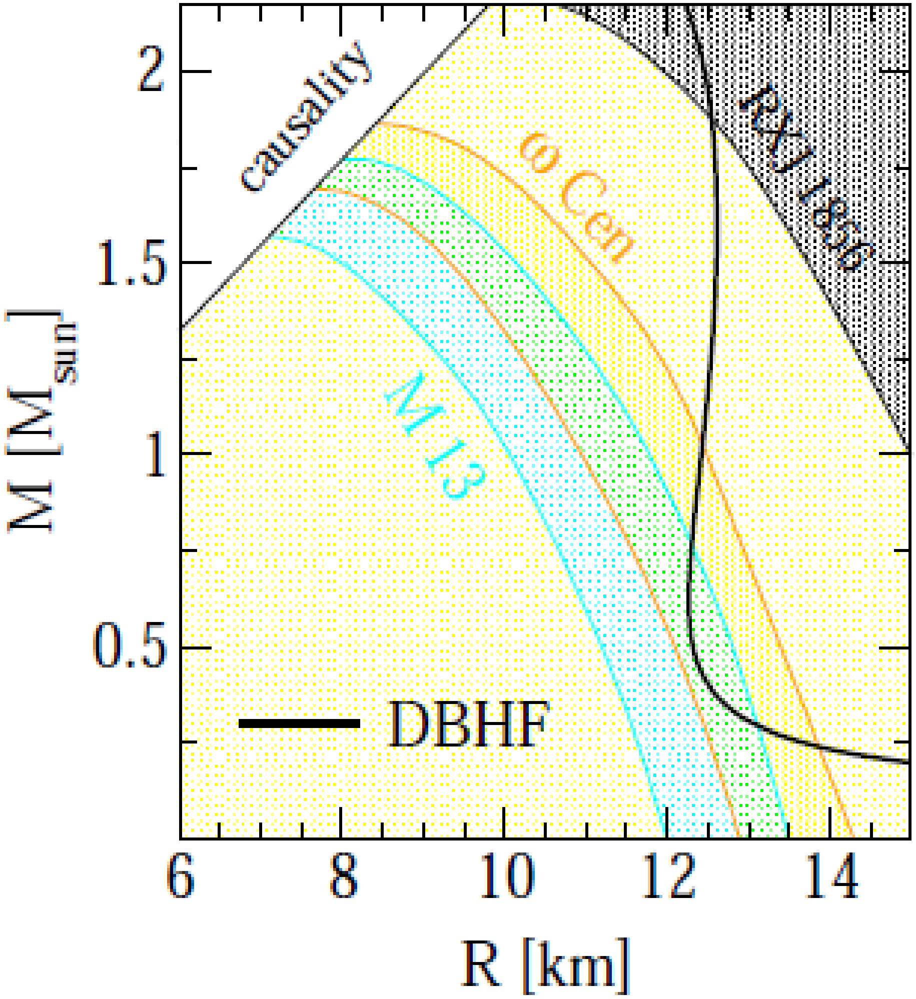

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Lower limit from RXJ 1856 incompatible with ω Cen and M13 ?

... unless the latter sources emit X-rays from “hot spots” → lower limit on R

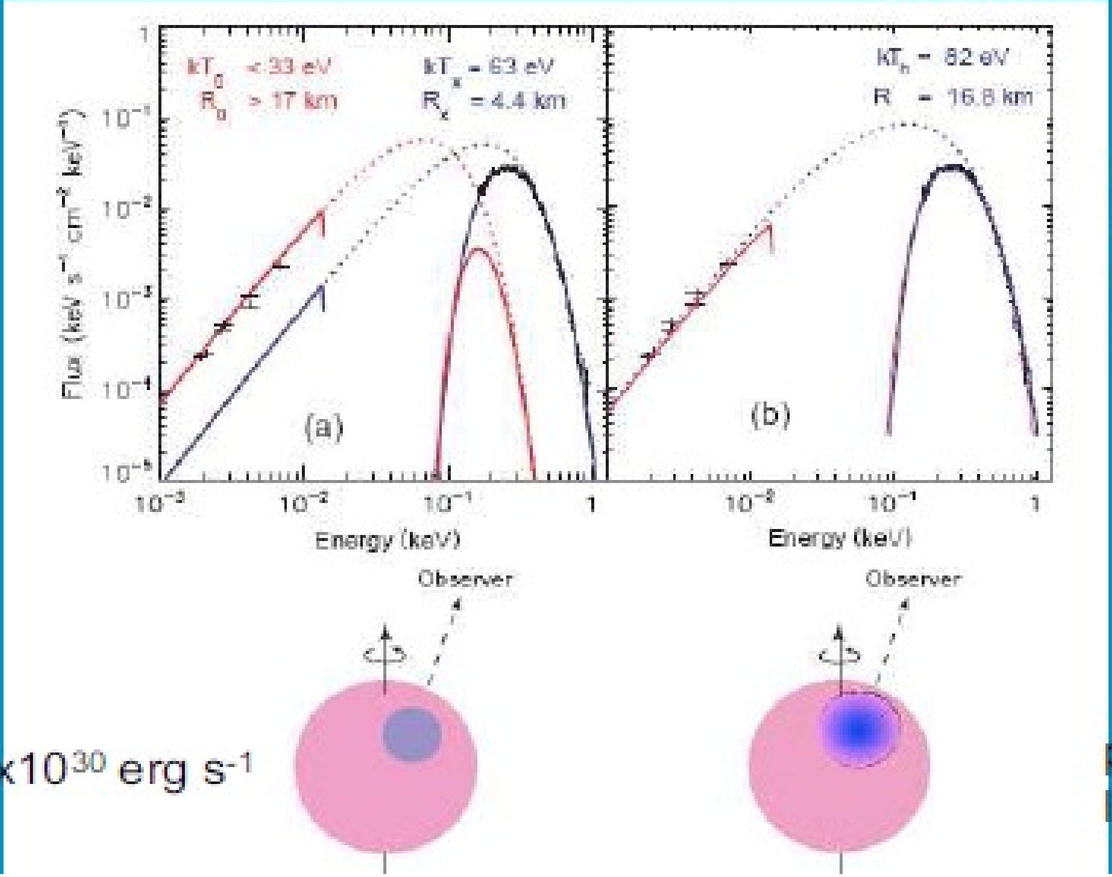
The lesson learned from RX J1856

blackbody fits to the optical and X-ray spectra of RX J1856.5-3754 (Trümper,2004)

radius determination ⇒ EoS ⇒ state of matter at high densities

two-component model

model with continuous T-distribution



completely featureless X-ray spectrum: condensed surface?
⇒ strong B?

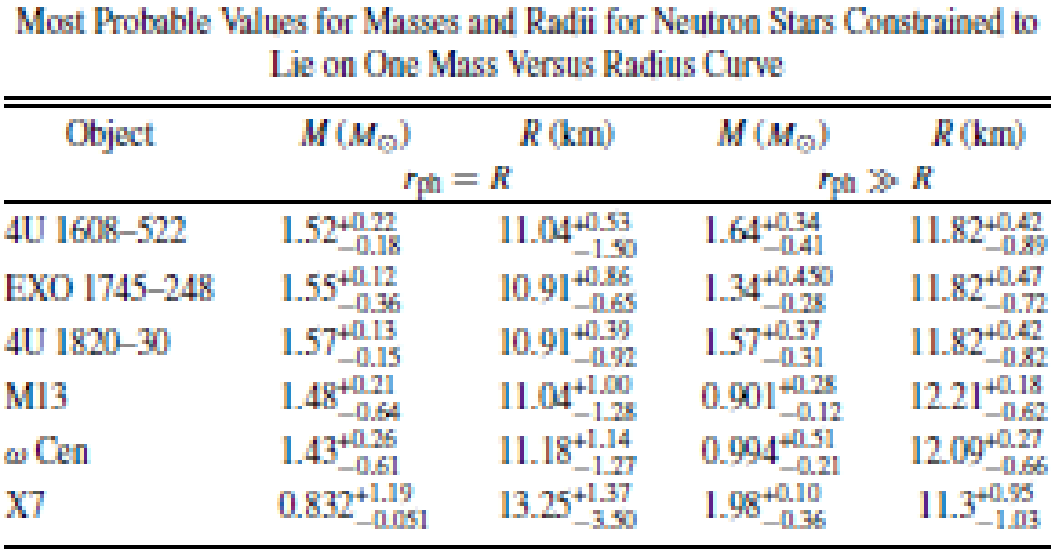
L_x =5.4x10^{30} erg s^{-1}

pulsed fraction < 1% ⇒
line of sight || rotation axis?

X-ray emitting region is a “hot spot”, J. Trumper et al., Nucl. Phys. Proc. Suppl. 132 (2004) 560

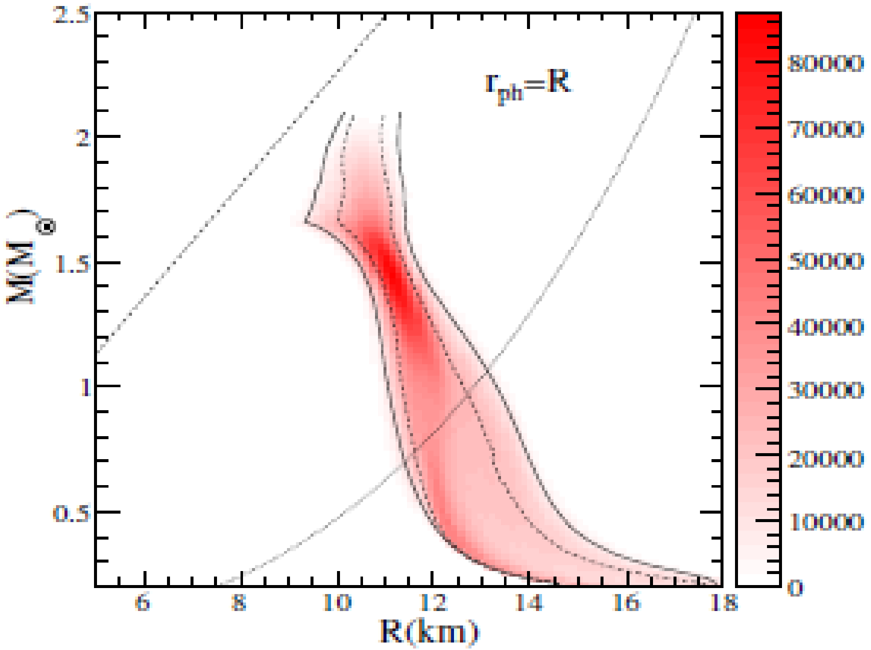
Goal 1: Measure the cold EoS !

Bayesian TOV analysis:
Steiner, Lattimer, Brown, ApJ 722 (2010) 33



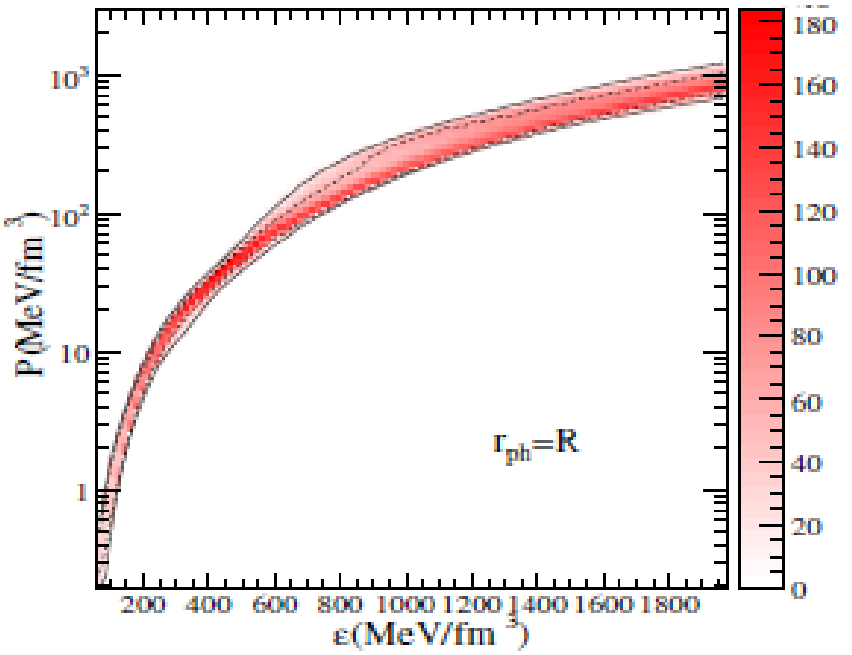
Most Probable Values for Masses and Radii for Neutron Stars Constrained to Lie on One Mass Versus Radius Curve

Object	$M\ (M_\odot)$	R (km)	$M\ (M_\odot)$	R (km)
	$r_{ph} = R$		$r_{ph} \gg R$	
4U 1608–522	$1.52^{+0.22}_{-0.18}$	$11.04^{+0.53}_{-1.50}$	$1.64^{+0.34}_{-0.41}$	$11.82^{+0.42}_{-0.89}$
EXO 1745–248	$1.55^{+0.12}_{-0.36}$	$10.91^{+0.86}_{-0.65}$	$1.34^{+0.450}_{-0.28}$	$11.82^{+0.47}_{-0.72}$
4U 1820–30	$1.57^{+0.13}_{-0.15}$	$10.91^{+0.39}_{-0.92}$	$1.57^{+0.37}_{-0.31}$	$11.82^{+0.42}_{-0.82}$
M13	$1.48^{+0.21}_{-0.64}$	$11.04^{+1.00}_{-1.28}$	$0.901^{+0.28}_{-0.12}$	$12.21^{+0.18}_{-0.62}$
ω Cen	$1.43^{+0.26}_{-0.61}$	$11.18^{+1.14}_{-1.27}$	$0.994^{+0.51}_{-0.21}$	$12.09^{+0.27}_{-0.66}$
X7	$0.832^{+1.19}_{-0.051}$	$13.25^{+1.37}_{-3.50}$	$1.98^{+0.10}_{-0.36}$	$11.3^{+0.95}_{-1.03}$



Caution:
If optical spectra are not measured, the observed X-ray spectrum may not come from the entire surface But from a hot spot at the magnetic pole!
J. Trumper, Prog. Part. Nucl. Phys. 66 (2011) 674

Such systematic errors are not accounted for in Steiner et al. → M(R) is a lower limit → softer EoS



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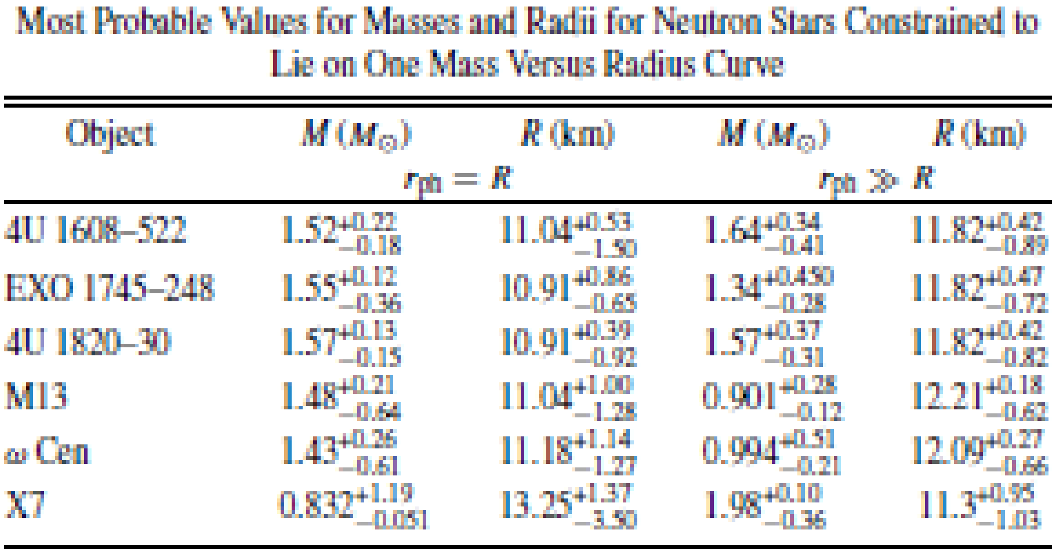

