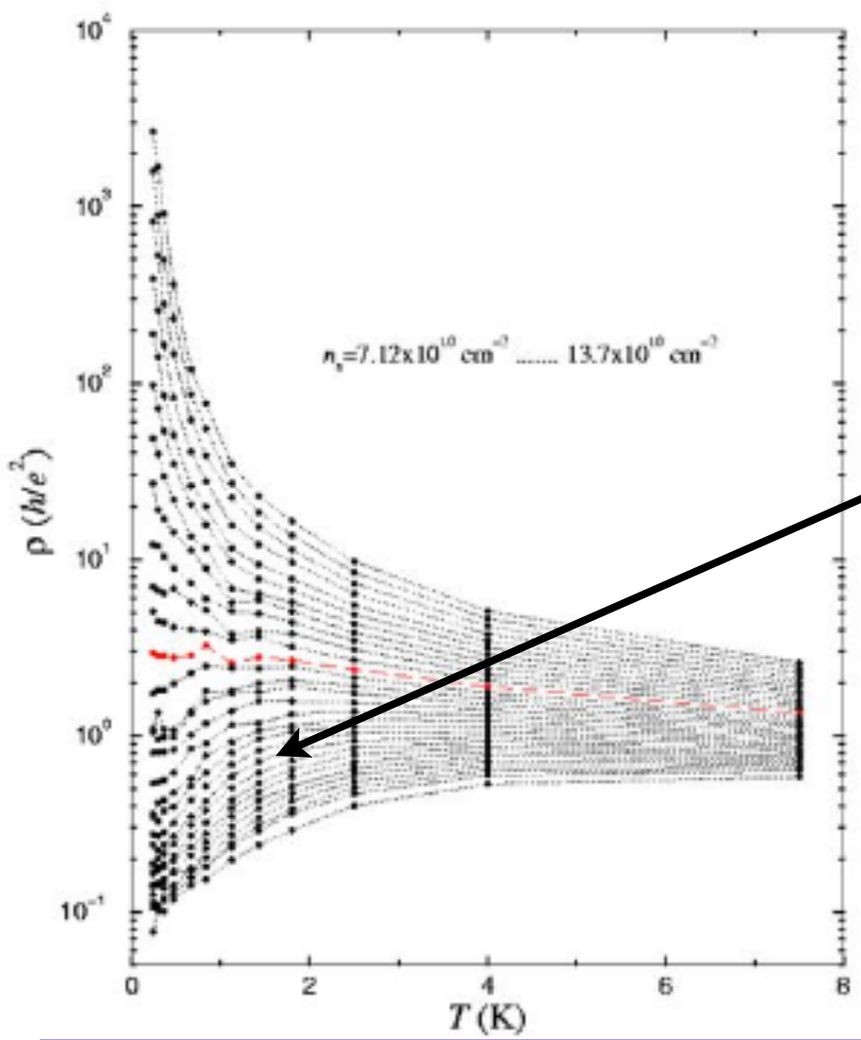
Bose metals as a disruption of the KT transition in thin films

D. Dalidovich
J. Wu

$$\beta = \frac{d \ln g(L)}{d \ln L} = d - 2$$

no metals for $d \leq 2$

2D MIT

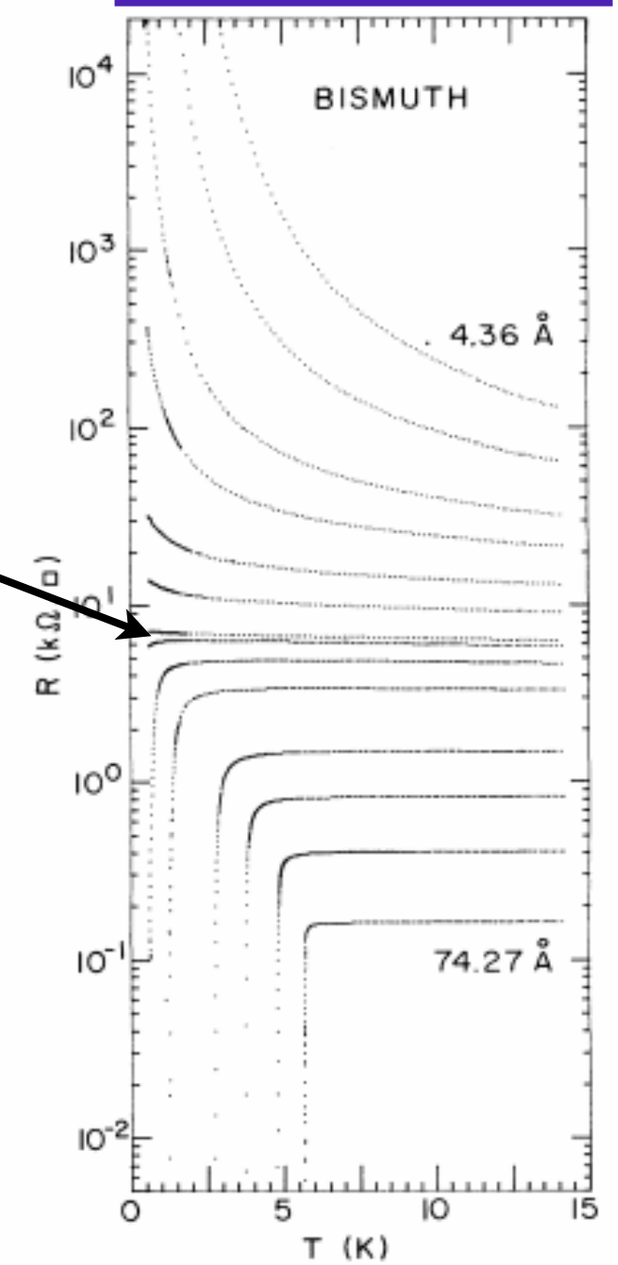


Kravchenko 1995

unresolved?

?

