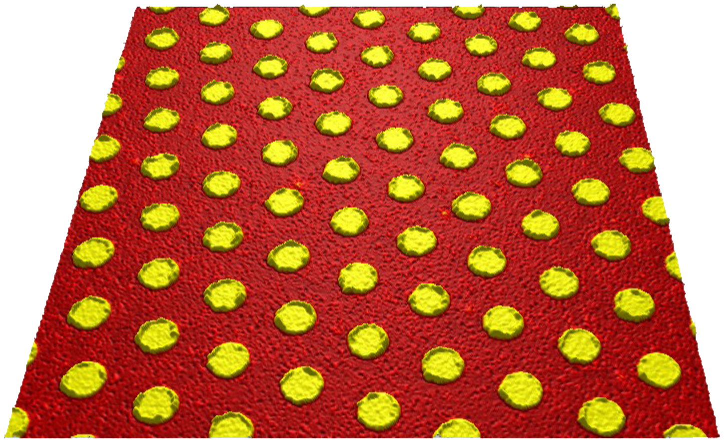
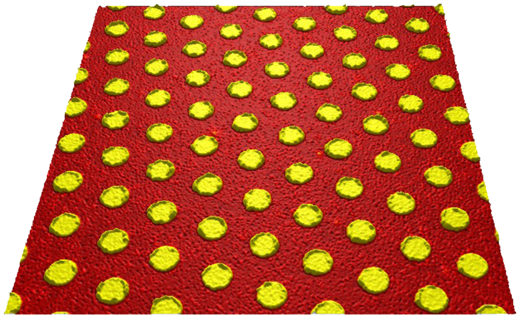
Dissipation and Proximity Effects in Nanostructured Superconductors

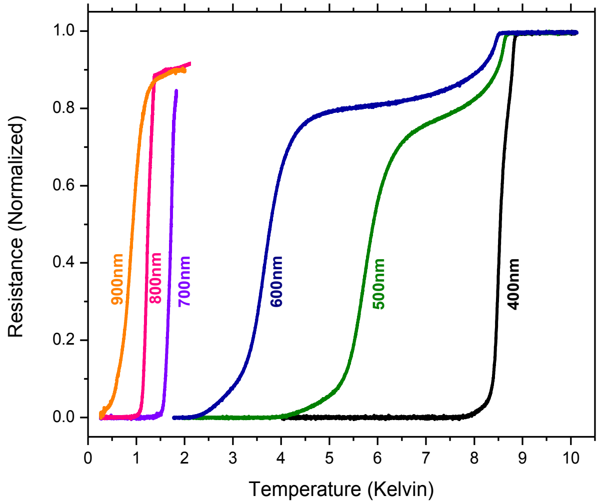
Nadya Mason
University of Illinois at Urbana-Champaign



Outline:

1. Dissipation in SIT
2. Superconducting island on metallic substrates
3. T_{BKT} vs. island spacing
4. Magnetic field effects: frustration, cusps in R vs T

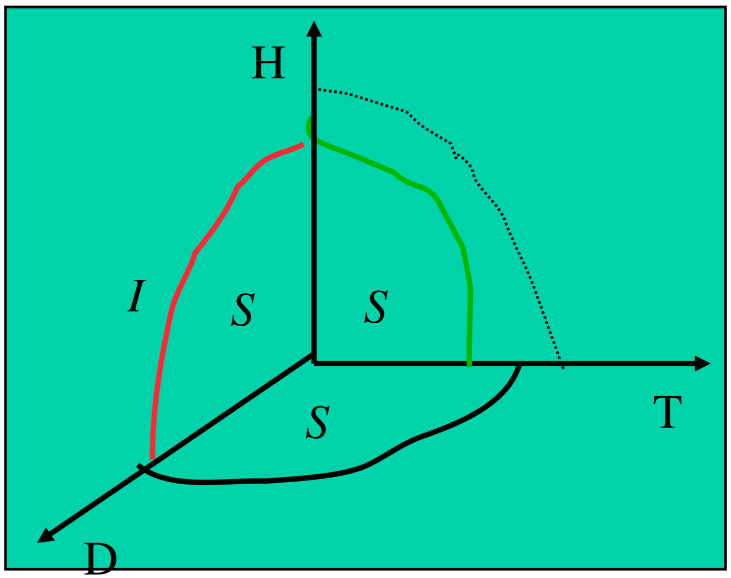




Preliminary data and analysis!

Serena Eley

It’s hard to let go of beloved thesis work …



Why study the 2D S-I Transition?

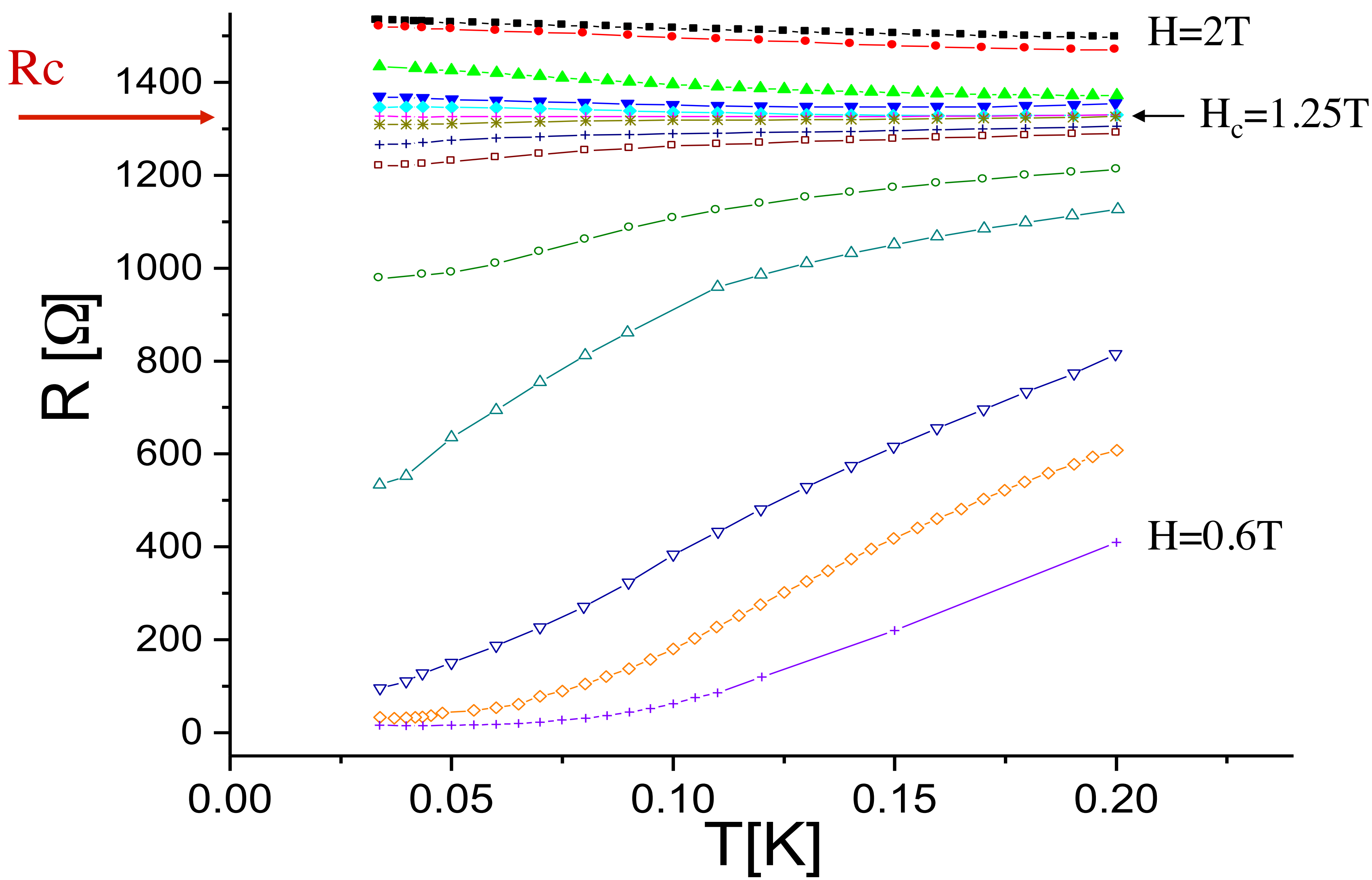
*System ideal for studying competition between: Cooper pairing, localization, Coulomb repulsion, disorder, dissipation

*This physics – physics of 2D *quantum phase transitions* – relevant to superconductor-insulator transition, quantum Hall liquid-plateau transition, Josephson-junction arrays, metal-insulator transition, high-T_c superconductors

*Role of disorder, phase separation, dissipation relevant to most 2D systems (e.g., high Tc, graphene)

What is role of dissipation in 2D superconducting transitions?

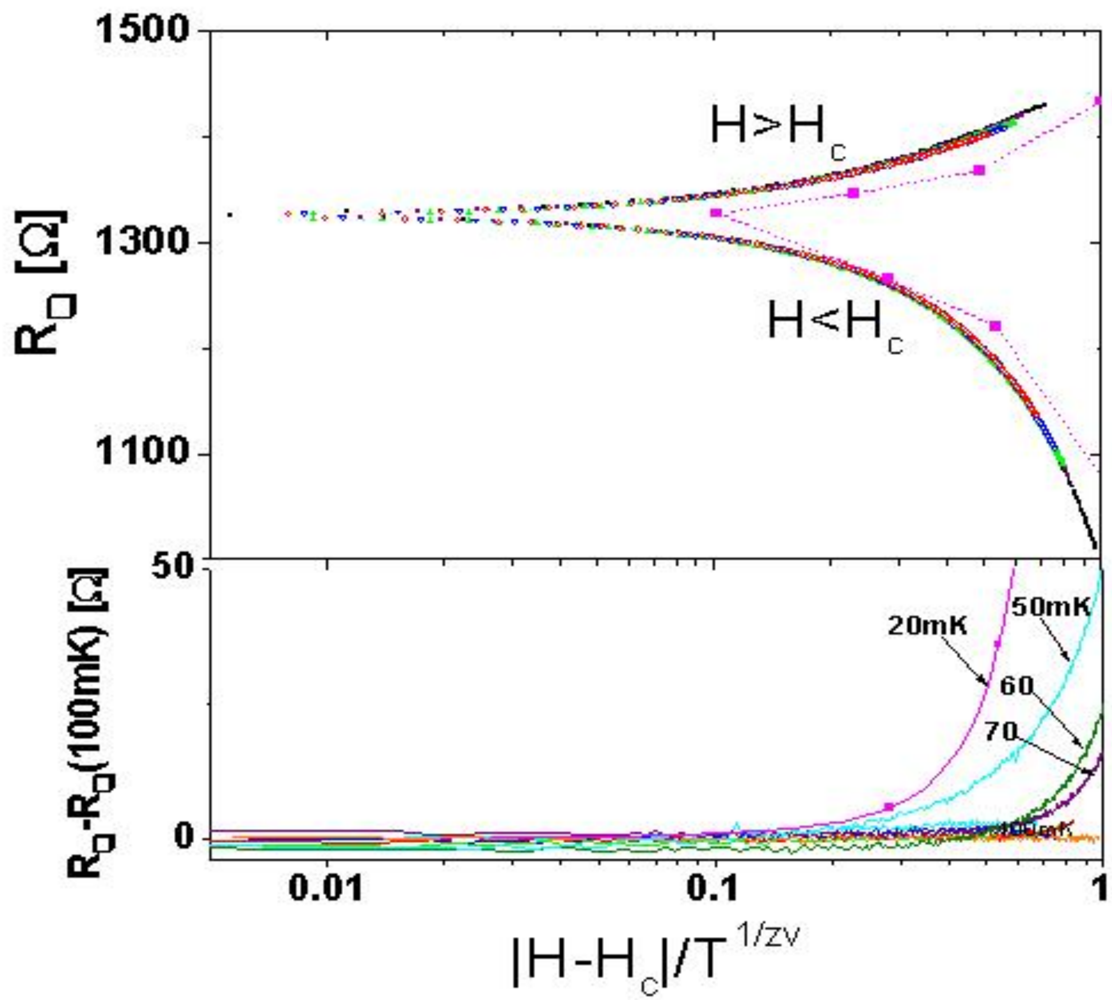
Experiments on $Mo_{43}Ge_{57}$ *: Low Temperature Metallic State*



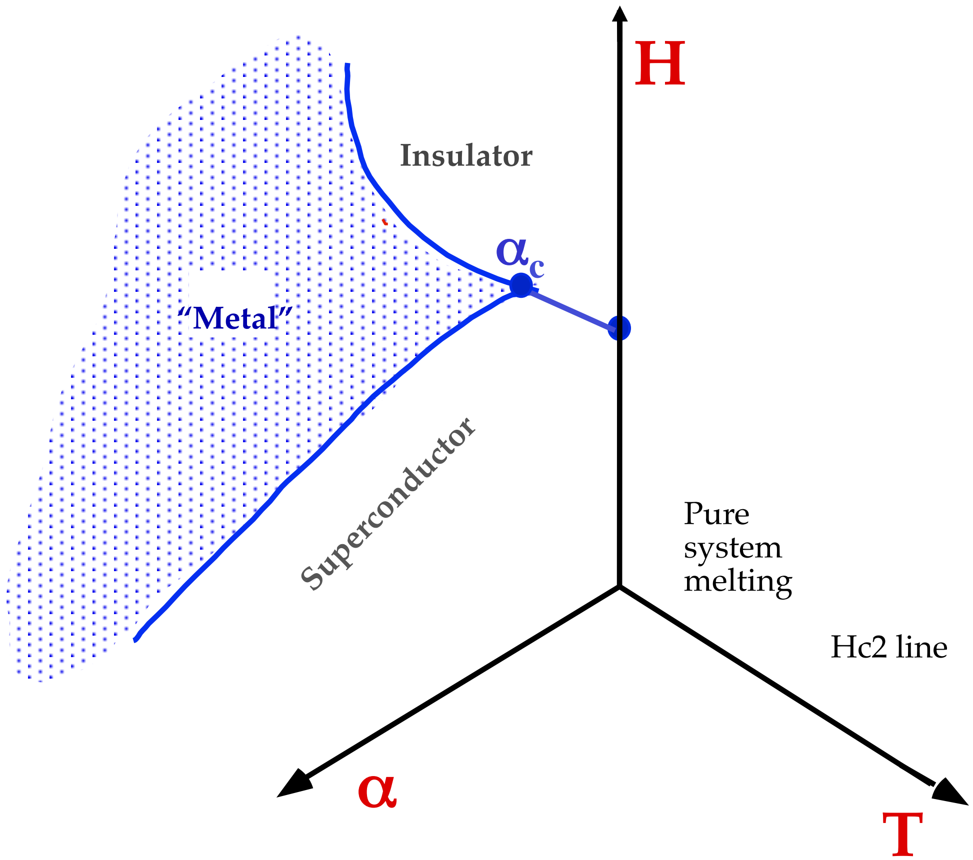
What is role of dissipation in 2D superconducting transitions?

Experiments on $Mo_{43}Ge_{57}$ *: Low Temperature Metallic State*

Disruption of Scaling at Low Temperatures



New parameter controls the dissipation:



α is a (temperature like) parameter that controls the dissipation

But what causes dissipation? What tunes α?

Theoretical explanations of metallic state:

Homogeneous Bose metal:

- D. Das and S. Doniach, PRB 60, 1261 (1999), PRB 64, 134511 (2001)
  Quantum frustration in coupled X-Y model (charge/phase order) → Bose metal

- D. Dalidovich and P. Phillips, PRL 84, 737 (2000), PRB 64, 052507 (2001)f
  Dissipation in junction array → metal

Phase Separated, junction-like:

- M. Feigel'man and A. Larkin, Chem.Phys. 235, 107 (1998), cond-matt/9908075
  Superconducting islands embedded in dirty metallic film; superconducting-normal transition as function of intergrain coupling

- B. Spivak, A. Zyuzin, M. Hruska, PRB 64, 132502 (2001)
  Fluctuating superconducting grains in a metallic matrix → metal-superconductor transition; low resistance metallic state dominated by Andreev reflections

- E. Shimshoni, A. Auerbach, A. Kapitulnik, PRL 80, 3352 (1998)
  Disorder causes phase separation; Dissipative quantum tunneling of vortices (Cooper pairs) between phase separated regions of insulator (superconductor); percolative transition

Modify properties of transition with metallic plane near sample …

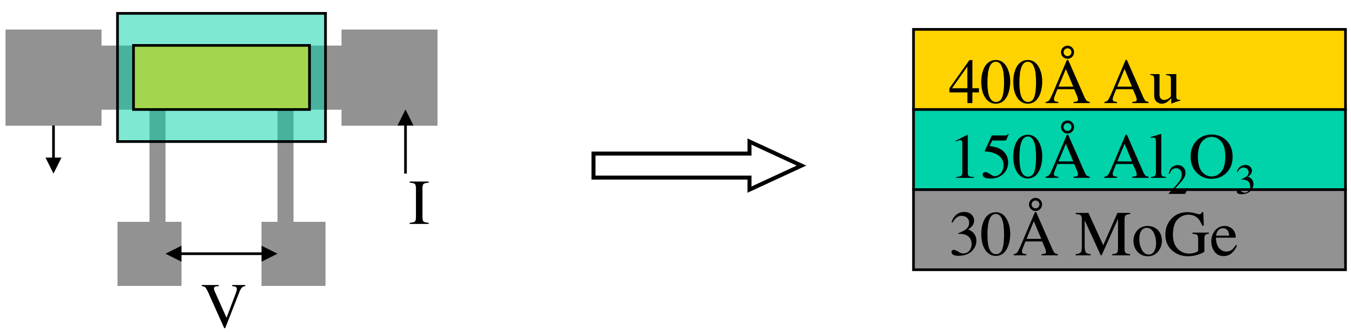
★ Metallic plane could change dissipative environment

Caldeira-Leggett model:

- Dissipative bath: Collection of harmonic oscillators
- Dissipation is Ohmic
- Strength of coupling a $\propto$ 1/R

