Chiral symmetry restoration by parity doubling and the structure of neutron stars

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Introduction

We discuss the implications of the chiral symmetry restoration by parity doubling of baryons on the mass-radius relation for compact stars. Most important for this study are the nucleon (neutron, proton) and N(1535) states. We also consider the threshold for the direct URCA process for which a new relationship is given. We show that the existence of high-mass stars might not necessarily signal the deconfinement of quarks.

SU(2) Hybrid QMN model

- Thermodynamic potential in the mean-field approximation

$$\Omega = V_\sigma + V_\omega + V_\rho + V_b + \sum_x \Omega_x, \quad x = p_\pm, n_\pm, u, d$$

$$\Omega_x = \gamma_x \int \frac{\mathrm{d}^3 p}{(2\pi)^3}\, T\left[\ln(1-n_x) + \ln(1-\bar{n}_x)\right]$$

- Hadrons
  - coupled to σ, $\boldsymbol{\pi}$, ω, ρ and b
  - parity doubling structure ($m_{p_\pm} = m_{n_\pm} \equiv m_\pm$)

$$m_\pm = \frac{1}{2}\left[\sqrt{(g_1+g_2)^2\sigma^2 + 4m_0^2} \mp (g_1 - g_2)\sigma\right] \xrightarrow{\sigma\to 0} m_0$$

- Quarks
  - coupled to σ and b
  - Standard linear sigma for quarks ($m_u = m_d \equiv m_q$)

