Exotic states at boundary of quark matter

Mannque Rho
Saclay
(HIM, September 2006)

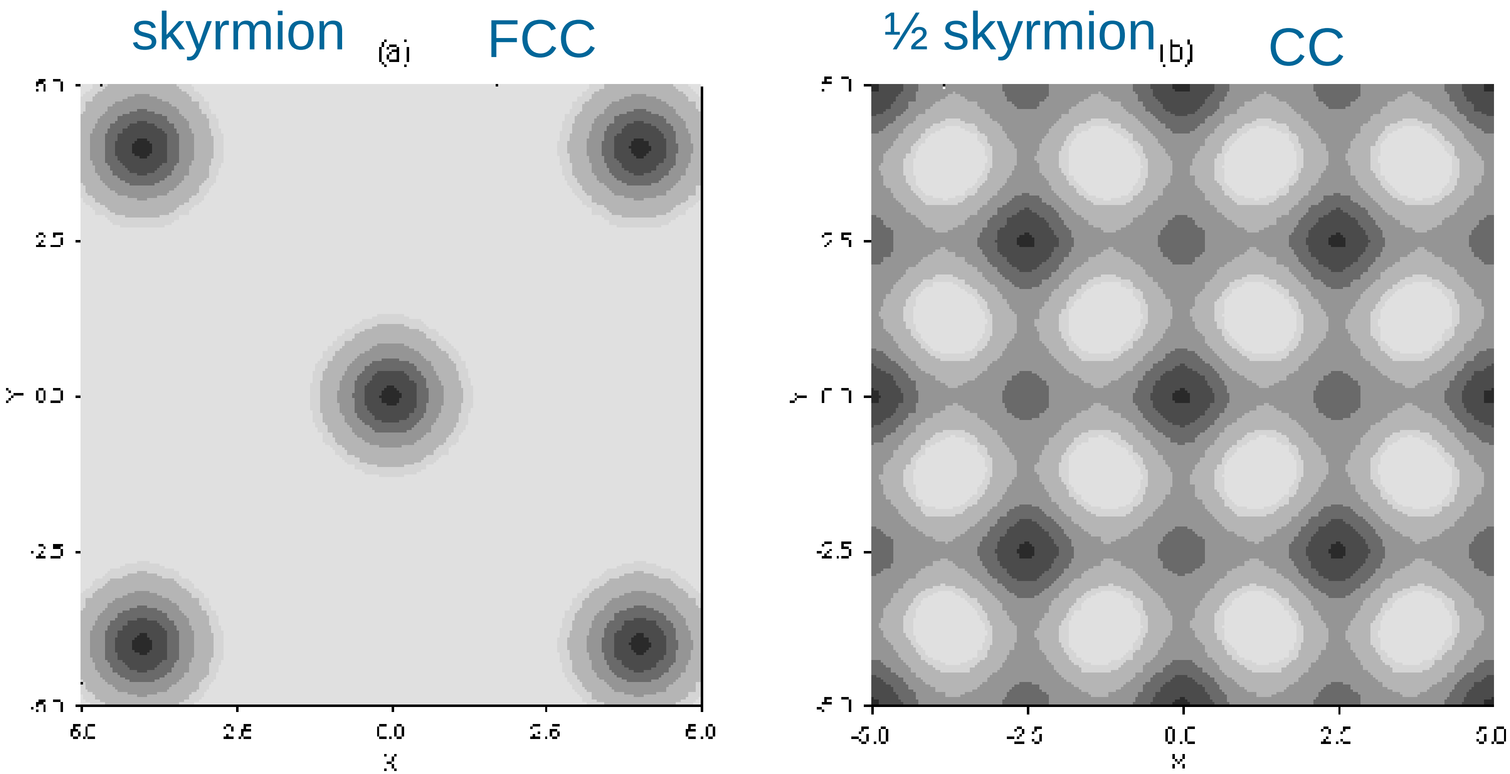
Puzzling observation

(KIAS in 2002)

Skyrmions in FCC crystal to simulate dense hadronic matter

Byung-Yoon Park and collaborators observed at some density $n_{1/2s}$ a "phase transition" from a skyrmion to 2 "half-skyrmions," a structure discovered by Goldhaber and Manton in 1987.

Transition from skyrmion to half-skyrmion at density $n_{1/2s}$



Park, Min, Rho, Vento 2002

Curiouser, curiouser …

As a skyrmion fractionizes into two 1/2-skyrmions at $n = n_{1/2}$, chiral symmetry is "restored"

$$\langle\bar{\psi}\psi\rangle \sim f_\pi \langle \exp(i\pi/f)\rangle = 0$$

But $f_\pi \neq 0$

"Pseudo-gap" phenomenon
(e.g. High T superconductivity)

Theoretical fluke or something real?

- 2002: Crystal artifact …Let's ignore it ..
- 2006: Wait, there is something there …

What’s skyrmion and why skyrmion now
In 2006?

New development, AdS/QCD or holographic dual QCD, revives once again the skyrmions

