

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

M. Marczenko, D. Blaschke, K. Redlich, C. Sasaki

Institute of Theoretical Physics
University of Wrocław, Poland

arXiv:1805.06886 [nucl-th]

XIIIth Quark Confinement and the Hadron Spectrum
Maynooth University
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Common approach to QCD equation of state

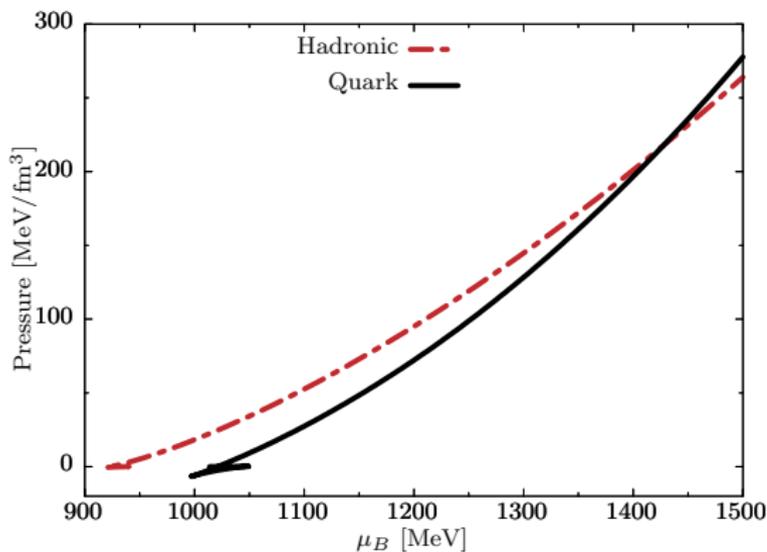
Hadronic EoS: p^+ , n^+
(incomplete chiral physics)

+

Quark EoS
(chiral physics)

↓

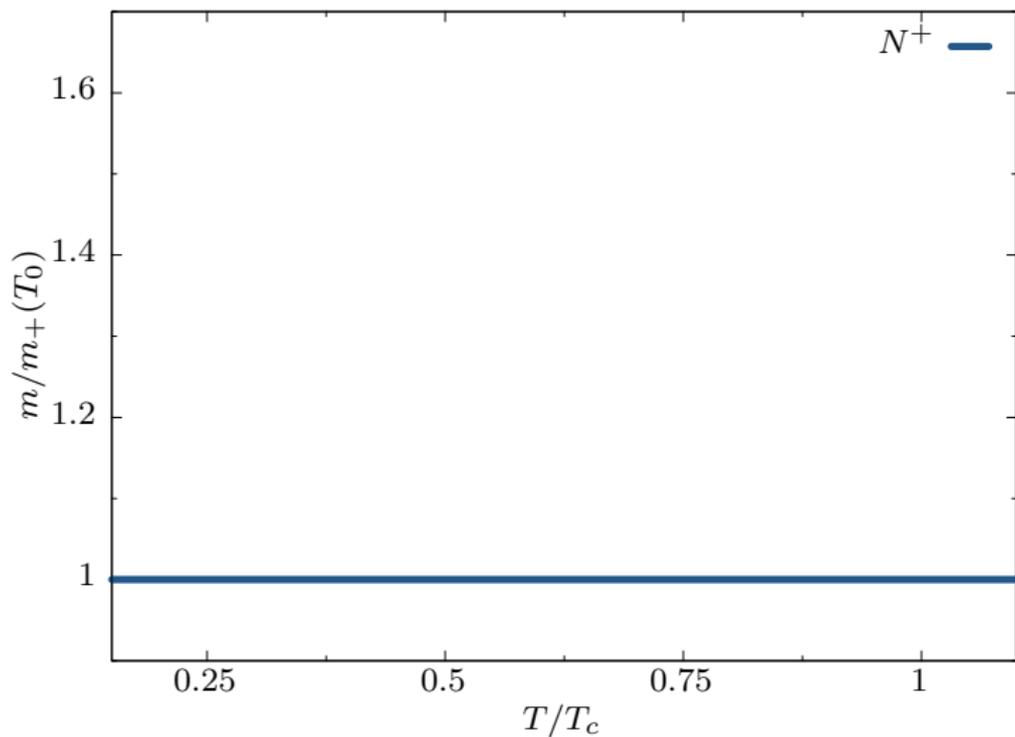
Maxwell construction
(deconfinement)



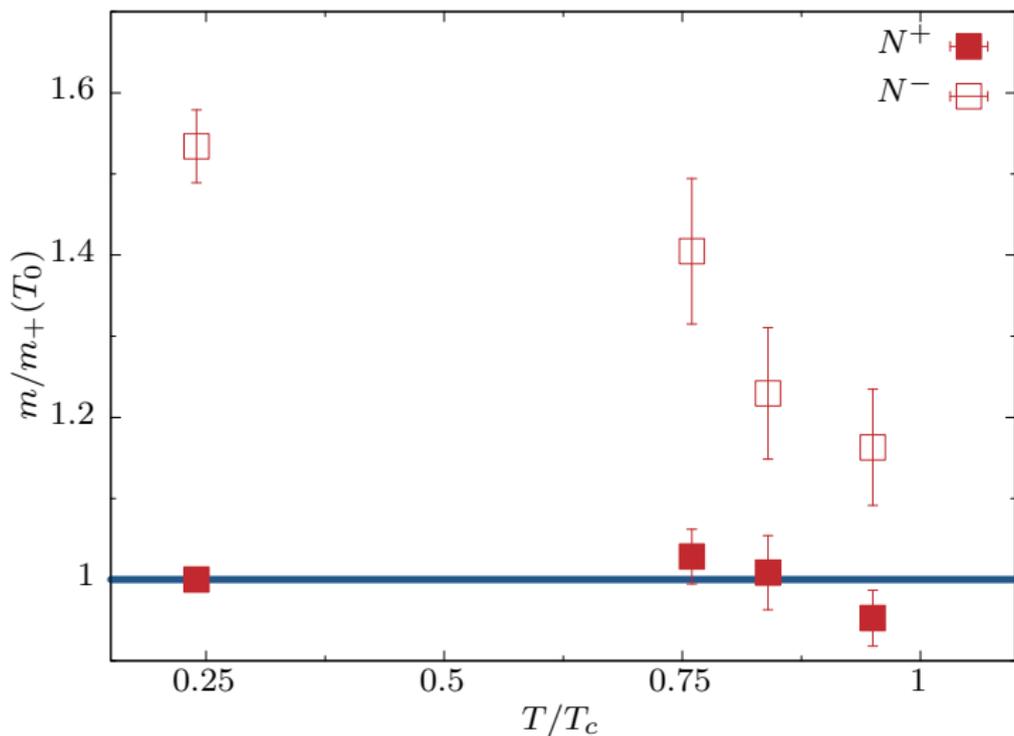
courtesy: N.-U. F. Bastian

- 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

$$I(J^P) = \frac{1}{2}(\frac{1}{2}^+) \text{ Status: } ****$$

n

$$I(J^P) = \frac{1}{2}(\frac{1}{2}^+) \text{ Status: } ****$$

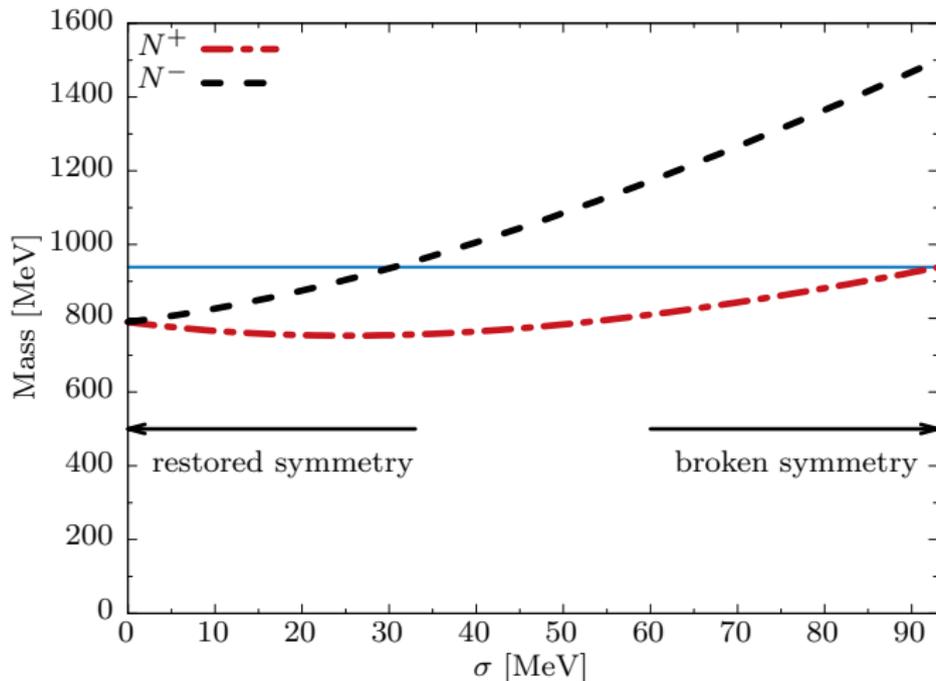
$N(1535) 1/2^-$

$$I(J^P) = \frac{1}{2}(\frac{1}{2}^-) \text{ Status: } ****$$

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)

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

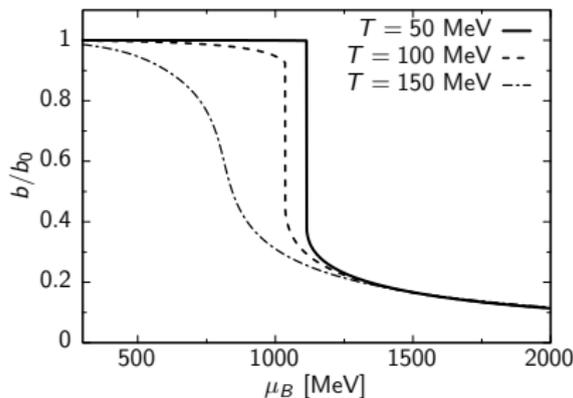


Parity doublet model + quark-meson coupling



Statistical confinement:

- UV cutoff for nucleons: $f_N \rightarrow \theta(\alpha^2 b^2 - \mathbf{p}^2) f_N$
- IR cutoff for quarks: $f_q \rightarrow \theta(\mathbf{p}^2 - b^2) f_q$
- α - model parameter



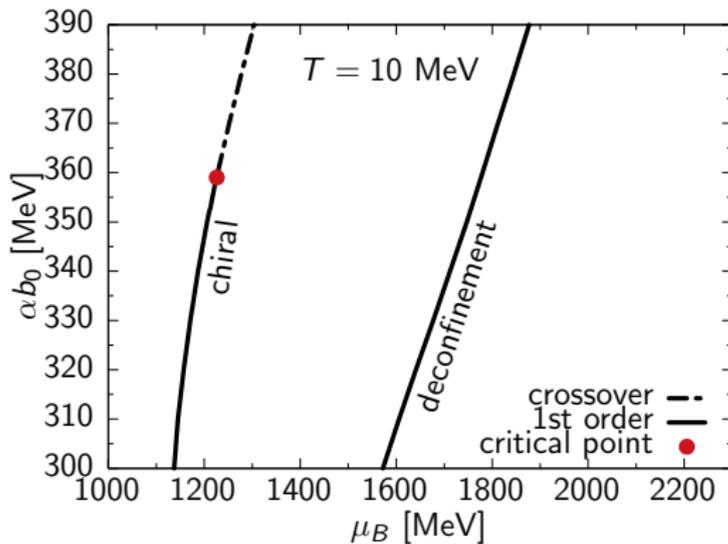
- b - scalar field

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

$$\begin{aligned} b(\mu_B = 0) &> 0 && \text{favors nucleons} \\ b(\mu_B \rightarrow \infty) &= 0 && \text{favors quarks} \end{aligned}$$

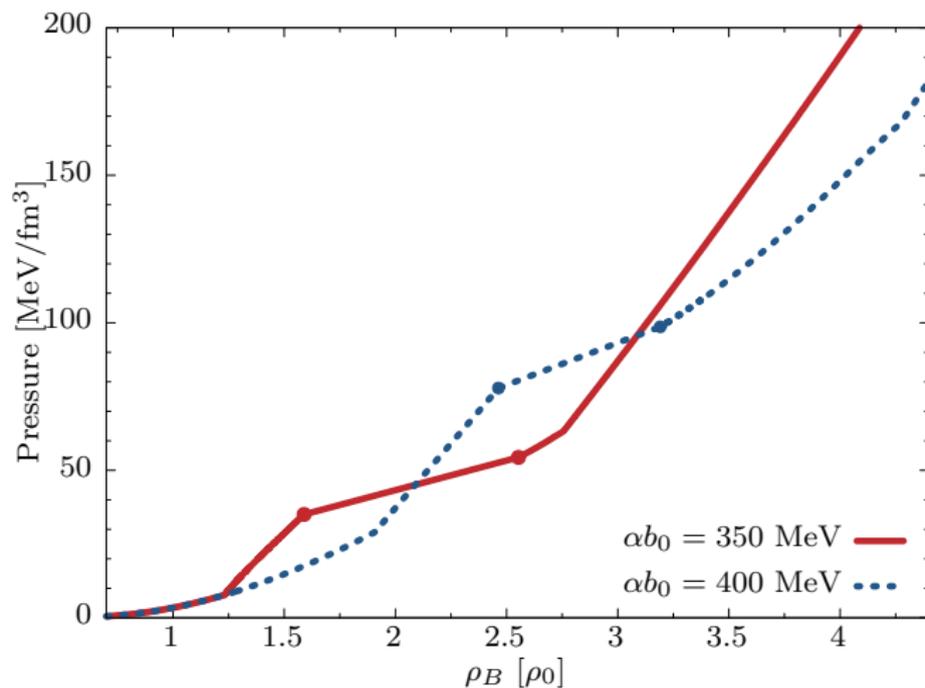
Model phase diagram for isospin-symmetric matter

- 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)



