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

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National Science Centre
Poland

Common approach to EoS

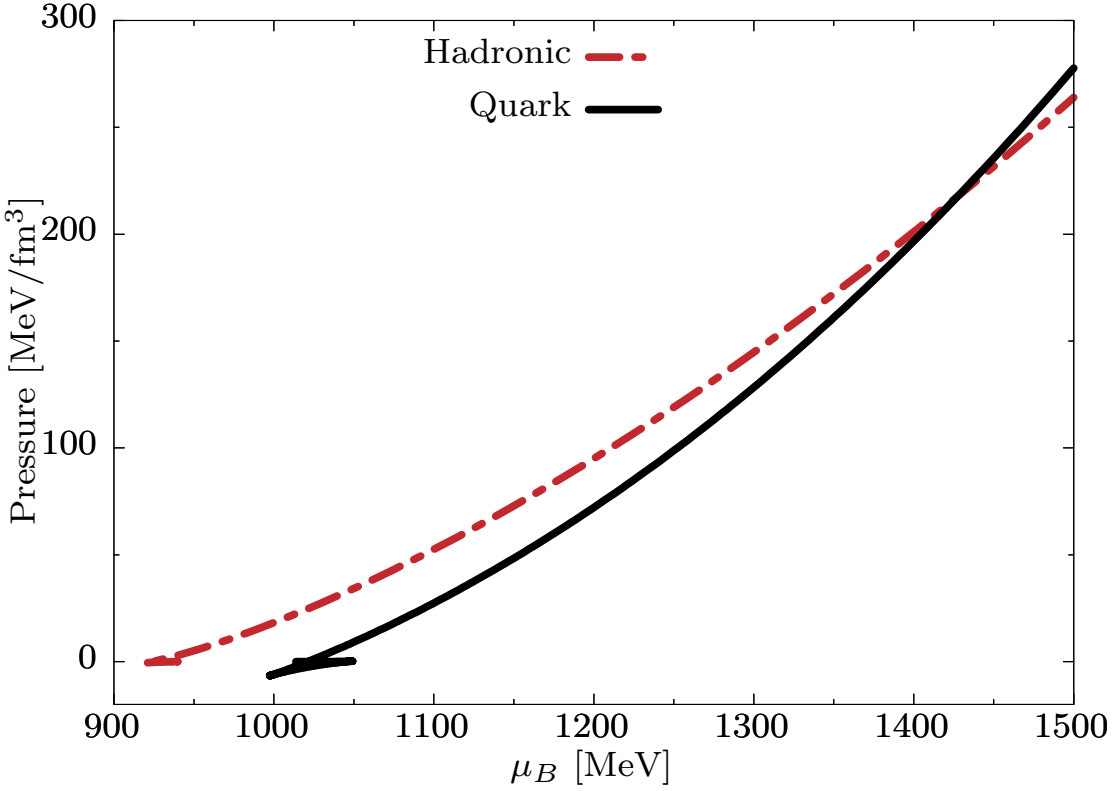
Hadronic EoS: p^+, n^+
(incomplete chiral physics)

$+$

Quark EoS
(chiral physics)

$\downarrow$

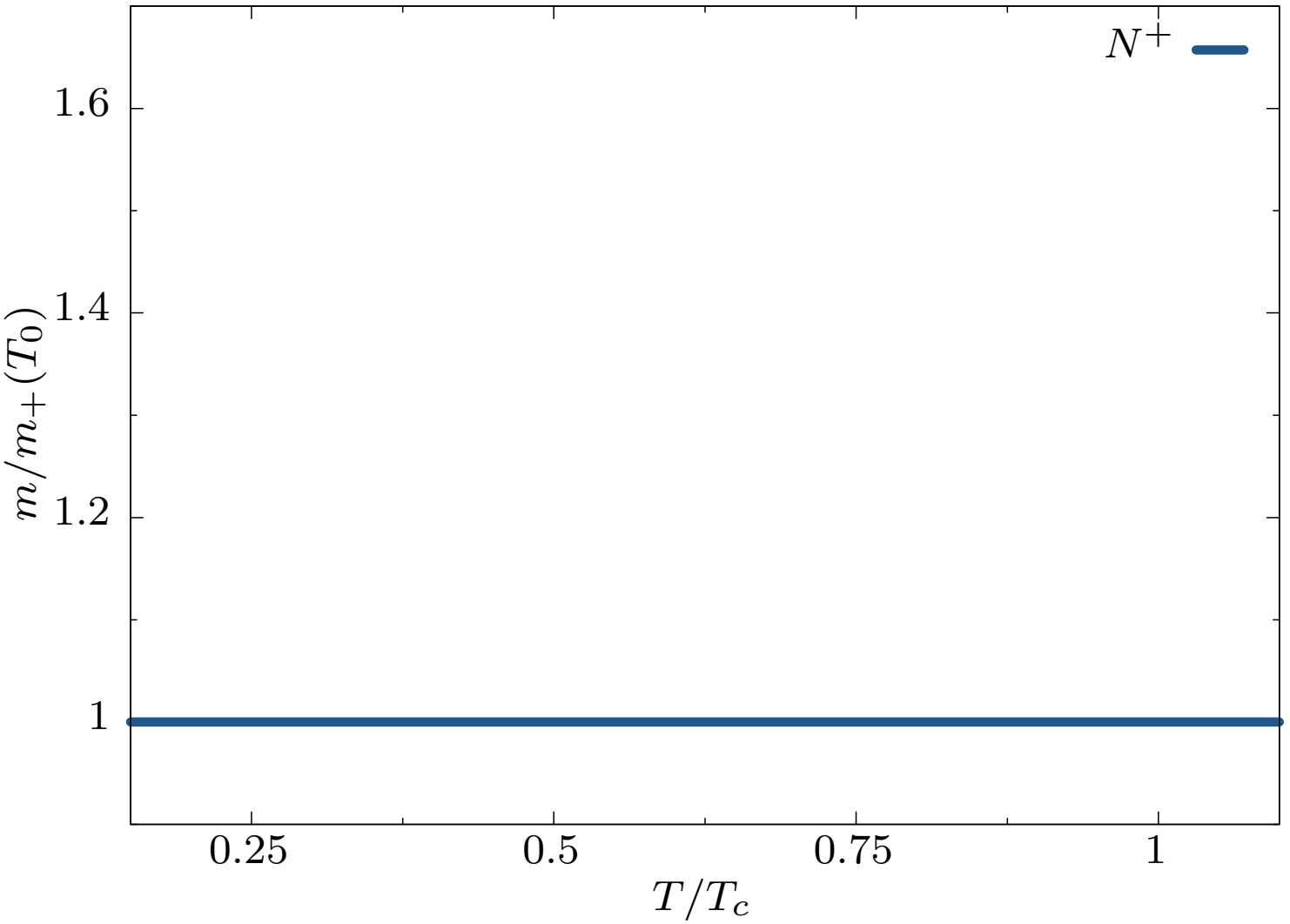
Maxwell construction
(deconfinement)



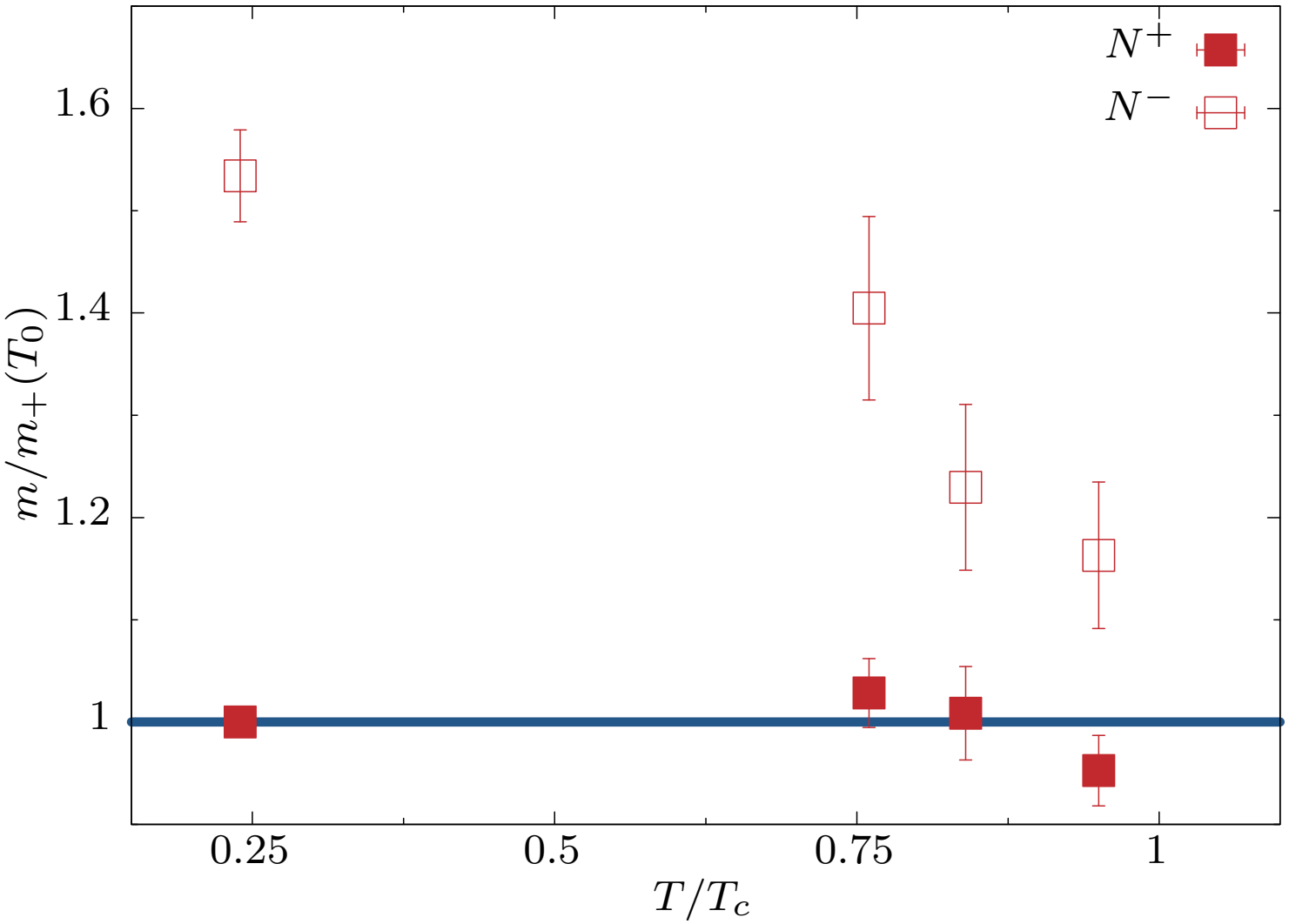
courtesy: N.-U. F. Bastian

- Striking problem: No chiral physics in the resulting EoS

Common approach to EoS



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

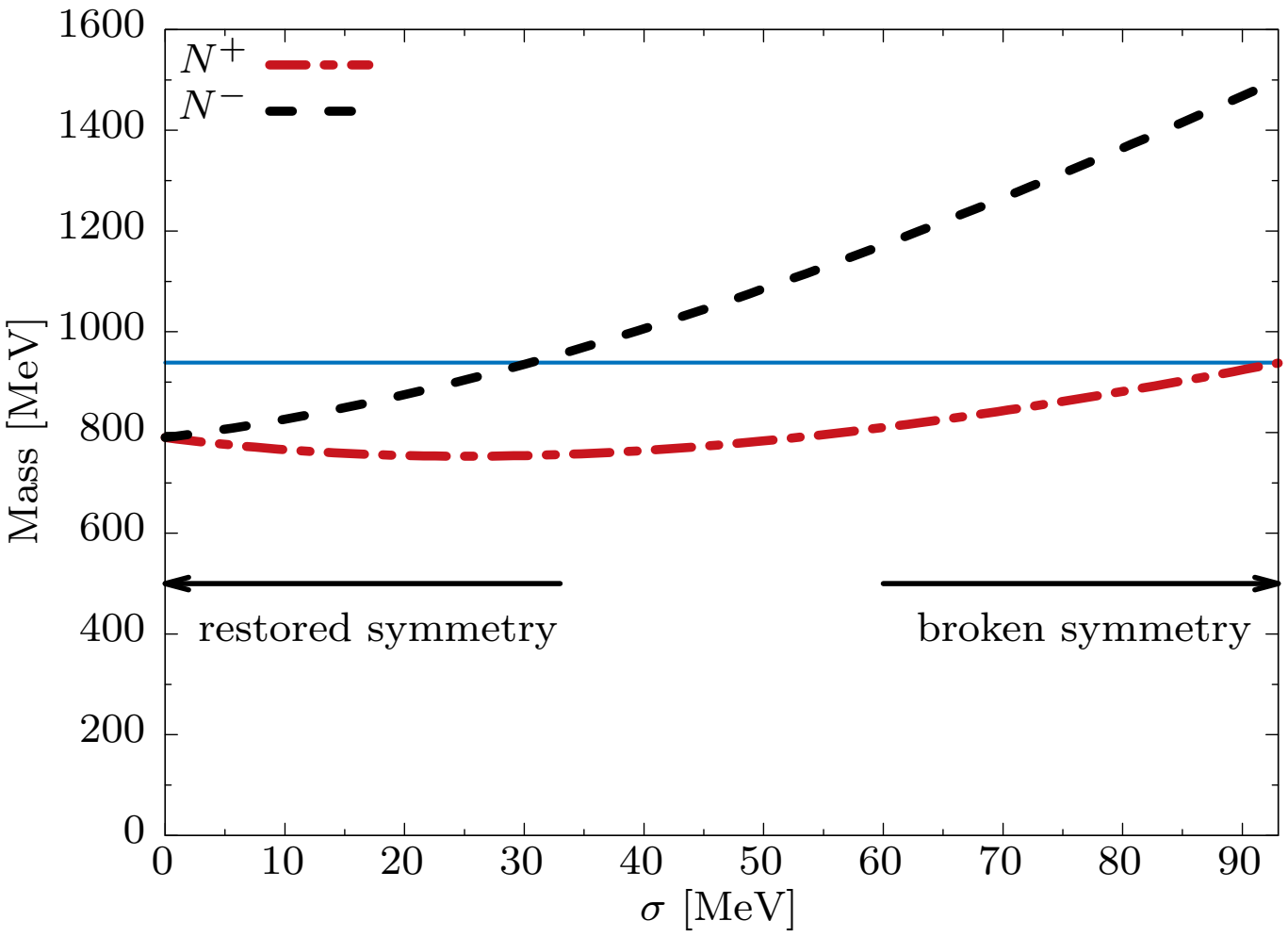
Particle Identification

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** (1989)

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



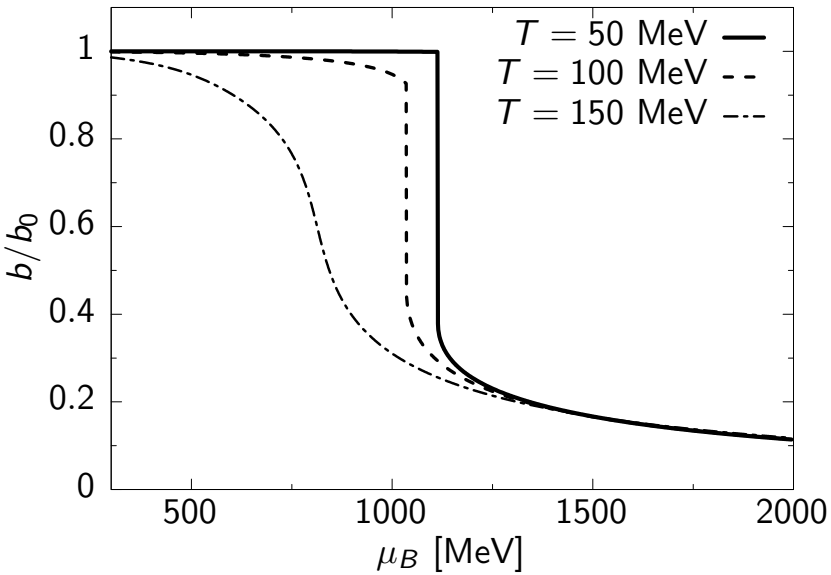
Hybrid Quark-Meson-Nucleon Model Benić, Mishustin, Sasaki, PRD **91** (2015)

