Some theoretical advances in dense QCD phase transition

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ATHIC talk, 2025

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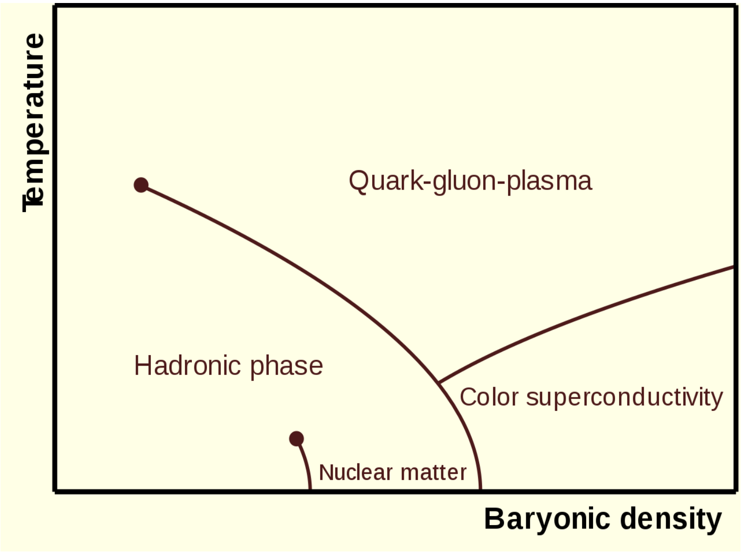
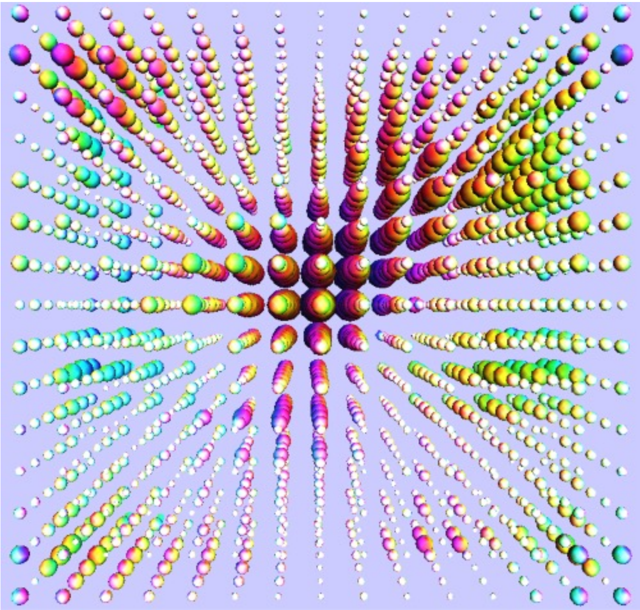
Phys.Rev.D 100 (2019) 3, 034015

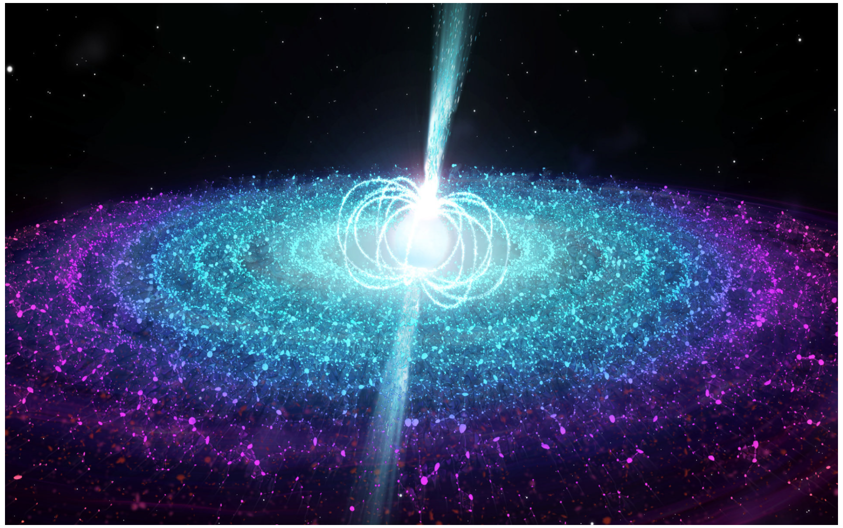
My Research



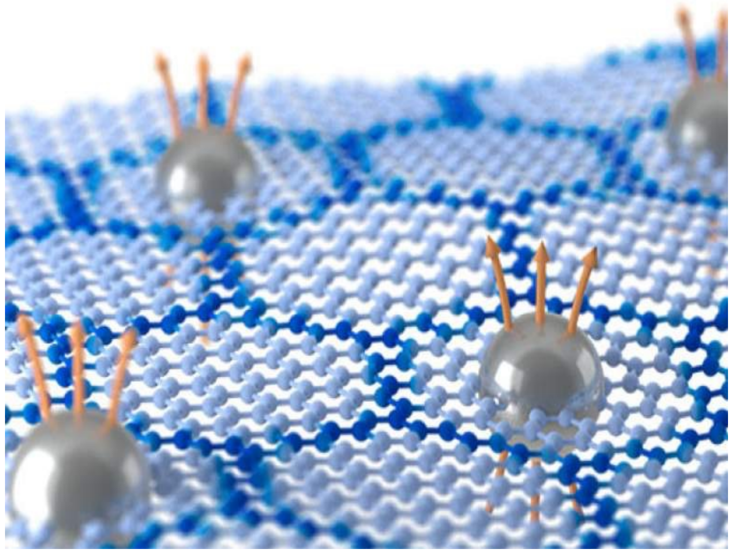
The QCD phase diagram



Lattice formulations of quantum field theories.

