Inter-layer coherence length and the critical temperature anisotropy of $La_{2-x}Sr_xCO_4$

PhD Seminar By: **Itay Mangel**

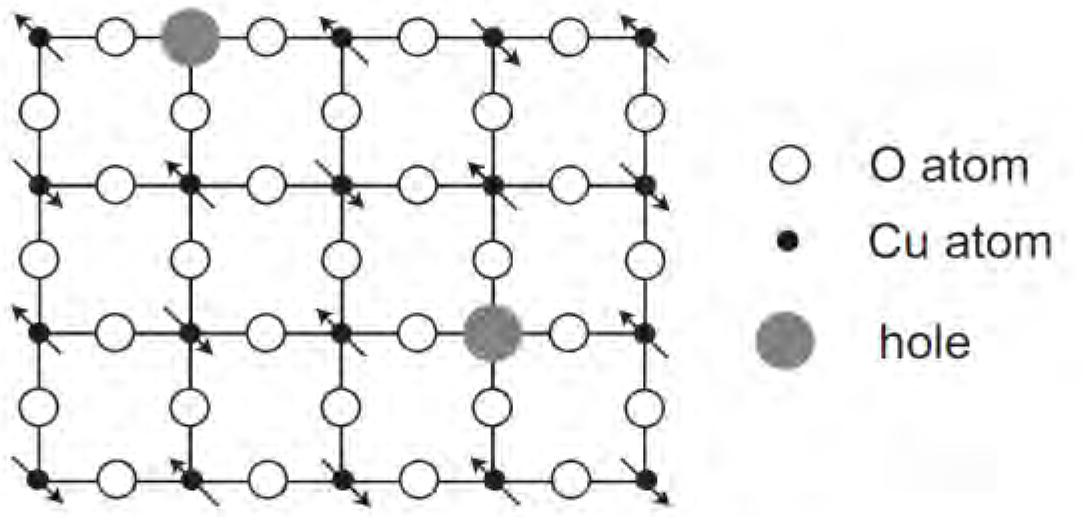
Supervisor: **Prof. Amit Keren**

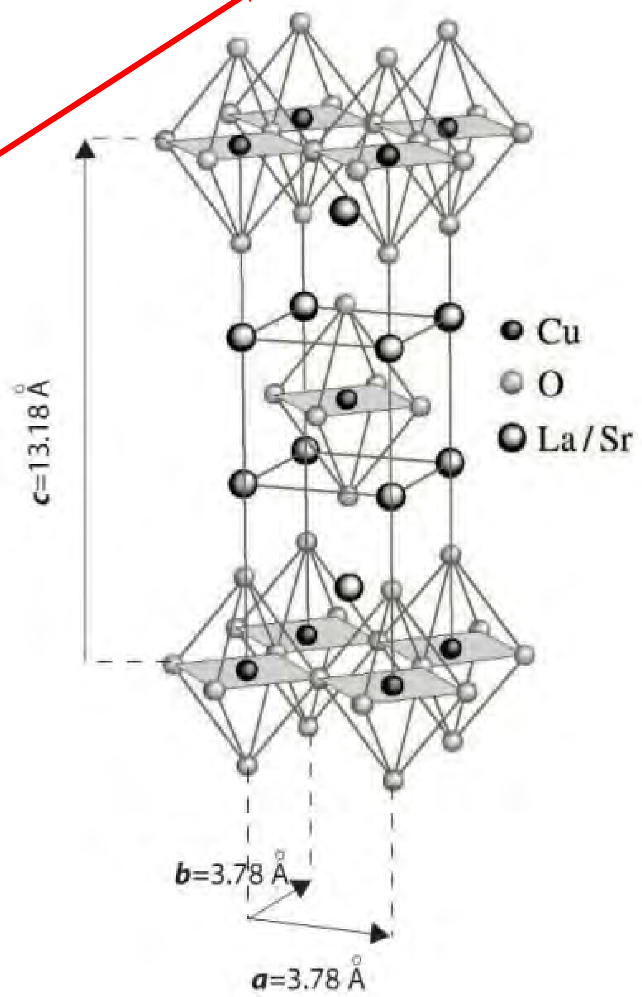
Technion, Haifa, Israel

The Cuprate Family

$La_{2-x}Sr_xCuO_4$

- High temperature superconductors – “HTSC”.
- Nearly tetragonal unit cell with layers of CuO_2 planes.
- Doping by changing the rear-earth metal atoms concentration – “x”.





Andrea Damascelli, Zahid Hussain, and Zhi-Xun Shen
Angle-resolved photoemission studies of the cuprate superconductors. Rev. Mod. Phys. **75**, 473 – Published 17 April 2003

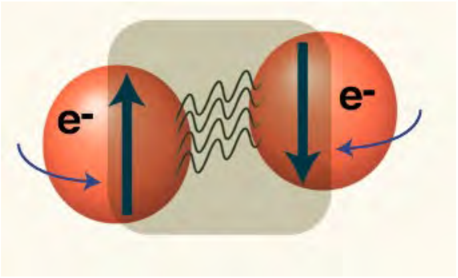
Definition of Coherence-Length ξ

$$F_{GL} = \int_{sc} \left[\alpha |\Psi|^2 + \frac{\beta}{2} |\Psi|^4 + \frac{1}{2m} \left| \left(\frac{\hbar}{i} \nabla - \frac{q}{c} \mathbf{A} \right) \Psi \right|^2 \right] + \int_{R^3} \frac{(\nabla \times A)^2}{8\pi} d\mathbf{r}$$

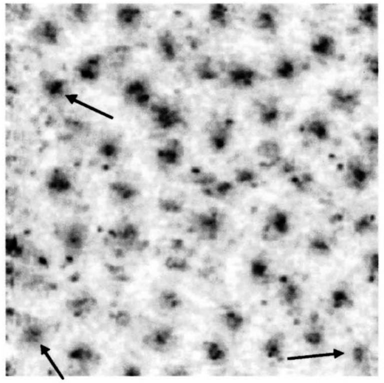
$$\xi^2 = \frac{\hbar^2}{2m|\alpha|}$$

$j_c \propto p_c \sim \hbar / \xi$

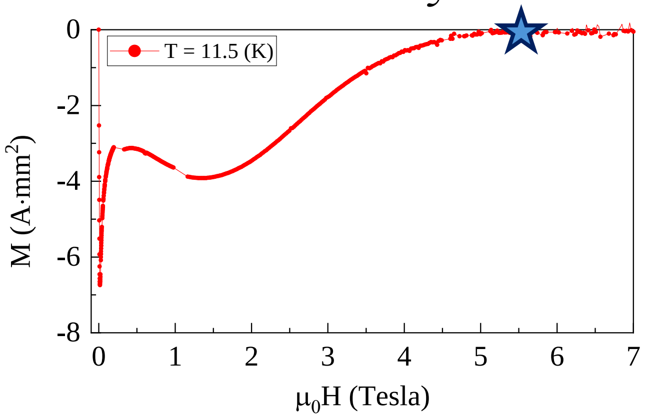
Cooper pair size ~ ξ



Vortex Size ~ ξ



$$\mu_0 H_{c2} = \frac{\Phi_0}{2\pi\xi^2}$$



The Importance of ξ_c

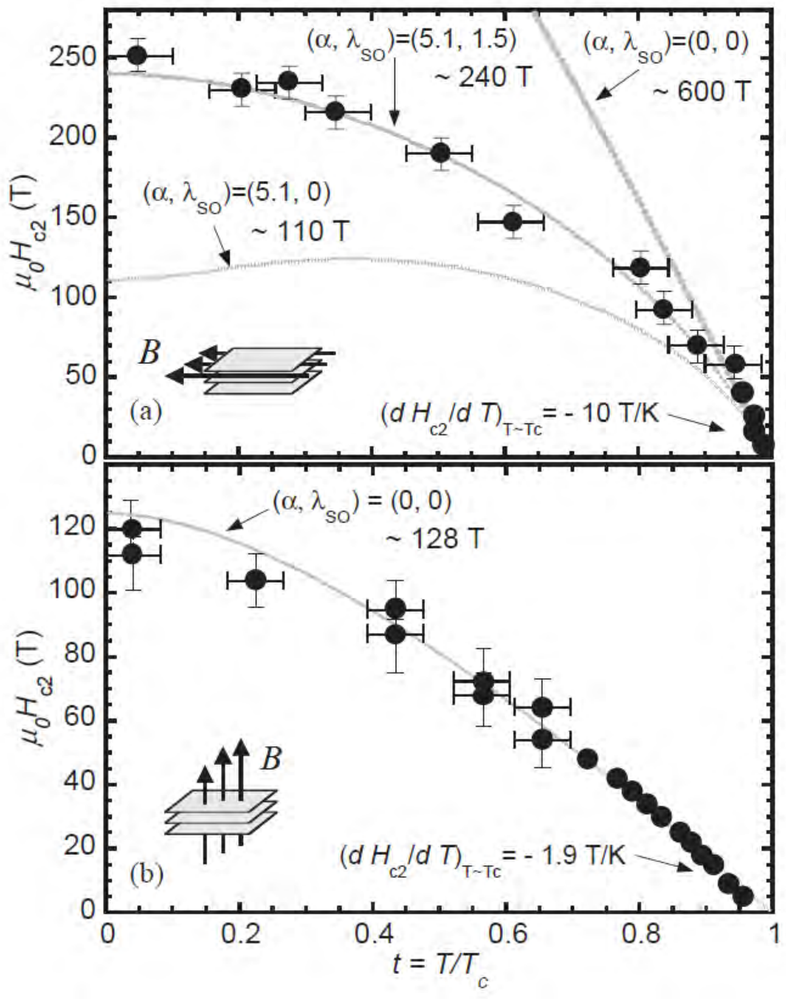
ξ_c relates to the SC gap and the Fermi velocity by:

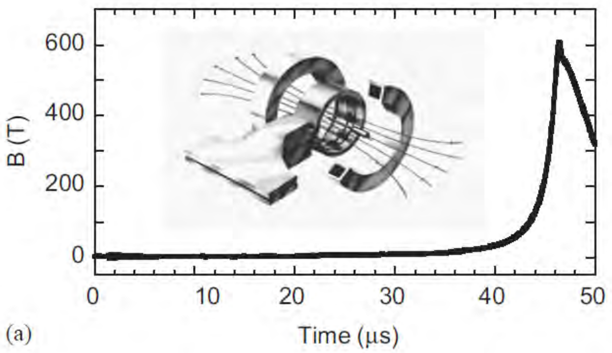
$$\frac{1}{\xi_c} = \frac{\pi\Delta}{\hbar V_f}.$$

Measuring ξ_c can give this **unknown** ratio for parameters in the c direction.

Unfortunately, neither Δ nor V_f in the *c* direction are known from independent measurement so we cannot separate the numbers.

Direct Measurements



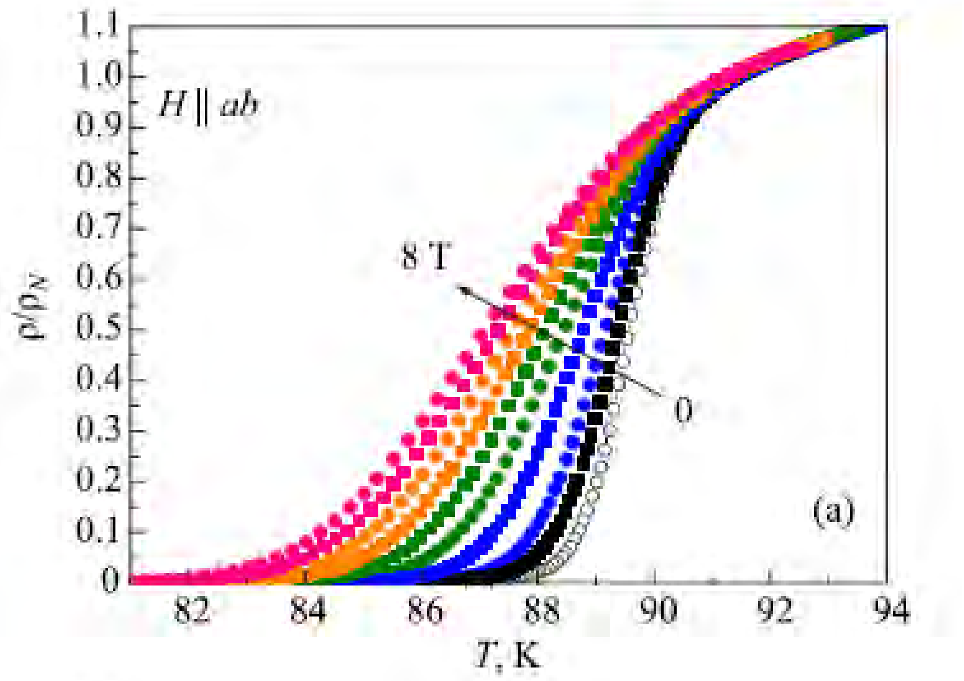


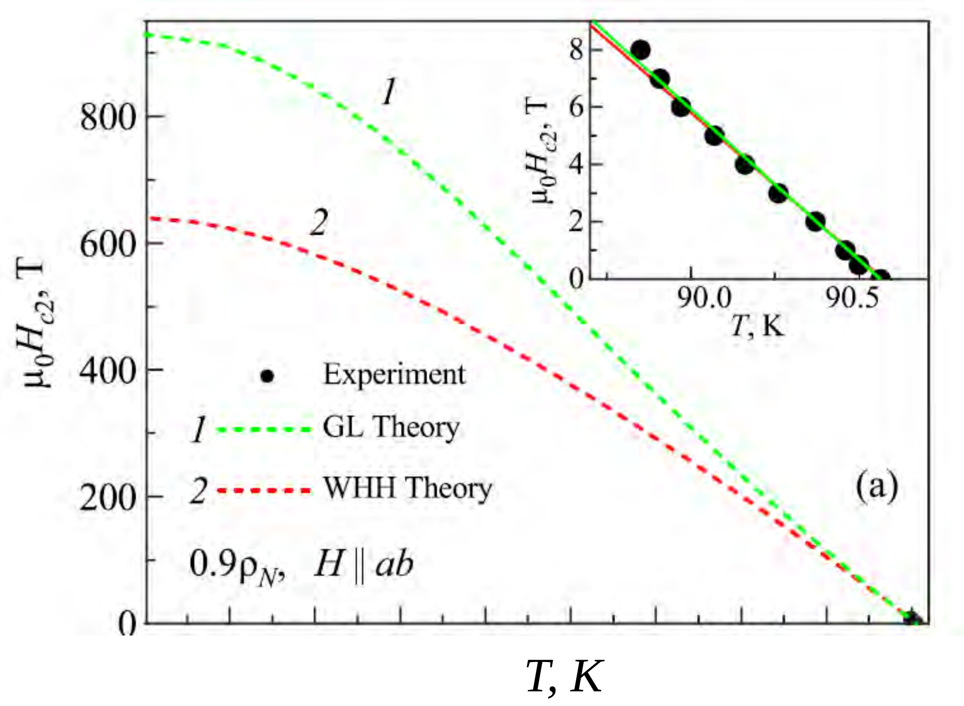
T. Sekitani et al. Physica B 346–347 (2004) 319–324: ξ_c=0.86 nm.

($YBa_2Cu_3O_{7-\delta}$)

- Non equilibrium

Measurement Near T_c and Extrapolation to Low T



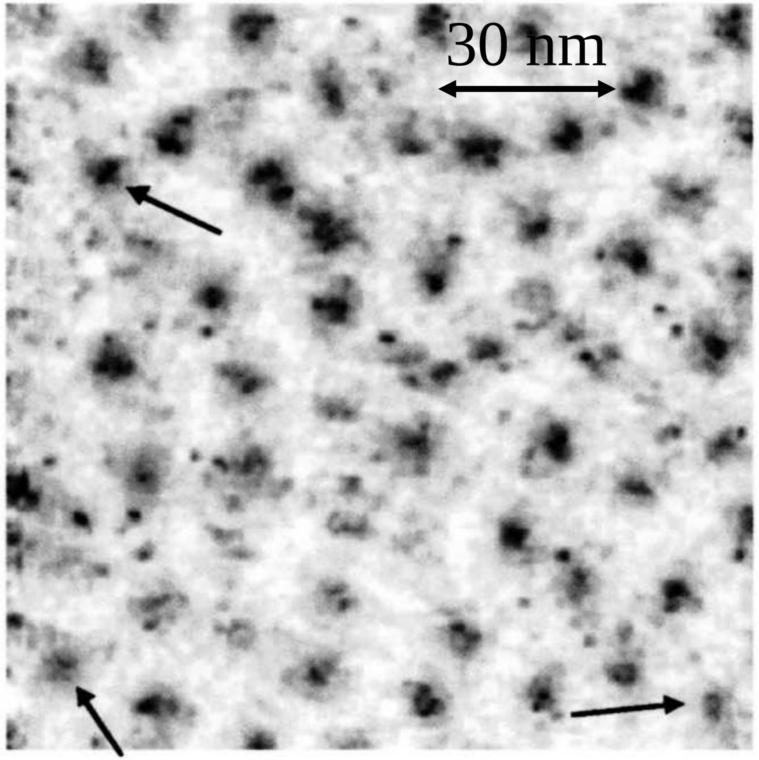


E. V. Petrenko Low Temperature Physics 48, 755 (2022): ξ_c=0.3 nm.

($YBa_2Cu_3O_{7-\delta}$)

- Different theories give different values

STM Studies of Vortex Cores in Bi2212



S. H. Pan…J. C. Davis, PRL 85, 1536 (2000)

ξ_{ab}=2.2(3) nm

- Require atomically smooth surface (cleaving)
- Sensitive to defects

The London Equation

Faraday: $$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} = -\frac{\partial}{\partial t} \nabla \times \mathbf{A}$$

Integration: $$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} + \nabla \mathcal{V}$$

Josephson: $$\mathcal{V} = \frac{\hbar}{q} \frac{\partial \varphi}{\partial t}$$

Free acceleration on a narrow ring: $$\mathbf{j} = nq\mathbf{v} = \frac{nq^2}{m} \int_0^t \mathbf{E} dt = -\frac{nq^2}{m} (\mathbf{A} - \frac{\hbar}{q} \nabla \varphi)$$

Stiffness: $$\rho_s \equiv \frac{nq^2}{m}$$

London Eq. is valid in a broader range than this derivation; it is obtained from F_{GL} if