Parity doublet model + quark-meson coupling

$$\Downarrow$$

Statistical confinement:

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



- b - scalar field

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

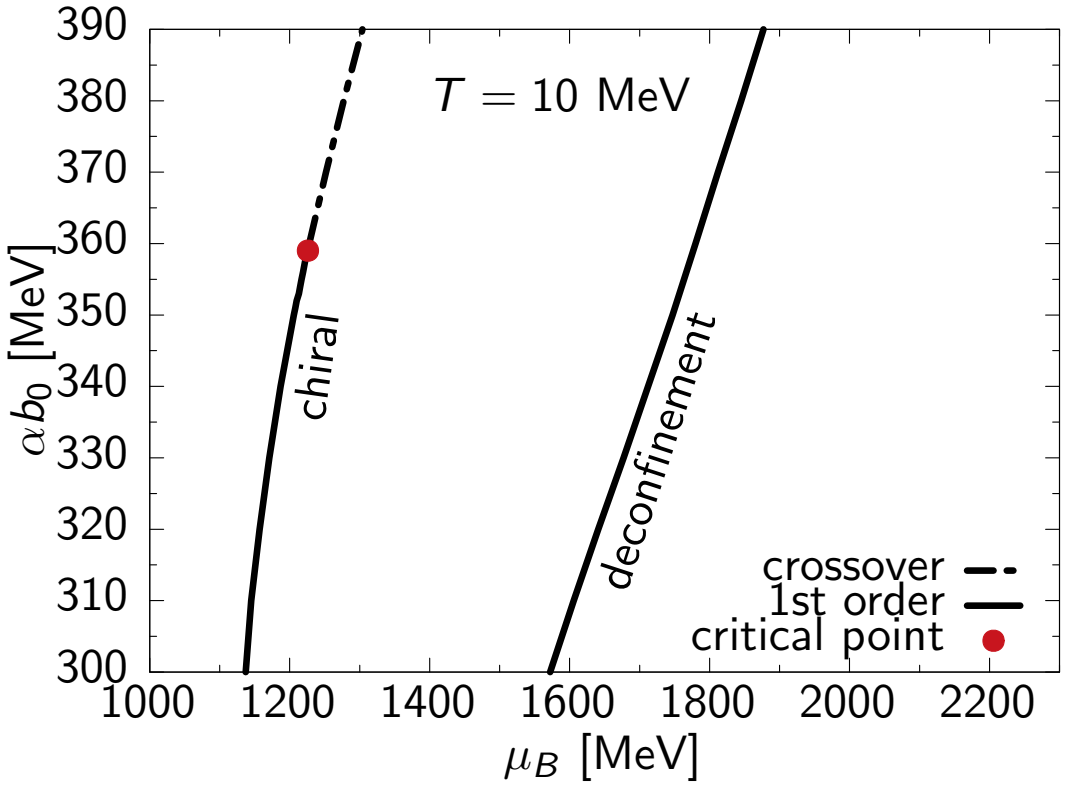
$b(\mu_B = 0) > 0$ favors nucleons

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

Phase Diagram for Isospin-Symmetric Matter

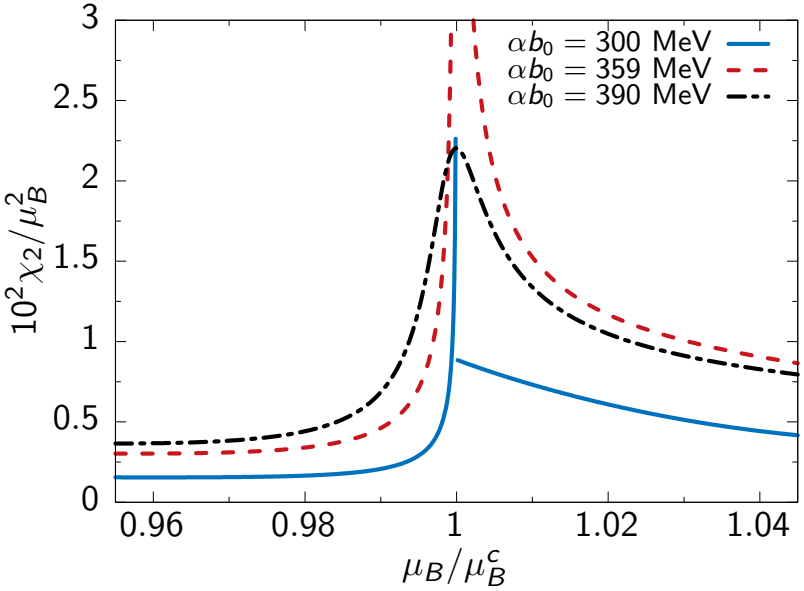
- 1st order deconfinement transition
- Order of chiral transition (from low to high α)

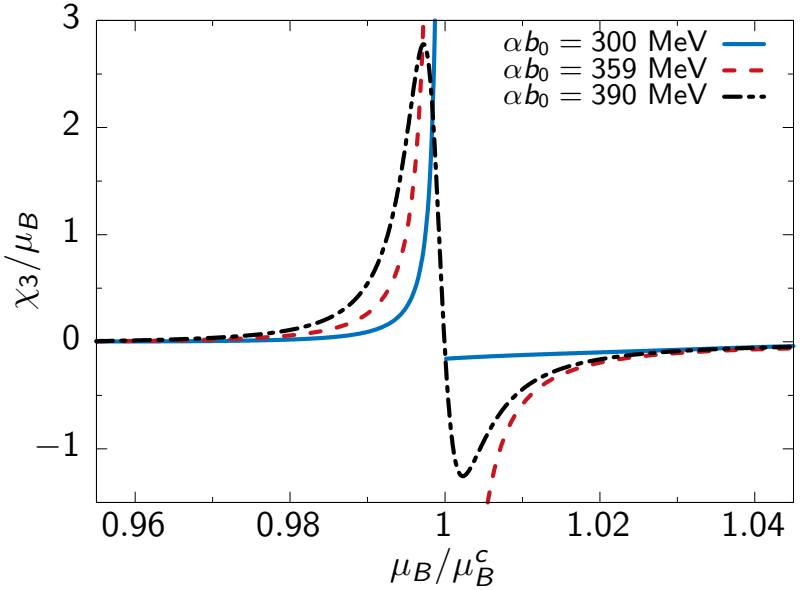
  1st order $\longrightarrow$ critical point $\longrightarrow$ crossover
- Sequential phase transitions (may coincide for smaller m_0)

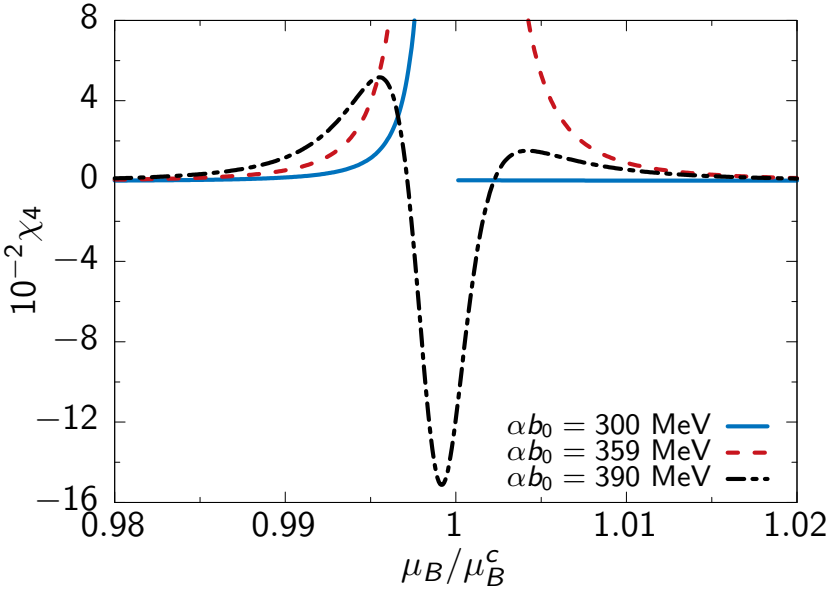


MM, C. Sasaki, Phys. Rev. D **97** 036011 (2018)

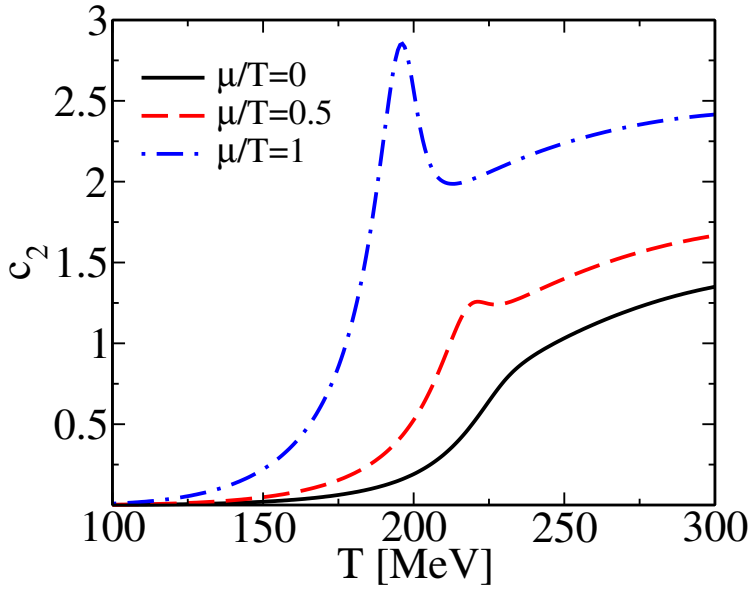
Higher-Order Cumulants

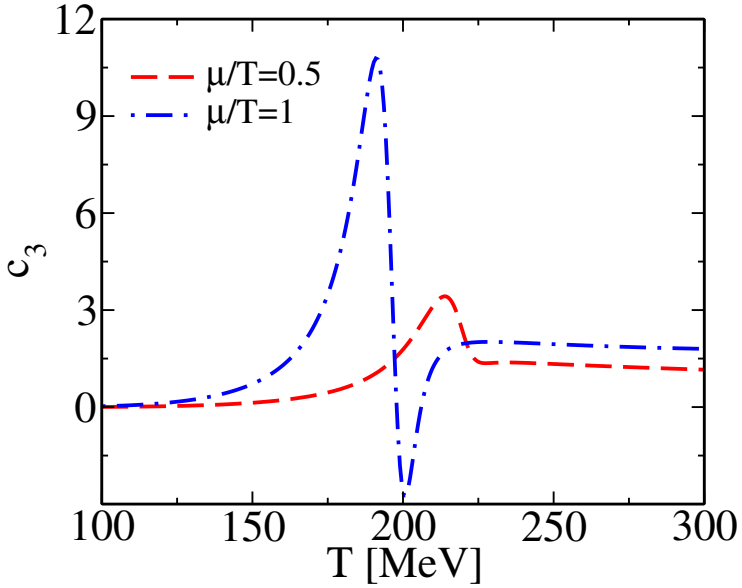


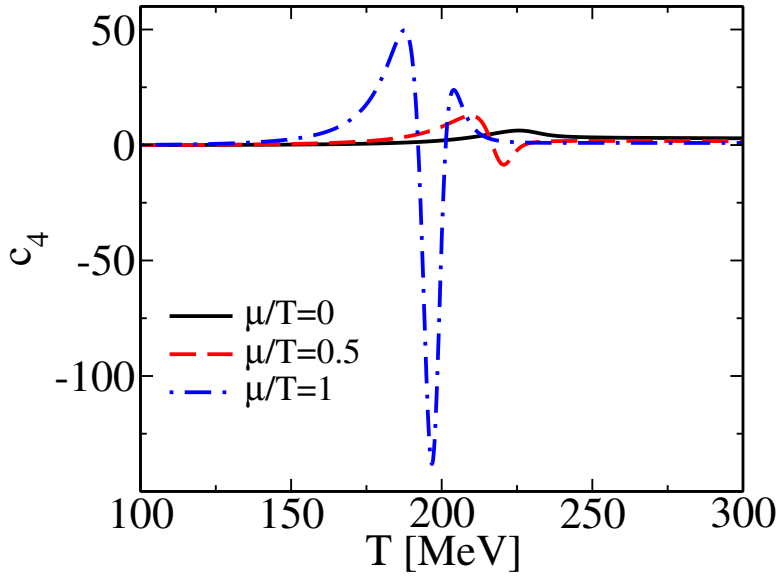




Higher-Order Cumulants in pQM model Skokov, Friman, Redlich, PRC **83** (2011)

