Quarkyonic Chiral Spirals

Toru Kojo (RBRC)

In collaboration with

Y. Hidaka (Kyoto U.), L. McLerran (RBRC/BNL), R. Pisarski (BNL)

Contents

Dense QCD at T=0 : Confining aspects

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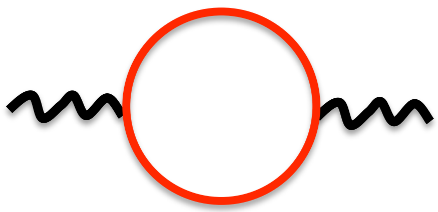
Allowed phase space differs → Different screening effects

e.g.)



$$M_D \sim N_c^{-1/2} \times f(\mu)$$

Dense QCD at T=0 : Confining aspects

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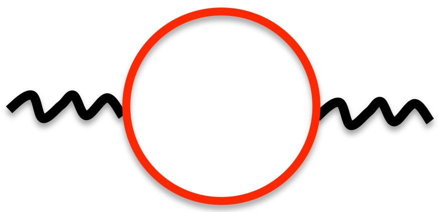

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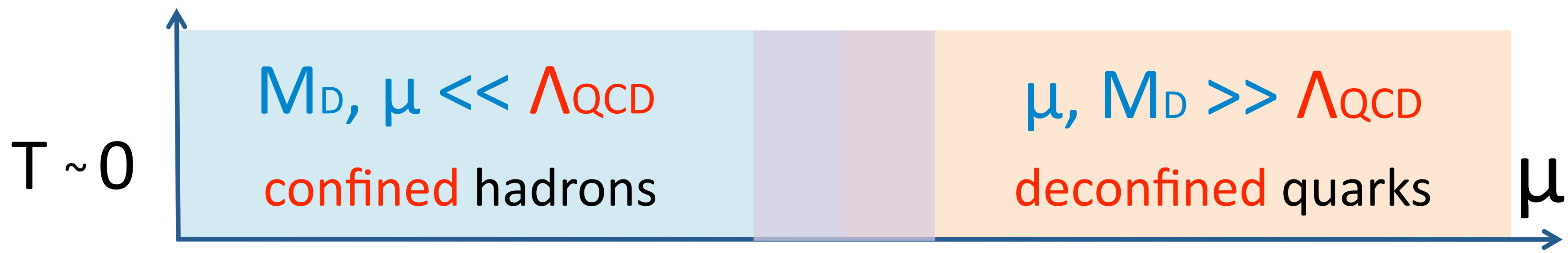

Dense QCD at T=0 : Confining aspects

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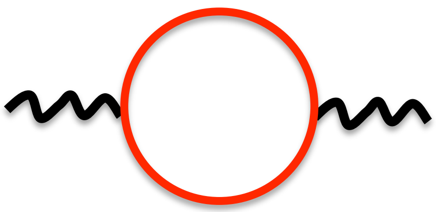

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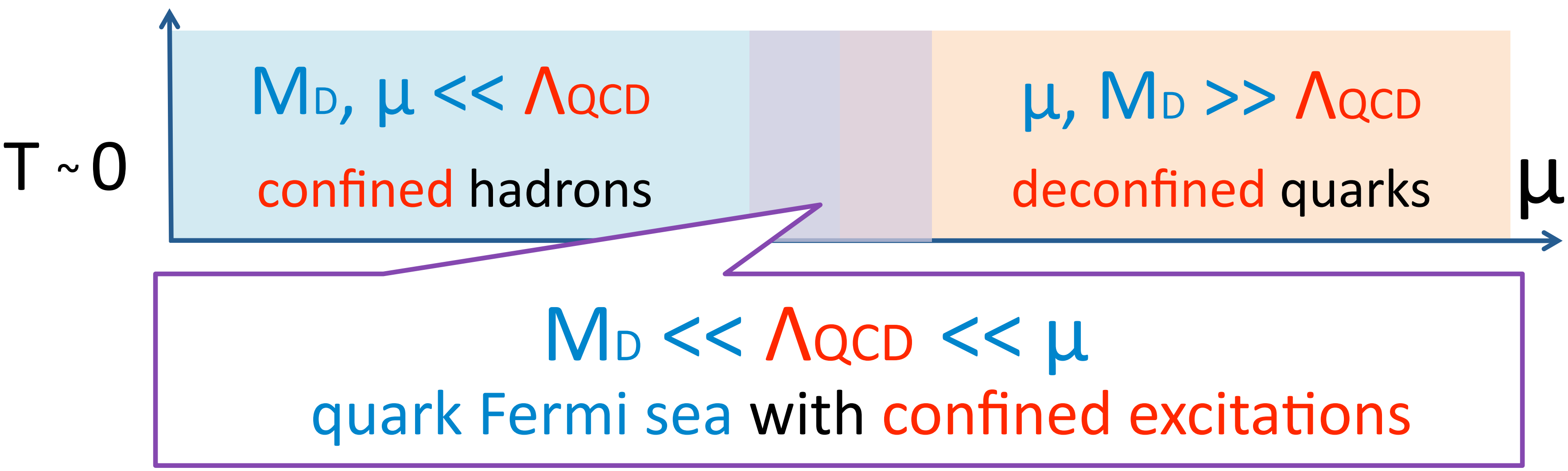
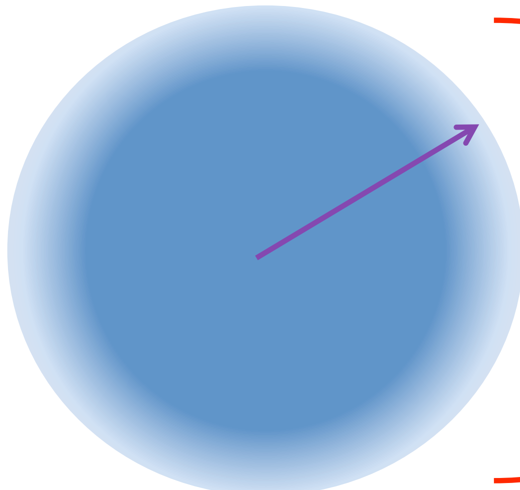


Quarkyonic Matter

McLerran & Pisarski (2007) $(M_D << \Lambda_{QCD} << \mu)$



As a total,
color singlet

$\rightarrow$ deconfined quarks

Quarkyonic Matter

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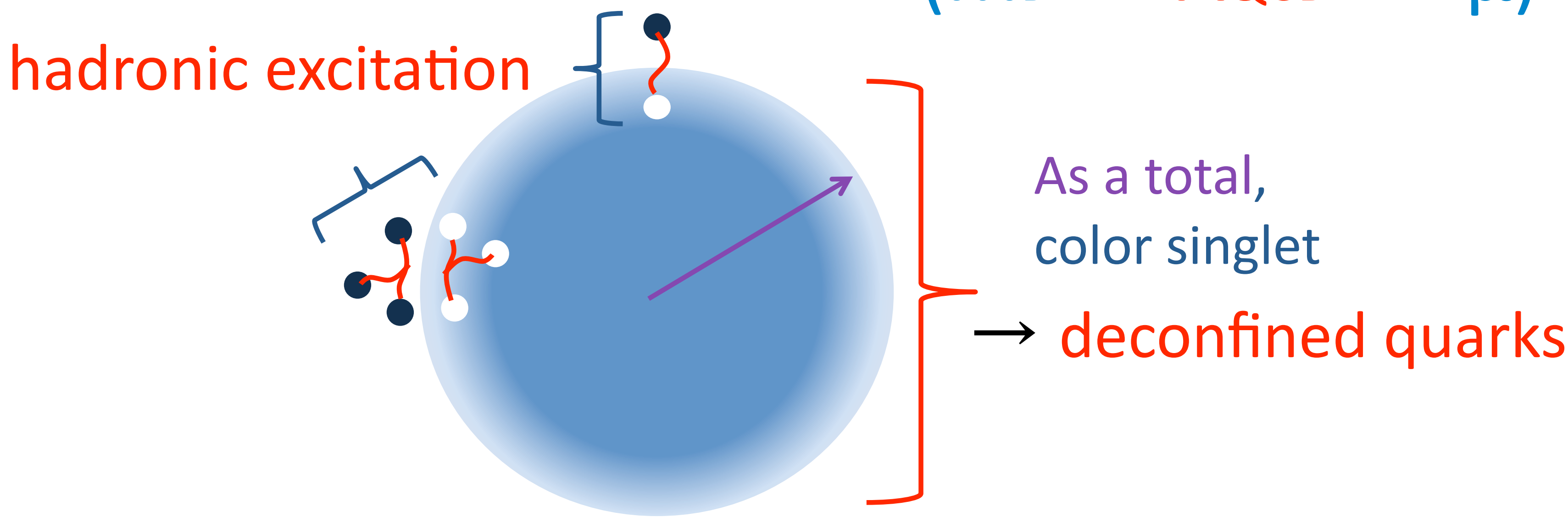

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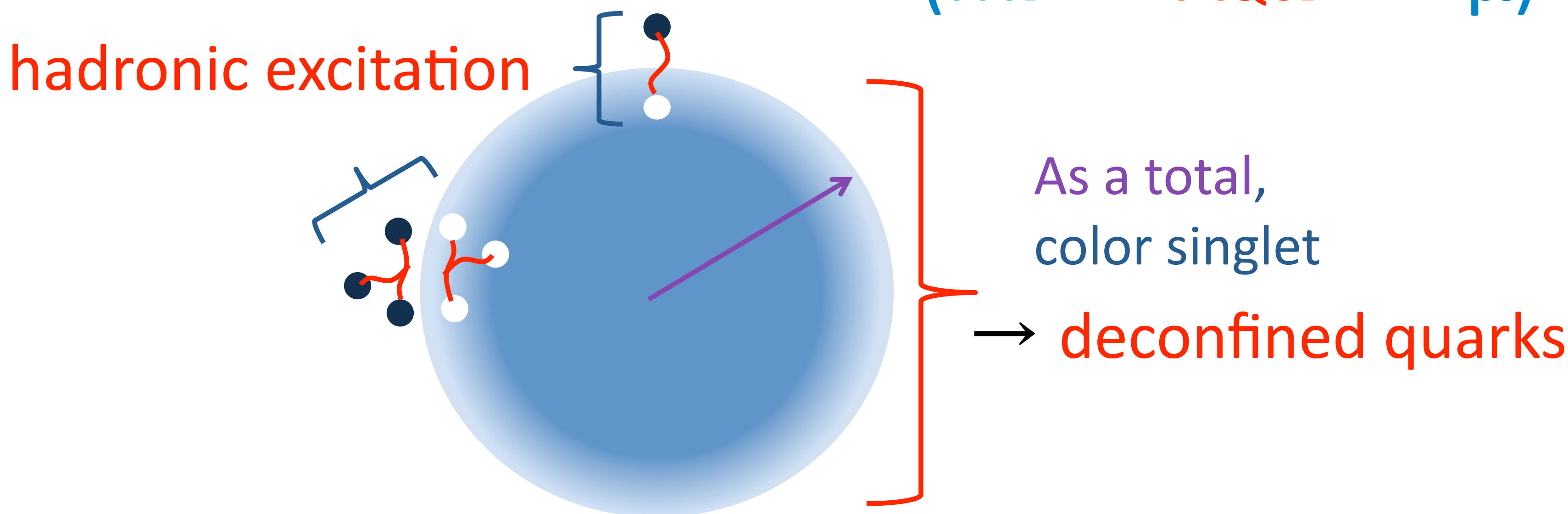

