Melting of the vortex lattice: A story from images

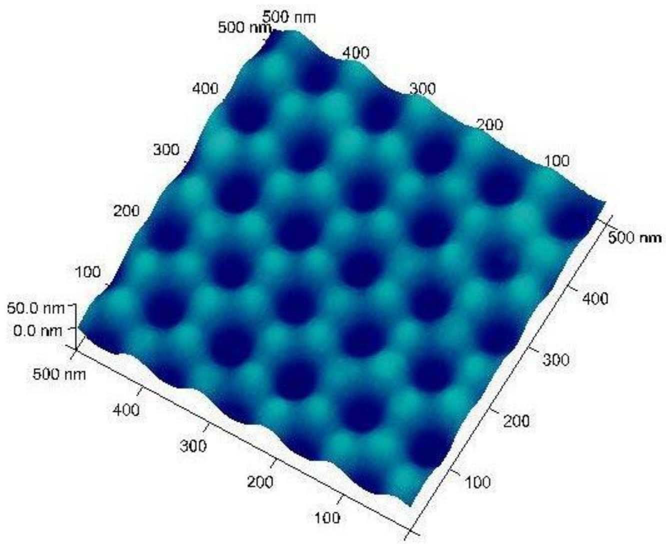
Pratap Raychaudhuri

Somesh Ganguli, Indranil Roy, Harkirat Singh, Rini Ganguly (measurements)

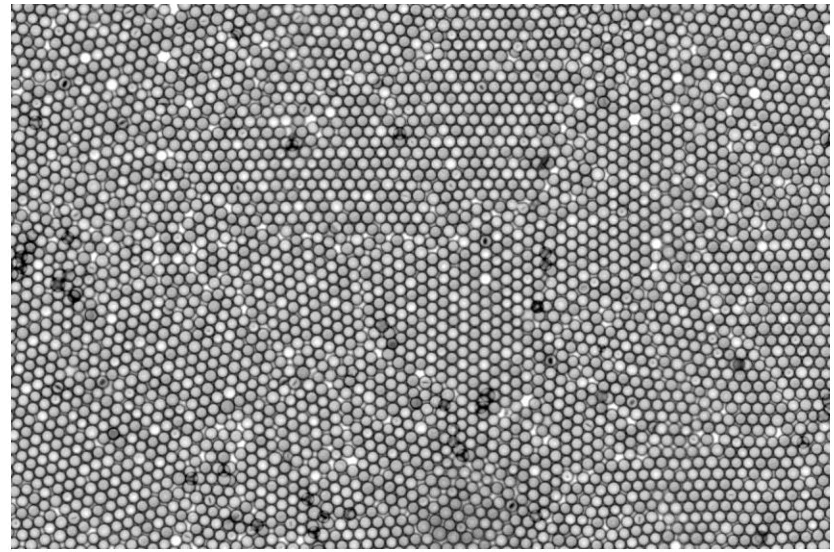
Vivas Bagwe, Parasharam Shirage, Arumugam Thamizhavel (crystal growth)

Special thanks to Arun Grover, Shobo Bhattacharya , Deepak Dhar and Valerii Vinokur

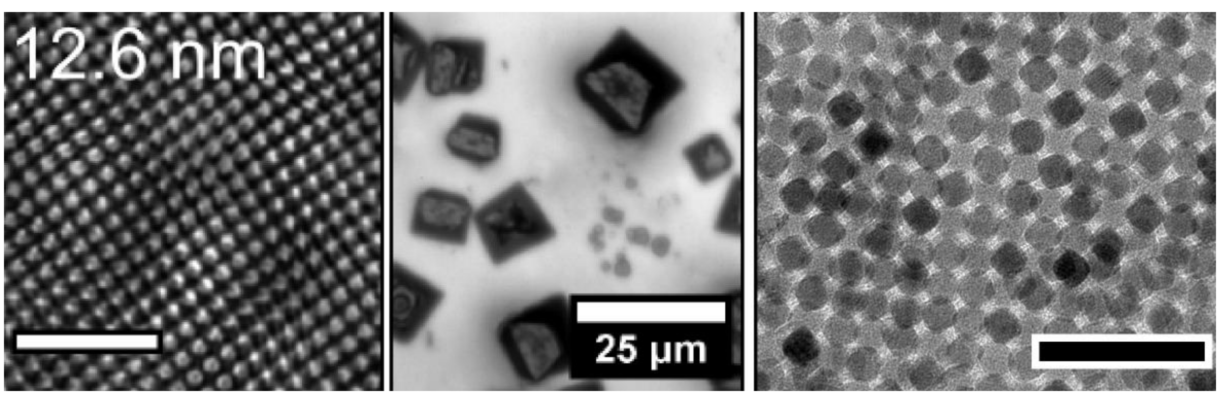
Periodic structures



Self assembled alumina template



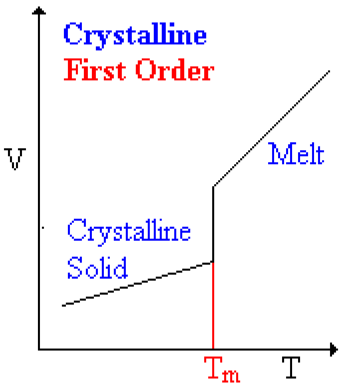
Spherical Glass particle in water

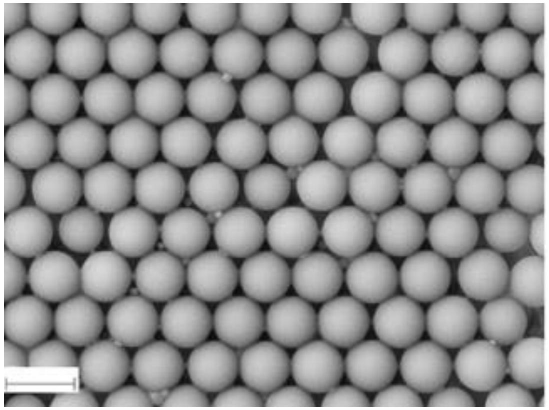


"Self-assembly of iron oxide nanocrystals2" by Erik Wetterskog et al.

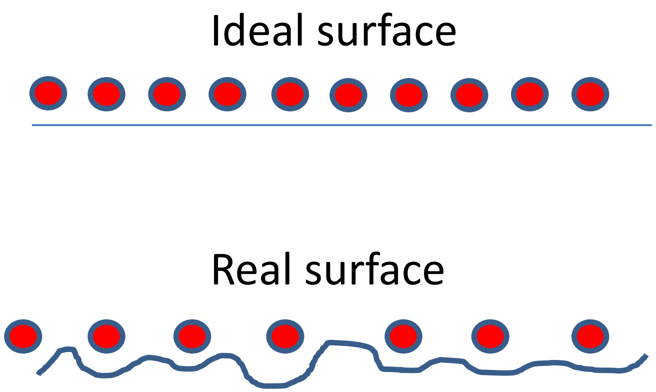
"… no one can give a real proof, or even a good qualitative reason, as to why the ground state of almost all assemblage of atoms are regular rather than irregular in nature."

P. W. Anderson in ***Concepts in Solids***



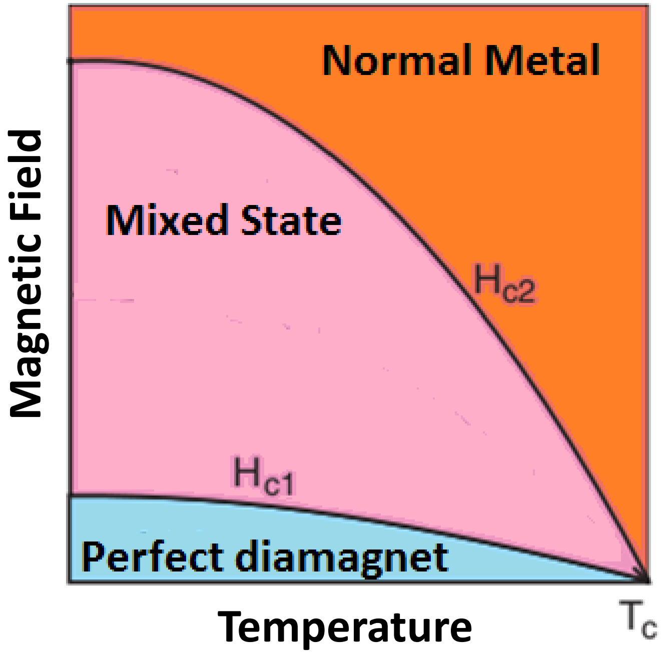


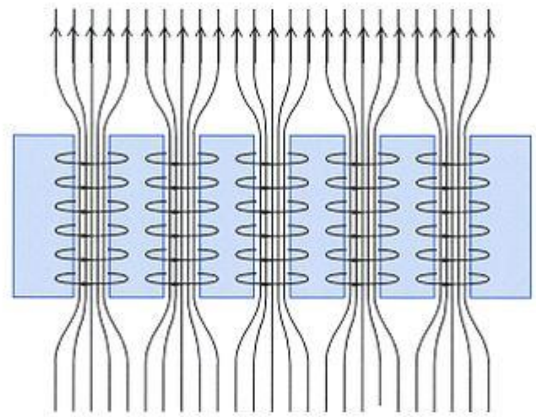
Coll et al. Nanoscale Research Letters 2013, 8:26

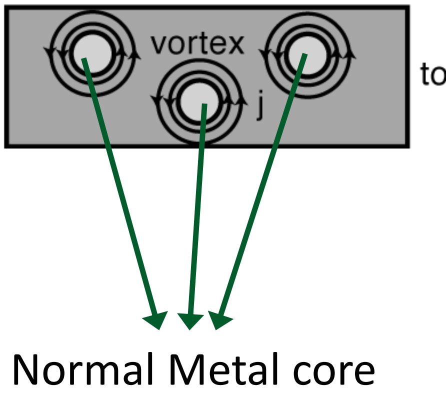


- **How does the melting of a solid get affected by random pinning?**

The mixed state in Type II superconductors





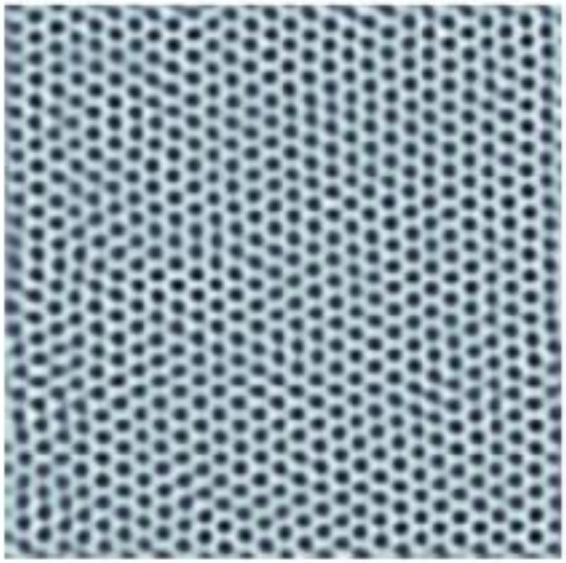


Magnetic flux lines having flux ϕ_0 =(h/2e)

Vortices

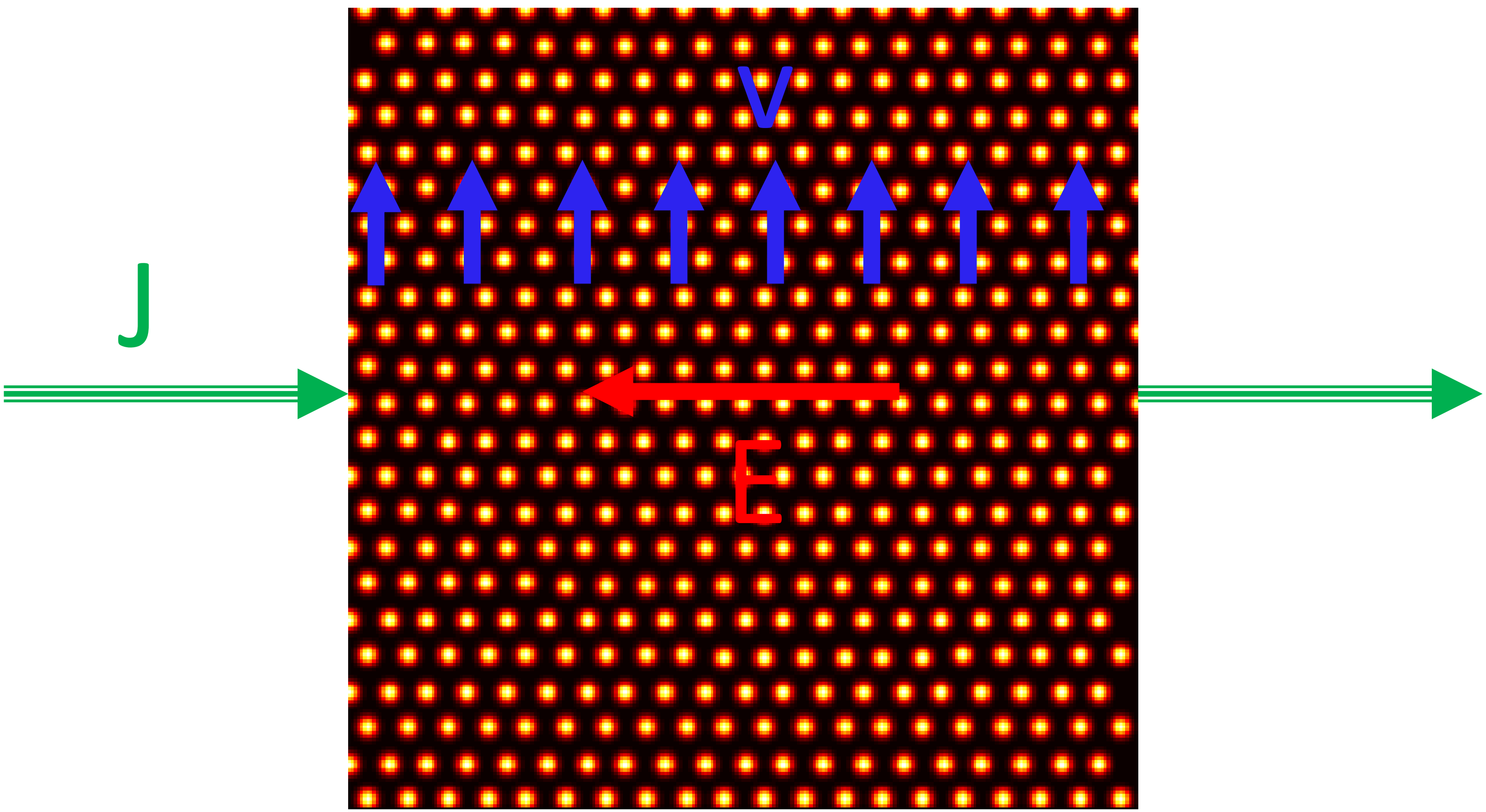
$$V_{eff}(r) = \frac{\Phi_0^{*2}}{8\pi^2\lambda^2} K_0(r/\lambda)$$

$$K_0(r/\lambda) \approx \begin{cases} \ln(\lambda/r) & r \lesssim \lambda; \\ \sqrt{\frac{\pi\lambda}{2r}} e^{-r/\lambda} & r \gg \lambda. \end{cases}$$



The vortex lattice

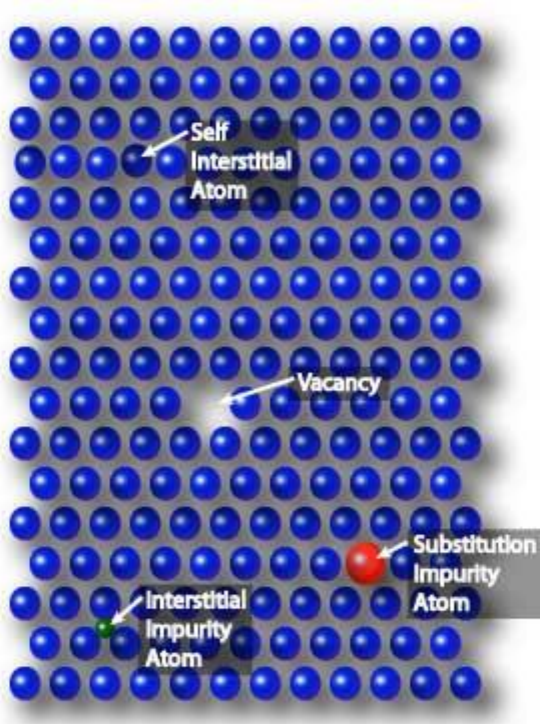
To be or Not to be (a superconductor)

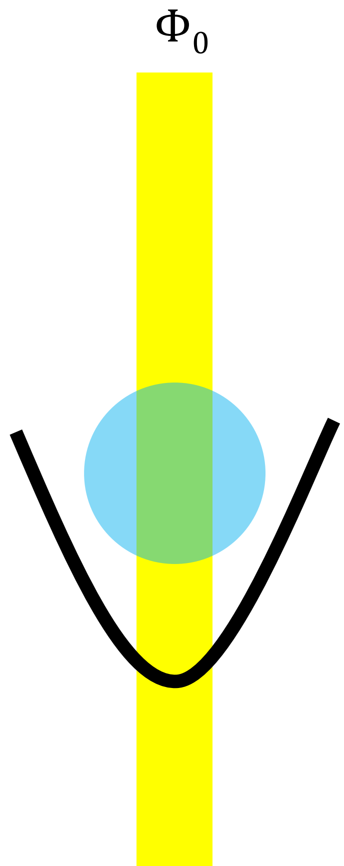


Finite Power dissipation: P = **J • E**

Zero resistance state is destroyed

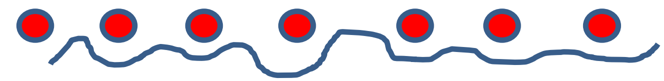
Random Pinning

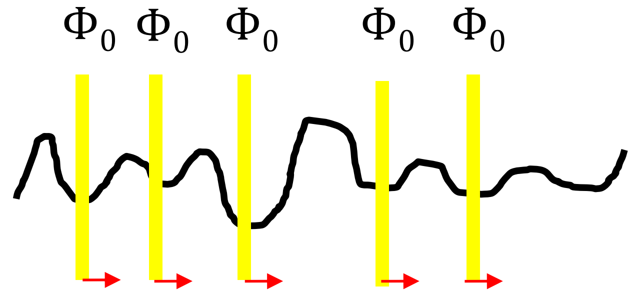


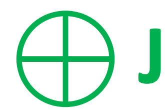


Defects act as a potential minimum for the vortex

Real surface







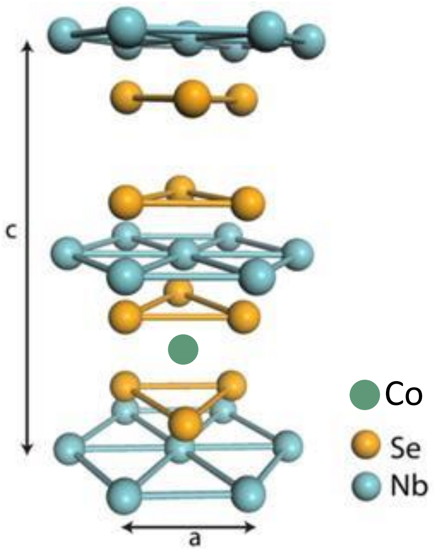
Each vortex will be trapped in a defect site.

