

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

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arXiv:1711.05521 [hep-ph]

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# Outline

## 1 Description of cold and dense QCD matter

- Hadronic parity doublet model
- Hybrid quark-meson-nucleon model

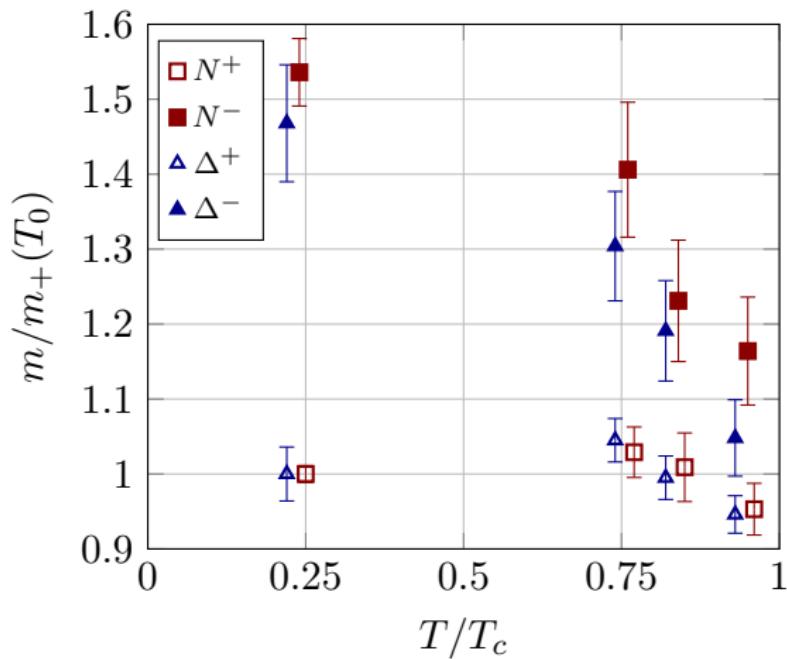
## 2 Results

- Equation of state and model phase diagram
- Net-baryon number fluctuations

## 3 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  $SU(2)_L \times SU(2)_R$

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

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

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

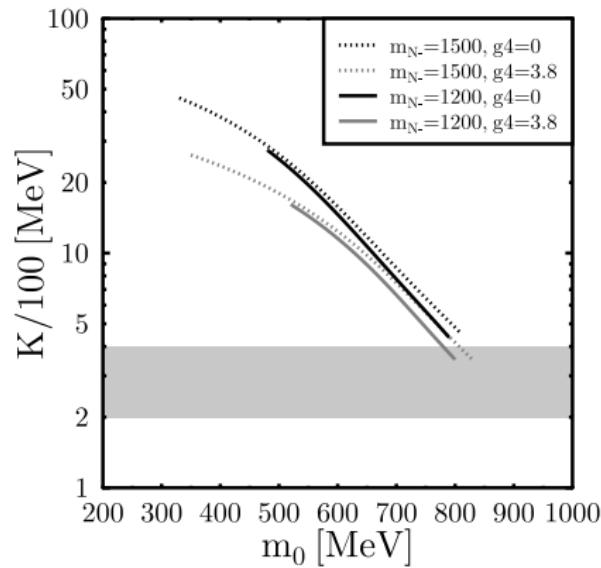
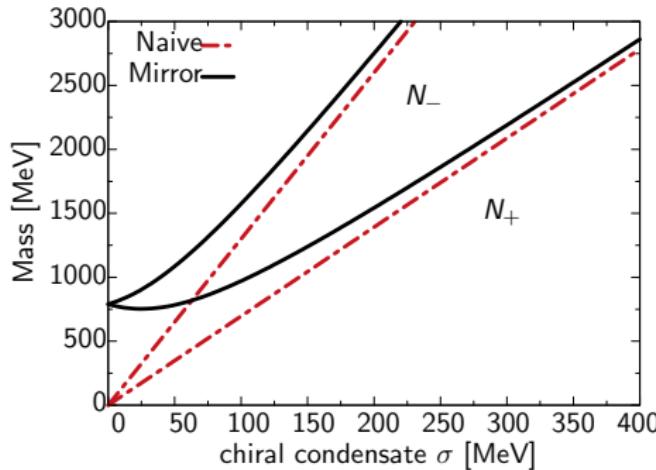
$$\mathcal{L} = \mathcal{L}_N + \sum_{k=1,2} g_k \bar{\psi}_k (\sigma \pm i\gamma_5 \boldsymbol{\tau} \cdot \boldsymbol{\pi}) \psi_k - g_\omega \bar{\psi}_k \psi \psi_k + \mathcal{L}_M$$

- Fermions coupled to bosons:  $\sigma, \pi, \omega$
- $\mathcal{L}_M \rightarrow$  Linear  $\sigma$ -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



# Hybrid quark-meson-nucleon model

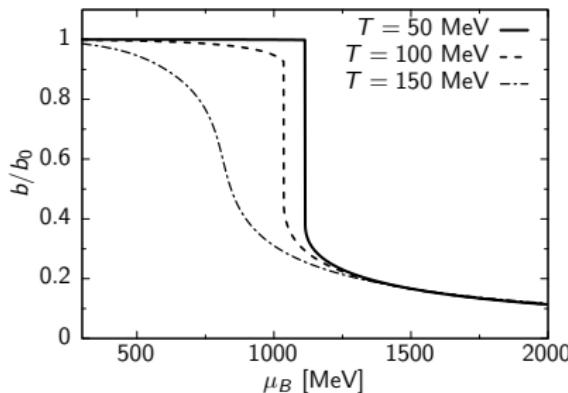
Benić et al, Phys. Rev. D 91, 125034 (2015)

Parity doublet model + quark-meson coupling

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

Statistical confinement:

- IR cutoff for quarks:  $f_q \rightarrow \theta(\mathbf{p}^2 - b^2) f_q$
- UV cutoff for nucleons:  $f_\pm \rightarrow \theta(\alpha^2 b^2 - \mathbf{p}^2) f_\pm$
- $\alpha$  - new model parameter (to be studied here)



- $b$  - scalar field

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

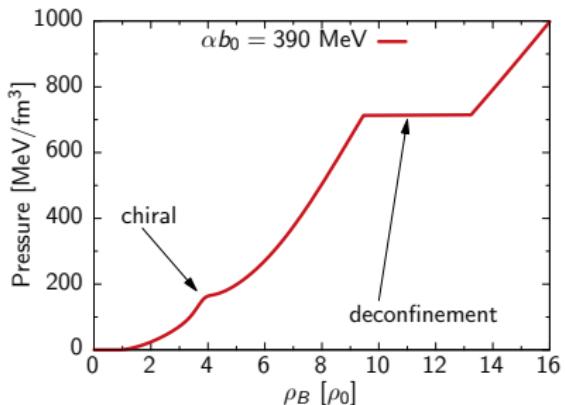
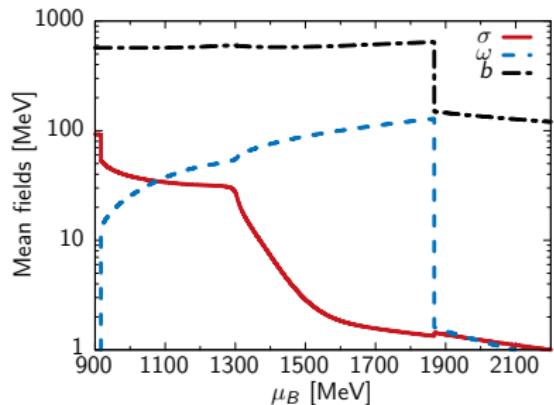
$$\begin{aligned} b(\mu_B = 0) &> 0 && \text{favors nucleons} \\ b(\mu_B \rightarrow \infty) &= 0 && \text{favors quarks} \end{aligned}$$

