Nuclear Symmetry Energy in QCD degree of freedom

Phys. Rev. C87 (2013) 015204 (arXiv:1209.0080)
Eur. Phys. J. A50 (2014) 16
Some preliminary results

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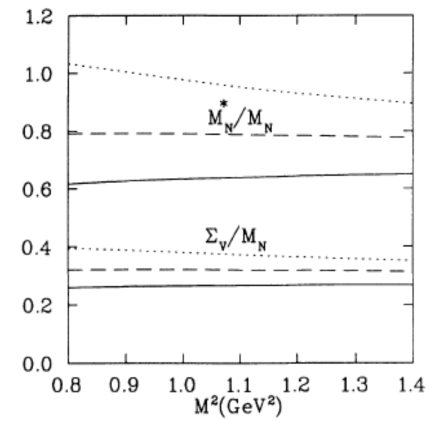
Motivation and Outline

- Nuclear phenomenology – QCD sum rule

$$U \simeq S + V\gamma^0$$

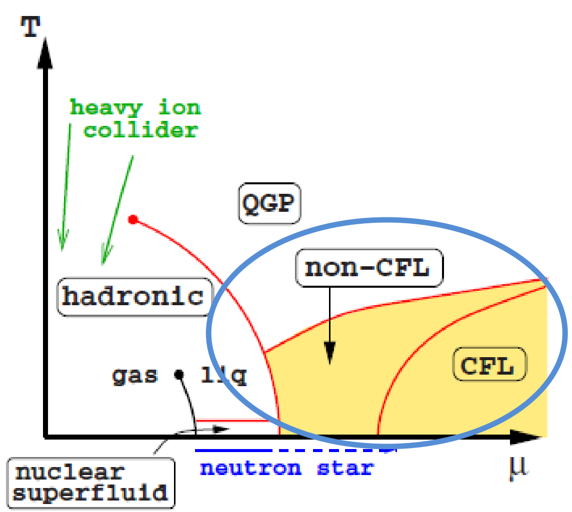
$$G(q) = \frac{1}{\not{q} - M_n - \Sigma(q)} \rightarrow \lambda^2 \frac{\not{q} + \boxed{M^*} - \boxed{\not{u}\Sigma_v}}{(q_0 - E_q)(q_0 - \bar{E}_0)}$$

$$\boxed{M^* < M_n} \qquad \boxed{\Sigma_v > 0}$$



Physical Review C49, 464 (1993)
(Thomas Cohen et al.)

- Extremely high density matter?
  – QCD itself is main dynamics



Rev. Mod. Phys. 80, 1455 (2008) (M. G. Alford et al.)

Cold matter Symmetry Energy from

$$\mathcal{Z}_\Omega = \mathrm{Tr}\exp\left[-\beta(\hat{H} - \vec{\mu}\cdot\hat{\vec{N}})\right]$$

$$= \int [D(\text{fields})] \exp\left[-\int_0^\beta d\tau \int x^3 \mathcal{L}_E(\text{fields})\right]$$

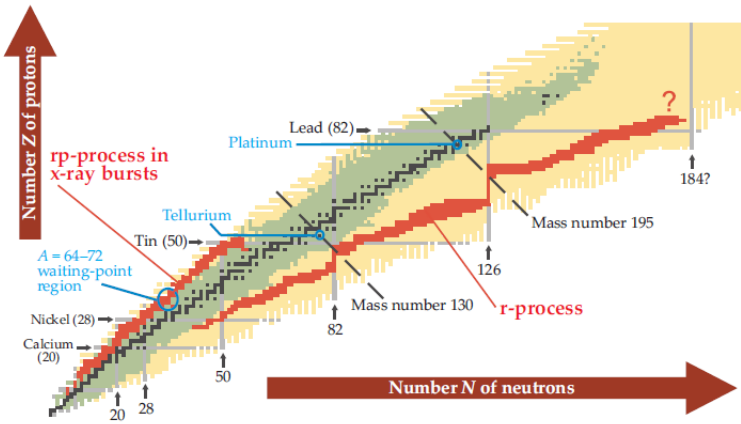
Hard Dense Loop resummation
Color BCS pairing

Nuclear Symmetry Energy

- From equation of state

Bethe-Weisaker formula

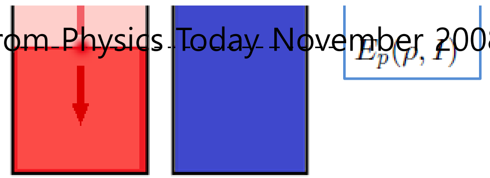
$$m_{tot} = Nm_n + Zm_p - E_B/c^2$$
$$E_B = a_V A - a_S A^{\frac{2}{3}} - a_C(Z(Z-1))A^{-\frac{1}{3}} - a_A I^2 A + \delta(A,Z)$$
$$I = (N-Z)/A$$



(Quoted from Physics Today November 2008)

In continuous matter

$$\bar{E}(\rho_N, I) = \bar{E}(\rho_N) + \bar{E}_{sym}(\rho_N) I^2 + \cdots$$
$$I = (\rho_n - \rho_p)/\rho$$



(Asymmetric)

$$\overline{E} = \frac{1}{\int d^3k_n d^3k_p} \int d^3k_n d^3k_p E(\rho_n, \rho_p)$$
$$\Rightarrow E_{sym} = \frac{1}{2I} \cdot (\bar{E}_n - \bar{E}_p)$$ (Up to linear density order)

- RMFT propagator

$$G(q) = -i \int d^4x e^{iqx} \langle \Psi_0 | \mathrm{T}[\psi(x)\bar{\psi}(0)] | \Psi_0 \rangle = \frac{1}{\not{q} - M_n - \Sigma(q)} \to \lambda^2 \frac{\not{q} + M^* - \not{u}\Sigma_v}{(q_0 - E_q)(q_0 - \bar{E}_0)}$$

QCD Sum Rule

- Correlation function

$$\Pi(q) \equiv i \int d^4x \, e^{iqx} \langle \Psi_0 | \mathrm{T}[\eta(x)\bar{\eta}(0)] | \Psi_0 \rangle$$
$$= \Pi_s(q^2, q\cdot u) + \Pi_q(q^2, q\cdot u)\not{q} + \Pi_u(q^2, q\cdot u)\not{u}$$

$$\eta(x) = \epsilon_{abc}[u_a^T(x) C \gamma_\mu u_b(x)] \gamma_5 \gamma^\mu d_c(x)$$

Ioffe's interpolating field for proton

- Energy dispersion relation and OPE

$$\Pi_i(q_0, |\vec{q}|) = \frac{1}{2\pi i} \int_{-\infty}^{\infty} d\omega \frac{2\mathrm{Im}\Pi_i(\omega, |\vec{q}|)}{\omega - q_0} + \text{polynomials}$$

