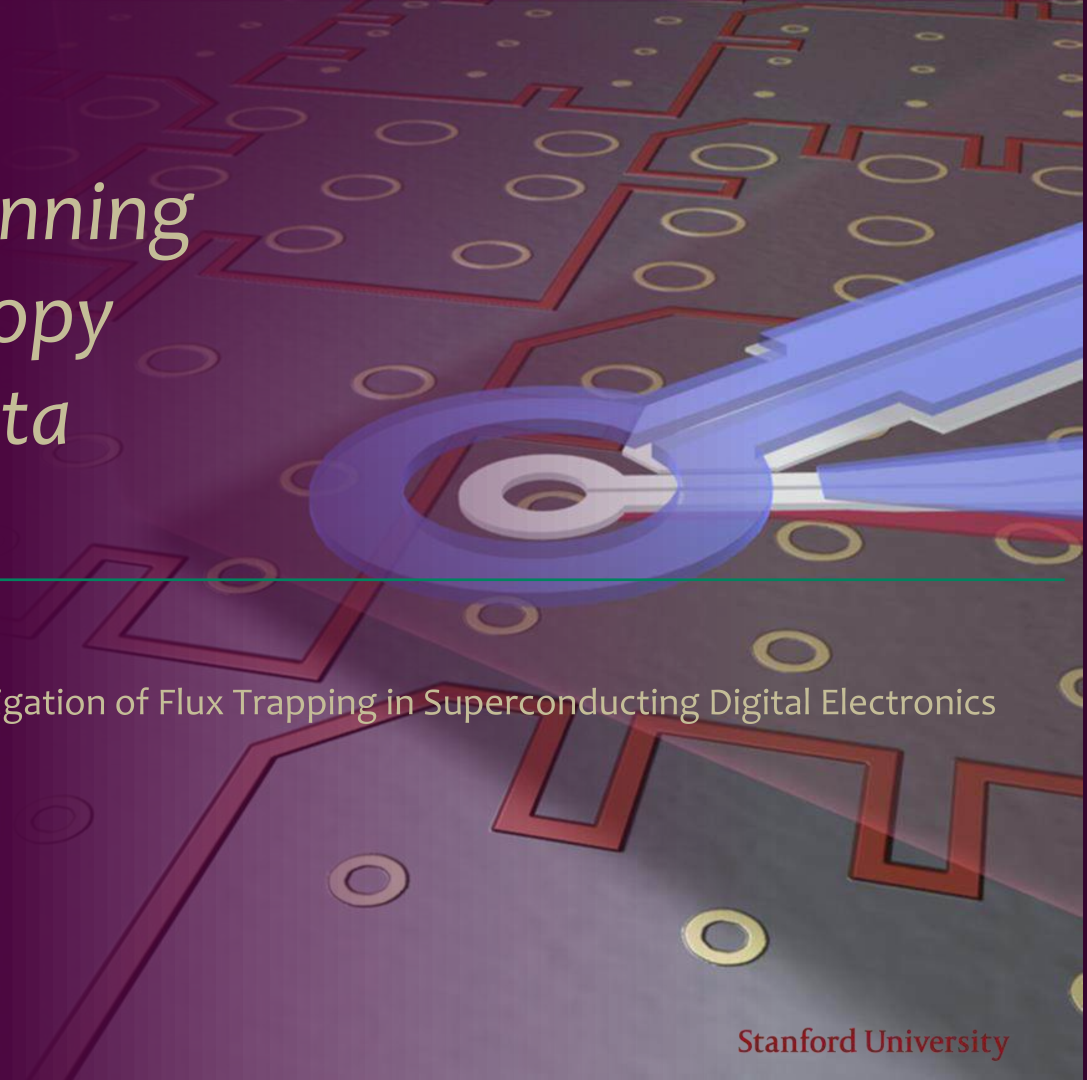
Title and Abstract

- **Title:** Optimizing Scanning SQUID Microscopy for Efficient Data Acquisition
- **Abstract:** Scanning SQUID Microscopy is a powerful technique for imaging magnetic fields, magnetic susceptibility, and current flow with high sensitivity. This presentation will discuss key considerations for acquiring meaningful data from SQUID microscopy images of superconducting circuits, including optimizing scan parameters, understanding noise sources, and interpreting image features. We will also explore strategies for increasing sample throughput.

Optimizing Scanning SQUID Microscopy for Efficient Data Acquisition



Kam Moler

Workshop on Detection and Mitigation of Flux Trapping in Superconducting Digital Electronics