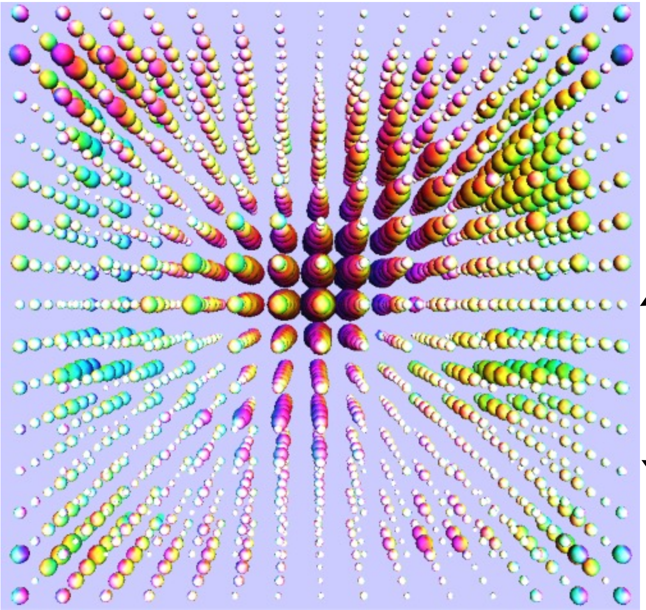


Nuclear astrophysics

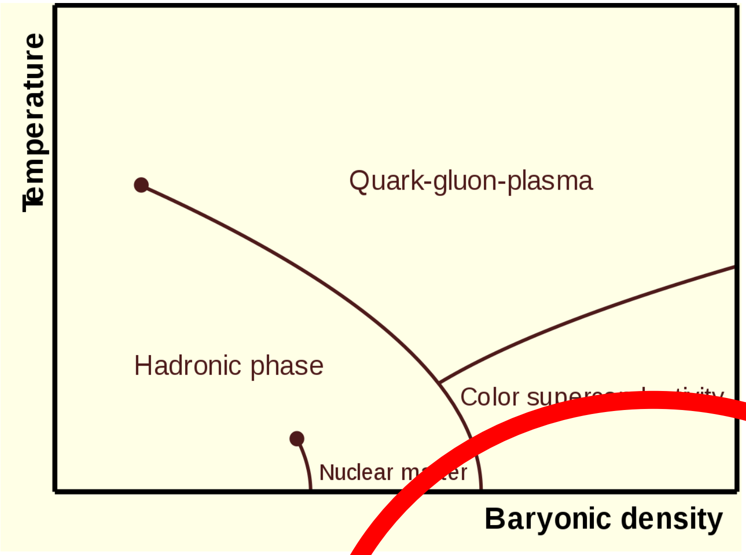


Topological phases of matter in quantum materials

My Research

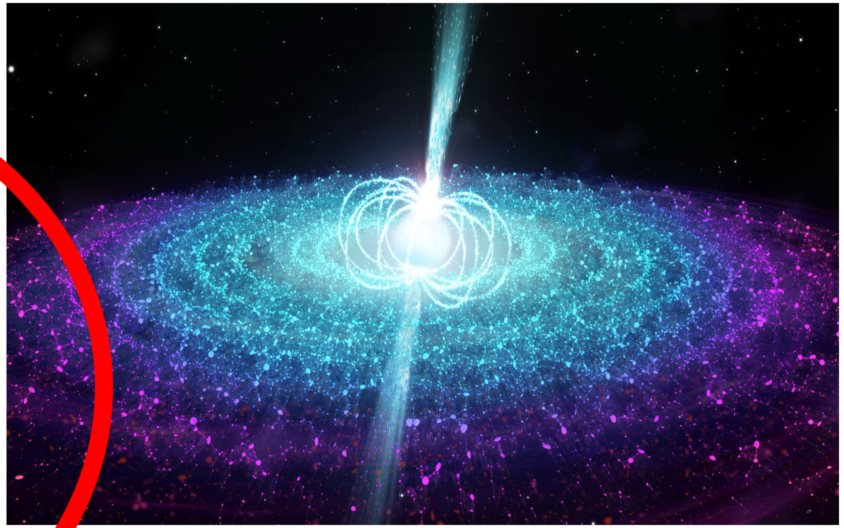


Lattice formulations of quantum field theories.

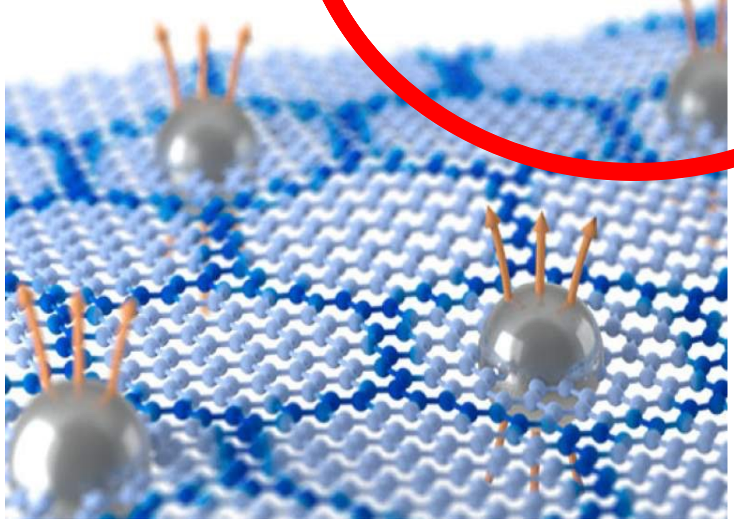


The QCD phase diagram

This talk

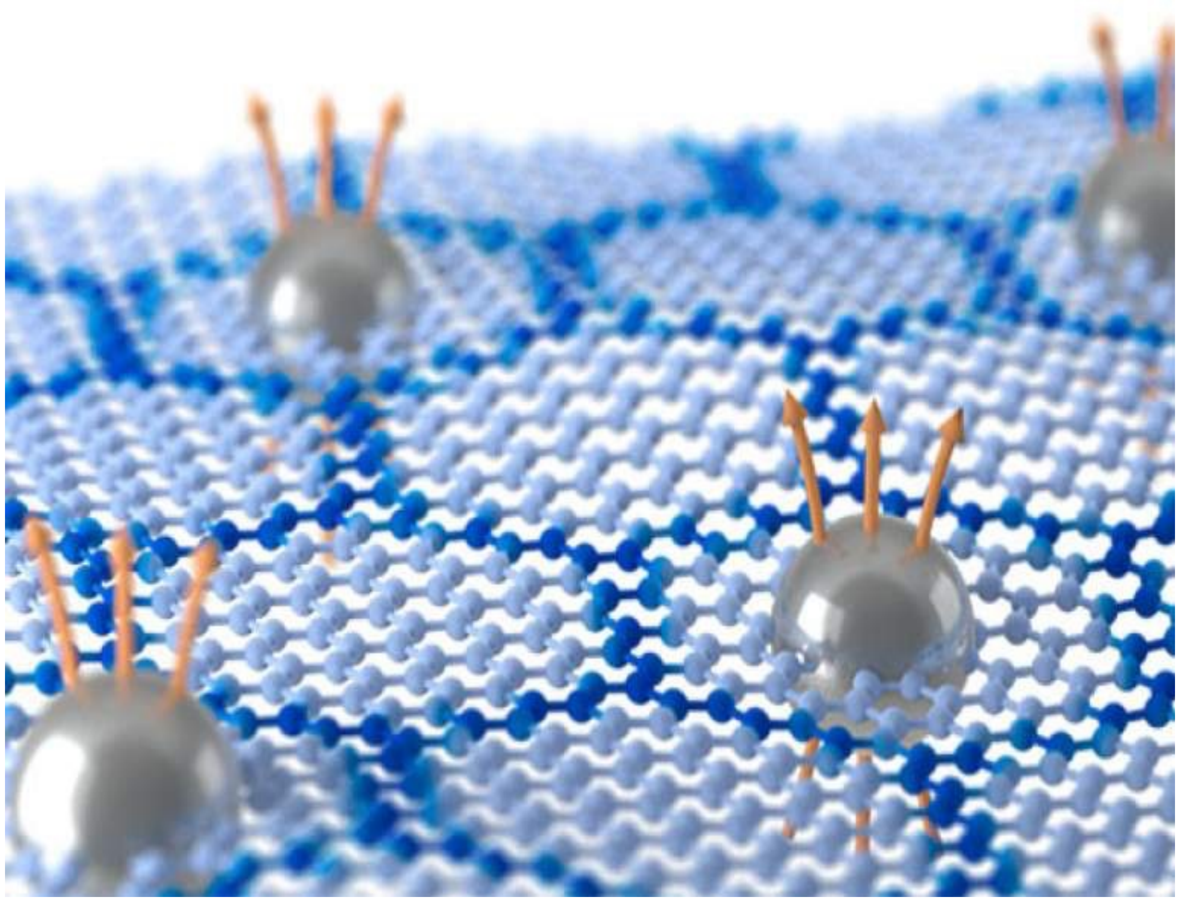


Nuclear astrophysics and axion physics



Topological phases of matter in quantum materials

Background: topological phases



Anyons: fractional statistics

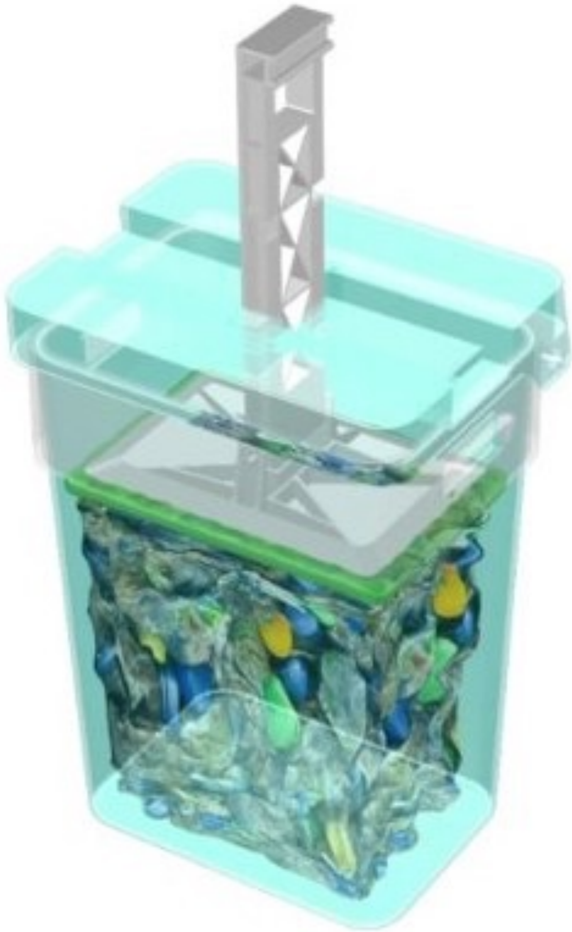
Nonabelian anyons, Majorana zero modes: Topological quantum computing

Properties of these excitations are tied to the topological phase boundaries in quantum materials.