2D IST

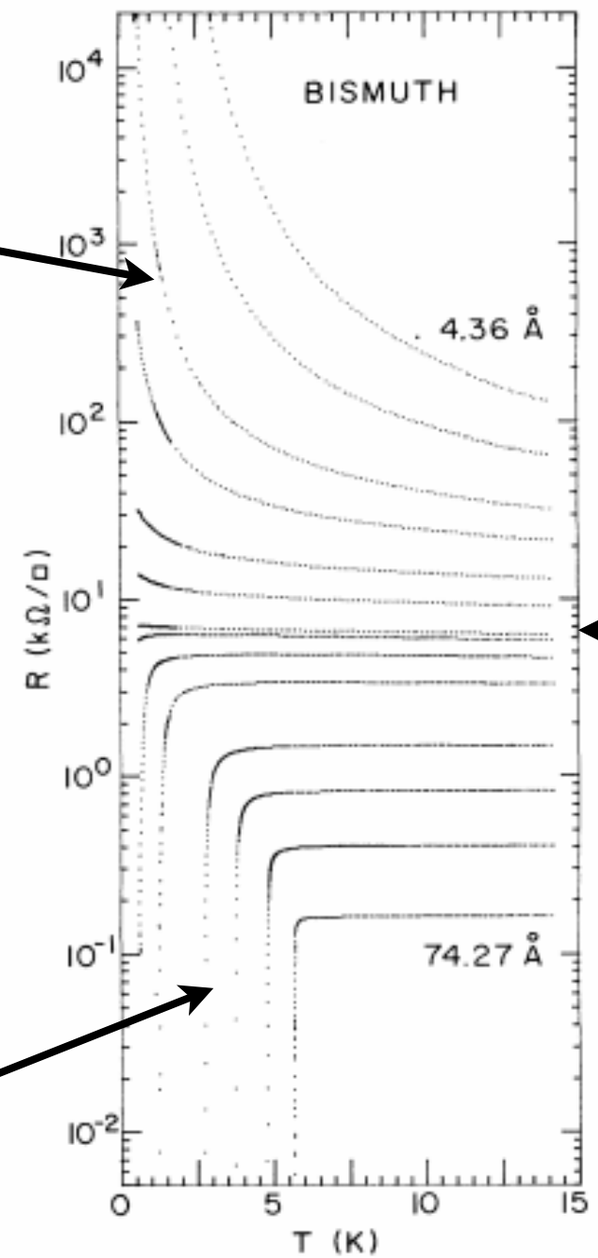


Goldman 1989

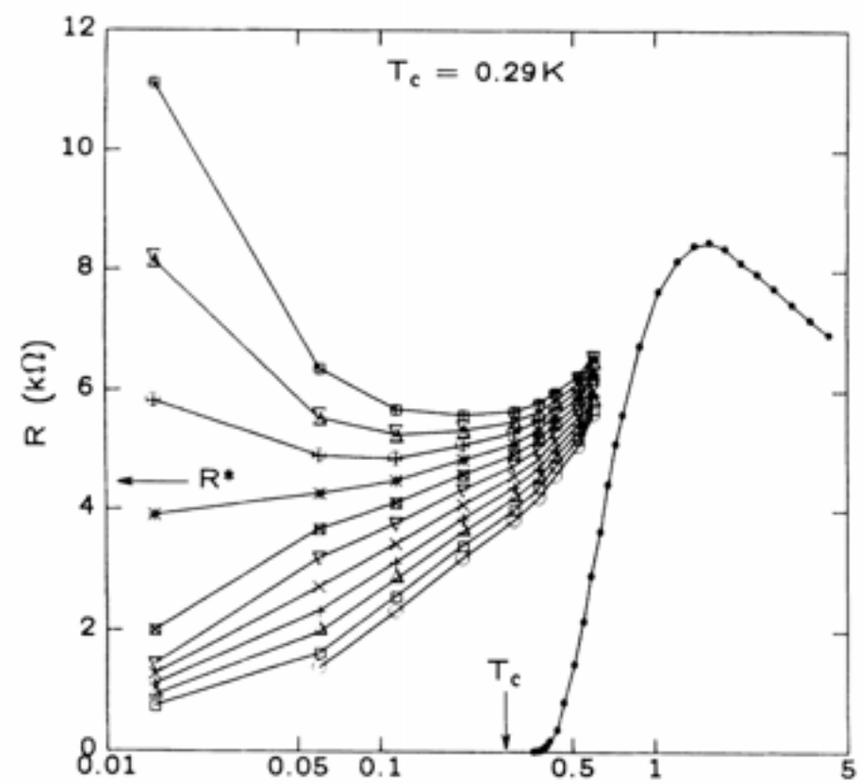
insulator-superconductor transition

insulator

superconductor



$\rho = h/4e^2$



Hebard/Paalanen

phase-only critical bosons

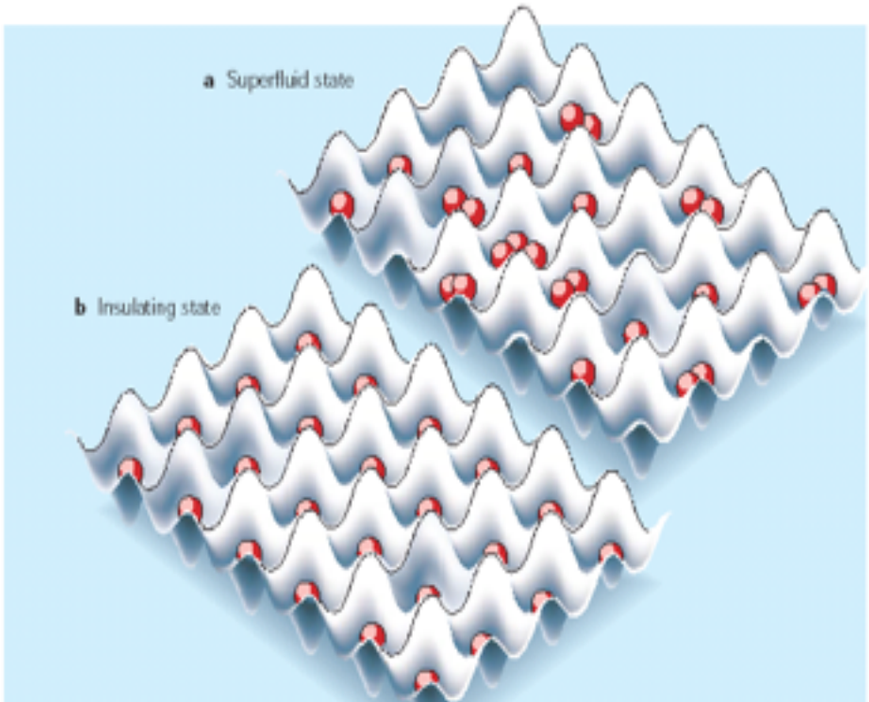
$$H = E_C \sum_i p_{\theta_i}^2 + J \sum_{\langle ij \rangle} \cos(\theta_i - \theta_j)$$

$$\frac{\partial}{\partial \theta_i} \longleftrightarrow \theta_i$$

$\langle n_i \rangle \neq 0$ $\quad$ g_c $\quad$ $\langle \theta_i \rangle \neq 0$

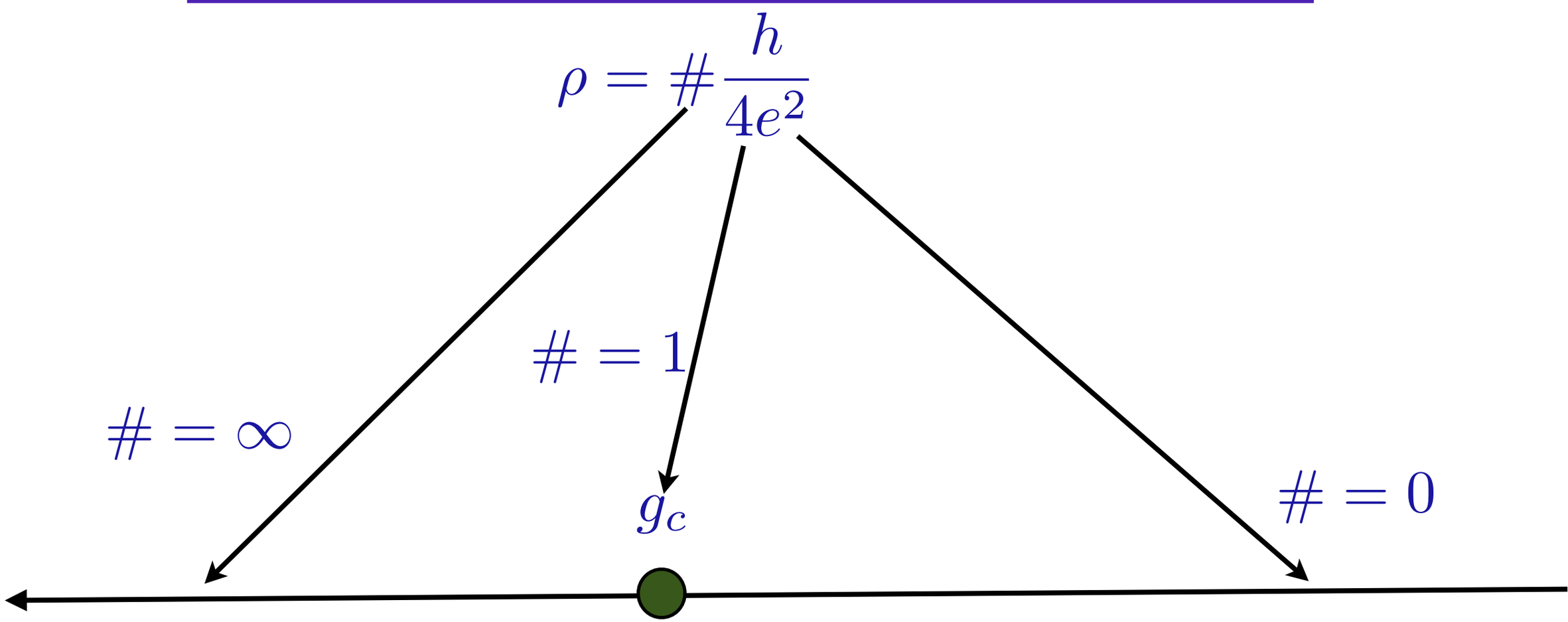
$g = E_C / J$

$$\Delta\theta \Delta n \geq \hbar$$



vortex-particle duality
(MPAF 1990)

