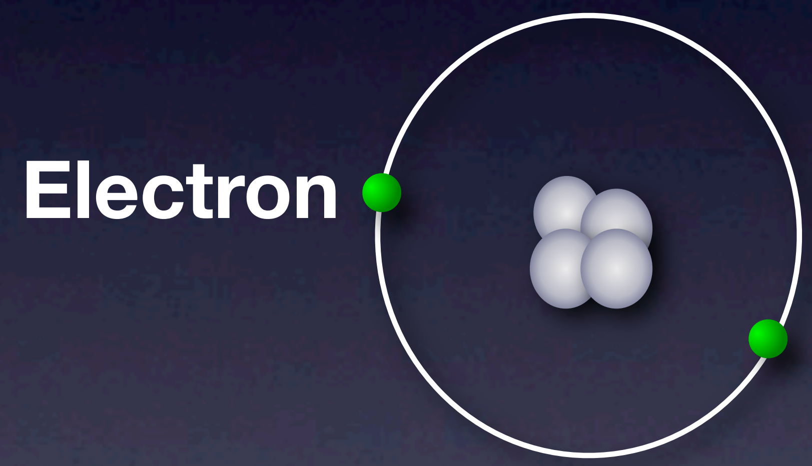
Cold and dense QCD matter

GCOE sympodium Feb. 15, 2010

Yoshimasa Hidaka

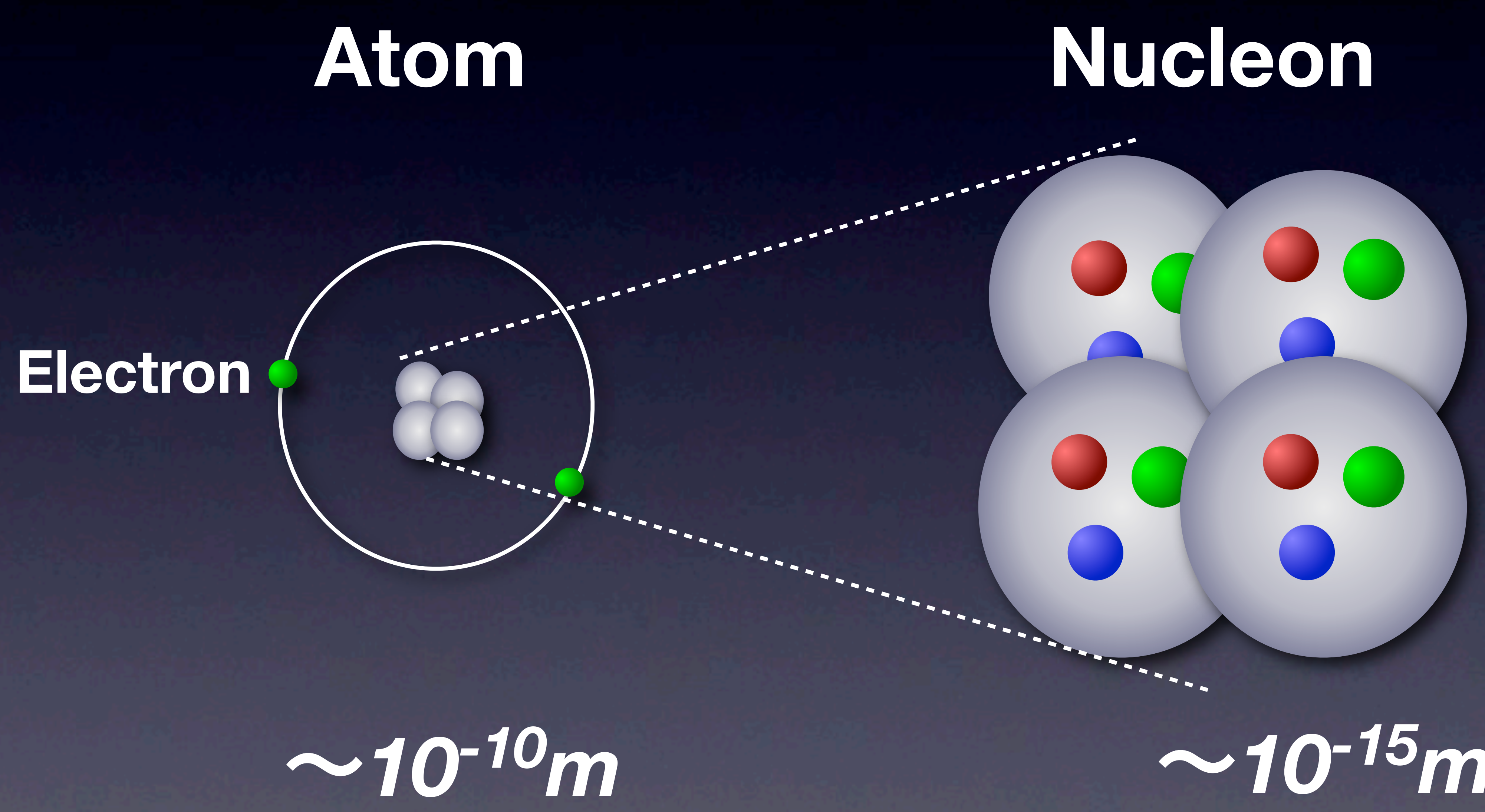
Quantum ChromoDynamics

Atom



～10^{-10}m

Quantum ChromoDynamics



Quantum **E**lectro**D**ynamics

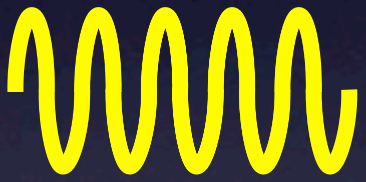
U(1) gauge theory

Electron

small mass, spin *1/2*

charge: ***-1***

Photon

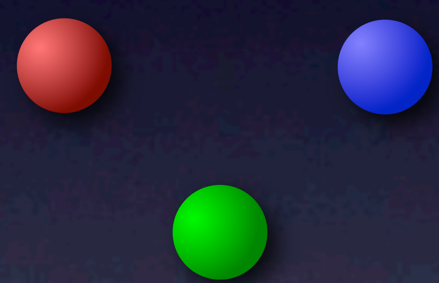
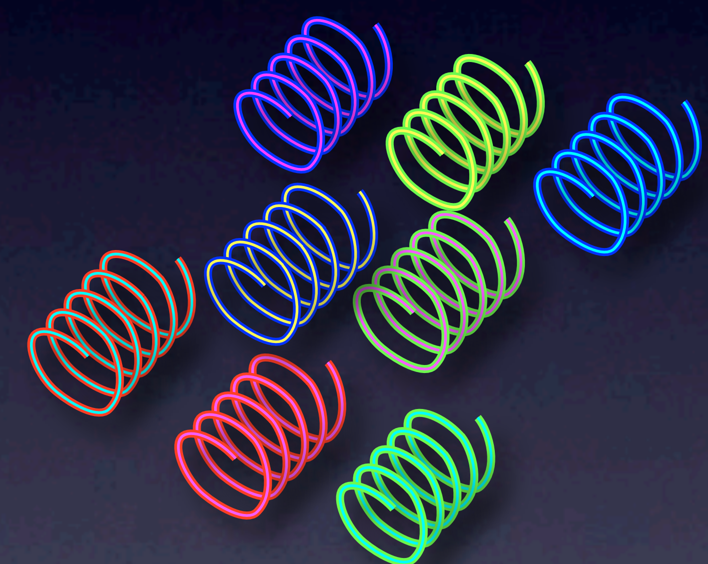


massless, spin *1*

0

Quantum ChromoDynamics

SU(3) gauge theory

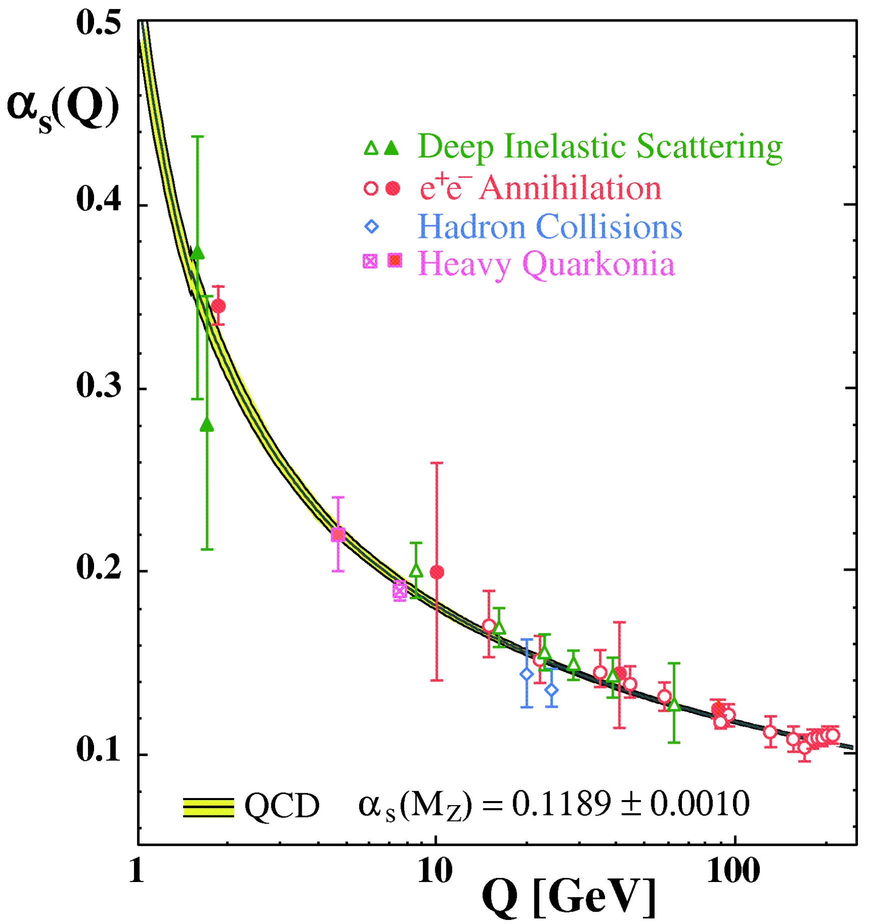
Quark	Gluon
	
small mass, spin *1/2*	massless, spin *1*
color charge: *3* (R,G,B)	*8*

Quantum ChromoDynamics

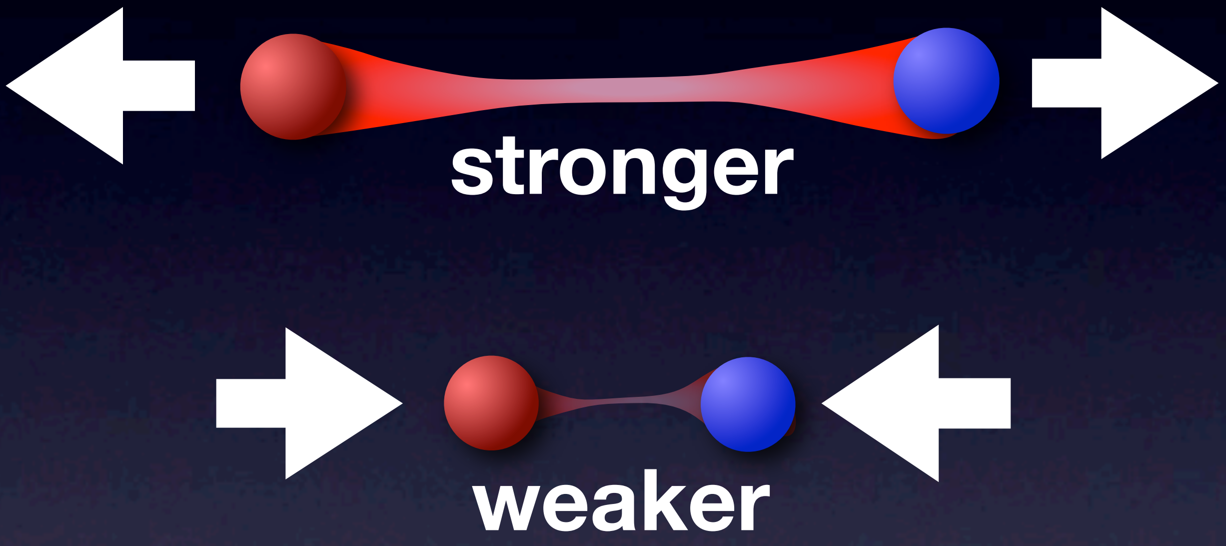
- Asymptotic freedom
- Confinement
- Chiral symmetry breaking

Asymptotic freedom

D. Gross, H. Politzer, F. Wilczek



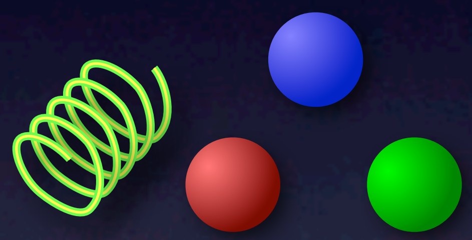
Bethke, Prog. Part. Nucl .Phys. 58:35(2007)



At high energy scale, interaction becomes weaker

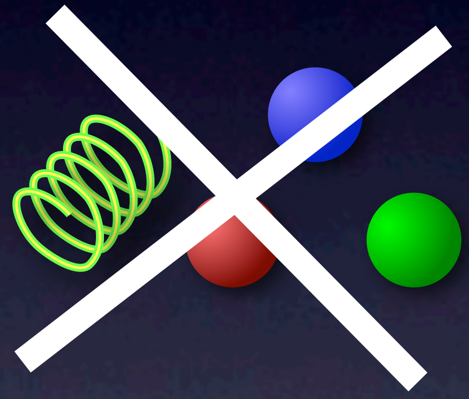
Quantum ChromoDynamics

Confinement



Quantum ChromoDynamics

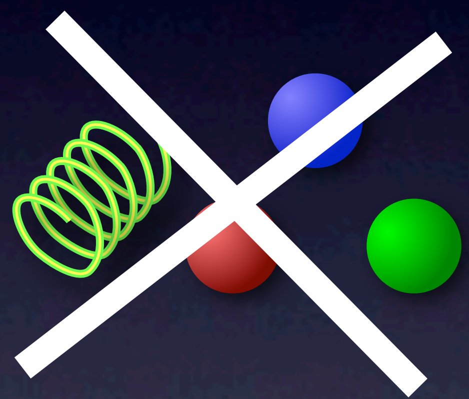
Confinement



No free quarks
and gluons

Quantum ChromoDynamics

Confinement

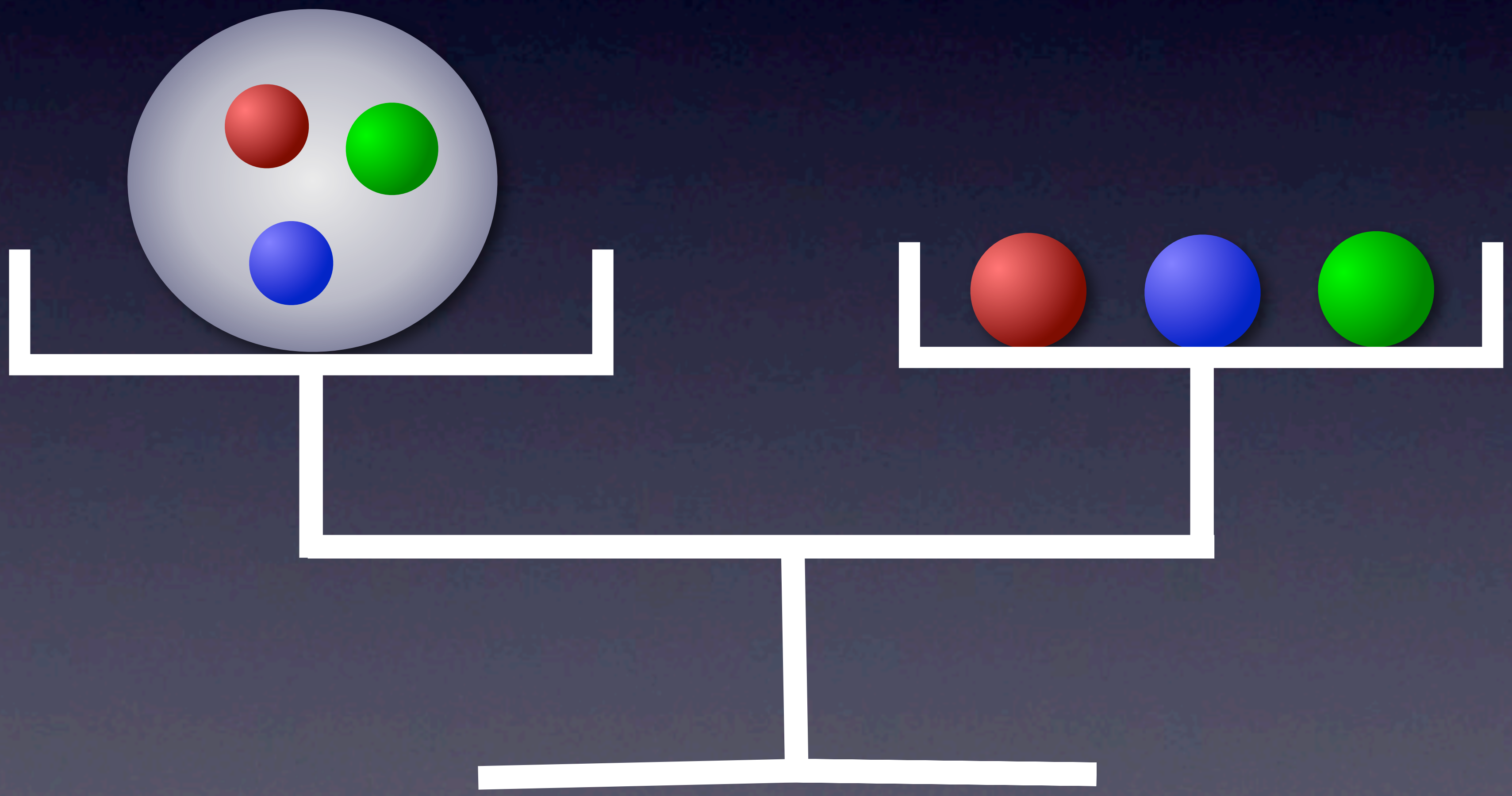


No free quarks
and gluons

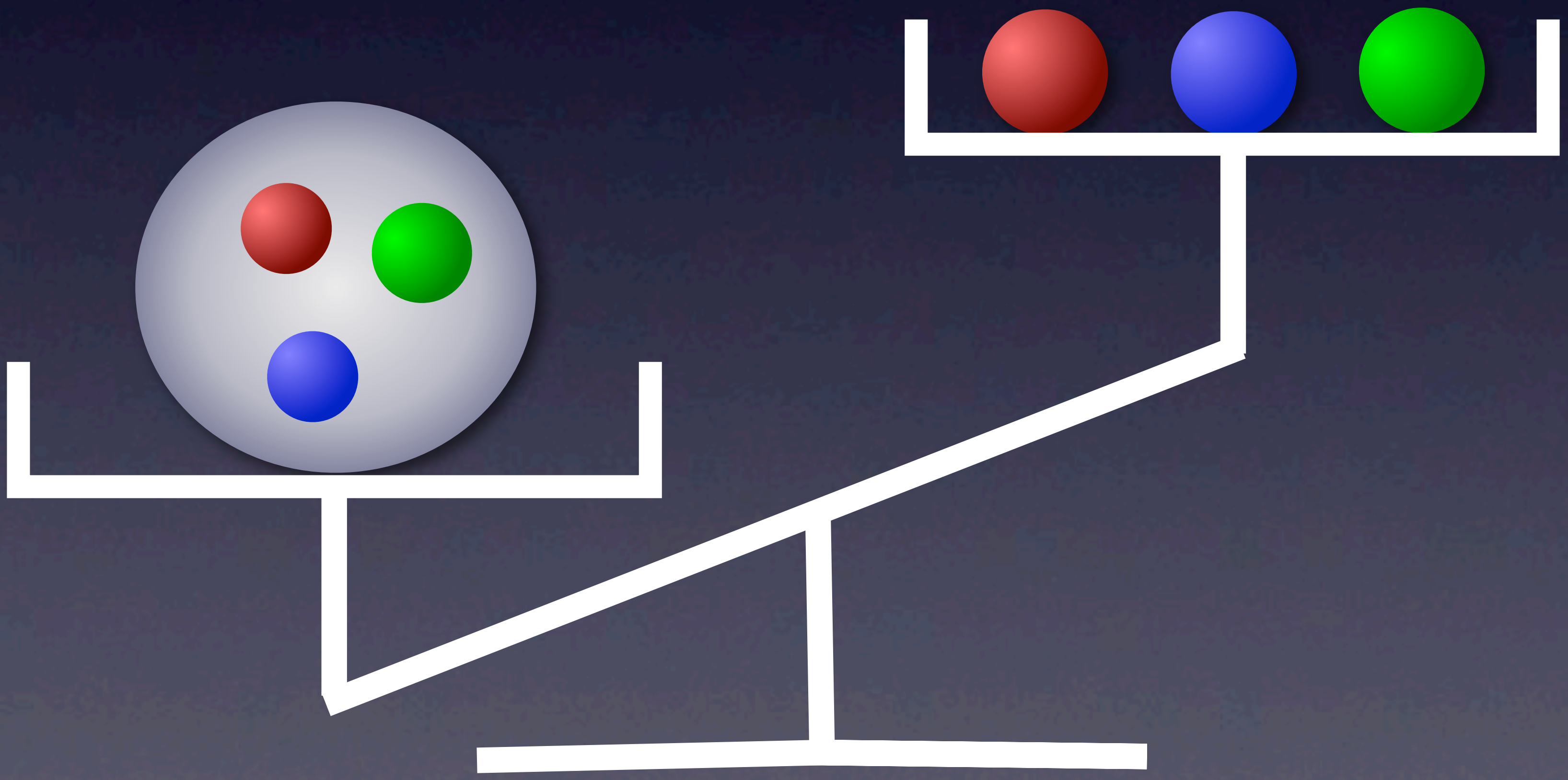
Baryons (proton, neutron, ...
and mesons (pion, Kaon,...)