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

- Mean field approximation  $\rightarrow$  gap equations

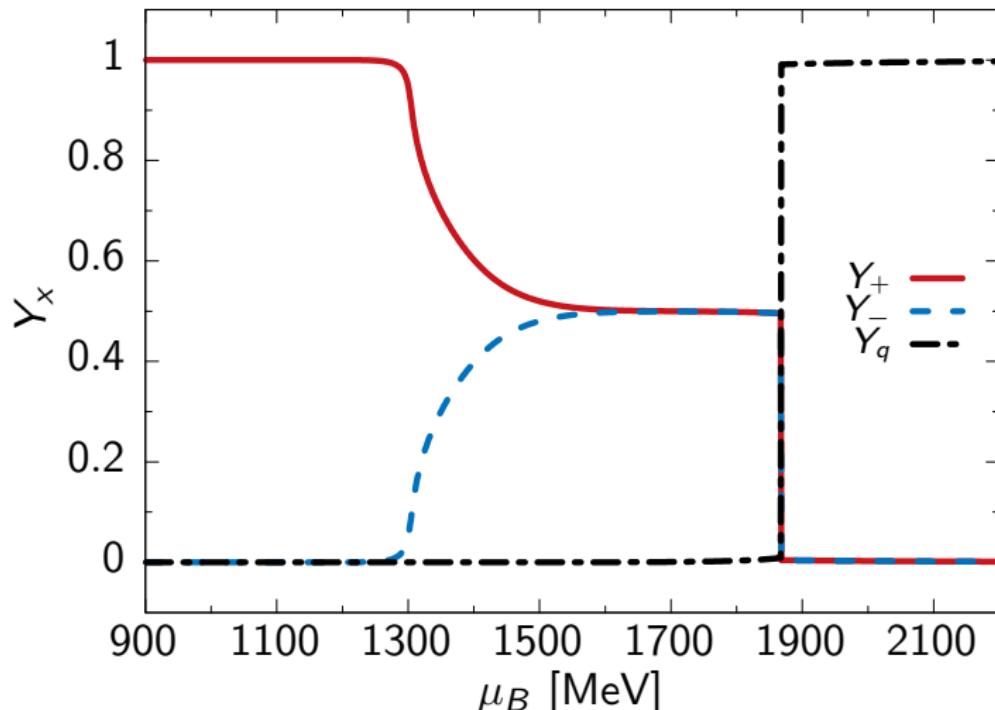
$$\frac{\partial \Omega}{\partial \sigma} = \frac{\partial \Omega}{\partial \omega} = \frac{\partial \Omega}{\partial b} = 0$$

- 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)

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

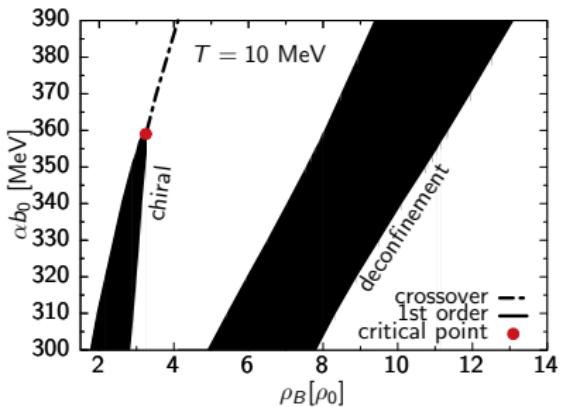
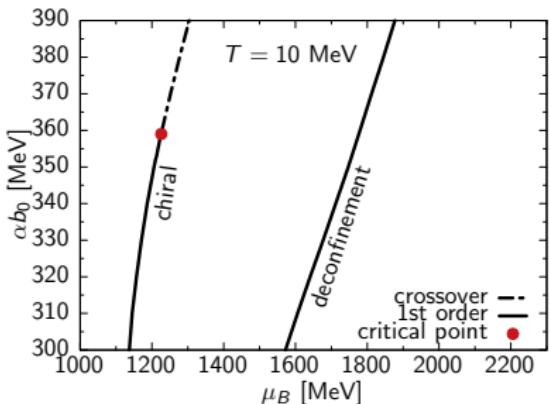


# Model phase diagram at $T = 10$ MeV

- Order of chiral transition (from low to high  $\alpha$ )

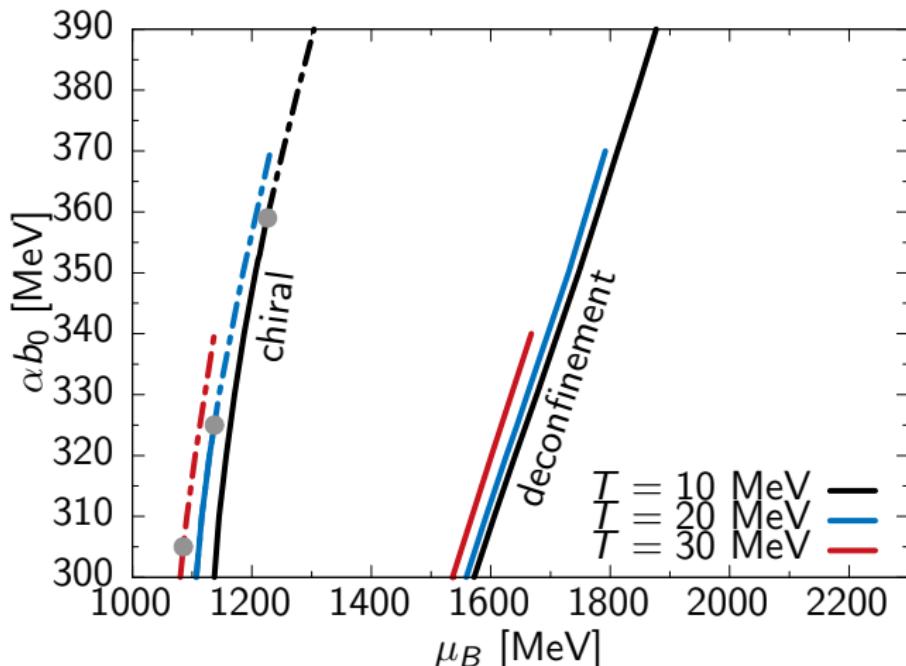
1st order → **Critical Point** → crossover

- Deconfinement always of 1st order (by the choice of  $V_b$ )
- high  $m_0 \rightarrow$  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: $\chi_2$ at $T = 10$ MeV

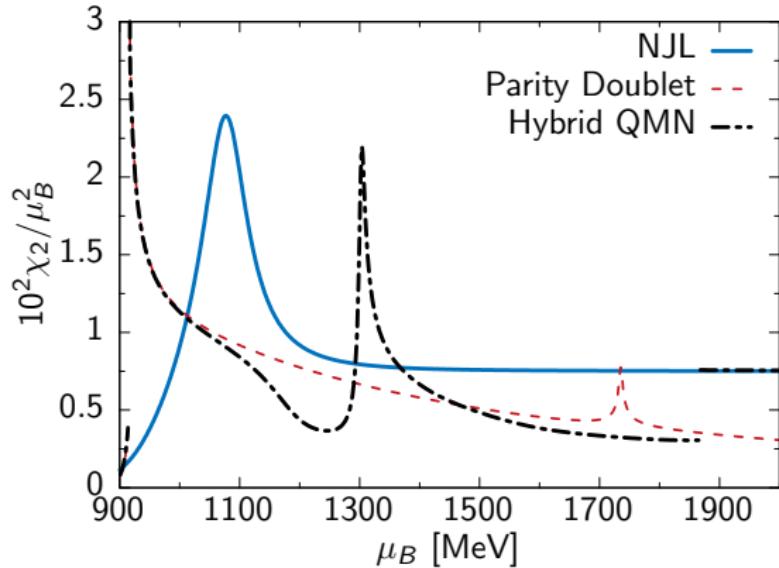
- NJL: no confinement mechanism
- Parity doublet: wrong asymptotics