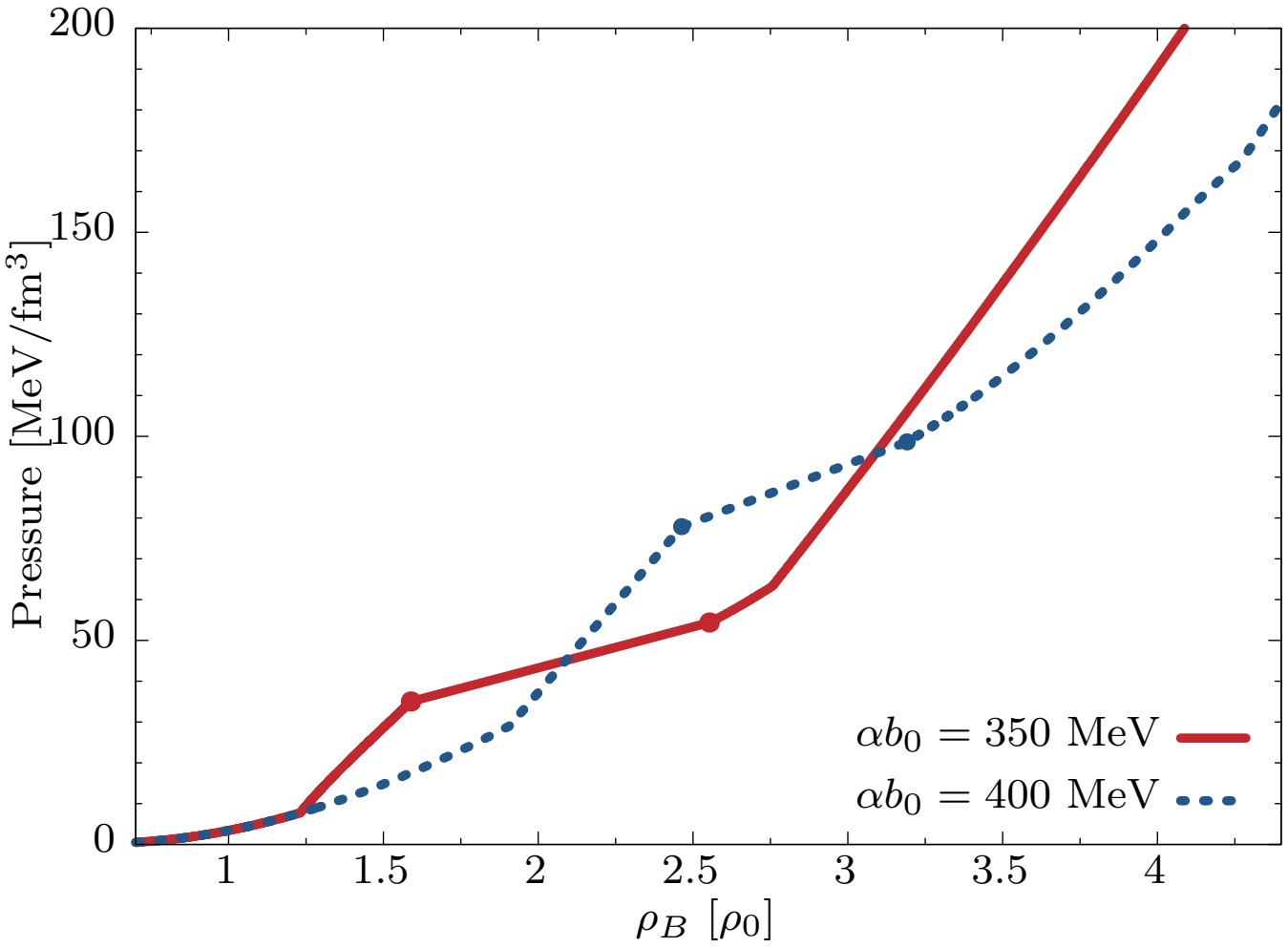






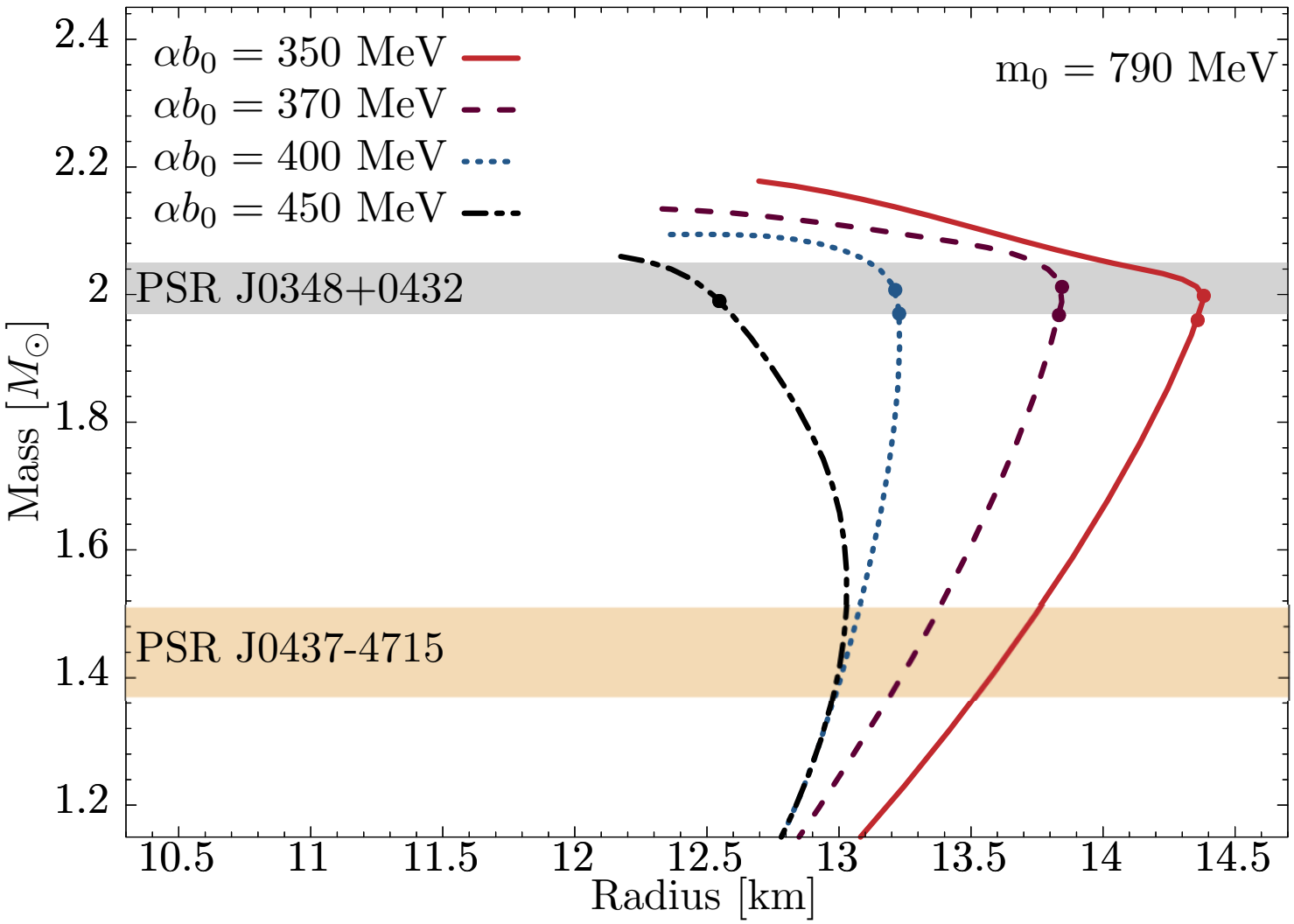
Equation of State Under NS Conditions

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

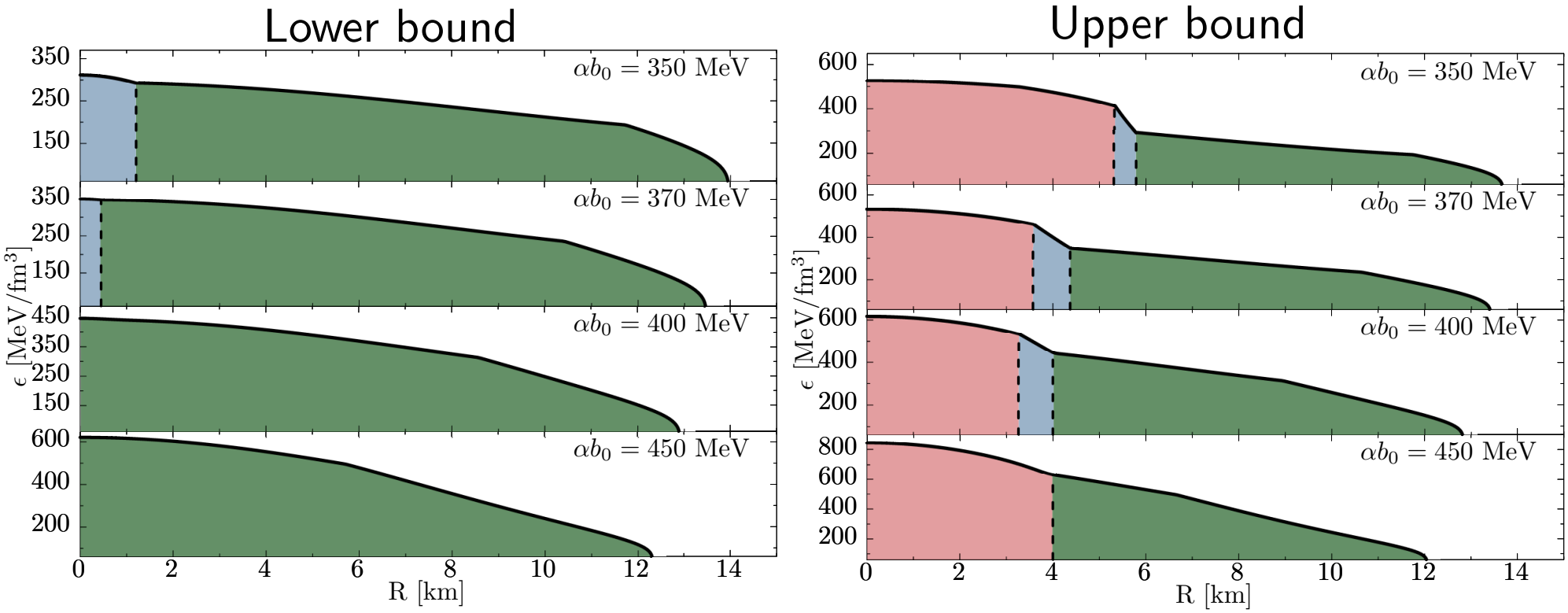


Mass-Radius Relation

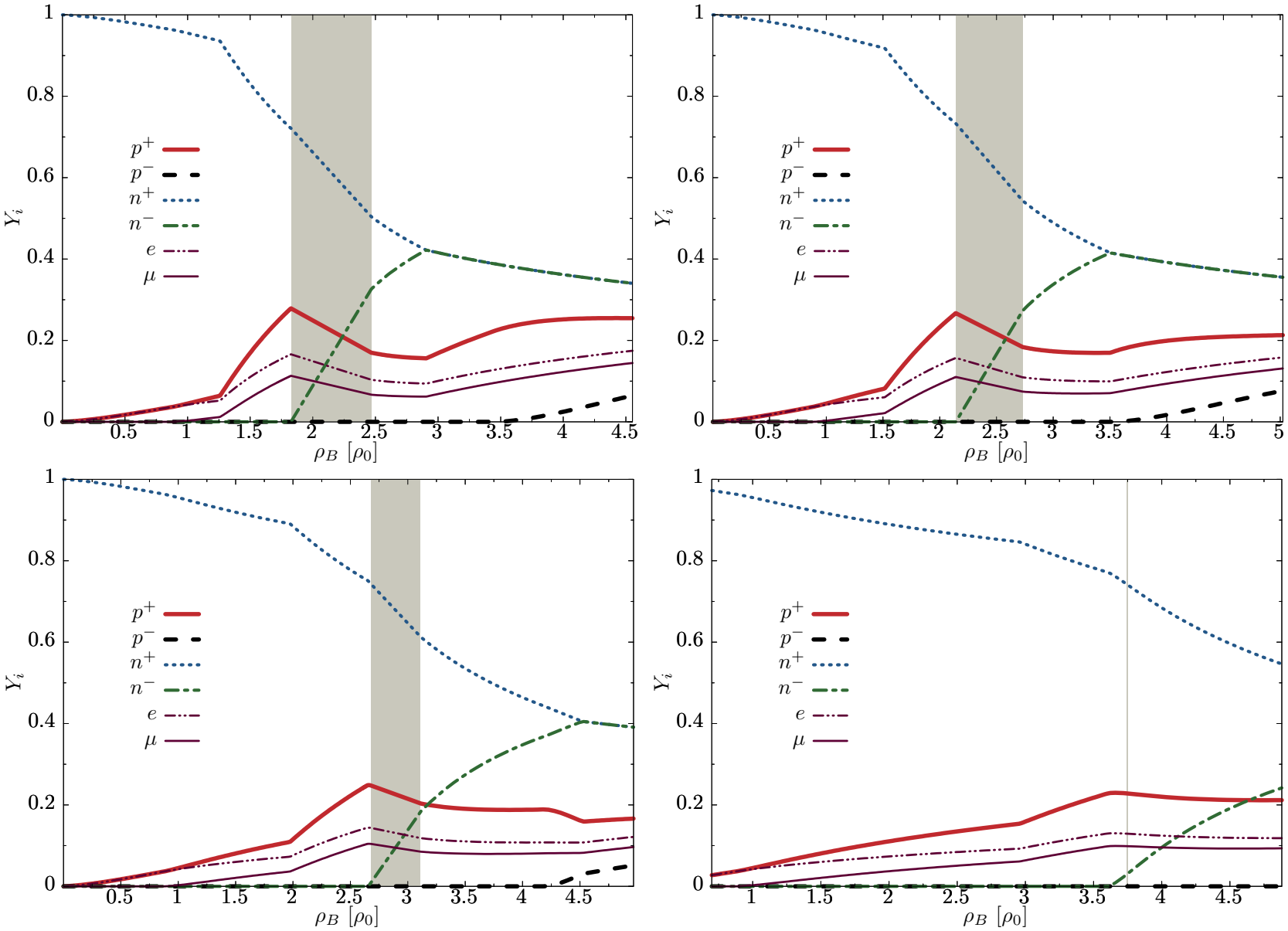
- chiral transition in high-mass part of the sequence
- $2M_\odot$ with chirally restored but confined core
- deconfinement above $2M_\odot$



Different Realizations of 2.01(4) $M_\odot$ Stars



Composition of a Compact Star Matter



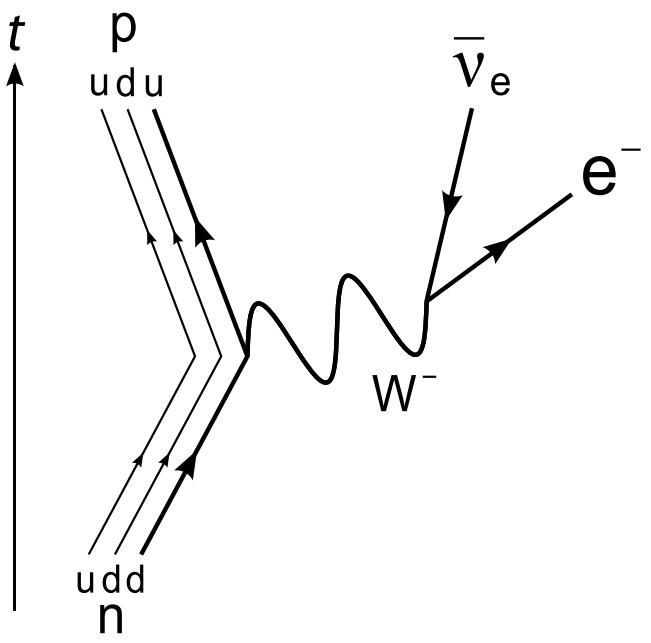
Threshold for Direct URCA: Conventional Scenario

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

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

- Momentum conservation

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



$$Y_{p^+} = \frac{1}{1 + (1 + \sqrt[3]{Y_e})^3} \Rightarrow 11\% - 15\%, \qquad Y_e = \frac{\rho_e}{\rho_e + \rho_\mu}$$

