Spontaneous electromagnetic superconductivity **of vacuum** induced by (very) strong magnetic field

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Based on:

M.Ch., Phys. Rev. D 82, 085011 (2010) [arXiv:1008.1055]

M.Ch., Phys. Rev. Lett. 106, 142003 (2011) [arXiv:1101.0117]

J. Van Doorsselaere, H. Verschelde, M.Ch.,
Phys. Rev. D 85, 045002 (2012) [arXiv:1111.4401]

+ arXiv:1104.3767 + arXiv:1104.4404 + ...

What is «very strong» field? Typical values:

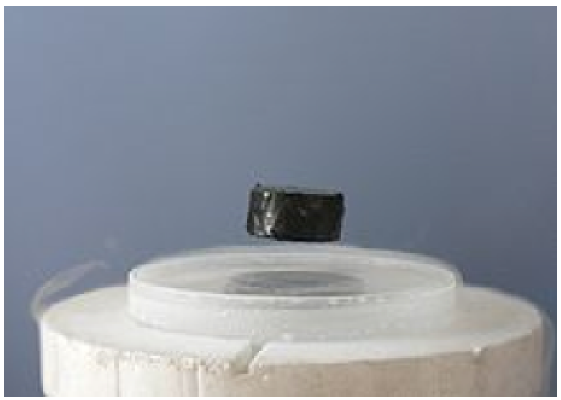
- Thinking — human brain: 10^{-12} Tesla
- Earth's magnetic field: 10^{-5} Tesla
- Refrigerator magnet: 10^{-3} Tesla
- Loudspeaker magnet: 1 Tesla
- Levitating frogs: 10 Tesla
- Strongest field in Lab: 10^{3} Tesla
- Typical neutron star: 10^{6} Tesla
- Magnetar: $10^{7 \ldots 9}$ Tesla
- Heavy-ion collisions: 10^{15} Tesla (and higher)
- Early Universe: even (much) higher

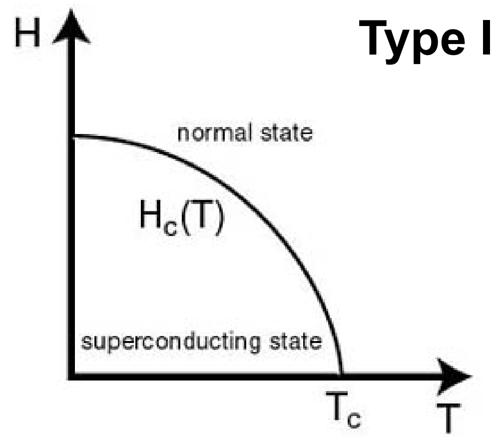
IgNobel 2000 by A.Geim (got Nobel 2010 for graphene)

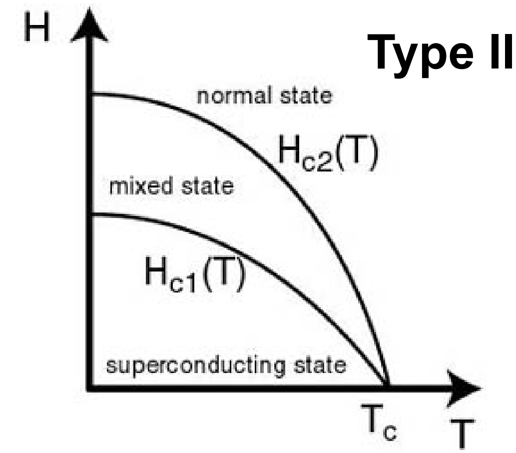
Destructive explosion

Superconductivity

Discovered by Kamerlingh Onnes at the Leiden University
100 years ago, at 4:00 p.m. April 8, 1911 (Saturday).







I. Any superconductor has zero electrical DC resistance

II. Any superconductor is an enemy of the magnetic field:

1) weak magnetic fields are expelled by all superconductors (the Meissner effect)

2) strong enough magnetic field always kills superconductivity

Our claim:

In a background of strong enough magnetic field the vacuum becomes a superconductor.

The superconductivity emerges in empty space. Literally, "nothing becomes a superconductor".

Some features of the superconducting state of vacuum:

1. spontaneously emerges above the critical magnetic field

$$B_c \simeq 10^{16}\ \text{Tesla} = 10^{20}\ \text{Gauss} \longleftarrow$$

can be reached in experiments!

or

$$eB_c \simeq m_\rho^2 \simeq 31\, m_\pi^2 \simeq 0.6\ \text{GeV}^2$$

2. conventional Meissner effect does not exist

The claim seemingly contradicts textbooks which state that:

1. Superconductor is a material (= a form of matter, not an empty space)
2. Weak magnetic fields are suppressed by superconductivity
3. Strong magnetic fields destroy superconductivity

1+4 approaches to the problem:

0. General arguments; (this talk)

1. Effective bosonic model for electrodynamics of ρ mesons based on vector meson dominance
   [M.Ch., PRD 2010; arXiv:1008.1055] (this talk)

2. Effective fermionic model (the Nambu-Jona-Lasinio model)
   [M.Ch., PRL 2011; arXiv:1101.0117] ~~(this talk)~~

3. Nonperturbative effective models based on gauge/gravity duality (utilizing AdS/CFT duality)
   [Callebaut, Dudal, Verschelde (Gent U., Belgium), arXiv:1105.2217];
   [Erdmenger, Kerner, Strydom (Munich, Germany), arXiv:1106.4551]
   ~~(this talk)~~

5. First-principle numerical simulation of vacuum
   [ITEP Lattice Group, Moscow, Russia, arXiv:1104.3767] (this talk)

Key players: ρ mesons and vacuum

- ρ mesons:

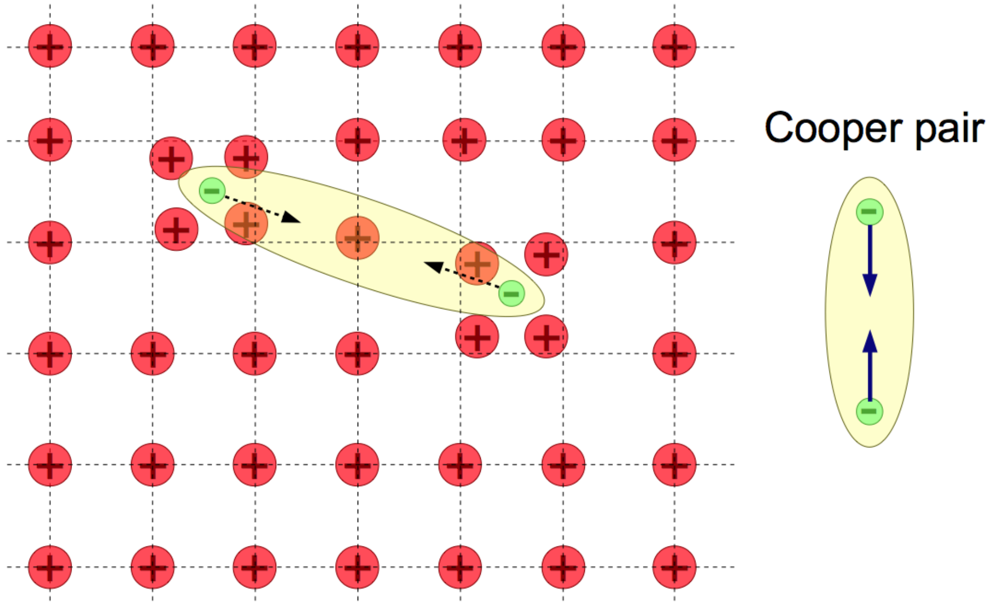
- electrically charged ($q = \pm e$) and neutral ($q=0$) particles
- spin: s=1, vector particles
- quark contents: $\rho^{+} = u\bar{d}$, $\rho^{-} = d\bar{u}$, $\rho^{\mathbf{0}} = (u\bar{u} - d\bar{d})/2^{1/2}$
- mass: m_{ρ}=775.5 MeV (approximately 1550 electron masses)
- lifetime: τ_{ρ}=1.35 fm/c (very short: size of the ρ meson is 0.5 fm)

- vacuum: QED+QCD, zero tempertature and density

Conventional BCS superconductivity

1) The Cooper pair is the relevant degree of freedom!

2) The electrons are bounded into the Cooper pairs by the (attractive) phonon exchange.



Three basic ingredients:

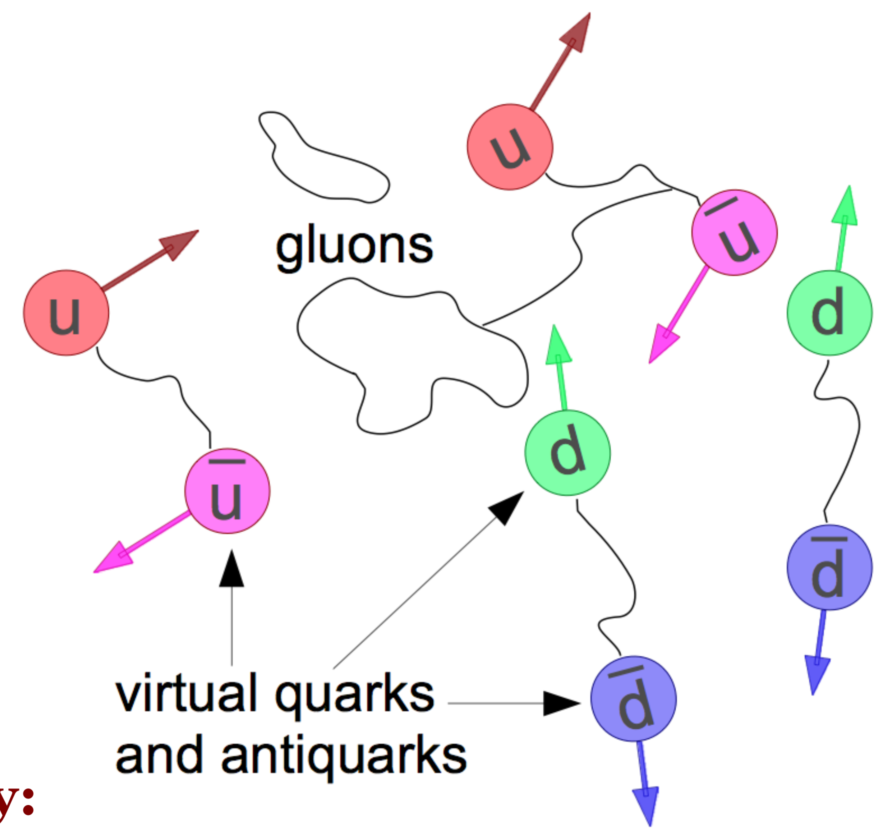
A) the presence of carriers of electric charge (of electric current);

B) the reduction of physics from (3+1) to (1+1) dimensions;

C) the attractive interaction between the like-charged particles.

Real vacuum, no magnetic field

1) Boiling soup of everything.
Virtual particles and antiparticles (electrons, positrons, photons, gluons, quarks, antiquarks ...) are created and annihilated every moment.



2) Net electric charge is zero.
An insulator, obviously.

3) We are interested in "strongly interacting" sector of the theory:

a) quarks and antiquarks,

i) *u* quark has electric charge $q_u = +2\, e/3$

ii) *d* quark has electric charge $q_d = -\, e/3$

b) gluons (an analogue of photons, no electric charge) "glue" quarks into bounds states, "hadrons" (neutrons, protons, etc).

