

Matter in Extreme Conditions

Francesco Sannino

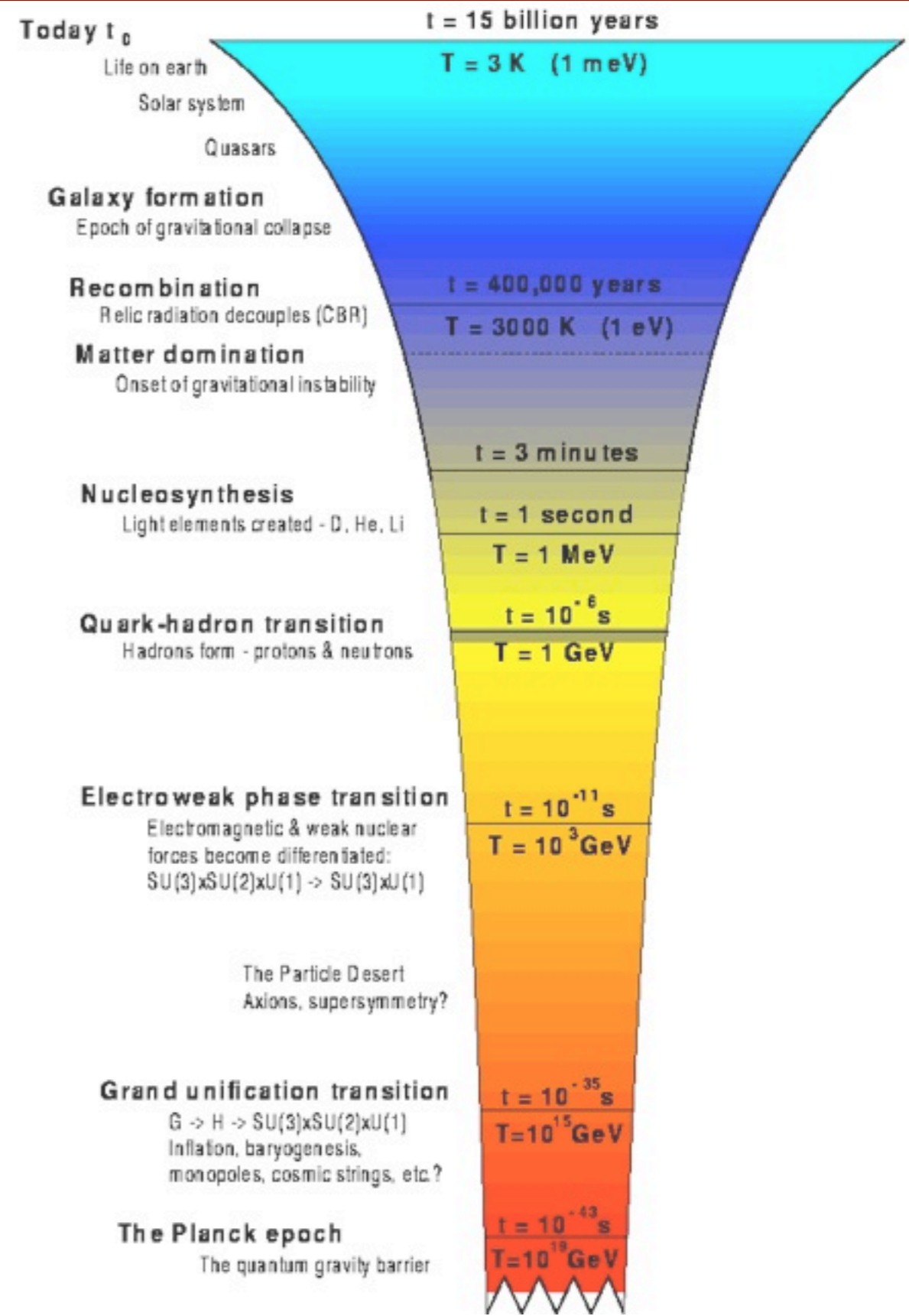
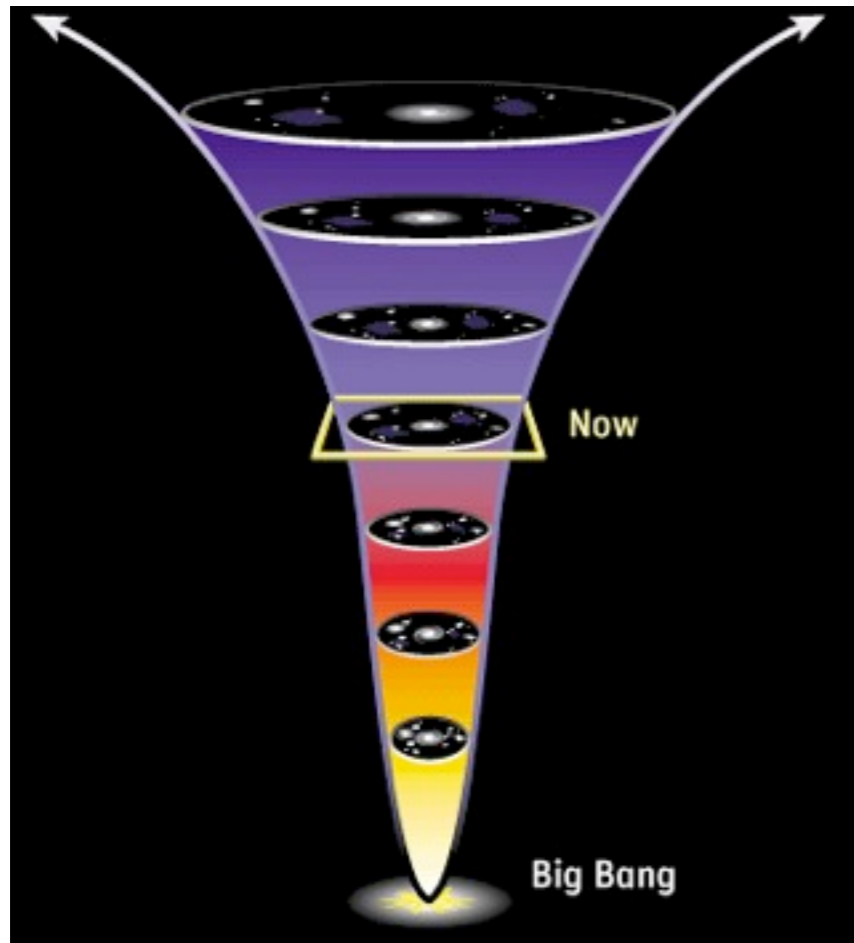
CP³ - Origins



