TECHNION
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of Technology

Critical Behavior of $La_{2-x}Sr_xCuO_4$ Superconducting Stiffness Anisotropy as a Function of Doping and Measuring Coherence Length ξ in Zero Magnetic Induction B.

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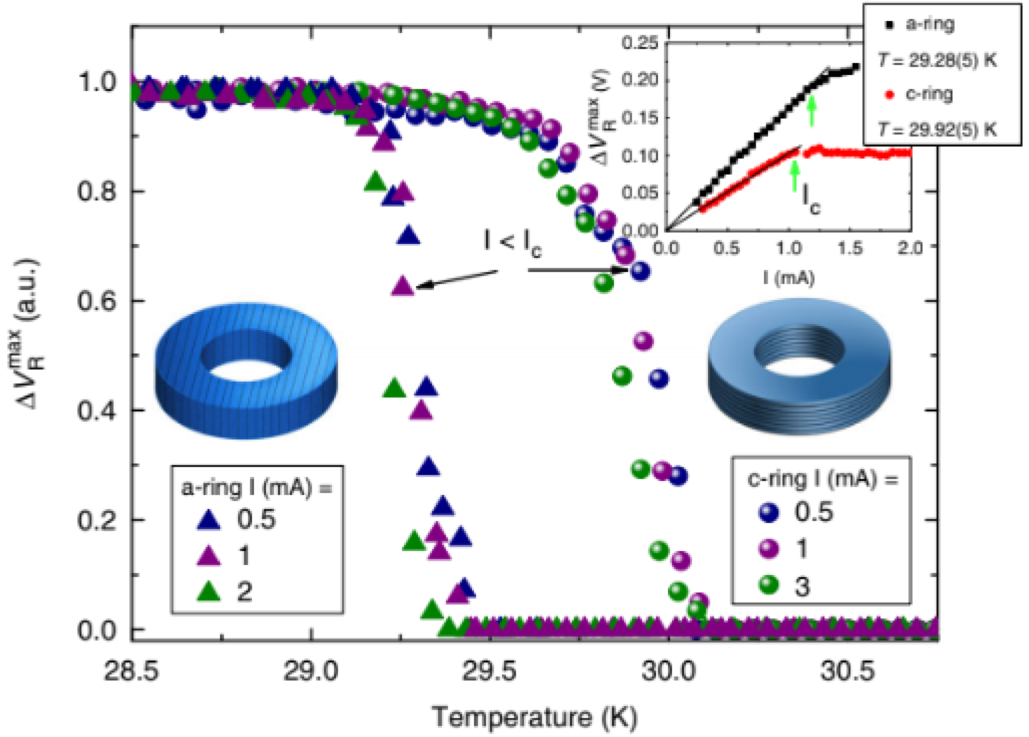
Motivation

The anisotropy of superconductivity in Cuprates and the difference between parameters in/out of CuO_2 plane is a well-known phenomena.

Kapon *et al.* showed a 0.7 (K) difference in T_c of 1/8 doping in LSCO.



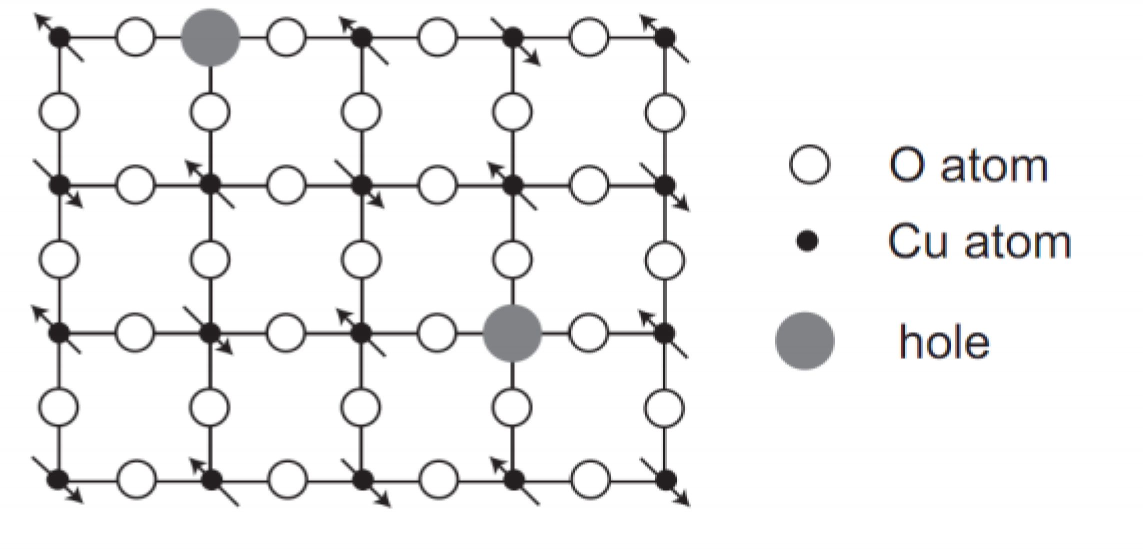
We wanted to check the doping dependence of this T_c difference.

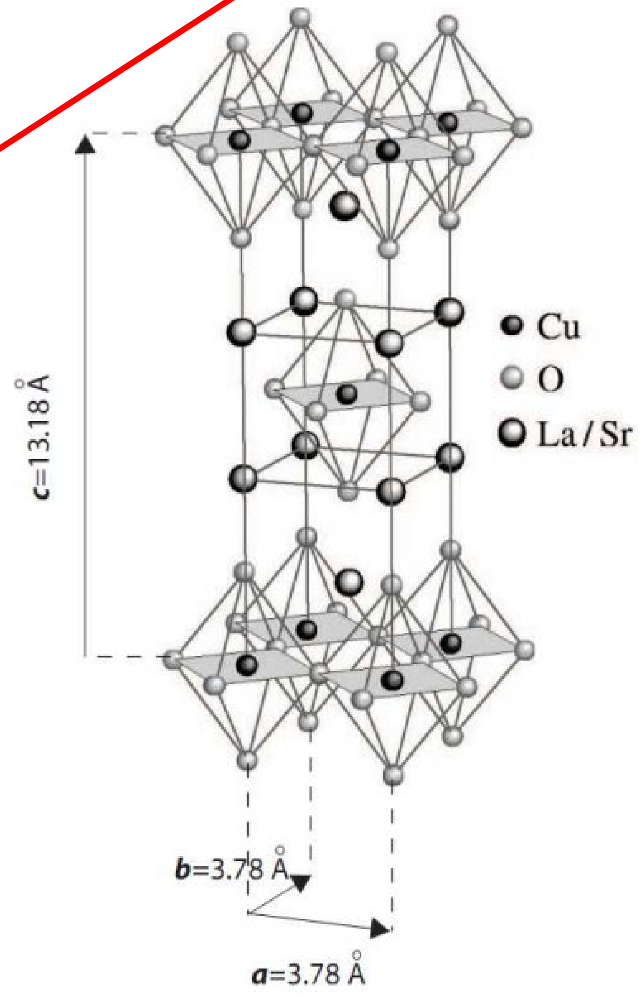
Kapon Itzik, Salman Zaher, Mangel Itay, Prokscha Thomas, Gavish Nir, Keren Amit
Phase transition in the cuprates from a magnetic-field-free stiffness meter viewpoint. Nature Communications volume 10, Article number: 2463 (2019)

The Cuprate Family

$La_{2-x}Sr_xCuO_4$

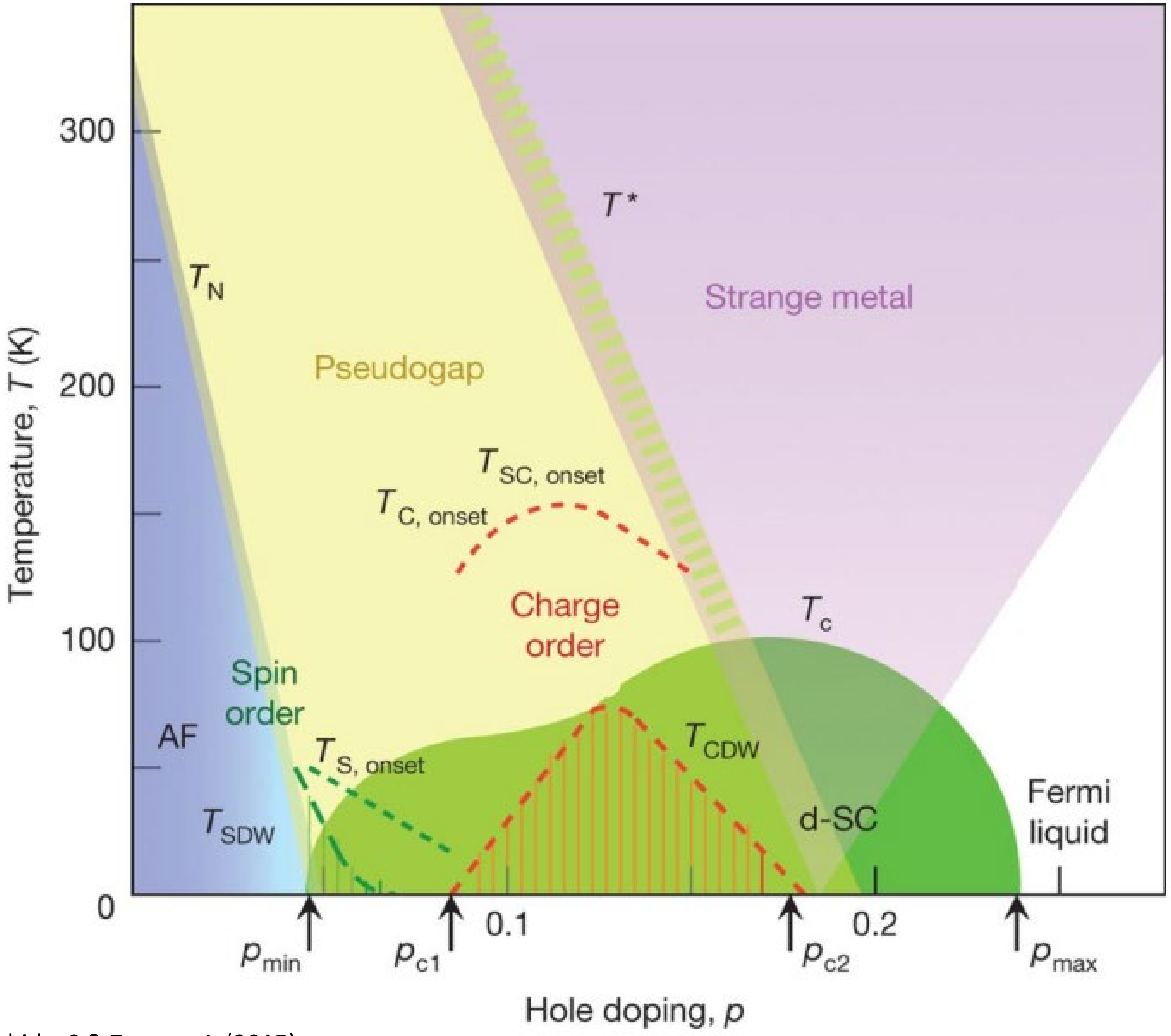
- High temperature superconductors – “HTSC”.
- Nearly tetragonal unit cell with layers of CuO_2 planes.
- Doping by changing the rear-earth metal atoms concentration – “x”.