The vacuum in strong magnetic field

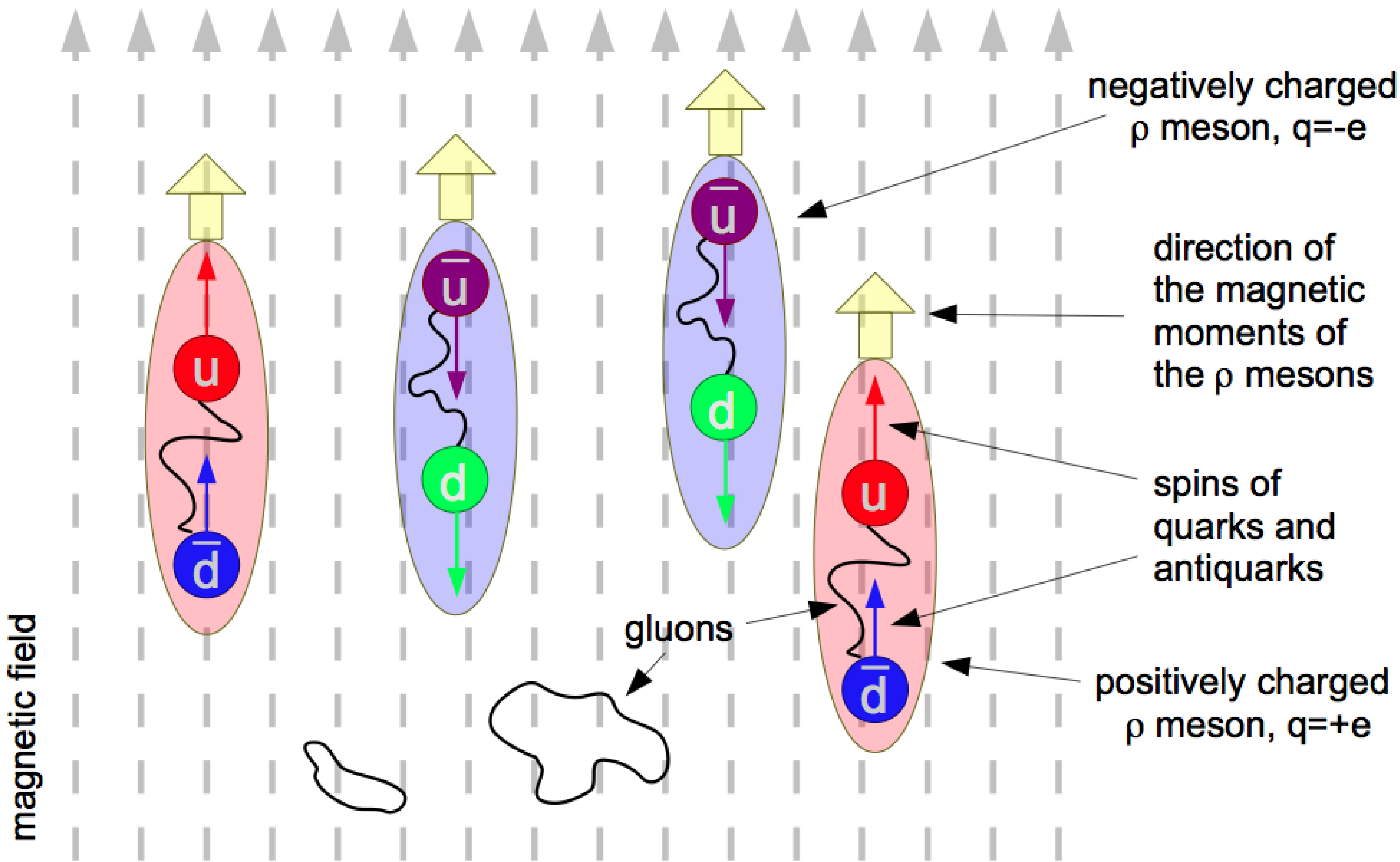
Ingredients needed for possible superconductivity:

A. **Presence of electric charges?**
Yes, we have them: there are virtual particles which may potentially become "real" (= pop up from the vacuum) and make the vacuum (super)conducting.

B. **Reduction to 1+1 dimensions?**
Yes, we have this phenomenon: in a very strong magnetic field the dynamics of electrically charged particles (quarks, in our case) becomes effectively one-dimensional, because the particles tend to move along the magnetic field only.

C. **Attractive interaction between the like-charged particles?**
Yes, we have it: the gluons provide attractive interaction between the quarks and antiquarks ($q_u = +2\,e/3$ and $q_{\bar{d}} = +e/3$)

Strong magnetic field, picture



Charged relativistic particles in magnetic field

- Energy of a relativistic particle in the external magnetic field B_{ext}:

$$\varepsilon^2_{n,s_z}(p_z) = p_z^2 + (2n - 2s_z + 1)eB_{\mathrm{ext}} + m^2$$

momentum along the magnetic field axis → p_z^2

nonnegative integer number → n

projection of spin on the magnetic field axis → s_z

(the external magnetic field is directed along the *z*-axis)

- Masses of ρ mesons and pions in the external magnetic field

$$m^2_{\pi^\pm}(B_{\mathrm{ext}}) = m^2_{\pi^\pm} + eB_{\mathrm{ext}}$$ becomes heavier

$$m^2_{\rho^\pm}(B_{\mathrm{ext}}) = m^2_{\rho^\pm} - eB_{\mathrm{ext}}$$ becomes lighter

$$\rho^\pm \to \pi^\pm \pi^0$$

- Masses of ρ mesons and pions:

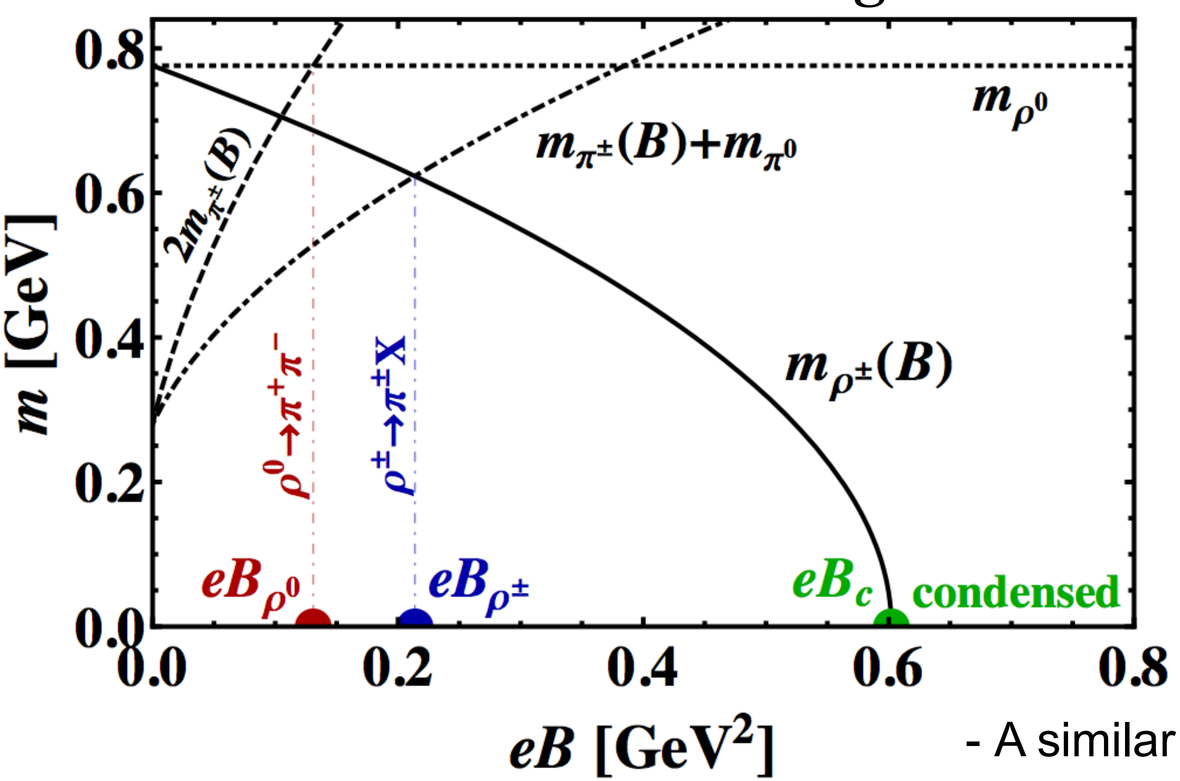
$$m_\pi = 139.6\,\mathrm{MeV}\,, \qquad m_\rho = 775.5\,\mathrm{MeV}$$