December 13, 2024

Yokohama National University

Stanford University

General Considerations for Scanned Probe Sensors

spatial resolution

spatial range

measured functionality

sensitivity, eg magnetic

- field
- flux
- force
- force gradient
- spin
- current

bandwidth

operating range, eg T, B, P

invasiveness

interpretability

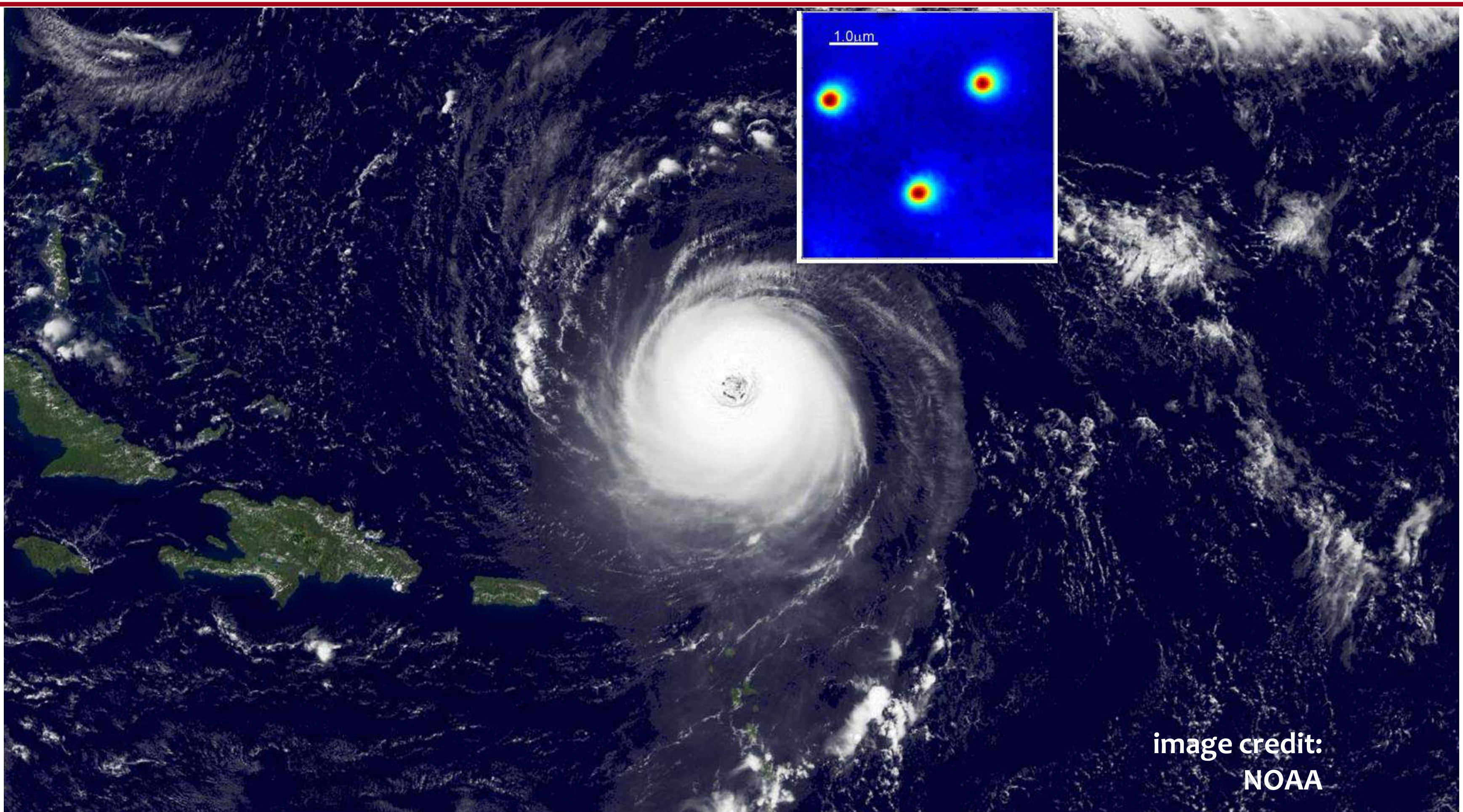
ease of use

throughput

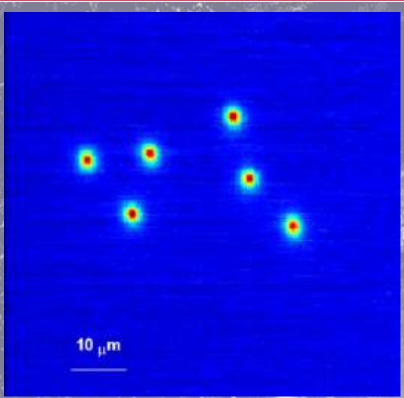
Many magnetic imaging techniques can see vortices

- Scanning solid state sensors
  - Magnetic Force Microscopy
  - Superconducting QUantum Interference Devices
  - Hall probes
  - GMR
  - STM
- Beam-based techniques
  - SEMPA
  - Lorentz microscopy
  - TEM holography
  - X-rays, eg XMCD
- Optical/sensor techniques
  - Specialized magneto-optics
  - NV centers
  - Cold atom clouds and chips

Vortices with Quantized Magnetic Flux in Quantum Systems

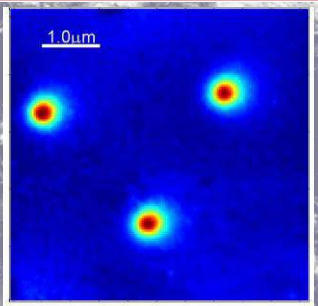


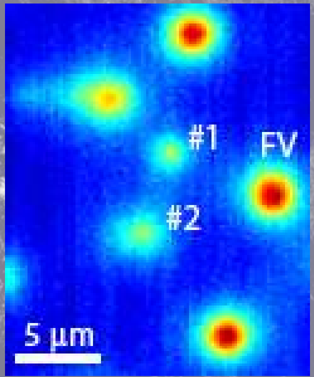
Vortices with Quantized Magnetic Flux in Quantum Systems



