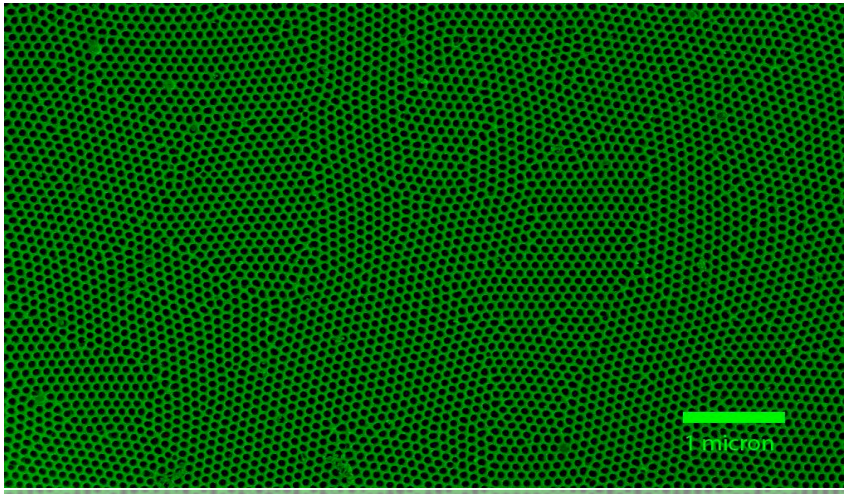
Localized Cooper Pairs in Nano-honeycomb Films



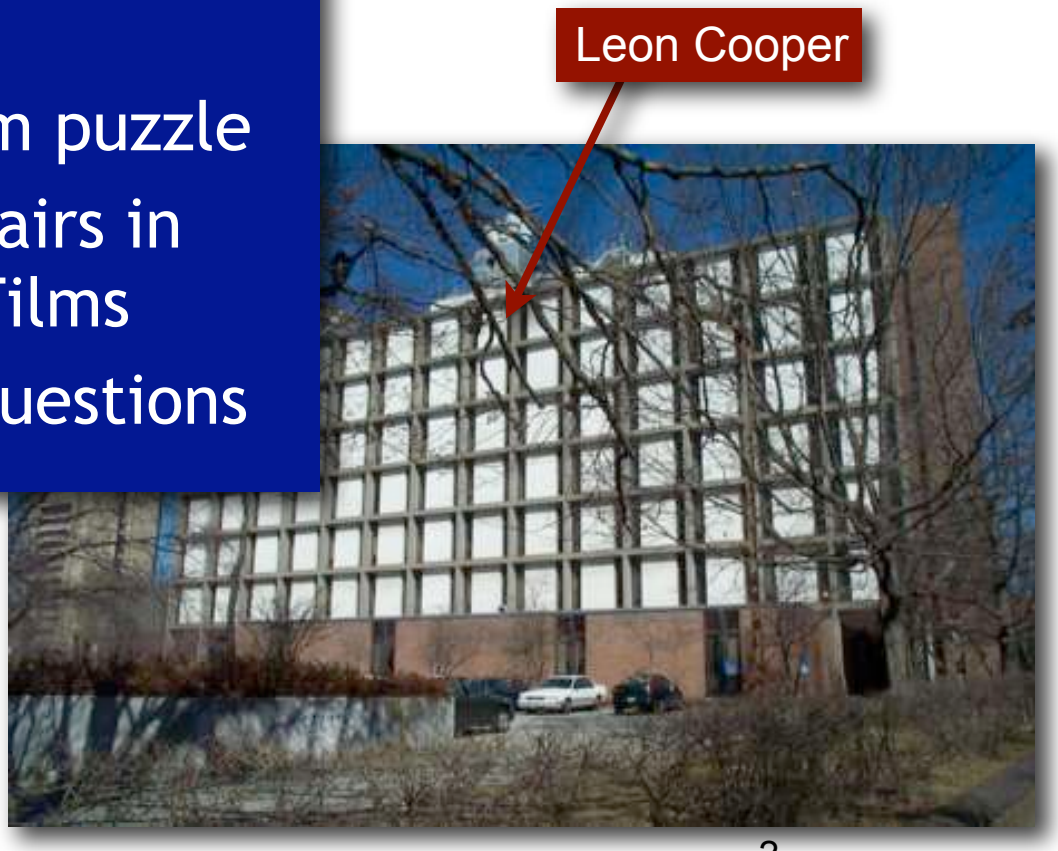
Michael Stewart, Hung Nguyen, Shawna Hollen, Jimmy Xu, Aijun Yin, Jeff Shainline

James Valles, Brown University

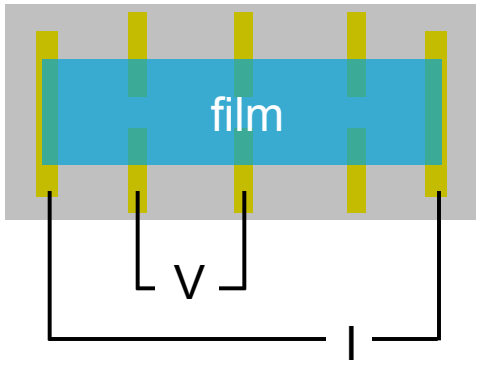
KITP Low Dimensions Conference, Feb 27, 2009

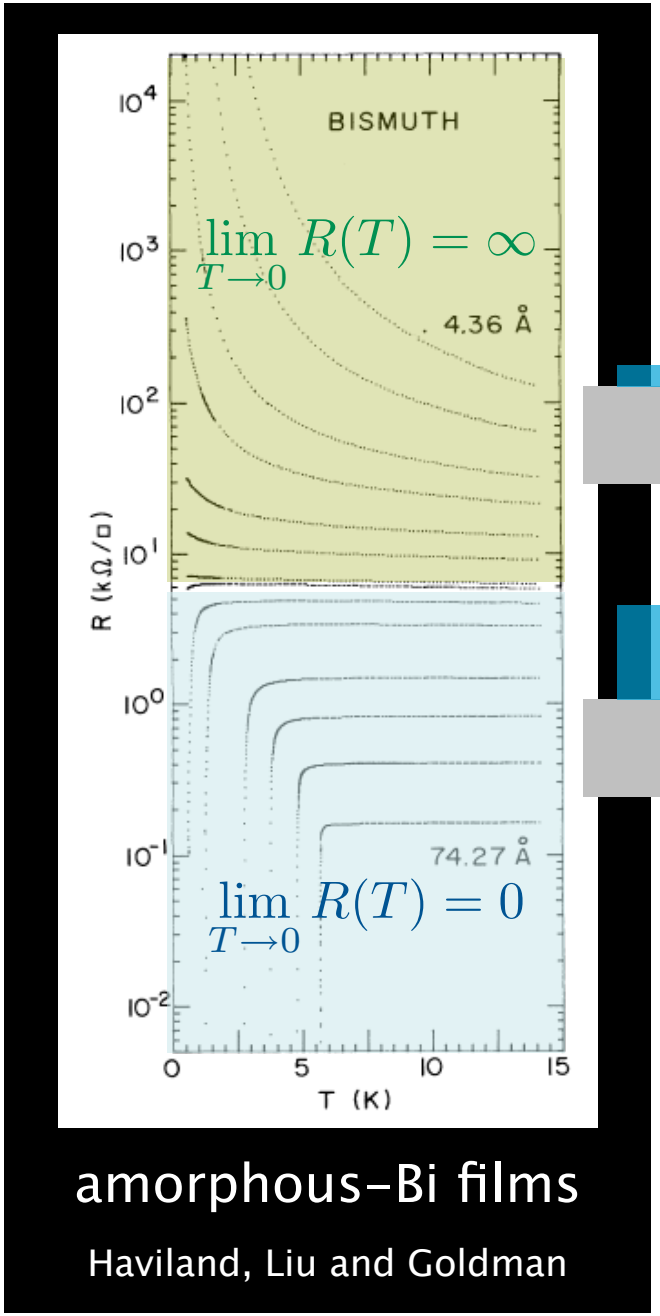
Localized Cooper Pairs in Nano-honeycomb Films

- Superconductor Insulator Transitions (SIT's)
- The amorphous film puzzle
- Watching Cooper Pairs in Nano-honeycomb Films
- Comparisons and questions



Thickness tuned SIT





amorphous-Bi films

Haviland, Liu and Goldman

What's the insulating phase?

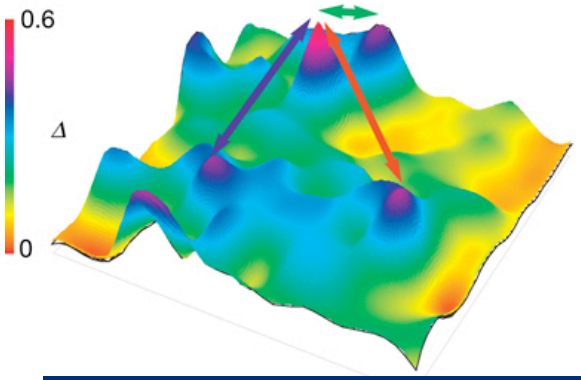
localized Cooper pairs (bosons)

or

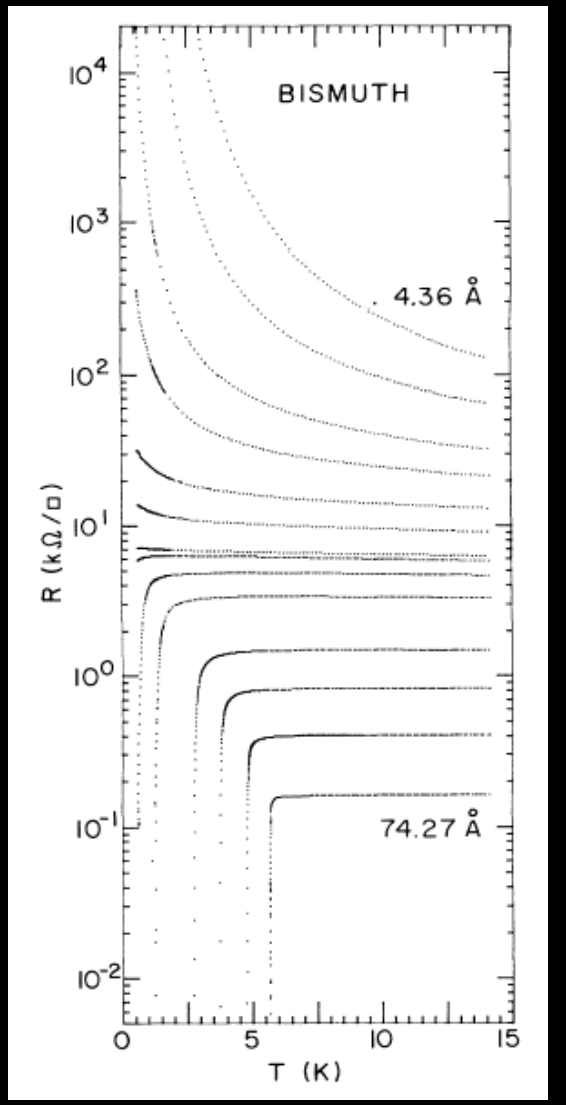
localized electrons (fermions)

or

novel mixture



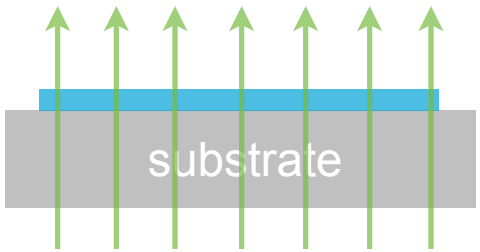
Amplitude variations in a magnetic field
Yonatan Dubi, Yigal Meir & Yshai Avishai, Nature(2007)



