Nernst Effect as a Probe of Quantum Criticality near a Superconductor-Insulator Transition

Arnab Roy, ES & Aviad Frydman [PRL **121**, 047003 (2018)];

Earlier theory work with Yeshayahu Atzmon [PRB **87**, 054510 (2013)]

Nernst Effect as a Probe of Quantum Criticality near a Superconductor-Insulator Transition

Outline

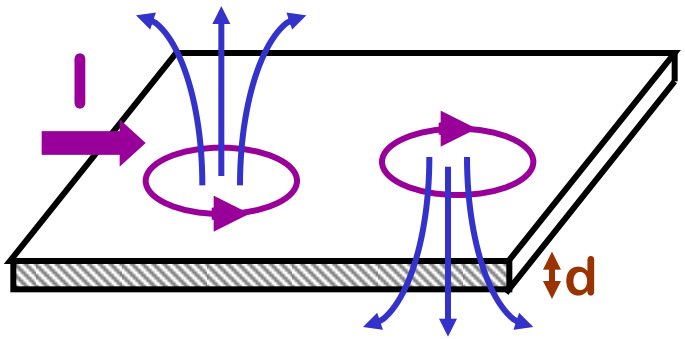
- The Superconductor-Insulator transition
- Off-diagonal thermoelectric effects: probes of fragile superconductivity
- Nernst effect near the SIT - theory: quasi-1D toy model (Josephson ladder)
- Nernst effect near the SIT – experimental results; quantum critical scaling in 2D

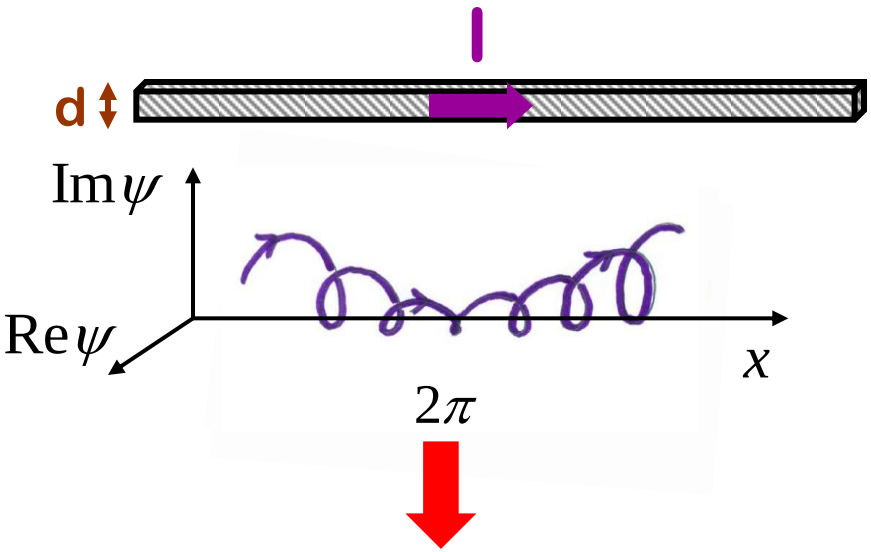
Superconductor-Insulator Transition

Films (2D)

$$d \ll \xi$$

Wires (1D)





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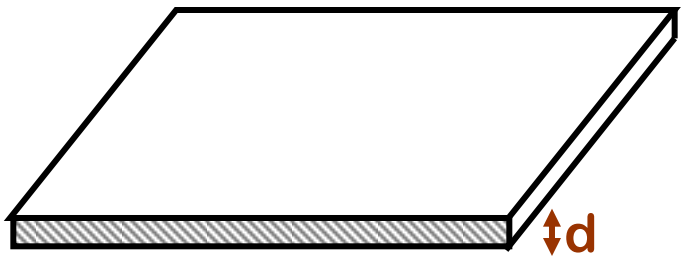

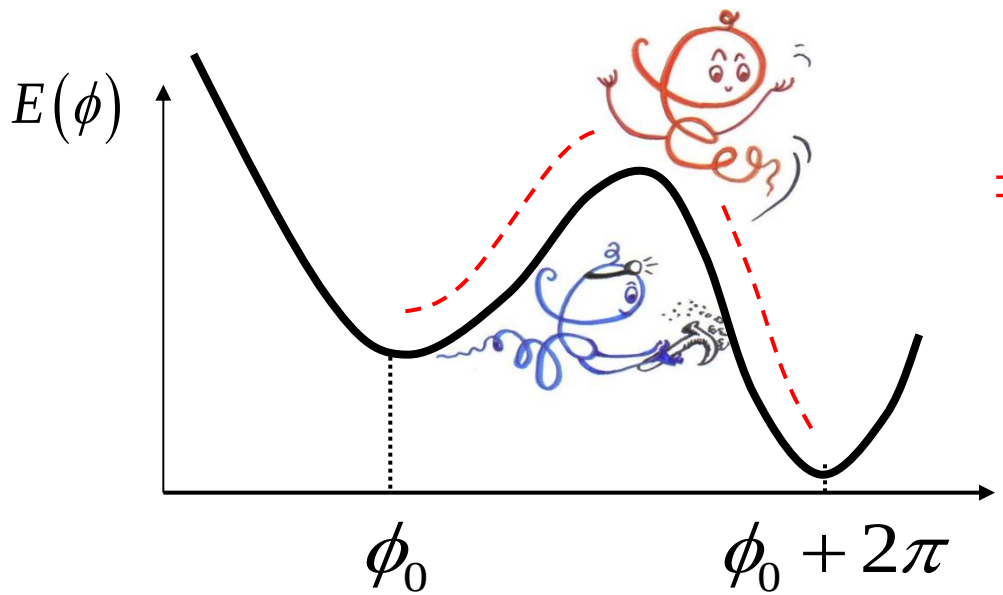

$$\Rightarrow V = \frac{h}{2e}\left\langle \frac{d\phi}{dt} \right\rangle$$

Superconductor-Insulator Transition

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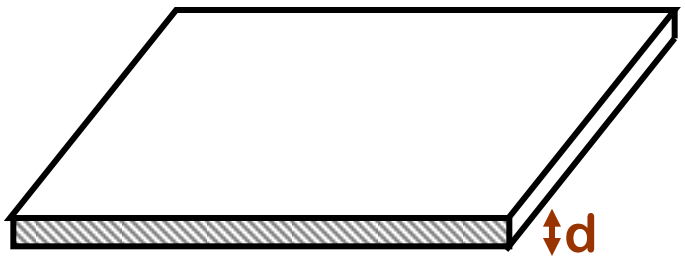
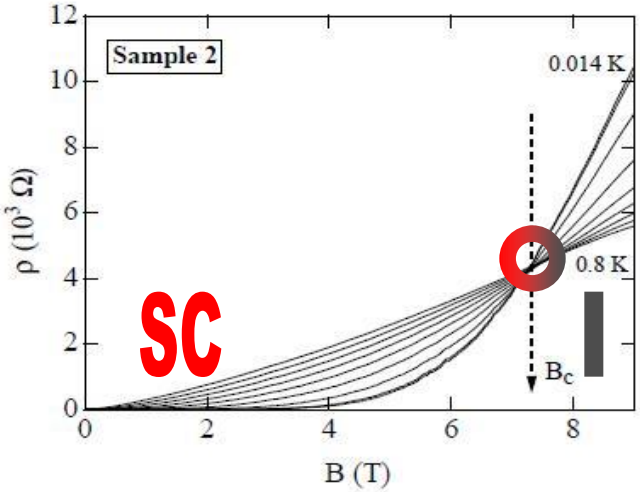
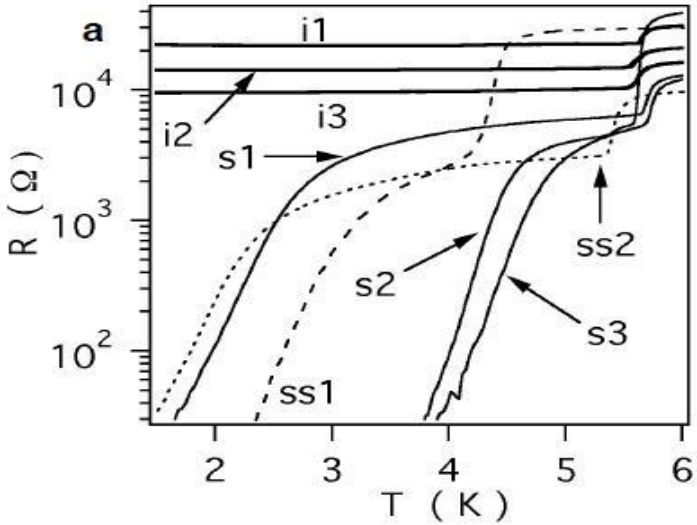


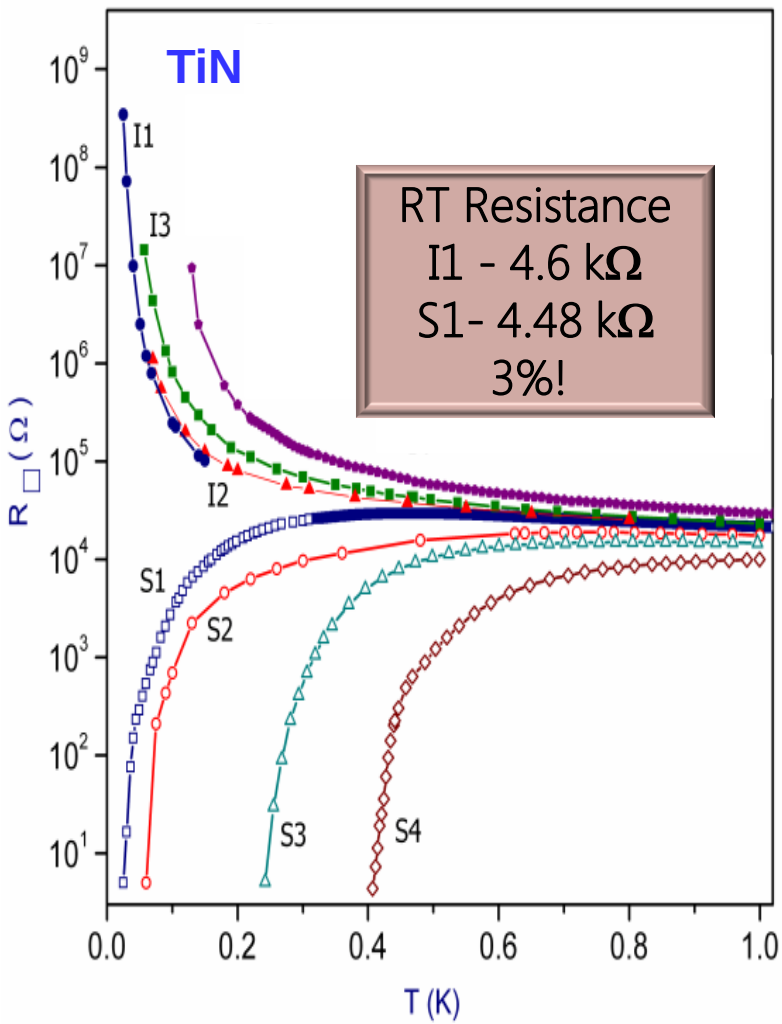
Sambandamurthy *et al.* (2006)

Bezryadin, Lau & Tinkham (2000)