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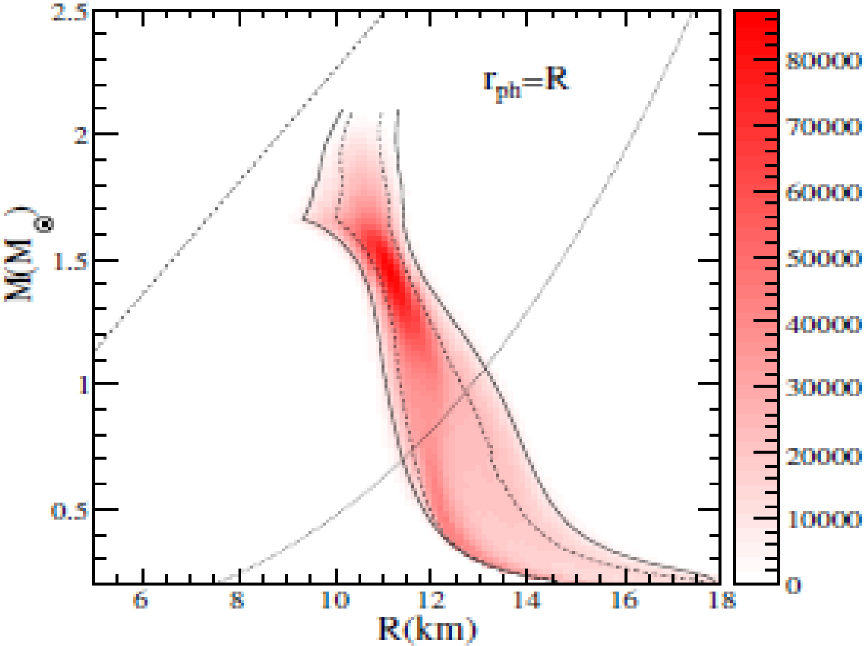
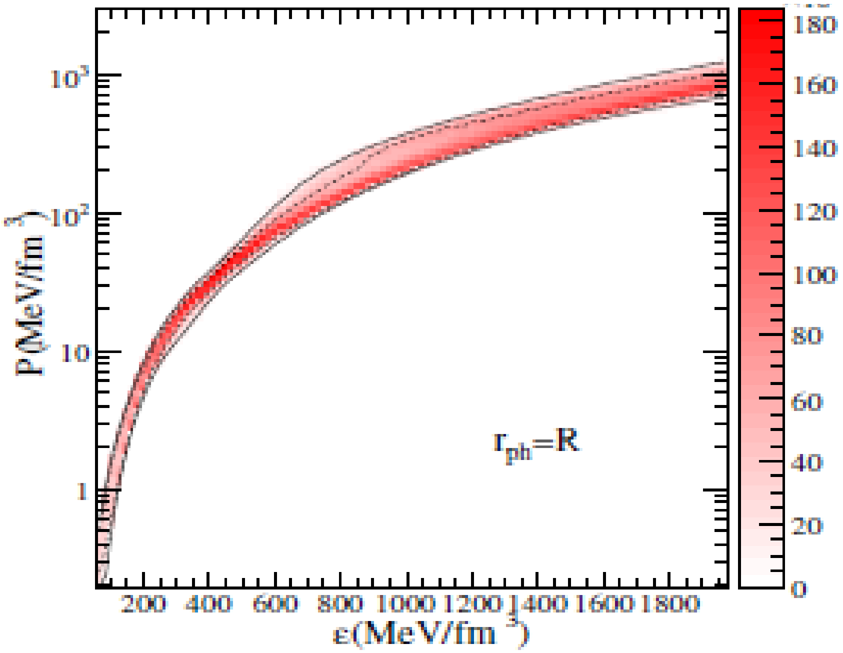
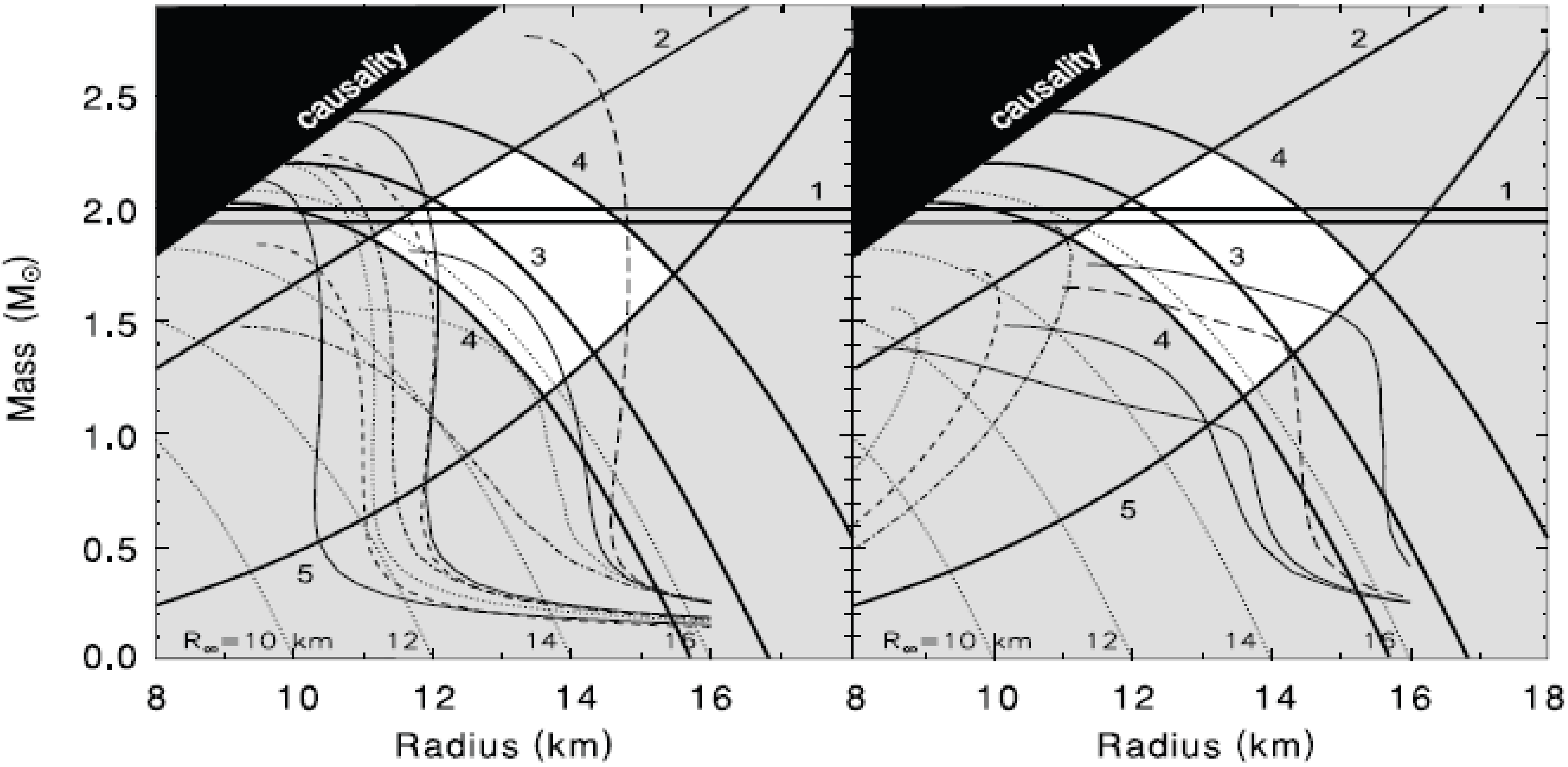




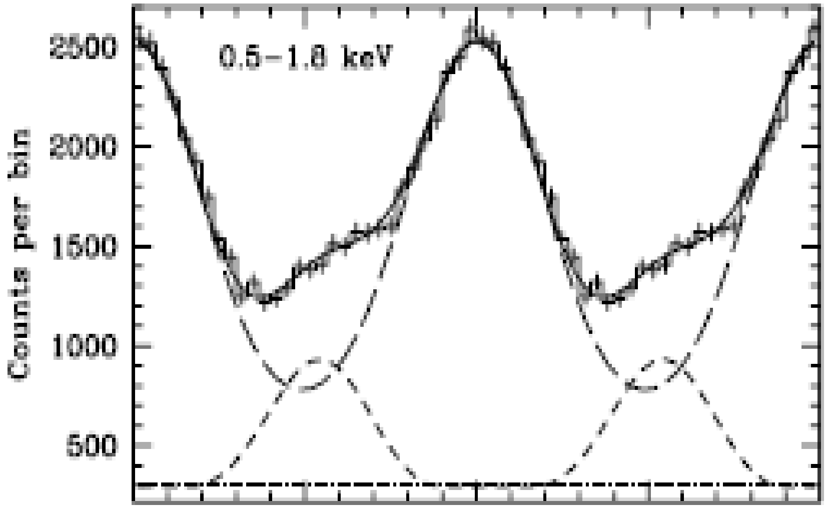
Which constraints can be trusted ?

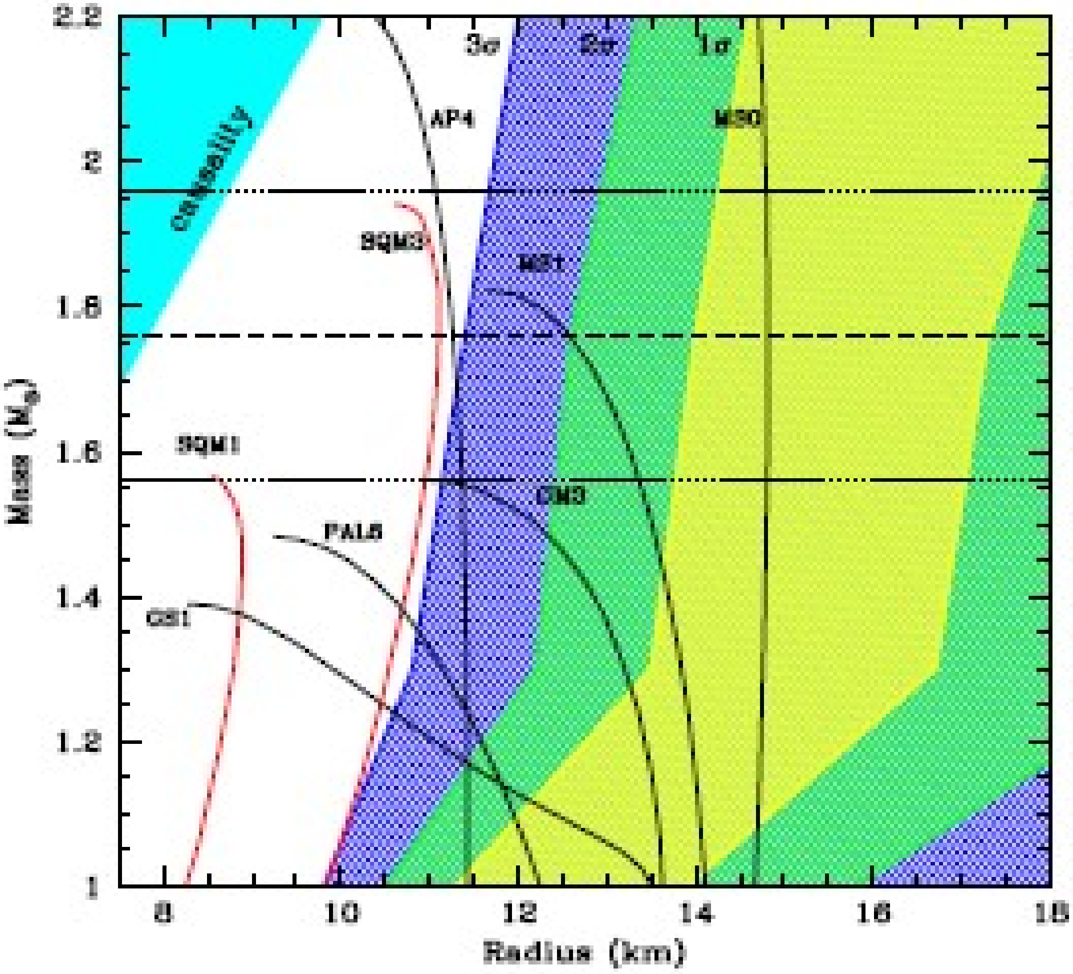


1 – Largest mass J1614 – 2230 (Demorest et al. 2010)
2 – Maximum gravity XTE 1814 – 338 (Bhattacharyya et al. (2005)
3 – Minimum radius RXJ 1856 – 3754 (Trumper et al. 2004)
4 – Radius, 90% confidence limits LMXB X7 in 47 Tuc (Heinke et al. 2006)
5 – Largest spin frequency J1748 – 2446 (Hessels et al. 2006)

Which constraints can be trusted ?

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 = 3x10^8 G



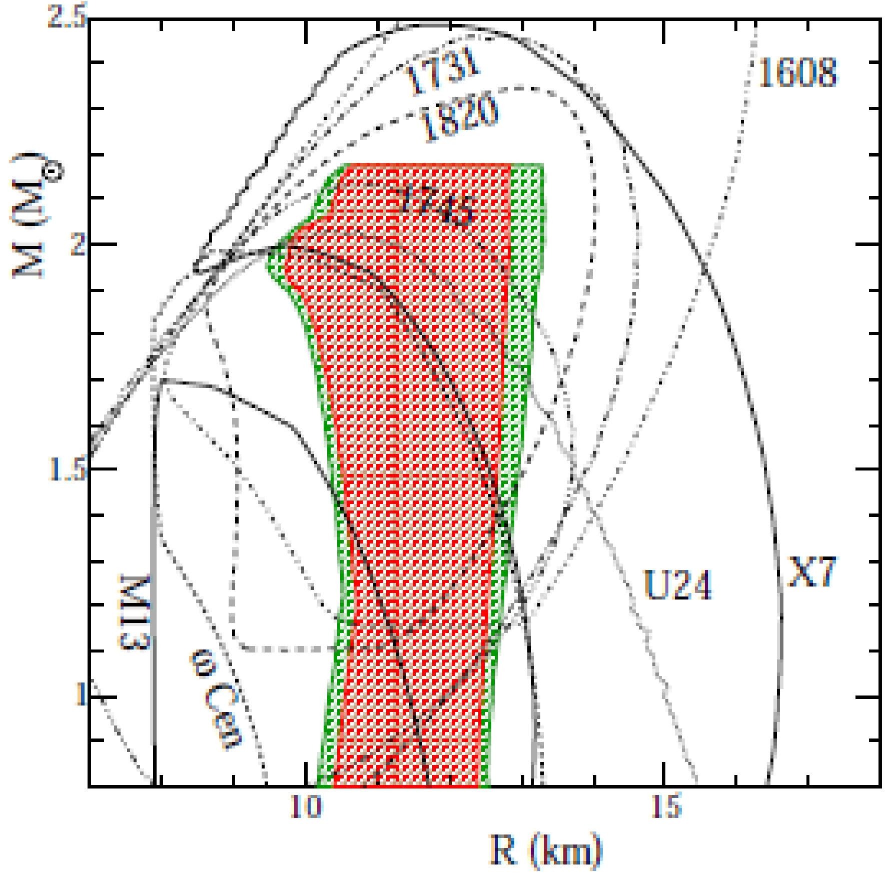


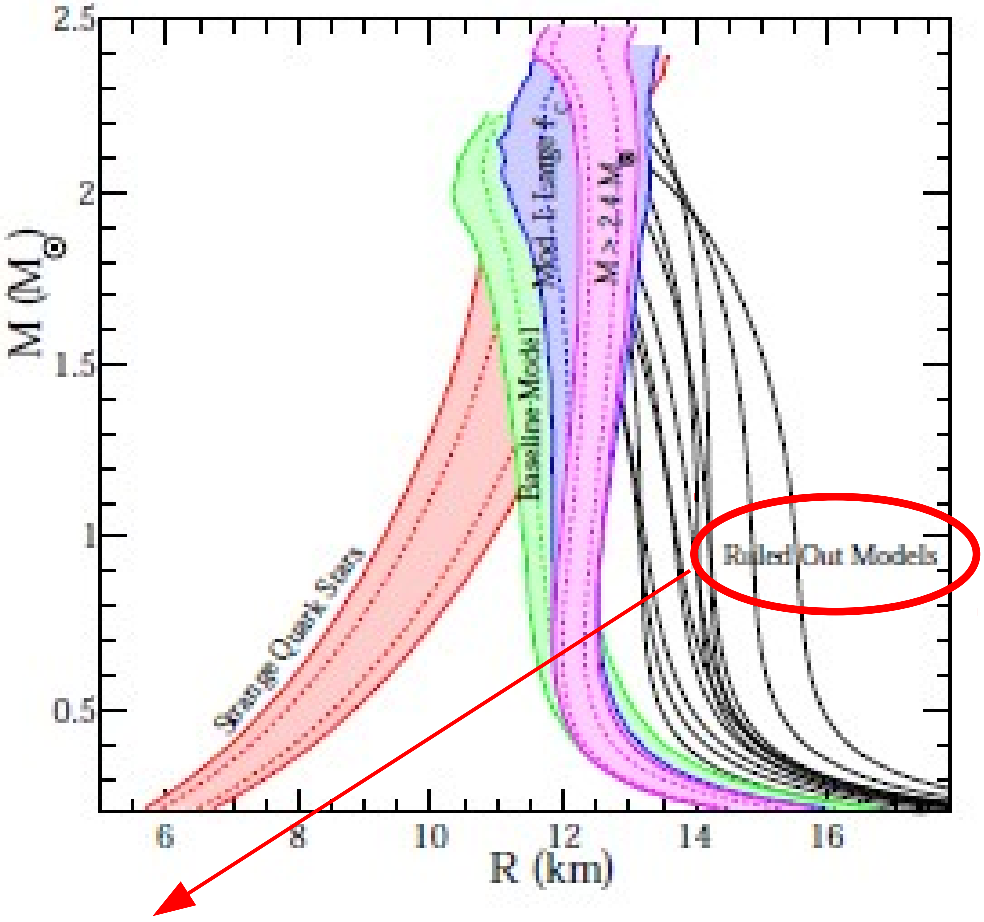
Three thermal component fit
R > 11.1 km (at 3 sigma level)
M = 1.76 M_sun

S. Bogdanov, arxiv:1211.6113 (2012)

Which constraints require caution ?

