BROWN

Experimental Insights into the Insulators that Form at the Superconductor to Insulator Transition

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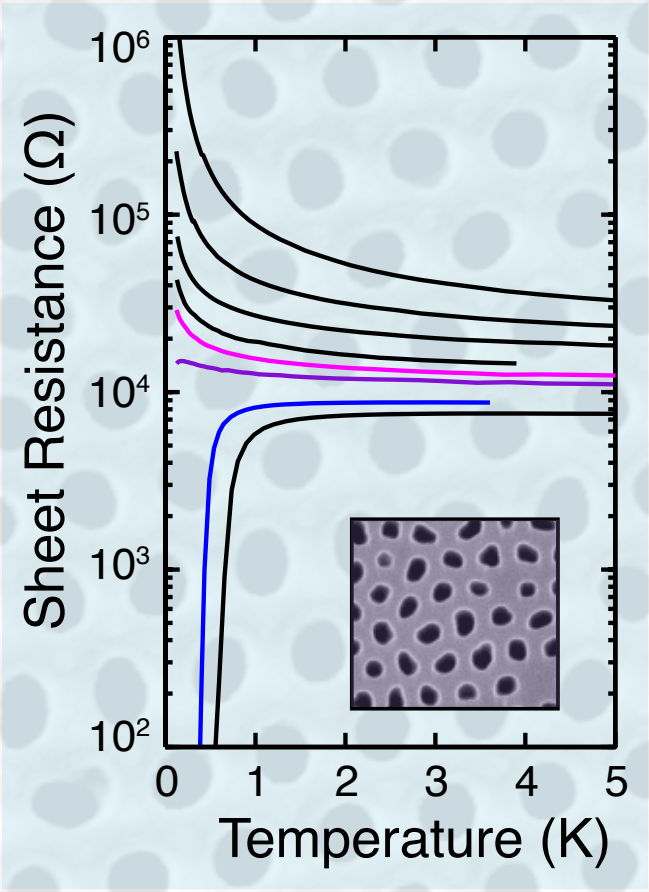
MTI Workshop

Nonconventional Insulators
November 12th, 2012

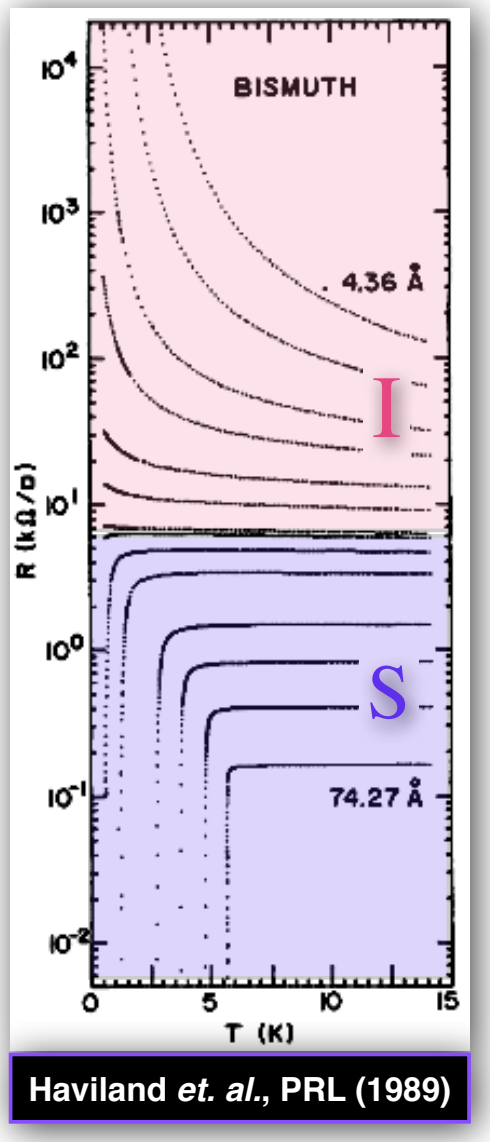
Experimenters

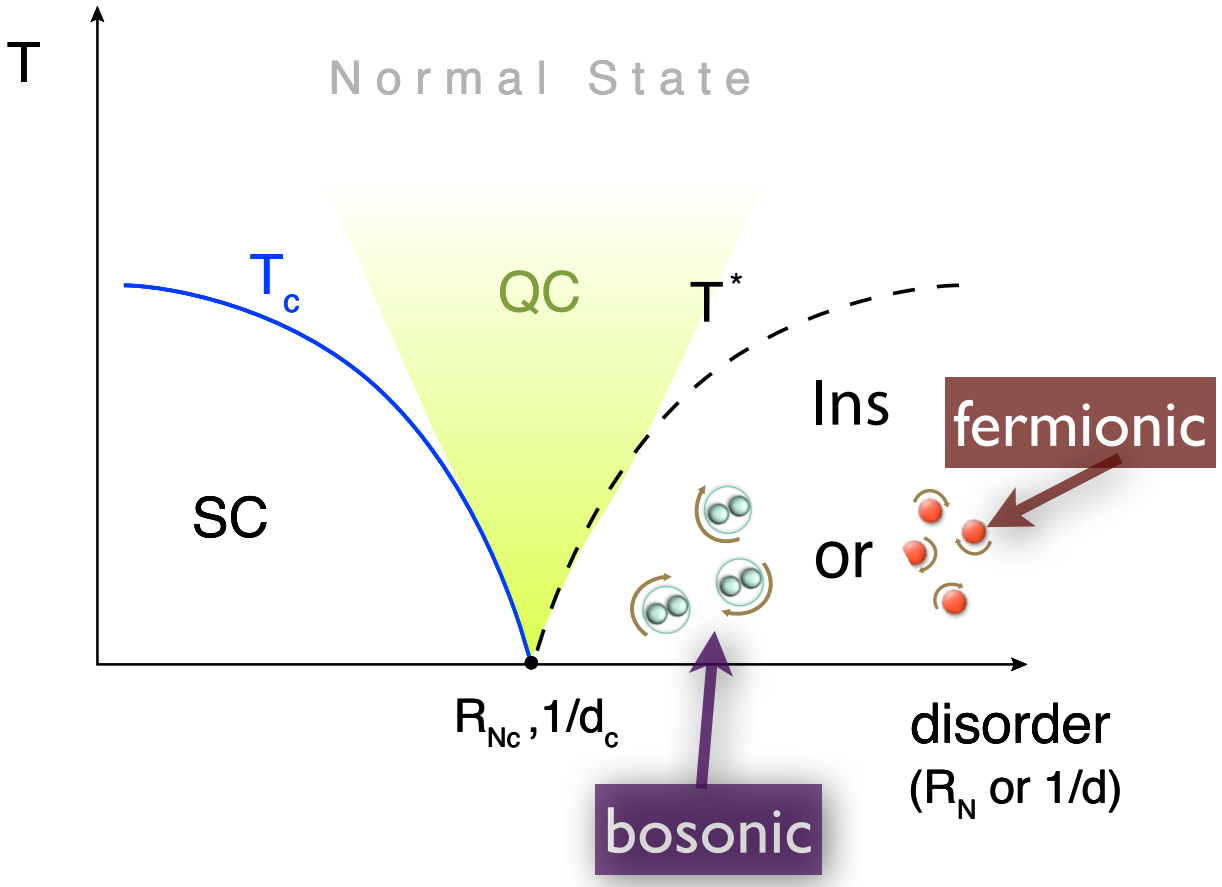
Outline

- Disorder Tuned SIT's
  - *ubiquitous*
  - *Two types?*
- NanoHoneyComb Film Patterning
  - *probe phase coherence*
- Hilly NHC Films
  - *Bosonic SIT*
- Flat NHC Films
  - *Fermionic SIT*
- Open questions

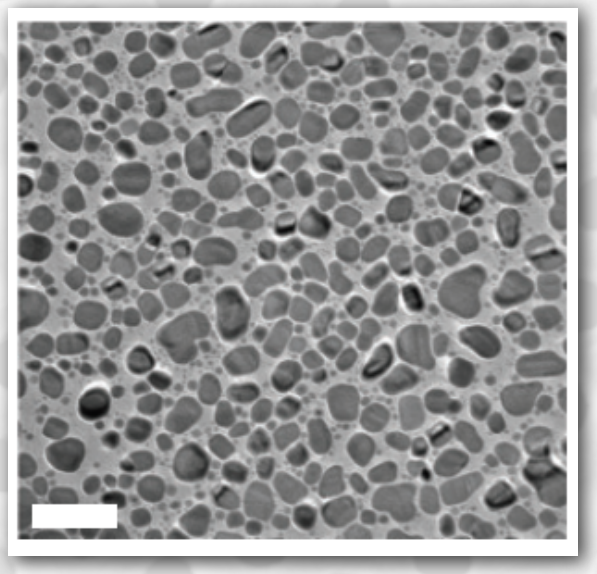


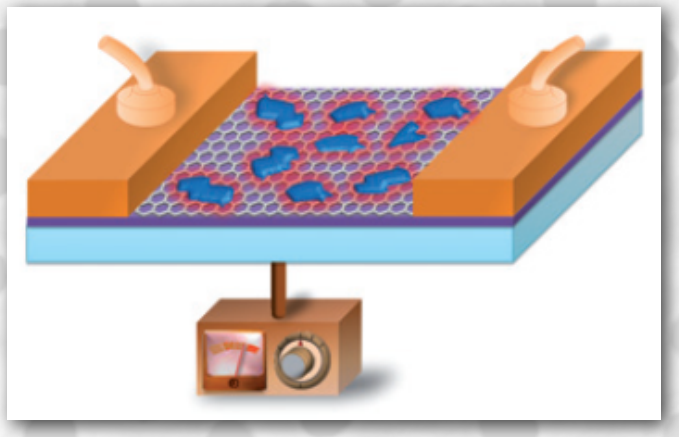
Disorder Tuned SIT

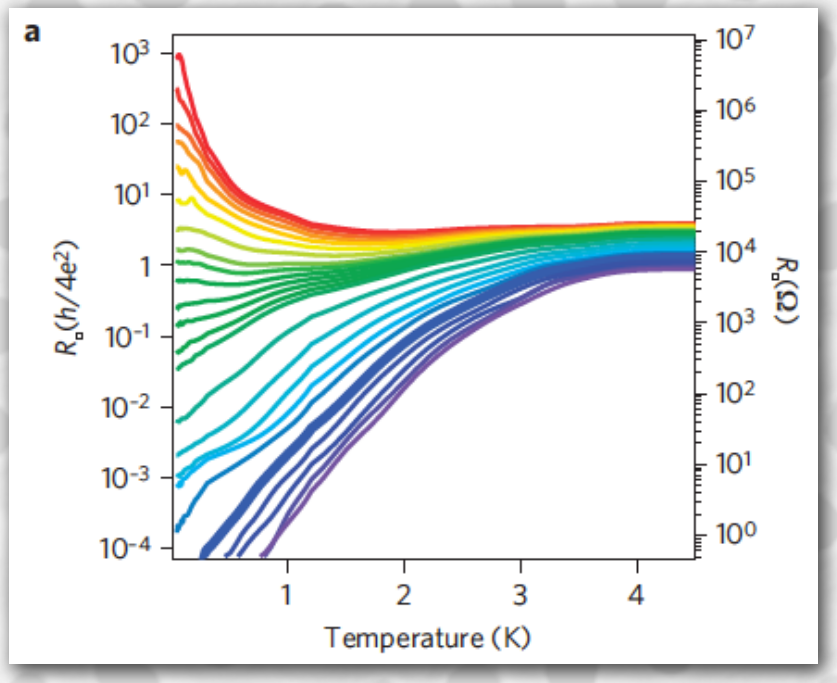




Sn on Graphene - Gated SIT



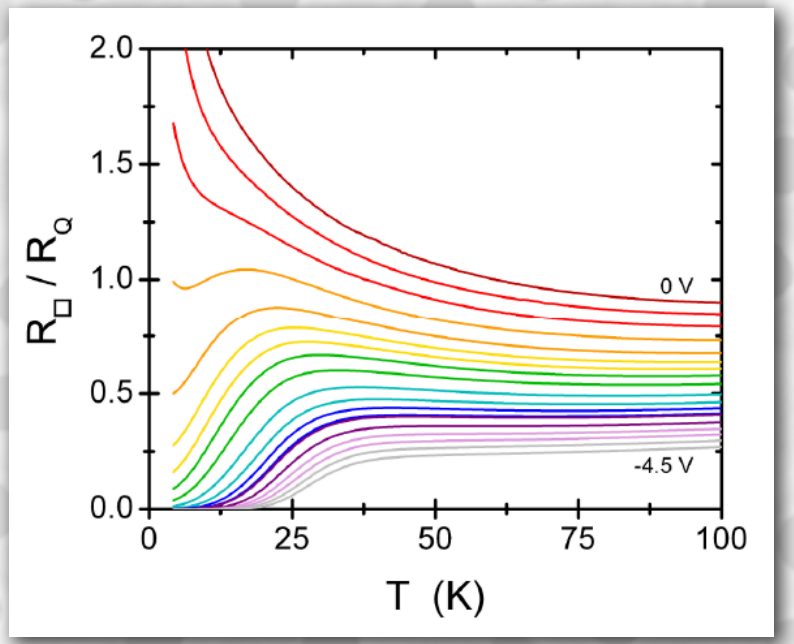


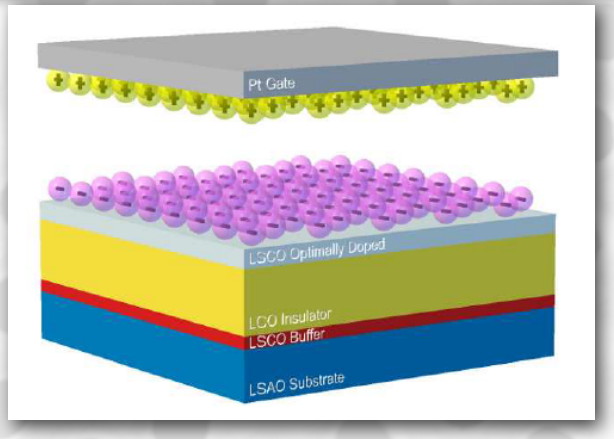


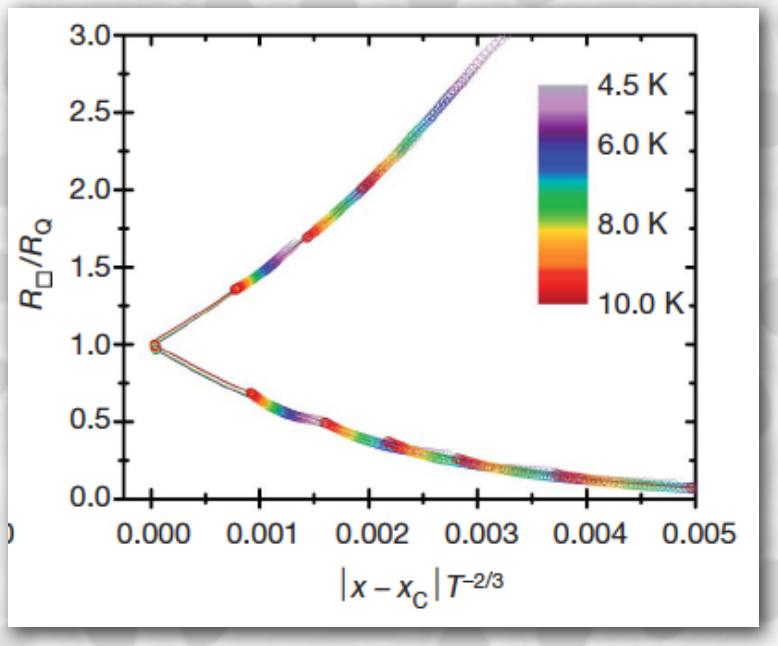
$R_c \sim h/(2e)^2$

Adrien Allain, Zheng Han and Vincent Bouchiat, Nat. Mater. 2012

Thin LaSrCuO - Gated SIT







$R_c \sim h/(2e)^2$

Bollinger, Bozovic and coworkers, Nature 2011

Disorder driven SIT

R_N increase weakens

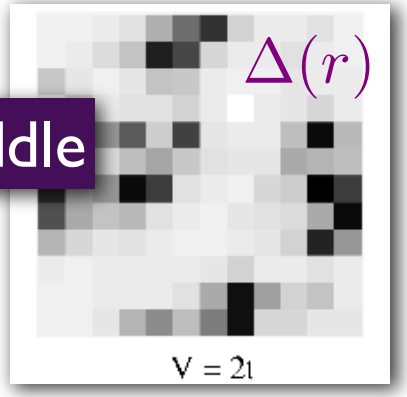
$$\psi = \Delta^{\frac{1}{2}} e^{i\phi}$$

