Phase diagram of strongly interacting four-fermion theory

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Outline

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- A four-fermion lattice model

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- Mass generation without breaking any symmetries

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- Extension to a model of Yukawa-Higgs type

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- Mass generation without breaking any symmetries
- Extension to a model of Yukawa-Higgs type
- A continuum model with topological defects which recovers lattice model upon discretization (if time permits)

Motivation: a (reduced) staggered fermion model

$$S = \sum_{x,\mu} \psi^a \eta_\mu \Delta_\mu \psi^a - \frac{G^2}{4} \sum_x \epsilon^{abcd} \psi^a \psi^b \psi^c \psi^d$$

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Massless phase $G < G_c^1$,narrow broken phase $G_c^1 < G < G_c^2$, Strong coupling: *massive* phase $G > G_c^2$ $SO(4)$ symmetry restored

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Momentum space

$$F(p) = \frac{i\sqrt{6G^2}\sum_\mu sinp_\mu}{\sum_\mu sin^2 p_\mu + m_F^2} \qquad B(p) = \frac{8(6G^2)}{4\sum_\mu sin^2 p_\mu + m_B^2}$$

where $m_F^2 = 4(6G^2) - 2$ and $m_B^2 = 4(6G^2) - 8$

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In the limit $G \to \infty \quad G^2 < \epsilon_{abcd}\psi^a\psi^b\psi^c\psi^d >$ tends to a constant
Fermions are massive at strong coupling.This corresponds to pairing of elementary fermion ψ with composite fermion $\Psi_a = \epsilon_{abcd}\psi^b\psi^c\psi^d$
Four fermion condensate can be thought of as a bilinear formed from Ψ_a and ψ^a

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$\kappa = 0$ is our original four-fermion model with symmetric mass generation

Coleman-Weinberg effective potential

The question of spontaneous symmetry breaking can be examined by computing the effective potential for ϕ_+

$$S_{eff}(\phi_+) = -\frac{1}{2} Tr \ln(\eta.\Delta + \varepsilon(x) G\phi_+)$$

Assume a constant

$$\phi_+ = \mu \begin{pmatrix} i\sigma_2 & 0 \\ 0 & i\sigma_2 \end{pmatrix}$$

and diagonalize the kinetic operator

$$S_{eff}(\phi_+) = -\frac{1}{4} tr[\ln |(\Delta_\mu^2 - m^2)|]$$

where $m = G^2\mu^2$ and tr denotes a functional trace

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where $m = G^2 \mu^2$ and *tr* denotes a functional trace
The $\varepsilon(x)$ factor is important to get an effective potential of symmetry breaking type because $\{\varepsilon(x), \eta_\mu \Delta^\mu\} = 0$

Positivity of S_{eff}

Computing the functional trace in momentum space the effective potential takes the form

$V_{eff} = -\frac{1}{4}\int d^4p \ln|\frac{\tilde{p}_\mu^2+m^2}{\tilde{p}_\mu^2}|$ where $\tilde{p}_\mu = 2isin(p_\mu)$

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$V_{eff} = -\frac{\alpha}{4}(\phi_+^o)^2 + \frac{\beta}{4}(\phi_+^o)^4$ where ϕ_+^o denotes VEV of ϕ_+
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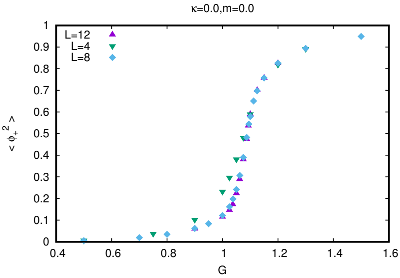
where $\alpha = \int d^4p \frac{1}{\tilde{p}_\mu^2}$ and $\beta = \int d^4p \frac{1}{\tilde{p}_\mu^2 4}$

This argument doesn't generalize to non-local $SO(4)$ invariant bilinears breaking the shift symmetry. To understand the phase structure fully turn to (RHMC) simulation