A. Steiner, J. Lattimer, E. Brown, ApJ Lett. 765 (2013) L5



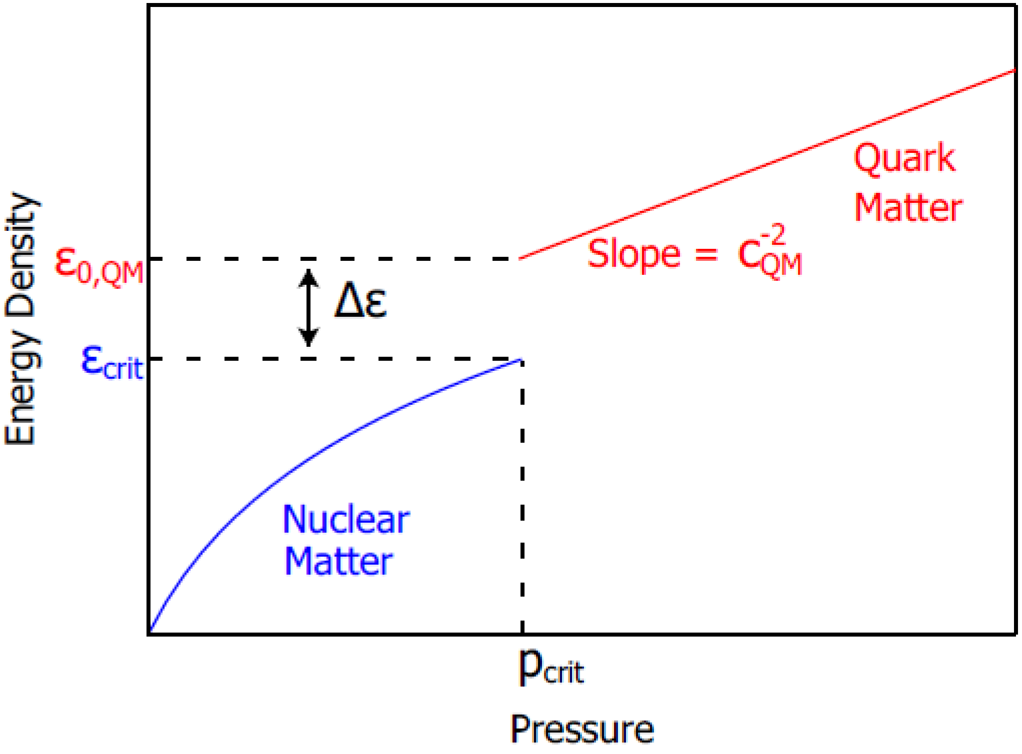


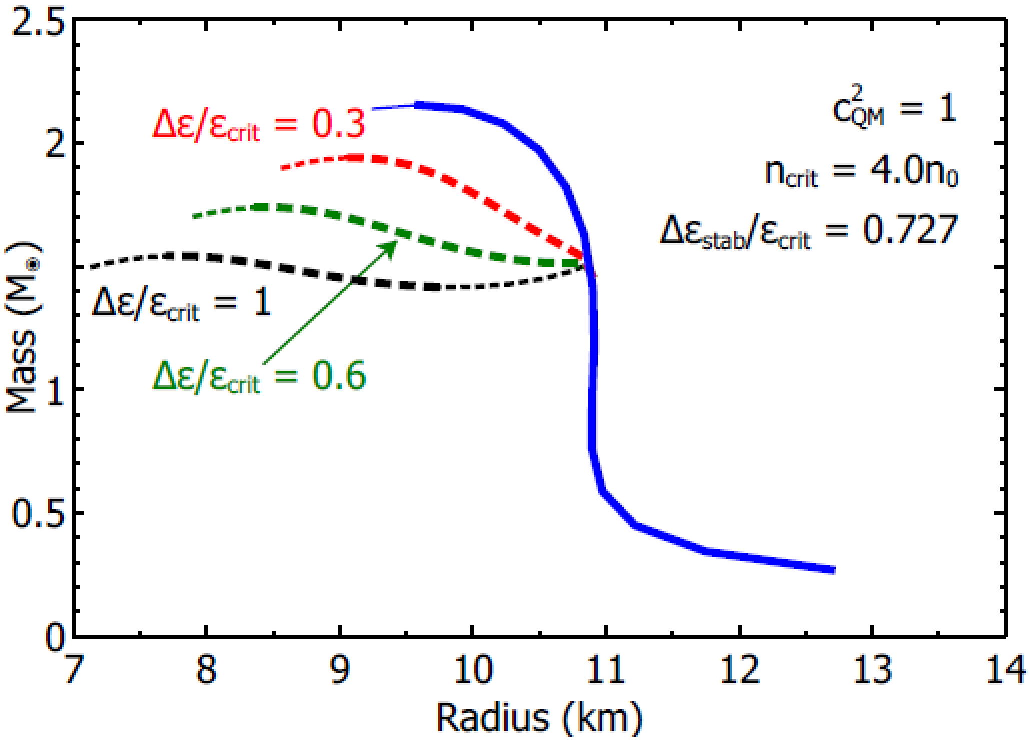
"Ruled out models" - too strong a conclusion!
M(R) constraint is a lower limit, which is itself included in that from RX J1856, which is one of the best known sources.

Goal 2: Be lucky – detect a 1st order PT

Alford, Han, Prakash, arxiv:1302.4732

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"**.

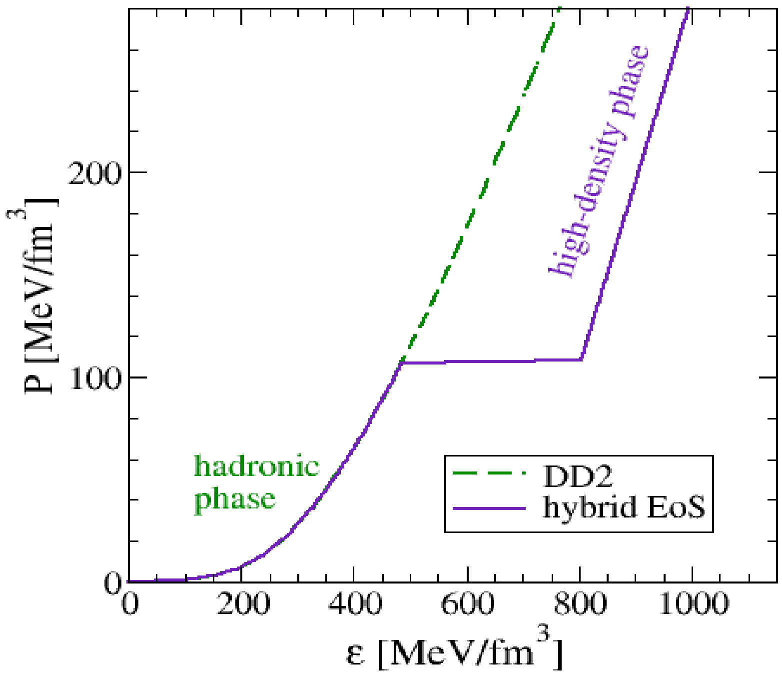


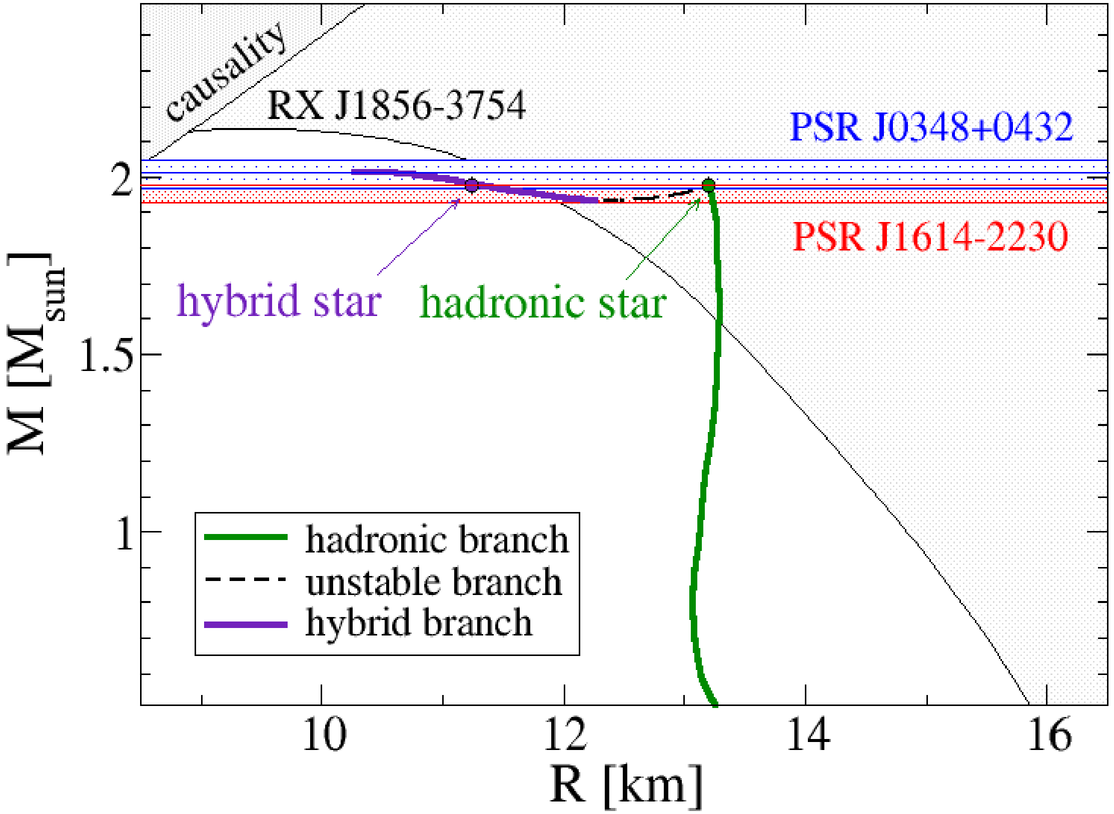


Measuring two **disconnected populations** of compact stars in the M-R diagram would be the **detection of a first order phase transition** in compact star matter and thus the indirect proof for the existence of a **critical endpoint (CEP) in the QCD phase diagram**!

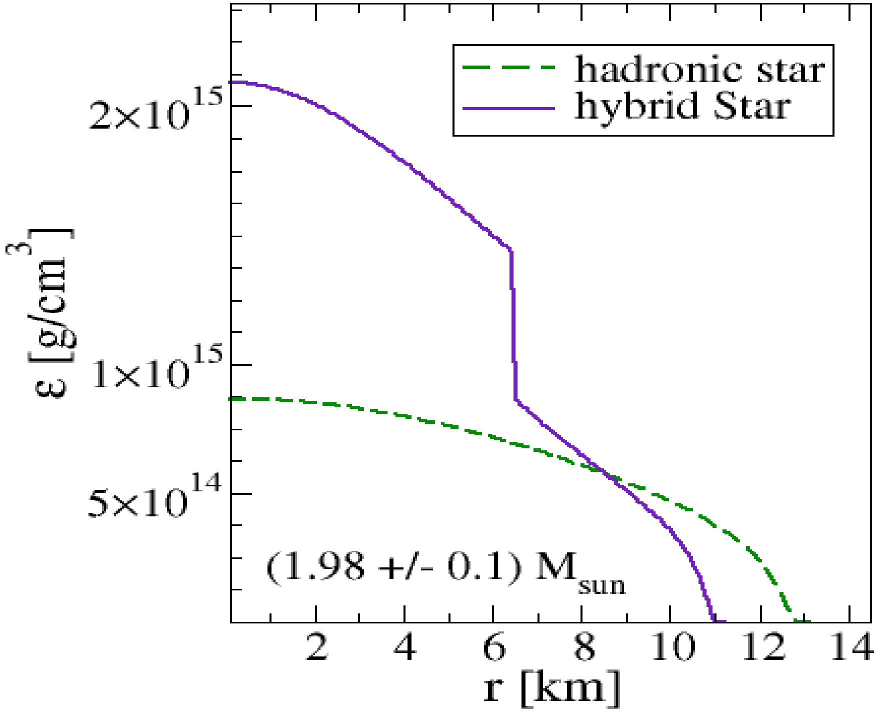
Goal 2: Observe High-Mass Twin Stars

Twins prove exitence of **disconnected populations**
(third family) in the M-R diagram
Consequence of a **first order phase transition**
Question: Do twins prove the 1st order phase trans.?





Alvarez & Blaschke, arxiv:1304.7758



A QCD-based hybrid EoS - nonlocal PNJL model

DB, Alvarez Castillo, Benic, Contrera, Lastowiecki, arxiv:1302.6275 (2012)

$$\mathscr{L} = \bar{q}(i\not{\partial} - m_0)q + \mathscr{L}_{\rm int} + \mathscr{U}(\Phi)\,,$$

$$\mathscr{L}_{\rm int} = -\frac{G_S}{2}\left[j_S(x)\,j_S(x) + j_P(x)\,j_P(x) - j_p(x)\,j_p(x)\right] - \frac{G_V}{2}\,j_V(x)\,j_V(x),$$

$$j_a(x) = \int d^4z\, g(z)\,\bar{q}\left(x+\frac{z}{2}\right)\Gamma_a\, q\left(x-\frac{z}{2}\right),\quad a = S,P,V\,,\quad (\Gamma_S,\Gamma_P,\Gamma_V) = (\mathbb{1}, i\gamma_5\vec{\tau}, \gamma_0)$$

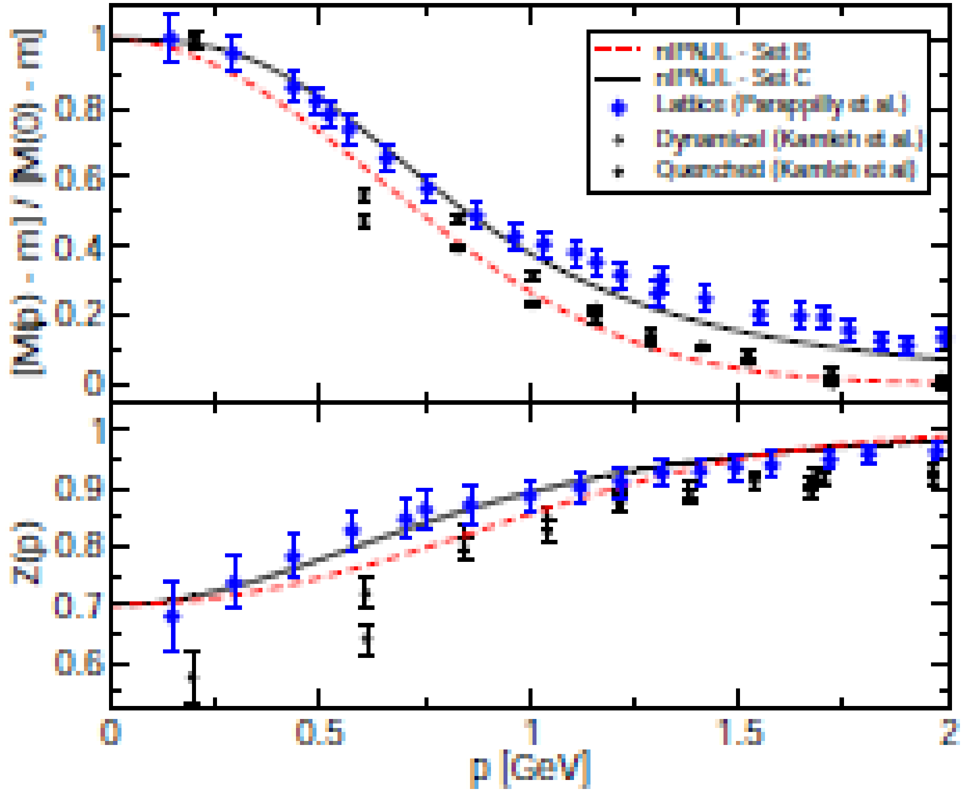
$$j_p(x) = \int d^4z\, f(z)\,\bar{q}\left(x+\frac{z}{2}\right)\frac{i\overleftrightarrow{\not{\partial}}}{2\,\kappa_p}\, q\left(x-\frac{z}{2}\right),\quad u(x')\overleftrightarrow{\partial}v(x) = u(x')\partial_x v(x) - \partial_{x'}u(x')\,v(x)$$

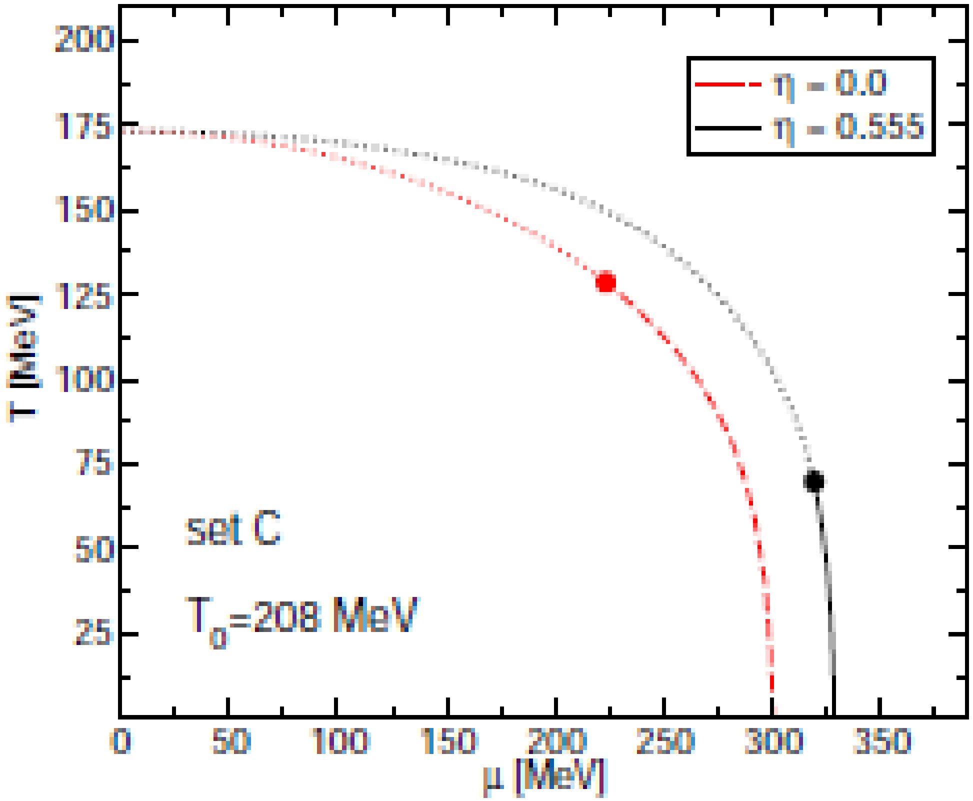
$$\mathscr{U}(\Phi, T, \mu) = (a_0 T^4 + a_1\mu^4 + a_2 T^2\mu^2)\Phi^2 + a_3 T_0^4 \ln(1 - 6\Phi^2 + 8\Phi^3 - 3\Phi^4)\,,$$

$$\boxed{\Omega^{\rm MFA} = -4T\sum_{n,c}\int\frac{d^3\vec{p}}{(2\pi)^3}\ln\left[\frac{(\tilde{\rho}^c_{n,\vec{p}})^2 + M^2(\rho^c_{n,\vec{p}})}{Z^2(\rho^c_{n,\vec{p}})}\right] + \frac{\sigma_1^2 + \kappa_p^2\,\sigma_2^2}{2\,G_S} - \frac{\omega^2}{2G_V} + \mathscr{U}(\Phi, T)\,,}$$

$$M(p) = Z(p)\,[m + \sigma_1\, g(p)]\,,\quad Z(p) = [1 - \sigma_2\, f(p)]^{-1}\,.\quad \tilde{\mu} = \mu - \omega\, g(p)\, Z(p)\,.$$

