FFLO States in Holographic Superconductors

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Work in progress with J. Alsup and S. Siopsis, first results in [arXiv:1208.4582 [hep-th]]
Dedicated to the memory of Petros Skamagoulis

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Outline

Introduction

The application of the AdS/CFT correspondence to condense matter physics has developed into one of the most productive topics of string theory.

Holographic principle: understanding strongly coupled phenomena of condensed matter physics by studying their weakly coupled gravity duals.

Applications to:

- Conventional and unconventional superfluids and superconductors
  [S. A. Hartnoll, C. P. Herzog, and G. T. Horowitz, Phys. Rev. Lett. **101**, 031601 (2008)]
- Fermi liquids
  [S. Bhattacharyya, V. E. Hubeny, S. Minwalla and M. Rangamani, JHEP **0802**, 045 (2008)]
- Quantum phase transitions
  [M. Cubrovic, J. Zaanen and K. Schalm, Science **325**, 439 (2009)]

In cuprates and iron pnictides which are high-Tc superconductors it was found that competing orders coexist indicating that there is a breaking of the lattice symmetries. This breaking introduces inhomogeneities.

Spatially inhomogeneous phases appear in:

- Models with spontaneous modulation of the electronic charge (CDW) and spin density (SDW), below a critical temperature T_c.

  [A. Aperis, P. Kotetes, E. Papantonopoulos, G. Siopsis, P. Skamagoulis and G. Varelogiannis, Phys. Lett. B **702**, 181 (2011)]

  [R. Flauger, E. Pajer and S. Papanikolaou, Phys. Rev. D **83**, 064009 (2011)]
- Strong magnetic field induces inhomogeneous structures in holographic superconductors.

  [T. Albash and C. V. Johnson, JHEP **0809**, 121 (2008), [arXiv:0804.3466 [hep-th]]]
- Spatially modulated phases were generated in five-dimensional Einstein-Maxwell theory with a Chern-Simons term.

  [K. Maeda, M. Natsuume and T. Okamura, Phys. Rev. D **81**, 026002 (2010), [arXiv:0910.4475 [hep-th]]]
- Inhomogeneous structures were also investigated in holographic superconductors including domain wall like defects.

  [V. Keranen, E. Keski-Vakkuri, S. Nowling and K. P. Yogendran, Phys. Rev. D **80**, 121901 (2009) [arXiv:0906.5217 [hep-th]]]

Holographic principle: Homogeneous superfuilds

- The gravity sector consists of a system with a black hole and a charged scalar field, in which the black hole admits scalar hair at temperature smaller than a critical temperature, while there is no scalar hair at larger temperatures.

- This breaking of the Abelian $U(1)$ symmetry corresponds in the boundary theory to a scalar operator which condenses at a critical temperature proportional to the charged density of the scalar potential.

- Fluctuations of the vector potential below the critical temperature give the frequency dependent conductivity in the boundary theory.

Holographic principle: Inhomogeneous superfuilds

- Introduce a modulated chemical potential which is translated into a modulated boundary value for the electrostatic potential in the AdS black hole gravity background.
- From an Einstein-Maxwell scalar system solutions can be obtained, which below a critical temperature show that the system undergoes a phase transition and a condensate can develop with a non vanishing modulation. Depending on what symmetries are broken, the modulated condensate corresponds to ordered states like CDW or SDW in the boundary.

FFLO states

- Appearance of FFLO states

⋇ Modulated order parameters appear as competing phases with normal superconducting phases in superconductor-ferromagnetic (S/F) systems.

⋇ Strong magnetic field, coupled to the spins of the conduction electrons, gives rise to a separation of the Fermi surfaces corresponding to electrons with opposite spins. If the separation is too high, the pairing is destroyed and there is a transition from the superconducting state to the normal one (paramagnetic effect).