Chiral symmetry

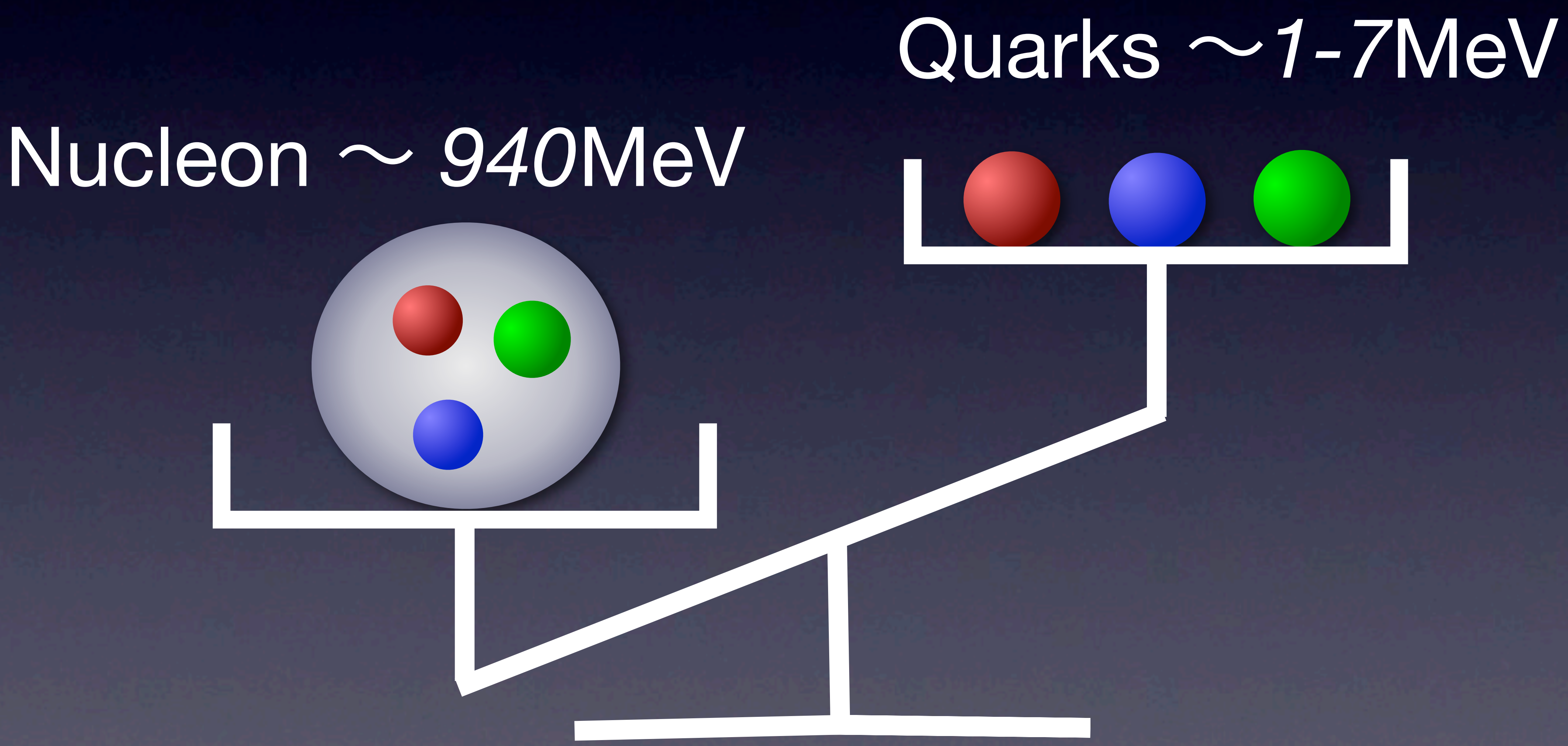
= a symmetry of massless quarks



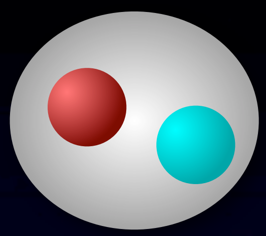
Chiral symmetry breaking

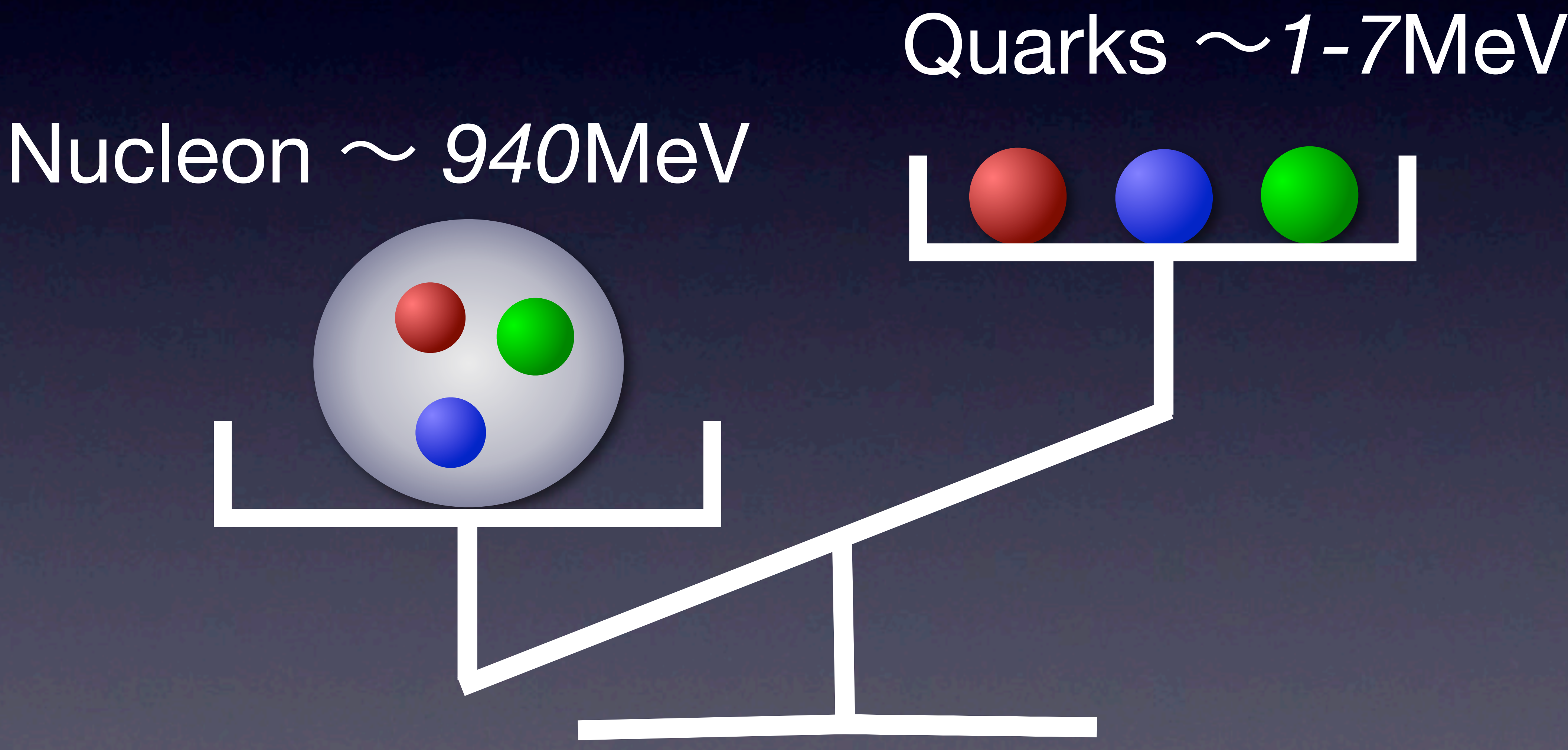


Chiral symmetry breaking



Chiral symmetry breaking


Light pion as Nambu-Goldstone boson



Y. Nambu, spontaneous symmetry breaking

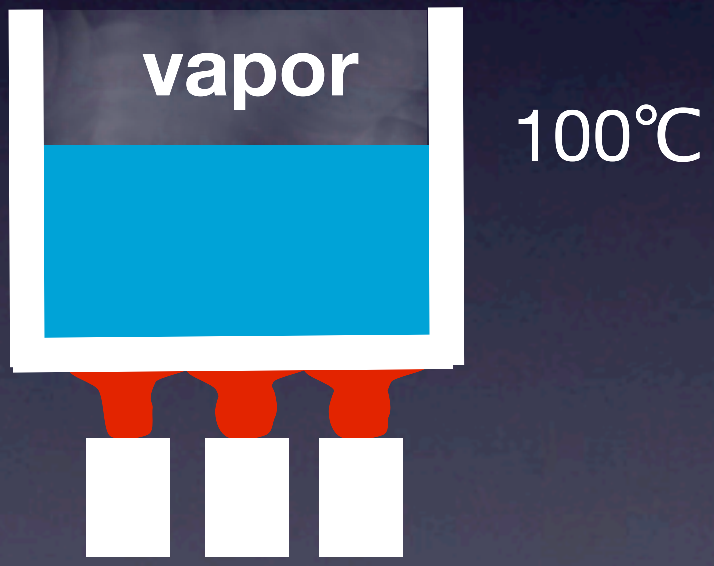
What happens in Extreme conditions?