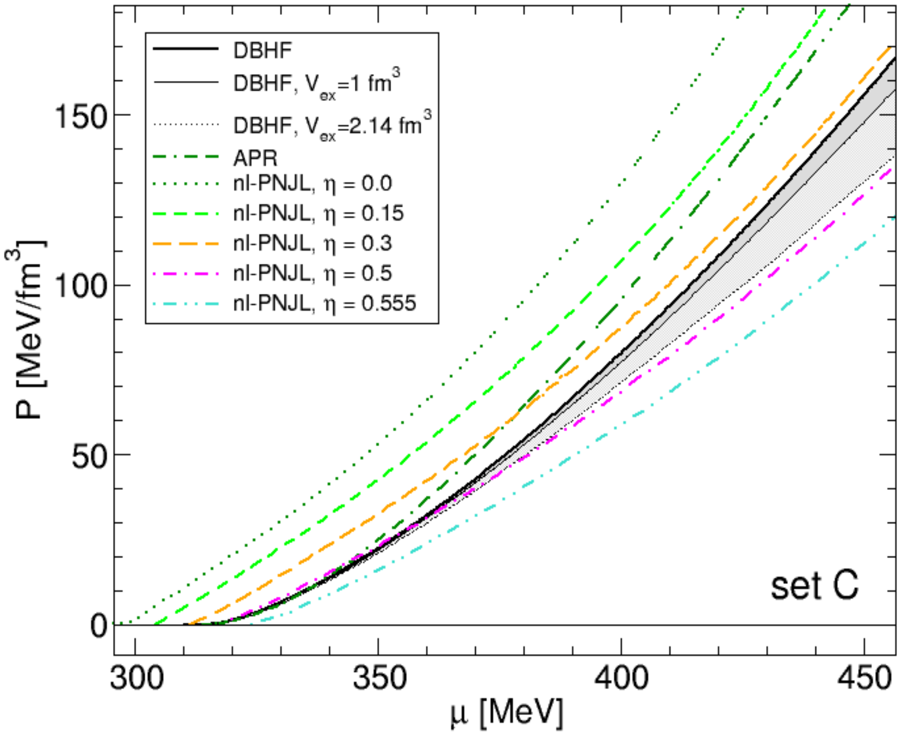
A QCD-based hybrid EoS

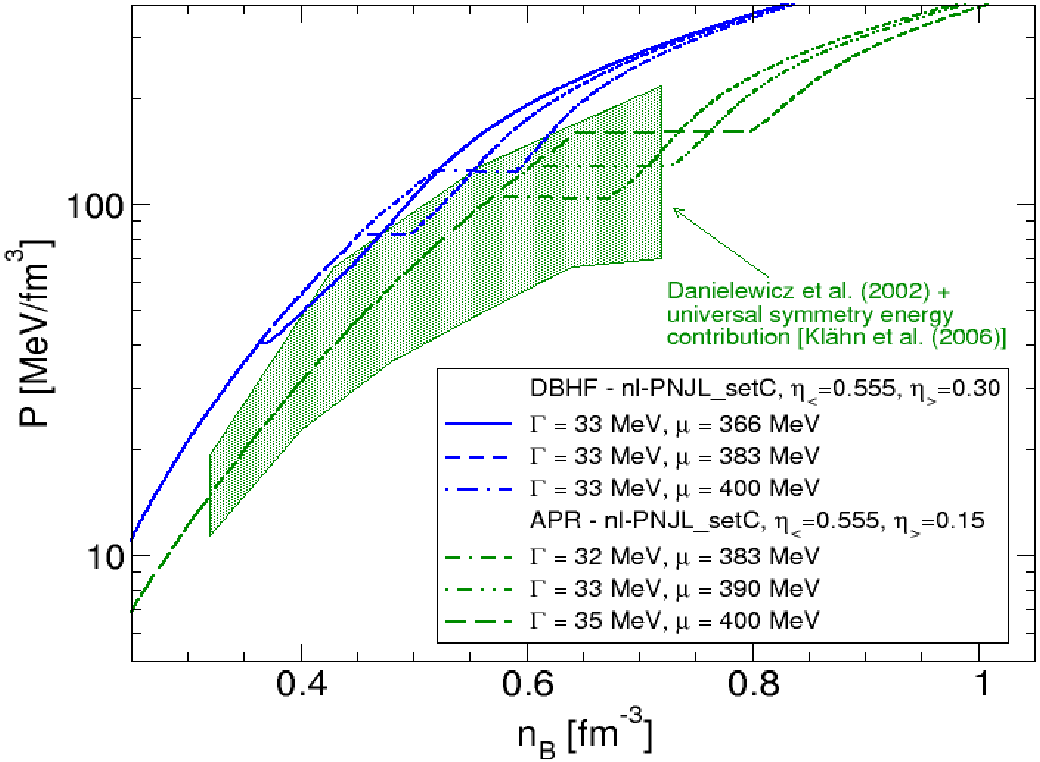




- Formfactors of the nonlocal chiral quark model fixed by comparison with M(p) and Z(p) from lattice QCD calculations of the quark propagator [Parapilly et al. PRD 73 (2006)
- Vector coupling strength adjusted to describe the slope of the pseudocritical temperature In accordance with lattice QCD [Kaczmarek et al., PRD 83 (2011) 014504]
- CEP does not vanish !! Controversial discussion, see Hell et al., arxiv:1212.4017 (2012)

A QCD-based hybrid EoS





- for strong vector coupling nuclear matter is stable at low densities
- for small vector coupling quark matter is stable at high densities
- for intermediate couplings → masquerade problem [Alford et al. ApJ 629 (2005) 969]

Here:

(A) Maxwell construction

$$P_Q(\mu_c) = P_H(\mu_c)$$

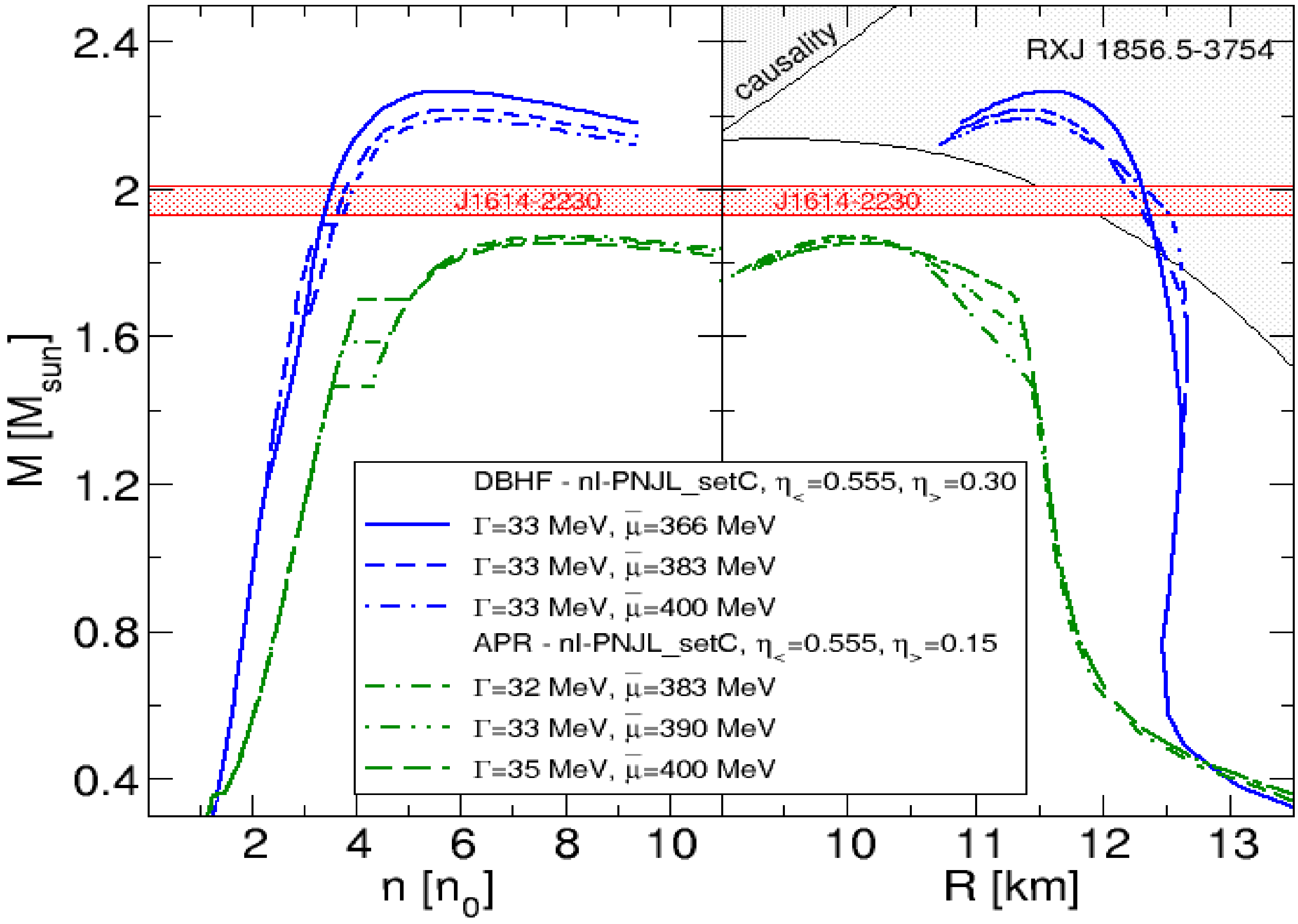
H = DBHF, APR; Q = nl-PNJL

(B) mu-dependent vector coupling:

$$P_Q(\mu) = P(0,\mu;\eta_<)\, f_<(\mu) + P(0,\mu;\eta_>)\, f_>(\mu)\,,$$

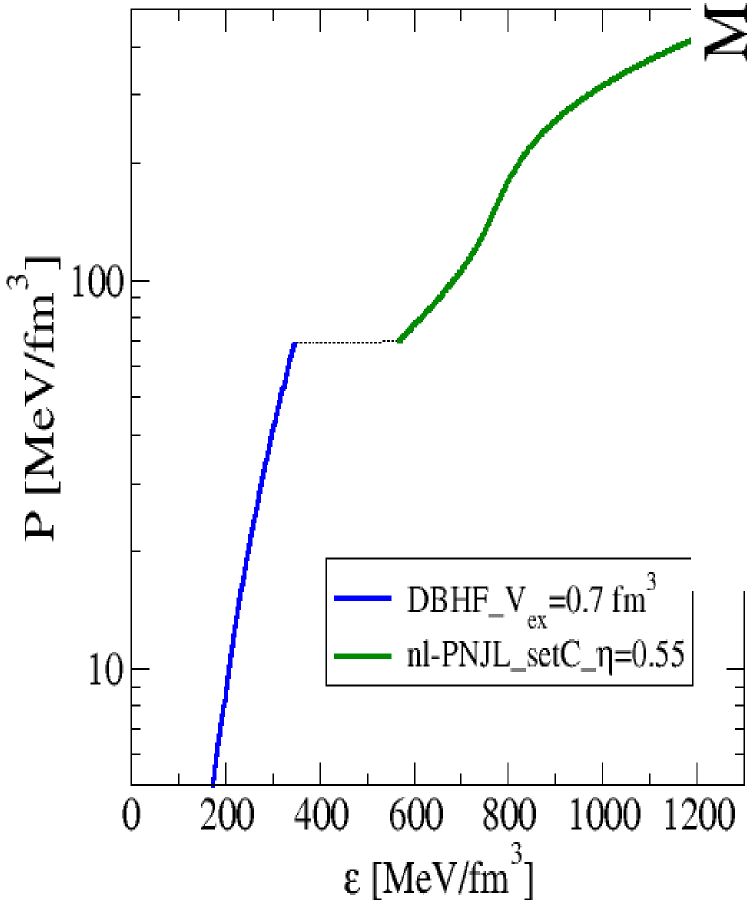
$$f_{\lessgtr}(\mu) = \frac{1}{2}\left[1 \mp \tanh\left(\frac{\mu-\bar{\mu}}{\Gamma}\right)\right]\,.$$

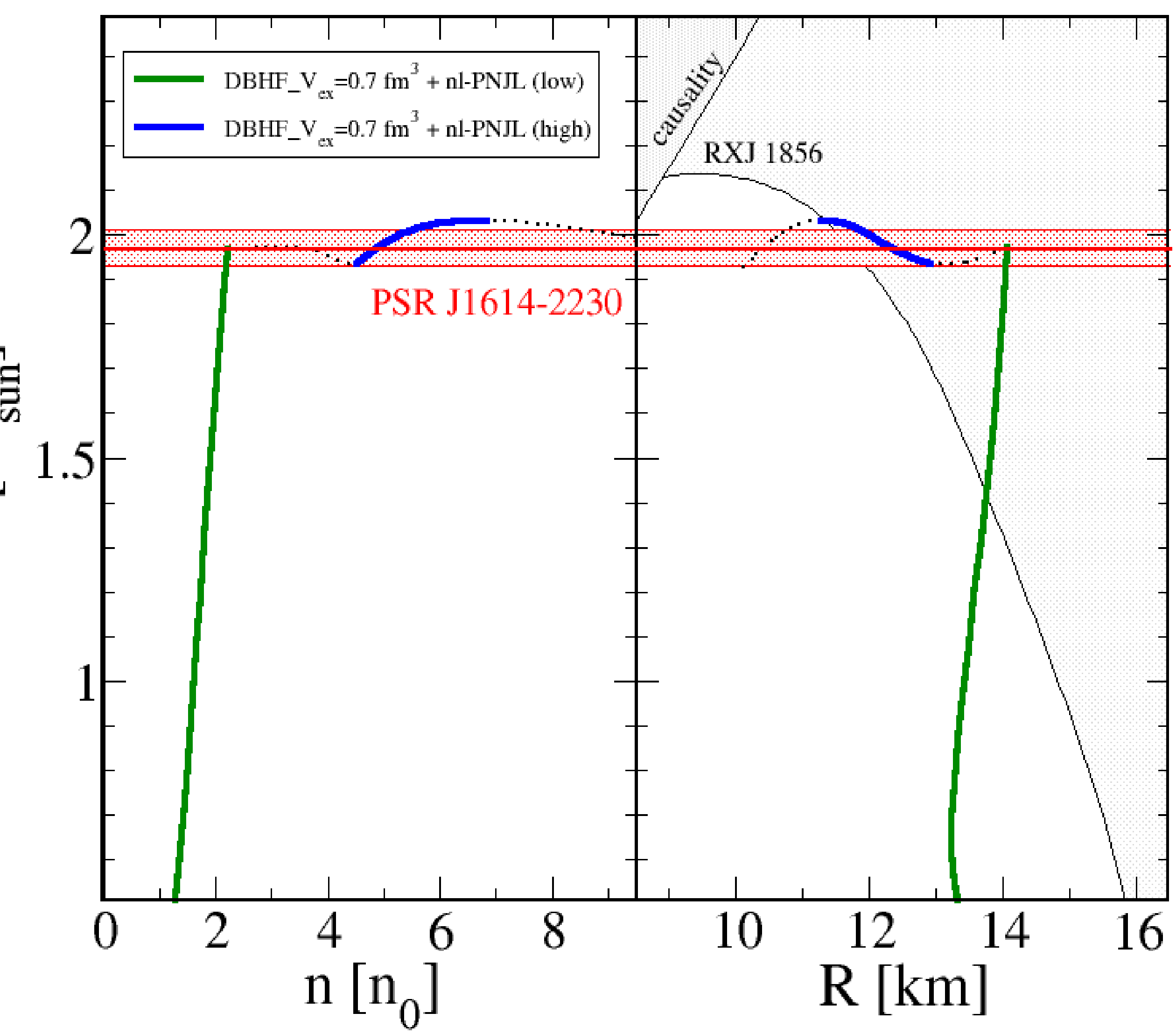
Result 1: hybrid stars fulfill Demorest and RXJ1856



DB, Alvarez Castillo, Benic, Contrera, Lastowiecki, arxiv:1302.6275 (2012)

Result 2:
High mass twins
are possible !



