Net-baryon number fluctuations in the quark-meson-nucleon model at finite density

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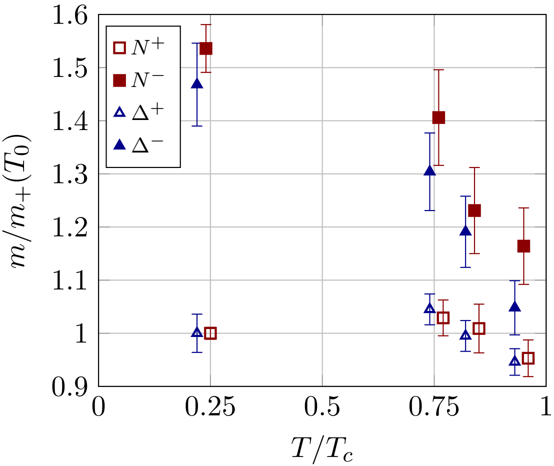
Outline

1. Description of cold and dense QCD matter
   - Parity doublet model
   - Hybrid quark-meson-nucleon model
2. Results
   - Equation of state and model phase diagram
   - Net-baryon number fluctuations
3. First astrophysical applications
   - Repulsion in quark sector
   - $M - R$ relation in symmetric matter
4. Conclusions

Parity doubling in $N_f = 2 + 1$ LQCD Aarts *et al*, JHEP **1706**, 034 (2017)



Despite unphysical $m_\pi \approx 384$ MeV and $T_c \approx 185$ MeV:

- Imprint of chiral symmetry restoration
- Signature of parity-doublet structure

Realization 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

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

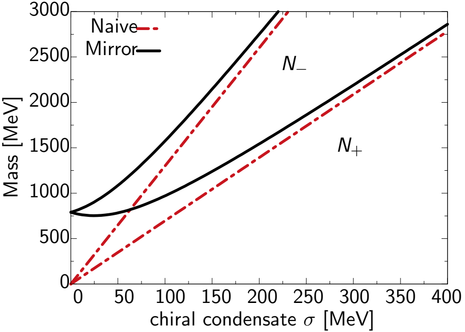
$$\mathcal{L} = \mathcal{L}_N + \sum_{k=1,2} g_k \bar{\psi}_k \left(\sigma \pm i\gamma_5 \boldsymbol{\tau} \cdot \boldsymbol{\pi} \right) \psi_k - g_\omega \bar{\psi}_k \omega\!\!\!/ \psi_k + \mathcal{L}_M$$

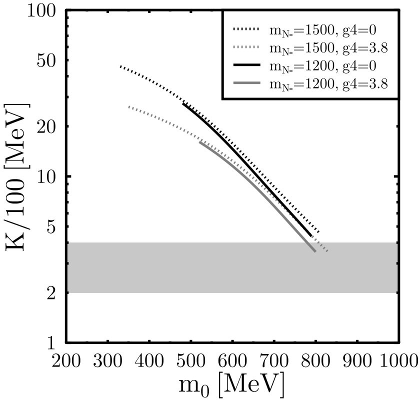
  - Fermions coupled to bosons: σ, π, ω
  - $\mathcal{L}_M \to$ Linear σ-model

Parity doublet mass structure: $(\psi_1, \psi_2) \rightarrow (N_+, N_-)$

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

- particle identification: $N_+ \rightarrow N(939)$, $N_- \rightarrow N(1535)$
- high $m_0 \sim 790$ MeV favored by incompressibility and LQCD





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

Hybrid quark-meson-nucleon model
Benić *et al*, Phys. Rev. D **91**, 125034 (2015)

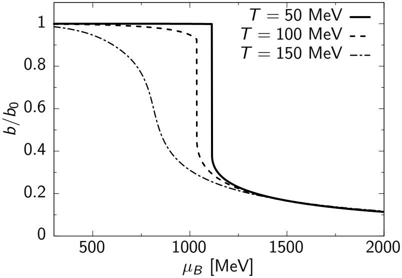
Parity doublet model + quark-meson coupling

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

Statistical confinement:

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

- α - new model parameter (to be studied here)



- 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

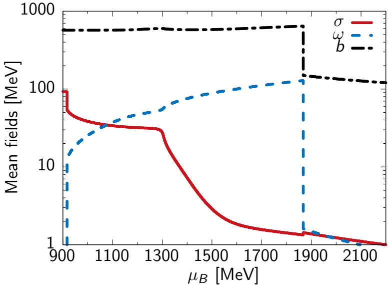
$b(\mu_B \to \infty) = 0$ favors quarks

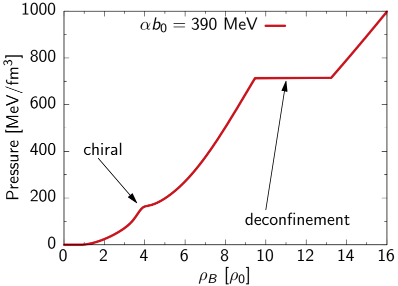
Results at $T = 10$ MeV ($\alpha b_0 = 390$ MeV)