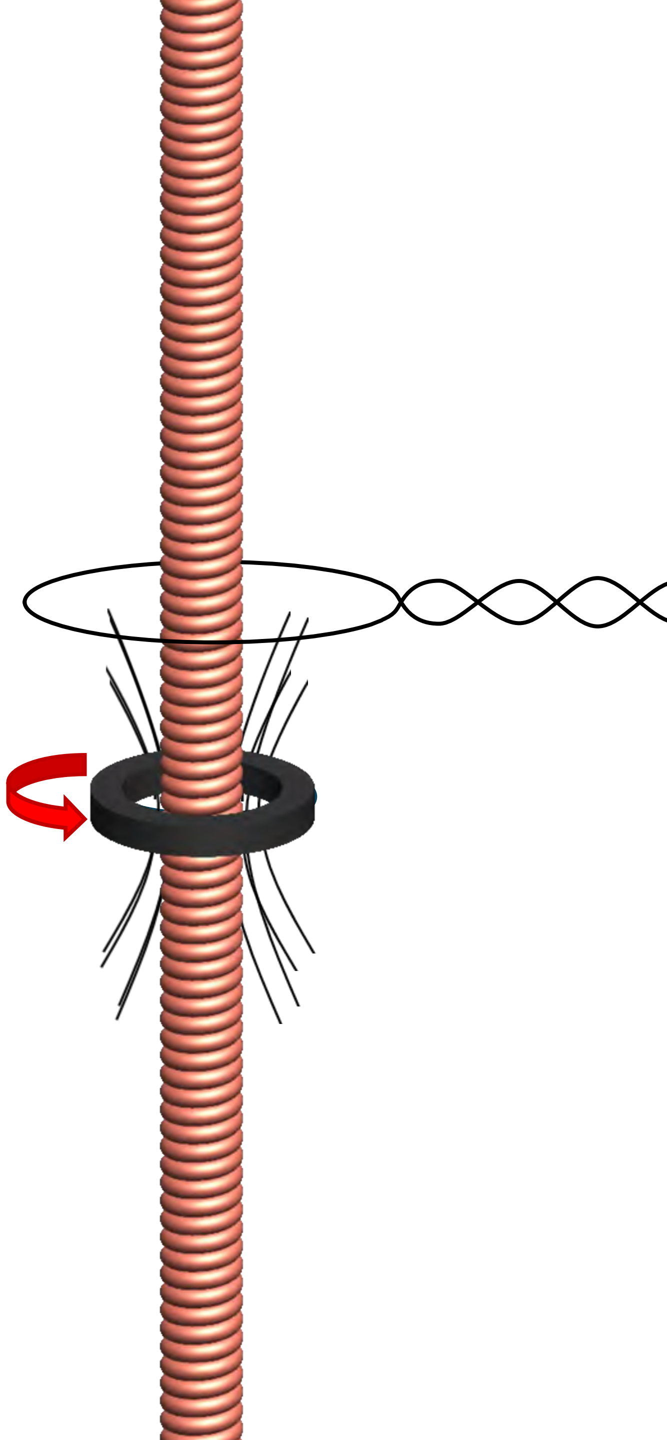
$$\Psi = \psi e^{i\varphi},\ \psi^2 \to n,\ \varphi \to phase,\ \mathrm{q} \to 2e,$$

The Principal of Operation

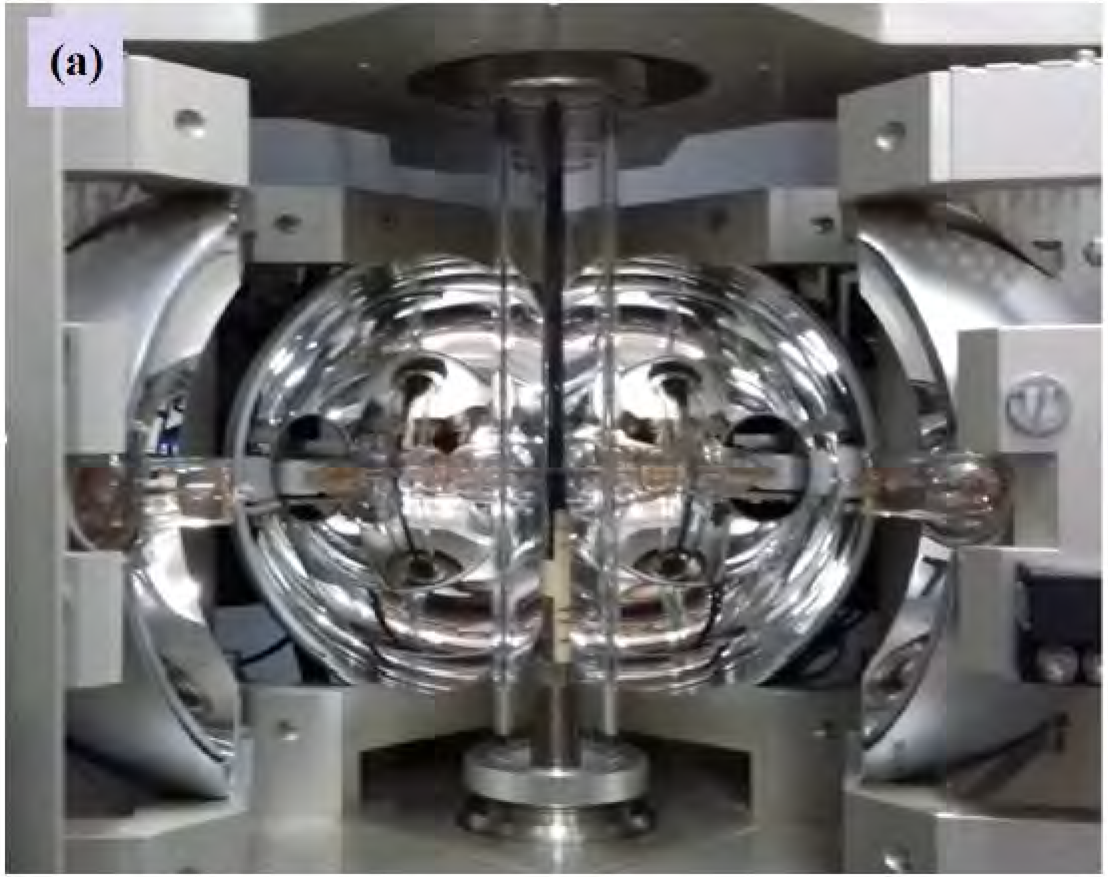
- Use infinitely long coil in the center of a superconducting ring to generate **A** with **B=0**.
- **A** creates $\boldsymbol{j}_s$.
- $\boldsymbol{j}_s$ creates magnetic moment $\boldsymbol{m}$.
- We measure $\boldsymbol{m}$ by moving the ring inside a pickup loop.
- We drive **A** until linearity between **A** and $\boldsymbol{j}_s$ breaks, or change the temperature wile the currant in the coil is fixed.

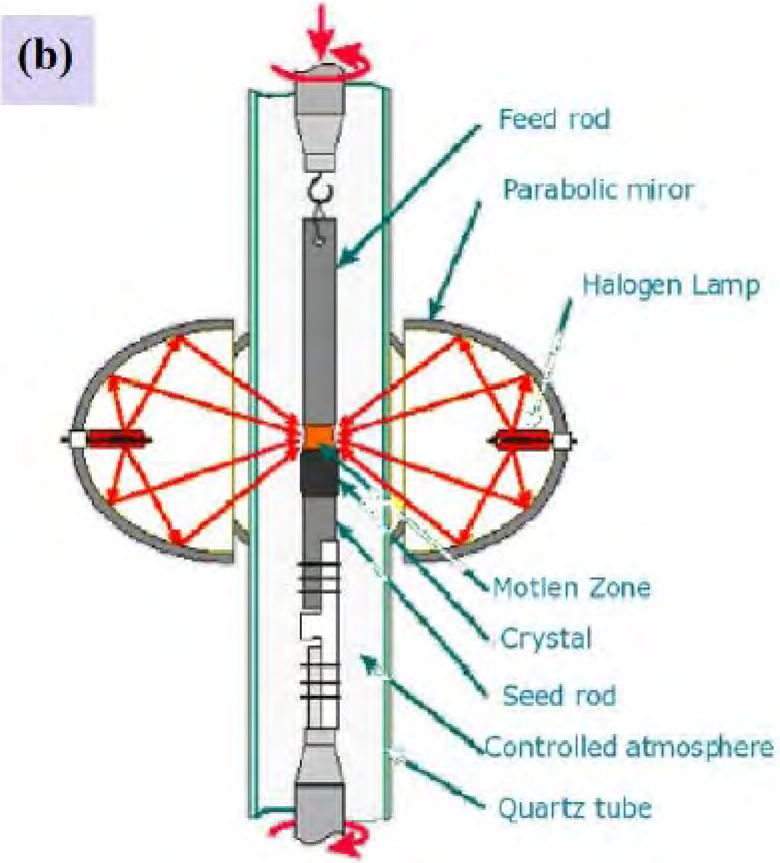
$\mathbf{B} = 0$

$\boldsymbol{j}_s = -\rho_s \mathbf{A}$



Travelling Solvent Floating Zone Furnace

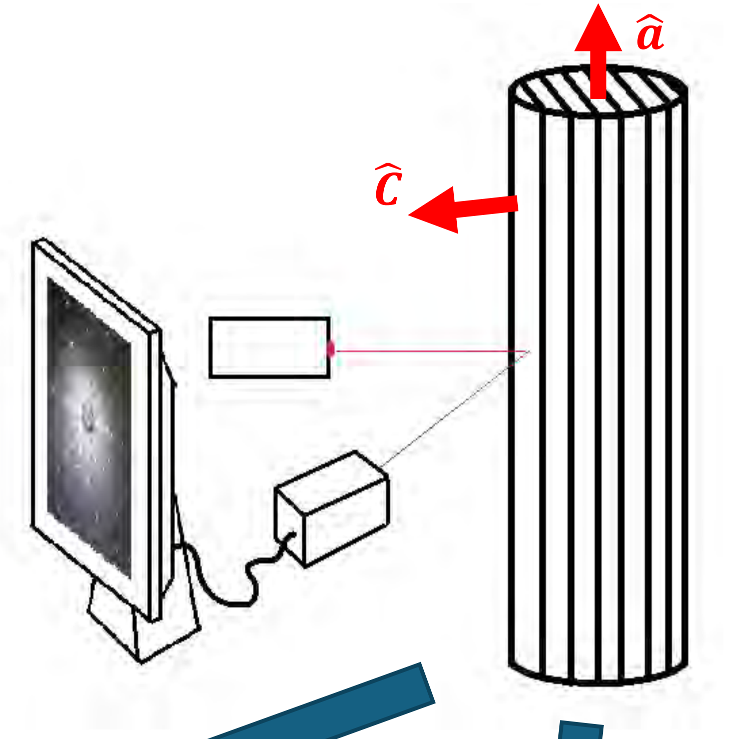


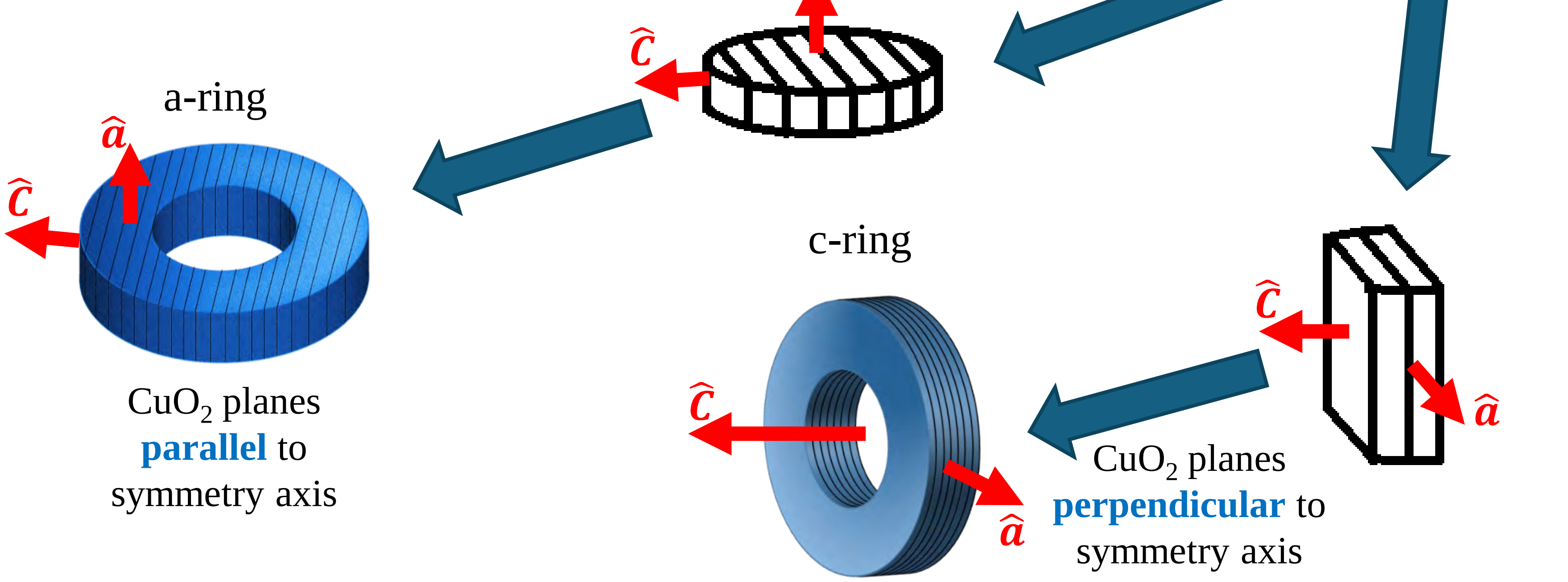


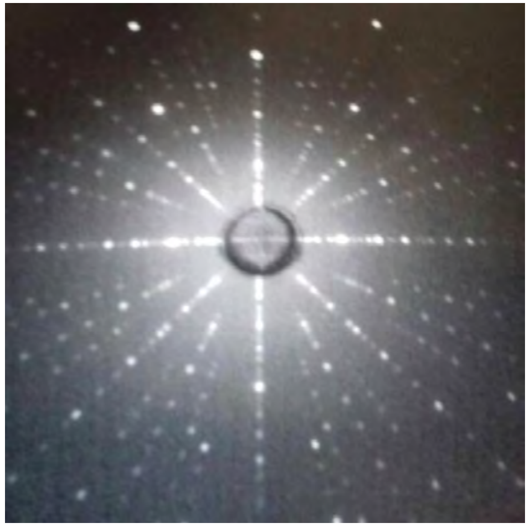
Single Crystals

Rings making

- The single crystal is checked and orientated using x-ray Laue diffraction.
- Using diamond disk saw to cut ac-plates and ab-plates.
- Cutting the rings out of the plates using femtosecond-laser.

