Towards a Unified EoS for Multi-Messenger Astronomy

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Criticality in QCD and the Hadron Resonance Gas

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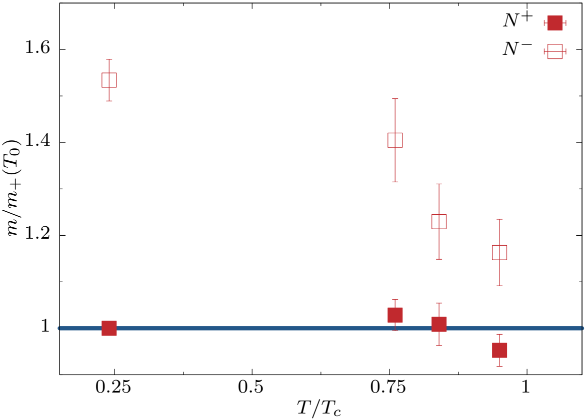
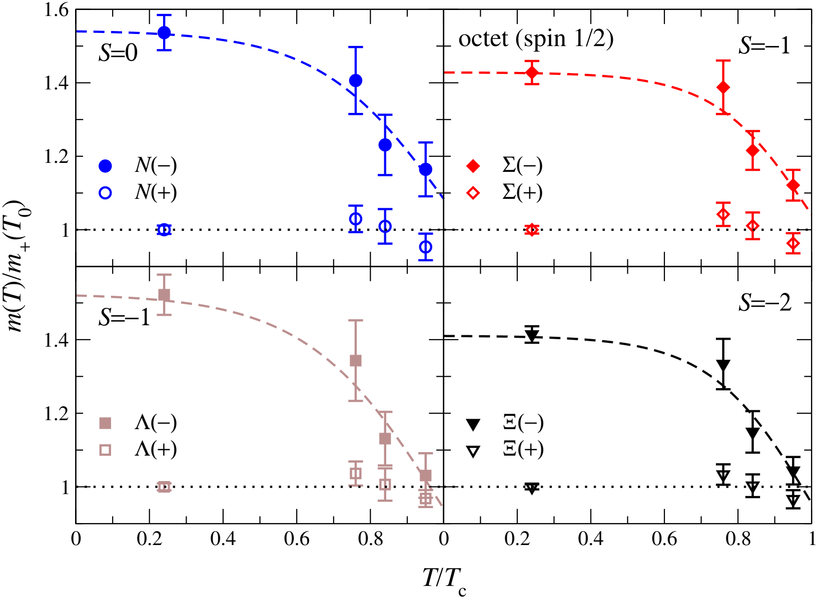
Parity Doubling in Lattice QCD Aarts *et al*, JHEP **1706**, 034 (2017)

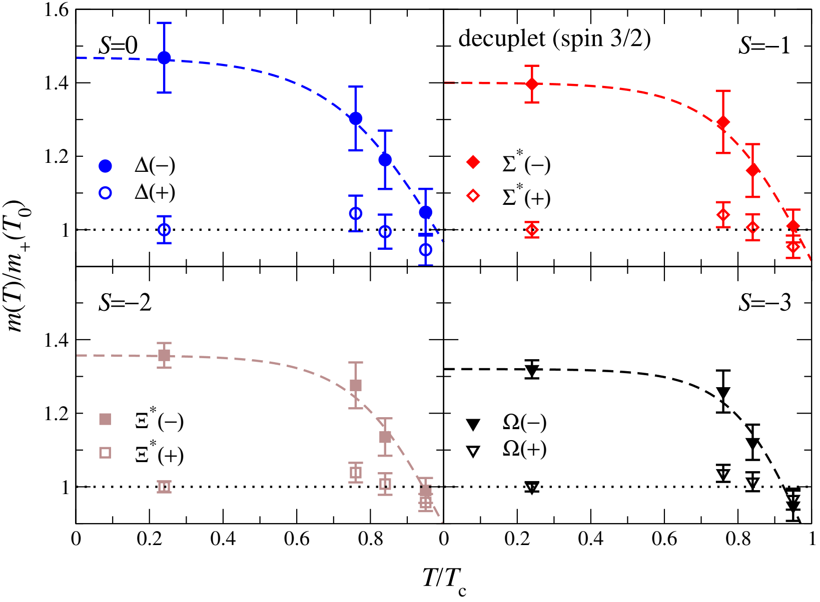


- Imprint of chiral symmetry restoration in the baryonic sector
- $N^{\pm}$ remain massive around T_c
- Expected to occur in cold and dense nuclear matter as well