- Mean field approximation $\rightarrow$ gap equations

$$\frac{\partial\Omega}{\partial\sigma} = \frac{\partial\Omega}{\partial\omega} = \frac{\partial\Omega}{\partial b} = 0$$

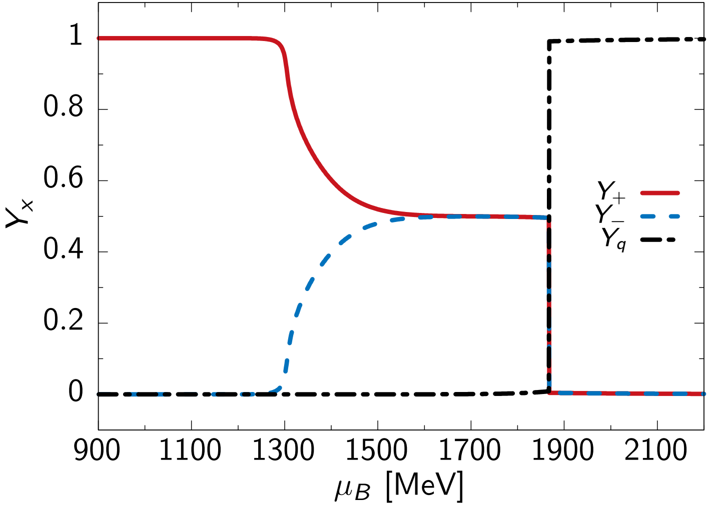
- Fixed to the nuclear groundstate properties at $T = 0$:
  - Binding energy: $E/A - m_+ = -16$ MeV
  - Saturation density: $\rho_0 = 0.16\ \text{fm}^{-3}$





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

$$Y_x = \frac{\rho_x}{\rho_+ + \rho_- + \rho_q}$$

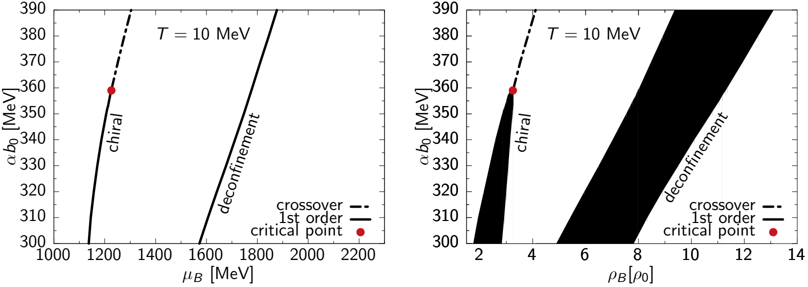


Model phase diagram at $T = 10$ MeV

- Order of chiral transition (from low to high α)

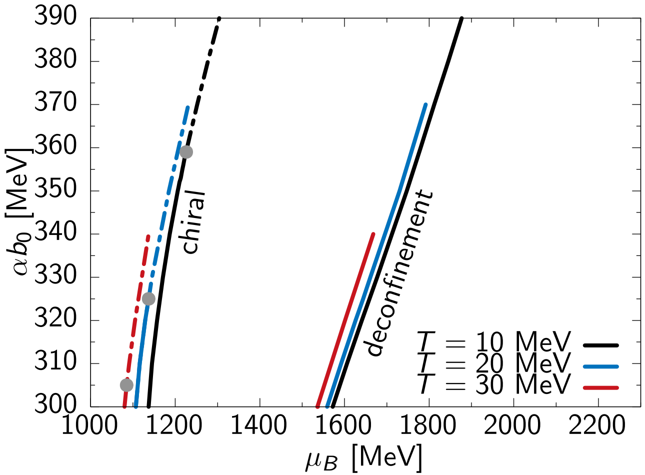
$$\text{1st order} \rightarrow \textcolor{red}{\text{Critical Point}} \rightarrow \text{crossover}$$

- Deconfinement always of 1st order (by the choice of V_b)
- high m_0 → separated transitions (may coincide for smaller m_0)



Model phase diagram at higher temperatures

- Thermal excitations → quarks appear before deconfinement
- Quark density $< 1\%$ of total density at deconfinement



Higher-order cumulants: χ_2 at $T = 10$ MeV

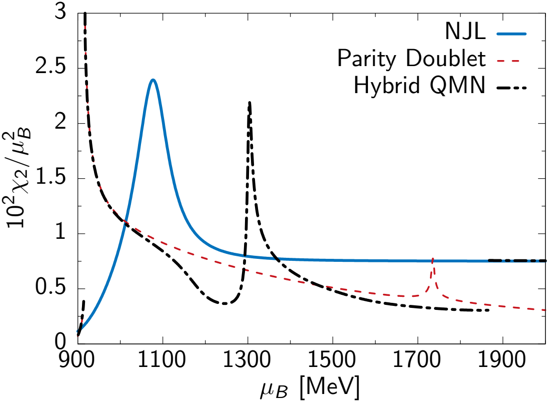
- Parity doublet: wrong asymptotics
- NJL: no confinement mechanism

HQMN resembles all these features

- Confinement mechanism **strengthens** chiral transition
- Higher-order cumulants **less sensitive** to deconfinement