Phase structure from numerical simulation

Phase structure from numerical simulation



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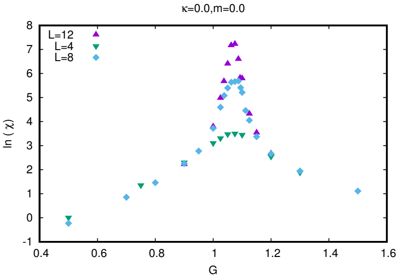

$\frac{1}{V}\sum_x < \chi^a(x)\chi^b(x)\chi^a(0)\chi^b(0) >$

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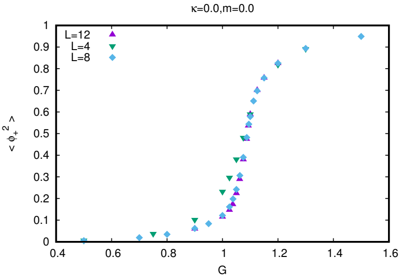

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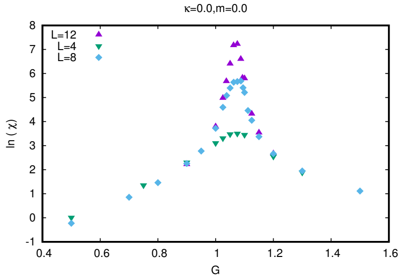

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Connected susceptibility $\chi_{conn} = \frac{1}{V} \sum_x < \chi^a(x)\chi^b(x)\chi^a(0)\chi^b(0) >$
$\chi_{conn} \sim L^4$ in the transition region $G = 1.05$

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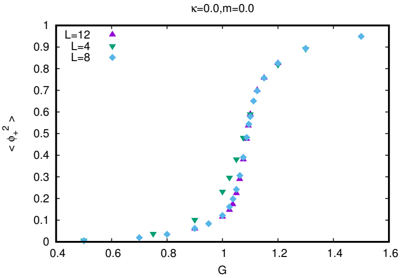

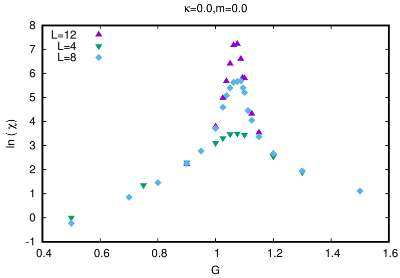

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To look for spontaneous symmetry breaking we augment the action with a symmetry breaking $m\sum_x \varepsilon\psi^a\psi^b$ term and scan in $m \to 0$ limit while $V \to \infty$

Narrow broken phase

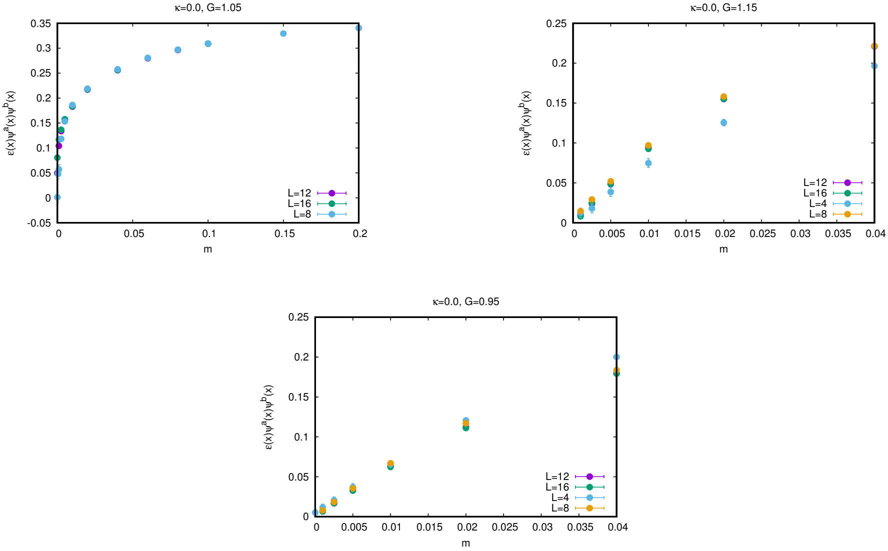

Figure: Left : $G = 1.05$, Right : $G = 1.15$, Bottom : $G = 0.95$

Phase structure with non-zero κ

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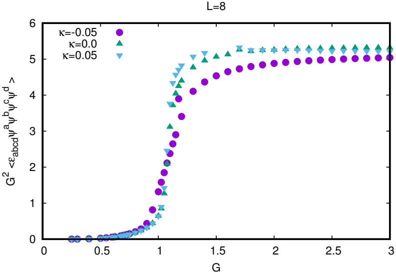