⋇ A a new state could be formed, close to the transition line. This state, known as the FFLO state, has the feature of exhibiting an order parameter, which is not a constant, but has a space variation.
[P. Fulde and R. A. Ferrell, Phys. Rev. 135, A550 (1964)]
[A. I. Larkin and Y. N. Ovchinnikov, Zh. Eksp. Teor. Fiz. 47, 1136 (1964) [Sov. Phys. JETP 20, 762 (1965)]]

⋇ The space modulation arises because the electron pair has nonzero total momentum, and it leads to the possibility of a nonuniform or anisotropic ground state, breaking translational and rotational symmetries.

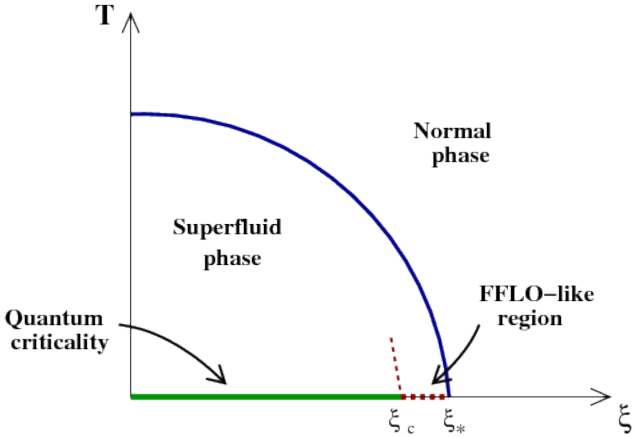


Figure: The (qualitative) phase diagram of holographic superfluids. At zero temperature, a quantum critical point is found for velocities below a critical value, ξ_c where $\xi = A_x/\mu$ is the superfluid velocity. Above ξ_c the system enters a more anisotropic phase.

(This figure appears in D. Arean, M. Bertolini, C. Krishnan and T. Prochazka, JHEP **1109**, 131 (2011))

▶ Generalized Ginzburg-Landau expansion: FFLO states

In the standard Ginzburg-Landau functional

$$F = a|\psi|^2 + \gamma|\vec{\nabla}\psi|^2 + \frac{b}{2}|\psi|^4$$

where ψ is the superconducting order parameter, the coefficient a vanishes at the transition temperature T_c. At $T < T_c$, the coefficient a is negative and the minimum of F occurs for a uniform superconducting state with $|\psi|^2 = -a/b$.

In the case of the paramagnetic effect all the coefficients in the F functional will be proportional to the magnetic field B. Then the coefficient γ changes its sign at a point in the (B, T) phase diagram indicating that the minimum of the functional does not correspond to a uniform state, and a spatial variation of the order parameter decreases the energy of the system.

To describe such a situation it is necessary to add a higher order derivative term in the expansion of F:

$$F_G = a(B,T)|\psi|^2 + \gamma(B,T)|\vec{\nabla}\psi|^2 + \frac{\eta(B,T)}{2}|\vec{\nabla}^2\psi|^2 + \frac{b(B,T)}{2}|\psi|^4$$

(See the review A. I. Buzdin, Rev. Mod. Phys. **77**, 935 (2005))

▶ Attemps to generate gravity duals of FFLO states

※ A theory resulting from a consistent truncation of low energy type IIB string theory was considered with action

$$S_{IIB} = \int d^5x\sqrt{-g}\Big[R - \frac{L^2}{3}F_{ab}F^{ab} + \frac{1}{4}\left(\frac{2L}{3}\right)^3 \epsilon^{abcde}F_{ab}F_{cd}A_e + -\frac{1}{2}\left((\partial_a\psi)^2 + \sinh^2\psi(\partial_a\theta - 2A_a)^2 - \frac{6}{L^2}\cosh^2\left(\frac{\psi}{2}\right)(5-\cosh\psi)\right)\Big]$$

were the scalar was splitted into a phase and its modulus in the form $\psi e^{i\theta}$. The Abelian gauge field A was dual to an R-symmetry in the boundary field theory and the scalar field has R-charge $R = 2$.