Amplitude Reduction*
repulsive Coulomb interactions
compete with pairing interactions

$$\Delta, T_{co} \to 0$$

Phase Fluctuations°
potential fluctuations locally
enhance pairing interactions

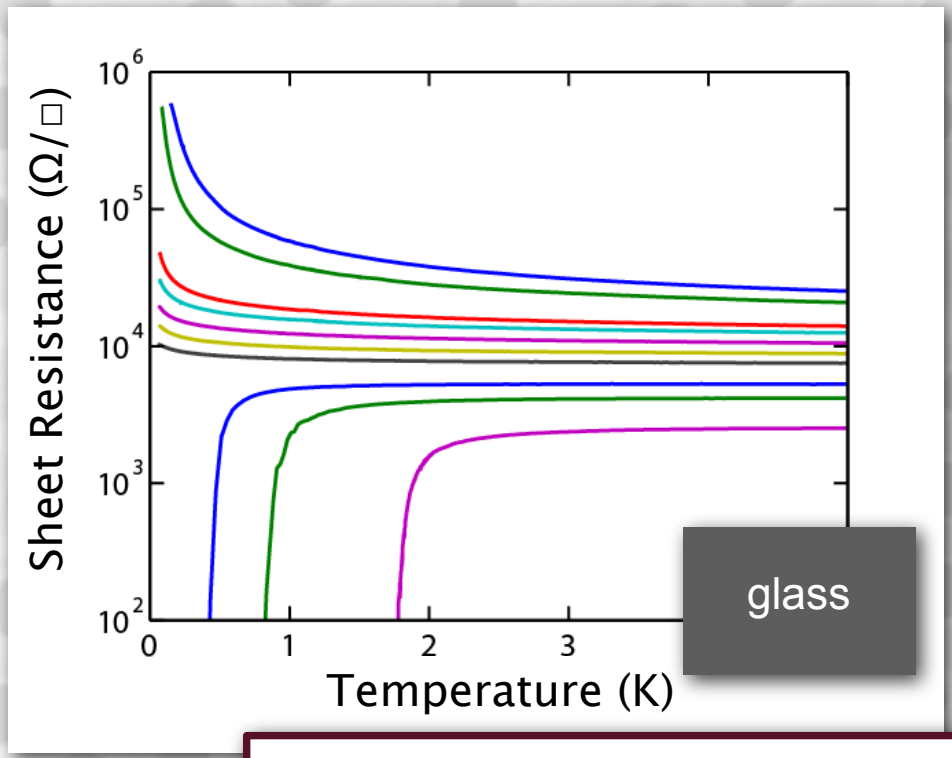
Cooper pairs puddle



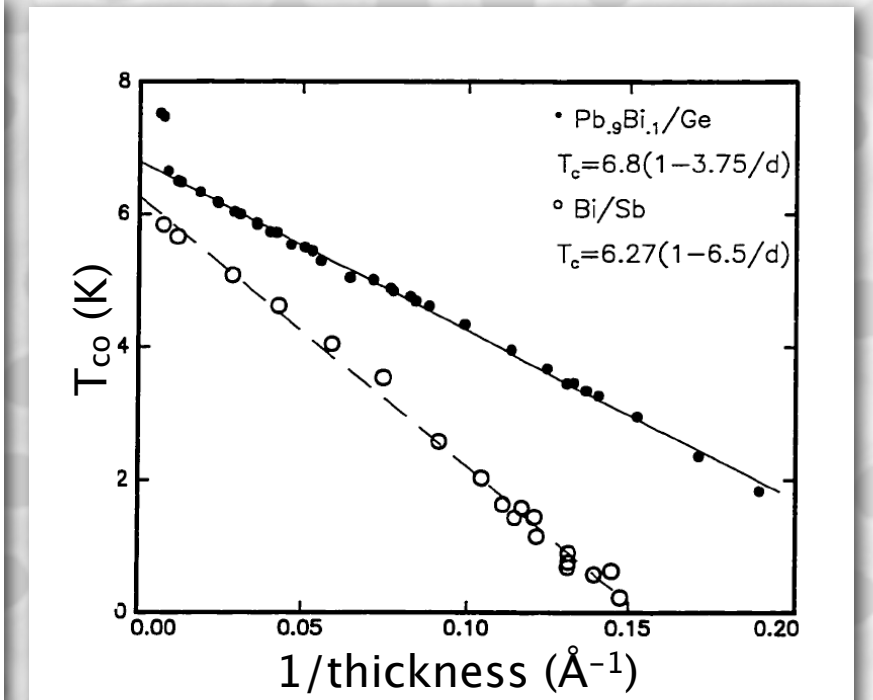
*Finkel'stein, Belitz

°Trivedi, Dubi, Meir, Feigel'man, Larkin

Quench Condensed a-Bi Films on Glass



glass

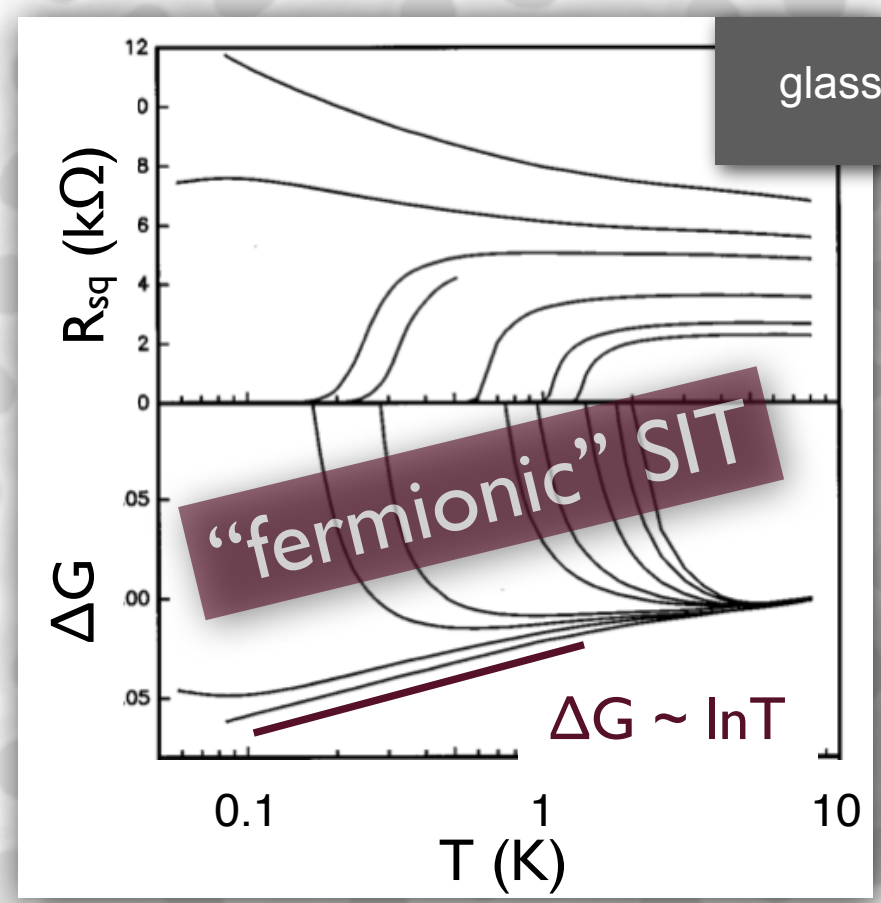


$$T_c = T_{c,bulk}\left(1 - \frac{d_{SIT}}{d_{Bi}}\right)$$

Amplitude Reduction

Quench Condensed a-Bi Films

Amorphous Bi Films

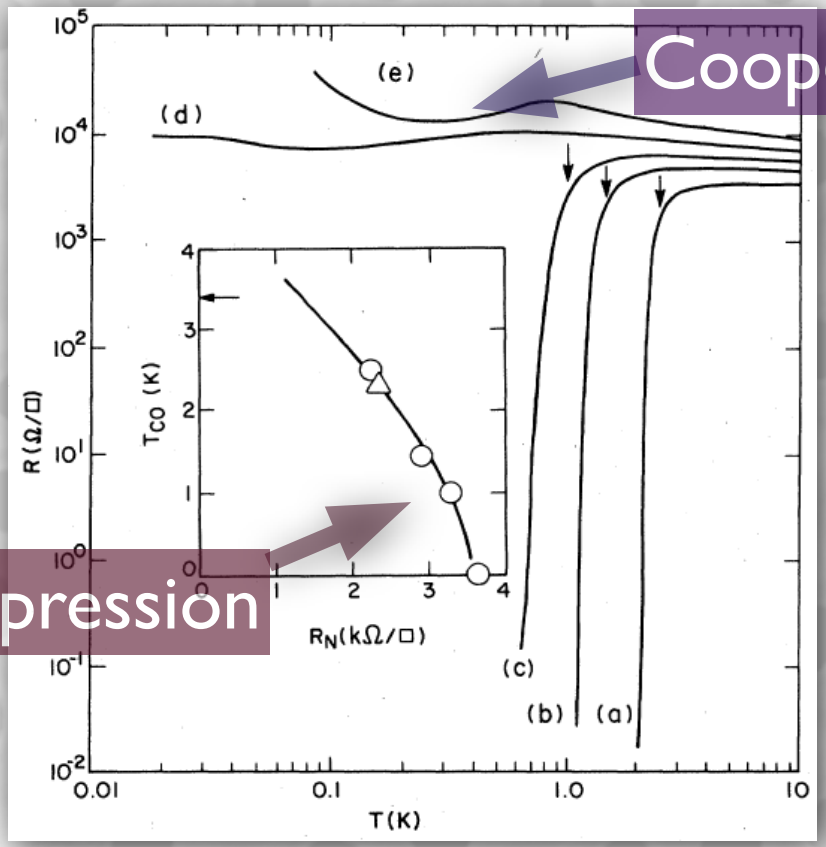


Insulator of unpaired electrons

Chervenak and Valles (1999)

A Conundrum

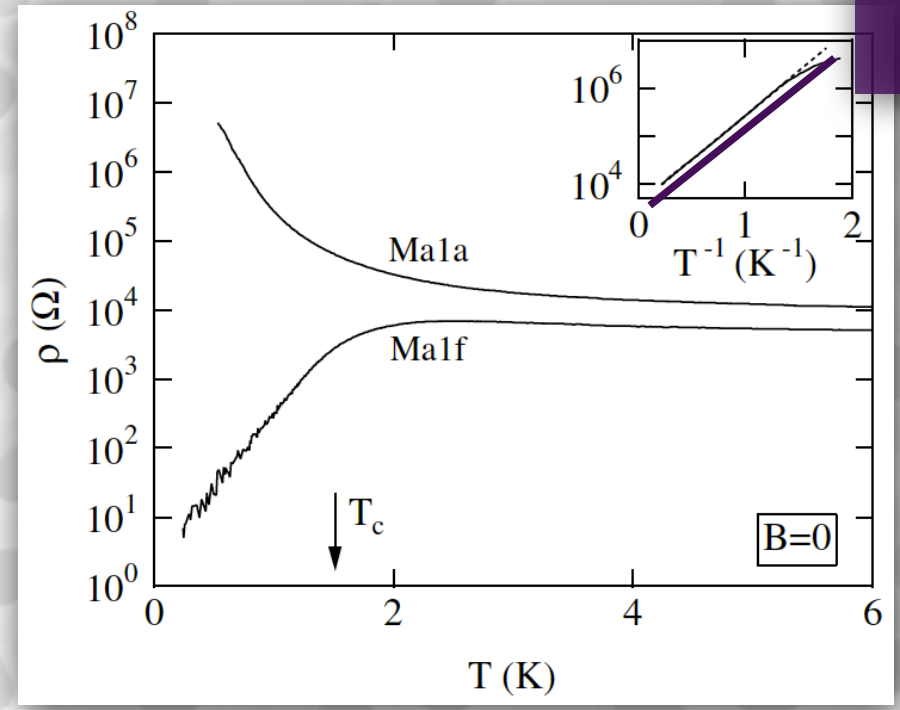
Indium Oxide - *another uniformly disordered film*



Hebard and Paalanen, Phys Rev B (1984)

A Conundrum

Indium Oxide - *another uniformly disordered film*



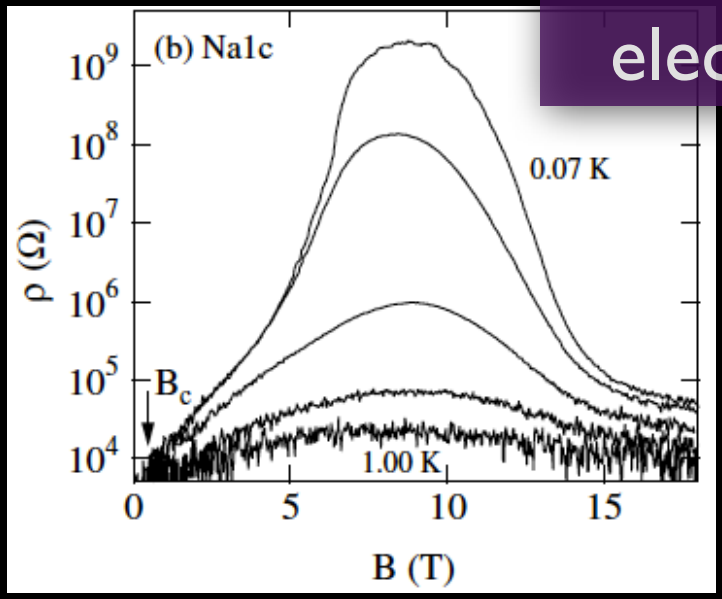
Strongly localized insulator

$R \sim \exp(T_o/T)$

Sambandamurthy et al., Phys Rev Lett (2004)

A Conundrum

Indium Oxide - *another uniformly disordered film*



Magnetoresistance Peak!

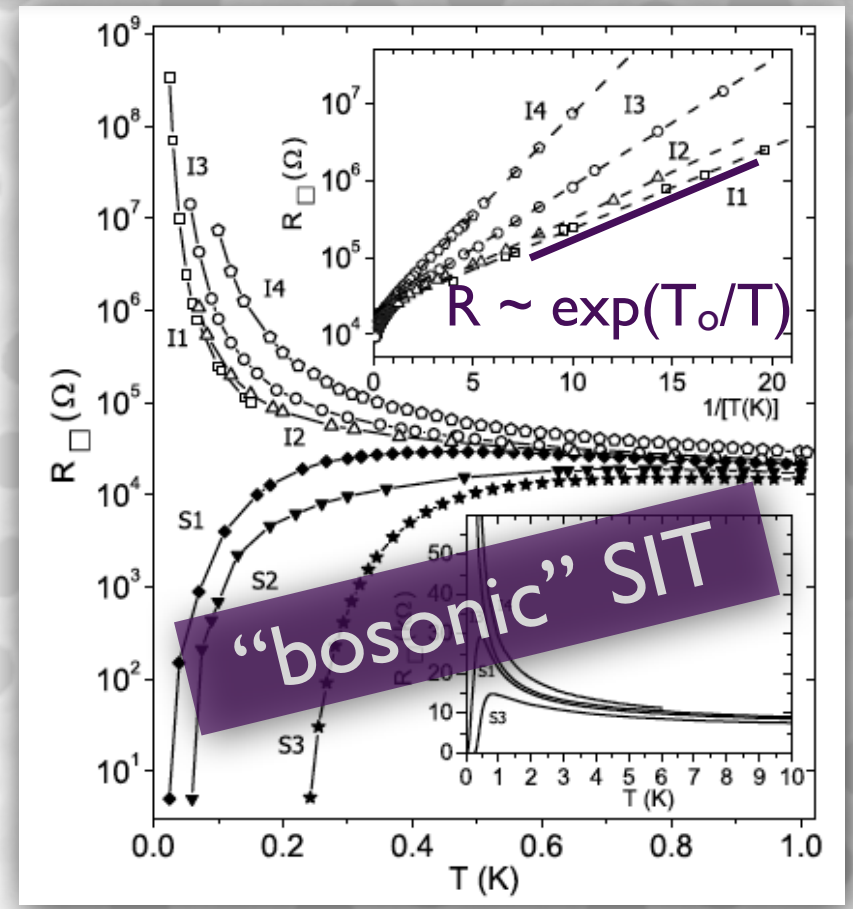
Too big for single electron transport!

Localized Cooper pairs?

