Constraining quark matter inside hybrid stars

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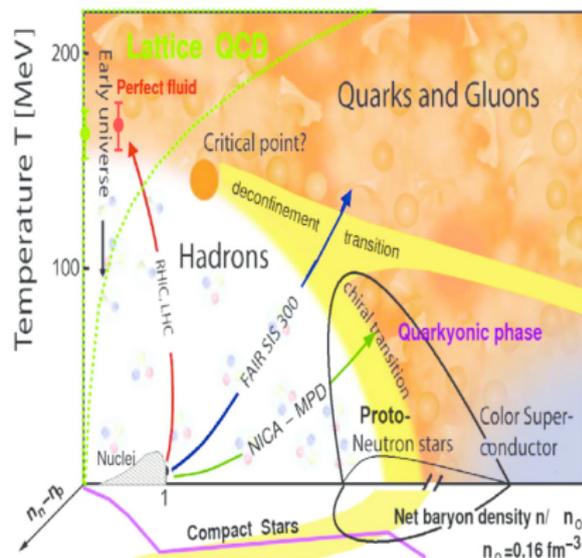*Collaborators:* György Wolf, Jürgen Schaffner-Bielich

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

Linear sigma model

Simple effective model that realizes global chiral symmetry: $SU(1)$ linear sigma model:

$$\mathcal{L} = \bar{\Psi} \left[i\slashed{D} - g(\sigma + i\pi\gamma_5) \right] \Psi + \tfrac{1}{2} \left[(\partial_\mu \sigma)^2 + (\partial_\mu \pi)^2 \right] - V(\sigma, \pi)$$

Mesonic potential: $V(\sigma, \pi) = \frac{\lambda}{4}(\sigma^2 + \pi^2 - f^2)^2, \; \lambda > 0$

Spontaneous symmetry breaking: $(\sigma, \pi) \to (f + \sigma, \pi)$
$\hookrightarrow$ generates mass for the fermion: $m_q = gf$ (Goldberger–Treiman relation)
$\hookrightarrow$ Nambu–Goldstone boson: $m_\pi = 0$, $m_\sigma = \sqrt{2\lambda f^2}$

Including thermal contribution from quarks $\to$ symmetry is restored at high temperature and density
$\hookrightarrow$ $SU(3)$ theories describe vacuum phenomenology and chiral phase transition successfully

Motivation
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The eLSM
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Results
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Summary
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eLSM Particle content

- Vector and Axial-vector meson nonets

$$V^\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\omega_N + \rho^0}{\sqrt{2}} & \rho^+ & K^{\star+} \\ \rho^- & \frac{\omega_N - \rho^0}{\sqrt{2}} & K^{\star 0} \\ K^{\star-} & \bar{K}^{\star 0} & \omega_S \end{pmatrix}^\mu \qquad A^\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{f_{1N} + a_1^0}{\sqrt{2}} & a_1^+ & K_1^+ \\ a_1^- & \frac{f_{1N} - a_1^0}{\sqrt{2}} & K_1^0 \\ K_1^- & \bar{K}_1^0 & f_{1S} \end{pmatrix}^\mu$$

$\rho \to \rho(770), K^\star \to K^\star(894)$ $a_1 \to a_1(1230), K_1 \to K_1(1270)$
$\omega_N \to \omega(782), \omega_S \to \phi(1020)$ $f_{1N} \to f_1(1280), f_{1S} \to f_1(1426)$