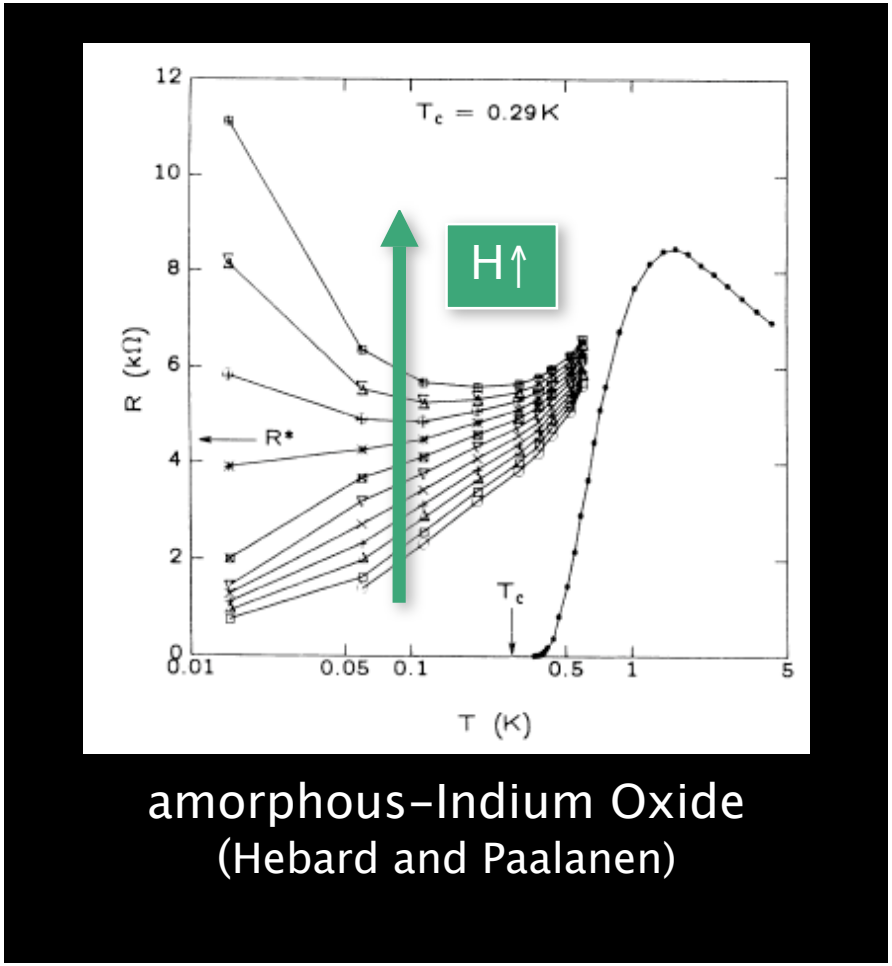
amorphous-Bi films

Haviland, Liu and Goldman

Magnetic Field Tuned SIT

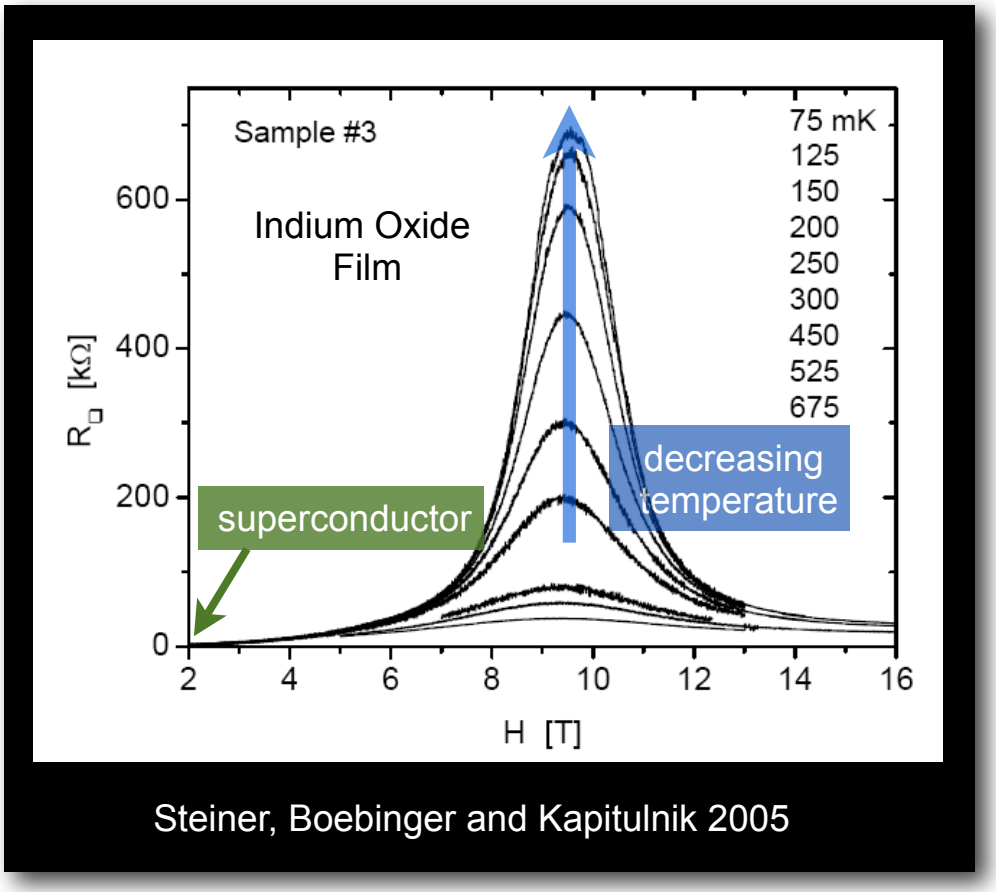


magnetic field, H



amorphous-Indium Oxide
(Hebard and Paalanen)

Spectacular Peaks...



Steiner, Boebinger and Kapitulnik 2005

Destroying Superconductivity

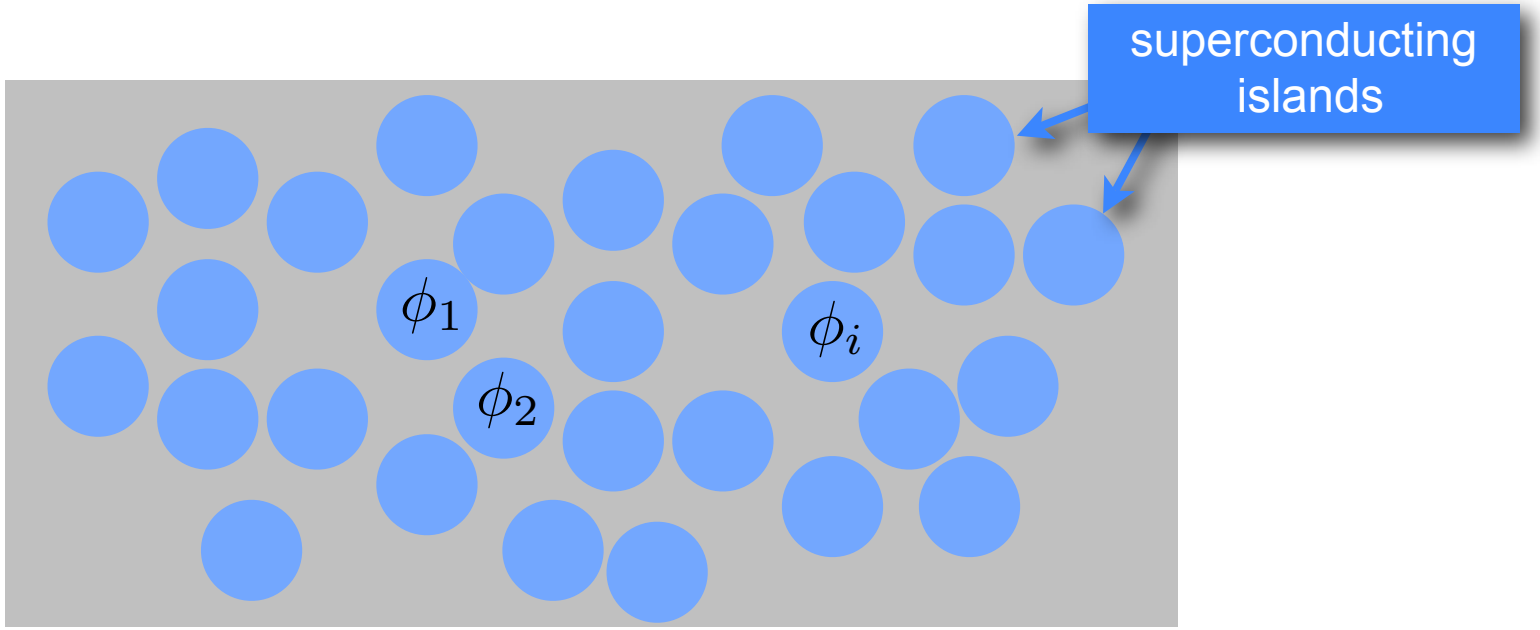
$$\Psi = \Delta^{1/2} e^{i\phi}$$

Create phase fluctuations

$$\frac{\partial \phi_{12}}{\partial t} \propto V_{12} \neq 0 \quad \text{and} \quad \nabla \phi \propto J_s \neq 0$$

gives resistance, maintains pairing!

Imagine an islanded film

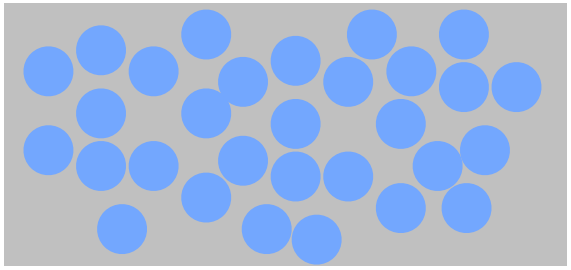


Does this film superconduct?

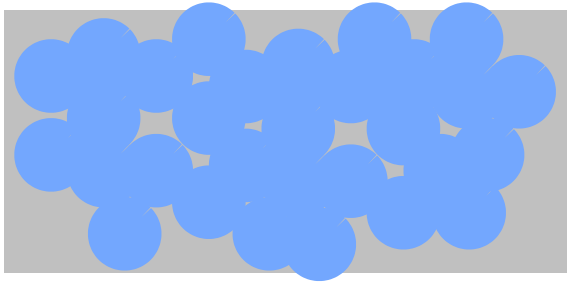
or, equivalently

Do the islands become phase coherent?

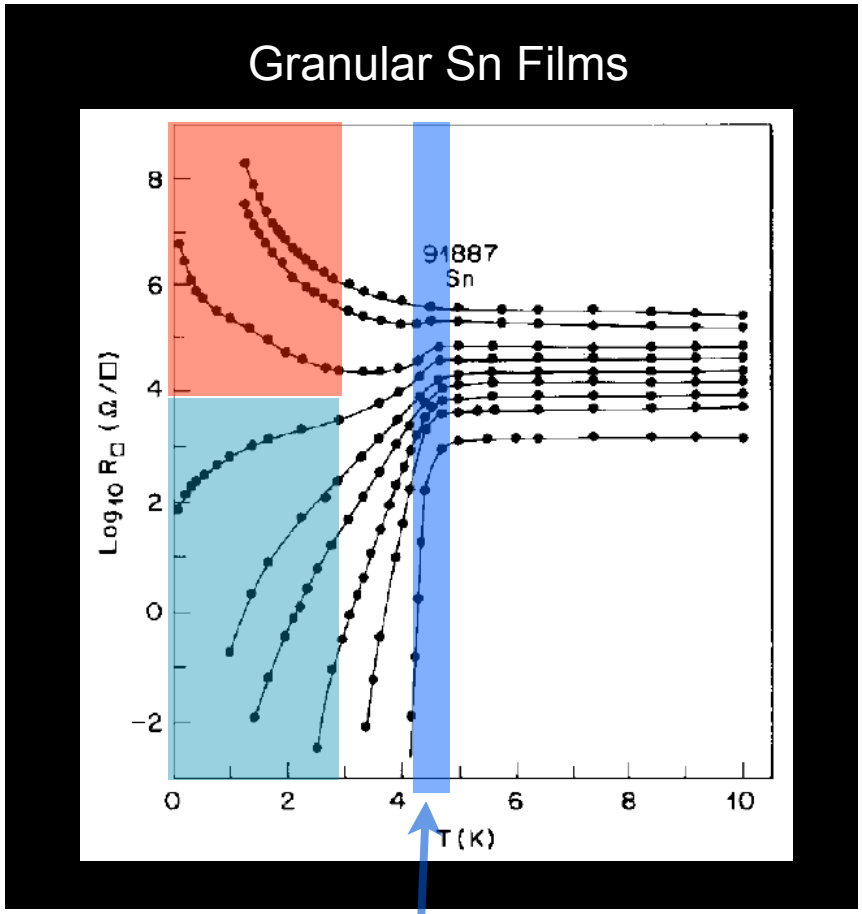
SIT via Phase Fluctuations



Insulating
phases on islands incoherent



Superconducting
phases on islands coherent



Island Tc is constant while phase fluctuates

SIT via Phase Fluctuations

Insulator:
Cooper pairs localized to islands

$$\delta N_{cp} = 0$$

Phase fluctuations large

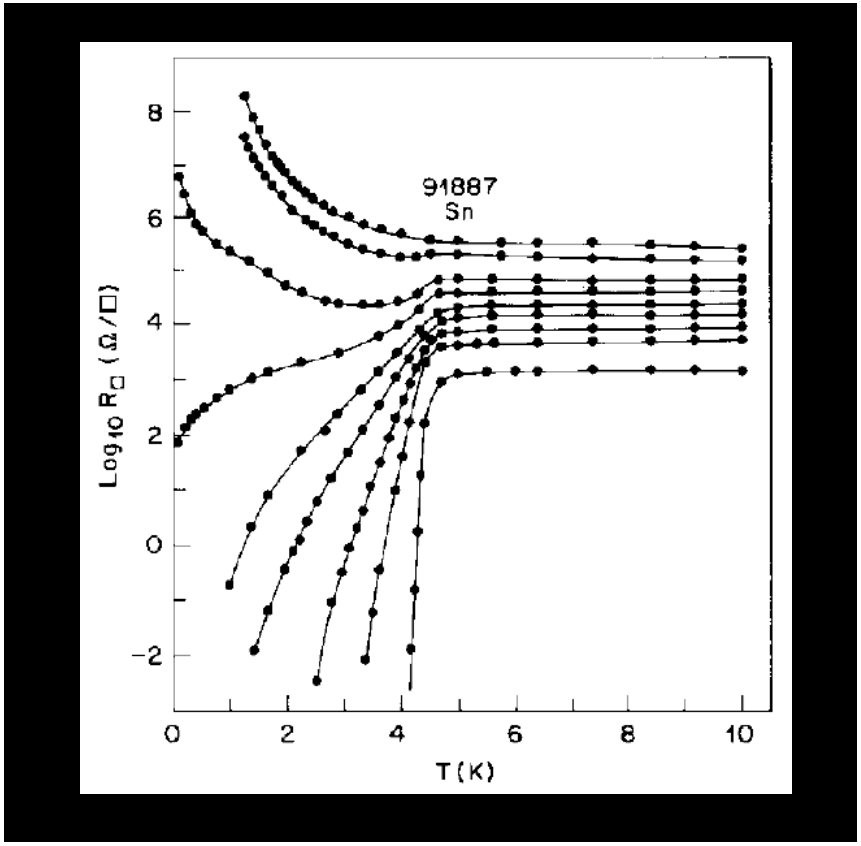
$$\delta\phi \neq 0$$

Superconductor:
Cooper pairs delocalized

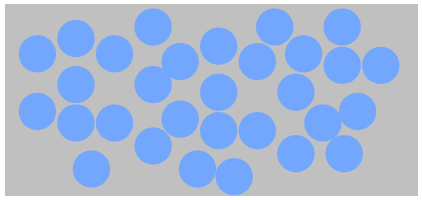
$$\delta N_{cp} \neq 0$$

Phase fluctuations small

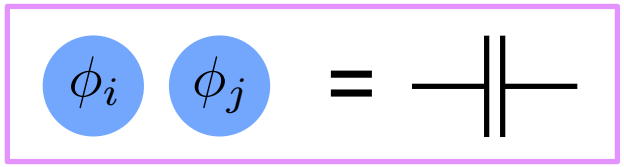
$$\delta\phi = 0$$



Phase and number uncertainty relation: $\delta N_{cp}\delta\phi \geq 1$



Josephson Junction Array (JJA) Model of the SIT



Model neighboring grains:
capacitance, *C* tunneling rate, E_J

$$H \sim \sum_{i,j} \left[\frac{(2e)^2}{C} N_{cp,i} N_{cp,j} - E_J(cos(\phi_i - \phi_j - A_{i,j})) \right]$$

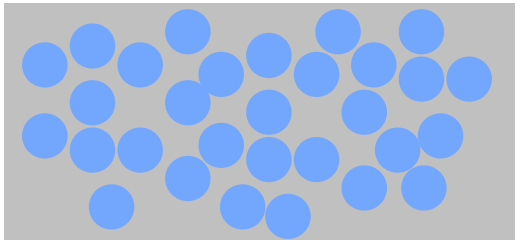
$$E_c = \frac{(2e)^2}{C} >> E_J$$

discourages charge fluctuations

$$E_J >> E_c$$

discourages phase fluctuations

JJA SIT Model

- Predicts bosonic insulators!
- Qualitatively works for 
- Does it work for all systems?

