Chiral Symmetry Restoration by Parity Doubling and the Structure of Neutron Stars

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National Science Centre Poland

Common Approach to EoS

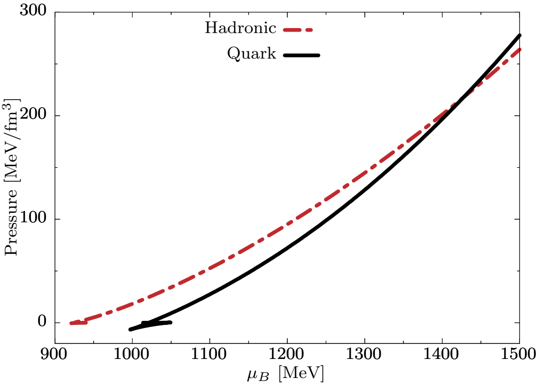
Hadronic EoS: p^+, n^+
(incomplete chiral physics)

$+$

Quark EoS
(chiral physics)

$\downarrow$

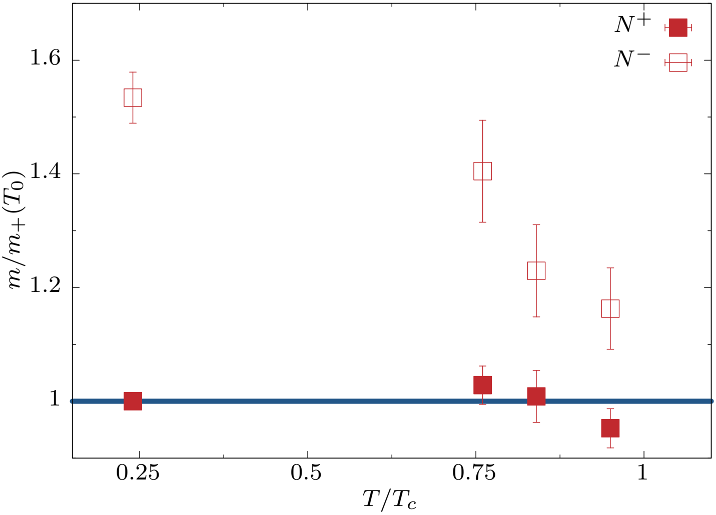
Maxwell Construction
(deconfinement)



Courtesy: N.-U. F. Bastian

- Striking problem: No chiral physics in the resulting EoS

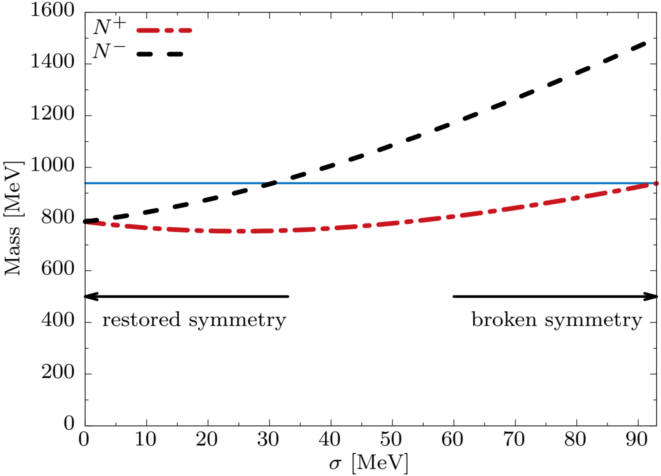
Parity Doubling in Lattice QCD Aarts *et al*, JHEP **1706**, 034 (2017)



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

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

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



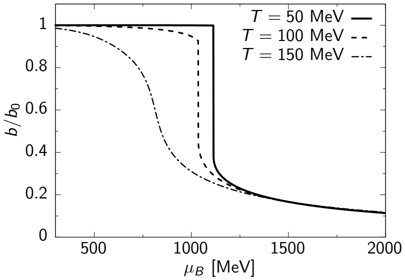
Hybrid Quark-Meson-Nucleon Model Benić, Mishustin, Sasaki, PRD **91** (2015)

Parity Doublet Model + Quark-Meson Coupling

$\Downarrow$

Statistical Confinement:

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

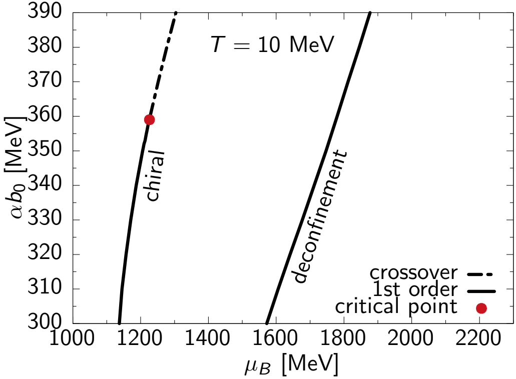
$b(\mu_B \rightarrow \infty) = 0$ favors quarks