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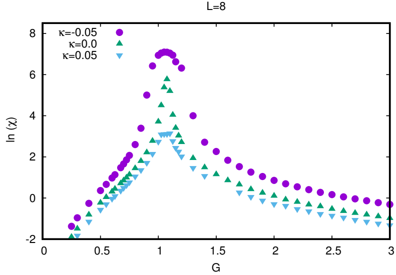

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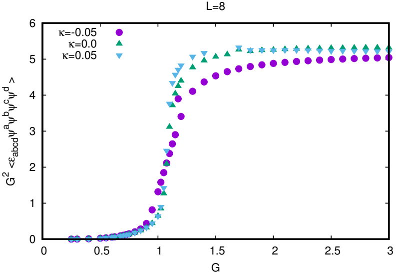

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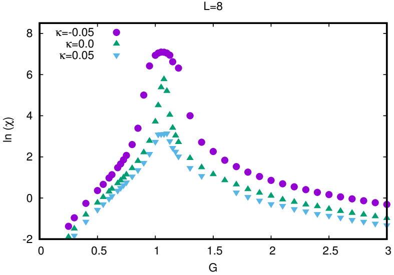

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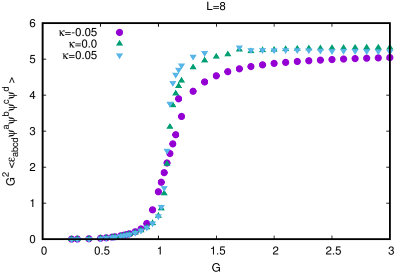

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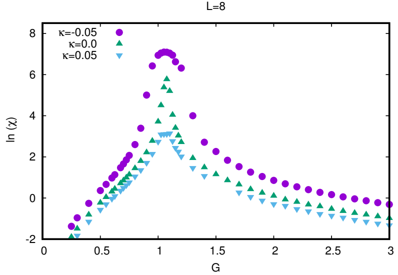

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In both cases the four-fermion condensate exists

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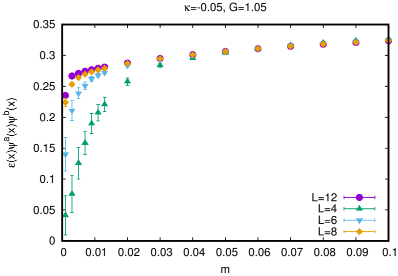

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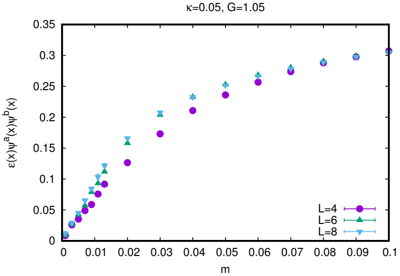

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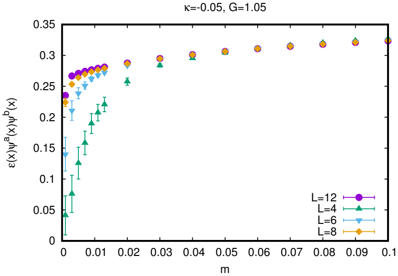