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: $\chi_3$ at $T = 10$ MeV

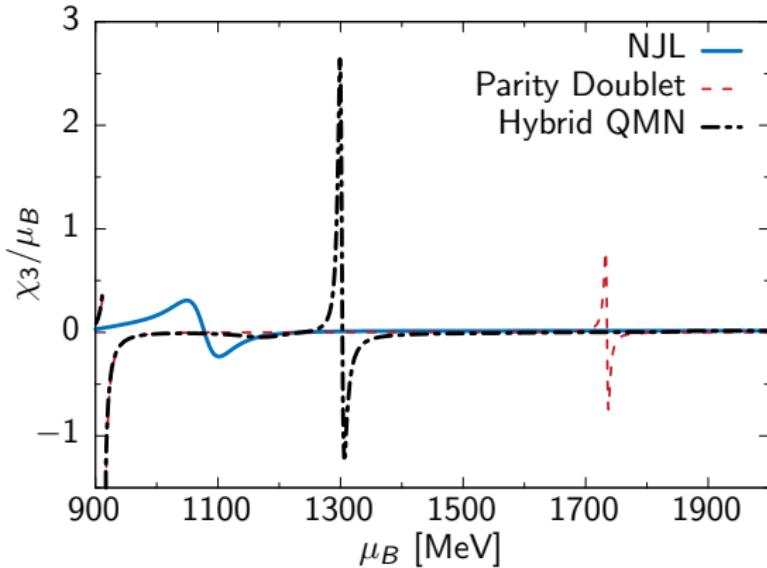
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Generalized susceptibilities

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



## Higher-order cumulants: $\chi_4$ at $T = 10$ MeV

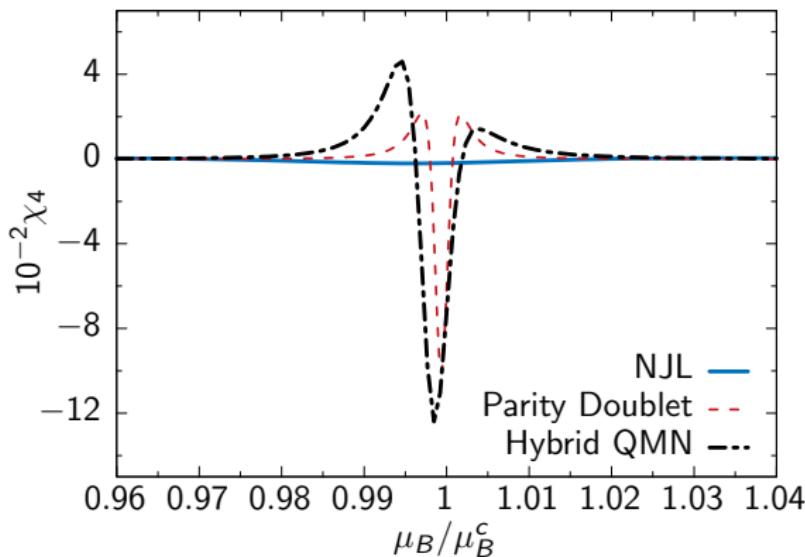
- NJL: no confinement mechanism
- Parity doublet: wrong asymptotics

HQMN resembles all these features

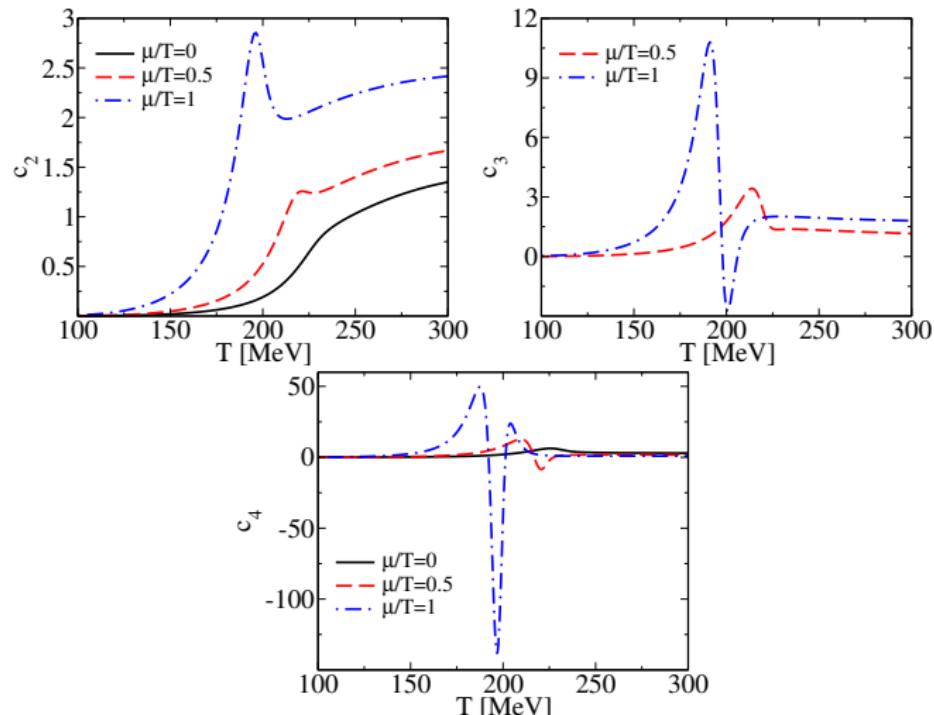
- Confinement mechanism **strengthens** chiral transition
- Higher-order cumulants **less sensitive** to deconfinement

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)

# Conclusions

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

- Influence of statistical confinement on chiral transition:
  - triggered at **much earlier** baryon chemical potential
  - **strengthened** in comparison to the hadronic-model result
- Higher-order cumulants rather **insensitive** to deconfinement:
  - Influence of different potentials → crossover transition
  - connection to a symmetry of QCD

QCD-like theory → A. Cherman *et al*, Phys. Rev. Lett. **119** (2017) no.22, 222001

Work in progress:

- Inclusion of strangeness
- Astrophysical applications

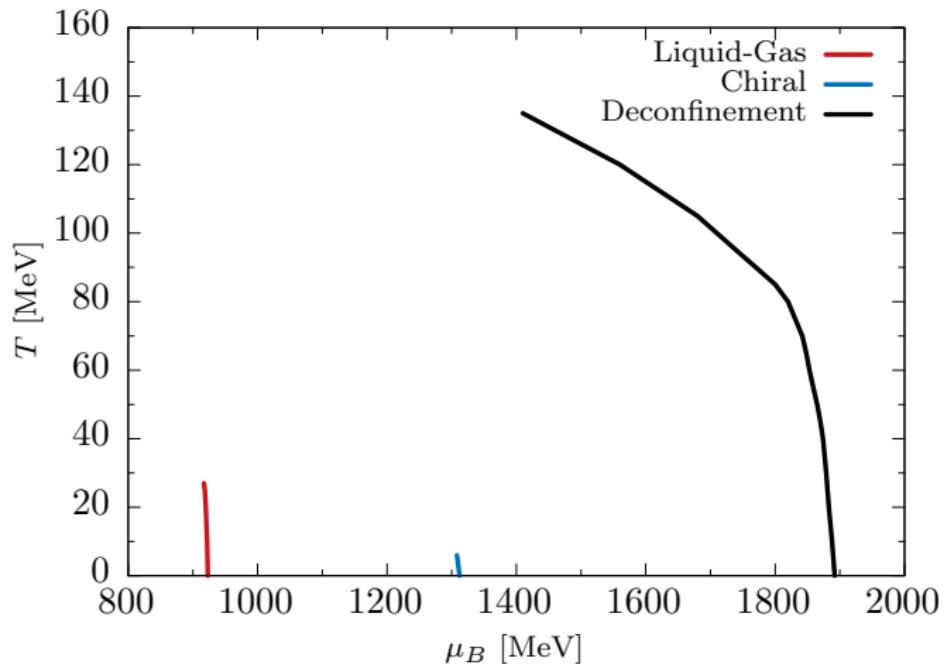
Thank you for your attention

# Full HQMN model Lagrangian

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

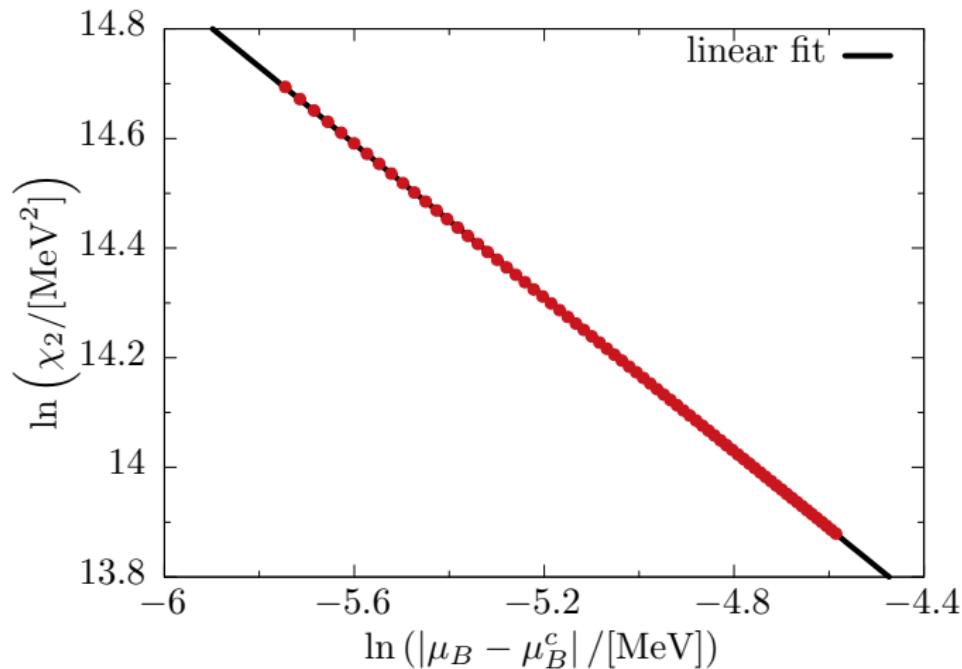
$$\begin{aligned}\mathcal{L}_N &= \sum_{k=1,2} \bar{\psi}_k i\cancel{\partial} \psi_k + m_0 (\bar{\psi}_2 \gamma_5 \psi_1 - \bar{\psi}_1 \gamma_5 \psi_2) \\ &\quad + \sum_{k=1,2} g_k \bar{\psi}_k (\sigma \pm i\gamma_5 \boldsymbol{\tau} \cdot \boldsymbol{\pi}) \psi_k - g_\omega \bar{\psi}_k \psi \psi_k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

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



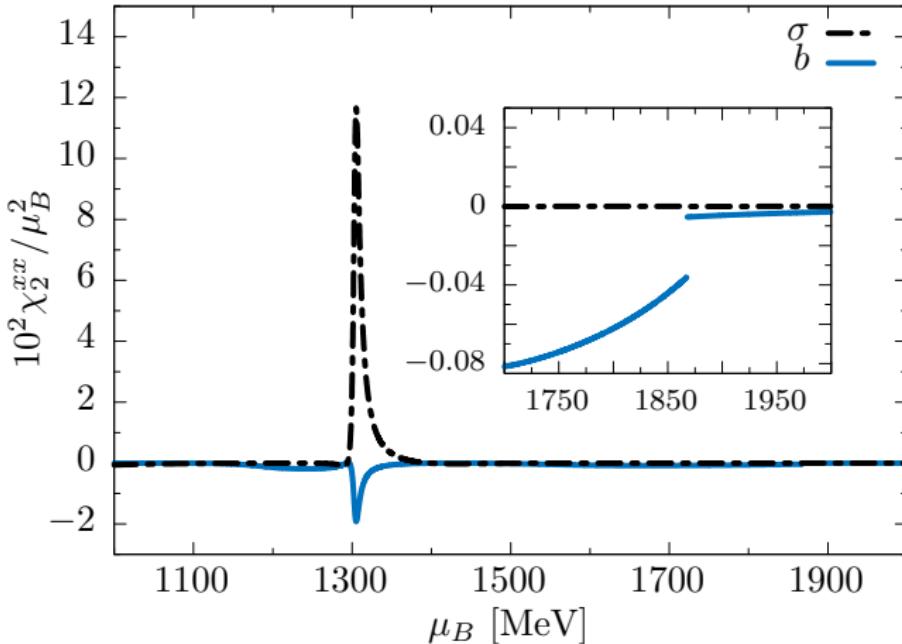
## Critical Behavior of $\chi_2$ at $T = 10$ MeV

$$\ln \chi_2 = -\epsilon |\mu_B - \mu_B^c| + r \quad \rightarrow \quad \epsilon \approx 0.67$$

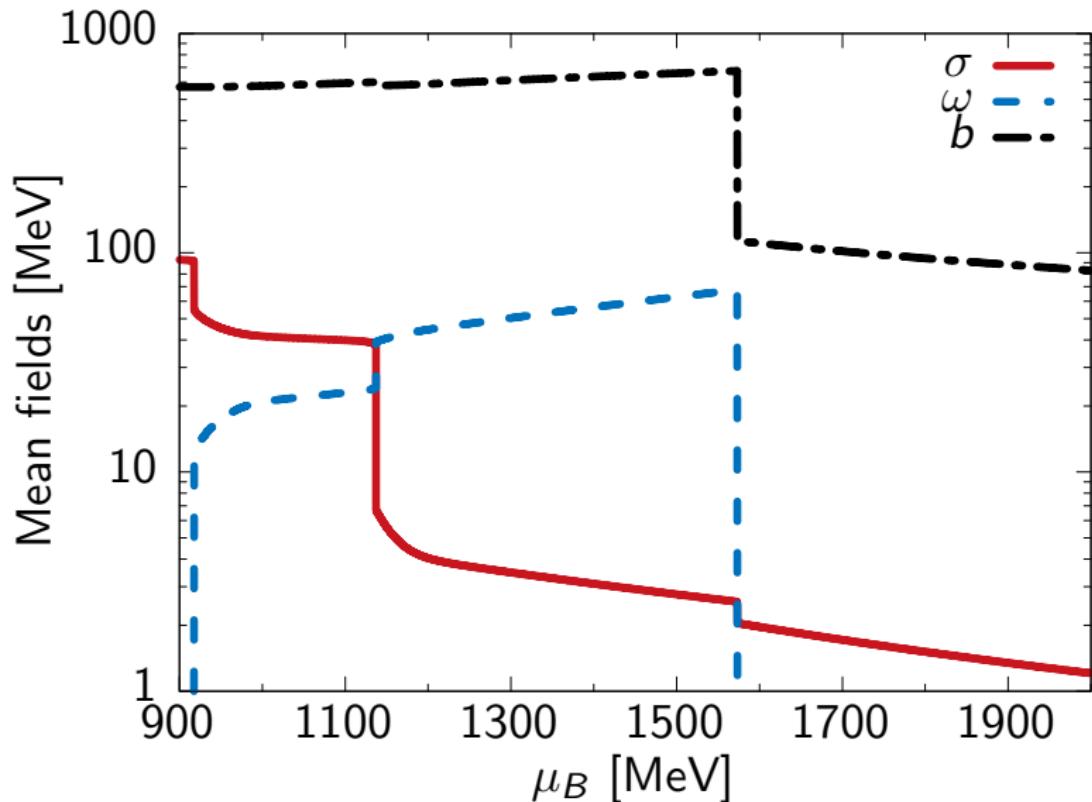


## Diagonal contributions to $\chi_2$ ( $\alpha b_0 = 390$ MeV)

$$\chi_2 = \sum_{x,y} \chi_2^{xy} = - \sum_{x,y} \frac{\partial^2 \Omega}{\partial x \partial y} \frac{\partial x}{\partial \mu_B} \frac{\partial y}{\partial \mu_B}, \quad x, y = \mu_B, \sigma, \omega, b$$