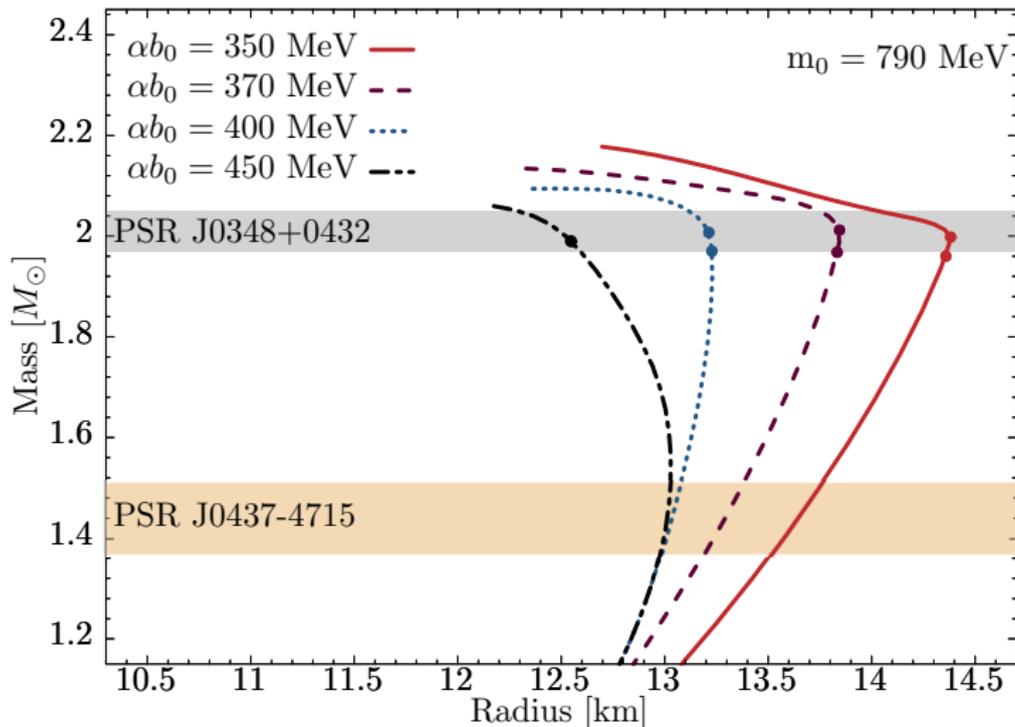
Equation of state under NS conditions

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

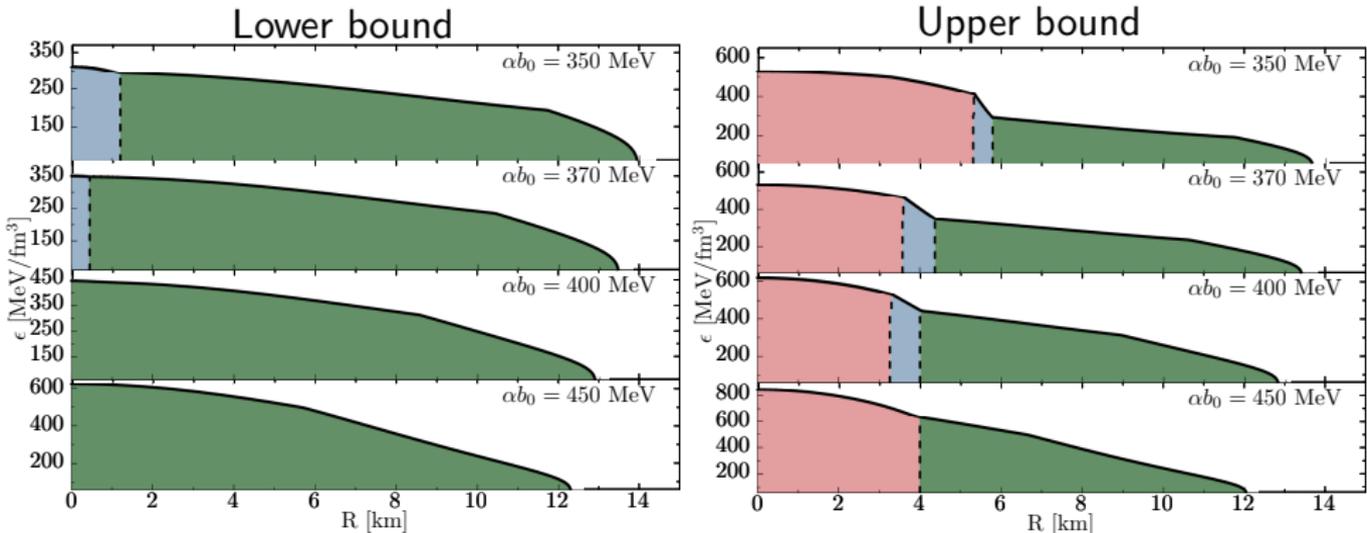


Mass-radius relation

- 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



Threshold for direct URCA: conventional scenario

- d.o.f.: p^+ , n^+ , e , μ

- Charge neutrality

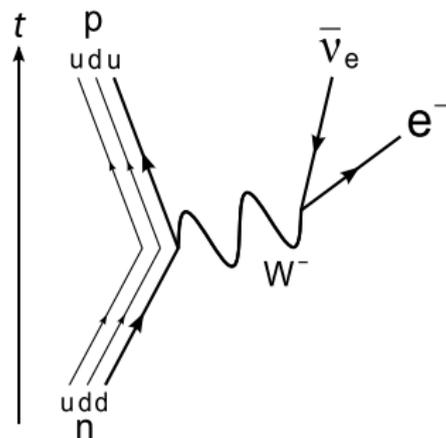
$$\rho_{p^+} = \rho_e + \rho_\mu$$

- Momentum conservation

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

- Proton Fraction 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

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

- Proton Fraction 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

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

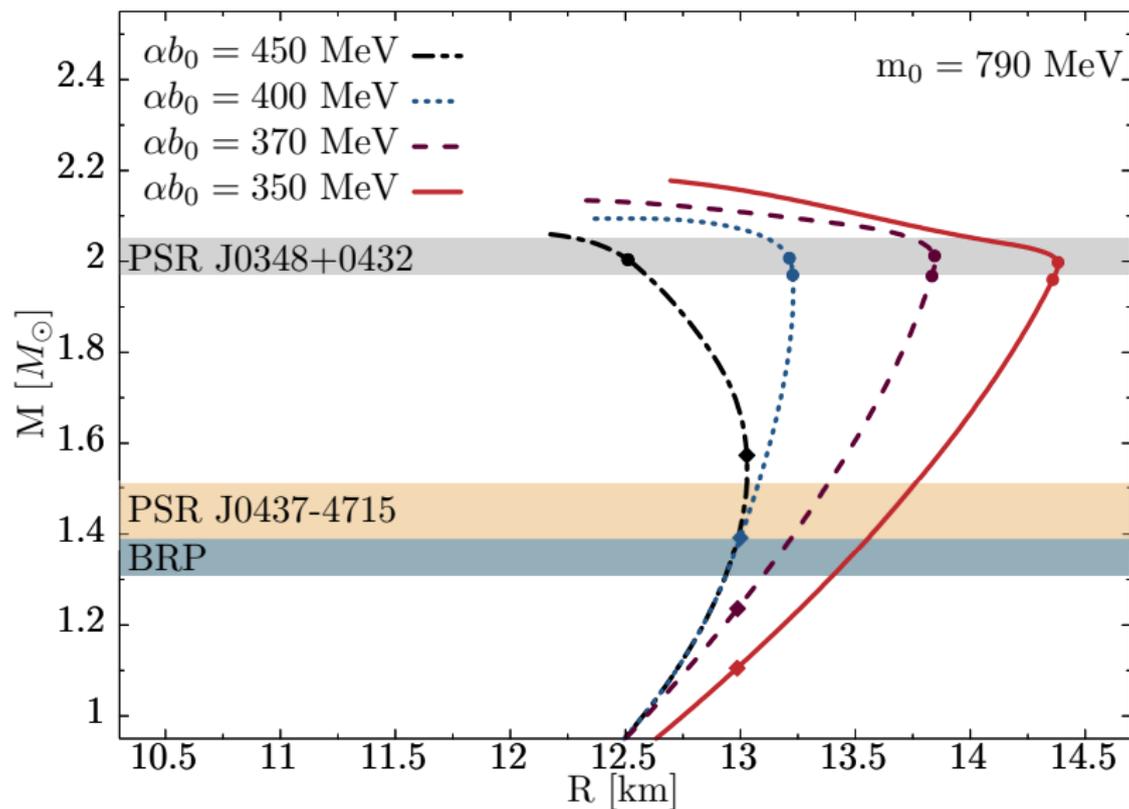
- Momentum conservation

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

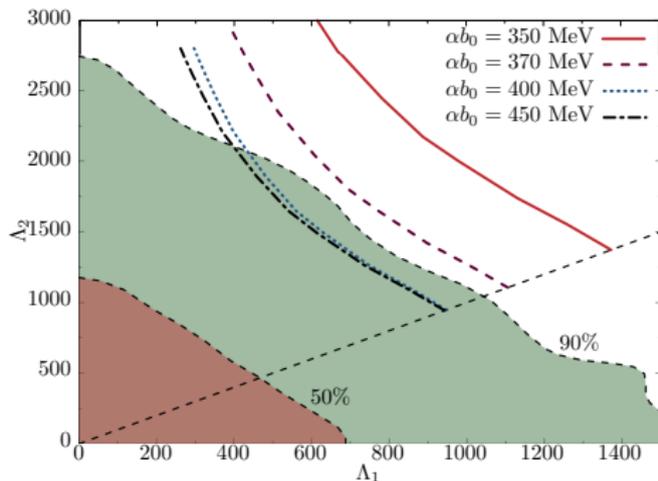
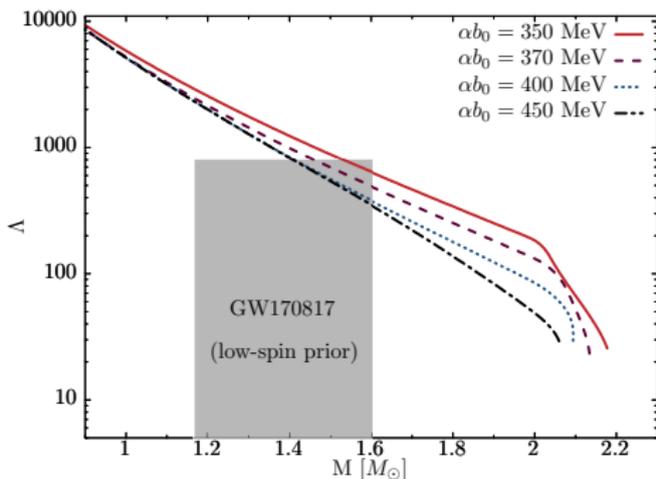
- Proton Fraction Threshold

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

Threshold for direct URCA

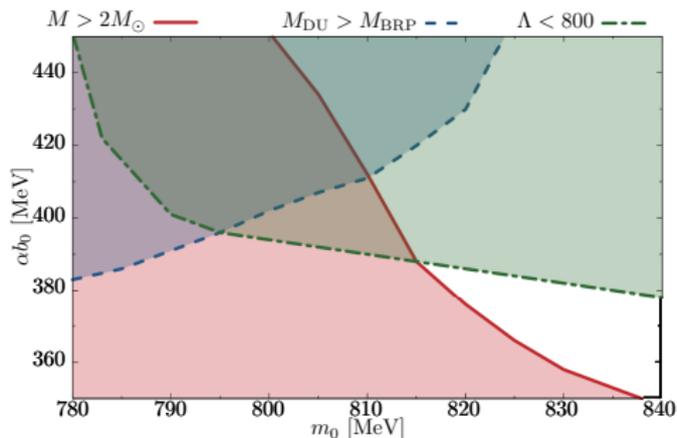


Constraints from GW170817

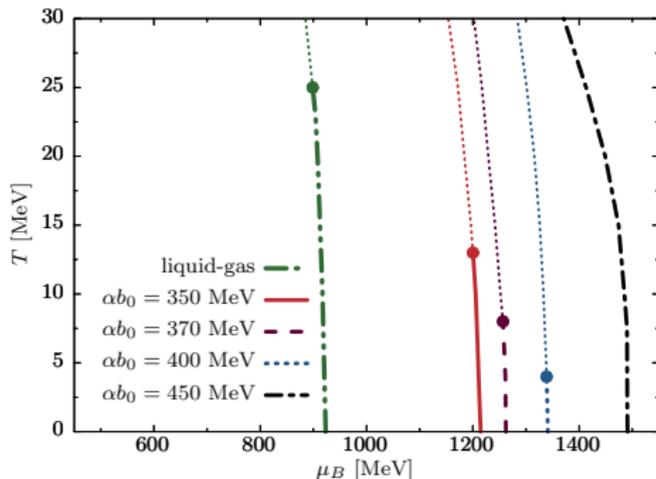


- stiff EoS are rather excluded
- constraint on radius $R < 13.6$ km at $1.4 M_\odot$

Back to symmetric-matter QCD Phase Diagram



- $2M_{\odot} \rightarrow$ stiff EoS
- DU \rightarrow soft EoS
- TD \rightarrow soft EoS



- CEP at low T or even absent!

Conclusions

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

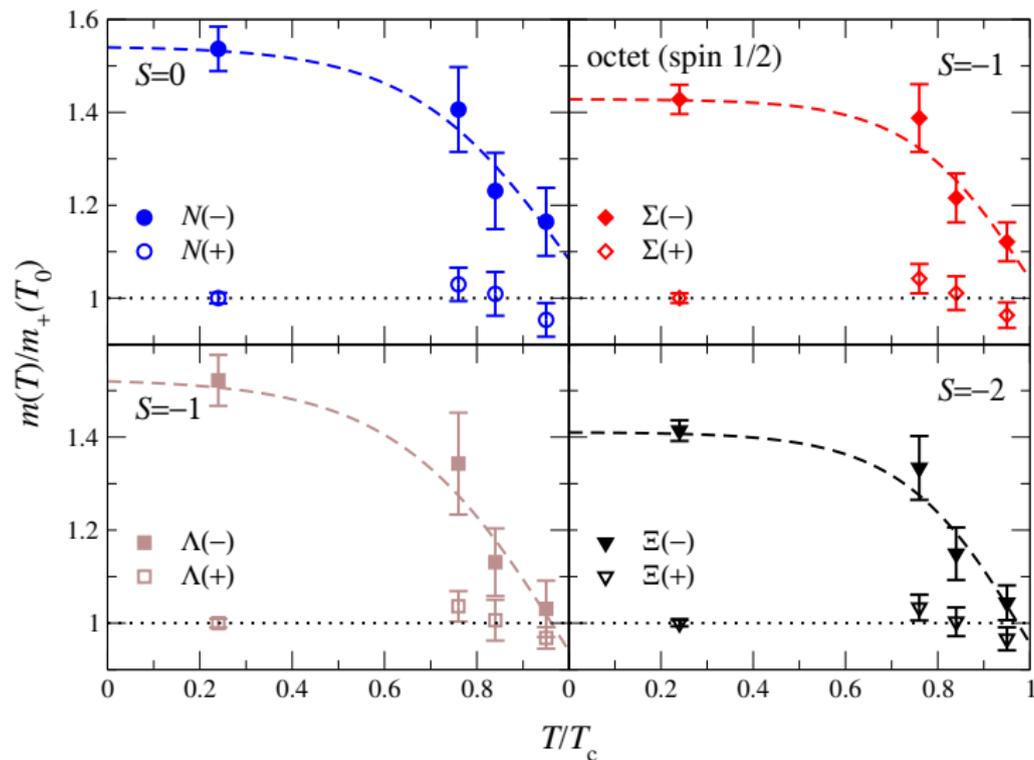
- $2M_{\odot}$ with **chirally restored** but **confined** core
- High-mass stars \rightarrow **not necessarily** signal of **deconfinement**
- Parity doubling \rightarrow **modification** of direct URCA threshold
 - new estimate for the proton fraction threshold
 - impact on neutron star cooling
- QCD phase diagram with CEP at rather low temperature

