Structure and Dynamics of a pinned vortex liquid in ultrathin superconducting films

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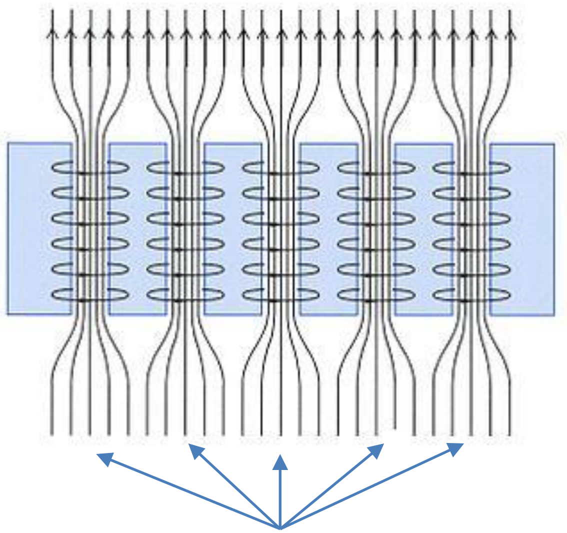
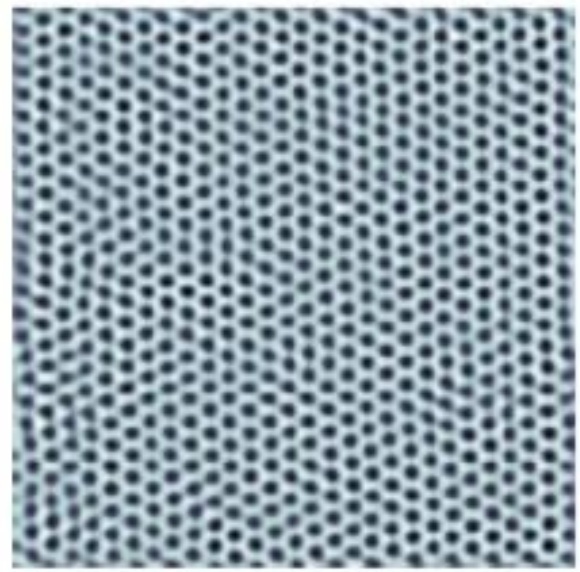
The vortex lattice: An archetypal crystalline system



$$\Phi_0 = \frac{h}{2e}$$

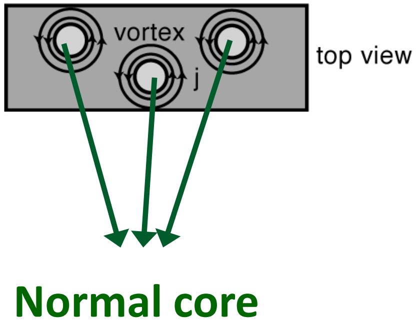


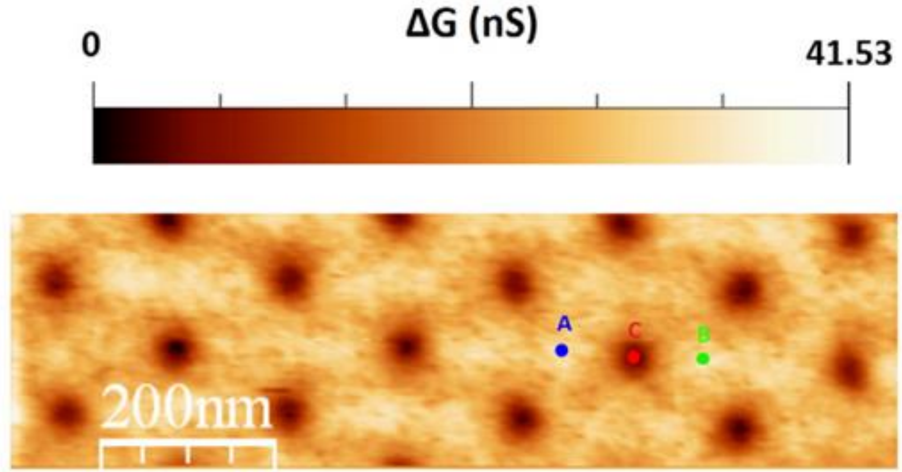
The vortex lattice in a $NbSe_2$ single crystal

- One would expect the vortex lattice to melt at a characteristic temperature or magnetic field.
- **Yet vortex liquid states are rare.**
- In conventional bulk superconductors thermal fluctuations alone is not enough to melt the vortex lattice. Exception: High T_c cuprates.

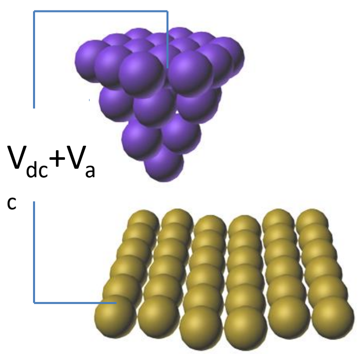
Where can one observe vortex liquid? How is it different from regular liquids?

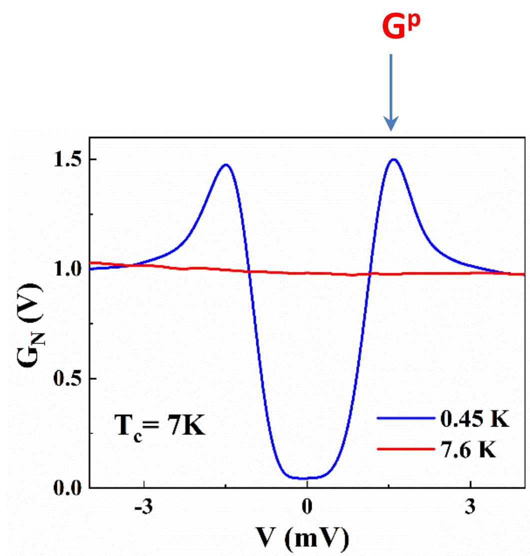
How to image the vortex lattice using STM?

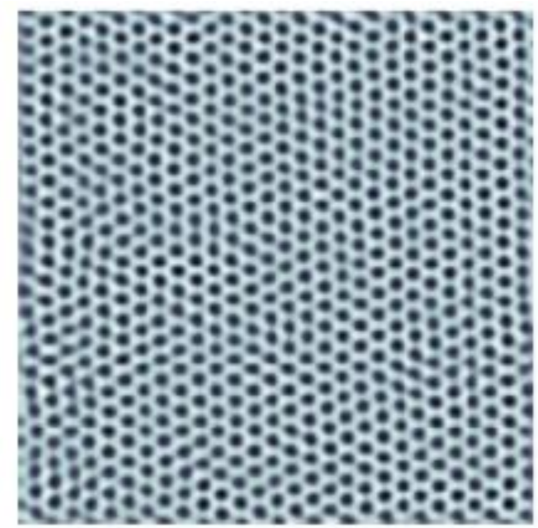




$G(V_{dc}) = I_{ac}/V_{ac}$





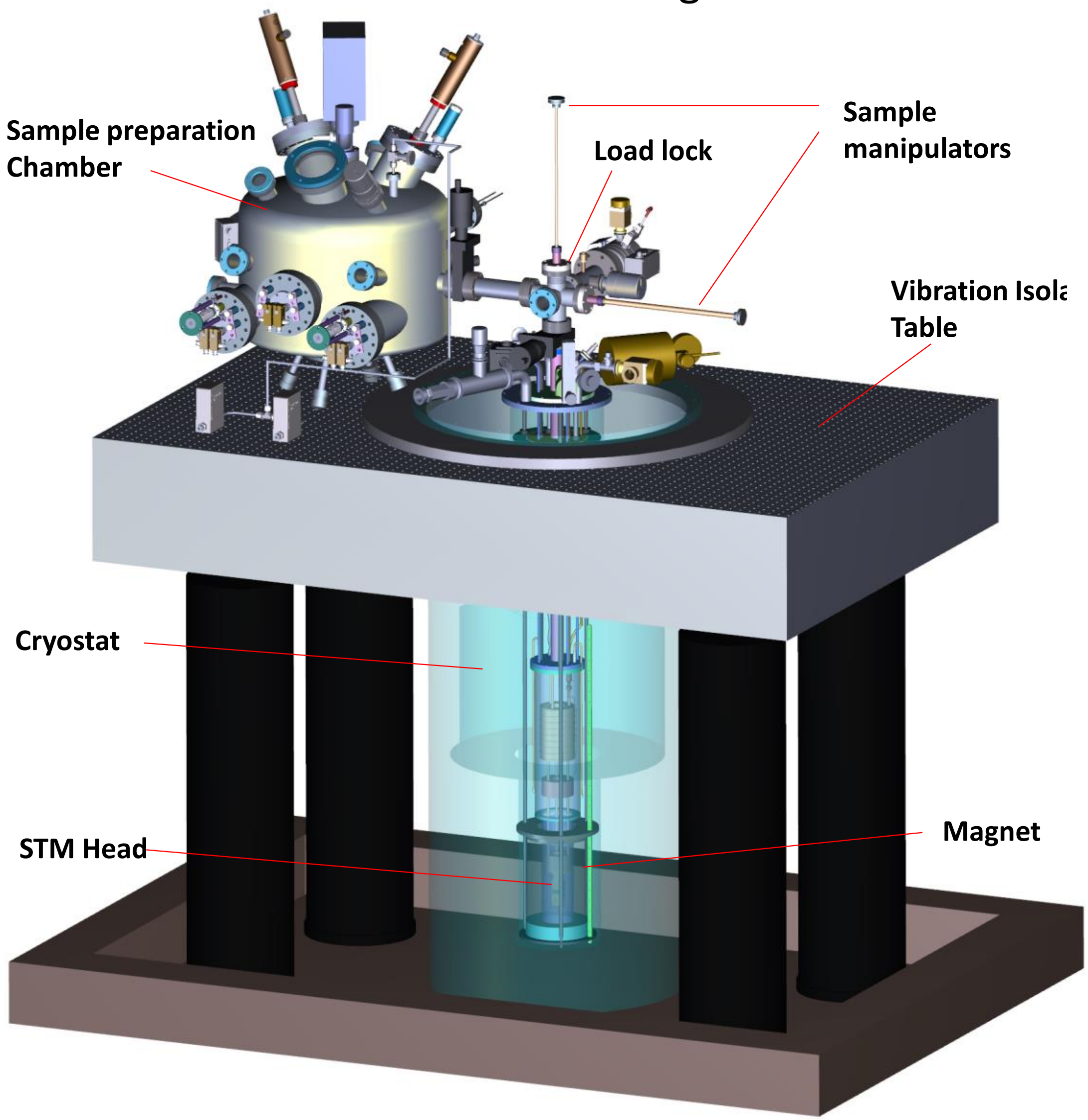


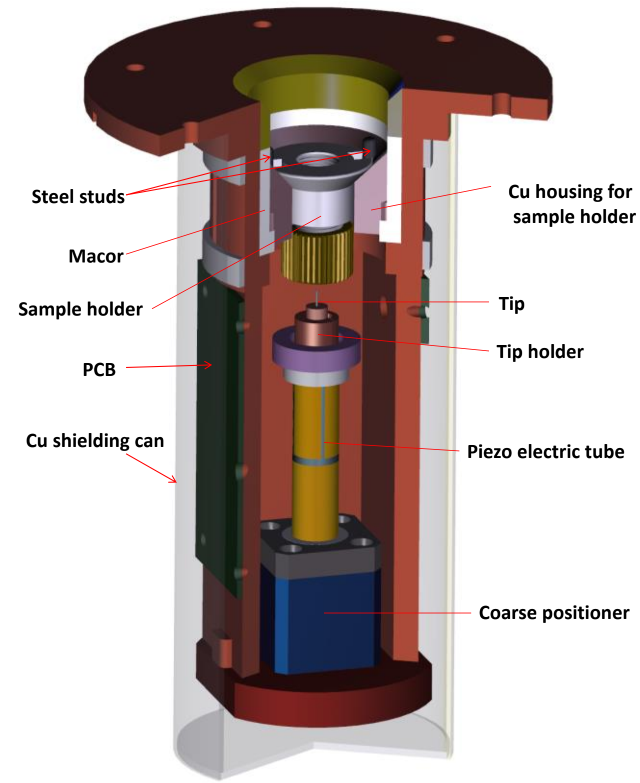
Our Toy: The TIFR milli-Kelvin *Scanning Tunneling Microscope*

Lowest temperature:

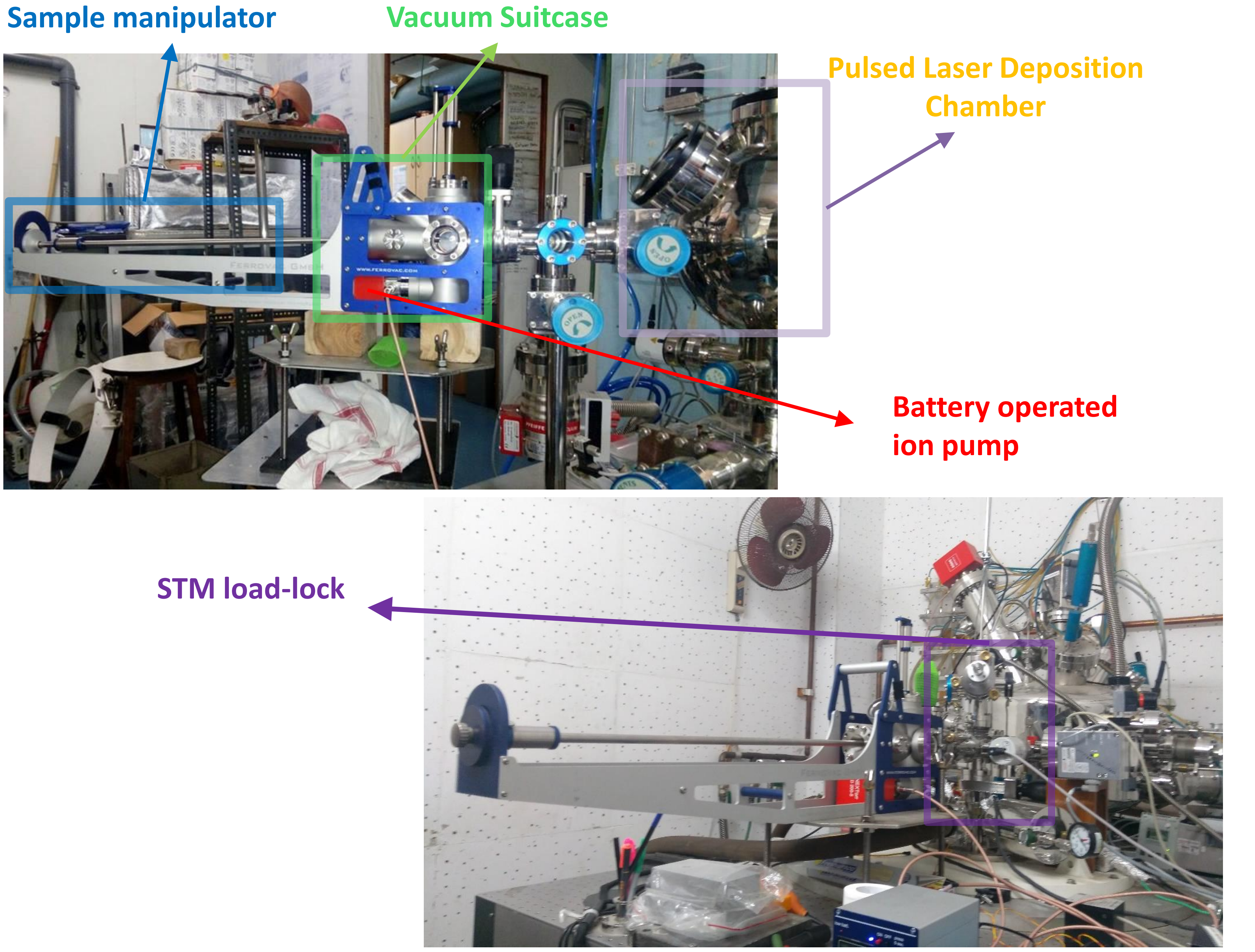
350 mK

Magnetic field: 9 T

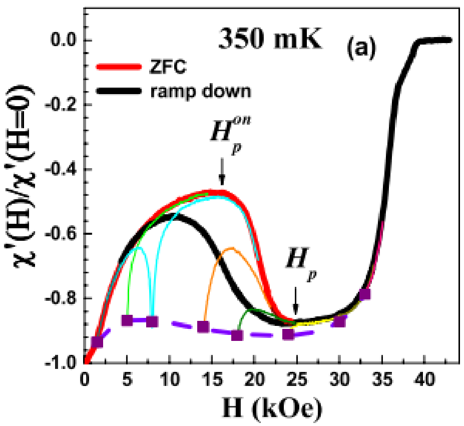


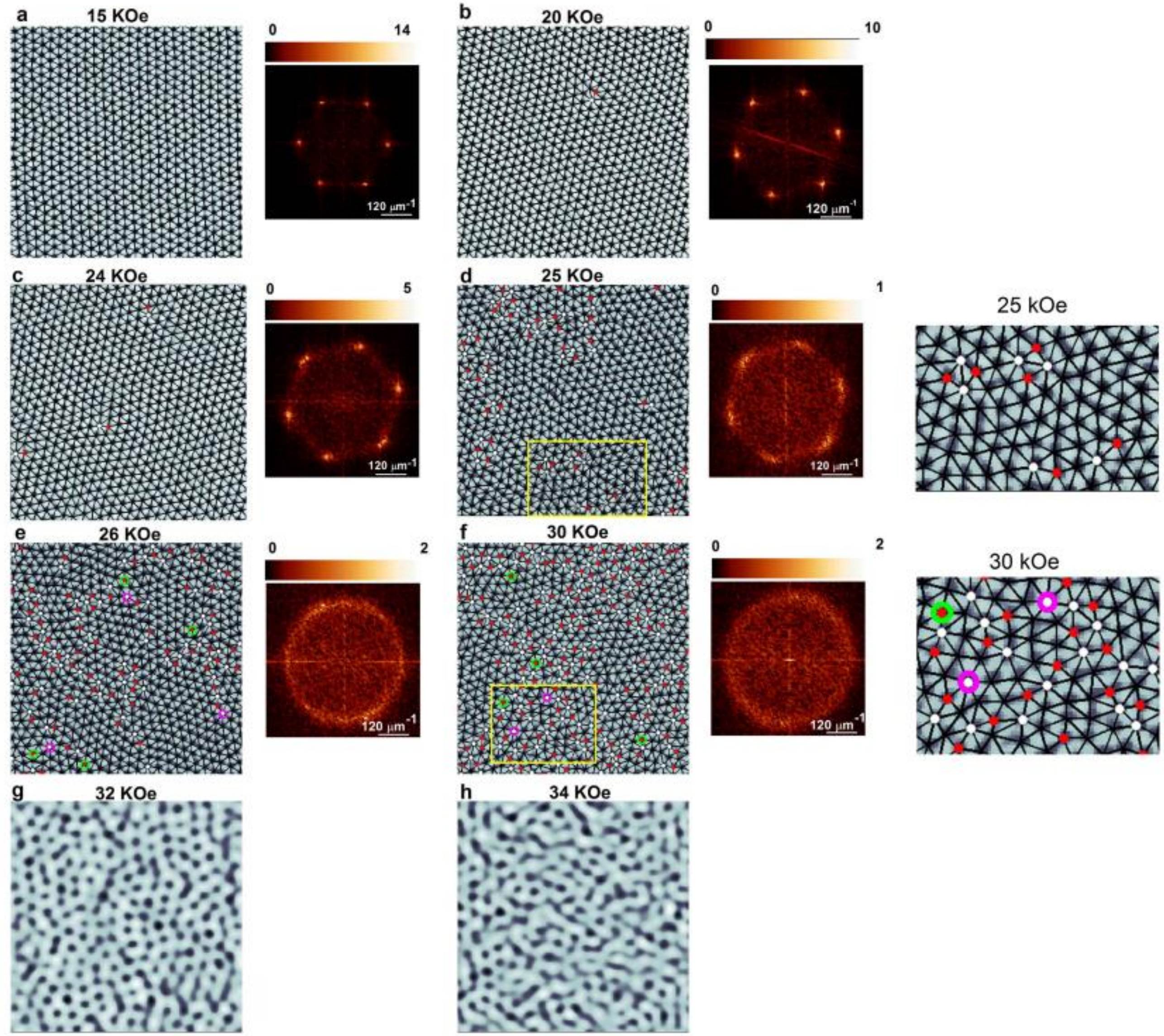


Review of Scientific Instruments **84**, 123905 (2013).

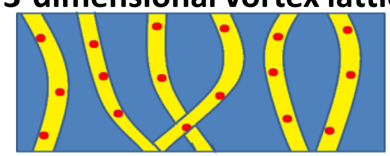

Sample manipulator
Vacuum Suitcase
Pulsed Laser Deposition Chamber
Battery operated ion pump
STM load-lock

Pinning induced amorphization: bulk $NbSe_2$





3-dimensional vortex lattice



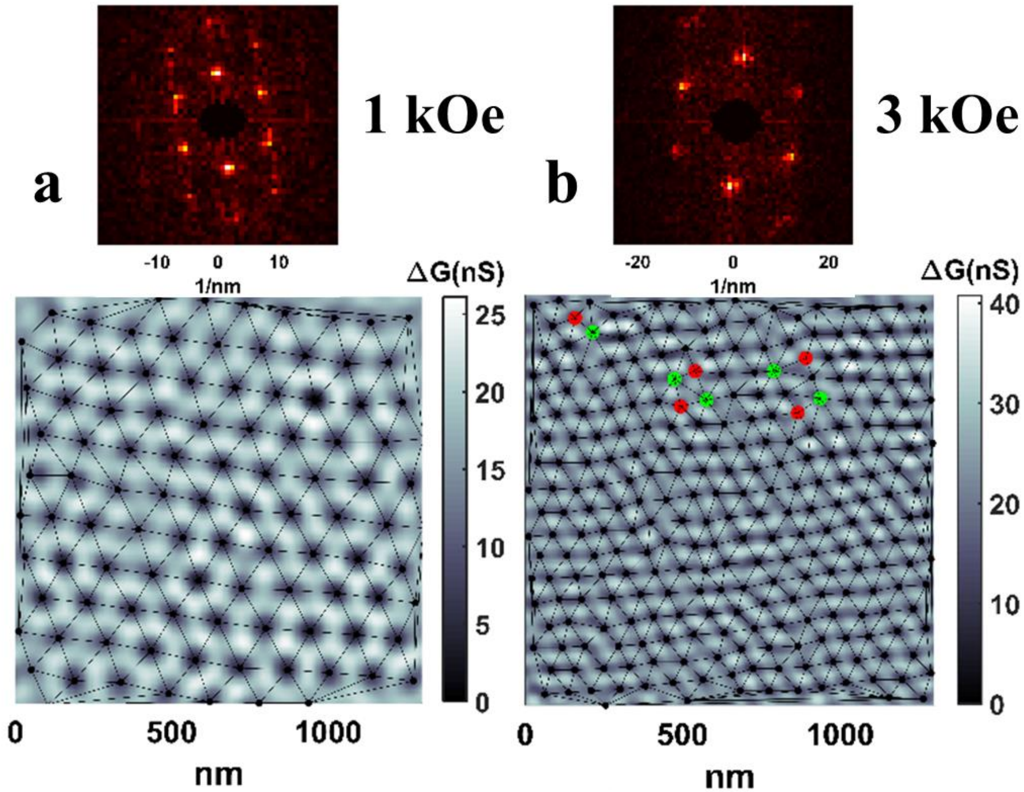
2-dimensional vortex lattice

Scientific Reports 5, 10613 (2015); Phys. Rev. B **93,** 144503 (2016).

Evidence of vortex liquid: *a*-MoGe thin film

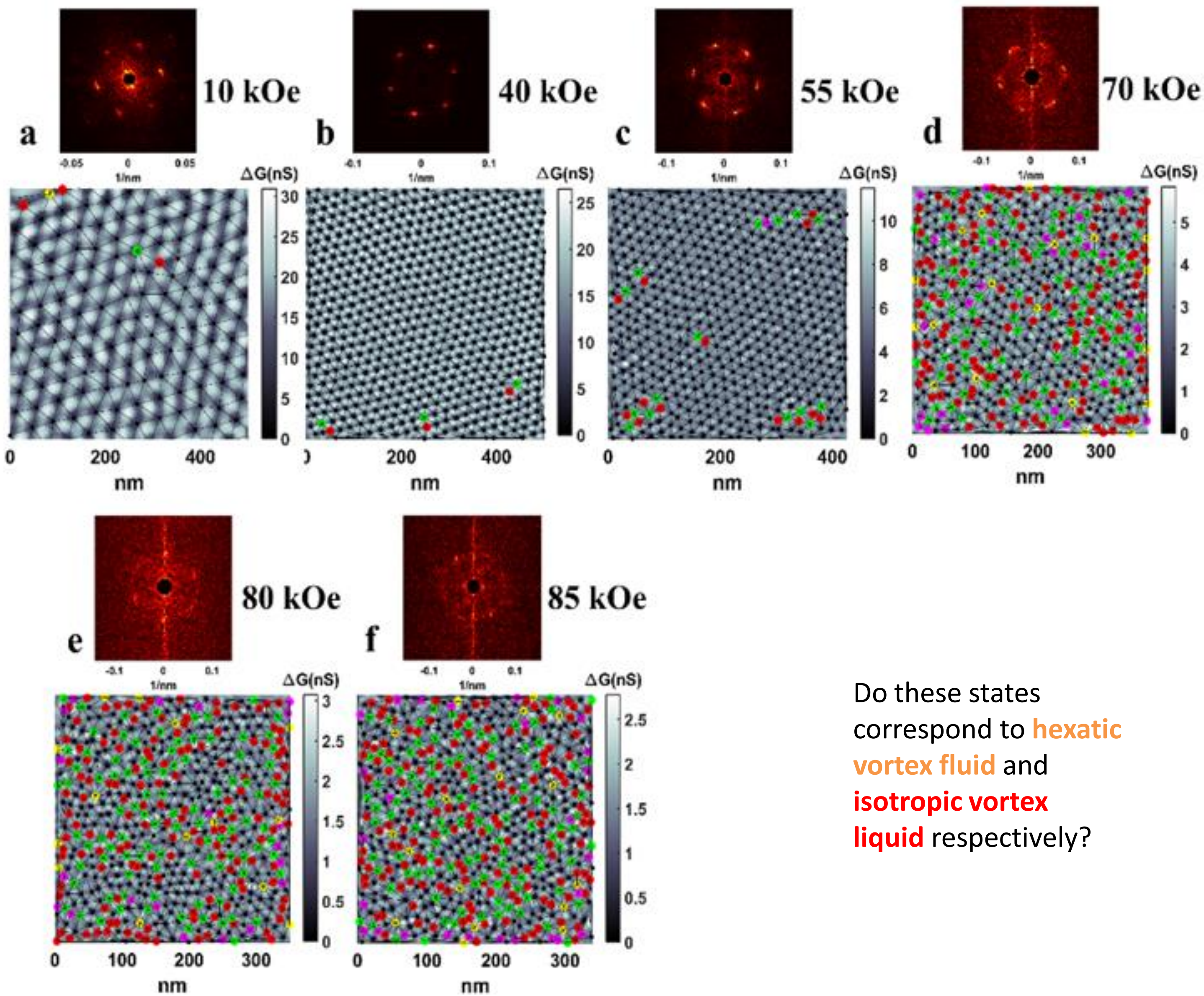
Very Weak pinning

Thickness: 20 nm



Real space evolution of the vortex lattice

Orientational order up to 70 kOe



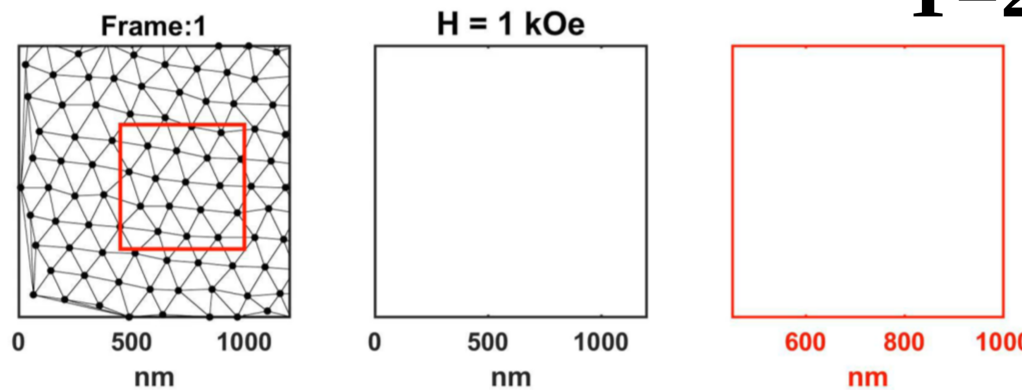
Fully disordered state

Do these states correspond to **hexatic vortex fluid** and **isotropic vortex liquid** respectively?

