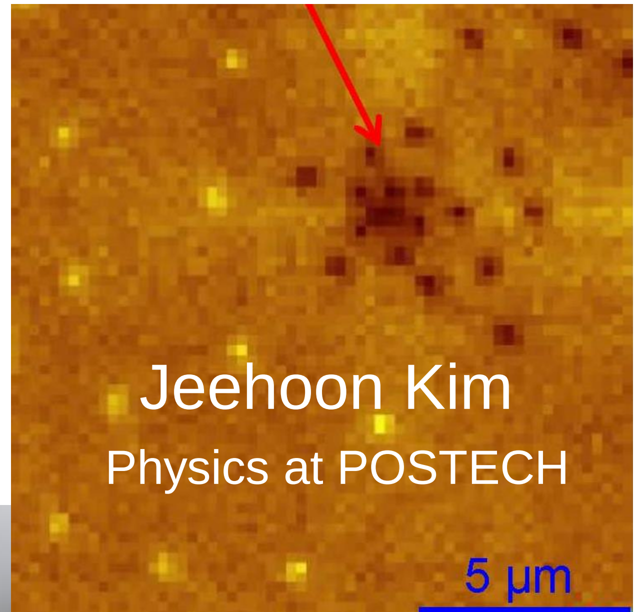
Investigation of superconductivity by MFM

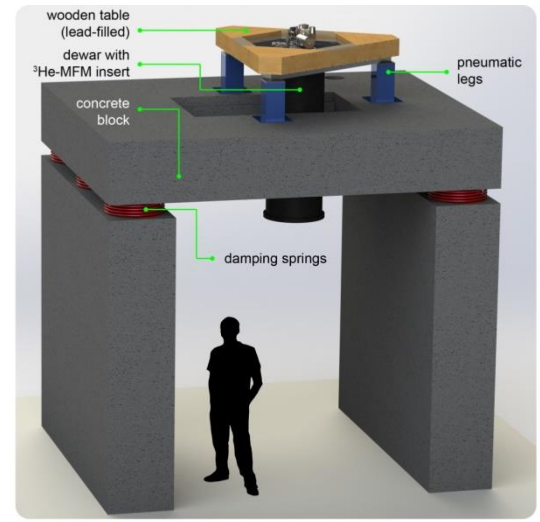
MAGNETIC FORCE MICROSCOPY LAB

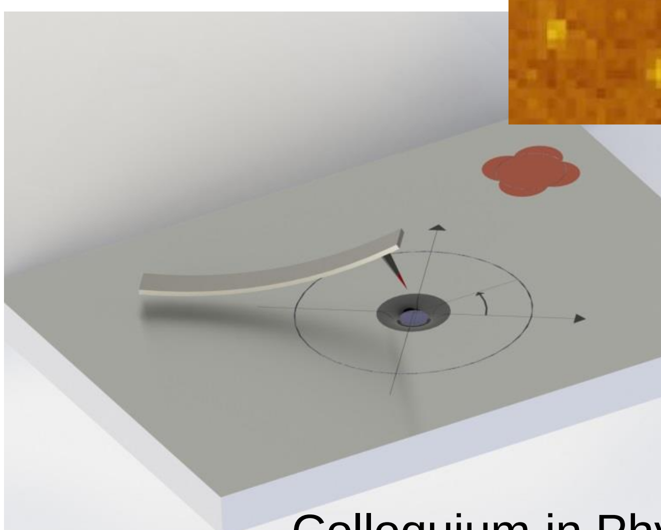


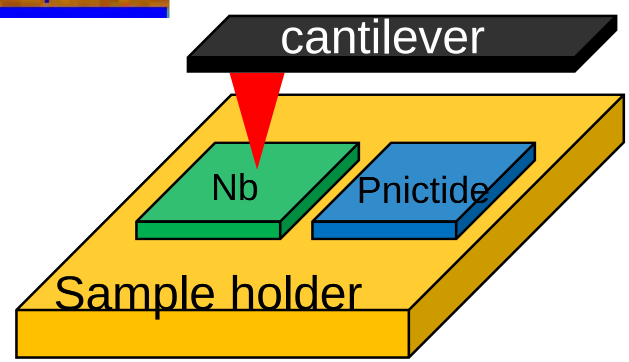
Jeehoon Kim

Physics at POSTECH

^{3}He MFM







Colloquium in Physics
Korea University

April 12, 2017

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POSTECH Researchers

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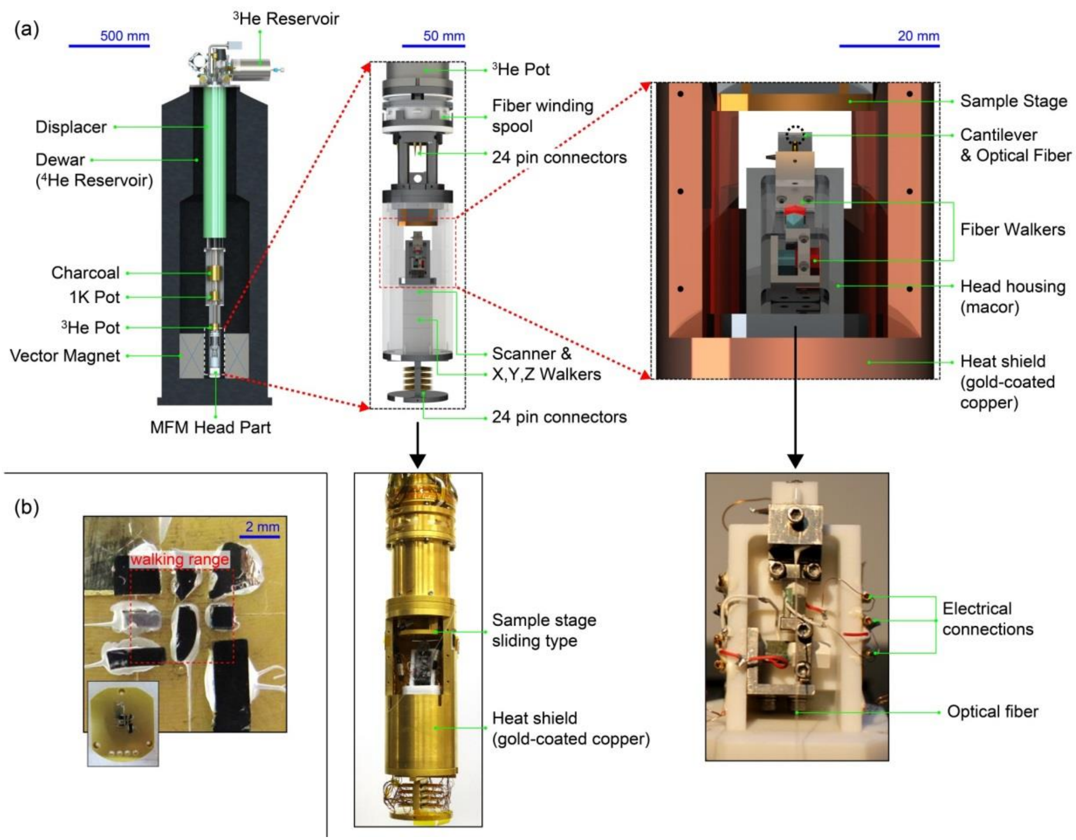
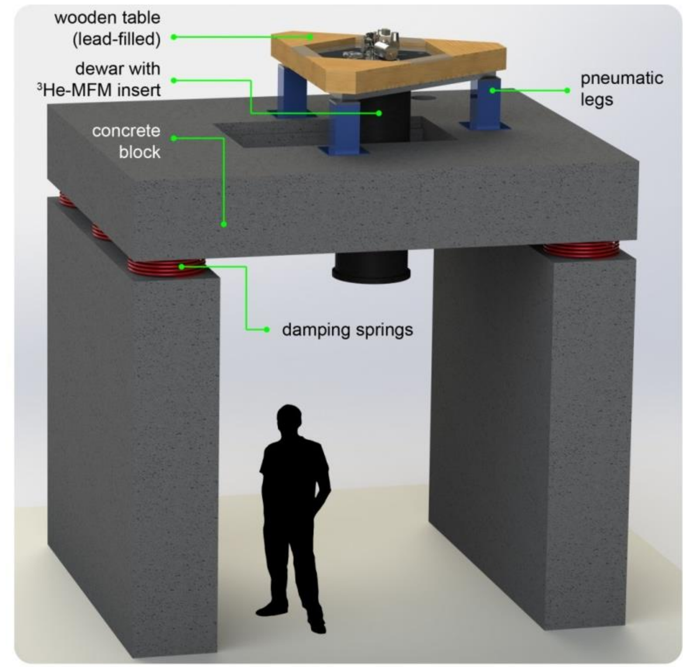
Samples from Dr. Bauer (LANL) and Prof. Cava (Princeton)

^{3}He MFM: T = 0.3 K and $\mathbf{H}_{xyz}$=2-2-9 T



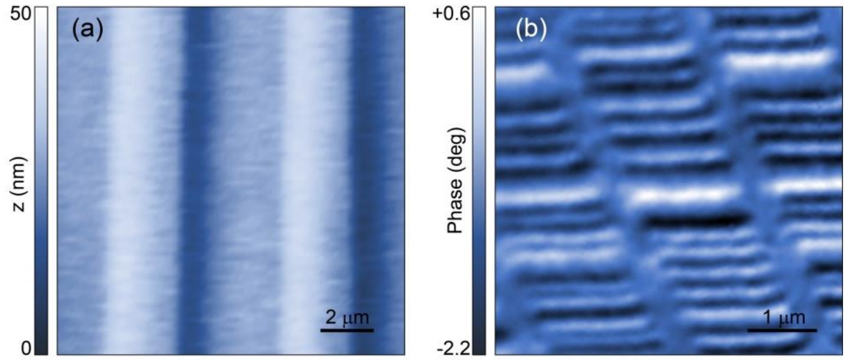


Sample temperature

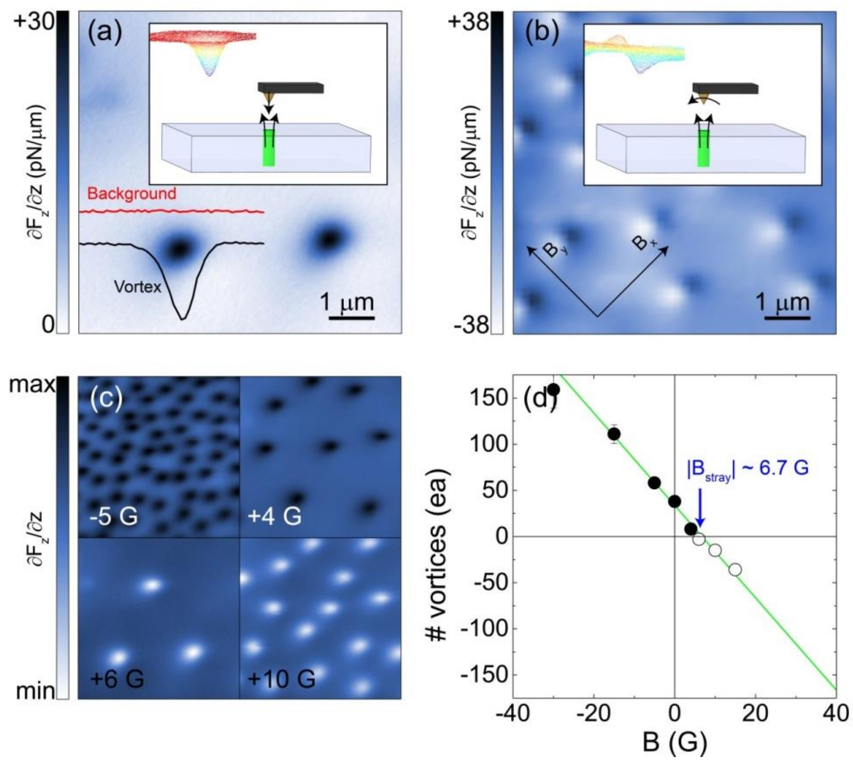
Base temperature: 0.3 K (3He)
3D vector magnet: $\mathbf{H}_{xyz}$ = 2T-2T-9T
Anti-vibration room

