Composite fermions and the 2D field-tuned superconductor-insulator transition

Michael Mulligan (Stanford)

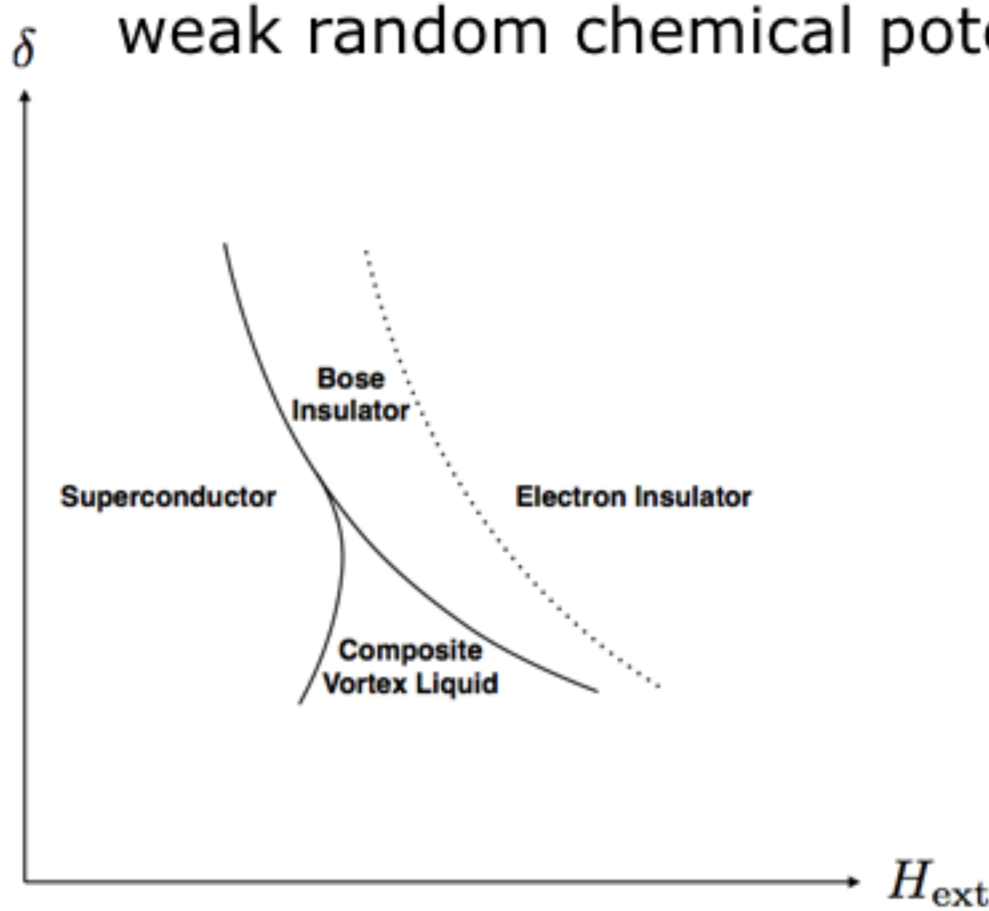
MM and Sri Raghu, arXiv:1509.07865

This talk is about the **metallic behavior** that occurs when superconductivity is destroyed by a perpendicular magnetic field in a disordered thin film, such as InO, MoGe, and Ta.

We **suggest** that the metal is a direct analog of the **composite Fermi liquid** seen in quantum Hall systems (near a half-filled Landau level).

The composite fermions here are composite vortices (vortices attached to 1 flux quantum of emergent gauge flux).

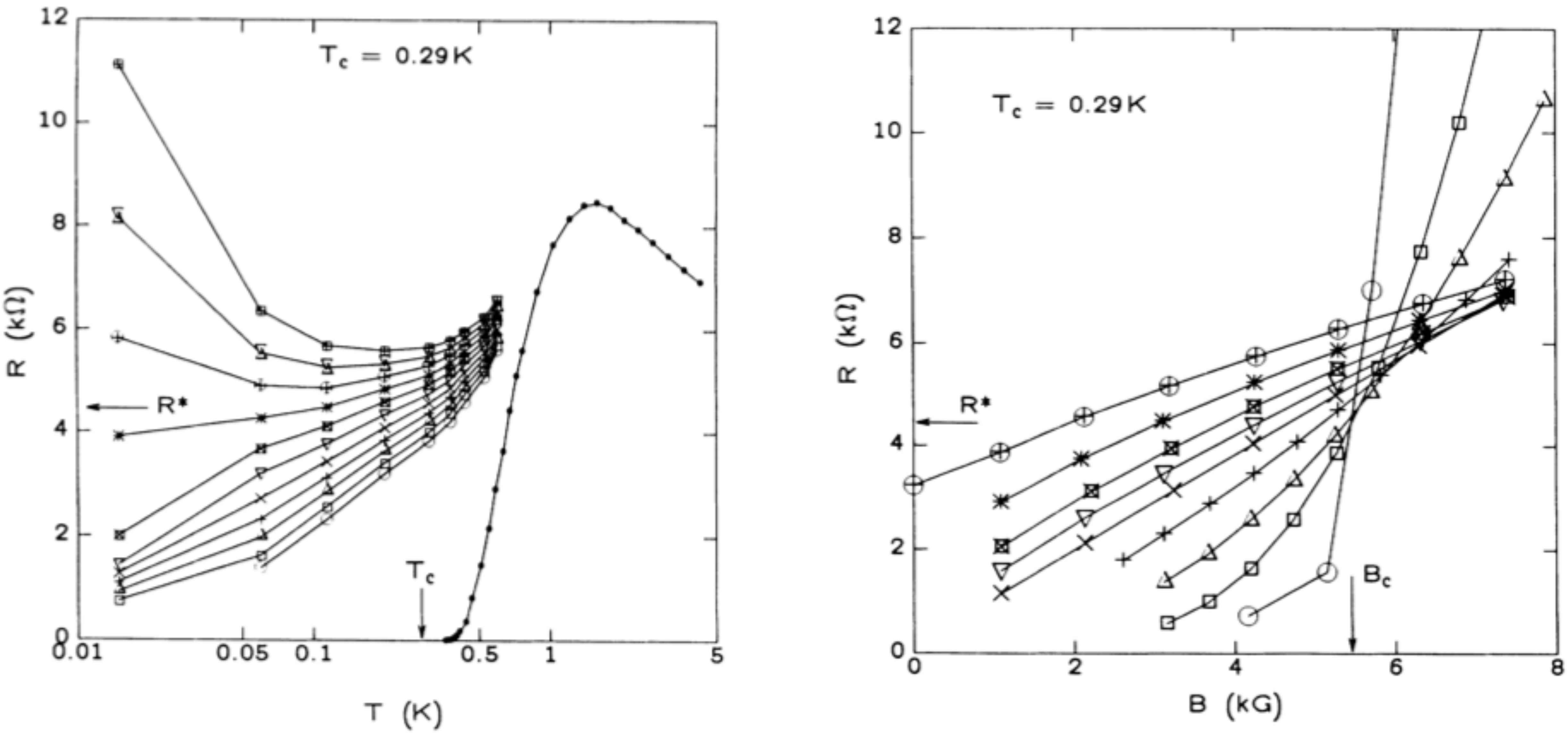
The composite vortex liquid is a non-Fermi liquid and is stable to weak random chemical potential disorder.



Magnetic Field-tuned
Superconductor-Insulator transitions

Hebard, Palaanen (1990).