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

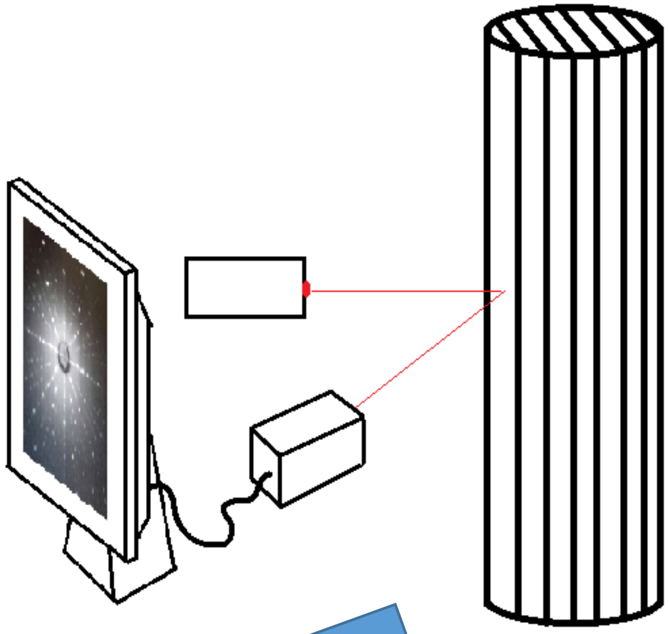
Phase Diagram of Cuprates

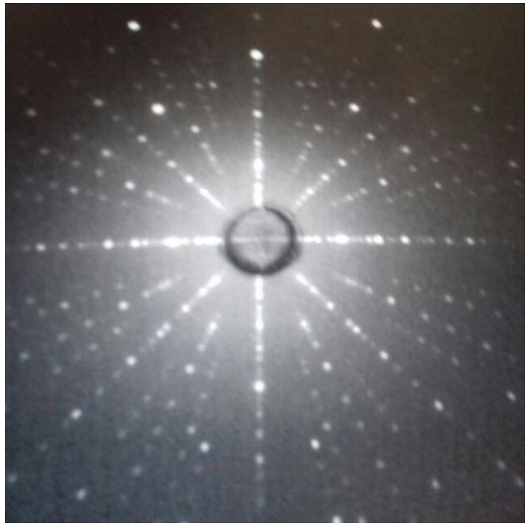


Keimer, B & A Kivelson, S & R Norman, M & Uchida, S & Zaanen, J. (2015).
From quantum matter to high-temperature superconductivity in copper oxides. Nature. 518. 179-86. 10.1038/nature14165.

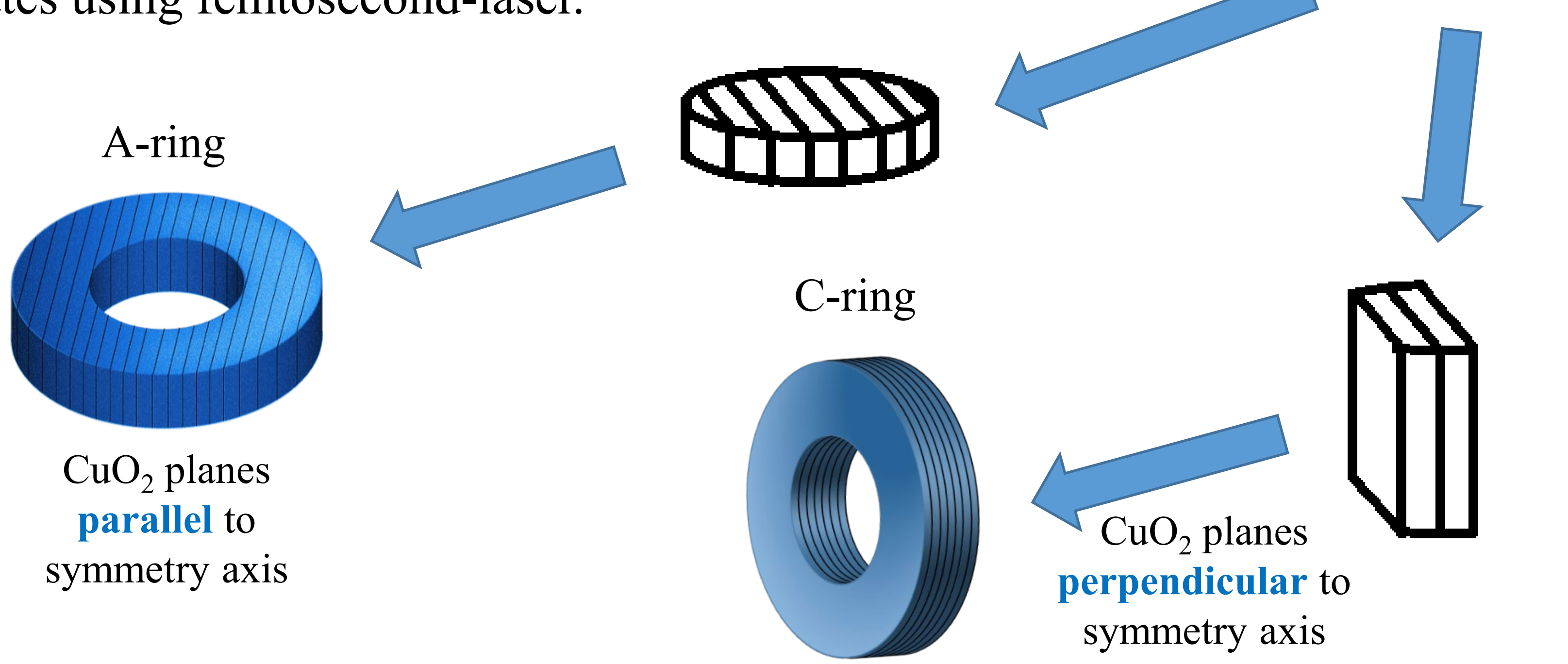
Rings making

- 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



The London Equation

The superconducting stiffness is defined by: $\mathbf{J}_s = \rho_s(\frac{\hbar c}{e^*}\nabla\varphi - \mathbf{A})$

Where φ is the phase of the complex order parameter $\psi = |\psi| e^{i\varphi(x)}$.

When $\nabla\varphi = 0$ we get the London Equation:

$$\mathbf{J}_s = -\rho_s \mathbf{A}$$

The Meissner Effect

London $\mathbf{J}_s = -\rho_s \mathbf{A}$

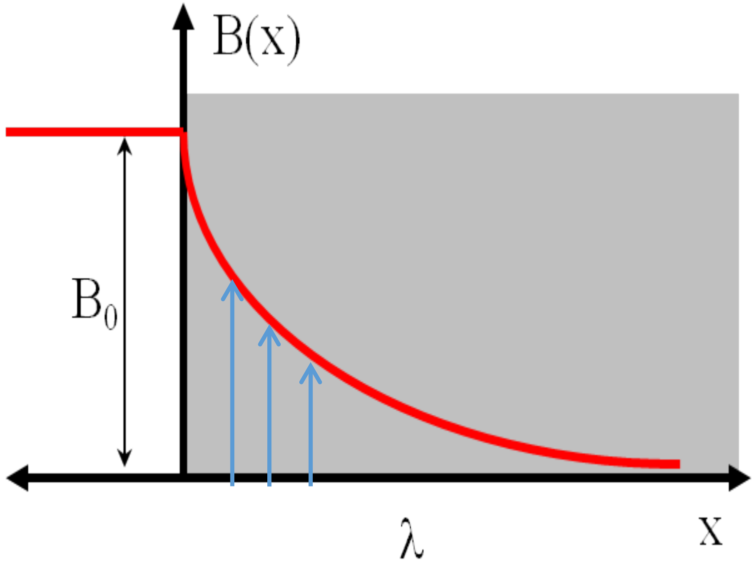
Maxwell $\nabla \times \nabla \times \mathbf{B} = \mu_0 \nabla \times \mathbf{J}$

Solution $B(x) = B_0 \exp(-x/\lambda)$

$\rho_s = 1/(\mu_o \lambda^2)$

ρ_s is the **stiffness**.

λ is the **penetration depth**.



One usually measures λ by applying a magnetic field. We want to measure ρ_s directly.

Principal of Operation

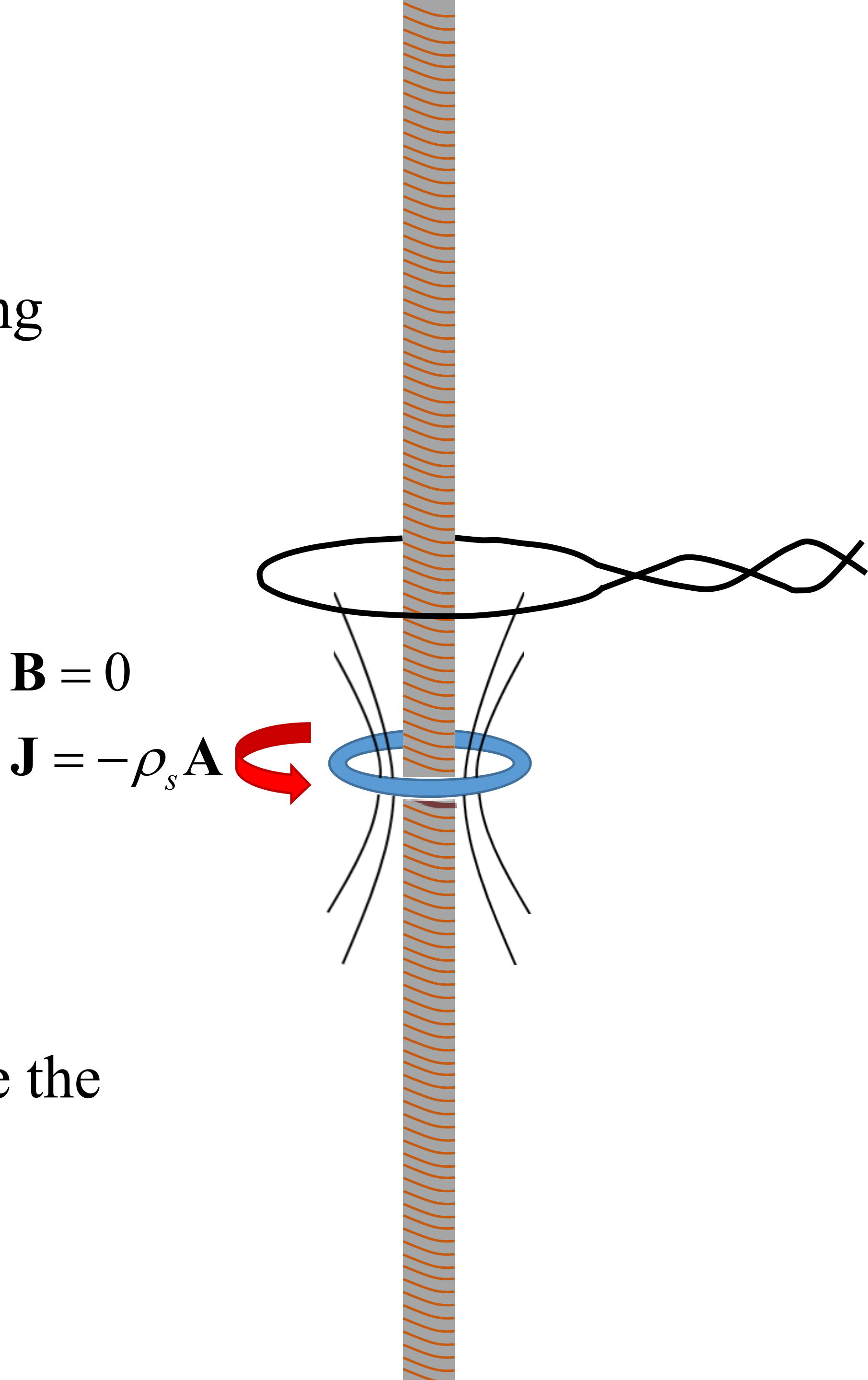
- Use infinitely long coil in the center of a superconducting ring to generate **A** with **B=0**.

- **A** creates **J**.

- **J** creates magnetic moment ***m***.

- We measure ***m*** by moving the ring inside a pickup loop.

- We drive ***A*** until linearity between ***A*** and ***J*** breaks, or change the temperature wile the currant in the coil is fixed.

