Cooper Pairs in Insulators

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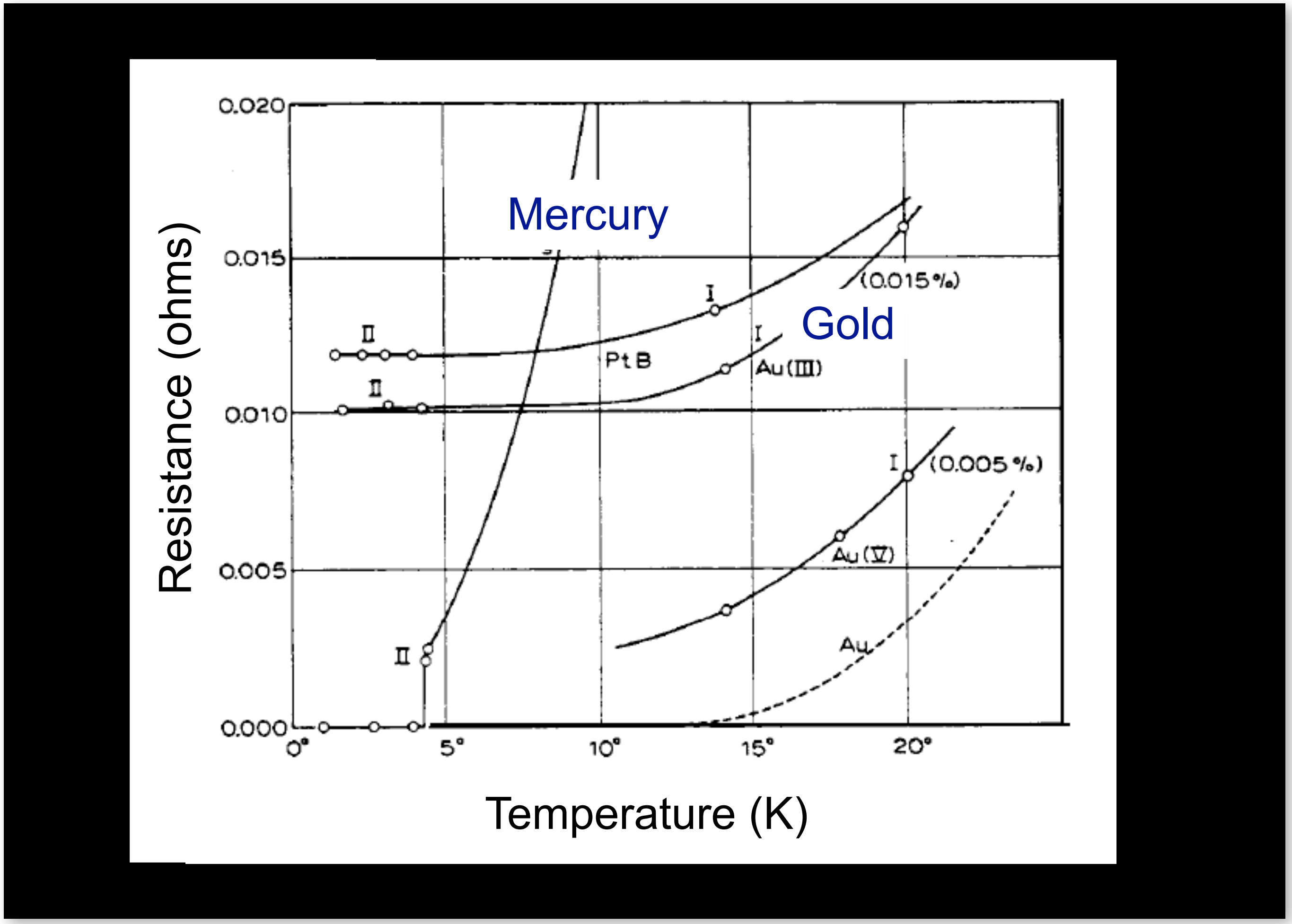
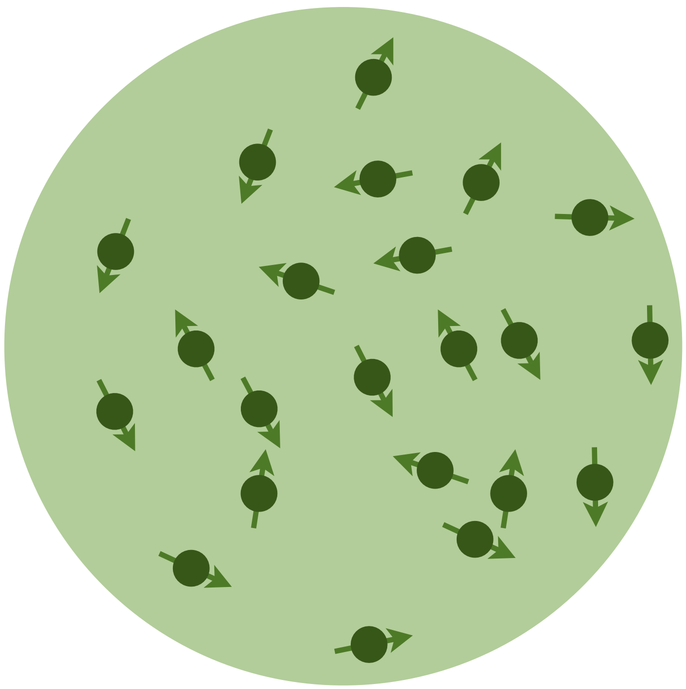
1911 Discovery of Superconductivity



From K. Onnes Nobel Lecture, December 11, 1913

46 years later....BCS theory

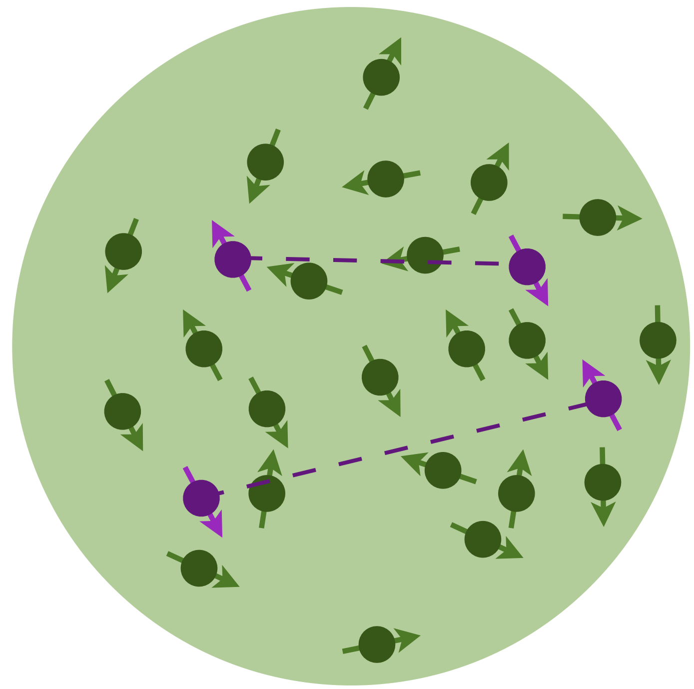
Bardeen, Cooper and Schrieffer



$T>T_c$

metal

nearly free Fermi gas



$T<T_c$

superconductor

Fermi gas with pairing correlations

BCS Ground State

$$|\psi_\phi\rangle = \prod_k (|u_k| + |v_k| e^{i\phi} c^*_{k\uparrow} c^*_{-k\downarrow}) |\varphi_0\rangle$$

the unpaired

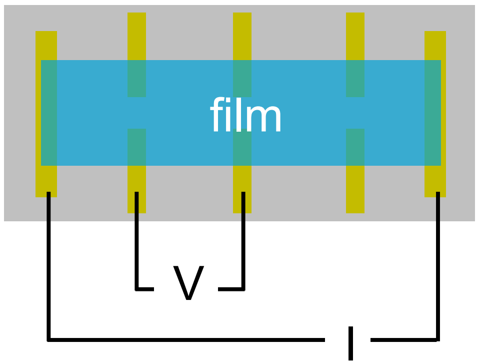
pairing with definite phase

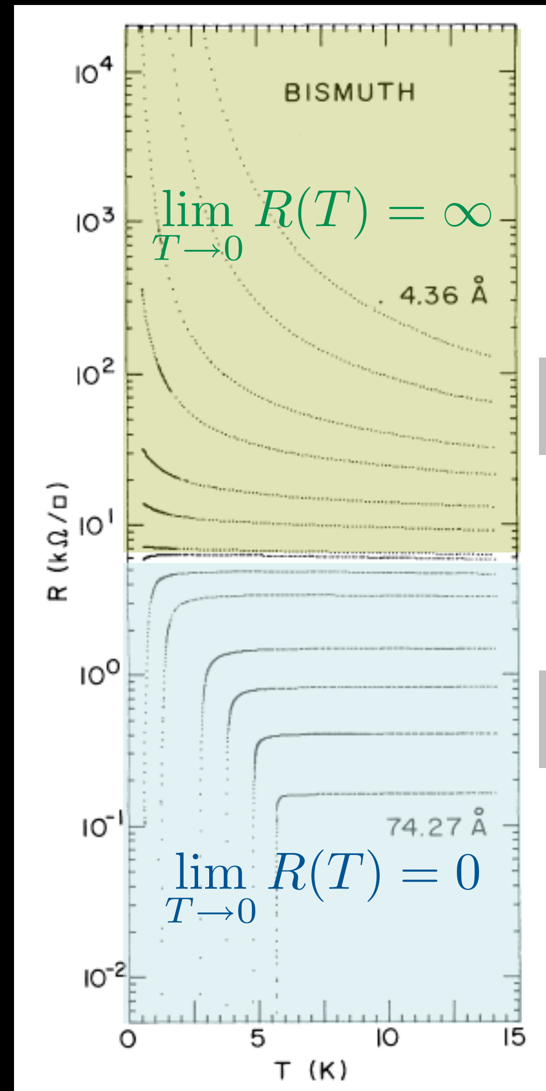
vacuum state

"Cooper" pairing correlations through the exchange of virtual phonons

Pairs (bosons) condense into a macroscopic quantum state with zero resistance

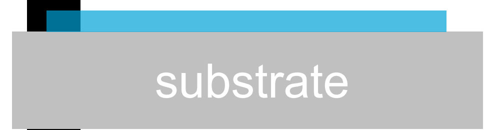
Superconductor to Insulator Transition (SIT)

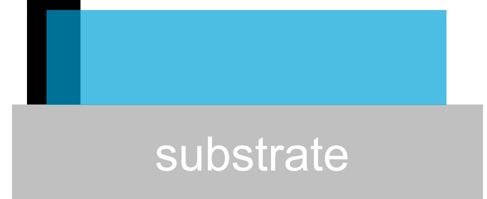




amorphous–Bi films

Haviland, Liu and Goldman





Insulators in 2D

What's the insulating phase?