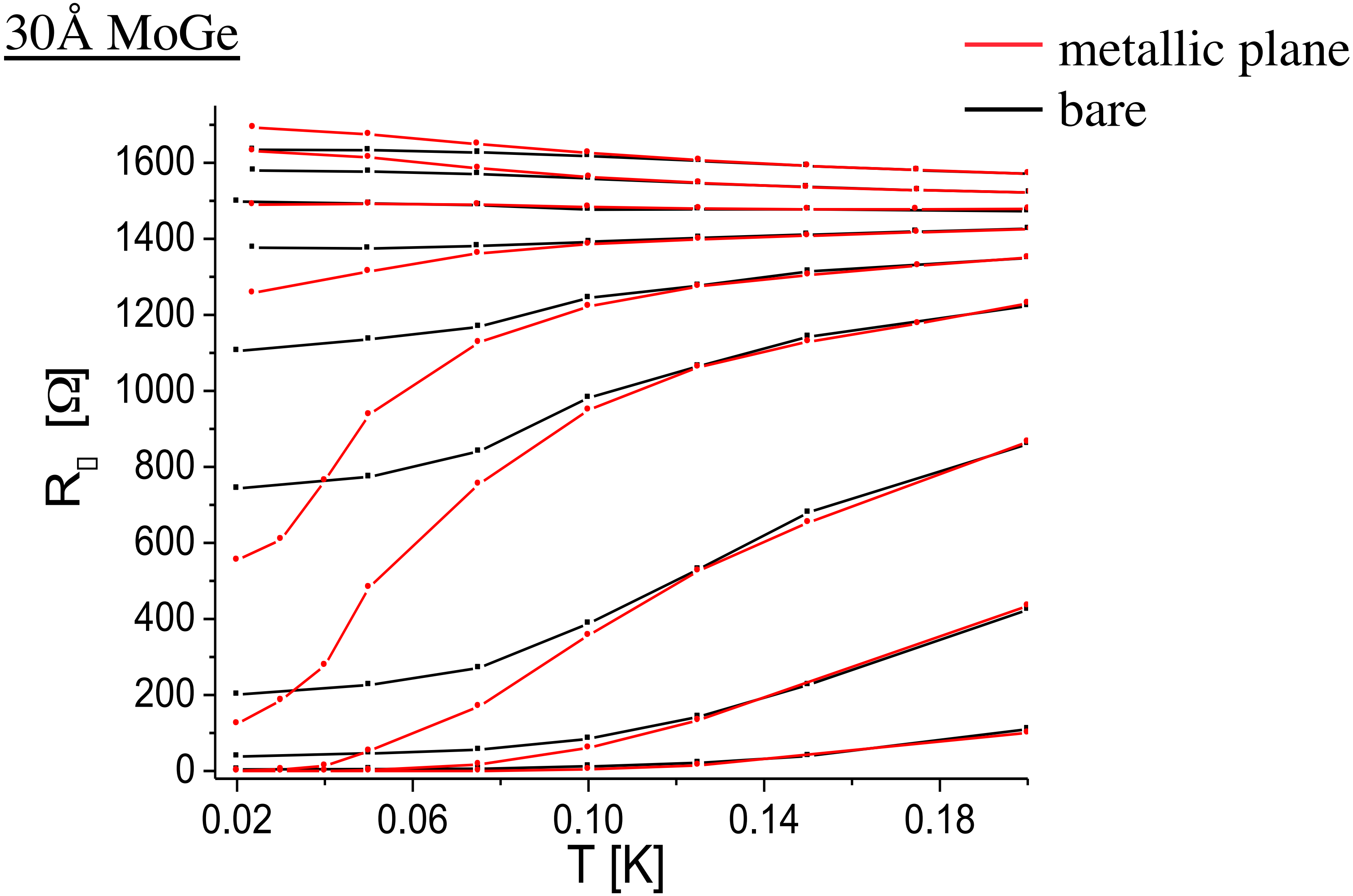
$$\textit{dissipation} \sim 1/R$$

(also like shunt resistance in Josephson junction)



Modify properties of transition with metallic plane near sample …

Enhanced superconductivity with metallic plane

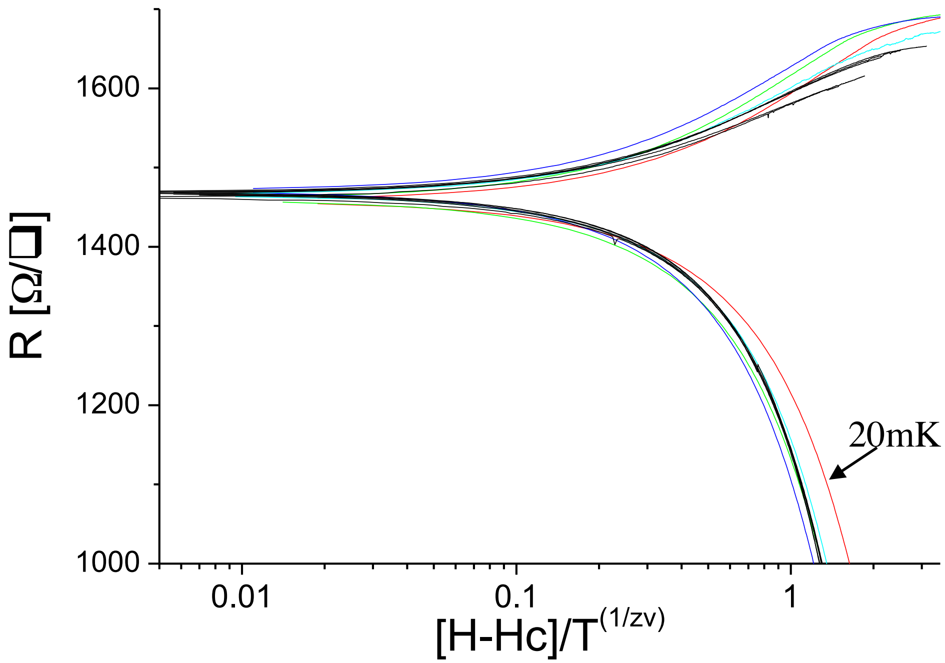


Modify properties of transition with metallic plane near sample …

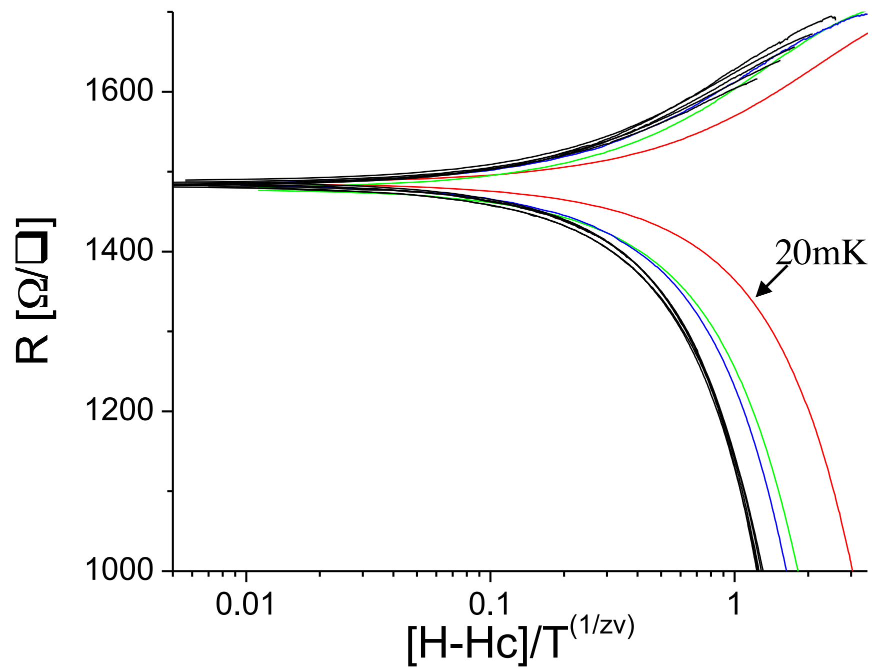
Improved scaling with metallic plane

Scaling for z=1 …

ground plane



bare



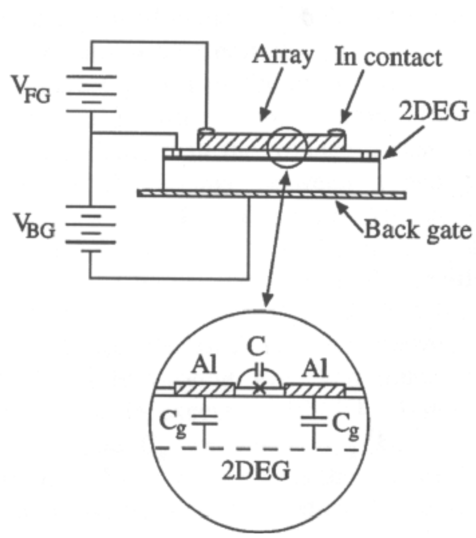
T=20-200mK

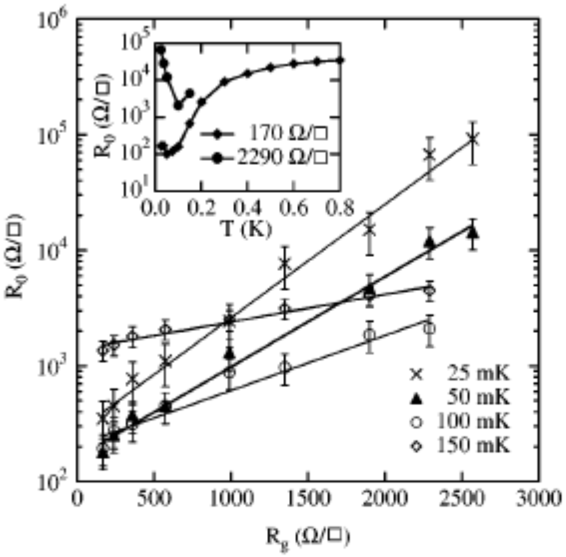
Analagous Dissipative Phase Transition in Josephson junction arrays:

Rimberg et al, PRL **78**, 2632 (1997)

"Dissipation-Driven Superconductor-Insulator Transition in a Two-Dimensional Josephson-Junction Array"

Capacitive coupling to resistance …





Quantum fluctuations of phase interact with ground plane

→ ***coupling to dissipation damps fluctuations and pins superconductivity***

Analagous Dissipative Phase Transition in Josephson junction arrays:

Or coupling can be Ohmic …

Superconductor-Insulator Transition in a Tunable Dissipative Environment

Karl-Heinz Wagenblast,[1,2] Anne van Otterlo,[2] Gerd Schön,[1] and Gergely T. Zimányi[2]
[1] *Institut für Theoretische Festkörperphysik, Universität Karlsruhe, D-76128 Karlsruhe, Germany*
[2] *Physics Department, University of California, Davis, California 95616*
(Received 1 May 1997)

We study the influence of a tunable dissipative environment on the dynamics of Josephson junction arrays near the superconductor-insulator transition. The experimental realization of the environment is a two dimensional electron gas coupled capacitively to the array. This setup allows for the well controlled tuning of the dissipation by changing the resistance of the two dimensional electron gas. The capacitive coupling cuts off the dissipation at low frequencies. We determine the phase diagram and calculate the temperature and dissipation dependence of the array conductivity. We find good agreement with recent experimental results. [S0031-9007(97)04157-4]

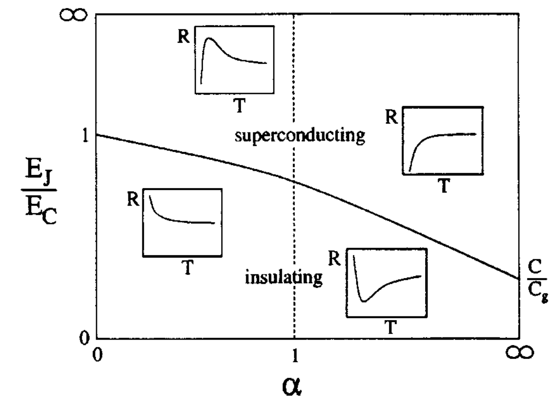


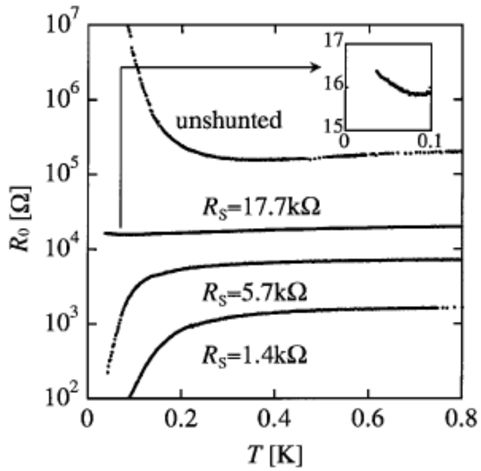
FIG. 2. Phase diagram of an array coupled capacitively to a 2DEG. The insets show the array resistance R as a function of the temperature T in the different regions.

VOLUME 85, NUMBER 9 PHYSICAL REVIEW LETTERS 28 AUGUST 2000

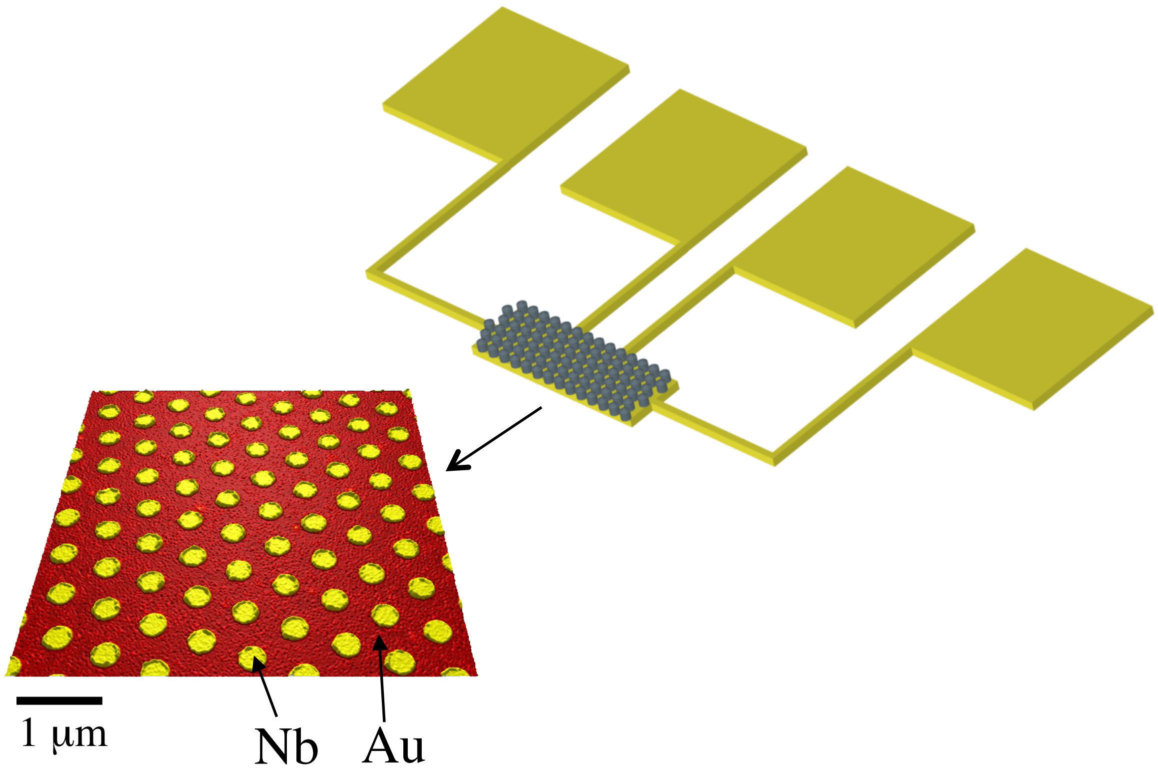
Superconductor-Insulator Transition in a Two-Dimensional Array of Resistively Shunted Small Josephson Junctions

Yamaguchi Takahide,[1,2] Ryuta Yagi,[1] Akinobu Kanda,[1,2] Youiti Ootuka,[1,2] and Shun-ichi Kobayashi[3]
[1] *Institute of Physics, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, 305-8571, Japan*
[2] *CREST, Japan Science and Technology Corporation, 4-1-8, Honcho, Kawaguchi, 332-0012, Japan*
[3] *The Institute of Physical and Chemical Research (RIKEN), 2-1 Hirosawa, Wako, 351-0198, Japan*
(Received 11 April 2000)

We have fabricated two-dimensional (2D) small-Josephson-junction arrays of which each Al-AlO_x-Al junction is shunted by a Cr resistor. The arrays with large junction resistance and large charging energy show a transition from insulating to superconducting behavior when the shunt resistance is lowered below a critical value, which is close to $2R_Q$ ($R_Q \equiv h/4e^2 = 6.45$ kΩ). The measured phase diagram is consistent with theories of quantum-fluctuation-driven and dissipation-driven phase transitions in the 2D Josephson-junction array with Ohmic shunt resistors.