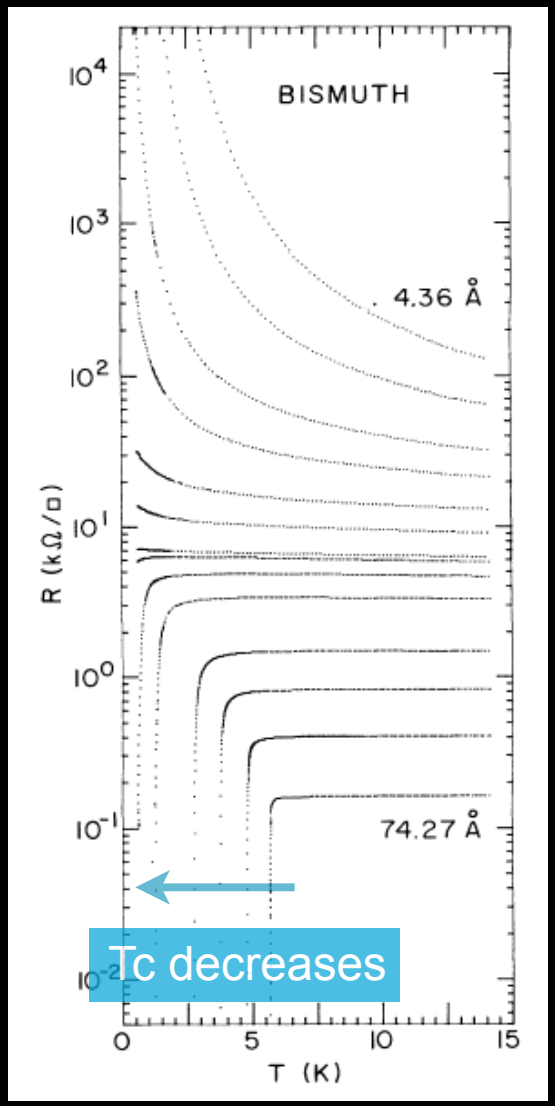
Destroying Superconductivity

$$\Psi = \Delta^{1/2} e^{i\phi}$$

Reduce the amplitude

$$\Delta \rightarrow \qquad T_c \rightarrow 0 \qquad n_{cp} \rightarrow 0$$

ground state of fermions



amorphous-Bi films

Haviland, Liu and Goldman

SIT via Amplitude Reduction?

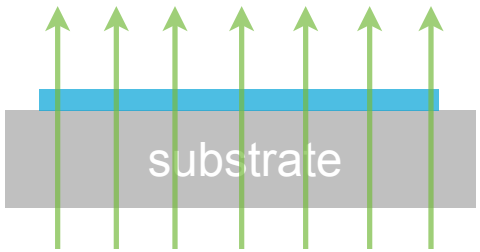
Thin **homogeneous**, **amorphous** films

high Tc low Tc

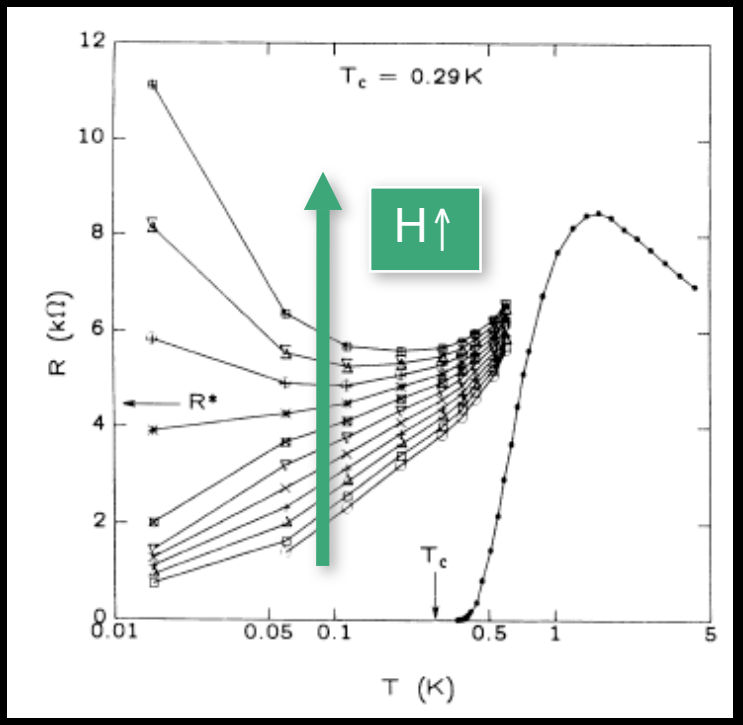
Idea: Decrease T_c by decreasing n_{sc} by decreasing the film thickness

suggests the insulator does not have pairs.....

But, amorphous Indium Oxide...



magnetic field, H

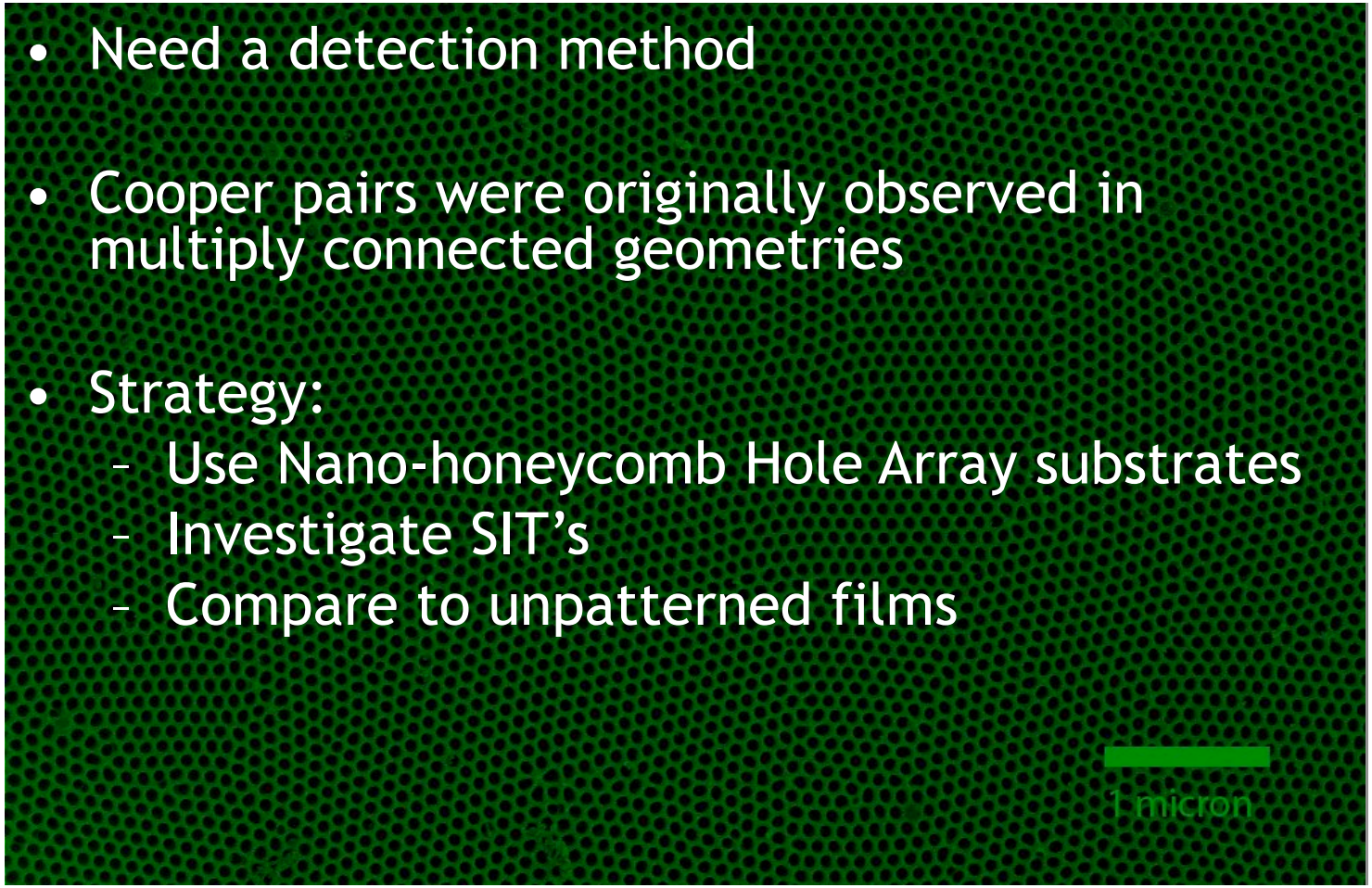


amorphous-Indium Oxide
(Hebard and Paalanen)

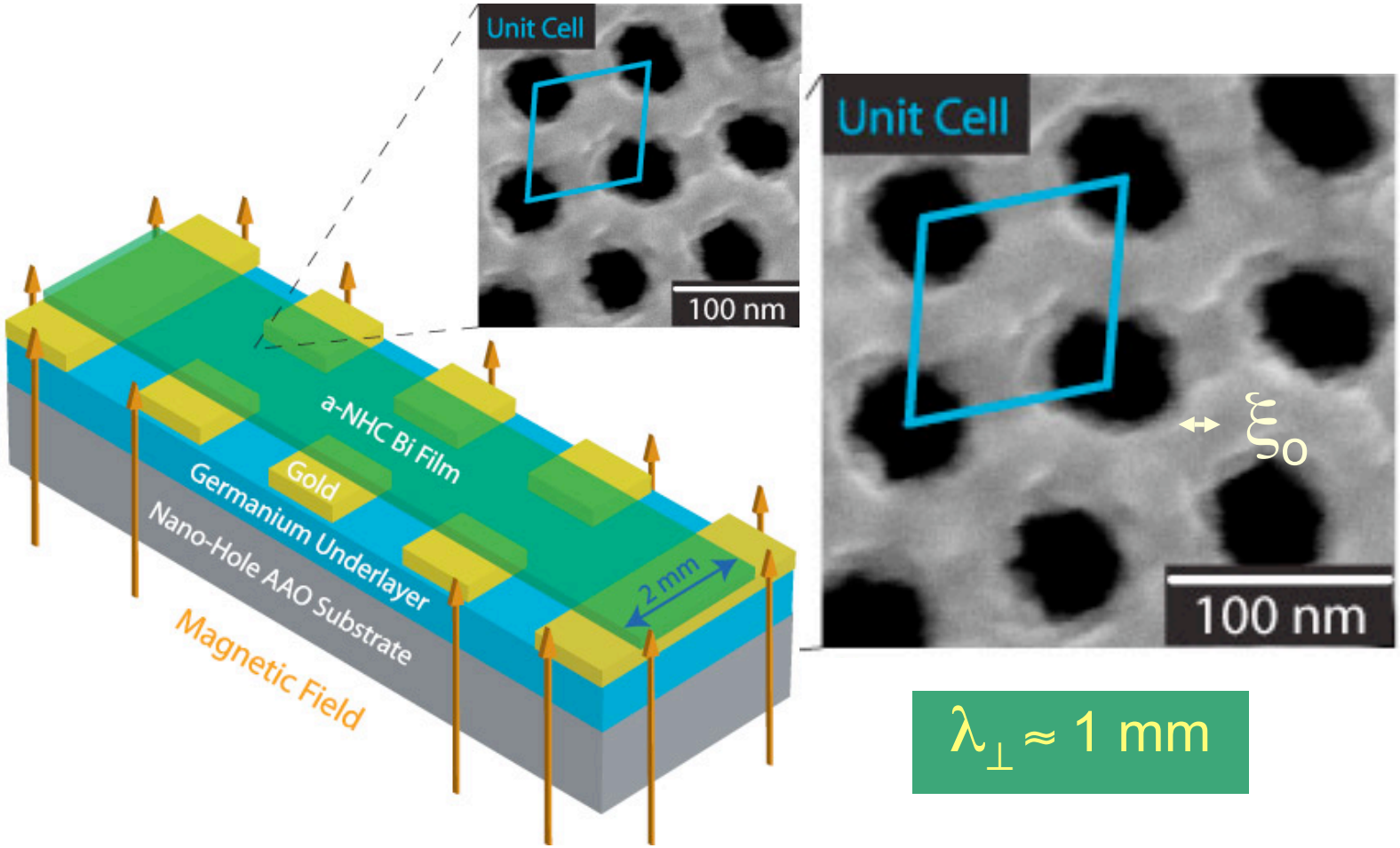
....looks like phase destruction

Cooper Pairs in amorphous films?