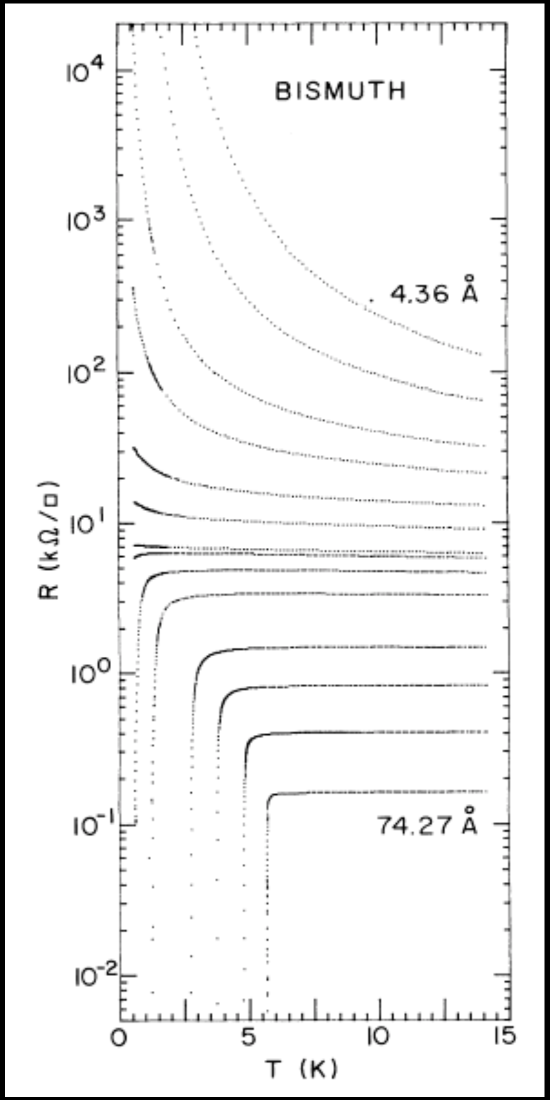
localized Cooper pairs (bosons)

or

localized electrons (fermions)

or

novel mixture



amorphous–Bi films

Haviland, Liu and Goldman

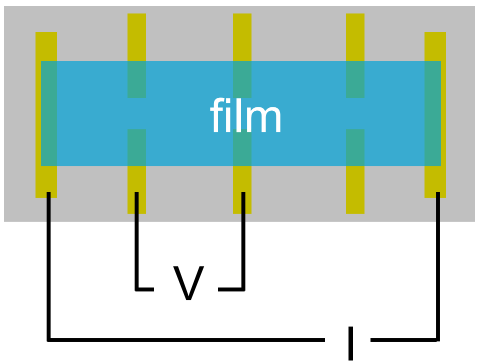
Cooper Pairs in Insulators

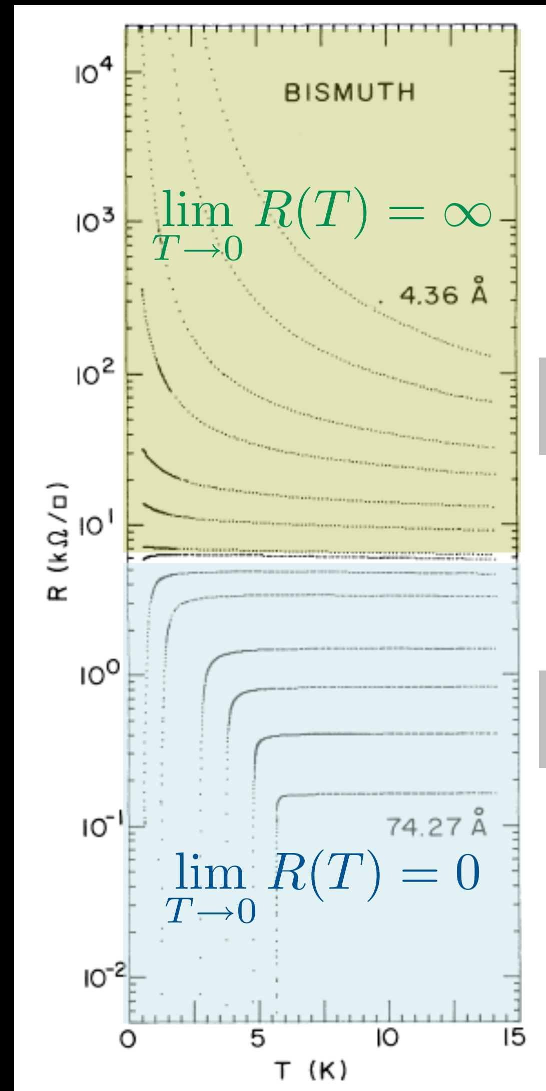
- Superconductor to Insulator Transitions
- Destroying Superconducting Order

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

- Bosonic vs. Fermionic Insulators
- Cooper Pair (Boson) Detection

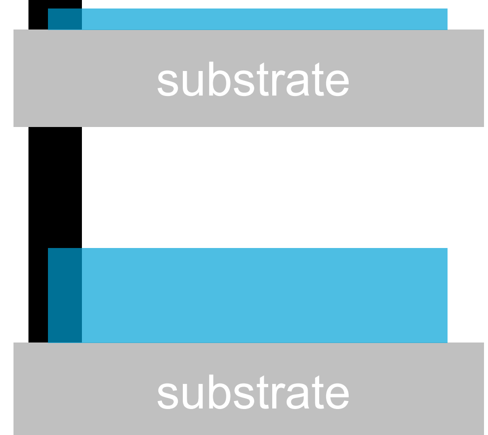
Thickness tuned SIT



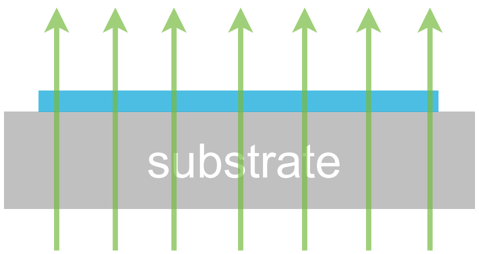


amorphous–Bi films

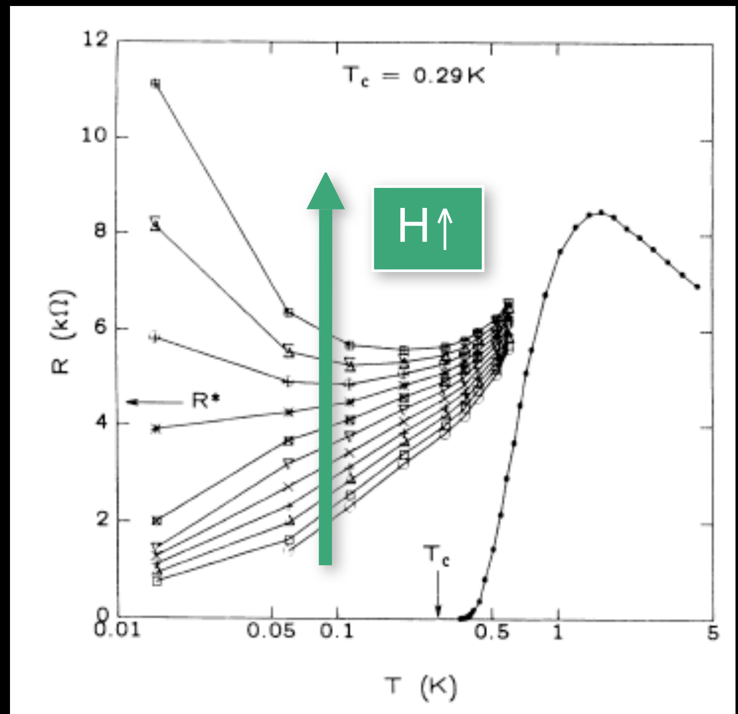
Haviland, Liu and Goldman



Magnetic Field Tuned SIT

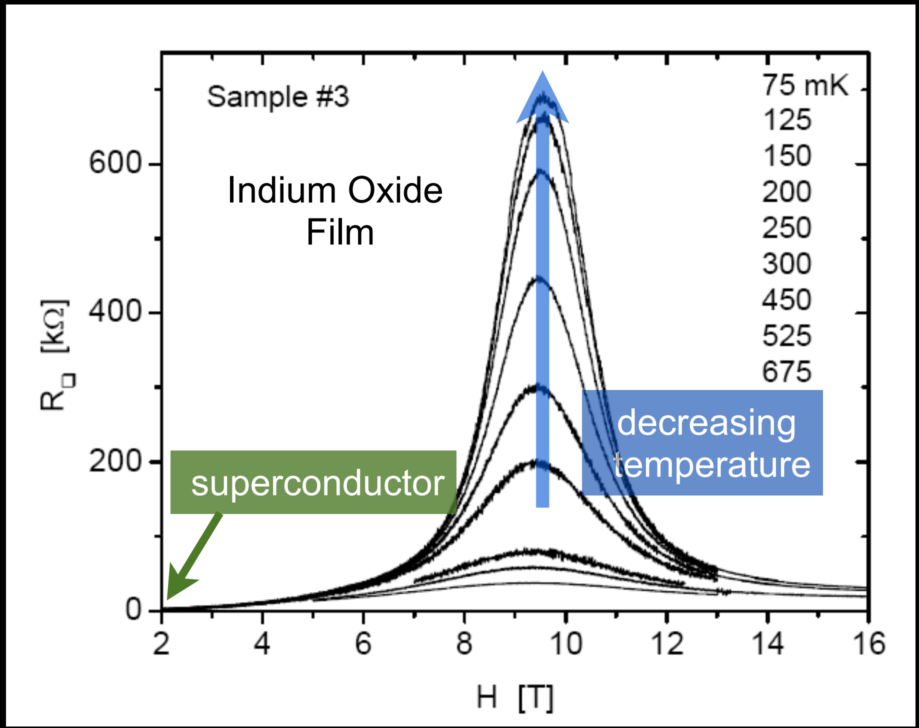


magnetic field, H



amorphous–Indium Oxide
(Hebard and Paalanen)

Superinsulator!