- Scalar $\left(\sim \bar{q}_i q_j \right)$ and pseudoscalar $\left(\sim \bar{q}_i \gamma_5 q_j \right)$ meson nonets
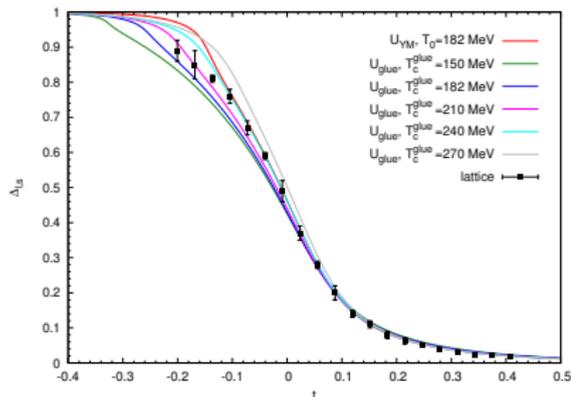
$$\Phi_S = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\sigma_N + a_0^0}{\sqrt{2}} & a_0^+ & K_0^{\star+} \\ a_0^- & \frac{\sigma_N - a_0^0}{\sqrt{2}} & K_0^{\star 0} \\ K_0^{\star-} & \bar{K}_0^{\star 0} & \sigma_S \end{pmatrix} \qquad \Phi_{PS} = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\eta_N + \pi^0}{\sqrt{2}} & \pi^+ & K^+ \\ \pi^- & \frac{\eta_N - \pi^0}{\sqrt{2}} & K^0 \\ K^- & \bar{K}^0 & \eta_S \end{pmatrix}$$

multiple possible assignments $\pi \to \pi(138), K \to K(495)$
mixing in the $\sigma_N - \sigma_S$ sector   mixing: $\eta_N, \eta_S \to \eta(548), \eta'(958)$

Spontaneous symmetry breaking: $\sigma_{N/S}$ acquire nonzero expectation values $\phi_{N/S}$

fields shifted by their expectation value: $\sigma_{N/S} \to \sigma_{N/S} + \phi_{N/S}$

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Results at zero chemical potential

– subtracted chiral condensate:

$$\Delta_{l,s} = \frac{\left(\Phi_N - \frac{h_N}{h_S} \cdot \Phi_S\right)\Big|_T}{\left(\Phi_N - \frac{h_N}{h_S} \cdot \Phi_S\right)\Big|_{T=0}}$$

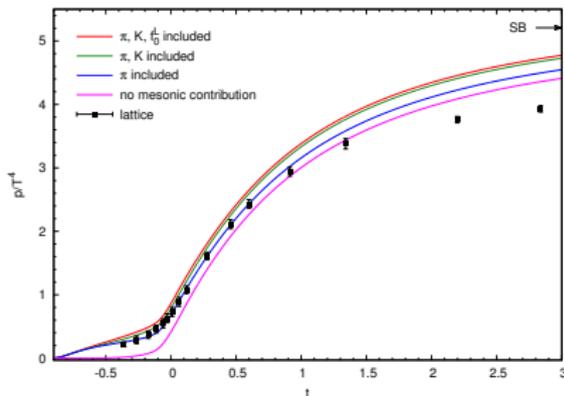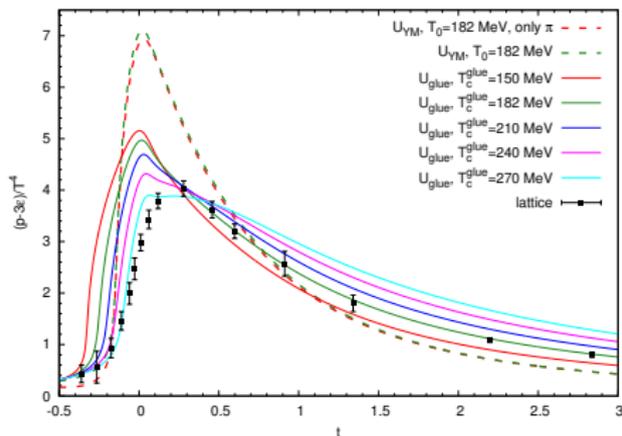– good agreement with the lattice result of Borsányi *et al.*, JHEP 1009, 073 (2010)

– pions dominate the pressure at small T
– contribution of the kaons is important
– at high T the pressure overshoots the lattice data of Borsányi *et al.*, JHEP 1011, 077 (2010)

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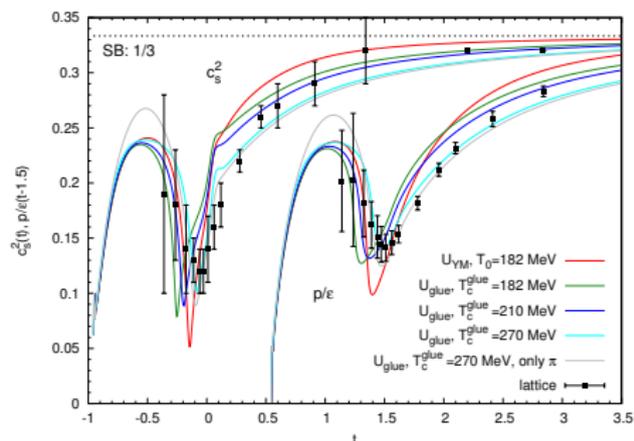○○