Condensation of ρ mesons

The $\rho^{\pm}$ mesons become massless and condense at the critical value of the external magnetic field

$$B_c = \frac{m_\rho^2}{e} \approx 10^{16}\,\text{Tesla}$$

masses in the external magnetic field



Kinematical impossibility of dominant decay modes

The pion becomes heavier while the rho meson becomes lighter

- The decay $\rho^{\pm} \to \pi^{\pm}\pi^{0}$ stops at certain value of the magnetic field

$$m_{\rho^\pm}(B_{\rho^\pm}) = m_{\pi^\pm}(B_{\rho^\pm}) + m_{\pi^0}$$

- A similar statement is true for $\rho^0 \to \pi^+\pi^-$

Electrodynamics of ρ mesons

- Lagrangian (based on vector dominance models):

$$\mathcal{L} = -\frac{1}{4}\, F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\, \rho^{\dagger}_{\mu\nu}\rho^{\mu\nu} + m_\rho^2\, \rho^{\dagger}_{\mu}\rho^{\mu}$$
$$-\frac{1}{4}\, \rho^{(0)}_{\mu\nu}\rho^{(0)\mu\nu} + \frac{m_\rho^2}{2}\, \rho^{(0)}_{\mu}\rho^{(0)\mu} + \frac{e}{2g_s}\, F^{\mu\nu}\rho^{(0)}_{\mu\nu}$$

Nonminimal coupling leads to *g=2*

- Tensor quantities

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu\,,$$
$$f^{(0)}_{\mu\nu} = \partial_\mu \rho^{(0)}_\nu - \partial_\nu \rho^{(0)}_\mu\,,$$
$$\rho^{(0)}_{\mu\nu} = f^{(0)}_{\mu\nu} - i g_s (\rho^\dagger_\mu \rho_\nu - \rho_\mu \rho^\dagger_\nu)$$
$$\rho_{\mu\nu} = D_\mu \rho_\nu - D_\nu \rho_\mu\,,$$

- Gauge invariance

$$U(1): \quad \begin{cases} \rho^{(0)}_\mu(x) & \rightarrow \quad \rho^{(0)}_\mu(x)\,, \\ \rho_\mu(x) & \rightarrow \quad e^{i\omega(x)}\rho_\mu(x)\,, \\ A_\mu(x) & \rightarrow \quad A_\mu(x) + \partial_\mu \omega(x) \end{cases}$$

- Covariant derivative

$$D_\mu = \partial_\mu + i g_s \rho^{(0)}_\mu - i e A_\mu$$

- Kawarabayashi-Suzuki-Riadzuddin-Fayyazuddin relation

$$g_s \equiv g_{\rho\pi\pi} = \frac{m_\rho}{\sqrt{2} f_\pi} = 5.88$$
$$g_s \gg e \equiv \sqrt{4\pi\alpha_{\mathrm{e.m.}}} \approx 0.303$$

[D. Djukanovic, M. R. Schindler, J. Gegelia, S. Scherer, PRL (2005)]

Homogeneous approximation

- Energy density:

$$\epsilon \equiv T_{00} = \frac{1}{2}F_{0i}^2 + \frac{1}{4}F_{ij}^2 + \frac{1}{2}\left(\rho_{0i}^{(0)}\right)^2 + \frac{1}{4}\left(\rho_{ij}^{(0)}\right)^2$$

$$+\frac{m_\rho^2}{2}\left[\left(\rho_0^{(0)}\right)^2 + \left(\rho_i^{(0)}\right)^2\right] + \rho_{0i}^\dagger \rho_{0i} + \frac{1}{2}\rho_{ij}^\dagger \rho_{ij}$$

$$+m_\rho^2(\rho_0^\dagger \rho_0 + \rho_i^\dagger \rho_i) - \frac{e}{g_s}F_{0i}\rho_{0i}^{(0)} - \frac{e}{2g_s}F_{ij}\rho_{ij}^{(0)}$$

- Disregard kinetic terms (for a moment) and apply B_{ext}:

$$\epsilon_0^{(2)}(\rho_\mu) = ieB_{\text{ext}}(\rho_1^\dagger \rho_2 - \rho_2^\dagger \rho_1) + m_\rho^2 \rho_\mu^\dagger \rho_\mu$$

$$= \sum_{a,b=1}^{2} \rho_a^\dagger \mathcal{M}_{ab}\rho_b + m_\rho^2(\rho_0^\dagger \rho_0 + \rho_3^\dagger \rho_3)$$

$$\mathcal{M} = \begin{pmatrix} m_\rho^2 & ieB_{\text{ext}} \\ -ieB_{\text{ext}} & m_\rho^2 \end{pmatrix}$$

mass matrix

$$\vec{B} = (0, 0, B)$$

- Eigenvalues and eigenvectors of the mass matrix:

$$\mu_\pm^2 = m_\rho^2 \pm eB_{\text{ext}}\,, \qquad \rho_\pm = \frac{1}{\sqrt{2}}(\rho_1 \pm i\rho_2)$$

At the critical value of the magnetic field: imaginary mass (=condensation)!

