UNIVERSITY OF Southampton

Gravity seminar

Quark-hadron continuity under rotation

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March 21(Thu.), 2019

Based on the work

PHYSICAL REVIEW D **99,** 036004 (2019)

Continuity of vortices from the hadronic to the color-flavor locked phase in dense matter

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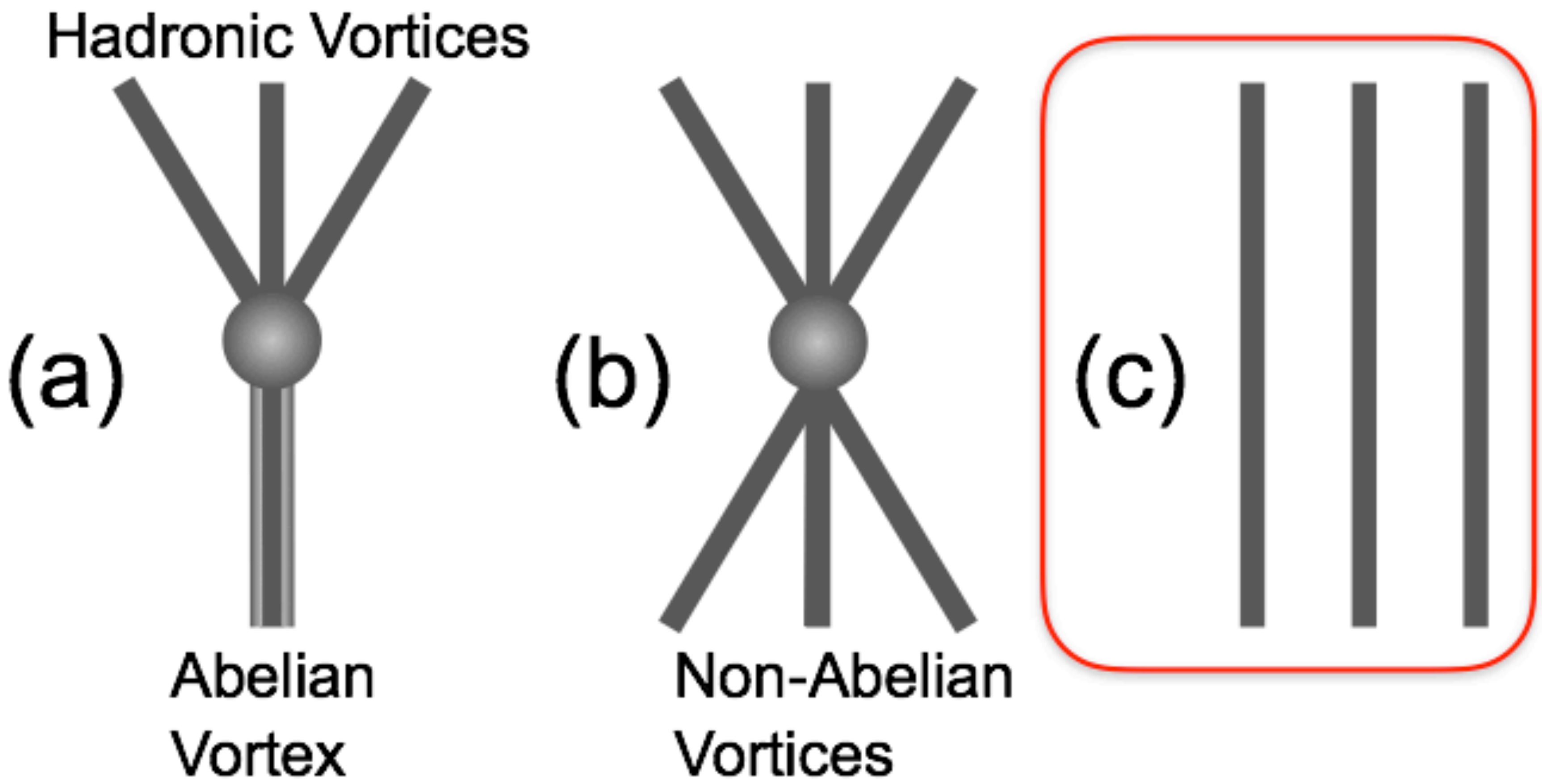
(Received 21 March 2018; published 7 February 2019)

We study how vortices in dense superfluid hadronic matter can connect to vortices in superfluid quark matter, as in rotating neutron stars, focusing on the extent to which quark-hadron continuity can be maintained. As we show, a singly quantized vortex in three-flavor symmetric hadronic matter can connect smoothly to a singly quantized non-Abelian vortex in three-flavor symmetric quark matter in the color-flavor locked phase, without the necessity for boojums appearing at the transition.

Question

Non-Abelian CFL vortices ~ Hadronic vortices



Physics = Fertile research arena of Matters and Space-time

★ What matters are made of ?

★ How matters are created and change in different conditions?

★ How the universe was born and will be?