$$\alpha - \mathrm{InO}_x$$

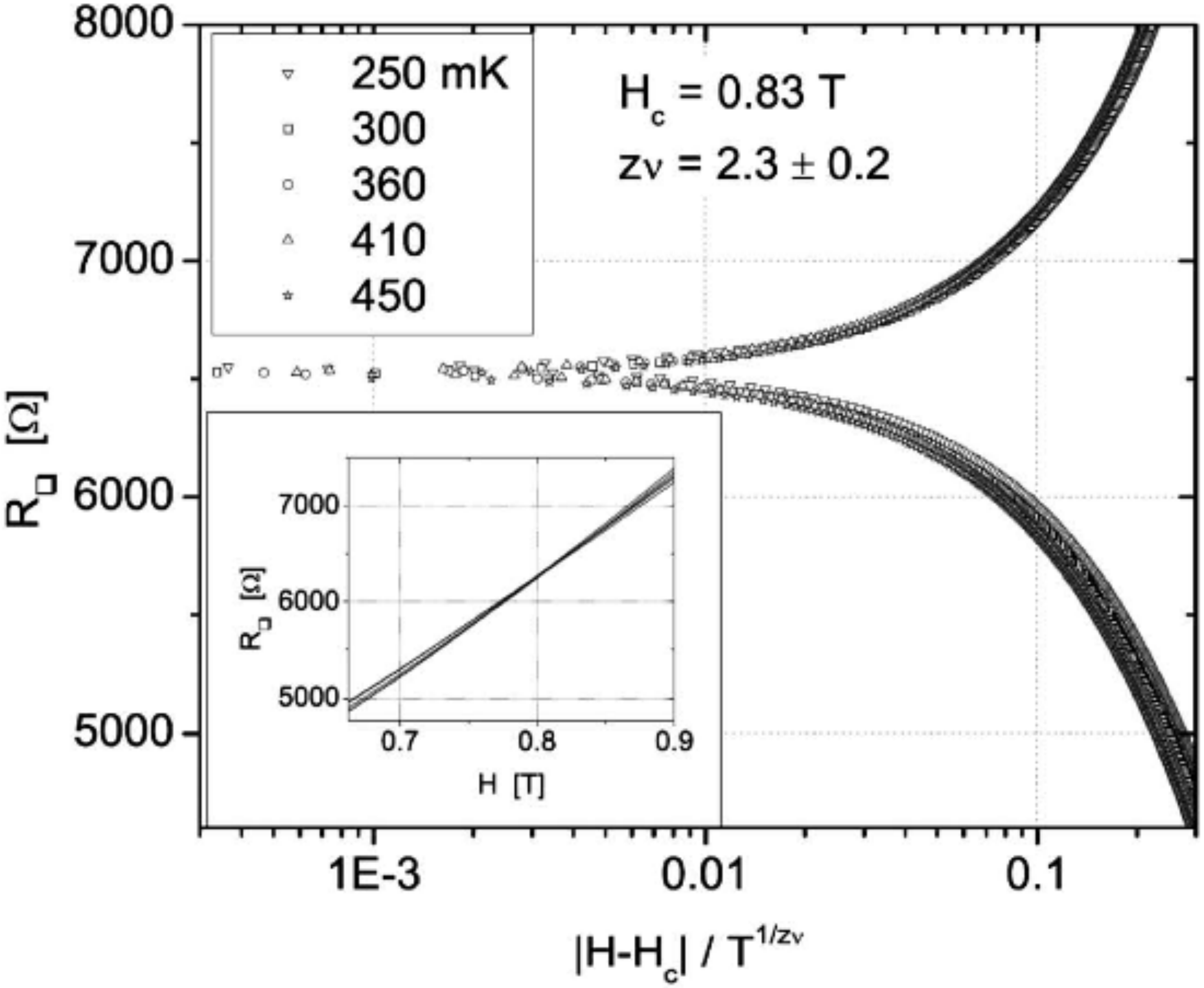


$$R^* \lesssim R_q = h/4e^2$$

Magnetic Field-tuned Superconductor-Insulator transitions

Steiner, Breznay, Kapitulnik, PRB (2008).

InO_x



$$\xi \sim |B - B_c|^{-\nu}$$

$$\xi_\tau \sim |B - B_c|^{-\nu z}$$

$$T \sim 1/\xi_\tau$$

$$\nu z \approx \frac{7}{3}$$

Similar exponents in QH plateau transitions

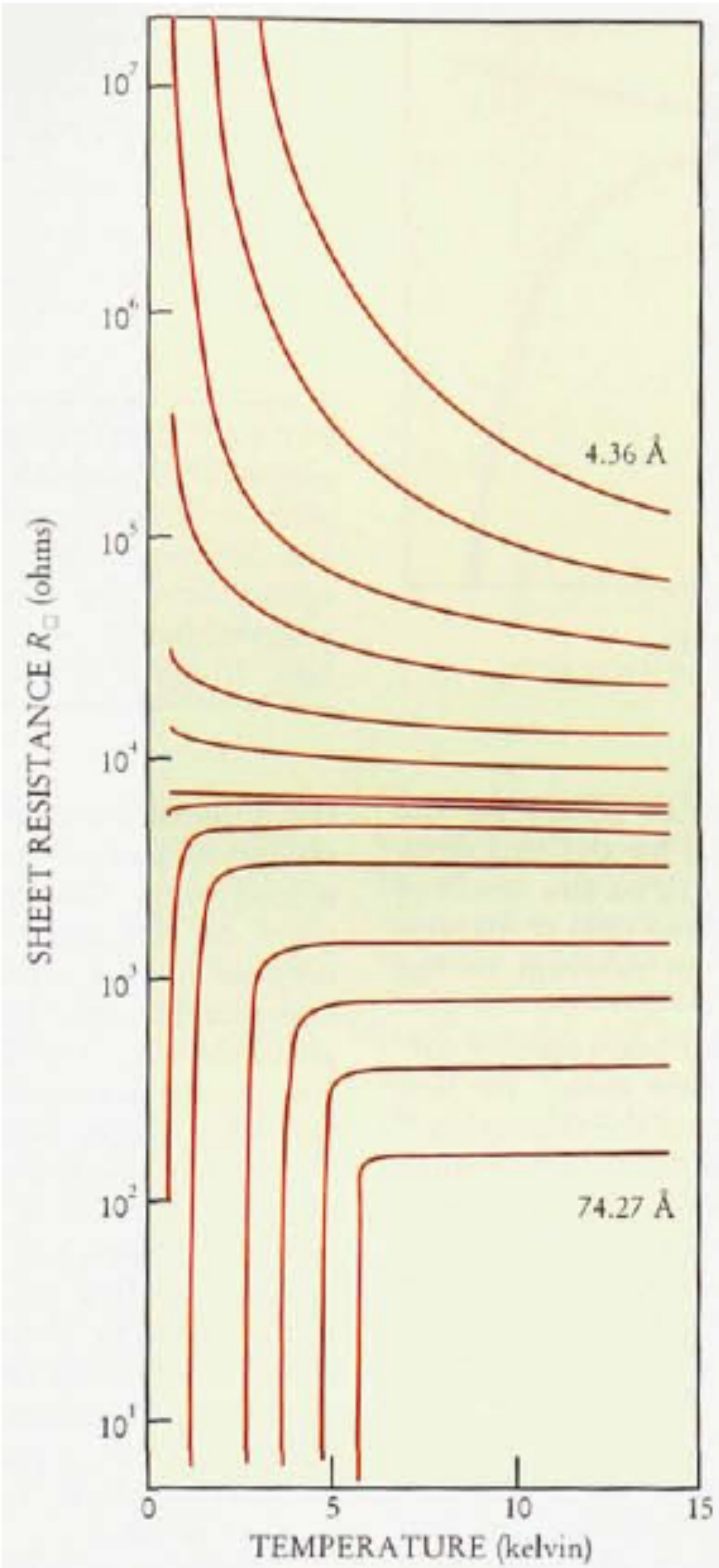
$$R_Q = h/4e2 \approx 6.45k\Omega/\Box$$

Evidence of 1 parameter scaling: $R = R_Q f\left(\frac{|B - B_c|}{T^{1/\nu z}}\right)$

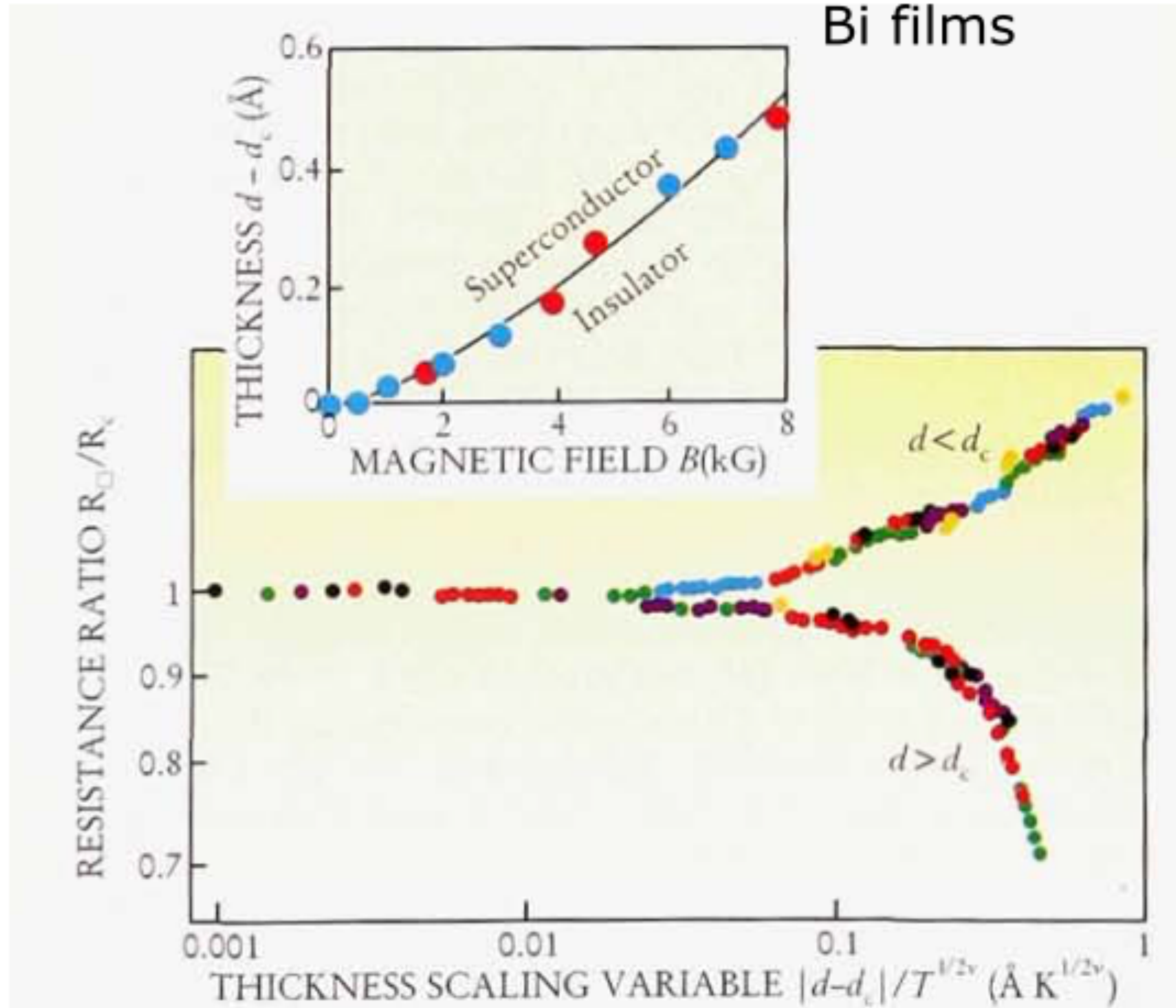
continuous quantum phase transition

Disorder-tuned
Superconductor-Insulator transitions

Markovic, Goldman, Phys. Today (1998)



Bi films



Magnetic field vs. disorder tuning

With both disorder and magnetic fields present:
Superconducting and insulating phases only (strictly) occur at T=0 in **2D** due to thermally-assisted vortex hopping when T>0.

Field tuned SIT is **not** in the same universality class as disorder tuned SIT.

Field tuning: broken time-reversal symmetry, unscreened vorticity (one component plasma of vortices).

Disorder tuning: time-reversal is preserved, no net vorticity, line of finite T transitions extending from the T=0 transition point.