Homogeneous approximation (II)

- The condensate of the rho mesons: $\rho_1 = -i\rho_2 = \rho$

- The energy of the condensed state:

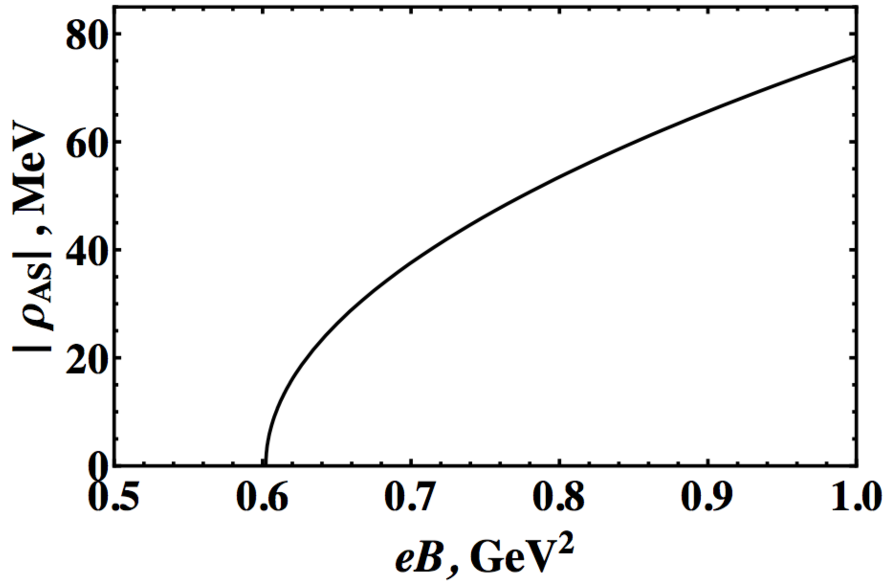
$$\epsilon_0(\rho) = \frac{1}{2} B_{\rm ext}^2 + 2(m_\rho^2 - eB_{\rm ext})\,|\rho|^2 + 2g_s^2\,|\rho|^4$$

(basically, a Ginzburg-Landau potential for an s-wave superconductivity!)

- The amplitude of the condensate:

$$|\rho|_0 = \begin{cases} \sqrt{\frac{e(B_{\rm ext} - B_c)}{2g_s^2}}, & B_{\rm ext} \geqslant B_c \\ 0, & B_{\rm ext} < B_c \end{cases}$$

(qualitatively the same picture in NJL)



Second order (quantum) phase transition, critical exponent = 1/2

Structure of the condensates

In terms of quarks, the state $\rho_1 = -i\rho_2 = \rho$ implies

$$\langle \bar{u}\gamma_1 d\rangle = \rho(x_\perp)\,, \qquad \langle \bar{u}\gamma_2 d\rangle = i\rho(x_\perp)$$

Depend on transverse coordinates only

(the same results in different models, for example, in Nambu-Jona-Lasinio)

$$\vec{B} = (0, 0, B)$$

$U(1)_{\rm e.m.}$: $\rho(x) \to e^{i\omega(x)}\rho(x)$ Abelian gauge symmetry

$O(2)_{\rm rot}$: $\rho(x) \to e^{i\varphi}\rho(x)$ Rotations around B-axis

- The condensate "locks" rotations around field axis and gauge transformations:

$$U(1)_{\rm e.m.} \times O(2)_{\rm rot} \to U(1)_{\rm locked}$$

Basic features of ρ meson condensation

- The condensate of the ρ mesons appears in a form of an inhomogeneous state, analogous to the Abrikosov lattice in the mixed state of type-II superconductors.

A similar state, the vortex state of W bosons, may appear in Electroweak model in the strong external magnetic field [Ambjorn, Olesen (1989)]

- The condensate forms a lattice, which is made of the new type of topological defects, the ρ vortices.

- The emergence of the condensate of the charged ρ mesons induces spontaneous condensation of the neutral ρ mesons.

- The condensate of charged ρ mesons implies superconductivity.
- The condensate of neutral ρ mesons implies superfluidity.

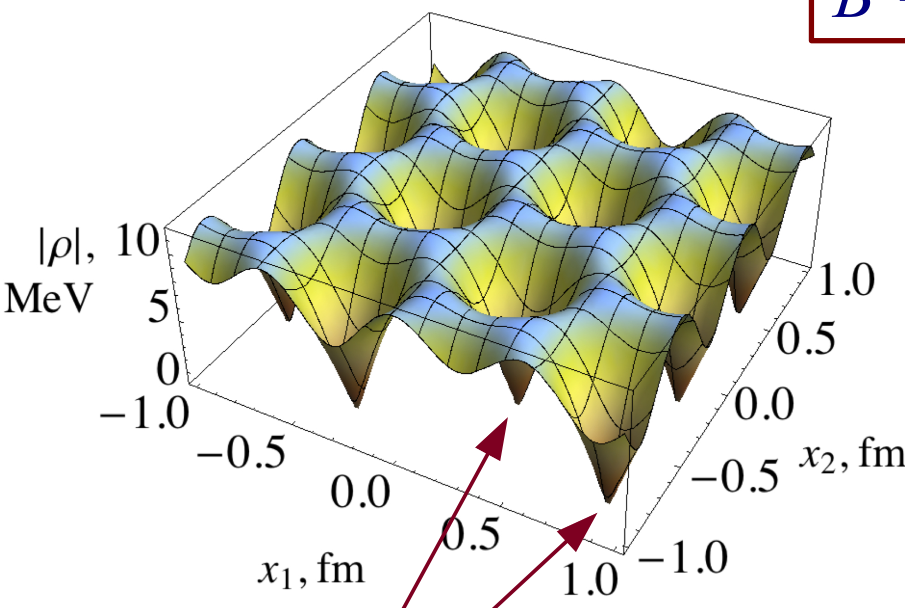
- Unusual optical properties of the superconducting state:
It is a metamaterial ("perfect lens" optical phenomenon) with negative electrical permittivity (ε), negative magnetic permeability (μ), negative index of refraction (n) [Smolyaninov, PRL 107, 253903 (2011)].