Steiner, Boebinger and Kapitulnik 2005

SIT's or IST's, who cares?

- Occur in many systems:
  - Pb, Bi, Indium Oxide, TiN, high Tc SCs
  - share universal qualities
- Example of a quantum phase transition
  - tuned by: thickness, magnetic field, electric field (i.e. non-thermal parameters)
- What are the ground states of electron systems?

Order Parameter for Superconductor

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

complex order parameter or macroscopic wavefunction

Phase

Currents $J_s \propto \hbar \nabla \phi$

Voltages $V_{12} \propto \frac{\hbar}{2e} \frac{\partial \phi_{12}}{\partial t}$

Amplitude

$$\Psi^* \Psi = \Delta$$

$$\Delta \propto T_c \propto n_{cp}$$

Destroying Superconductivity

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

Create phase fluctuations

$\frac{\partial \phi_{12}}{\partial t} \propto V_{12} \neq 0$ and $\nabla \phi \propto J_s \neq 0$ gives resistance!

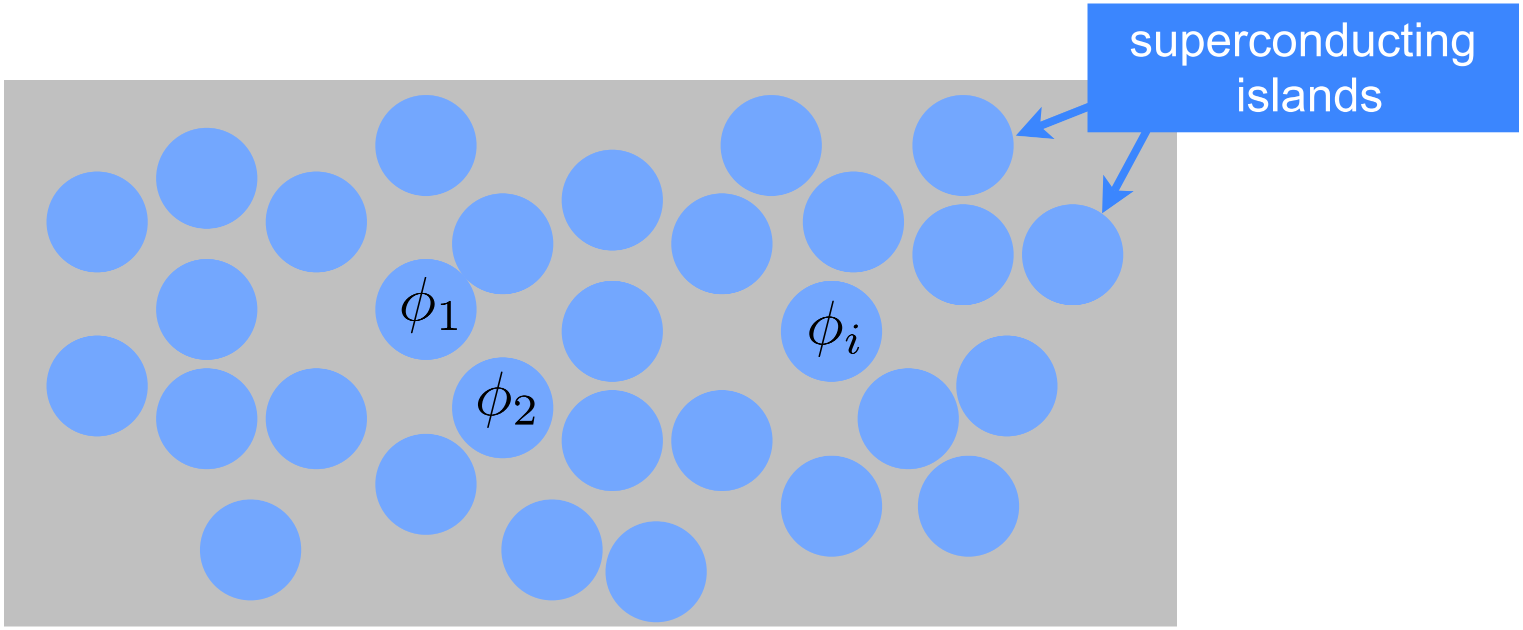
ground state of bosons (Cooper pairs)

Reduce the amplitude

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

ground state of fermions

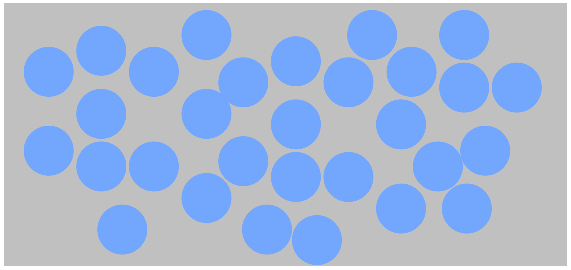
Imagine an islanded film



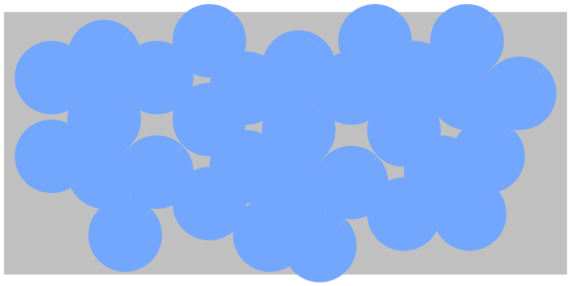
Does this film superconduct?
or, equivalently
Do the islands become phase coherent?