This talk is about field-tuned SITs.

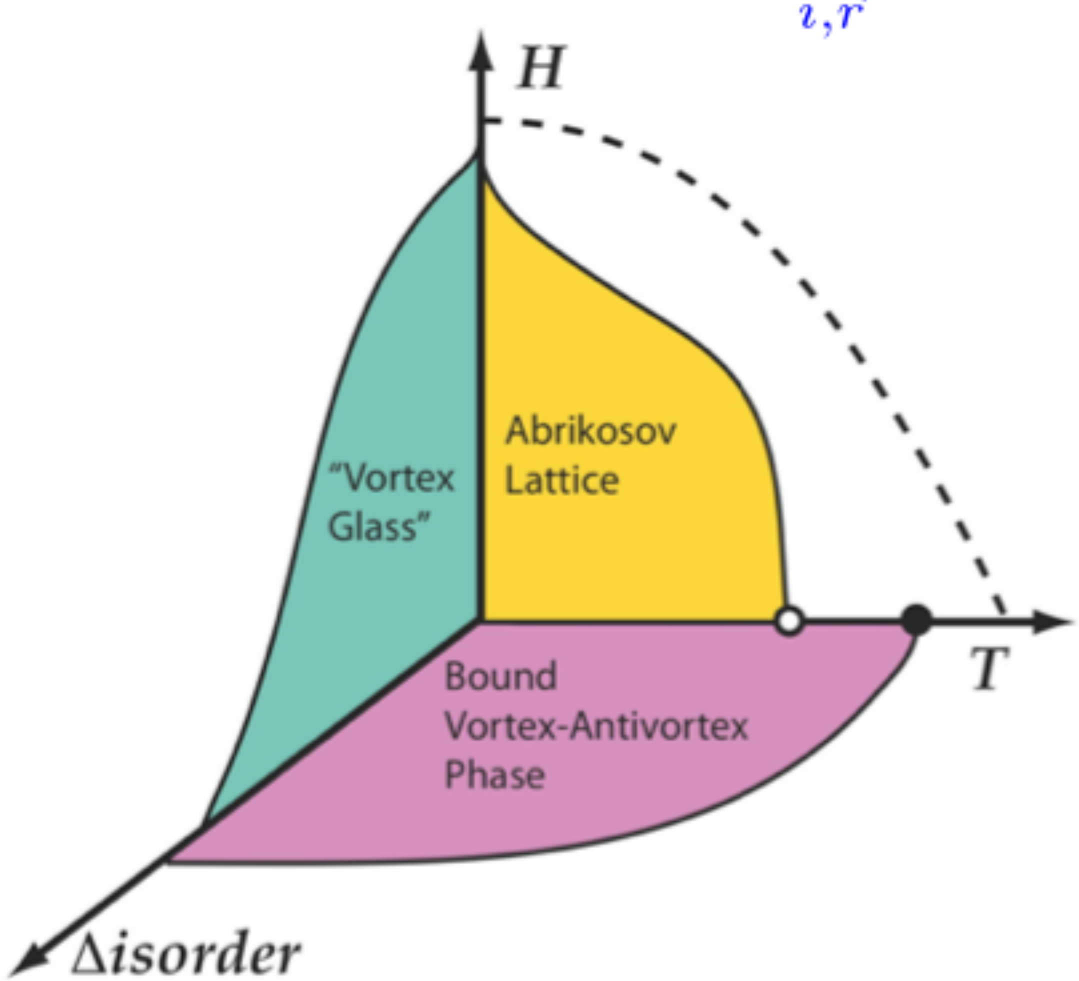
Dirty boson theory

M. Fisher (1990).
M. Fisher, G. Grinstein, S. Girvin (1990).

$$\Psi_{\text{Cooper pair}} = n e^{i\theta} \qquad [\theta(\vec{r}), n(\vec{r}')] = i\hbar$$

$$H_1 = \frac{1}{2} \sum_{\vec{r},\vec{r}'} \Big(n(\vec{r}) - \langle n(\vec{r}\rangle \Big) V_{\vec{r},\vec{r}'} \Big(n(\vec{r}') - \langle n(\vec{r}')\rangle \Big),$$

$$H_2 = -\sum_{i,\vec{r}} J_{i,\vec{r}} \cos\Big(\Delta_i \theta(\vec{r}) + e_* A_i(\vec{r})\Big)$$



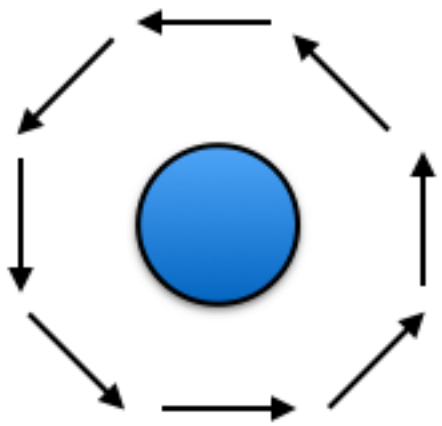
Superconductor: Cooper-pair condensate, phase is ordered

Insulator: Cooper-pair localization, density is ordered

In **both** the SC and Insulator, there is **finite** superfluid stiffness.

Particle-vortex duality

$$n = \vec{\nabla} \times \vec{a} \qquad \vec{J} = \vec{e} \times \hat{z} \qquad \vec{\nabla} \cdot \vec{e} = 2\pi \left(n_v - n_v^0\right)$$



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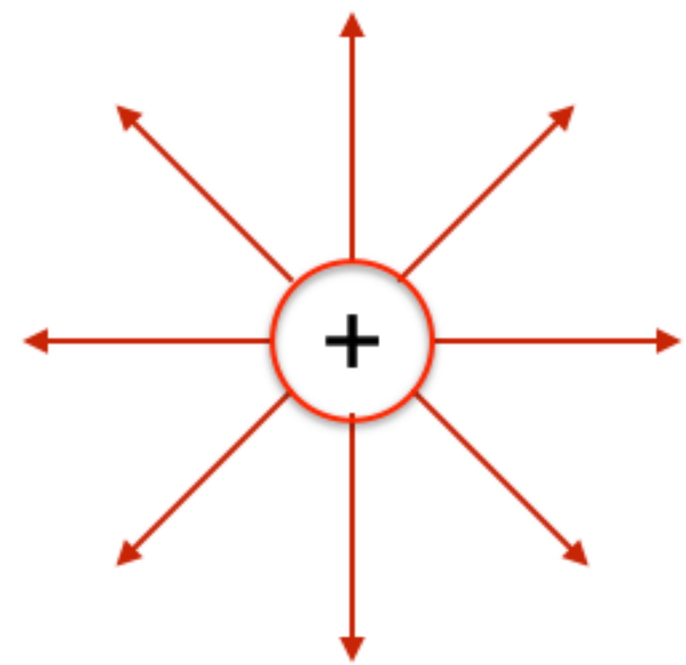


$\dfrac{hc}{2e}$ vortex

positive charge

$$\Psi_{\text{Cooper pair}} = n e^{i\theta} \qquad \Psi_{\text{vortex}} = n_v e^{i\phi}$$

$\langle \theta \rangle \neq 0$ $\langle \phi \rangle \neq 0$

B

SC Ins

Bosons at Unit Filling Fraction

clean superconductors $\langle n(\vec{r})\rangle = n_e/2$

disordered superconductors $\langle n(\vec{r})\rangle \sim \frac{n_e}{3}\frac{\ell^2}{\hbar D/(k_B T_c)}$

Abrikosov et al.'s book

In MoGe films $\langle n(\vec{r})\rangle \sim 2\times 10^{14} m^{-2} \sim 10^{-3} n_e$

$$b_{\mathrm{v}} = \langle n(\vec{r})\rangle \Phi_0 \sim 0.5T$$

Transitions and metallic phases occur near bosons at unit filling fraction:

Yazdani, Kapitulnik (1994)

$$\langle n(\vec{r})\rangle/(B/\Phi_0) = 1$$

similar estimates obtain for InO and Ta films

Self duality

A useful theoretical anchor point, is the self-dual limit, where mobile Cooper pairs and mobile vortices behave similarly (same Hamiltonians). Self-duality only applies close to the SIT.

In many cases, approximate self-duality is helpful in interpreting, even observed in, the experiments. Makes previous estimate precise.

Self-duality at the SIT: $\langle n \rangle = \langle n_v \rangle \qquad \langle \dot{n} \rangle = \langle \dot{n}_v \rangle$

$$V = \frac{h}{2e} \langle \dot{n}_v \rangle \qquad I = 2e \langle \dot{n} \rangle$$

