Chiral Thermodynamics of Dense QCD
— Baryons, Glueballs and Polyakov loops —

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References

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- W.-G.Paeng, H.K.Lee, M.Rho, C.S., Phys. Rev. D **85**, 054022 (2012).
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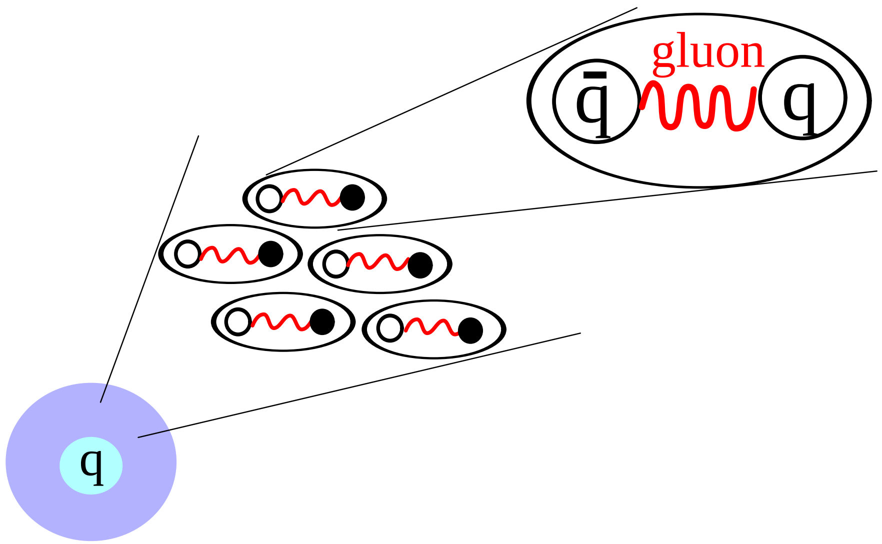
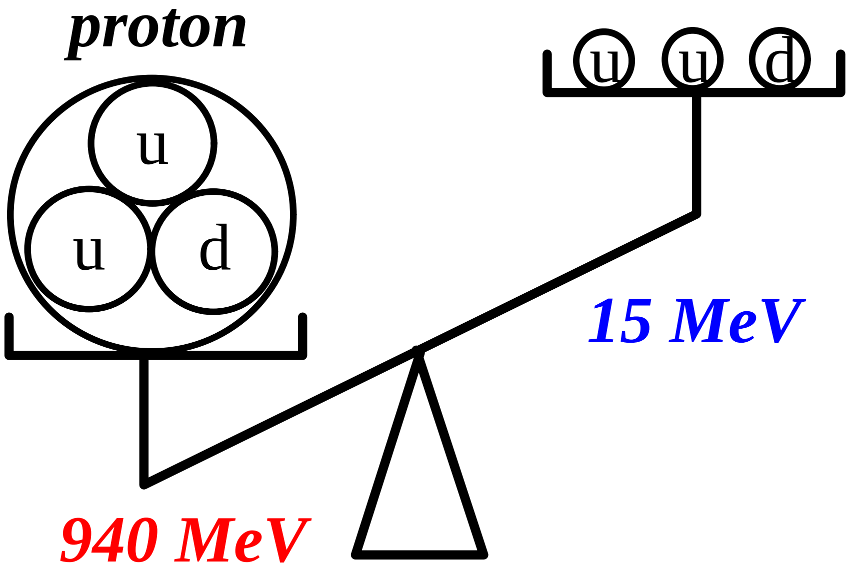
- C.S. and K. Redlich, to appear on arXiv.

I. Main Objectives

Origin of hadron masses?