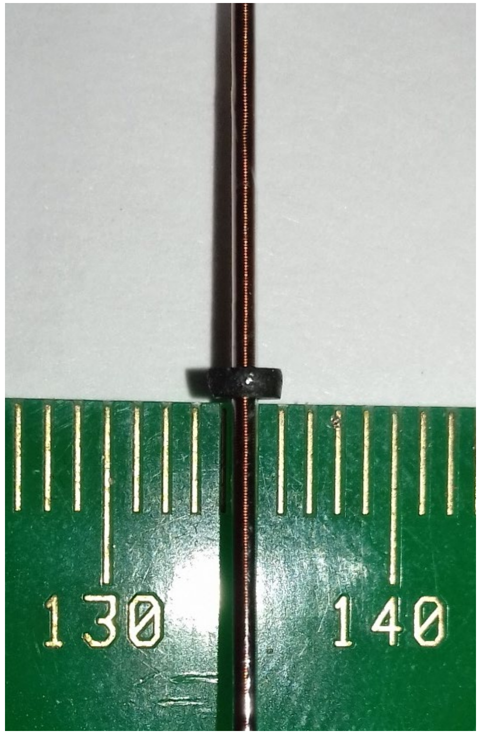


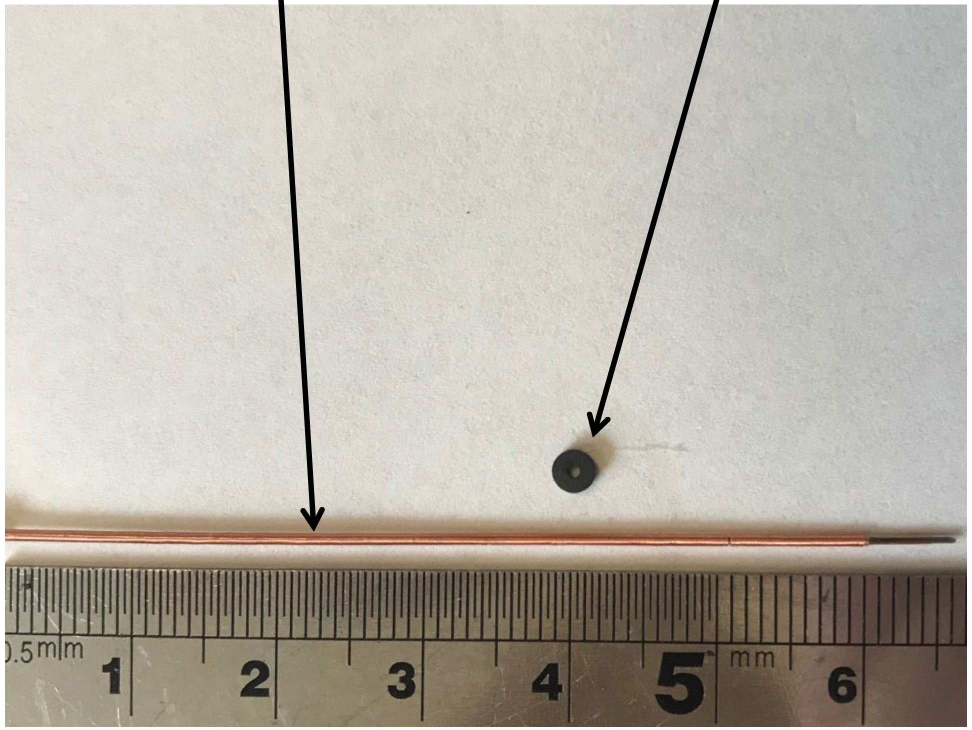
Experimental Setup

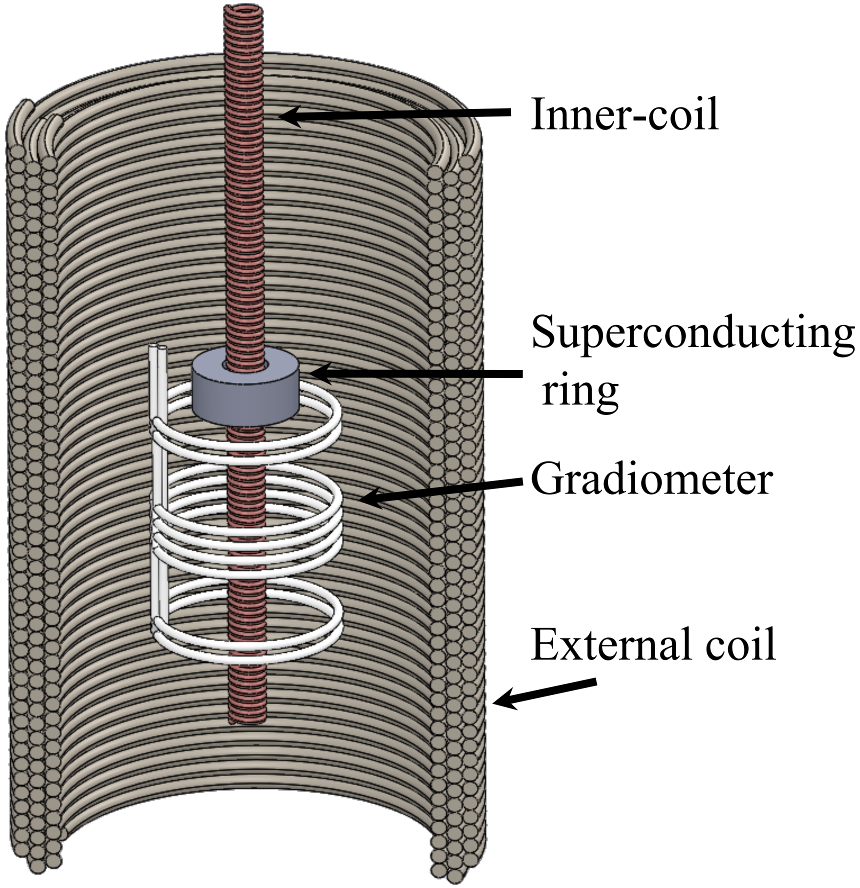
60mm **superconducting**-coil
4 layers, 2400 turns,
102 μm wire,
0.96mm outer diameter.
Made out of TiNb

60mm **coper**-coil
2 layers, 1214 turns,
50 μm wire,
0.82mm outer diameter.

LSCO Ring
1mm inner hole diameter
3mm outer diameter
1mm height.







Superconducting Quantum Interference Device "SQUID"

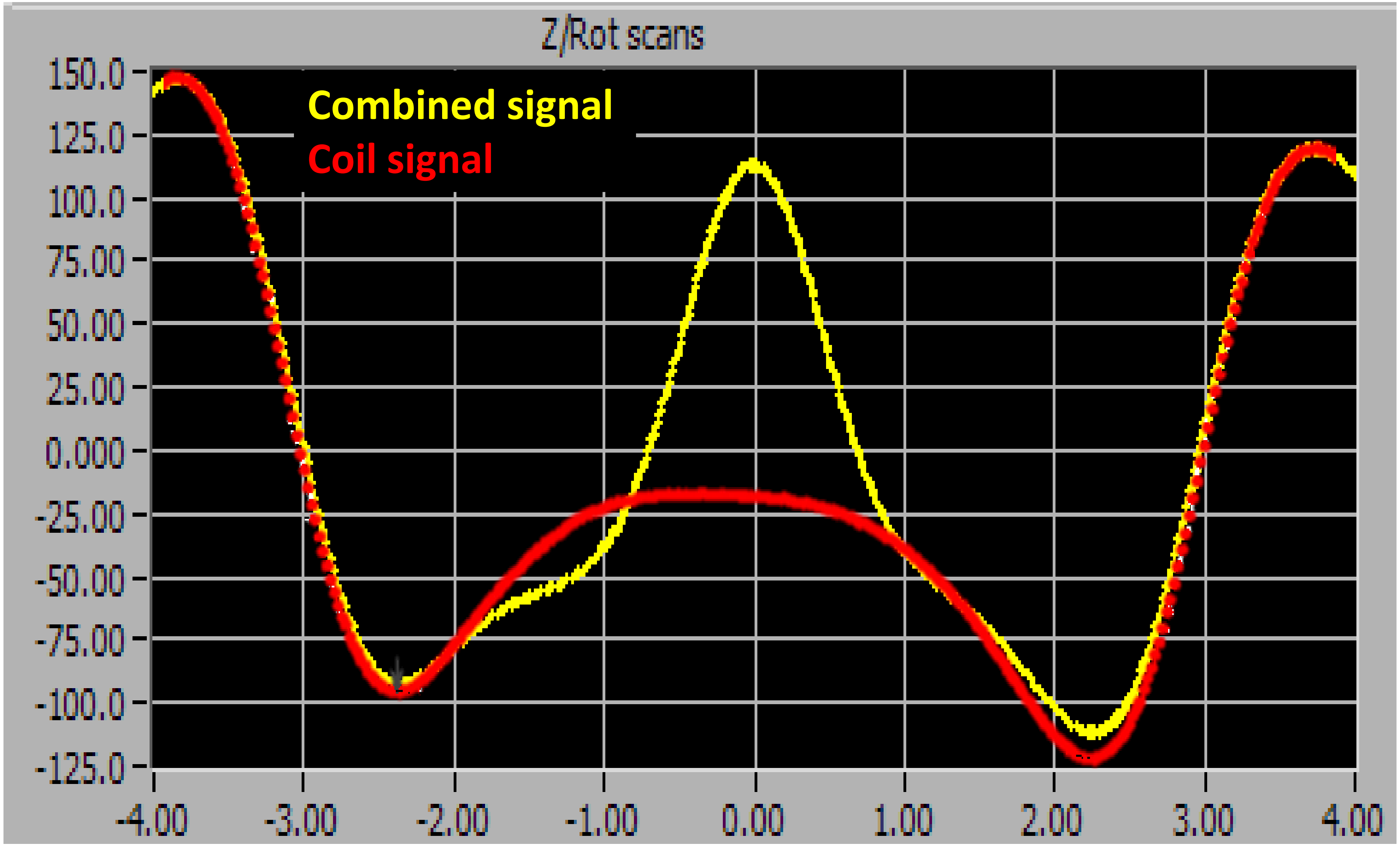
The magnetic flux through pickup loop is connected to the SQUID with a Flux Transformer and the measured voltage is:

$$V_{SQUID} = K \cdot \Phi^{pl}$$

This magnetic flux is proportional to the samples vector potential via:

$$\Phi^{pl} = \iint_{pl} B \cdot da = \oint_{pl} A \cdot dl = 2\pi r_{pl} A(r_{pl})$$

The Signal



Z/Rot scans
Combined signal
Coil signal
150.0
125.0
100.0
75.00
50.00
25.00
0.000
-25.00
-50.00
-75.00
-100.0
-125.0
-4.00
-3.00
-2.00
-1.00
0.00
1.00
2.00
3.00
4.00

Extracting the Stiffness

$$\mathbf{J} = -\rho_s \mathbf{A}$$

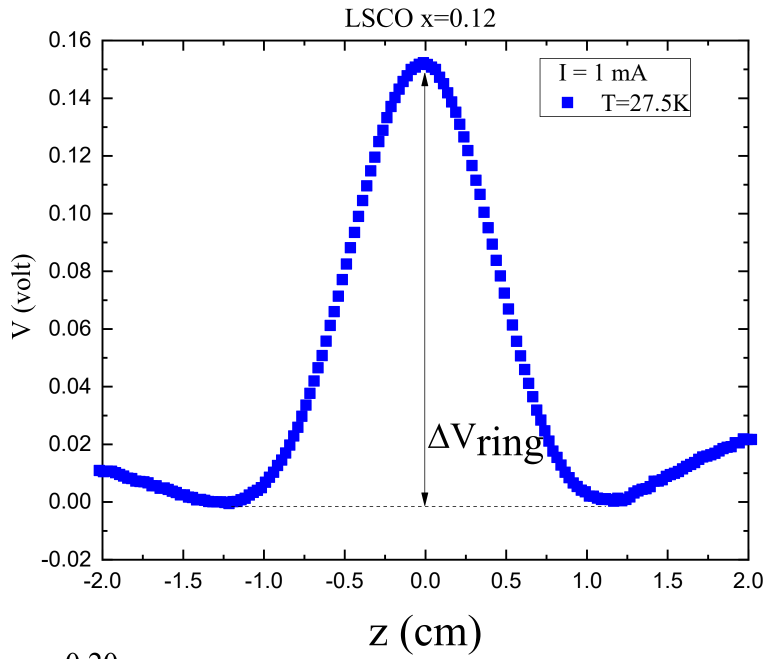
The important quantity is:

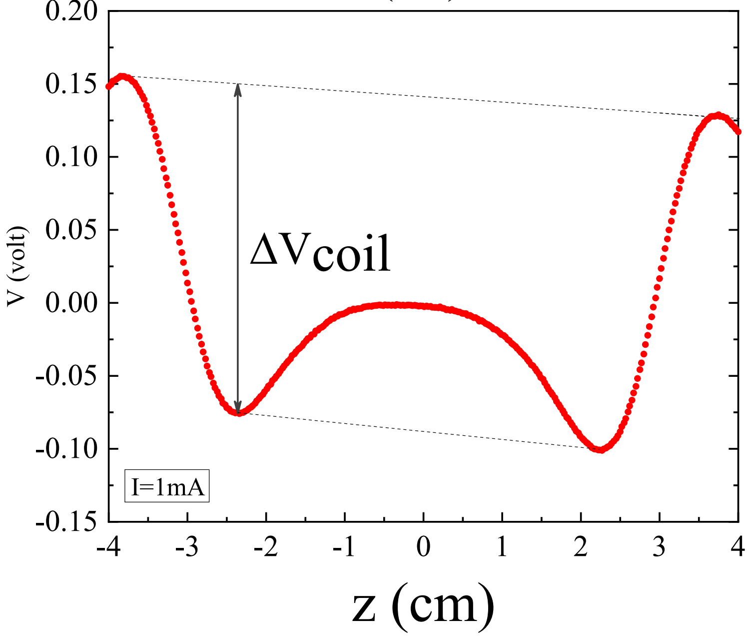
$$\frac{\Delta V_{ring}}{\Delta V_{coil}} = G \frac{A_{ring}(r_{pl})}{A_{coil}(r_{pl})}$$

r_{pl} is the radius of the pickup loop.