insulator-superconductor transition

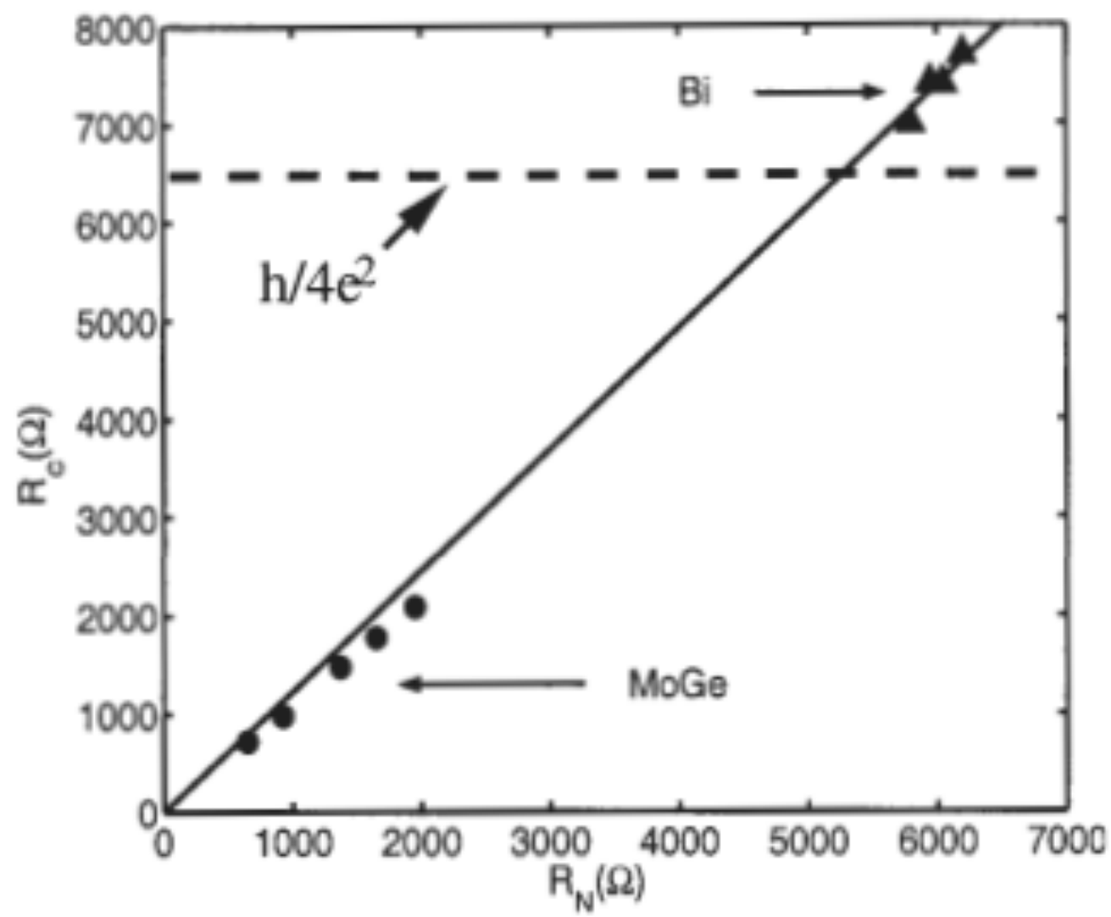


$$G(k,\omega) = k^{d/2-\eta} F\left(\frac{\omega}{k^z}\right)$$

anomalous dimension

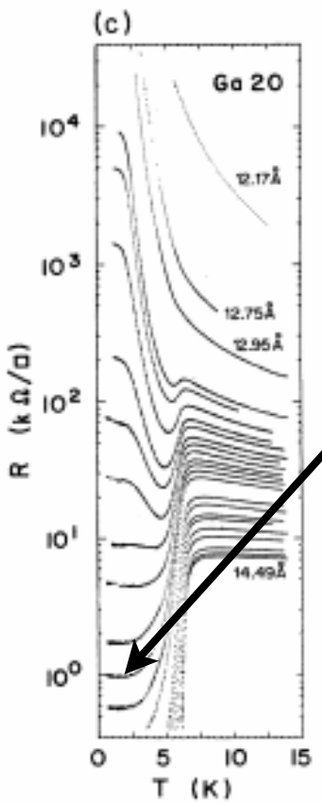
does this theory
really work?

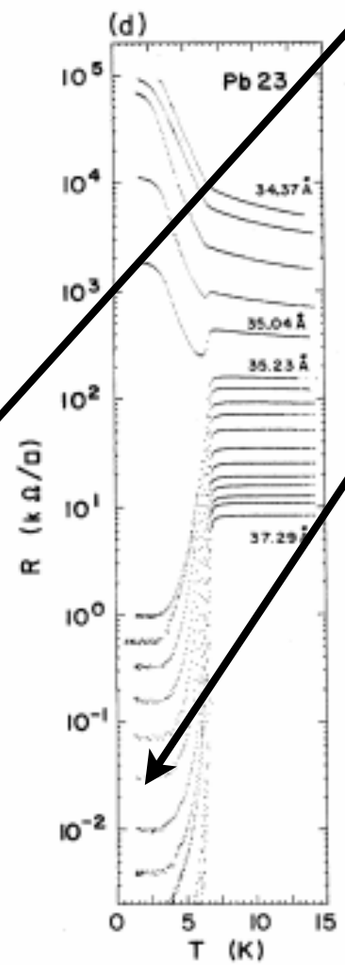
non-universality of ρ_c

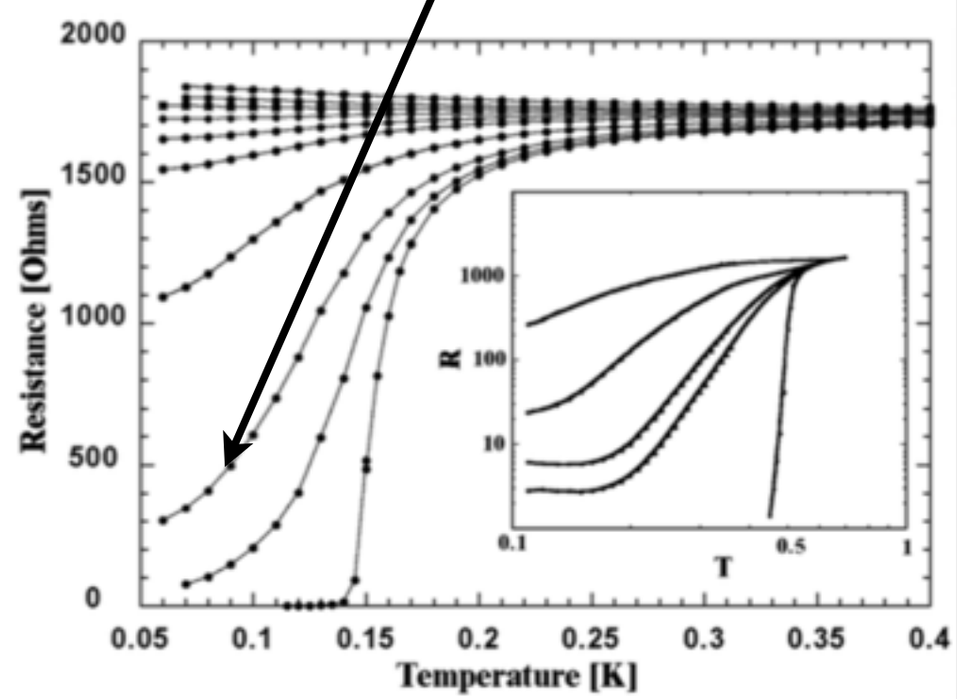


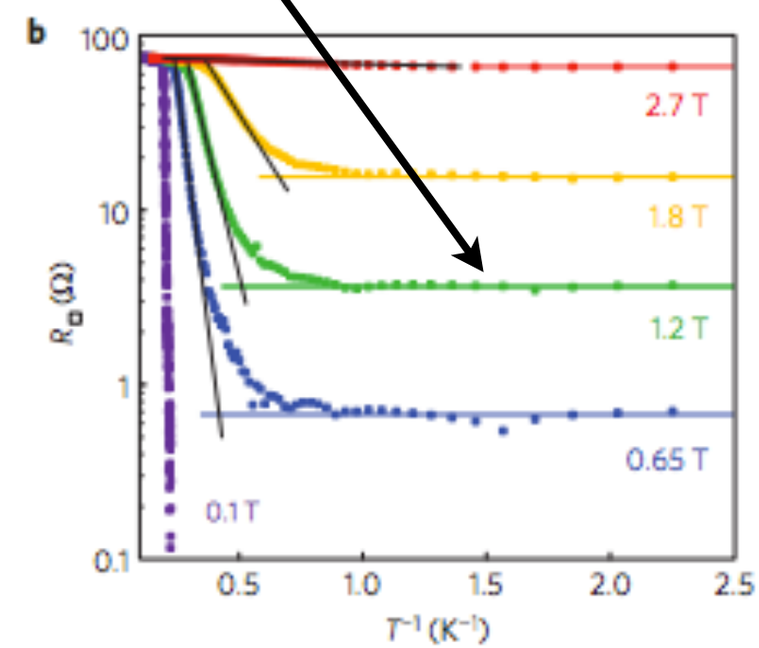
?

is a metallic phase for bosons possible?









1989

1990

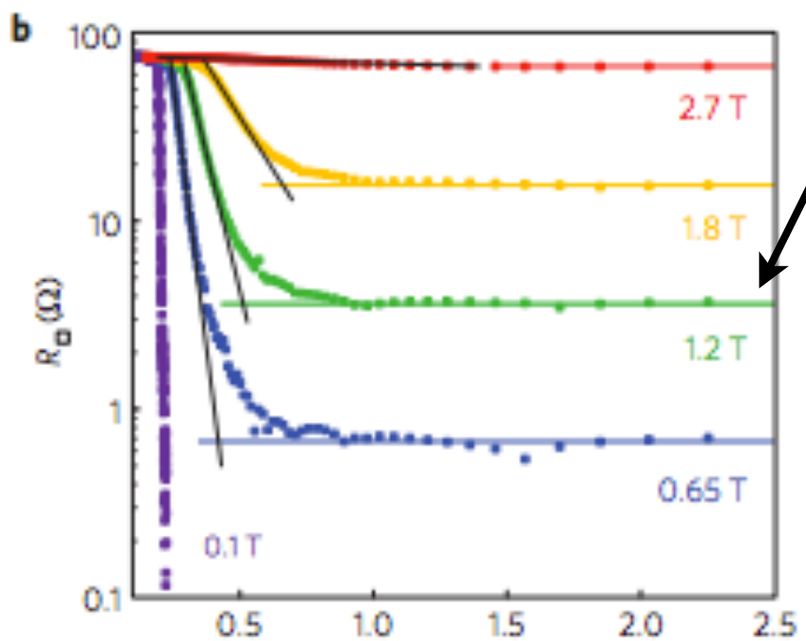
2016

LETTERS
PUBLISHED ONLINE: 7 DECEMBER 2015 | DOI: 10.1038/NPHYS3579
nature physics

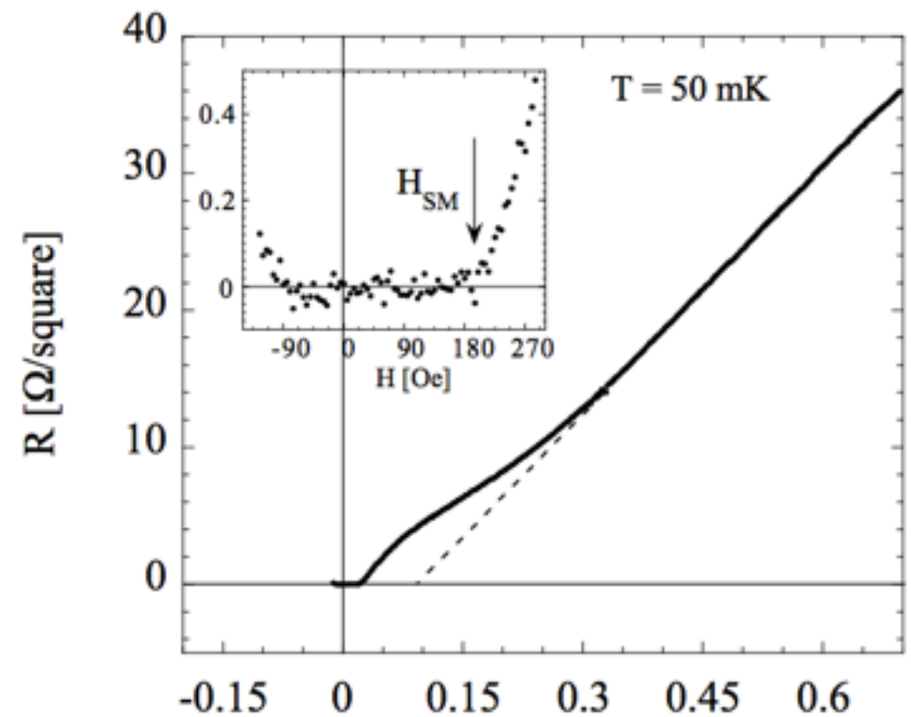
Nature of the quantum metal in a two-dimensional crystalline superconductor