Water in extreme condition

Hot

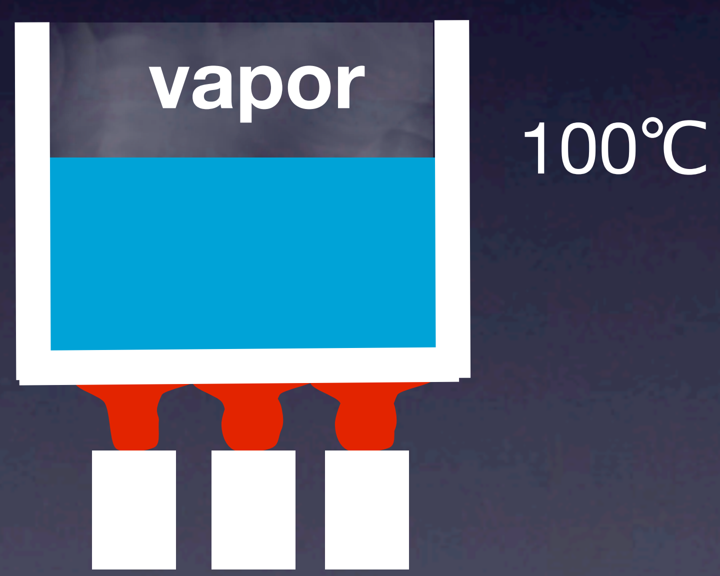
Water in extreme condition

Hot



Water in extreme condition

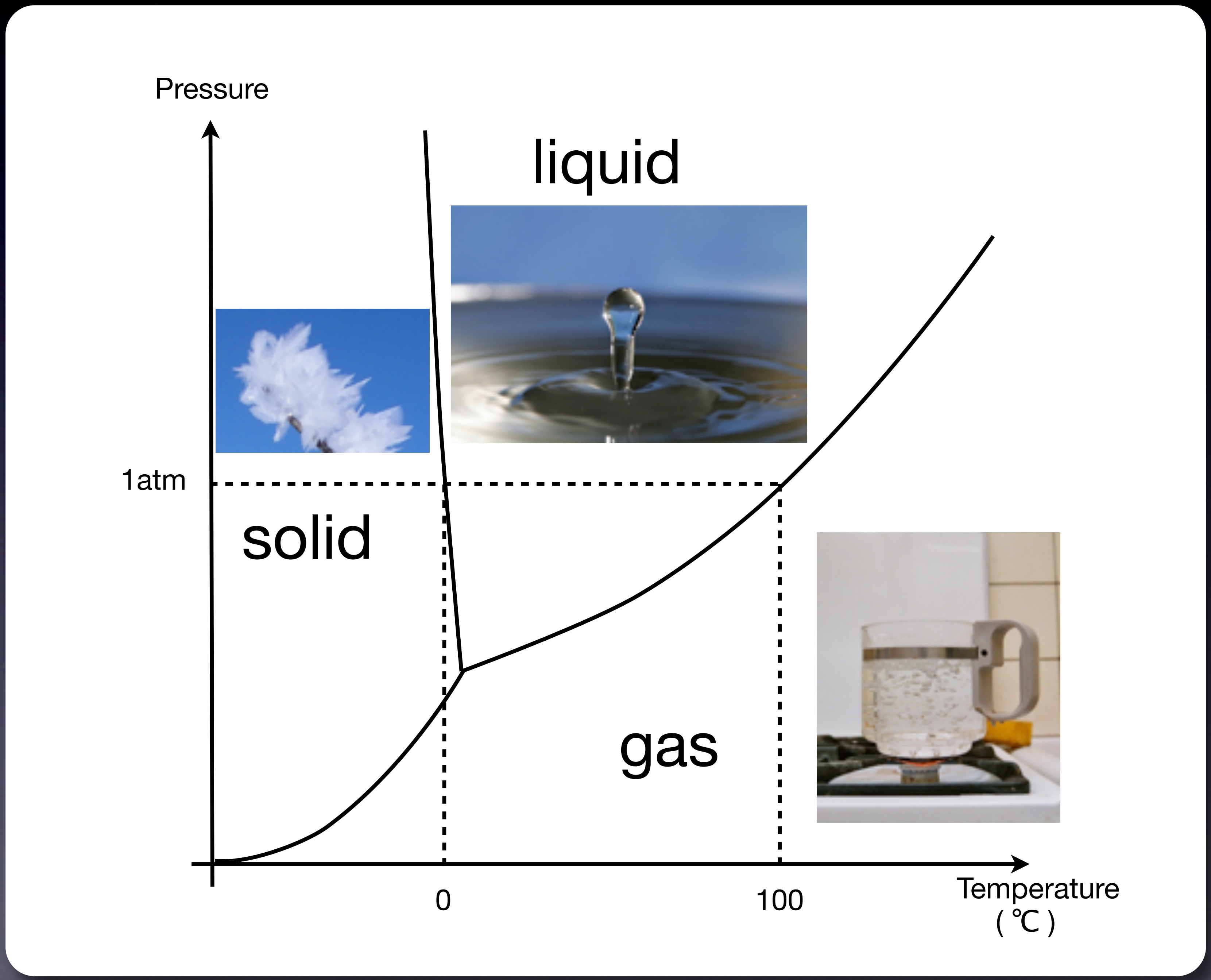
Hot **Dense, cold**



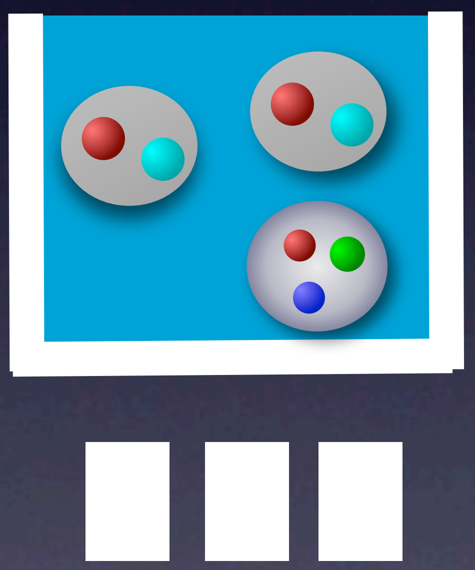
Water in extreme condition

Hot | **Dense, cold**

Phase diagram of water

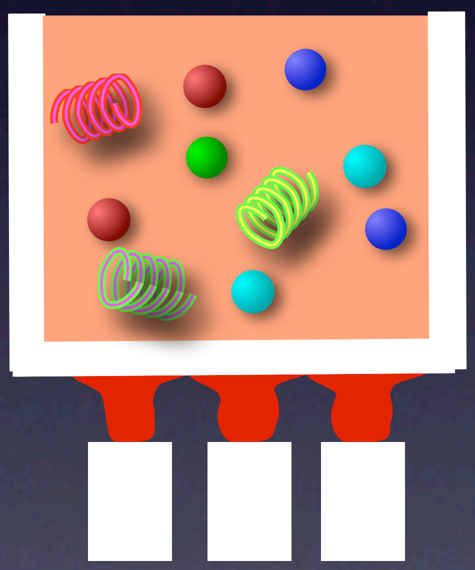


QCD in Extreme Conditions



QCD in Extreme Conditions

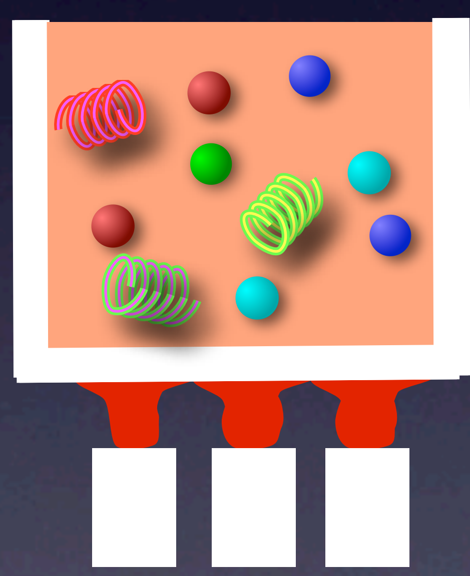
Hot



Quark Gluon Plasma
$\sim 2 \times 10^{12}$ ℃

QCD in Extreme Conditions

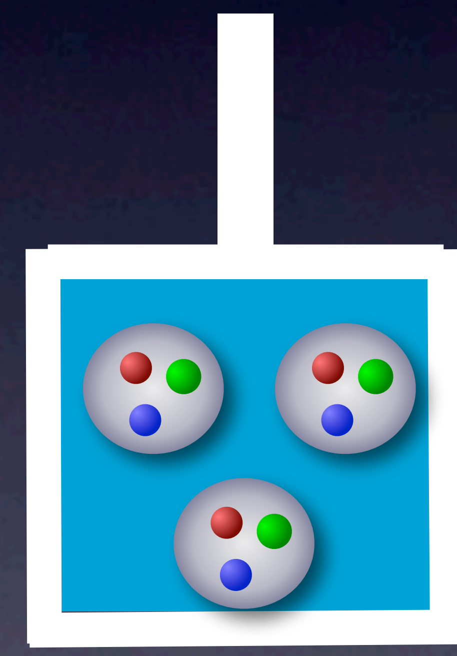
Hot



Quark Gluon Plasma

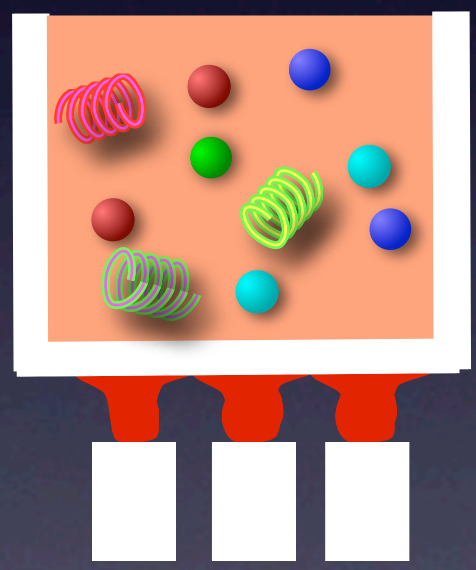
～2×10^{12} ℃

Dense



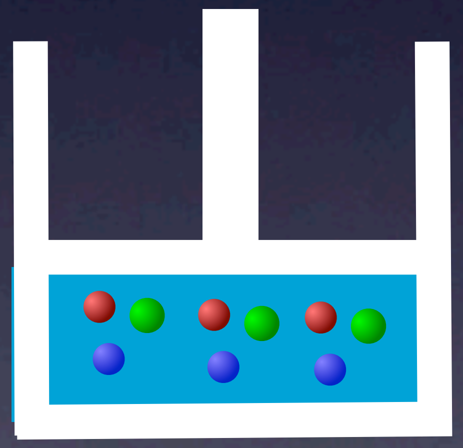
QCD in Extreme Conditions

Hot



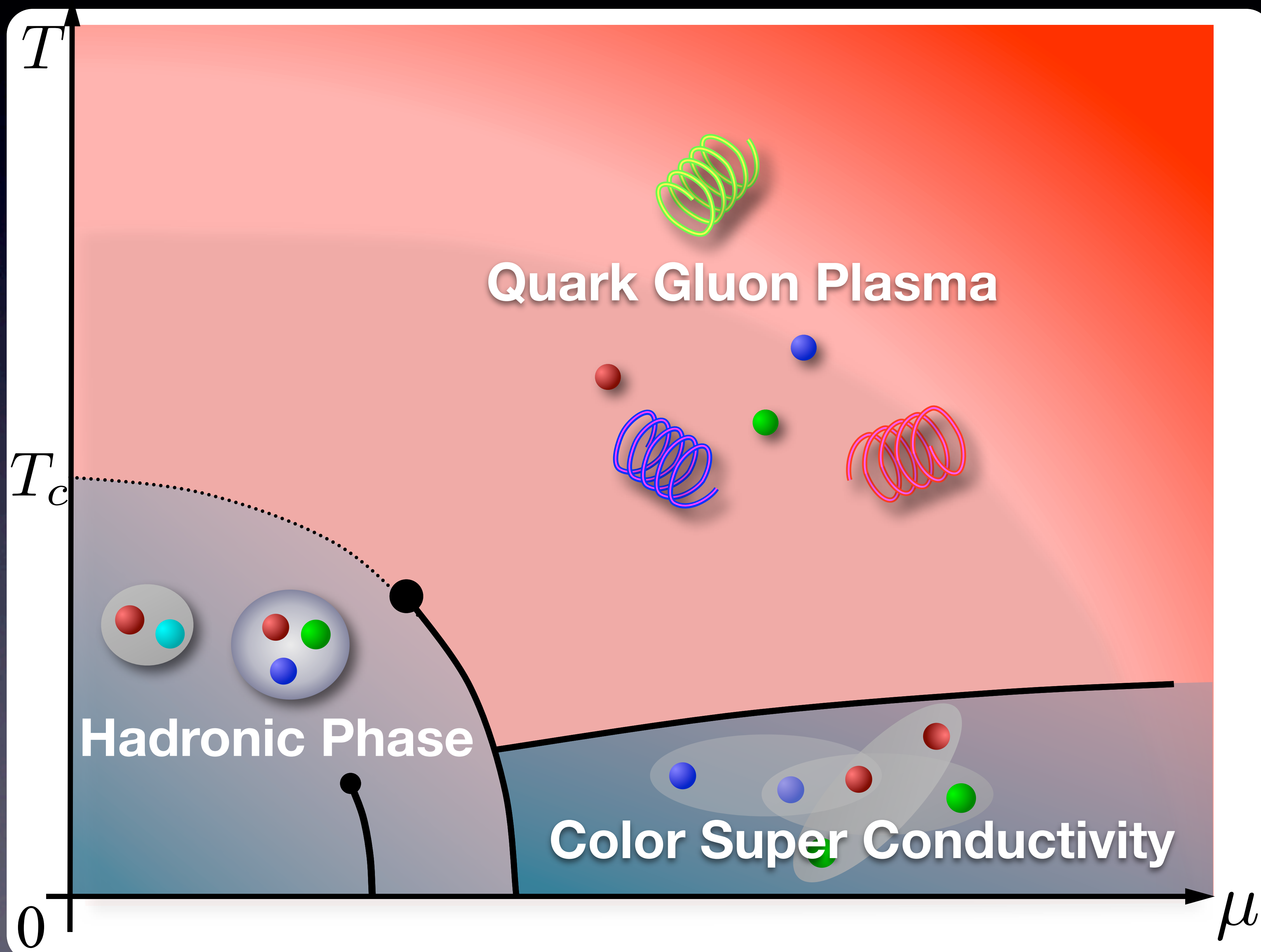
Quark Gluon Plasma
〜2×10^{12} ℃

Dense

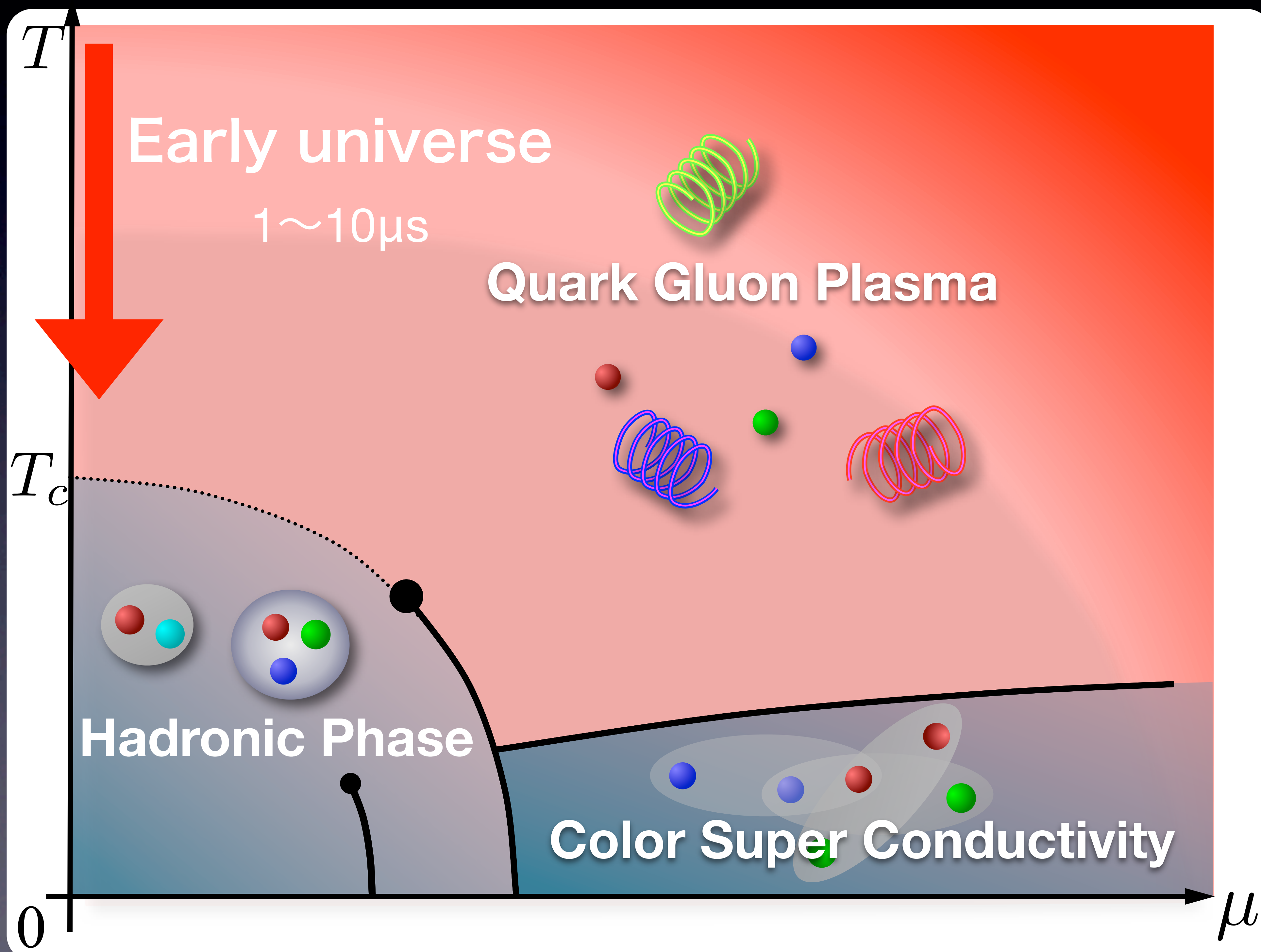


Quark matter

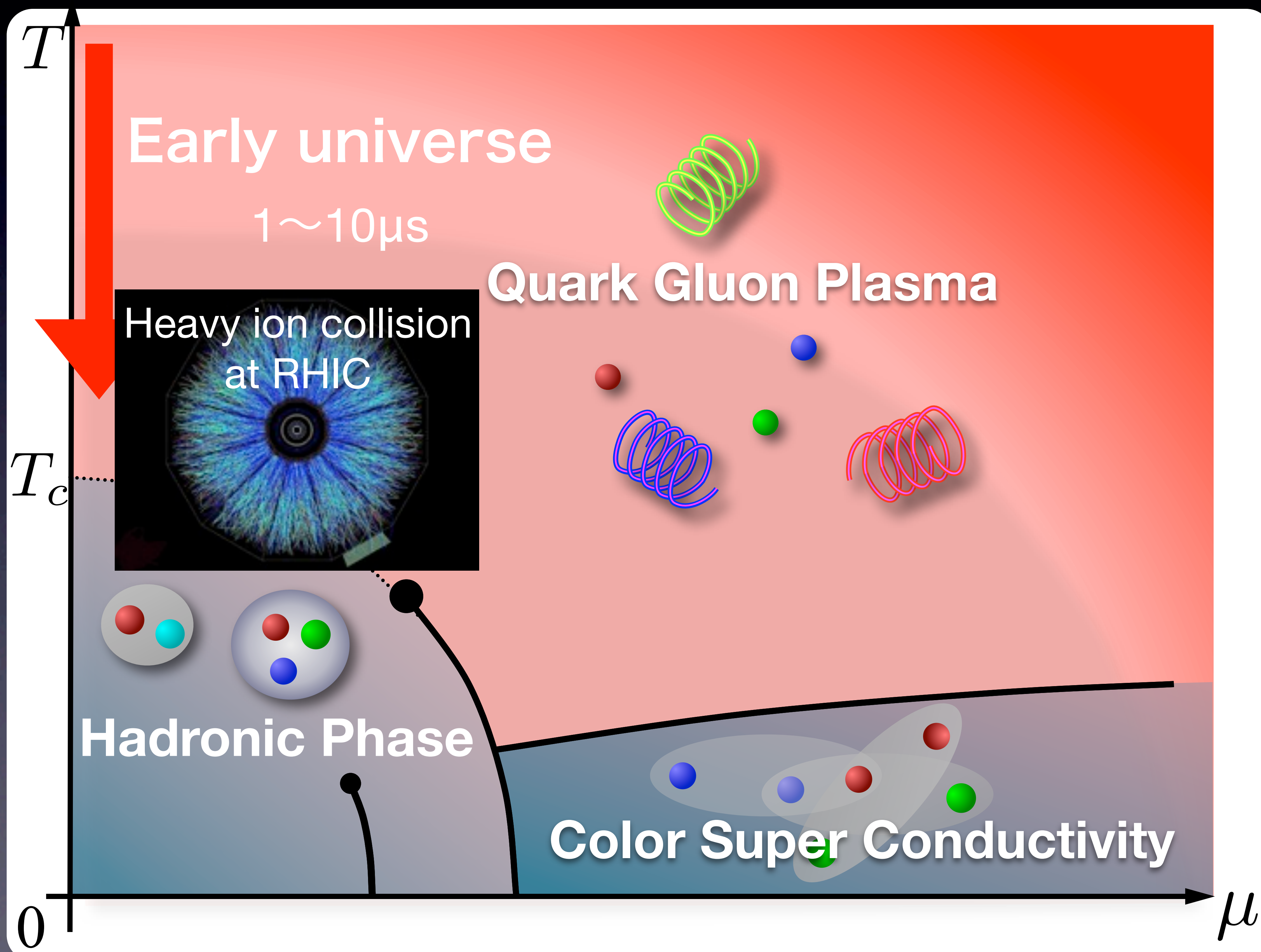
QCD Phase diagram



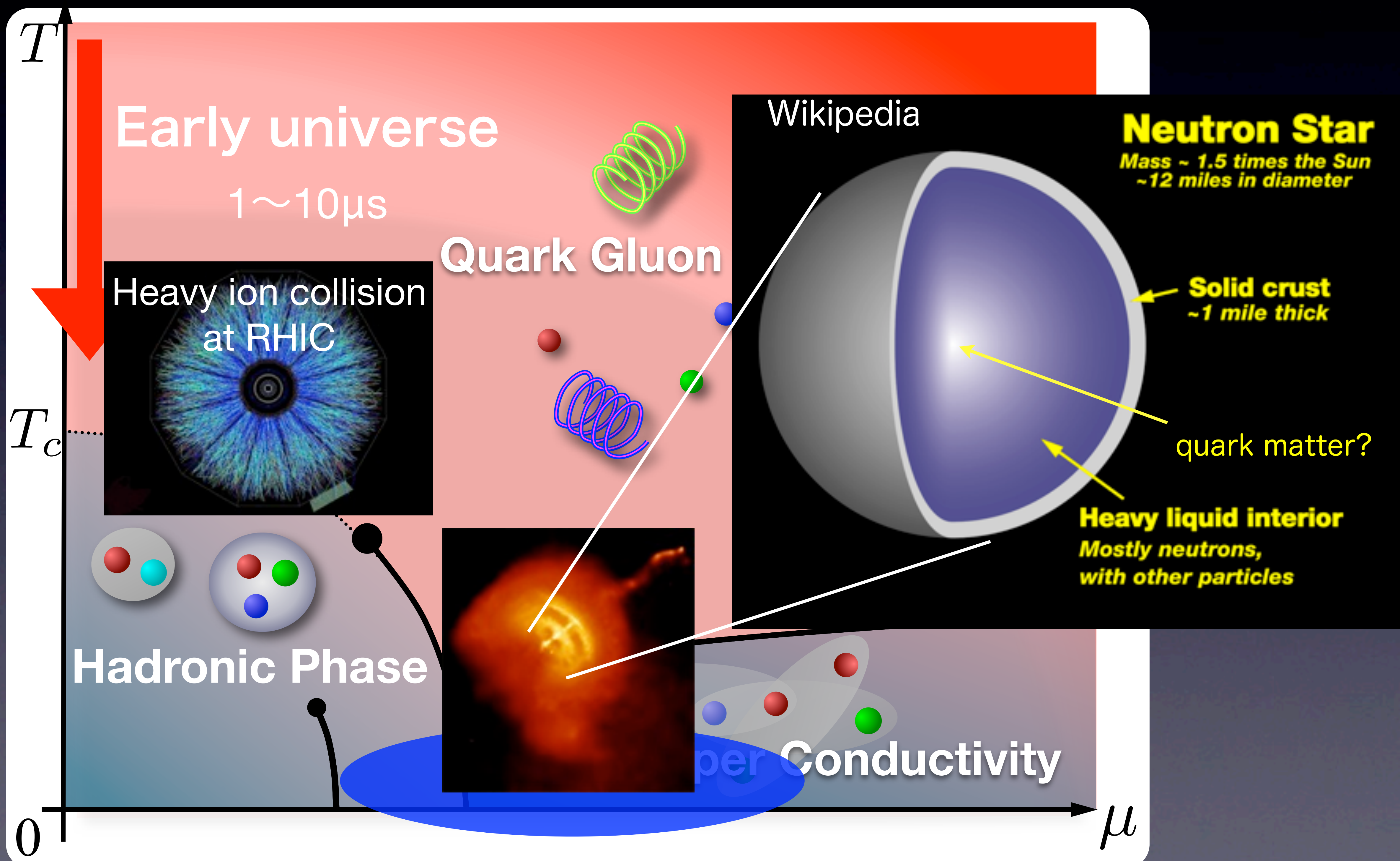
QCD Phase diagram



QCD Phase diagram

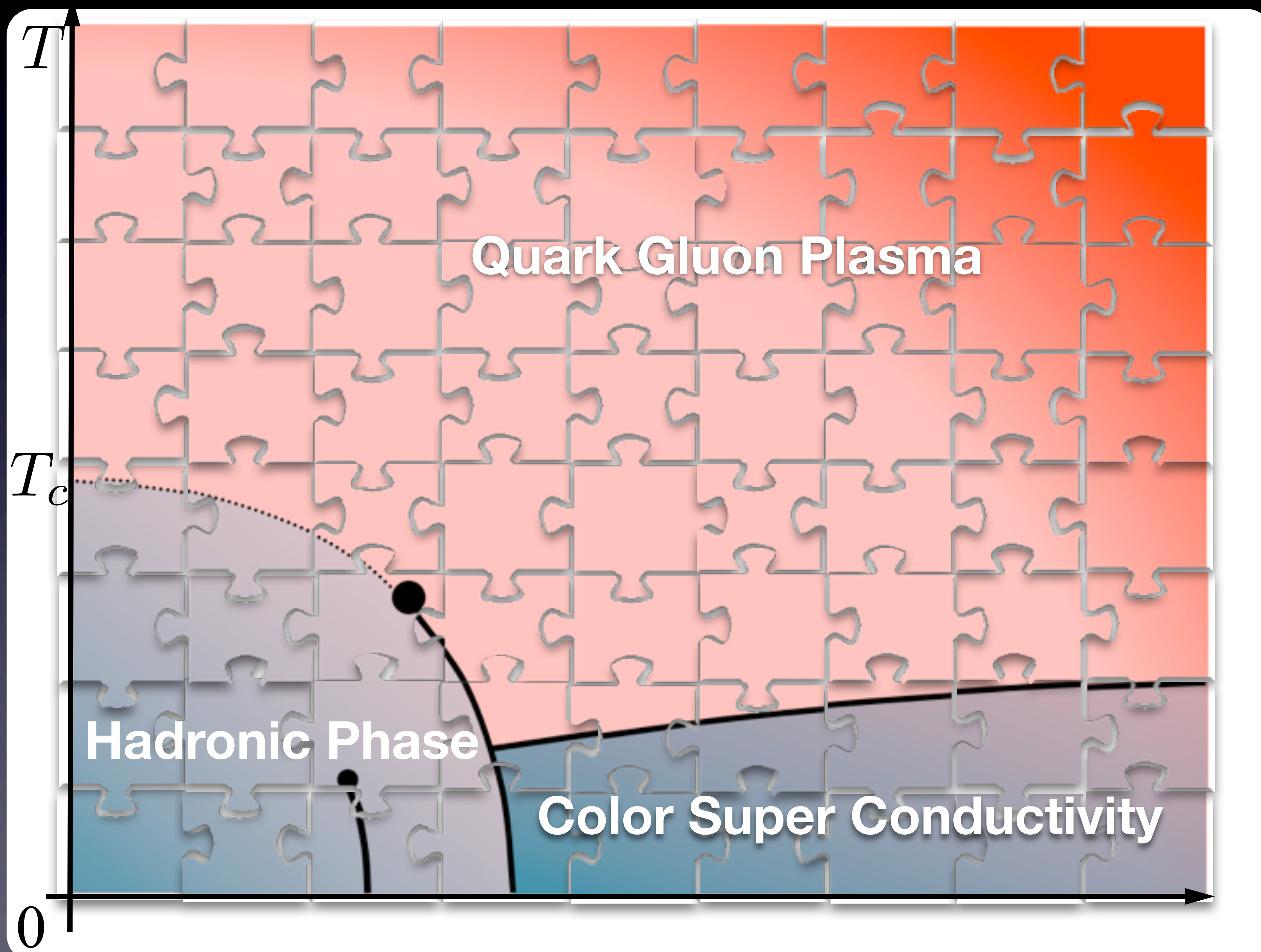


QCD Phase diagram

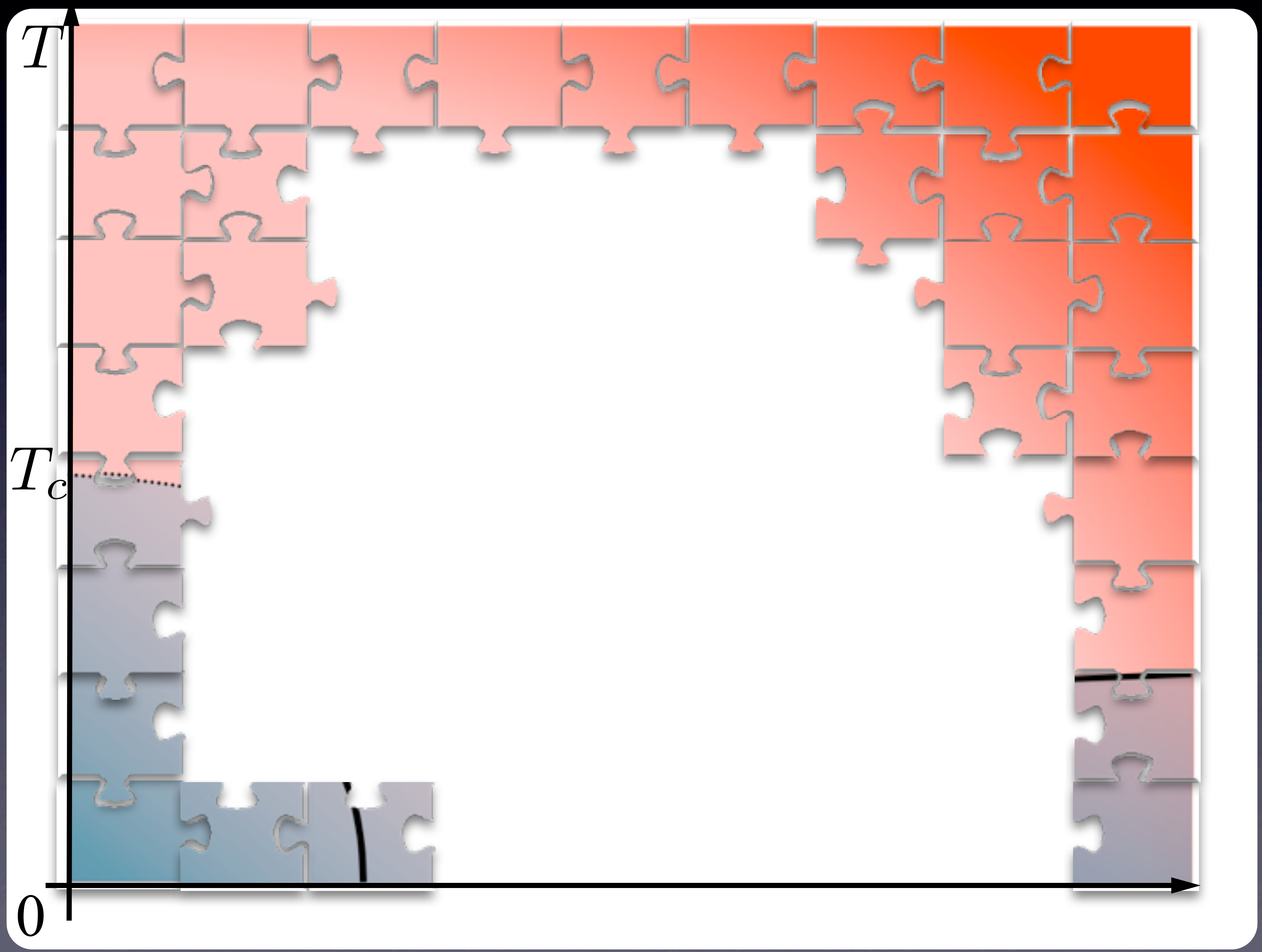


Inside of neutron stars

