Particle-hole symmetry in the metallic phase of disordered 2D superconductors

Nicholas P. Breznay

3 August 2017
(Intertwined) Order, Fluctuations, and Strong Correlations
KITP / UCSB

Acknowledgments

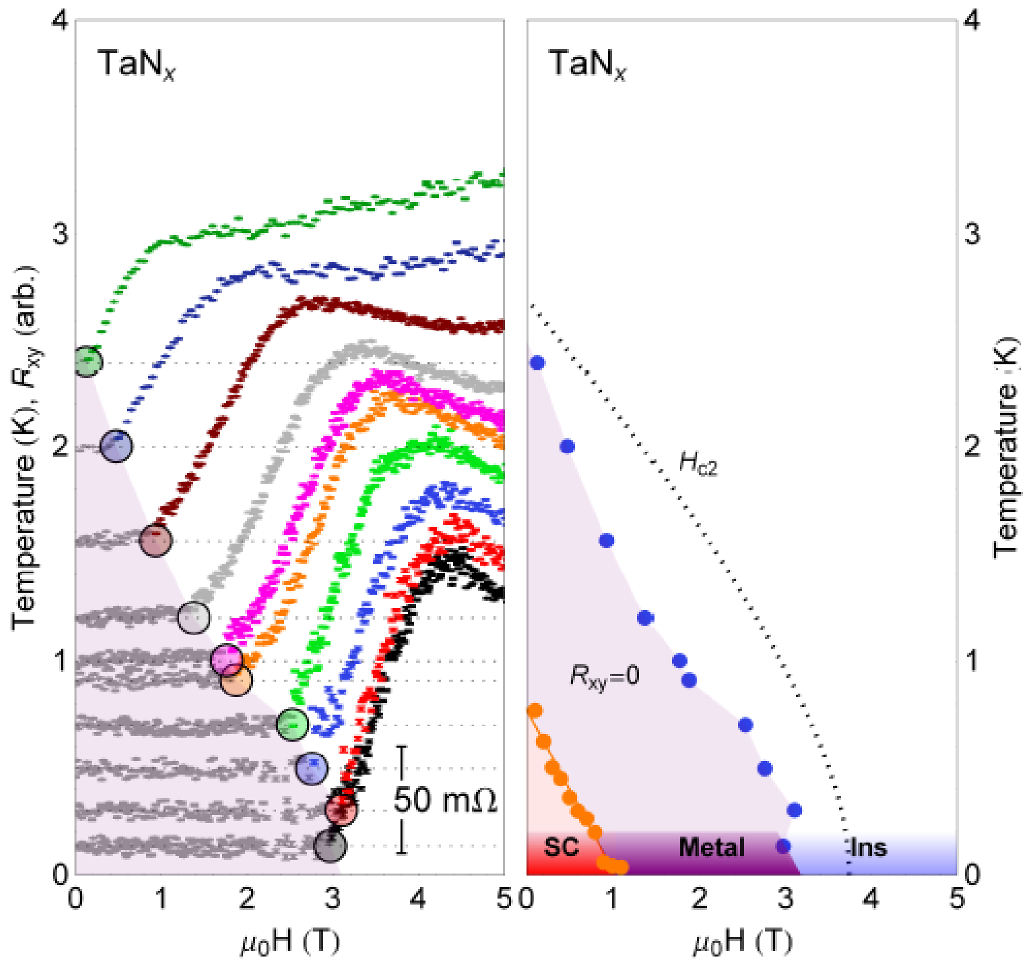
Aharon Kapitulnik
Stanford University

Myles Steiner
NREL

Mihir Tendulkar
Stanford University

Steven Kivelson
Stanford University

Punchline: ρ_{xy} evidence for a robust "failed SC" metal near the SIT



Particle-hole symmetry in the metallic phase near the SIT

(1) Motivation & Background

→ dogma: no metals in 2D
→ rich phase diagram of disordered 2D superconductors
→ trivial "quantum metal" at the SIT
→ weak insulators ($\rho \sim 1$ kOhm) show metallic behavior across all systems

(2) Key question

→ What does the metallic state near the SIT in weakly insulating films have to do with superconductivity?

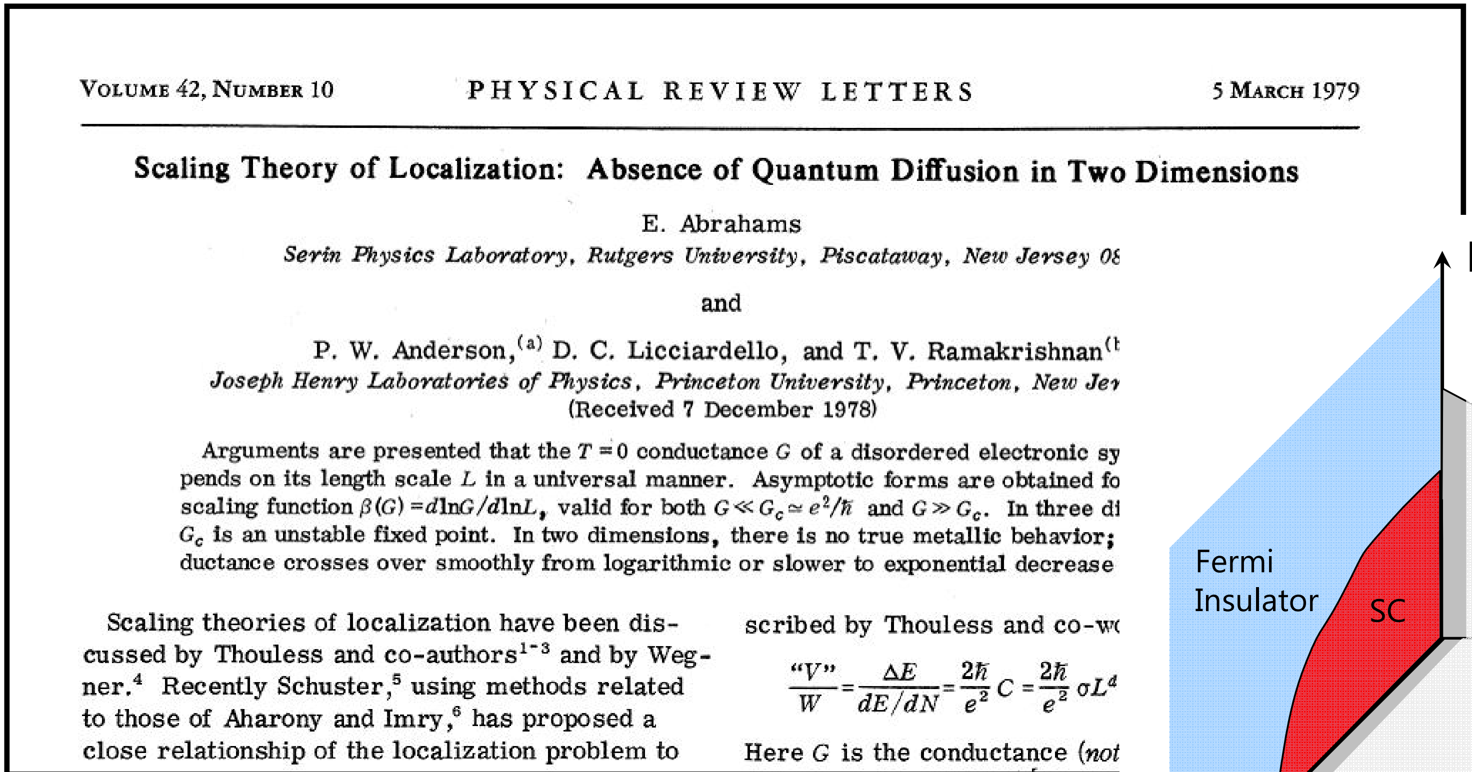
(3) Data on InO_x, TaN_x films

→ Characteristic fields from MR, Hall
→ Common behavior

(4) Phase diagram of weakly insulating 2D SC

→ PHS from "failed superconductivity" in the metallic phase
→ Other recent work

Quantum diffusion and the hunt for a 2D metal



VOLUME 42, NUMBER 10 PHYSICAL REVIEW LETTERS 5 MARCH 1979

Scaling Theory of Localization: Absence of Quantum Diffusion in Two Dimensions

E. Abrahams
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and

P. W. Anderson,[a] D. C. Licciardello, and T. V. Ramakrishnan[b
Joseph Henry Laboratories of Physics, Princeton University, Princeton, New Jer
(Received 7 December 1978)

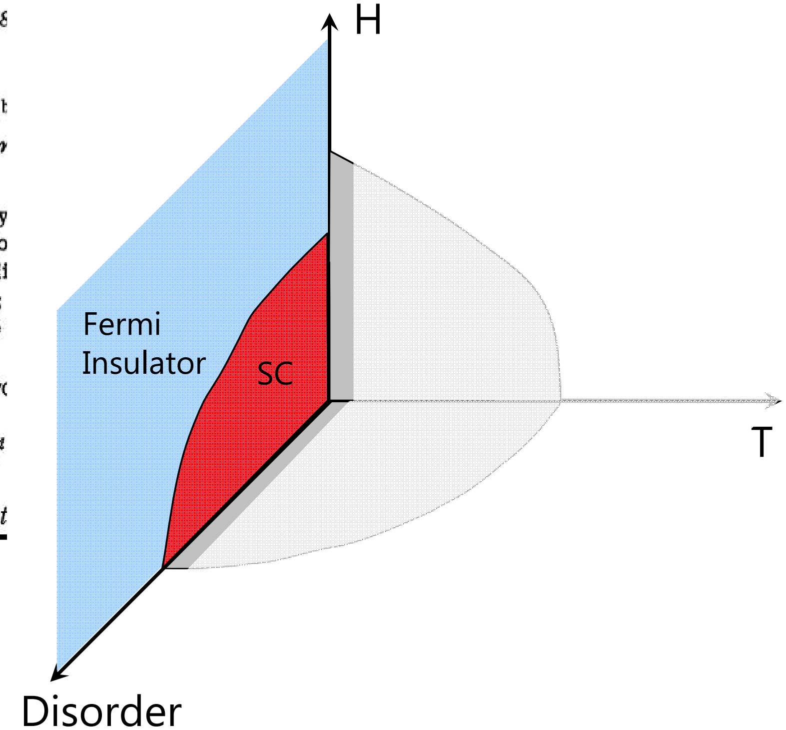
Arguments are presented that the $T=0$ conductance G of a disordered electronic sy pends on its length scale L in a universal manner. Asymptotic forms are obtained fo scaling function $\beta(G)=d\ln G/d\ln L$, valid for both $G \ll G_c \simeq e^2/\hbar$ and $G \gg G_c$. In three di G_c is an unstable fixed point. In two dimensions, there is no true metallic behavior; ductance crosses over smoothly from logarithmic or slower to exponential decrease

Scaling theories of localization have been discussed by Thouless and co-authors[1-3] and by Wegner.[4] Recently Schuster,[5] using methods related to those of Aharony and Imry,[6] has proposed a close relationship of the localization problem to

scribed by Thouless and co-w

$$\frac{``V"}{W} = \frac{\Delta E}{dE/dN} = \frac{2\hbar}{e^2} C = \frac{2\hbar}{e^2} \sigma L^{d}$$

Here G is the conductance (*not*



- Strict distinction between metals and insulators only valid at T = 0
- Interactions stabilize SC

Metallic “state” in presence of SC interactions

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VOLUME 64, NUMBER 5 PHYSICAL REVIEW LETTERS 29 JANUARY 1990

Presence of Quantum Diffusion in Two Dimensions: Universal Resistance at the Superconductor-Insulator Transition

Matthew P. A. Fisher and G. Grinstein
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Physics Department, Swain Hall West 117, Indiana University, Bloomington, Indiana 47405
(Received 17 November 1989)

