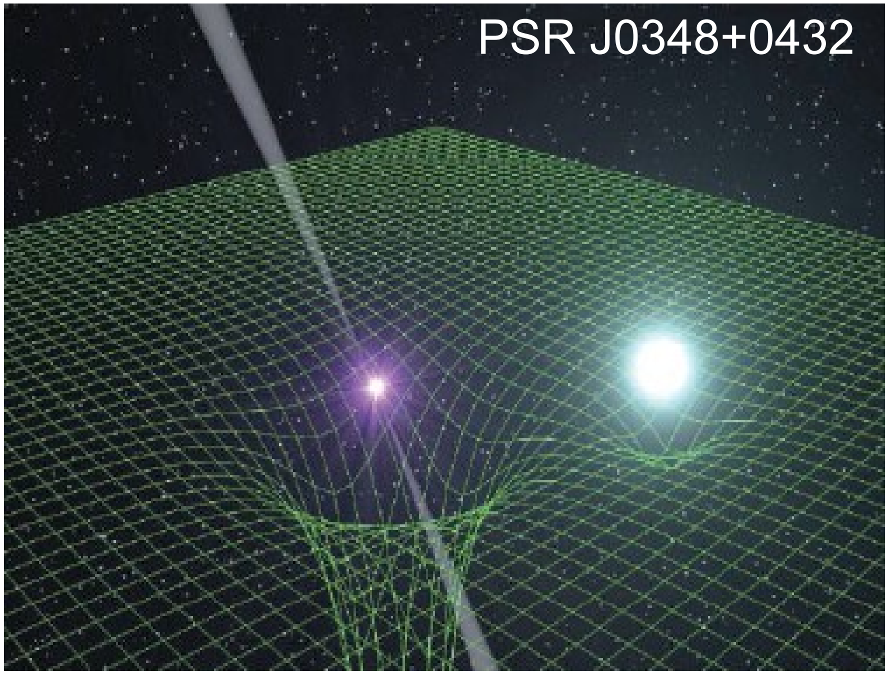
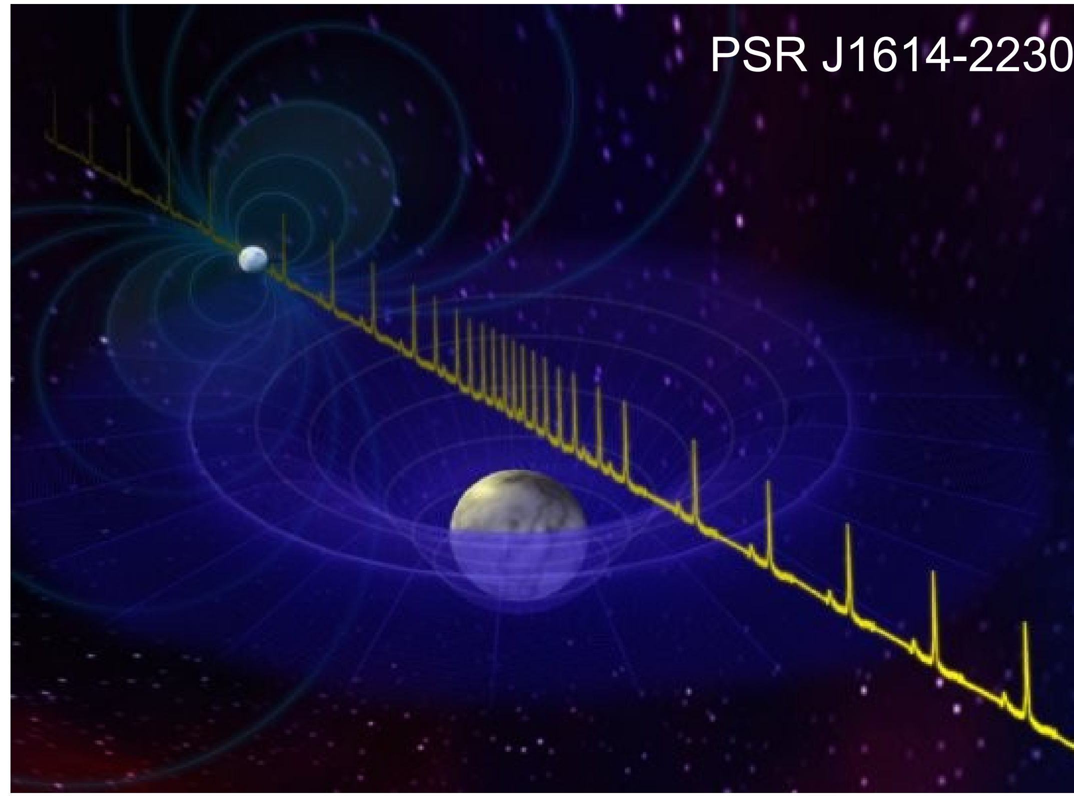
# A new class of EoS for astrophysical applications

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




Antoniadis et al., Science 340 (2013) 448
Demorest et al., Nature 467 (2010) 1081




Astro-Coffee, FIAS, Universitaet Frankfurt, 12.05.2015

DUBNA

JINR

NAVI

NARODOWE CENTRUM NAUKI

Uniwersytet Wrocławski

# A new class of EoS for astrophysical applications

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

1. Pauli blocking among baryons --> Microscopic justification for EVA
2. Stiff quark matter at high densities --> New wine in old barrels
3. Rotation & high-mass twin stars
4. New Bayesian Analysis Scheme

*The New is often the well-forgotten Old*

EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

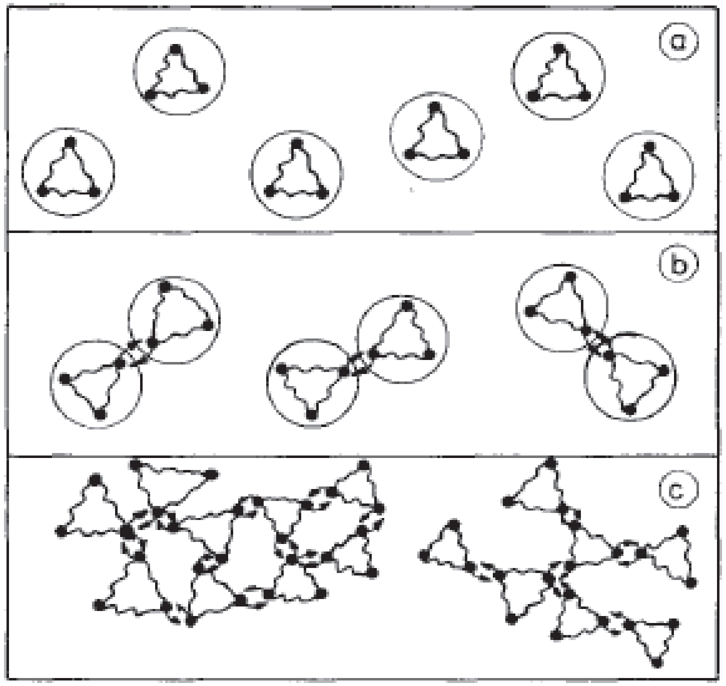
Astro-Coffee, FIAS, Universitaet Frankfurt, 12.05.2015

JINR DUBNA

NARODOWE CENTRUM NAUKI

Uniwersytet Wrocławski

# 1. Pauli blocking among baryons

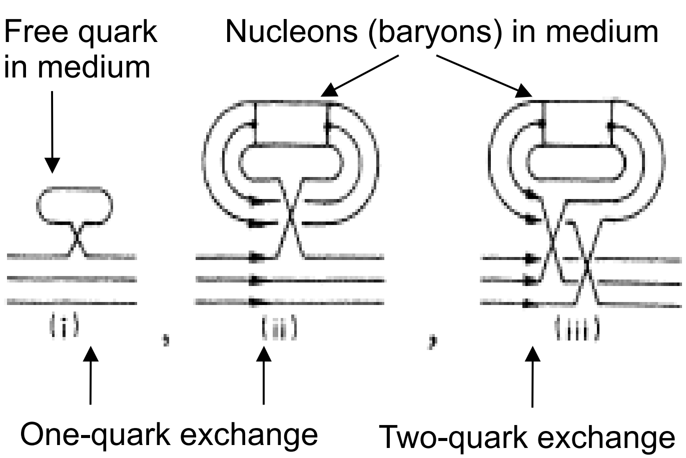


a) Low density: Fermi gas of nucleons (baryons)

b) ~ saturation: Quark exchange interaction and Pauli blocking among nucleons (baryons)

c) high density: Quark cluster matter (string-flip model ...)

Roepke & Schulz, Z. Phys. C 35, 379 (1987); Roepke, DB, Schulz, PRD 34, 3499 (1986)




Nucleon (baryon) self-energy --> Energy shift

$$
\begin{aligned}
\Delta E^{\mathrm{Pauli}}_{\nu P} = & \sum_{123} |\psi_{\nu P}(123)|^2 [E(1)+E(2)+E(3)-E^0_{\nu P}][f_{\alpha_1}(1)+f_{\alpha_2}(2)+f_{\alpha_3}(3)] \\
& + \sum_{123}\sum_{456}\sum_{\nu' P'} \psi^*_{\nu P}(123)\psi_{\nu' P'}(456) f_3(E^0_{\nu' P'})\{\delta_{36}\psi_{\nu P}(123)\psi^*_{\nu' P'}(456) - \psi_{\nu P}(453)\psi^*_{\nu' P'}(126)\} \\
& \times [E(1)+E(2)+E(3)+E(4)+E(5)+E(6)-E^0_{\nu P}-E^0_{\nu' P'}] \\
= & \Delta E^{\mathrm{Pauli,free}}_{\nu P} + \Delta E^{\mathrm{Pauli,bound}}_{\nu P} .
\end{aligned}
$$

# 1. Pauli blocking among baryons - details

$$\Sigma_\nu(p, p_{Fn}, p_{Fp}) = \sum_{\nu'=\{n,p\}} \sum_{\alpha=1,2} C^{(\alpha)}_{\nu\nu'} W_\alpha(p_{F\nu'}, p)$$

$$W_\alpha(p_{F\nu'}, p) = \frac{\Omega}{2\pi^2}\int_0^{p_{F\nu'}} p'^2 \bar{V}^{(\alpha)}(p,p')dp';$$

$$\bar{V}^{(\alpha)}(p,p') = \frac{1}{2}\int_{-1}^{1} V^{(\alpha)}(\vec{p},\vec{p}\,')dz;$$

$$V^{(\alpha)}(\vec{p},\vec{p}\,') = \frac{V_0 b}{\Omega m}\left(\frac{15}{2} - \lambda_\alpha^2(\vec{p}-\vec{p}\,')^2\right)\exp(-\lambda_\alpha^2(\vec{p}-\vec{p}\,')^2).$$

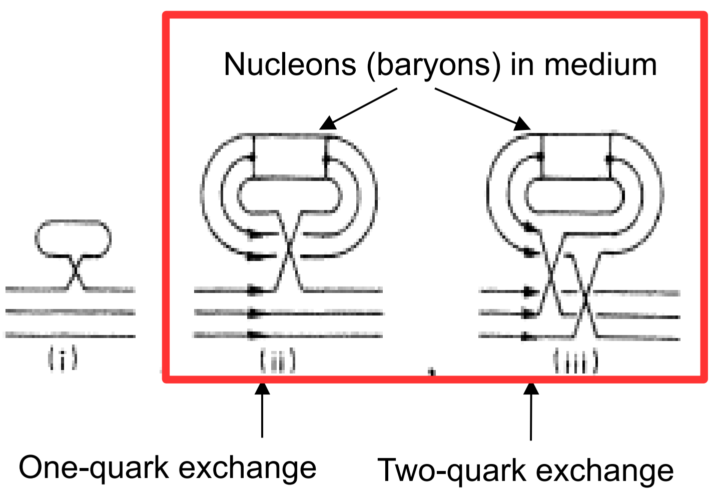
| | $C^{(1)}_{n\ \nu}$ | $C^{(2)}_{n\ \nu}$ |
|---|---|---|
| neutron | $-\frac{96}{243}$ | $\frac{10}{27}$ |
| proton | $-\frac{28}{81}$ | $\frac{8}{27}$ |

$$b^{-2} = \sqrt{3}m\omega$$

$$\omega = 178.425 \text{ MeV}$$

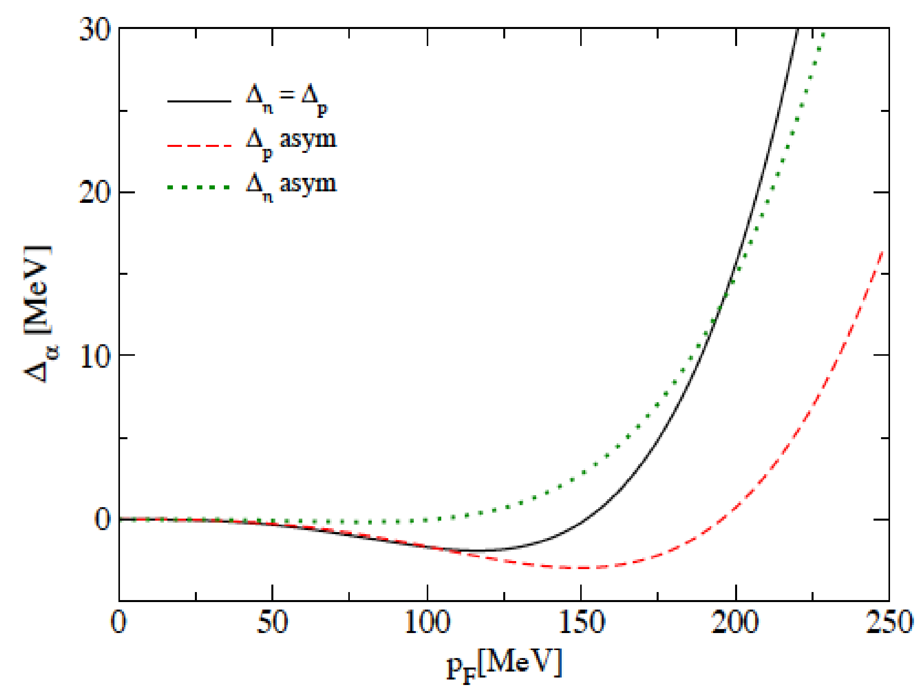
$$m = 350 \text{ MeV} \qquad b = 0.6 \text{ fm}$$

$$V_0 = \frac{9\sqrt{3}\pi^{3/2}}{2} \text{ and } \lambda_\alpha = \frac{b}{\sqrt{3\alpha}}.$$



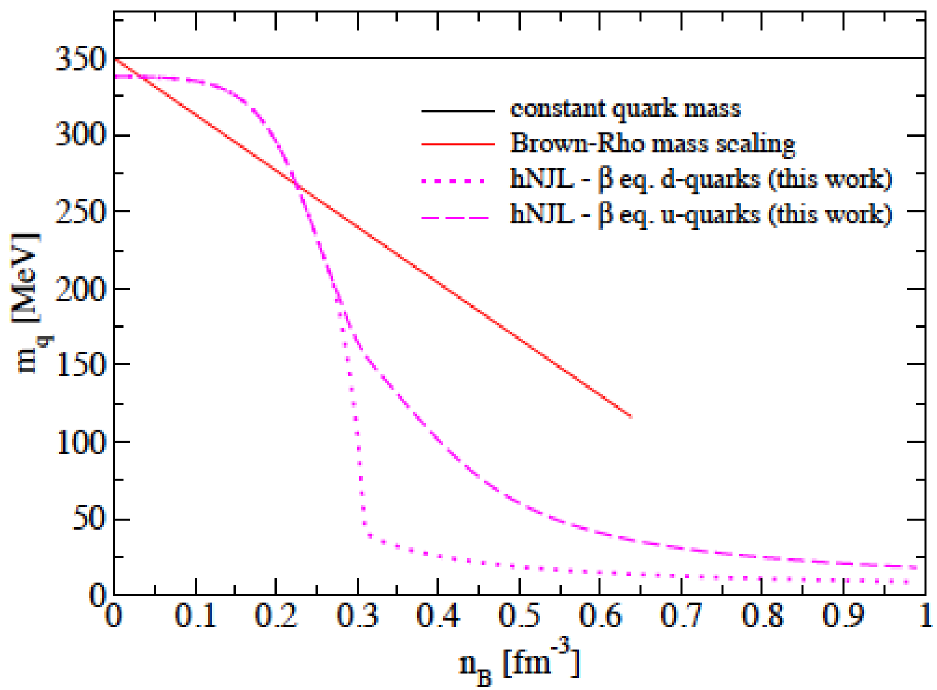

$$W_\alpha(p_{F\nu'}, p) = \frac{V_0 b}{32\pi^2\lambda_\alpha^4 m}\{12\lambda_\alpha\sqrt{\pi}\,[\mathrm{erf}\,(\lambda_\alpha(p_{F\nu'}-p)) + \mathrm{erf}\,(\lambda_\alpha(p_{F\nu'}+p))]$$
$$+ \frac{1}{p}[\,(11 - 2\lambda_\alpha^2\, p_{F\nu'}(p_{F\nu'}+p))\,\mathrm{e}^{-\lambda_\alpha^2(p_{F\nu'}+p)^2}$$
$$+ (11 - 2\lambda_\alpha^2\, p_{F\nu'}(p_{F\nu'}-p))\,\mathrm{e}^{-\lambda_\alpha^2(p_{F\nu'}-p)^2}]\}$$

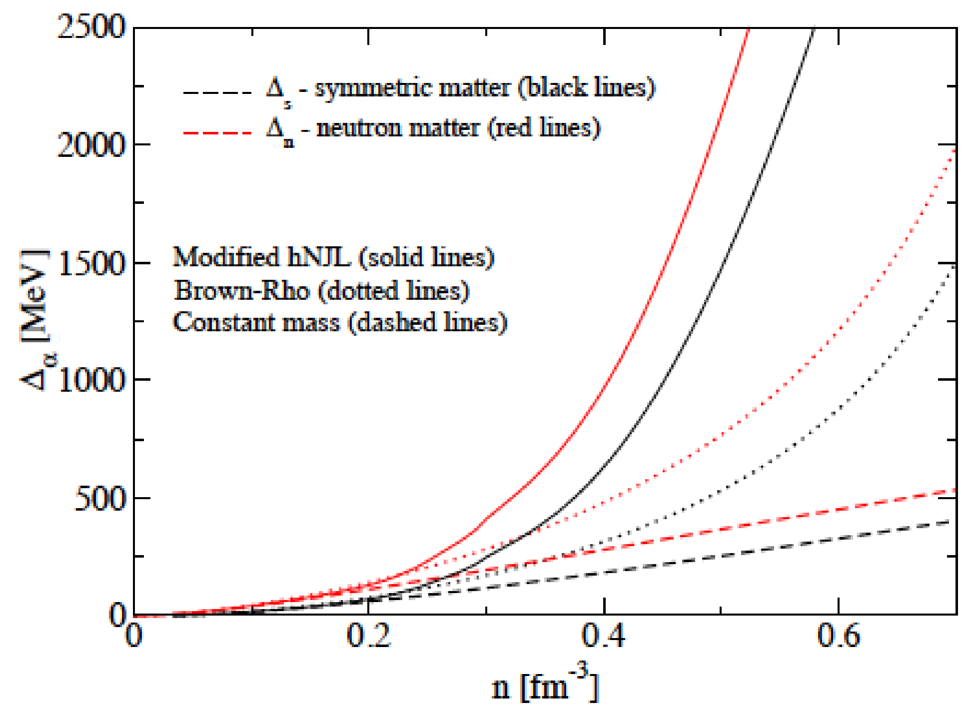
$$\Delta^{Pauli}_{\nu_A,P} = \frac{1}{24\sqrt{3\pi}}\frac{b}{m}\sum_{\nu'}[15a_{\nu,\nu'}P_F(\nu')^3 + \frac{17}{12}b_{\nu,\nu'}b^2(P^2+P_F(\nu')^2)P_F(\nu')^3]$$



# 1. Pauli blocking among baryons – details

## New aspect: chiral restoration --> dropping quark mass




## Increased baryon swelling at supersaturation densities:
## --> dramatic enhancement of the Pauli repulsion !!

D.B., H. Grigorian, G. Roepke: “Quark exchange effects in dense nuclear matter”, STSM 2014

# 1. Pauli blocking among baryons – results

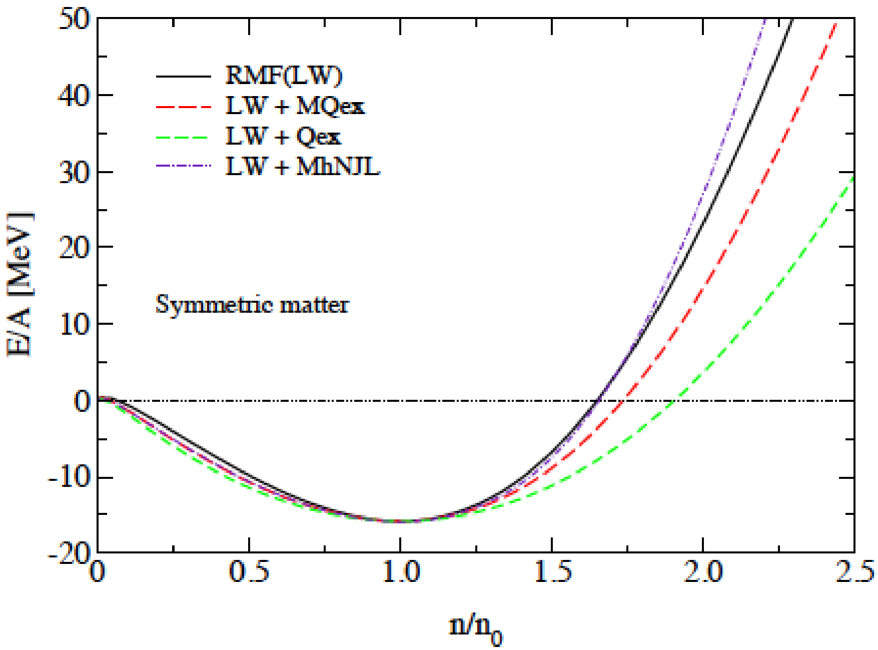
**New EoS: Joining RMF (Linear Walecka) for pointlike baryons with chiral Pauli blocking**

$$
\begin{aligned}
p &= \frac{1}{4\pi^2}\sum_\nu\left[-E_\nu^* m_\nu^{*2} p_{F\nu} + \frac{2}{3}E_\nu^* p_{F\nu}^3 + m_\nu^{*4}\log\left(\frac{E_\nu^* + p_{F\nu}}{m_\nu^*}\right)\right] \\
&+ \frac{1}{2}\left(\frac{g_\omega}{m_\omega}\right)^2 n^2 - \frac{1}{2}\left(\frac{g_\sigma}{m_\sigma}\right)^2 n_s^2 + p_{ex}; \\
\epsilon &= \frac{1}{4\pi^2}\sum_\nu\left[2\,E_\nu^{*3} p_{F\nu} - E_\nu^* m_\nu^{*2} p_{F\nu} - m_\nu^{*4}\log\left(\frac{E_I^* + p_{F\nu}}{m_\nu^*}\right)\right] \\
&+ \frac{1}{2}\left(\frac{g_\omega}{m_\omega}\right)^2 n^2 + \frac{1}{2}\left(\frac{g_\sigma}{m_\sigma}\right)^2 n_s^2 + \epsilon_{ex},
\end{aligned}
$$

$$
\begin{aligned}
\mu_{ex,\nu} &= \Delta_\nu(n,x) = \Sigma_\nu(p_{F,\nu}; p_{Fn,}, p_{Fp}), \\
\epsilon_{ex} &= \sum_\nu \int_0^n dn'\{x\Delta_p(n',x) + (1-x)\Delta_n(n',x)\}, \\
p_{ex} &= \sum_\nu \mu_{ex,\nu}\, n_\nu - \epsilon_{ex},
\end{aligned}
$$

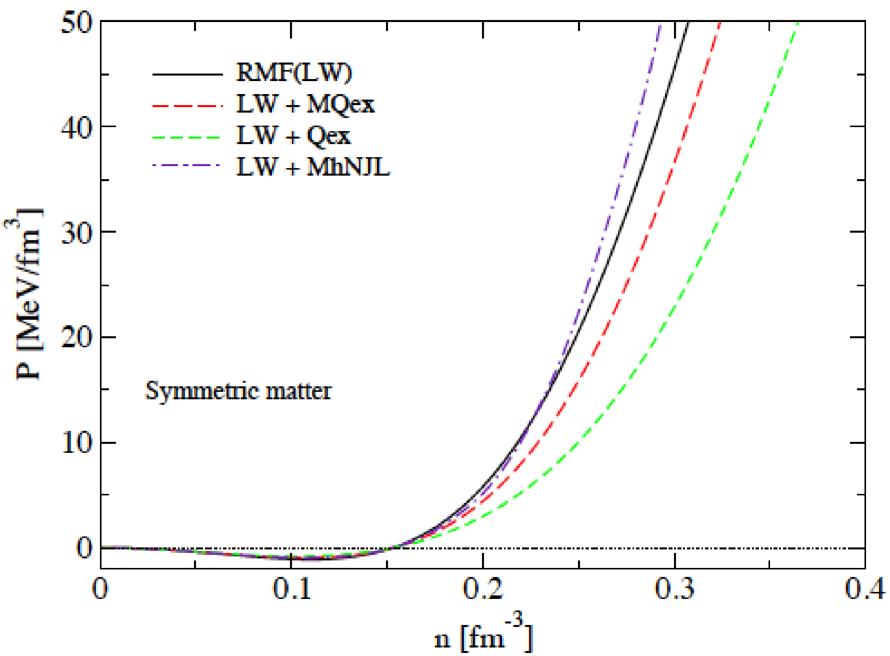
$$
\begin{aligned}
n_{s,\nu} &= \frac{m_\nu^*}{\pi^2}\left[E_\nu^* p_{F\nu} - m_\nu^{*2}\log\left(\frac{E_\nu^* + p_{F\nu}}{m_\nu^*}\right)\right], \\
E_\nu^* &= \sqrt{m_\nu^{*2} + p_{F\nu}^2} \\
n_\nu &= \frac{p_{F\nu}^3}{3\pi^2}, \\
m_\nu^* &= m_\nu - \left(\frac{g_\sigma}{m_\sigma}\right)^2 n_{s,\nu}, \\
\mu_\nu &= E_\nu^* + \left(\frac{g_\omega}{m_\omega}\right)^2 n_\nu + \mu_{ex,\nu}.
\end{aligned}
$$

# 1. Pauli blocking among baryons – results

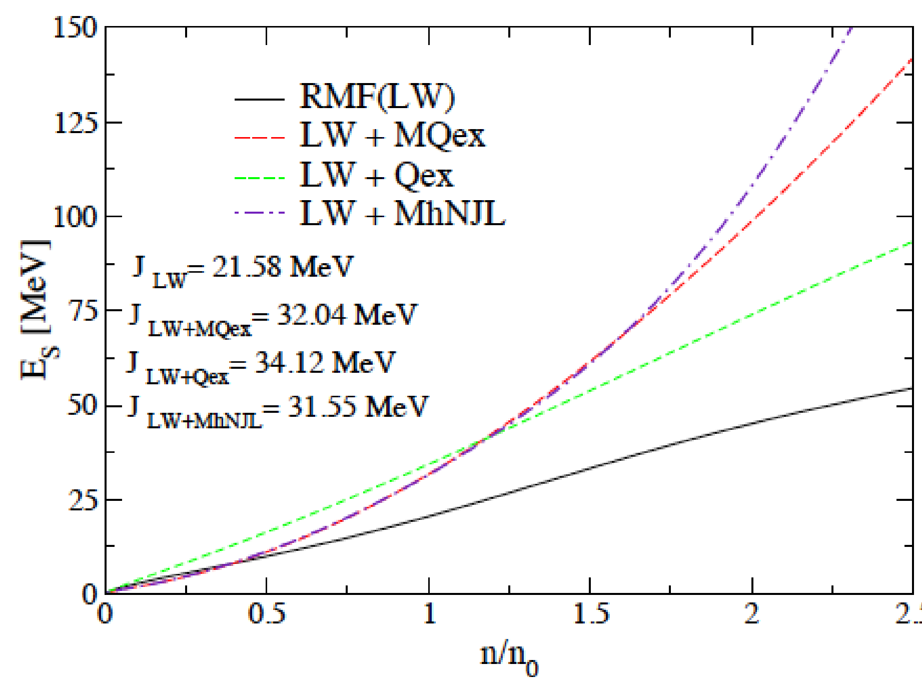



Parametrization: from saturation properties

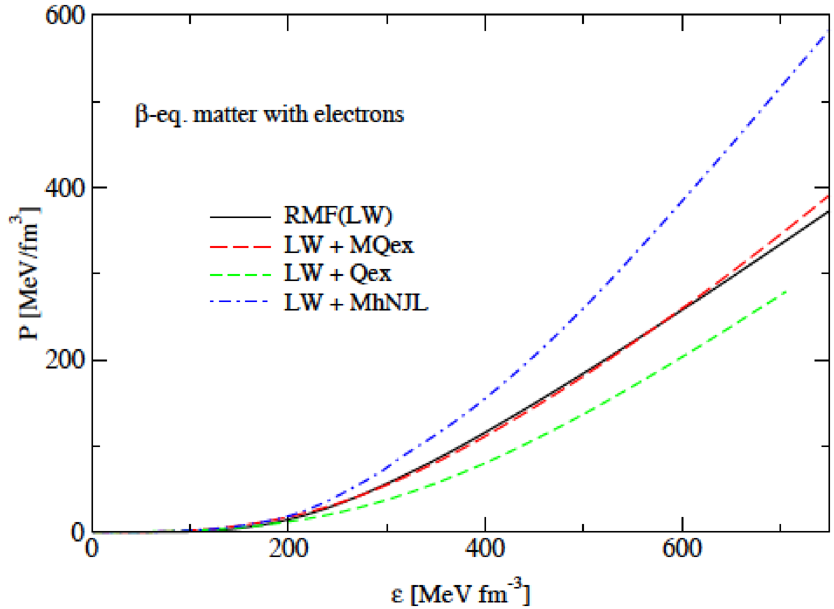
| | $(g_\omega/m_\omega)^2$[fm$^2$] | $(g_\sigma/m_\sigma)^2$ [fm$^2$] |
|---|---|---|
| RMF (LW) | 11.6582 | 15.2883 |
| LW+Qex | 6.11035 | 9.91197 |
| LW+MQex | 6.59170 | 13.29118 |
| LW+MhNJL | 9.25683 | 13.9474 |