Sambandamurthy et al., Phys. Rev. Lett. (2004)

A Conundrum

TiN - *uniformly disordered as well*

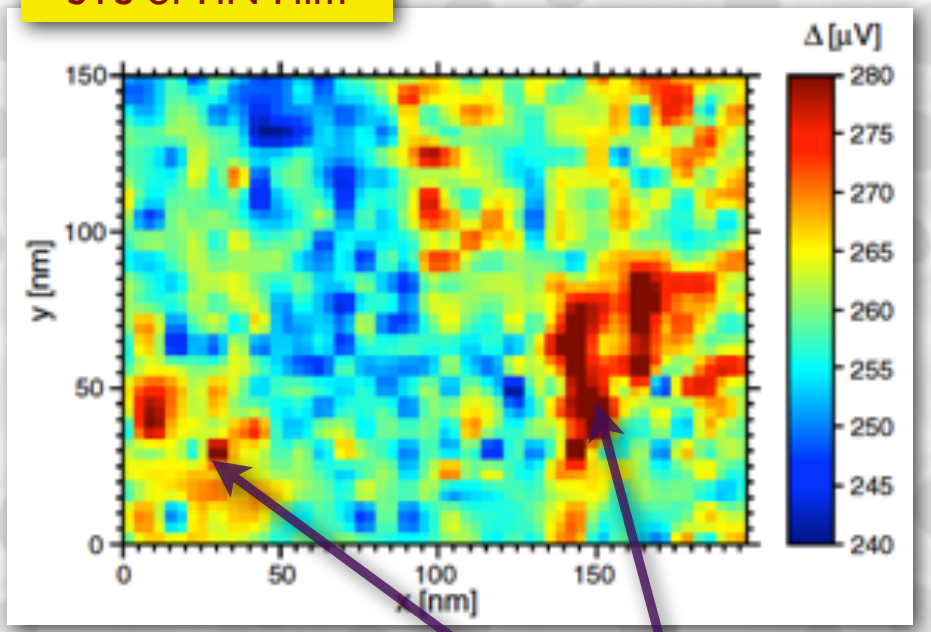


T. I. Baturina et al., Physica C (2008)

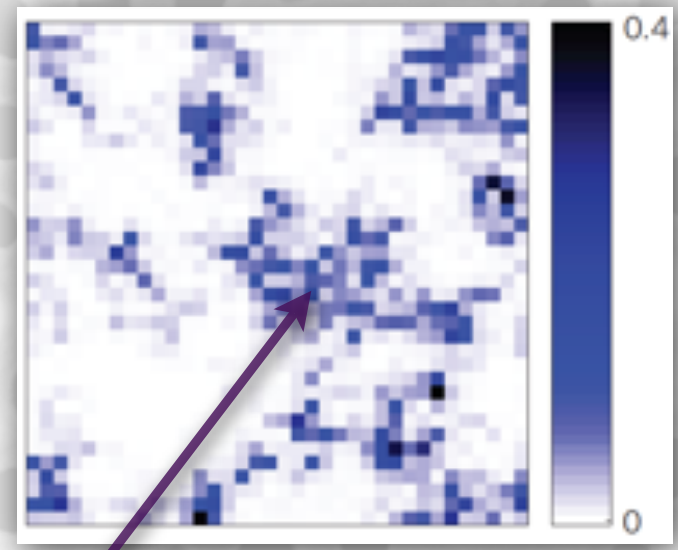
Emergent Granularity

Short scale disorder gives:

STS of TiN Film



Pairing amplitude from Quantum Monte Carlo



Incipient Cooper Pair Islands

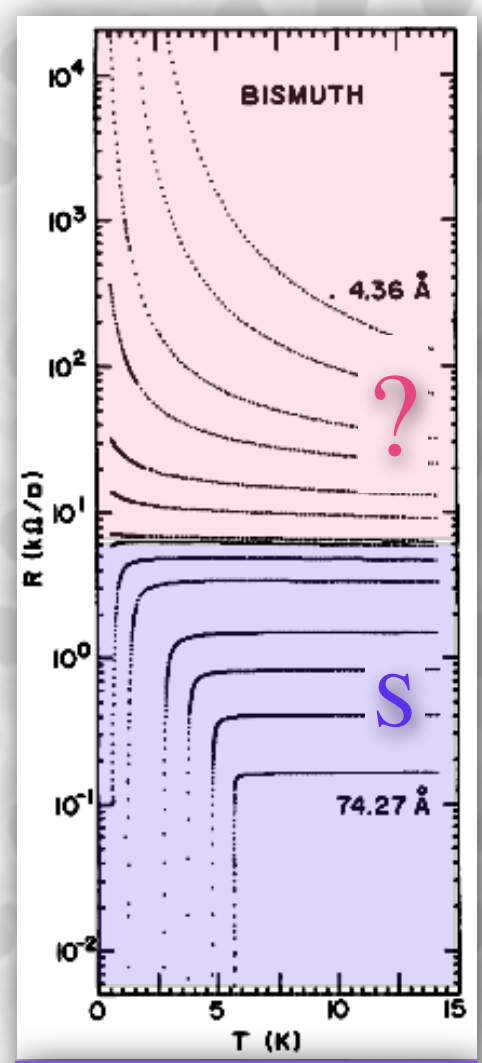
B. Sacepe et al.(2008)

Bouadim et al. (2011)

Questions

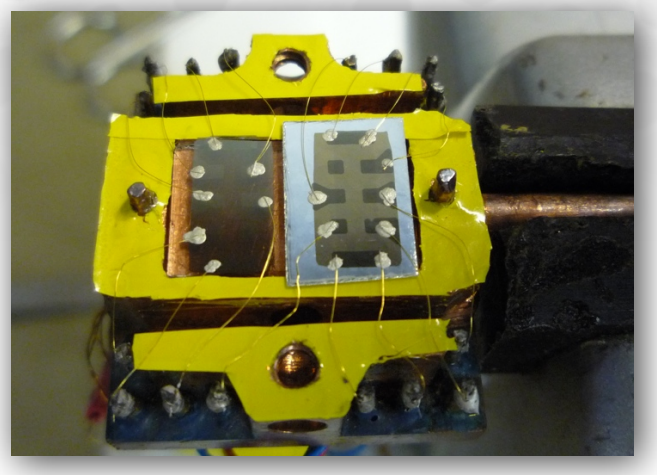
Is a-Bi SIT actually fermionic?
Or, are all SIT's bosonic?

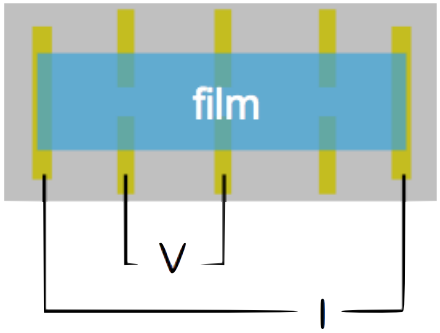
How does a-Bi differ from Indium Oxide and TiN?

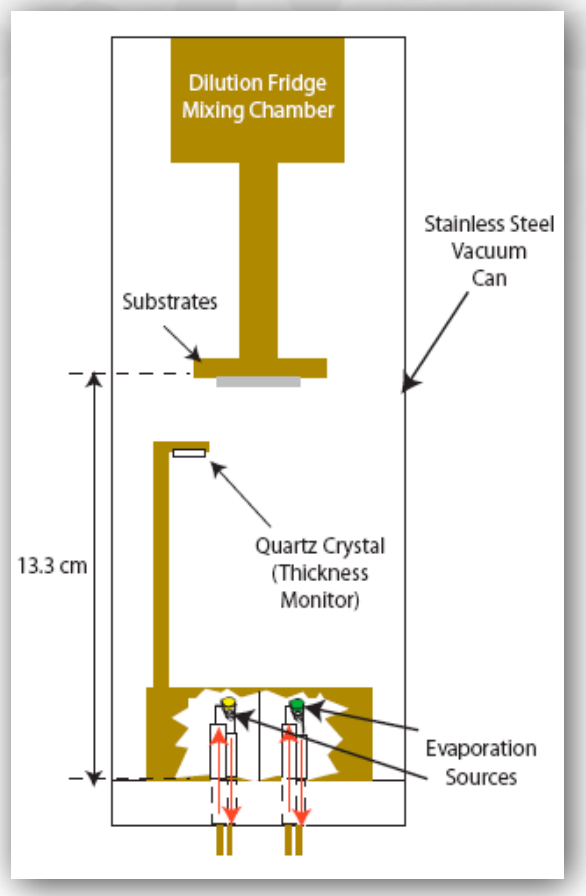


Haviland *et. al.*, PRL (1989)

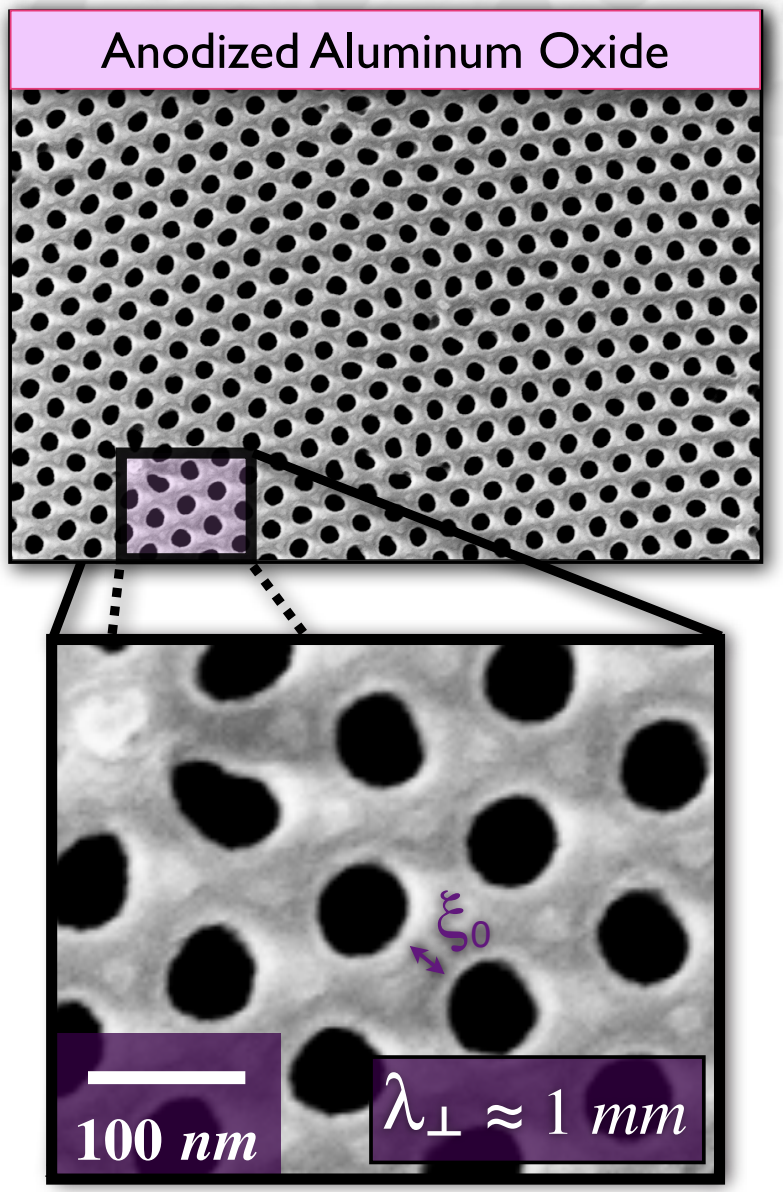
Experimental techniques



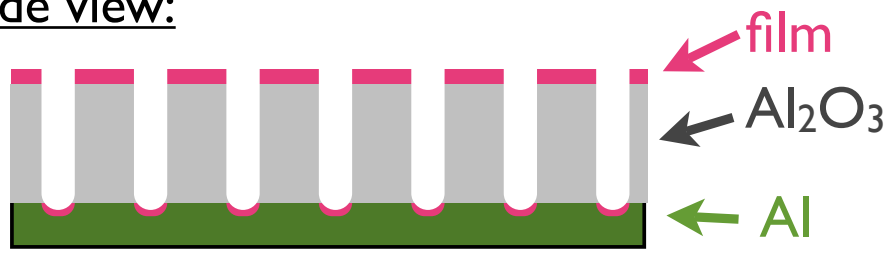




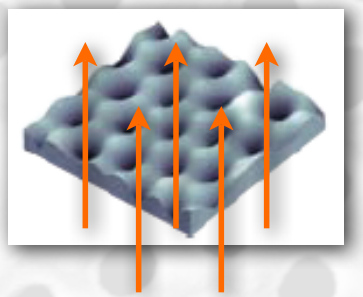
NanoHoneyComb (NHC) substrates

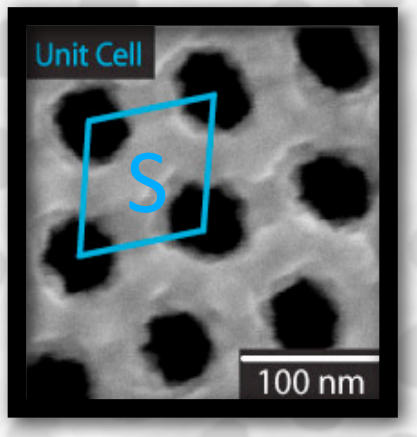


side view:



Detecting Cooper Pair Phase Coherence





$$H_M = \frac{h}{2eS} \quad \text{period}$$

$$f = \frac{H}{H_M} \quad \text{frustration}$$

Charge in a magnetic field

$$\vec{p}_{\,canonical} = \vec{p} + q\vec{A}$$

Cooper pair phase obeys

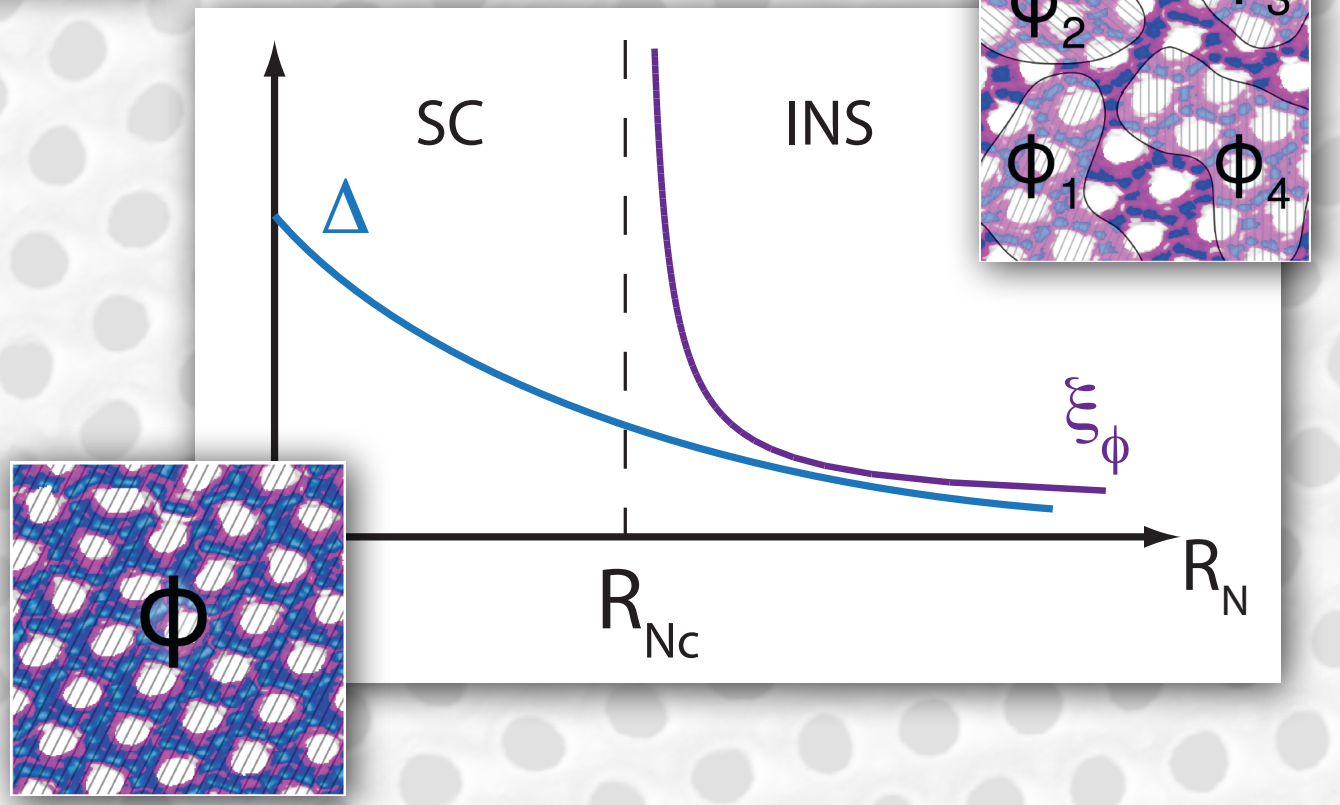
$$\hbar\nabla\phi = 2e(\vec{A} + \Lambda\vec{J}_s)$$