SIT via Phase Fluctuations

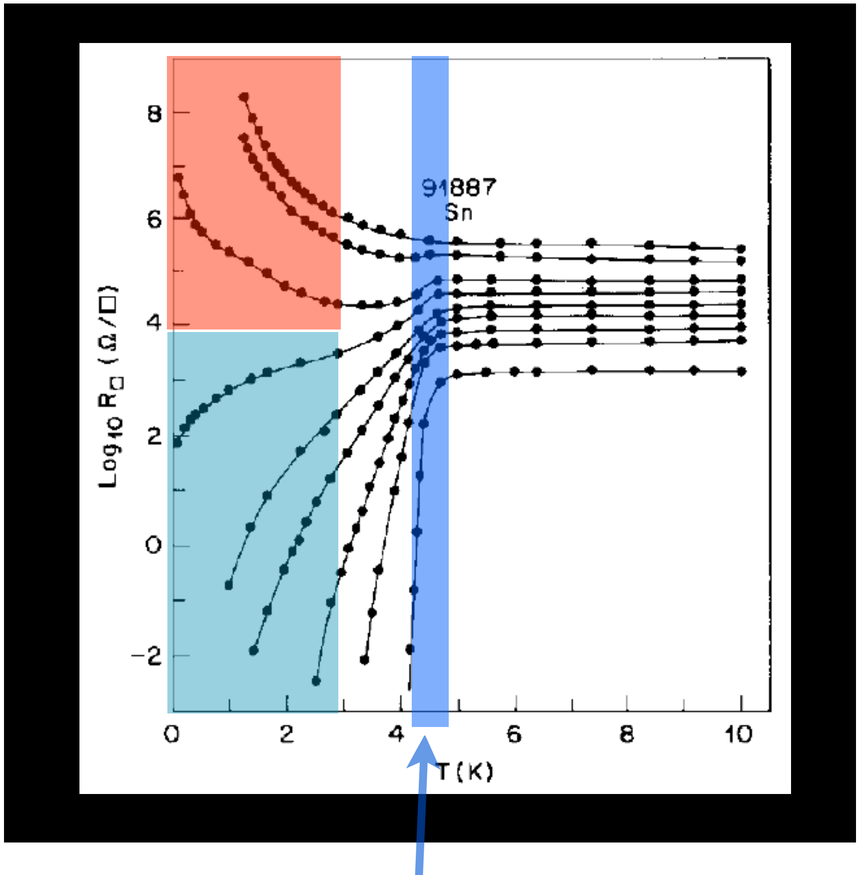
Islanded films



Insulating
phases on islands incoherent



Superconducting
phases on islands coherent



Island Tc is constant while phase fluctuates

Phase Fluctuations in Islanded Films

Insulator:
Cooper pairs localized to islands

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

Phase fluctuations large

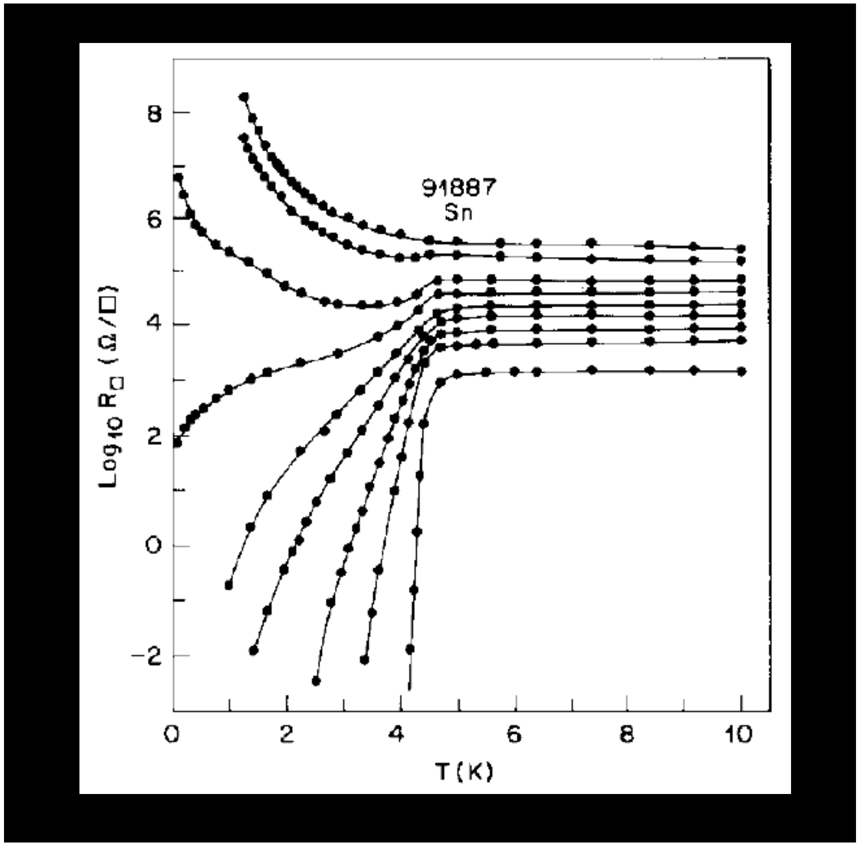
$$\delta\phi \neq 0$$

Superconductor:
Cooper pairs delocalized

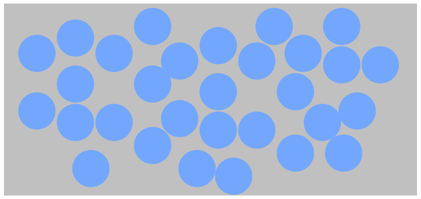
$$\delta N_{cp} \neq 0$$

Phase fluctuations small

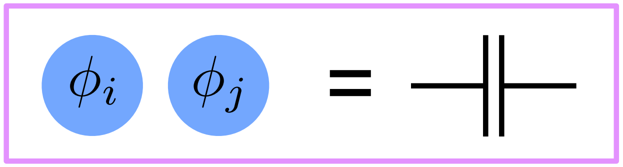
$$\delta\phi = 0$$



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

Model Hamiltonian: $H \sim \sum_{i,j}[-\frac{(2e)^2}{C}N_{cp,i}N_{cp,j} - E_j(cos(\phi_i - \phi_j)]]$

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

discourages charge fluctuations

$$E_j >> E_c$$

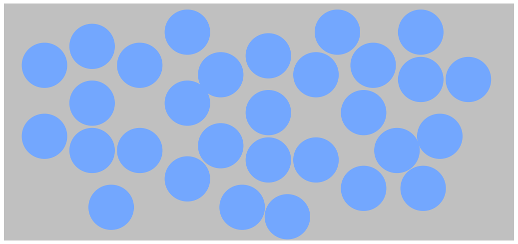
discourages phase fluctuations

JJA SIT Model

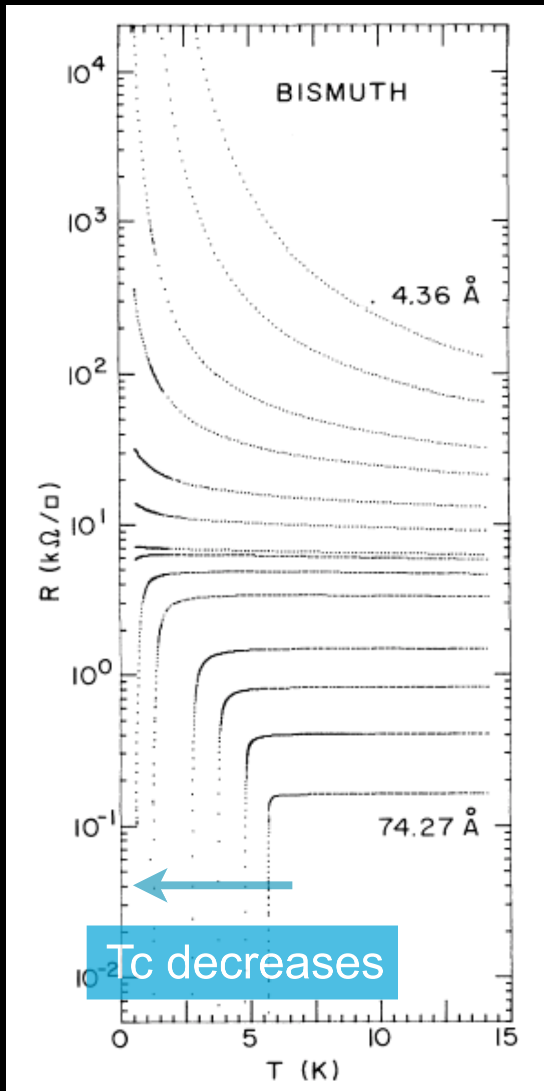
SIT competition between a localizing, E_c, and delocalizing, E_j, energy scales

Predicts insulators with Cooper pairs!

Works for



Does it work for all systems?

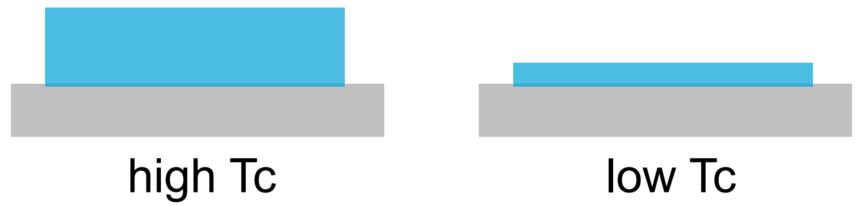


amorphous–Bi films

Haviland, Liu and Goldman

SIT via Amplitude Reduction?