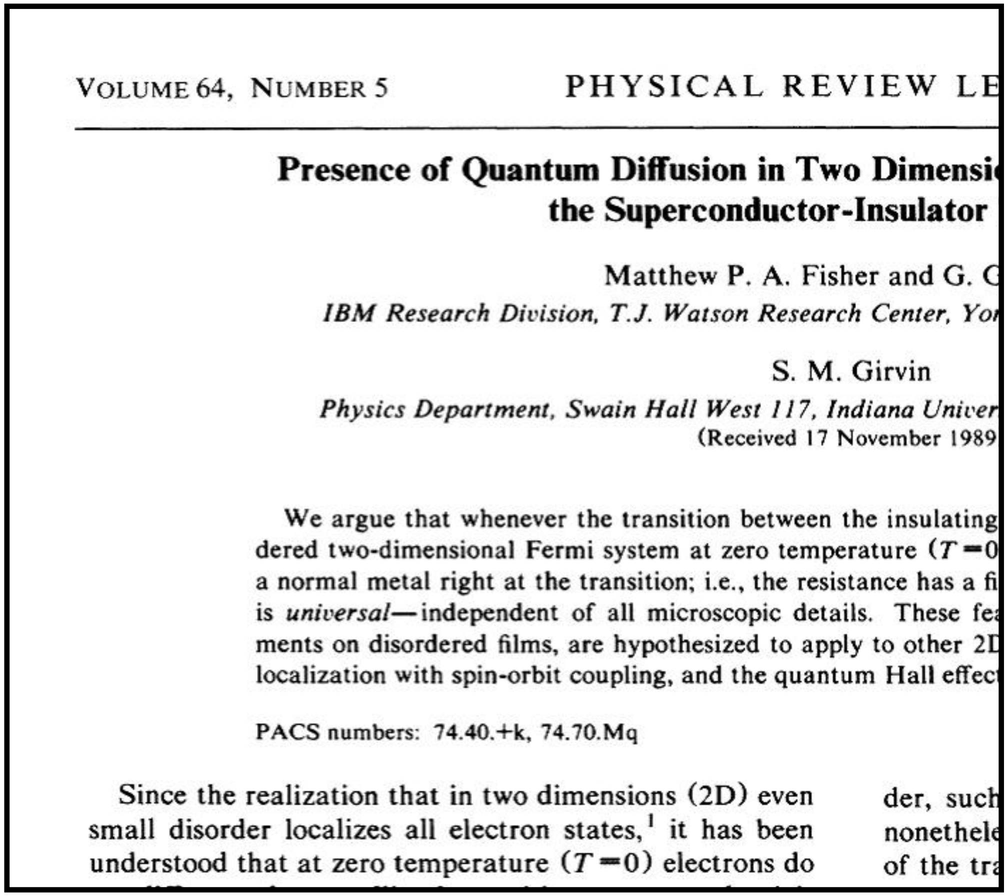
We argue that whenever the transition between the insulating and superconducting phases of a disordered two-dimensional Fermi system at zero temperature ($T=0$) is continuous, the system behaves like a normal metal right at the transition; i.e., the resistance has a finite, nonzero value at $T=0$. This value is *universal*—independent of all microscopic details. These features, consistent with recent measurements on disordered films, are hypothesized to apply to other 2D transitions at $T=0$, such as Anderson localization with spin-orbit coupling, and the quantum Hall effect.

PACS numbers: 74.40.+k, 74.70.Mq

Since the realization that in two dimensions (2D) even small disorder localizes all electron states,[1] it has been understood that at zero temperature ($T=0$) electrons do

der, such a description is clearly inadequate. It seems nonetheless likely that the asymptotic critical properties of the transition are insensitive to the obvious difference

A Bose metal at the SIT critical point



VOLUME 64, NUMBER 5 PHYSICAL REVIEW LE

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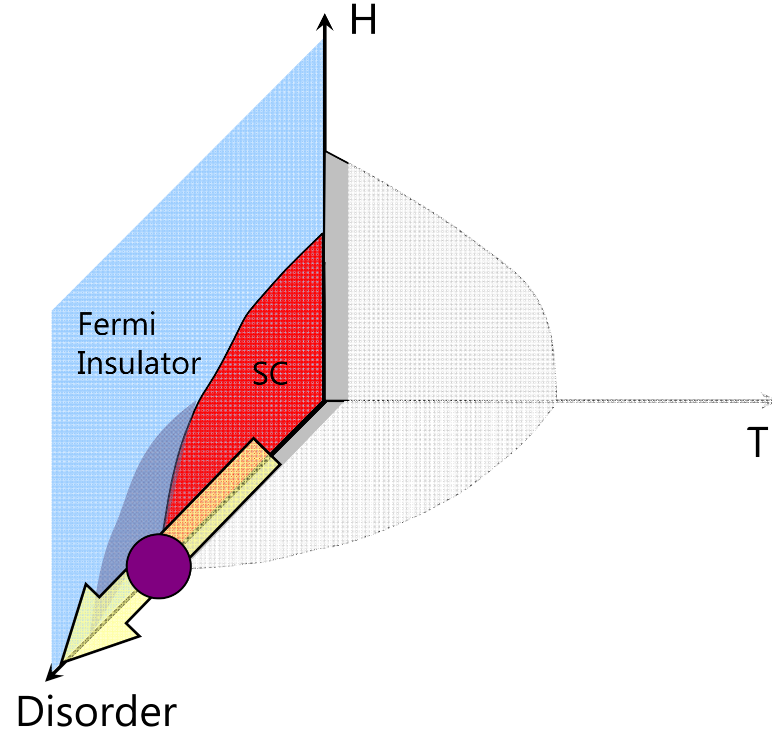
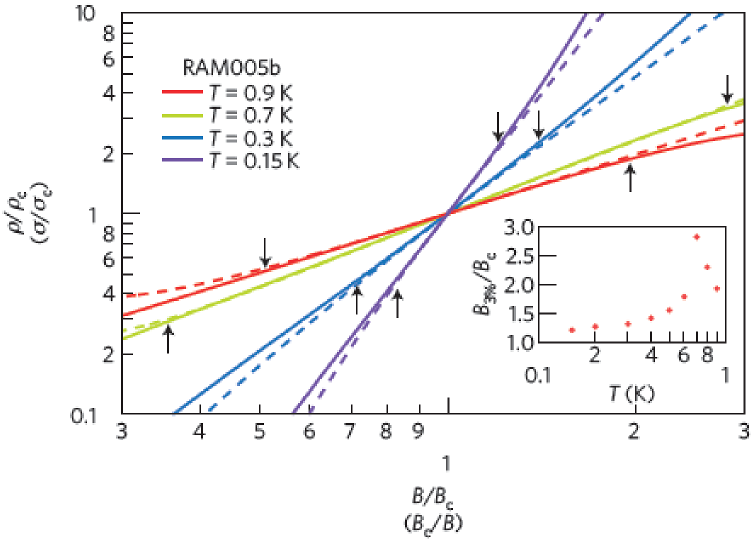


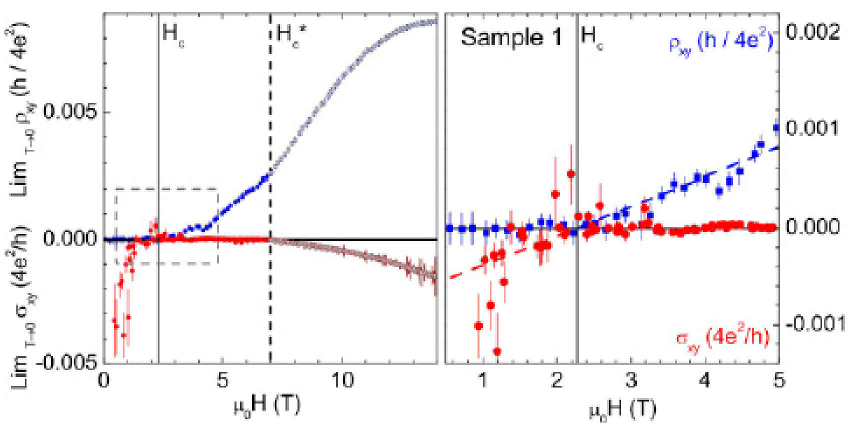
- Fisher proposes a metallic point separating SC, (Bose) insulator

Goldman and Markovic, Phys. Tod. (1998)

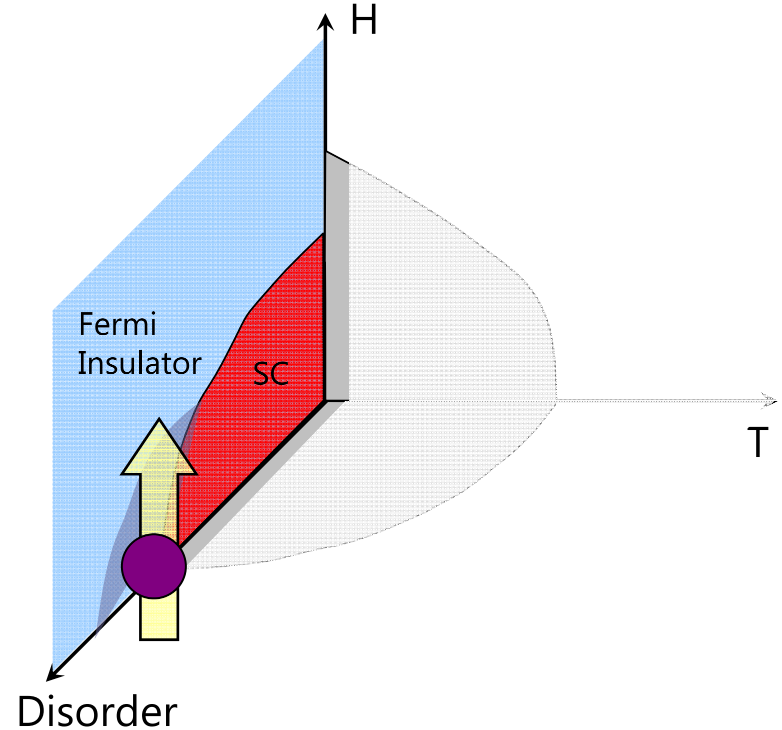
A Bose metal at the (dual) SIT critical point



Ovadia, Shahar Nat. Phys. (2013)



NPB, M. A. Steiner, S. A. Kivelson, A. Kapitulnik PNAS (2016)

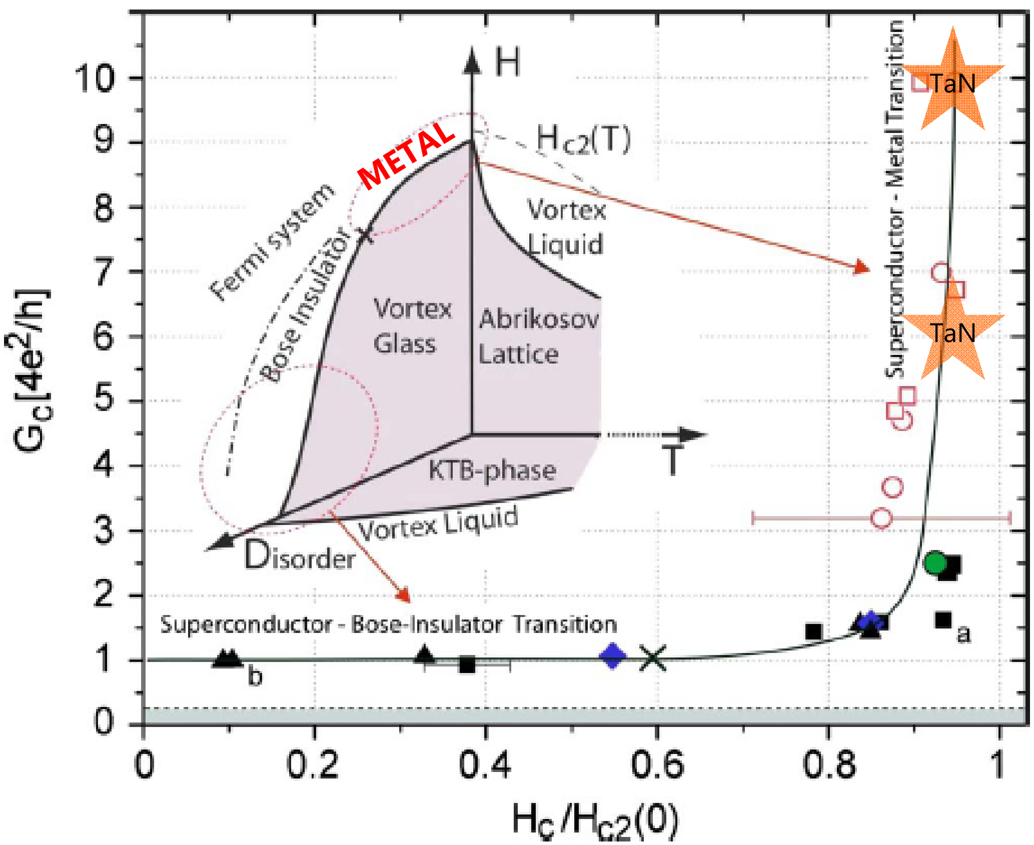


- Fisher proposes a metallic ‘point’ separating SC, insulator
- Dirty bosons description (self-dual → ρ_c ~ $h/4e^2$, scaling)

Goldman and Markovic, Phys. Tod. (1998)

Unified phenomenology in the strong, weak disorder limits

- Regimes of behavior for TiN, InOx, Ta, MoGe, TaN_x, …
- Characterized by behavior near the breakdown of SC: G_c, H_c, scaling, **metal**