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

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

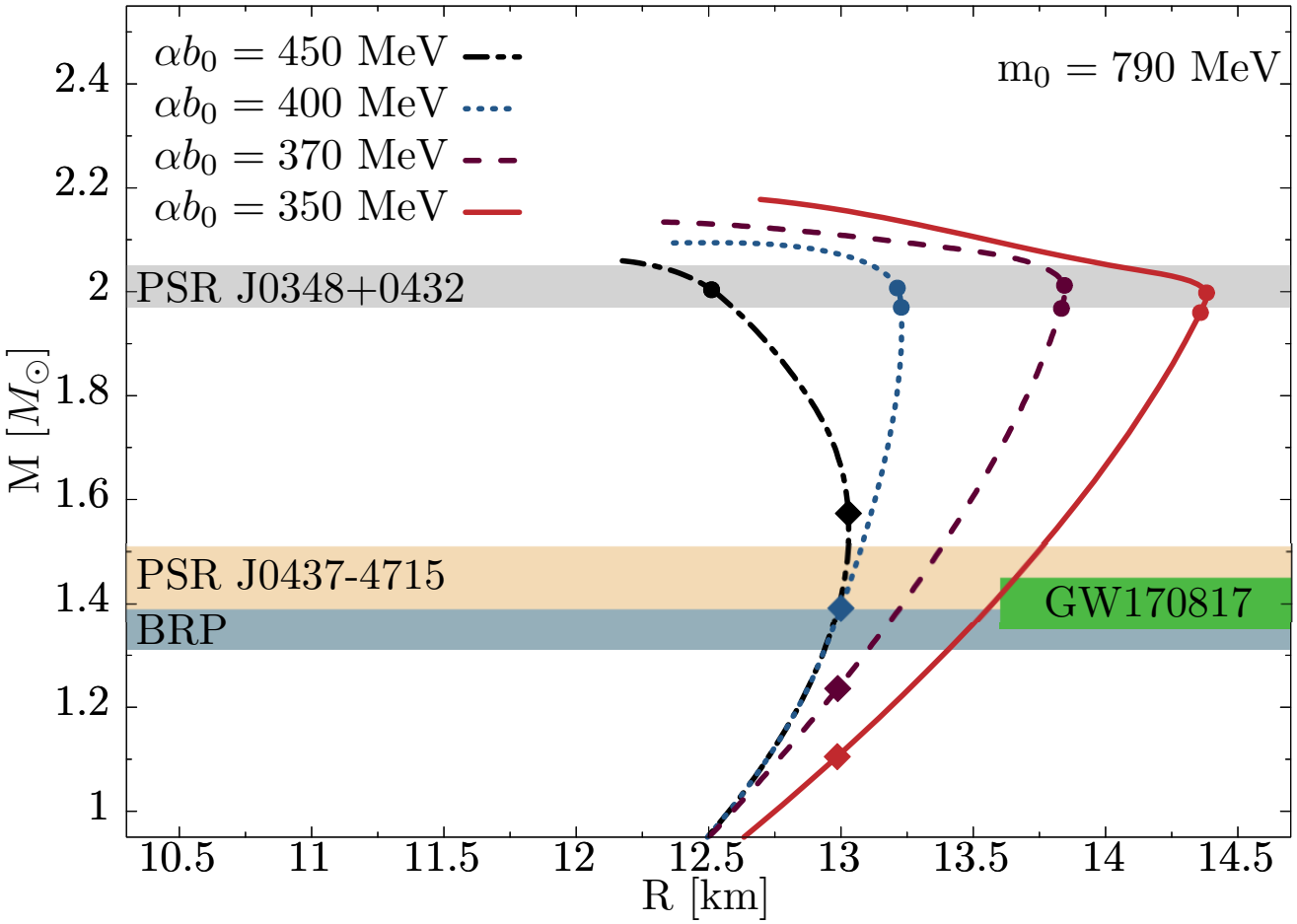
- Momentum conservation

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

- Proton Fraction Threshold

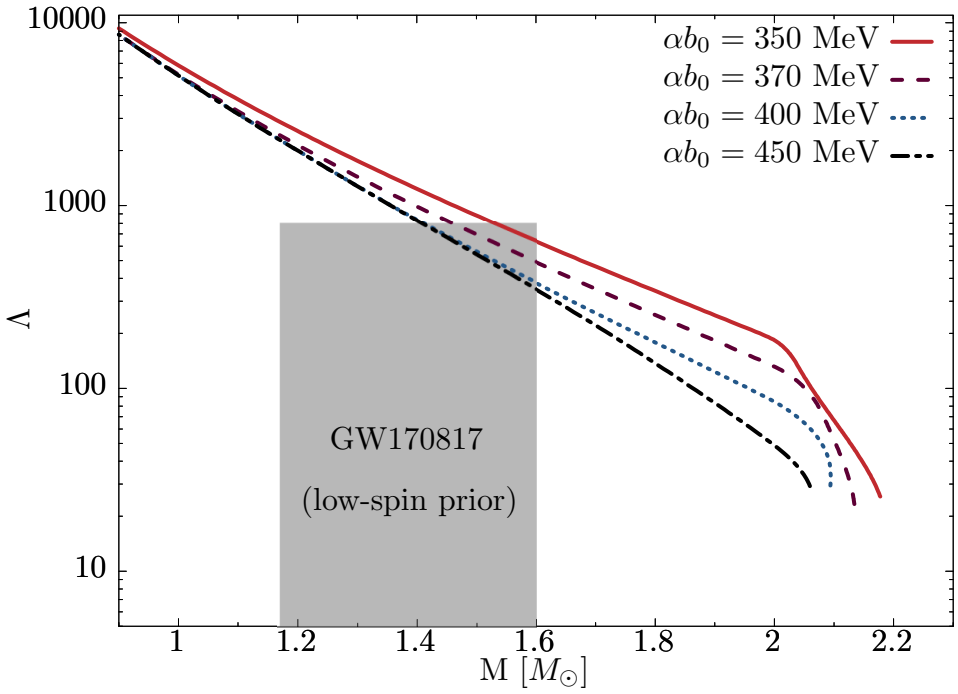
$$\frac{1}{1 + (1 + \sqrt[3]{Y_e})^3} \Rightarrow 8\% - 11\%$$

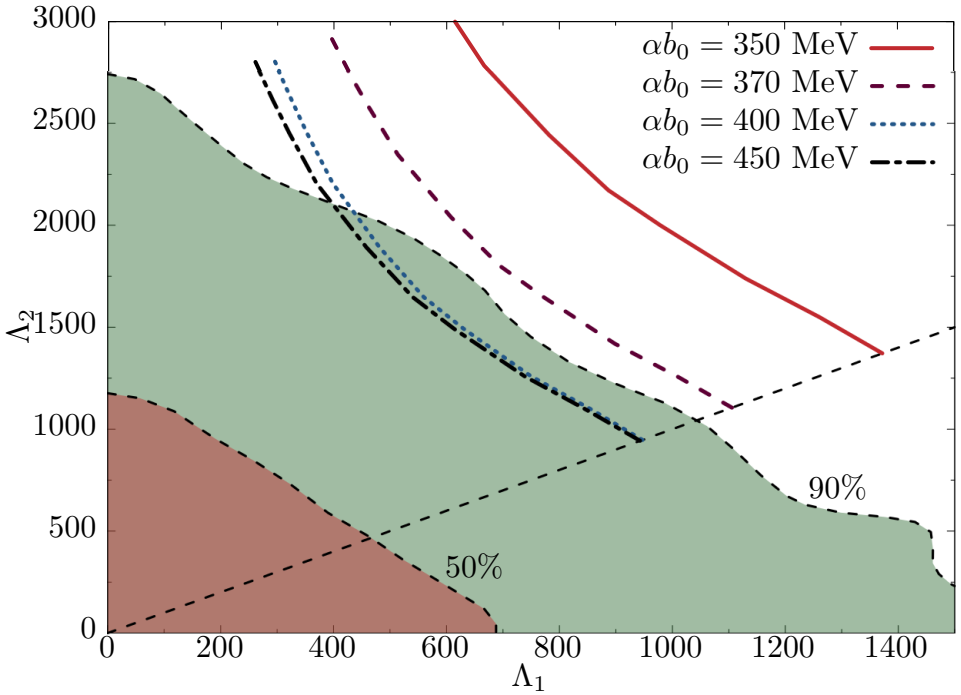
Threshold for Direct URCA



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

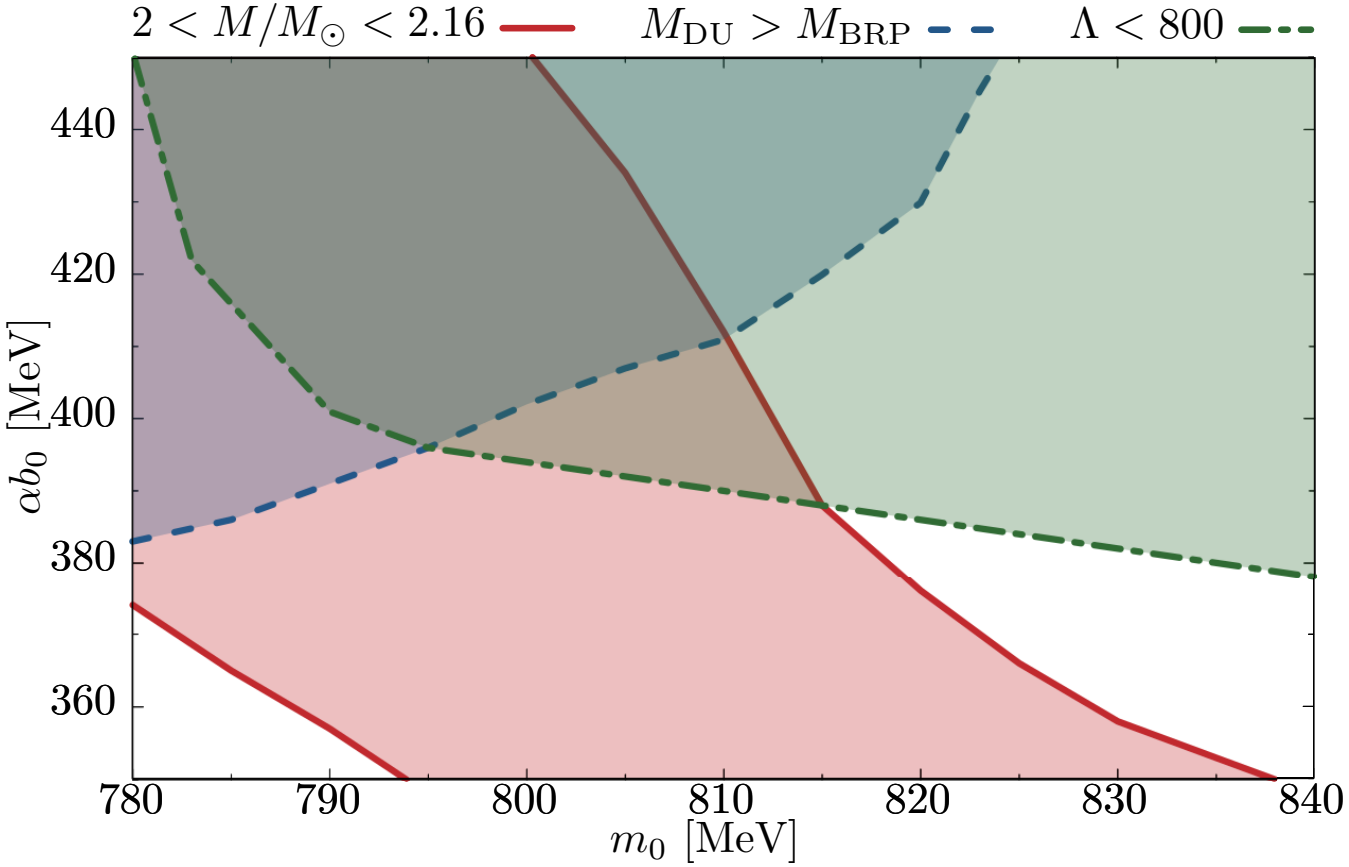
Constraints from GW170817





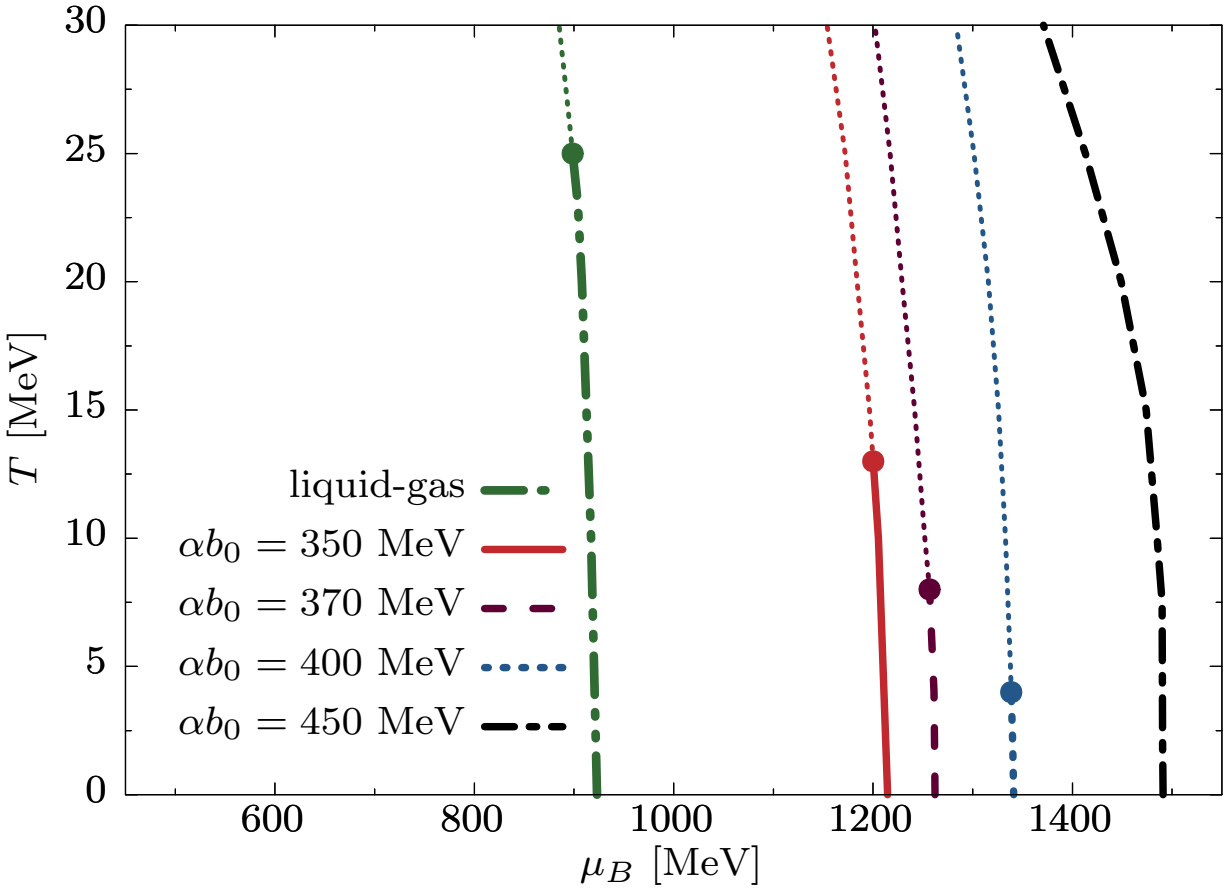
- $\Lambda = \frac{2}{3} k_2 C^{-5}$, where $C = M/R$ is compactness
- stiff EoS are rather excluded
- constraint on radius $R < 13.6$ km at 1.4 $M_\odot$

Compilation of All Constraints



- $2M_\odot \longrightarrow$ stiff EoS
- Direct Urca $\longrightarrow$ soft EoS
- Tidal Deformability $\longrightarrow$ soft EoS

Back to Symmetric-Matter Phase Diagram



- Critical Point at low temperature or even absent!