- spontaneous chiral symmetry breaking $\cdots$ dynamics of strong int., $\Lambda_{\rm QCD}$





- scale symmetry breaking $(x^\mu \to e^\tau x^\mu)$ $\cdots$ emergence of a scale in QCD

$$\partial_\mu J^\mu = T^\mu_\mu = -\left(\frac{11}{24}N_c - \frac{1}{12}N_f\right)\frac{\alpha_s}{\pi}G_{\mu\nu}G^{\mu\nu} + \sum_f m_f \bar{q}_f q_f$$

- chiral SB and trace anomaly closely related $\longrightarrow$ hadron masses

$$m_H = \mathcal{F}\left(\text{CSB}\,,\text{non-CSB}\right)$$

Baryons near chiral symmetry restoration

- m_N at χ-symmetry restoration? $\cdots$ dynamical origin of nucleon mass?
  - standard assignment: DχSB generates entire masses. $\quad m_N \overset{\sigma\to 0}{\to} 0$

$$\psi_L \to L\,\psi_L\,, \quad \psi_R \to R\,\psi_R \quad \Rightarrow \text{ no } \bar{\psi}\psi$$

  - mirror assignment: DχSB generates mass difference of parity doublers.

$$m_{N_+} \overset{\sigma\to 0}{\to} m_{N_-} = m_0 \neq 0$$ [Detar-Kunihiro (89)]

$$\psi_{1L} \to L\,\psi_{1L}\,, \quad \psi_{1R} \to R\,\psi_{1R}\,, \quad \psi_{2L} \to R\,\psi_{2L}\,, \quad \psi_{2R} \to L\,\psi_{2R}$$

$$\mathcal{L}_m = m_0\left(\bar{\psi}_2\gamma_5\psi_1 - \bar{\psi}_1\gamma_5\psi_2\right) \;\Rightarrow\; m_{N_\pm} = \frac{1}{2}\left[\sqrt{c_1\sigma^2 + 4m_0^2} \mp c_2\sigma\right]$$

- how large is m_0?
  - vacuum: 300 MeV from $N^* \to N\pi$ [DeTar-Kunihiro (89), Nemoto et al. (98)]
  - nuclear matter: $800 \overset{\text{4quark}}{\Rightarrow} 500$ MeV [Zschiesche et al. (07), Gallas et al. (11)]
  - finite $T \simeq T_{\rm ch}$: 200 MeV from $\langle G_{\mu\nu}G^{\mu\nu}\rangle_T$ [CS-Lee-Paeng-Rho (11)]

Role of scalar bosons in nuclear matter

- how to have empirical saturation in Walecka model? [e.g., Serot-Walecka (97)]
  - Walecka "classic" (w/o chiral symmetry)

    $$\mathcal{L} = \bar{N}\left(i\partial\!\!\!/ - g_V \omega\!\!\!/ - M + g_s \phi\right) N + \mathcal{L}_{\text{kin+mass}}(\omega) + \mathcal{L}_{\text{kin+mass}}(\phi) - |\kappa|\phi^3 + |\lambda|\phi^4$$

    with appropriate parameters, NM saturation properties
  - Walecka model with chiral symmetry (LσM)

    $$\mathcal{L} = \bar{N}\left(i\partial\!\!\!/ - g_V \omega\!\!\!/ - M + g_\pi \sigma\right) N + \mathcal{L}_{\text{kin+mass}}(\omega) + \mathcal{L}_{\text{kin+mass}}(\sigma) - |\tilde{\kappa}|\sigma^3 - |\tilde{\lambda}|\sigma^4$$

    chiral symmetry: the signs and magnitudes of interactions

  however,

  $*$ wrong sign in σ^4

  $*$ too large $\tilde{\kappa} \gg \kappa$

  $\Rightarrow$ no stable ground state! [Kerman-Miller (74)]

  $\Rightarrow$ $\phi \neq \sigma$ and thus sigma-meson part needs to be modified.

- **Q. what is the scalar boson ϕ?**

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  A. a mixture of quarkonia, tetraquarks and glueballs

  – tetraquarks in scaler phenomenology at $T = \rho = 0$ [Jaffe (77)]

  – a mixture of a quarkonium and tetraquark at ρ_0: successful with binding energy, saturation point and compressibility [Gallas et al. (11)]

  – origin of chirally invariant mass m_0: a part of gluon condensate surviving in chiral restored phase [Lee-Rho (09), CS-Lee-Paeng-Rho (10)]

- **towards chiral restoration:**
  scalar meson gets lighter $\Rightarrow$ O(4) multiplet with pions $(\vec{\pi}, s)$

How does Walecka's scalar transmute into the 4th component of O(4) multiplet?