Parity Doubling for Light Baryons
Aarts *et al*, PRD **99** (2019)

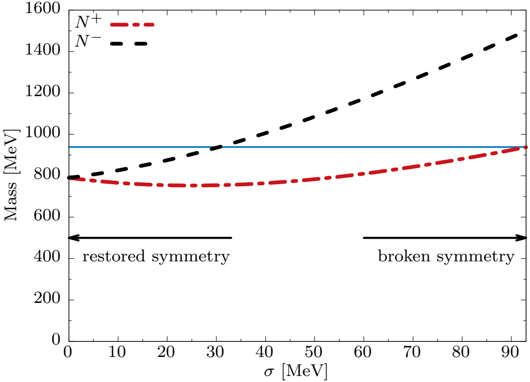


Parity Doubling for Light Baryons Aarts *et al*, PRD **99** (2019)



Parity Doubling in SU(2) Chiral Models DeTar, Kunihiro PRD **39** (1989)

$$m^{\pm} = \frac{1}{2}\left[\sqrt{4m_0^2 + c_1^2\sigma^2} \mp c_2\sigma\right] \xrightarrow{\sigma\to 0} m_0$$



$\leftarrow N(1535)$

$\leftarrow N(939)$

- The model has been applied to hot and dense hadronic matter, neutron stars, as well as the vacuum phenomenology of QCD

Hybrid Quark-Meson-Nucleon Model

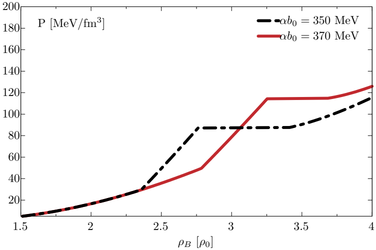
Benić, Mishustin, Sasaki, PRD **91** (2015)

Parity Doublet Model $+$ Quark-Meson Coupling

Statistical Confinement

UV cutoff: $\theta\left(\underset{\substack{\uparrow \\ \text{model parameter}}}{\alpha^2} b^2 - \boldsymbol{p}^2\right) f_N$ $\quad + \quad$ IR cutoff: $\theta\left(\boldsymbol{p}^2 - b^2\right) f_q$

- similar scaling as in Ex. Vol. approaches: smaller values $\longrightarrow$ earlier onset of stiffening



const $b \longrightarrow$ scalar field b

$\downarrow$

generated from potential

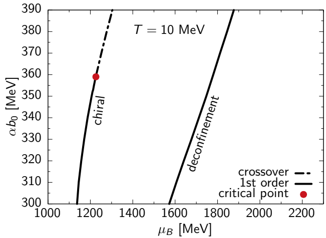
$\downarrow$

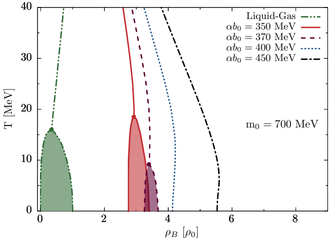
$b > 0$ favors nucleons

$b \to 0$ favors quarks

- Constrained by nuclear GS, compressibility, symmetry energy

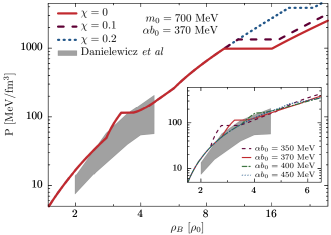
Phase Structure in Isospin-Symmetric Matter



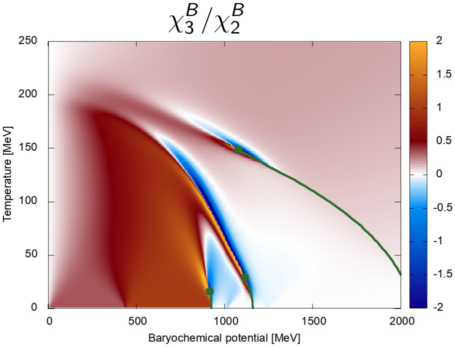


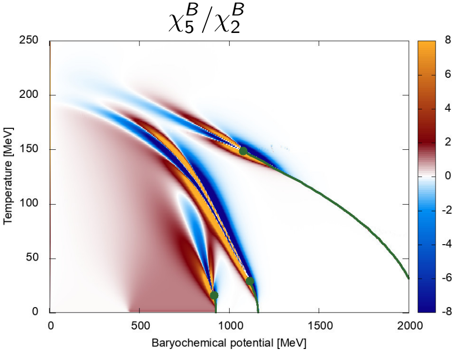
- Sequential phase transitions
  - $\alpha \rightarrow$ Critical Point ($T_c^{\rm chiral} \lesssim 40$ MeV)
  - 1st Order Deconfinement Transition
- Quark-vector coupling: $g^q = \chi g^N$
  - onset of quarks shifted
- χPT within the proton flow constraint
- possible signals in dilepton production