QCD at low energy=Hidden gauge symmetry theory

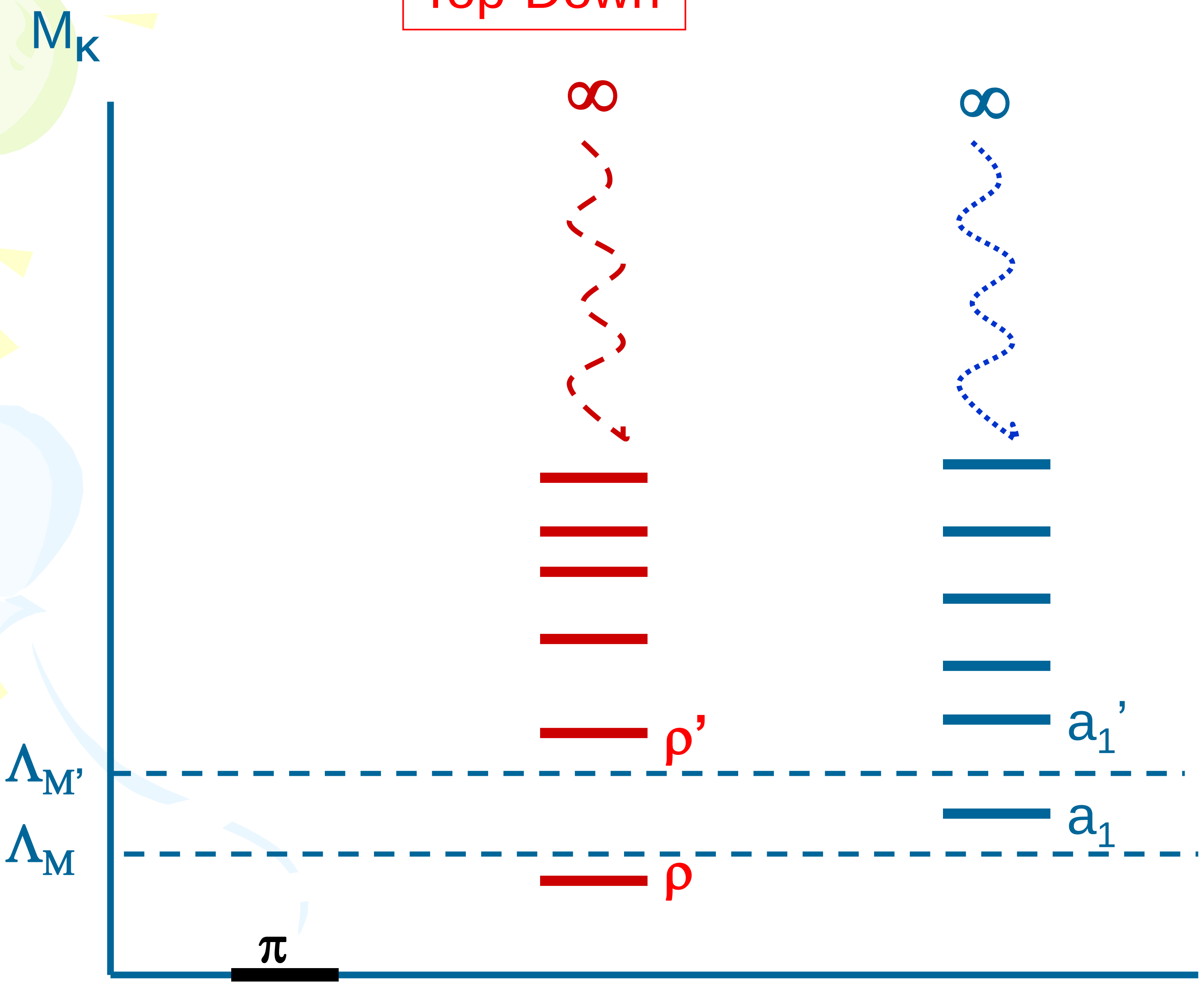
- Top down: *Reduction from string*

  Holographic dual QCD leads to low-energy physics described in 4D by an infinite tower of vector mesons: ρ, a_1, ρ' , a_1' , … , plus π. Integrate out all but π and ρ and couple them gauge invariantly.

- Bottom up: *Emergence from pions*

  At low energy $E<<\Lambda$, physics is given by chiral Lagrangian of π, say, in Sugawara form $U=\exp(i\pi/f_\pi)$.

Top-Down



Notion of emergent gauge fields

Write electron field e(x) as a product of a boson field b(x) and a new fermion field f(x);

$$e(x) = b(x) f^{\dagger}(x)$$

e(x) is unchanged under the transformation

$$b(x) \rightarrow e^{ih(x)} b(x),$$
$$f(x) \rightarrow e^{ih(x)} f(x);$$

- ❖ This "redundancy" can be made into a U(1) gauge invariance by introducing a gauge field a_μ (x) ⟶ "spinon"/ "holon" story of high T superconductivity…
- ❖ A similar story of Faddeev-Niemi idea of color confinement …

Bottom-up

• At very low energy, the notion of effective field theory involving chiral symmetry dictates that

$$L = \frac{f_\pi^2}{4\pi} Tr\{\partial_\mu U^+ \partial^\mu U\} + \bullet\bullet\bullet$$

The ellipsis stands for higher derivatives, pion mass (χSB) ...

• As energy increases toward the vector meson mass (say, m_ρ), theory breaks down and one powerful way to proceed is to resort to "hidden gauge symmetry" strategy, which is an "emerging field".

HLS (emergent) gauge field

Vector mesons ρ_μ emerge as hidden gauge bosons

$$U = e^{i\pi/f_\pi} = \xi_L^+ \xi_R = \xi_L^+ h(x)^+ h(x) \xi_R$$

$$\xi_{L(R)} = e^{\mp i\pi/2f_\pi} e^{is/2f_s}$$

Redundant field to be eaten up to make the ρ massive

Invariance $\quad \xi_{L,R} \to h(x)\xi_{L,R}$

$$h(x) \in SU(N_F)$$

⇒ SU(N_F) local gauge theory with $\rho_\mu \in$ SU(N_F)

This is hidden local symmetry theory of Harada and Yamawaki

→ BR scaling

In a nut-shell

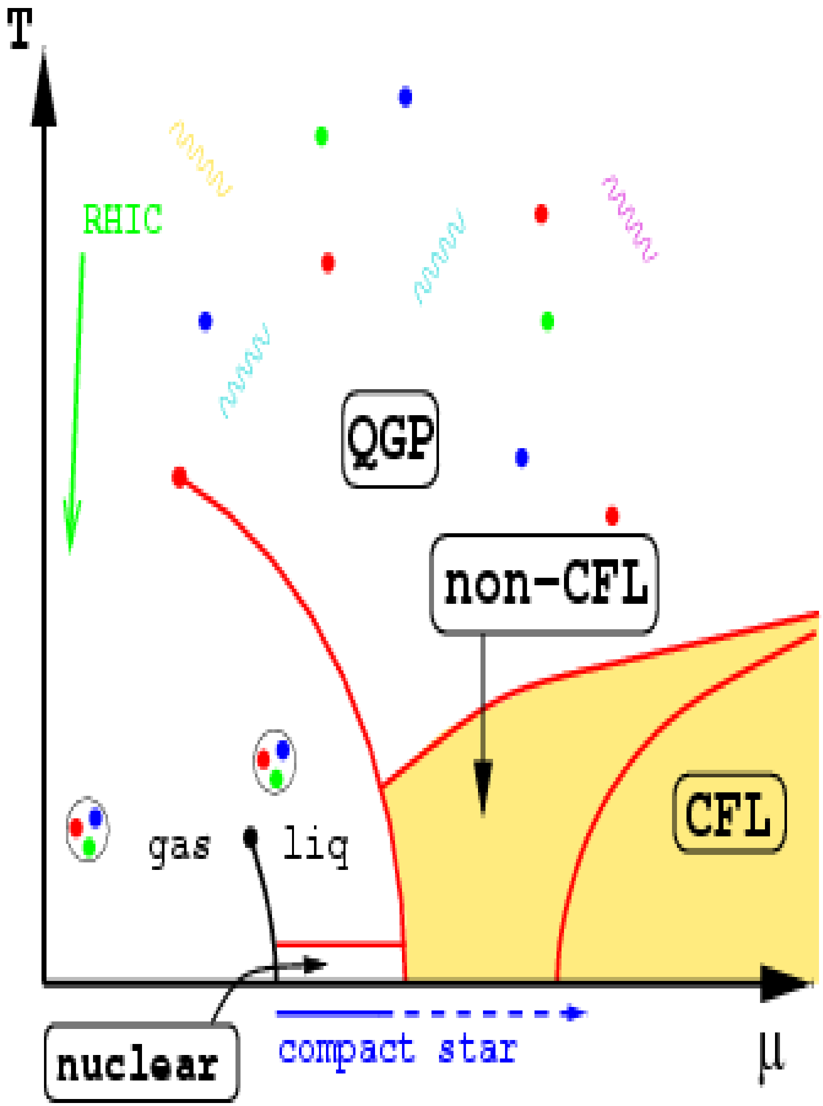
If low-energy QCD has only mesons, where are the baryons ?