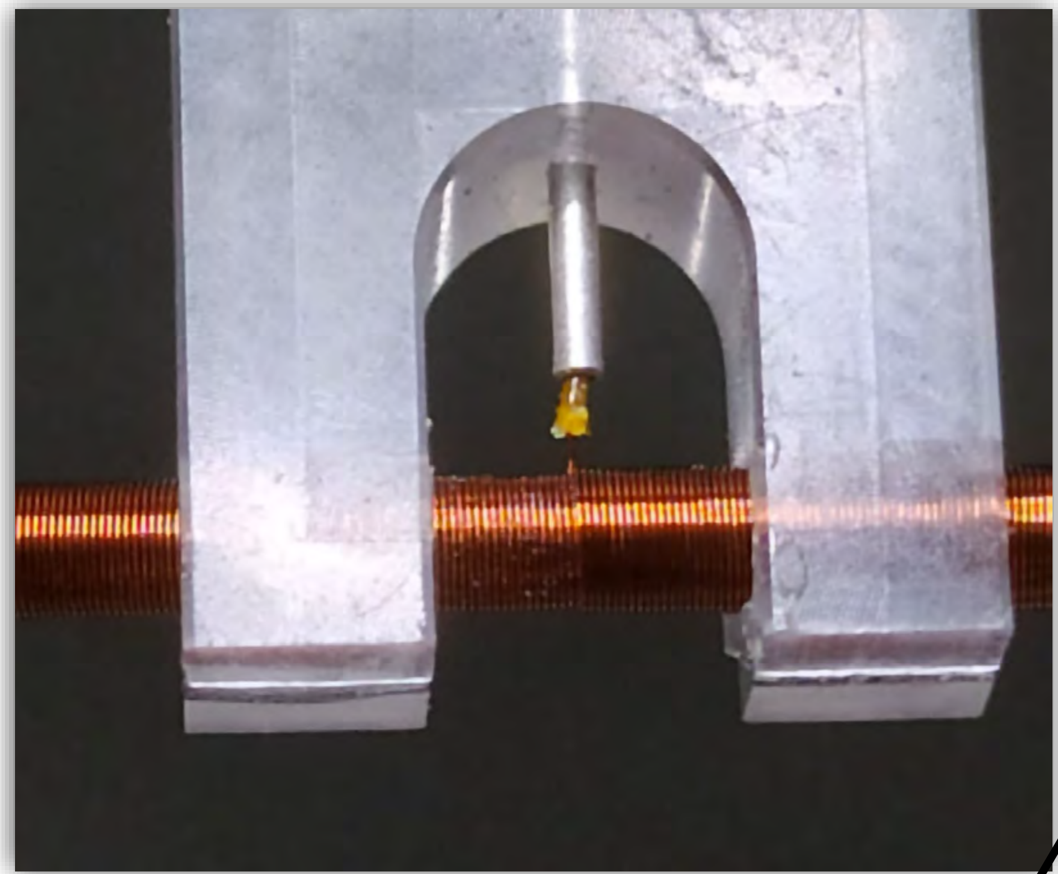




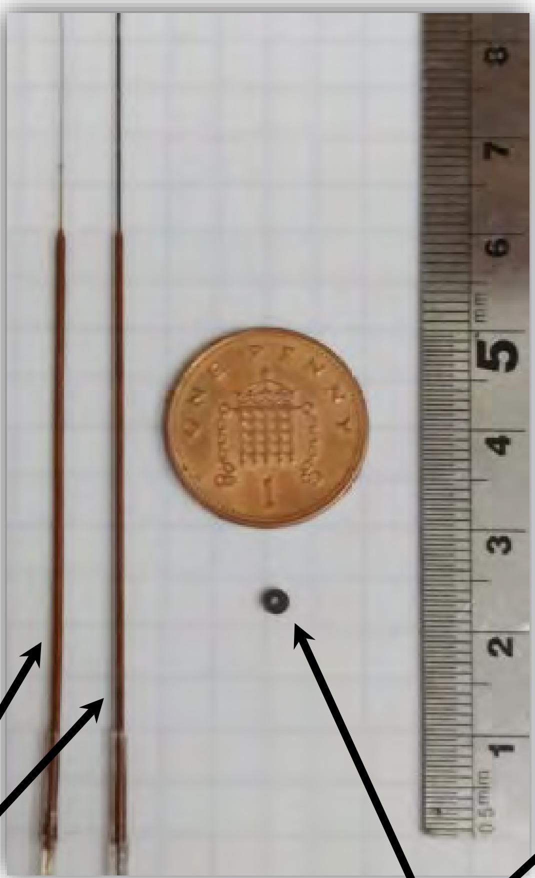

Laue picture of c-direction

Coil Winding

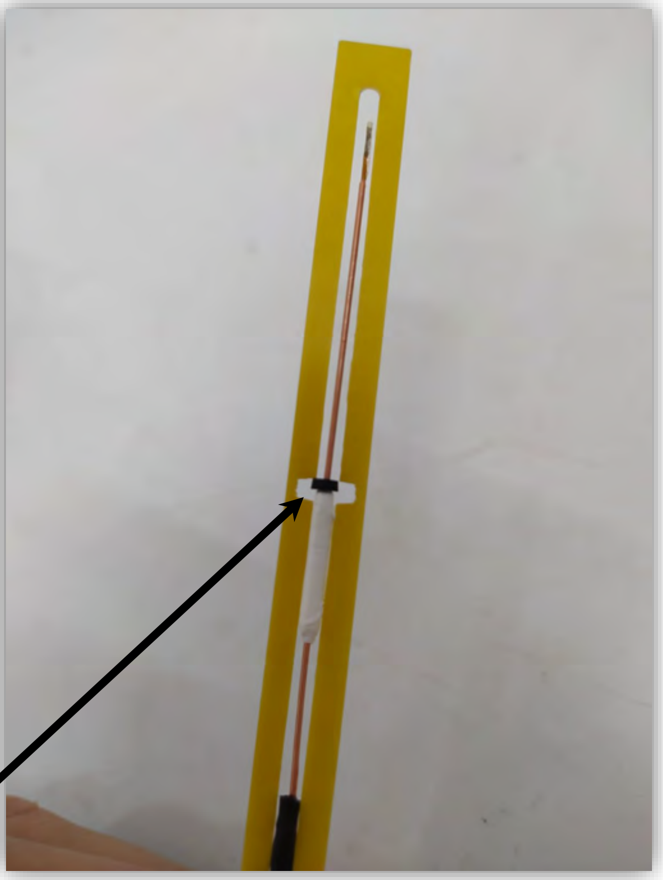
Layers winding



Proportions



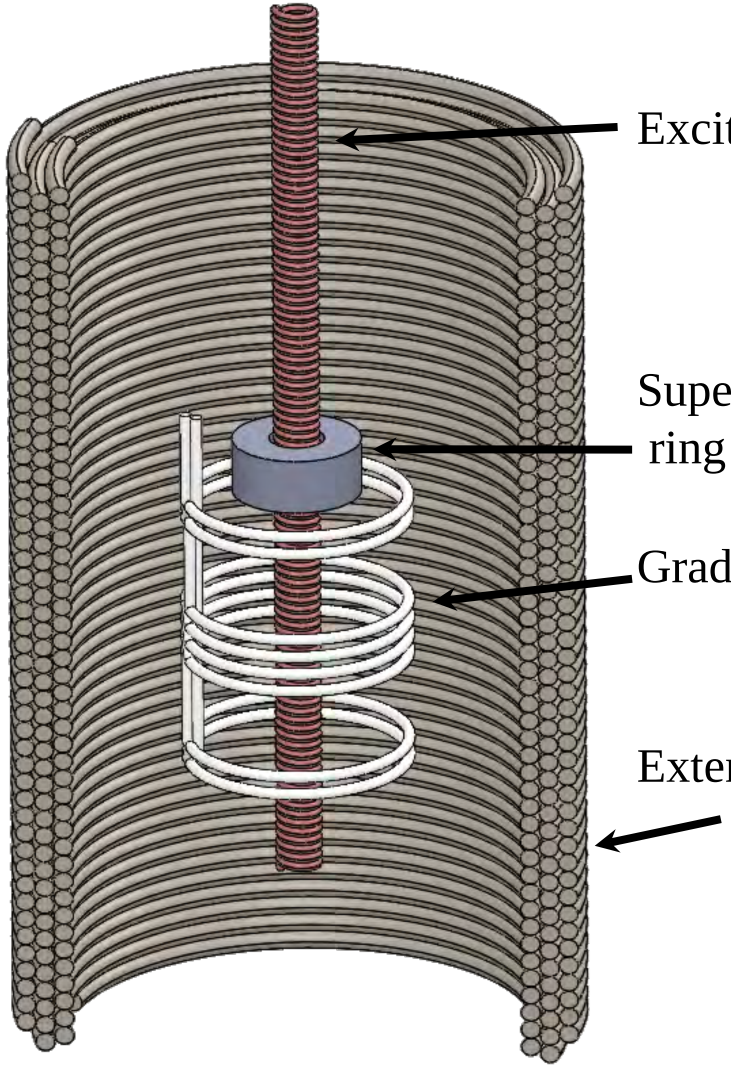
Mounting the ring



60 mm long
Excitation-coils

SC LSCO ring

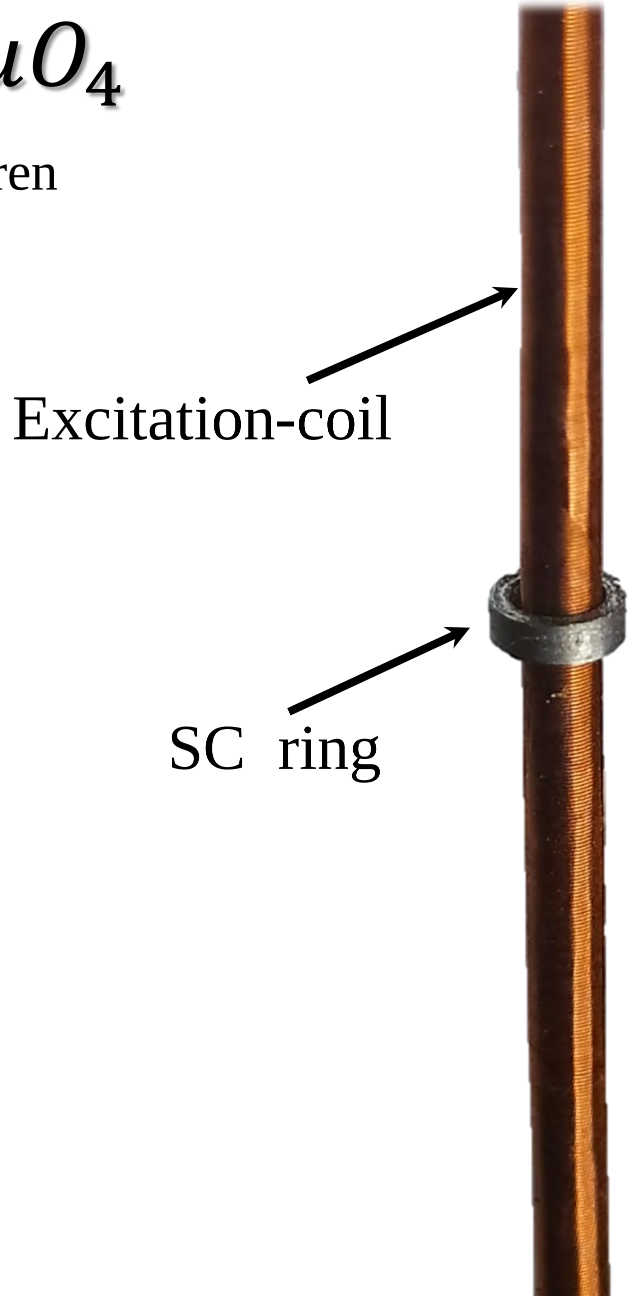
Experimental Setup



Ground-state interplane superconducting coherence length of $La_{1.875}Sr_{0.125}CuO_4$

Itay Mangel, and Amit Keren

superconducting-coil:
60mm length
8 layers
4800 turns
1.95mm outer diameter
TiNb, 102 μm wire



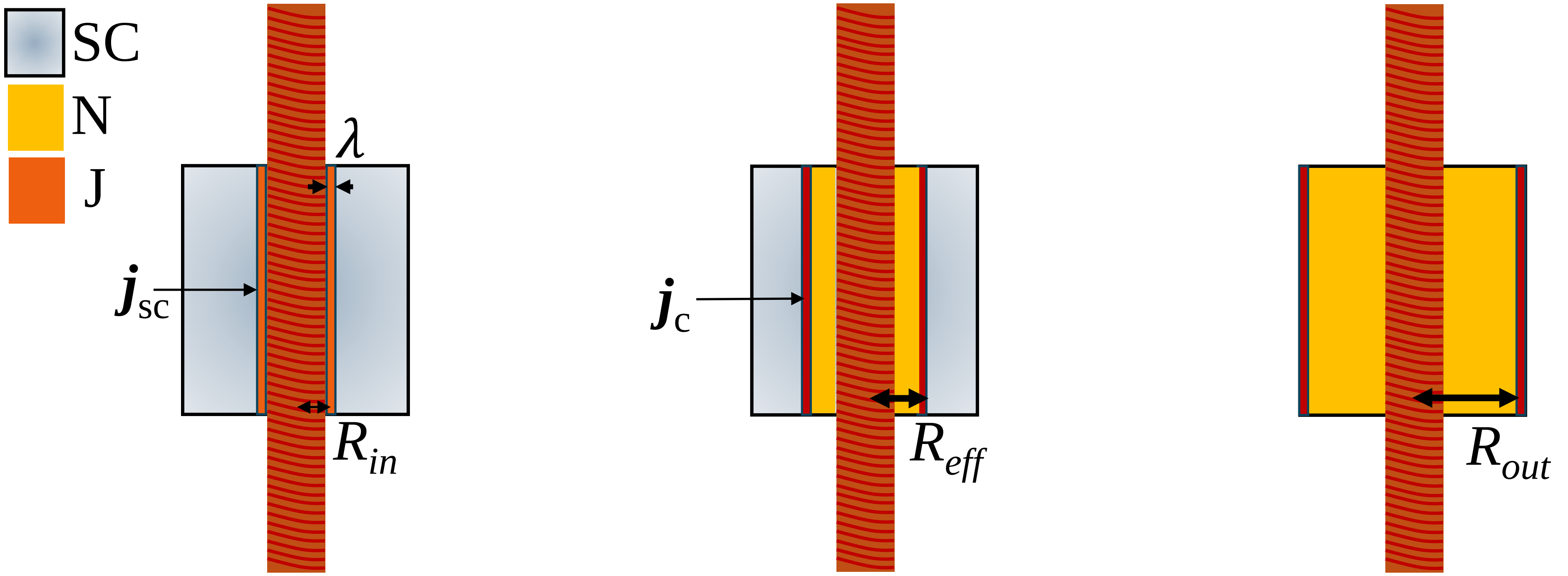
PHYSICAL REVIEW B 109, 094519 (2024) - doi: 10.1103/PhysRevB.109.094519

From critical flux to ξ

Evolution of the screening SC current with increasing flux (left to right)

Critical flux

$\Phi = \mu_0 \boldsymbol{j}_{sc} \lambda \pi R_{in}^2$ $\Phi = \mu_0 \boldsymbol{j}_{c} \lambda \pi R_{eff}^2$ $\Phi_c = \mu_0 j_c \lambda \pi R_{out}^2$



Back of the Envelop Explanation

Current definition

$$j = e^* n v = \frac{1}{\mu_0 \lambda^2} \frac{1}{e^*} m^* v$$

Critical flux

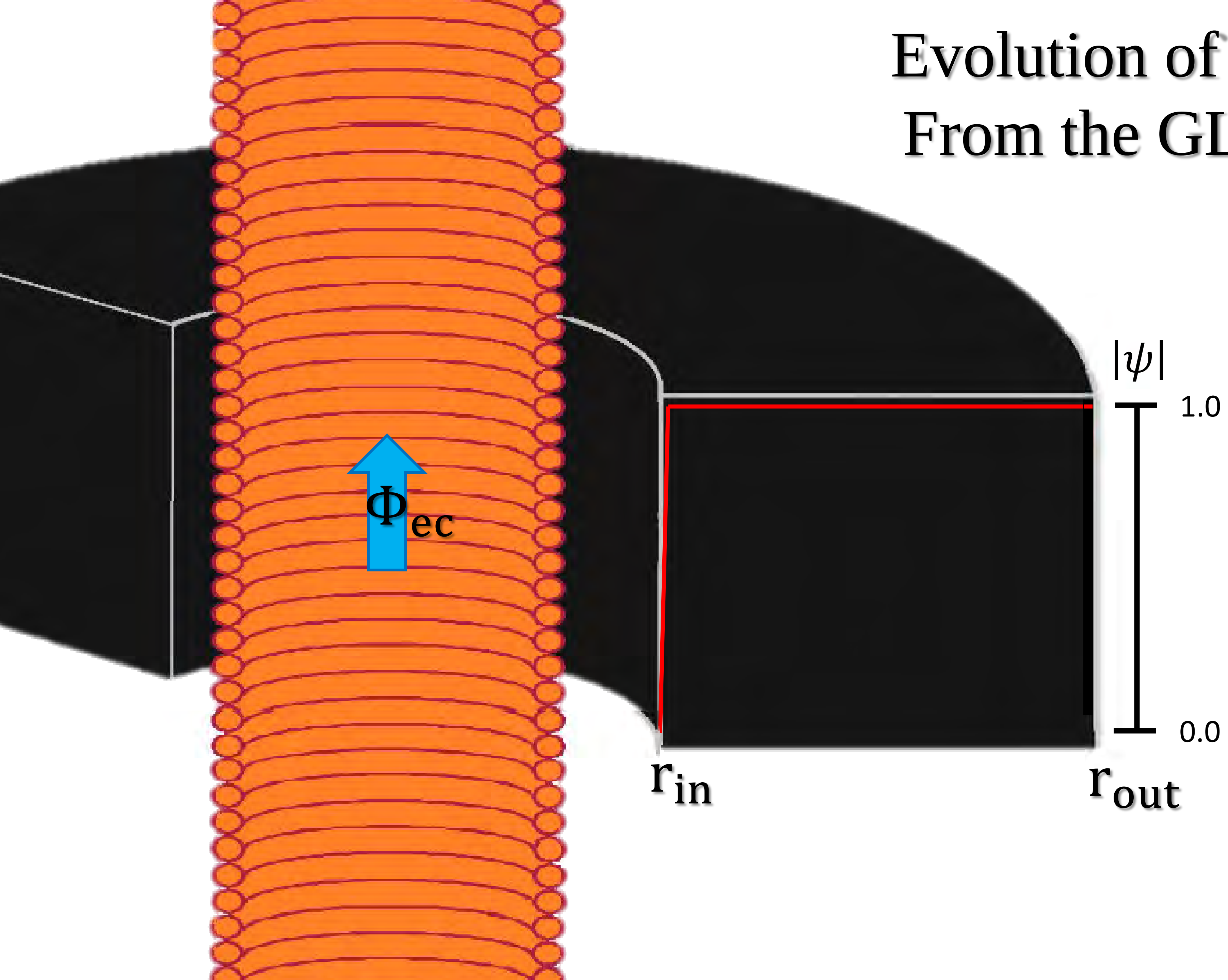
$$\Phi_c = \mu_0 j_c \lambda \pi R_{out}^2$$