$\Rightarrow$ flux periodic properties

$$H_M = \frac{h}{2eS}$$

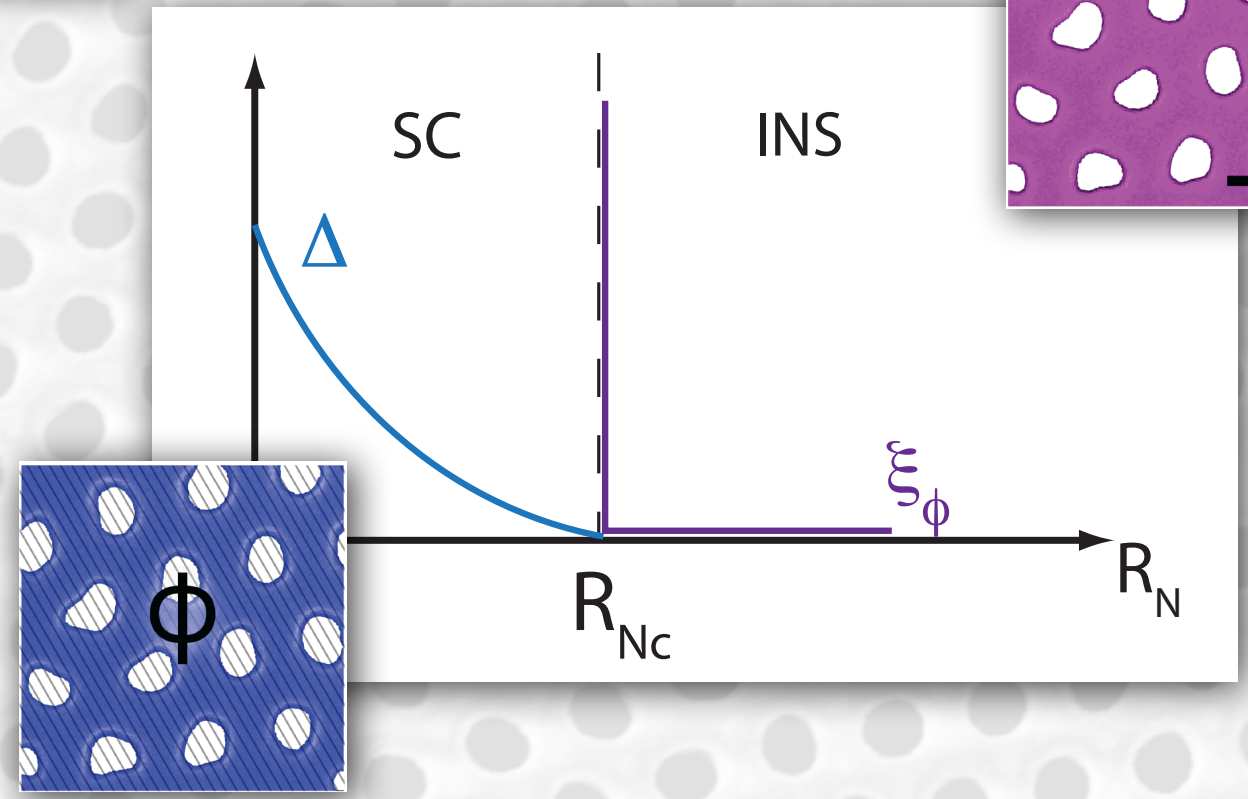
Bosonic SIT's

$$\psi = \Delta^{\frac{1}{2}} e^{i\phi}$$

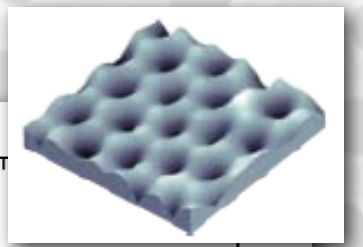


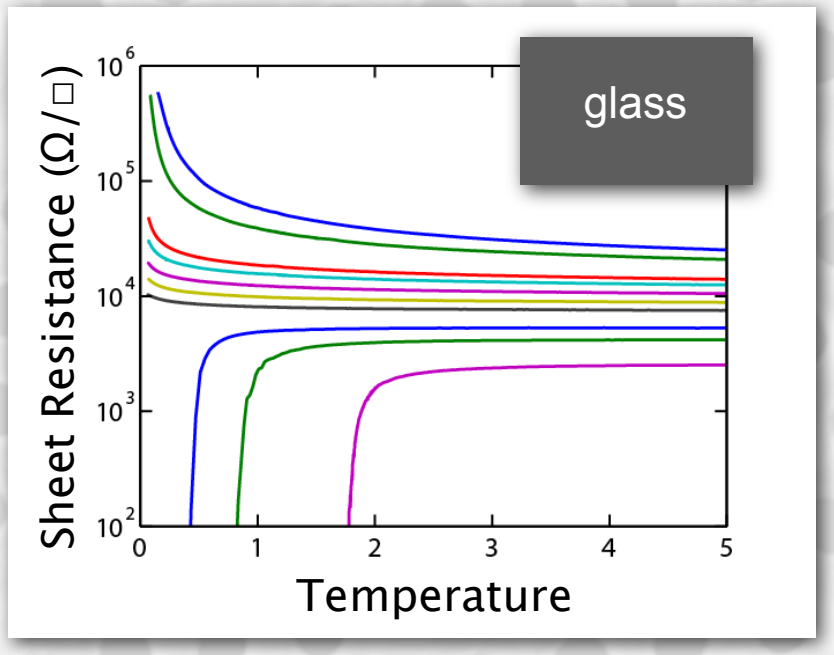
Fermionic SIT's

$$\psi = \Delta^{\frac{1}{2}} e^{i\phi}$$



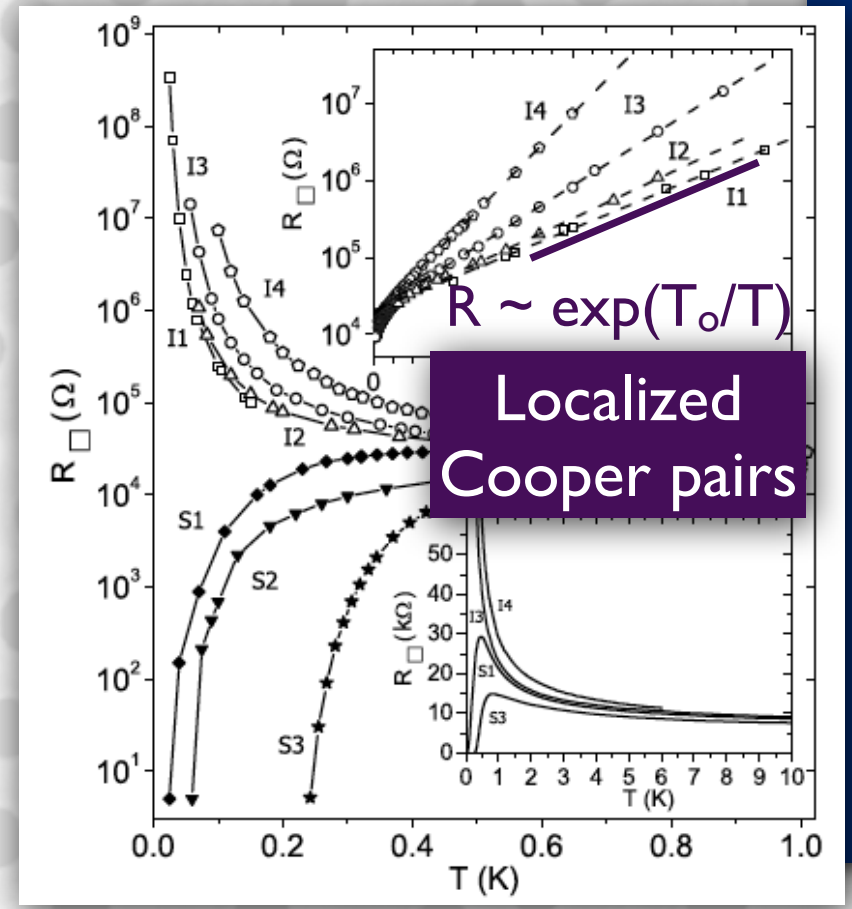
SIT of Hilly AAO Films



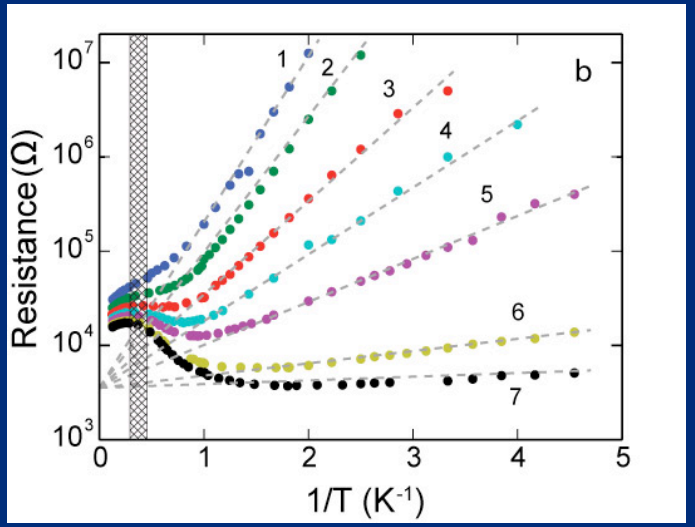


Hard Gap in Insulator

TiN Films



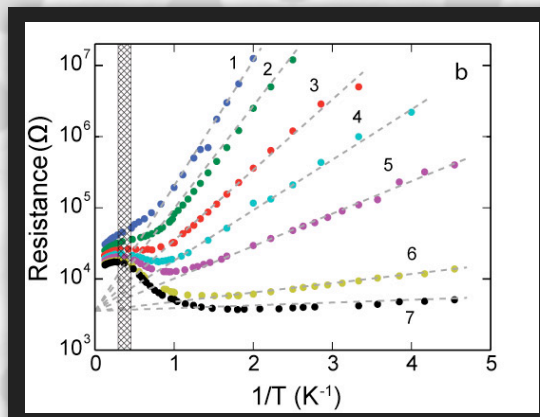
AAO NHC films



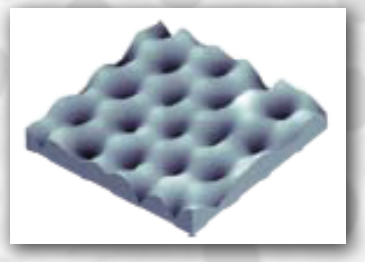
$R=R_0 \exp(T_o/T)$

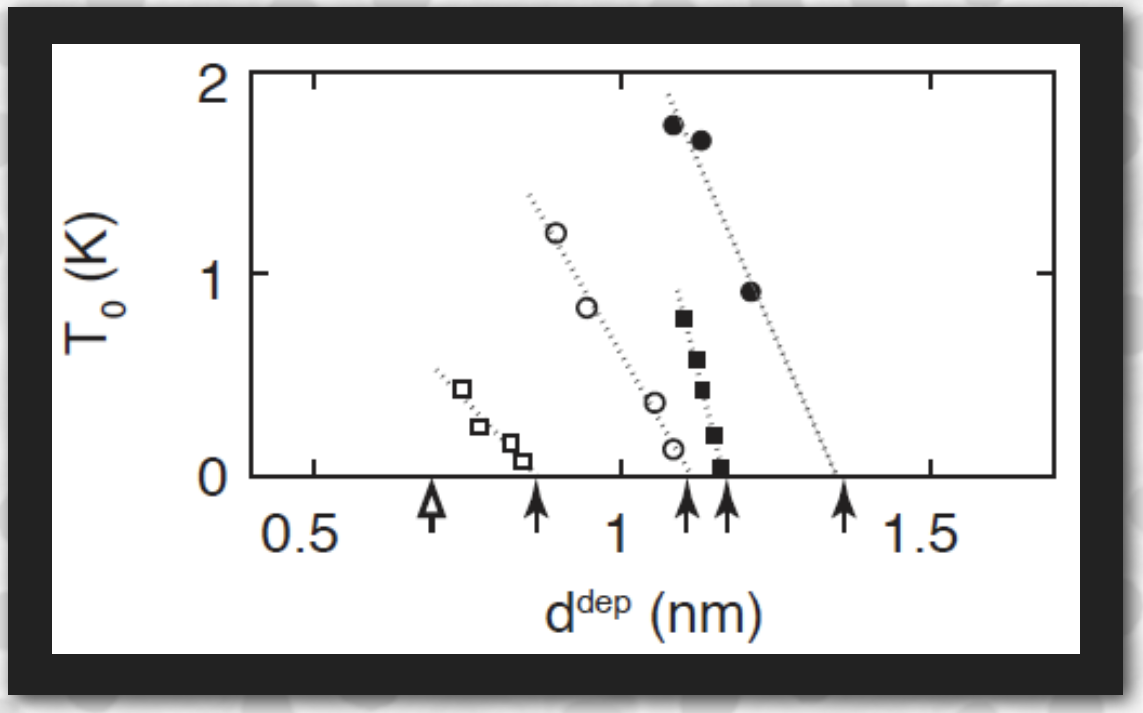
MD Stewart et al., Science 318, 1273-1275 (2007)