The eLSM
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Results at zero chemical potential

Scaled interaction measure

Speed of sound and p/ϵ

For large temperature the speed of sound approaches the conformal limit $c_s^2 \to 1/3$

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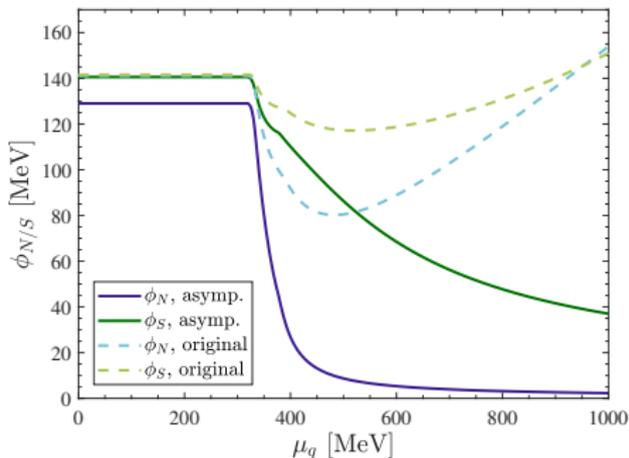○○○●○

Results
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Summary
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Ingredients for hybrid stars 1

For hybrid stars we need the EoS at high density and $T = 0$:

▶ we need to introduce non-zero vector condensates

▶ free electron gas + β-equilibrium

▶ charge neutrality: $\frac{2}{3}n_u - \frac{1}{3}n_d - \frac{1}{3}n_s - n_e = 0$

▶ 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

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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

$$\varepsilon(n) = \varepsilon_H(n)f_-(n) + \varepsilon_Q(n)f_+(n),$$

$$f_\pm(n) = \frac{1}{2}\left(1 \pm \tanh\left(\frac{n - \bar{n}}{\Gamma}\right)\right)$$

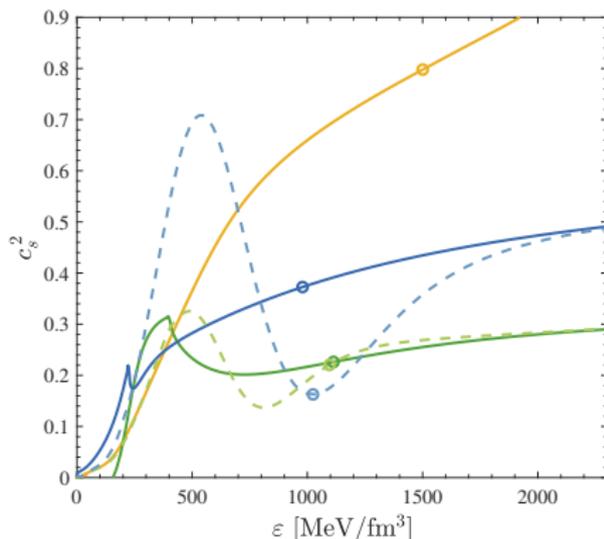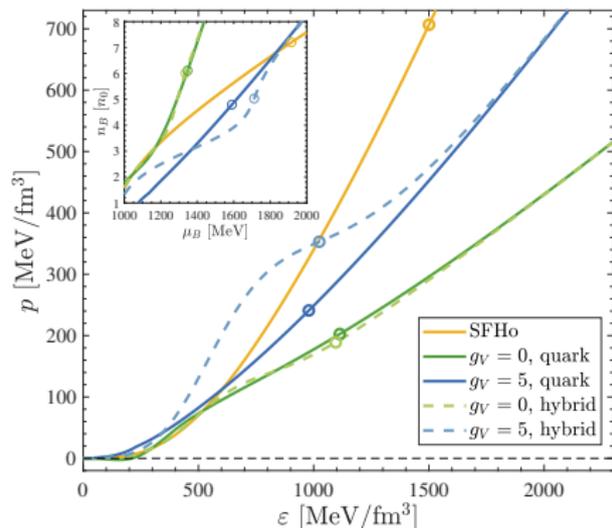 2. $p(\mu)$ interpolation with polynomial