- Need a detection method
- Cooper pairs were originally observed in multiply connected geometries
- Strategy:
  - Use Nano-honeycomb Hole Array substrates
  - Investigate SIT's
  - Compare to unpatterned films

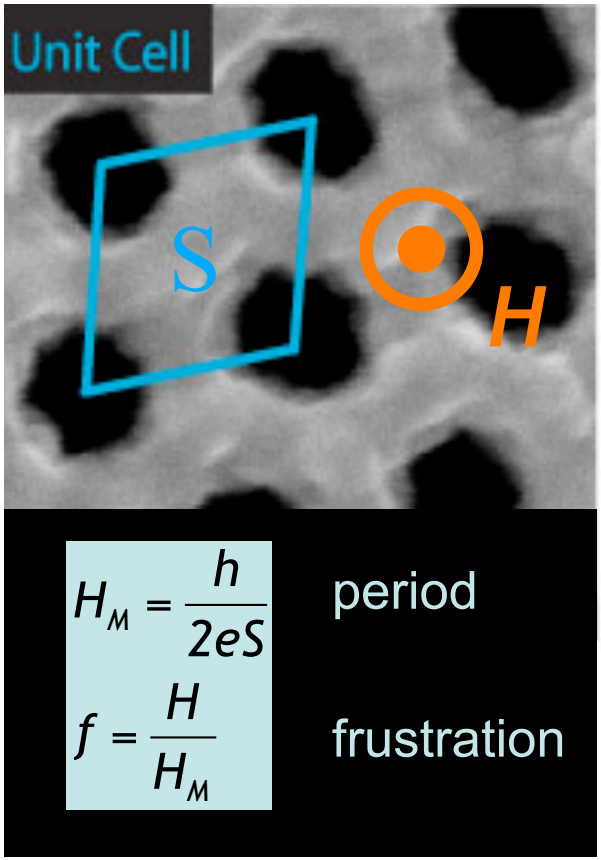


Nano-honeycomb Films



$\lambda_\perp \approx 1$ mm

Cooper Pair Detection (q=2e)



Charge in a magnetic field

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

Cooper pair phase obeys

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

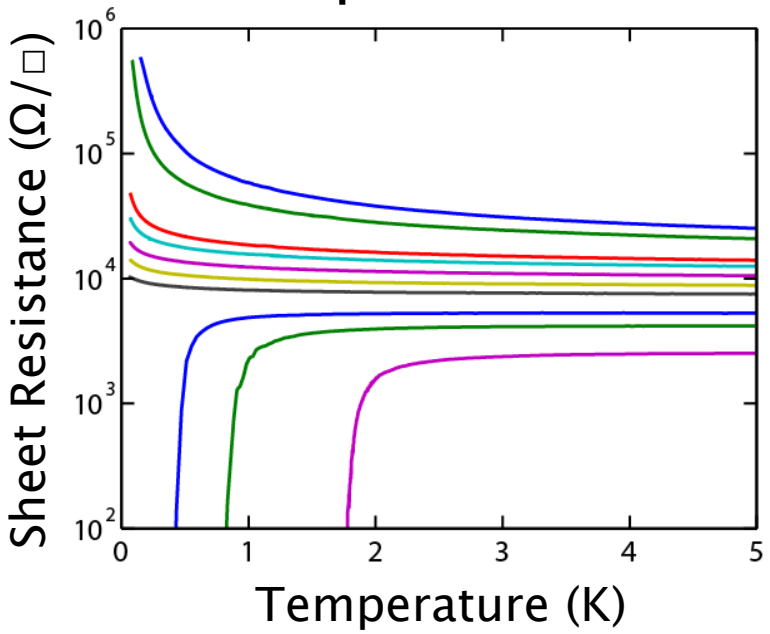
$\Rightarrow$ flux periodic properties

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

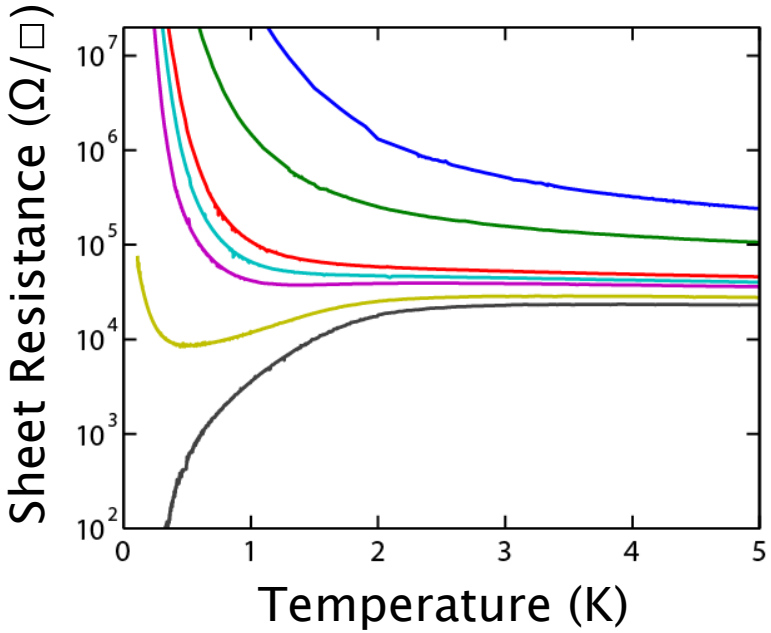
Thickness Tuned SIT's

amorphous Bi films

Unpatterned

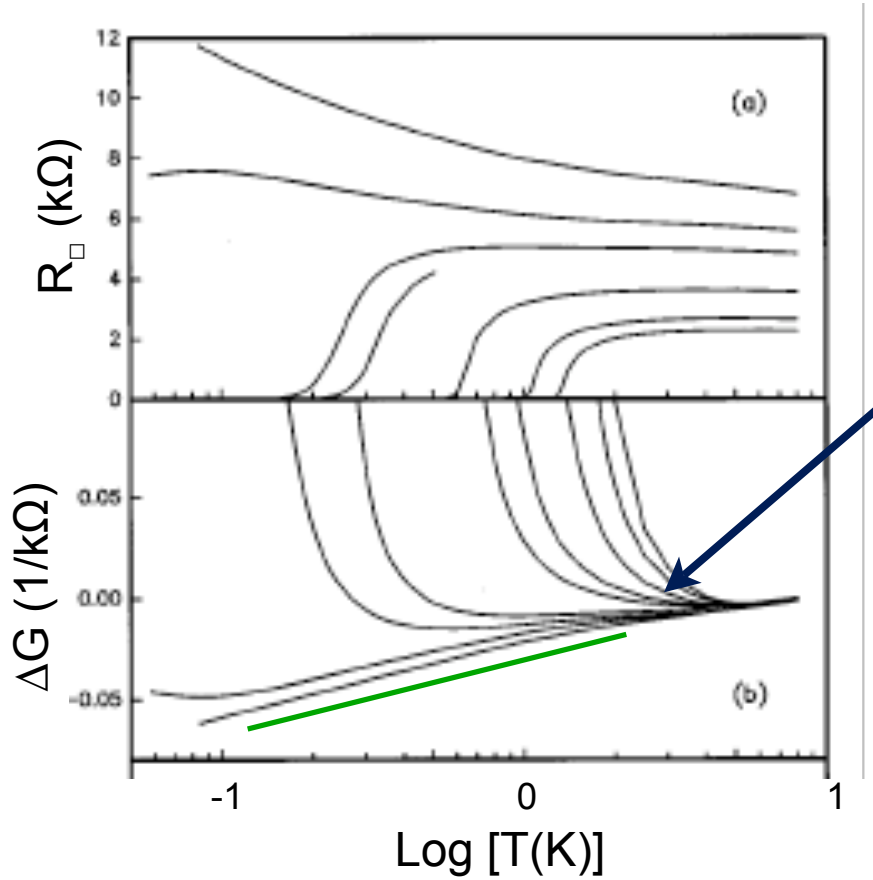


Nano-honeycomb



Features: Reentrance, stronger insulator, broad superconducting transition

Unpatterned films make "weak" insulators



Insulator's conductance:

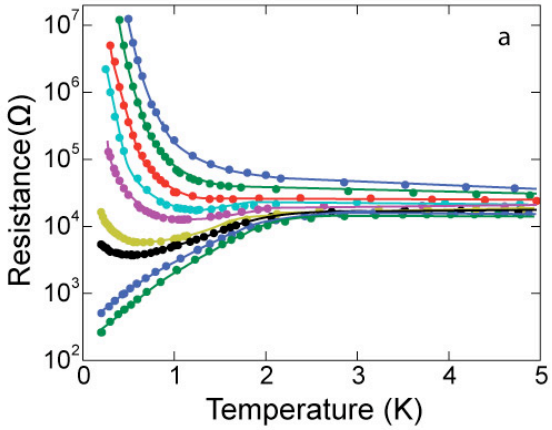
$$\Delta G \sim log(T)$$

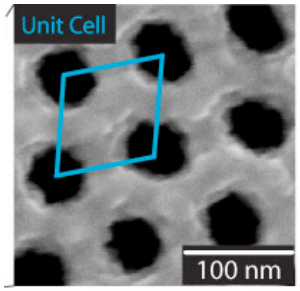
⇒ weakly localized insulator of fermions

IST of a-Bi/Sb films

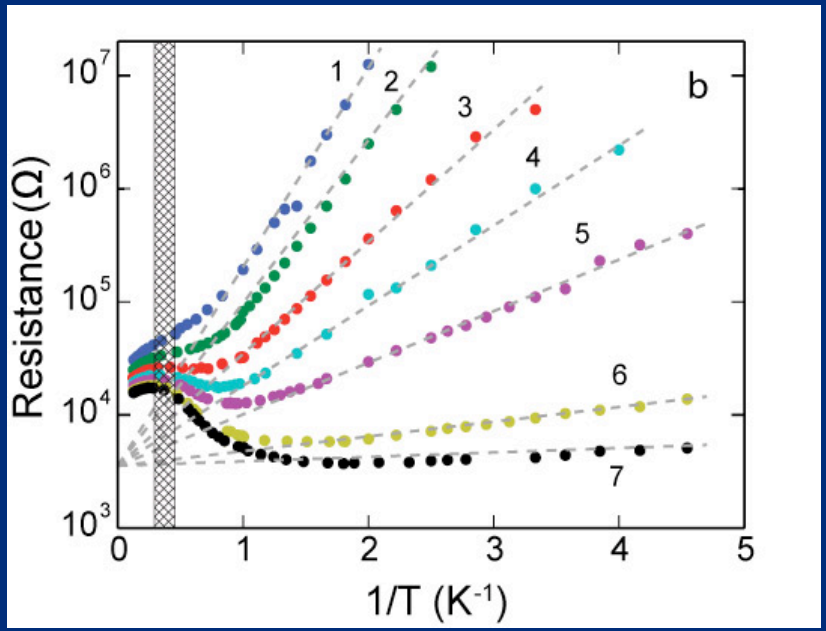
PRB 59, 11209 (1999)