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

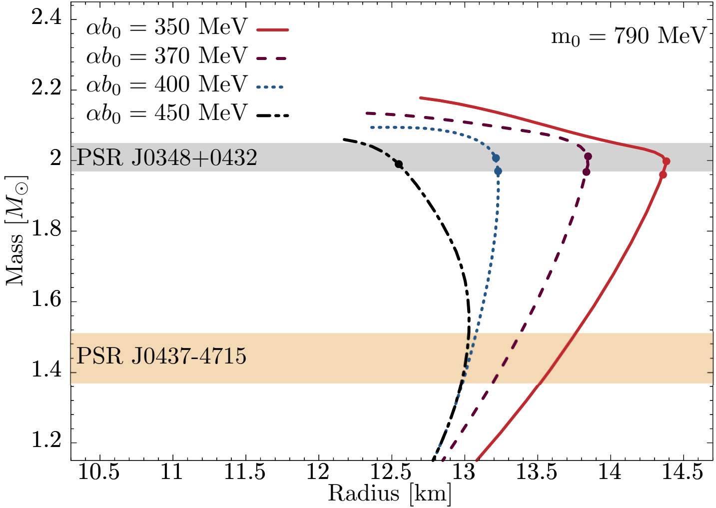
- Sequential phase transitions (may coincide for smaller m_0)



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

Mass-Radius Relation

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



Threshold for Direct URCA Lattimer, Pethick, Prakash, Haensel, PRL **66** (1991)

- Conventional Scenario
  - d.o.f.: p^+, n^+, e, μ
- Charge Neutrality

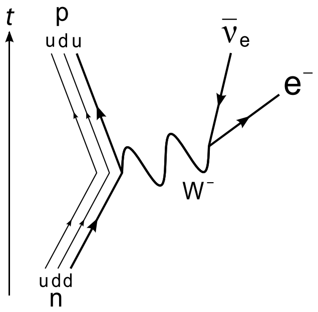
$$\rho_{p^+} = \rho_e + \rho_\mu$$

- Momentum Conservation

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

- 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

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

- 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

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

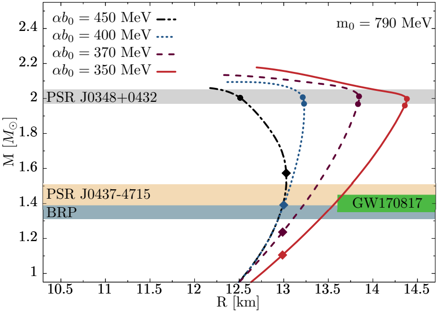
- Momentum Conservation

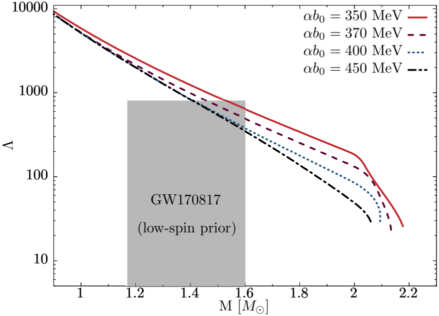
$$f_{n^+} \leqslant f_{p^+} + f_e$$

- Proton Fraction Threshold

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

Constraints from Binary Radio Pulsar and GW170817

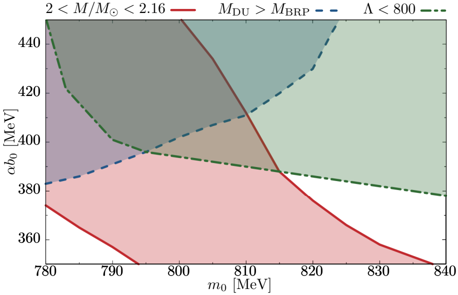


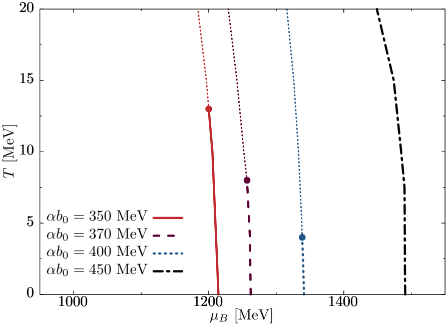


- DU triggered already in chirally broken phase
- DU excluded below BRP (due to cooling phenomenology)

- Soft EoS favored
- Constraint on radius $R < 13.6$ km at 1.4 $M_\odot$

Compilation of All Constraints





- $2M_\odot$ $\longrightarrow$ stiff EoS
- DU $\longrightarrow$ soft EoS
- TD $\longrightarrow$ soft EoS

- CP at low T or even absent!