$$p(\mu_B) = \sum_{m=0}^{N} C_m \mu_B^m, \quad \mu_{BL} < \mu_B < \mu_{BU},$$

  the C_m coefficients are obtained by matching the pressure and its derivatives at the boundary points

↪ 4 tunable parameters altogether: m_σ, g_V, $\bar{n}$, Γ (or μ_{BL}, μ_{BU})

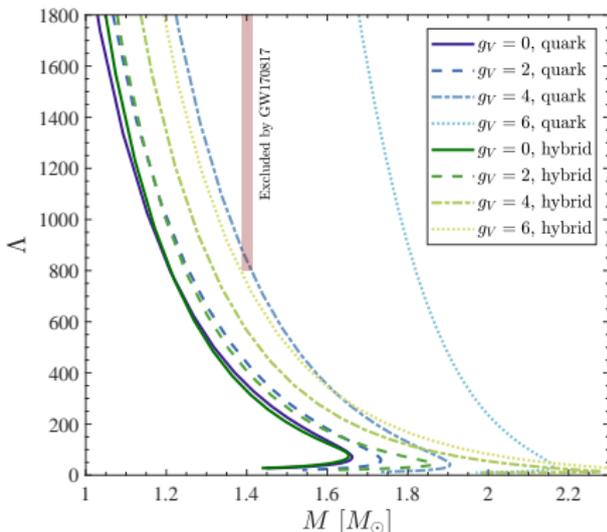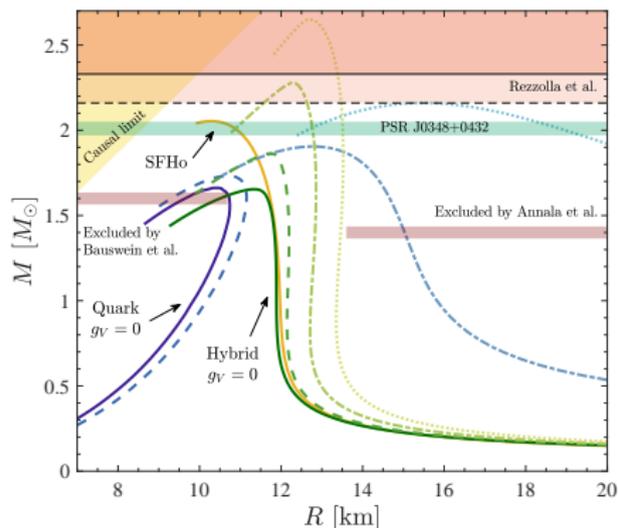↪ we use the $\varepsilon(n)$ interpolation with $\bar{n} = 3.5n_0$ and $\Gamma = 1.5n_0$ as our standard choice