QCD Phase diagram

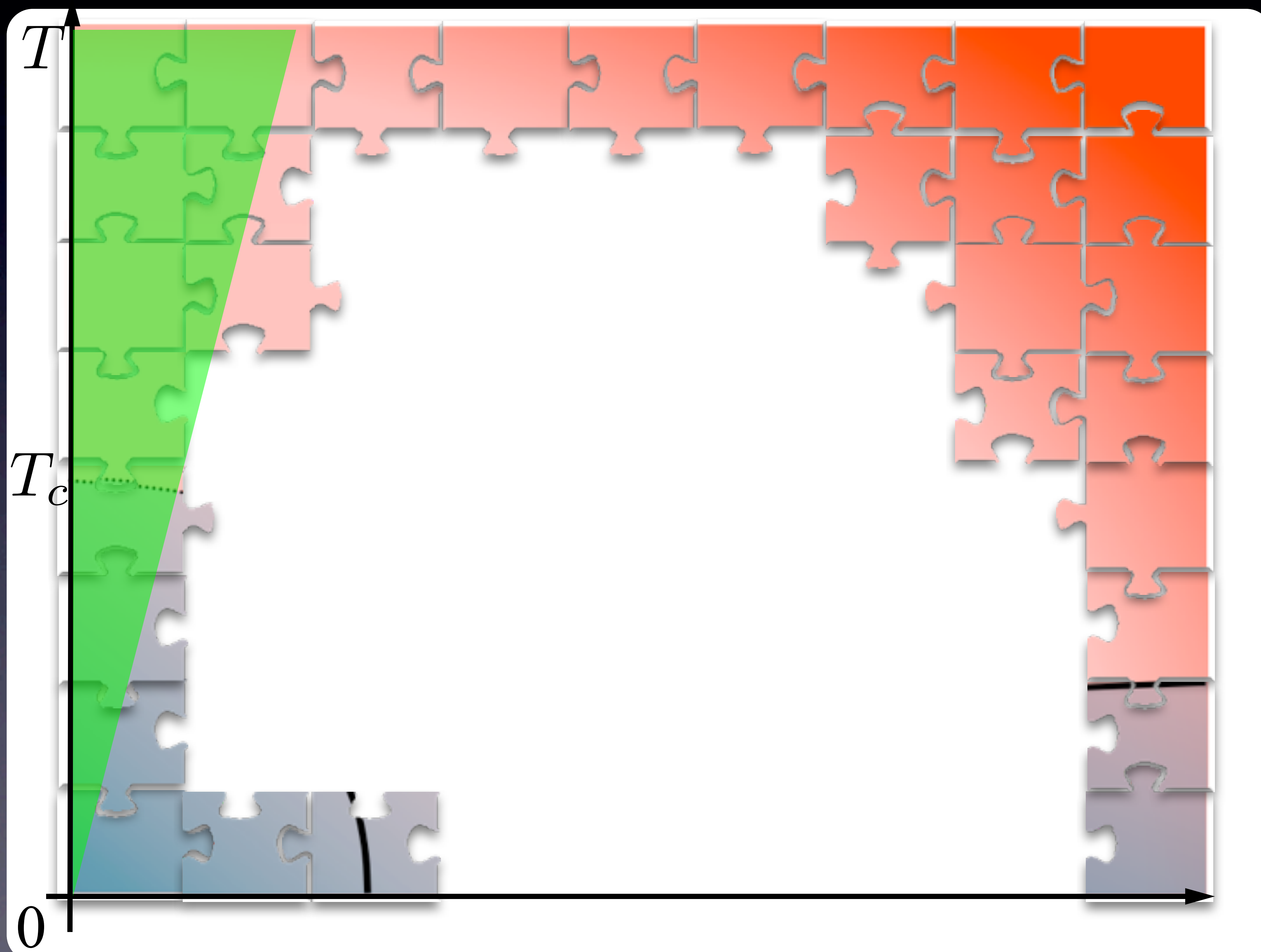


QCD Phase diagram



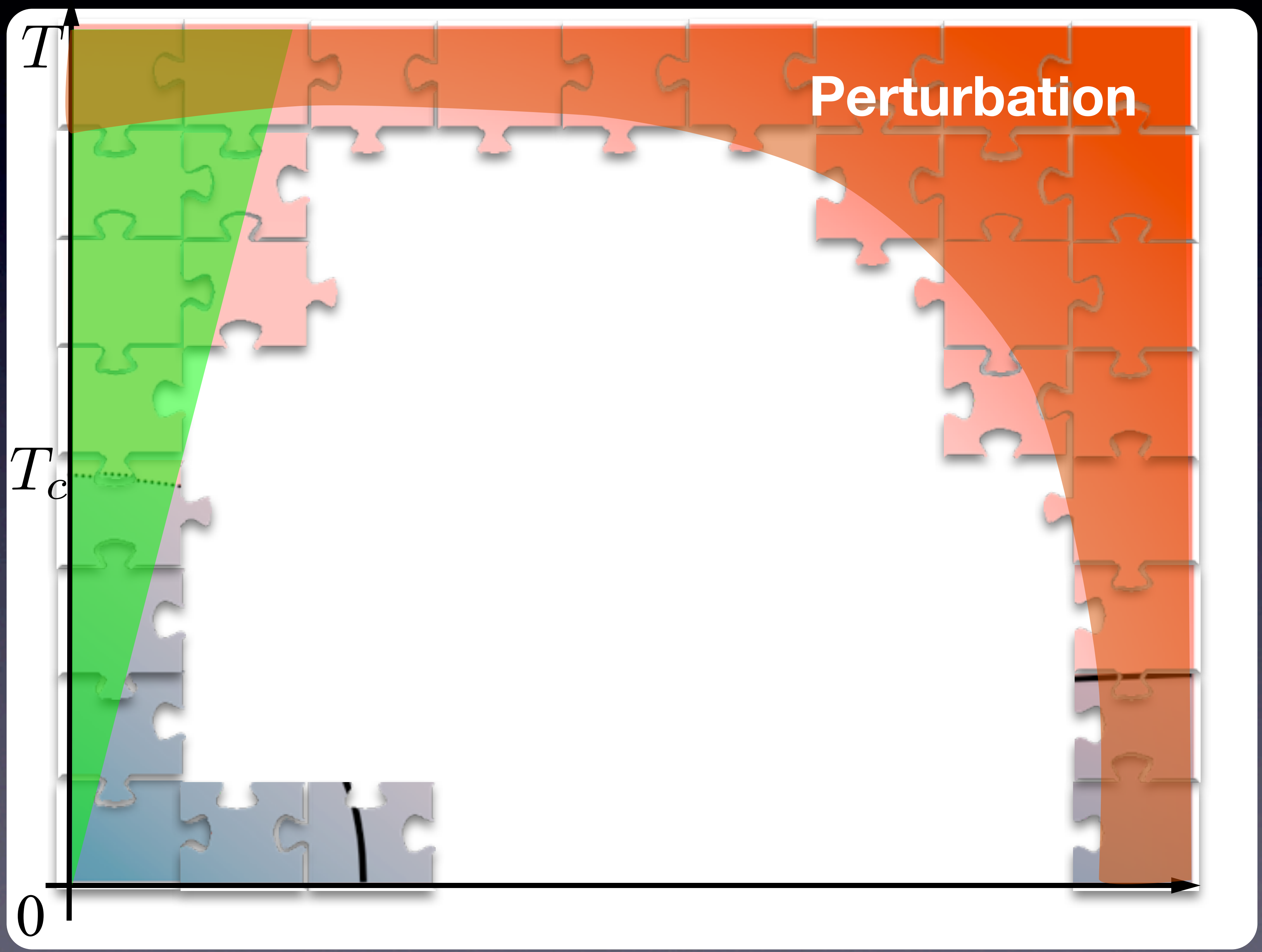
QCD Phase diagram

Lattice QCD



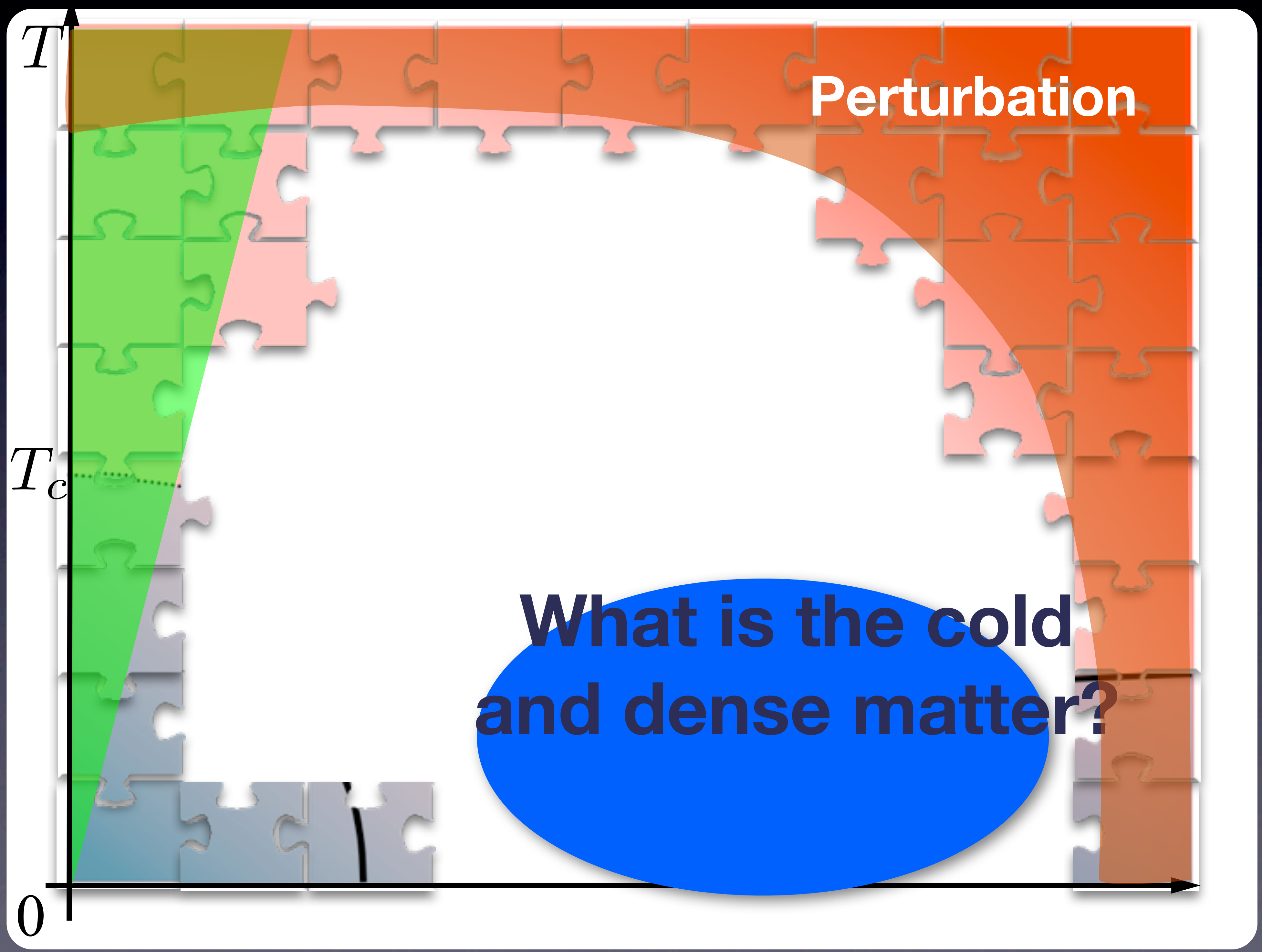
QCD Phase diagram

Lattice QCD

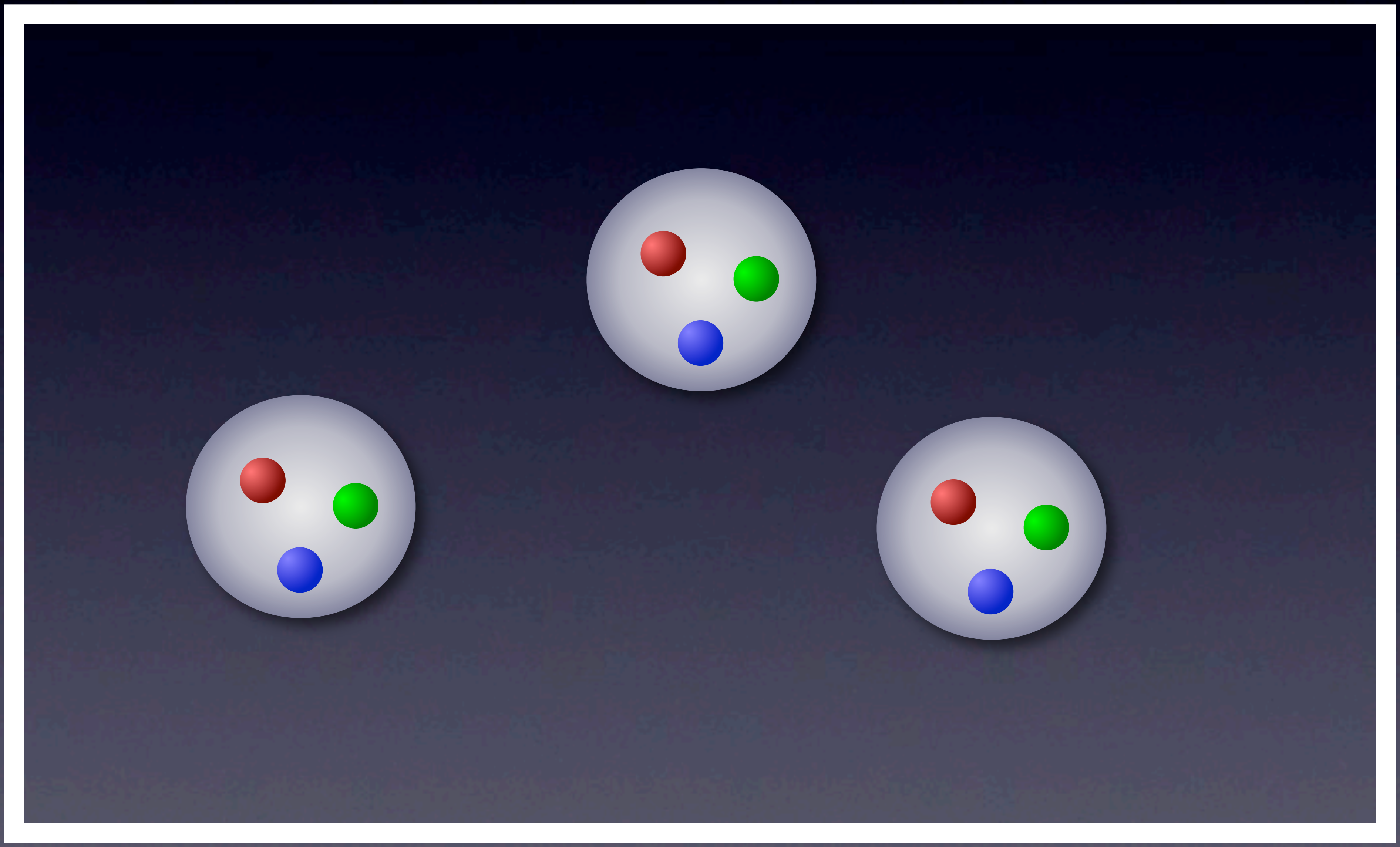


QCD Phase diagram

Lattice QCD

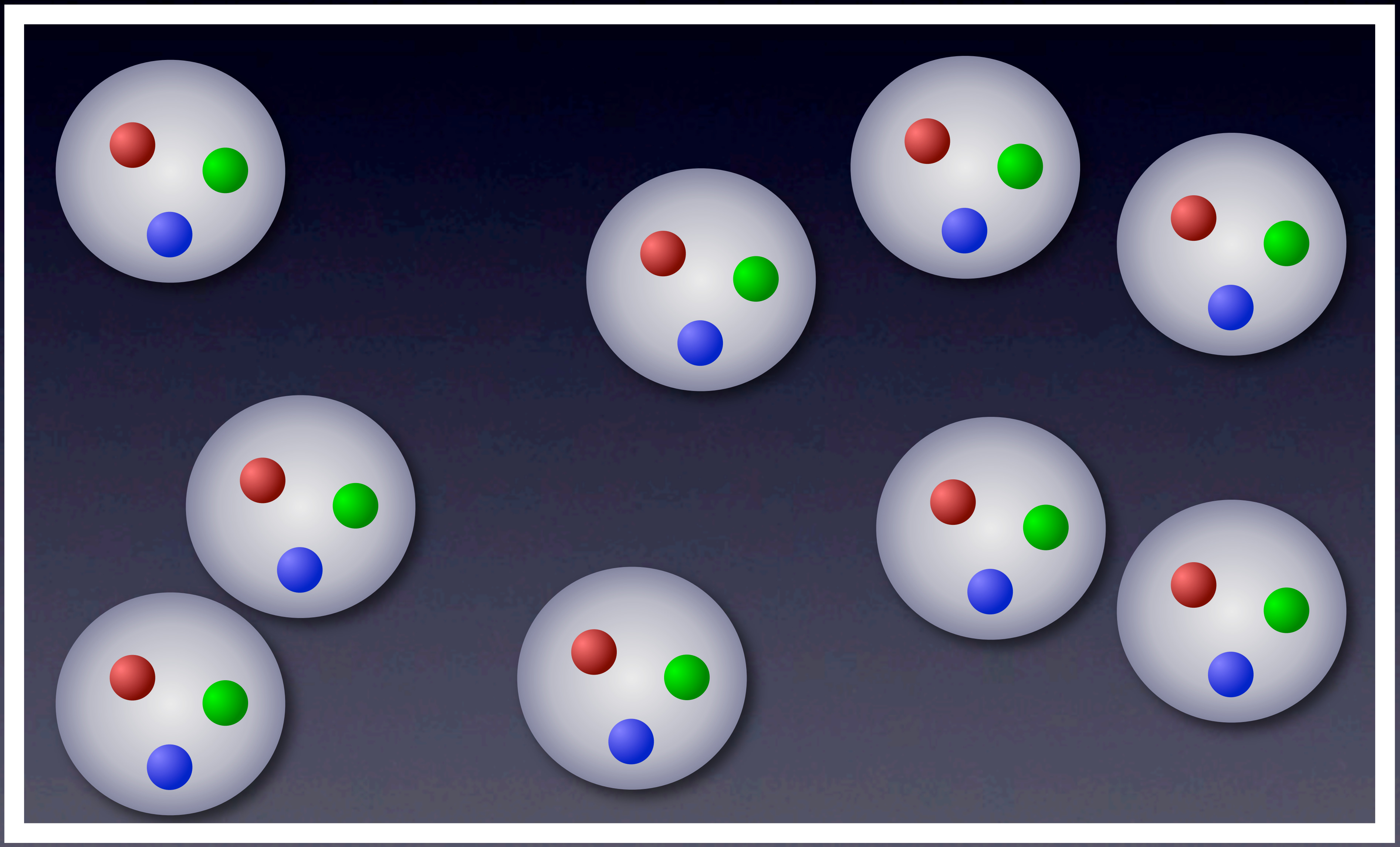


From dilute to dense



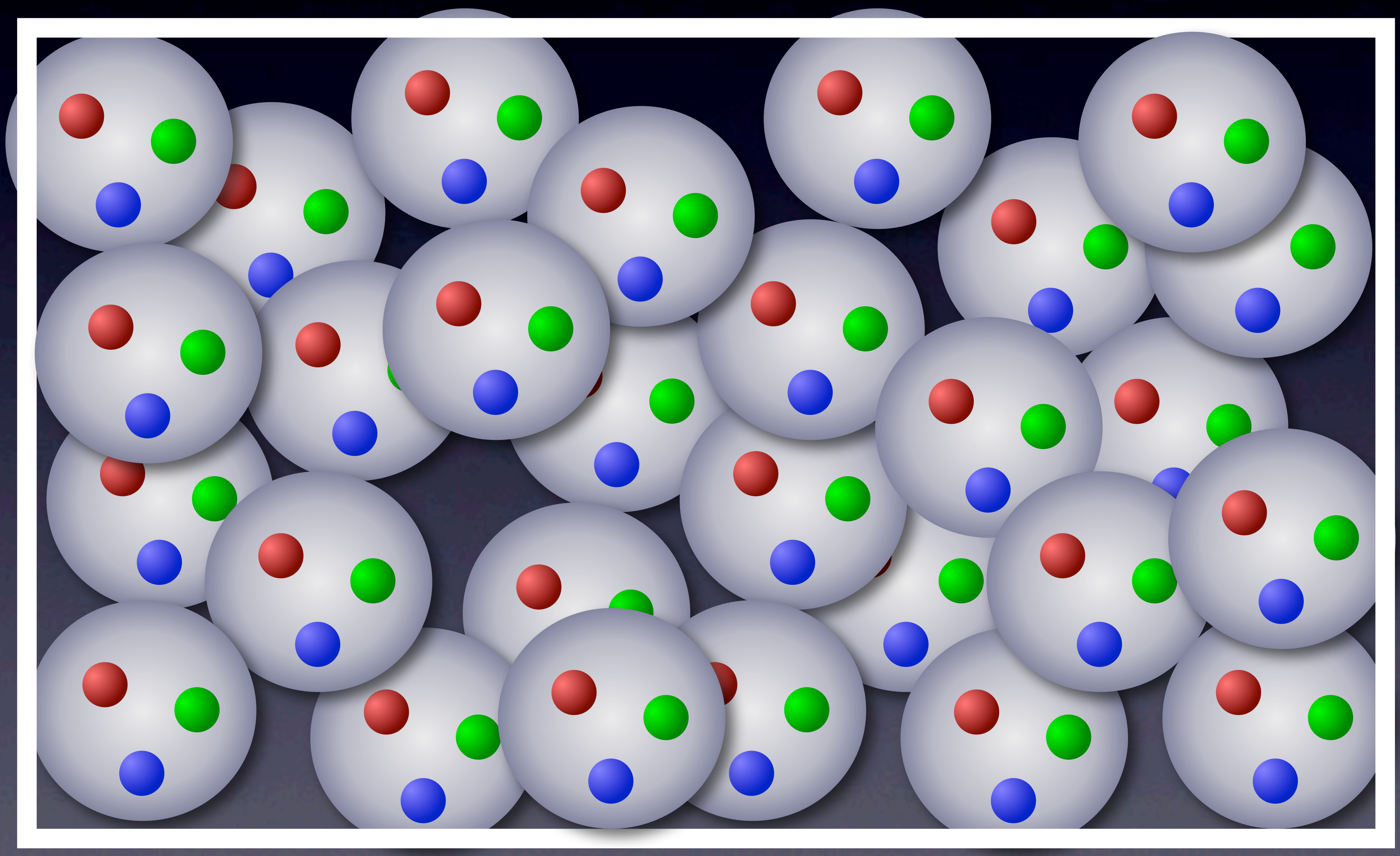
Gas of nucleons.

Nuclear matter



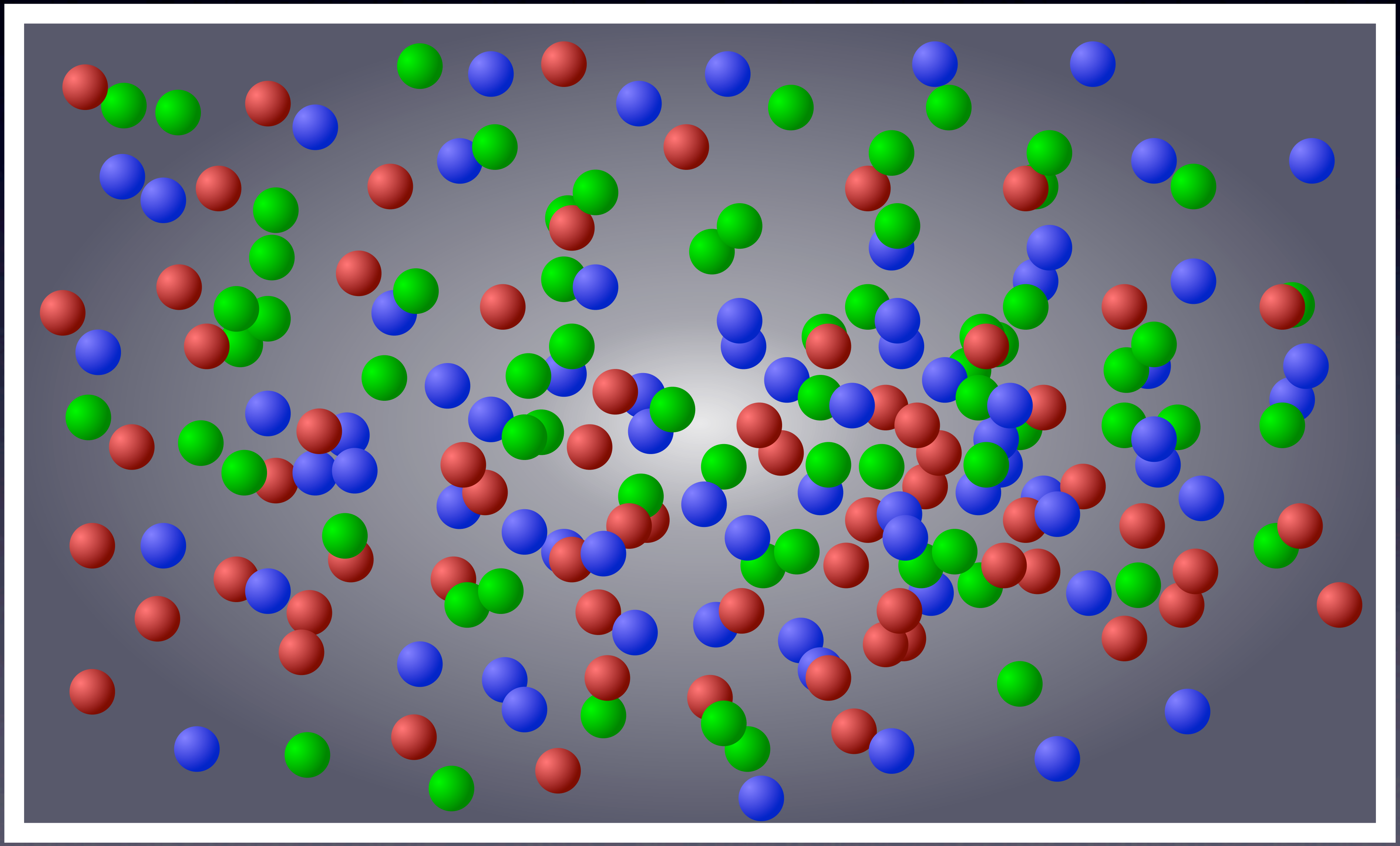
Fermi liquid of nucleons.
Pion condensation, ...

More dense..



Nucleons start overlapping.

Quarks highly degenerate.



Boundary of nucleon vanishes, and quark Fermi-sea is formed.

Is this matter deconfined?

Is this matter deconfined?

Ordinary scenario: Yes.

Is this matter deconfined?

Ordinary scenario: Yes.

Deconfined quarks,
and gluons.

Is this matter deconfined?

Ordinary scenario: Yes.

Deconfined quarks,
and gluons.

color super conductivities,...

Is this matter deconfined?

Is this matter deconfined?

New scenario: No!

Is this matter deconfined?

New scenario: No!

There is a window of confined matter with quark Fermi-sea.

This is true at least, in large-N_c.

