From quantum spin liquids to composite fermi liquids through topological insulators

T. Senthil (MIT)

With Chong Wang,
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C. Wang, and TS, arXiv:1505.03520 (PR X 2016), arXiv:1505.05141 (PR X 2015)

C. Wang and TS, arXiv:1507.08290 (PR B 2016): Synthesis and physical pictures

C. Wang and TS, arXiv:1604.06807

Related work:
Son, arXiv:1502.03446 (PR X 2015); M. Metlitski and A. Vishwanath, arXiv:1505.05142.

Deep connections between 3 apparently different problems

Wang, TS, 2015
Metlitski, Vishwanath, 2015

Many new insights/results.

Quantum spin liquids in 3d
(eg, in quantum spin ice)

Effects of strong correlations on 3d
topological insulators/superconductors

Half-filled Landau level of
2d electron gas:
Composite fermi liquids

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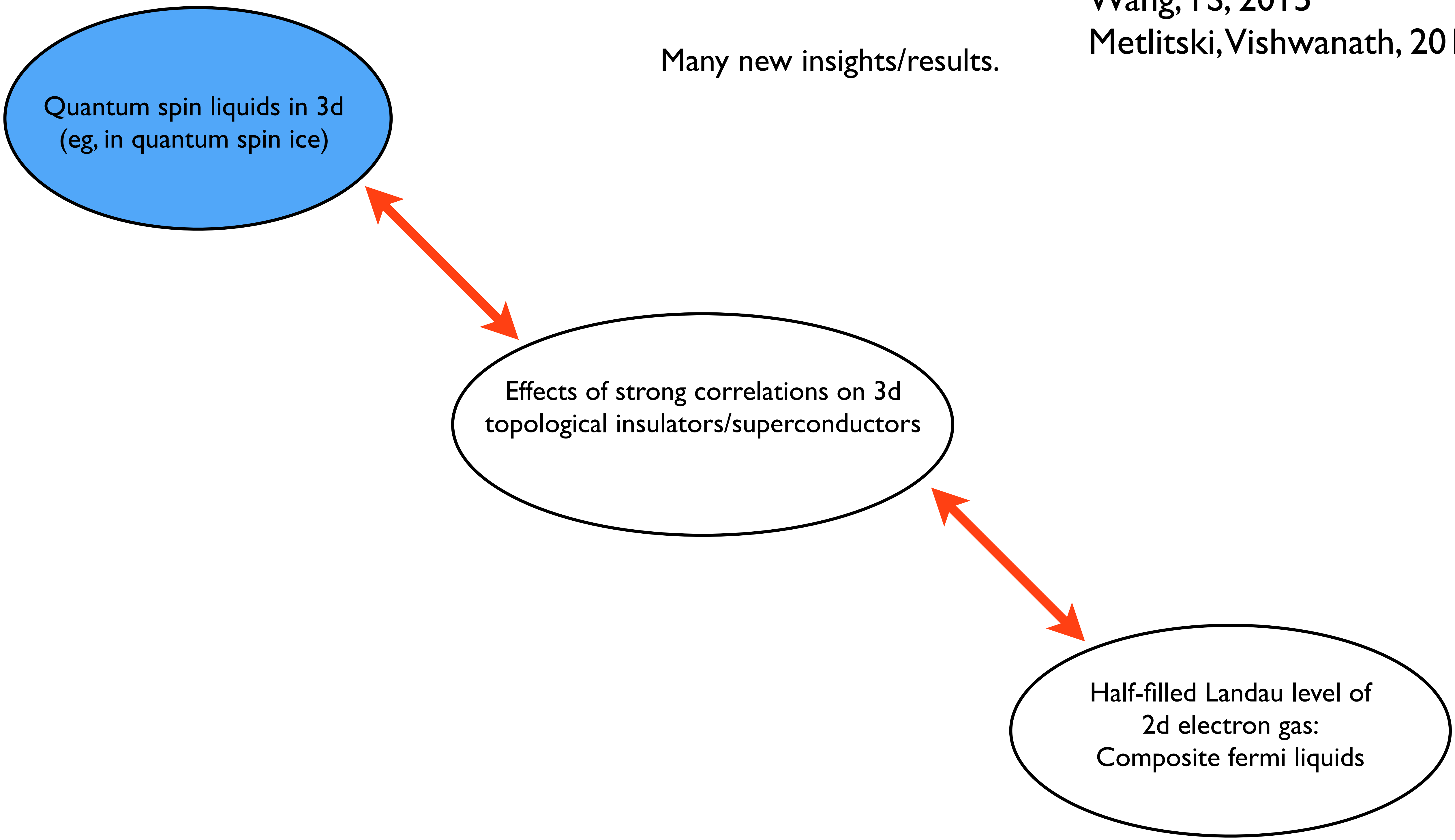


Theory of quantum spin liquids: new paradigms for collective behavior in quantum condensed matter

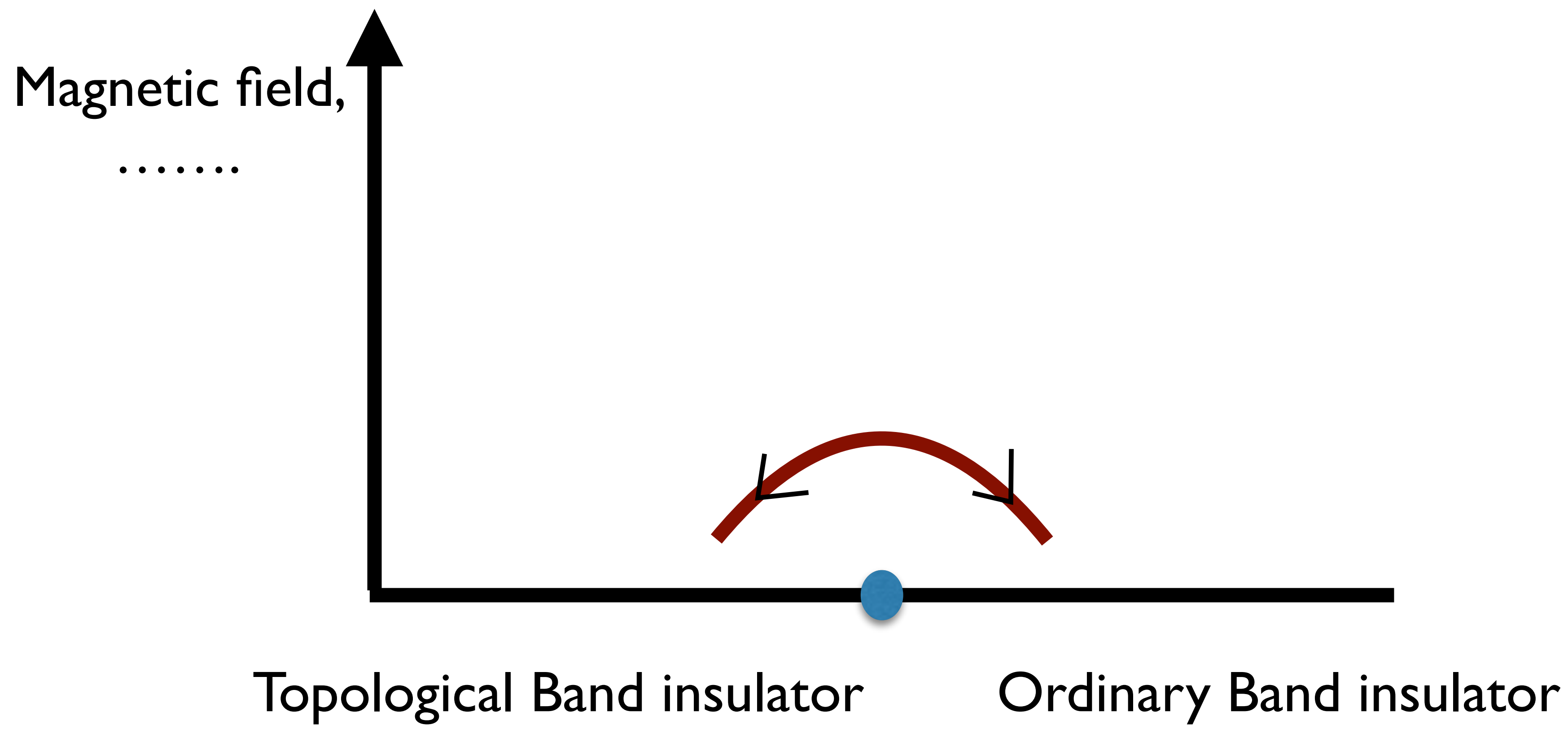
- emergence of gauge interactions

- emergence of fractional quantum numbers

Though not directly related, study of topological insulators teach us many useful things about spin liquids.

