Thermodynamics of Dense Baryonic Matter in EFTs

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Outline:

1. Introduction: baryons near chiral symmetry restoration
2. Thermodynamics of hadronic matter in a parity doublet model
3. "Confinement" in models, anomaly matching

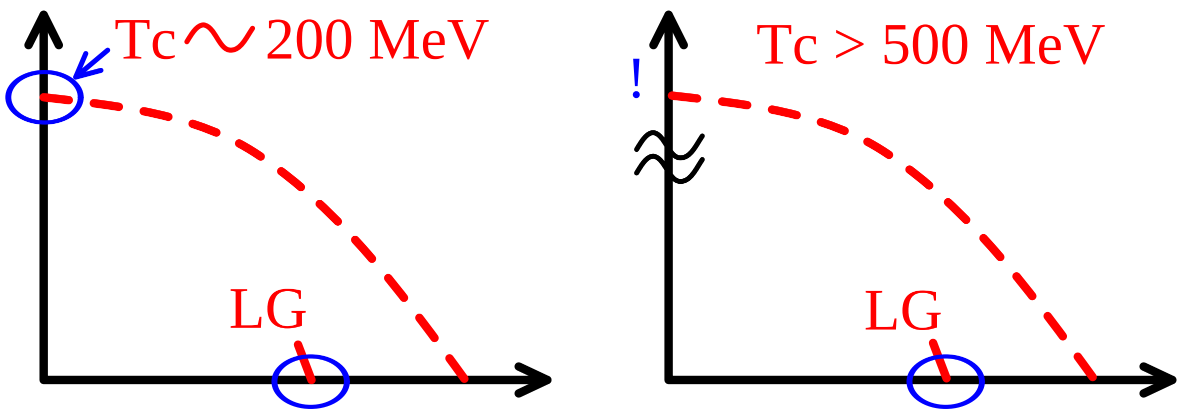
Baryons near chiral symmetry restoration?

- standard (naive): DχSB generates masses $\quad m_N \overset{\sigma\to 0}{\to} 0$
- parity doublet (mirror): DχSB generates mass difference
  $m_{N_+} \overset{\sigma\to 0}{\to} m_{N_-} = m_0 \neq 0$ [Detar-Kunihiro (89)]
- emergence of a scale in QCD: trace anomaly $\Theta^\mu_\mu = \frac{\beta}{2g}G^2 + m(1+\gamma)\bar{q}q$
  $\Rightarrow M_B \propto \langle B|G^2|B\rangle$ & $\langle G^2\rangle^{\rm lattice}_{T_\chi} \neq 0$
- naive vs. mirror: not yet discriminated
  - axial couplings: $g_A^{++} = g_A^{--}$ (naive) $\quad g_A^{++} = -g_A^{--}$ (mirror)
    cf. other chiral invariant operators allowed [Jaffe-Pirjol-Scardicchio (06)]
    cf. lattice QCD: $g_A^{--} = 0.2 \pm 0.3$ [Takahashi-Kunihiro (07)]
    AdS/QCD: $g_A^{++} = 0.73\,,\ g_A^{--} = 0.38$ [Hashimoto-Sakai-Sugimoto (08)]
  - which state is the true chiral partner of $N(940)$?
    if $N(1535)$ then $m_0 = 270$ MeV (from $\Gamma^{(\rm exp)}(N^* \to N\pi) = 70$ MeV)
    $\Leftrightarrow$ cannot reproduce $\Gamma^{(\rm exp)}(N^* \to N\eta) \sim 80$ MeV
    a speculative candidate closer to N? and/or large OZI-violation?

Dense nuclear matter in chiral models

- **nuclear matter: known properties**
  - binding energy: $E/A(\rho_0) - m_N = -16$ MeV
  - saturation density: $\rho_0 = 0.16$ fm^{-3}
  - incompressibility: $K = 9\rho_0^2\partial^2(E/A)/\partial\rho^2|_{\rho=\rho_0} = 200\text{-}400$ MeV

- **parity doublet model vs. other models**
  - LSM: no stable ground state corr. to nuclear matter [Kerman-Miller (74)]
  - nucleonic NJL: possible if 4F vector and 8F scalar-vector int. incld.
    [Koch-Biro-Kunz-Mosel (87), Buballa (96), Mishustin-Satarov-Greiner (03)]
  - PDM: possible if $m_0 \sim 800$ MeV [Zschiesche-Tolos-Schaffner-Bielich-Pisarski (07)]



- **cold nuclear matter in parity doublet model** [Zschiesche et al. (07)]
  - 2 nucleon fields