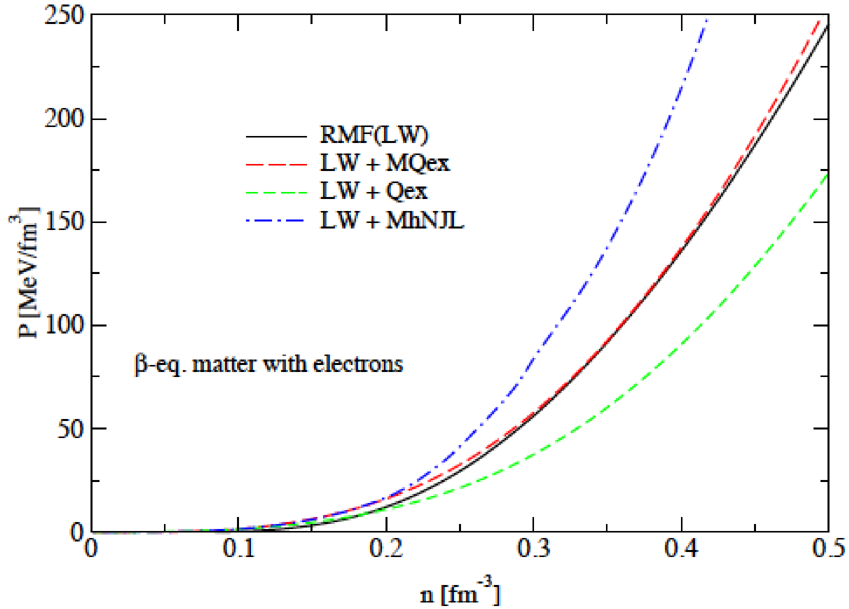


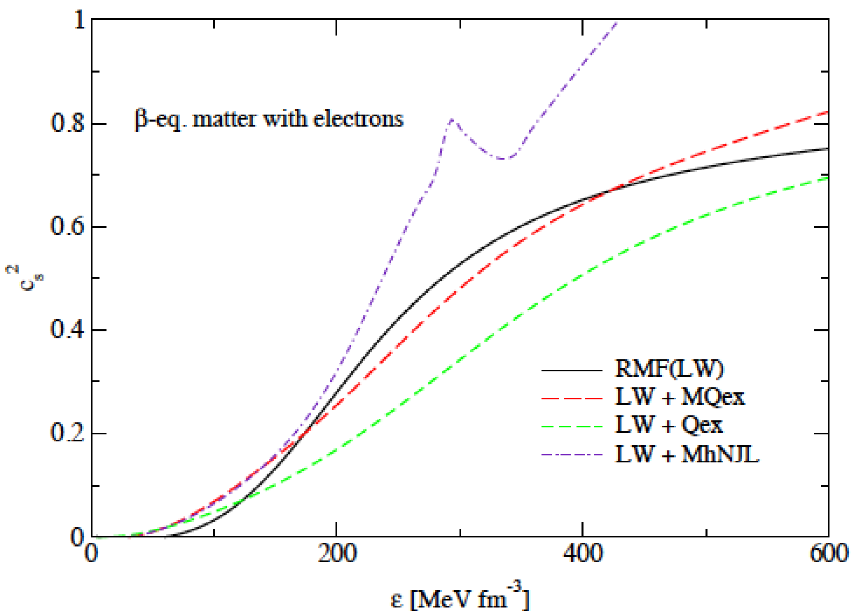

Prediction: symmetry energy

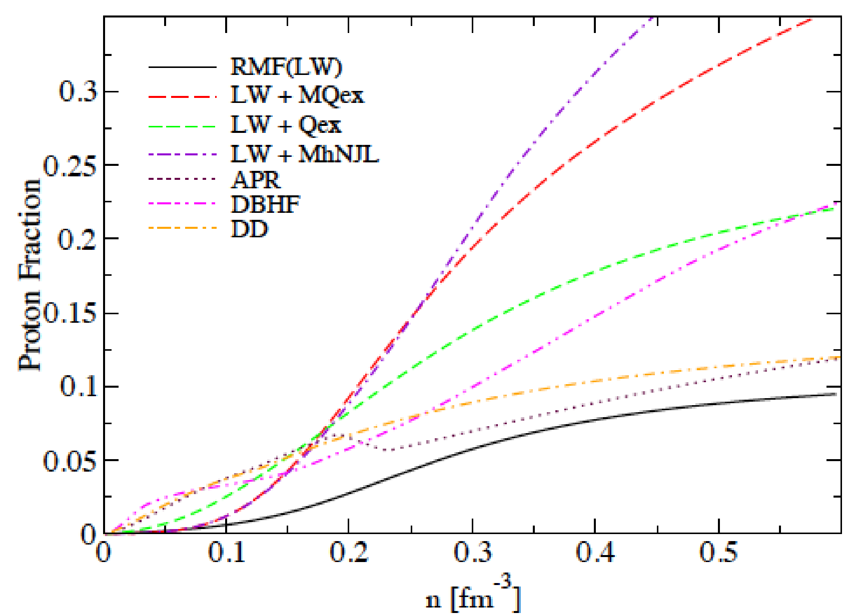


# 1. Pauli blocking among baryons – results

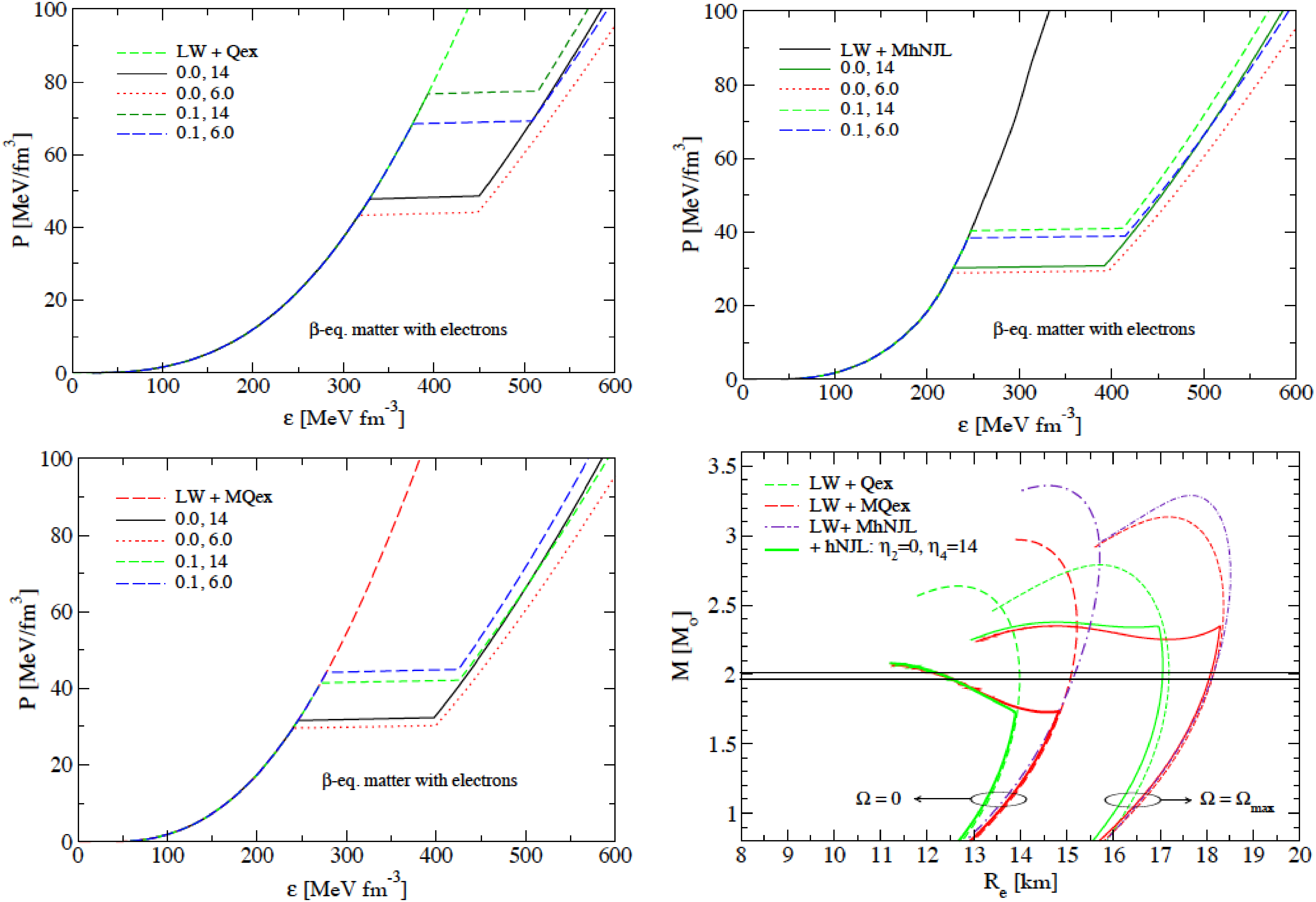


# 1. Pauli blocking among baryons – results



# 1. Pauli blocking among baryons – Summary

Pauli blocking selfenergy (cluster meanfield) calculable in potential models for baryon structure

Partial replacement of other short-range repulsion mechanisms (vector meson exchange)

Modern aspects:
- onset of chiral symmetry restoration enhances nucleon swelling and Pauli blocking at high n
- quark exchange among baryons -> six-quark wavefunction -> "bag melting" -> deconfinement

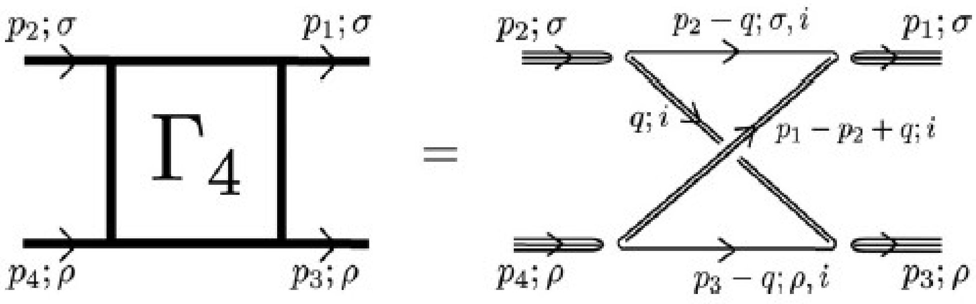
Chiral stiffening of nuclear matter --> reduces onset density for deconfinement

Hybrid EoS:
Convenient generalization of RMF models,
Take care: eventually aspects of quark exchange already in density dependent vertices!

Other baryons:
- hyperons
- deltas
Again calculable, partially done in nonrelativistic quark exchange models, chiral effects not yet!

Relativistic generalization:
Box diagrams of quark-diquark model ...

K. Maeda, Ann. Phys. 326 (2011) 1032



# 1. Pauli blocking effect → Excluded volume

Well known from modeling dissociation of clusters in the supernova EoS:

- excluded volume: Lattimer-Swesty (1991), Shen-Toki-Oyematsu-Sumiyoshi (1996), ...
- Pauli blocking: Roepke-Grigo-Sumiyoshi-Shen (2003), Typel et al. PRC 81 (2010)
- excl. Vol. vs. Pauli blocking: Hempel, Schaffner-Bielich, Typel, Roepke PRC 84 (2011)

**Here:** nucleons as quark clusters with finite size --> excluded volume effect !

Available volume fraction: $$\Phi = V_{\rm av}/V = 1 - v \sum_{i=n,p} n_i, \quad v = \frac{1}{2}\frac{4\pi}{3}(2r_{\rm nuc})^3 = 4V_{\rm nuc}$$

Equations of state for T=0 nuclear matter:
$$p_{\rm tot}(\mu_n, \mu_p) = \frac{1}{\Phi} \sum_{i=n,p} p_i + p_{\rm mes},$$
$$\varepsilon_{\rm tot}(\mu_n, \mu_p) = -p_{\rm tot} + \sum_{i=n,p} \mu_i n_i,$$

$$p_i = \frac{1}{4}\left(E_i n_i - m_i^* n_i^{(s)}\right),$$

$$n_i = \frac{\Phi}{3\pi^3} k_i^3,$$

$$n_i^{(s)} = \frac{\Phi m_i^*}{2\pi^2}\left[E_i k_i - (m_i^*)^2 \ln \frac{k_i + E_i}{m_i^*}\right],$$

$$E_i = \sqrt{k_i^2 + (m_i^*)^2} = \mu_i - V_i - \frac{v}{\Phi} \sum_{j=p,n} p_j,$$

Effective mass: $m_i^* = m_i - S_i.$

Scalar meanfield: $S_i \sim n_i^{(s)}$

Vector meanfield: $V_i \sim n_i$

# 2. Stiff quark matter at high densities

S. Benic, Eur. Phys. J. A 50, 111 (2014)

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

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

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

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

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

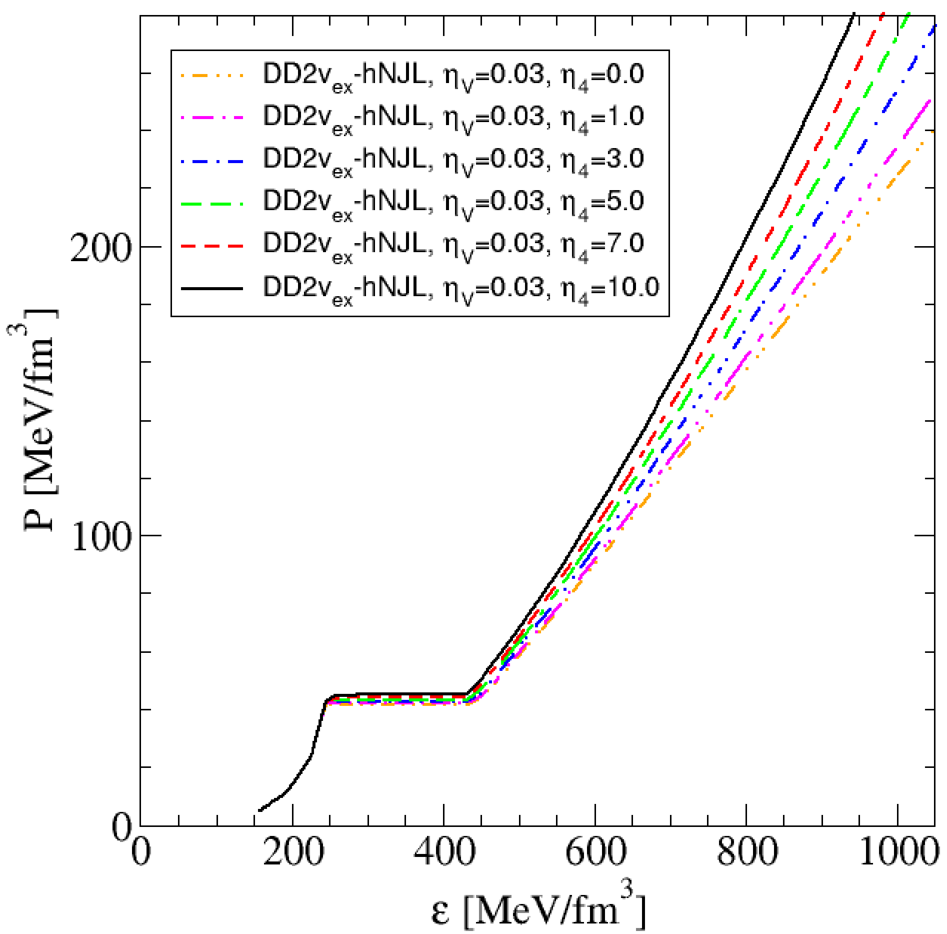
$$U = \frac{g_{20}}{\Lambda^2}\langle\bar{q}q\rangle^2 + 3\frac{g_{40}}{\Lambda^8}\langle\bar{q}q\rangle^4 - 3\frac{g_{22}}{\Lambda^8}\langle\bar{q}q\rangle^2\langle q^\dagger q\rangle^2 - \frac{g_{02}}{\Lambda^2}\langle q^\dagger q\rangle^2 - 3\frac{g_{04}}{\Lambda^8}\langle q^\dagger q\rangle^4 \,.$$

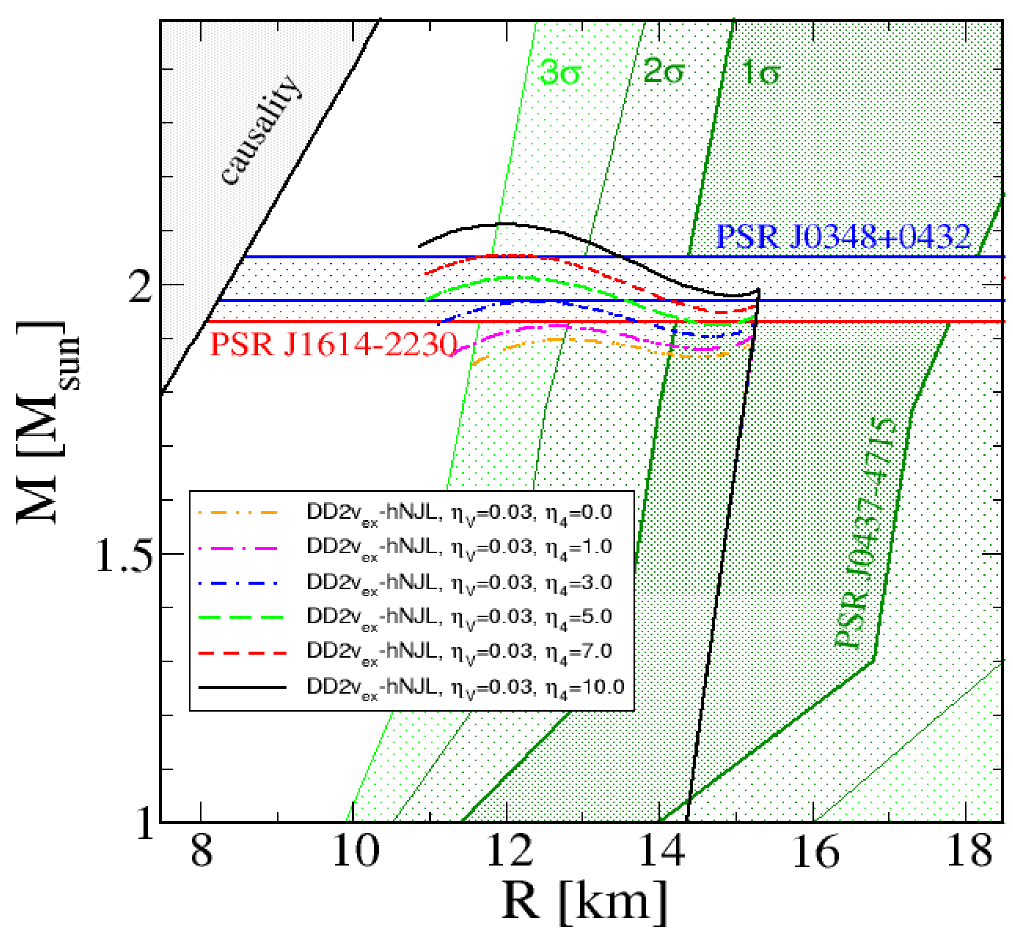
**Thermodynamic Potential:**

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

# Result: high-mass twins ↔ 1st order PT

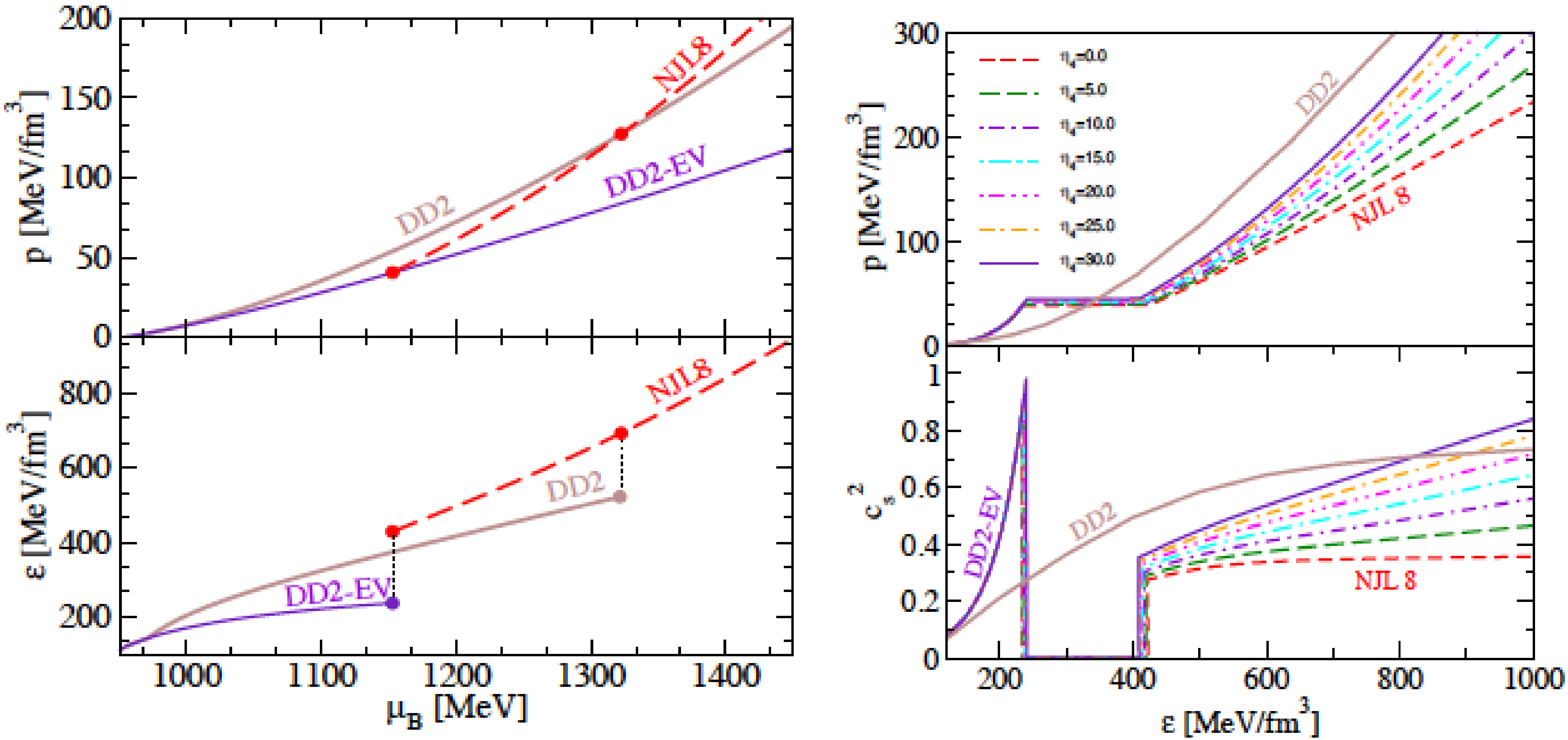
S. Benic, D. Blaschke, D. Alvarez-Castillo, T. Fischer, S. Typel, arxiv:1411.2856




**Hybrid EoS supports M-R sequences with high-mass twin compact stars**

# 2. Stiff quark matter at high densities

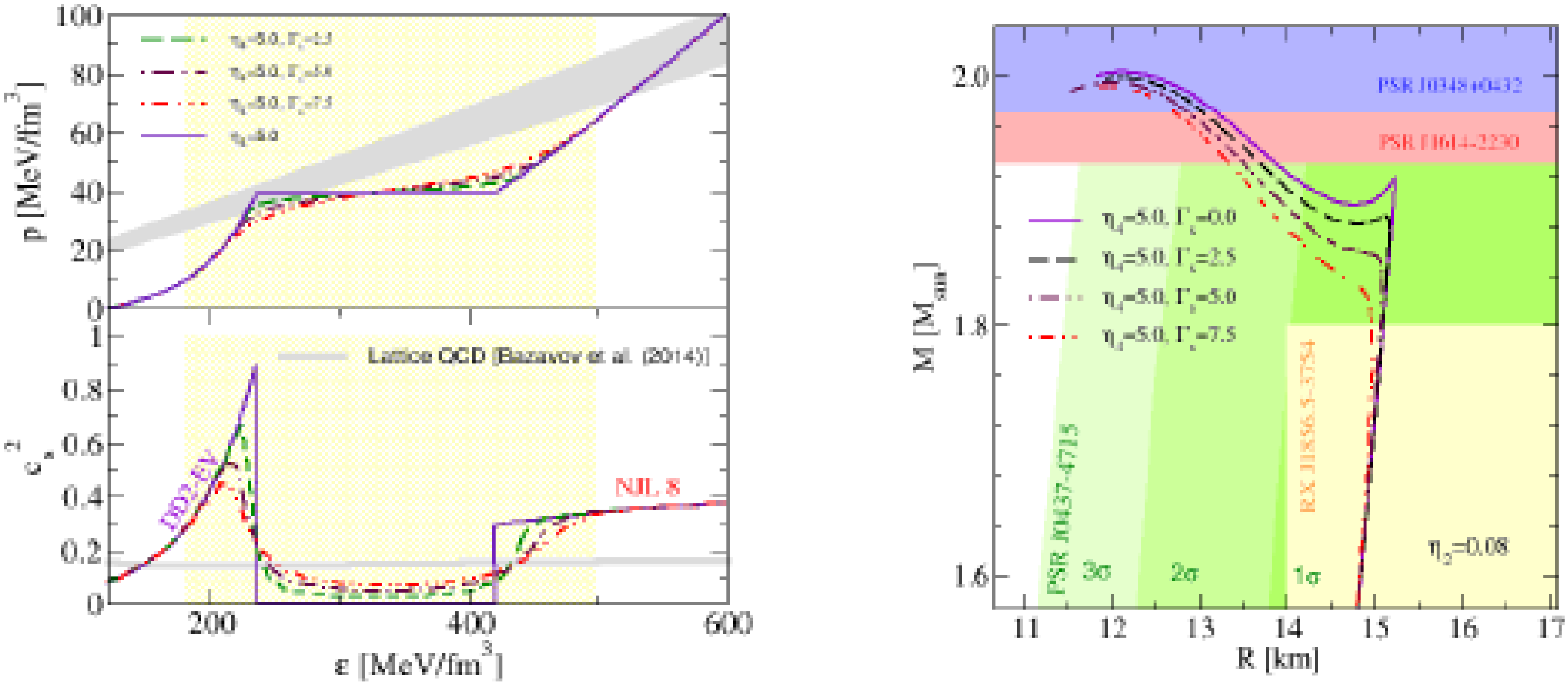



Here: Stiffening of dense hadronic matter by excluded volume in density-dependent RMF

S. Benic, D.B., D. Alvarez-Castillo, T. Fischer, S. Typel, A&A 577, A40 (2015) - STSM 2014

# 2. Stiff quark matter at high densities

Estimate effects of structures in the phase transition region (“pasta”)




High-mass Twins relatively robust against “smoothing” the Maxwell transition construction

D. Alvarez-Castillo, D.B., arxiv:1412.8463

# 3. Rotation

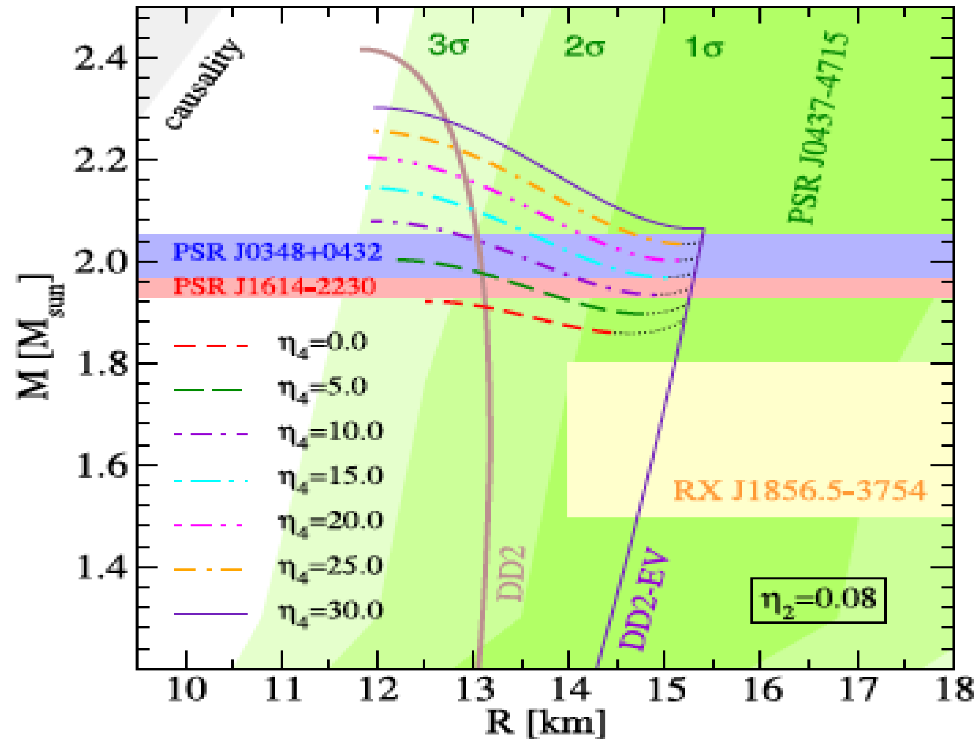
- existence of 2 M_sun pulsars and possibility of high-mass twins raises question for their inner structure: (Q)uark or (N)ucleon core ??
  --> degenerate solutions
  --> transition from N to Q branch

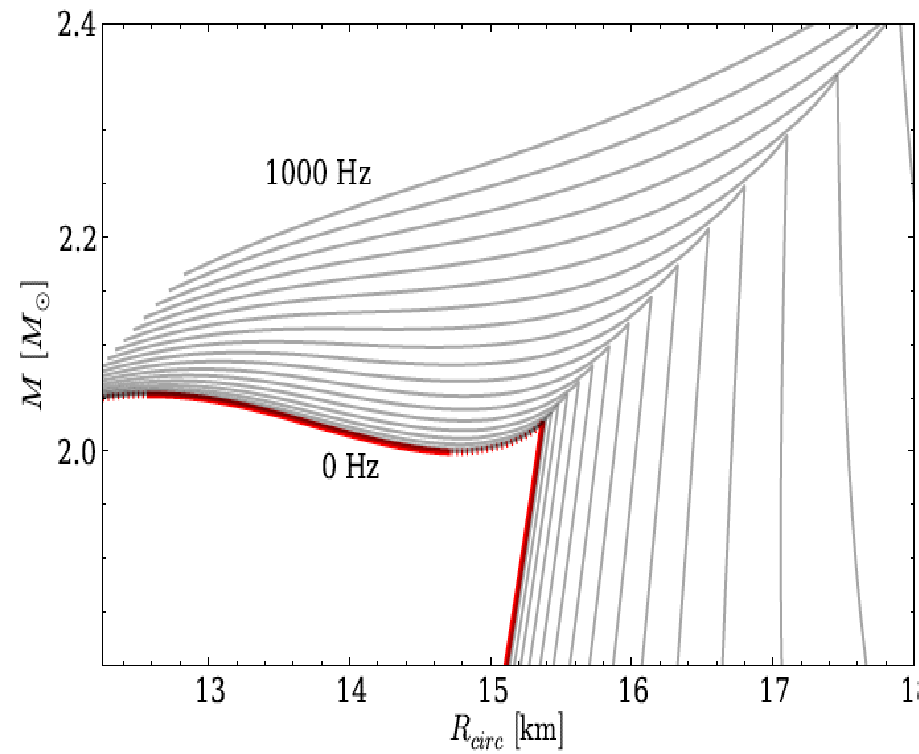
- PSR J1614-2230 is millisecond pulsar, period P = 3.41 ms, consider rotation !

- transitions N --> Q must be considered for rotating configurations:
  --> how fast can they be?

(angular momentum J and baryon mass should be conserved simultaneously)

- similar scenario as fast radio bursts (Falcke-Rezzolla, 2013) or braking index (Glendenning-Pei-Weber, 1997)




M. Bejger, D.B., work in preparation (2015)

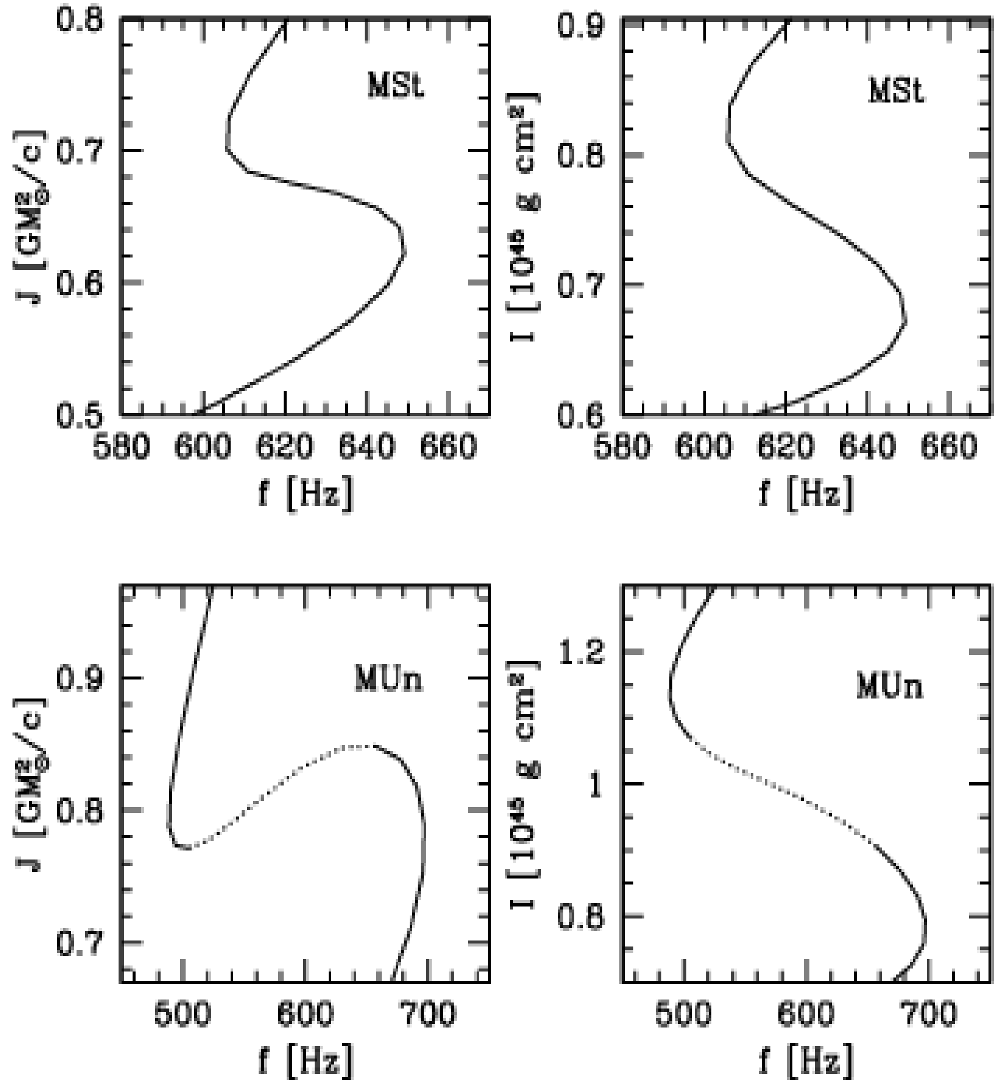
# 3.1. Rotation and stability

- ⋆ Back-bending is connected to the existence of a minimum of $M_b$ along $f = const.$ sequence,
- ⋆ *Change in stability* corresponds to extremum of $M$ or $M_b$ at fixed $J$:

$$\left(\frac{\partial M}{\partial \lambda_c}\right)_J = 0, \quad \left(\frac{\partial M_b}{\partial \lambda_c}\right)_J = 0,$$

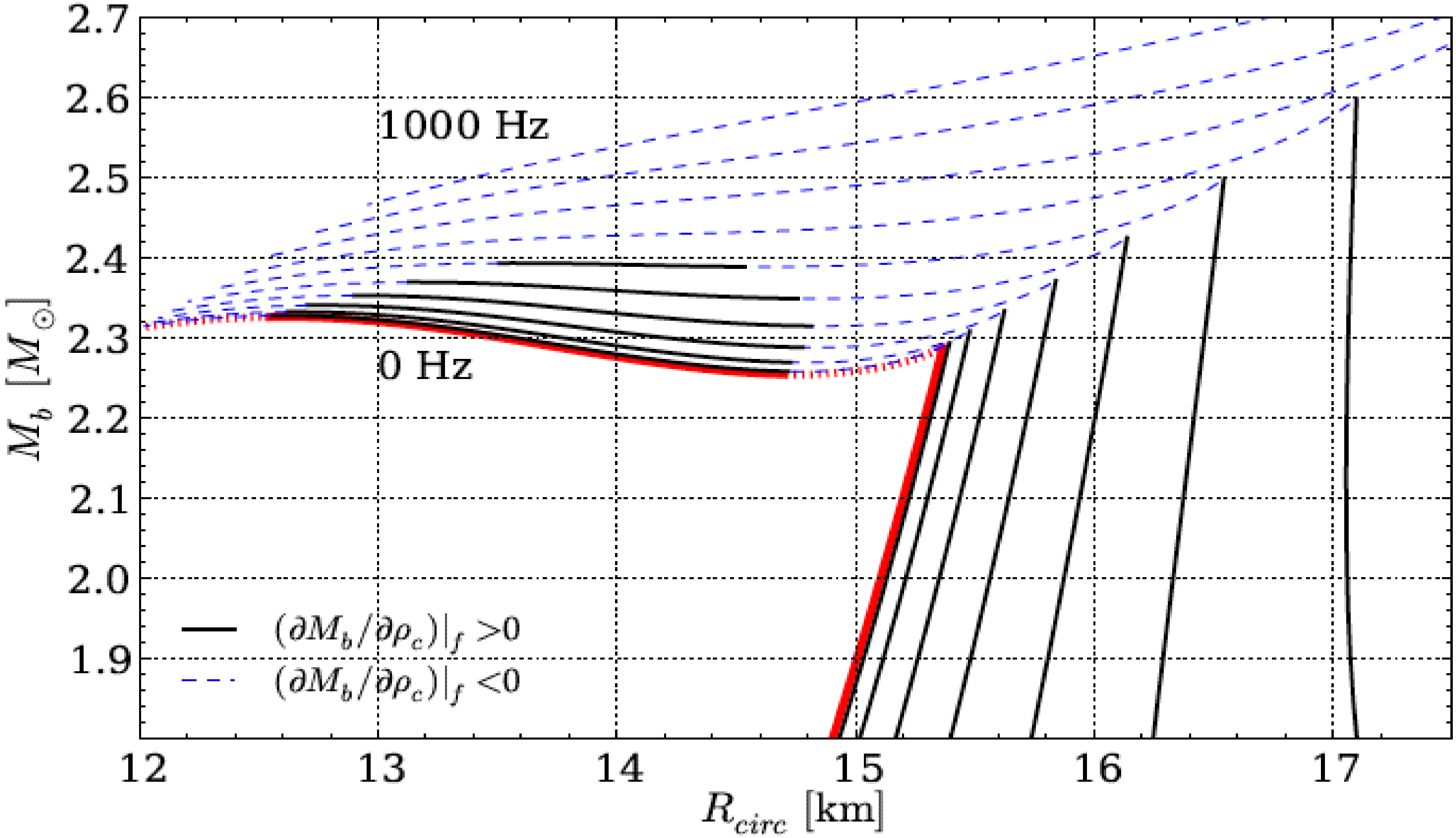
or to extremum of $J$ at fixed either $M$ or $M_b$:

$$\left(\frac{\partial J}{\partial \lambda_c}\right)_M = 0, \quad \left(\frac{\partial J}{\partial \lambda_c}\right)_{M_b} = 0.$$