Generalized susceptibilities

$$\chi_n = \frac{1}{\mu_B^{n-4}} \frac{\partial^n \Omega}{\partial \mu_B^n}$$



Higher-order cumulants: χ_3 at $T = 10$ MeV

- Parity doublet: wrong asymptotics
- NJL: no confinement mechanism

HQMN resembles all these features

- Confinement mechanism **strengthens** chiral transition
- Higher-order cumulants **less sensitive** to deconfinement

Generalized susceptibilities

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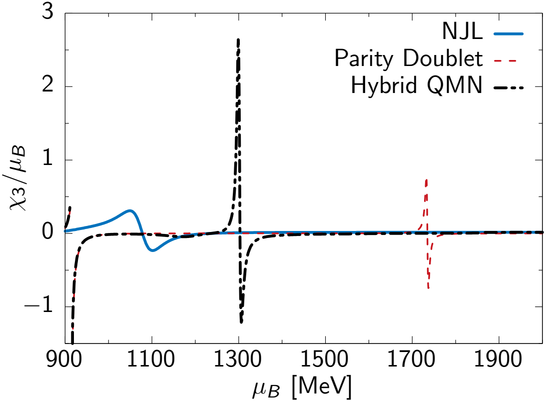


Higher-order cumulants: χ_4 at $T = 10$ MeV

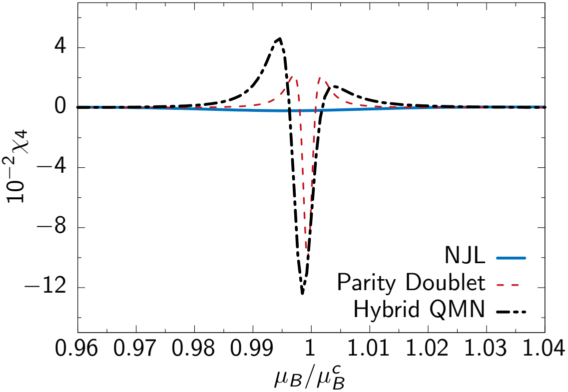
- Parity doublet: wrong asymptotics
- NJL: no confinement mechanism

HQMN resembles all these features

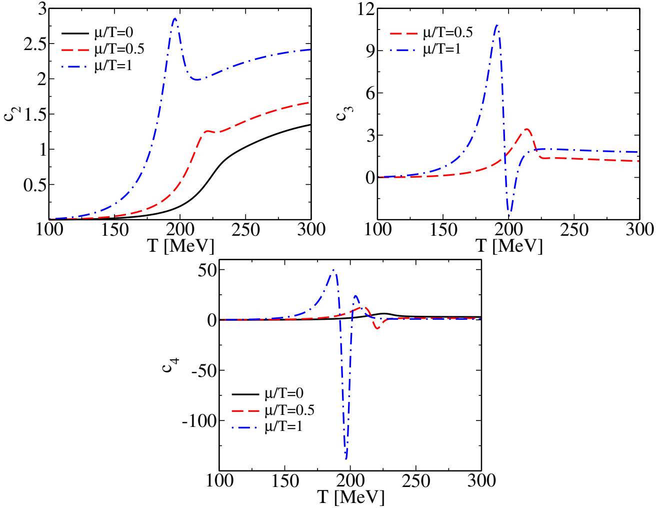
- Confinement mechanism **strengthens** chiral transition
- Higher-order cumulants **less sensitive** to deconfinement