Superconductor-Insulator Transition



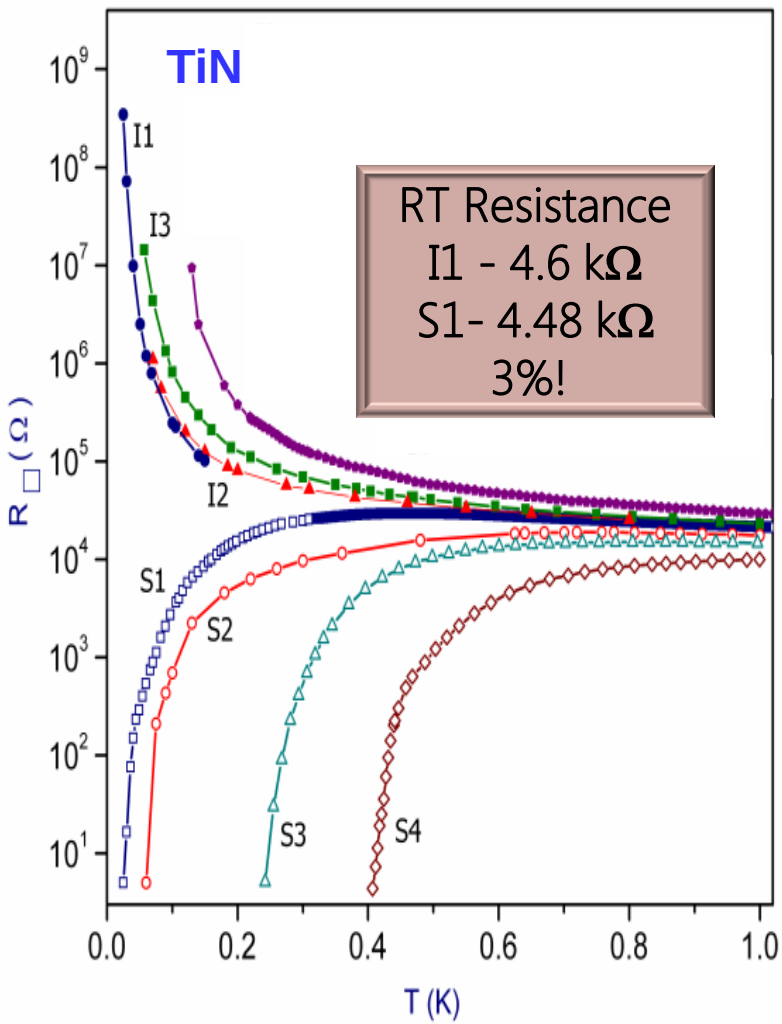
Baturina et.al. PRL (2007)

Aharon Kapitulnik
Allen Goldman
Art Hebard
Matthew Fisher

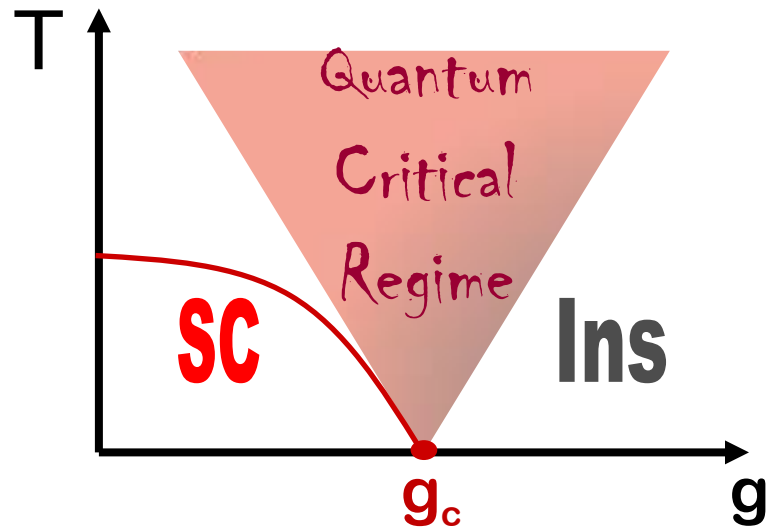
2015 Buckley condensed matter physics prize:

"For discovery and pioneering investigations of the superconductor-insulator transition, a paradigm for quantum phase transitions."

Superconductor-Insulator Transition



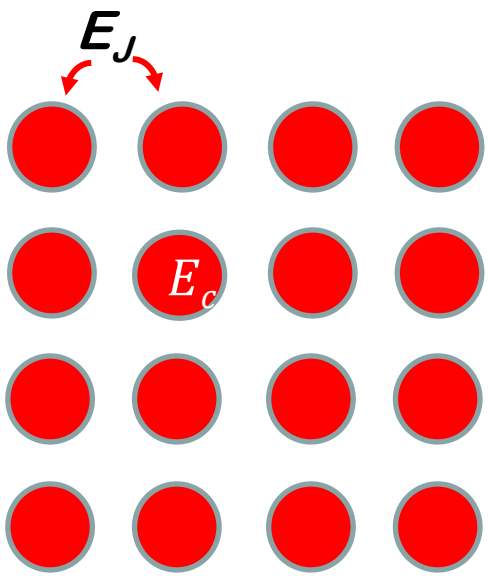
Baturina et.al. PRL (2007)



- Disorder
- Thickness
- Magnetic field
- Electric field
- Chemical composition
- .....

SIT Quantum Critical Point

Clean limit



$$\xi \sim |\Delta g|^{-\nu}$$

$$\xi_\tau \sim \xi^z$$

$$g = \frac{E_c}{E_J}$$

If particle hole symmetry is obeyed the SIT can be mapped to a classical 3D XY model

$\nu \approx 2/3$ **Z=1**

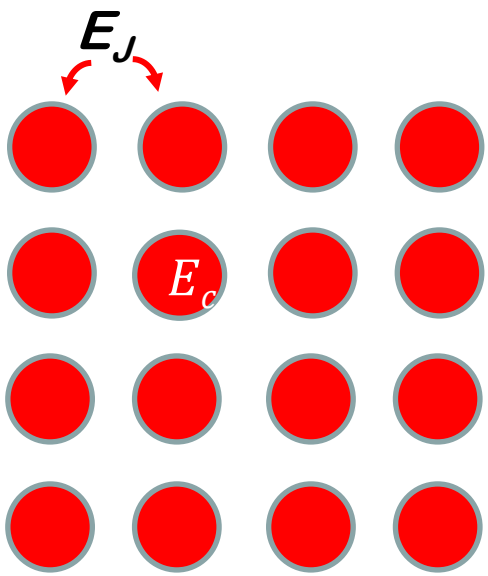
SIT Quantum Critical Point

Clean limit

$$\xi \sim |\Delta g|^{-\nu}$$

$$\xi_\tau \sim \xi^z$$

Dirty limit



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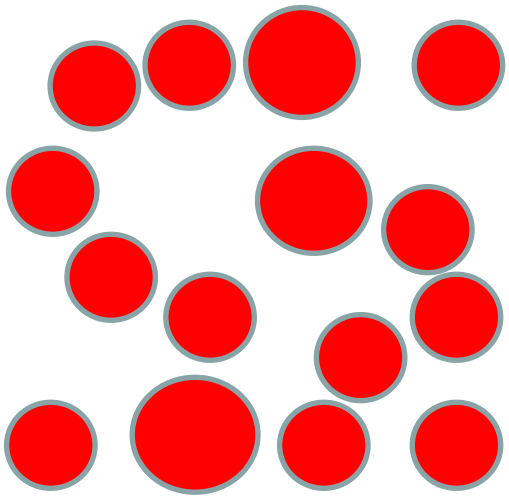


An intermediate "Bose glass"

If particle hole symmetry is obeyed the SIT can be mapped to a classical 3D XY model

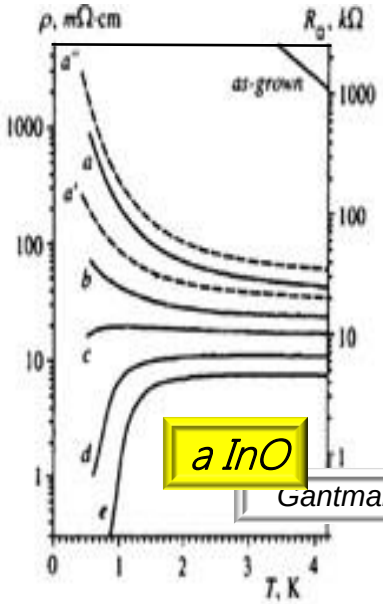
$\nu \approx 2/3$ **Z=1**

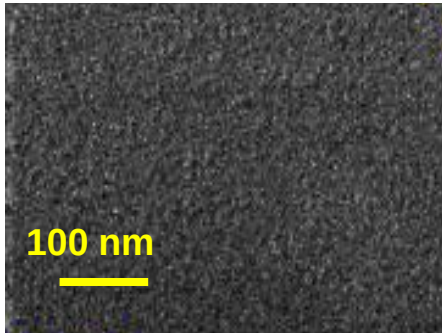
$\nu \geq 1$ **Z=1** (Coulomb interactions)

T. Vojta *et al.* (2016, 2017):

$\nu \approx 1.1$ **Z≈1.5**

Emergent electronic granularity

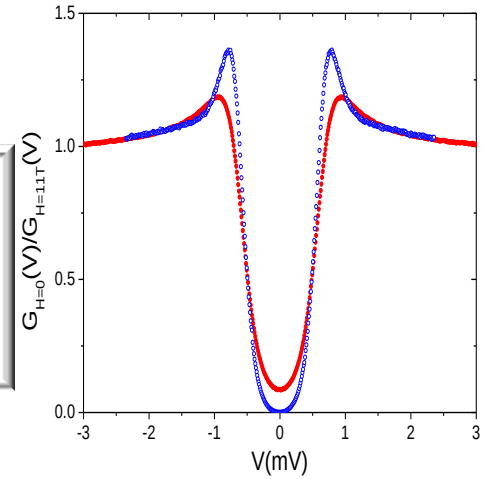




a InO

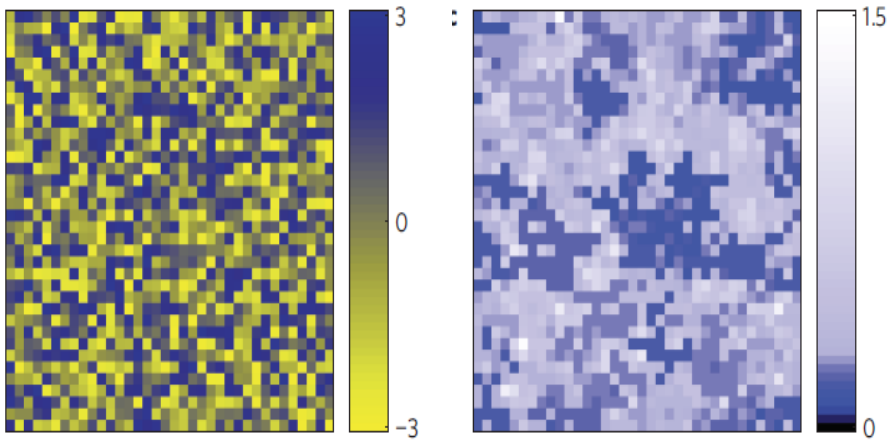
Gantmakher et-al, JETP (1996)

The amplitude of the superconducting order parameter does not vanish at the QPT and ξ is relatively unchanged



Sherman, Kopnov, Shahar AF, PRL. (2012)

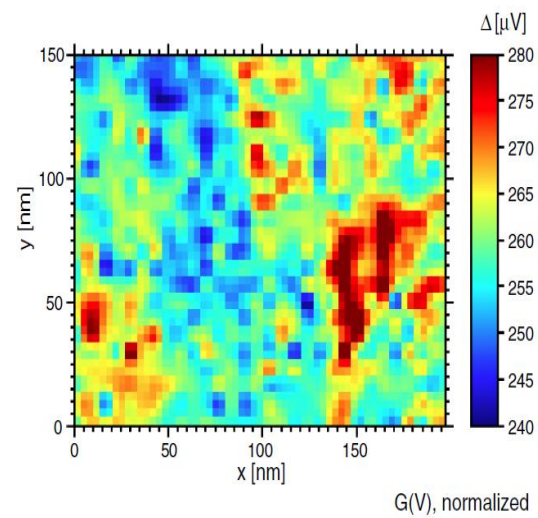
Theory



$$\psi=\psi_0 e^{i\theta}$$

Bouadim et-al, Nat. Physics (2011)

Experiment

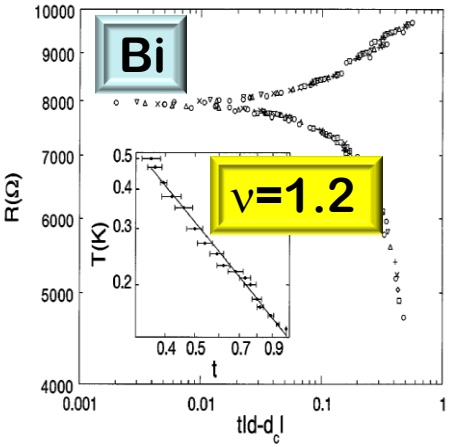


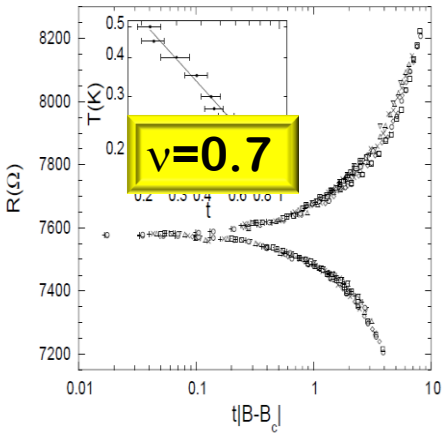
Sacepe et-al, Nat. Phys. (2008)