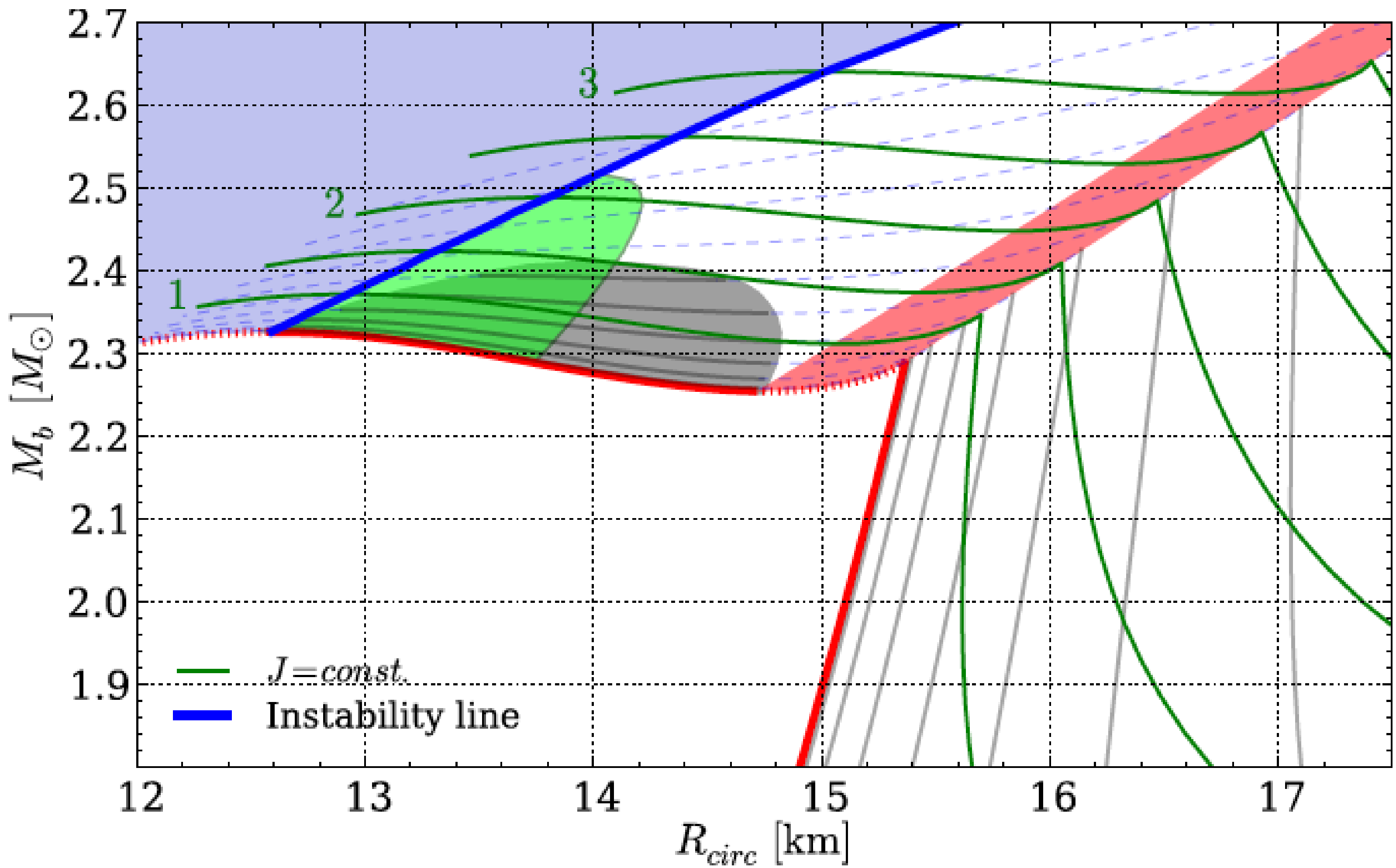

Zdunik, Bejger, Haensel, Gourgoulhon, A&A 450 (2006) 747

# 3.1. Rotation and stability



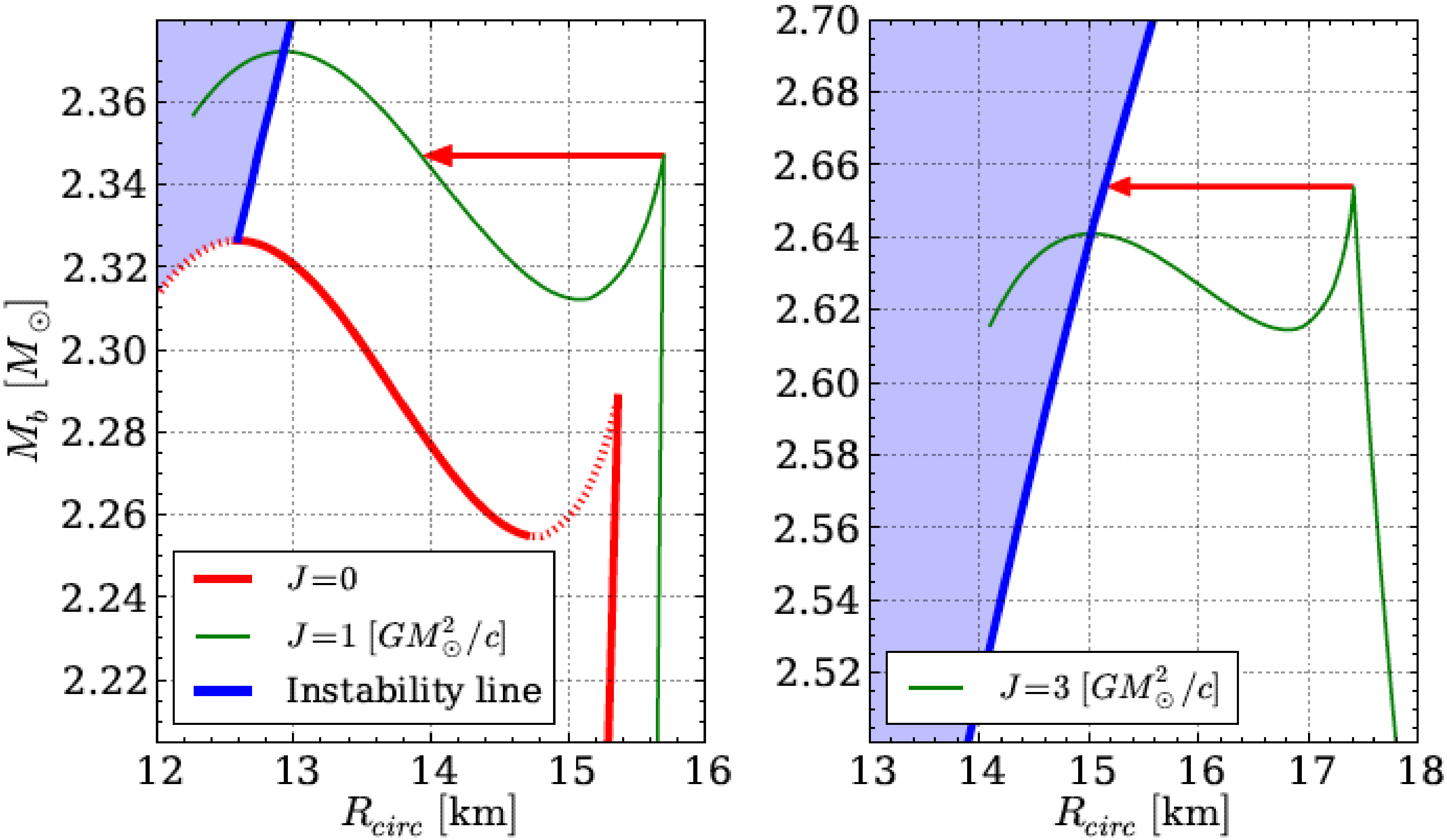

Large regions of backbending phenomenon
(NS spins up while losing angular momentum due to the dense matter EoS)

# 3.1. Rotation and stability



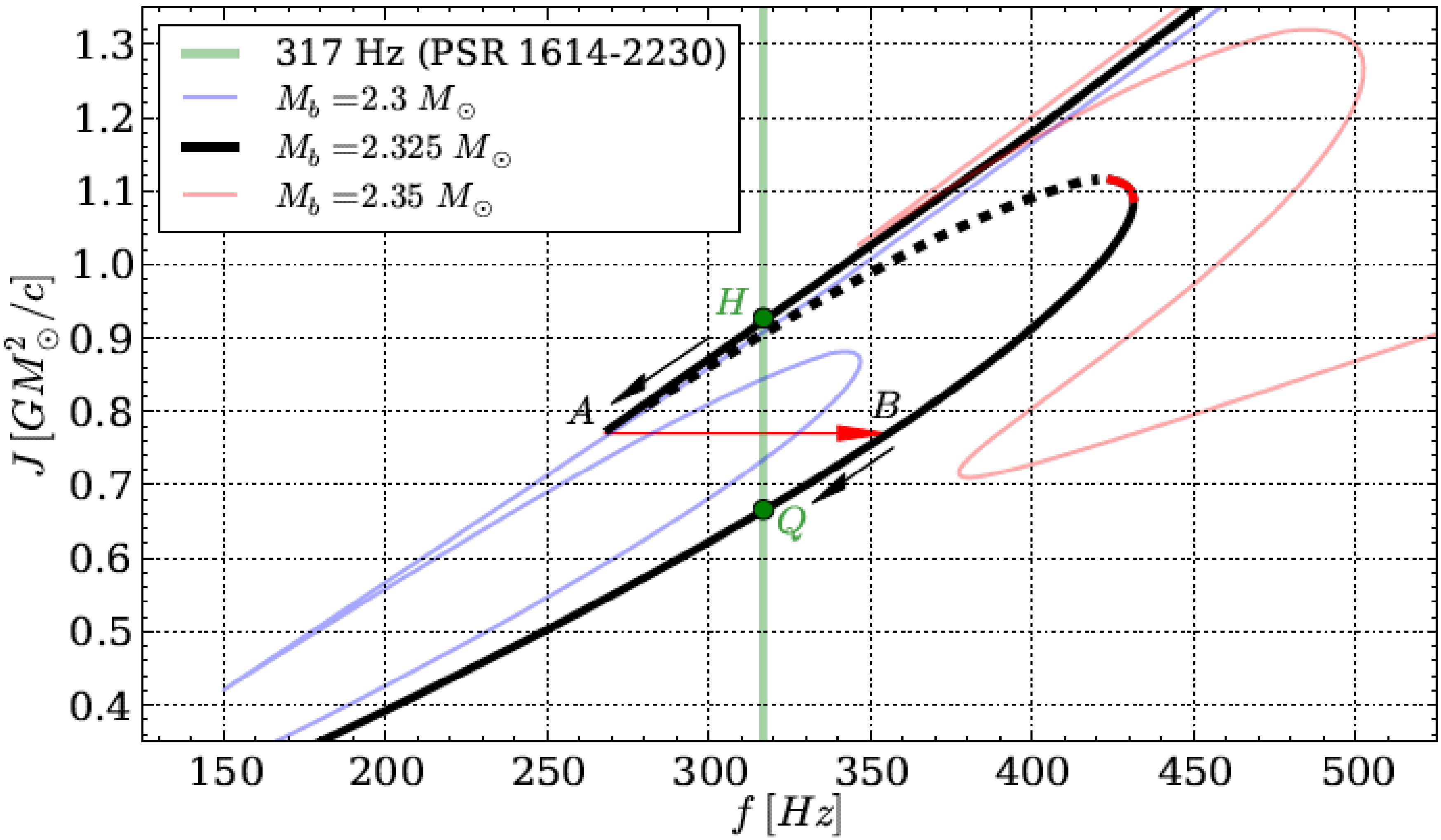

Red region - strong phase-transition instability,
Blue region - unstable w.r.t axisymmetric oscillations,
Grey region - no back-bending,
Green region - stable twin branch reached after the mini-collapse from the tip of $J = const.$ curve, along $M_b = const.$

# 3.1. Rotation and stability



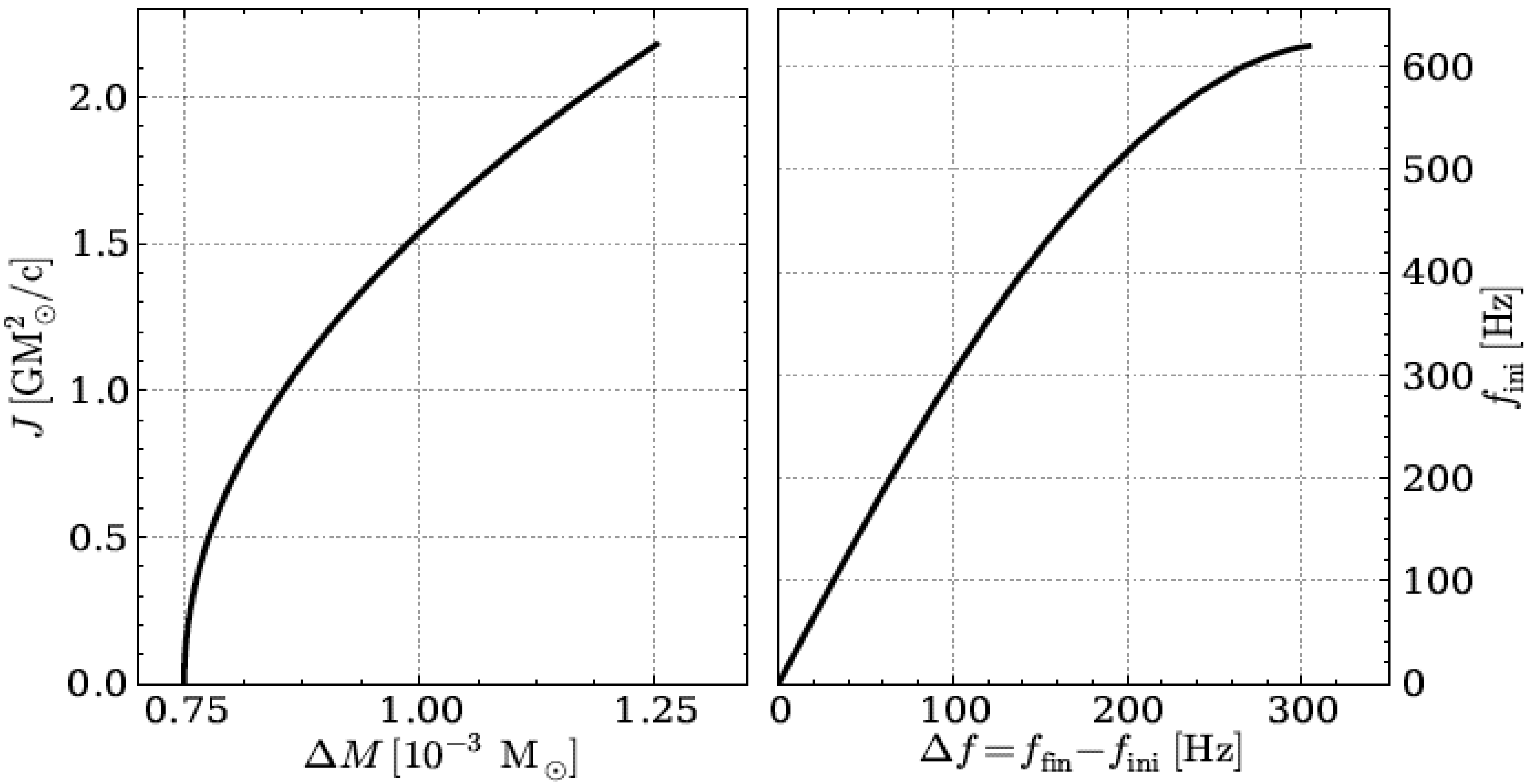

Stars with too much angular momentum *e.g., spun-up by accretion* end up in the instability.

# 3.2. Constraints from mass and frequency




For NSs with measured gravitational mass *M* and frequency - possibility to put limits on $M_b$, *J*, moment of inertia *I*, core EOS composition etc.

# 3.3. Energy release and spin-up (glitch)




**Left panel**: energy release (difference in the gravitational mass) vs $J$ of the configuration entering the strong phase-transition instability.
**Right panel**: spin-up $\Delta f$ (difference between the final and initial spin frequency) against the spin frequency of the initial configuration.

# 3. Rotation - summary

This type of instability EOS provides a ”natural” explanation for:

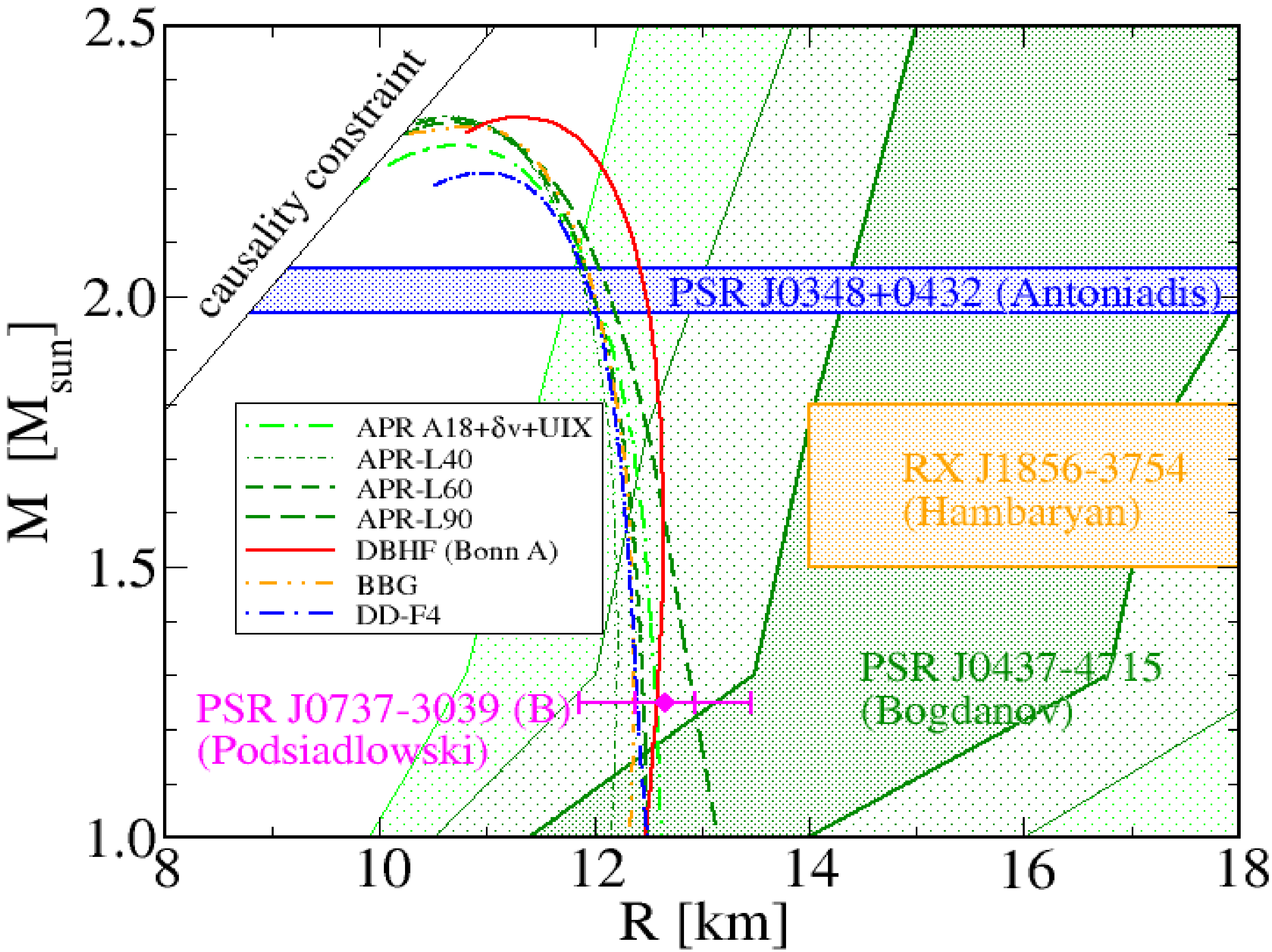
- ⋆ Lack of back-bending in radiopulsar timing,
- ⋆ Spin frequency cut-off at some moderate (but >716 Hz) frequency,
- ⋆ Falcke & Rezzolla Fast Radio Burst (FRB) engine
  - ⋆ catastrophic mini-collapse to the second branch (or to a black hole),
  - ⋆ massive rearrangement of the magnetic field → energy emission.

Astrophysical predictions:

- ⋆ Way to constraint on $M_b$, $J$, $I$, core EOS etc.,
- ⋆ Specific shape of NS-BH mass function (no mass gap?)
- → population of massive, low B-field NSs (radio-dead?),
- → population of massive, high B-field NSs (collapse enhances the field?),
- ⋆ Characteristic burst-like signature in GW emission during the mini-collapse.

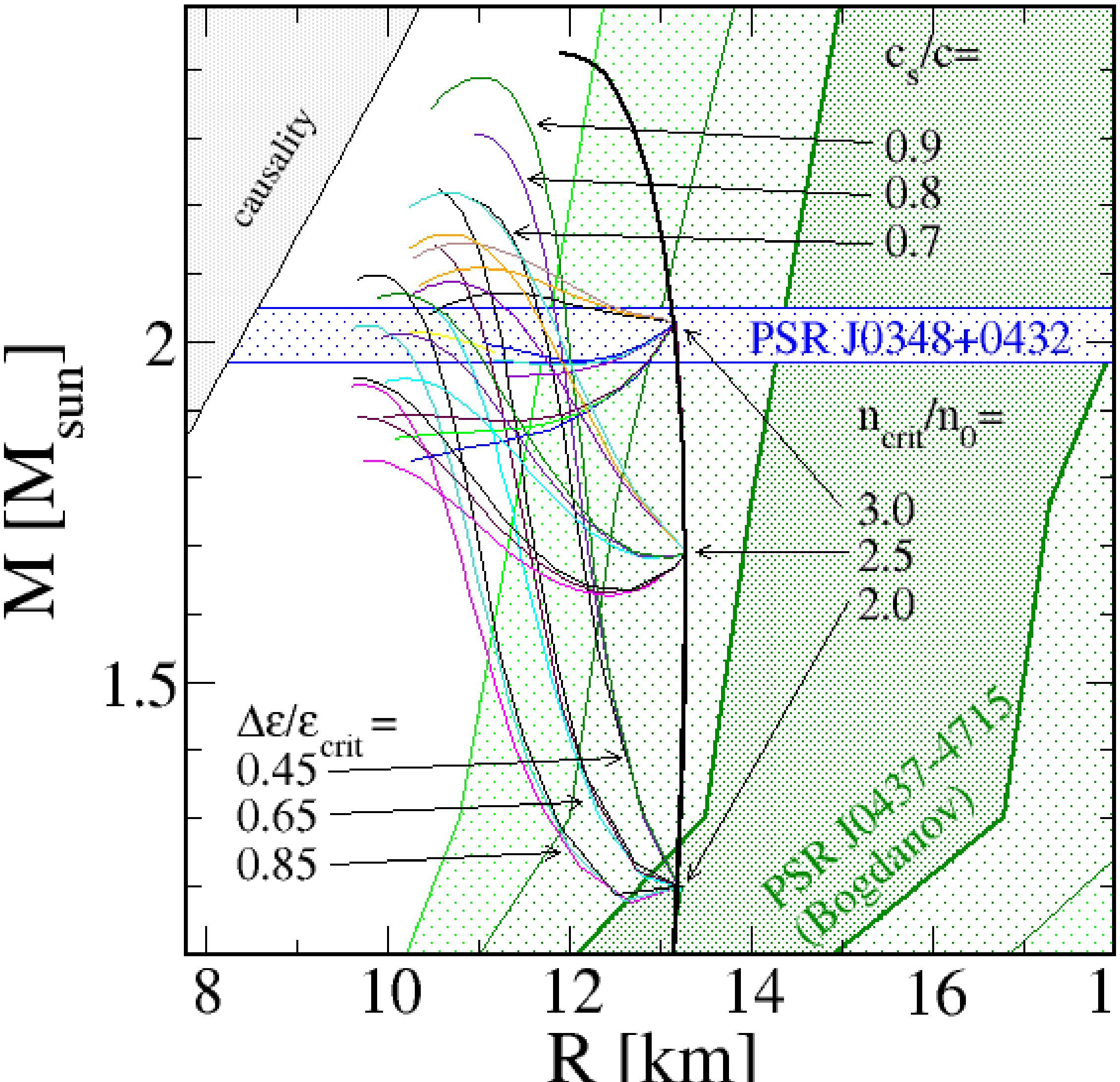
# 4. New Bayesian Analysis scheme

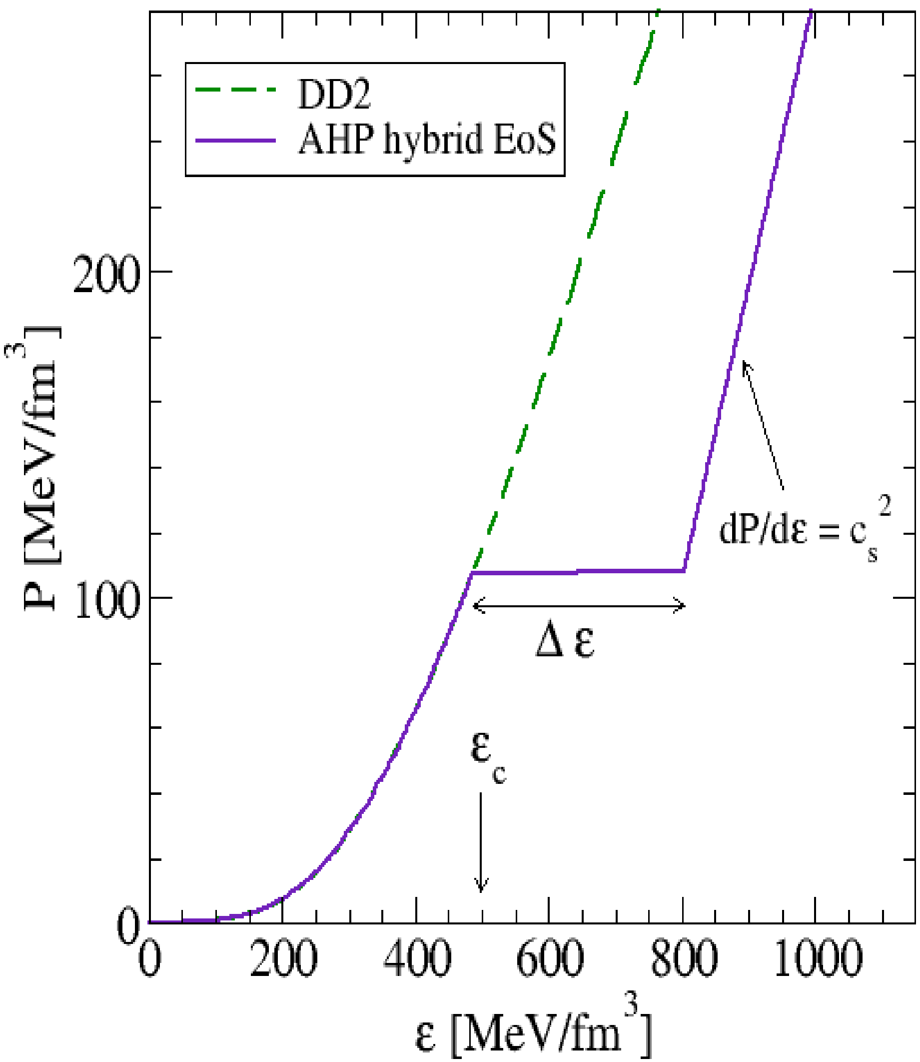
# Disjunct M-R constraints for Bayesian analysis !




Alvarez, Ayriyan, Blaschke, Grigorian, J. Phys. Conf. Ser. (2014)

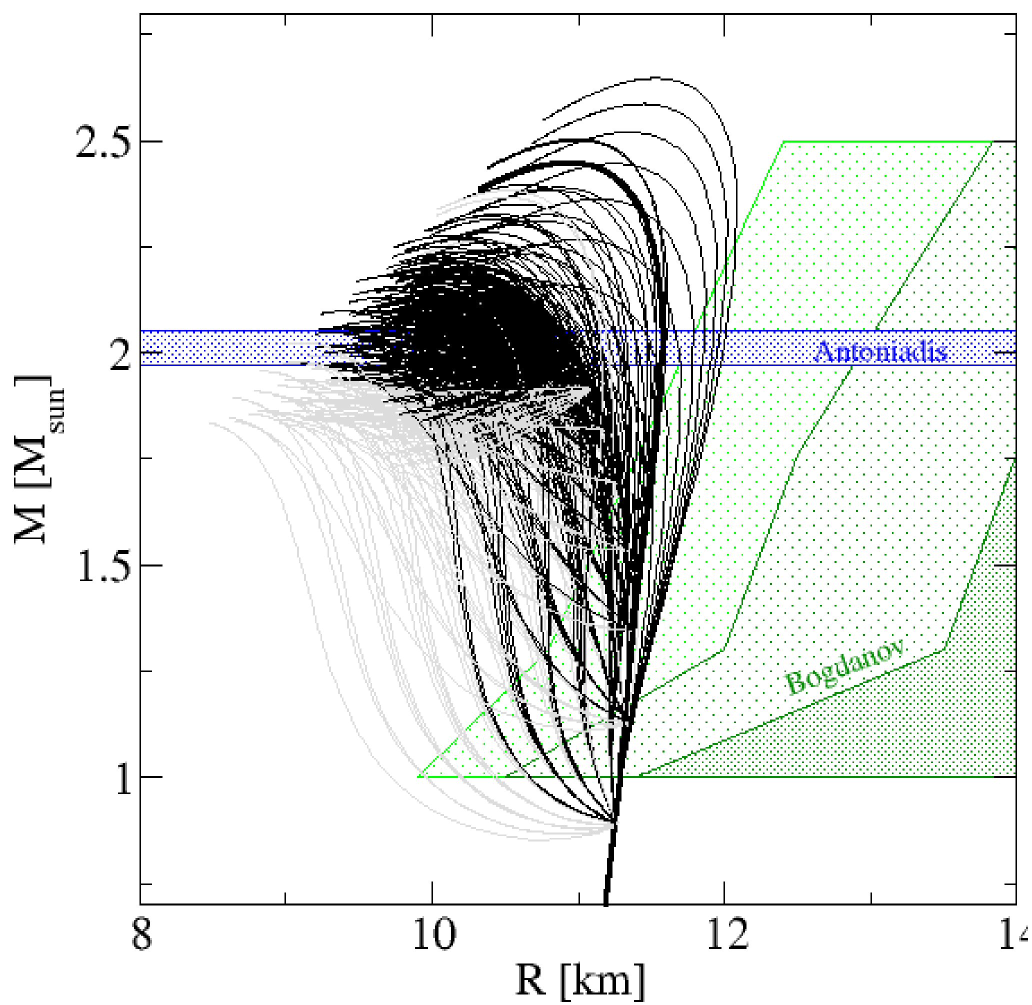
# Disjunct M-R constraints for Bayesian analysis !