A. W. Tsen[1], B. Hunt[1†], Y. D. Kim[2], Z. J. Yuan[3], S. Jia[3,4], R. J. Cava[5], J. Hone[2], P. Kim[6], C. R. Dean[1*] and A. N. Pasupathy[1*]

metal below H_{c2}



activated region shifts to lower T as H increases



mason/kapitulnik (2000)

not a refrigeration artifact

↓

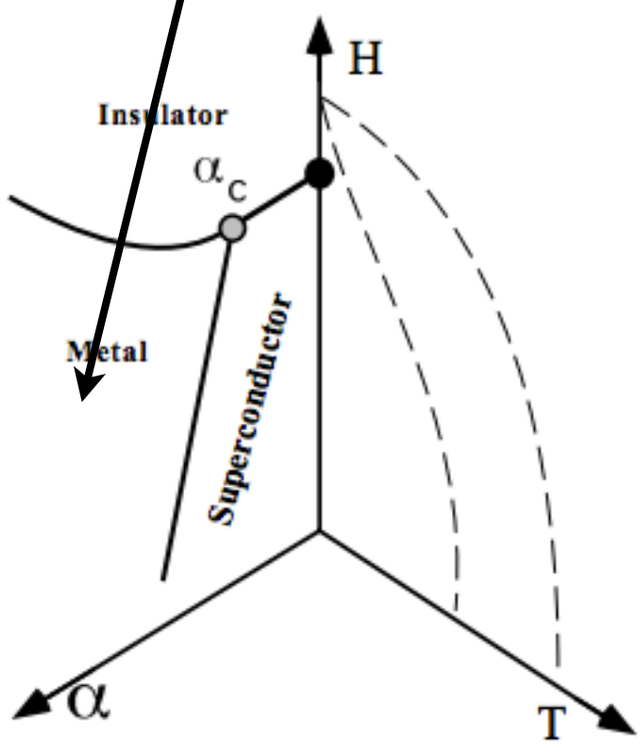
bose metal

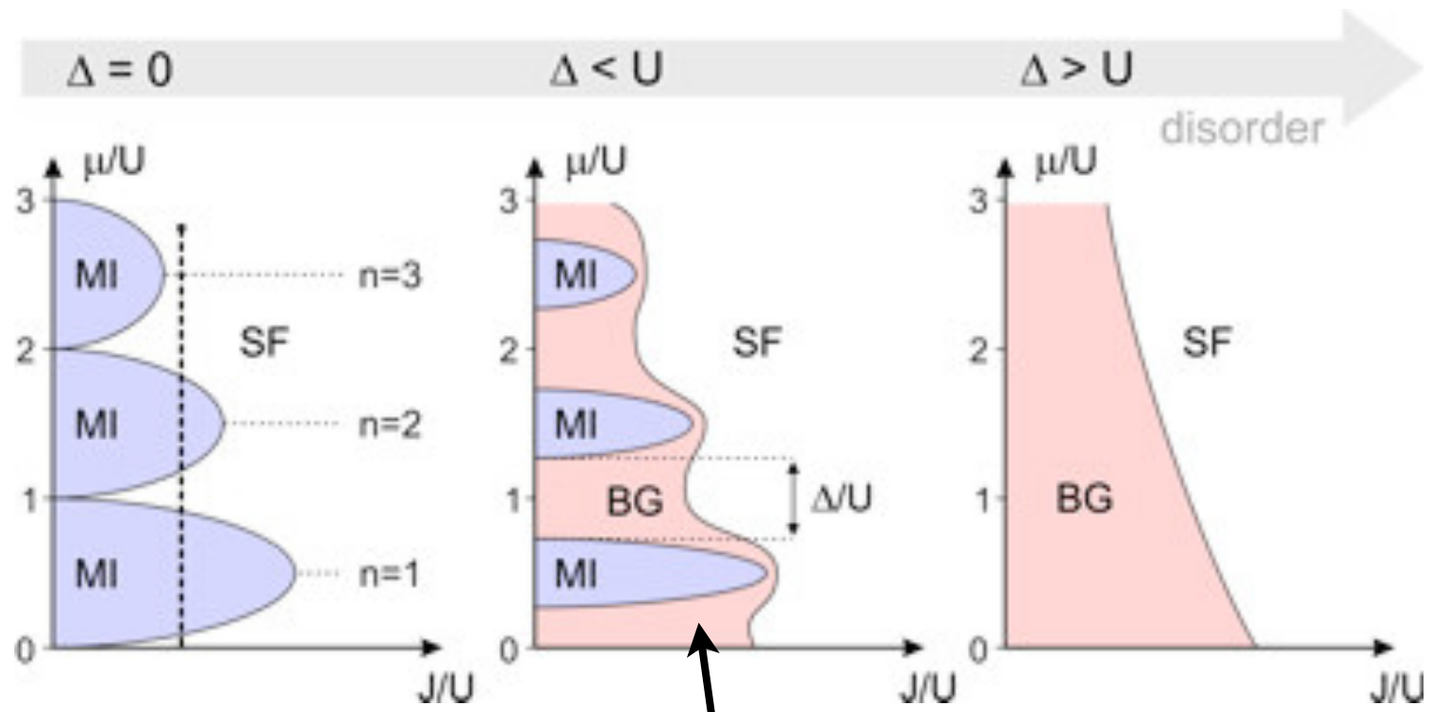
$$\rho \propto (H - H_{\mathrm{SM}})^{\gamma} \quad \gamma \approx 3$$

phases disrupting superconductivity

dissipation (Kapitulnik)

Bose-Hubbard model (disordered)



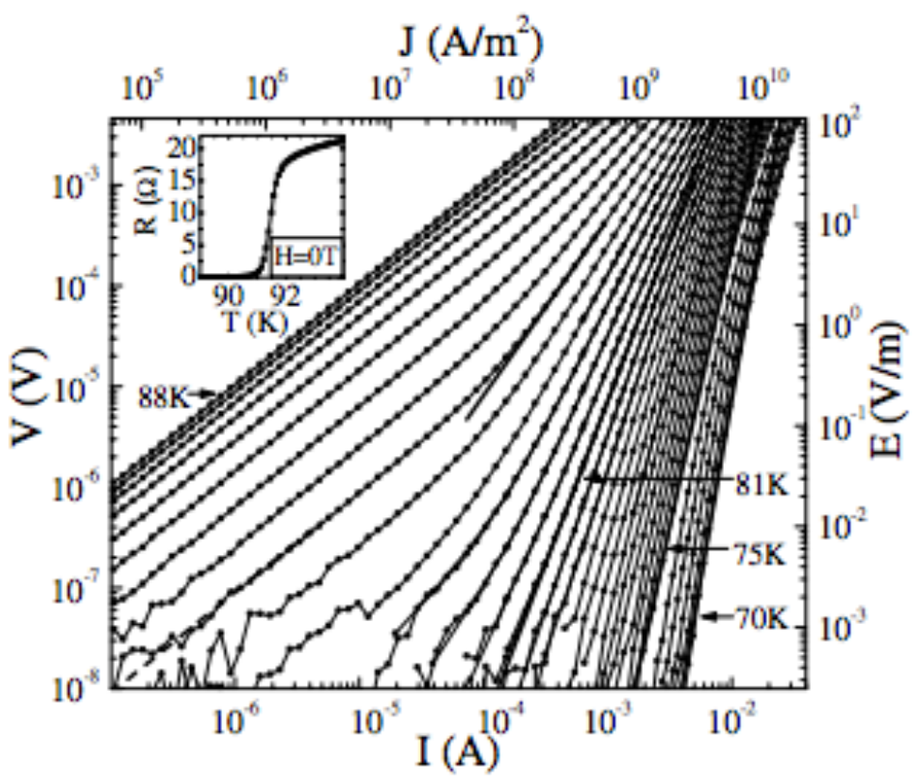


disorder-localised insulator (short-range hopping)

Do Superconductors Have Zero Resistance in a Magnetic Field?

D. R. Strachan,* M. C. Sullivan, P. Fournier, S. P. Pai, T. Venkatesan, and C. J. Lobb
Center for Superconductivity Research, University of Maryland, College Park, Maryland 20742
(Received 31 October 2000; published 23 July 2001)

We show that dc voltage versus current measurements of a $YBa_2Cu_3O_{7-\delta}$ film in a magnetic field can be collapsed onto scaling functions proposed by Fisher *et al.* [Phys. Rev. B **43**, 130 (1991)] as is widely reported in the literature. We find, however, that good data collapse is achieved for a wide range of critical exponents and temperatures. These results strongly suggest that agreement with scaling alone does not prove the existence of a phase transition. We propose a criterion to determine if the data collapse is valid, and thus if a phase transition occurs. To our knowledge, none of the data reported in the literature meet our criterion.