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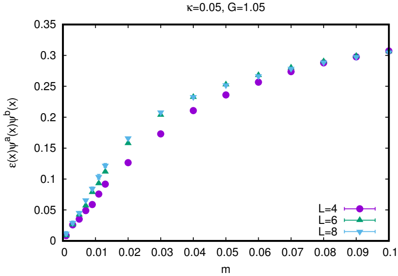
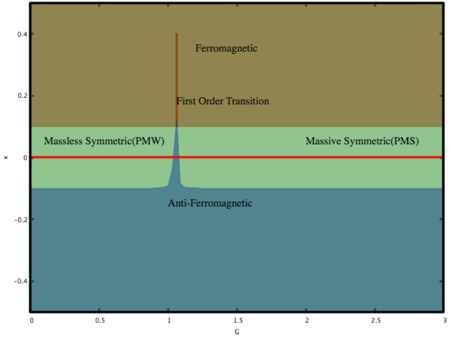


$\kappa = 0.05$

No spontaneous symmetry breaking with small positive κ
This gives a preliminary phase diagram with four different phases

Preliminary Phase Diagram



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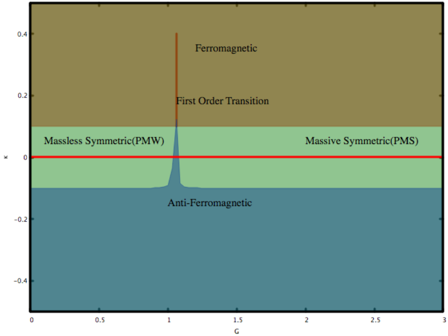

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A model based on Kähler-Dirac fermions discretizes to the staggered fermion model studied **arXiv:1708.06715v2**

Starting Point

Consider 4 Majorana spinors with action

$$S = \int d^4x \sum_{A=1}^{4} \overline{\psi}^A \gamma.\partial\, \psi^A$$

The global symmetry is $G = SO_F(4) \times SO_{Lorentz}(4)$ under which

$$\psi \to L_{\alpha\beta} \psi^B_\beta F^T_{BA}$$

Focus on diagonal subgroup D where $L = F$ under which $\psi \to \Psi$ with Ψ a 4×4 matrix

$$S = \int d^4x \, \mathrm{Tr}\left(\Psi\, \gamma.\partial\, \Psi\right) \quad \text{with } \overline{\Psi} = C\Psi^T C^{-1} = \Psi$$

take 4 copies and add $SO(4)$ invariant interaction

$$\delta S = -G^2 \int d^4x \, \mathrm{Tr}\left(\Psi^a \Psi^b\right) \mathrm{Tr}\left(\Psi^c \Psi^d\right) \epsilon^{abcd}$$

Notice ..

Interaction breaks global symmetry G down to diagonal subgroup D
Additional $SO(4)$ symmetry prevents bilinear mass terms
For small G expect four fermi term irrelevant and get 16 massless Majorana fermions.

Introduce lattice

$$\Psi^a = \sum_b^{16} \gamma^{x+b} \chi^a(x+b) \quad \text{with } b_\mu = 0,1 \qquad \gamma^{x+b} = \prod_{\mu=1}^{4} \gamma_\mu^{x_\mu + b_\mu}$$

If $\partial_\mu \to \Delta_\mu^S$ and do traces

Staggered action !

Auxiliary field

$$S = S_0 + \int d^4x \left[G\phi_+^{ab}\mathrm{Tr}\left(\Psi^a\Psi^b\right) + \frac{1}{2}\left(\phi_+^{ab}\right)^2 \right]$$

where ϕ_+ transforms in adj rep of $SU_+(2)$ subgroup of $SO(4) = SU_+(2) \times SU_-(2)$.

Integrate over fermions $\mathrm{Pf}\left(\gamma.\partial + G\phi_+\right)$. Additional $SU_-(2)$ shows real, positive. Effective action:

$$S_{\mathrm{eff}}(\phi_+) = \frac{1}{2}\phi_+^2 - \frac{1}{4}\mathrm{tr}\ln\left(-\partial^2 + G^2\phi_+^2 + G\gamma.\partial\phi_+\right)$$

If ϕ_+ constant find symmetry breaking potential

$$\phi_+^a = \mu n^a \quad \text{with } n^a n^a = 1 \quad \text{vacuum manifold } S^2$$

Effective Action

Assume broken phase and expand in powers of $\frac{1}{m}$ with $m = \mu G$

$$S_{\text{eff}} = \frac{1}{m^2} \int d^4x \, (\partial_\mu n^a)^2 + \frac{1}{m^4} \int d^4x \, \left(\epsilon^{abc} \partial_\mu n^a \times \partial_\nu n^b\right)^2 + \dots$$