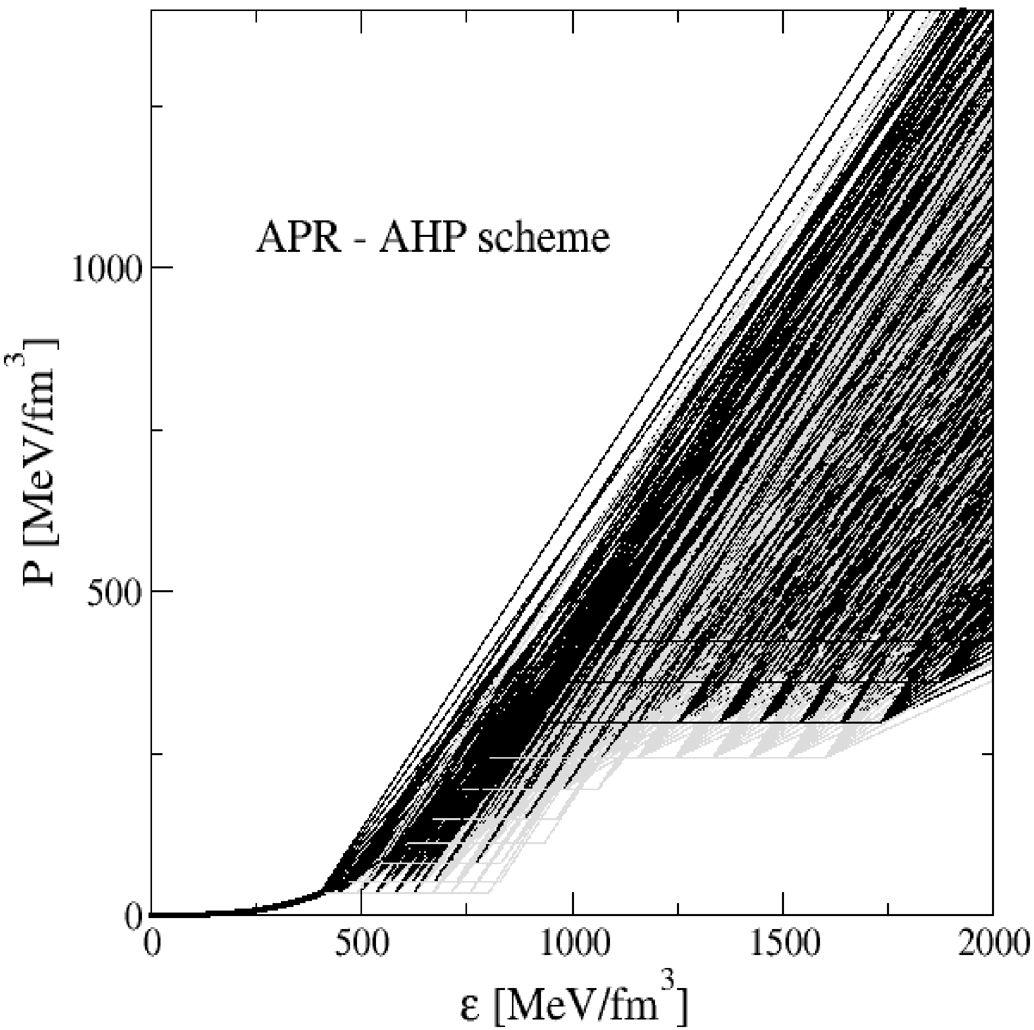



Blaschke, Grigorian, Alvarez, Ayriyan, J. Phys. Conf. Ser. 496 (2014) 012002

# Disjunct M-R constraints for Bayesian analysis !




Blaschke, Grigorian, Alvarez, Ayriyan, J. Phys. Conf. Ser. 496 (2014) 012002

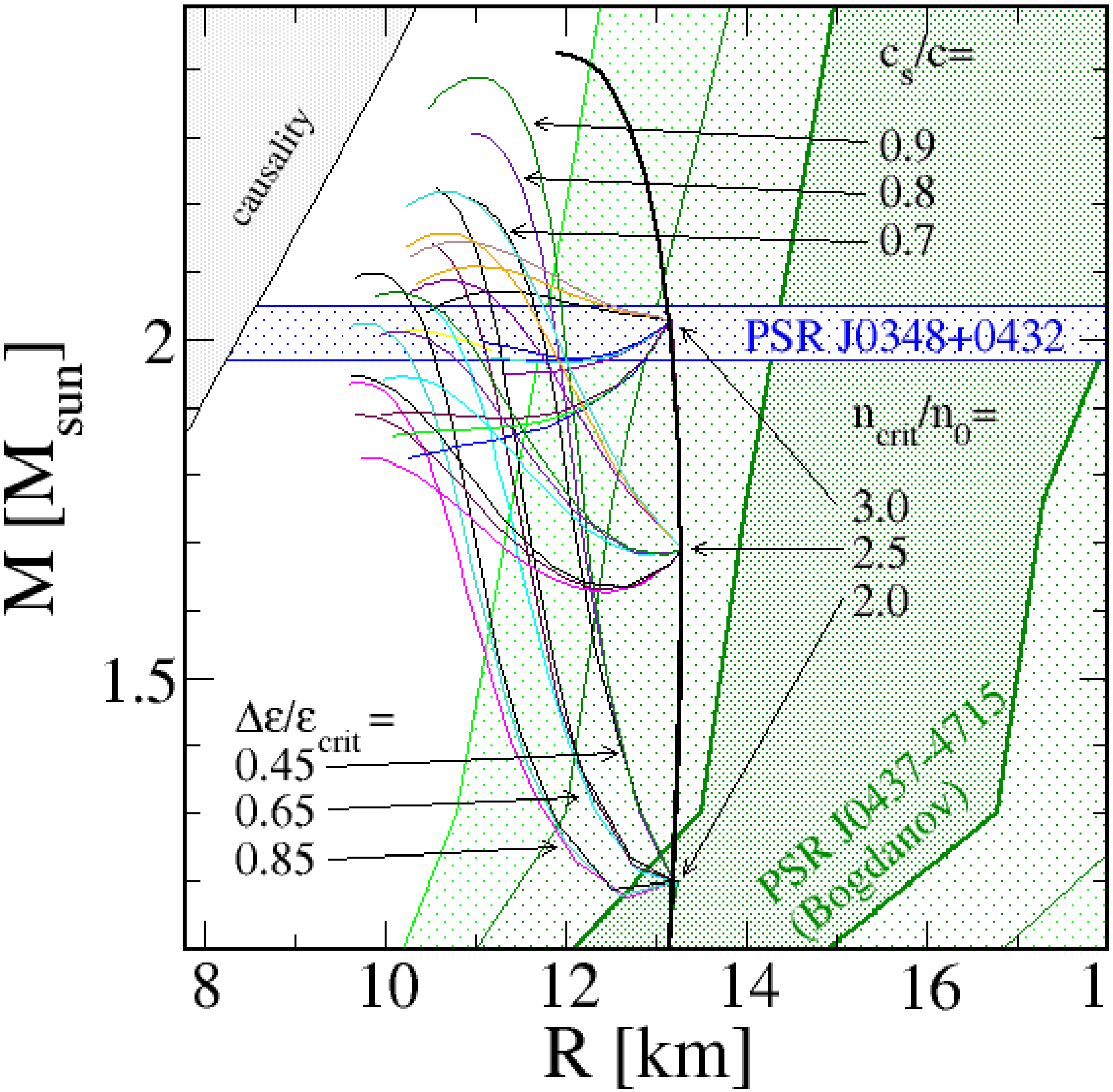
# Phase transition? Measure different radii at 2Mo !

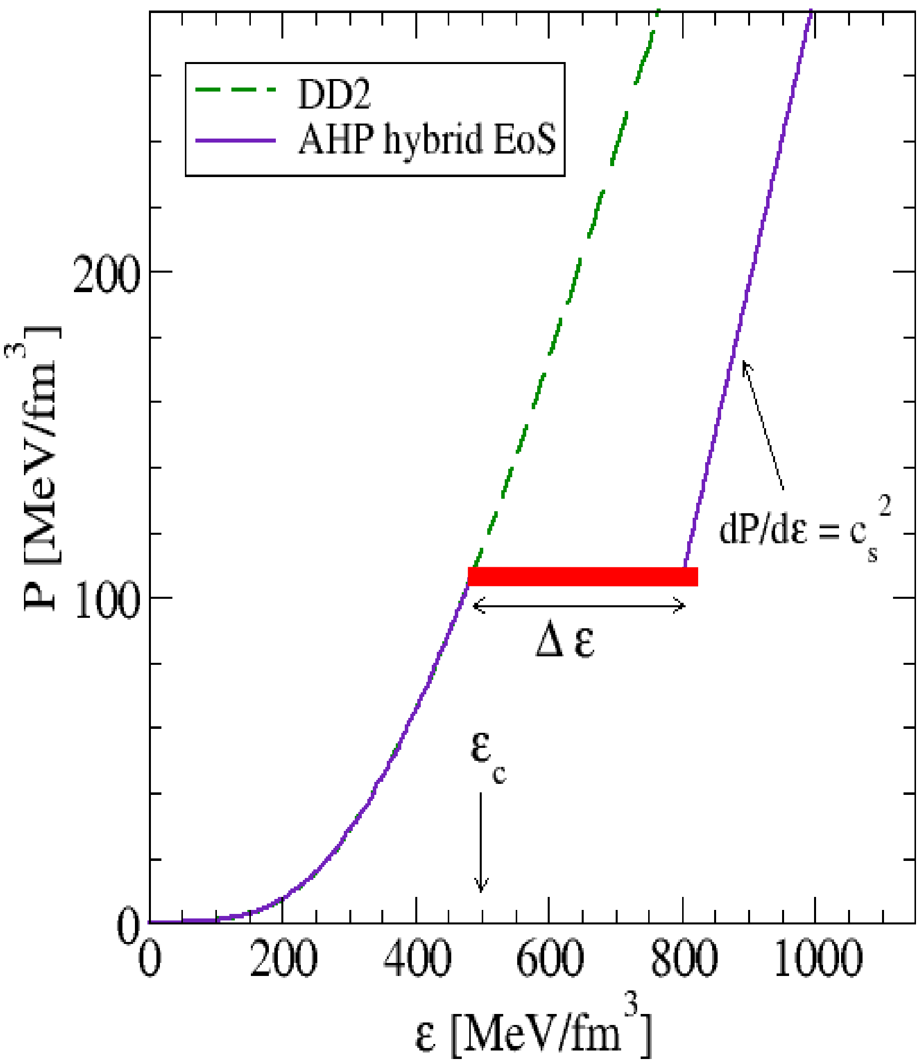
"Now let us travel into future. It is year **2017**, some new, reliable NS radius measurement methods are discovered and were used to find the size of two most massive pulsars, which still are PSR J0348+0432 and PSR J1614-2230. **The community was shocked** when received the results of observations: one radius is $13 \pm 0.5\ \mathrm{km}$, while the other is $11 \pm 0.5\ \mathrm{km}$!"

– *Michał Sokołowski*, Master Thesis, 2014

**Alvarez, Ayriyan, Blaschke, Grigorian, Sokolowski (in progress, 2014)**

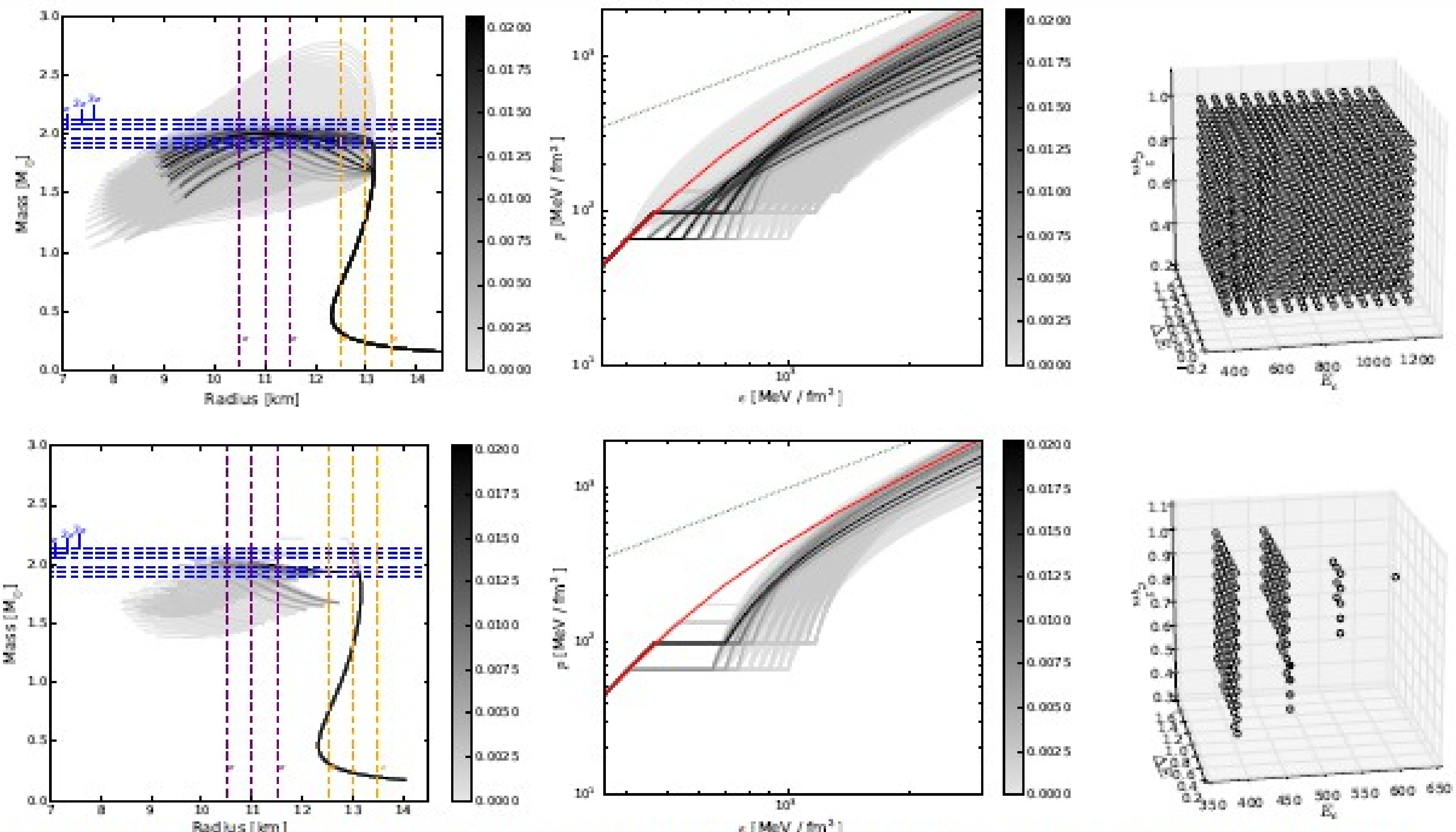
# Phase transition? Measure different radii at 2Mo !




**Alvarez, Ayriyan, Blaschke, Grigorian, Sokolowski, arxiv:1412.8226 (2014)**

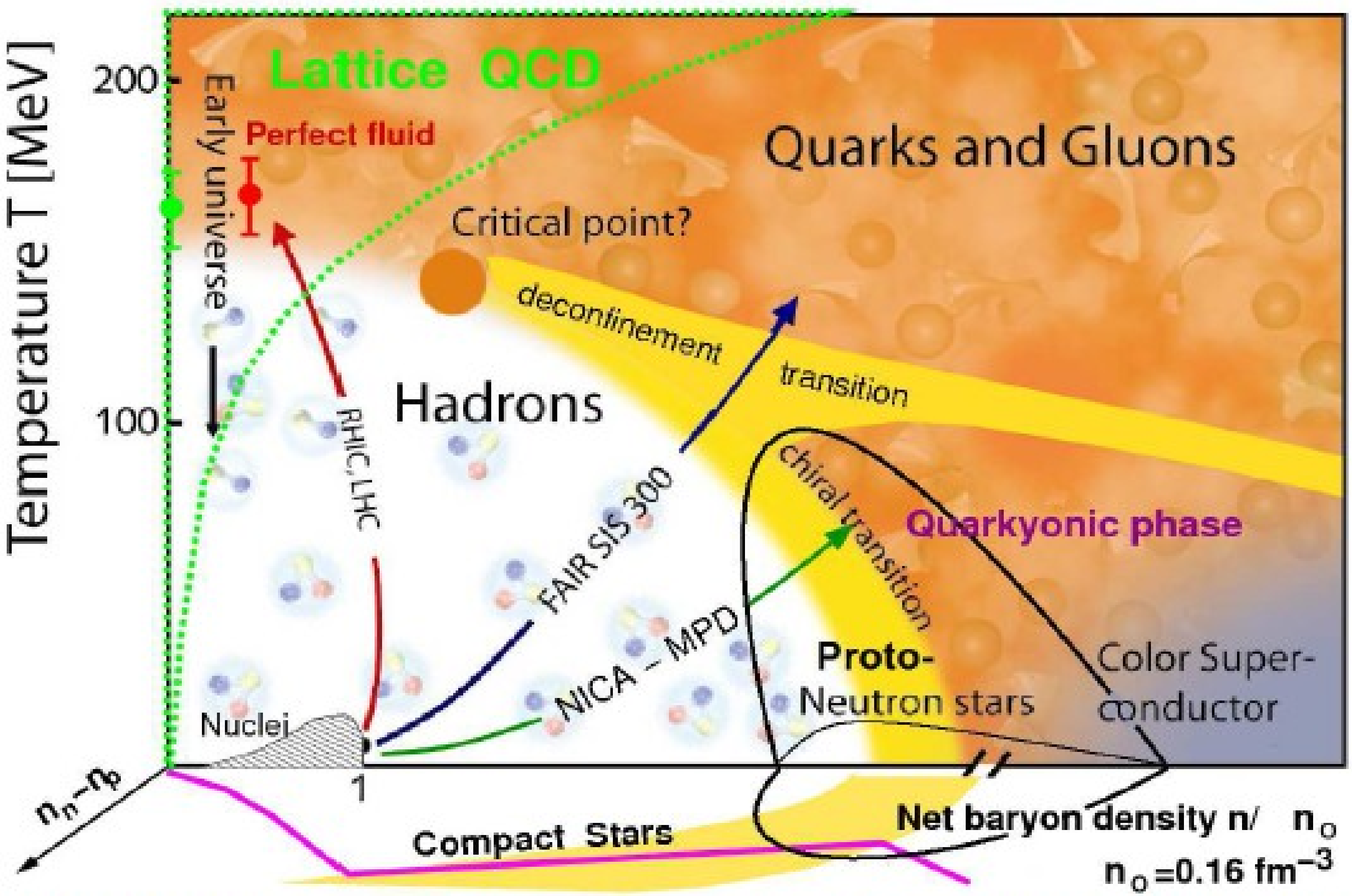
# Phase transition? Measure different radii at 2Mo !




BA of HEoS models based on pure DD2 with fictitious radius measurements.

Alvarez, Ayriyan, Blaschke, Grigorian, Sokolowski, arxiv:1412.8226 (2014)

# Support a CEP in QCD phase diagram with Astrophysics?




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

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

# Summary: New Class of Hybrid EoS

**Modern topics (selected):**

- QCD phase diagram: critical point (D. Alvarez, DB, S. Benic et al.)
- Hyperon puzzle (M. Baldo et al.; P. Haensel at al..; ...)
- Direct Urca problem  (T. Klaehn et al.)
- Supernova explosion mechanism  (T. Fischer et al.)

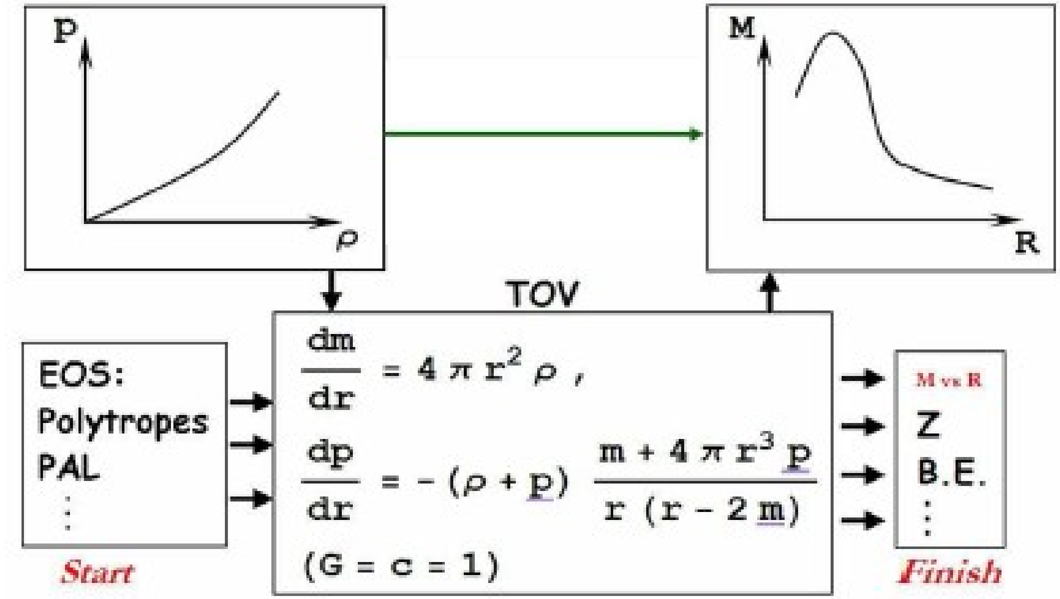
**Solutions can be provided by**

- Stiffening of hadronic matter by quark substructure effects
  (Pauli blocking: DB, H.Grigorian, G.Roepke → excluded vol: S.Typel)
- Stiffening of quark matter at high densities
  (e.g., by multiquark interactions: S. Benic et al.)
- Resulting early onset of quark matter and large latent heat

**Cross-talk with Heavy-Ion Collision Experiments**

# 5. Rescue kit slides ...

# Goal 1: Measure the cold EoS !



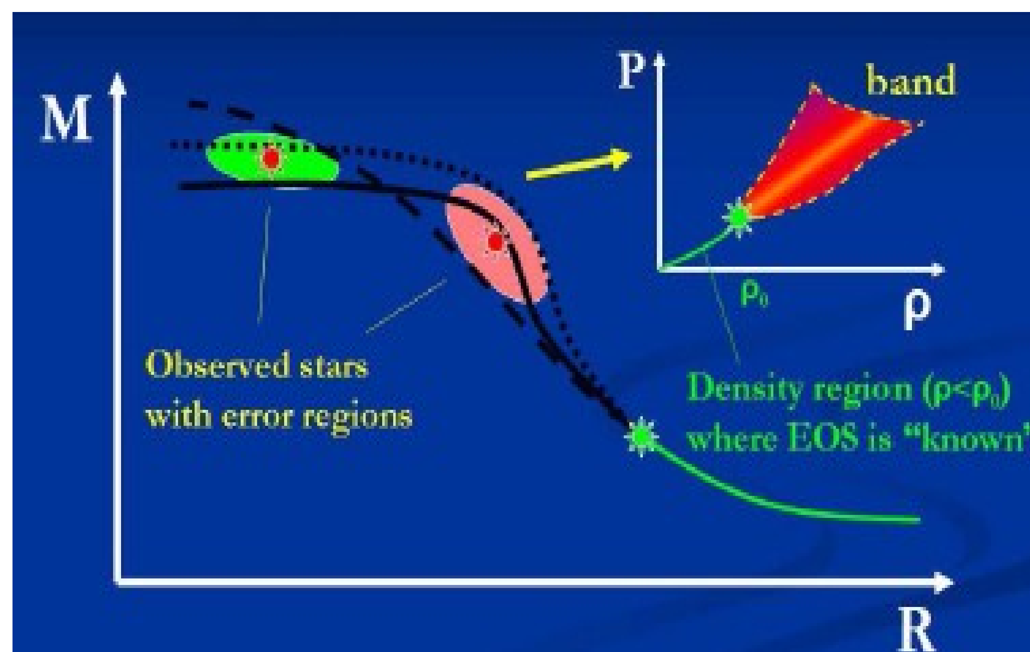

**Direct approach:**

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

**Idea: Invert the approach**

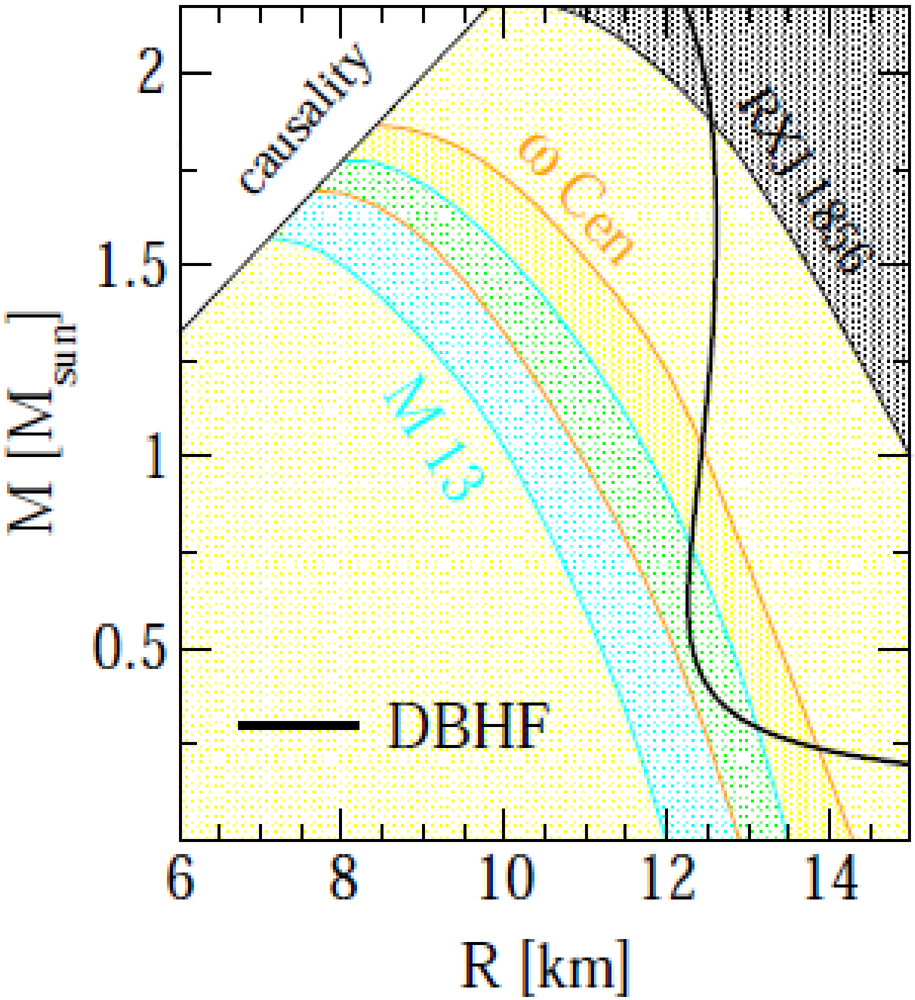
Given M(R) → find the EoS

**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 $T_\infty$

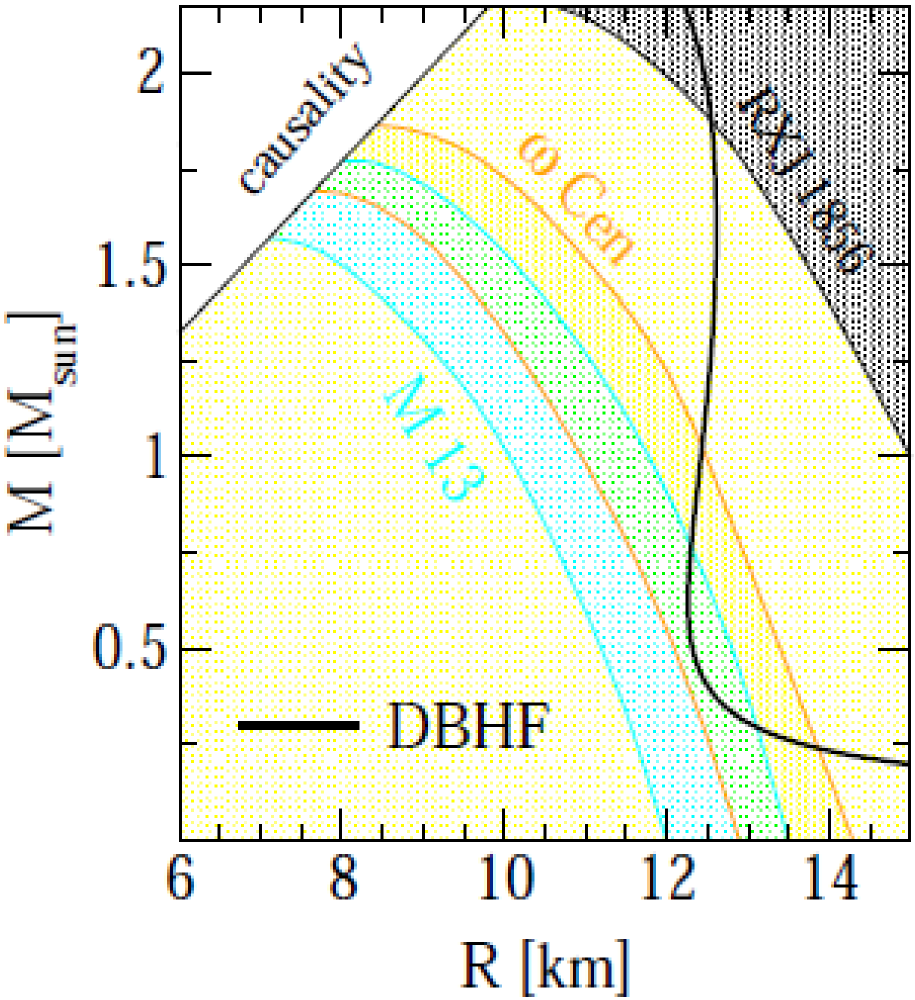
→ photospheric radius

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

| Object | $R_\infty$ [km] | Reference |
|---|---|---|
| RXJ 1856 | 16.8 | Trümper et al. (2004) |
| $\omega$Cen | 13.6 $\pm$0.3 | Gendre et al. (2003) |
| M13 | 12.8 $\pm$0.4 | Gendre et al. (2004) |

Lower limit from RXJ 1856 incompatible with $\omega$ Cen and M13 ?

# Measure masses and radii of CS!




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

→ effective temperature $T_\infty$

→ photospheric radius

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

| Object | $R_\infty$ [km] | Reference |
|---|---|---|
| RXJ 1856 | 16.8 | Trümper et al. (2004) |
| $\omega$Cen | 13.6 $\pm$0.3 | Gendre et al. (2003) |
| M13 | 12.8 $\pm$0.4 | Gendre et al. (2004) |

Lower limit from RXJ 1856 incompatible with $\omega$ Cen and M13 ?

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

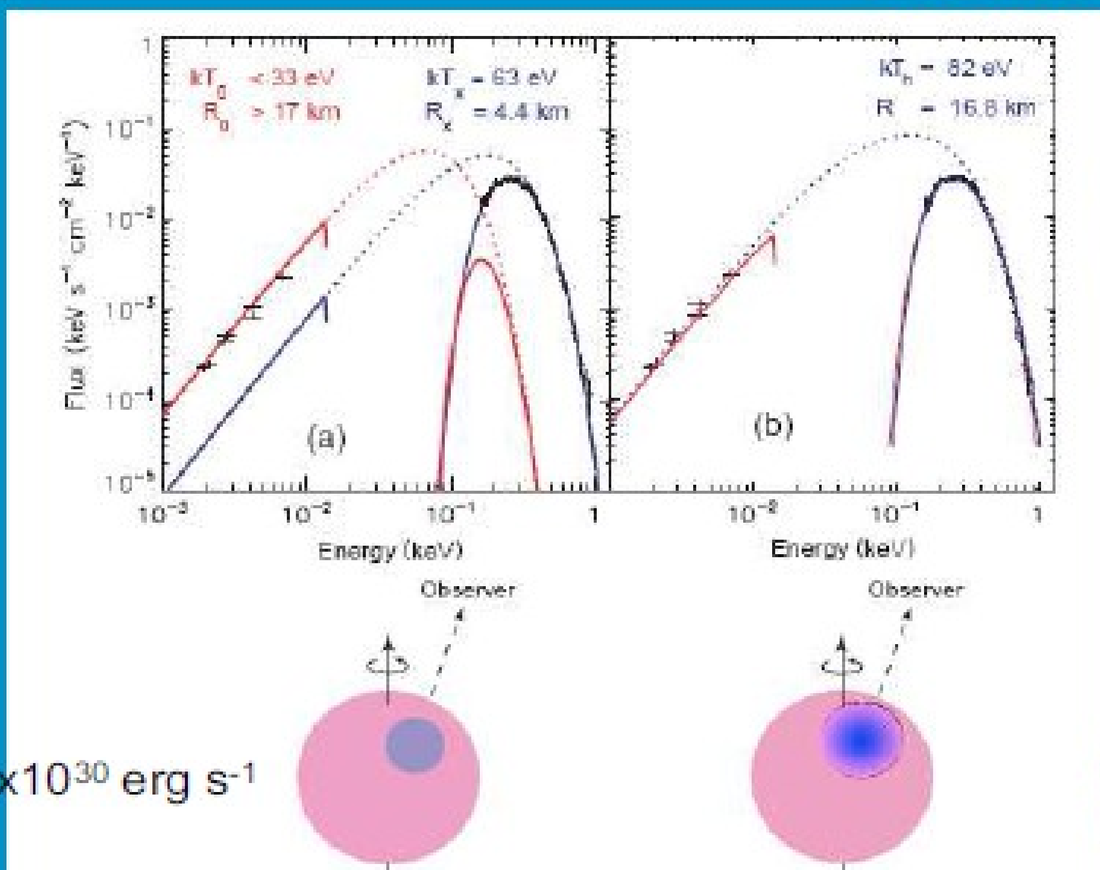
# The lesson learned from RX J1856

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?

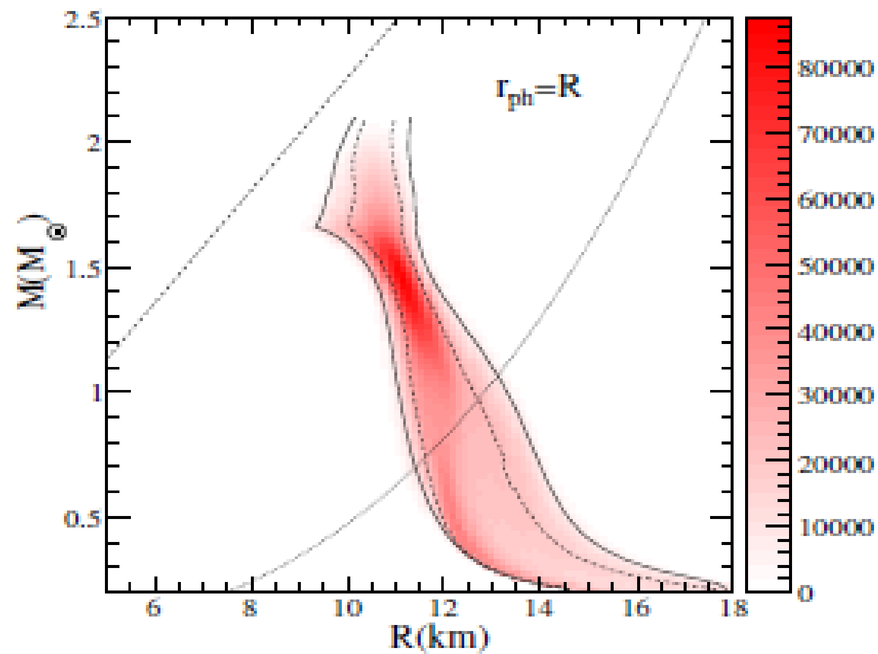
X-ray emitting region is a "hot spot", J. Trumper et al., Nucl. Phys. Proc. Suppl. 132 (2004) 560

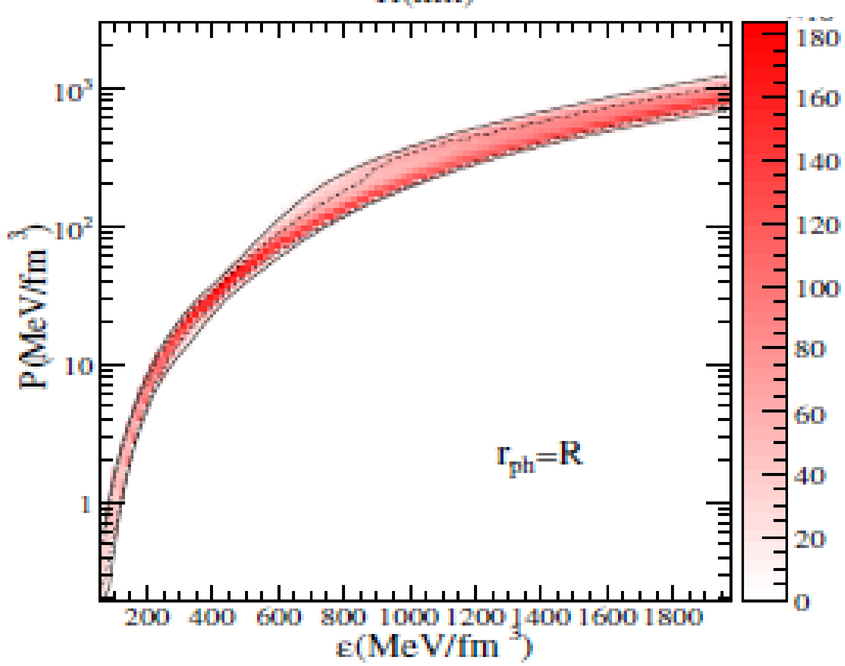
# Goal 1: Measure the cold EoS !