Want to study model system of 2D superconductor with known dissipation → **superconducting islands on metallic films**



Tunable parameters:

•island size (~ 200nm) → tunes fluctuations

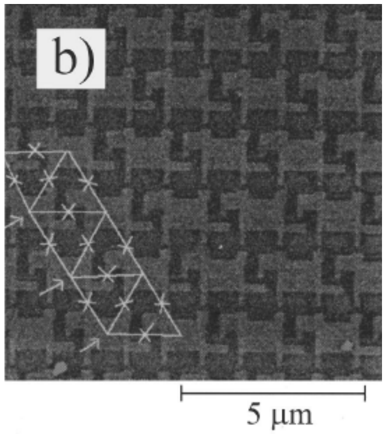
• island spacing (400 – 900nm) → tunes dissipation

• materials (here, use Nb islands on Au 4-pt patterns)

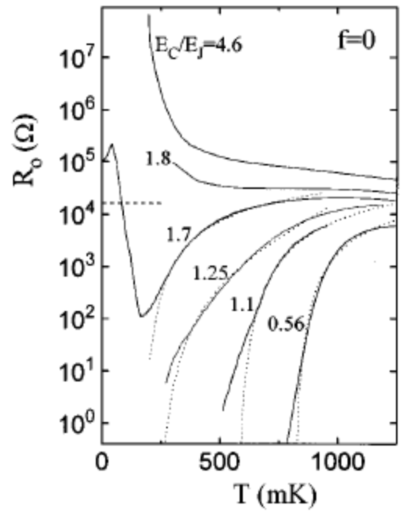
• 10,000-30,000 islands → individual junction properties don't dominate

- known dissipation introduced via normal metal
- intrinsically phase-separated

Different from Josephson junction array …

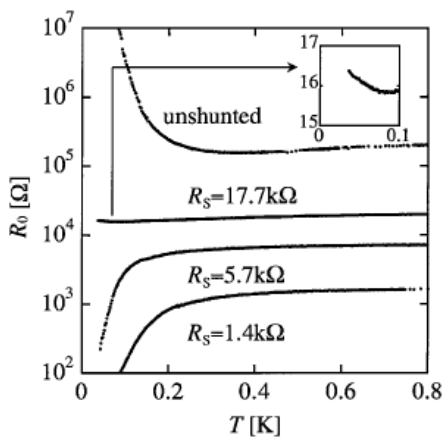


van der Zant *et al*, PRB (1996)



And from resistively shunted JJ arrays …

Takahide *et al*, PRl (2000)



We study:
- smaller junctions
- smaller coupling resistance
- effect of intrinsic resistance

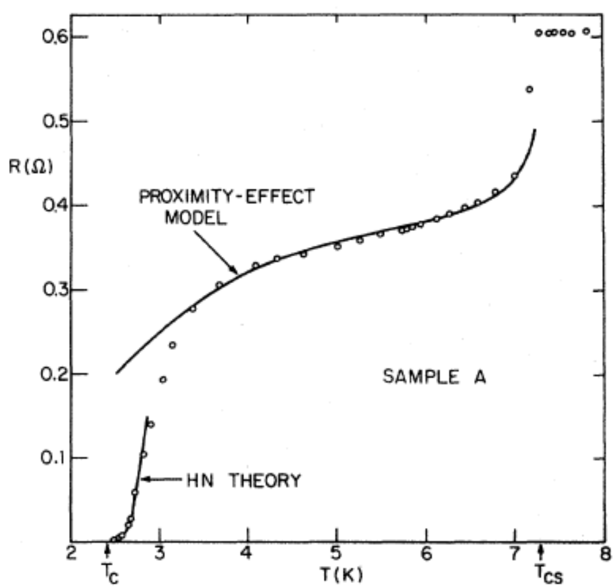
Similar to some (long ago!) work on proximity coupled arrays …

PHYSICAL REVIEW B VOLUME 26, NUMBER 9 1 NOVEMBER 1982

Resistive transition in two-dimensional arrays of superconducting weak links

David W. Abraham, C. J. Lobb, M. Tinkham, and T. M. Klapwijk*
Department of Physics and Division of Applied Sciences, Harvard University, Cambridge, Massachusetts 02138
(Received 8 June 1982; revised manuscript received 5 August 1982)

We present results of measurements on large arrays of PbBi/Cu proximity-effect junctions. Extrapolation of the critical current measured at low temperature to the region at and above T_c allows us to describe the initial drop in resistance by a simple model of the proximity effect, and also to define an appropriate effective temperature $\tilde{T} \cong E_J(T_c)T/E_J(T)$ for describing the vortex-unbinding transition. Nonlinear I-V curves above T_c are described by a crossover function whose form is consistent with the theory of Halperin and Nelson.



New focus on:
- dissipation
- island size and spacing

Low T metallic state?
Is SC enhanced by resistance?

New theories about this system …

PHYSICAL REVIEW B **77**, 214523 (2008)

Theory of quantum metal to superconductor transitions in highly conducting systems

B. Spivak
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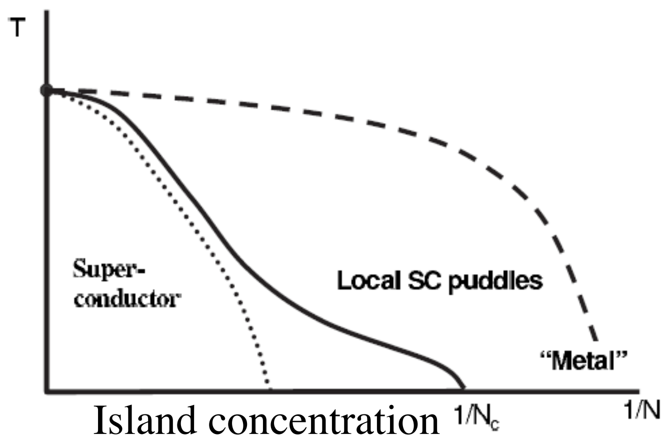
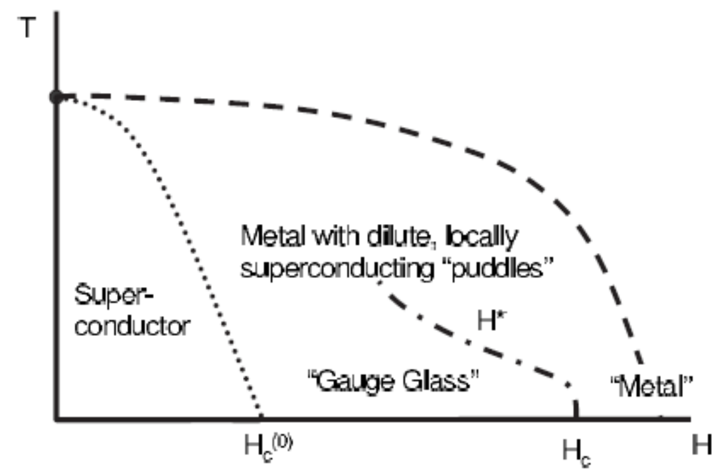
P. Oreto and S. A. Kivelson
Department of Physics, Stanford University, Stanford, California 94305, USA
(Received 4 April 2008; revised manuscript received 24 May 2008; published 24 June 2008)

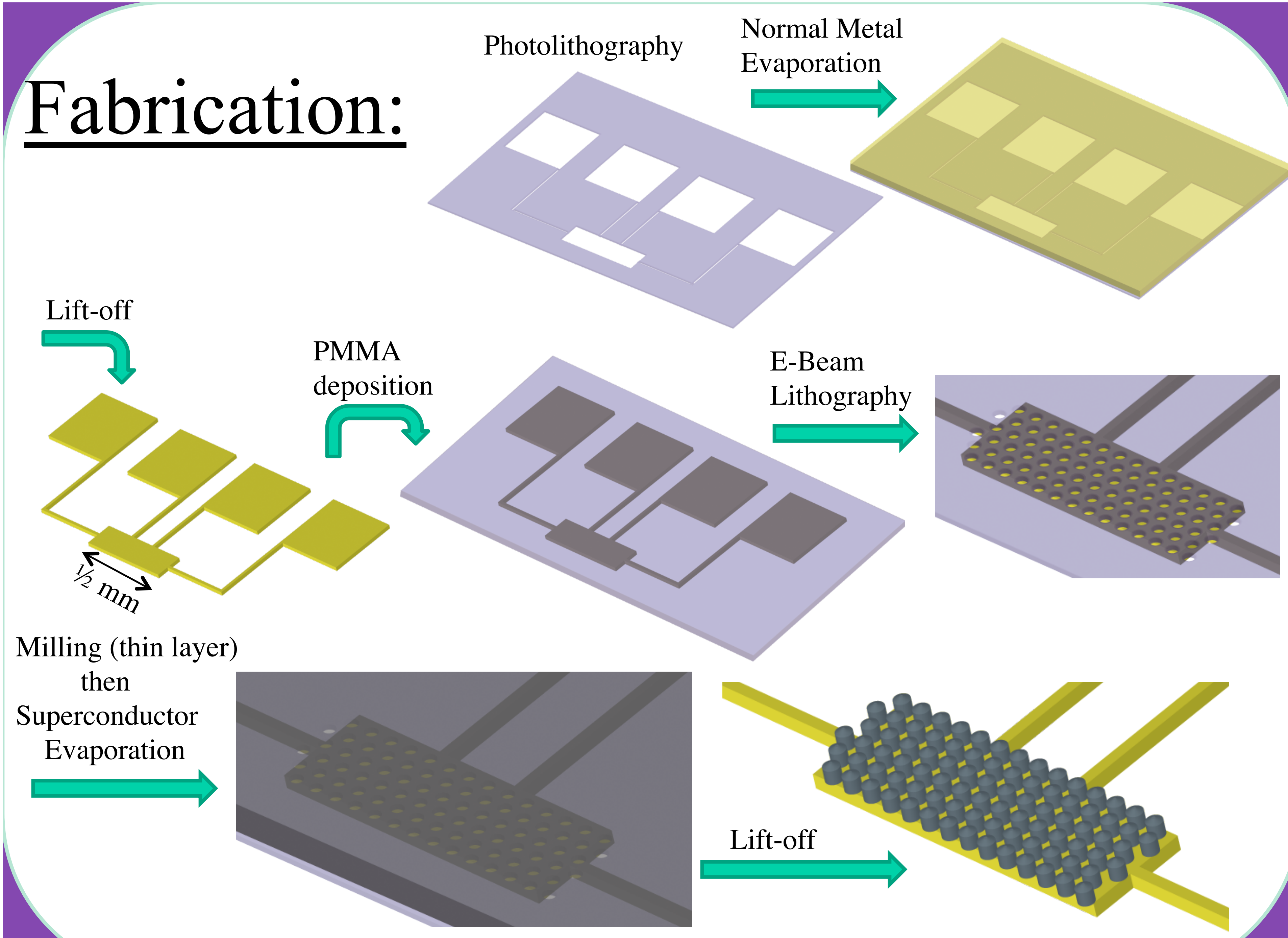




Josephson coupling between puddles: $J_{ij} \equiv J(\mathbf{r}_i, \mathbf{r}_j) \propto C_{ij} \dfrac{\nu V_i V_j}{|\mathbf{r}_i - \mathbf{r}_j|^D} \exp\left[-\dfrac{|\mathbf{r}_i - \mathbf{r}_j|}{L_T} \right]$

Quantum fluctuations for: $N_c \sim \begin{cases} \bar{R}^{-2} \exp(-Z' \sqrt{G_{2D}}) & \text{in } D=2 \text{ at } T=0 \\ \bar{R}^{-3} \exp(-Z G^{\text{eff}}) & \text{in } D=3 \text{ at } T=0. \end{cases}$

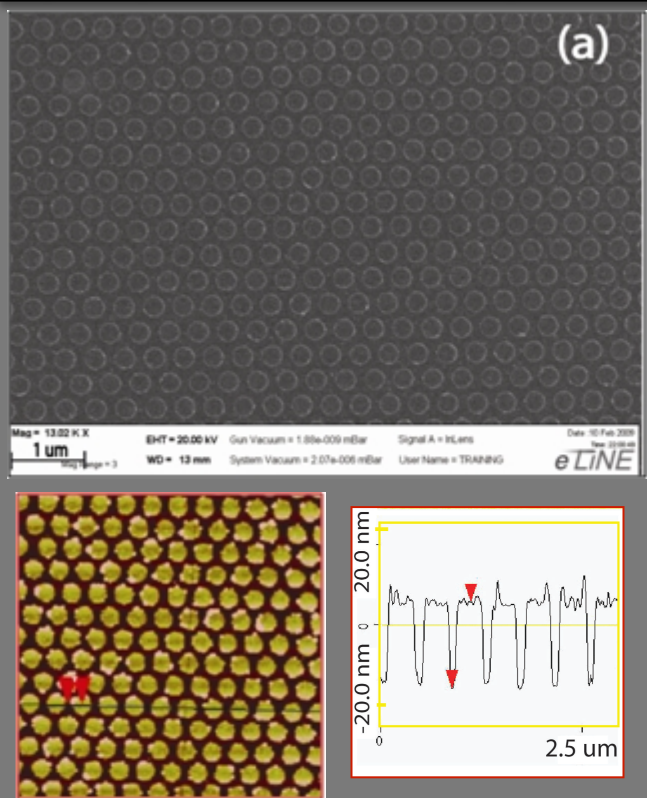
Fabrication:



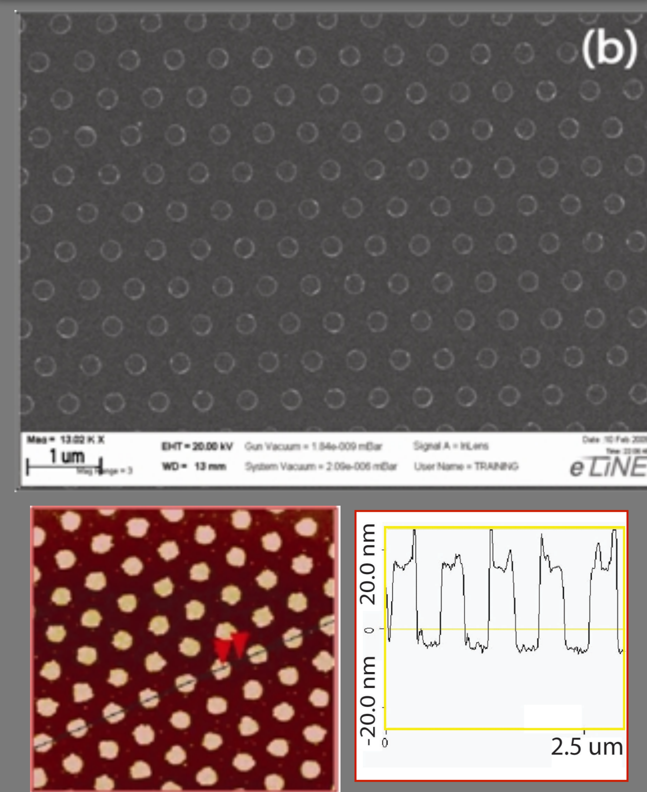
Devices

Superconductor: Nb (50nm); Normal Metal: Au (6nm); Dot Diameter: 260 nm

Spacing: 400nm (140nm edges)



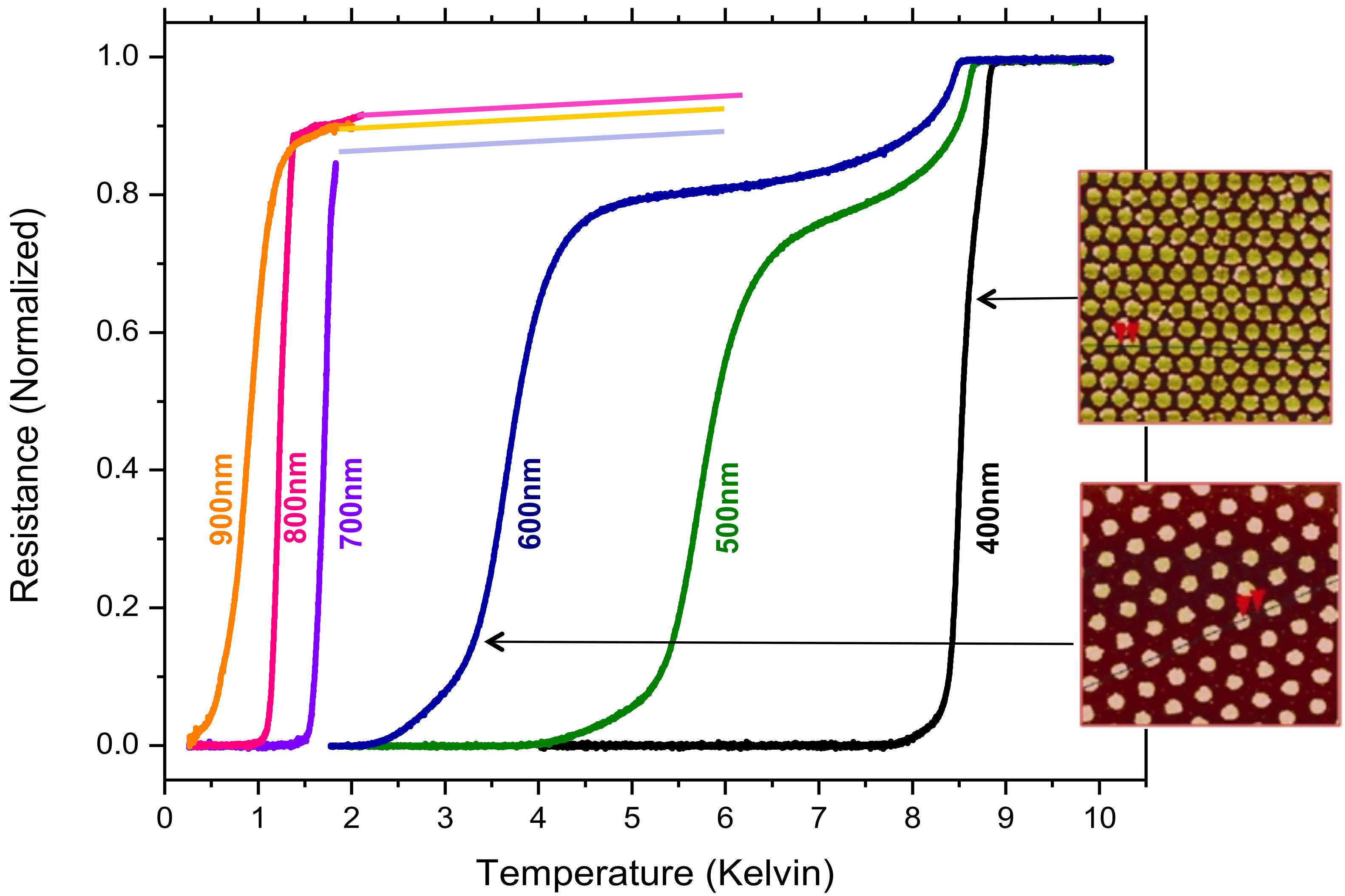
Spacing: 600nm (340nm edges)