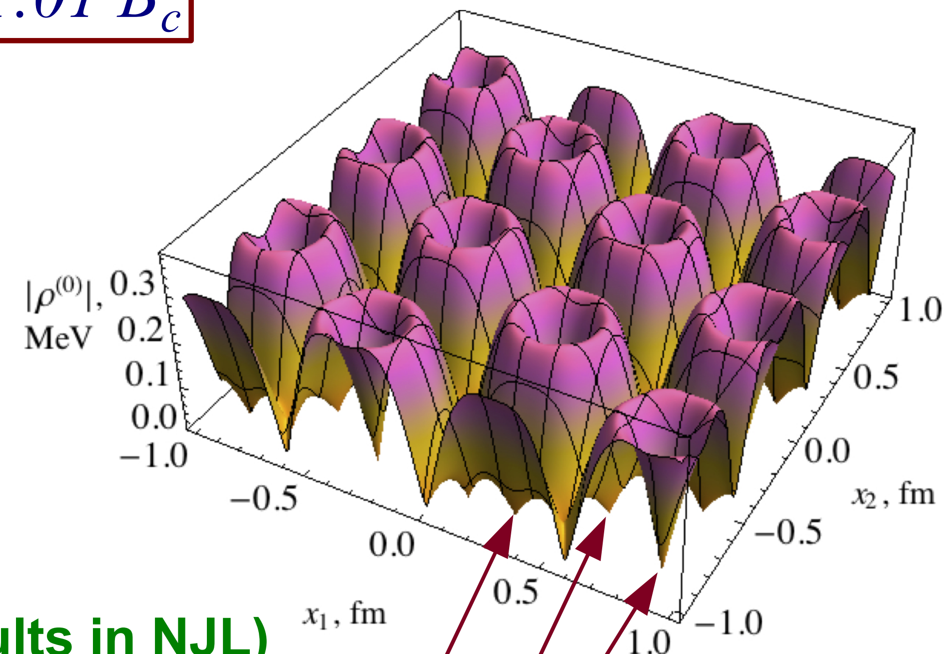
Solution for condensates of ρ mesons

Superconducting condensate
(charged rho mesons)

$B = 1.01\ B_c$

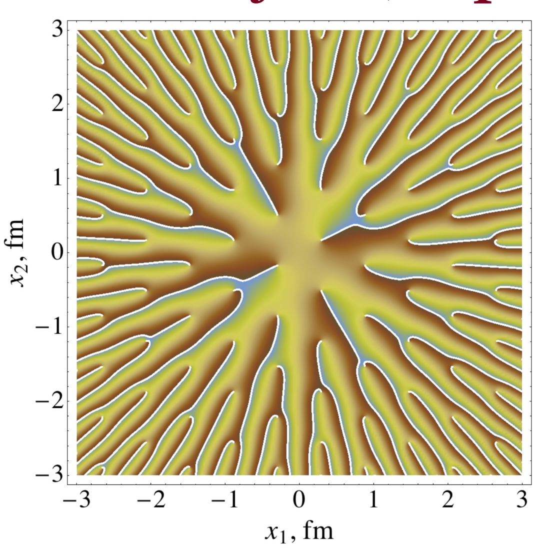
Superfluid condensate
(neutral rho mesons)



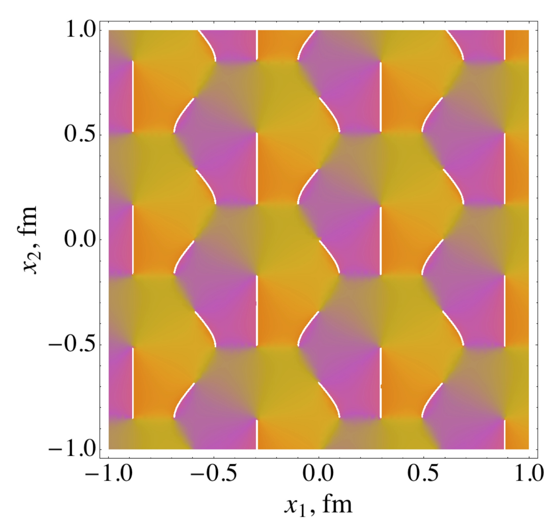


(similar results in NJL)