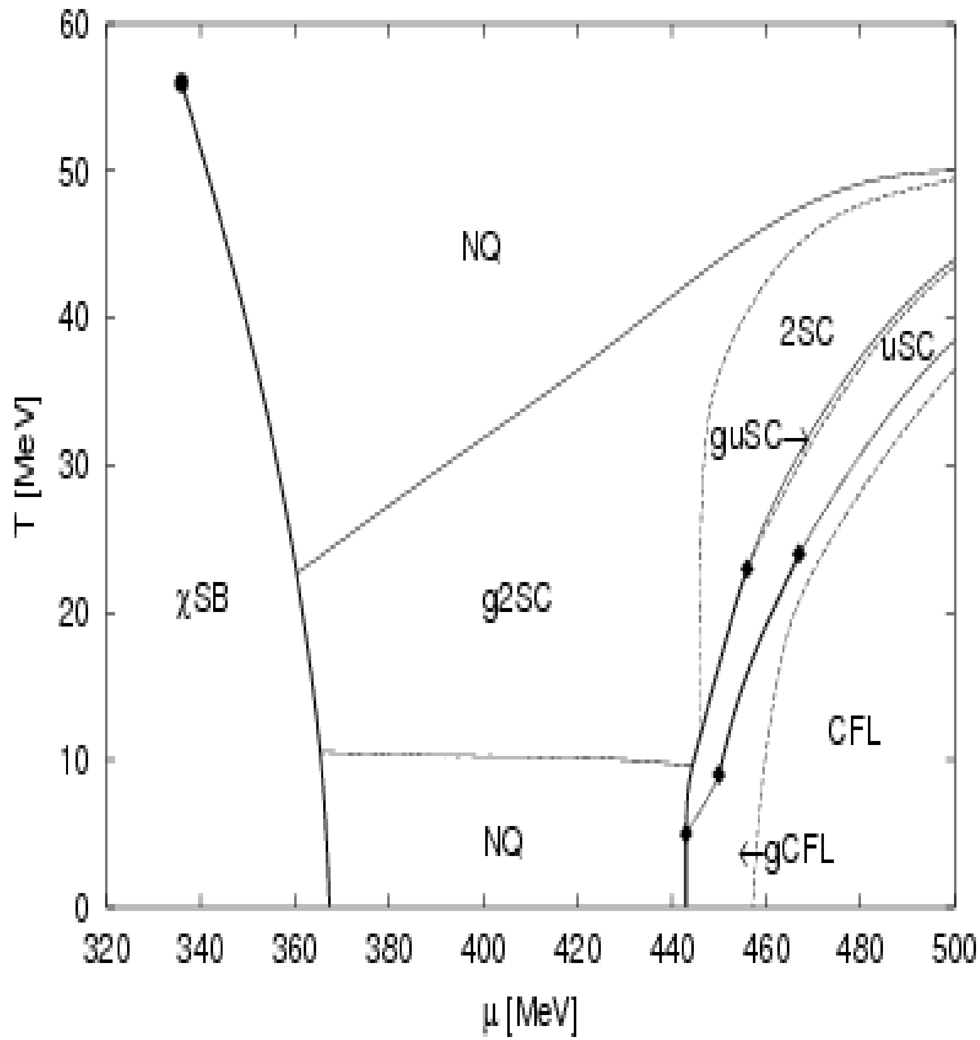
- Skyrme (1960): skyrmion $\leftrightarrow$ Witten (1983): QCD baryon at $N_C \rightarrow \infty$
- AdS/QCD (2004): skyrmion $\leftrightarrow$ "D4 brane wrapped around S^4"
  $\leftrightarrow$ Instanton in x_1, x_2, x_3, z
- With the vector meson (ρ_μ) plus the pion, the soliton is in Skyrme-Wu-Yang hedgehog (for π and ρ)

➢ Question: What does the ρ field do to skyrmions at high density/temperature?