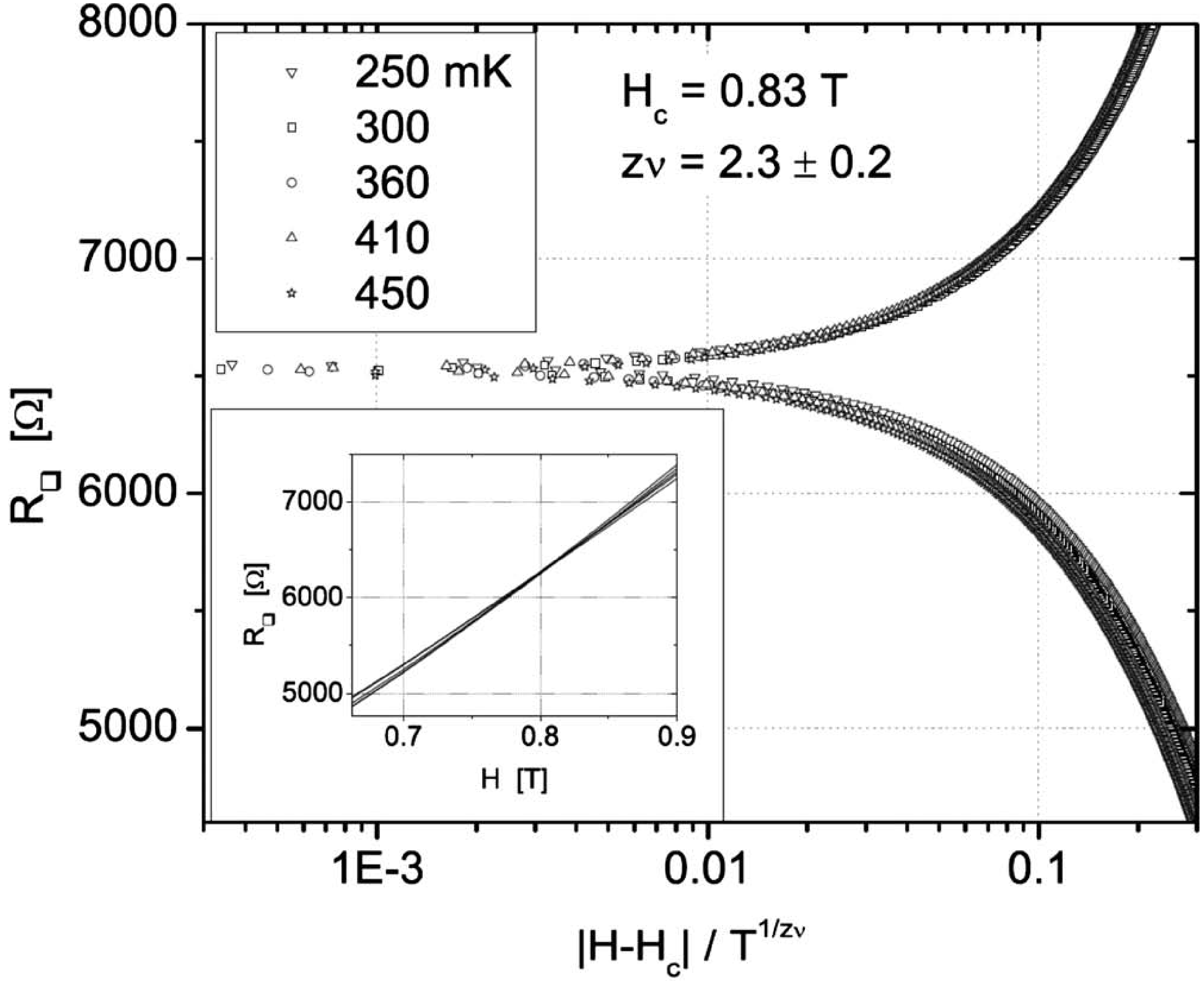
"Consequence" of self-duality: universal critical resistance

$$R^* = V/I \approx \frac{h}{4e^2} \approx 6.45 k\Omega/\Box$$

Observation of self-duality

Steiner, Breznay, Kapitulnik, (2008).

InO_x



More precise consequence of self-duality at the SIT:

$$R_{xx}^2 + R_{xy}^2 = R_Q^2$$

$$R_Q = h/4e^2 \approx 6.45k\Omega/\Box$$

Note: self-duality imposes a bound on R_{xx} at the SIT given Hall resistance.

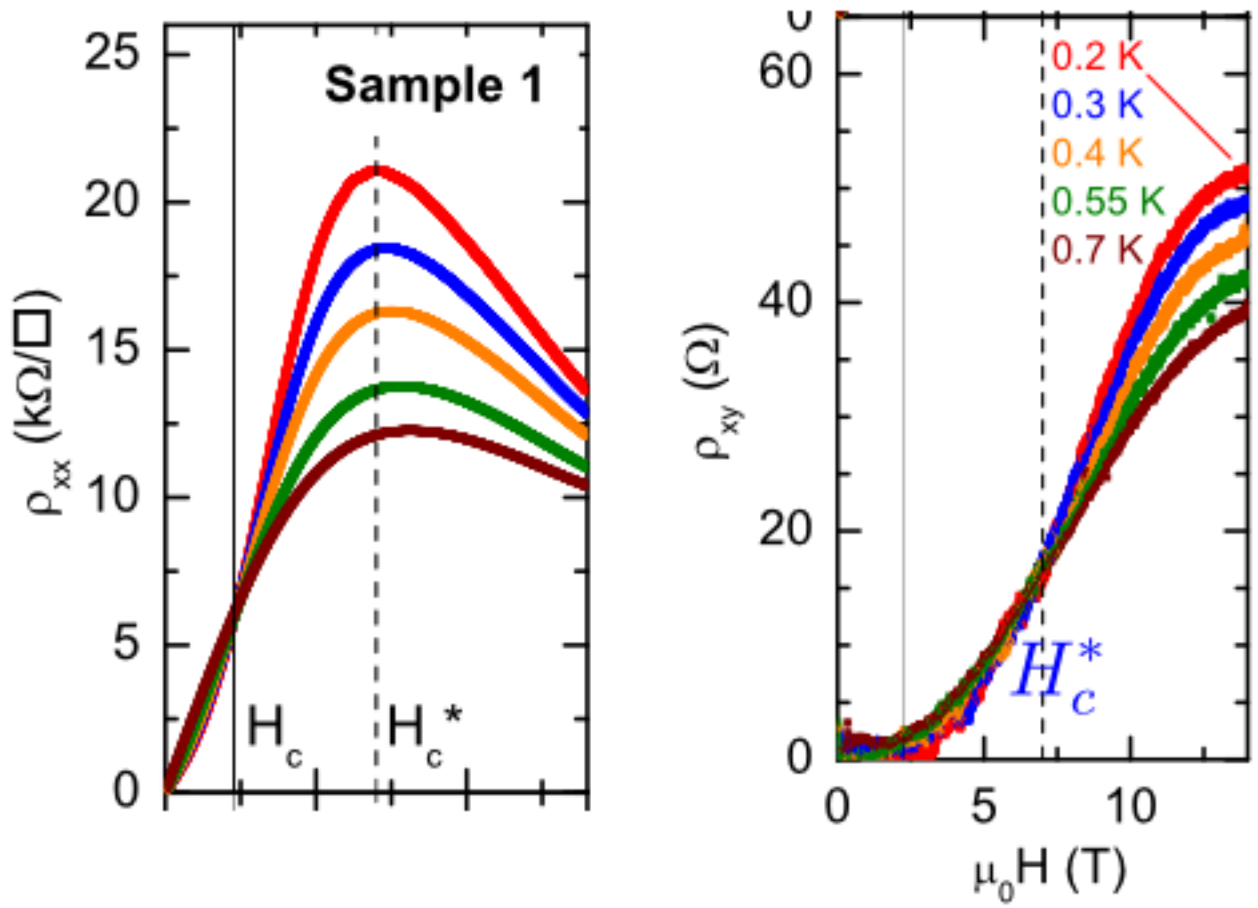
More explicit verification of self-duality by Breznay et al., 1504.08115.

Successes of dirty boson theory

(i) **Positive** magnetoresistance in the insulator for fields up to $2H_c$.

Breznay *et al.*, 1504.08115

Paalanen, Hebard, Ruel, (1992).



(ii) Finite superfluid response in the insulator. R. Crane et al., (2007).

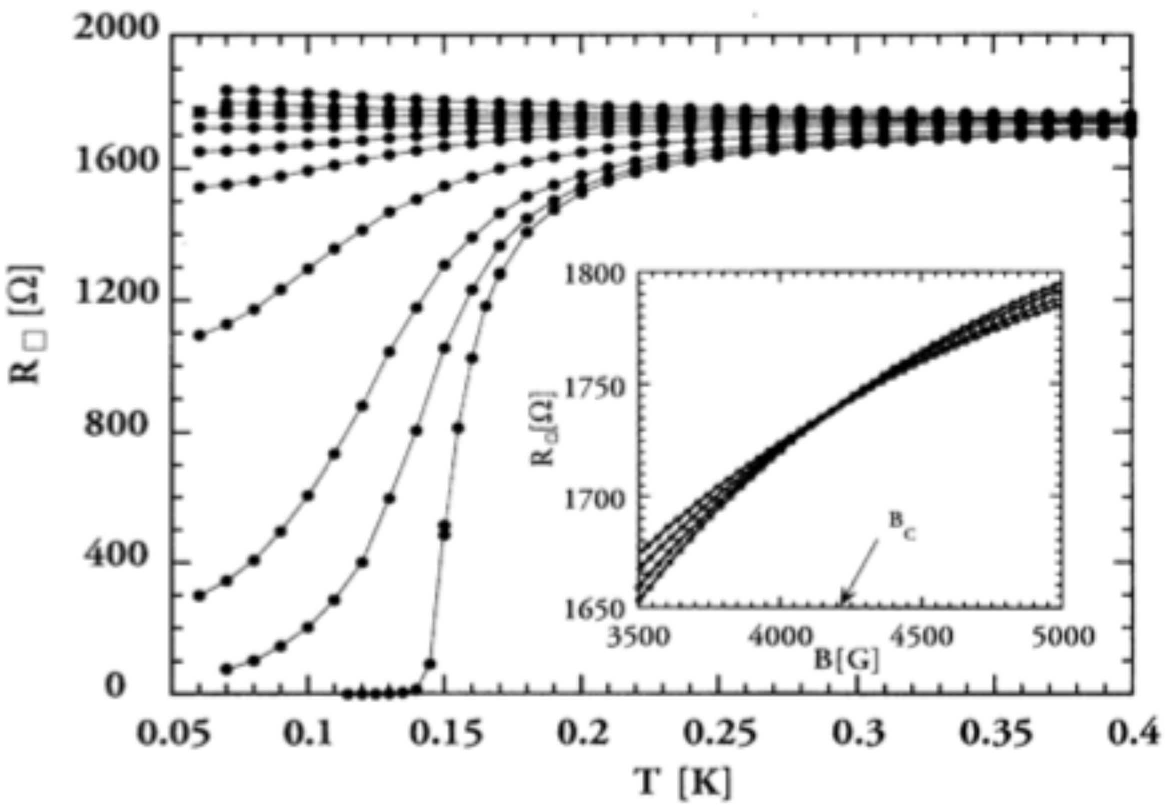
Both are evidence in favor of a "Bose" insulator (localized Cooper pairs).