Resistivity scaling

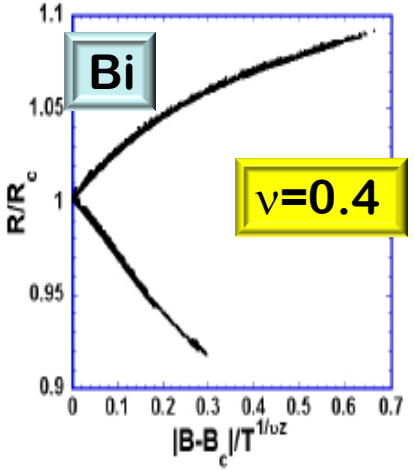
$$\xi \sim |\Delta g|^{-\nu}, \quad \xi_T \sim \xi^z$$

$$R(\Delta g, T) = R_c\, f(\Delta g\, T^{-1/\nu z})$$

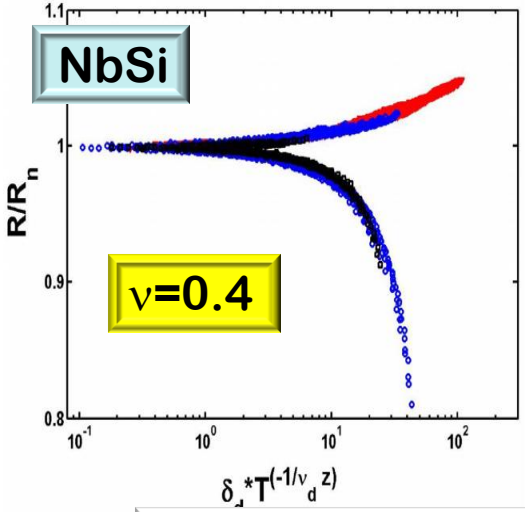




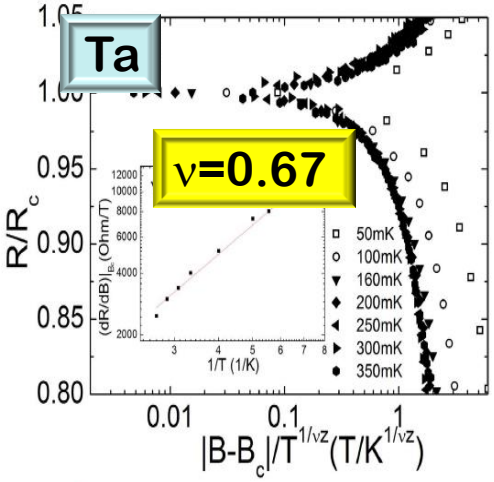
Markovic and Goldman. PRL (1998)



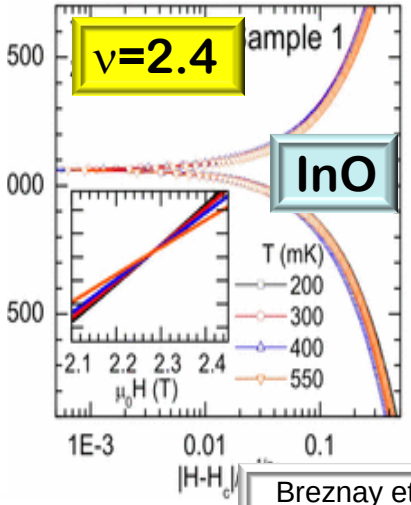
Lin and Goldman. PRL (2009)



Marache-Kikuchi et.al. PRB (2008)

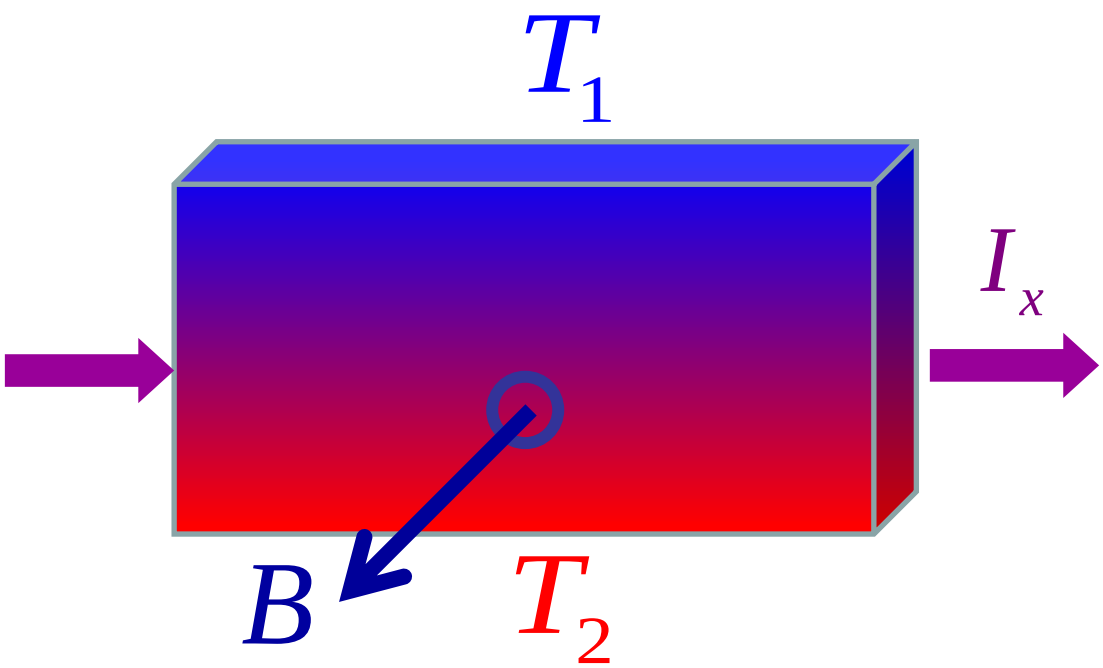


Park et.al. (2017)



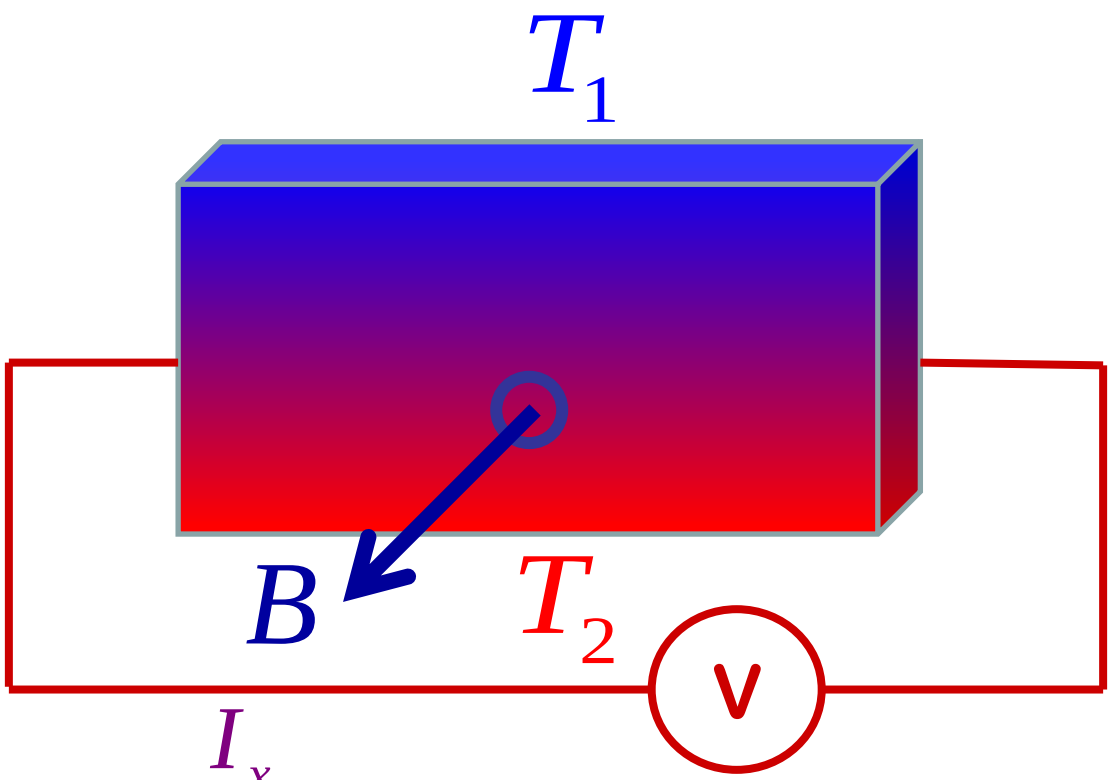
Breznay et.al. PNAS (2016)

The off-diagonal Peltier and Nernst effects



$$\alpha_{xy} \equiv \frac{I_x}{\nabla_y T}$$

The off-diagonal Peltier and Nernst effects



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$$\nu \equiv \frac{V}{\left|\nabla T_y B\right|}$$

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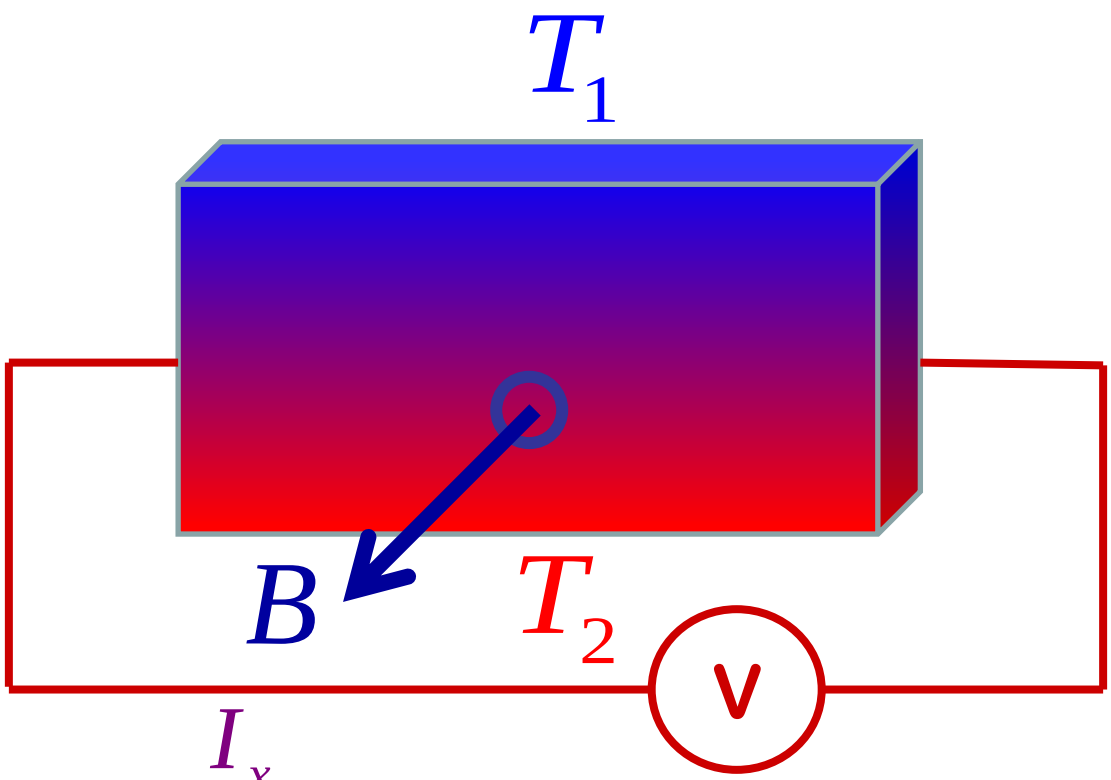