Generalized susceptibilities

$$\chi_n = \frac{1}{\mu_B^{n-4}} \frac{\partial^n \Omega}{\partial \mu_B^n}$$

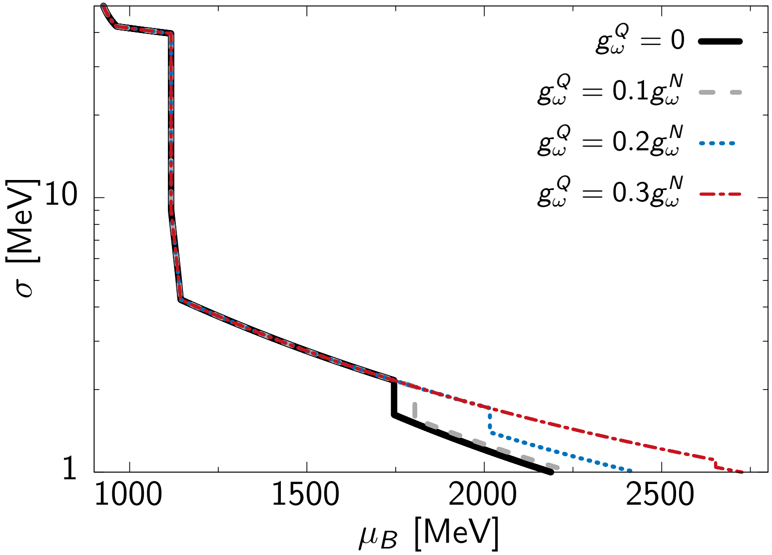


Higher-order cumulants in pQM model

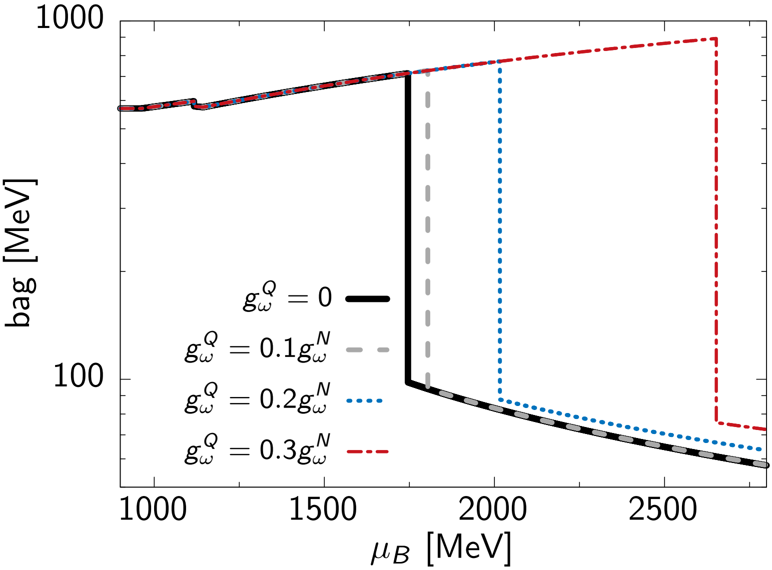


Skokov *et al*, Phys. Rev. D **83** 054904 (2011)

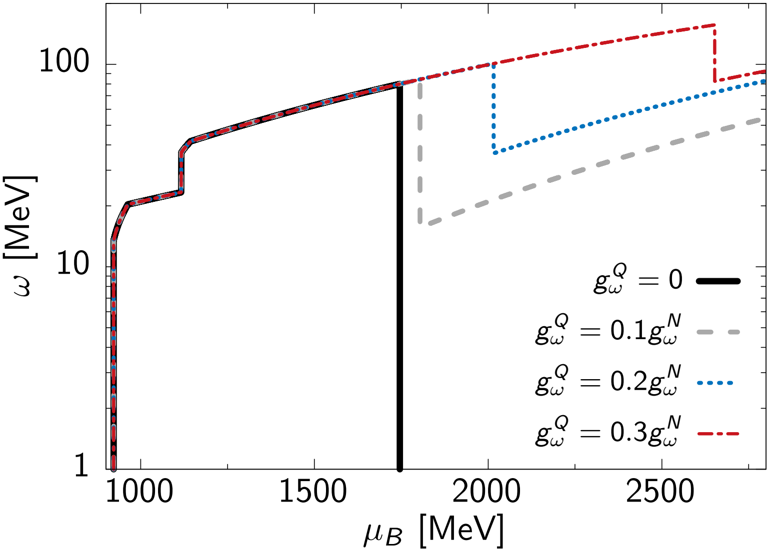
Mean Fields ($\alpha b_0 = 300$ MeV)



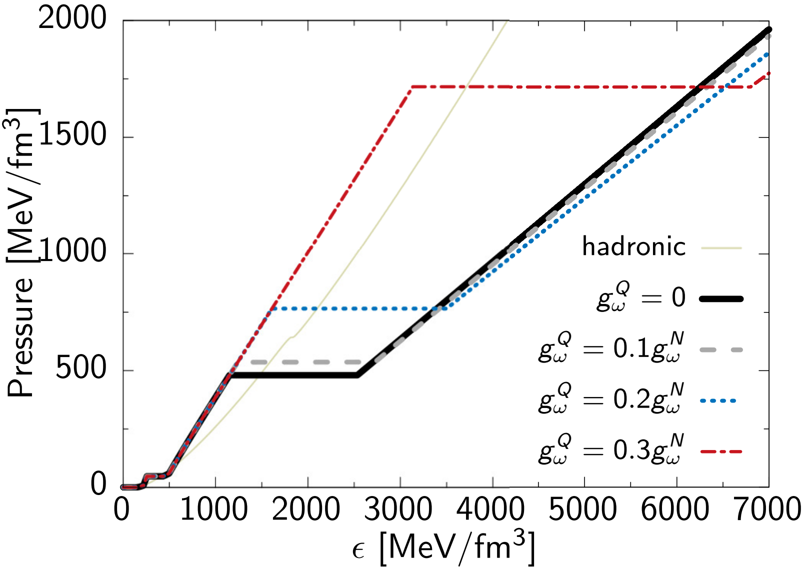
Mean Fields ($\alpha b_0 = 300$ MeV)