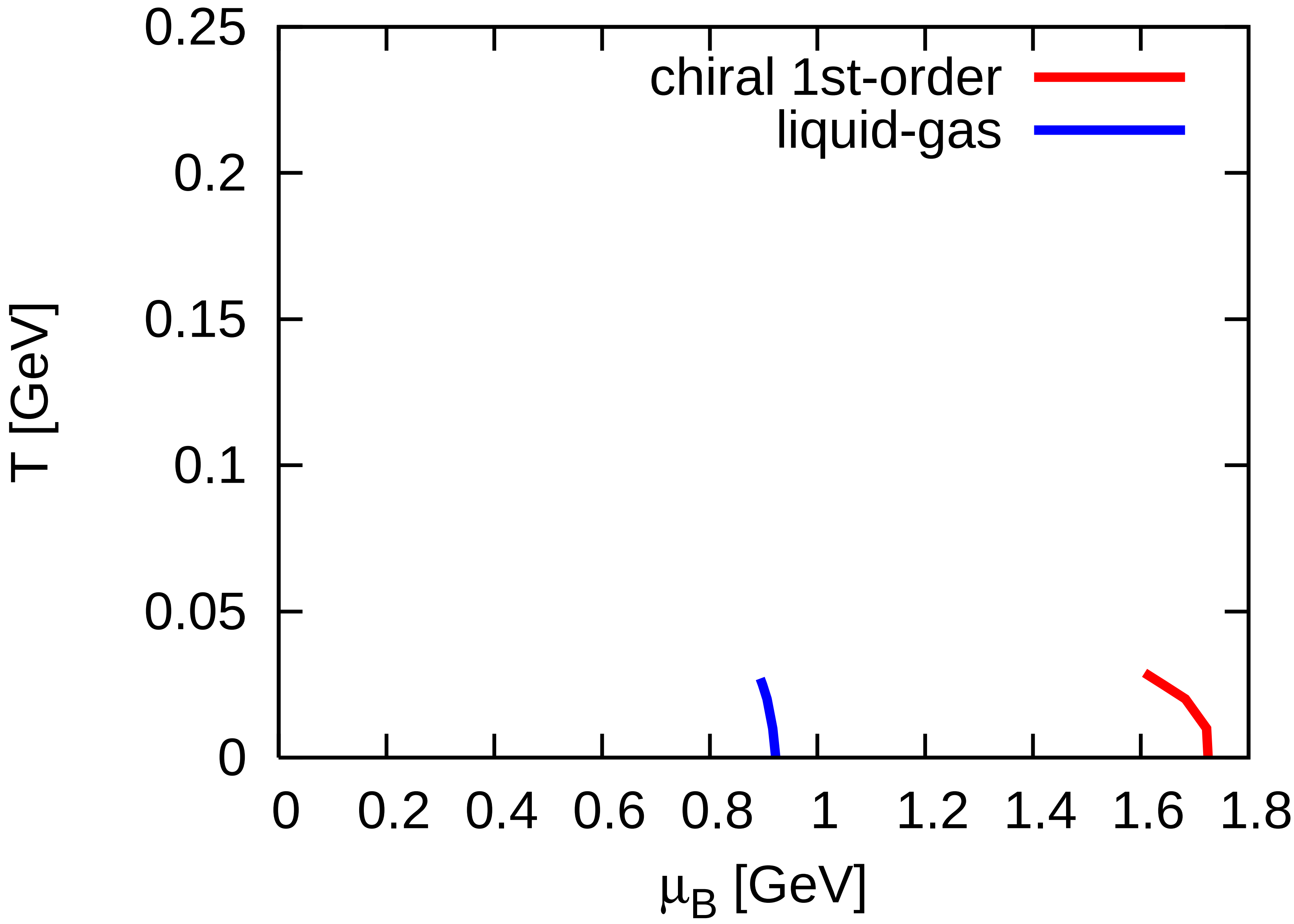
$$\psi_{1L} : (1/2, 0) \quad \psi_{1R} : (0, 1/2)$$
$$\psi_{2L} : (0, 1/2) \quad \psi_{2R} : (1/2, 0)$$