^{3}He MFM: Test results

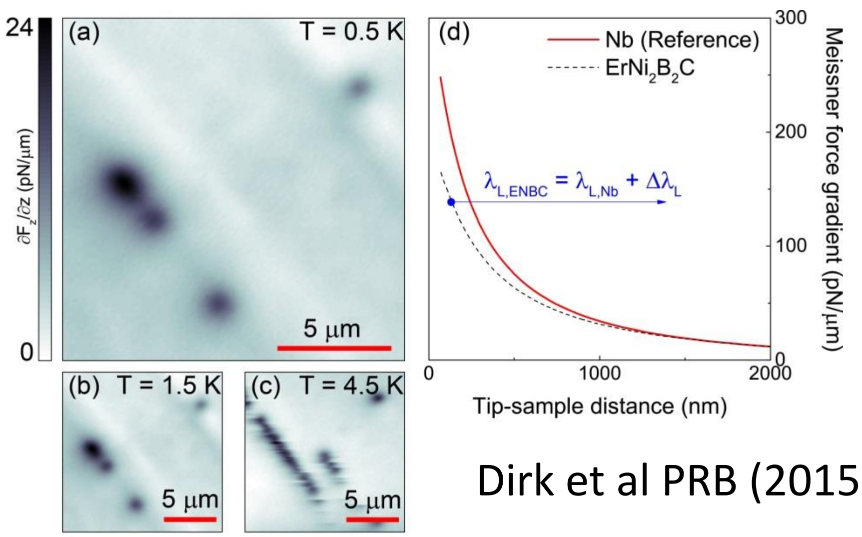
AFM MFM



Demonstration of a vector field in Nb



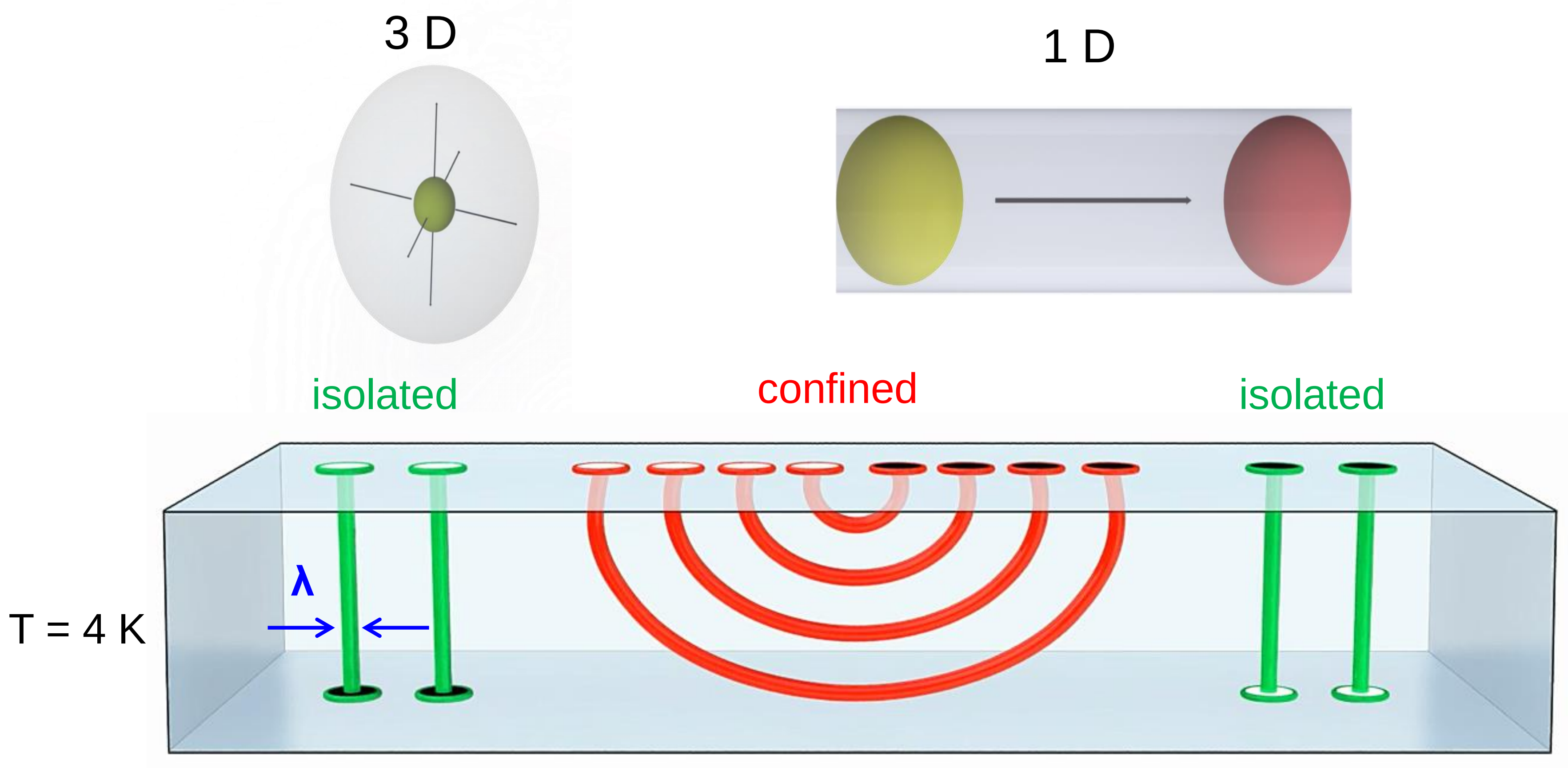
Vortices and FM in $ErNi_2B_2C$



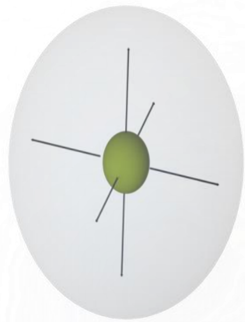
Dirk et al PRB (2015)

Yang et al RSI (2016)

Confinement in Vortices



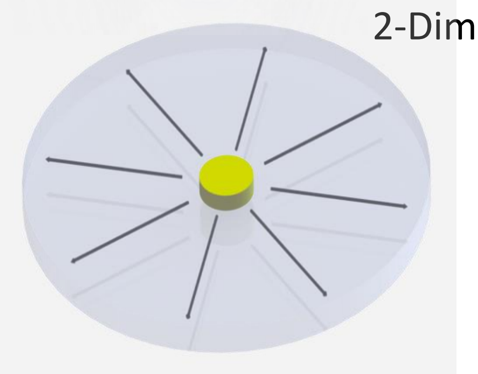
Potential form in 3d, 2d, and 1d from Gauss's law



3-Dimension

$$\int \vec{E}\cdot\overrightarrow{ds} = \frac{Q}{\varepsilon_0} \qquad E = \frac{Q}{4\pi\varepsilon_0}\frac{1}{r^2}$$

$$E\cdot 4\pi r^2 = \frac{Q}{\varepsilon_0} \qquad V = \frac{Q}{4\pi\varepsilon_0}\frac{1}{r}$$



2-Dimension

$$\int \vec{E}\cdot\overrightarrow{ds} = \frac{\sigma}{\varepsilon_0} \qquad E = \frac{\sigma}{2\pi\varepsilon_0}\frac{1}{r}$$

$$E\cdot 2\pi r = \frac{\sigma}{\varepsilon_0} \qquad V = -\frac{\sigma}{2\pi\varepsilon_0}\ln r$$

1-Dimension

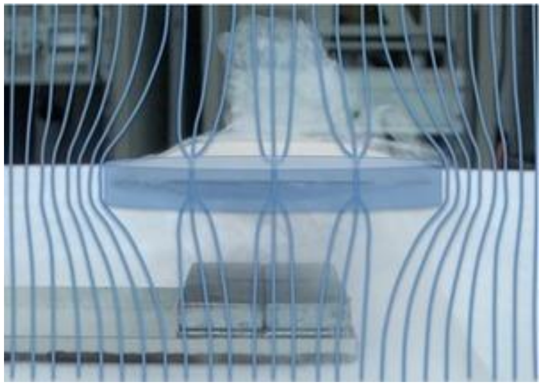
confinement

$$\int \vec{E}\cdot\overrightarrow{ds} = \frac{\lambda}{\varepsilon_0} \qquad E = \frac{\lambda}{\varepsilon_0}$$

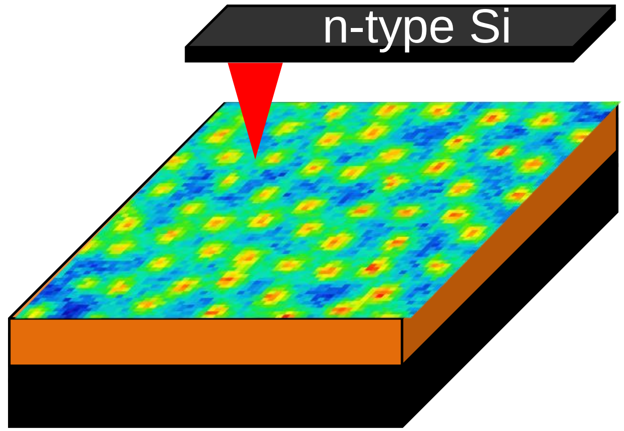
$$V = -\frac{\lambda}{\varepsilon_0} r$$

Linear potential in condensed matter

Meissner force: levitation

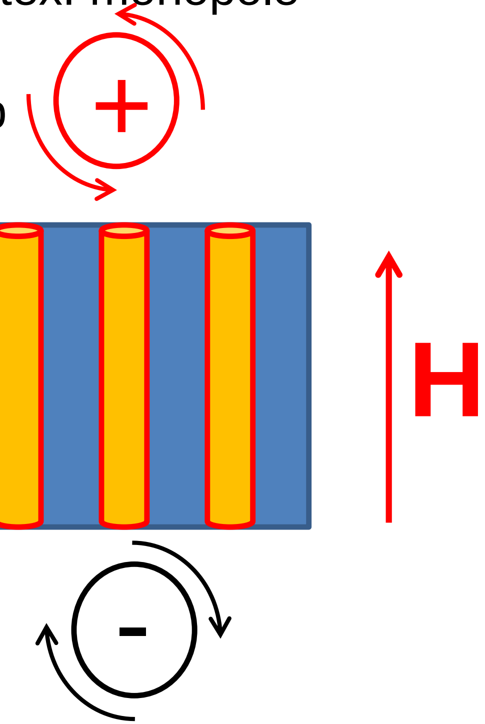


MFM: tip and magnet



vortex: monopole

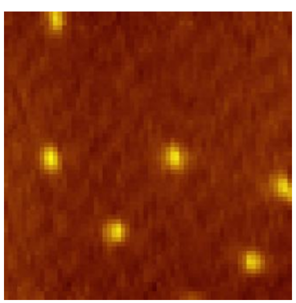
top



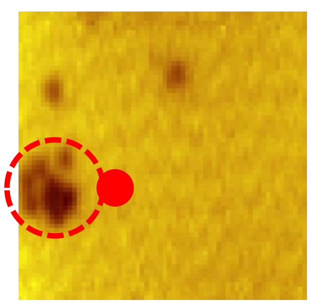
bottom

antivortex: anti monopole

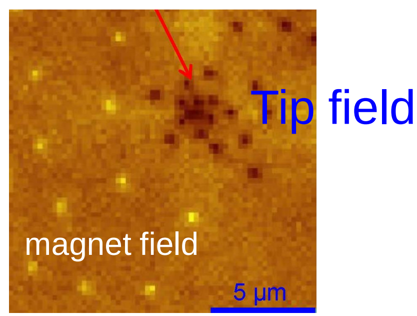
external field



Tip field



Coexistence of V-AV



Why do we see vortices below H_{c1}?