In this paper we have focused on the absence of a vanishing dc resistance—the popular definition of a superconductor. One can also use ac measurements [21] to probe an Ohmic to inductive transition in complex linear impedance [22]. However, we are not aware of ac measurements that demonstrate the Ohmic to inductive transition in *both* magnitude and phase, which is necessary for agreement with scaling. A critical comparison between dc and ac on the same sample would be important for this issue.

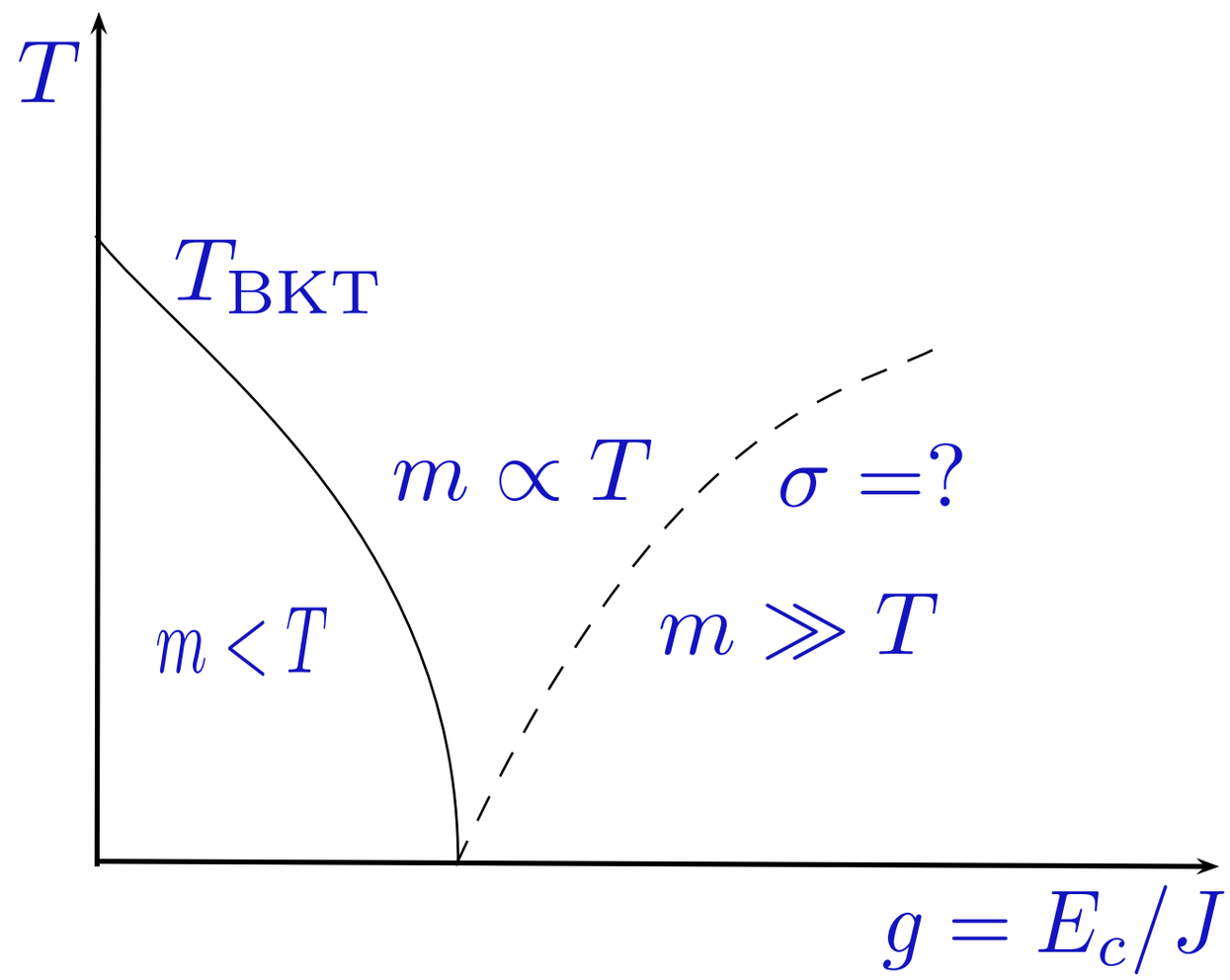
In conclusion, we have found that a data collapse is not sufficient evidence for a transition to zero resistance since the critical temperature at which this occurs is not uniquely determined. In addition to obeying scaling, I-V data must also satisfy the opposite concavity signature we propose in order to determine a T_g below which the resistance vanishes. Since our I-V data plus many in the literature do not show this signature, a transition to zero resistance has not yet been demonstrated despite the fact that much of the data scales. Furthermore, this signature can be used as a criterion to judge future I-V data in order to help settle the controversy surrounding critical phenomena in the high-temperature superconductors.

is a Bose metal possible?

$$\sigma_{\rm dc} = \lim_{T\to 0} \lim_{\omega\to 0} \sigma(\omega, T)$$

collision-dominated transport Damle/Sachdev (hydrodynamic regime)

$$H = E_C \sum_i p_{\theta_i}^2 + J \sum_{\langle ij \rangle} \cos(\theta_i - \theta_j)$$



qp collisions

$$n \propto e^{-m/T}$$

$$\tau \propto e^{m/T}$$

$$\sigma \propto n\tau \sim O(1)$$

$$\boxed{\sigma = \frac{2}{\pi}\frac{e^{*2}}{h}}$$

the insulator is a metal

but it is fragile

$$\frac{1}{\tau} \to \frac{1}{\tau} + \eta$$

$$\sigma \to 0$$

dissipation

$$F[\psi] = \int d^2r \int d\tau \left\{ \left[\left(\nabla + \frac{ie^*}{\hbar} \vec{A}(\vec{r},\tau) \right) \psi^*(\vec{r},\tau) \right] \right.$$

$$\cdot \left[\left(\nabla - \frac{ie^*}{\hbar} \vec{A}(\vec{r},\tau) \right) \psi(\vec{r},\tau) \right]$$

$$\left. + \kappa^2 \left| \partial_\tau \psi(\vec{r},\tau) \right|^2 + m^2 \left| \psi(\vec{r},\tau) \right|^2 \right\} + L_{\mathrm{dis}}$$

$$L_{\mathrm{dis}} = \eta \sum_{\vec{k},\omega_n} |\omega_n| |\psi(\vec{k},\omega_n)|^2$$

ohmic dissipation

127,000 hits

conductivity

$$\sigma(\omega) = \frac{(e^*)^2}{2\pi\hbar\omega}\int_0^\infty k^3 dk \int_{-\infty}^{\infty} \coth\frac{z}{2T} dz \left[(G^R(z) - G^A(z)) \right.$$
$$\left. [G^R(z) + G^A(z) - G^R(z+\omega) - G^A(z-\omega)]\right].$$

$$G^{R(A)}(z) = (k^2 + m^2 - \kappa^2 z^2 \mp i\eta z)^{-1}$$

$$\sigma(\omega = 0) = \frac{(e^*)^2}{2\pi h}\int_0^\infty k^3 dk \int_{-\infty}^{\infty} \frac{dx}{\sinh^2 x} \times \frac{8\eta^2 T^2 x^2}{[(\epsilon_k^2 - 4T^2\kappa^2 x^2)^2 + 4T^2\eta^2 x^2]^2}$$

$$\sigma = \frac{2e^2}{\pi h}\frac{\pi\kappa^2 T}{\eta}\ln\frac{\kappa T}{m} \qquad \eta/\kappa \ll m$$

include interactions

$$m = \kappa T \exp\left(-\frac{2\pi|\Delta|}{UT}\right) \qquad |\Delta| \gg \kappa T \gg \eta/\kappa$$

$$\Delta = \delta + U[\Lambda + O(\eta/\kappa)]/4\pi\kappa$$

$$\sigma = \frac{2e^2}{\pi h}\frac{\pi\kappa^2 T}{\eta}\ln\frac{\kappa T}{m} \qquad \eta/\kappa \ll m$$

$$\sigma = \frac{4e^2}{h}\frac{\pi\kappa^2|\Delta|}{\eta U} \qquad \eta/\kappa < m$$

T-independent conductivity

but conductivity diverges at low T

$$\sigma = (e^2/h)\exp\left(\frac{4\pi|\Delta|}{UT}\right) \qquad \kappa T < \eta/\kappa$$

dissipation alone is not enough

disorder

$$H = -E_C \sum_i \left(\frac{\partial}{\partial \theta_i}\right)^2 - \sum_{\langle i,j \rangle} J_{ij} \cos(\theta_i - \theta_j)$$

$$P(J_{ij}) = 1/\sqrt{2\pi J^2} \exp -(J_{ij} - J_0)^2/2J^2$$

3-phases

phase glass

paramagnet

superconductor

$$\ln[Z] = \lim_{n\to 0}([Z^n]-1)/n$$

$$\mathbf{S}_i = (\cos\theta_i, \sin\theta_i)$$

$$Q^{ab}_{\mu\nu}(\vec{k},\vec{k}',\tau,\tau') = \langle S^a_\mu(\vec{k},\tau) S^b_\nu(\vec{k}',\tau')\rangle$$

$$D(\tau-\tau') = \lim_{n\to 0}\frac{1}{Mn}\langle Q^{aa}_{\mu\mu}(\vec{k},\vec{k}',\tau,\tau')\rangle$$