Particle Physics & Origin of Mass

Strong Interactions 2010

Early Universe



Compact Objects

Neutron Stars

Radius

$$R \simeq 10 \text{ Km}$$

Mass

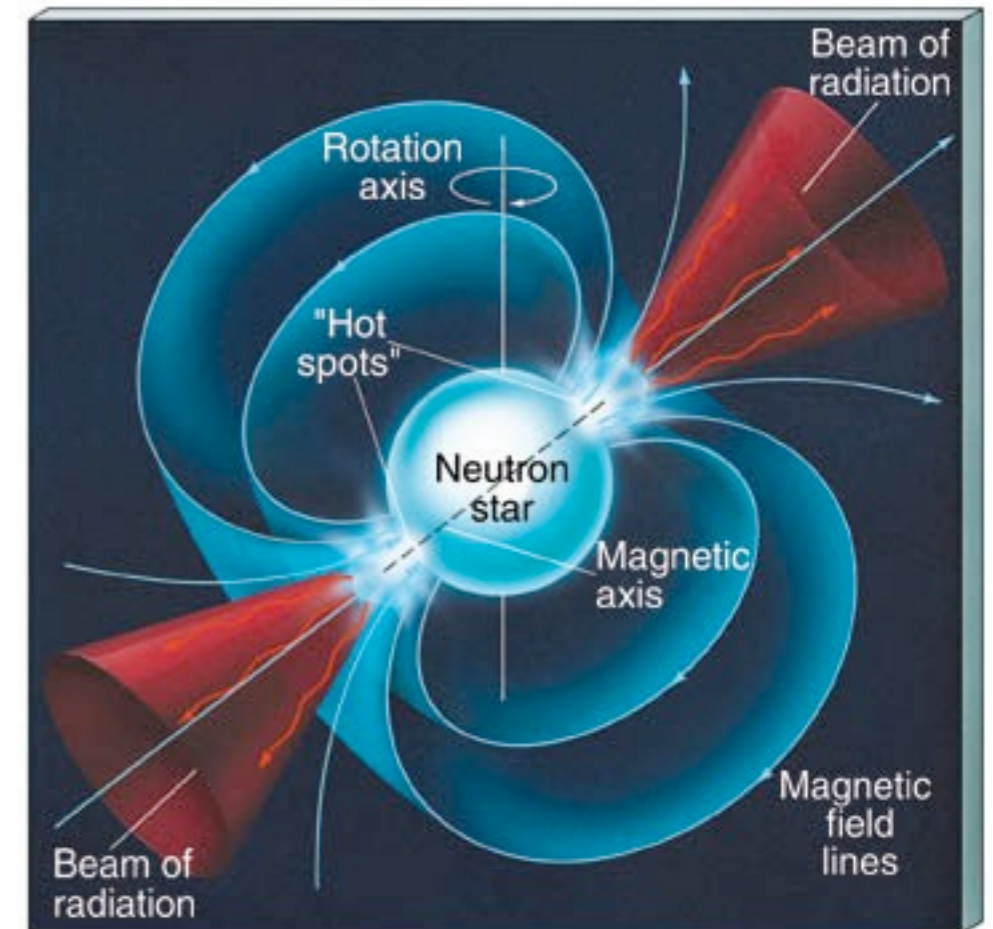
$$1.25M_{\odot} \leq M \leq 2M_{\odot}$$