**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 | $M$ ($M_\odot$) $r_{ph} = R$ | $R$ (km) $r_{ph} = R$ | $M$ ($M_\odot$) $r_{ph} \gg R$ | $R$ (km) $r_{ph} \gg R$ |
|---|---|---|---|---|
| 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 | $1.48^{+0.21}_{-0.64}$ | $11.04^{+1.00}_{-1.28}$ | $0.901^{+0.28}_{-0.12}$ | $12.21^{+0.18}_{-0.62}$ |
| $\omega$ 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 | $0.832^{+1.19}_{-0.051}$ | $13.25^{+1.37}_{-3.50}$ | $1.98^{+0.10}_{-0.36}$ | $11.3^{+0.95}_{-1.03}$ |

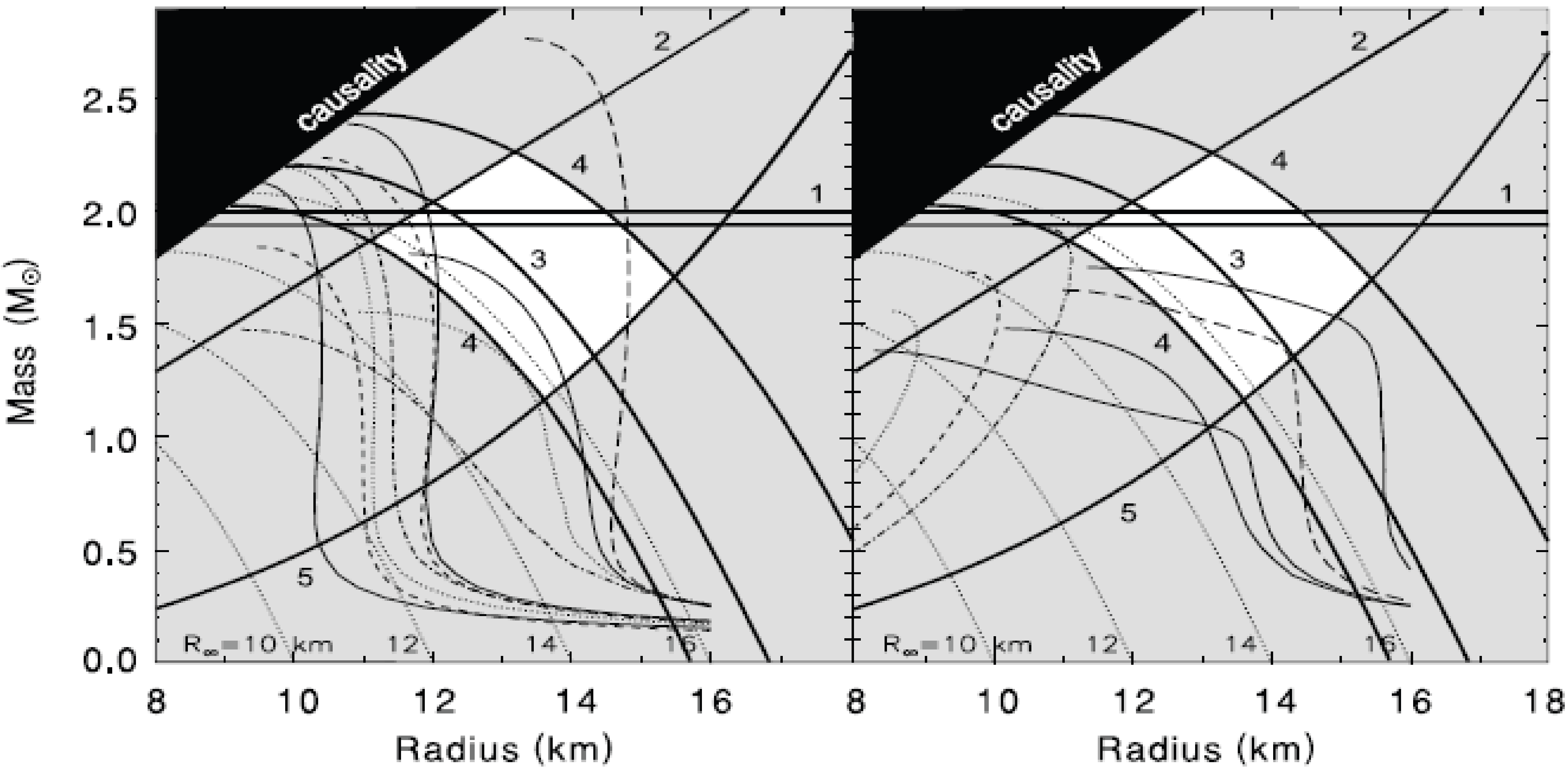



**Caution:**
If optical spectra are not measured, the observed X-ray spectrum may not come from the entire surface But from a hot spot at the magnetic pole!
J. Trumper, Prog. Part. Nucl. Phys. 66 (2011) 674

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

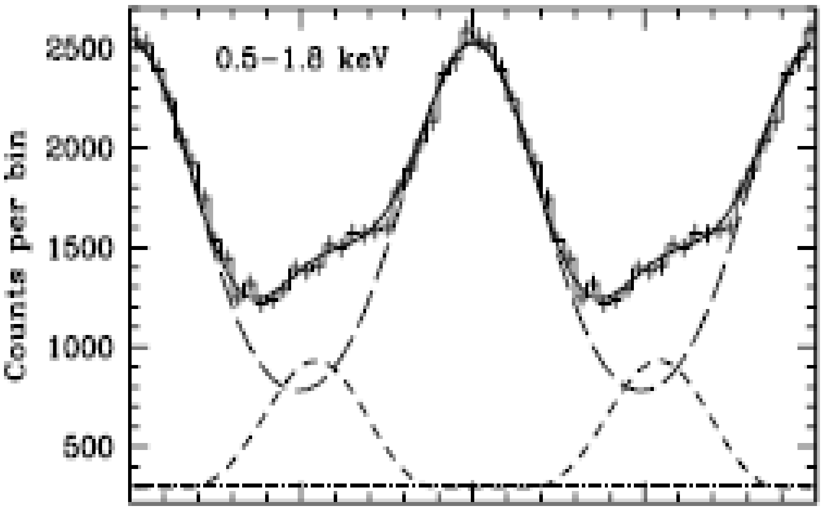
# Which constraints can be trusted ?

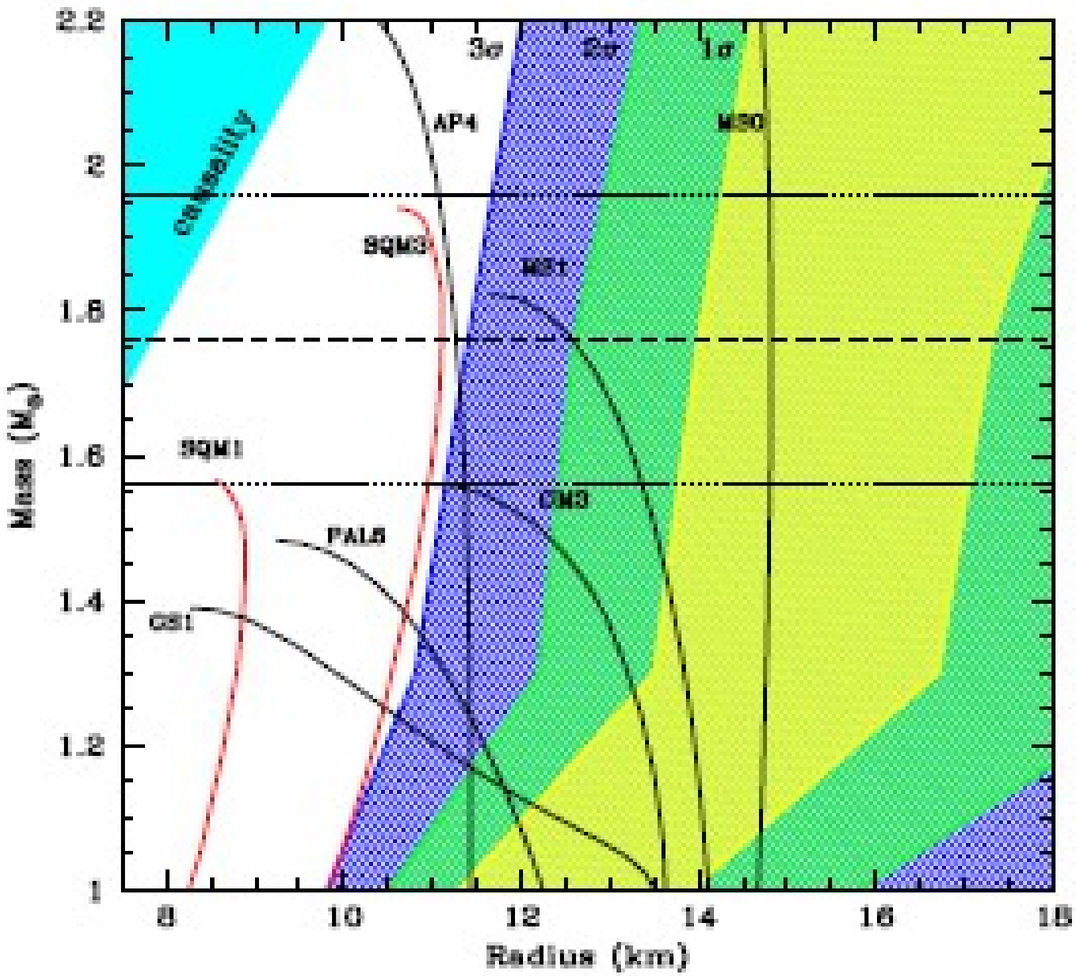



1 – Largest mass J1614 – 2230 (Demorest et al. 2010)
2 – Maximum gravity XTE 1814 – 338 (Bhattacharyya et al. (2005)
3 – Minimum radius RXJ 1856 – 3754 (Trumper et al. 2004)
4 – Radius, 90% confidence limits LMXB X7 in 47 Tuc (Heinke et al. 2006)
5 – Largest spin frequency J1748 – 2446 (Hessels et al.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



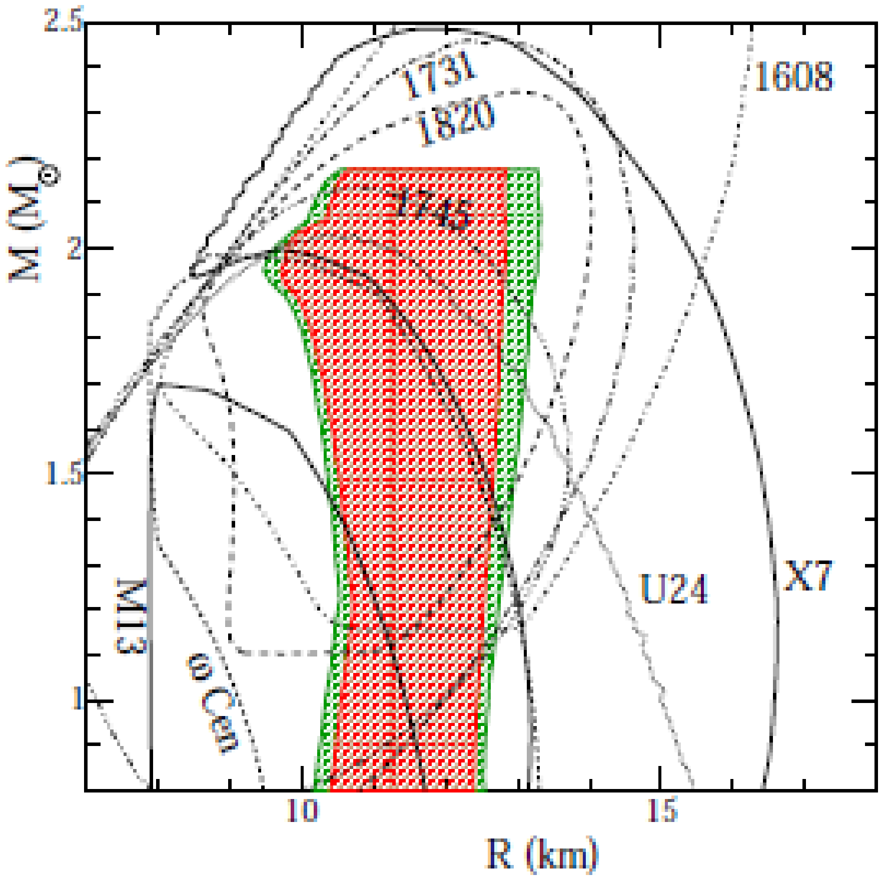



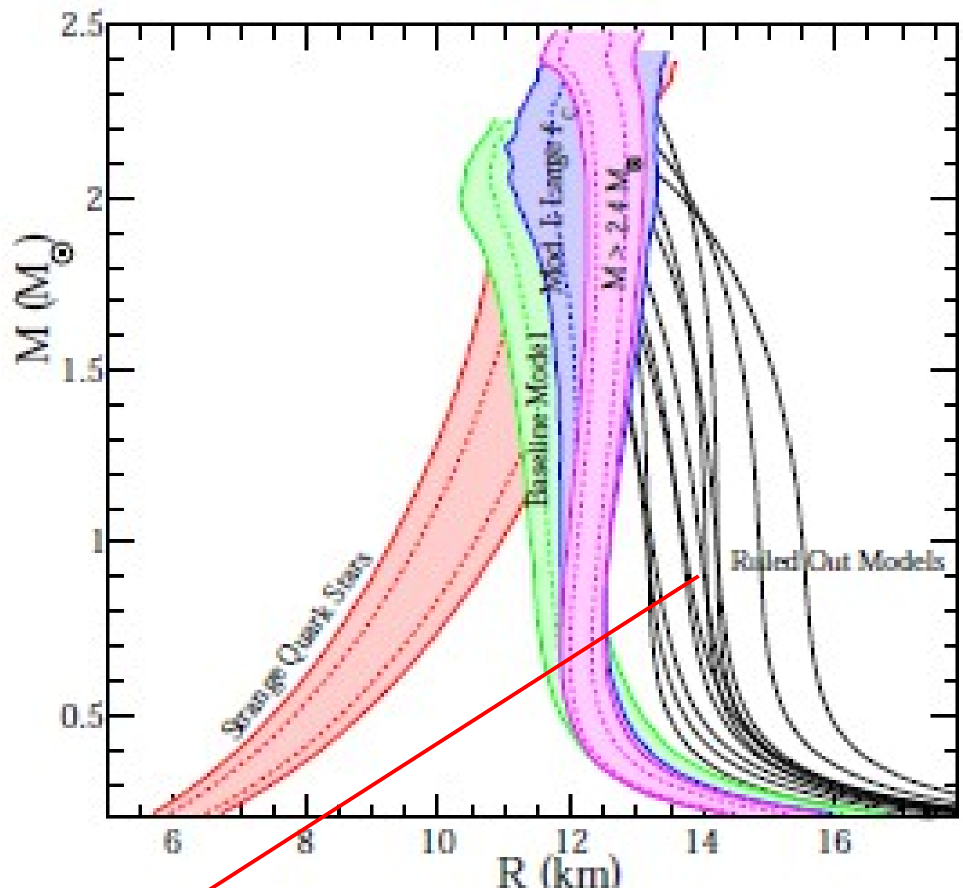

Three thermal component fit
R > 11.1 km (at 3 sigma level)
M = 1.76 M_sun

S. Bogdanov, arxiv:1211.6113 (2012)

# Which constraints require caution ?

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



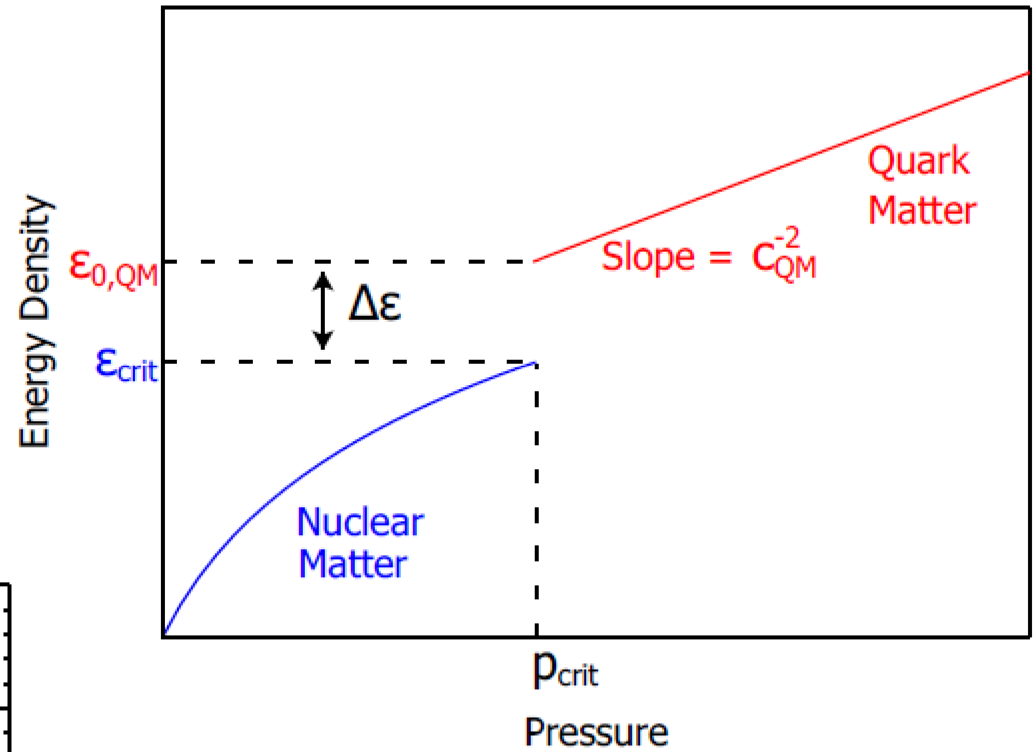



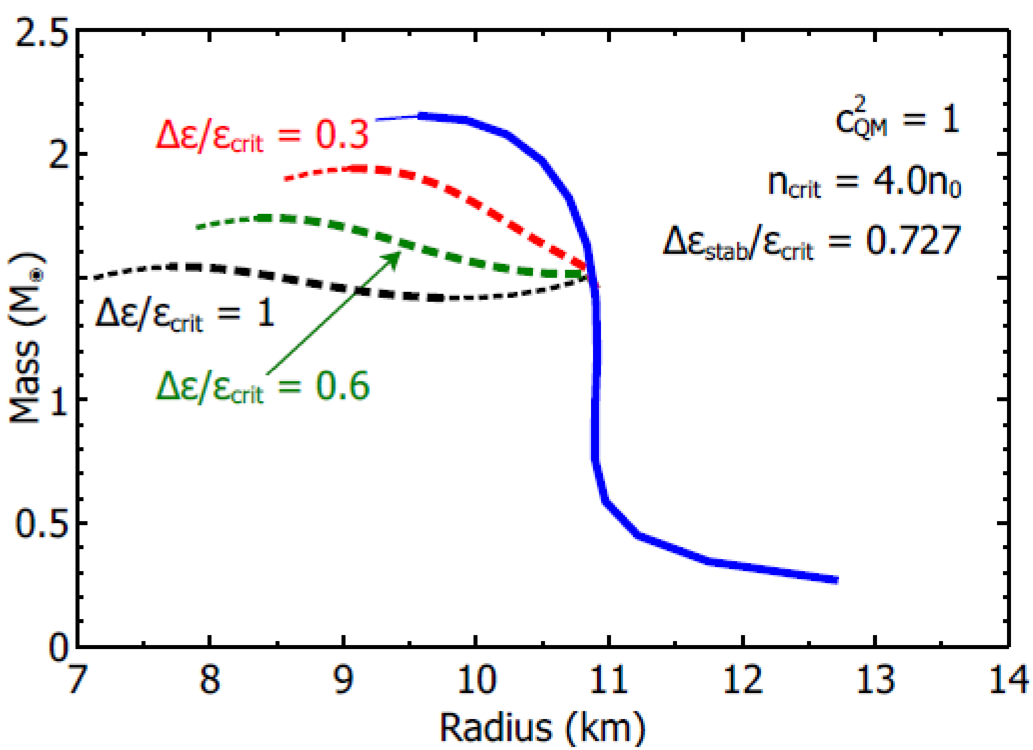

**"Ruled out models" - too strong a conclusion!**
**M(R) constraint is a lower limit, which is itself included in that from RX J1856, which is one of the best known sources.**

# 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"**.

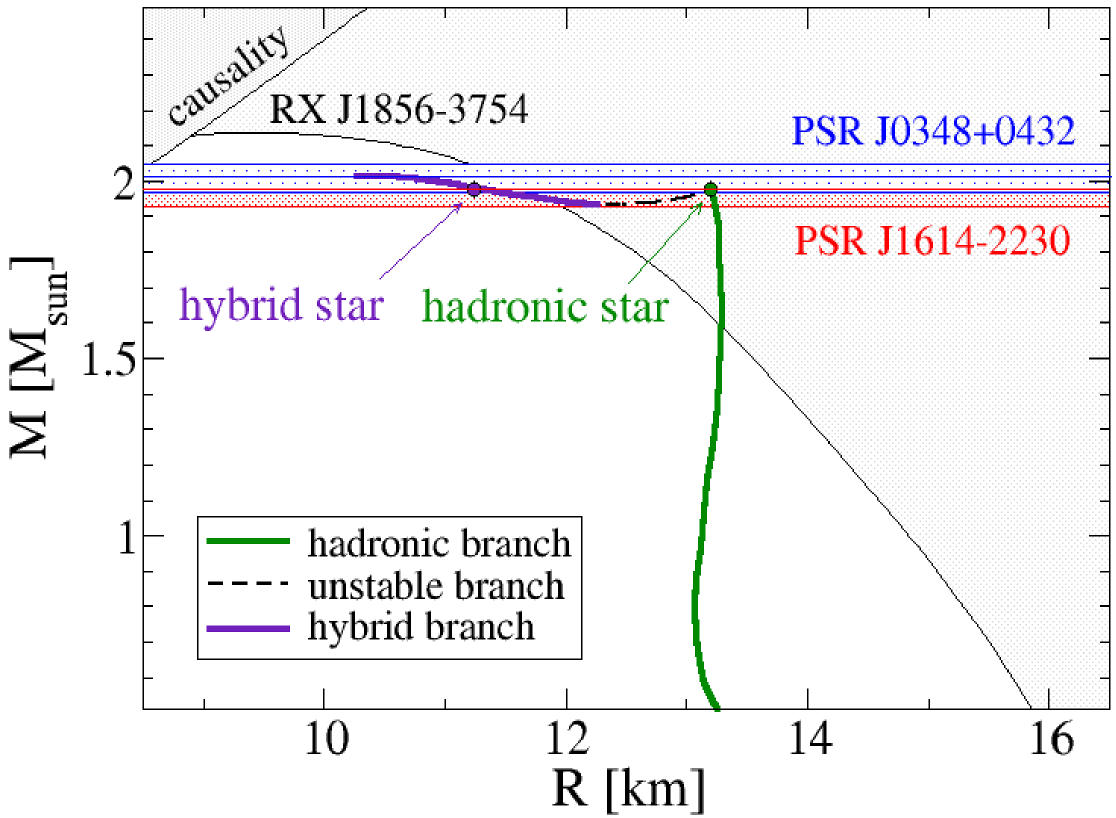


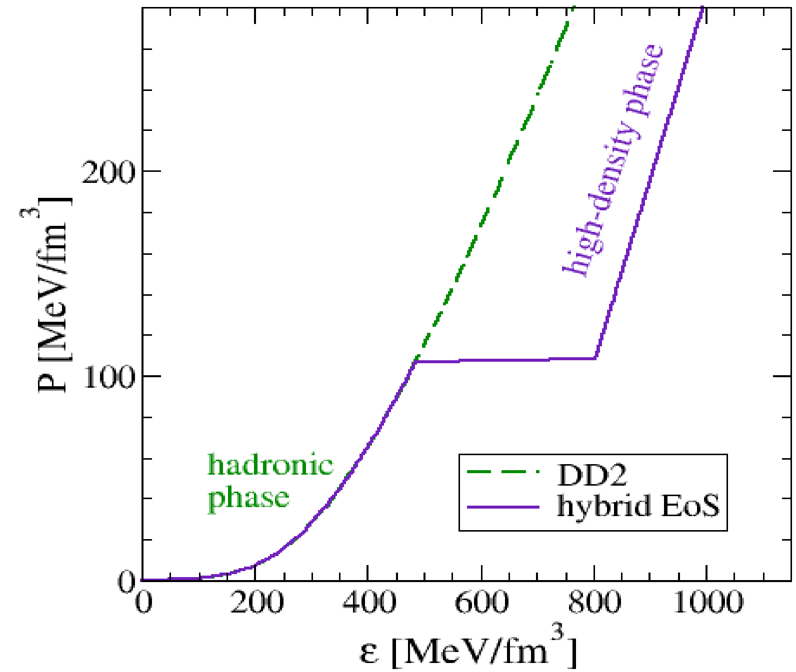



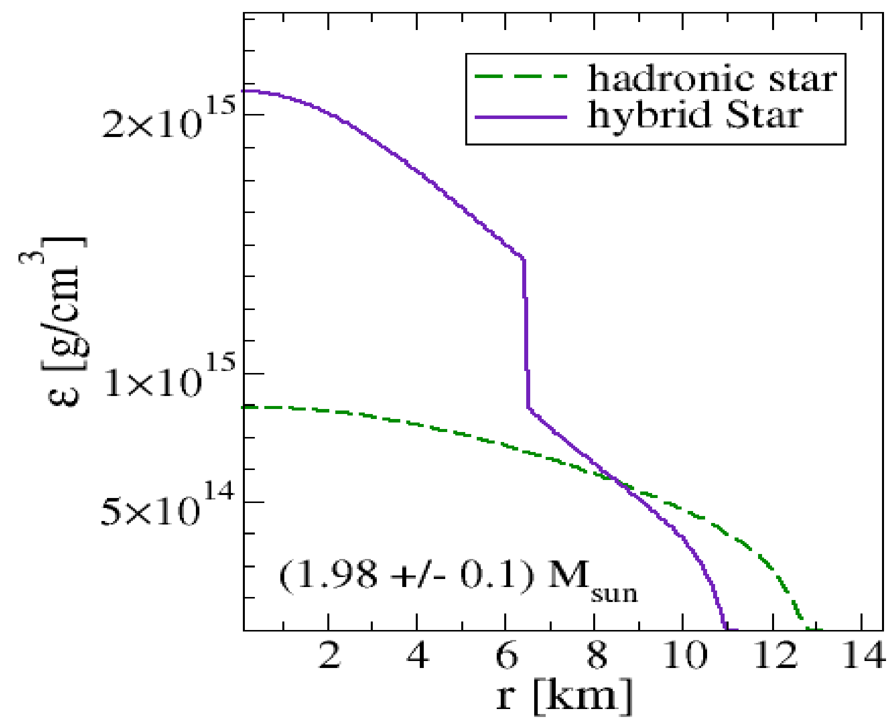

Measuring two **disconnected populations** of compact stars in the M-R diagram would be the **detection of a first order phase transition** in compact star matter and thus the indirect proof for the existence of a **critical endpoint (CEP) in the QCD phase diagram**!

# 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.?

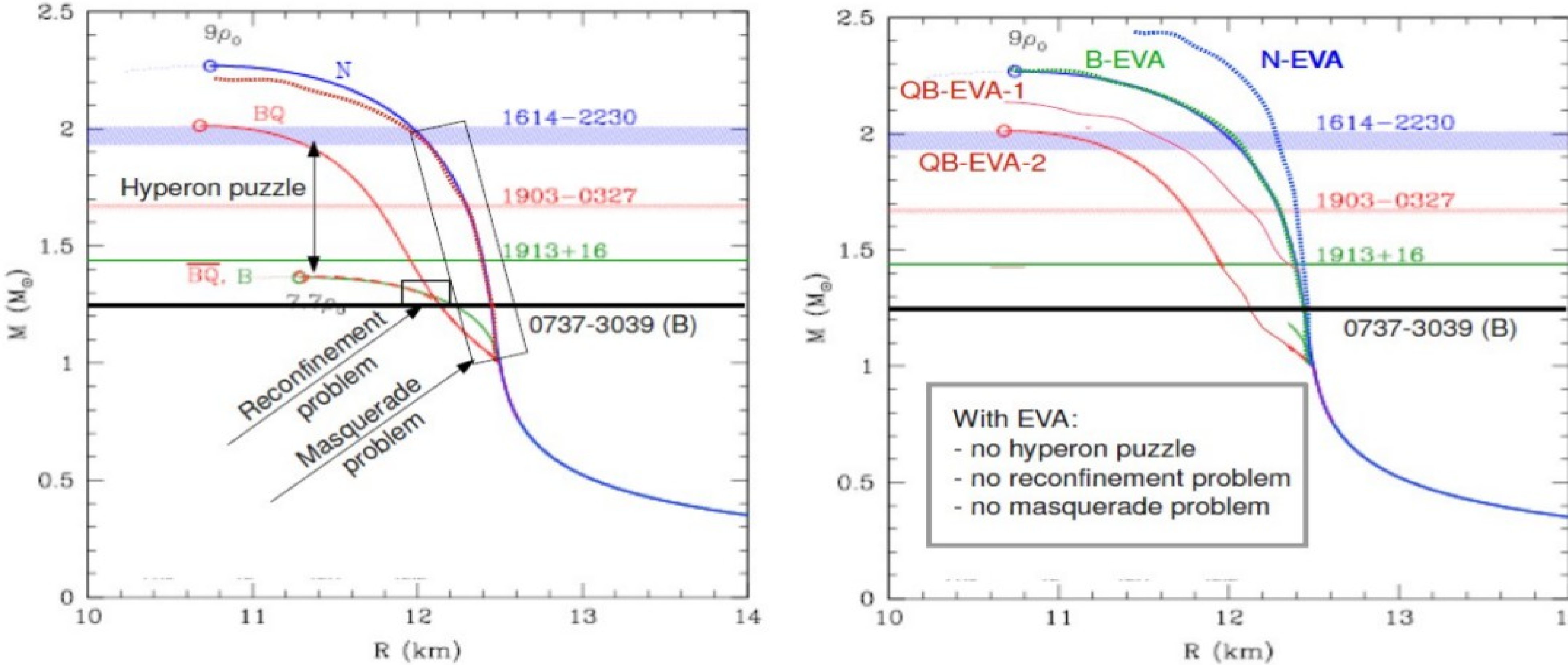



Alvarez & Blaschke, arxiv:1304.7758

# Hyperon puzzle & quark matter




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.