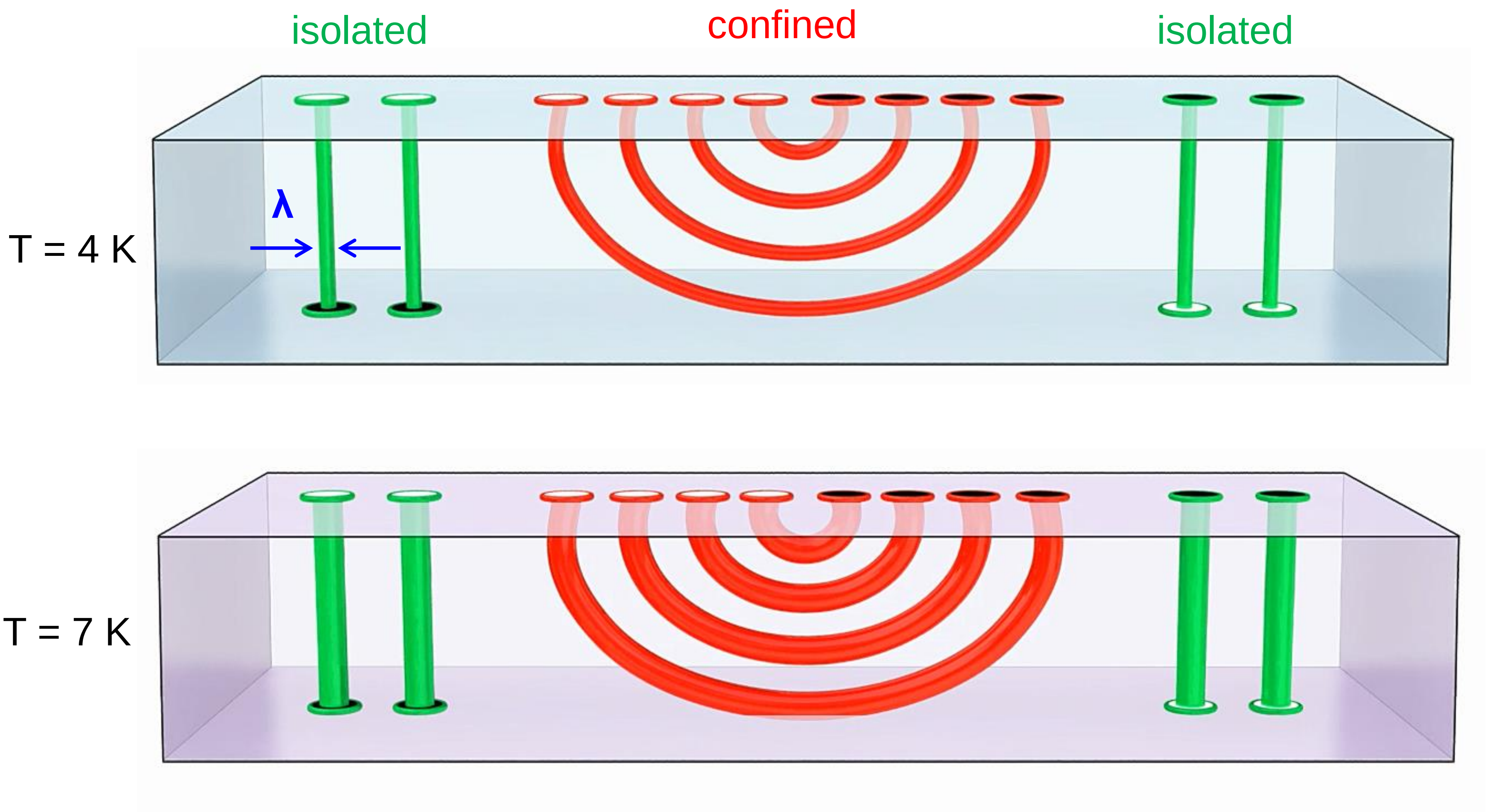
Pinning from imperfections

Vortex itself is a V-AV pair!

What is force between them?

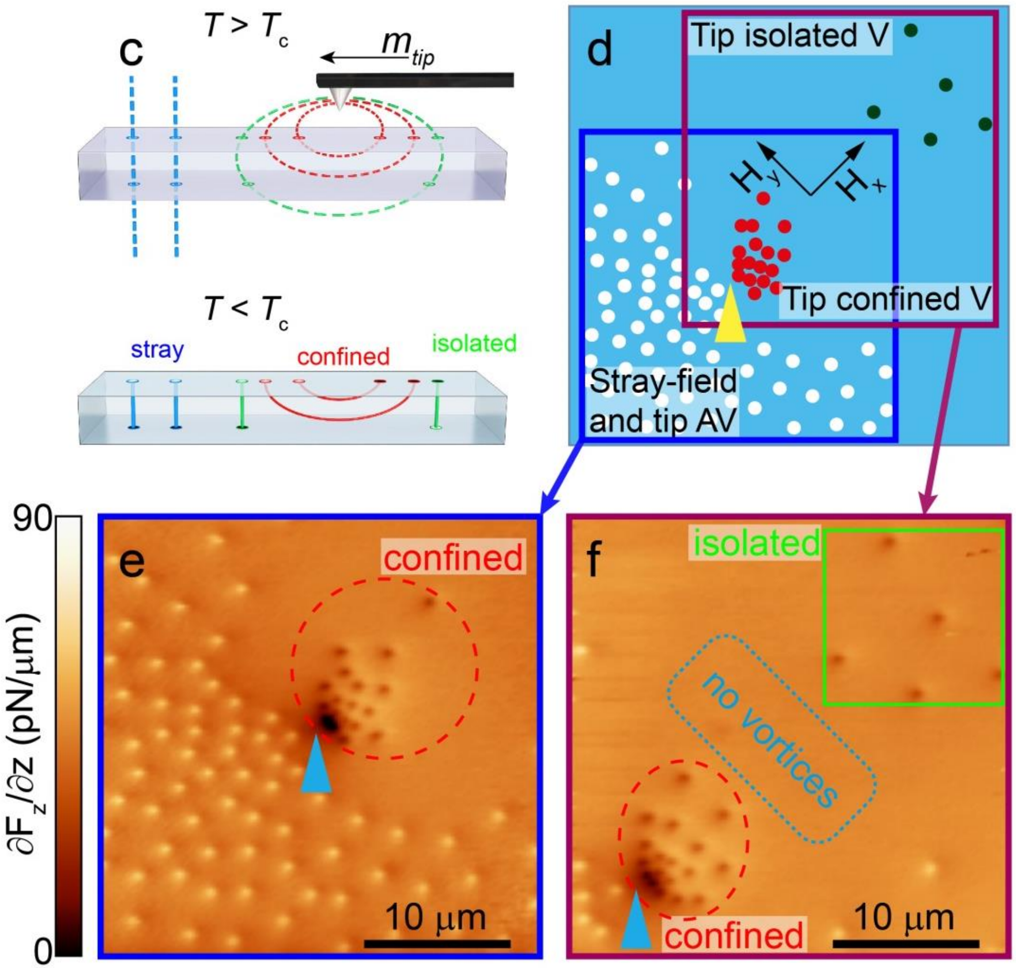
How can you observe and measure?

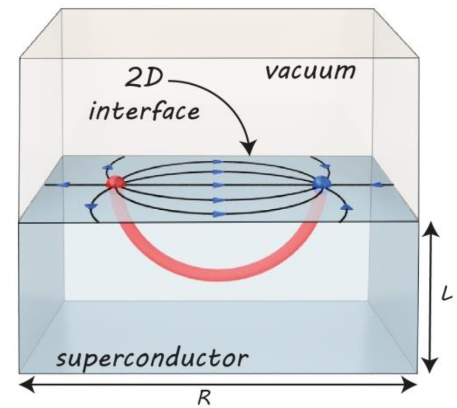
Isolated vortices vs. Confined vortices

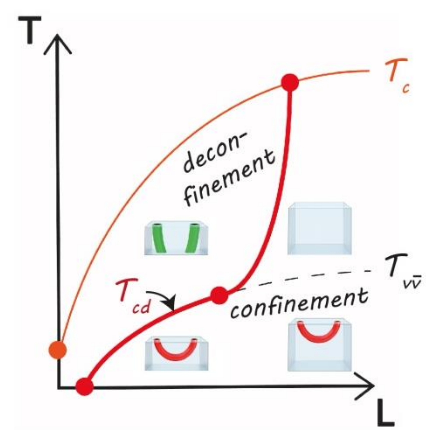


Creation of confined vortices: Animation

Creating confined by an in-plane tip moment: Exp.

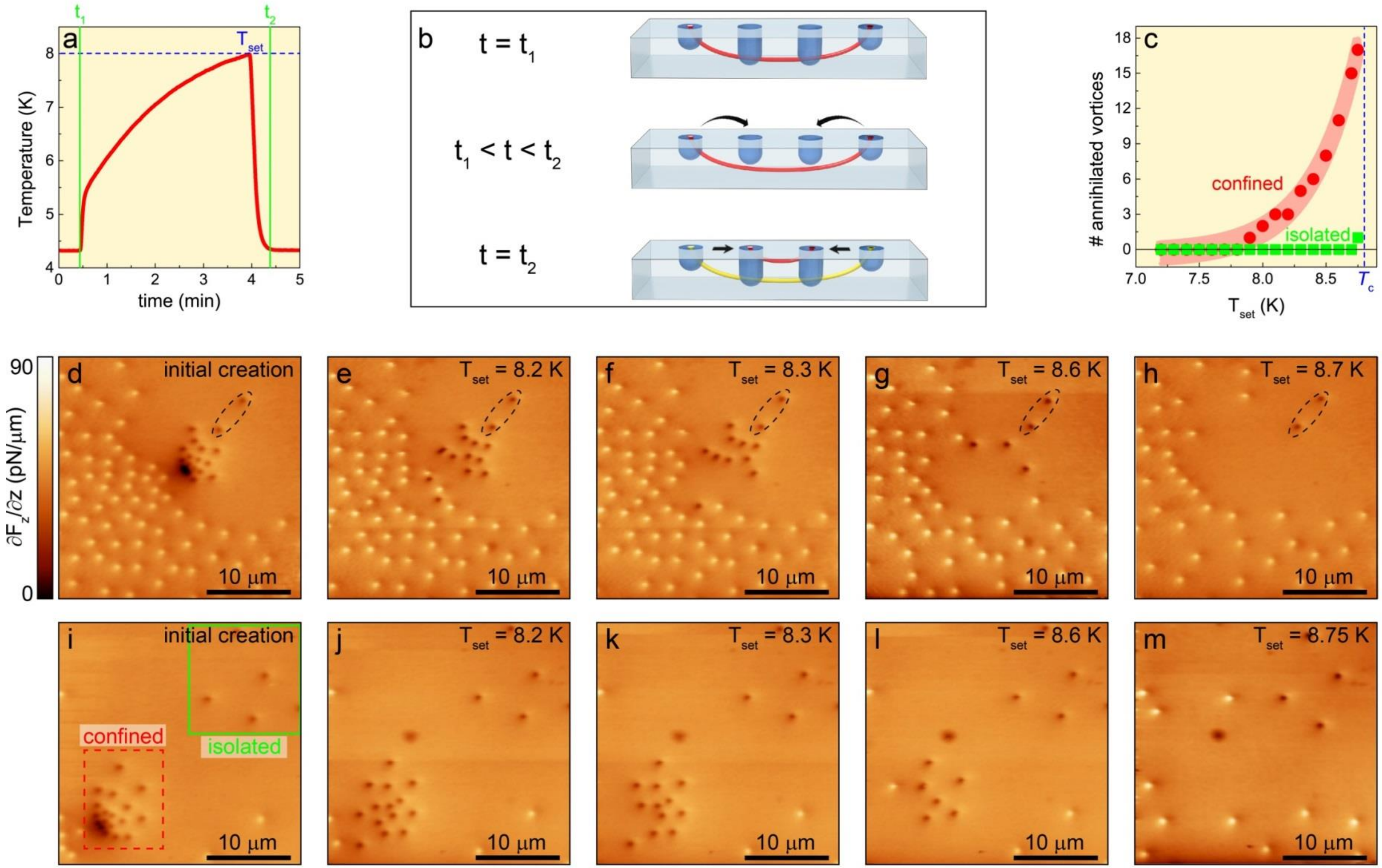






1. External antivortices 2. *Confined* vortices and antivortices
3. Isolated vortices and antivortices : different interations among them

