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

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Common approach to QCD equation of state

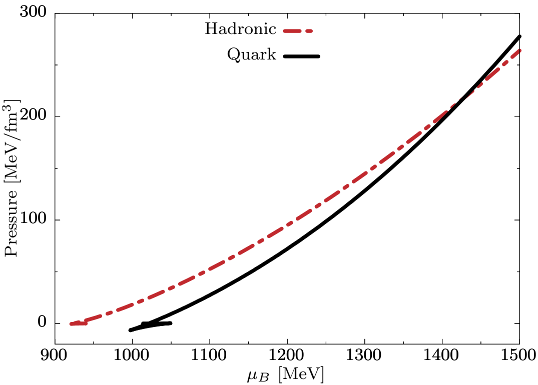
Hadronic EoS: p^+, n^+
(incomplete chiral physics)

$+$

Quark EoS
(chiral physics)

$\downarrow$

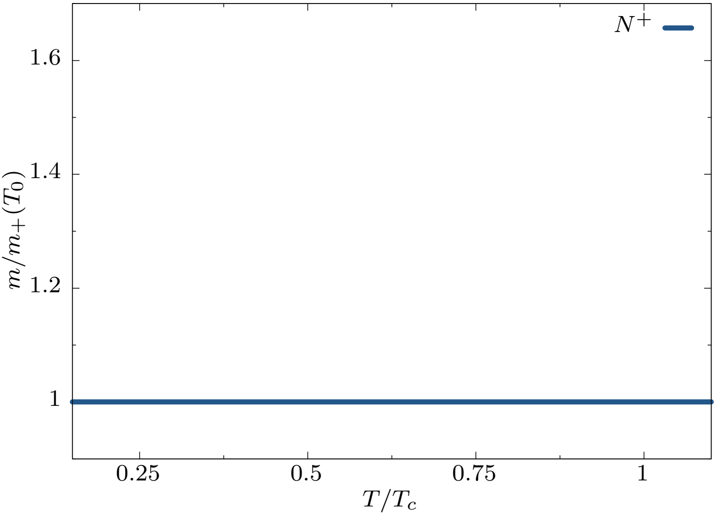
Maxwell construction
(deconfinement)



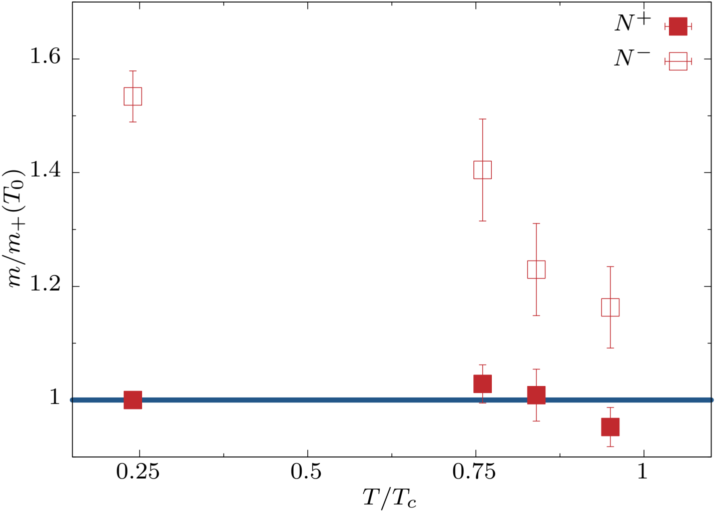
courtesy: N.-U. F. Bastian

- Striking problem: No chiral physics in the resulting EoS

Common approach to QCD equation of state



Parity doubling in lattice QCD Aarts *et al*, JHEP **1706**, 034 (2017)



- Imprint of chiral symmetry restoration in the baryonic sector
- Expected to occur at low temperature

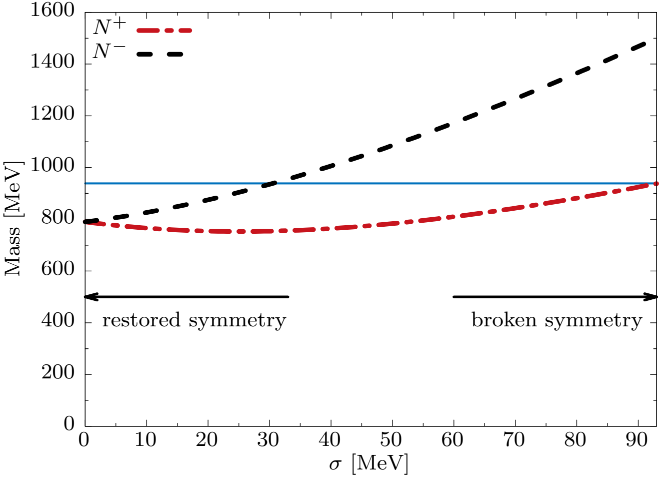
Particle identification

p	$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: $****$
n	$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: $****$
$N(1535)\ 1/2^-$	$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$ Status: $****$