Activation Energy Vanishes at SIT



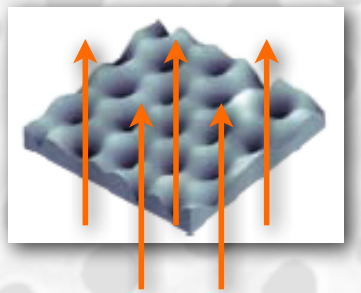
$$R = R_0 exp(T_o/T)$$

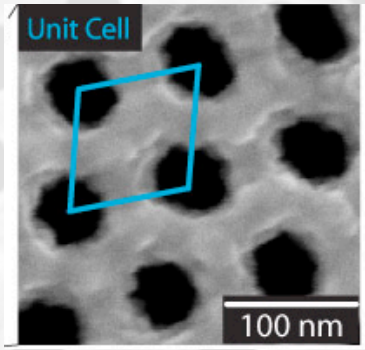




Data from 4 series' of films

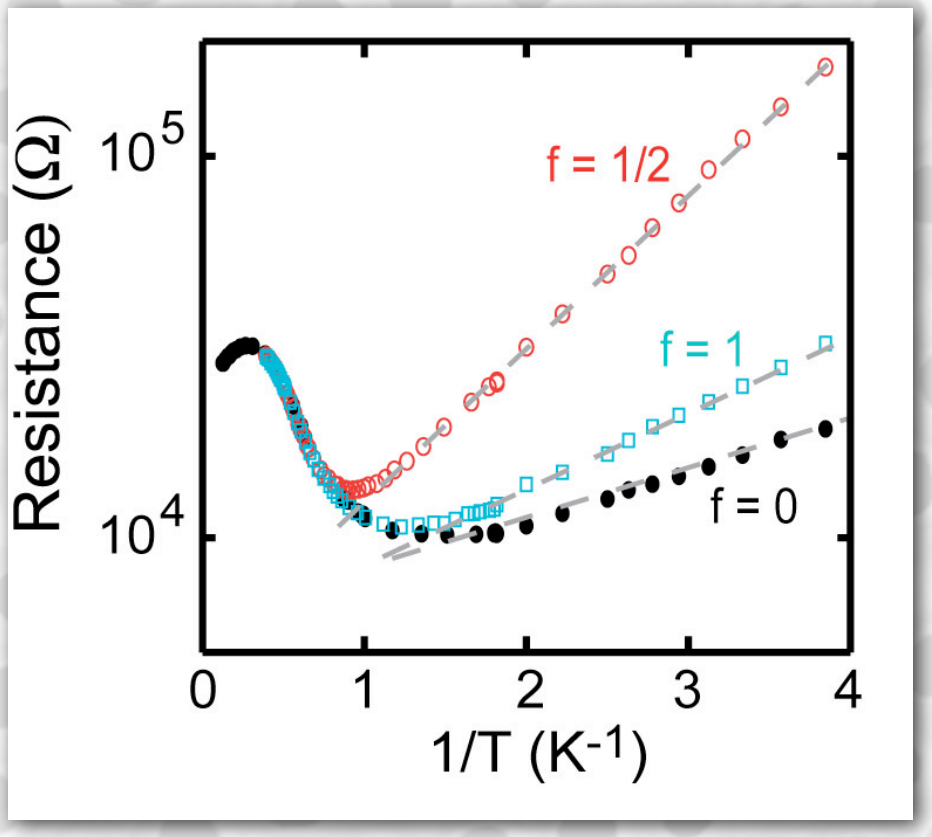
Insulating Film in Magnetic Field



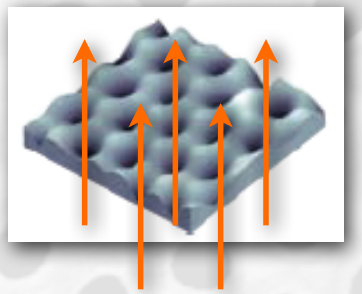


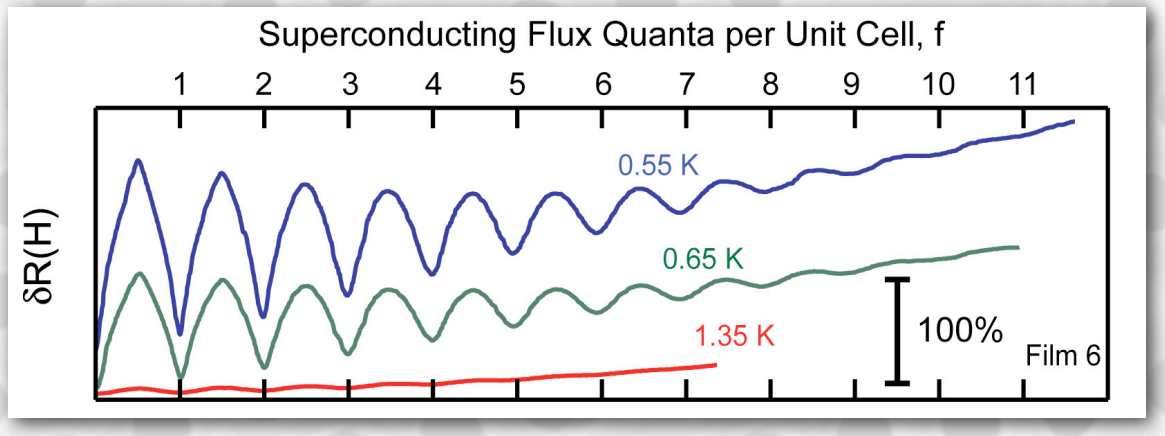
$H\odot$

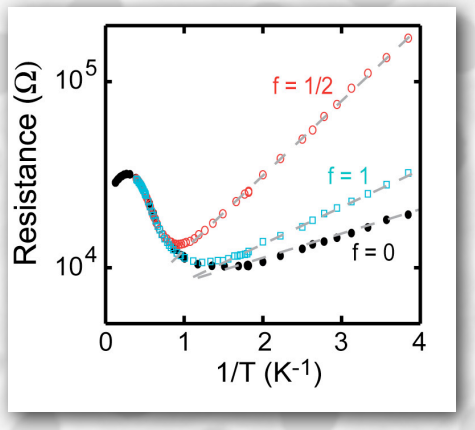
$f = H/H_M$



“Little Parks”Oscillations in Insulators







1) Period: $H_M = h/2eS$

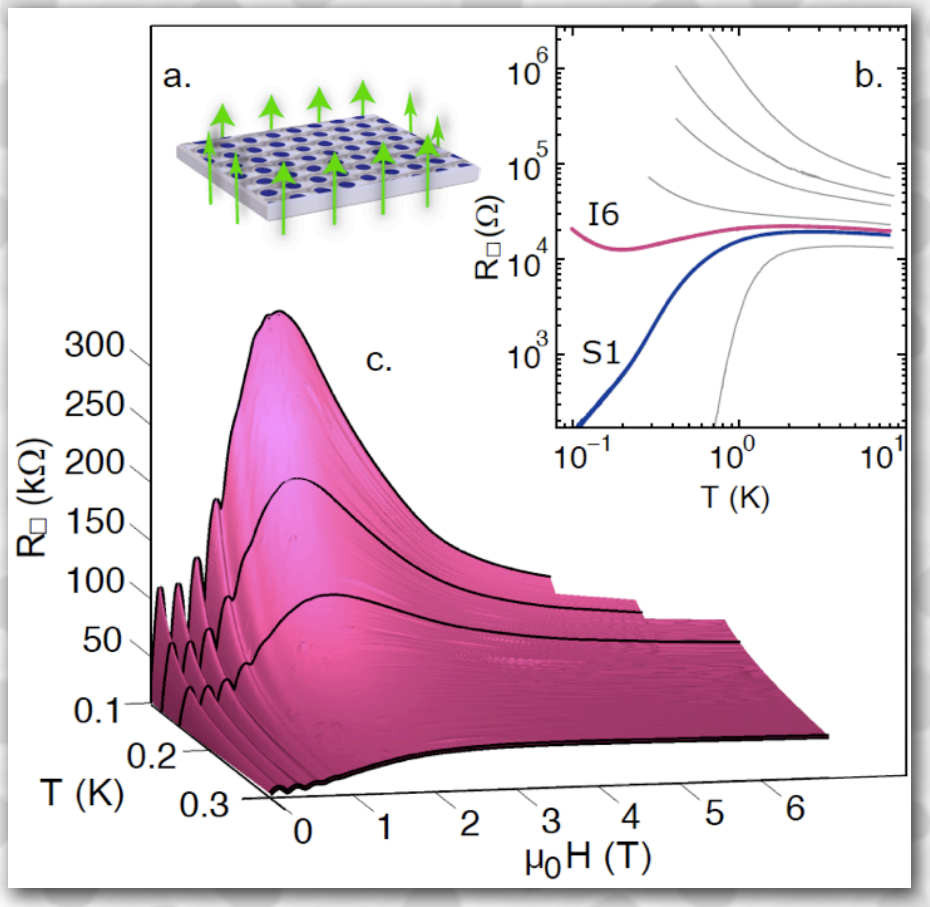
   ⇒ Cooper pairs in insulator

2) Activation energy oscillates

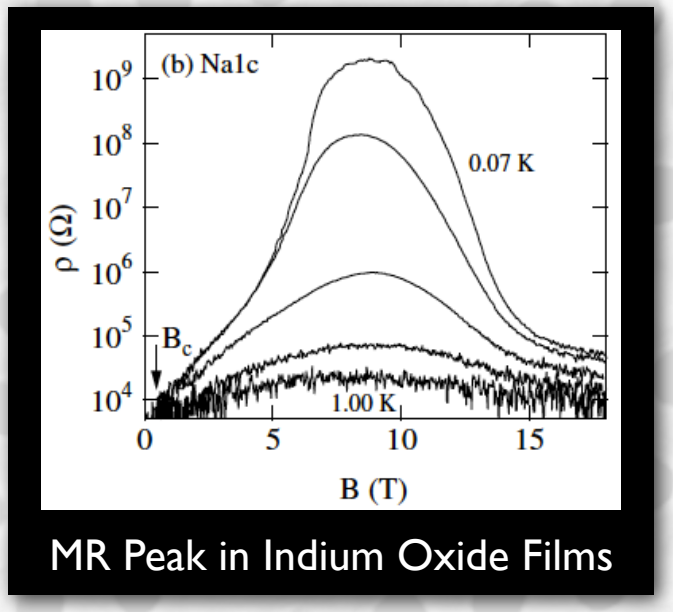
   ⇒ Cooper pair transport

MD Stewart et al., Science 318, 1273-1275 (2007)

Hilly AAO Films - High Magnetic Fields



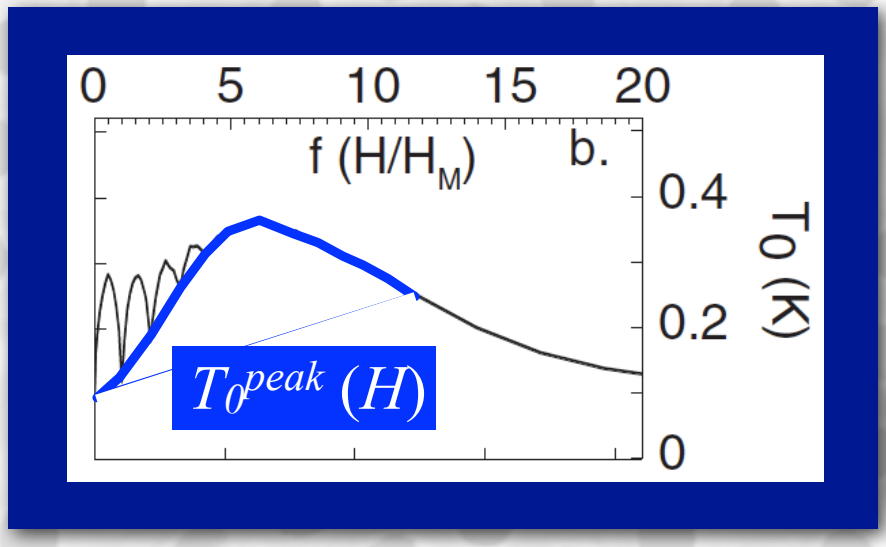
HQ Nguyen, SM Hollen et al., Phys. Rev. Lett. **103**, e157001 (2009)



MR Peak in Indium Oxide Films

Sambandamurthy et al., Phys. Rev. Lett. (2004)

Activation Energy in Magnetic Field



Composed of two terms:

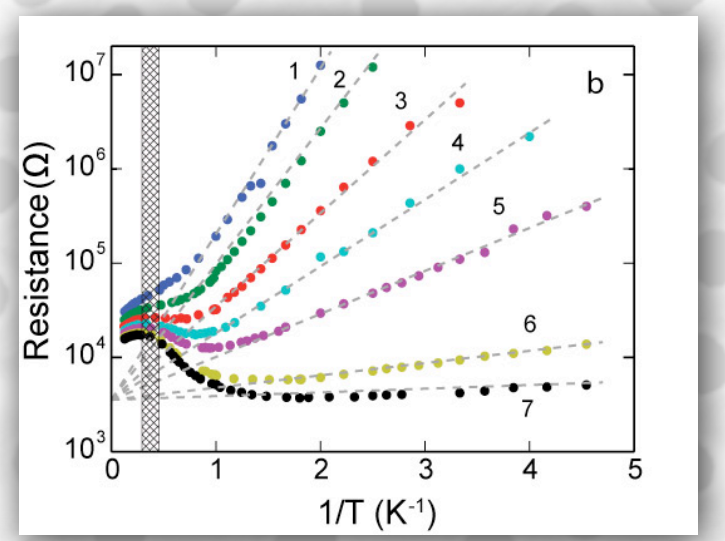
$$T_0(H) = T_0^{peak}(H) + T_0^{osc}(H)$$

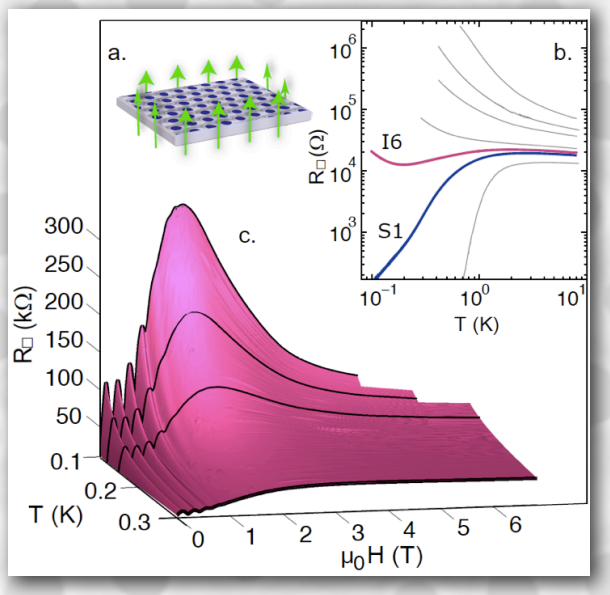
$$-E_J|\cos(\phi_i - \phi_j - 2\pi A_{ij}/\Phi_0)|$$

a-Bi on Hilly AAO

Insulator:

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

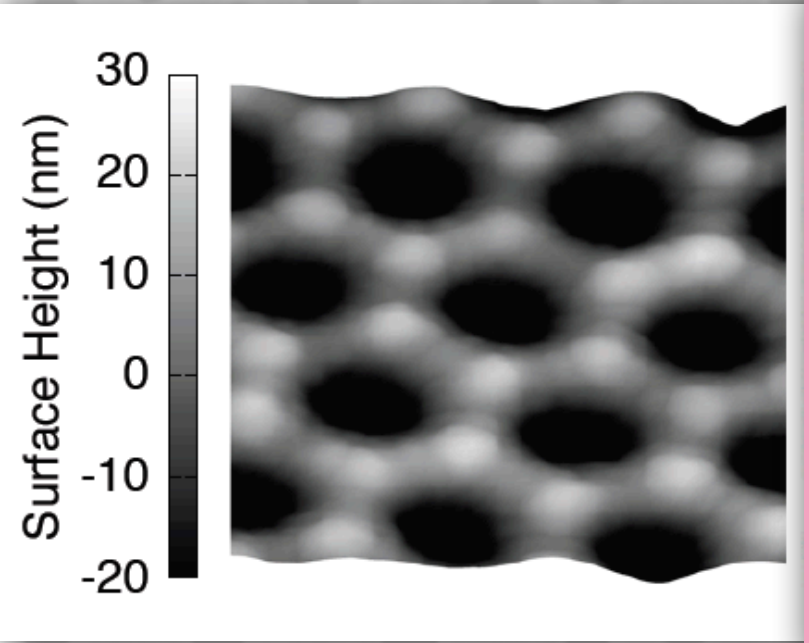




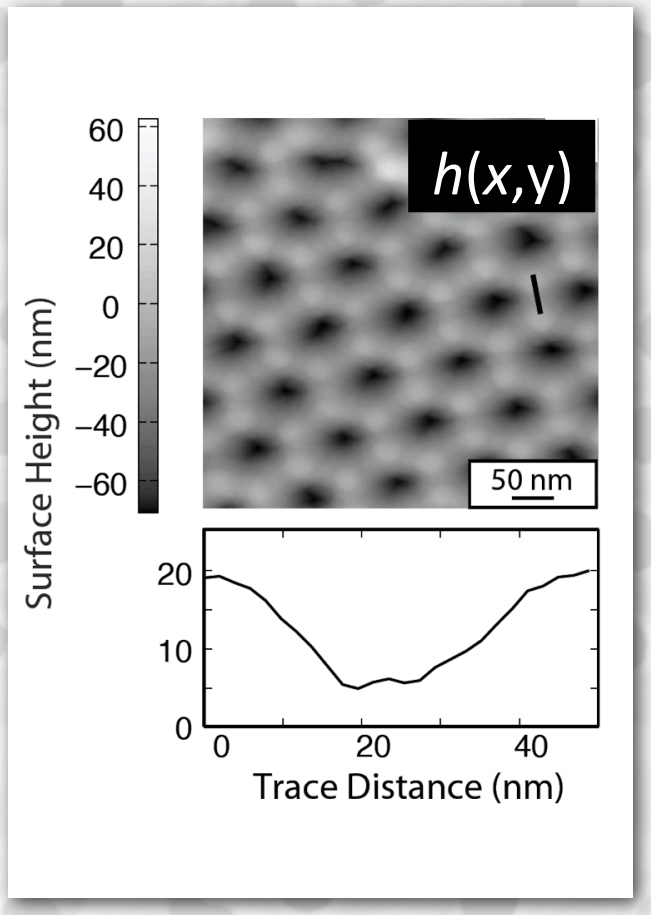
Magneto-resistance oscillations in Insulator and Superconductor

Superconductor to Cooper Pair Insulator Transition

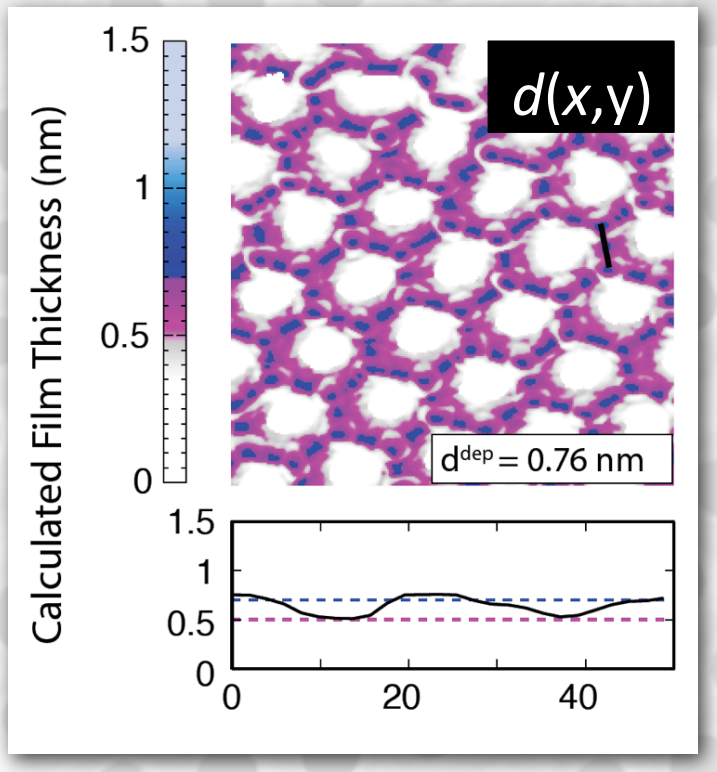
What's Localizing the Cooper Pairs?



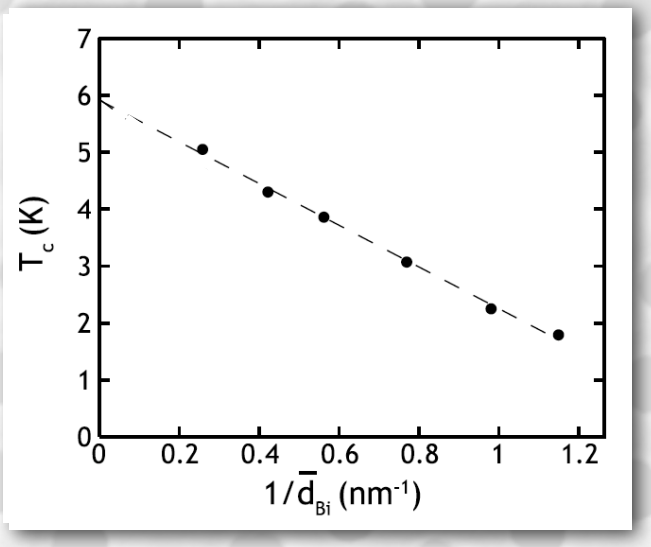
Film Thickness Variations



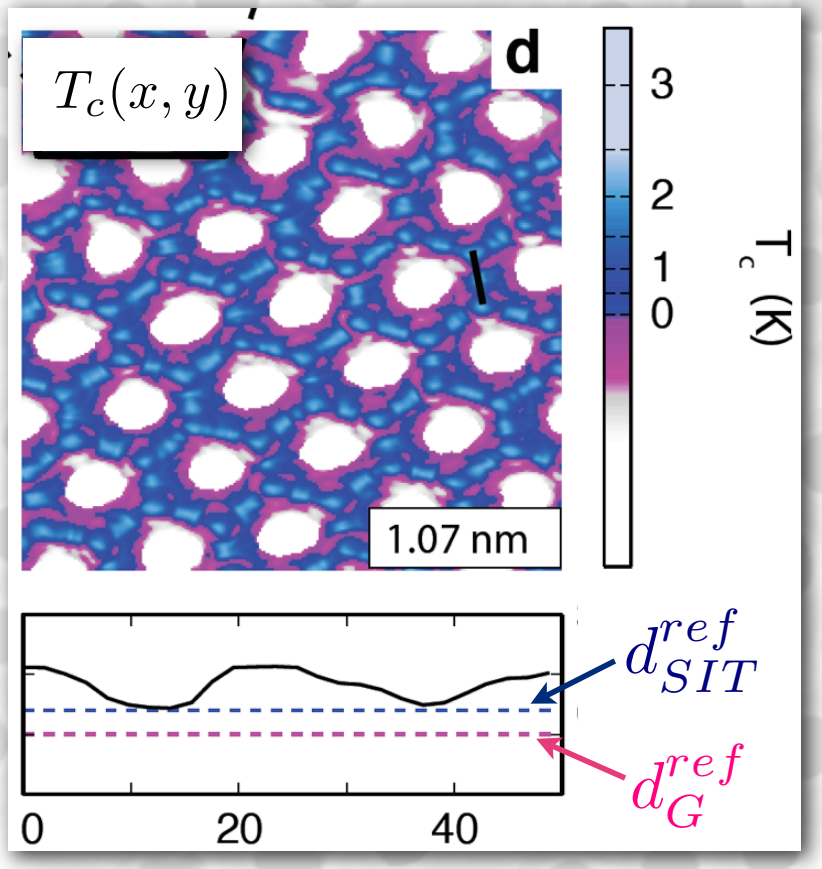
$$d(x,y) = d^{ref}\frac{1}{\sqrt{1+(\nabla h(x,y))^2}}$$