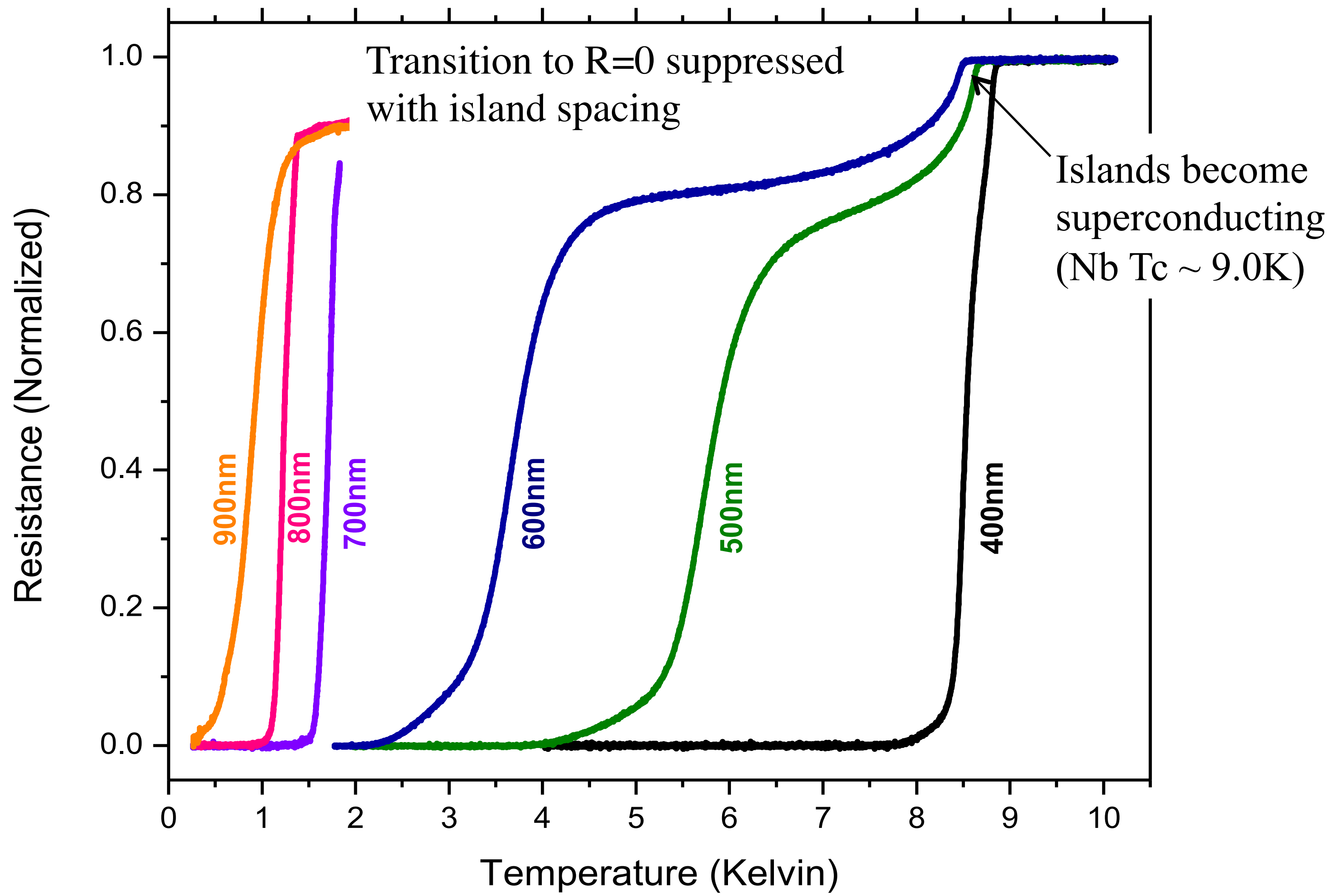
Studied six different arrays:

Island spacings = 400nm, 500nm, 600nm, 700nm, 800nm, 900nm

Resistance vs. temperature for various island spacing

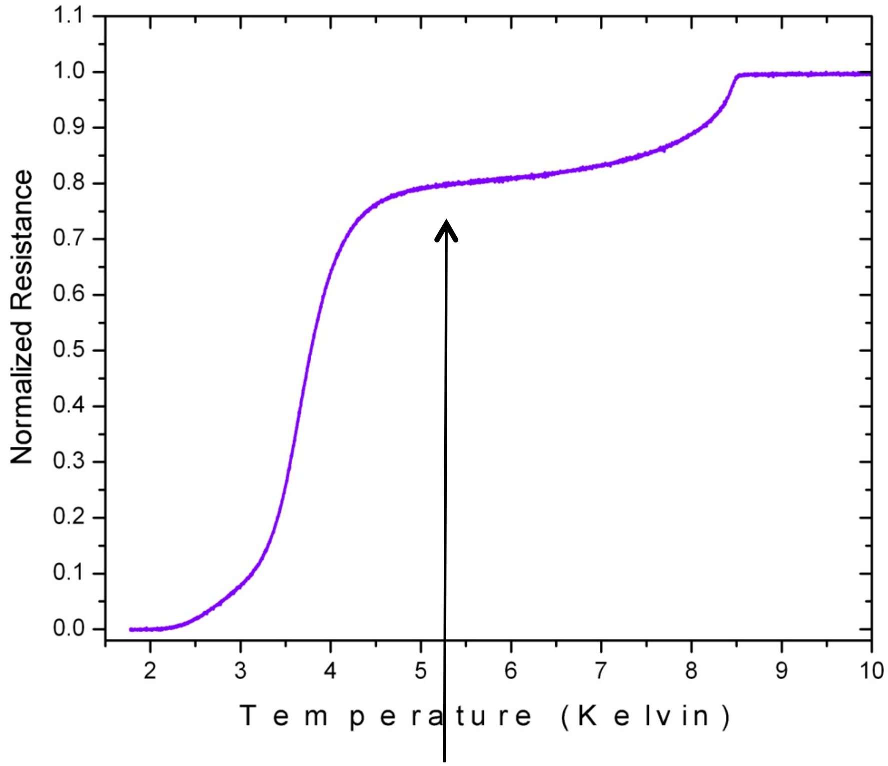


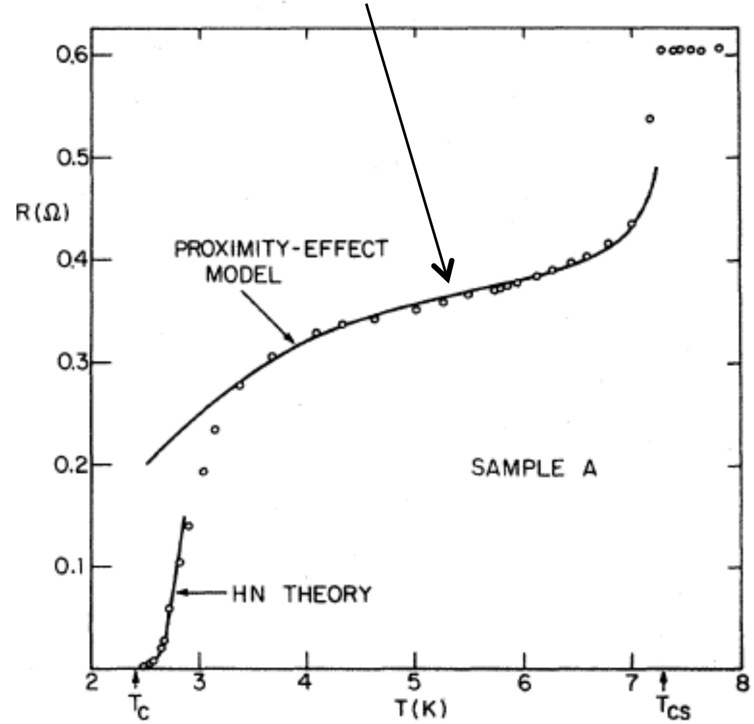
Resistance vs. temperature for various island spacing



Resistance vs. temperature, 600nm island spacing

coupling between islands reduced by thermal fluctuations





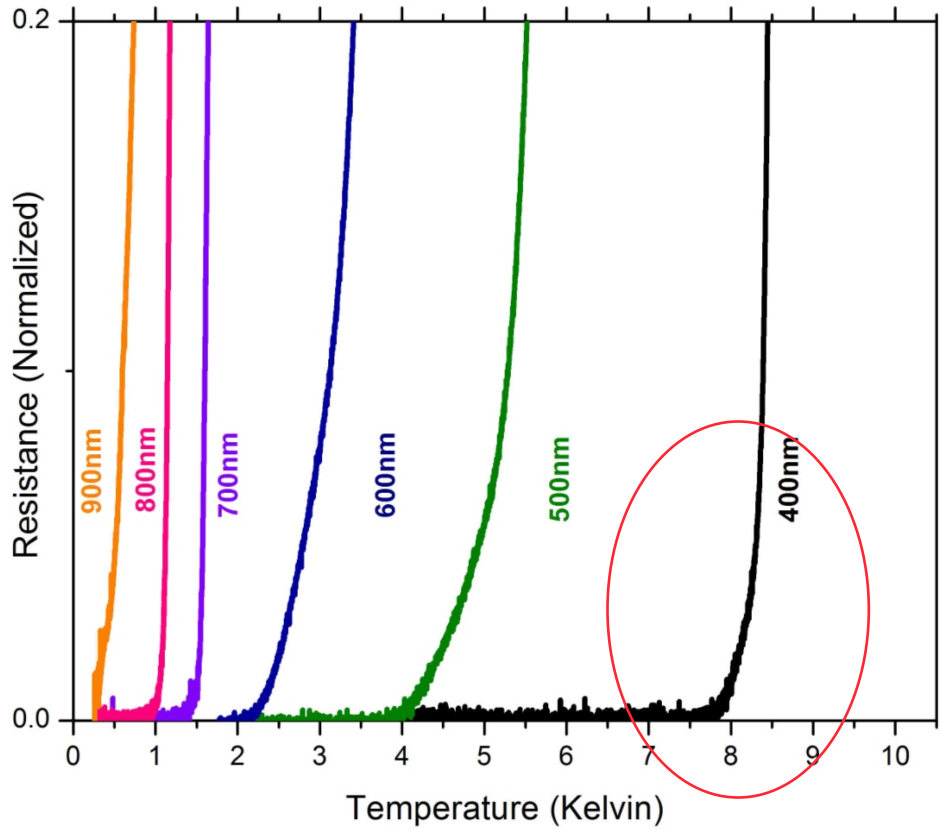
Abraham, Lobb, Tinkham, Klapwijk, PRB 1982

$$\xi_N = \sqrt{\frac{\hbar D_N}{k_B T}}$$ increases until islands fully Josephson coupled

(size of superconducting region doesn't change much)

Low-temperature region is superconducting

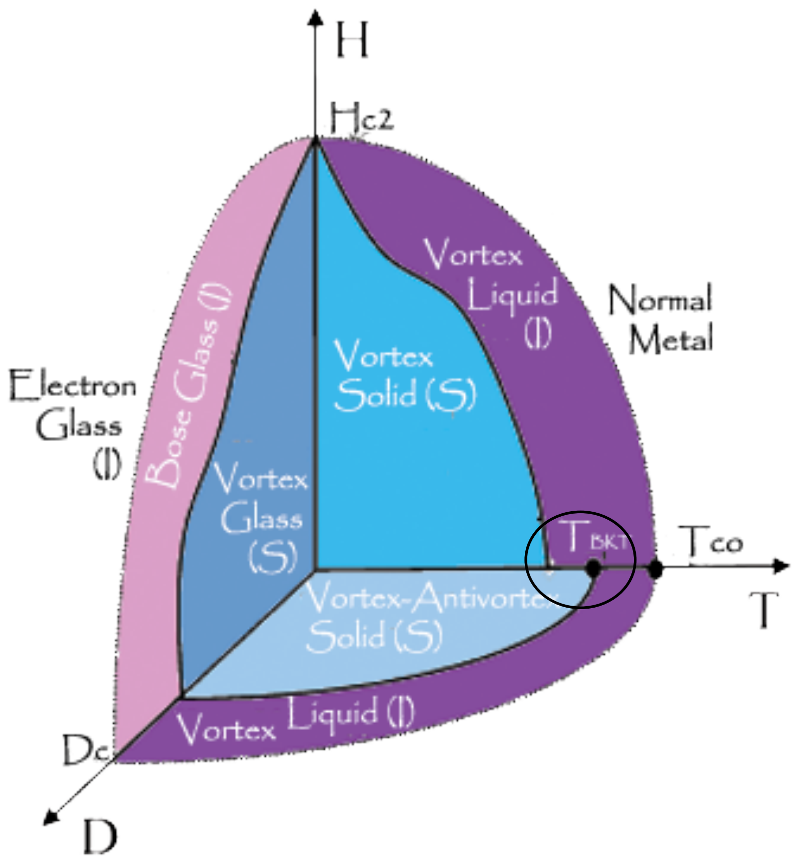
- Do not observe normal metal "tails" or re-entrant superconductor or metal effects



Focus on transition to R=0

BKT transition

Vortex-antivortex unbinding for 2D superconducting system



$$V \propto I^{a(T)}$$

$$a(T) = \frac{\pi E_J(T)}{k_B T} + 1 = \frac{2T_{KT}}{T} + 1$$

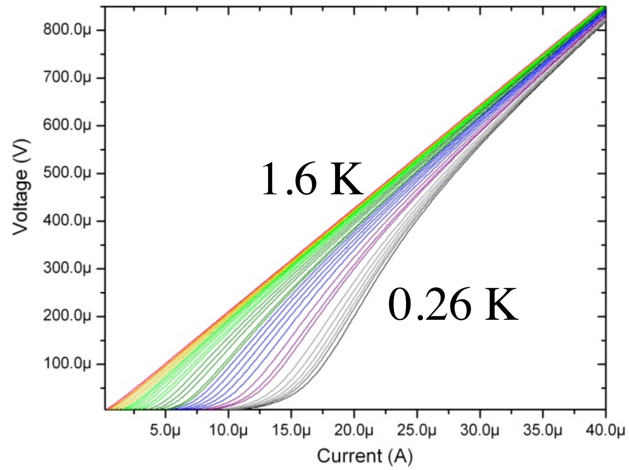
$a(T)=1$ above T_{KT} (linear IV)

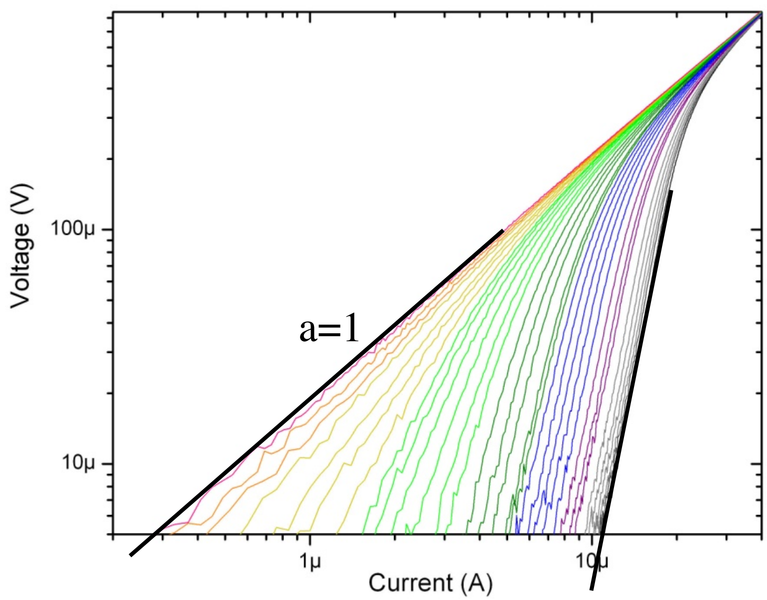
Current driven vortices just below T_{KT}:

$$a(T_{KT})=3$$

BKT transition

700nm island spacing

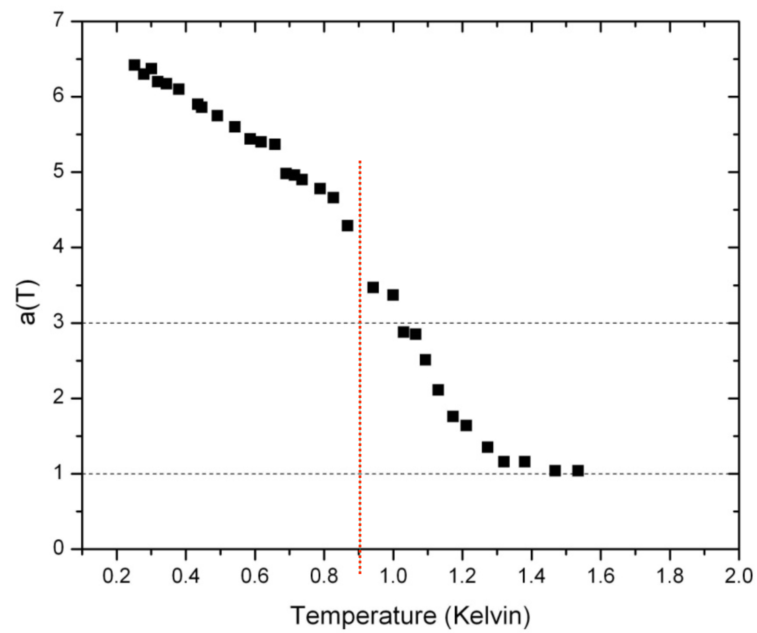




$$V \propto I^{a(T)}$$

$$a(T) = \frac{\pi E_J(T)}{k_B T} + 1 = \frac{2T_{KT}}{T} + 1$$

$a(T_{KT})=3$



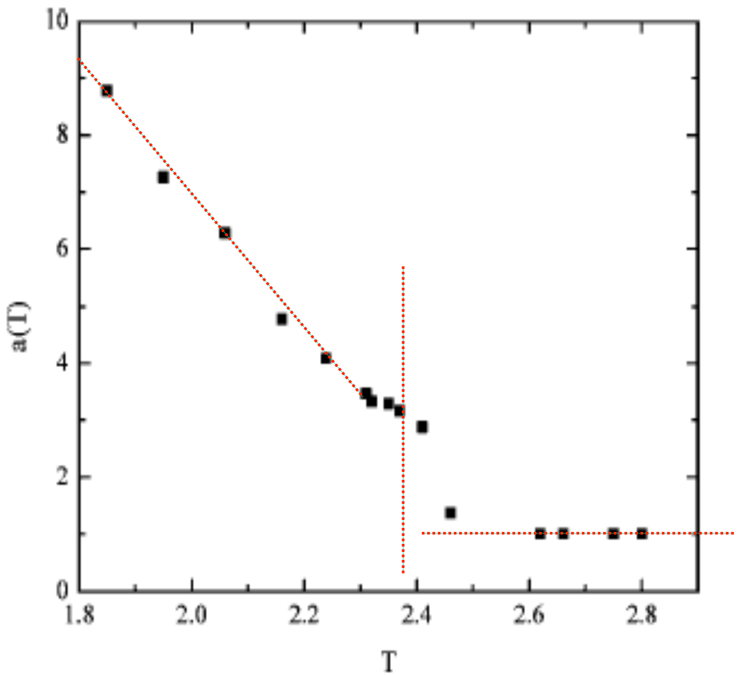
BKT transition!