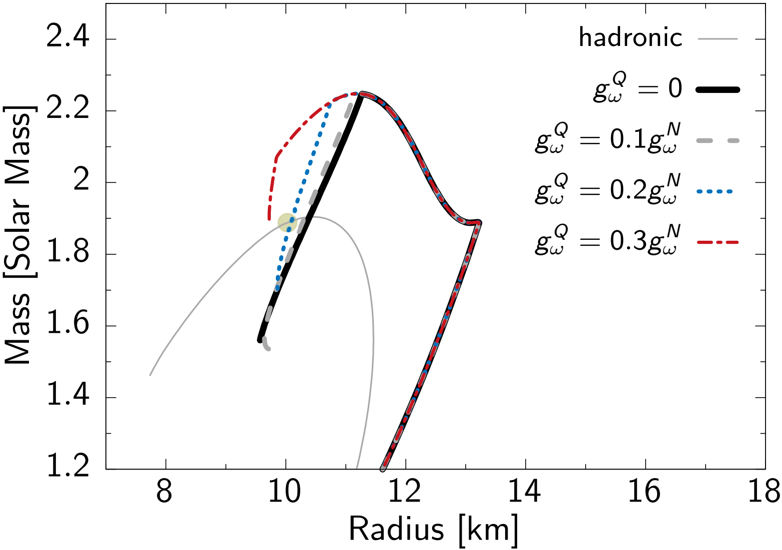
Mean Fields ($\alpha b_0 = 300$ MeV)



EoS ($\alpha b_0 = 300$ MeV)



$M - R$ relation ($\alpha b_0 = 300$ MeV)



Conclusions

Hybrid QMN model offers a unified approach to cold and dense QCD matter:

- Statistical confinement $\rightarrow$ **strengthened** chiral transition
- Higher-order cumulants rather **insensitive** to deconfinement
  - Influence of different potentials $\rightarrow$ crossover transition
  - connection to a symmetry of QCD

Future perspectives:

- Extension to higher temperatures
- Extenstion to $2 + 1$ flavor
- Beyond-mean-field calculations

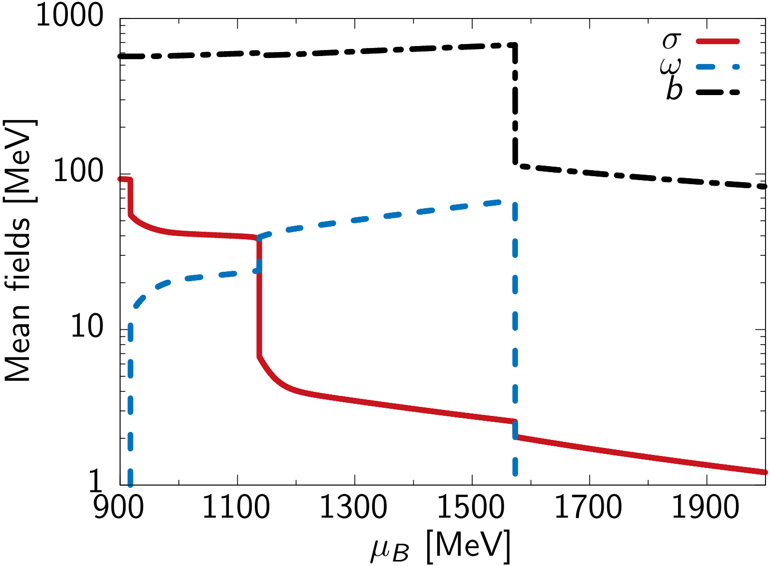
Thank you for your attention

Full HQMN model Lagrangian

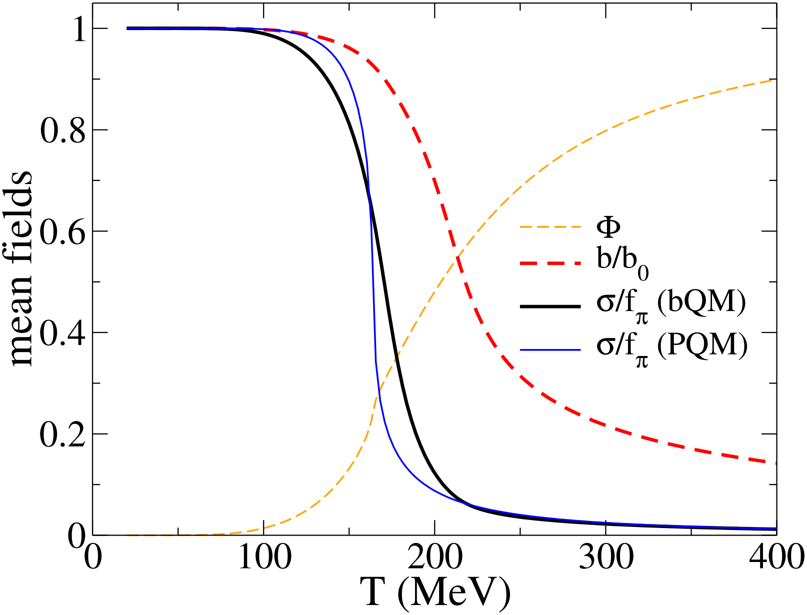
- $\mathcal{L} = \mathcal{L}_N + \mathcal{L}_M + \mathcal{L}_q$