Lesson of topological insulators

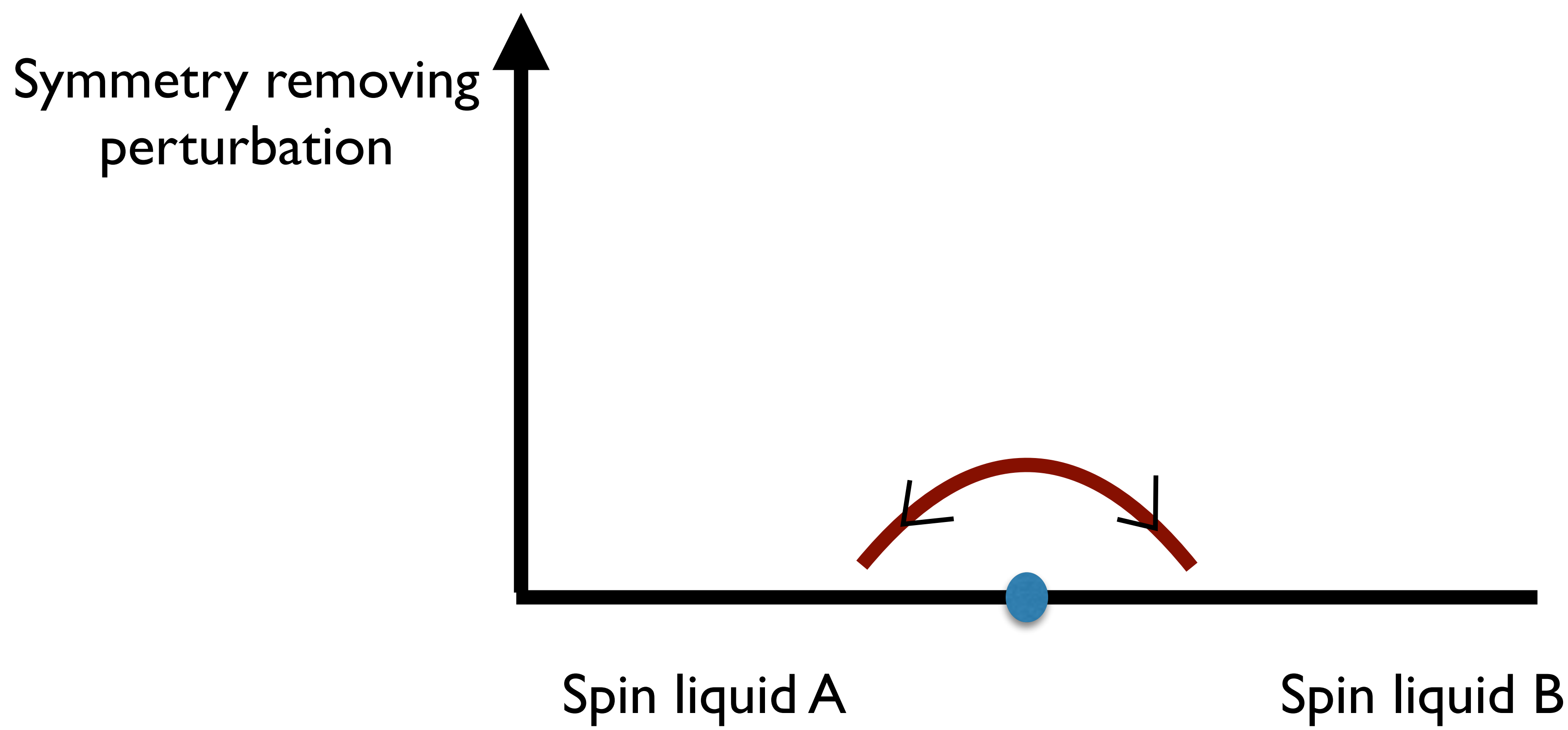
Symmetry can protect distinction between two symmetry unbroken phases.



Quantum spin liquids and symmetry

Broad question:

Quantum spin liquid phases distinguished purely by (unbroken) symmetry?



Symmetry can be ``fractionalized'' : symmetry distinctions more severe than for band insulators !

Crucial for this talk: quantum spin liquids in 3d with an emergent ``photon”.

Let there be (artificial) light.....

19th century dream:
Light as a collective mode of some material (``ether'')

21st century(*):
??Quantum phases of spin/boson systems with an emergent excitation that behaves like a photon??

Such phases can indeed exist as
`quantum spin liquids' of spin/boson systems in 3d.

Terminology: U(1) quantum spin liquid (as there is an emergent U(1) gauge field associated with the photon).

(*)See however Foerster, Nielsen, Ninomiya, 1983

Microscopic models with emergent photons

1. O. Motrunich and T. Senthil, Phys. Rev. Lett. (2002)
(Boson Hubbard models - a quantum ice)

2. Michael Hermele, Matthew P. A. Fisher, and Leon Balents, Phys. Rev. B (2004).
(Quantum spin ice models)

3. R. Moessner and S. L. Sondhi, Phys. Rev. B (2003)
(Quantum dimer models)

Numerical simulations:

1. Argha Banerjee, Sergei V. Isakov, Kedar Damle, and Yong Baek Kim
Phys. Rev. Lett. (2008).

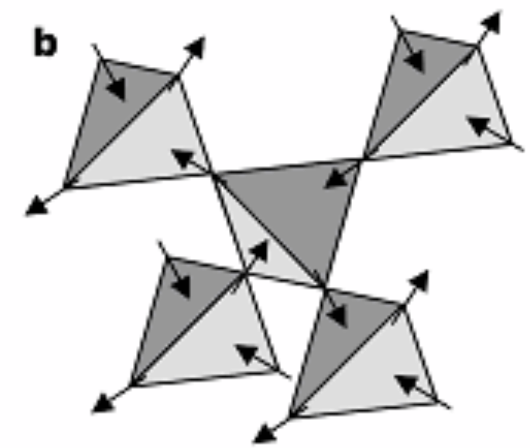
2. Nic Shannon, Olga Sikora, Frank Pollmann, Karlo Penc, and Peter Fulde
Phys. Rev. Lett. (2012).

Experiment?

Possibility of U(1) quantum spin liquids in ``quantum spin ice" materials

$Yb_2Ti_2O_7$, $Pr_2Zr_2O_7$, $Pr_2Sn_2O_7$, $Tb_2Ti_2O_7$..?

Expt: Gaulin, Broholm, Ong, …..
Theory: Gingras, Balents,



Spin ice

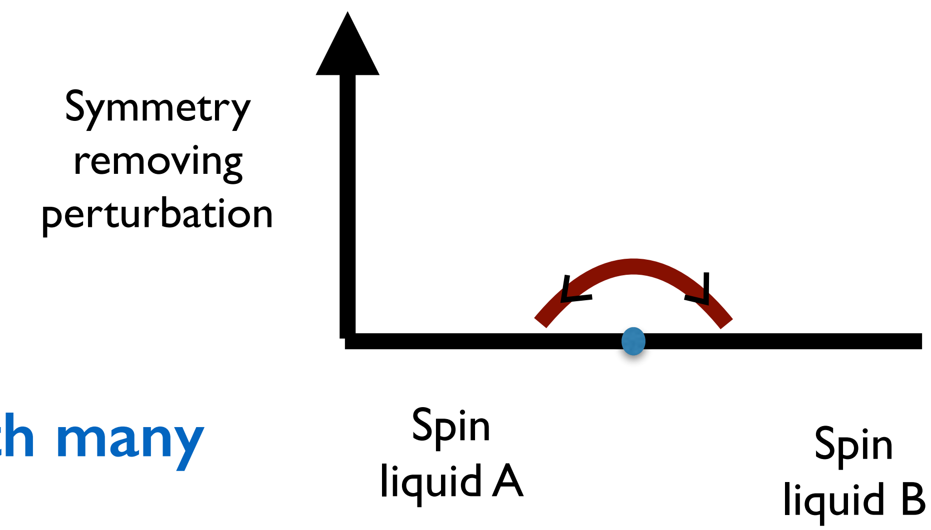
1. Complicated microscopic models! Hard to reliably solve even numerically except in special limits.
2. No symmetry except time reversal, space group.