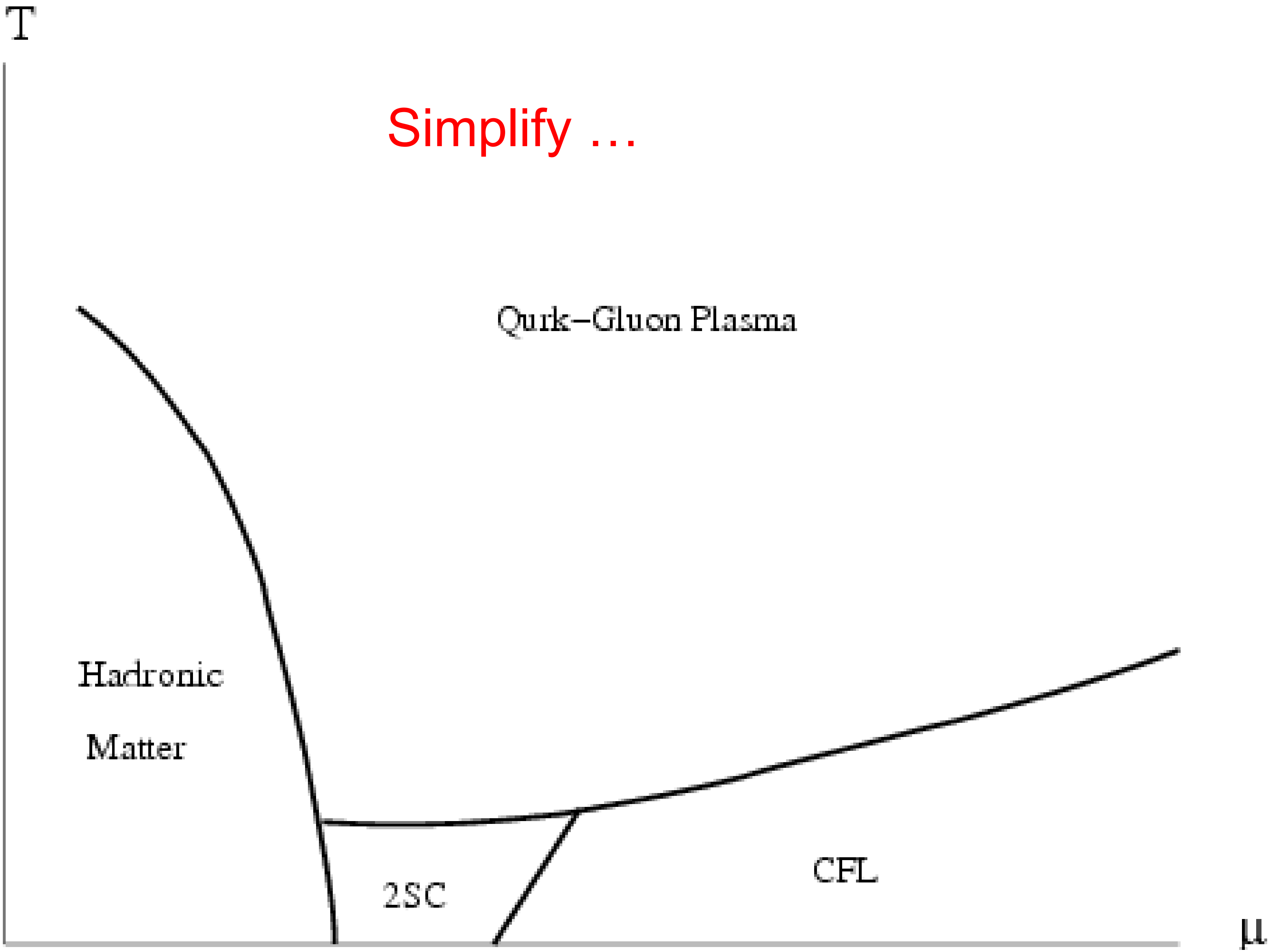
Today's prediction

Thanks to Alford

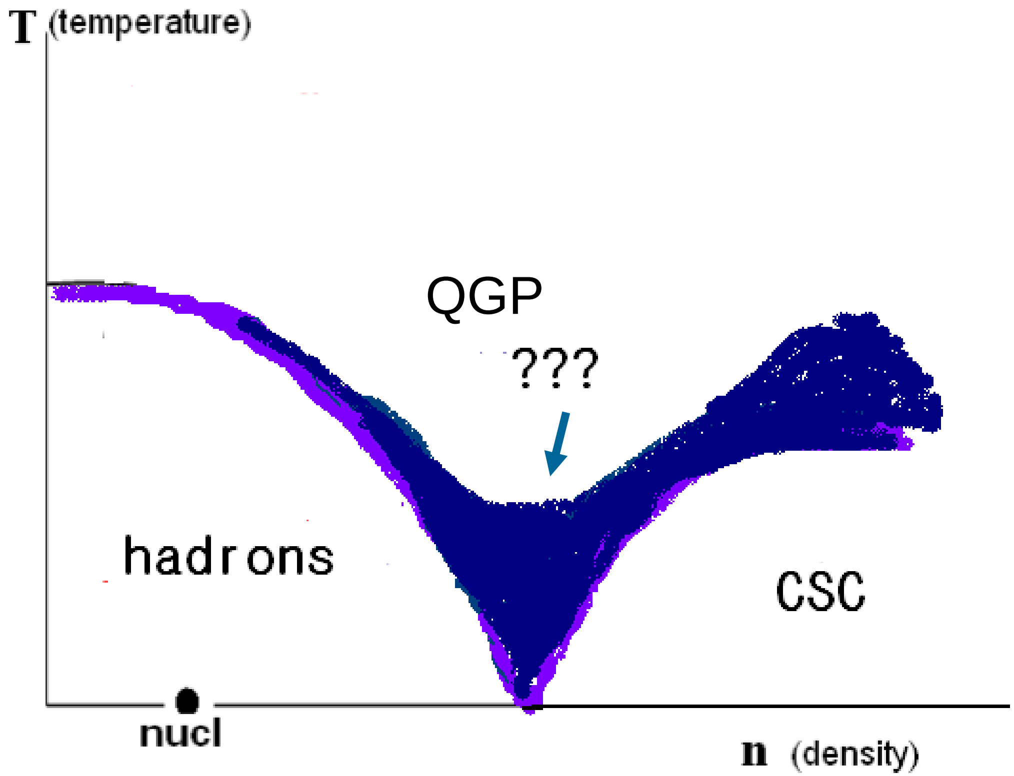




Simplify …



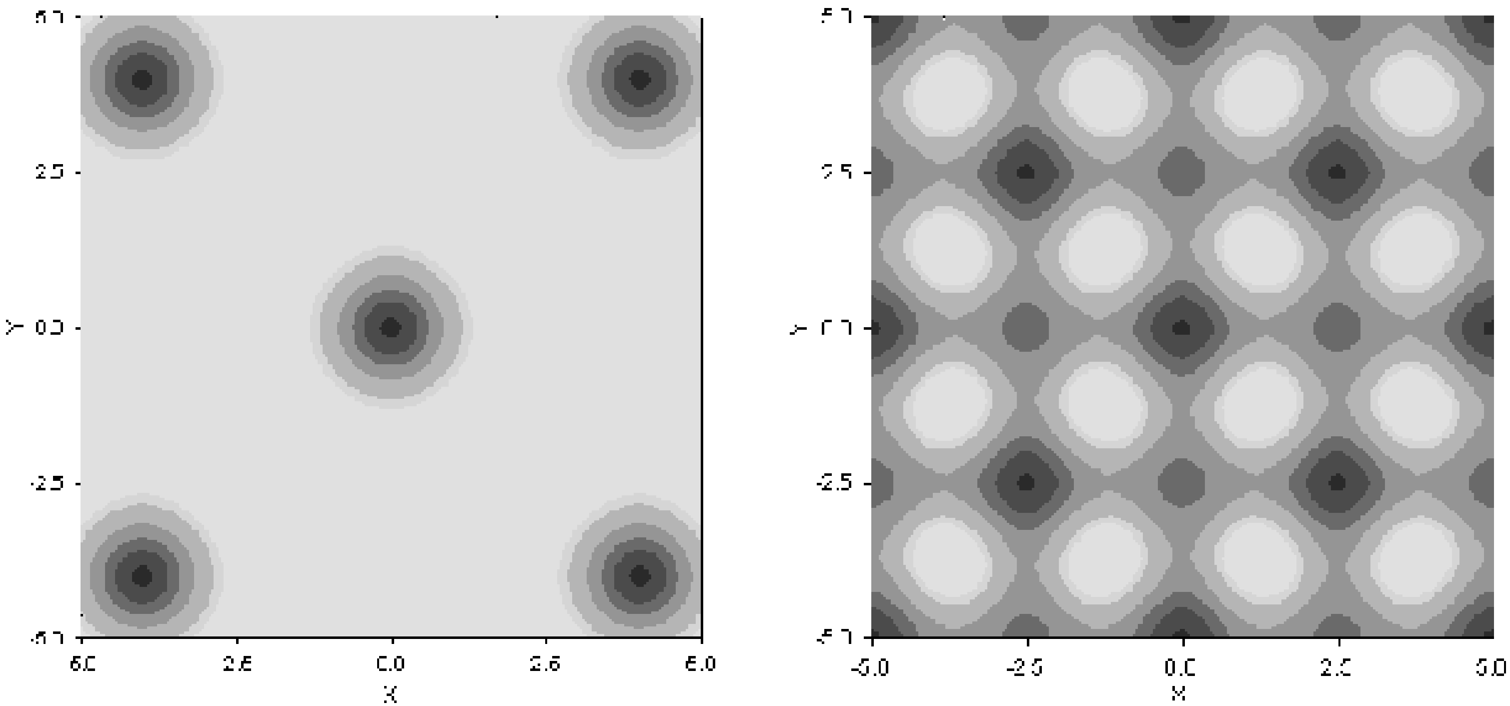
My picture: phase structure



Transition from skyrmion to 1/2-skyrmions at density $n_{1/2s}$

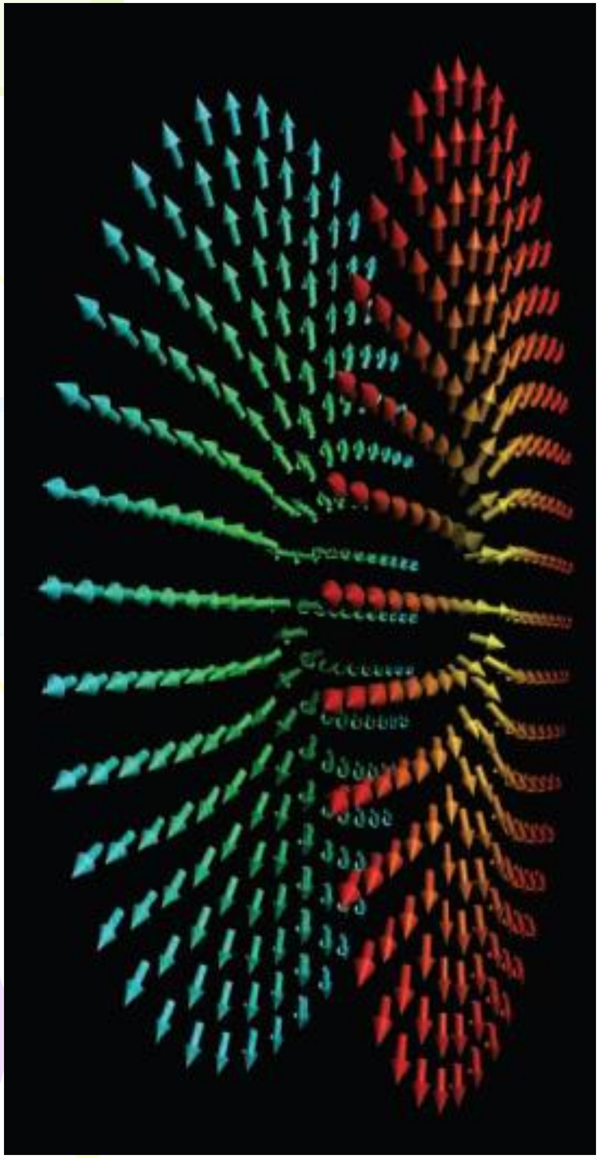
skyrmion (a) FCC