  - Lagrangian

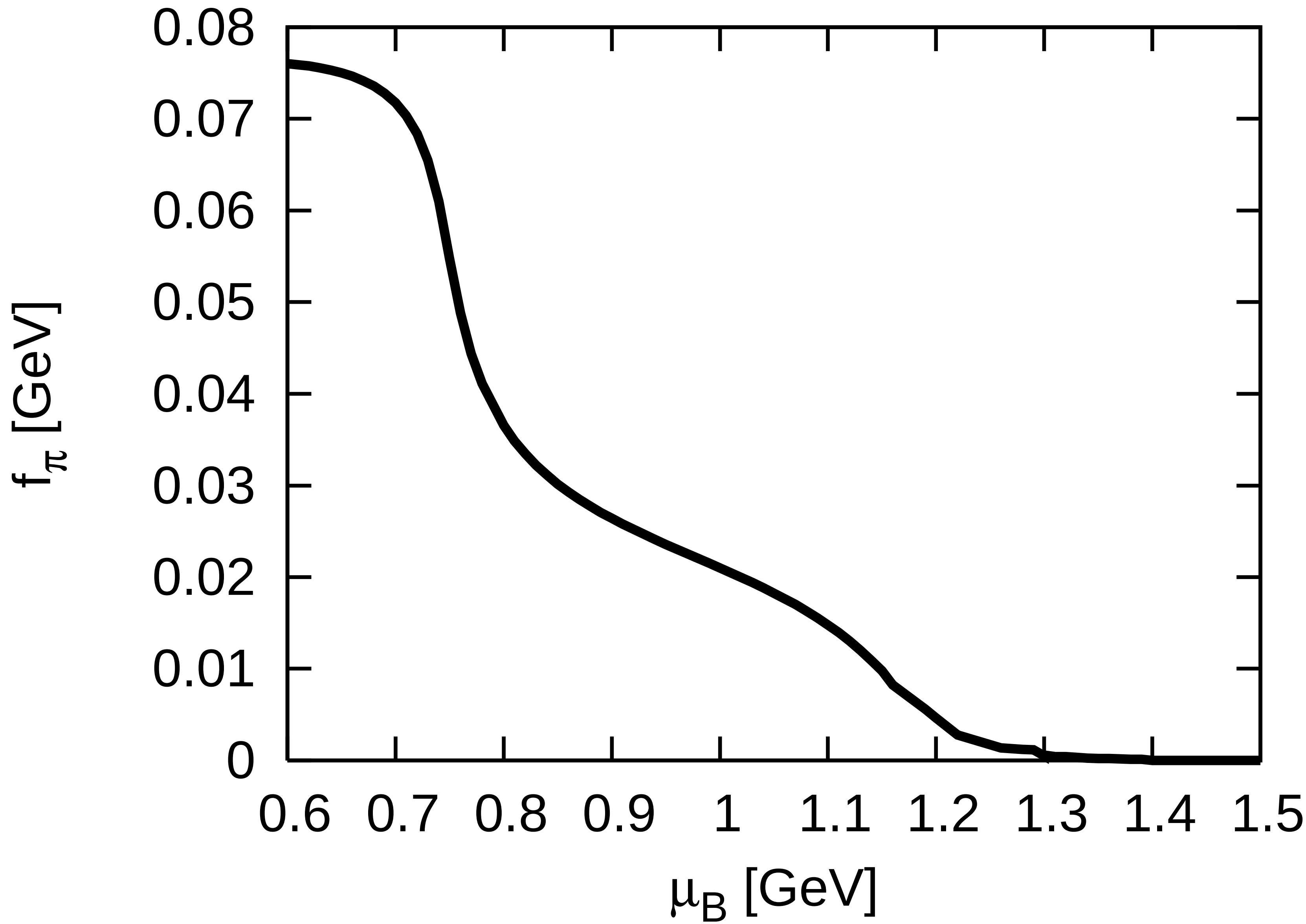
$$\begin{aligned} \mathcal{L} &= \bar{\psi}_1 i \partial\!\!\!/ \psi_1 + \bar{\psi}_2 i \partial\!\!\!/ \psi_2 + m_0 \left(\bar{\psi}_2 \gamma_5 \psi_1 - \bar{\psi}_1 \gamma_5 \psi_2 \right) \\ &\quad + a \bar{\psi}_1 (\sigma + i \gamma_5 \vec{\tau} \cdot \vec{\pi}) \psi_1 + b \bar{\psi}_2 (\sigma - i \gamma_5 \vec{\tau} \cdot \vec{\pi}) \psi_2 - g_\omega \bar{\psi}_1 \omega\!\!\!/ \psi_1 - g_\omega \bar{\psi}_2 \omega\!\!\!/ \psi_2 + \mathcal{L}_M \,, \\ \mathcal{L}_M &= \frac{1}{2} \partial_\mu \sigma \partial^\mu \sigma + \frac{1}{2} \partial_\mu \pi \partial^\mu \pi + \frac{1}{2} \bar{\mu}^2 (\sigma^2 + \vec{\pi}^2) - \frac{\lambda}{4} (\sigma^2 + \vec{\pi}^2)^2 + \epsilon \sigma \\ &\quad - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu + (g_4)^4 (\omega_\mu \omega^\mu)^2 \end{aligned}$$

  - masses: $m_\pm = \frac{1}{2} \left[\sqrt{(a+b)^2 \sigma^2 + 4 m_0^2} \mp (a-b) \sigma \right]$
  - thermodynamics of the model [CS-Mishustin (2010)]
    liquid-gas transition and chiral crossover/transition