They analyzed the theory and they found that when the superfluid velocity $\xi = A_{x,0}/\mu$ becomes too large the anisotropy becomes too strong to be washed out in the IR. They conjectured that this behaviour may be connected with anisotropic FFLO phase.

[D. Arean, M. Bertolini, C. Krishnan and T. Prochazka, JHEP **1109**, 131 (2011)]]

※ A s-wave unbalanced unconventional superconductor in $2+1$ dimensions was considered with action

$$S=\frac{1}{2\kappa_4^2}\int dx^4\sqrt{-g}\left[\mathcal{R}+\frac{6}{L^2}-\frac{1}{4}F_{ab}F^{ab}-\frac{1}{4}Y_{ab}Y^{ab}-V(|\psi|)-|\partial\psi-iqA\psi|^2\right]$$

The Maxwell field A_a (resp. B_a) with field strength $F=dA$ (resp. $Y=dB$) is the holographic dual of the $U(1)_A$ "charge" (resp. $U(1)_B$ "spin") current of the $2+1$ dimensional field theory. The following ansatz for the fields was considered

$$\psi=\psi(r),\quad A_a dx^a=\phi(r)dt,\quad B_a dx^a=v(r)dt$$

and the vector fields at the boundary were given by

$$\begin{aligned}\phi(r) &= \mu-\frac{\rho}{r}+\ldots \quad \text{as} \quad r\to\infty\,,\\ v(r) &= \delta\mu-\frac{\delta\rho}{r}+\ldots \quad \text{as} \quad r\to\infty\end{aligned}$$

They analyzed the theory but no evidence for a FFLO state was found.

[F. Bigazzi, A. L. Cotrone, D. Musso, N. P. Fokeeva and D. Seminara, JHEP **1202**, 078 (2012) [arXiv:1111.6601 [hep-th]]

Holographic FFLO states

Consider the action

$$S = \int d^4x\sqrt{-g}\left[\frac{R + 6/L^2}{16\pi G} - \frac{1}{4}F_{AB}F^{AB} - \frac{1}{4}\mathcal{F}_{AB}\mathcal{F}^{AB}\right]$$

where $F_{AB} = \partial_A A_B - \partial_B A_A$, $\mathcal{F}_{AB} = \partial_A \mathcal{A}_B - \partial_B \mathcal{A}_A$ are the field strengths of the $U(1)$ potentials A_A and $\mathcal{A}_A$, respectively.
The Einstein-Maxwell equations admit a solution which is a four-dimensional AdS black hole of two $U(1)$ charges,

$$ds^2 = \frac{1}{z^2}\left[-h(z)dt^2 + \frac{dz^2}{h(z)} + dx^2 + dy^2\right]$$

with the horizon radius set at $z = 1$.

The two sets of Maxwell equations admit solutions of the form, respectively,

$$A_t = \mu\,(1-z)\ ,\quad A_z = A_x = A_y = 0$$

and

$$\mathcal{A}_y = \mathcal{B}x\ ,\quad \mathcal{A}_t = \mathcal{A}_x = \mathcal{A}_z = 0$$

with corresponding field strengths having non-vanishing components for an electric and a magnetic field in the z-direction, respectively,

$$F_{tz} = -F_{zt} = \mu\ \ ,\qquad \mathcal{F}_{xy} = -\mathcal{F}_{yx} = \mathcal{B}$$

Then from the Einstein equations we obtain

$$h(z) = 1 - \left(1 + \frac{\mathcal{B}^2 + \mu^2}{4}\right) z^3 + \frac{\mathcal{B}^2 + \mu^2}{4} z^4$$

The Hawking temperature is

$$T = -\frac{h'(1)}{4\pi} = \frac{3}{4\pi}\left[1 - \frac{\mathcal{B}^2 + \mu^2}{12}\right]$$