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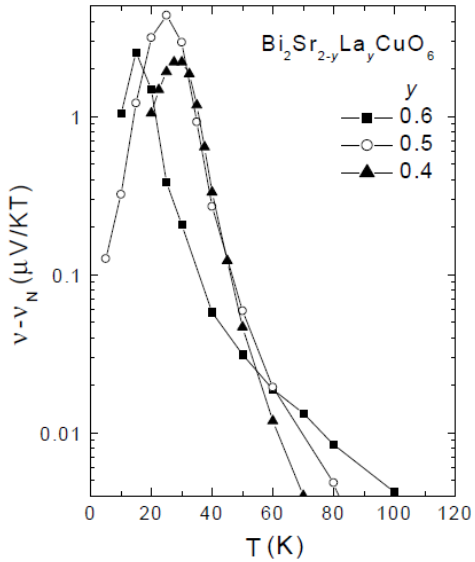
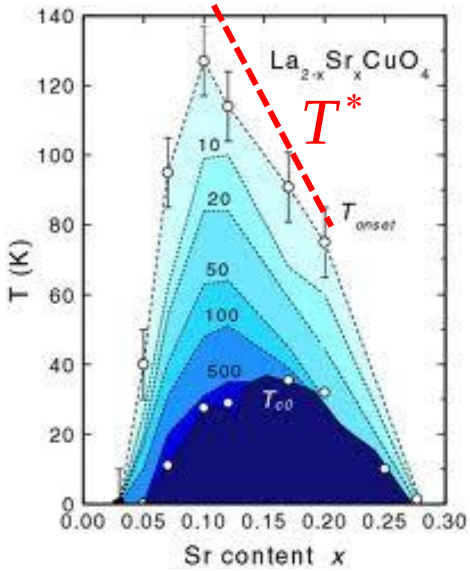
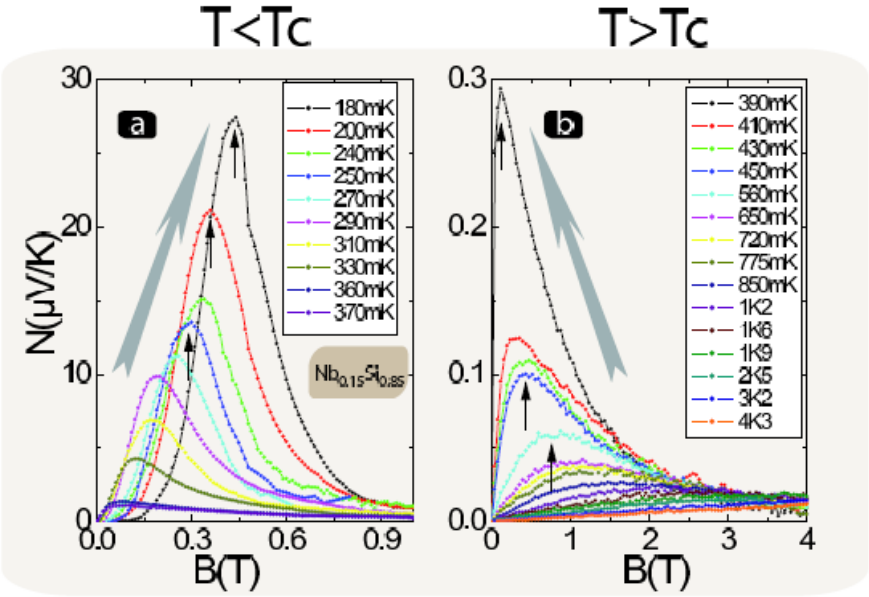
Nernst effect in fluctuating superconductors

The pseudogap regime of Cuprates
(Ong's group, 2000):





Near Tc of thin films (NbSi, InO)
(Behnia's group, 2009):



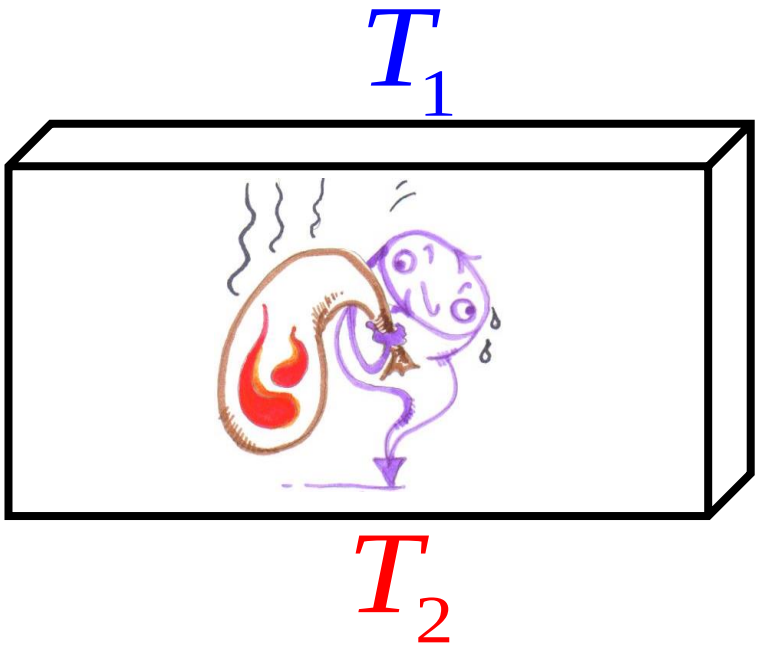
Signature of thermal SC fluctuations!

Theories:

Gaussian (AL)
- Ullah & Dorsey (1990)
- Ussishkin, Sondhi & Huse (2002)
- Michaeli & Finkelstein (2009)
- Serbyn et al. (2011)

Vortex liquid
- Podolsky, Raghu & Vishwanath (2007)
- Wachtel & Orgad (2014)

QCP
- Hartnoll *et al.* (2007); Bhaseen, Green, Sondhi (2009)



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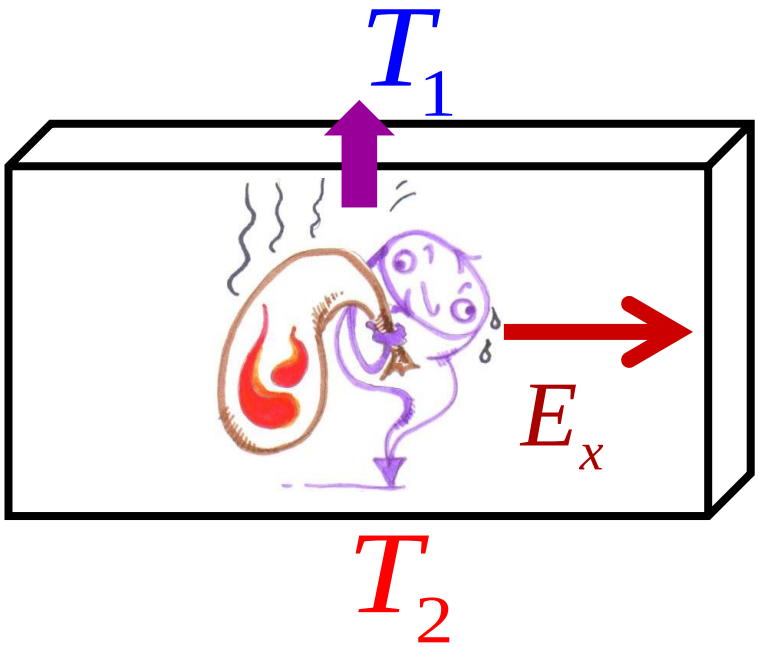

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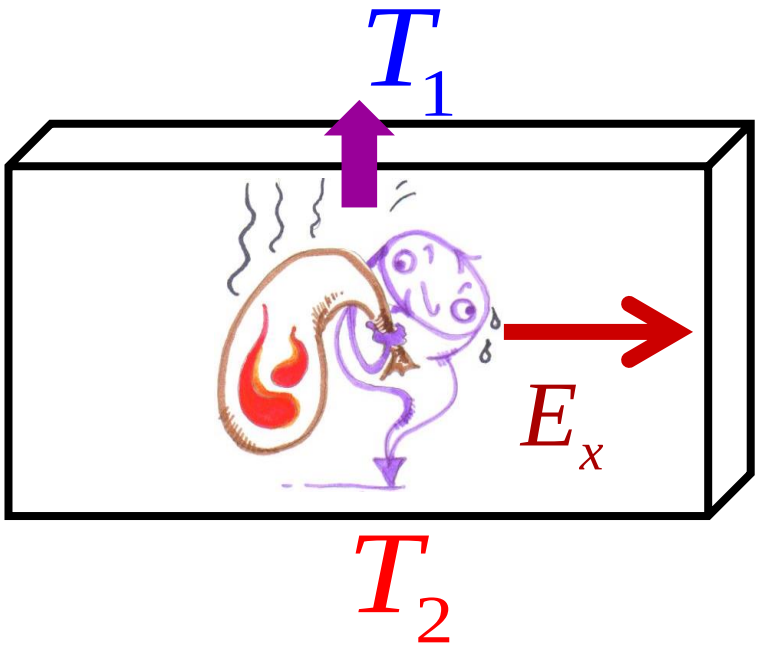
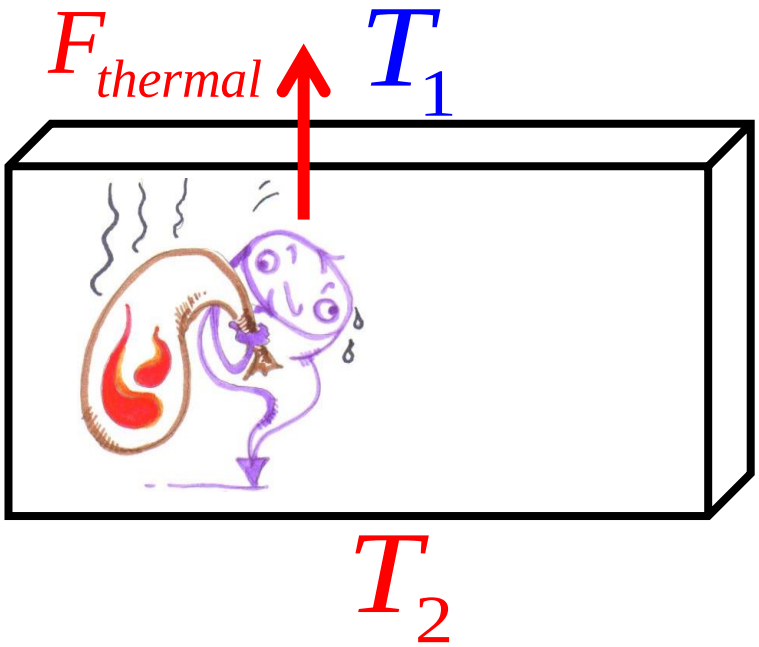


$$\nu \equiv \frac{V}{\left|\nabla T_y B\right|} = \frac{R_{xx}\alpha_{xy} - \cancel{\alpha_{xx} R_{xy}}}{B}$$

α_{xy} : A dual "thermopower"



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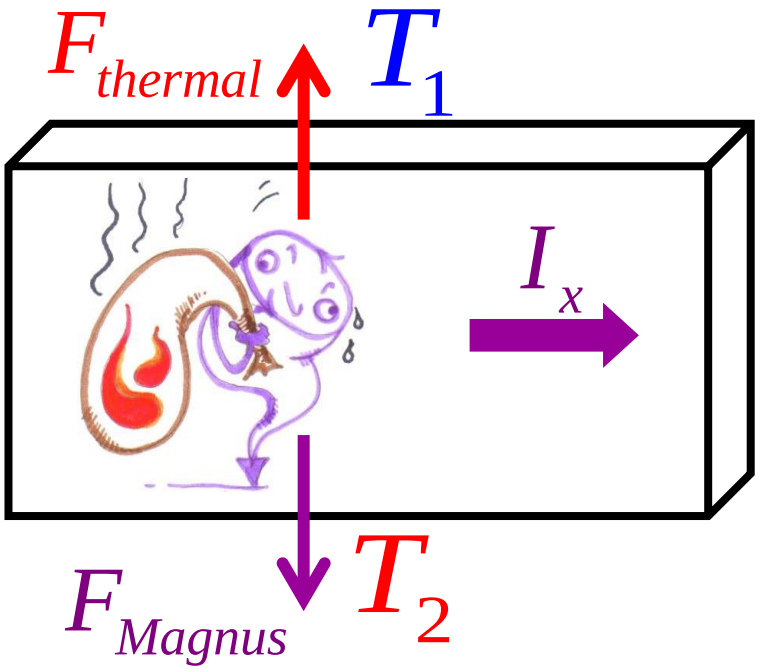

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α_{xy} : A dual "thermopower"