BKT transition

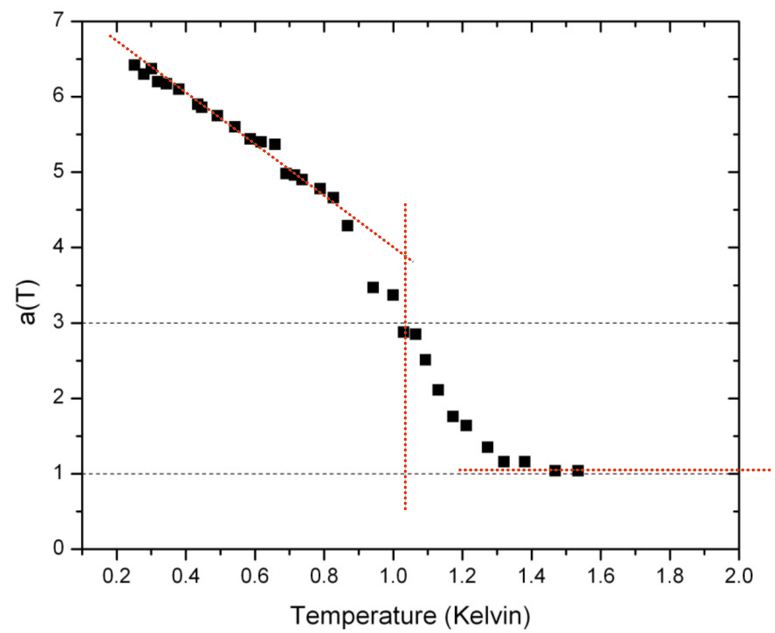
$$V \propto I^{a(T)}$$

$$a(T) = \frac{\pi E_J(T)}{k_B T} + 1 = \frac{2T_{KT}}{T} + 1$$

$a(T_{KT})=3$



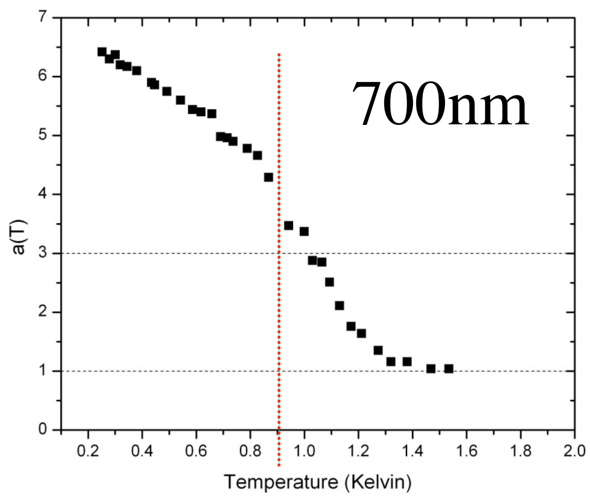
From Lobb, Abraham, Tinkham PRB,1982

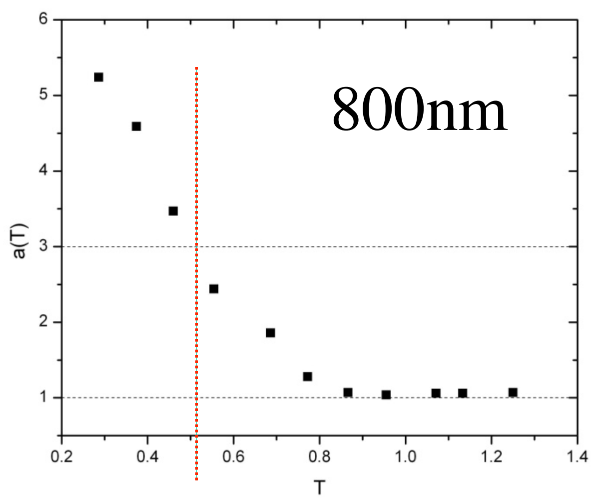


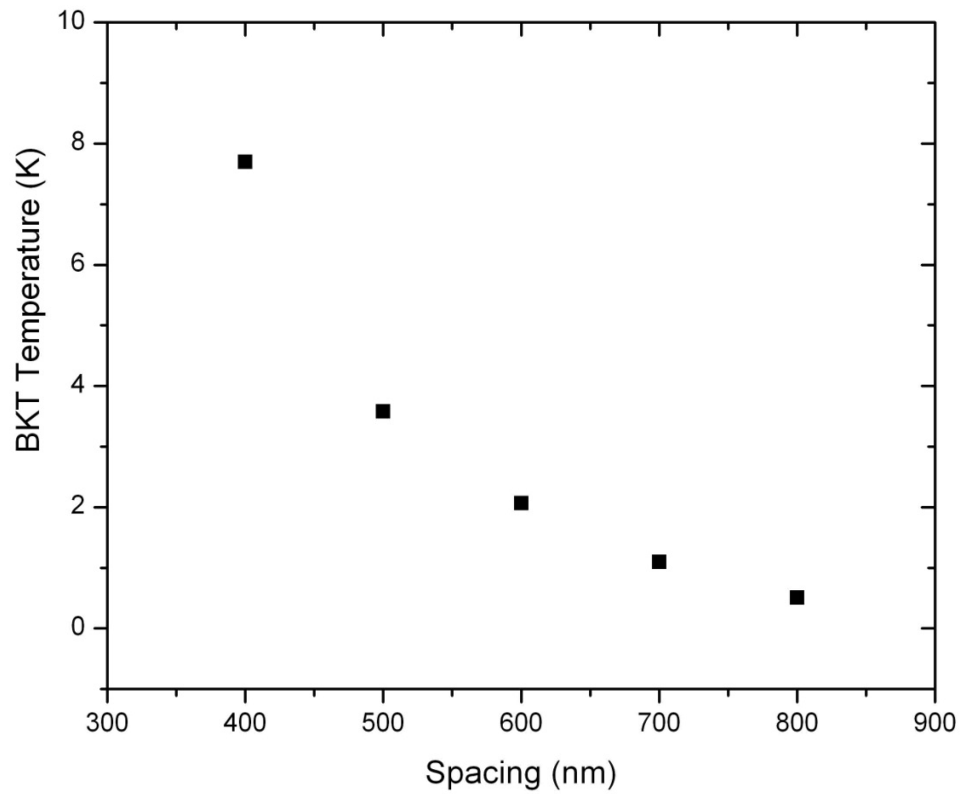
BKT transition!

BKT transition for various island spacings

$V \propto I^{a(T)}$ $a(T_{KT})=3$

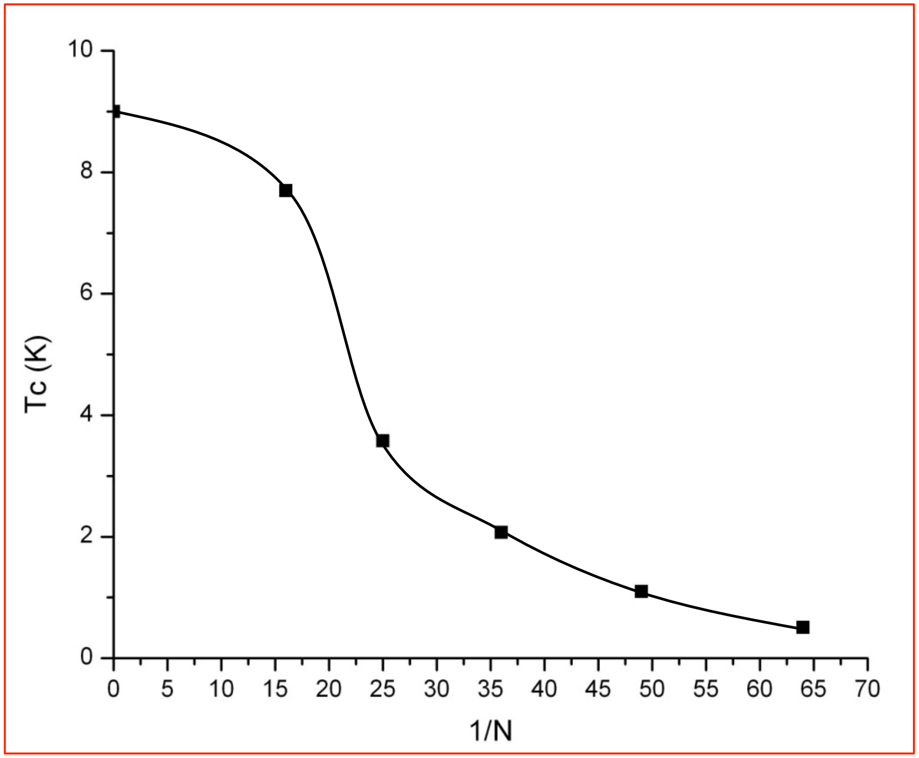


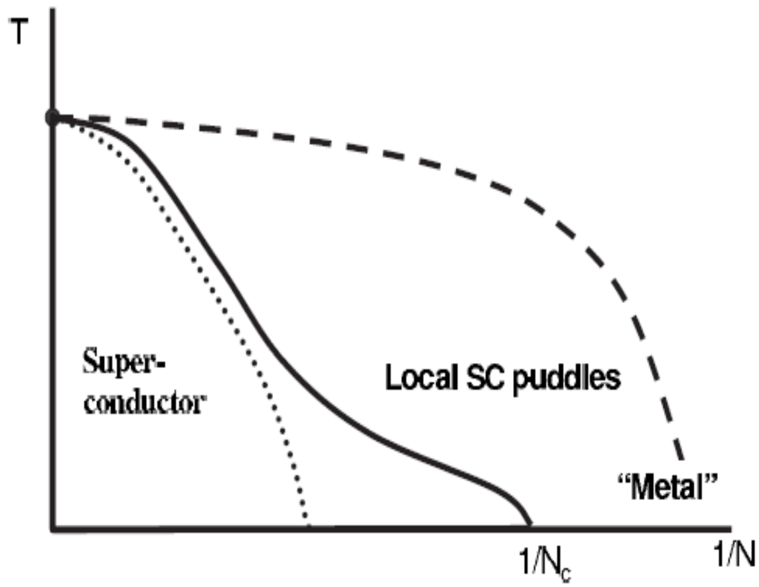




Superconducting transition as function of island spacings

Transition temperature vs.
inverse island density





Spivak et al, PRB (2008)

Qualitatively consistent with predicted island-distance dependence of Tc

Josephson coupling as function of island spacing

$T_c \sim$ Josephson coupling, E_J

Josephson coupling between puddles: $$J_{ij} \equiv J(\mathbf{r}_i, \mathbf{r}_j) \propto C_{ij} \frac{\nu V_i V_j}{|\mathbf{r}_i - \mathbf{r}_j|^D} \exp\left[- \frac{|\mathbf{r}_i - \mathbf{r}_j|}{L_T} \right]$$

Normal metal coherence length ~ Thouless length: $$\zeta_N \sim L_T = \sqrt{\frac{\mathrm{h} D}{k_B T}}$$

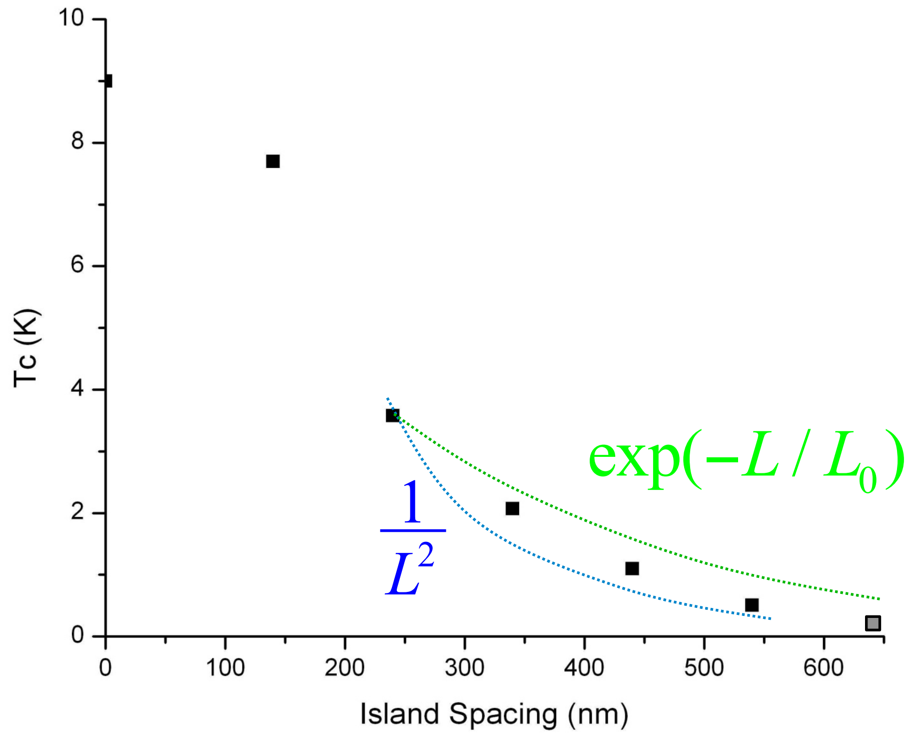
Diffusion length: $$D = \frac{1}{\rho v_F e^2} = 114\ cm^2 / s \qquad \Rightarrow L_T = (740nm) T^{-1/2}$$

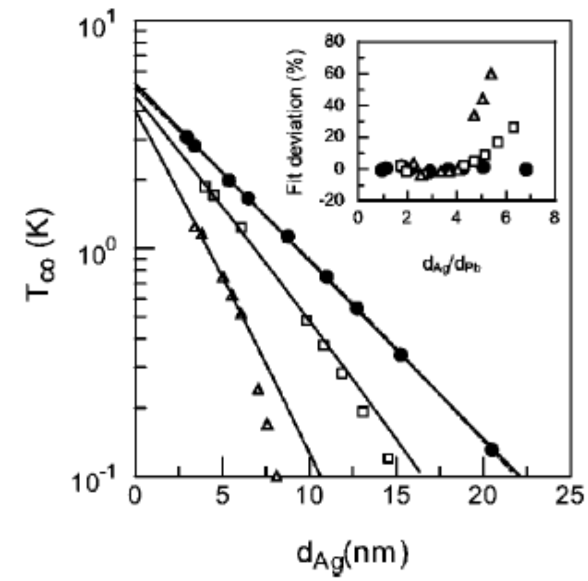
Using as *L* the distance between island edges:

L (nm)	L_T (nm) (at T_{KT})	L/L_T
140	266	.53
240	391	.61
340	514	.66
440	705	.62
540	1046	.52

- Transition occurs at approx. same L/L_T for each array
- Enhancement of coupling with spacing, then decrease
- For $L \sim L_T$, $T_c \sim E_J \sim 1/L^2$

Superconducting transition as function of island spacings





Pb & Ag grains
Kouh and Valles, PRB 2003

All "classical" fluctuations. Expect quantum fluctuations for:

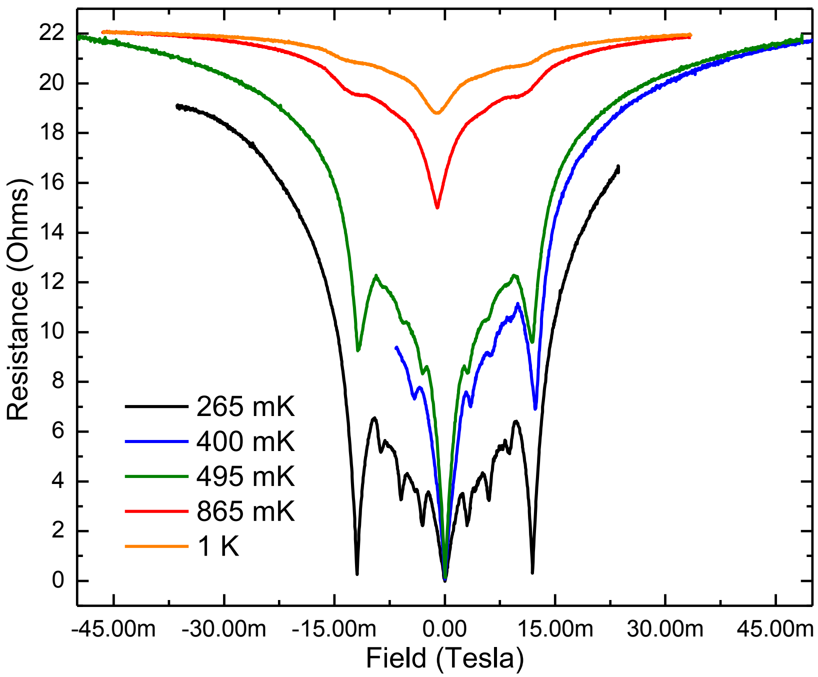
$$N_C \sim [\exp(-\sqrt{g})]^{1/2}$$

g~ $G/G_{quantum}$ ~ 25KΩ/5Ω → L ~ $1/N_c$ ~ exp(30)

Want R > 500Ω to see quantum critical region

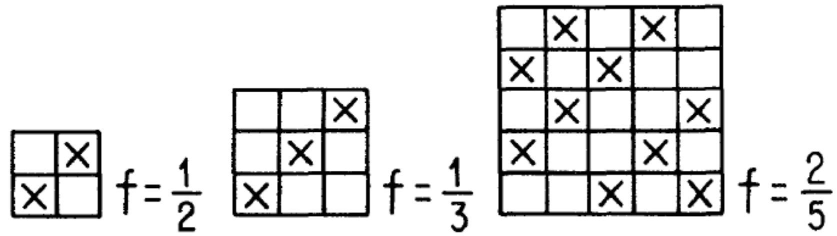
Magnetic Field Behavior

R vs. B: Frustration effects!