T_c Map



$$T_c(x,y) = T_{c,bulk}\left(1 - \frac{d_{SIT}^{ref}}{d(x,y)}\right)$$

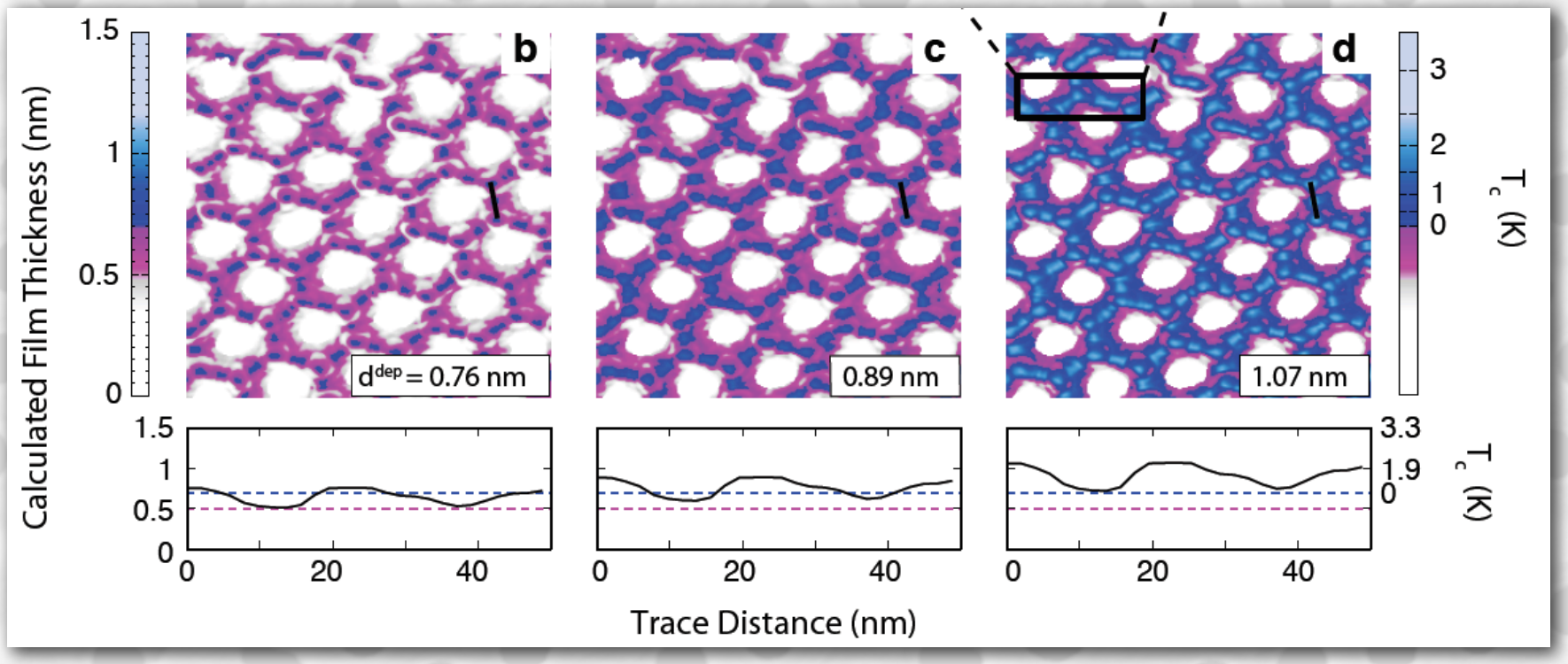


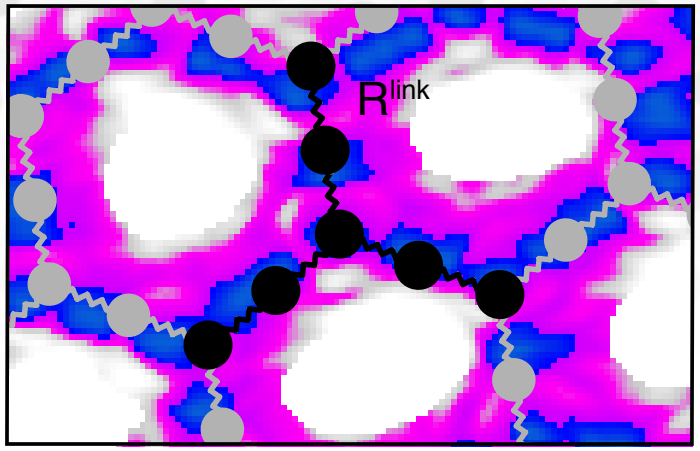
Coupling Constant Map thru the SIT

just conducting

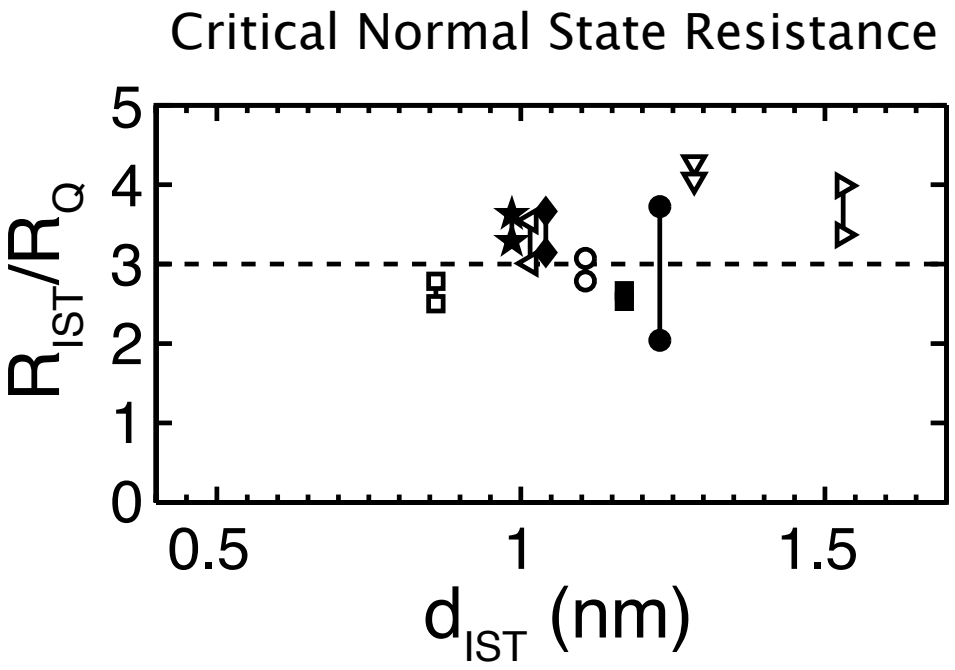
Cooper Pair Insulator

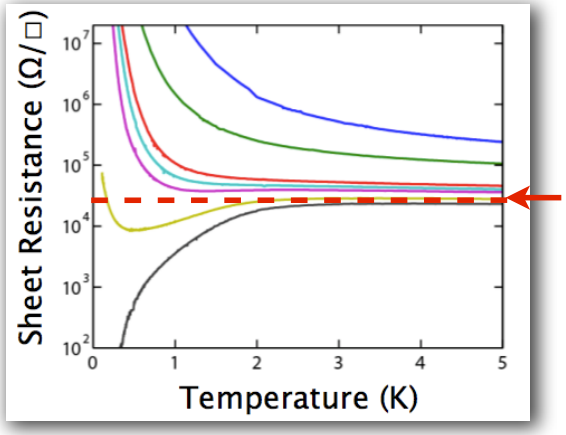
at SIT





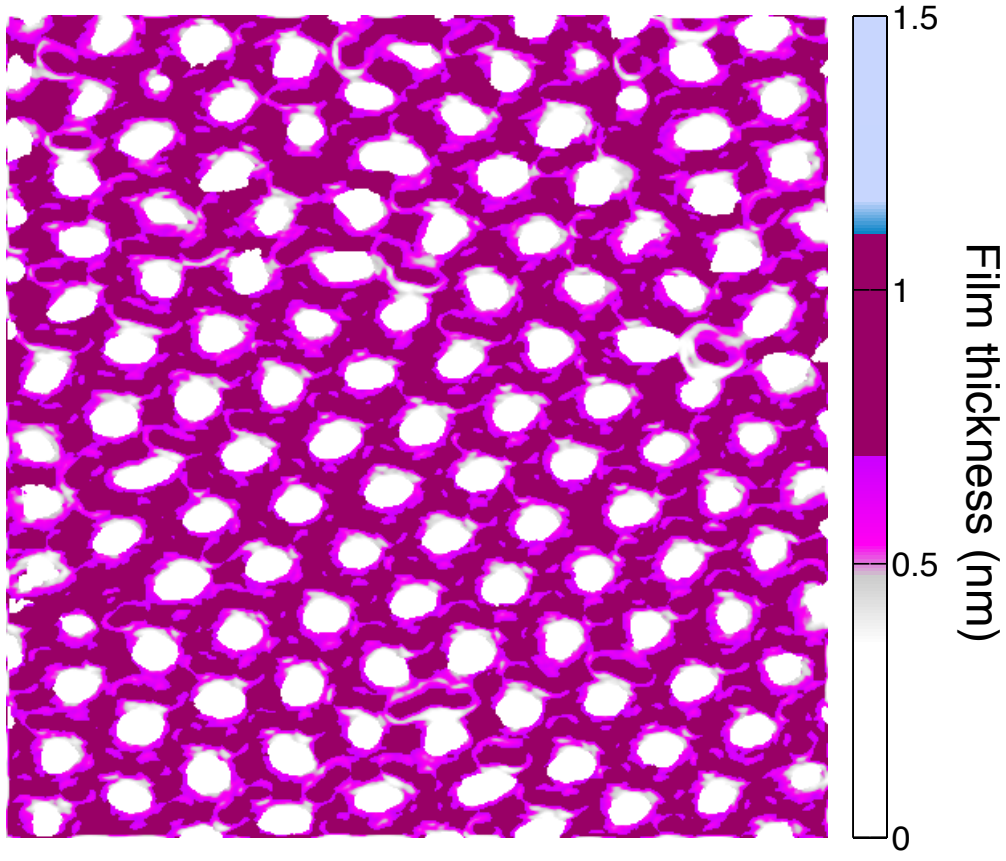
$$R_{\square} = 3R^{\text{link}}$$

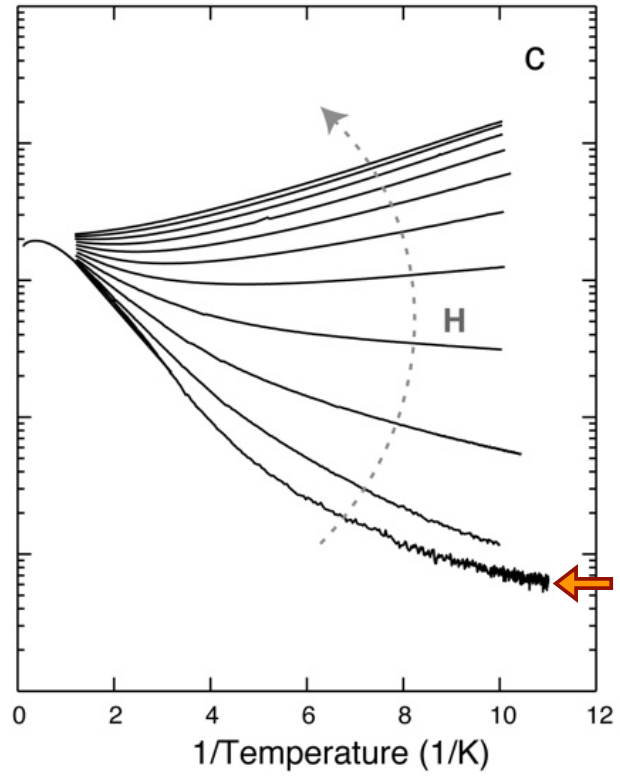


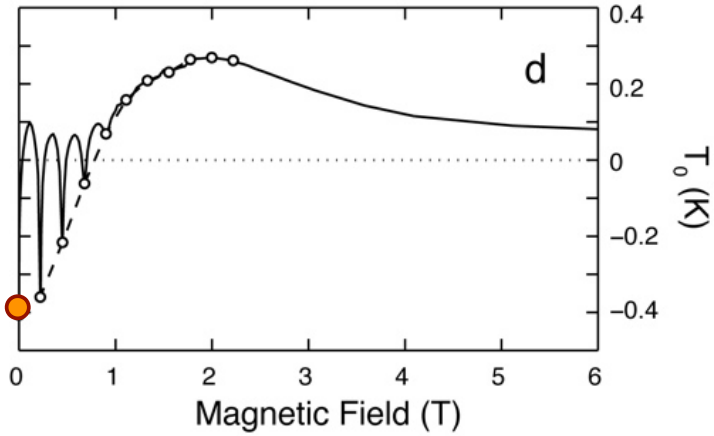


$$R^{\text{link}}_{IST} \approx R_Q$$

Islands in field



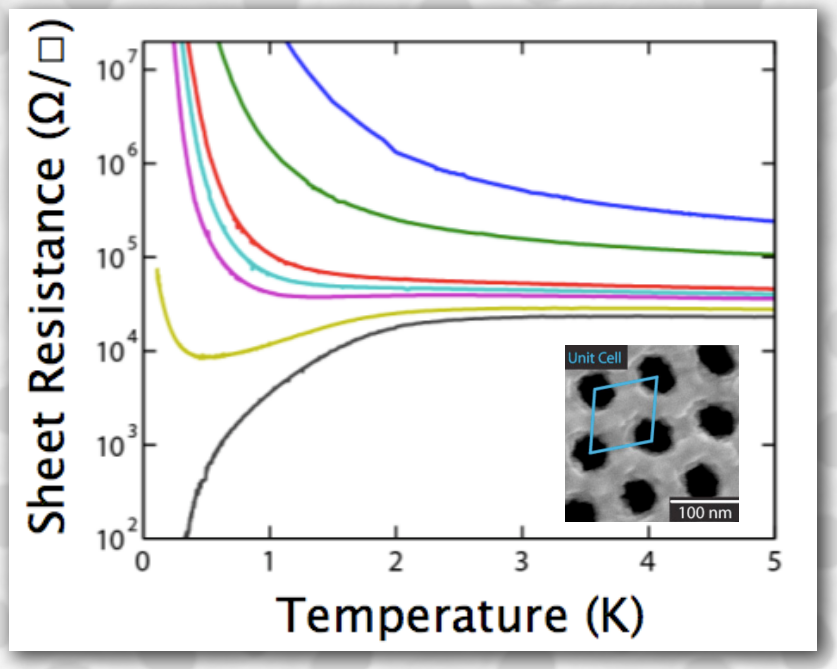




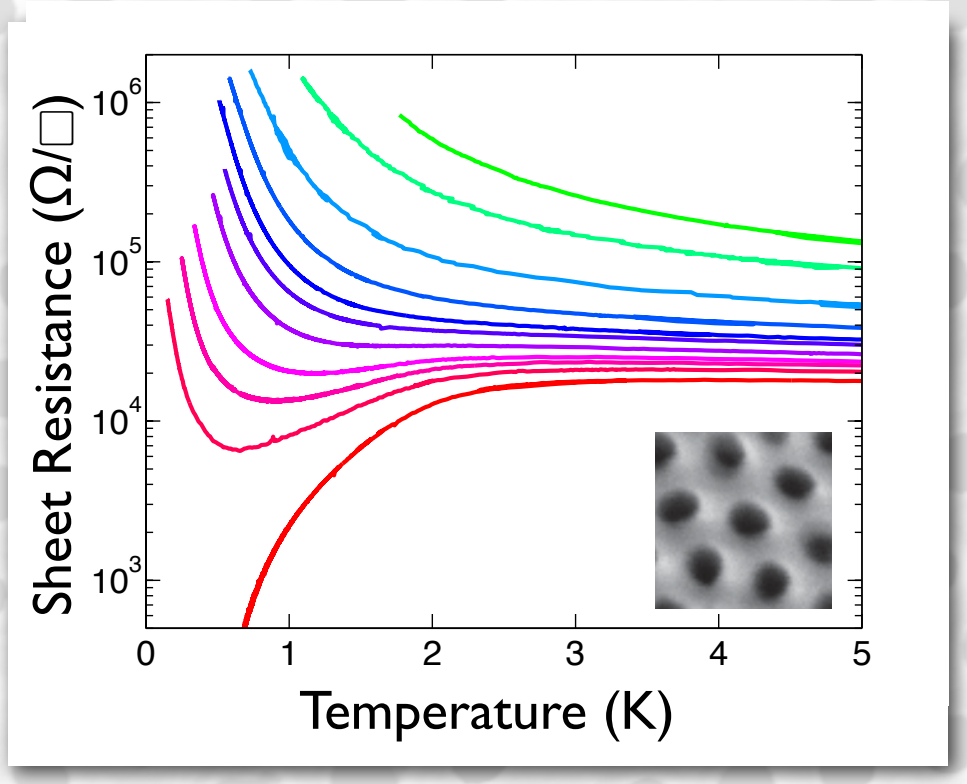
$$H_{c2} = 7.12\mathrm{T}(1 - 0.7\mathrm{nm}/d)$$

