Title: Strange metals and a continuous Mott transition: Accessing novel strongly correlated electron physics in quasi-1D

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Abstract: In this talk, I will present recent work aimed at tackling two cornerstone problems in the field of strongly correlated electrons---(1) conducting non-Fermi liquid electronic fluids and (2) the continuous Mott metal-insulator transition---via controlled numerical and analytical studies of concrete electronic models in quasi-one-dimension. The former is motivated strongly by the enigmatic "strange metal" central to the cuprates, while the latter is pertinent to, e.g., the spin-liquid candidate 2D triangular
lattice organic materials \kappa-(BEDT-TTF)_{2}Cu_{2}(CN)_{3} and EtMe_{3}Sb[Pd(dmit)_{2}]_{2}. In the first part of the talk, I will focus on point (1) and discuss our realization on the two-leg ladder of a novel non-Fermi liquid quantum phase---the "d-wave metal"---which we construct by placing the charge sector of the electronic system into a "Bose metal" with strong d-wave correlations. Importantly, this phase is non-perturbative in that it cannot be accessed starting from free electrons and slowly turning on interactions. Remarkably, we are able to realize this strange metal as the ground state of reasonable microscopic Hamiltonian by augmenting the t-J model with a simple, local four-site ring-exchange interaction. In the second half of the talk, I will discuss recent work on various half-filled electronic models on the two-leg triangular strip in which we have identified a continuous Mott transition between a metal and "spin Bose metal", where the latter is a novel
Mott-insulating spin-liquid phase obtained from the former by gapping out only the overall charge mode at strong coupling. Our Mott transition is shown to be in the XY universality class and thus
constitutes a clear and direct quasi-1D analog of the elegant higher-dimensional scenario recently proposed by Senthil [1]. Finally, I will touch on the potential relevance of these studies to the actual 2D materials which inspired them: the cuprates and the organics.

[1] T. Senthil, PRB 78, 045109 (2008).

Strange metals and a continuous Mott transition: Accessing novel strongly correlated physics in quasi-1D

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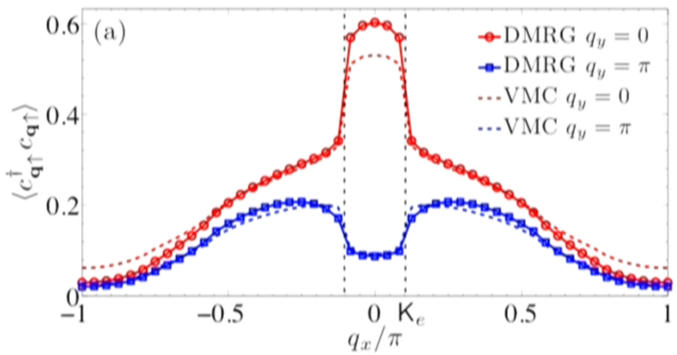
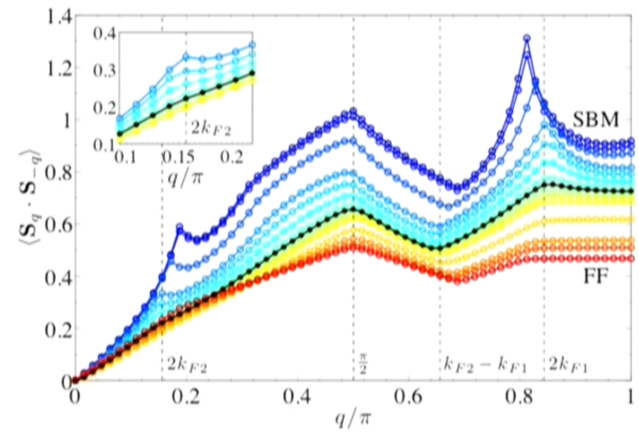
References:

- Hongchen Jiang, Matt Block, Ryan Mishmash, Jim Garrison, Donna Sheng, Lesik Motrunich, and Matthew Fisher, Nature (2013)
- Ryan Mishmash, Ivan Gonzalez, Roger Melko, Lesik Motrunich, and Matthew Fisher, in preparation

Outline: Two main topics

- Non-Fermi liquids
  - System in mind: the cuprates
  - Eye towards *the* strange metal
  - Jiang *et al.*, Nature (2013)
- Mott transition
  - System in mind: the organics
  - Nature of metal-spin liquid transition
  - RVM *et al.*, to be submitted



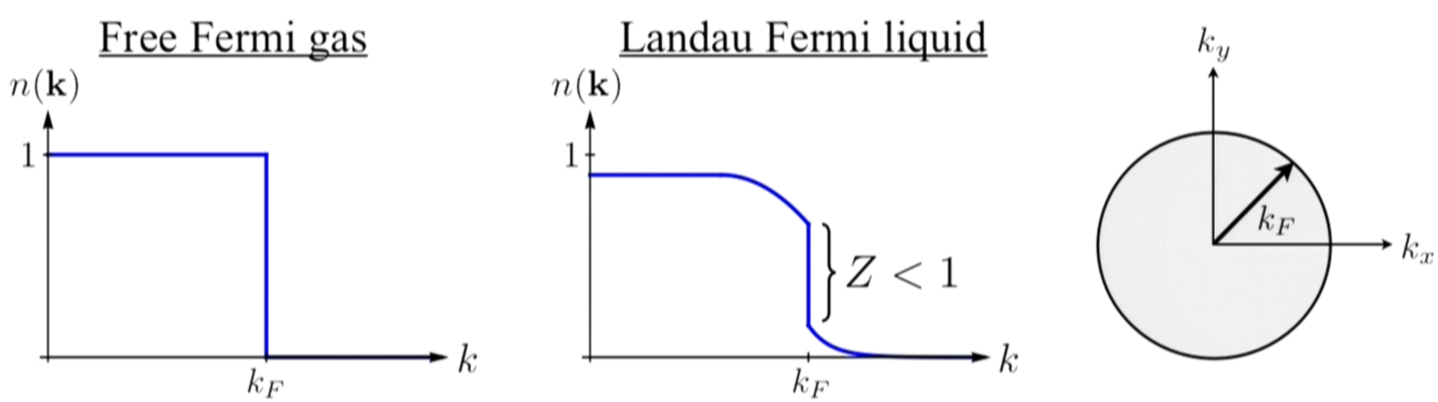


__Common theme: Quasi-1D__

- Highly controlled studies
- Clear analogs of 2D physics

Introduction I: Fermi and non-Fermi liquid metals

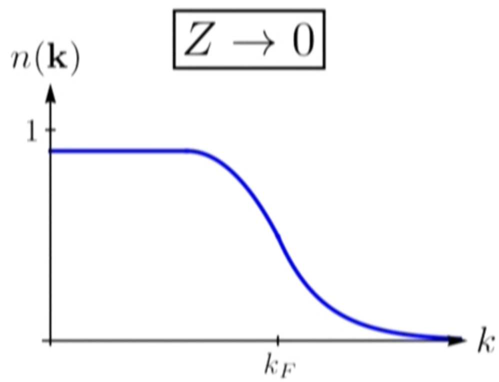
- Our main goal: Construct an example (any example!) of a 2D *non-Fermi liquid metal* (NFL)
- First: What is a *Fermi liquid metal* (FL)?
  - Focus on the momentum distribution function: $n(\mathbf{k}) = \langle c^\dagger_{\mathbf{k}} c_{\mathbf{k}} \rangle$

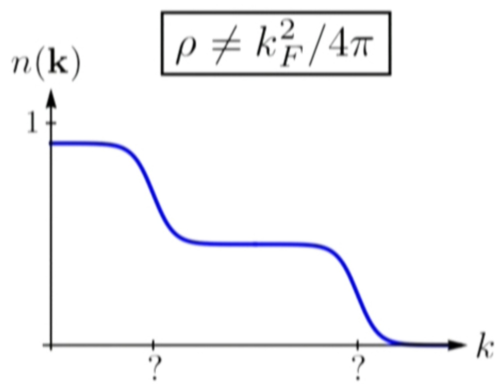


  - Some basic characteristics of a Fermi liquid
    - Nonvanishing "quasiparticle weight": $Z \neq 0$
    - Luttinger's volume theorem: density $= \rho = k_F^2/4\pi$

On to non-Fermi liquids (NFLs)

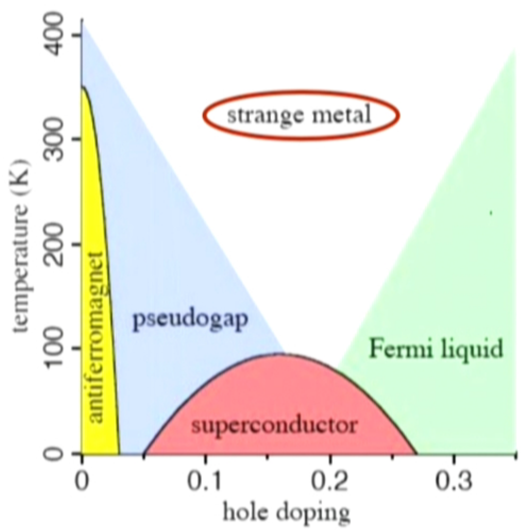
- NFLs are defined by what they are *not* ... NFL $\equiv \overline{\text{FL}}$
- Possible violations of Fermi liquid theory ...
  - Vanishing quasiparticle weight (cf. Luttinger liquid in 1D): $Z \to 0$
  - Singular surface(s) that violates Luttinger's theorem: $\rho \neq k_F^2/4\pi$
  - Anomalous thermodynamics/transport, e.g., resistivity $\sim T$
  - Etc.