Is this matter deconfined?

New scenario: No!

There is a window of confined matter
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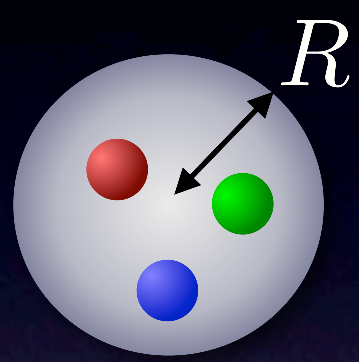
⇒ Quarkyonic matter

Quarkyonic matter

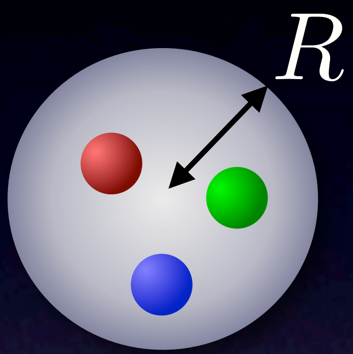


$R \sim 1/\Lambda_{\mathrm{QCD}}$:Scale of QCD

m_D :Scale of Screening

μ :Scale of density

Quarkyonic matter



$R \sim 1/\Lambda_{\mathrm{QCD}}$:Scale of QCD

m_D :Scale of Screening

μ :Scale of density

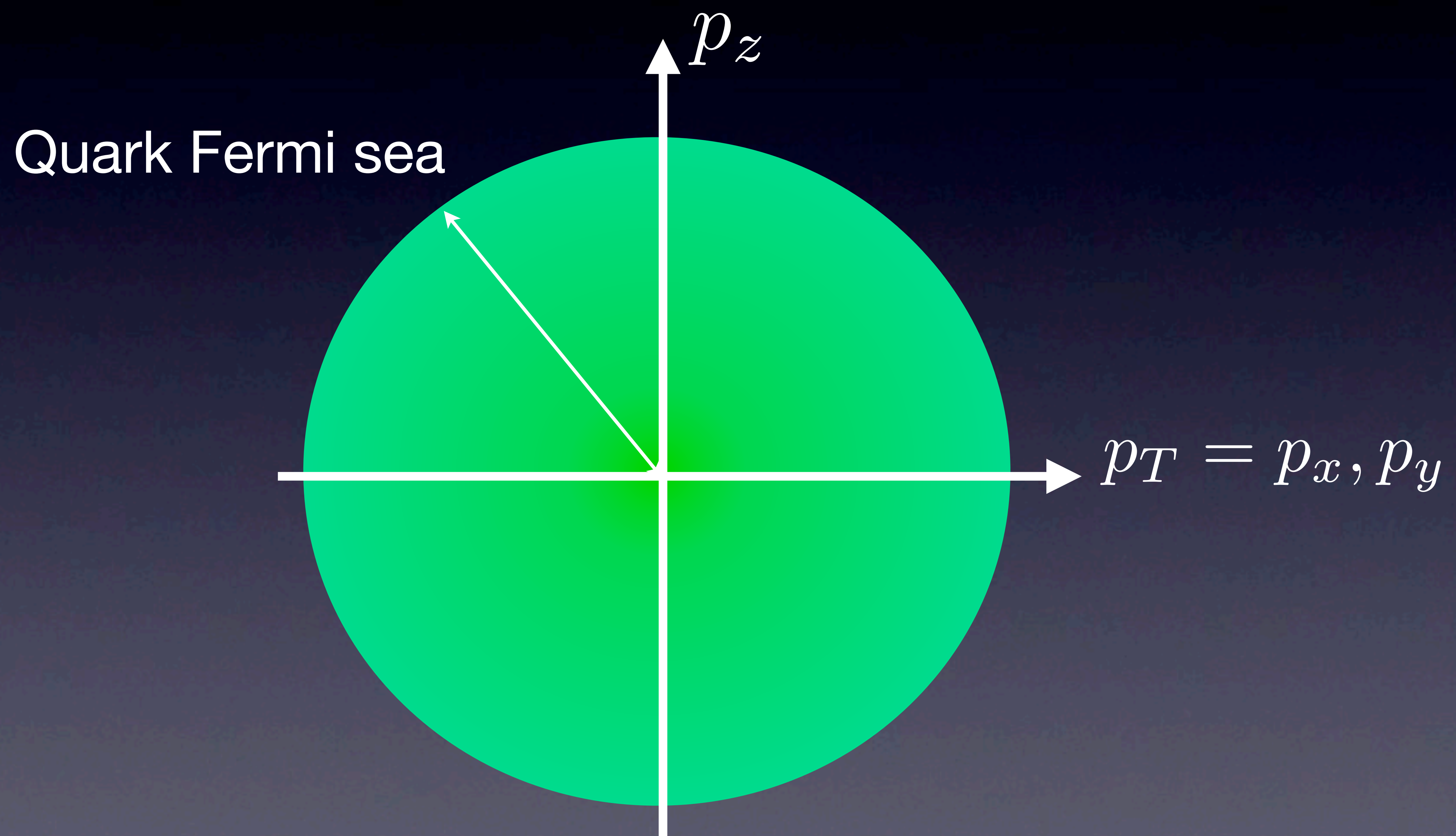
Quarkyonic limit

Dense: $\mu \gg \Lambda_{\mathrm{QCD}}$

Confined: $\Lambda_{\mathrm{QCD}} \gg m_D$

Quarkyonic matter

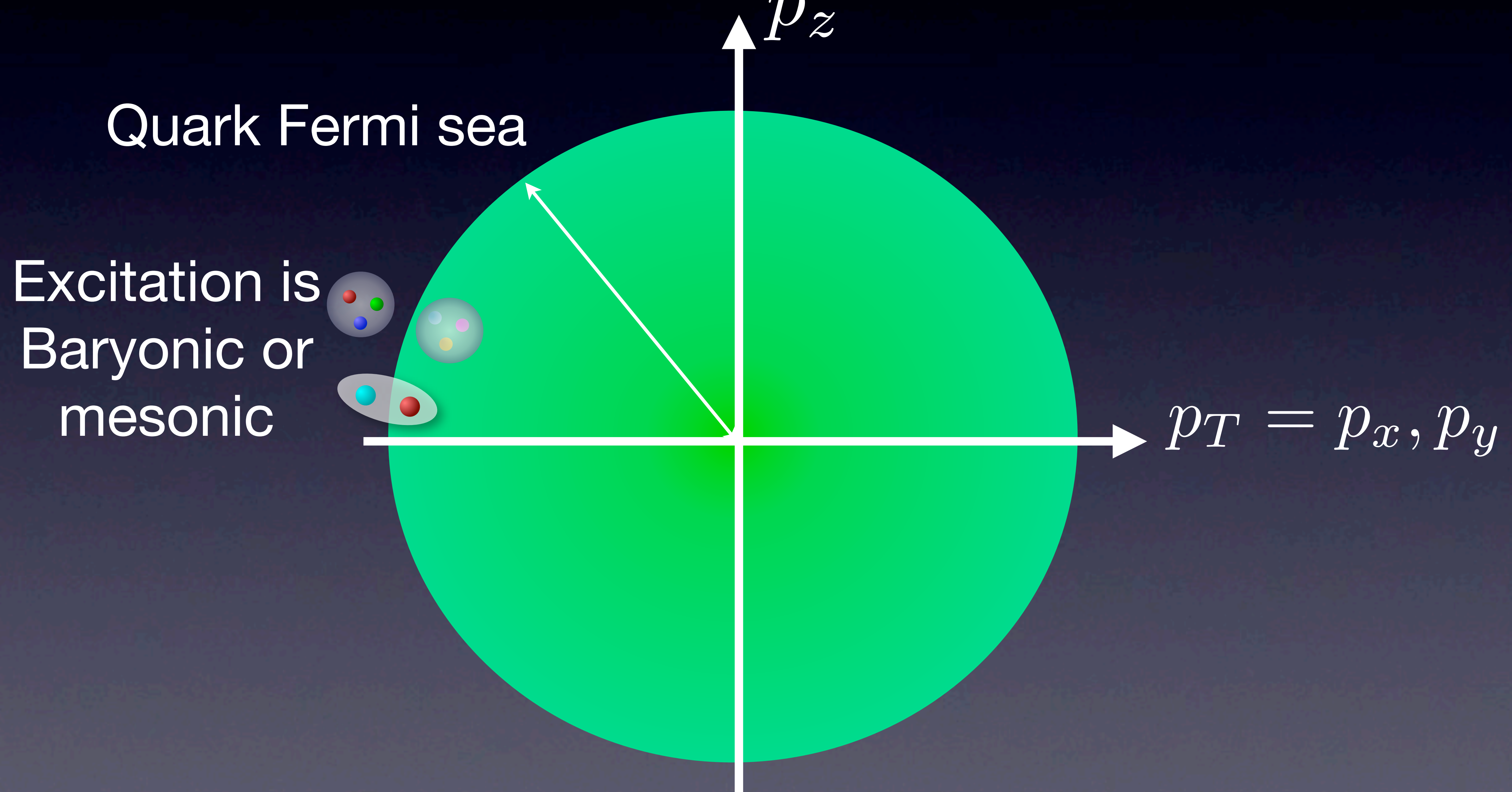
Larry McLerran and Robert Pisarski (2007)



Quark + Baryonic = Quarkyonic

Quarkyonic matter

Larry McLerran and Robert Pisarski (2007)



Quark + Baryonic = Quarkyonic

How about chiral symmetry?

Chiral symmetry

$\langle \bar{\psi}\psi \rangle$ **Order parameter**

Chiral symmetry

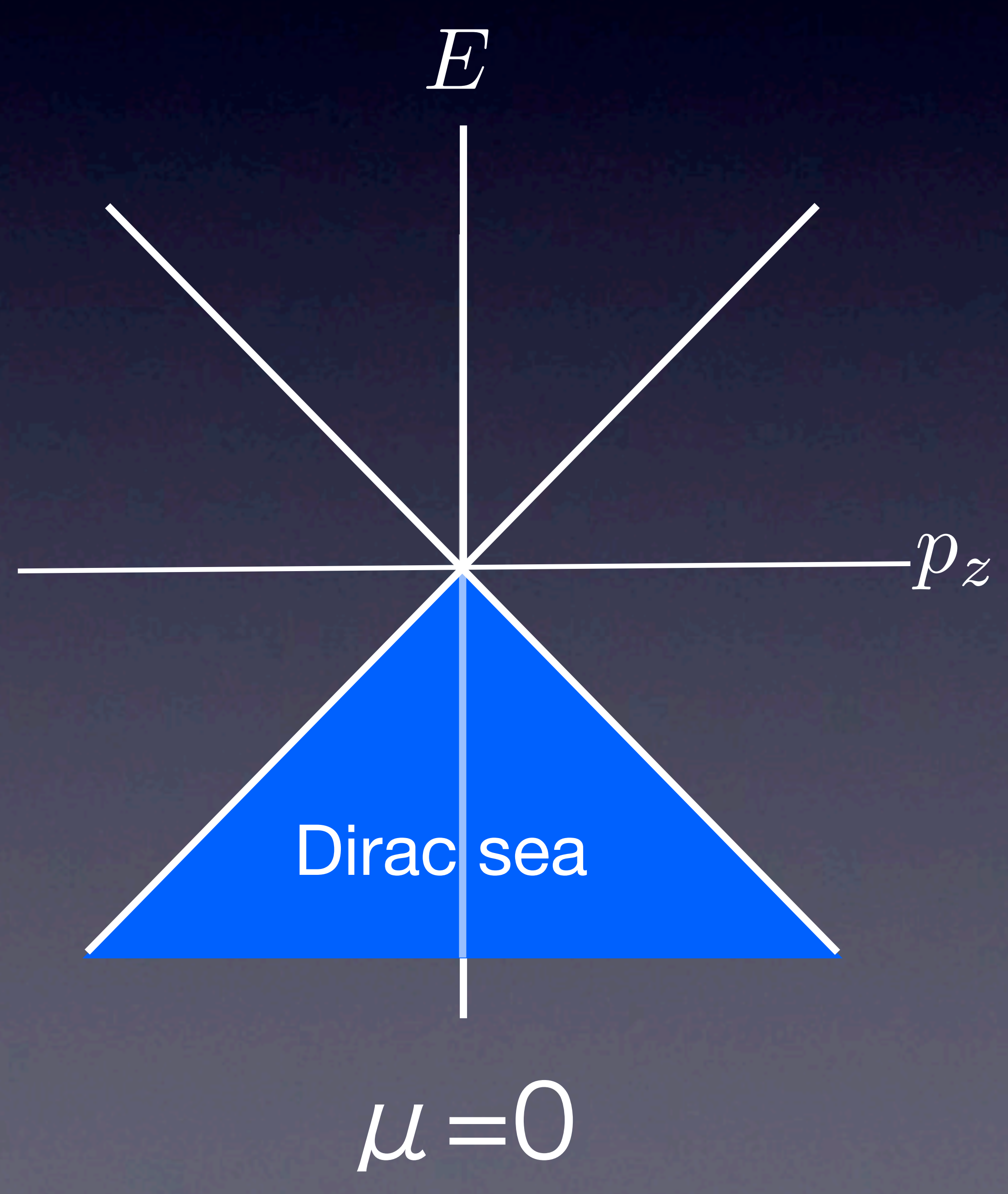
$\langle \bar{\psi}\psi \rangle$ **Order parameter**

⇕

In vacuum, quark anti-quark pairing.
In medium, quark anti-quark pairing
or quark hole pairing.