Sr_2RuO_4

✗ no chiral currents





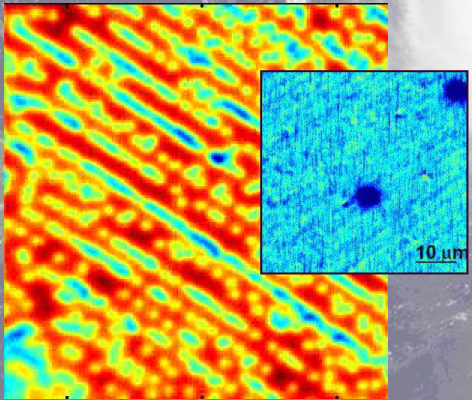
$YBa_2Cu_3O_{7-\delta}$

✓ anisotropic pinning potentials

✓ vortices act like elastic strings

✓ interlayer vortices at $7-\delta = 6.34$

✗ no visons at any δ

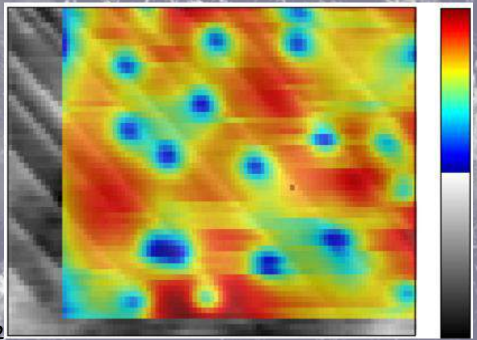


$ErNi_2B_2C$

✓ vortices pin on twin boundaries in AFM state

✗ no spontaneous vortex lattice in magnetic state

✓ nanoscale magnetic texture in magnetic state

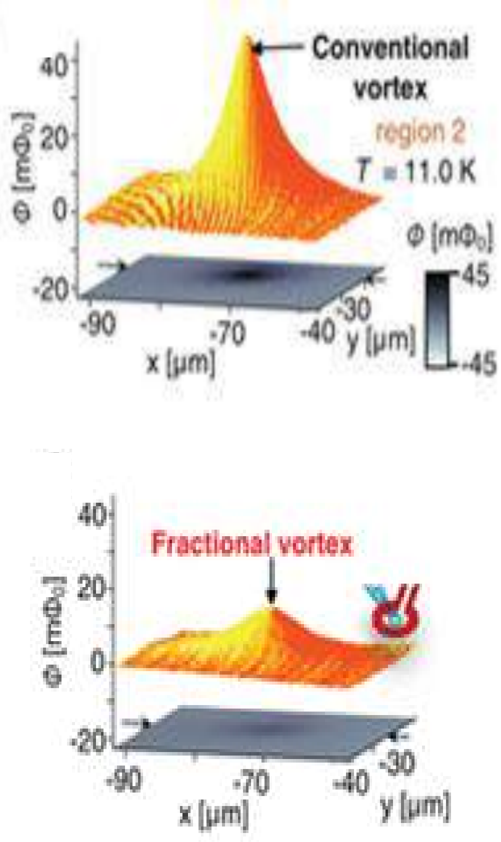


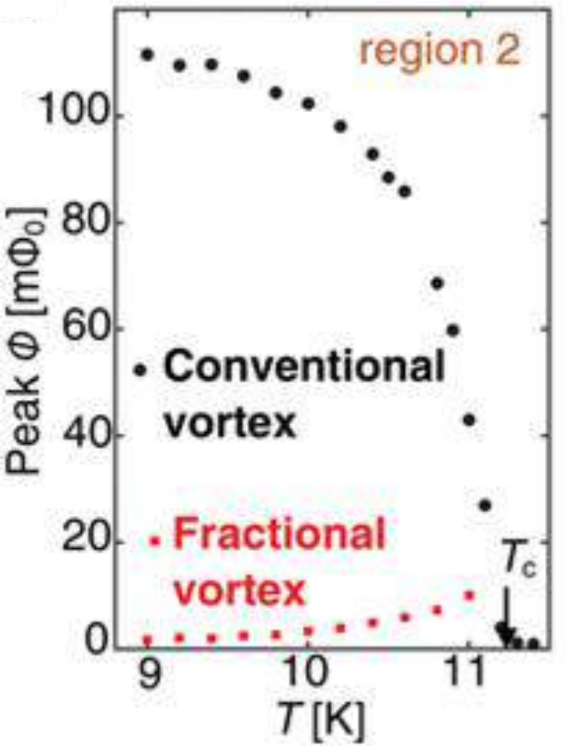
$Ba(Fe_{1-x}Co_x)_2As_2$

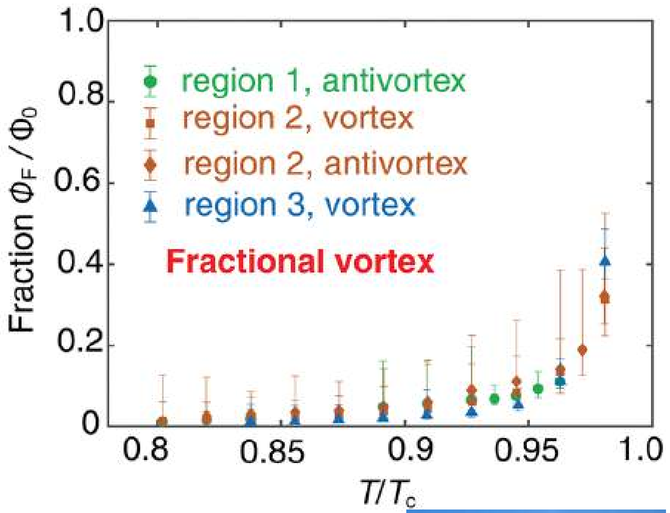
✓ twin boundaries act as barrier to vortex motion

✓ enhanced superfluid density at twin boundaries

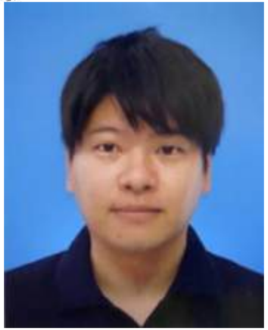
Observations of Un-quantized Vortices in $Ba_{1-x}K_xFe_2As_2$ (x = 0.77)







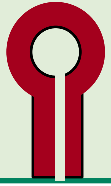
Yusuke Iguchi *et al.*, Superconducting vortices carrying a temperature-dependent fraction of the flux quantum. *Science* **380**, 1244-1247(2023).