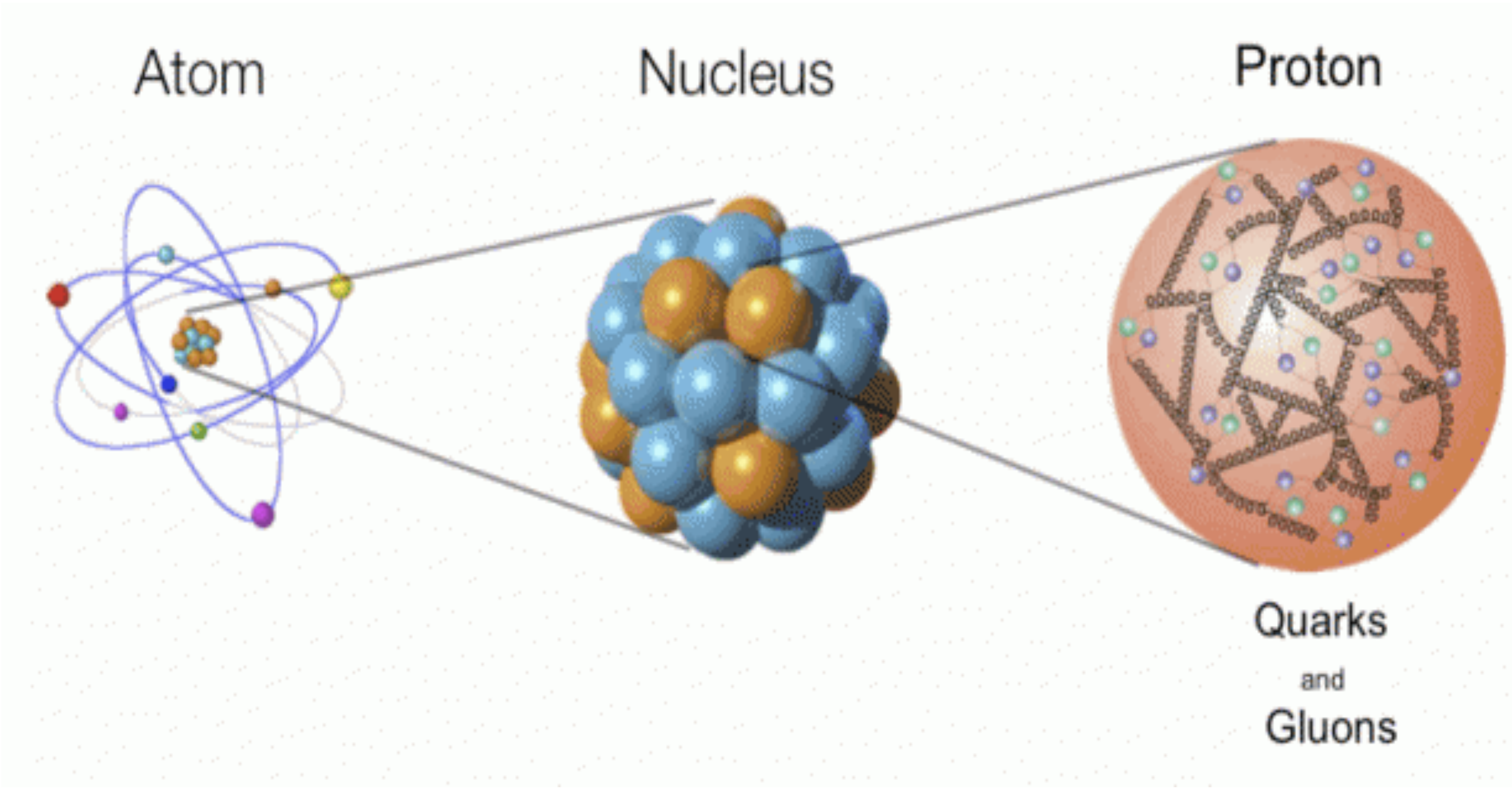
Motivation: relevance of topological phases to dense QCD

Can recent developments in topological quantum phases in condensed matter physics reveal new features of the QCD phase diagram?

Study of extreme densities and temperatures

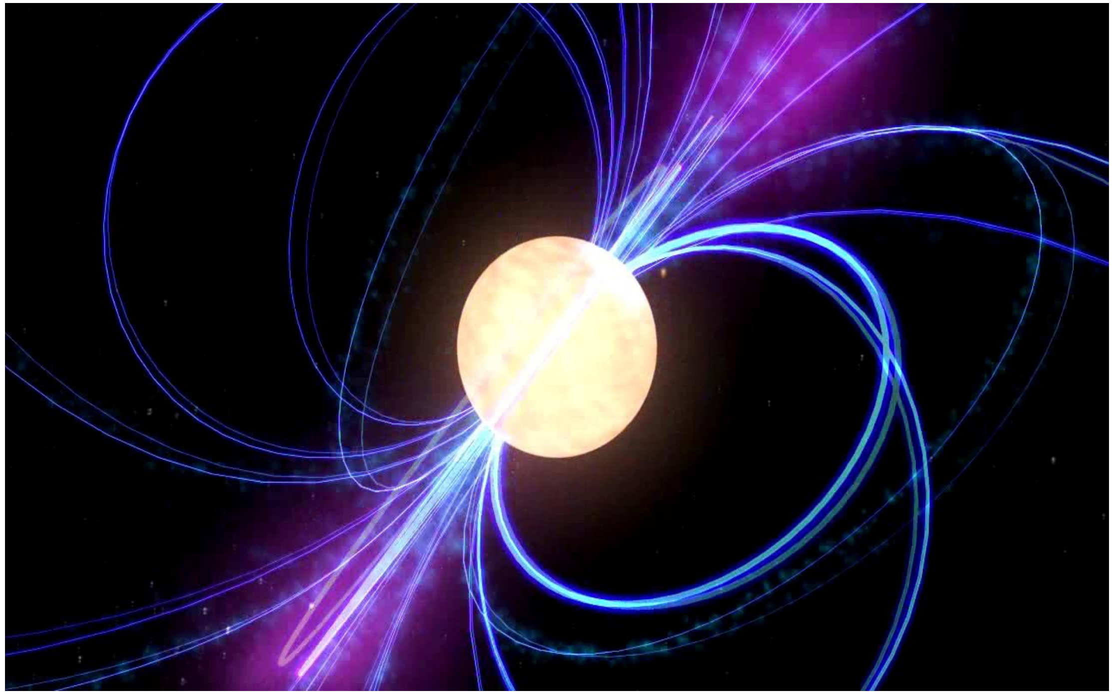


Conditions so extreme that strong nuclear force becomes important



Why care about extreme density ? Cores of neutron stars.

- A giant ball of neutrons.
- Radius about 10-12 kilometers.
- Mass about a few solar masses.
- Low temperature.