Contains **all possible hadronic resonance states** in **QCD degree of freedom**

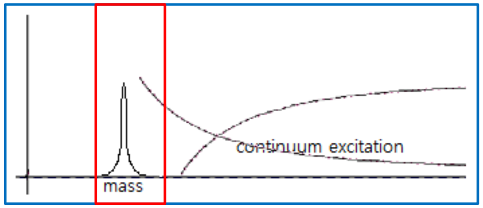
- Phenomenological ansatz in **hadronic degree of freedom**

$$\Pi(q_0, |\vec{q}|) \sim \frac{1}{(q^\mu - \tilde{\Sigma}_v^\mu)\gamma_\mu - M_N^*}$$

Equating both sides, hadronic quantum number can be expressed in QCD degree of freedom

- Weighting - Borel transformation

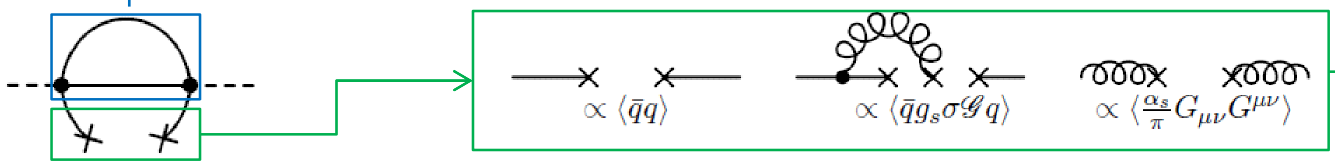
$$\mathcal{B}[\Pi_i(q_0, |\vec{q}|)] \equiv \lim_{\substack{-q_0^2, n \to \infty \\ -q_0^2/n = M^2}} \frac{(-q_0^2)^{n+1}}{n!} \left(\frac{\partial}{\partial q_0^2} \right)^n \Pi_i(q_0, |\vec{q}|)$$



QCD Sum Rule

- Operator Product Expansion

$$\Pi_i(q_0,|\vec{q}|) = \frac{1}{2\pi i}\int_{-\infty}^{\infty} d\omega \frac{2\mathrm{Im}\Pi_i(\omega,|\vec{q}|)}{\omega - q_0} + \text{polynomials} = \sum_n C_n^i(q^2,q_0^2)\langle \hat{O}_n\rangle_{\rho,I}$$



Non-perturbative contribution

- In-medium condensate near normal nuclear density

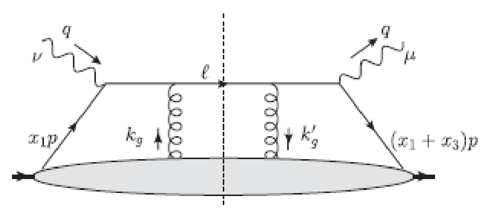
$$\langle \hat{O}_{u,d}\rangle_{\rho,I} = \langle \hat{O}_{u,d}\rangle_{\text{vac}} + (\langle p|\hat{O}_0|p\rangle \mp \langle p|\hat{O}_1|p\rangle I)\rho$$

Medium property can be accounted by nucleon expectation value x density

- Multi-quark operators (Twist-4)

$$\langle(\bar{q}_1\gamma^\alpha\gamma_5 t^A q_1)(\bar{q}_2\gamma^\beta\gamma_5 t^A q_2)\rangle_p$$
$$\langle(\bar{q}_1\gamma^\alpha t^A q_1)(\bar{q}_2\gamma^\beta t^A q_2)\rangle_p$$

can be estimated from DIS experiments data

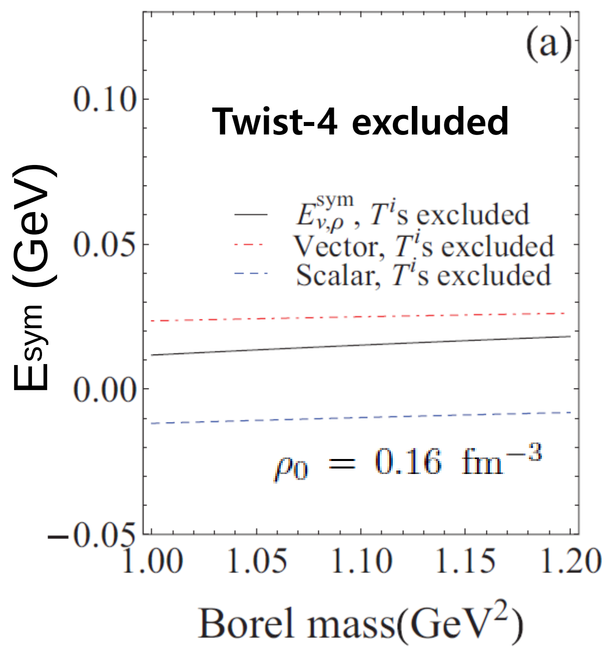


(a)

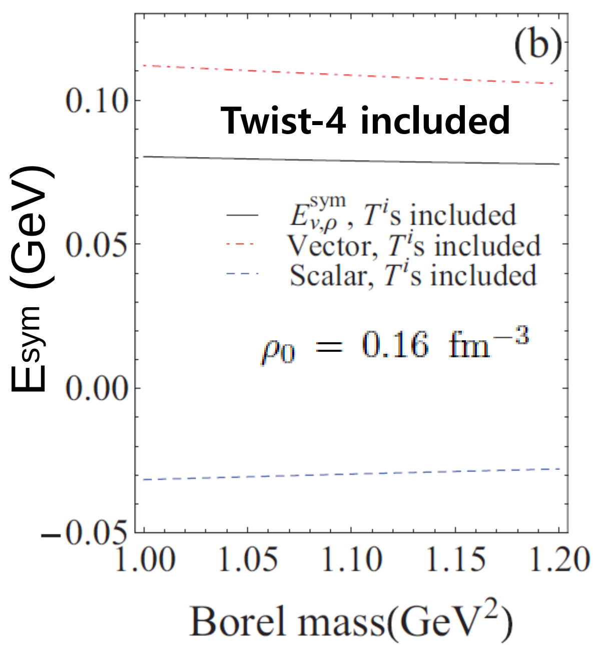
Nuclear Symmetry Energy from QCD SR

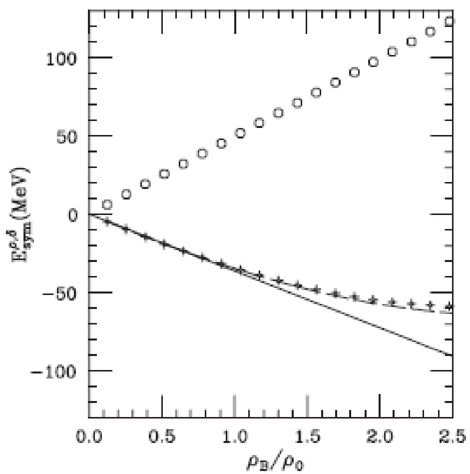
- **Iso-vector** scalar / vector decomposition

$\langle \bar{d}d \rangle - \langle \bar{u}u \rangle \quad \langle d^\dagger d \rangle - \langle u^\dagger u \rangle$



$\langle (\bar{d}\Gamma^\mu d)(\bar{d}\Gamma^\nu d) \rangle - \langle (\bar{u}\Gamma^\mu u)(\bar{u}\Gamma^\mu u) \rangle$





Physics Report, 410, 335 (2005)
(V. Baran et al.)