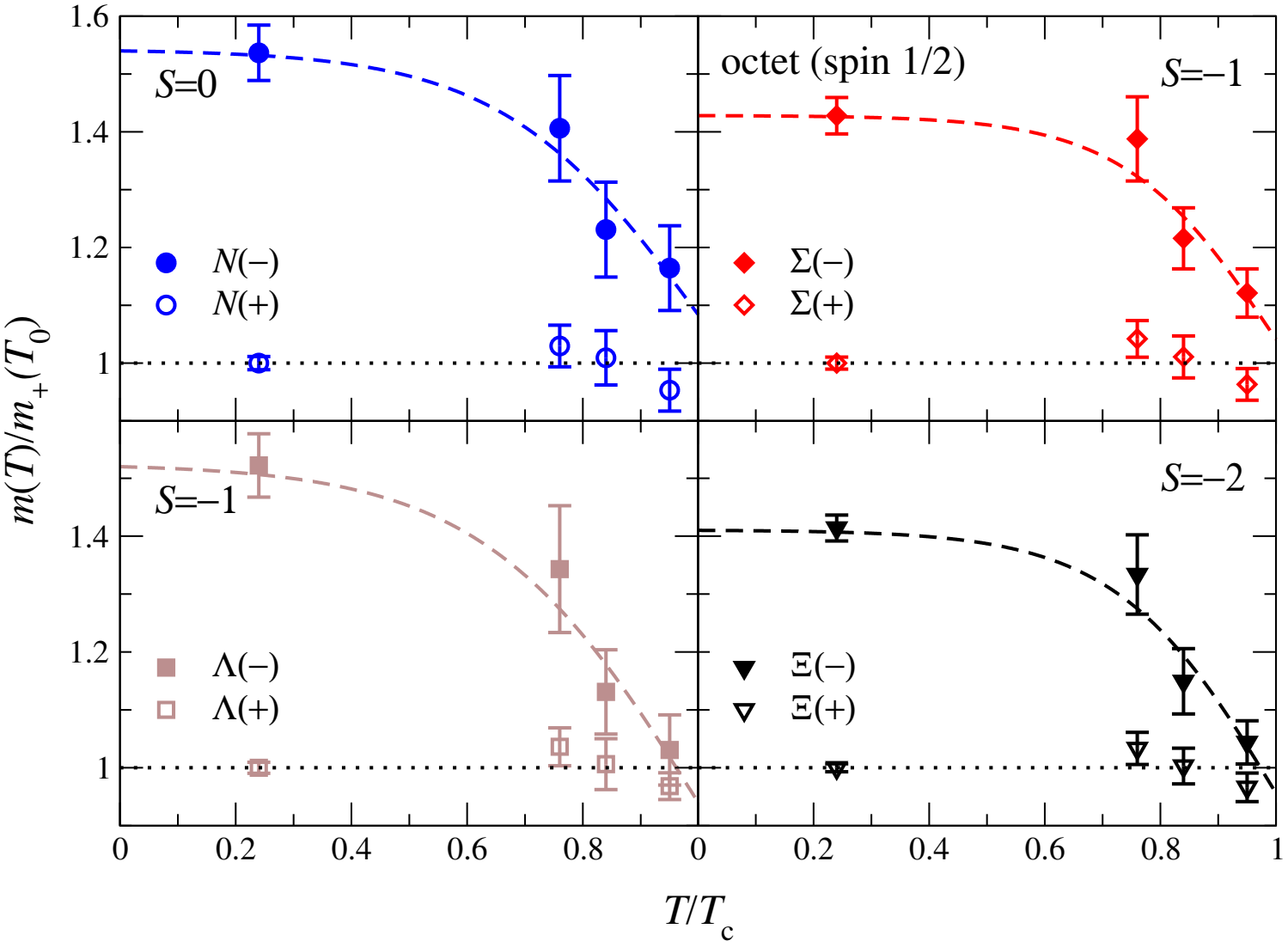
Conclusions

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

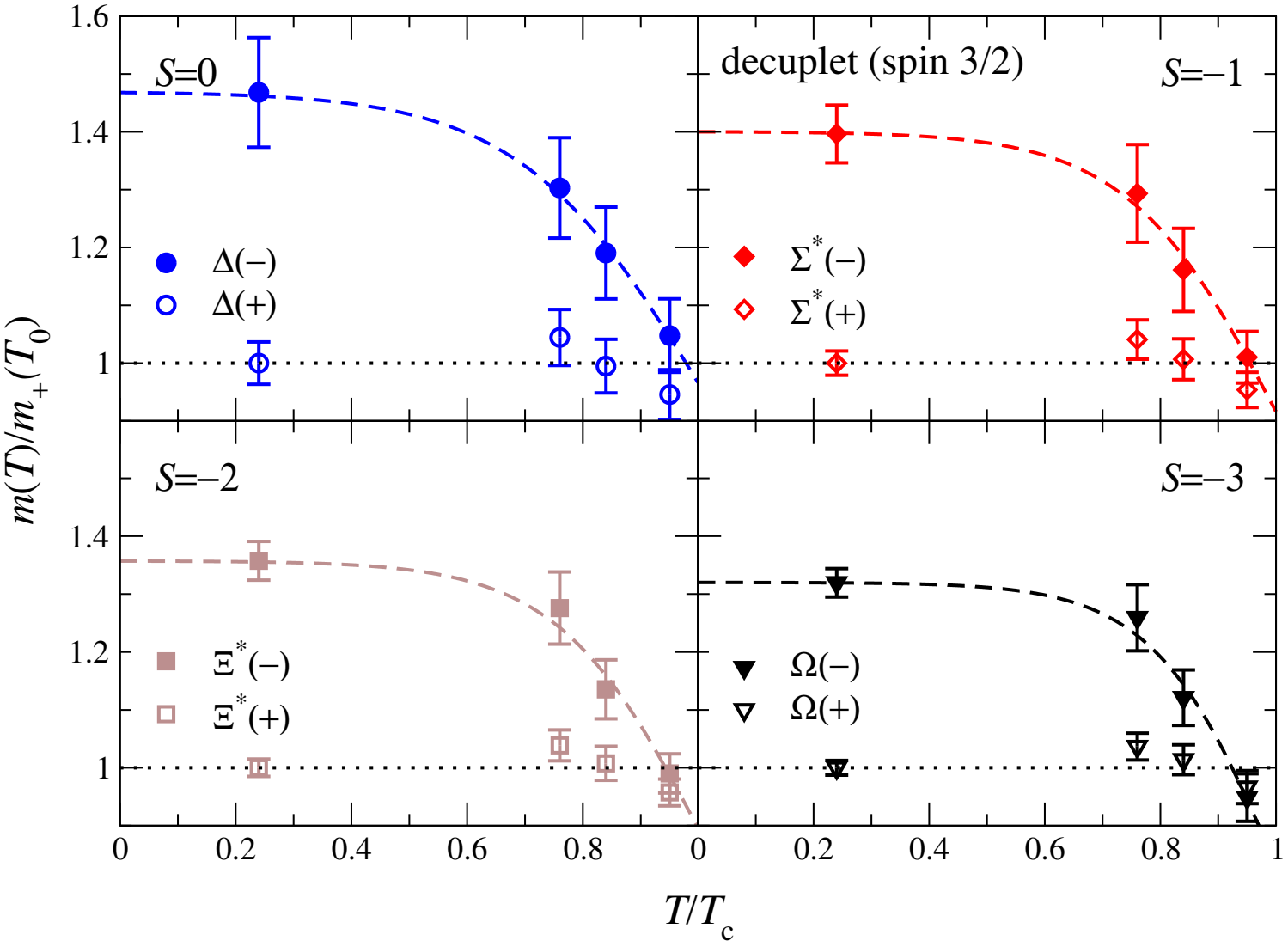
- $2M_\odot$ with chirally restored but confined core
- High-mass stars $\rightarrow$ not necessarily signal of deconfinement
- Parity doubling $\rightarrow$ modification of direct URCA threshold
  - new estimate for the proton fraction threshold
  - impact on neutron star cooling
- Phase diagram with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

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)



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)

$$\mathcal{L} = \mathcal{L}_N + \mathcal{L}_M + \sum_{k=1,2} g_k \bar{\psi}_k \left(\sigma \pm i\gamma_5 \boldsymbol{\tau} \cdot \boldsymbol{\pi} \right) \psi_k - g_\omega \bar{\psi}_k \not{\omega} \psi_k$$

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

Full HQMN model Lagrangian

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

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

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

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

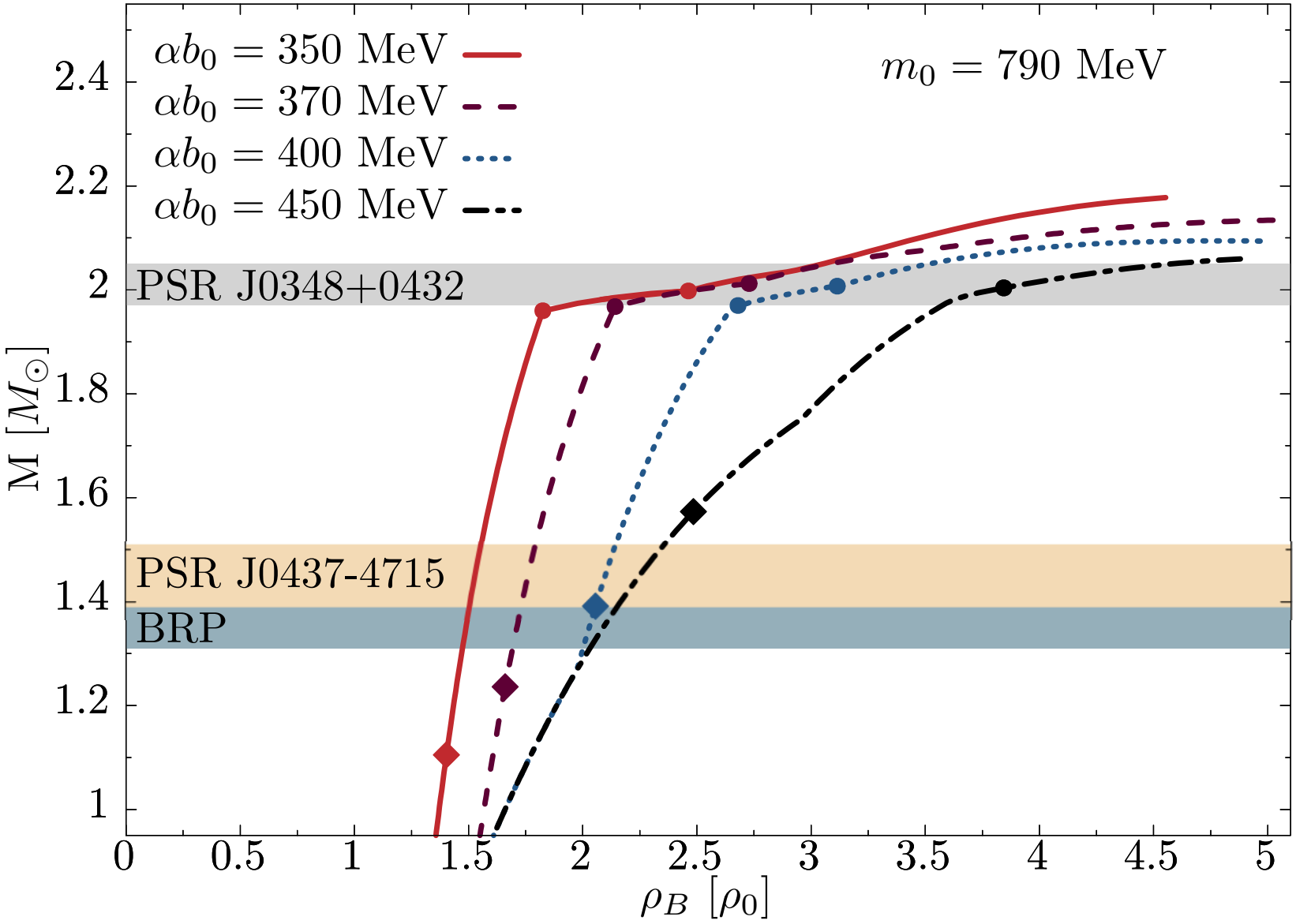
$$\mathcal{L}_M = \frac{1}{2}(\partial_\mu \sigma)^2 + \frac{1}{2}(\partial_\mu \boldsymbol{\pi})^2 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - V_\sigma - V_\omega - V_b$$

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

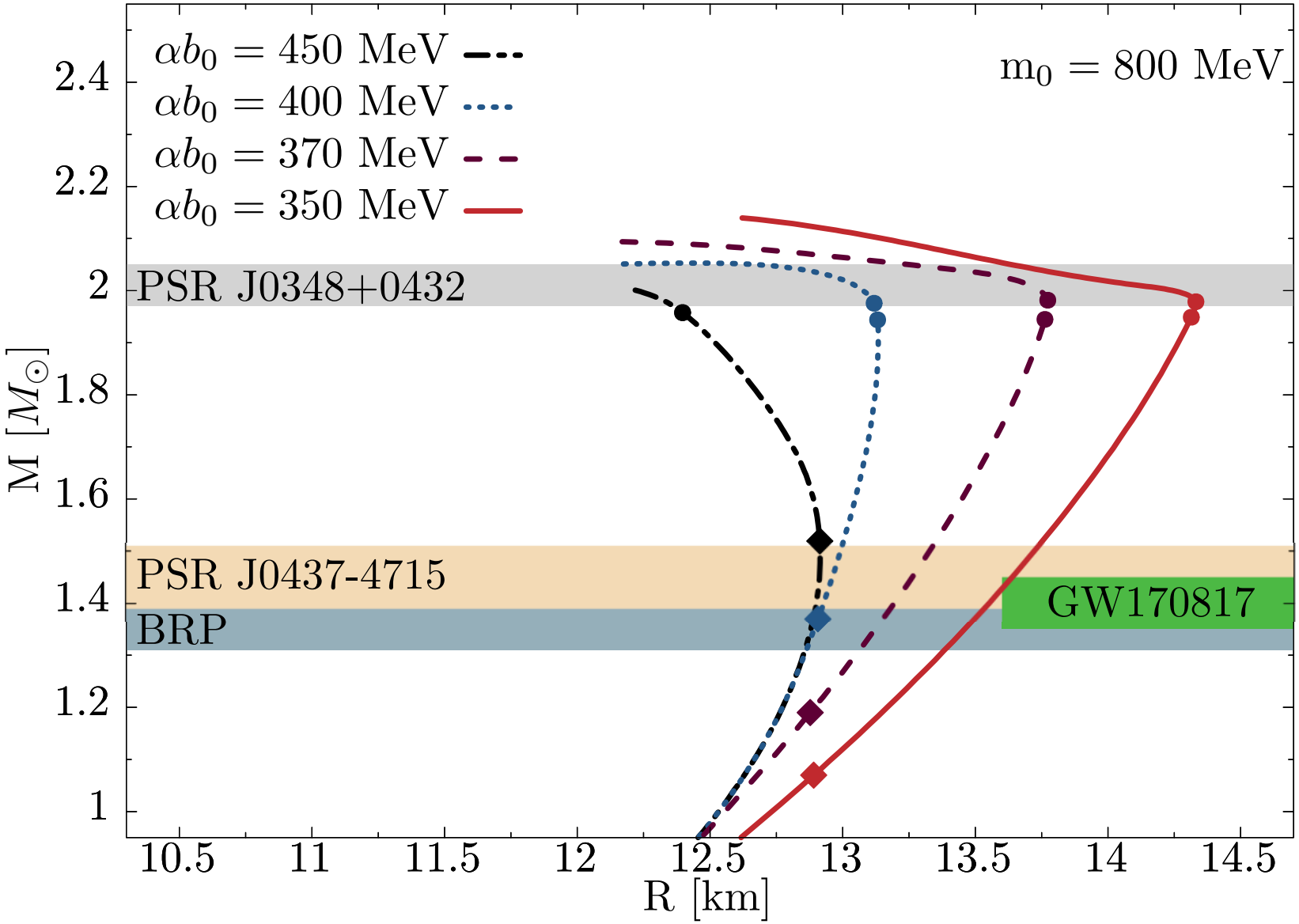
$$V_\omega = -\frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu$$