$G \sim 1$ is the Gradiometer geometrical factor.

So we need to calculate $A_{ring}(\lambda)$ and invert it.





Extracting the Stiffness

Maxwell: $\nabla\times\nabla\times\mathbf{A}_{ring}=-\mu_0\mathbf{J}(\mathbf{r})$ **London**: $\mathbf{J}(\mathbf{r})=-\rho_s\mathbf{A}_{tot}=-\dfrac{1}{\mu_o\lambda^2}\left(\mathbf{A}_{coil}+\mathbf{A}_{ring}\right)$

Combining the two equations, and switching to unit-less variables:

$$\mathbf{A}(r,z)=\frac{A_{ring}(r,z)}{A_{coil}(r_{PL})}\hat{\theta},\ r,z,\lambda\rightarrow r,z,\lambda/r_{PL}$$

we get the PDE:

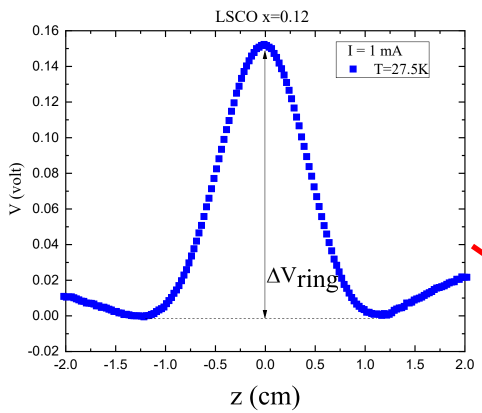
$$\boxed{\frac{\partial^2 A}{\partial z^2}+\frac{\partial^2 A}{\partial r^2}+\frac{1}{r}\frac{\partial A}{\partial r}-\frac{A}{r^2}=\frac{1}{\lambda^2}\left(A+\frac{1}{r}\right)}$$

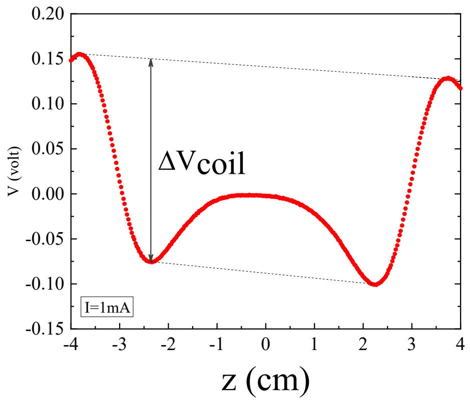
Boundary conditions:

$$A(r=0,z)=A(r\rightarrow\infty,z)=A(r,z\rightarrow\pm\infty)=0$$

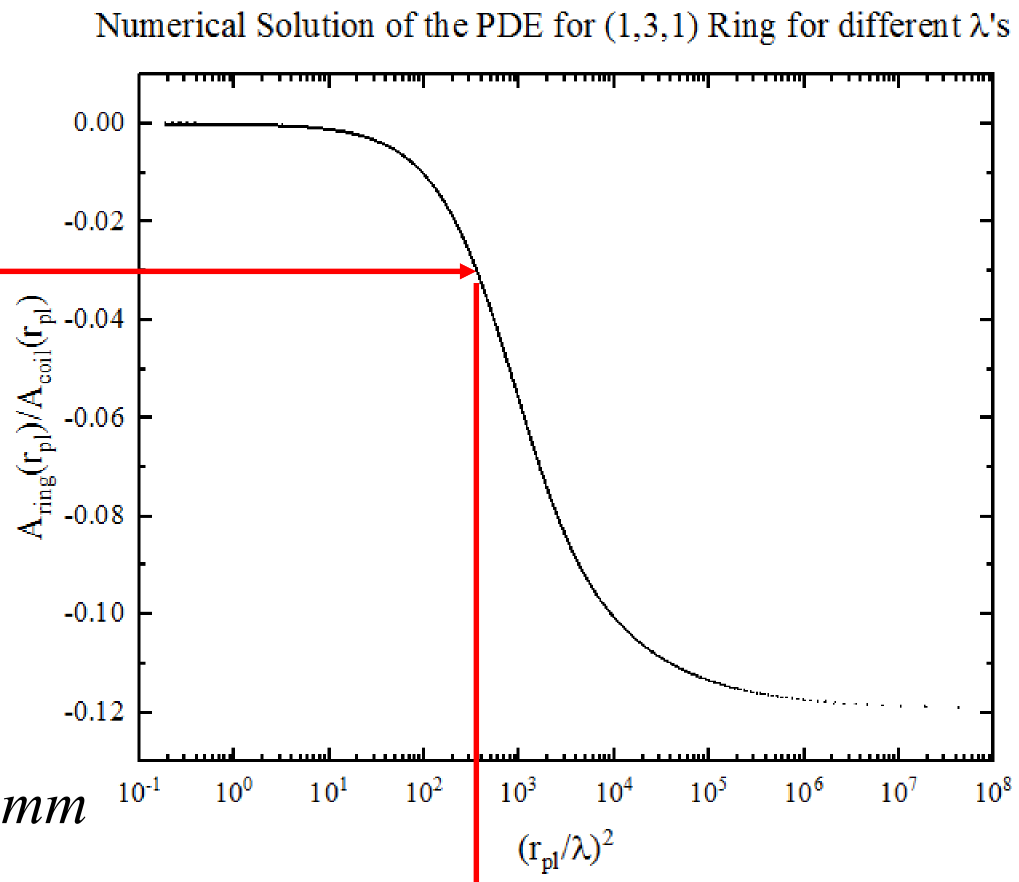
Outside the ring $\lambda\rightarrow\infty$.

Extracting the Stiffness





$$\frac{\Delta V_{ring}}{\Delta V_{coil}} = G\frac{A_{ring}(r_{pl})}{A_{coil}(r_{pl})}$$



λ

- Measurements are accurate for: $0.1 \le \lambda \le 3mm$
- G can be calibrated from the measurements and the simulation for low temperatures and short λ.

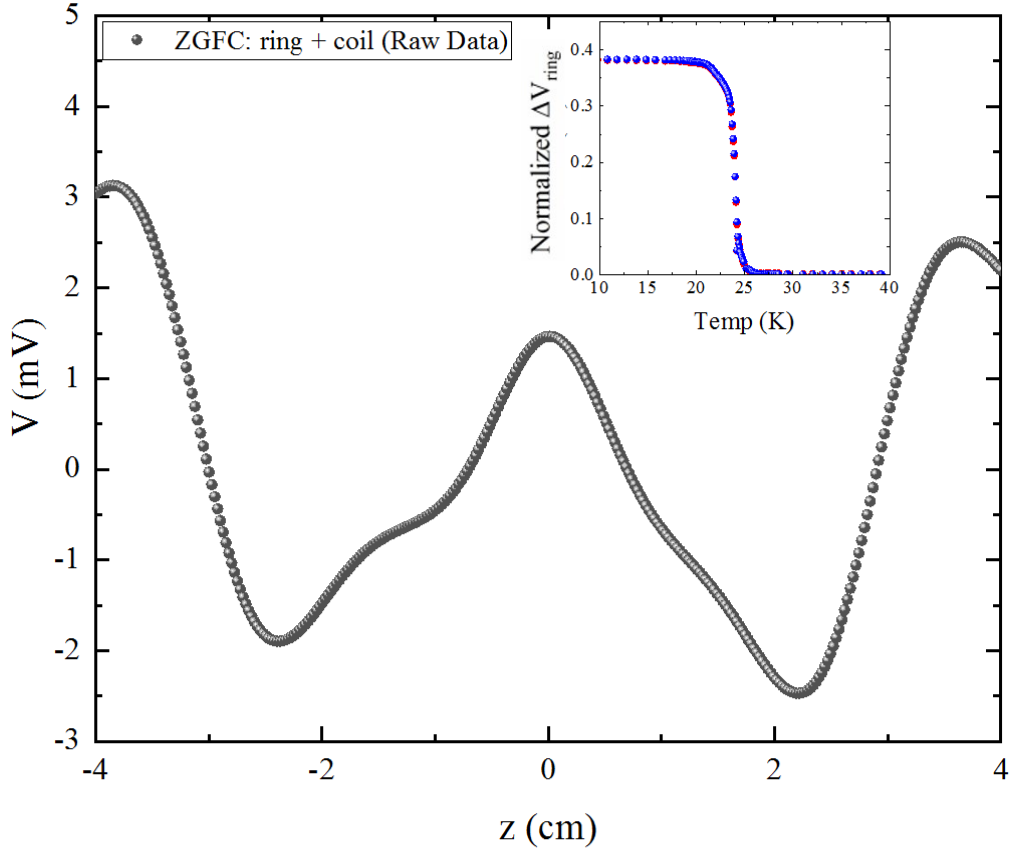
Cooling Protocols

Zero Gauge Field Cooling
Cooling below Tc, turning the current on.

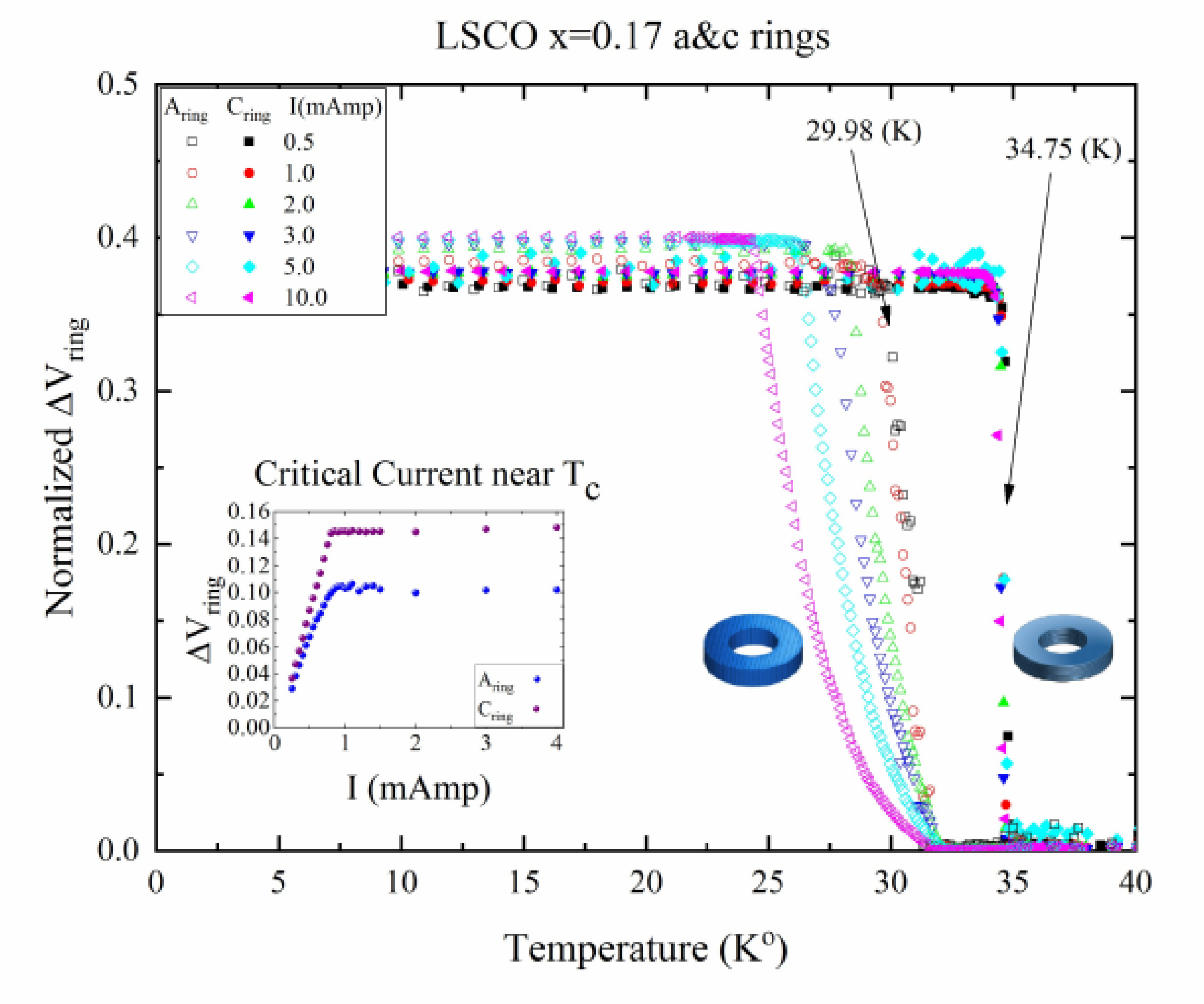
Gauge Field Cooling
Turning the current on, cooling below Tc,
turning the current off. (now $\nabla\phi \neq 0$)

$$\mathbf{J}_s = \rho_s\left(\frac{\hbar c}{e^*}\nabla\varphi - \mathbf{A}\right)$$