½ skyrmion (b) CC



Park, Min, Rho, Vento 2002

Deconfined 1/2-skyrmions (???)



$$U = \xi_L^+ \xi_R = \xi_L^+ h(x)^+ h(x) \xi_R$$

"Left-antimeron (LM)" **"Right-meron (RM)"**

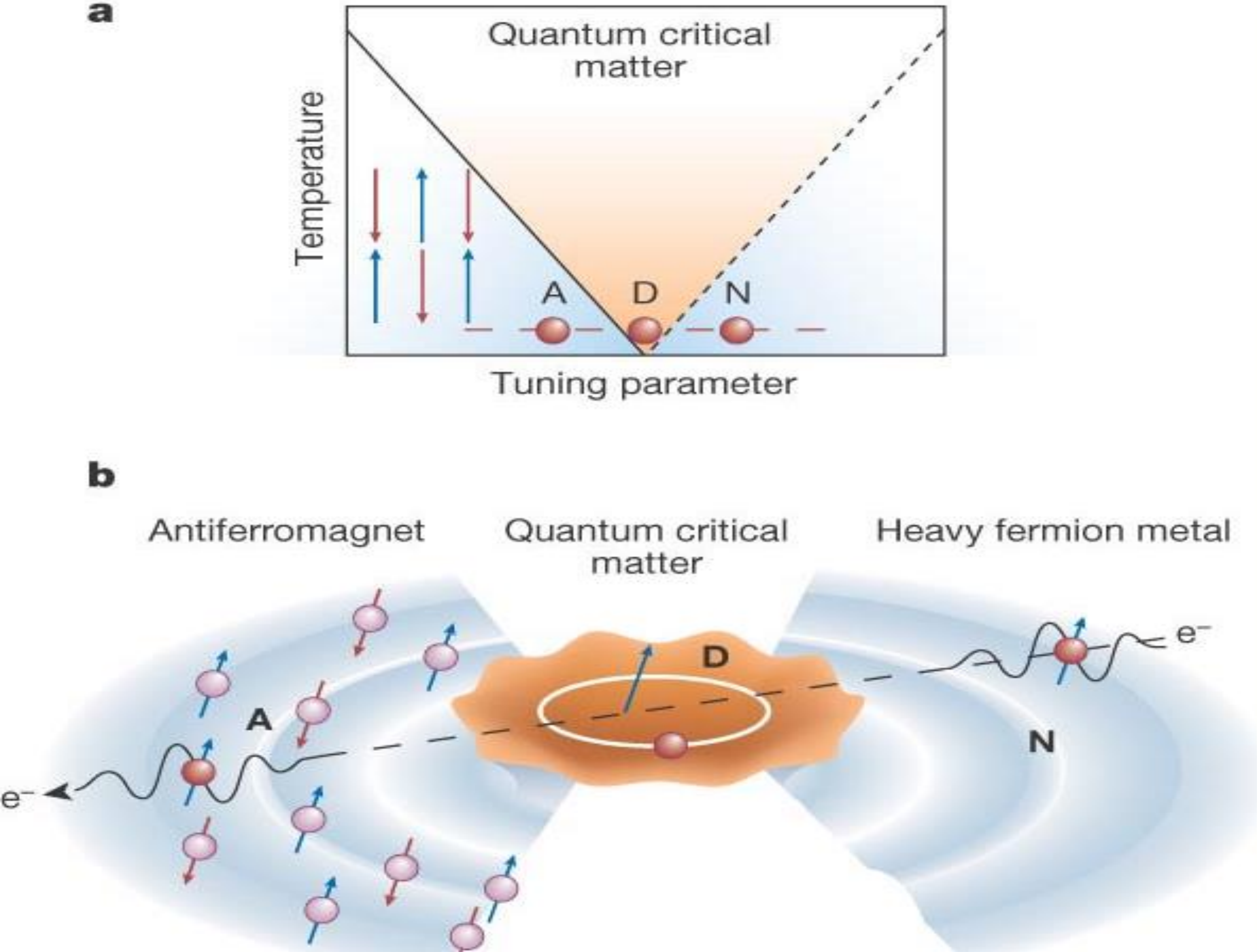
The hedgehog in ρ_μ ("instanton") binds LM and RM into a single skyrmion in the hadronic (confined) phase (and in CFL).