- **phase diagram in PDM**: $m_{N_-} = 1.5$ GeV



• **pion decay constant at an intermediate temperature**



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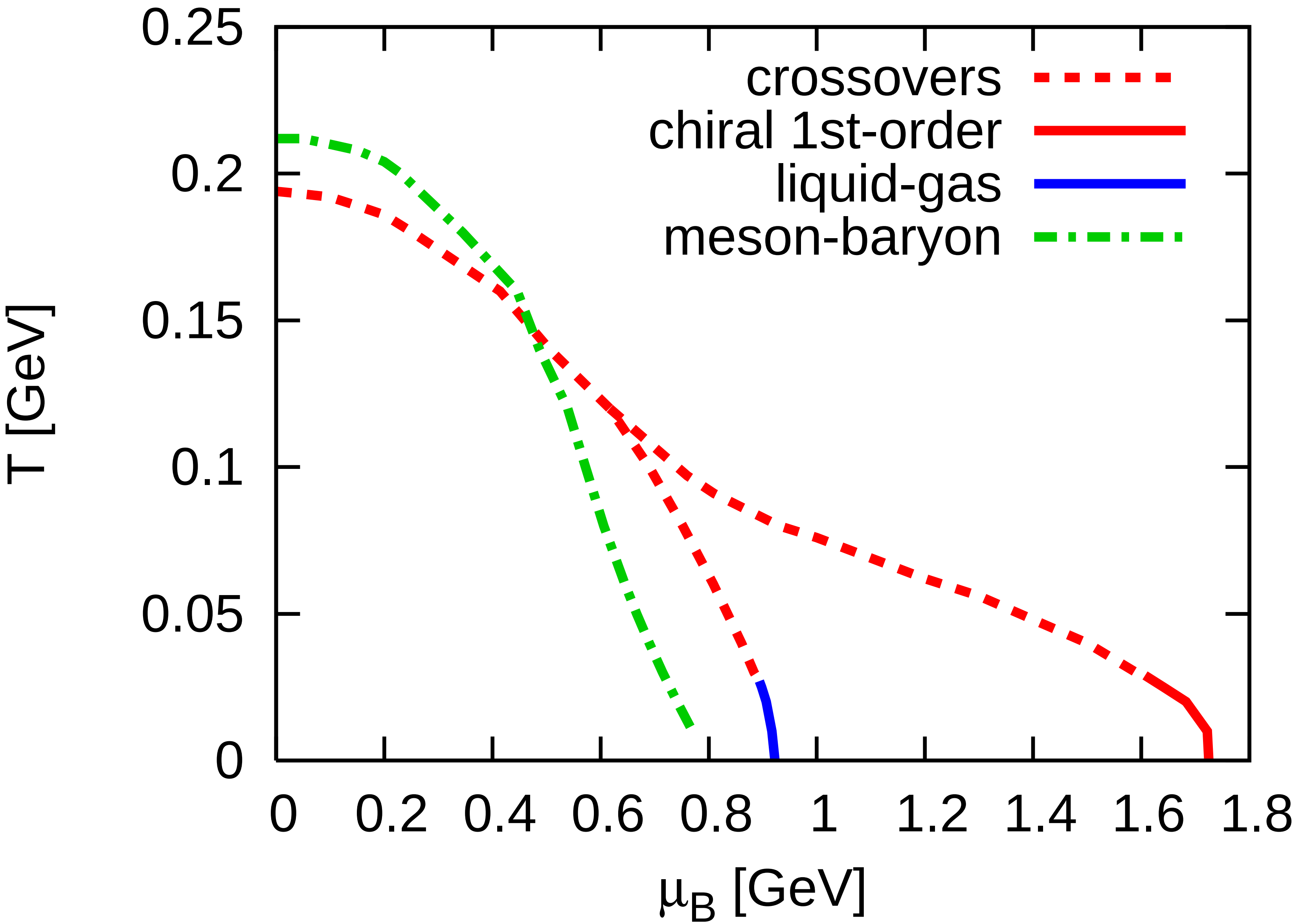
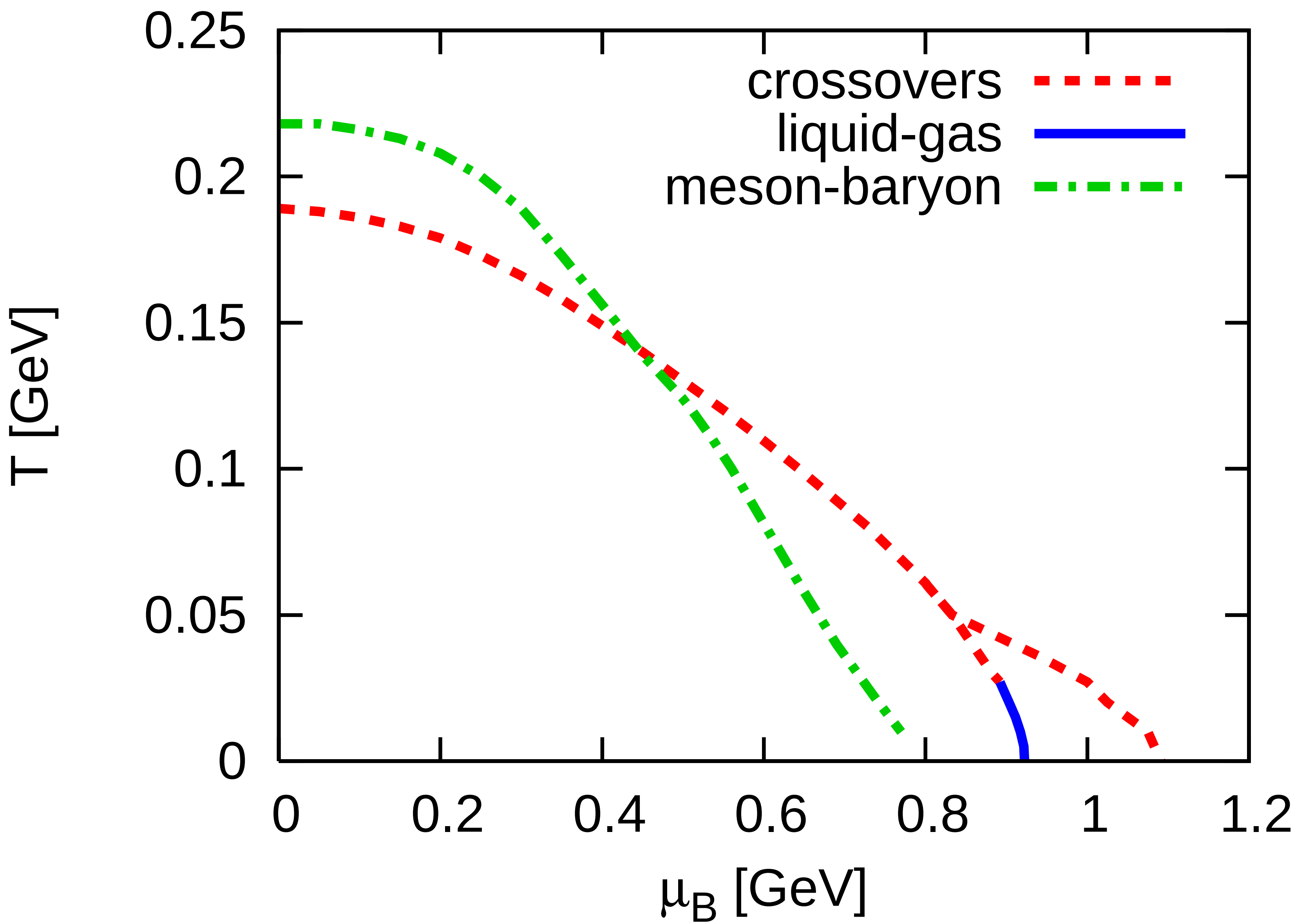
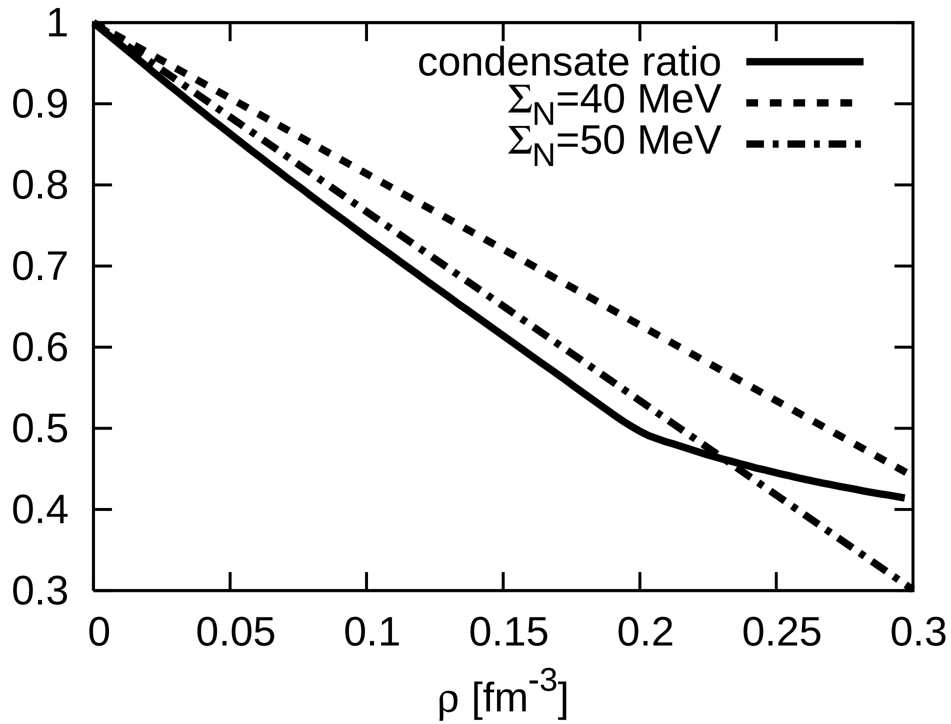