We now consider a scalar field ϕ, of mass m, and $U(1)^2$ charge $(q,0)$, with the action

$$S = \int d^4x\sqrt{-g}\left[|D_A\phi|^2 - m^2|\phi|^2\right]$$

where $D_A = \partial_A + iqA_A$.
The asymptotic behavior (as $z \to 0$) of the scalar field is

$$\phi \sim z^{\Delta} \quad , \qquad \Delta(\Delta - 3) = m^2$$

For a given mass, there are, in general, two choices of Δ,

$$\Delta = \Delta_{\pm} = \frac{3}{2} \pm \sqrt{\frac{9}{4} + m^2}$$

leading to two distinct physical systems.

As we lower the temperature, an instability arises and the system undergoes a second-order phase transition with the black hole developing hair. This occurs at a critical tempearture T_c which is found by solving the scalar wave equation in the above background,

$$\partial_z^2\phi + \left[\frac{h'}{h} - \frac{2}{z}\right]\partial_z\phi + \frac{1}{h}\nabla_2^2\phi - \frac{1}{h}\left[\frac{m^2}{z^2} - q^2\frac{A_t^2}{h}\right]\phi = 0$$

Although the above wave equation possesses (x, y)-dependent solutions, the symmetric solution dominates and the hair that forms has no (x, y) dependence. To see this, let us introduce x-dependence and consider a static scalar field of the form

$$\phi(z, x, y) = \psi(z)e^{iQx}$$

The wave equation becomes

$$\psi'' + \left[\frac{h'}{h} - \frac{2}{z}\right]\psi' - \frac{Q^2}{h}\psi - \frac{1}{h}\left[\frac{m^2}{z^2} - q^2\frac{A_t^2}{h}\right]\psi = 0$$

There is a scaling symmetry

$$
\begin{aligned}
z &\to \lambda z \ , \quad x \to \lambda x \ , \quad Q \to Q/\lambda \ , \\
\mu &\to \mu/\lambda \ , \quad \mathcal{B} \to \mathcal{B}/\lambda^2 \ , \quad T \to T/\lambda
\end{aligned}
$$

so we work only with scale-invariant quantities, such as T/μ, $\mathcal{B}/\mu^2$, Q/μ, etc. It is convenient to introduce the scale-invariant parameter

$$
\beta = \frac{\sqrt{\mathcal{B}}}{q\mu}
$$

to describe the effect of the magnetic field $\mathcal{B}$ of the second $U(1)$.

The system is defined uniquely by specifying the parameters q and Δ. Then the critical temperature at which the second-order phase transition occurs is,

$$\frac{T_c}{\mu} = \frac{T}{\mu_c} = \frac{3}{4\pi\mu_c}\left[1 - \frac{\mu_c^2(1+q^4\beta^4\mu_c^2)}{12}\right]$$

For $Q = 0$, we recover the homogeneous solution. As we increase β, the temperature decreases. For a given $\beta > 0$, the black hole is of the Reissner-Nordström form with effective chemical potential

$$\mu_{\text{eff}}^2 = \mu_c^2(1+q^4\beta^4\mu_c^2)$$

The scalar wave equation is the same as its counterpart in a Reissner-Nordström background, but with effective charge

$$q_{\text{eff}}^2 = \frac{q^2}{1+q^4\beta^4\mu_c^2}$$

so that $q_{\text{eff}}\mu_{\text{eff}} = q\mu_c$.