Inducing a CPI phase in a-$Pb_{0.9}Bi_{0.1}$ films

amorphous Bi



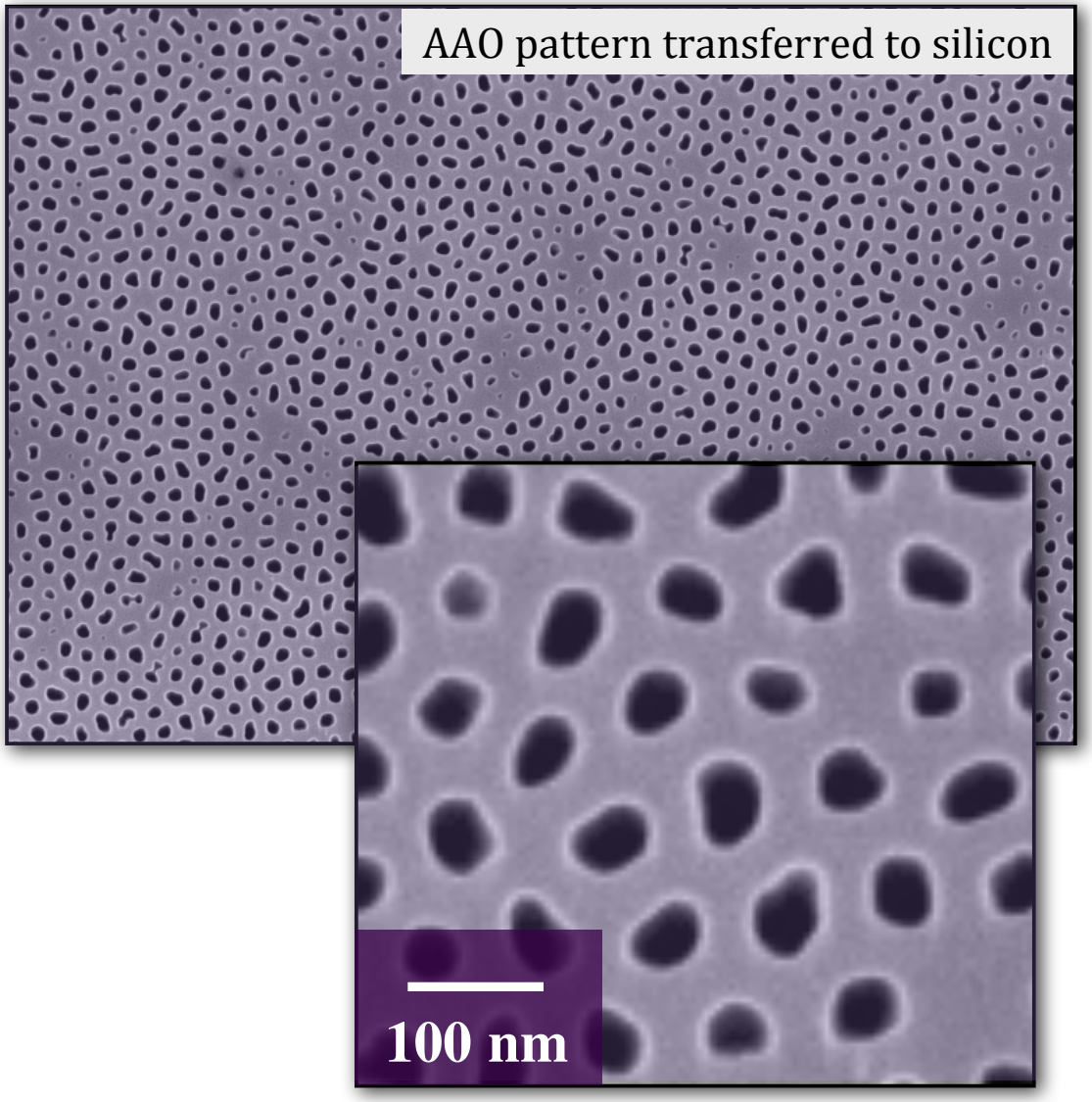
amorphous $Pb_{0.9}Bi_{0.1}$



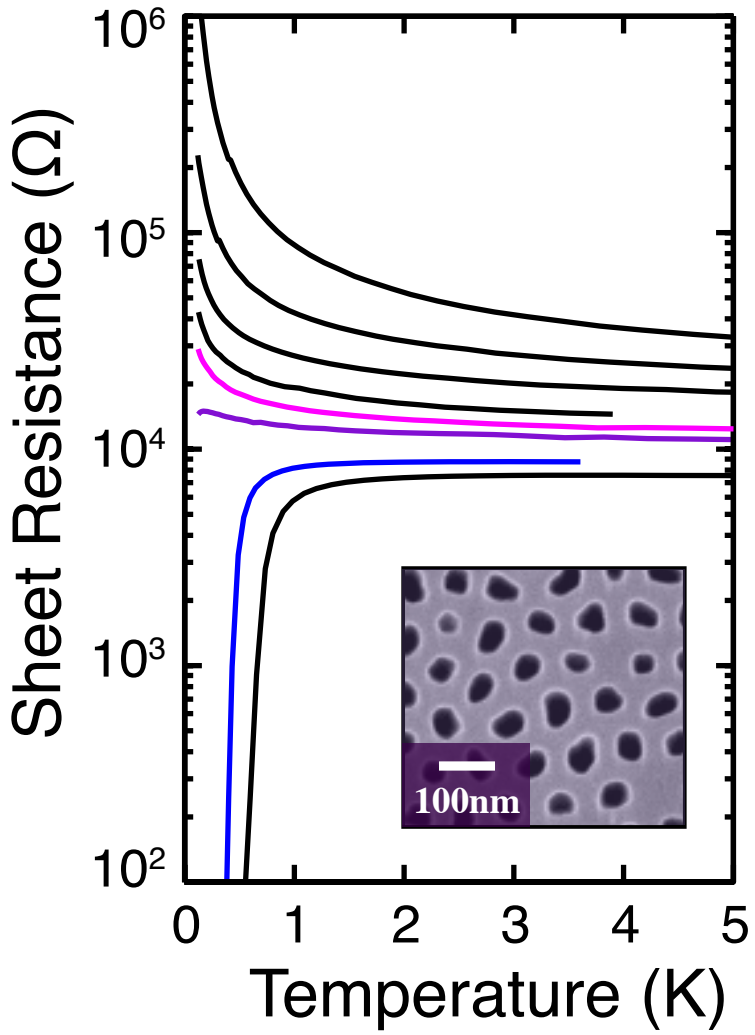
✓ **SITs of a-PbBi films are qualitatively similar to a-Bi**

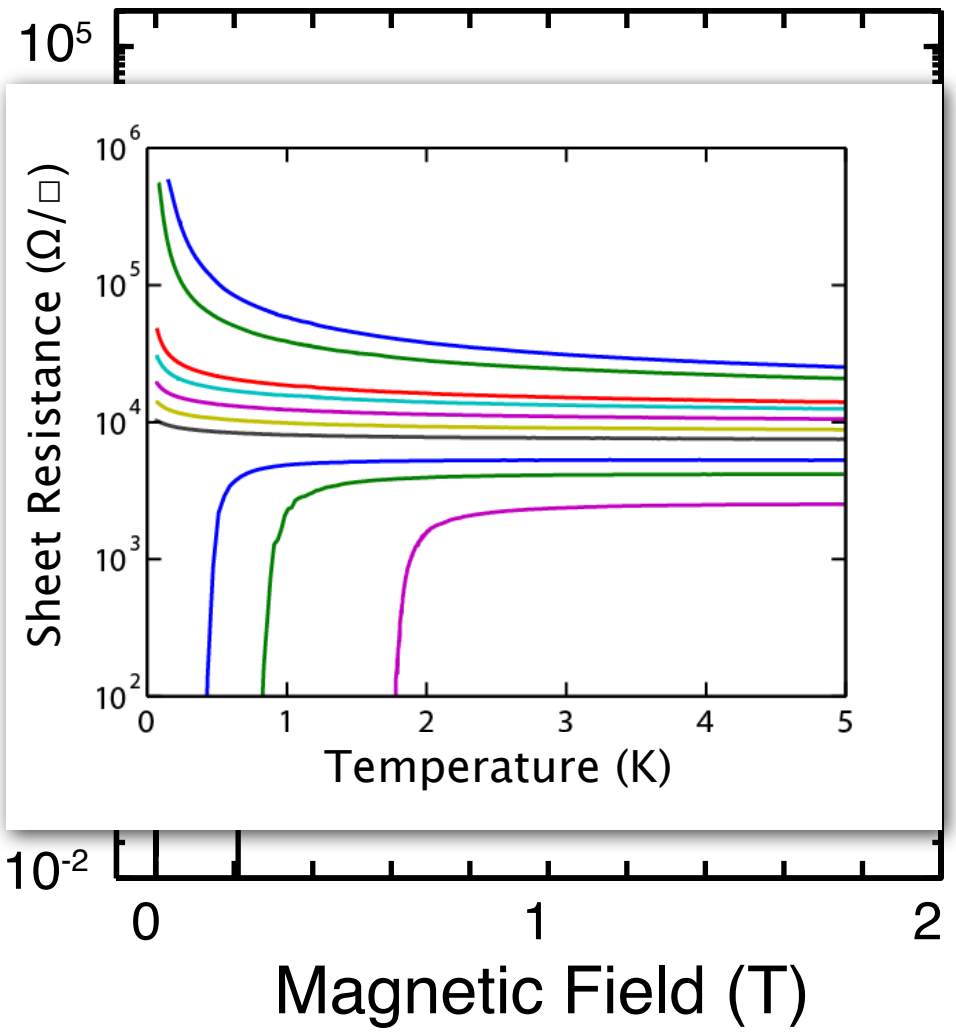
Flat holey substrates

- Films will be uniform, like those on glass
- Hole array allows for Cooper Pair detection