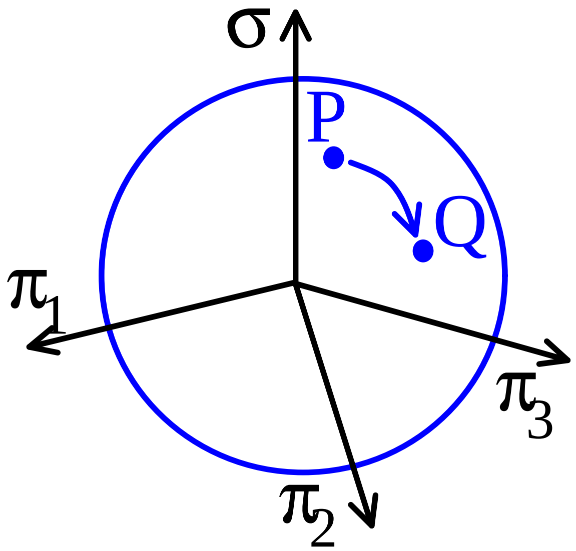
$\Rightarrow$ combine chiral symmetry breaking and trace anomaly in a single theory

II. Transmutation of a Scalar

Role of scalar mesons: nonlinear vs linear

- nonlinear realization of chiral symmetry
  d.o.f.: pions, NO scalar mesons   loops: chiral perturbation theory
- near χSR: scalar meson gets lighter $\Rightarrow$ O(4) multiplet with pions $(s, \vec{\pi})$

- **from linear to non-linear basis, or the other way around**



$P \longrightarrow Q$: chiral transformation

$$\Phi = \sigma + i\vec{\tau}\cdot\vec{\pi} \qquad f_\pi = \sqrt{\sigma^2 + \vec{\pi}^2}$$

$$= (\sigma_0 + \tilde{\sigma})U\,, \quad U = e^{-i\vec{\tau}\cdot\vec{\pi}/f_\pi}$$

$$\Rightarrow \mathcal{L} = \frac{f_\pi^2}{4}\mathrm{tr}\left[\partial_\mu U^\dagger \partial^\mu U\right]$$

- **two-component gluon condensate** [Miransky-Gsynin (89), Lee-Rho (09)]
  - trace anomaly in QCD

$$\partial_\mu J^\mu = T^\mu_\mu \propto \langle H|G^2|H\rangle\,, \quad H = \text{quarkonium, glueballs, etc.}$$

  - decomposition

$$\langle H|G^2|H\rangle = \underbrace{\langle G^2\rangle_{\rm soft}}_{\chi\text{SB}\,,\,N_cN_f} + \underbrace{\langle G^2\rangle_{\rm hard}}_{\text{CSB}\,,\,N_c^2}$$

  - from Lattice EoS: gluon *decondensation* at finite T [Miller (07)]

$$\langle G^2\rangle_{T_{\rm chiral}} \simeq \frac{1}{2}\langle G^2\rangle_{T=0} \quad \Rightarrow \quad \text{melting}\,\langle G^2\rangle_{\rm soft}$$

  - soft and hard dilatons

$$V(\chi) = V(\chi_s) + V(\chi_h)\,, \quad V_i = \frac{1}{4}B_i\left(\frac{\chi_i}{F_{\chi_i}}\right)^4\left[\ln\left(\frac{\chi_i}{F_{\chi_i}}\right)^4 - 1\right]$$

  - **role of hard dilaton**
    origin of m_0, bag "function": $B(T_{\rm chiral}) \simeq \frac{1}{2}B(T=0)$

- **transmutation of a scalar from NLSM to LSM** [Beane-van Kolck (94)]