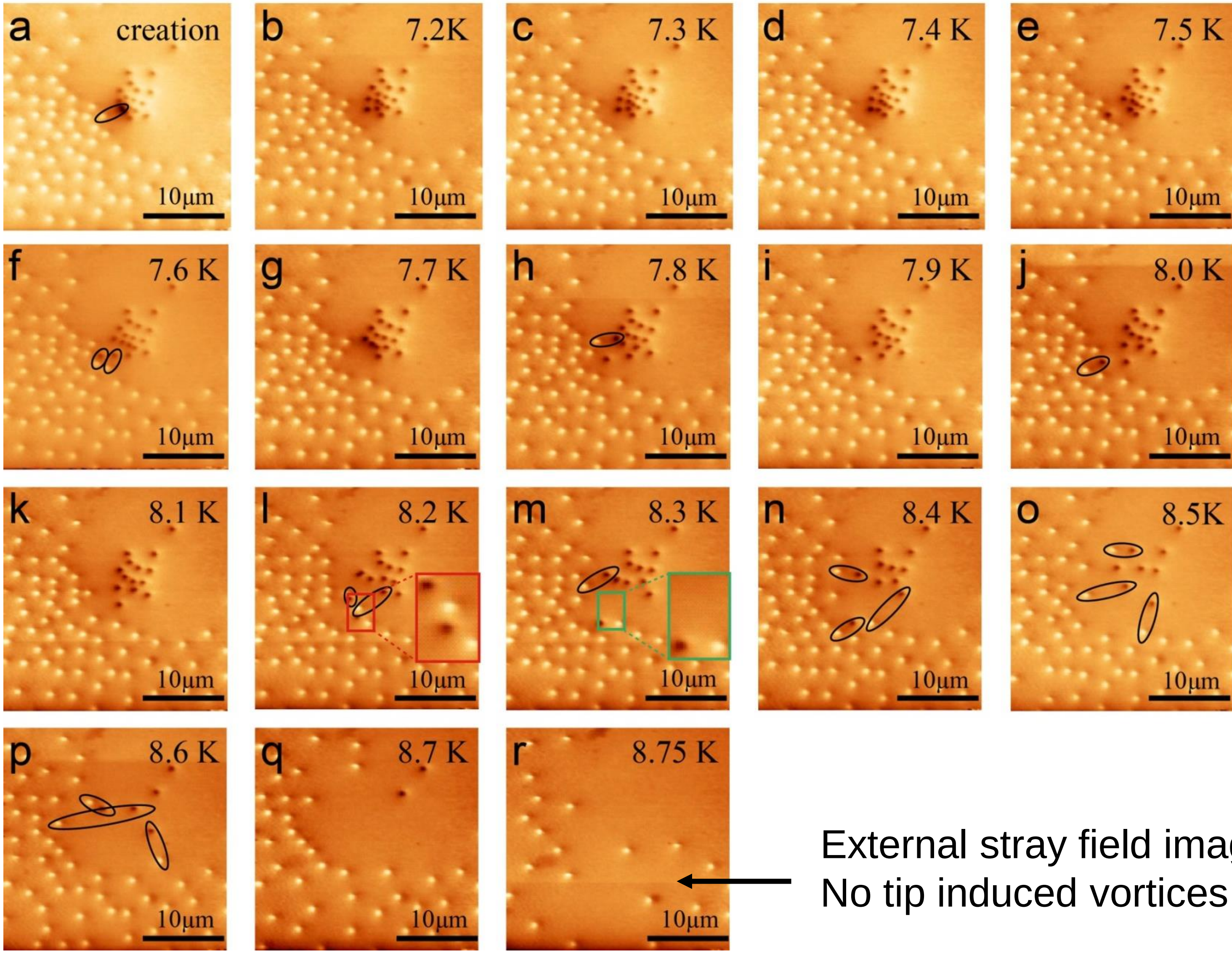
Isolated vs. Confined: Temperature dependence



Confined: unidirectional motion

Isolated: no motion

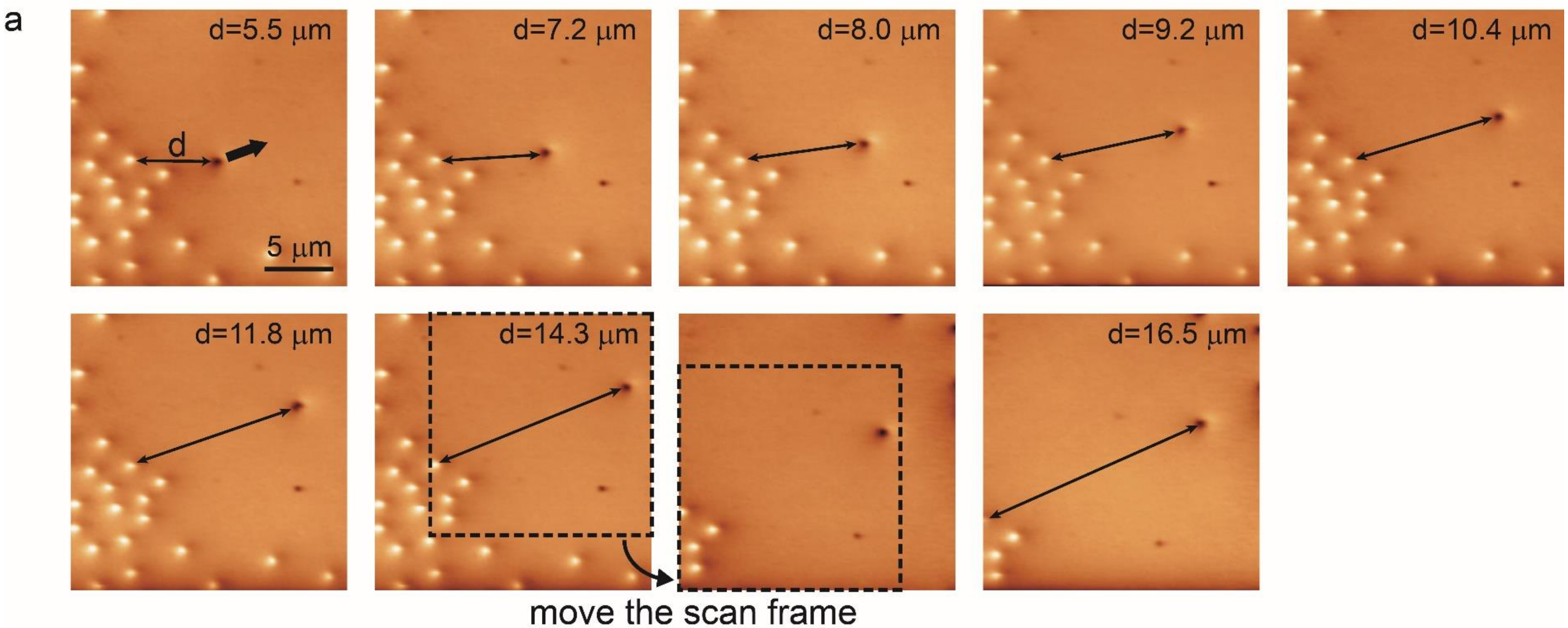
Temperature dependence of Confined: Full data set



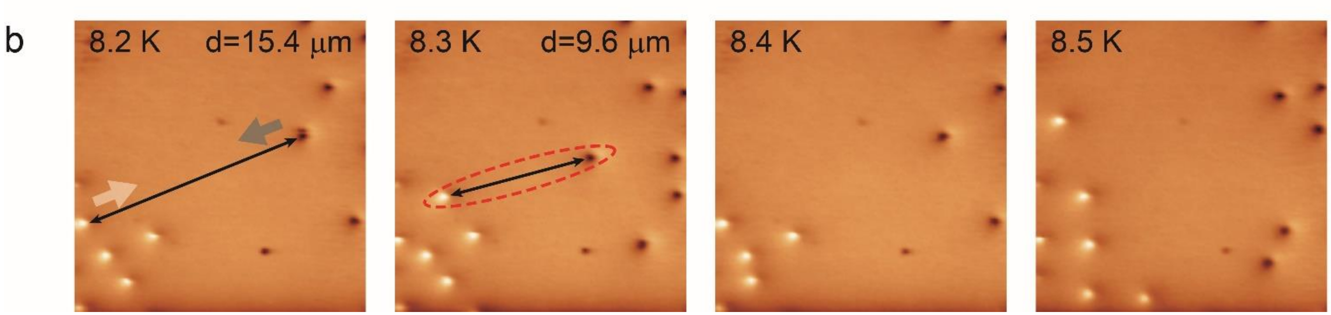
External stray field image:
No tip induced vortices

Confined single vortex: Manipulation and *T* dependence

Manipulation

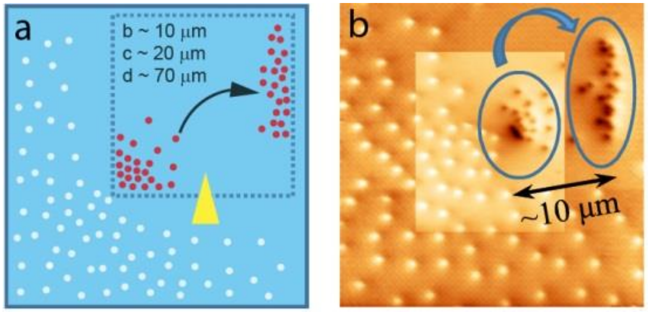


Temperature evolution

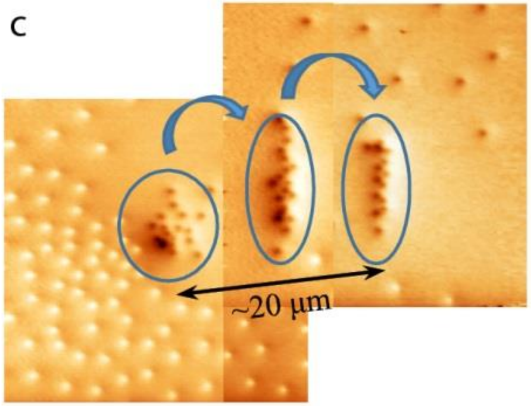


Manipulation of Confined vortices: Animation

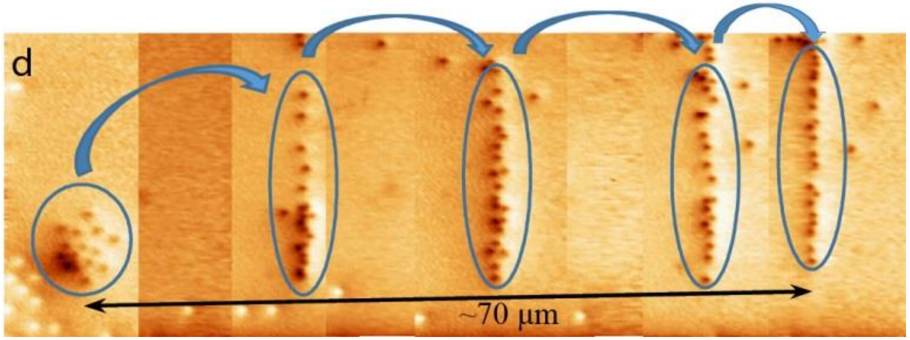
Manipulation of Confined vortices: Experiment