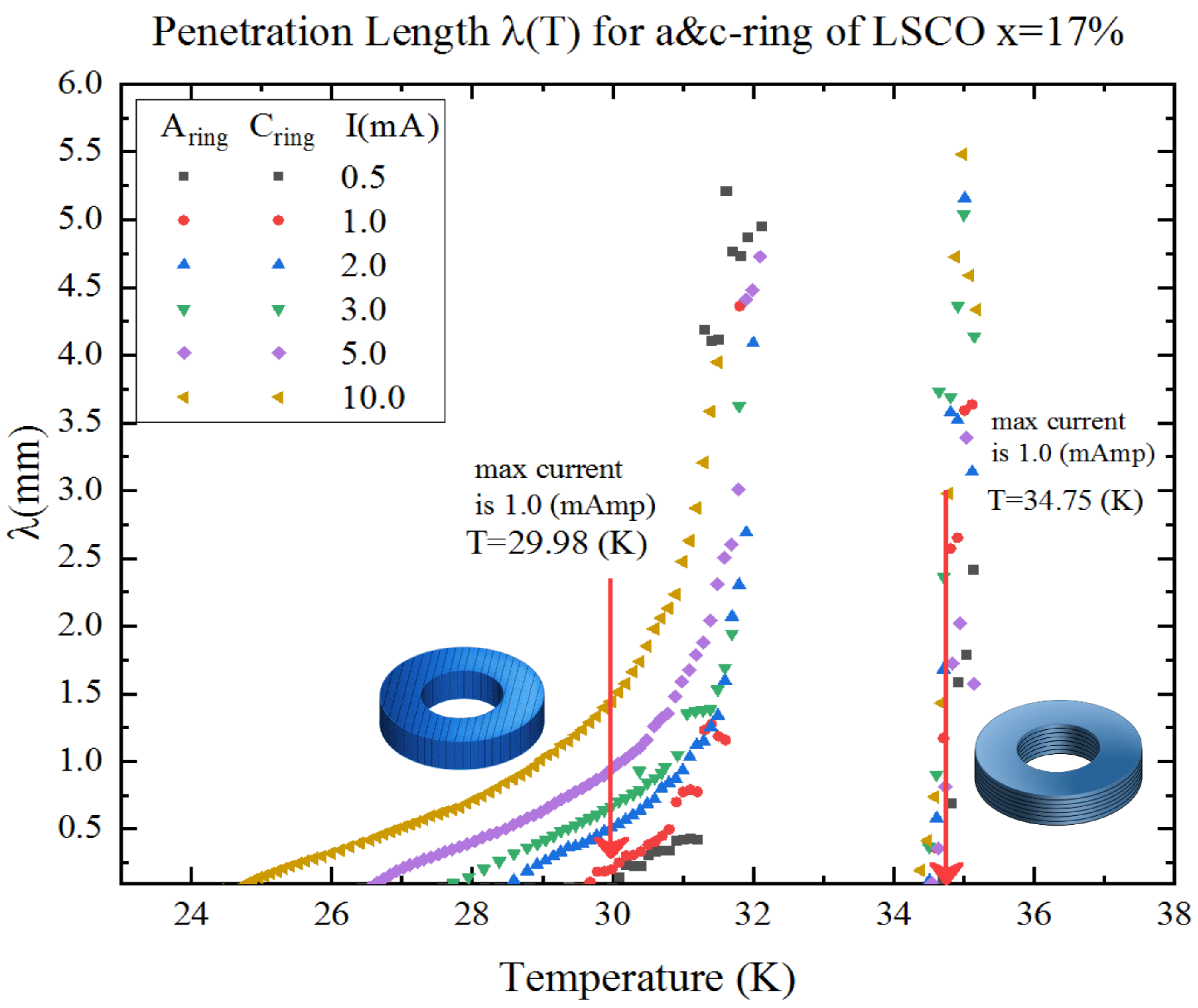
Comparing Gauge Field Cooling and Zero Gauge Field Cooling with LSCO x=22% a-ring
The current in the coil is 10.0 (mAmp)