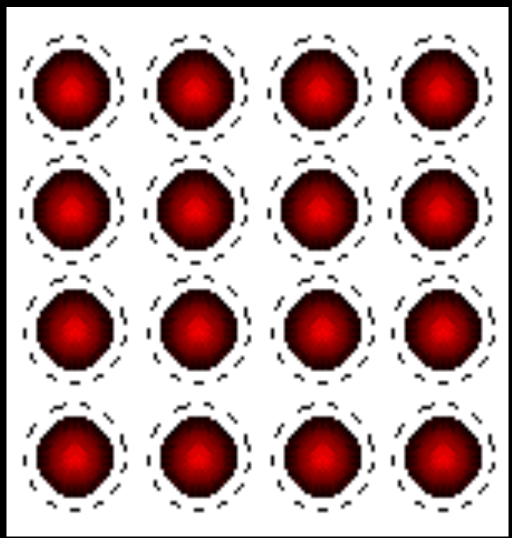
Approaches: Experiment, Observation, Theory, Computer

A child-like question:

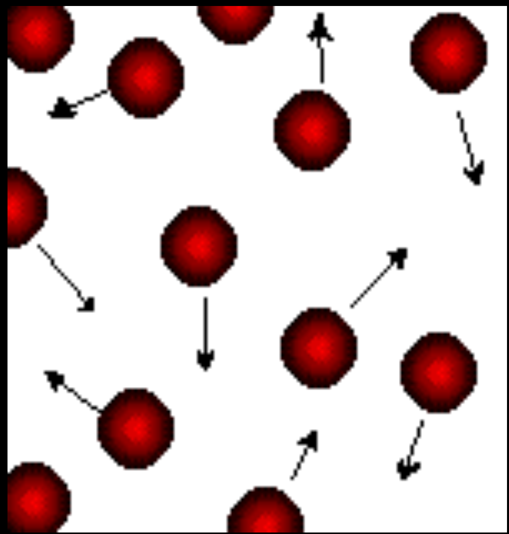
What happens to matter
as we squeeze it harder and harder,
and/or make it hotter and hotter?

Phases of Matter

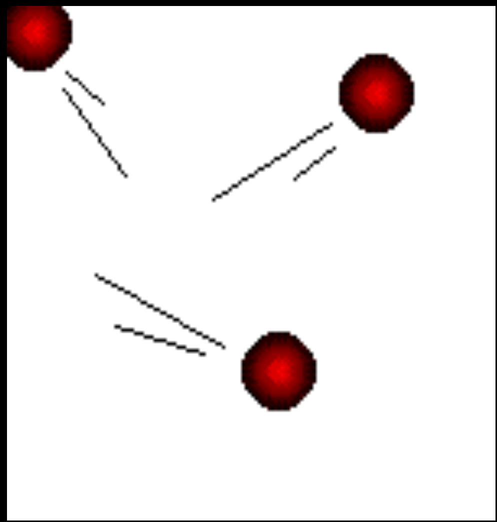
Ex.) H_2O



Solid(ice)



Liquid(water)

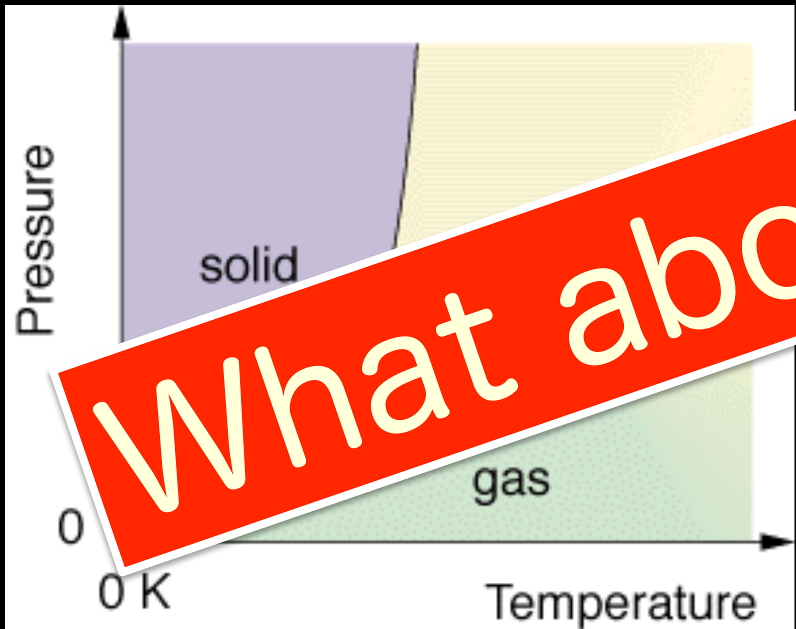


Gas(vapor)