⇒ Intimately related to thermodynamic quantities

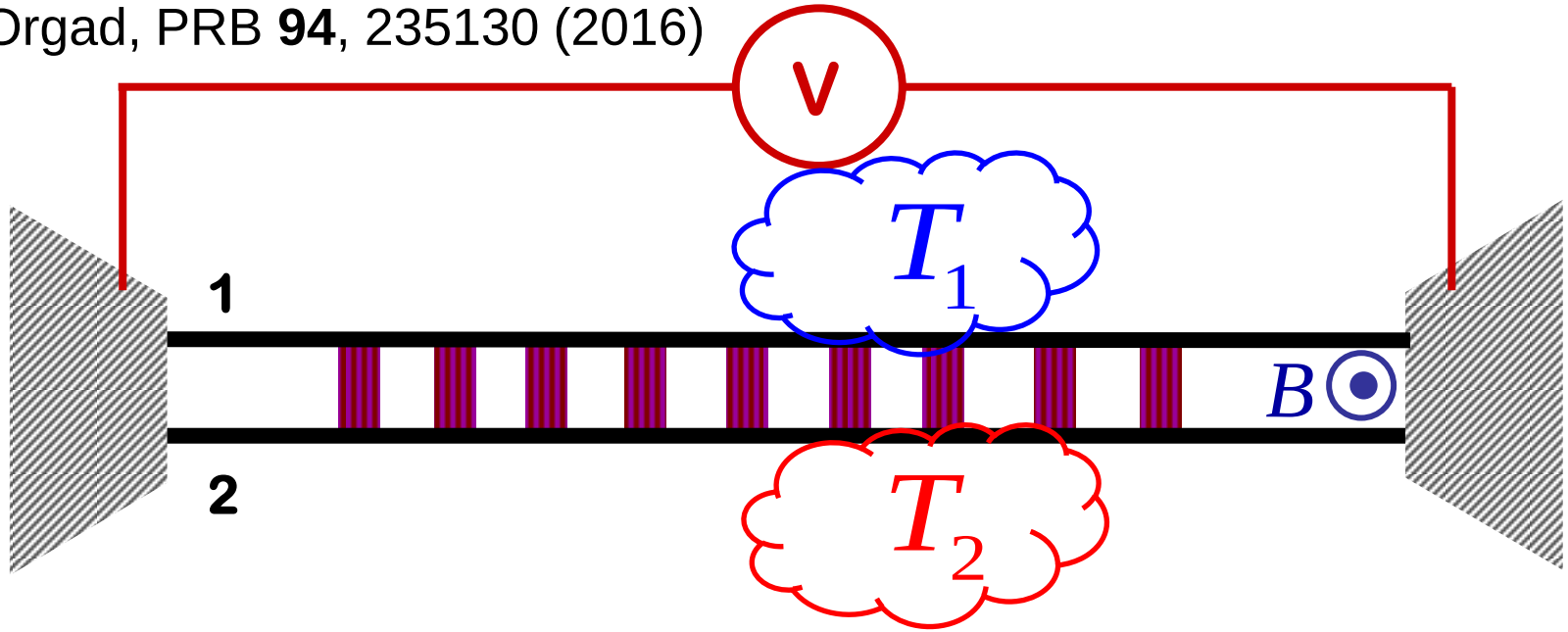
- $\alpha_{xy} \sim -s / B$ **[for Galilean invariant systems – Cooper, Halperin & Ruzin (1997); Bergman & Oganesyan (2010)].**

⇒ **A sensitive spectrometric probe**

- **Associated with diamagnetism:** $\alpha_{xy} \sim -M / T$

The superconducting ladder: a minimal model for Nernst effect near SC/I transitions

Y. Atzmon & ES, PRB **87**, 054510 (2013); see also: Y. Schattner, V. Oganesyan & D. Orgad, PRB **94**, 235130 (2016)



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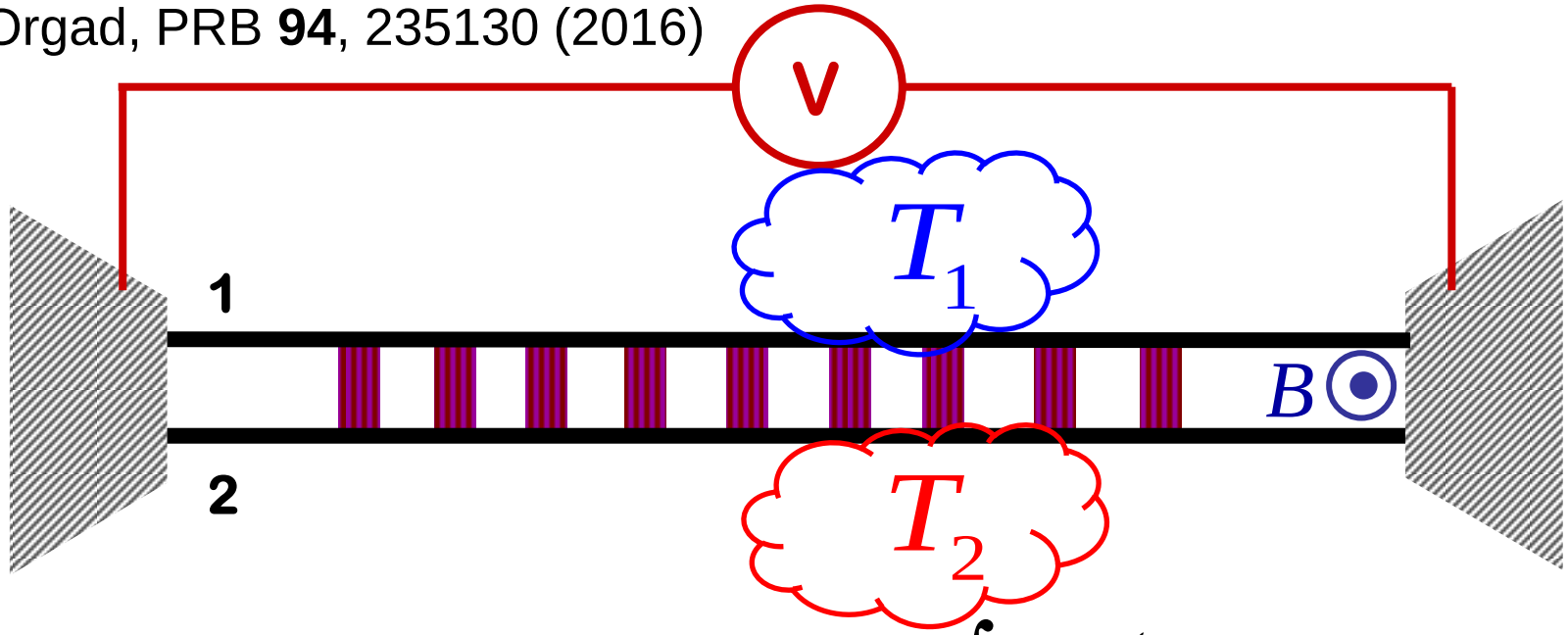

$$H = H_0 + H_J + H_{dis} \qquad H_J = -J\int \cos\left(\phi_1 - \phi_2 - q(B)x\right)$$

$$H_0 = H_1 + H_2 \qquad H_{dis} = \sum_{n=1,2}\int dx\varsigma_n(x)\cos\left\{2\theta_n(x)\right\}$$

$$H_n = \frac{u}{2\pi}\int dx\left[K\left(\partial_x\theta_n\right)^2 + \frac{1}{K}\left(\partial_x\phi_n\right)^2\right]$$

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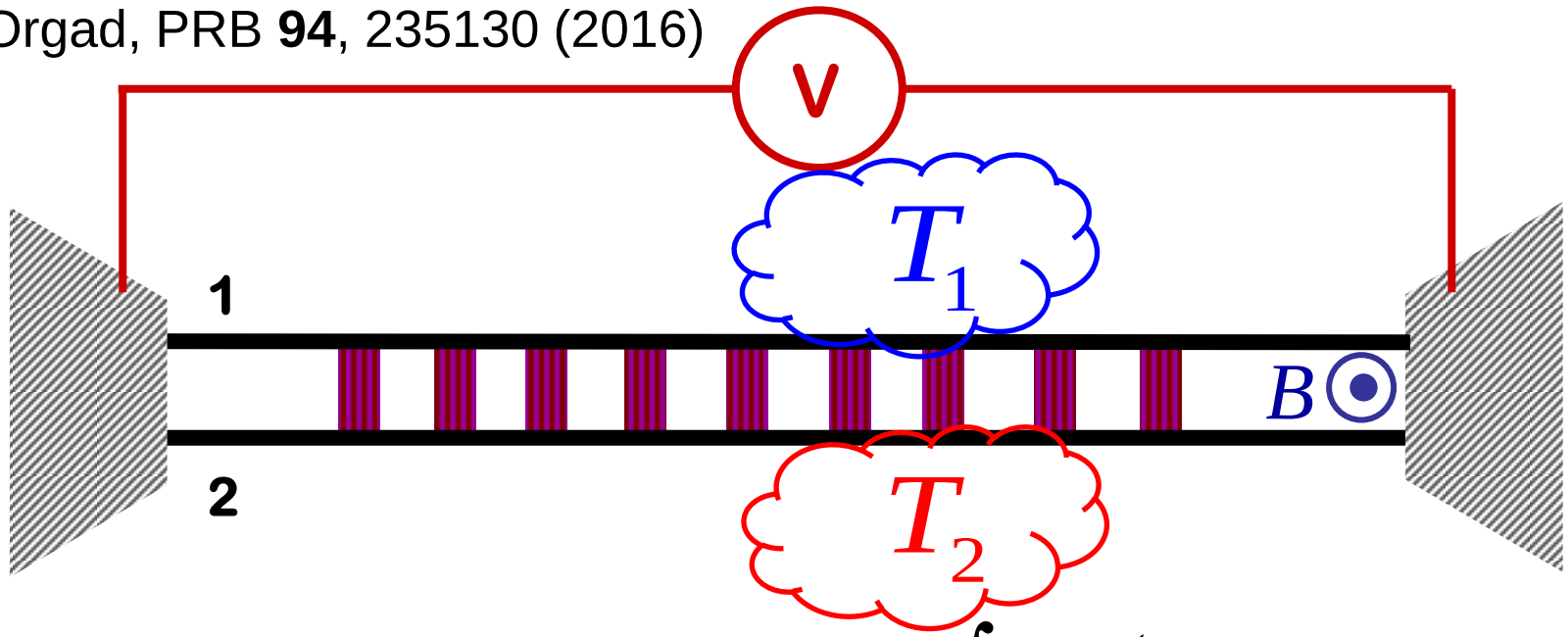

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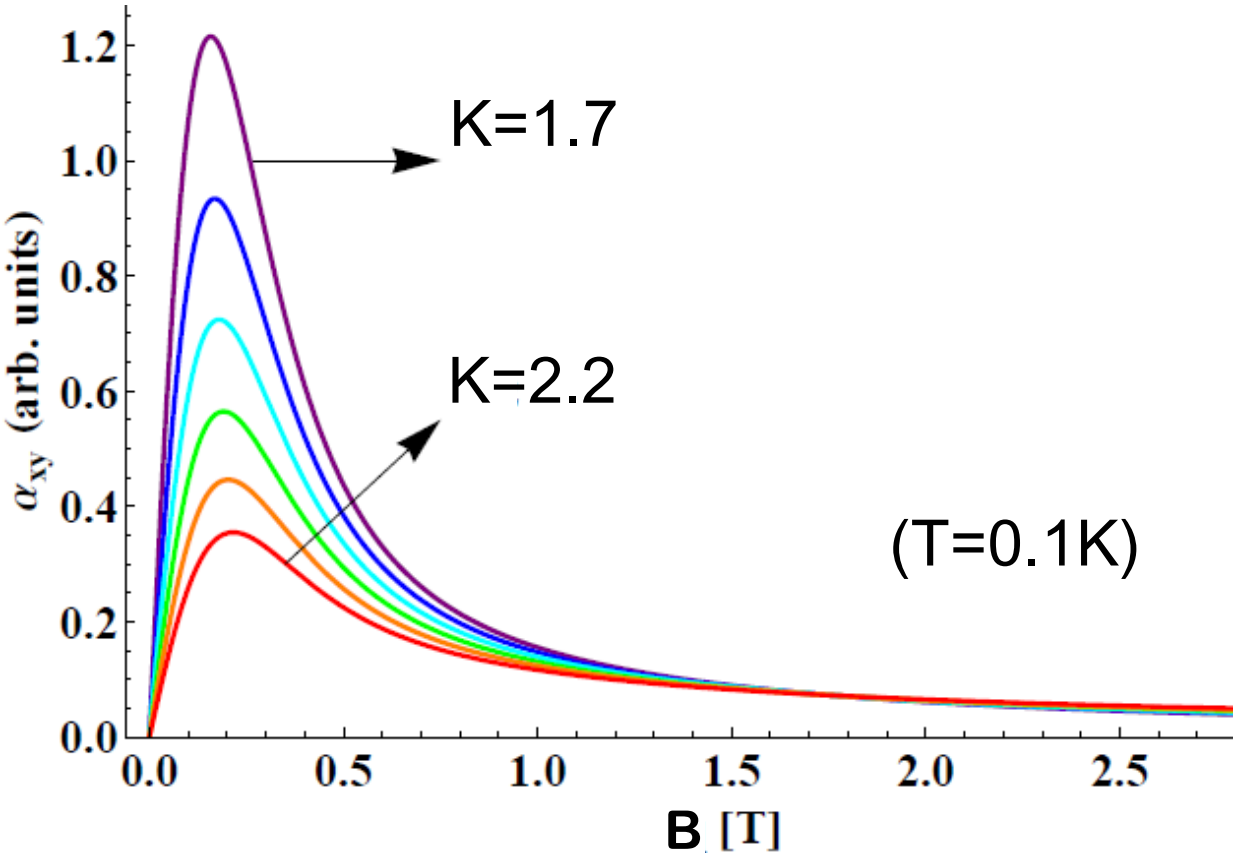
$$H_n = \frac{u}{2\pi}\int dx\left[K\left(\partial_x\theta_n\right)^2 + \frac{1}{K}\left(\partial_x\phi_n\right)^2\right] \qquad K \propto \sqrt{\frac{E_c}{E_J}}$$