# Exploring hybrid star matter at NICA

T.Klähn (1), D.Blaschke (1,2), F.Weber (3)

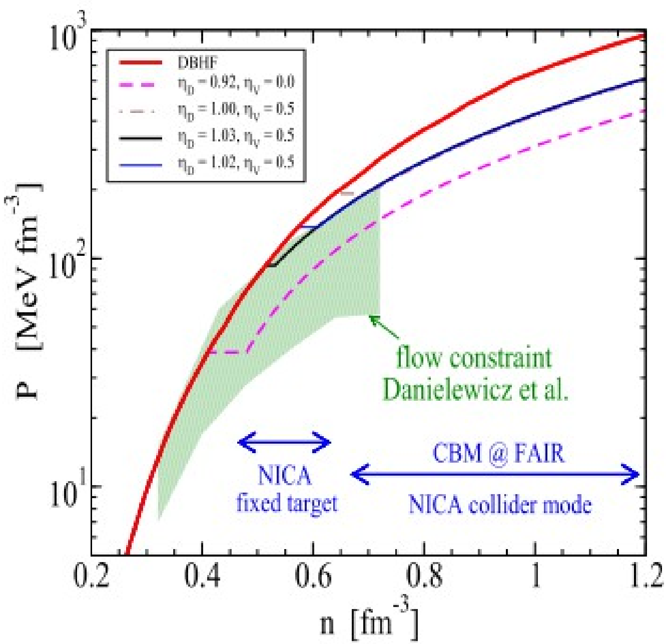
(1) Institute for Theoretical Physics, University of Wroclaw, Poland

(2) Joint Institute for Nuclear Research, Dubna

(3) Department of Physics, San Diego State University, USA

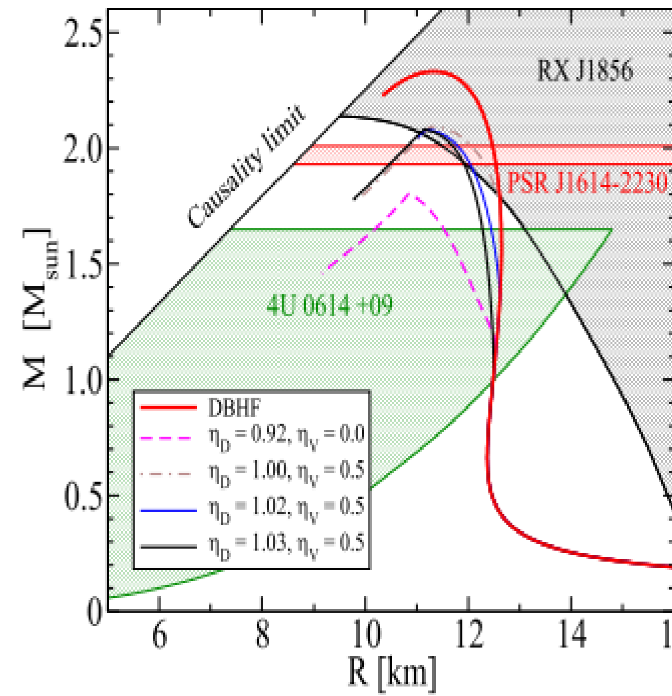
## Heavy-Ion Collisions

## Compact Stars




- stiff EoS (at flow limit)
- low ncrit (at NICA fixT)
- soft EoS (dashed line)

- high Mmax (J1614-2230)
- low Monset (all NS hybrid)
- excluded (J1614-2230)



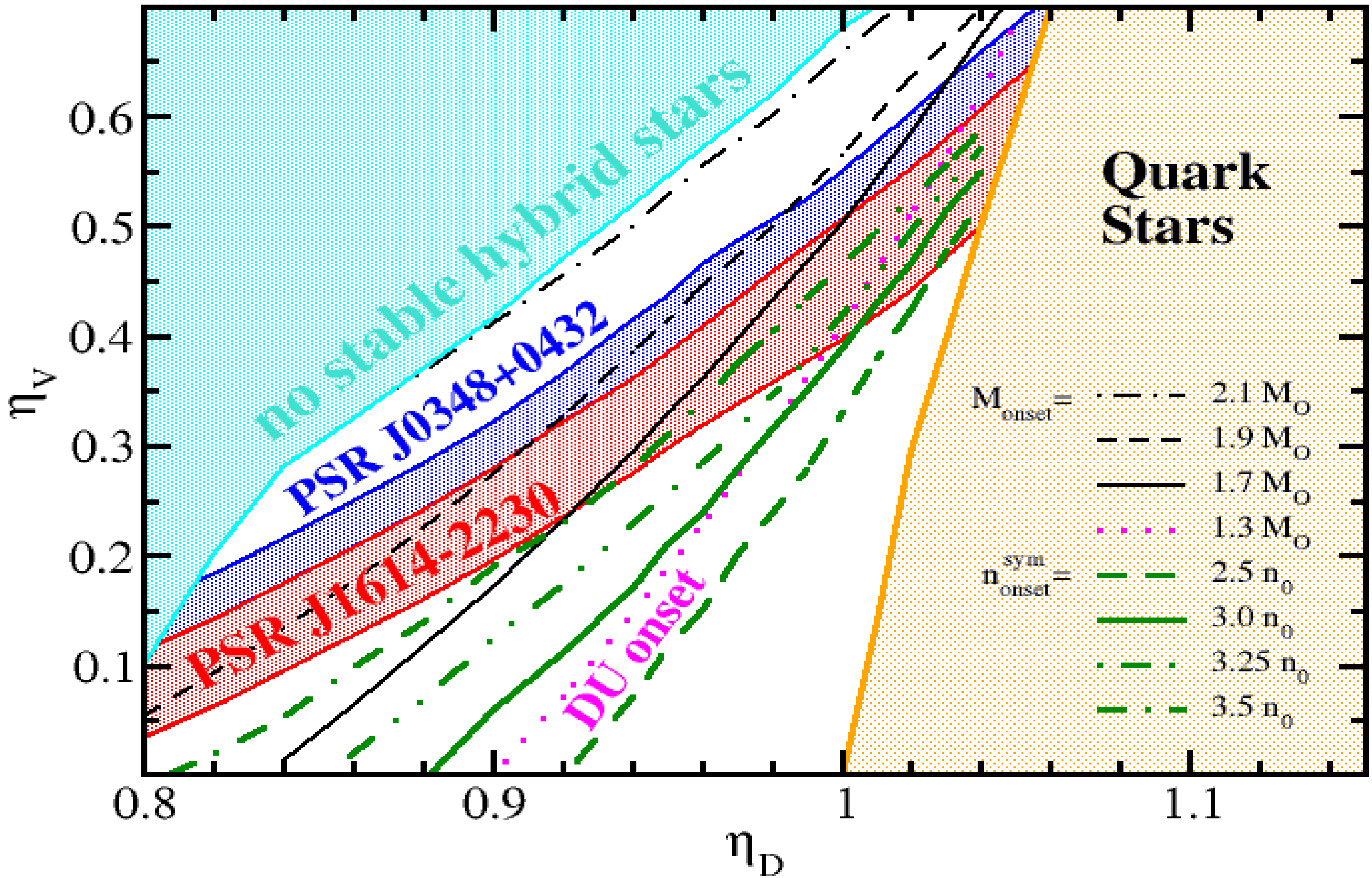

## Proposal:

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**

**NICA White Paper, http://theor.jinr.ru → BLTP TWikipages**

# Quark matter in 2Msun neutron stars?
# → only color superconducting + vector int.




T. Klahn et al., PRD 88 (2013) 085001; arxiv:1307.696

# Baryon substructure effect (EVA)

**Excluded volume approximation (EVA)):**

$$p_{\rm ex}(\mu,T) \;=\; p(\tilde{\mu},T)\;,\;\; \tilde{\mu} = \mu - v_0(\mu,T)p_{\rm ex}(\mu,T)$$

$$n_{\rm ex}(\mu,T) \;=\; \frac{\partial p_{\rm ex}}{\partial \mu} = \frac{\partial \tilde{\mu}}{\partial \mu}\,\frac{\partial p(\tilde{\mu},T)}{\partial \tilde{\mu}} \;=\; \left[1 - v_0 n_{\rm ex}(\mu,T) - \frac{\partial v_0}{\partial \mu} p_{\rm ex}(\mu,T)\right] n(\tilde{\mu},T)$$

**Thermodynamic consistency:**

$$\epsilon_{\rm ex}(\mu,T) = -p_{\rm ex}(\mu,T) + \mu n_{\rm ex}(\mu,T) + T s_{\rm ex}(\mu,T)$$

**Parametrization of excluded volume with nonlinear dependence on the chemical potential:**

$$v_0(\mu,T) = (4\pi/3)r^3(\mu)\;\;,\;\; r^3(\mu) = r_0 + r_1(\mu/\mu_c)^2 + r_2(\mu/\mu_c)^4$$

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

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

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

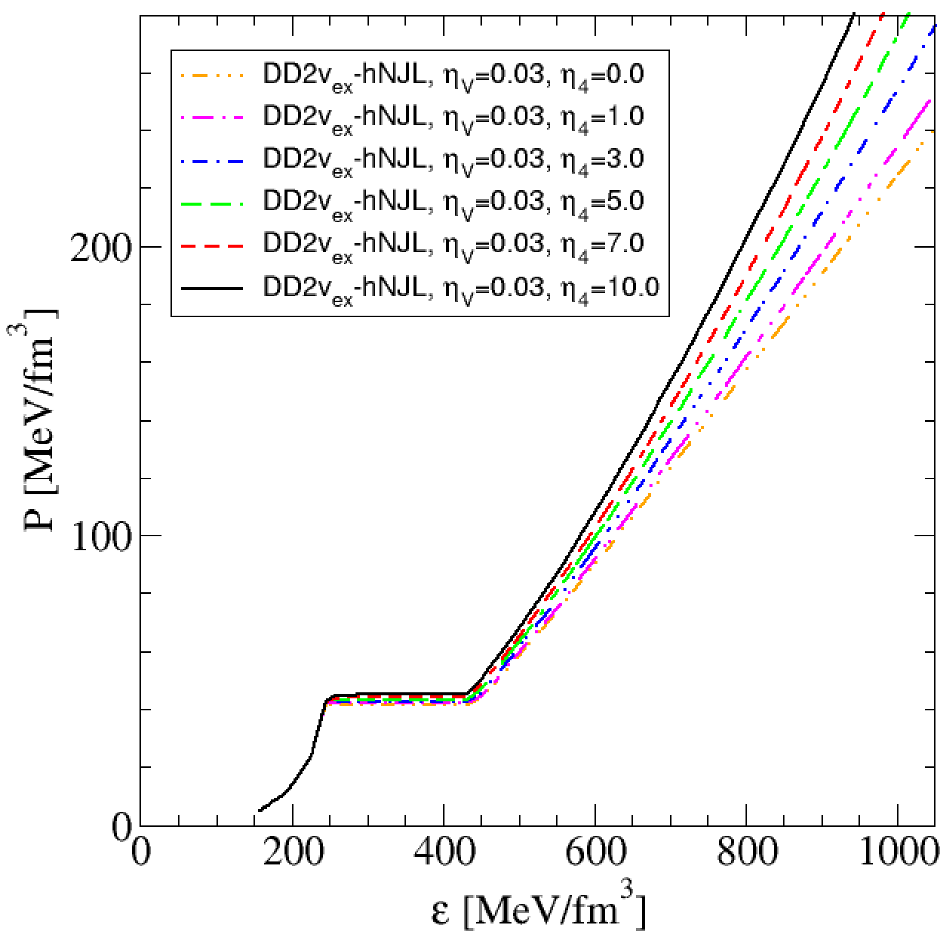
$$U = \frac{g_{20}}{\Lambda^2}\langle\bar{q}q\rangle^2 + 3\frac{g_{40}}{\Lambda^8}\langle\bar{q}q\rangle^4 - 3\frac{g_{22}}{\Lambda^8}\langle\bar{q}q\rangle^2\langle q^\dagger q\rangle^2 - \frac{g_{02}}{\Lambda^2}\langle q^\dagger q\rangle^2 - 3\frac{g_{04}}{\Lambda^8}\langle q^\dagger q\rangle^4\ .$$

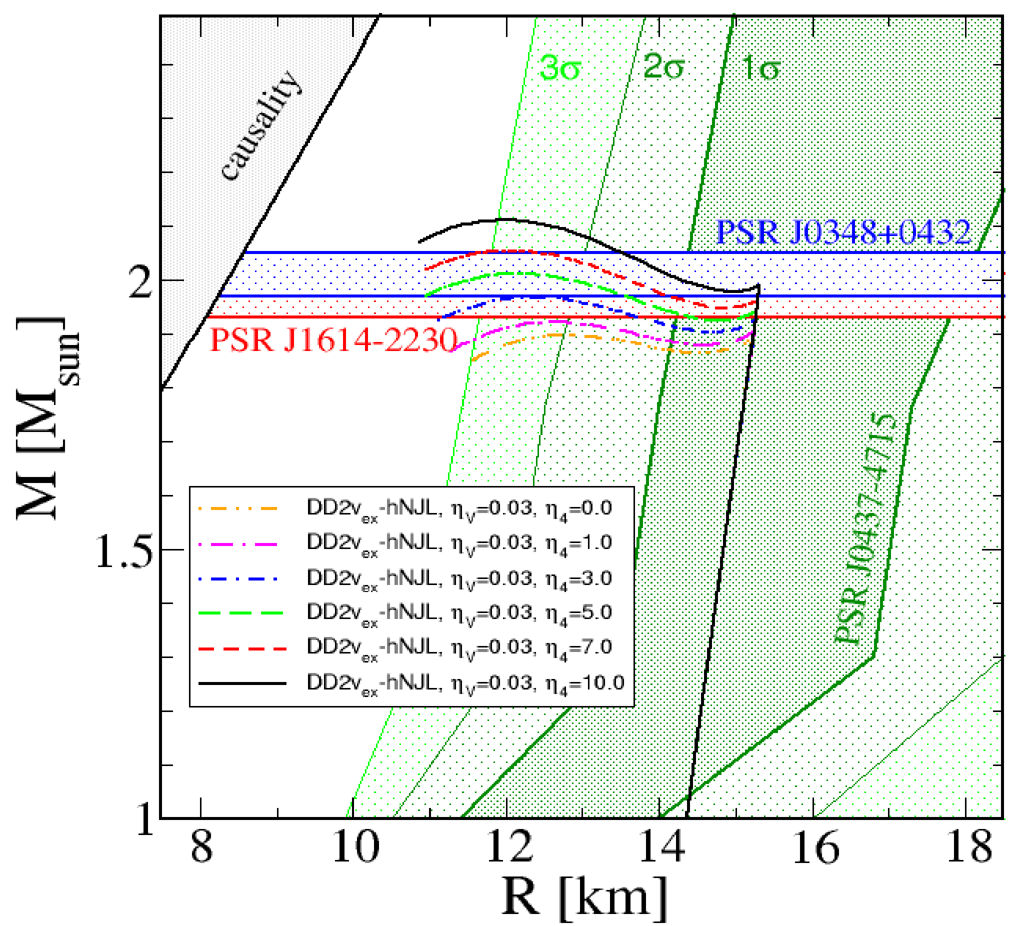
**Thermodynamic Potential:**

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

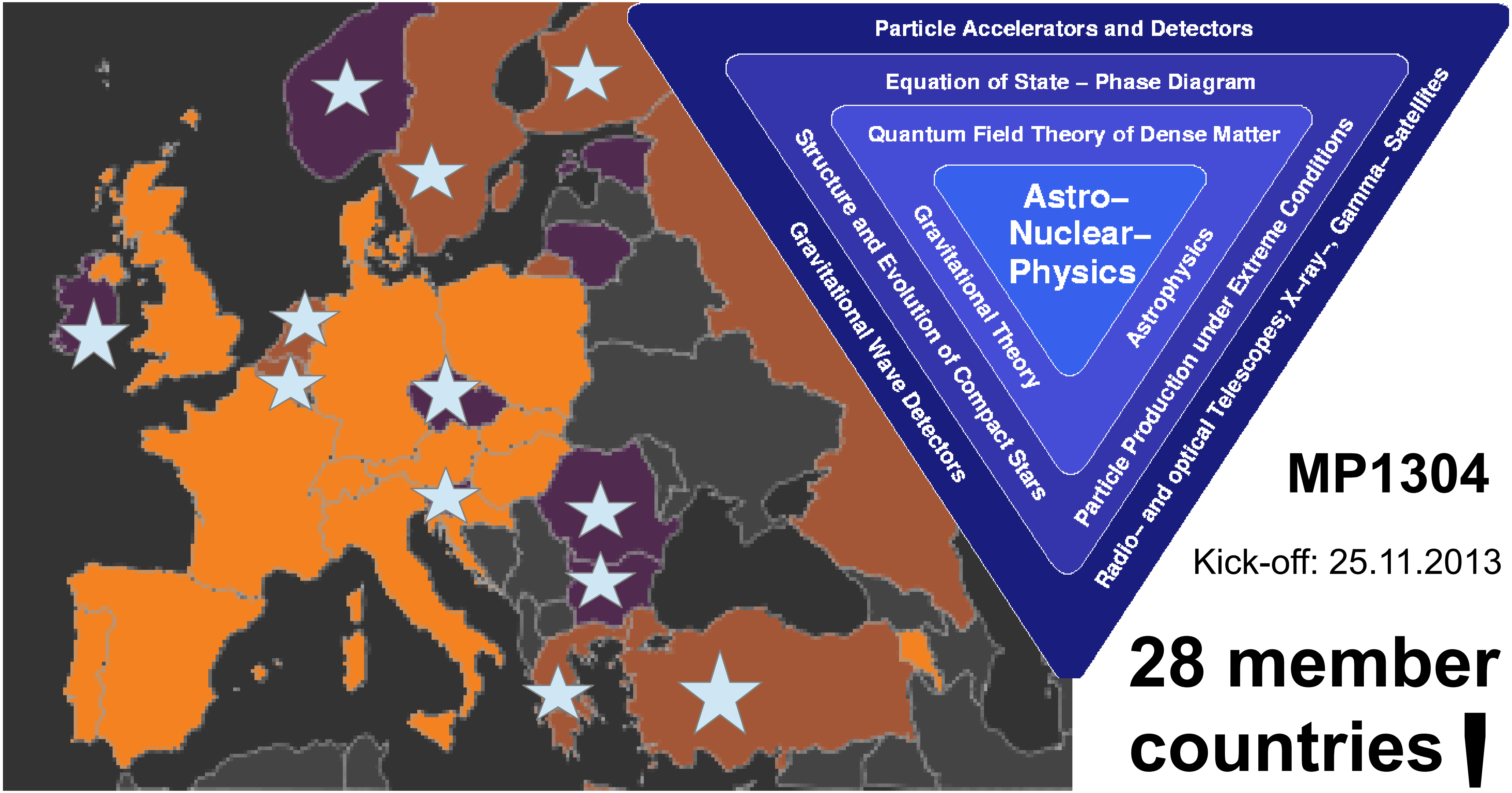
# Result: high-mass twins ↔ 1st order PT

S. Benic, D. Blaschke, D. Alvarez-Castillo, T. Fischer, S. Typel, arxiv:1411.2856




**Hybrid EoS supports M-R sequences with high-mass twin compact stars**




**MP1304**

Kick-off: 25.11.2013

**28 member countries !**

**New** compstar **!**

cost
EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

**http://compstar.uni-frankfurt.de**

# A QCD-based hybrid EoS - nonlocal PNJL model

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

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

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

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

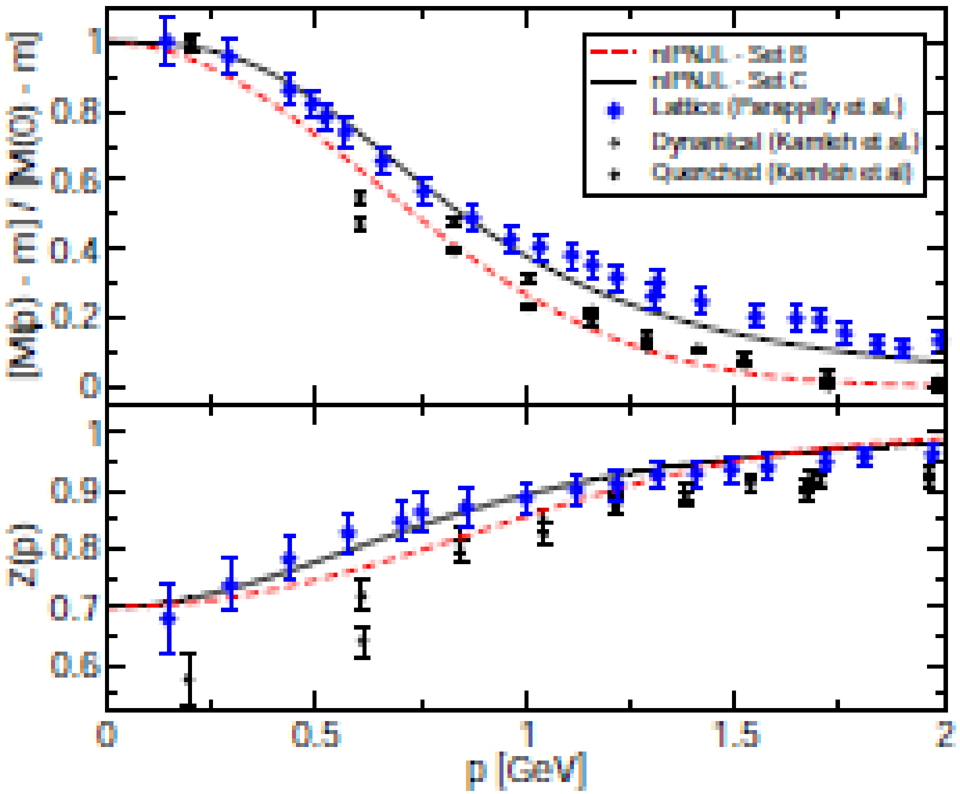
$$j_p(x) = \int d^4z\, f(z)\, \bar{q}\left(x+\frac{z}{2}\right) \frac{i\overleftrightarrow{\not{\partial}}}{2\,\kappa_p} q\left(x-\frac{z}{2}\right) , \quad u(x')\overleftrightarrow{\partial} v(x) = u(x')\partial_x v(x) - \partial_{x'} u(x') v(x)$$

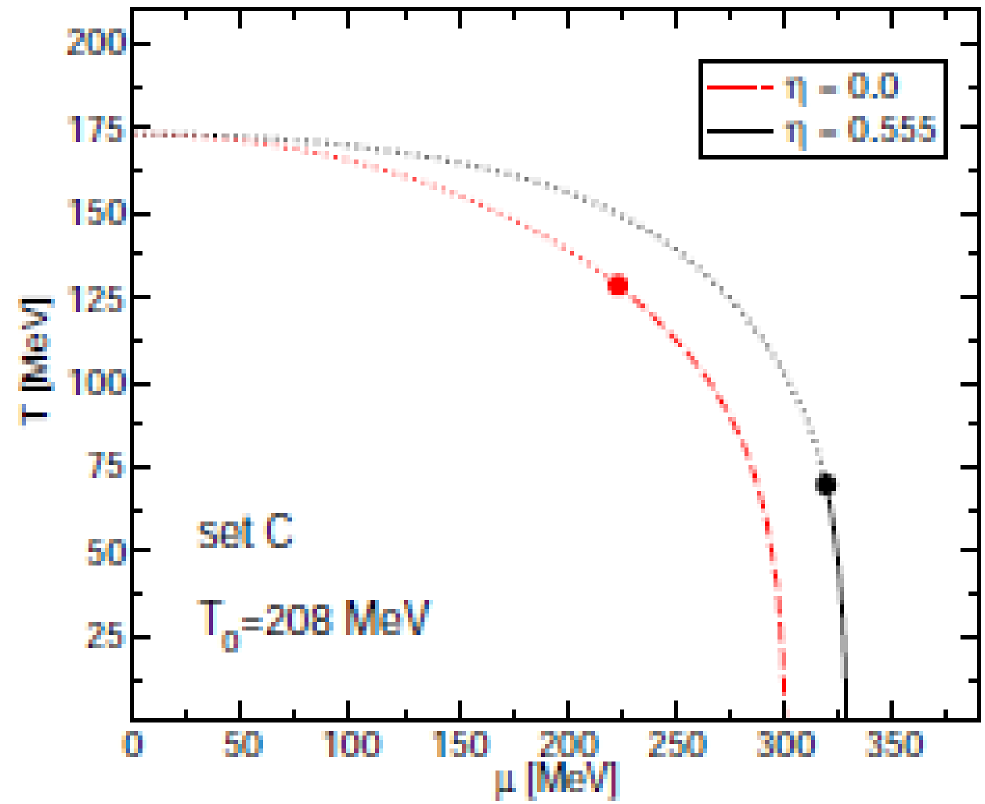
$$\mathscr{U}(\Phi, T, \mu) = (a_0 T^4 + a_1 \mu^4 + a_2 T^2 \mu^2)\Phi^2 + a_3 T_0^4 \ln(1 - 6\Phi^2 + 8\Phi^3 - 3\Phi^4) ,$$

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

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

# A QCD-based hybrid EoS



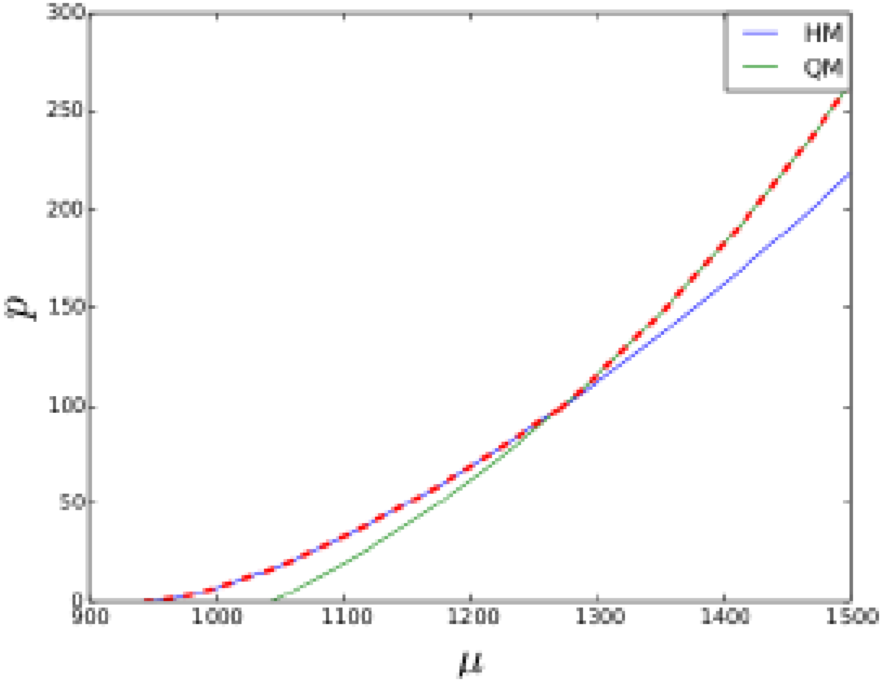

- Formfactors of the nonlocal chiral quark model fixed by comparison with M(p) and Z(p) from lattice QCD calculations of the quark propagator [Parapilly et al. PRD 73 (2006)

- Vector coupling strength adjusted to describe the slope of the pseudocritical temperature In accordance with lattice QCD [Kaczmarek et al., PRD 83 (2011) 014504]

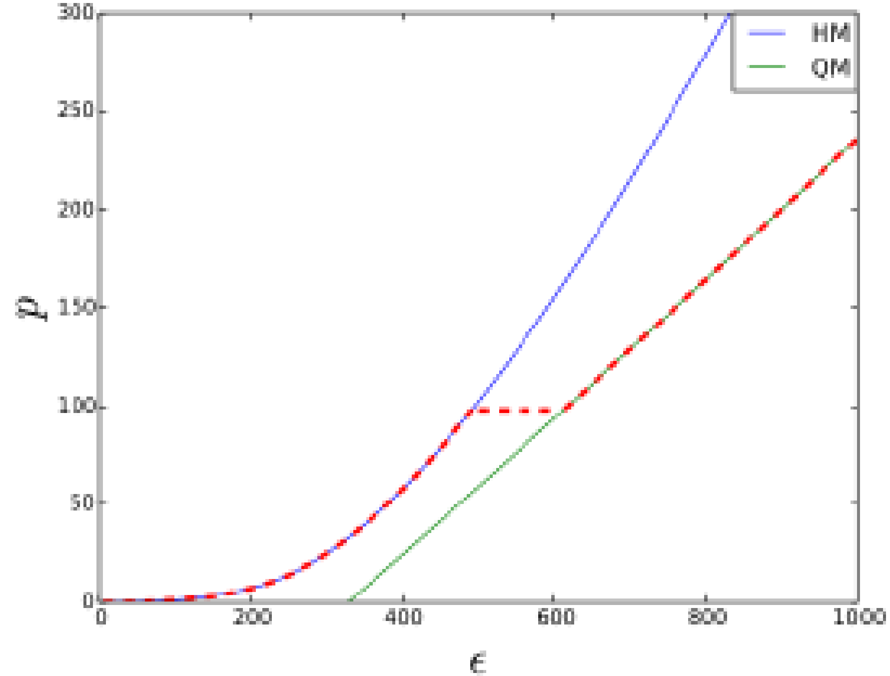
- CEP does not vanish !! Controversial discussion, see Hell et al., arxiv:1212.4017 (2012)

# A QCD-based hybrid EoS

## Maxwell construction of hybrid EoS

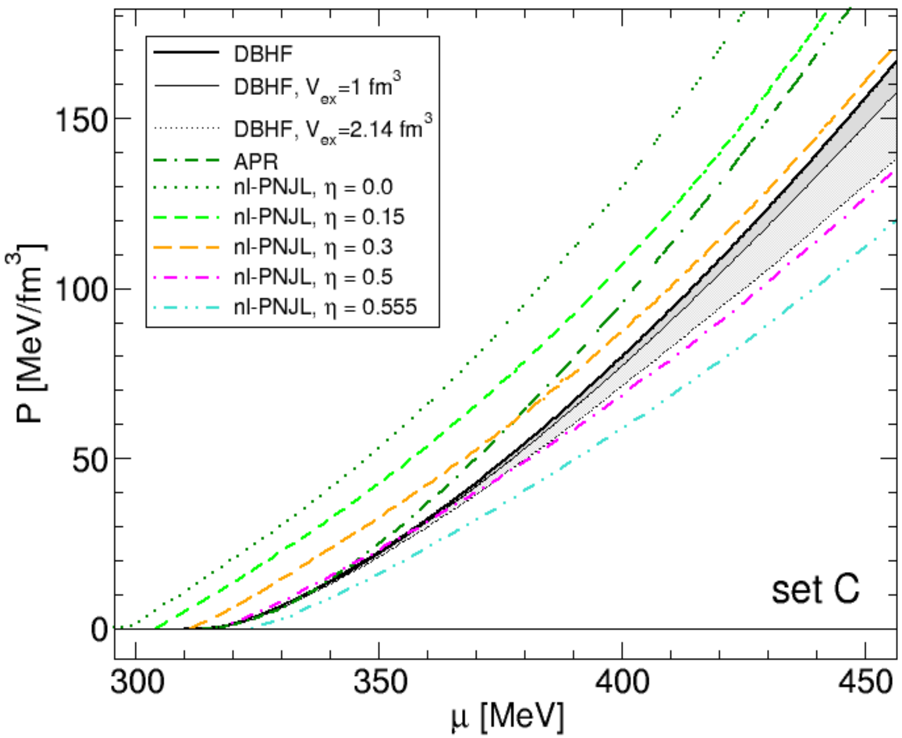


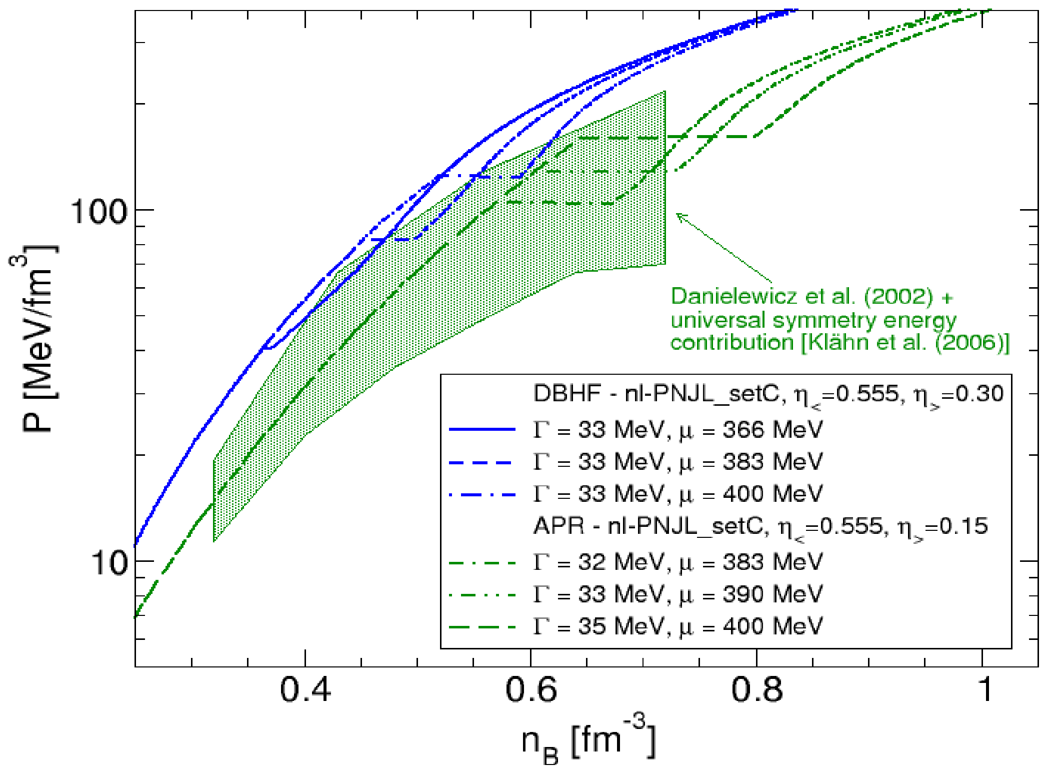

(A) $p(\mu)$ functions.




(B) $p(\epsilon)$ functions.