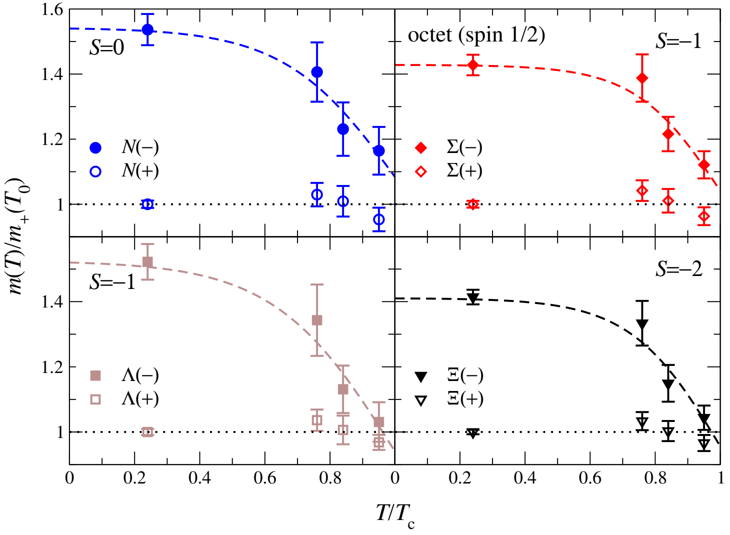
Conclusions

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

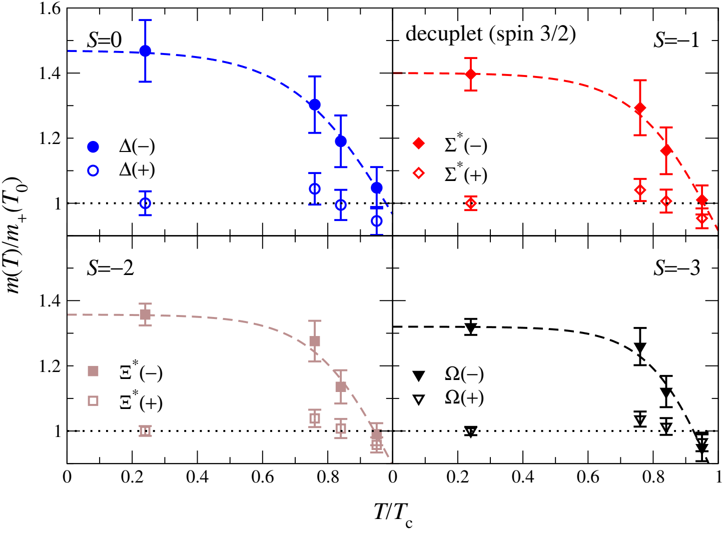
- $2M_{\odot}$ with chirally restored but still confined core
- High-mass stars $\rightarrow$ not necessarily signal of deconfinement
- Parity doubling $\rightarrow$ modification of direct URCA threshold
  - new estimate for the proton fraction threshold
  - impact on neutron star cooling
- Astrophysical Constraints $\rightarrow$ CP at low T or even absent

Thank You

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



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



Particle Identification

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

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

Parity doubling in chiral models DeTar, Kunihiro Phys. Rev. D **39** 2805 (1989)

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

$$\mathcal{L}_N = i\bar{\psi}_1 \partial\!\!\!/ \psi_1 + i\bar{\psi}_2 \partial\!\!\!/ \psi_2 + m_0 \left(\bar{\psi}_1 \gamma_5 \psi_2 - \bar{\psi}_2 \gamma_5 \psi_1 \right)$$

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

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

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

Full HQMN model Lagrangian

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

$$\mathcal{L}_N = \sum_{k=1,2} \bar{\psi}_k i\partial\!\!\!/ \psi_k + m_0 \left(\bar{\psi}_2\gamma_5\psi_1 - \bar{\psi}_1\gamma_5\psi_2\right)$$

$$+ \sum_{k=1,2} g_k\bar{\psi}_k \left(\sigma \pm i\gamma_5 \boldsymbol{\tau}\cdot\boldsymbol{\pi}\right)\psi_k - g_\omega\bar{\psi}_k \omega\!\!\!/ \psi_k$$

$$\mathcal{L}_q = \bar{q}i\partial\!\!\!/ q + g_q\bar{q}\left(\sigma + i\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}\right) q$$