Transverse Peltier coefficient

$$\alpha_{xy} \sim J^2 T^{K(B)-2} \mathbb{F}_K \left(\frac{B}{T} \right)$$



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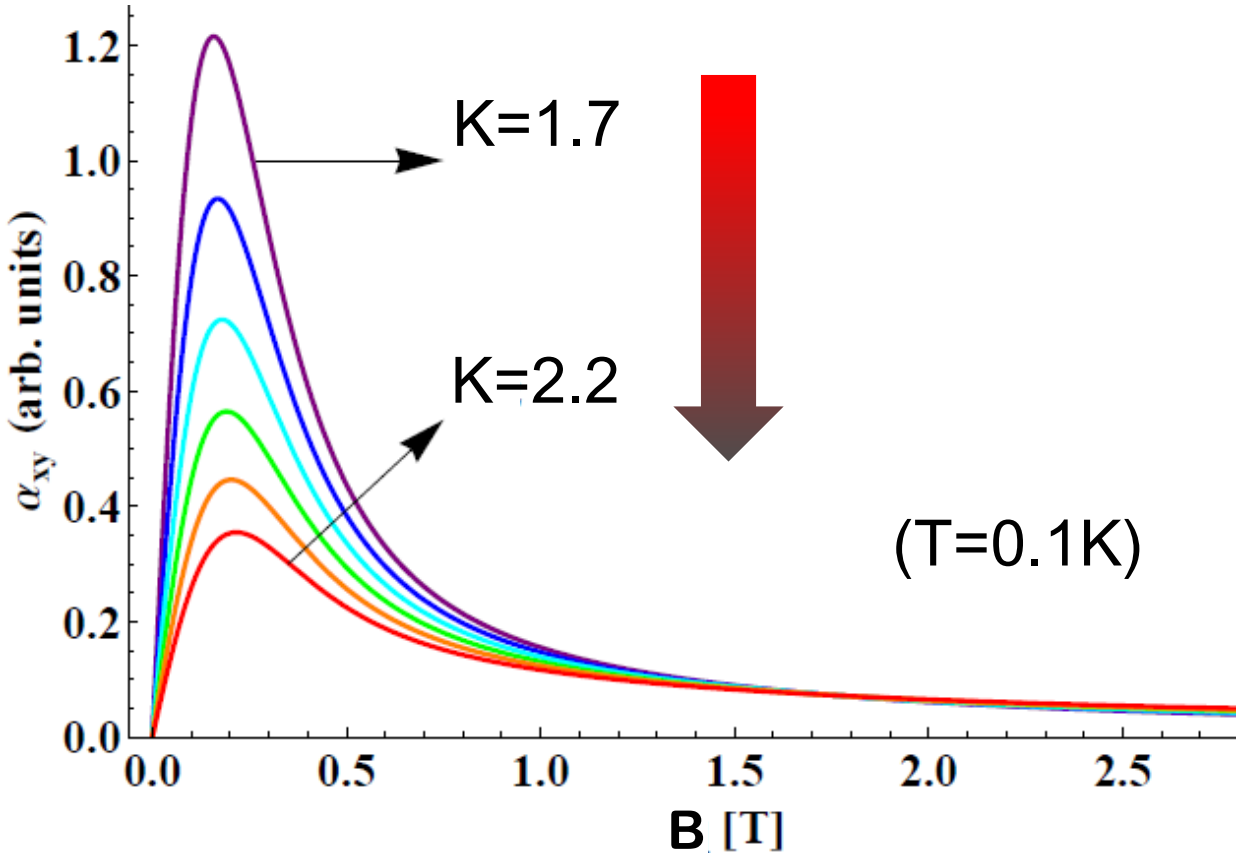
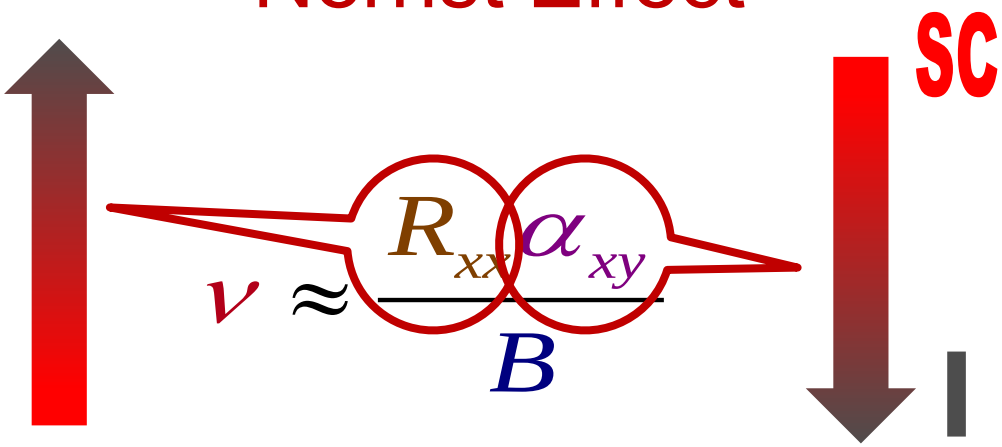
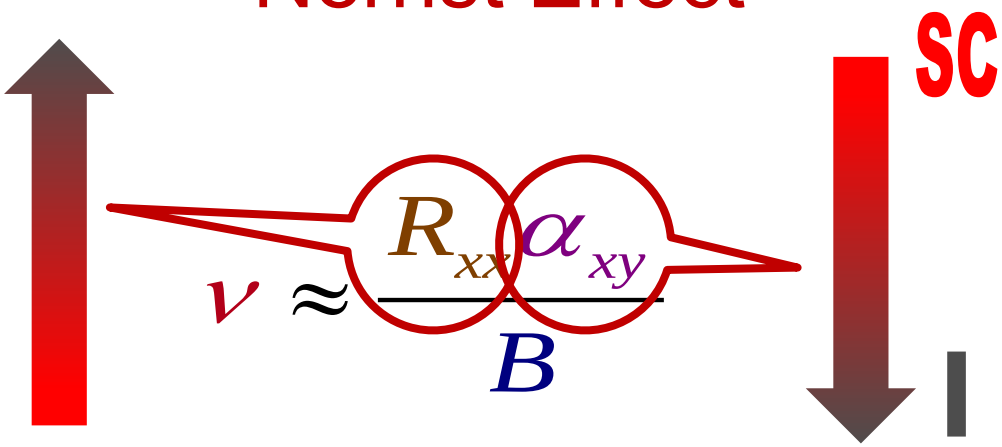
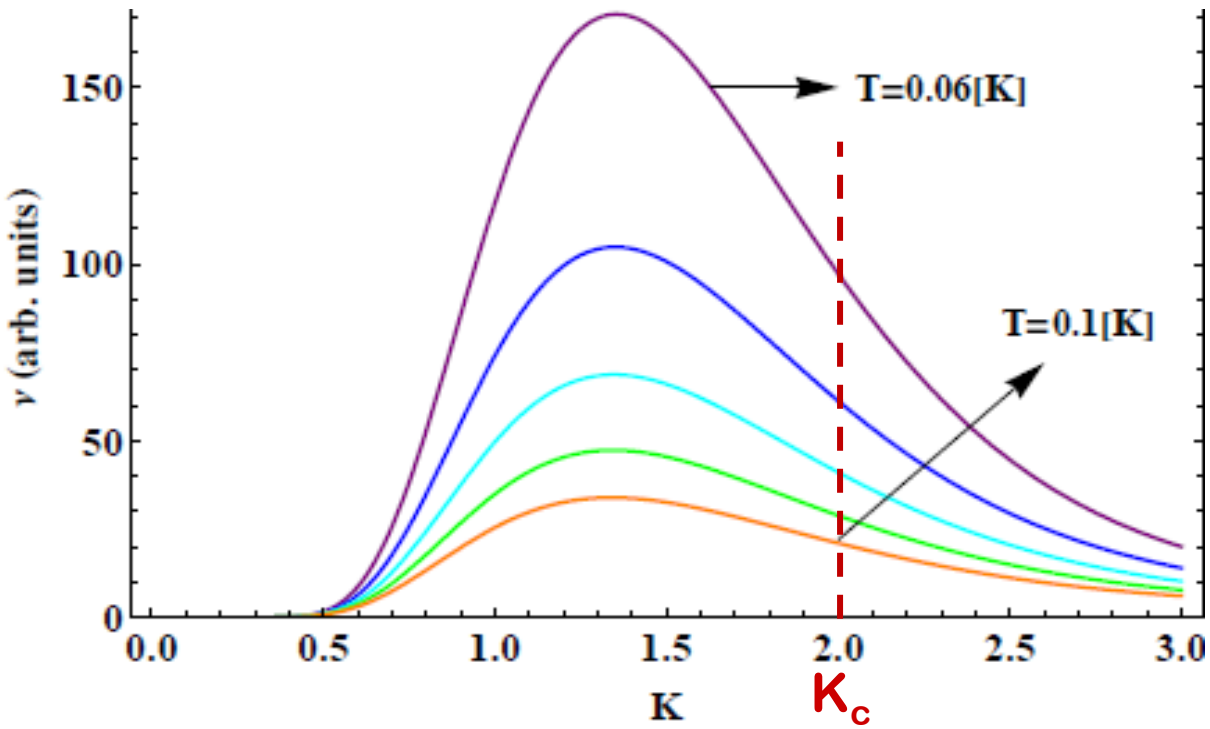


