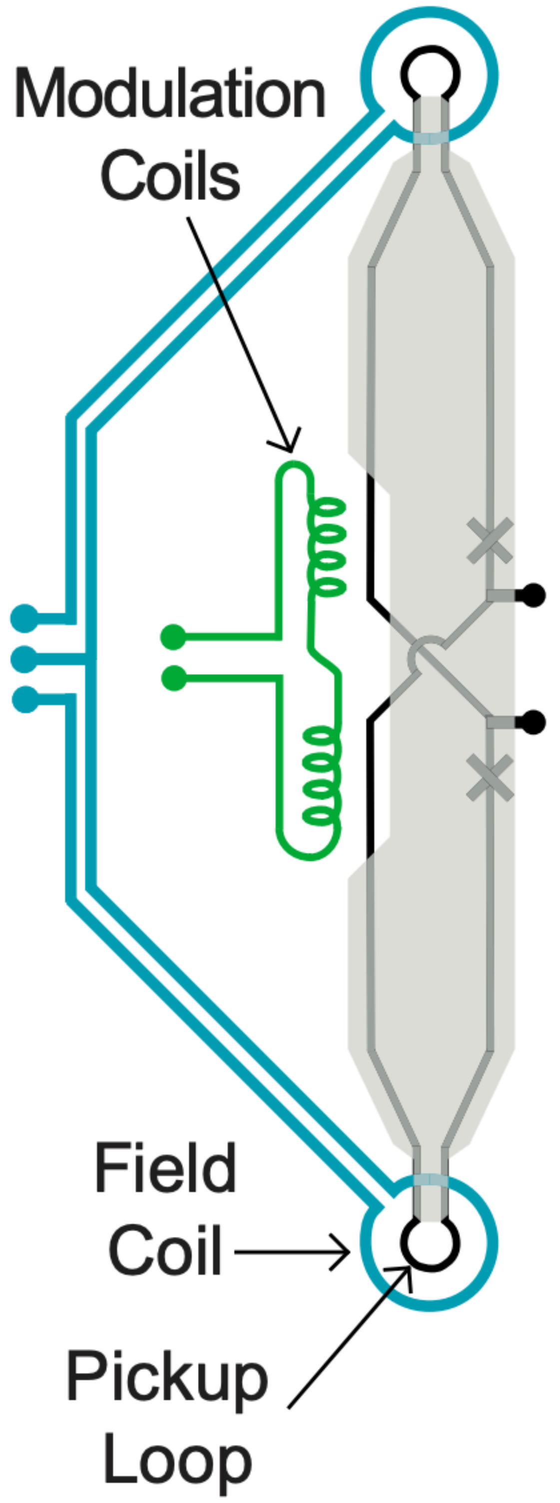
Cryogen-free variable temperature scanning SQUID microscope

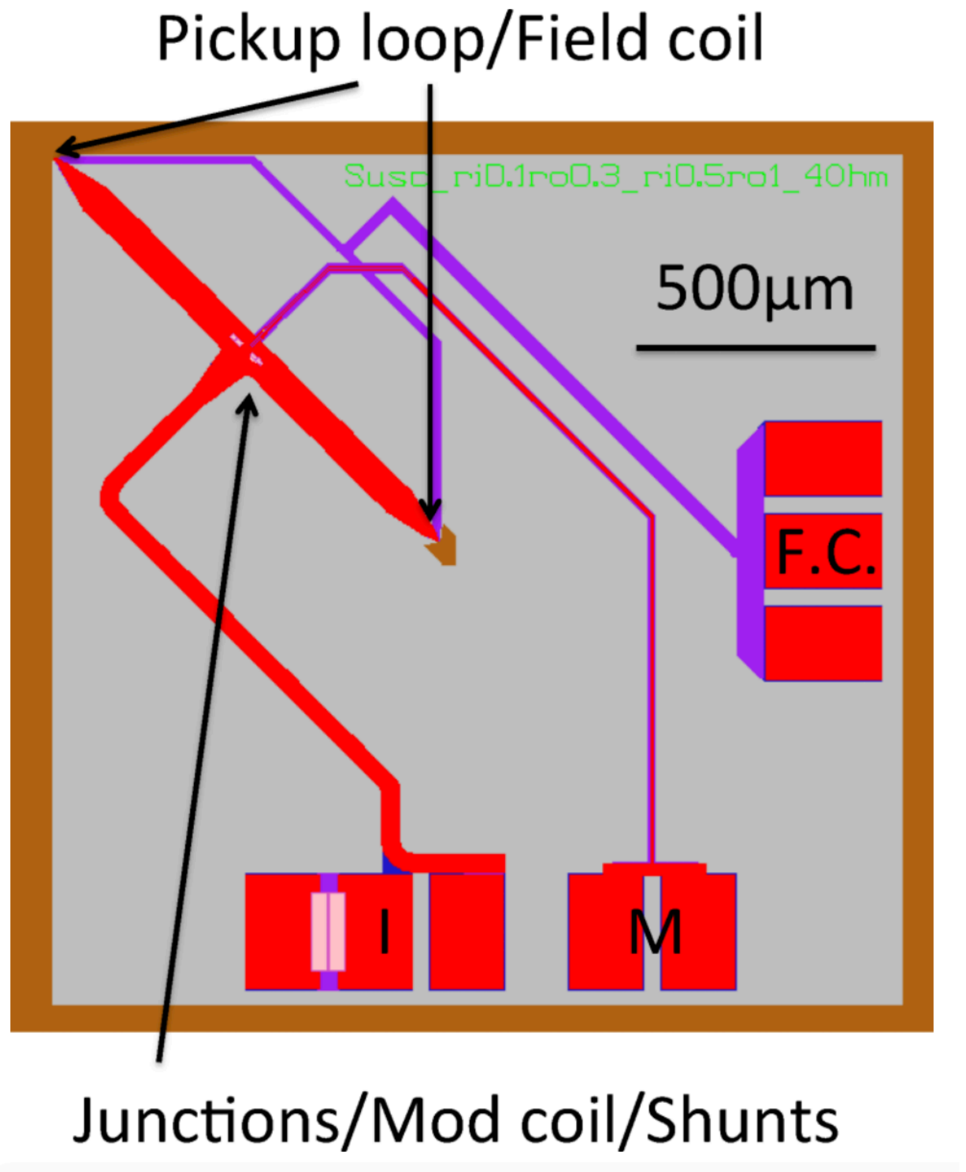
Logan Bishop-Van Horn, Zheng Cui, John R. Kirtley, & Kathryn A. Moler

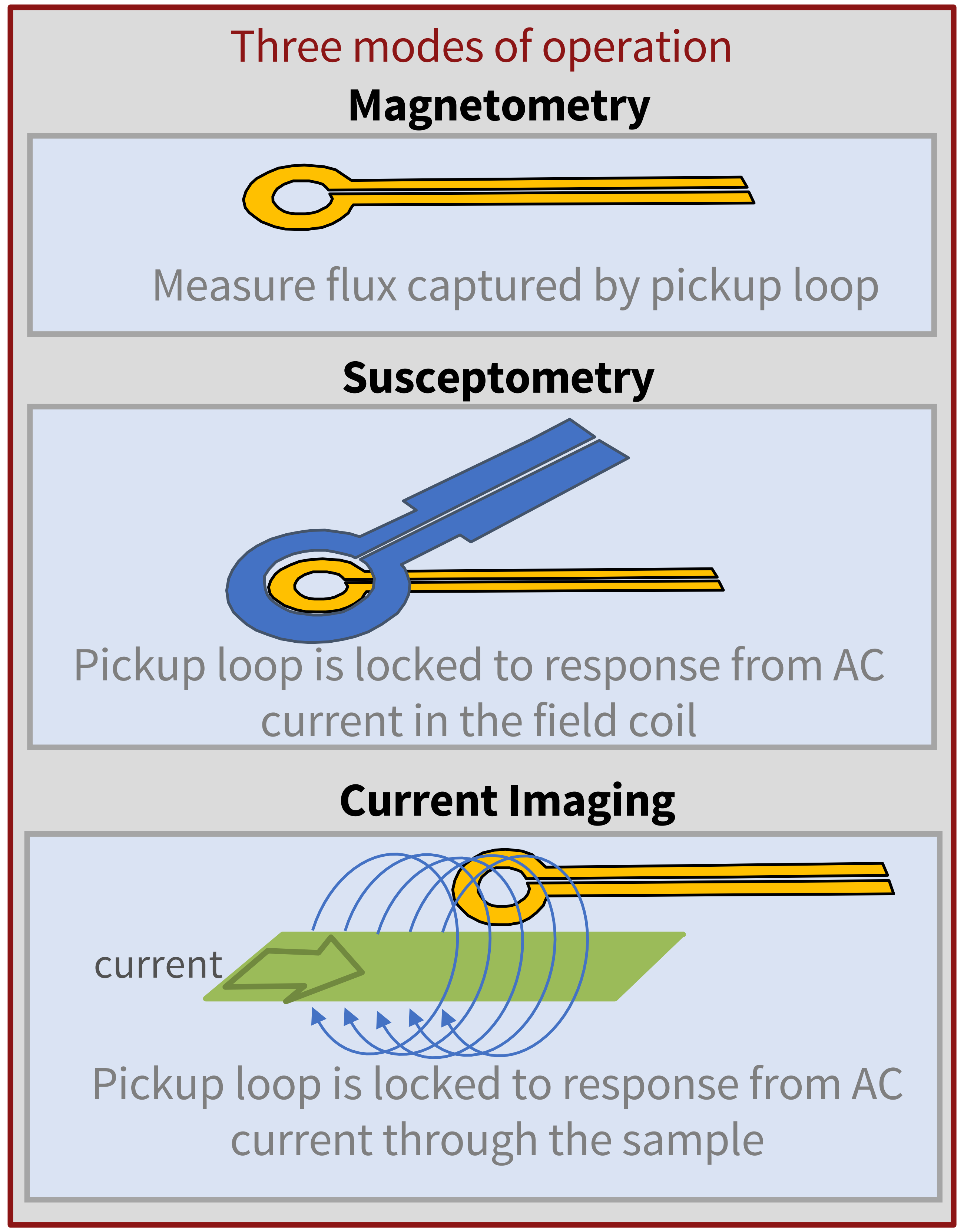
APS March Meeting 2019

arXiv:1812.03215, accepted @ RSI.