Stiffness vs Temperature



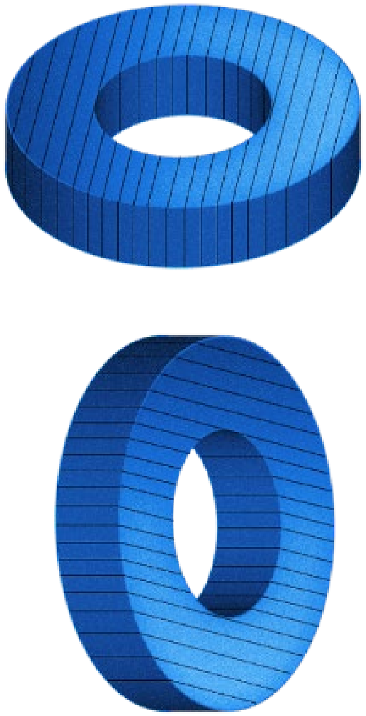
λ vs Temperature



Magnetic Moment Measurement

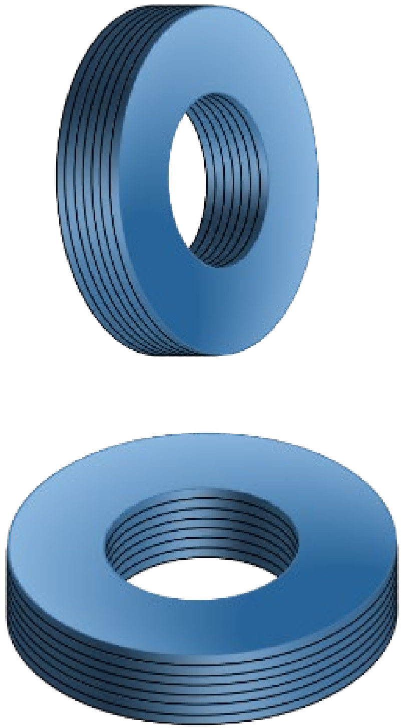
A-ring

CuO_2 planes
parallel to
symmetry axis

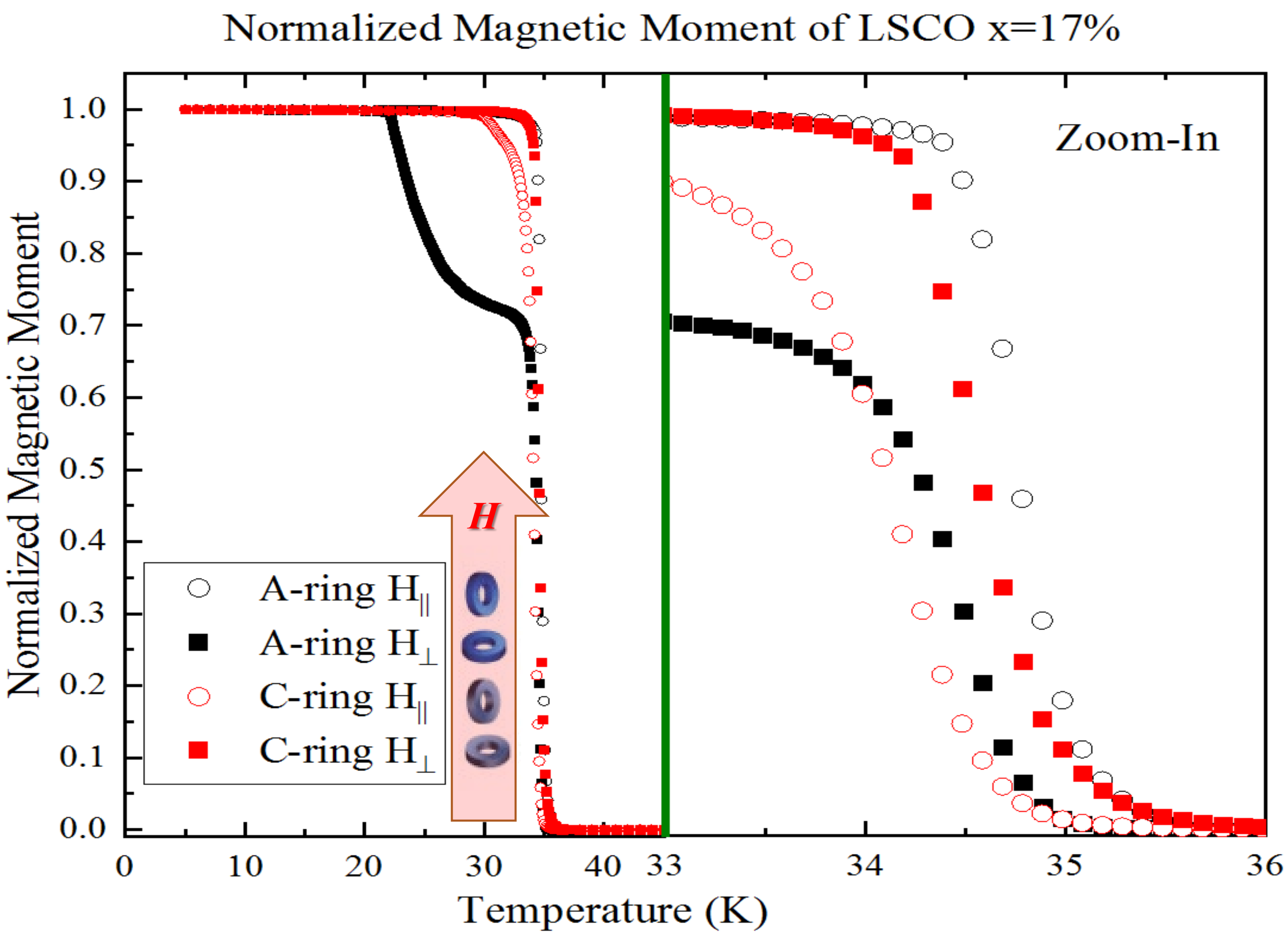


C-ring

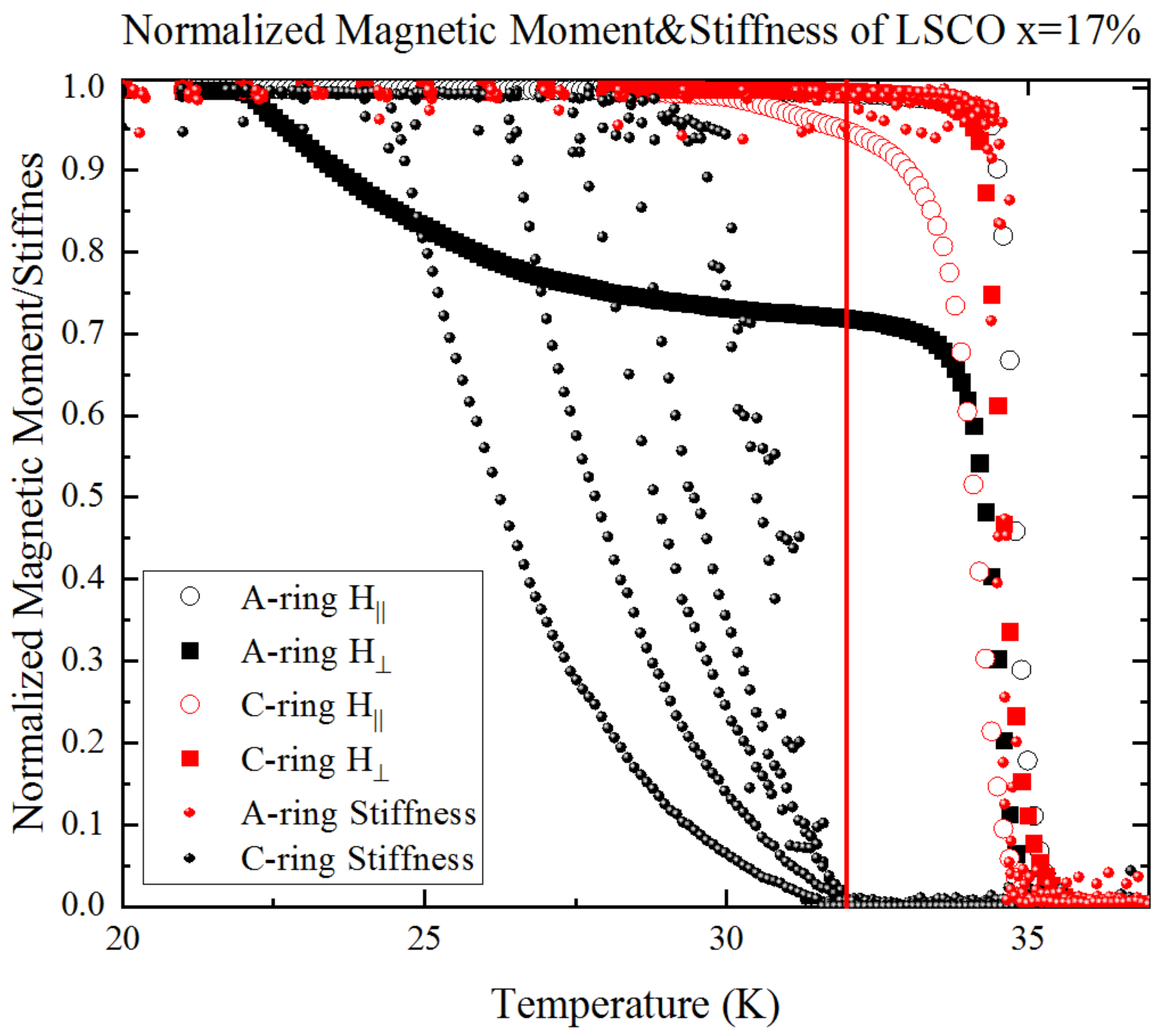
CuO_2 planes
perpendicular to
symmetry axis