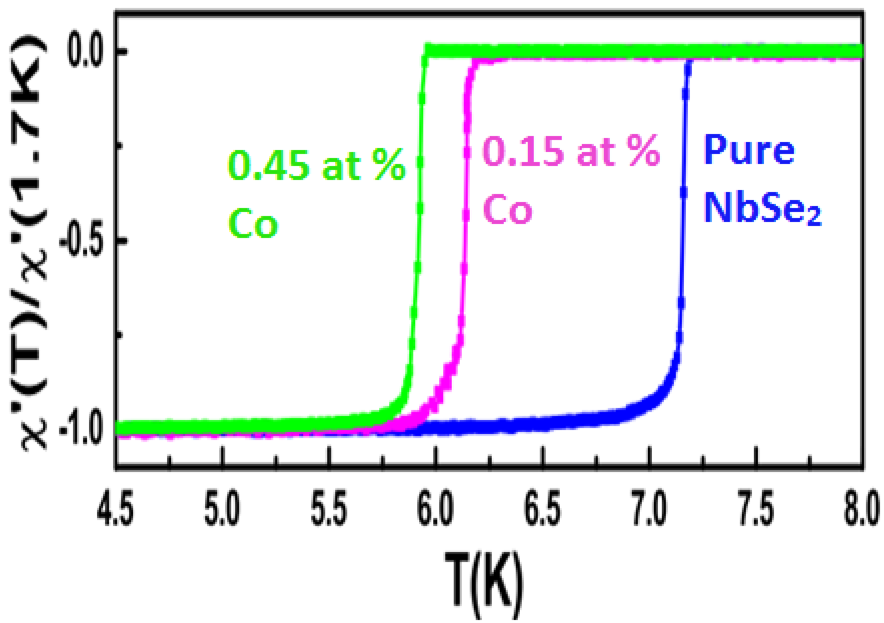
$$\textit{Force} \propto J \times \Phi_0$$

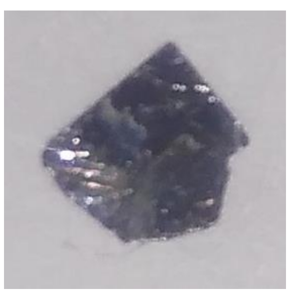
The vortices will move only when the ***Force*** is larger than a critical value.

Finite critical current : $\mathbf{J_c}$

Our Model system: Co-intercalated $NbSe_2$

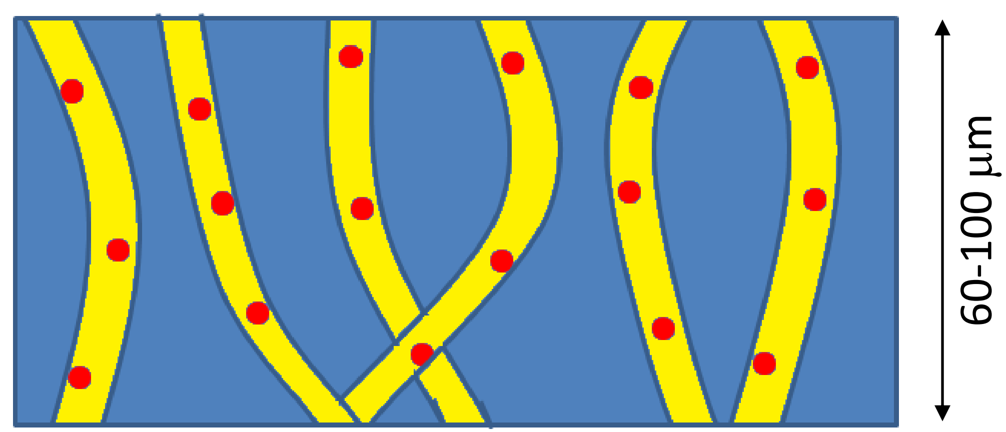




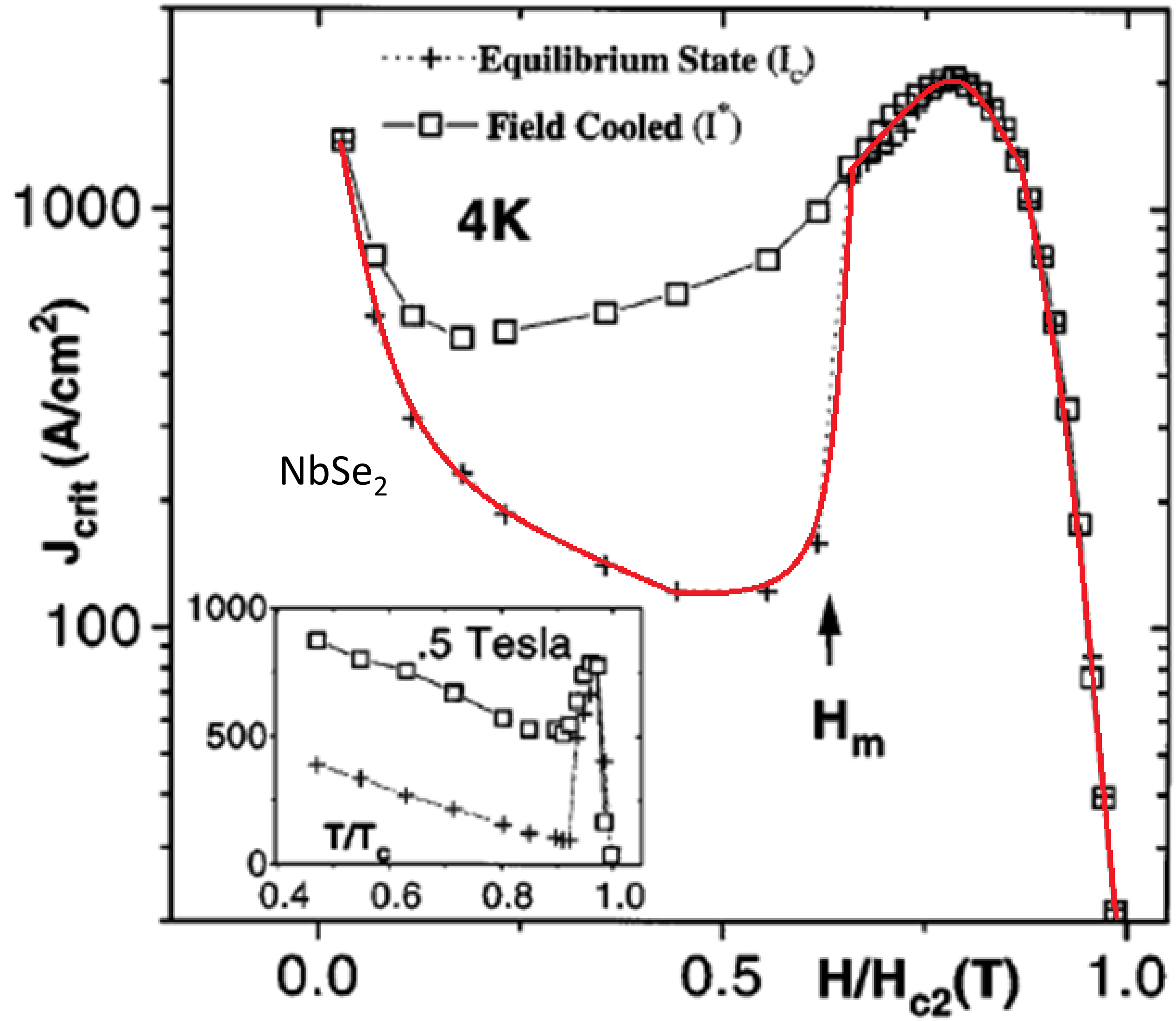


Single crystal flake with thickness 60-100 μm.

3-dimensional vortex lattice

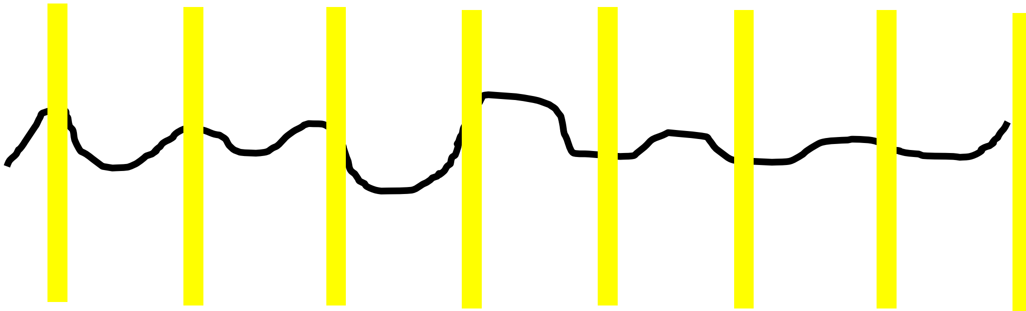


The peak effect



Henderson et al, Phys. Rev. Lett. **77**, 2077 (1996)

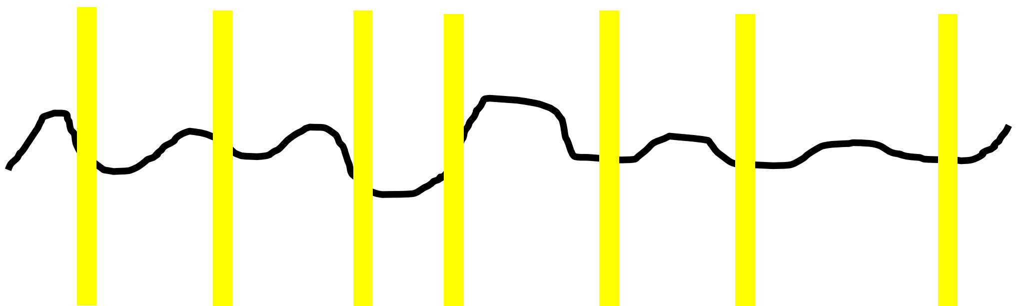
Perfect order (Interaction >>> Random pinning)



No Net force on the vortex lattice

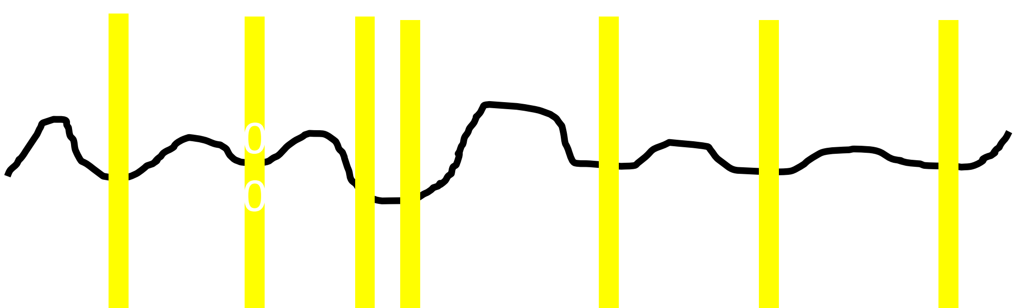
$J_c \approx 0$

Order slightly relaxed (Interaction ~ Random pinning)



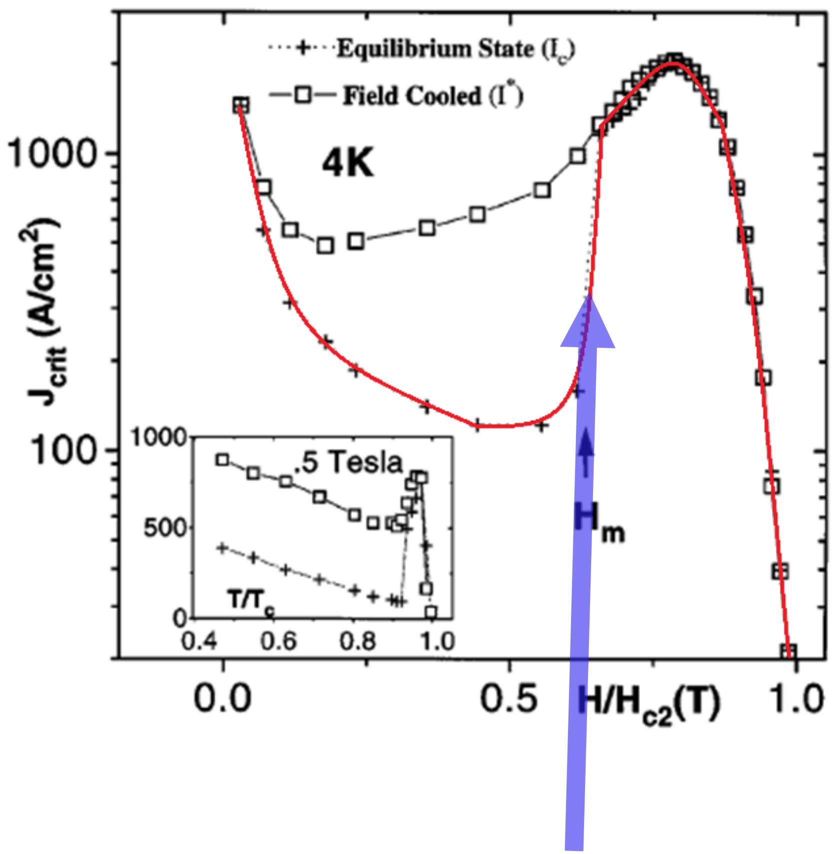
$J_c \neq 0$

Completely disordered (Interaction << Random pinning)



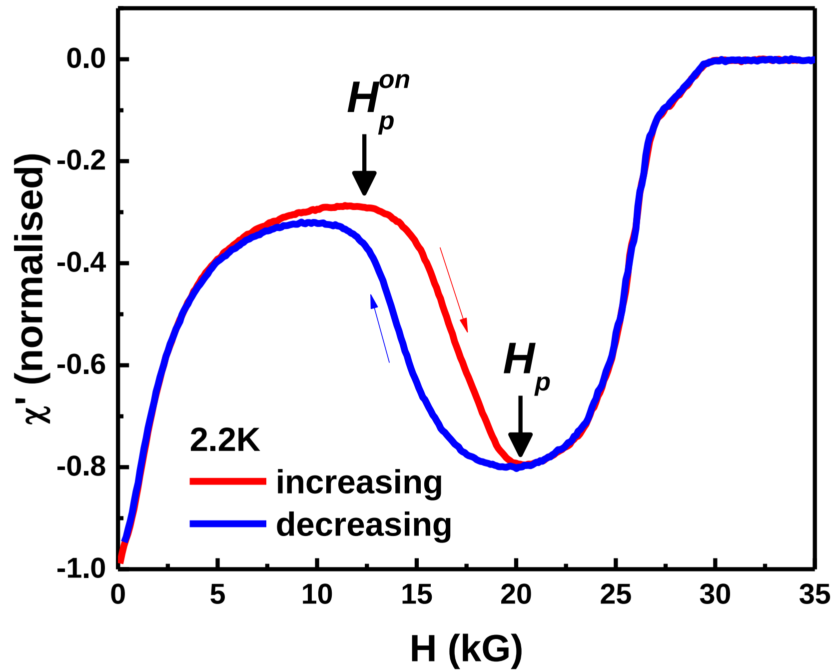
Large J_c

The peak effect

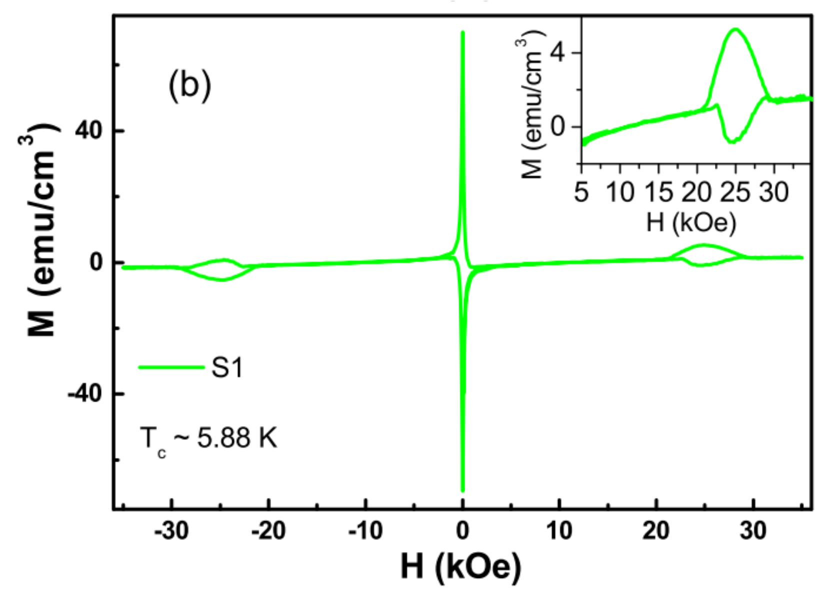


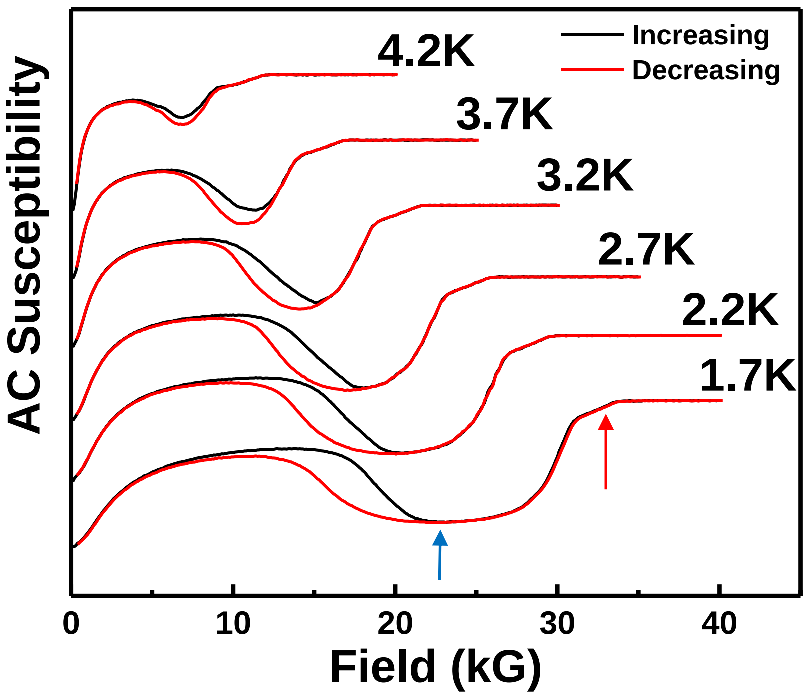
Order-disorder transition of the vortex lattice (melting)