Critical momentum

$$m^* v_c = \frac{\hbar}{\sqrt{3}\xi}$$

$$\frac{\Phi_c}{\Phi_0} = \frac{r_{out}^2}{\sqrt{12}\xi\lambda}$$

Evolution of $|\psi|$ $with$ Φ_{ec} From the GL Free Energy



The two Ginzburg-Landau equations

$$\boldsymbol{F} = \int_{R^3} \frac{|\boldsymbol{\nabla} \times \boldsymbol{A}|}{8\pi} d\boldsymbol{x} + \int_{SC} \left[\frac{1}{2m^*} \left| \left(\frac{\hbar}{i} \boldsymbol{\nabla} - \frac{e^*}{c} \boldsymbol{A} \right) \psi \right|^2 + \alpha |\psi|^2 + \frac{\beta}{2} |\psi|^4 \right] d\boldsymbol{x}$$

$$J \equiv \frac{\Phi_{ec}}{\Phi_0}, \Phi_0 = \frac{2\pi\hbar c}{e^*}$$

$$\frac{\delta \boldsymbol{F}}{\delta \psi} = 0$$

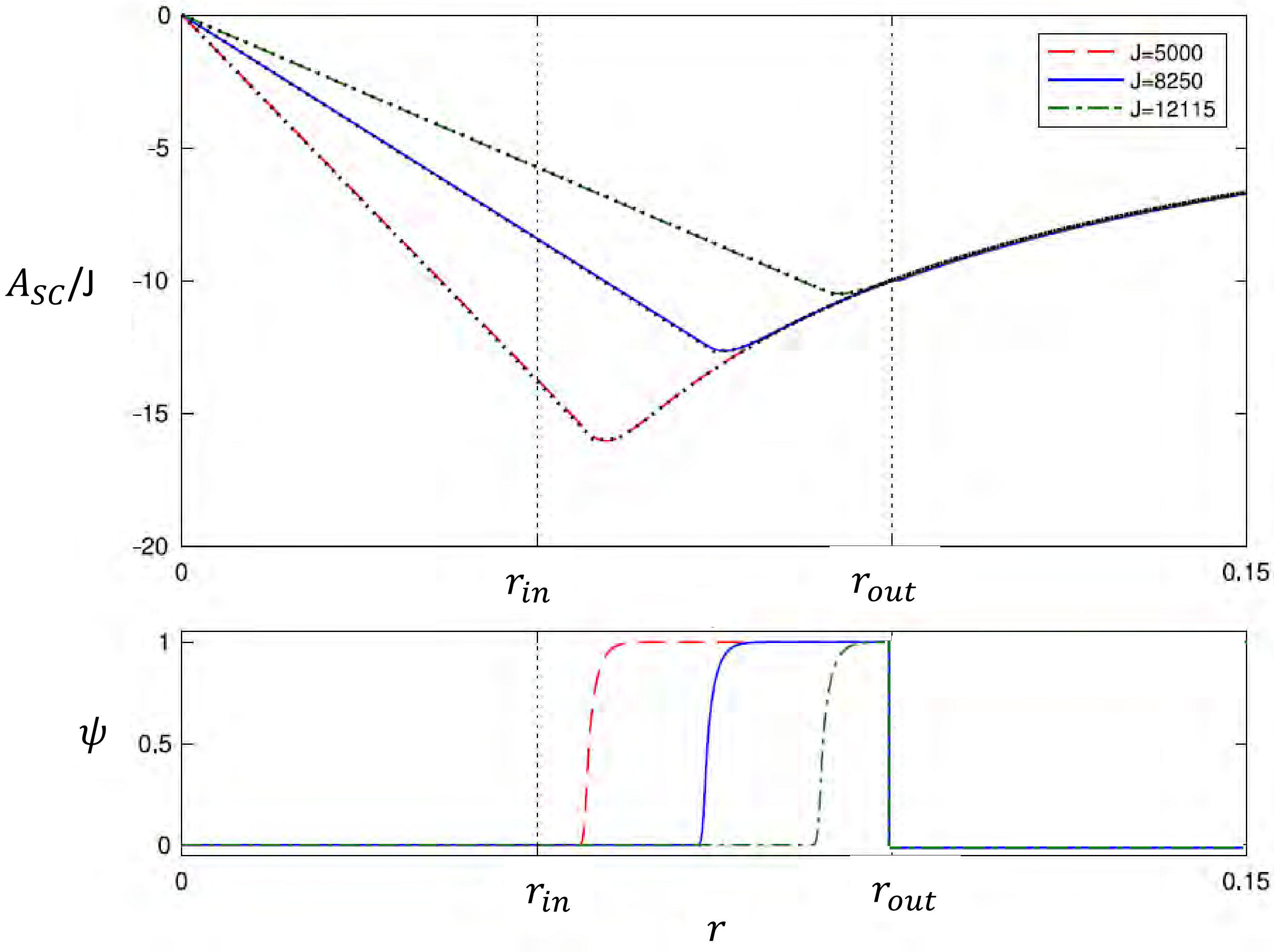
$$\xi^2 \left(\psi''(r) - \frac{\psi'(r)}{r} \right) = \psi^3(r) - \left(1 - \xi^2 \left(A_{SC}(r) + \frac{J - m}{r} \right)^2 \right) \psi(r)$$

$$\frac{\delta \boldsymbol{F}}{\delta A_{SC}} = 0$$

$$A''_{SC}(r) + \frac{A'_{SC}(r)}{r} - \frac{A_{SC}(r)}{r^2} = \frac{1}{\lambda^2} \left(A_{SC}(r) + \frac{J - m}{r} \right) \psi^3(r)$$

N. Gavish, O. Kenneth, A. Keren, Physica D 415 132767 1 (2021).

Superconductivity destroyed in part of ring



As long as $\psi = 1$ somewhere inside the SC, $\frac{A}{J} = constant$ outside.

$$\frac{\Phi_c}{\Phi_0} = \frac{r_{out}^2}{\sqrt{8}\xi\lambda}$$

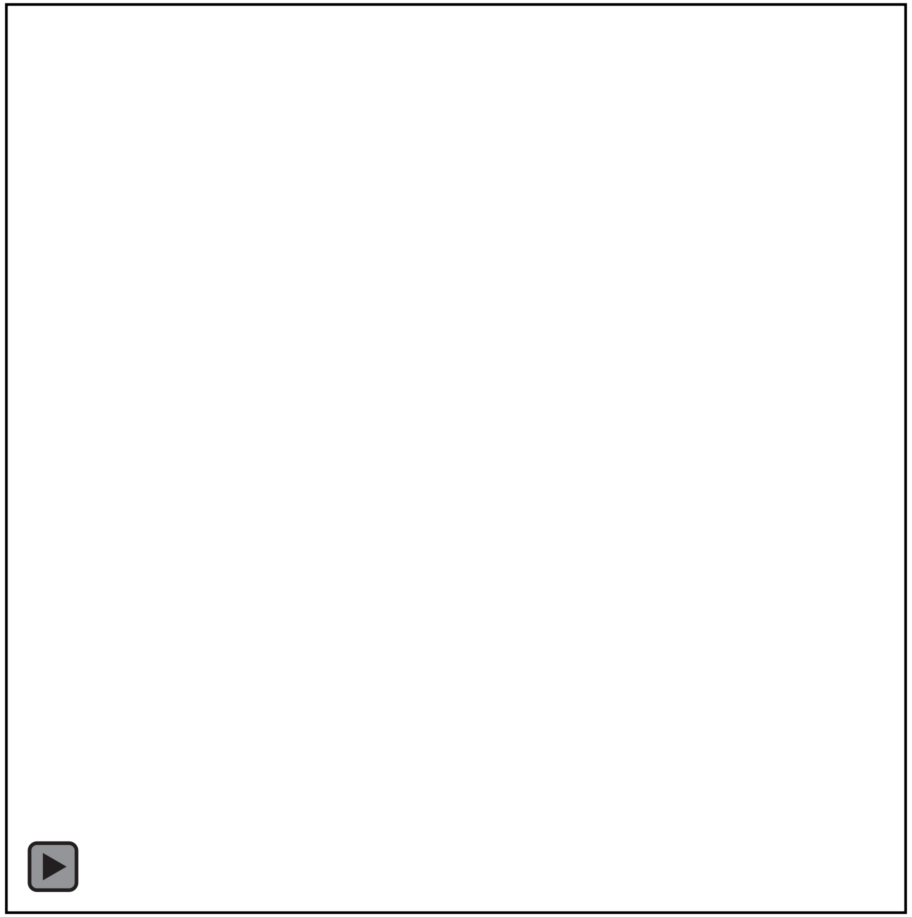
Phase Slip

Upon cooling with **A**=0, $\nabla\varphi = 0$.

Increasing **A** keeps $\nabla\varphi = 0$.

Until the current exceeds J_c.

$$\mathbf{j} = -\rho_s\left(\mathbf{A} - \frac{\hbar}{q}\nabla\varphi\right)$$



Test case, for Nb-rings

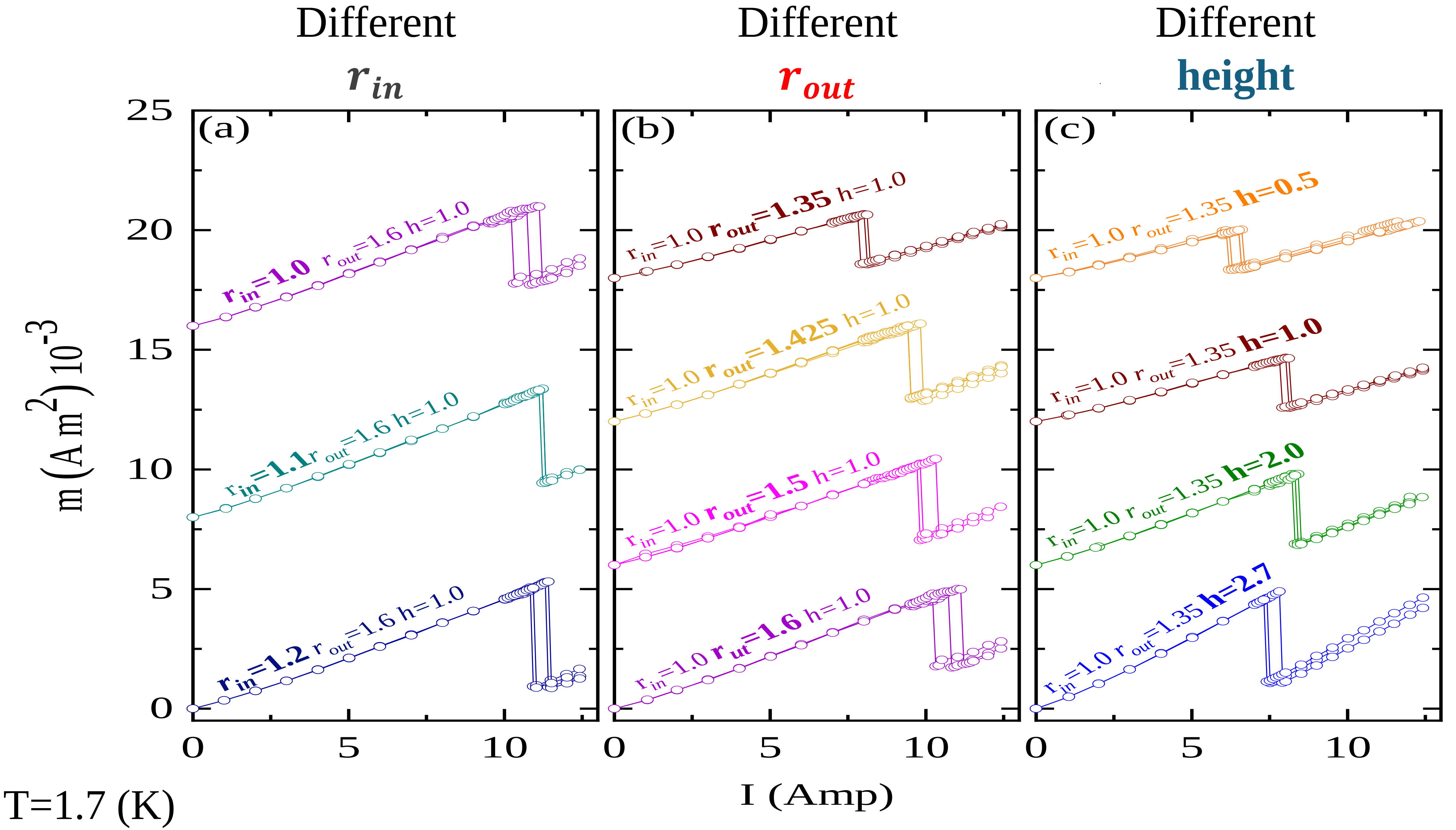
Different r_{in}

Different r_{out}

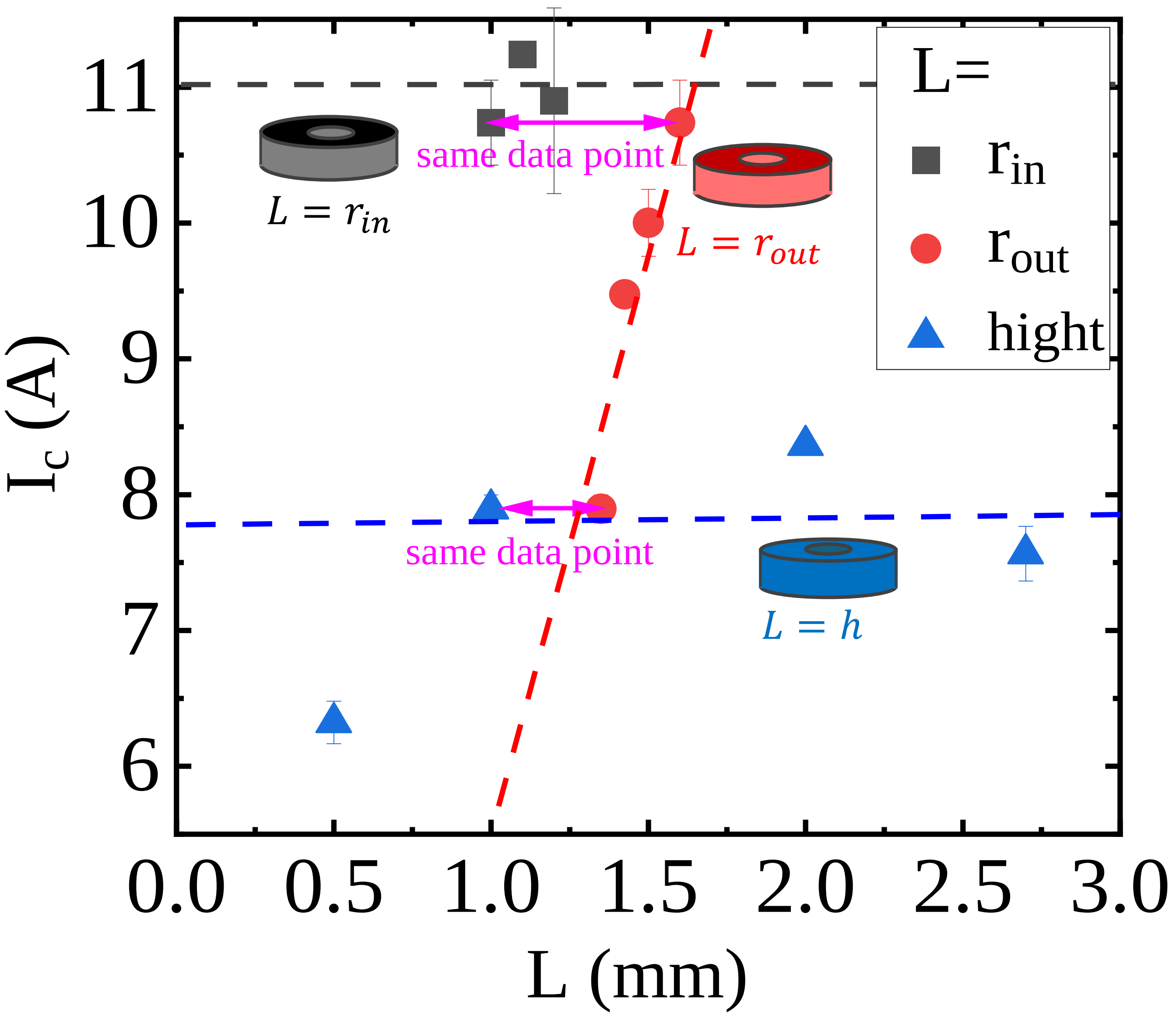
Different **height**

$$\frac{\Phi_c}{\Phi_0} = \frac{r_{out}^2}{\sqrt{8}\xi\lambda}$$

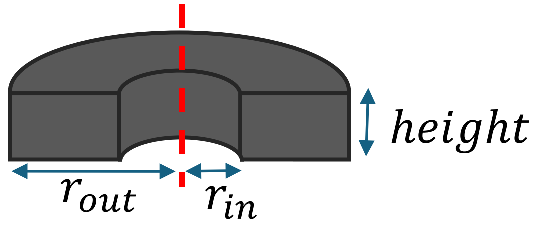
Test case, for Nb-rings



Results

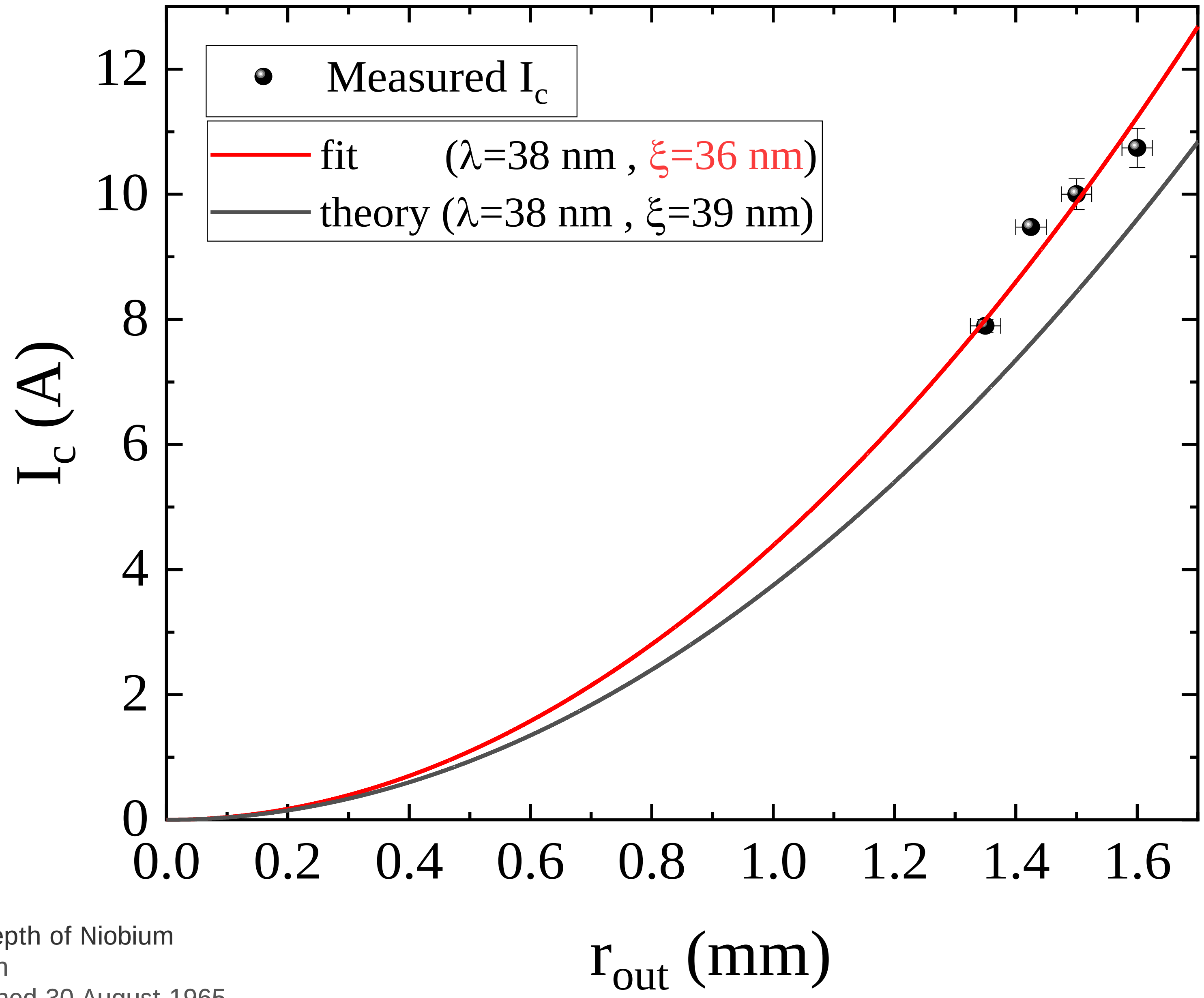


$$\frac{\Phi_c}{\Phi_0} = \frac{r_{out}^2}{\sqrt{8}\xi\lambda}$$



T=1.7 (K)