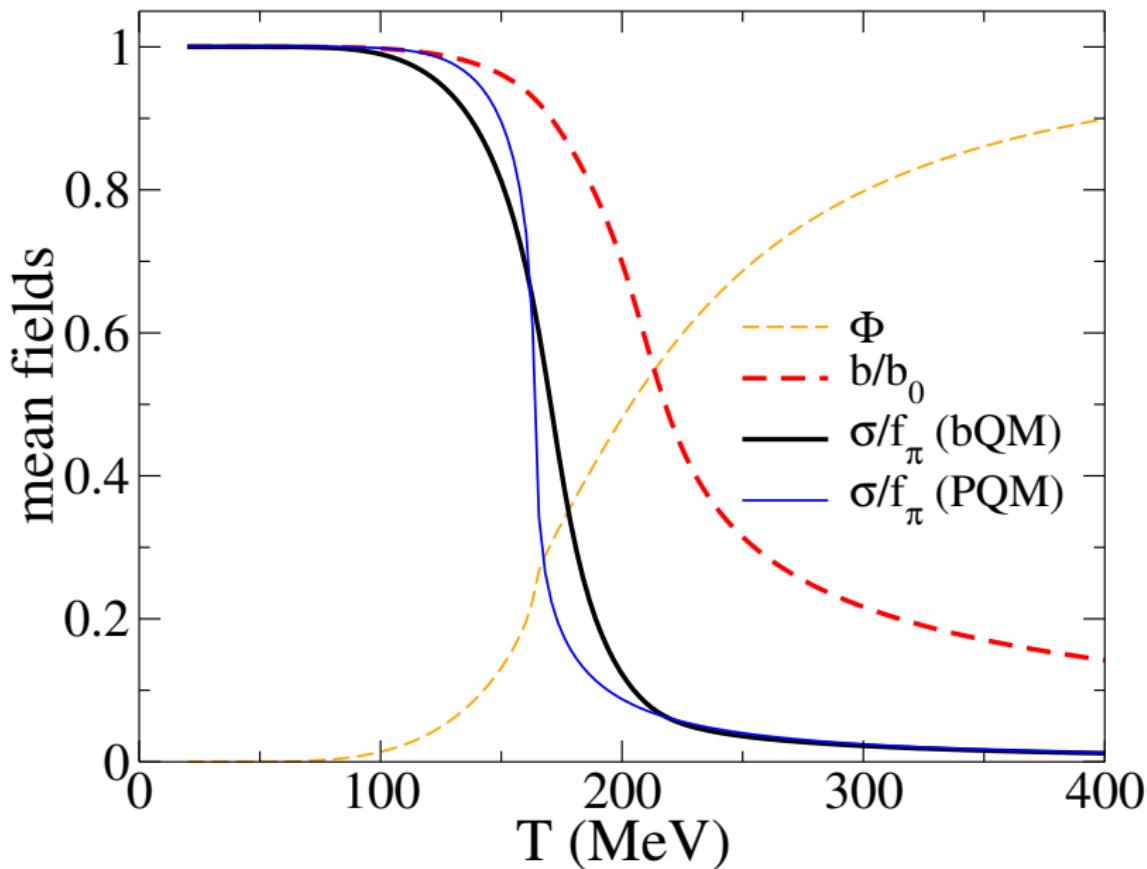


# Mean fields at $T = 10$ MeV ( $\alpha b_0 = 300$ MeV)

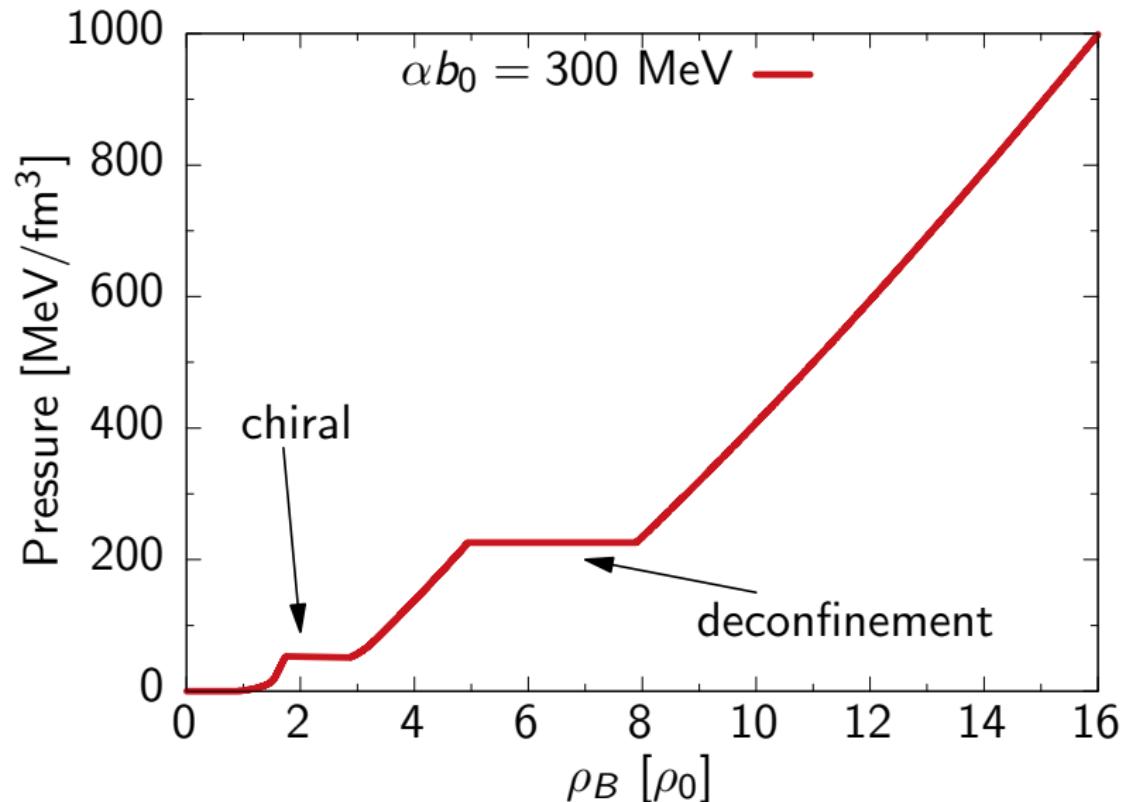


# bQM vs PQM

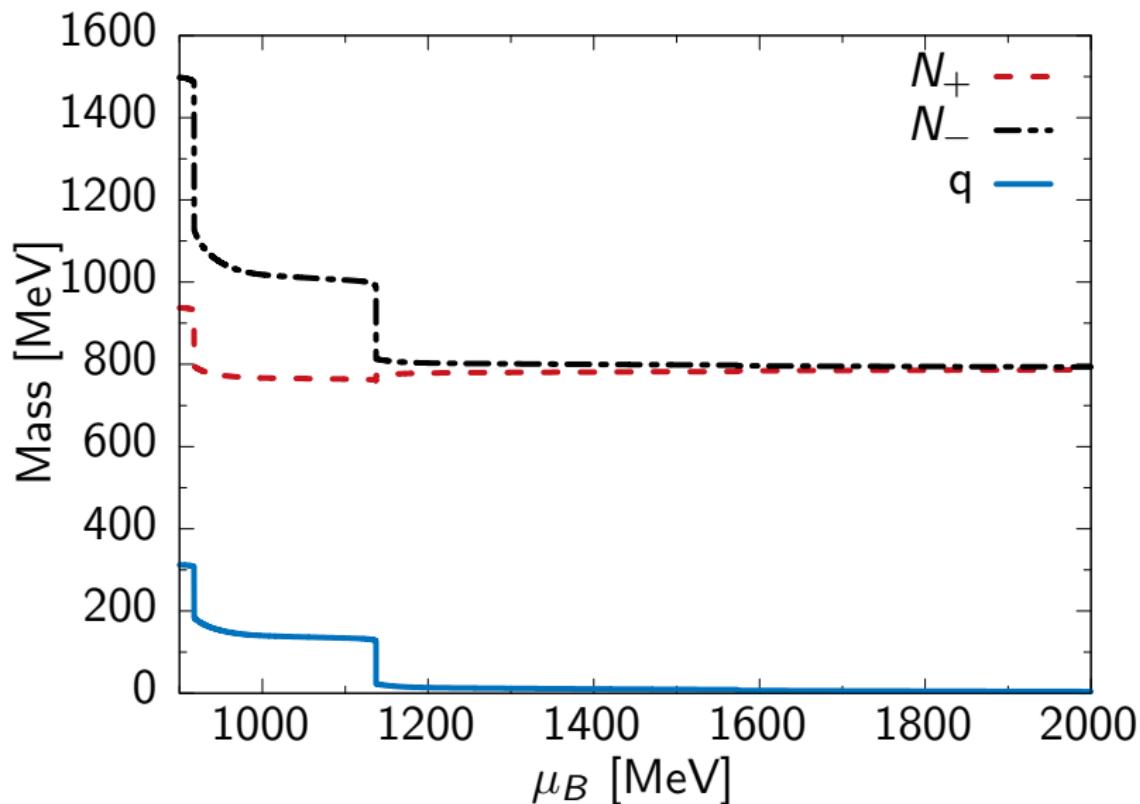
Benić *et al*, Phys. Rev. D **91**, 125034 (2015)