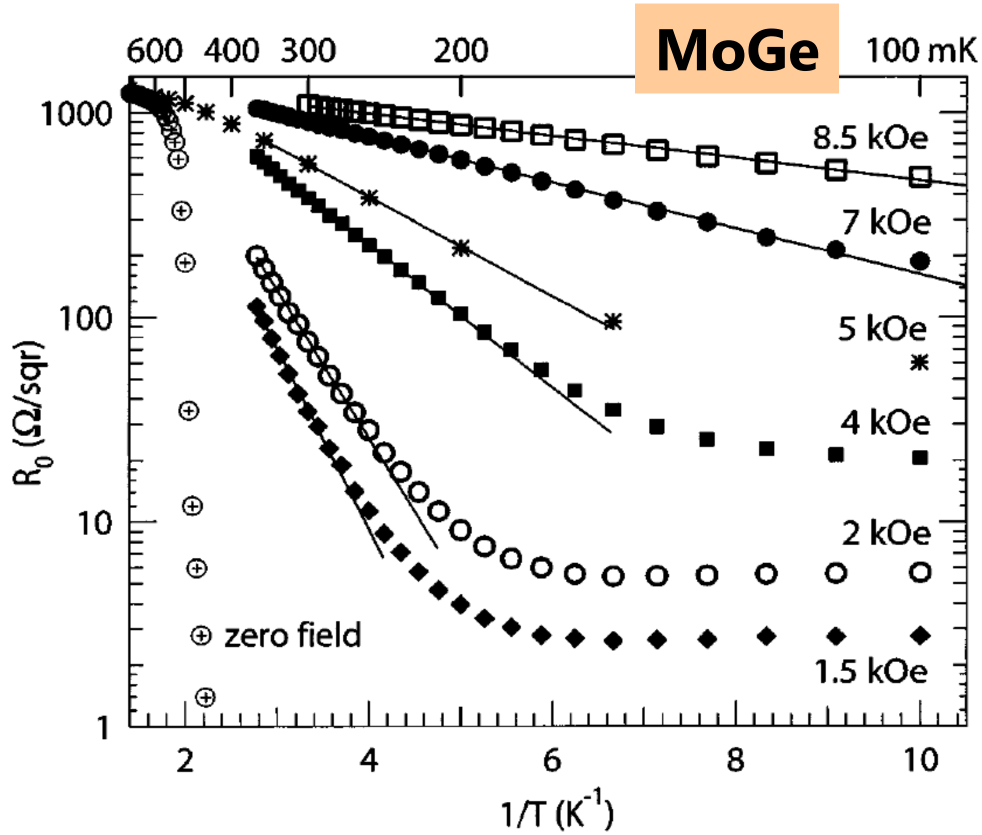
Steiner NPB Kapitulnik *PRB* **77** 212501 (2008)

Metallic state - Ephron et al. (1996)

- ρ_{xx} ~ 1.35 kΩ , T_C ~ 0.5 K
- Activated behavior at high T:

$$R(T) = R_0 \exp(T_0 / T)$$

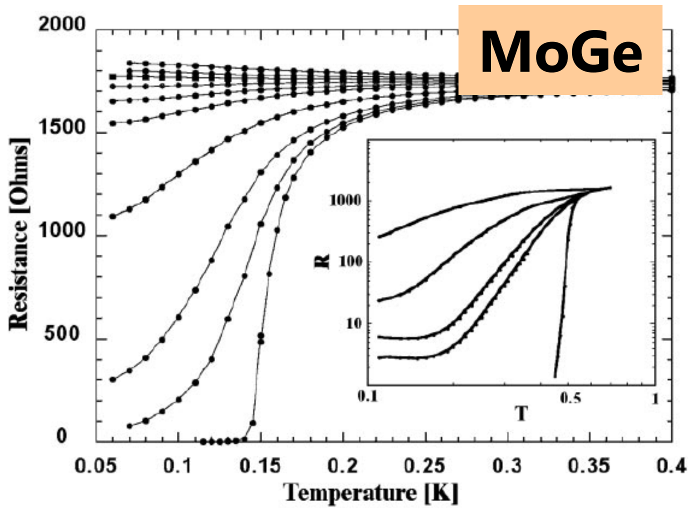
… disappears at low T!



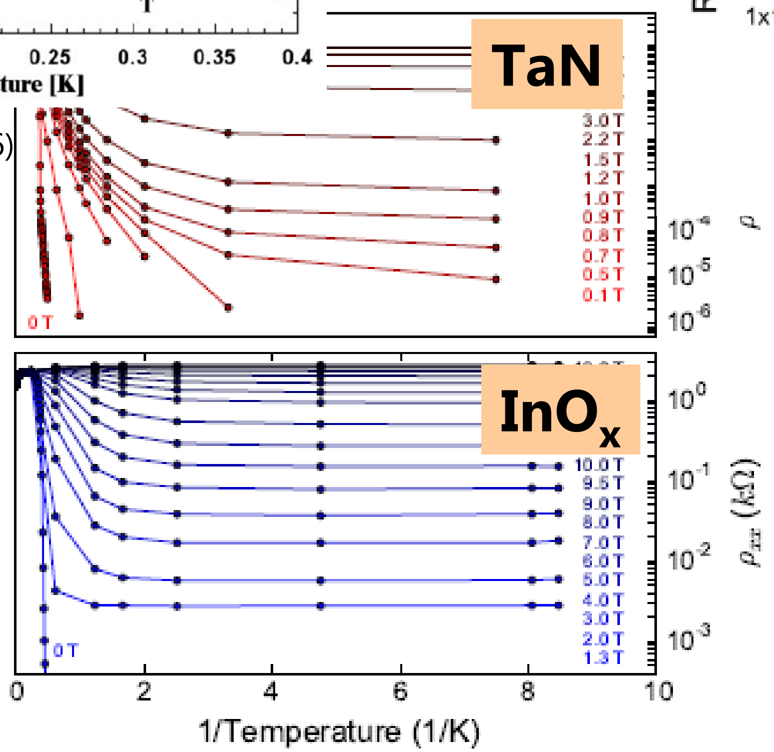
"… we do not exclude the possibility of a novel quantum mechanical process or phase lurking behind our lowest temperature data."

Ephron Yazdani Kapitulnik Beasley *PRL* **79** 1529 (1996)

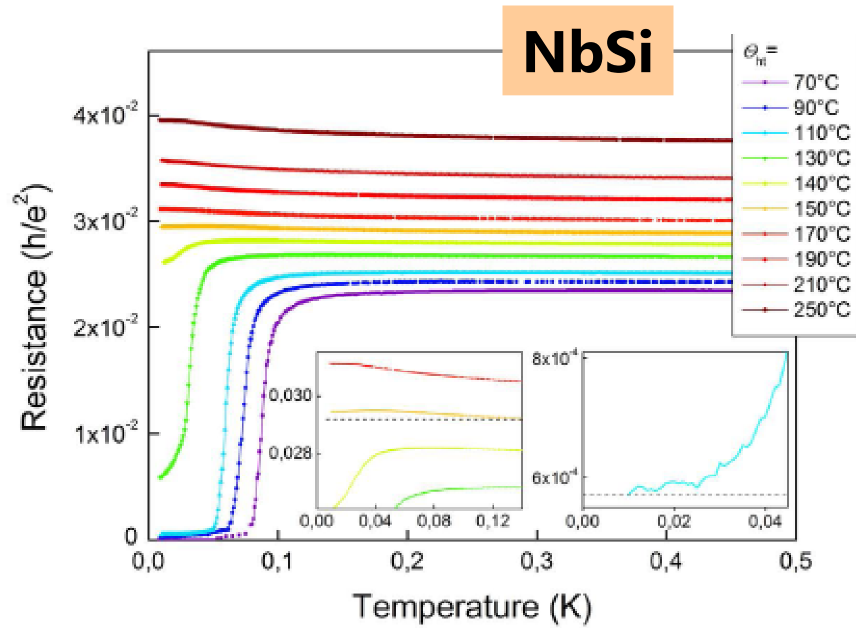
Metallic state – Amorphous metal alloy films

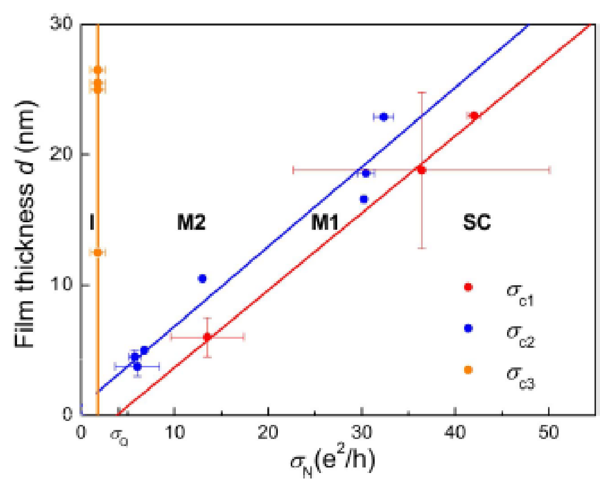


Yazdan &, Kapitulnik *(*1996)
Mason & Kapitulnik (1999, 2000, 2002)



NPB, A. Kapitulnik *(*2017)

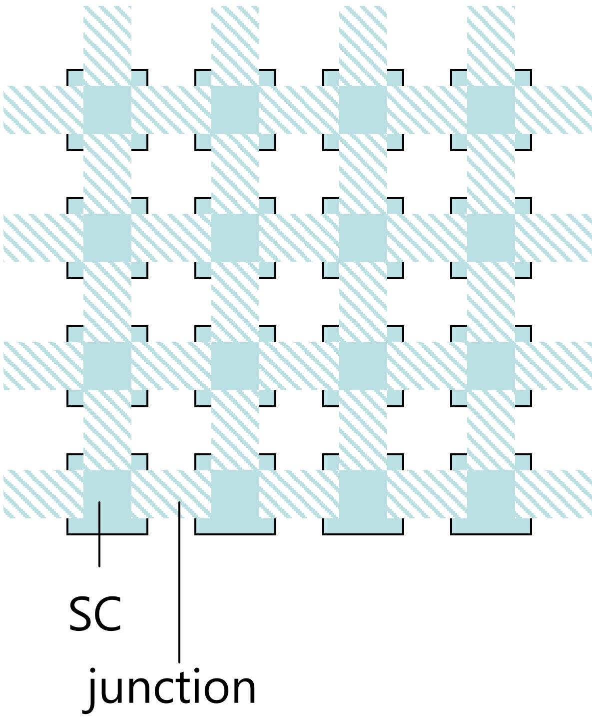


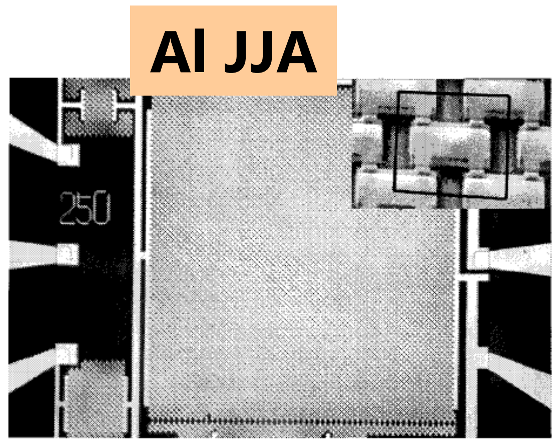


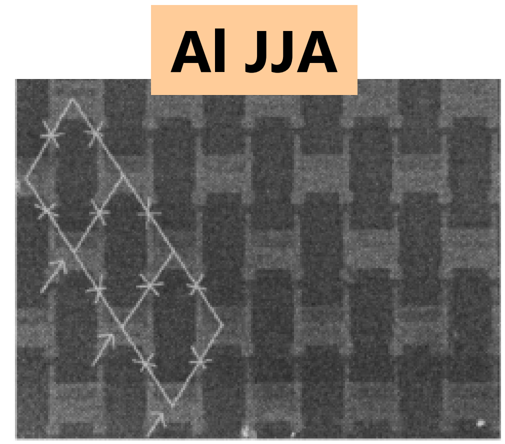
F. Couedo et al. *Sci. Rep.* *(*2016)

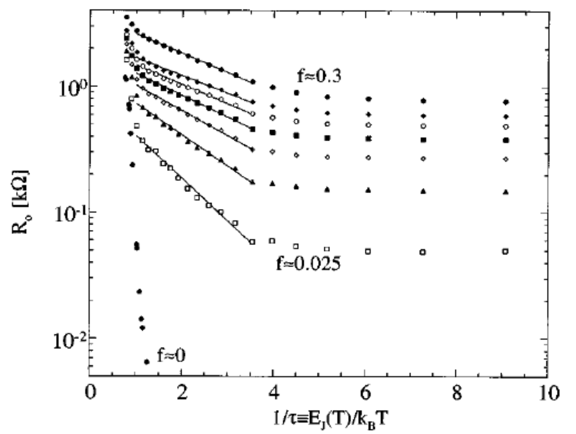
Metallic state – Josephson Junction Arrays

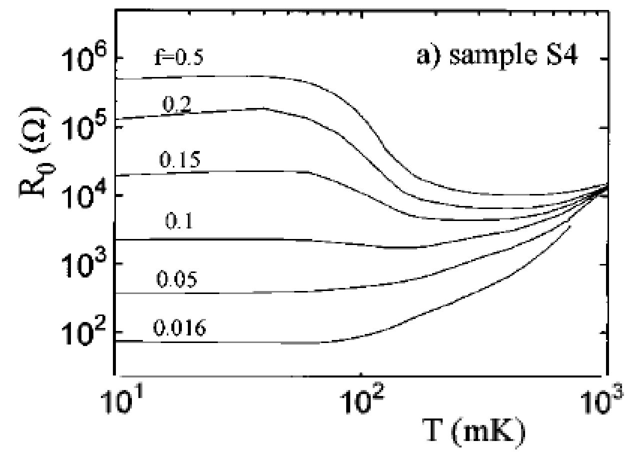
- Same universality class as thin-film SIT





