Roles of Axial Anomaly on Neutral Strongly Interacting Matter

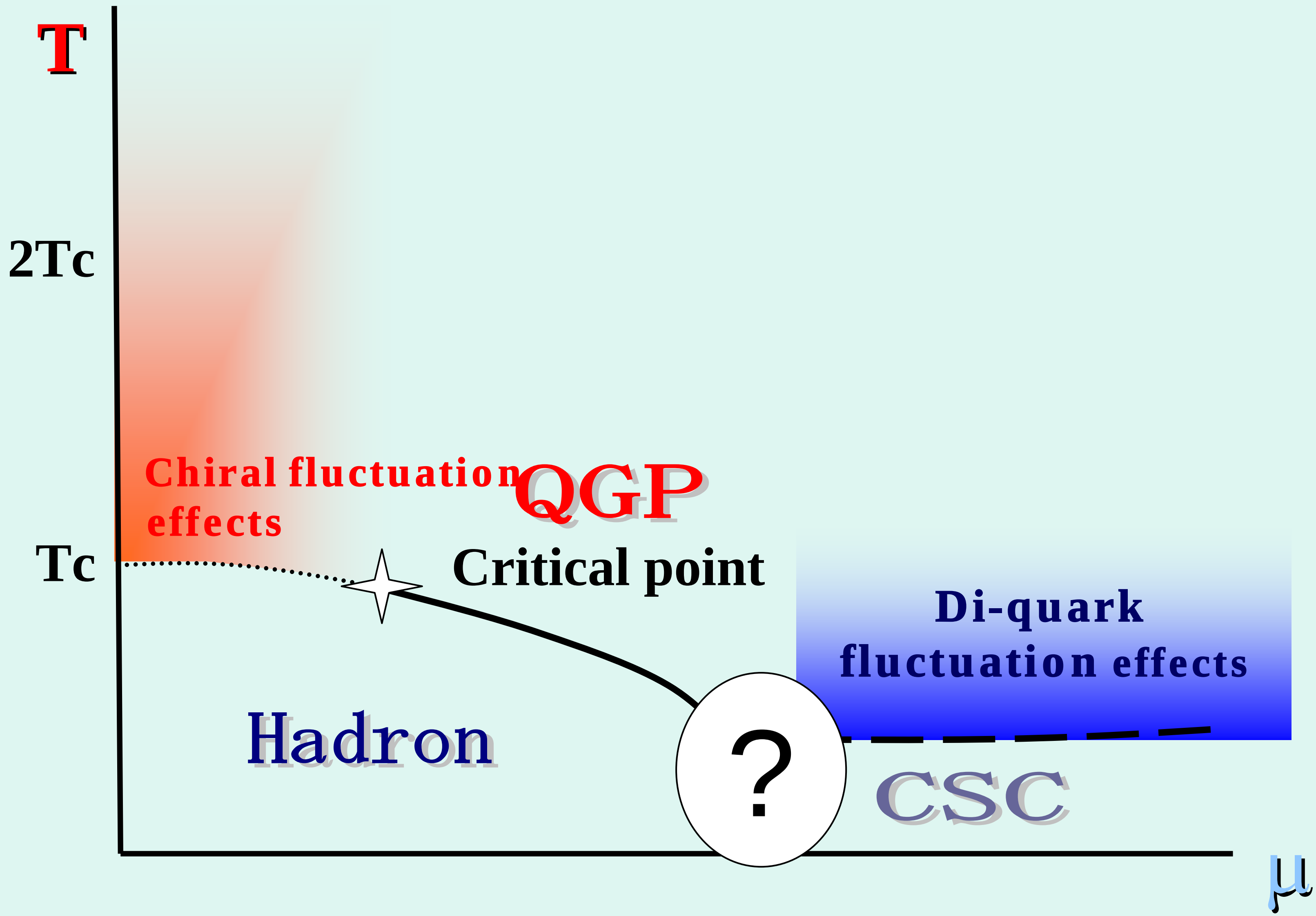
--- New Critical Points at Low Temperature and the Absence of Chromomagnetic Instabilty ---

Z. Zhang and T. Kunihiro

Z. Zhang and T.K., arXiv:1102.3263 [hep-ph], PRD in press.

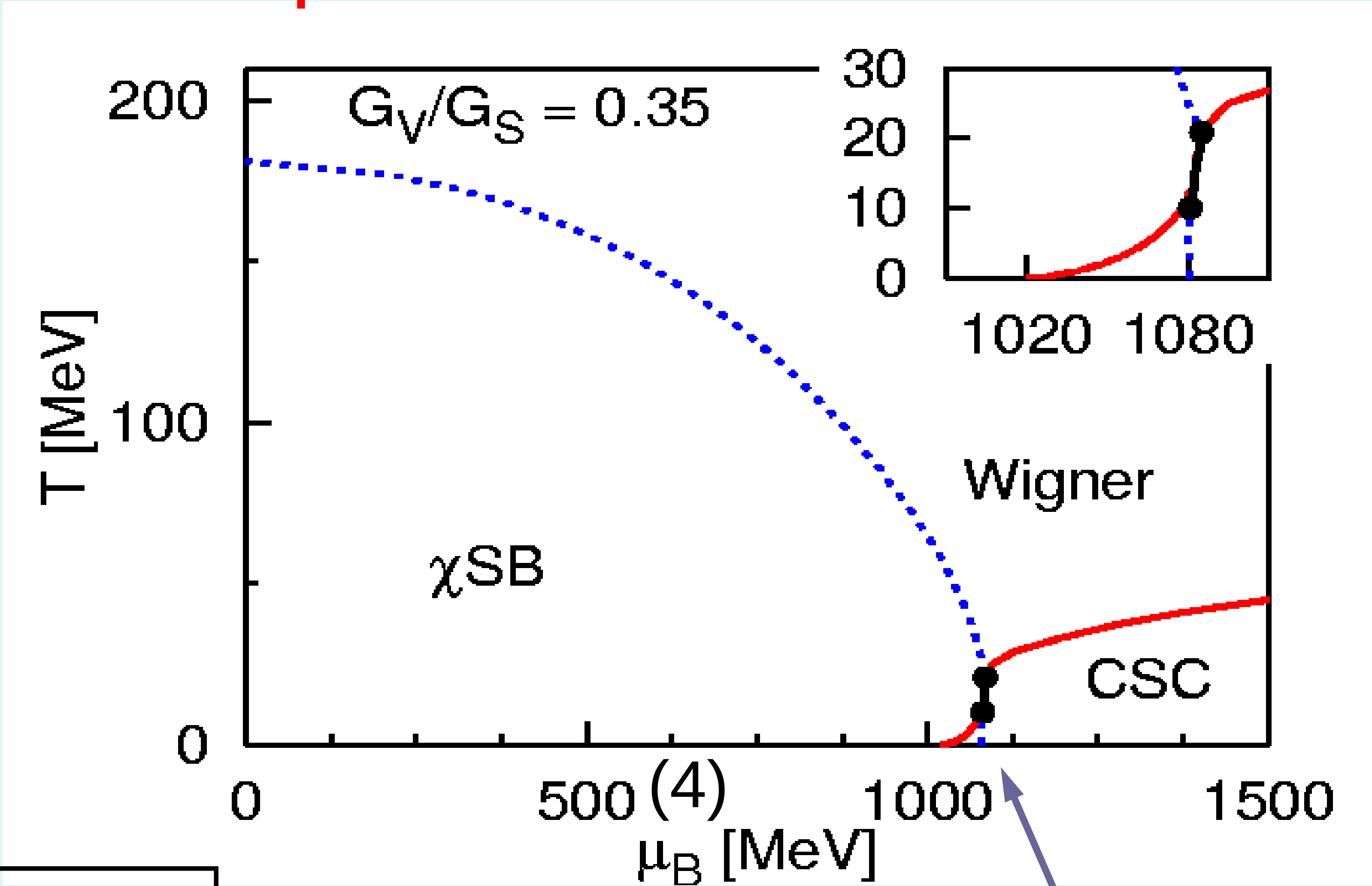
Quark Matter 2011, May 23-28, 2011

Conjectured QCD phase diagram



With color superconductivity transition incorporated: Two critical end point!