- Comparison with RMFT result

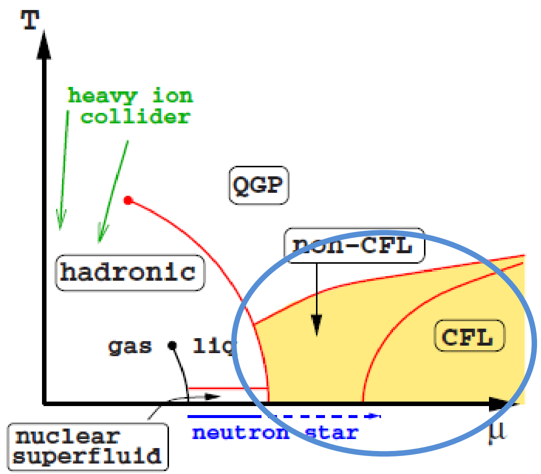
$$E^{sym}_V = \frac{1}{2}\left[f_\rho - f_\delta \left(\frac{m^*}{E^*_F} \right) \right] \rho_B$$

Iso-vector meson exchange

High density behavior -> high density dependence of condensates

At extremely high density?

- QCD phase transition



- In $1/\mu \ll 1/\Lambda_{\rm QCD}$ region, **QCD** can be immediately applicable
- Statistical partition function for dense QCD

$$\mathcal{Z}_\Omega = \mathrm{Tr}\exp\left[-\beta(\hat{H} - \vec{\mu}\cdot\hat{\vec{N}})\right]$$
$$= \int [D(\text{fields})]\exp\left[-\int_0^\beta d\tau \int x^3 \mathcal{L}_E(\text{fields})\right]$$

- Normal QM phase - BCS paired phase

- Euclidean Lagrangian for dense QCD **at normal phase**

$$\mathcal{L}_E = \frac{1}{4}F^a_{\mu\nu}F^a_{\mu\nu} + \frac{1}{2\xi}(\partial_\mu A^a_\mu)^2 + \bar{\eta}^a(\partial^2\delta_{ab} + g f_{abc}\partial_\mu A^c_\mu)\eta^b$$
$$+ \sum_f^{n_f}\left[\psi_f^\dagger\partial_\tau\psi_f + \bar{\psi}_f(-i\gamma^i\partial_i + m_f)\psi_f - \mu_f\psi_f^\dagger\psi_f - g\bar{\psi}_f \not{A}\psi_f\right]$$

$$\int \frac{d^4Q}{(2\pi)^4} \equiv T\sum_n \int \frac{d^3q}{(2\pi)^3}, \quad Q_\mu = (-\omega, \vec{q})$$

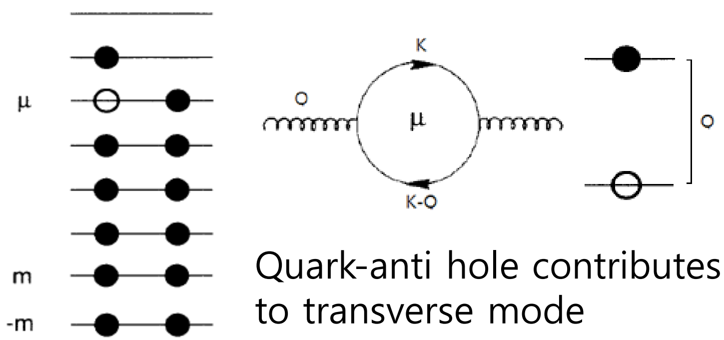
$\omega_n = (2n+1)\pi/\beta$ (For fermion)

$\omega_n = 2n\pi/\beta$ (For boson)

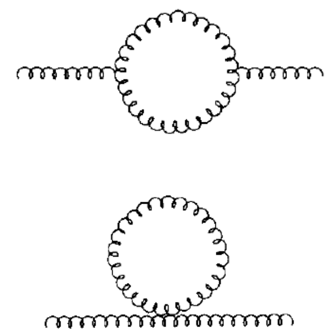
Continuous energy integration -> Discrete sum over Matsubara frequency

Hard Dense Loop resumation

- Quark-hole excitation is dominant ($Q \sim T \leq g\mu$)



Quark-anti hole contributes to transverse mode



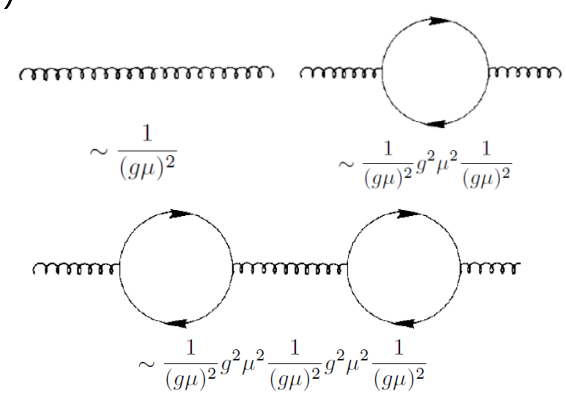
Gluon/Ghost contribution is negligible at $Q \sim T \leq g\mu$

- Gluon self energy in cold matter ($Q \sim T \leq g\mu$)

$$\Pi_{\mu\nu}(Q) = g^2 \mathrm{Tr}\left[\gamma_\mu S_F(K)\gamma_\nu S_F(K-Q)\right]$$
$$= \frac{1}{2} g^2 \left(\sum_f \frac{\mu_f^2}{\pi^2}\right) \int \frac{d\Omega}{4\pi} \left(\delta_{\mu 4}\delta_{\nu 4} + \hat{K}_\mu \hat{K}_\nu \frac{i\omega}{Q \cdot \hat{K}}\right)$$

$\sim g^2\mu^2$ order

Phys. Rev. D.53.5866 (1996) C. Manuel
Phys. Rev. D.48.1390 (1993) J. P. Blaizot and J. Y. Ollitrault



All equivalent 1PI diagrams should be resumed!