Objectives:

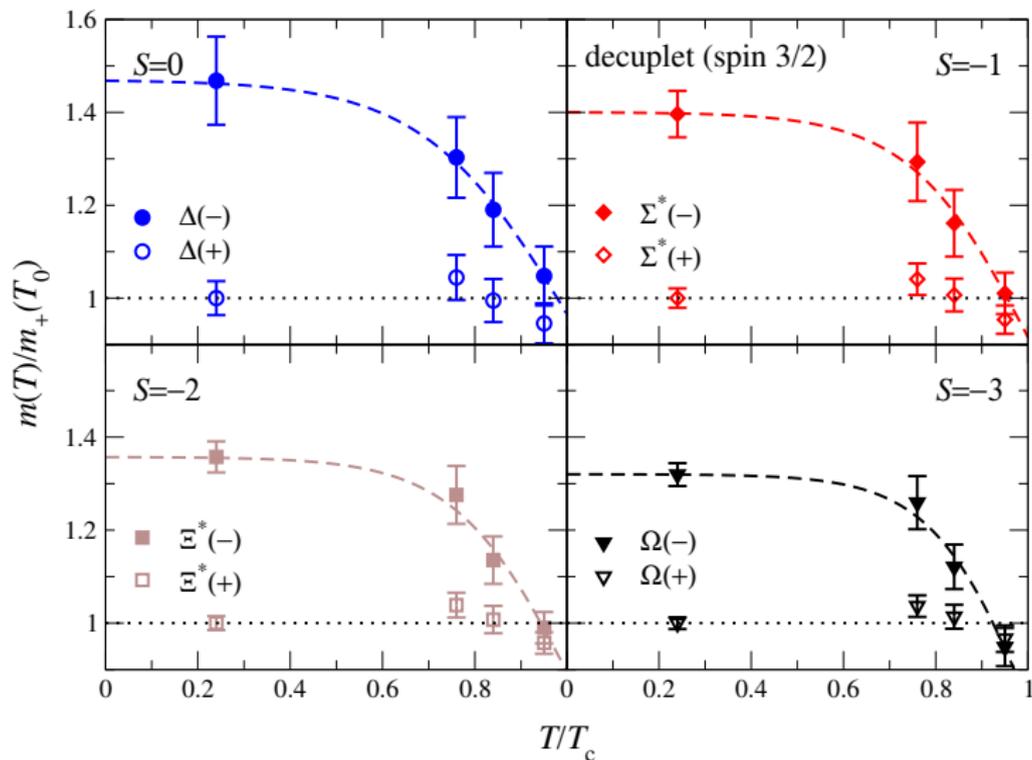
- parity doubling for hyperons (Λ , Δ , Σ , Ξ , Ω)
- deconfinement \rightarrow yet another family of neutron stars

Thank you for your attention

Parity Doubling for Light Baryons Aarts et al, arXiv:1710.08294 (2017)



Parity Doubling for Light Baryons Aarts et al, arXiv:1710.08294 (2017)



- Naive and **mirror** assignments under $SU(2)_L \times SU(2)_R$

$$\mathcal{L}_N = i\bar{\psi}_1 \not{\partial} \psi_1 + i\bar{\psi}_2 \not{\partial} \psi_2 + m_0 (\bar{\psi}_1 \gamma_5 \psi_2 - \bar{\psi}_2 \gamma_5 \psi_1)$$

For finite m_0 , chiral symmetry is

- explicitly broken under naive assignment
 - remains unbroken under **mirror** assignment
- Parity doublet model for cold and dense nuclear matter

Hatsuda, Prakash, Phys.Lett. B **224** (1989)

Zschieche et al, Phys. Rev. C **75**, 055202 (2007)

$$\mathcal{L} = \mathcal{L}_N + \mathcal{L}_M + \sum_{k=1,2} g_k \bar{\psi}_k (\sigma \pm i\gamma_5 \boldsymbol{\tau} \cdot \boldsymbol{\pi}) \psi_k - g_\omega \bar{\psi}_k \psi \psi_k$$

- Fermions coupled to bosons: σ , π , ω
- $\mathcal{L}_M \rightarrow$ Linear σ -model

Full HQMN model Lagrangian

$$\blacksquare \mathcal{L} = \mathcal{L}_N + \mathcal{L}_M + \mathcal{L}_q$$

$$\begin{aligned} \mathcal{L}_N &= \sum_{k=1,2} \bar{\psi}_k i \not{\partial} \psi_k + m_0 (\bar{\psi}_2 \gamma_5 \psi_1 - \bar{\psi}_1 \gamma_5 \psi_2) \\ &+ \sum_{k=1,2} g_k \bar{\psi}_k (\sigma \pm i \gamma_5 \boldsymbol{\tau} \cdot \boldsymbol{\pi}) \psi_k - g_\omega \bar{\psi}_k \psi_k \psi_k \end{aligned}$$

$$\mathcal{L}_q = \bar{q} i \not{\partial} q + g_q \bar{q} (\sigma + i \gamma_5 \boldsymbol{\tau} \cdot \boldsymbol{\pi}) q$$

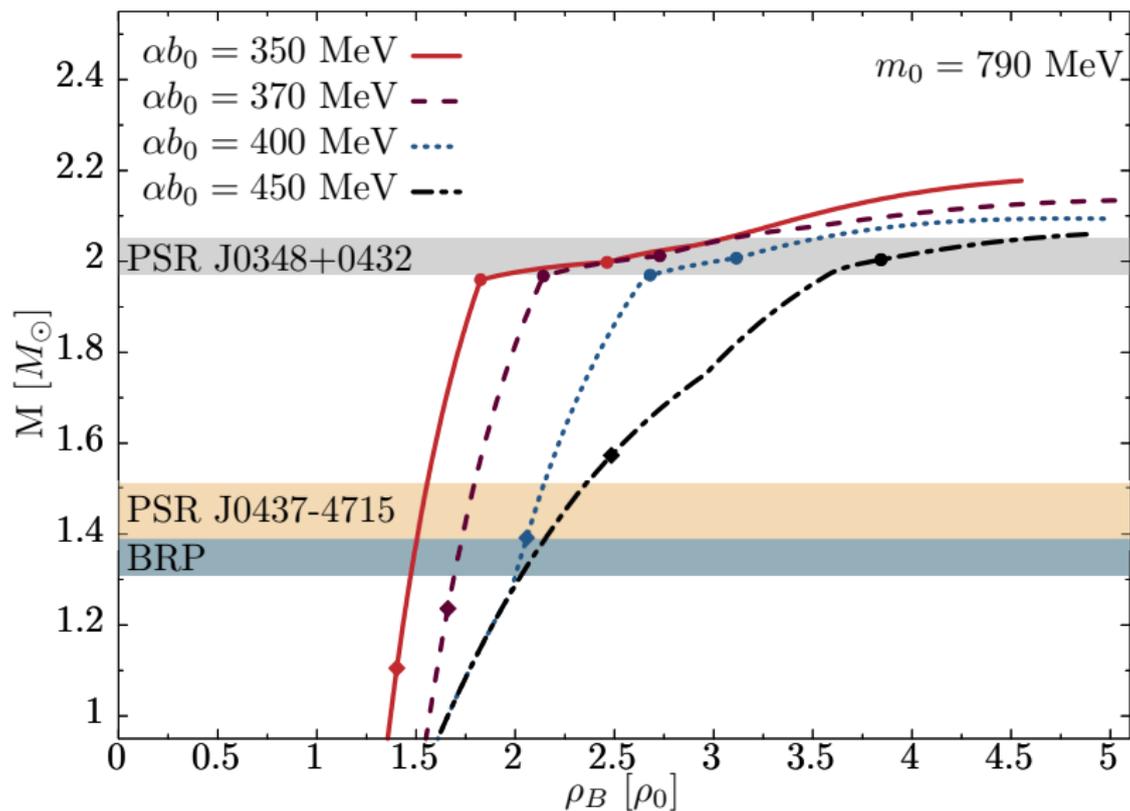
$$\mathcal{L}_M = \frac{1}{2} (\partial_\mu \sigma)^2 + \frac{1}{2} (\partial_\mu \boldsymbol{\pi})^2 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - V_\sigma - V_\omega - V_b$$

$$V_\sigma = -\frac{1}{2} \bar{\mu}^2 (\sigma^2 + \boldsymbol{\pi}^2) + \frac{\lambda}{4} (\sigma^2 + \boldsymbol{\pi}^2)^2 - \epsilon \sigma$$