M. Kitazawa, T. Koide, Y. Nemoto and T.K., PTP ('02)



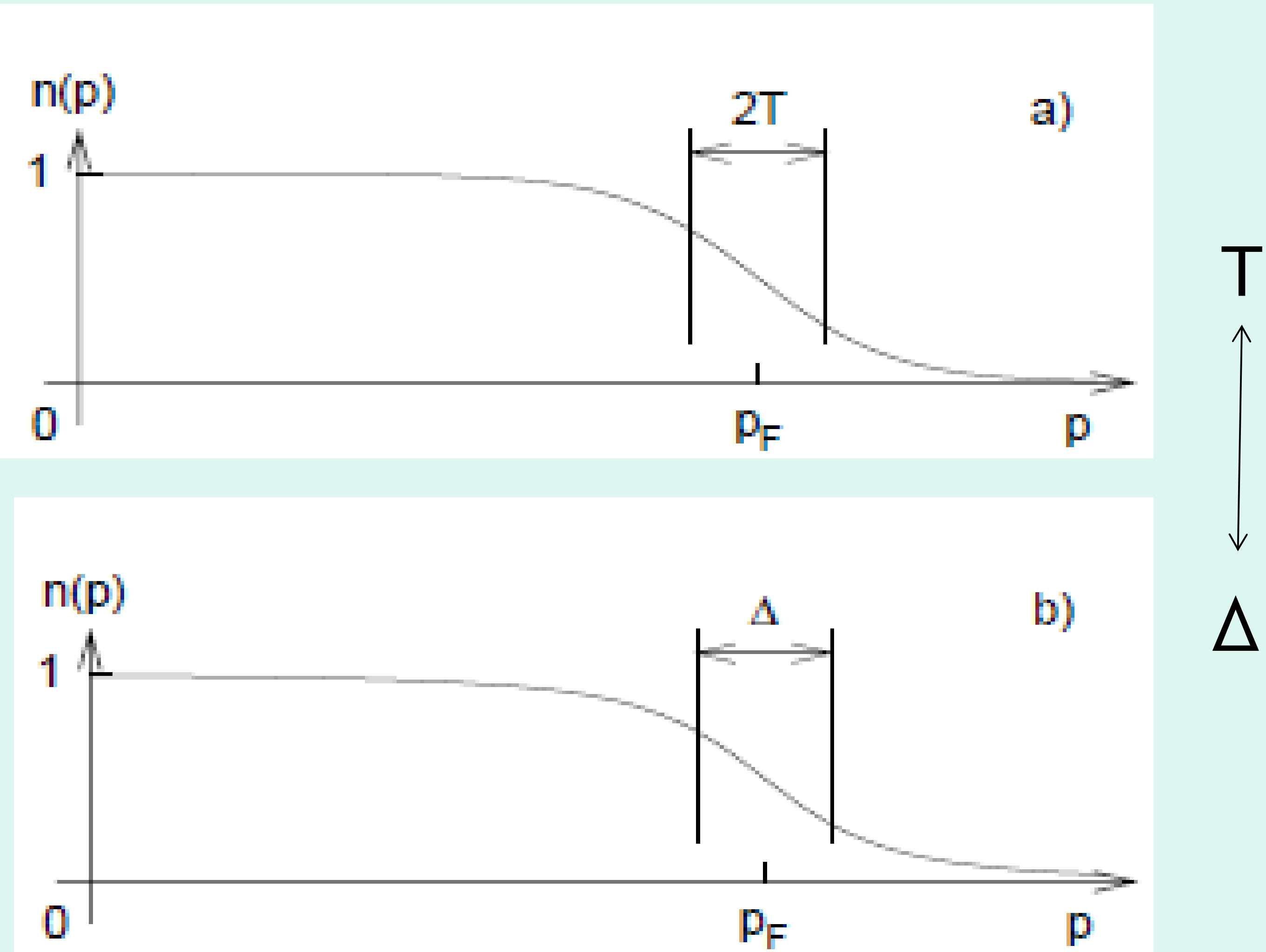
(4)

$G_V / G_S = 0.35$

Another end point appears from lower temperature, and hence **there can exist <u>two end points</u>** in some range of G_V**!**

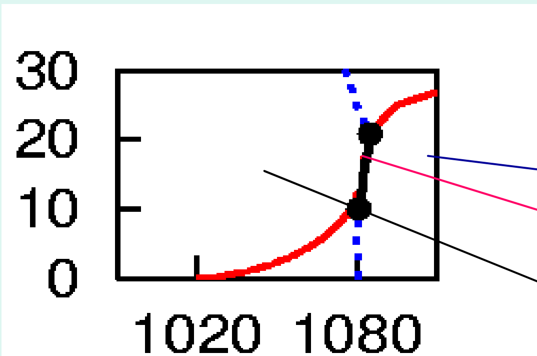
Similarity of the effect of temperature and pairing gap on the chiral condensate.

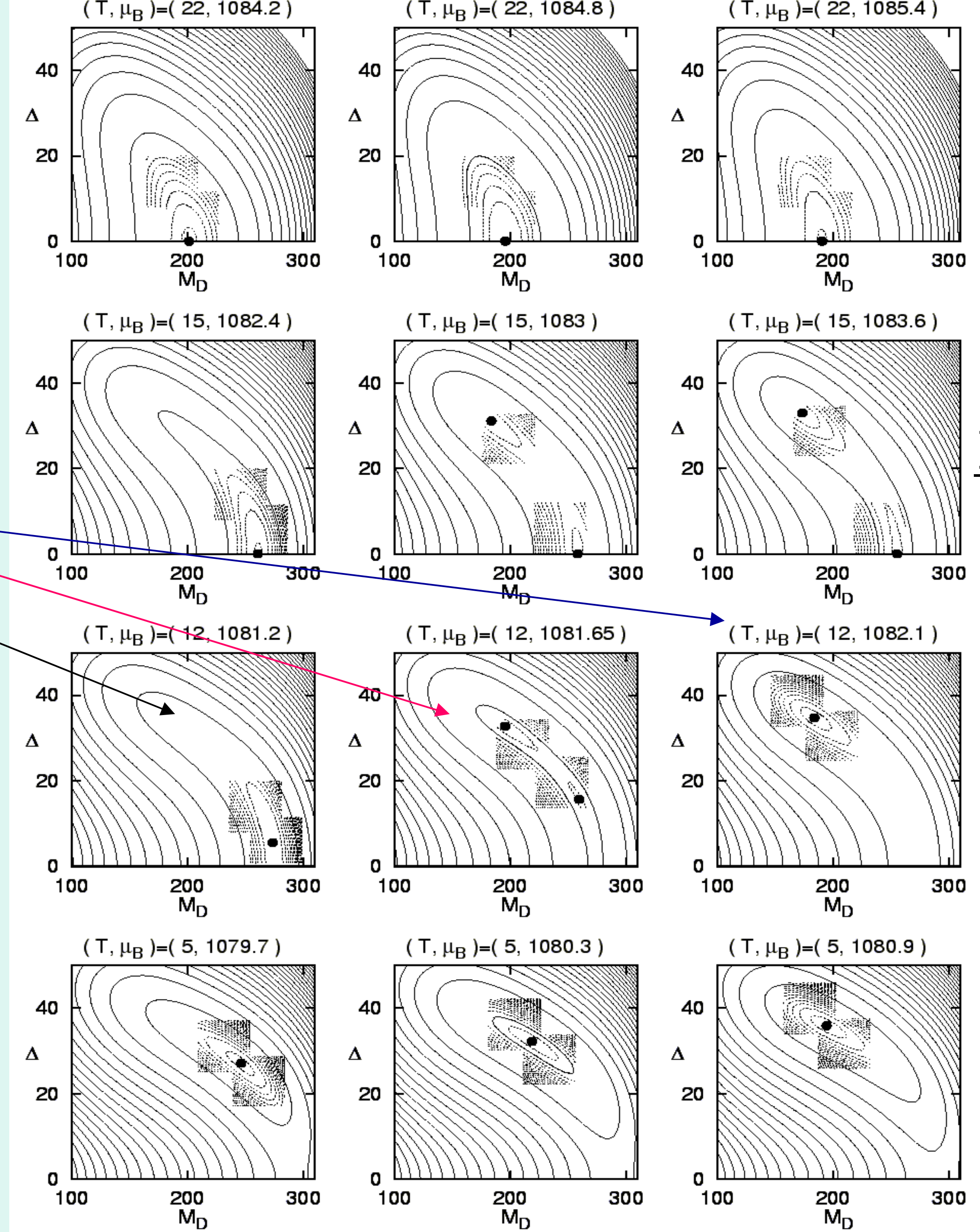
M. Kitazawa, T. Koide, T. Kunihiro
and Y. Nemoto,PTP, 110 (2003), 185:
arXiv:hep-ph/0307278