1. soft dilaton (gluonium) in a NLSM: $U = \xi^2 = e^{2i\pi/F_\pi}$, $\sqrt{\kappa} = F_\pi / F_{\chi_s}$

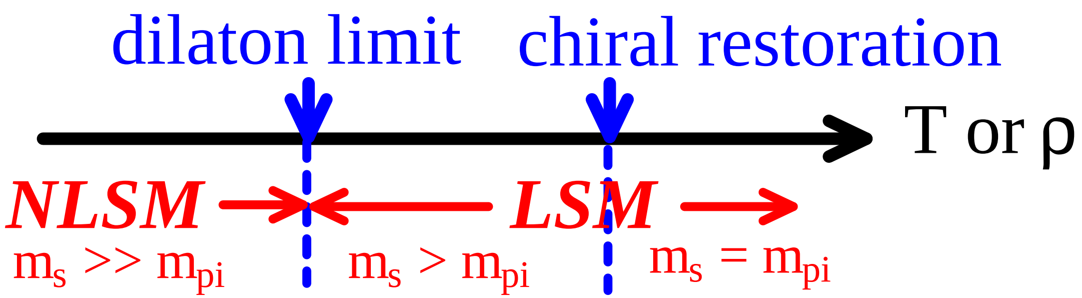
$$\mathcal{L} = \bar{\psi} i(\partial\!\!\!/ + V\!\!\!/)\psi + g_A \bar{\psi} A\!\!\!/ \gamma_5 \psi - m \left(\frac{\chi_s}{F_{\chi_s}}\right) \bar{\psi}\psi + \frac{F_\pi^2}{4}\left(\frac{\chi_s}{F_{\chi_s}}\right)^2 \mathrm{tr}\left[\partial_\mu U^\dagger \partial^\mu U\right] + \mathcal{L}(\chi_s)$$

2. linearization: $\Sigma = \sqrt{\kappa} U \chi = s + i\vec{\tau}\cdot\vec{\pi}$ & $B = \frac{1}{2}[(\xi + \xi^\dagger) - \gamma_5(\xi - \xi^\dagger)]\psi$

$$\mathcal{L} = \bar{B} i\partial\!\!\!/ B - \frac{m_N}{2F_\pi}\bar{B}\left[\Sigma + \Sigma^\dagger + \gamma_5\left(\Sigma - \Sigma^\dagger\right)\right]B + \frac{1}{4}\mathrm{tr}\left[\partial_\mu \Sigma \cdot \partial^\mu \Sigma^\dagger\right]$$
$$+ \frac{m_s^2}{64 F_\pi^2}\left(\mathrm{tr}\left[\Sigma\Sigma^\dagger\right]\right)^2 - \frac{m_s^2}{32 F_\pi^2}\left(\mathrm{tr}\left[\Sigma\Sigma^\dagger\right]\right)^2 \ln\left(\frac{\mathrm{tr}\left[\Sigma\Sigma^\dagger\right]}{2F_\pi^2}\right) + \mathcal{L}_{\mathrm{sing}}(1/\mathrm{tr}[\Sigma\Sigma^\dagger]; \kappa, g_A)$$

3. a LSM $\mathcal{L}(s, \vec{\pi}, B)$ emerges when $\kappa \to 1$ & $g_A \to 1$ (dilaton limit).

$$\mathcal{L}_{\mathrm{sing}} = (1-\kappa)\mathcal{F}(1/\mathrm{tr}[\Sigma\Sigma^\dagger]) + (1-g_A)\mathcal{G}(1/\mathrm{tr}[\Sigma\Sigma^\dagger]) \to 0$$



- **introduce vector mesons:** $(N\,,\pi\,,\rho\,,\omega\,,\chi)$ [CS-Lee-Paeng-Rho (2011)]

  hidden local symmetry (HLS) [Bando-Kugo-Uehara-Yamawaki-Yanagida (85)]

  – an extension of non-linear chiral Lagrangian: $U = \xi^2 \to \xi_L^\dagger \xi_R$