Quark Fermi sea + baryonic Fermi surface → Quarkyonic

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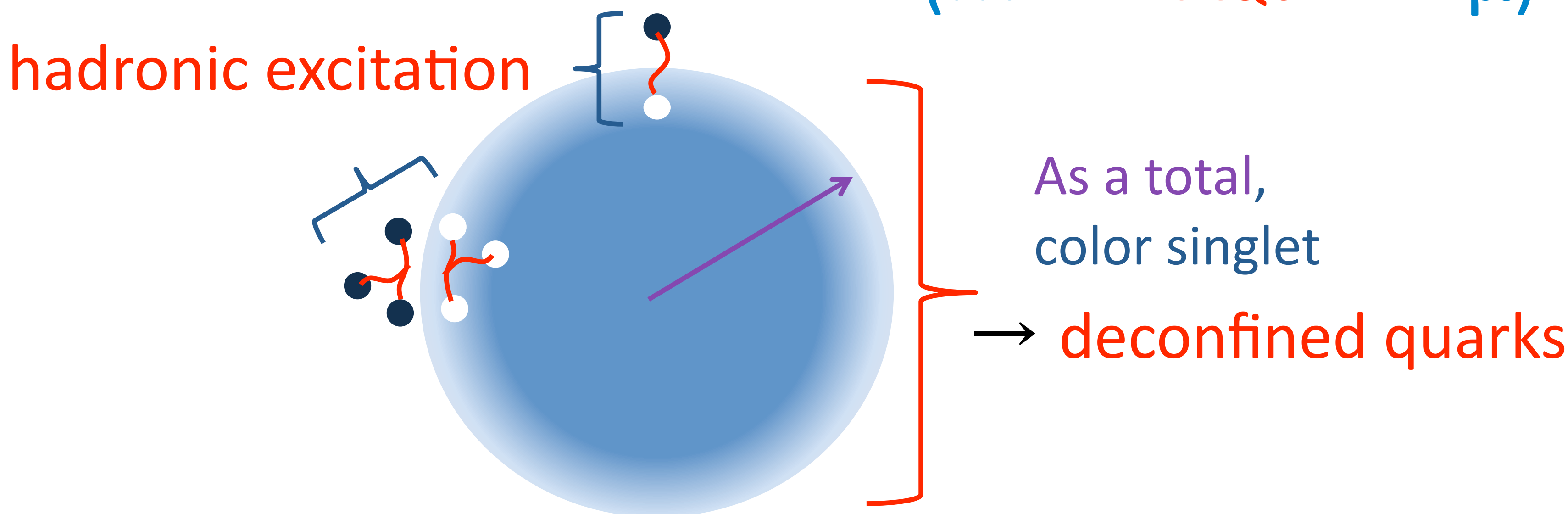


Quark Fermi sea + baryonic Fermi surface → Quarkyonic

- Large Nc: $M_D \sim N_c^{-1/2} \rightarrow 0$

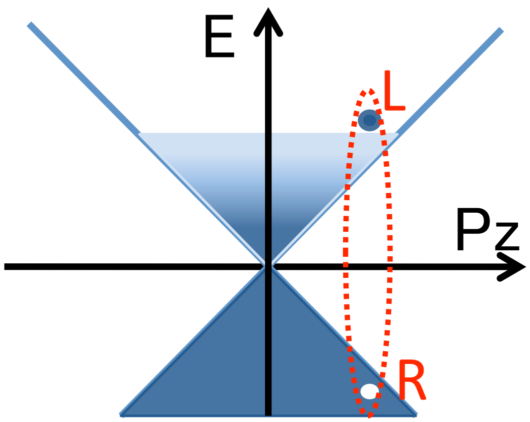
  Quarkyonic regime always holds.

  (so we can use vacuum gluon propagator)

Chiral Pairing Phenomena

- Candidates which spontaneously break Chiral Symmetry

Dirac Type



$P_{Tot}=0$ (uniform)

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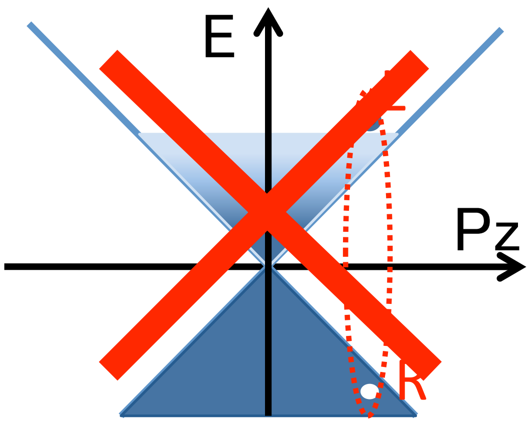

PTot=0 (uniform)

It costs large energy,
so does not occur spontaneously.

Chiral Pairing Phenomena

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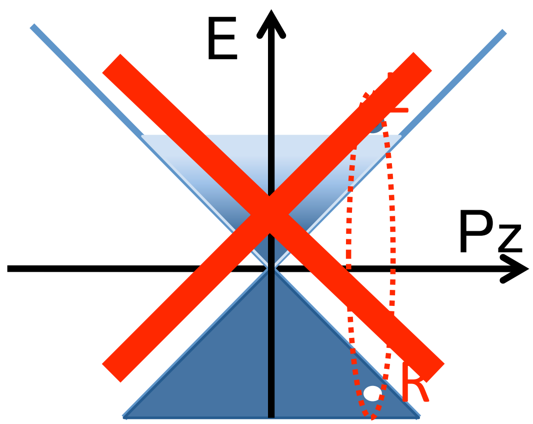
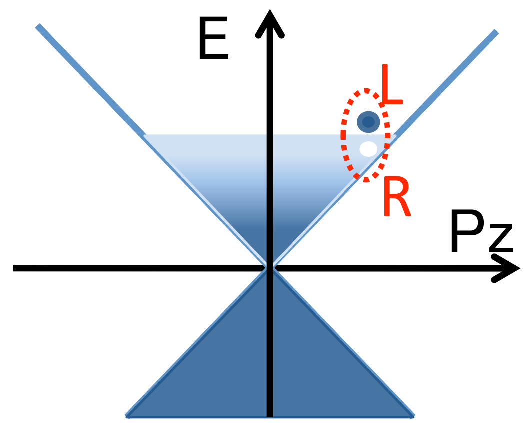


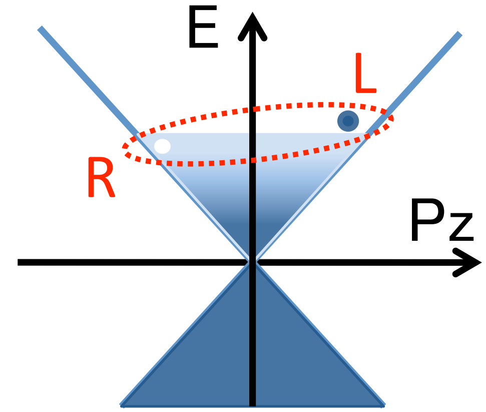
$P_{Tot}=0$ (uniform)

Exciton Type



$P_{Tot}=0$ (uniform)

Density wave

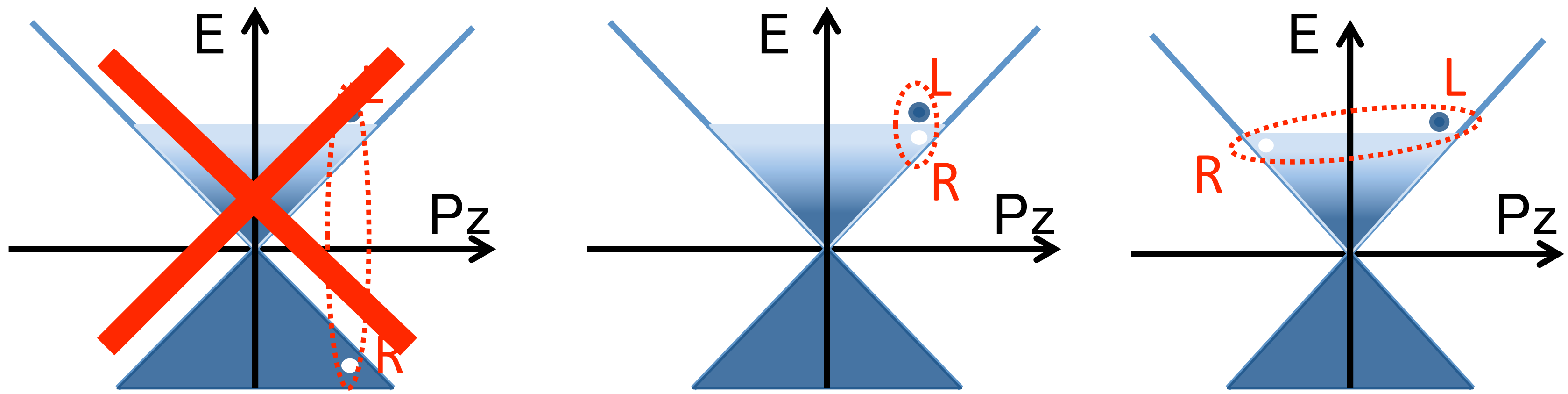


$P_{Tot}=2\mu$ (nonuniform)

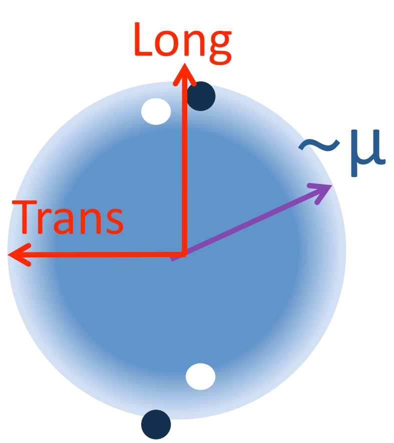
Chiral Pairing Phenomena

- Candidates which spontaneously break Chiral Symmetry

Dirac Type　　Exciton Type　　Density wave



$P_{Tot}=0$ (uniform)　　$P_{Tot}=0$ (uniform)　　$P_{Tot}=2\mu$ (nonuniform)



We will identify the most relevant pairing:
Exciton & Density wave solutions
will be treated and compared simultaneously.

Set up of the problem

- Confining propagator for quark-antiquark:

$$D_{\mu\nu} = C_F \times g_{\mu 0} g_{\nu 0} \times \frac{\sigma}{(\vec{p}^2)^2}$$ (linear rising type)

cf) leading part of Coulomb gauge propagator (ref: Gribov, Zwanziger)

But how to treat conf. model & non-uniform system??

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But how to treat conf. model & non-uniform system??

- 2 Expansion parameters in Quarkyonic limit

$1/N_c \to 0$: Vacuum propagator is not modified

(ref: Glozman, Wagenbrunn, PRD77:054027, 2008; Guo, Szczepaniak, arXiv:0902.1316 [hep-ph]).