C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016) and 2017

Parity doubling in SU(2) chiral models DeTar, Kunihiro PRD **39** 2805 (1989)

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



Hybrid quark-meson-nucleon model Benić, Mishustin, Sasaki, Phys. Rev. D **91** (2015)

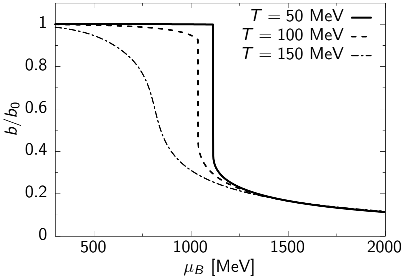
Parity doublet model + quark-meson coupling

$\Downarrow$

Statistical confinement:

- UV cutoff for nucleons: $f_N \to \theta\left(\alpha^2 b^2 - \boldsymbol{p}^2\right) f_N$
- IR cutoff for quarks: $f_q \to \theta\left(\boldsymbol{p}^2 - b^2\right) f_q$

- α - model parameter



- b - scalar field

$$V_b = -\frac{1}{2}\kappa_b^2 b^2 + \frac{1}{4}\lambda_b b^4$$

$b(\mu_B = 0) > 0$ favors nucleons

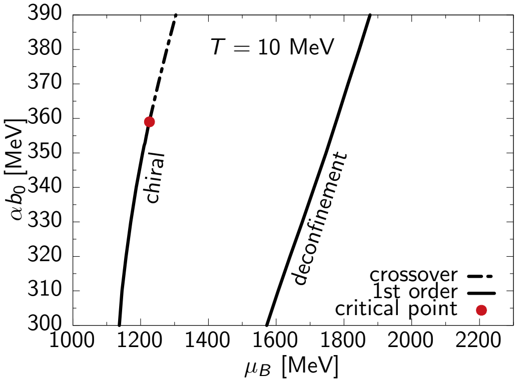
$b(\mu_B \to \infty) = 0$ favors quarks

Model phase diagram for isospin-symmetric matter

- 1st order deconfinement transition
- Order of chiral transition (from low to high α)

  1st order $\rightarrow$ critical point $\rightarrow$ crossover

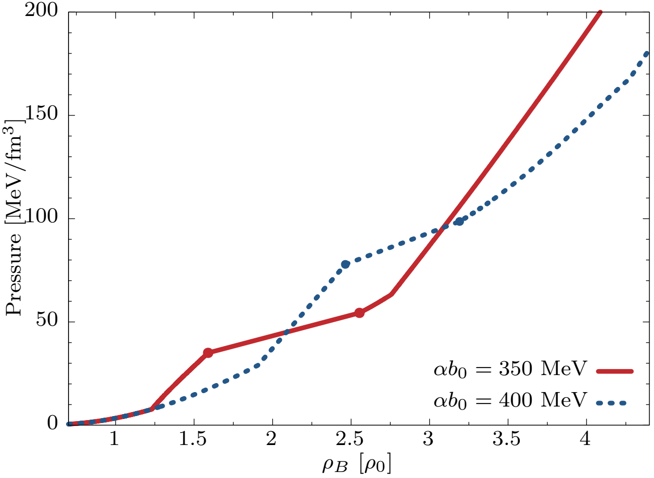
- Sequential phase transitions (may coincide for smaller m_0)



Marczenko, Sasaki, Phys. Rev. D **97** 036011 (2018)

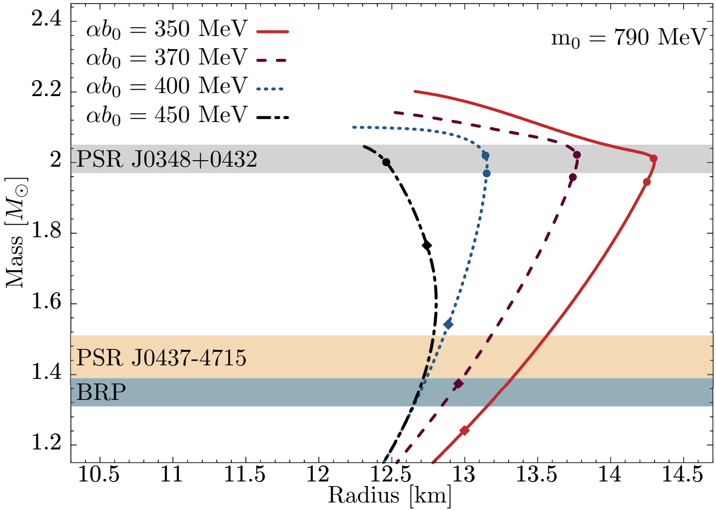
Equation of state under NS conditions

- $\alpha \rightarrow$ stiffening of EoS
- $\alpha \rightarrow$ strength of the chiral phase transition