Scanning SQUID microscopy



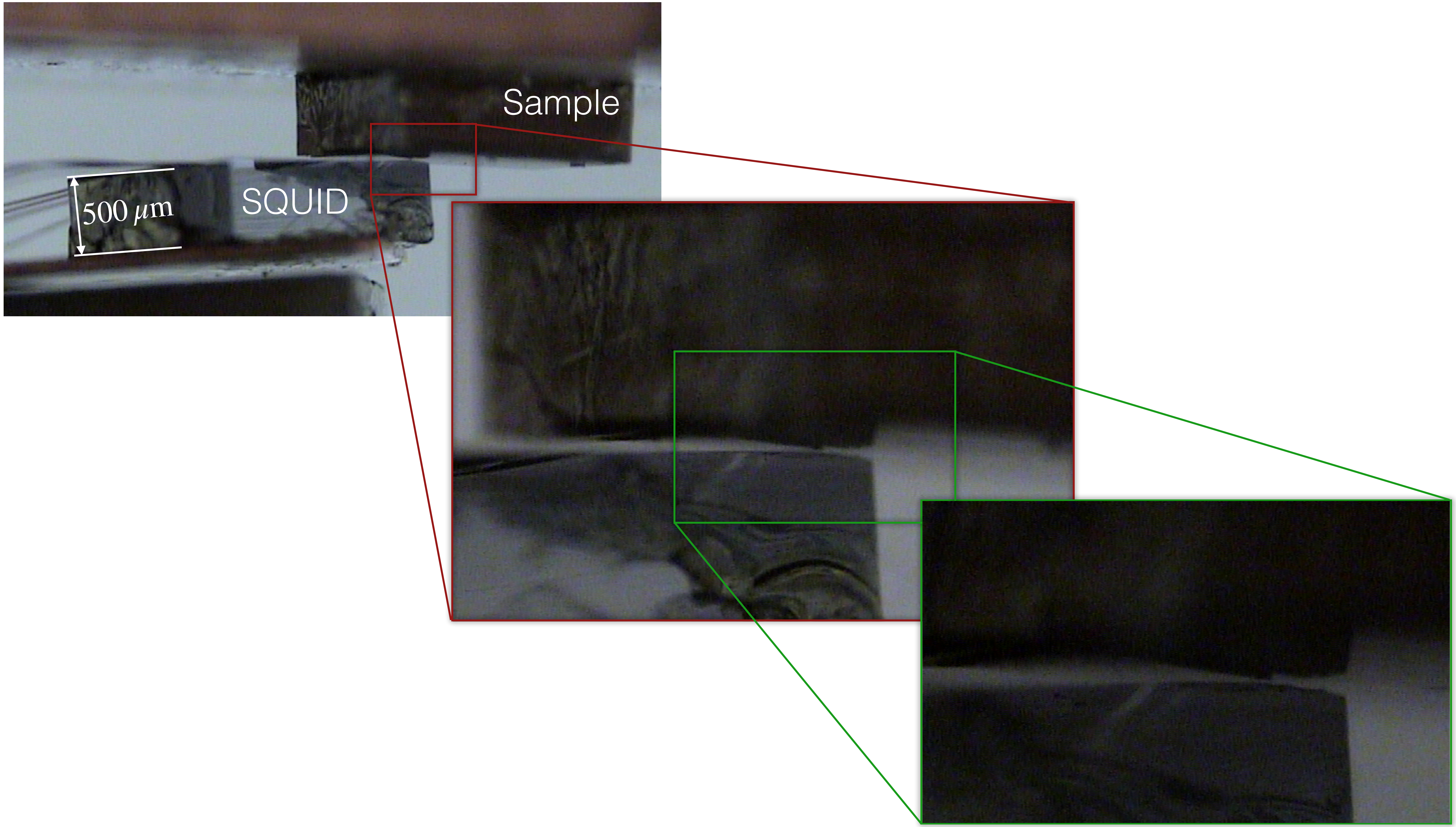


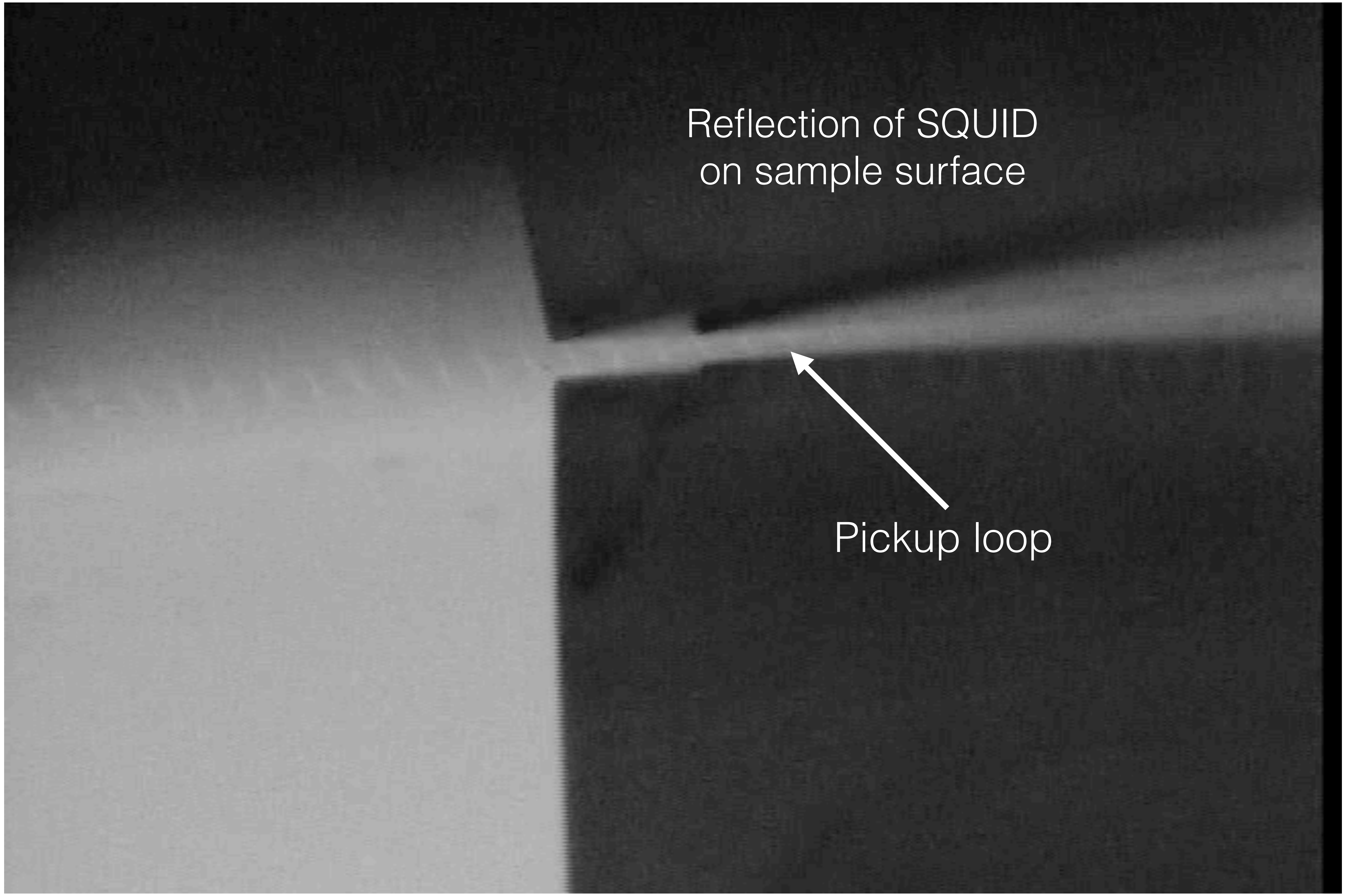


Sensitive to sensor-sample vibrations:

- Magnetometry in region of large flux gradient
- Susceptometry of strongly para/diamagnetic materials
- Measurements of ring-like samples (CPR)

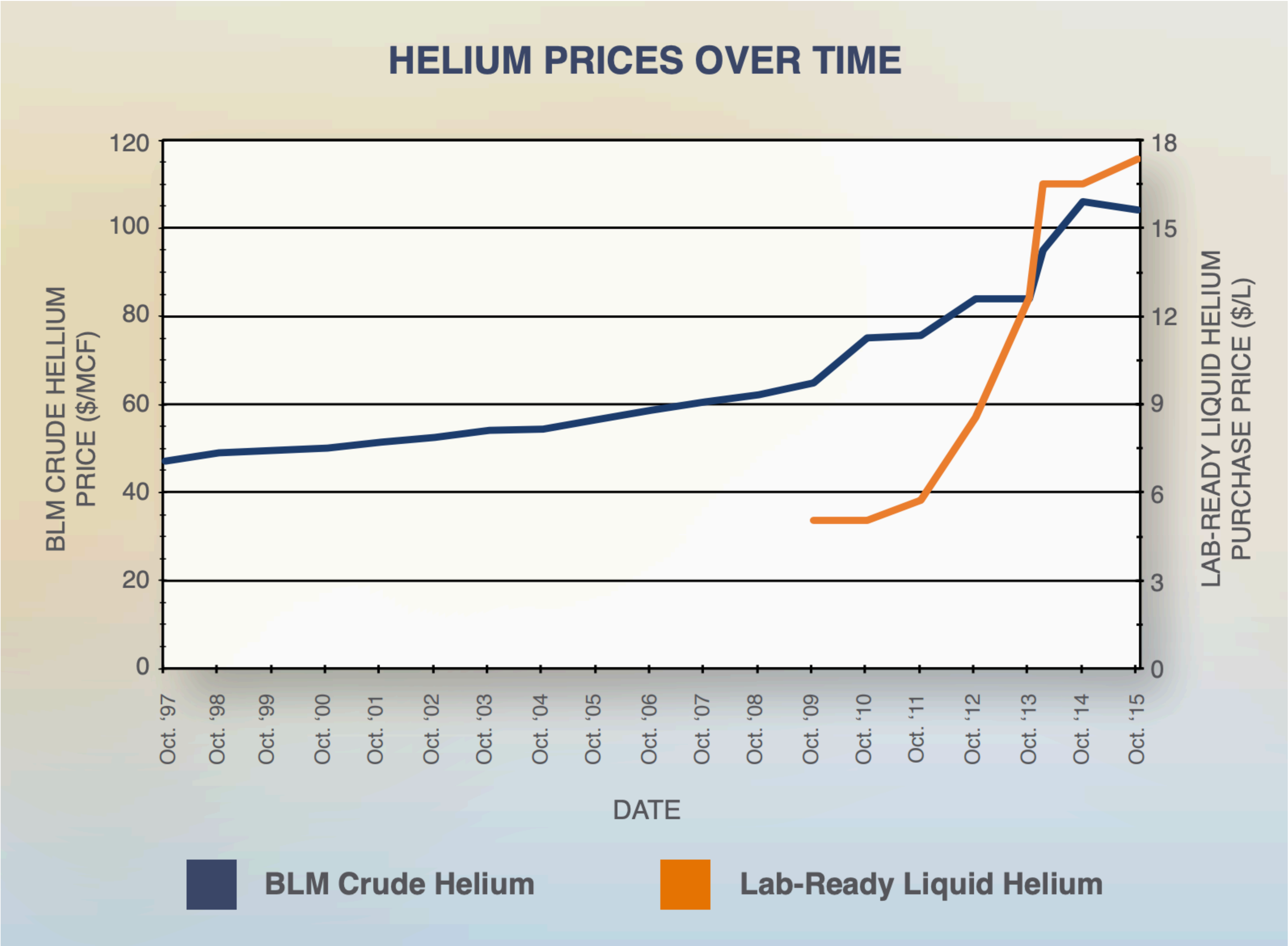
RSI **79**, 053704 (2008).
RSI **87**, 093702 (2016).


Sample
SQUID
500 μm


Reflection of SQUID
on sample surface
Pickup loop

Why cryogen-free?

Erratic helium prices create research havoc



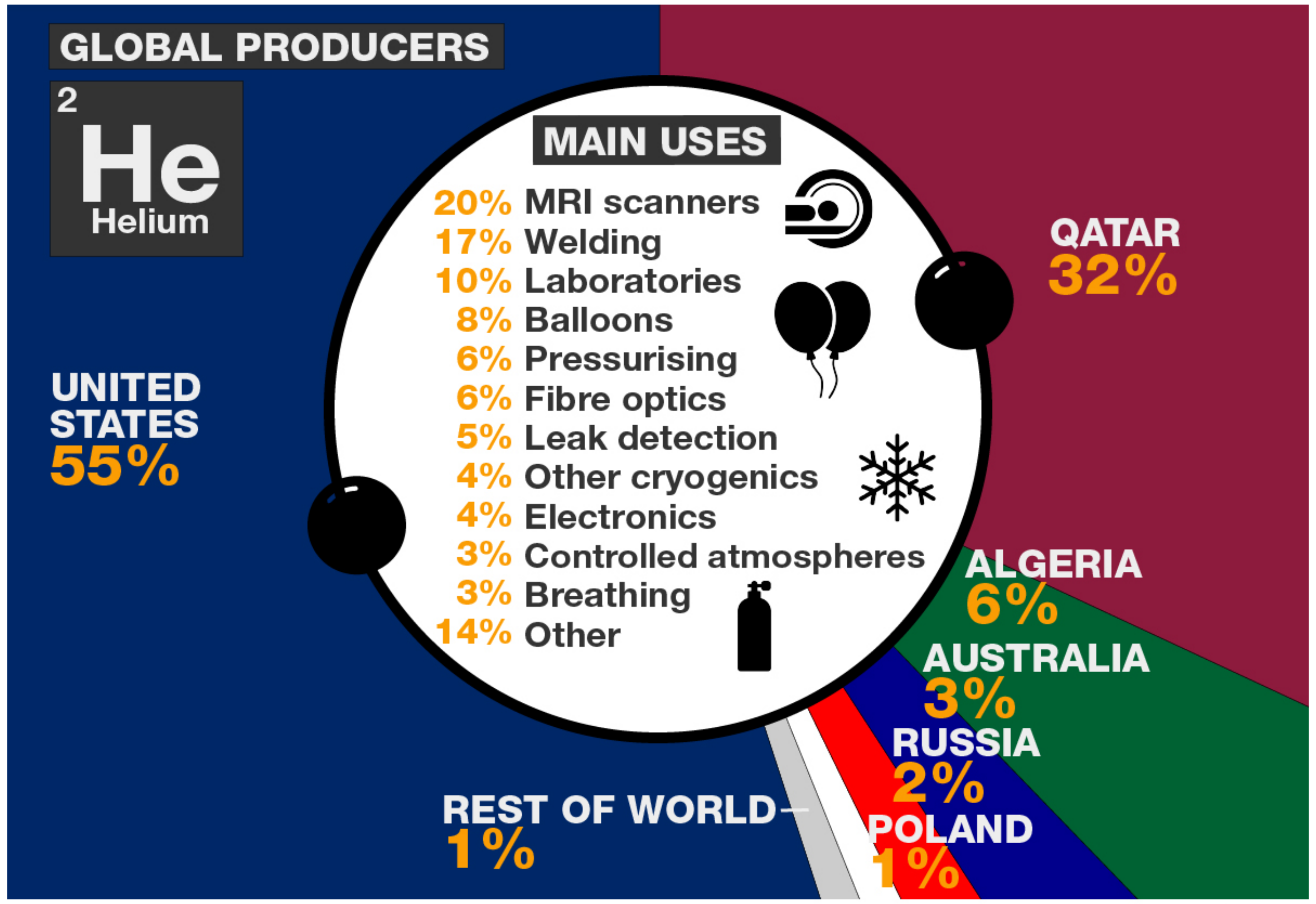
MICHAEL PERECKAS (CC BY 2.0)

PRICES FOR LIQUID HELIUM have soared in recent years, and some scientists are reporting difficulty in obtaining the essential commodity for low-temperature research.