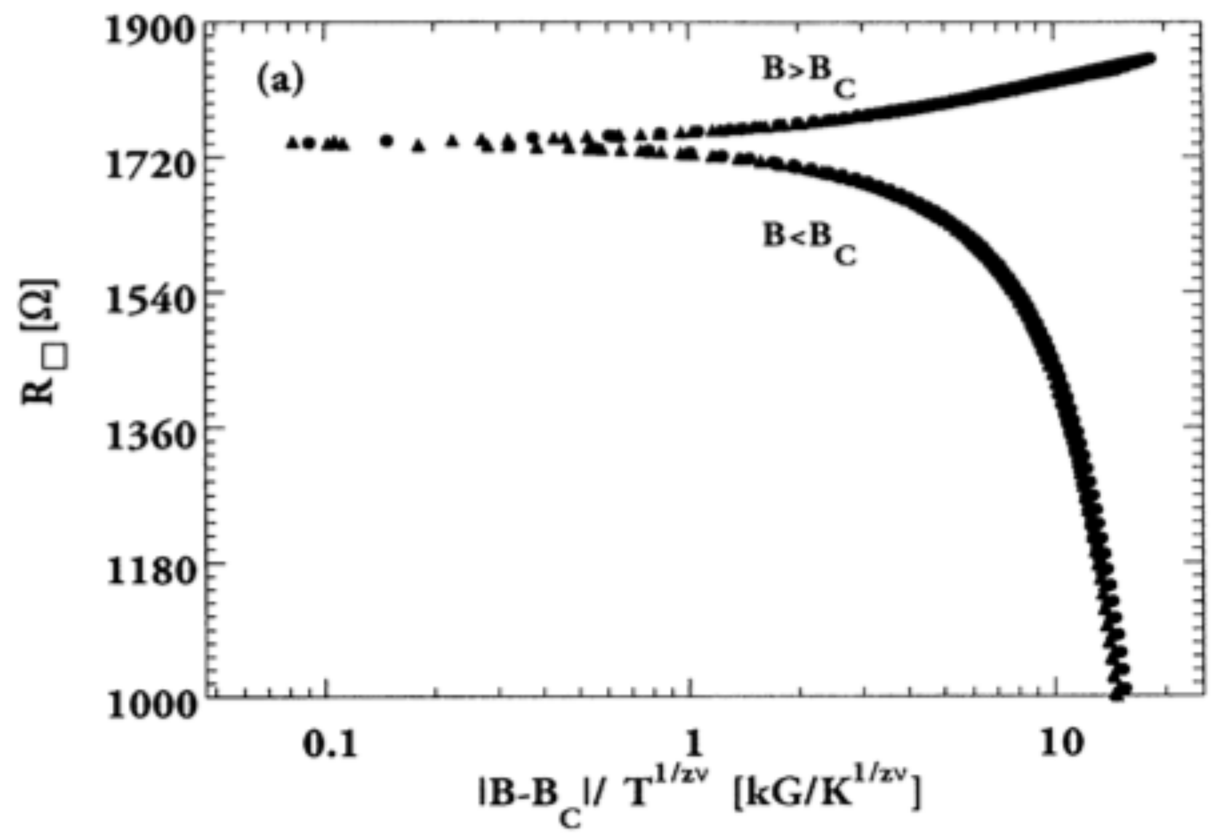
$H > H_c^*$: “Fermi” insulator (localized electrons).

Possible Challenge for the dirty boson theory

Yazdani, Kapitulnik, (1995).

$a-\mathrm{MoGe}$





Critical resistance is not h/(4e^2) in cleaner samples (small Hall resistance).

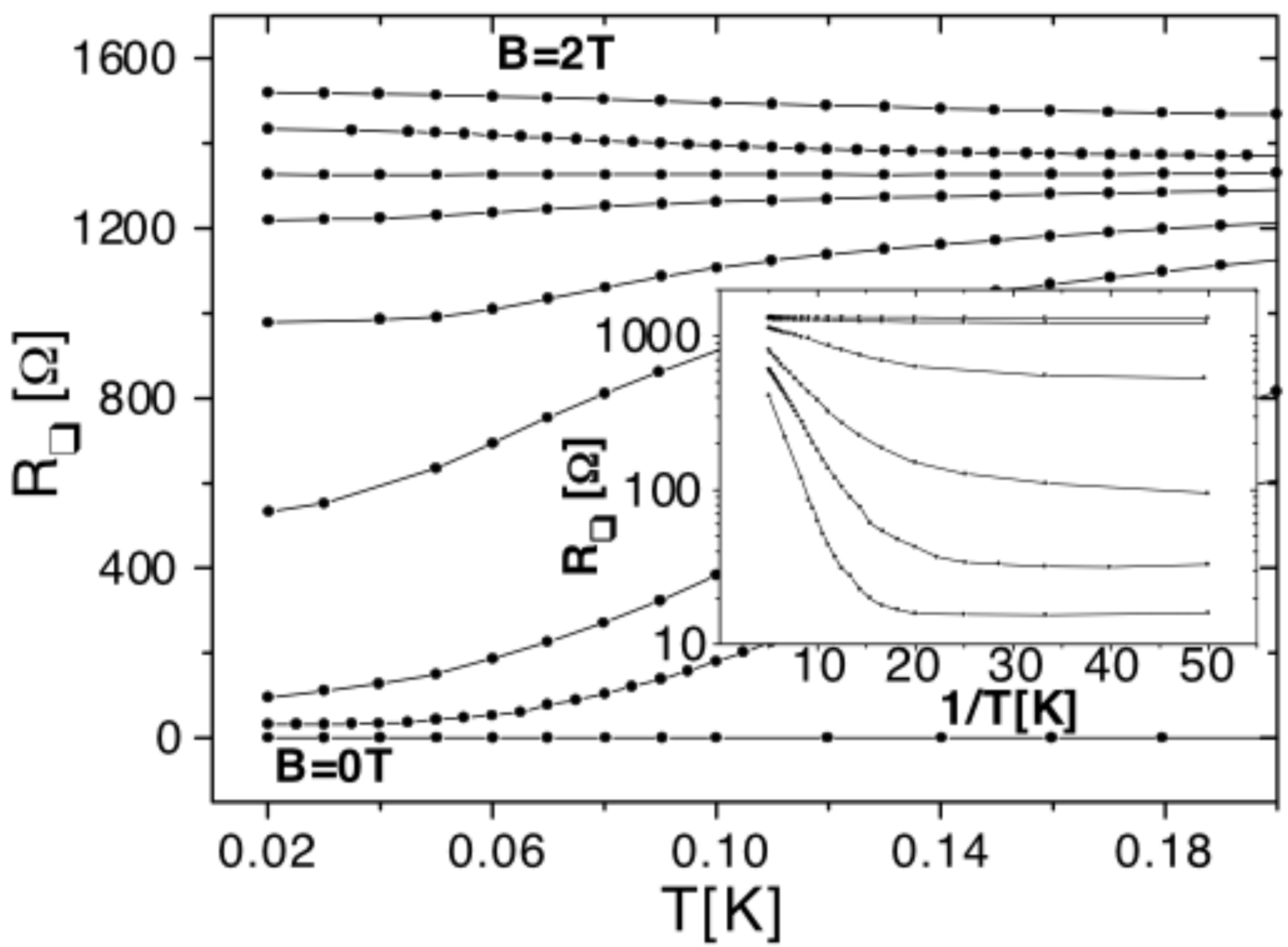
$$R_{xx}^2 + R_{xy}^2 = R_Q^2$$

The transition is still continuous and exhibits scaling.

THE Challenge for the dirty boson theory

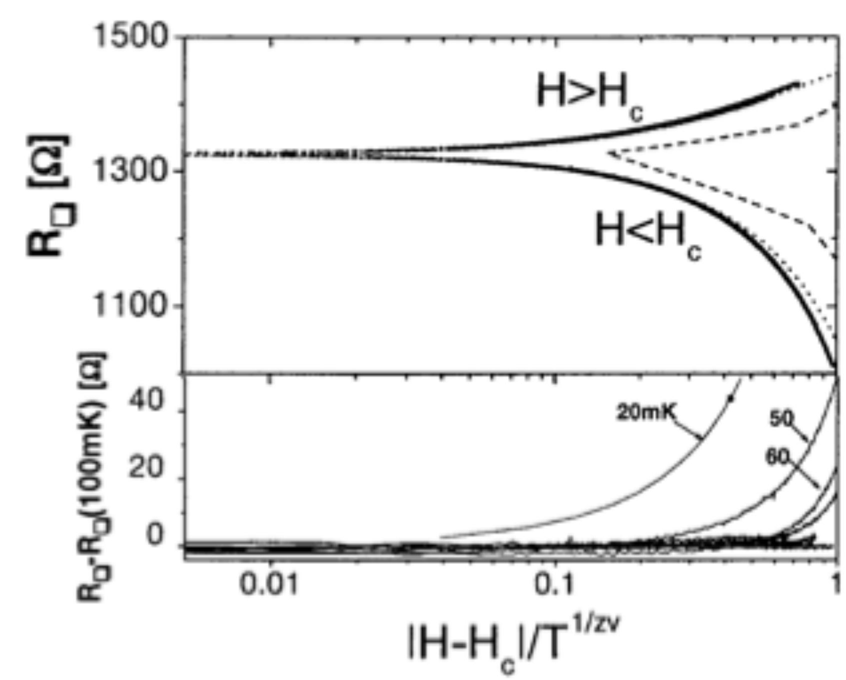
$$a - \mathrm{MoGe}$$

Mason, Kapitulnik, PRL (1999).



Resistivity is finite as T->0 over a range of fields.