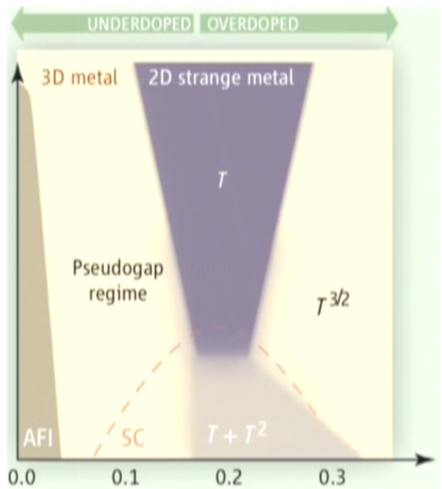




The most famous NFL: The "strange metal"

- Phase diagram of the cuprates



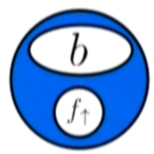


N. Hussey *et al.*, Science (2009)
G. Boebinger, Science (2009)

- Strange metal possibly an extended, zero-temperature *quantum phase*
- DISCLAIMER: In what follows, we are NOT claiming to have a theory of *this* strange metal ... but we have constructed and realized a *concrete* example of a quantum phase which is *a* strange metal

A theoretical framework for NFLs

- System in mind: Interacting electrons on 2D square lattice
- Slave-particle ("parton") construction: U(1) gauge theory
  - Electron = (bosonic "chargon") × (fermionic "spinon")
  - $c_s(\mathbf{r}) = b(\mathbf{r}) f_s(\mathbf{r}), \;\; s = \uparrow, \downarrow$
  - Spin-up electron =



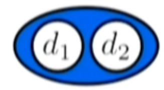
- Put spinons into Fermi sea (FS) state; then chargon crucial:

$$c_s(\mathbf{r}) = b(\mathbf{r}) f_s(\mathbf{r})$$

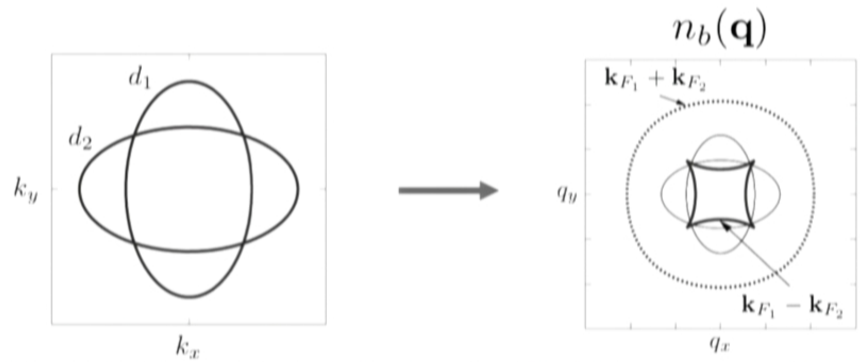
If chargons condense,
$\langle b(\mathbf{r}) \rangle \neq 0 \Rightarrow c_s(\mathbf{r}) \sim f_s(\mathbf{r}) \Rightarrow \mathrm{FL}$

If chargons DO NOT condense,
$\langle b(\mathbf{r}) \rangle = 0 \Rightarrow \mathrm{NFL}$

But ... bosons like to condense

- We need a "Bose metal" ...
  - That is, a conducting, yet uncondensed, quantum phase of 2D bosons
- To the rescue, the "*d*-wave Bose metal" (DBM)
  - Motrunich and Fisher, PRB (2007)
  - Slave-*fermion* decomposition of the boson: $b(\mathbf{r}) = d_1(\mathbf{r})d_2(\mathbf{r}) =$ 

  - d_1 and d_2 are taken to have (different) compressed Fermi surfaces
  - Exotic phase with critical "Bose surfaces" in momentum space, etc.

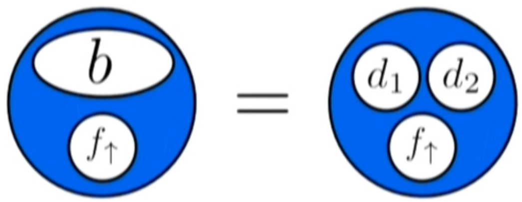


Constructing our NFL: The "*d*-wave metal"

- The key: Put chargons into the *d*-wave Bose metal phase
- All-fermionic decomposition of the electron:

$$c_s(\mathbf{r}) = b(\mathbf{r}) f_s(\mathbf{r}) = d_1(\mathbf{r}) d_2(\mathbf{r}) f_s(\mathbf{r})$$

- Spin-up electron =



- Important: Slave particles $\longleftrightarrow$ *variational wave functions*
  - For *d*-wave metal ("*d*-metal"), take product of three Slater determinants

$$\psi_c^{d-\mathrm{metal}}\left(\{\mathbf{r}_i^\uparrow\}, \{\mathbf{r}_i^\downarrow\}\right) = \psi_b^{\mathrm{DBM}} \times \psi_f^{\mathrm{FS}} = \psi_{d_1} \times \psi_{d_2} \times \psi_f^{\mathrm{FS}}$$

  - Time-reversal invariant analog of Laughlin: $\psi_c^{\mathrm{CFL}} = \psi_{\nu=1/2}^{\mathrm{Laughlin}} \times \psi_f^{\mathrm{FS}}$

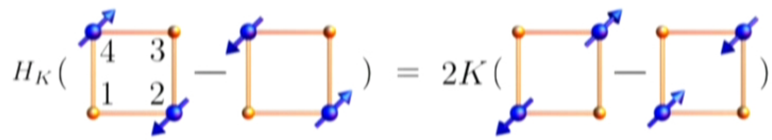
Finding our NFL: The "*t-J-K* model"

- Take famous *t-J* model and add 4-site "ring exchange" *K*

$$H = H_{tJ} + H_K, \quad \text{(no double-occupancy)}$$

$$H_{tJ} = -t \sum_{\langle i,j \rangle,\, s=\uparrow,\downarrow} \left(c^\dagger_{is} c_{js} + \text{H.c.} \right) + J \sum_{\langle i,j \rangle} \vec{S}_i \cdot \vec{S}_j,$$

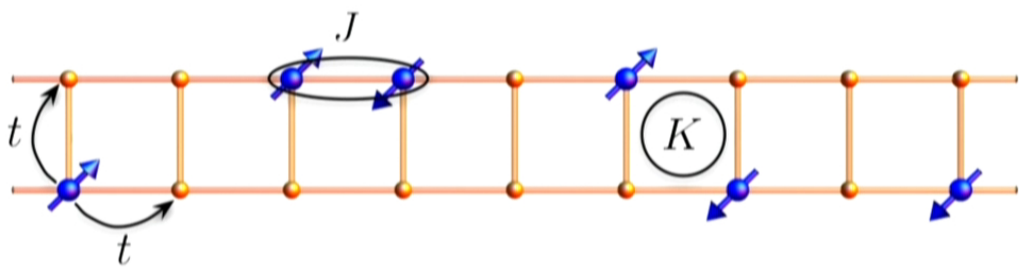
$$\boxed{H_K = 2K \sum_{\square} (\mathcal{S}^\dagger_{13} \mathcal{S}_{24} + \text{H.c.}),}$$



- Simple picture of why such ring-exchange terms are promising

How to access numerically and theoretically?

- Severe "sign problem" and "entanglement problem"
- But ... NFL *d*-metal and FL metal are distinguishable on *ladders*
  - A first step: Place *t-J-K* model on the 2-leg ladder

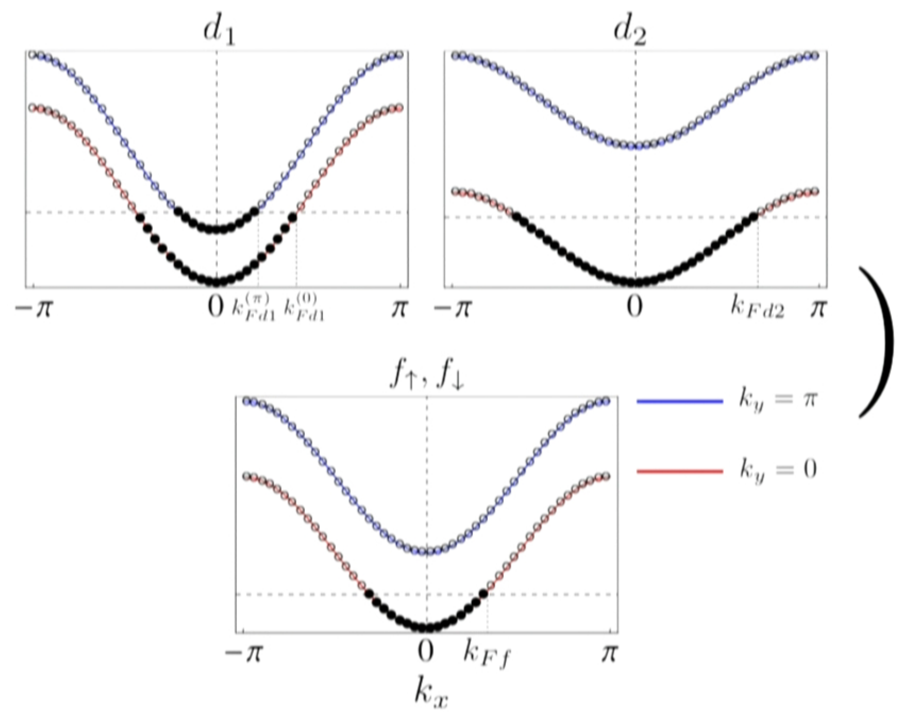


- Methods of attack: DMRG, VMC, bosonization
- Already shown to work for the *d*-wave *Bose* metal
  - 2 legs: Sheng *et al*., PRB (2008)
  - 3, 4 legs: Block, RVM, *et al*., PRL (2011); RVM, Block, *et al*., PRB (2011)