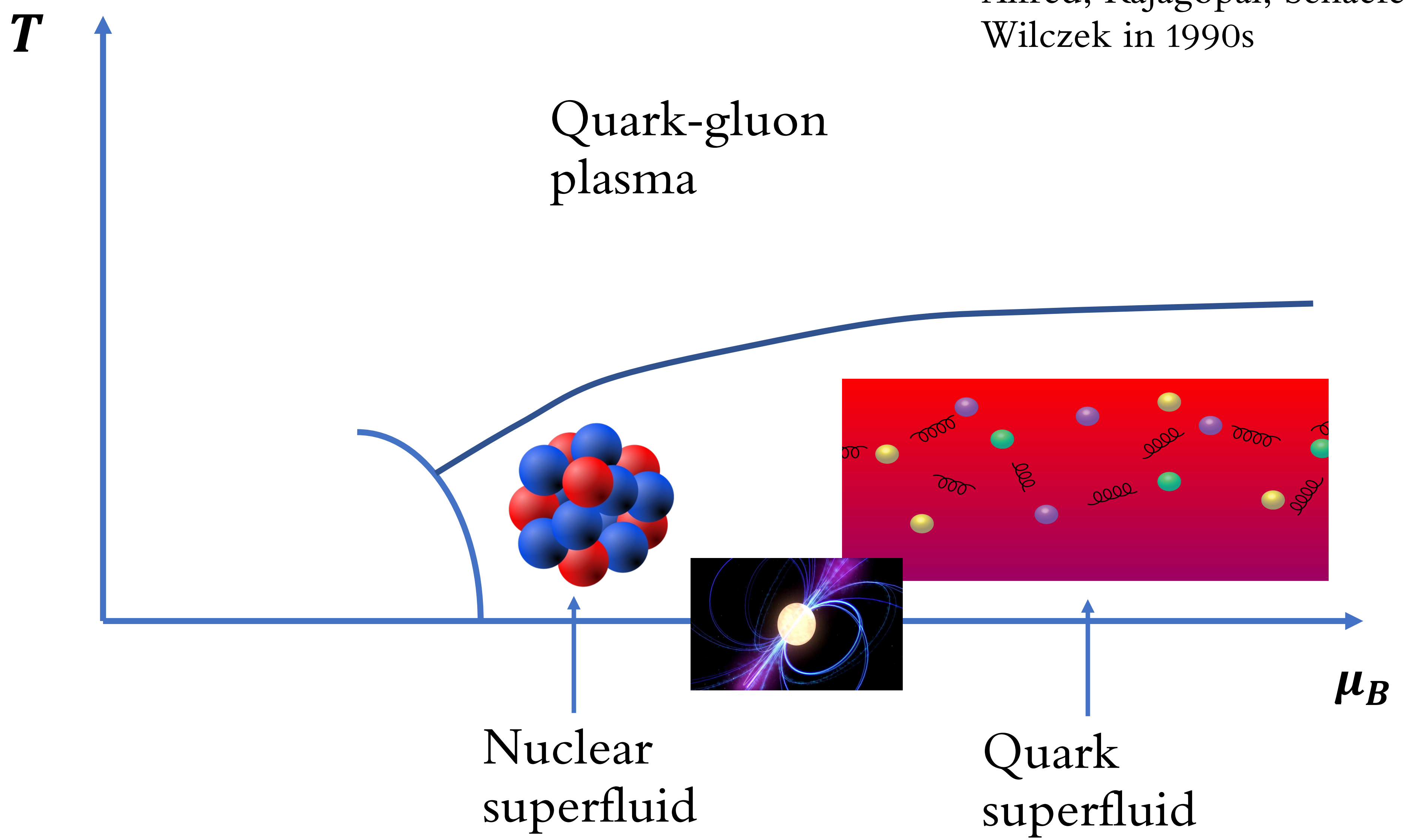


Neutron Stars, Supernovae

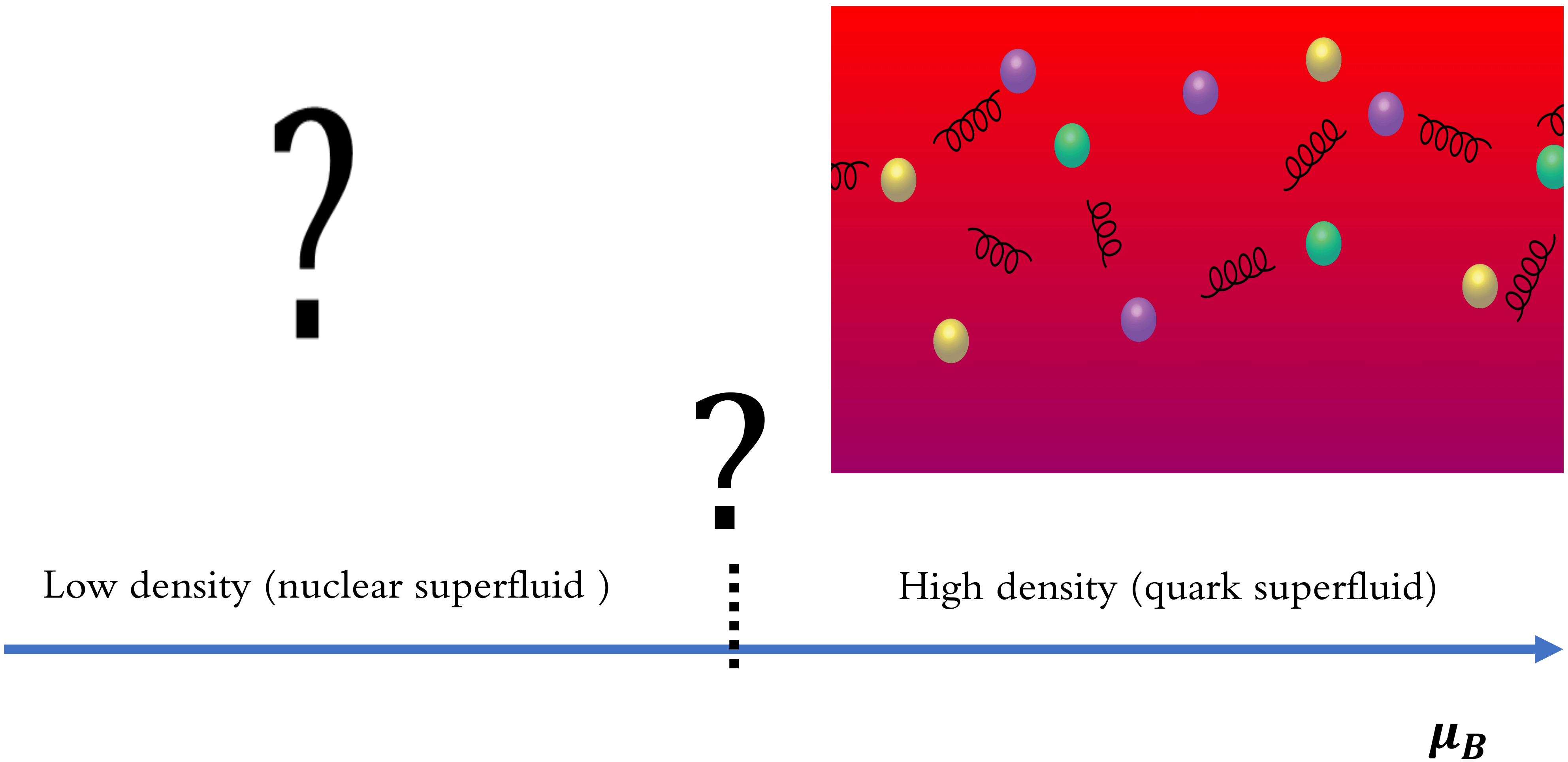
Credit : phys.org, NASA

Phase diagram of matter under extreme density.