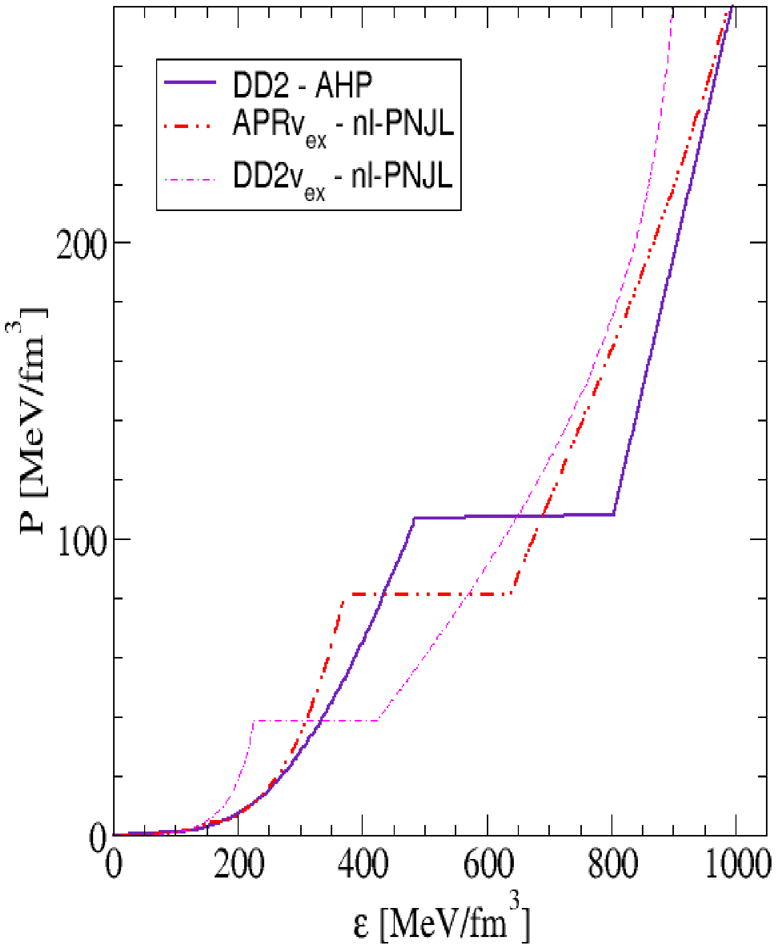


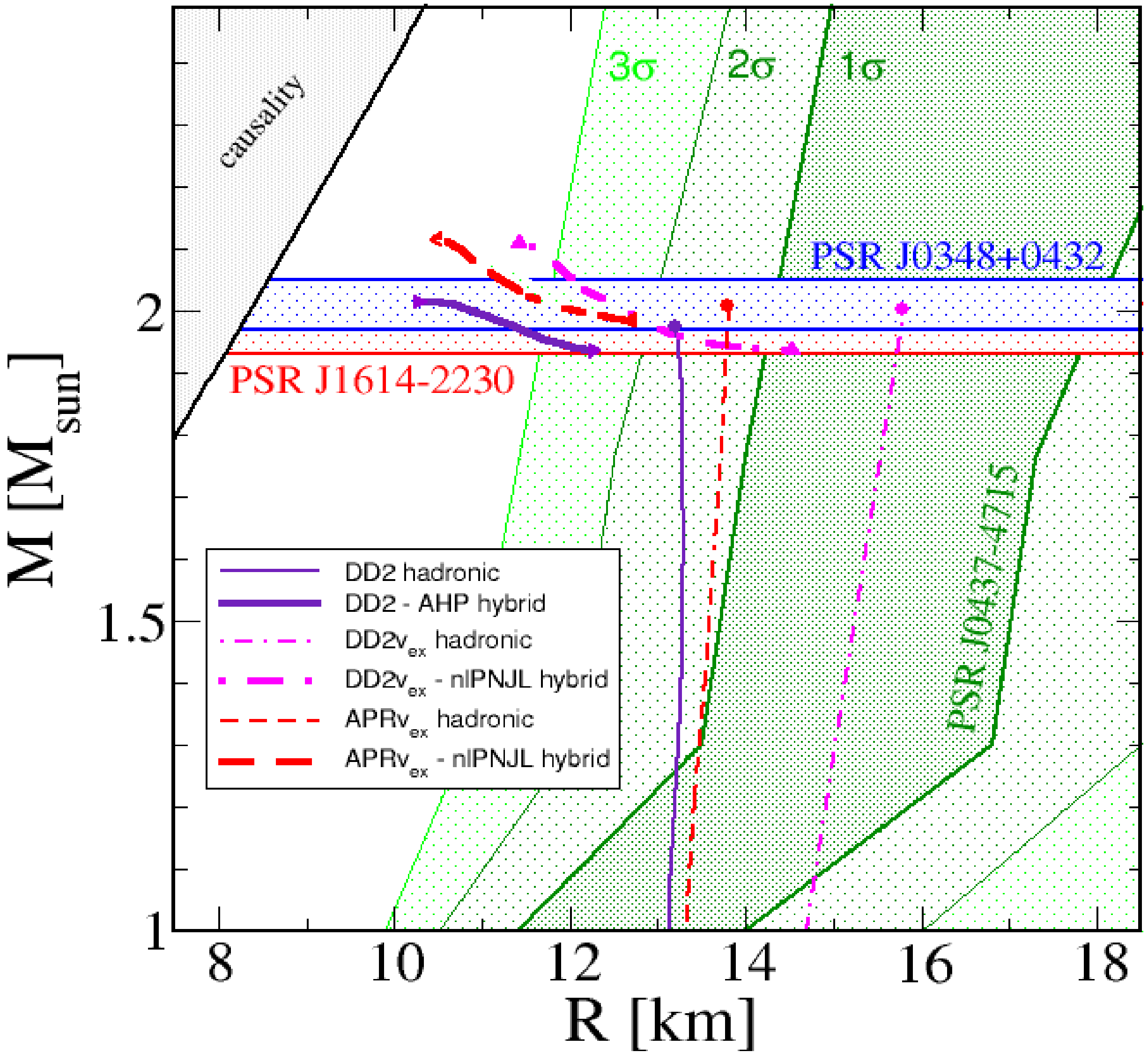
SUMMARY:

- excluded volume (quark Pauli blocking) in DBHF
- high-density quark matter slightly stiffer eta_v=0.25
- the scaled energy density jump (0.65) fulfills the twin condition of the schematic model by Alford et al. (2013)

→ **Find the disconnected star branches !!**

Result 3:
High mass twins:
more examples !





DB, Alvarez, Benic, arxiv: tomorrow

SUMMARY:

- excluded volume (quark Pauli blocking) important
- high-density quark matter slightly stiffer eta_v=0.25
- the scaled energy density jump (0.65) fulfills the twin condition of the schematic model by Alford et al. (2013)

→ Astronomers: Find disconnected star branches !!

Main Problem:
Measure Compact Star Radii!

Gravitational binding: double pulsar J0737-3039

Double Pulsar System J0737-3039

Pulsar A $P^{(A)}$ = 22.7 ms, $M^{(A)} \approx 1.338 M_\odot$

Pulsar B $P^{(B)}$ = 2.77 s, $M^{(B)} = 1.249 \pm 0.001 M_\odot$ (record!)

Progenitor ONeMg white dwarf, driven hydrodyn. unstable by

e^- captures on Mg & Ne; no mass-loss during collapse

Observational constraint for $M(M_N)$ from PSR J0737-3039:

- observed NSs gravitational mass (remnant star) $M^{(B)} = 1.248 - 1.250 M_\odot$
- critical baryon mass for ONeMg white dwarf $M_N^{(B)} = 1.366 - 1.375 M_\odot$

Theory: $M(M_N)$ characteristic for remnants EoS

$M = 4\pi \int_0^R \mathrm{d}r r^2 \varepsilon(r)$;

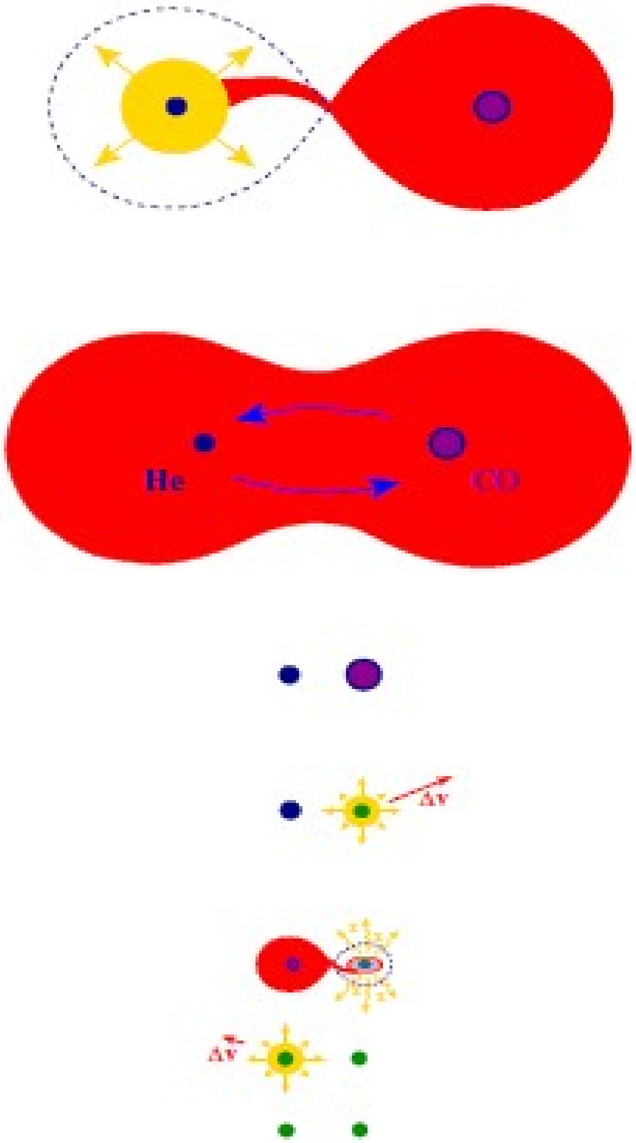
$M_N = u N_B = 4\pi u \int_0^R \mathrm{d}r \frac{r^2 n(r)}{\sqrt{1-2GM(r)/r}}$

(conversion of baryon number to mass by $u = 931.5$ MeV)

P. Podsiadlowski et al., Mon. Not. Roy. Astron. Soc. **361**, 1243 (2005)

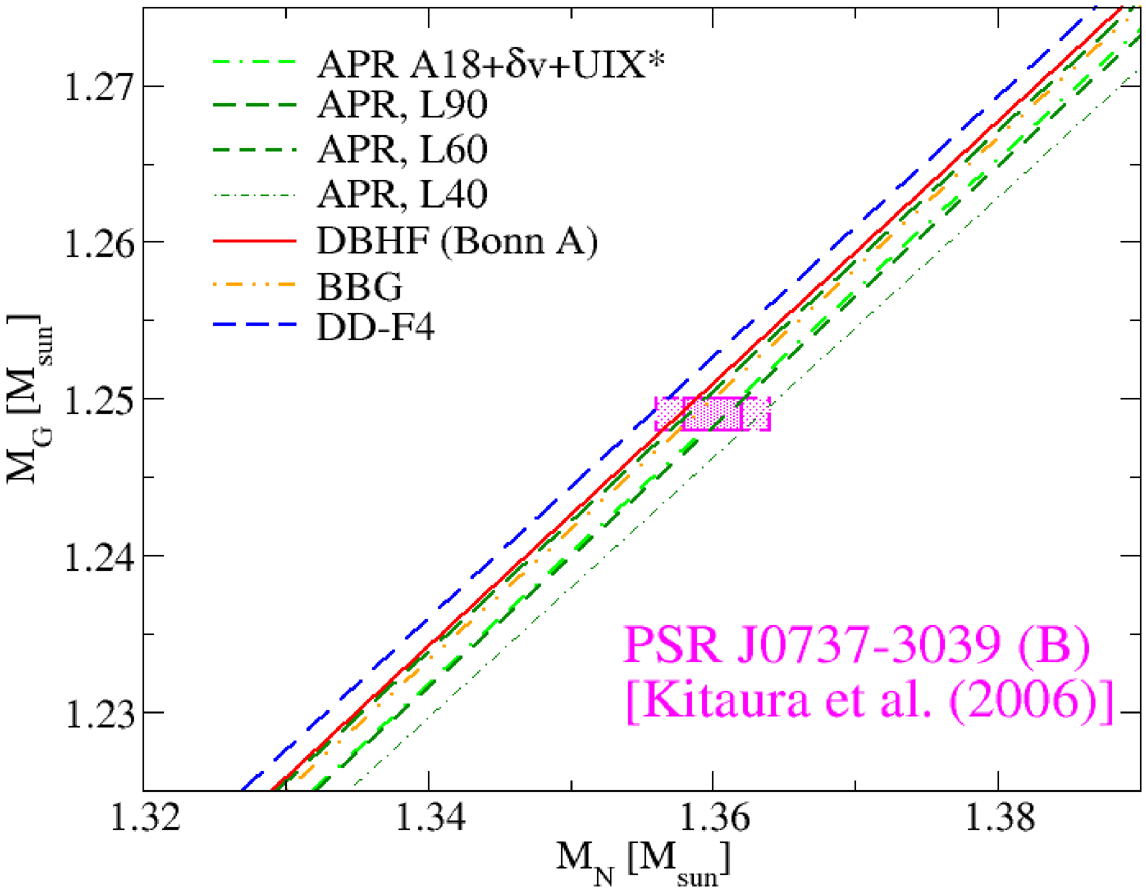
EoS constraint: double pulsar J0737-3039

Double core scenario:



Dewi et al., MNRAS (2006)

Baryon mass vs. gravitational mass - constraint or consistency check?

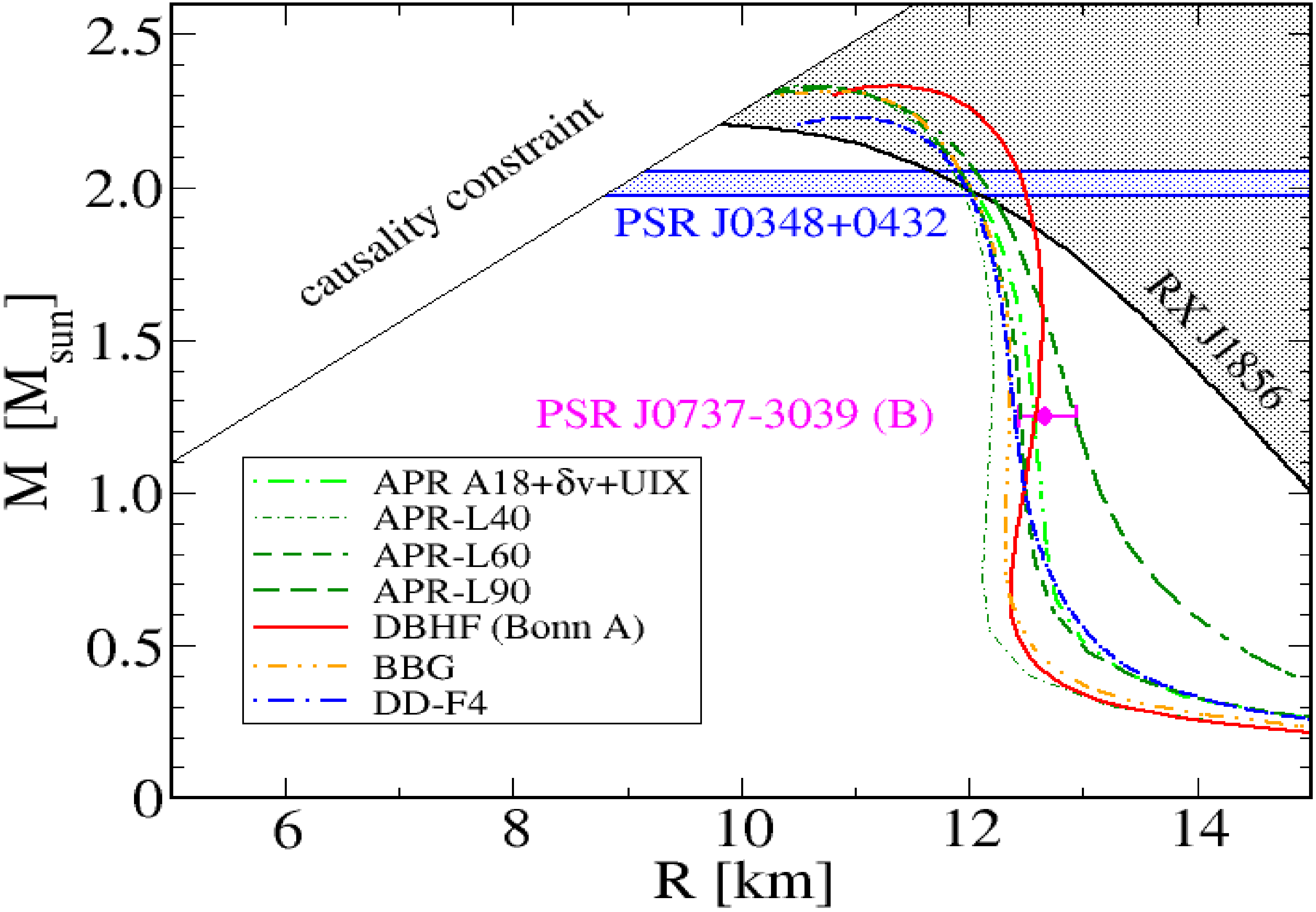


Podsiadlowski et al., MNRAS 361 (2005) 1243

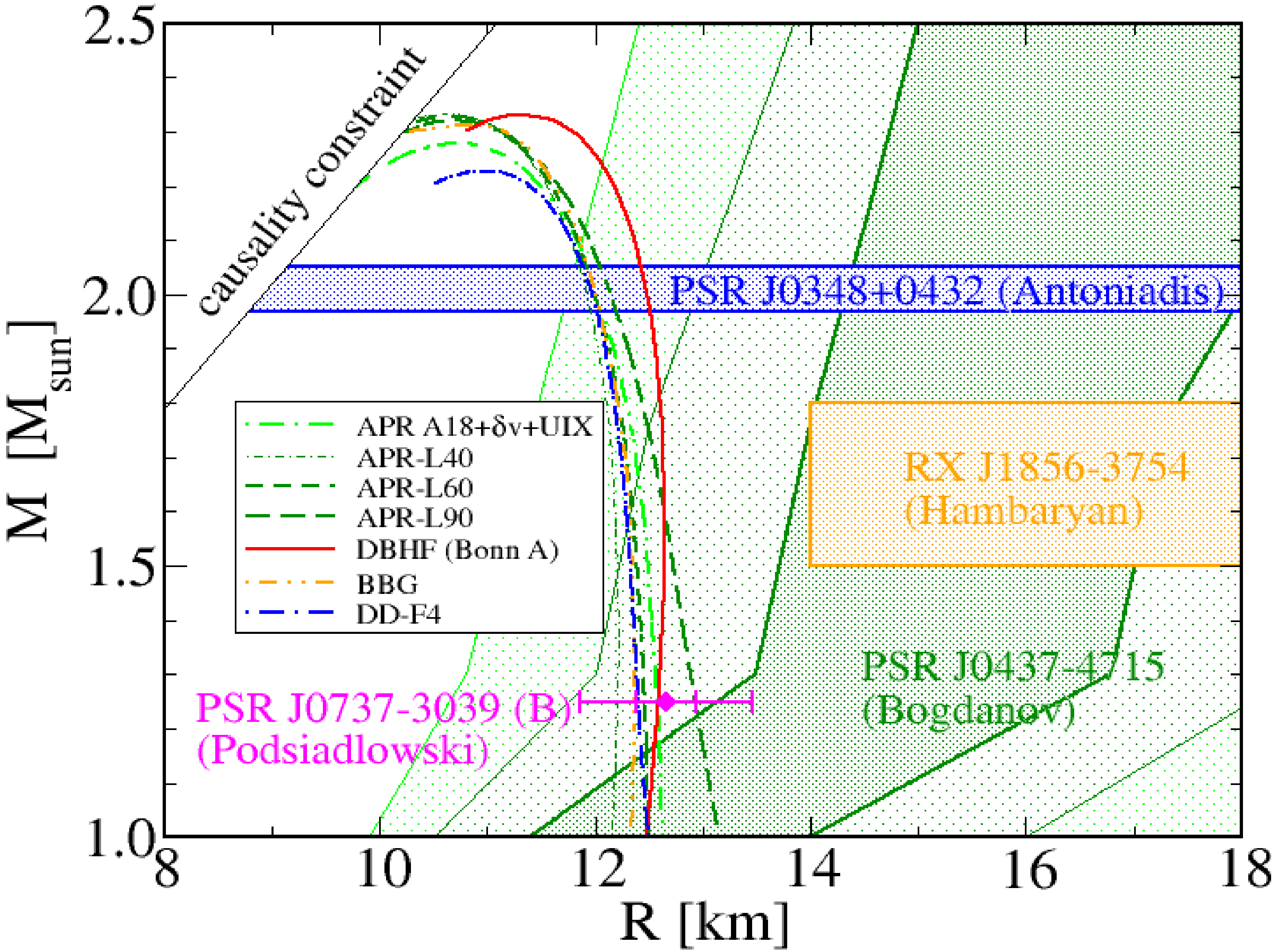
Kitaura, Janka, Hillebrandt, A& A (2006); [astro-ph/0512065]

D.B., T. Klähn, F. Weber, CBM Physics Book (2008)

Double pulsar: mass & radius ?!