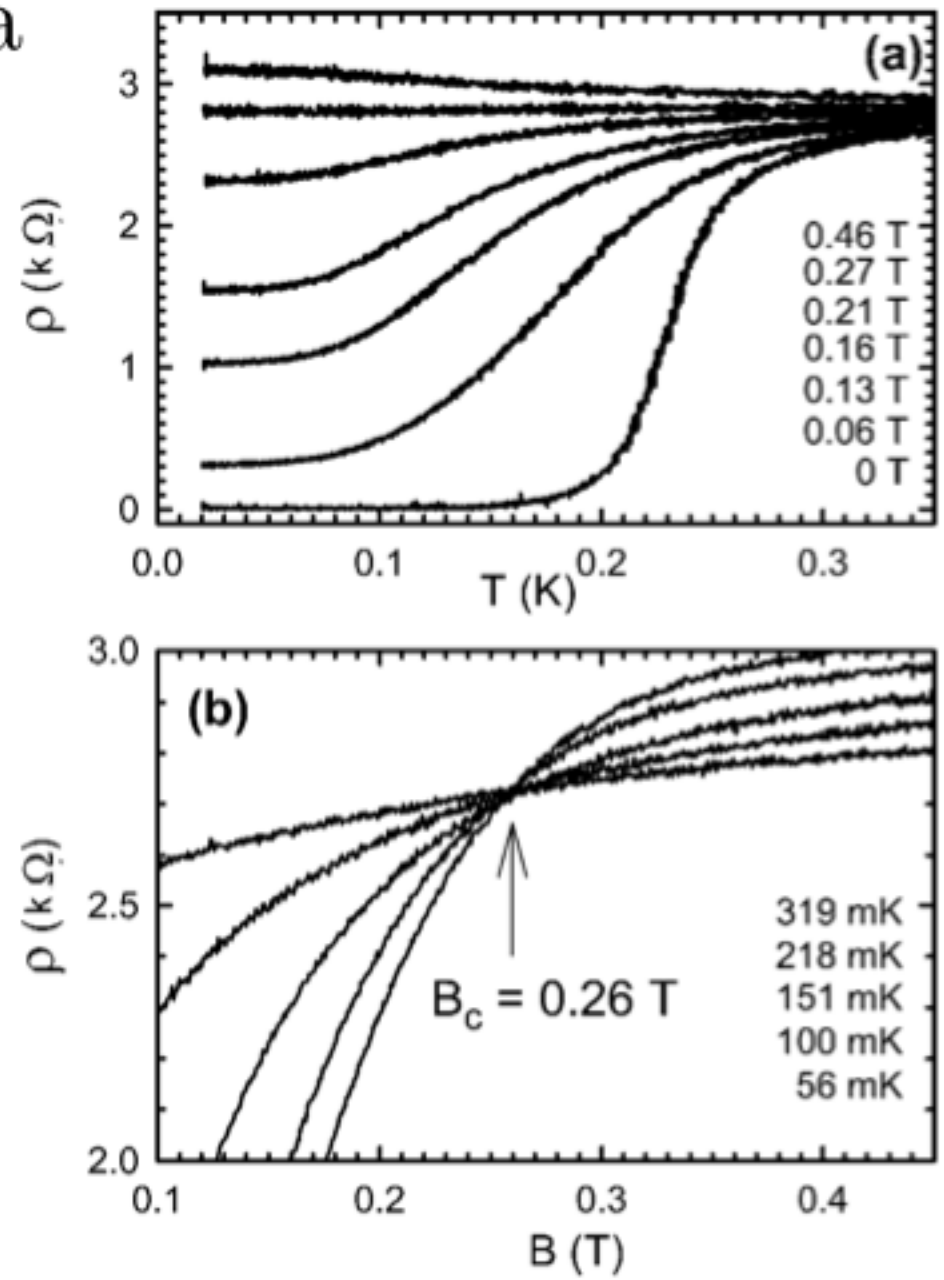
Value of T->0 resistivity is field and sample dependent.



Metallic phase is observed near the SIT. Lack of scaling.

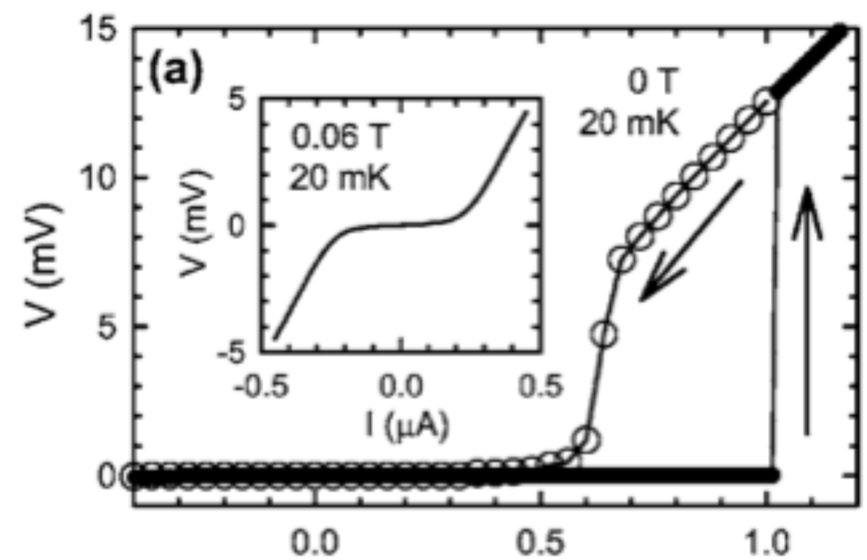
THE Challenge for the dirty boson theory

Ta



Qin, Vicente, Yoon, PRB (2006).

Metallic phase intervenes between SC and weak insulator.



SC and metal phases have distinct nonlinear IV characteristics.

Similar results in other “weakly disordered” films.

Phenomenological framework

In strongly disordered samples, self-duality is observed.
I will take the observation of self-duality as an experimental fact.
Self-duality: a property of the low energy fixed point at the SIT in strong disorder limit.

Less disorder: more fluctuations -> depinned Cooper pairs and vortices.
Self-duality is lost. What happens when self-duality breaks down?

Widely held belief: when vortices and cooper pairs are depinned, either one will condense -> ground state then is either a superconductor or an insulator. So no metallic phase!

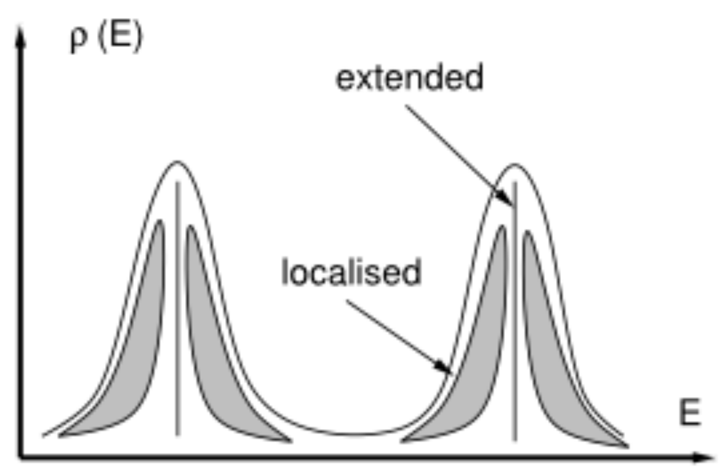
We will argue instead that the depinning leads to a metal, not to a condensation of vortices or cooper pairs!

Argument for a metallic point

Start at the self-dual point. $\langle n \rangle = \langle n_v \rangle$.

These vortices and Cooper pairs see each other as a quantum of flux.

Mean-field picture: Both Cooper pairs and vortices are in Landau levels. At self-duality they are both at filling fraction nu=1.

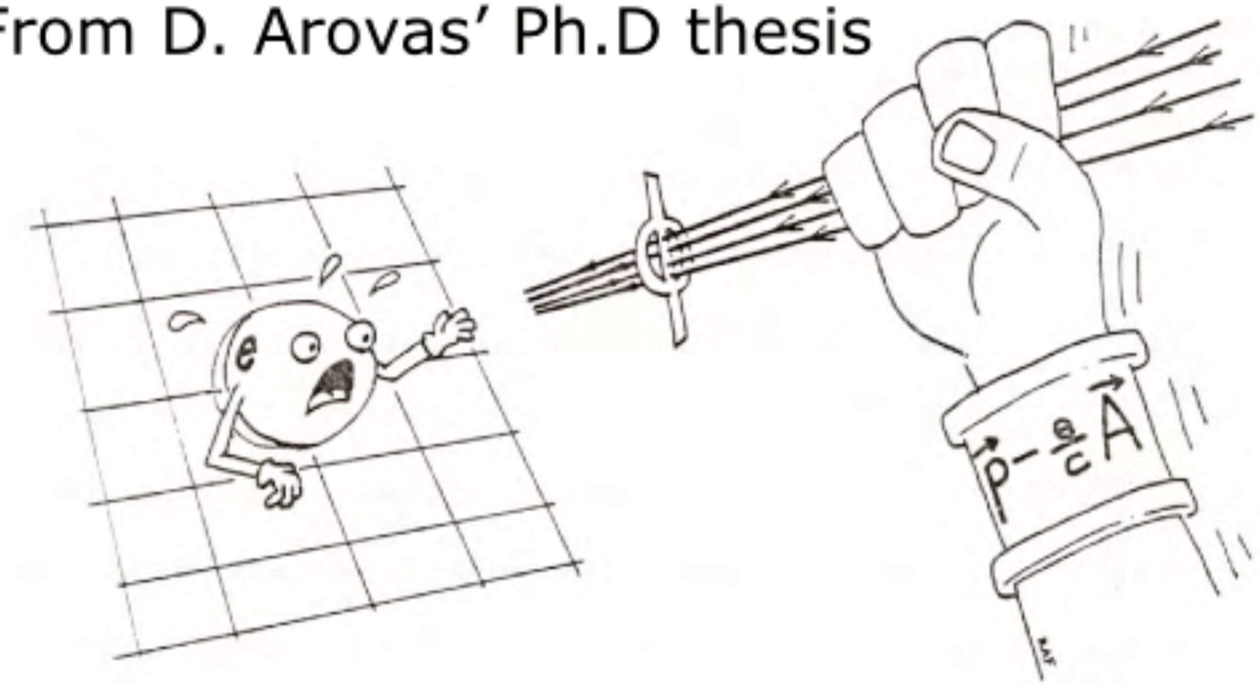


Landau levels with disorder.

