Bayesian analysis of hybrid EoS constraints with mass-radius data for compact stars

Recent results described in arXiv:1506.07755

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What if we have twins

Important questions

- Does hybrid neutron star exist?
- Does CEP exist on QCD phase diagram?

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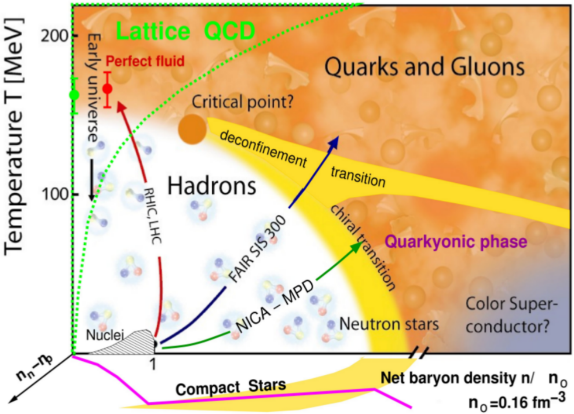
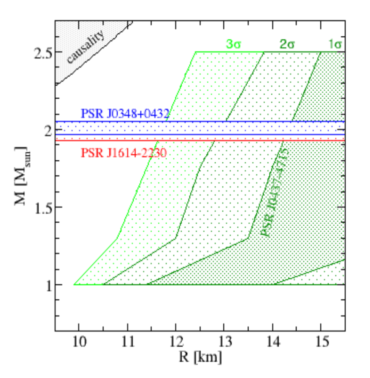
Existence of CEP at the QCD Phase Diagram



Topic for discussion!

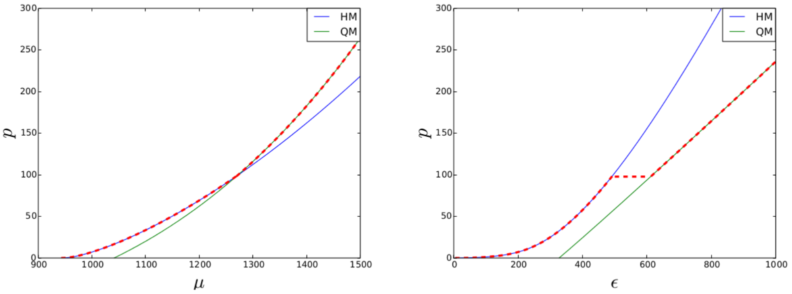
Mass and Radius Constraints

Radius and maximum mass constraints are given from PSR J0437-4715 (Bogdanov. Ast. J. **762**, 96) and PSR J0348+0432 (Antoniadis *et al.* Sci. **340**, 6131) correspondingly.



Maxwell Construction

Maxwell construction of hybrid EoS



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

$$p(\mu) = \max\left[p_H(\mu), p_Q(\mu)\right]$$

Hadronic matter EoS

Excluded-volume DD2

DD2 relativistic meanfield EoS was chosen for the analysis with an excluded volume correction **by S. Typel**.
This correction is applied at suprasaturation densities. In order to quantify the excluded volume effects, we introduce the closest packing parameter

$$\nu = 100 \times n_\nu \, \mathrm{fm}^3$$

where n_ν is the closest packing density.
The parameter ν was variated from 33 to 100, there were $N_1 = 29$ numbers of this parameter.

Quark matter EoS

Quark matter EoS with η_4 parameter

The quark matter was modelling by a two flavor Nambu-Jona-Lasinio (NJL) model with 8-quark interactions in the scalar and the vector channel **by S. Benic** [arXiv:1503.09145].
The η_2 – 4-quark vector couplings parameter was fixed (to describe hybrid stars with masses larger than $2M_{sun}$ [arXiv:1401.5380]) and the η_4 – 8-quark vector NJL couplings parameter was variated from 0 to 30 with step 1 (so, $N_2 = 31$).

Vector of Parameters

Vector of Parameters

For the BA, we have to sample the above defined parameter space and to that end we introduce a vector of the parameter values $\overrightarrow{\pi} = \{\nu, \eta_4\}$:

$$\overrightarrow{\pi}_i = \left\{\nu_{(k)}, \eta_{4(l)}\right\},$$

$i = 1 \ldots N$ (here $N = N_1 \times N_2$), $i = N_2 \times k + l$ and $k = 0 \ldots N_1 - 1$, $l = 0 \ldots N_2 - 1$

Qualification of the EoS models from Observation

Goal of the BA

To find posterior probabilities of the set of π_i taking into account the observational constraints.

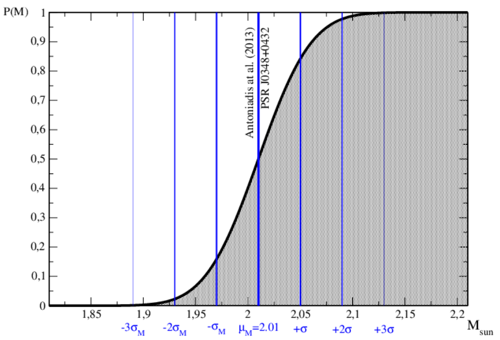
Unification of priori probabilities

$P(\pi_i) = 1/N \quad \text{for} \quad \forall\, i = 0..N-1.$

Calculation of Probabilities

Probability of Corresponding to Mass Constraint for π_i

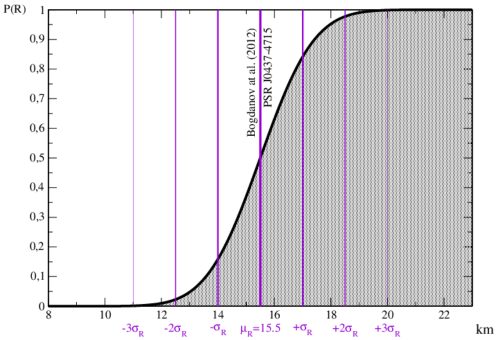
$P(E_A|\pi_i) = \Phi(M_i, \mu_A, \sigma_A)$, here M_i is max mass given by π_i.
$\mu_A = 2.01\ \mathrm{M}_\odot$ and $\sigma_A = 0.04\ \mathrm{M}_\odot$ [Antoniadis et al. Sci. 340].