Quantum spin ice, quantum spin liquids, and symmetry

An interesting conceptual question for theory:

What distinct kinds of U(1) quantum spin liquids with symmetry are possible?

Only physical symmetry - *Time reversal* x space group.



Surprisingly, this question is intertwined with many other profound issues in condensed matter physics.

Deep connections between 3 apparently different problems

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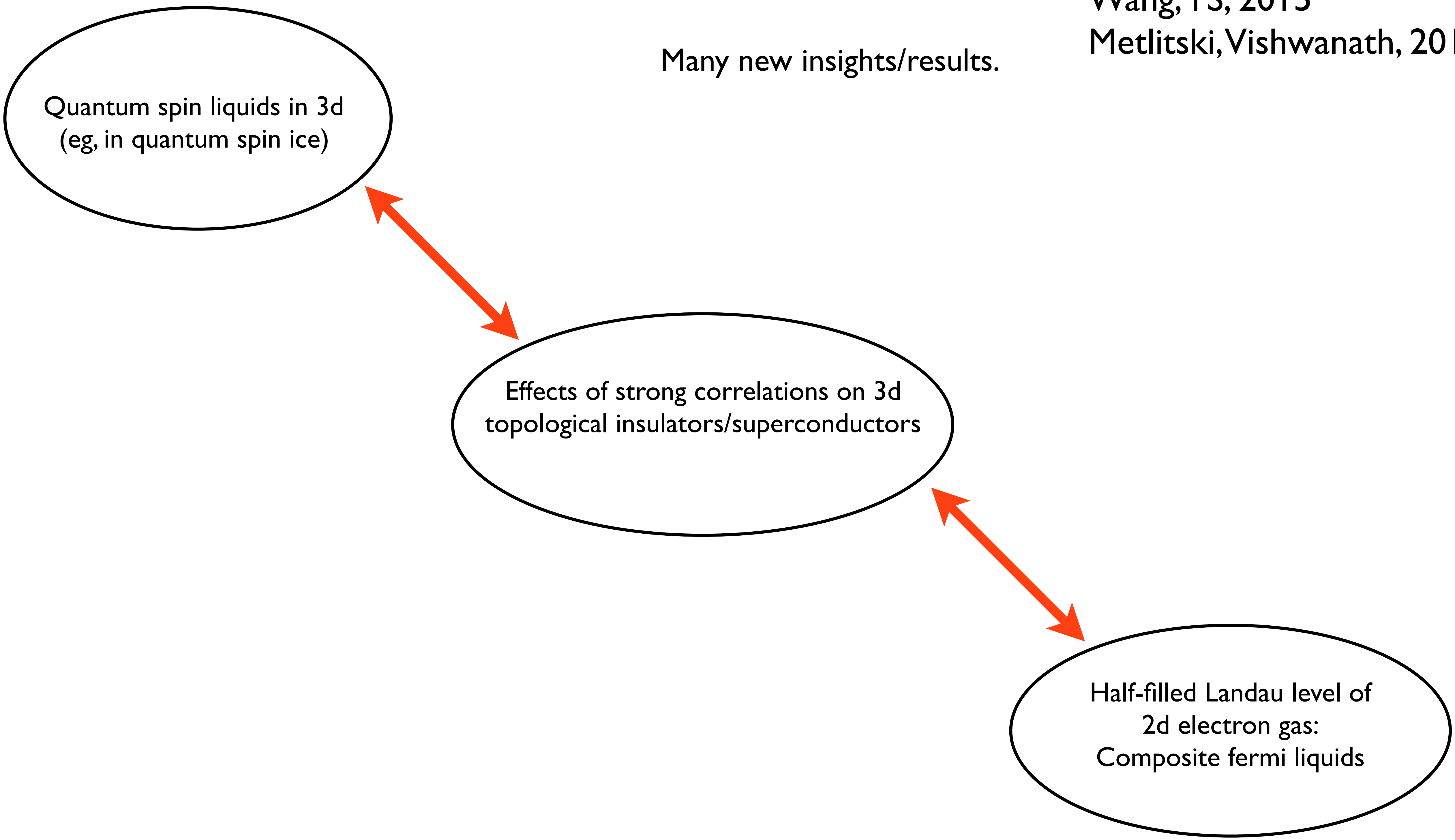
Metlitski, Vishwanath, 2015

Many new insights/results.



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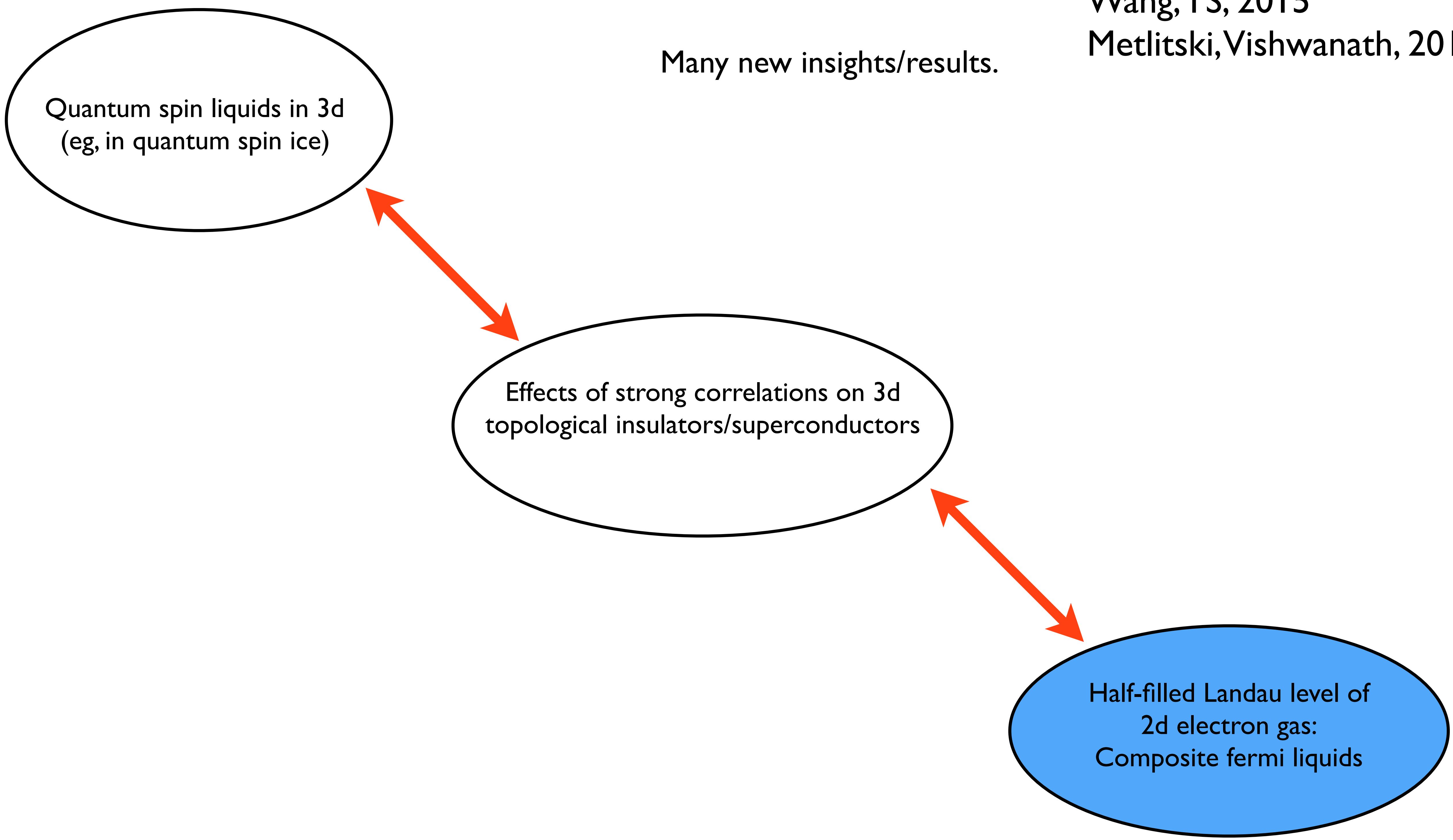