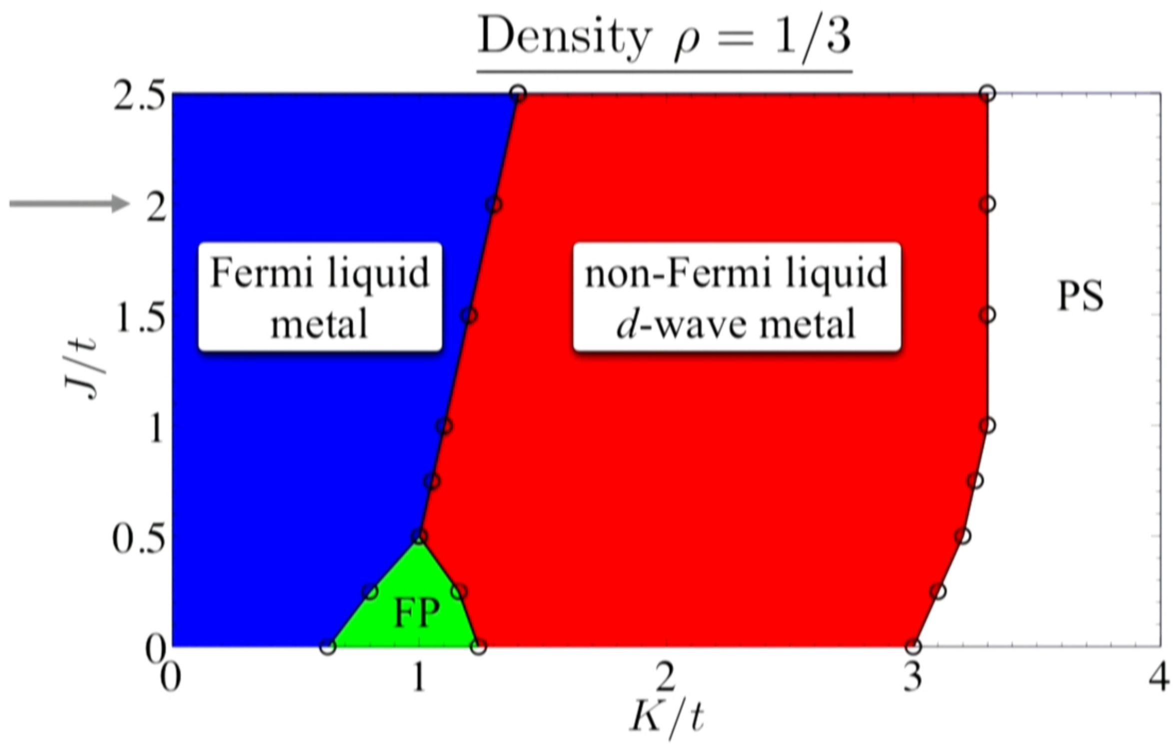
What does the *d*-metal look like on the 2-leg ladder?

From here on, fix electron density: $\rho = \frac{N_e}{2L_x} = \frac{1}{3}$, $\quad N_e = N_\uparrow + N_\downarrow$

$$\psi_c^{d-\mathrm{metal}} = \mathcal{P}_G \left(\quad \right)$$

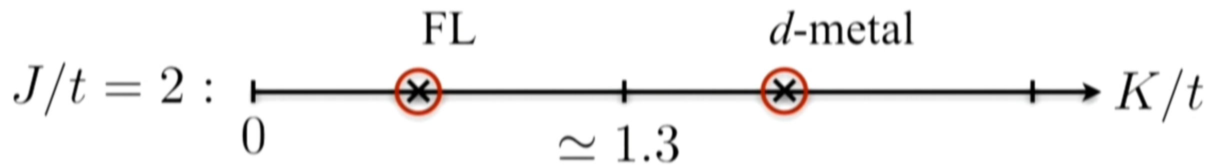


Phase diagram of t-J-K model (2-leg ladder)

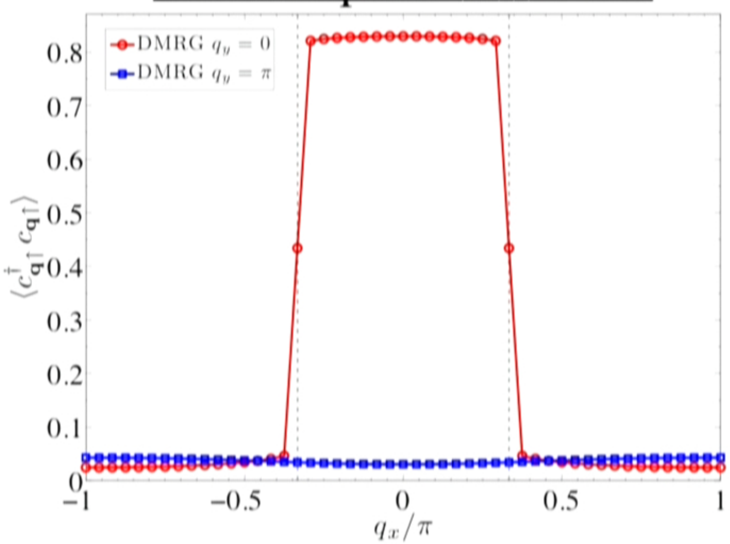


NB: On 2-leg ladder, by "Fermi liquid" we mean *conventional* Luttinger liquid

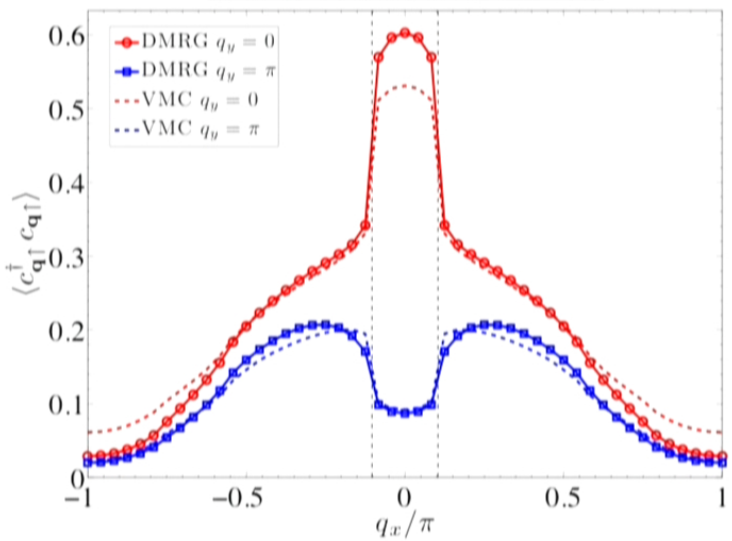
FL metal vs. NFL *d*-metal: Electron momentum distribution function



Fermi liquid: $K/t = 0.5$



d-metal: $K/t = 1.8$



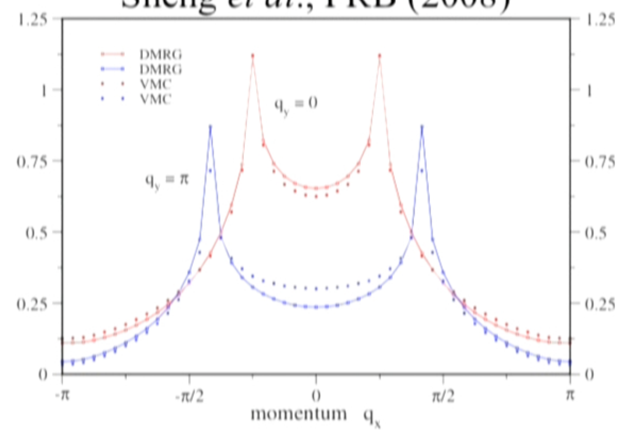
Note agreement between DMRG and VMC!

Can we understand this (crazy) behavior?