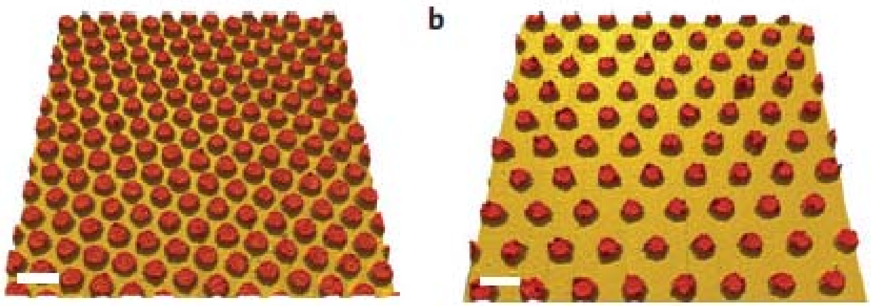


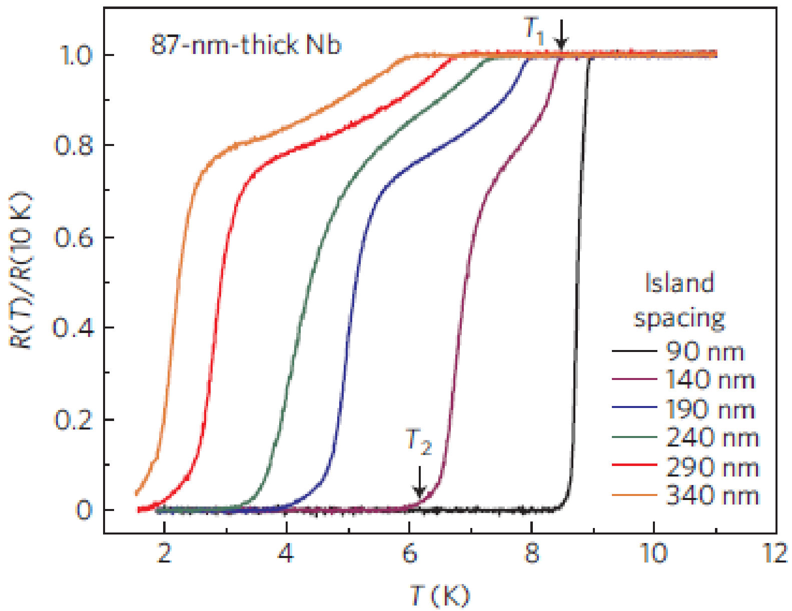




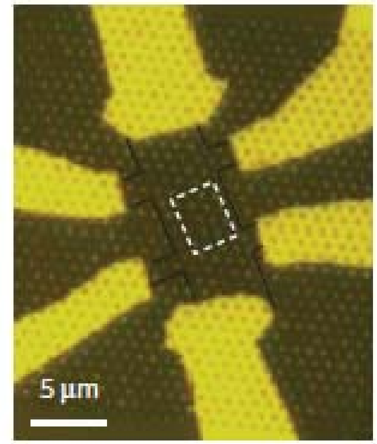
C. D. Chen et al. *PRB* 54 9449 (1996) van der Zant et al. *PRB* 54 10081 (1996)

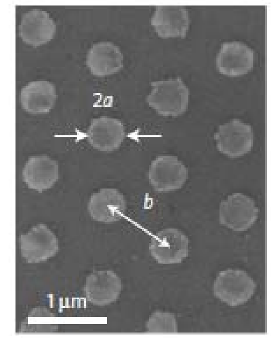
Nb on Au

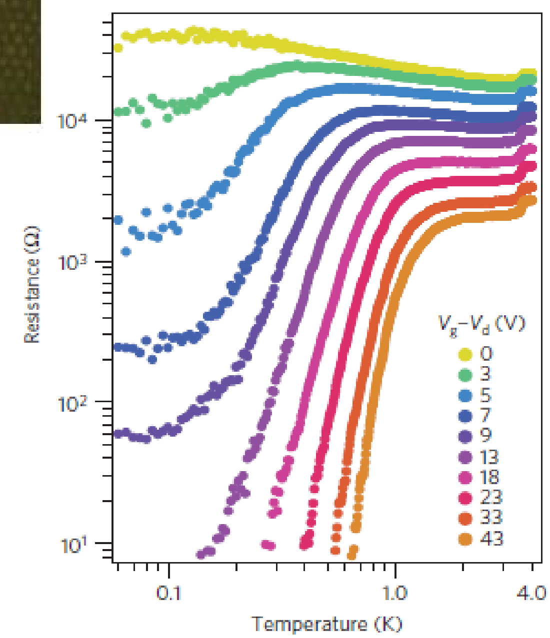




Sn on graphene



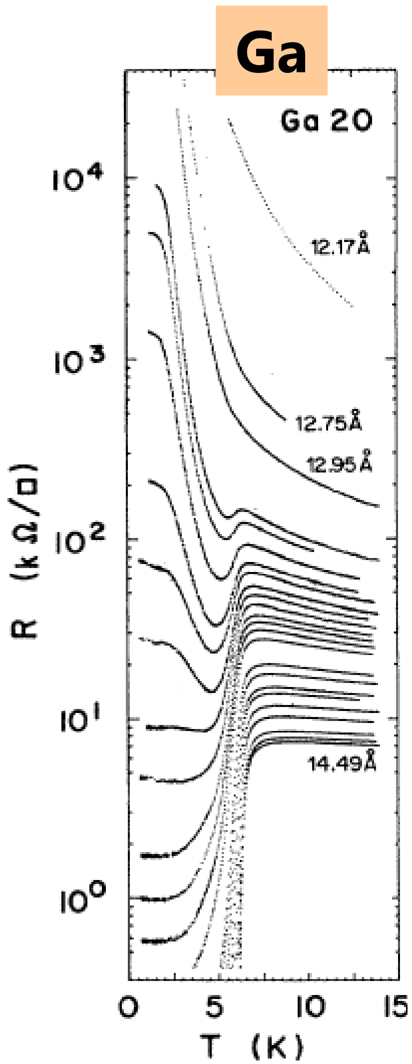


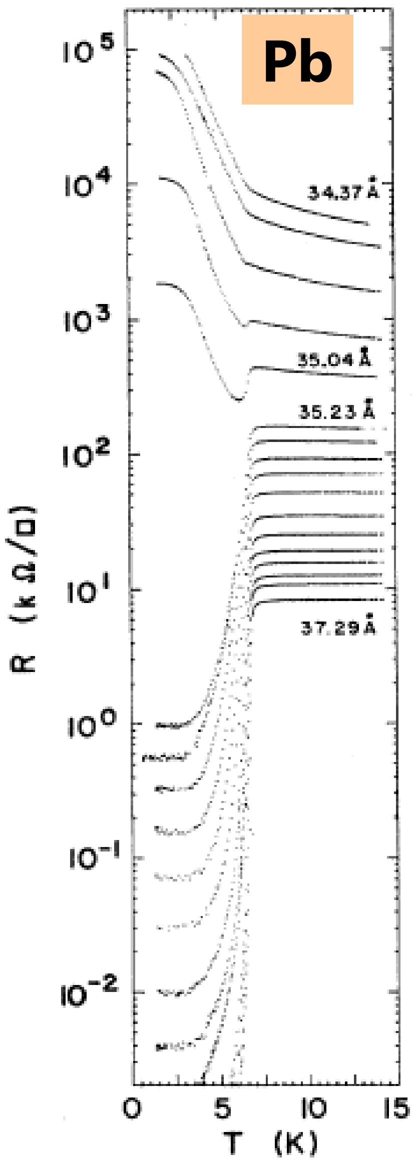


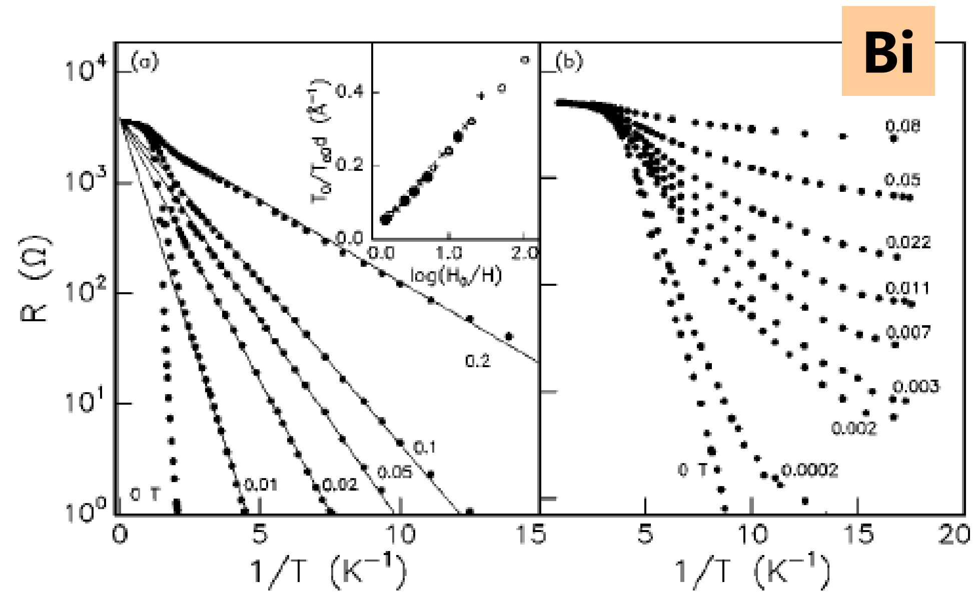
S. Eley, N. Mason et al. *Nature Physics* (2011)

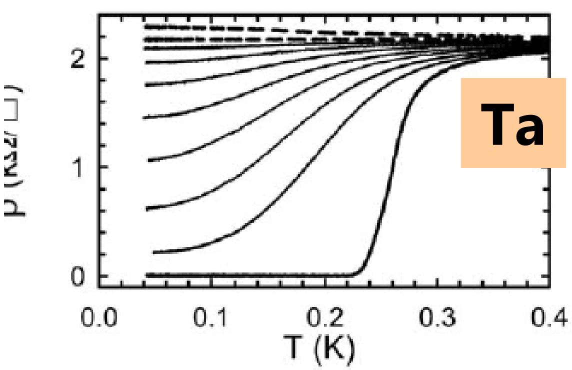
Z. Han et al. *Nature Physics* (2014)

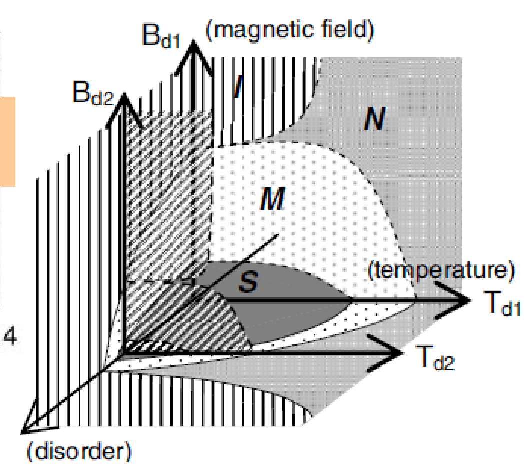
Metallic State – Elemental / granular metals