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

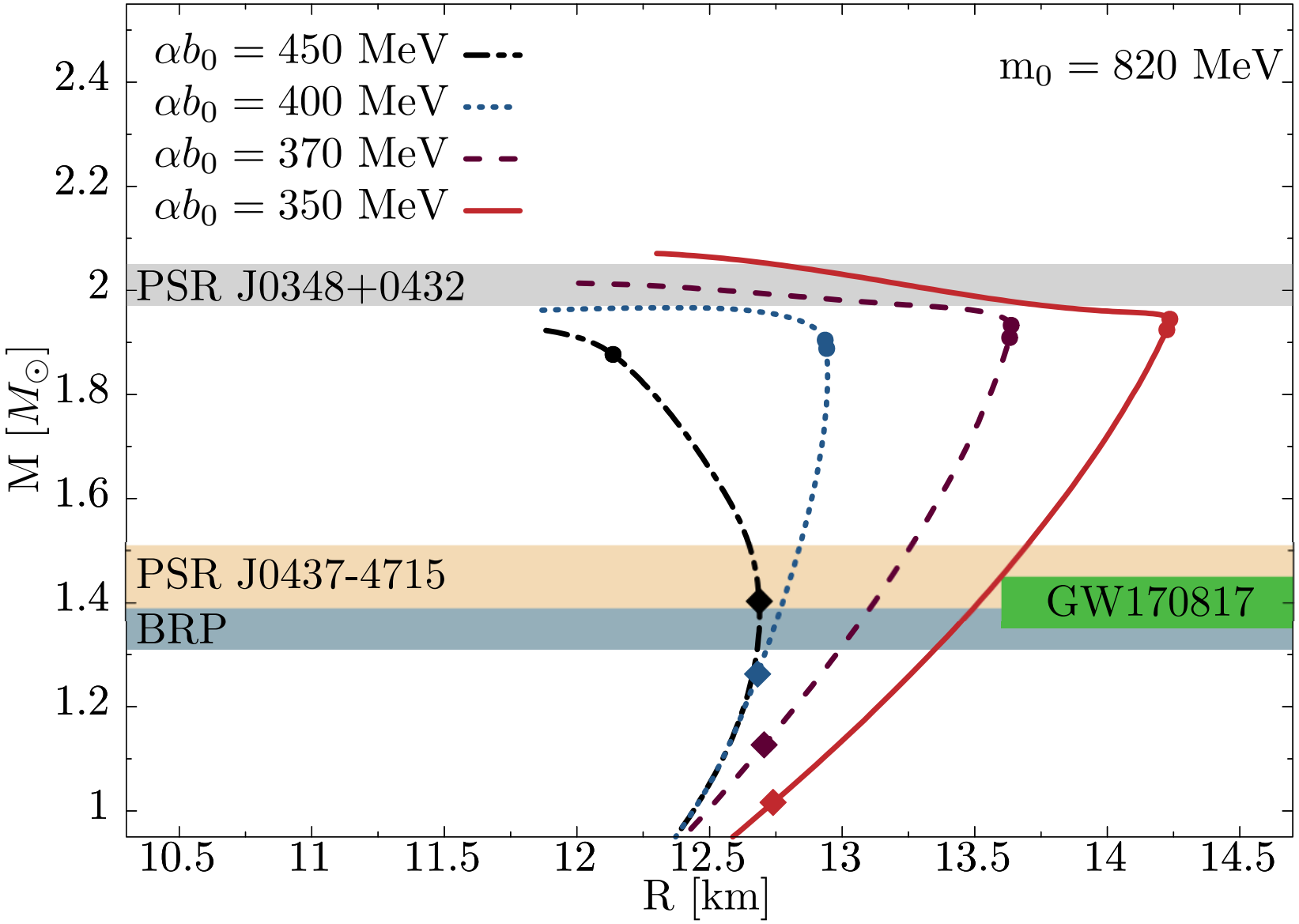
mass-density



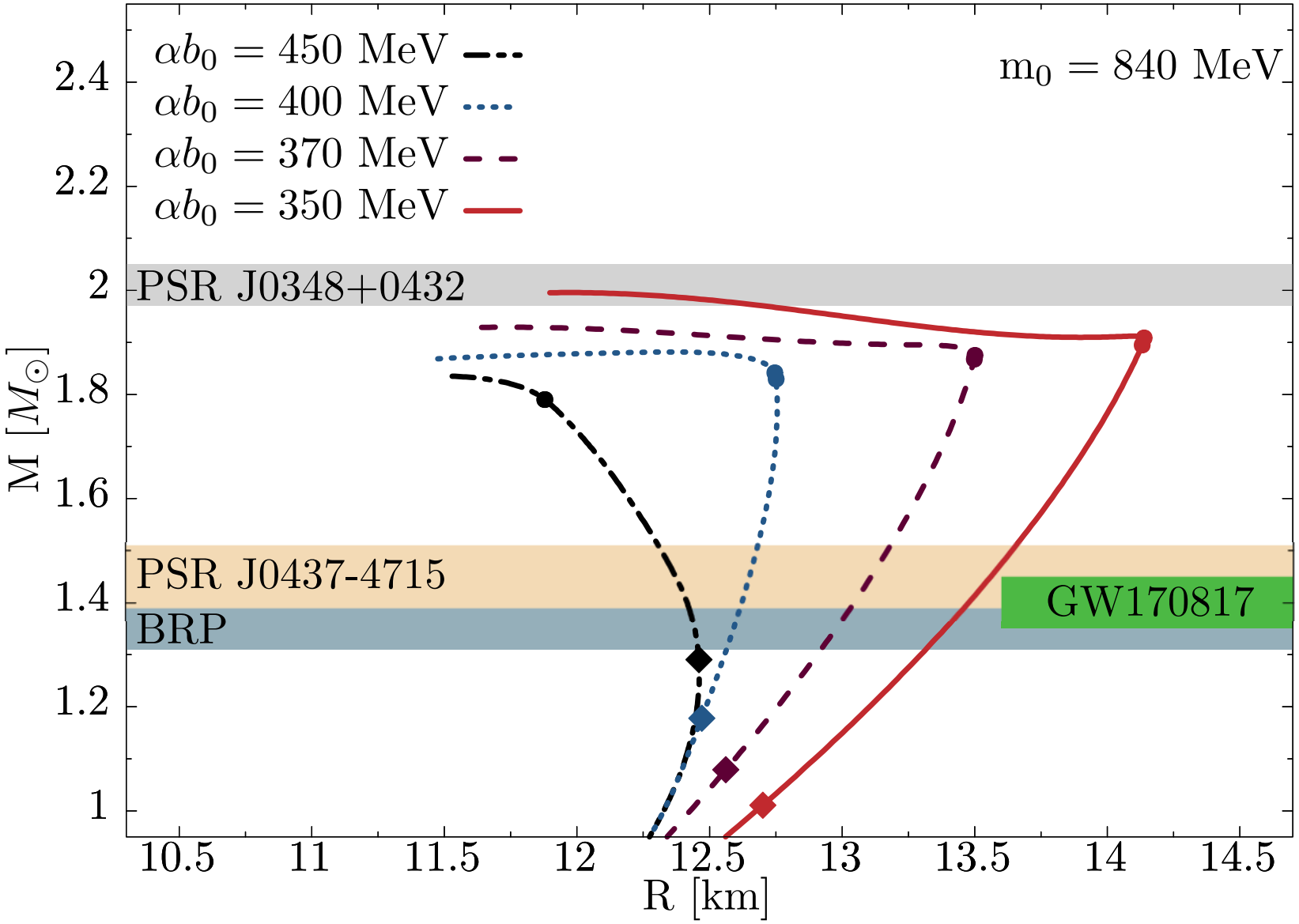
mass-radius


$\alpha b_0 = 450$ MeV
$\alpha b_0 = 400$ MeV
$\alpha b_0 = 370$ MeV
$\alpha b_0 = 350$ 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

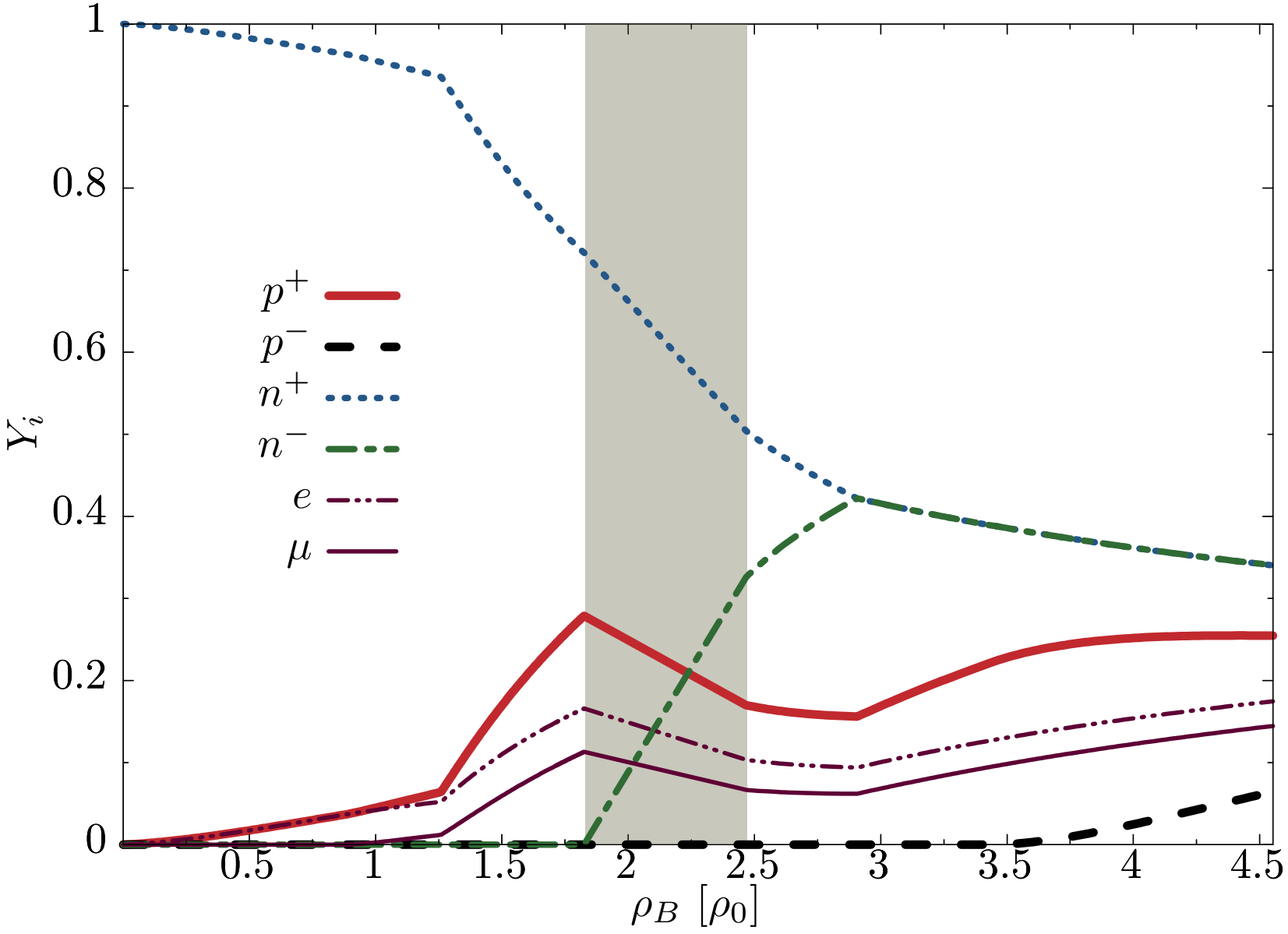
mass-radius


$\alpha b_0 = 450$ MeV
$\alpha b_0 = 400$ MeV
$\alpha b_0 = 370$ MeV
$\alpha b_0 = 350$ MeV
$m_0 = 820$ 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

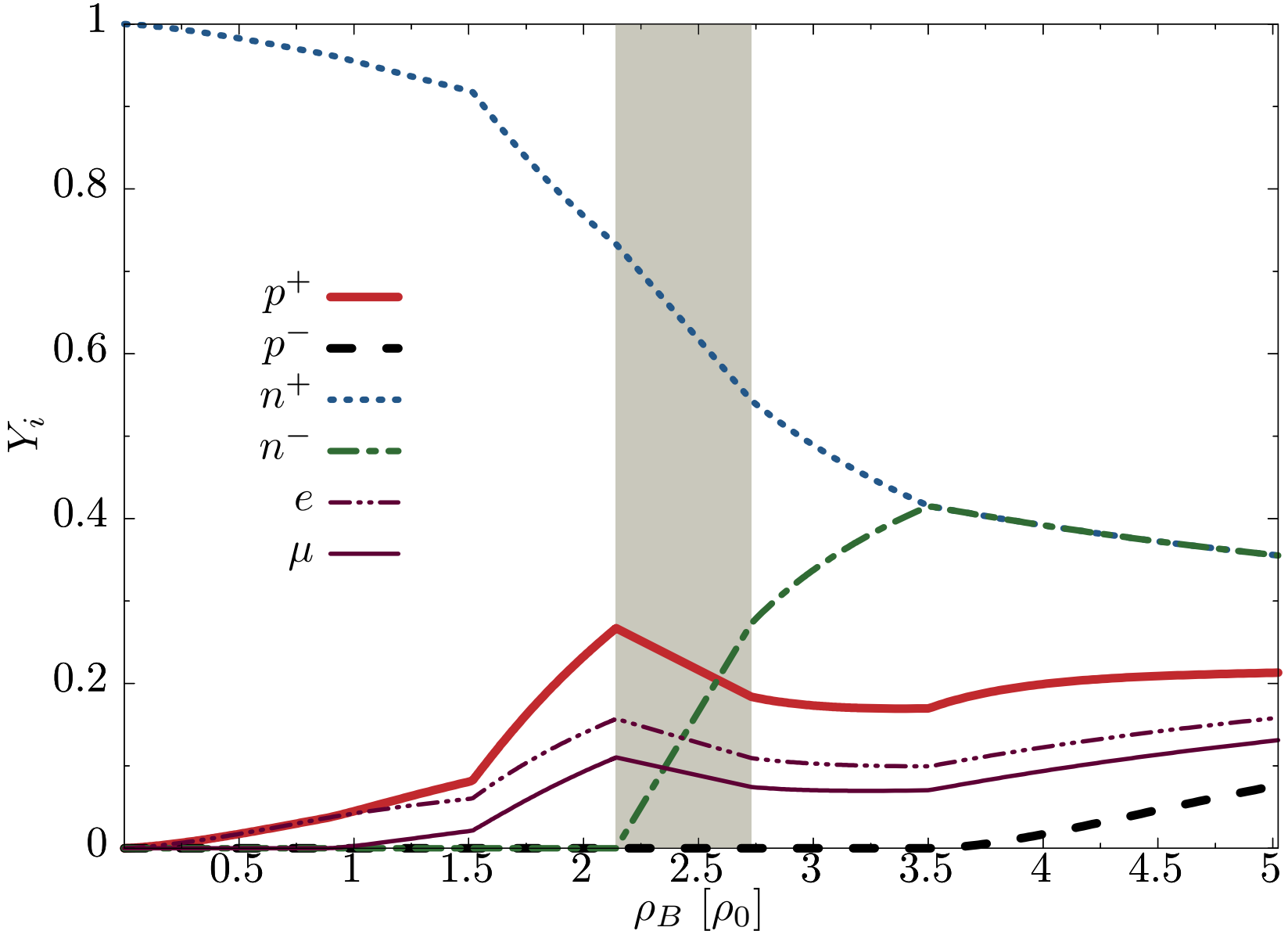
mass-radius


$\alpha b_0 = 450$ MeV
$\alpha b_0 = 400$ MeV
$\alpha b_0 = 370$ MeV
$\alpha b_0 = 350$ 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