10-μm manipulation

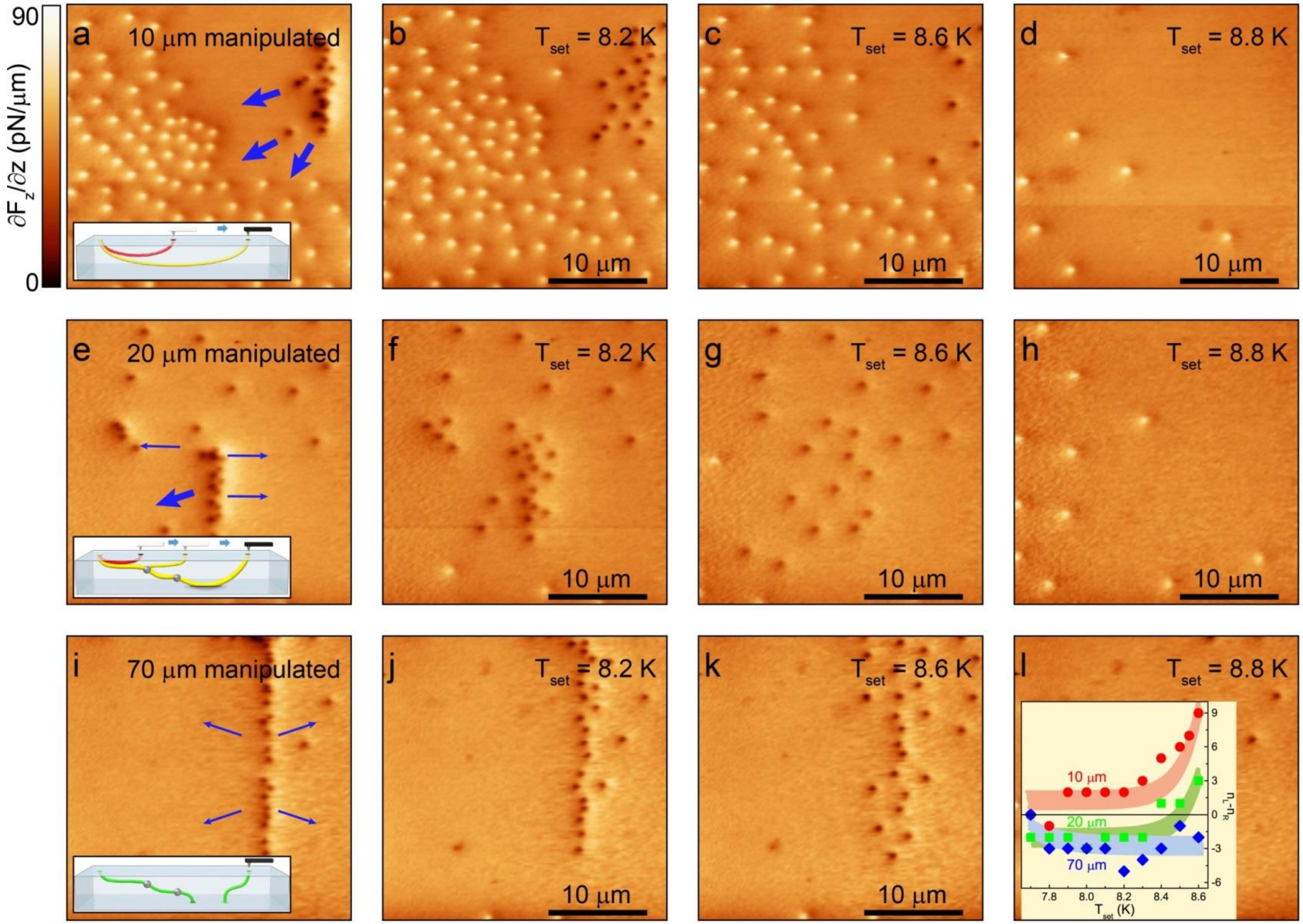


20-μm manipulation



70-μm manipulation

Manipulation of Confined vortices: Experimental data



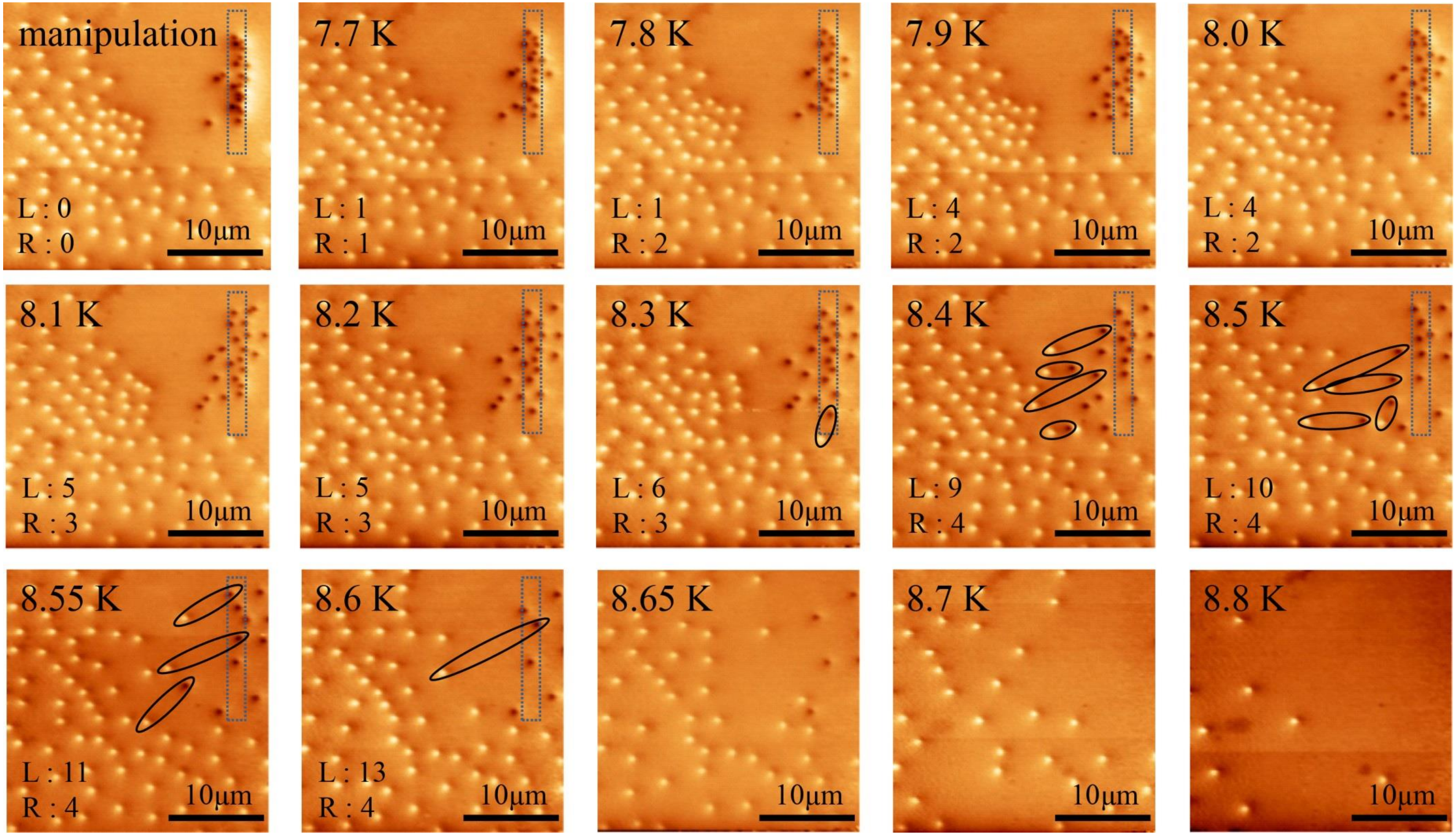
Unidirectional

Unidirectional
+ isotropic

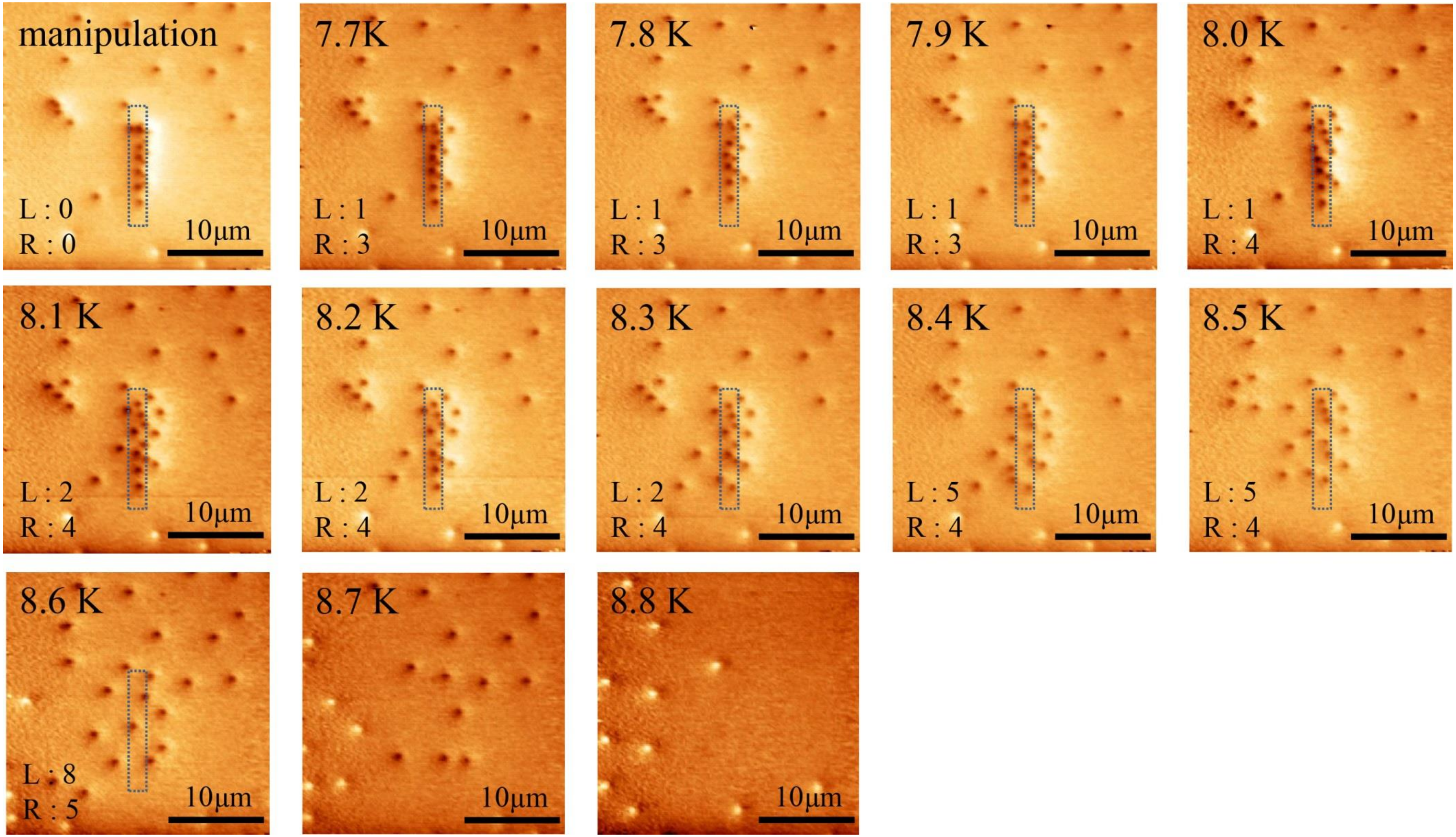
Isotropic

Phase transition from confined to deconfined!