Core temperature

$$10 \text{ keV} \leq T \leq 10 \text{ MeV}$$

Surface magnetic field

$$10^8 \text{ G} \leq B \leq 10^{14} \text{ G}$$



Rotational Period

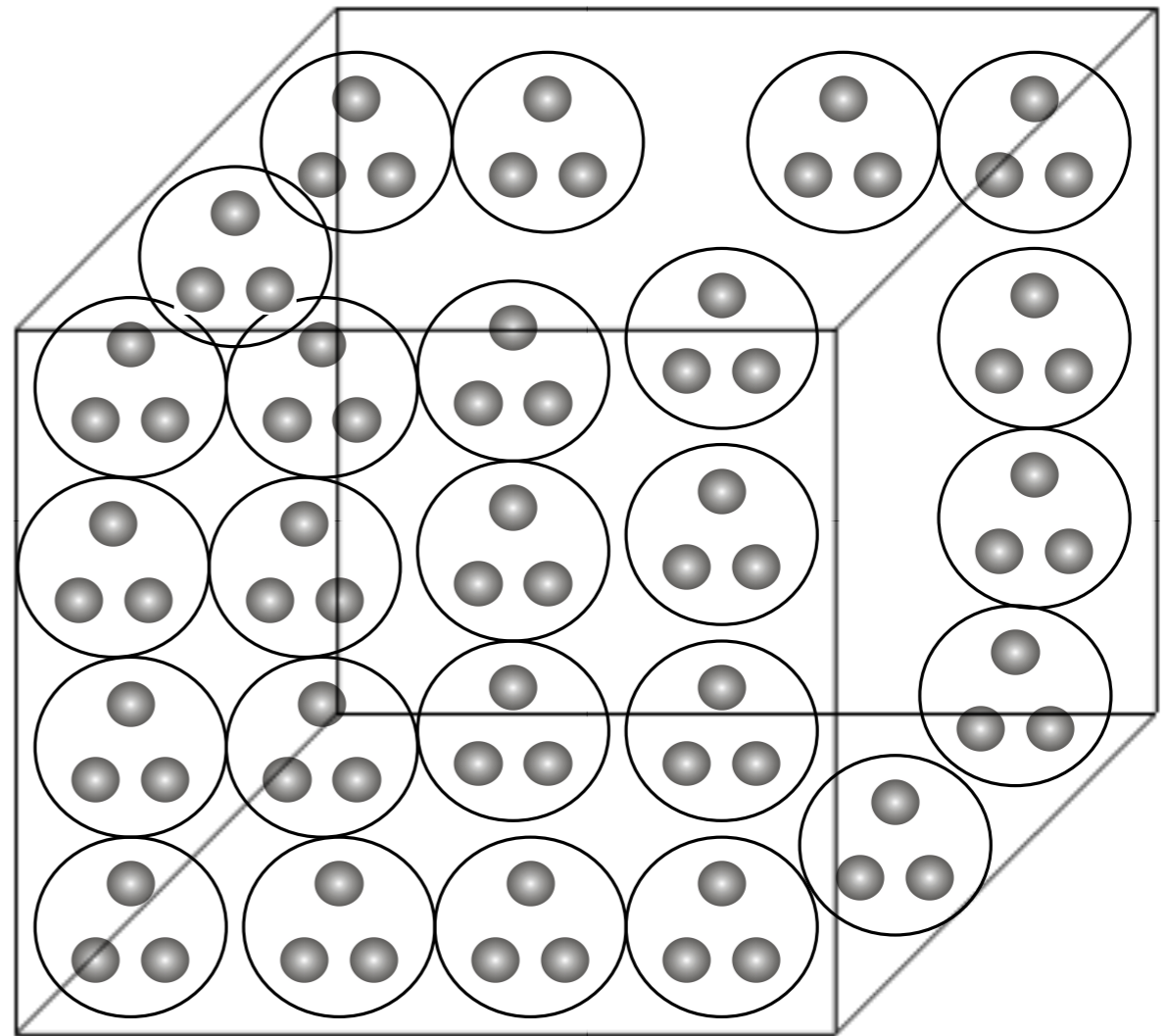
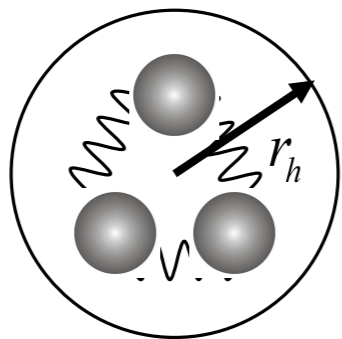
$$1.6 \text{ ms} \leq P \leq 12 \text{ s}$$

Central matter density:

$$\rho_c \geq 5\rho_0 \quad \rho_0 \approx 0.15 \text{ fm}^{-3}$$

Thermodynamics of QCD

$$r_h \sim 1 \text{ fm} \quad V_h \sim \frac{4}{3} \pi r_h^3$$

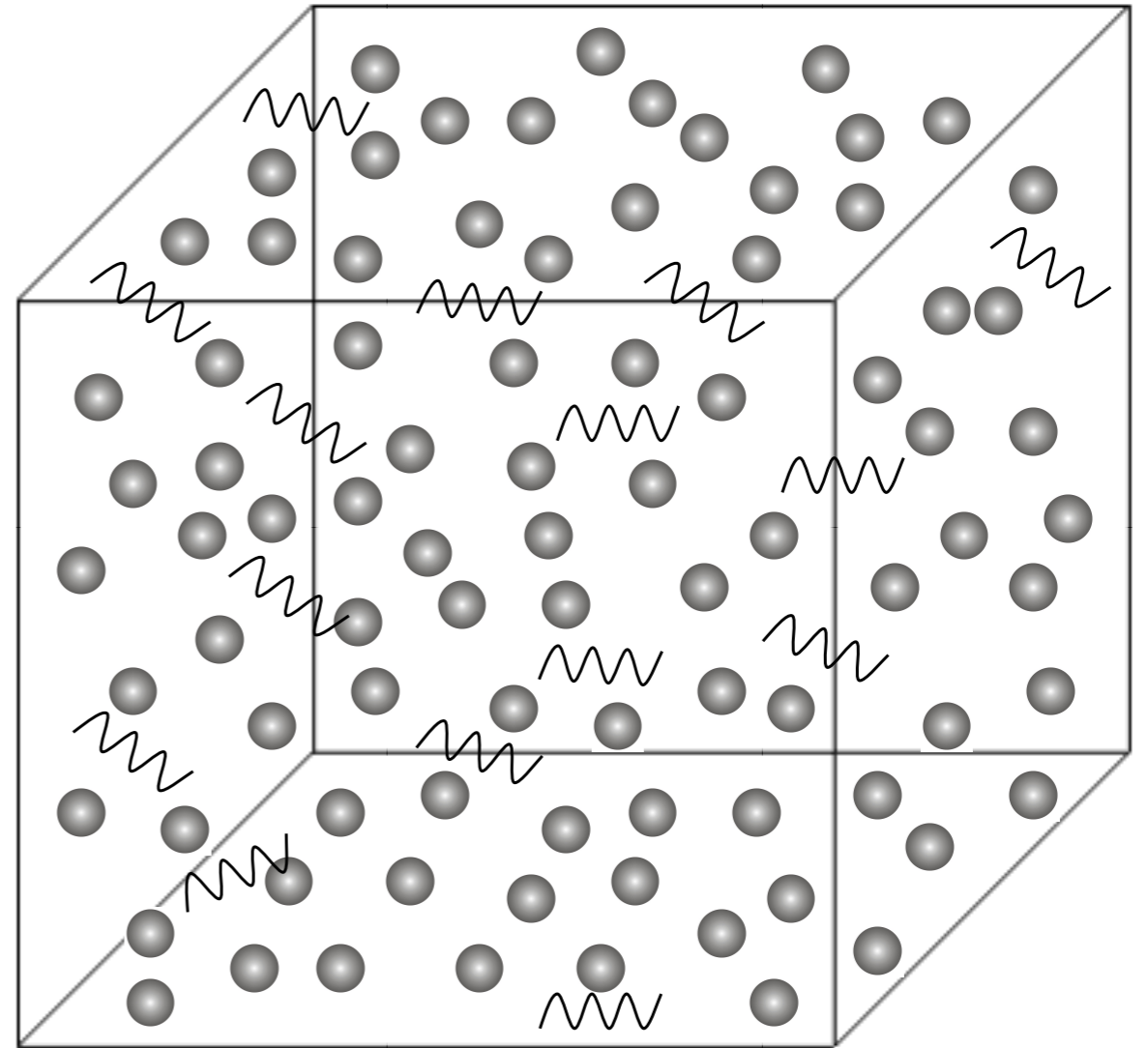


$$N = \frac{V}{V_h} \Rightarrow n_{\text{Critical}} \approx V_h^{-1}$$

Thermodynamics of QCD

Quarks and gluons are free

Entropy increase abruptly



QCD Phase Diagram

Increase matter density

Temperature:

Matter density increases due to energy collisions among hadrons

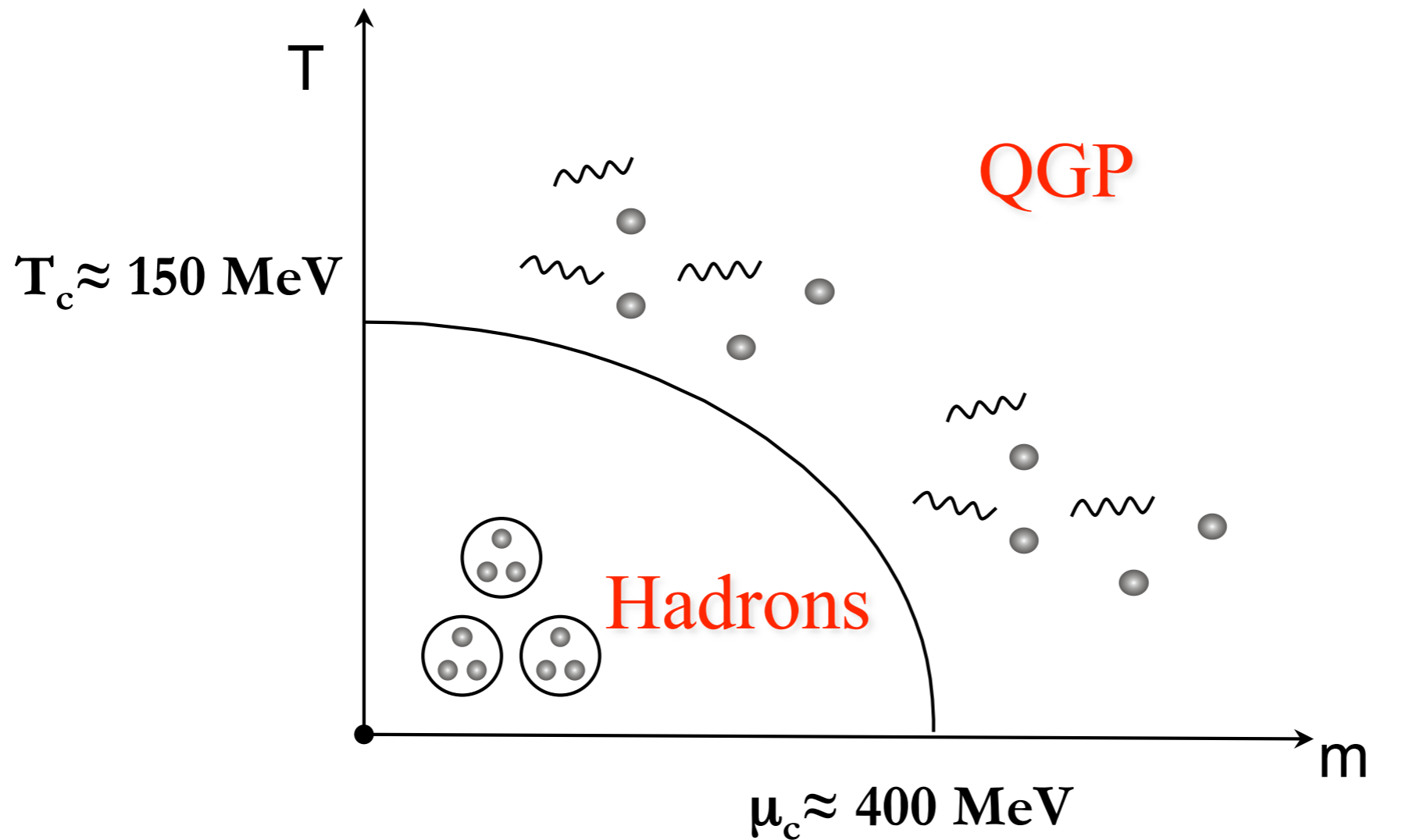
Baryonic Density:

Squeezing nuclei

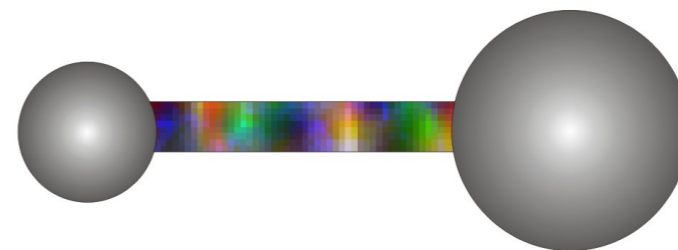
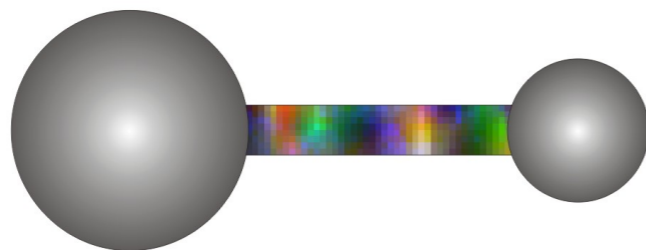
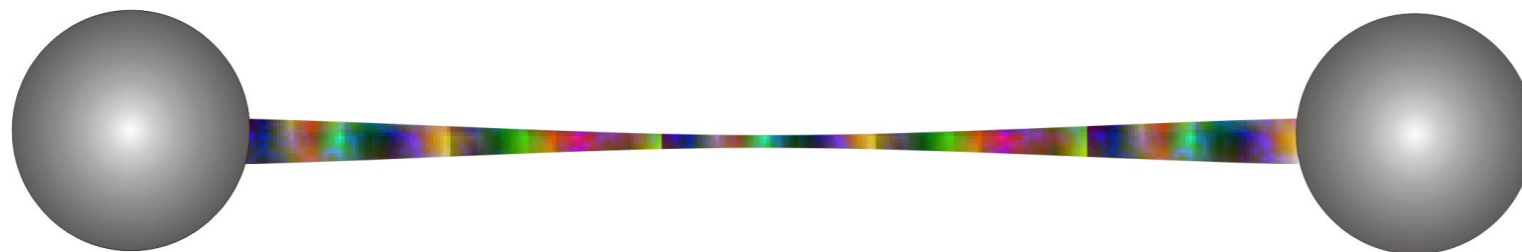
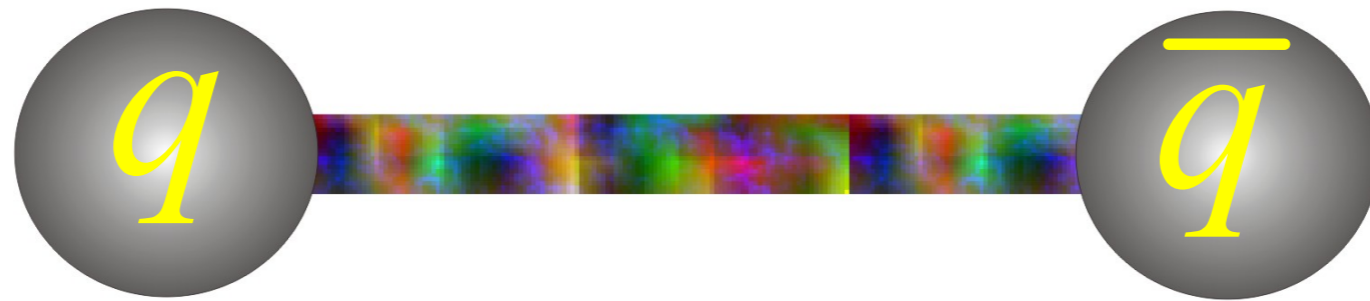
Simple relation:

$$\mu_B = 3\mu \sim \sqrt{m_N^2 + (3\pi^2 n_B)^{2/3}}$$

Simplest Phase Diagram



Confinement



Chiral Symmetry

Strong interactions are blind to flavors (up and down) & chirality.