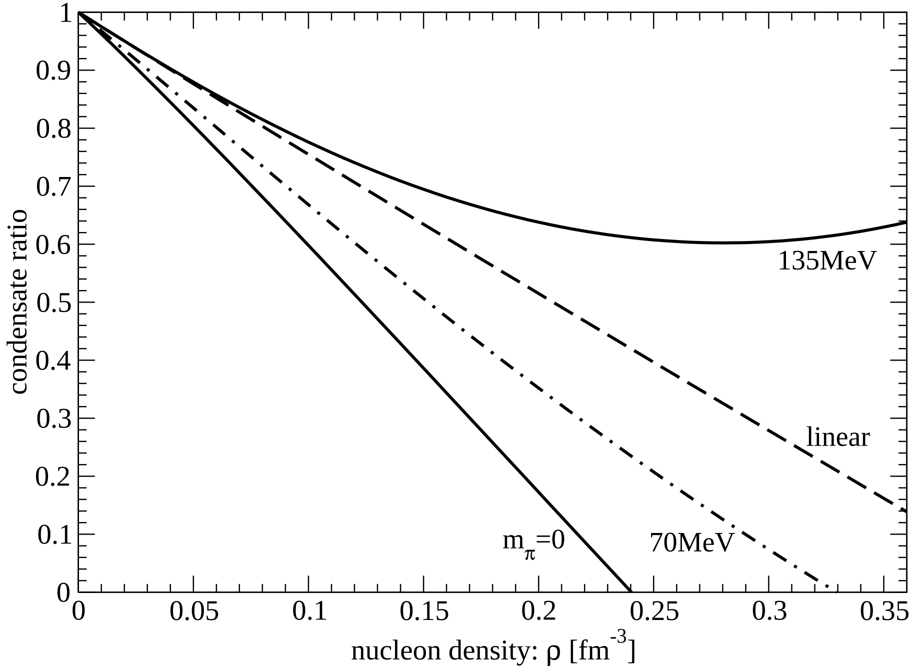
• **phase diagram in PDM**: $m_{N_-} = 1.2$ GeV



- **in-medium quark condensate and the low-energy theorem**

present MF model





up to the leading order in ρ:

$$R(\rho) = \frac{\langle \bar{q}q \rangle_\rho}{\langle \bar{q}q \rangle_{\rm vac}} = 1 - \frac{\Sigma_N}{m_\pi^2 f_\pi^2}\rho\,, \quad \Sigma_N = 45 \pm 8\,\text{MeV}$$

beyond linear-density-approximation:

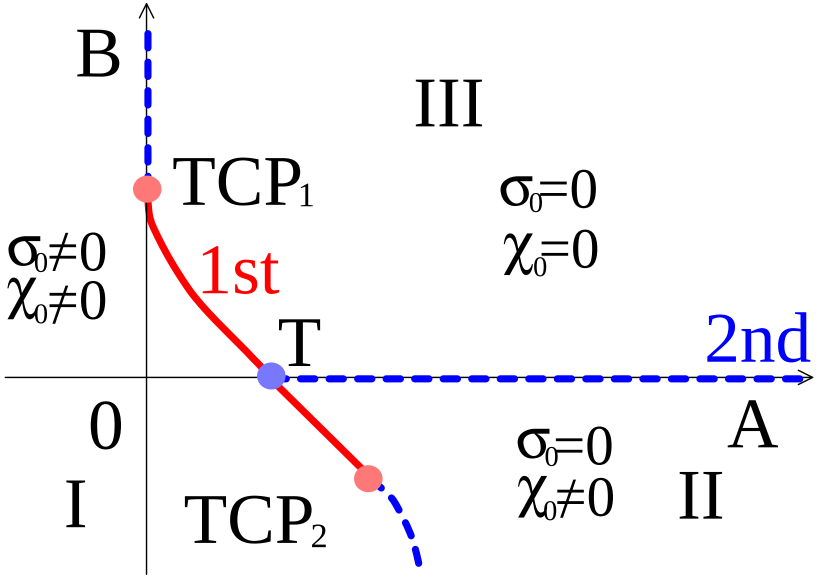
$$R^{(\rm PDM)}(\rho \sim 0.2\,\text{fm}^{-3}) \sim 0.5\,, \quad R^{(\rm ChPT)}(\rho \sim 0.2\,\text{fm}^{-3}) \sim 0.7$$

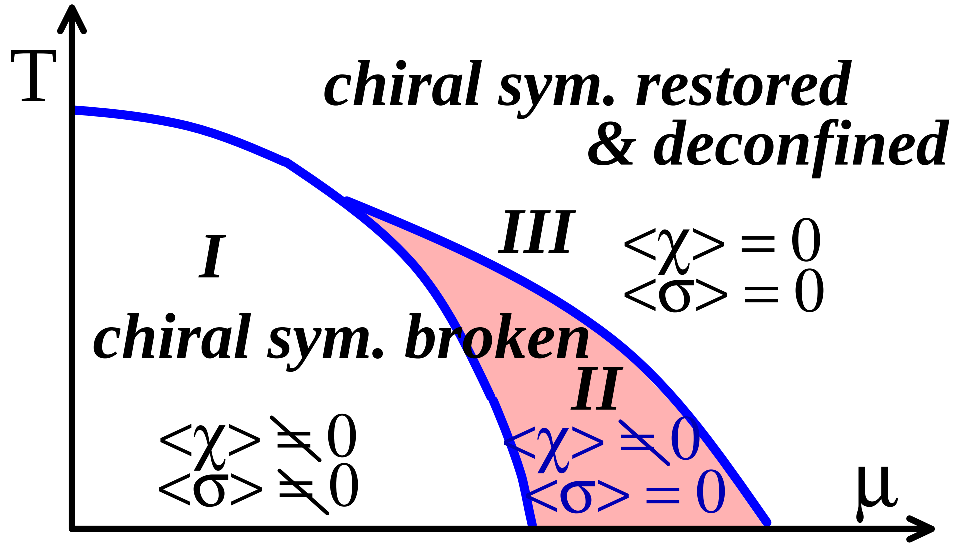
$\Rightarrow$ importance of two-pion exchange correlations with $\Delta(1232)$

Exotic phase? role of tetra-quark states

- **2 phases with broken symmetry: distinguished by** n_B

[Harada-CS-Takemoto (09)]





- symmetry breaking: $SU(N_f)_L \times SU(N_f)_R \to SU(N_f)_V \times Z_{N_f} \to SU(N_f)_V$
- order parameters: 2-quark state $\sigma \sim \bar{q}q$ and 4-quark state $\chi \sim (\bar{q}q)^2 + \bar{q}\bar{q}\text{-}qq$
- 3 phases from a Ginzburg-Landau potential $(V = A\sigma^2 + B\chi^2 + \cdots)$

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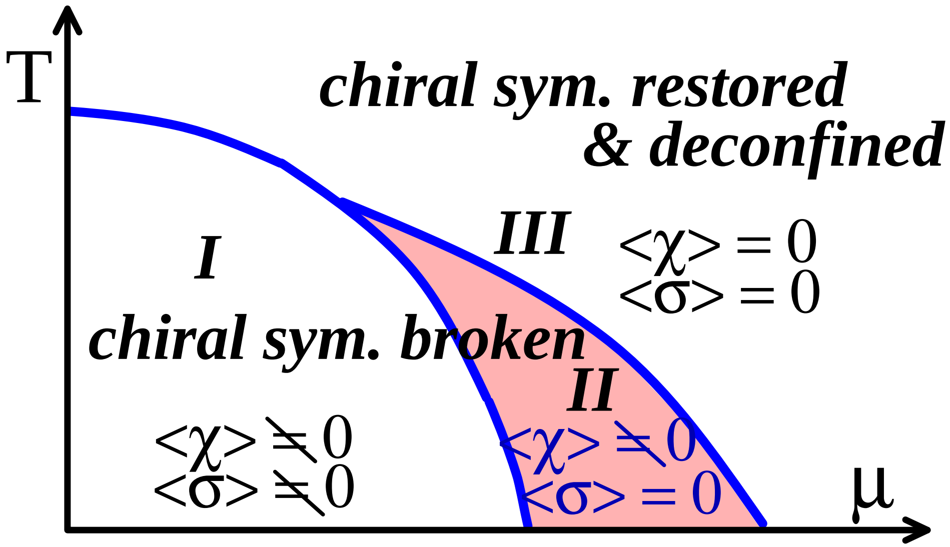