AC susceptibility



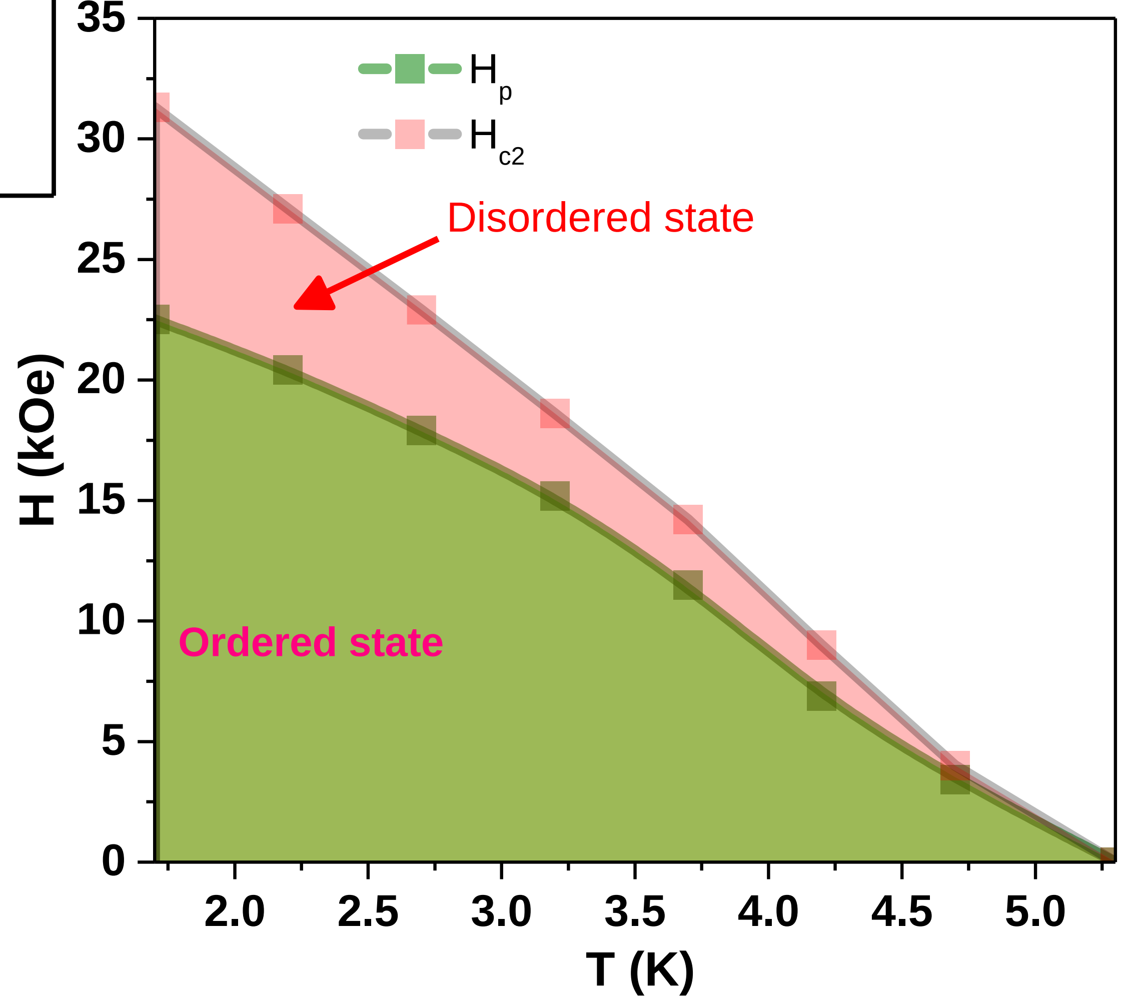
DC magnetization



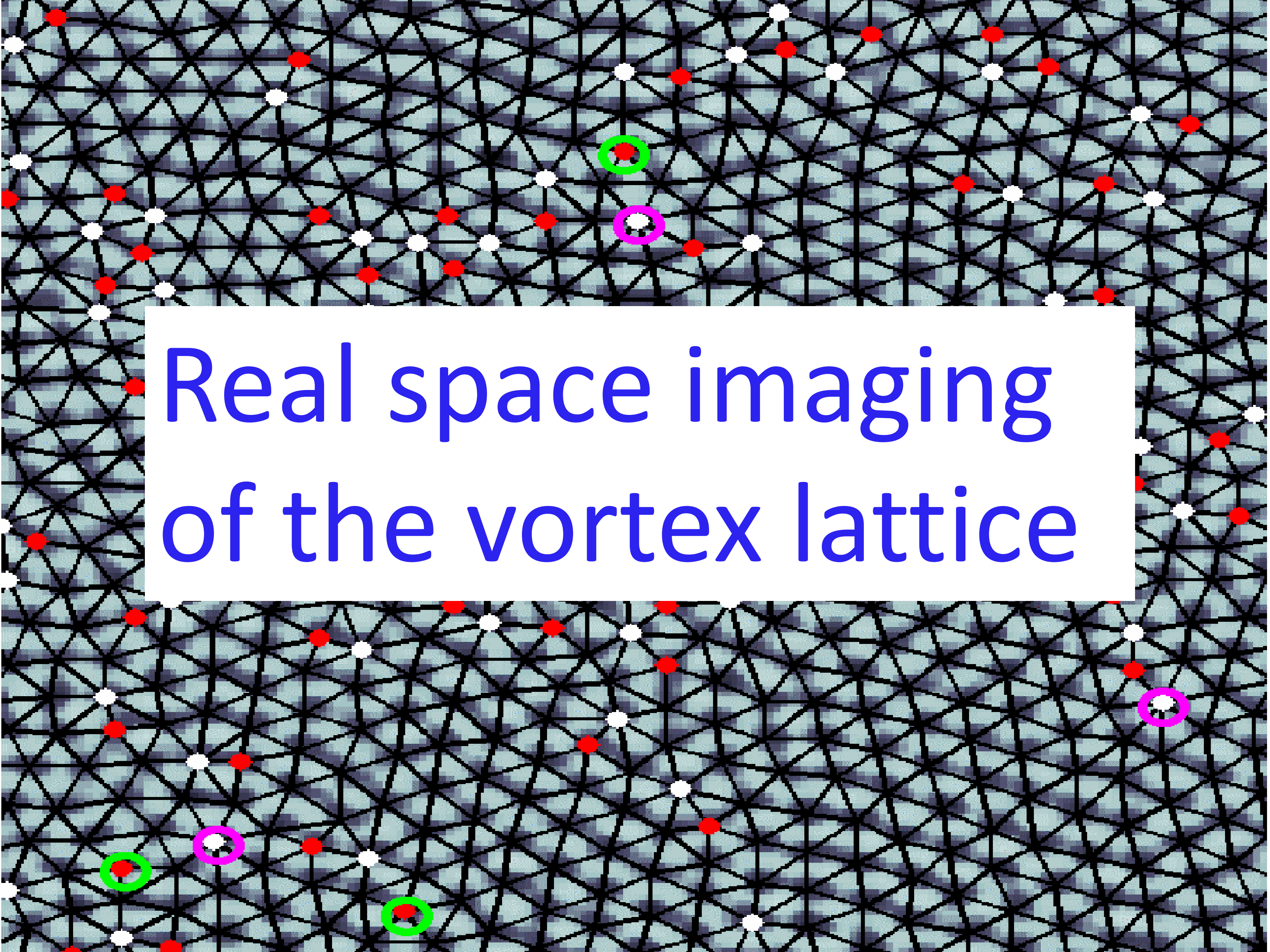


$Co_{0.0075}NbSe_2$

T_c ~ 5.3 K



Real space imaging of the vortex lattice

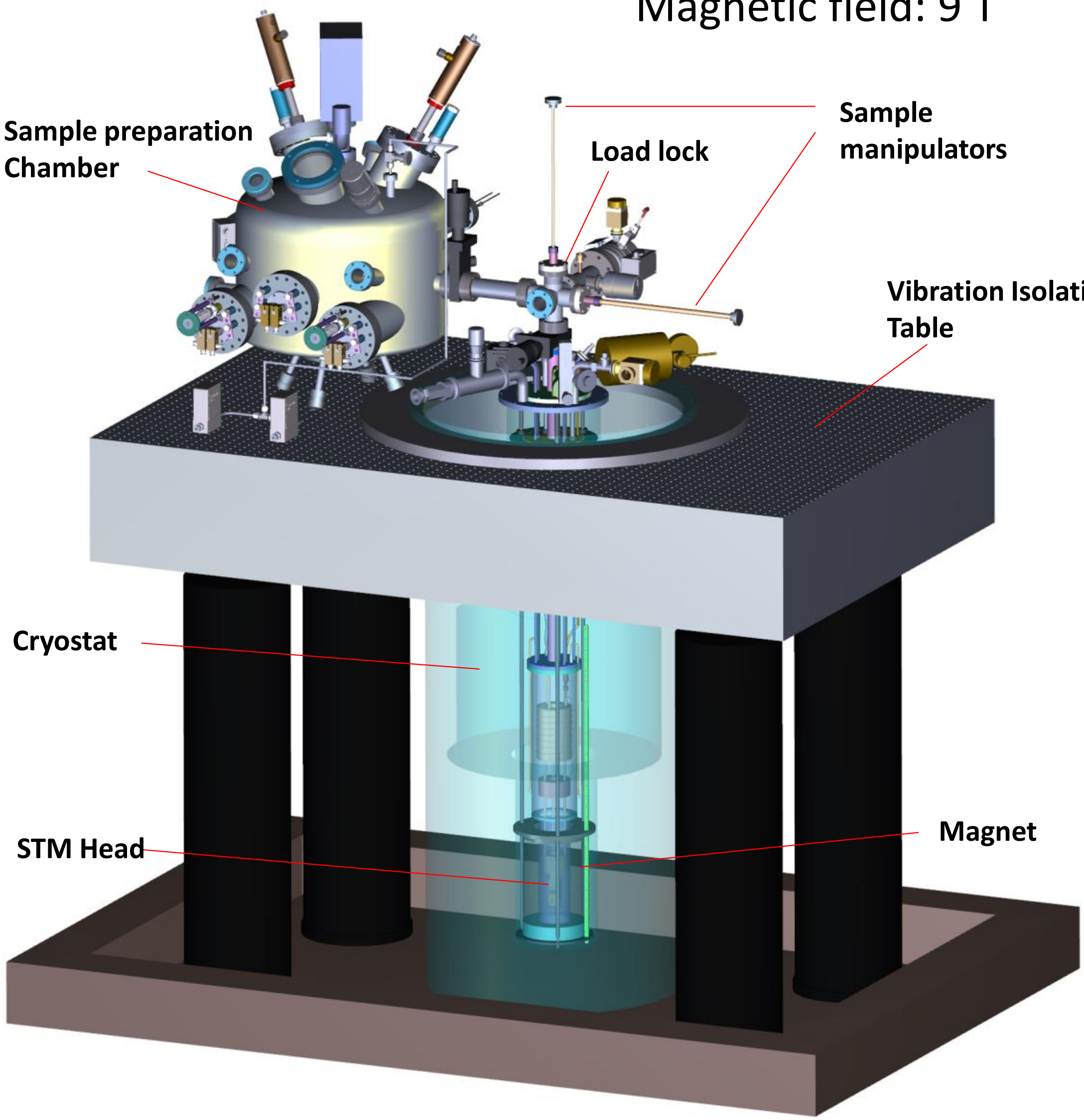


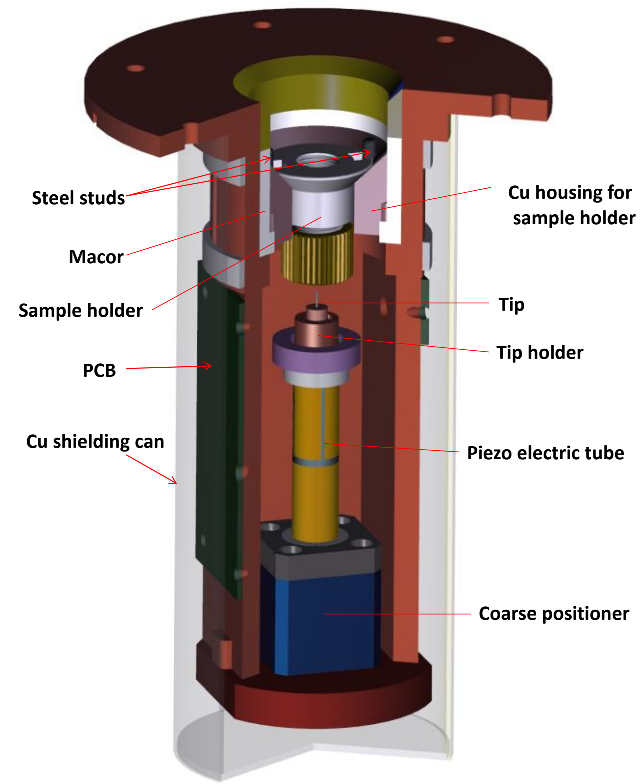
Our Toy: The TIFR milli-Kelvin STM

Lowest temperature:

300 mK

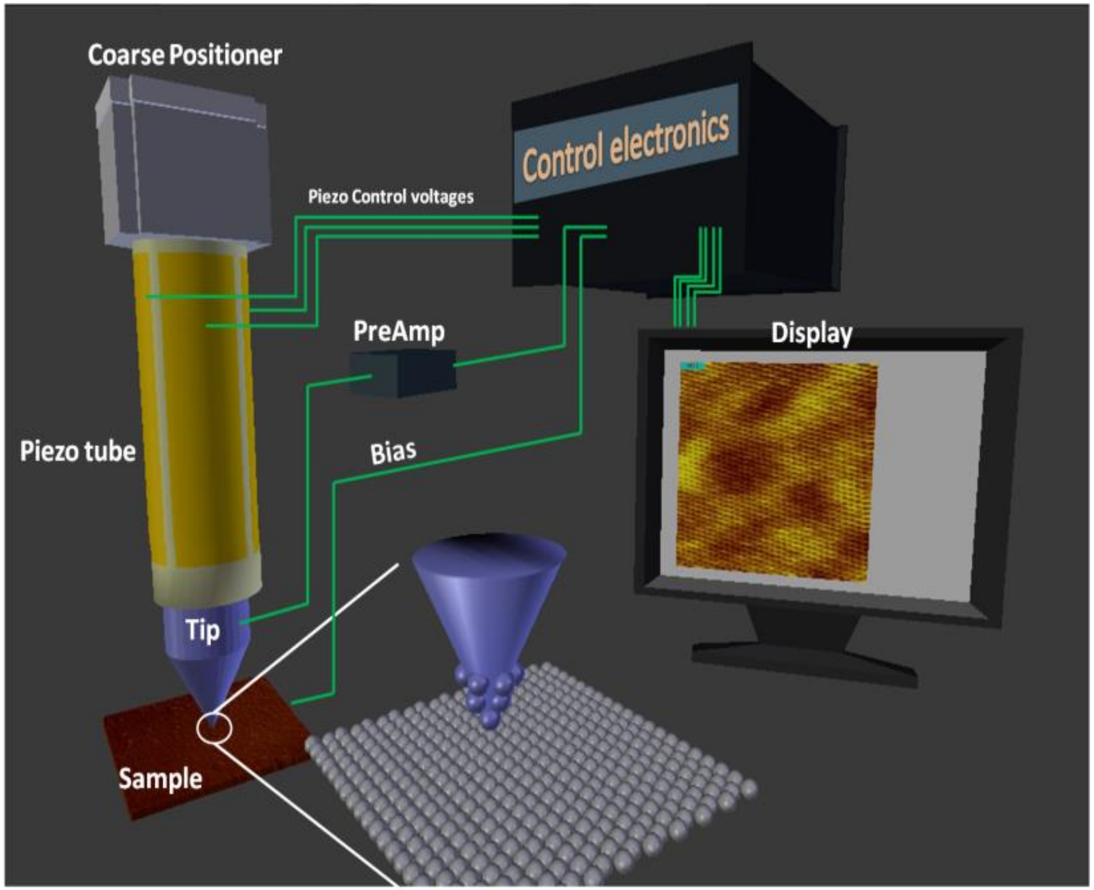
Magnetic field: 9 T





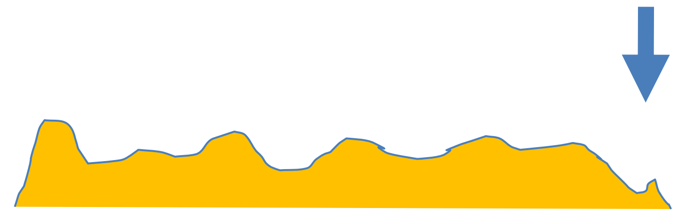
Review of Scientific Instruments **84**, 123905 (2013).