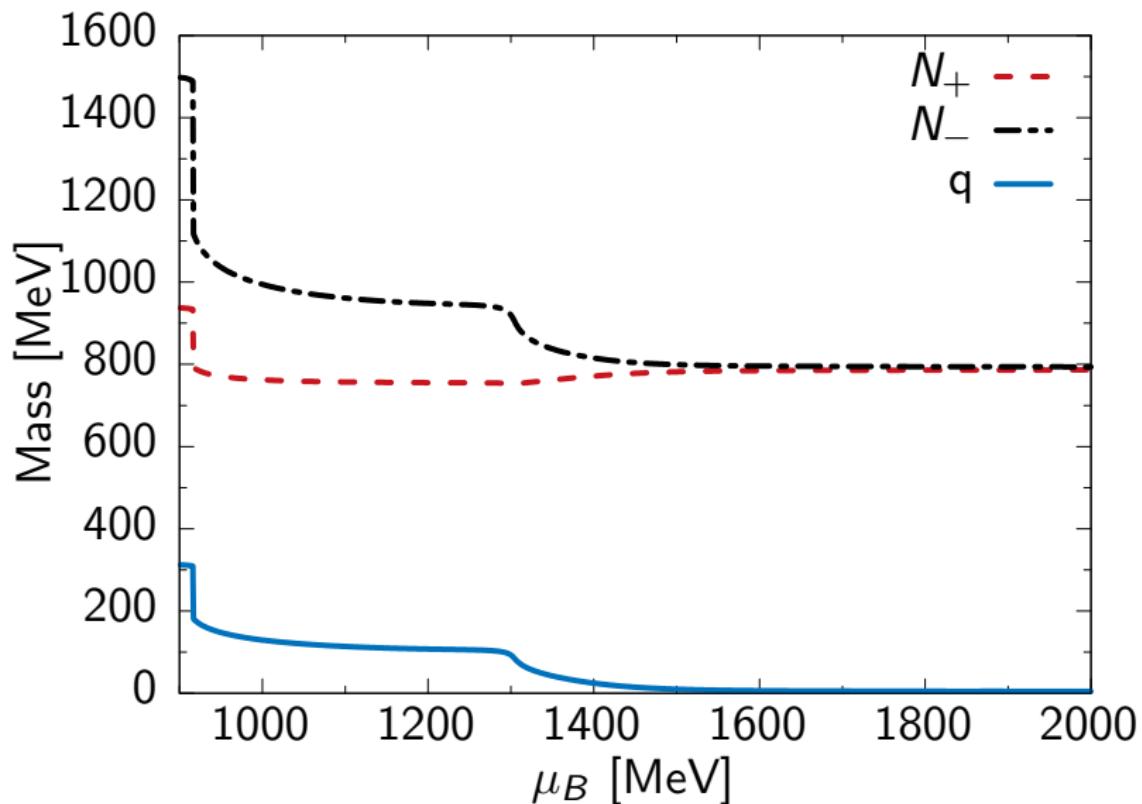
## Equation of state at $T = 10$ MeV ( $\alpha b_0 = 300$ MeV)



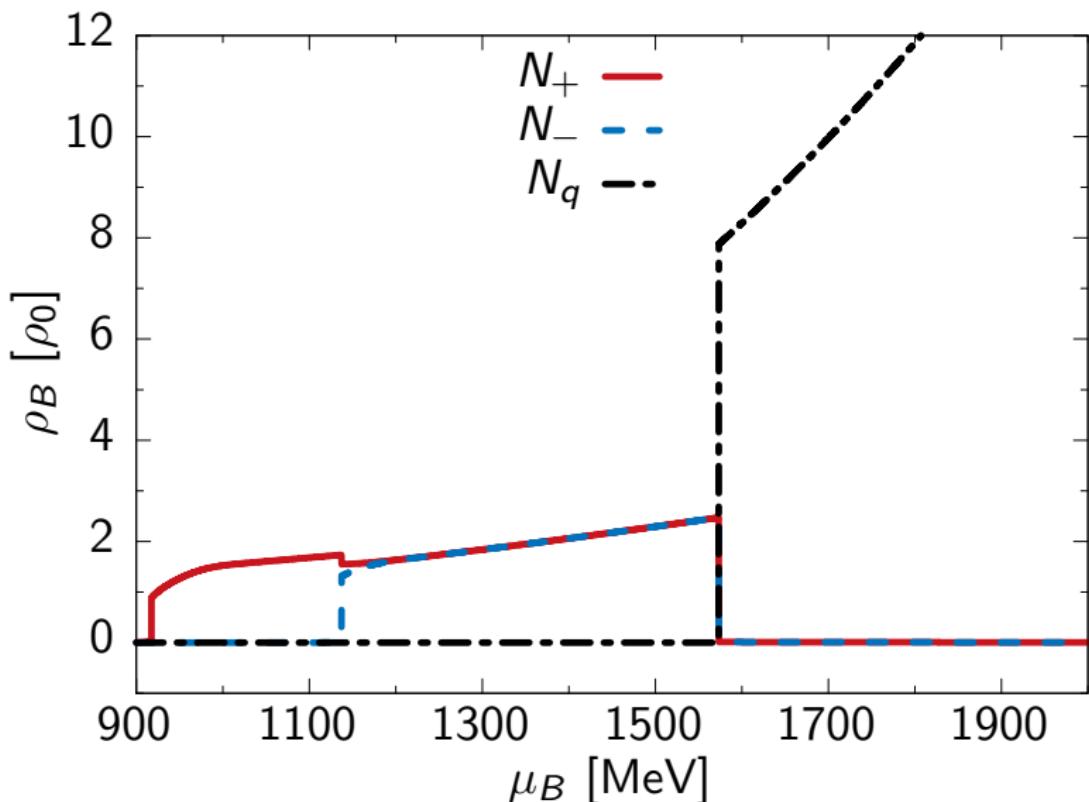
## Masses at $T = 10$ MeV ( $\alpha b_0 = 300$ MeV)