$\Lambda_{QCD}/\mu \to 0$: Factorization approximation

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$\Lambda_{QCD}/\mu \to 0$: Factorization approximation

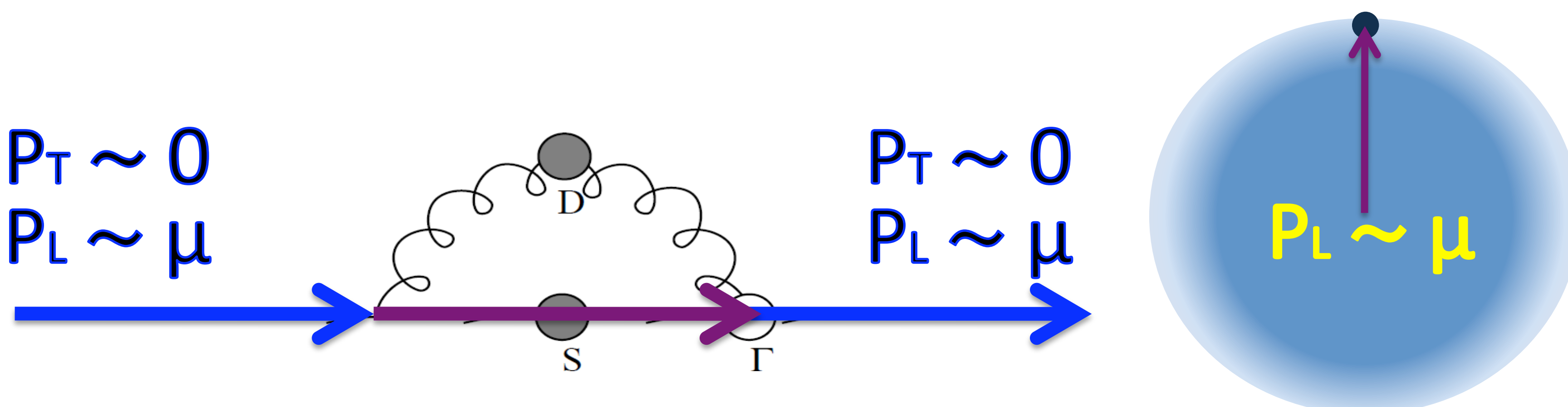
We will perform the dimensional reduction of nonperturbative self-consistent equations, Schwinger-Dyson & Bethe-Salpeter eqs.

e.g.) Dim. reduction of Schwinger-Dyson eq.

quark self-energy

including Σ

$$\not\Sigma(p) + \Sigma_m(p) = \int \frac{dk_4 dk_z d^2\vec{k}_T}{(2\pi)^4} \gamma_4 S(k) \gamma_4 \frac{\sigma}{|\vec{p} - \vec{k}|^4}$$



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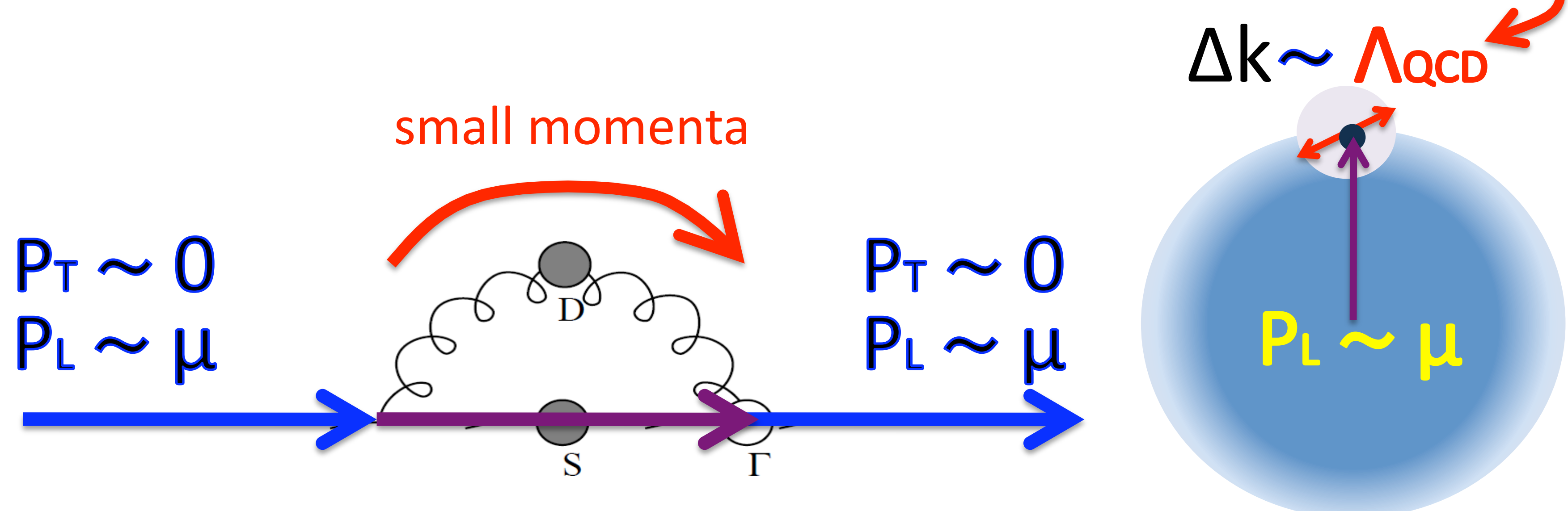
- Note1: Mom. restriction from **confining** interaction.



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quark self-energy

$$\not{\Sigma}(p) + \Sigma_m(p) = \int \frac{dk_4 dk_z d^2\vec{k}_T}{(2\pi)^4} \gamma_4 \underline{S(k)} \gamma_4 \frac{\sigma}{|\vec{p}-\vec{k}|^4}$$

- Note2: Suppression of transverse and mass parts:

$$S(k) = \gamma_0 S_0 - \gamma_z S_z - \vec{\gamma}_T \vec{S}_T + S_m$$

$\sim \mu$ $\sim \Lambda_{QCD}$

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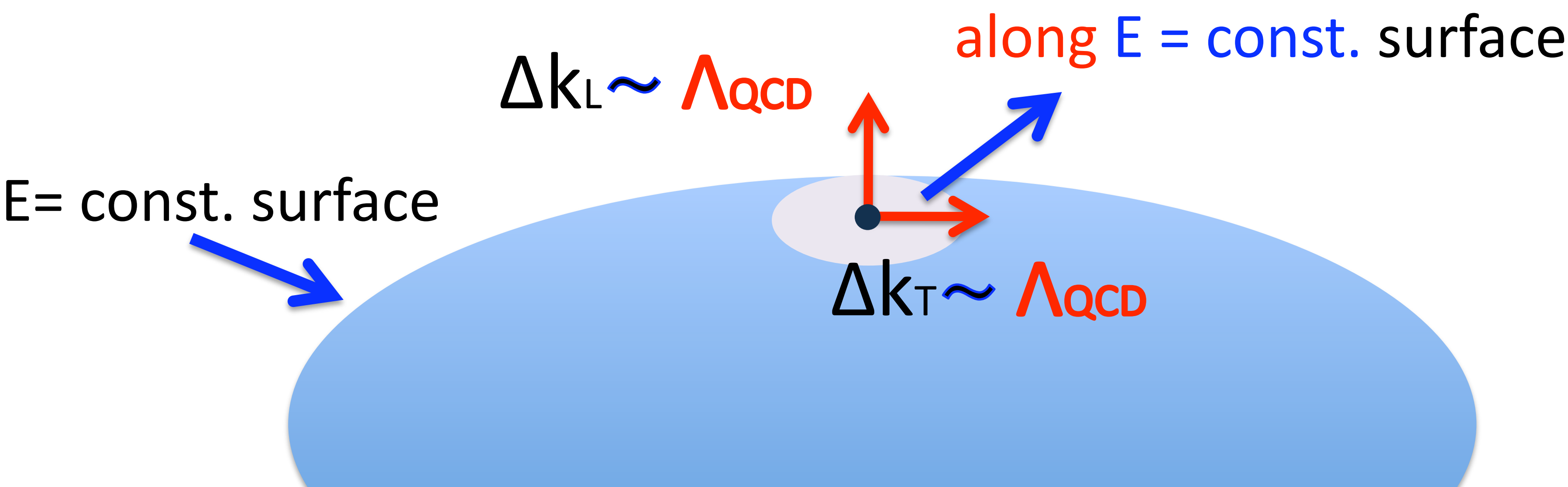
- Note3: quark energy is insensitive to small change of k_T :



e.g.) Dim. reduction of Schwinger-Dyson eq.

insensitive to kT

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factorization

$$\gamma_4 \Sigma_4 + \gamma_z \Sigma_z = \int \frac{dk_4 dk_z}{(2\pi)^2} \gamma_4 S(k_4, k_z, \underline{\vec{0}_T}) \gamma_4 \otimes \underline{\int \frac{d\vec{k}_T}{(2\pi)^2} \frac{\sigma}{|\vec{p}-\vec{k}|^4}}$$

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smearing

confining propagator in (1+1)D: $\boxed{\dfrac{\sigma}{2\pi} \dfrac{1}{|p_z - q_z|^2}}$

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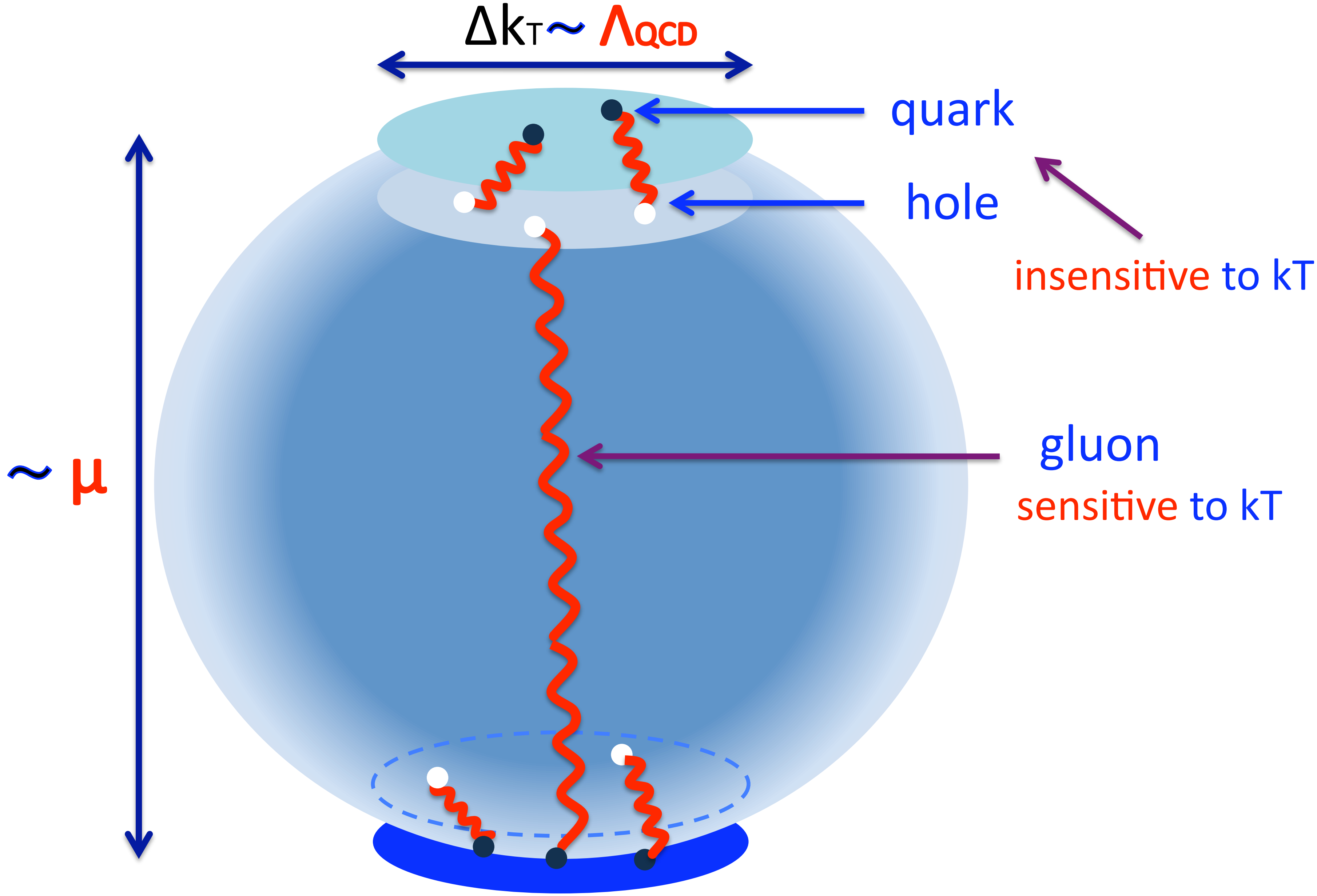
smearing

confining propagator in (1+1)D: $\boxed{\frac{\sigma}{2\pi} \frac{1}{|p_z - q_z|^2}}$