Disjunct M-R constraints for Bayesian analysis !



Alvarez, Ayriyan, Blaschke, Grigorian, … (work in progress, 2013)

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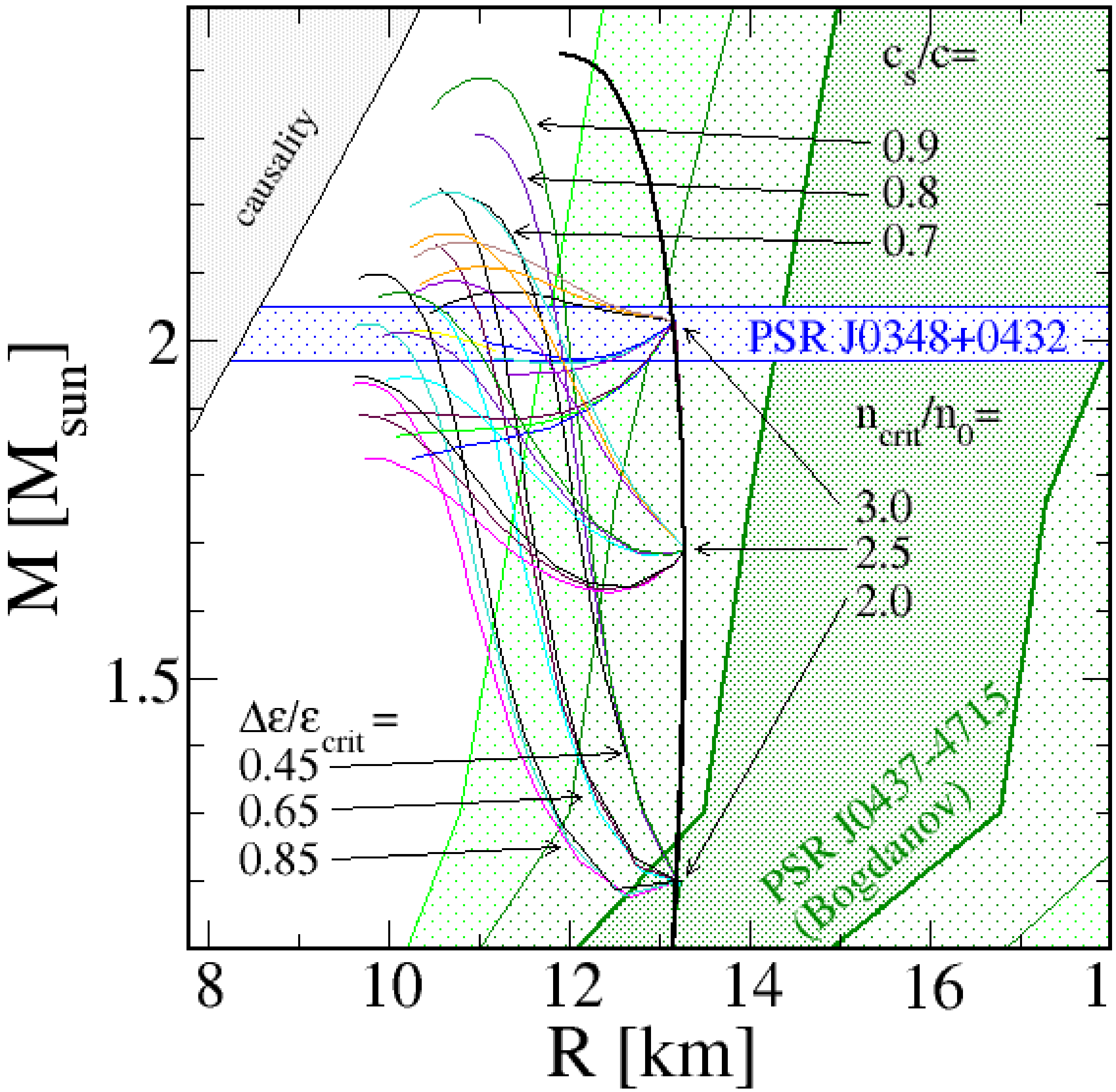

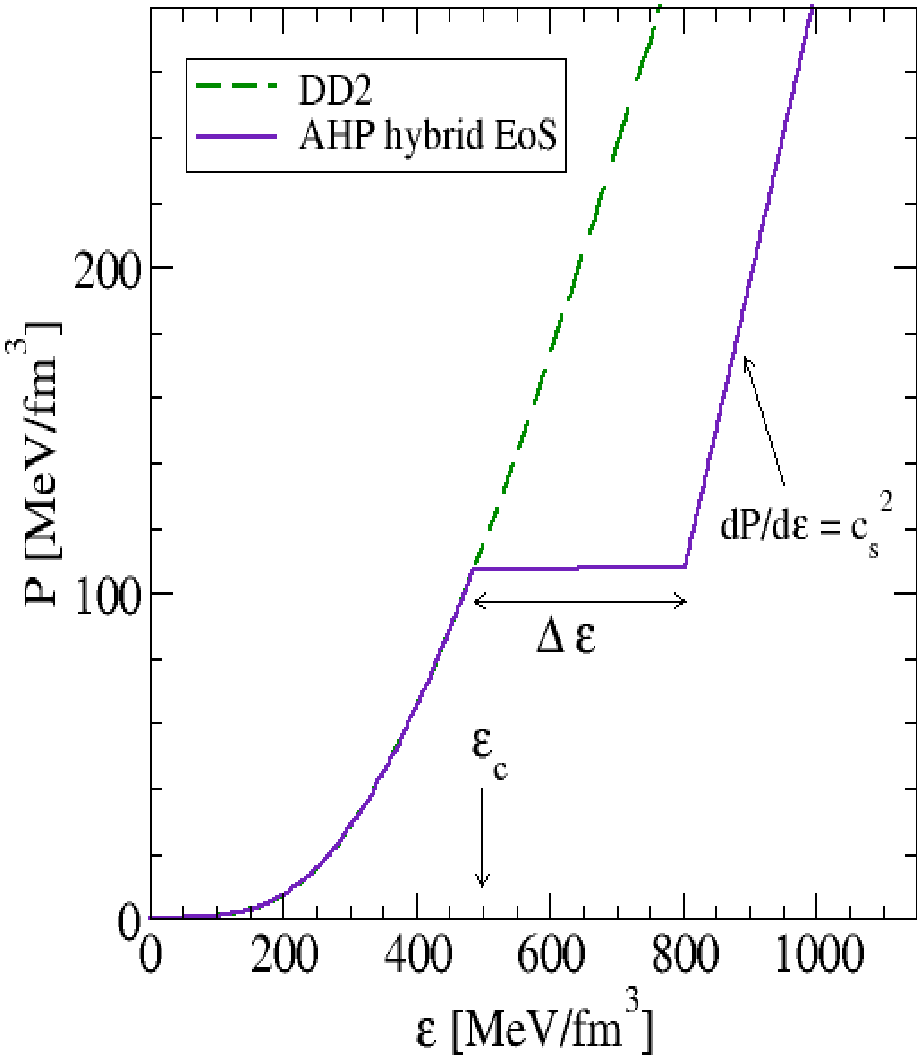

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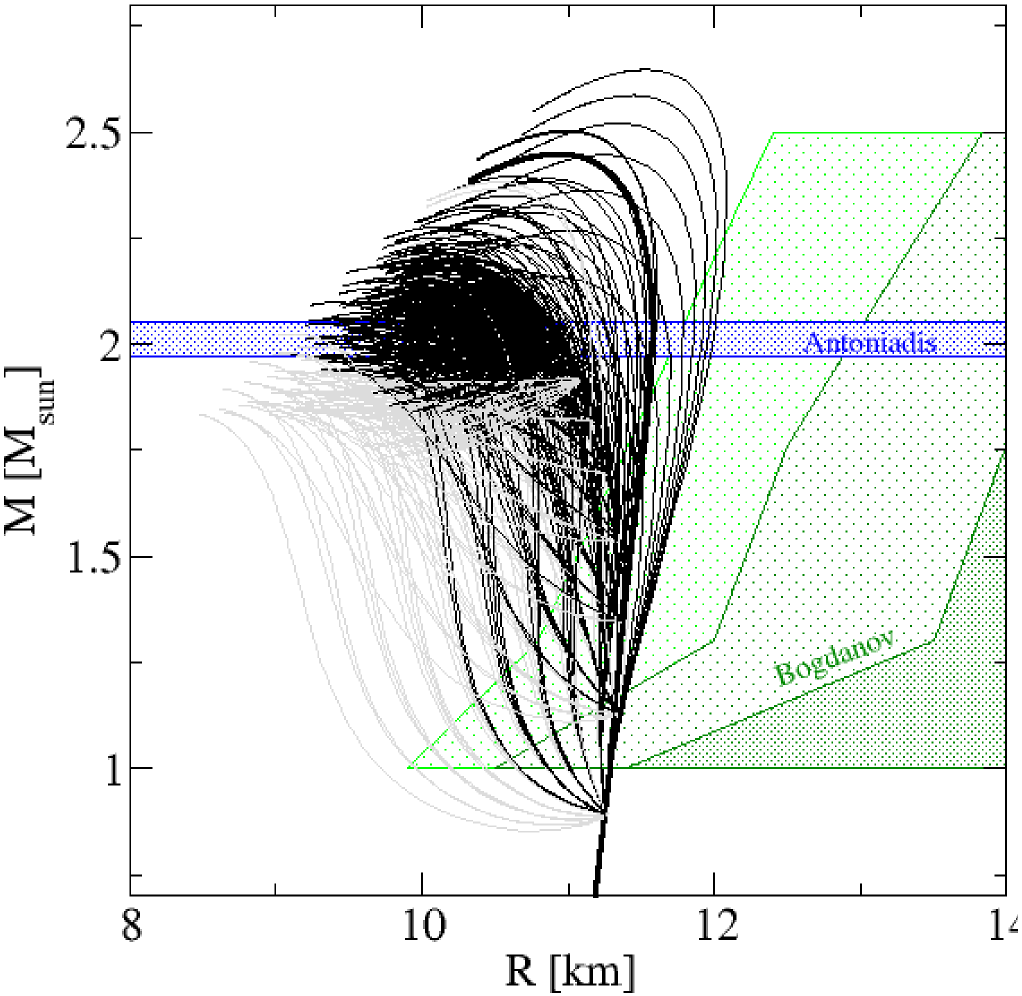
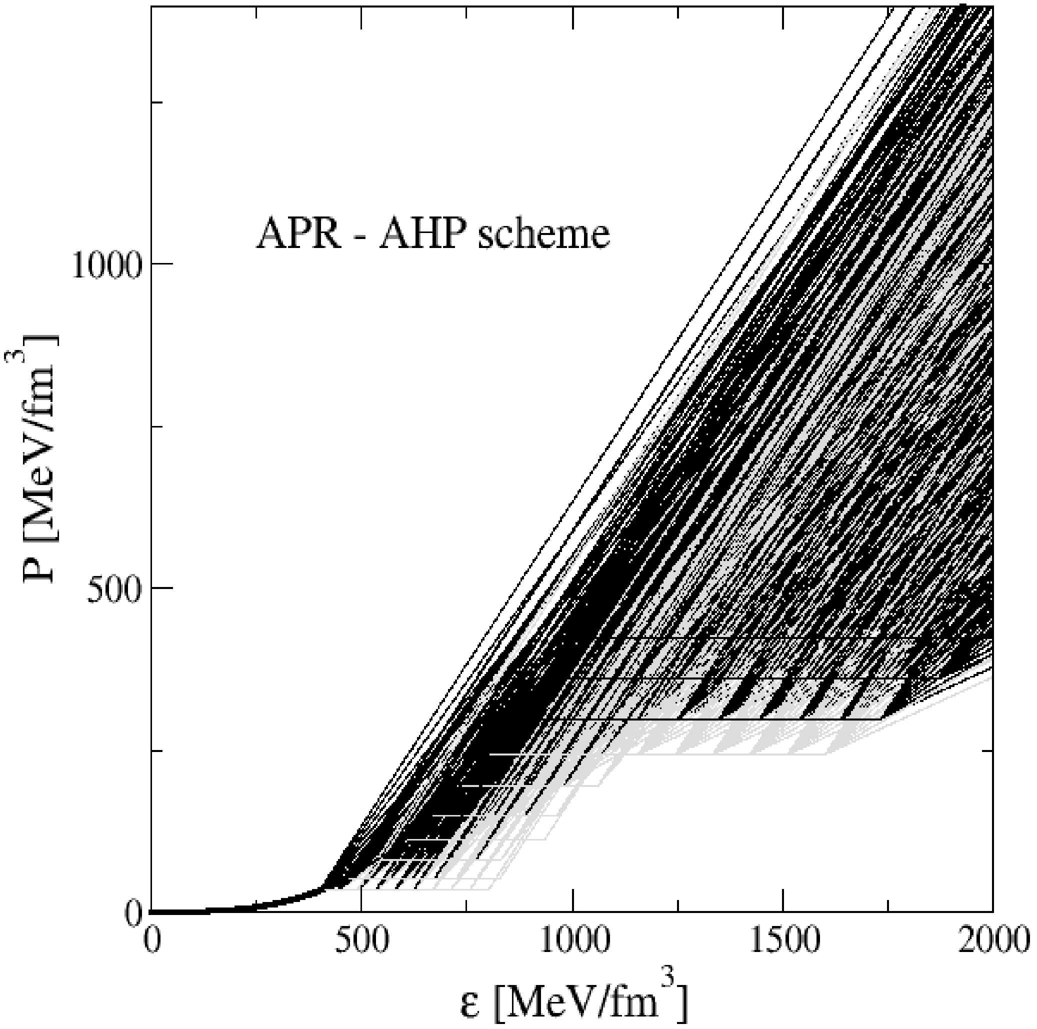
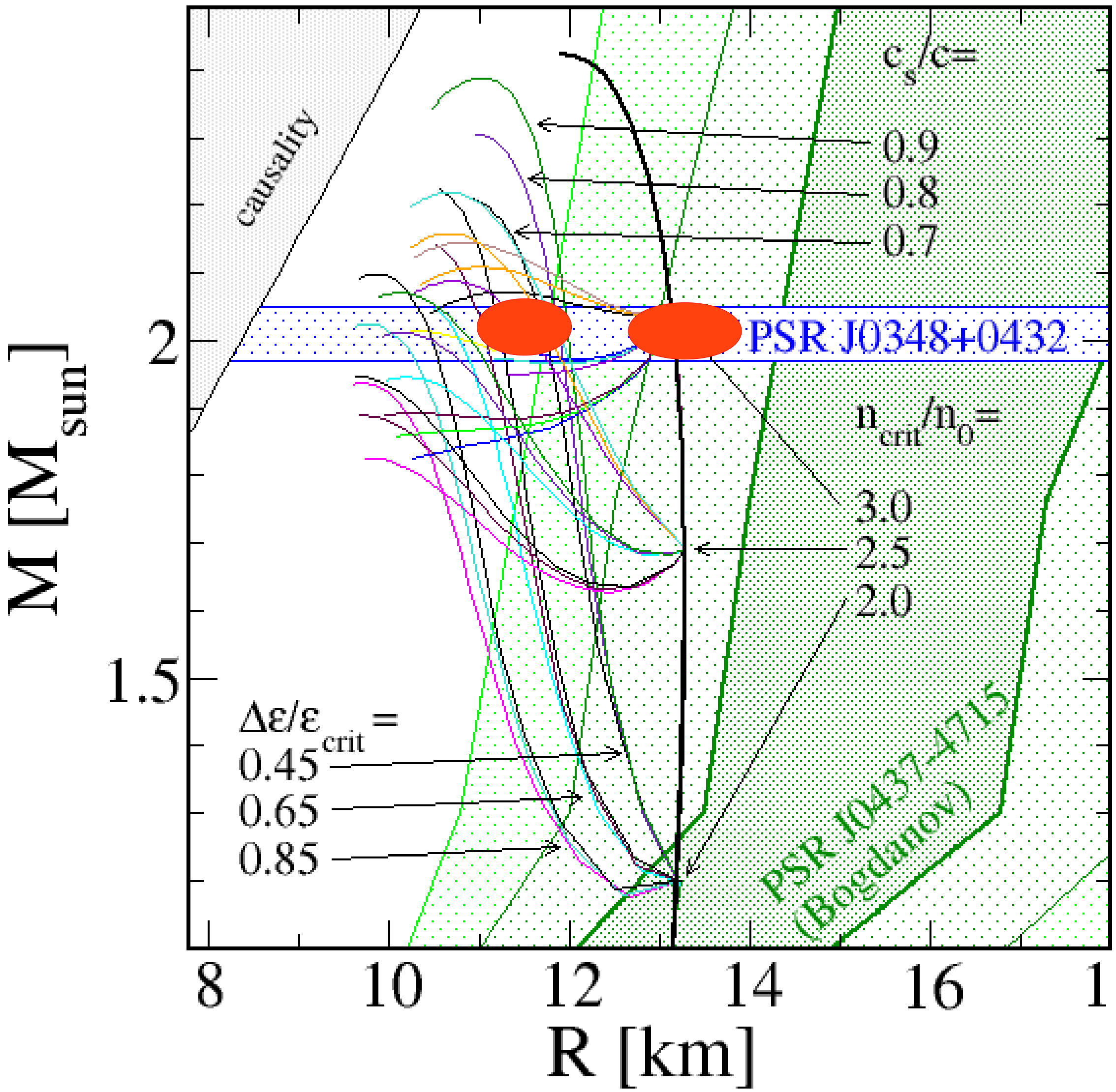
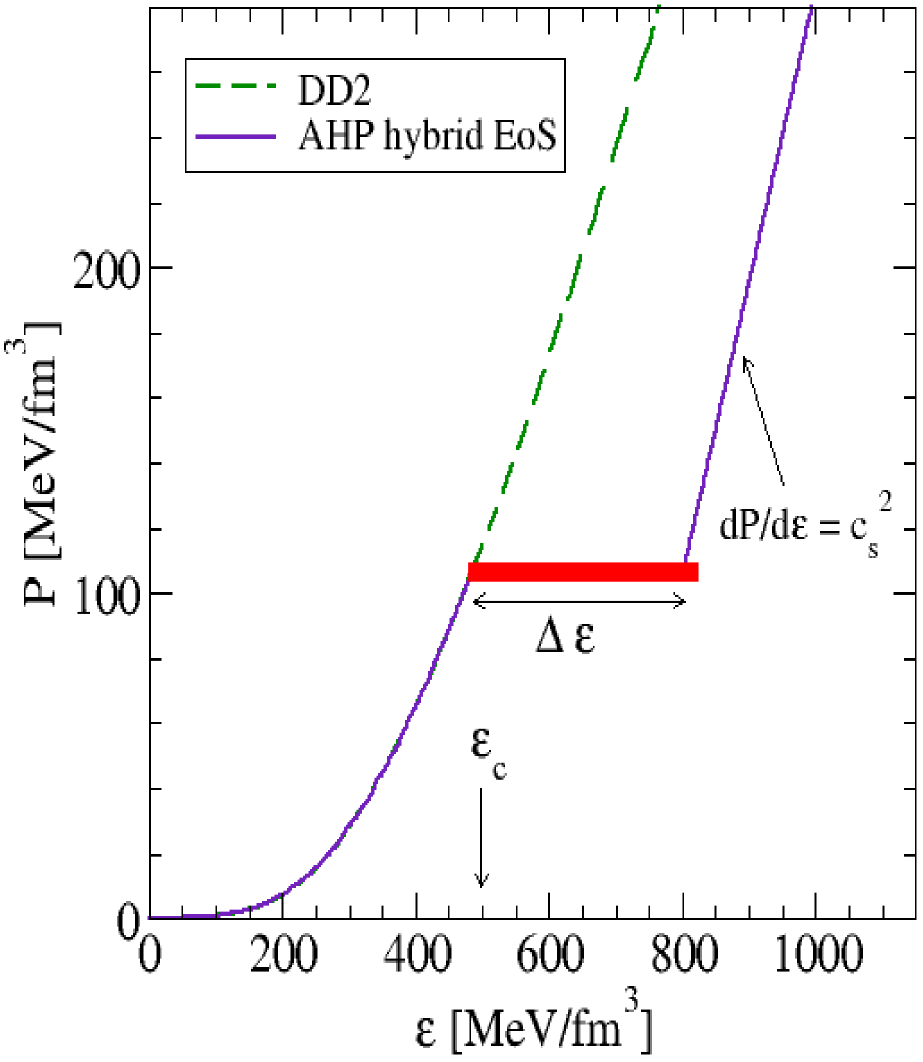




