Bayesian inference on quark matter from observations of neutron stars

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Motivation: QCD and neutron stars

- We can not solve QCD at large densities from first principles due to the sign problem.
- There are no experimental results in this region so far.
- We may use effective models to try to describe strongly interacting matter.
- Neutron stars may provide constraints for these models.
Ingredients for hybrid stars 1

We use the (axial) vector meson extended linear sigma model. For hybrid stars we need the EoS at high density and $T = 0$:

- we need to introduce non-zero vector condensates
- $\beta$-equilibrium + charge neutrality
- 5 field equations (no Polyakov-loop contribution)

→ a naive parametrization → chiral symmetry would be broken at high densities

→ investigating the asymptotic behavior we get an additional constraint for the parameters

→ we get $m_\sigma = 290$ MeV from parametrization
Ingredients for hybrid stars 2

Hybrid stars also have a **hadronic crust and outer core**:

- at low densities we use hadronic EoS’s (SFHo and DD2)
- we apply a smooth crossover between the two phases:
  1. \( \varepsilon(n) \) interpolation
     \[
     \varepsilon(n) = \varepsilon_H(n)f_-(n) + \varepsilon_Q(n)f_+(n),
     \]
     \[
     f_\pm(n) = \frac{1}{2} \left( 1 \pm \tanh \left( \frac{n-\bar{n}}{\Gamma} \right) \right)
     \]
  2. \( p(\mu) \) interpolation with polynomial
     \[
     p(\mu_B) = \sum_{m=0}^{N} C_m \mu_B^m, \quad \mu_{BL} < \mu_B < \mu_{BU},
     \]
     the \( C_m \) coefficients are obtained by matching the pressure and its derivatives at the boundary points

\( \leftrightarrow \) 4 tunable parameters altogether: \( m_\sigma, g_V, \bar{n}, \Gamma \) (or \( \mu_{BL}, \mu_{BU} \))

\( \leftrightarrow \) we use the \( \varepsilon(n) \) interpolation with \( \bar{n} = 3.5n_0 \) and \( \Gamma = 1.5n_0 \) as our standard choice
$M - R$ curves for different $g_V$'s

$\rightarrow$ larger vector couplings result in larger hybrid star masses
$\rightarrow$ maximum masses are increased due to the intermediate density stiffening of the hybrid EoS's
$\rightarrow$ large sigma masses (brighter tones) are excluded by upper radius constraints
Effect of sigma mass and phase transition

$\rightarrow$ maximum mass hybrid stars seem to reside in a small region, independent of the phase transition parameters$^1$
$\rightarrow$ with $m_\sigma = 290$ MeV $g_\nu$ is constrained to $2.5 < g_\nu < 4.3$

$^1$ similar results were found in *Cierniak & Blaschke, EPJ ST 229, 3663 (2020)*
Bayesian analysis results

→ low sigma meson mass and a narrow phase transition are preferred

→ the center of the phase transition is between $2.5n_0$ and $3.5n_0$
Conclusions

- we developed a model that describes vacuum phenomenology and finite temperature behaviour accurately
- we found that the maximum neutron star mass can be used to constrain the parameters of the model
- from our Bayesian analysis we found that $g_V \approx 3 - 3.5$, a low sigma meson mass and a narrow phase transition are preferred
- we still want to do a deeper analysis of all the astrophysical constraints