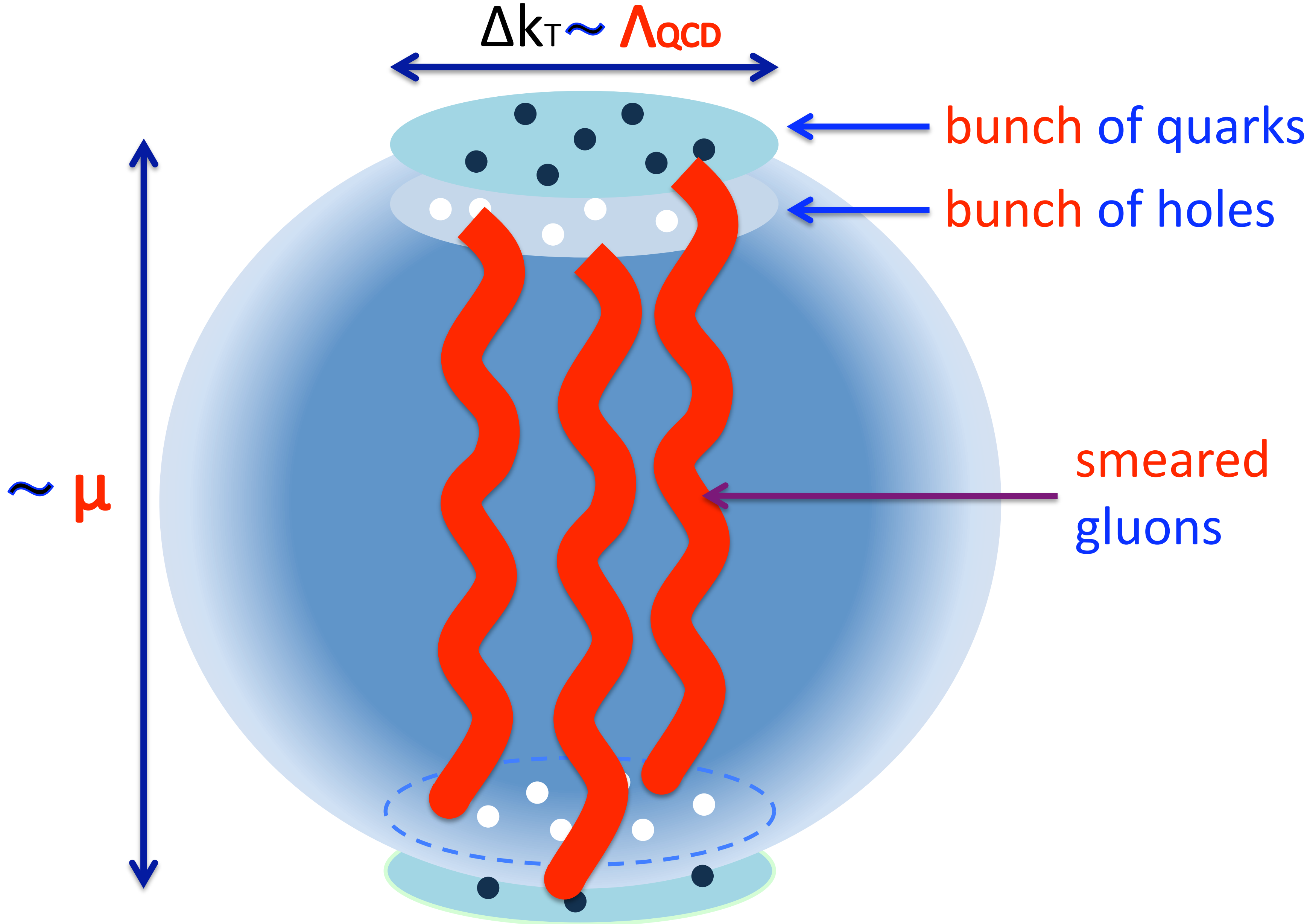
Schwinger-Dyson eq. in (1+1) D QCD in $A_1=0$ gauge

Bethe-Salpeter eq. can be also converted to (1+1)D

Catoon for Pairing dynamics before reduction



1+1 D dynamics of patches after reduction



Flavor Doubling

- At leading order of $1/N_c$ & Λ_{QCD}/μ

Dimensional reduction of Non-pert. self-consistent eqs :

4D "QCD" in Coulomb gauge $\longleftrightarrow$ 2D QCD in $A_1=0$ gauge

(confining model)

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- One immediate nontrivial consequence: $P_T/P_L \to 0$

Absence of γ_1, γ_2 $\longrightarrow$ Absence of spin mixing

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Absence of γ_1, γ_2 $\to$ Absence of spin mixing

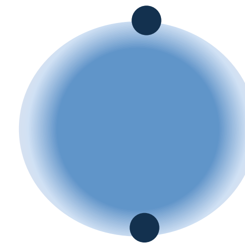
suppression of spin mixing		no angular d.o.f in (1+1) D
spin SU(2) x SU(Nf)	$\longleftrightarrow$	SU(2Nf)
(3+1)-D side		(1+1)-D side

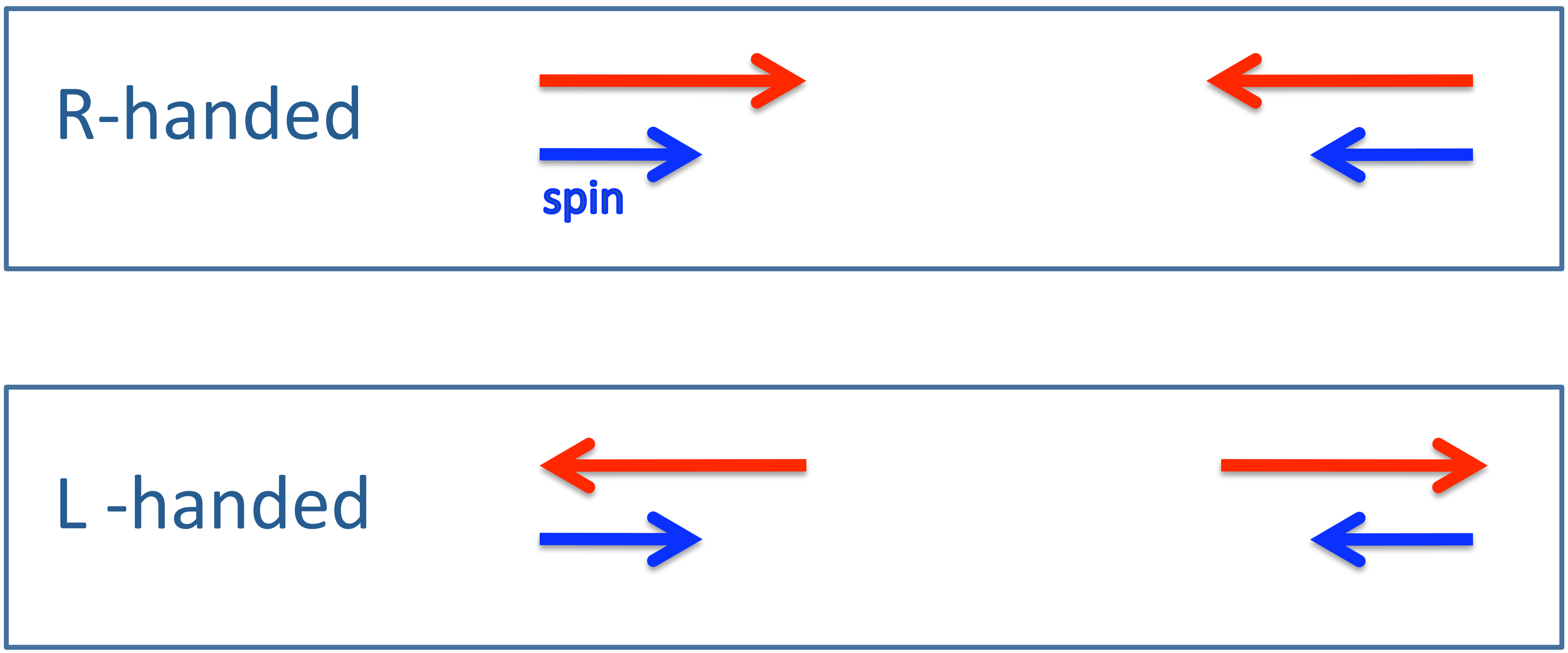
cf) Shuster & Son, NPB573, 434 (2000)

11/14

Flavor Multiplet

particle near north & south pole





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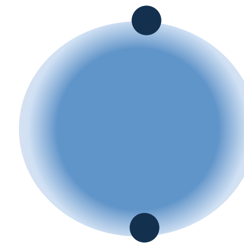

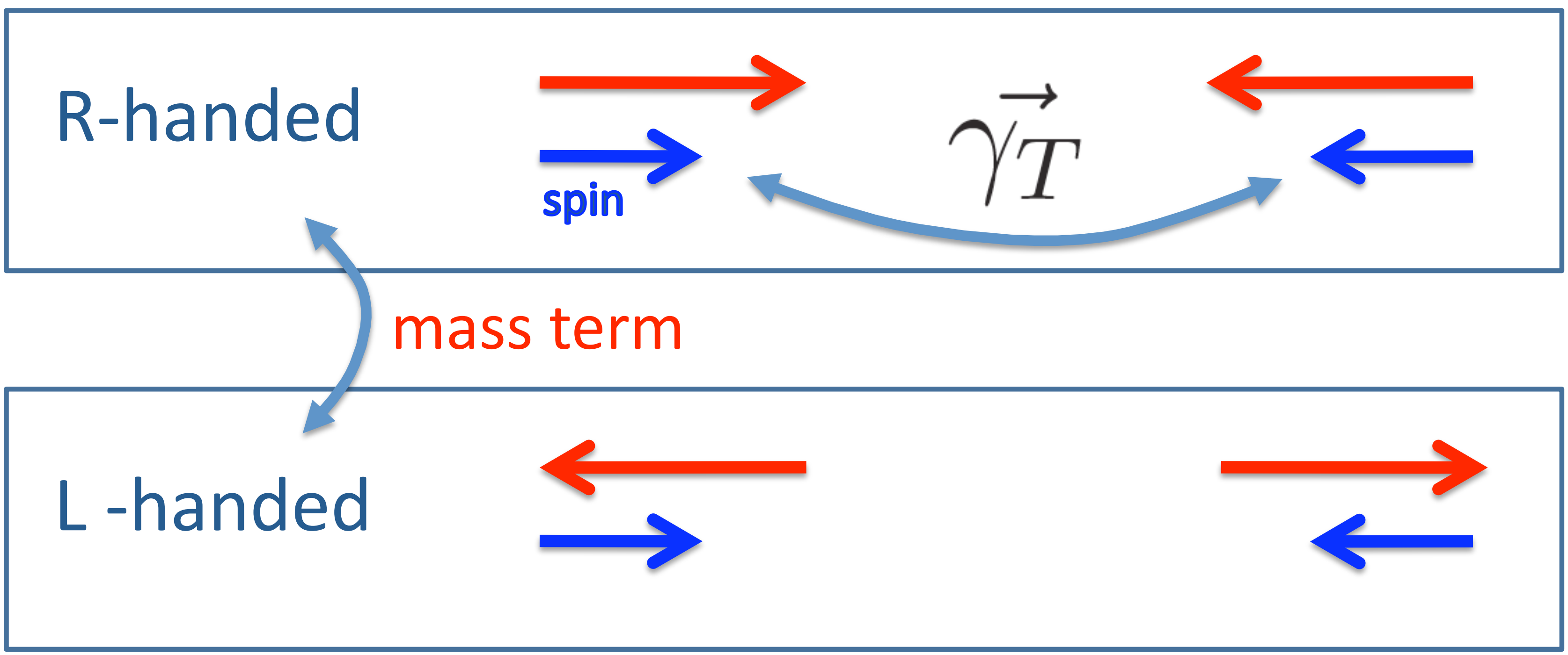

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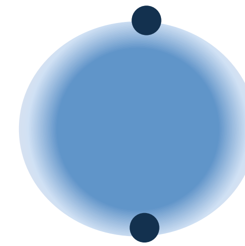