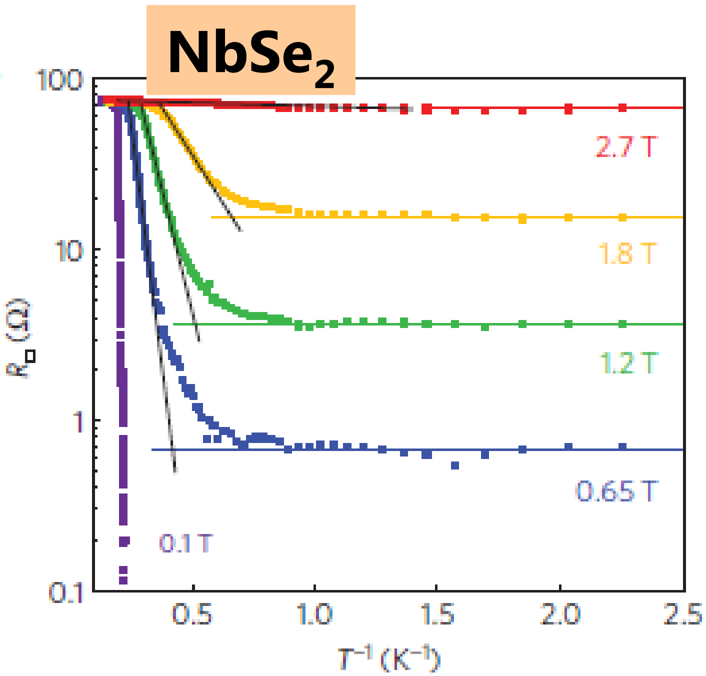


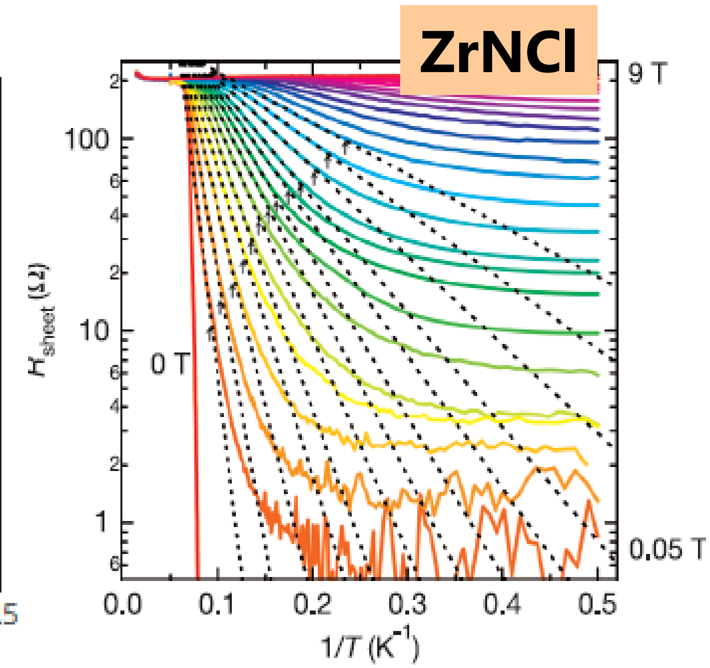


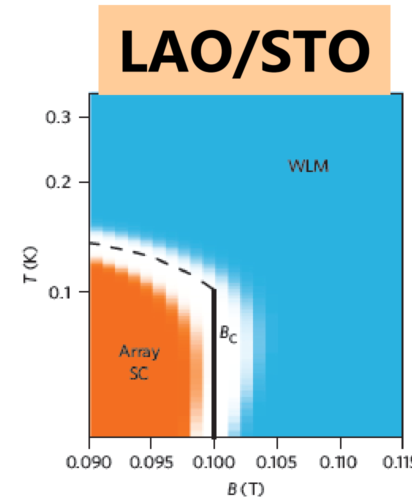


H. M. Jaeger et al. *PRB* 40, 182 (1989)   Y. Li, J. Yoon et al. *PRB* 81 020505 (2010)   J. A. Chervenak, J. M. Valles *PRB* 61 R9245 (2000)

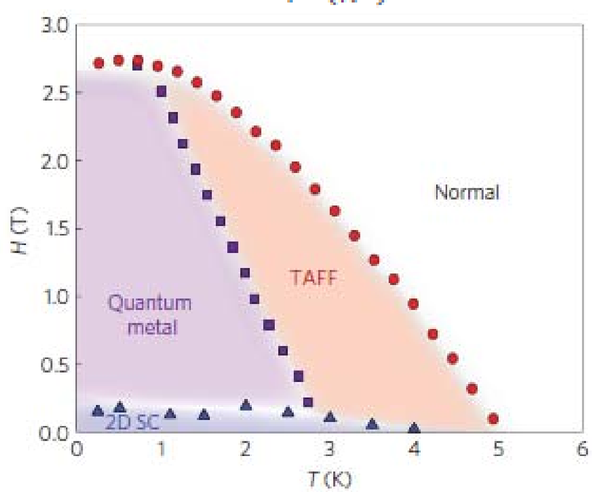
Metallic State – Crystalline materials (~100 Ω)

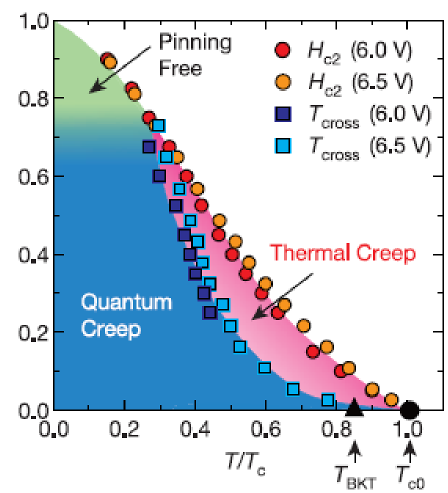


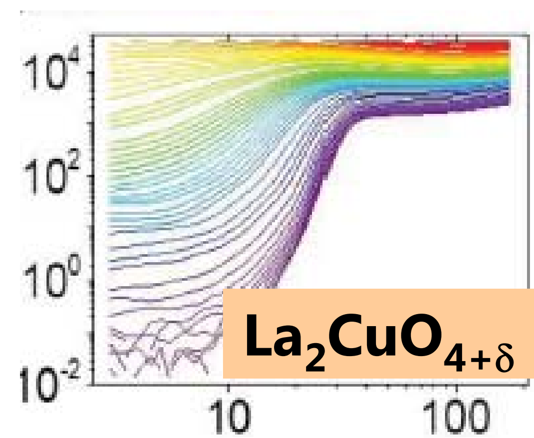




J. Biscaras et al. *Nat. Mat.* 12 (2013)







J. Garcia-Barriocanal, A. M. Goldman et al. Phys. Rev. B **87**, 024509 (2013)

A. W. Tsen, A. Pasupathy et al. *Nature Physics* (2016)

Y. Saito, Y. Iwasa et al. *Science* (2015)

Particle-hole symmetry in the metallic phase near the SIT

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→ rich phase diagram of disordered 2D superconductors
→ trivial "quantum metal" at the SIT
→ weak insulators (ρ ~ 1 kOhm) show metallic behavior across all systems

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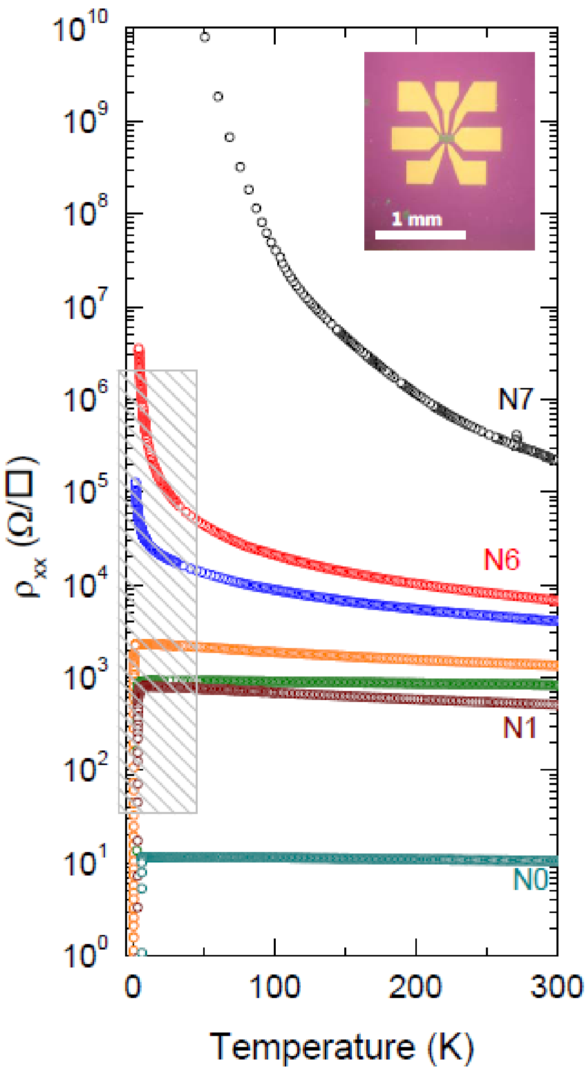
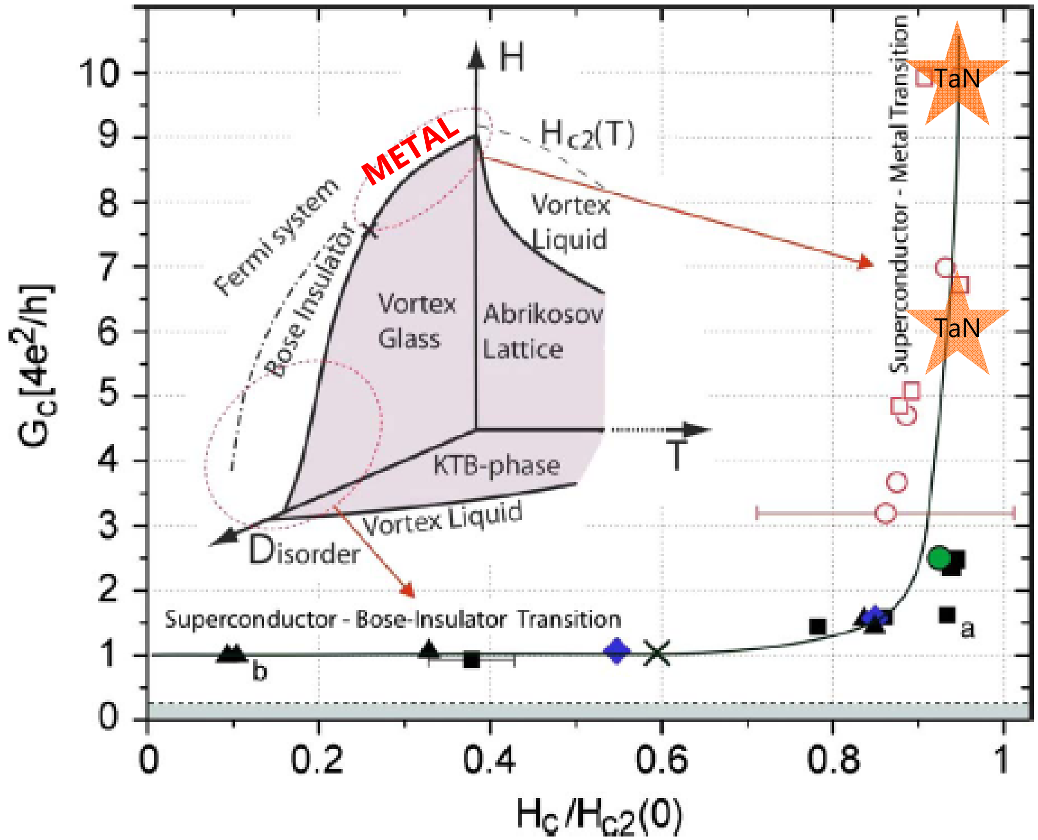
→ What does the metallic state near the SIT in weakly insulating films have to do with superconductivity?

(3) Data on InO_x, TaN_x films
→ Characteristic fields from MR, Hall
→ Common behavior

(4) Phase diagram of weakly insulating 2D SC
→ PHS from "failed superconductivity" in the metallic phase
→ Recent finite-frequency studies

Disorder and field-tuned SIT in Tantalum Nitride





NPB, M. Tendulkar, L. Zhang, S.-C. Lee, A. Kapitulnik (arXiv:1705.01732)

Steiner NPB Kapitulnik *PRB* **77** 212501 (2008)