- "Simple" explanation (parton mean field): $n_e = n_b \otimes n_f$

Sheng *et al.*, PRB (2008)

$n_b =$



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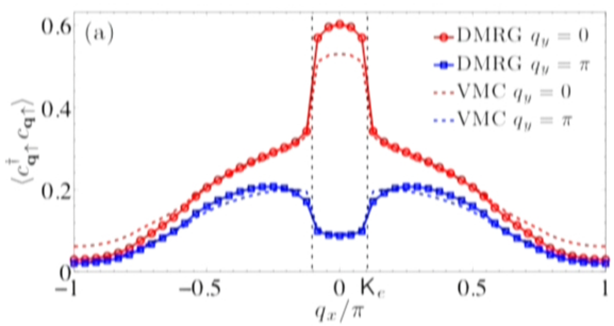
$n_e =$



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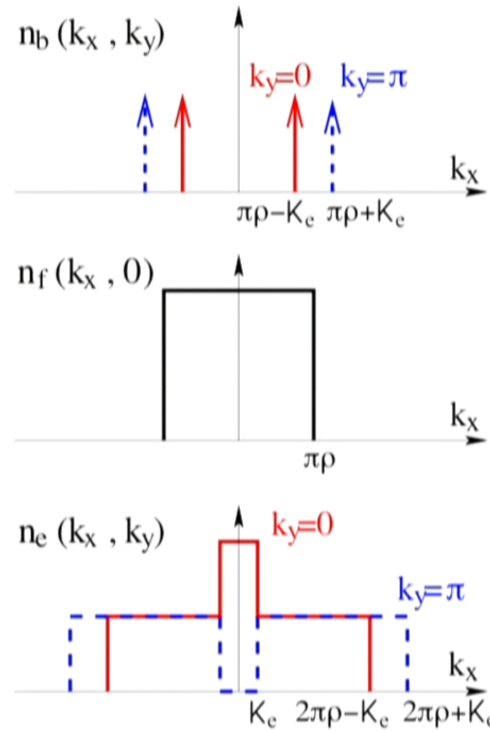
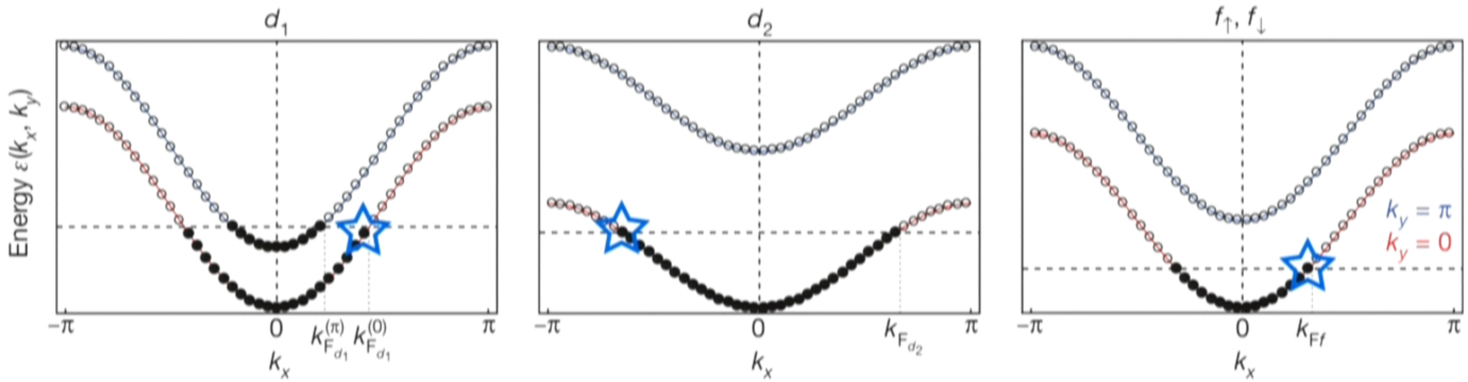


What does bosonized gauge theory say?

- "Amperean rule" predicts an "enhanced electron" at wavevector K_e



Pinned by gauge fluctuations

$$\text{"electron at } \mathsf{K}_e\text{"} = d_{1R}^{(q_y)}\, d_{2L}\, f_{\uparrow R} \sim e^{i(\overbrace{c_a\theta_a + c_A\theta_A}+\cdots)}$$

$$\mathsf{K}_e = k_{Fd_1}^{(q_y)} - k_{Fd_2} + k_{Ff} = \frac{k_{Fd_1}^{(0)} - k_{Fd_1}^{(\pi)}}{2}$$

What have we done and where to go?

- Constructed an explicit example of a NFL, the "*d*-wave metal"
- Strong evidence *d*-wave metal is stable on the 2-leg ladder
  - Techniques: DMRG, VMC, bosonization
  - Jiang, *et al*., Nature (2013)
- Important: Our 2-leg *d*-wave metal phase is *non-perturbative*
  - (Likely) cannot be realized using a weak-coupling Luttinger approach
- Ongoing work
  - Higher densities on the 2-leg ladder / variational study in full 2D
- Future work
  - More seriously consider 2D theory and match to cuprate phenomenology?
  - Estimate ring term in cuprates with *ab initio* methods?

What does the *d*-metal look like on the 2-leg ladder?

From here on, fix electron density: $\rho = \frac{N_e}{2L_x} = \frac{1}{3}$, $\quad N_e = N_\uparrow + N_\downarrow$

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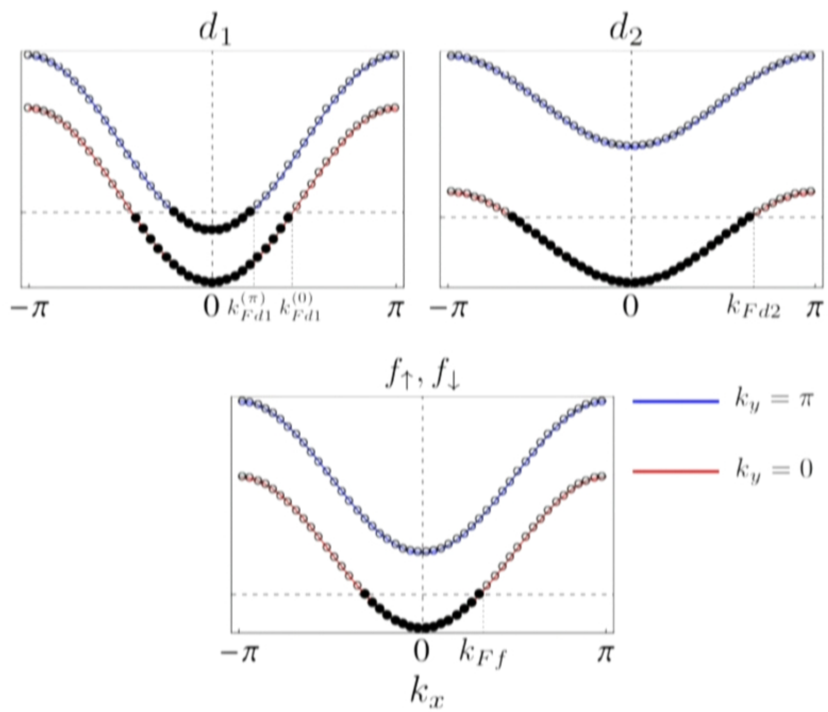

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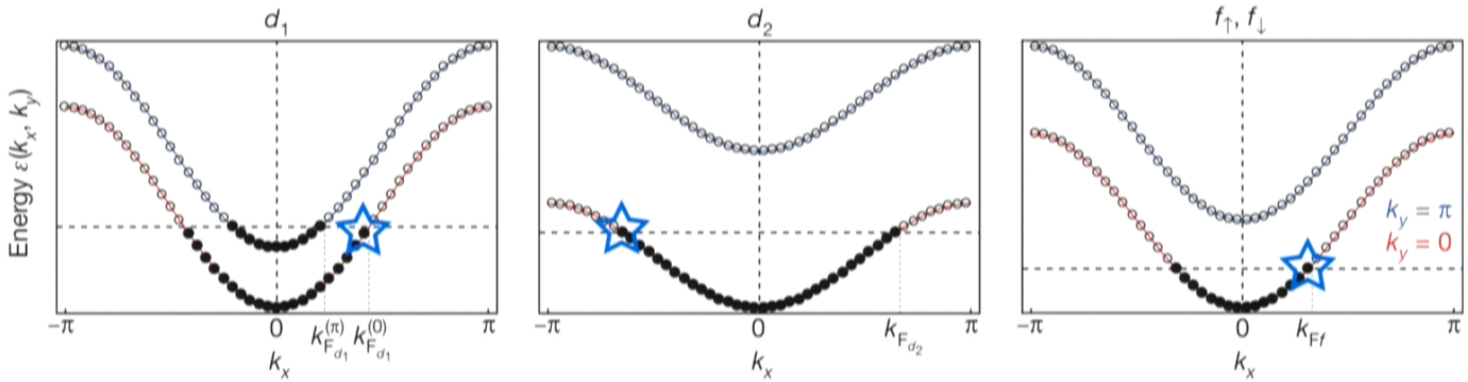