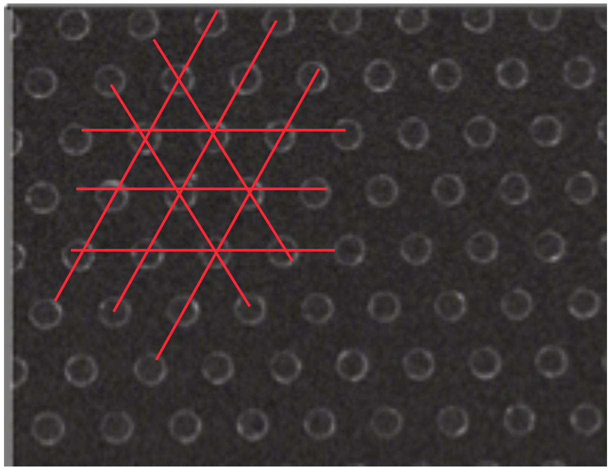


$f = \Phi/\Phi_0 = \Phi_0$ per plaquette

pinning sites at center of each plaquette → low R for f = n/m

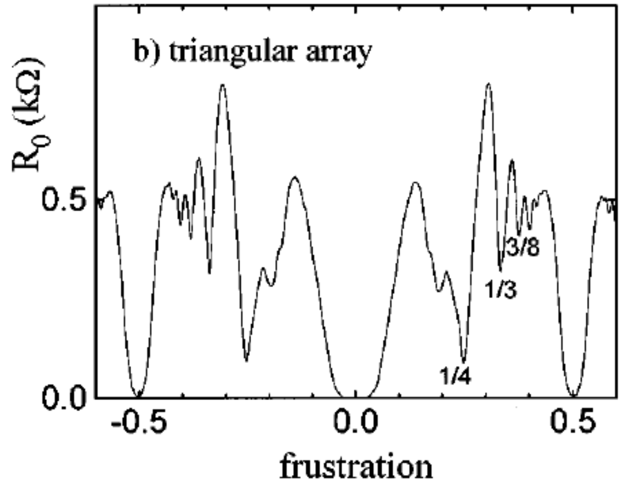


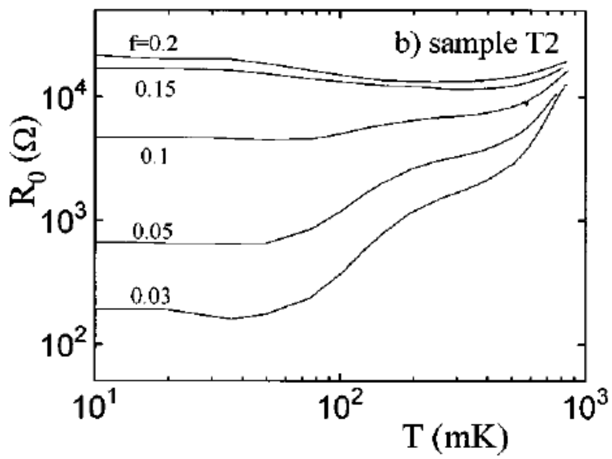
triangular array



Magnetic Field Behavior
Frustration effects

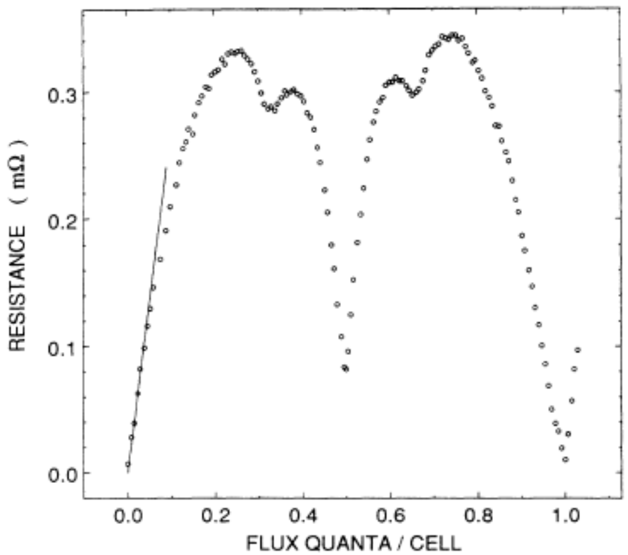
Well known in JJ arrays





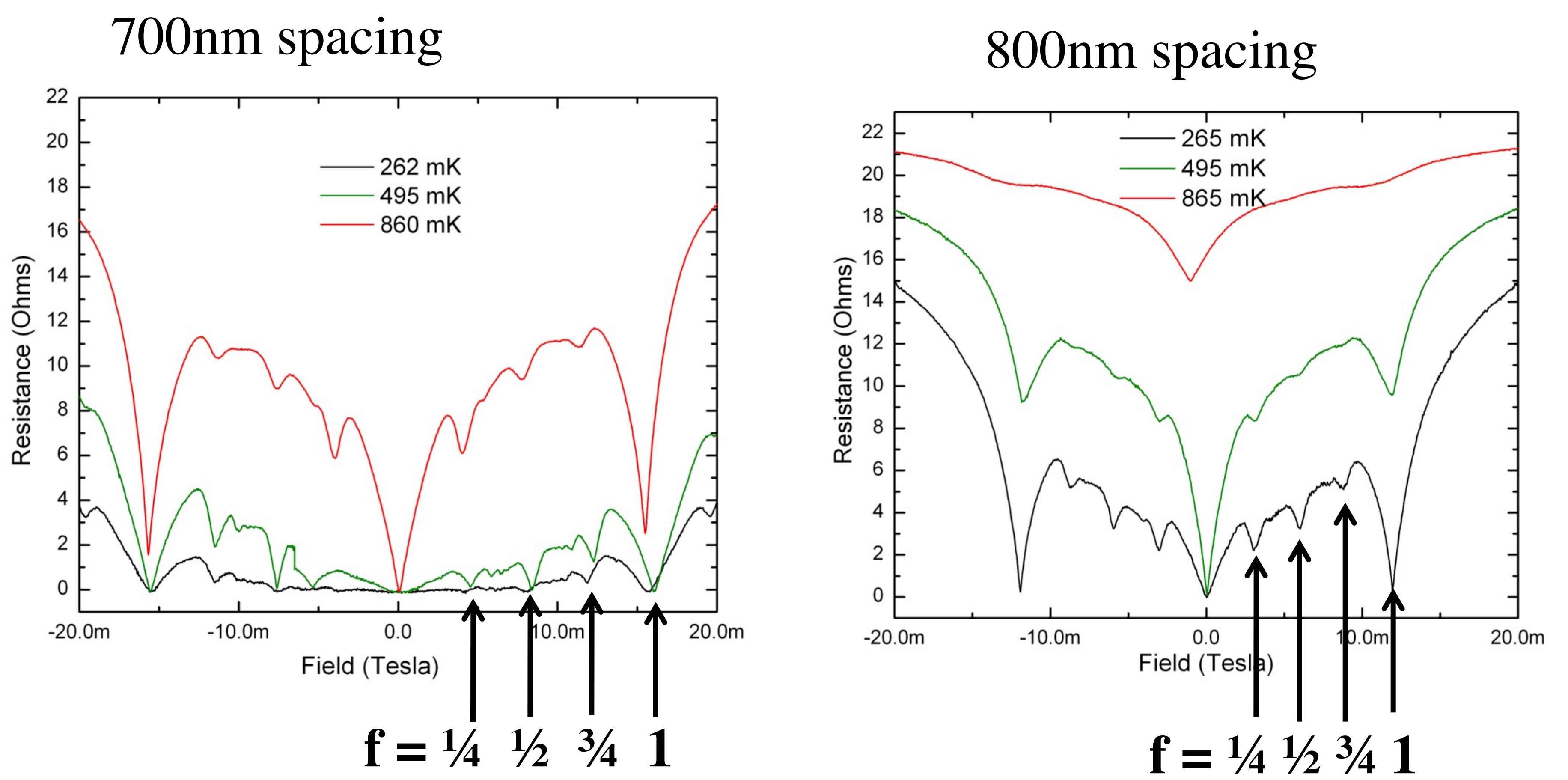
van der Zant *et al*, PRB 1996

and in proximity coupled arrays



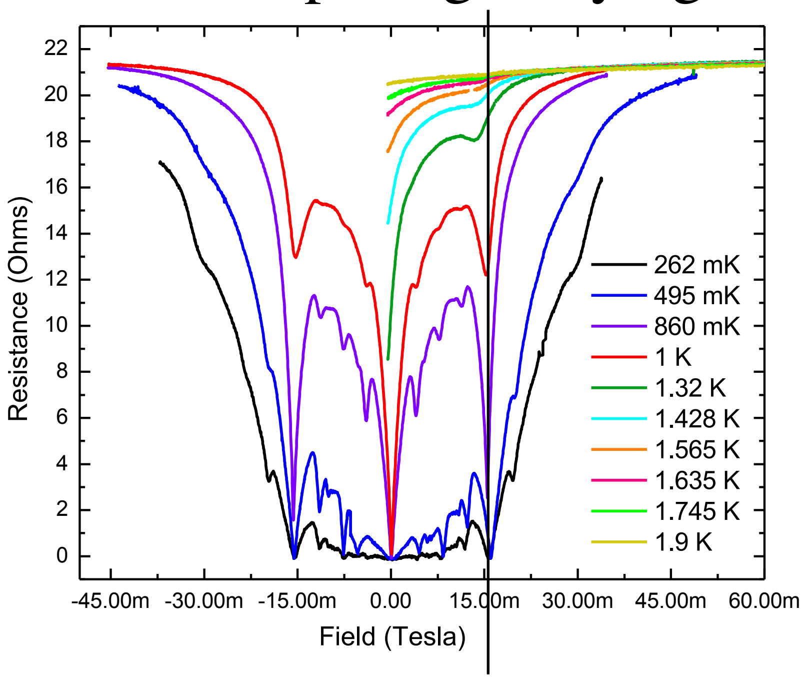
Nb-Cu-Nb
Rzchowski *et al*, PRB 1990

Magnetic Field Behavior
Frustration effects

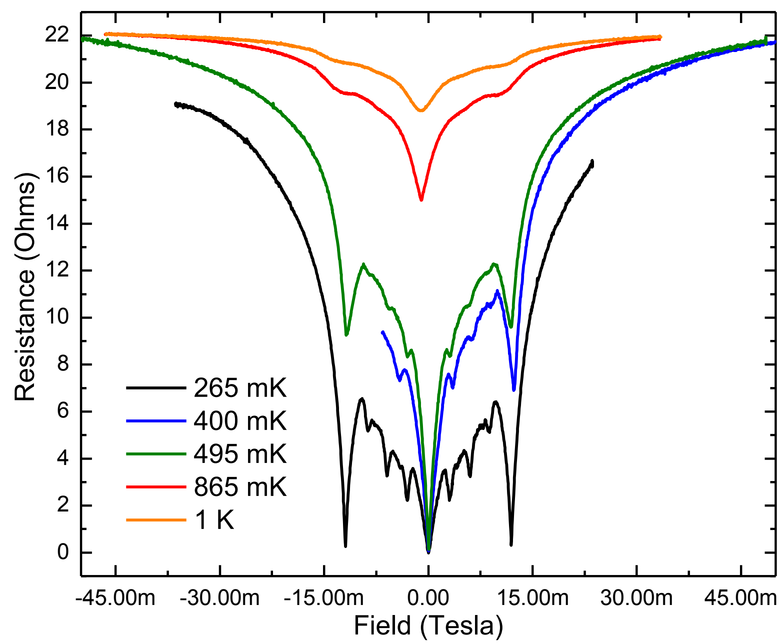


Magnetic Field Behavior
Frustration effects

700nm spacing: varying T



800nm spacing: varying T

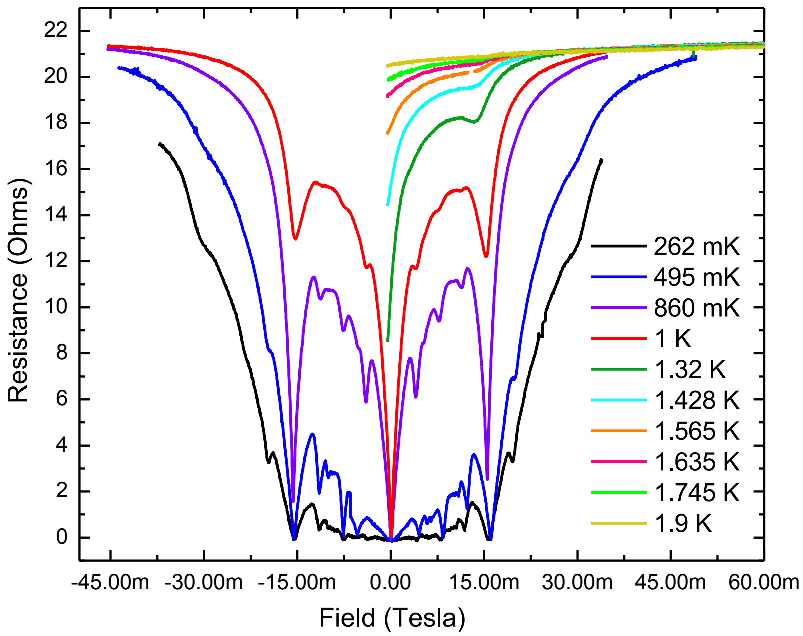


Structure diminishes with increasing T

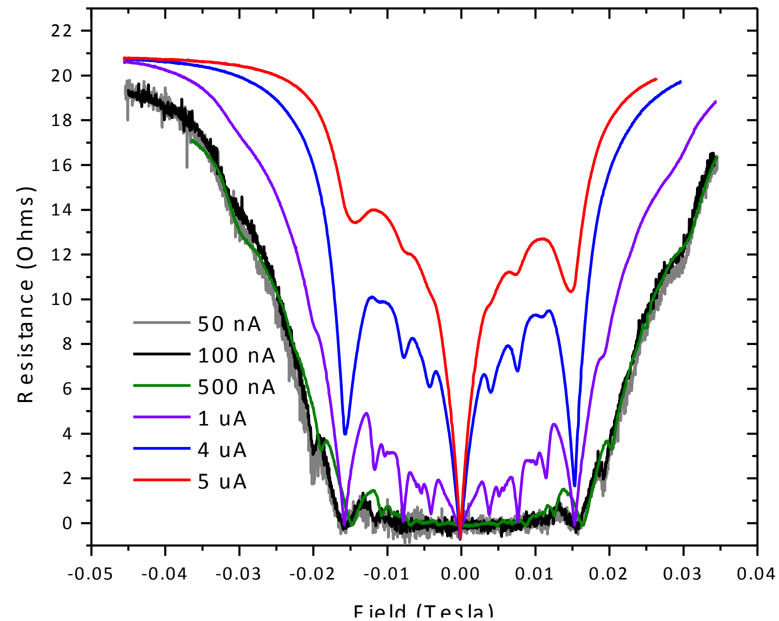
For low T, field where dips occur constant