PHYSICS TODAY | JANUARY 2017

Who produces the world's helium?

Helium is the second-most abundant chemical element in the universe but only a handful of countries actually capture and store it, making the market extremely competitive and unstable.



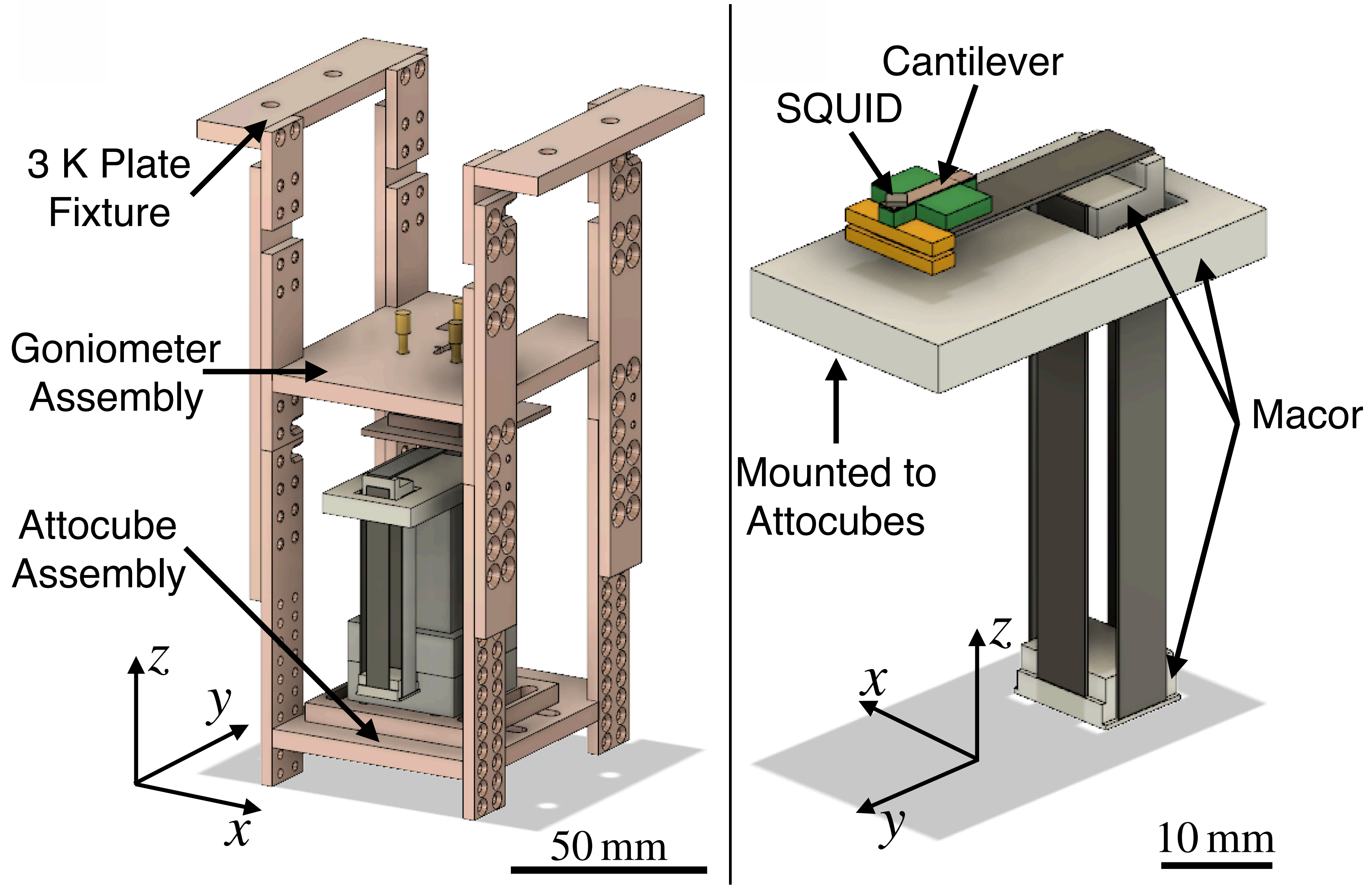
Source: USGS, Helium-One
Icons: Sergey Demushkin, Adrien Coquet, Assaf Katz, Synonymsof - Noun Project

ALJAZEERA

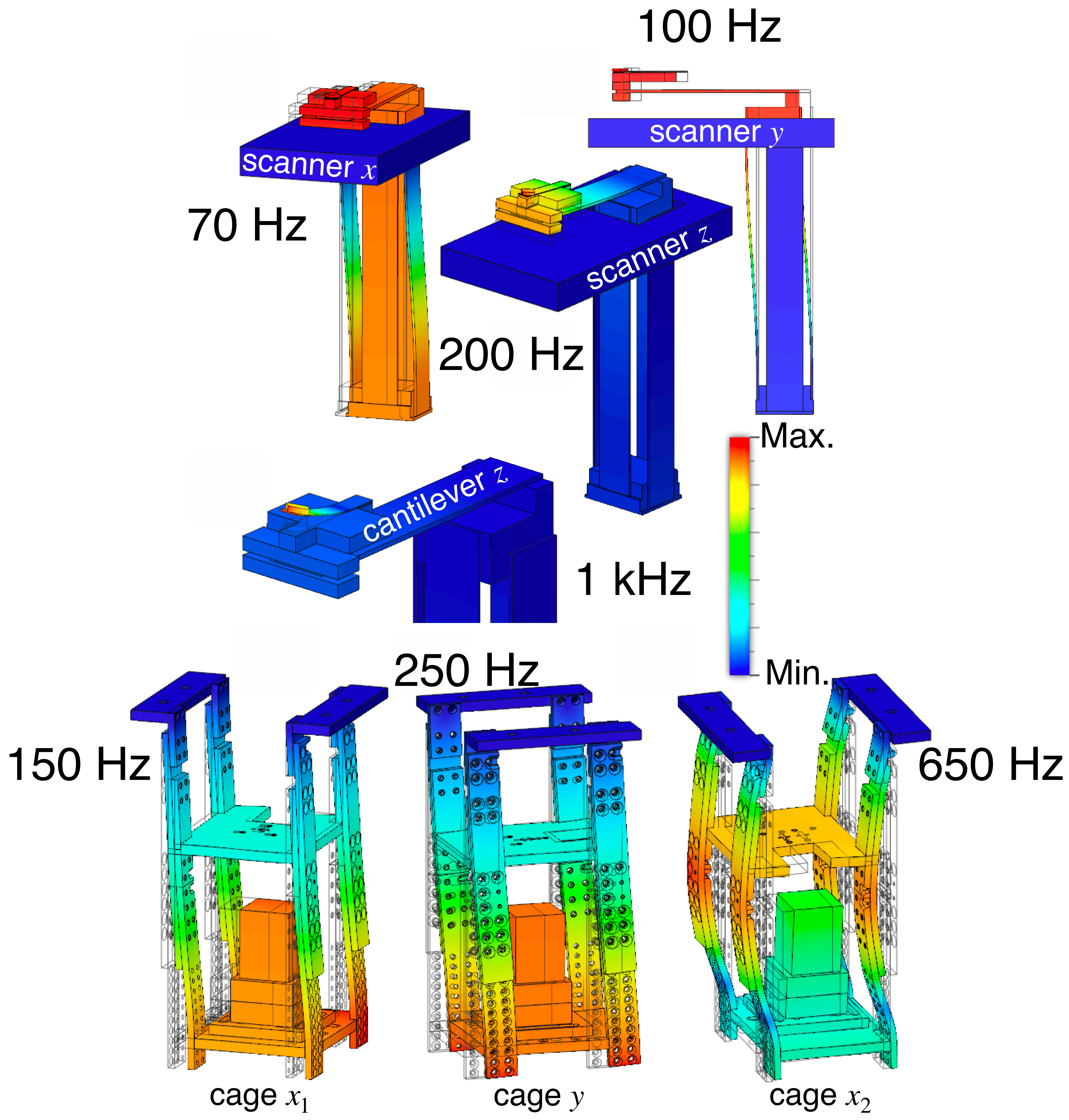
\+ large experimental volume, no interruptions due to He transfers, etc.

Physics Today **70**, 1, 26 (2017).
APS Report: Responding to the U.S. Research Community's Liquid Helium Crisis.

Microscope design



- Piezo scanner optimized for scan range and linearity
- SQUD mounted on Cu cantilever to capacitively detect contact with sample
- Attocube stack for coarse positioning
- Open, modular Cu “cage” for experimental flexibility
- Mounted in a Bluefors LD-4K pulse tube cryocooler (base temp: 3 K)



Simulated mechanical modes
(and their estimated frequencies)

Scanner design: RSI **66**, 2520 (1995).

Vibration characterization

Measure noise in the SQUID flux signal in a region of sharp flux gradient (vortex in Nb film):

$$\Phi(x,y,z_0,t) \approx \Phi(0,0,z_0) + \nabla\Phi(x,y,z)\Big|_{z=z_0} \cdot \mathbf{r}(t) + \eta(t)$$

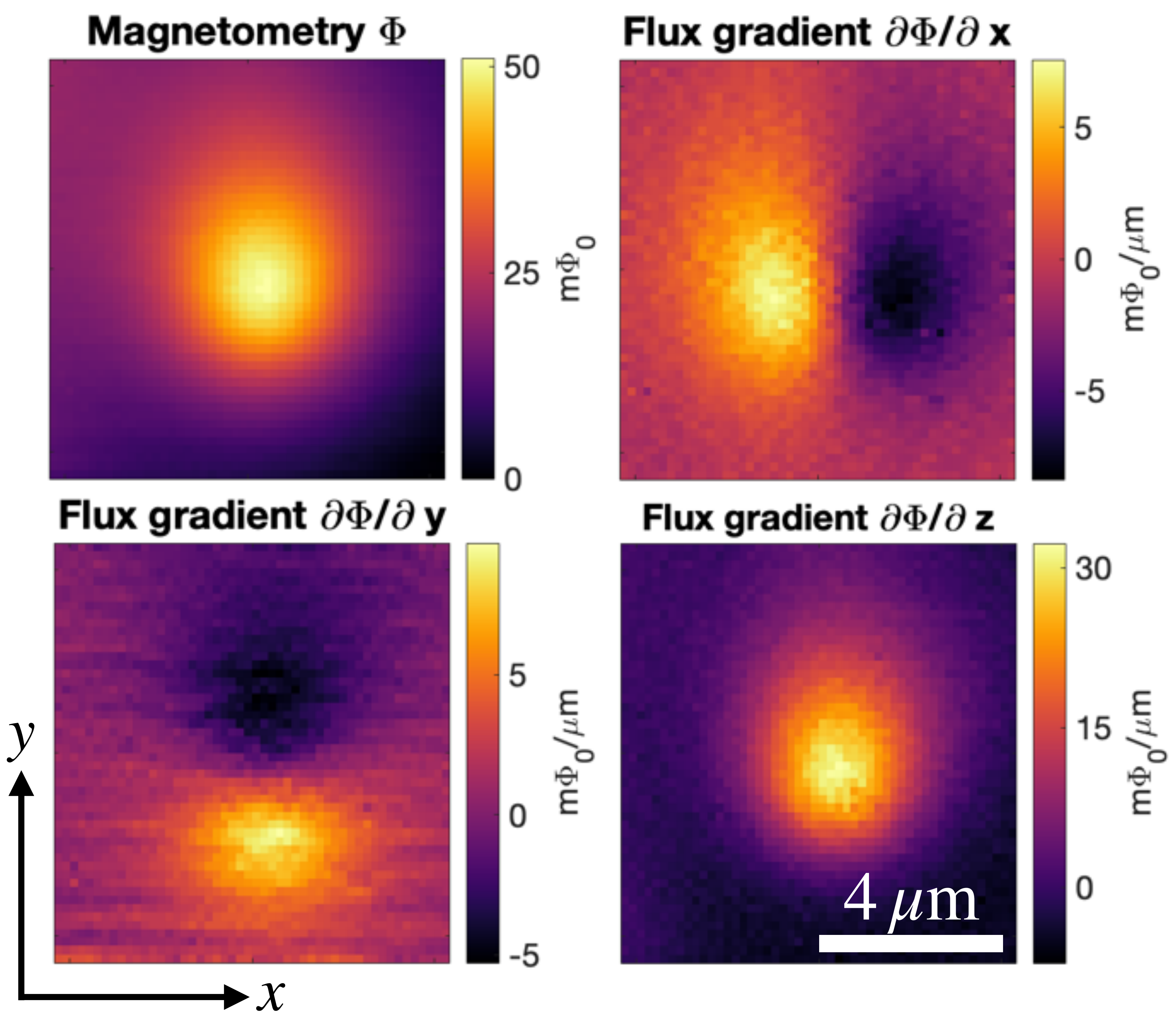
- **Measured flux** → $\Phi(x,y,z_0,t)$
- **Actual flux at height z_0 above center of vortex** → $\Phi(0,0,z_0)$
- **Flux gradient** → $\nabla\Phi(x,y,z)\big|_{z=z_0}$
- **SQUID position** → $\mathbf{r}(t)$
- **Position-independent noise** → $\eta(t)$