1/2-filled Landau level: the problem

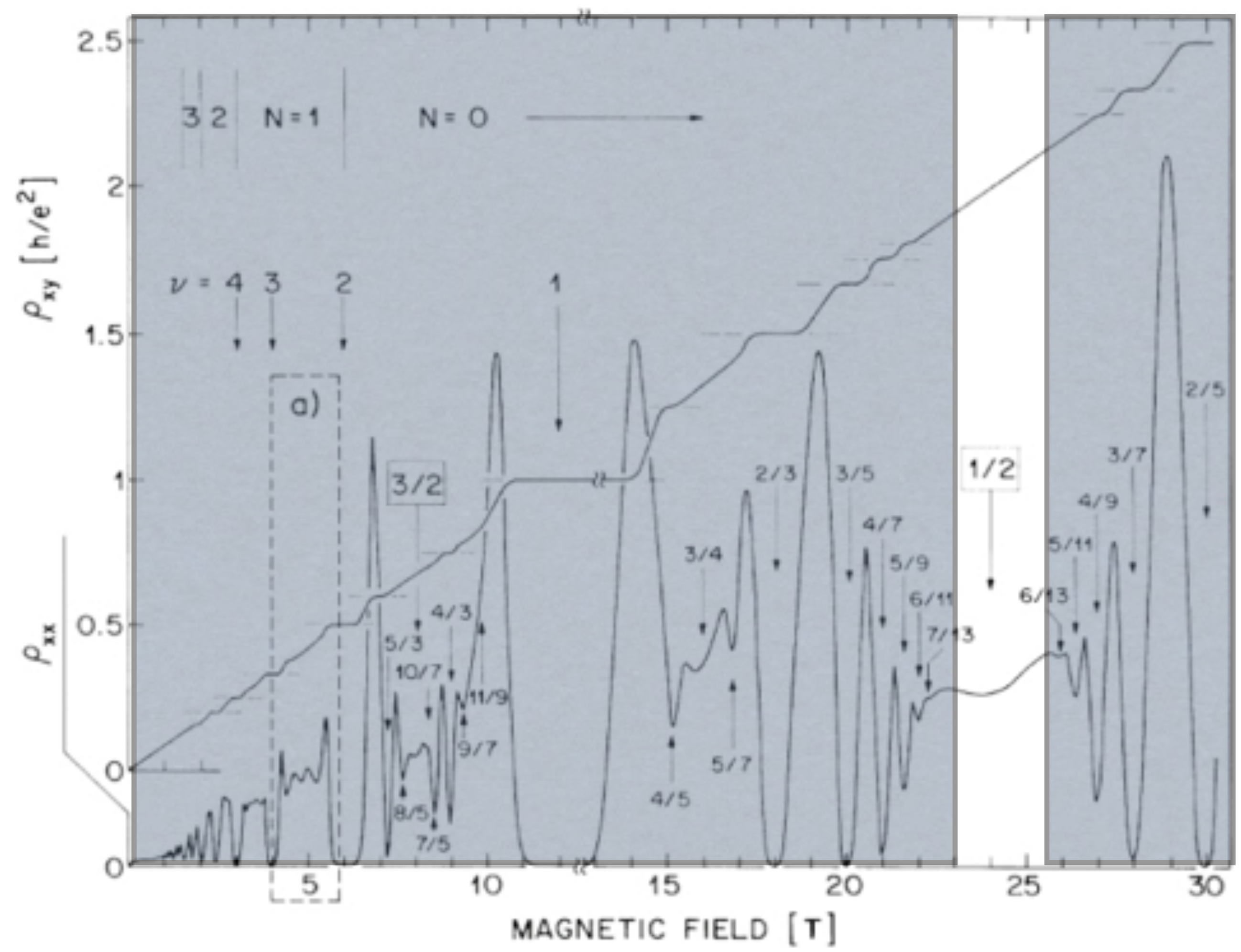
2d electron gas in a strong magnetic field in the ``quantum Hall regime"

Filling factor ν = 1,2., 3, ... (IQHE)

ν = 1/3, 1/5, ... (FQHE)

ν = 1/2 ???

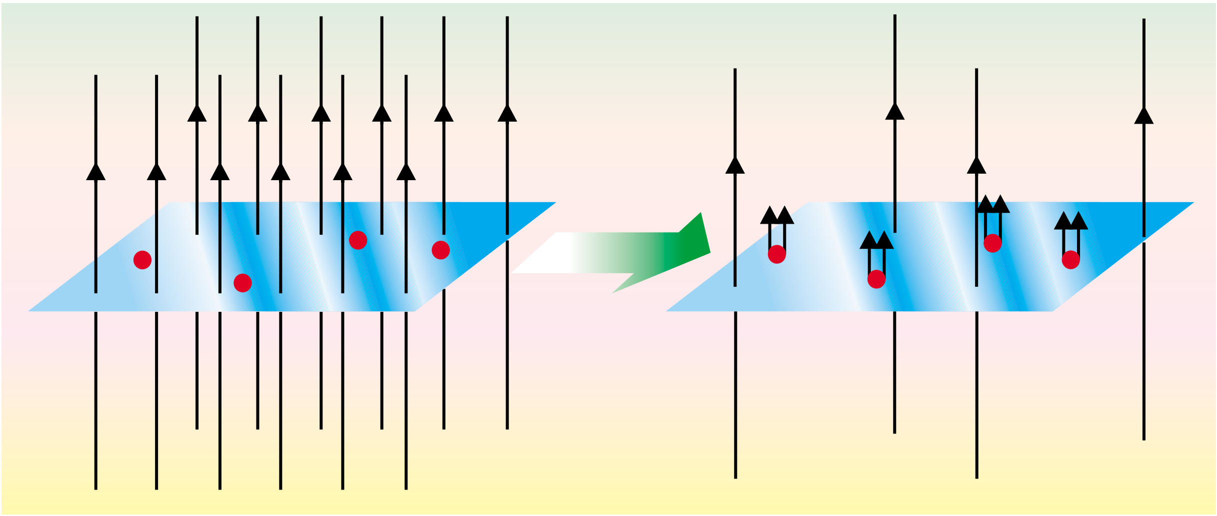
Experiment: Metal with $\rho_{xx} \neq 0$, $\rho_{xy} \neq 0$, but $\rho_{xx} \ll \rho_{xy}$.



Composite fermi liquid theory
(Halperin, Lee, Read (HLR) 1993)

Bind 2 flux quanta to electron:
Form composite fermions (Jain 89)
moving in effective field
B* = B - 4πρ

At ν = 1/2, B* = 0



=> form Fermi surface of composite fermions

Effective theory:

$$\mathcal{L} = \bar{\psi}_{CF}\left(i\partial_t - a_0 - iA_0^{ext} + \frac{(\vec{\nabla} - i(\vec{a} + \vec{A}^{ext})^2}{2m}\right)\psi_{CF} + \frac{1}{4\pi}a_\mu\epsilon_{\mu\nu\lambda}\partial_\nu a_\lambda \quad (1)$$

Some experimental verification of composite fermions

Many groups: Willett, Stormer, Tsui, Shayegan, Goldman,.....

Examples:

1. Slightly away from $\nu = 1/2$, $B^* = B - 4\pi\rho \neq 0$ but much reduced from external field B.

=> composite fermions move in cyclotron orbits with radius >> electron cyclotron radius

(see. eg, in frequency shift of surface acoustic wave, focusing,..)

