Revisiting Composite Fermi Liquids

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References

- CW, T. Senthil, 1505.05141; 1507.08290; 1604.06807
- In progress with N. Cooper, A. Stern, B. Halperin

- Related works:
- D. T. Son, 1502.03446
- M. Metlitski, A. Vishwanath, 1505.05142
- D. Mross, J. Alicea, O. Motrunich, 1510.08455; 1605.03582
- ……

Outline

- Introduction: Composite fermi liquids (CFL)
- Dirac CFL at half-filling
- New insights/puzzles from old HLR
- A duality between the two approaches?
- Predictions for transport

Half-filled Landau level

- $2D$ electrons in $\vec{B} = B\hat{z} \to$ Landau levels (LL)
- LL degeneracy $\sim \Phi/2\pi$
- Partial filling: huge degeneracy lifted by interaction $\to$ FQHE, etc.
- $\nu = 1/2$: a compressible state

Composite fermions

- Composite fermion (CF): electron + two vortices (4π-flux)
- At $\nu = \frac{1}{2}$: CF sees no flux on average $\rightarrow$ fermi surface $\oplus$ Chern-Simons gauge field (Halperin, Lee, Read, 1993)
- At $\nu = \frac{n}{2n+1}$: CF fill Landau levels $\rightarrow$ Jain sequence of FQHE

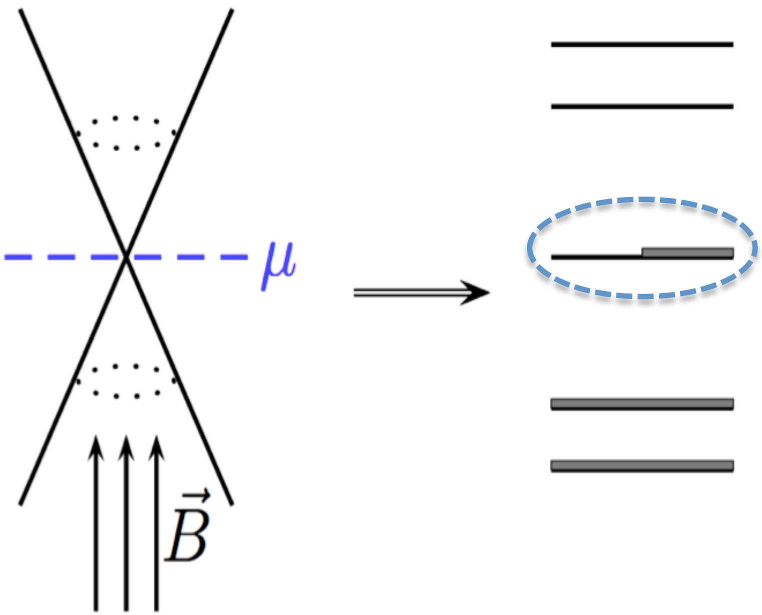
$$\mathcal{L}[\psi, \psi^\dagger, a_\mu + A_\mu] + \frac{1}{8\pi} a da + \ldots$$

Particle-hole symmetry

vs.

- Particle-hole symmetry: emergent at lowest LL $m_e \to 0$
- Anti-unitary $\mathcal{PH}$: $c_i \to c_i^\dagger$
- An old puzzle: HLR theory not manifestly PH-symmetric

Half-filled LL from Dirac fermion



- Finite magnetic field: half-filled Landau level
- Same as 2DEG at $\nu = 1/2$
- Particle-hole symmetry unbroken

$$\mathcal{CT} : \Psi \to i\sigma_2 \Psi^\dagger$$

Dirac-QED duality

$$i\bar{\Psi}\not{D}_A\Psi \quad \leftrightarrow \quad i\bar{\chi}\not{D}_a\chi - \frac{1}{4\pi}adA$$

$$B/4\pi \quad \leftrightarrow \quad n_\chi$$

$$\mathcal{CT}: \Psi \to i\sigma_2\Psi^\dagger \quad \leftrightarrow \quad \mathcal{T}: \chi \to i\sigma_2\chi$$

"Fermionic particle-vortex duality"

(Son; Wang, Senthil; Metlitski, Vishwanath; Mross, Alicea, Motrunich)

Can be formulated more precisely

(Seiber, Senthil, CW, Witten)

Dual picture: $i\bar{\chi}\not{D}_a\chi - \frac{1}{4\pi}adA$

Finite field = finite vortex density

$$n_\chi = \frac{B}{4\pi}$$

Simplest solution: a Fermi surface of dual Dirac fermions!

Particle-hole acts like time-reversal

$$\mathcal{T} : \chi \to i\sigma_2\chi,\ \ \mathcal{T}^2 = (-1)^{N_\chi}$$

Dirac CFL

- Composite fermions look like TI surface!
- Compared with HLR:
  no Chern-Simons term, but a Berry phase of π
- Numerical evidence:
  suppression of certain $2k_f$ singularity
  (Geraedts, et. al, 2015)

What about the good old HLR?