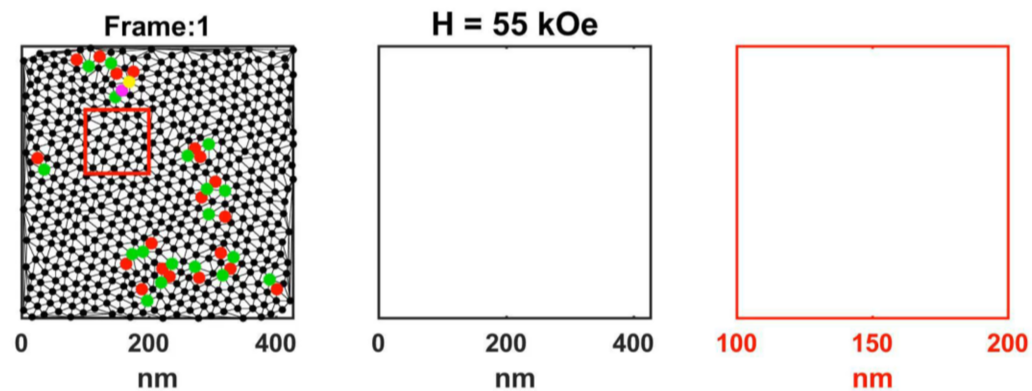
Looking at the Dynamics

T=2K

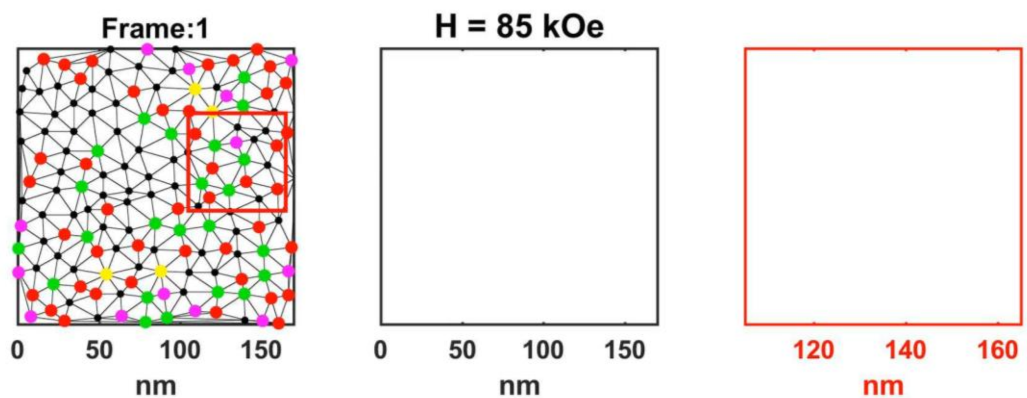
Vortex solid phase



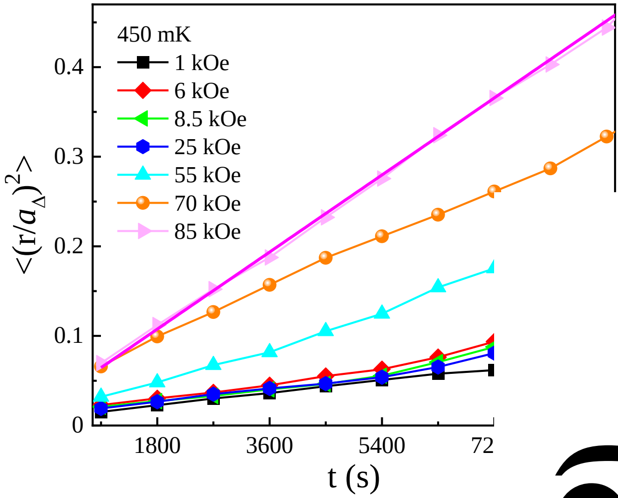
Hexatic vortex liquid



Isotropic vortex liquid



Solid to liquid transition in transport

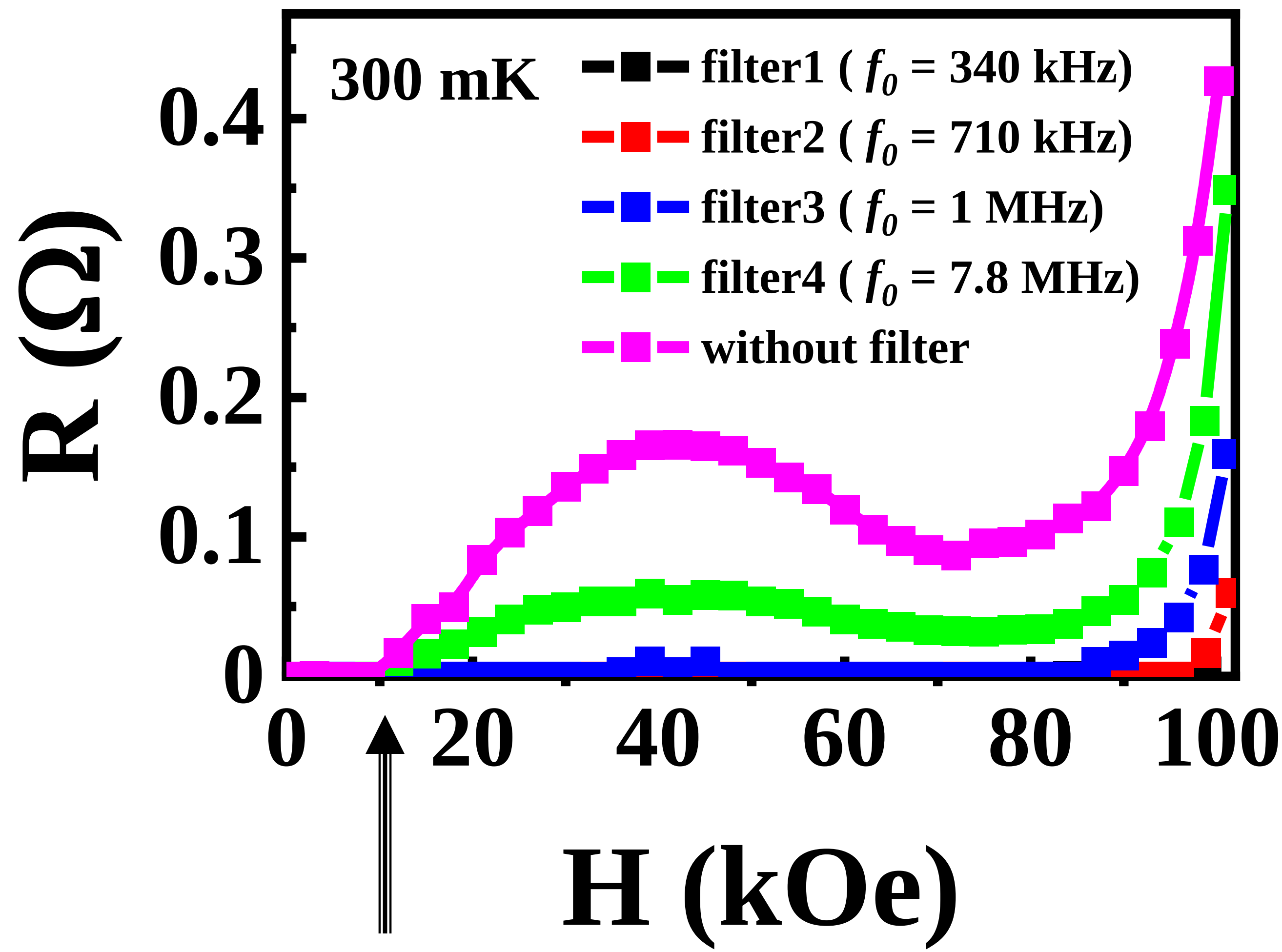


$$D = 3.236\,32 \times 10^{-21}\ \mathrm{m^2/s}$$

$$\eta = \frac{1}{\mu d} = \frac{k_B T}{D d} = 1.370\,63 \times$$

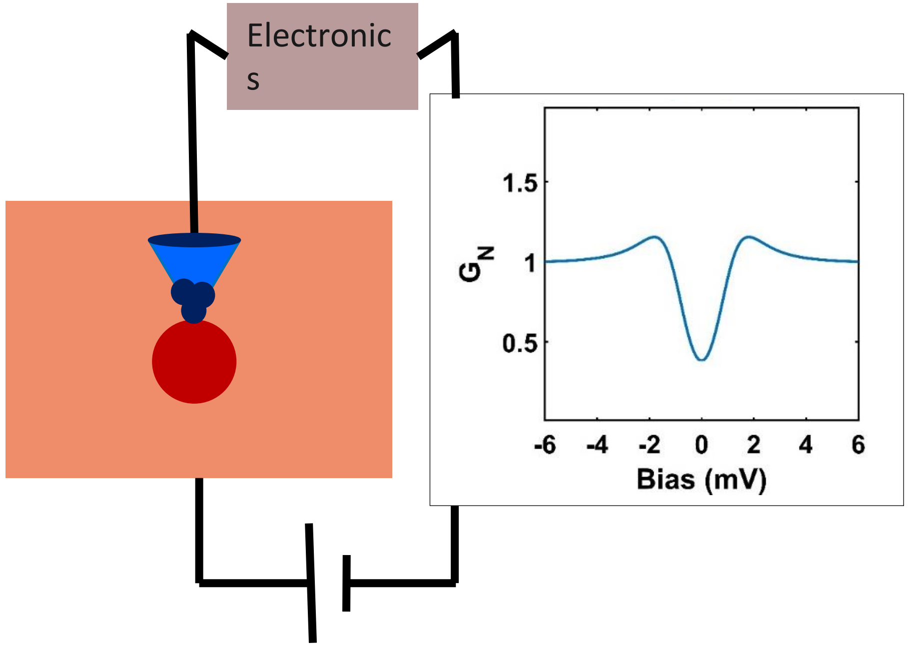
$$\rho_{TAFF} = B \times \frac{\Phi_0}{\eta} = 1.28$$

Phys. Rev. B **100**, 214518



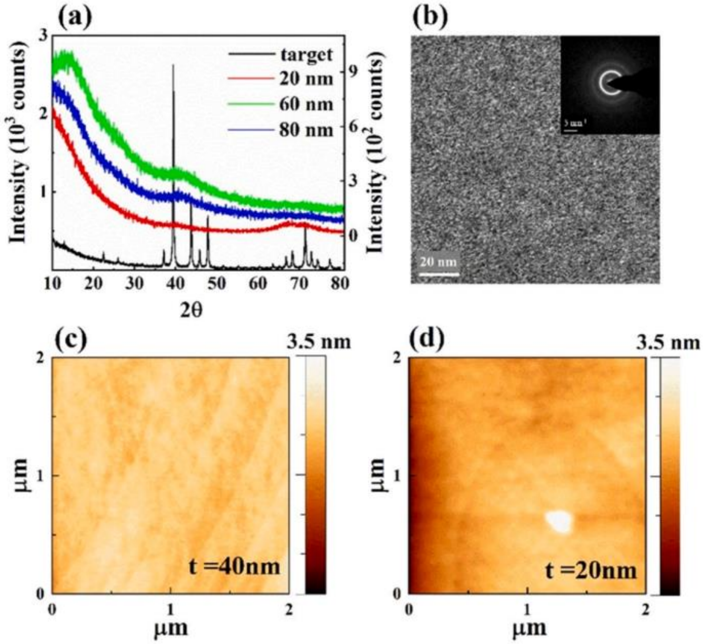
Solid to liquid transition: Marked by Extreme sensitivity

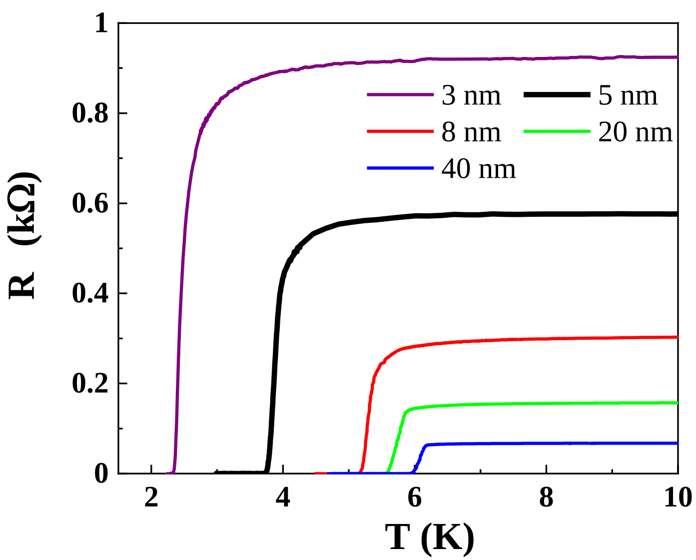
Dichotomy between transport and STS measurements

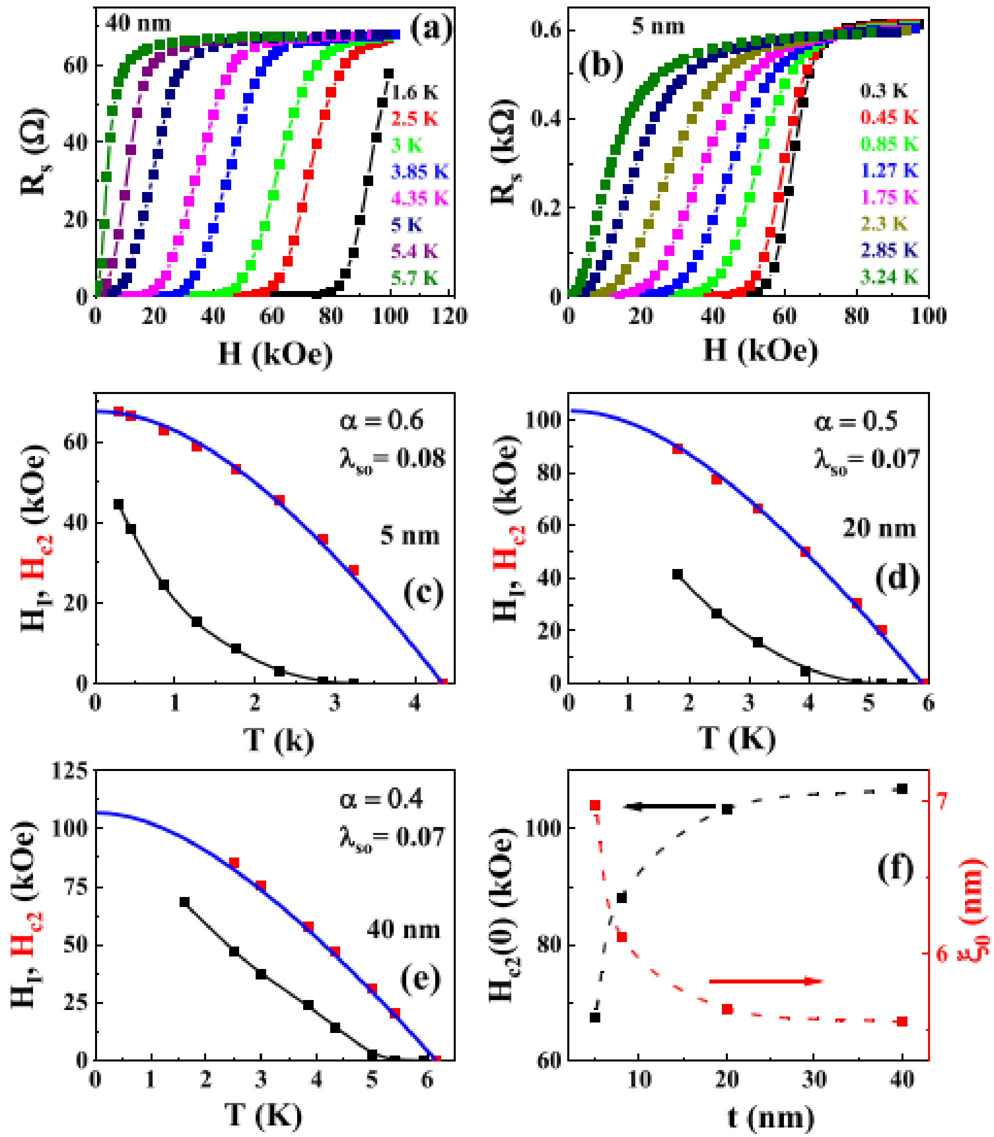


- STS is a slow measurement. Each image is acquired over 15-30 minutes and the conductance at each pixel is integrated over several msec.
- If individual vortices can be seen using STS then their diffusivity is too small to give any measurable resistance.
- If one observes a finite resistance, the vortices have to move very fast and one would observe an uniform average response everywhere.

The enigma of a-Re_xZr

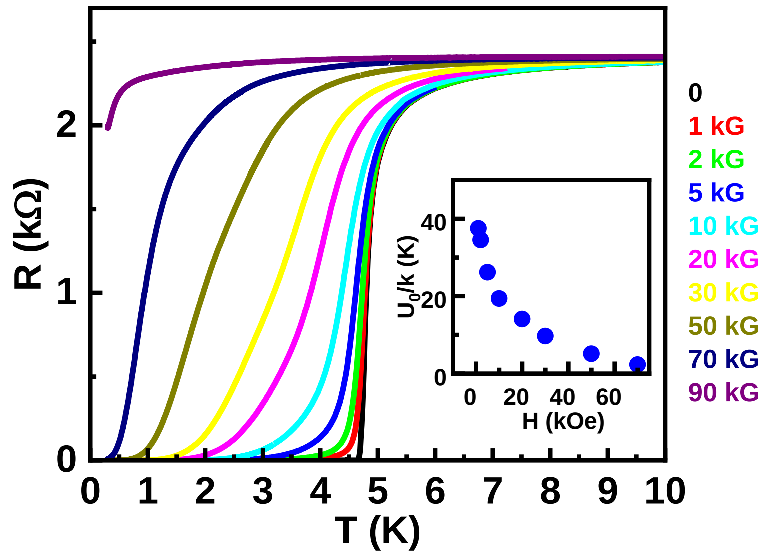




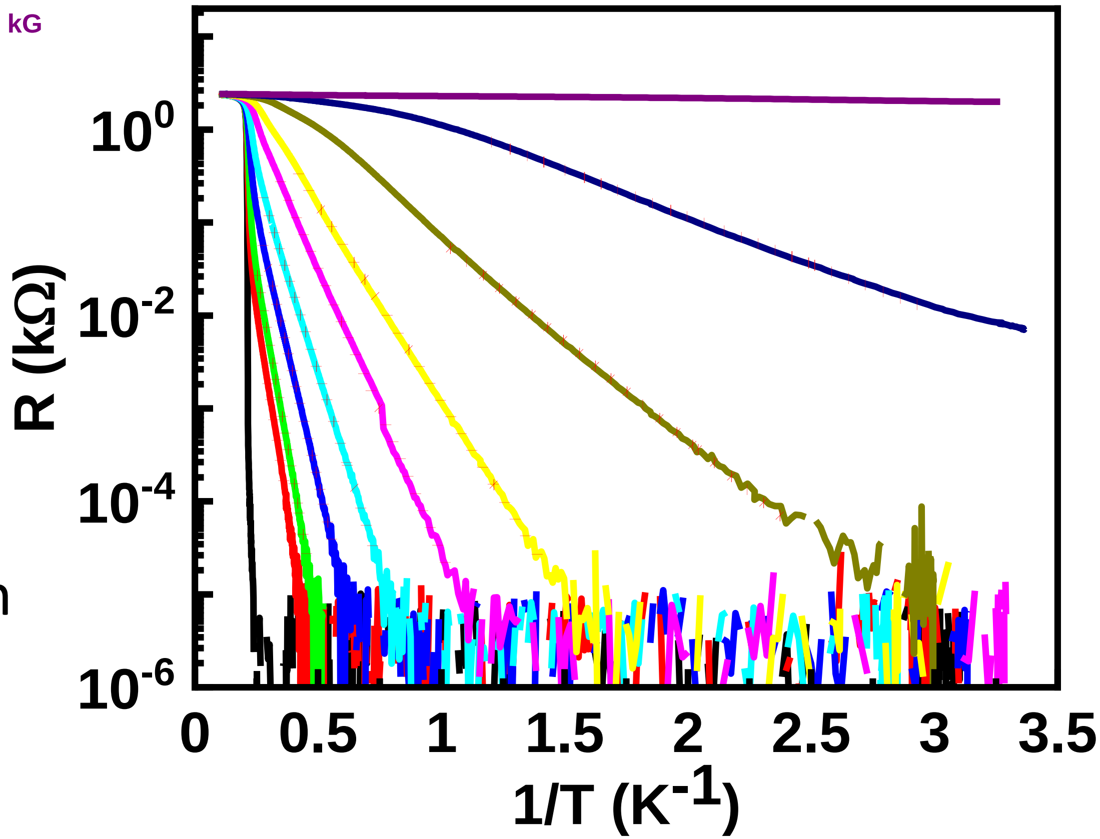


Journal of Alloys and Compounds **877,** 160258 (2021)

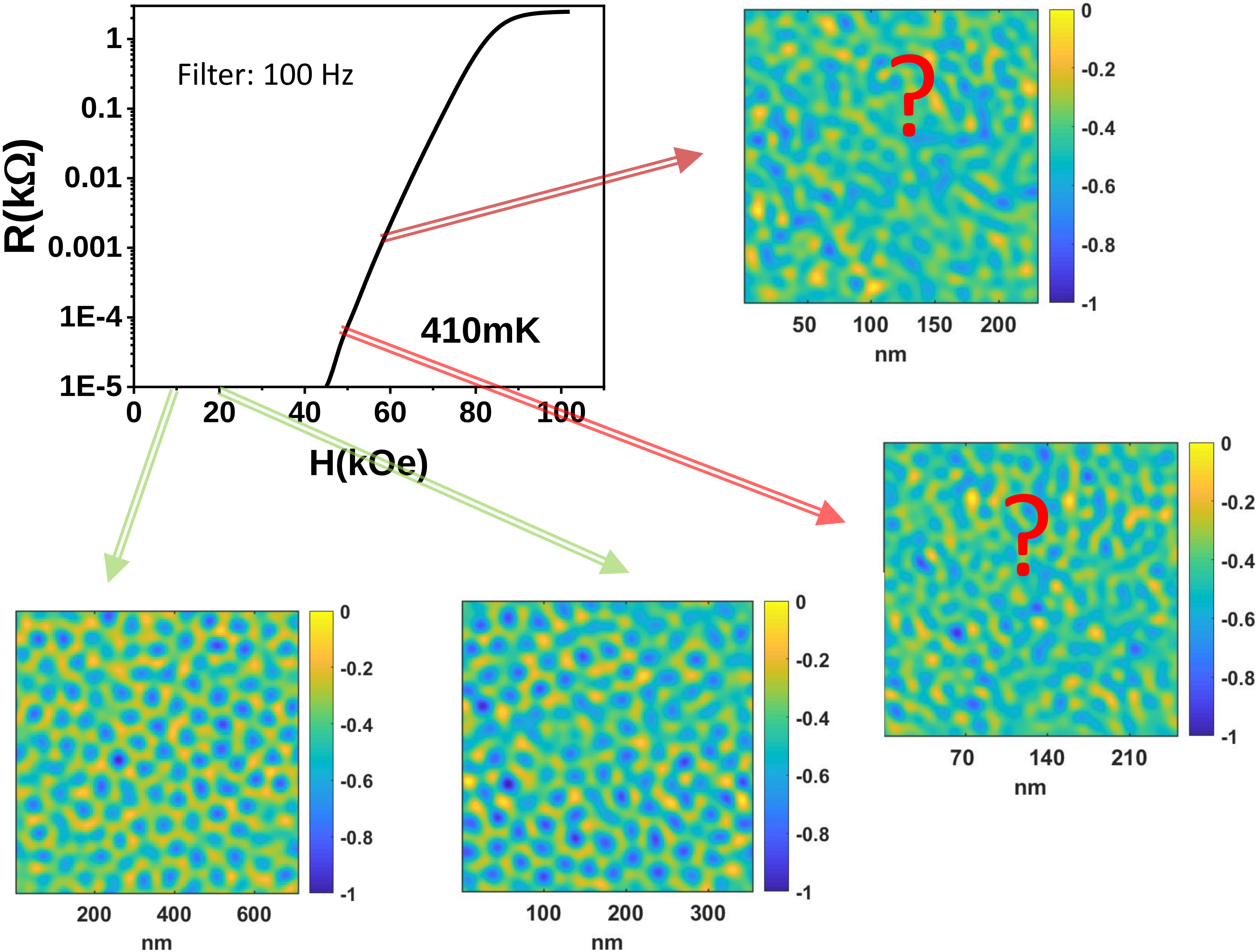
5 nm thick a-Re_xZr thin film



$R=R_0 \exp(-U(H)/kT)$

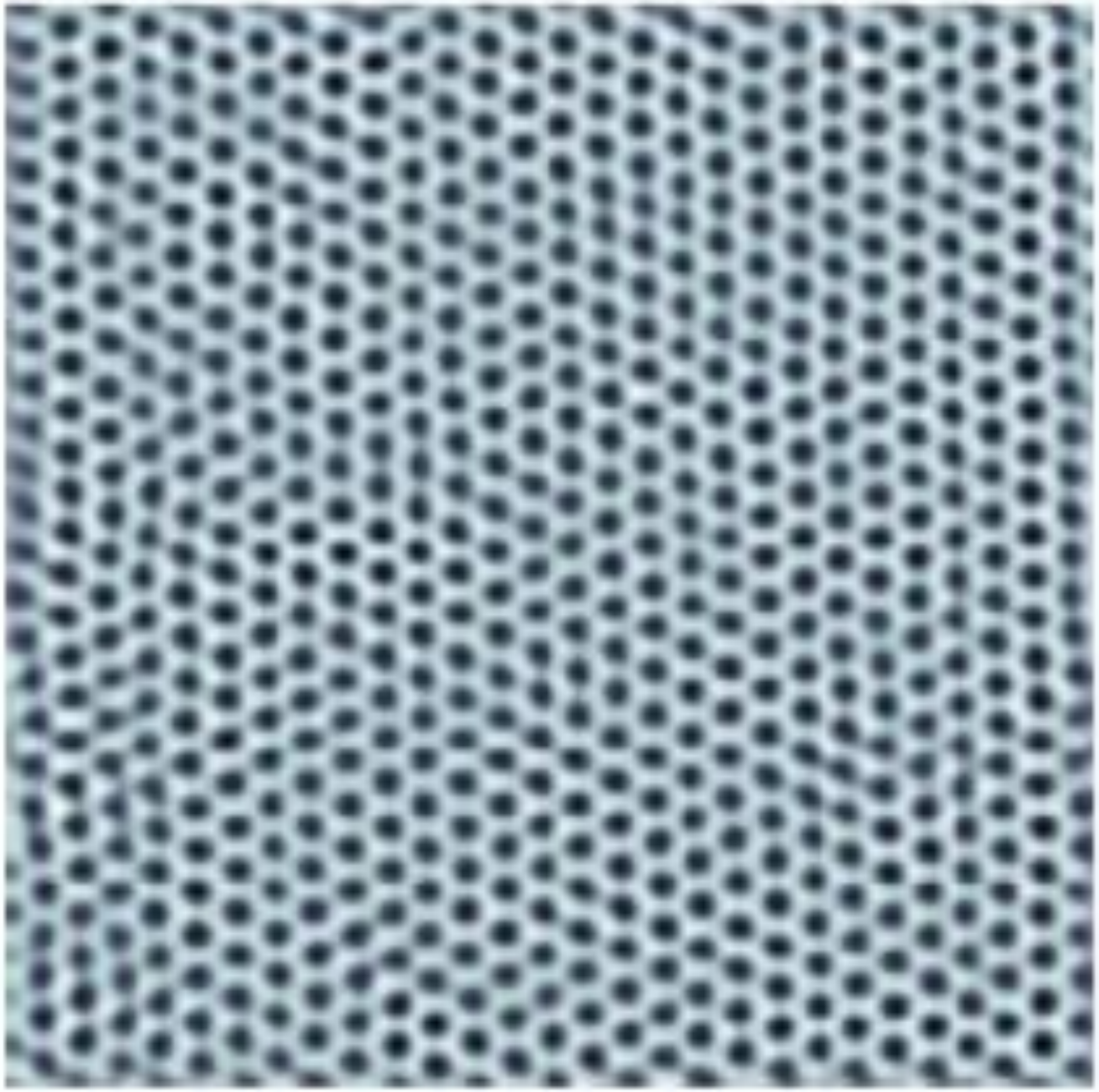


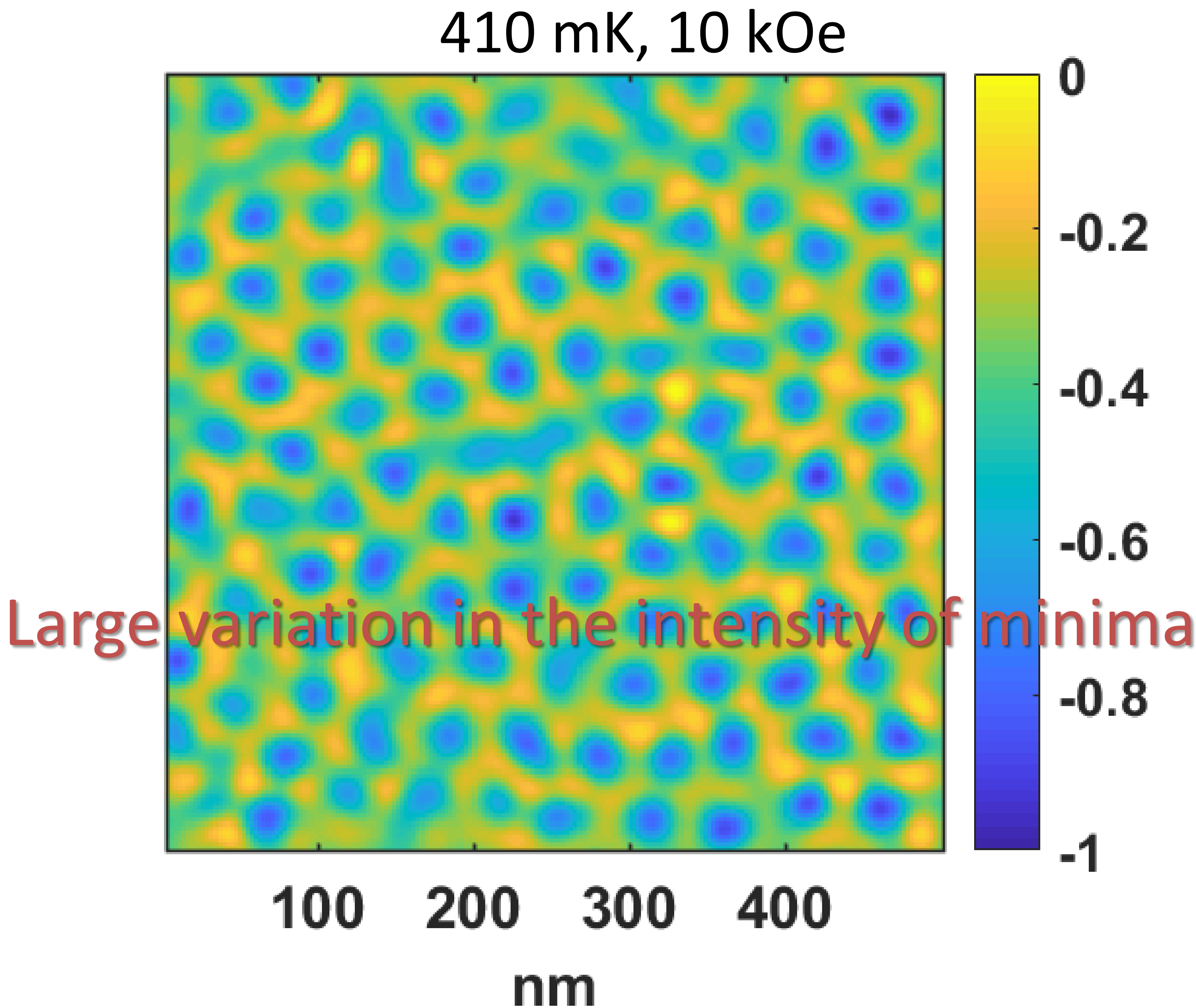
No Signature of a transition to a vortex glass.