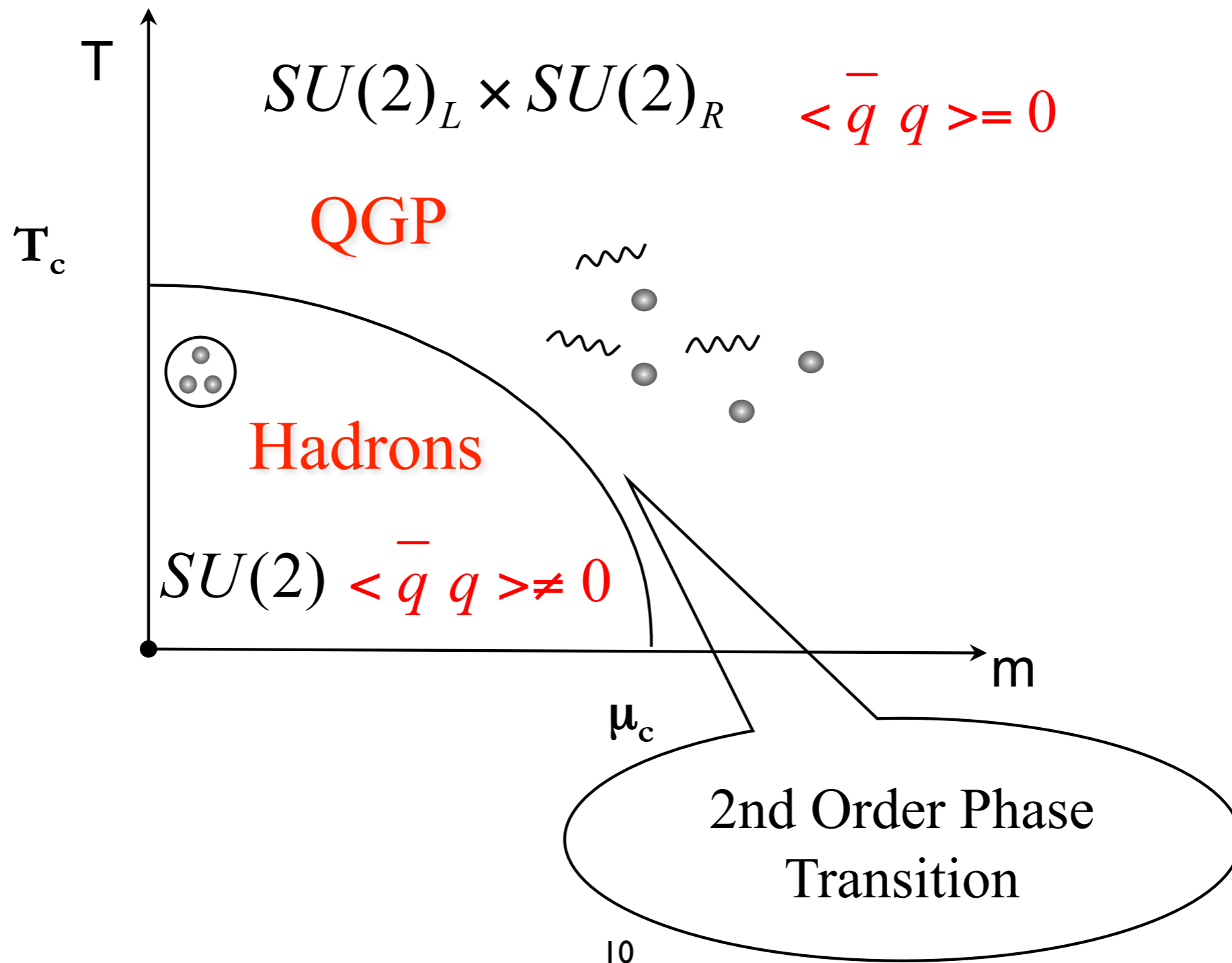


$$G = SU(2)_L \times SU(2)_R$$

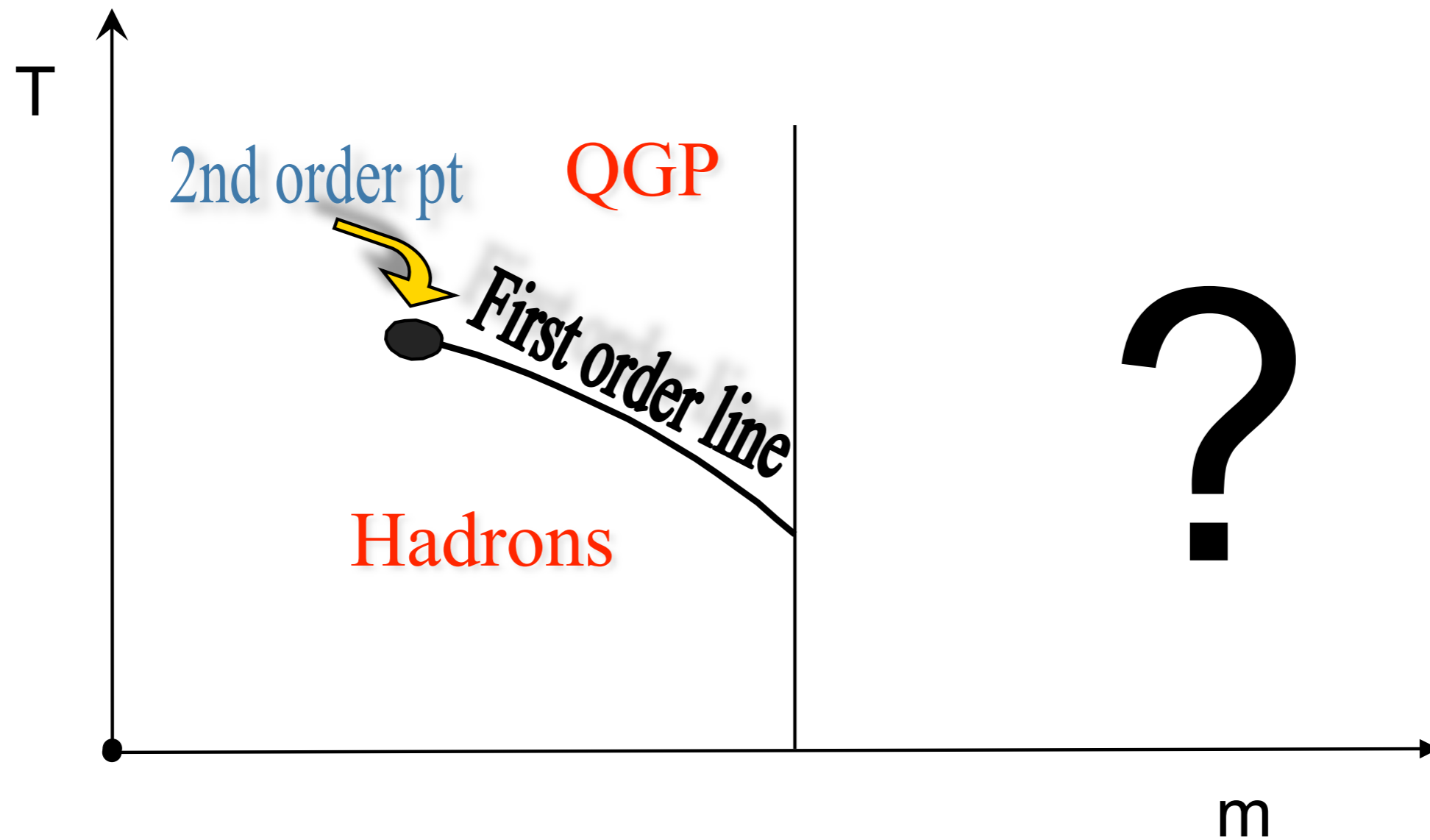
$$\langle \bar{q}_{R,f} q_L^{f'} \rangle \quad \downarrow \quad \text{Hadronic phase}$$