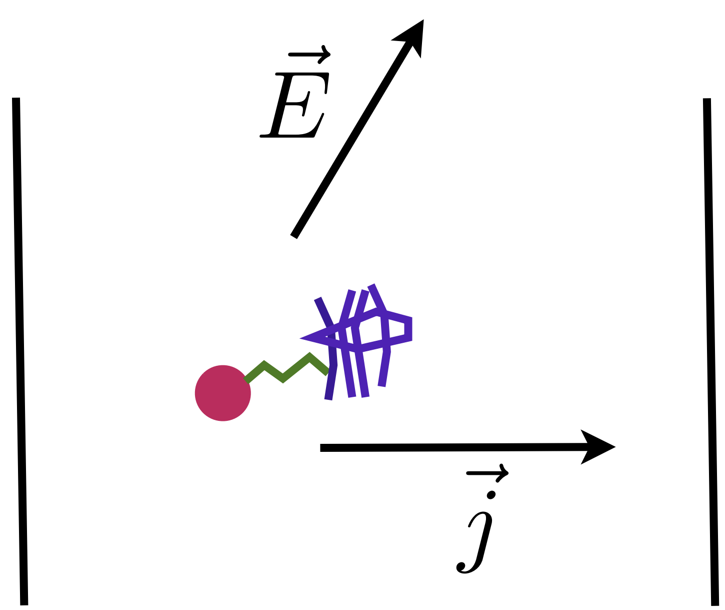
2. Confirmation of composite fermion Fermi surface (geometric resonances, Shubnikov-deHaas oscillations)

3. Successful description of many FQHE states at $\nu = n/(2n+1)$ in terms of filled composite fermion Landau levels (Jain) and prediction of activation energy gaps (as composite fermion cyclotron frequency) (HLR)

Transport phenomenology of composite fermi liquids

Electrical current = current of composite fermions

but the motion of attached flux induces additional transverse voltage drop.



$$\vec{E} = \overleftrightarrow{\rho*}\vec{j} + \frac{2h}{e^2}\hat{z} \times \vec{j}$$

ρ^*_{ij}: resistivity tensor of composite fermions.

Measured resistivity tensor $\rho_{ij} = \rho^*_{ij} + \frac{2h}{e^2}\epsilon_{ij}$

$(\epsilon_{ij} = -\epsilon_{ji})$

$\rho_{xx} \ll \rho_{xy} \sim \frac{2h}{e^2} \Rightarrow \sigma_{xx} \simeq \frac{\rho_{xx}}{\rho_{xy}^2}$

Heat transport and Wiedemann-Franz violation in composite fermi liquids

Wang, TS, 2015

When composite fermions move, they directly transport heat => very different heat and electrical transport

Conventional metal @ $T \to 0$ (even at $B \neq 0$, with disorder, interactions):

Heat conductivity $\kappa_{xx} = L_0 T \sigma_{xx}$ ("Wiedemann-Franz law")
Lorenz number $L_0 = \frac{\pi^2 k_B^2}{3e^2}$

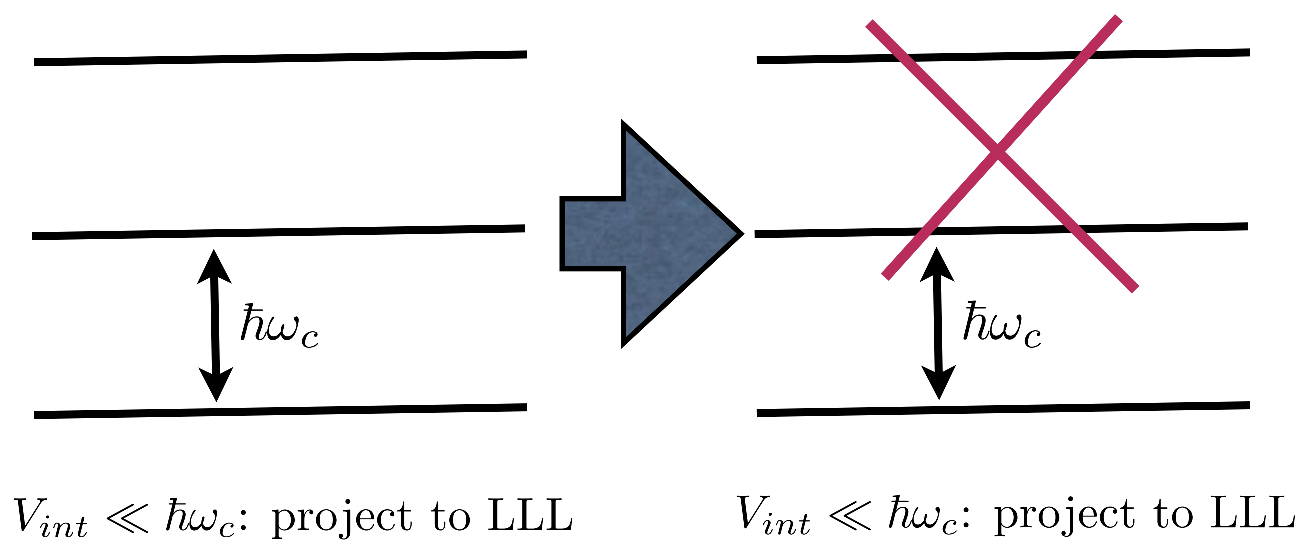
Composite fermi liquids: $\kappa_{xx} \neq L_0 T \sigma_{xx}$ but $\kappa_{xx} = L_0 T \frac{\left(e^2/2h\right)^2}{\sigma_{xx}}$

Then $\frac{\kappa_{xx}}{L_0 T \sigma_{xx}} = \left(\frac{\rho_{xy}}{\rho_{xx}}\right)^2 > 10^3$

Huge violation of conventional Wiedemann-Franz !

Unfinished business in theory

1. Theory should be defineable within the Lowest Landau Level (LLL) but HLR is not in the LLL.



Many refinements in the late 90s (Shankar, Murthy; Read; Halperin, Stern, Simon, van Oppen; D.-H. Lee, Pasquier, Haldane,.......) but dust never settled.

2. Particle-hole symmetry

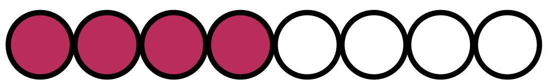
A symmetry of the LLL Hamiltonian (with eg, 2-body interactions) but not manifest in HLR.

Issue identified in the 90s (Grotov, Gan, Lee, Kivelson, 96; Lee 98) but no resolution.

Particle-hole symmetry in LLL

At $\nu = 1/2$, regard LLL as either ``half-empty or half-full'':

Start from empty level, fill half the LLL



or start from filled LL and remove half the electrons

Particle-hole symmetry: formal implementation

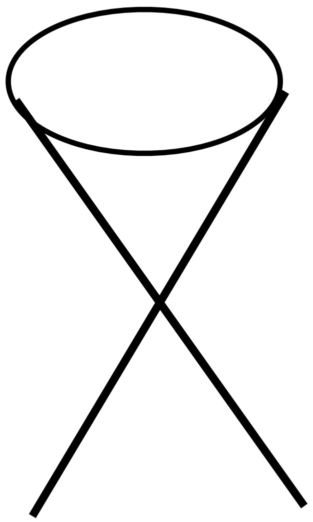
Electron operator $\psi(x,y) \simeq \sum_m \phi_m(x,y) c_m$ after restriction to LLL.
($\phi_m(x,y)$: various single particle wave functions in LLL).

Particle-hole: **Antiunitary symmetry** C
$C\psi C^{-1} = \psi^\dagger = \sum_m \phi_m^*(x,y) c_m^\dagger$

Symmetry of 1/2-LLL with, eg, 2-body interaction is (at least) U(1) X C

Particle-hole symmetric CFL: a proposal

Is the Composite Fermion a Dirac Particle? (Son , 2015)



Composite fermion ψ_v forms a single Dirac cone tuned away from neutrality:

Anti-unitary p/h (C) acts in same way as time reversal usually does on Dirac fermion:

$$C\psi_v C^{-1} = i\sigma_y \psi_v \Rightarrow C^2 \psi_v C^{-2} = -\psi_v$$

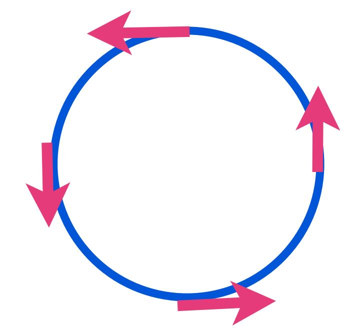
Composite fermion is Kramers doublet under C.

Particle-hole symmetric CFL: a proposal (cont'd) (Son, 2015)

Effective Lagrangian

$$\mathcal{L} = i\bar{\psi}_v \left(\partial\!\!\!/ + i a\!\!\!/\right) \psi_v - \mu_v \bar{\psi}_v \gamma_0 \psi_v + \frac{1}{4\pi} \epsilon_{\mu\nu\lambda} A_\mu \partial_\nu a_\lambda \; + \mathcal{L}_{bg}[A_\mu]$$

Low energy theory: focus on states near Fermi surface.