Chiral symmetry?

Consider quarkyonic limit, $\mu \gg \Lambda_{\rm QCD}$



Chiral symmetry?

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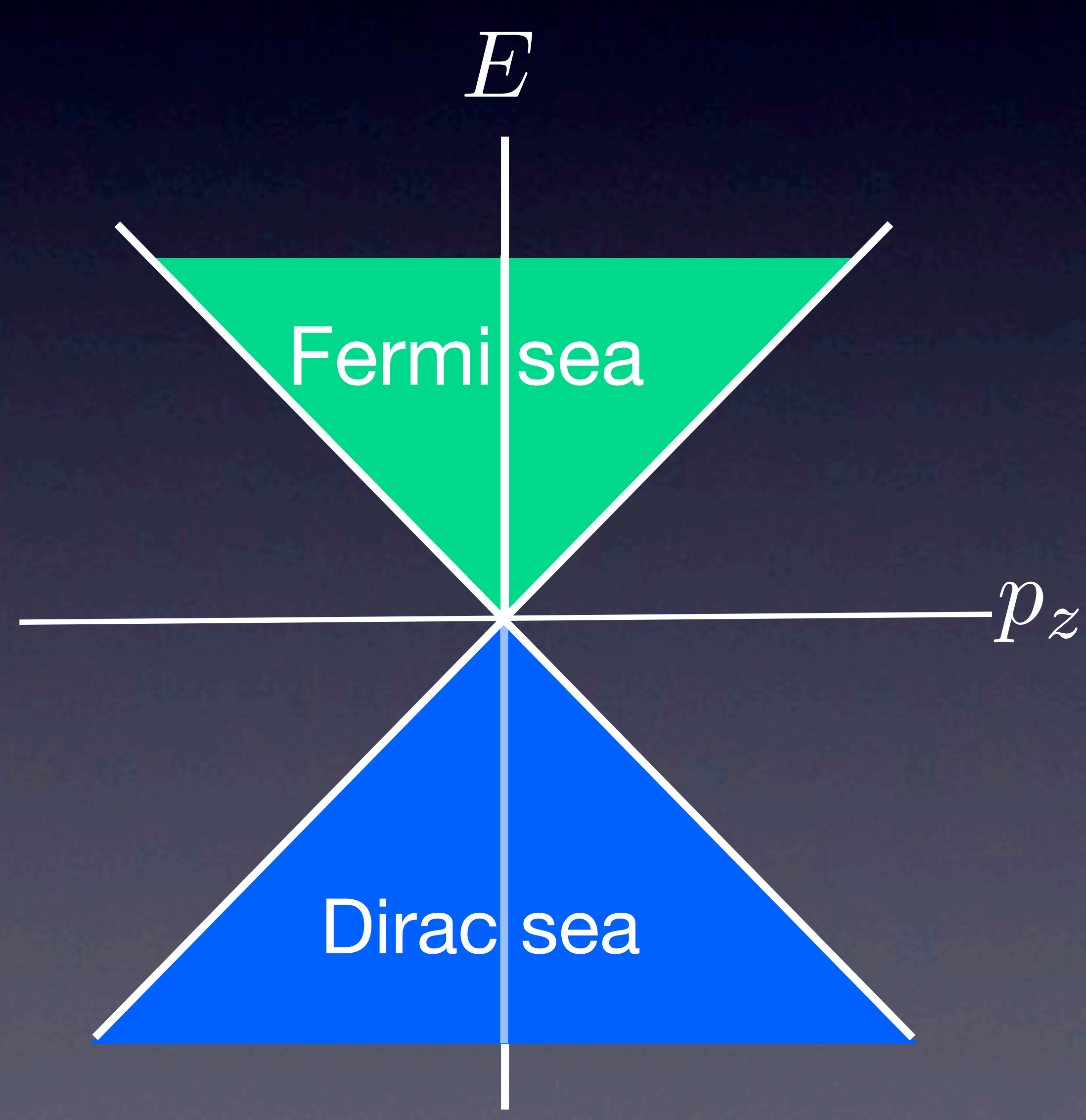
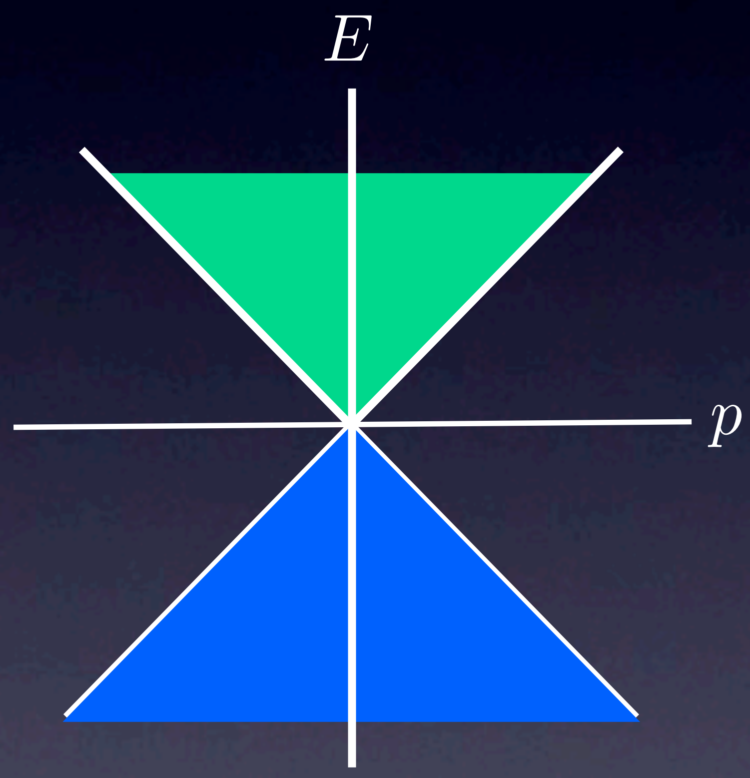


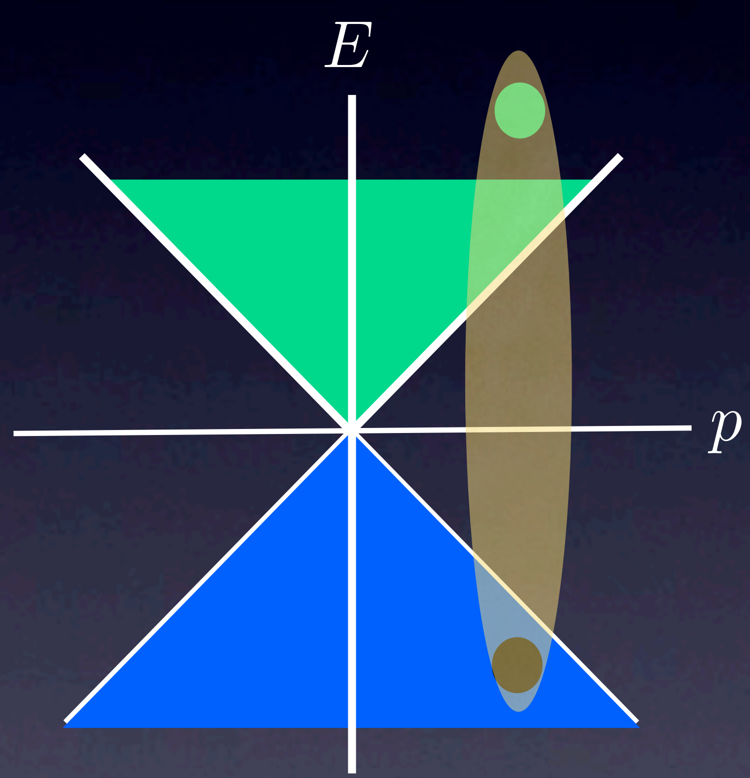
$\mu \neq 0$

Possible pairing patterns



Possible pairing patterns

Dirac Type



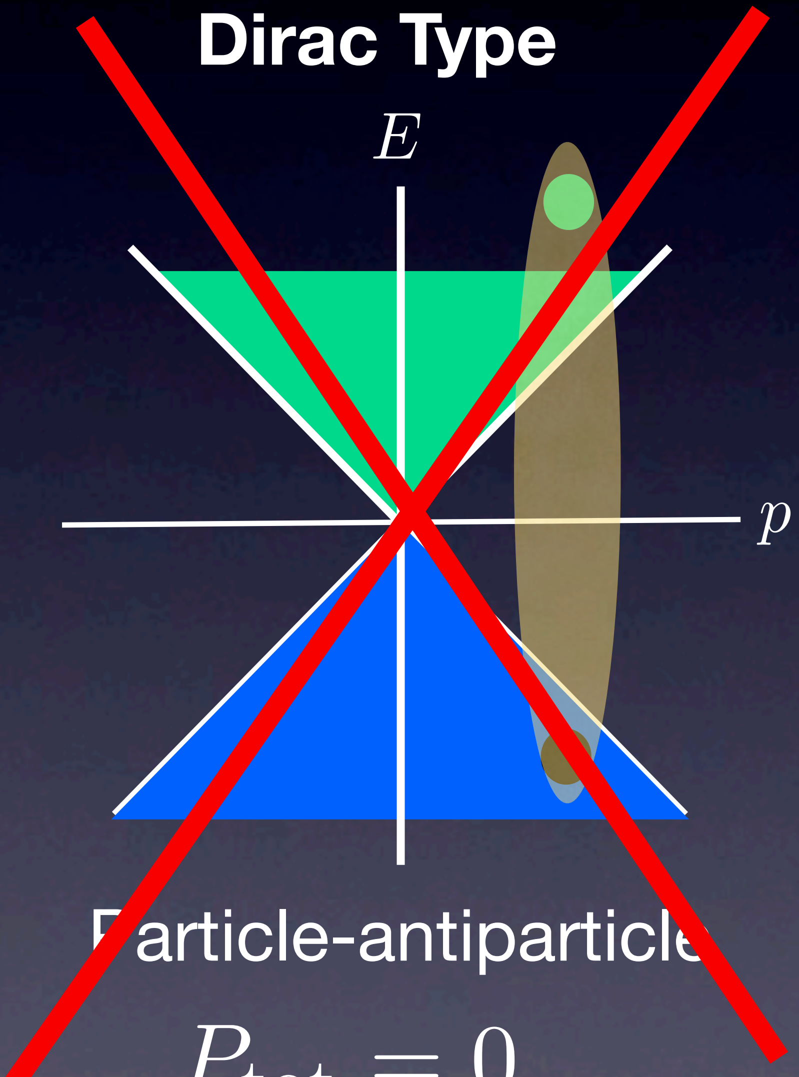
Particle-antiparticle

$P_{\mathrm{tot}} = 0$

homogeneous

Possible pairing patterns

Dirac Type



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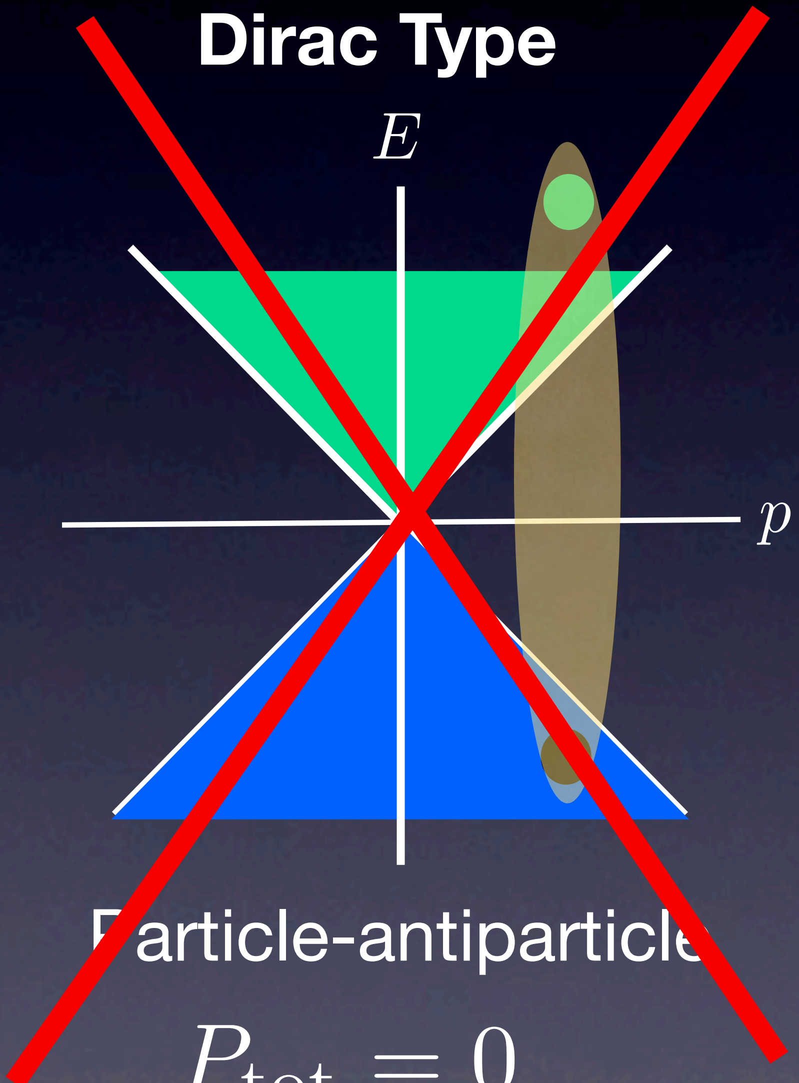

Particle-antiparticle

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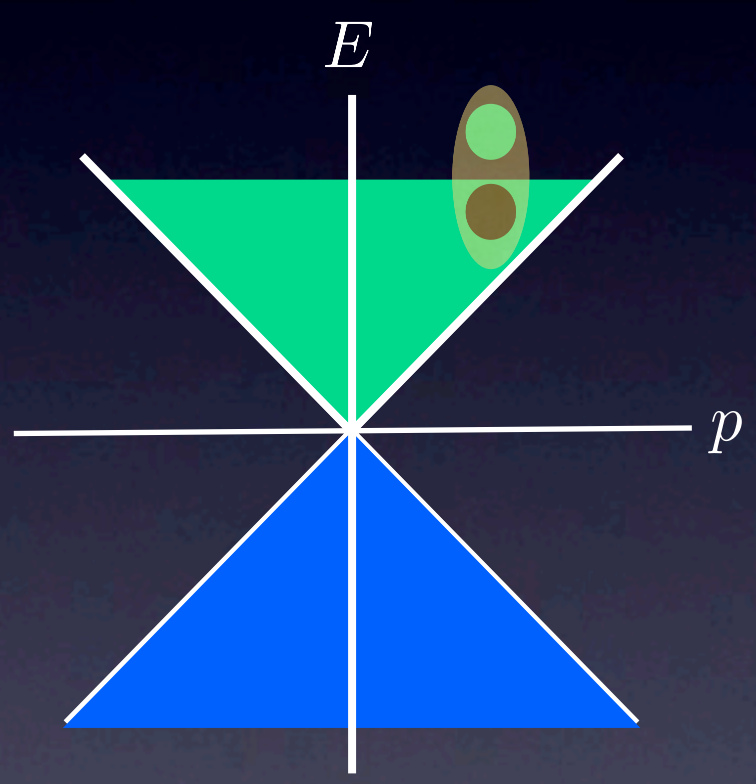
Exciton Type