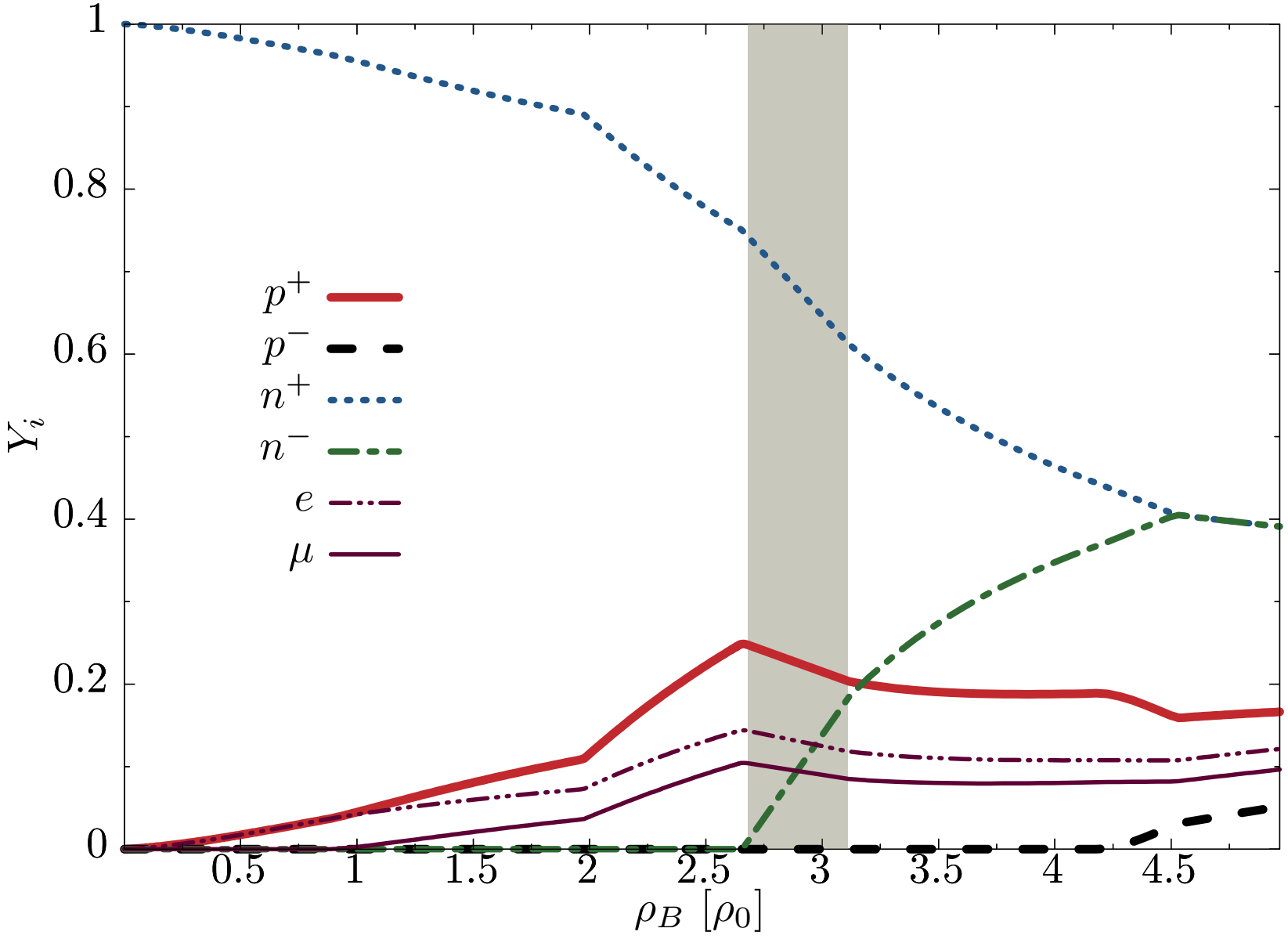
Matter composition ($\alpha b_0 = 350$ MeV)



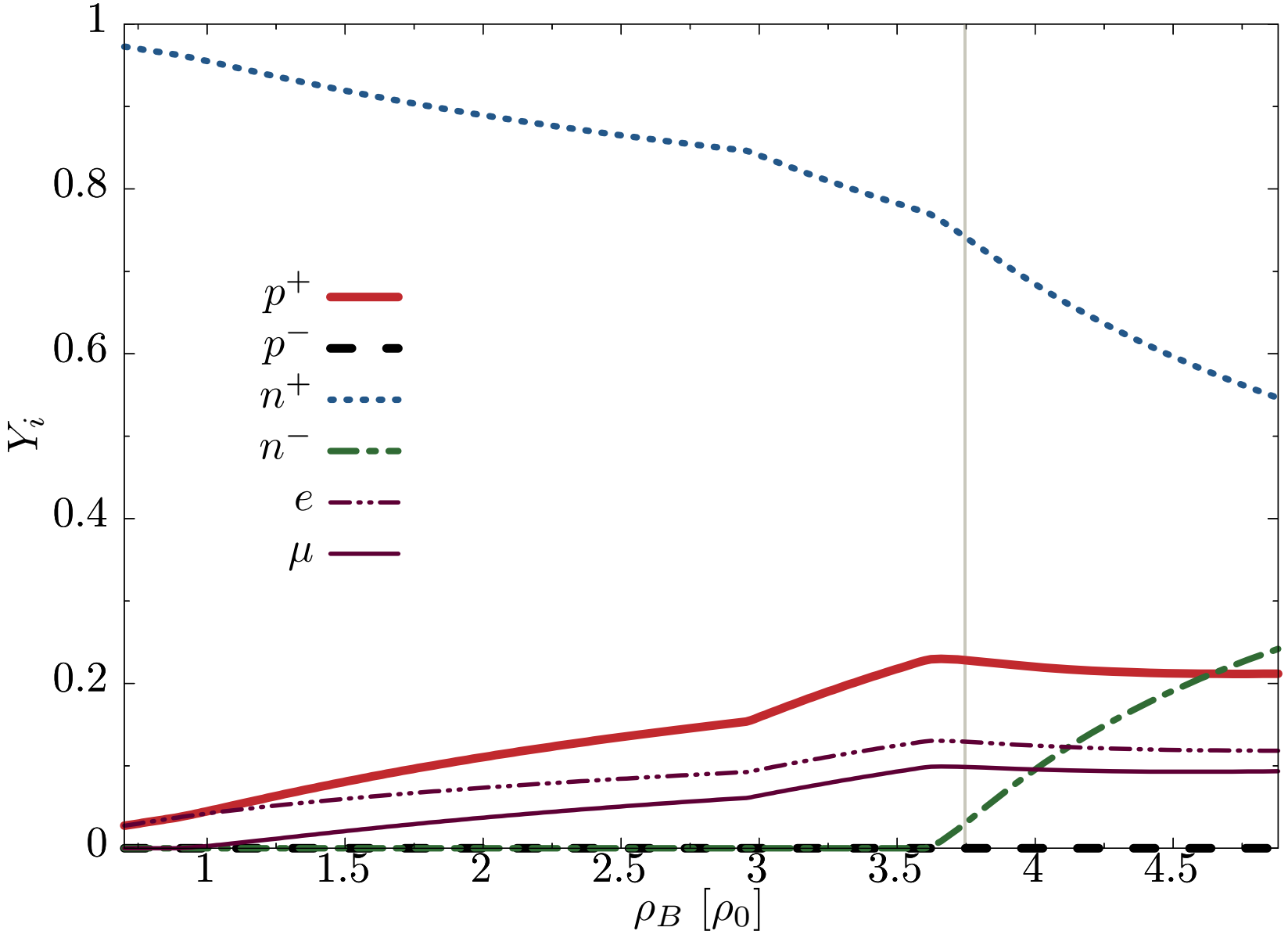
Matter composition ($\alpha b_0 = 370$ MeV)



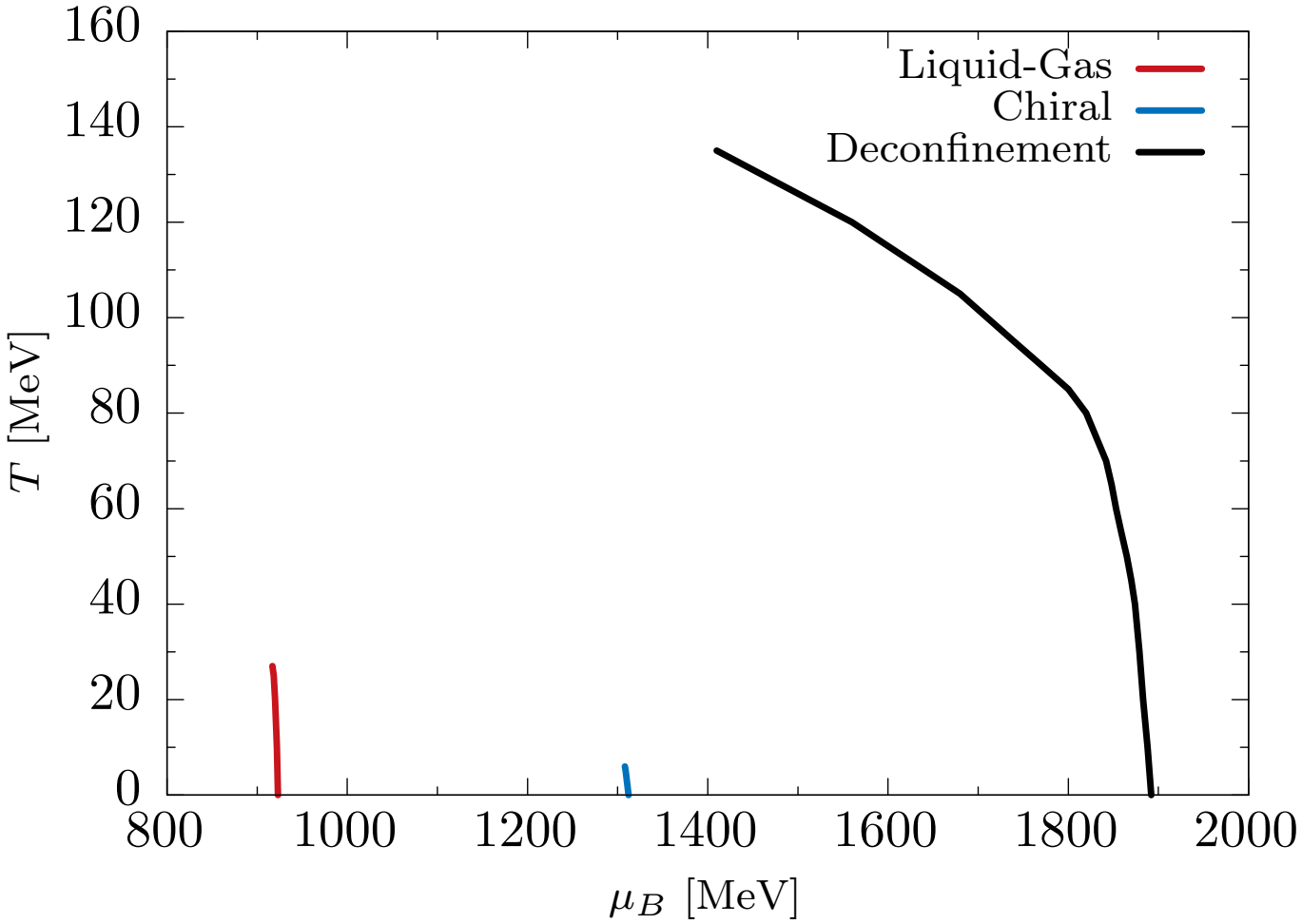
Matter composition ($\alpha b_0 = 400$ MeV)



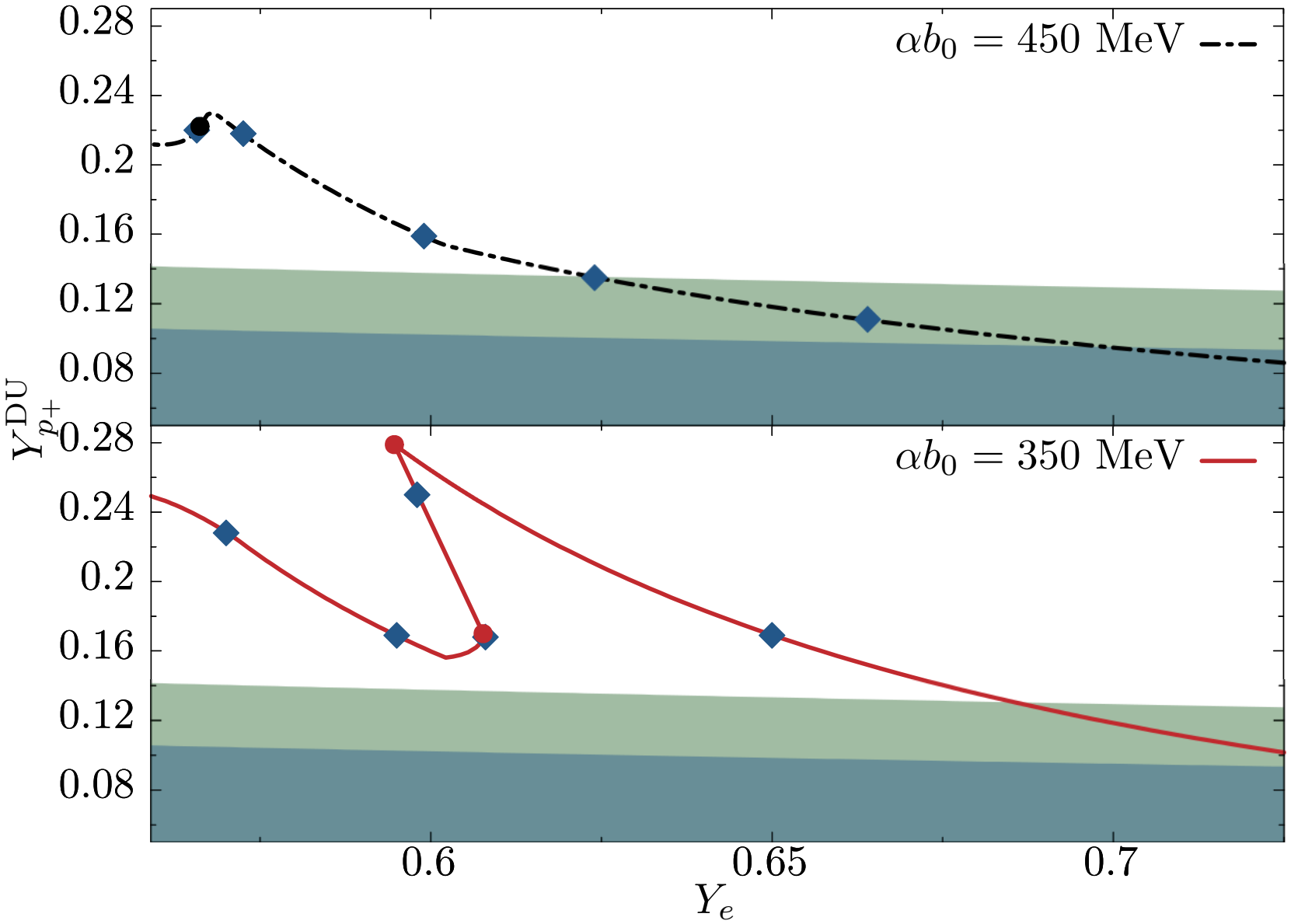
Matter composition ($\alpha b_0 = 450$ MeV)