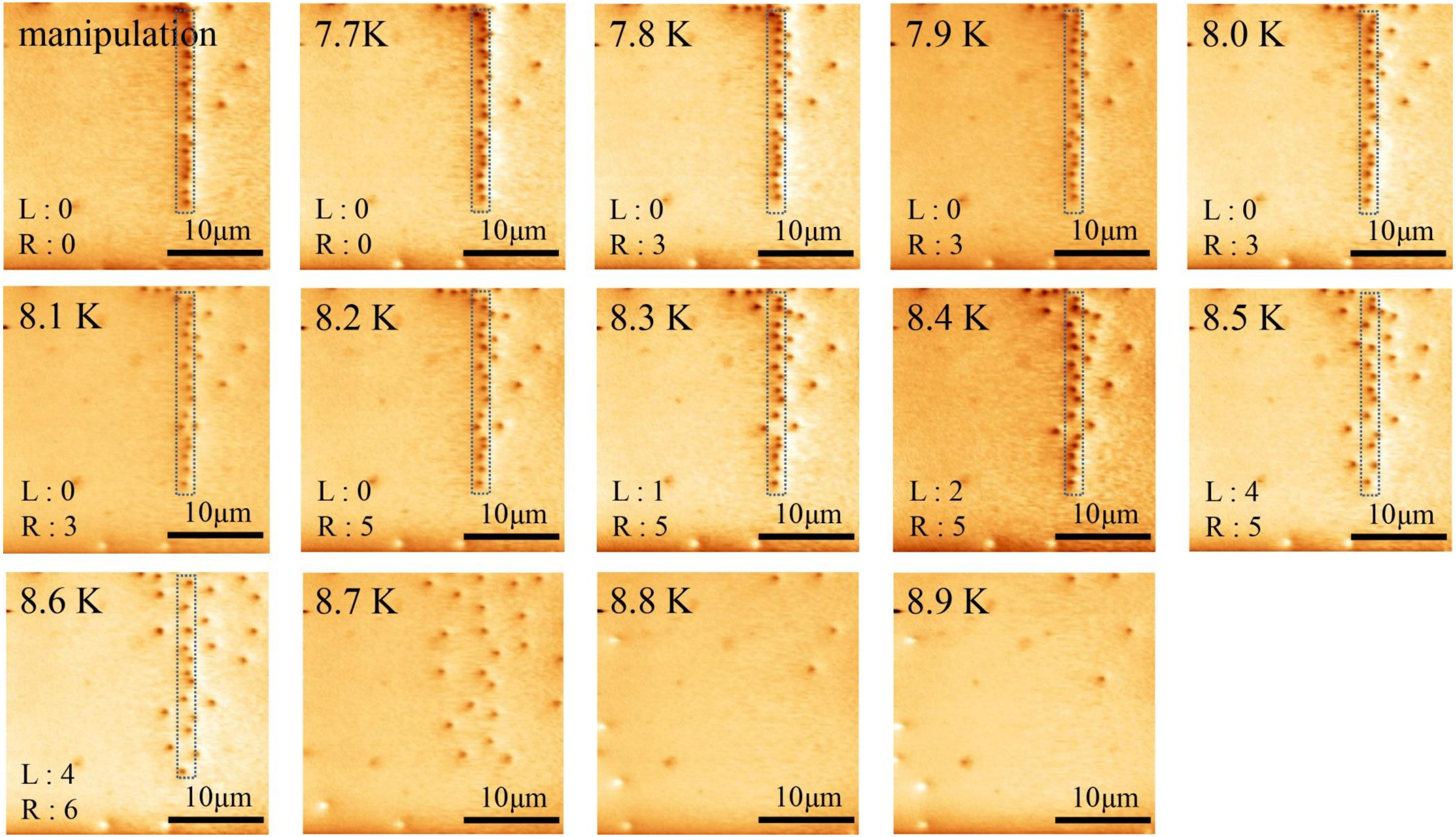
10-µm Manipulation: Unidirectional



20-μm Manipulation: Directional + Isotropic



70-μm Manipulation: Isotropic



Theoretical calculation: Linear potential

$$G = F_{n0} + \int_0^L dz \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} dxdy \left[\alpha |\psi|^2 + \frac{\beta}{2} |\psi|^4 + \frac{1}{2m^*} \left| \left(\frac{\hbar}{i} \nabla - \frac{e^*}{c} \mathbf{A} \right) \psi \right|^2 + \frac{\mathbf{h}^2}{2\mu_0} - \mathbf{h} \cdot \mathbf{H_a} \right]$$

$$G_s^1 = F_{n0} + \int_0^L dz \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} dxdy \cdot$$

Single vortex

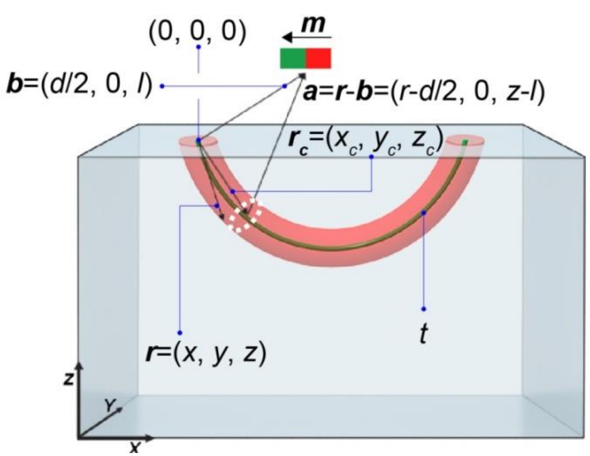
$$\cdot \left[\alpha |\psi|^2 + \frac{\beta}{2} |\psi|^4 + \frac{\mathbf{h}^2}{2\mu_0} + \frac{1}{2m^*} \left| \left(\frac{\hbar}{i} \nabla - e^* \mathbf{A} \right) \psi \right|^2 - \mathbf{h} \cdot \mathbf{H_a} \right]$$

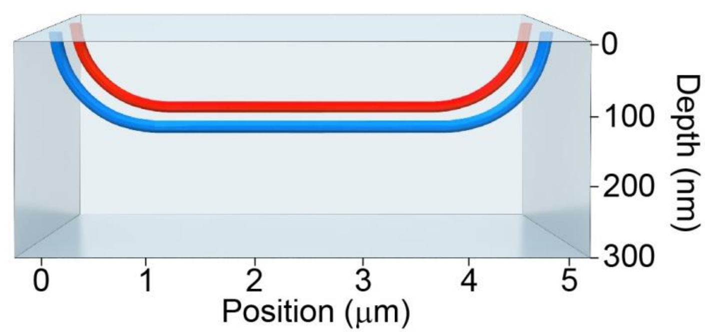
$$G_s^0 = F_{n0} + \int_0^L dz \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} dxdy \left[\alpha |\psi|^2 + \frac{\beta}{2} |\psi|^4 \right]$$

No vortex

constant

$$G_v^1 = \iint_A \left[\frac{\mathbf{h}^2}{2\mu_0} + \frac{\lambda^2}{2\mu_0} |\nabla \times \mathbf{h}|^2 - \mathbf{h} \cdot \mathbf{H_a} \right] dAdt \approx \int \frac{\pi \lambda^2 C_0^2}{\mu_0} \frac{\xi}{\lambda} K_0\left(\frac{\xi}{\lambda}\right) K_1\left(\frac{\xi}{\lambda}\right) dt = \epsilon_v \int dt$$





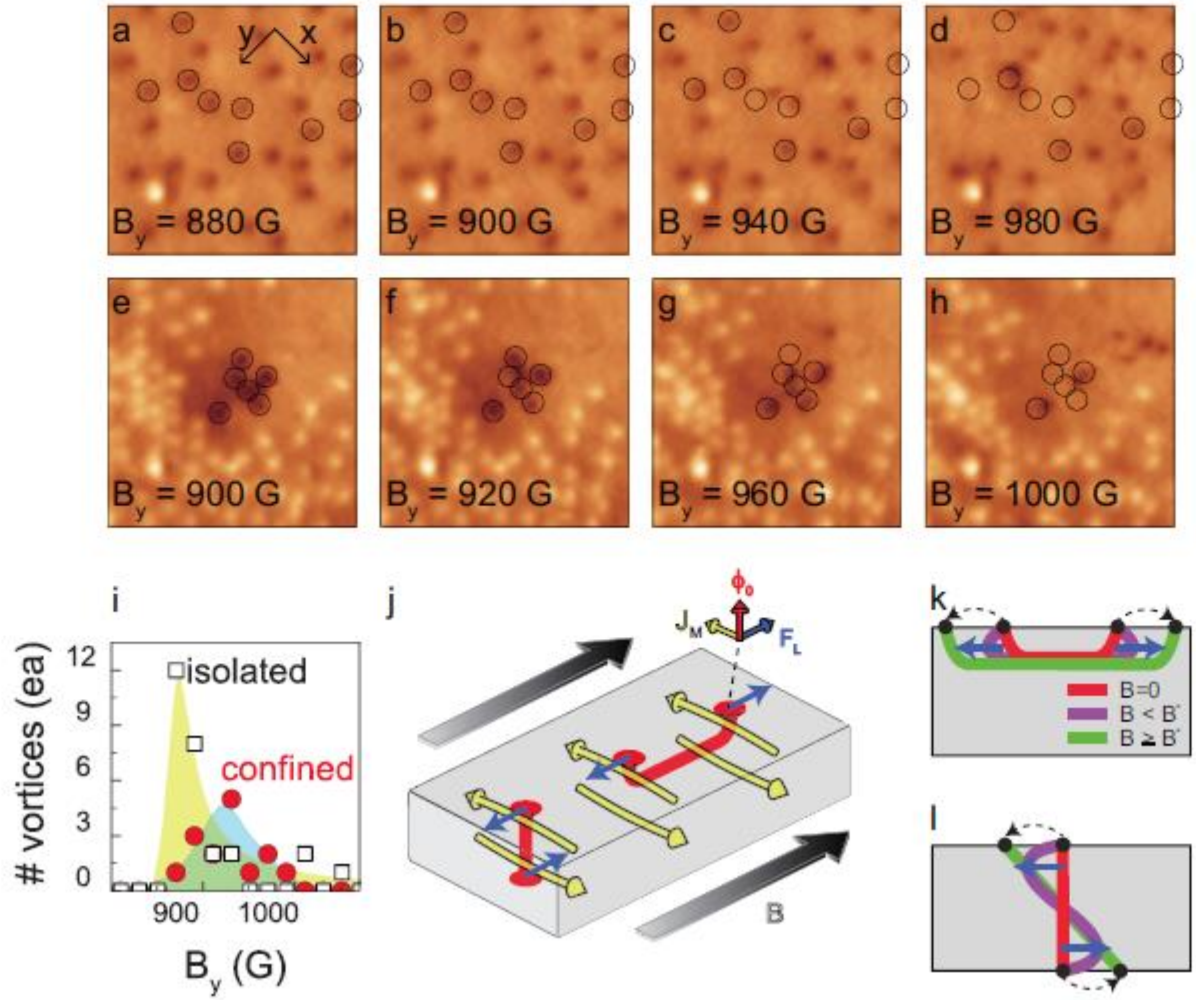
Vortex free energy ∝ arc-length of vortex trajectory: Linear potential

Confinement force measurement

Meissner current induced manipulation: local pinning force measurement

isolated

CVAVP



$$\mathbf{J_M} = -\frac{B_{ext}}{\mu_0 \lambda_L \cosh(a/\lambda_L)} \sinh(z/\lambda_L)\hat{\mathbf{x}}$$