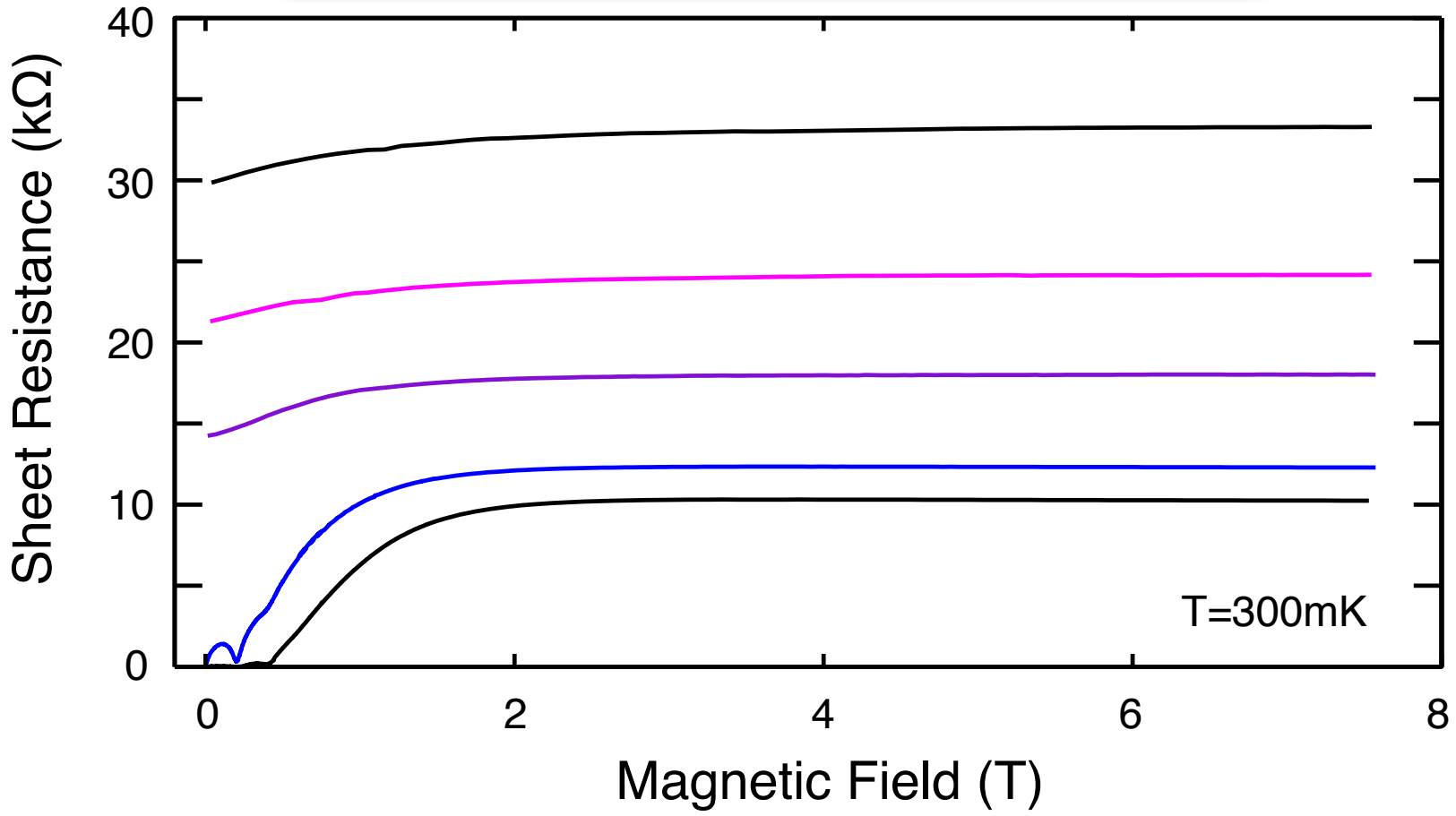
a-Bi films on Flat Si





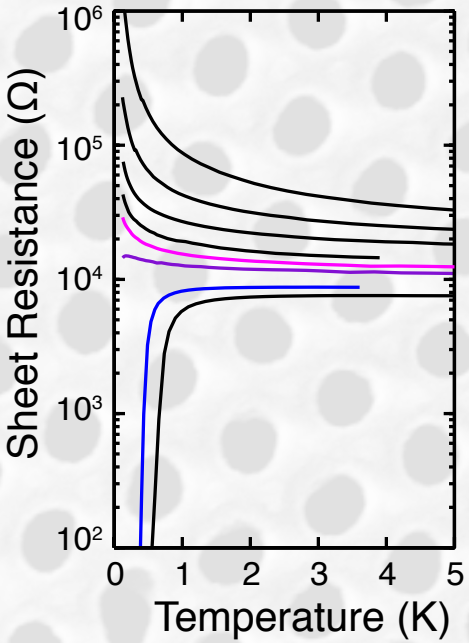
a-Bi films on Flat Si

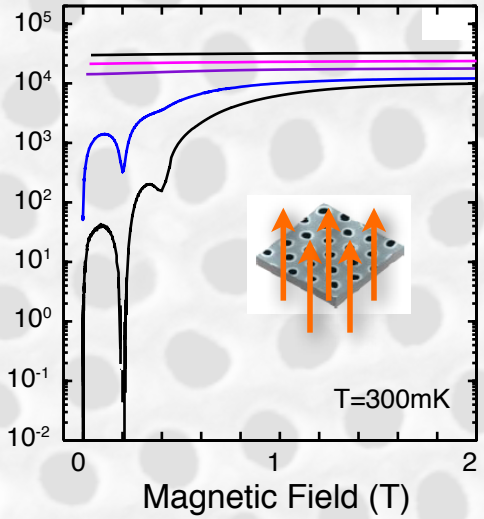
also, no magnetoresistance peak



a-Bi on Flat Si

SIT resembles a-Bi on glass

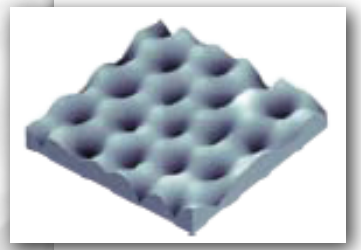


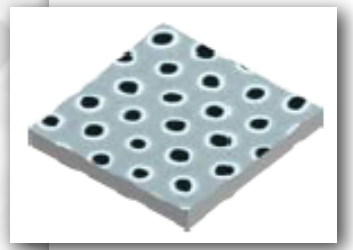


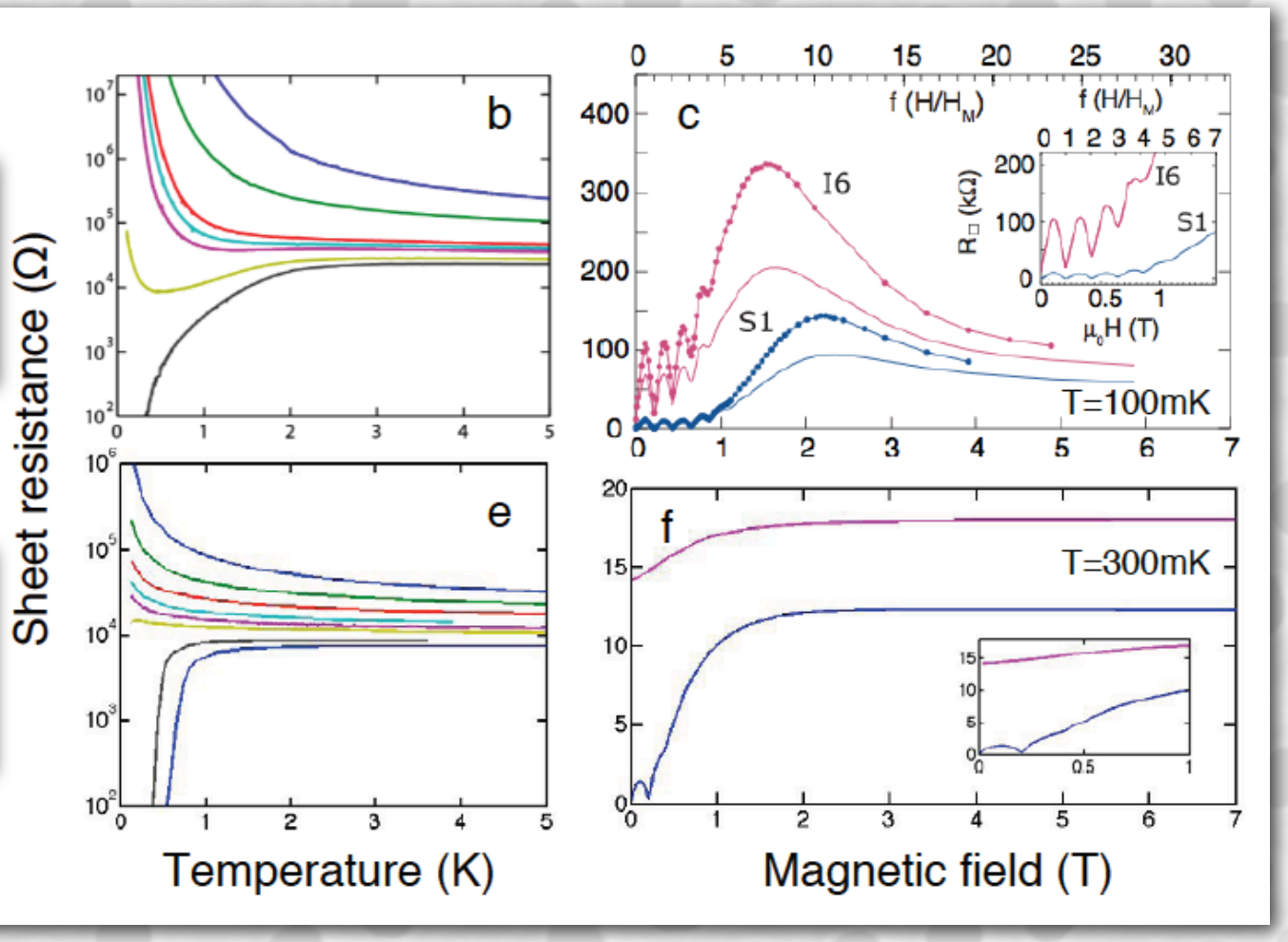
Magneto-resistance Oscillations *only* in Superconductors

Superconductor to Unpaired Electron Insulator Transition

Disorder Tuned SITs in a-Bi Films

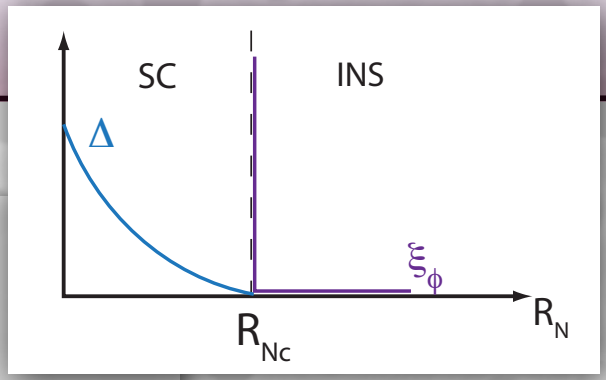






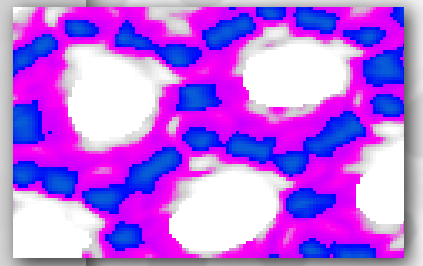
Bosonic and Fermionic SIT's using a single material!

Conclusions

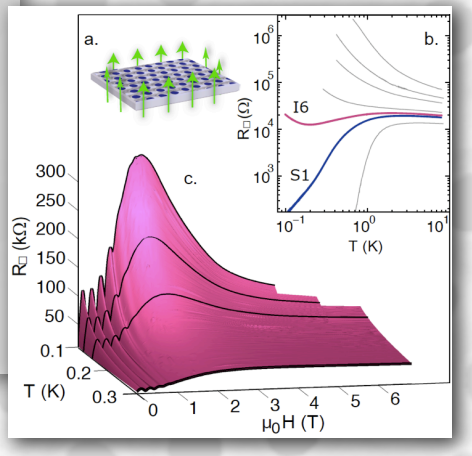


- Support for fermionic SITs

- NHC film undulations drive Cooper pair localization
  - -can create CPI in another material
  - -flat film exhibits fermionic SIT



- Undulation model:
  - -weak links control SIT
  - -SIT critical resistance is about $h/4e^2$
  - -qualitative explanation for MR peak



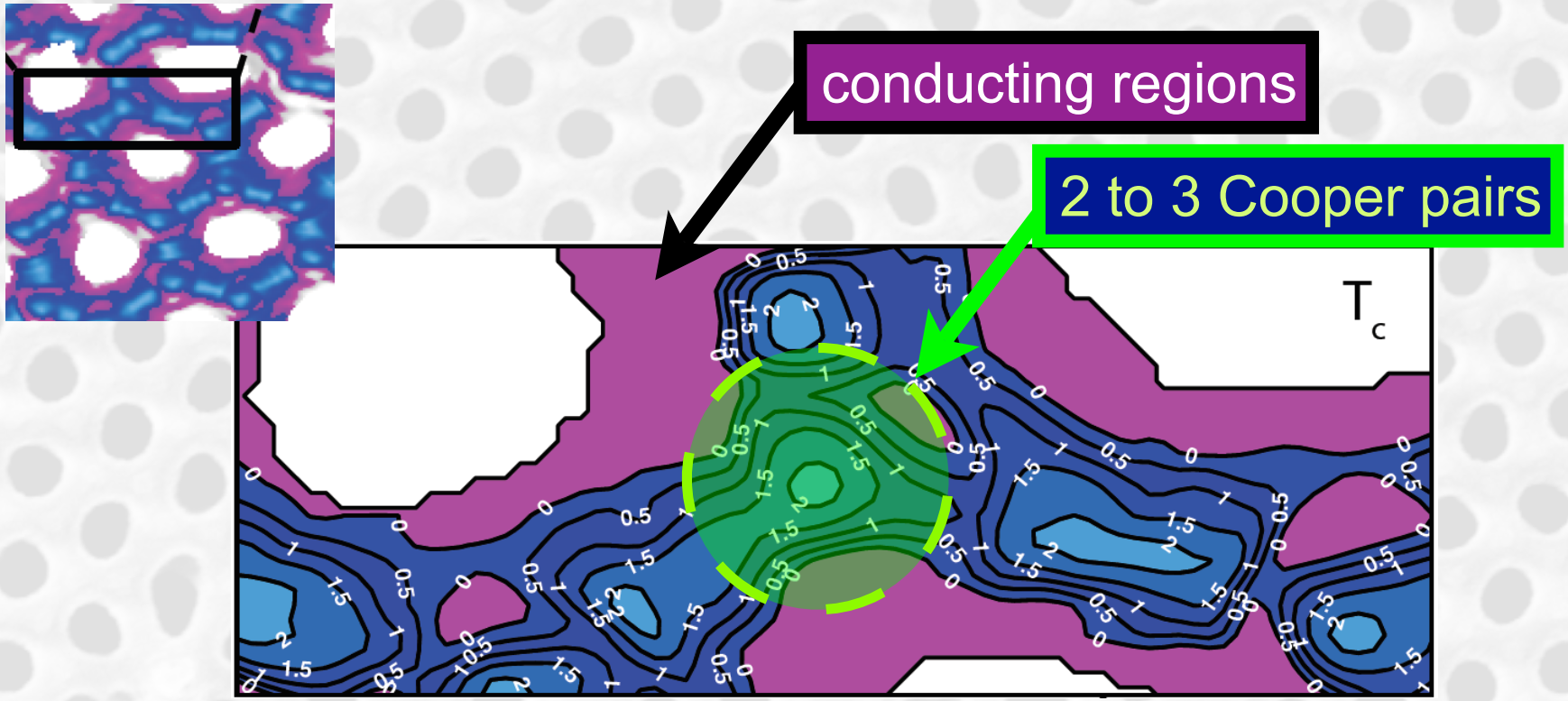
Questions

- How strong must undulations be to get a Cooper pair insulator?

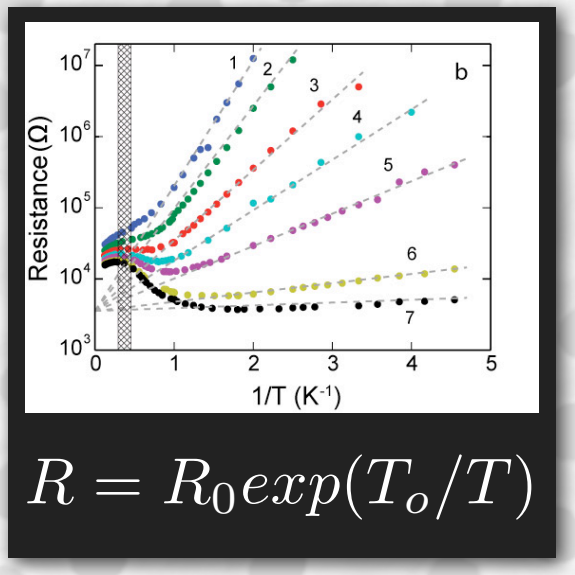
- Does "charging" or "disorder" control the insulating gap?

- How large are the localized Cooper pair states?

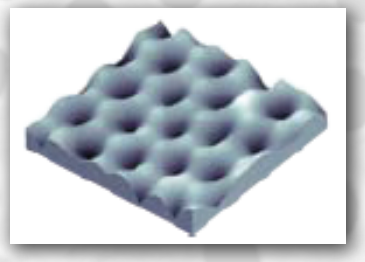
Critical Undulation Strength for CPI?

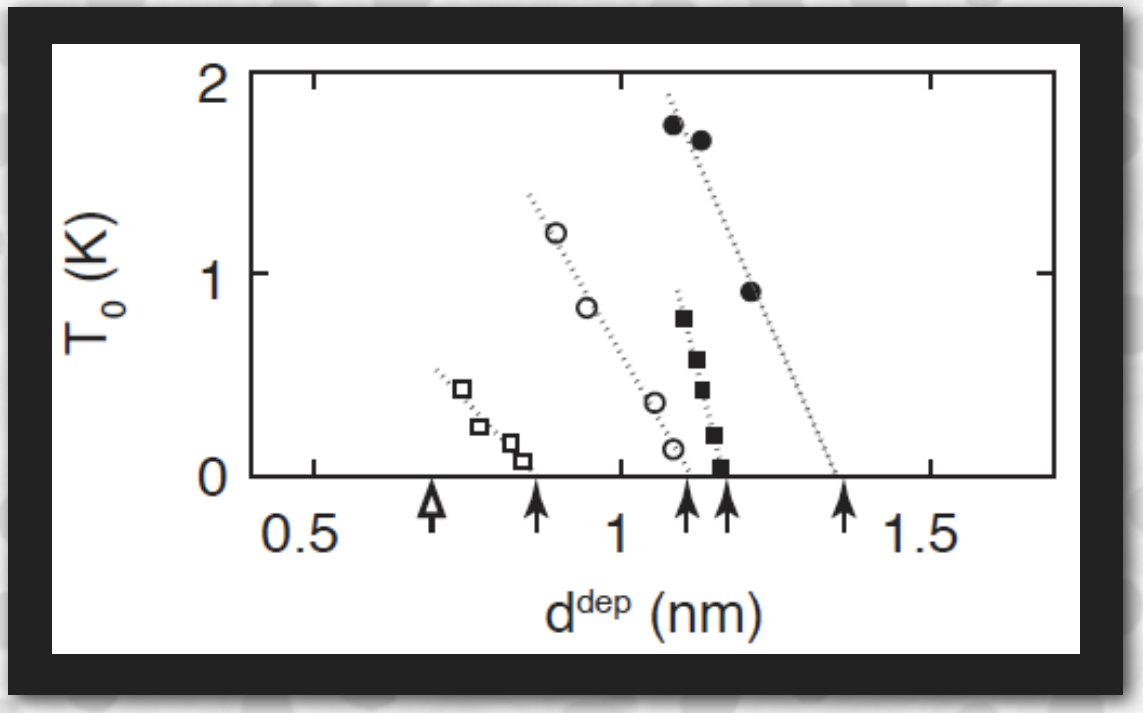


Is the gap from charging or disorder?

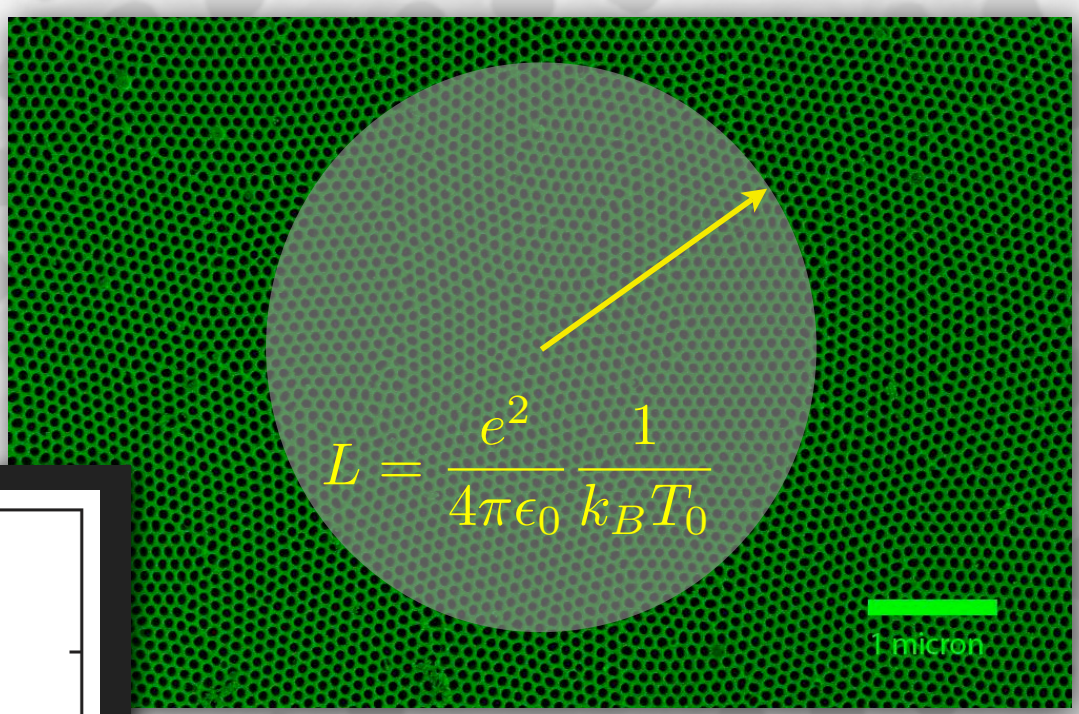


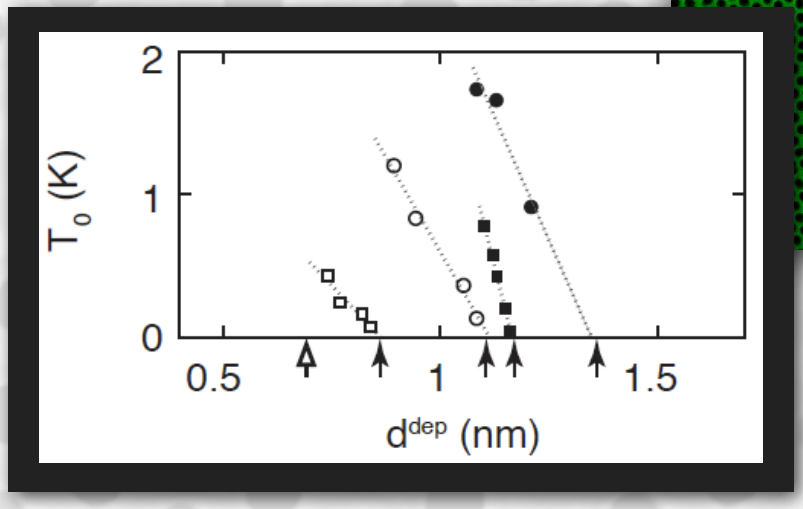
$$R = R_0 exp(T_o/T)$$





Size of the Localized States?





for charging energy dominating and T_0~0.5 K