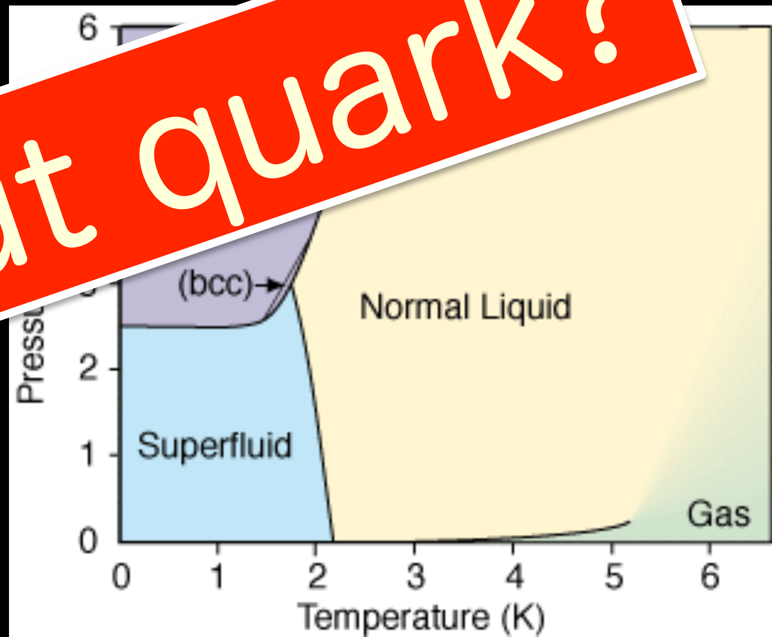
→ T, P

Phase diagrams

H_2O



^{4}H



What about quark?

http://boojum.hut.fi/research/theory/typicalpt.html

Convention

★ Phases are described by symmetries of underlying theory

★ What is the theory of quarks? What are the symmetries?

Properties of

strongly-interacting matter

⬇

Quantum field theory

with Non-Abelian symmetry

⬇

Quantum Chromo Dynamics

QCD

QCD Lagrangian (Han-Nambu, 1965)

$$L_{QCD} = \overline{q}^{\alpha}\left(i\gamma_{\mu}D^{\mu} - m_{q}\right)_{\alpha\beta} q^{\beta} - \frac{1}{4}F^{a}_{\mu\nu}F^{a\mu\nu}$$

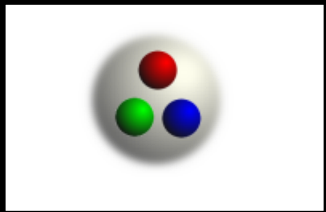
Just one line, but very rich i… math

T… kind of new ideas

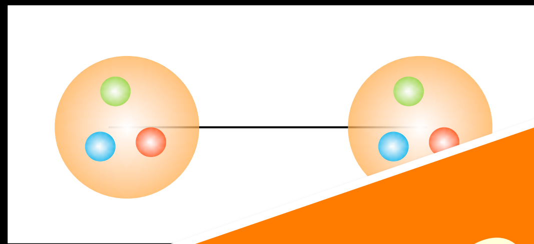
Yes! We love QCD ♥

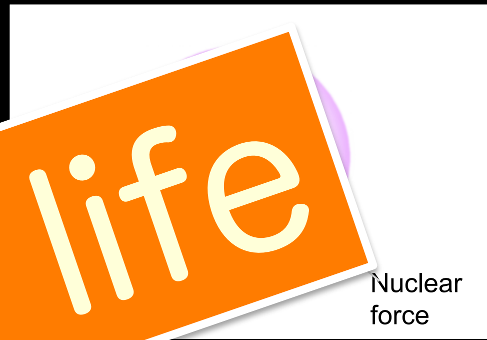
Grand Challenge

- Space-time evolution of QCD matter -



Hadrons



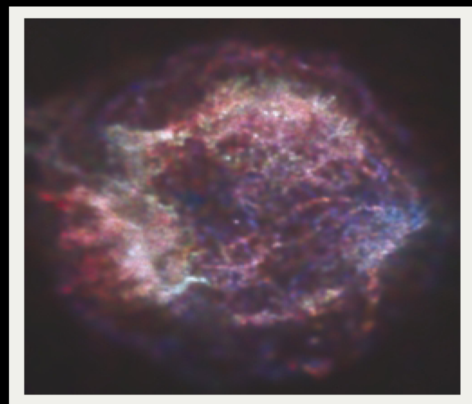


Nuclei

No QCD, no life

Early universe

Neutron/quark star



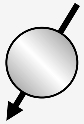
Supernovae

The answer to the ultimate question

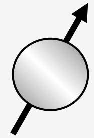
"Why the matter of our universe can be stable?"

■Symmetries of QCD and their breaking patterns

Chiral basis :



$$q_L = \frac{1}{2}(1-\gamma_5)q, \qquad q_R = \frac{1}{2}(1+\gamma_5)q$$



QCD Lagrangian :

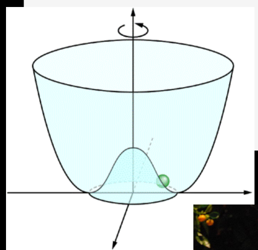
$$\mathcal{L}_{cl} = \mathcal{L}_{cl}(q_L, A) + \mathcal{L}_{cl}(q_R, A) - (\bar{q}_L m q_R + \bar{q}_R m q_L)$$

classical QCD symmetry (m=0)

$$\mathcal{G} = SU(3)_C \times [SU(N_f)_L \times SU(N_f)_R] \times U(1)_B \times U(1)_A$$

Quantum QCD vacuum (m=0)