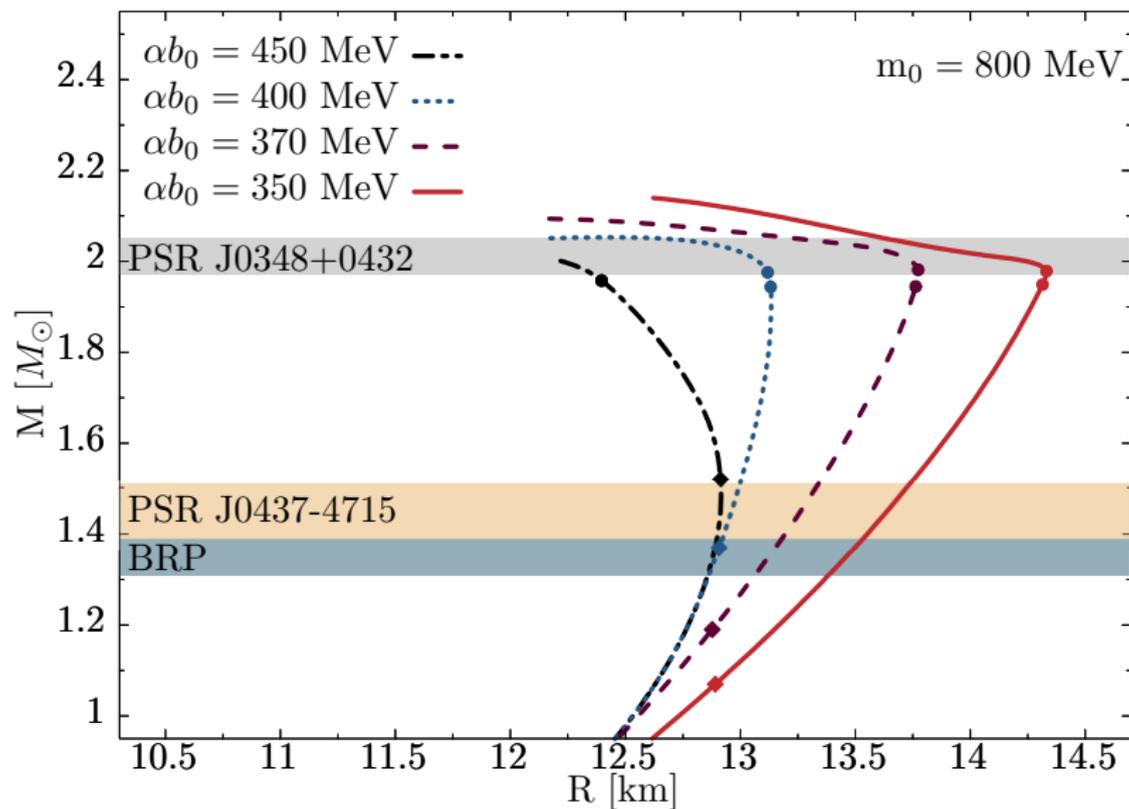
$$V_\omega = -\frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu$$