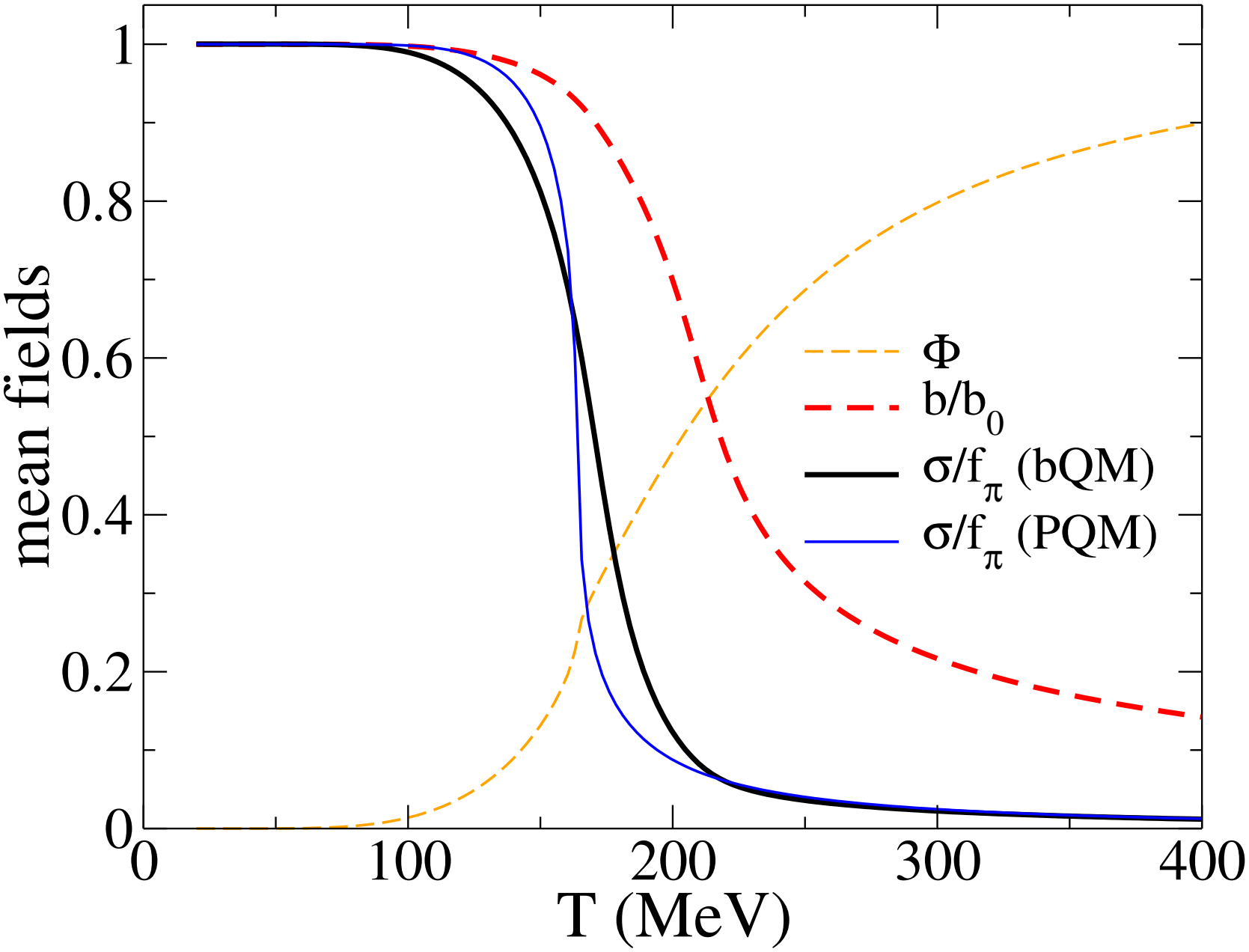
Phase diagram in $(T - \mu_B)$-plane ($\alpha b_0 = 310$ MeV)



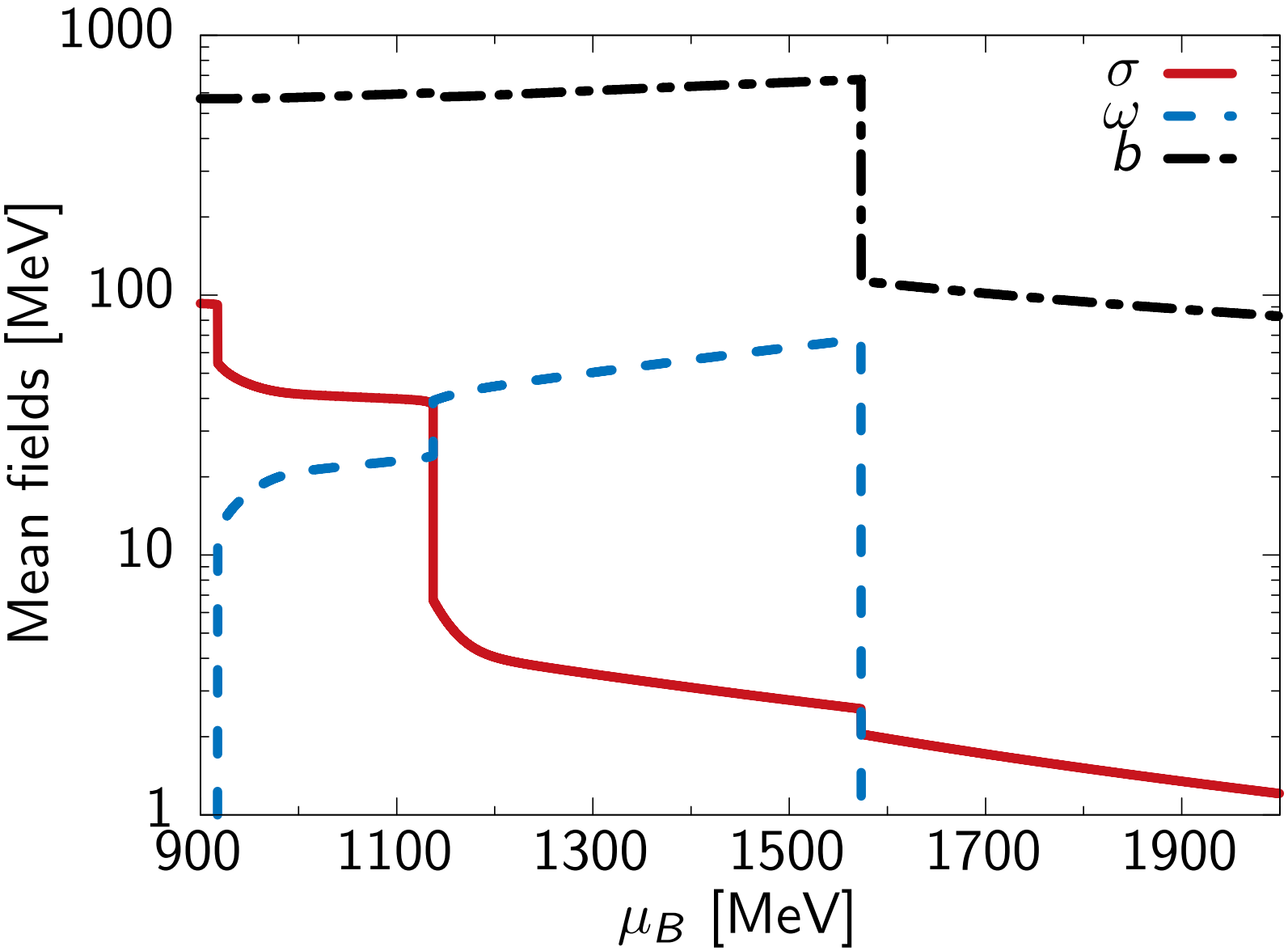
Threshold for direct URCA



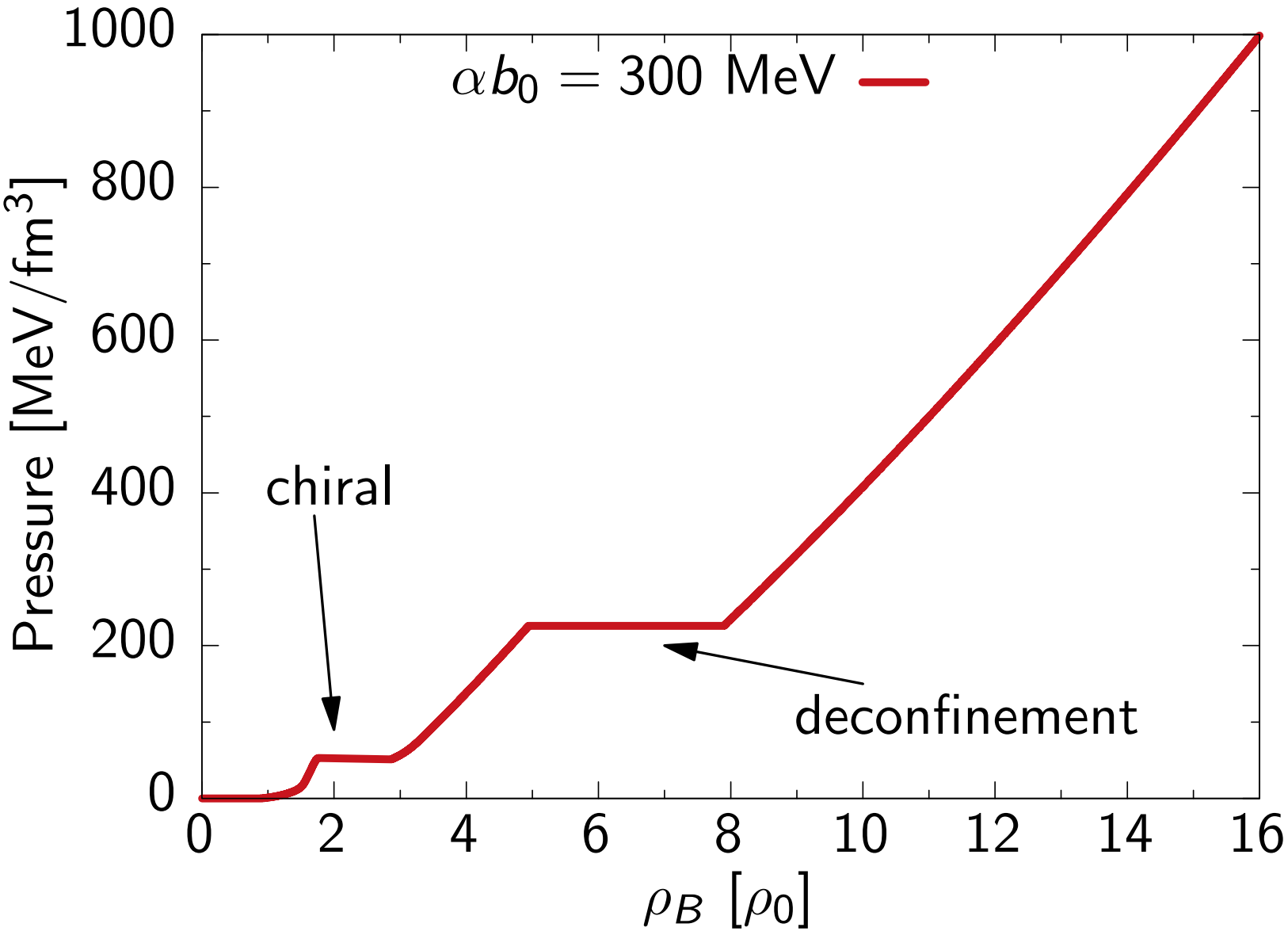
bQM vs PQM Benić *et al*, Phys. Rev. D **91**, 125034 (2015)



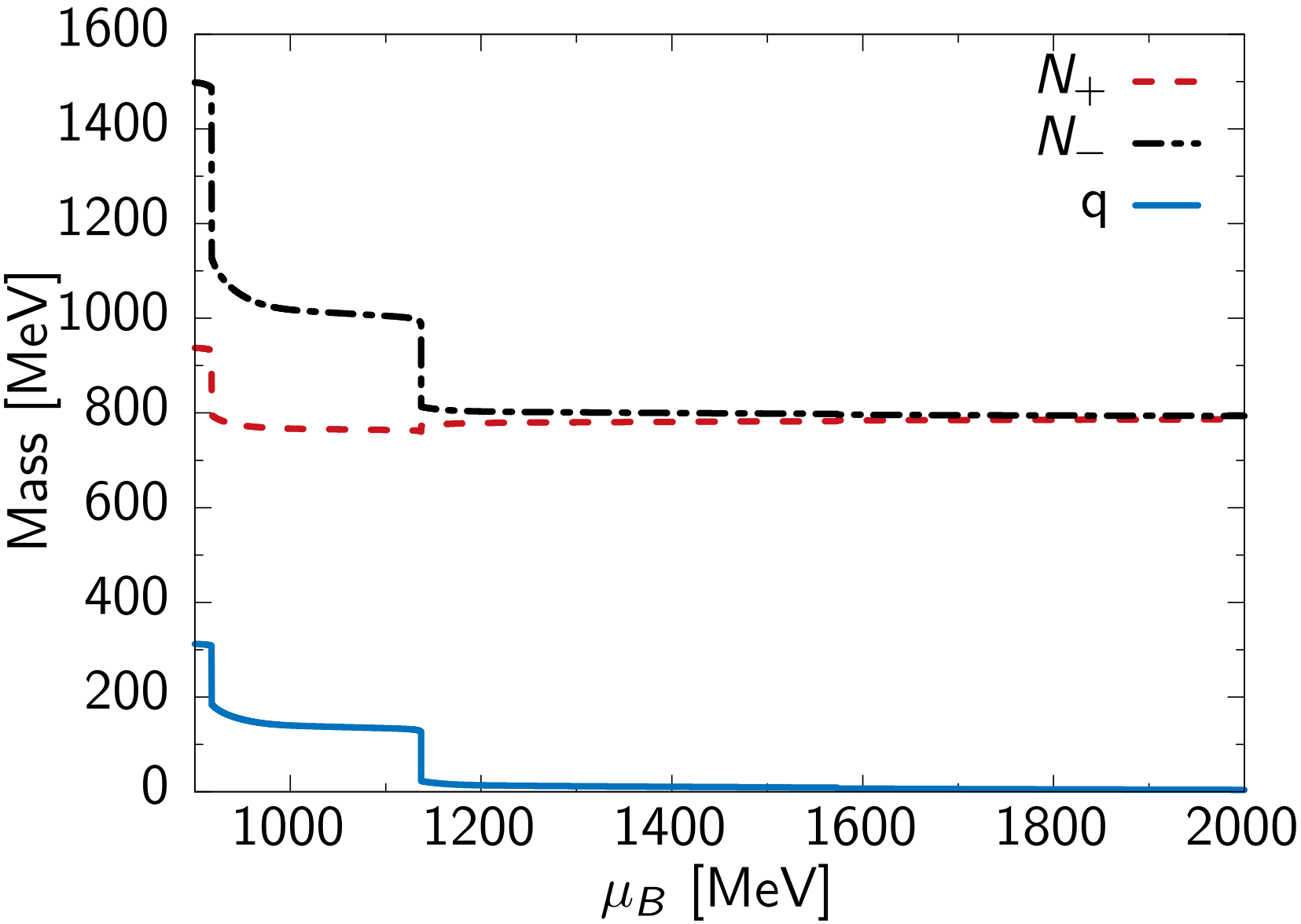
Mean fields at $T = 10$ MeV ($\alpha b_0 = 300$ MeV)



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)