NHC film insulator is strongly localized



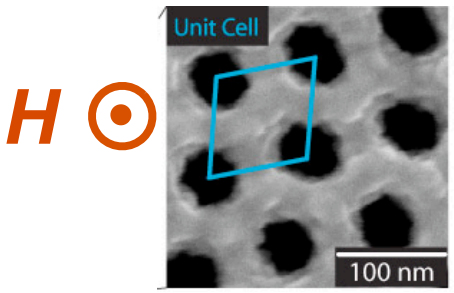


NHC films

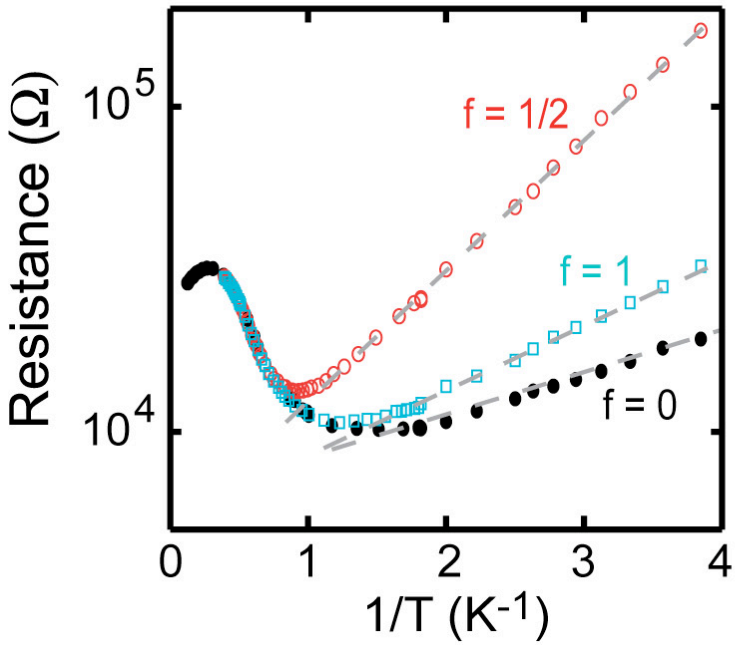


$R=R_0 \exp(-T_o/T)$

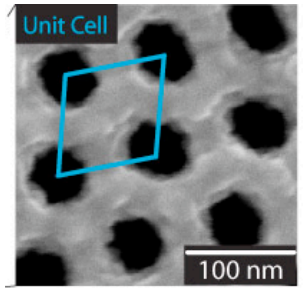
Insulating NHC Film in Magnetic Field

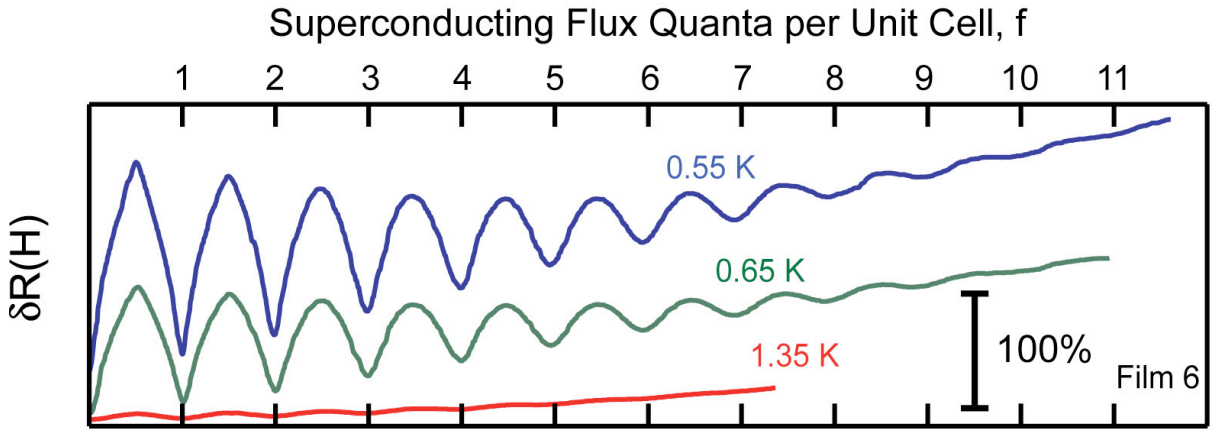


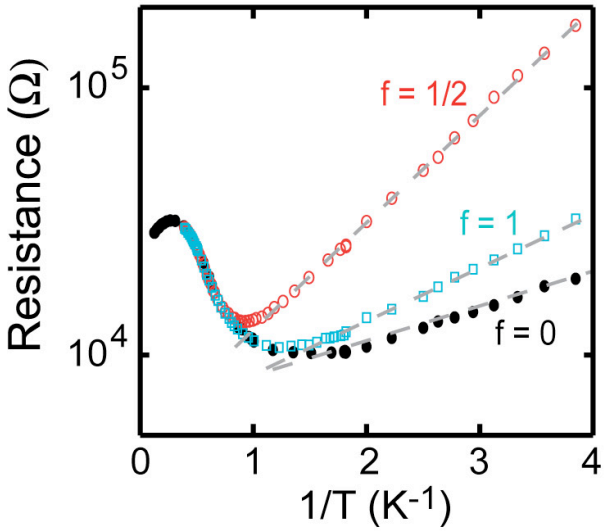
$f = H/H_M$



Insulator exhibits flux oscillations!





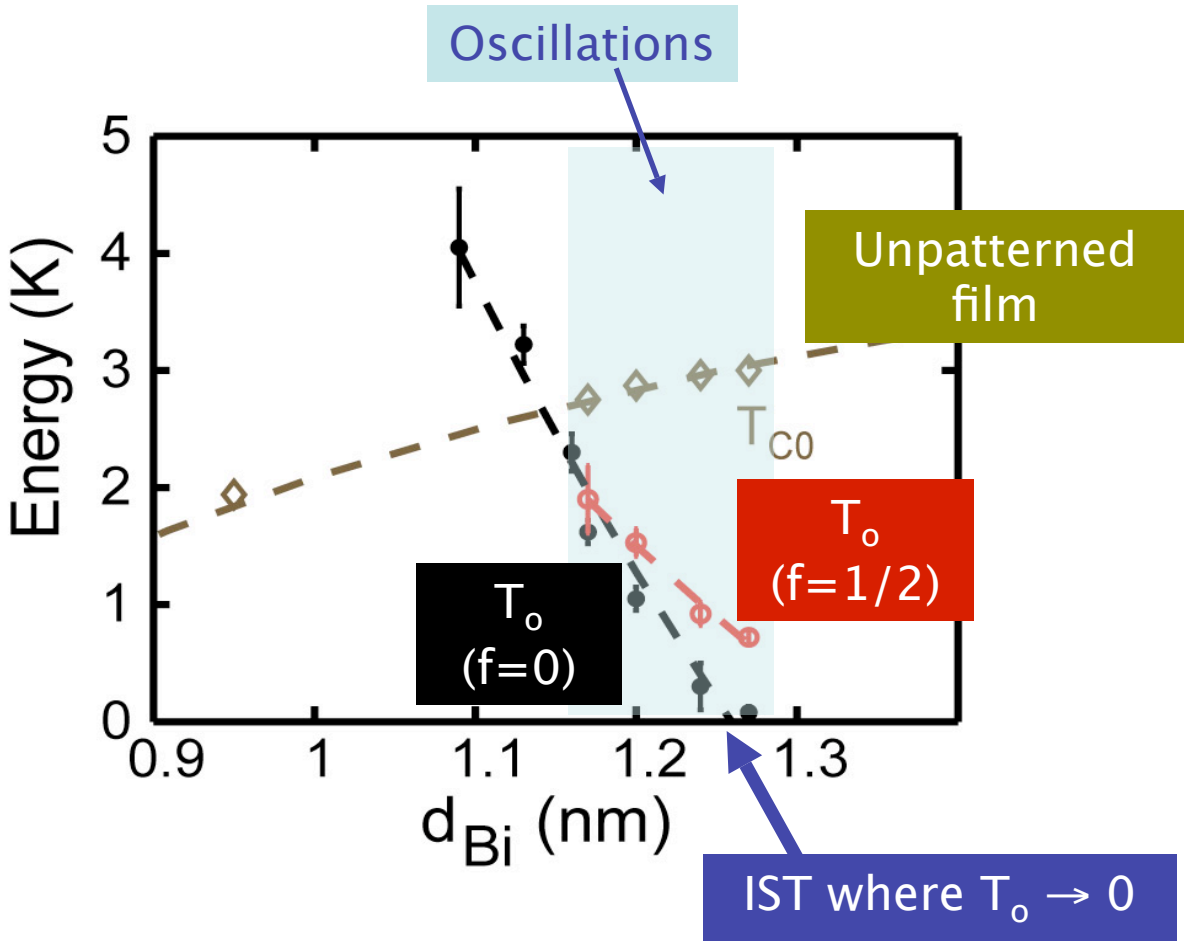


1) Period: $H_M = h/2eS$

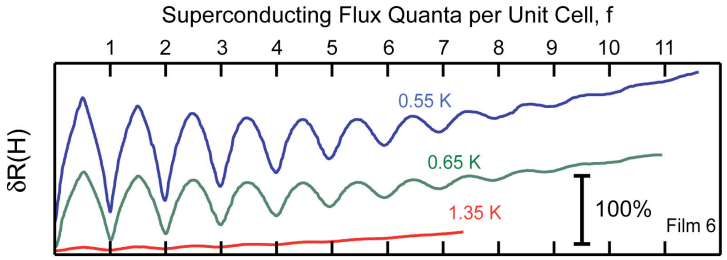
$\Rightarrow$ 2e charge carriers

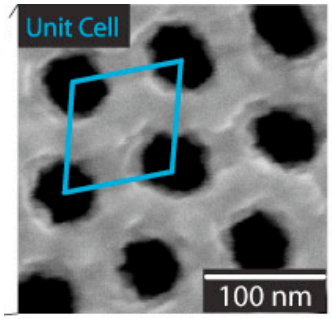
2) Activation energy oscillates

Energy scales in the insulator



Questions?





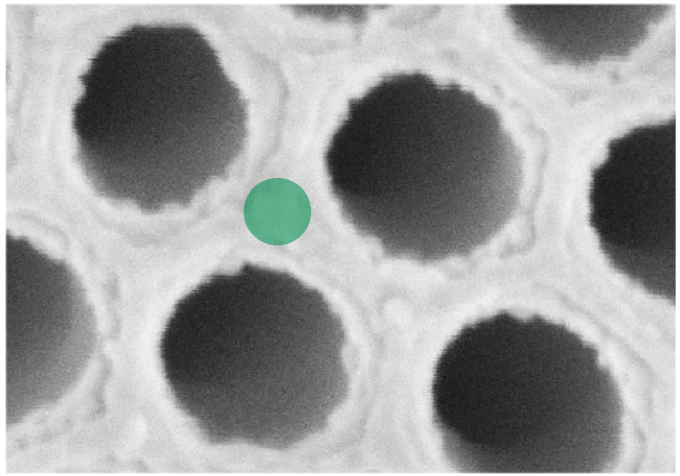
- What's the transport process near IST? far from IST?
- What's localizing the CP's?
- How localized are the CP's?

know $\xi_{loc} > S^{1/2}$

Nearest neighbor hopping?

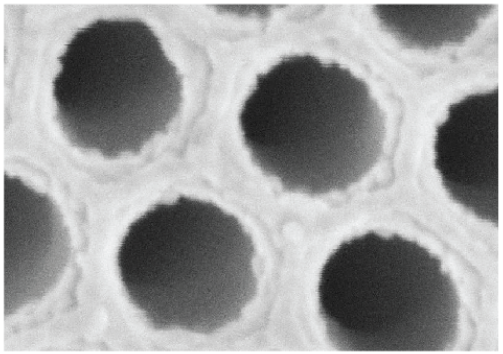
$$T_0 = (g(E_F)\pi\xi_{loc}^2 d)^{-1}$$

For $T_0 = 1$ K, need $\xi_{loc} < 10$ nm



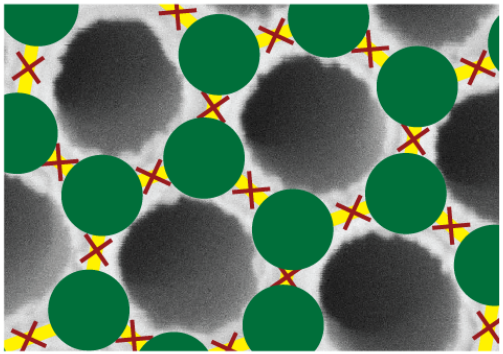
which is too small for oscillations.

Does JJA physics apply?

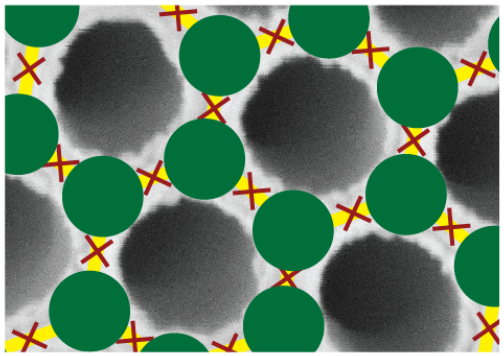


?

=



JJA picture



Estimate :

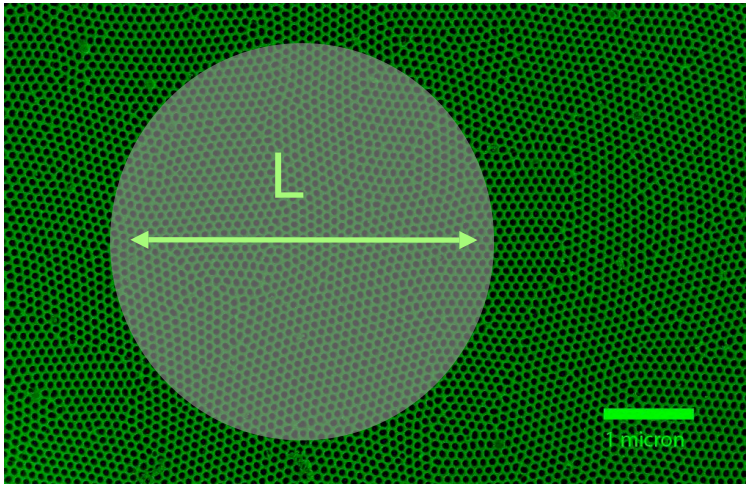
$$E_c \cong \frac{4e^2}{\varepsilon\varepsilon_0 L}$$