$$m_q = g_\sigma \sigma \xrightarrow{\sigma\to 0} 0$$

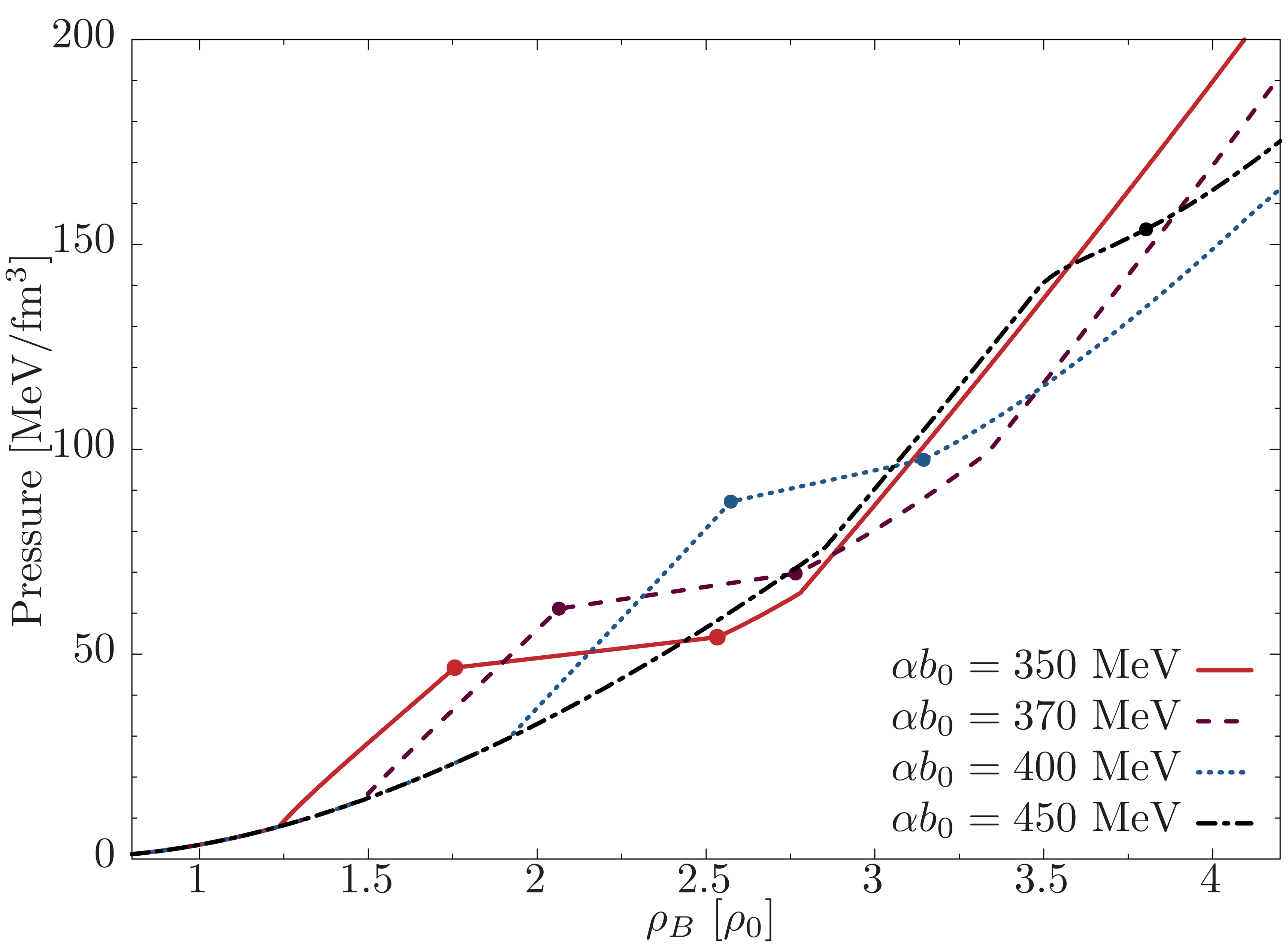
Statistical (de)confinement

- Modification of the Fermi-Dirac distrubition functions

$$n_q = \theta\left(\mathbf{p}^2 - b^2\right) f_q \qquad n_\pm = \theta\left(\alpha^2 b^2 - \mathbf{p}^2\right) f_\pm$$

- α - an external parameter to be studied here
- Uncertainty principle $\to$ size of a hadron $\sim 1/b$
- b is promoted to a field generated by a scalar potential $V_b \sim -b^2 + b^4$
- b is not an order parameter (it is not connected to any fundamental QCD symmetry)!

Equation of State under the NS conditions



Equation of state for different values of the α parameter under the NS conditions. Circles indicate the onset and restoration of the chiral phase transition.

References

[1] S. Benic, I. Mishustin and C. Sasaki, Phys. Rev. D **91**, 125034 (2015)

[2] M. Marczenko and C. Sasaki, Phys. Rev. D **97**, 036011 (2018)

[3] M. Marczenko, D. Blaschke, K. Redlich and C. Sasaki, arXiv:1805.06886

Direct URCA threshold

- direct URCA process

$$n_+ \to p_+ + e + \bar{\nu}_e$$

- Proton fraction

$$Y_{p_+} = \frac{\rho_{p_+}}{\rho_{p_+} + \rho_{n_+} + \rho_{p_-} + \rho_{n_-}}$$