Edwards-Anderson order parameter

$$\Psi^a_\mu(\vec{k},\tau) = \langle S^a_\mu(\vec{k},\tau)\rangle$$

SC order

free energy

$$\mathcal{F}[\Psi, Q] = \mathcal{F}_{\rm SG}(Q) + \sum_{a,\mu,k,\omega_n} (k^2 + \omega_n^2 + m^2)|\Psi^a_\mu(\vec{k},\omega_n)|^2$$

$$-\frac{1}{\kappa t}\int d^d x \int d\tau_1 d\tau_2 \sum_{a,b,\mu,\nu} \Psi^a_\mu(x,\tau_1)\Psi^b_\nu(x,\tau_2)Q^{ab}_{\mu\nu}(x,\tau_1,\tau_2)$$

new term

$$+U\int d\tau \sum_{a,\mu}\left[\Psi^a_\mu(x,\tau)\Psi^a_\mu(x,\tau)\right]^2$$

$$Q^{ab}_{\mu\nu}(\vec{k},\omega_1,\omega_2) = \beta(2\pi)^d\delta^d(k)\delta_{\mu\nu}\left[D(\omega_1)\delta_{\omega_1+\omega_2,0}\delta_{ab} + \beta\delta_{\omega_1,0}\delta_{\omega_2,0}q^{ab}\right].$$

$$D(\omega) = -|\omega|/\kappa$$

$$z = 2$$

similar problem

$$\mathcal{F}_{\text{gauss}} = \sum_{a,\vec{k},\omega_n} (k^2 + \omega_n^2 + \eta|\omega_n| + m^2)|\psi^a(\vec{k},\omega_n)|^2$$

$$-\beta q \sum_{a,b,\vec{k},\omega_n} \delta_{\omega_n,0}\psi^a(\vec{k},\omega_n)[\psi^b(\vec{k},\omega_n)]^*$$

new term propagator is replica off-diagonal

$$G_{ab}^{(0)}(\vec{k},\omega_n) = G_0(\vec{k},\omega_n)\delta_{ab} + \beta G_0^2(\vec{k},\omega_n) q \delta_{\omega_n,0}$$

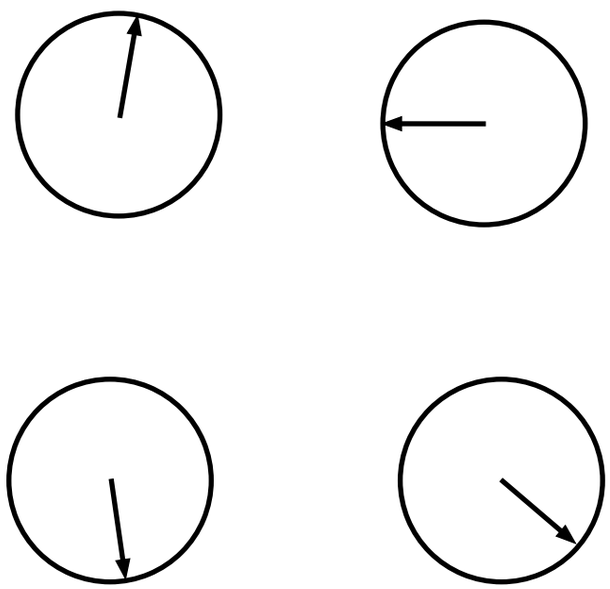
conductivity

$$\sigma(\omega = 0, T \to 0) = \frac{2}{3} \frac{\eta q_{\mathrm{EA}}}{m^4} \frac{e^{*2}}{h} \qquad z = 2$$

$$\boxed{\propto (g - g_c)^{-2z\nu}}$$

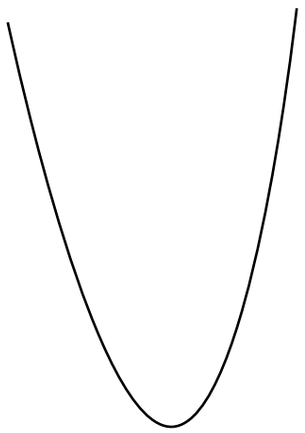
experiments: $\rho \propto (H - H_{\mathrm{SM}})^{\gamma} \quad \gamma \approx 3$

is a phase glass stiff?

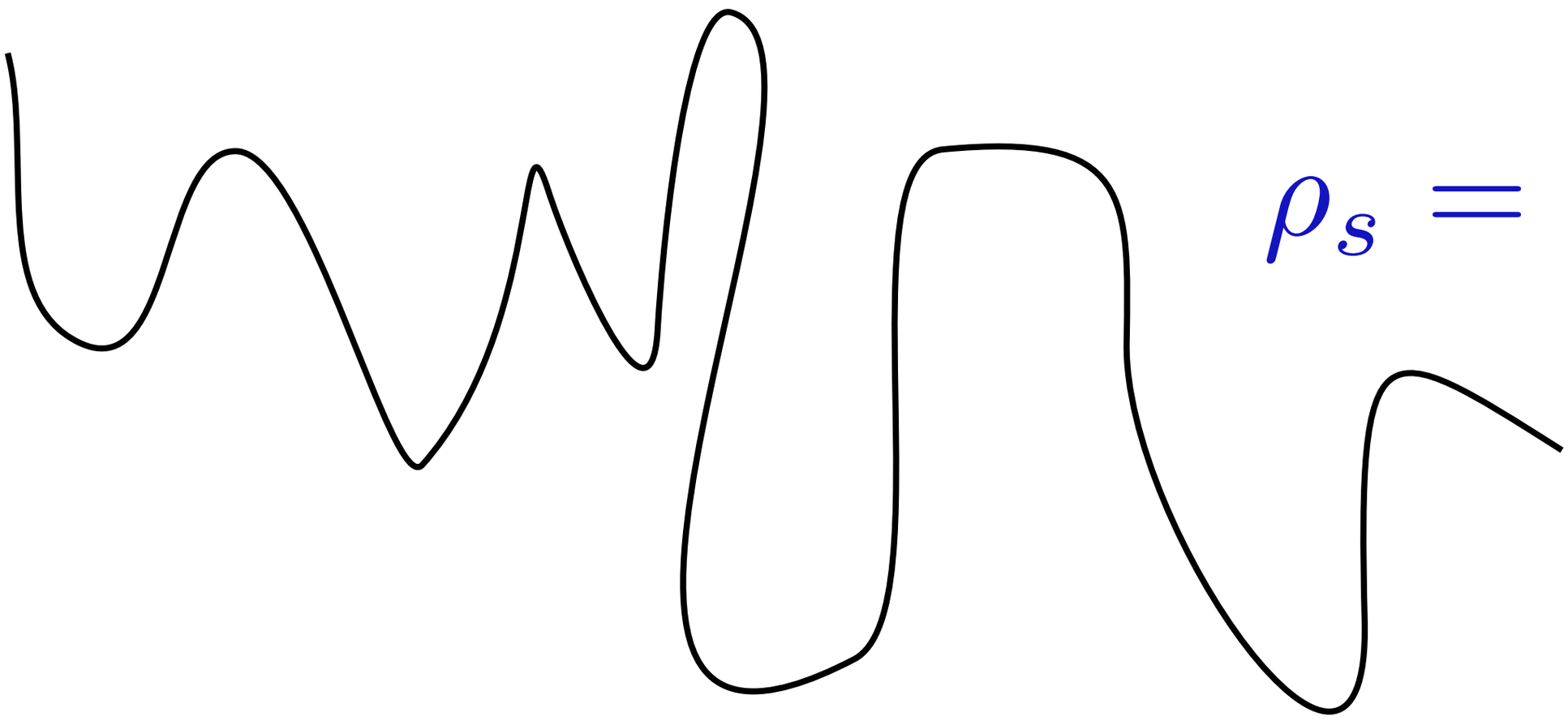


$$\Delta F \propto \rho_s k^2?$$

energy landscape



$\rho_s \neq 0$



$\rho_s = 0$

VOLUME 81, NUMBER 21 PHYSICAL REVIEW LETTERS 23 NOVEMBER 1998

$$\Delta E \propto L^{\theta}$$

$$\theta < 0$$ no stiffness

Numerical Study of Order in a Gauge Glass Model

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Department of Physics, Brown University, Providence, Rhode Island 02912

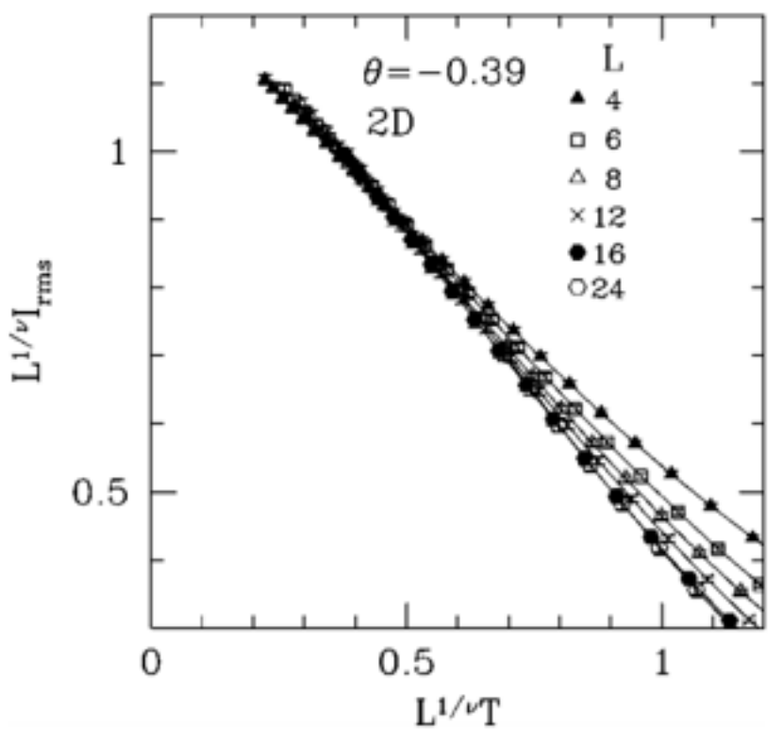

FIG. 3. Scaling plot of the root-mean-square current I_{rms} in two dimensions according to the form expected if $T_c=0$, Eq. (10). We see acceptable scaling of the data at low temperatures. Deviations at higher T are presumably due to corrections to scaling. This plot is for $\theta \equiv -1/\nu = -0.39$.