An instability occurs for all values of q_{eff}, including $q_{\text{eff}} = 0$, if $\Delta \leq \Delta_*$, where $\Delta_* = \Delta_+$ for $m^2 = -\frac{3}{2}$, or explicitly,

$$\Delta_* = \frac{3+\sqrt{3}}{2} \approx 2.366$$

For $\Delta \leq \Delta_*$, β can increase indefinitely. The critical temperature has a minimum value and as $\beta \to \infty$, T_c diverges.
For $\Delta > \Delta_*$, q_{eff} has a minimum value at which the critical temperature vanishes and the black hole attains extremality. This is found by considering the limit of the near horizon region. One obtains

$$q_{\text{eff}} \geq q_{\text{min}} \quad , \qquad q_{\text{min}}^2 = \frac{3 + 2\Delta(\Delta - 3)}{4}$$

At the minimum ($T_c = 0$), $\mu_{\text{eff}}^2 = 12$, and β attains its maximum value,

$$\beta \leq \beta_{\text{max}} \quad , \qquad \beta_{\text{max}}^4 = \frac{1}{12 q_{\text{min}}^2} \left(\frac{1}{q_{\text{min}}^2} - \frac{1}{q^2} \right)$$

This limit is reminiscent of the Chandrasekhar and Clogston limit in a S/F system, in which a ferromagnet at $T = 0$ cannot remain a superconductor with a uniform condensate.
[B. S. Chandrasekhar, Appl. Phys. Lett. 1, 7 (1962). A. M. Clogston, Phys. Rev. Lett. 9, 266 (1962)]

In the inhomogeneous case ($Q \neq 0$), the above argument still holds with the replacement $m^2 \to m^2 + Q^2$. The effect of this modification is to increase the minimum effective charge to

$$q_{\text{min}}^2 = \frac{3 + 2\Delta(\Delta - 3) + 2Q^2}{4}$$

and thus decrease the maximum value of β.

We always obtain a critical temperature which is lower than the corresponding critical temperature (for same β) in the homogeneous case ($Q = 0$).

Now let us add a magnetic interaction term to the action,

$$S_{\text{int}} = \xi \int d^4x \sqrt{-g}\, |\mathcal{F}^{AB} \partial_B \phi|^2$$

The wave equation is modified to

$$\begin{aligned} \psi'' + \left[\frac{h'}{h} - \frac{2}{z}\right]\psi' - \frac{Q^2}{h}\left[1 - \xi \mathcal{B}^2 z^4\right]\psi & \\ -\frac{1}{h}\left[\frac{m^2}{z^2} - q^2 \frac{A_t^2}{h}\right]\psi &= 0 \end{aligned}$$

Evidently, if we set $Q = 0$, the effect of the interaction term (1) disappears, therefore the homogeneous solution is unaltered. For $Q \neq 0$, we obtain modified solutions. The behavior is shown in figure 4. The figure also displays the effect of Q on $\beta_{\max}$ (1) for $\xi = 0$.

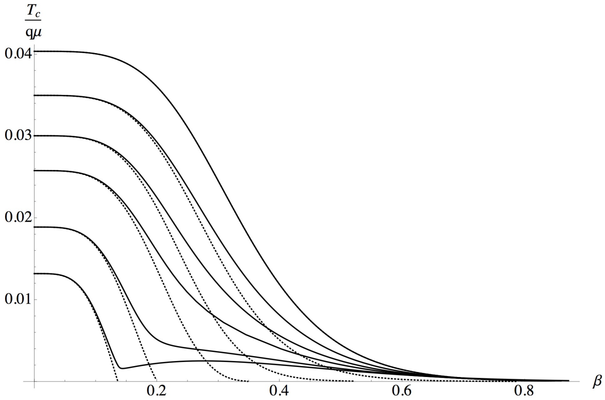


Figure: The critical temperature *vs.* the magnetic field numerically calculated with $q = 10$ and $\Delta = 5/2$. The dotted lines are calculated with $\xi = 0$ while the solid use $\xi = .10$. Starting from the top, on the vertical axis, the lines are $\frac{Q^2}{(q\mu)^2} = 0,\ .05,\ .10,\ .15,\ .25,$ and $.35$.

The interaction term alters the near horizon limit of the theory so that $m^2 \to m^2 + Q^2\left(1 - \xi q^4 \beta^4 \mu_c^4\right)$.