Nernst Effect

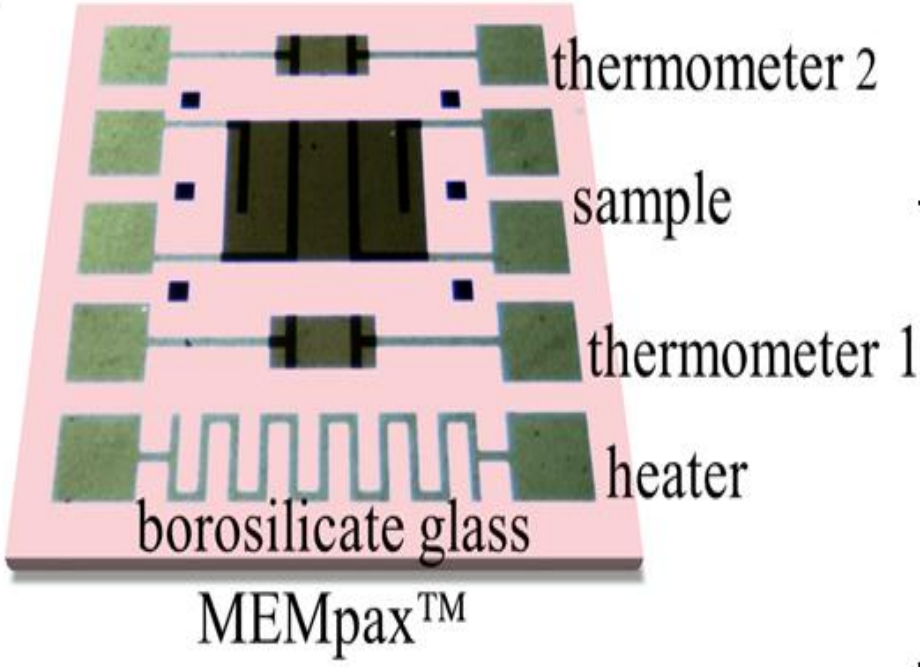


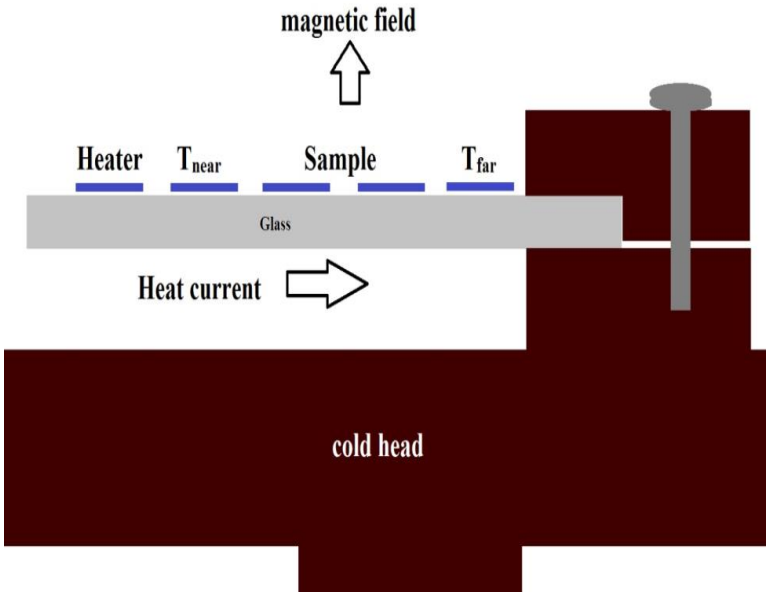
Nernst Effect



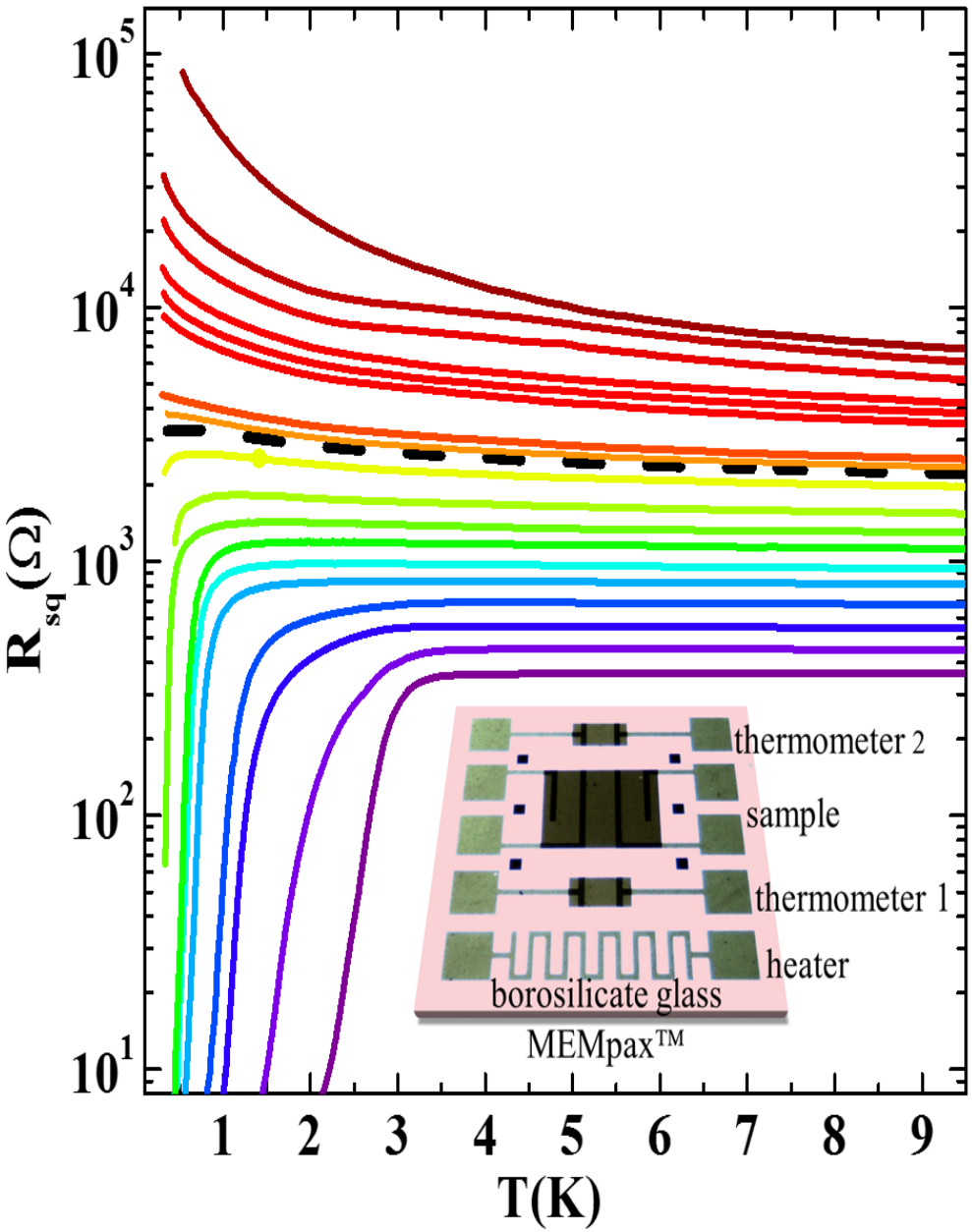


Experimental setup

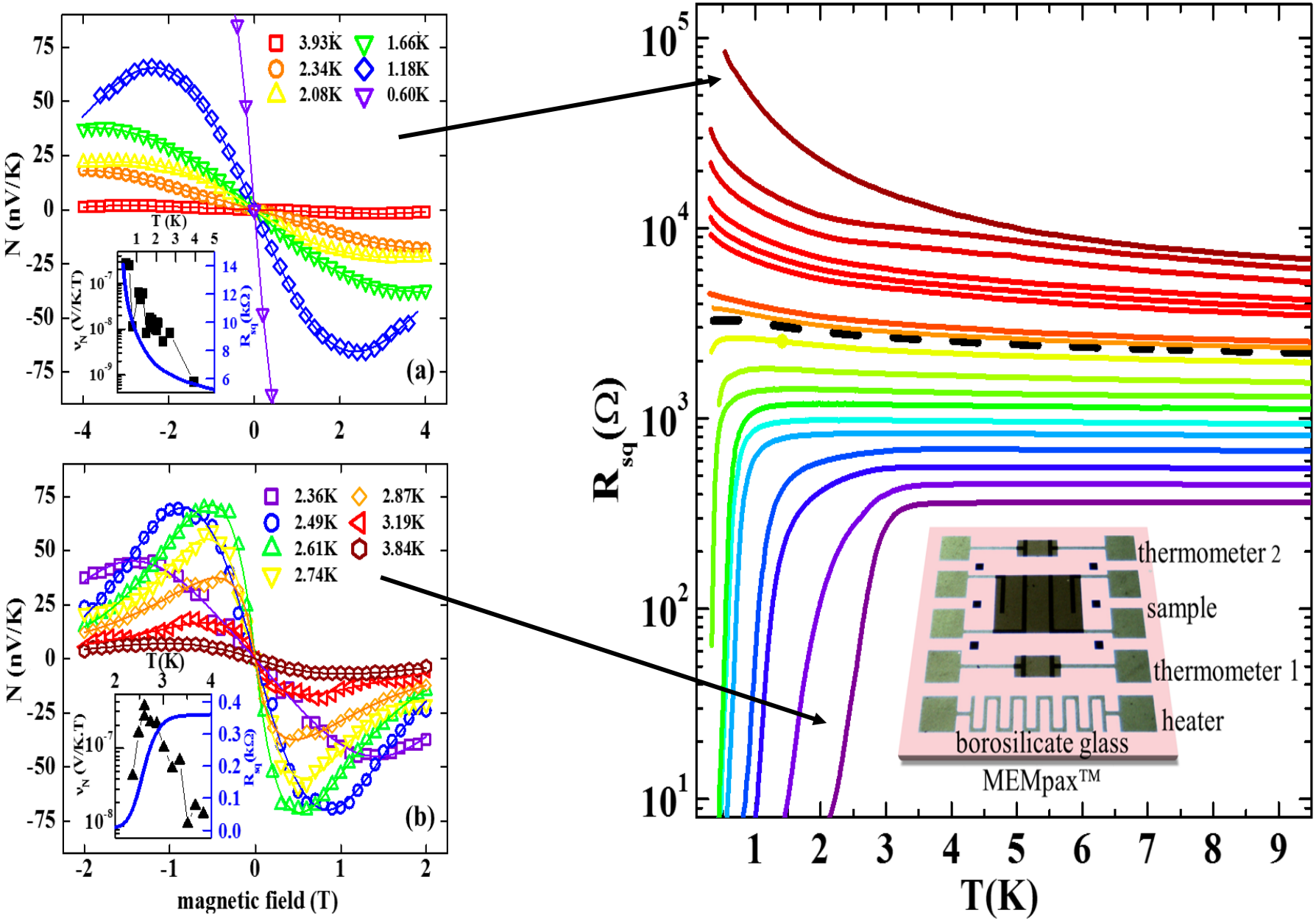




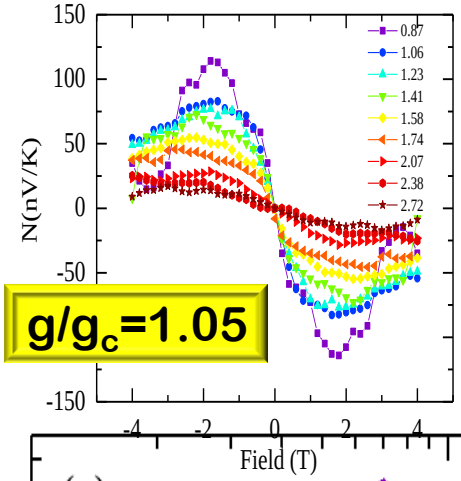
Nernst through the SIT



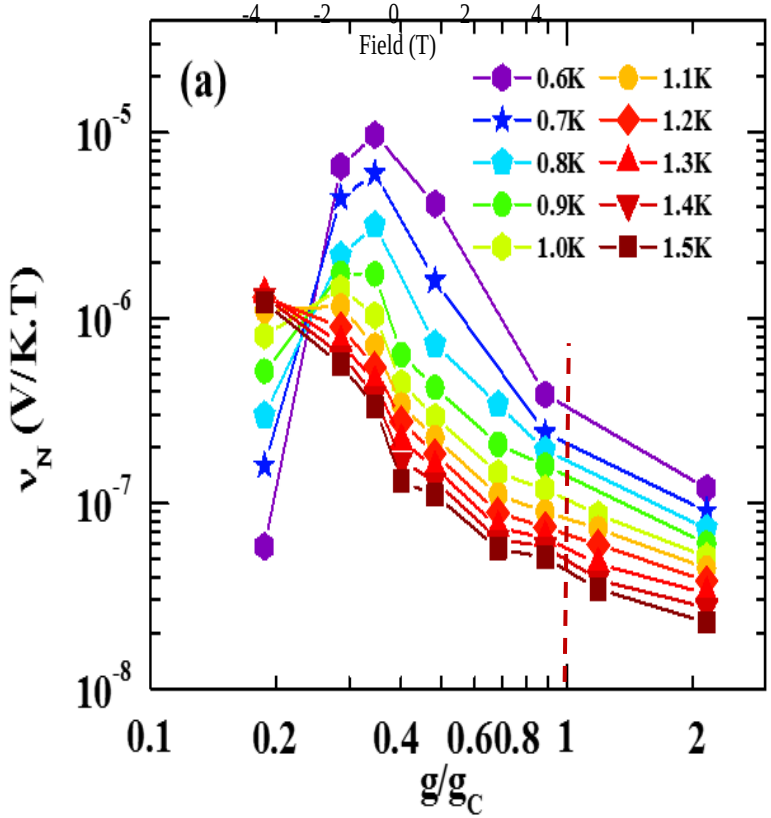
Nernst through the SIT

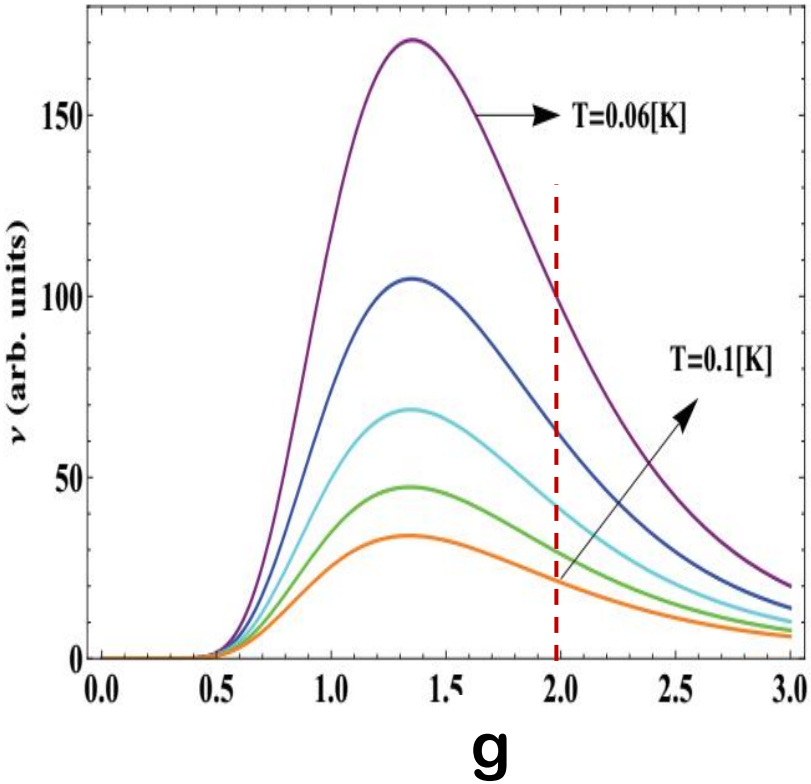


Nernst through the SIT



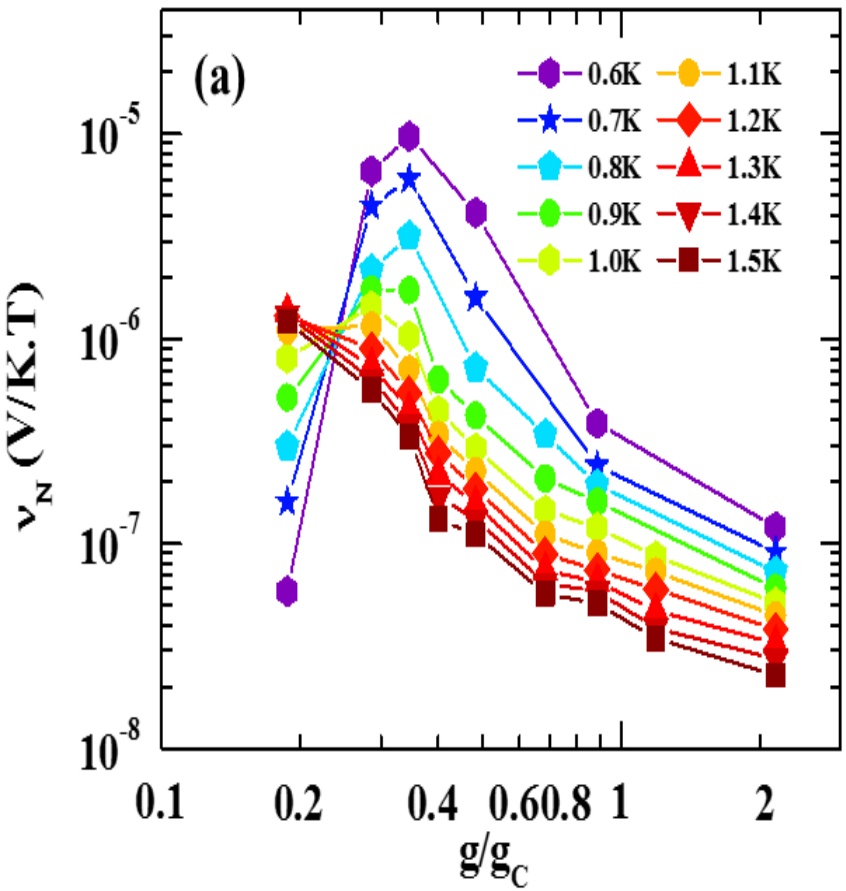
$$\nu \approx \frac{R_{xx}\alpha_{xy}}{B}$$

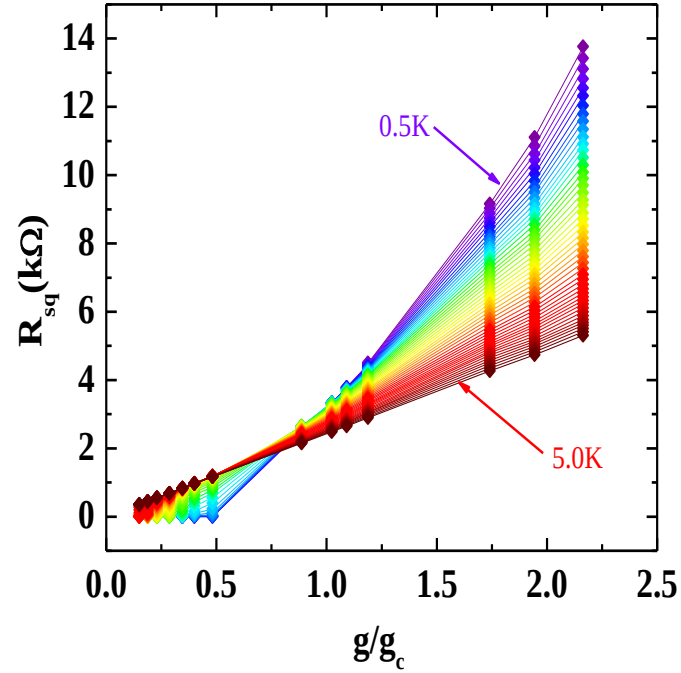


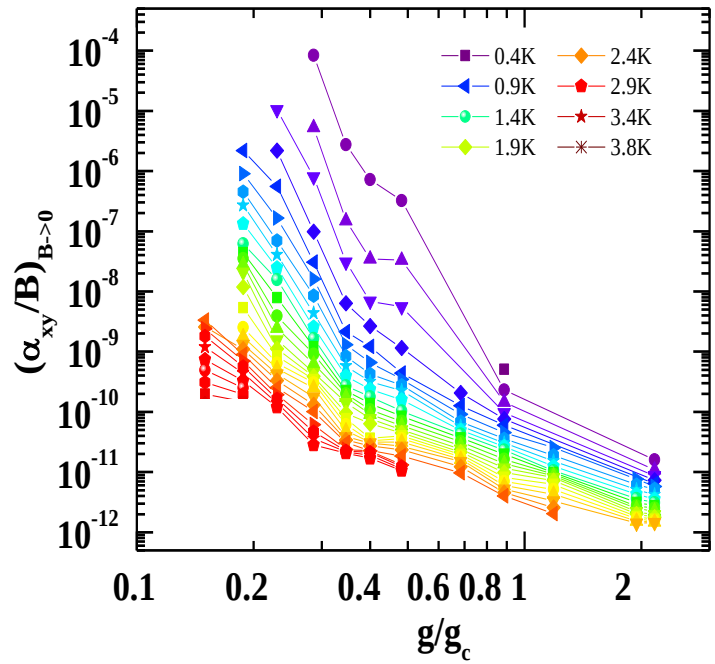


Atzmon and Shimshoni, PRB (2013)

$$\alpha_{xy}(T) = \frac{\nu(T)}{\rho_{xx}(T)}$$







Quantum Critical Scaling

$$[J_e] = [t]^{-1}[x]^{-(d-1)} \Rightarrow J_e \sim T^{1+(d-1)/z} F_e\left(\frac{B}{T^{2/z}}, \frac{\nabla T}{T^{1+1/z}}, \frac{|\Delta g|^{\nu}}{T^{1/z}}\right)$$

$$\alpha_{xy} = \frac{J_e^x}{\nabla_y T}$$