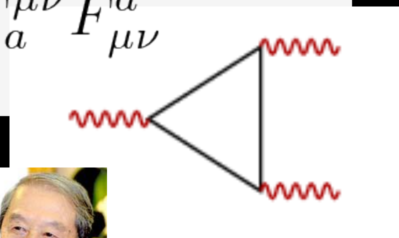
Chiral condensate :
spontaneous mass generation



$$\langle \bar{q}_R q_L \rangle \neq 0$$

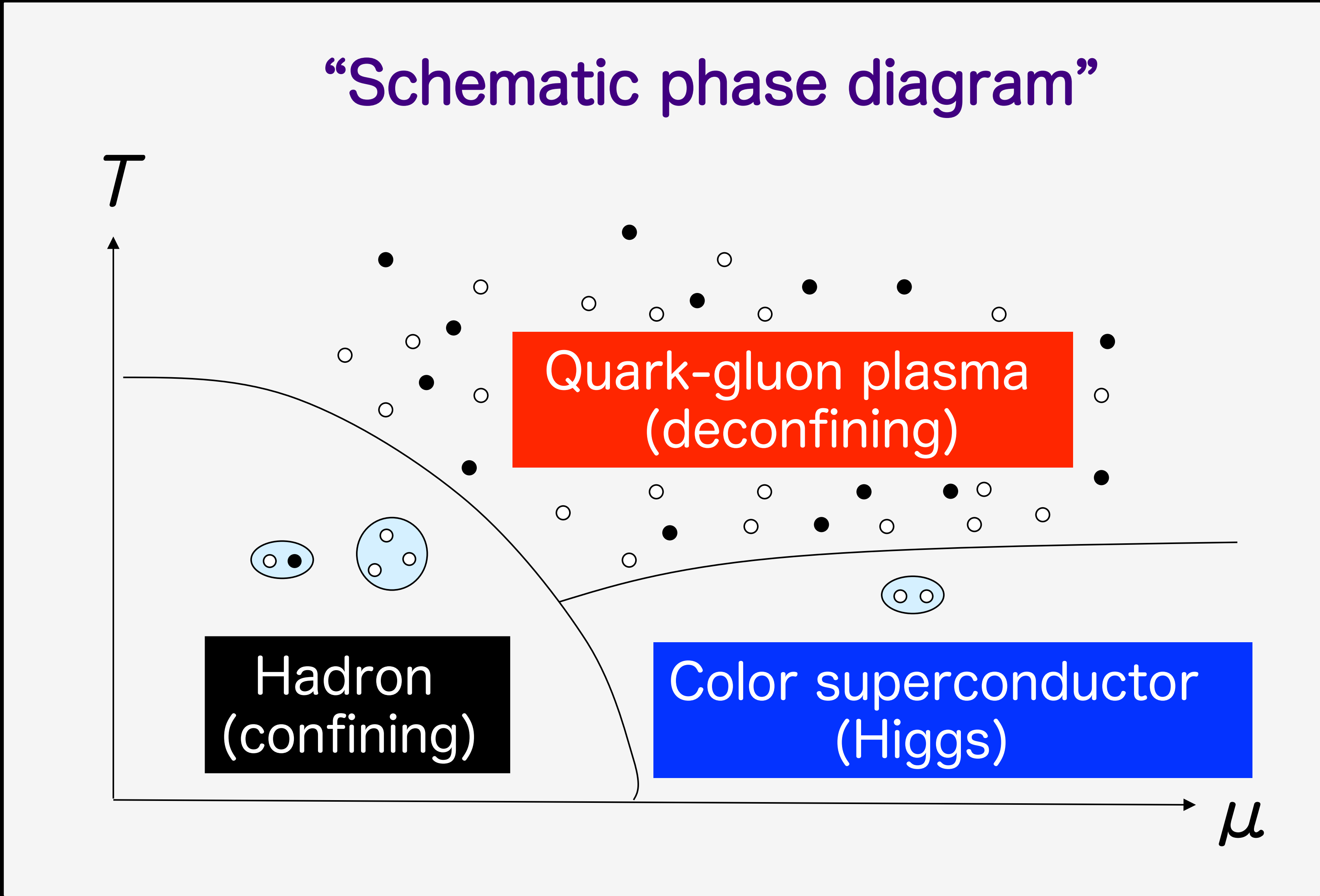
Axial anomaly :
quantum violation of $U(1)_A$

$$\partial_\mu J^\mu_A = -2N_f \frac{\alpha_s}{8\pi} F^{\mu\nu}_a \tilde{F}^a_{\mu\nu}$$