Hard Dense Loop resumation

- Projection along polarization

Euclidean propagator

$$*D_{\mu\nu} = \frac{1}{Q^2 + \delta\Pi^L} P^L_{\mu\nu} + \frac{1}{Q^2 + \delta\Pi^T} P^T_{\mu\nu} + \frac{1}{f_e} \frac{Q_\mu Q_\nu}{Q^2}$$

$$P^T_{ij} = \delta_{ij} - \hat{q}_i \hat{q}_j, \, P^T_{44} = P^T_{4i} = 0$$

$$P^L_{\mu\nu} = \delta_{\mu\nu} - \frac{Q_\mu Q_\nu}{Q^2} - P^T_{\mu\nu}$$

Longitudinal and transverse part

$$\delta\Pi^L(Q) = 2\sum_f \left(\frac{1}{2} g^2 \frac{\mu_f^2}{\pi^2}\right) \frac{Q^2}{q^2} \left(1 - \left(\frac{i\omega}{q}\right) Q_0\left(\frac{i\omega}{q}\right)\right) \Rightarrow 2m_g^2 = g^2 \frac{\mu_f^2}{\pi^2}$$ (In w->0 limit)

$$\delta\Pi^T(Q) = \sum_f \left(\frac{1}{2} g^2 \frac{\mu_f^2}{\pi^2}\right) \left(\frac{i\omega}{q}\right) \left[\left(1 - \left(\frac{i\omega}{q}\right)^2\right) Q_0\left(\frac{i\omega}{q}\right) + \left(\frac{i\omega}{q}\right)\right] \Rightarrow 0$$

- Debye mass and effective Lagrangian

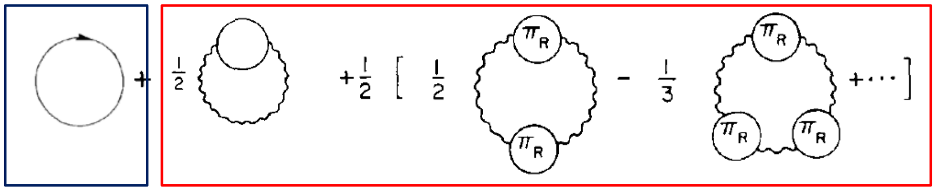
Effective Lagrangian for soft gluon in cold dense matter

$$\mathcal{L} = -\frac{1}{4} F^2 \to \frac{1}{2} A_\mu (-Q^2 g^{\mu\nu} + \boxed{M_g^2 P_L^{\mu\nu}} + O(\omega/q) P_T^{\mu\nu} + \cdots) A_\nu$$

Debye mass from HDL

HDL resumed thermodynamic potential

- Relevant ring diagrams



Where  in $T \leq g\mu$ limit

$$\Omega(\mu) = -\left[\frac{1}{4}\sum_f \frac{\mu_f^4}{\pi^2} + \alpha_s^2 \frac{2}{\pi}\left(\sum_f \frac{\mu_f^2}{\pi^2}\right)^2 \left[\Lambda_1 - \Lambda_2 - \alpha \ln 2 - \ln\left(\sum_f \frac{\mu_f^2}{\pi^2}\frac{1}{\mu^2}\right)\Lambda_1\right] - \alpha_s^2 \ln \alpha_s \frac{2}{\pi}\left(\sum_f \frac{\mu_f^2}{\pi^2}\right)^2 \Lambda_1\right]$$

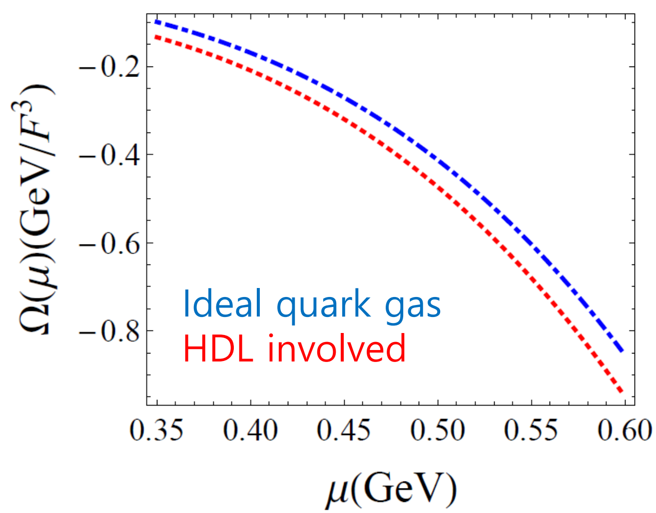
- Thermodynamic quantities can be obtained from $\Omega(\mu)$

$$\Omega(\mu) = \langle \hat{H} \rangle - \vec{\mu} \cdot \langle \hat{\vec{N}} \rangle = -\frac{1}{\beta V} \ln \mathcal{Z}_\Omega,$$

$$\rho_i(\mu) = \frac{\langle \hat{N}_i \rangle}{V} = \frac{1}{\beta V}\frac{\partial}{\partial \mu_i} \ln \mathcal{Z}_\Omega,$$

$$\epsilon(\mu) = \frac{\langle \hat{H} \rangle}{V} = -\frac{1}{V}\left(\frac{\partial}{\partial \beta} - \frac{1}{\beta}\vec{\mu} \cdot \frac{\partial}{\partial \vec{\mu}}\right) \ln \mathcal{Z}_\Omega,$$

$$I_B = \frac{\rho_3}{\rho_B} = 3\frac{\rho_u - \rho_d}{\rho_u + \rho_d} \qquad \mu_d^u = \mu\left(1 \pm \frac{1}{3} I_B\right)^{\frac{1}{3}}$$



Symmetry Energy at normal phase

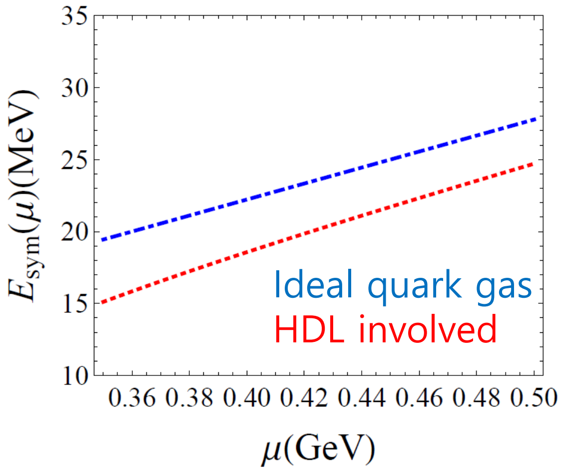
- **Symmetry Energy**

$$\frac{\epsilon(\mu, I_B)}{\rho(\mu, I_B)} = \frac{E(\mu, I_B)}{N_B}$$

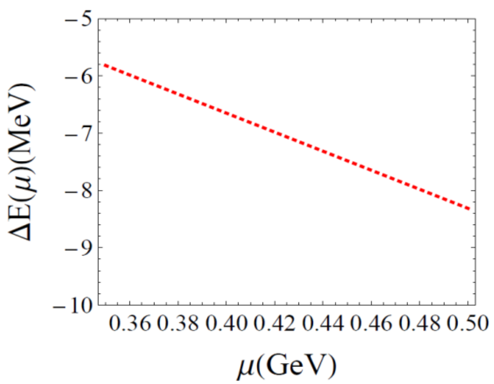
$$= \bar{E}(\mu, I_B) = \bar{E}(\mu) + \bar{E}_{sym}(\mu) I_B^2 + \cdots$$