Magnetic Field Behavior
Frustration effects

700nm spacing: varying T



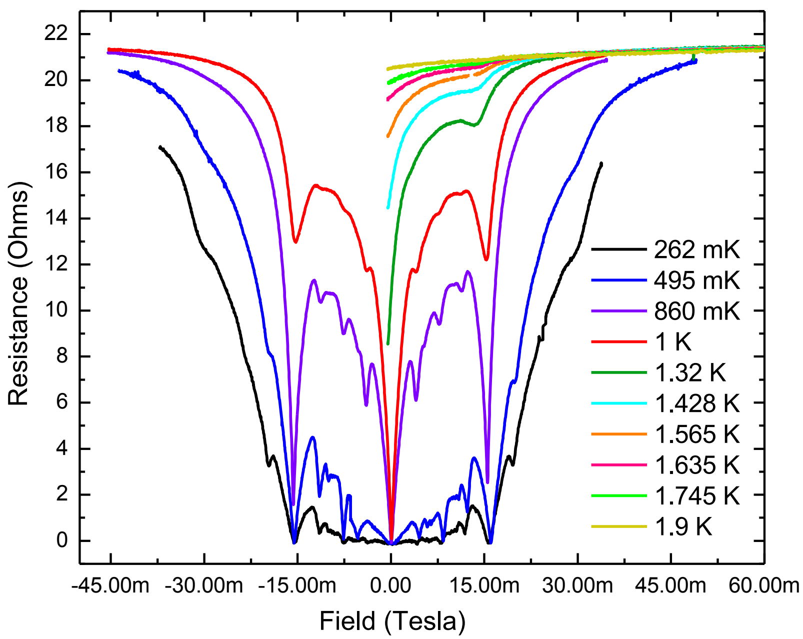
varying applied current, I



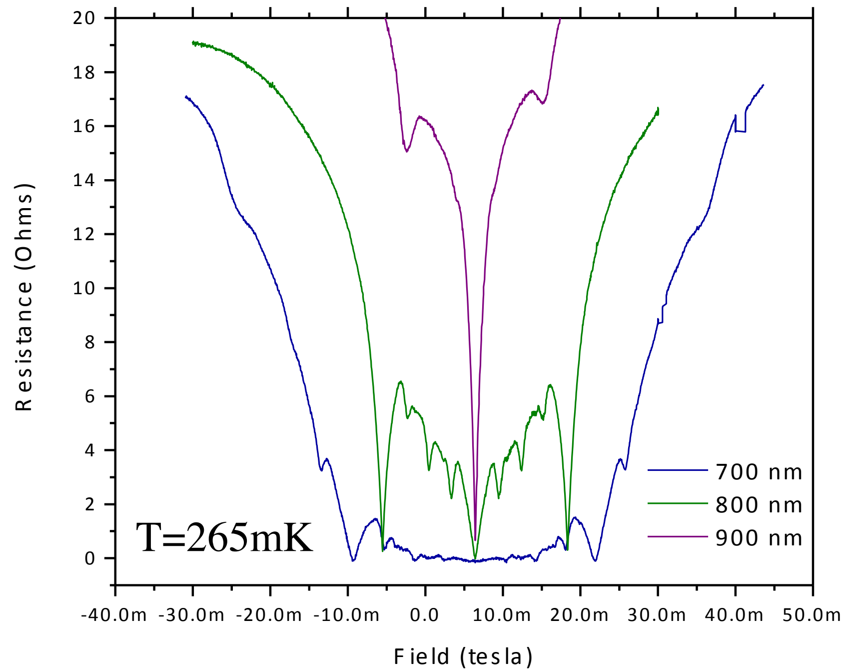
Current and temperature have similar effect → depinning weakly trapped vortex arrays

Magnetic Field Behavior
Frustration effects

700nm spacing



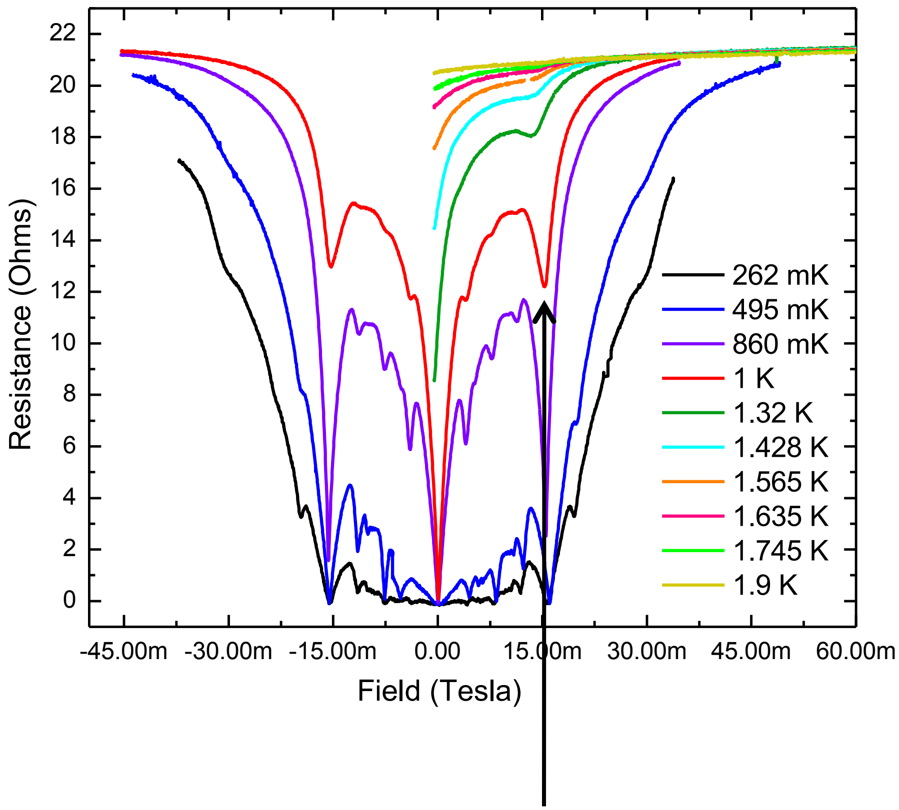
Varying array spacings



- Increasing array spacing and temperature have similar effect
- Increasing spacing decreases f ~ 1/area

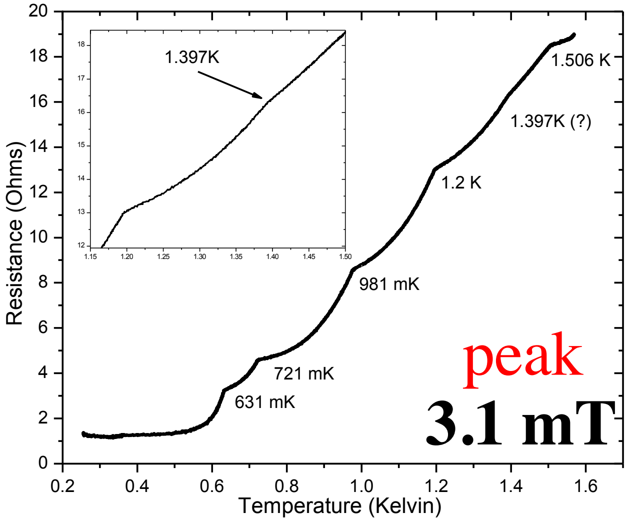
Magnetic Field Behavior
Frustration effects

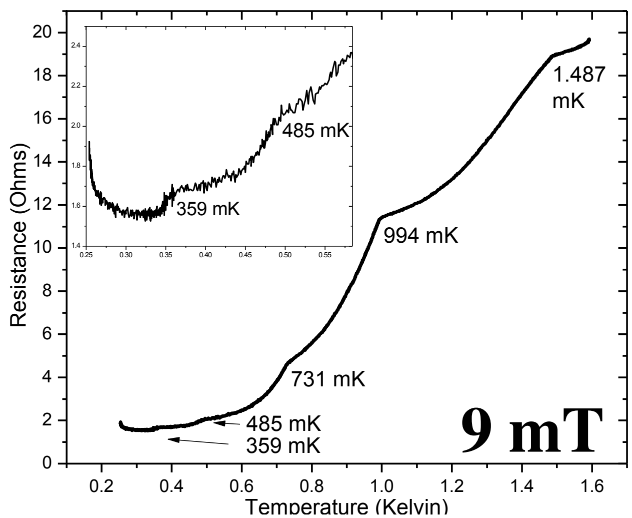
700nm spacing

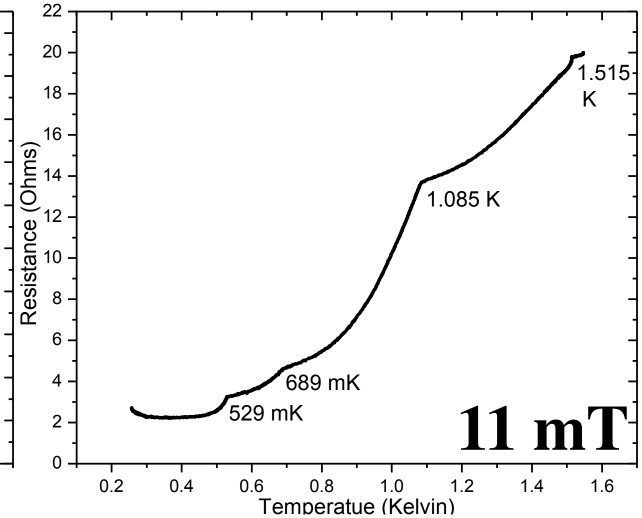


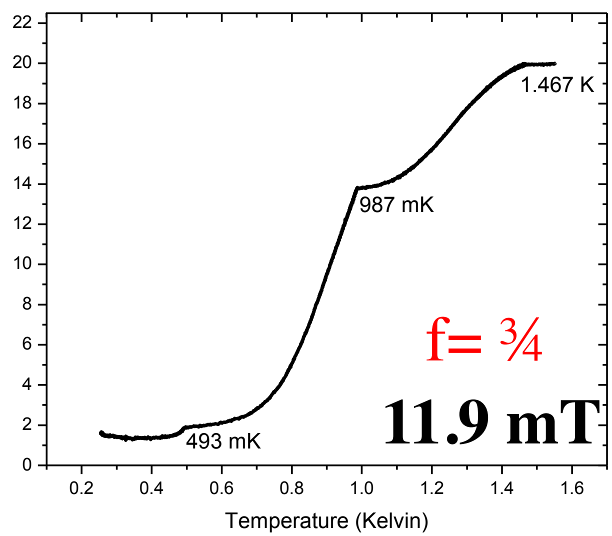
Now fix field and vary T

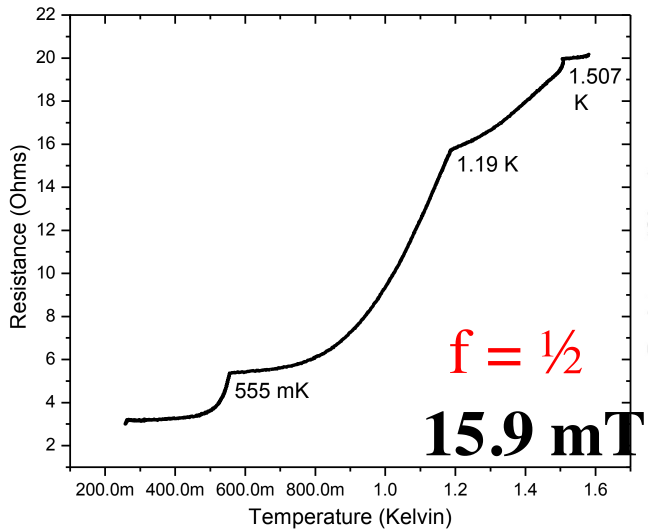
Resistance versus Temperature at fixed Fields (700nm spacing)

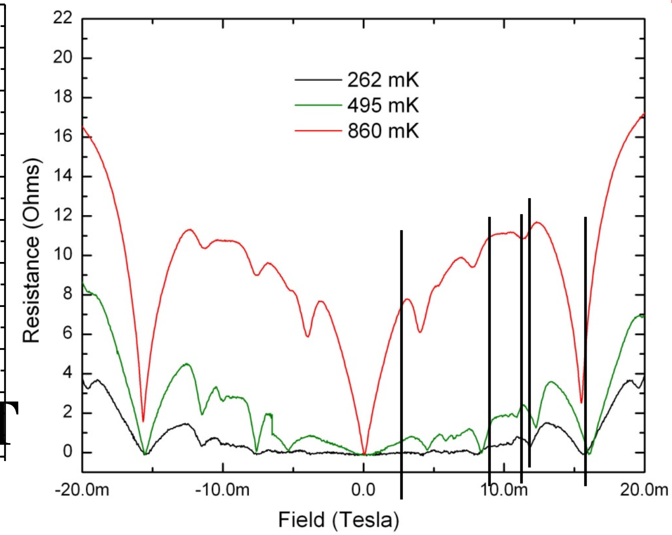




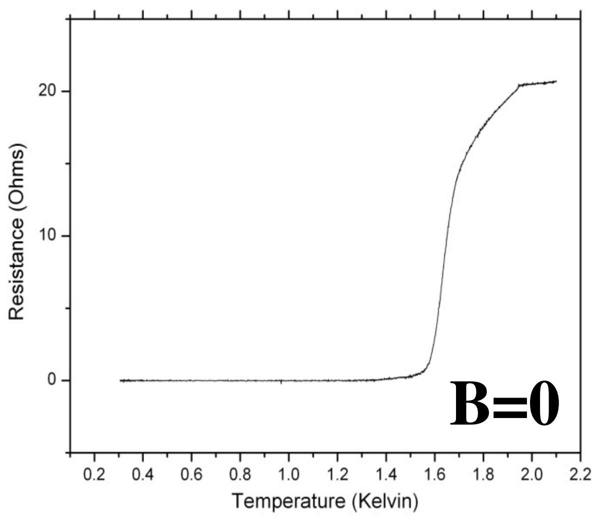


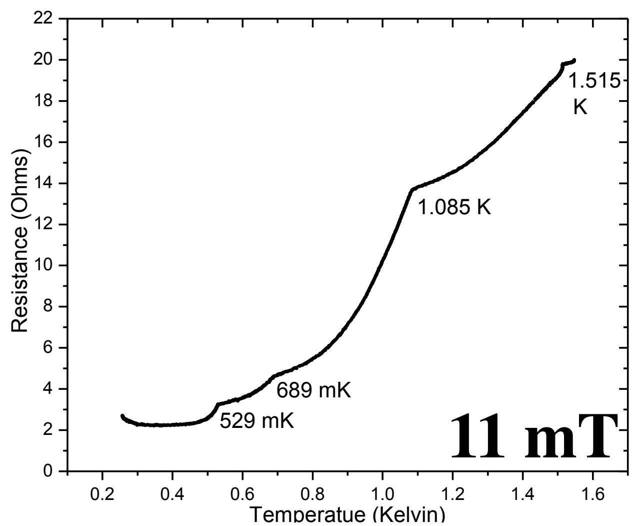


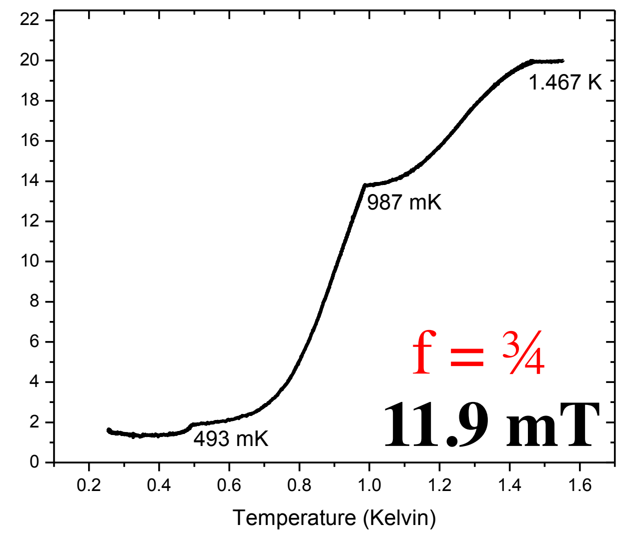




Resistance versus Temperature at fixed Fields (700nm spacing)







Multiple transitions at finite T?
Metal-superconductor phase separation?
"Row" switching?

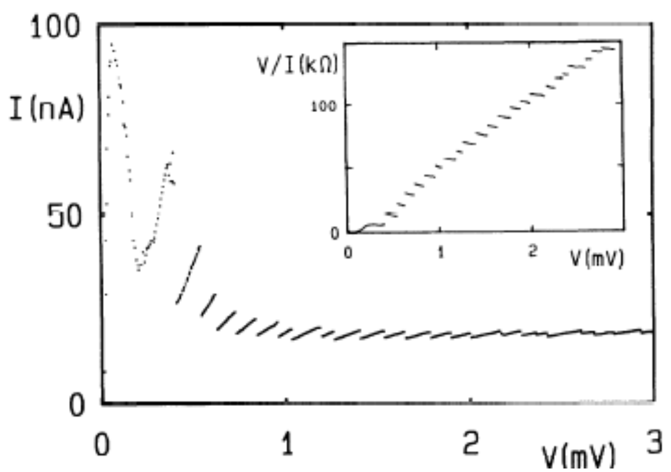
Coherent switching of rows of vortices …

PHYSICAL REVIEW B VOLUME 38, NUMBER 4 1 AUGUST 1988

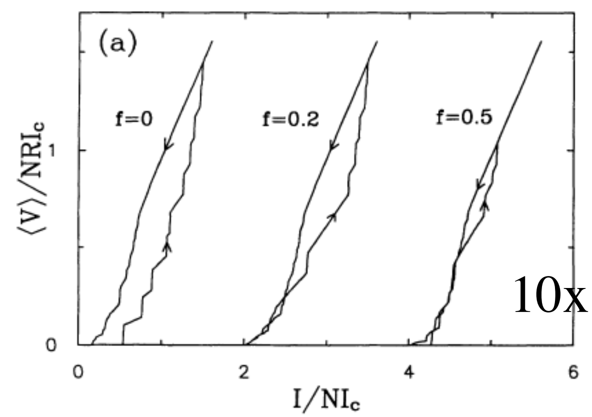
Coherent phase slip in arrays of underdamped Josephson tunnel junctions

H. S. J. van der Zant, C. J. Muller, L. J. Geerligs, C. J. P. M. Harmans, and J. E. Mooij
Department of Applied Physics, Delft University of Technology, P. O. Box 5046, 2600 GA Delft, The Netherlands
(Received 16 May 1988).

In hysteretic *I-V* characteristics of two-dimensional Josephson junction arrays resistance steps are observed. These steps are explained by switching into a coherent phase-slip state of rows of junctions across the whole array.