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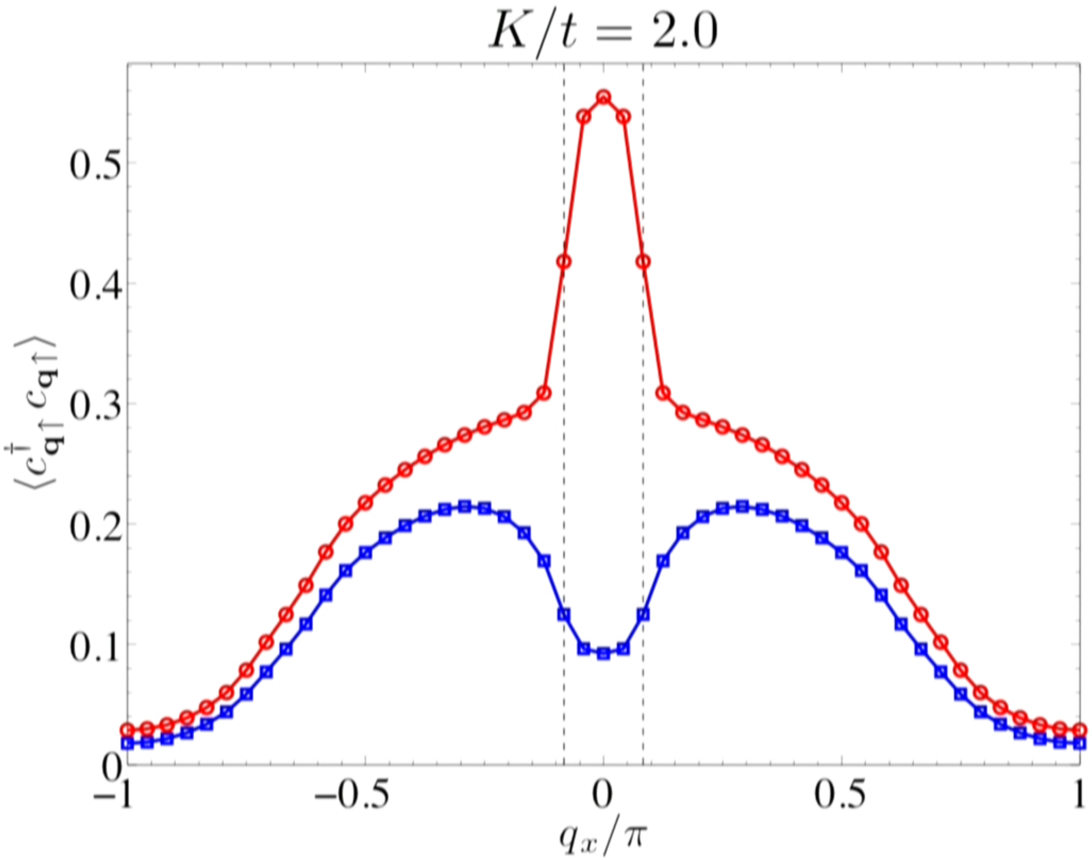
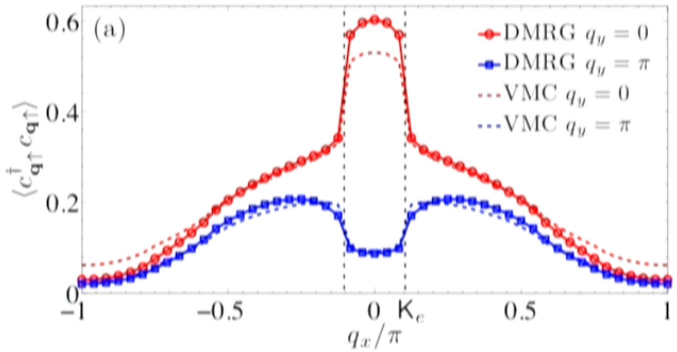
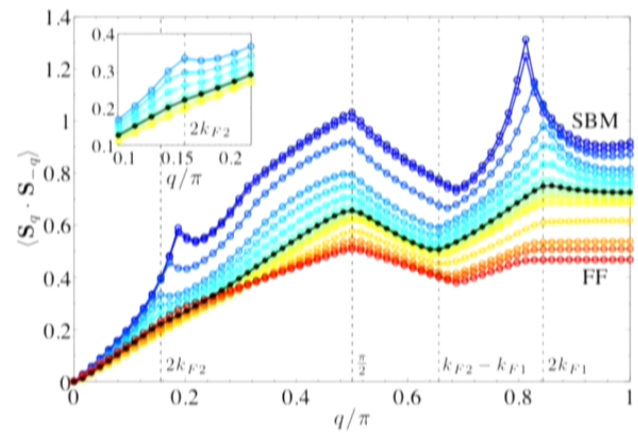
Evolution with ring-exchange K in DMRG



Outline: Two main topics

- Non-Fermi liquids
  - System in mind: the cuprates
  - Eye towards *the* strange metal
  - Jiang *et al.*, Nature (2013)
- Mott transition
  - System in mind: the organics
  - Nature of metal-spin liquid transition?
  - RVM *et al.*, to be submitted





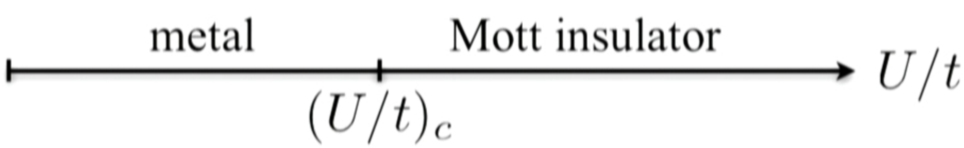
Common theme: Quasi-1D

- Highly controlled studies
- Clear analogs of 2D physics

Introduction II: The Mott transition

- System in mind: Electrons at half filling + Coulomb repulsion
- Good ole Hubbard model ...

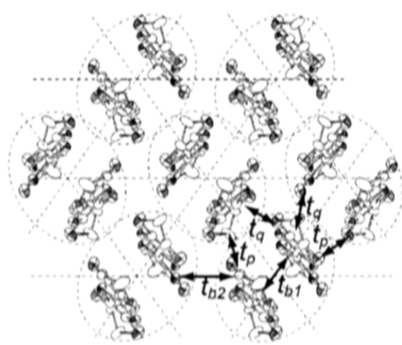
$$H = -t \sum_{\langle i,j \rangle} \left(c^\dagger_{i\alpha} c_{j\alpha} + \mathrm{H.c} \right) + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

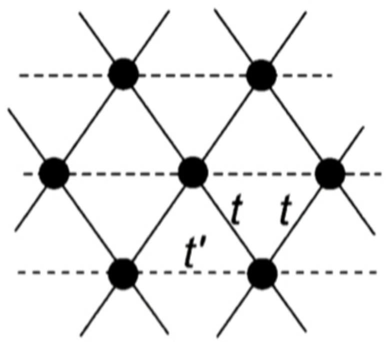


- Big questions: What is the nature of the $T = 0$ Mott transition?
  Can it ever be 2nd order (continuous)???

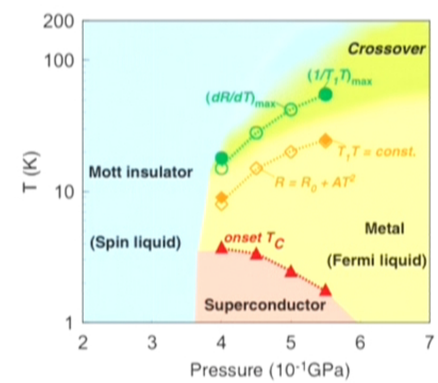
Organic spin liquids to the rescue

- Quasi-2D triangular lattice layered organic spin liquid materials
  - κ-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$ = "κ-ET"
  - EtMe$_3$Sb[Pd(dmit)$_2$]$_2$ = "DMIT"
- Insulators with no magnetic order down to $T \ll J$
- Can drive a Mott transition to a metal under moderate pressure!!!





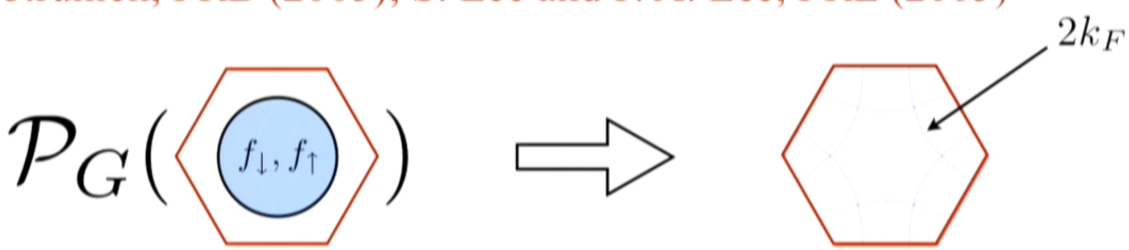
Shimuzi *et al.*, PRL (2003)



Kurosaki *et al.*, PRL (2005)

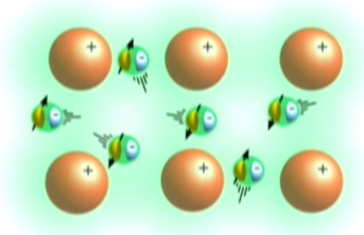
What is the nature of these spin liquids?

- Important: They are formed by "*weak*" Mott insulators
  - *U*/*t* is large, but not too large, so small charge gap
  - Substantial local fluctuations inside charge correlation length
  - Heisenberg model likely not sufficient description (another ring term!)
- Specific heat, etc., point to many low-lying spin excitations
- A very appealing theoretical starting point:
  - Spinon Fermi surface + U(1) gauge field = "spin Bose metal" (SBM)
  - Motrunich, PRB (2005); S. Lee and P. A. Lee, PRL (2005)

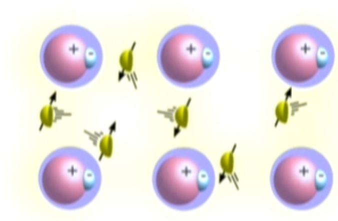


Continuous Mott transition a distinct possibility

- Spin sector of the SBM ≈ spin sector of a Fermi-liquid metal
  - Across the Mott transition, spin basically comes along for the ride
- 2D: Senthil (2008) [3D: Podolsky *et al.*, PRL (2009)]
  - $c_s(\mathbf{r}) = b(\mathbf{r}) f_s(\mathbf{r}) = e^{i\phi_{\mathbf{r}}} f_s(\mathbf{r})$
  - Spinon and chargon decouple near Mott transition
  - Puts electronic Mott transition into same universality class as for bosons!