Fadeev-Skyrme term - supports solitons

Analysis easier if change variables:

$$n^a(x)\sigma^a = U^\dagger(x)\sigma_3 U(x)$$

Mapping invariant under

Local $U(1)$

$$U(x) \to e^{i\sigma_3 \beta(x)} U(x)$$

Also global $SU(2)$ symmetry: $U(x) \to U(x)G$

Effective Action II

$$S_{\text{eff}} = \frac{1}{m^2}\int d^4x \, \text{tr}\left[(D_\mu U)^\dagger (D_\mu U)\right] + \frac{1}{m^4}\int d^4x \, F_{\mu\nu}^2$$

where $D_\mu = \partial_\mu + iA_\mu\sigma_3$.

Topological defects

As $m \to \infty$ set $D_\mu U = 0$ for large r. Find

$$A_\mu = \frac{i}{2}\text{tr}\left(\partial_\mu U U^\dagger \sigma_3\right) \qquad \text{and}$$

$$S = b\int d^4x \, \frac{1}{4}\text{tr}\left(\partial_\mu U \partial_\nu U^\dagger \sigma_3\right)^2 \qquad \text{with}$$

$$U = \begin{pmatrix} \alpha_1 + i\alpha_2 & -\alpha_3 + i\alpha_4 \\ \alpha_3 + i\alpha_4 & \alpha_1 - i\alpha_2 \end{pmatrix} \quad \alpha_i = \frac{x_i}{r}$$

Hopf map: $\Pi_3(S^2) = Z$

Role of defects ?

Topological charge gotten from $\int \epsilon_{\mu\nu\rho\lambda} F_{\mu\nu} F_{\rho\lambda}$.

Action $\int F_{\mu\nu}^2$ of single defect $S_{\text{Hopf}} \sim \ln V$

Recall 2D XY model

Single vortex has log divergent action. Pair of vortices has finite action and logarithmic interaction

Conjecture something similar here - pairs of Hopf-antiHopf defects bind in pairs. Play no role for small G but unbind to populate vacuum as $G \to \infty$.

Fermion mass

$$
\begin{aligned}
G_F(x,y) &= \langle \Psi^a(x)\Psi^a(y)\rangle \\
&= \mathrm{tr}\left[\frac{-\gamma_\mu\partial_\mu + m\,n^a\sigma^a}{\left(-\partial_\mu^2 + m^2 + mP\right)}\right]
\end{aligned} \tag{1}
$$

where

$$
P = \gamma_\mu\left(\partial_\mu U^\dagger(x)\sigma_3 U(x) + U^\dagger(x)\sigma_3\partial_\mu U(x)\right)
$$

Far from core $P = 0$ and

$$
G_F(x,y) = \frac{-\gamma_\mu\partial_\mu}{-\Box + m^2}
$$

Fermions acquire mass without breaking symmetries !

Phase structure

As G increased generically expect 3 phases

- $G < G_c^1$ free massless fermions. Trivial IR fixed point. Lorentz and flavor symmetries restored.
- $G_c^1 < G < G_c^2$ Phase with broken $SO(4)$ symmetry. Fermion mass determined by bilinear condensate. Conventional NJL scenario.
- $G > G_c^2$ Four fermion condensate. Auxiliary field picture - proliferation of topological defects. Fermions acquire masses propagating in this background. IR behavior depends on whether phase transition at G_c^2 continuous ..

Summary/Prospects

- Introduced a model based of Kähler-Dirac fermions that discretizes to staggered fermion models studied recently.
- In broken phase topological defects are possible. Give an understanding of how fermions acquire mass at strong coupling without breaking symmetries.

Critical exponents ?
Nature of continuum symmetries ? Is theory Lorentz invariant ?
Can we use this as mechanism for gapping mirrror states in Eichten-Preskill approaches to constructing chiral lattice gauge theories ?

Thank you!

Collaborators

Simon Catterall , David Schaich

Funding and computing resources

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