Contour of ω with $G_V/G_S=0.35$

M. Kitazawa, et al ('02)





T=

22MeV

15MeV

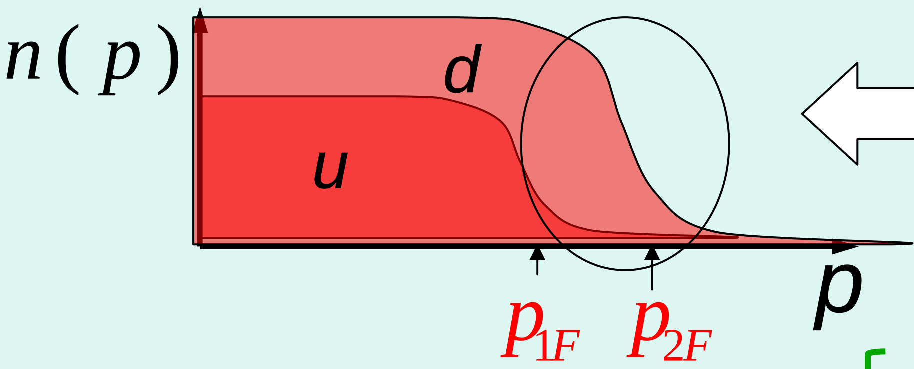
12MeV

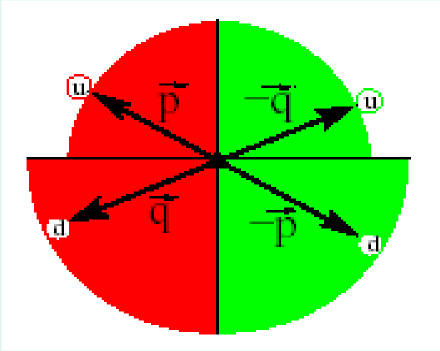
5MeV

μ

Very shallow or soft for creating diquark-chiral condensation!

Abnormal thermal behavior of diquark energy gap in charge-neutral quark matter



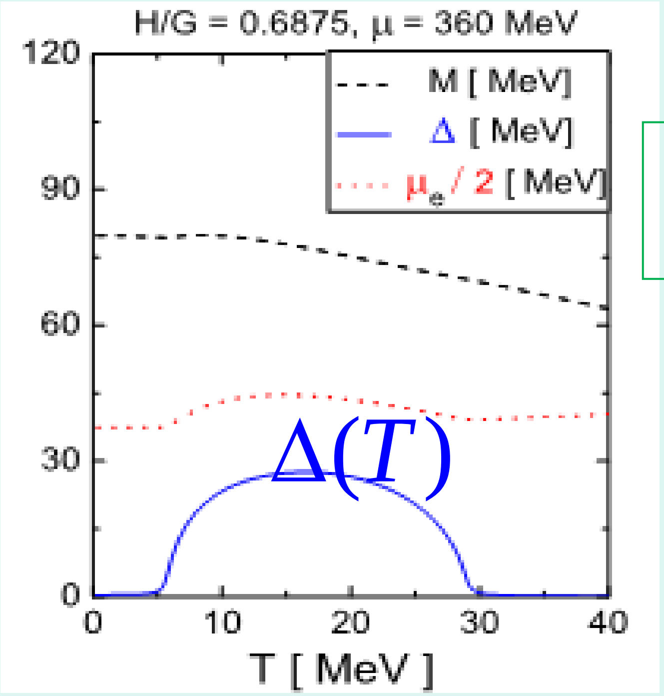


Smearing by T induces the pairing!

Double effects of T :

- Melting the condensate
- More and more components take part in cooper pairing

Competition between these two effects gives rise to abormal thermal behavior of diquark condensate



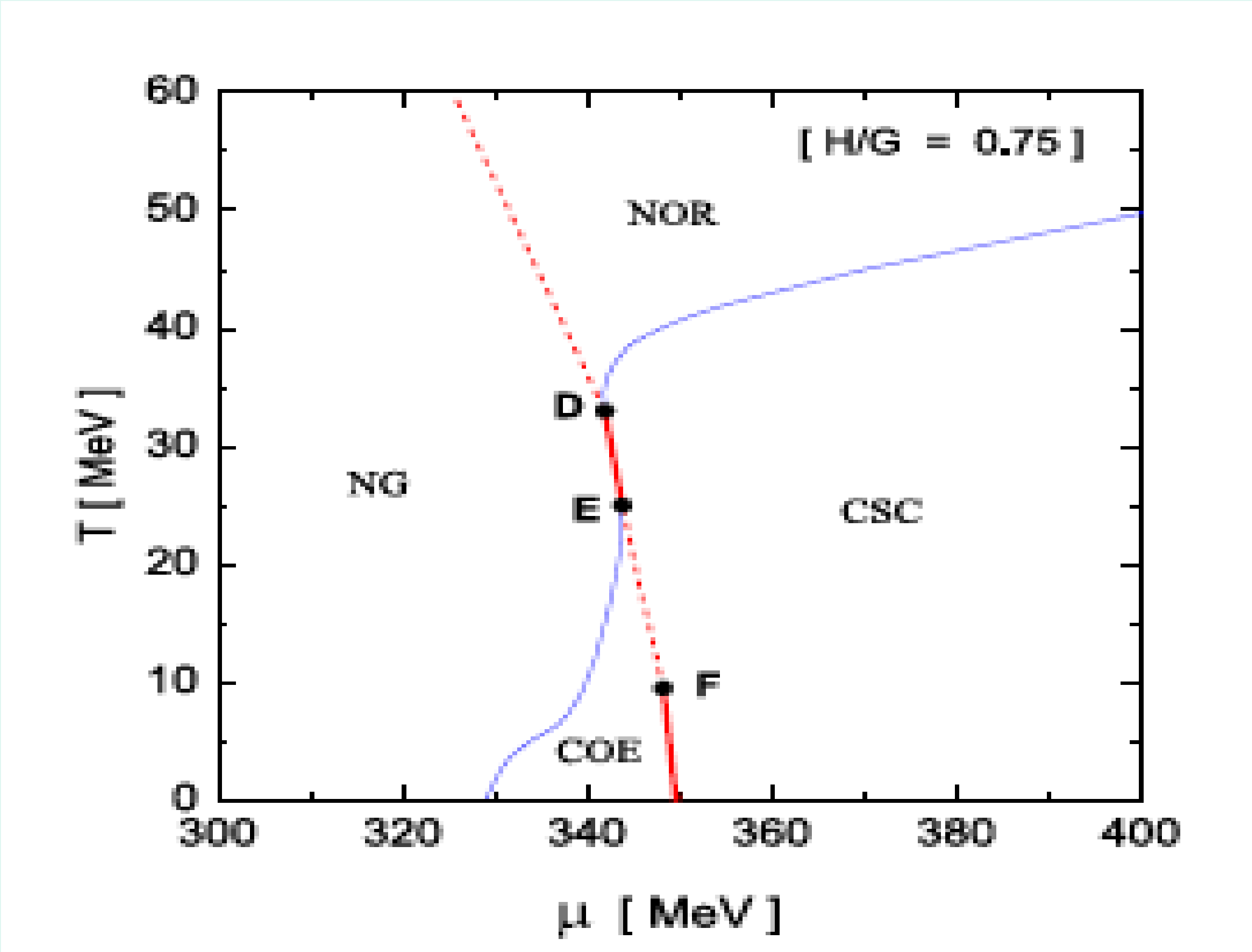
Enhancing the competition between chiral condensate and diquark condensate for somewhat larger T, leading to a nontrivial impact on chiral phase transition

Shovkovy and Huang, PLB 564, (2003) 205

Effects of Charge neutrality on QCD phase diagram

Z. Zhang, K. Fukushima, T.K., PRD79, 014004 (2009)

- QCD phase diagram with chiral and CSC transitions with charge neutrality
- Pairing with mismatched Fermi surface
- Competition between chiral and CSC
- Charge neutrality play a role similar to the vector-vector(density-density) interactin and leads to proliferation of critical points.