Metal: $\langle b(\mathbf{r}) \rangle \neq 0$

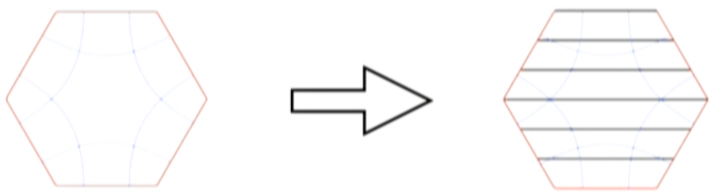


Spin Bose metal: $\langle b(\mathbf{r}) \rangle = 0$

(from Mross and Senthil)

Our goal:
Access this physics with controlled numerics

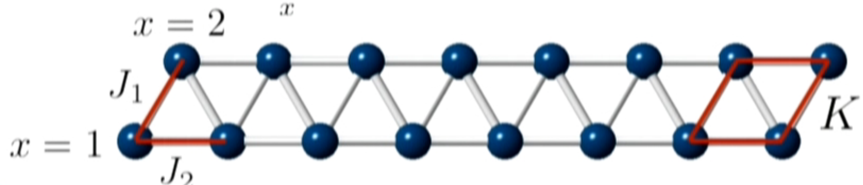
- Place triangular lattice on the 2-leg ladder (same program as for *d*-metal)
  - "Fermi/Bose surfaces" → "Fermi/Bose points"



- 2-leg SBM: Sheng, Motrunich, and Fisher, PRB (2009)
  - EXTENSIVE evidence for SBM on zigzag strip (2-leg triangular lattice)
  - Pure spin model: Heisenberg + 4-site cyclic ring exchange

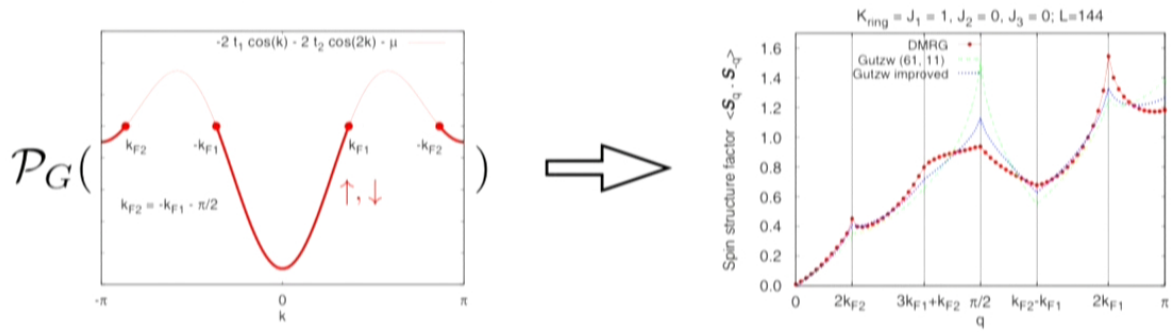
$$H_{\text{Heis}} + H_{\text{ring}} = \sum_x [2J_1 \mathbf{S}(x)\cdot\mathbf{S}(x+1) + 2J_2 \mathbf{S}(x)\cdot\mathbf{S}(x+2) + K(P_{x,x+2,x+3,x+1} + \text{h.c.})]$$

$$P_{1234}|\sigma_1,\sigma_2,\sigma_3,\sigma_4\rangle \to |\sigma_4,\sigma_1,\sigma_2,\sigma_3\rangle$$

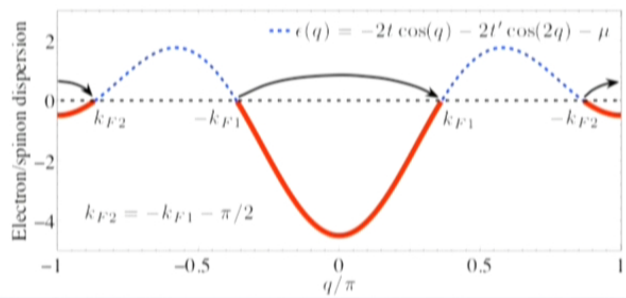


Two views of the 2-leg (2-band) SBM

- *Spinons* coupled to U(1) gauge field [Sheng *et al*. (2009)]



- Start with *real electrons* and gap out only overall charge mode $\theta_{\rho+}$
  - 8-fermion umklapp term at strong interactions drives KT-like Mott transition
  - C2S2 to C1S2=SBM (CαSβ: α gapless charge modes, β gapless spin modes)



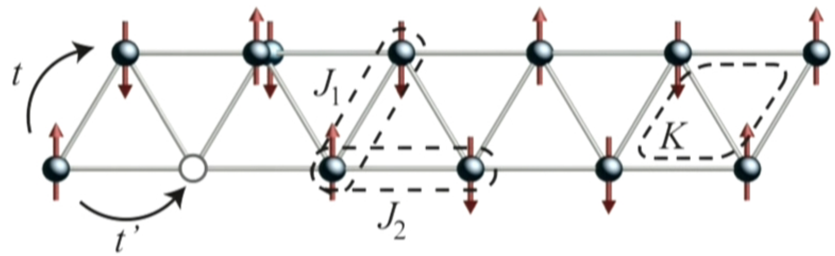
$$\mathcal{L} = \underbrace{\mathcal{L}_0^\rho + \mathcal{L}_0^\sigma}_{\text{C2S2 2-band metal with 4 gapless modes, say } \{\theta_{\rho\pm}, \theta_{\sigma\pm}\}} + \underbrace{2v_8\cos(4\theta_{\rho+})}_{\text{umklapp } H_8}$$

But what *Hamiltonians* should we consider?

$$H = -t \sum_i \left(c^\dagger_{i,\alpha} c_{i+1,\alpha} + \text{H.c} \right) - t' \sum_i \left(c^\dagger_{i,\alpha} c_{i+2,\alpha} + \text{H.c} \right) + H_{\text{int}}$$

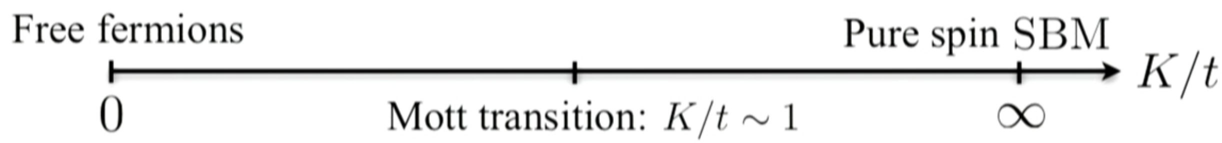
- Hubbard model: $H_{\text{int}} = U \sum_i n_{i\uparrow} n_{i\downarrow}$
  - Guidance from weak-coupling RG [Balents and Fisher, PRB (1996)]
  - Metal likely spin gapped (C1S0), so insulator likely spin gapped (C0S0)
- Hubbard model with longer-ranged repulsion: $H_{\text{int}} = \frac{1}{2} \sum_{i,j} V_{ij}\, n_i n_j$
  - Lai and Motrunich, PRB **81**, 045105 (2010)
  - Can fight spin gap tendencies in metal with extended repulsion
- Electron hopping + ring model: $H_{\text{int}} = H_{\text{Heis}} + H_{\text{ring}}$
  - For interactions, take spin model from Sheng *et al.* (2009)
  - Guaranteed C1S2 = SBM insulator for large enough ring coupling K

Focus here on the "t-t'-J_1-J_2-K" model



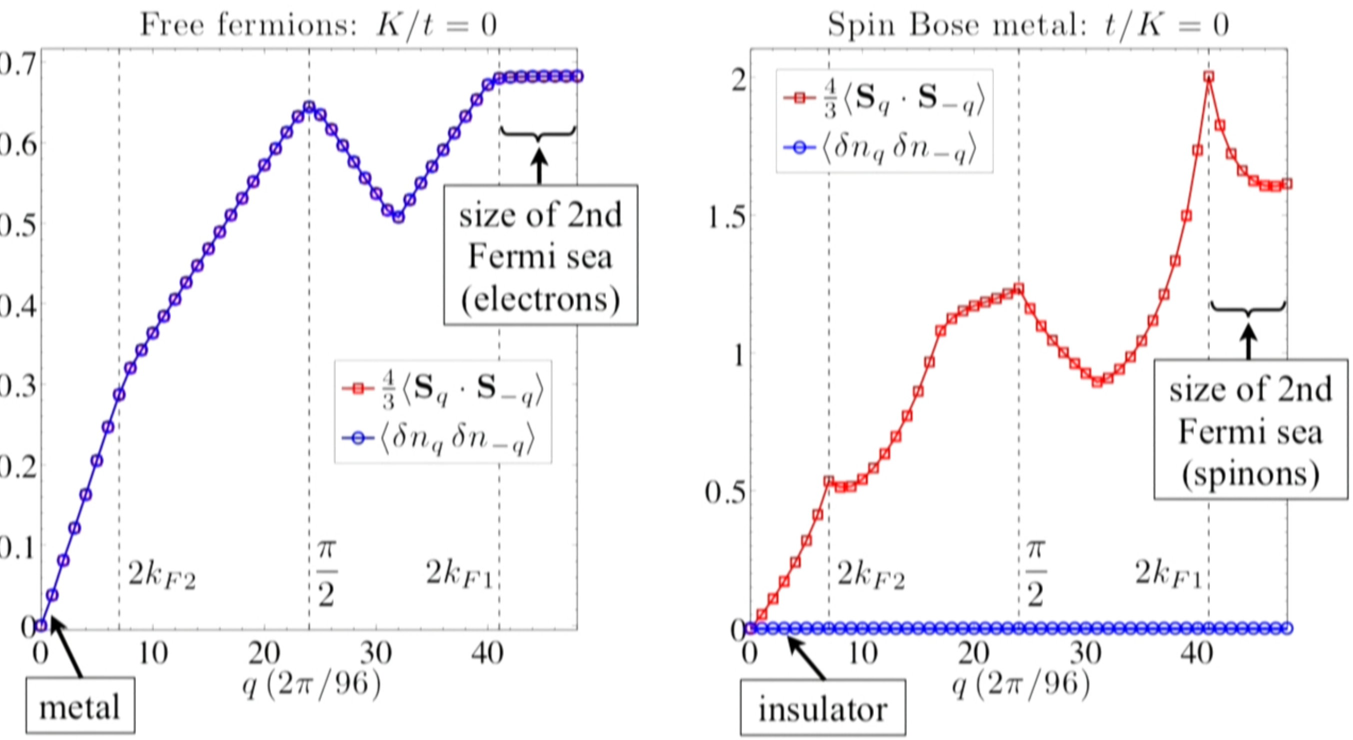
RVM, Gonzalez, Melko, Motrunich, and Fisher, in prep.