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

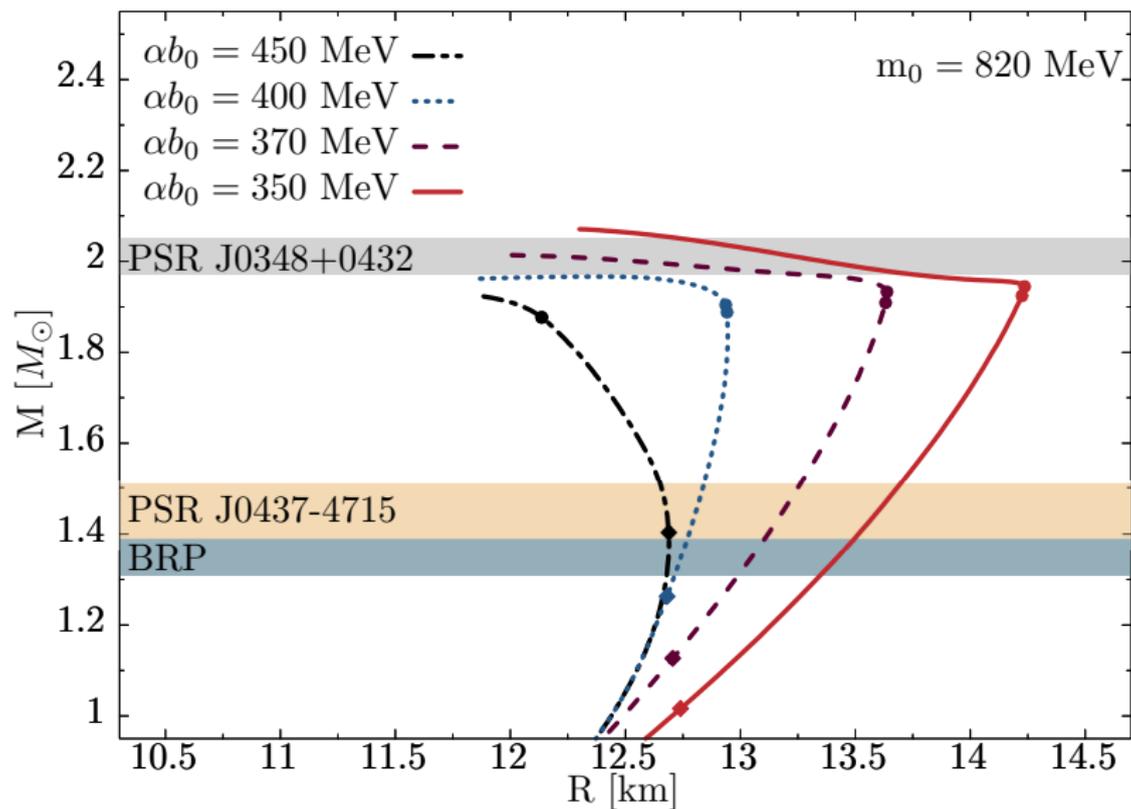
mass-density



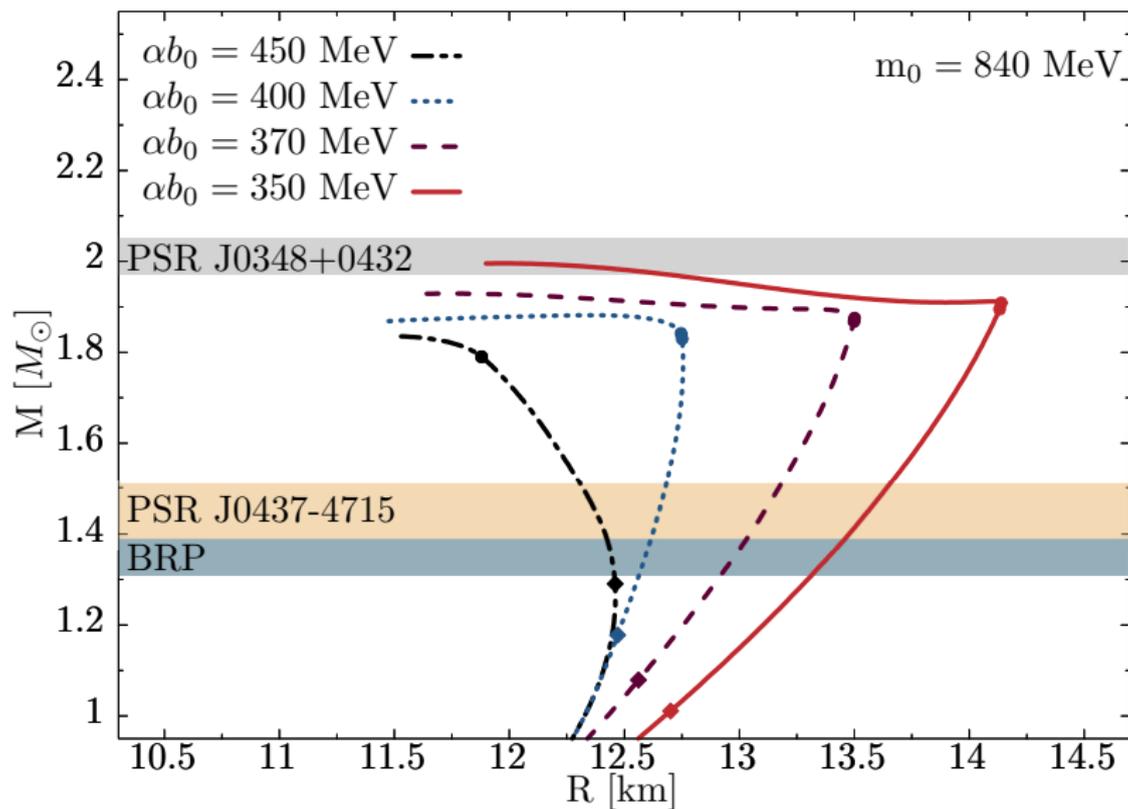
mass-radius



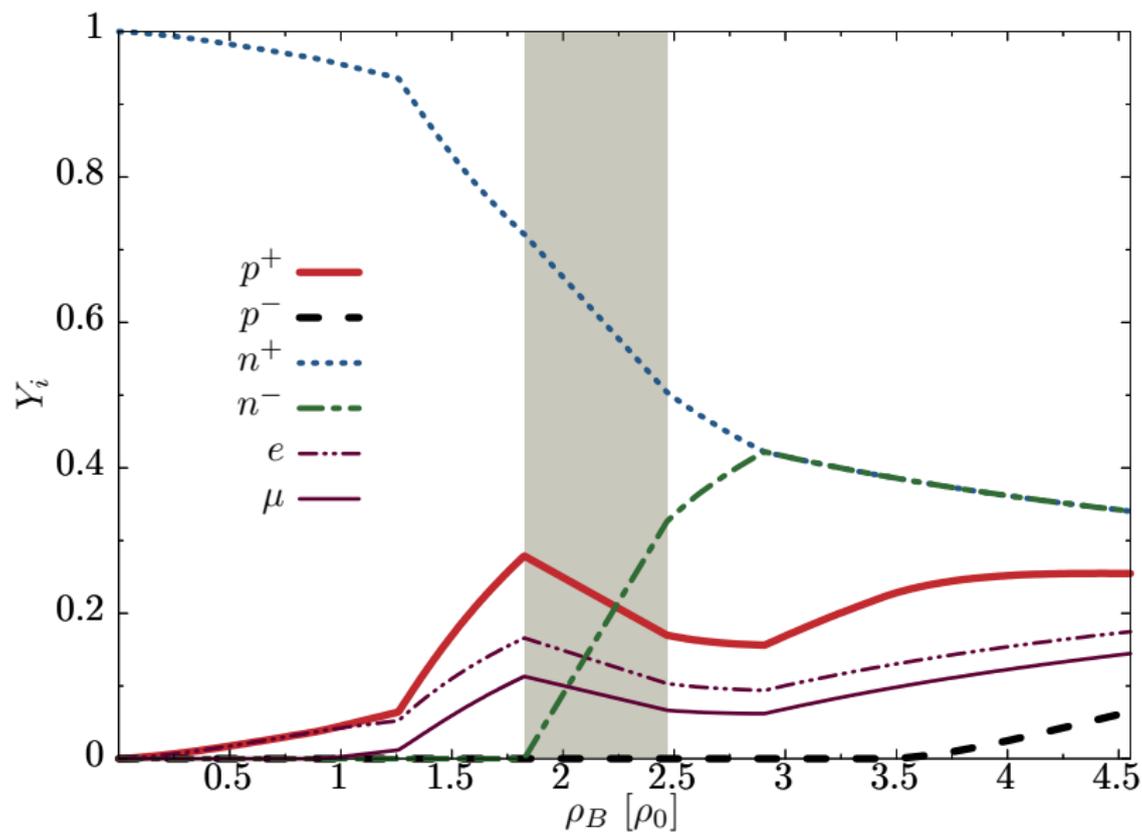
mass-radius



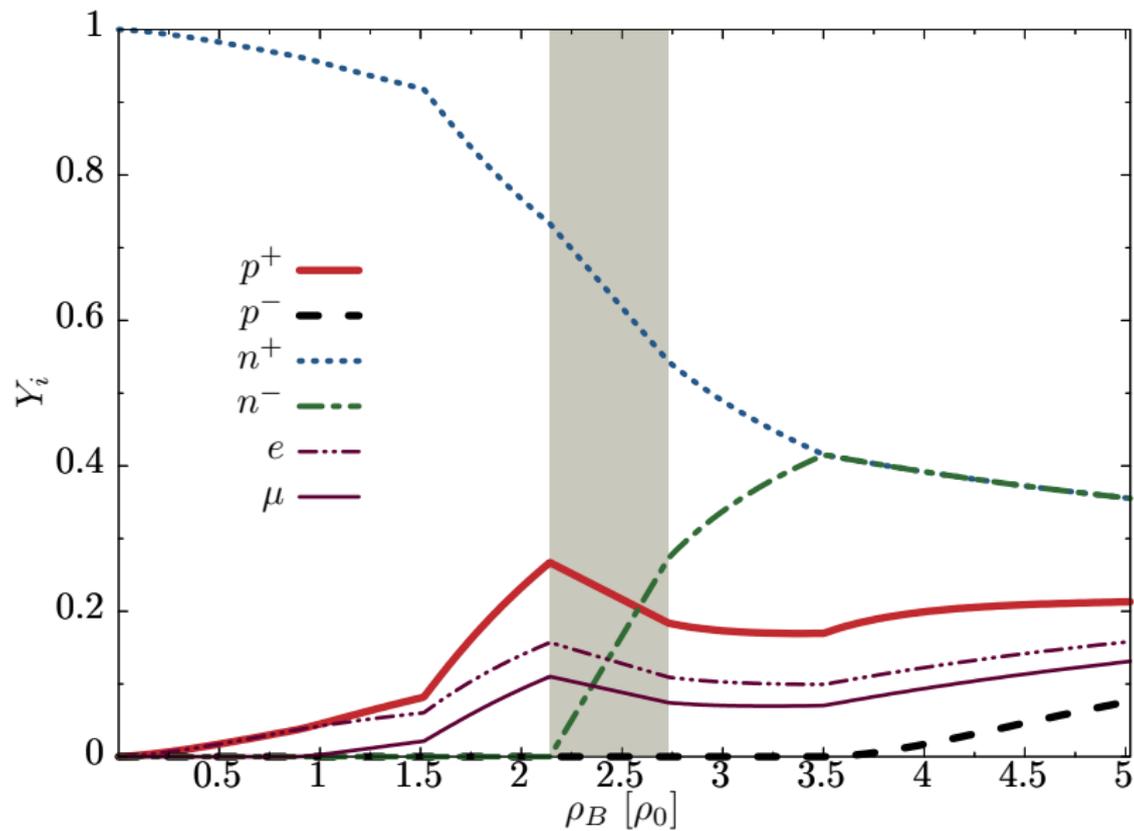
mass-radius



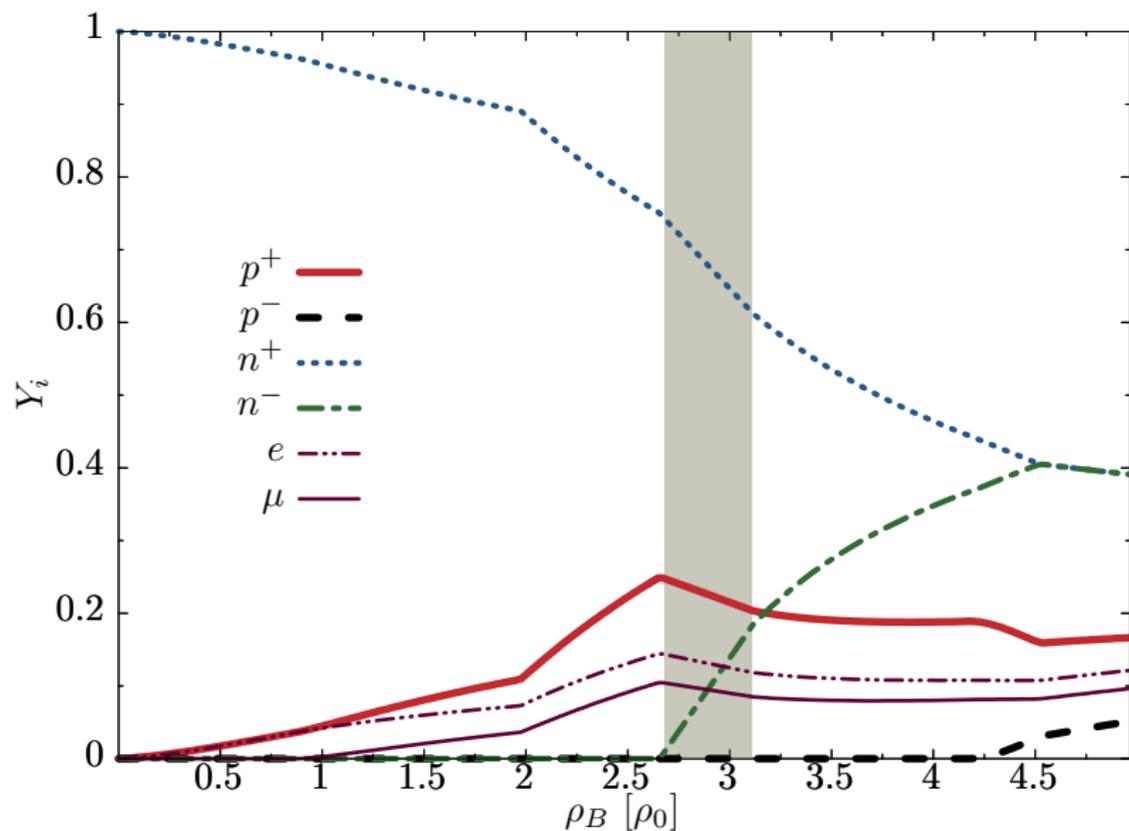
Matter composition ($\alpha b_0 = 350$ MeV)



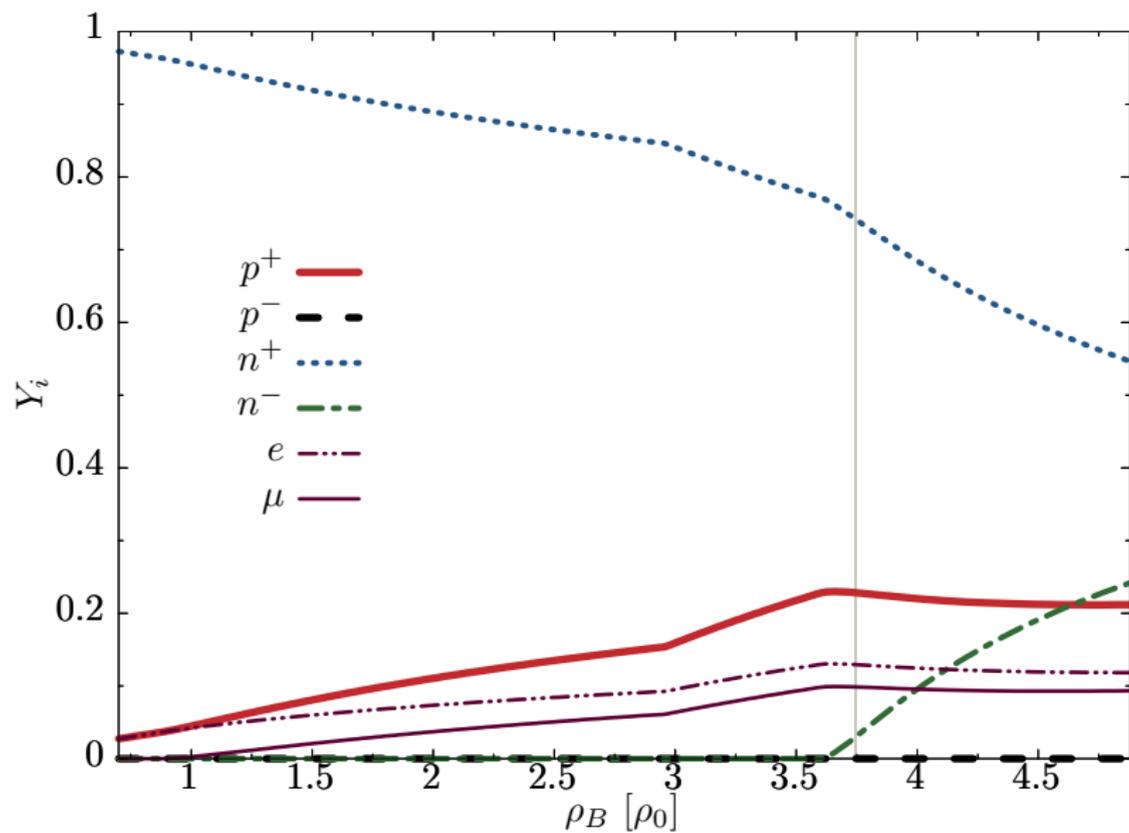
Matter composition ($\alpha b_0 = 370$ MeV)