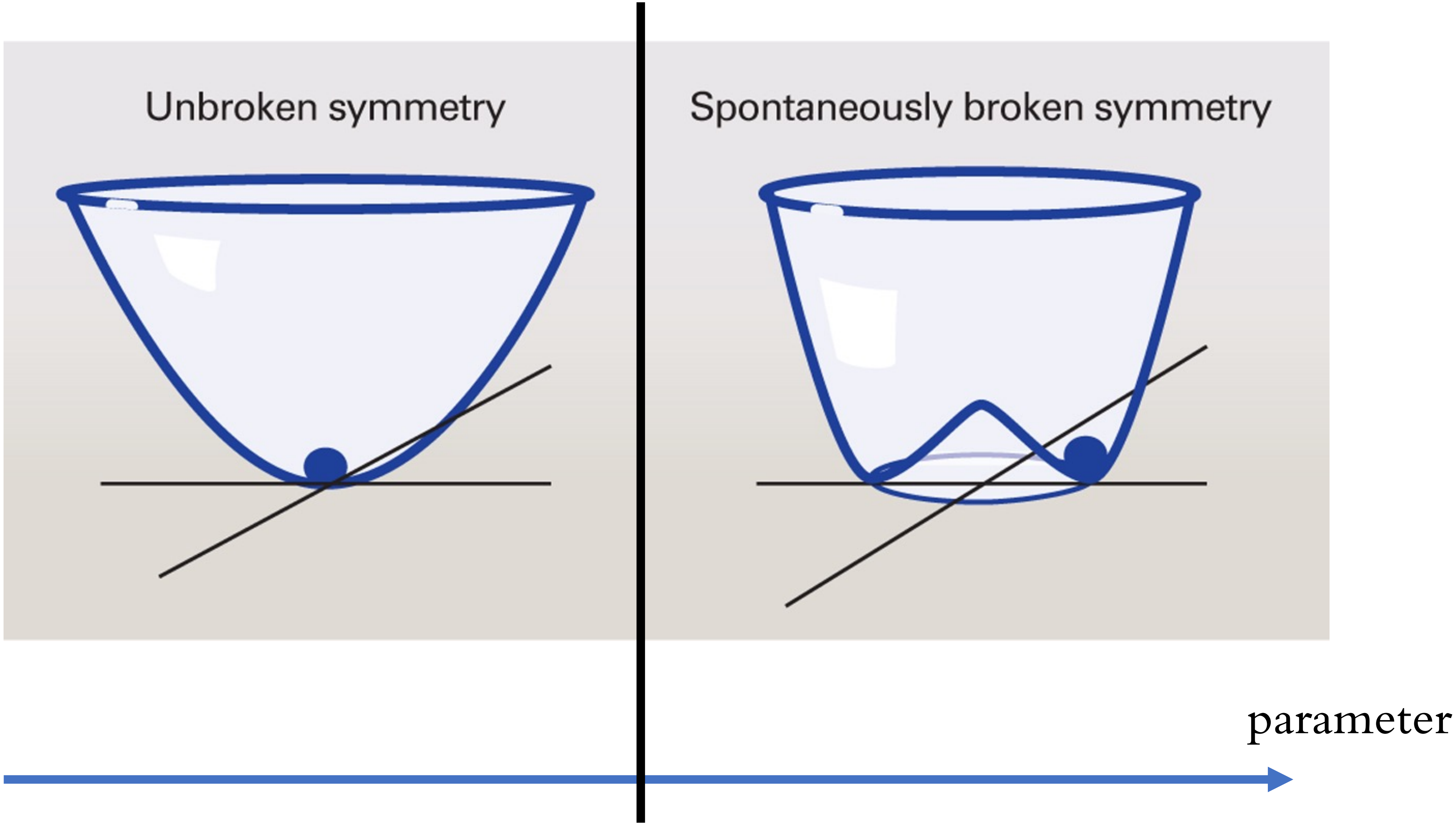
Alfred, Rajagopal, Schaefer, Wilczek in 1990s



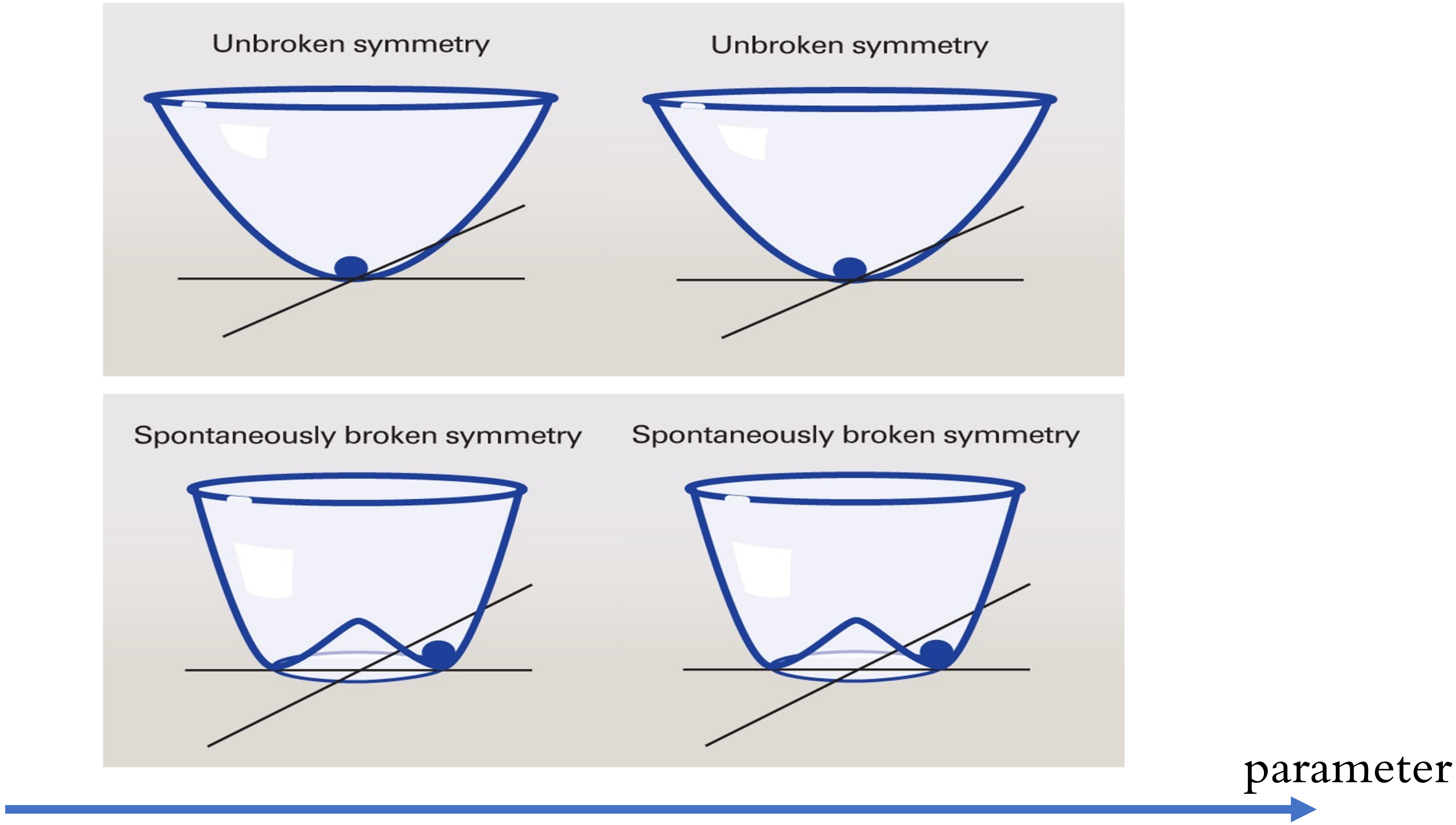
Is there a sharp distinction between nuclear and quark superfluid purely based on strong dynamics alone ?



Standard approach : symmetry/Landau paradigm for phase transition



Standard approach : symmetry/Landau paradigm for continuity



Dense QCD: Landau paradigm

- All three quarks are massless for the purpose of the talk.
- This sharpens the question we are asking.