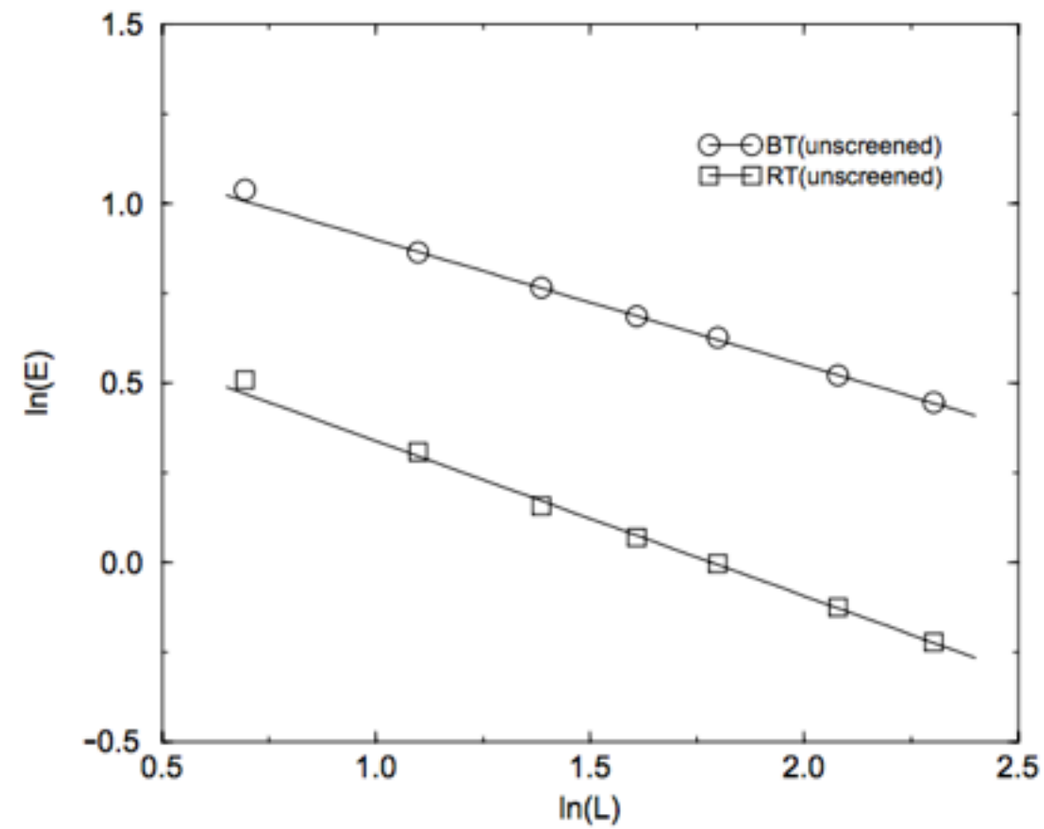

FIG. 1. Size L dependence of domain wall energy in 2D. Both RT and BT measurements are shown. Solid lines are power-law fits. Error bars are not shown if smaller than symbol size.

PHYSICAL REVIEW B **66**, 224507 (2002)

Numerical studies of the two- and three-dimensional gauge glass at low temperature

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Do Superconductors Have Zero Resistance in a Magnetic Field?

D.R. Strachan,* M.C. Sullivan, P. Fournier, S.P. Pai, T. Venkatesan, and C.J. Lobb
Center for Superconductivity Research, University of Maryland, College Park, Maryland 20742
(Received 31 October 2000; published 23 July 2001)

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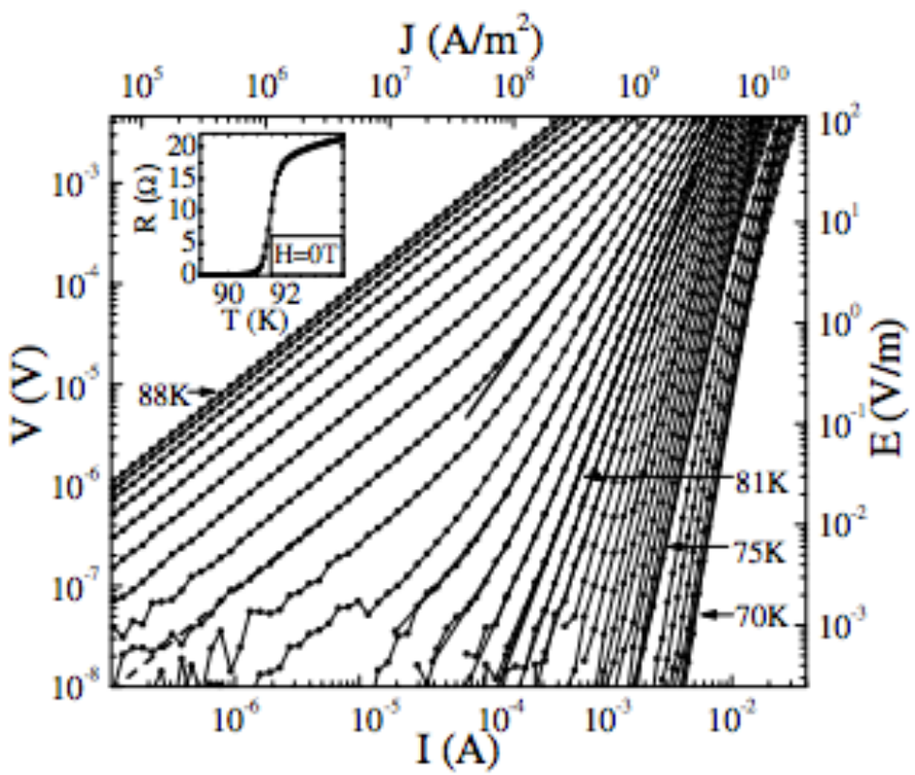


No

bose metal

$$\mathcal{F}_{\text{gauss}} = \sum_{a,\vec{k},\omega_n} (k^2 + \omega_n^2 + \eta|\omega_n| + m^2)|\psi^a(\vec{k},\omega_n)|^2$$

$$-\beta q \sum_{a,b,\vec{k},\omega_n} \delta_{\omega_n,0}\psi^a(\vec{k},\omega_n)[\psi^b(\vec{k},\omega_n)]^*$$

glassy physics

is the ground state of bosons in a finite magnetic field?

is the vortex glass a metal?