- Lagrangian has no particle-hole symmetry

$$\mathcal{L}[\psi, \psi^\dagger, a_\mu] + \frac{1}{8\pi} ada + ...$$

- But what about the actual low energy theory?
- Need to calculate measurable quantities

Observable I: Hall Conductance

- Particle-hole symmetry requires

$$\sigma_{xy} = 1/2$$

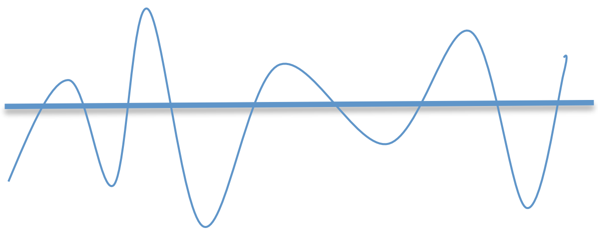
- With disorder, need composite fermions to have

$$\sigma_{xy}^{CF} = -1/2$$

- Where does this come from? Contradiction?

Lee, Krotov, Gan, Kivelson, 96

- Disorder in HLR: random field + random potential



$$\nabla \times \delta \mathbf{a} = -4\pi \delta n_\psi$$

- Leading order: only keep the field – effective time-reversal symmetry

  – no CF hall conductance $\sim O(k_F l)$

- Subleading: time-reversal broken by field+potential

  – CF hall conductance $\sim O(1)$

The magic/the puzzle

- Within certain approximation scheme:

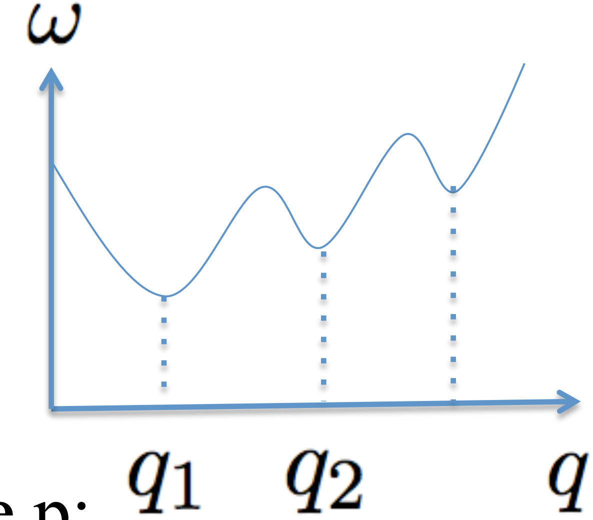
$$\sigma_{xy}^{CF} = -1/2$$

(In progress, with N. Cooper, A. Stern, B. Halperin)

- Even more puzzling: no need to take strict LLL limit, finite electron mass is OK

- Emergent particle-hole symmetry?

Observable II: magneto-roton minima



- Gapped excitations in Jain states at

$$\nu = \frac{p}{2p+1}$$

- Semi-classical calculation at large p:

$$q_n \sim \frac{1}{|p|}$$

(Simon, Halperin, 93)

- Asymmetry between p and -(p+1)? Need to go to $\sim O(\frac{1}{p^2})$

Another puzzle

- Within certain scheme:

$$q_n(p) = q_n(-p-1)$$

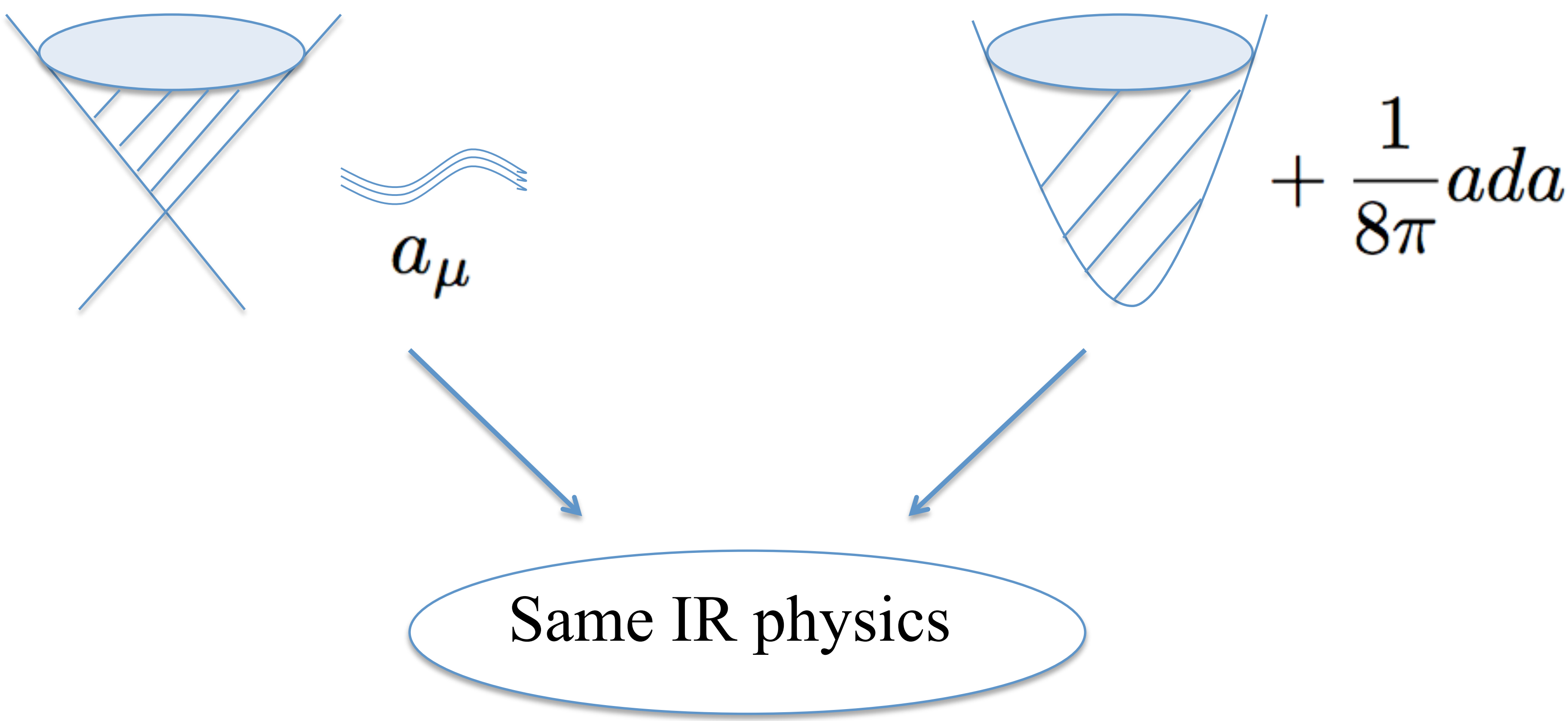
(In progress, with N. Cooper, A. Stern, B. Halperin)

- Again: no need to take strict LLL limit, finite electron mass is OK

- Emergent particle-hole symmetry?

Duality?

- Postulate: HLR is dual to Dirac CFL at low frequency, long wavelength



Not as crazy as it sounds

- Same phase diagram (Jain sequence, Pfaffian states…)

- IR physical observables that can be calculated from both sides do agree

- PH symmetry non-manifest in HLR,
  but compatible in the IR (many such examples)

- Somewhat unconventional:
  both involve a Fermi surface

- This means that HLR is applicable even in strict LLL

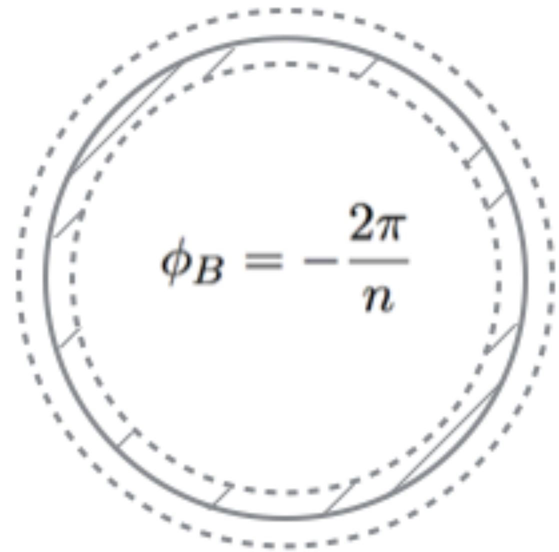
- And Dirac CFL is applicable even when $m_e > 0$
  – emergent PH symmetry in real world

- The previous puzzles (both in IR) easily explained

Generalize to CFL at $\nu = 1/n$

- Dual description: CF Fermi surface Berry phase

$$\phi_B = -\frac{2\pi}{n} = -2\pi\nu$$



- No Chern-Simons term for a_μ

- A "quantum vortex theory" of CFL

(CW, Senthil, 16)

Predictions

- With weak disorder:

$$\kappa_{xy} = (1-\nu)\frac{\pi^2 k_B^2 T}{3h}$$

- With unpolarized spin:

$$\sigma_{xy}^{spin} = -\nu$$

- Non-zero Nernst effect (Potter, Serbyn, Vishwanath, 15)

- Same results from HLR

Summary

- Dirac CFL: manifestly particle-hole symmetric
- HLR: Emergent particle-hole symmetry?
- Duality between different theories of CFL?
- A quantum vortex theory of composite fermi liquid
- Predictions for transport

Thank you!