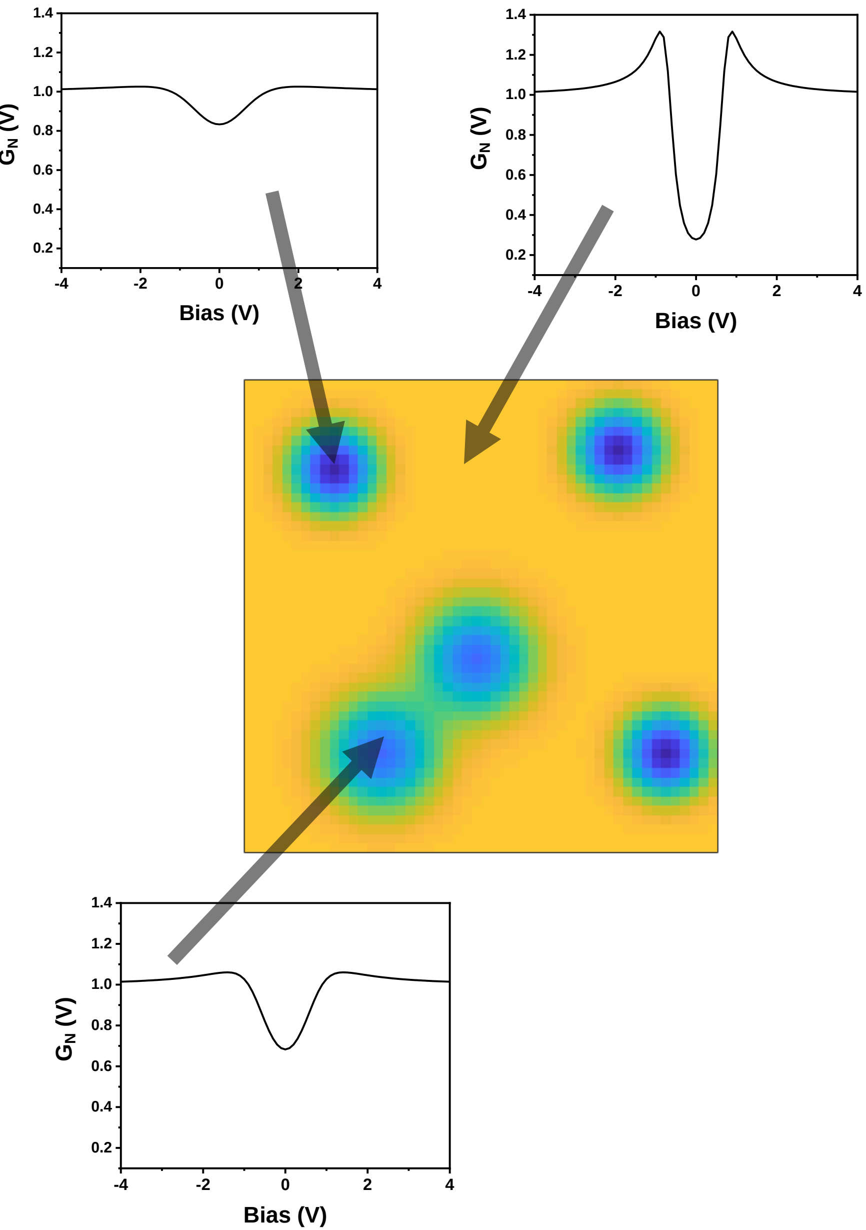
Filter: 100 Hz
410mK
R(kΩ)
H(kOe)
1
0.1
0.01
0.001
1E-4
1E-5
0
20
40
60
80
100
?
?
nm
0
-0.2
-0.4
-0.6
-0.8
-1
50
100
150
200
70
140
210
400
600
300

$NbSe_2$ single crystal: 400 mK, 10 kOe




410 mK, 10 kOe
0
-0.2
-0.4
-0.6
-0.8
-1
100
200
300
400
nm
Large variation in the intensity of minima

STS measurement in a pinned vortex liquid



In the presence of pinning…

Vortices will spend longer time close to the pinning centres.

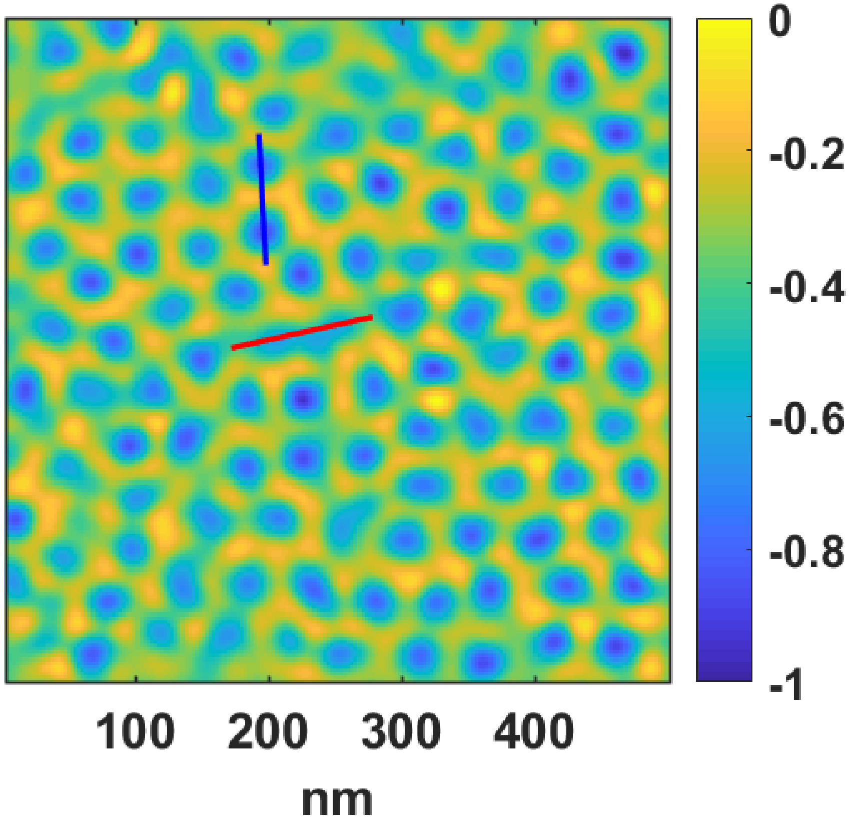
The locations will show a minima in G(V) but the depth of the minima will be shallower than the one corresponding to a static vortex at that location.

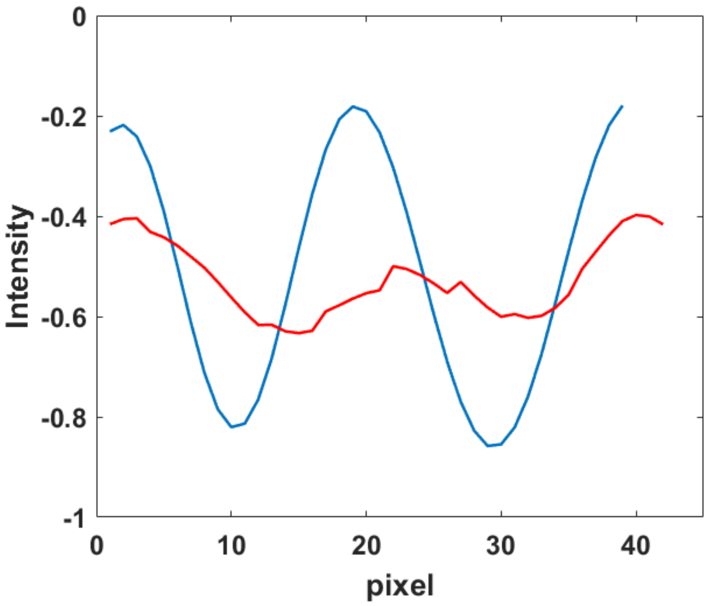
The depth of the minima is a metric of the probability of finding a vortex at that location.

Diffusive motion of vortices will happen through hops between these preferential sites.

If some vortex is completely localised at some pinning site that location will display a deep minimum.

Vortices with different degree of localisation





Deep minima corresponding to strongly localized vortices

Shallow minima corresponding to weakly localized vortices

Finding Motion Paths

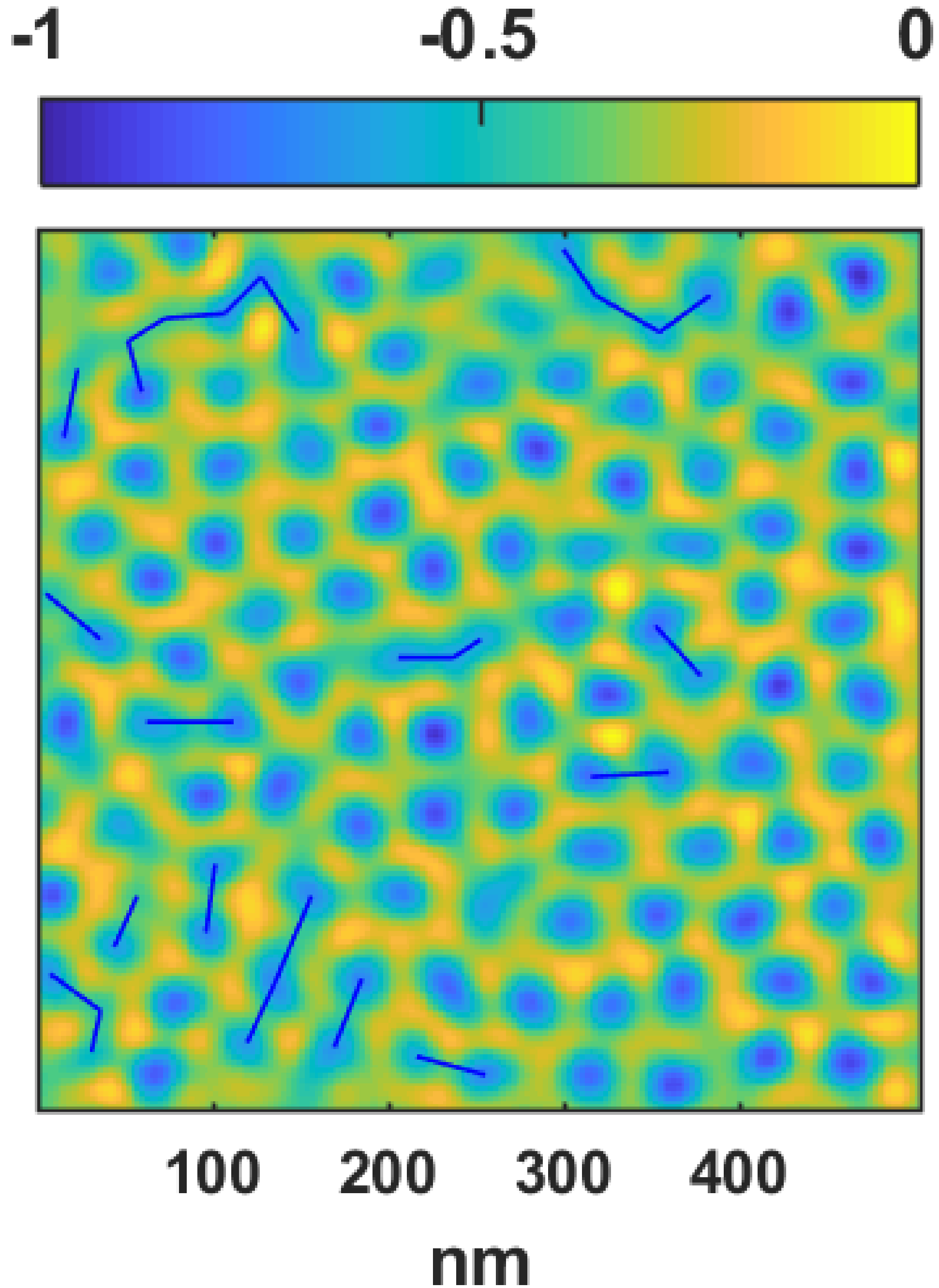
Join any two neighbouring minima for which,

(i) The value of $G_N > -0.8$

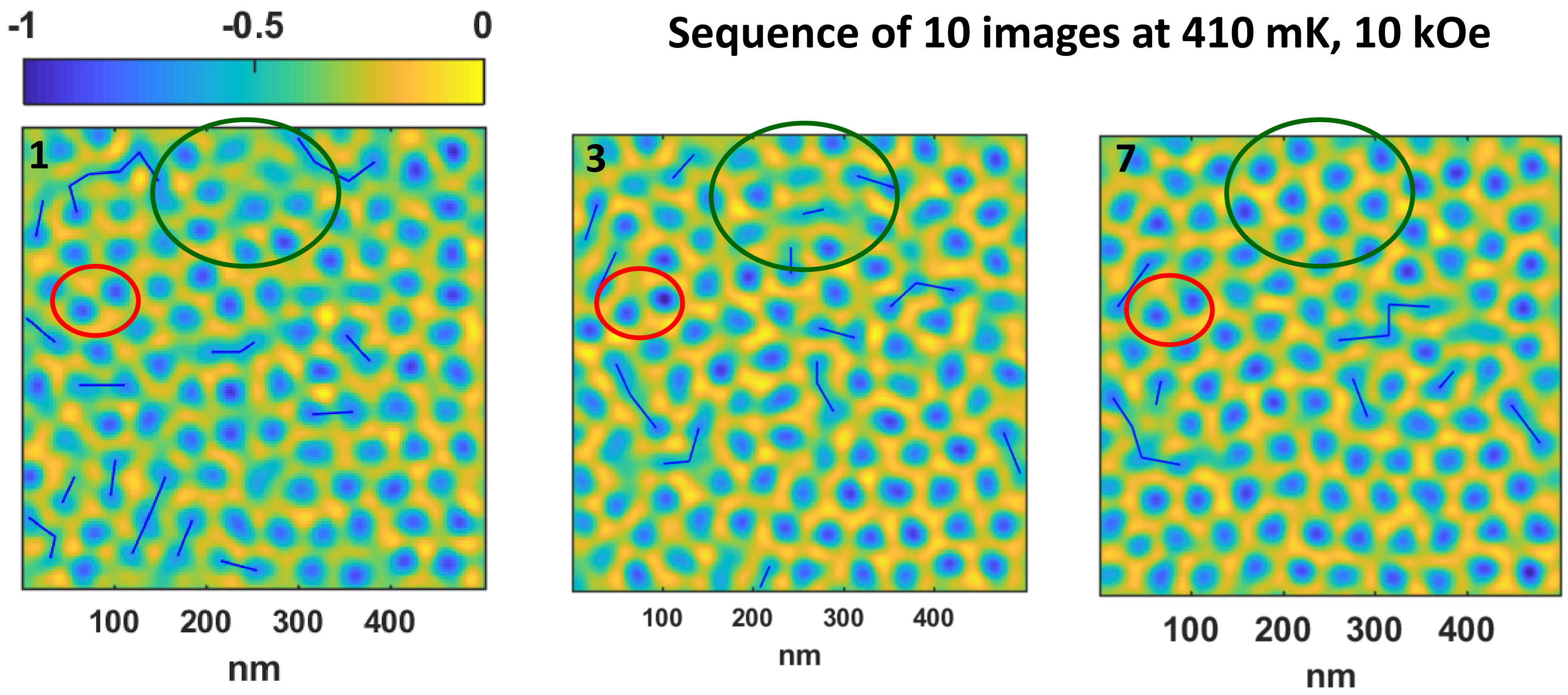
and

(ii) The value of G_N along the line joining the minima is < -0.4

Not the complete story…



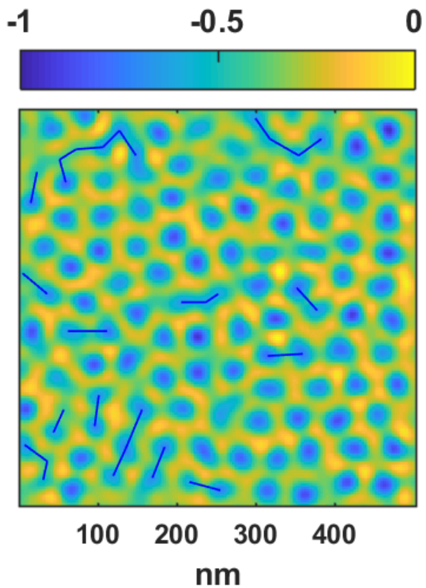
Sequence of 10 images at 410 mK, 10 kOe



Why this change?

- The preferred sites are determined by a combination of **pinning potential and the confining potential created by neighbouring vortices.**
- Some vortices get trapped in an in an intermediate pinning center while hopping between two minima: **Incomplete hops.**

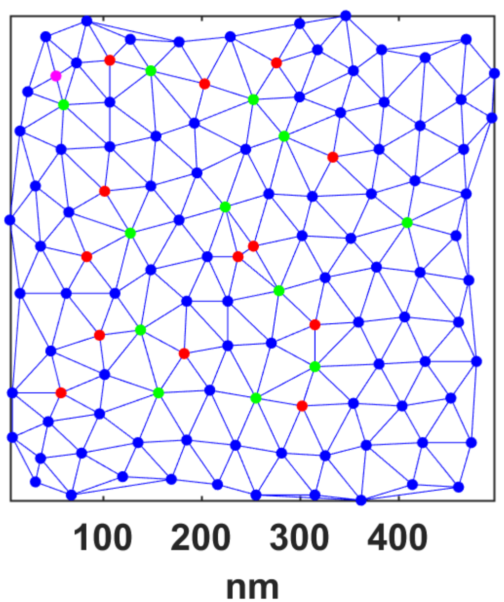
Relationship between Structure and Dynamics

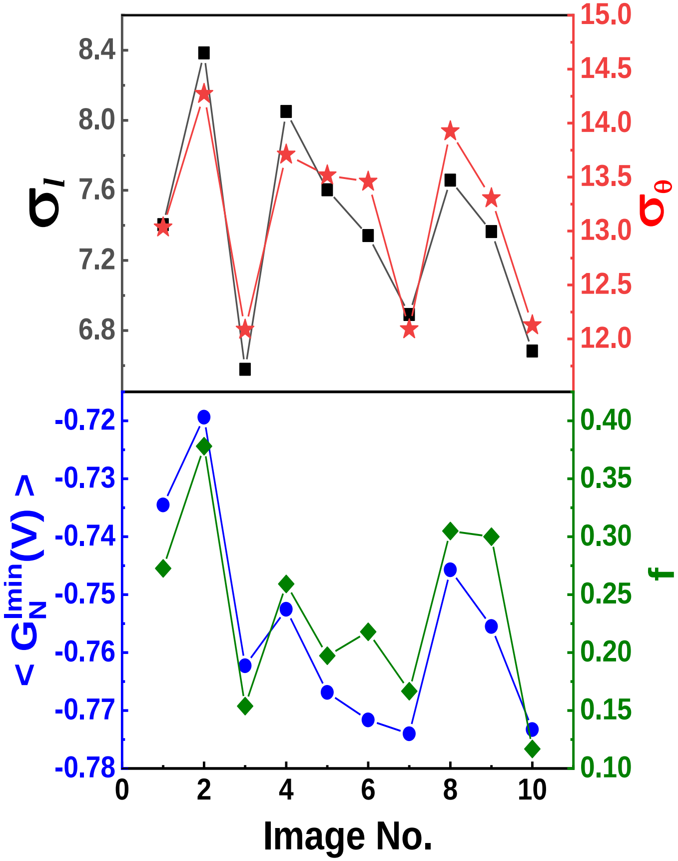


$$\sigma_l = \left(\frac{1}{N_l}\sum_i (l_i - a_H)^2\right)^{1/2} \qquad \sigma_\theta = \left(\frac{1}{N_\theta}\sum_j (\theta_j - 60^\circ)^2\right)^{1/2}$$

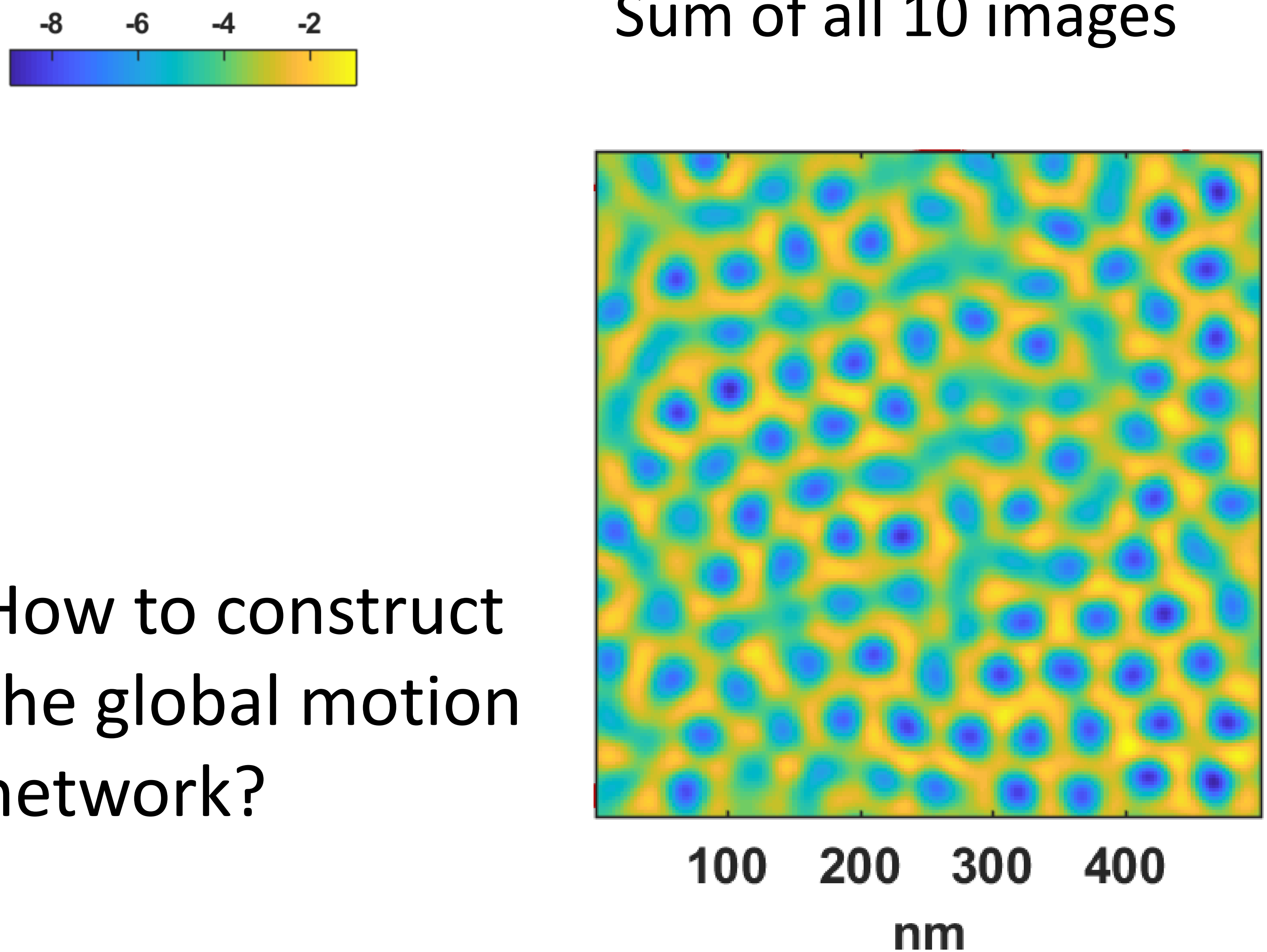
$\langle G_N^{lmin}(V)\rangle$: average intensity of the minima

f : fraction of vortices on movement network





Sum of all 10 images



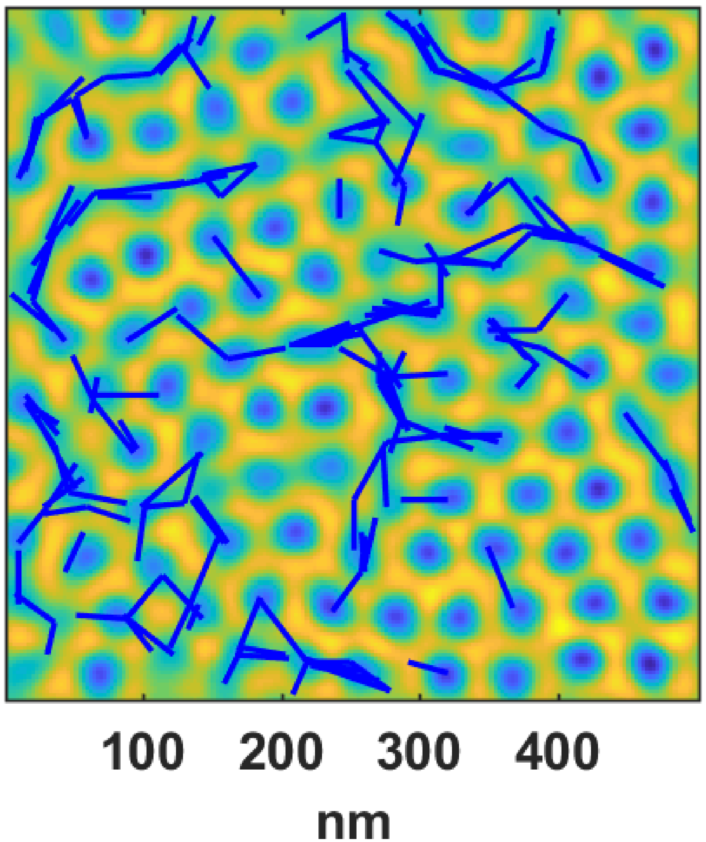
How to construct the global motion network?