Bosons at nu=1 related to fermions in zero field via flux attachment, a more “useful” description.

Flux attachment

From D. Arovas' Ph.D thesis



Threading odd number of flux quanta per particle converts bosons to fermions *(and vice-versa).*

flux quantum: $\phi_0 = \frac{hc}{q} = 2\pi$

$$\mathcal{L}_0 = \psi^\dagger\Big(i\partial_t + \tilde{A}_t + \frac{1}{2m_v}(\partial_j - i\tilde{A}_i)^2\Big)\psi,$$

$$\mathcal{L}_{\rm gauge} = -e_*\frac{1}{2\pi}\epsilon_{\mu\nu\rho}\tilde{A}_\mu\partial_\nu A_\rho + \frac{e_*^2}{4\pi}\epsilon_{\mu\nu\rho}A_\mu\partial_\nu A_\rho,$$

$$\mathcal{L}_{\rm int} = -\frac{1}{2}\int d^2\vec{r}'\Big(\psi^\dagger\psi(\vec{r}) - n_{\rm v}\Big)\tilde{V}_{\vec{r},\vec{r}'}\Big(\psi^\dagger\psi(\vec{r}') - n_{\rm v}\Big).$$

Attach 1 flux quantum to vortices -> composite vortices (fermions).

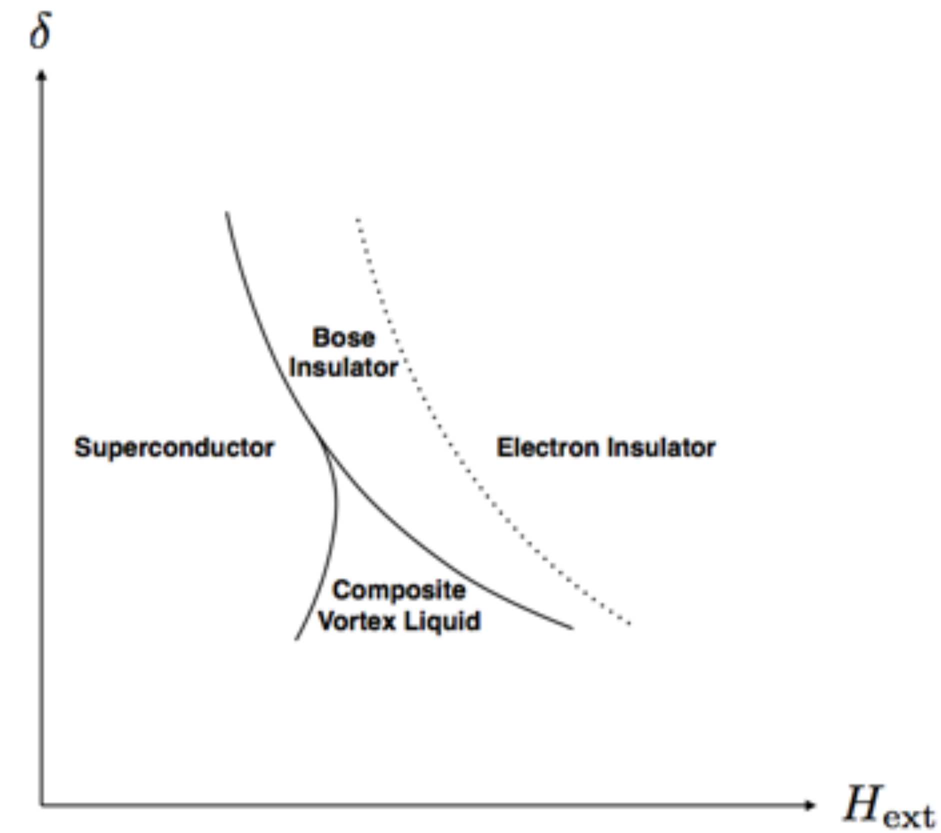
Response

$$\sigma_{xx} = \frac{e_*^2}{h}\frac{\sigma_{xx}^{\rm cv}}{(\sigma_{xx}^{\rm cv})^2 + (\sigma_{xy}^{\rm cv})^2},$$

$$\sigma_{xy} = -\frac{e_*^2}{h}\left(1 + \frac{\sigma_{xy}^{\rm cv}}{(\sigma_{xx}^{\rm cv})^2 + (\sigma_{xy}^{\rm cv})^2}\right),$$

$$\rho_{xx} = \frac{h}{e_*^2}\frac{\sigma_{xx}^{\rm cv}}{(\sigma_{xx}^{\rm cv})^2 + (1+\sigma_{xy}^{\rm cv})^2},$$

$$\rho_{xy} = \frac{h}{e_*^2}\left(1 - \frac{1+\sigma_{xy}^{\rm cv}}{(\sigma_{xx}^{\rm cv})^2 + (1+\sigma_{xy}^{\rm cv})^2}\right).$$



electron superconductor

$$\sigma_{xx}^{\rm cv}(T \to 0) = 0;\ \sigma_{xy}^{\rm cv}(T \to 0) = 0$$

C.V. Anderson Insulator

Bose/Fermi Insulator

$$\sigma_{xx}^{\rm cv}(T \to 0) = 0,\ \sigma_{xy}^{\rm cv}(T \to 0) = -1$$

C.V. IQHE

Summary of Proposal

Boson vacuum: vortices and Cooper pairs each at nu=1.

Lowering disorder: strongly fluctuating interacting bosons in Landau levels with disorder.

Fermion vacuum: Fermi sea of composite vortices, zero net flux + disorder.

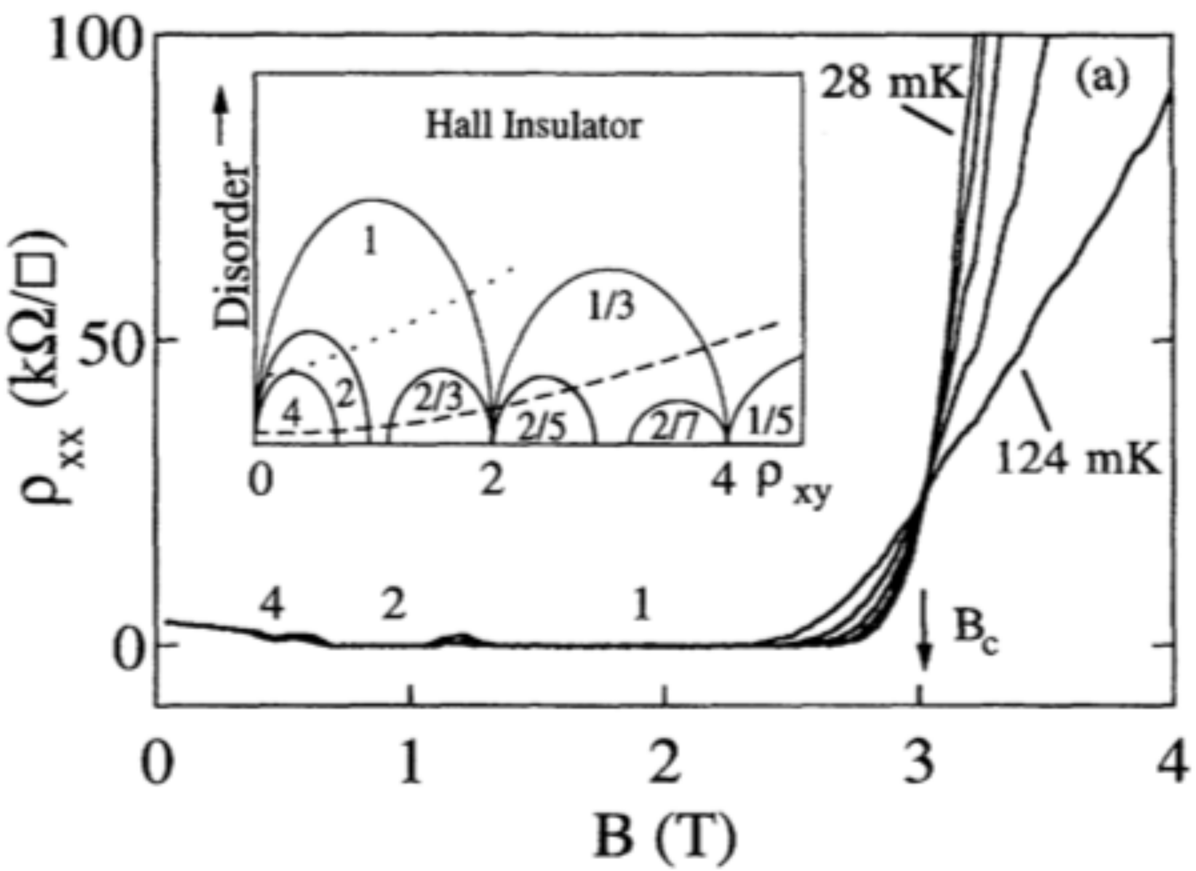
Reducing disorder: composite vortex critical point broadens into a *phase.*

Analogous phenomena occur in quantum Hall systems as disorder is reduced.

Related quantum Hall phenomena

Quantum Hall to insulator transition in low mobility 2DEGs:

Shahar *et al.*, PRL (1995).



Plateau transition occurs at a critical field.