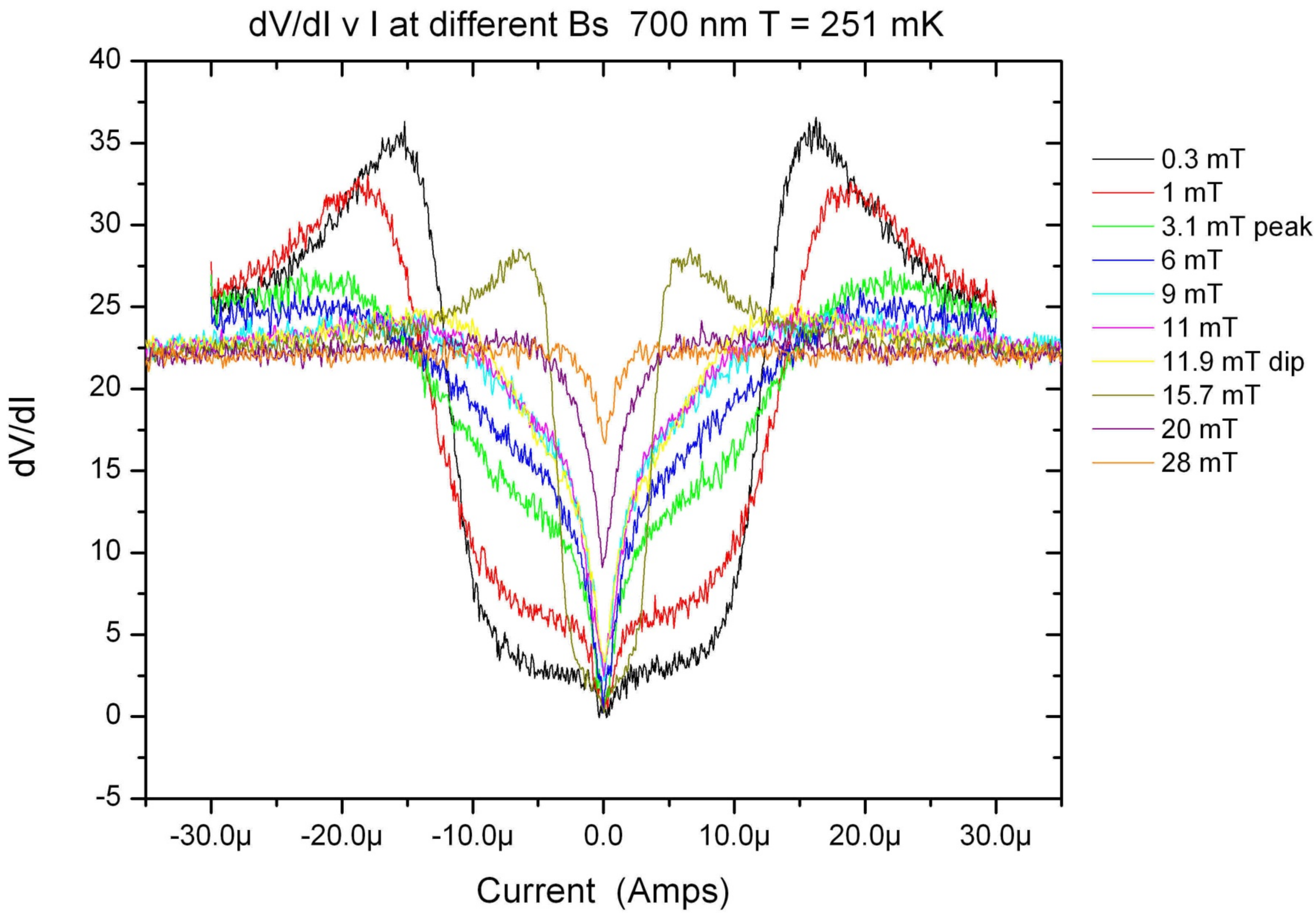
Yu & Stroud, PRB (1992)



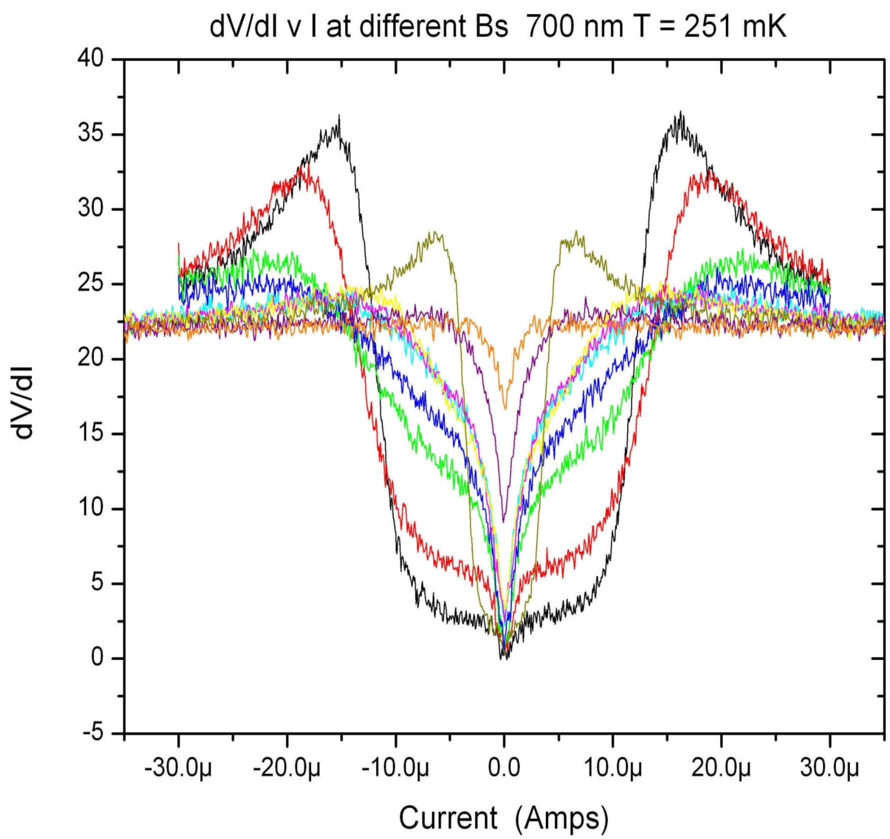
10x10 array

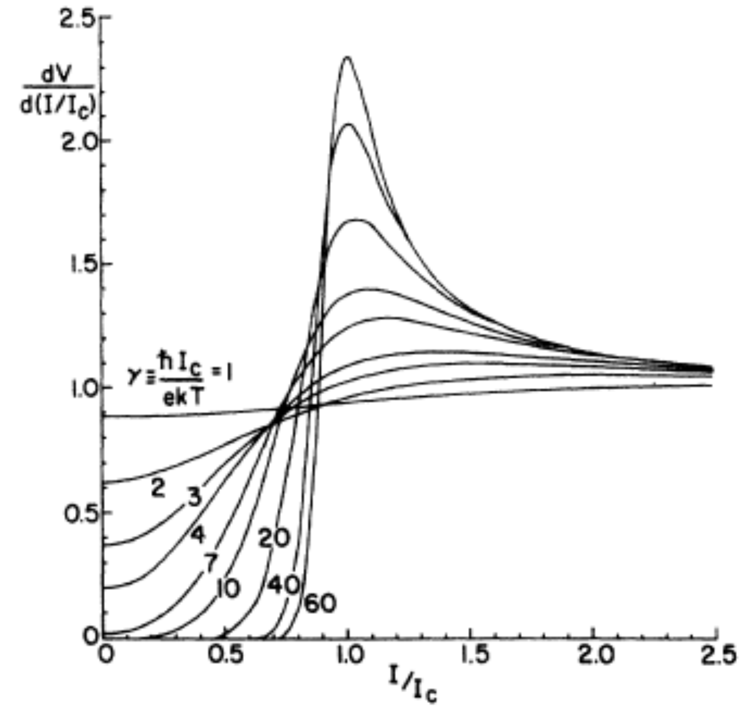
Predicted even for homogeneous arrays if under-damped
(under-damped: hysteretic, sharp transition. But damping ~ 1/R)
BUT: should be washed out at higher temp, should be washed out by larger junction number

IV characteristics



IV characteristics

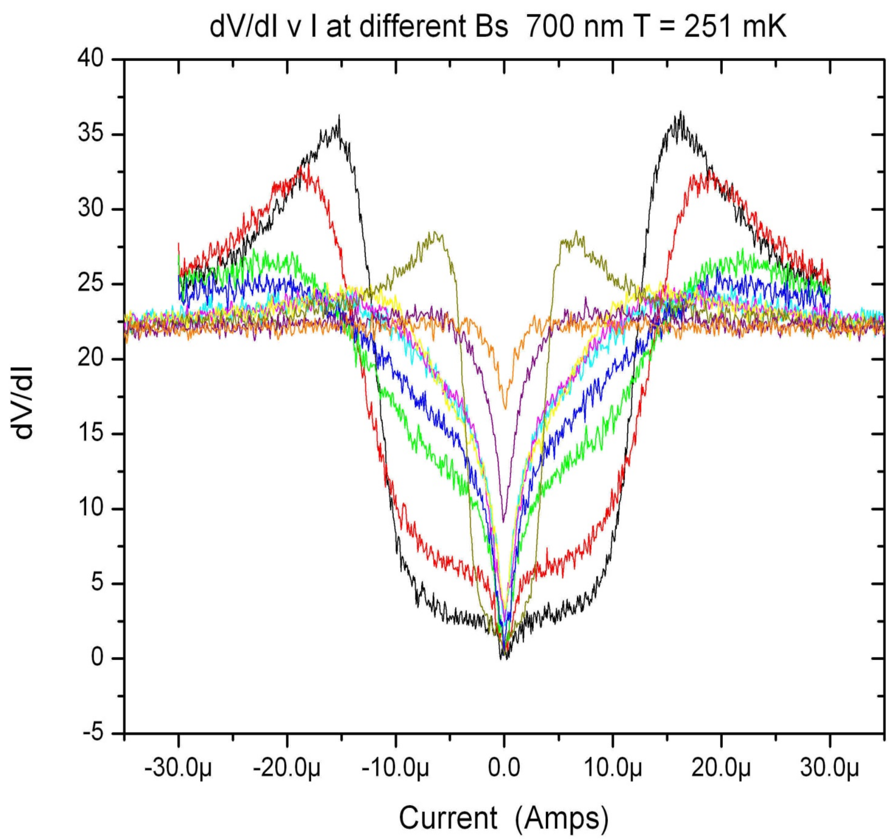


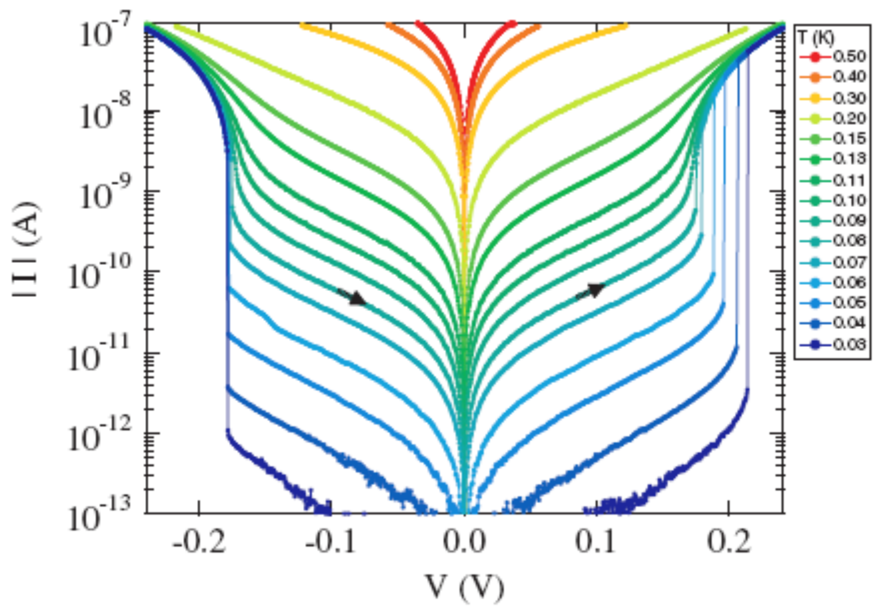


Falco PRB 1974

Similar to dynamics of vortices in JJ array

IV characteristics

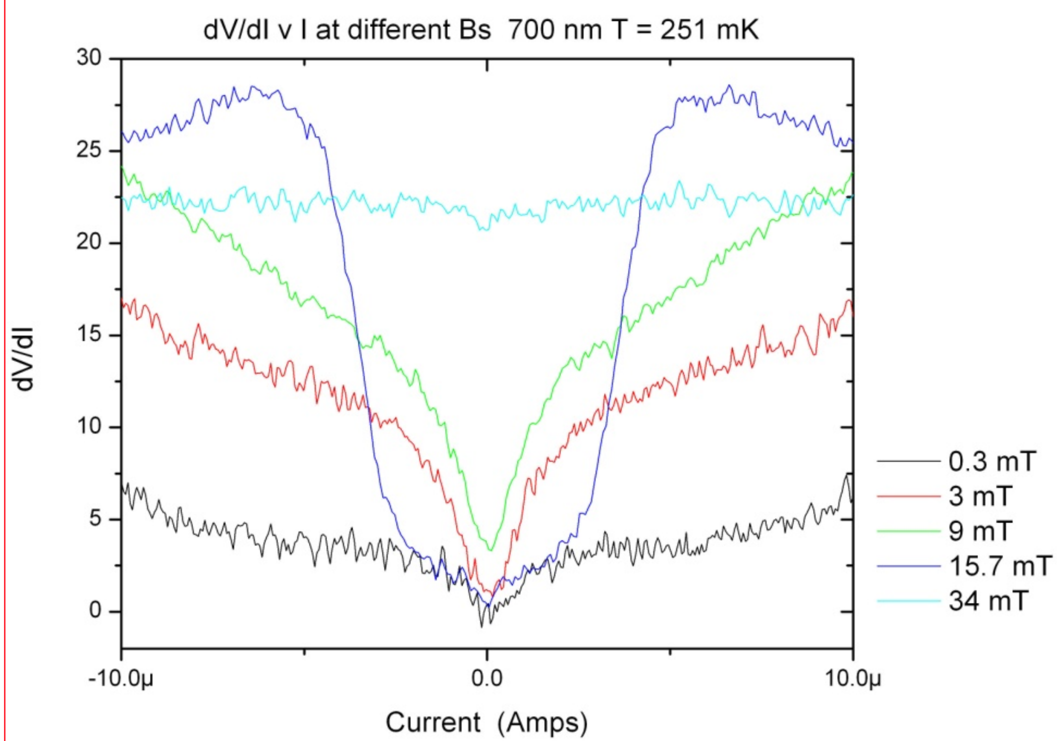


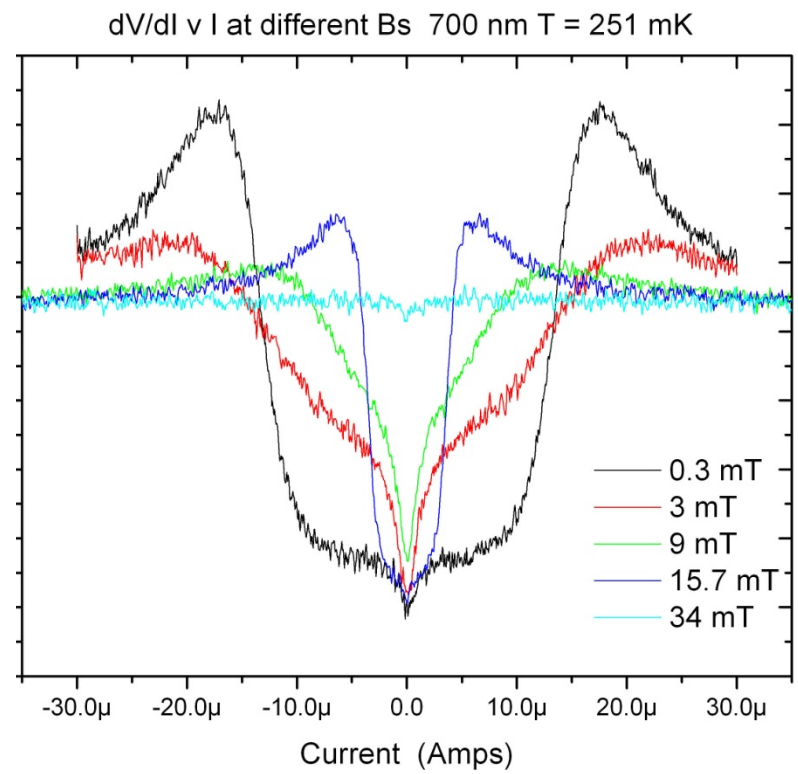


Ovadia, Sacepe, Shahar
PRL 2009

Cusp-like behavior similar to that seen for electron heating

IV characteristics



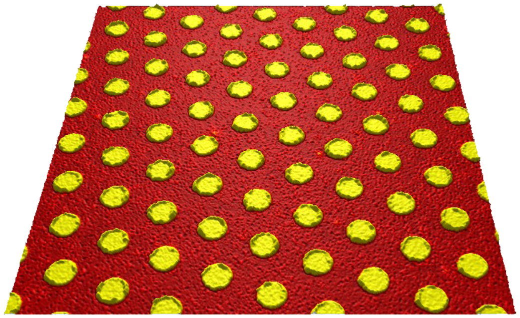


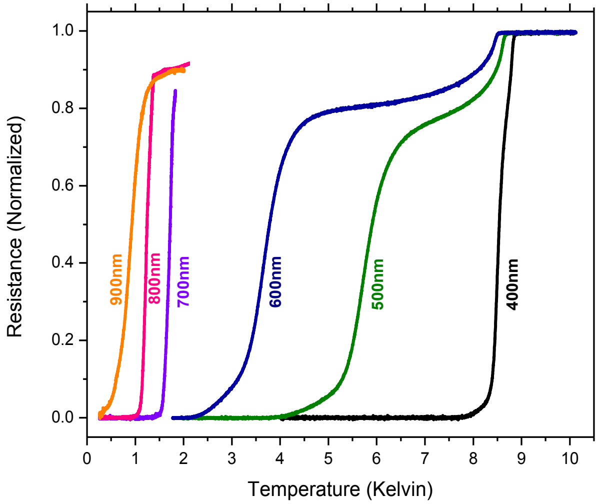
No evidence of multiple steps in IV

Evidence of bulk depinning of vortices, Ic varies with f

Conclusions:

- Superconducting island on metallic substrates = tunable proximity coupled systems
- Evidence for T_{BKT} , consistent with predictions as function of island spacing
- Magnetic field effects: frustration, cusps in R vs T, maybe evidence of correlated vortex motion





Future Work:

-Lower temperature, larger spacing

- Introduce disorder
- More resistive metal → graphene

700 nm

Resistance versus Temperature at fixed Fields