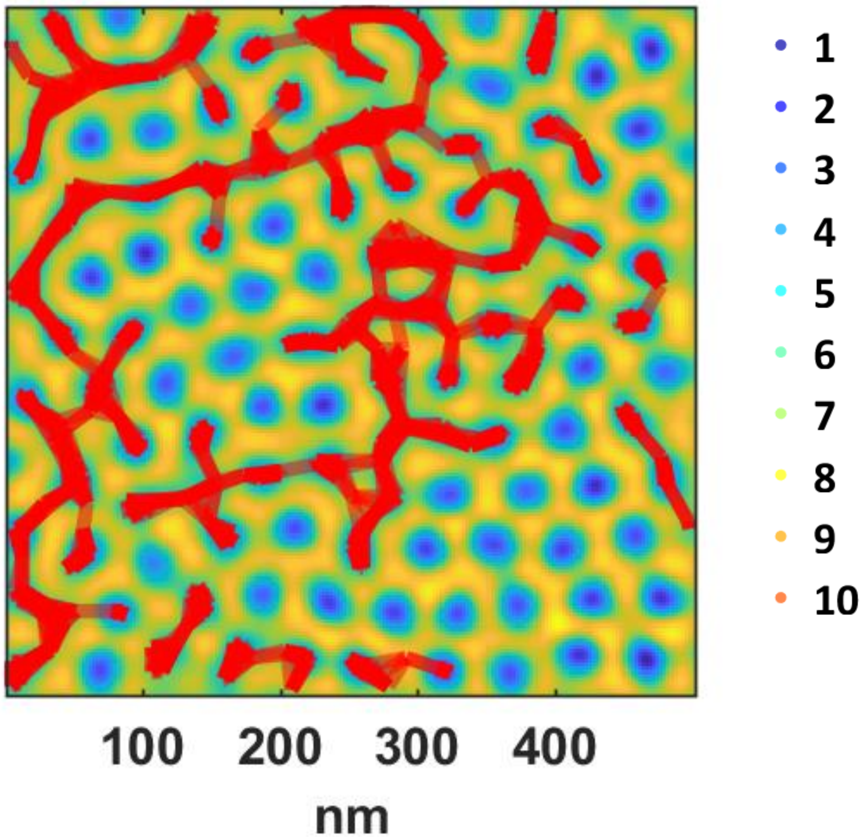
Superpose all **Blue paths**

(Sum of Complete hops)

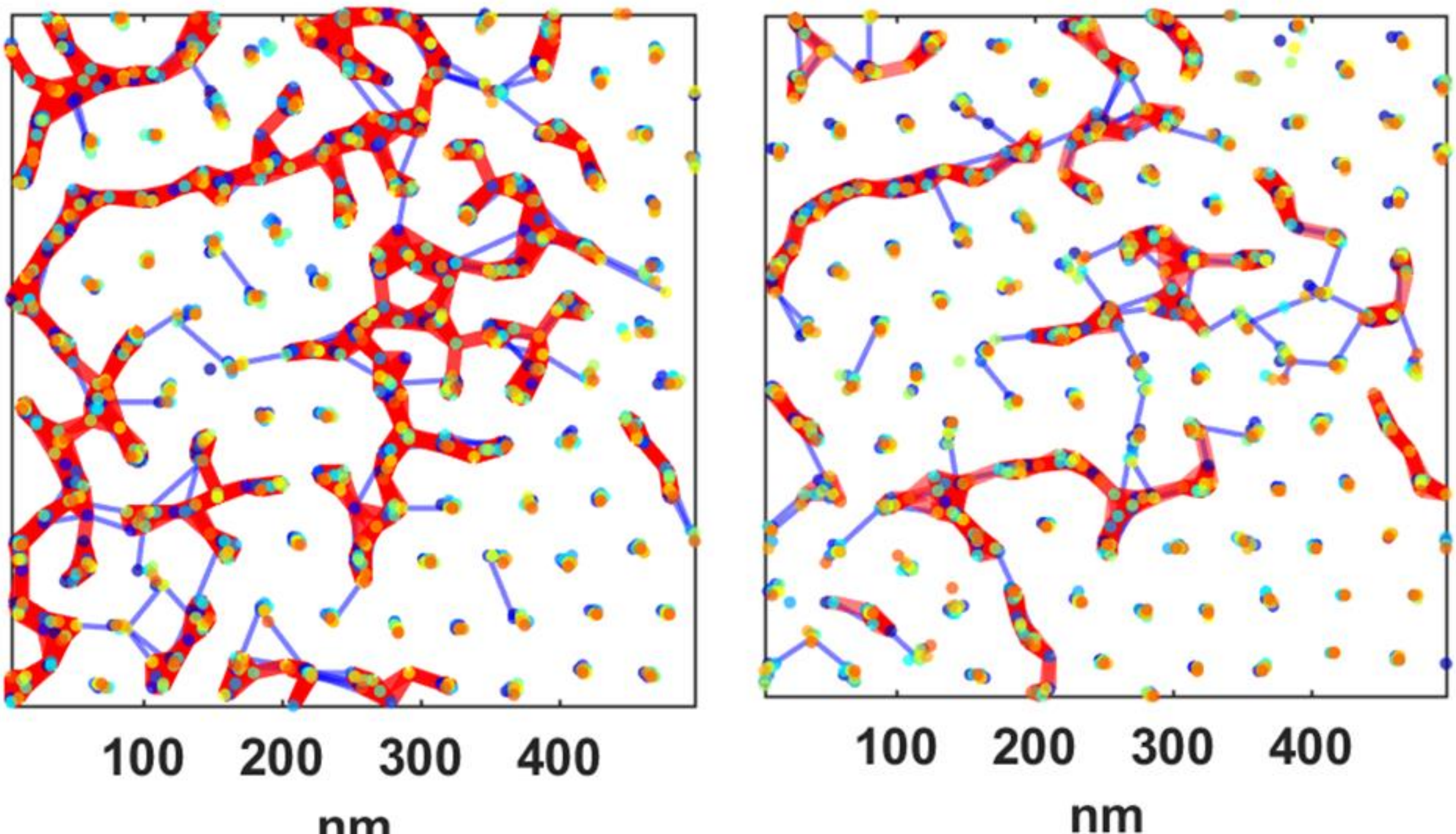
Connecting the **incomplete hops**

(Connecting minima that are closer than $0.5a_H$)

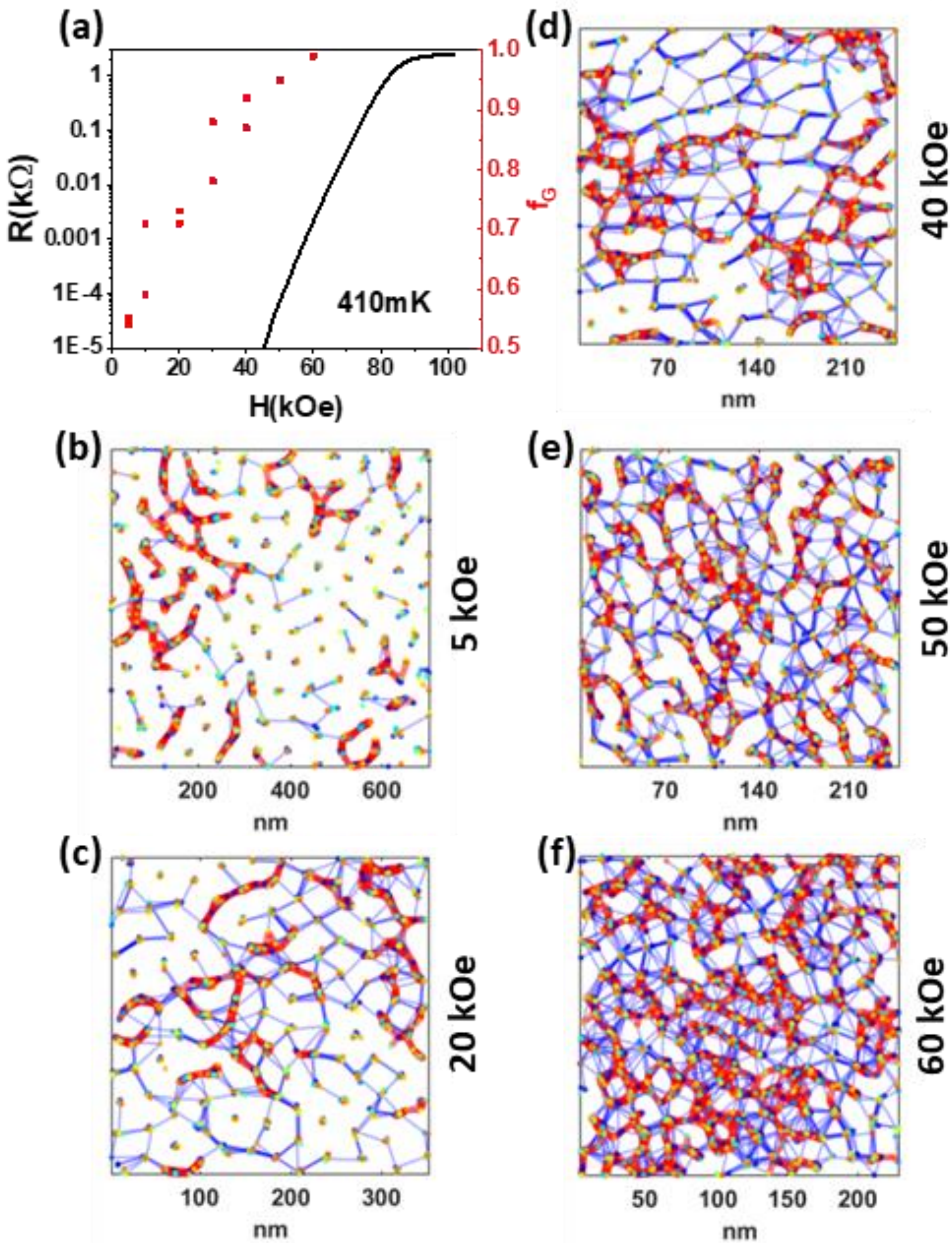




Overall Motion paths: Red Network + Blue Network



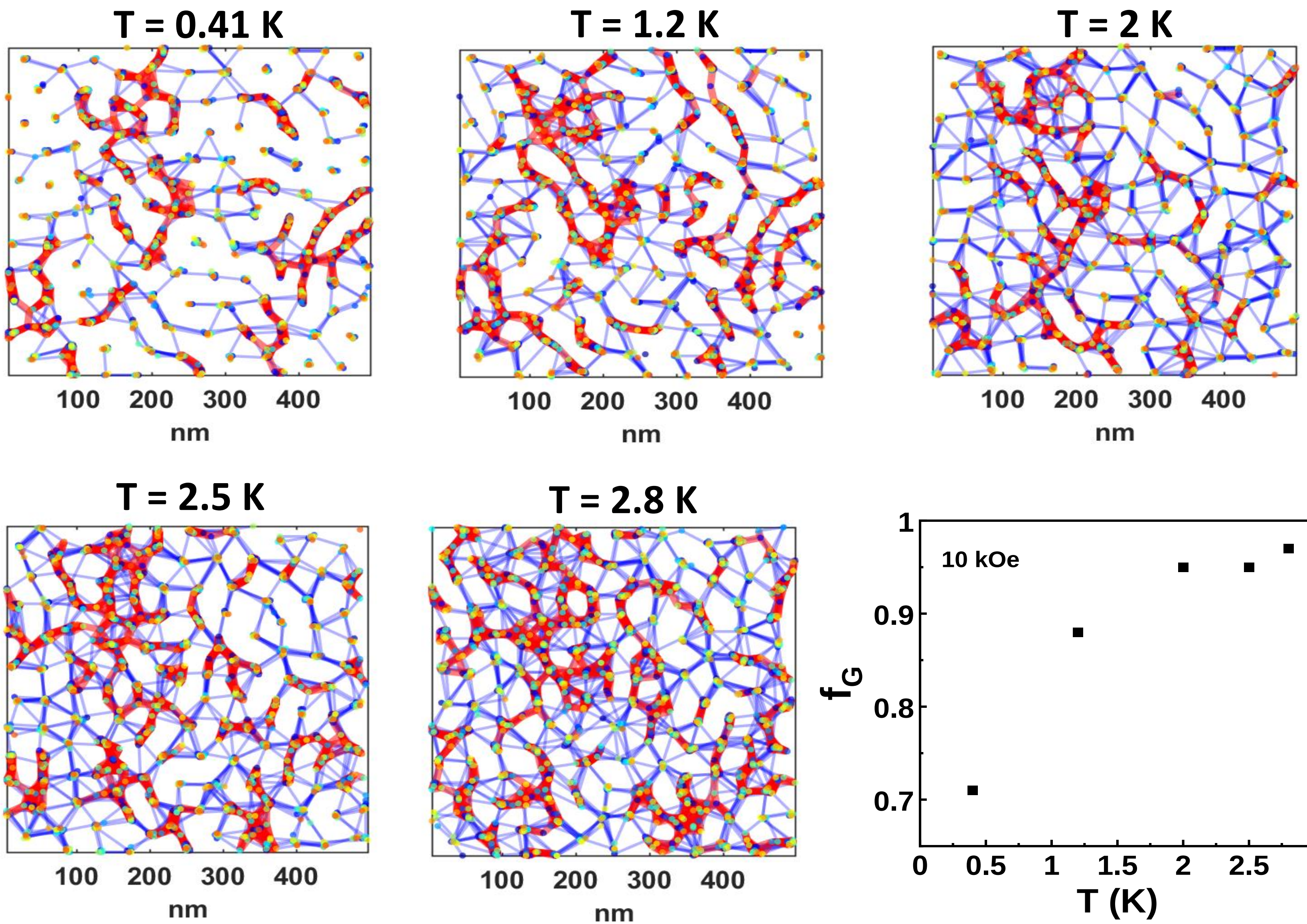
Magnetic field evolution of network paths

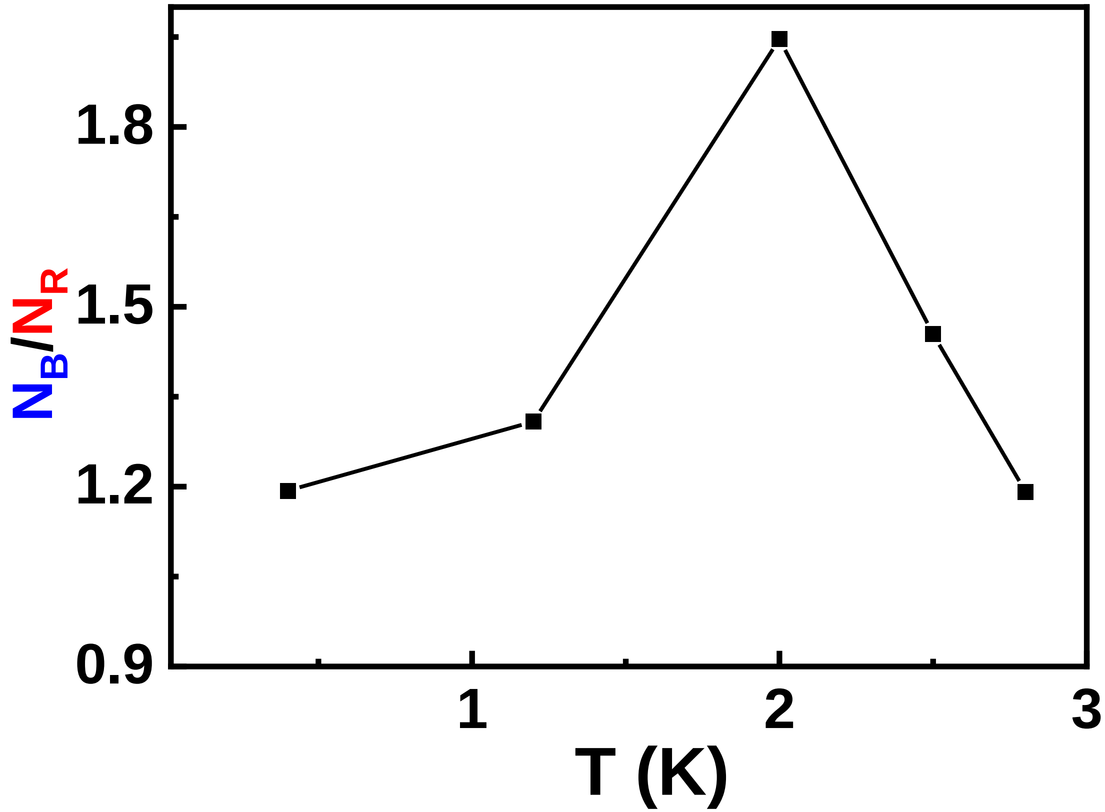


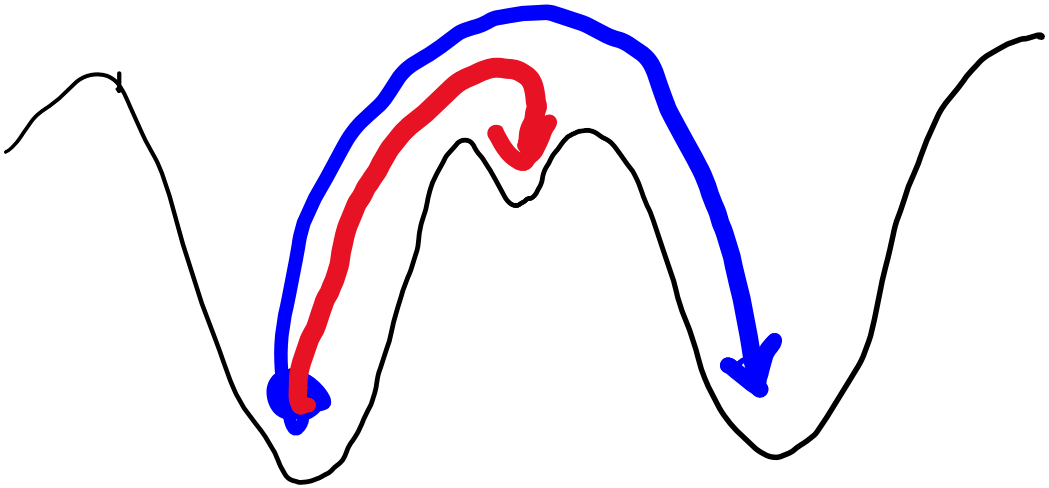
f_G – fraction of vortices that are on the motion path.

No Signature of a Glass transition!

10 kOe : Temperature Evolution

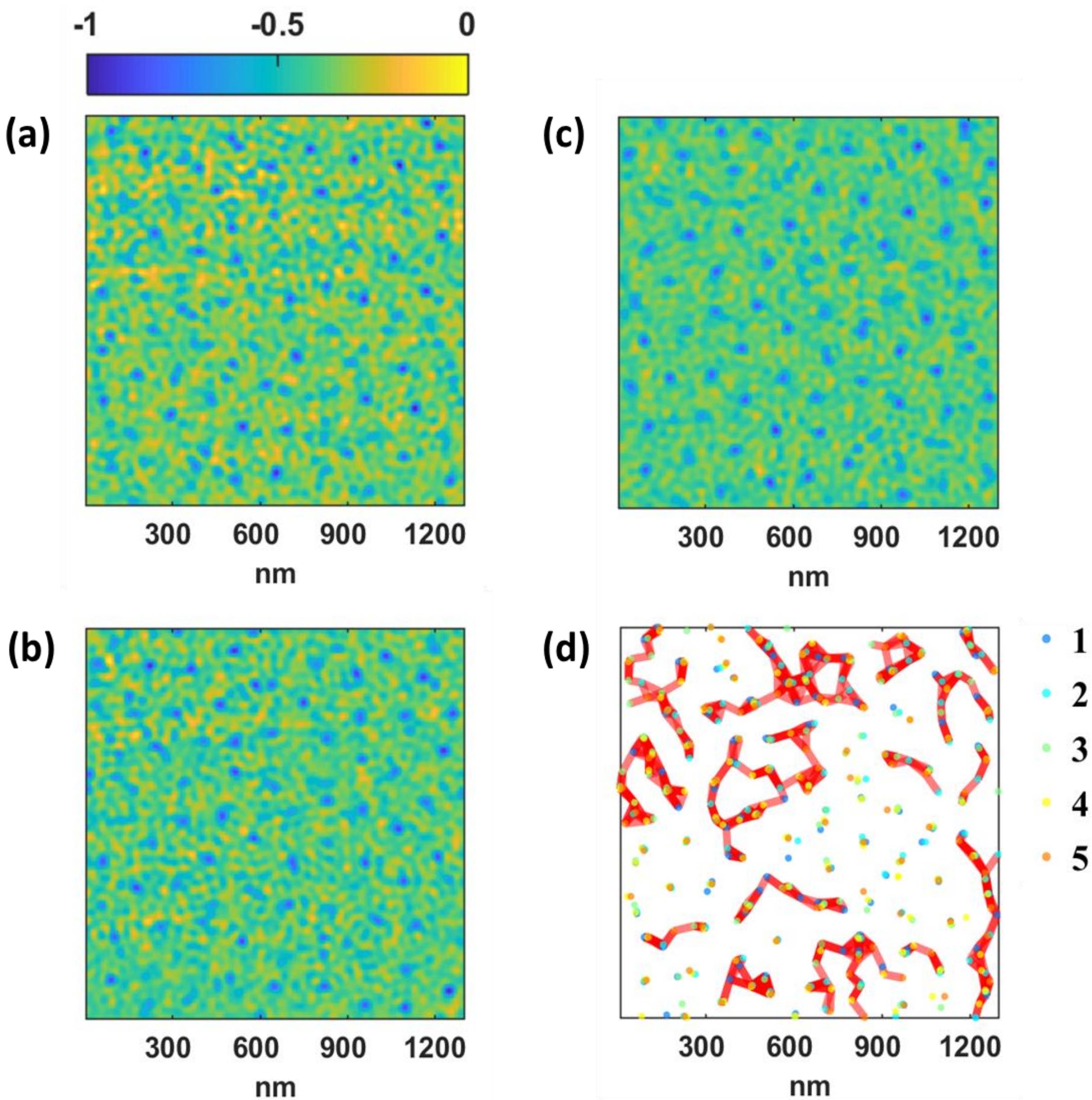




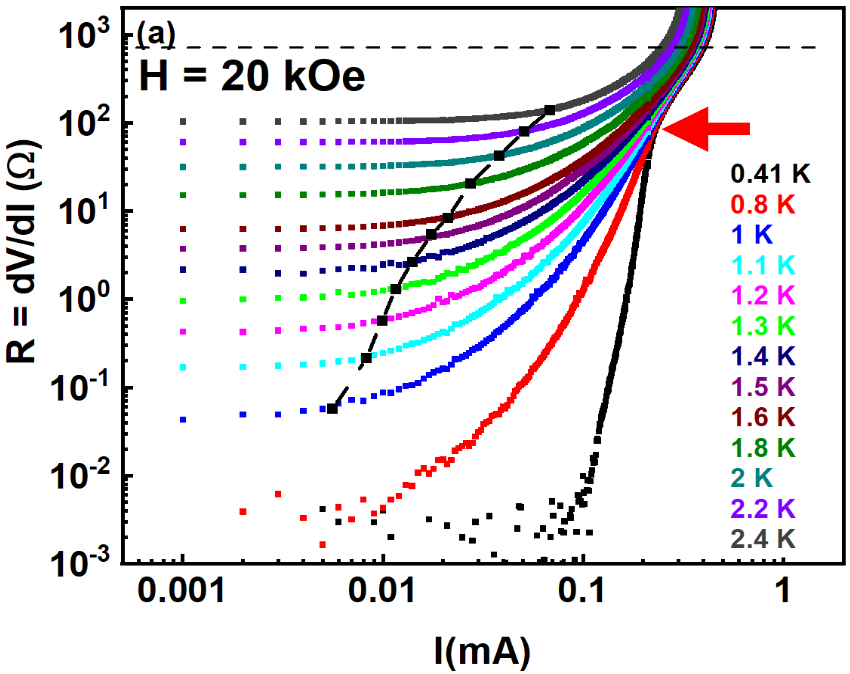


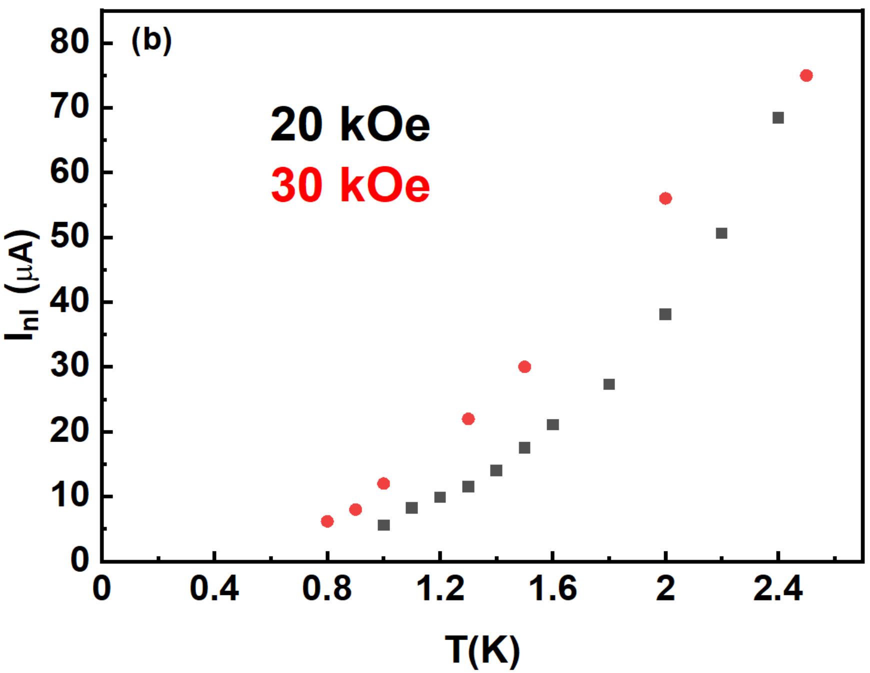
As the temperature increases the Red hops become less probable.

1 kOe, 410 mK : No complete hops



Understanding transport peculiarity





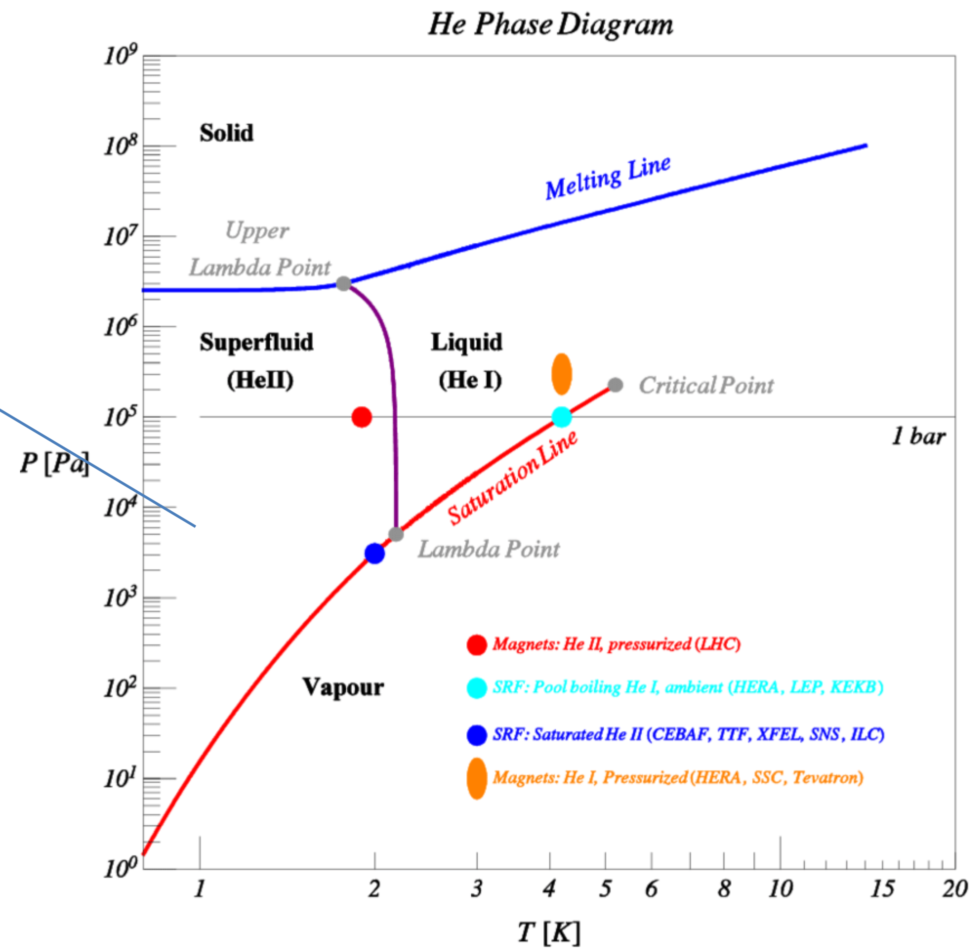
Conclusions

- We have shown the formation of a inhomogeneous "pinned" vortex liquid in 5 nm thick a-Re_xZr thin film through STS and transport measurement.
- The movement of vortices in this liquid is through a network of percolating tracks.
- Our analysis resolves the dichotomy between transport and STS measurements to visualise pinned vortex liquid.

THANK YOU

Zero Point
Fluctuation prevents
a solid from forming.

Quantum fluid



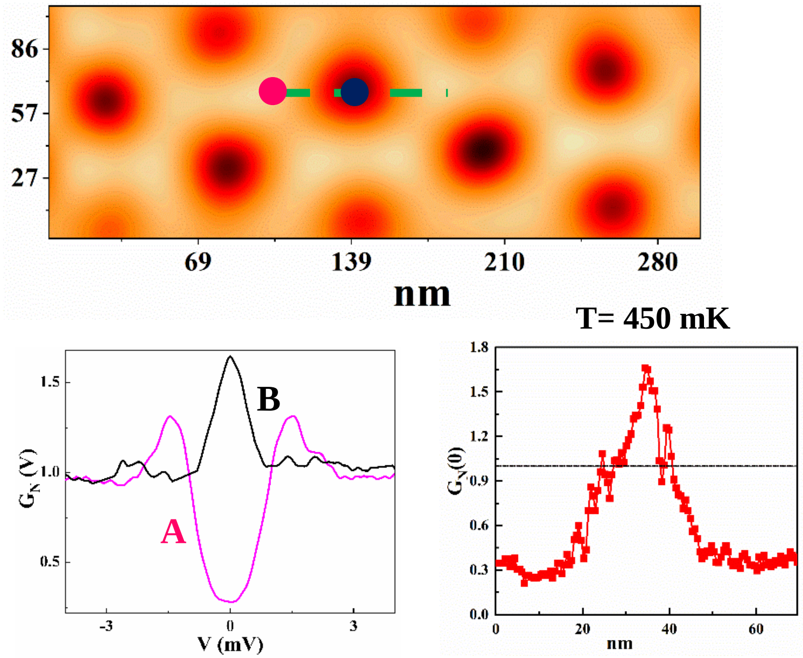
Are there other solids or fluids where we can see ramifications of zero point fluctuations?

$$\Delta a = \left(\frac{\hbar}{m\omega}\right)^{1/2} = \frac{\hbar^{1/2}}{(km)^{1/4}}$$

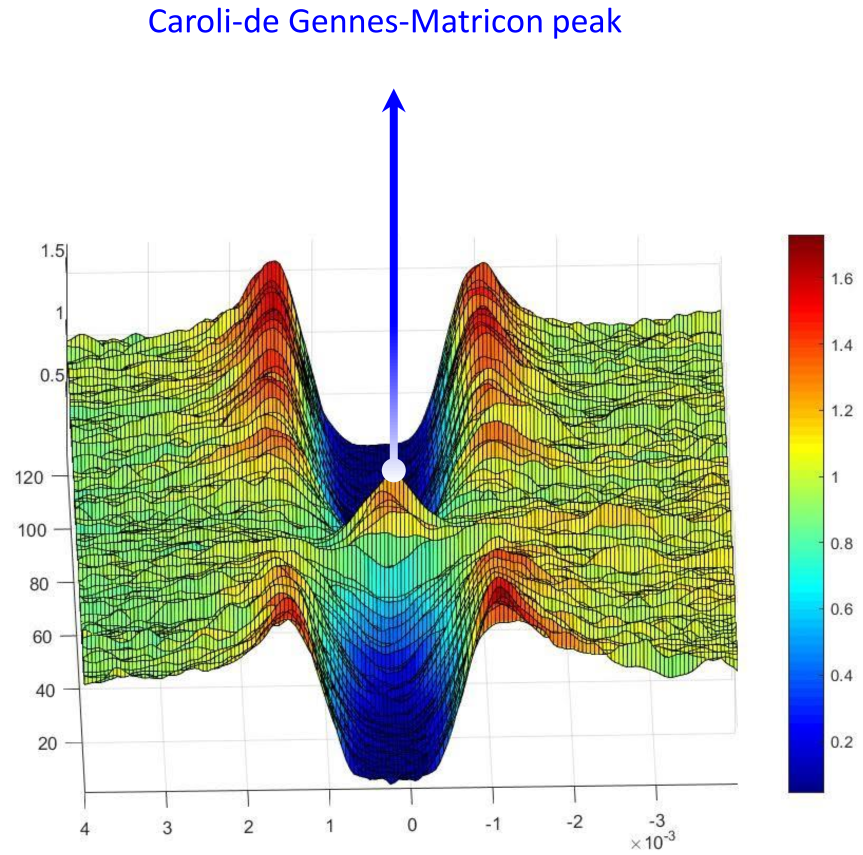
Inside the vortex core

Clean limit

Sample: $NbSe_2$ single crystal



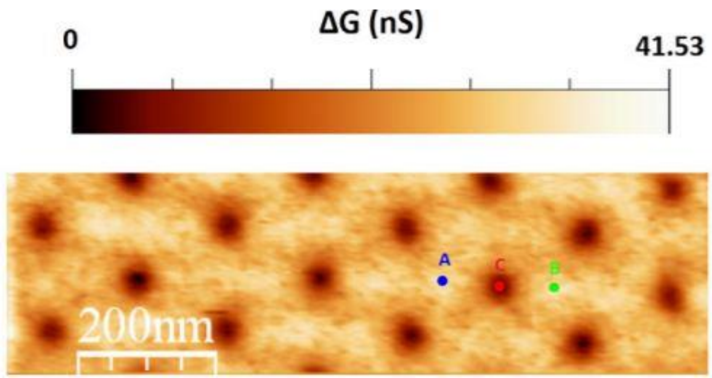
- **Peak (more than unity) is observed at the zero bias conductance due to formation of bound state by the normal electrons, Known as Caroli-de Gennes-Matricon state.**