$$\mathcal{L}_N = \sum_{k=1,2} \bar{\psi}_k i \partial\!\!\!/ \psi_k + m_0 \left(\bar{\psi}_2 \gamma_5 \psi_1 - \bar{\psi}_1 \gamma_5 \psi_2 \right)$$
$$+ \sum_{k=1,2} g_k \bar{\psi}_k \left(\sigma \pm i \gamma_5 \boldsymbol{\tau} \cdot \boldsymbol{\pi} \right) \psi_k - g_\omega \bar{\psi}_k \omega\!\!\!/ \psi_k$$
$$\mathcal{L}_q = \bar{q} i \partial\!\!\!/ q + g_q \bar{q} \left(\sigma + i \gamma_5 \boldsymbol{\tau} \cdot \boldsymbol{\pi} \right) q$$
$$\mathcal{L}_M = \frac{1}{2} (\partial_\mu \sigma)^2 + \frac{1}{2} (\partial_\mu \boldsymbol{\pi})^2 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - V_\sigma - V_\omega - V_b$$
$$V_\sigma = -\frac{1}{2} \bar{\mu}^2 \left(\sigma^2 + \boldsymbol{\pi}^2 \right) + \frac{\lambda}{4} (\sigma^2 + \boldsymbol{\pi}^2)^2 - \epsilon \sigma$$
$$V_\omega = -\frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu$$
$$V_b = -\frac{1}{2} \kappa_b^2 b^2 + \frac{1}{4} \lambda_b b^4$$

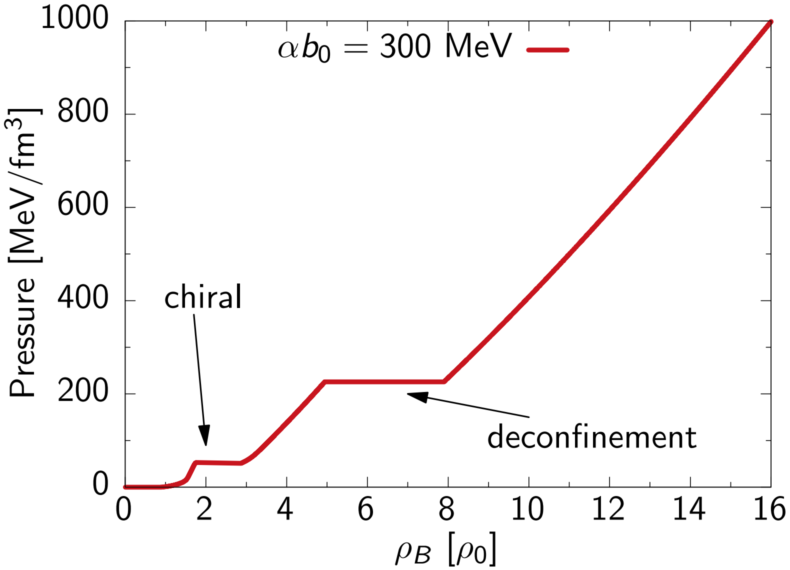
Mean fields at $T = 10$ MeV ($\alpha b_0 = 300$ MeV)



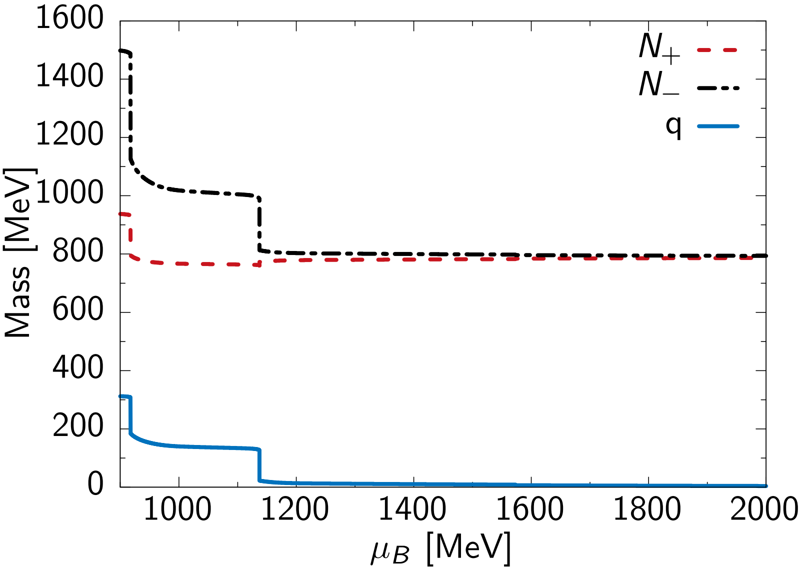
bQM vs PQM Benić *et al*, Phys. Rev. D **91**, 125034 (2015)