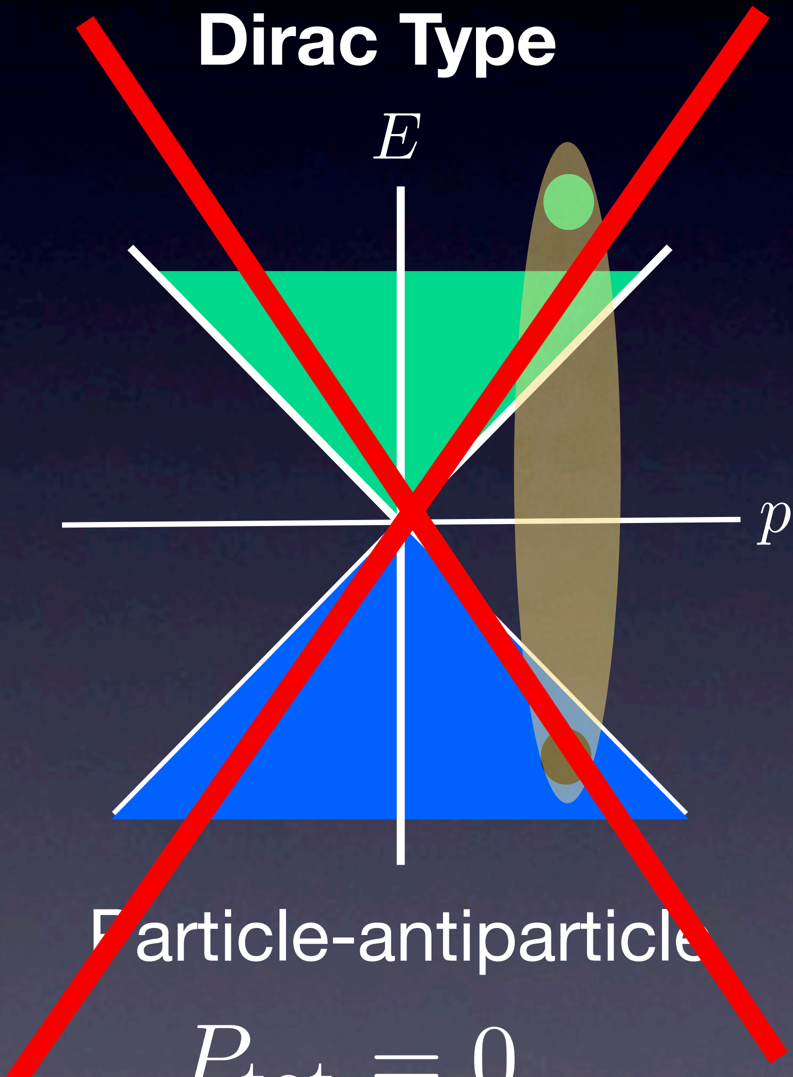
Particle-hole

$P_{\text{tot}} = 0$

homogeneous

Possible pairing patterns

Dirac Type

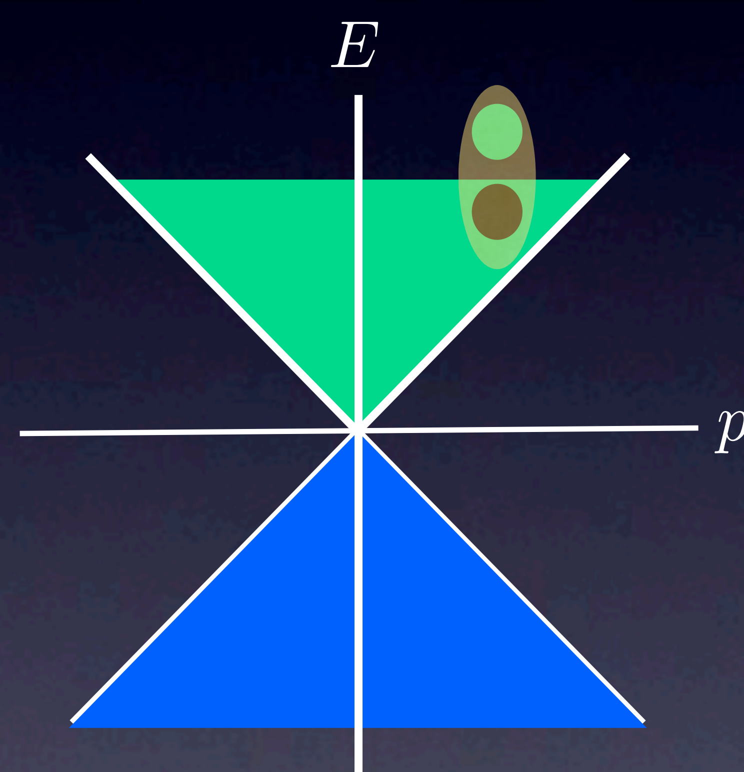


Particle-antiparticle

$$P_{\text{tot}} = 0$$

homogeneous

Exciton Type

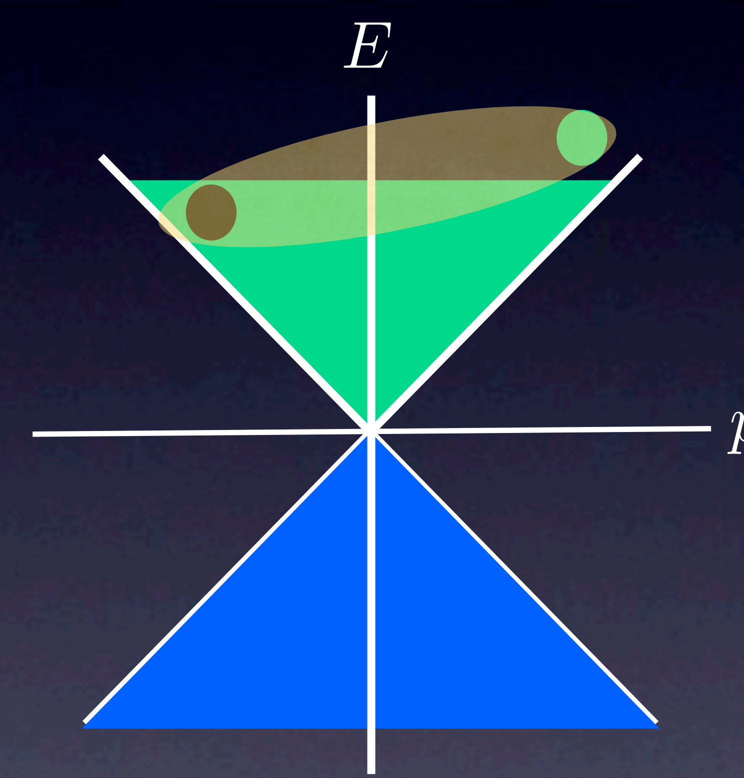


Particle-hole

$$P_{\text{tot}} = 0$$

homogeneous

Density Wave Type



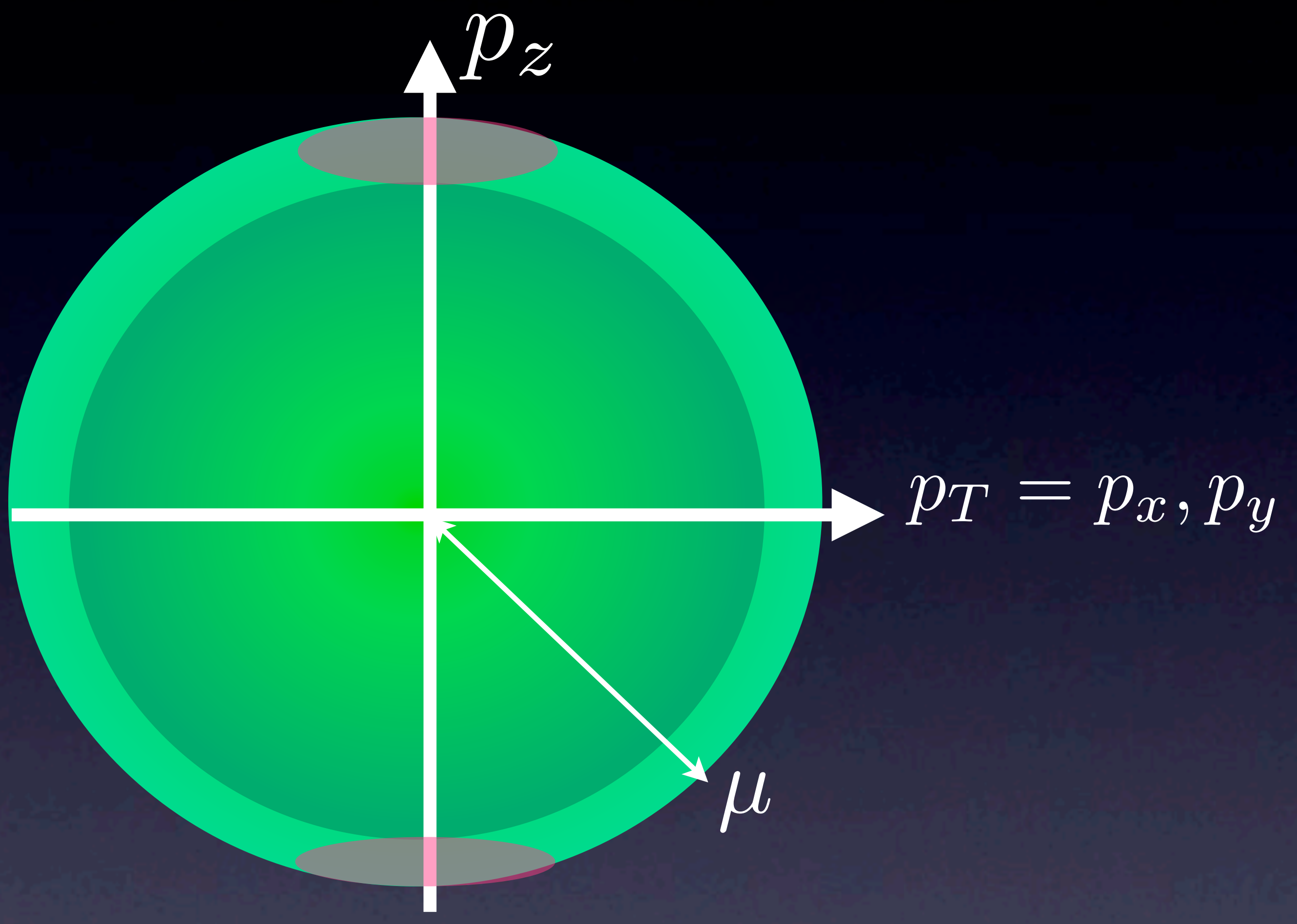
Particle-hole

$$P_{\text{tot}} = 2\mu$$

inhomogeneous

Perturbative
Deryagin, Grigoriev, & Rubakov ('92),
Shuster & Son ('99),
Rapp, Shuryak, and Zahed ('00).

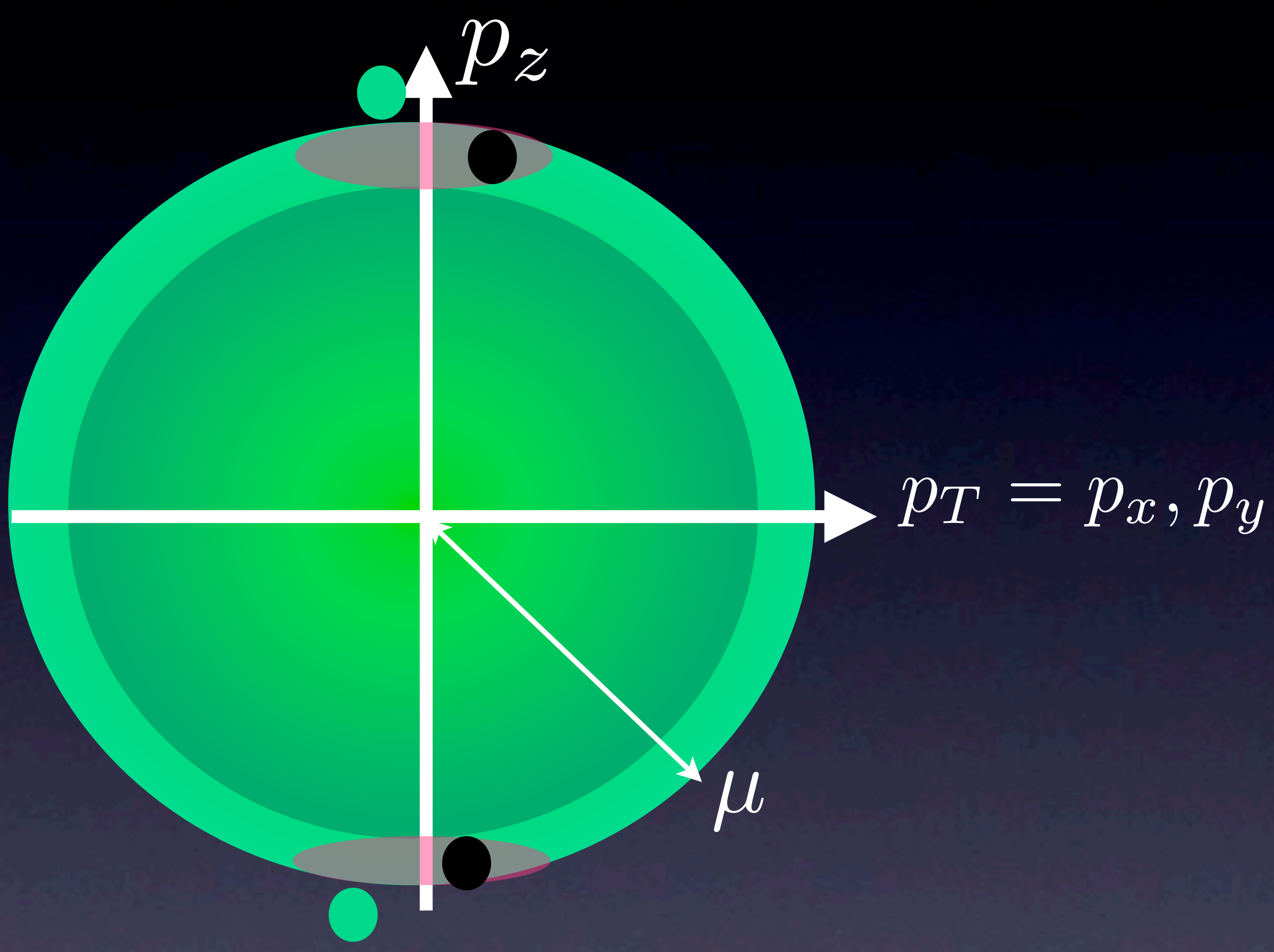
Consider near a Fermi surface at $p_z = p_F$



Consider near a Fermi surface at $p_z = p_F$

$$\frac{P_T}{P_z} \sim \frac{\Lambda_{\rm QCD}}{\mu} \ll 1$$

Transverse component
can be neglected.



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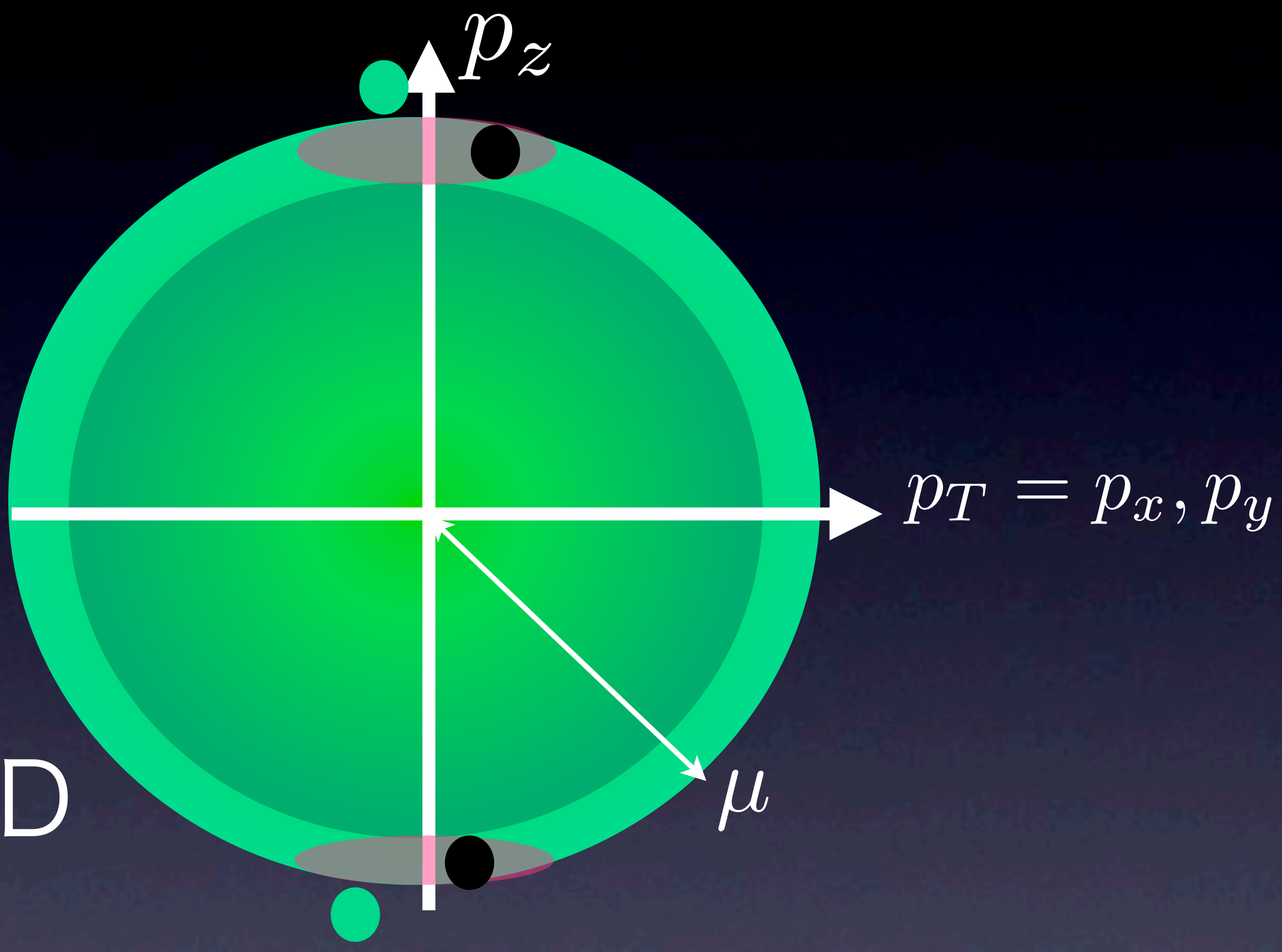

Quarks: effectively 1+1D
Gluons: 3+1D

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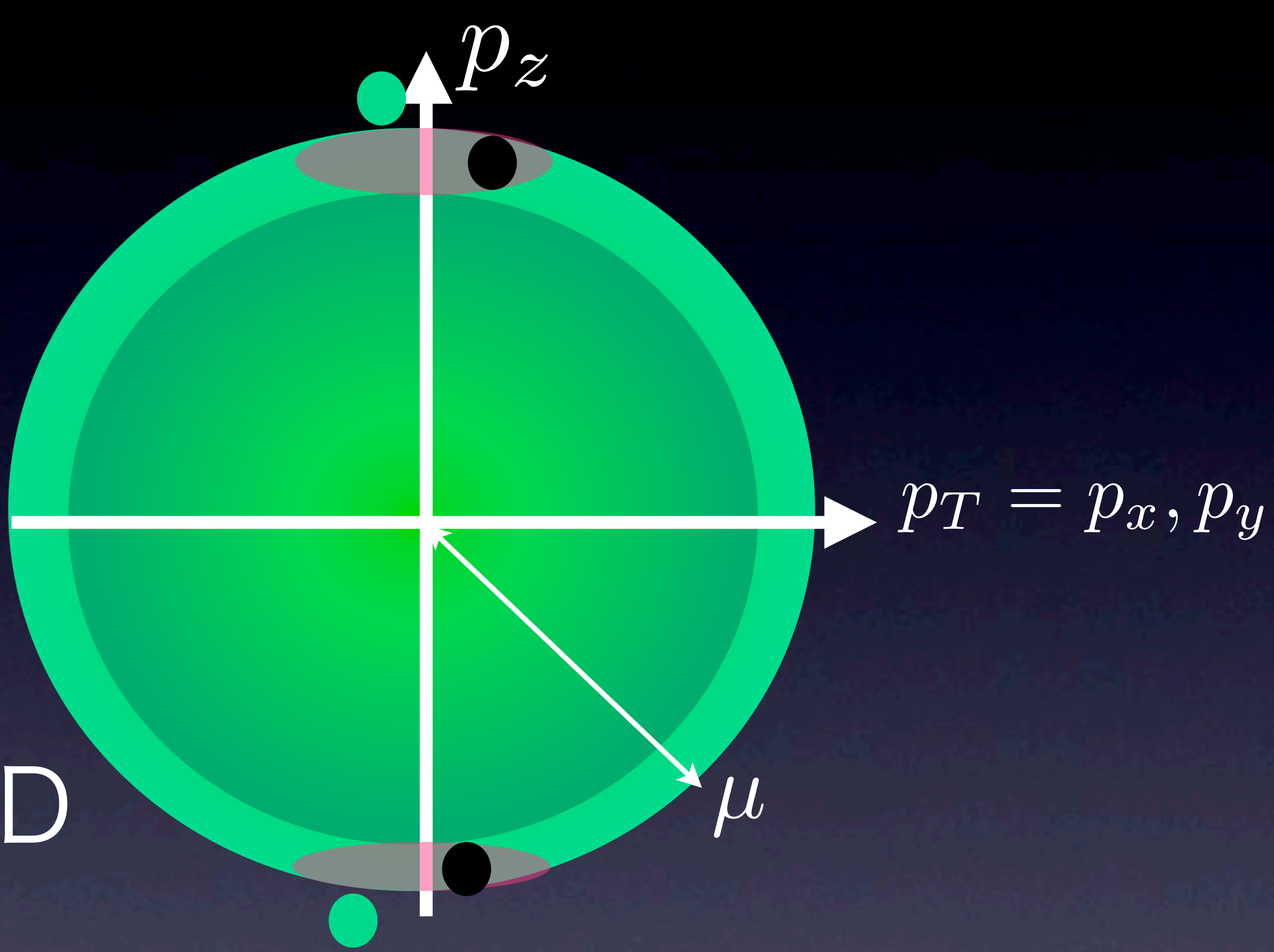

Quarks: effectively 1+1D
Gluons: 3+1D

Integrating over transverse momentum of gluon

⇨ **Effective model in 1+1D.**

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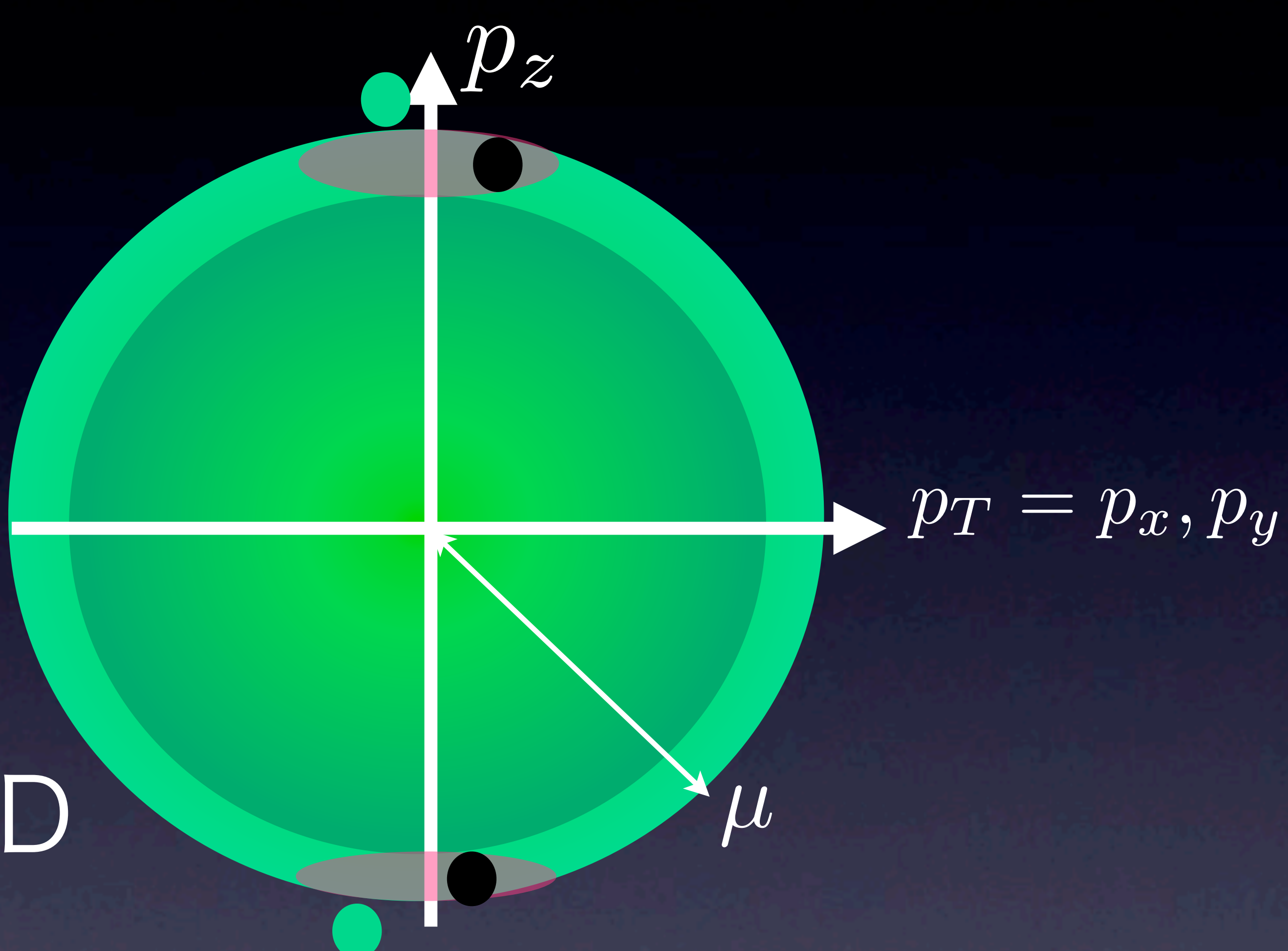
Transverse component can be neglected.