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

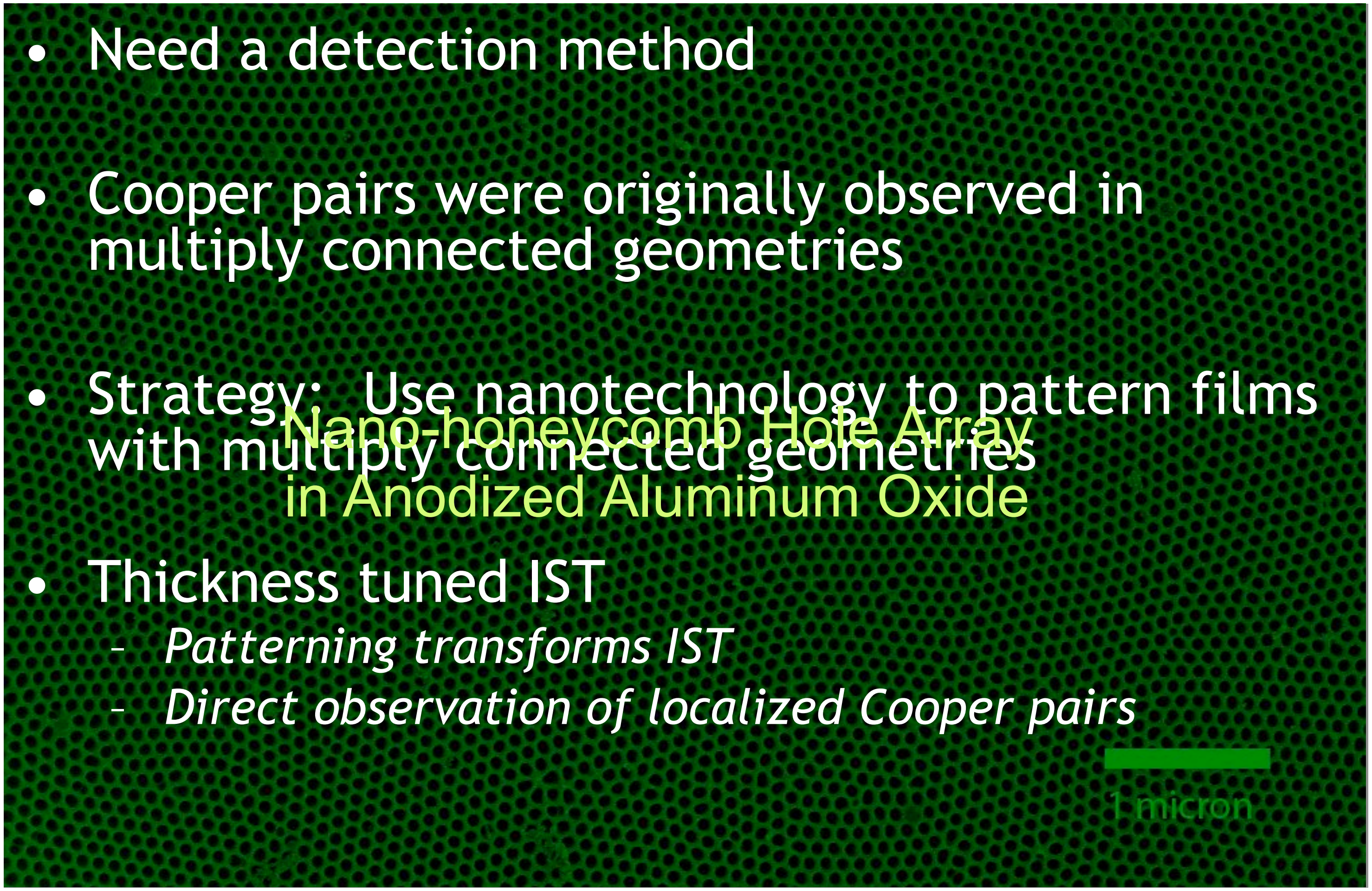


Idea: Decrease T_c by decreasing n_{sc} by decreasing the film thickness

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

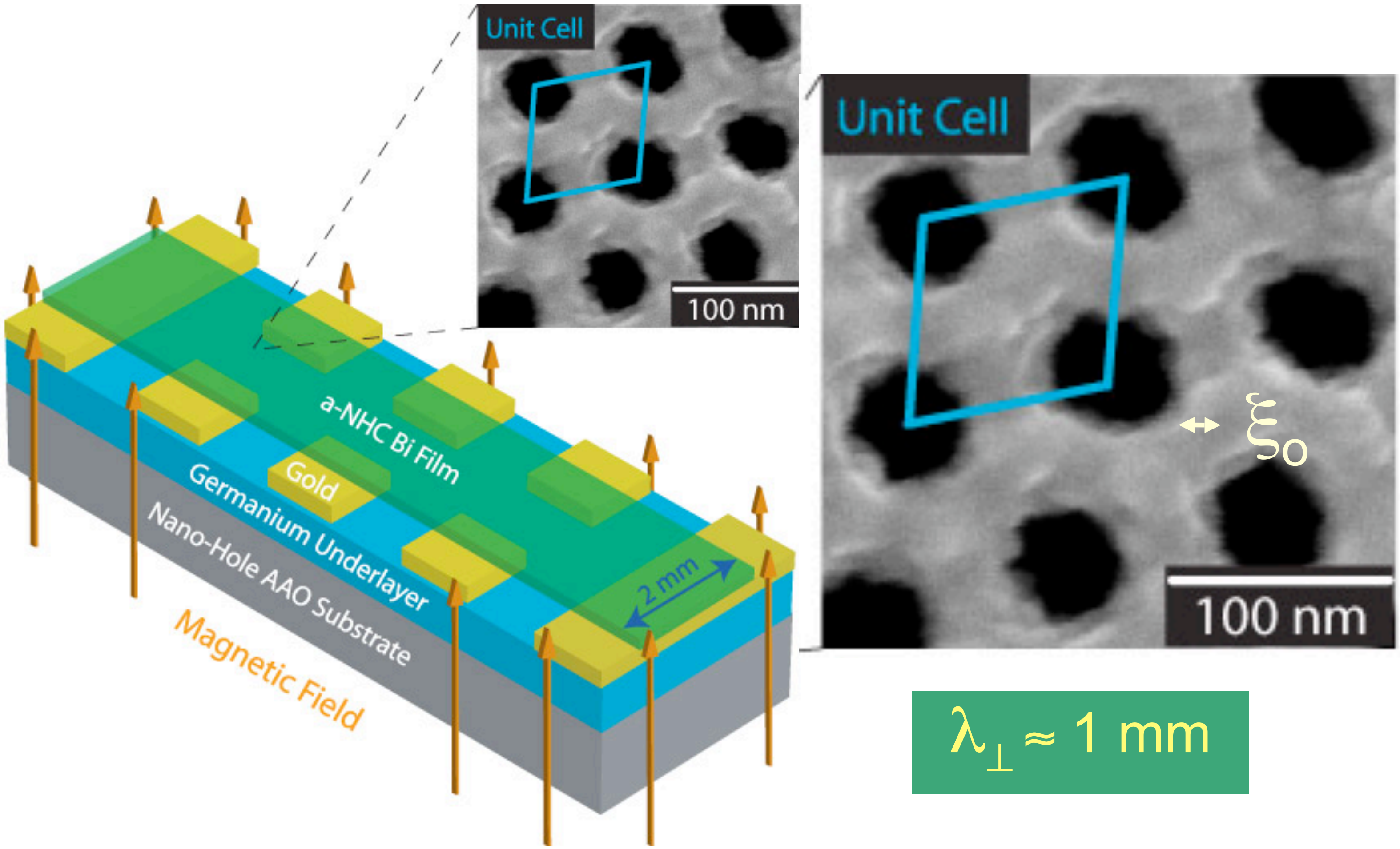
Cooper Pairs in amorphous films?

- Need a detection method
- Cooper pairs were originally observed in multiply connected geometries
- Strategy: Use nanotechnology to pattern films with multiply connected geometries
- Thickness tuned IST
  - *Patterning transforms IST*
  - *Direct observation of localized Cooper pairs*



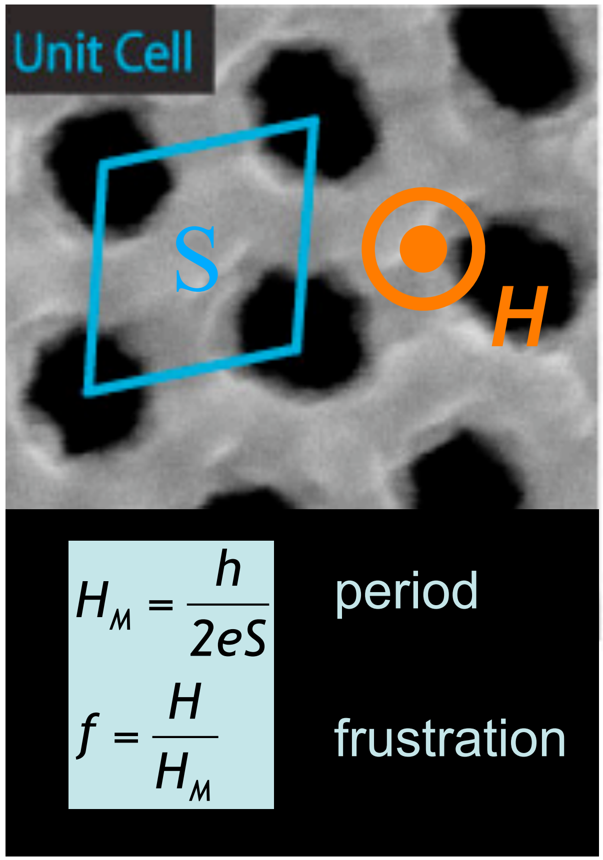
Experimenters

Nano-honeycomb Films



$\lambda_{\perp} \approx 1$ mm

Cooper Pair Detection (q=2e)