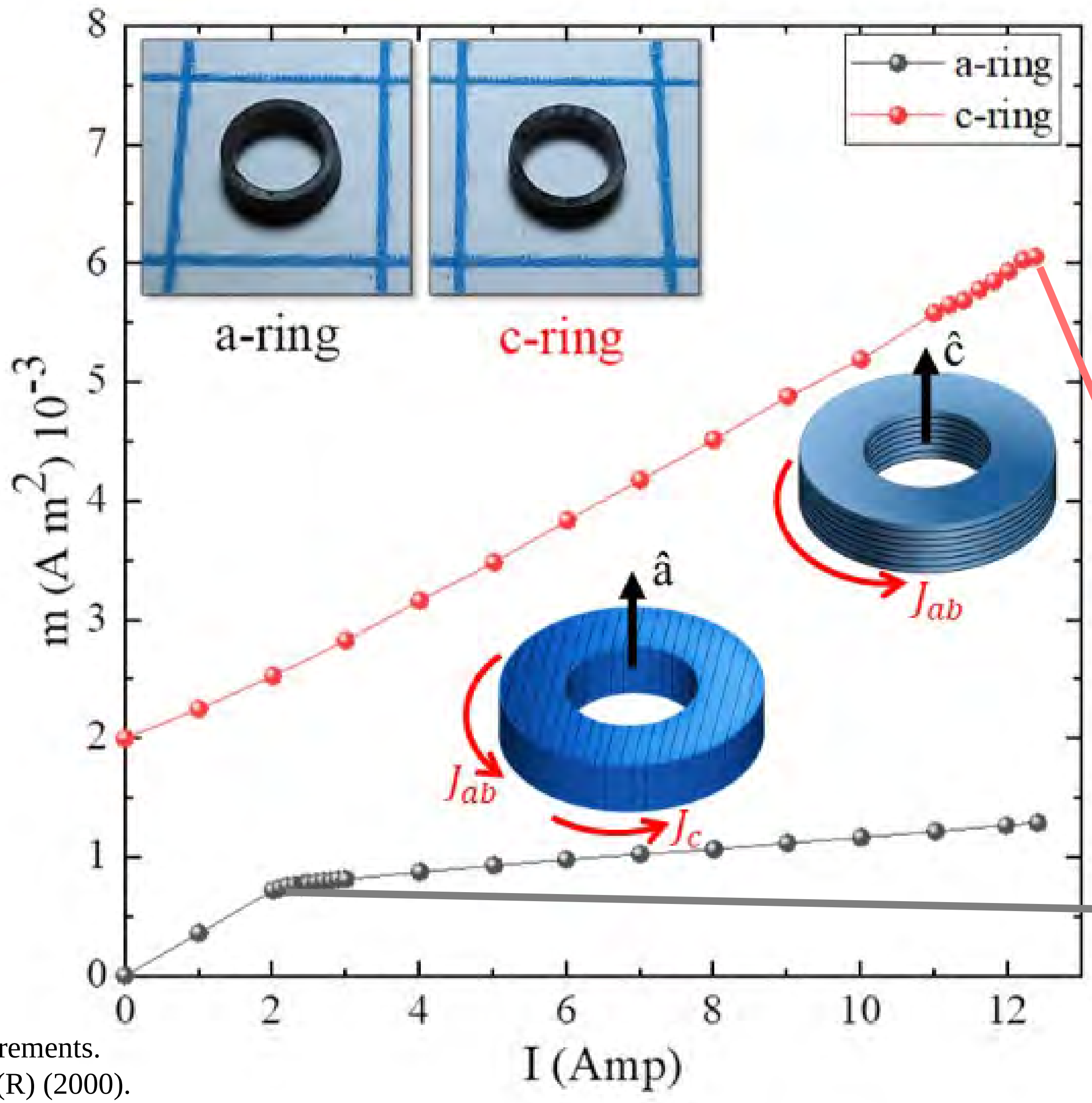
Results



$$\frac{\Phi_c}{\Phi_0} = \frac{r_{out}^2}{\sqrt{8}\xi\lambda}$$

Superconducting Penetration Depth of Niobium
B. W. Maxfield and W. L. McLean
Phys. Rev. **139**, A1515 – Published 30 August 1965

Measurements of LSCO



$$\frac{\Phi_c}{\Phi_0} = \frac{r_{out}^2}{\sqrt{8}\xi\lambda}$$

$\xi_{ab} < 2.3nm$

$\xi_c = 1.3 \pm 0.4nm$

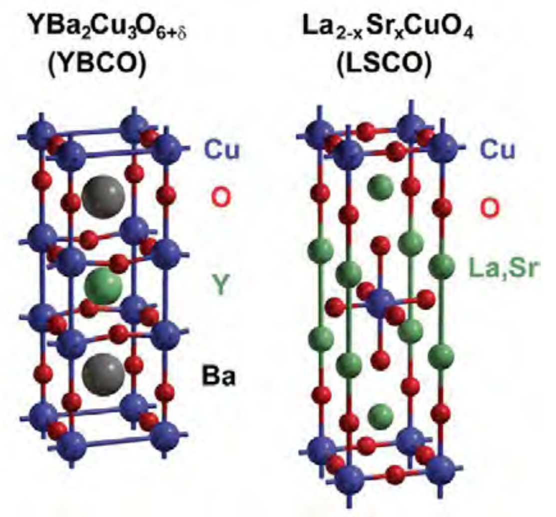
λ_c = 4500 nm, Low field susceptibility measurements.
C. Panagopoulos, et-al, Phys. Rev. B 61, R3808(R) (2000).

λ_{ab} = 350 nm, LE-μSR
I. Kapon, et-al, Nat. Commun. 10, 2463 (2019)

Ground State ξ

$$\frac{\Phi_c}{\Phi_0} = \frac{r_{out}^2}{\sqrt{8}\xi\lambda}$$

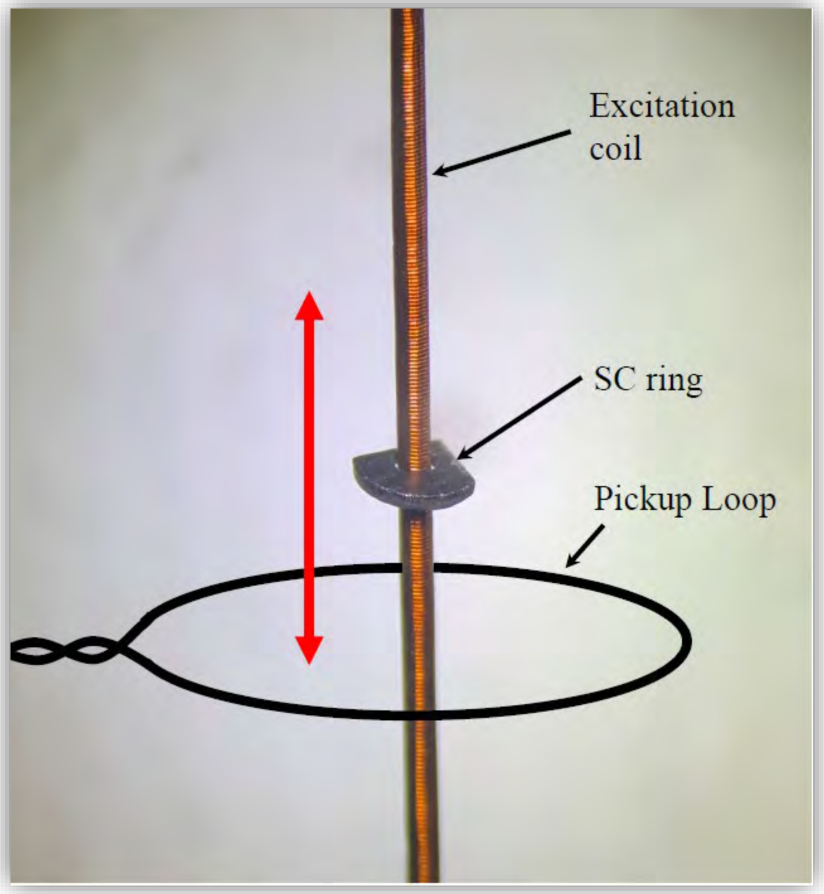
- Only changing R_{out} affects the critical flux.
- We found good agreement between the experiment and our new derivation, and the values of ξ and λ for Niobium.
- We applied our technique on LSCO and found $\xi_{ab} < 2.3$nm, and $\xi_c = 1.3 \pm 0.4$nm ($\xi_c^{YBCO} \simeq$ 0.3-0.9 nm).
- ξ_c and ξ_{ab} where found similar, so ξ is isotropic at $T \to 0$.



Uniaxial Pressure Study of Charge Density Waves in a High-T_c Cuprate Superconductor, 2022, ISBN : 978-3-030-99897-4, Hun-ho Kim

The Two critical temperatures conundrum in $La_{1.83}Sr_{0.17}CuO_4$

Abhisek Samanta, Itay Mangel*, Amit Keren, Daniel P. Arovas, Assa Auerbach



SciPost Phys. 16,148 (2024) - doi: 10.21468/SciPostPhys.16.6.148

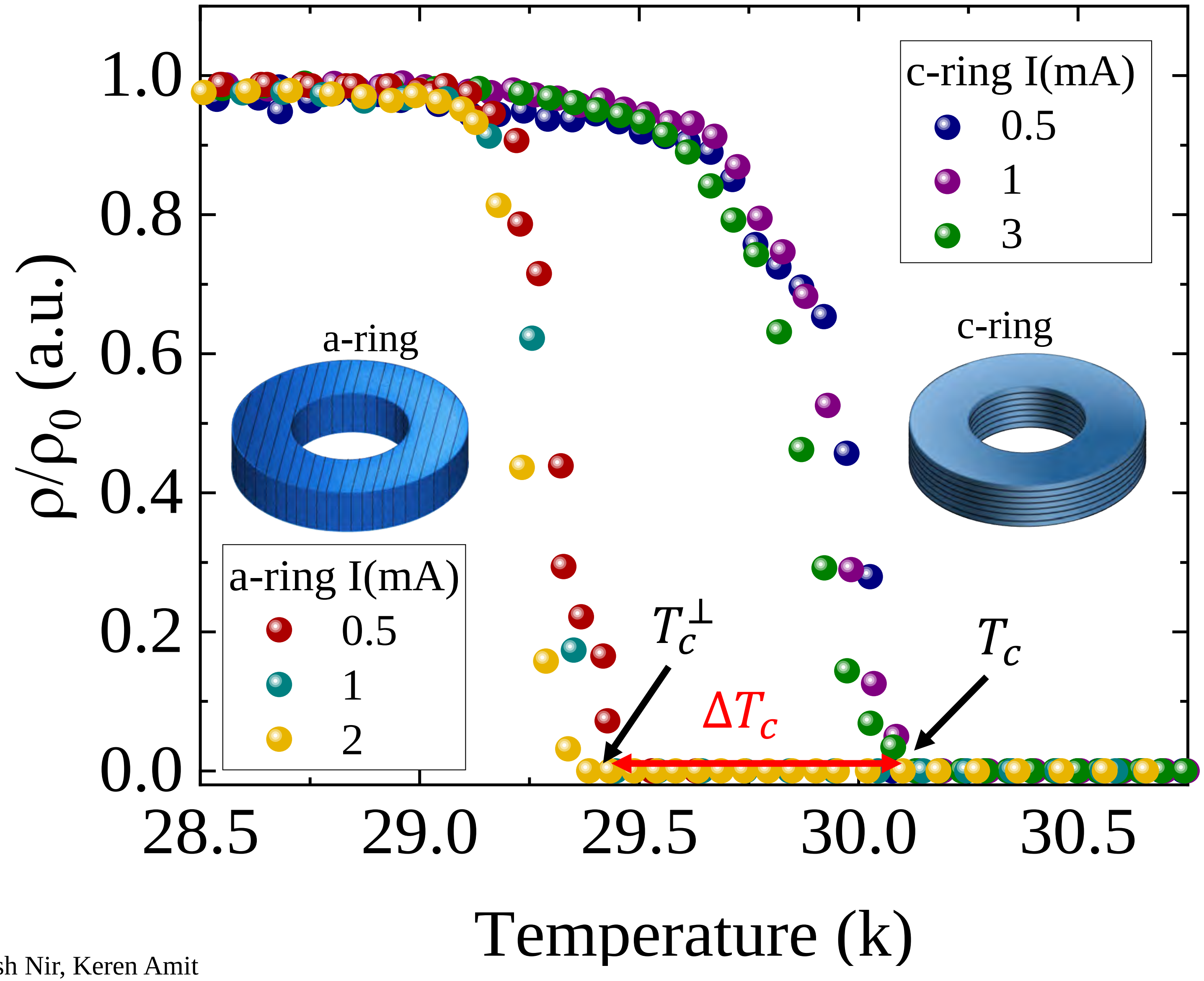
Initial Observation

Kapon et al found a ΔT_c = 0.64 (k) for rings with different plane orientations for x=1/8.

Sharp transition (no tail).

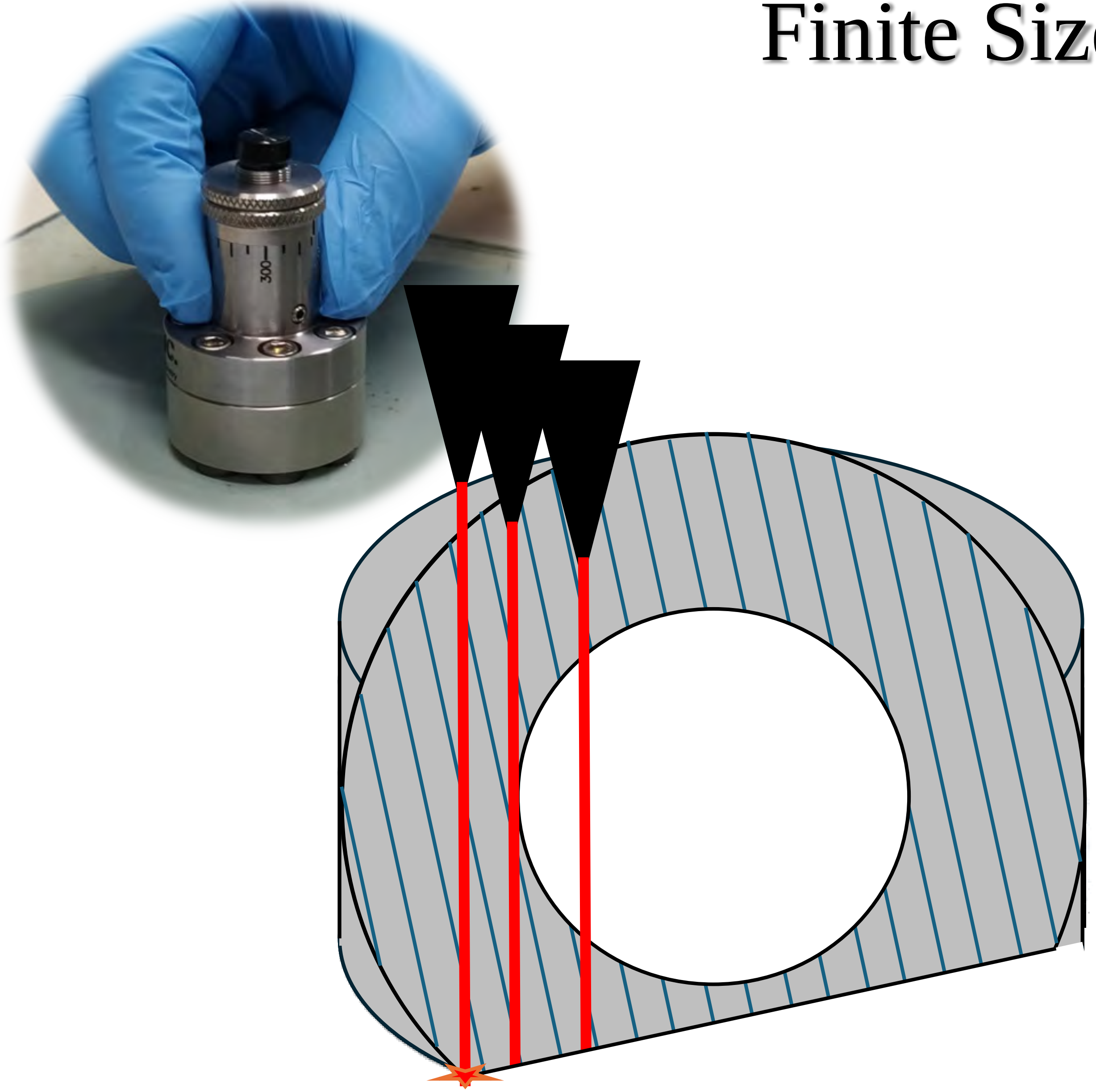
A 3D system should have only one T_c

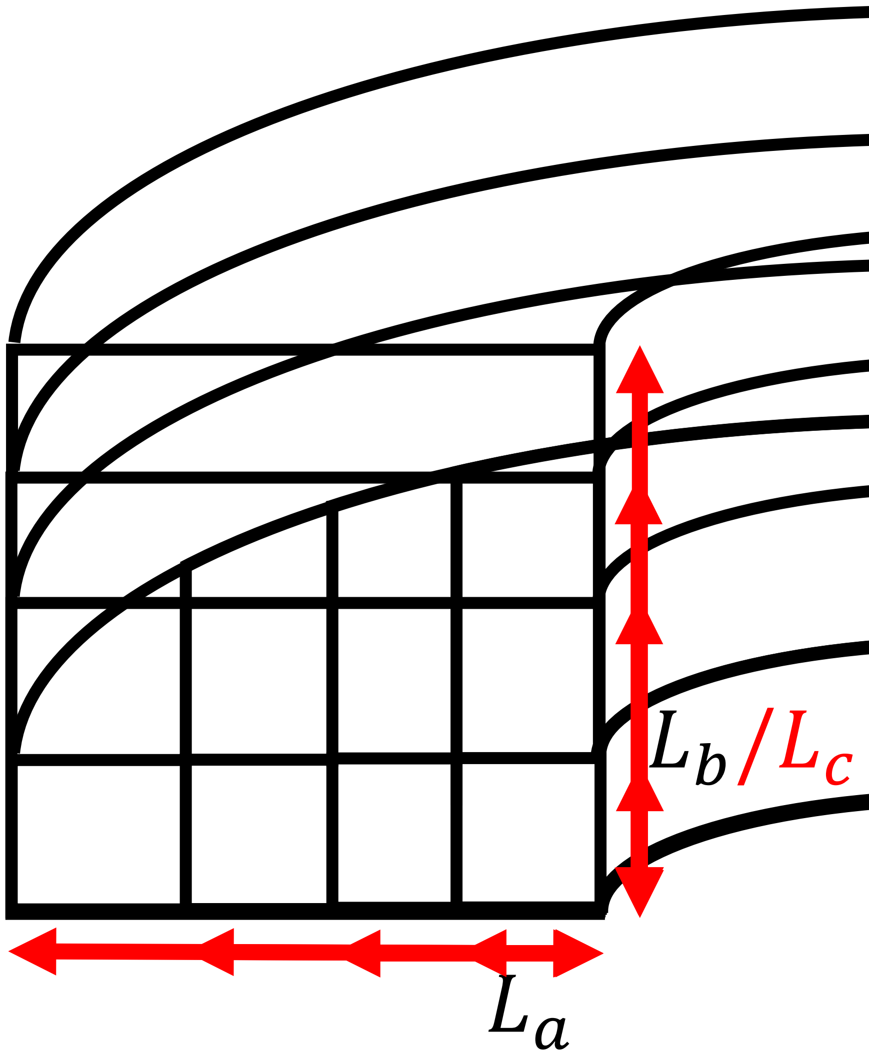
We want to check the origin of this T_c difference. **We suspect a finite size effect.**

