Bayesian study of quark matter inside hybrid stars

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22nd Zimányi Winter Workshop, 5-9 December 2022

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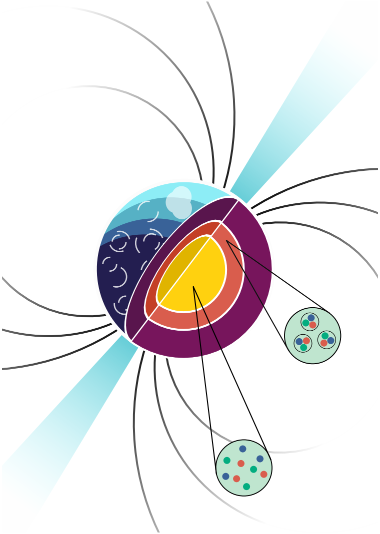
Supported by the ÚNKP-22-3 New National Excellence Program of the Ministry for Innovation and Technology.

Motivation: QCD and neutron stars



- At high densities quarks might be deconfined from hadrons
- The possibility of hybrid stars with quark cores is supported by recent studies[a]
- Effective quark models are available that are based on chiral symmetry restoration and meson vacuum phenomenology
- We can combine these models with constraints from QCD and astrophysics

[a] Annala et al., Nature Phys. 16 (2020) 9, 907-910

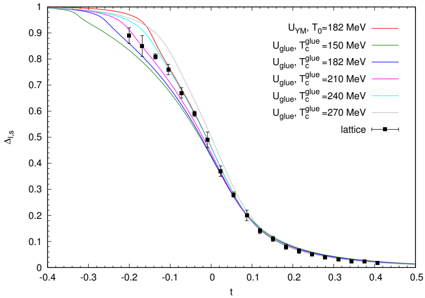
Ingredients for hybrid stars 1

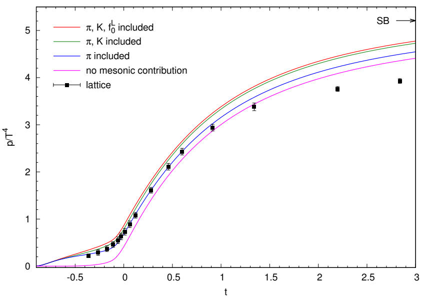
We use the (axial)vector meson extended linear sigma model[1]

↪ SU(3) constituent quark–meson model with the complete (pseudo)scalar and (axial)vector meson nonets

↪ parameterized with meson vacuum masses and decay widths

↪ agrees well with lattice results at finite temperature





[1] Kovács et al., Phys. Rev. D 93 (2016) 11, 114014

Ingredients for hybrid stars 2

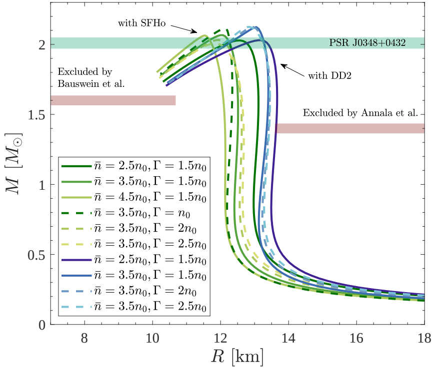
Hybrid stars also have a hadronic crust and outer core:

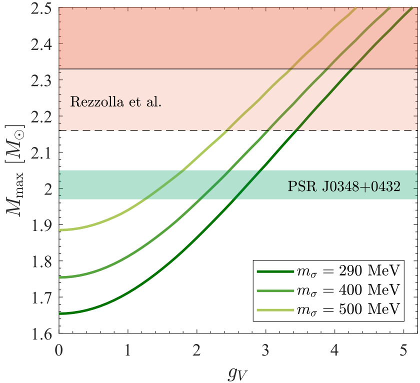
- at low densities we use hadronic EoSs:
  ↪ the SFHo EoS to represent soft hadronic EoSs
  ↪ the DD2 as a stiff EoS
- we apply a smooth connection between the two phases:
  ↪ $\varepsilon(n_B)$ interpolation with polynomial

$$\varepsilon(n_B) = \sum_{m=0}^{N} C_m n_B^m \,, \quad n_{BL} < n_B < n_{BU},$$

  the C_m coefficients are obtained by matching the pressure and its derivatives at the boundary points
- we are left with 4 tunable parameters:
  ↪ 2 from the constituent quark model: m_σ, g_V
  ↪ 2 describing the concatenation: $\bar{n}$, Γ