Meaning of Dirac?

As CF goes around FS, pick up π Berry phase.

Plan of talk

A. Understanding the p/h symmetric composite fermi liquid

1.. Connection to surface of 3d topological insulators - field theoretic justification

(C. Wang, TS, arXiv:1505.05141; M. Metlitski, A. Vishwanath, 1505.05142.)

2. Simple physical picture of the particle-hole symmetric composite fermion

(C. Wang, TS, arXiv:1507.08290)

3. Numerical calculations

(Scott D. Geraedts, Michael P. Zaletel, Roger S. K. Mong, Max A. Metlitski, Ashvin Vishwanath, Olexei I. Motrunich, arXiv: 1508.04140)

B. Composite Fermi liquids in LLL at generic ν:
Quantum vortex liquids with Fermi surface Berry phases

(Wang, TS, to appear)

Plan of talk

Focus in this talk;

<u>A. Understanding the p/h symmetric composite fermi liquid</u>

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Time permitting

B. Composite Fermi liquids in LLL at generic ν:
Quantum vortex liquids with Fermi surface Berry phases
(Wang, TS, arXiv: 1604.06807)

1/2-filled LL and correlated TI surfaces

Derivation of p/h symmetric composite fermi liquid theory

(C. Wang, TS, 15; M. Metlitski, A. Vishwanath, 15)

p/h symmetric LL as a surface of a 3d fermionic topological insulator: Preliminaries

Consider (initially free) fermions with ``weird'' action of time-reversal (denote C):

$C \rho C^{-1} = - \rho$

ρ = conserved ``charge'' density.

Full symmetry = U(1) x C
(called class AIII in Topological Insulator/Superconductor literature*)

*distinct symmetry from usual spin-orbit coupled insulators which have U(1) $\ltimes$ C symmetry (i.e, ρ is usually even under time reversal).

p/h symmetric LL as a surface of 3d fermion SPT (cont'd)

Surface: Single massless Dirac fermion

C symmetry guarantees that surface Dirac cone is exactly at neutrality.

$$\mathcal{L} = \bar{\psi}\left(-i\not{\partial} + \not{A}\right)\psi + \ldots.$$

external probe gauge field

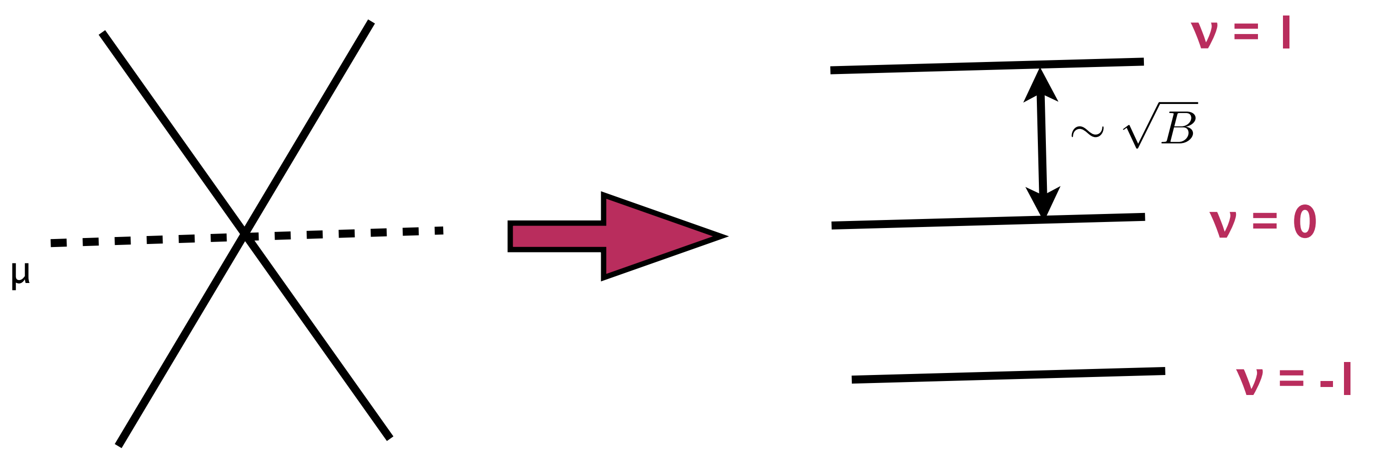
2-component fermion

p/h symmetric LL as a surface of 3d fermion SPT (cont'd)

ρ is odd under C => `electric current' is even.

External E-fields are odd but external B-fields are even.

=> Can perturb surface Dirac cone with external B-field.



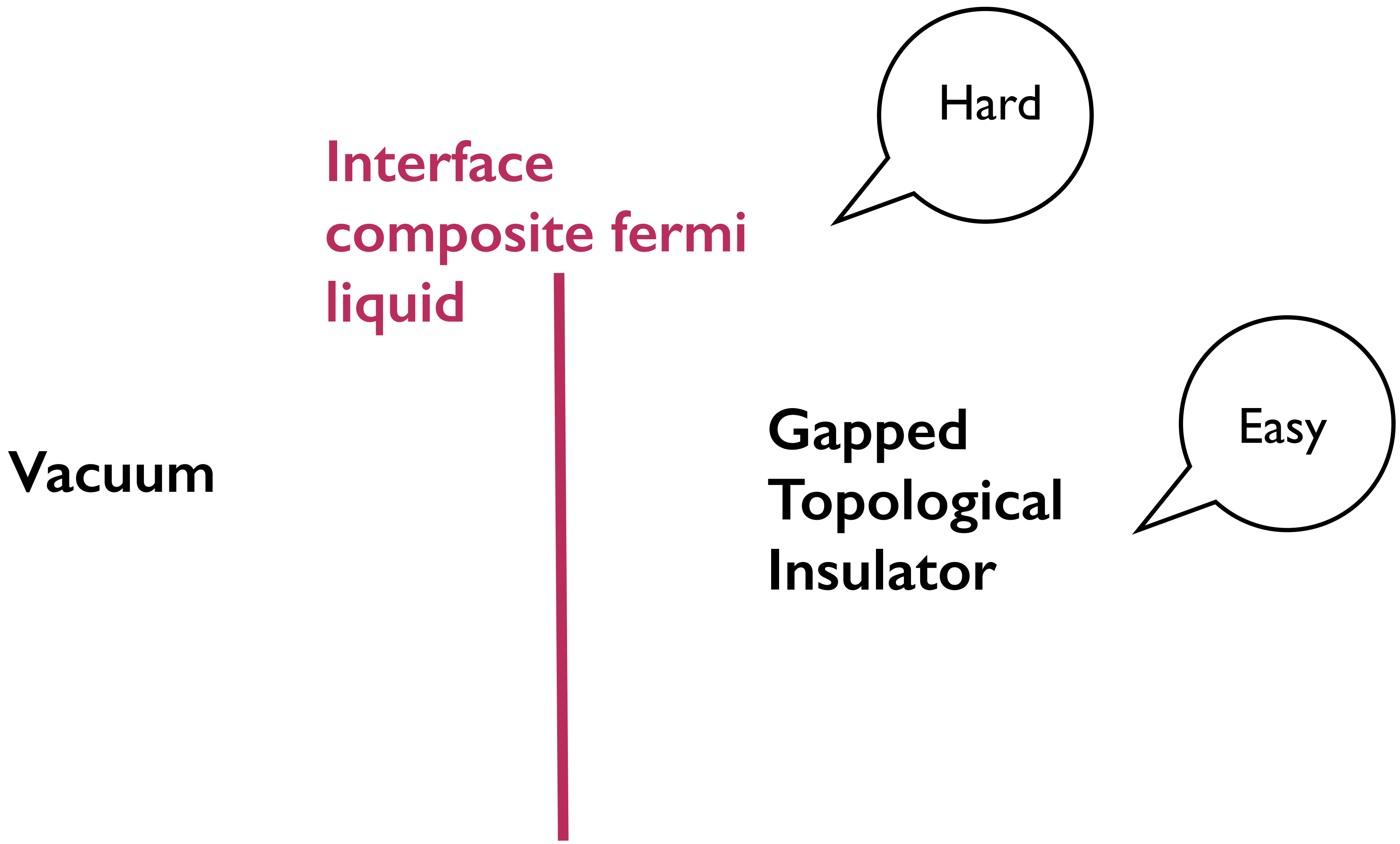
C-symmetry: ν = 0 LL is exactly half-filled.