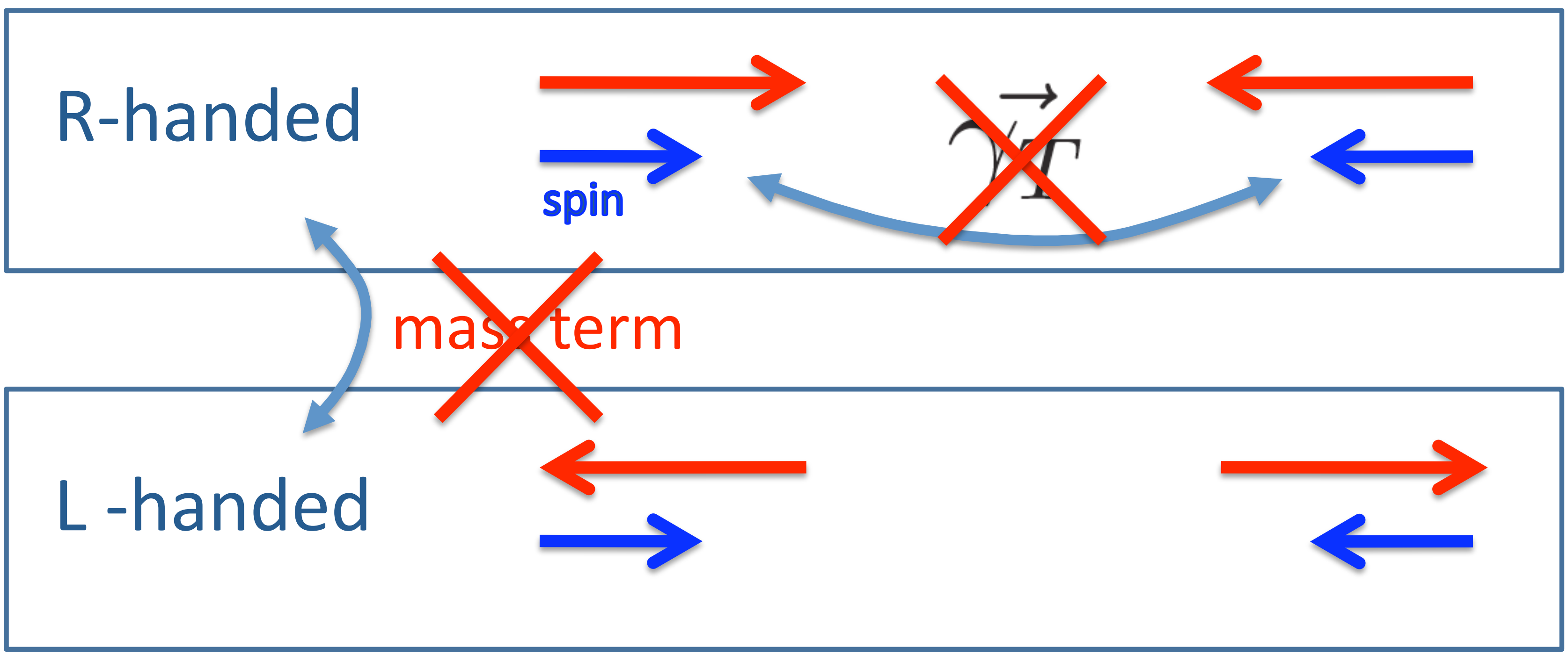

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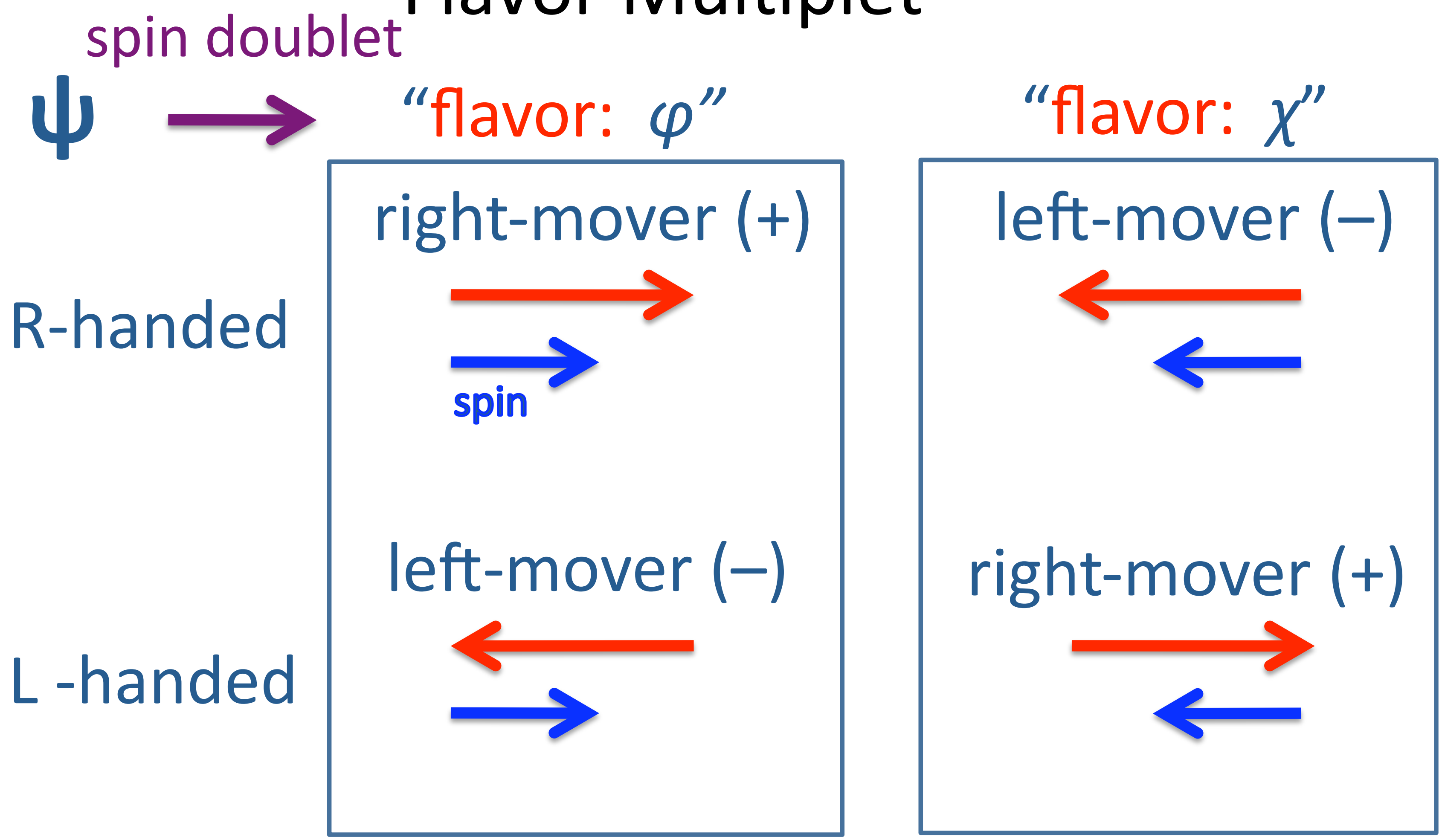

Moving direction: (1+1)D "chirality"

(3+1)D – CPT sym. directly convert to (1+1)D ones

Relations between composite operators

- 1-flavor (3+1)D operators without spin mixing:

$$\bar{\psi}\psi \qquad \bar{\psi}\gamma^0\psi \qquad \bar{\psi}\gamma^z\psi \qquad \bar{\psi}\gamma^0\gamma^z\psi$$

$$\downarrow \qquad\qquad \downarrow \qquad\qquad \downarrow \qquad\qquad \downarrow$$

$$\bar{\Psi}\Psi \qquad \bar{\Psi}\Gamma^0\Psi \qquad \bar{\Psi}\Gamma^z\Psi \qquad \bar{\Psi}\Gamma^5\Psi$$

Flavor singlet in (1+1)D

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$$\bar{\Psi}\Psi \qquad \bar{\Psi}\Gamma^0\Psi \qquad \bar{\Psi}\Gamma^z\Psi \qquad \bar{\Psi}\Gamma^5\Psi$$

Flavor singlet in (1+1)D

- All others have spin mixing:

ex) $\bar{\psi}\gamma^5\psi \rightarrow \bar{\Psi}\tau_3\Psi$

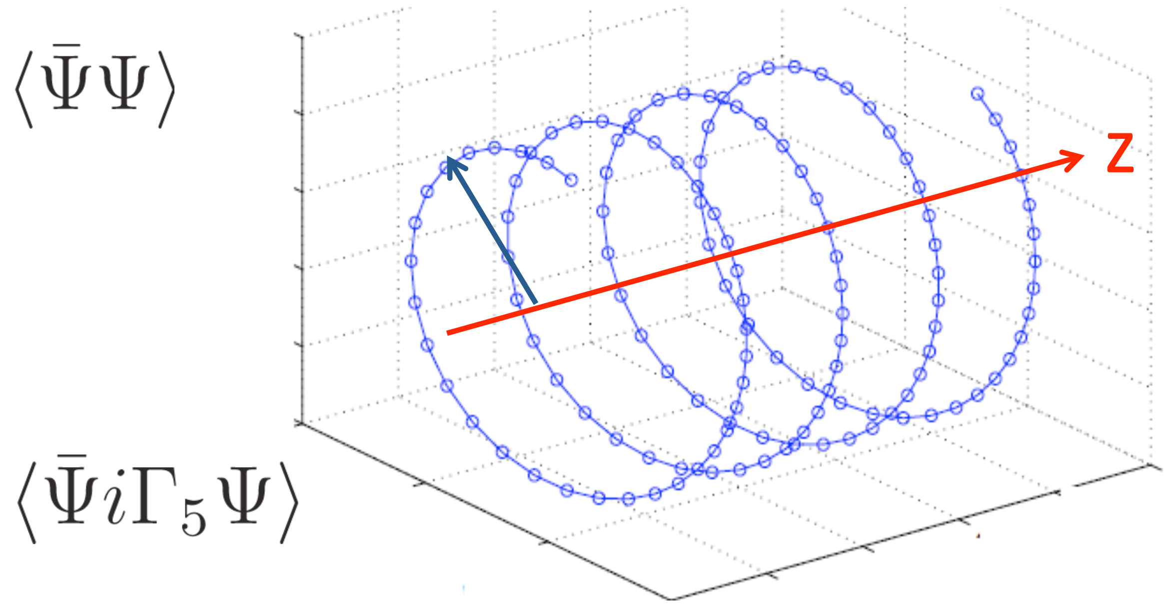
$\bar{\psi}\gamma^1\psi \rightarrow \bar{\Psi}\tau_2\Psi$