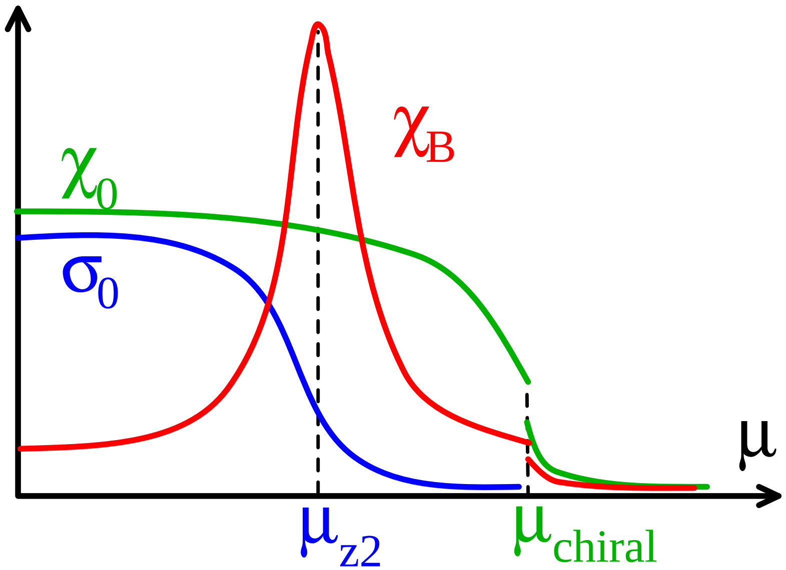

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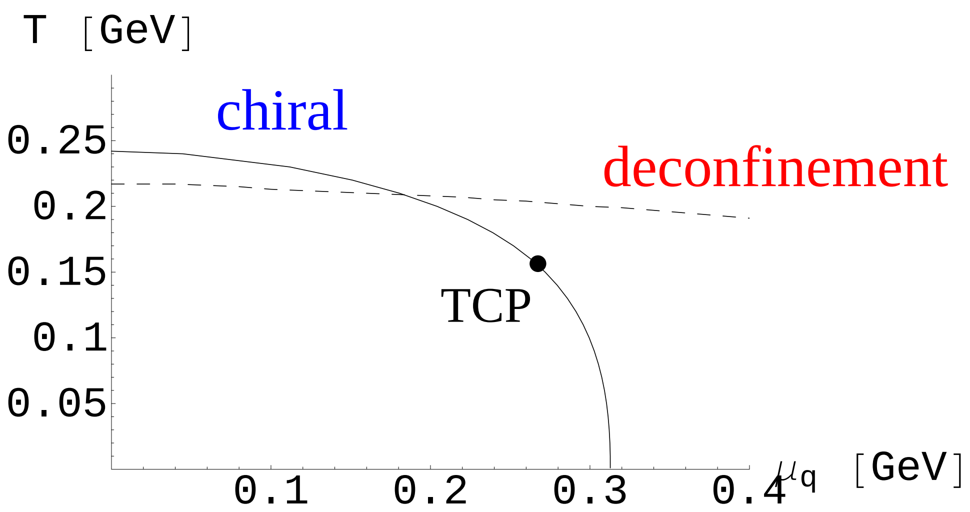
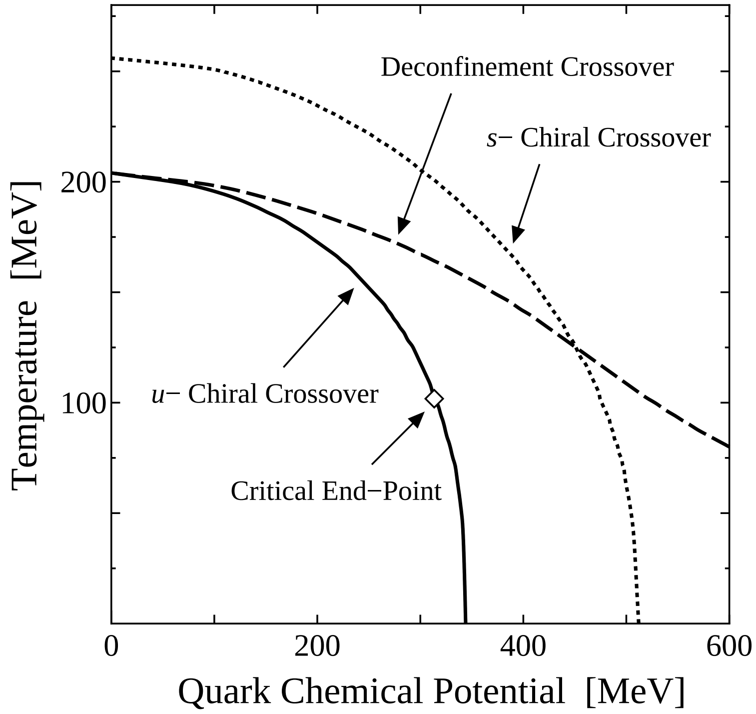
  I-II: χ_B max. $(\sigma \to 0)$