The scanning tunneling microscope: Principle



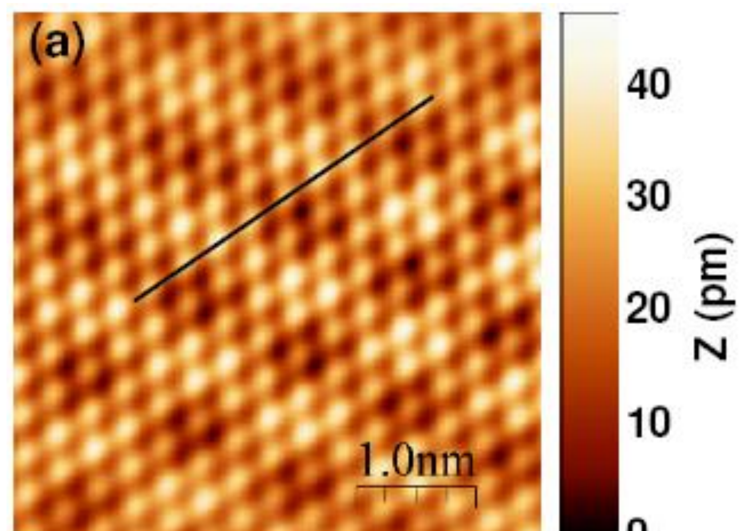
Tunneling Current

$$I \propto e^{-\kappa d}$$

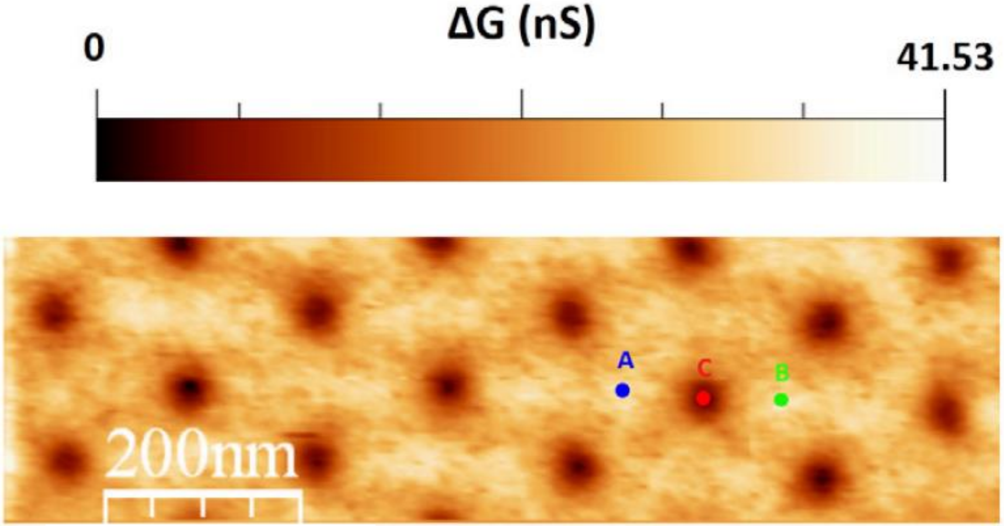


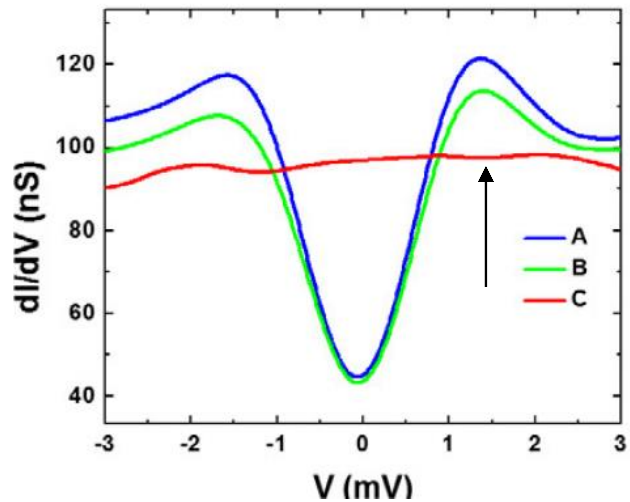
Topography by tracking current: Constant height mode

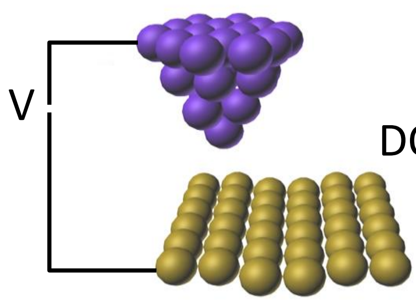
Tracking the height: Constant current mode



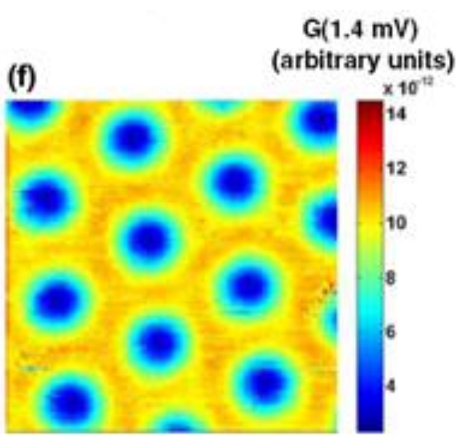
$NbSe_2$ single crystal (Grown by P. Shirage and A. Thamizhavel)

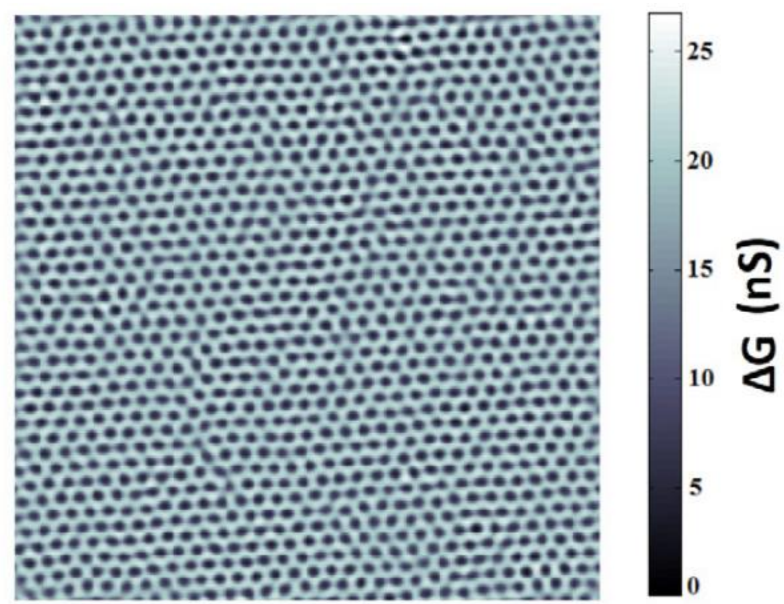

ΔG (nS)
0
41.53
A
C
B
200nm


dI/dV (nS)
V (mV)
A
B
C

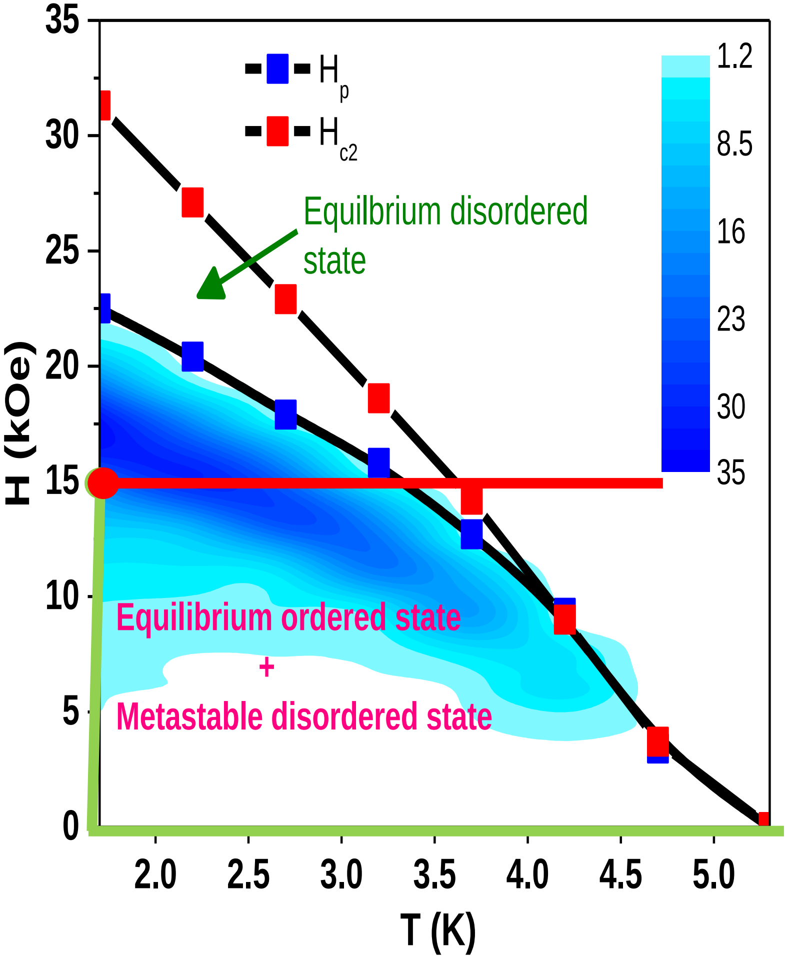

V

DOS ∝ dI/dV


(f)
G(1.4 mV)
(arbitrary units)

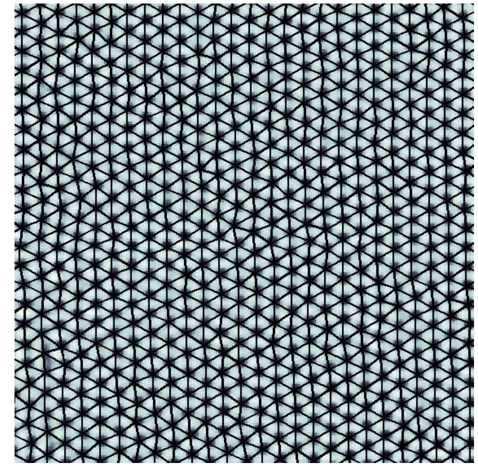

ΔG (nS)

2nd effect of pinning: Formation of metastable states



Zero field Cooled

Ordered State

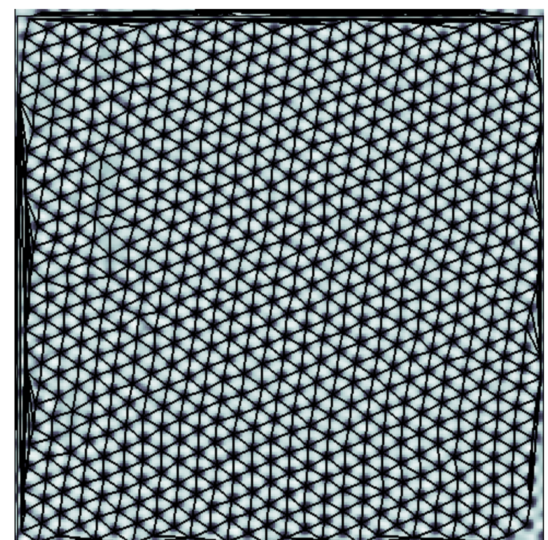


Field Cooled

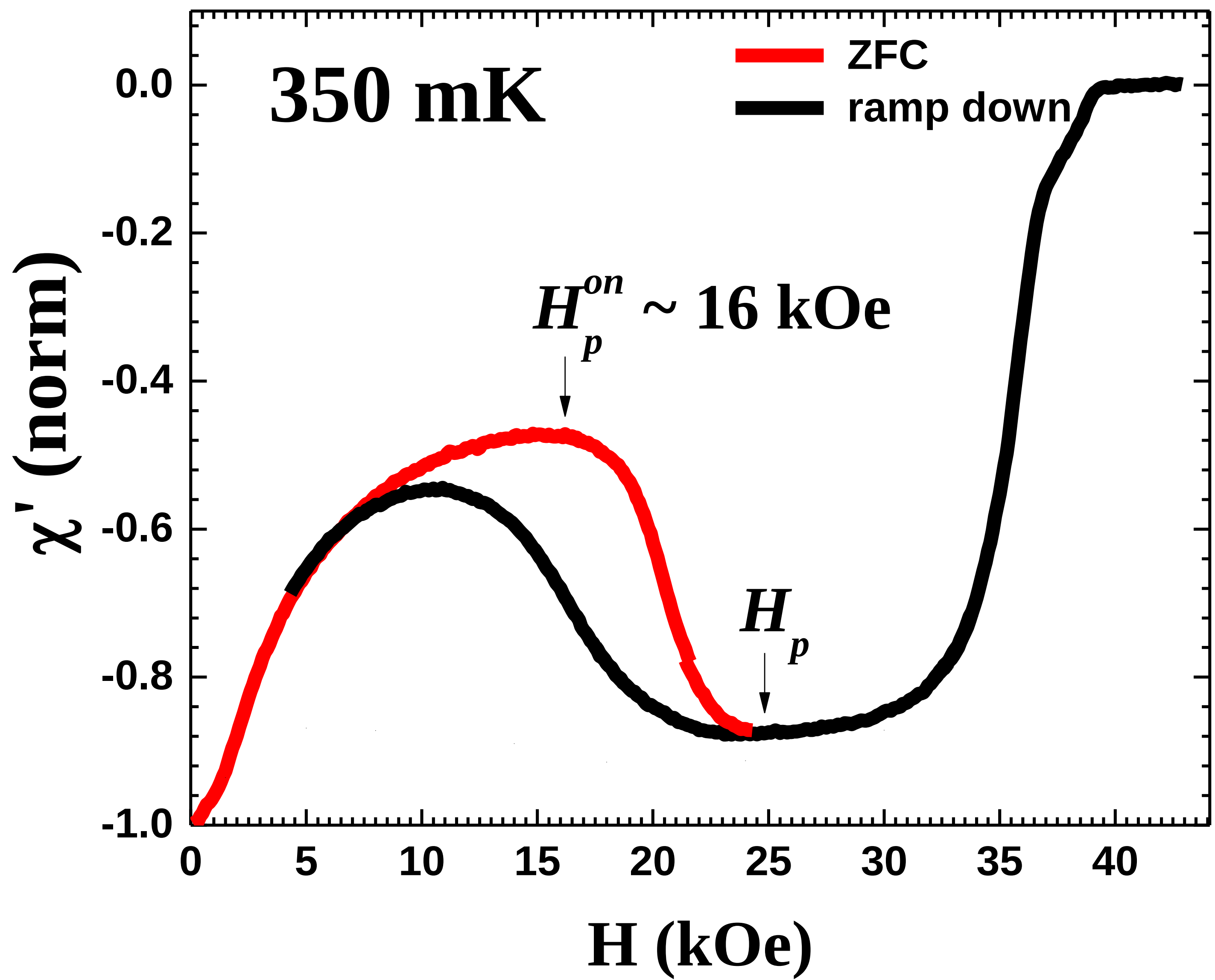
Then magnetic field pulse of 900 Oe

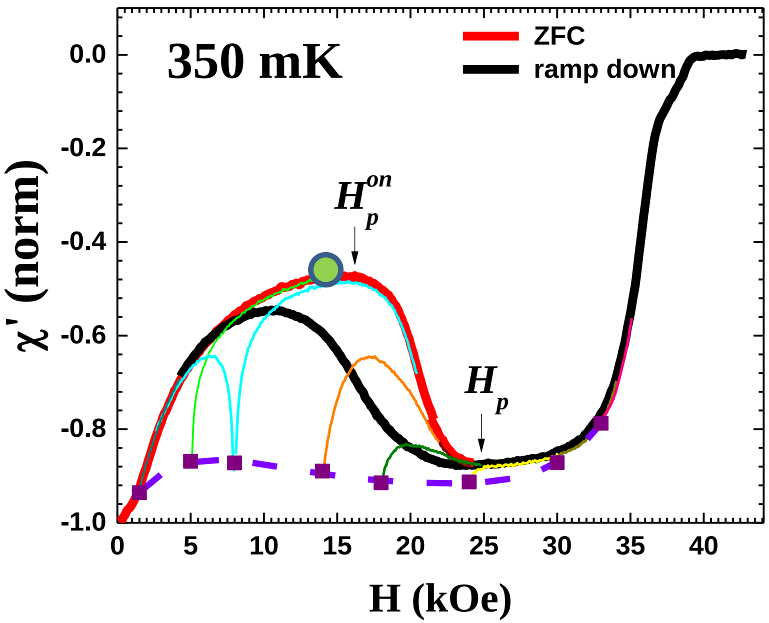
Field Cooled

Ordered State

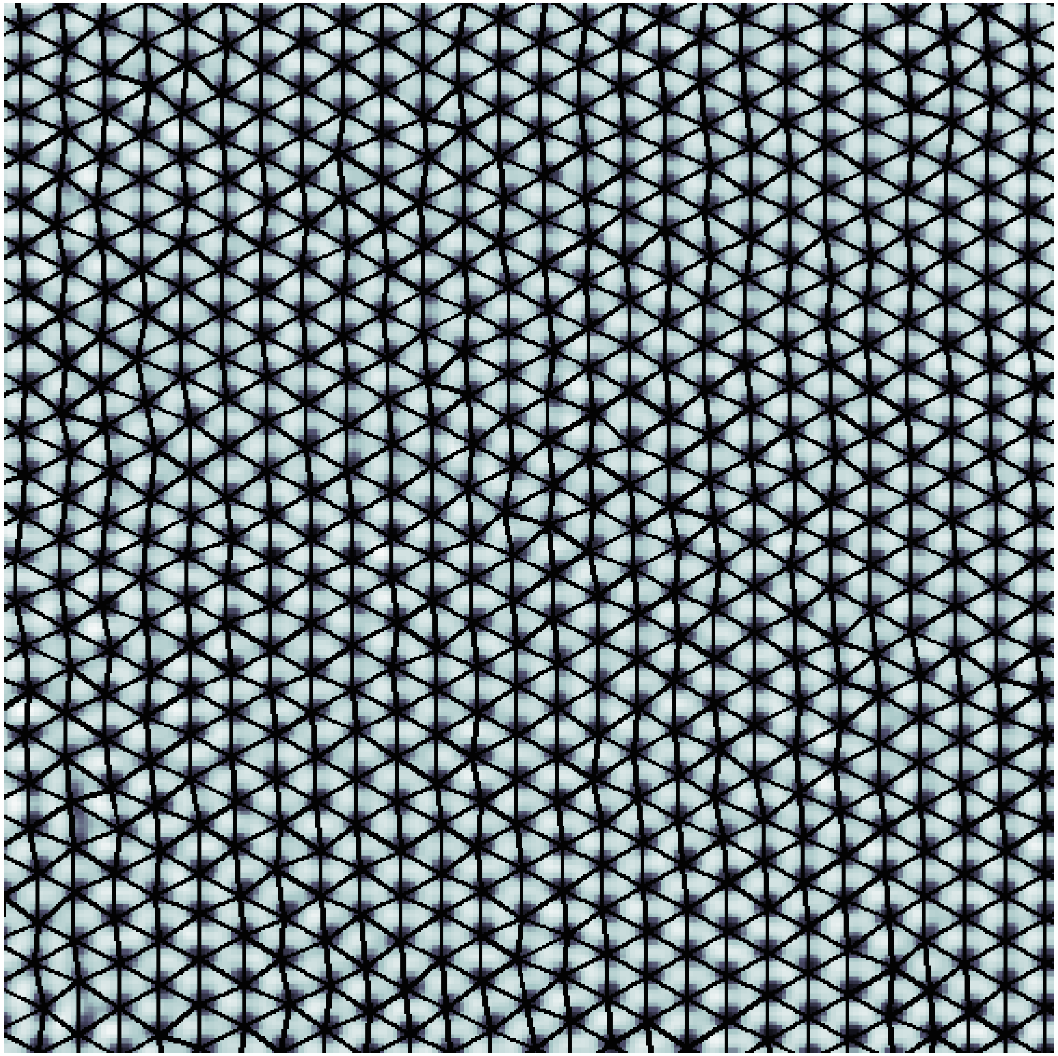


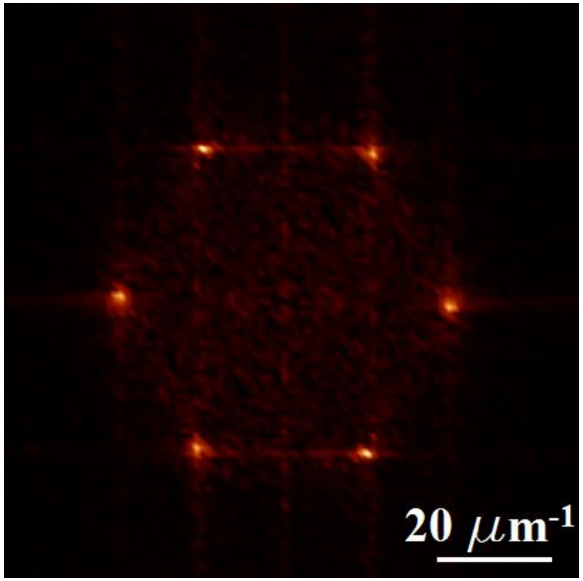
Real space evolution of the vortex lattice across the order-disorder transition