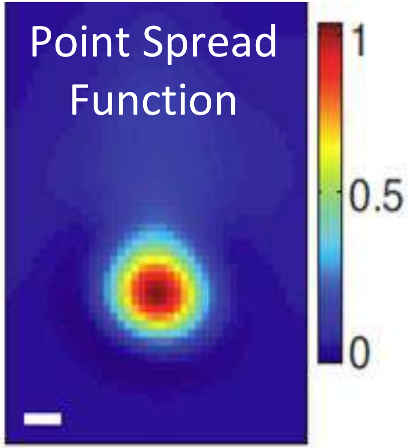


Scanning SQUID Microscopy

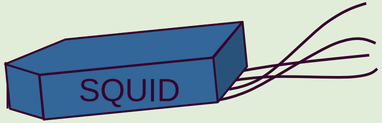
Spatial Resolution

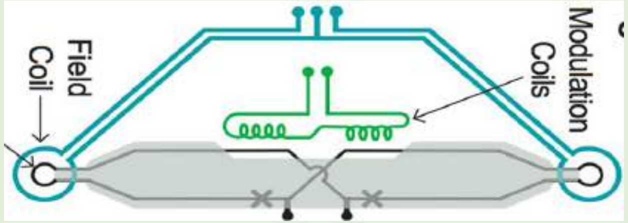
Pickup Loop 0.2-5.0 µm





Gradiometric & Shielded
Designed for scanning
Linear response
On-chip field coil



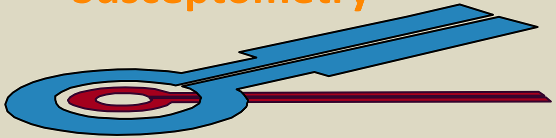


Modes of operation

Magnetometr y

Field captured by pickup loop.