Combined effect of Vector Interaction and Charge Neutrality constraint

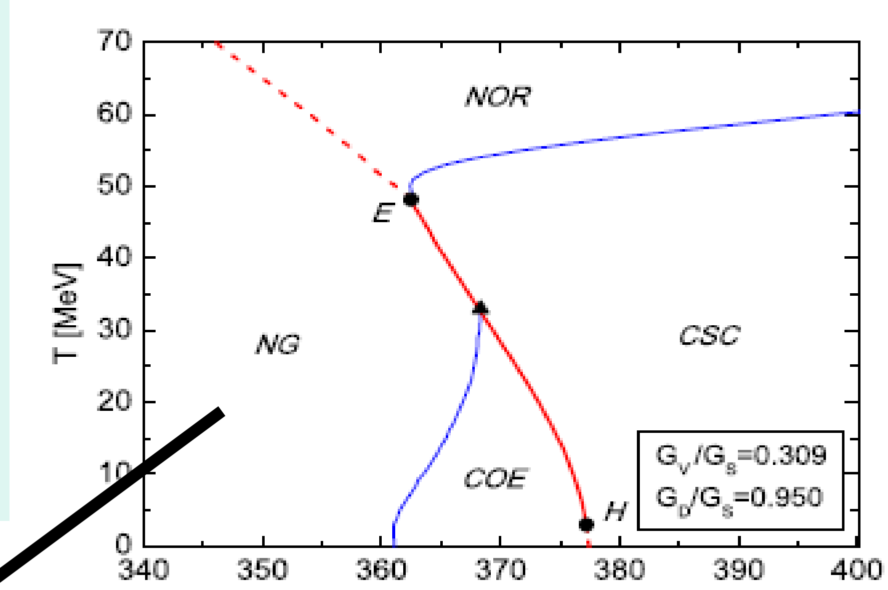
Z. Zhang and T. K., Phys.Rev.D80:014015,2009

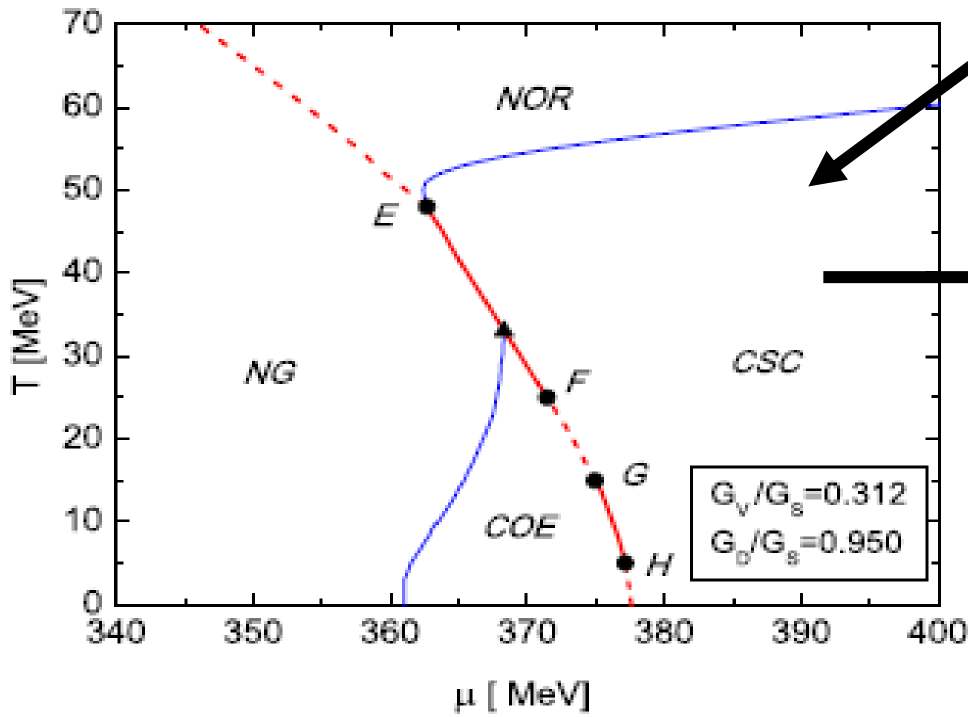
2+1 flavor case

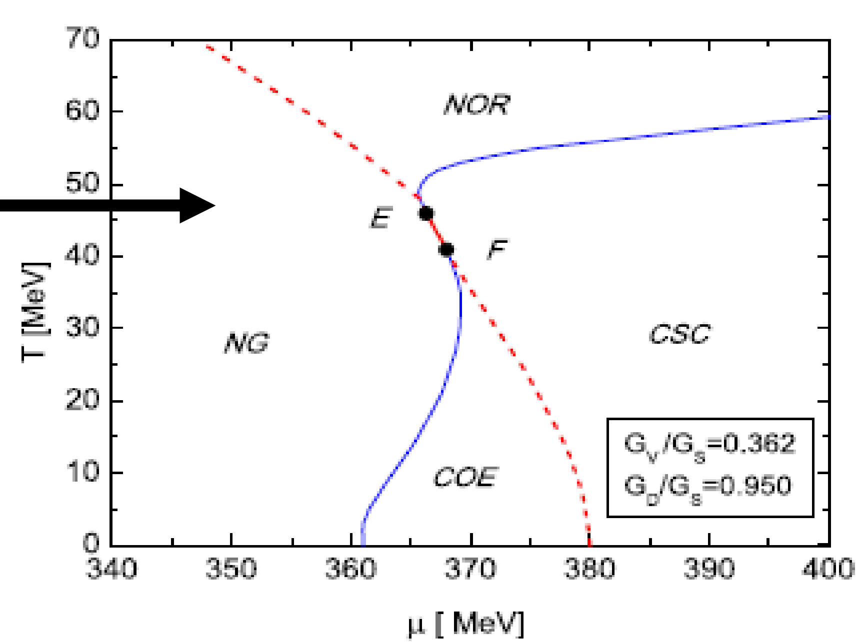
$m_{u,d} = 5.5\mathrm{MeV}$

$m_s = 140\mathrm{MeV}$

Emergence of multiple critical points!







Effects of
an anomaly term inducing the chiral and diquark mixing

a la Hatsuda-Tachibana-Yamamoto-Baym (2006)