Alvarez, Ayriyan, Blaschke, Grigorian, … (work in progress, 2013)

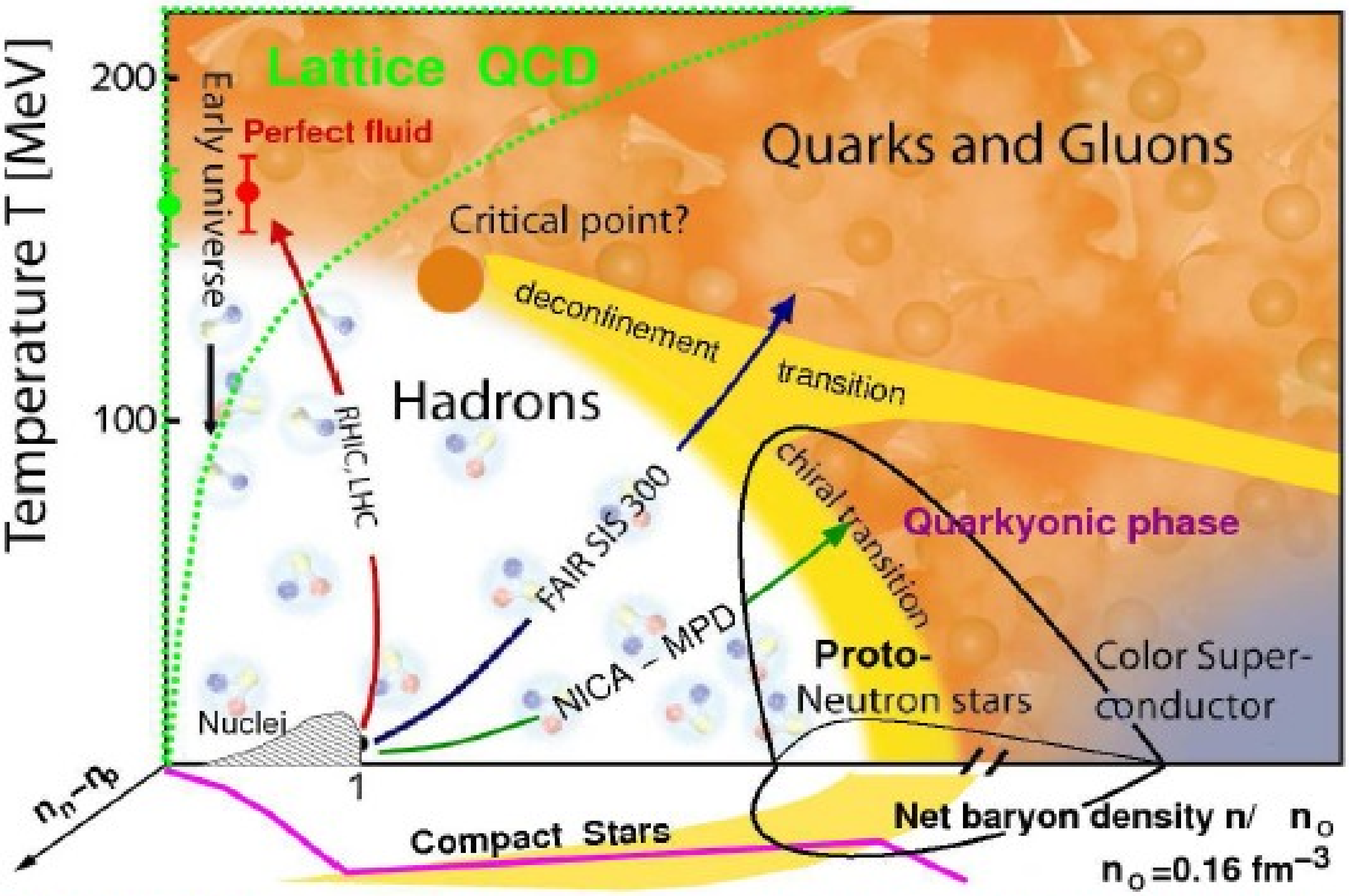
Phase transition? Measure different radii at 2Mo !





Alvarez, Ayriyan, Blaschke, Grigorian, … (work in progress, 2013)

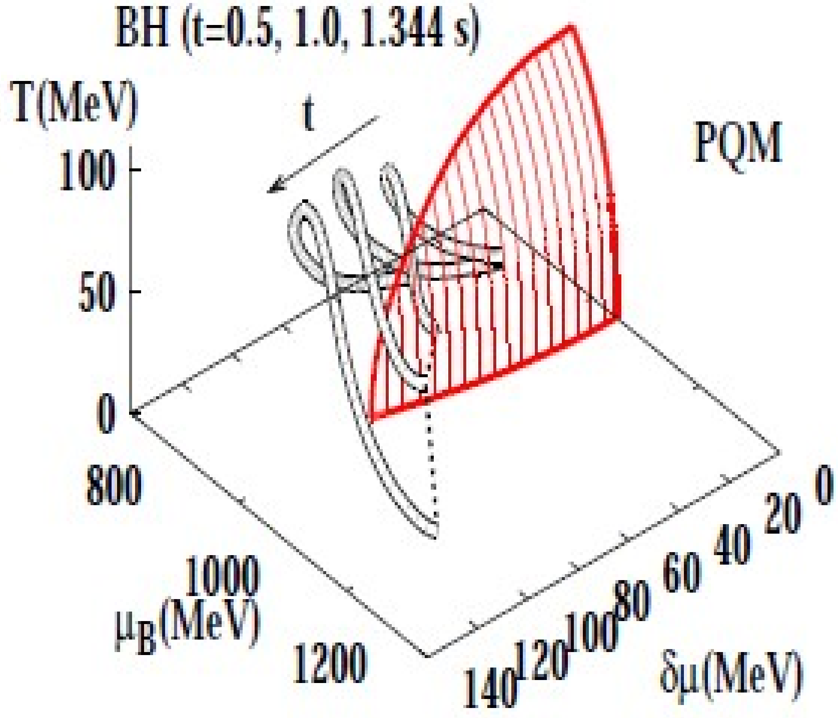
How to probe the line of CEP's in Astrophysics?

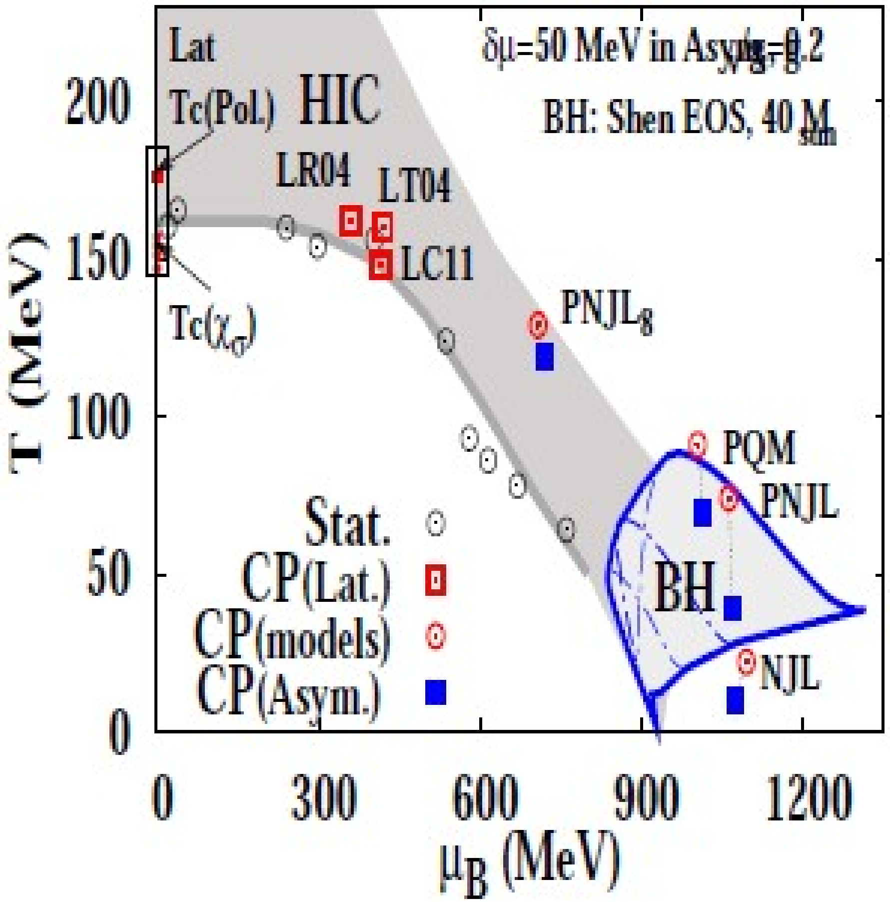


NICA White Paper, `http://theor.jinr.ru/twiki-cgi/view/NICA/WebHome`

How to probe the line of CEP's in Astrophysics?

→ by sweeping (“flyby”) the critical line in SN collapse and BH formation



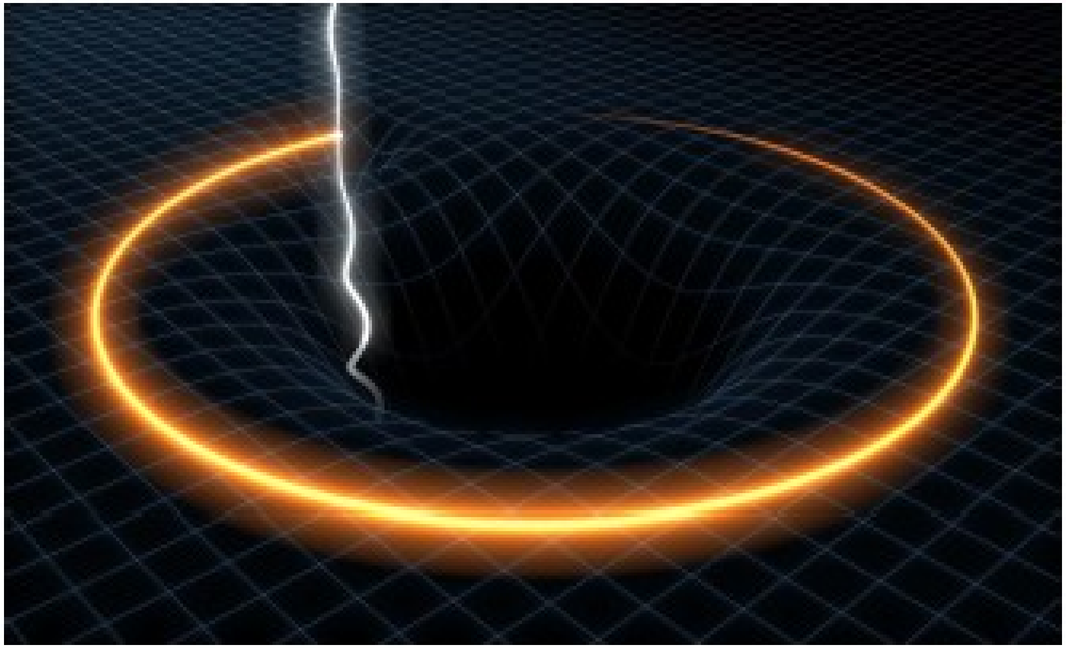


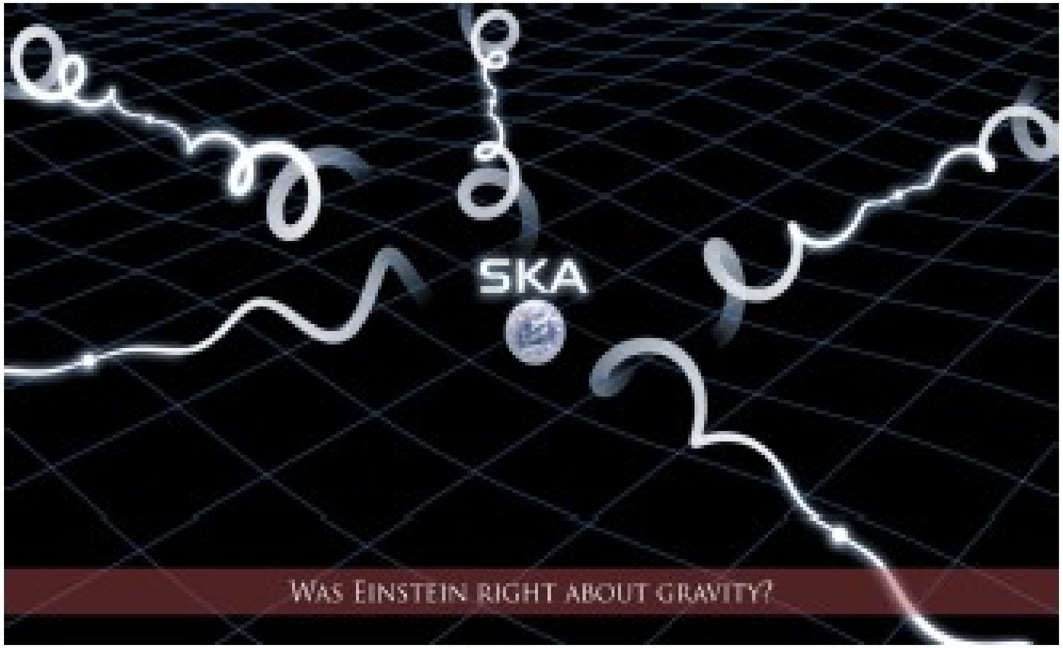
A. Ohnishi, H. Ueda, T. Nakano, M. Ruggieri, K. Sumiyoshi, Phys. Lett. B 704, (2011) 284.