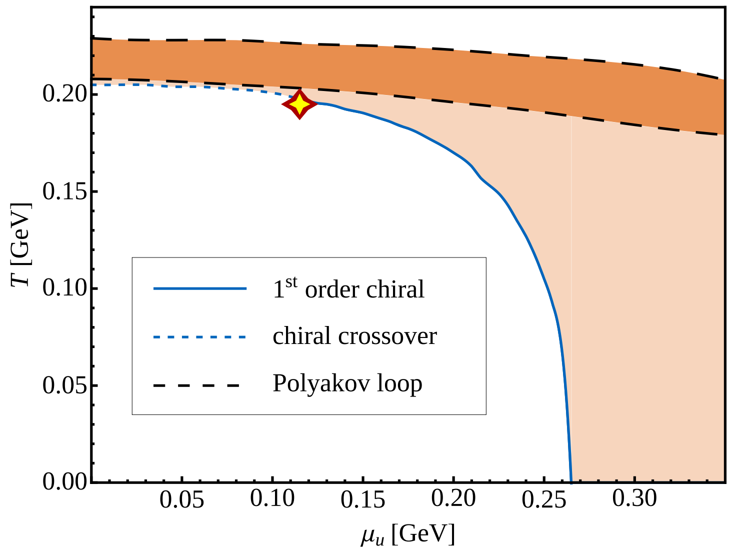
  II-III: χ_B no much change (no Yukawa term $\bar{N}N\chi$ in phase II)
- χ_B max. along Z_2 restoration line : baryons more activated

What is constraint on phases in quantum field theories?

- **phase diagram from PNJL models: 3 regions**







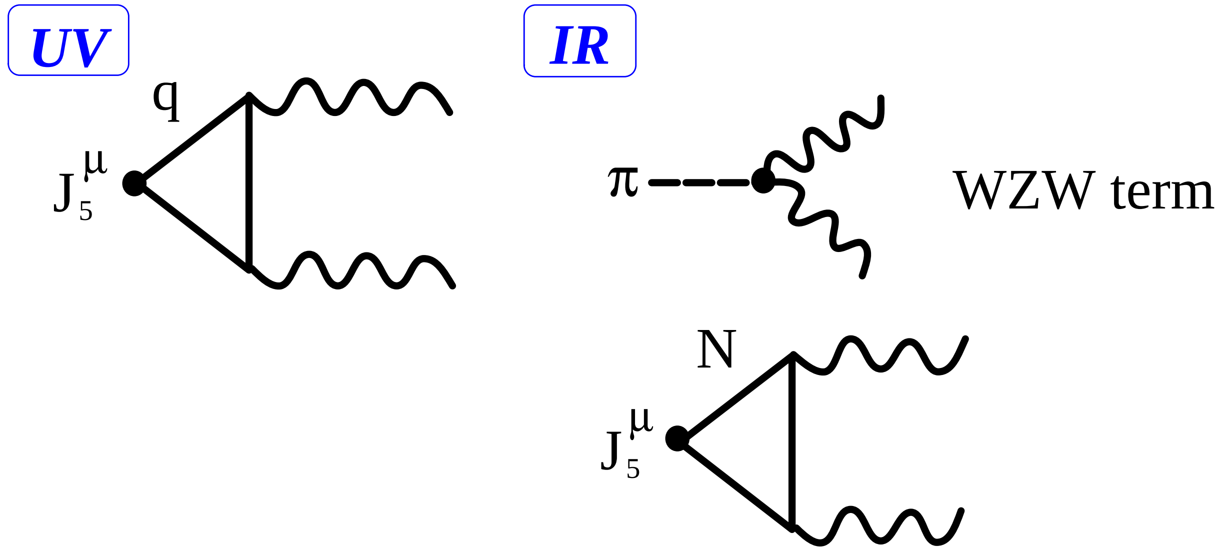
[upper-left] CS-Friman-Redlich (06)

[upper-right] Fukushima (08)

[lower] Hell-Roessner-Cristoforetti-Weise (09)

confinement in Wigner-Weyl phase?

- **anomaly matching between UV and IR theories**



– chirally restored phase: no NG boson thus no WZW term

– triangle diagrams with baryons: matched for $N_f = 2$ but not for $N_f = 3$

triangle graph $\propto$ tr$[T^a\{Q, Q\}]$ [Shifman (89)]

$$N_f = 2 : \text{(quark)}\ 3Nc/9 = 1 \quad \text{(hadron)} \ \ = 1$$

$$N_f = 3 : \text{(quark)}\ 3Nc/9 = 1 \quad \text{(hadron)} \ \ = 0$$

anomalies can match only if the system is deconfined.

Summary and prospects

- **dense nuclear matter and its modeling**
  - saturation properties $\Rightarrow$ parity doublet model
  - meson-baryon "transition": a trace of LG transition
  - $SU(N_f)_L \times SU(N_f)_R \times Z_{N_f}$ in dense matter
    $\Rightarrow$ a model for 2- and 4-quark states
  - enhancement of χ_B associated with Z_{N_f} symmetry restoration
    baryons are more activated in this *broken* phase.
- **anomaly matching in matter**
  - any gapless mode other than pions?
- **origin of hadron masses**
  - trace anomaly and hadron mass generation?
  - how to discriminate two scenarios (naive vs. mirror)?