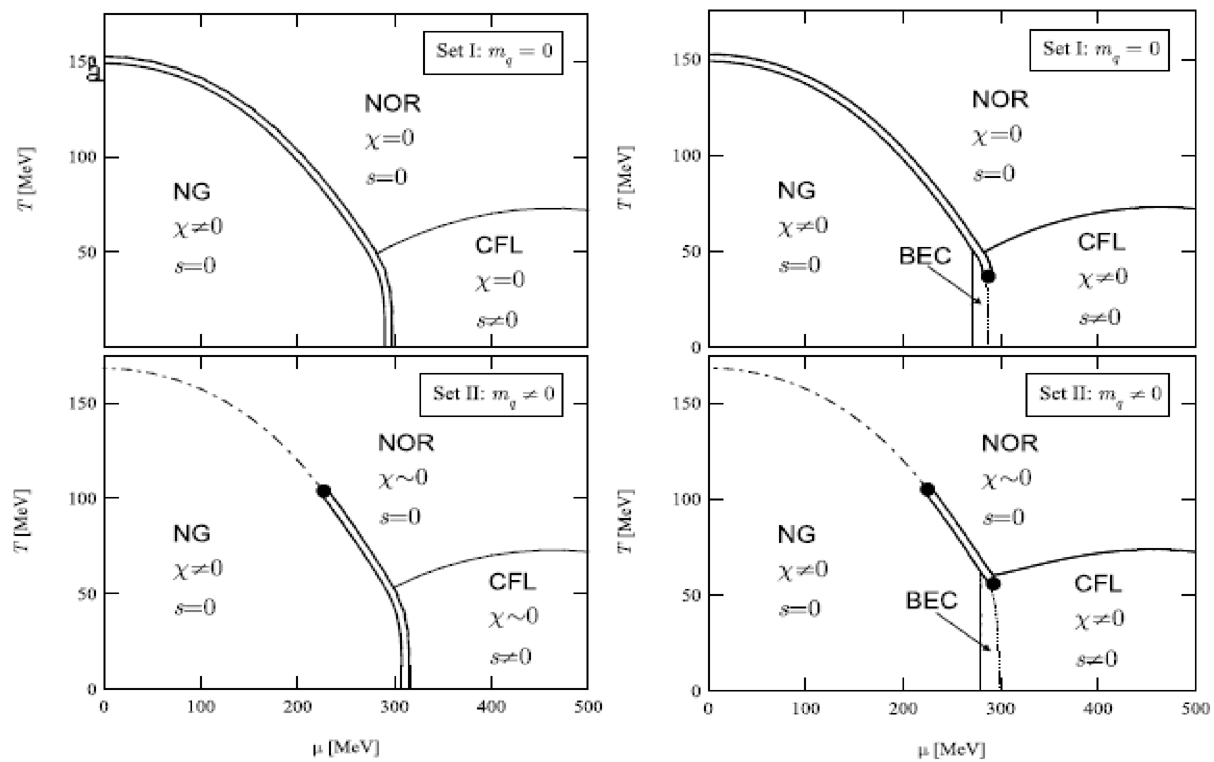
$$\mathcal{L}_{\chi d}^{(6)} = \frac{K'}{8} \sum_{i,j,k=1}^{3} \sum_{\pm} \left[(\psi t_i^f t_k^c (1 \pm \gamma_5) \psi_C)(\bar{\psi} t_j^f t_k^c (1 \pm \gamma_5) \bar{\psi}_C)(\bar{\psi}_i (1 \pm \gamma_5) \psi_j) \right]$$

$$M_i = m - 4G_S \sigma_i + K|\varepsilon_{ijk}|\sigma_j \sigma_k + \frac{K'}{4}|s_i|^2 \qquad \Delta_i = 2(G_D - \frac{K'}{4}\sigma_i) s_i$$

(A) Flavor-symmetric case:

Abuki et al, PRD81 (2010), 125010

The anomaly seems to induce a new critical point in low-T region extending zero temperature in the flavor-symmetric case! Is it robust?

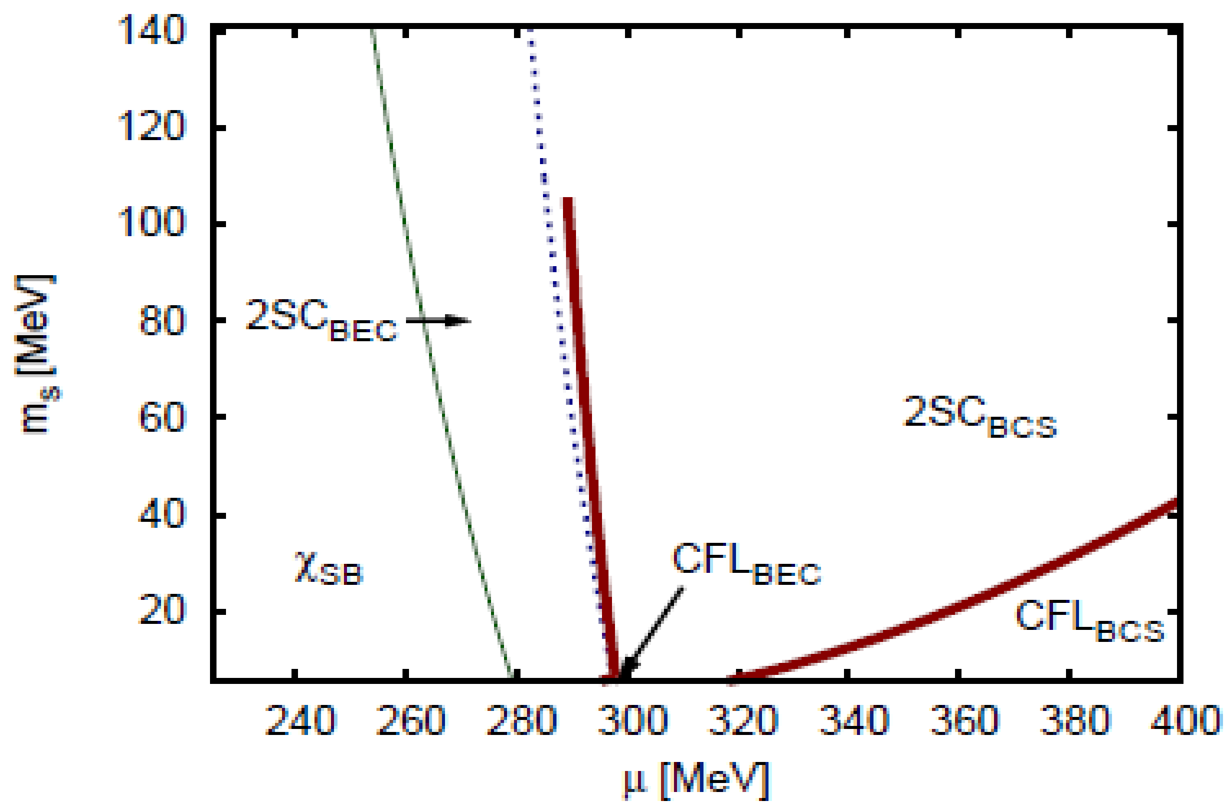


(a): $K'=0$ (b): $K'\neq0$

(B) Realistic case with massive strange quark;

$m_u = m_d = 5.5$ MeV << $m_s = 140.7$ MeV

H. Basler and M. Buballa, (2010)



Notice!
Without charge neutrality nor vector interaction.

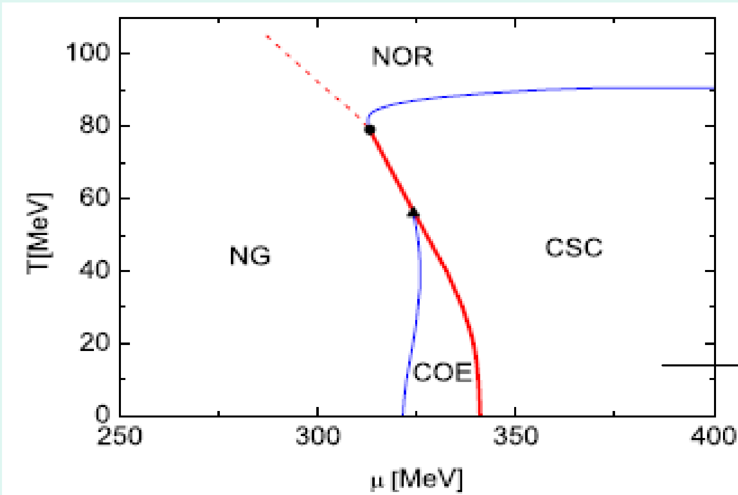
phases and new endpoints. On the other hand, the low-temperature critical endpoint, which was found earlier in the same model without 2SC pairing, is almost removed from the phase diagram and cannot be reached from the low-density chirally broken phase without crossing a preceding first-order phase boundary. For physical quark masses no additional critical endpoint is found.