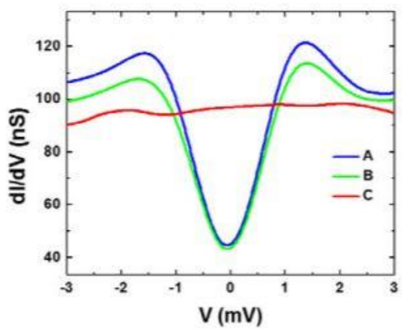


Inside the vortex core

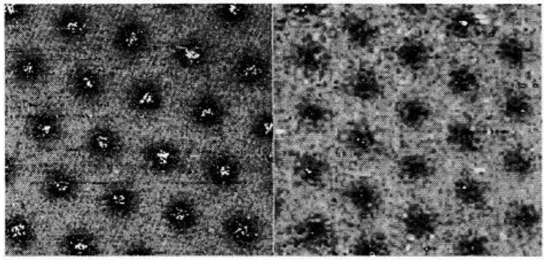
Dirty limit

Sample: Co doped Nbse$_2$ **(J. Phys.: Con. Mat. 28 (2016) 165701)**

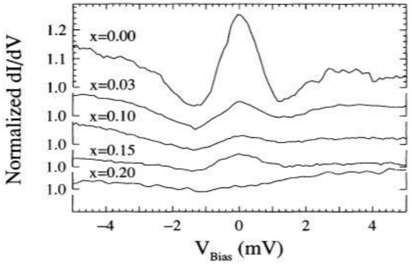




Sample: 2H-Nb$_{1-x}$ Ta$_x$Se$_2$ (ref: Phys. Rev. Lett. 67, 1650 (1991))

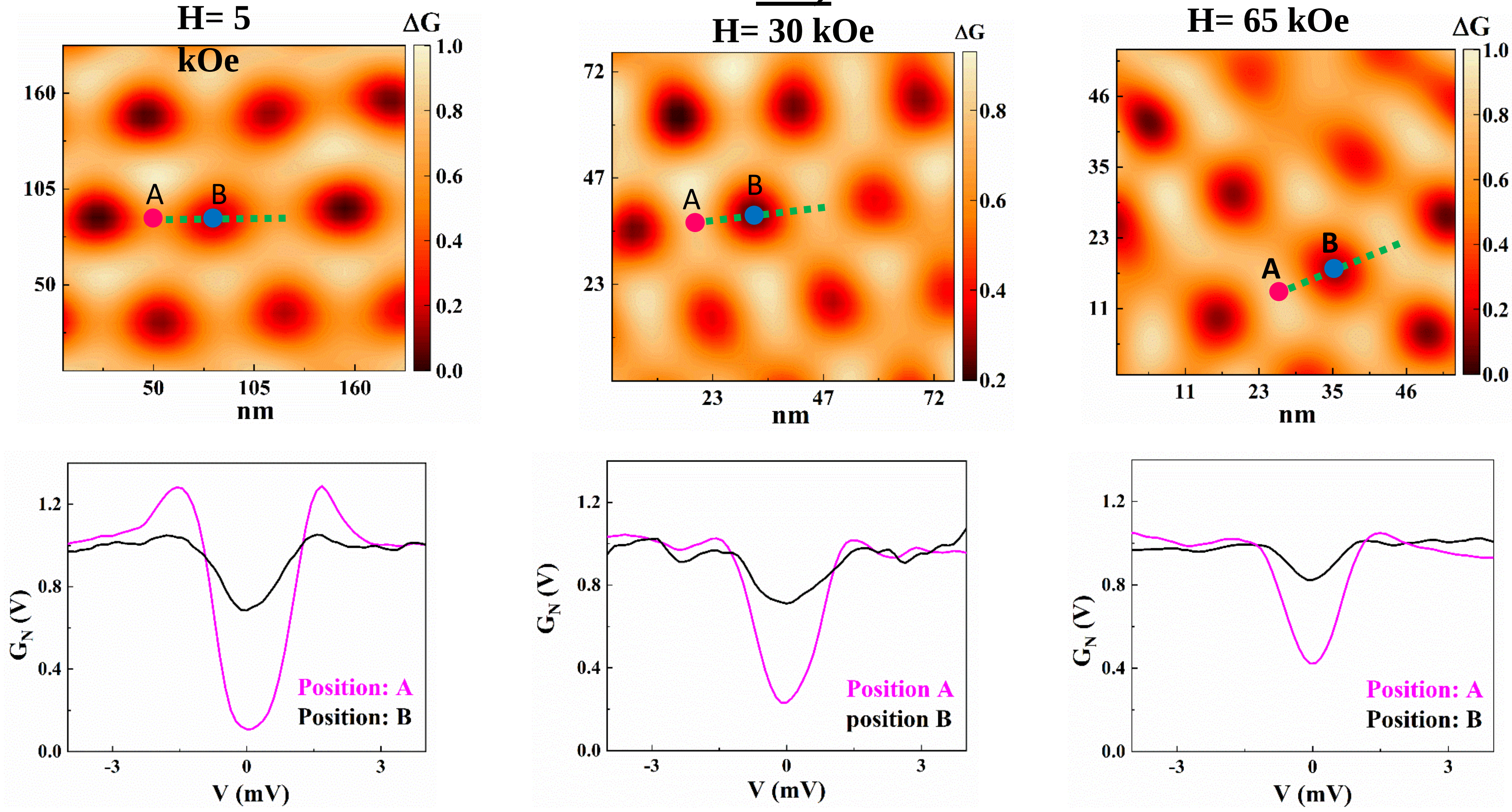


x=0 **x=0.**

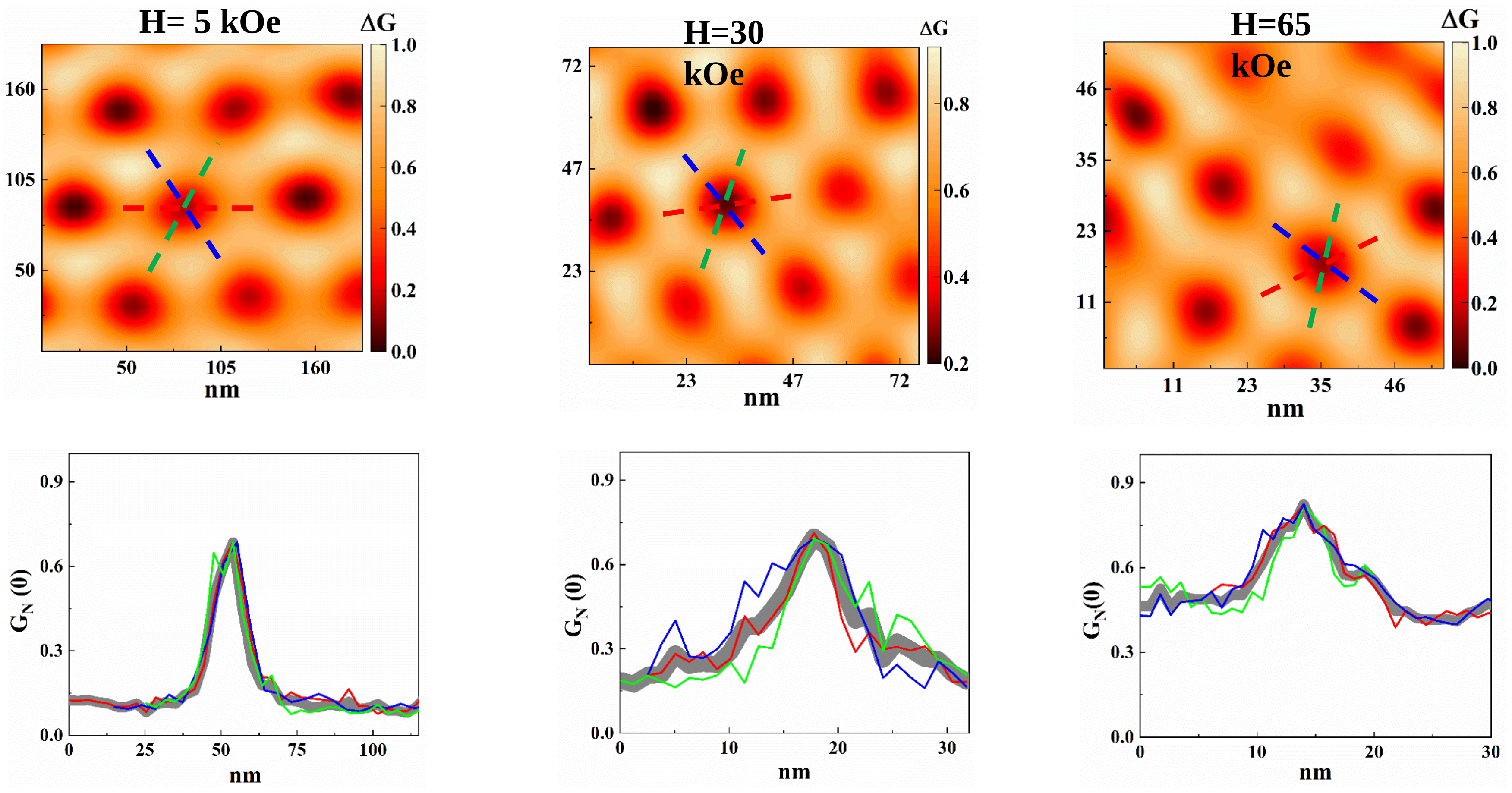


- **No peak is observed inside the vortex core in the dirty limit**
- ***a*-MoGe is even more dirtier sample ($l \sim 1.42$ Å and $\frac{\Delta_0 \tau}{\hbar} = 0.069 \ll 1$)**

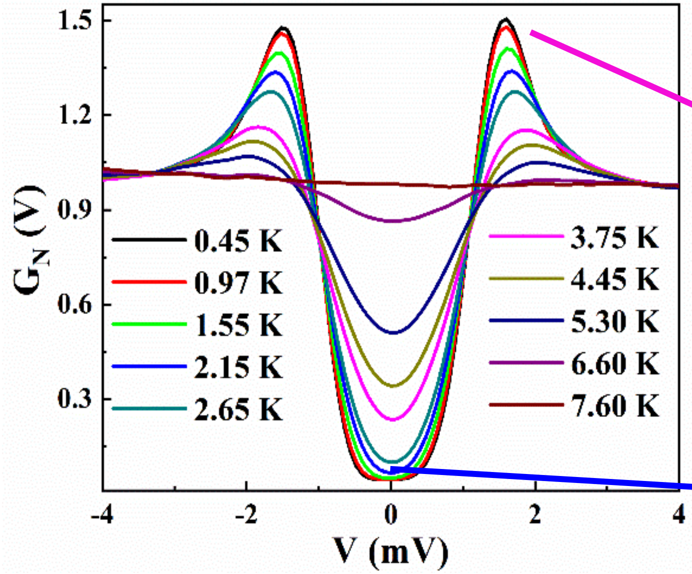
Unusual Results: Soft gap inside the vortex core in MoGe thin film(T=450 mK)

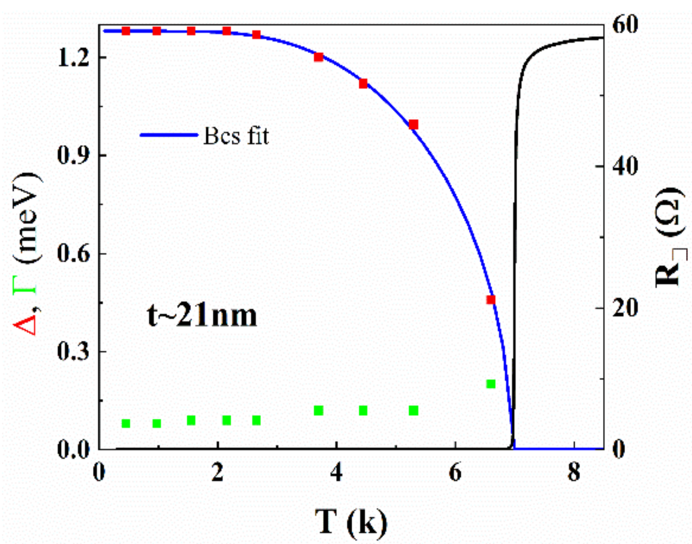


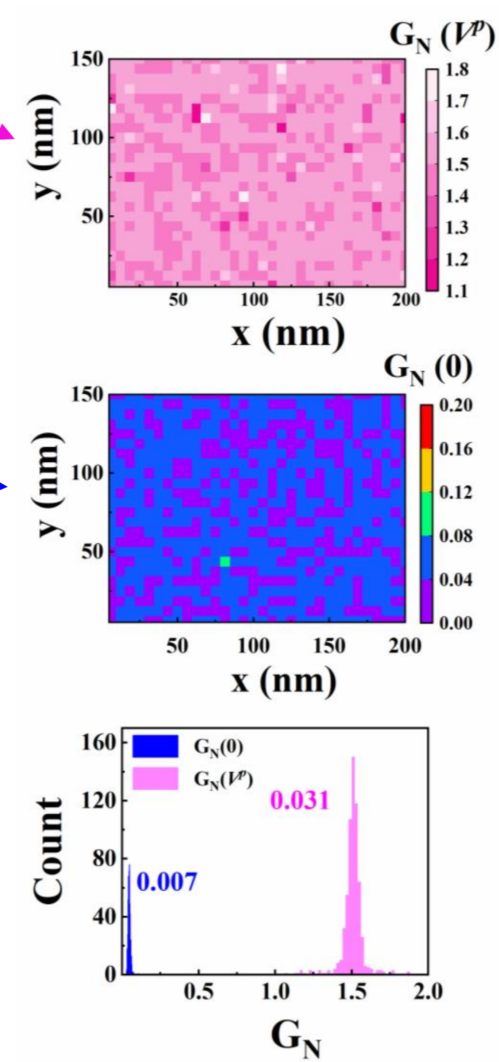
Spatial variation of normalized Zero bias conductance (G_N (0))



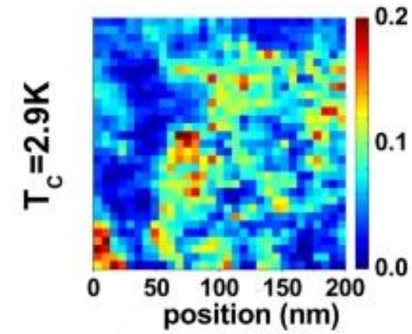
Homogeneous superconducting state

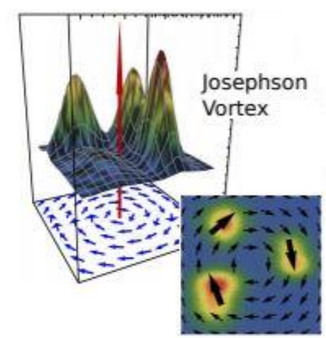






Disordered NbN

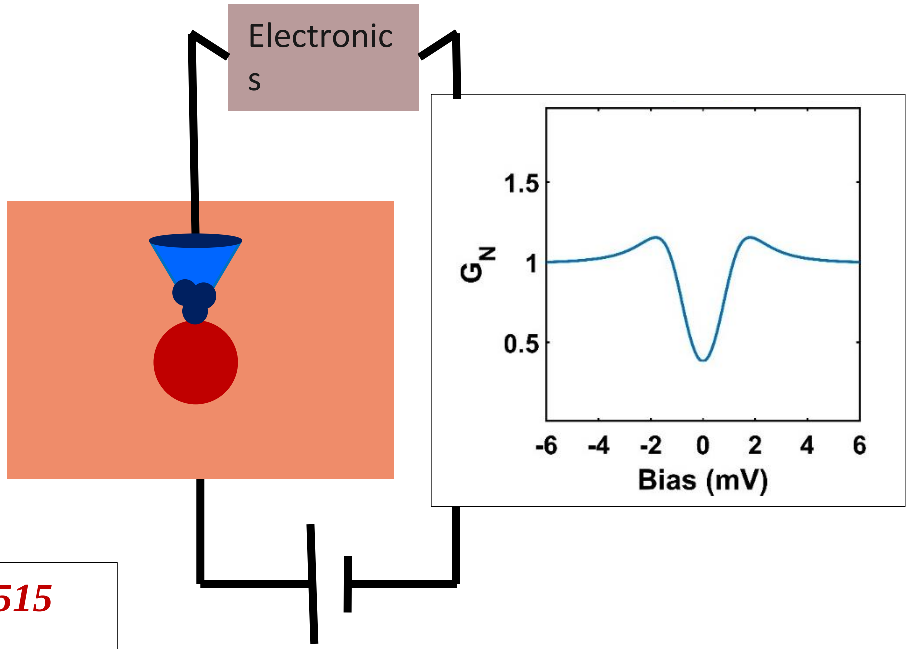




Proposed Explanation: Fast vibration of vortices

- *For a slow measurement like STS/M, spectra at the core will be admixture of both superconducting and normal states, give rise to a soft gap inside the vortex core.*

Q. How do we verify this?



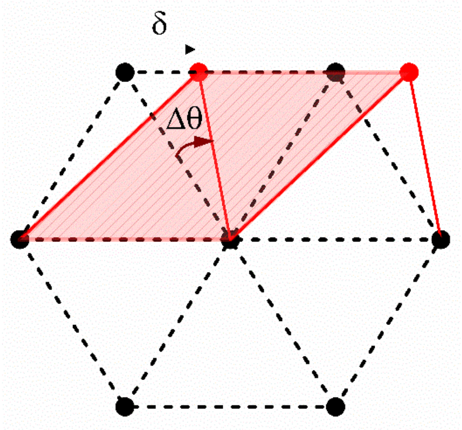
L. Bartosch and S. Sachdev , Phys. Rev. B 74, 144515 (2006); Annals of Physics 321, 1528 (2006)

Amplitude & frequency of the vibration

- Vibration of vortices is analogous to the vibration of atoms in 2d solid

- Einstein approximation

- $C_{11} >> C_{66}$ → vibrational mode of vortices is transverse



- Elastic energy due to displacement of δ=Δa (amplitude of the vibration),

$$E = \frac{1}{2} C_{66} \left(\frac{\Delta a}{a}\right)^2 Ad = \frac{1}{2}\left(\frac{\emptyset_0^2 d}{16\pi\mu_0\lambda^2 a^2}\right)(\Delta a)^2$$

A= area of shaded unit cell.

a= lattice constant; d= thickness of the sample; $C_{66} = \frac{\emptyset_0 H}{16\pi\mu_0\lambda^2}$ (isotropic superconductor)

$$\omega = \sqrt{\frac{\emptyset_0^2 d}{16\pi\mu_0\lambda^2 a^2 m_v}} = \frac{1}{a}\sqrt{\frac{K}{m_v}} = \omega_0\sqrt{\frac{H}{H_{c2}}}$$

- **Quantum zero-point motion:** $\hbar\omega = m_v \omega^2 (\Delta a)^2$

$$\frac{\Delta a}{a} = \left(\frac{\hbar^2}{K m_v}\right)^{1/4} \frac{1}{\sqrt{a}} \propto H^{1/4}$$

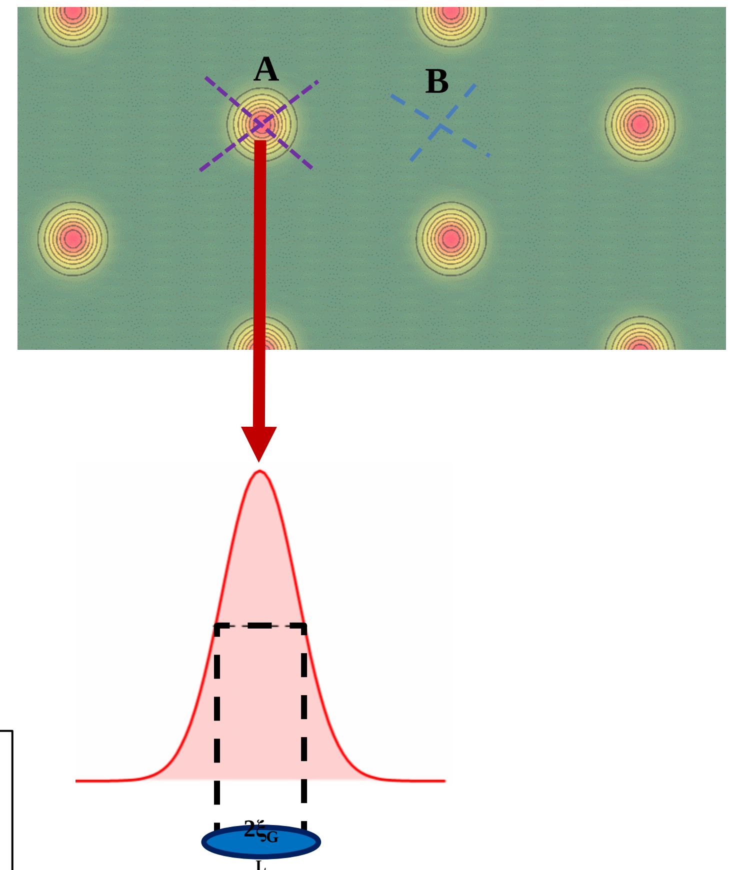
- **For Thermal fluctuation:** $m_v \omega^2 (\Delta a)^2 \sim k_B T$

$$\frac{\Delta a}{a} \sim \sqrt{\frac{k_B T}{K}}$$

- **Our obtained form of amplitude (for zero-point motion) is very similar (expect 0.6 pre-factor), given in ref:** *Annals of Physics 321, 1528 (2006)*

Strategy to find $\Delta a/a$ from our experimental results

Step1: Simulation of single static vortex



Assumptions:

- Spectra inside the vortex core is flat (position A)
- Spectra far away from the core follows BCS nature (position B)
- Spectra, G (r, V) varies across the boundary as gaussian nature,

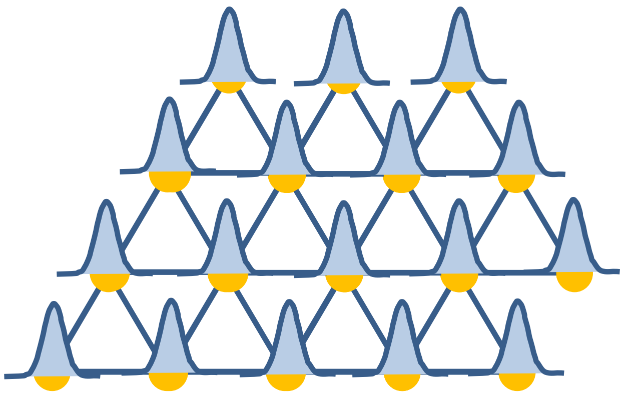
$$w(r) = \sqrt{\frac{\beta}{\pi}}\exp[-\beta r^2]$$

We fix, $\beta = \frac{4\log(2)}{(FWHM)^2}$; $FWHM \sim 2\xi_{GL}$

Conductance map for single vortex,

$$G_N(r,V) = \left(\frac{w(r)}{w_{max}(r)}\right) * G_N^{core} + \left[1 - \left(\frac{w(r)}{w_{max}(r)}\right)\right] G_N^{BCS}$$

Step 2: Simulation of full conductance map for static vortex lattice



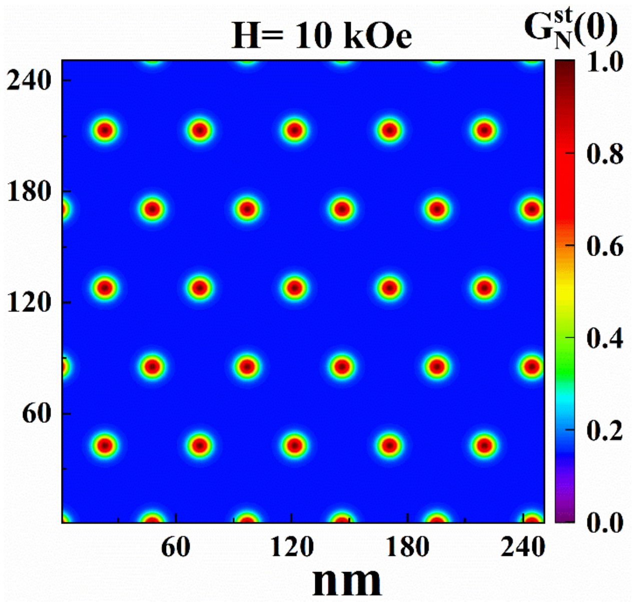
Vortex lattice

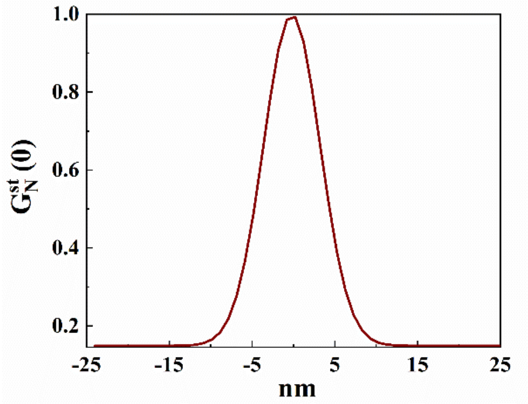
$$a_1 = a_0[1,0];$$

$$a_2 = a_0\left[\frac{1}{2}, \frac{\sqrt{3}}{2}\right]$$

$$a_0 = 1.07\sqrt{\frac{\emptyset_0}{H}} = lattice\ constant$$

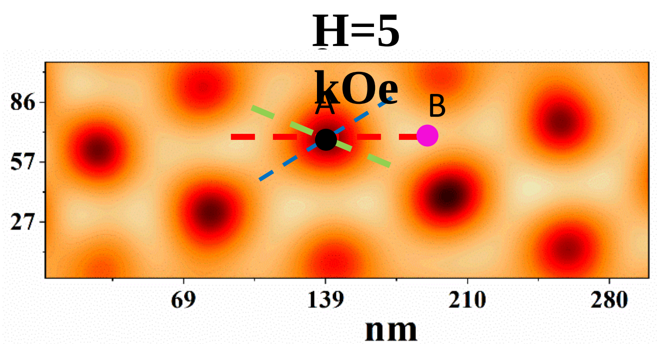
$$G_N^{st}(V,r) = \frac{\sum_i G_N(r-r_i,V)}{[\sum_i G_N(r-r_i,V=0)]_{max}}$$

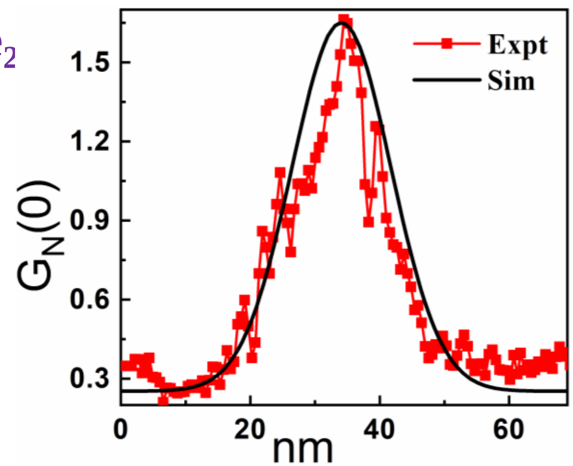


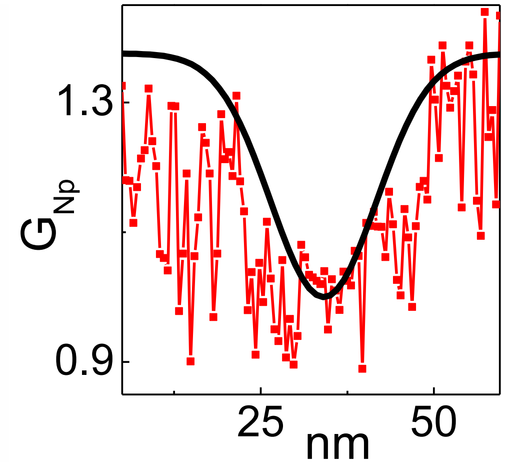


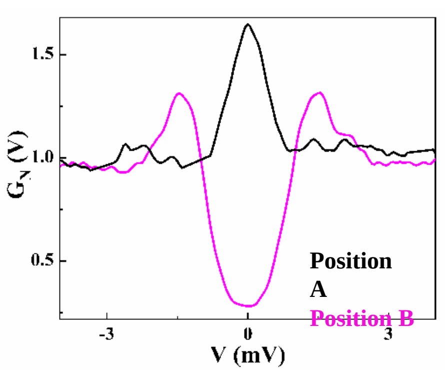
Consistency check: static vortex lattice simulation

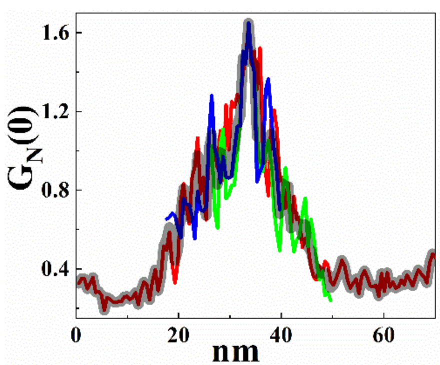
Case study: Vortex core in clean $NbSe_2$







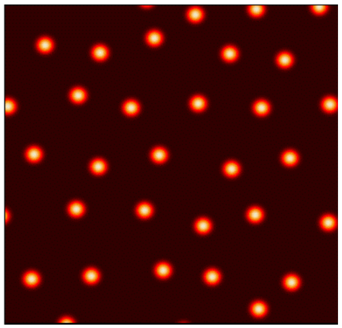




$$G_N^{st}(V,r) = 1.6\frac{\sum_i G_N(r-r_i,V)}{[\sum_i G_N(r-r_i,V=0)]_{max}}$$

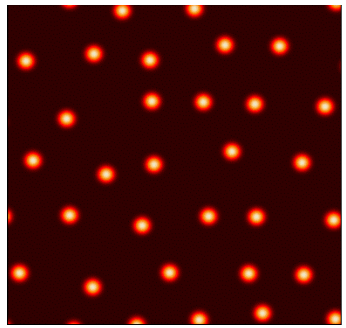
- Our empirical interpolation formula fits well with our experimental observations.
- The value of FWHM is used for the fitting matches exactly with the coherence length value, obtained from upper critical field.