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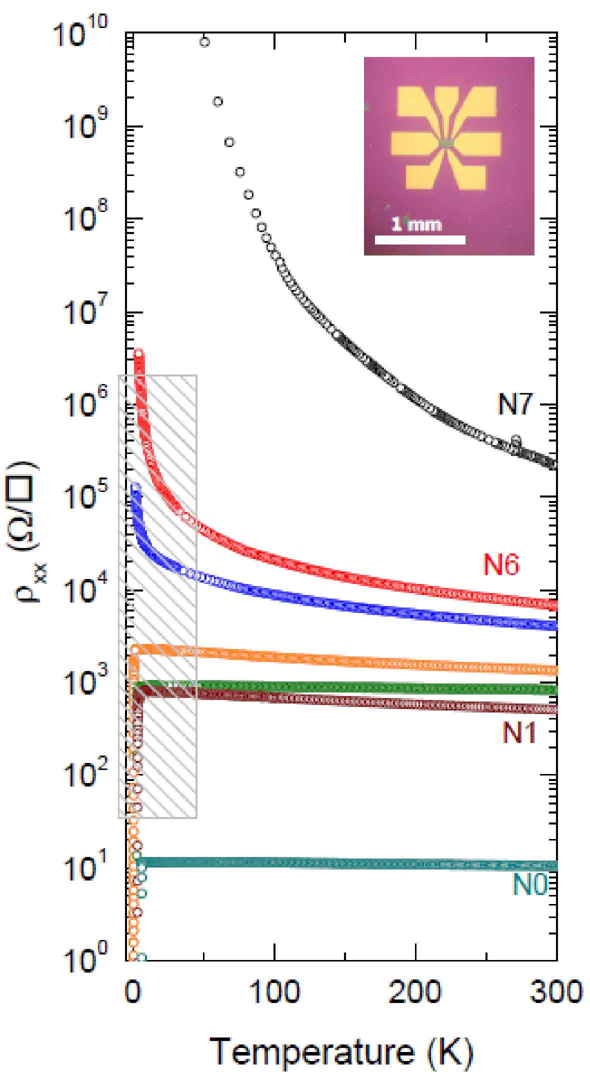
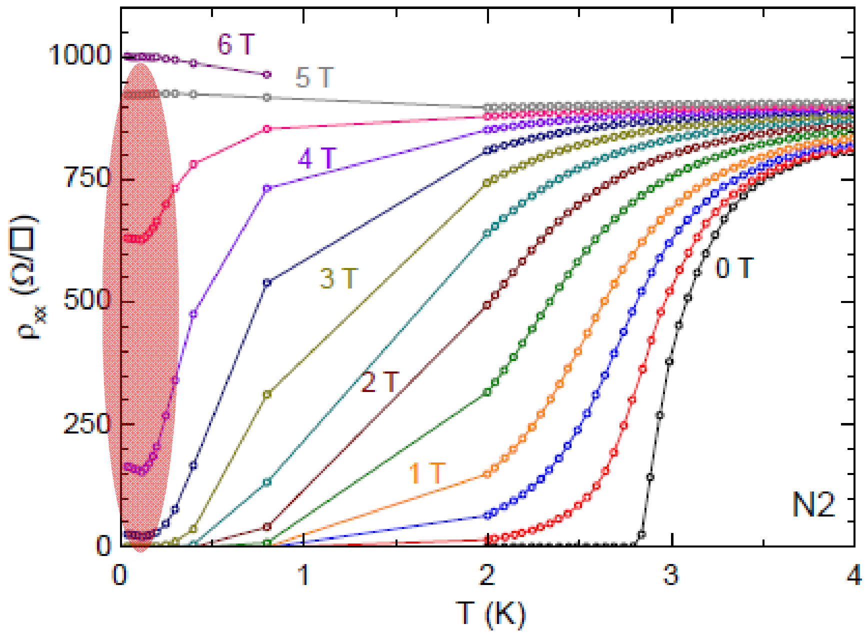
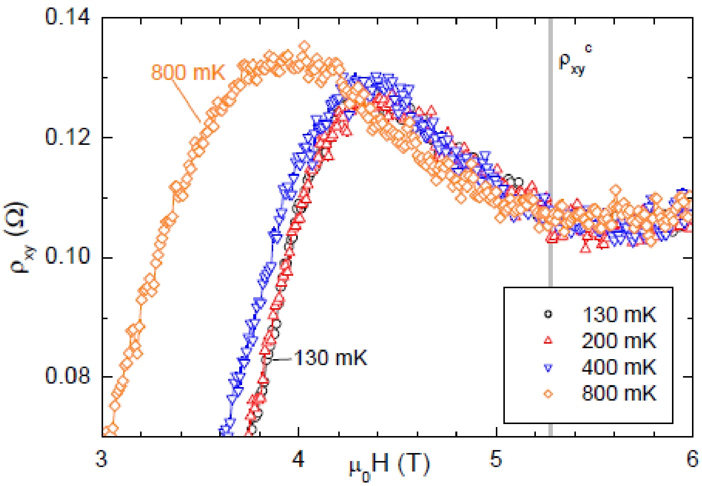


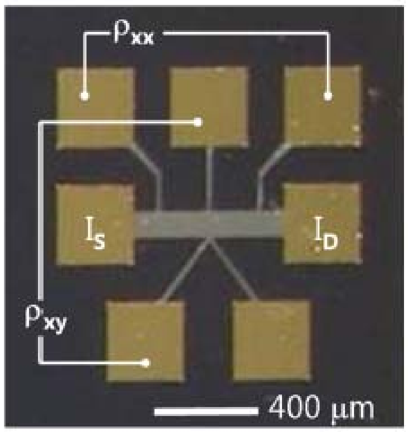


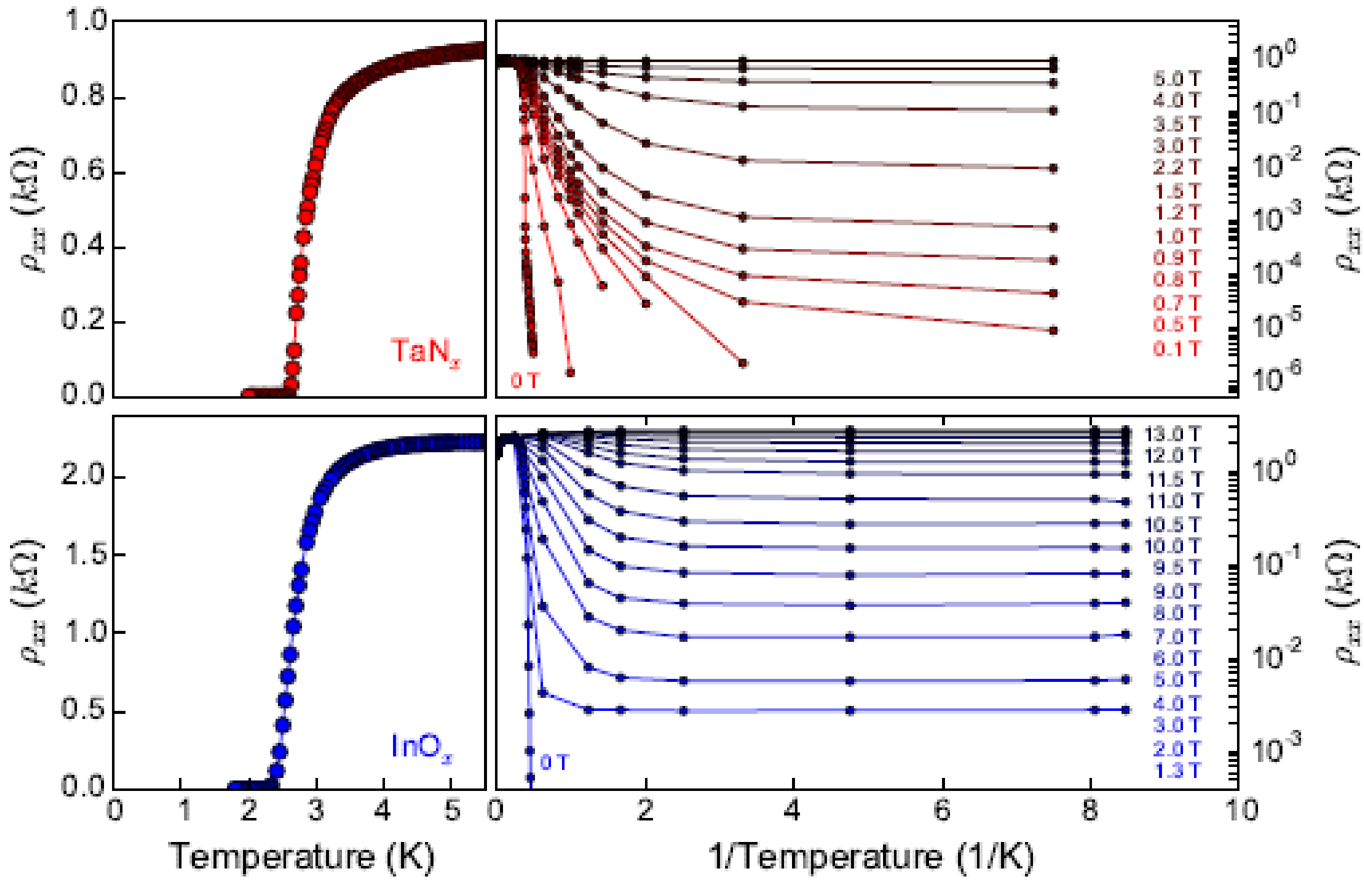


NPB, M. Tendulkar, L. Zhang, S.-C. Lee, A. Kapitulnik (arXiv:1705.01732)

Results – evidence for metallic saturation in two materials

- Two amorphous materials proximal to the SIT: TaN_x, InO_x





N. P. Breznay & A. Kapitulnik (2017)

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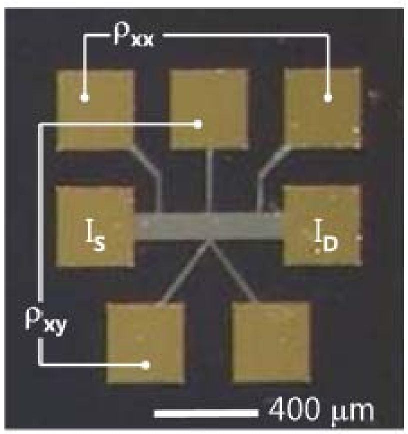
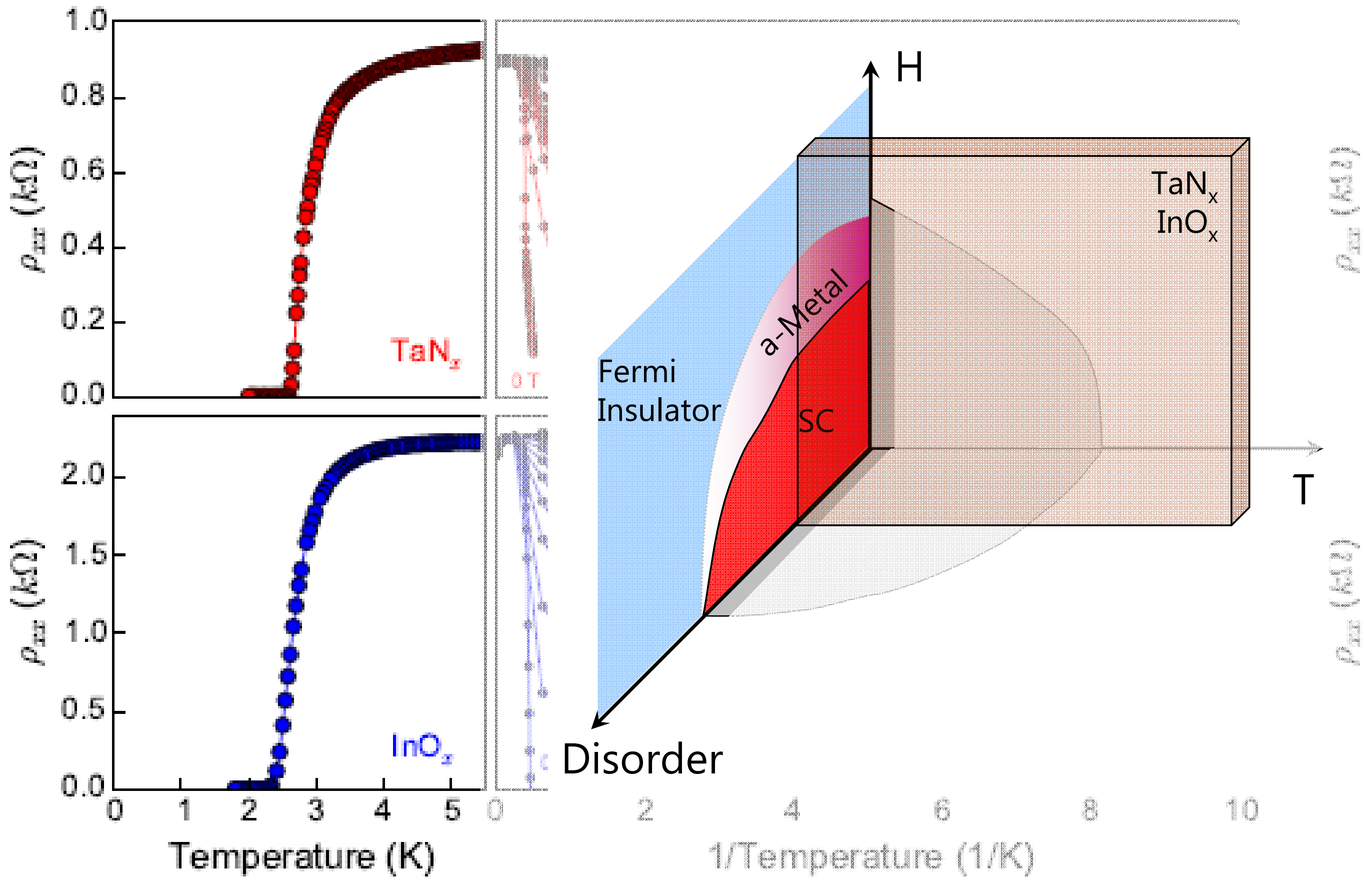
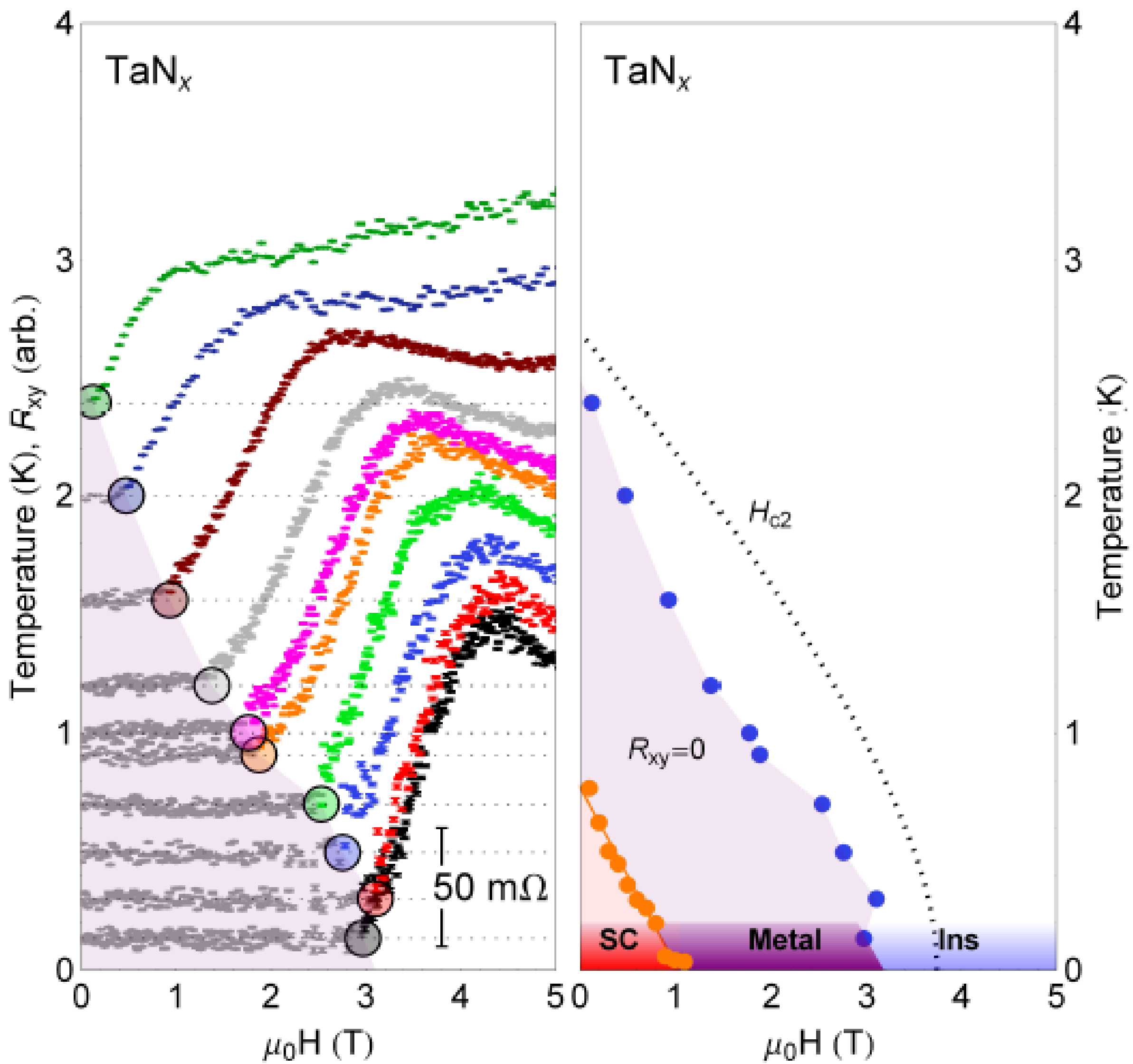