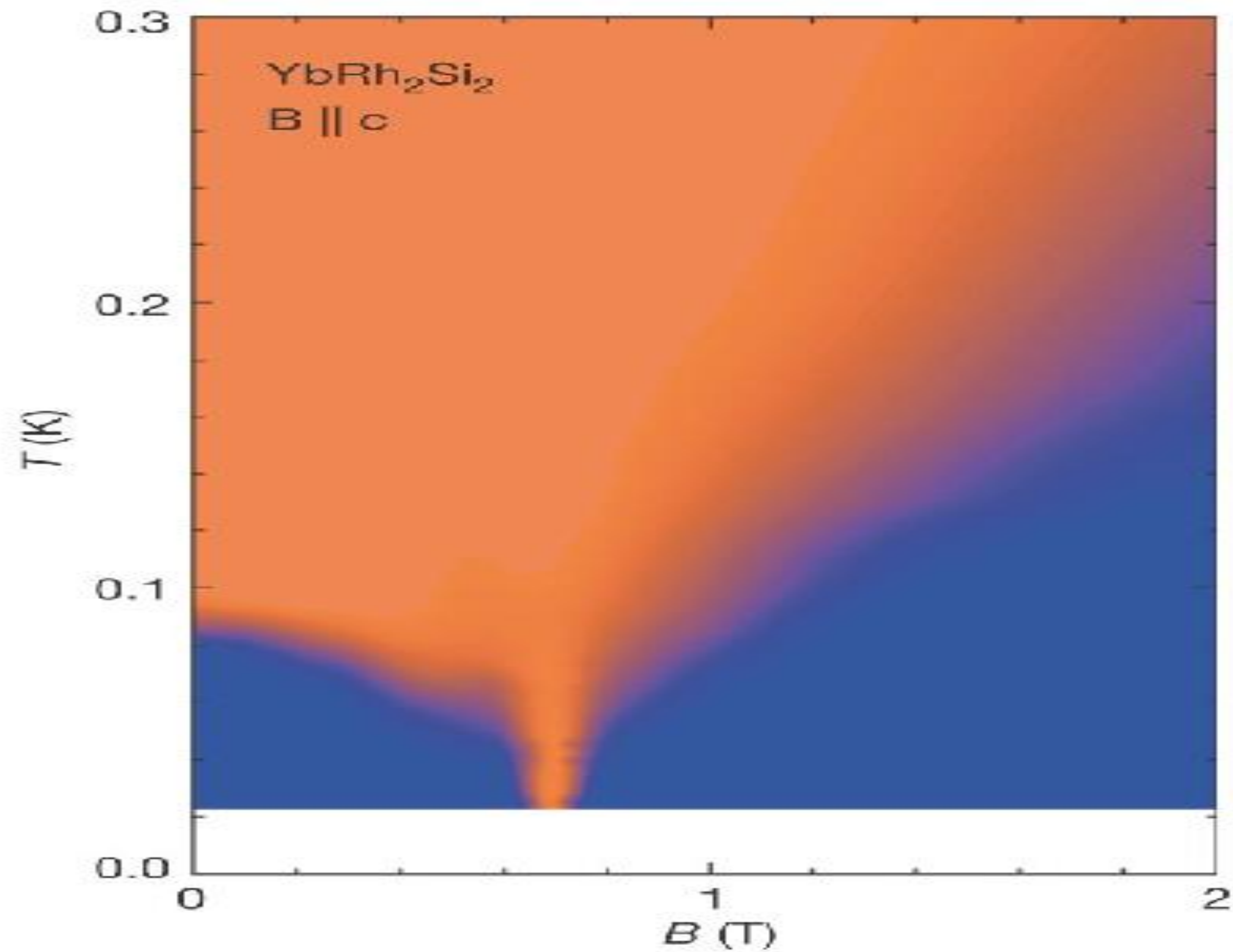
When the vector decouples so that the hedgehog is ineffective, then the ½-skrymions (LM and RM) get deconfined and become the relevant degrees of freedom.

"BR scaling" alias Harada-Yamawaki's VM says that at the chiral PT, the gauge coupling goes to zero, so the decoupling!!

A tantalizing analogy
To condensed matter

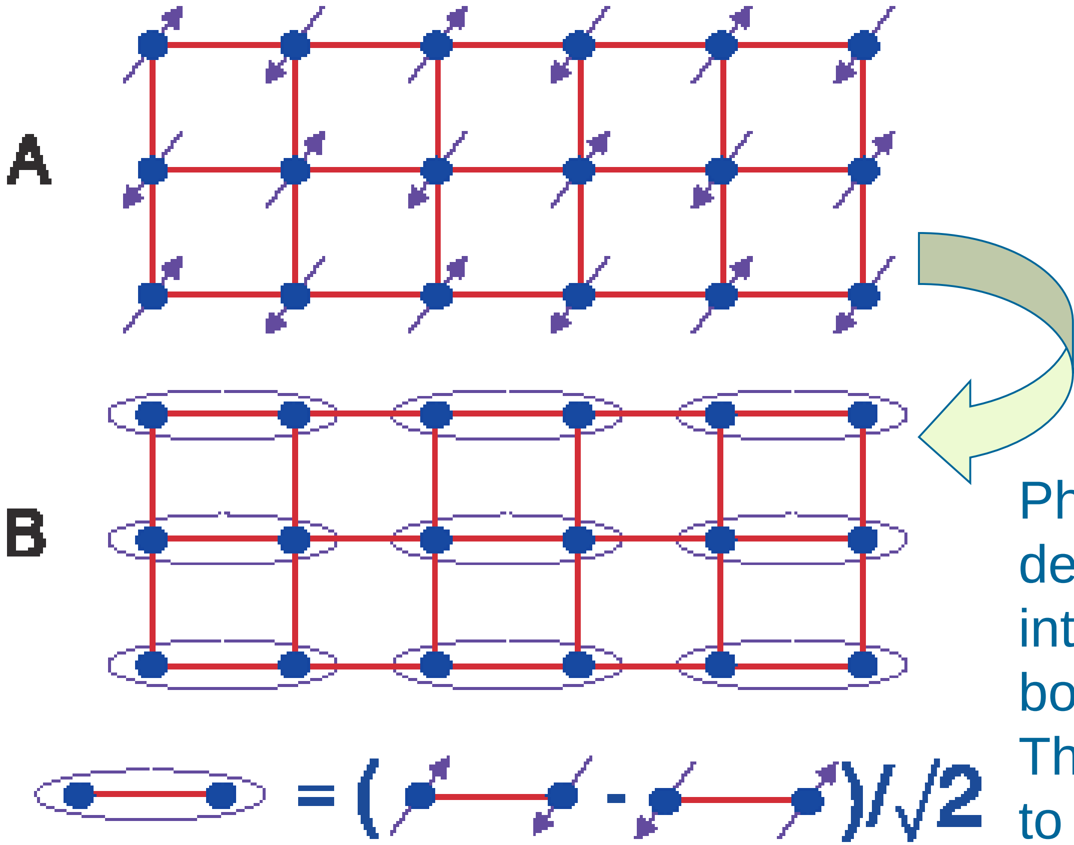
Perhaps a generic feature in
All strongly correlated matter ?