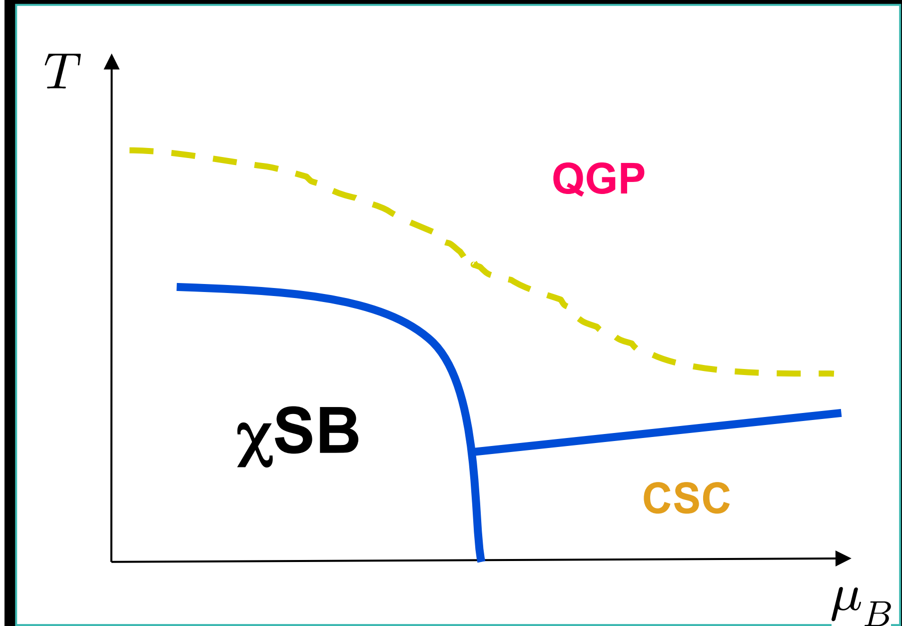


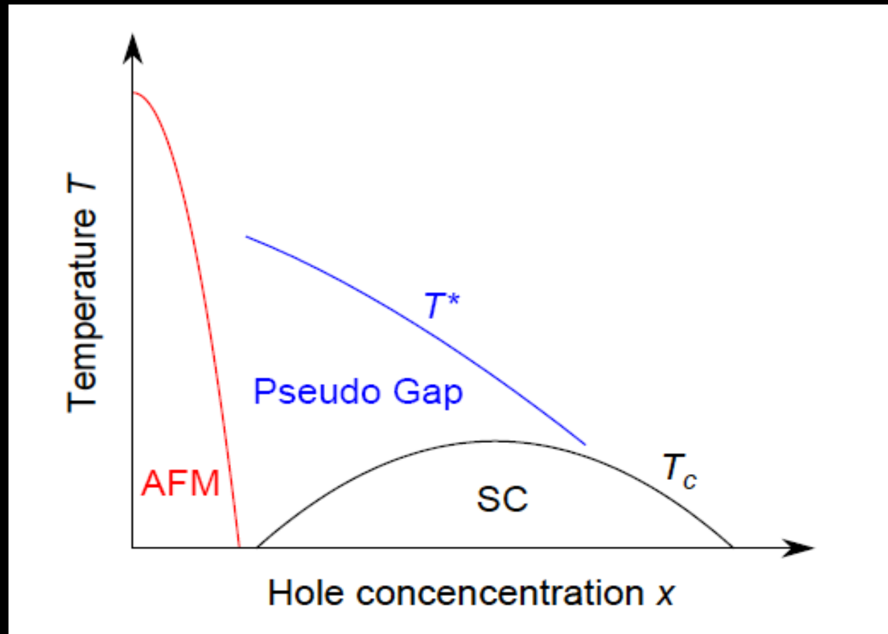
$$SU(3)_C \times SU(N_f)_{L+R} \times U(1)_B$$

QCD phase diagram via Occam's razor



Similarity between QCD and High T_c Superconductor





Common features in QCD, HTS, and ultracold atoms

1. Competition among different orders
2. Strong coupling/correlation

Idea of Quark-Hadron continuity

hep-ph/9811473

3 flavor hadron matte

is *smoothly* c... d to

3 ... quark matter

a... baryon density is increased

Impacts on NS physics?

Table of Quark-Hadron continuity

Phase	Hadronic (confinement)	Color-flavor locked(Higgs)
Symmetry breaking Pattern	$SU(3)_L \times SU(3)_R \times U(1)_B \rightarrow SU(3)_{L+R}$	$SU(3)_L \times SU(3)_R \times SU(3)_C \times U(1)_B \rightarrow SU(3)_{L+R+C}$
Order parameter	chiral condensate	diquak condensate
$U(1)_B$	broken in the dibaryon channels	broken by *d*
Elementary Excitations	Pseudo-scalar mesons (π etc)	NG bosons
	vector mesons (ρ etc)	massive gluons
	baryons	massive quarks (CFL gap)