N. P. Breznay & A. Kapitulnik (2017)

Zero Hall effect in TaN_x

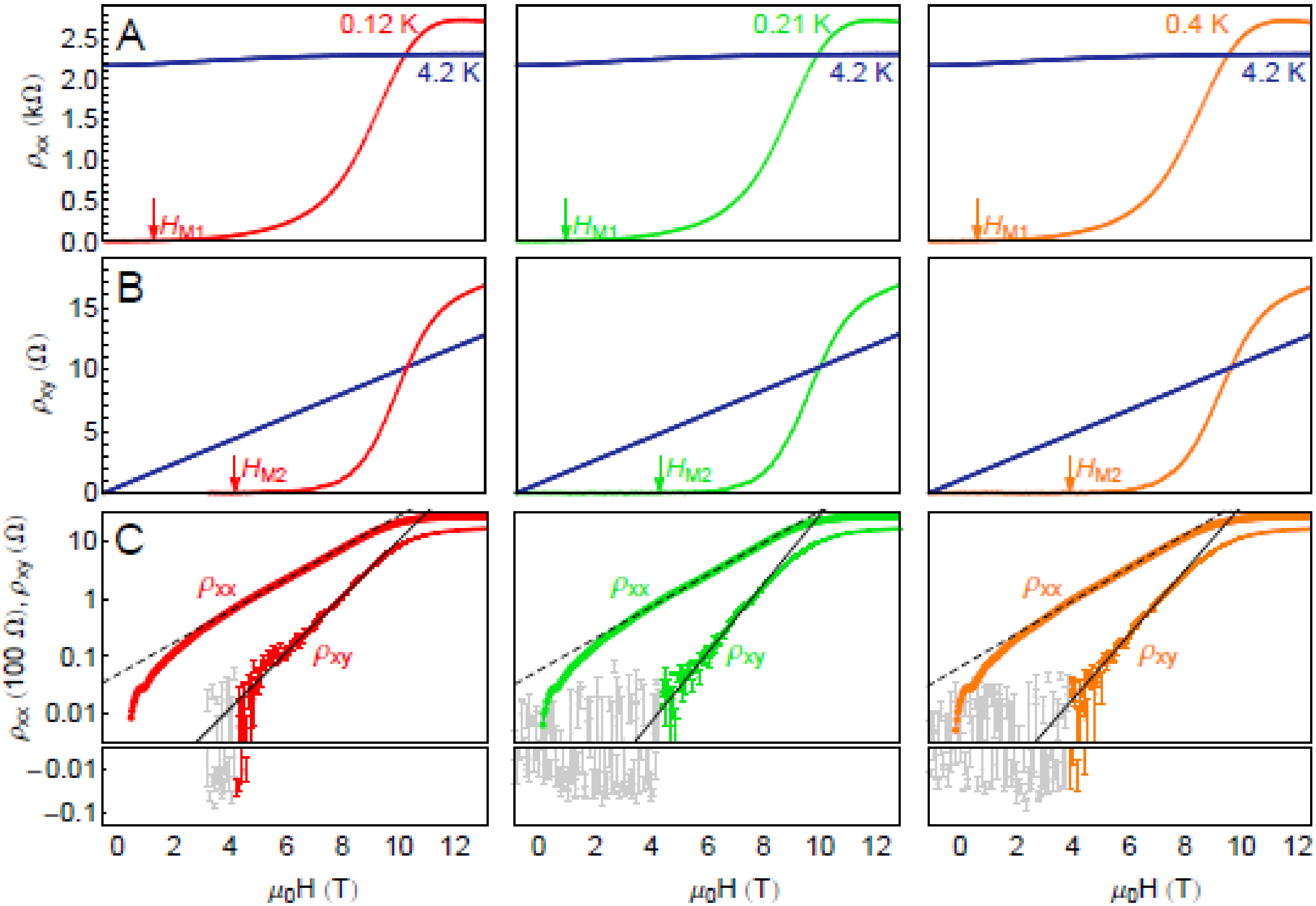
- Measure ρ_{xy} in the T → 0 limit



InO_x: Regimes of behavior in ρ_{xx}, ρ_{xy}

- $\rho_{xx} \rightarrow 0$ at H_{M1}
- $\rho_{xy} \rightarrow 0$ at H_{M2}

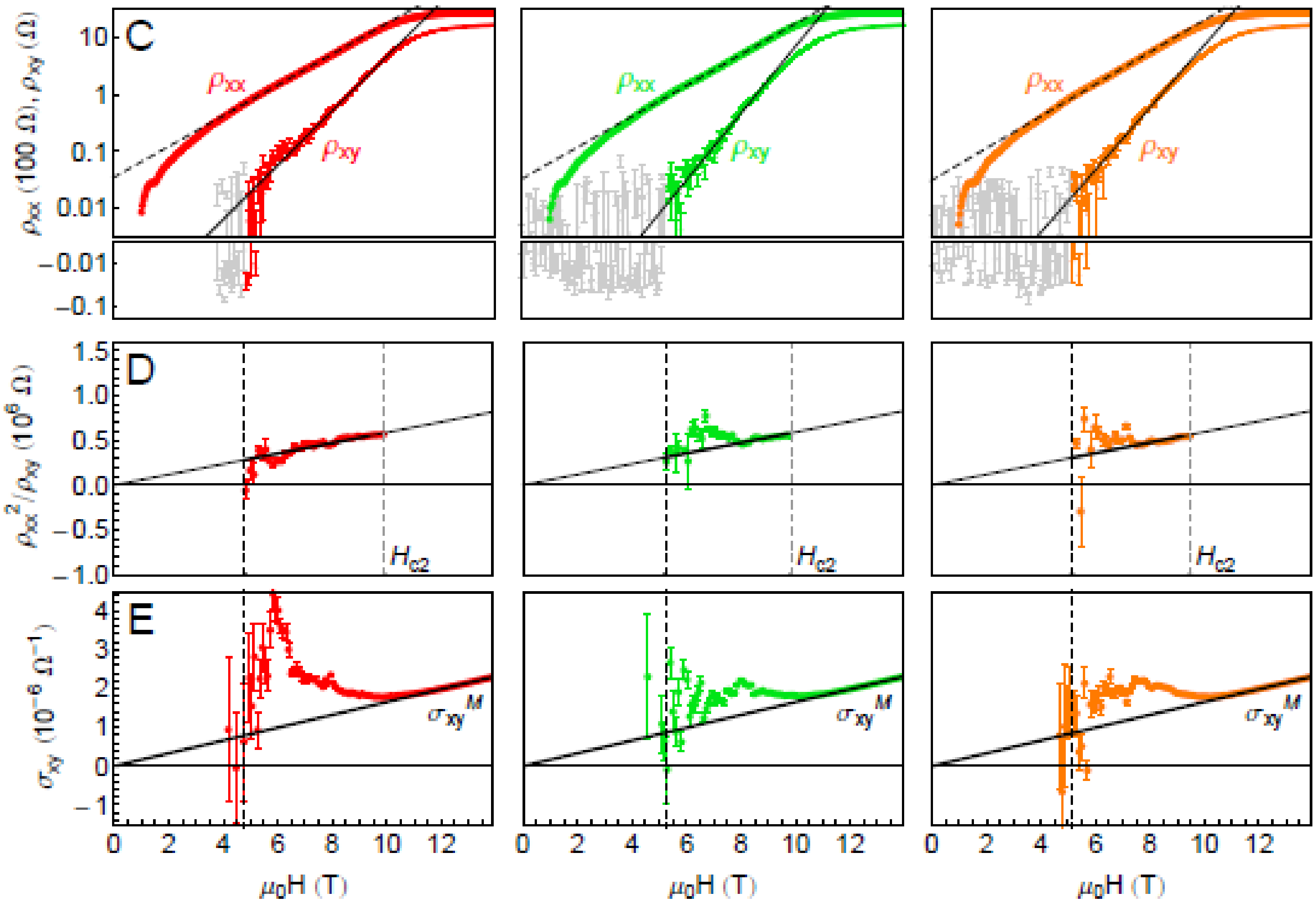
→ track with T



120 mK　　210 mK　　400 mK

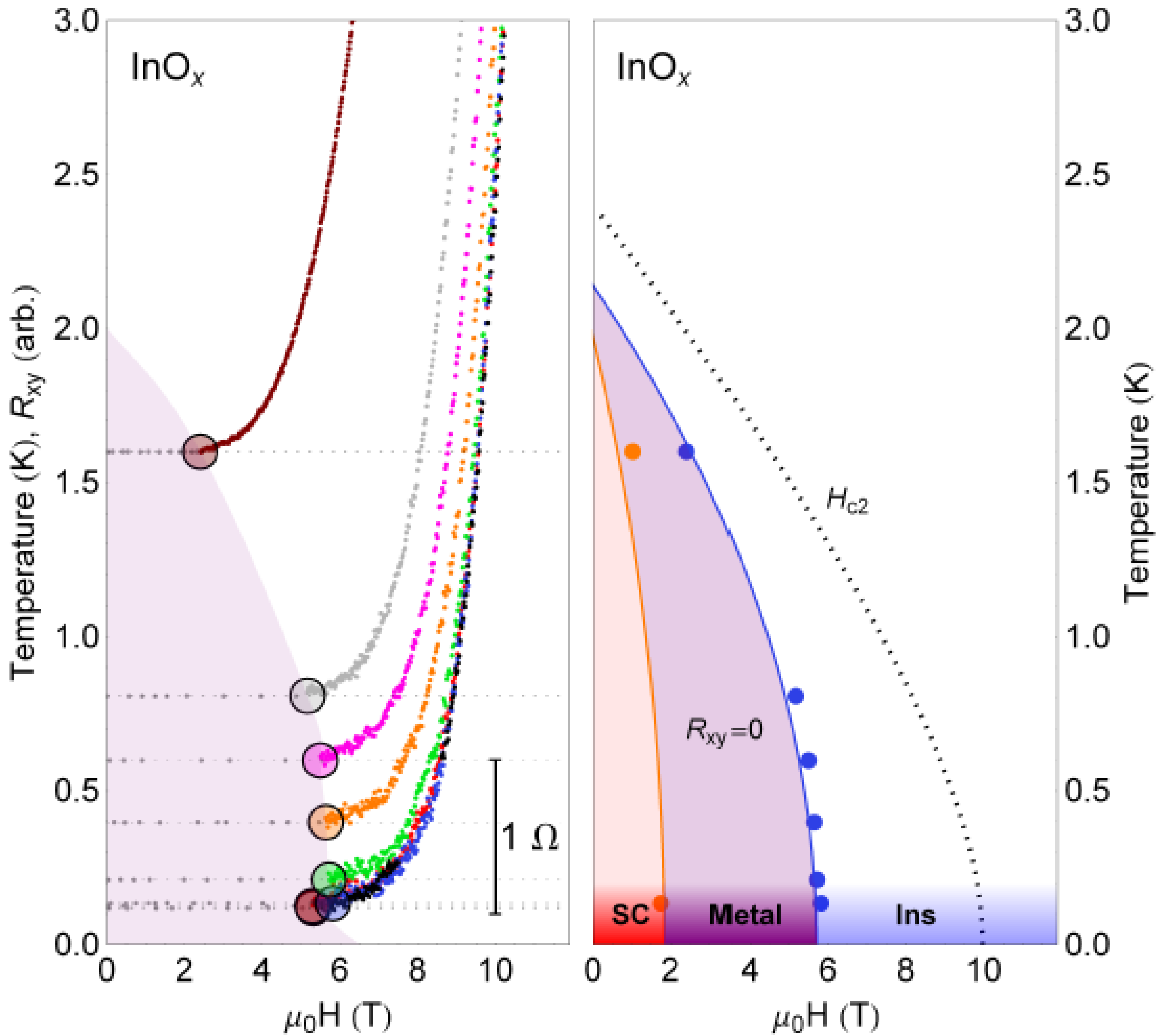
InO_x: Scaling behavior at higher field

- $\rho_{xx} \rightarrow 0$ at H_{M1}
- $\rho_{xy} \rightarrow 0$ at H_{M2}
- $\rho_{xx}^2/\rho_{xy} \sim H$ (vortex state)
- $\sigma_{xy} \rightarrow \sigma^M$ (above H_{c2})



120 mK 210 mK 400 mK

InOx Hall effect

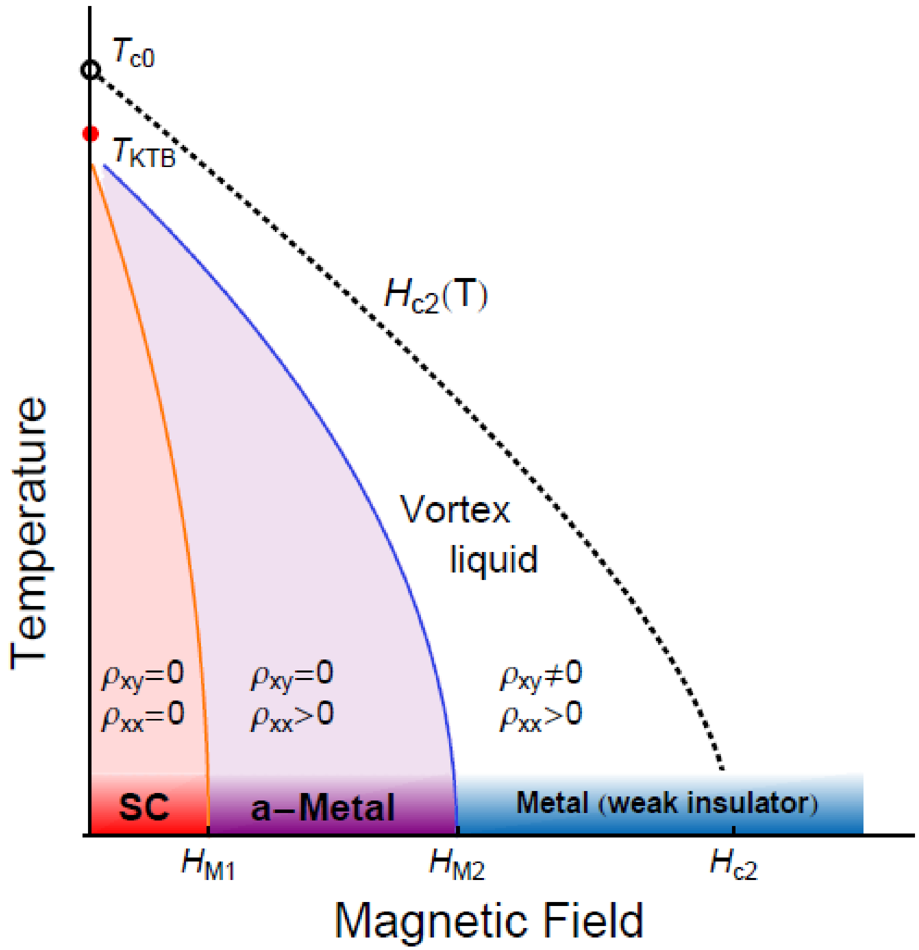


Phase diagram for a weakly disordered 2D superconductor

- In the anomalous metallic state:
  - ρ_{xx} saturates > 0
  - Zero Hall effect

→ Particle-hole symmetry retained in the "quantum metal" phase

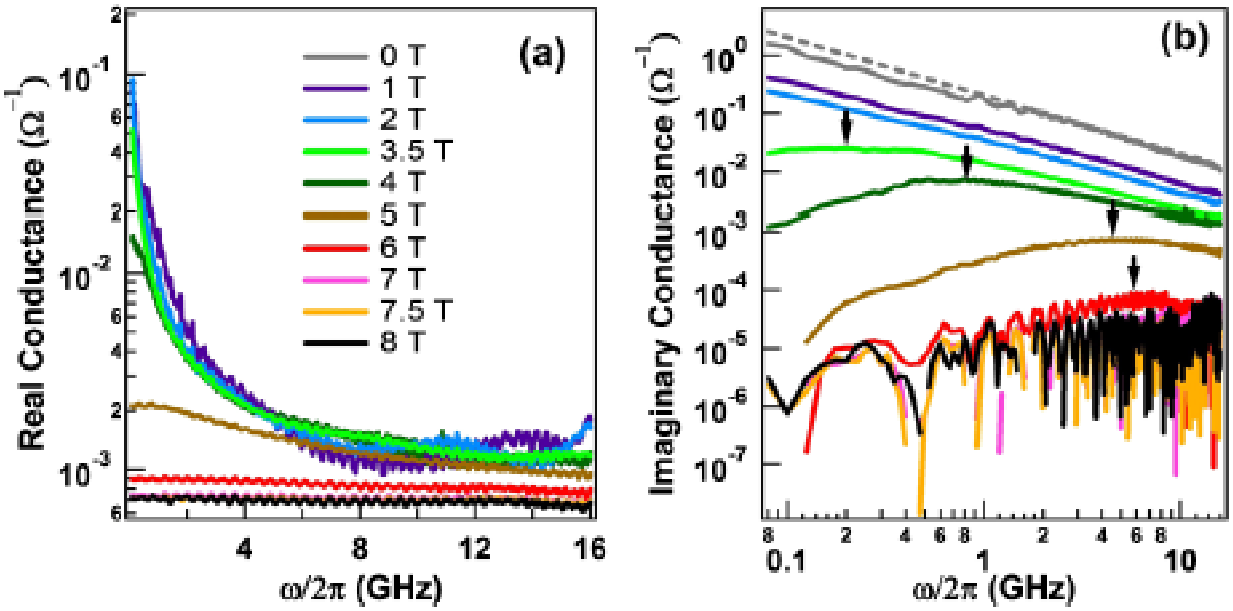
→ metal appears to remember PHS from the disrupted superconducting state

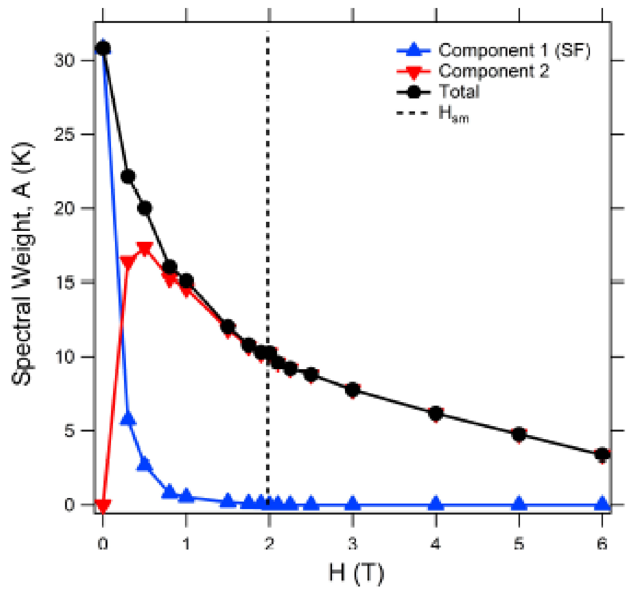


No cyclotron resonance in the anomalous metallic state

- Microwave spectroscopy of amorphous InO_x films (N. P. Armitage/JHU)