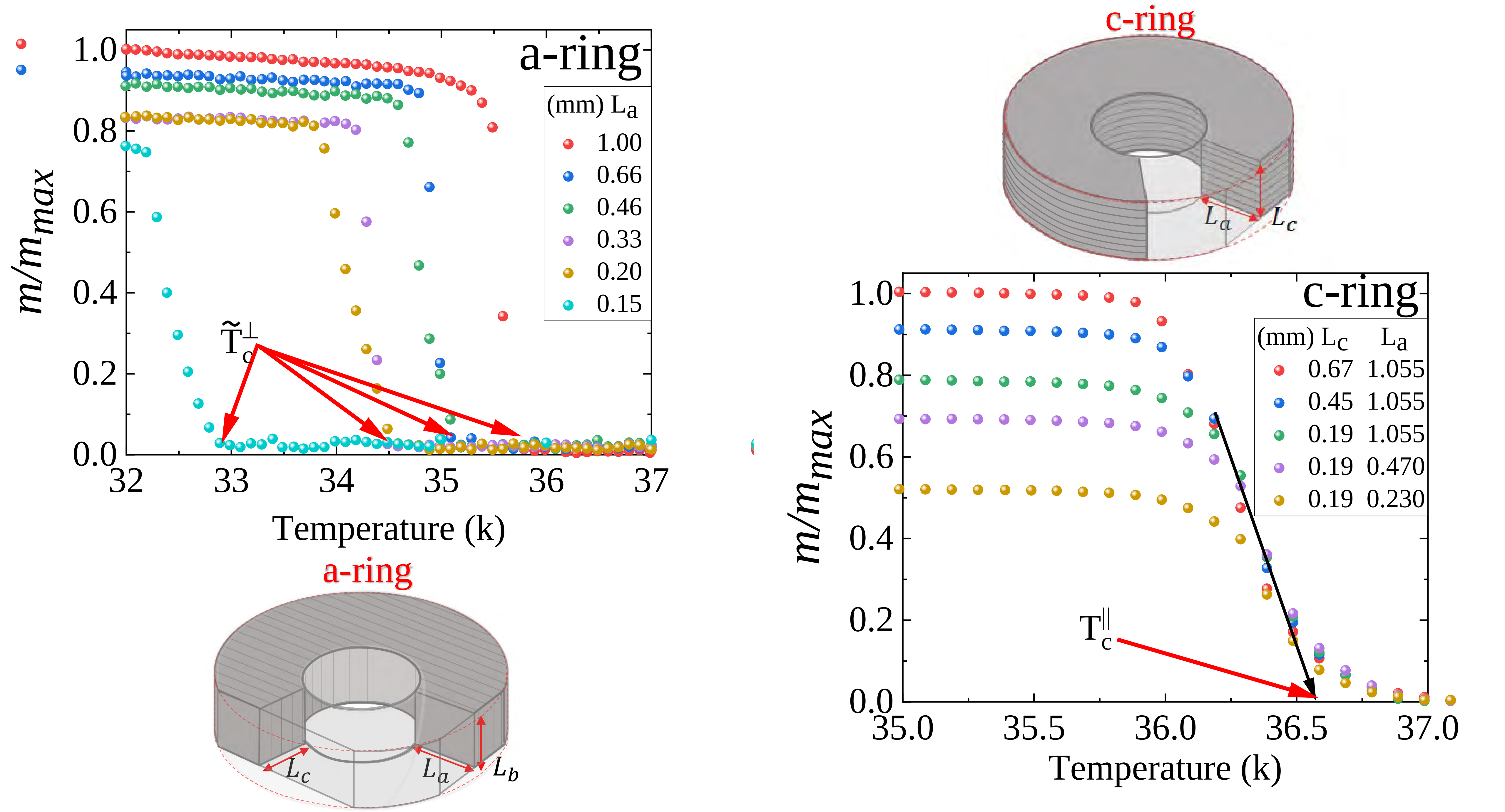


Kapon Itzik, Salman Zaher, Mangel Itay, Prokscha Thomas, Gavish Nir, Keren Amit
Phase transition in the cuprates from a magnetic-field-free stiffness meter viewpoint. Nature Communications volume 10, Article number: 2463 (2019)

Finite Size Effect







a-ring
m/m_max
Temperature (k)
(mm) La
1.00
0.66
0.46
0.33
0.20
0.15
T̃c⊥
Lc
La
Lb
c-ring
(mm) Lc La
0.67 1.055
0.45 1.055
0.19 1.055
0.19 0.470
0.19 0.230
Tc∥

Theory

Correlated disorder (e.g. planes with various T_c's) is estimated from the upper tail of the transition. The tail is narrower than ΔT_c.

- We map the problem to an anisotropic classical XY model on a finite crystal.
- The apparent ΔT_c is estimated from a 1D Josephson junction array with vanishing coupling towards T_c.
- We evaluate the array's stiffness $\rho_\perp$.

Effective Model

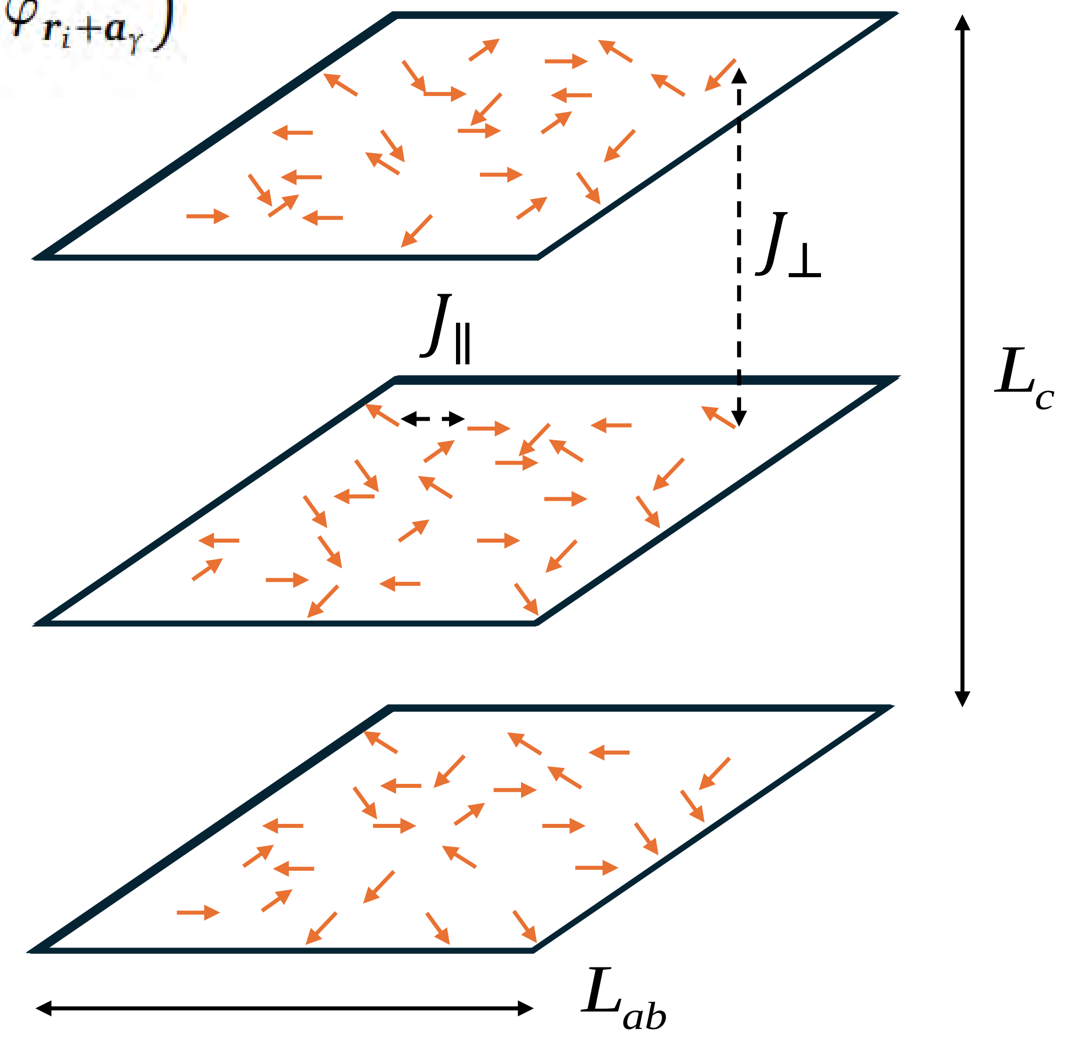
$\alpha = J_{\perp}/J_{\parallel}$

$$H_{3dXY} = -\sum_{i}\sum_{\gamma} J_{\gamma} \cos\left(\varphi_{\boldsymbol{r}_i} - \varphi_{\boldsymbol{r}_i + \boldsymbol{a}_{\gamma}}\right)$$

$$\rho_{3dXY} \xrightarrow[\alpha \to 0]{T \to T_c} \rho_{1dXY} \xrightarrow{L \gg a} \rho_{LL}$$

High Temperature

$$H_{3dXY} = -\sum_i \sum_\gamma J_\gamma \cos\left(\varphi_{\mathbf{r}_i} - \varphi_{\mathbf{r}_i + \mathbf{a}_\gamma}\right)$$

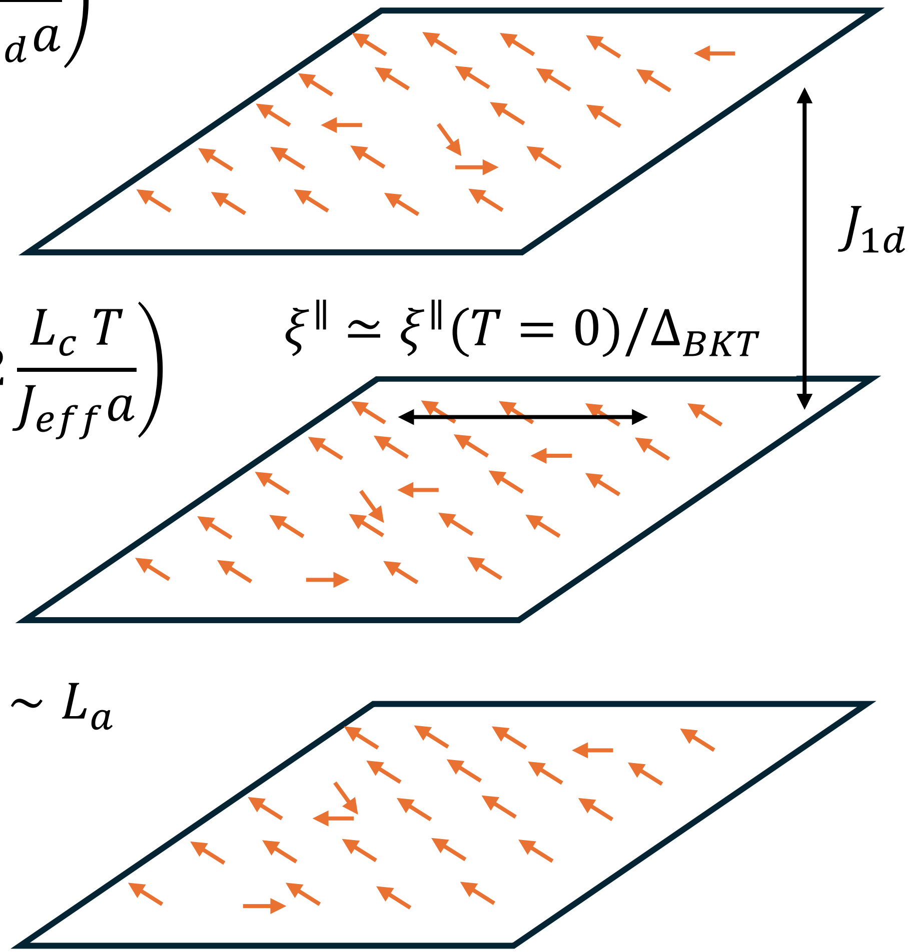


Temperature Just Below T_c

$$t \equiv \left(\frac{T_c - T}{T_c - T_{BKT}}\right)$$

$$\rho^{\perp}_{LL}[T] \simeq J_{1d}\, a 20 \exp\left(-0.472\,\frac{L_c\, T}{J_{1d} a}\right)$$

$$\rho^{\perp}_{eff}[T] \simeq 20\; a\, J_{eff} \exp\left(-0.472\,\frac{L_c\, T}{J_{eff} a}\right)$$



$$\xi^{\parallel} \simeq \xi^{\parallel}(T=0)/\Delta_{BKT}$$

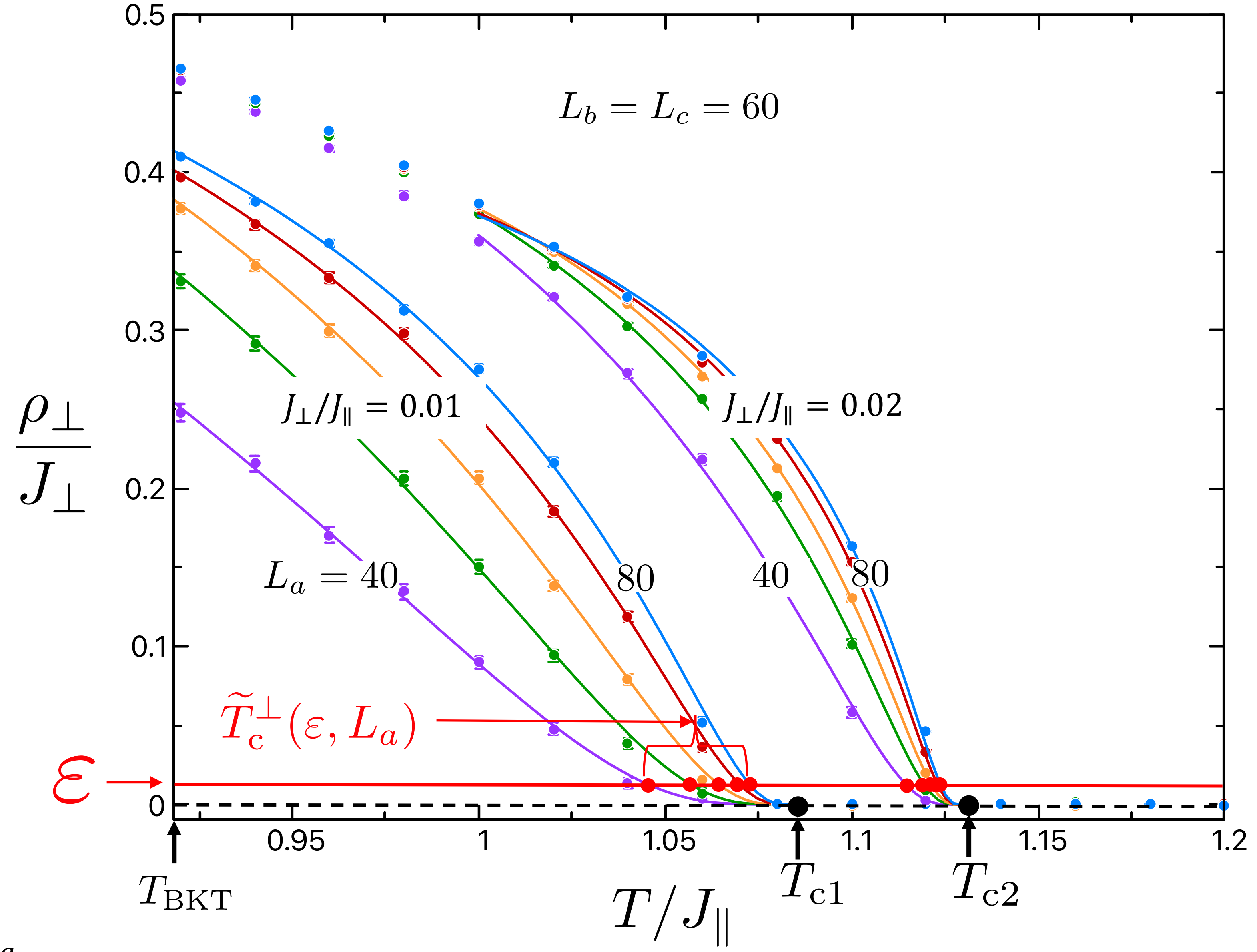
$$J_{1d}[T] \;\; \rightarrow J_{eff}[T] = \frac{L_a L_b}{(\xi^{\parallel})^2} J^{\perp} \Delta^2[T]$$

$T \sim T_c, \Delta^2[T] \sim \Delta^2_{BKT} t^{-2\beta}$ and $L_c \sim L_a$

$$\rho_{\perp} \sim J^{\perp}\; \exp\left(-\frac{A\, J_{\parallel}/J_{\perp}}{(1 - T/T_c) L_a}\right)$$

There is a threshold for the detection; it is a game of big versus small numbers and $\frac{\Delta T_c}{T_c} \simeq A \frac{\alpha^{-1}}{L_a}$.