Calculation of Probabilities

Probability of Corresponding to Radius Constraint for π_i

$P(E_B|\pi_i) = \Phi(R_i, \mu_B, \sigma_B)$, here R_i is max radius given by π_i.
$\mu_B = 15.5$ km and $\sigma_B = 1.5$ km [Bogdanov/Hambaryan et al.].



Calculation of Probabilities

Probability of All Constraints for π_i

Taking to the account assumption that these measurements are independent on each other we can calculate complete conditional probability:

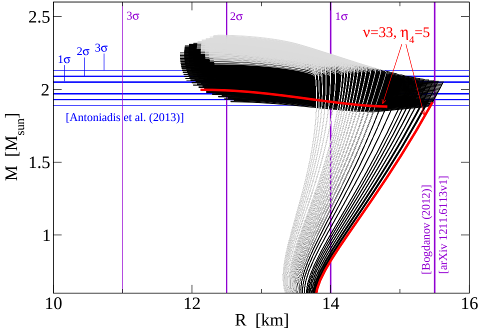
$$P\left(E\left|\pi_i\right.\right) = P\left(E_A\left|\pi_i\right.\right) \times P\left(E_B\left|\pi_i\right.\right)$$

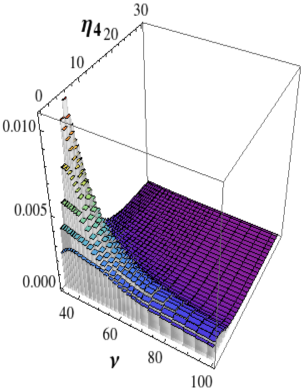
Calculation of *a posteriori* Probabilities of π_i

Now, we can calculate posterior probability of π_i:

$$P\left(\pi_i\left|E\right.\right) = \frac{P\left(E\left|\pi_i\right.\right) P\left(\pi_i\right)}{\sum_{j=0}^{N-1} P\left(E\left|\pi_j\right.\right) P\left(\pi_j\right)}$$

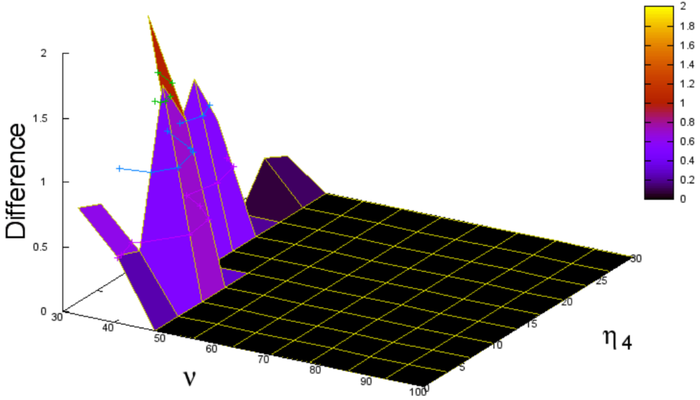
Results for Maxwell EoS models based on DD2 and NJL8



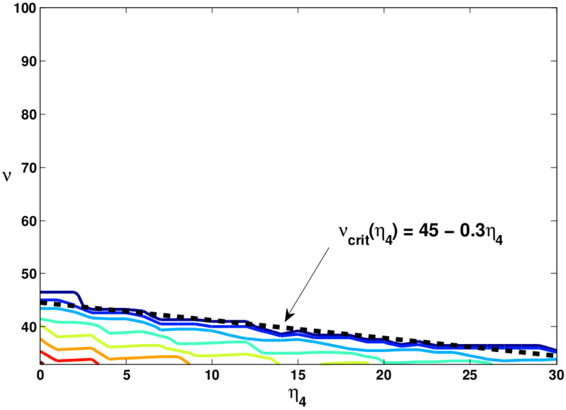


Bayesian analysis of the Maxweel HEoS models based on excluded volume DD2 and NJL8.

Results for Maxwell EoS models based on DD2 and NJL8



Results for Maxwell EoS models based on DD2 and NJL8



Conclusions

- The most probable models exhibit high-mass twin star configurations with quite distinguishable radii, differing by about 2 km.
- The region of the most probable models in the two-dimensional parameter space is sufficiently narrow, covering the ranges $33 < \nu < 38$ and $3 < \eta_4 < 7$.
- The existence of the horizontal branch signals a strong first order deconfinement phase transition and is a feature accessible to verification by observation. To that end, **at least for two high-mass pulsars** with masses $\sim 2\ M_\odot$ (like PSR J1614-2230 and PSR J0348+0432) **the radii should be measured** to sufficient accuracy and turn out to be significantly different.

"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 km, while the other is 11 $\pm$ 0.5 km!"

– *Michał Sokołowski*, Master Thesis, 2014