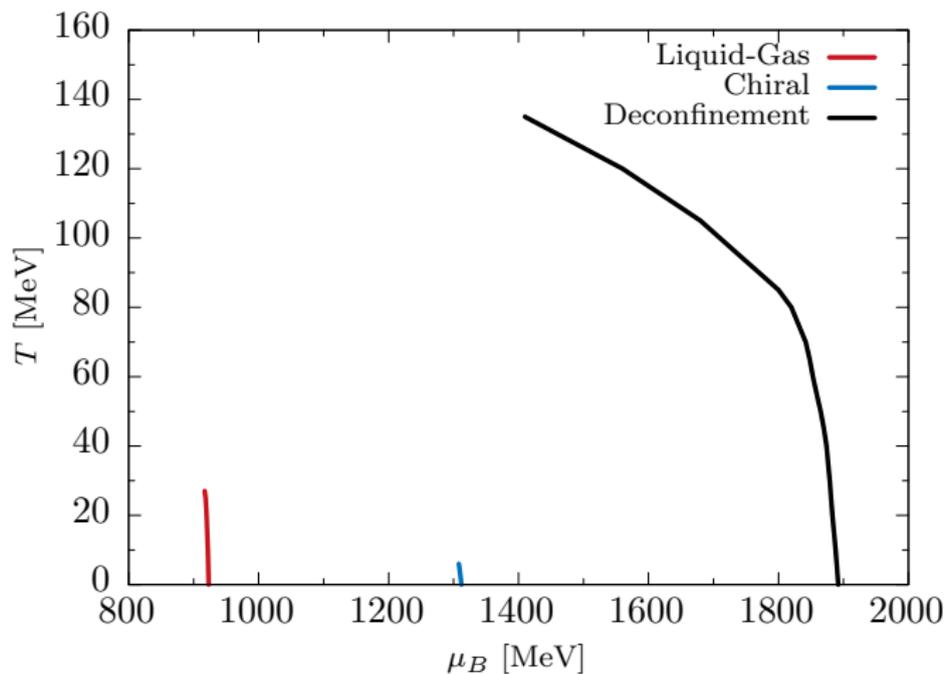
Matter composition ($\alpha b_0 = 400 \text{ MeV}$)



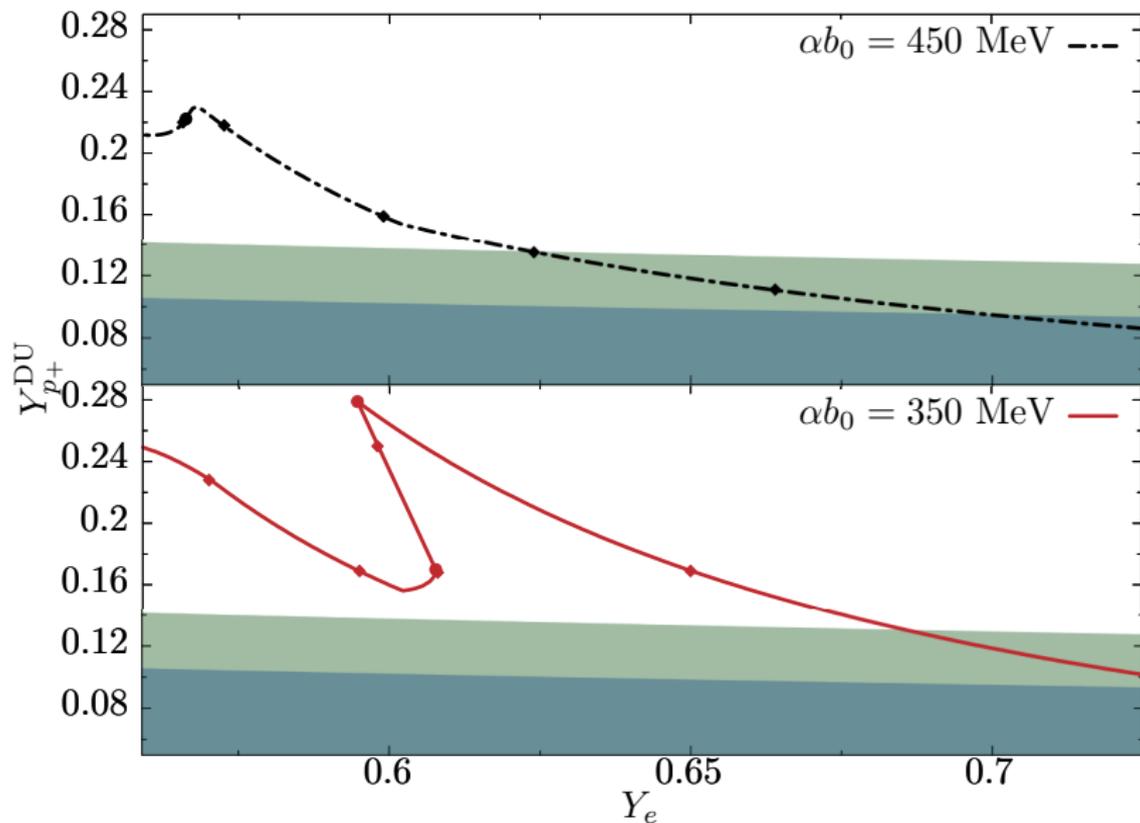
Matter composition ($\alpha b_0 = 450$ MeV)

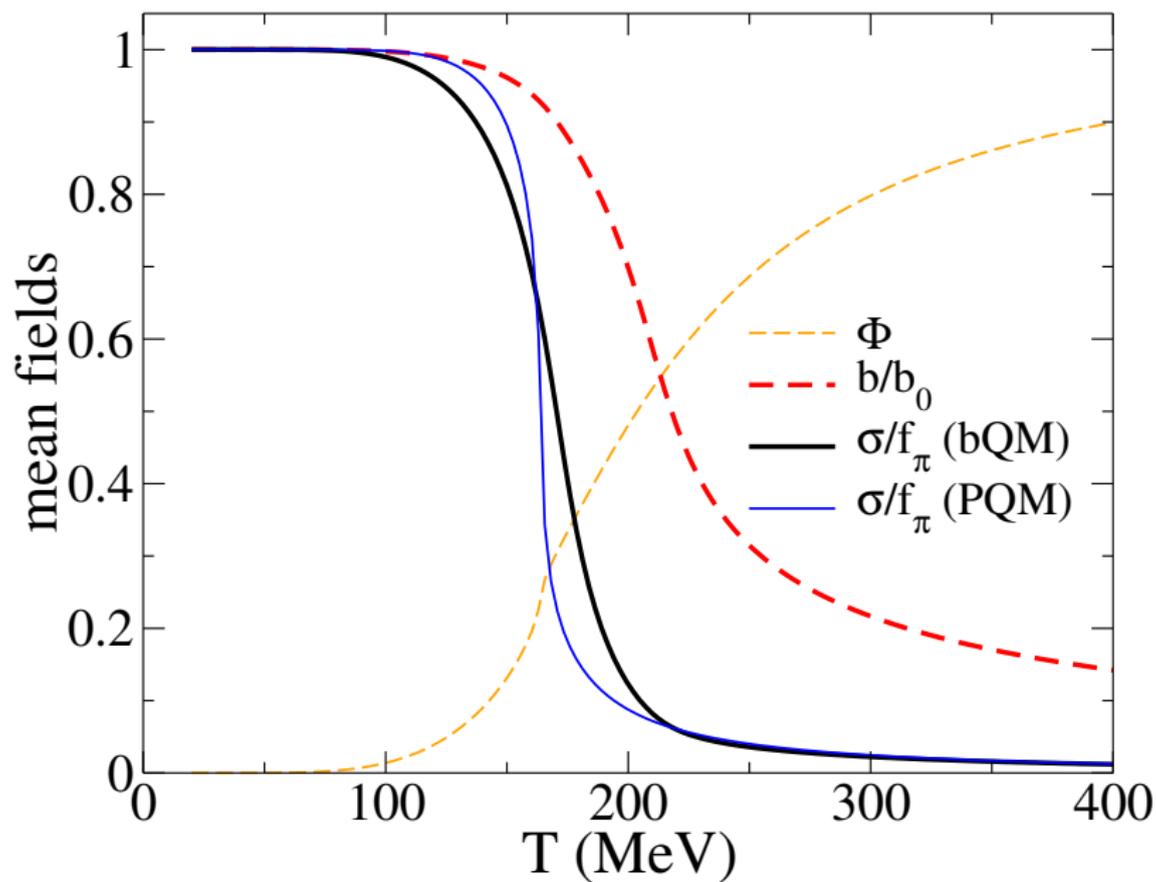


Phase diagram in $(T - \mu_B)$ -plane ($\alpha b_0 = 310 \text{ MeV}$)