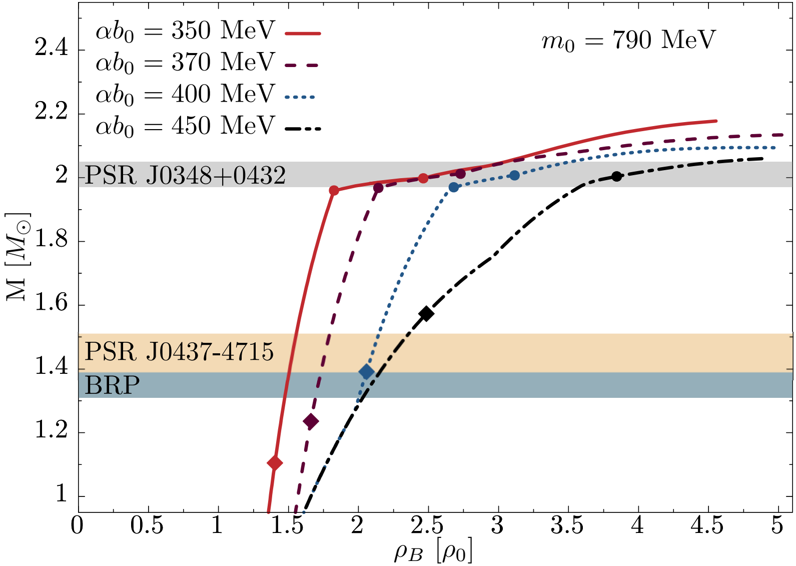
$$\mathcal{L}_M = \frac{1}{2}(\partial_\mu\sigma)^2 + \frac{1}{2}(\partial_\mu\boldsymbol{\pi})^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - V_\sigma - V_\omega - V_b$$

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

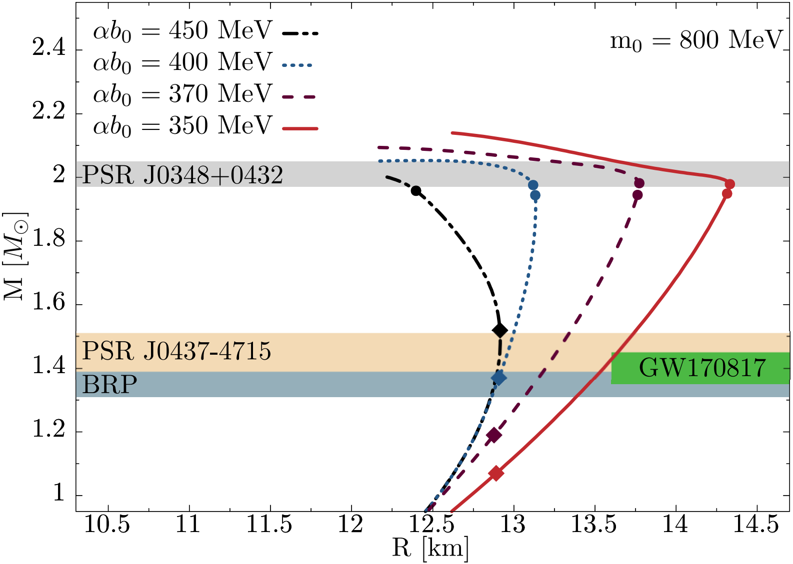
$$V_\omega = -\frac{1}{2}m_\omega^2\omega_\mu\omega^\mu$$