Constraints from maximum mass





↪ maximum mass hybrid stars reside in a small region, independent of the phase transition parameters[2]

↪ with $m_\sigma = 290$ MeV g_V is constrained to $2.5 < g_V < 4.3$

[2] similar results were found in *Cierniak & Blaschke, EPJ ST 229 (2020), 3663*

Bayesian analysis with astrophysical observations

Bayes' theorem:

$$p(\vartheta|\mathrm{data}) = \frac{p(\mathrm{data}|\vartheta)p(\vartheta)}{p(\mathrm{data})}$$

$$p(\mathrm{data}|\vartheta) = p(M_{\mathrm{max}}|\vartheta)p(\mathrm{NICER}|\vartheta)p(\tilde{\Lambda}|\vartheta)$$

↪ Lower limit on maximum mass from 2 $M_\odot$ NS observations

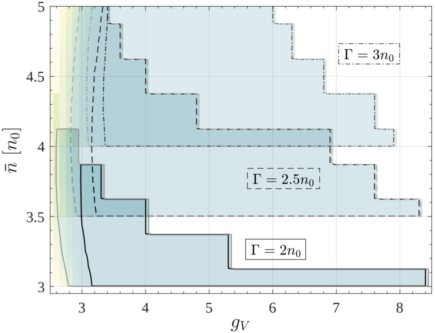
↪ Mass-radius probability densities from observations of PSR J0030+0451 and PSR J0740+6620 with NICER

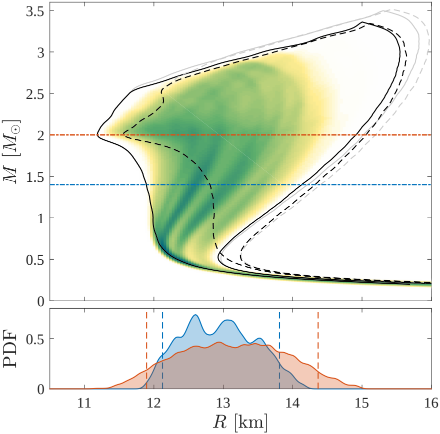
↪ Tidal deformability data from LVC for GW170817 + constraint from no prompt collapse to BH

↪ Upper mass constraint from hypermassive NS hypothesis[3]

[3] Rezzolla, Most & Weih, Astrophys. J. Lett. 852 (2018) 2, L25

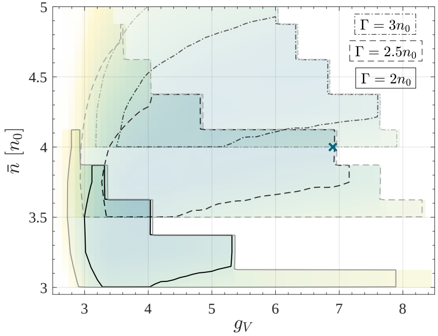
Bayesian priors

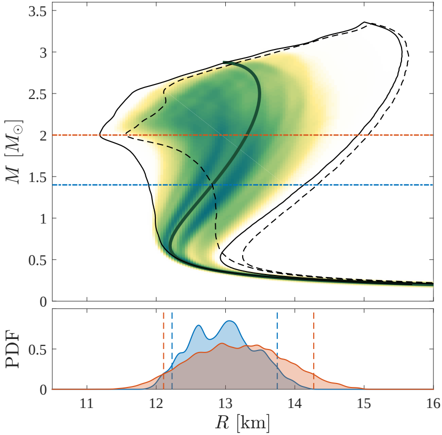




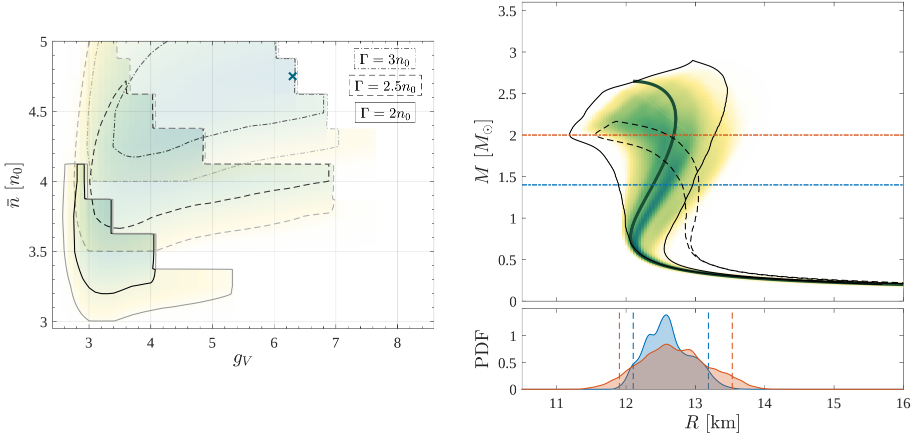
↪ small radii are constrained by our constituent quark model