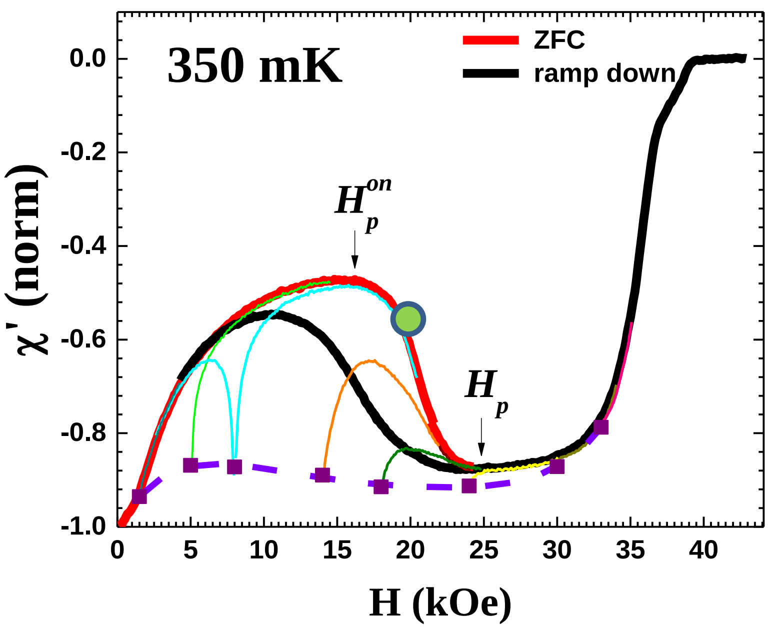
15 kOe

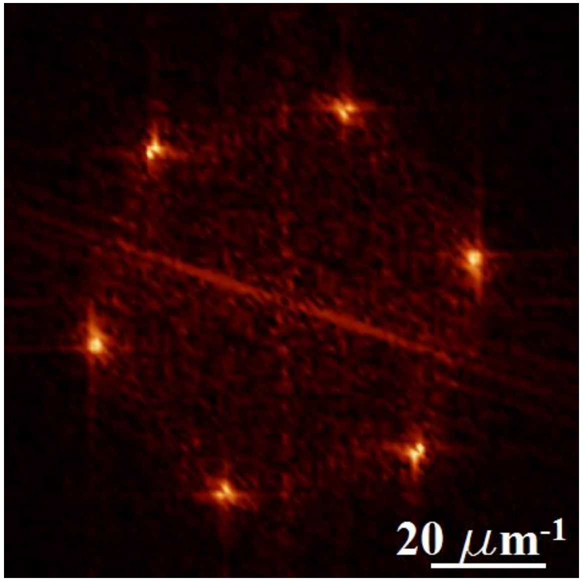


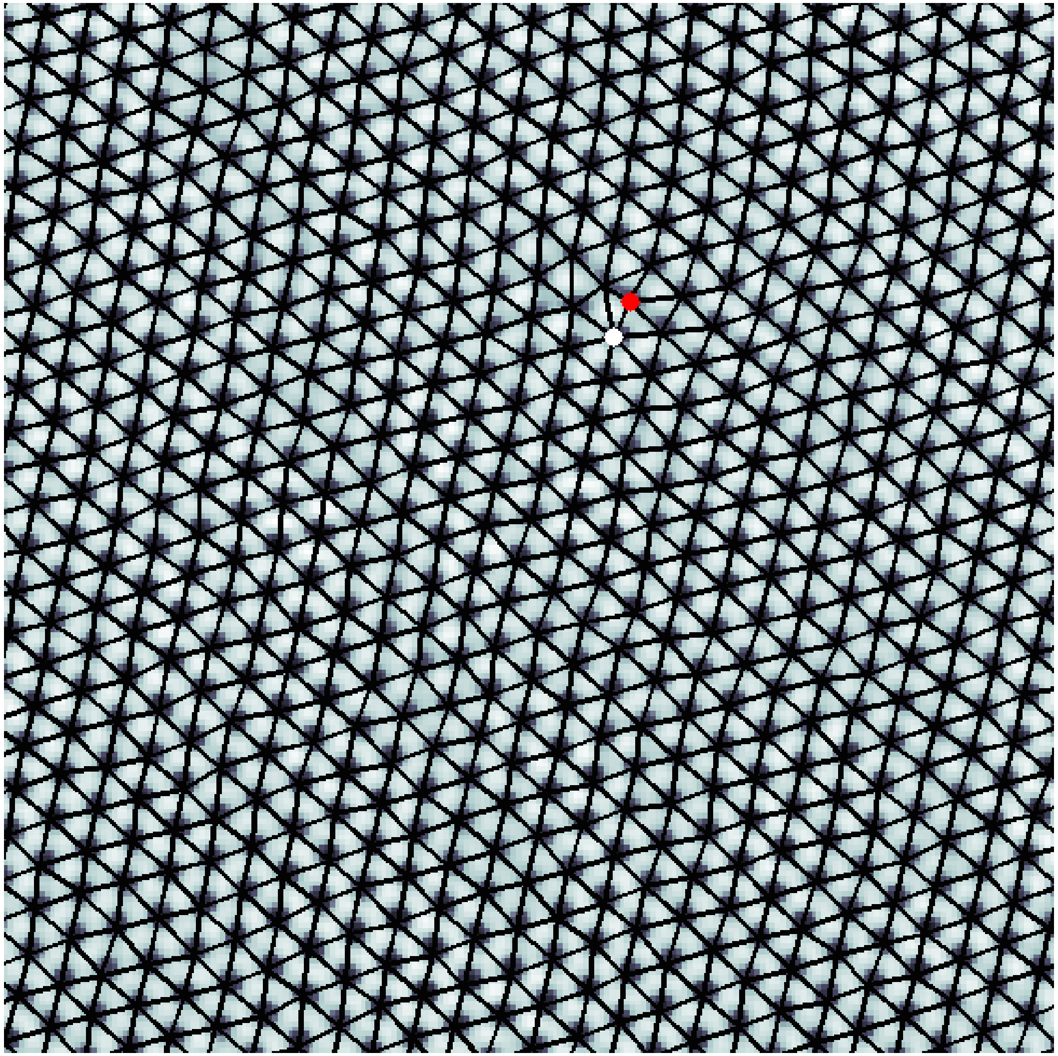


Dislocations appear (Orientational Glass)

20 kOe

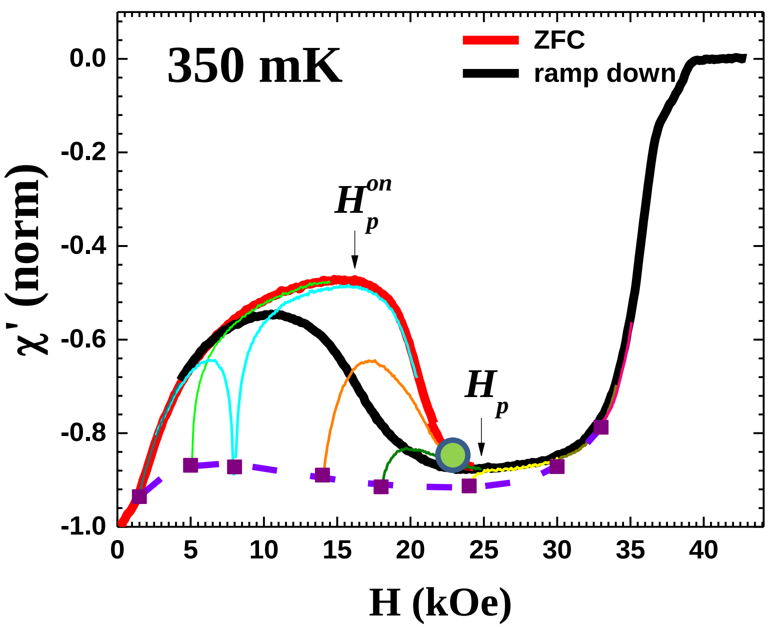


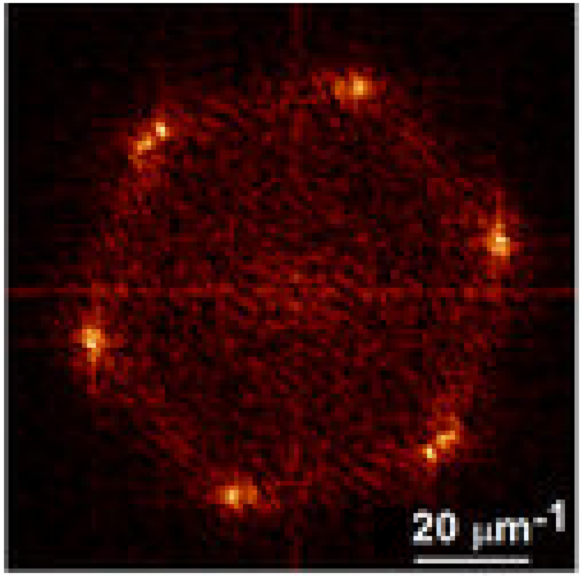


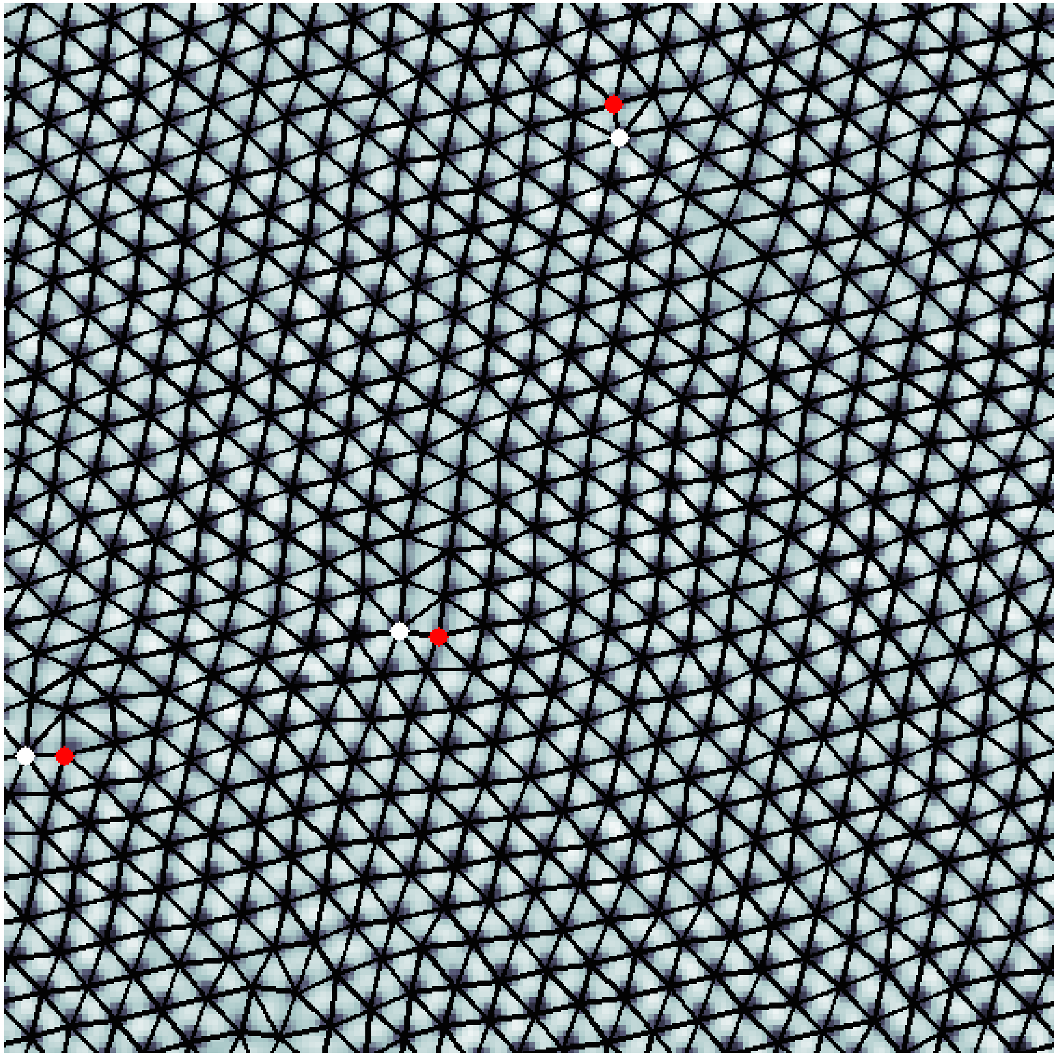


More dislocations (Orientational Glass)

24 kOe

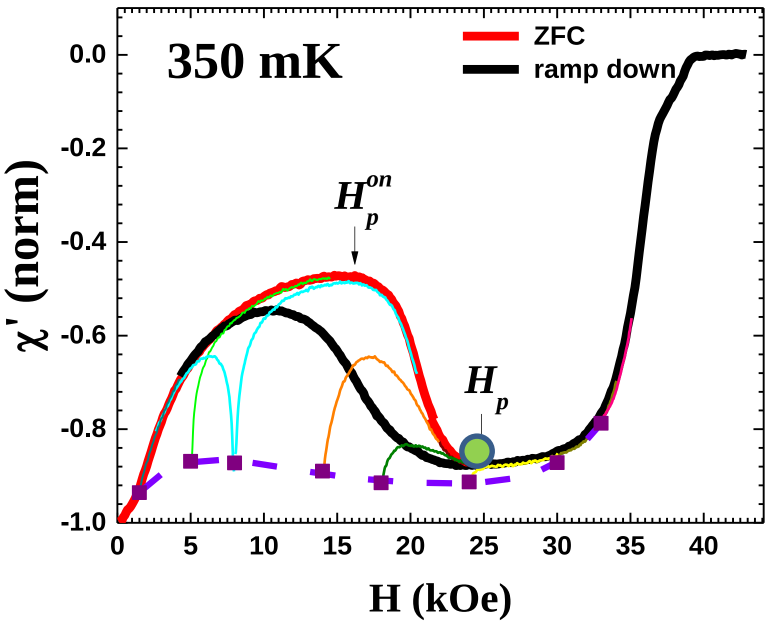


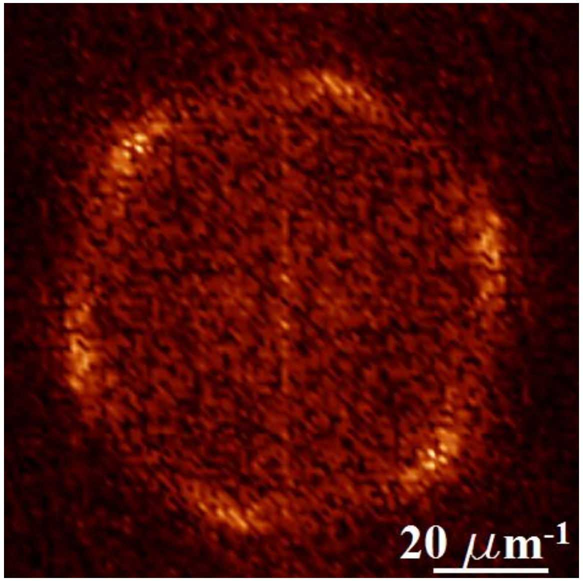


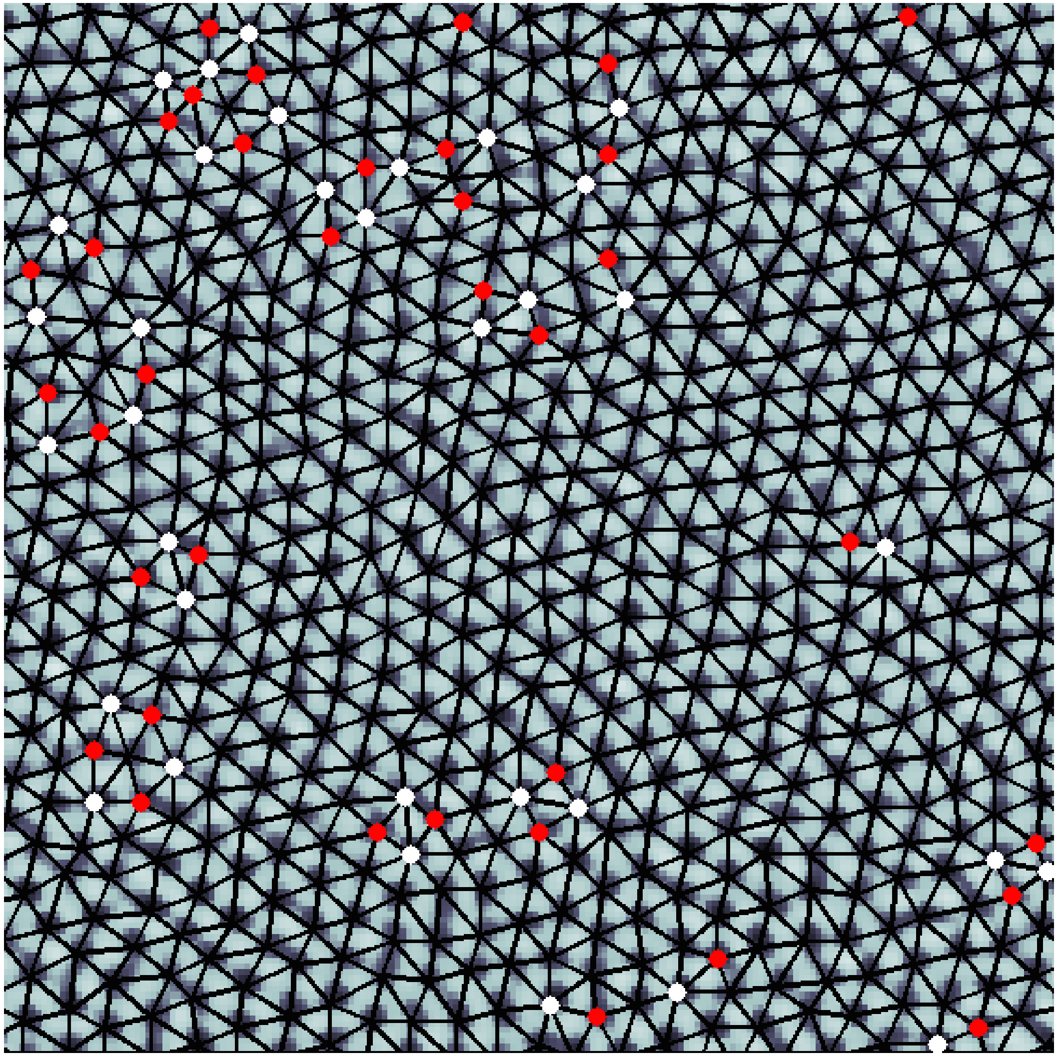


More Dislocations (Orientational Glass)