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

mass-density

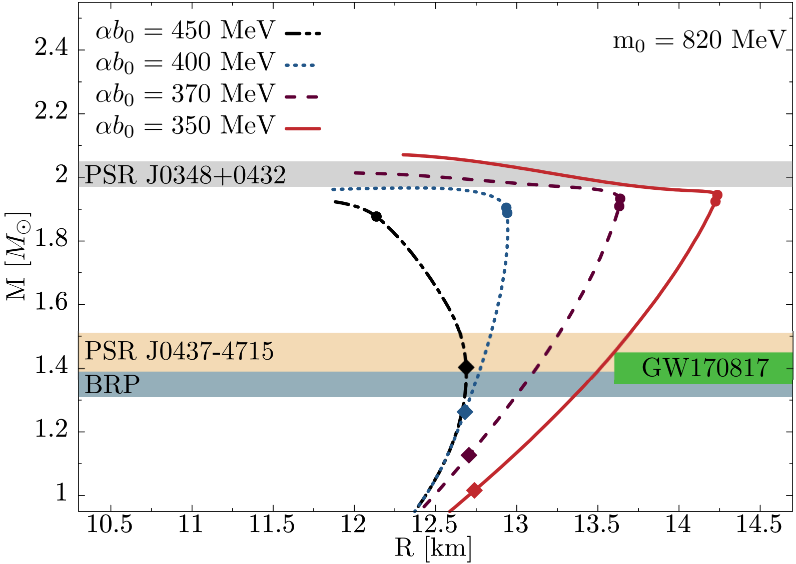


mass-radius



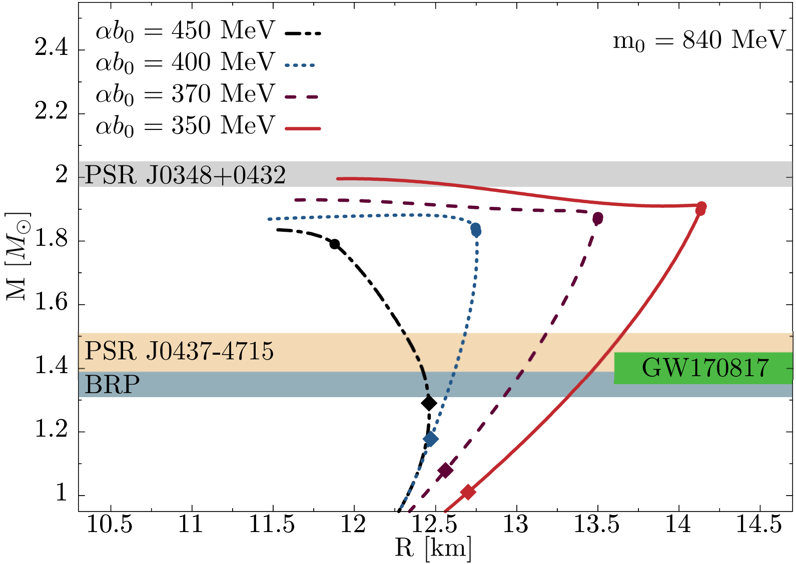
αb_0 = 450 MeV
αb_0 = 400 MeV
αb_0 = 370 MeV
αb_0 = 350 MeV
m_0 = 800 MeV
PSR J0348+0432
PSR J0437-4715
BRP
GW170817
M [$M_\odot$]
R [km]
2.4
2.2
2
1.8
1.6
1.4
1.2
1
10.5
11
11.5
12
12.5
13
13.5
14
14.5

mass-radius



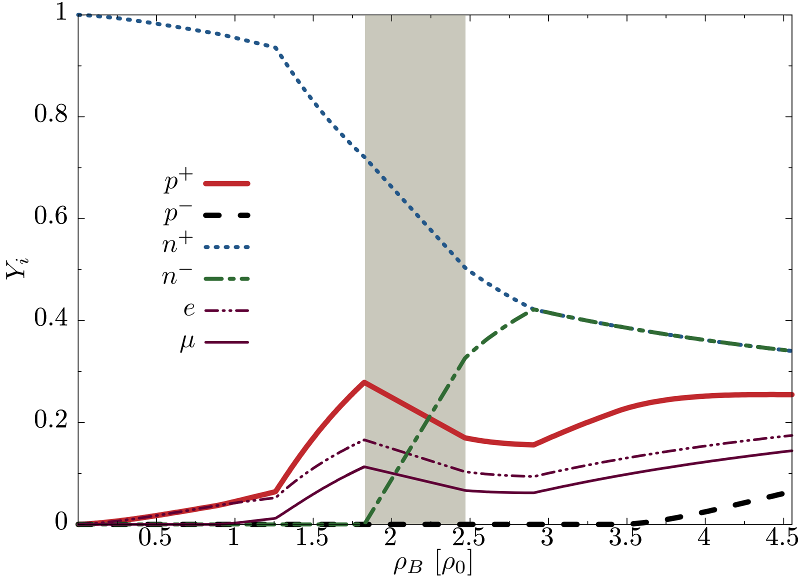
αb_0 = 450 MeV
αb_0 = 400 MeV
αb_0 = 370 MeV
αb_0 = 350 MeV
m_0 = 820 MeV
PSR J0348+0432
PSR J0437-4715
BRP
GW170817
2.4
2.2
2
1.8
1.6
1.4
1.2
1
M [$M_\odot$]
10.5
11
11.5
12
12.5
13
13.5
14
14.5
R [km]