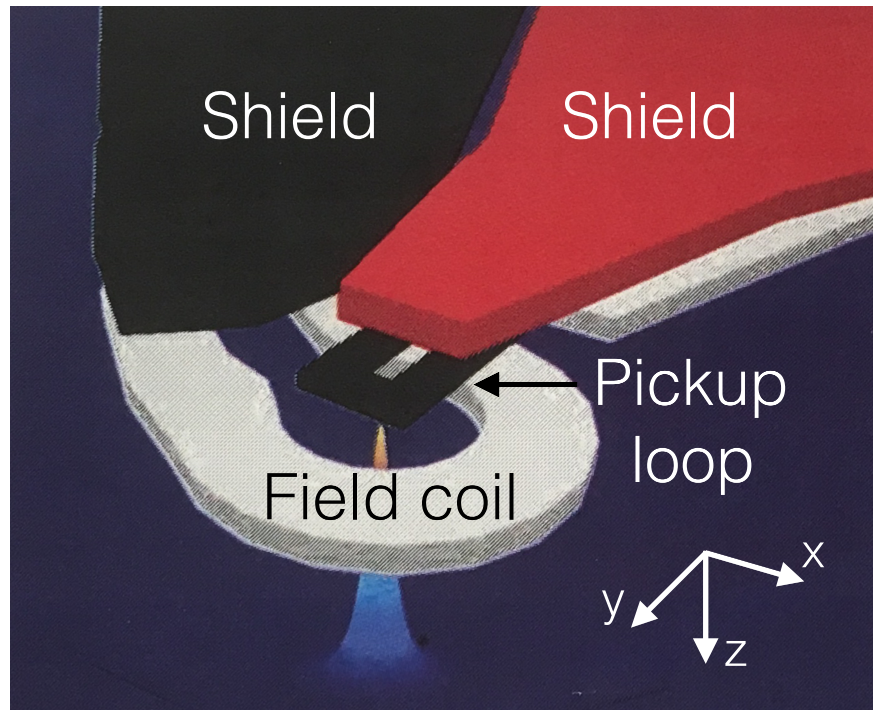
Fourier transform:

$$|\tilde{\Phi}(x,y,z_0,f)| \approx \left| \nabla\tilde{\Phi}(x,y,z)\Big|_{z=z_0} \cdot \tilde{\mathbf{r}}(f) + \tilde{\eta}(f) \right|$$

$$\tilde{\mathbf{r}}(f) = \tilde{\rho}(f)[\cos\tilde{\theta}(f)\hat{\mathbf{x}} + \sin\tilde{\theta}(f)\hat{\mathbf{y}}] + \tilde{z}(f)\hat{\mathbf{z}}$$

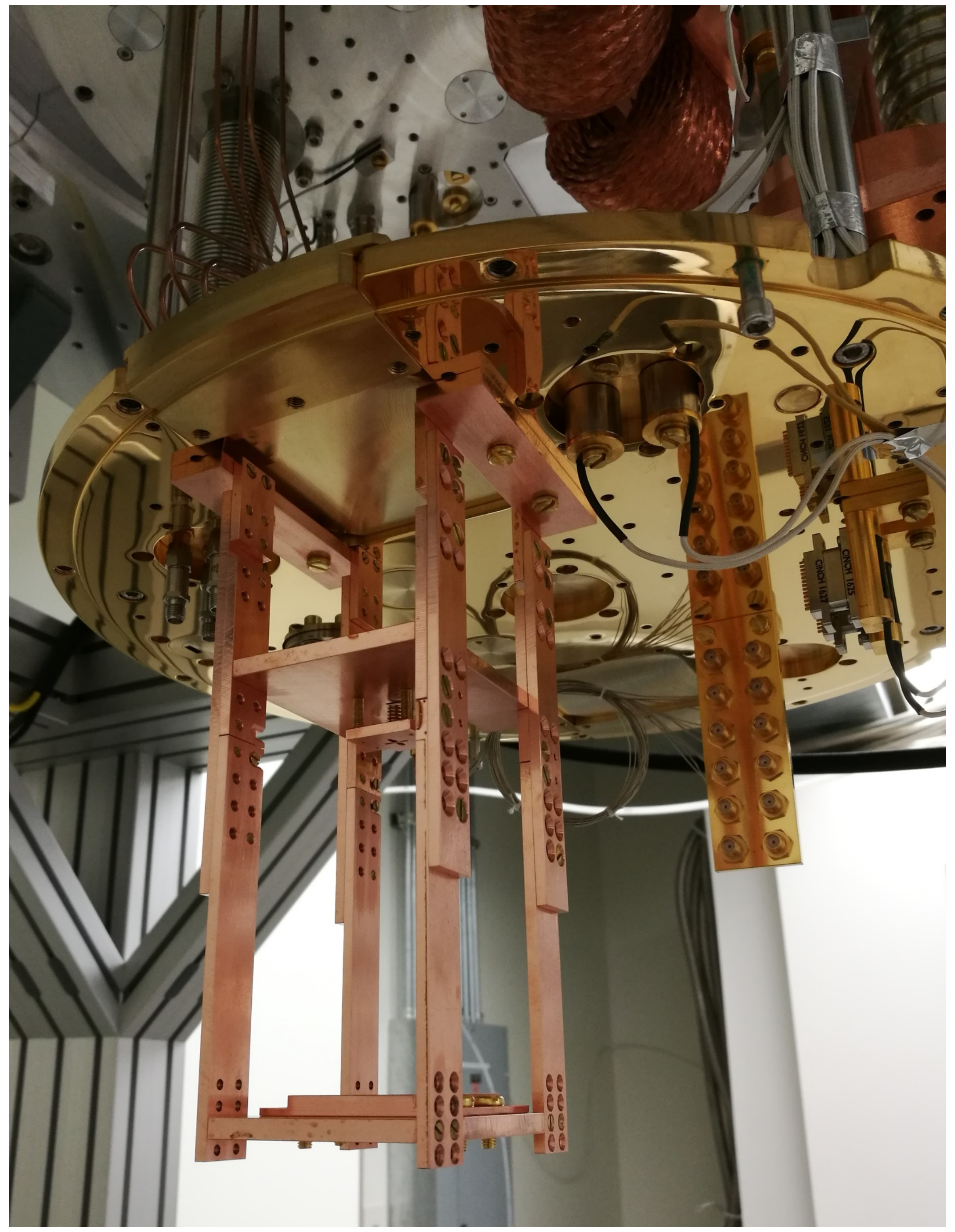
Fit with $\tilde{\rho}(f)$, $\tilde{\theta}(f)$, $\tilde{z}(f)$, $\tilde{\eta}(f)$ as free parameters.





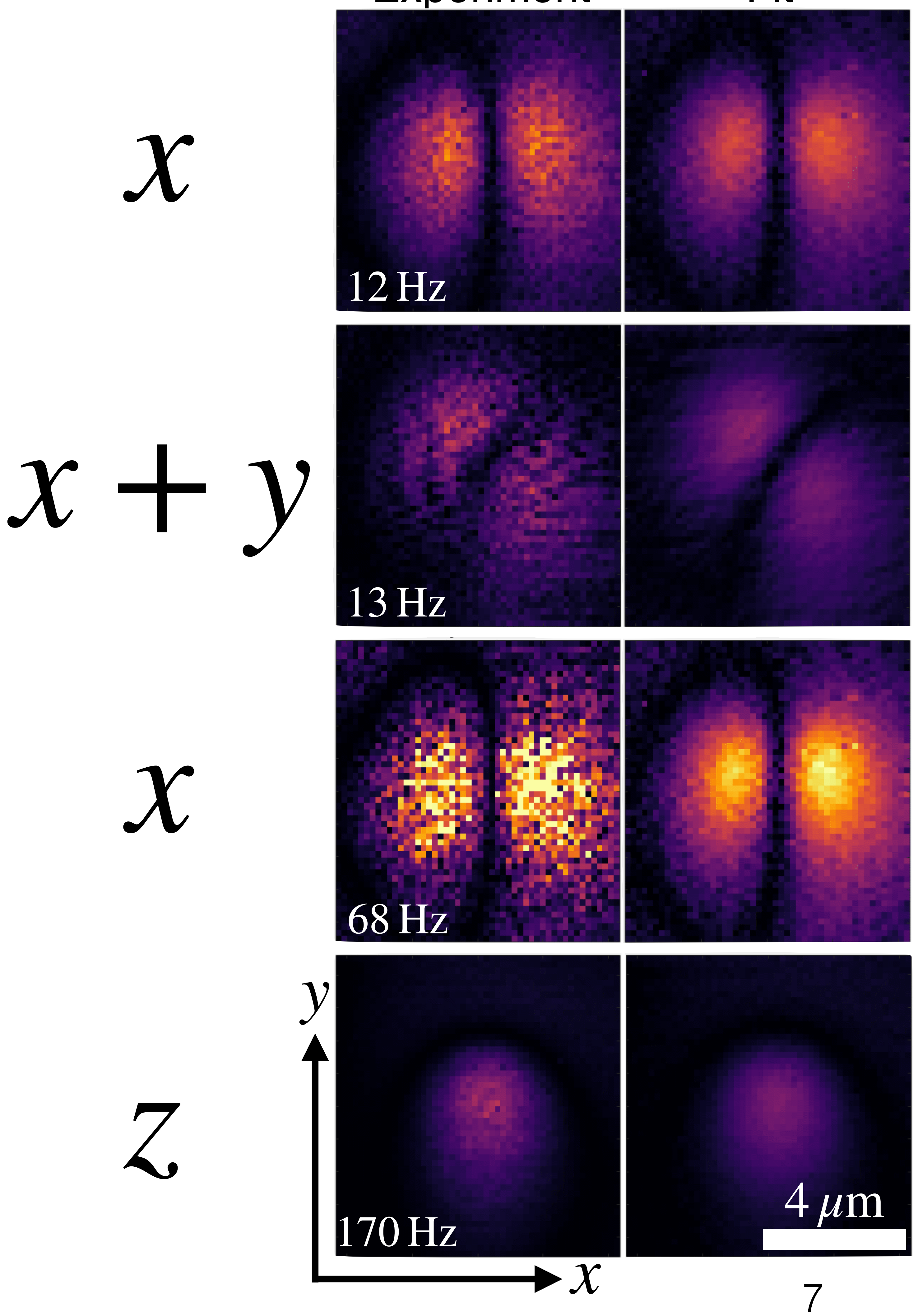
APL **109**, 232601 (2016).