25 kOe

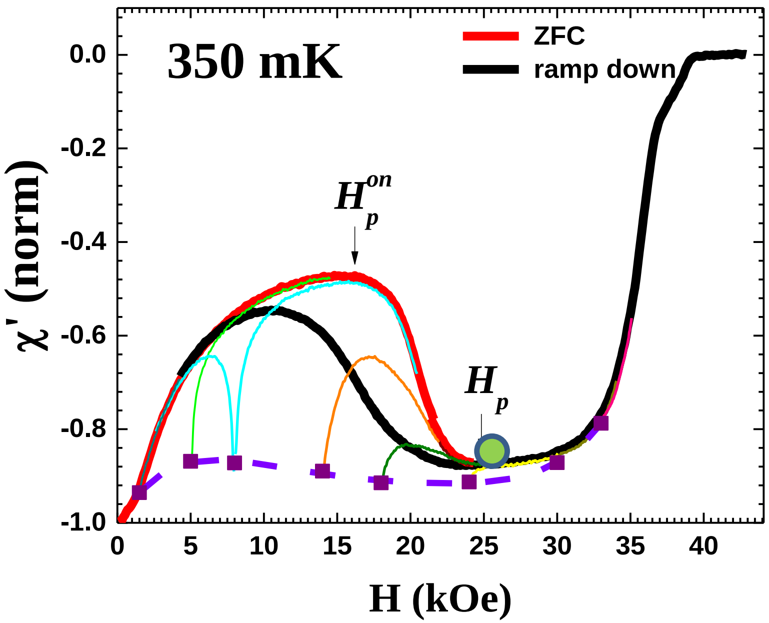


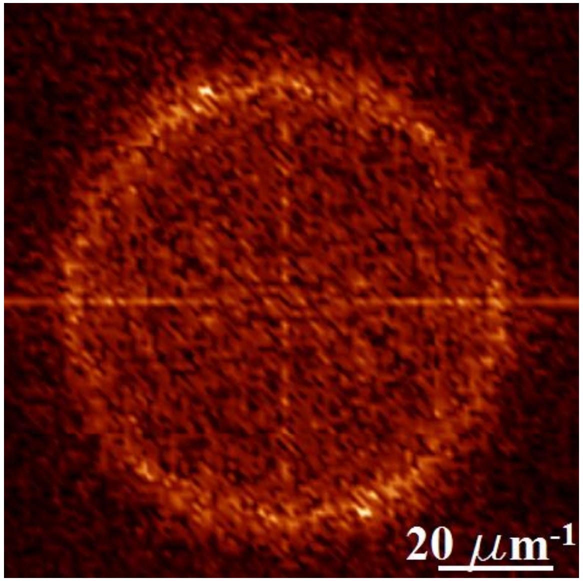


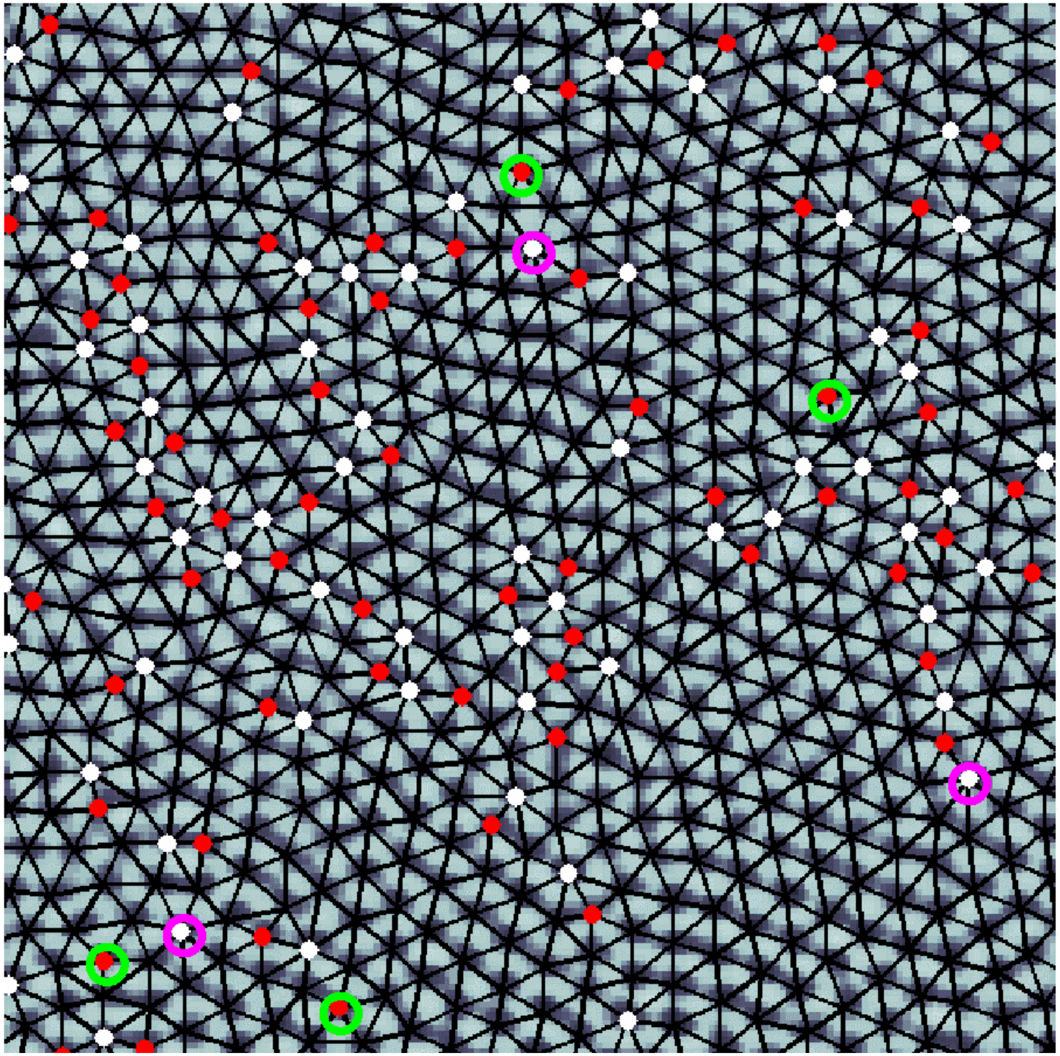


Disclinations appear (Vortex Glass)

26 kOe

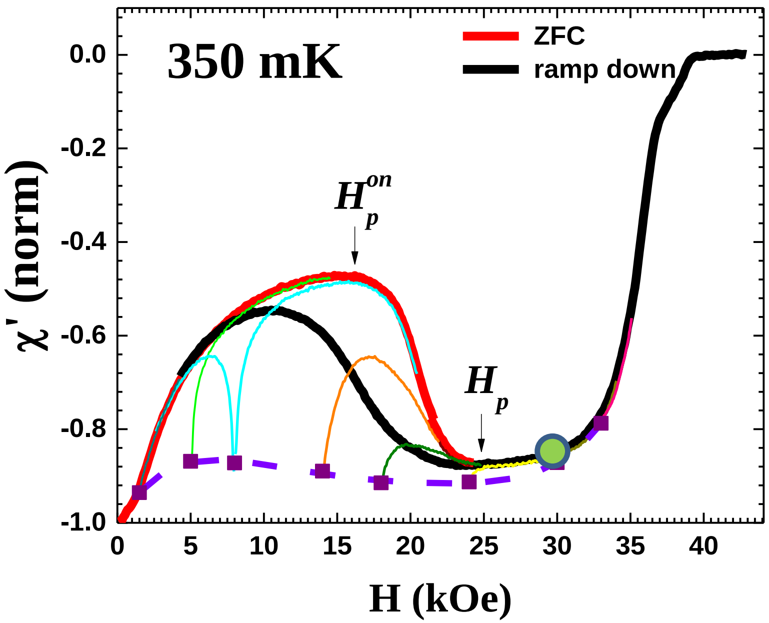


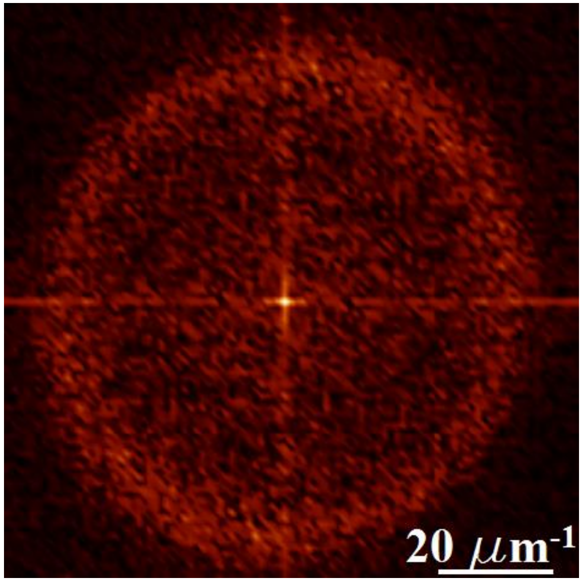


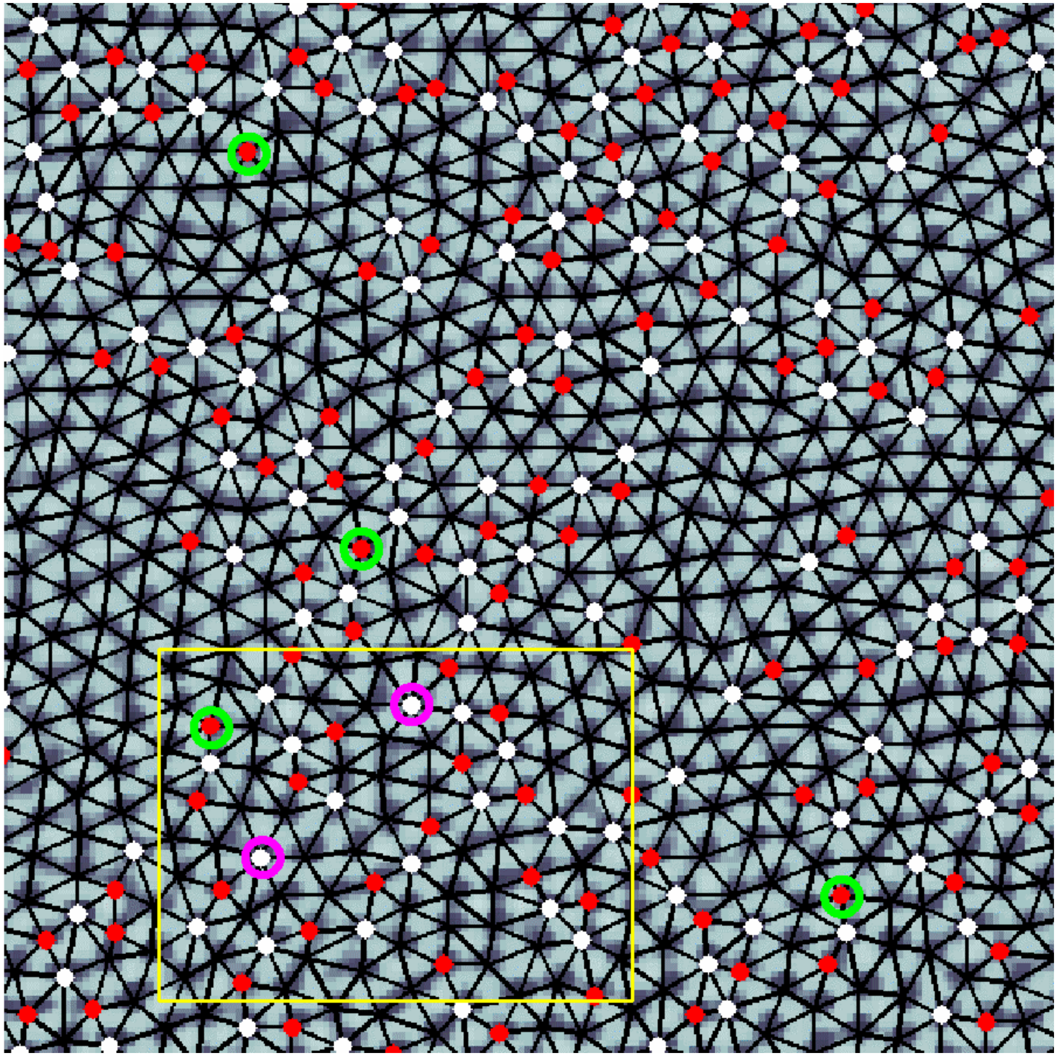


Disclinations appear (Vortex Glass)

30 kOe

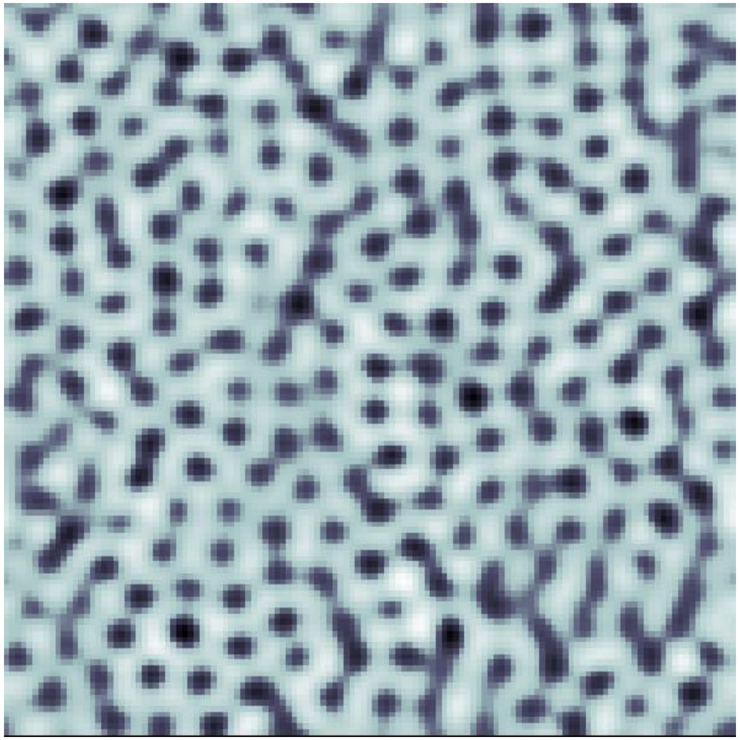




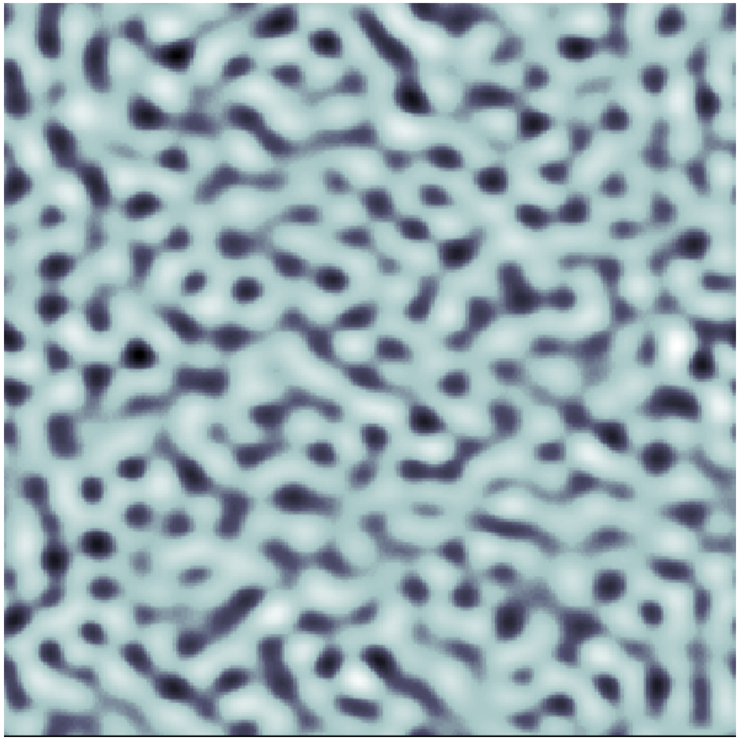


Movement of vortices: melting

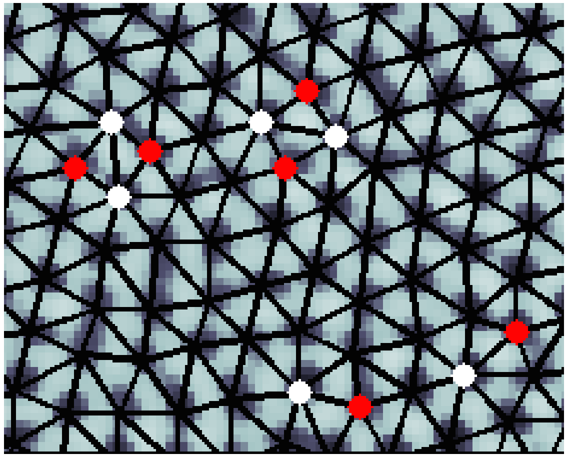
32 kOe



34 kOe

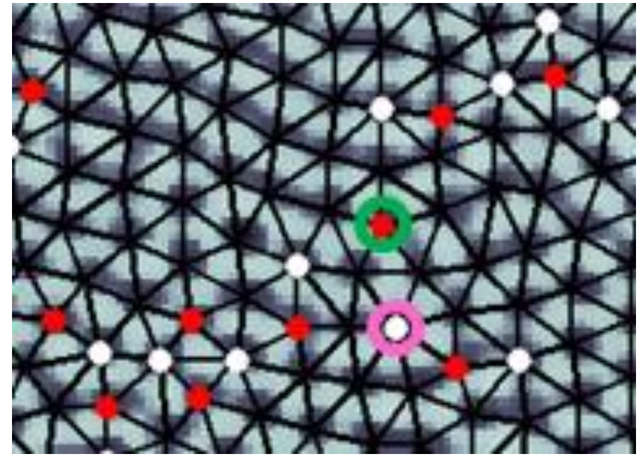


Dislocations



Destroys the long range positional order **but** does not destroy the long-range orientational order.

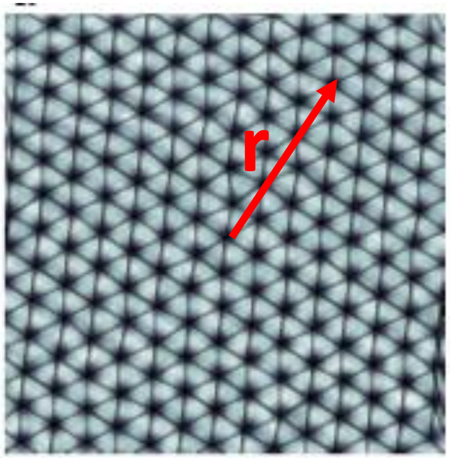
Disclinations

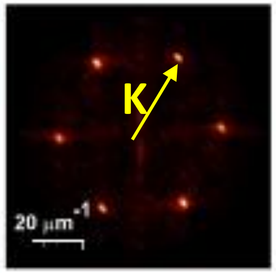


Destroys **both** long-range positional and orientational order.