A realization of Fradkin-Shenker complementarity

Diquark condensations

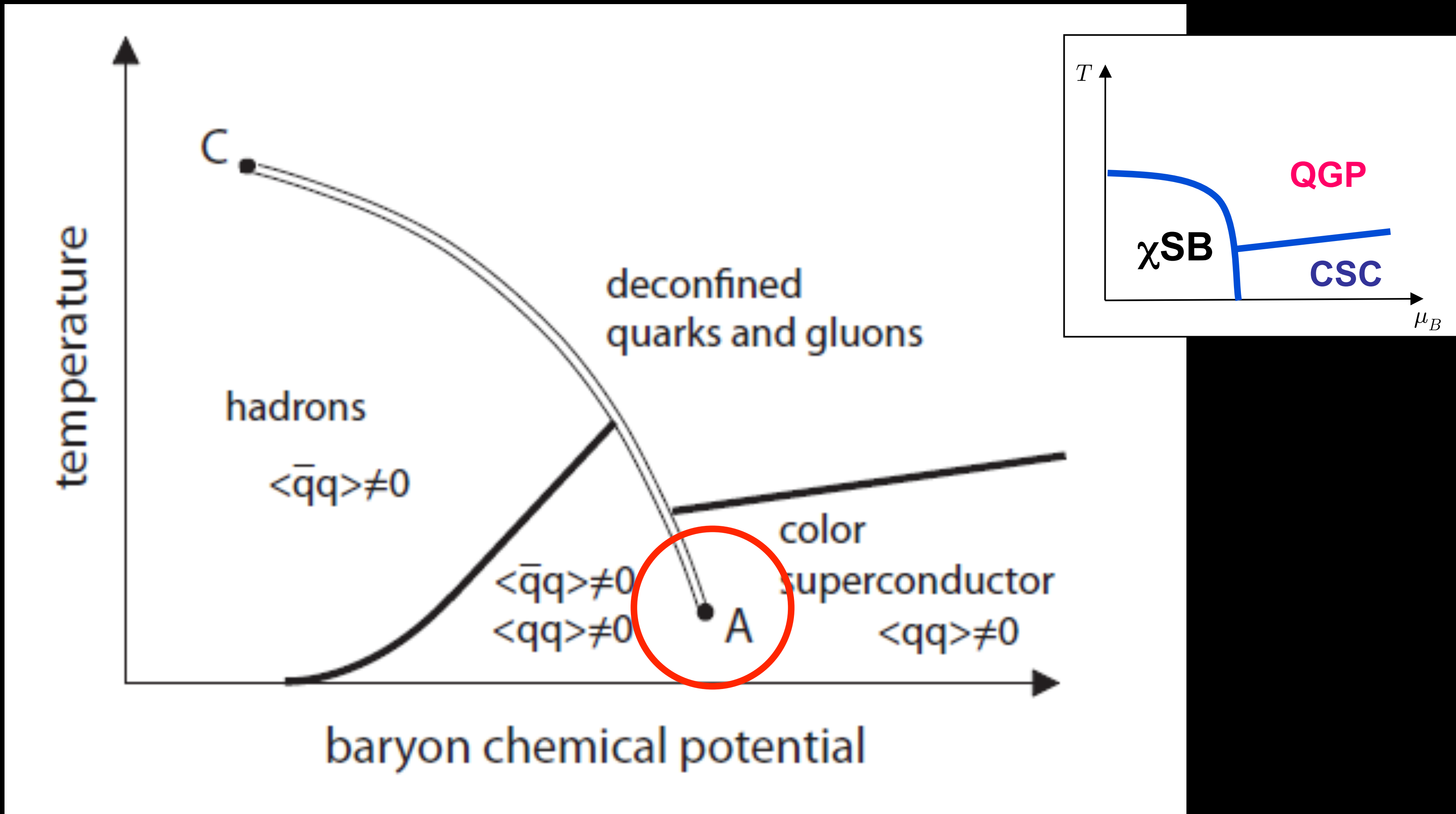
N_f=2 (2-flavor colorsuperconductivity [2SC])

$$\left\langle q_{\alpha i} C \gamma_5 q_{\beta j} \right\rangle \propto \Delta_{2SC} \varepsilon^{\alpha\beta 3} \varepsilon^{ij}$$

N_f=3 (Color-flavor locking [CFL])

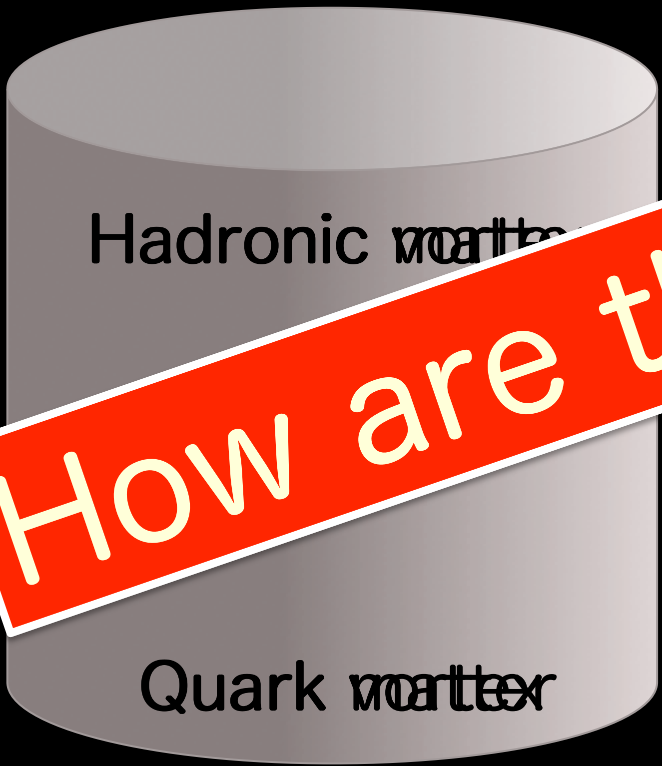
$$\left\langle q_{\alpha i} C \gamma_5 q_{\beta j} \right\rangle = \Delta_{CFL} \varepsilon_{\alpha\beta I} \varepsilon^{ijI} \propto \Delta_{CFL} \left(\delta_\alpha^i \delta_\beta^j - \delta_\alpha^j \delta_\beta^i \right)$$

"Anomaly driven critical point in high density QCD as a realization of quark-hadron continuity"



Yamamoto, Hatsuda, Baym & Tachibana, PRL 97 ('06)

Thought experiment



Pour quarks

into

adronic matter

ower: Quark matter

How are they connected?