# 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:**

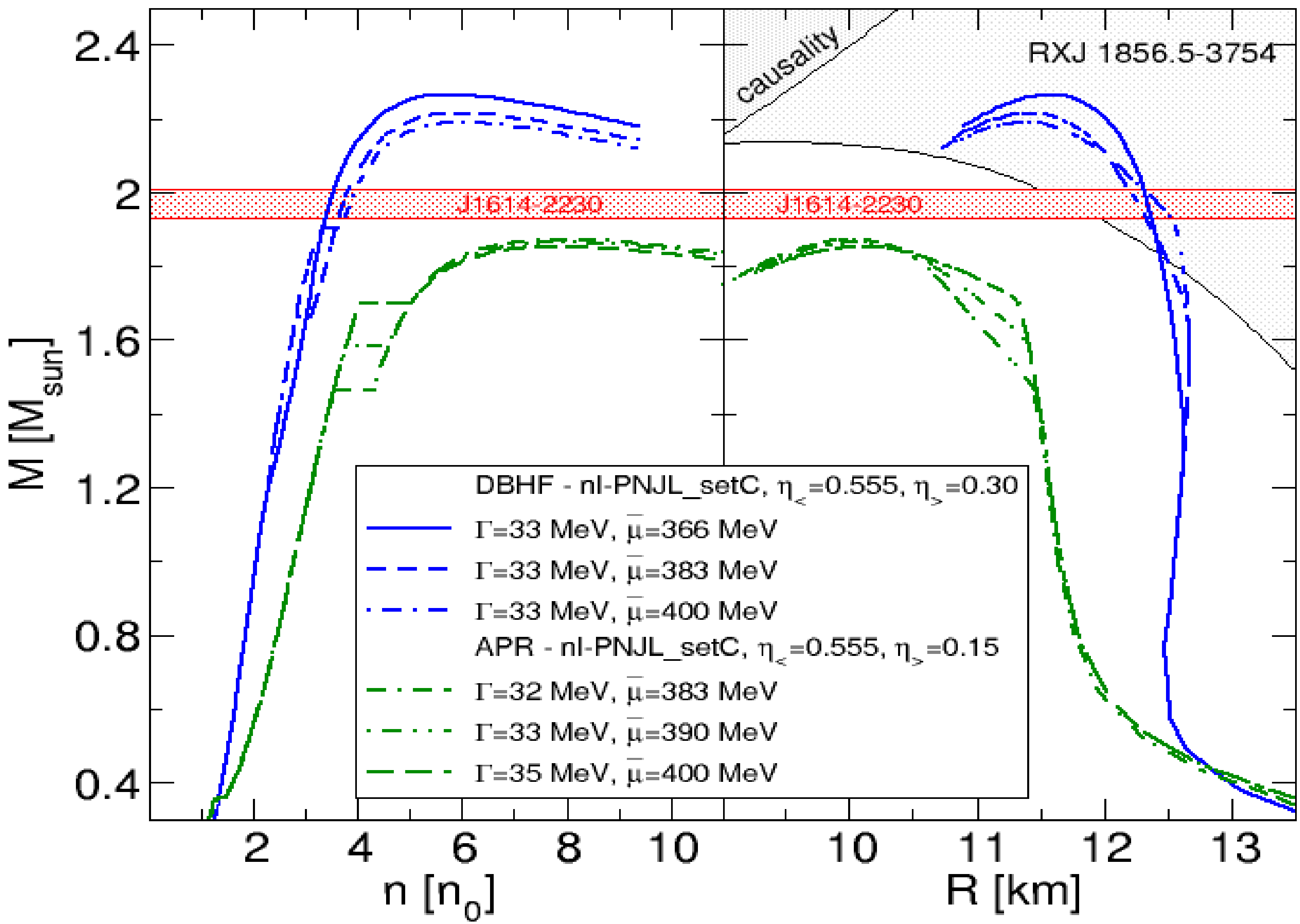
(A) Maxwell construction $P_Q(\mu_c) = P_H(\mu_c)$ H = DBHF, APR; Q = nl-PNJL

(B) mu-dependent vector coupling:

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

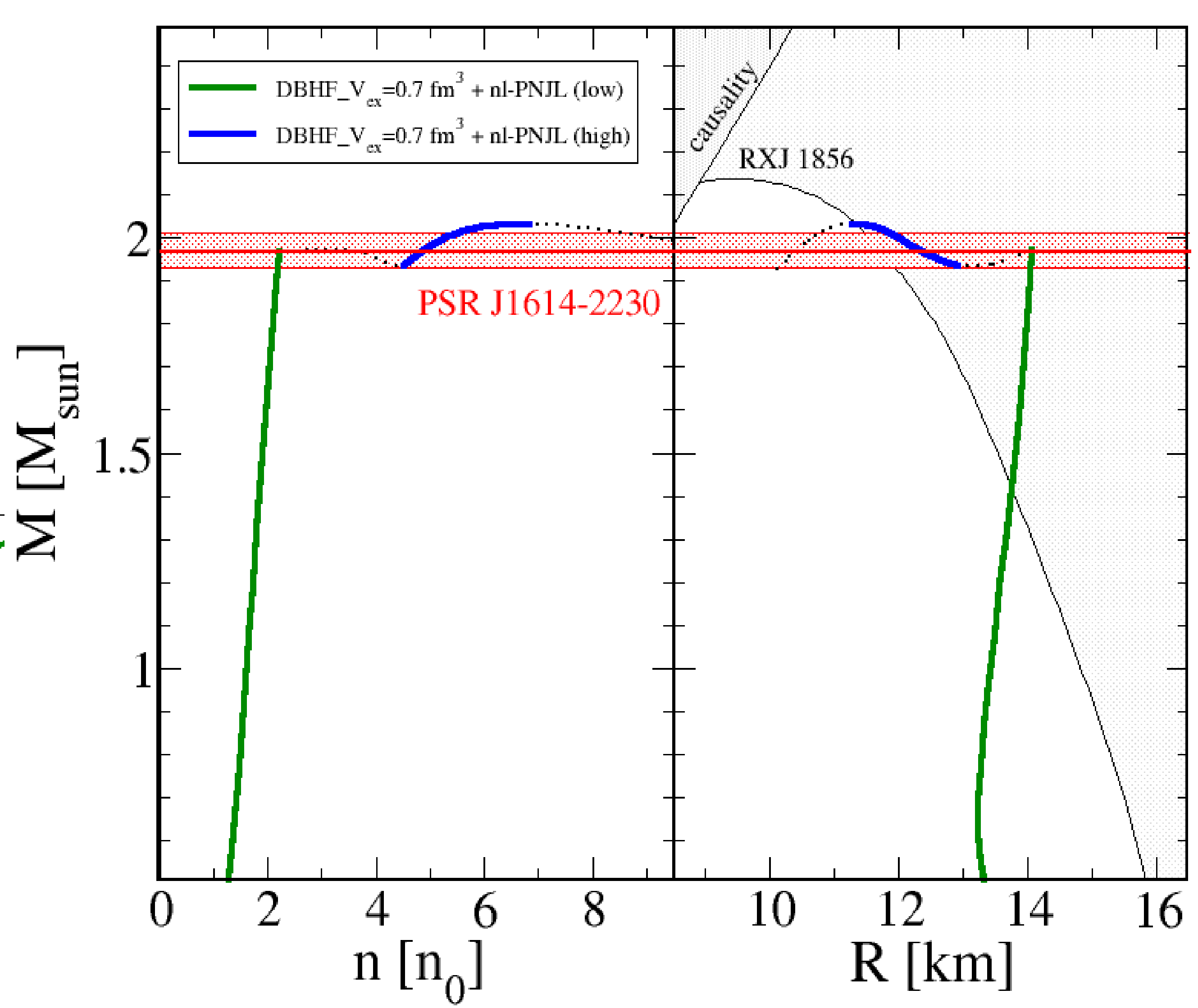
$$f_{\lessgtr}(\mu) = \frac{1}{2}\left[1 \mp \tanh\left(\frac{\mu-\bar{\mu}}{\Gamma}\right)\right]\,.$$

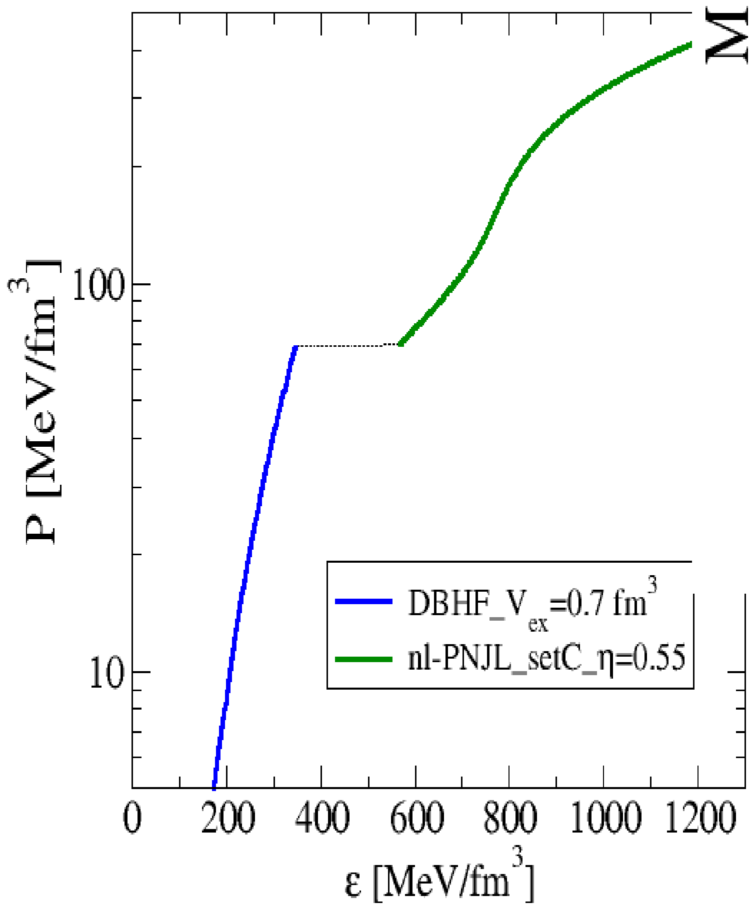
# Result 1: hybrid stars fulfill Demorest and RXJ1856




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

# Result 2:
# High mass twins are possible !

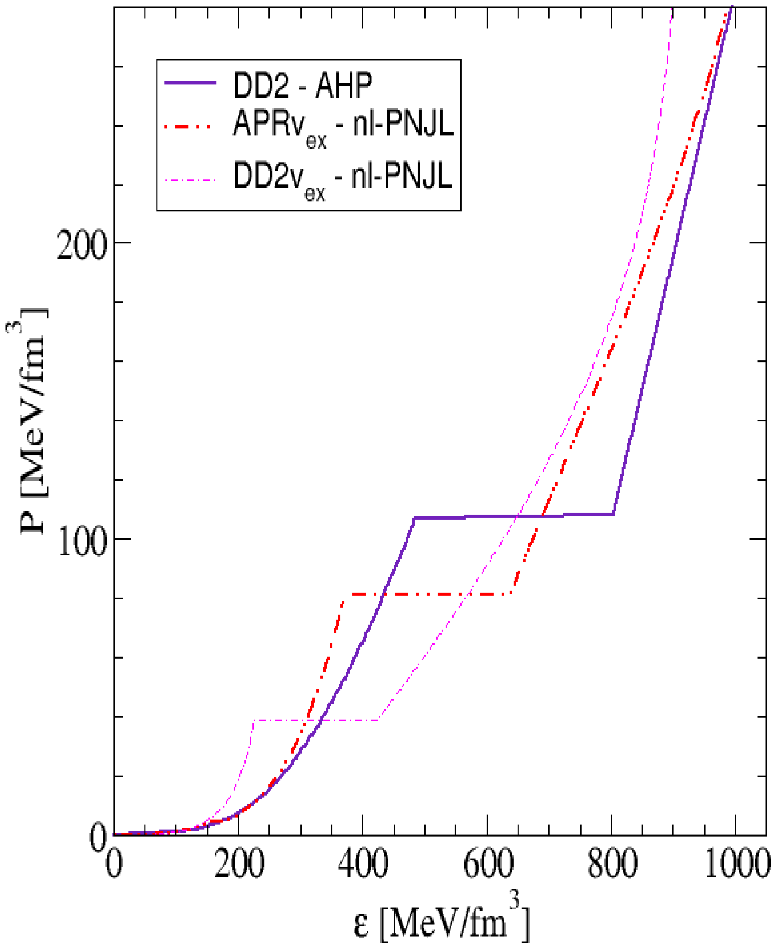


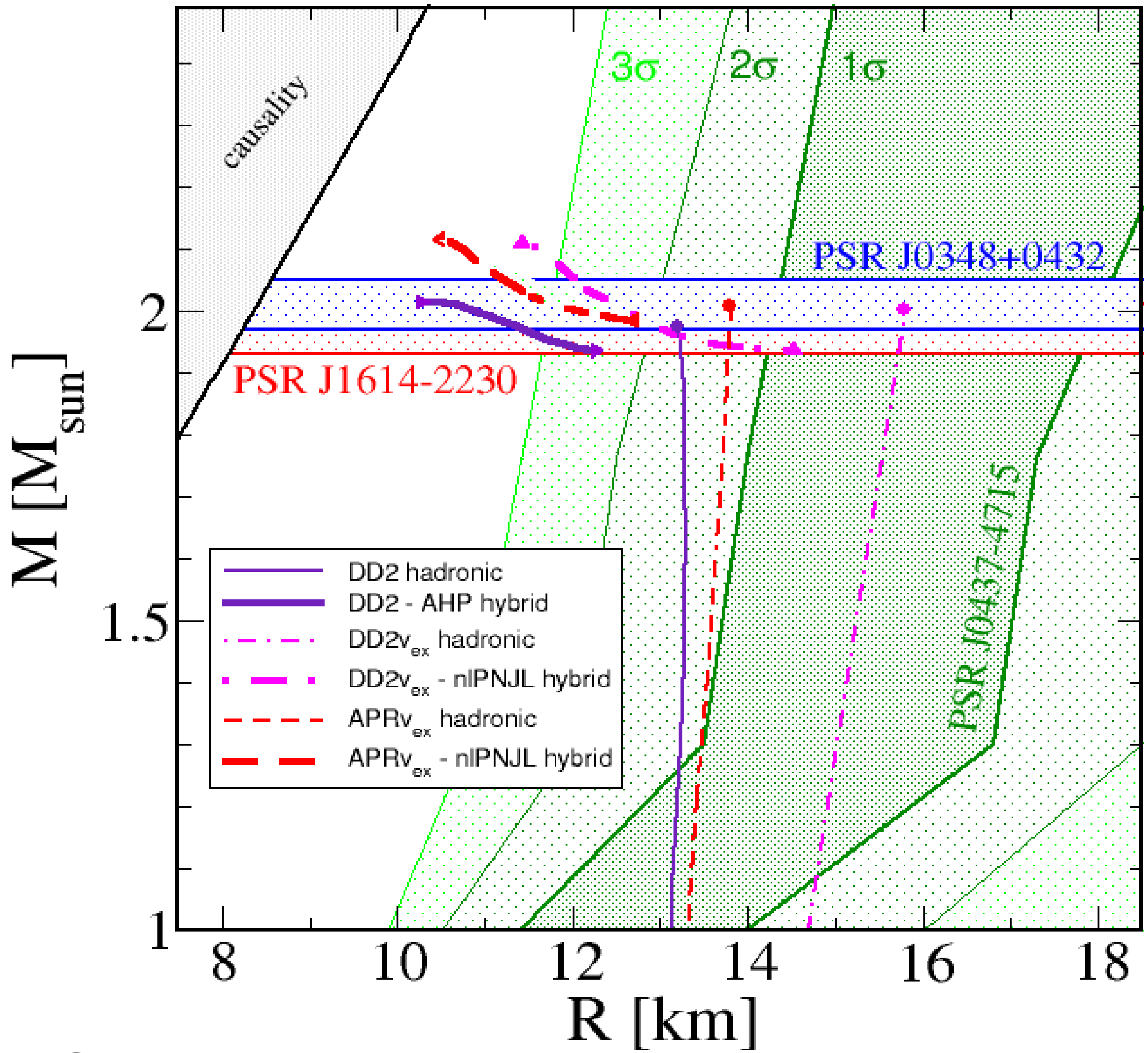




**SUMMARY:**
- excluded volume (quark Pauli blocking) in DBHF
- high-density quark matter slightly stiffer eta_v=0.25
- the scaled energy density jump (0.65) fulfills the twin condition of the schematic model by Alford et al. (2013)

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

# Result 3:
# High mass twins:
# more examples !




**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 !!**

**DB, Alvarez, Benic, arxiv: tomorrow**

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

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

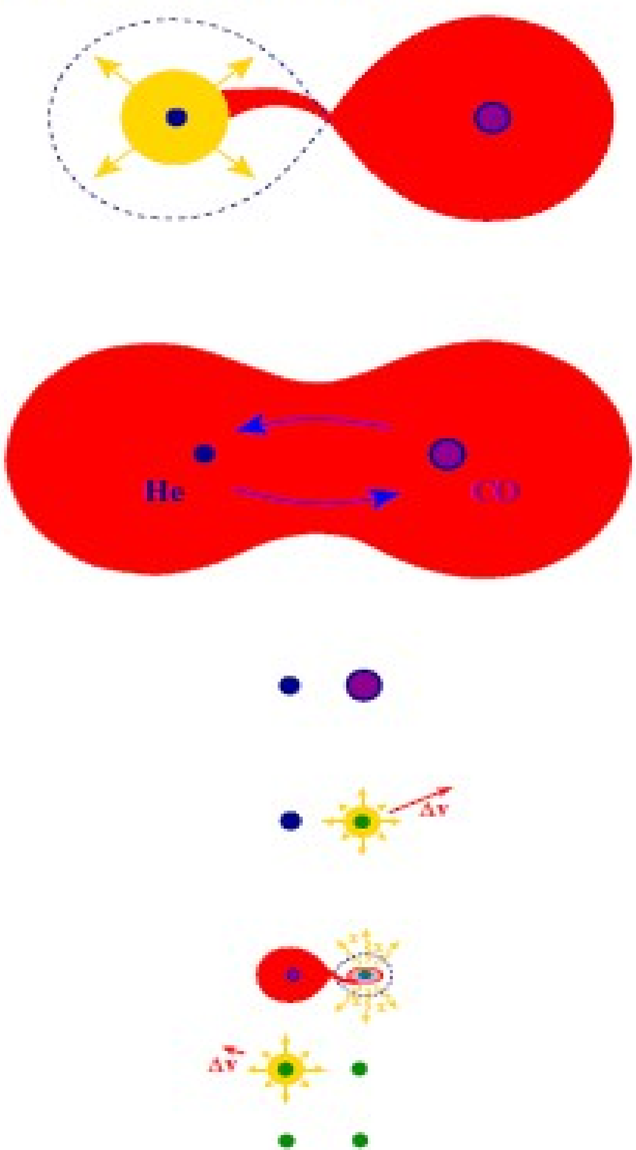
$M_N = u N_B = 4\pi u \int_0^R \mathrm{d}r \frac{r^2 n(r)}{\sqrt{1-2GM(r)/r}}$

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

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

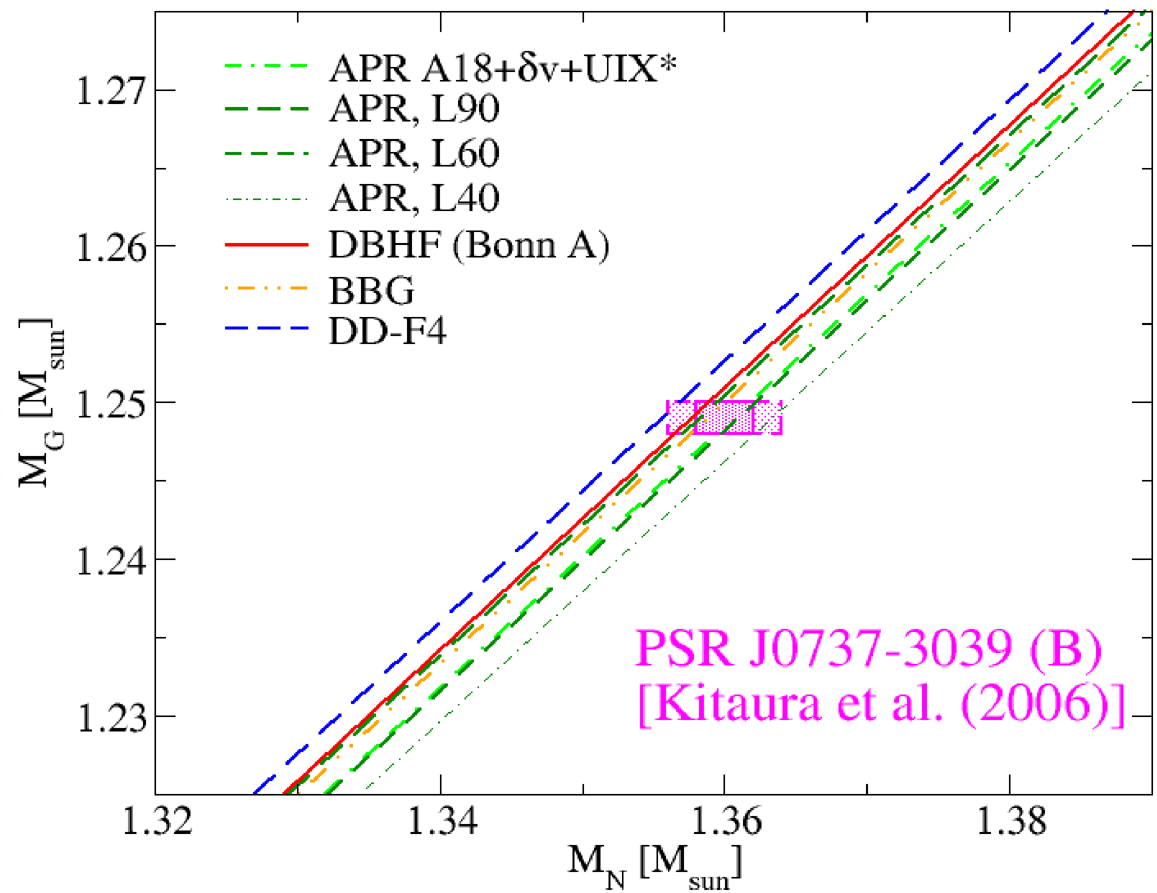
# EoS constraint: double pulsar J0737-3039

**Double core scenario:**




Dewi et al., MNRAS (2006)

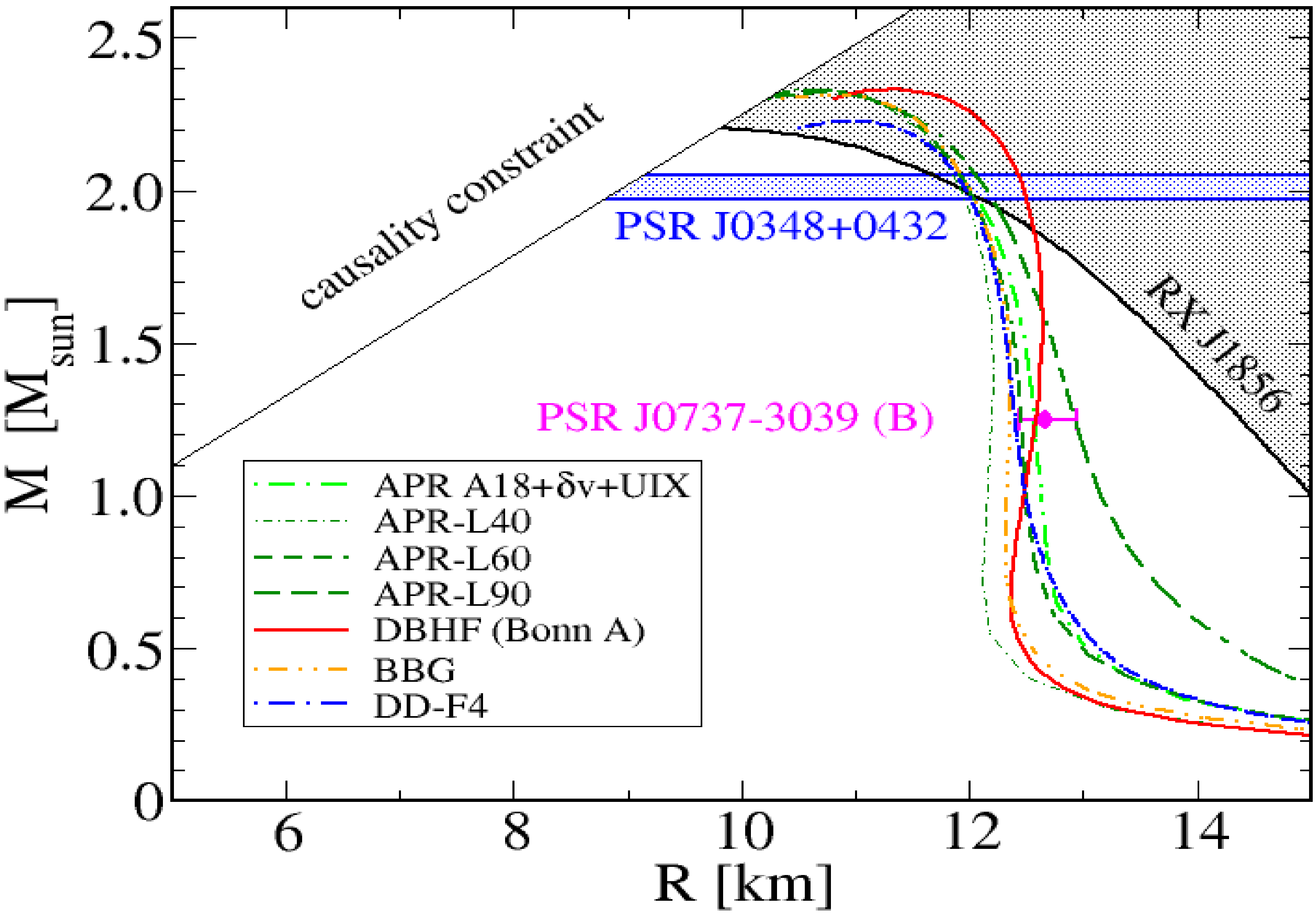
**Baryon mass vs. gravitational mass - constraint or consistency check?**



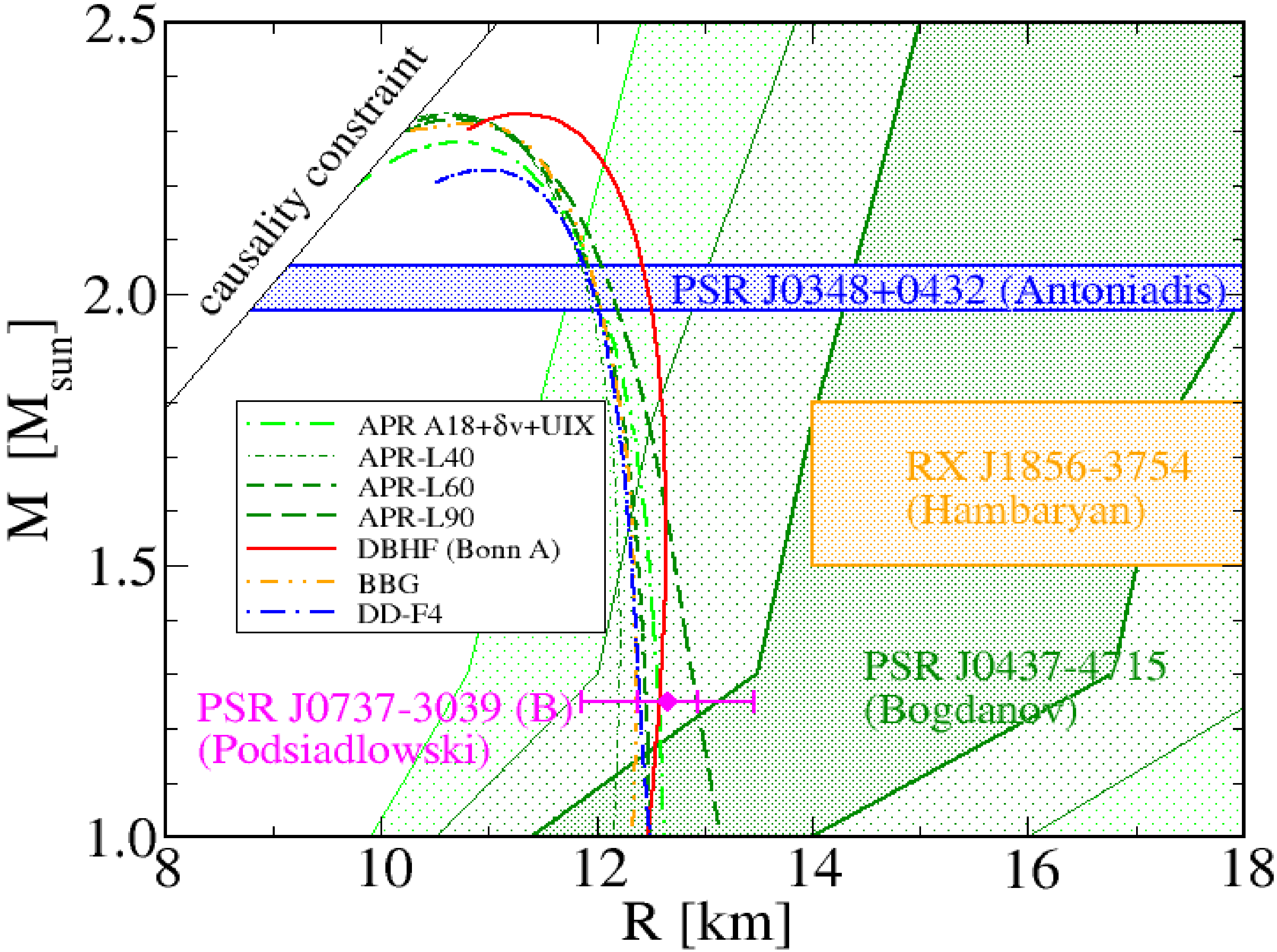

Podsiadlowski et al., MNRAS 361 (2005) 1243
Kitaura, Janka, Hillebrandt, A& A (2006); [astro-ph/0512065]

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

# Double pulsar: mass & radius ?!

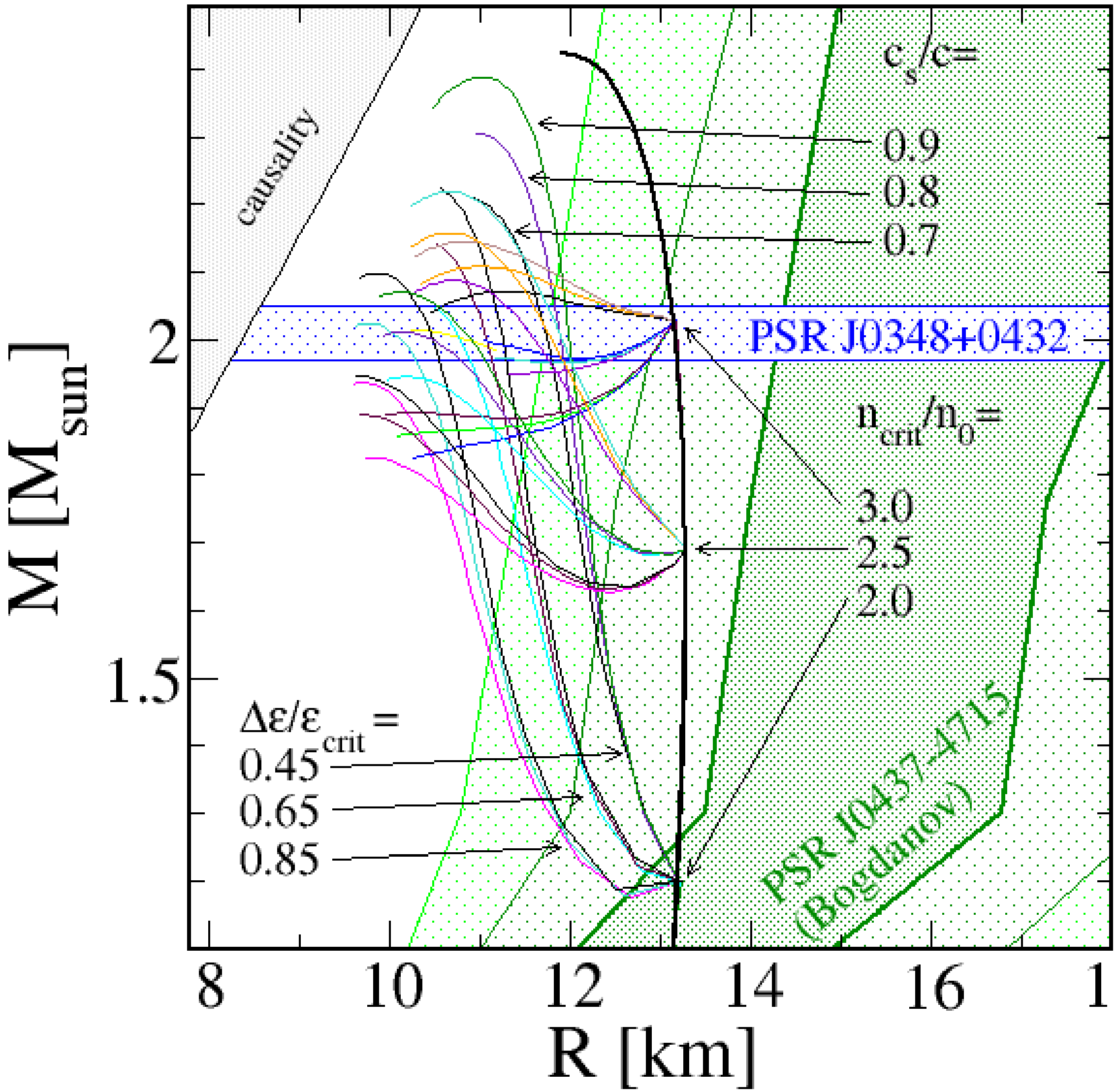


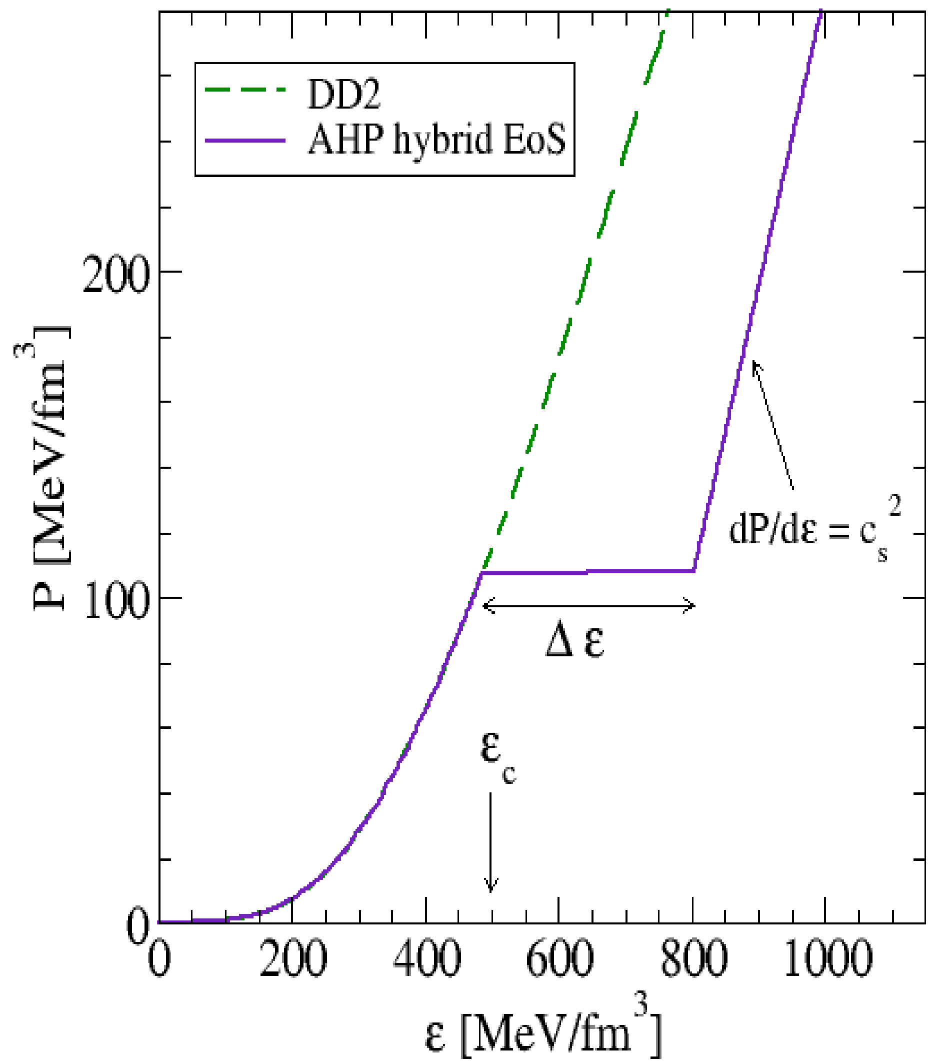
# Disjunct M-R constraints for Bayesian analysis !