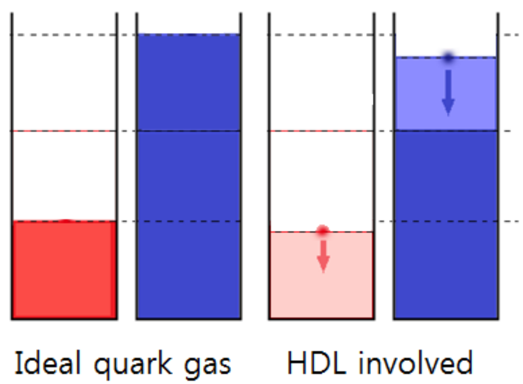
$$\bar{E}_{sym}(\mu) = \frac{1}{2!} \frac{\partial^2}{\partial I_B^2} \bar{E}(\mu, I_B).$$

$$= \boxed{\widetilde{E}^{q,0}_{sym}(\mu)} + \boxed{\widetilde{E}^{g,HDL}_{sym}(\mu)}$$



- HDL correction suppress Quasi-Fermi sea



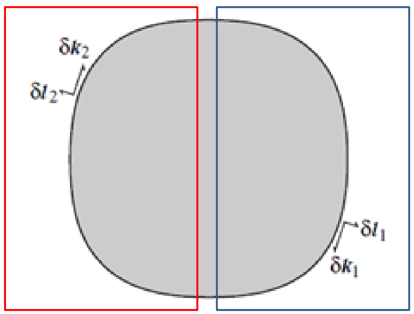


As density becomes higher,
suppression becomes stronger

The difference between quasi-Fermi seas becomes smaller
-> Costs less energy than ideal gas
-> **Reduced symmetry energy**

Color Superconductivity

- **BCS** Pairing near **Fermi sea**



- In terms of effective interaction near Fermi sea

  $$S_{4q} \sim \left(\psi^\dagger(-p_f)\psi(-p_i)\right)\left(\psi^\dagger(p_f)\psi(p_i)\right)$$

  is marginal along to Fermi velocity
- Fermion – conjugated fermion interaction
- When V<0 two states form **a condensate (gap)**

- **Wilsonian HDET** and **Nambu-Gorkov** formalism

  - BCS action as Fermion – conjugated Fermion

  $$S_{BCS} \sim \frac{1}{2}\left[\psi(-p)^T C\Delta(p)\psi(p) + \psi(p)\tilde{\Delta}(p)C\bar{\psi}^T(-p)\right]$$

  - HDET Lagrangian - Irrelevant high energy excitation has been integrated out

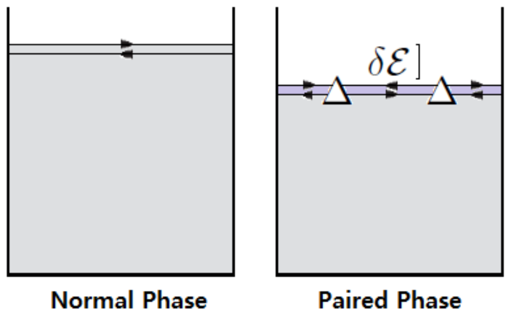
$$\mathcal{L}_D = \sum_{\vec{v}}{}' \left[\psi^\dagger iV\cdot D\psi - \psi^\dagger \frac{1}{2\mu + i\tilde{V}\cdot D} D_\perp^2 \psi\right]$$

Diagrammatically described gapped quasi-state

-> $S_\Delta(l) = \dfrac{l_0 + l_v}{l_0^2 - l_v^2 - \Delta^2}\gamma_0$

Color BCS paired state

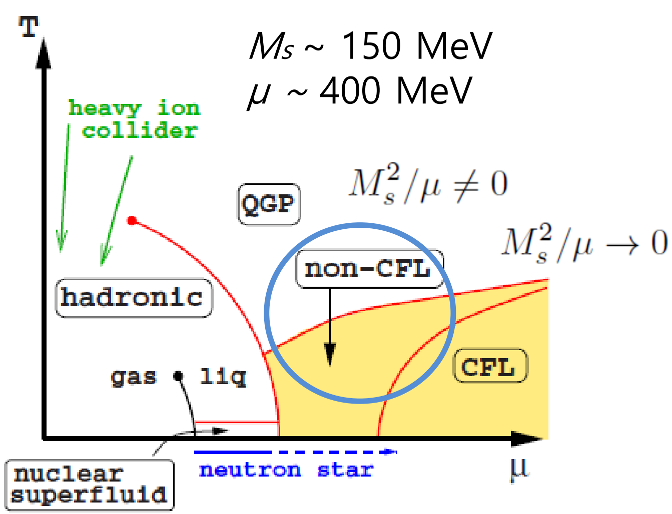
- **BCS** Pairing locks the gapped quasi-states



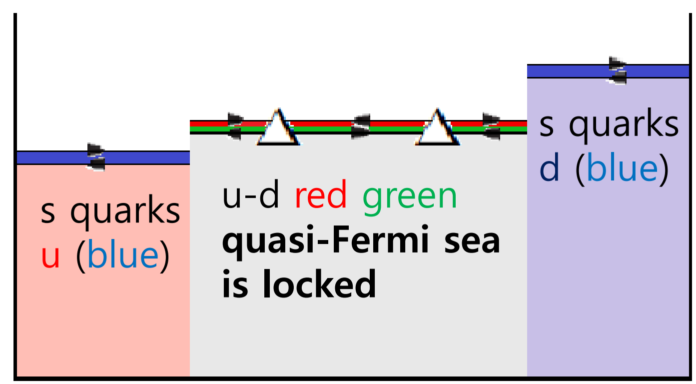
- In QCD, color anti-triplet gluon exchange interaction is attractive (V<0)
- $\langle \psi_a^\alpha C \gamma_5 \psi_b^\beta \rangle \sim \Delta_1 \epsilon^{\alpha\beta 1} \epsilon_{ab1} + \Delta_2 \epsilon^{\alpha\beta 2} \epsilon_{ab2} + \boxed{\Delta_3 \epsilon^{\alpha\beta 3} \epsilon_{ab3}}$
- In non negligible M_s^2/μ **2SC** state is favored

- **2 color superconductivity**

$M_s \sim 150$ MeV
$\mu \sim 400$ MeV



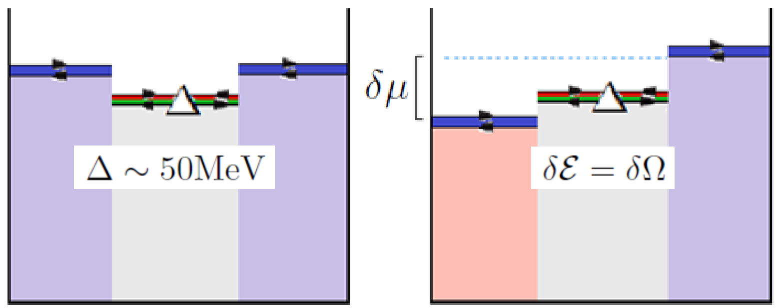
In 2SC phase, u-d red-green states are gapped