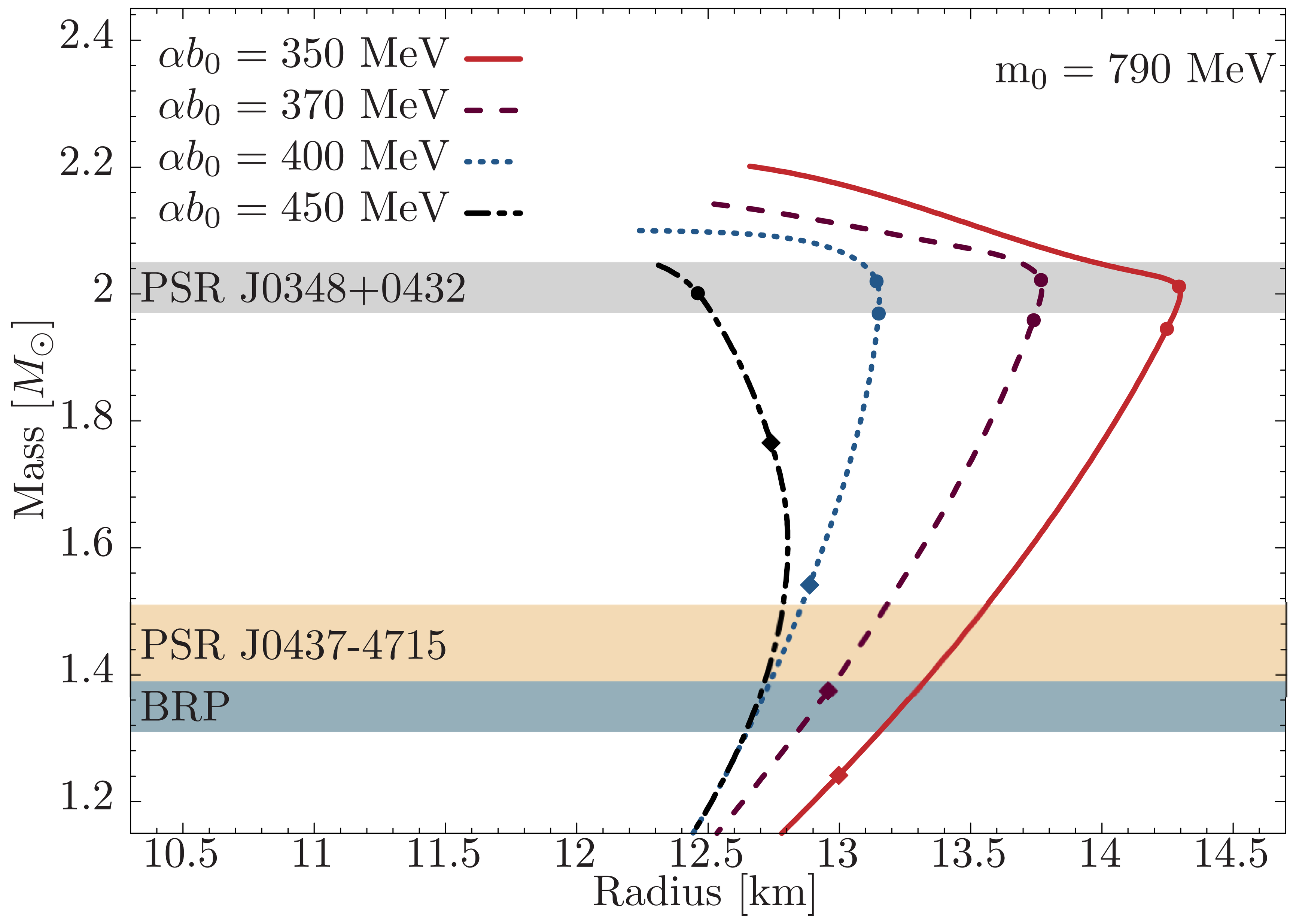
- Chiral symmetry broken

$$\frac{1}{1 + \left(1 + \sqrt[3]{Y_e}\right)^3} \approx 11 - 15\%$$

- Chiral symmetry restored

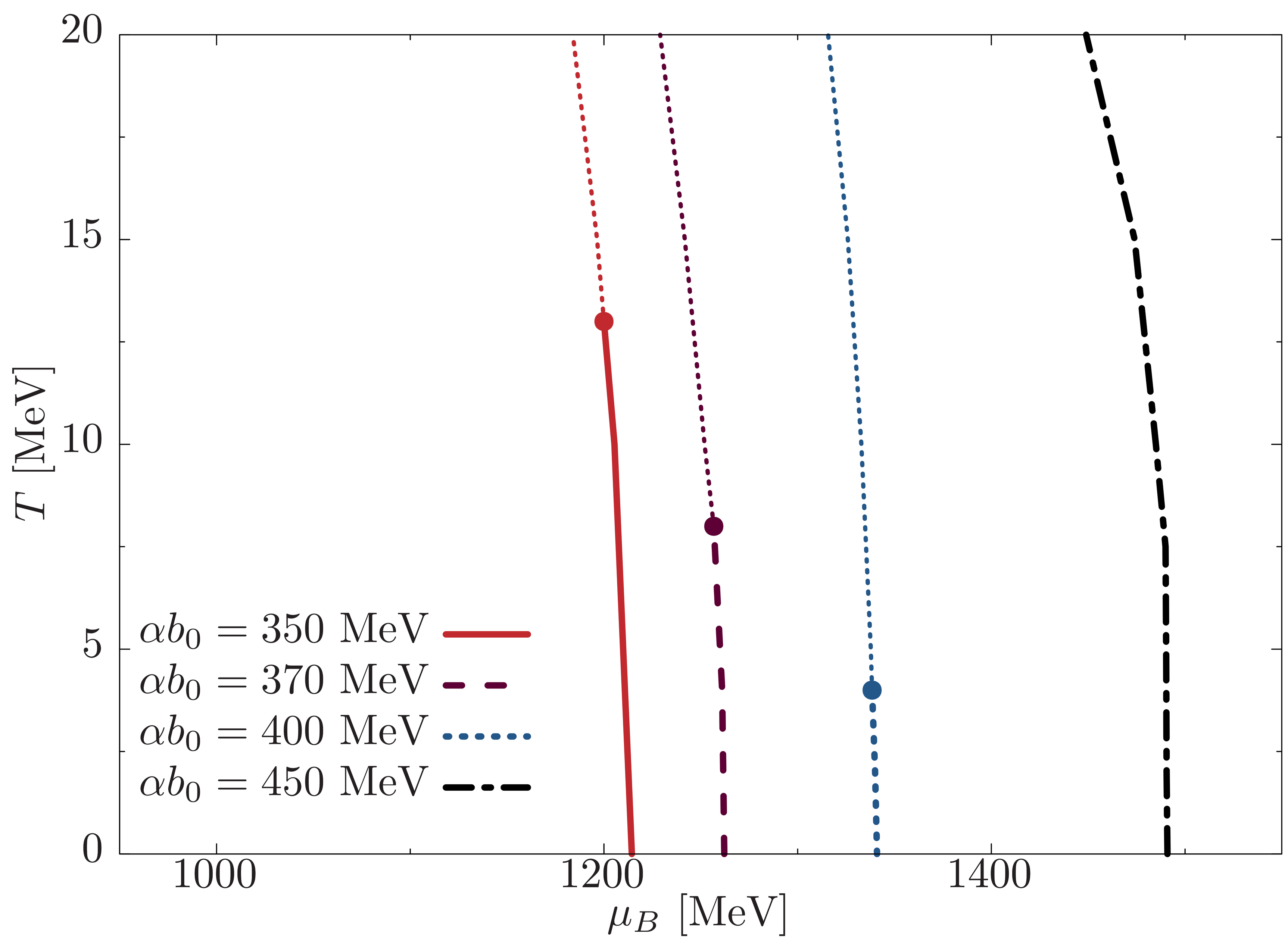
$$\frac{1}{1 + \left(1 + \sqrt[3]{2Y_e}\right)^3} \approx 8 - 11\%$$

Neutron Star Structure



Mass-radius relations. Circles indicate the onset and restoration of the chiral phase transition, diamonds indicate the direct URCA threshold.

QCD phase diagram for isospin-symmetric matter



Predicted low-temperature QCD phase diagram for isospin-symmetric matter. Shown are the chiral phase transitions for different values of α. The transitions from hadrons to quarks happen at higher barochemical potentials and are not shown here.

Summary

- High-mass stars & phase transition $\to$ not necessarily signal for deconfinement
- Parity doubling $\to$ lower estimate for direct URCA threshold in the chirally restored phase.

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