Step 3: Simulation for the random vibration
(Born-Oppenheimer Approximation: Retardation Neglected)



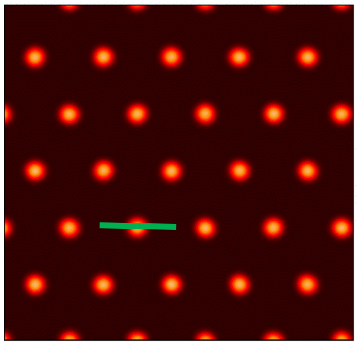
Time Snap: 1

$+ \ldots +$



Time Snap: 200

Average



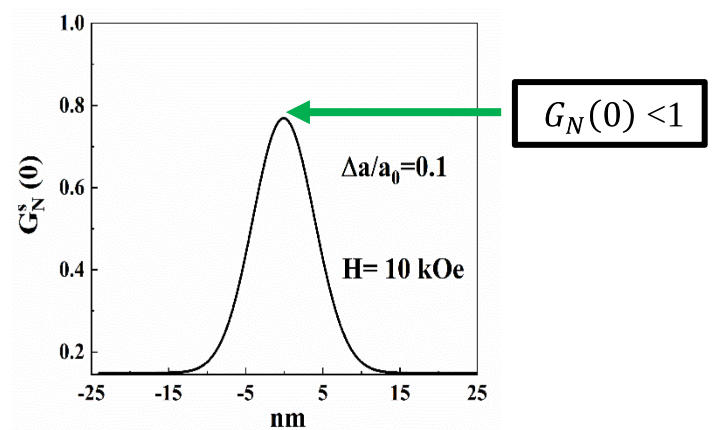
$G_N^s(0, \mathrm{r}, 0.1a_0)$

- Vortex position, $\vec{r}_i \rightarrow \vec{r}_i + \delta\vec{r}$

$$0 \leq \delta\vec{r} \leq \Delta a(amplitude\ of\ the\ vibration)$$

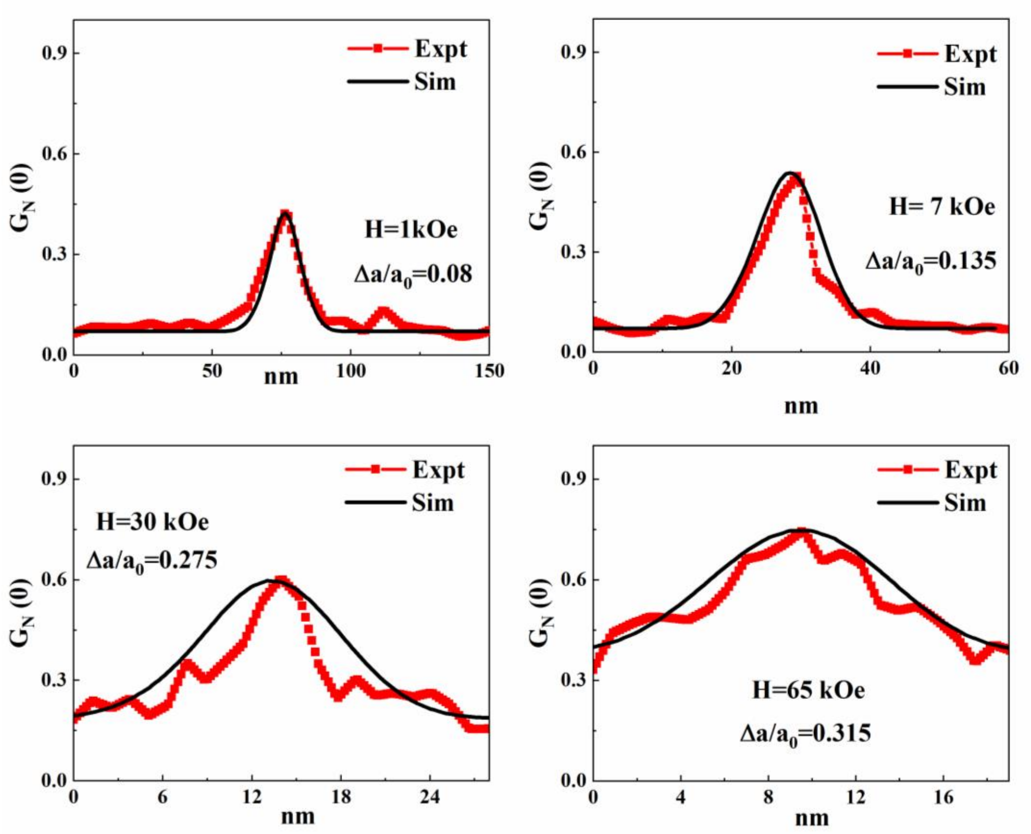
- We perform the simulation over such 200 realizations
- Grand average normalized conductance map,

$$G_N^s(V, r, \Delta a) = \frac{1}{200}\sum_{K=1}^{200} G_N^{st,k}(V, r, \Delta a) = \langle G_N^{st}(V, r, \Delta a)\rangle$$

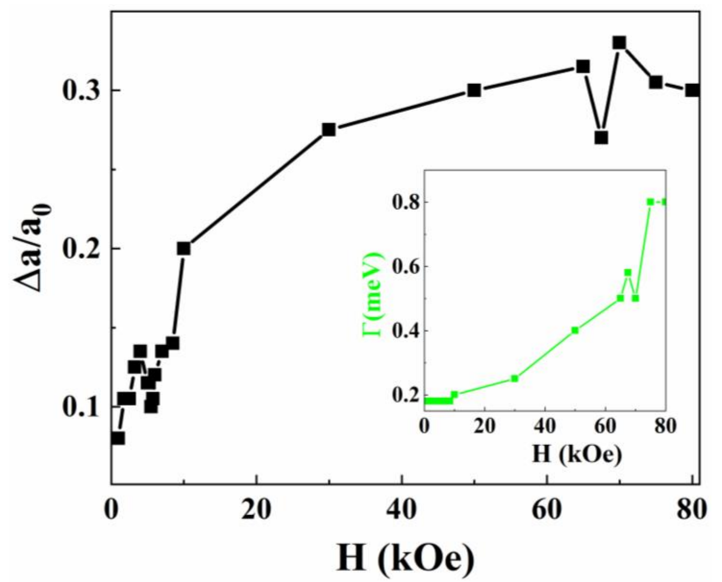


Step 4: comparing with experimental results (*a*-MoGe thin films)

- We take $\Delta a/a_0$ and Γ as the fitting parameters.

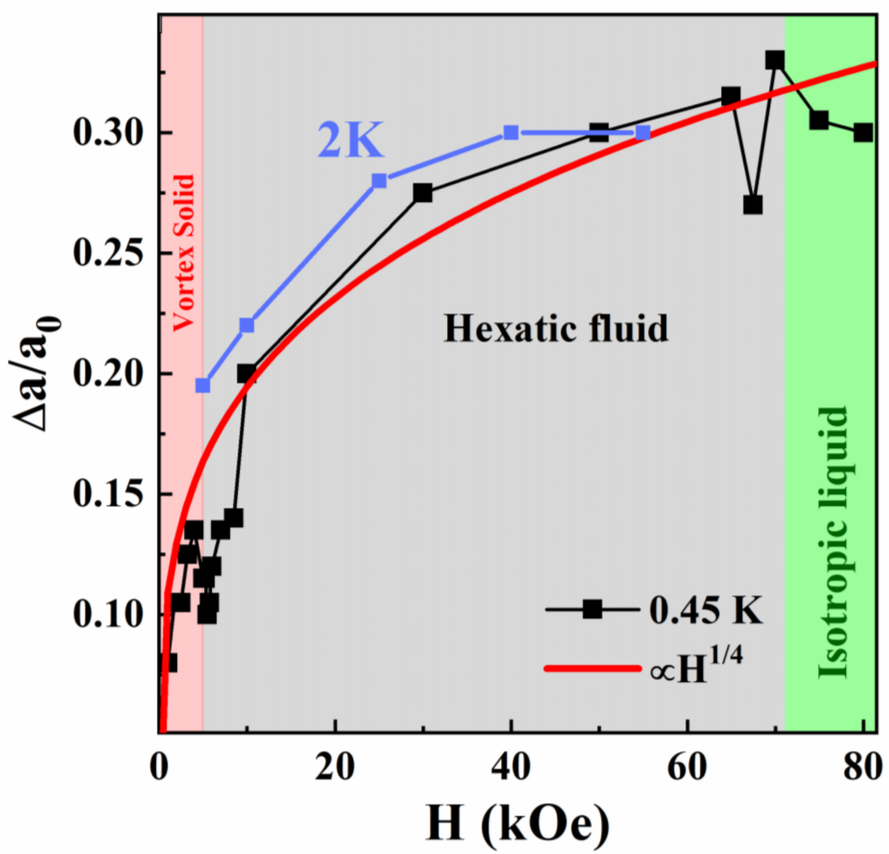


Magnetic field variation of Fitting parameter



- Both $\Delta a/a_0$ and Γ are increasing with magnetic field.

Conclusion: Quantum zero-point motion



- Two dips appear in the field variation of $\Delta a/a_0$ close to the phase boundaries: vortex solid- hexatic fluid and hexatic fluid to isotropic liquid. These anomalies most likely due to the anharmonicity of the confining potential.
- The magnetic field variation of $\Delta a/a_0$ matches well with the field dependent form, expected from Quantum zero-point motion of vortices.

Calculation of vortex mass

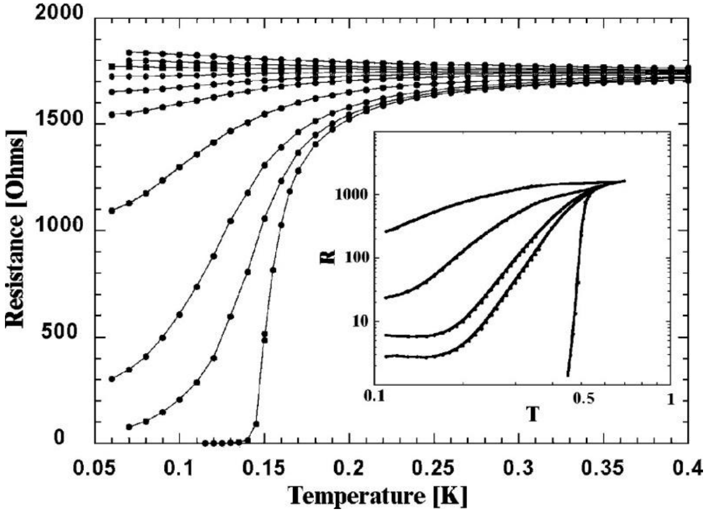
1. *From fitting parameters,*

$$m_v = \left(\frac{\hbar}{1.075}\right)^2 \frac{1}{K_0 \emptyset_0 A^4} \approx 36 m_e$$

2. *From carrier density,*

$$m_v = \frac{2}{\pi^3} m_e K_F d = \frac{2}{\pi^3} m_e (3\pi^2 n)^{1/3} d \approx 32 m_e$$

The superconductor – bad metal transition



Yazdani and Kapitulnik– PRL 74, 3037 (1995)

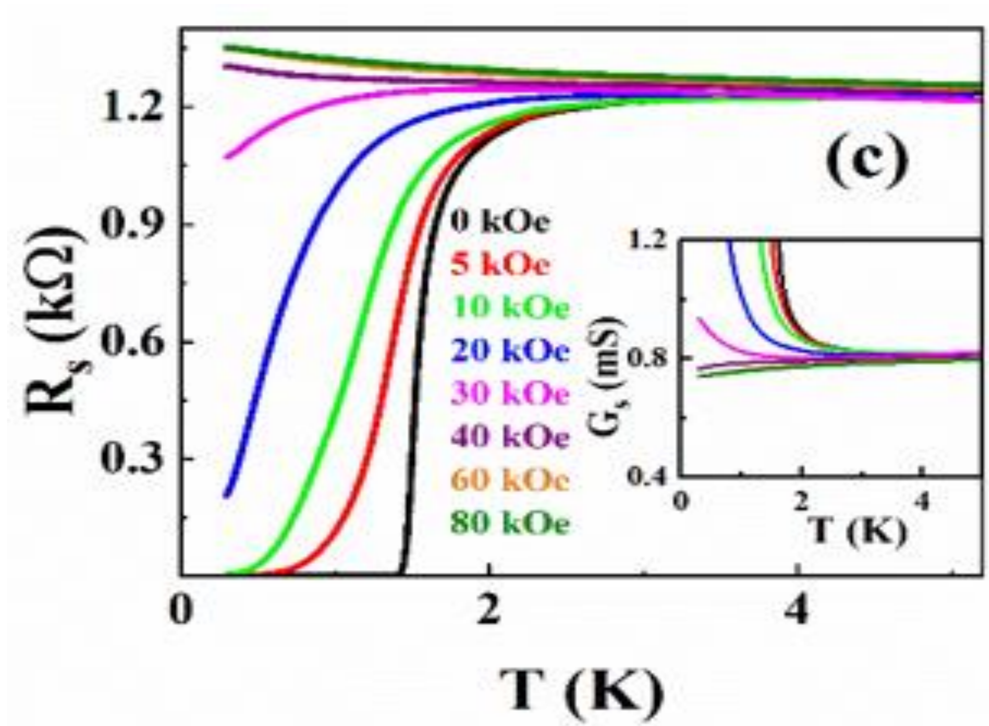
Superconductor below B_c

Bad metal above B_c

$$\frac{dR}{dT} < 0 \ \text{ but } G(T \rightarrow 0) \text{ is finite}$$

Is this bad metal also made of Cooper pairs that are in a dissipative state?

2 nm thick *a*-MoGe

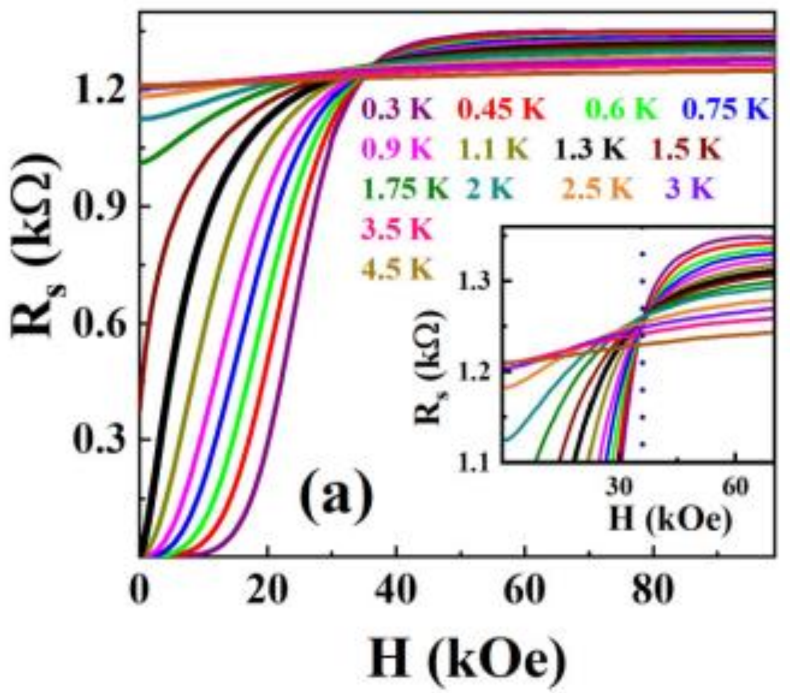


Surajit Dutta

John Jesudasan

Phys. Rev. B **105**, L140503 (2022)

The Critical Field: H_c

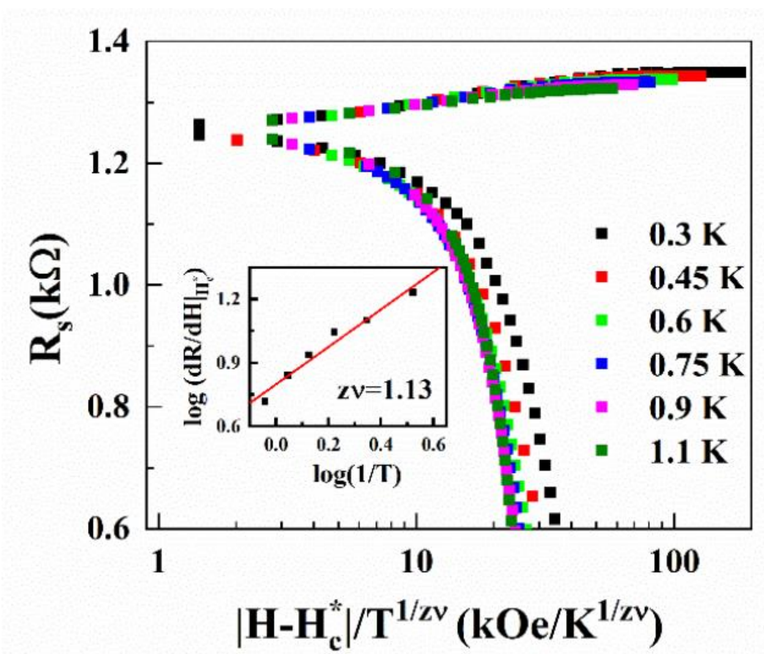


Bad Metal Above 36 kOe

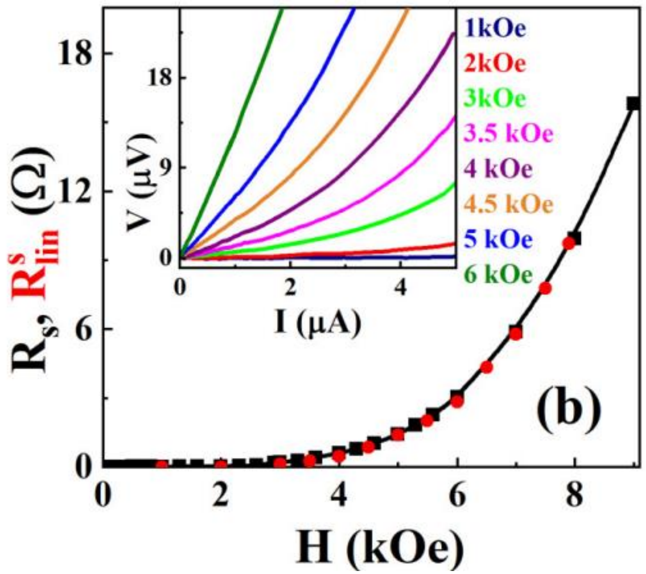
Is this a Critical Field: H_c

$$R_S(H,T) = R_c^* f\left(C_a \frac{|H - H_c^*|}{T^{\frac{1}{z\nu}}}\right)$$

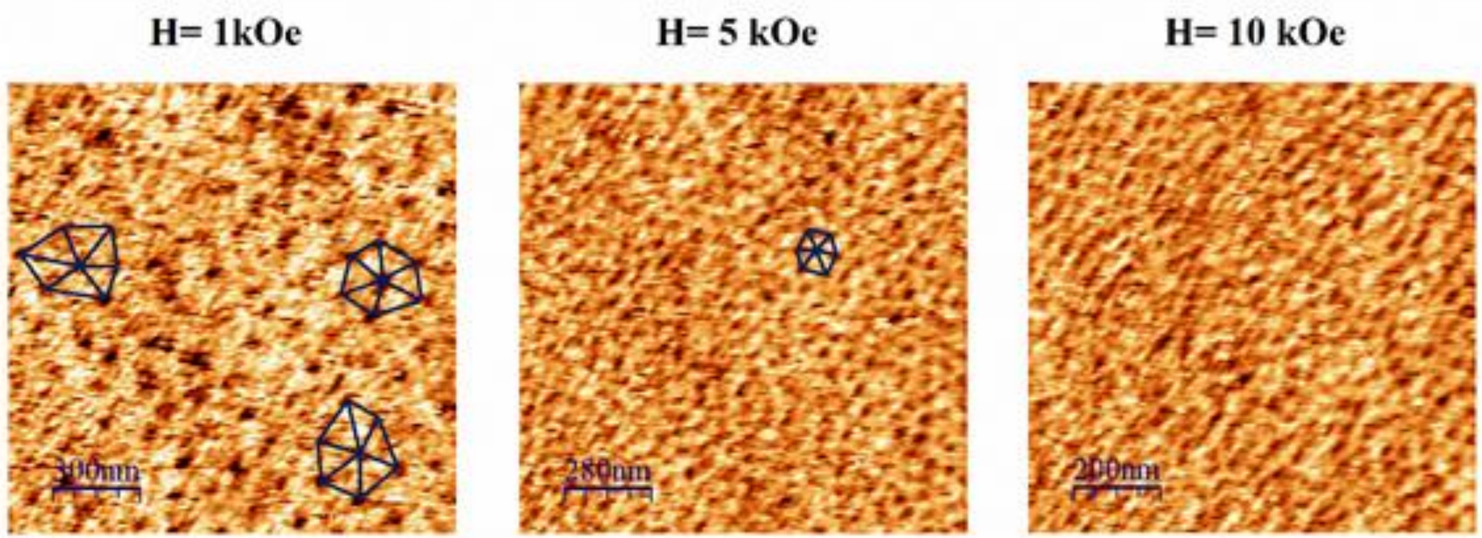
$$\left.\frac{dR}{dH}\right|_{H=H_c^*} \propto R_c^* T^{-\frac{1}{\nu z}} f'(0)$$



Melting of the Vortex Lattice

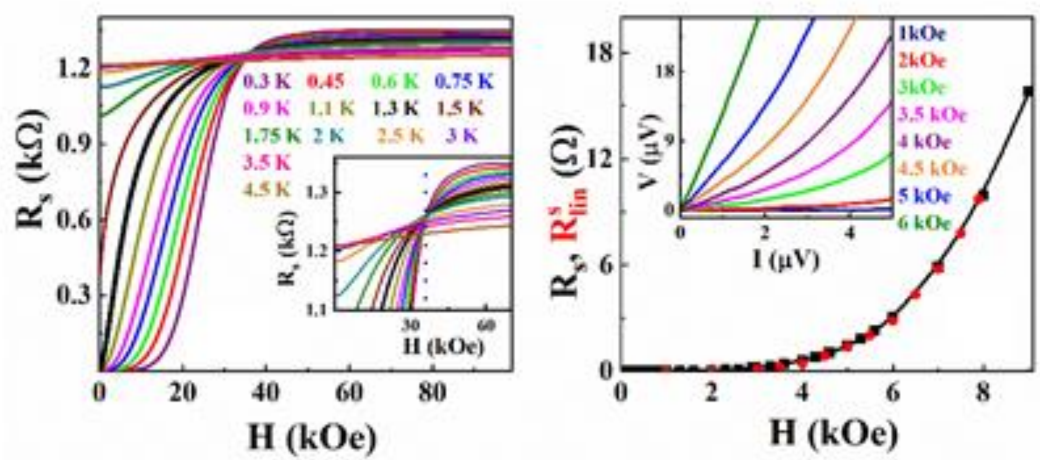


Vortex liquid above 3 kOe



450 mK

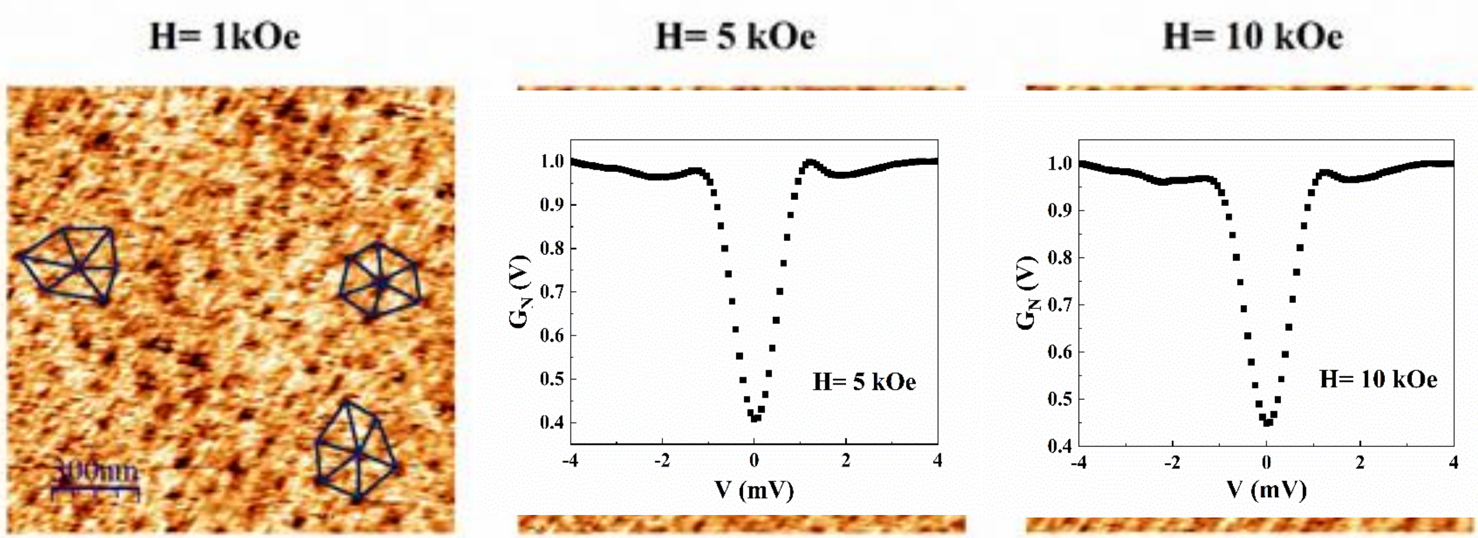
Evolution with magnetic field



Bad metal above 36 kOe

Vortex liquid above 3 kOe

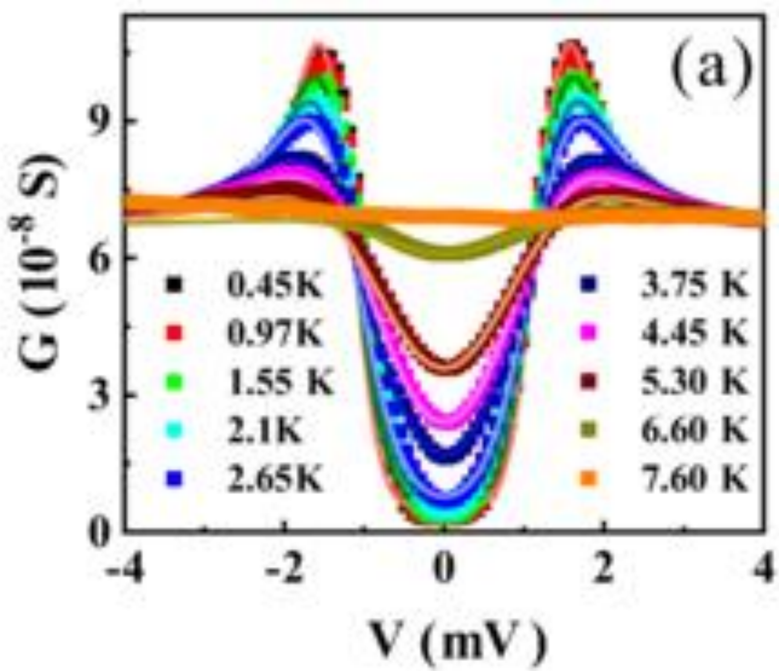
Do Cooper pairs survive in the bad metal?