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

LOFT - the Large Observatory For x-ray Timing

Main Science Objective of the LOFT MIssion:
Study of matter in ultradense environments and under strong gravity

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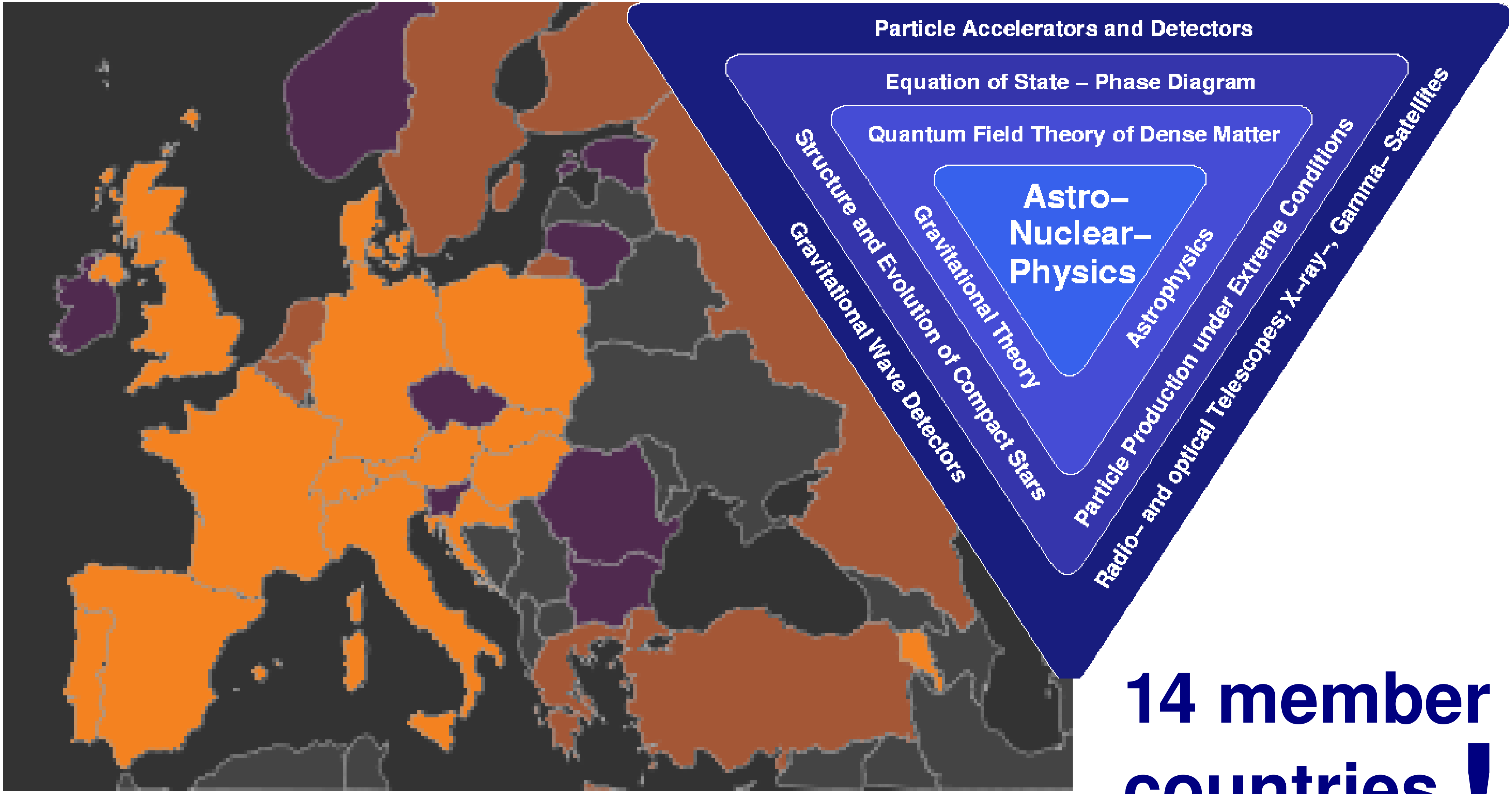


Particle Accelerators and Detectors

Equation of State – Phase Diagram

Quantum Field Theory of Dense Matter

Astro–Nuclear–Physics

Gravitational Theory

Astrophysics

Structure and Evolution of Compact Stars

Particle Production under Extreme Conditions

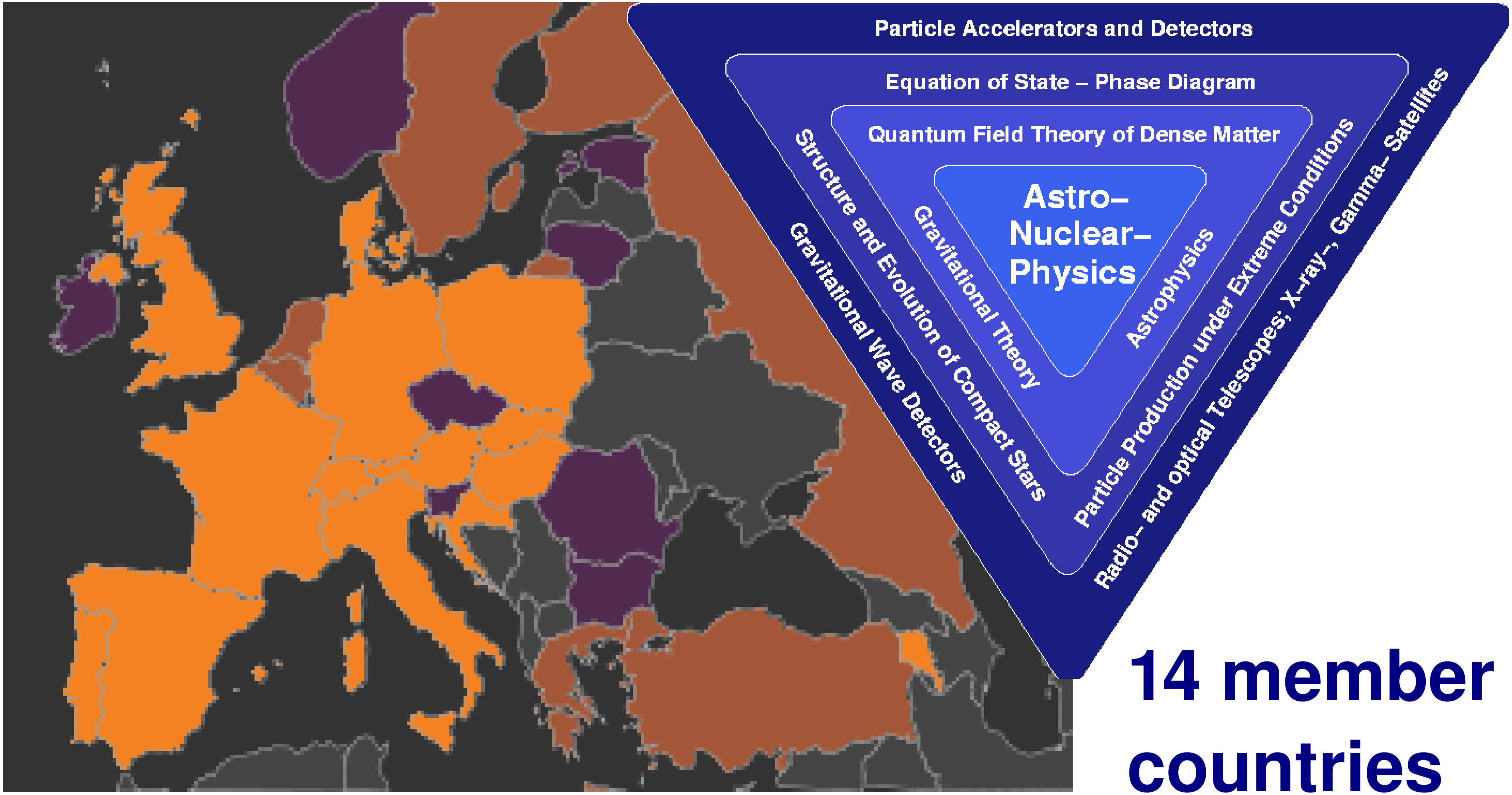
Gravitational Wave Detectors

Radio– and optical Telescopes; X–ray–, Gamma– Satellites

14 member countries !

comp star

(2008-2013)



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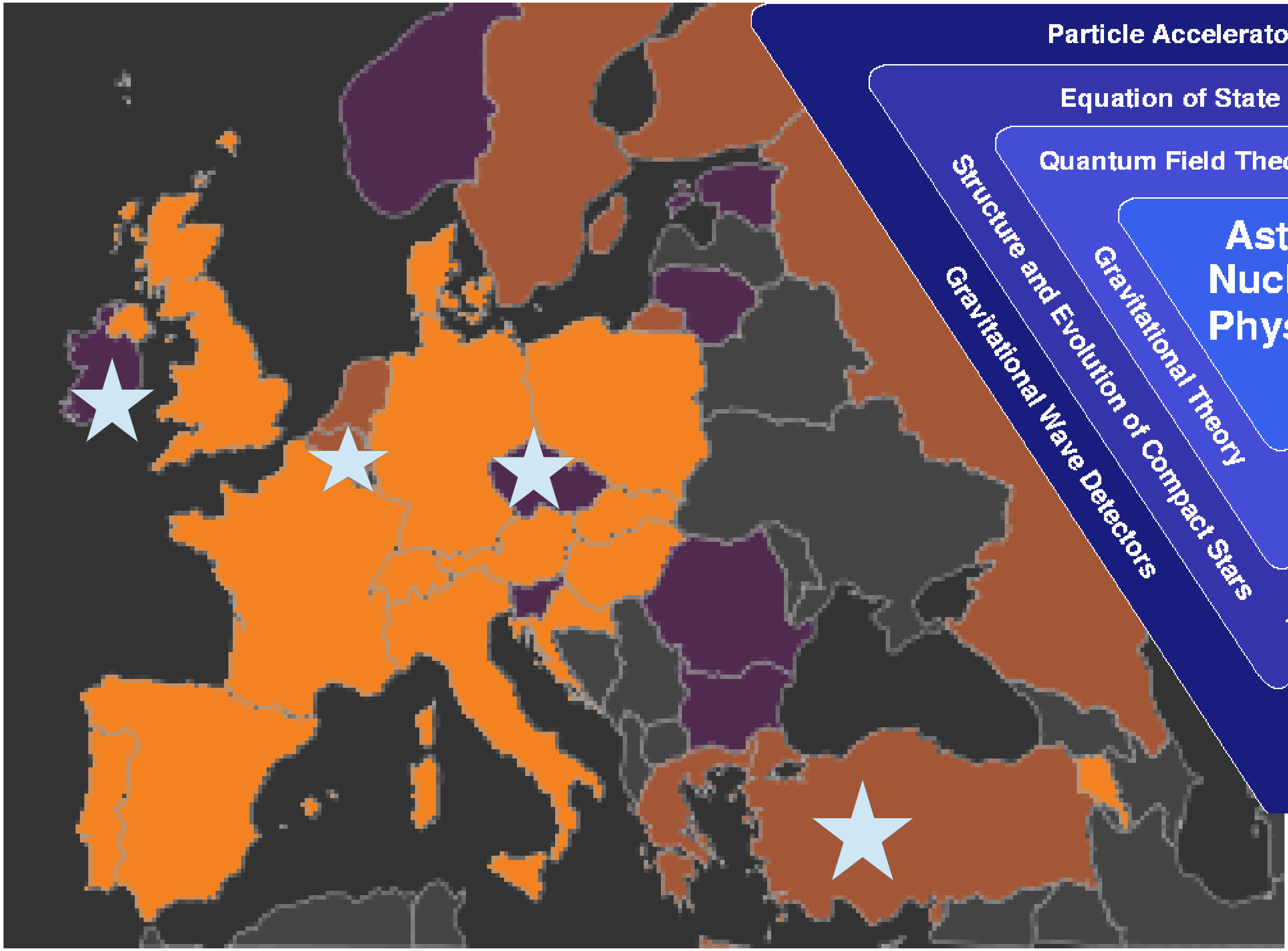
New comp star **?**



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by Oct. 9, 2013:

18 member countries !

New compstar !

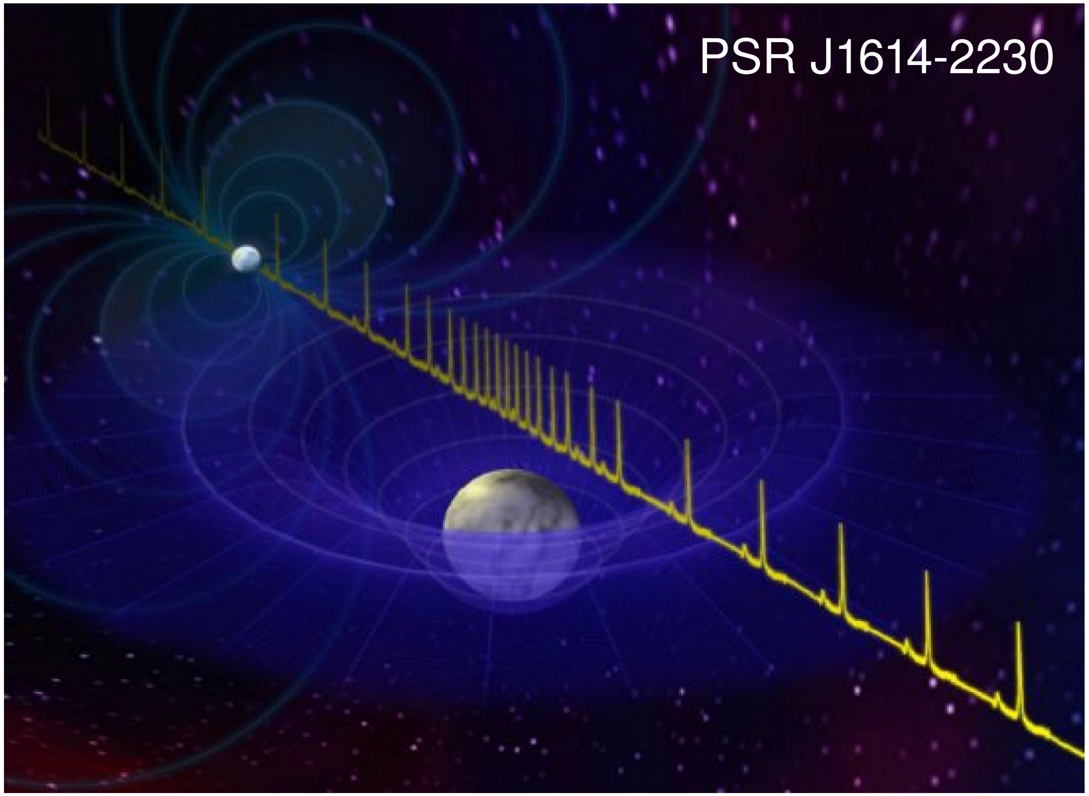
cost
EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

Kick-off: Brussels, November 25, 2013

Proving the CEP with Compact Stars?

David Blaschke (University of Wroclaw, Poland & JINR Dubna, Russia)

1. Goal: Find 1st order PT
2. Observation: M & R
3. Theory: QCD based EoS
4. Holy Grail: Twins !
5. Hot: BH formation
6. Future: LOFT, SKA, …

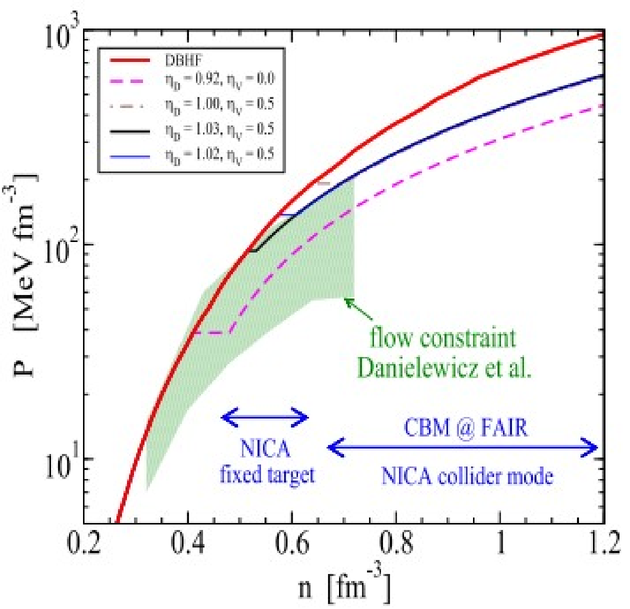


Exploring hybrid star matter at NICA

T.Klähn (1), D.Blaschke (1,2), F.Weber (3)
(1) Institute for Theoretical Physics, University of Wroclaw, Poland
(2) Joint Institute for Nuclear Research, Dubna
(3) Department of Physics, San Diego State University, USA

Heavy-Ion Collisions

Compact Stars



- stiff EoS (at flow limit)

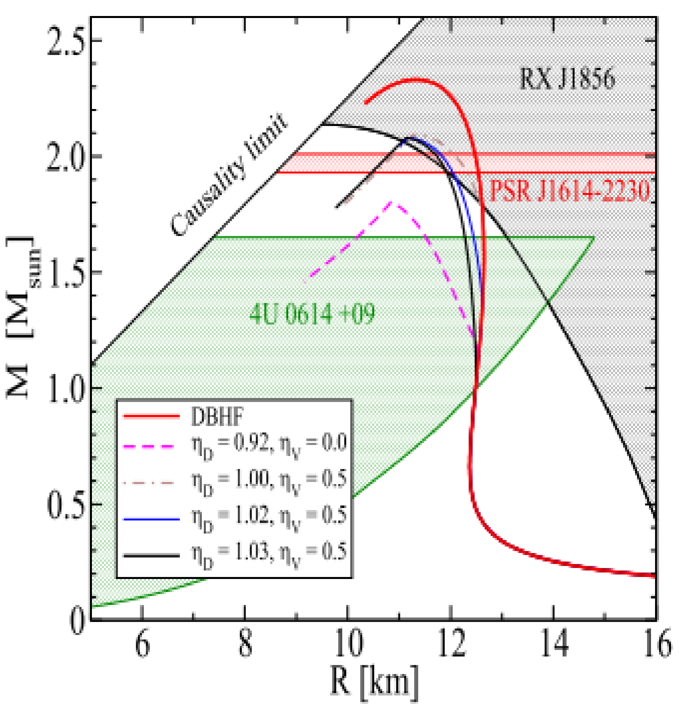
- low n_{crit} (at NICA fixT)

- soft EoS (dashed line)

- high M_{max} (J1614-2230)

- low M_{onset} (all NS hybrid)

- excluded (J1614-2230)



Proposal:

1. Measure transverse and elliptic flow for a wide range of energies (densities) at NICA and perform Danielewicz's flow data analysis ---> constrain stiffness of high density EoS
2. Provide lower bound for onset of mixed phase ---> constrain QM onset in hybrid stars

„The CBM Physics Book“, Springer LNP 841 (2011), pp.158-181