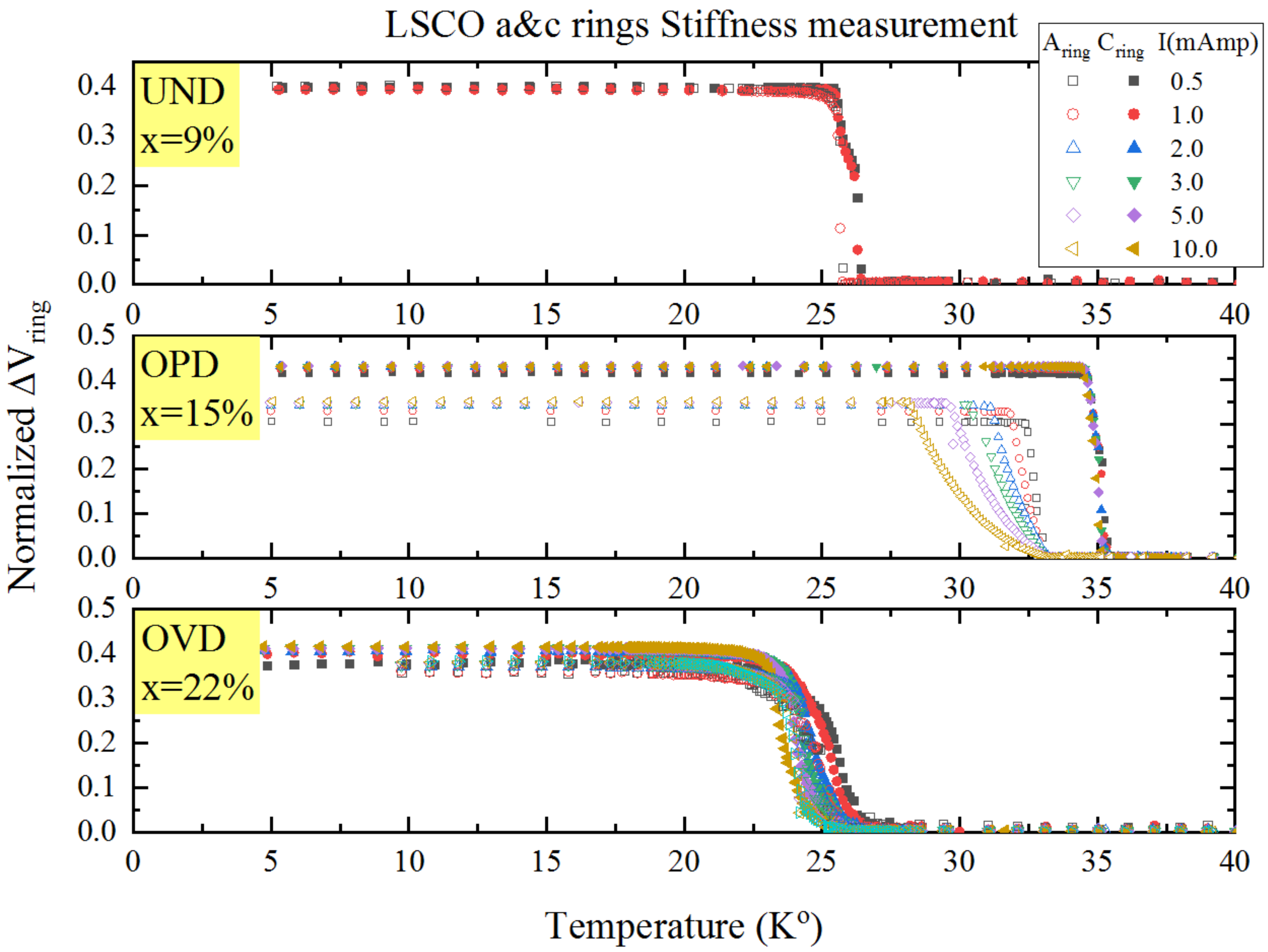
Magnetization vs Temperature



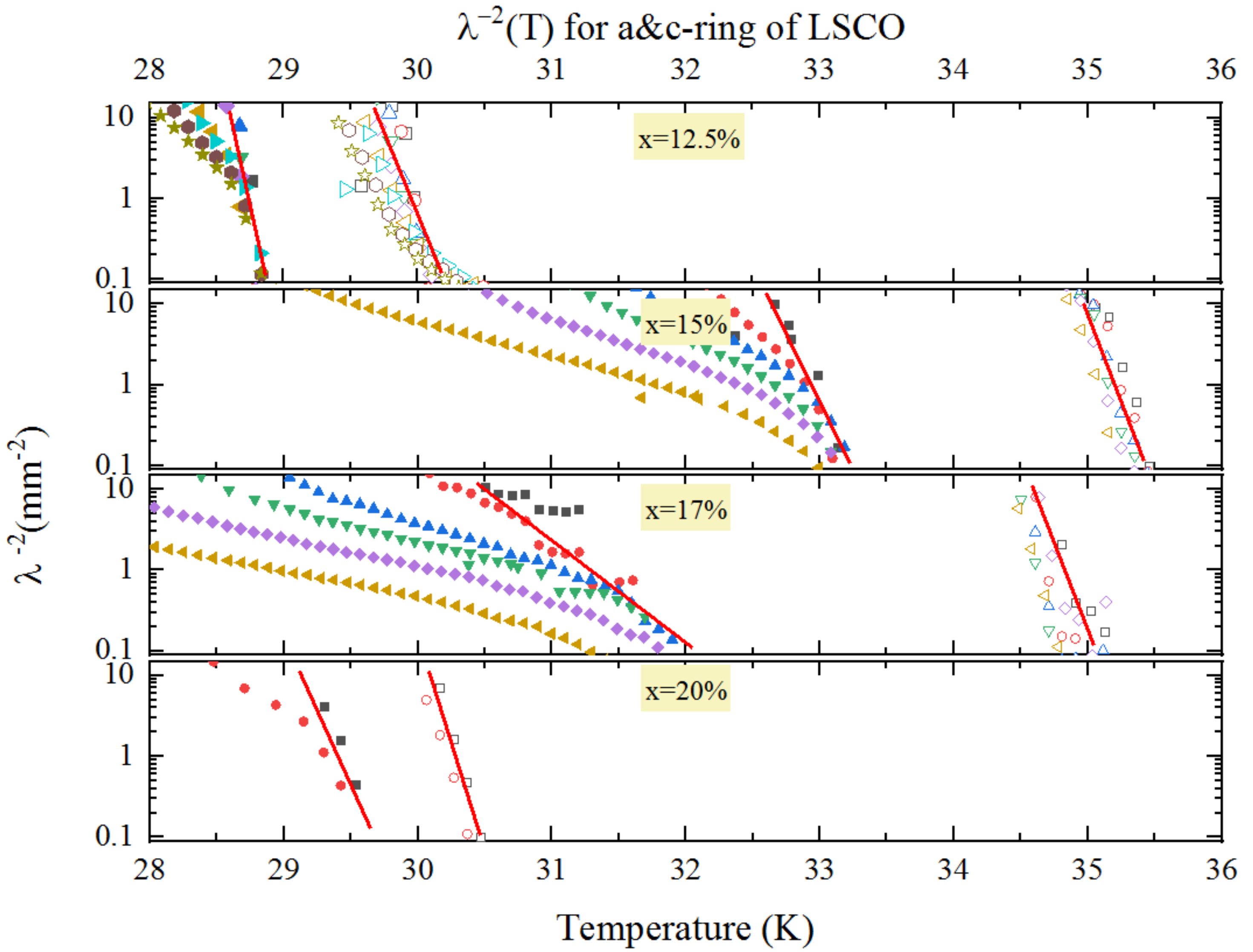
Magnetization vs Temperature



Stiffness vs Temperature

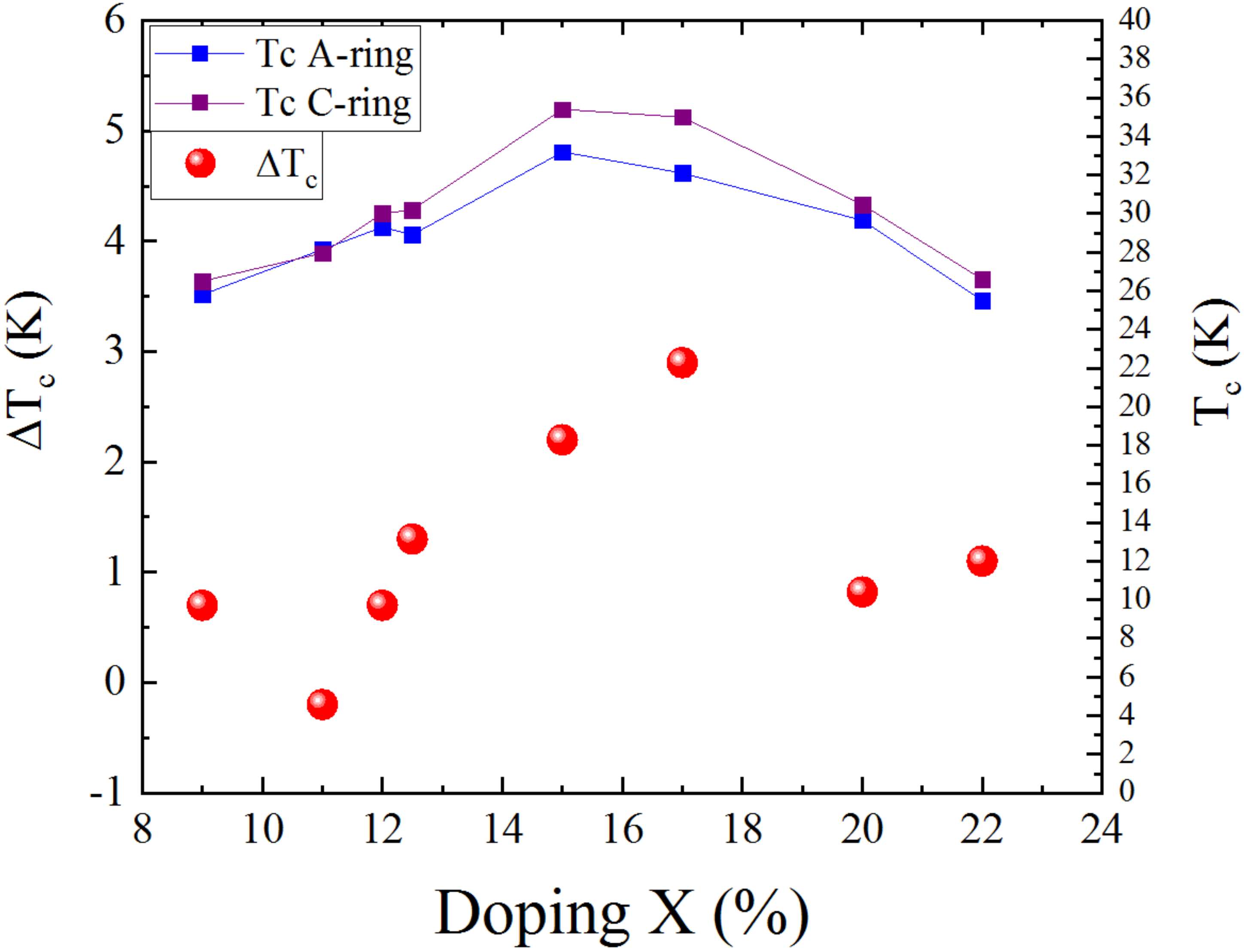


λ vs Temperature

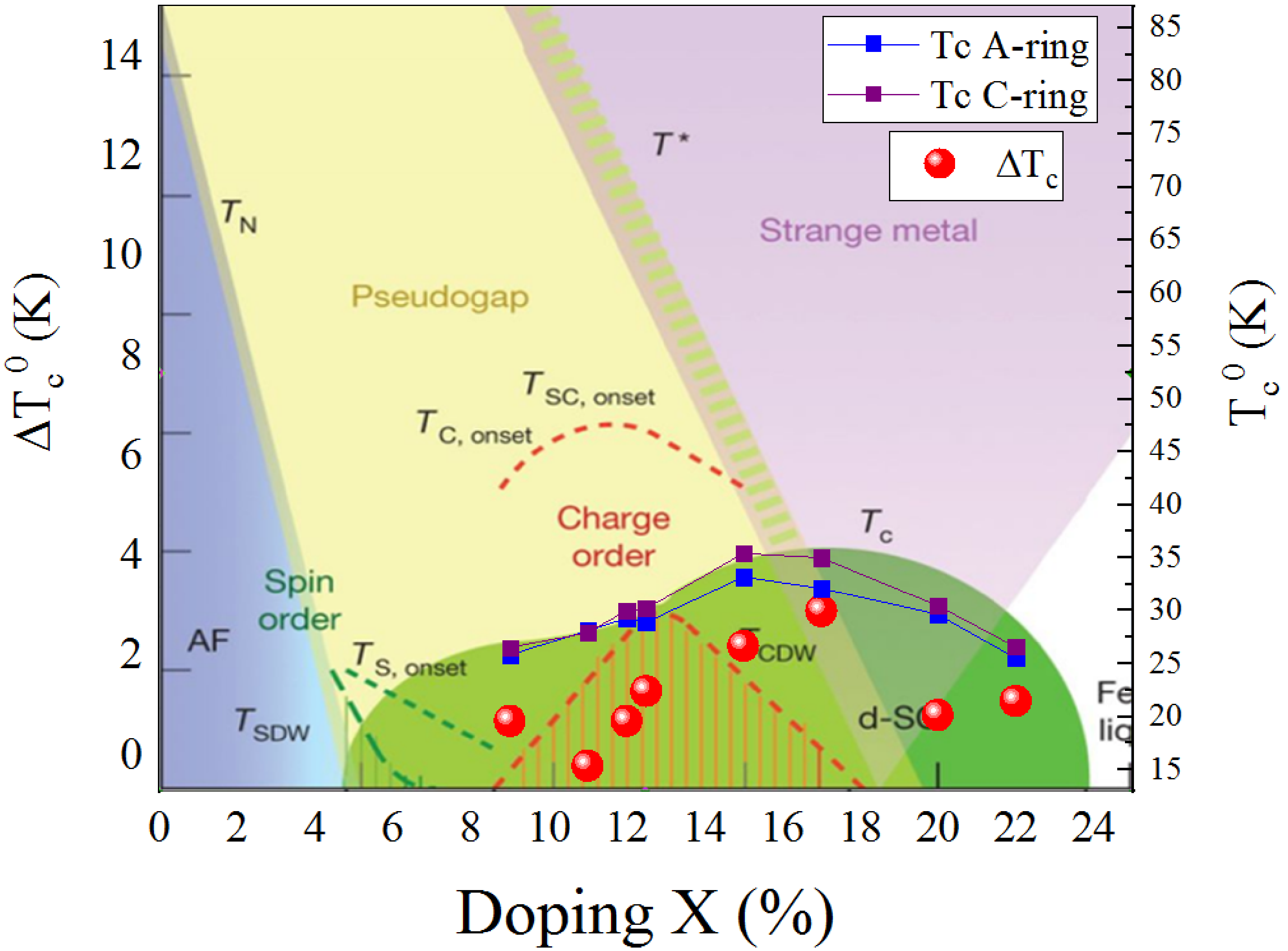


The Phase Diagram

Phase Diagrams of Anisotropy in LSCO



The Phase Diagram



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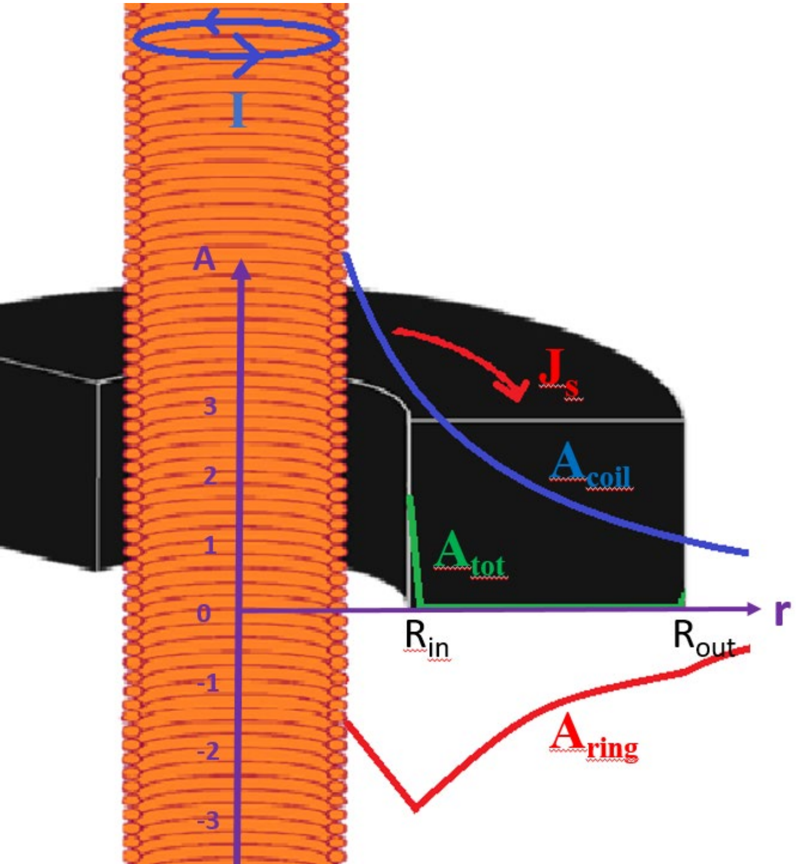
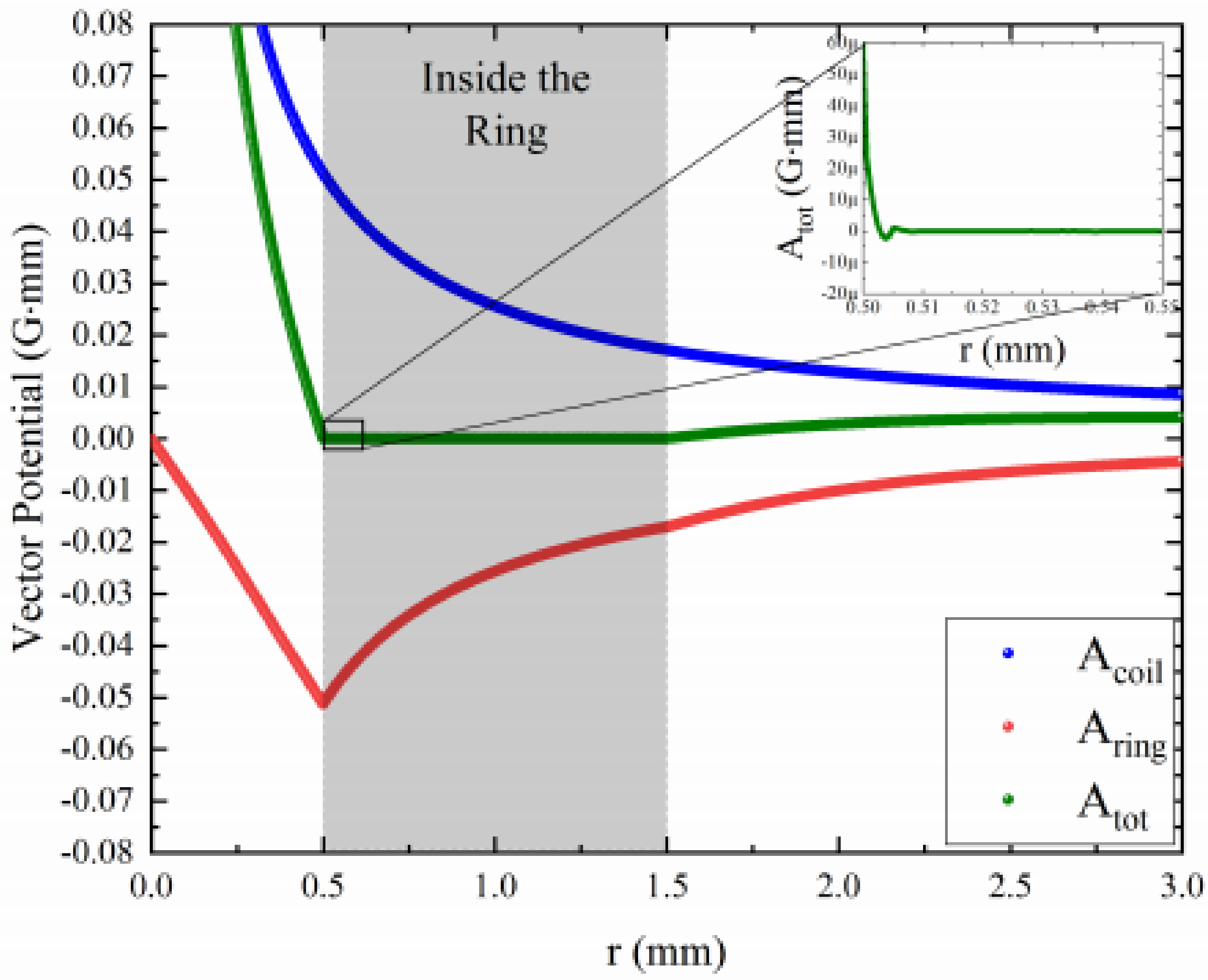
From quantum matter to high-temperature superconductivity in copper oxides. Nature. 518. 179-86. 10.1038/nature14165.