Susceptometry

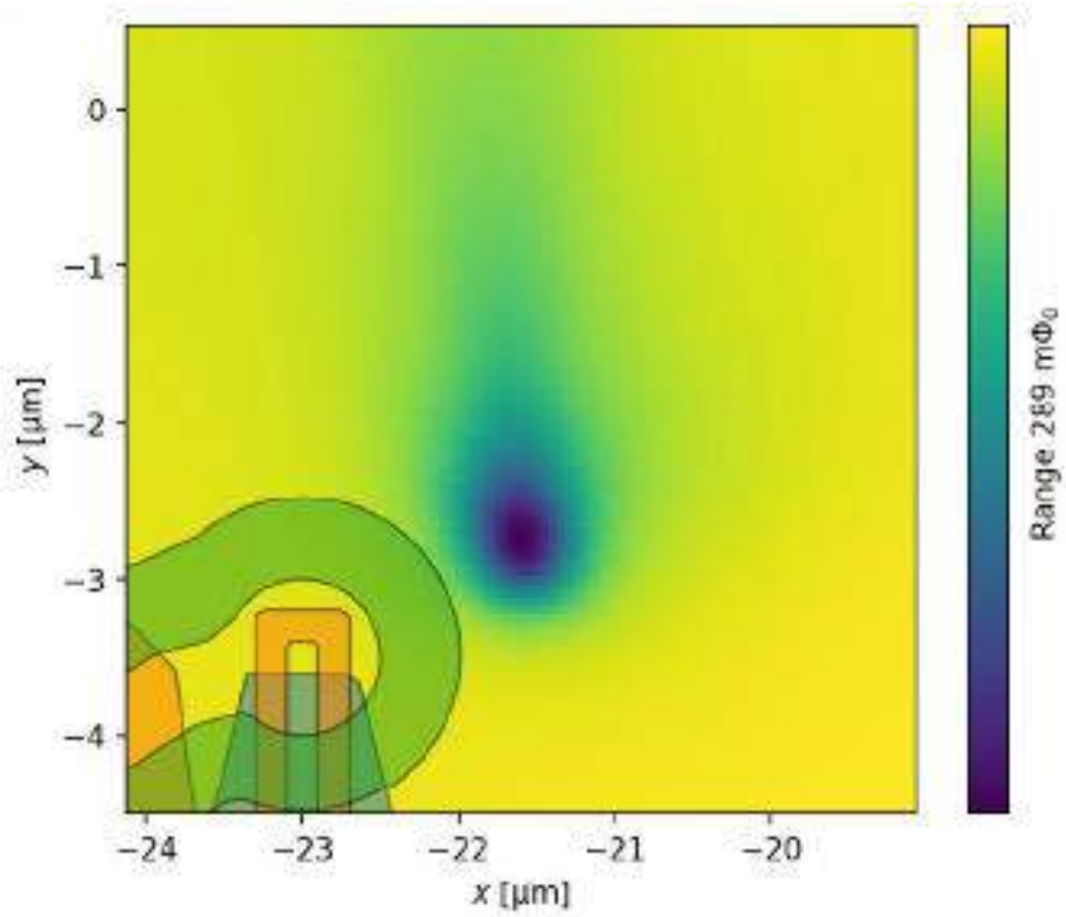


pickup loop is locked to response from AC current in the field coil

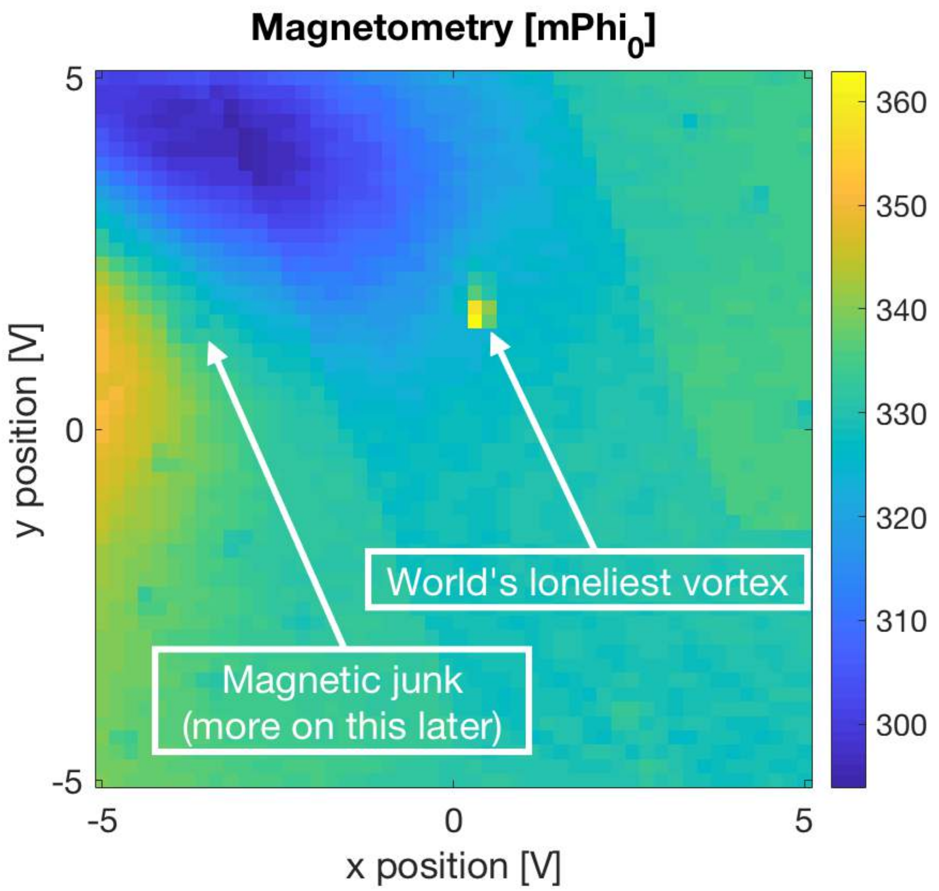
Current Imaging

curren
t pickup loop is locked to response from AC current through the sample.