For L = 50 nm, $E_c = 10^4 K/\varepsilon$

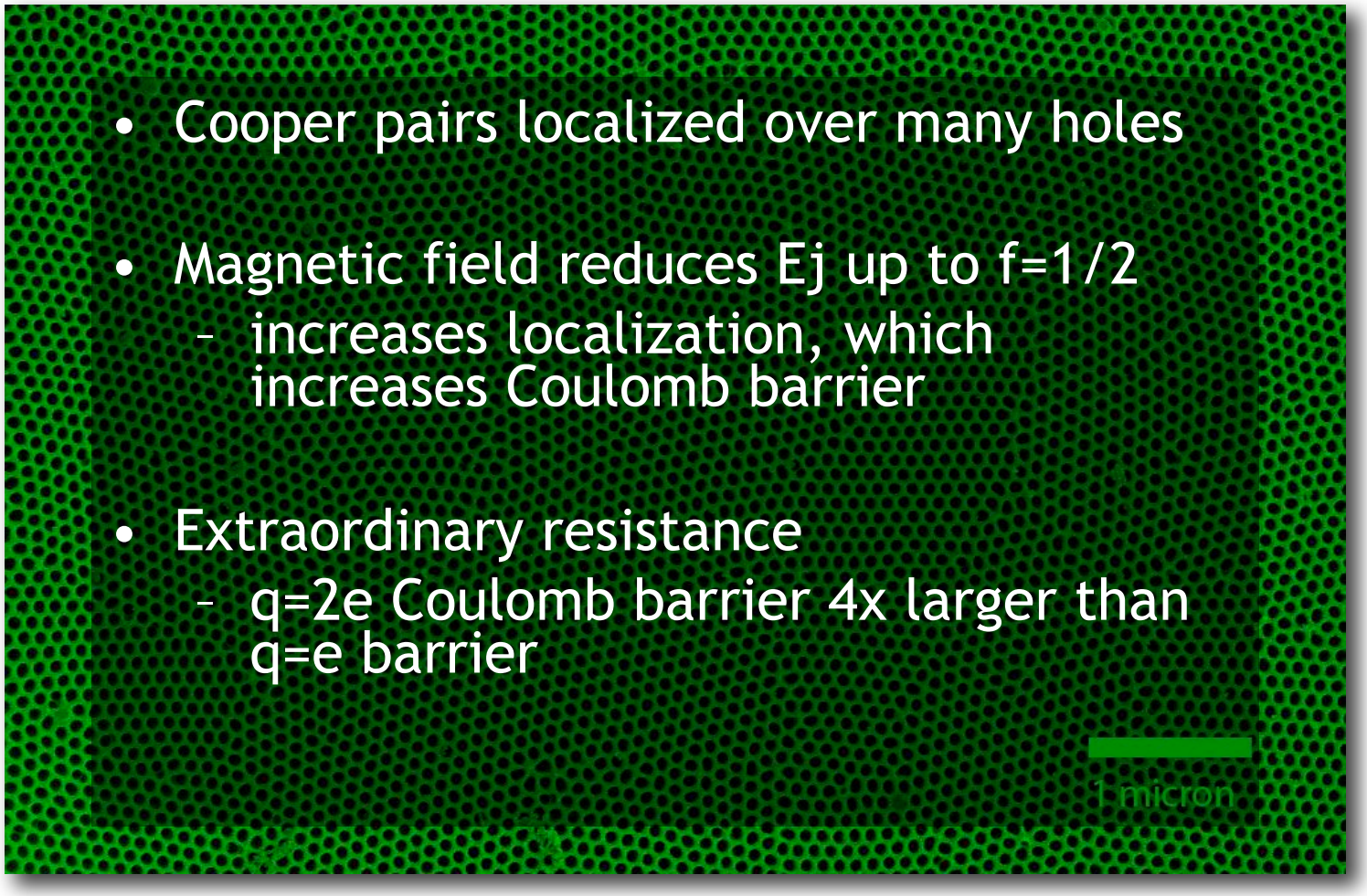
Too large to be relevant!

Effective islands encompass many holes?