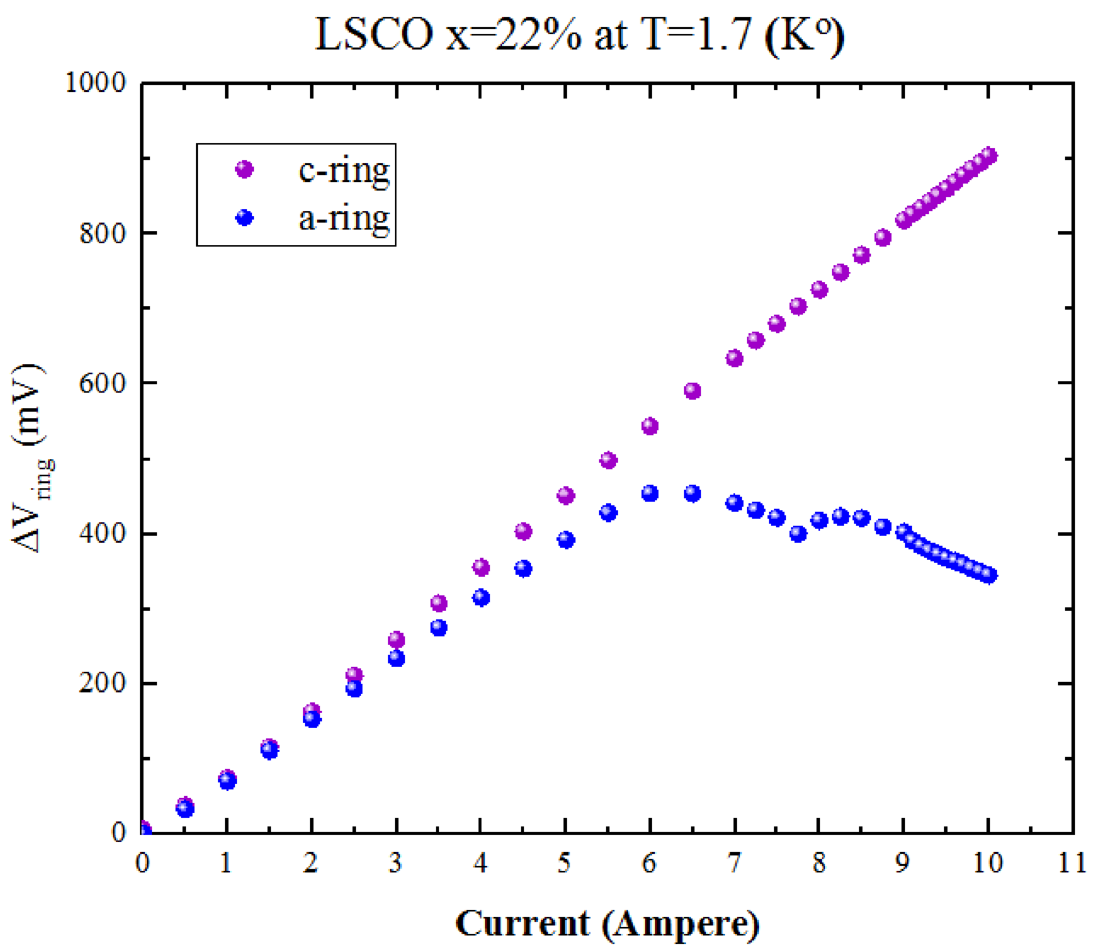
The critical **A**

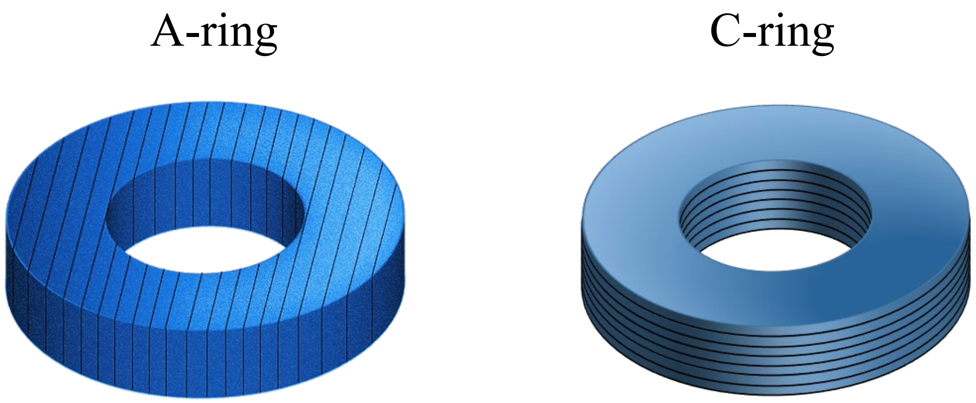
$$\xi = \frac{\hbar c}{2e\sqrt{3}A^{c}_{Tot}(r_{in})}$$





ξ of $La_{2-x}Sr_xCuO_4$ for A and C rings





CuO_2 planes **parallel** to symmetry axis

CuO_2 planes **perpendicular** to symmetry axis

- In LSCO x=22% A-ring a clear break from linearity is observed.
- In LSCO x=22% C-ring we do not reach a critical vector potential $A_c(r_{in})$.

The Implications to ξ

For LSCO x>15%, λ=300nm (Low Energy μSR).

Solving the PDE for this λ and using $I^c > 10$ Amp for x=22% we find

$$\xi < 4\ nm$$

One can also measure ξ using the relation $\xi = \sqrt{\dfrac{\Phi_0}{2\pi H_{c2}}}$

The cuprates acceptable value is ~2 nm and requires a field ~100 T.

Conclusions

- The difference in T_c observed in x=1/8 doping was just the tip of the iceberg.
- The new phase diagram is dome-like with it's maximum near OPD and a drop at the quantum critical point.
- The new method of measuring ξ works at $T \rightarrow 0$ and we can determine ξ_c.
- A factor 2 in A_{Tot} will allow ξ measurements for all doping in both directions.

Thank you!

The Group

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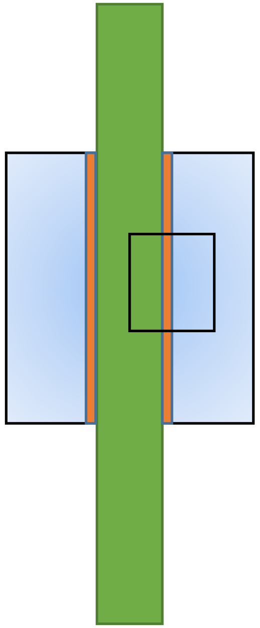
Galina Bazalitski Anna Eyal Leonid Iomin Itzik Kapon

Thank you!

Critical Current Density at $T \to 0$

- We can calculate the critical current density using a simple argument.

- Consider an Ampere loop.
  - There is no field inside the coil since the SC rejects it.
  - There is no field inside the SC.
  - So the total current crossing the loop is zero.
  - In the SC the current is limited to a region of length λ next to the inner rim.



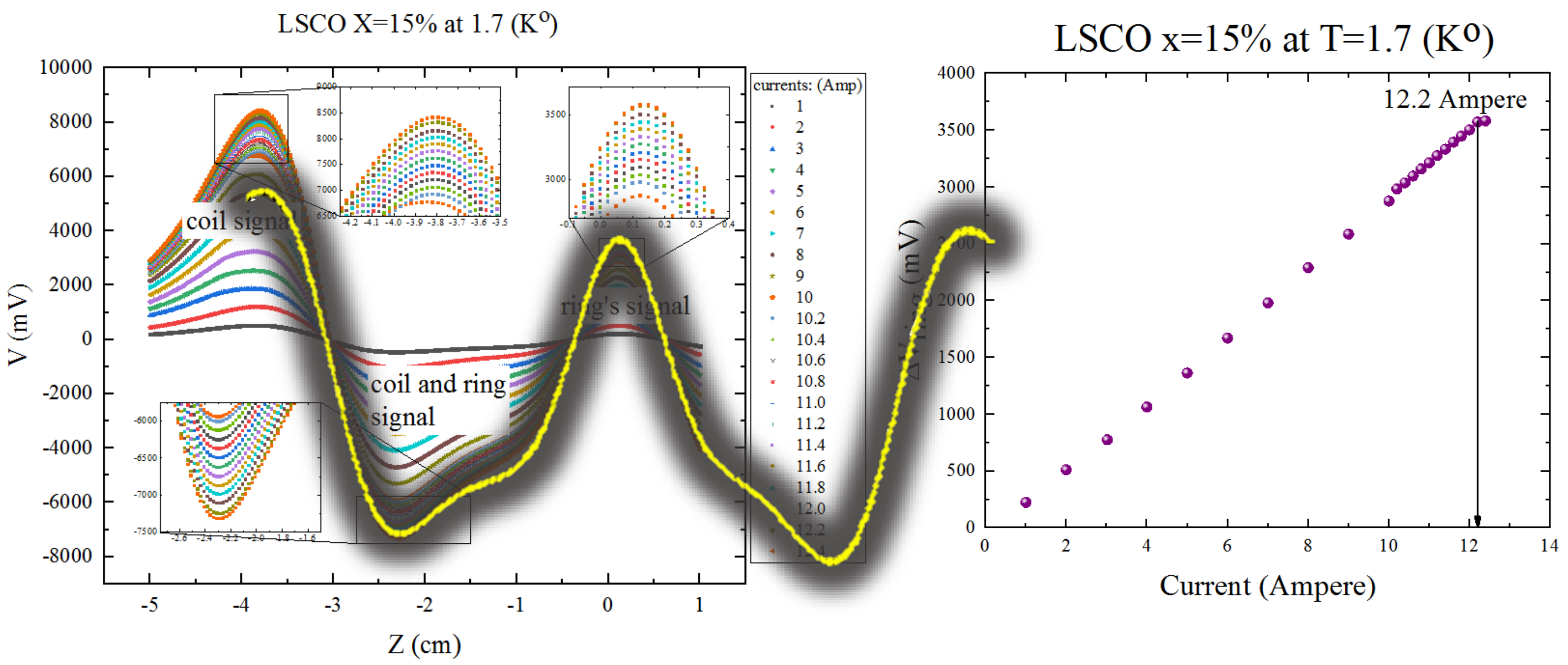
$$J(r) = Je^{-(r-r_{in})/\lambda}$$

$$I_{ring} = l \cdot \int_{r_{in}}^{r_{out}} J(r) \cdot dr = l\lambda J(1-e^{-(r_{out}-r_{in})/\lambda}) \approx l\lambda J$$

$$0 = \oint \mathbf{B} \cdot dl = \int \mathbf{J} d\mathbf{a} \Rightarrow Inl = J\lambda l \Rightarrow J = In/\lambda$$

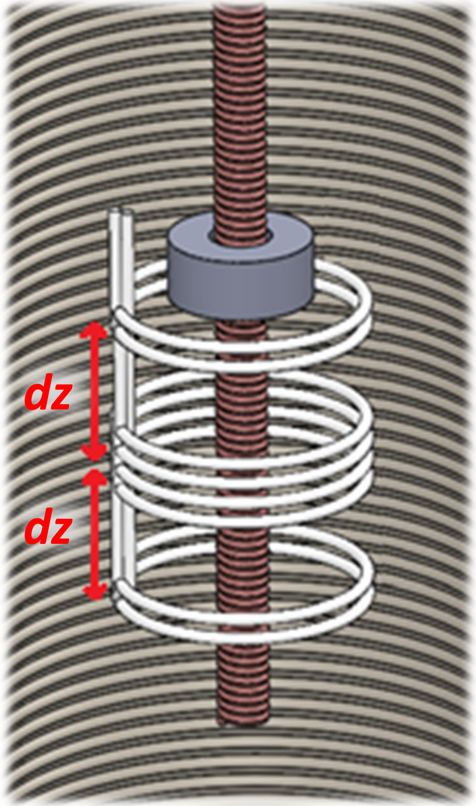
$$J_c > 10 \text{ Amp} \times 40 \text{ turns/mm}/300 \times 10^{-6} mm \sim 1.3 \times 10^{8} \text{ Amp/cm}^2$$

Coil With 6 Winding Layers



If this break is true then: $\xi \leq 2.94\ nm$ (?). **Needs to be confirmed !**

The Gradiometer "G" factor



- The gradiometer is maid of 8 pickup loops with different winding direction.

- The SQUID signal is proportional to the flux from all 8 pickup loops.

$$V_{SQUID} = K \cdot \Sigma_{all-pl} 2\pi r_{pl} \cdot A^{pl}(r_{pl}, z - z_{pl}) = K \cdot 2\pi r_{pl} \cdot A^{gradiometer}(r_{pl}, z)$$

- Calculating: $\dfrac{\Delta A_{ring}^{gradiometer}}{A_{ring}^{pl}(r_{pl}, z=0)} = 1.7$, $\dfrac{\Delta A_{ring}^{gradiometer}}{A_{coil}^{pl}(z=0)} = 0.47$

- Then: $\dfrac{\Delta V_{ring}}{\Delta V_{coil}} = \dfrac{\Delta A_{ring}^{gradiometer}}{\Delta A_{coil}^{gradiometer}} = G\dfrac{A_{ring}(R_{PL})}{A_{coil}(R_{PL})}$ where: $G = \dfrac{1.7}{0.47} \approx 3.62$

The Phase Diagram

Phase Diagrams of Anisotropy in LSCO