Bayesian results: NICER





Bayesian results: NICER + GW170817



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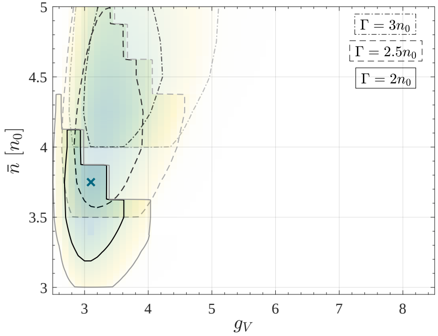
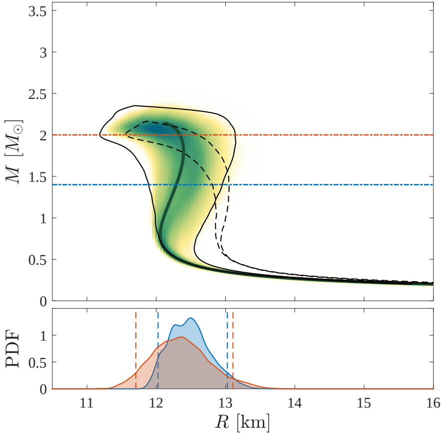
Bayesian results: NICER + GW170817 + M_{max}

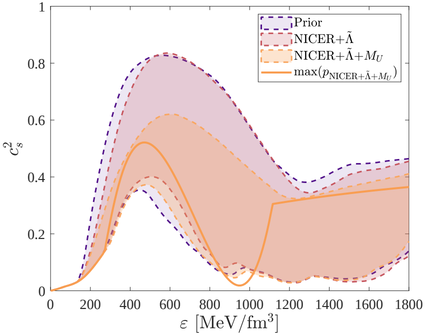




Summary

Conclusions

- we combined particle physics with astrophysical constraints
- we found that the maximum neutron star mass can be used to constrain the parameters of the model ($2.5 < g_V < 4.3$)
- from our Bayesian analysis we found that an intermediate density stiffening is preferred, and pure quark matter below $\sim 4n_0$ is disfavoured



Phys.Rev.D 105, 103014 (2020)

Prior constraints

↪ Flat prior in parameter space

↪ Unstable and acausal EoSs are excluded: $0 \leq c_s \leq 1$

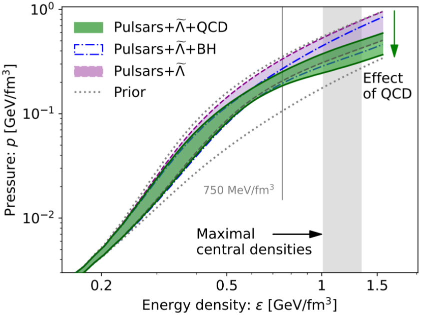
↪ EoS should also be compatible with pQCD calculations:

$$\Delta p_{\mathrm{min}} < \Delta p < \Delta p_{\mathrm{max}}$$

$$\Delta p_{\mathrm{min}} = \frac{\mu_{\mathrm{QCD}}^2 - \mu_{\mathrm{NS}}^2}{2} \frac{n_{\mathrm{NS}}}{\mu_{\mathrm{NS}}}$$

$$\Delta p_{\mathrm{max}} = \frac{\mu_{\mathrm{QCD}}^2 - \mu_{\mathrm{NS}}^2}{2} \frac{n_{\mathrm{QCD}}}{\mu_{\mathrm{QCD}}}$$

n_{QCD}	μ_{QCD}	p_{QCD}
6.47 $1/\mathrm{fm}^3$	2.6 GeV	3823 $\mathrm{MeV}/\mathrm{fm}^3$



The effect of the pQCD constraint, *Gorda, Komoltsev & Kurkela, arXiv: 2204.11877*

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Posteriors for different phase transition parameters