Sasaki, PLB (2020)



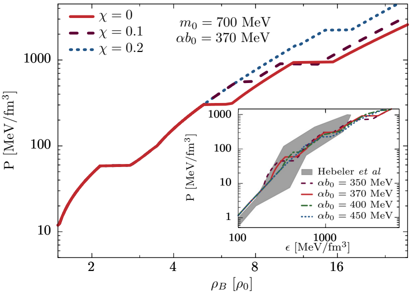
Isospin-Symmetric Phase Diagram

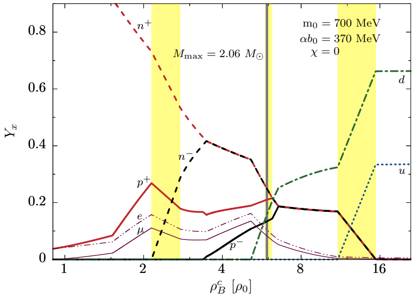




- Rich structure: clear separation into three regions at low T $\rightarrow$ 3 CEPs
  - confined & χSB; confined & χSR; deconfined
- Interplay btw. LG and chiral transition important at intermediate T
- Signal from chiral PT seems stronger than LG at higher temperature?
- Deconfinement at high μ_B

EoS in Asymmetric Matter, $T = 0$, MM, Blaschke, Redlich, Sasaki, arXiv:2004.09566

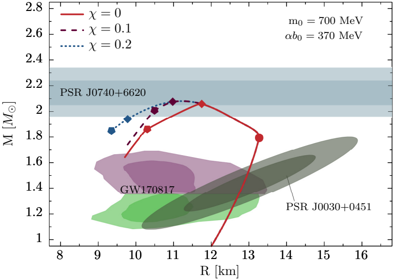


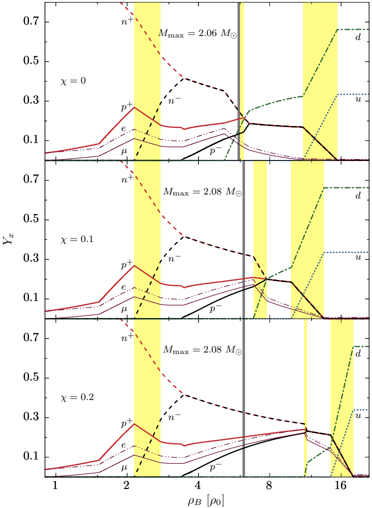


- Quark appearence splits due to asymmetry: additional intermediate phase
  - confined & χSB; confined & χSR; confined & χSR & d quark; deconfined
- Possible indication of quarkyonic phase
- cooling and transport properties?
  - relevant for thermal and rotational evolution of compact stars

Blaschke, Sandin, Klähn, Berdermann, PRC (2009)

Mass-Radius Profile and Particle Content





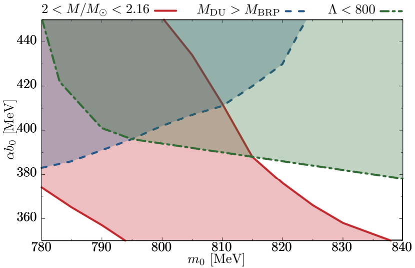
- Flattening due to chiral symmetry restoration, not deconfinement
- $M_{\max}$ reached in hadronic branch
- Quarks always in unstable branch
- Onset of quarks possibly reduced by attractive diquark interaction

Klähn *et al*, PLB (2007)

Multi-Messenger Astronomy: Tension Between Constraints

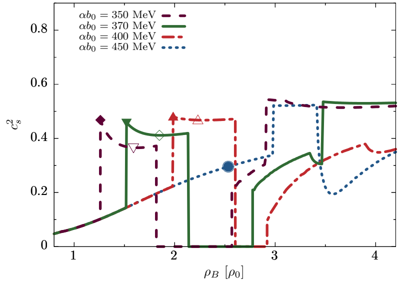
- Tidal deformability from GW170817 → soft pressure at $\sim 2\rho_0$
- $2\ M_\odot$ observations → high pressure at $\gtrsim 2\rho_0$