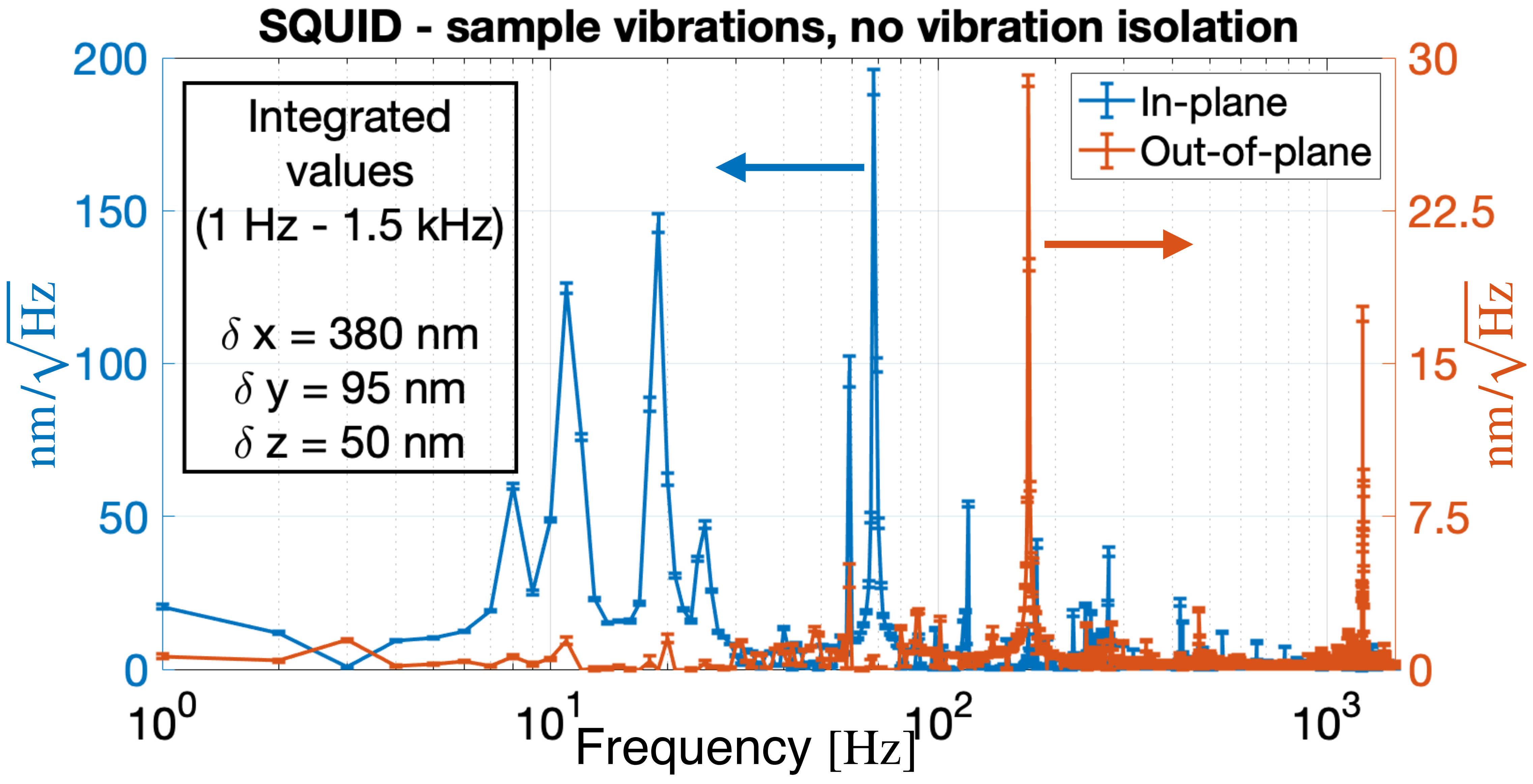
Without vibration isolation



Copper cage mounted rigidly to 3 K plate of Bluefors fridge

Noise SD vs. position

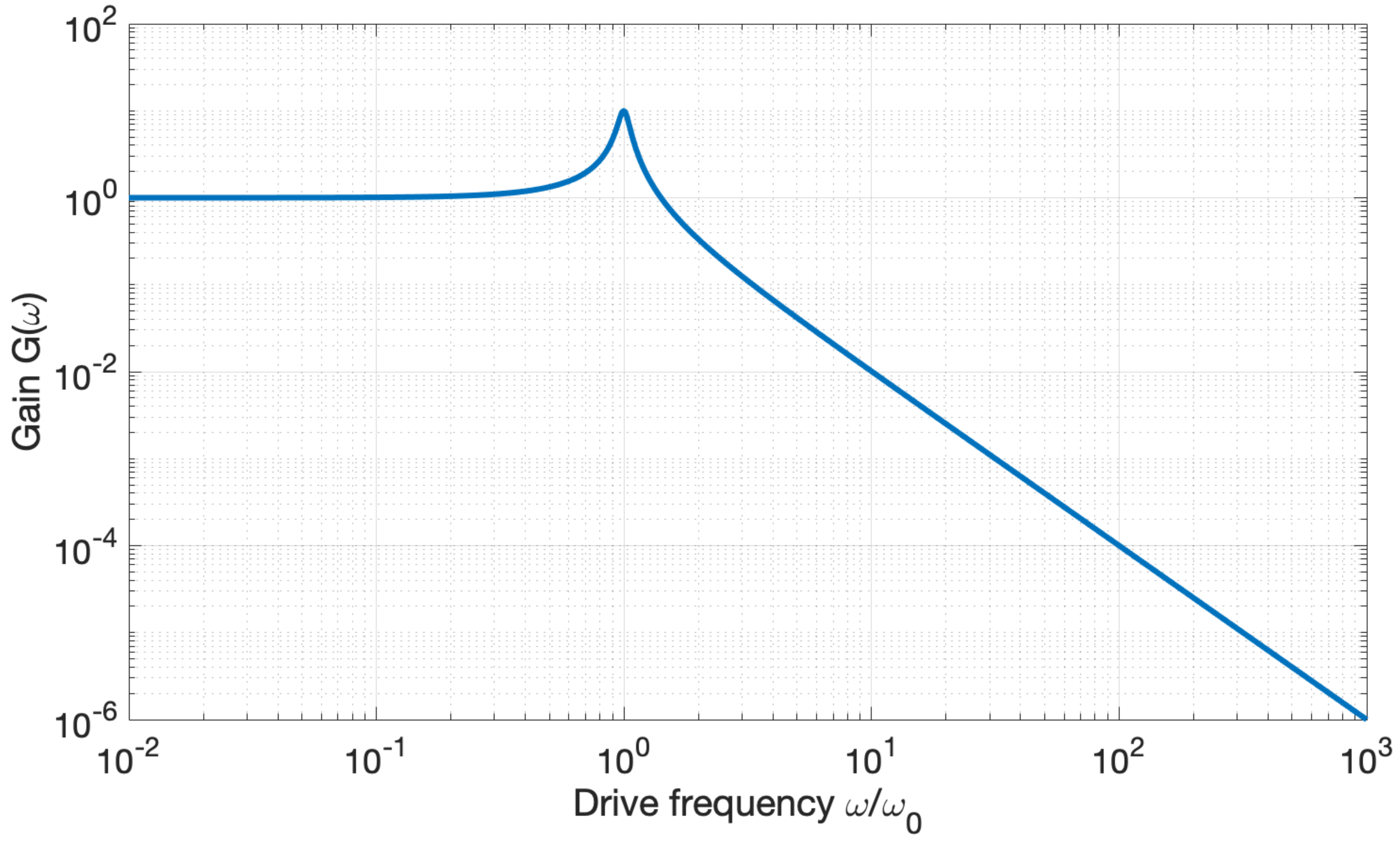


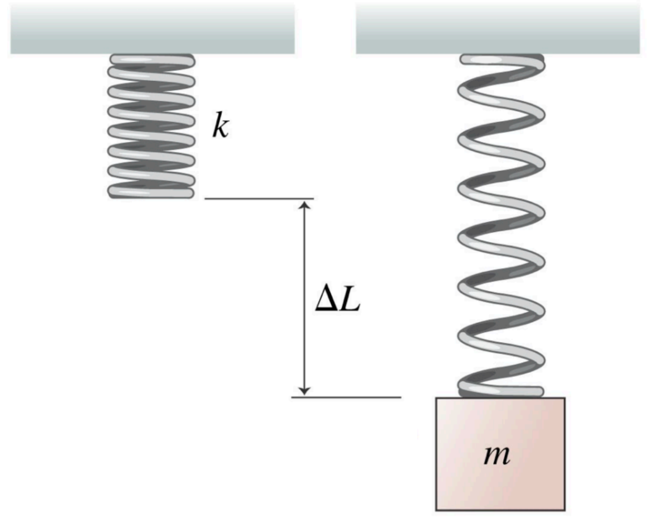


Passive vibration isolation

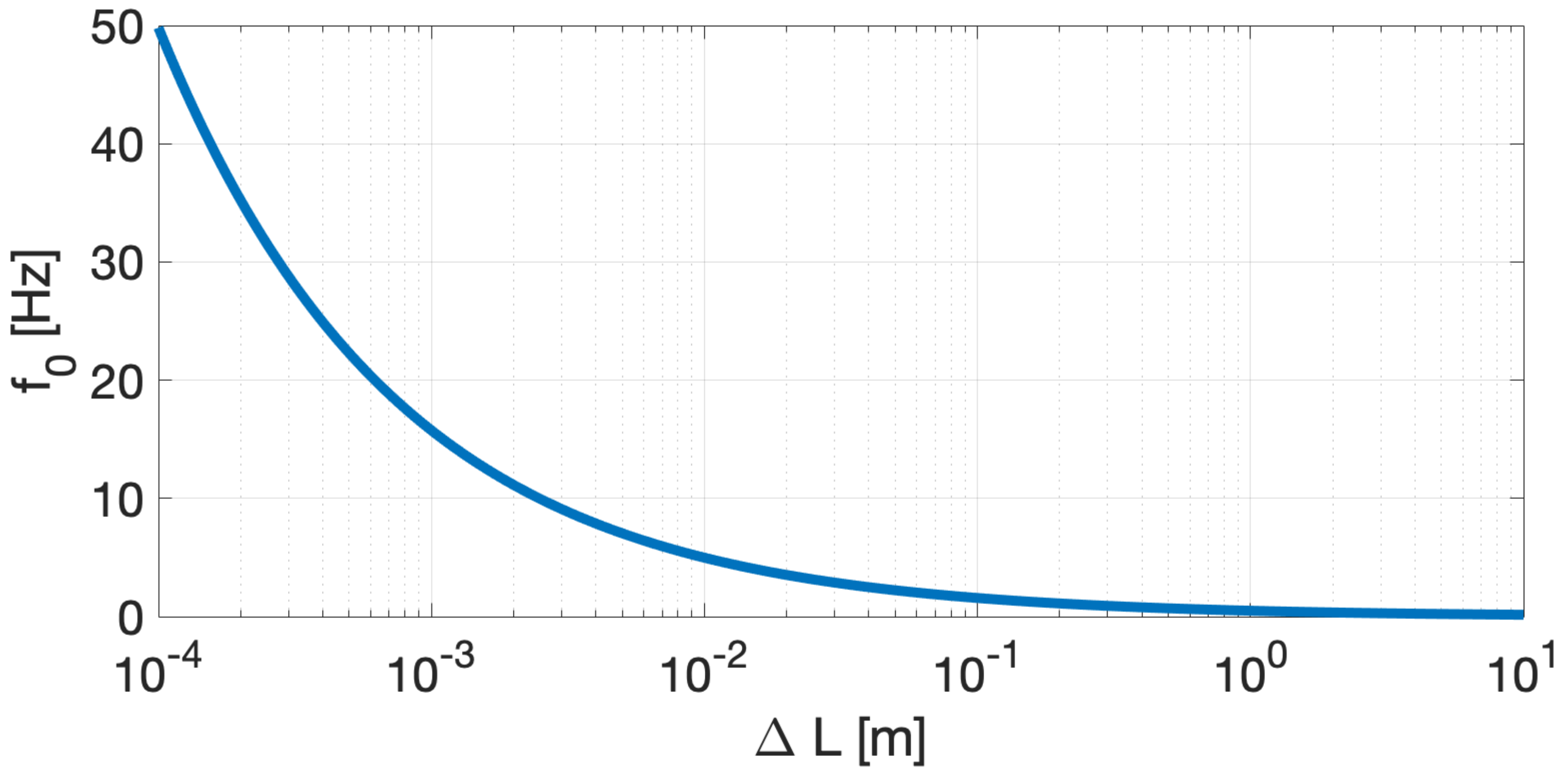
Harmonic oscillator as low-pass filter

$$G(\omega) = \frac{\omega_0^2}{\sqrt{(\omega^2 - \omega_0^2)^2 + (\omega\omega_0/Q)^2}}$$