Quantifying the positional and orientational order

Positional Order





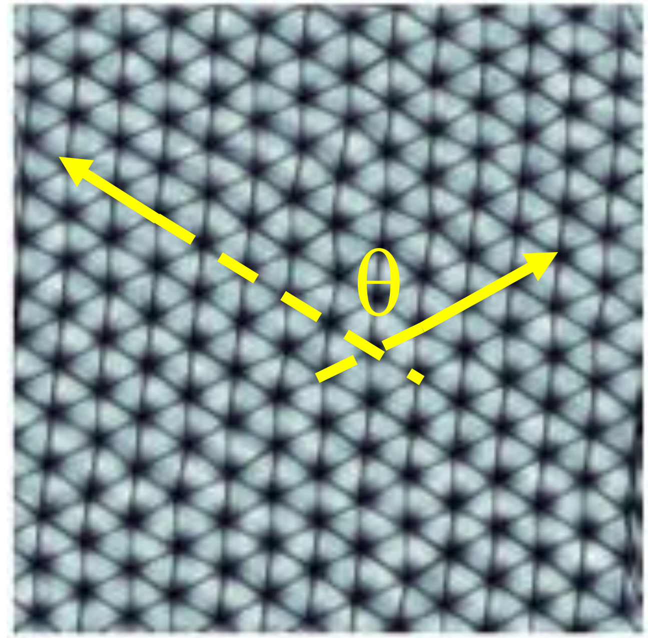
K – reciprocal lattice vector
r – any lattice vector

For a perfect lattice

$$\cos \bar{K} \cdot \bar{r} = 1$$

$$G_{\bar{K}}(r) = \langle \cos \bar{K} \cdot \bar{r} \rangle$$

Orientational Order



For a perfect lattice

$$\cos(6\theta) = 1$$

$$G_6(r) = \langle \cos 6(\theta(\bar{r}) - \theta(0)) \rangle$$

Solid, liquid and everything in between

Perfect order:

$$G_{\overline{K}}(r \to \infty) = 1$$

$$G_6(r \to \infty) = 1$$

Long Range order:

$$G_{\overline{K}}(r \to \infty) \to const$$

$$G_6(r \to \infty) \to const$$

Disorder:

$$G_{\overline{K}}(r \to \infty) = e^{-r/\xi_p}$$

$$G_6(r \to \infty) = e^{-r/\xi_{or}}$$

Quasi long range order

$$G_{\overline{K}}(r \to \infty) \propto 1/r^a$$

or

$$G_6(r \to \infty) \propto 1/r^b$$

Bragg Glass State

(Quasi long-range positional order)

$$G_{\overline{K}}(r \to \infty) \propto 1/r^a$$

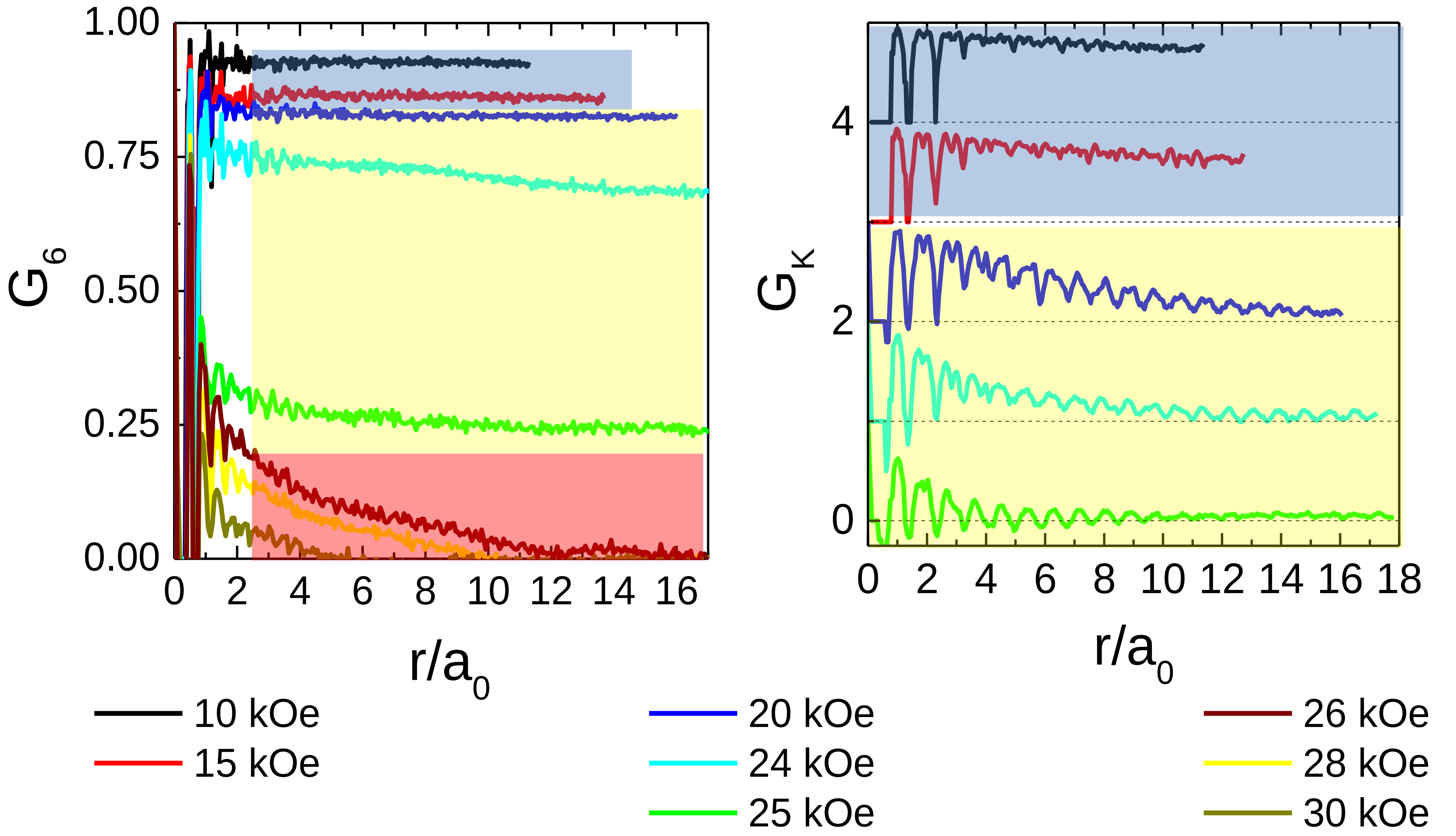
$$G_6(r \to \infty) \to const$$

Hexatic State

(Quasi long-range orientational order)

$$G_{\overline{K}}(r \to \infty) = e^{-r/\xi_p}$$

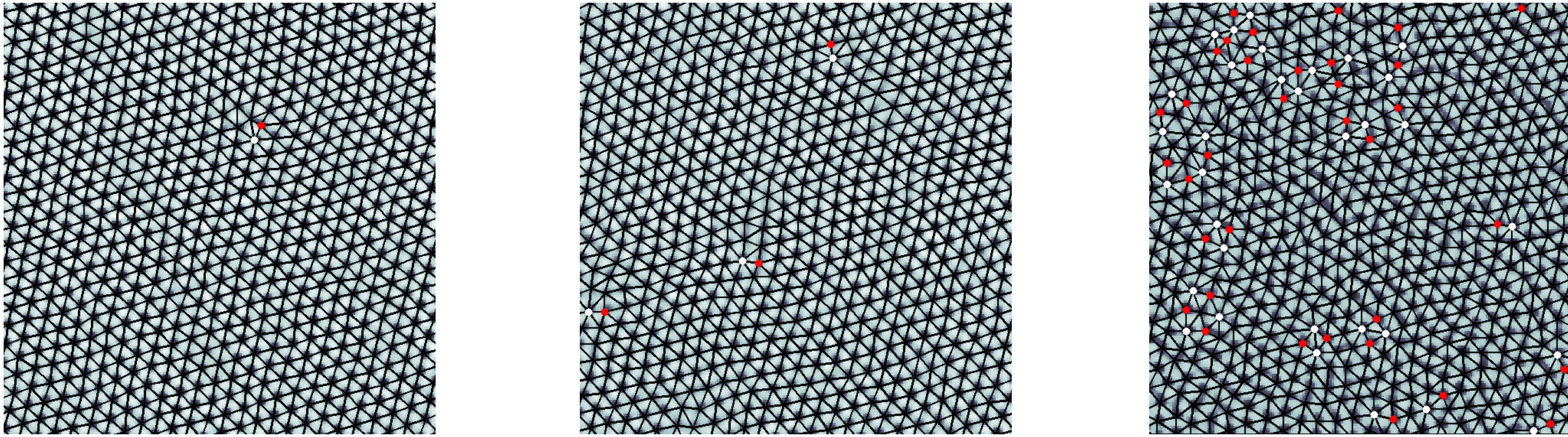
$$G_6(r \to \infty) \propto 1/r^b$$



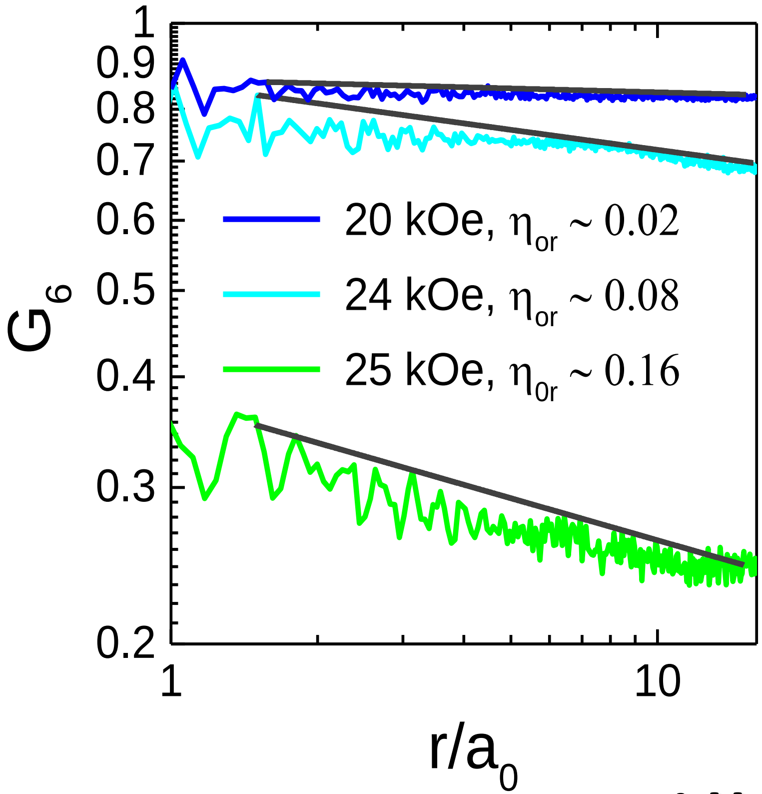
Ordered VL
Long range orientational order and slow decay of orientational order.

?
Slow decay of orientational order and fast decay of positional order

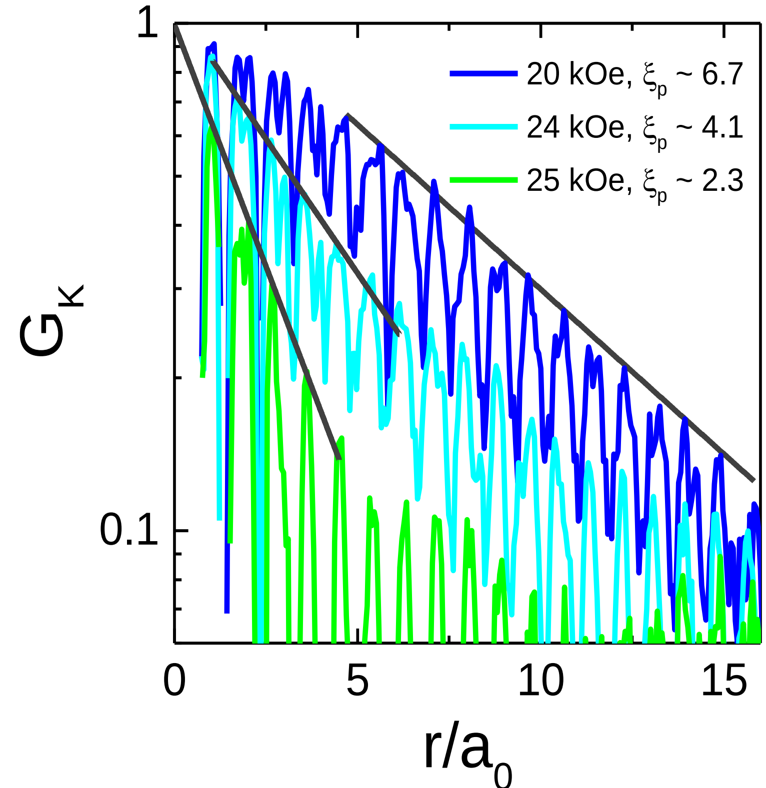
Vortex Glass
Exponential decay of (positional) and orientational order



(Quasi) long-range orientational order



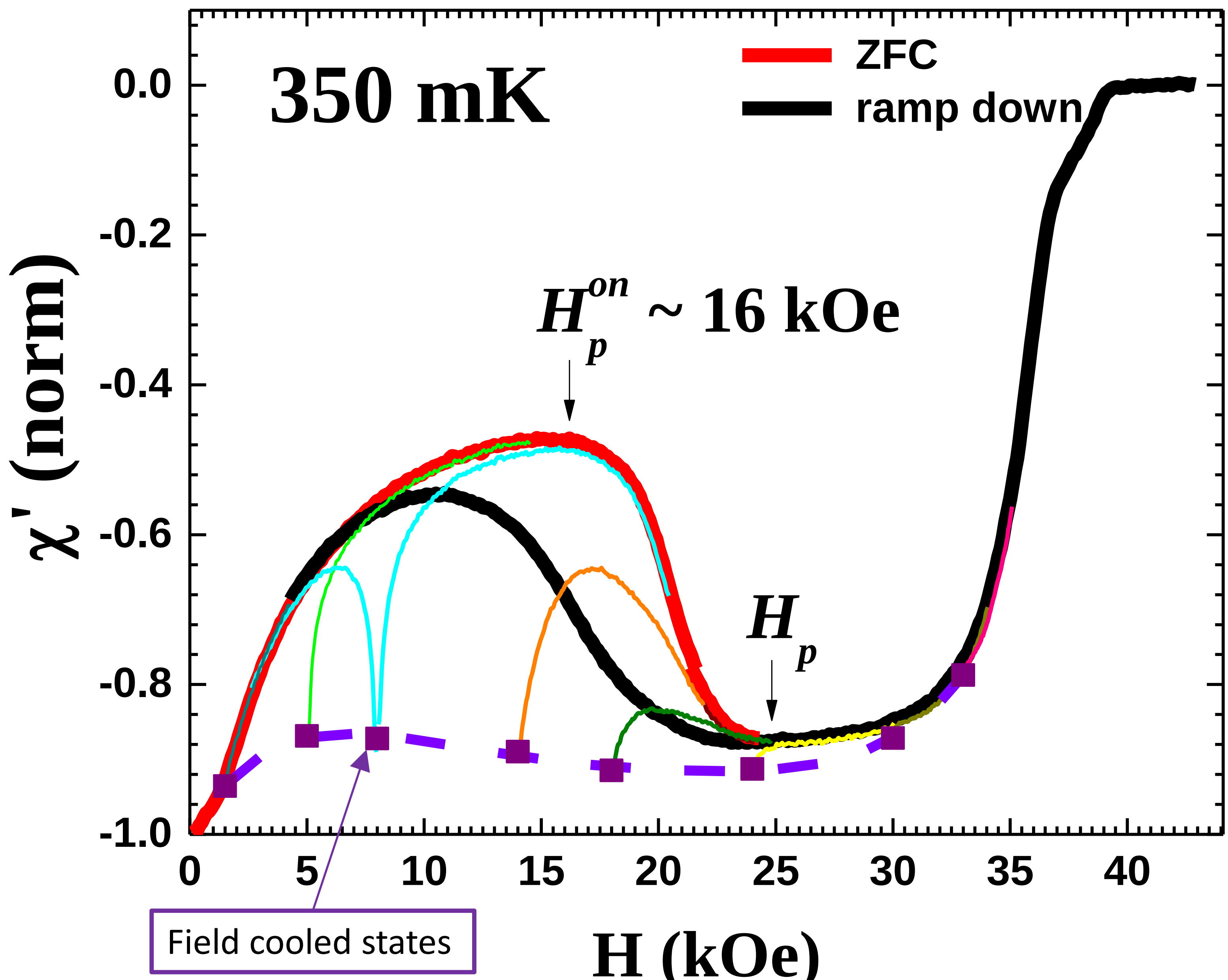
Short-range positional order



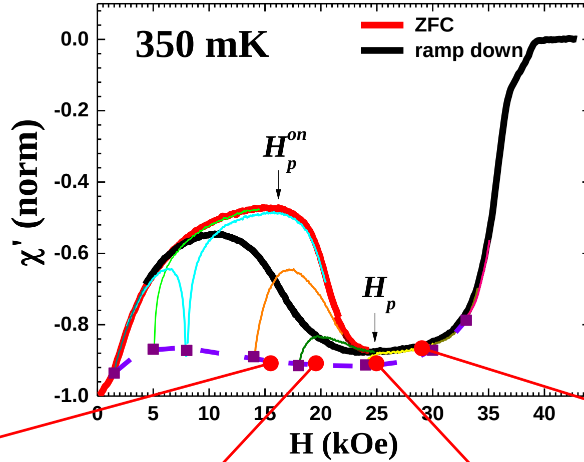
Orientational "Glass"