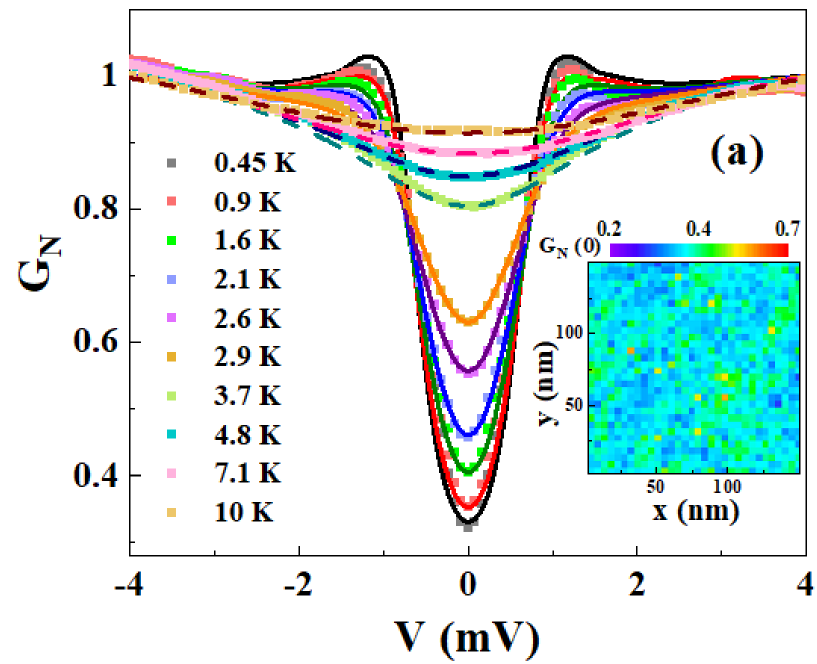
450 mK

Fitting Tunnelling Spectra

Thick MoGe (20 nm): BCS superconductor



2 nm thick MoGe



$$\Gamma^D \approx 0$$

BCS + Dynes DOS

$$N_s^{BCS}(E) = \left| Re\left\{ \frac{E - i\Gamma^D}{\sqrt{(E - i\Gamma^D)^2 - \Delta^2}} \right\} \right|$$

$$G(V,T) = G_0 \int_{-\infty}^{\infty} dE \, \frac{1}{kT} \frac{e^{\frac{E+eV}{kT}}}{\left(1 + e^{\frac{E+eV}{kT}}\right)^2} N(E)$$

Coherence peaks broadened *and* Large zero bias conductance

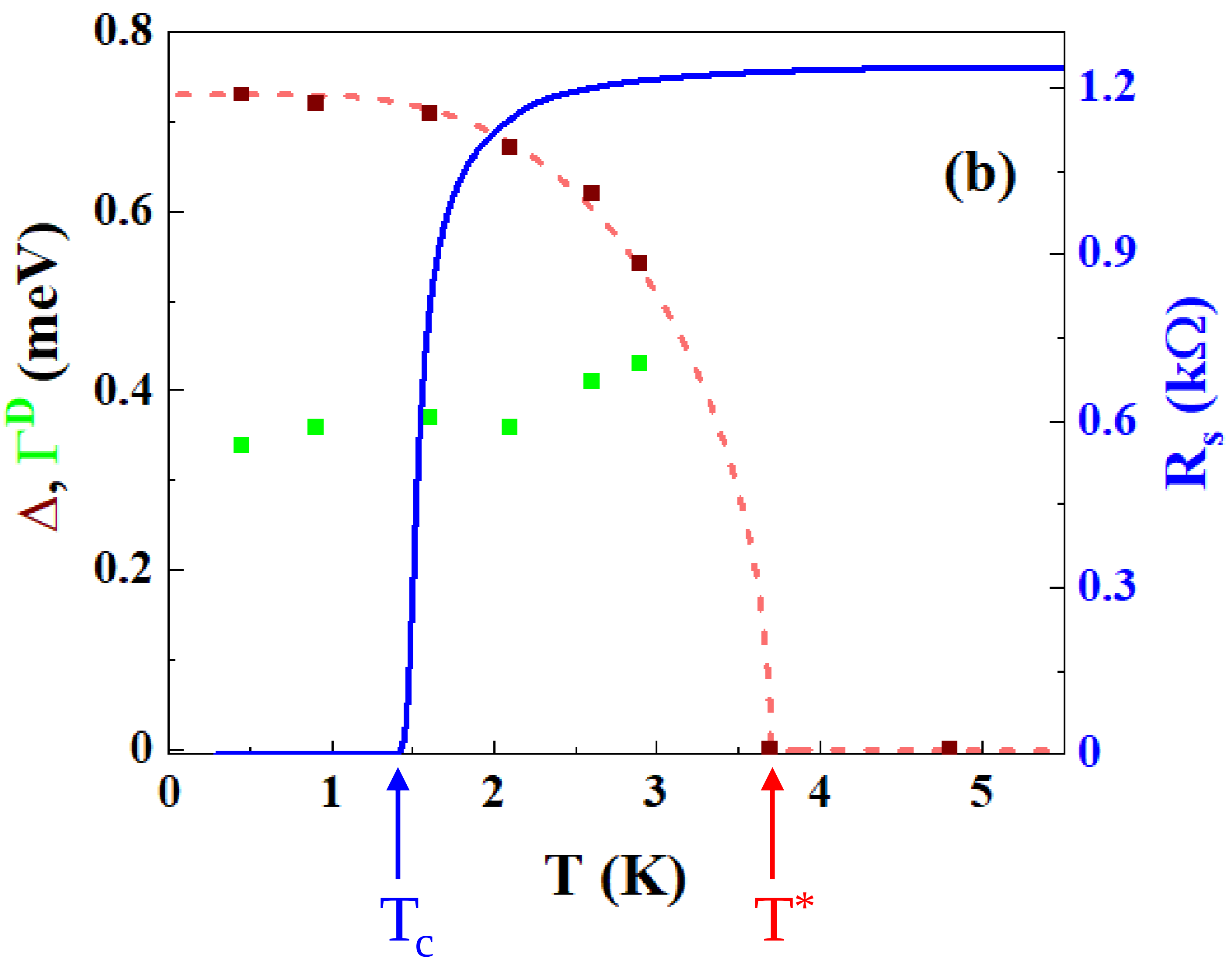
$$\boldsymbol{\Gamma^D \neq 0}$$

A broad V-shaped background coming from diffusive e-e Coulomb interactions:
Altshuler-Aronov anomaly

$$\boldsymbol{N(E) = N_s^{BCS}(E) N_N^{AA}(\Omega)}$$

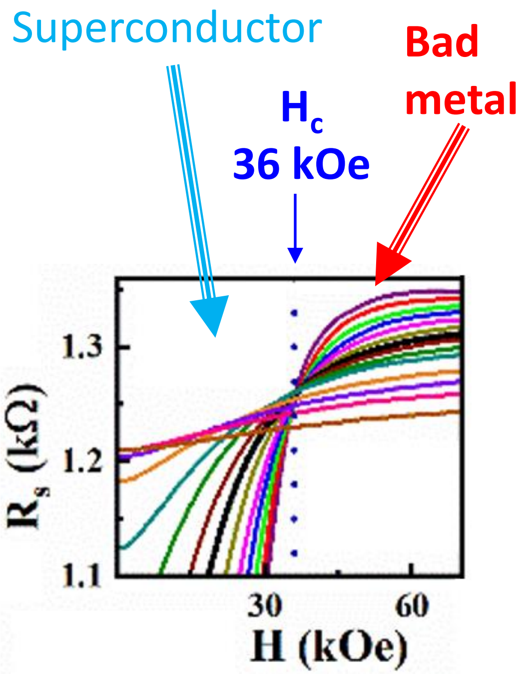
$$\boldsymbol{\Omega = Re\left[\sqrt{(E - i\Gamma^D)^2 - \Delta^2}\right]}$$

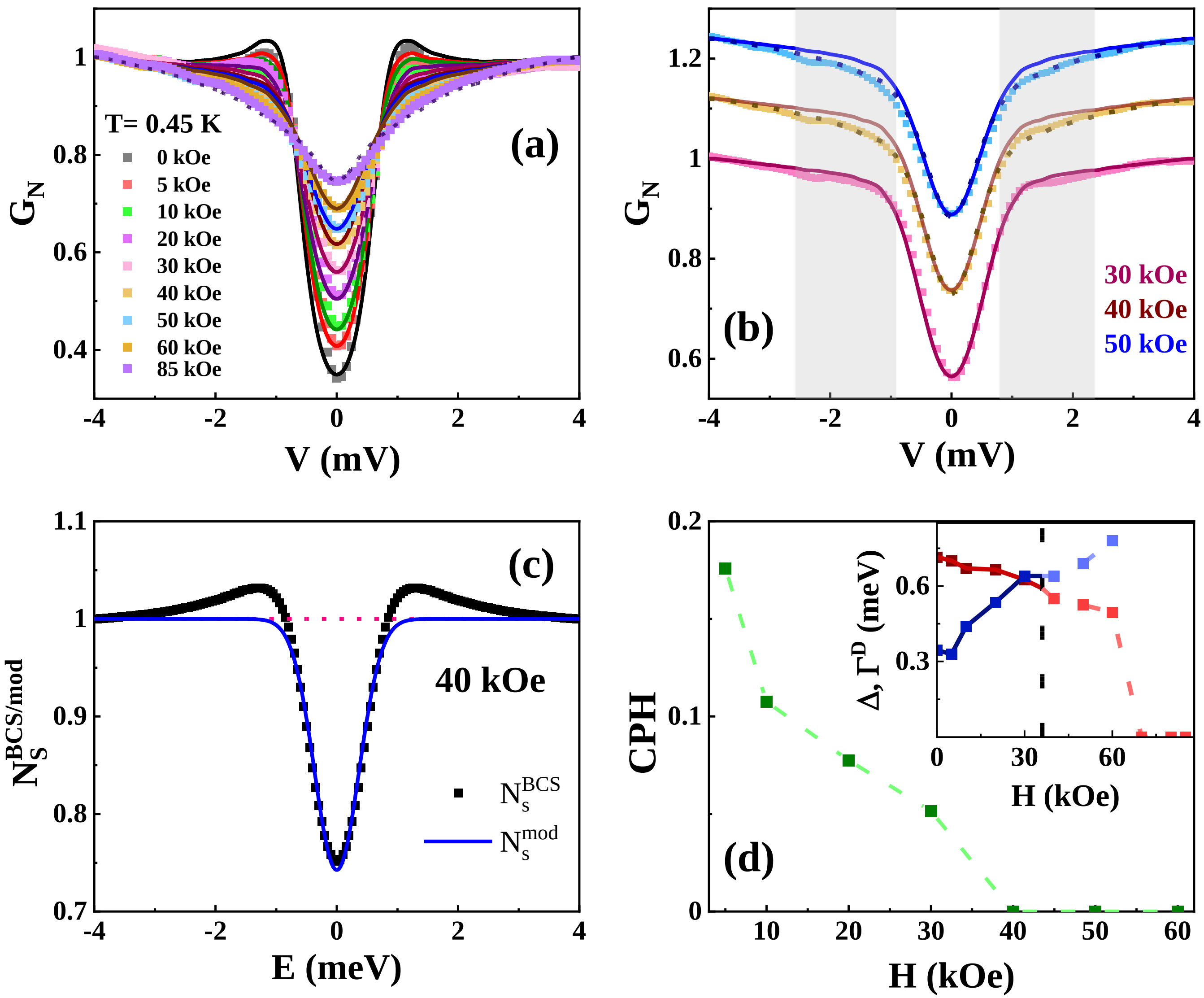
Zero field Δ and R_s with temperature



Evolution of tunnelling spectra with magnetic field

450 mK





*H**-no Gap in spectra

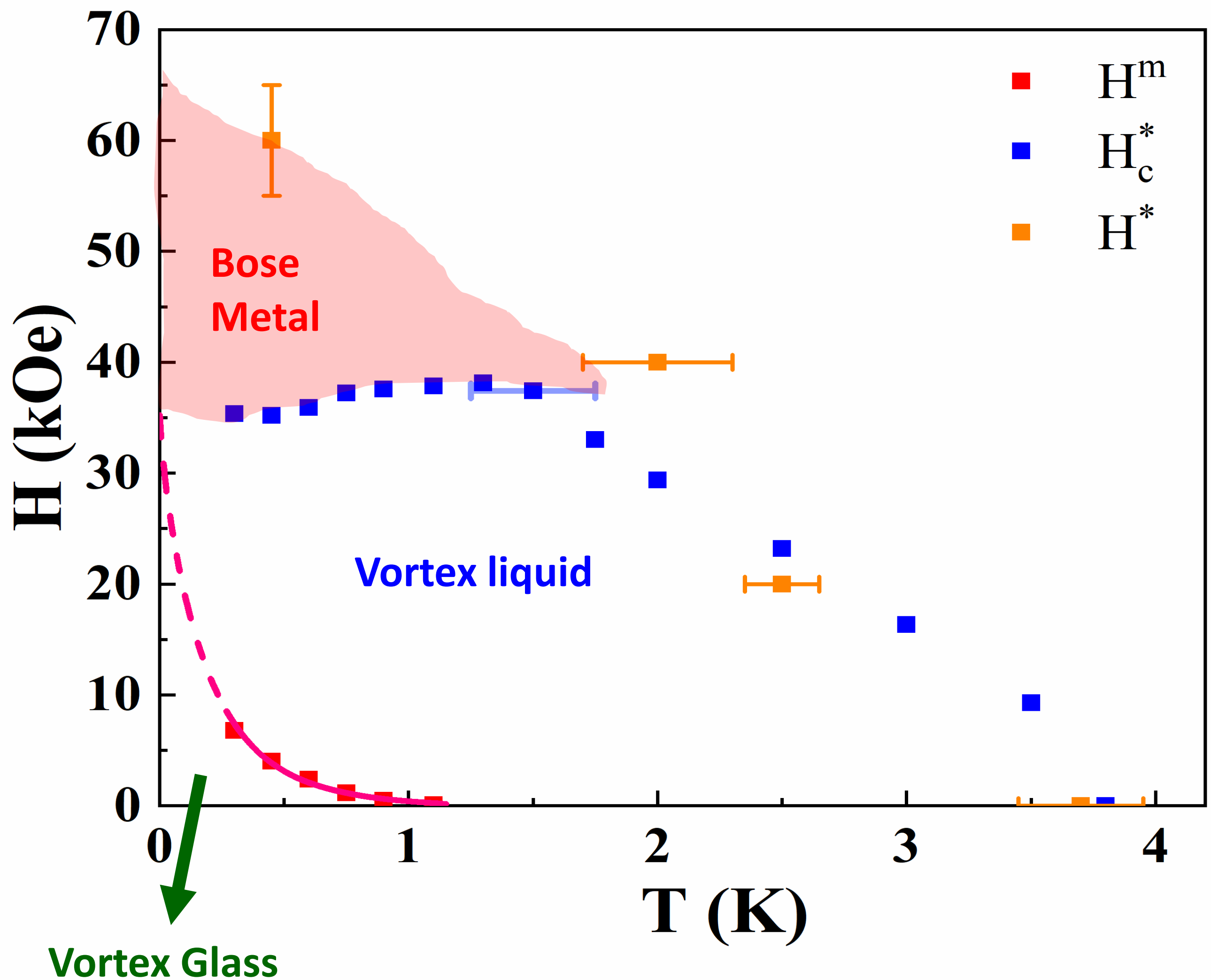
$H_c<H<H^*$

Gap but no coherence peak

$H<H_c$

Usual BCS+Γ^D

Phase Diagram

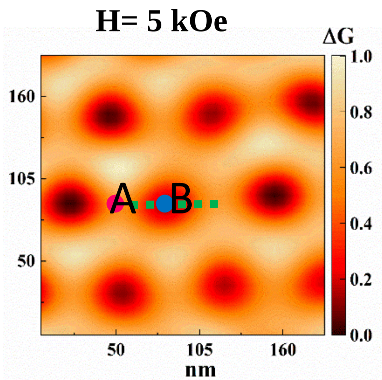


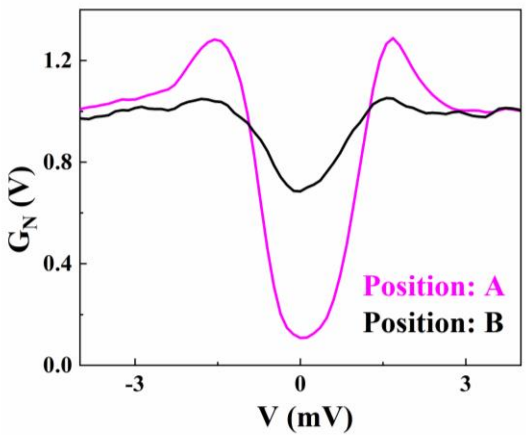
What is the Bose Metal?

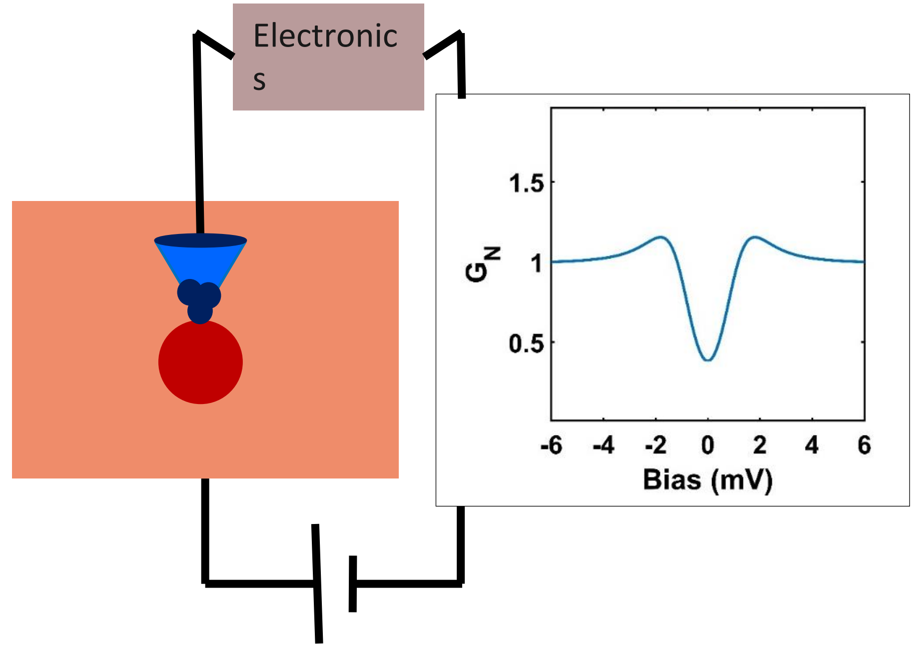
Conjecture

Zero point fluctuation of vortices would be much larger for 2nm thick sample

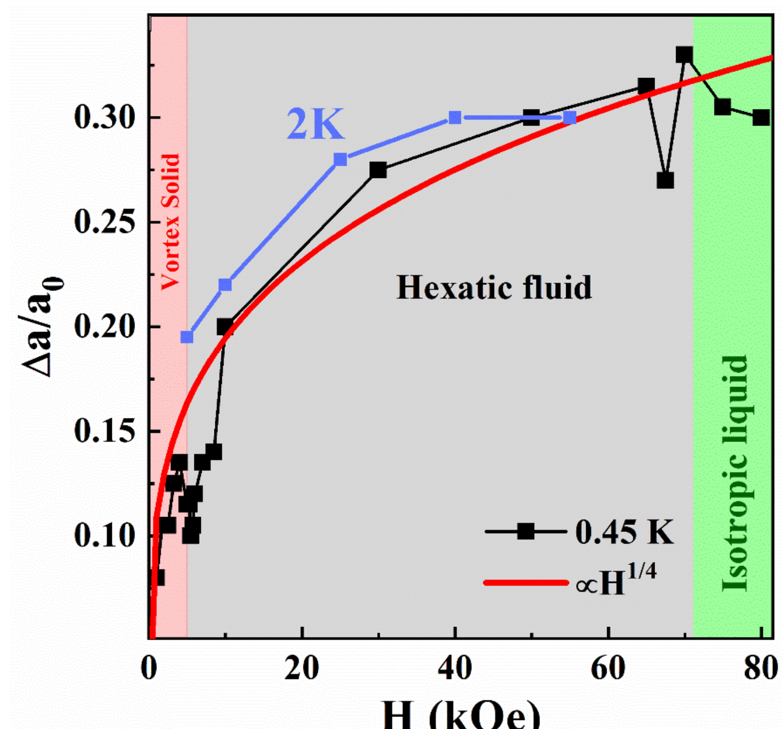
The transition at H_c is from a classical vortex fluid to a quantum vortex fluid







20 nm thick MoGe



$\Delta a = \left(\frac{\hbar}{m\omega}\right)^{1/2}$ ← Amplitude

1. *From fitting parameters,*

$$m_v = \left(\frac{\hbar}{1.075}\right)^2 \frac{1}{K_0 \emptyset_0 A^4} \approx \mathbf{36}\boldsymbol{m_e}$$

2. *Theoretical estimate*

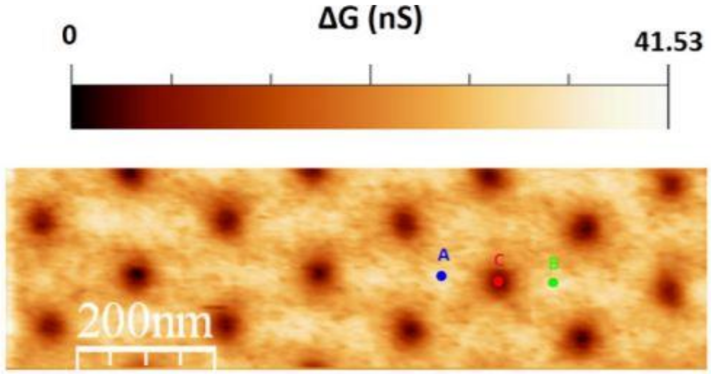
$$m_v = \frac{2}{\pi^3} m_e K_F d = \frac{2}{\pi^3} m_e (3\pi^2 n)^{1/3} d \approx 32 m_e$$

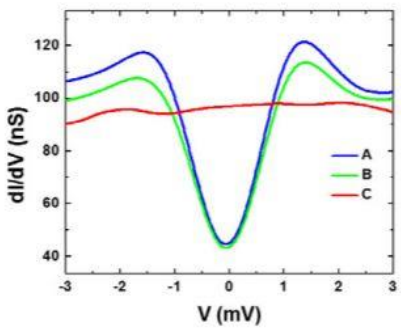
Surajit Dutta et al, Phys. Rev B 103, 214512 (2021)

Inside the vortex core

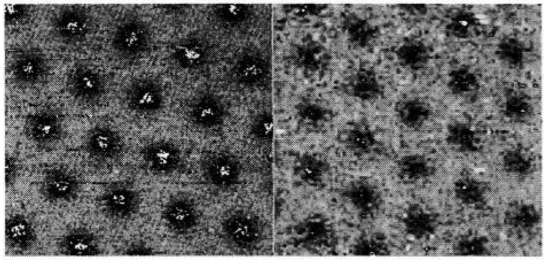
Dirty limit

Sample: Co doped $NbSe_2$ **(J. Phys.: Con. Mat. 28 (2016) 165701)**

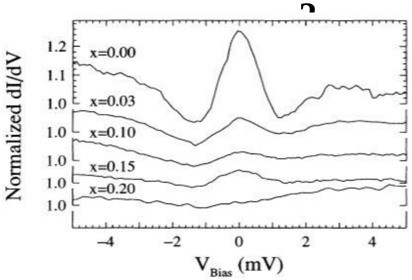




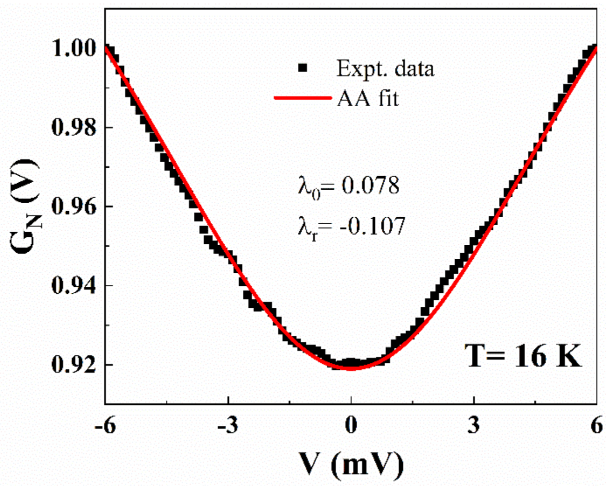
Sample: 2H-Nb_{1-x} Ta_xSe_2 (ref: Phys. Rev. Lett. 67, 1650 (1991))



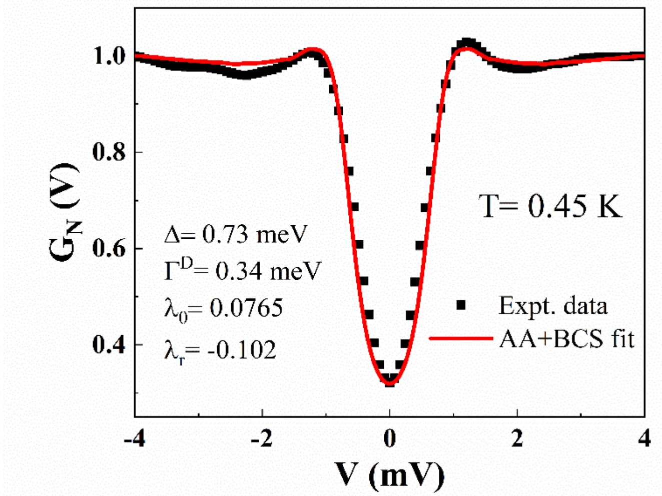
x=0 **x=0.2**



- **No peak is observed inside the vortex core in the dirty limit**
- ***a*-MoGe is even more dirtier sample ($l \sim 1.42$ Å and $\frac{\Delta_0 \tau}{\hbar} = 0.069 \ll 1$)**



Zero magnetic field



$$G(V,T) = G_0 \int_{-\infty}^{\infty} dE \frac{1}{kT} \frac{e^{\frac{E+eV}{kT}}}{\left(1+e^{\frac{E+eV}{kT}}\right)^2} N_N^{AA}(E)$$

$$N_N^{AA}(E) = 1 + \lambda_0(1-3\lambda_r) f_d(E,\Gamma_n)$$

$$f_d(E,\Gamma_n) = -\frac{1}{2}\int_0^{\Gamma/kT} dx \frac{x}{x^2+\left(\frac{\Gamma_n}{kT}\right)^2} \frac{\sinh(x)}{\cosh(x)+\cosh\left(\frac{E}{kT}\right)}$$

$$\Gamma = 10\ eV; \Gamma_n = 0.2\ meV$$

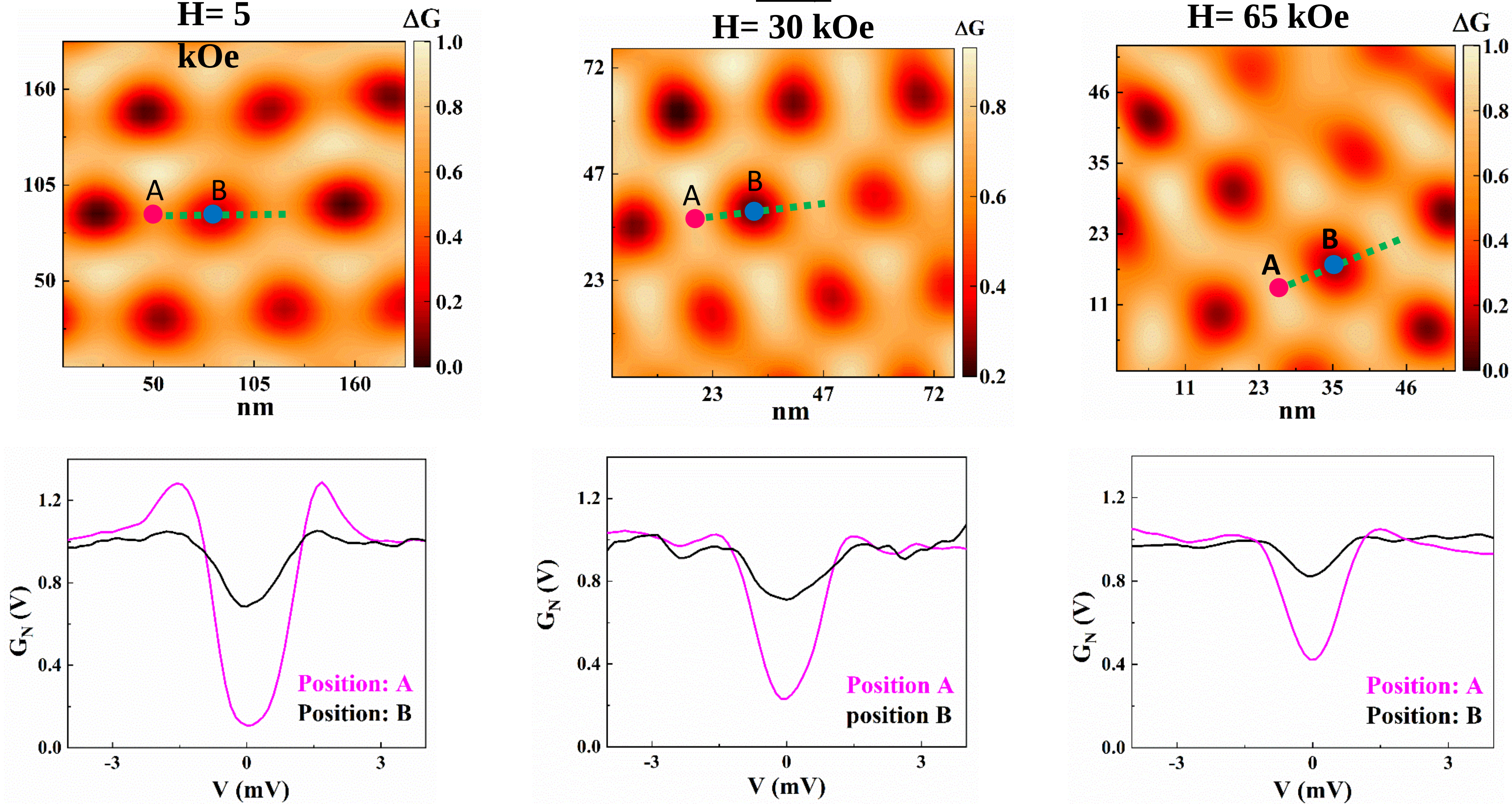
$$G(V,T) = G_0 \int_{-\infty}^{\infty} dE \frac{1}{kT} \frac{e^{\frac{E+eV}{kT}}}{\left(1+e^{\frac{E+eV}{kT}}\right)^2} N_N^{AA}(E) N_S^{BCS}(E)$$

$$N_N^{AA}(E) = 1 + \lambda_0(1-3\lambda_r) f_d(E,\Gamma_n) \ \& \ N_S^{BCS} = \left| Re\left[\frac{E-i\Gamma^D}{(E-i\Gamma^D)^2-\Delta^2}\right]\right|$$

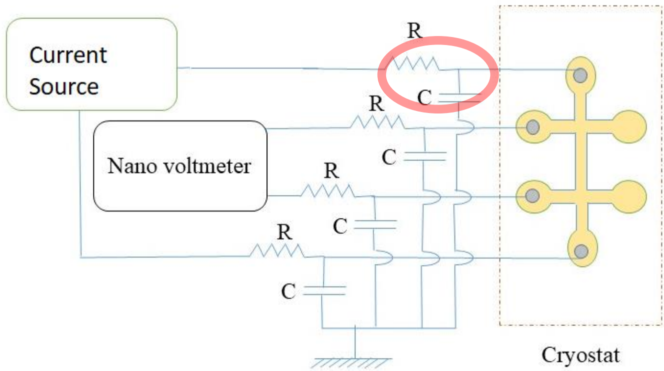
$$f_d(E,\Gamma_n) = -\frac{1}{2}\int_0^{\Gamma/kT} dx \frac{x}{x^2+\left(\frac{\Gamma_n}{kT}\right)^2} \frac{\sinh(x)}{\cosh(x)+\cosh\left(\frac{\Omega(E)}{kT}\right)}$$

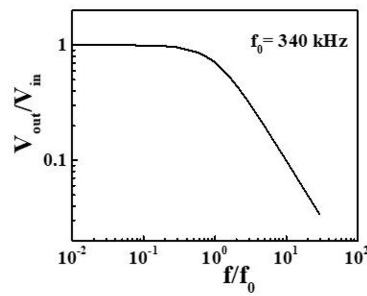
$$\Omega(E) = Re\left[\sqrt{(E-i\Gamma^D)^2-\Delta^2}\right]$$

Unusual Results: Soft gap inside the vortex core in MoGe thin film(T=450 mK)

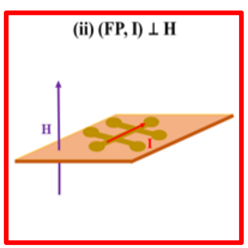


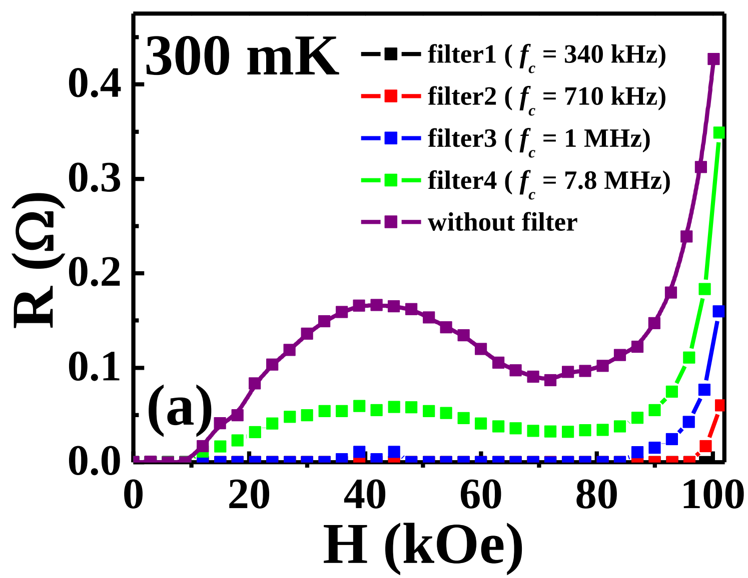
Extreme sensitivity in the vortex state





I^{dc} = 80 μA << I_c

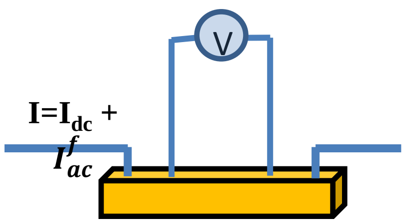


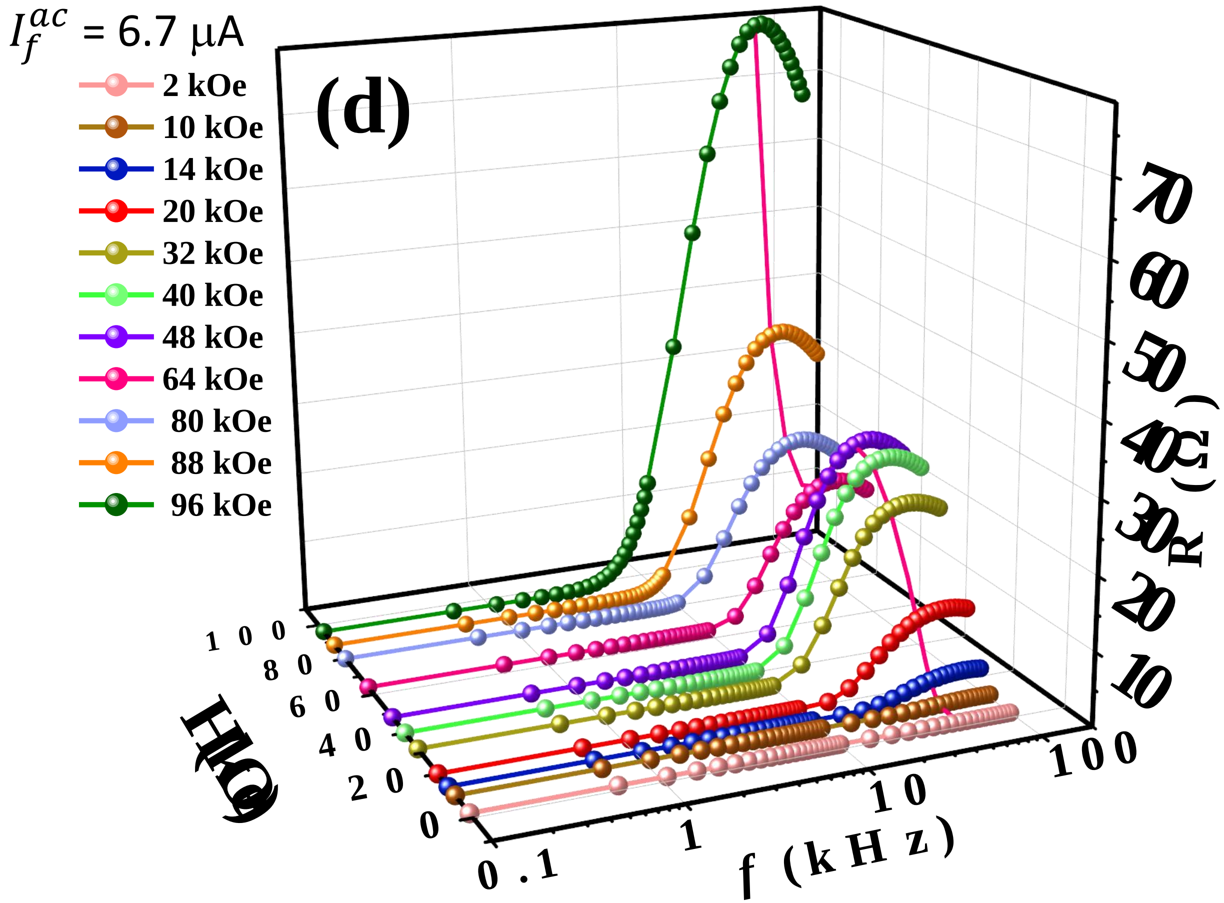


Effect of ambient electromagnetic radiation.