Low energy physics: project to 0LL

With interactions => map to usual half-filled LL

Comments

Implication: Study p/h symmetric half-filled LL level by studying correlated surface states of such 3d fermion topological insulators.

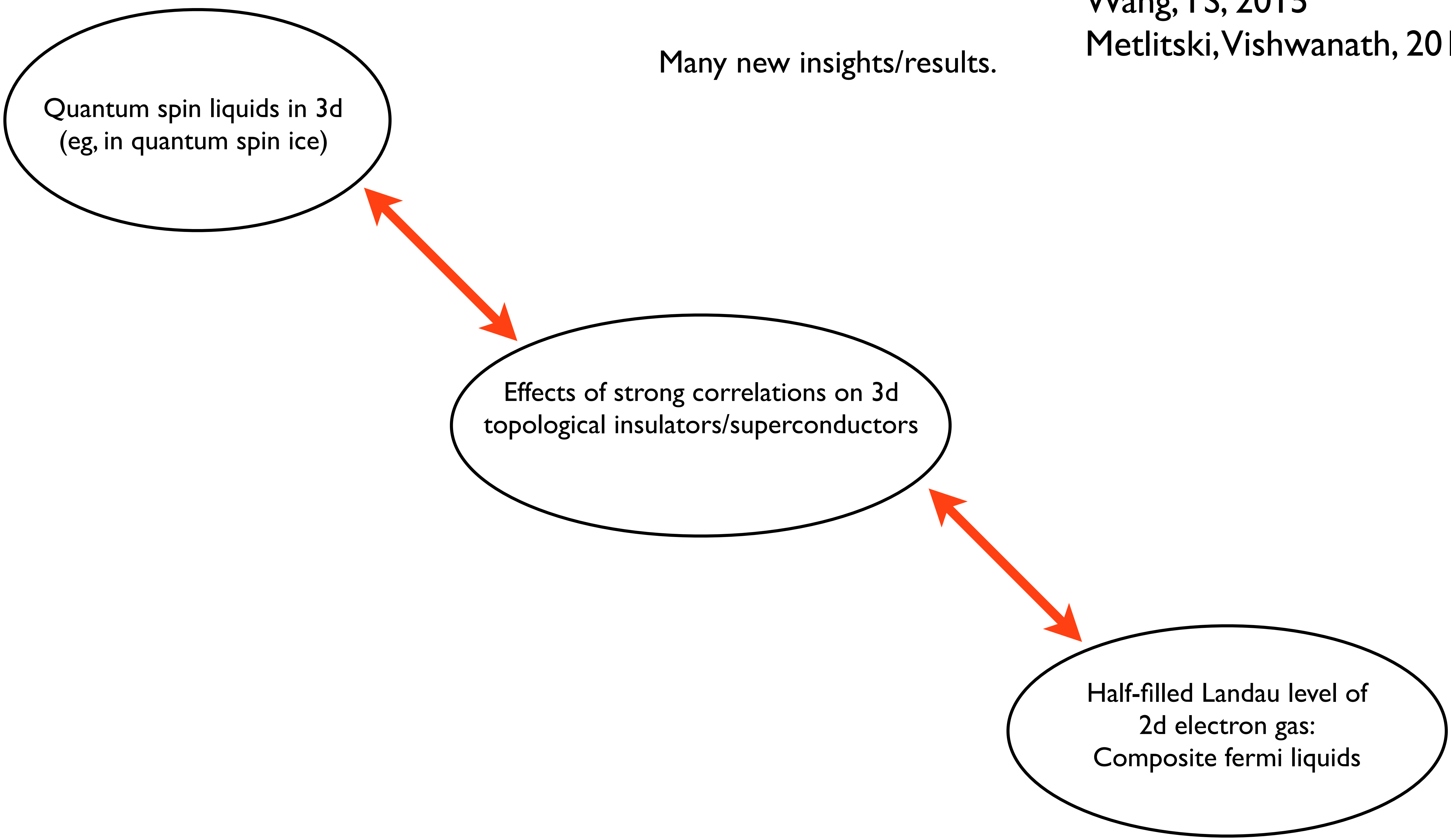


Exploit understanding of relatively trivial bulk TI to learn about non-trivial correlated surface state.

Deep connections between 3 apparently different problems

Wang, TS, 2015
Metlitski, Vishwanath, 2015

Many new insights/results.



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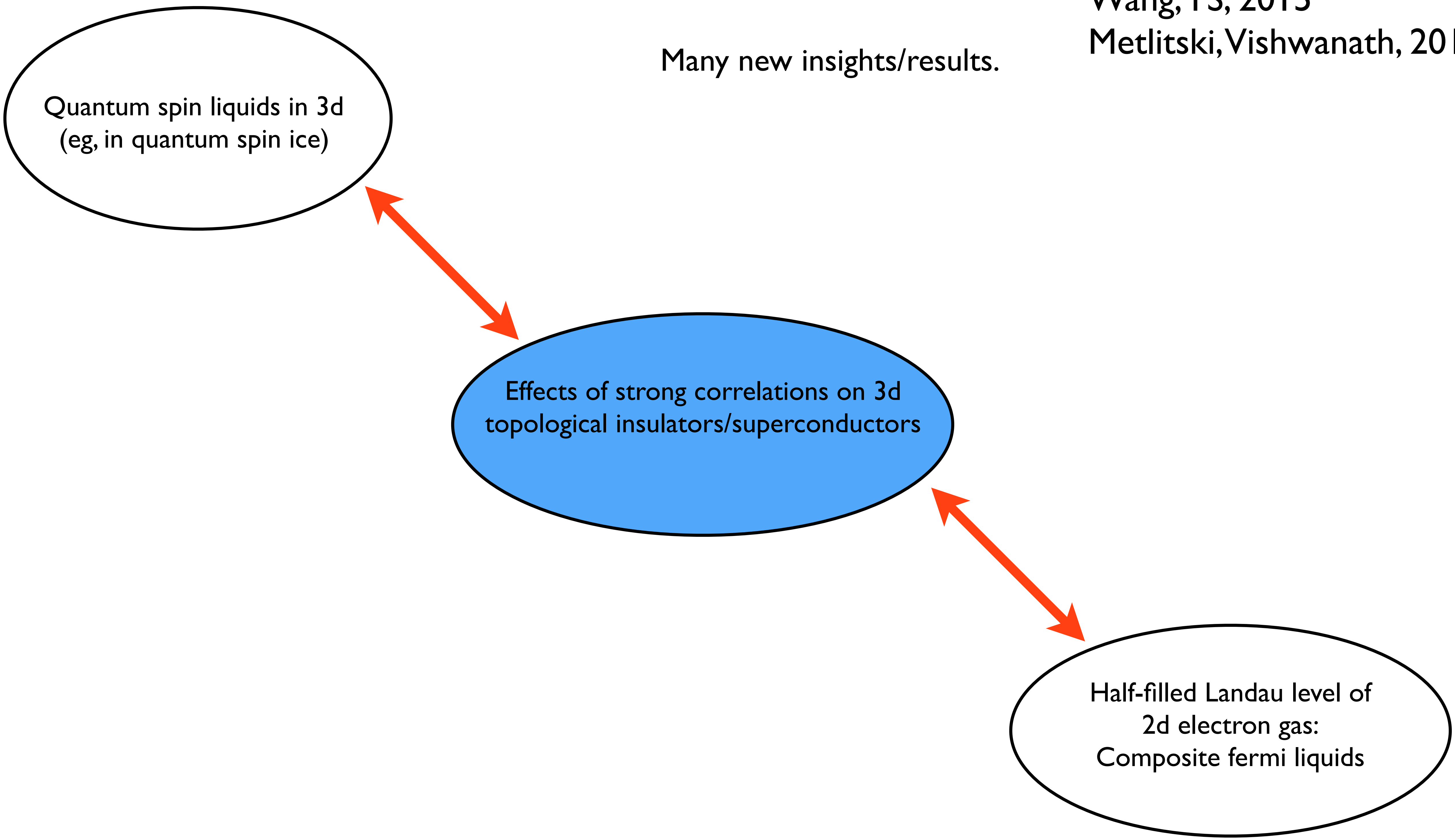


How to study physics of strongly correlated topological insulators?