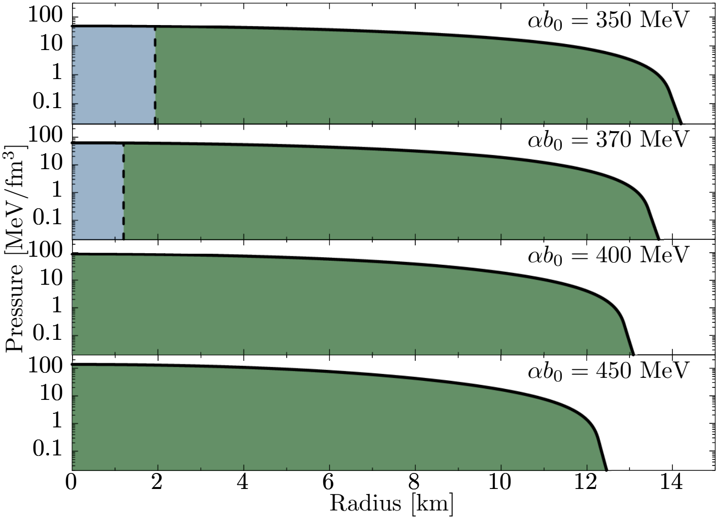


Mass-radius relation

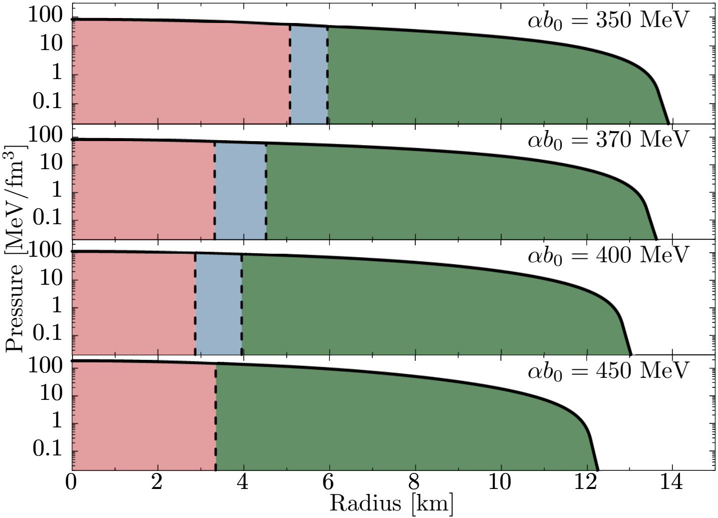
- chiral transition in high-mass part of the sequence
- $2M_\odot$ with chirally restored and confined core
- deconfinement above $2M_\odot$



Different realizations of $2M_\odot$ stars (lower band)



Different realizations of $2M_\odot$ stars (upper band)



Threshold for direct URCA: conventional scenario

- d.o.f.: p^+, n^+, e, μ
- Charge neutrality

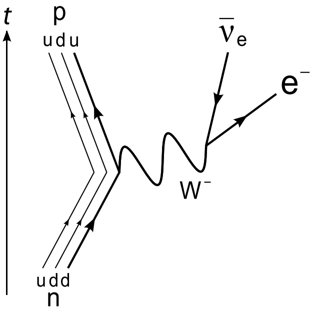
$$\rho_{p^+} = \rho_e + \rho_\mu$$

- Momentum conservation

$$f_{n^+} \leqslant f_{p^+} + f_e$$

- Threshold

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



Threshold for direct URCA: parity doubling

- χ-symmetry broken
  - d.o.f.: p^+, n^+, e, μ
- Charge neutrality

$$\rho_{p^+} = \rho_e + \rho_\mu$$

- Momentum conservation

$$f_{n^+} \leqslant f_{p^+} + f_e$$

- Threshold

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

- χ-symmetry restored:
  - d.o.f.: p^+, n^+, p^-, n^-, e, μ
- Charge neutrality:

$$\rho_{p^+} + \rho_{p^-} = 2\rho_{p^+} = \rho_e + \rho_\mu$$

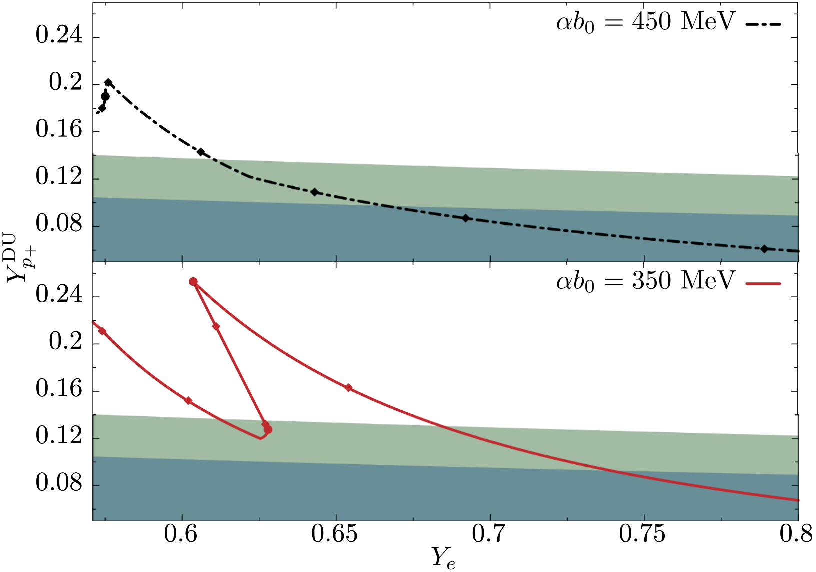
- Momentum conservation

$$f_{n^+} \leqslant f_{p^+} + f_e$$

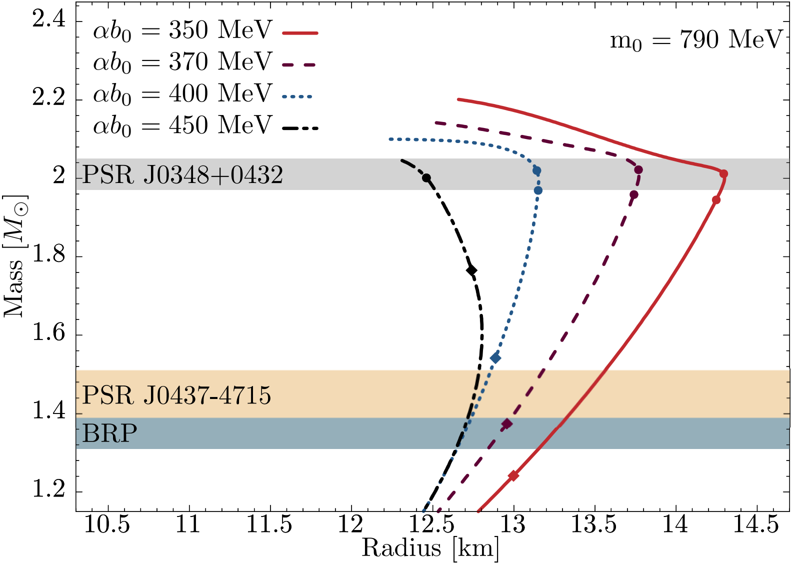
- Threshold

$$\frac{1}{1 + (1 + \sqrt[3]{Y_e})^3} \Rightarrow 8\% - 11\%$$

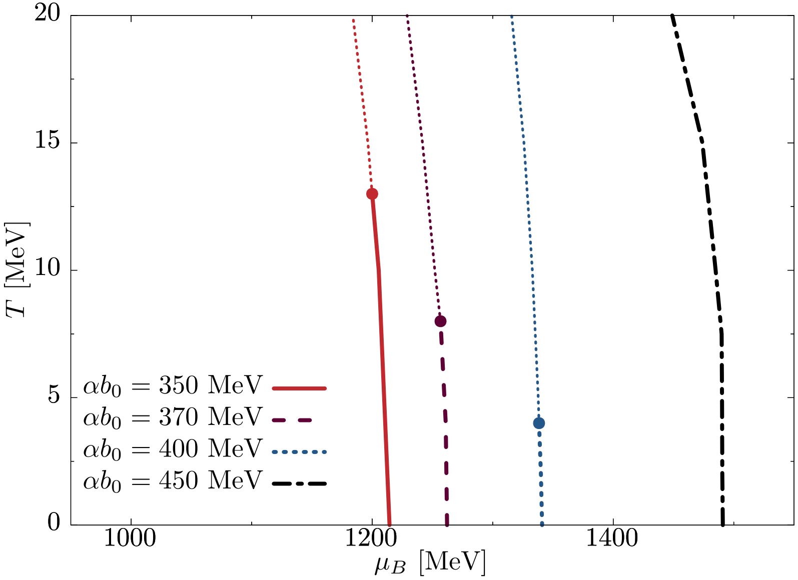
Threshold for direct URCA



Threshold for direct URCA



Back to symmetric-matter QCD phase diagram



Conclusions

Parity doubling yields non-trivial implications for the physics of neutron stars:

- $2M_\odot$ with chirally restored but confined core
- High-mass stars → not necessarily signal of deconfinement
- Parity doubling → modification of direct URCA threshold
  - impact on neutron star cooling

Objectives:

- parity doubling for hyperons (Λ, Δ, Σ, Ξ, Ω)
- deconfinement → yet another family of neutron stars

Thank you for your attention