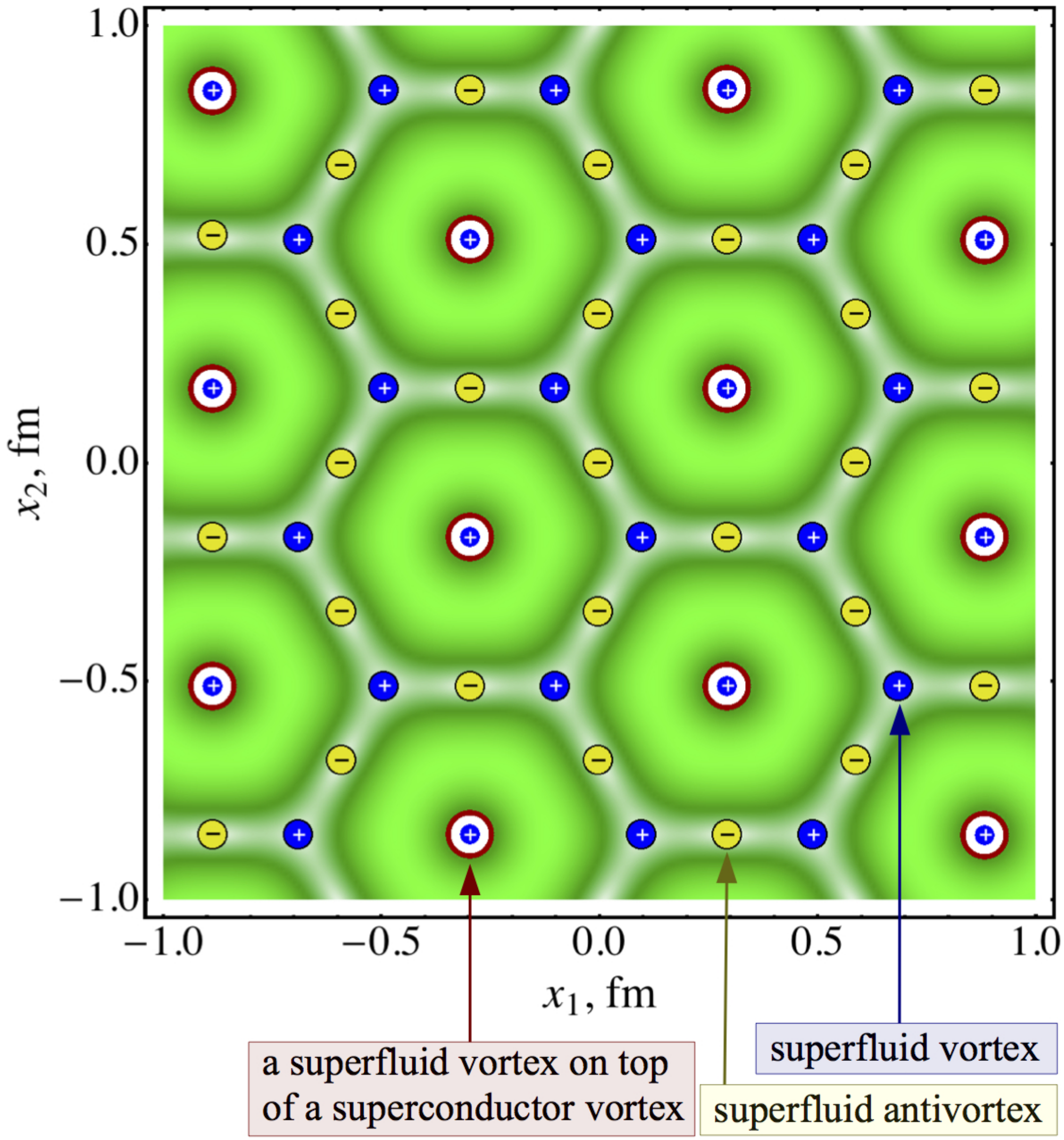
New objects, topological vortices, made of the rho-condensates



The phases of the rho-meson fields wind around vortex centers, at which the condensates vanish.



Topological structure of the ρ mesons condensates



Anisotropic superconductivity
(via an analogue of the London equations)

- Apply a weak electric field ***E*** to an ordinary superconductor
- Then one gets accelerating electric current along the electric field:

$$\frac{\partial \vec{J}_{\rm GL}}{\partial t} = m_A^2 \vec{E}$$ [London equation]

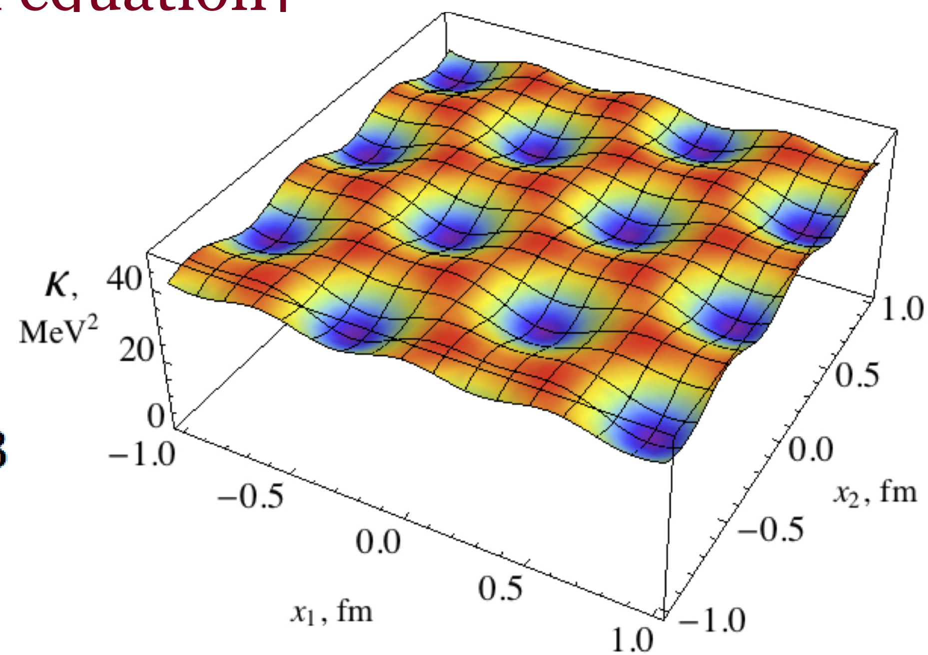
- In the QCDxQED vacuum, we get an accelerating electric current along the magnetic field ***B***:

$$\frac{\partial}{\partial t}\langle J_3 \rangle = -\frac{2e^3}{g_s^2}(B_{\rm ext} - B_c)E_3$$

$$\frac{\partial}{\partial t}\langle J_1 \rangle = \frac{\partial}{\partial t}\langle J_2 \rangle = 0$$

$$(\text{for } B \geqslant B_c)$$

Written for an electric current averaged over one elementary (unit) rho-vortex cell



(similar results in NJL)

Basic features of ρ meson condensation, results
(now we are solving the full set of equations of motion)

- The condensate of the ρ mesons appears in a form of an inhomogeneous state, analogous to the Abrikosov lattice in the mixed state of type-II superconductors.

A similar state, the vortex state of W bosons, may appear in Electroweak model in the strong external magnetic field [Ambjorn, Olesen (1989)]

- The condensate forms a lattice, which is made of the new type of topological defects, the ρ vortices.

- The emergence of the condensate of the charged ρ mesons induces spontaneous condensation of the neutral ρ mesons.

- The condensate of charged ρ mesons implies <u>superconductivity</u>.

- The condensate of neutral ρ mesons implies <u>superfluidity</u>.