Simulations

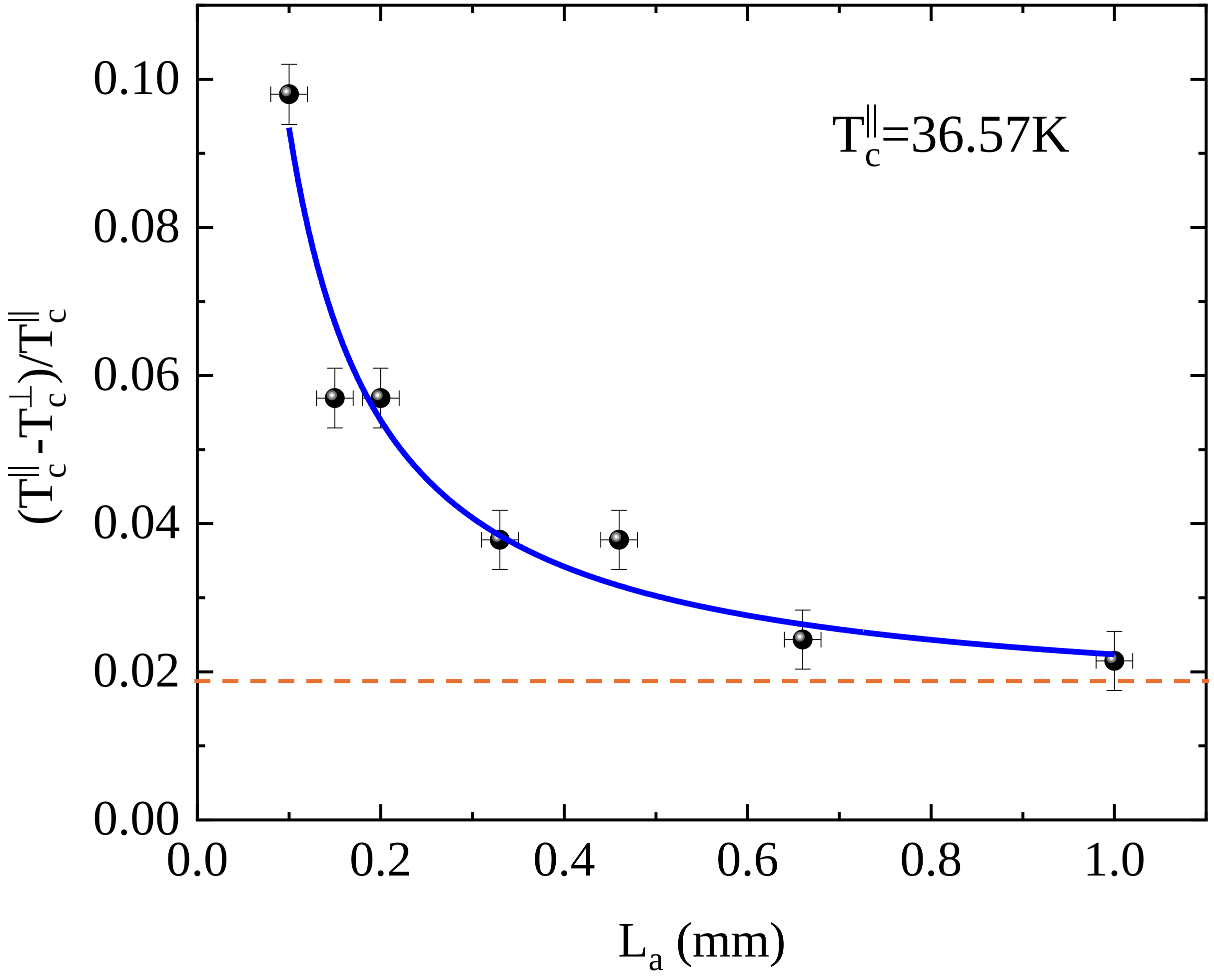


$J_\perp/J_\parallel \equiv$ anisotropy

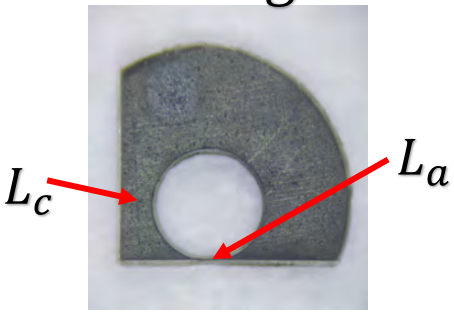
The lengths L_i are normalized by the in-plane lattice vector a

Theory vs Experiment

c-ring



a-ring



$$\frac{\Delta T_c}{T_c} \simeq A \frac{J_\parallel / J_\perp}{L_a}.$$

$$\frac{J_\perp}{J_\parallel}(T \to T_c) \sim 4 \times 10^{-5}$$

$$\frac{J_\perp}{J_\parallel}(T \to 0) \sim 4 \times 10^{-3}$$

c-axis superfluid response and pseudogap in high-Tc superconductors
C. Panagopoulos, J. R. Cooper, T. Xiang, Y. S. Wang, and C. W. Chu
Phys. Rev. B **61**, R3808(R) – Published 1 February 2000

The two T_c conundrum

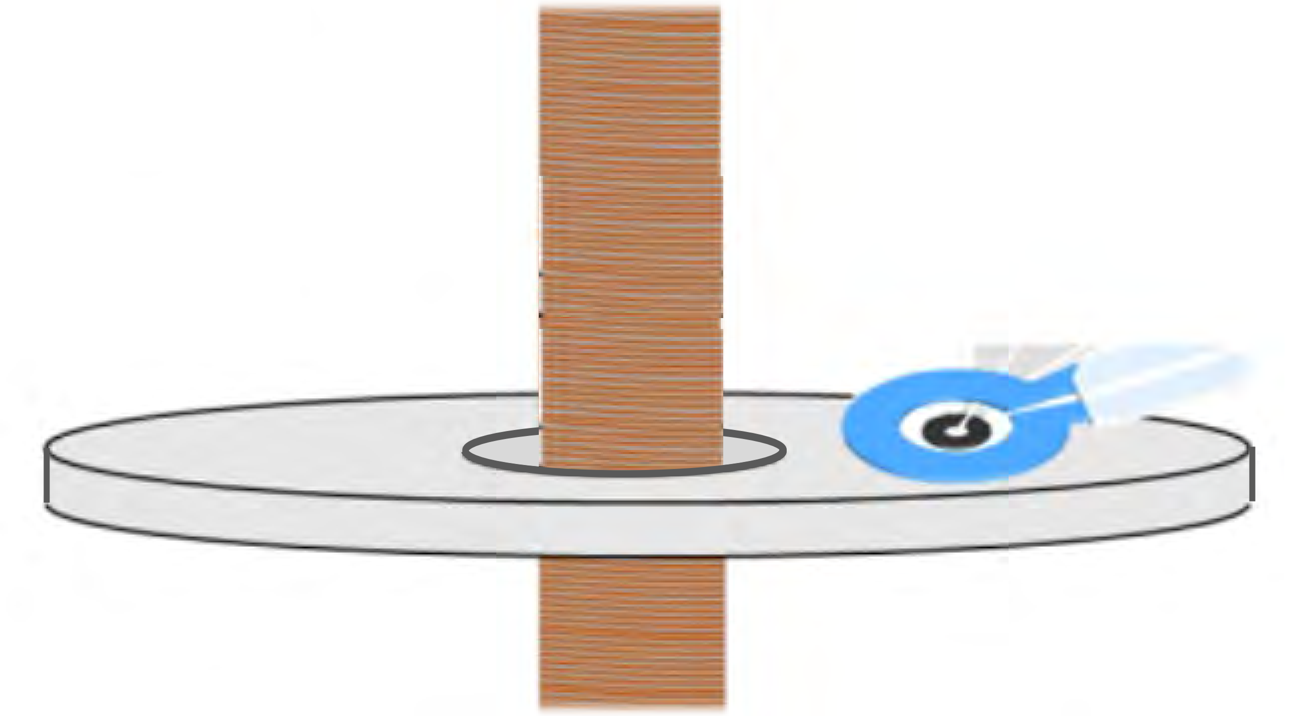
- The finite size effect is responsible for the apparent ΔT_c.
- The anisotropy is stronger close to T_c. $\frac{J_\perp}{J_\parallel}(T \to T_c) \sim 4 \times 10^{-5}$.

Mixed superconducting state without applied magnetic field

Alex Khanukov, Itay Mangel, Shai Wissberg, Amit Keren, and Beena Kalisky

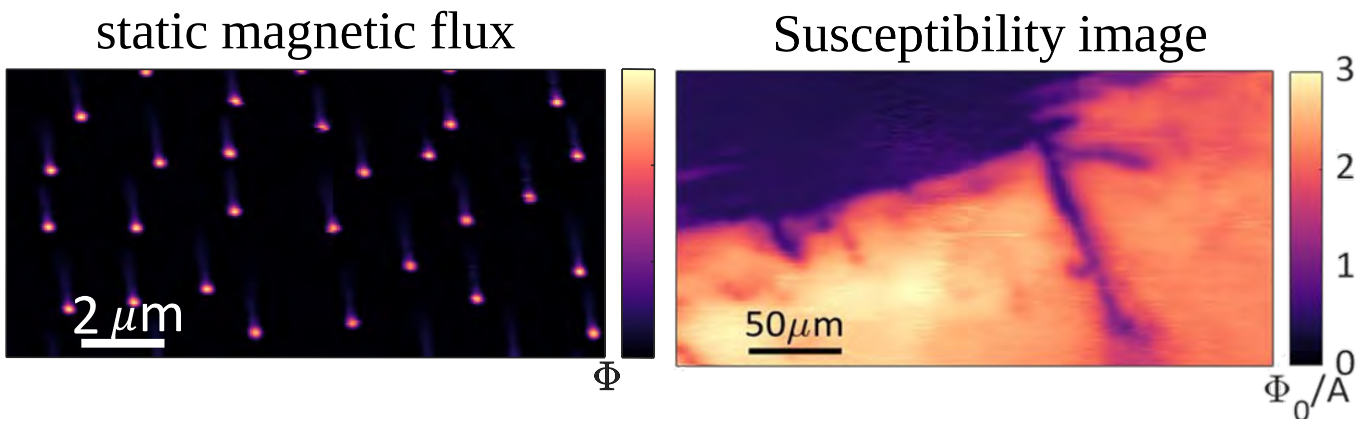
Coil:
60 mm long, 0.7 mm outer diameter, 6 layers, 7200 windings. windings, and is made of NbTi.

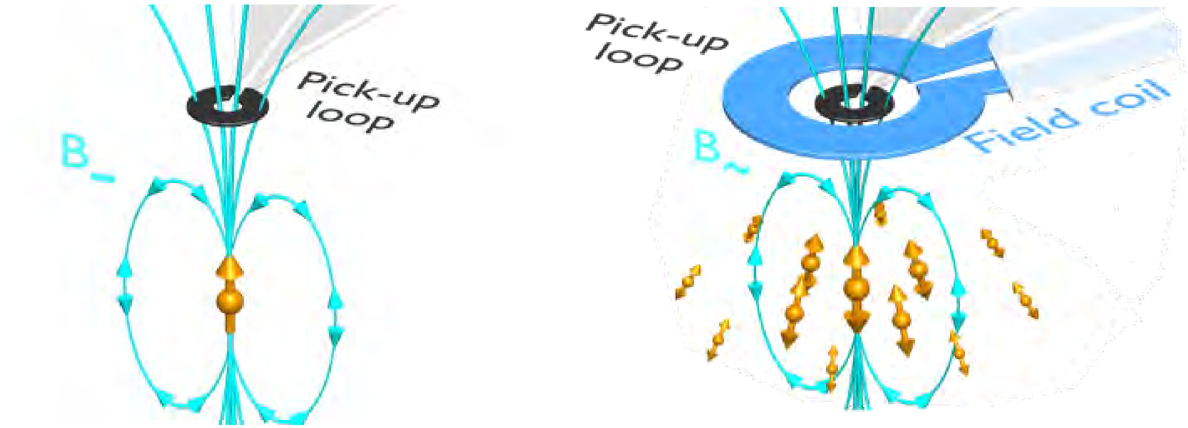
Rings:
8 nm of MoSi on Si substrate



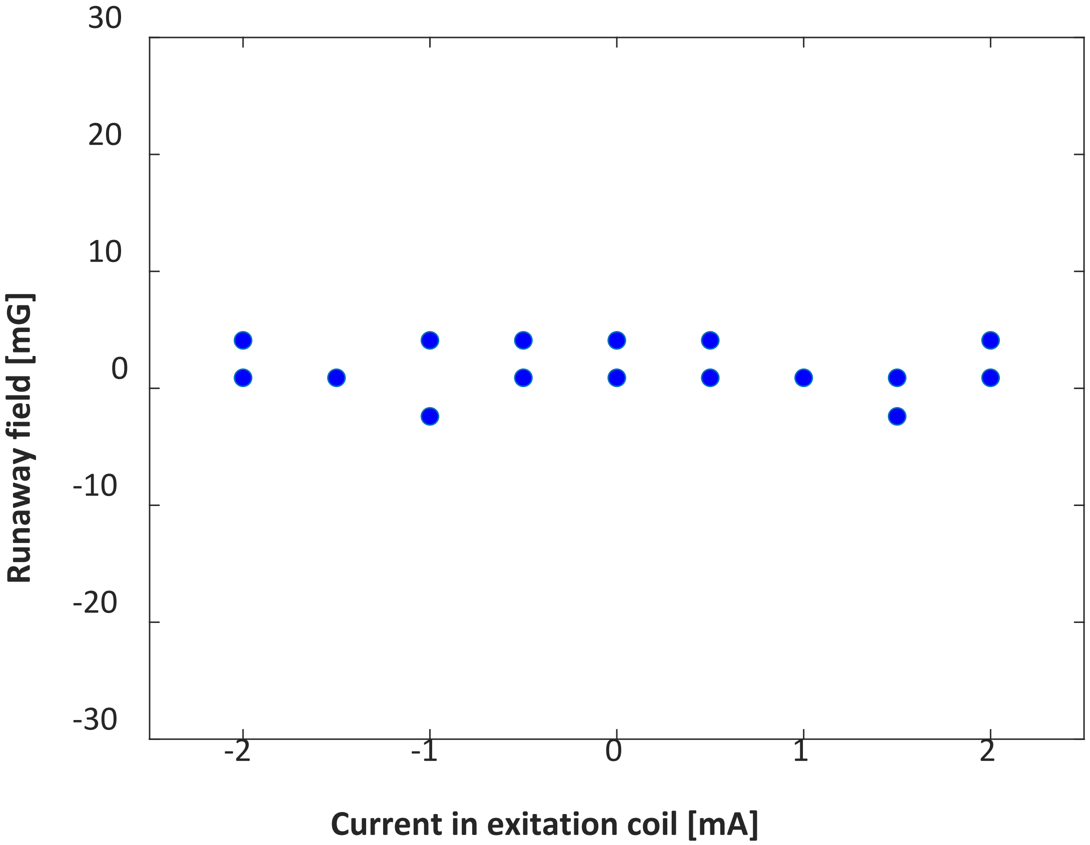
PHYSICAL REVIEW B 106, 144510 (2022)- doi: 10.1103/PhysRevB.106.144510