Example of Magnetometry

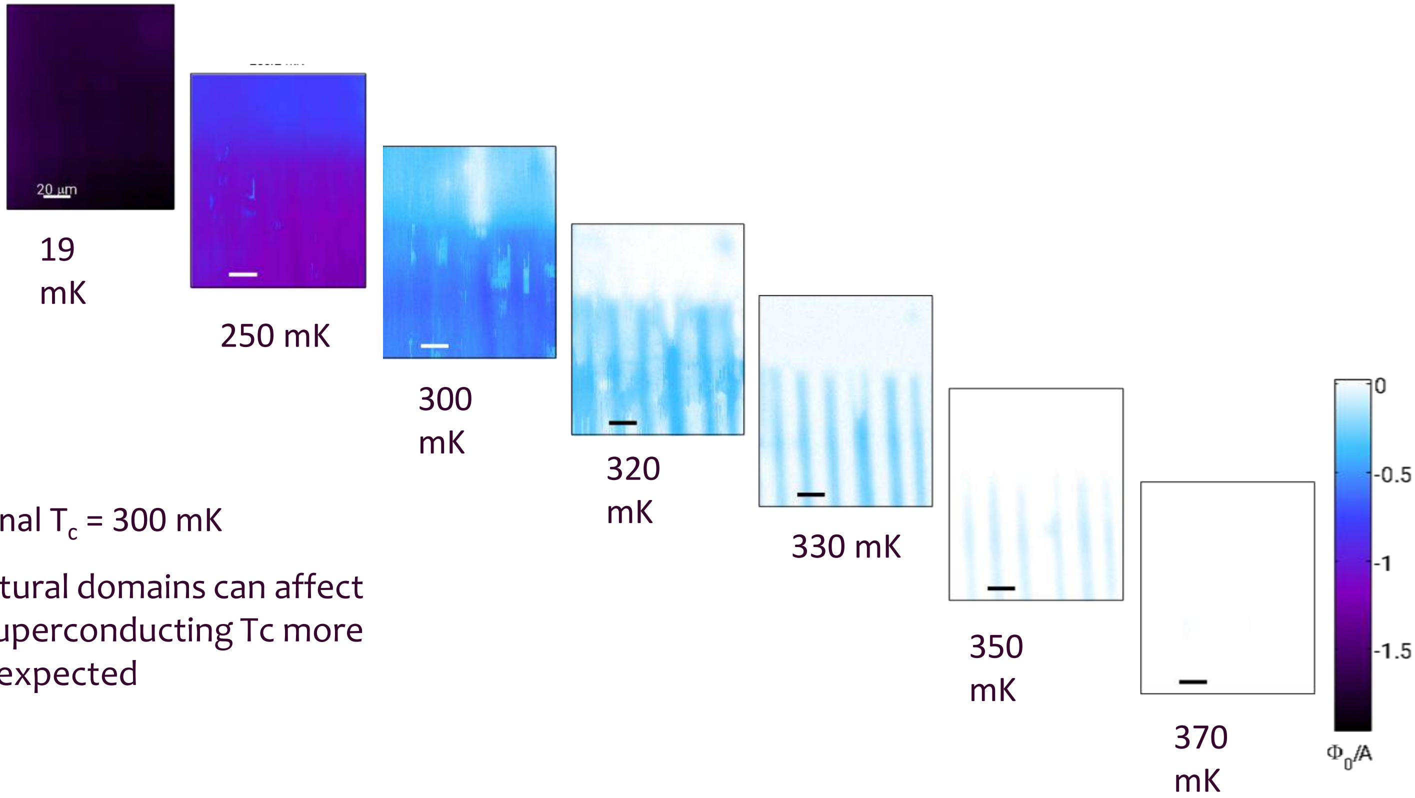


Example of Magnetometry



Example of Susceptometry

Inferring local critical temperatures and superfluid density from susceptibility

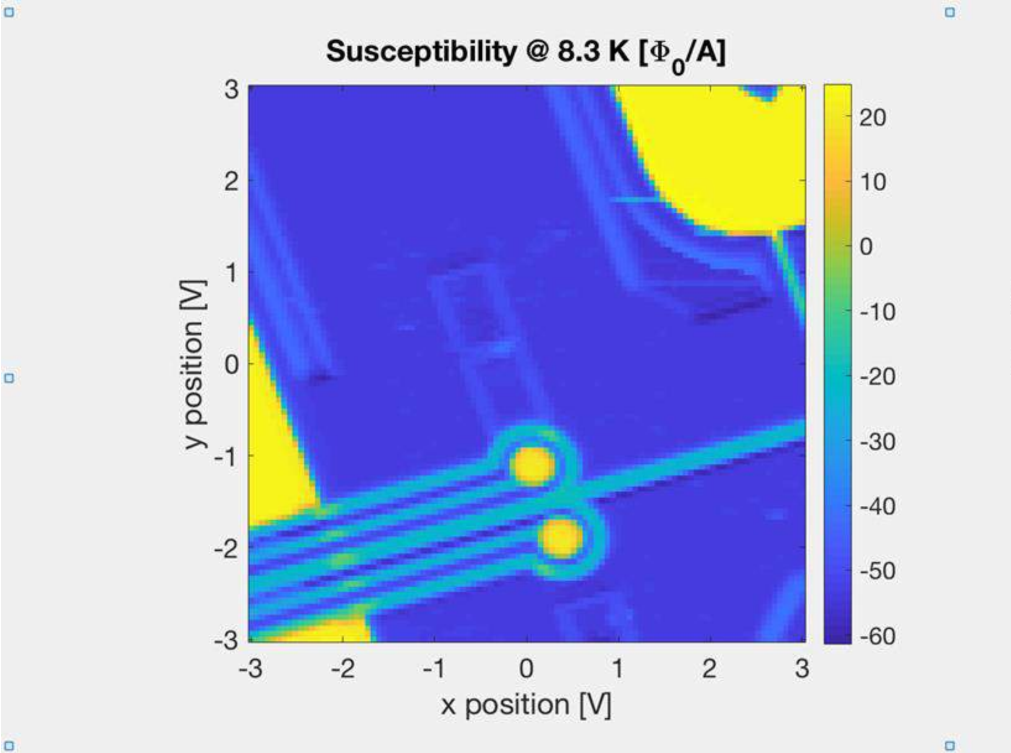


Nominal T_c = 300 mK

Structural domains can affect the superconducting Tc more than expected

Example of Susceptometry

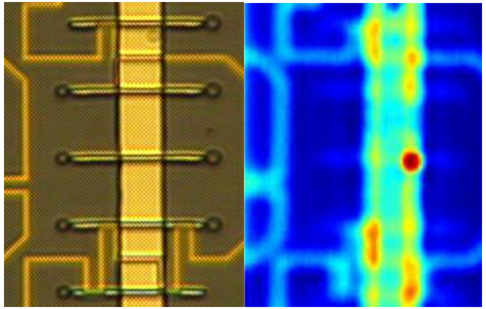
Inferring local critical temperatures and superfluid density from susceptibility

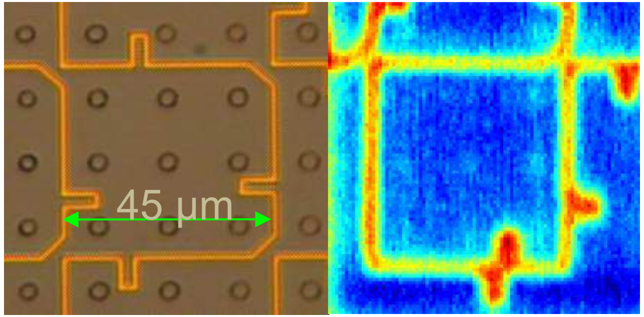


Example of Susceptometry

Paramagnetic Signal from (Unexpected) Spin Impurities

Optical Image Susceptibility Image

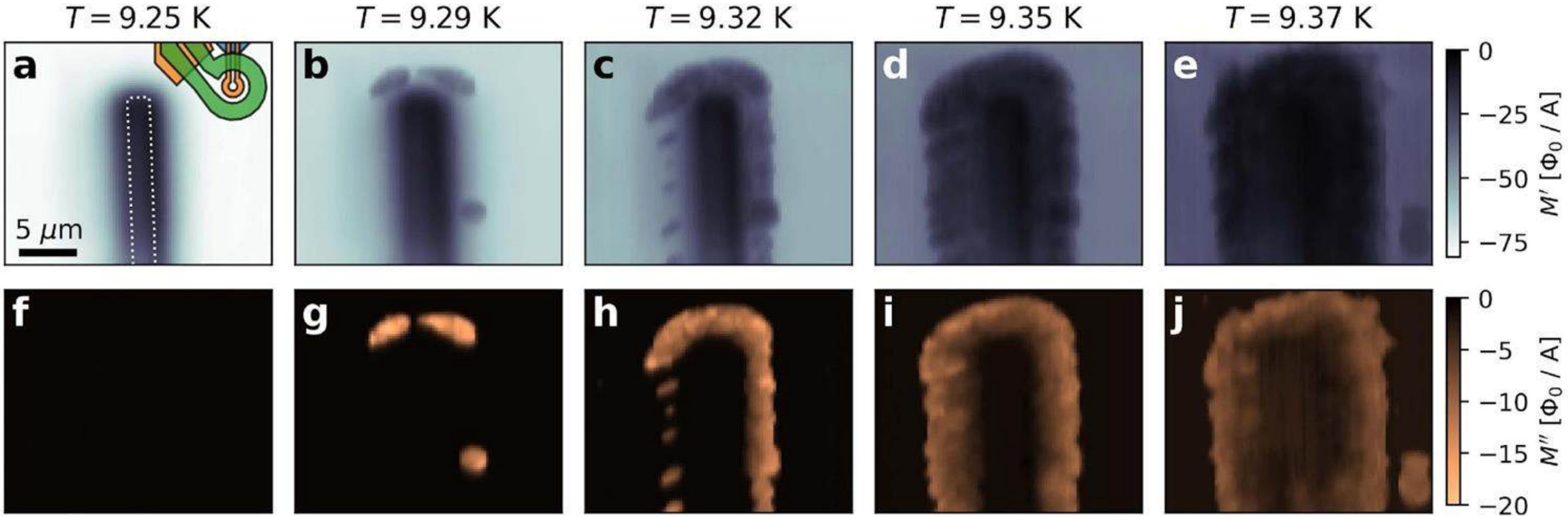




- Low-T susceptibility signal of gold films indicates an area spin density of ~$4\text{x}10^5$ µm^{-2}
- Similar to density postulated as cause of excess flux noise observed in SQUIDs and superconducting qubits