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

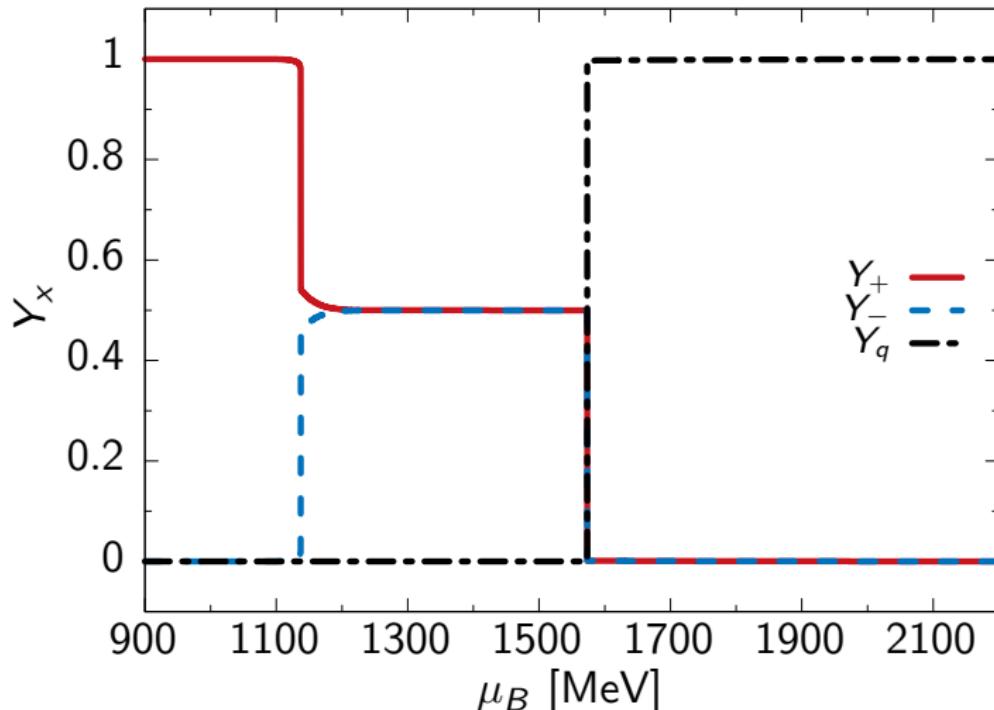


# Net-baryon density at $T = 10$ MeV ( $\alpha b_0 = 300$ MeV)

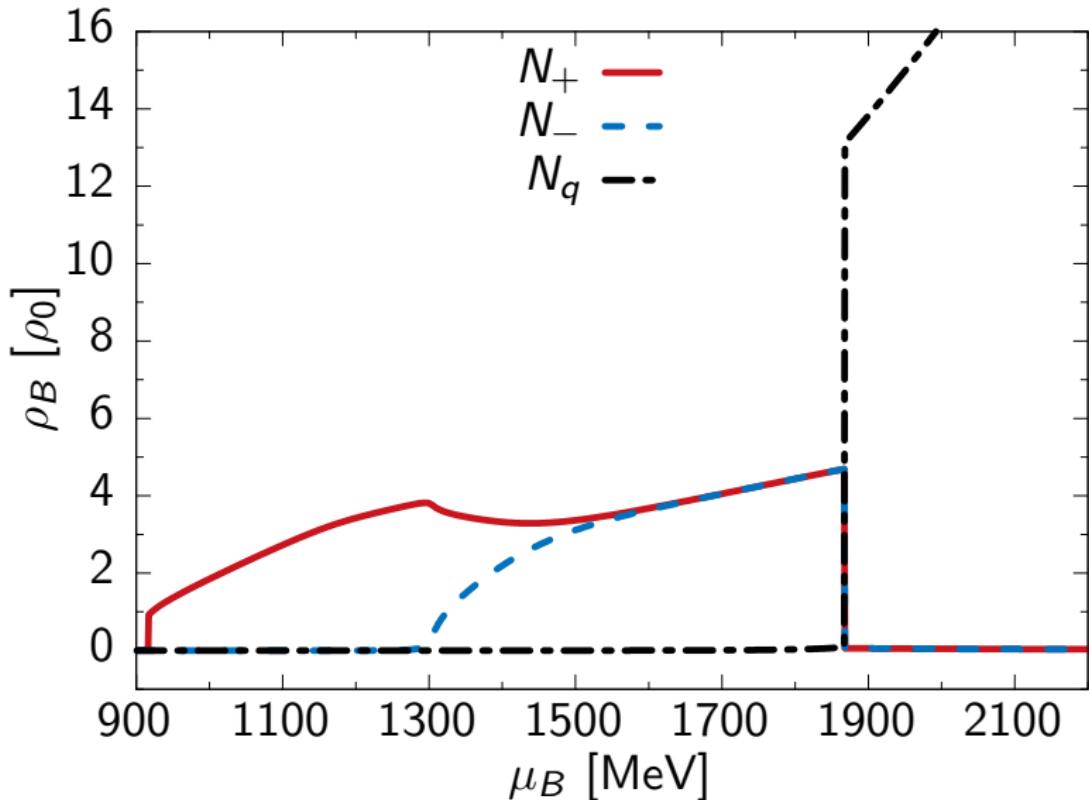


## Matter composition at $T = 10$ MeV ( $\alpha b_0 = 300$ MeV)

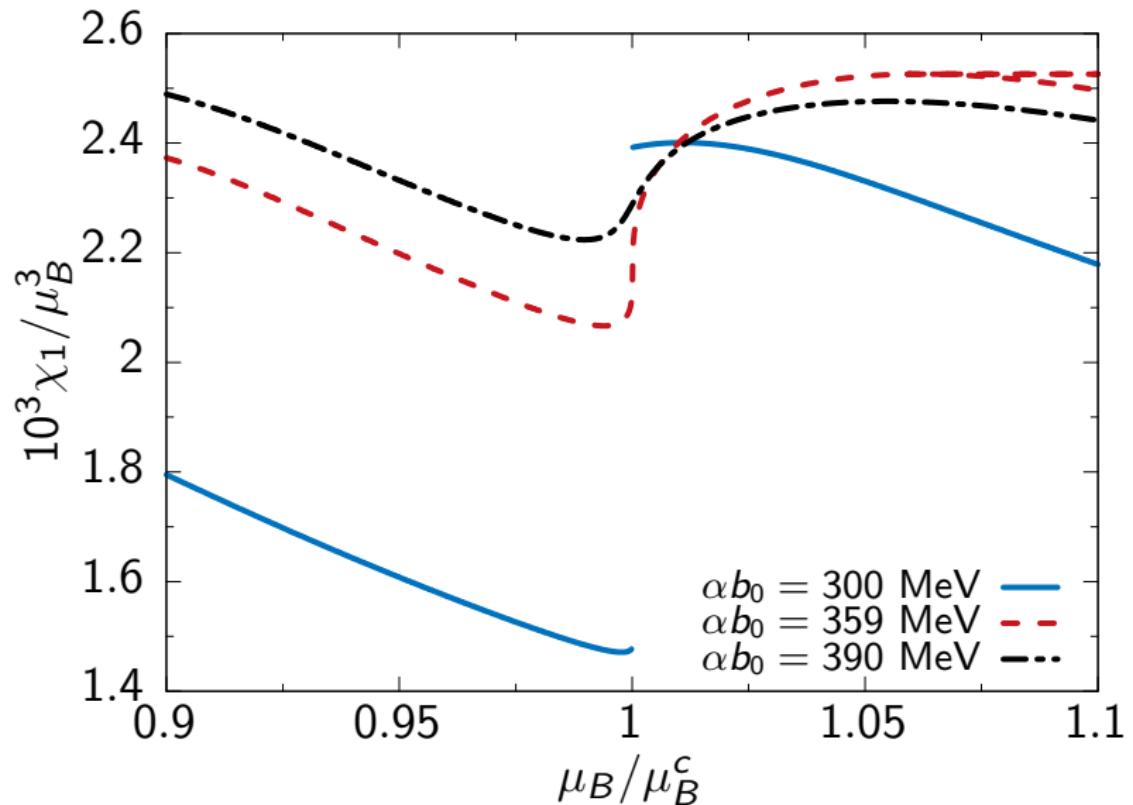
$$Y_x = \frac{\rho_x}{\rho_+ + \rho_- + \rho_q}$$