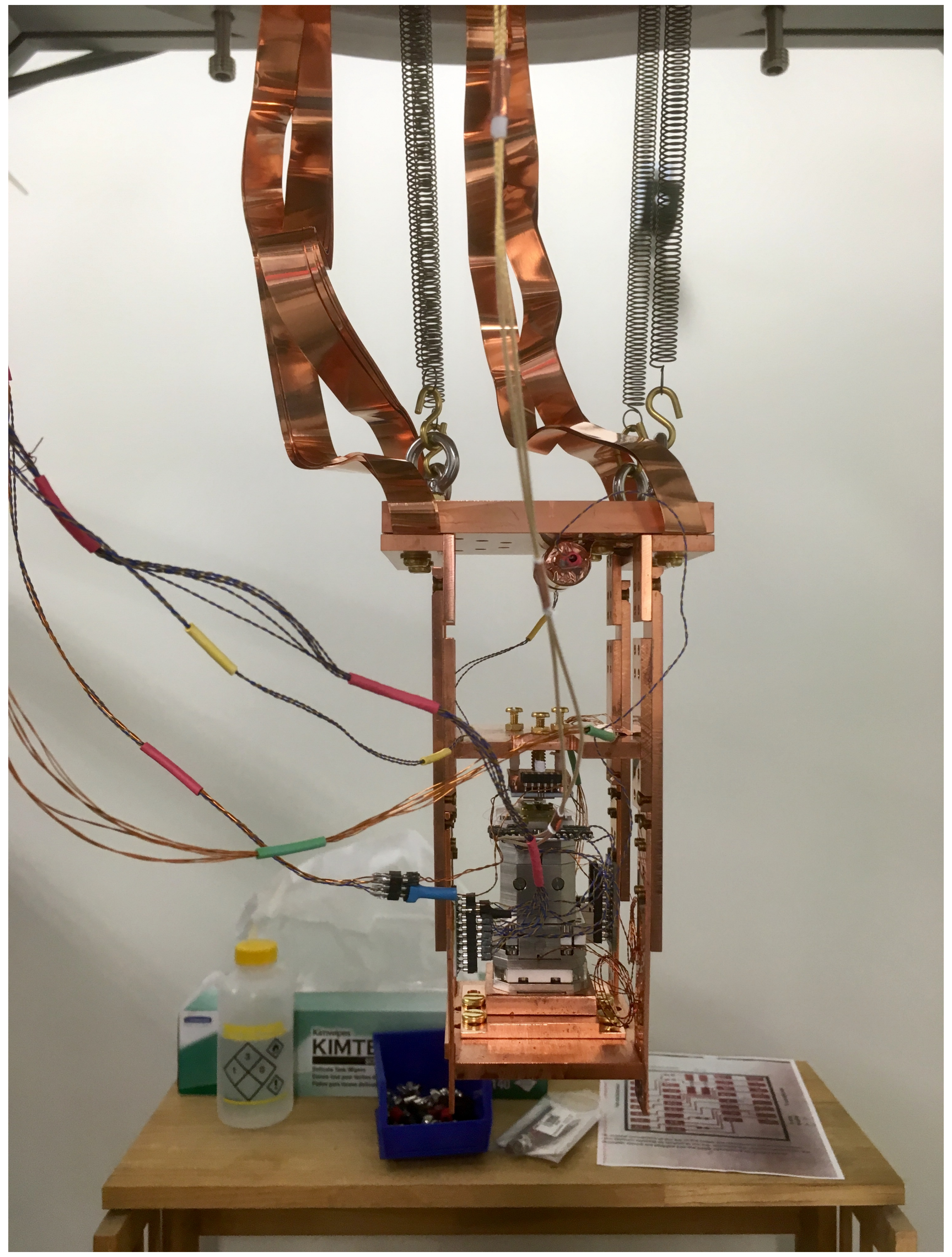




$$2\pi f_0 = \sqrt{\frac{g}{\Delta L}}$$

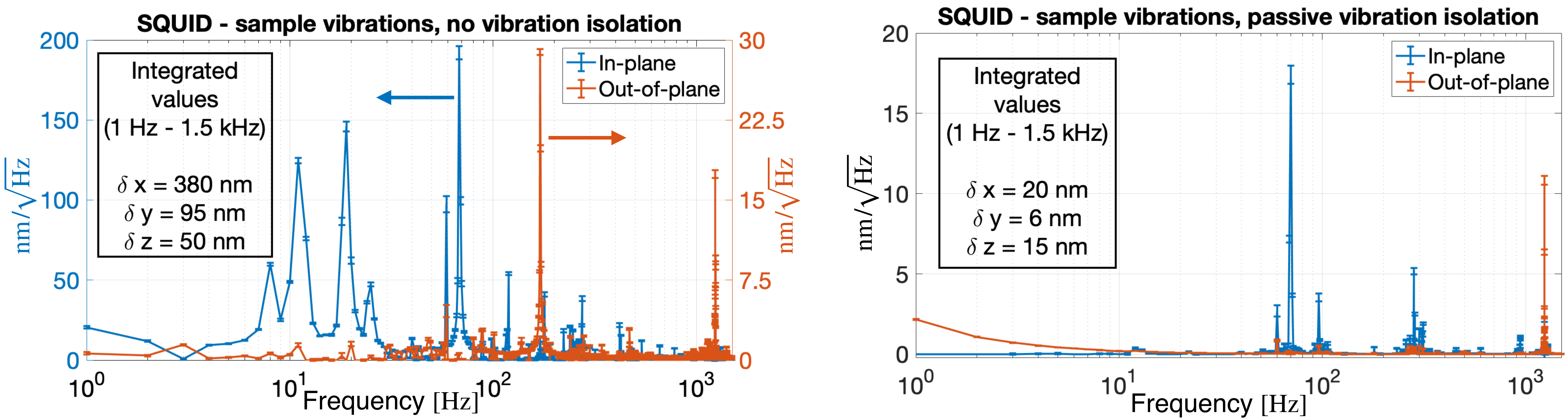


$$\Delta L \approx 10\,\text{cm} \rightarrow f_0 \approx 1.6\,\text{Hz}$$



Other approaches:
SGM (DR): RSI **84**, 033703 (2013).
STM (DR): RSI **85**, 035112 (2014).
MRFM (DR): RSI, **90**, 015112 (2019).