Anisotropic superconductivity
(Lorentz-covariant form of the London equations)

We are working in the vacuum, thus the transport equations may be rewritten in a Lorentz-covariant form:

Electric current averaged over one elementary rho-vortex cell

$$\partial_{[\mu,} j_{\nu]} = \kappa \frac{(F \cdot \widetilde{F})}{(F \cdot F)} \widetilde{F}_{\mu\nu}$$

A scalar function of Lorentz invariants.
In this particular model:

$\kappa = (e^3/g_s^2)(\sqrt{(F \cdot F)/2} - B_c)$

(slightly different form of κ function in NJL)

Lorentz invariants:

$(F \cdot \widetilde{F}) = F^{\mu\nu} \widetilde{F}_{\mu\nu} \equiv 4(\vec{B} \cdot \vec{E})$

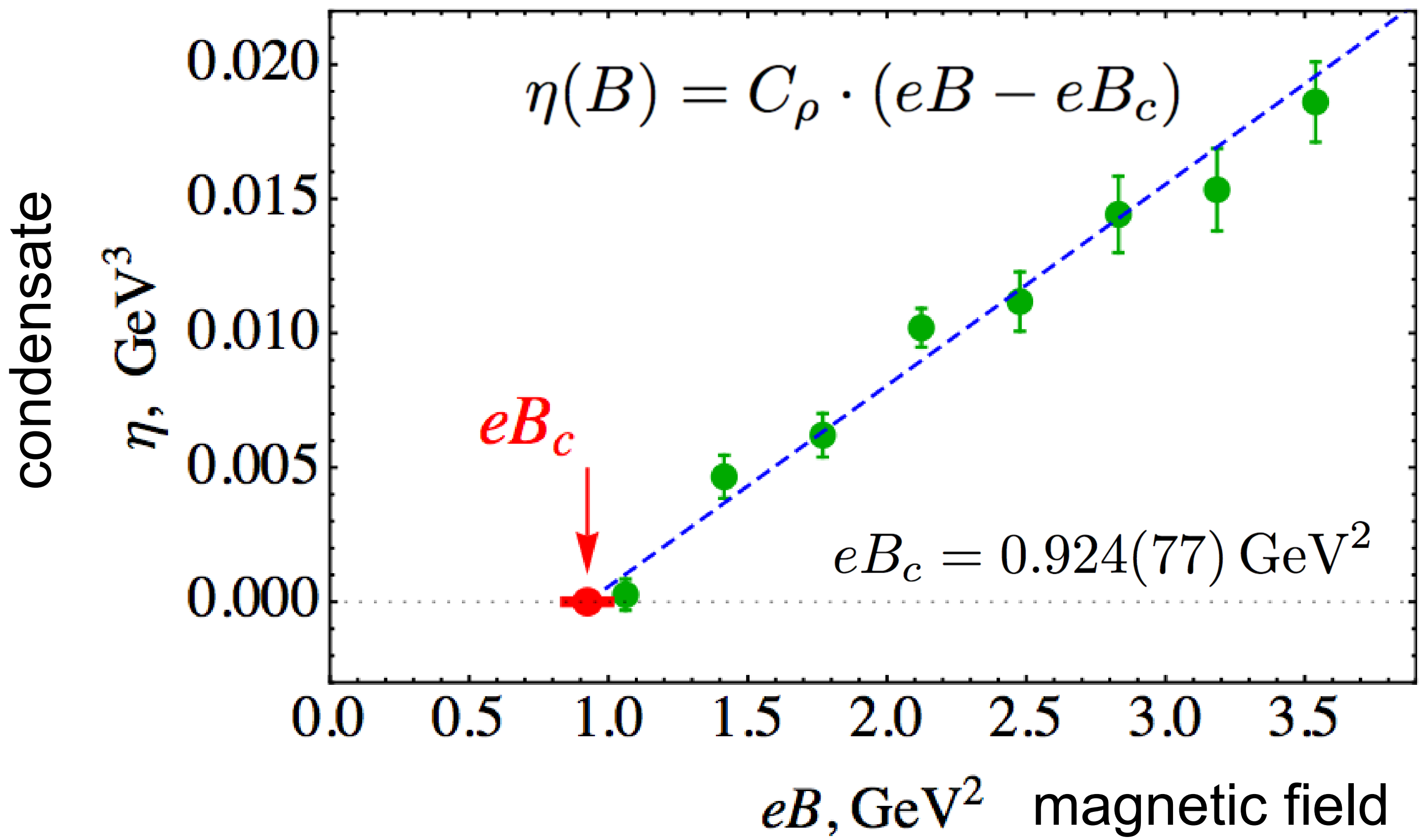
$(F \cdot F) = F^{\mu\nu} F_{\mu\nu} \equiv 2(\vec{B}^2 - \vec{E}^2)$

$\widetilde{F}_{\mu\nu} = \frac{1}{2} \varepsilon_{\mu\nu\alpha\beta} F^{\alpha\beta}$

Numerical simulations of vacuum in the magnetic field background

V.Braguta, P. Buividovich, M. Polikarpov, M.Ch., arXiv:1104.3767

Numerical simulation: $B_c = (1.56 \pm 0.13) \cdot 10^{16}\,\text{Tesla}$



Theory:

$$B_c = \frac{m_\rho^2}{e} \approx 10^{16}\,\text{Tesla}$$

$$\eta \sim \sqrt{B - B_c}$$

for $B \geqslant B_c$

[qualitatively realistic vacuum, quantitative results may receive corrections (20%-50% typically)]

Too strong magnetic field?

$$B_c = \frac{m_\rho^2}{e} \approx 10^{16}\,\text{Tesla}$$

Over-critical magnetic fields (of the strength $B \sim 2\,B_c$) may be generated in ultraperiferal heavy-ion collisions (duration is short, however – clarifications are needed)

W. T. Deng and X. G. Huang,
Phys.Rev. C85 (2012) 044907 [arXiv:1201.5108]

A bit of dreams (in deep verification stage):

Signatures of the superconducting state of the vacuum could possibly be found in ultra-periferal heavy-ion collisions at LHC.
[ultra-periferal: cold vacuum is exposed to strong magnetic field]

Early Universe?

Conclusions

- In a sufficiently strong magnetic field condensates with $\rho^{\pm}$ meson quantum numbers are formed spontaneously via a second order phase transition with the critical exponent 1/2.

- The vacuum (= no matter present, = empty space, = nothing) becomes electromagnetically superconducting.

- The superfluidity of the neutral ρ^{0} mesons emerges as well.

- The superconductivity is anisotropic: the vacuum behaves as a superconductor only along the axis of the magnetic field.

- New type of tological defects,"ρ vortices", emerge.

- The ρ vortices form Abrikosov-type lattice in transverse directions.

- The Meissner effect is absent.