(They will show no flavored condensation)

Flavor non-singlet in (1+1)D

Chiral Spirals in (1+1)D

- At μ ≠ 0: periodic structure (crystal) which oscillates in space.



cf) ▪ Chiral Gross Neveu model (with continuous chiral symmetry)

Schon & Thies, hep-ph/0003195; 0008175; Thies, 06010243

Basar & Dunne, 0806.2659; Basar, Dunne & Thies, 0903.1868

▪ \`tHooft model, massive quark (1-flavor)

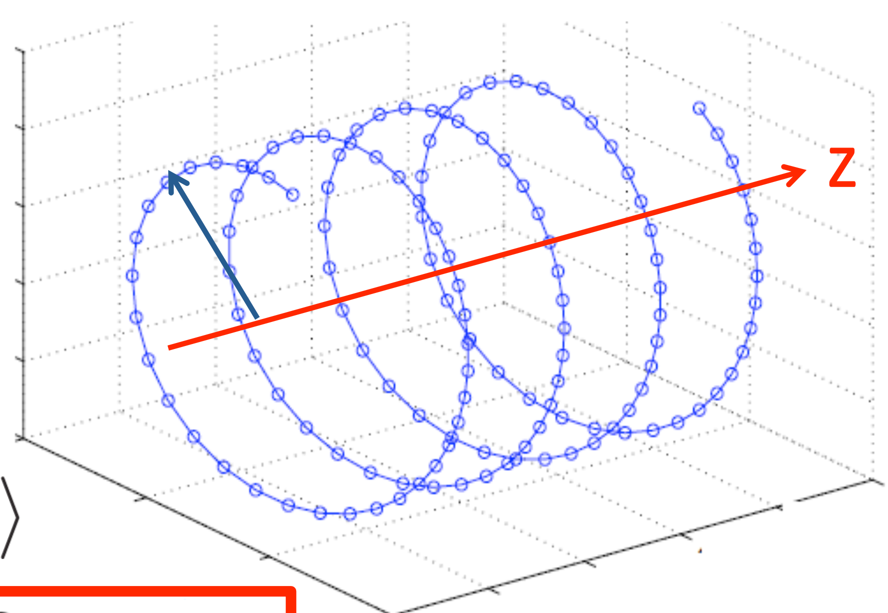
B. Bringoltz, 0901.4035

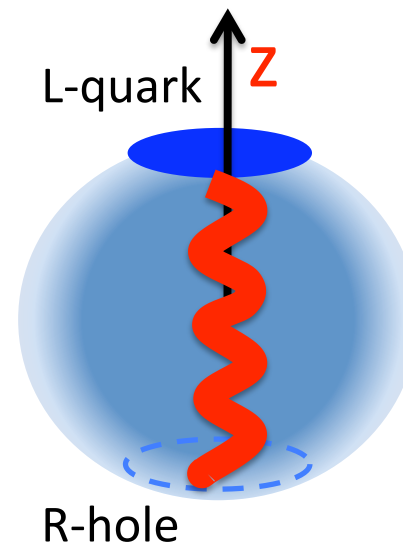
Quarkyonic Chiral Spirals in (3+1)D

- Chiral rotation evolves in the longitudinal direction:

$\langle \bar{\Psi}\Psi \rangle$

$$\boxed{\langle \bar{\psi}\psi \rangle}$$





$\langle \bar{\Psi} i \Gamma_5 \Psi \rangle$

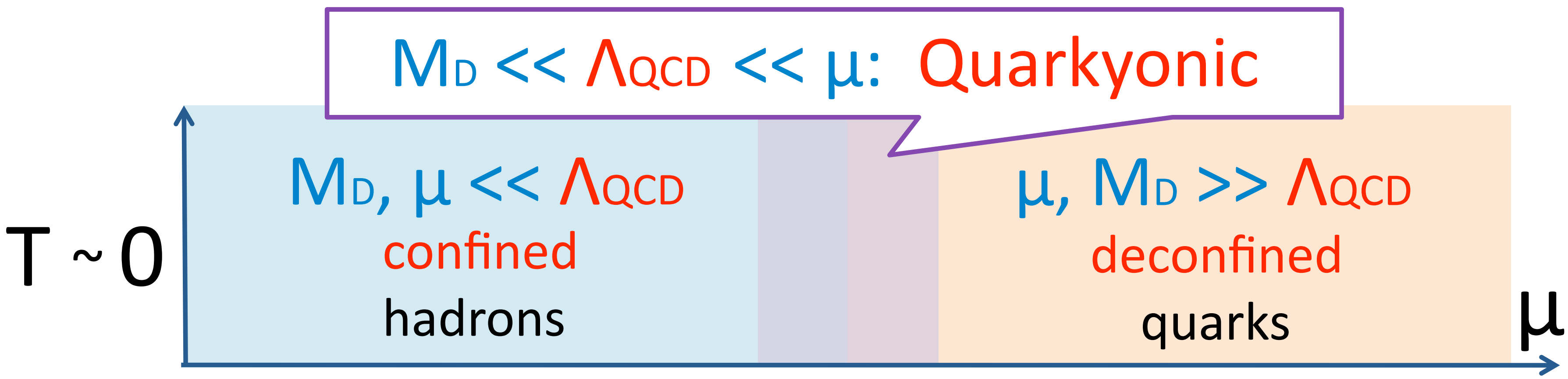
$$\boxed{\langle \bar{\psi}\gamma^0\gamma^z\psi \rangle}$$

(not conventional pion condensate in nuclear matter)

- Baryon number is spatially constant.
- No other condensates appear in quarkyonic limit.

Summary of large Nc, low T phase diagram

Confining aspects



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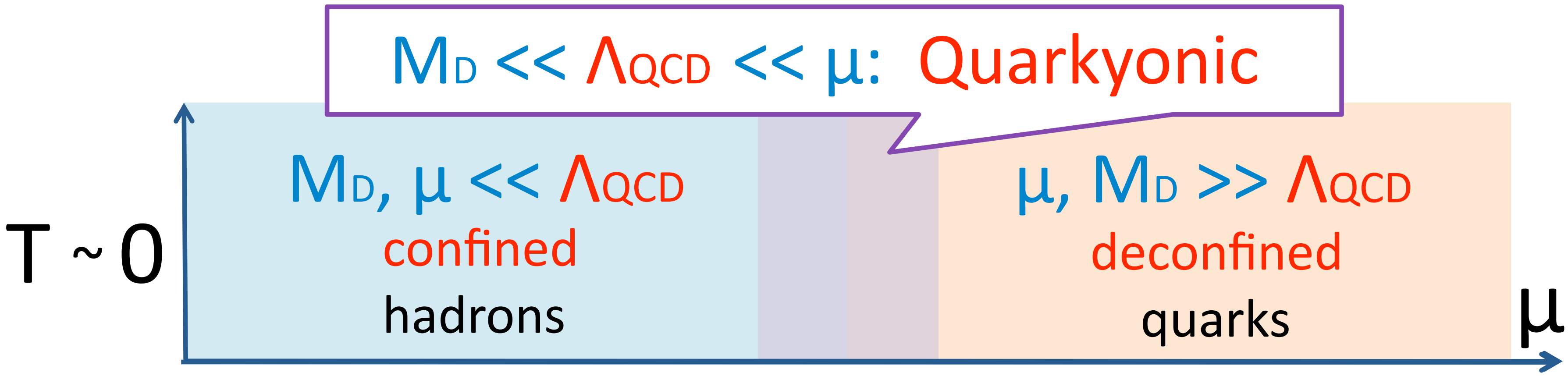
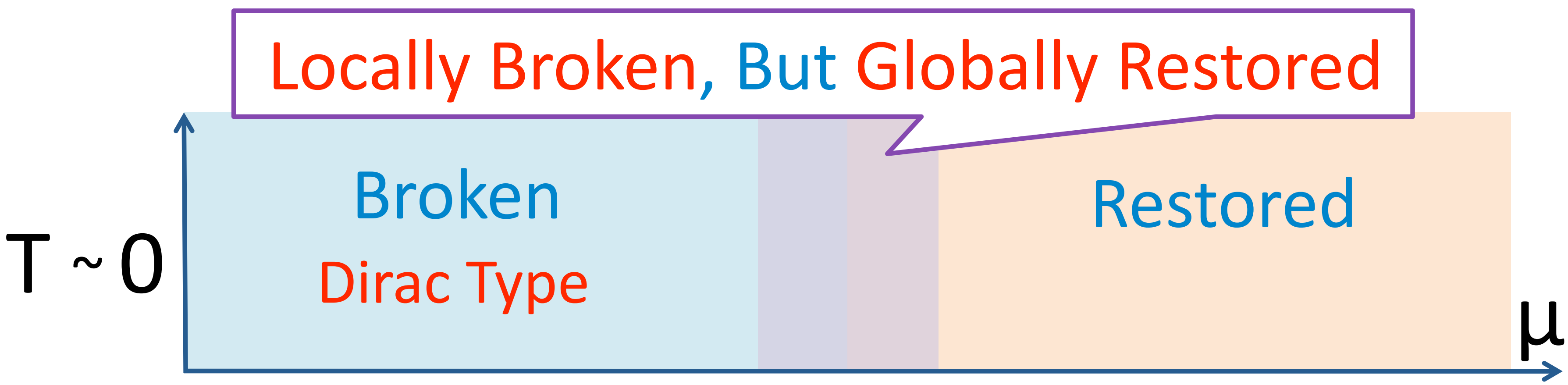


Chiral aspects



Topics not discussed in this talk

(Please ask in discussion time or personally during workshop)

- Origin of self-energy divergences and how to avoid it.

  - Quark pole need not to disappear in linear confinement model.