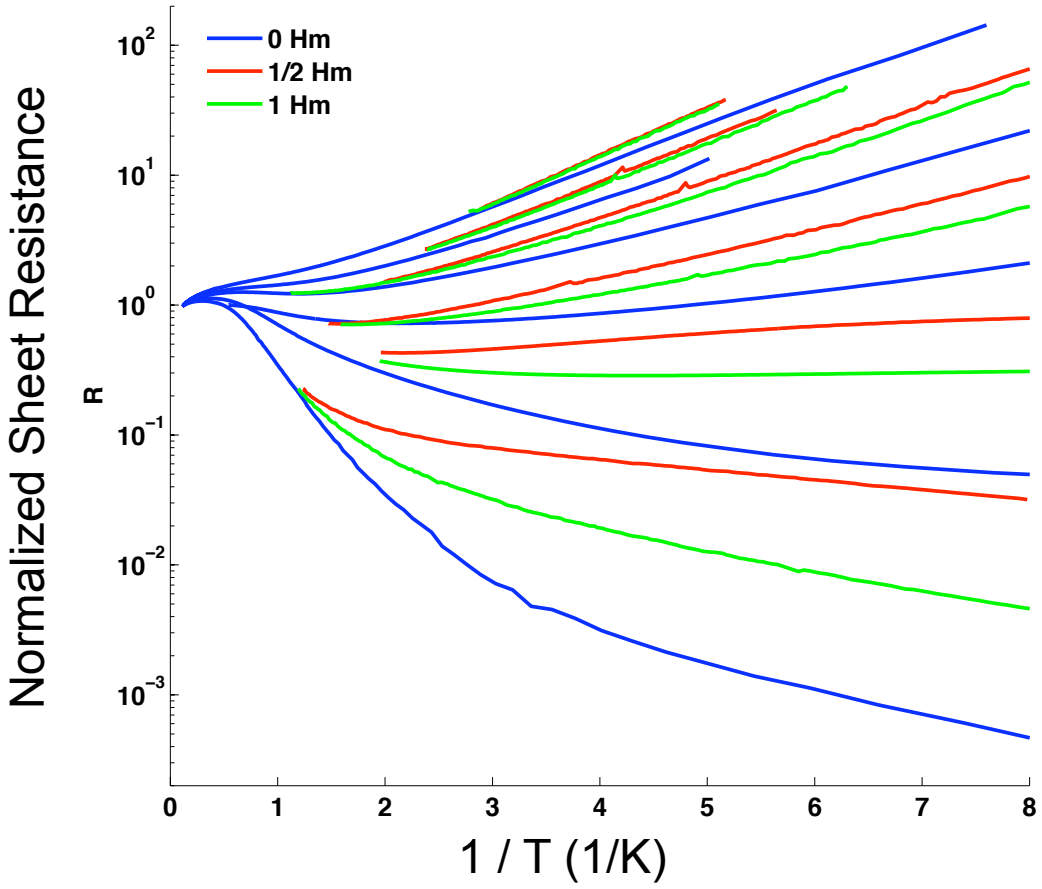
--- Need 1000's of holes



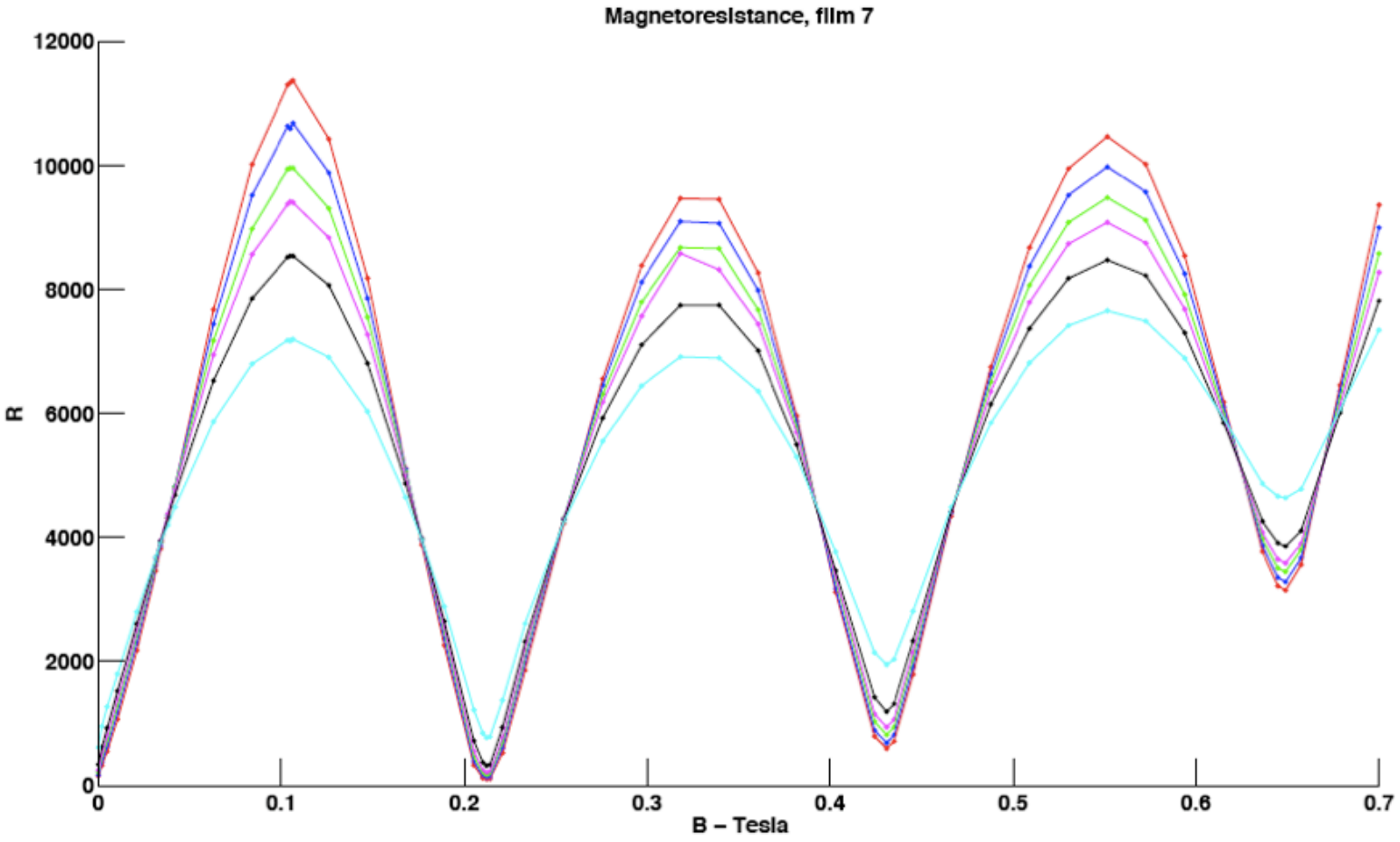
Tentative Picture of Insulator



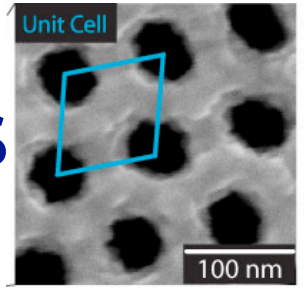
Oscillations persist into SC phase

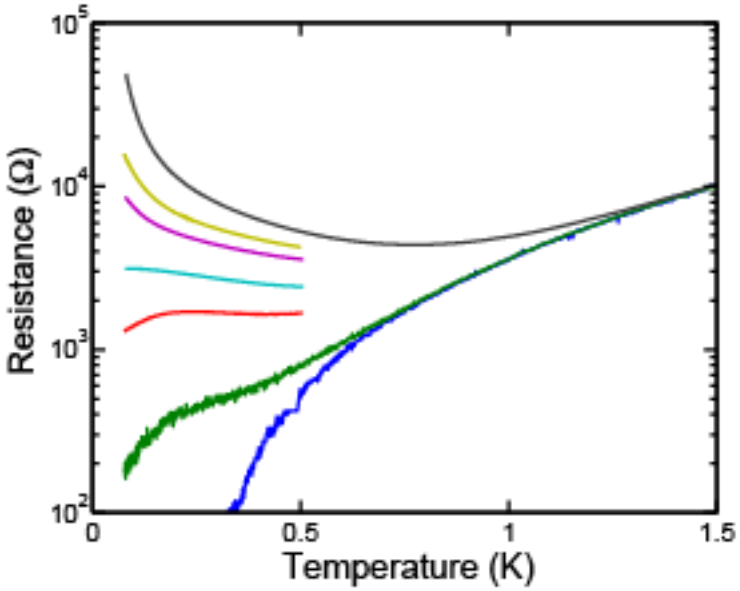


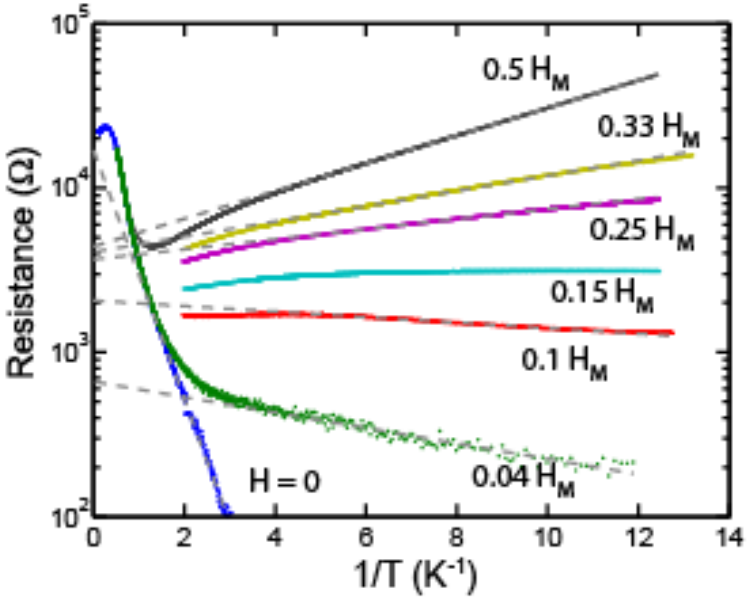
Multiple Field Tuned SIT's



Field tuned SIT – NHC films

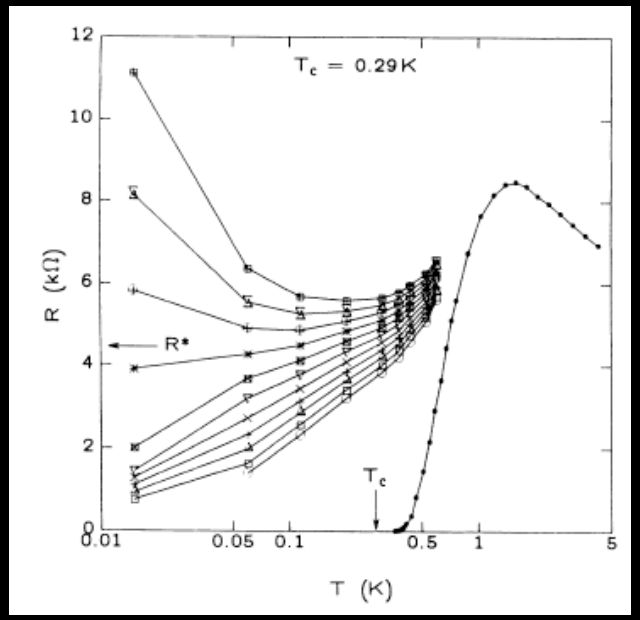






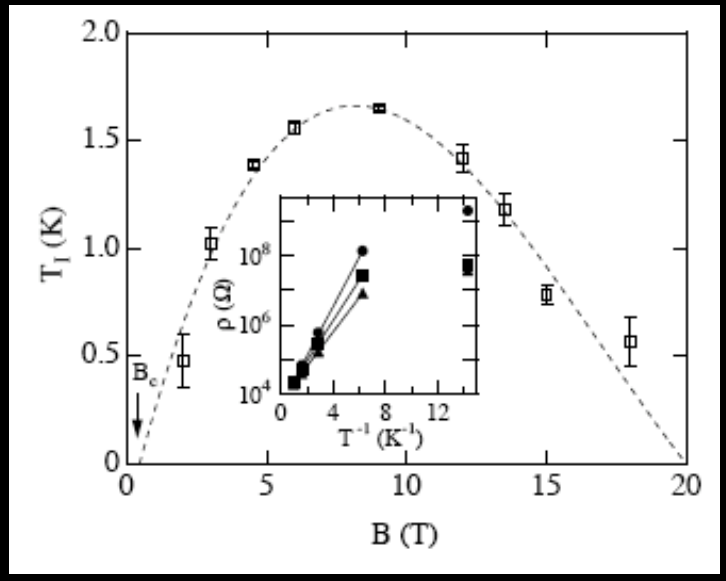
1. Reentrant
2. Parameterize data - $R=R_o\exp(T_o(H)/T)$
3. Nearly metallic around the critical point.

Comparison to Unpatterned Indium Oxide Films



Reentrance

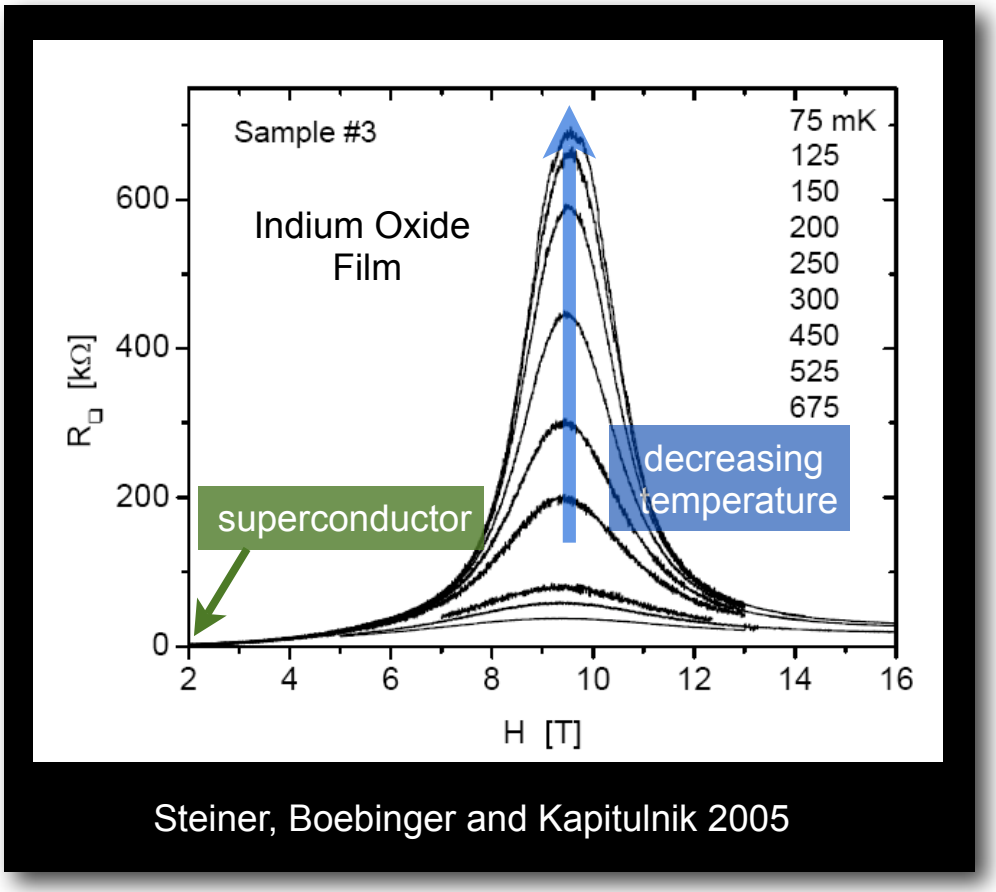
Hebard and Paalanen, PRL 65, 927 (1990)



Activated

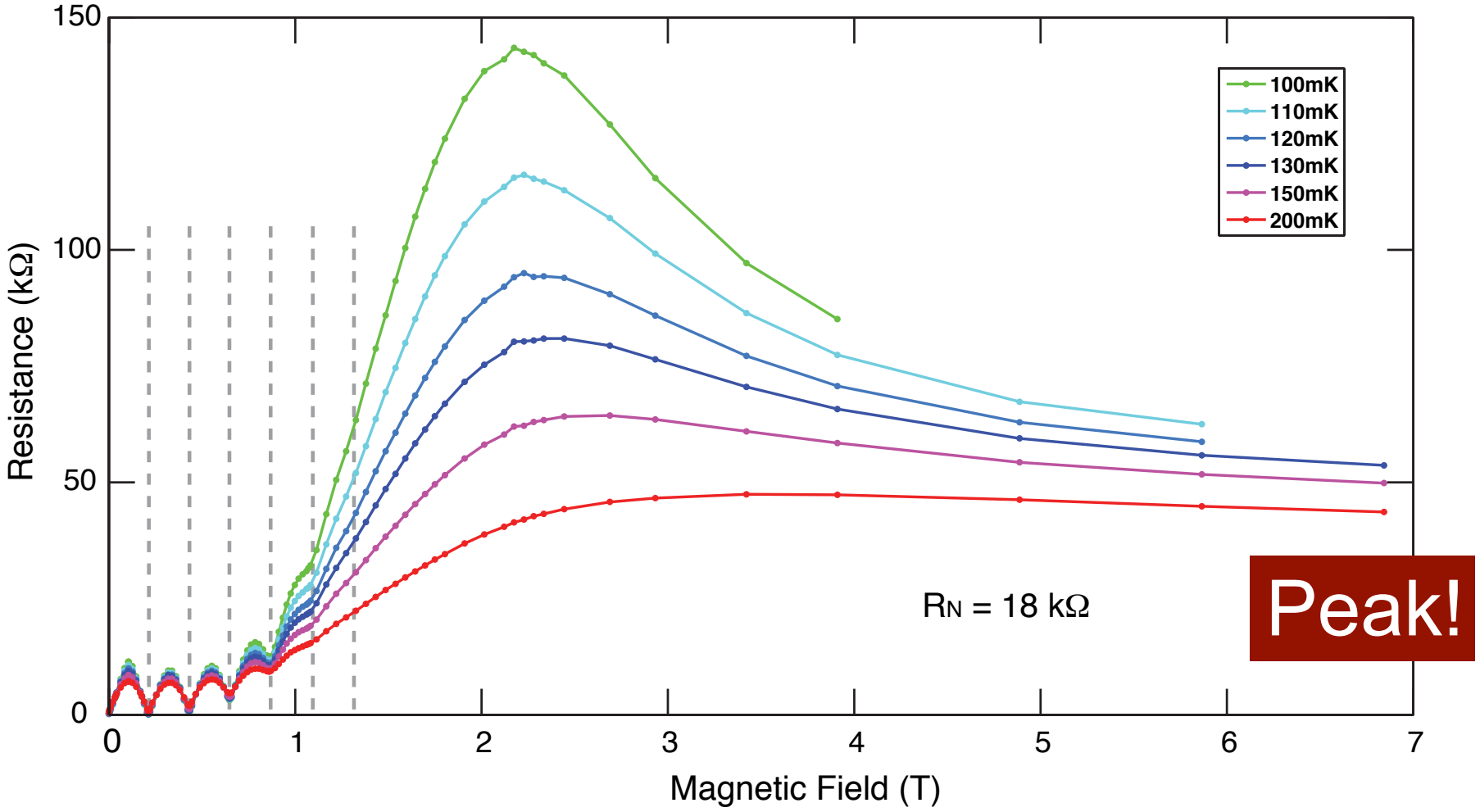
Sambandamurthy et al., PRL 107005 (2004)

Spectacular Peaks...