Only s quarks and u-d blue quarks are liberal

Asymmetrization in 2SC phase

- **Only** **Blue state (1/3)** can affect iso-spin asymmetry



- BCS phase remains in $\delta\mu < (1/\sqrt{2})\Delta \sim \Lambda$
  (Phys. Rev. Lett. 9, 266 (1962) A. M. Clogston)

- Only u-d blue states can be asymmetrized
- The other 4 gapped quasi-states are **locked**

- In HDET formalism $\delta\mathcal{E} = \delta\Omega = -\sum_{ud,rg} \frac{\mu_f^2}{\pi^2}\left[\Lambda\sqrt{\Lambda^2+\Delta^2} + \Delta^2 \ln((\Lambda + \sqrt{\Lambda^2+\Delta^2})/\Delta)\right]$

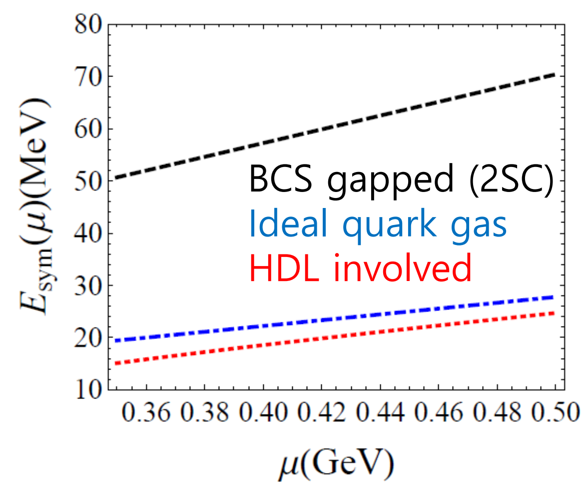
- **Symmetry energy**

$$\frac{\epsilon(\mu,\Delta,I_{B_\Delta})}{\rho(\mu,\Delta,I_{B_\Delta})} = \frac{E(\mu,\Delta,I_{B_\Delta})}{N_{B_\Delta}}$$

$$= \bar{E}(\mu,\Delta) + \bar{E}_{sym}(\mu,\Delta) I_{B_\Delta}^2 + \cdots$$

$$\bar{E}_{sym}(\mu,\Delta) = \frac{1}{2}\frac{\partial^2}{\partial I_{B_\Delta}^2}\bar{E}_\Delta(\mu, I_{B_\Delta})$$

$$I_{B_\Delta} = 3\frac{\rho_d - \rho_u}{\rho_d + \rho_u} \times \frac{1}{3}$$



Quasi-fermion state in 2SC phase

- Meissner mass effect?

Quasi-fermion in gapped state

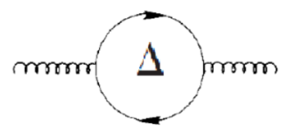
$$S_\Delta(l) = \frac{l_0 + l_v}{l_0^2 - l_v^2 - \Delta^2}\gamma_0$$

Fermion in ungapped state

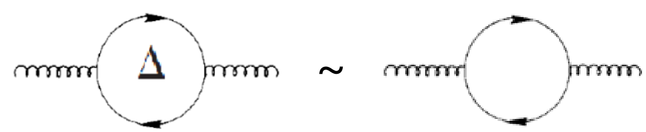
$$S(l) = \frac{l_0 + l_v}{l_0^2 - l_v^2}\gamma_0$$

- Gapped states and dense loop

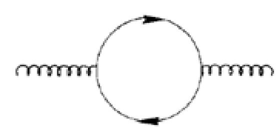
1) If gap size is quite large $\Delta \sim g\mu$
   -> matter loop do not have hard contribution
   -> do not need resummation -> **reduction vanish**



2) But if gap size is quite small $\Delta < g\mu$
   -> needs resummation -> **reduction remains**



3) For ungapped quark loop -> **reduction remains**



High density effective formalism

- **2SC** description as linear combination of Gellman matrices

Gapped and un-gapped quasi-state

$$\psi_{+,\alpha i} = \sum_{A=0}^{5} \frac{(\tilde{\lambda}_A)_{\alpha i}}{\sqrt{2}} \psi_+^A \qquad \tilde{\lambda}_0 = \frac{1}{\sqrt{3}}\lambda_8 + \sqrt{\frac{2}{3}}\lambda_0; \quad \tilde{\lambda}_A = \lambda_A\,(A=1,2,3);\ \tilde{\lambda}_4 = \frac{\lambda_{4-i5}}{\sqrt{2}};\ \tilde{\lambda}_5 = \frac{\lambda_{6-i7}}{\sqrt{2}}$$

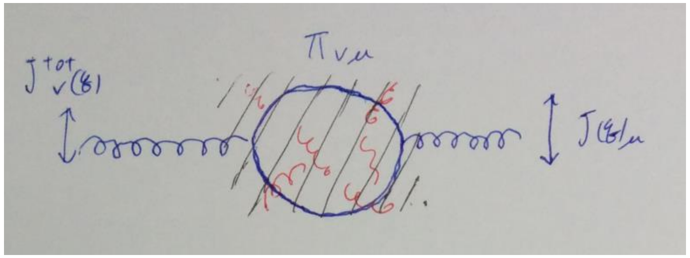
Effective Lagrangian

$$\mathcal{L}_D = \sum_{\vec{v}} \sum_{A,B=0}^{5} \chi^{A\dagger} \begin{pmatrix} iTr[\tilde{T}_A V \cdot D \tilde{T}_B] & \Delta_{AB} \\ \Delta_{AB} & iTr[\tilde{T}_A^* \tilde{V} \cdot D^* \tilde{T}_B^*] \end{pmatrix} \chi^B + (L \to R) . \quad \tilde{T}_A = \frac{\tilde{\lambda}_A}{\sqrt{2}} \qquad (A = 0, \ldots, 5)$$

$\chi = \begin{pmatrix} \psi_+ \\ C\psi_-^* \end{pmatrix}$ + and – represents Fermi velocity

Determines gluon-quasi Fermion coupling

- Gluon self energy as kernel for linear response

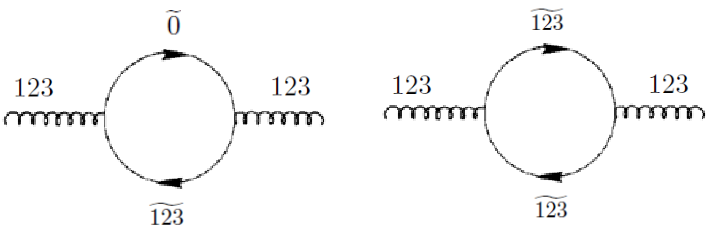


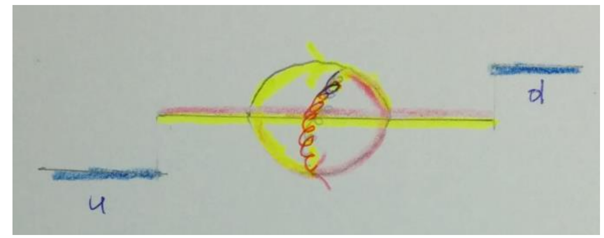
$$\begin{aligned} J_\mu^{A,\mathrm{ind}}(P) &= J_\mu^{A,\mathrm{tot}}(P) - \mathbf{J}_\mu^A(P) \\ &= i[(D^{-1})_{\mu\nu}^{AB}(P) - (\mathcal{D}^{-1})_{\mu\nu}^{AB}(P)]\langle A^{B,\nu}(P)\rangle \\ &\equiv \Pi_{\mu\nu}^{AB}(P)\langle A^{B,\nu}(P)\rangle, \end{aligned}$$

$$\langle A_\mu^A(P)\rangle = -i\mathcal{D}_{\mu\nu}^{AB}(P)\mathbf{J}^{\nu,B}(P)$$