  – vector mesons $V = \rho, \omega$ introduced as gauge bosons of HLS (redundancy in decomposition of U)

results:

– dilaton limit: $\kappa = 1$ and $g_A = g_V$ (common to "naive" and mirror)

cf. $g_A = 1$ recovers algebraic sum rules [Beane-van Kolck (94)]

– consequence: VN repulsion suppressed $g_{VN} = g\,(1 - g_V) \to 0$

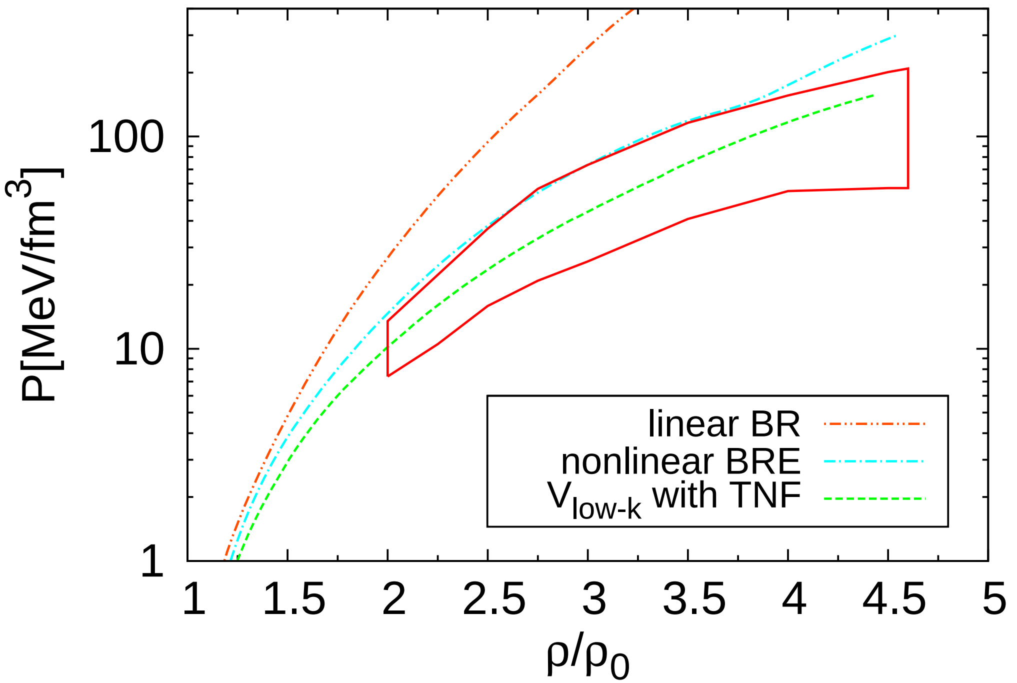
  * **softer equation of state at high density**
  * **two-body repulsion via vector-meson exchanges suppressed**
  * **symmetry energy suppressed:** $E_{\rm sym} \propto g_{\rho N}^2$