The modifications are most pronounced for large β leading to temperatures which are higher than the critical temperature of the corresponding homogeneous solution.

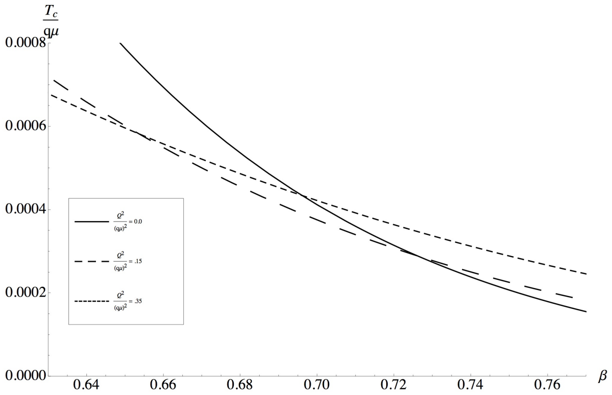


Figure: The top line on the left-hand side of the graph corresponds to the homogeneous solution, with lines $\frac{Q^2}{(q\mu)^2} = .15, .35$ below. The critical temperature of the homogeneous solution is found to decrease below the inhomogeneous lines for large β. We used $q = 10$, $\Delta = 5/2$, and $\xi = .10$.

Geometrical generation of holographic FFLO states

To generate the gravity dual of a FFLO state there must be a direct coupling of the magnetic field to the scalar field which condenses.

Why not generate this coupling geometrically?

Consider again the action

$$S=\int d^4x\sqrt{-g}\left[\frac{R+6/L^2}{16\pi G}-\frac{1}{4}F_{AB}F^{AB}-\frac{1}{4}\mathcal{F}_{AB}\mathcal{F}^{AB}\right]$$

The Maxwell equations have as solutions

$$A_t=\mu\,(1-z)\ \ ,\ \ A_z=A_x=A_y=0$$

and

$$\mathcal{A}_t=\delta\mu(1-z)\ ,\ \ \mathcal{A}_z=\mathcal{A}_x=\mathcal{A}_y=0$$

with corresponding field strengths having non-vanishing components for electric fields in the z-direction, respectively,

$$F_{tz}=-F_{zt}=\mu\ \ ,\quad \mathcal{F}_{tz}=-\mathcal{F}_{zt}=\delta\mu$$

Then from the Einstein equations we obtain

$$h(z) = 1 - \left(1 + \frac{\mu^2 + \delta\mu^2}{4}\right) z^3 + \frac{\mu^2 + \delta\mu^2}{4} z^4$$

The Hawking temperature is

$$T = -\frac{h'(1)}{4\pi} = \frac{3}{4\pi}\left[1 - \frac{\mu^2 + \delta\mu^2}{12}\right]$$

In the limit $\mu, \delta\mu \to 0$ we recover the Schwarzschild black hole.
We now consider a scalar field ϕ, of mass m, and $U(1)^2$ charge $(q, 0)$, coupled to the Einstein tensor. The action is

$$S = \int d^4x\sqrt{-g}\left[\left(g^{AB} + \xi G^{AB}\right)(D_A\phi)^* D_B\phi - m^2|\phi|^2\right]$$

where $D_A = \partial_A + iqA_A$ and G_{AB} is the Einstein tensor.

For $\xi = 0$ the analysis goes through as before.