→ No FL fermionic excitations





W. Liu, N. P. Armitage et al. *PRL* **111** 067003 (2013)
Y. Wang, N. P. Armitage et al. (arXiv, 2017)

Summary & Outlook

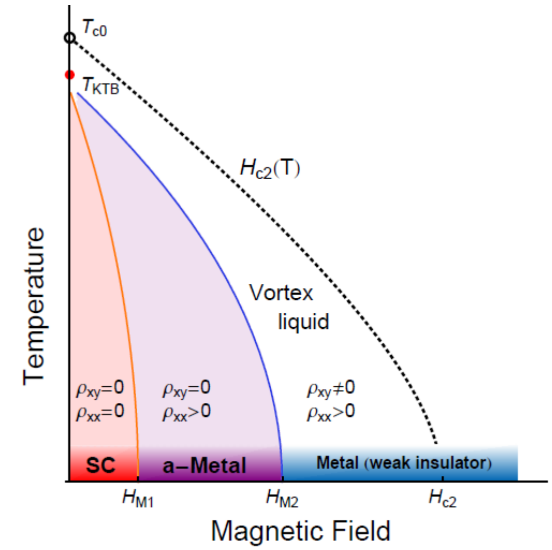
- Unavoidable, robust, exciting evidence for an anomalous metallic phase in 2D superconductors
→ amorphous films, JJAs, nanostructures, crystalline materials

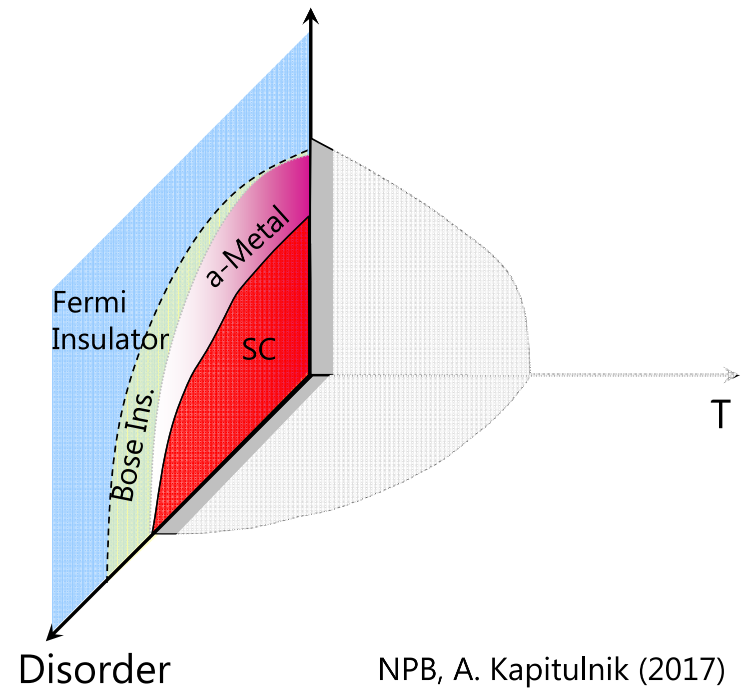
- Zero Hall effect within the broad metallic phase region
- Indicates particle-hole symmetry from disrupted SC state

Q: How is the anomalous metal connected to the direct (self-dual) SIT?

Q: Bose metal / Inhomogeniety / composite Fermions

→ Next talk (S. Raghu, Stanford)





NPB, A. Kapitulnik (2017)

Thanks to many project collaborators

Steve Kivelson, Myles Steiner, Mihir Tendulkar, Li Zhang, Sang-Chul Lee, Mac Beasley, Ted Geballe, Aharon Kapitulnik
Stanford University

Karen Michaeli, Konstantin Tikhonov, Sasha Finkel'stein
Texas A&M, Weitzmann Institute

Alexey Suslov, Tim Murphy
NHMFL Tallahassee

Ian Hayes, Alejandro Ruiz, Alex Frano, Mitchell Maciorski, Xue Fan, Gilbert Lopez, Jeffrey Wirjo, Maiya Vranas, James Analytis
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