a
Quantum critical
matter
Temperature
A
D
N
Tuning parameter
b
Antiferromagnet
Quantum critical
matter
Heavy fermion metal
D
A
N
e⁻
e⁻


YbRh$_2$Si$_2$
B || c
0.3
0.2
0.1
0.0
T (K)
0
1
2
B (T)

- Exist ~ 3 Different Scenarios
- *Scenario*: “Deconfined Quantum Critical Phenomenon”

Senthil et al, Nature (2004)



A: magnetic Néel ground state

B: VBS quantum paramagnet

Phase change takes place through deconfinement of a skyrmion into 2 half-skyrmions at the boundary.
The ½-skyrmions are confined to each other in both phases by hedgehog gauge field (HGF).
Deconfinement occurs when HGF is "decoupled".

Senthil et al, Nature 303 (2004) 1490

O(3) nonlinear sigma model for the Néel phase

$$S = \frac{1}{2g}\int d\tau \int d^2 r [(\partial_\tau \hat{n})^2 + (i\nabla_r \hat{n})^2]$$

$$+ iS \sum_r (-1)^r A_r$$

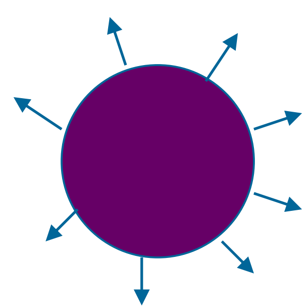
Order parameter

Berry phase

$$Q = \frac{1}{4\pi}\int d^2 r\, \hat{n}\cdot\partial_x \hat{n}\times\partial_y \hat{n}$$

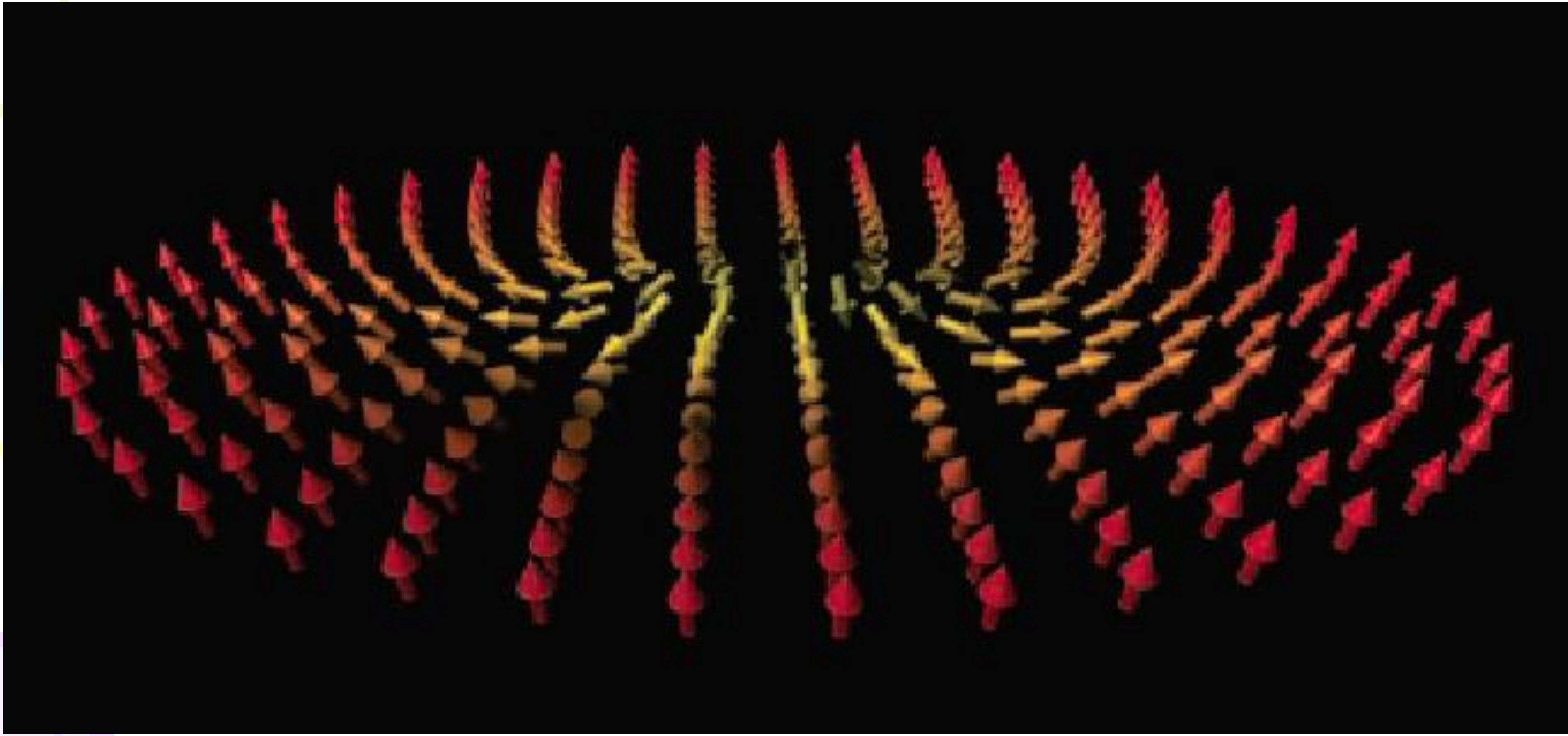
Non-trivial topology with hedgehog

“skyrmion”



Q=1 skyrmion

“Hedgehog”