Gluon self energy in 2SC phase

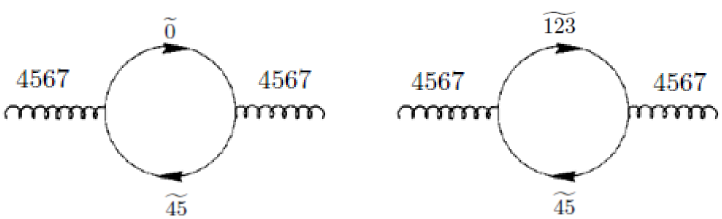
- Adjoint color 1,2,3 only couple with gapped states
  - In p->0 limit, $\Pi^{\mu\nu}_{ab}(0) = 0$
  - Gluons are trapped in gapped state
  - Symmetry energy do not reduced by **HDL**

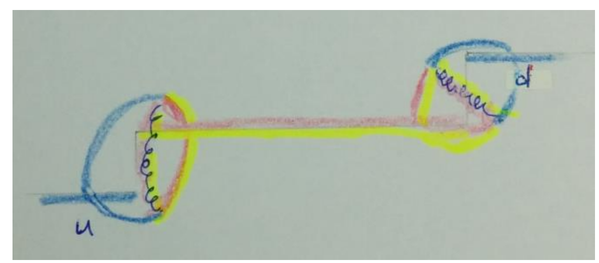




Adjoint 1,2,3 trapped in BCS gap state

- Adjoint color 4,5,6,7 partially couple with gapped state
  - In p->0 $\Pi^{00}_{ab}(0) = \frac{3}{2}m_g^2 \quad -\Pi^{ij}_{ab}(0) = \frac{1}{2}m_g^2$
  - Transition from gapped-ungapped state
  - **HDL** through asymmetric Fermi sea can contribute reduction of symmetry energy

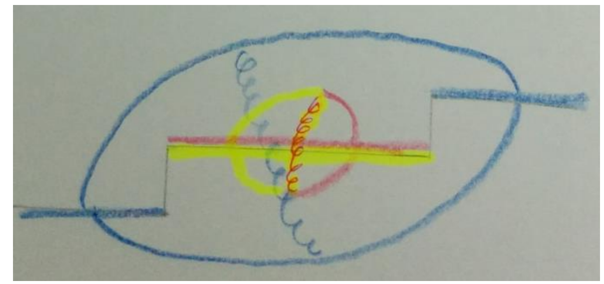




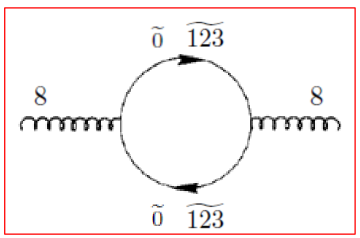
Adjoint 4,5,6,7 mediate transition between BCS gapped – ungapped state

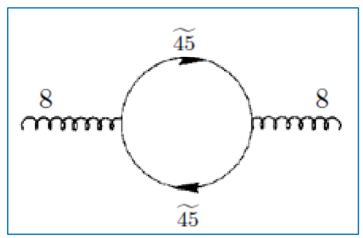
Gluon self energy in 2SC phase

- Adjoint color 8
  - In p->0 limit, $\Pi^{00}_{ab}(0) = 3m_g^2 \quad -\Pi^{ij}_{ab}(0) = \frac{1}{3}m_g^2$
  - **HDL** from gapped loop -> locked in symmetric gapped sea
  - **HDL** from ungapped loop -> can be asymmetrized as in normal phase



Adjoint 8 has contributions from gapped loop and ungapped loop



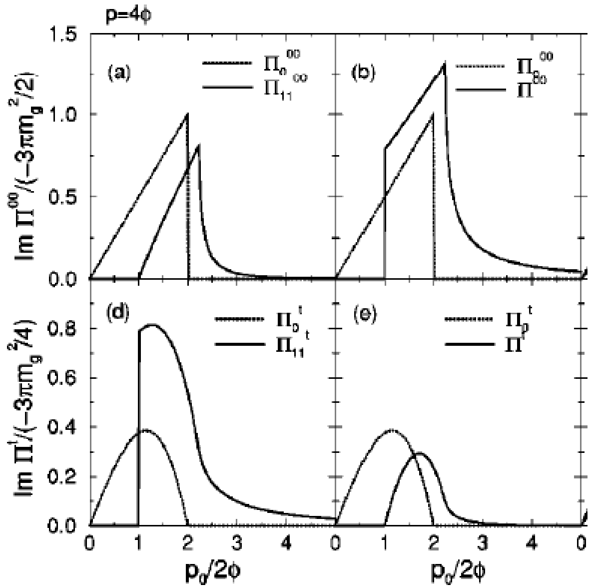


- All gapped state can be liberated at $T, \delta\mu > (1/\sqrt{2})\Delta$

- **Reduction from HDL significantly dropped**

Recent works

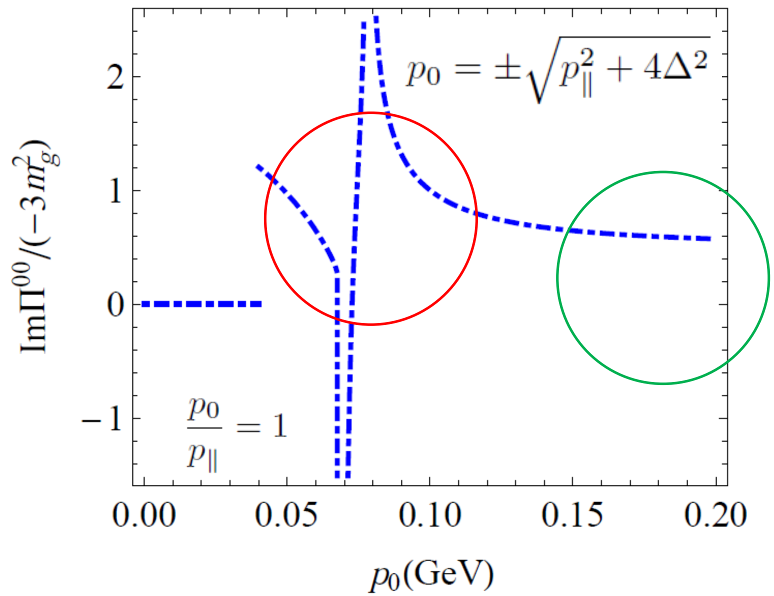
- Calculation in TFT



(PRD 64, 094003 (2001) Dirk H. Rishke)