Cannot use band theory - need other methods

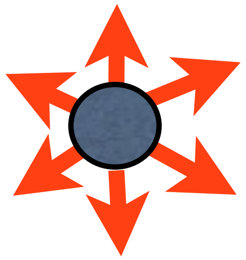
Very useful strategy: couple to a weakly fluctuating dynamical \`electromagnetic' field.

Interpretation of resulting state: a quantum spin liquid with an emergent photon where the \`electric charge' forms a topological insulator.

A powerful ***conceptual*** tool

A `gedanken' experiment:

Probe the fate of a magnetic monopole inside the material
(after coupling electrons to a dynamical ``electromagnetic" field).



Thinking about the monopole is a profoundly simple way to non-perturbatively constrain the physics of the material.

Reminder: Elementary monopole is a source of hc/e magnetic flux.

Monopoles and topological insulators

Ordinary insulator: hc/e monopoles have $q = 0$.

Topological insulator with U(1) x C symmetry:

hc/e monopoles have fractional charge $q = \pm e/2$.
(related to magneto-electric response $\theta = \pi$, Qi, Hughes, Zhang 09; Rozenberg, Franz, 10)

2hc/e monopole can be electrically neutral (bind the two hc/e monopoles with $q = \pm e/2$).

Can show that this neutral 2hc/e monopole a Kramers doublet under C, and is a fermion. (Wang, Potter , Senthil, 13; Metlitski, Kane, Fisher, 13)

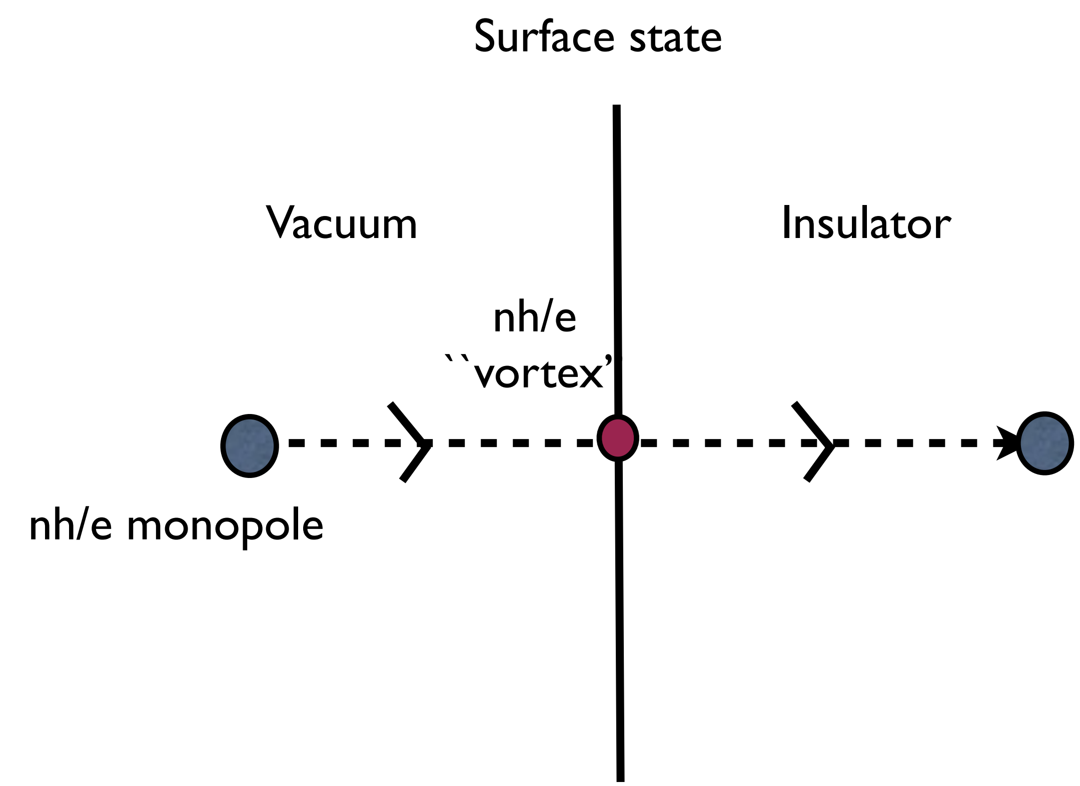
- identify with composite fermion

Surface magnetic field and bulk magnetic monopoles

Build up magnetic field B at surface by moving magnetic monopoles from vacuum to inside of TI.

Moving strength-n monopole => surface magnetic flux increases by $2\pi n$.

Monopoles inside TI are non-trivial => monopole insertion leaves behind non-trivial surface excitation.



A remarkable duality

Can view this 3d quantum state of matter in two equivalent ``dual" ways.

1. Topological insulator of electric fermion (with no magnetic flux)

or

2. Topological insulator of neutral 2hc/2 magnetic monopole (= composite fermion)

Consequences for surface: Justification of Dirac CF theory

Each time surface flux increases by 2hc/e, we add a neutral Kramers doublet fermion to surface - identify with composite fermion.

Surface magnetic field B => density $B/4\pi$ of neutral composite fermions.

Duality of Surface theory (fermionic version of charge-vortex duality):

\`Electric' picture: Dirac cone of electric fermions in B-field (= Half-filled LL problem)

Dual \`magnetic' theory: Dirac cone of neutral composite fermions at
finite density + U(1) gauge field (= proposed Dirac composite fermion theory)

Composite fermi liquids as vortex metals

HLR/Jain composite fermion: Charge - flux composites

Particle-hole symmetric composite fermion: Neutral vortex

Describe CFL as a vortex liquid metal formed by neutral fermionic vortices.

Vortex metal description:

- Simple understanding of transport
(similar to other 2d quantum vortex metals, eg, in Galitski, Refael, Fisher, TS, 06)

- Extensions to CFLs away from $\nu = 1/2$

Transport in the CFL

1. Longitudinal electrical conductivity $\propto$ composite fermion resistivity (natural from vortex liquid point of view)

   Hall conductivity $= \frac{e^2}{2h}$ (exactly)

2. Longitudinal thermal conductivity $=$ composite fermion thermal conductivity

   Wiedemann-Franz violation (Wang, TS, 15)

   $$\frac{\kappa_{xx}}{L_0 T \sigma_{xx}} = \left(\frac{\rho_{xy}}{\rho_{xx}}\right)^2 > 10^3$$

   L_0: free electron Lorenz number

   (Also actually in HLR)

3. Thermoelectric transport:

   Vortex metal: Nernst effect from mobile vortices unlike HLR (Potter et al, 15)

Composite Fermi liquids in LLL at generic ν: Quantum vortex liquids with Fermi surface Berry phases

Wang, TS, 2016

General $\nu = 1/(2q)$ but with LLL restriction:

Attach 2q vortices to electron.

LLL => neutral fermionic vortex distinct from Jain/HLR composite fermion (many people in late 1990s)

Effective theory must have no Chern-Simons term for internal gauge field to ensure this.

Trade Chern-Simons term for Fermi surface Berry phase $\phi_B = -2\pi\nu$

Effective Lagrangian

$$\mathcal{L} = \mathcal{L}_{\phi_B}[\psi_v, a_\mu] - \frac{1}{4q\pi}\epsilon_{\mu\nu\lambda}a_\mu\partial_\nu A_\lambda + \frac{1}{8q\pi}\epsilon_{\mu\nu\lambda}A_\mu\partial_\nu A_\lambda.$$

Unified viewpoint on CFLs of fermions and of bosons at $\nu = 1$ (Read 98; Alicea et al 05)

Comments/summary

1. Old issue of p/h symmetry in half-filled Landau level: simple, elegant answer

General viewpoint: Regard LLL composite fermi liquid as a quantum metal of neutral fermionic vortices (Fermi surface Berry phases even without p/h symmetry)

2. Surprising, powerful connection to correlated 3d TI surfaces and to quantum spin liquid theory

3. Many other related results

-- classification of time reversal invariant 3d spin liquids with emergent gapless photon

- particle-vortex duality for 2+1-d massless Dirac fermions

- - clarification of many aspects of correlated surfaces of 3d TIs

……..