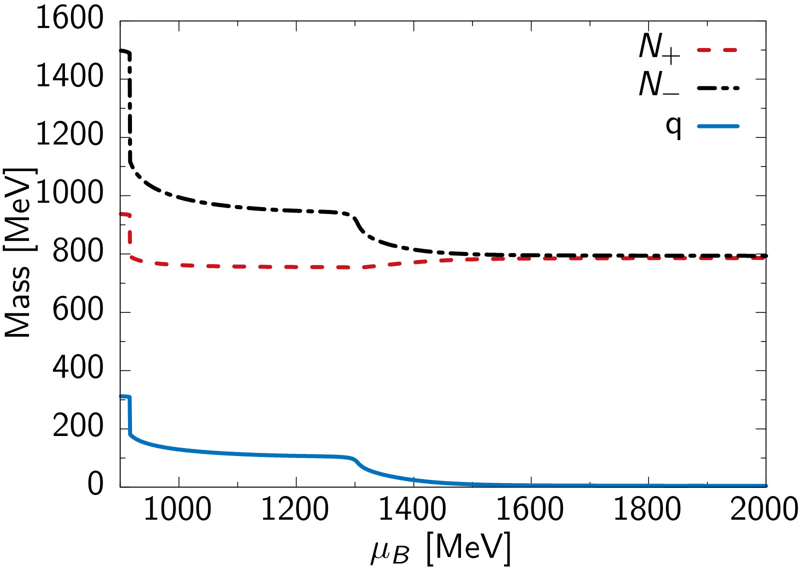
Equation of state at $T = 10$ MeV ($\alpha b_0 = 300$ MeV)



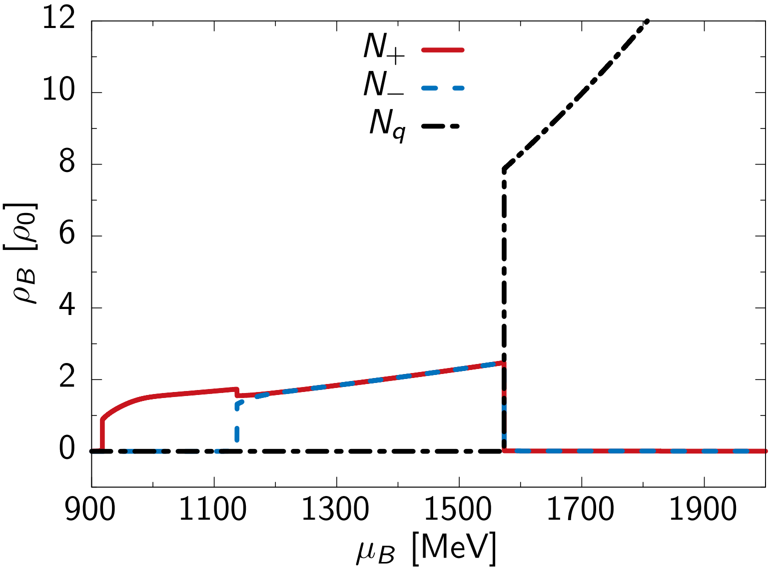
Masses at $T = 10$ MeV ($\alpha b_0 = 300$ MeV)



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



Net-baryon density at $T = 10$ MeV ($\alpha b_0 = 300$ MeV)



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

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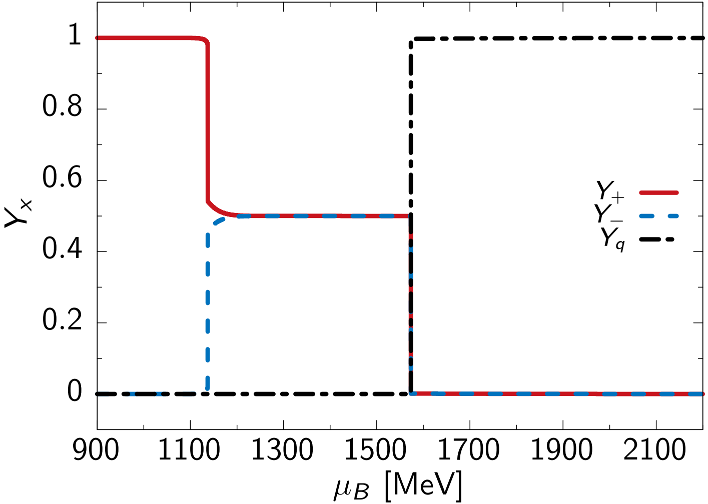
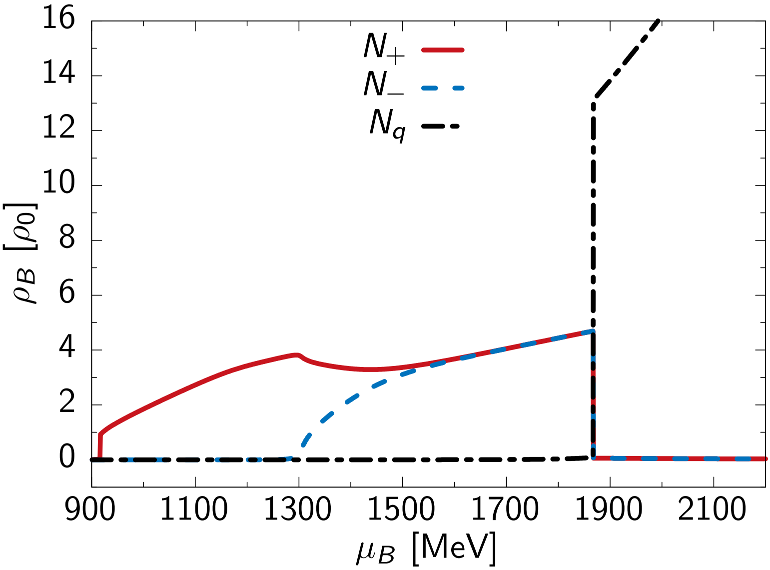
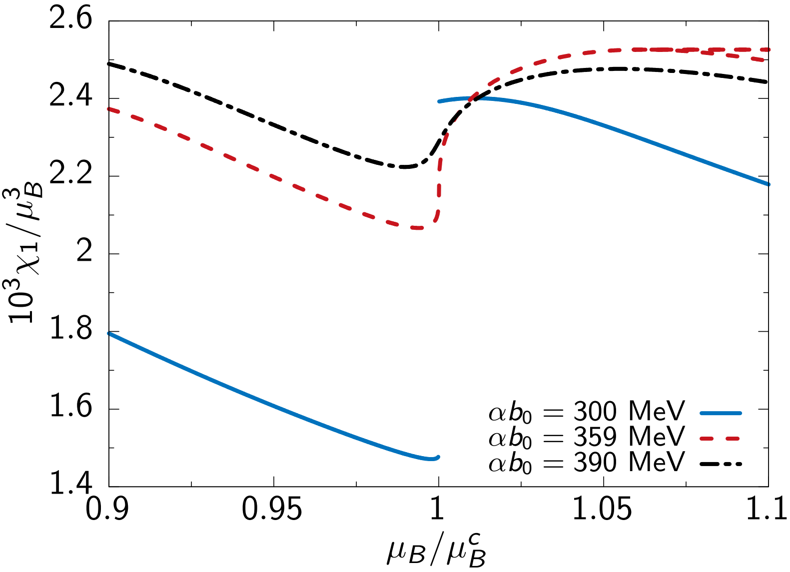