mass-radius

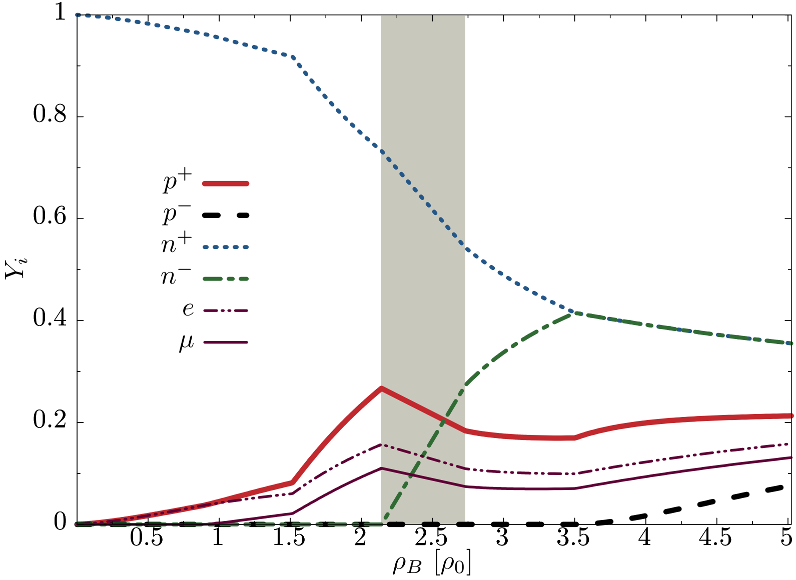


αb_0 = 450 MeV
αb_0 = 400 MeV
αb_0 = 370 MeV
αb_0 = 350 MeV
m_0 = 840 MeV
PSR J0348+0432
PSR J0437-4715
BRP
GW170817
M [$M_\odot$]
R [km]
2.4
2.2
2
1.8
1.6
1.4
1.2
1
10.5
11
11.5
12
12.5
13
13.5
14
14.5

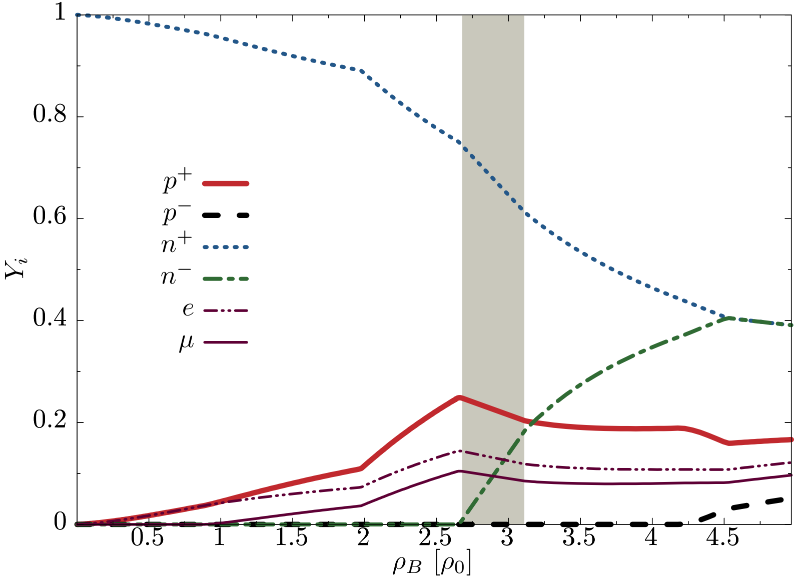
Matter composition ($\alpha b_0 = 350$ MeV)



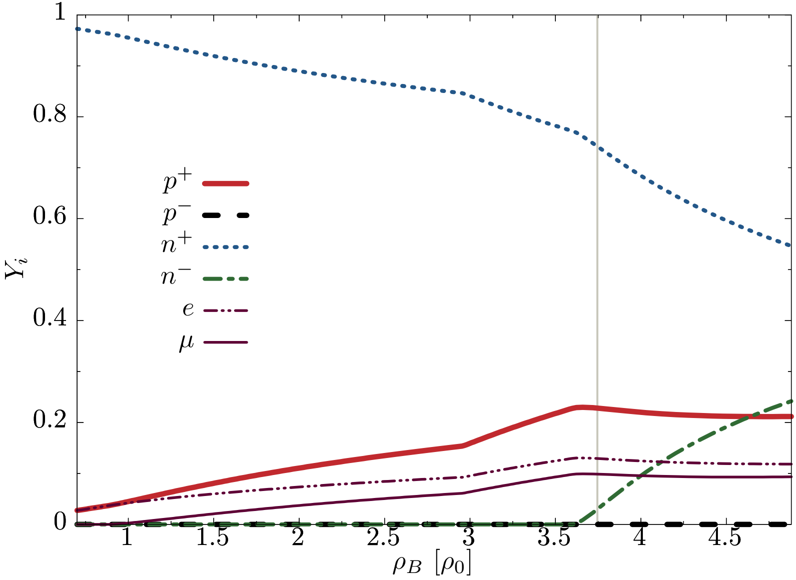
Matter composition ($\alpha b_0 = 370$ MeV)