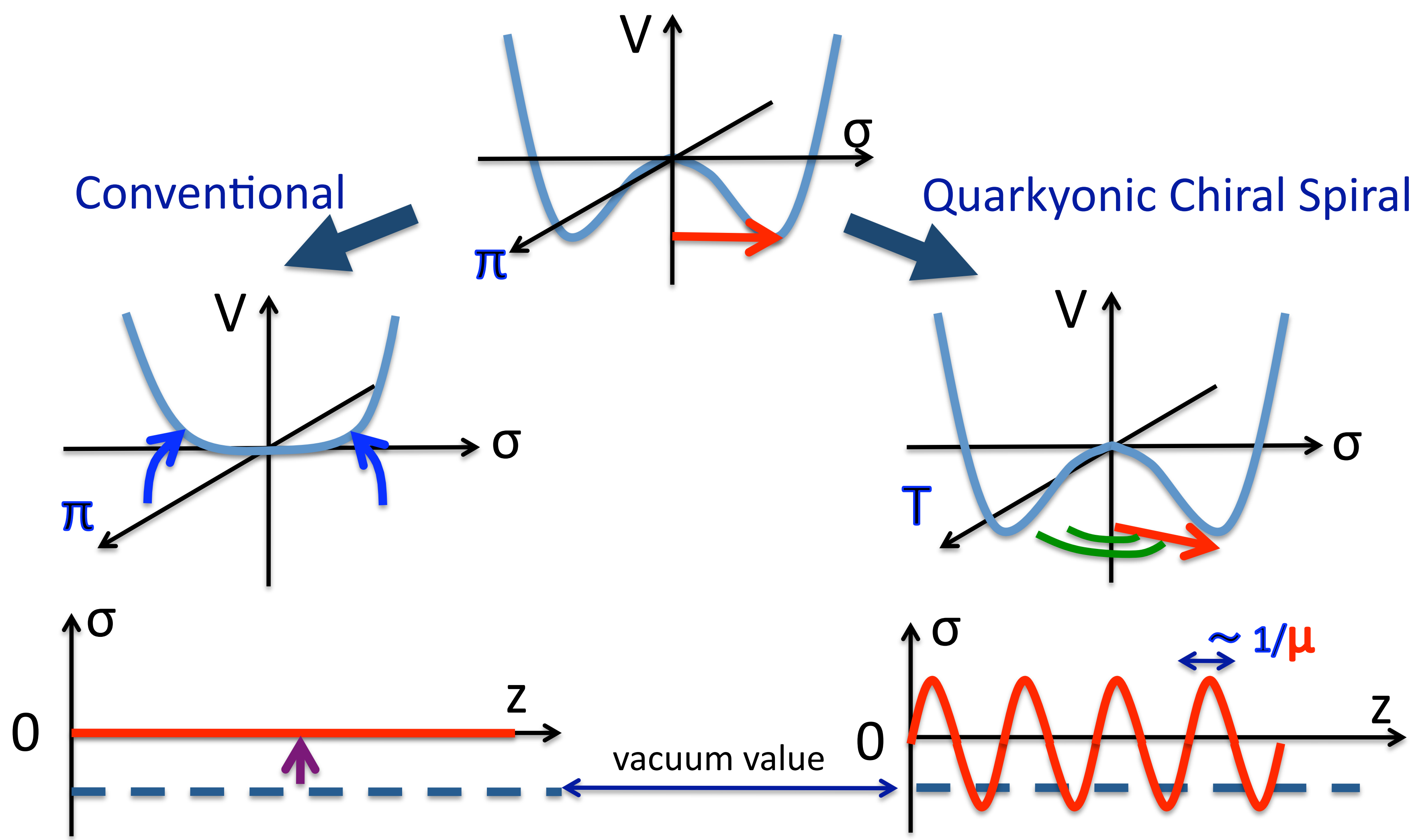
- Explicit example of quarkyonic matter:

  - 1+1 D large Nc QCD has a quark Fermi sea but confined spectra.

- Beyond single patch pairing.

  - Issues on rotational invariance, working in progress.

Summary: Chiral sym. breaking/restoration



zero everywhere.

nonzero locally, but globally zero!

Why Chiral Rotation in (1+1)D ?

- Key observation: Moving direction = (1+1)D Chirality

$$\langle \bar\varphi_- \varphi_+ \rangle = \Delta e^{\underline{2i\mu z}} \qquad \langle \bar\varphi_+ \varphi_- \rangle = \Delta e^{\underline{-2i\mu z}}$$

Opposite phase

$$\boxed{\langle \bar\varphi \Gamma_5 \varphi \rangle = \langle \bar\varphi_- \varphi_+ \rangle - \langle \bar\varphi_+ \varphi_- \rangle = \Delta i \sin 2\mu z \neq 0}$$

Density wave of $\bar\Psi\Psi$ inevitably accompanies $\bar\Psi\Gamma^5\Psi$

(1+1)D: Chiral Density wave → Chiral Spiral

2nd Dictionary: μ = 0 & μ ≠ 0 in (1+1)D

- μ ≠ 0 2D QCD can be mapped onto μ = 0 2D QCD

$$\Psi' = e^{i\mu z \Gamma_5}\Psi$$: chiral rotation (or boost)

$$\boxed{\underbrace{\bar{\Psi}\left[i\Gamma^\mu \partial_\mu + \mu\Gamma^0\right]\Psi}_{(\mu \neq 0)} \rightarrow \underbrace{\bar{\Psi}' i\Gamma^\mu \partial_\mu \Psi'}_{(\mu = 0)}}$$

(due to special geometric property of 2D Fermi sea)

- Dictionary between μ = 0 & μ ≠ 0 condensates:

μ = 0 | μ ≠ 0

$$\langle \bar{\Psi}'\Psi' \rangle \rightarrow \langle \bar{\Psi}\Psi \rangle \cos(2\mu z) + \langle \bar{\Psi} i\Gamma_5 \Psi \rangle \sin(2\mu z)$$

$$\underbrace{\langle \bar{\Psi}'\Gamma^0\Psi' \rangle}_{(=0)} \rightarrow \underbrace{\langle \bar{\Psi}'\Gamma^0\Psi' \rangle}_{(=0)} + \underline{\frac{\mu}{2\pi}}$$

induced by anomaly

"correct baryon number"

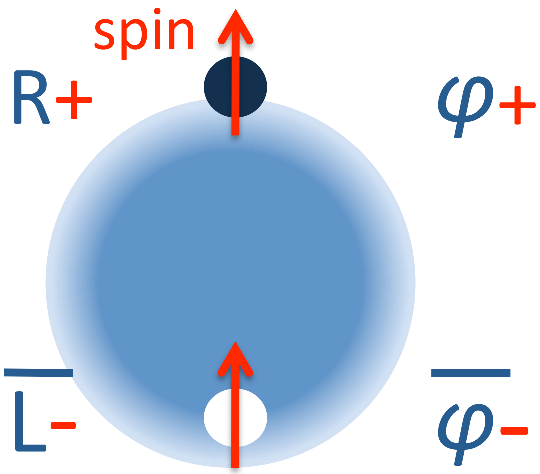
Chiral Density Wave VS Chiral Exciton

IF dimensionally reduced models respect "flavor" symmetry

→ there is no chiral exciton condensates:

Chiral Density Wave

→ R+ $\overline{\text{L-}}$ pairing



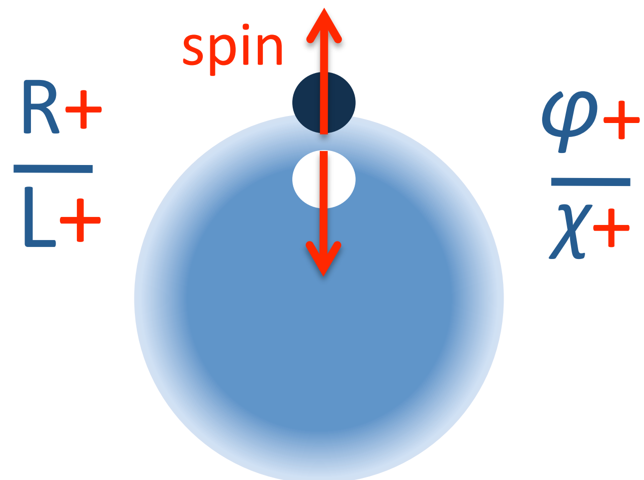
same spin
in 3+1 D
↕
same "flavor"
in 1+1 D

Possible (1+1)D flavor singlet

$$\bar{\Psi}\Psi \qquad \bar{\Psi}\Gamma^5\Psi$$

Chiral Exciton

→ R+ $\overline{\text{L+}}$ pairing



No flavor singlet pairing

→ No chiral exciton!

Preceding works on the chiral density waves

(Many works, so incomplete list)

- **Nuclear matter or Skyrme matter:**

  Migdal '71, Sawyer & Scalapino '72.. : effective lagrangian for nucleons and pions

- **Quark matter:**

  Perturbative regime with Coulomb type gluon propagator:

  Deryagin, Grigoriev, & Rubakov '92: Schwinger-Dyson eq. in large Nc

  Shuster & Son, hep-ph/9905448: Dimensional reduction of Bethe-Salpeter eq.

  Rapp, Shuryak, and Zahed, hep-ph/0008207: Schwinger-Dyson eq.

  Effective model:

  Nakano & Tatsumi, hep-ph/0411350, D. Nickel, 0906.5295

  Nonperturbative regime with linear rising gluon propagator:

  → Present work

4, A closer look at QCS

Coleman's theorem & Strong chiral phase fluctuations

Excitation modes in quarkyonic limit

- Fermionic action for (1+1)D QCD:

$$S = \int d^2x [\Psi_+ i\partial_- \Psi_+ + \Psi_- i\partial_+ \Psi_-] \quad \text{+ gauge int.}$$

- Bosonized version:

U(1) free bosons & Wess-Zumino-Novikov-Witten action :

(Non-linear σ model + Wess-Zumino term)

"Charge – Flavor – Color Separation"

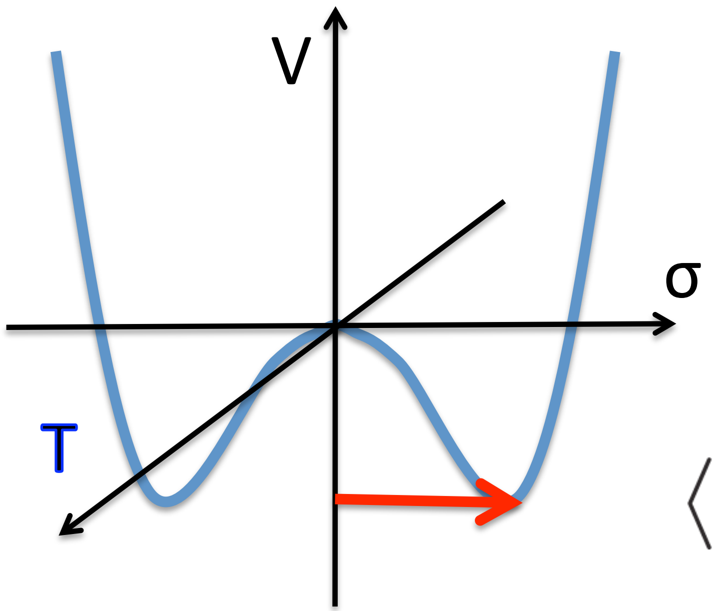
$$S = \underbrace{S_{U(1)}[\phi] + S^{flavor}_{k=N_c}[g]}_{\text{conformal inv.}} + \underbrace{S^{color}_{k=N_f}[h] \ \text{+ gauge int.}}_{\text{dimensionful}}$$

$4N_f^2$ gapless phase modes

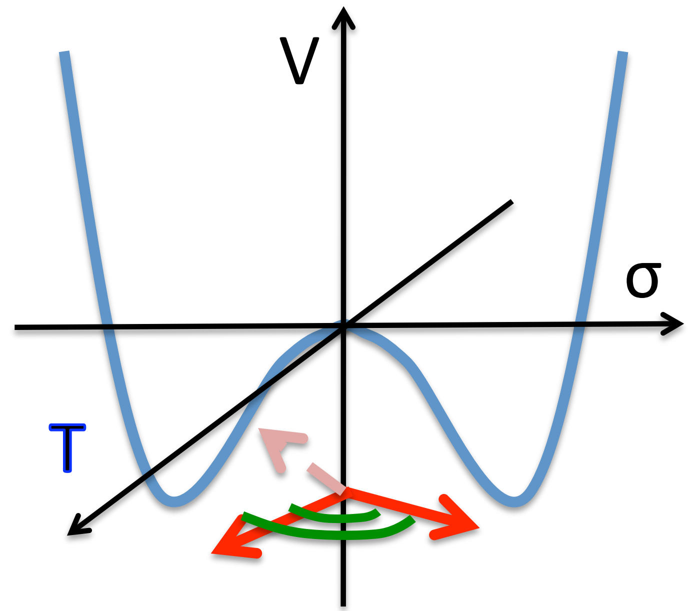
gapped phase modes

Coleman's theorem ?