Quarks: effectively 1+1D

Gluons: 3+1D

Integrating over transverse momentum of gluon

➡ **Effective model in 1+1D.**

Density Wave Type **Exciton Type**

Consider near a Fermi surface at $p_z = p_F$

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Transverse component
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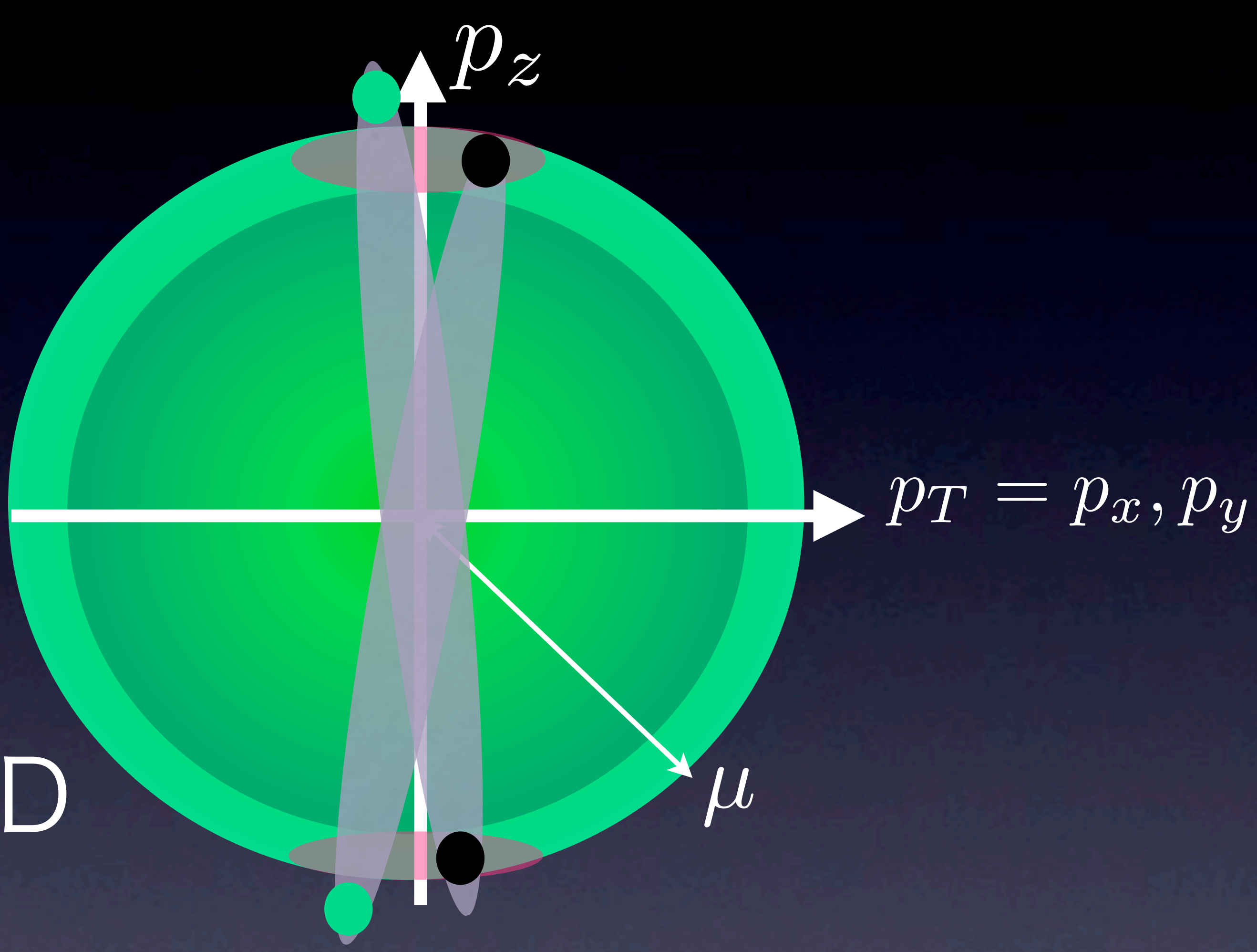


Quarks: effectively 1+1D
Gluons: 3+1D

Integrating over transverse momentum of gluon

➡ **Effective model in 1+1D.**

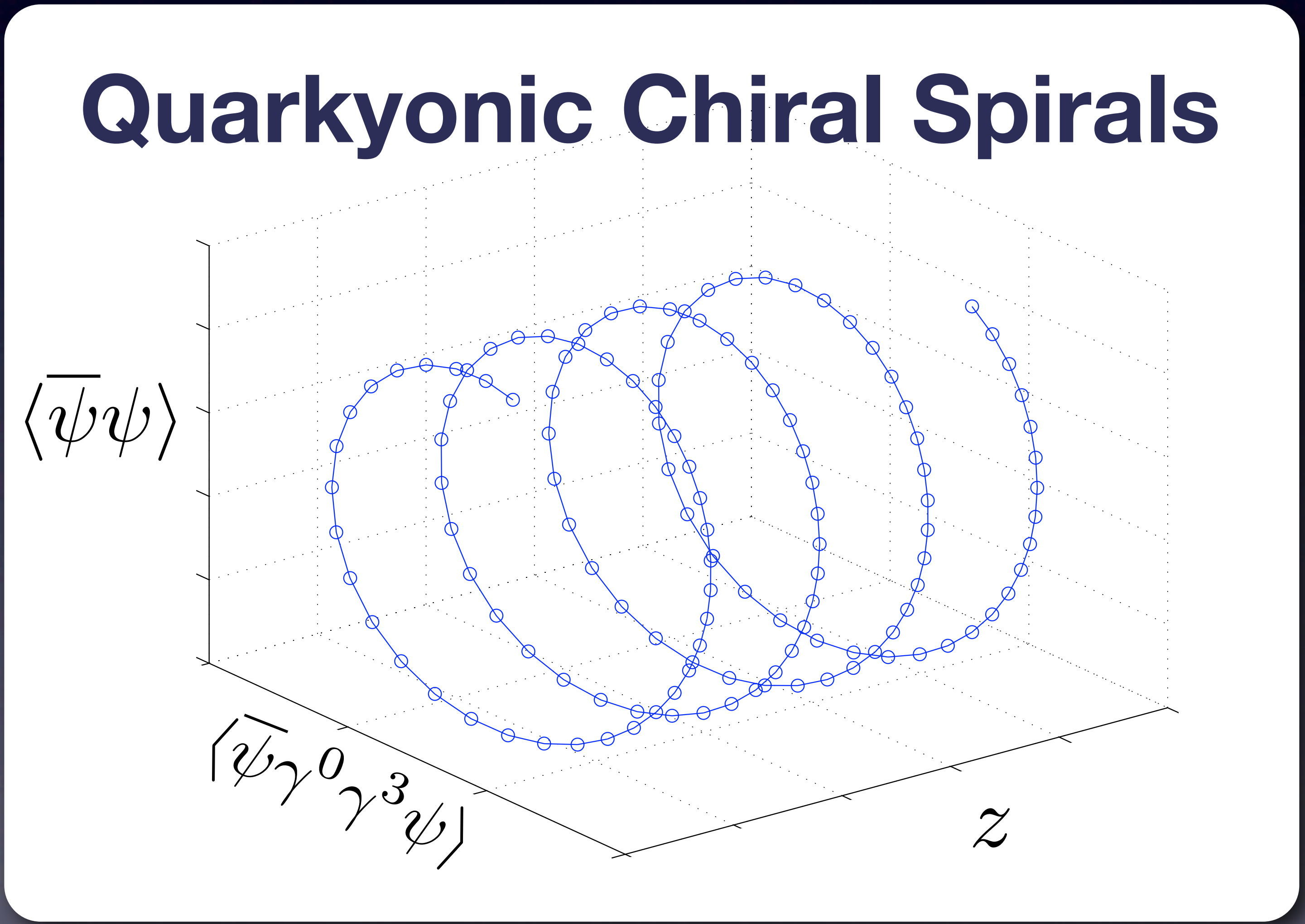
Density Wave Type **Exciton Type**

Quarkyonic chiral spirals

T. Kojo, Y.H., L. McLerran, and R. Pisarski

Nonuniform condensation realizes.

$\langle\overline{\psi}\psi\rangle = C\cos(2\mu z)$ $\quad\langle\overline{\psi}\gamma^0\gamma^3\psi\rangle = C\sin(2\mu z)$ *C=const*



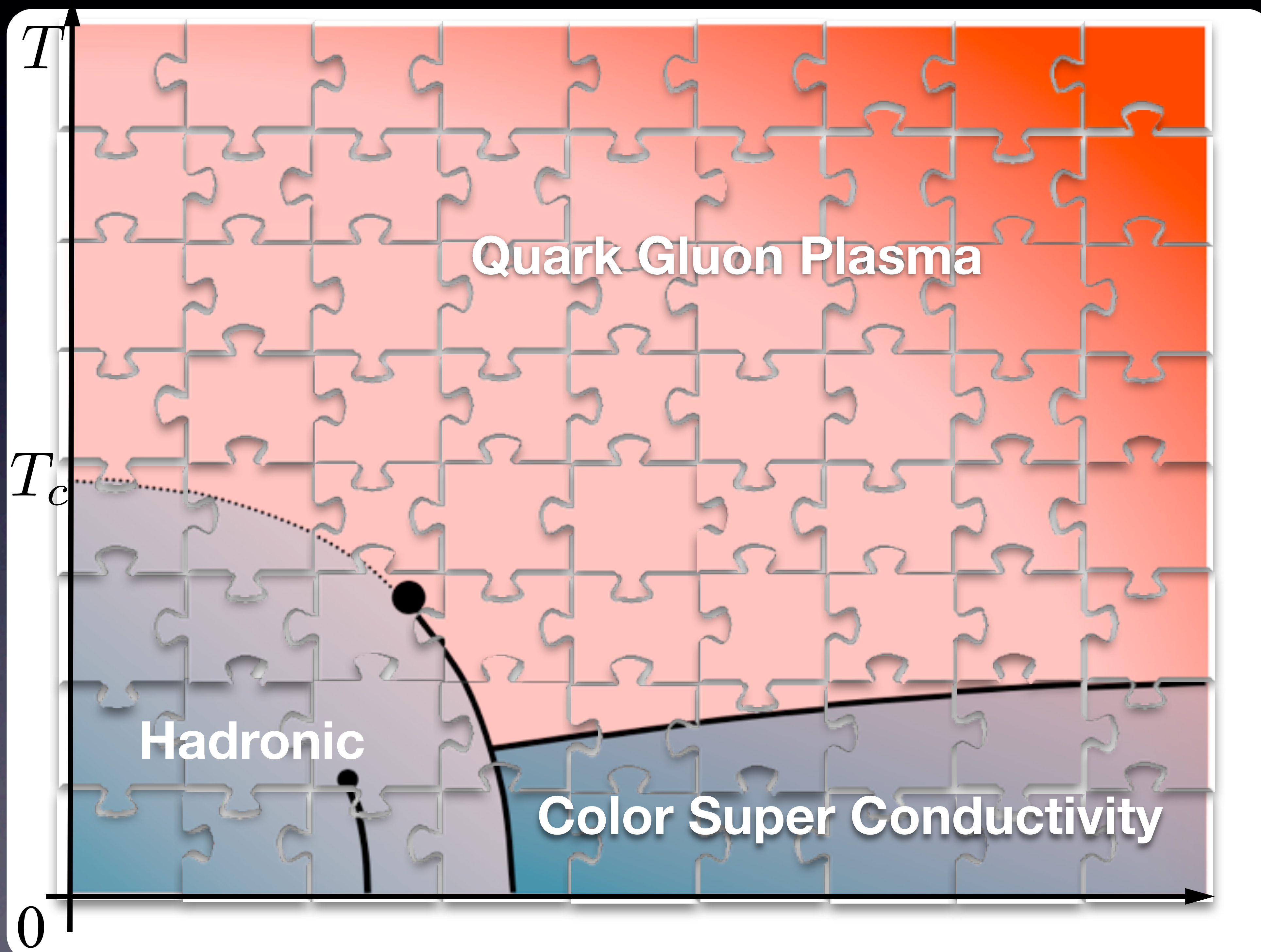
Chiral symmetry:

locally broken,

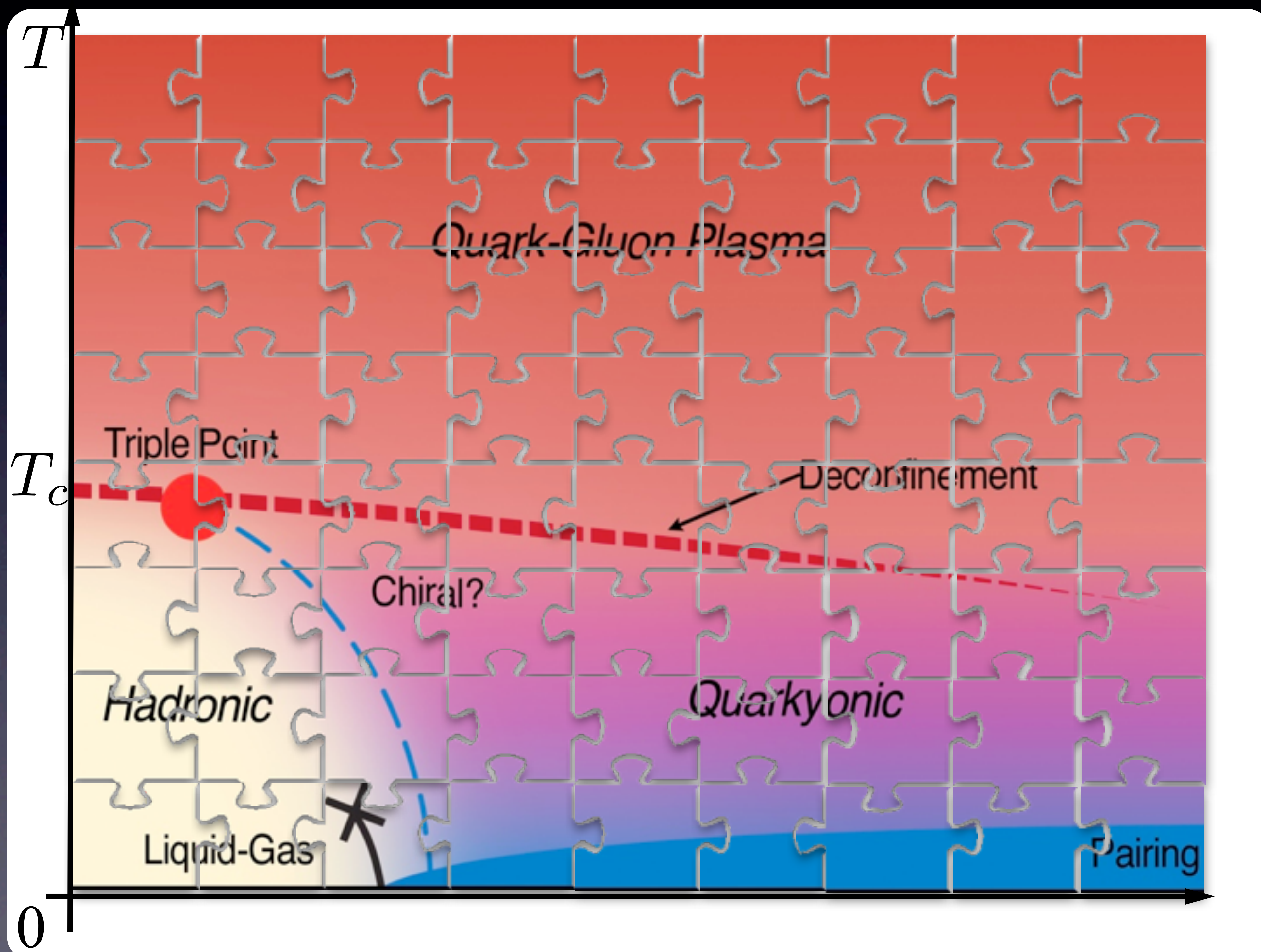
globally restored.

Baryon number is spatially const.

Summary

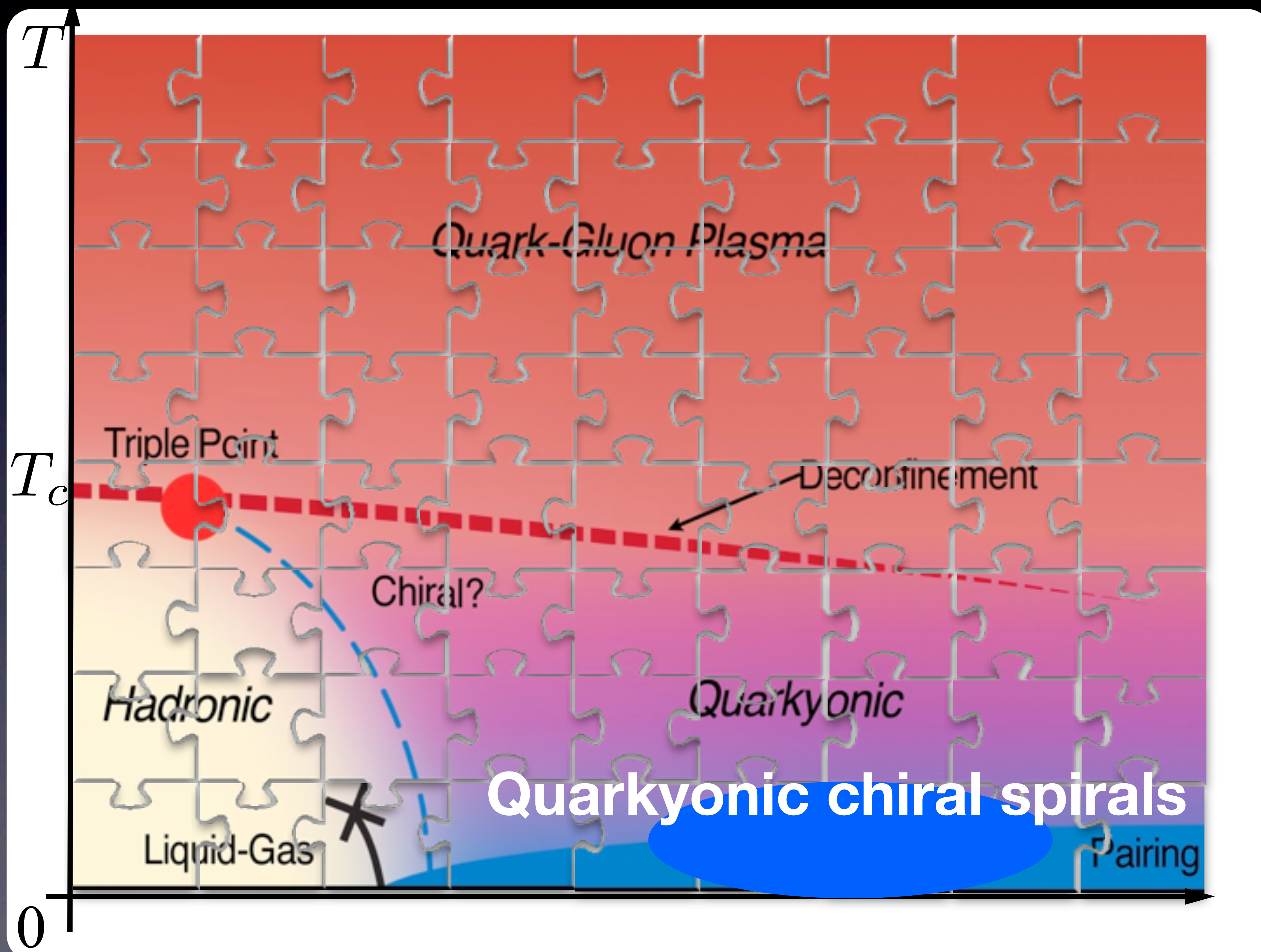

T
T_c
0
Quark Gluon Plasma
Hadronic
Color Super Conductivity

Summary



T
T_c
0
Quark-Gluon Plasma
Triple Point
Decoonfinement
Chiral?
Hadronic
Quarkyonic
Liquid-Gas
Pairing

Summary



T
T_c
0
Quark-Gluon Plasma
Triple Point
Deconfinement
Chiral?
Hadronic
Quarkyonic
Quarkyonic chiral spirals
Liquid-Gas
Pairing