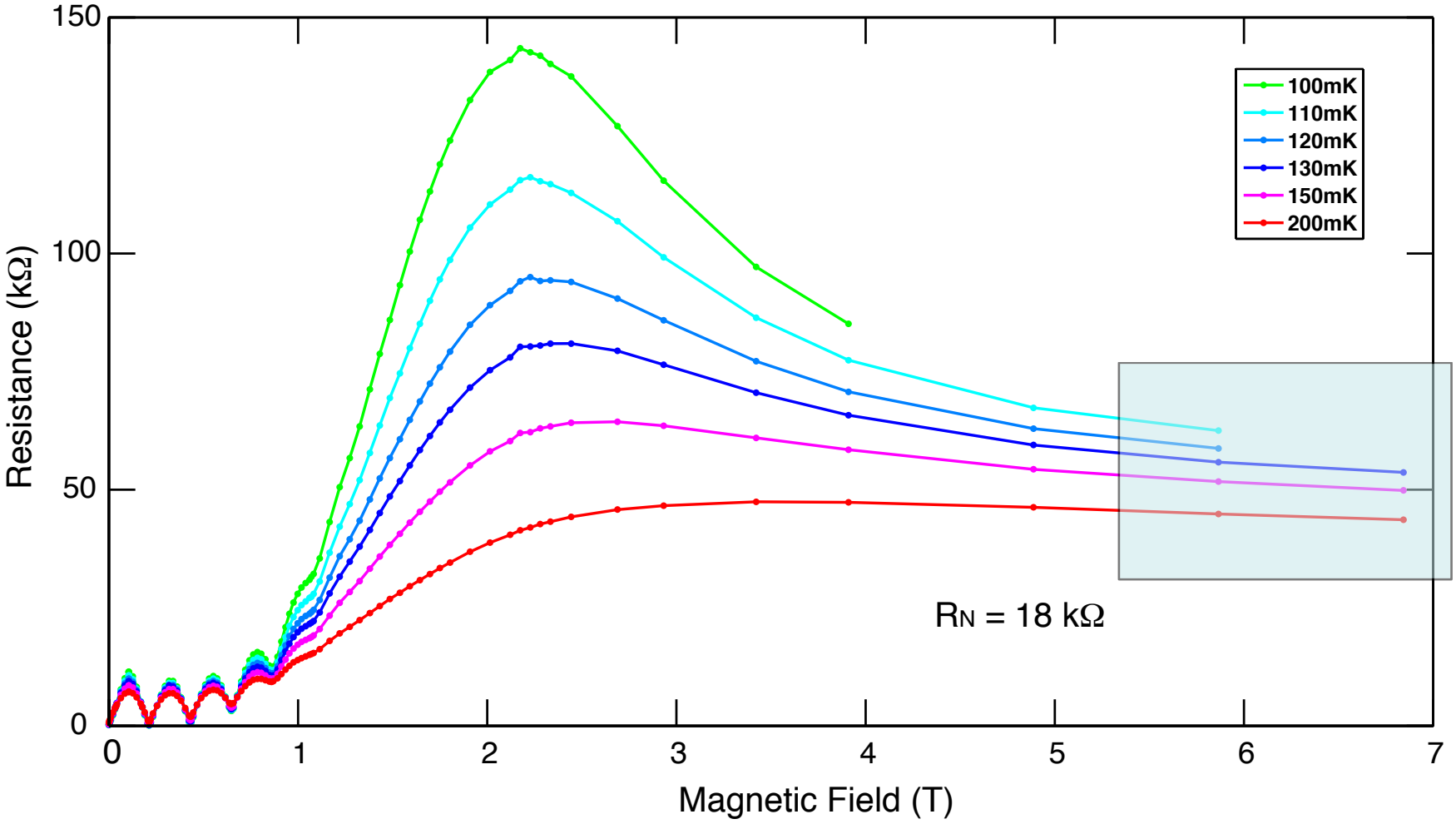


Steiner, Boebinger and Kapitulnik 2005

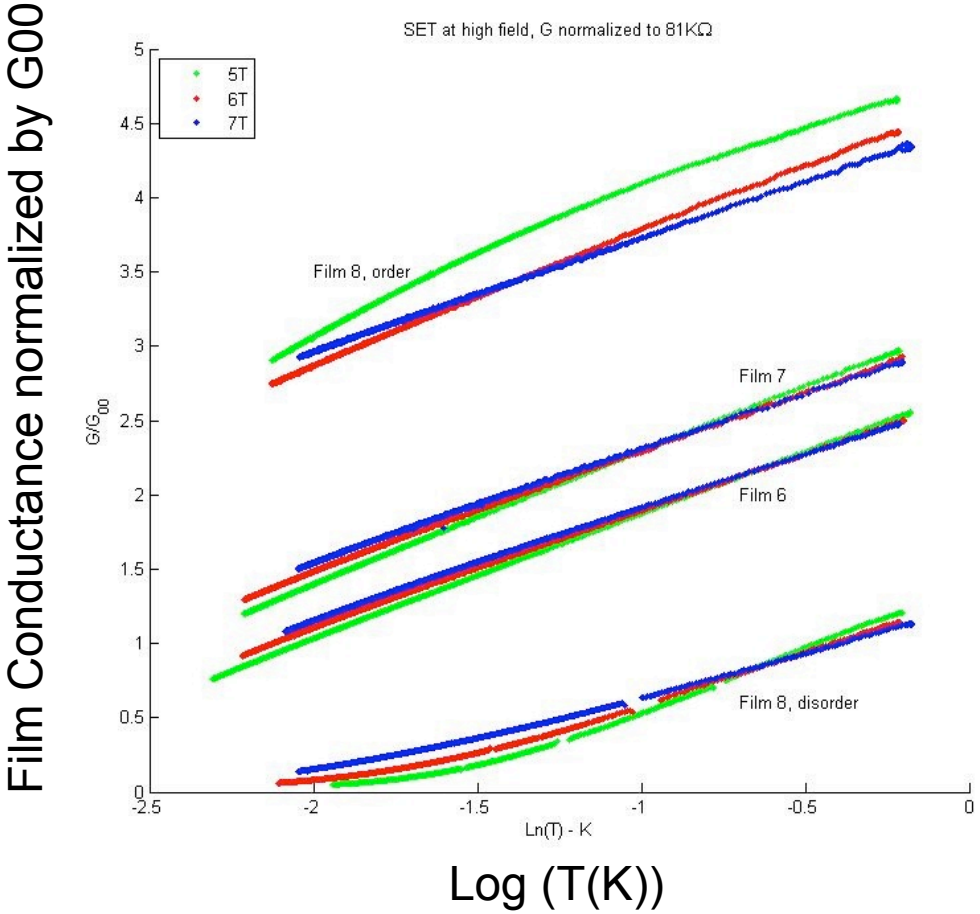
High Magnetic Fields



High Magnetic Fields



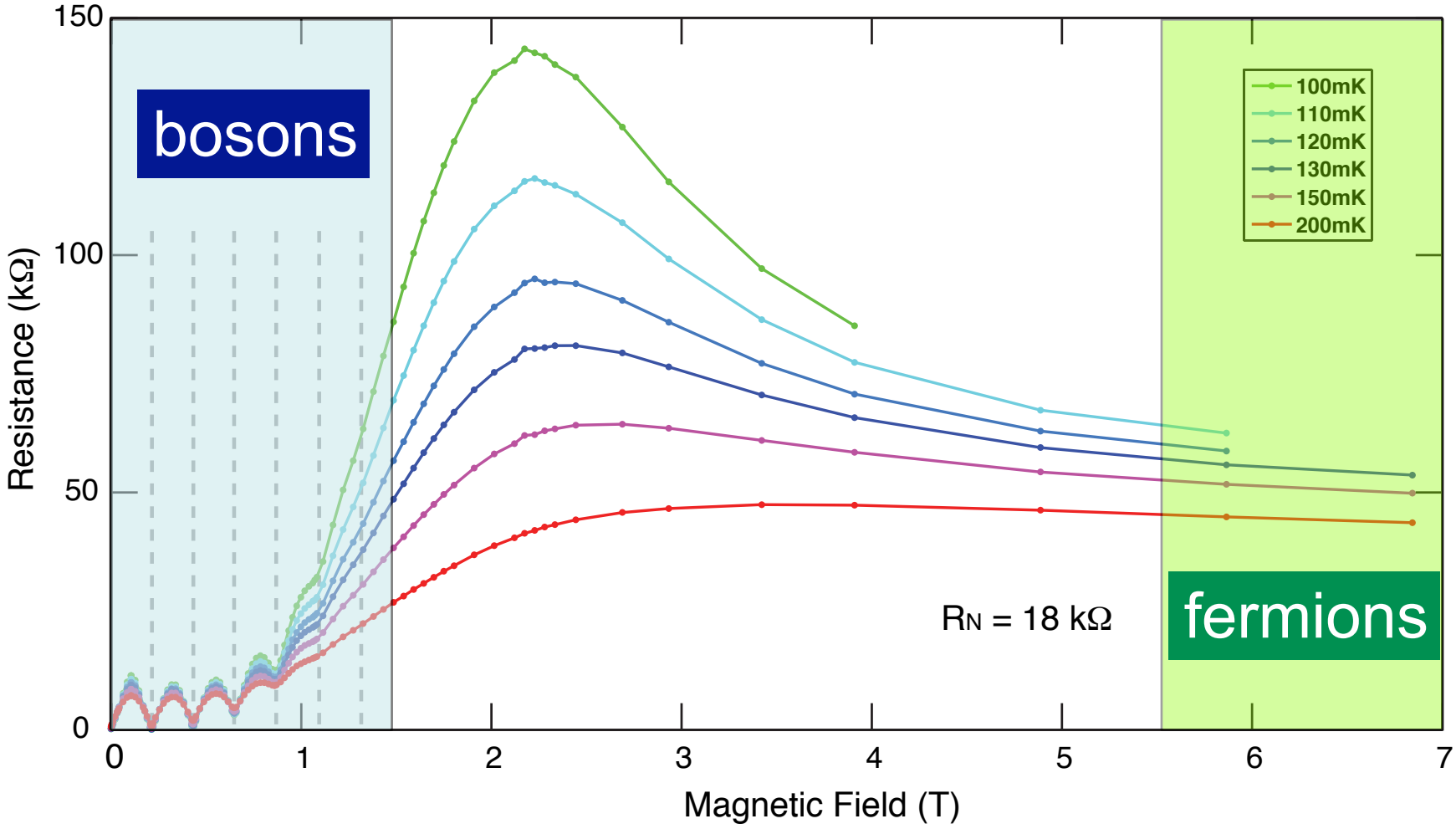
At the Highest Fields



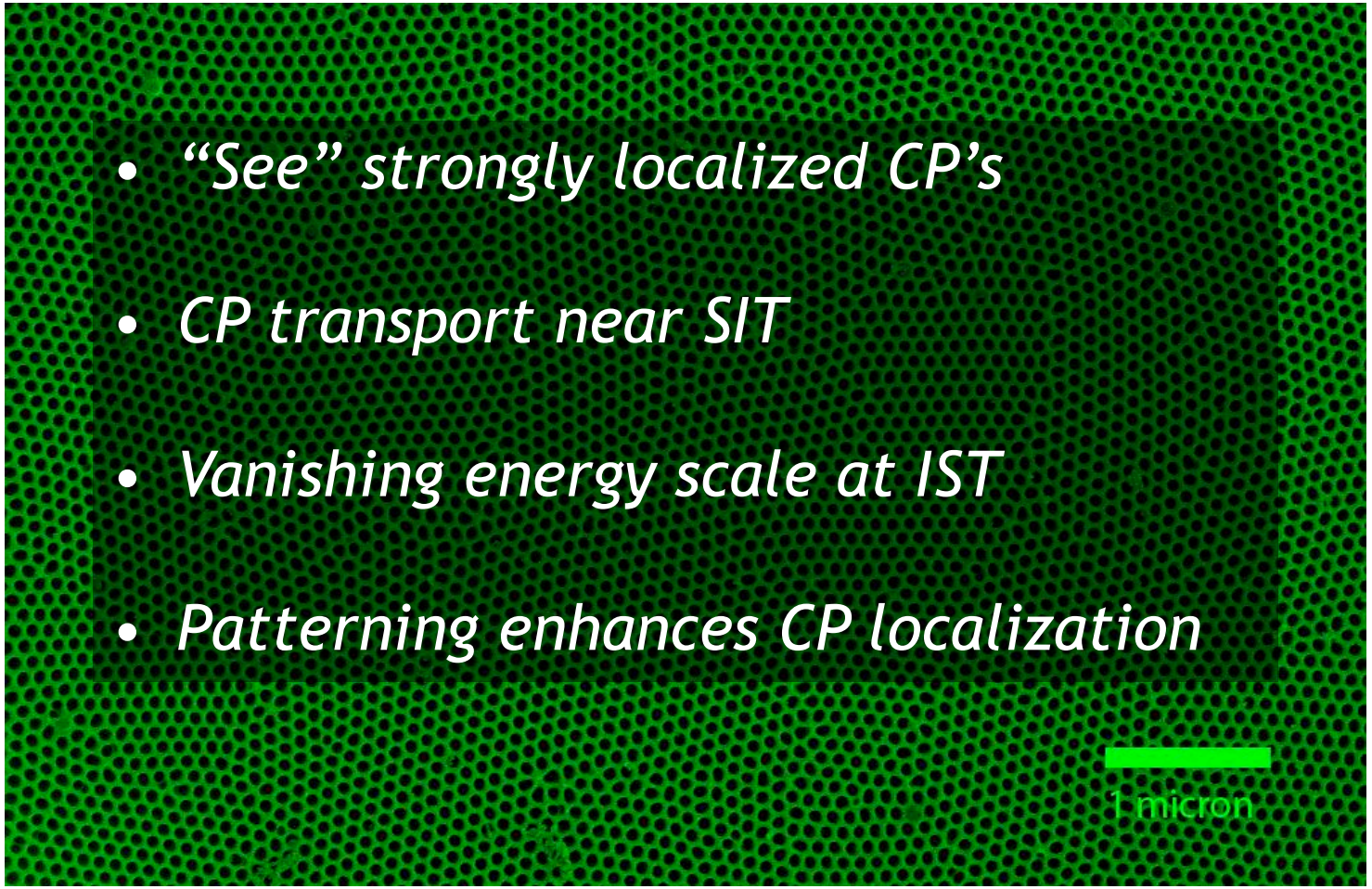
$$\Delta G \sim log(T)$$

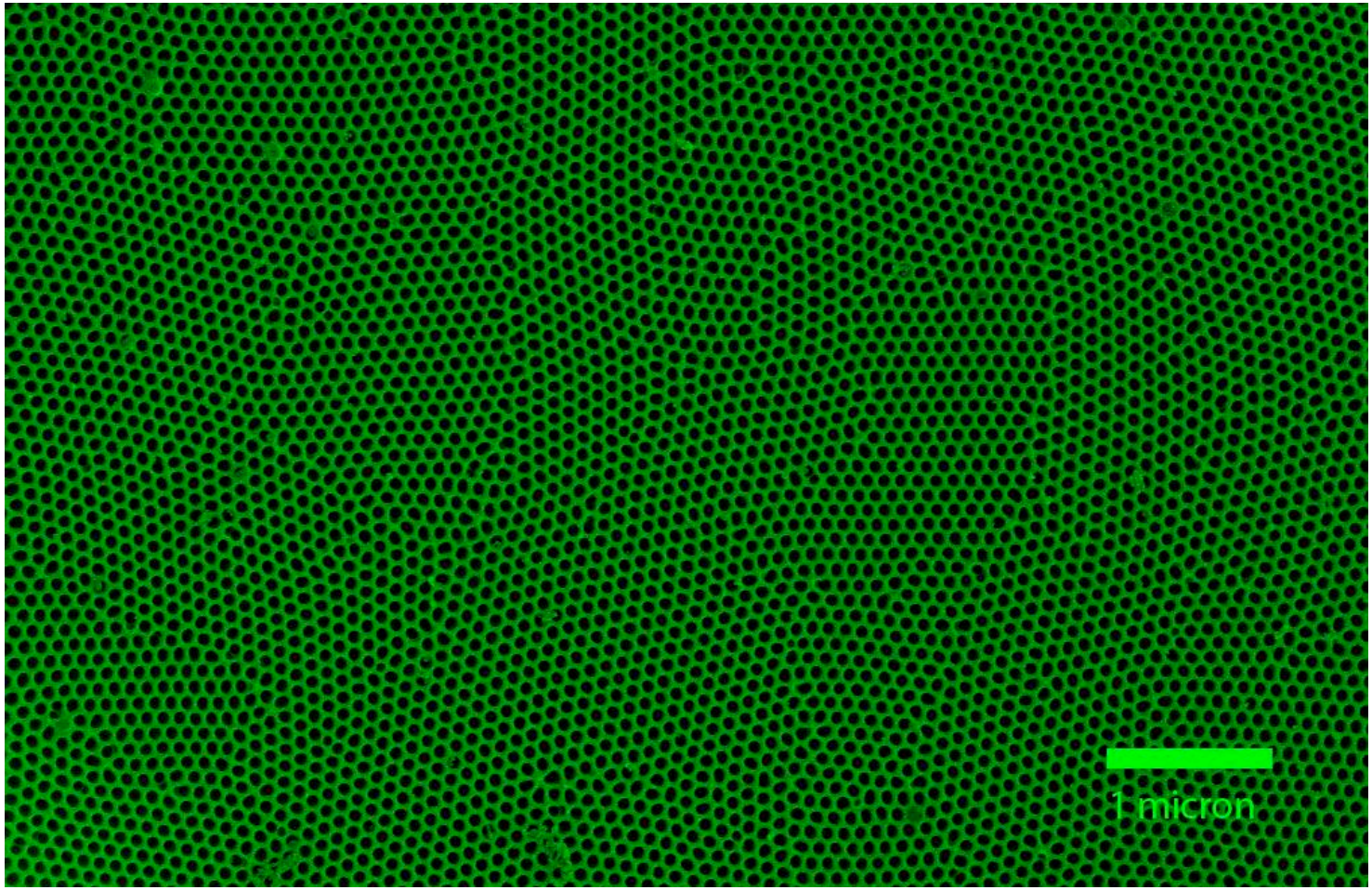
Fermion's are back!

High Magnetic Fields



Thickness tuned IST in NHC Films




1 micron