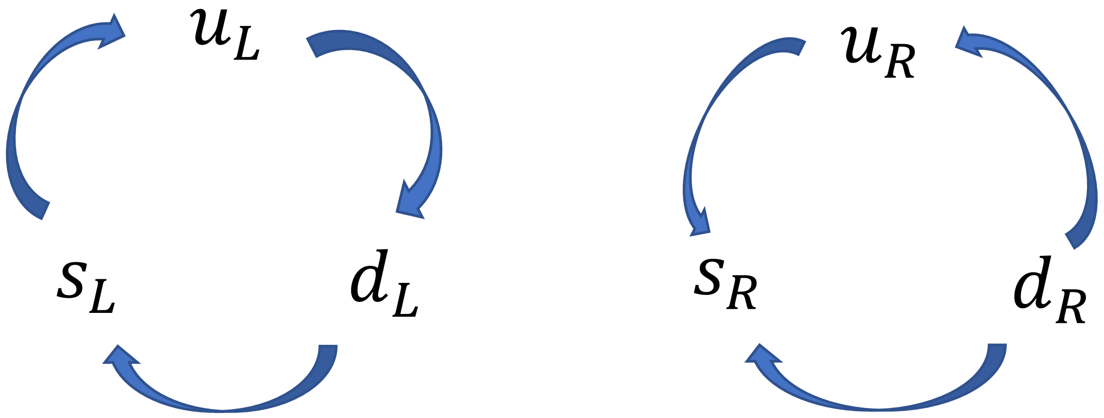
Symmetries of the theory

Baryon number/ quark number

N = baryon field= (qqq)

$$N \rightarrow e^{i\alpha} N$$

Chiral symmetry (in the massless limit)



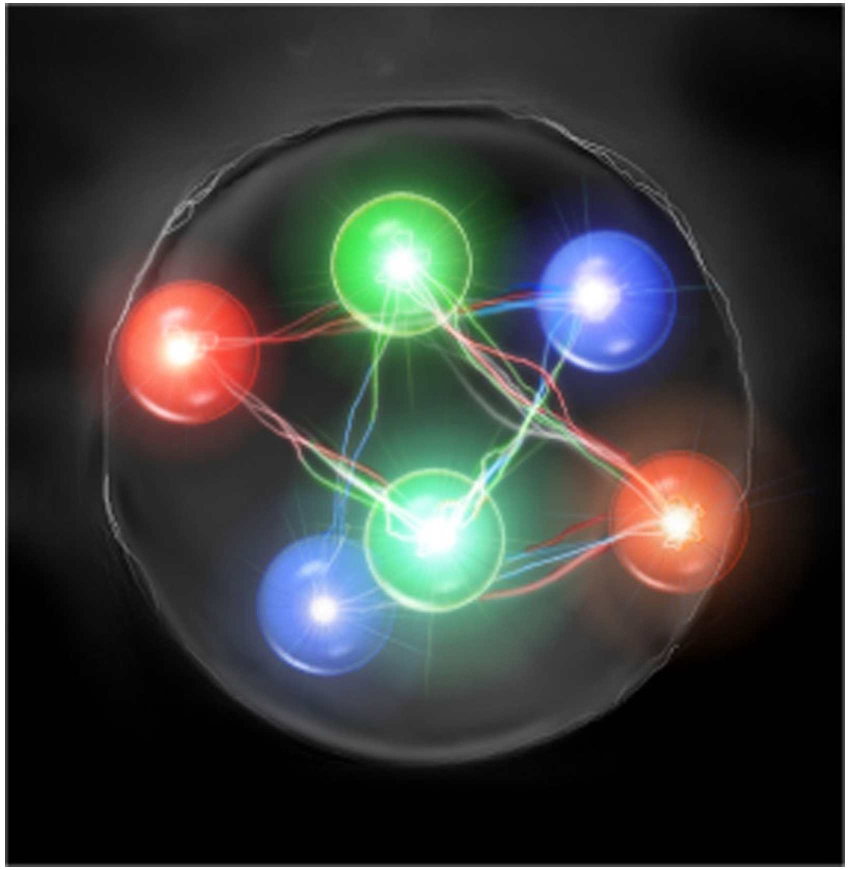
Quark field = q

Nuclear regime (low density): <u>superfluidity</u>

- BEC of bound state of two baryons $\langle NN \rangle = \langle (qqq)(qqq) \rangle \neq 0.$

$$\cancel{U(1)_B}$$

- quark-antiquark condensate $\langle \bar{q}q \rangle \neq 0$ breaks chiral symmetry.



Cartoon of a dibaryon

Asymptotically high density: <u>superfluidity</u>

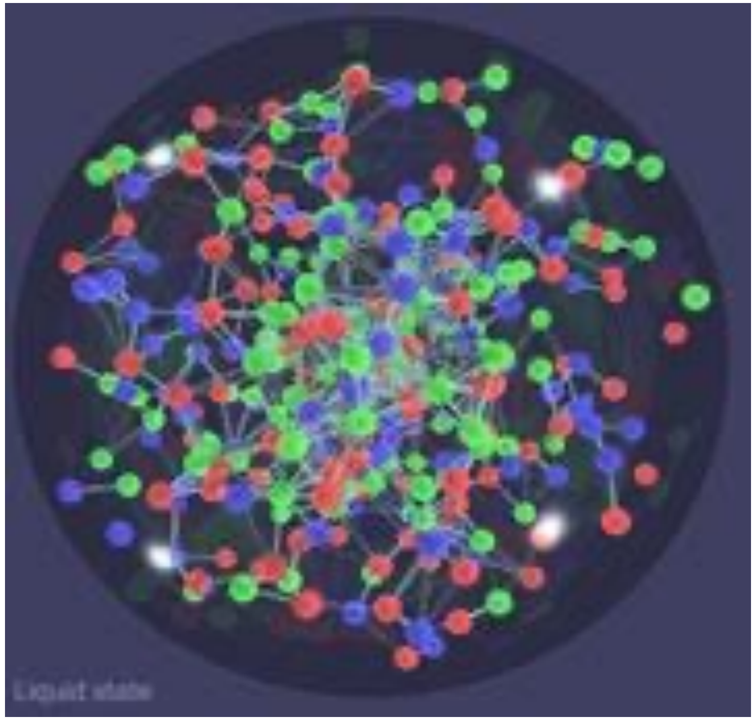
- Fermi sphere of quarks.
- BCS instability at the Fermi surface.
- Cooper pairs of quarks (CFL matter).

(Rajagopal, Alford, Son, Wilczek, Rischke, Schefer)

$\langle qq \rangle \neq 0$ Baryon number broken

$\langle \bar{q}\, q\, \bar{q}\, q \rangle \neq 0$ Chiral symmetry broken

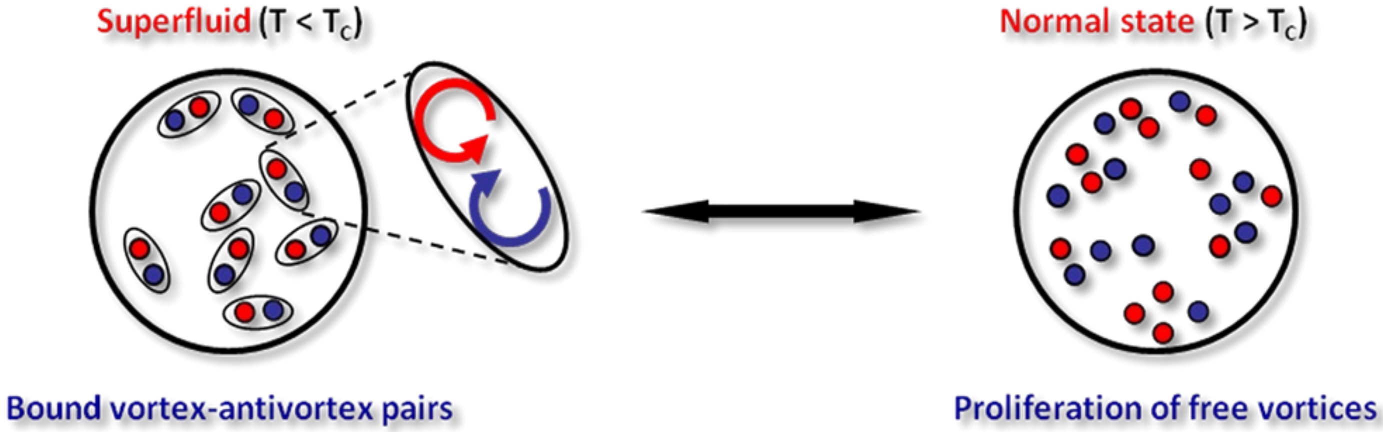
Continuity from the point of view of Landau paradigm