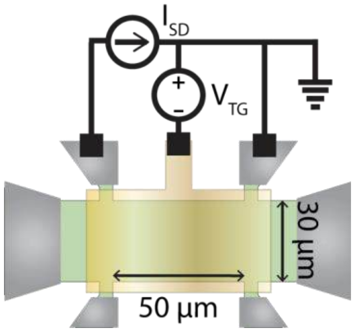
Example of Susceptometry

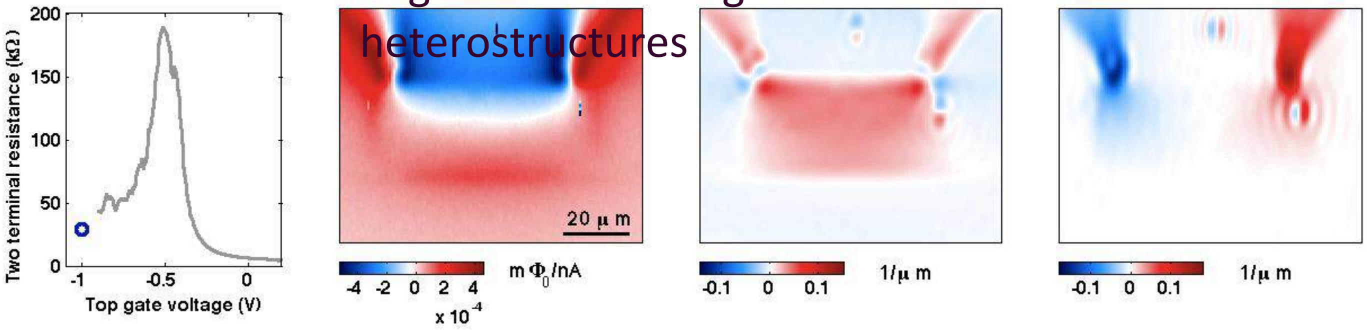
Vortex Entry near a Nb slot



Example of Imaging Current Flow

Edge Currents in HgTe heterostructures

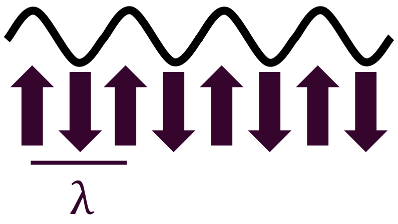




Sensor height limits spatial resolution

Hypothetical periodic field at a surface

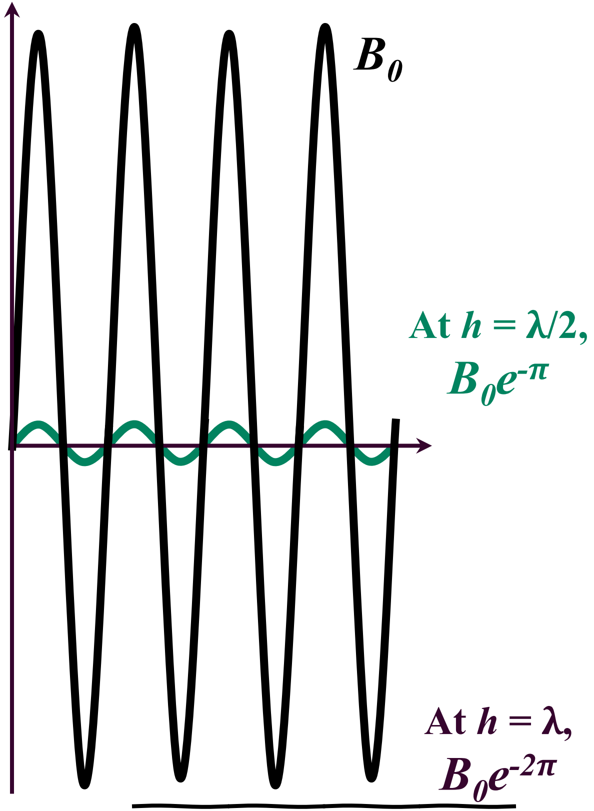
$$B_z(x, z=0) = B_0 \cos(kx)$$



$$k = {}^{2\pi}\!/_{\lambda}$$

Resulting magnetic field at a distance *h*

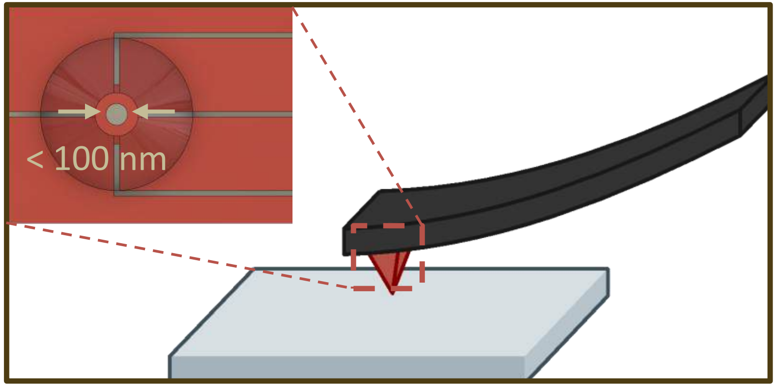
$$B_z(x, z=h) = B_0 \exp(-kh)\cos(kx)$$



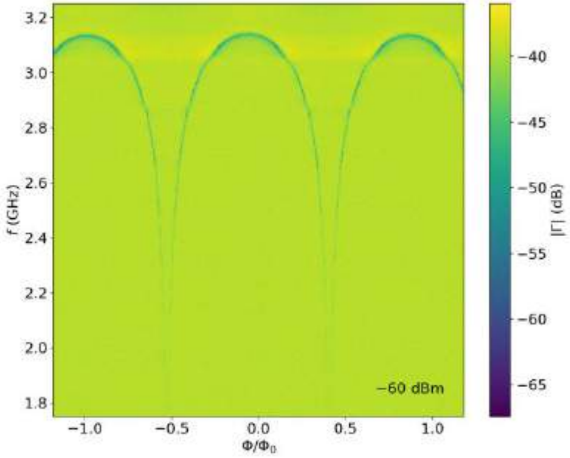
Exponential suppression of periodic signals with height on a length scale of $\lambda/2\pi$