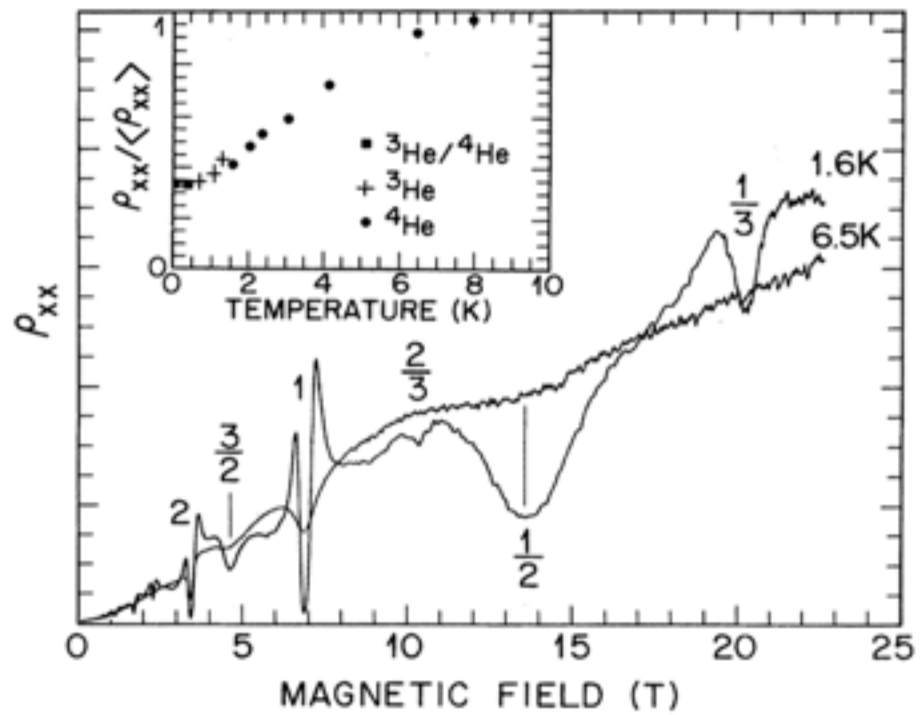
The critical resistance is again "universal," close to h/e^2.

Magnetic field induces "holes" into a filled LL.

Holes <-> vortices.

Strong disorder: localized holes.

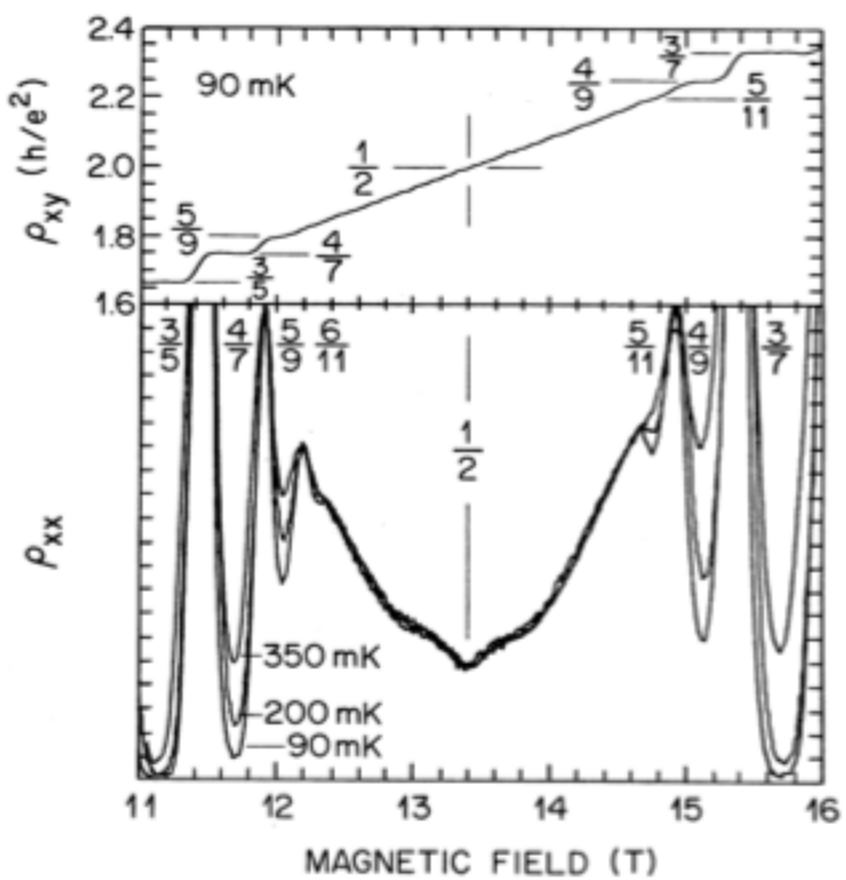
Plateau transition vs "evolution"



Holes <-> vortices.

Weak disorder: holes are delocalized in a range of fields.

Plateau "evolves" into neighboring plateau with an intervening metal-> CF metal.



2DEG

IQHE | Metal | ins → B

Thin Film

SC | Metal | ins → B

Considerations at weaker disorder

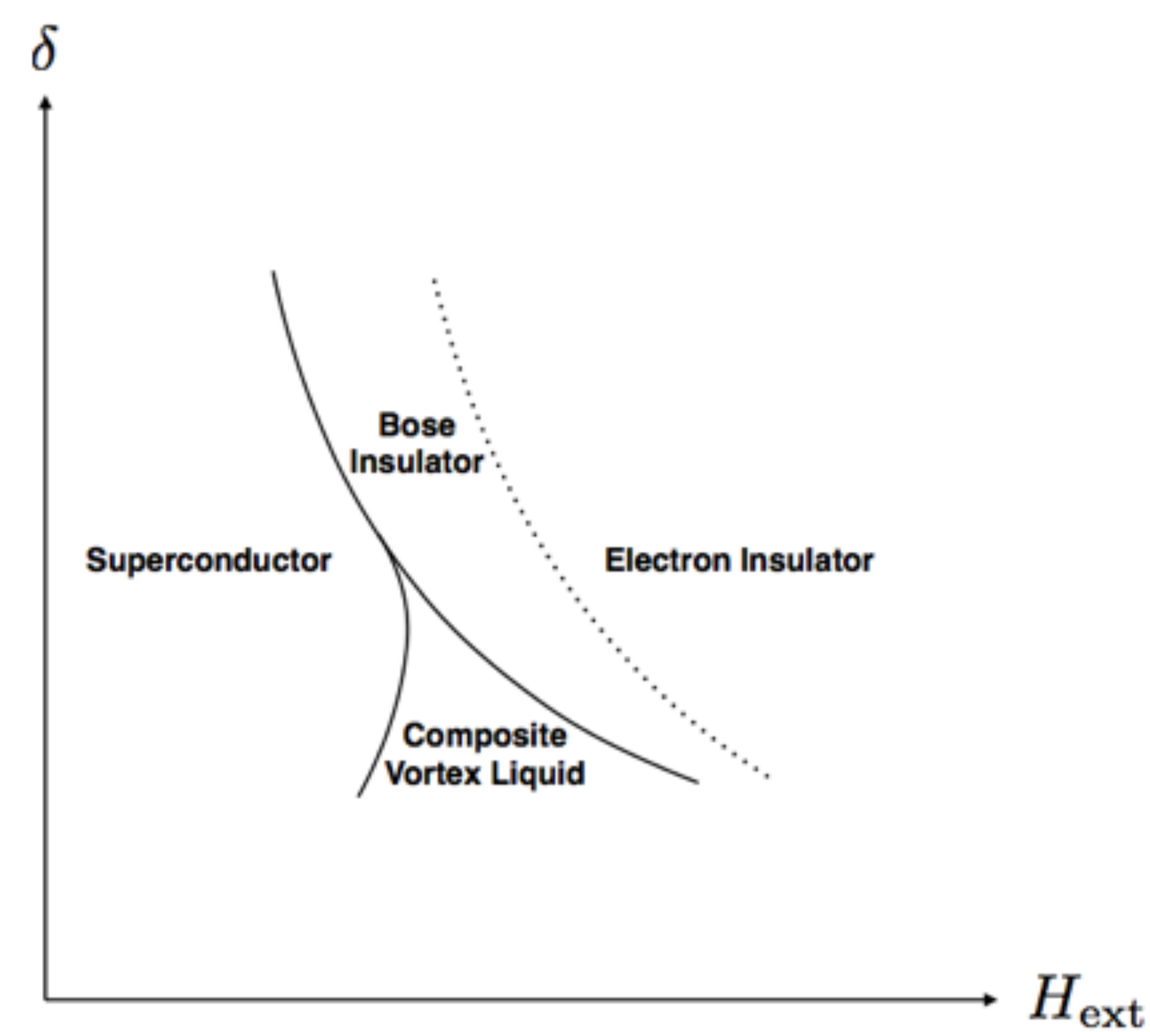
Weaker disorder: consider role of quantum corrections (weak-localization).

No weak-localization due to broken T (beta functions still naively localizing).
Due to CS mapping, random potential disorder for vortices -> random flux disorder for composite vortices.

Composite vortex metal stable to weak disorder.

Similar story in quantum Hall:

Weak-disorder destroys FQH states, nu=1/2 metallic state is stabilized to a phase.



Experimental consequences of a composite vortex metal

We have suggested that the metallic phase in the SIT is a composite vortex metal.

Testable predictions:

0) Existence of the metallic phase.

1) Linear heat capacity plus corrections.

2) Effective magnetic field changes sign near the critical field - large cyclotron orbits for composite vortices (quantum oscillations).

3) Composite vortex metal is a NFL: tunneling DOS vanishes as a power law. Power law is altered by gating the system.
In fact, this might not be surprising given the SC starting point.
However, even tunneling charge 2e Cooper pairs is suppressed.

4) Vanishing thermopower and Nernst signal at a self-dual point.

Looking further ahead

Detailed studies of metallic phase in SITs (DMRG).

Non-Fermi liquid effects in weak-disorder need to be studied systematically. Anomalous dimensions and quenched disorder?

Nature of the disorder-tuned SIT at zero field?

Similarities to T=0 metal-insulator transitions in Si MOSFETs?

Density tuned MIT in Si MOSFETS: metallic phase cannot be a CFL because T is preserved. Explanation for the metallic phase is lacking.