Charge in a magnetic field

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

Cooper pair phase obeys

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

$\Rightarrow$ flux quantization

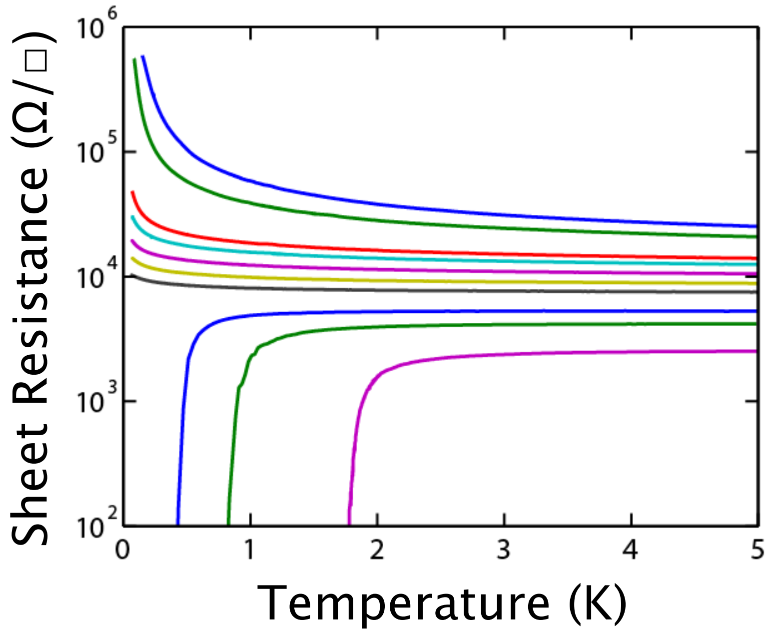
$$\Phi_0 = \frac{h}{2e}$$

$\Rightarrow$ flux periodic properties

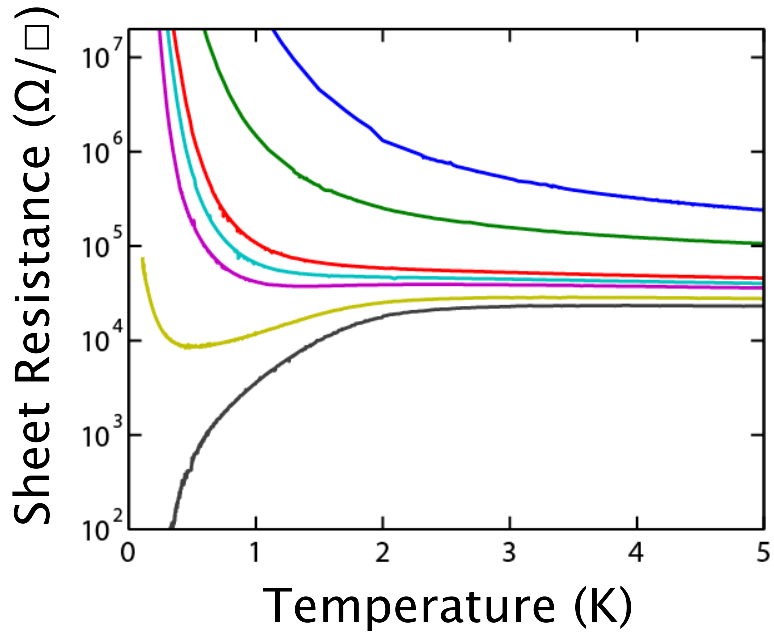
$$H_M = \frac{\Phi_0}{2eS}$$

Thickness Tuned IST's

Unpatterned

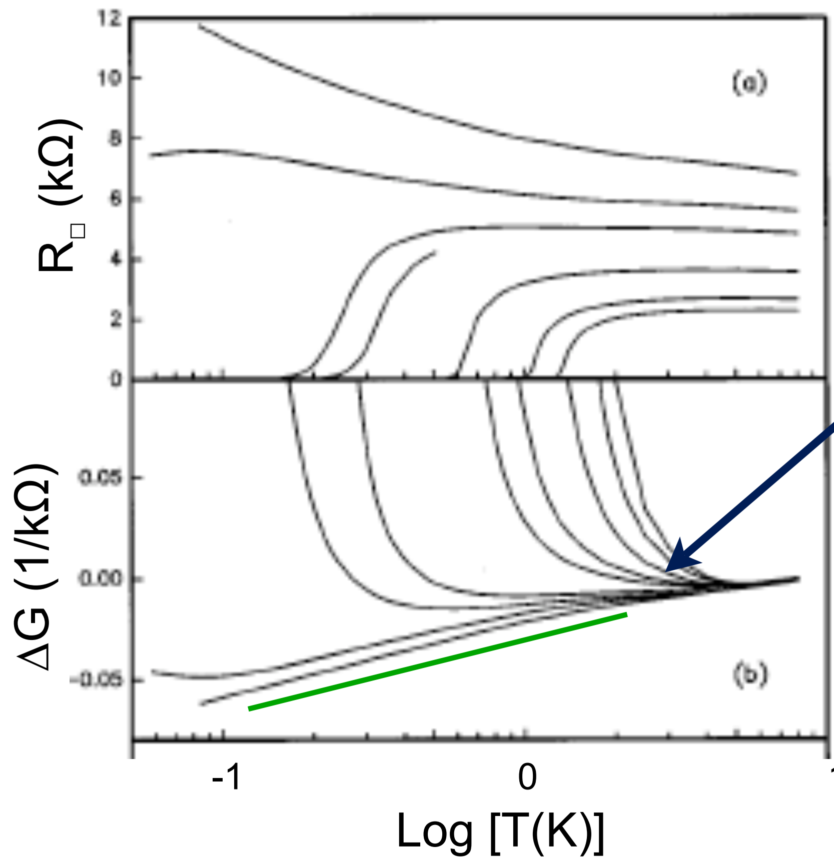


Nano-honeycomb



Features: Reentrance, stronger insulator, broad superconducting transition

Unpatterned Films make weak insulators



Insulator's conductance:

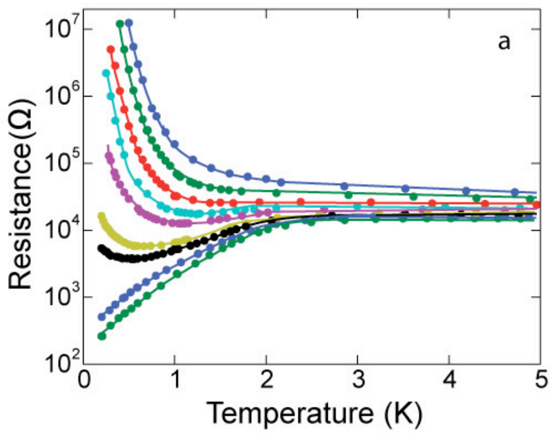
$$\Delta G \sim log(T)$$

⇒ weakly localized insulator of fermions

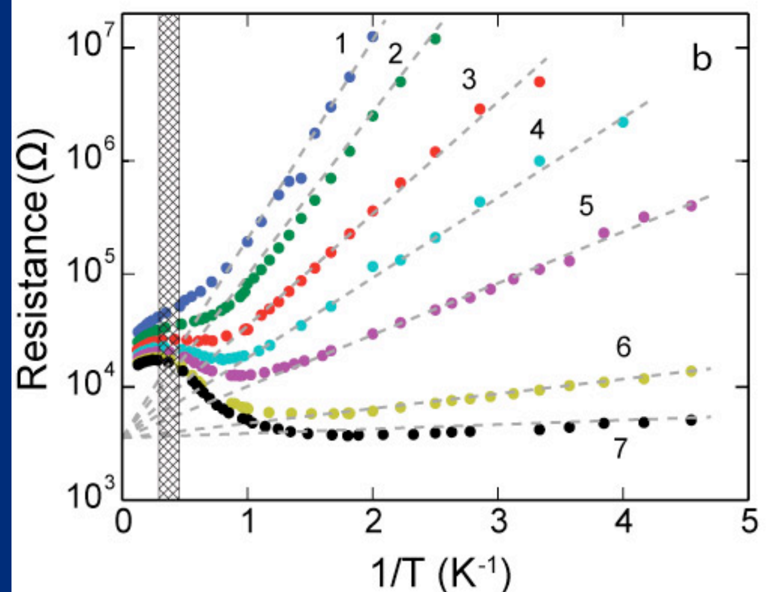
IST of a-Bi/Sb films

PRB 59, 11209 (1999)

Insulator is exponentially localized



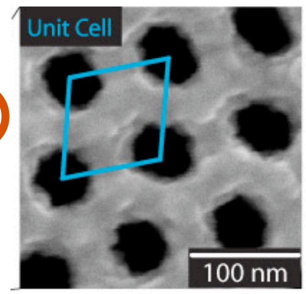
NHC films



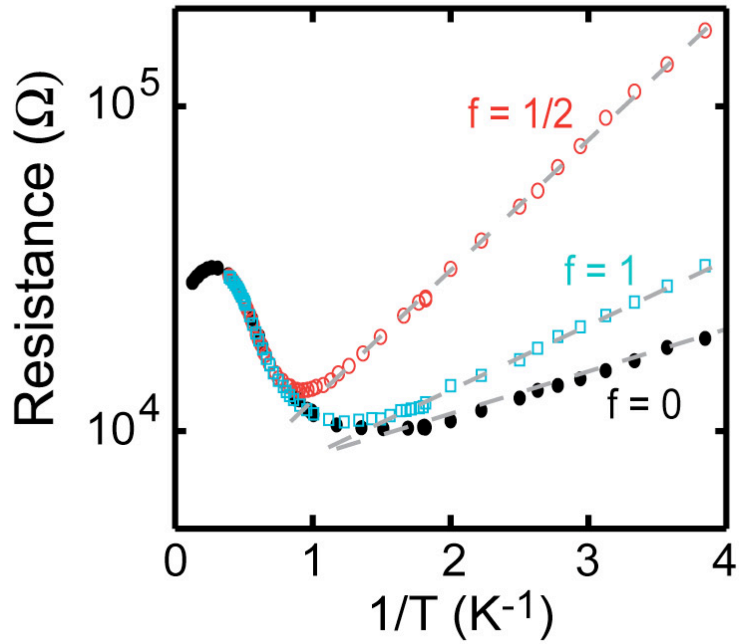
$$R=R_0 \exp(-T_o/T)$$

Insulating NHC Film in Magnetic Field

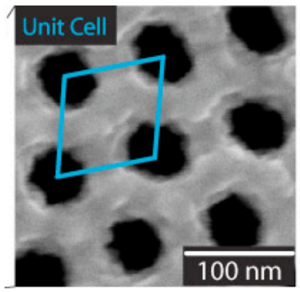
H ⊙

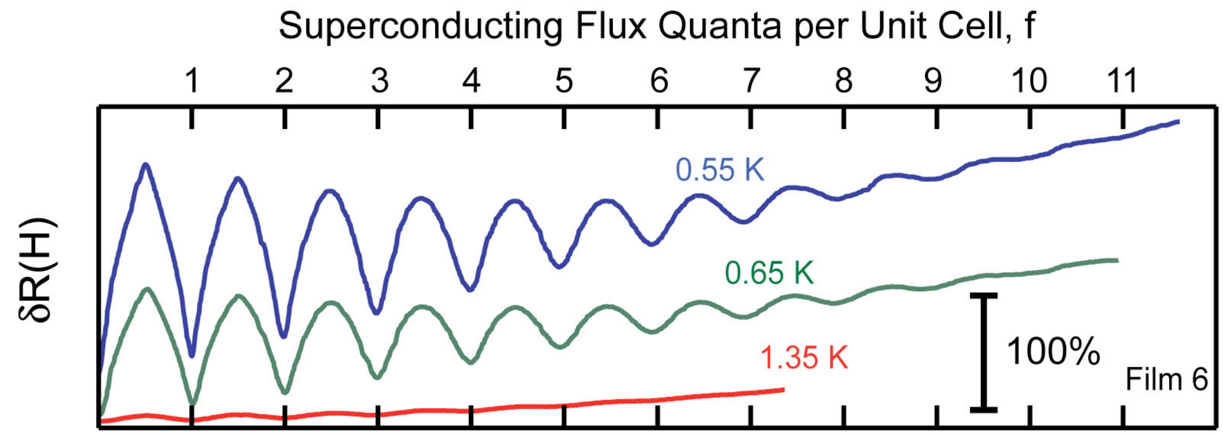


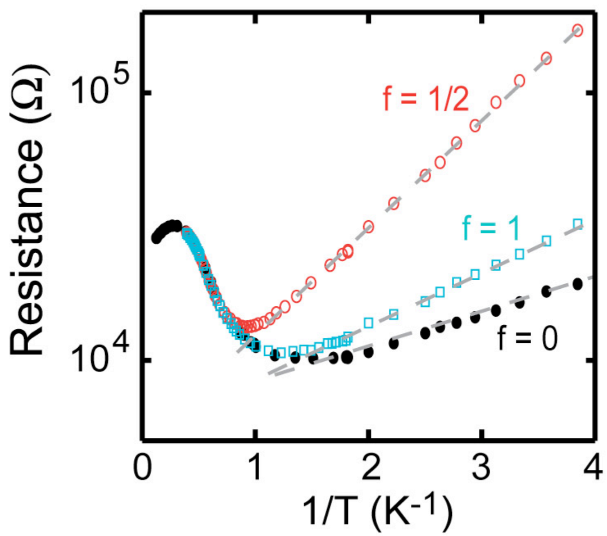
f= H/H_M



Insulator exhibits flux oscillations!