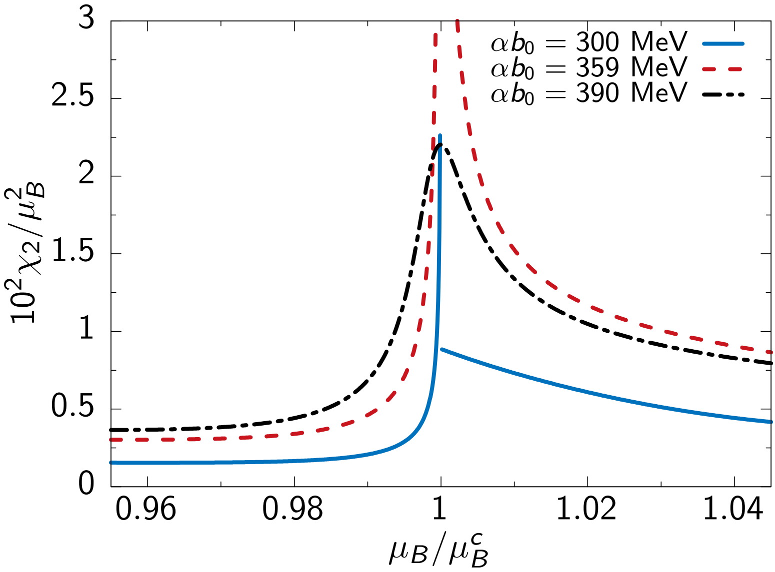
Net-baryon density at $T = 10$ MeV ($\alpha b_0 = 390$ MeV)



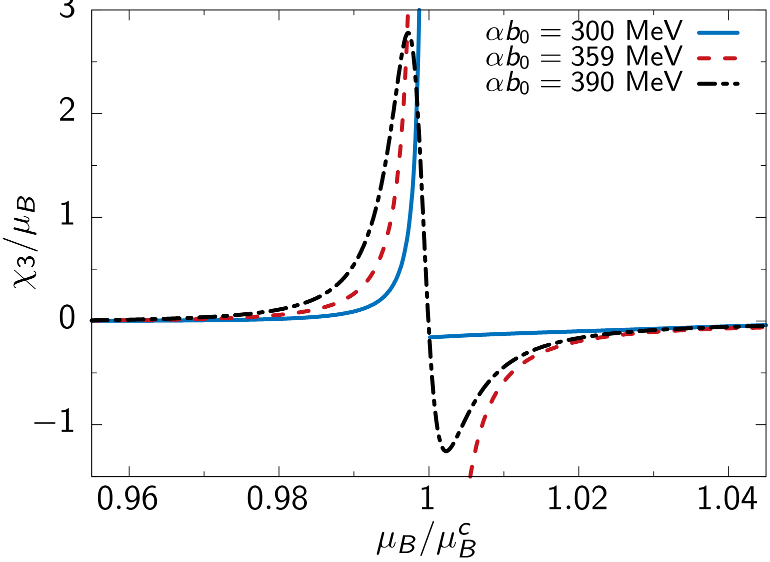
Net-baryon density at $T = 10$ MeV



Second-order cumulant at $T = 10$ MeV



Third-order cumulant at $T = 10$ MeV



Fourth-order cumulant at $T = 10$ MeV