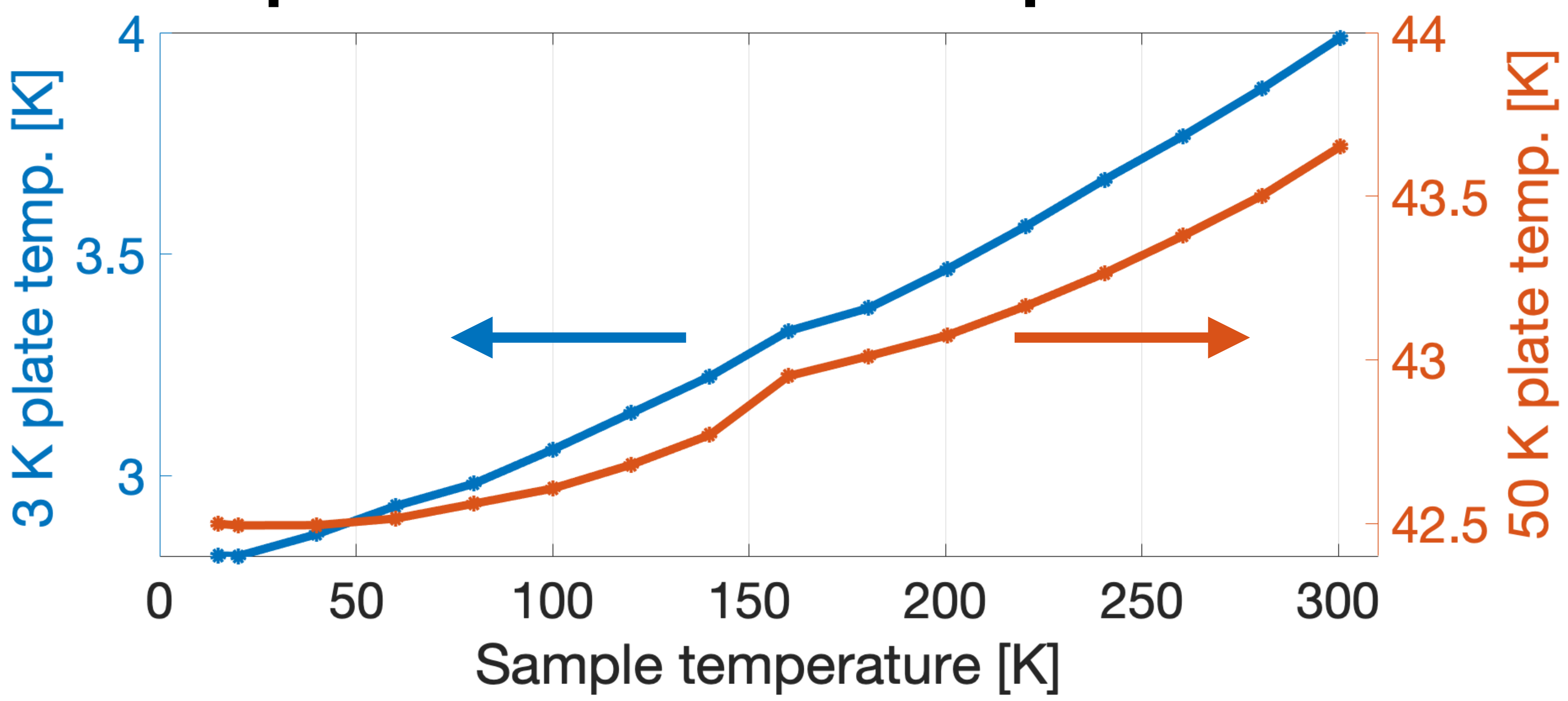
Passive vibration isolation

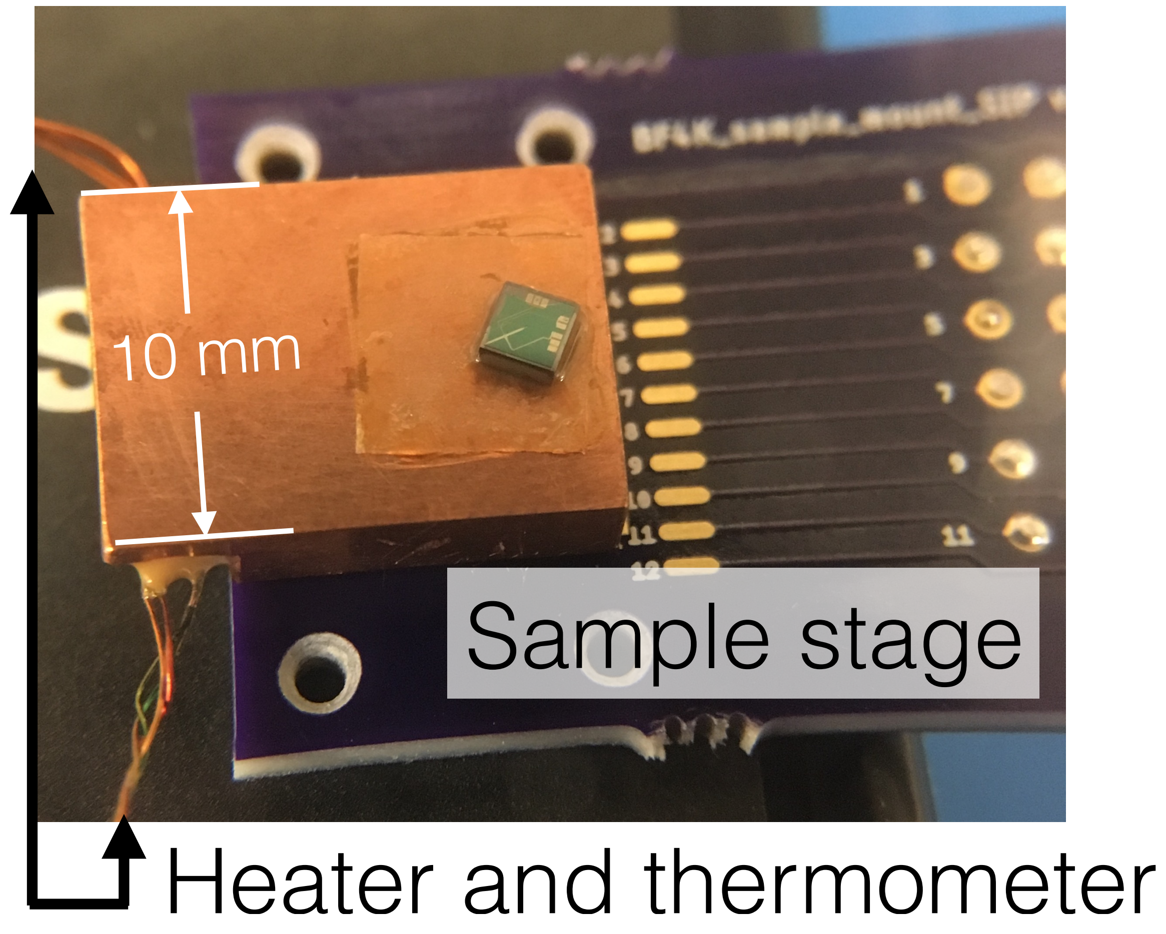


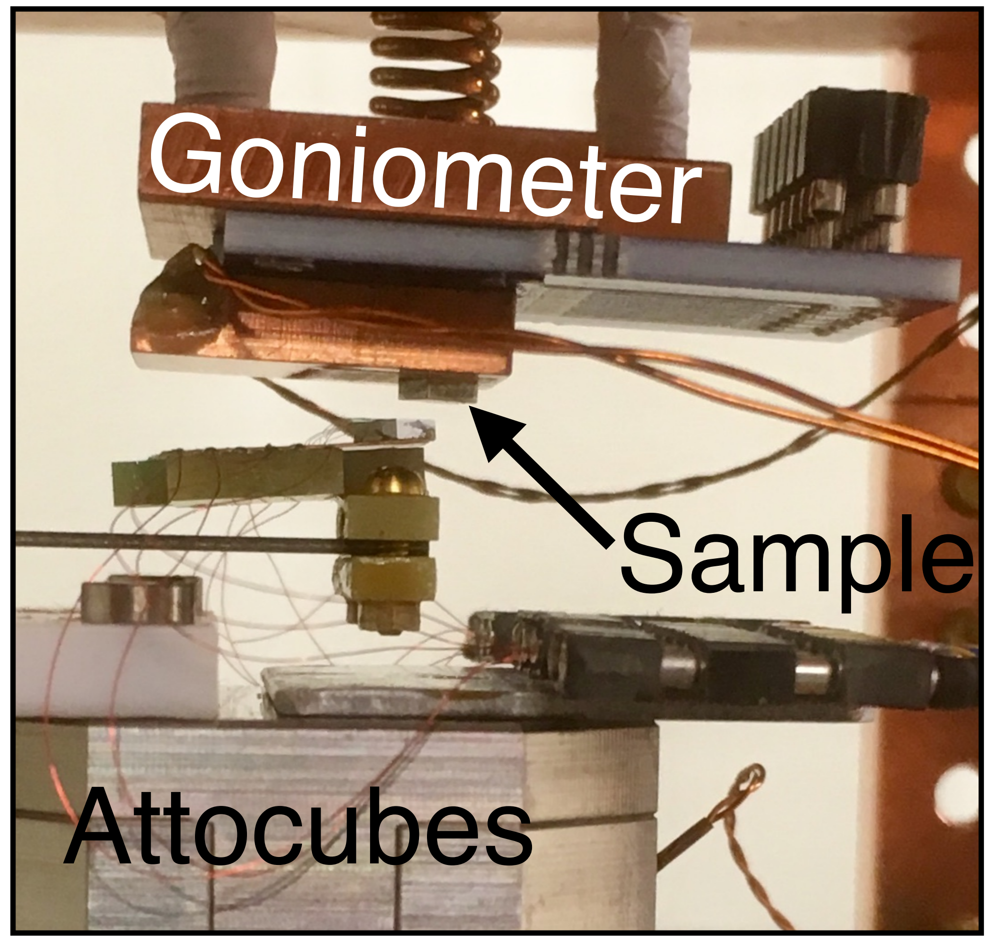
Thermal isolation for variable sample temperature operation

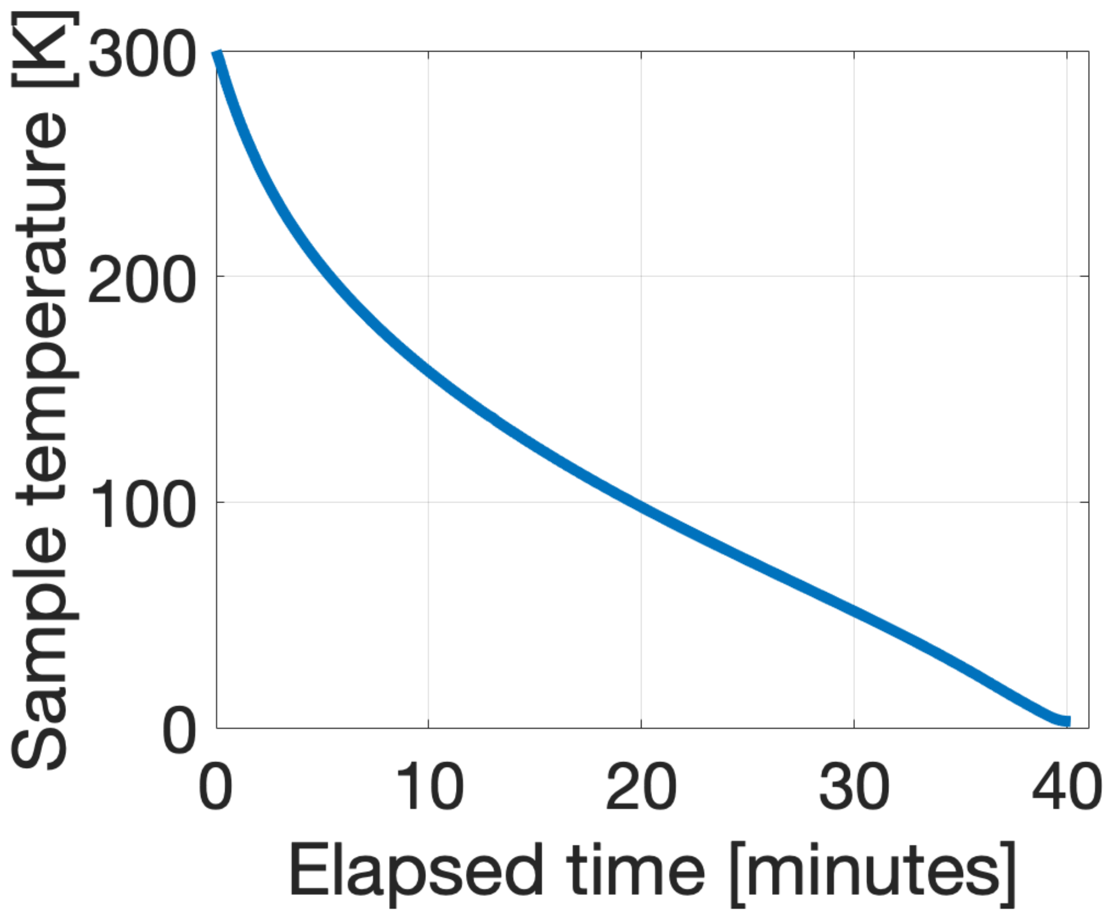
Interesting physics accessible with variable sample temperatures:

- High-T_C superconductors
- Magnetic or magnet/superconductor/semiconductor hybrid devices
- Hydrodynamic electron flow in condensed matter systems
- …









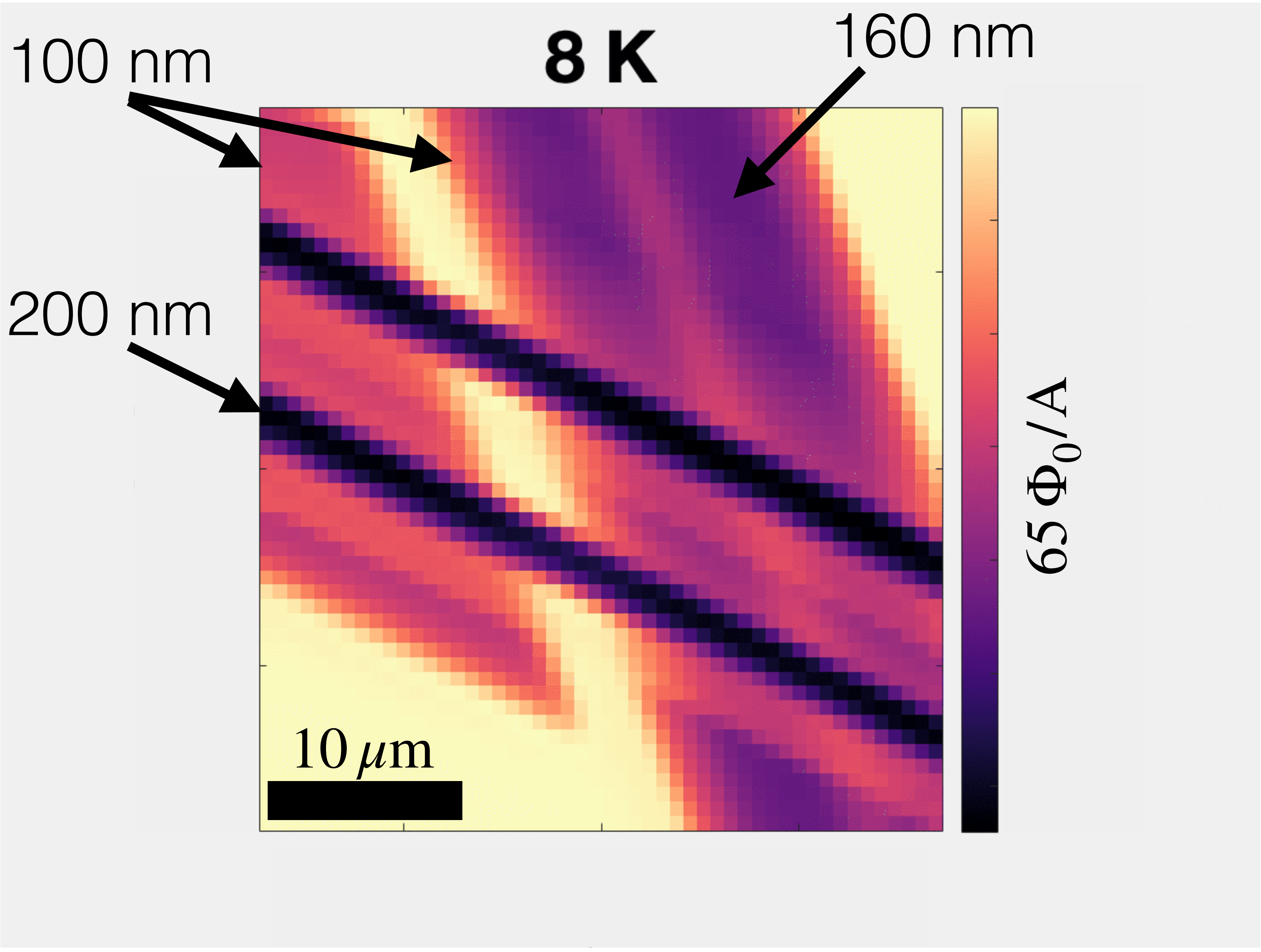
Implementation:

- Sample stage thermally isolated from cage by FR4 PCB substrate
- Sample stage leads isolated by vacuum and heat sunk directly to 3 K plate
- Sample stage cooling provided by heater leads
- Cryogen-free —> no need for exchange gas

Microscope heats up to ~9 K when sample is at 110 K due to conduction through FR4 PCB substrate.