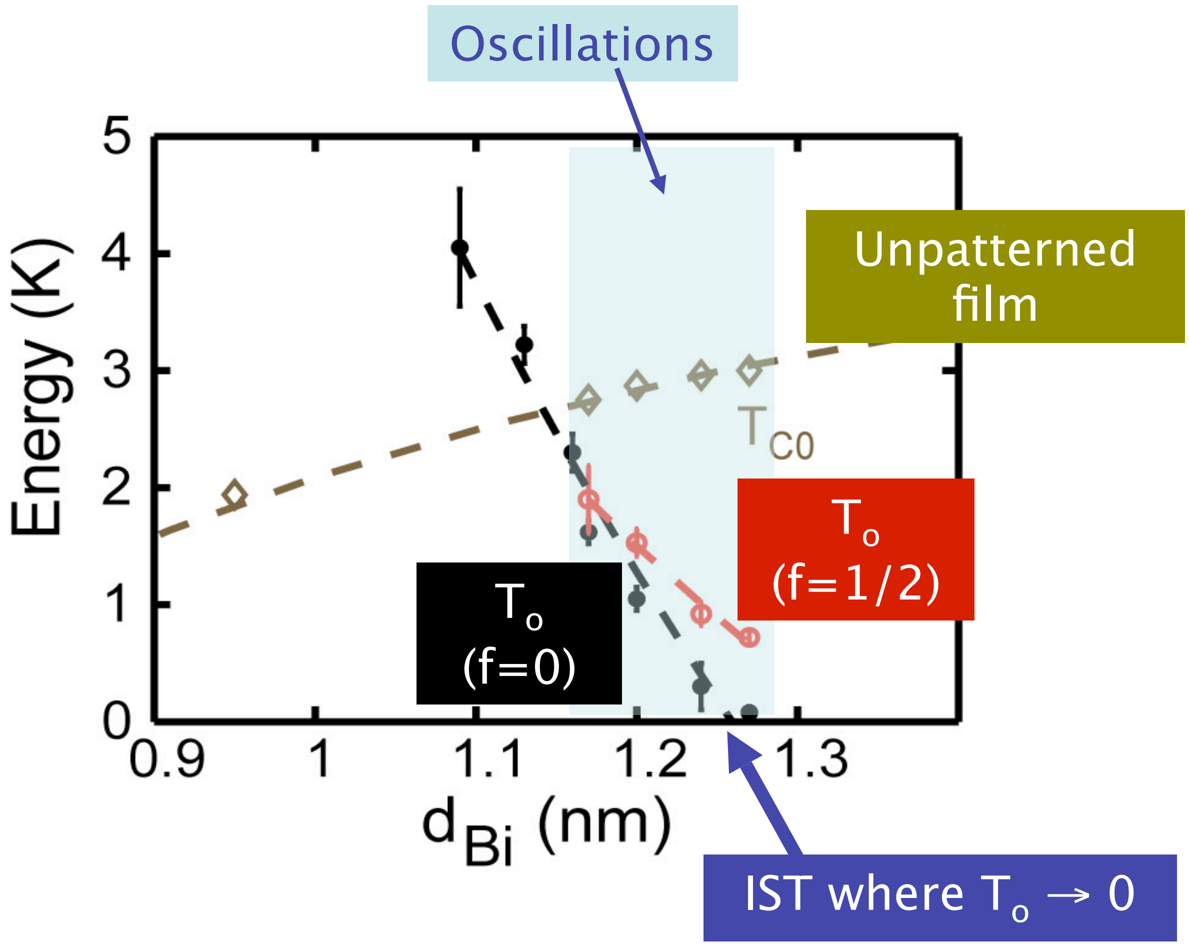


1) Period: $H_M = h/2eS$

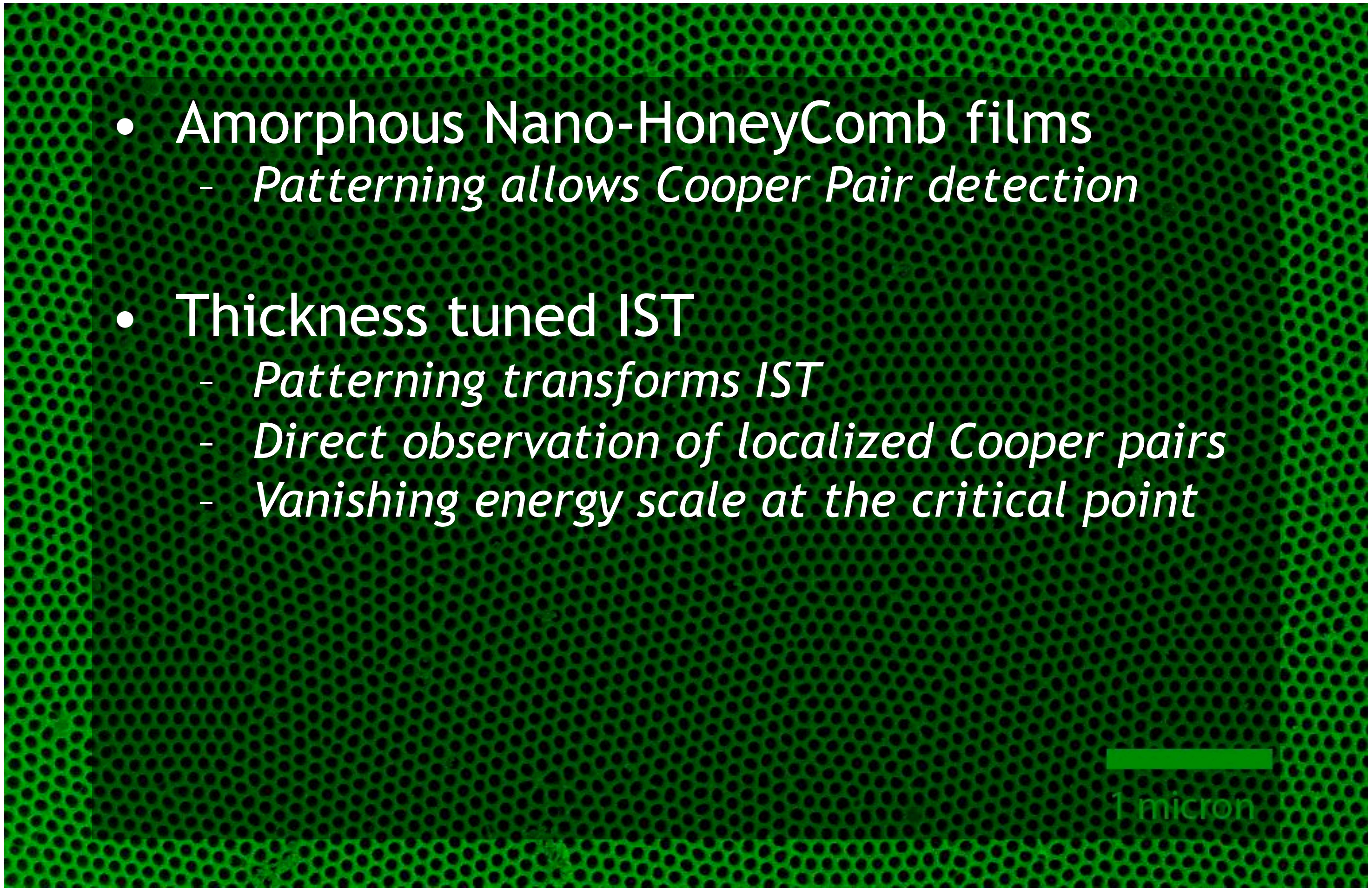
$\Rightarrow$ 2e charge carriers

2) Activation energy oscillates

Energy scales in the insulator

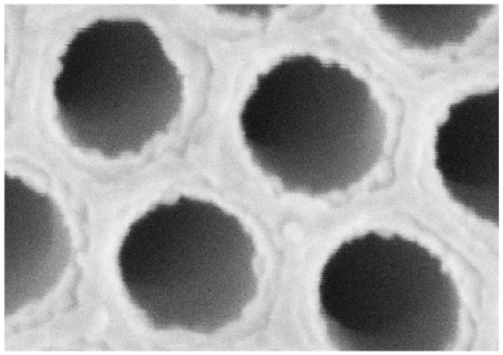


Cooper Pairs in Insulating Films

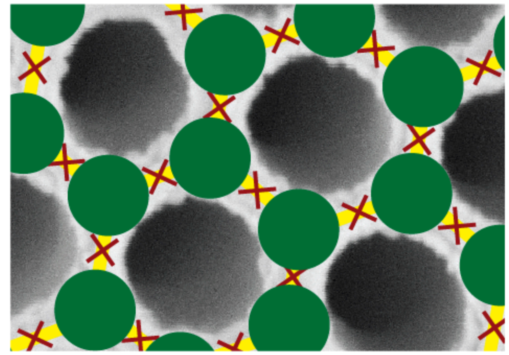


- Amorphous Nano-HoneyComb films
  - *Patterning allows Cooper Pair detection*
- Thickness tuned IST
  - *Patterning transforms IST*
  - *Direct observation of localized Cooper pairs*
  - *Vanishing energy scale at the critical point*

What governs the NHC film IST?