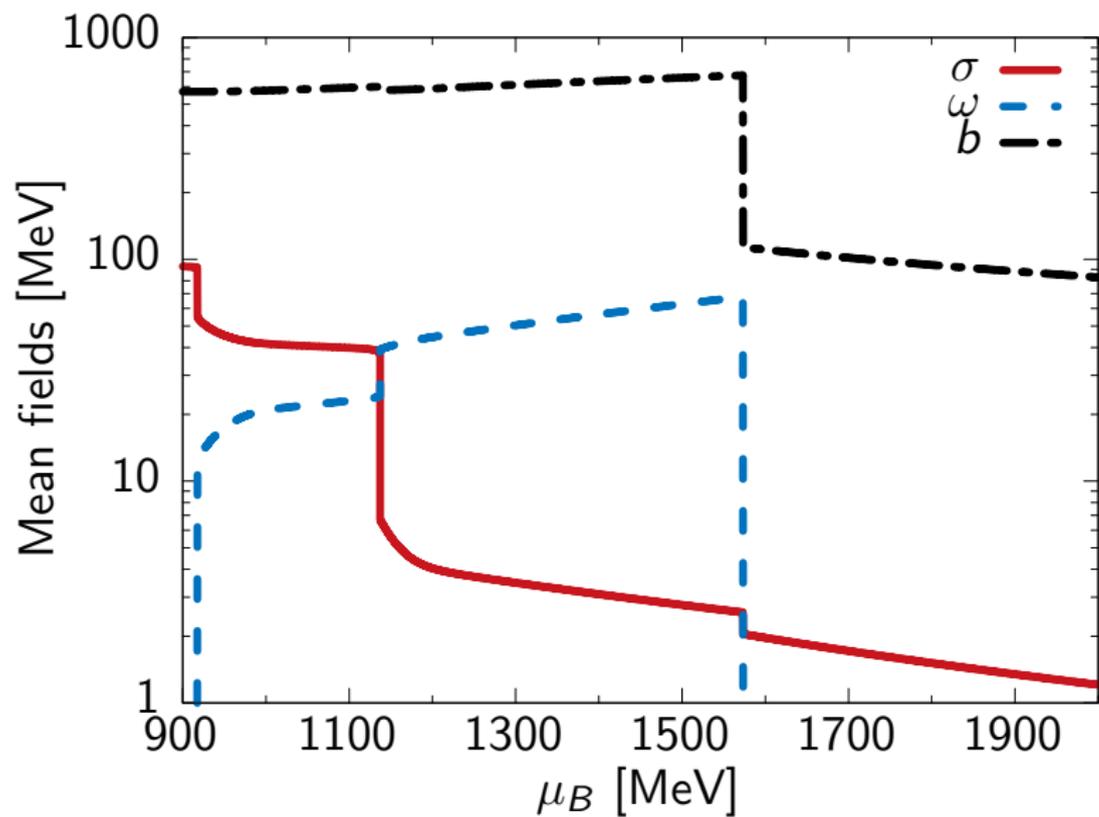


Threshold for direct URCA

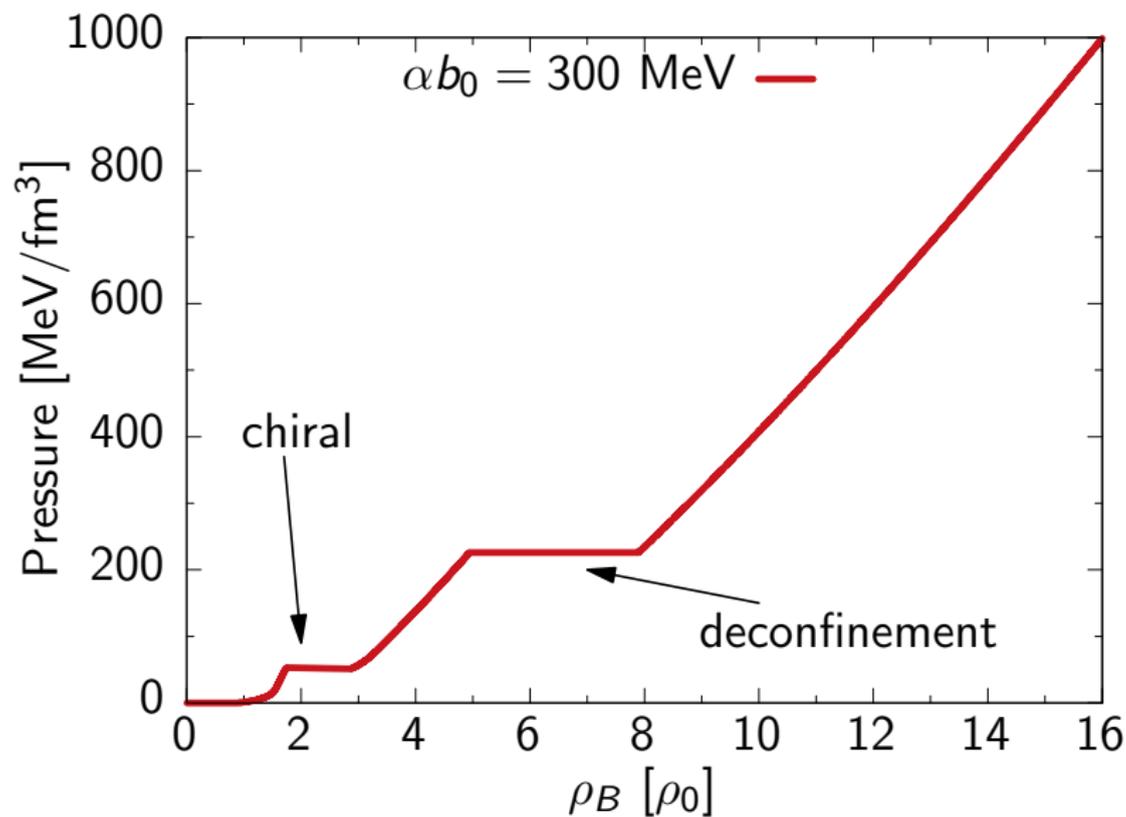




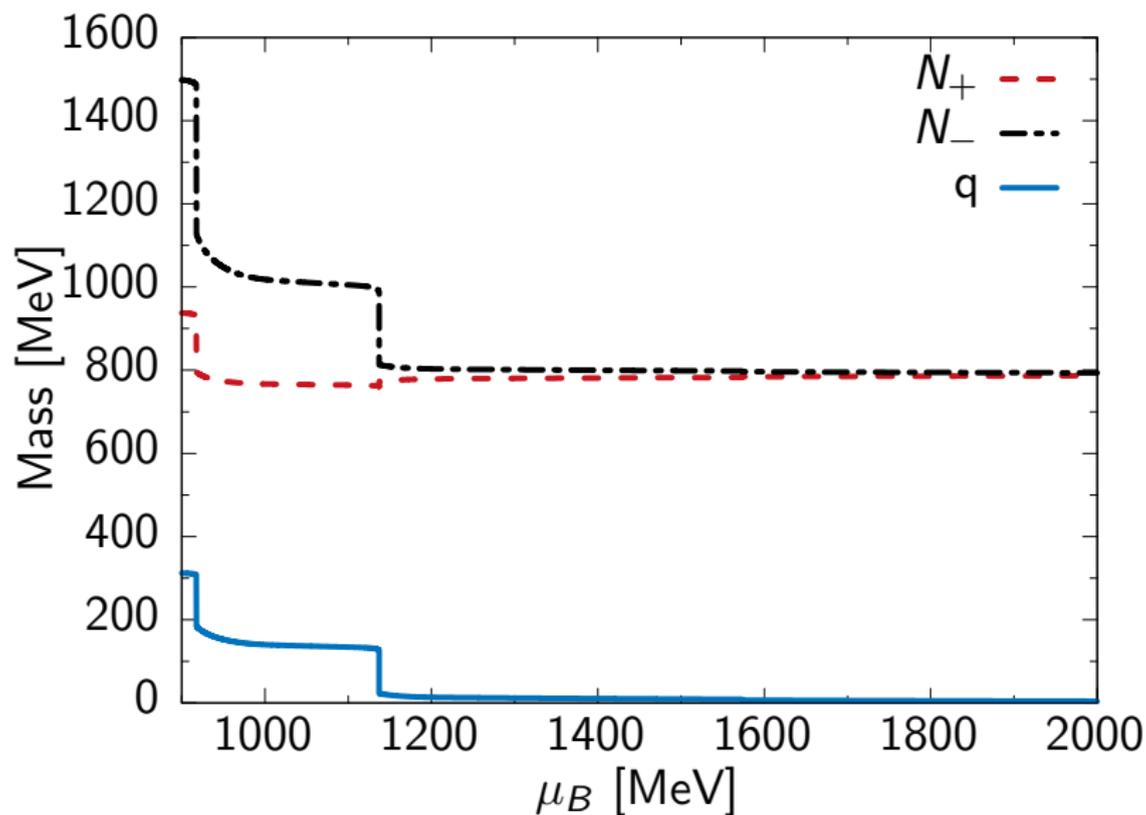
Mean fields at $T = 10$ MeV ($\alpha b_0 = 300$ MeV)



Equation of state at $T = 10$ MeV ($\alpha b_0 = 300$ MeV)



Masses at $T = 10$ MeV ($\alpha b_0 = 300$ MeV)



Masses at $T = 10$ MeV ($\alpha b_0 = 390$ MeV)