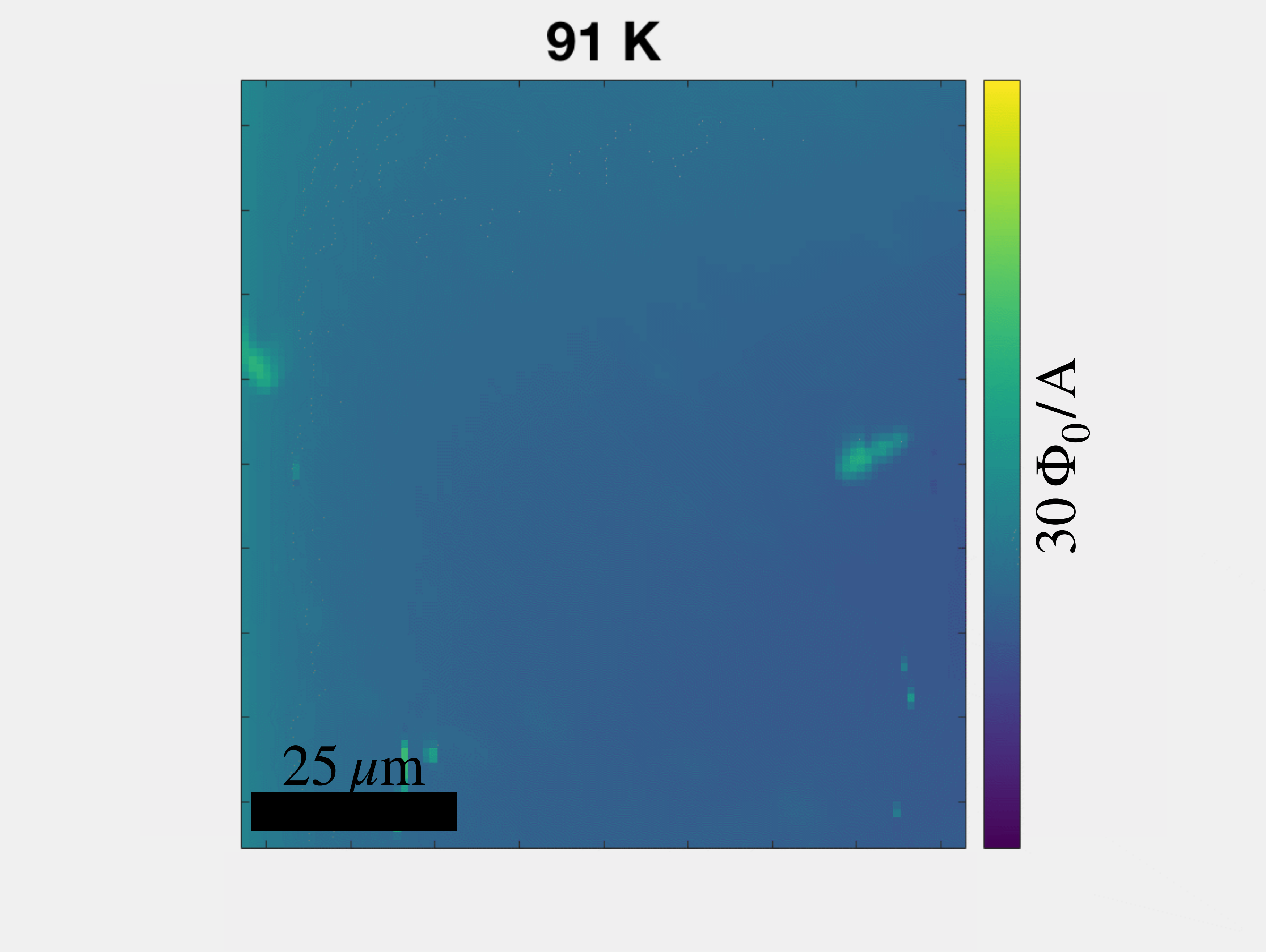
Variable temperature operation

Niobium tri-layer device

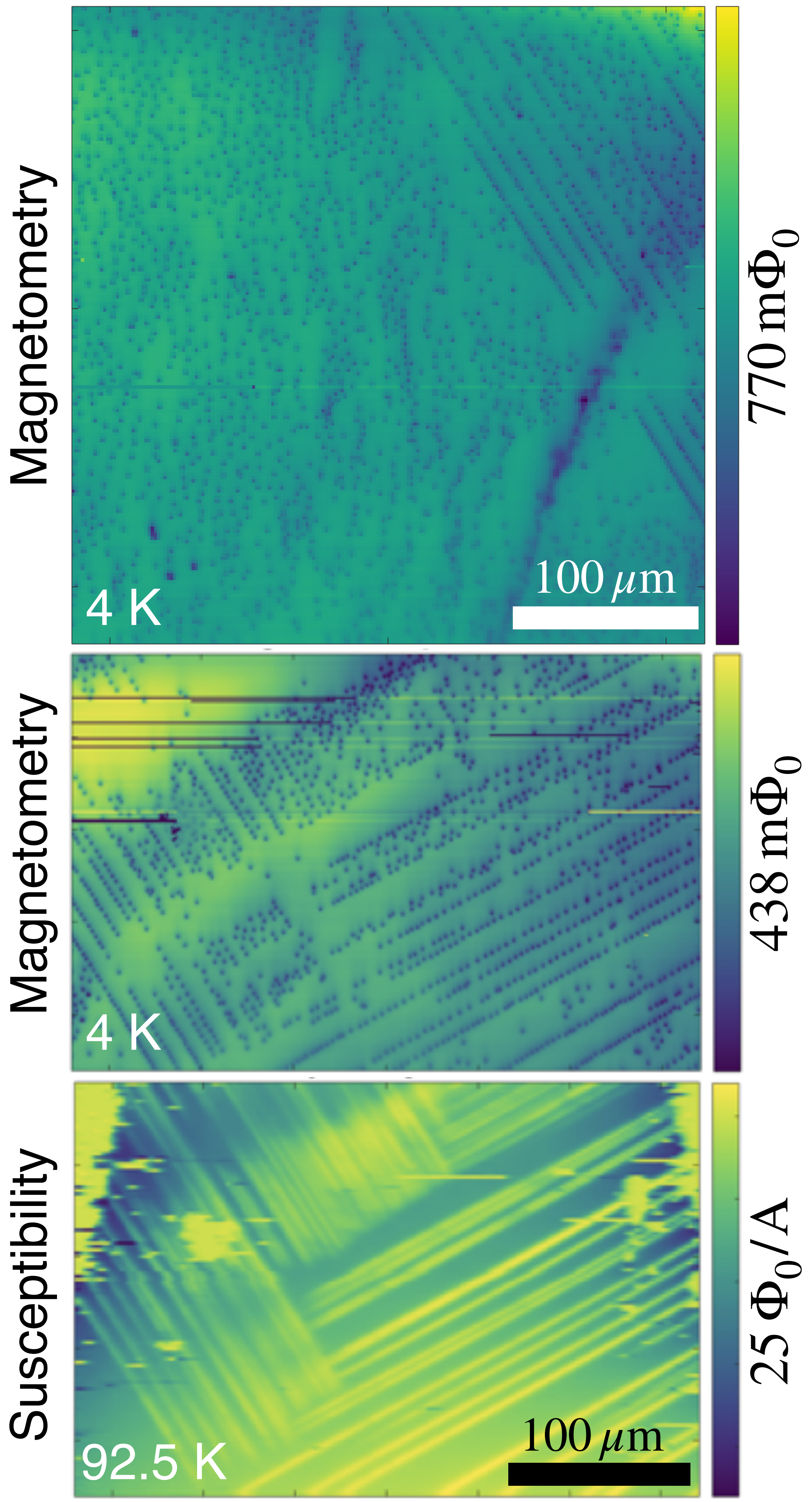


- Nominal T_C = 9.2 K
- Thinner layers have lower T_C

Twinned optimally-doped YBCO single crystal



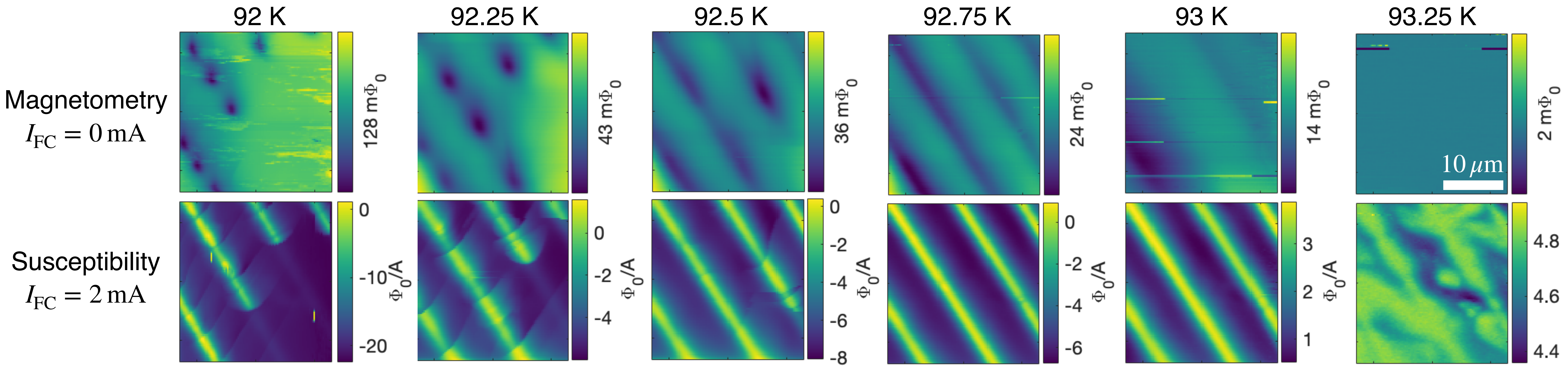
- Nominal T_C = 93 K
- Twin domain boundaries have lower T_C
- Vortices preferentially pin on twin domain boundaries



(darker <—> more diamagnetic)

YBCO provided by Ruixing Liang, Doug Bonn @ UBC.

Watching vortices "melt" at T_C



- Vortices trapped on twin domain boundaries after cooling in applied field
- Penetration depth diverges as T —> T_C, so flux in vortices becomes less localized
- Sharp features in susceptibility below 92.75 K are from vortices moving under Lorentz force from FC current

YBCO provided by Ruixing Liang, Doug Bonn @ UBC.

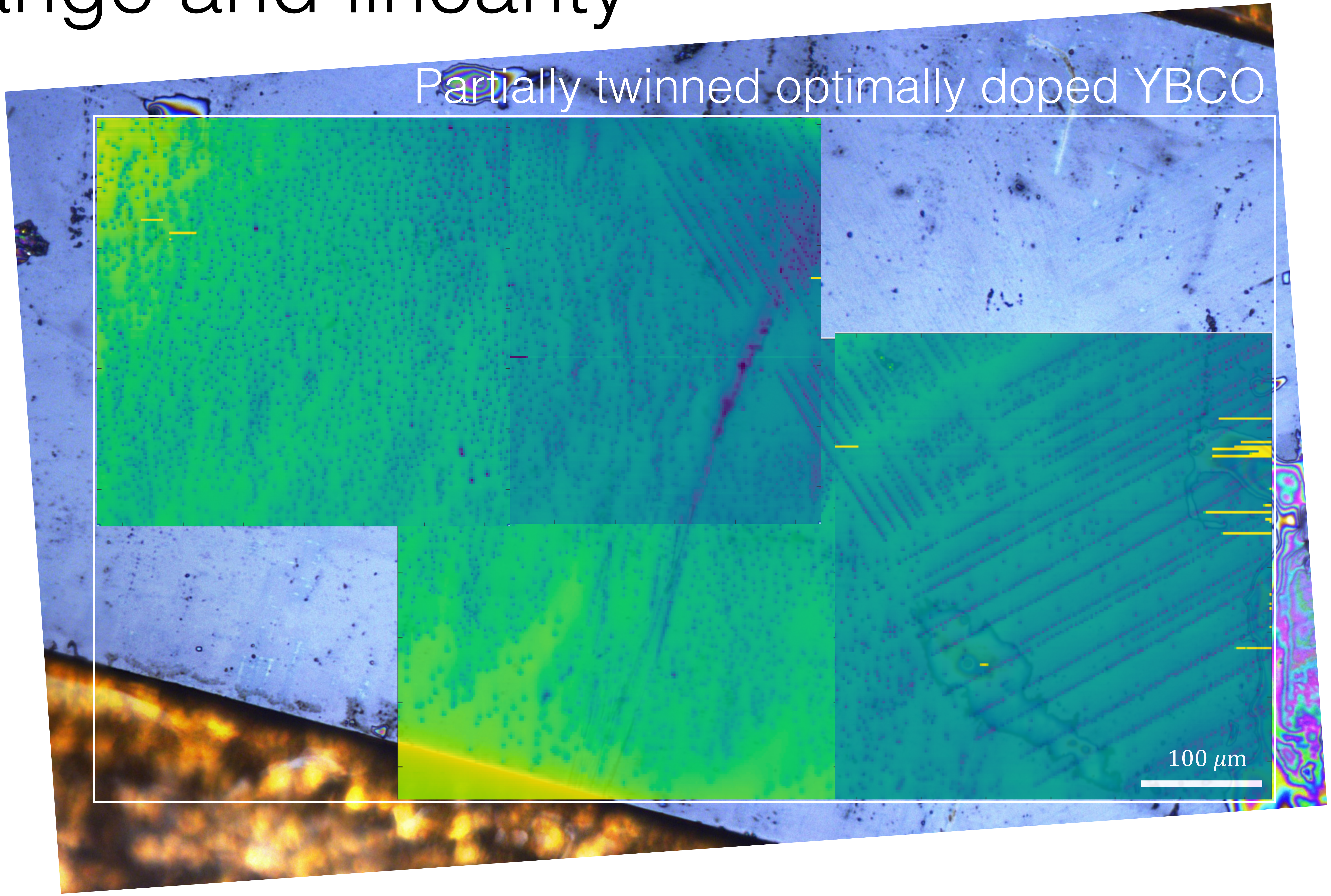
Conclusion

- Vibration-related noise reduced below our threshold for detection over most of frequency spectrum
- Microscope can measure samples at temperatures from 3K to 110 K
- Limiting factor is conduction through FR4 PCB substrate
  - FR4 thermal conductivity increases 10x from 3 K to 100 K
  - —> Decrease surface area and/or increase thickness of insulating layer between sample and microscope

Acknowledgments

- Ruixing Liang and Doug Bonn @ UBC for providing YBCO sample
- SQUID sensor development: NSF IMR-MIP Grant No. DMR0957616.
- This work: DOE Office of Science BES MSE, Contract No. DE-AC02- 76SF00515

Scan range and linearity



YBCO provided by Ruixing Liang, Doug Bonn @ UBC.