? =



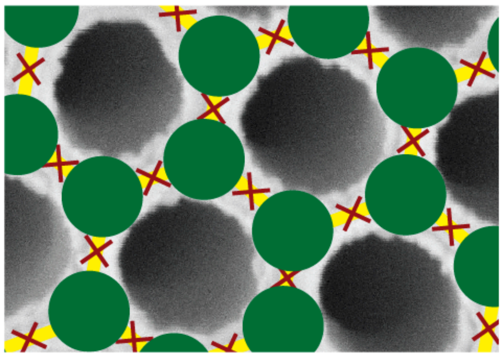
Josephson Junction Array physics?

localizing charging energies vs. delocalizing Josephson energies

$E_c > E_j$ gives an activated insulator

E_j oscillates in magnetic field

JJA picture



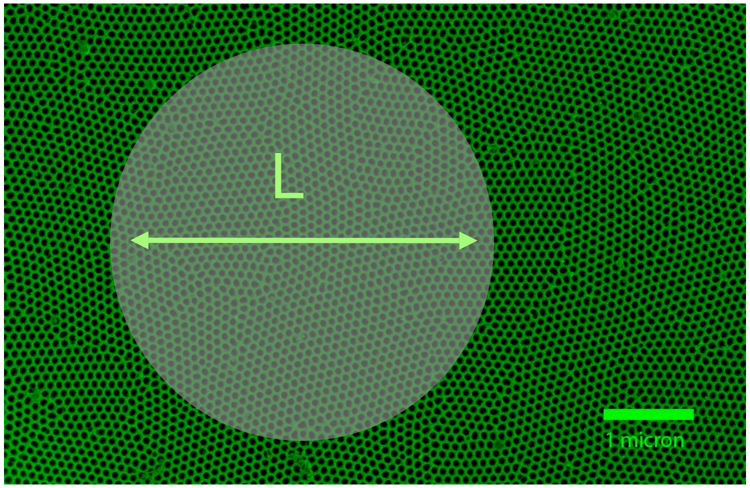
Estimate : $E_c \cong \dfrac{4e^2}{\varepsilon\varepsilon_0 L}$

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

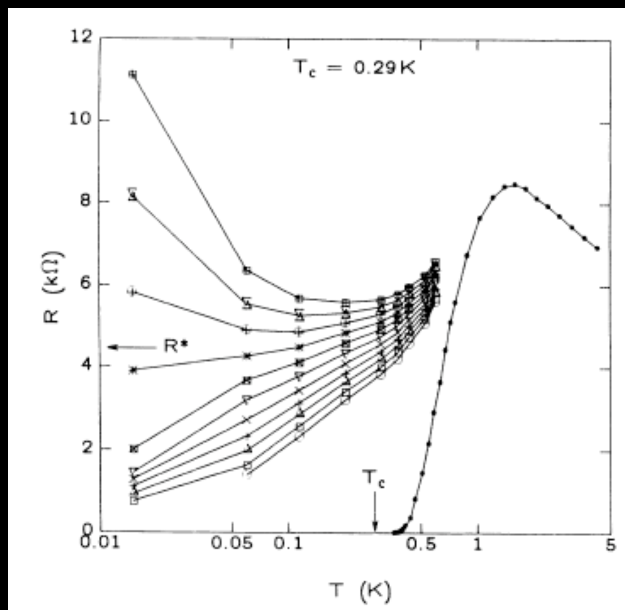
Too large to be relevant!

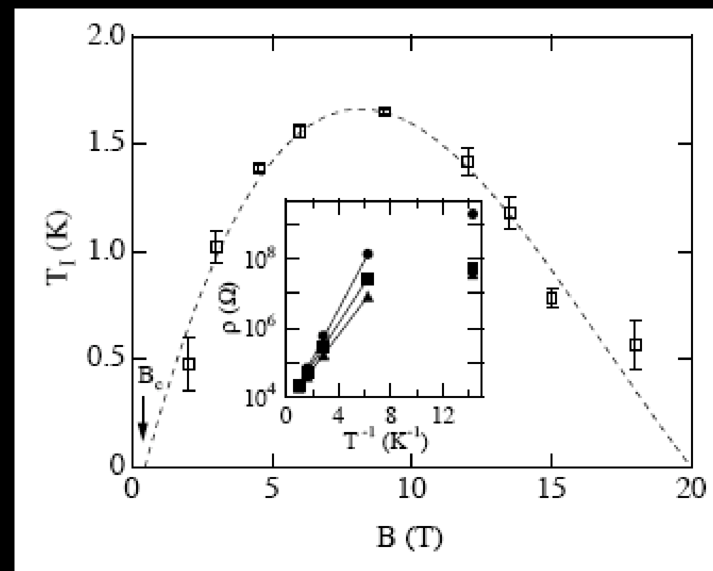
Effective islands encompass many holes?

--- Need 1000's of holes



Comparison to Unpatterned Indium Oxide Films





Reer

Hebard and P ., PRL

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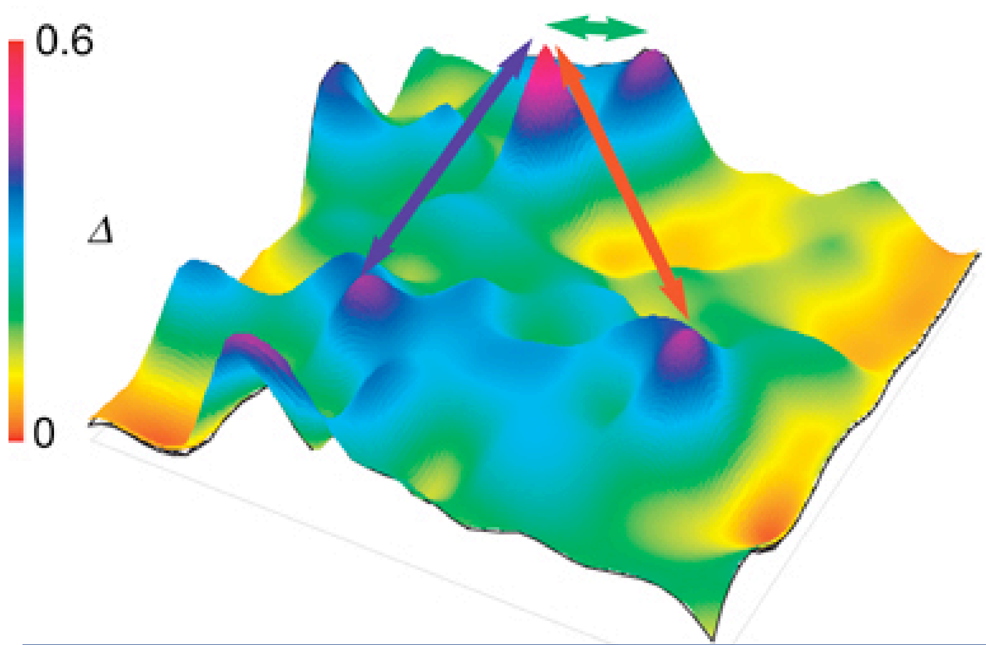
Spontaneous formation of a multiply connected geometry in magnetic field?

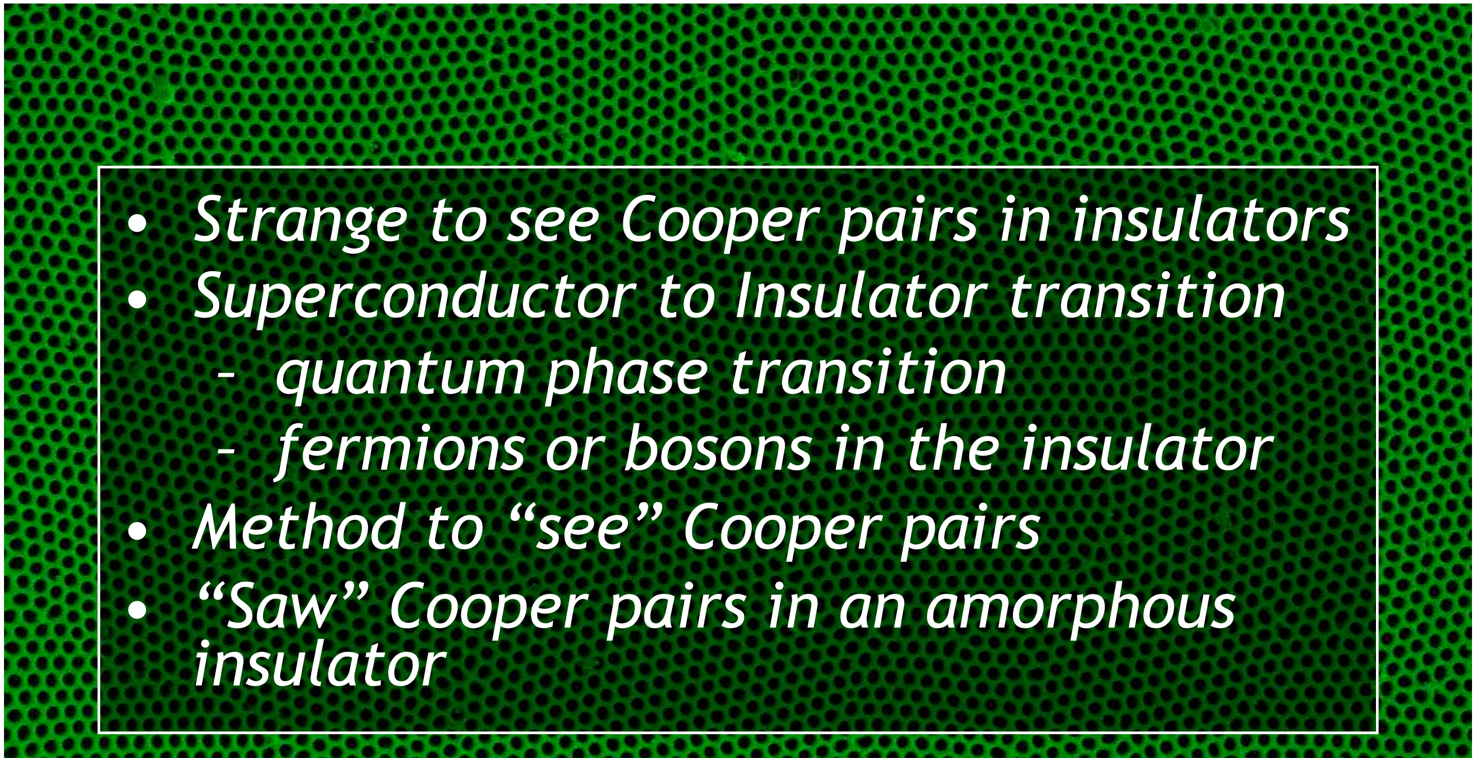
Spontaneous Islanding in Magnetic Field



Map of amplitude variations in a magnetic field from theory

Yonatan Dubi, Yigal Meir & Yshai Avishai, Nature 449, 876-880(18 October 2007)

Cooper Pairs in Insulators



- *Strange to see Cooper pairs in insulators*
- *Superconductor to Insulator transition*
  - *quantum phase transition*
  - *fermions or bosons in the insulator*
- *Method to “see” Cooper pairs*
- *“Saw” Cooper pairs in an amorphous insulator*