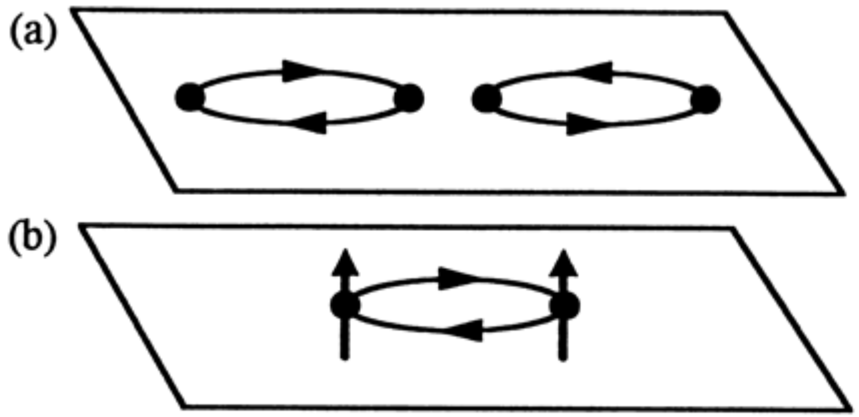
Cartoon of quark fermi liquid.

Quark Hadron continuity, Schaefer-Wilczek, 1999

Phase transition = change in symmetry ? Not necessarily..



B-K-T transition

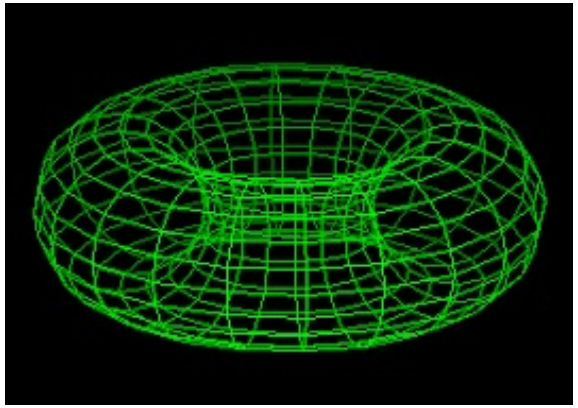


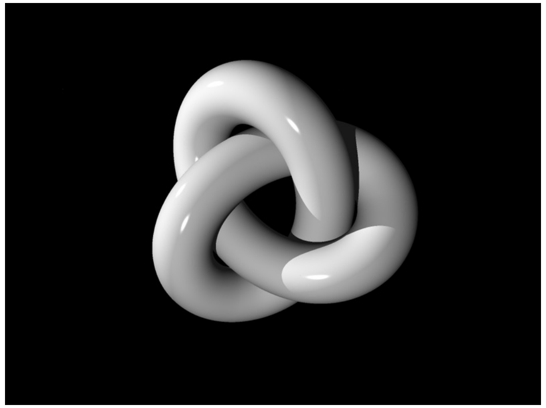
Fractional quantum hall effect

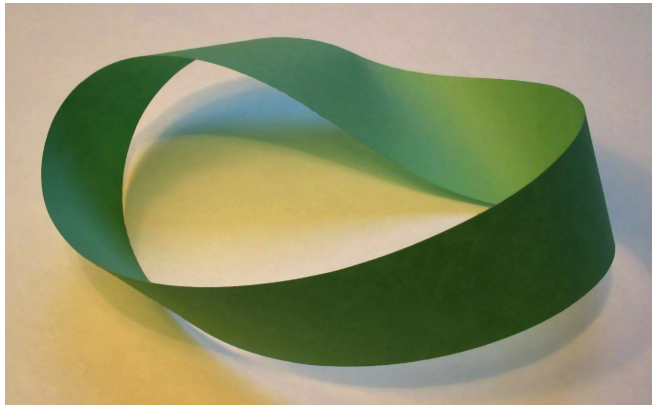
Credit: http://www-amop.phy.cam.ac.uk/amop-zh/Research3.html, http://www.pnas.org/content/96/16/8821

Phase transition detected by probing topology

Analyze theory on spatially compact manifolds



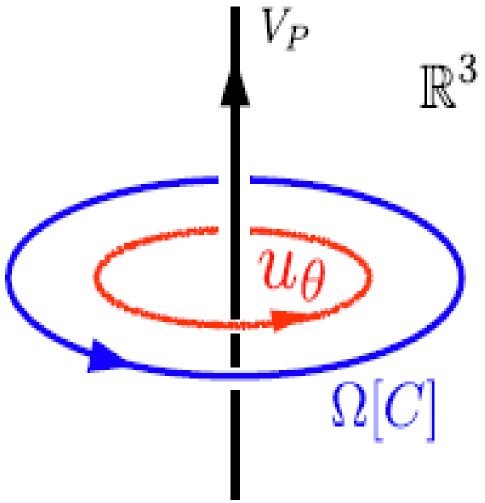




Or equivalently

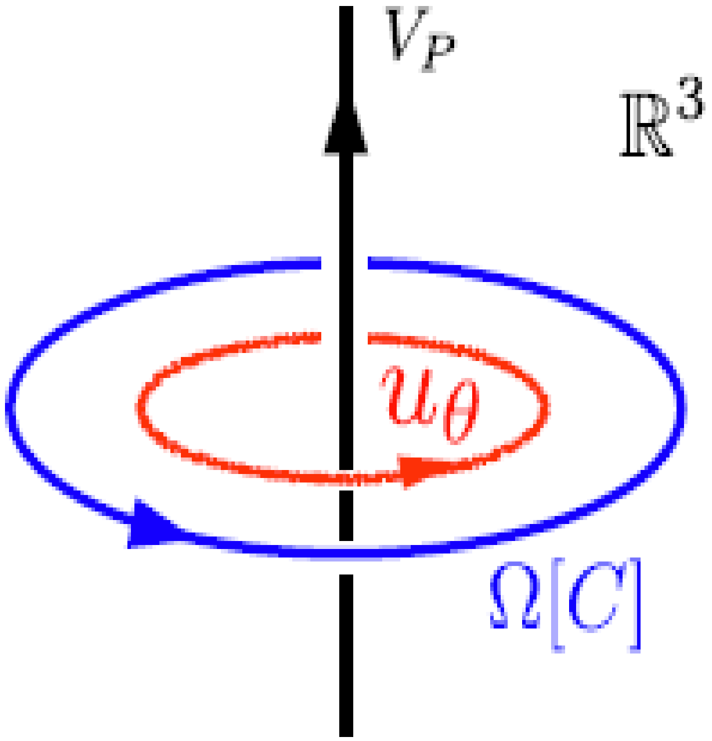
Look into topological field configurations in ordinary space-time : like vortices, flux tubes etc

Check Aharonov-Bohm phases.



We'll take this route for this talk.

Toy example ordinary superconducting flux-tube/vortex.