Sigma model

& Hidden gauge symmetry

$$\hat{n} = z^{+}\vec{\sigma}\, z$$

CP^1 parameterization

Invariance: $z \to h(x) z$

$$h(x) \in U(1)$$

⇒ Local gauge symmetry with U(1) gauge field A_μ

z = fractional spinon
=1/2- skyrmion
= “meron”

$$S = \int d\tau \int d^2 r\, L$$

$$L = \sum_{\alpha} |(\partial_{\mu} - iA_{\mu}) z_{\alpha}|^2 + s|z|^2 + u|z|^4 + \kappa(\varepsilon_{\mu\nu\lambda}\partial^{\nu} A^{\lambda})^2$$

Topological charge (skyrmion number)

$$Q = \frac{1}{4\pi} \int d^2 r\, \hat{n} \cdot \partial_x \hat{n} \times \partial_y \hat{n} \;\sim\; \int d^2 r (\partial_x A_y - \partial_y A_x)$$

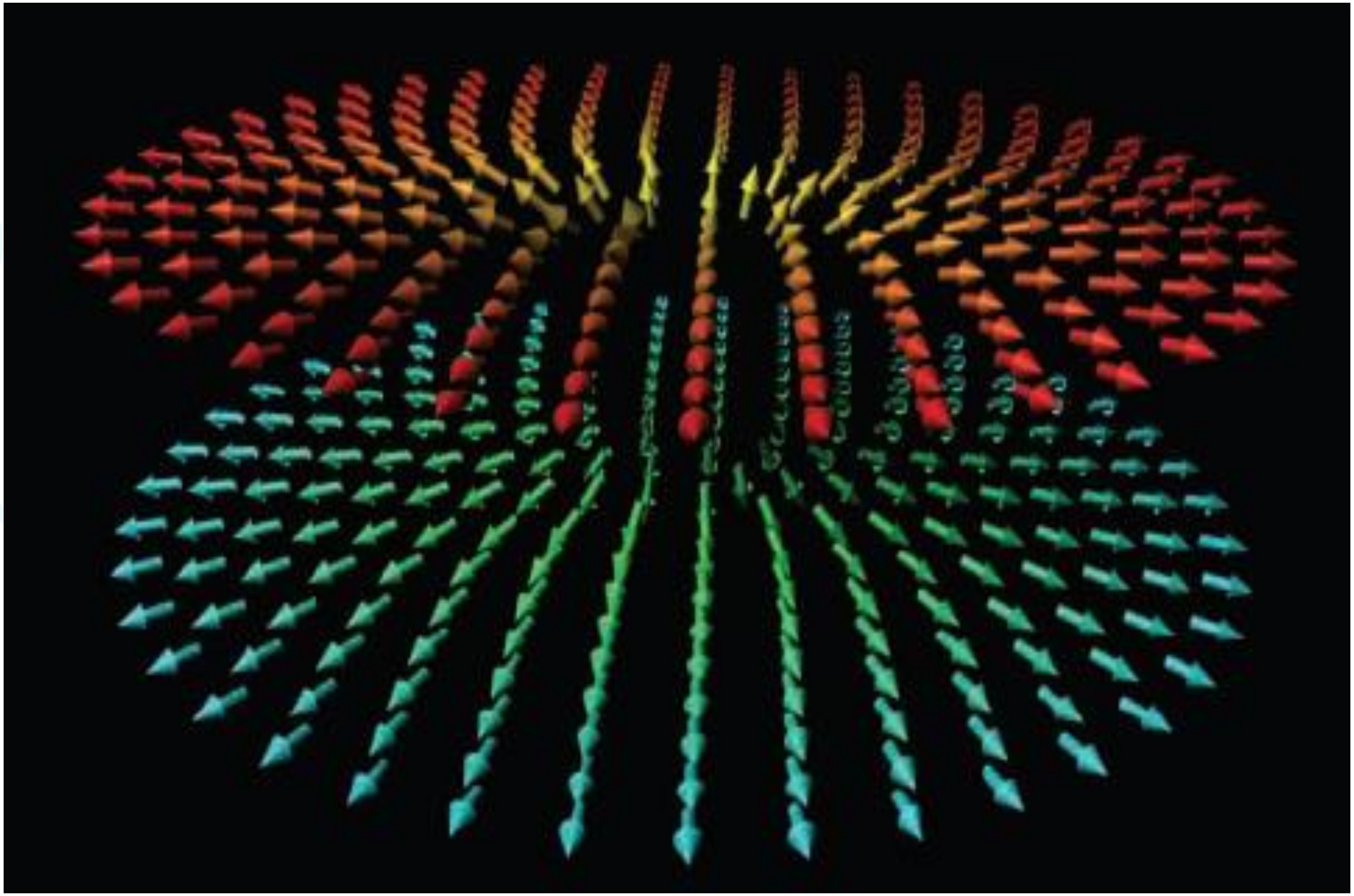
1/2-skyrmions are confined by topology

At the phase transition, the “monopole” (topology) becomes irrelevant and the 1/2-skyrmions get deconfined, the integer skyrmion number becoming non-conserved. This mechanism is not visible with the gauge field.

Senthil et al’s “deconfined quantum critical points”

Deconfined up-meron-down-antimeron

1/2- skyrmion

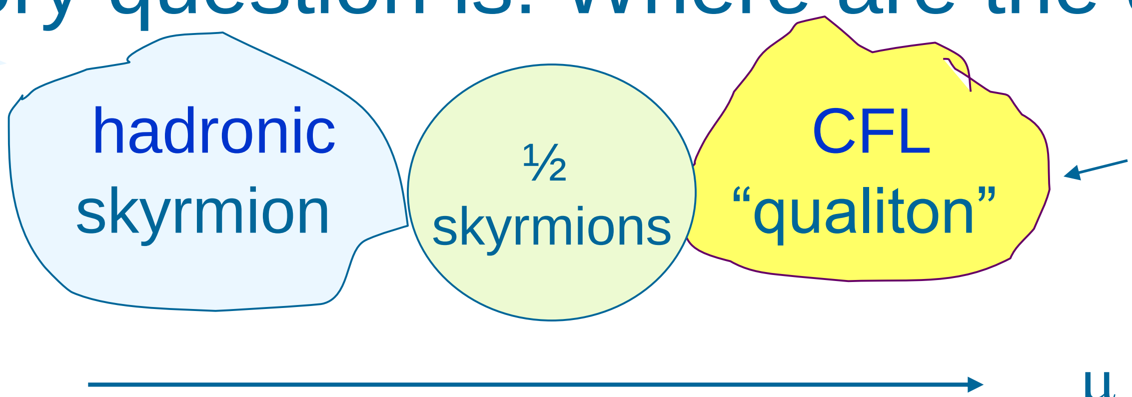


Conclusion

The HIM question is: Does the strongly correlated hadronic system exhibit similar quantum critical behaviors?

The theory question is: Where are the quarks?

Baryonic Matter:



Hong, Rho and Zahed 1999