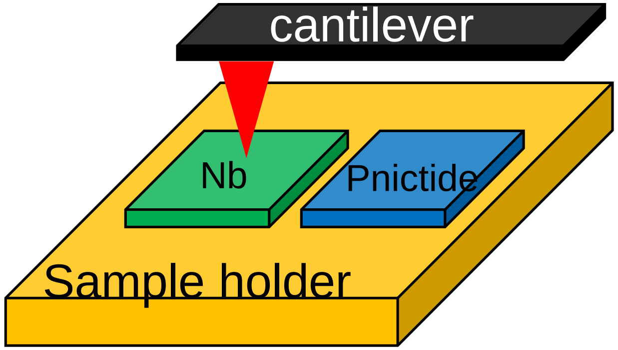
$$\mathbf{f_p} = \mathbf{J_M} \times \Phi_0 \hat{\mathbf{z}} = \frac{B_{ext}\Phi_0}{\mu_0 \lambda_L \cosh(a/\lambda_L)} \sinh(z/\lambda_L)\hat{\mathbf{y}}$$

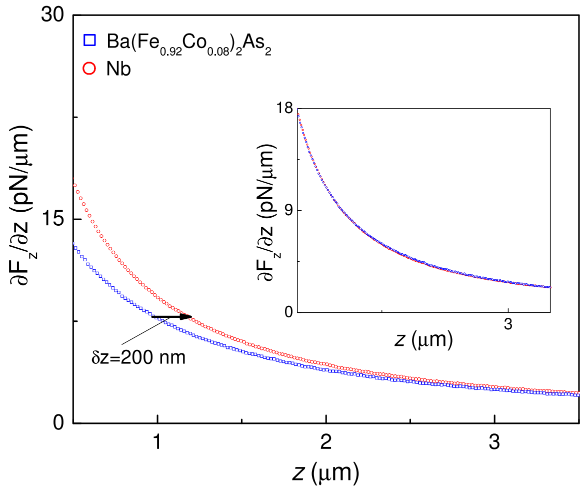
F_{exp}= 43 pN

$$F_t = \frac{\Phi_0^2}{4\pi\mu_0\lambda^2} K_0(\frac{\xi}{\lambda})^{[14]},$$

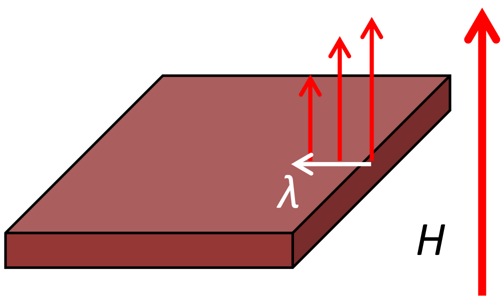
F_{theory}= 48 pN

Local magnetic penetration depth in MFM





Why Care about the Magnetic Penetration Depth?



$$H_c(T=0)=\frac{\Phi_0}{2\sqrt{2}\pi\lambda(0)\xi(0)}$$

$$J_0(T=0)=\frac{c\Phi_0}{12\sqrt{3}\pi^2\xi\lambda^2}$$

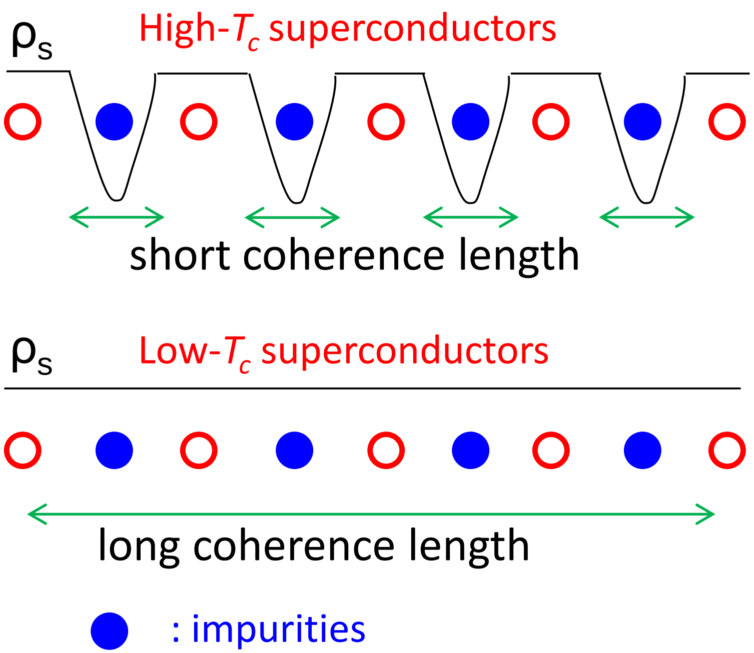
$$Gi=\frac{1}{2}\left[\frac{8\pi^2\gamma T_c\lambda^2}{\xi\Phi_0}\right]^2$$

- Two important parameters in superconductors: λ and ξ
- Superconducting properties: H_c (rf cavity), J_0, Gi (thermal fluctuations), *etc*

  ⟶ λ affects more than ξ
- Paring symmetry via measurement of λ(T):

  s-wave (exponential), d-wave (power law)
- Kinetic inductance: electronic performance in thin films (NbN films for single photon detector)

Why Care about the Magnetic Penetration Depth?



- λ in inhomogeneous superconductivity:
  Swiss cheese model (Tc - little change; lambda changes drastically)

- Uemura relation in the dirty limit:

$$\rho_{eff} = \frac{1}{\lambda_{eff}^2} \approx \frac{1}{\lambda_L^2}\frac{l}{\xi_0} \propto \Delta(0) \propto T_c$$

- Paring symmetry from pair breaking:
  λ as a function of a irradiation dose

- Type I or II superconductivity: Pb thin film

In this talk: λ(θ)

Conventional Techniques for λ Measurements

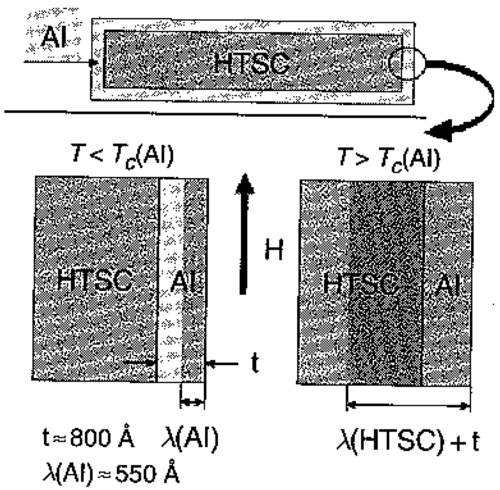


Figure 14.3 Schematics of the experiment used to measure the absolute value of the penetration depth by coating a high-T_c superconductor with low-T_c (Al in this case) material.

Figure courtesy of Prof. Poole, in Superconductivity

- Mutual inductance technique: drive and pickup coils on opposite sides of the film. (only works for films)
- μSR: measures second moment of the magnetic field distribution around a vortex, related to λ(0). (the vortex lattice and muon locations; only works for bulk samples)
- Reversible magnetization (SQUID): for clean samples
- Infrared reflectivity: measures anisotropy

$$\lambda(\omega) = 4\pi\omega\sigma(\omega)/c^2$$

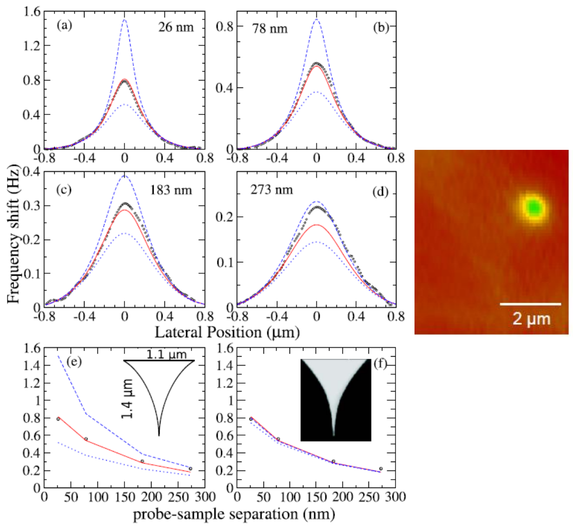
- Tunnel-diode resonator : coat with Al film (reference)

$$\lambda(HTSC) = \lambda(Al) + \frac{\Delta\lambda^{Al}(T_c) - t}{1 - \exp(-t/\lambda(Al))}$$

λ Measurement by MFM

Previous techniques by MFM

Vortex profile (LANL)



Nazaretski et al., APL 2009

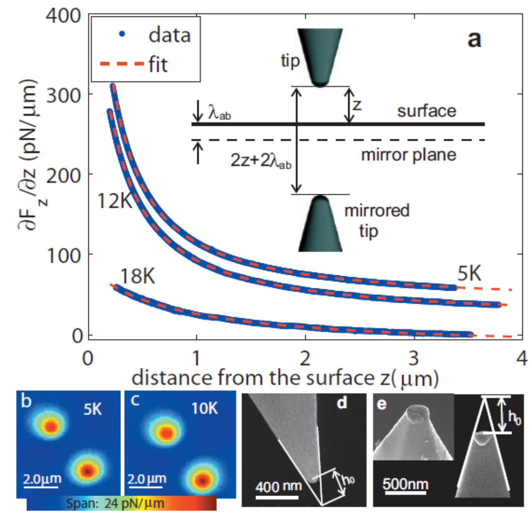
- Analysis of a single vortex profile for λ in MFM: requires an extensive numerical analysis for modeling the tip.

$$\frac{\partial f_z}{\partial z} = A\frac{M_{tip}\Phi_0}{(z+\lambda_{ab})^3}$$

A: Tip geometry, M_{tip}: Tip moment

- How would you measure λ without vortices?

Meissner (Stanford)



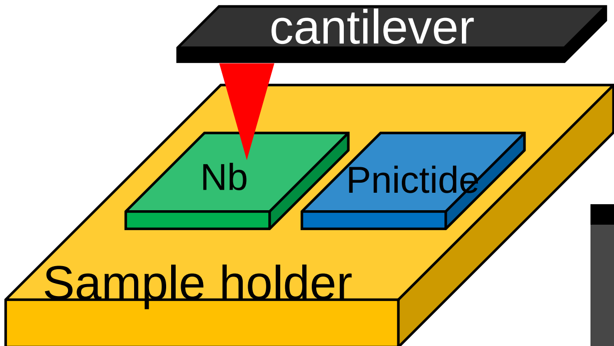
Luan et al., PRB 2010

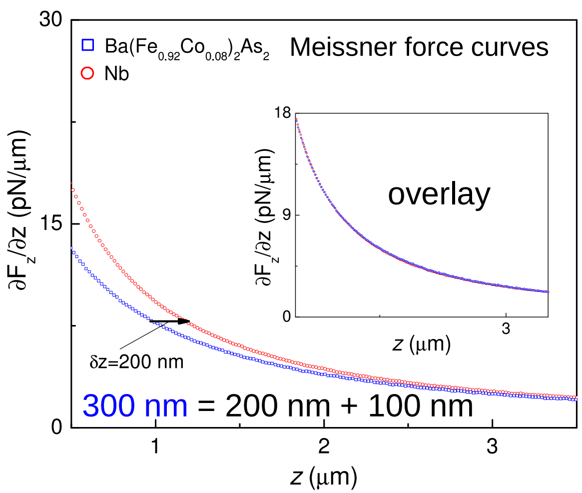
$$\frac{\partial f_z}{\partial z} - \frac{\partial f_z}{\partial z}\Big|_{z=\infty} = A\left(\frac{1}{z+\lambda_{ab}} + \frac{h_0}{[z+\lambda_{ab}]^2} + \frac{h_0^2}{2[z+\lambda_{ab}]^3}\right)$$

Successfully applied for Δλ measurements, but still use the fit (modeling of the tip geometry) to extract the absolute λ value.