$$SU(2)_V$$

Phase Diagram - Reloaded



Realistic Phase Diagram



Color Superconductivity

What happens to matter as you squeeze it harder and harder?

The naive perturbative QCD ground state is unstable towards the quark-quark condensation in the color antisymmetric channel.

$$\langle q(p)q(-p) \rangle \quad \text{wins over} \quad \langle \bar{q}(p)q(-p) \rangle$$

Color Superconductivity

Since the diquark is colored some gluons acquire a Meissner Mass.

This is similar to what happens in an ordinary superconductor.

In standard superconductivity the attractive force between the electrons is mediated by phonons. (the photon would provide a repulsive force between two electrons)

In color superconductivity the attractive force is mediated by the gluon themselves.

Major SC phases

If we consider light the up, the down and the strange quark we have the Color flavored Locked Phase (CFL).

If we consider light only the up and down quark we have the 2 flavor color superconductive phase.

CFL

The condensate is invariant only if we rotate color and flavor together [Color-Flavor-Locking]

Quasi – particle spectrum [Goldstones] have the same quantum numbers of pions, kaons etc.

2SC

Global Symmetries do NOT Break

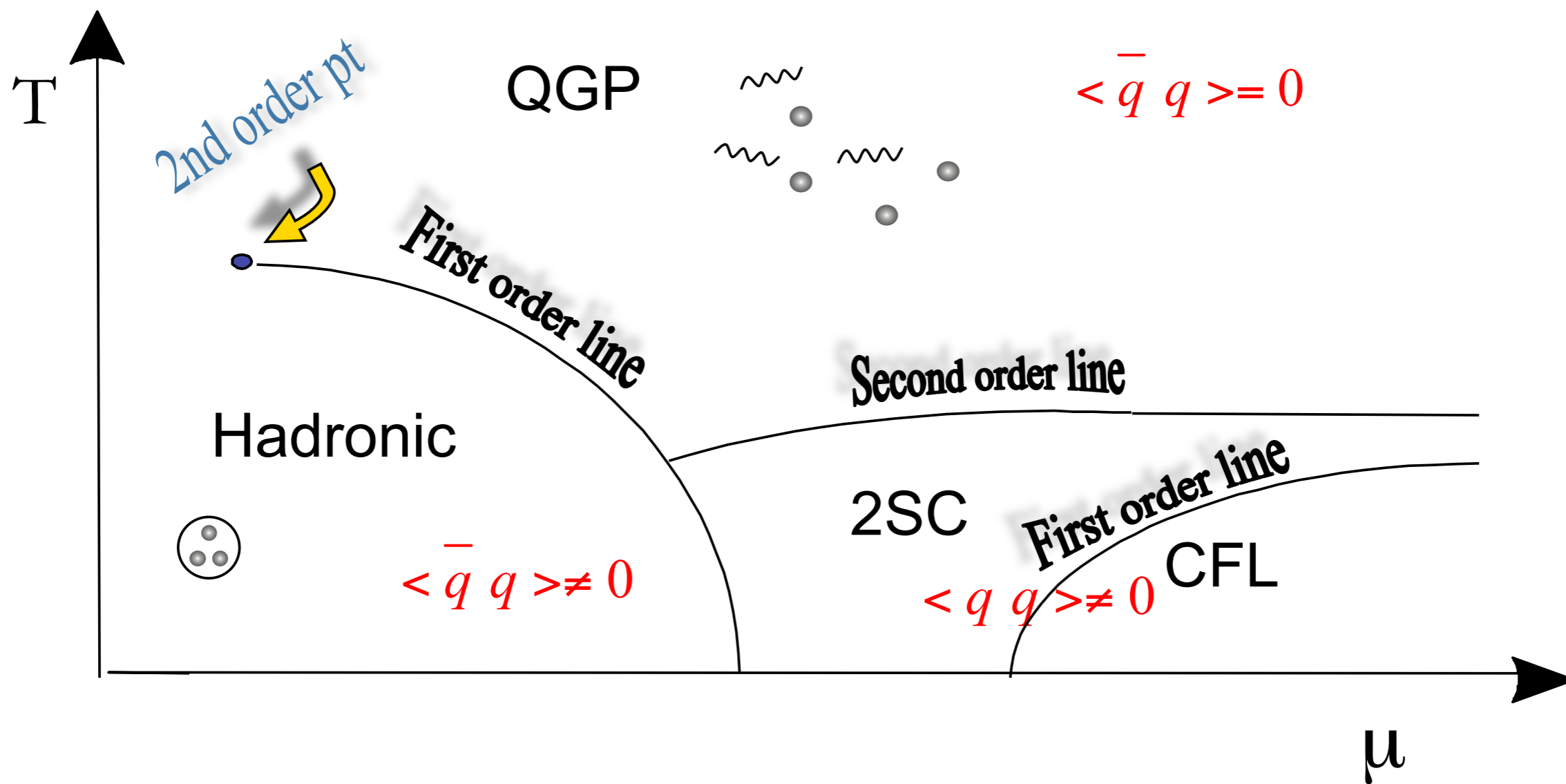
$$[SU_c(3)] \times SU_L(2) \times SU_R(2) \times U_B(1)$$