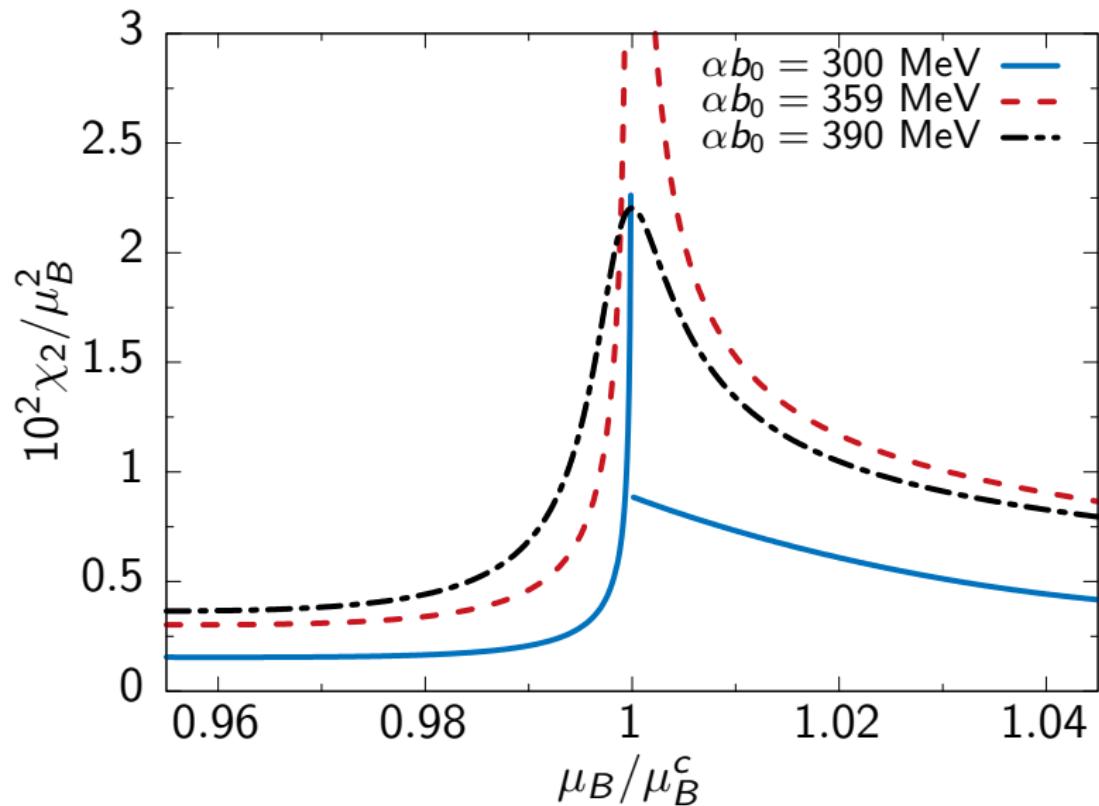
# Net-baryon density at $T = 10$ MeV ( $\alpha b_0 = 390$ MeV)



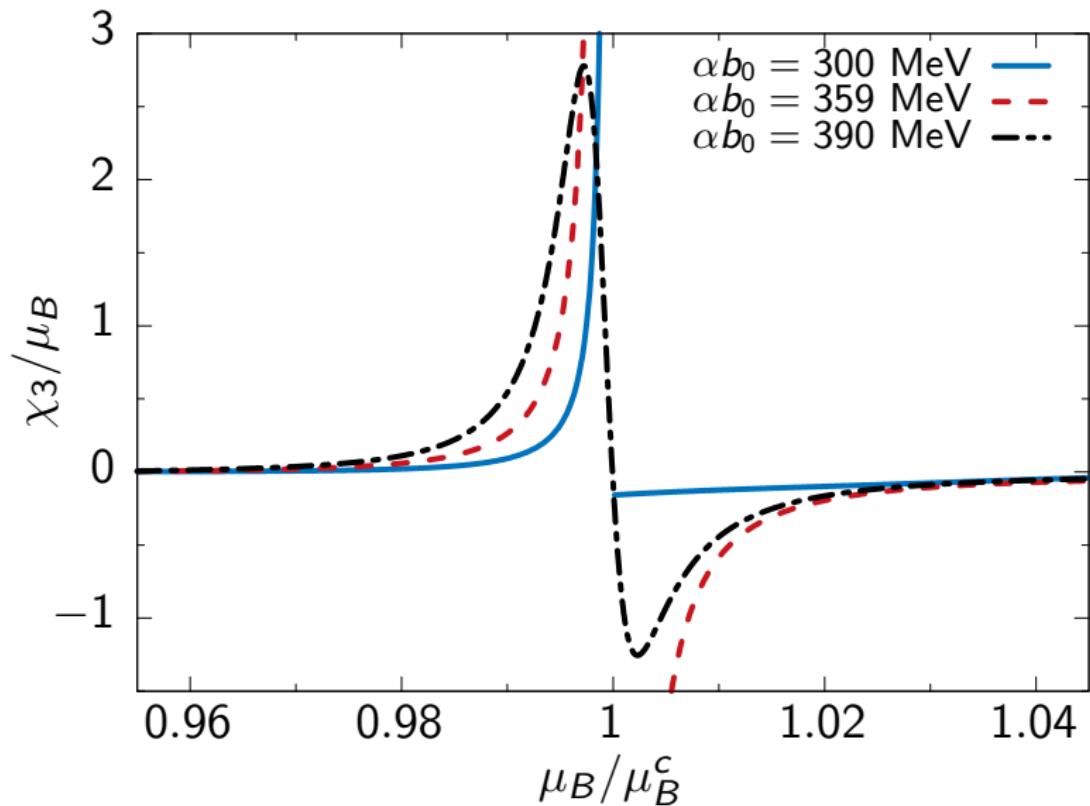
## Net-baryon density at $T = 10$ MeV



## Second-order cumulant at $T = 10$ MeV



## Third-order cumulant at $T = 10$ MeV



## Fourth-order cumulant at $T = 10$ MeV