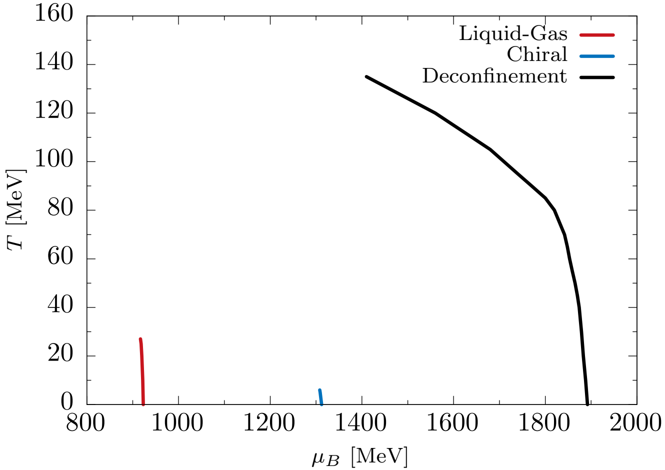
Matter composition ($\alpha b_0 = 400$ MeV)



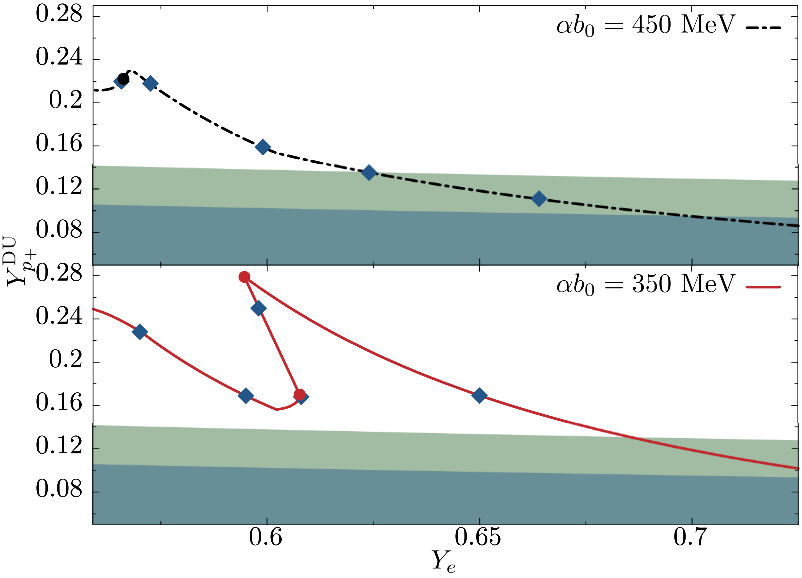
Matter composition ($\alpha b_0 = 450$ MeV)



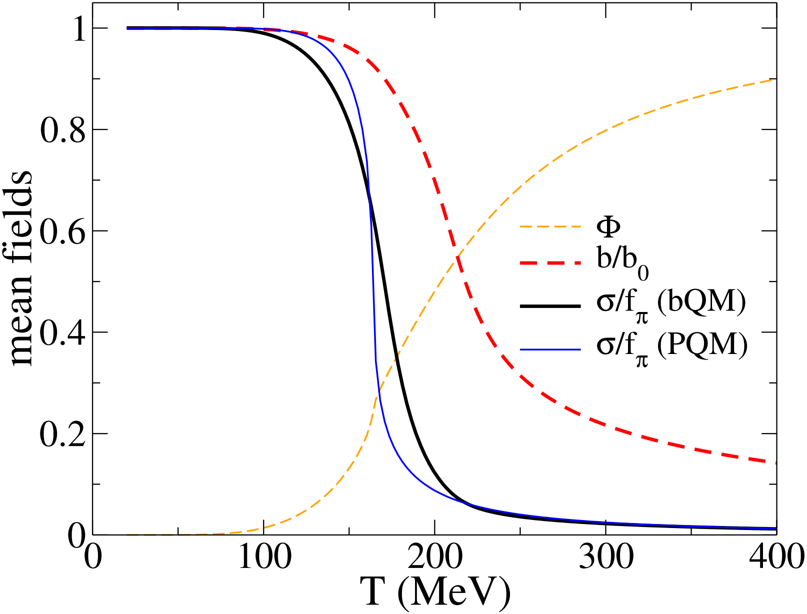
Phase diagram in $(T - \mu_B)$-plane $(\alpha b_0 = 310$ MeV$)$