Now let us consider the effect of the coupling to the Einstein tensor by setting $\xi \neq 0$

The wave equation is modified to

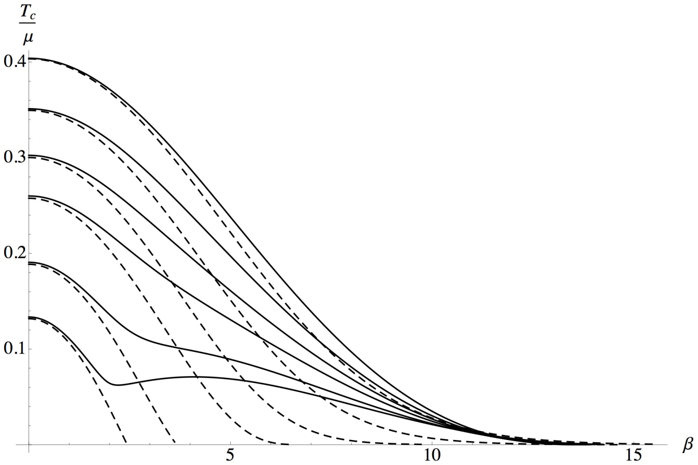
$$\psi'' + \left[\frac{h'}{h} + \frac{f'_+}{f_+} - \frac{2}{z}\right]\psi' - \frac{\tau}{h}\frac{f_-}{f_+}\psi - \frac{1}{h}\left[\frac{m^2}{z^2 f_+} - q^2\frac{A_t^2}{h}\right]\psi = 0$$

where

$$f_\pm = 1 + \xi\left[-3 \pm \frac{\mu^2 + \delta\mu^2}{4} z^4\right]$$

The boundary behavior is altered. As $z \to 0$, we obtain $\phi \sim z^\Delta$, where

$$\Delta = \Delta_\pm = \frac{3}{2} \pm \sqrt{\frac{9}{4} + \frac{m^2}{1 - 3\xi}}$$



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The coupling to the Einstein tensor alters the near horizon limit of the theory so that

$$m^2 \to \frac{m^2 + \tau f_-(1)}{f_+(1)}$$

The minimum effective charge is found by setting $T = 0$. Then $\mu_{\rm eff}^2 = \mu^2 + \delta\mu^2 = 12$, and $f_\pm(1) = 1 + \xi(-3 \pm 3)$. We deduce

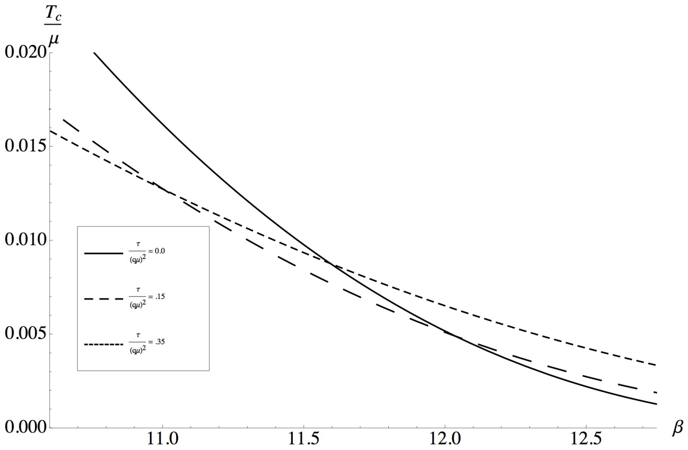
$$q_{\rm min}^2 = \frac{3 + 2\Delta(\Delta - 3) + 2(1 - 6\xi)\tau}{4}$$

For

$$\xi > \frac{1}{6}$$

the minimum charge, we get the maximum value of β, compared to the value in the homogeneous case ($\tau = 0$).

Thus, there is a neighborhood near zero temperature in which the inhomogeneous solution has higher critical temperature than the homogeneous one.



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Conclusions

We have developed a gravity dual of a FFLO state.

- With an interaction term:
  - Introduce two gauge fields one electric one magnetic, acting on spins
  - Introduce inhomogeneities. Temperature always lower than the homogeneous case
  - Introduce interaction term between magnetic field and scalar field. Temperature of inhomogeneous case higher than the homogeneous case. Generation of FFLO states.
- With a derivative coupling:
  - Introduce two gauge fields, the second one with unbalanced chemical potential
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