Our present work

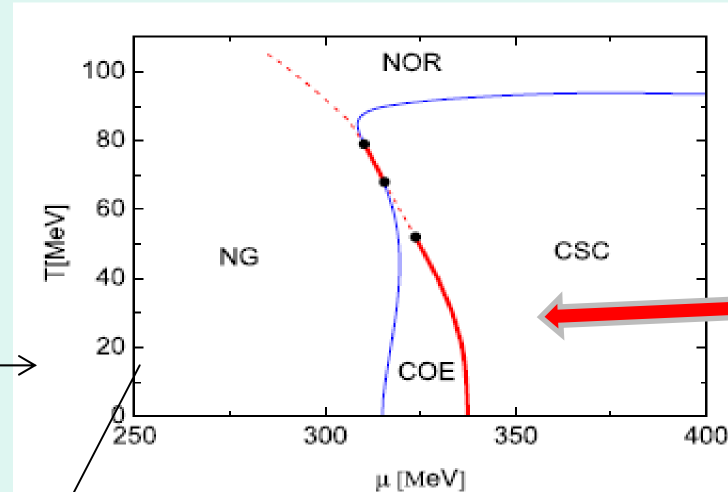
The anomaly term and G_v under charge-neutrality constraint

Z. Zhang and T.K., arXiv:1102.3263 [hep-ph], in press for PRD.

G_V=0:

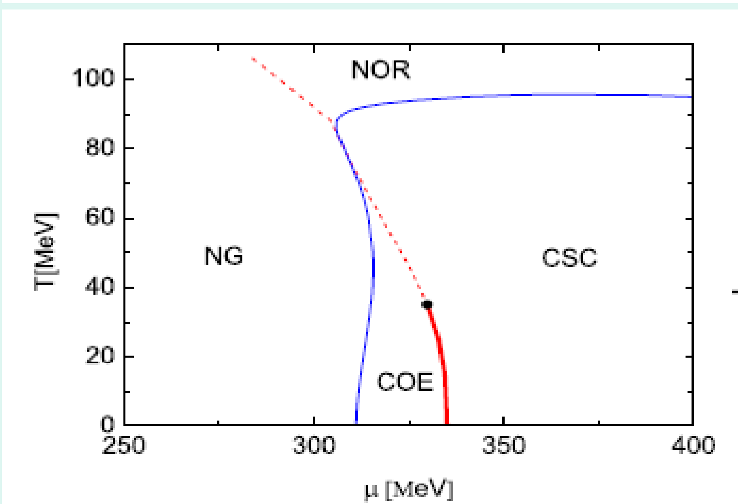


(a) $K'/K = 2.0$

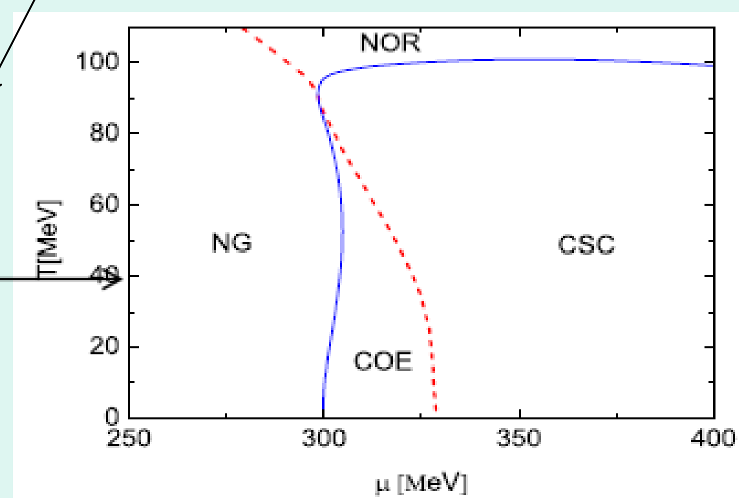


(b) $K'/K = 2.25$

due to the Mismatched Fermi surface



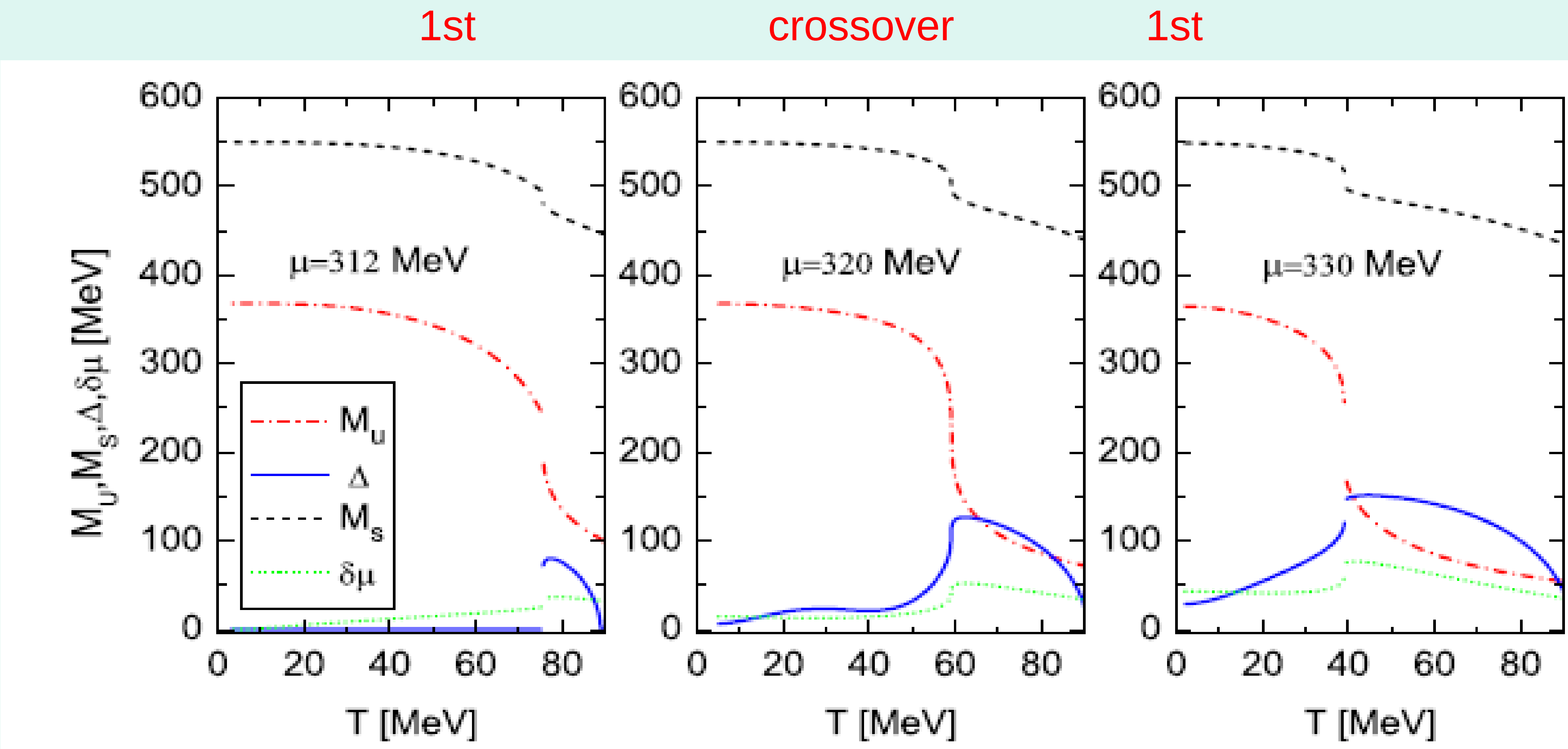
(c) $K'/K = 2.4$



(d) $K'/K = 2.8$

Otherwise, consistent with Basler-Buballa

Effect of mismatched Fermi sphere

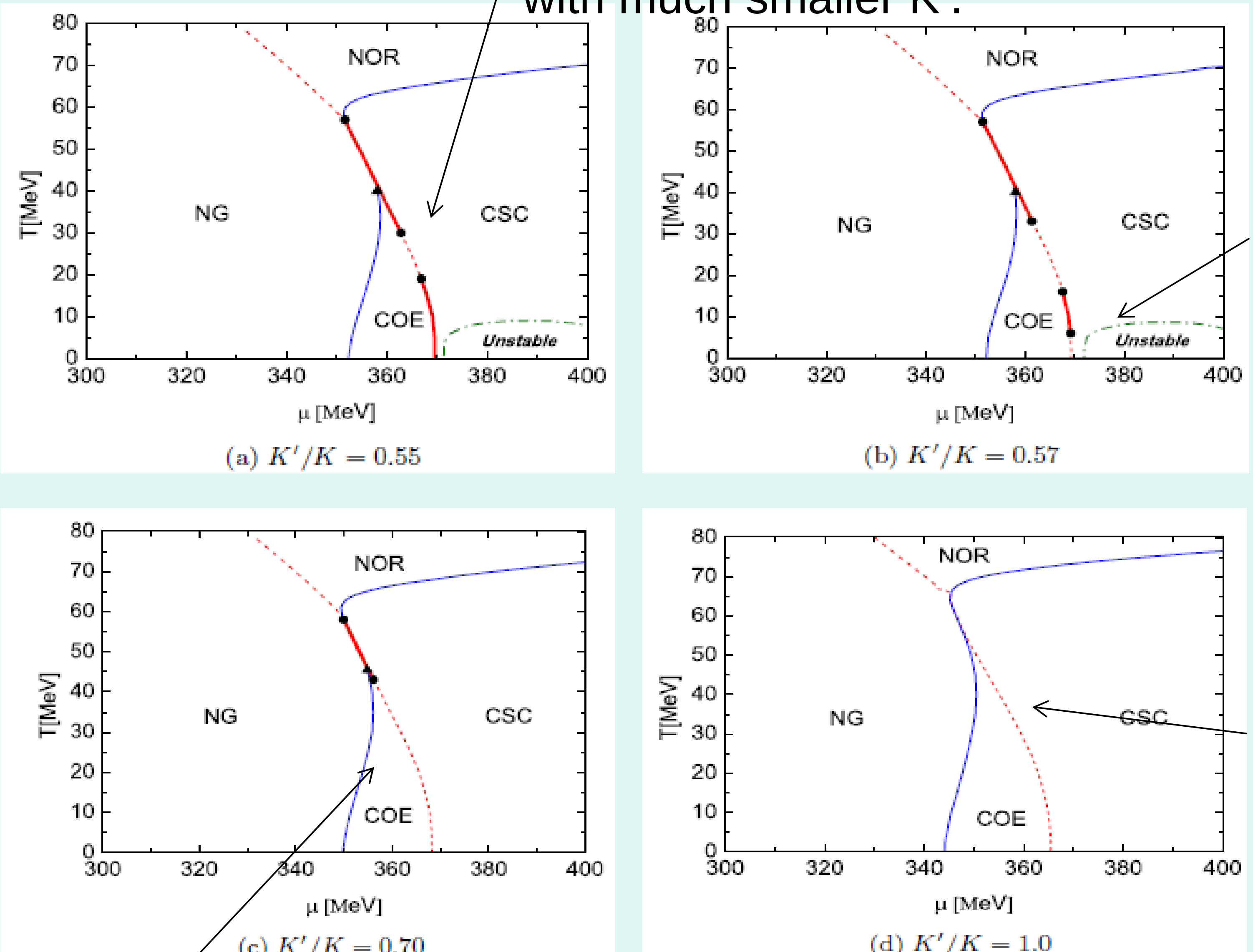


Owing to the mismatched Fermi sphere inherent in the charge-neutrality constrained system, the pairing gap is induced by the smearing of Fermi surface at moderated temperature!

Effects of G_v

G_V makes the ph.tr. a crossover at intermediate T with much smaller K'.

A crossover Region gets to appear, which starts from zero T.



(a) $K'/K = 0.55$

(b) $K'/K = 0.57$

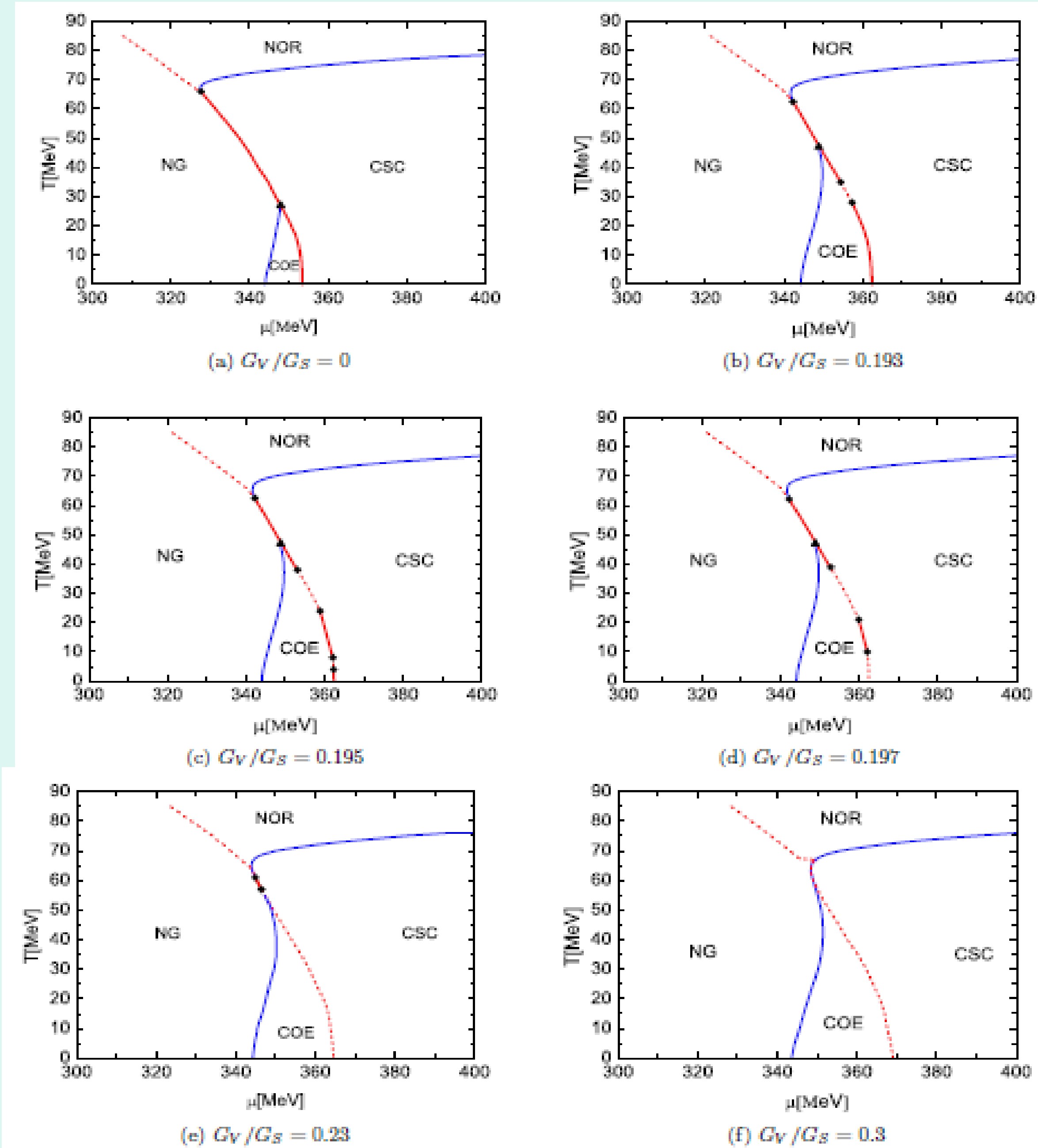
(c) $K'/K = 0.70$

(d) $K'/K = 1.0$

Eventually, the ph. tr becomes crossover in the whole T region.

This crossover region is extended to higher temperature region.