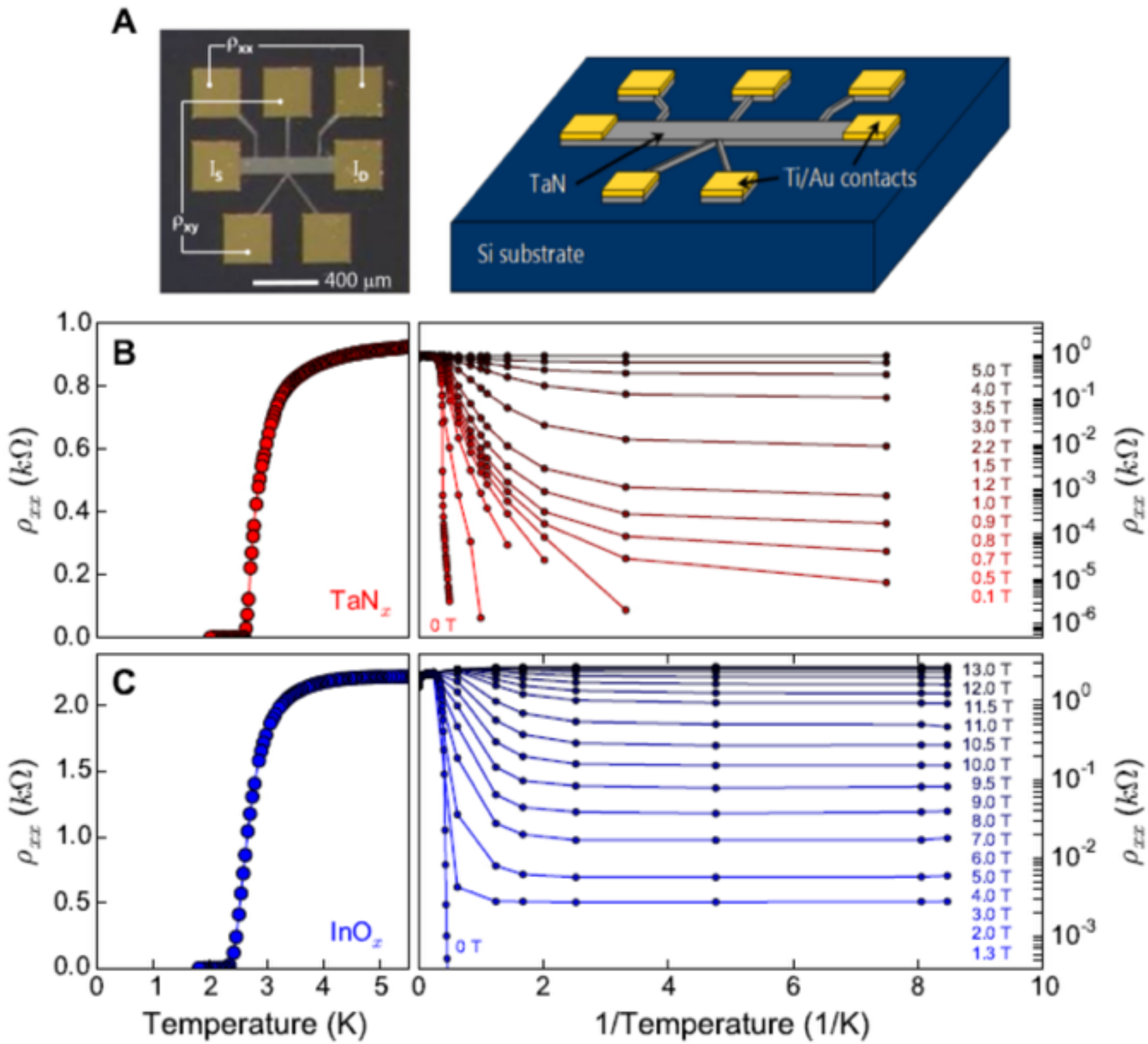
experiments+
theory
indicate
yes

what is z in the bose metal?

$z = 2$

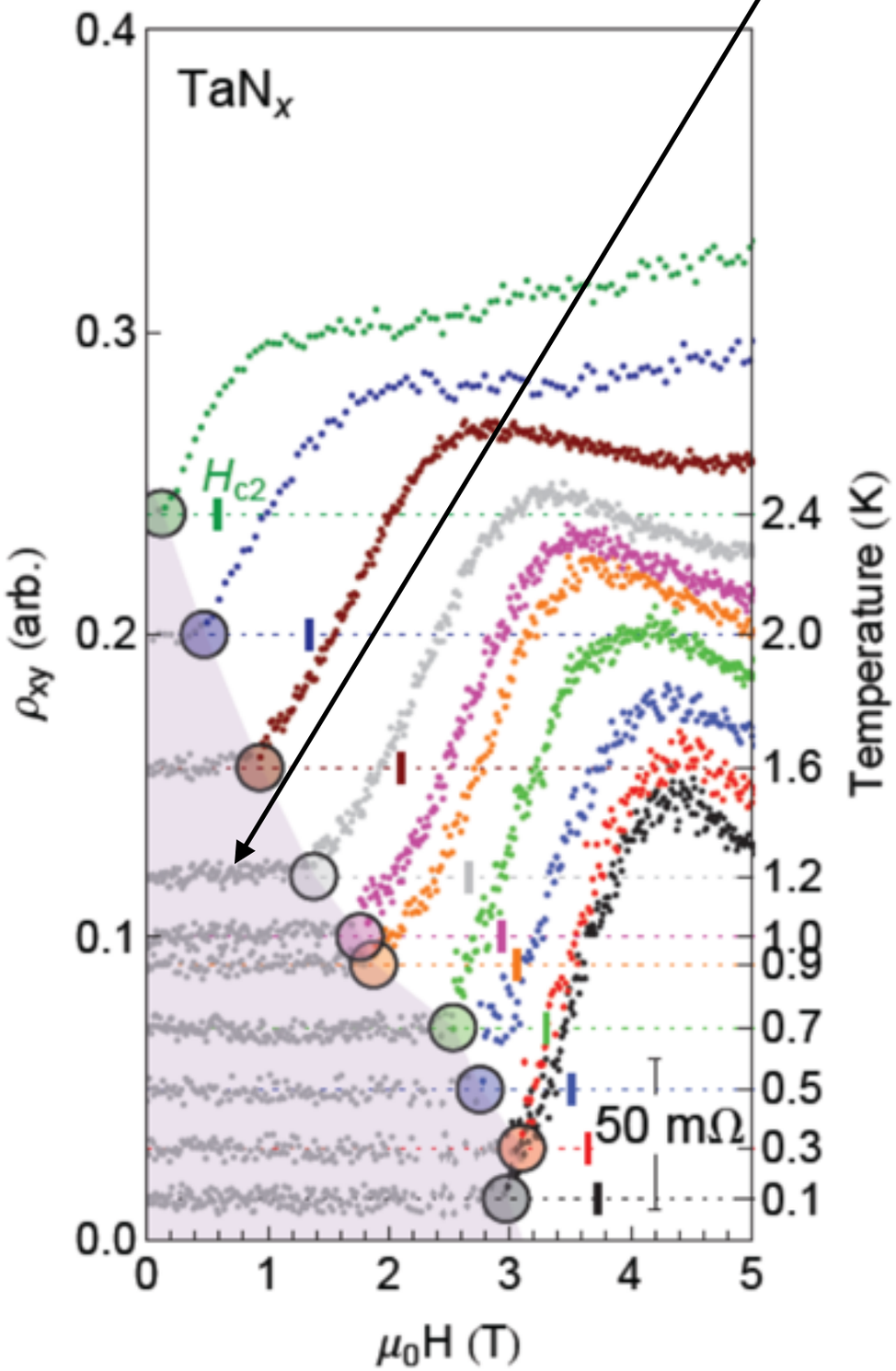
bose metal has particle hole symmetry (phase glass)

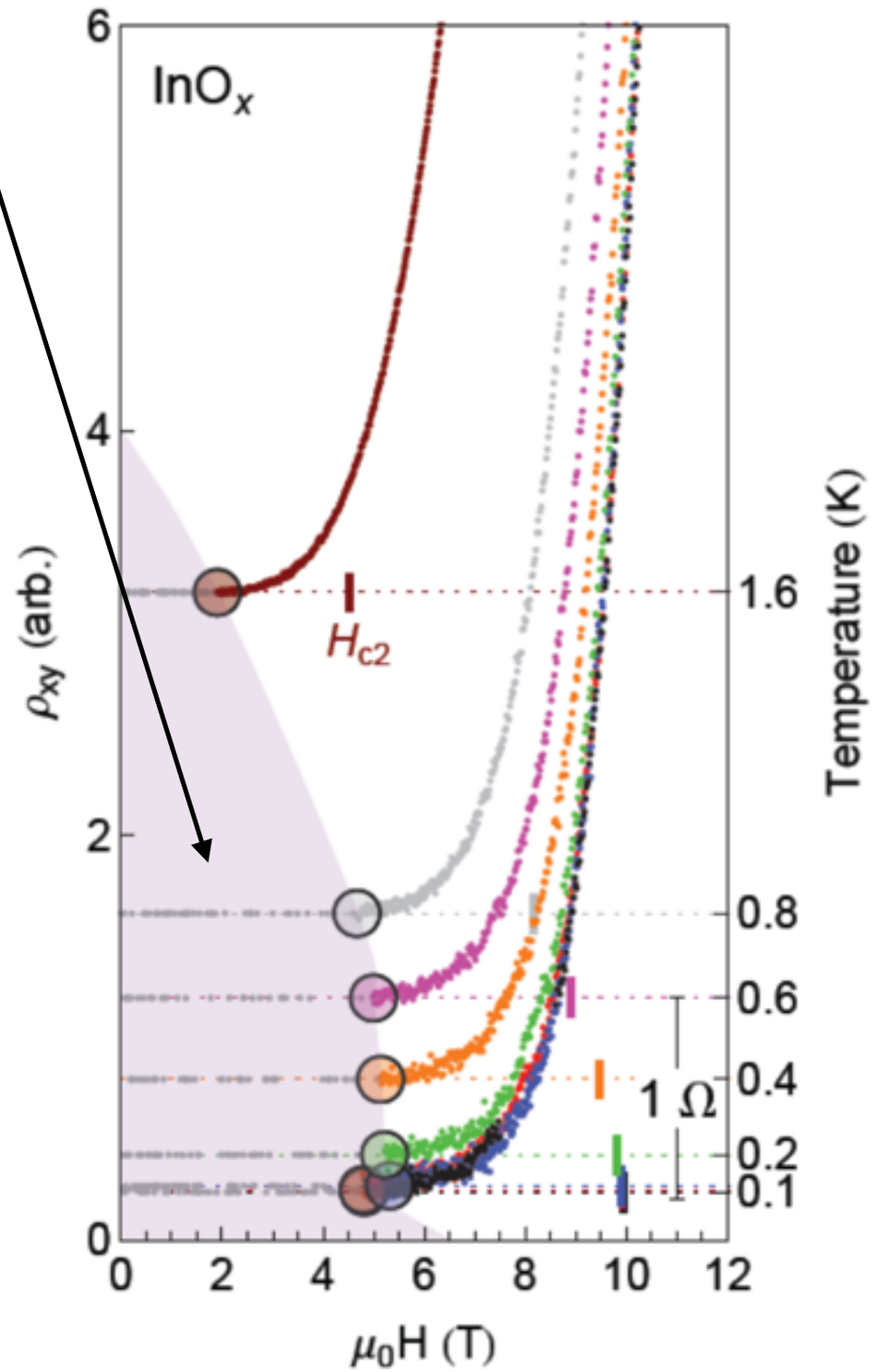
Breznay/Kapitulnik 2017



$\rho_{xy} = 0$

p-h symmetry





vortex glass is a metal