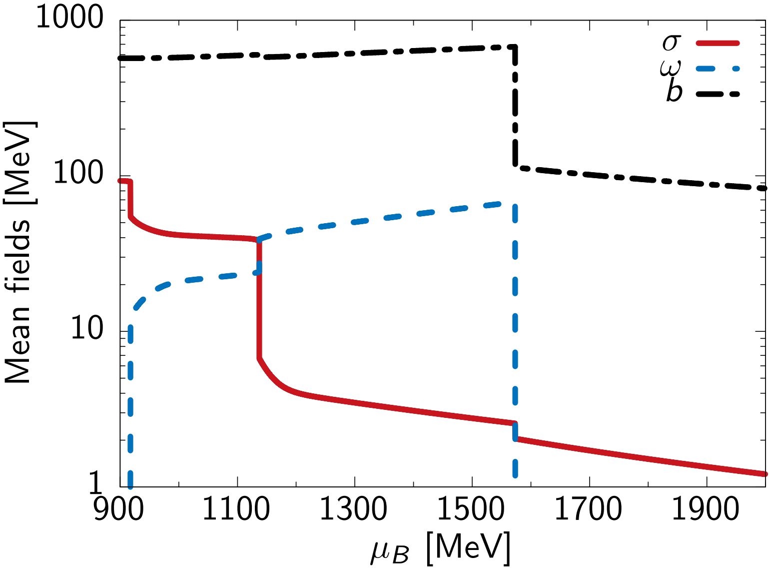
Threshold for direct URCA



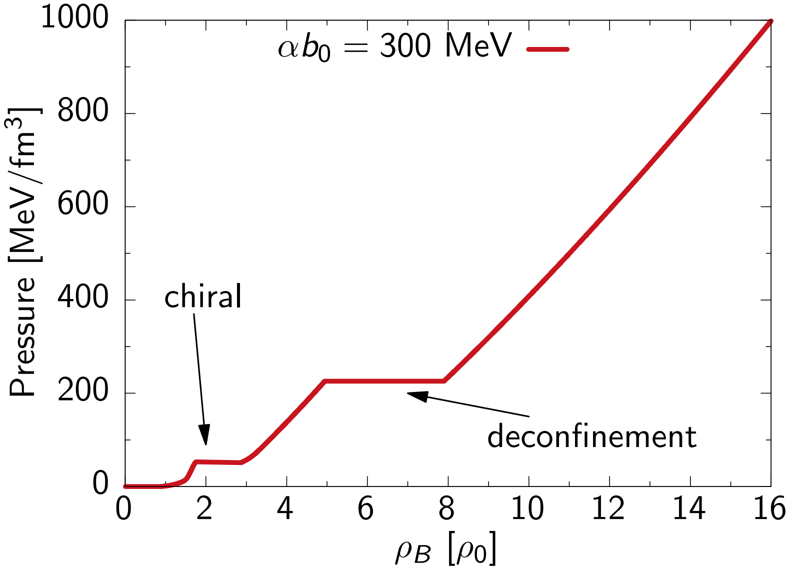
bQM vs PQM Benić *et al*, Phys. Rev. D **91**, 125034 (2015)



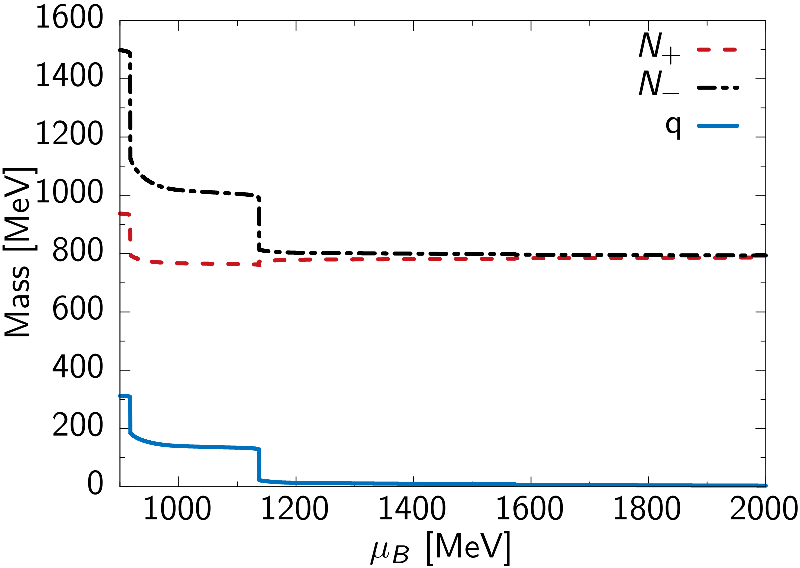
Mean fields at $T = 10$ MeV ($\alpha b_0 = 300$ MeV)



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)