G_V varied with K' /K fixed at 1



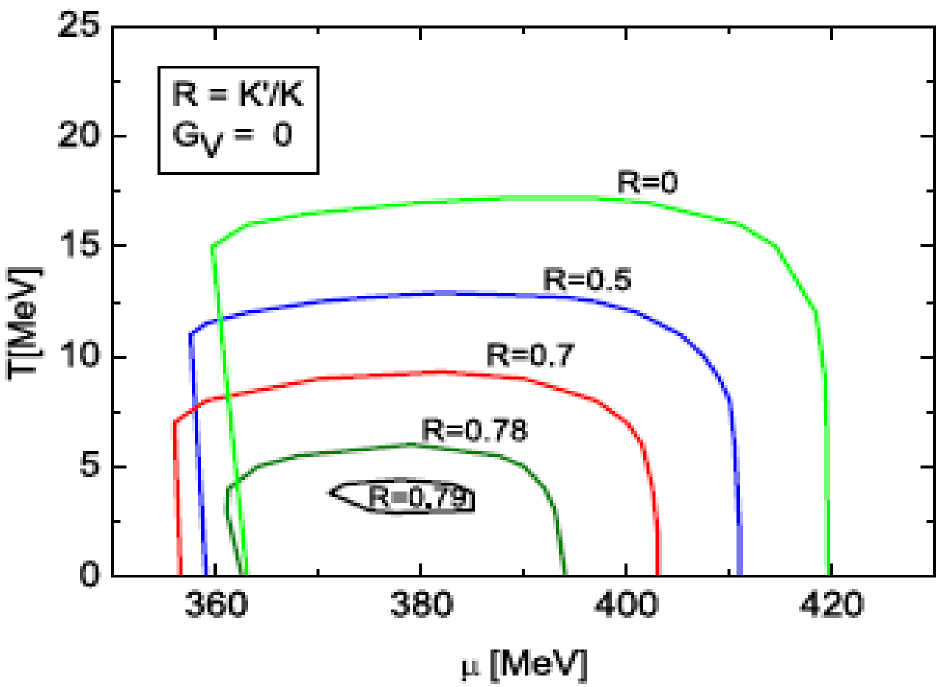
(a) $G_V/G_S = 0$
(b) $G_V/G_S = 0.193$
(c) $G_V/G_S = 0.195$
(d) $G_V/G_S = 0.197$
(e) $G_V/G_S = 0.23$
(f) $G_V/G_S = 0.3$

1. Effects of mismatched Fermi sphere by charge-neutrality

2. Then effect of G_V comes in to make ph. tr. at low T cross over.

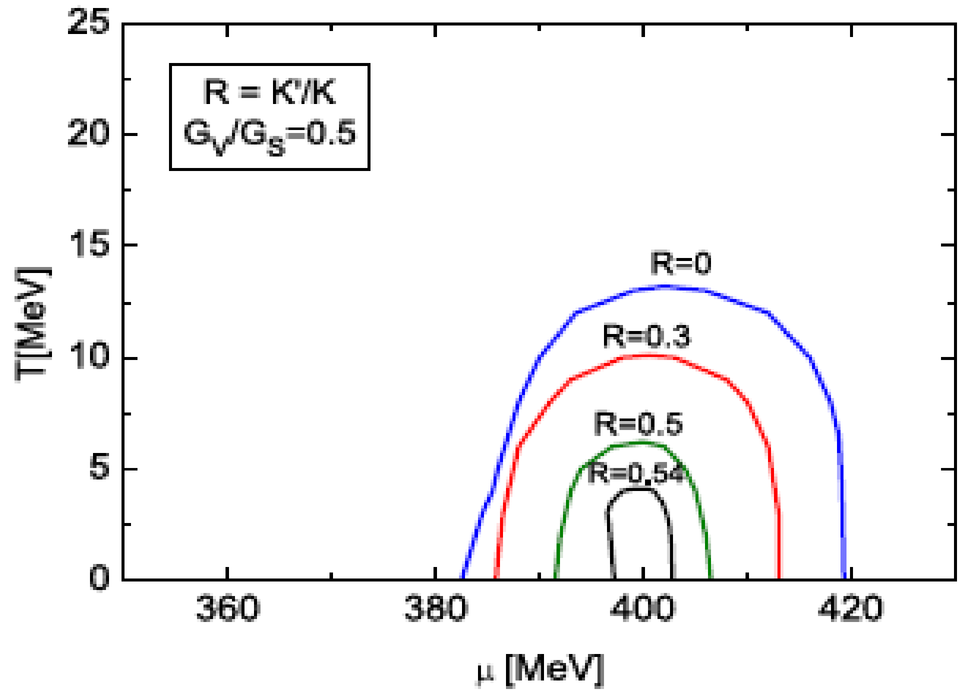
Fate of chromomagnetic instability

G_v=0



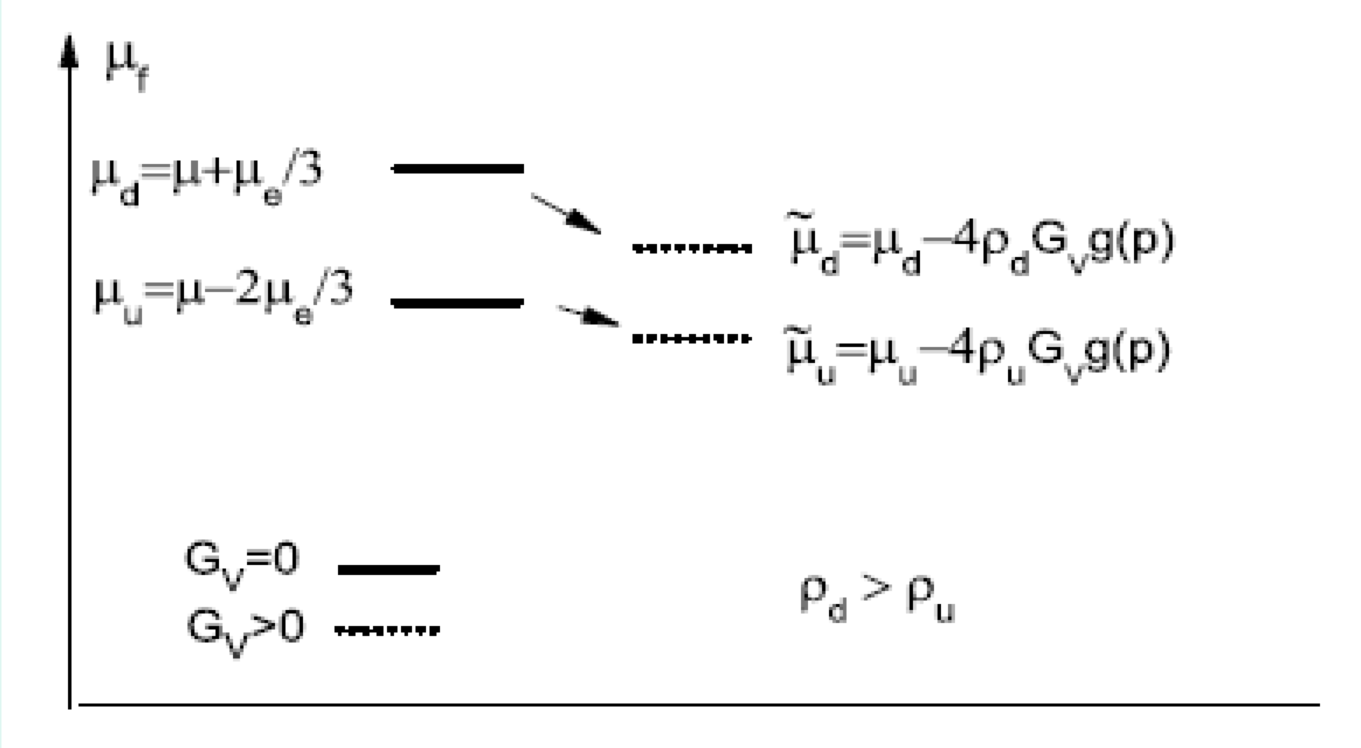
(a)

Finite G_V



(b)

Effects of the vector interaction on the effective chemical potentials



The vector interaction tends to suppress the mismatch of the Fermi spheres of the Cooper pairs.

⇩

Suppression of the Chromomagnetic instability!

4. Summary and concluding remarks

QCD phase diagram with vector interaction and axial anomaly terms under charge neutrality and beta-equilibrium constraints.

1. There are still a room of other structure of the QCD phase diagram with **multiple critical points** when the **color superconductivity** and the **vector interaction** are incorporated.
2. The new anomaly-induced interaction plays the similar role as G_V under charge- neutrality constraint.
3. The message to be taken in the present MF calculation:
   It seems that the QCD matter is **very soft** along the critical line when the color superconductivity is incorporated; there can be a good chance to see large fluctuations of various observables like **chiral-diquark-density** mixed fluctuations,

$$a\bar{q}_c q + b\bar{q}q + cq^\dagger q.$$