- Limit the parameter space



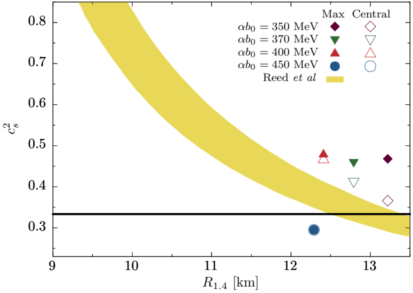
MM, Blaschke, Redlich, Sasaki, PRD (2018)

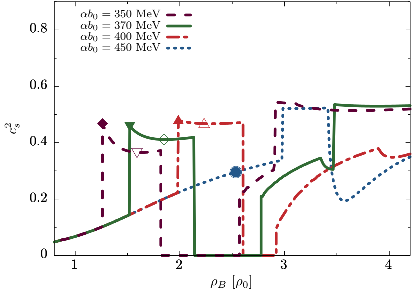
- Swift increase of pressure needed
- Large speed of sound at $\gtrsim 2\rho_0$



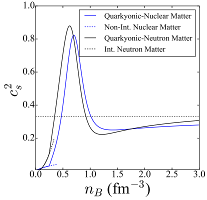
Marczenko, arXiv:2005.14535

Large c_s^2 and the nature of dense matter, Marczenko, arXiv:2005.14535





- Conformal limit broken already in $1.4 M_\odot$ NS
- Lower bound for c_s^2 of 1.4 $M_\odot$ NS Reed *et al* PRC (2020)
- Stiffening of EoS provided through the confining mechanism
- Similar to quarkyonic models



McLerran, Reddy, PRL 2019.

Conclusions

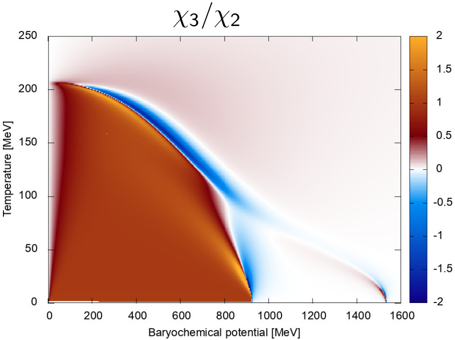
Hybrid QMN model - attempt at unified description of hadron-quark matter

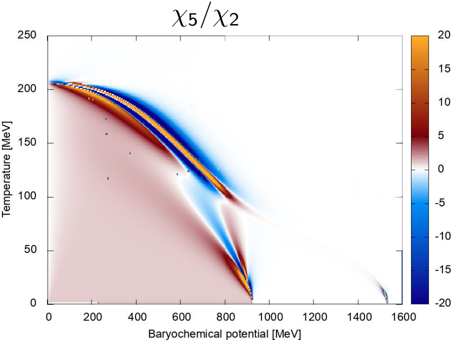
- Chiral symmetry restoration and deconfinement well separated;
  - quarkyonic matter scenario?
  - cooling and transport properties?
- 2 $M_\odot$ NS with chirally restored but confined core;
- Existence of hybrid stars rather excluded;
  - generalization to include CSC phase;
- Incorporating deconfinement essential factor in explaining the large-speed-of-sound scenario;

- Model well-suited for further applications in simulations of NS mergers, supernova events or HIC.

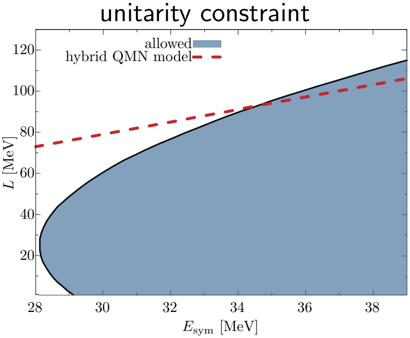
Thank You

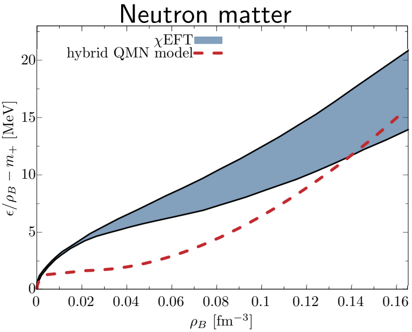
Parity Doublet Mode: Phase Diagram





Constraints





Speed of Sound in NS