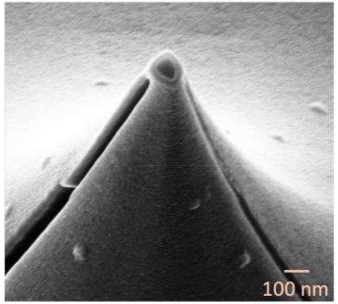
Possible Near-Term Improvements

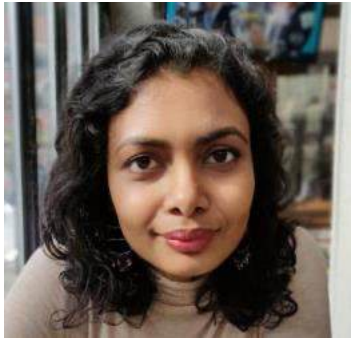
- FIB-fabricated SQUIDs
- RF (few GHz) SQUIDs
- Faster throughput



RF SQUID ~3 GHz modulation







With thanks to **Nabhanila Nandi**, Yusuke Iguchi, Elaine Taylor, and Charlotte Boettcher

WORKFLOW OPTIMIZATION FOR THROUGHPUT

With thanks to Logan Bishop-van Horn

Duration of each step of the workflow

Duration	Step
up to 2 hours	Load Sample(s)
15 hours	Cool Down
1-4 hours	Move to relevant region, scanning along the way for navigation
0.5 hours/image	Conduct experiments: collect image at various locations, temperatures, circuit parameters, etc.
~0.05 hours	Move to a neighboring region to scan for desired features or to create stitchable images; change parameters, including temperature, between images
14 hours	Warm Up

Opportunities for Faster Throughput

1. Reduce cooldown and warmup time
   - Different cryostats that allow faster turnaround
     - Rapid cooling cryostats, eg Kiutra
     - Sample exchange without warming up the whole cryostat
     - Liquid He probe (with recovery)
     - LN2 precooling
   - **Load multiple devices in each cooldown**
     - ~6 mm x 6 mm available in current cryostats

Opportunities for Faster Throughput

2. Increase physical scan speed
   - Depends on SNR and desired pixel density
   - When SNR is not an issue, the acquisition time for each image may be limited by the piezo raster speed.
     - Factors that limit the scan speed: mechanical resonances, heating, parasitic RC in fridge wiring
     - For a given geometry, there is a tradeoff between the range of the piezo scanner and the mechanical resonance frequency. Our “long-range” piezo scanners have mechanical resonances of 10s of Hz.

Image Acquisition to Find Vortices: Naïve Example

- lock-in time constant τ = 10 ms
  - Could be even less depending on expected SNR based on temperature + film thickness
- scan speed 20 pixels/second
  - Allow ~ 5 * τ seconds per pixel to avoid blurring from lock-in
- scan range ~(300 micron)^2
- pixel size (2 micron)^2
- 150^2 pixels / (20 pixels/second) = <u>**Total image acquisition time: ~ 20 minutes**.</u>

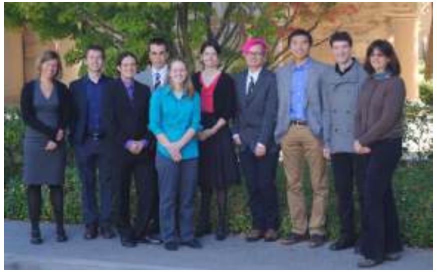
- Notes:
  1. Current scanning software is not optimized for scan speed; implementing these parameters will be straightforward.
  2. Magnetometry, susceptometry, and current flow can all be imaged simultaneously if vortices are strongly pinned
  3. If there are very large magnetic field gradients, scan rate may be limited by the slew rate of the feedback (especially for large SQUID pickup loops). In that case, you can either (1) trade off scan speed for sensitivity by using less gain on the room temperature preamplifier, or (2) trade off scan speed with spatial resolution and sensitivity by increasing SQUID standoff distance.

Opportunities for Faster Throughput

3. Improved sampling
    1. Optimize uniform rastered scans: develop algorithms, based on the most important use cases, to select the optimal pixel size, scan speed, and time constant.
    2. Develop non-uniform sampling techniques that focus on areas of interest : adapt the sampling density with non-uniform grids and (eventually) adaptive sampling algorithms.

Thank You

Katja Nowack, Ilya Sochnikov, Chris Watson, Phil Kratz, Johanna Palmstrom, Hilary Noad, **Eric Spanton,** Yihua Wang, Aaron Rosenberg.



Hilary Noad, Sam Davis, Phil Kratz, **Zheng Cui,** Ruby Shi, Aaron Rosenberg, John Kirtley, **Sean Hart,** Rahim Ullah, Chris Watson

Logan Bishop-Van Horn, Eli Mueller, Nabhanila Nandi, Yusuke Iguchi

SQUIDs

UC Denver: Martin Huber

IBM Yorktown Heights:

Gerald Gibson, Mark Ketchen

Stanford: John R. Kirtley

SIMES Moore CPN

EXTRA SLIDES