Then, rotate the bucket

Upper: Hadronic vortex

Lower: Quark vortex

Notations

$$\Phi\left(\vec{r},t\right)=\left|\Phi(\vec{r})\right|e^{i\phi(\vec{r})-i\mu t}\ :complex\ \ scalar$$

$$\phi\left(\vec{r},t\right)=p_{\nu}x^{\nu}=\vec{p}\cdot\vec{r}-\mu t,\quad \vec{v}=\frac{\vec{p}}{\mu}$$

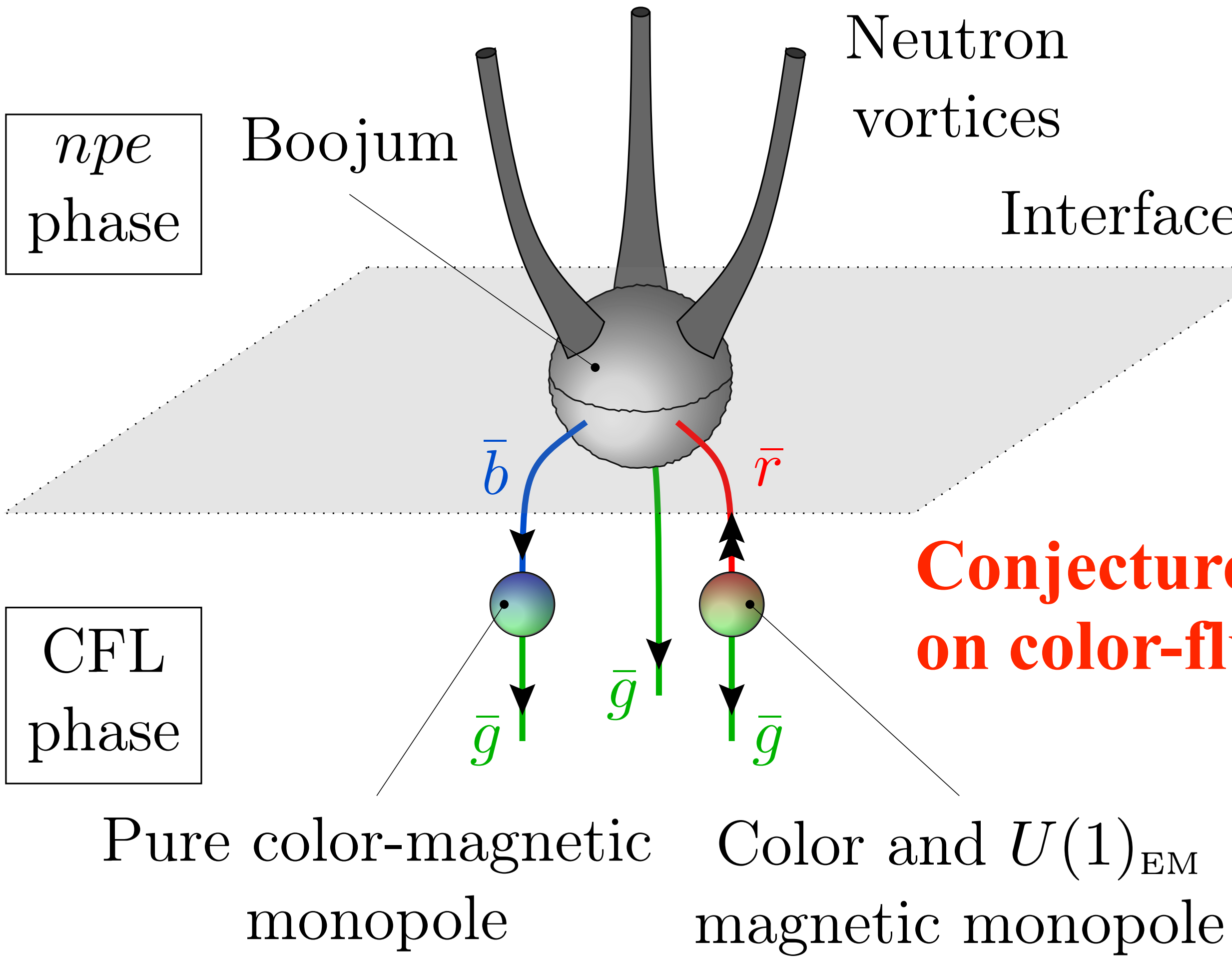
$$C\equiv\oint_{C}\vec{v}\cdot d\vec{l}\ \ =2\pi\frac{\nu}{\mu}\quad \nu:winding\ \ \#$$