**Alvarez, Ayriyan, Blaschke, Grigorian, J. Phys. Conf. Ser. (2014)**

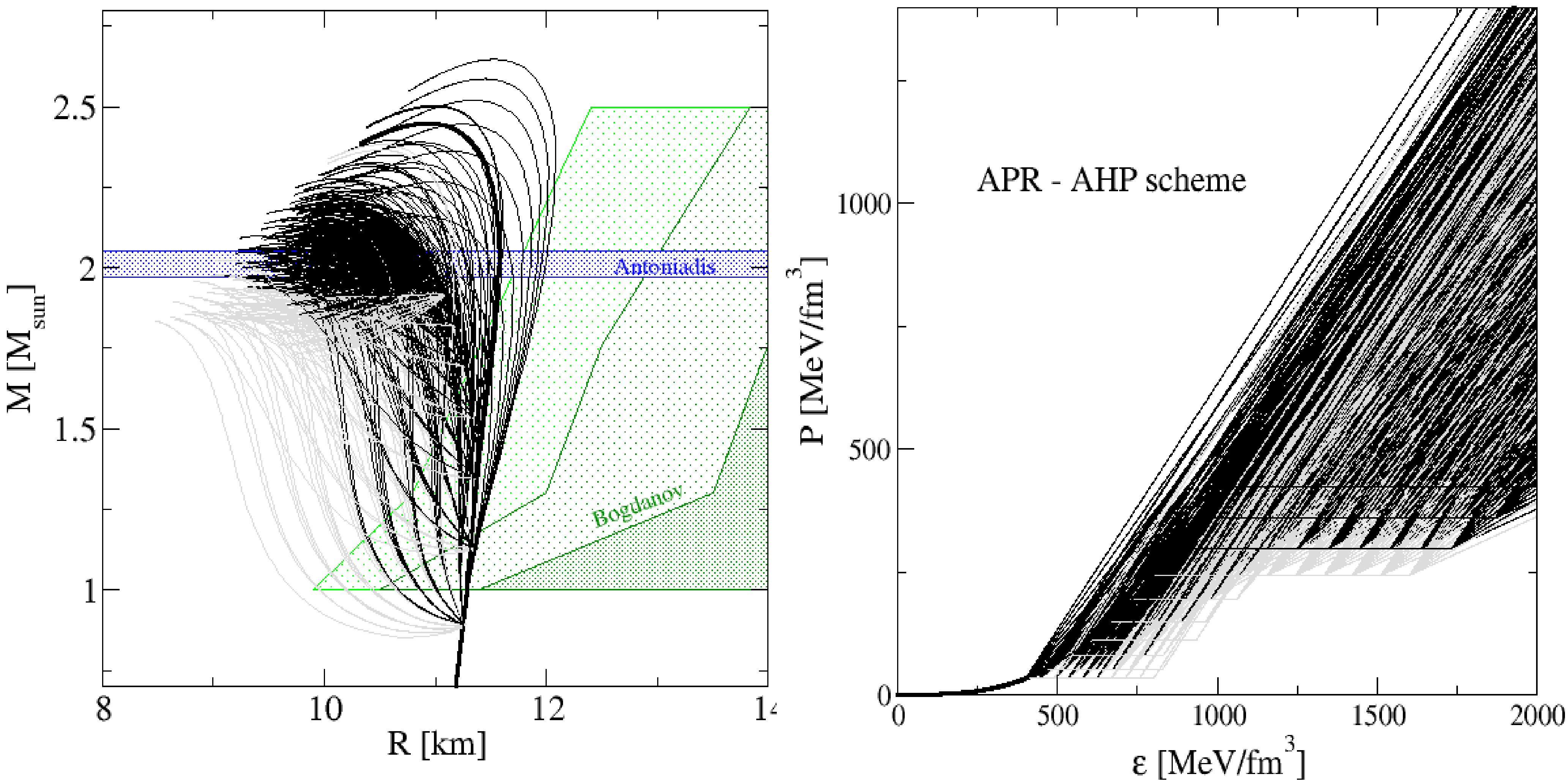
# Disjunct M-R constraints for Bayesian analysis !



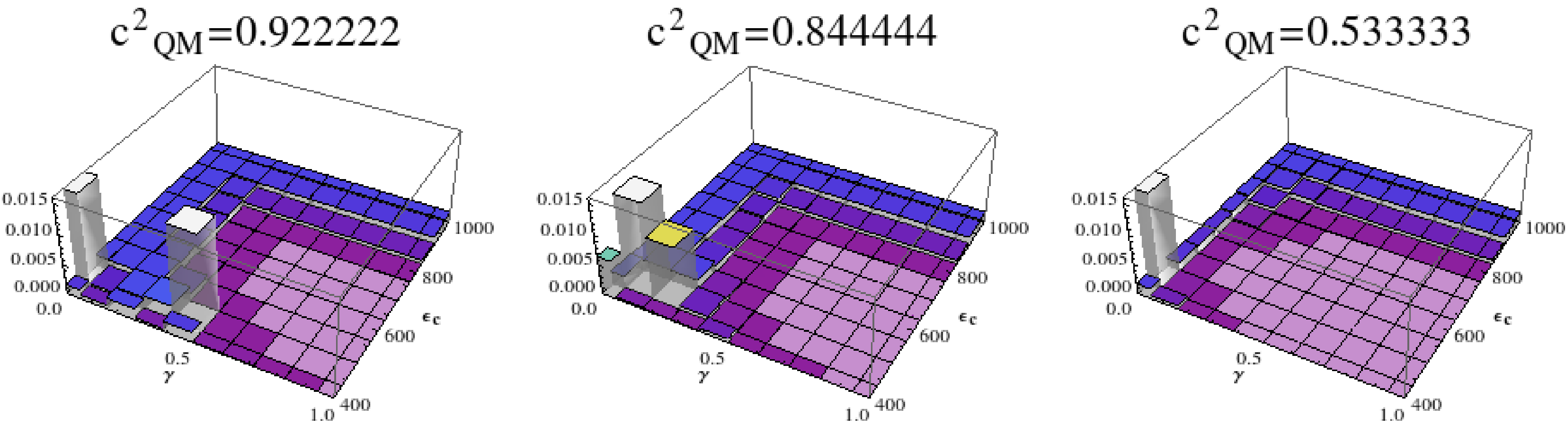

Blaschke, Grigorian, Alvarez, Ayriyan, J. Phys. Conf. Ser. 496 (2014) 012002

# Disjunct M-R constraints for Bayesian analysis !



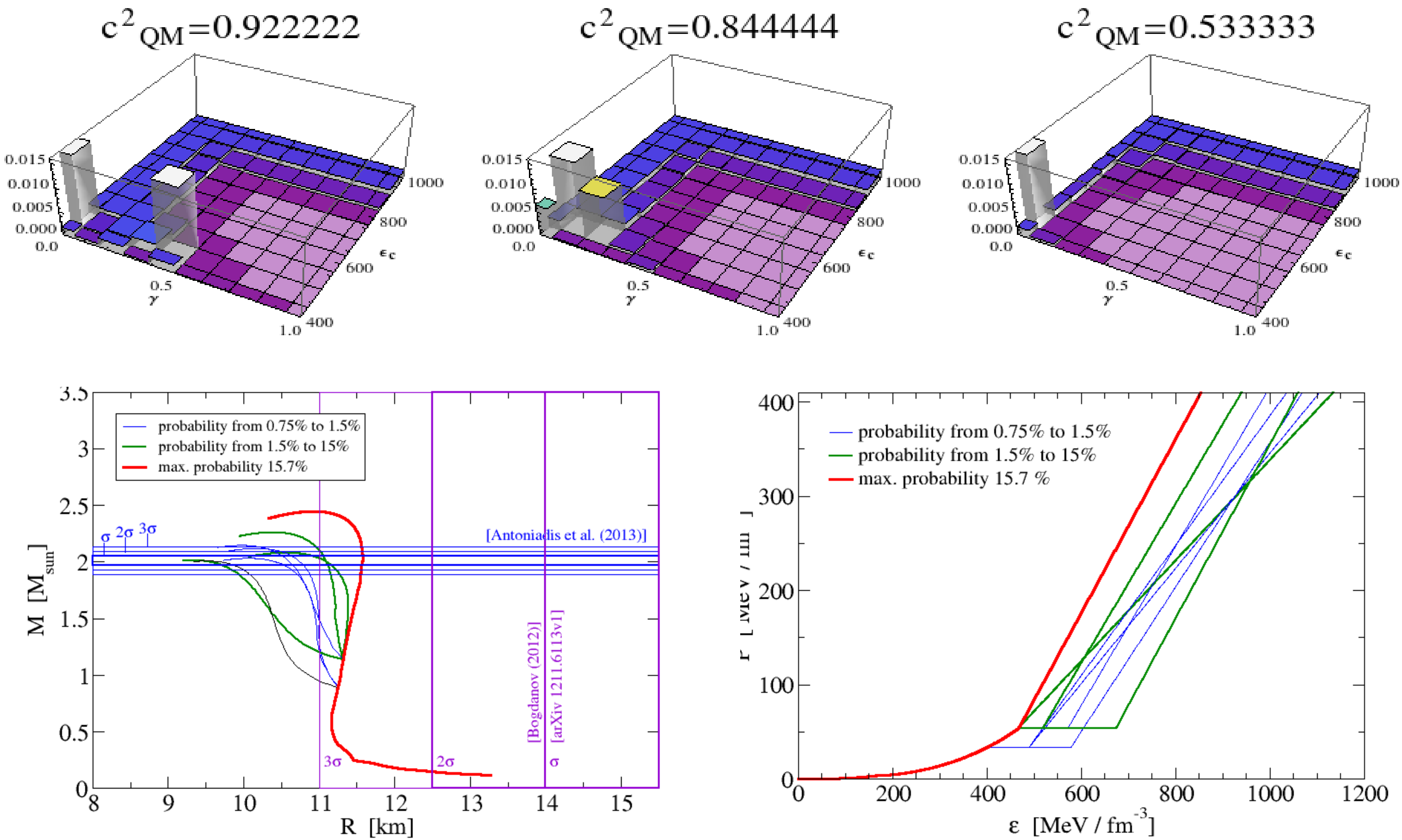

Blaschke, Grigorian, Alvarez, Ayriyan, J. Phys. Conf. Ser. 496 (2014) 012002

# Disjunct M-R constraints for Bayesian analysis !



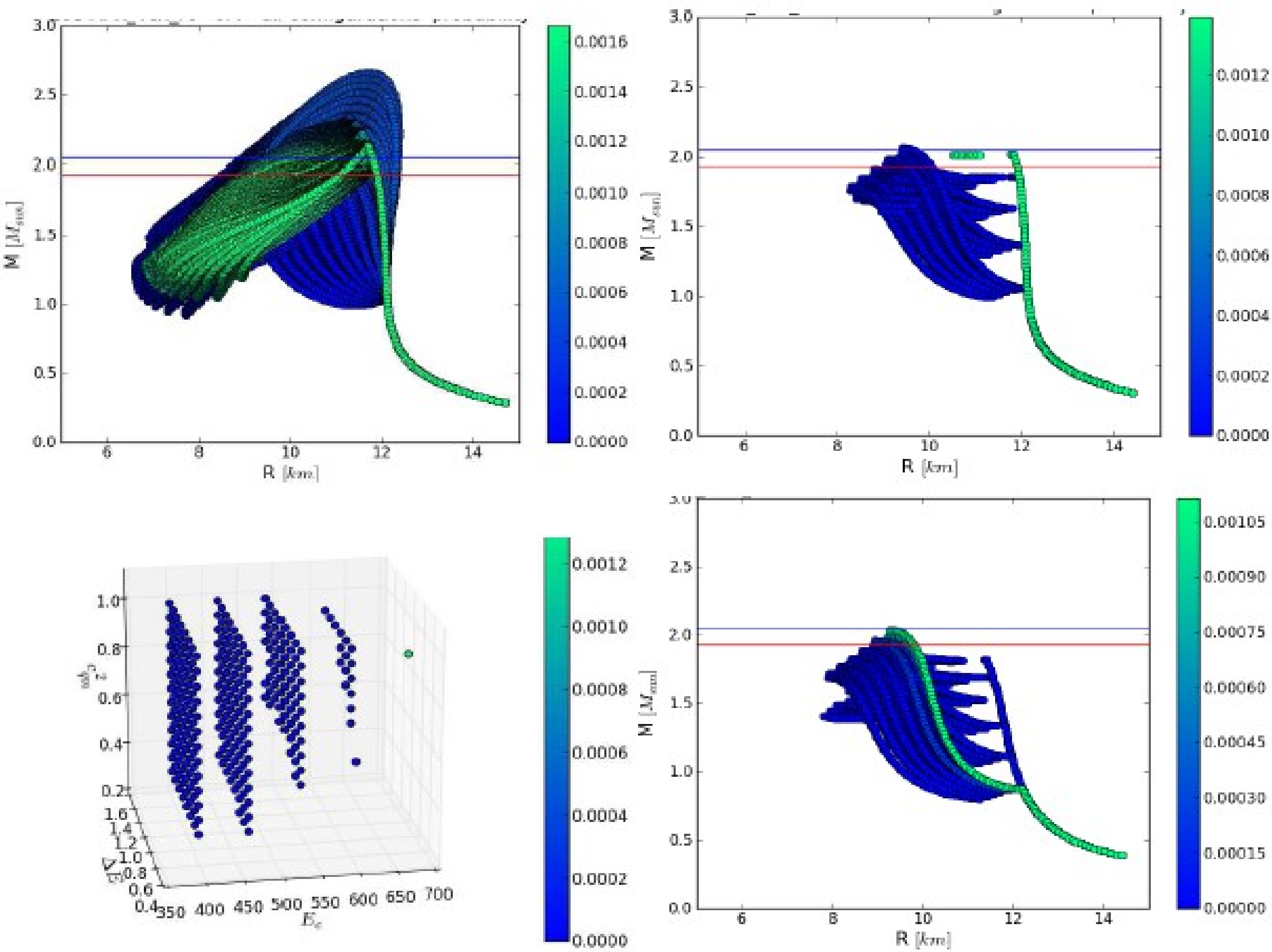

Blaschke, Grigorian, Alvarez, Ayriyan, J. Phys. Conf. Ser. 496 (2014) 012002

# Disjunct M-R constraints for Bayesian analysis !




Blaschke, Grigorian, Alvarez, Ayriyan, J. Phys. Conf. Ser. 496 (2014) 012002

# Phase transition? Measure different radii at 2Mo !




**APR EoS with excluded volume**

**APR EoS without excluded volume**

Alvarez, Ayriyan, Blaschke, Grigorian, Sokolowski (in progress, 2014)

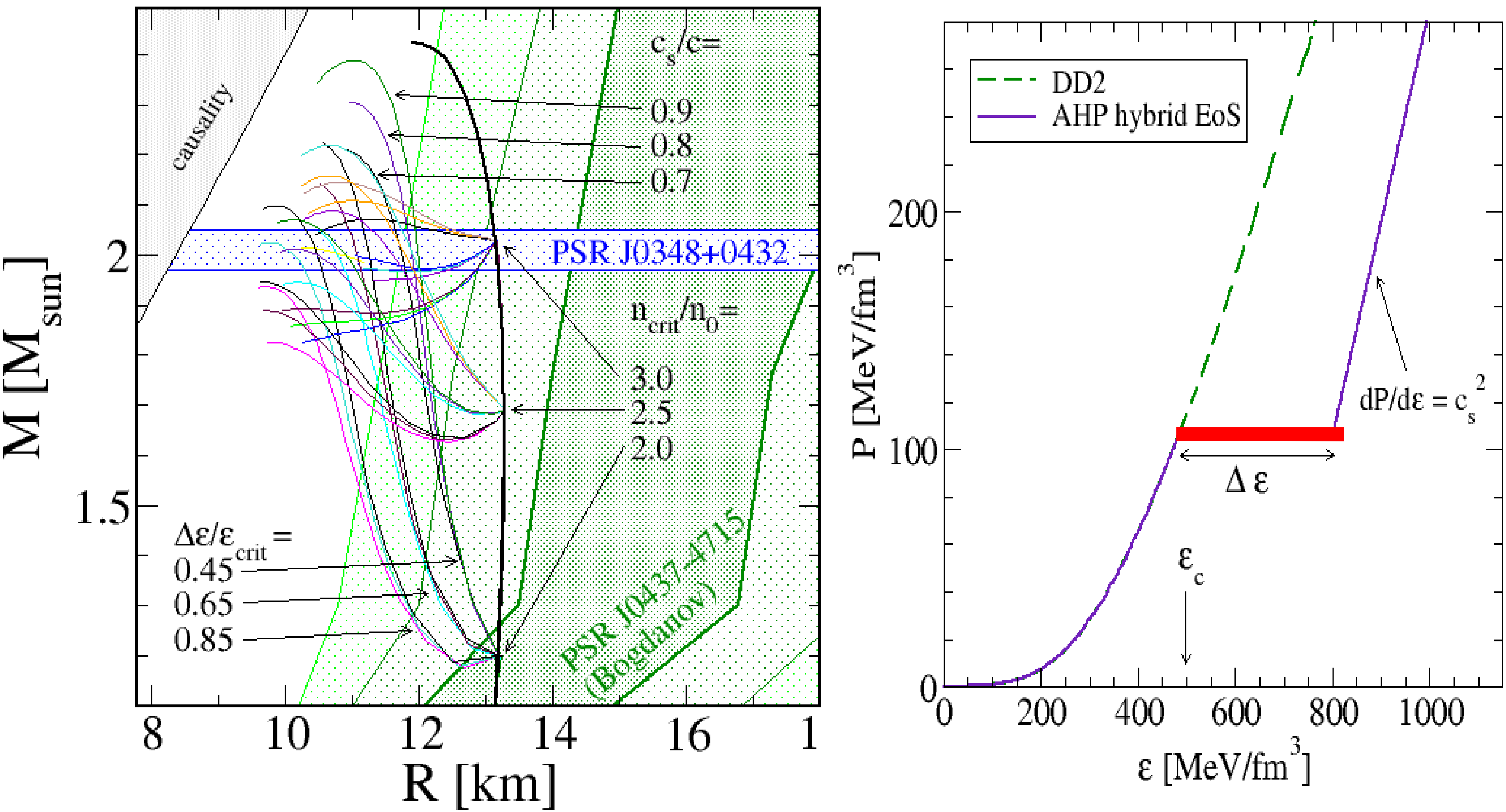
# Phase transition? Measure different radii at 2Mo !

"Now let us travel into future. It is year **2017**, some new, reliable NS radius measurement methods are discovered and were used to find the size of two most massive pulsars, which still are PSR J0348+0432 and PSR J1614-2230. **The community was shocked** when received the results of observations: one radius is $13 \pm 0.5\ \mathrm{km}$, while the other is $11 \pm 0.5\ \mathrm{km}$!"

– *Michał Sokołowski*, Master Thesis, 2014

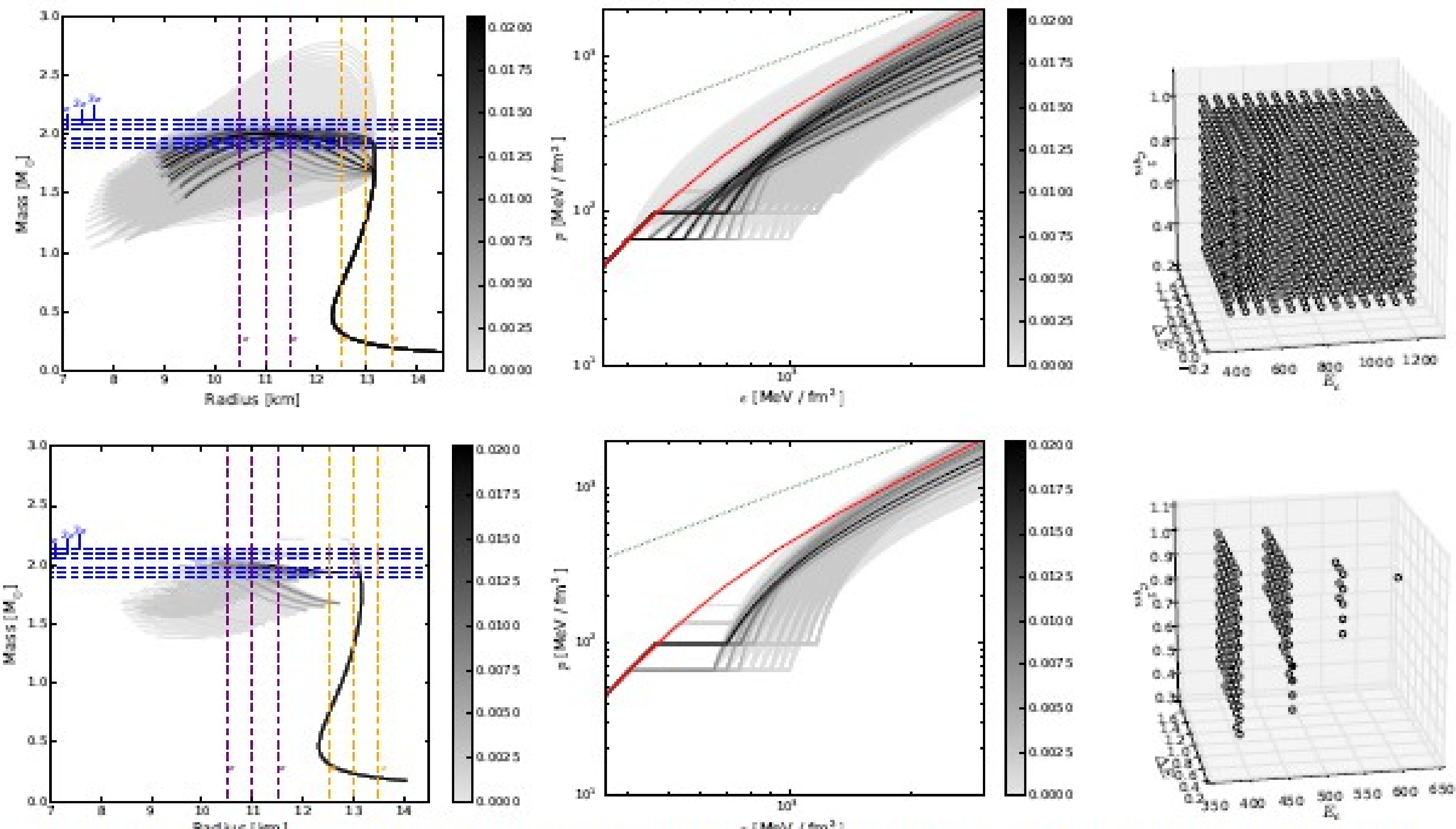
**Alvarez, Ayriyan, Blaschke, Grigorian, Sokolowski (in progress, 2014)**

# Phase transition? Measure different radii at 2Mo !




Alvarez, Ayriyan, Blaschke, Grigorian, Sokolowski (work in progress, 2014)

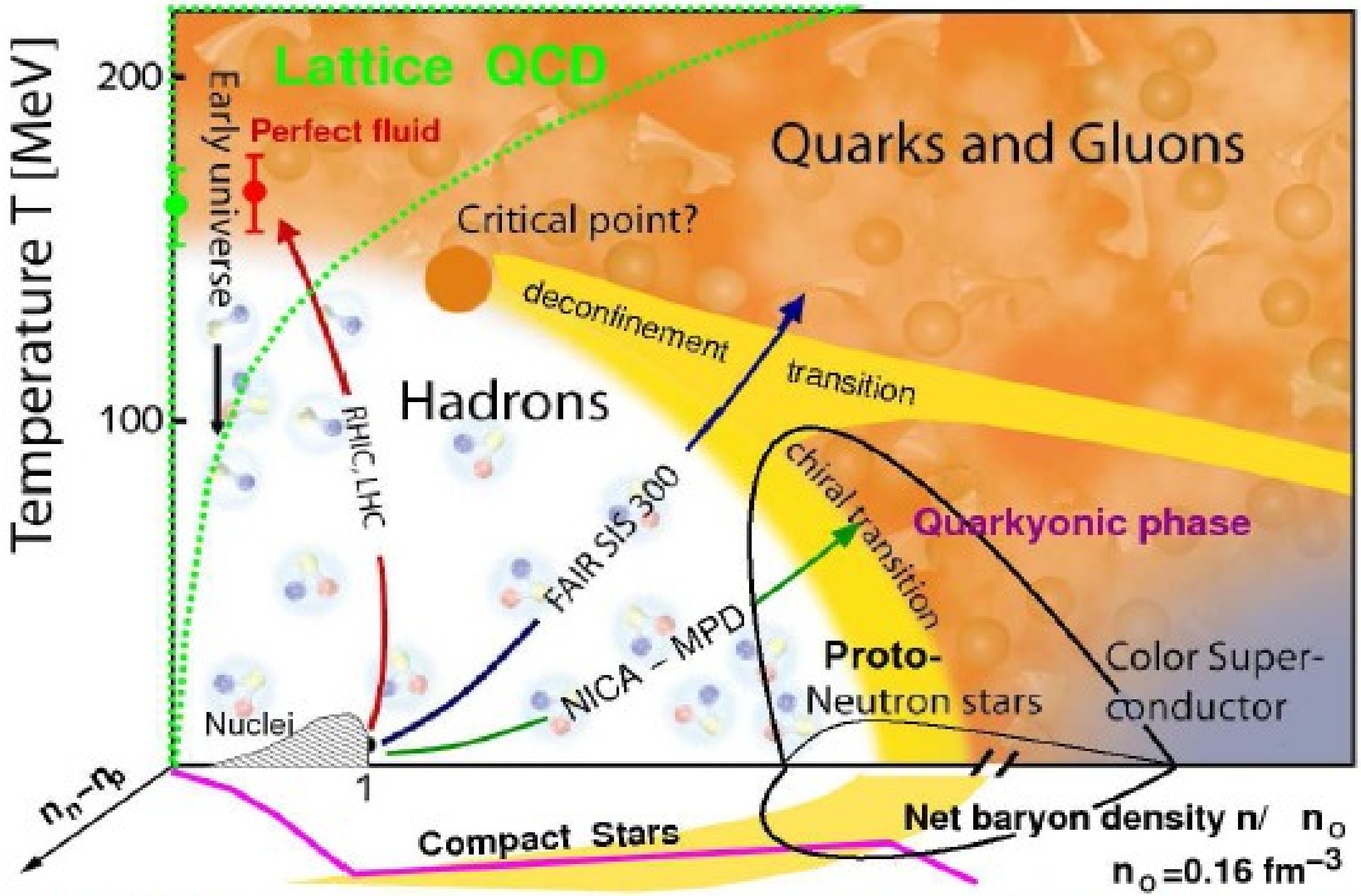
# Phase transition? Measure different radii at 2Mo !



BA of HEoS models based on pure DD2 with fictitious radius measurements.

Alvarez, Ayriyan, Blaschke, Grigorian, Sokolowski (work in progress, 2014)

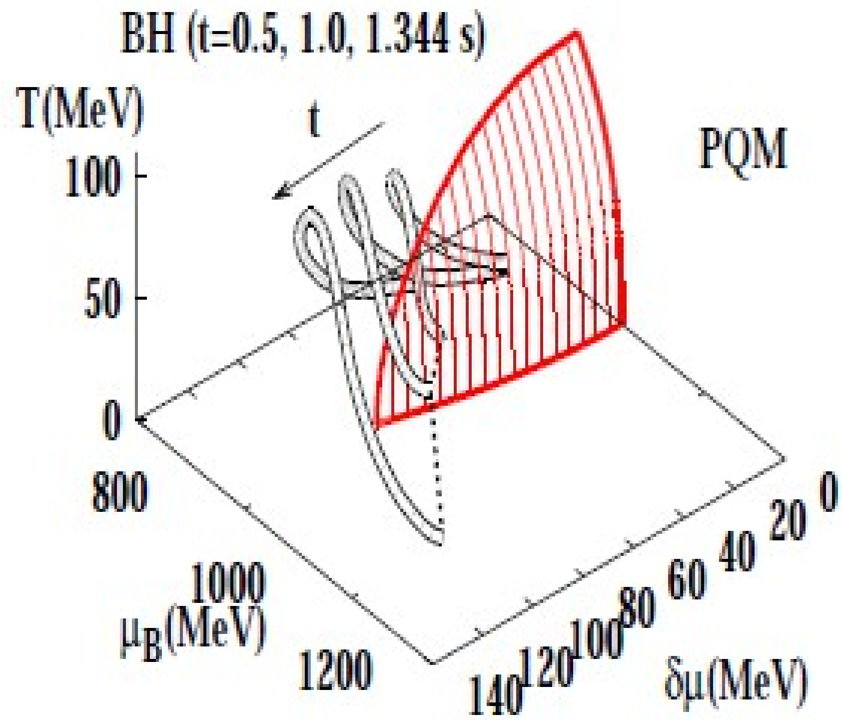
# How to probe the line of CEP's in Astrophysics?

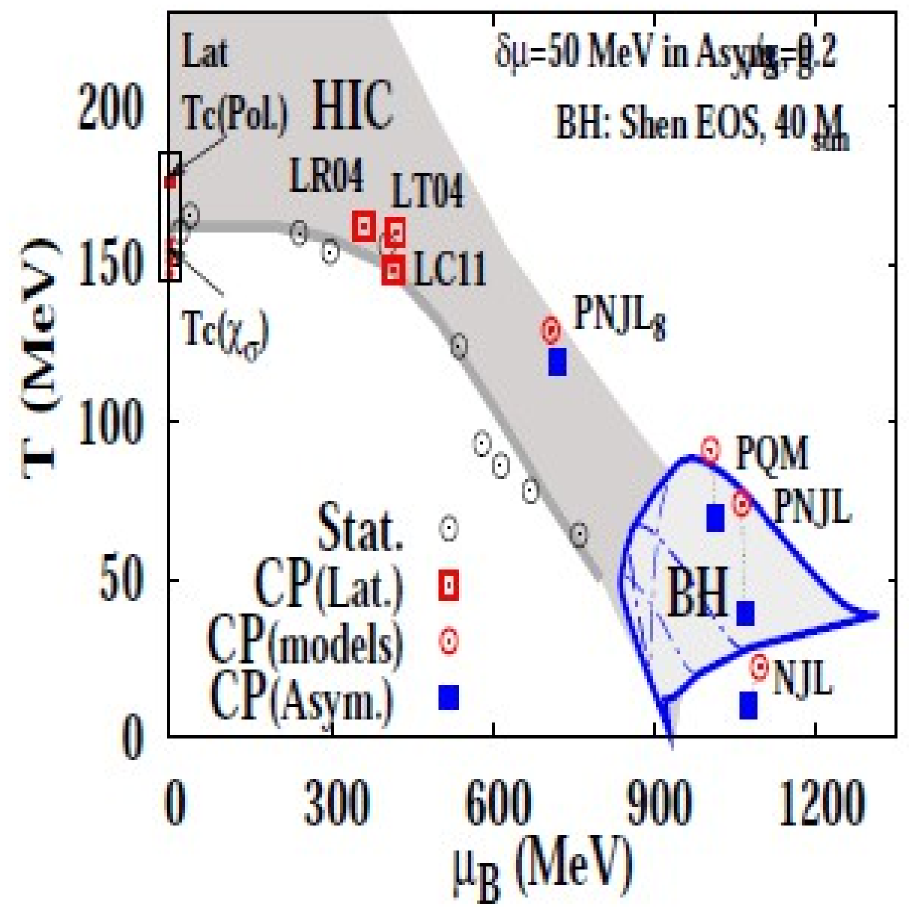



NICA White Paper, http://theor.jinr.ru/twiki-cgi/view/NICA/WebHome

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

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



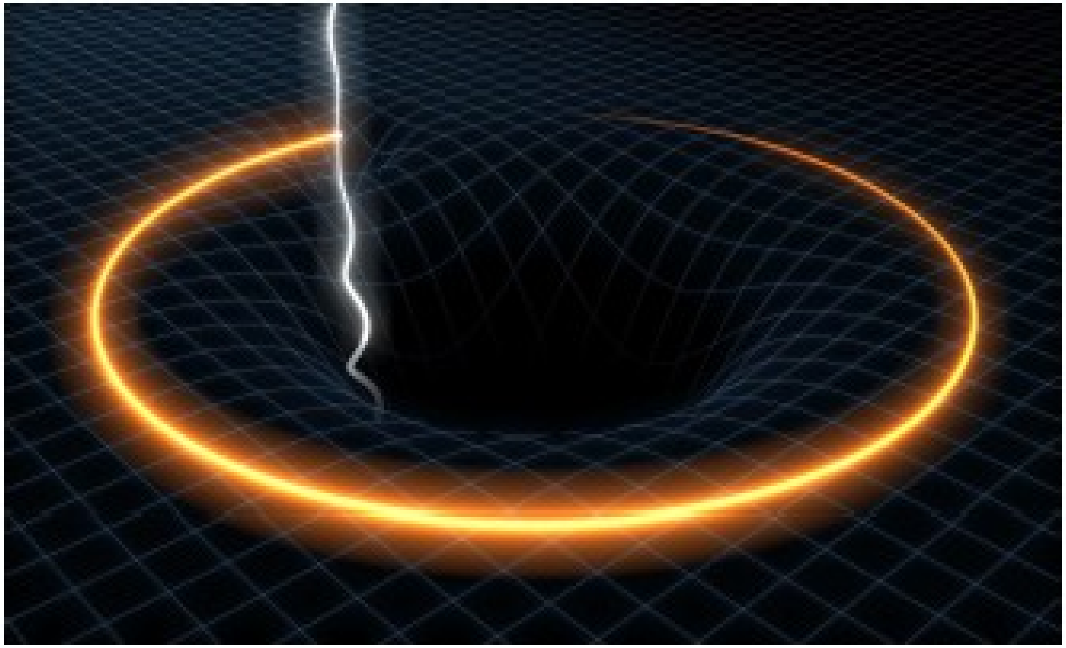



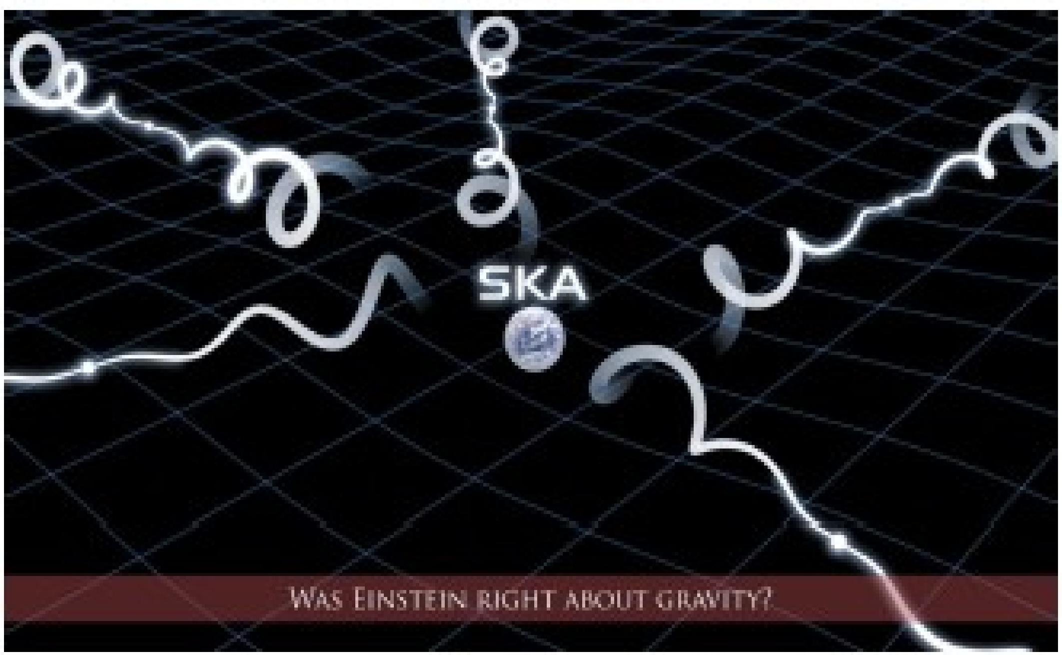

A. Ohnishi, H. Ueda, T. Nakano, M. Ruggieri, K. Sumiyoshi, Phys. Lett. B 704, (2011) 284.

# 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**