Our strategy: avoid modeling the tip and develop a reliable method.

Our approach: a comparative Meissner force experiment





Our λ measurements are featured in SuST

- Comparative experiment in MFM

$$F'_{Nb} = \frac{\partial f_z}{\partial z} = A\frac{M_{tip}\Phi_0}{(z_{Nb}+\lambda_{Nb})^3}$$

$$F'_{pnictide} = \frac{\partial f_z}{\partial z} = A\frac{M_{tip}\Phi_0}{(z_p+\lambda_{pnictide})^3}$$

$F'_{Nb} = F'_{pnictide}$ if $Z_{Nb}=Z_{pnictide}+\Delta Z$

: Then $\lambda_{pnictide}=\lambda_{Nb}$(100 nm) **+Δλ (=Δz)**

- No modeling of the tip
- Direct measurement
- Fast measurement
- Reliable measurement
- Measure 10 samples in a few hours

J. Kim et al., Supercond. Sci. Technol. **25**, 112001 (2012)

Direct, local – Inhomogeneity, High throughput

Summary of Techniques for λ Measurements

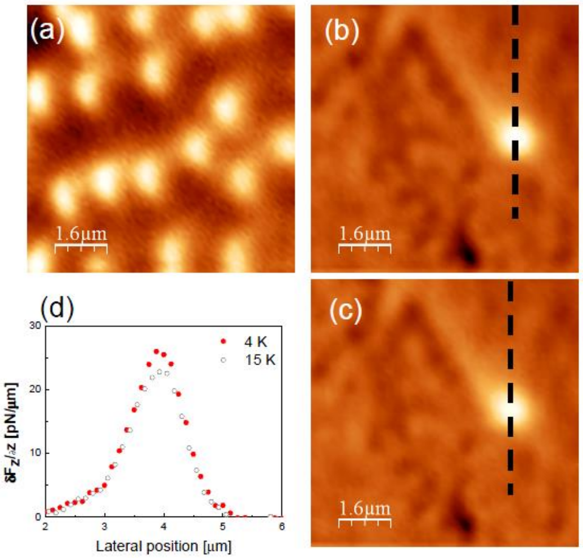
Technique	Absolute value of MPD	Sample shape bulk/film	Local probe	Temperature range	Number of samples measured	National facility or "table top"	Time per experiment
μSR	yes	bulk	no	> 50 mK	one	NF	weeks
Resonant cavity	no	bulk	no	> 1.2 K	one	TT	weeks
Scanning SQUID	no	bulk to thin film	yes (~μm)	> 1.2 K	one	TT	weeks
TDO	no	bulk	no	> 50 mK	one	TT	weeks
Mutual inductance	yes (fitting)	thin film	no	> 1.2 K	one	TT	weeks
Existing MFM "Meissner"	yes (fitting)	bulk	yes (~nm)	> 4 K	one	TT	weeks
Kim MFM "Meissner"	Yes (direct)	bulk to ultrathin film	yes (~nm)	> 0.5 K	more than ten	TT	few hours

We can work on more than 10 samples in few hours!
Comparative method: doping or irradiation dependence: draw correlations among samples of interest.

Results of λ measurements: One

MgB_2film (STI): dirty limit

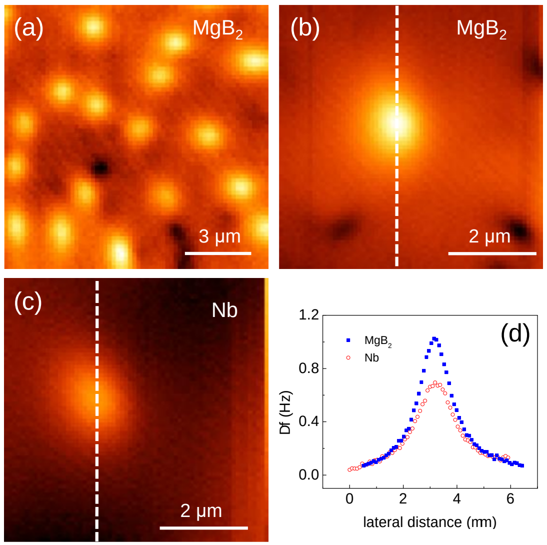
(Made by reactive evaporation)



- λ(0)=200 nm: dirty π band

MgB_2film (Temple U.): clean limit

(Made by hybrid physical chemical vapor deposition)



- λ(0)=50 nm: clean π band

Provide a potential venue for understanding multiband superconductivity (pnictides).
The degree of cleanness in the π band results in a drastic change of λ, and thus for vortex dynamics.
H_{c2} changes drastically from 10 T up to 60 T due to the two band nature.

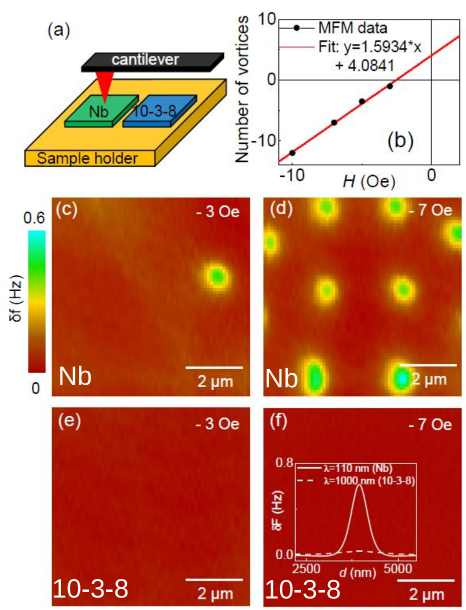
J. Kim, N. Haberkorn et al., PRB **86**, 024501 (2012)

J. Kim, N. Haberkorn et al., arXiv:1303.0352: SSC (2015)

Results of λ measurements: Two

$Ca_{10}(Pt_3As_8)[(Fe_{1-x}Pt_x)_2As_2]_5$

(pnictide family, 10-3-8)



- λ(0)=1000 nm: no vortices
- Large thermal fluctuations

J. Kim, N. Haberkorn et al., PRB **85**, 180504 (R) (2012)

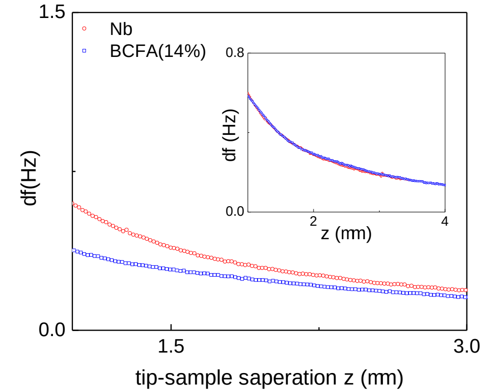
$$Gi = \frac{1}{2}\left[\frac{8\pi^2\gamma T_c \lambda^2}{\xi\Phi_0}\right]^2$$

Thermal fluctuations (Gi):

- produce flux creep & vortex liquid phases
- bad for applications

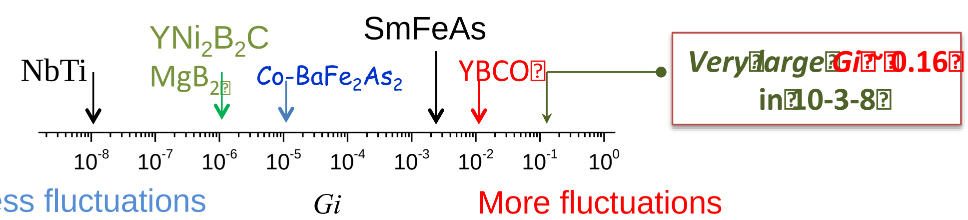
$Ba(Fe_{0.86}Co_{0.14})_2As_2$

(x=0.14,Heavily overdoped)



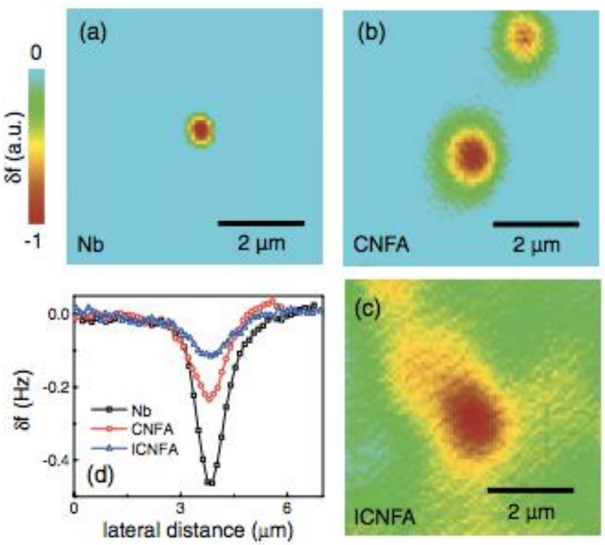
- Superconducting only after annealing
- λ(0)=600 nm
- Nanoscale inhomogeneities

J. Kim, N. Haberkorn et al., SSC (2015)



Results of λ measurements (Swiss cheese)

$Ca_{0.5}Na_{0.5}Fe_2As_2$



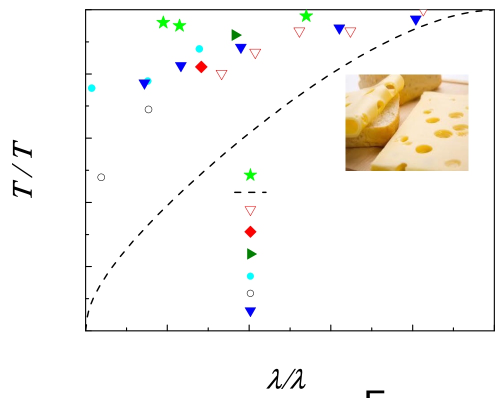
Proton irradiated: random point defects

	λ (nm)	T_c (K)
unirradiated	260	19.4
irradiated	430	17.8

J. Kim et al., PRB **86**, 144509 (2012)

Irradiation dependence

Swiss cheese model

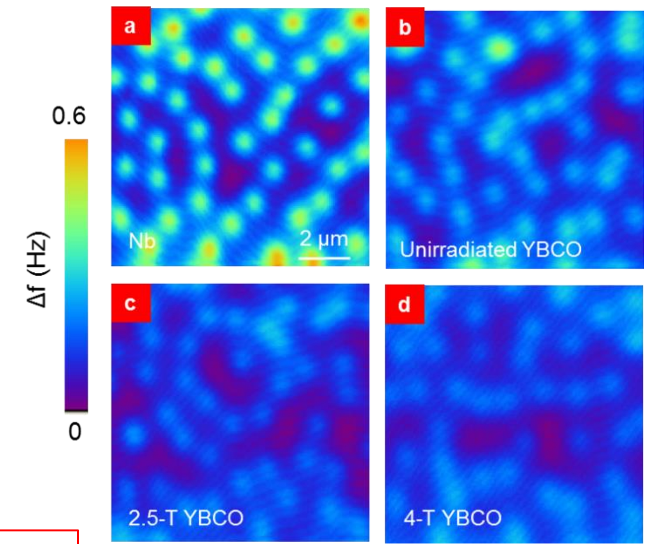


$$J_0(T=0) = \frac{c\Phi_0}{12\sqrt{3}\pi^2 \xi \lambda^2}$$

J_o, pinning, creep, vortex dynamics are directly related to λ, however no systematic studies have been made so far due to difficulty of λ measurement.

YBCO: NP or CD for J_c?
Think about Balance between pinning and intrinsic properties!!!

YBCO films



Heavy ion irradiated: correlated defects

	λ (nm)	T_c (K)
unirradiated	200	90.5
irradiated	320	87

in-preparation