- Imaginary part of gluon self energy
- In 2SC, no gluon mass in static limit (for adjoint 1,2,3)

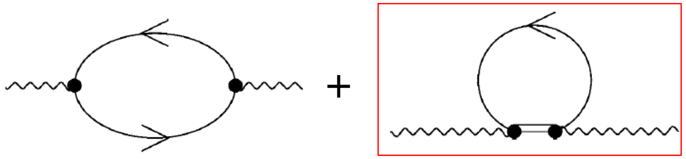
- Calculation in HDET



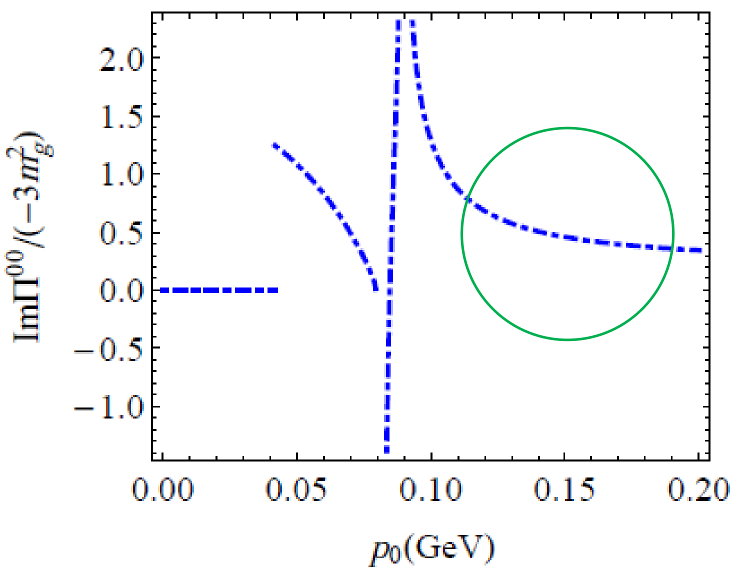
- Imaginary part of gluon self energy
- Two singularities
- Irrelevant loop correction needs

Recent works

- Irrelevant loop correction

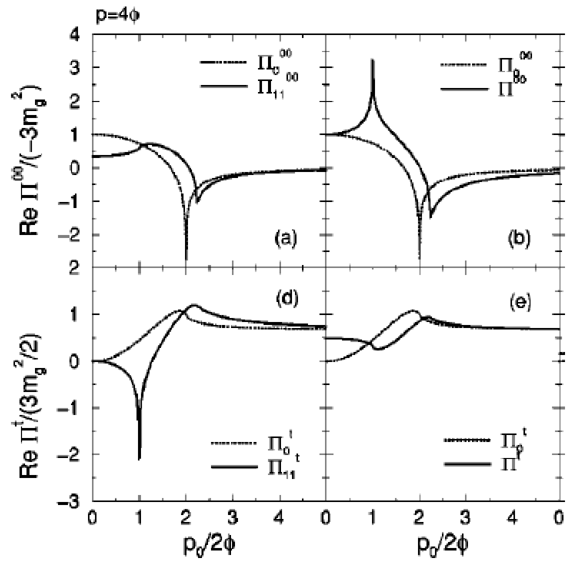


$$\mathcal{L}_D = \sum_{\vec{v}}{}' \left[\psi^\dagger i V \cdot D \psi - \psi^\dagger \frac{1}{2\mu + i\tilde{V}\cdot D} D_\perp^2 \psi \right]$$



- Real part can be obtained by dispersion relation

$$\mathrm{Re}\Pi(p_0, p) \equiv \frac{1}{\pi}\mathcal{P}\int_{-\infty}^{\infty} d\omega \frac{\mathrm{Im}\Pi(p_0, p)}{\omega - p_0}$$

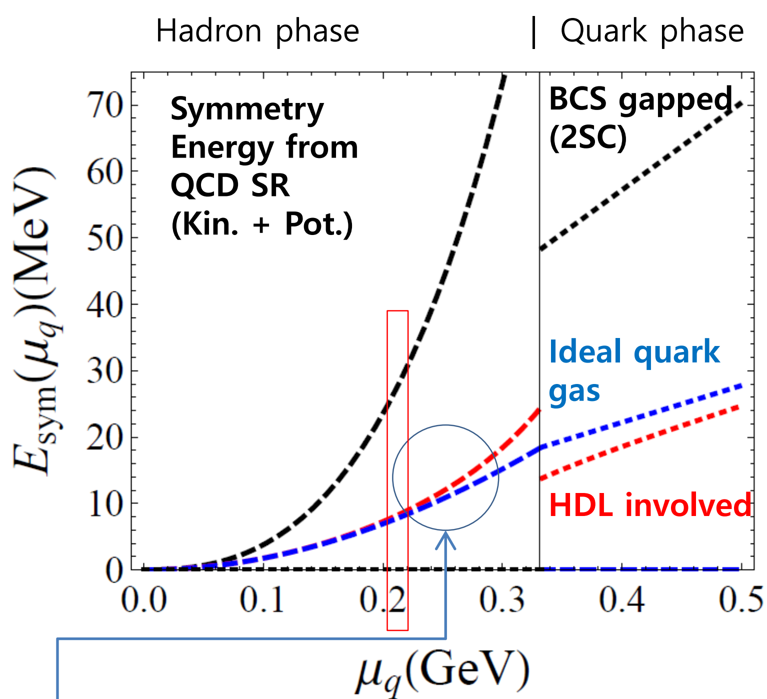


(PRD 64, 094003 (2001) Dirk H. Rishke)

- Real part of gluon self energy
- Scale comparison

Summary and Future goals

- **Nuclear Symmetry Energy** in hadron and quark phase

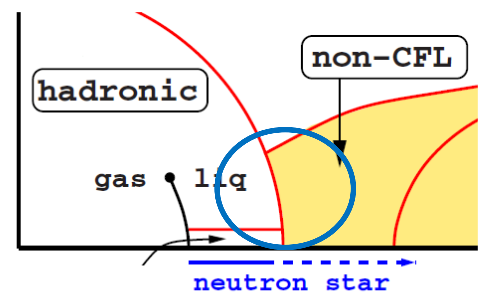


Kinetic part **(Ideal nucleon gas)**
Kinetic part **(QCD SR based interaction involved)**

- Evaluating gluon self energy by analytic calculation

Cold matter symmetry energy from **correct statistics** can be obtained

- Quark-hadron continuity?



Important quantum numbers?
(e.g. strangeness)
-> High density behavior at hadron phase