Circulation matching

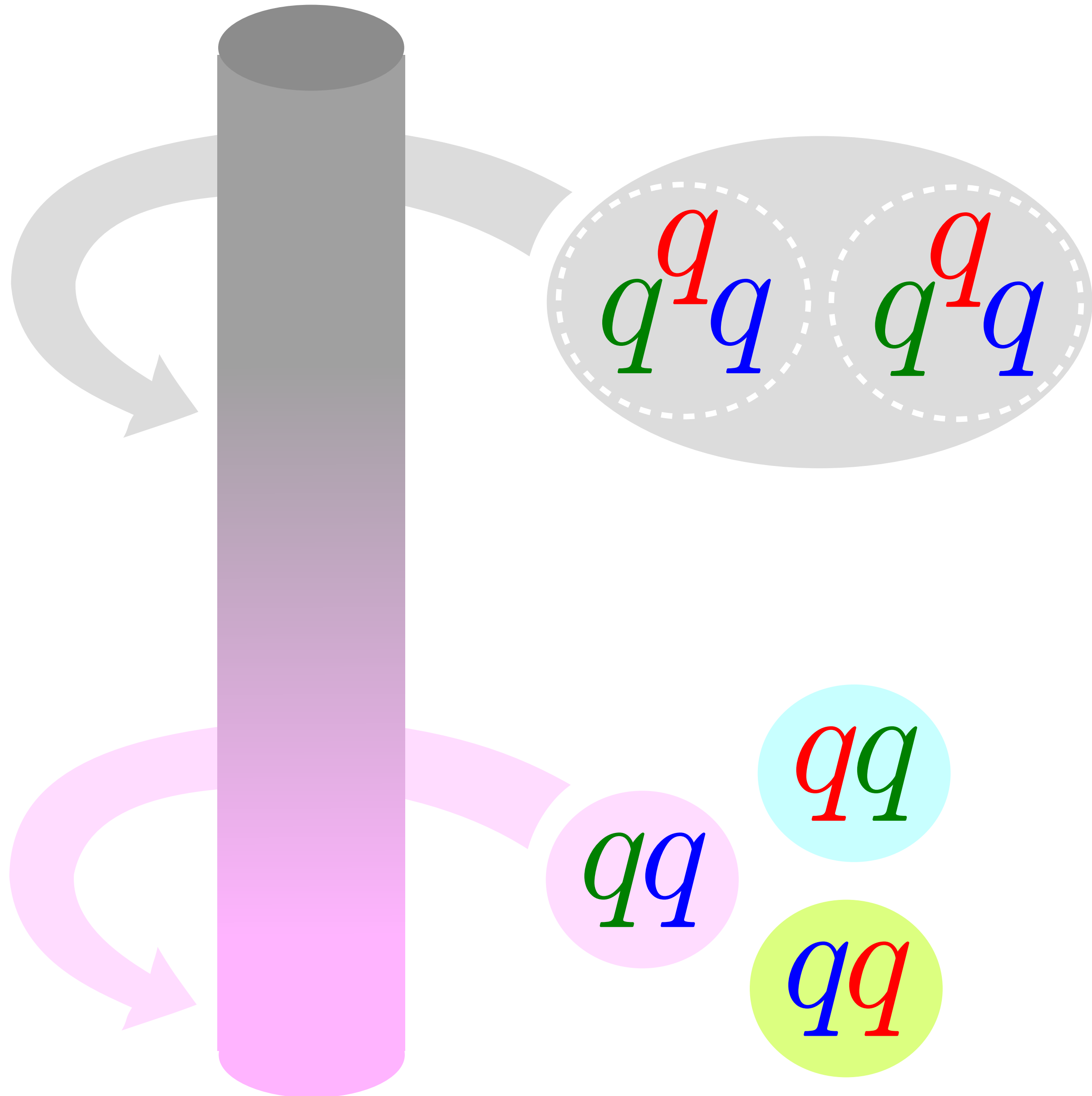
Boojum
(Wikipedia)

Non-Abelian CFL vortex

Cipiriani-Vinci-Nitta (2012)



Conjectured based on color-flux conservation


qqq
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Some more details

Color and flavor 3plet diquark order parameter

$$\hat{\Phi}^{\alpha i} \propto \varepsilon^{\alpha\beta\gamma}\varepsilon^{ijk} q_{\beta j} C\gamma_5 q_{\gamma k}$$

Φ diagonalized via color-flavor space rotation

$$\Phi = \begin{pmatrix} \Phi^{\bar{r}\bar{u}} & 0 & 0 \\ 0 & \Phi^{\bar{g}\bar{d}} & 0 \\ 0 & 0 & \Phi^{\bar{b}\bar{s}} \end{pmatrix}$$

Some more details

In this case,

$$C_{NA} = 2\pi \frac{\frac{1}{3}\nu_{NA}}{2\mu_q} = 2\pi \frac{\nu_{NA}}{2 \cdot 3\mu_q} = 2\pi \frac{\nu_{NA}}{2\mu_B}$$

→ $$\nu_H = \nu_{NA}$$

Some more details

What we (Alford *et al.*) discussed:

$$\hat{\Upsilon}^{ijk}(\vec{r}) \equiv \frac{1}{6}\epsilon_{\alpha\beta\gamma}\hat{\Phi}^{\alpha i}\hat{\Phi}^{\beta j}\hat{\Phi}^{\gamma k}$$

$$= \frac{1}{3}\epsilon^{kmn}(C\gamma_5)_{ab}\,\hat{B}_m^{i\,a}\,\hat{B}_n^{j\,b}$$

6 quark objects = 3 diquarks = 2 baryons

Quantum numbers match

Non-Abelian vortices = Flavor singlet + Non-singlets

$(\sim \Lambda\Lambda)$

Other topics

1. Flavor symmetry (breaking)

Flavor structure of vortices (e.g. Neutron superfluidity)

MWHC theorem

2. Vortex interaction

Ginzburg-Landau analysis

Summary of today's talk

① Quark-hadron continuity hypothesis (Fradkin/Shenker=Schafer/Wilczek)

② Study of superfluid vortices in light of QH continuity

③ Possible applications of our findings

Thank you！

感謝！