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Equation of state

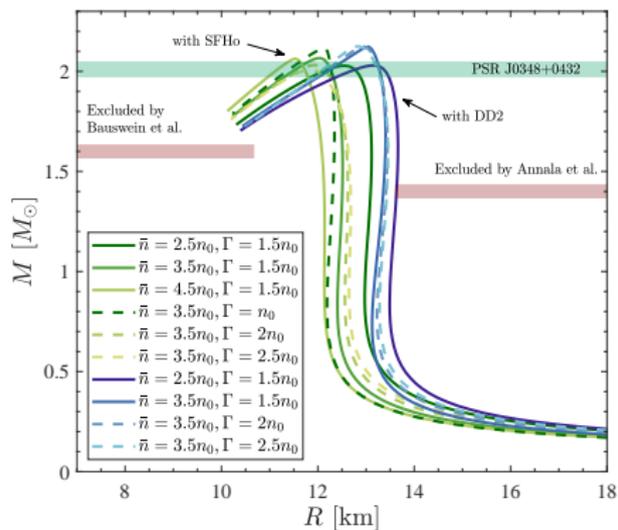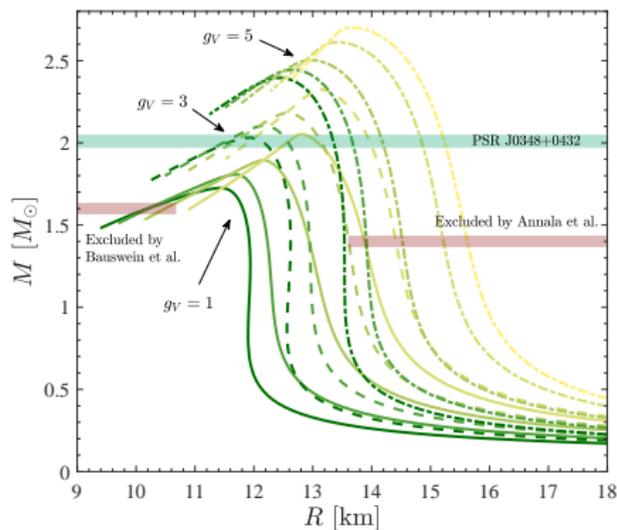↪ the concatenation results in a stiff intermediate density region for larger vector couplings

↪ the maximum density inside hybrid stars resides in the crossover region

$M - R$ curves for different g_V's

↪ larger vector couplings result in larger hybrid star masses

↪ maximum masses are increased due to the intermediate density stiffening of the hybrid EoS's

↪ with $m_\sigma = 290$ MeV g_V is constrained to $2.6 < g_V < 4.3$

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Effect of sigma mass and phase transition
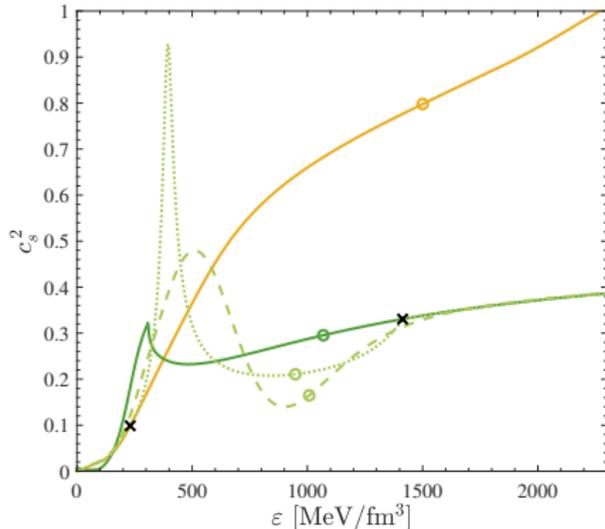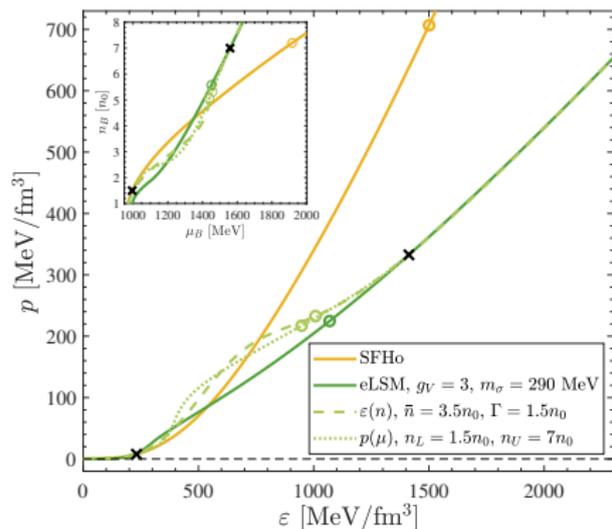

$\hookrightarrow$ large sigma masses (brighter tones) are excluded by upper radius constraints

$\hookrightarrow$ maximum mass hybrid stars seem to reside in a small region, independent of the phase transition parameters[1]