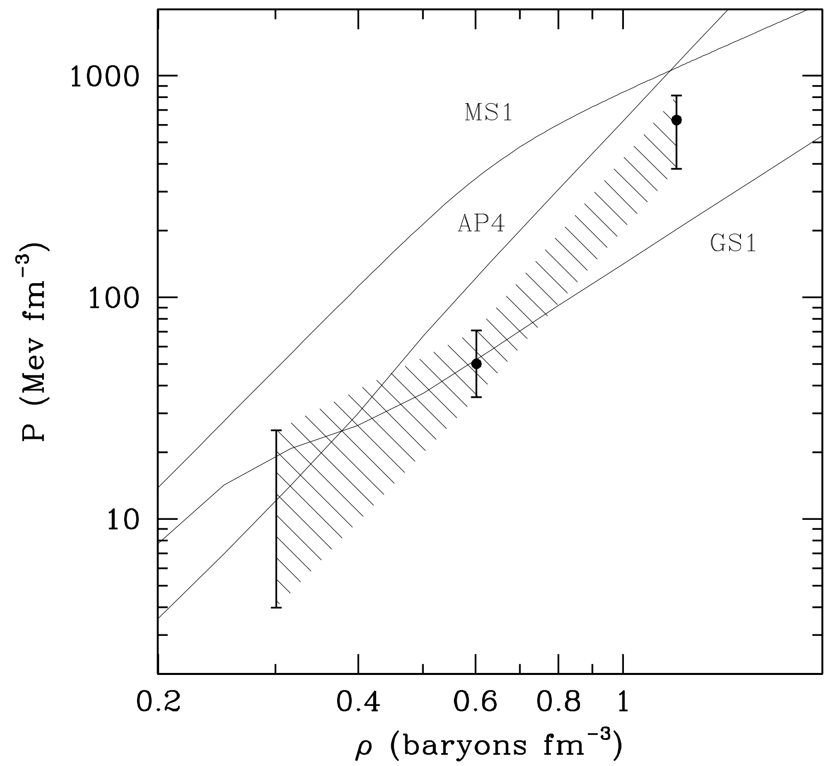
    energy per nucleon $E/A = E(\rho) + E_{\rm sym}(\rho)\alpha^2 + \cdots$ with asymmetric parameter $\alpha = (\rho_n - \rho_p)/(\rho_n + \rho_p)$

– unchanged at quantum level: IR fixed point $(g_A = g_V = 1)$

Implications, remarks and issues

symmetric/asymmetric nuclear matter EoS





symmetric matter [Dong et al. (11)]

with constraint from HIC [Danielewicz et al. (02)]

asymmetric matter [Ozel et al. (10)]

AP4,MS1:only nucleons, GS1:kaon cond.

- how does $E_{\rm sym}$ behave above ρ_0? onset of kaon condensation?
- softer EoS w/ quenching $g_{\rho N}$ vs. $1.97 M_\odot$ neutron star? [Demorest et al. (10)]

scaler modes and mixing

- 2-quark, 4-quark and glueball states, three-level crossing at T and ρ
- a toy model implementing chiral sym. and scale inv. [CS-Mishustin (11)]

$$\mathcal{L} = \mathcal{L}_{\mathrm{QM}}(\sigma, \vec{\pi}, q) + \mathcal{L}_{\mathrm{gauge}}(A_\mu) + \mathcal{L}_{\mathrm{glueball}}(\chi)$$

  – effective quark and gluon masses via condensates σ and χ
  – role of gluons: better description for energy density at high T
  – a large vacuum-mass $m_\sigma \sim 1$ GeV favored
    $\cdots$ constrained by interaction measure at $\mu = 0$ from Lattice QCD

what protects dilaton-limit fixed point?

- vector realization? [Georgi (89,90)]: $\rho_V \sim \rho_A$ but $f_\pi \neq 0$
- mended symmetry? [Weinberg (69,90)]: $(s\,,\pi\,,\rho\,,a_1)$ classified by 4 irreducible representations

III. Pure Yang-Mills Thermodynamics and Polyakov Loops

IV. Conclusions and Remarks

(I) dilaton-implemented chiral physics

- **an effective chiral Lagrangian with scale invariance**
  - dilaton limit associated with IR fixed point at quantum level
  - consequence: VN repulsive forces suppressed
  - common to standard and mirror assignments of chirality
- **at which T or ρ does dilaton limit set in?**
- **mixed scaler modes: quarkonium, tetraquarks, glueballs**
- **how to make a reliable estimate of m_0 in dense matter?**
- **what are phenomenological consequences on thermodynamics?**

  [Paeng-Lee-Rho-CS]

(II) role of Polyakov loops in quasi-particle approaches

- **derivation of gluon partition function from YM Lagrangian**
  - Polyakov loops naturally appear representing group character.
  - gluons are forbidden below T_c dynamically. a hybrid approach.
- **further thermodynamics vs. lattice QCD** [Lo-Friman-Kaczmarek-Redlich-CS]