Vortices and susceptibility maps

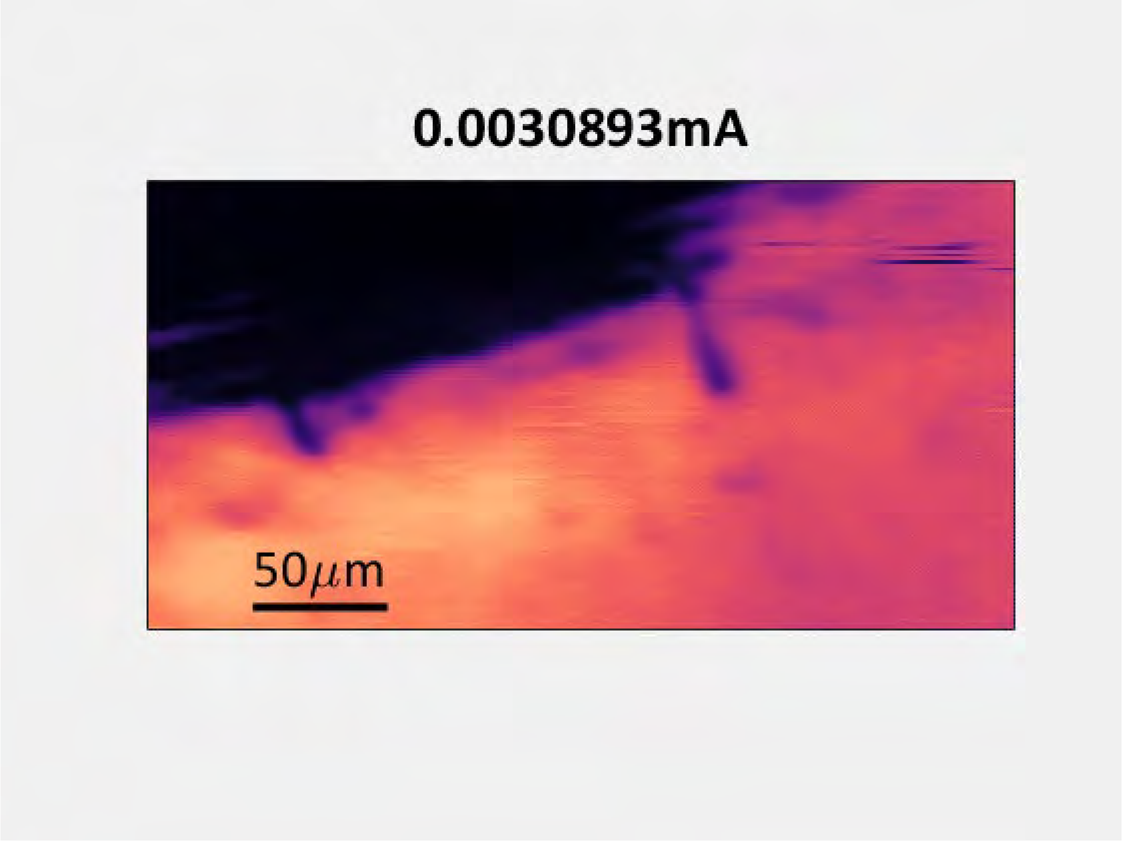




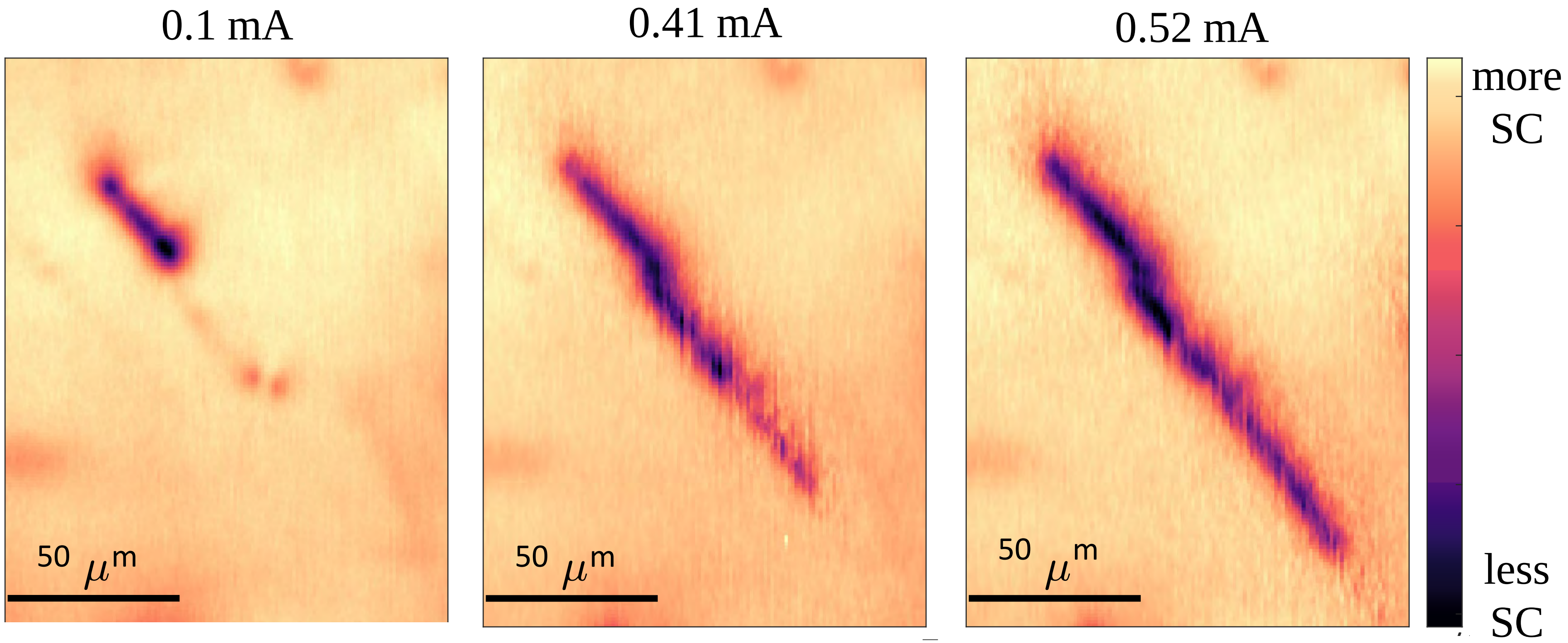
Magnetic field leakage



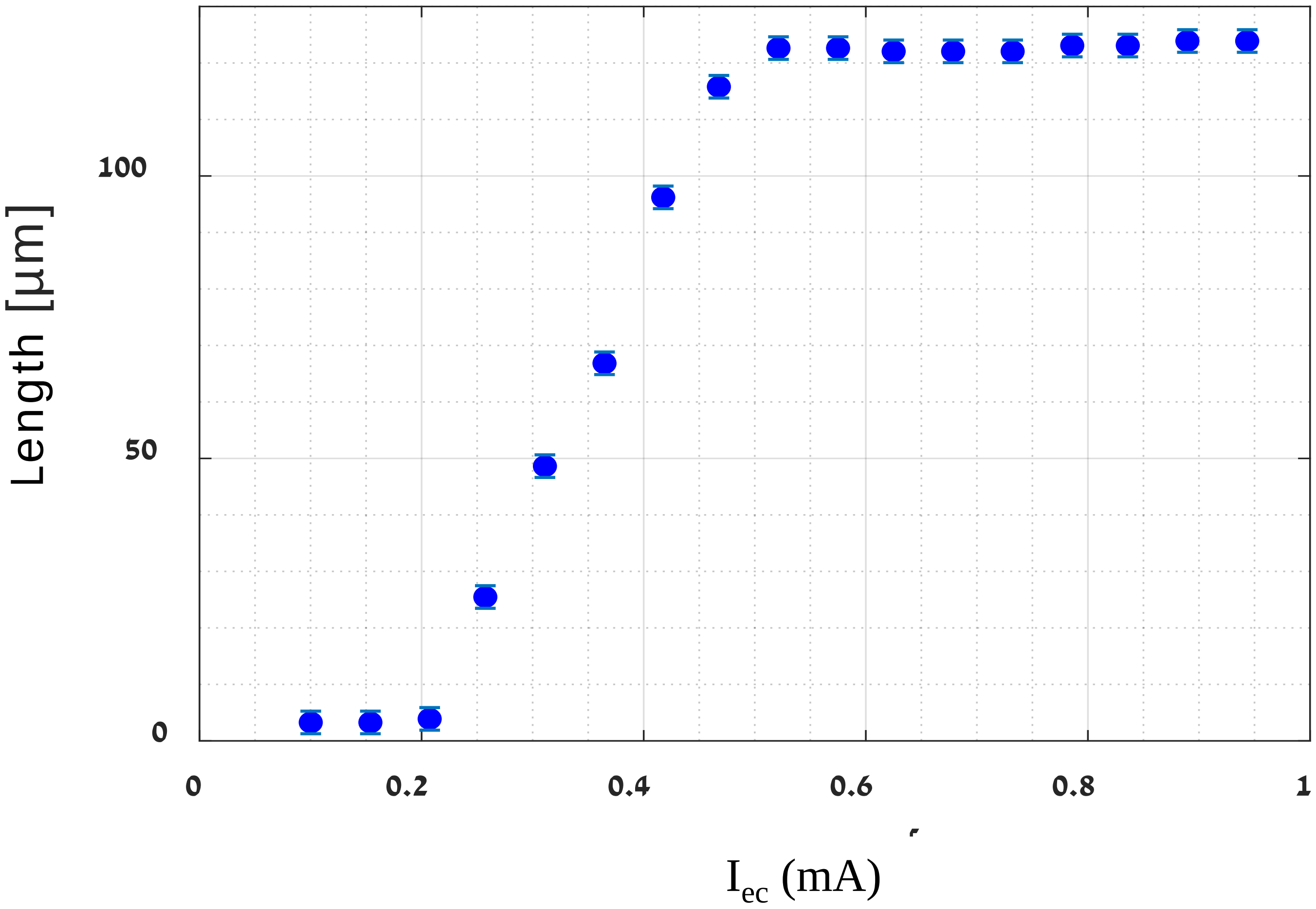
Streak growth from the inner rim



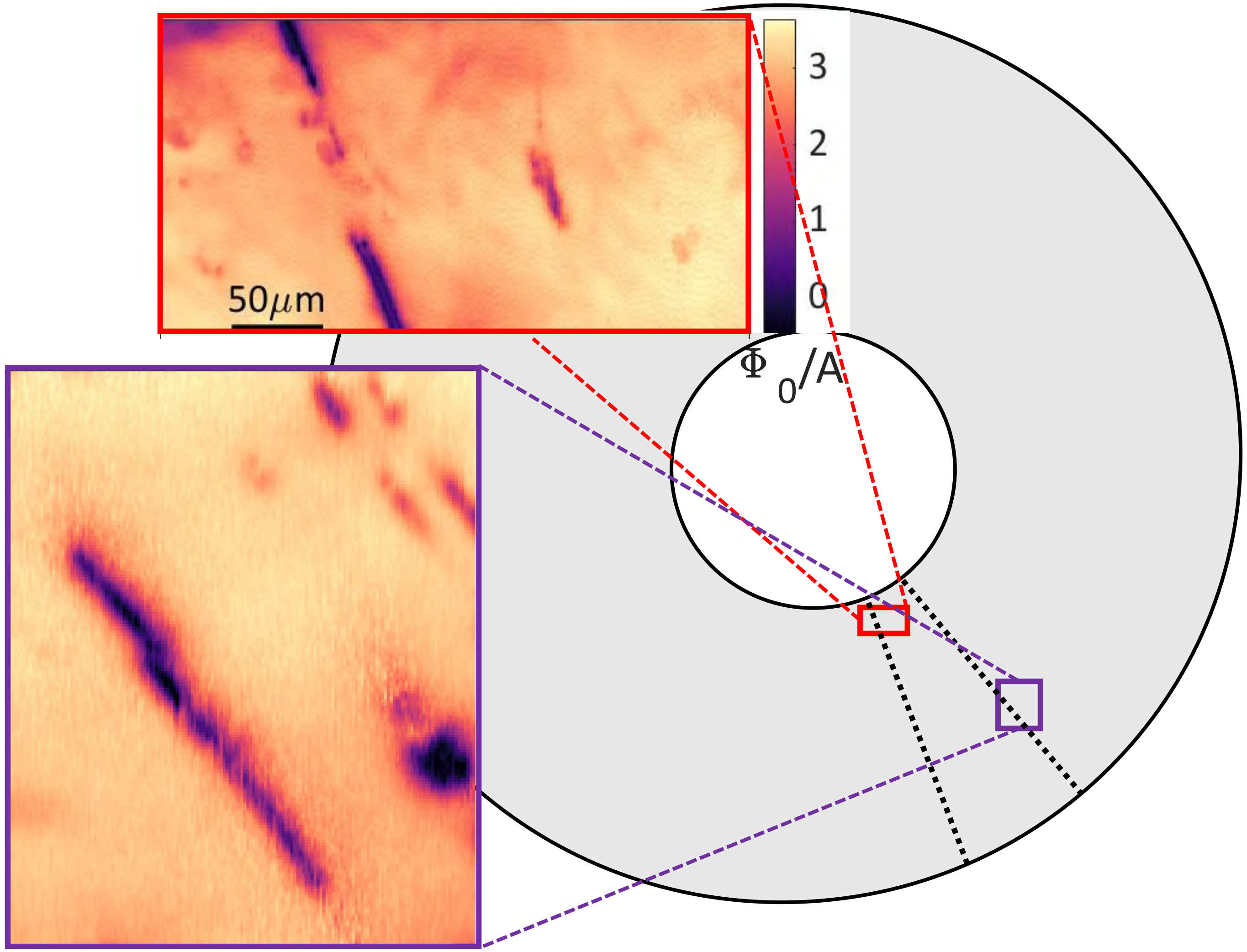
Growth of a streak from a mid-ring nucleation point



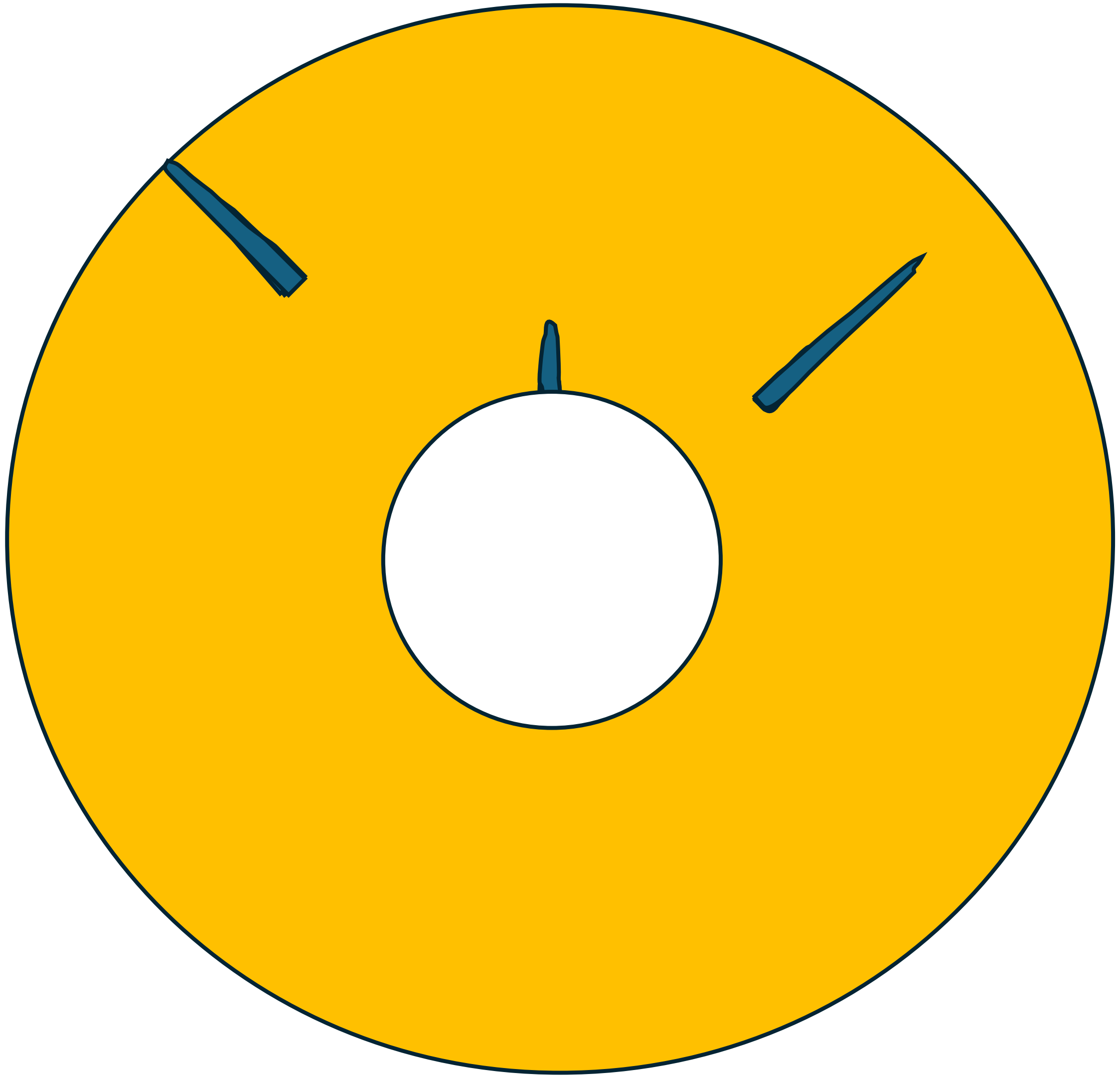
The maximum length



Radial growth of the streaks

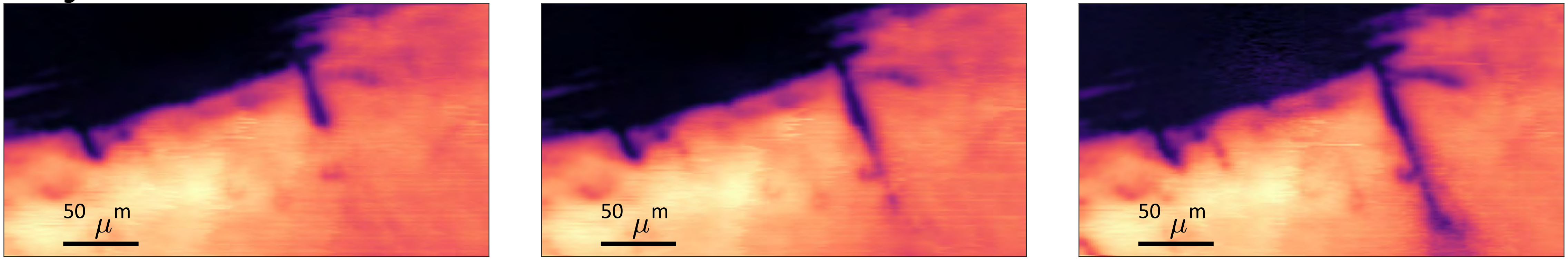


The emerging picture

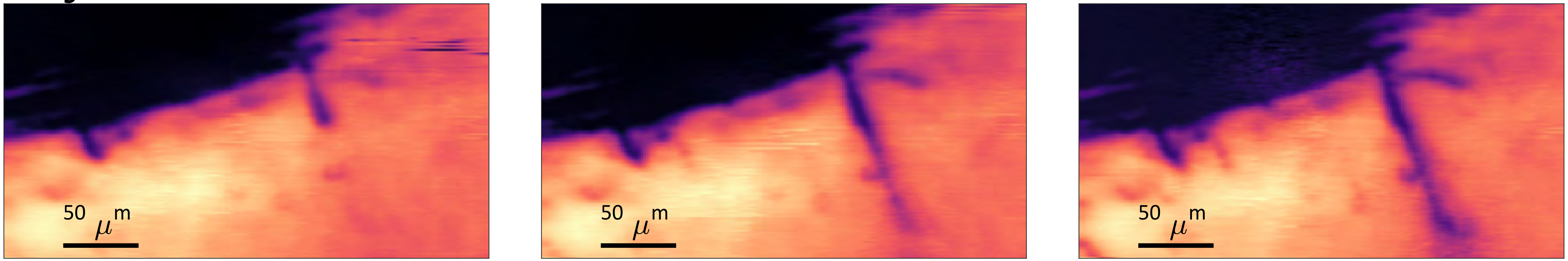


Reversibility and reproducibility

Cycle 1



Cycle 2



Scanning experiment summary

- $|\Psi|$ is destroyed in streaks instead of uniformly.
- But it is destroyed outward in a radial direction.
- The ring was only 8 nm thick of MoSi, compered to the 1 mm LSCO.

Thank You!