- Coleman's theorem: No Spontaneous sym. breaking in 2D



$\langle \rho \rangle \neq 0$



$\langle e^{i\theta} \rangle \neq 0$ (SSB)

$\langle e^{i\theta} \rangle = 0$ (No SSB)

IR divergence in (1+1)D
phase dynamics

- Phase fluctuations belong to:

Excitations (physical pion spectra)	ground state properties (No pion spectra)

2, How to solve

Dimensional reduction from (3+1)D to (1+1)D

Quasi-long range order & large Nc

- Local order parameters:

gapless modes gapped modes

$$\langle \bar{\Psi}_+ \Psi_- \rangle \sim \langle e^{i\sqrt{4\pi/N_c N_f}\,\phi} \rangle \otimes \langle \mathrm{tr} g \rangle \otimes \langle \mathrm{tr} h \rangle$$

$\langle e^{i\sqrt{4\pi/N_c N_f}\,\phi} \rangle \to 0$, $\langle \mathrm{tr} g \rangle \to 0$, $\langle \mathrm{tr} h \rangle \to$ finite

due to IR divergent phase dynamics

But this does not mean the system is in the usual symmetric phase!

- Non-Local order parameters:

$$\langle \bar{\Psi}_+ \Psi_-(x) \bar{\Psi}_- \Psi_+(0) \rangle \sim \begin{cases} \cancel{e^{-m|x|}} & \text{: symmetric phase} \\ \cancel{\langle \bar{\Psi}_+ \Psi_- \rangle^2} & \text{: long range order} \\ |x|^{\underline{-C/N_c}} & \text{: quasi-long range order} \end{cases}$$

(including disconnected pieces)

(power law)

Quasi-long range order & large Nc

- Local order parameters:

gapless modes gapped modes

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(including disconnected pieces)

large Nc limit (Witten `78)

(power law)

How neglected contributions affect the results?

- Neglected contributions in the dimensional reduction:

$$S(k) = \gamma_0 S_0 - \gamma_z S_z - \vec{\gamma}_T \vec{S}_T + S_m$$

$\sim \mu$ $\sim \Lambda_{QCD}$

(3+1)D		(1+1)D
spin mixing	$\rightarrow$	breaks the flavor symmetry explicitly
mass term	$\rightarrow$	acts as mass term

Expectations:

1, Explicit breaking regulate the IR divergent phase fluctuations, so that quasi-long range order becomes long range order.

2, Perturbation effects get smaller as μ increases, but still introduce arbitrary small explicit breaking, which stabilizes quasi-long range order to long range order.

(As for mass term, this is confirmed by Bringoltz analyses for massive `tHooft model.)

Final results should be closer to our large Nc results!

3, Two Dictionaries

- between (3+1)D & (1+1)D quantum numbers

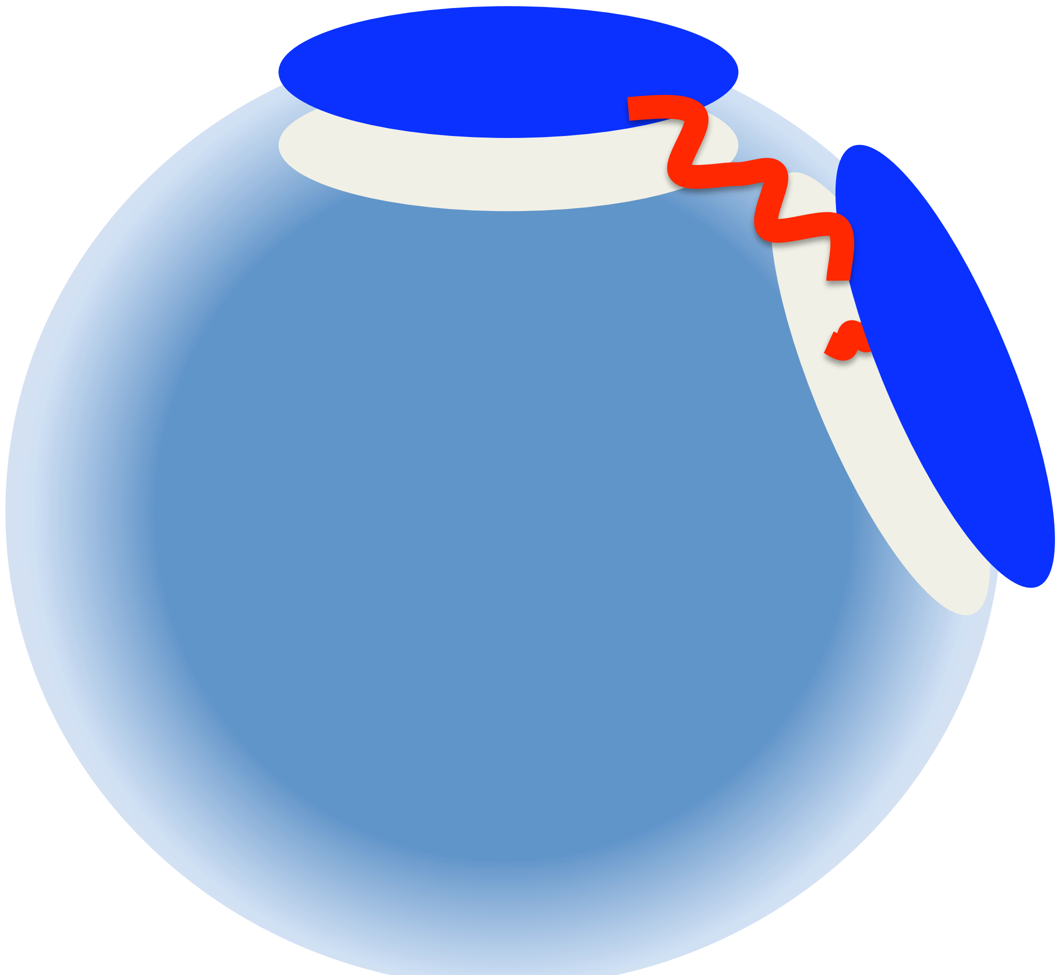
- between $\mu = 0$ & $\mu \neq 0$
condensates

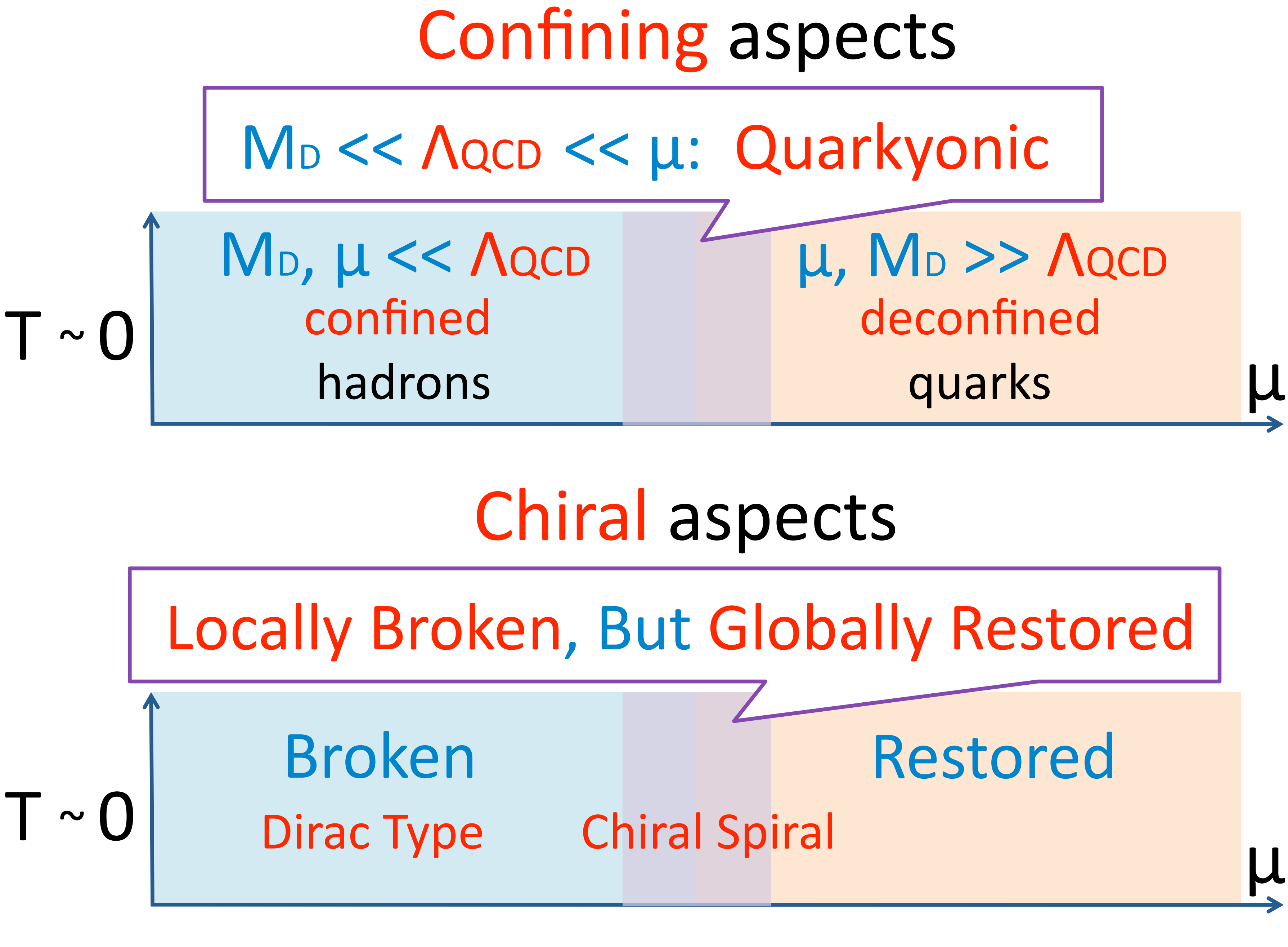
1, Introduction

Quarkyonic matter, chiral pairing phenomena

In this work, we will not discuss the interaction between different patches except those at the north or south poles.

(Since we did not find satisfactory treatments)




Confining aspects
M_D << Λ_QCD << μ: Quarkyonic
M_D, μ << Λ_QCD
confined
hadrons
μ, M_D >> Λ_QCD
deconfined
quarks
T ~ 0
μ
Chiral aspects
Locally Broken, But Globally Restored
Broken
Dirac Type
Chiral Spiral
Restored
T ~ 0
μ

Quarkyonic Matter near T=0

- Bulk properties: deconfined quarks in Fermi sea

  (All quarks contribute to Free energy, pressure, etc.)

- Phase structure: degrees of freedom near the Fermi surface

  cf) Superconducting phase is determined by dynamics near the Fermi surface.

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What is the excitation properties near the Fermi surface ?

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Is chiral symmetry broken in a Quarkyonic phase ?
If so, how ?