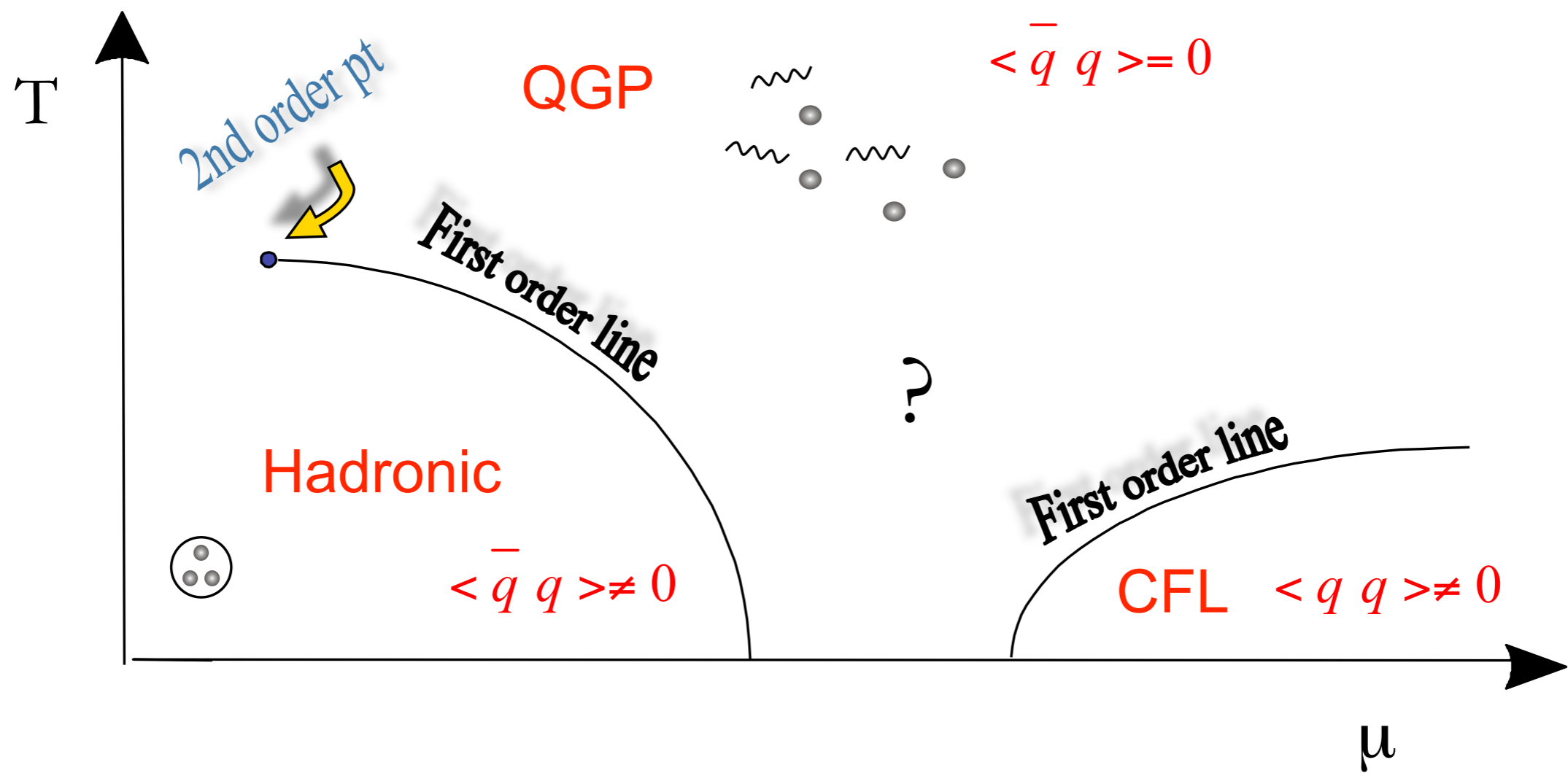
$$[SU_c(2)] \times SU_L(2) \times SU_R(2) \times U_{\tilde{B}}(1)$$

Two massless fermions: Like Proton and Neutron but actually are quarks in the direction 3 of color!

Phase Diagram



Phase Diagram



2 Questions

Is color superconductivity realized in Nature?

Are there more phases?