$$\Downarrow (d=2)$$

$$\boxed{\alpha_{xy} \sim \frac{B}{T^{2/z}} f_e\left(\frac{|\Delta g|^{\nu}}{T^{1/z}}\right)}$$

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$$[J_e] = [t]^{-1}[x]^{-(d-1)} \Rightarrow J_e \sim T^{1+(d-1)/z} F_e\left(\frac{B}{T^{2/z}}, \frac{\nabla T}{T^{1+1/z}}, \frac{|\Delta g|^{\nu}}{T^{1/z}}\right)$$

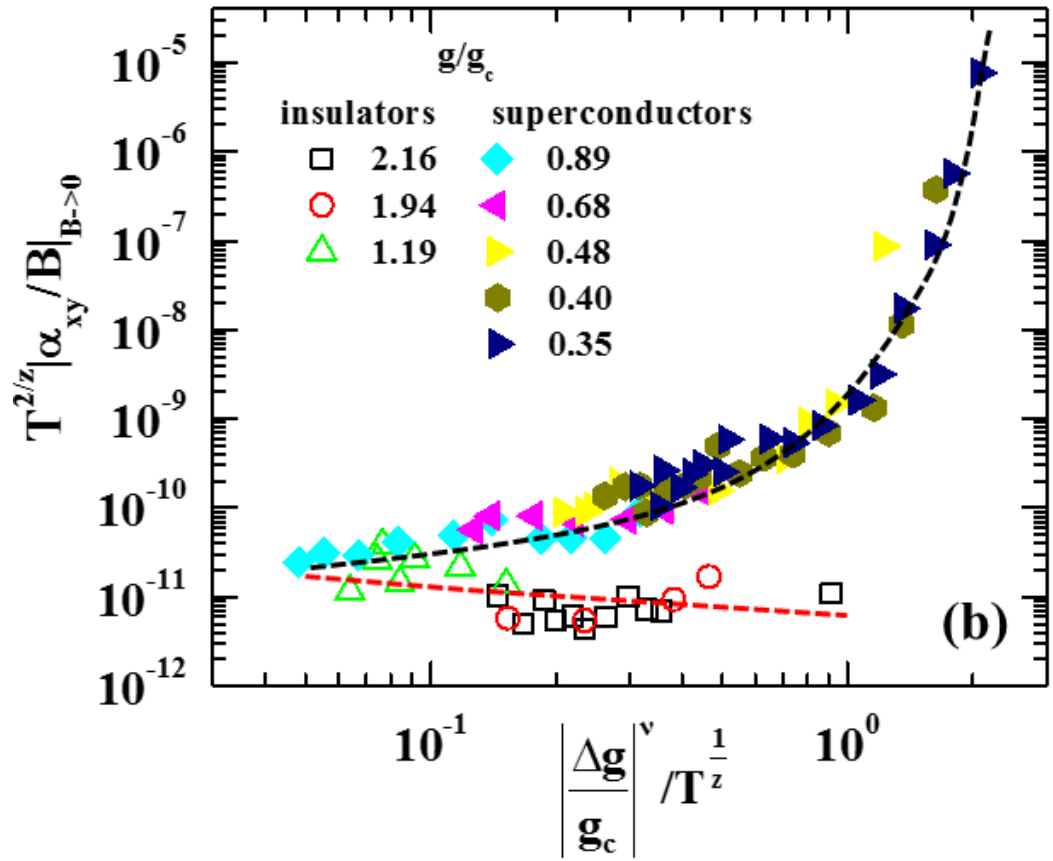
2+1D XY?

$\nu=0.7,\ z=1$

$$\alpha_{xy} = \frac{J_e^x}{\nabla_y T}$$

$$\Downarrow (d=2)$$

$$\boxed{\alpha_{xy} \sim \frac{B}{T^{2/z}} f_e\left(\frac{|\Delta g|^{\nu}}{T^{1/z}}\right)}$$



SUMMARY

- Quantum fluctuations lead to a measurable Nernst signal on both sides of the S-I transition
- A broad peak in ν near the quantum critical point: diamagnetism (vortex density) vs. resistance (vortex mobility) $\Rightarrow \nu \propto R_{xx}\alpha_{xy}$?
- Scaling analysis consistent with a clean (2+1)D XY-model