Phys. Rev. B 100, 214518 (2019)

Frequency dependence





Phys. Rev. B 100, 214518 (2019)

Summary

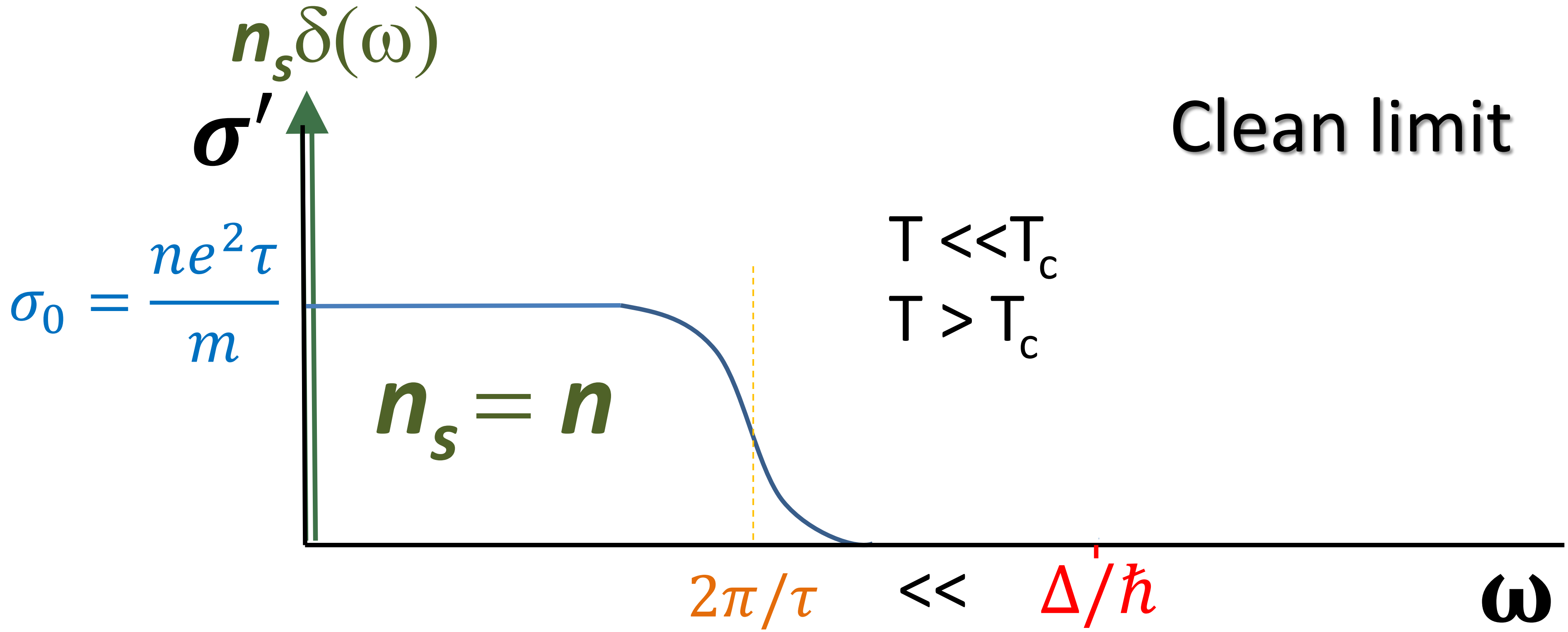
- We have shown that quantum zero point motion of the vortex core can give rise to a soft gap at the centre of the vortex.

- Whether the zero-point fluctuation can produce a quantum vortex fluid at T $\rightarrow$ 0 is a question that is yet to be investigated.

Thank you

(Strong) Disorder in conventional superconductors

The effect of disorder on J ($\propto n_s$)

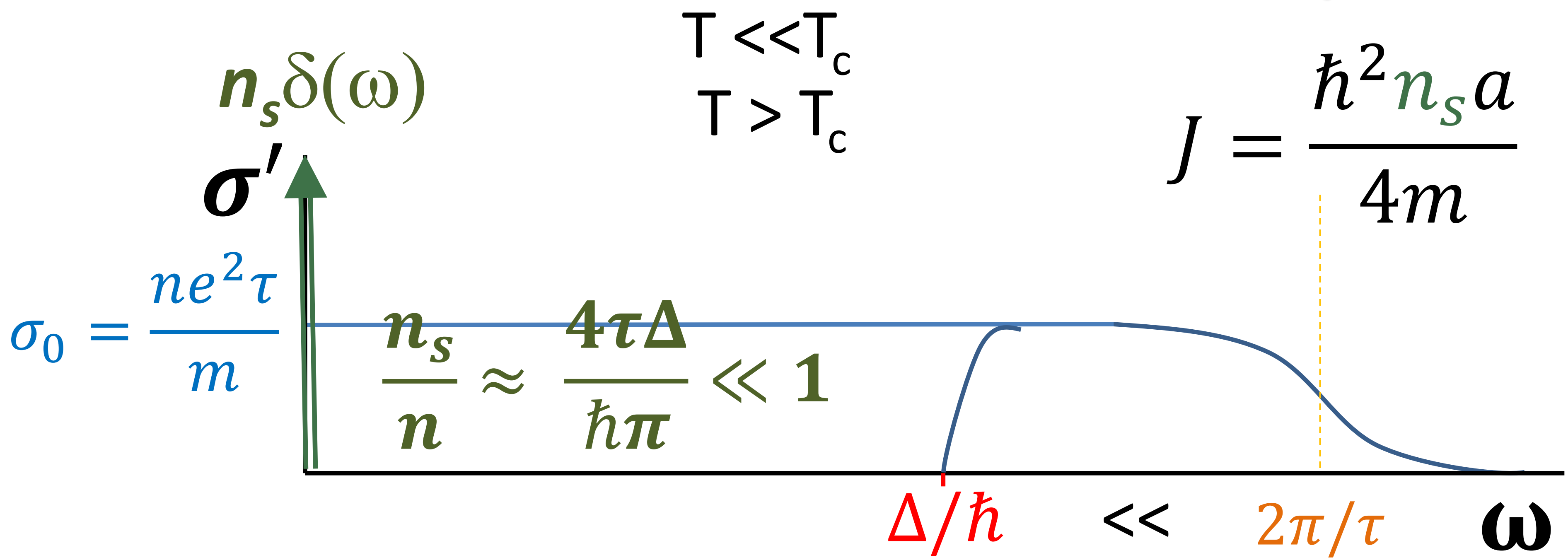


$$\int_0^\infty \sigma'(\omega)d\omega = \left(\frac{\pi}{2}\right)\frac{ne^2}{m}$$

(Strong) Disorder in conventional superconductors

The effect of disorder on J $(\propto n_s)$

Dirty limit



$$J = \frac{\hbar^2 n_s a}{4m}$$

NbN film T_c ~ 16 K

n_s/n ~ 0.001

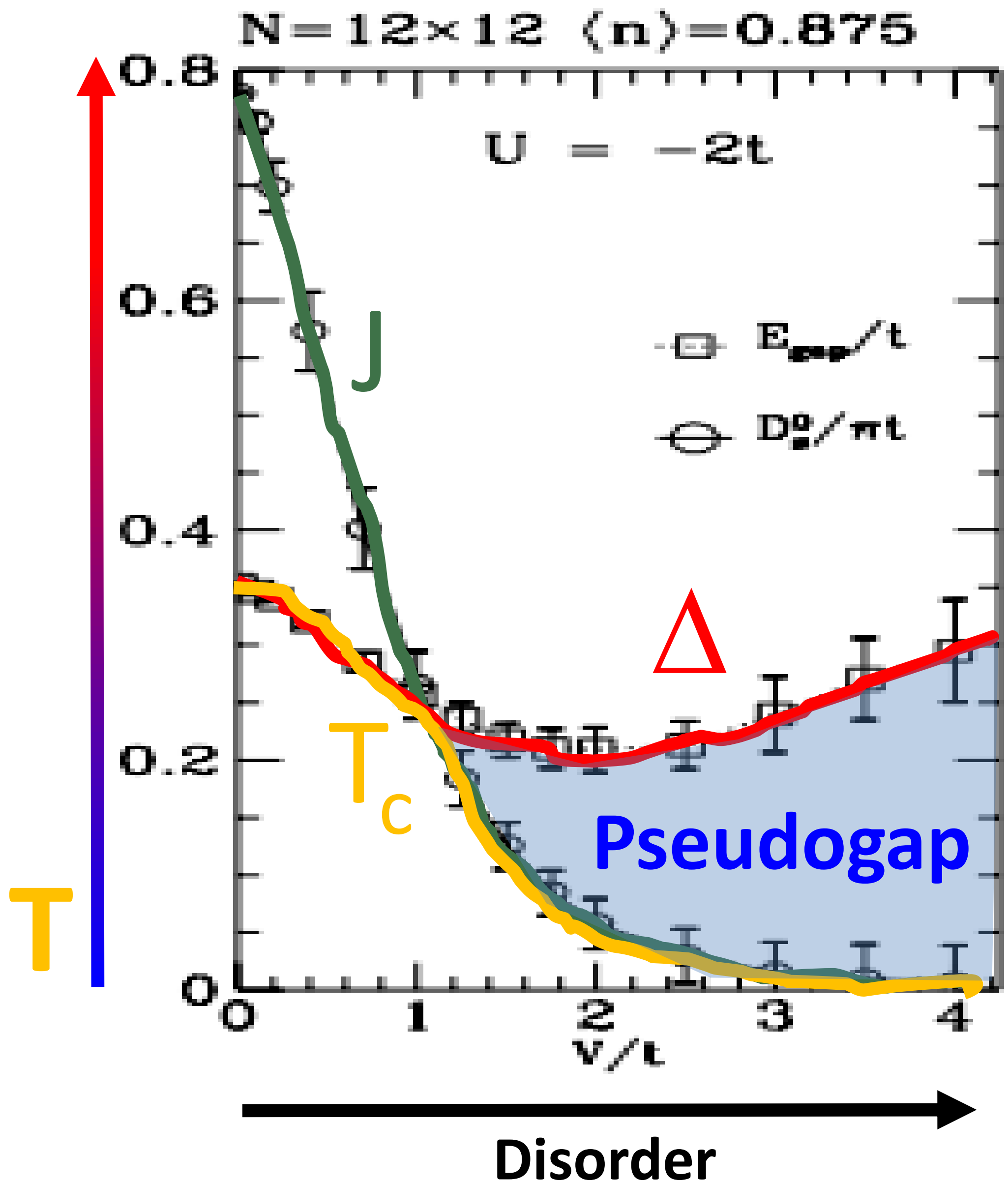
$$\int_0^\infty \sigma'(\omega)\,d\omega = \frac{\pi\Delta}{2\hbar}\frac{ne^2}{m}$$

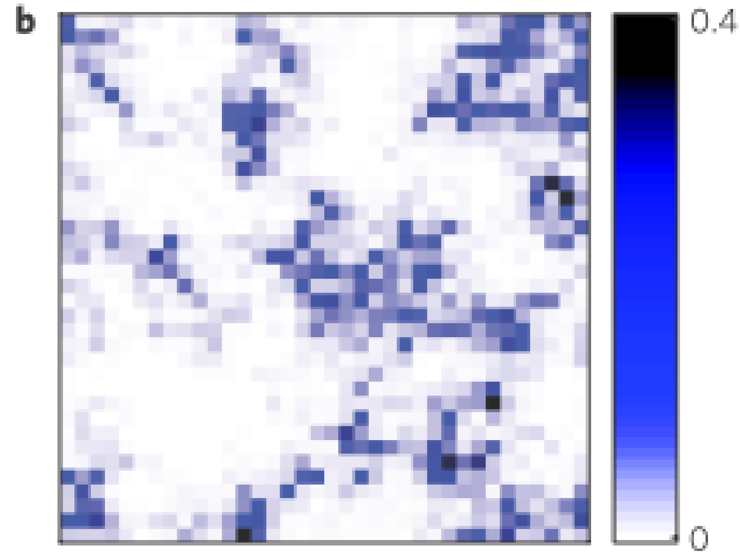
$$\lambda_{BCS}(0)^{-2} = \frac{\pi\mu_0\Delta}{\rho_N\hbar}$$

Role of Spatial Amplitude Fluctuations in Highly Disordered *s*-Wave Superconductors

ndini Trivedi
al Research, Mumbai 400005, India

$$n_{i\uparrow}n_{i\downarrow} + \sum_{i,\sigma}\left(V_i - \mu\right)n_{i\sigma}$$

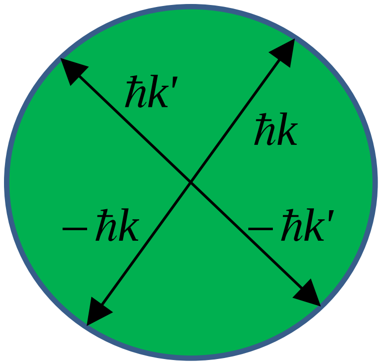




Bouadim et al., Nature Physics, 2012

Disorder in superconductors

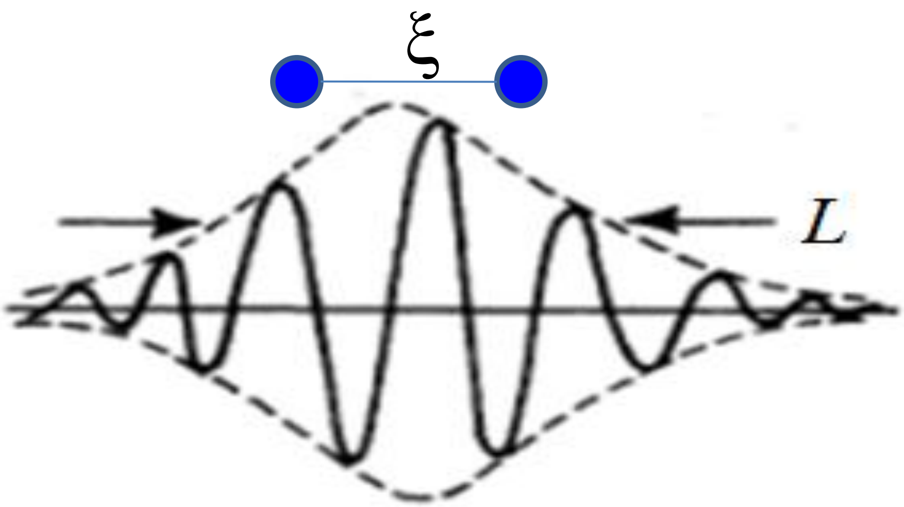
Anderson theorem: As long as the system remains fairly large, no amount of scattering which leaves the substance a metal, would be capable of actually destroying superconductivity.

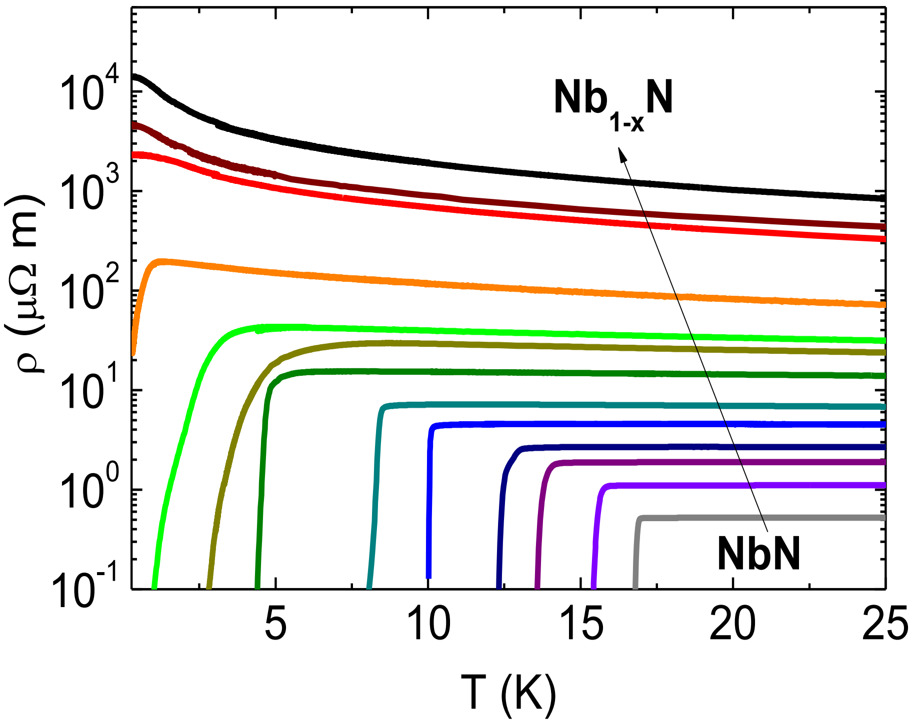


However, since the pairing interaction is not strongly dependent on the direction of k, the binding energy of the Copper pair, Δ will not significantly change.

T_c is not affected by disorder

Ma and Lee: The substance will remain a superconductor even when it becomes an Anderson insulator, as long as the localization length of the electrons, L, is larger than the coherence length, ξ.

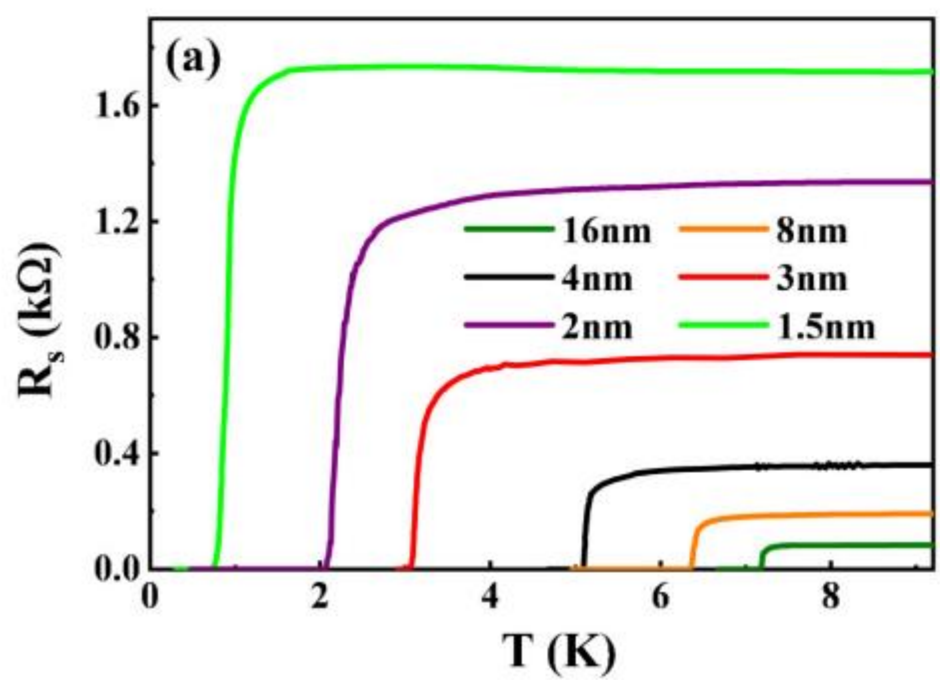




Strong Disorder does affect T_c !

NbN

MoGe



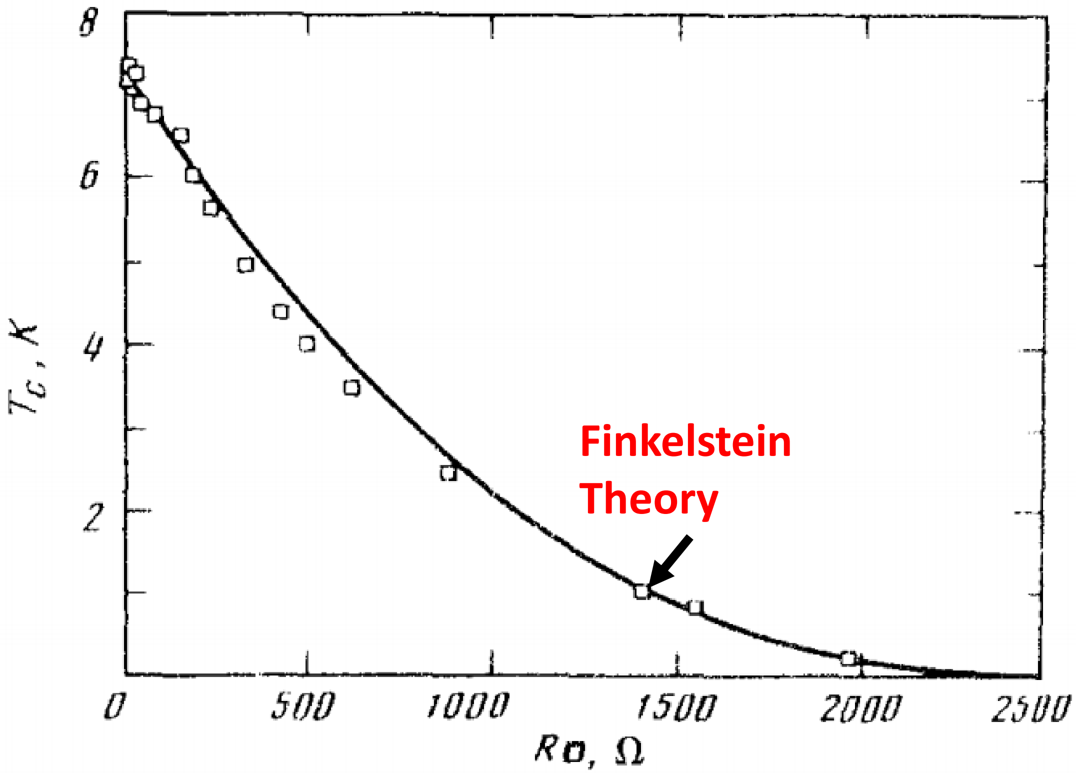
(Strong) Disorder in conventional superconductors

Finkelstein, **Anderson-Muttalib-Ramakrishnan**

- Coulomb interaction between electrons no longer effectively screened.
- The Coulomb repulsion partially cancels the electron-phonon attractive interaction.

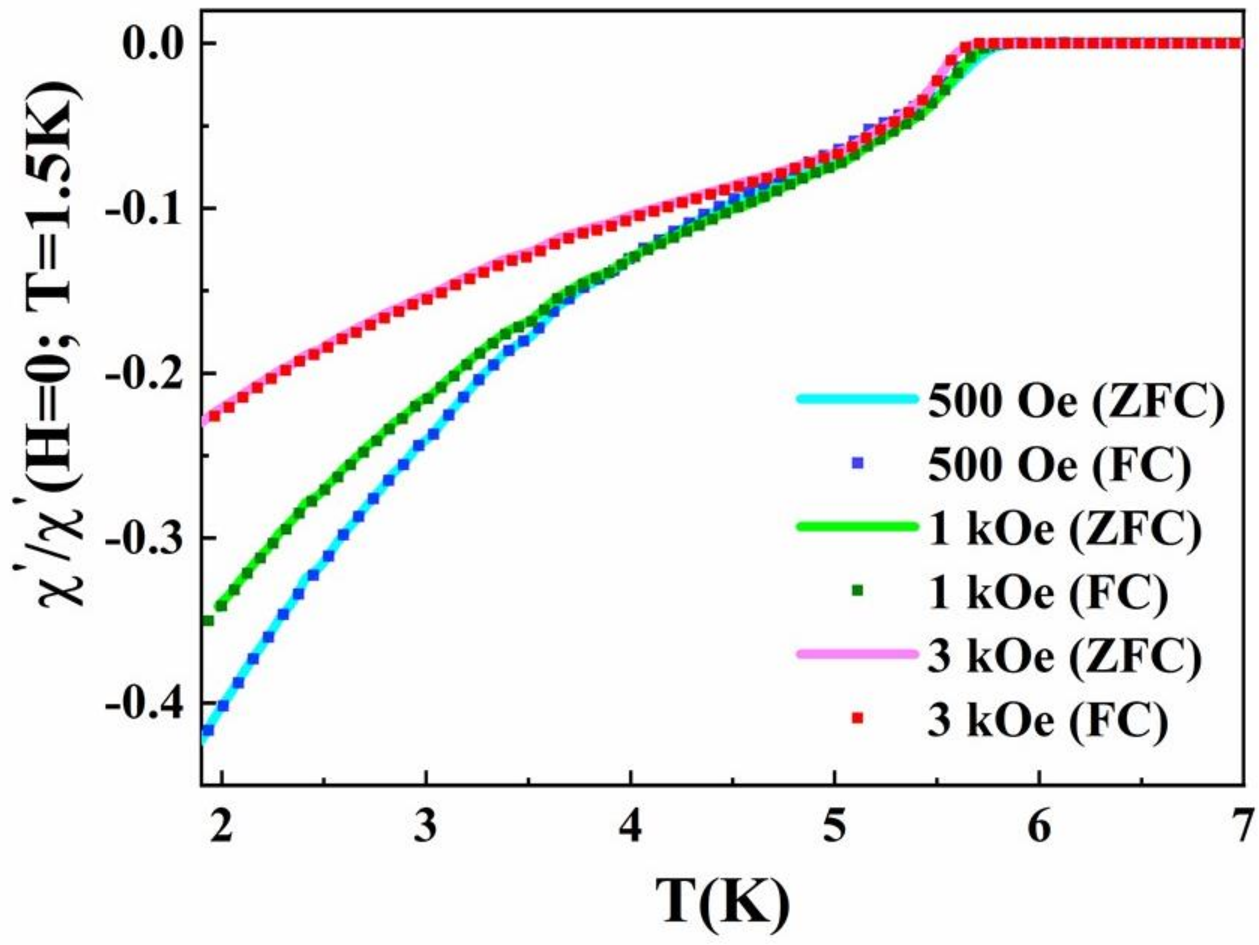
$$T_c \propto \Delta = h\Theta_D e^{-1/(N(0)V-\mu^*)}$$

Coulomb pseudopotential



J. M. Graybeal and M. R. Beasley
Phys. Rev. B **29**, 4167(R) (1984)

Characterization of pinning strength



No hysteresis between Field cooled (FC) & zero field cooled (ZFC)