- Choose parameters to match electron and spinon dispersions



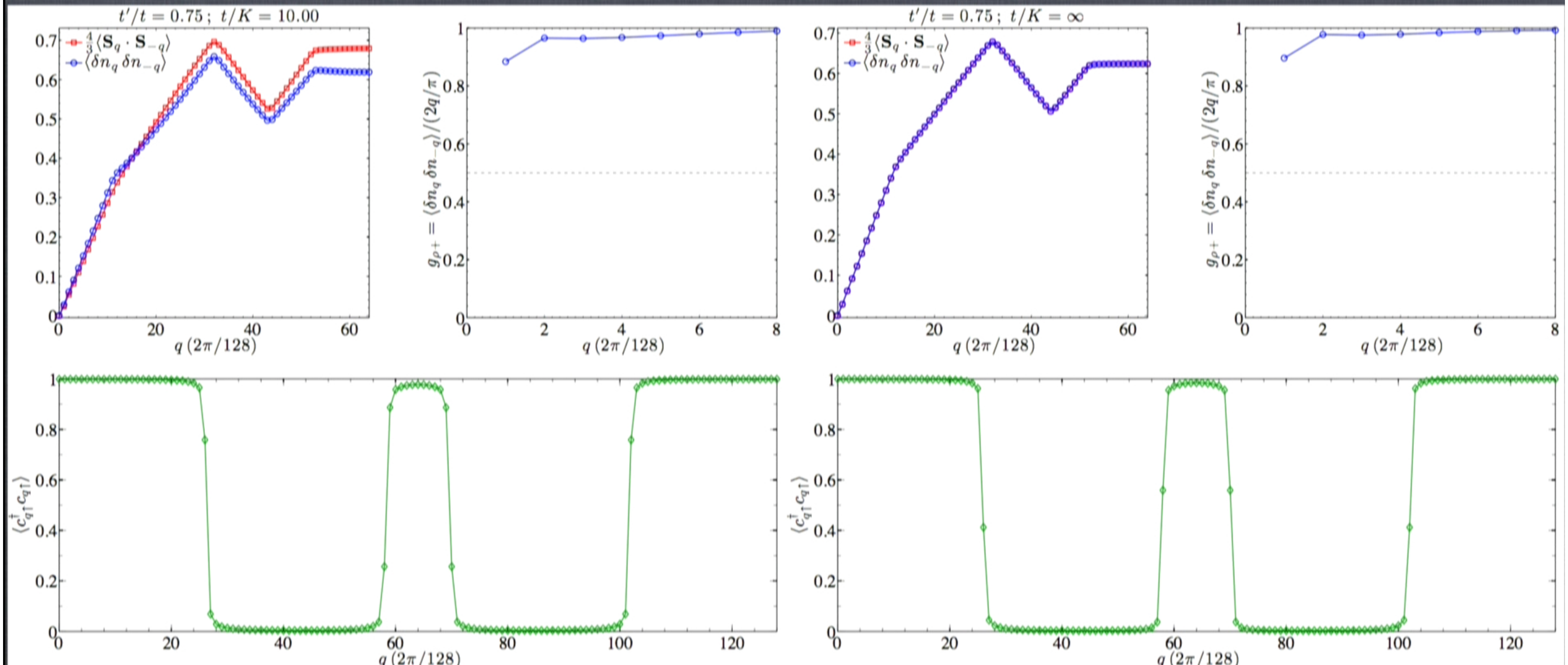
- Measures and diagnostics
  - Momentum space structure factors: $\langle c^\dagger_{q\sigma} c_{q\sigma} \rangle, \ \langle \mathbf{S}_q \cdot \mathbf{S}_{-q} \rangle, \ \langle \delta n_q \delta n_{-q} \rangle$
  - Overall spin and charge "Luttinger parameters": $g_{\sigma+}, \ g_{\rho+}$
  - $g_{\rho+}$ directly gives scaling dimension of umklapp: $\Delta[H_8] = 4g_{\rho+}$

2-band free fermion metal versus SBM

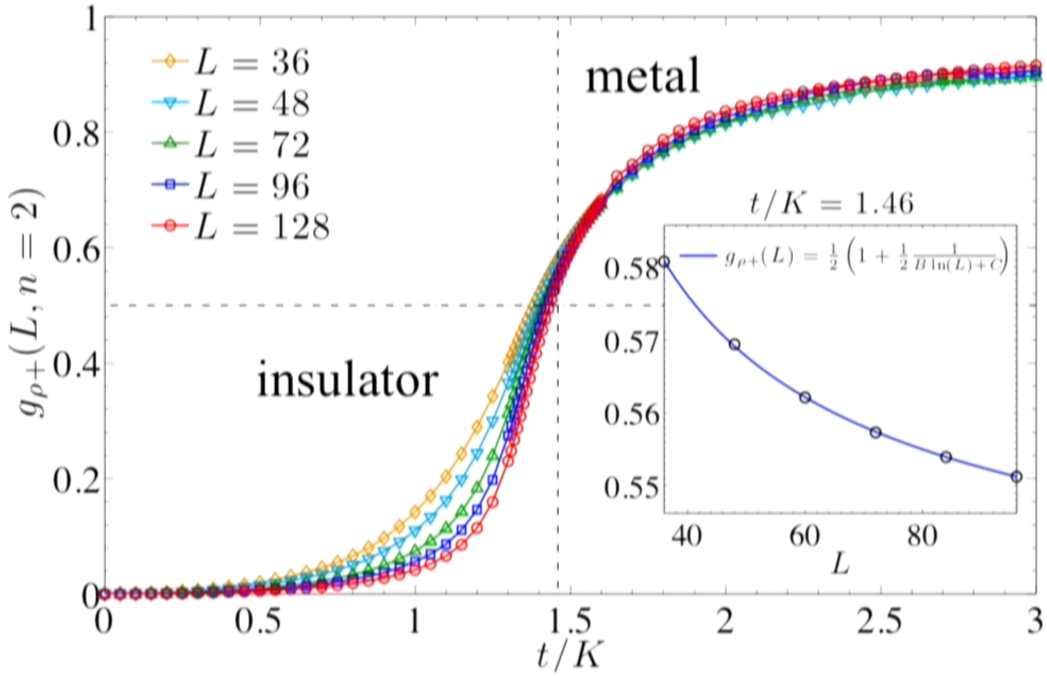


$\langle \mathbf{S}_q \cdot \mathbf{S}_{-q} \rangle$ = spin-spin structure factor

$\langle \delta n_q \, \delta n_{-q} \rangle$ = density-density structure factor


$t'/t = 0.75\,;\ t/K = 10.00$
$\frac{4}{3}\langle \mathbf{S}_q \cdot \mathbf{S}_{-q} \rangle$
$\langle \delta n_q\, \delta n_{-q} \rangle$
$q\,(2\pi/128)$
$g_{\rho+} = \langle \delta n_q\, \delta n_{-q} \rangle / (2q/\pi)$
$t'/t = 0.75\,;\ t/K = \infty$
$\langle c^\dagger_{q\uparrow} c_{q\uparrow} \rangle$