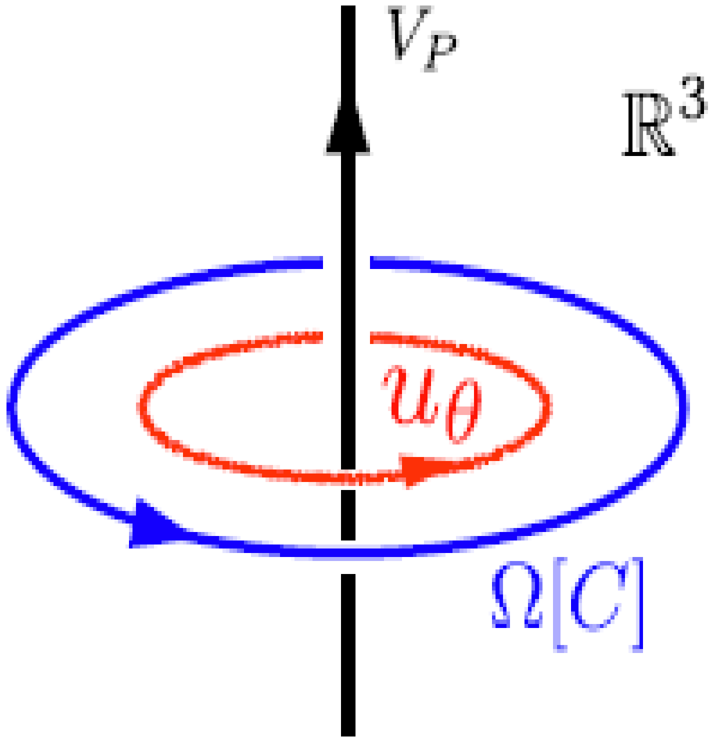


Two electron Cooper pair : $\langle ee \rangle = \psi$ winds around the vortex axis by one unit: $\psi \sim e^{i\theta}$.

$$E_\psi \sim |\mathrm{D_i}\psi|^2$$

Covariant derivative $\partial_i + i\,2\,e\,A_i$

Toy example ordinary superconducting flux-tube.



Minimize energy density with the gauge field ansatz $A = \frac{b}{r}\hat{\theta}$.

Result : $b = \frac{1}{2}$.

$$E_\psi \sim 0$$

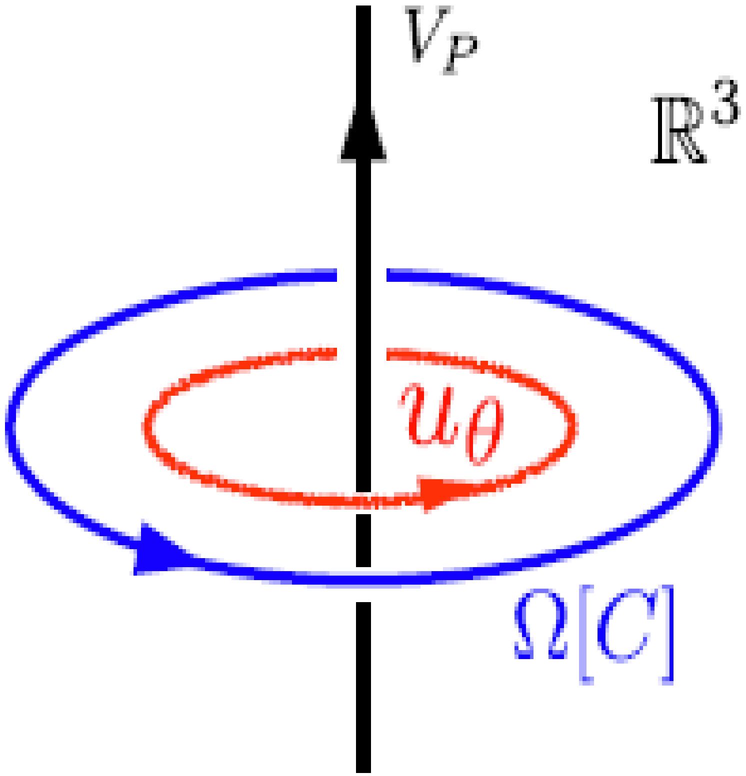
Aharonov – Bohm phase of $\Omega[C] = e^{i\,e\int A} = e^{i\pi} = -1$.

Coherent di-electron condensate (Cooper pair) is important

Hanson, Oganesyan, Sondhi Annals Of Physics vol. 313, 497 (2004)

Aharonov – Bohm (AB) phases around vortices in quark matter:

Consider vortex in coherent di-quark condensate in CFL quark matter



AB phase given by :

$$\Omega[C] \equiv e^{\pm\frac{2\pi i}{3}}$$

A quark field experiences this AB phase at high density quark matter.

Implications : nuclear matter

No coherent di-quark condensate expected over macroscopic length scales. $< qq > = 0$.

Trivial Aharonov-Bohm phase around vortices.

Phase Transition

If the AB phase around minimal nontrivial vortices in superfluid nuclear matter is trivial :

Phase transition between quark and nuclear matter.

Continuity ? (Unlikely, but not ruled out)

The vortices in nuclear matter have to exhibit the same Aharonov-Bohm phase as in quark matter!!

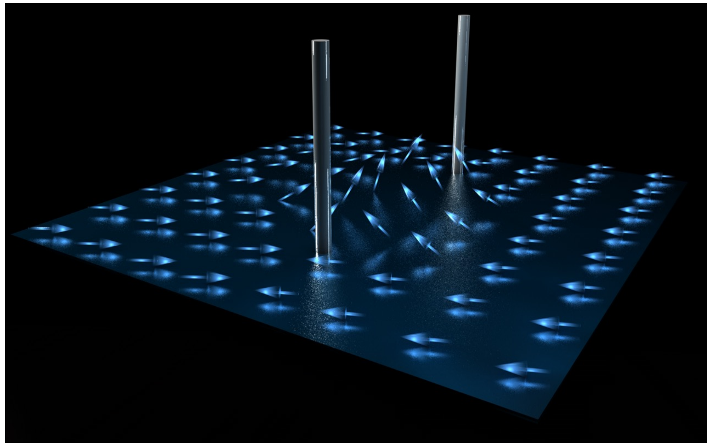
This would imply that nuclear matter carries signatures of QCD in the form of topological data.

See work by Yui Hayashi, 2023, 2024

Broader implications: topological quantum materials

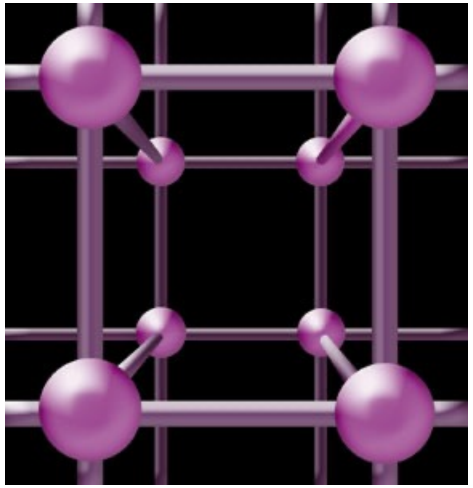
- Dense QCD is situated right at the edge of our understanding of emergent phenomena.
- Topological transitions in superfluid quantum matter not well understood.
- Dense QCD is providing insight into this problem.

What next ?



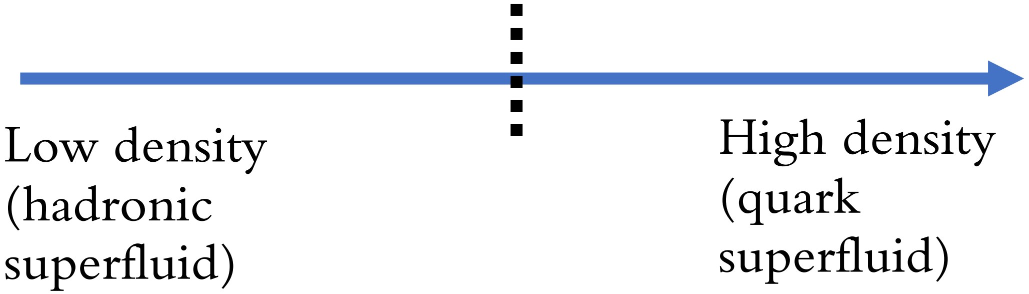
Design a simpler model to simulate dense QCD transition on tabletop

Think about neutron star observables



Future lattice simulations to answer this question

Order of the transition ?



Credit: mathematica, phys.org,

Thank you!