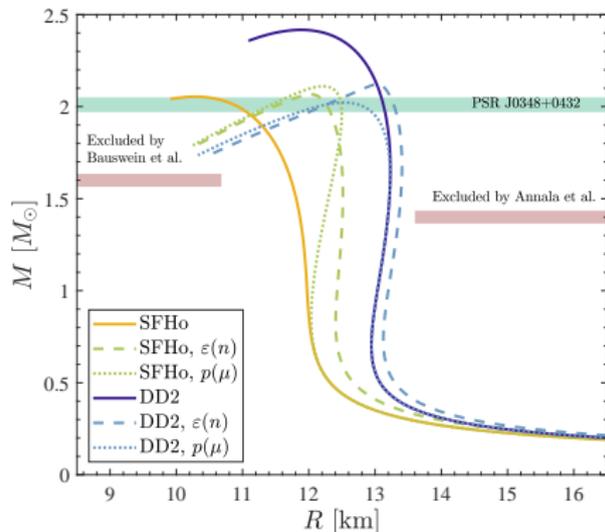[1]similar results were found in *Cierniak & Blaschke, EPJ ST 229, 3663 (2020)*

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Different concatenations

↪ the stiffer intermediate region also appears with the $p(\mu)$ interpolation

Different concatenations

$\hookrightarrow$ the stiffer intermediate region also appears with the $p(\mu)$ interpolation

$\hookrightarrow$ the maximum mass of hybrid stars is mainly determined by the EoS of the quark phase

$\hookrightarrow$ independent of concatenation method and hadronic EoS

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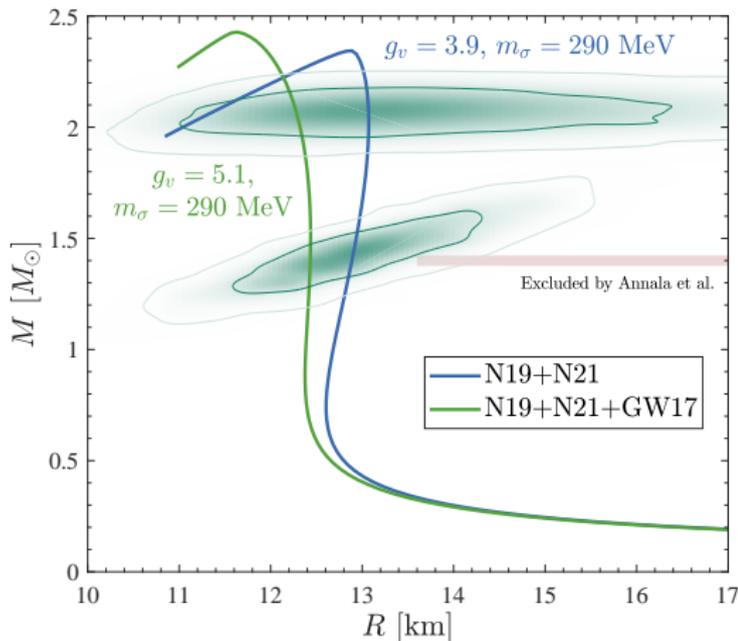
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Results from Bayesian analysis

$\hookrightarrow$ a lower sigma meson mass of $m_\sigma = 290$ MeV is preferred by astrophysical measurements

$\hookrightarrow$ we get $g_v \approx 5$ when considering GW170817 as well

$\hookrightarrow$ we can also estimate g_v using meson masses in a self-consistent approximation [1] $\rightarrow$ we get $g_v \approx 5$

$\hookrightarrow$ phase transition happens at around $3 - 4n_0$ for the highest probability curves

Figure shows M [$M_\odot$] vs R [km] with curves labeled $g_v = 3.9, m_\sigma = 290$ MeV; $g_v = 5.1, m_\sigma = 290$ MeV; Excluded by Annala et al.; legend N19+N21, N19+N21+GW17.

[1] Gy. Kovács et al., Phys. Rev. D 104, 056013 (2021)

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Summary

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 anlysis we found that $g_v \approx 5$ consistently with our self-consistent investigation, which gives $M_{\mathrm{max}} \approx 2.4 \ M_\odot$

Future work

▶ quantify the effect of using different constructions for phase transition

▶ investigate the allowed ranges of the constituent quark model parameters

▶ investigate what we can learn about the phase transition from the Bayesian analysis

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Thank you for your attention!