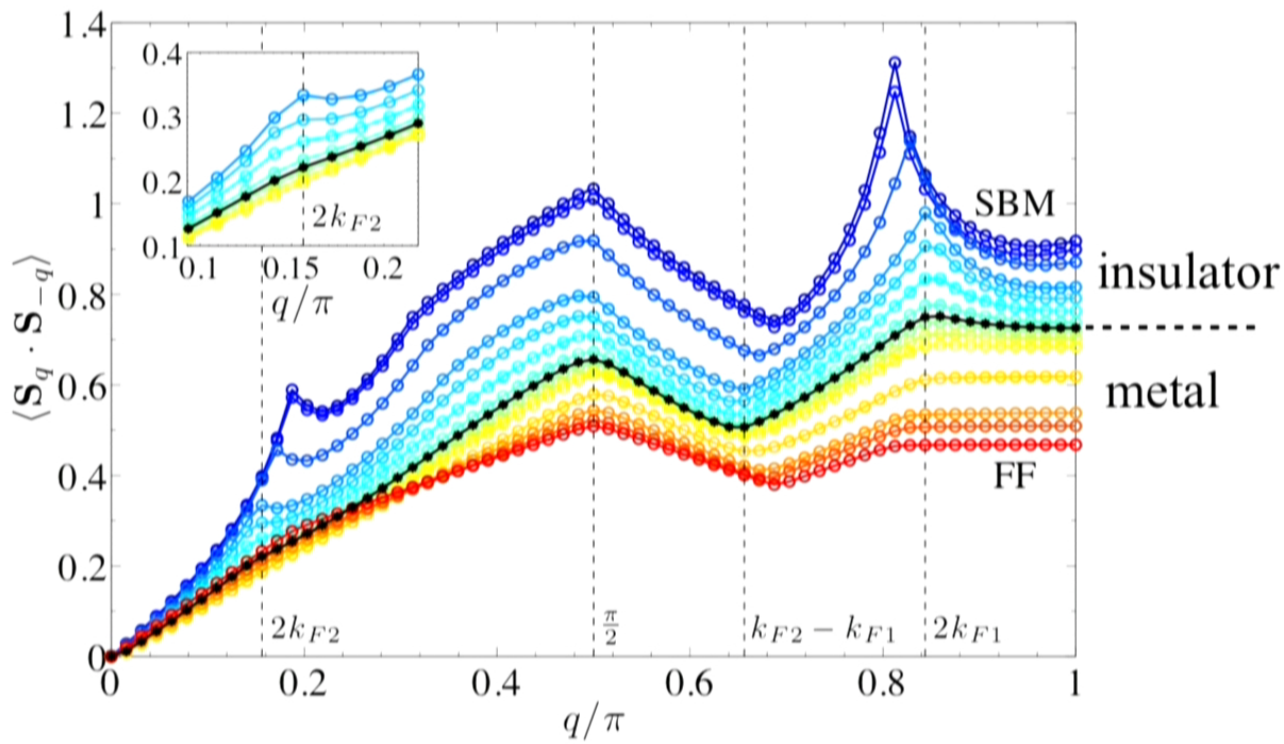
Evidence for Kosterlitz-Thouless scaling



Finite-size scaling form *at* KT transition: $g_{\rho+}(L) = \frac{1}{2}\left(1 + \frac{1}{2}\frac{1}{B\ln(L)+C}\right)$

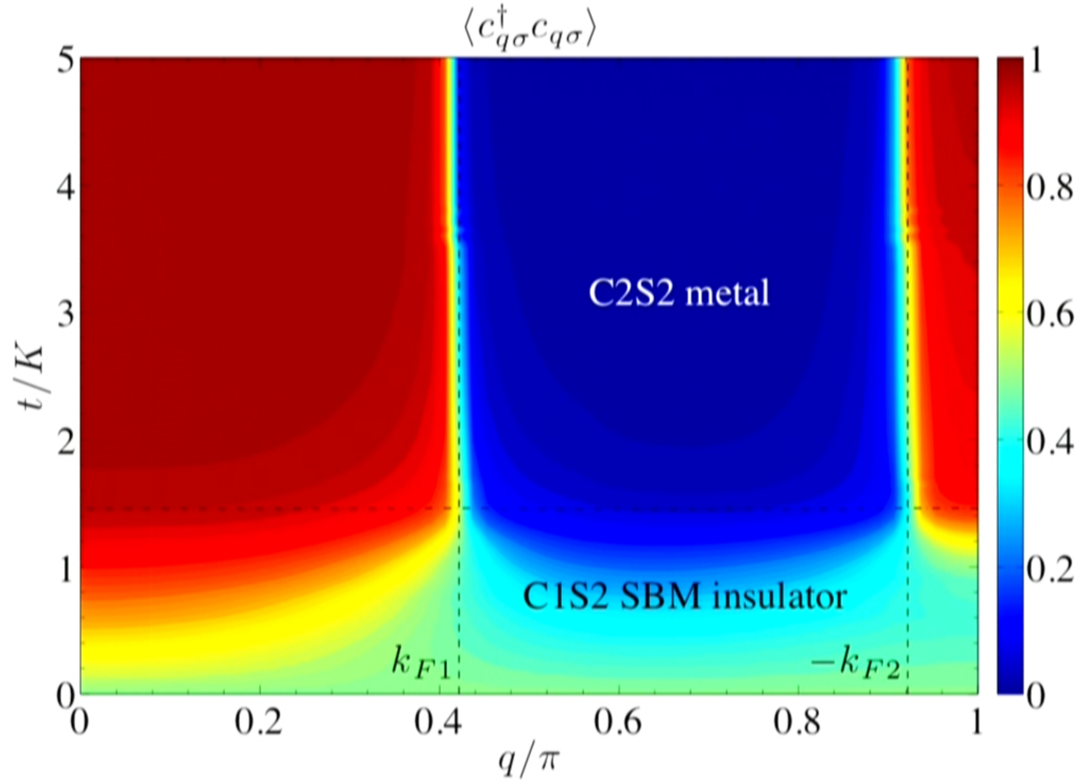
Clear (1+1)D analog of Senthil's (2+1)D scenario

Watching electrons become spinons



$$\mathbf{S}_Q \sim e^{\pm i\theta_{\rho+}}(\cdots) \quad \text{for} \quad Q = 2k_{Fa}, \pi/2$$

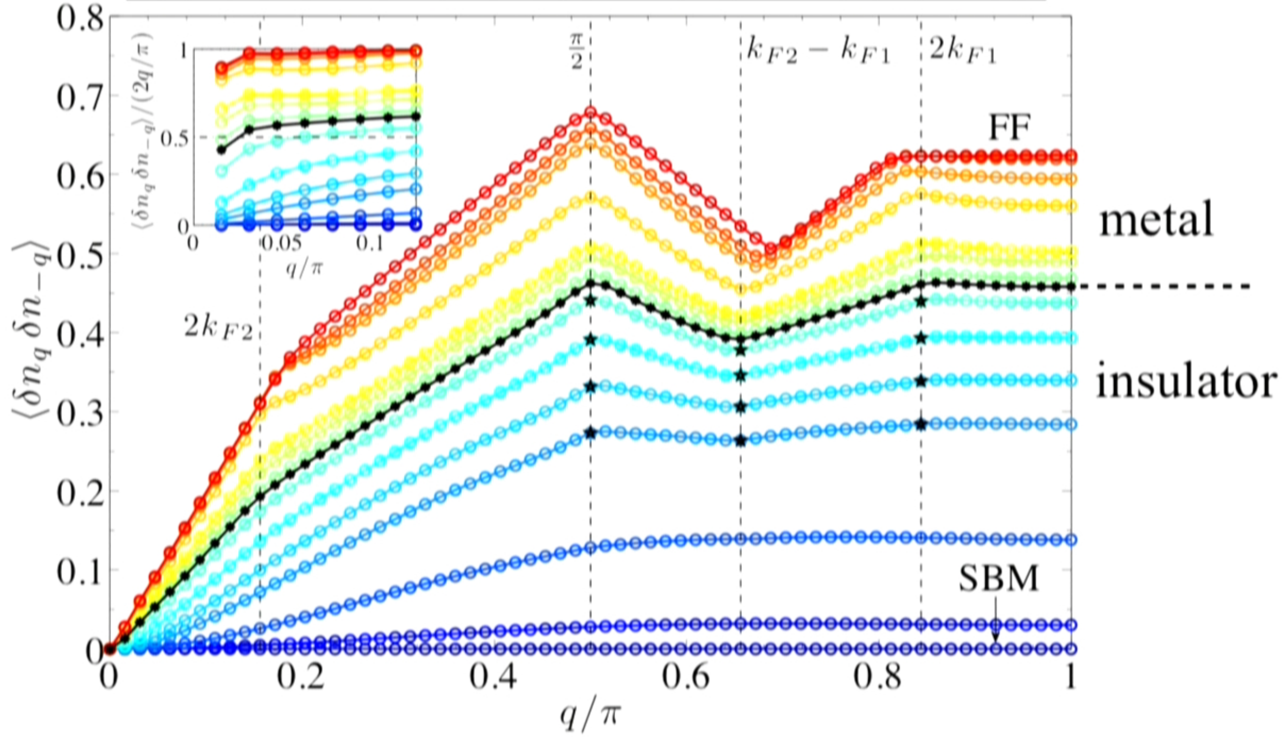
Continuous disappearance of Fermi surface



$$c_{Q\sigma} \sim e^{\frac{i}{2}(\phi_{\rho+} + \cdots)} \quad \text{for} \quad Q = k_{Fa}$$

Friedel oscillations in SBM insulator!

cf. Mross and Senthil, PRB **84**, 041102 (2011)



$$\delta n_Q \sim e^{\pm i\theta_{\rho+}}(\cdots) \quad \text{for} \quad Q = 2k_{Fa}, \pi/2$$

Conclusion and outlook: Connection to the organics?

- Hopping + ring model
  - Clear (1+1)D XY universality
  - 2D analog (if spin-gapped metal): SC to weak instability of SBM
  - After all, spin gapless Fermi liquid generally unstable at $T = 0$
- Extended Hubbard model
  - Still in progress
  - Similar phenomenology
  - Likely avoiding spin gap in metal
  - Long-ranged repulsion appropriate for κ-ET?
    - Nakamura *et al.*, JPSJ **78**, 083710 (2009)