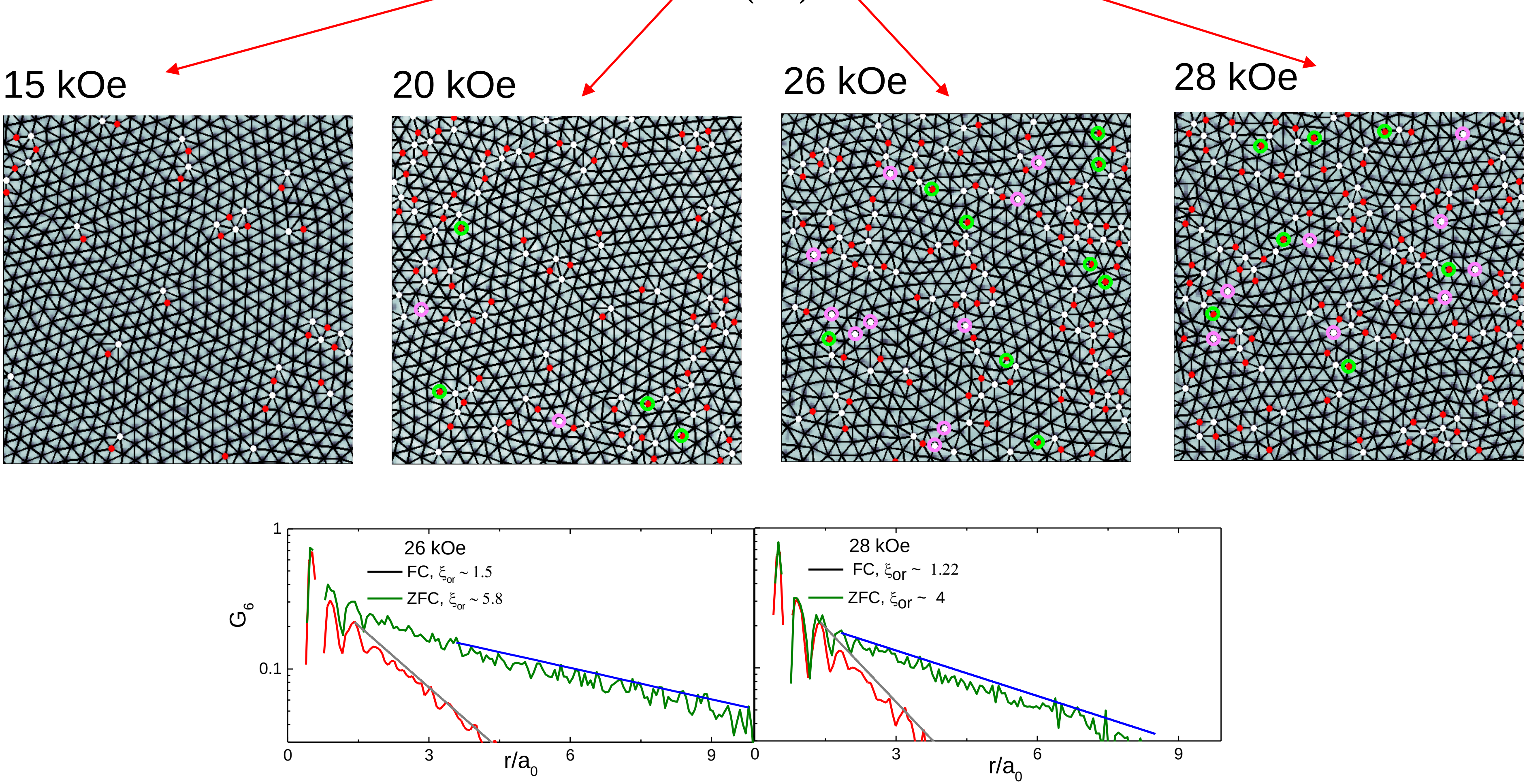
Hexatic State

The peak effect at 350 mK



The Field-cooled (metastable) states





Melting of a 2 dimensional crystal
(Berezinski, Kosterlitz, Thouless, Halperin, Nelson, Young)

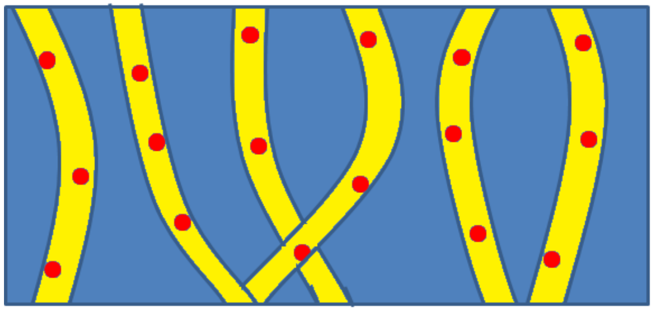
A 2D hexagonal crystal (under certain conditions) **can** melt through 2 continuous phase transitions.

At the 1st transition **dislocations** proliferate in the system creating an oriented fluid: The hexatic state. (Nematic state for liquid crystals.)

At the 2nd transition the **dislocations** dissociate into isolated disinclination creating an isotropic liquid.

Difference with our system

- **Three dimensional vortex lattice**
- **The presence of random pinning potential**
- No logarithmic interaction between vortices

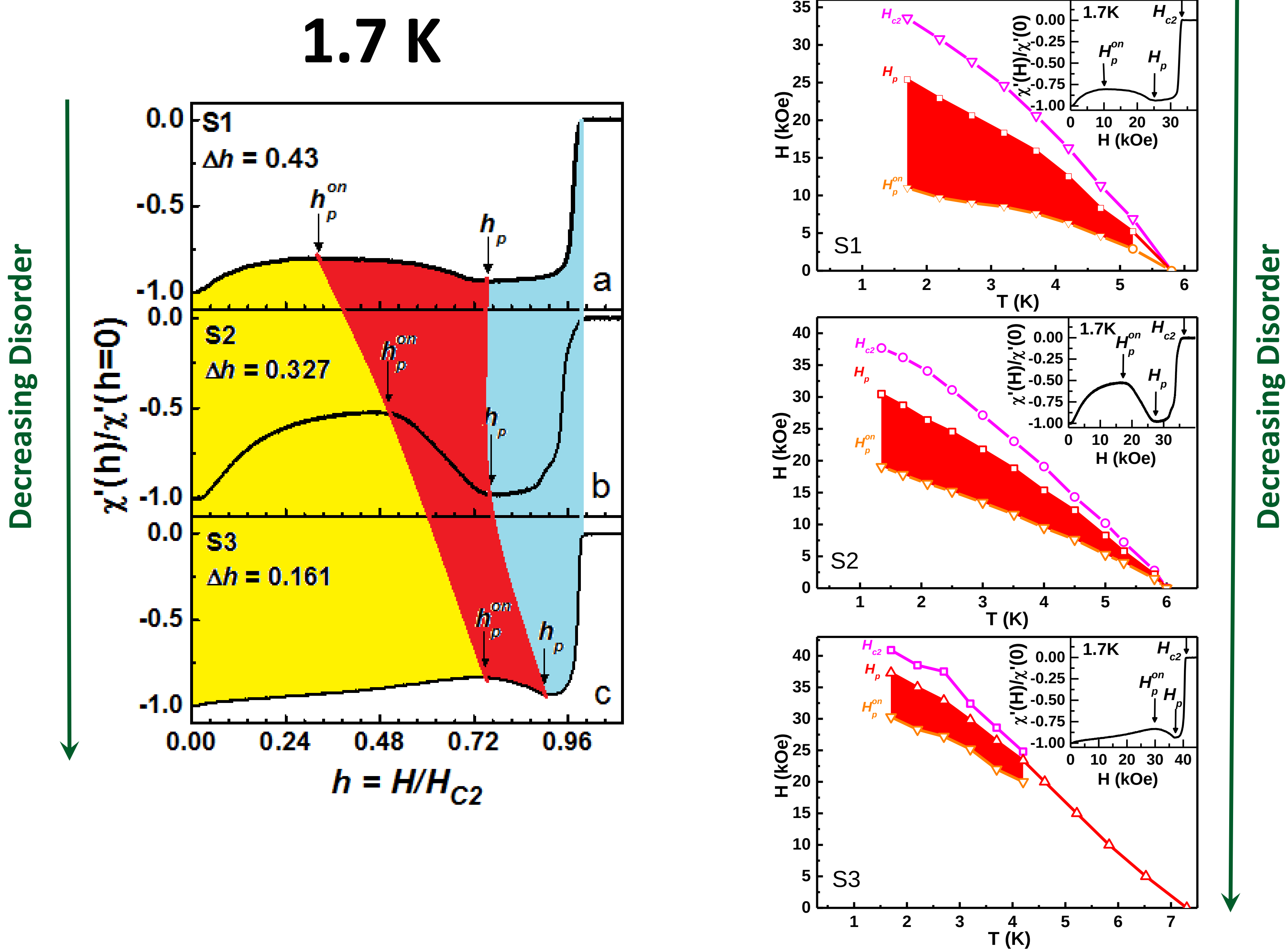


Two routes to *order to disorder* transition

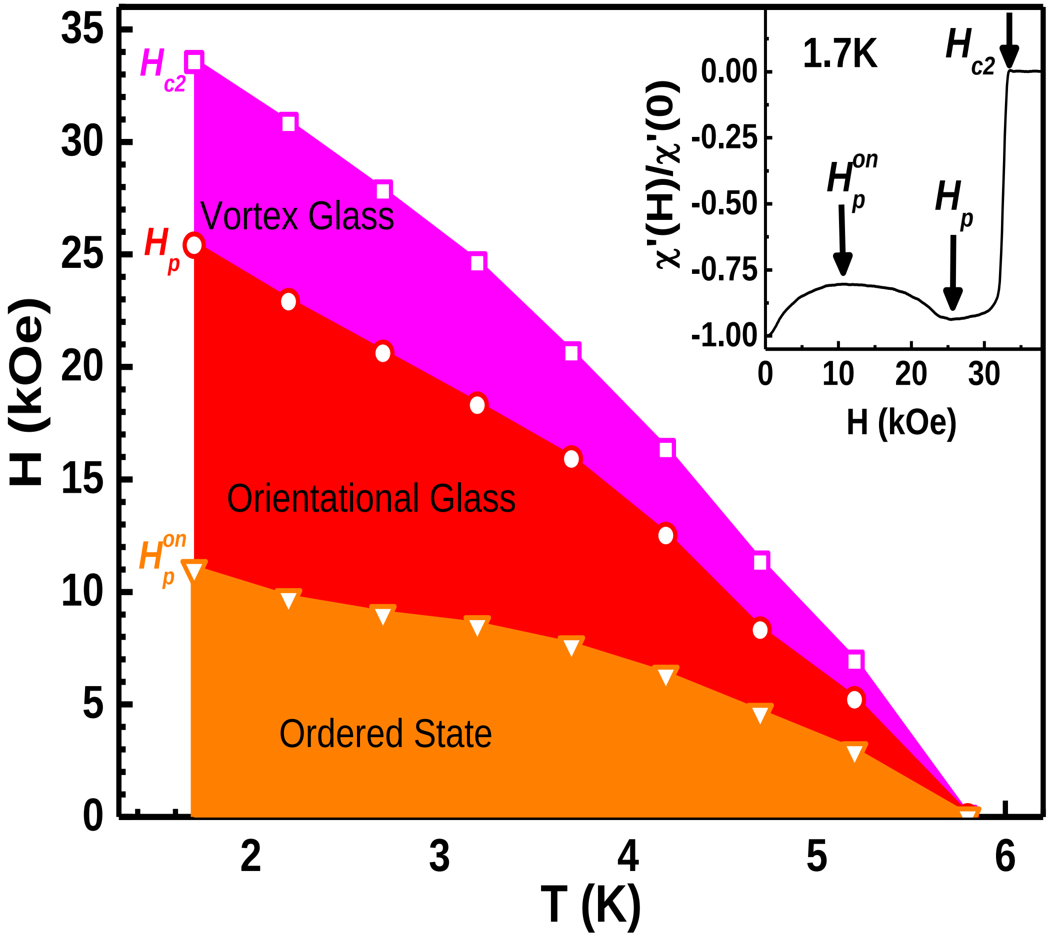
Conventional (thermal) melting

Disorder induced "melting": The melting is driven by the increase in positional entropy due to random potential

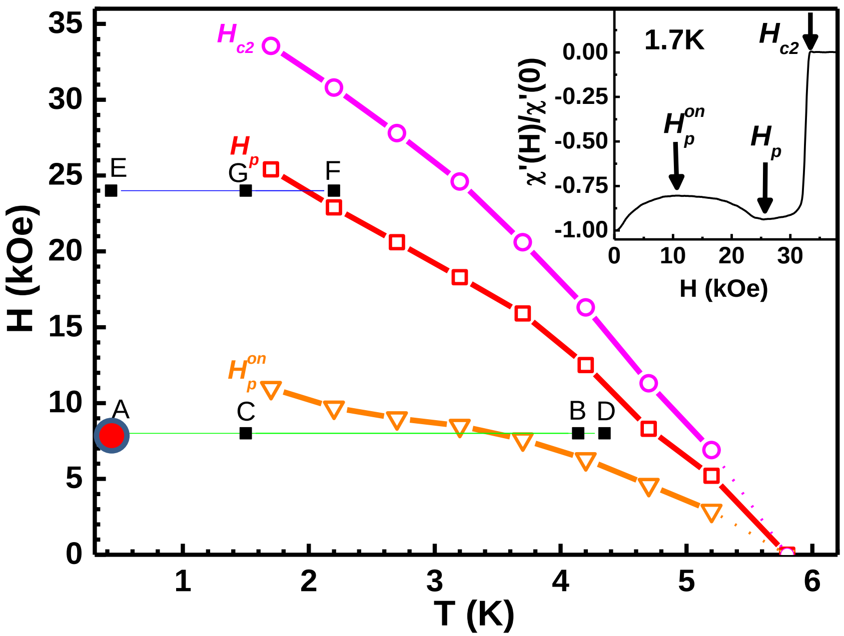
V. Vinokur et al, Physica C 295, 209 (1998)



1.7 K
Decreasing Disorder
S1
Δh = 0.43
S2
Δh = 0.327
S3
Δh = 0.161
a
b
c
χ'(h)/χ'(h=0)
h = H/HC2
T (K)
H (kOe)
1.7K
χ'(H)/χ'(0)
S1
S2
S3
Decreasing Disorder

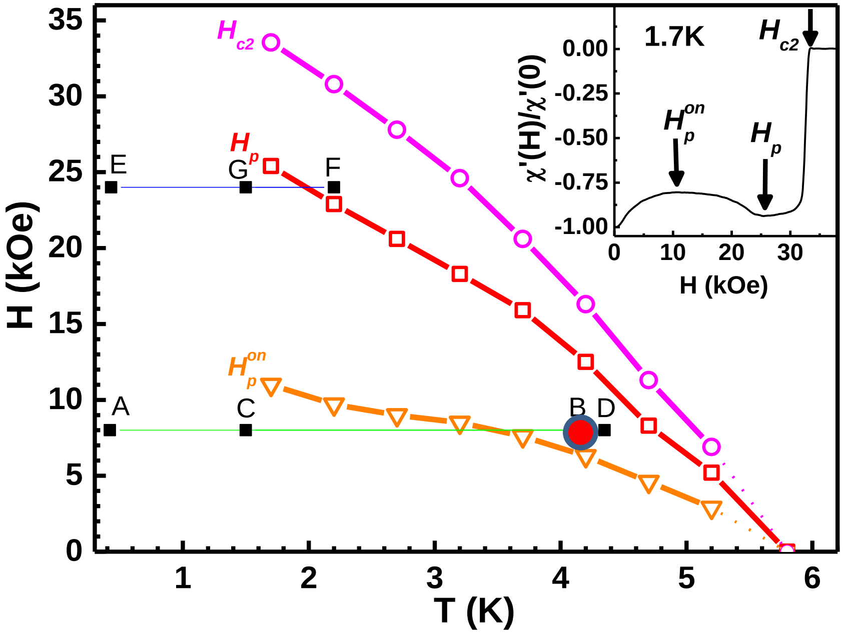


Are these 1st order phase transitions?

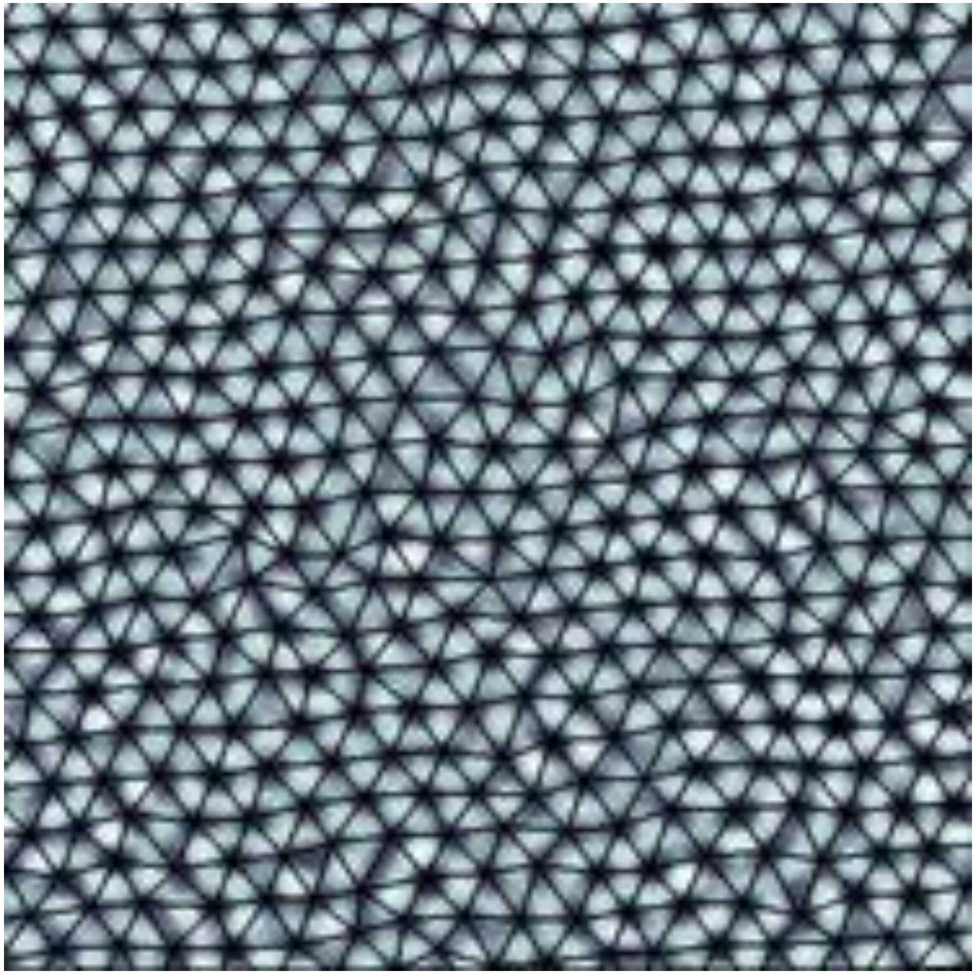


ZFC(420 mK) at 8 kOe

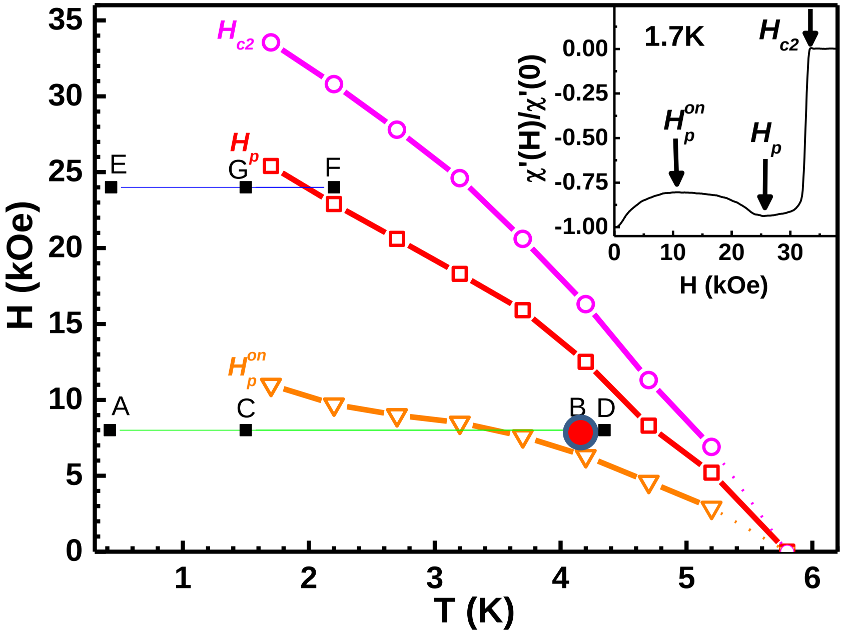
Ordered State



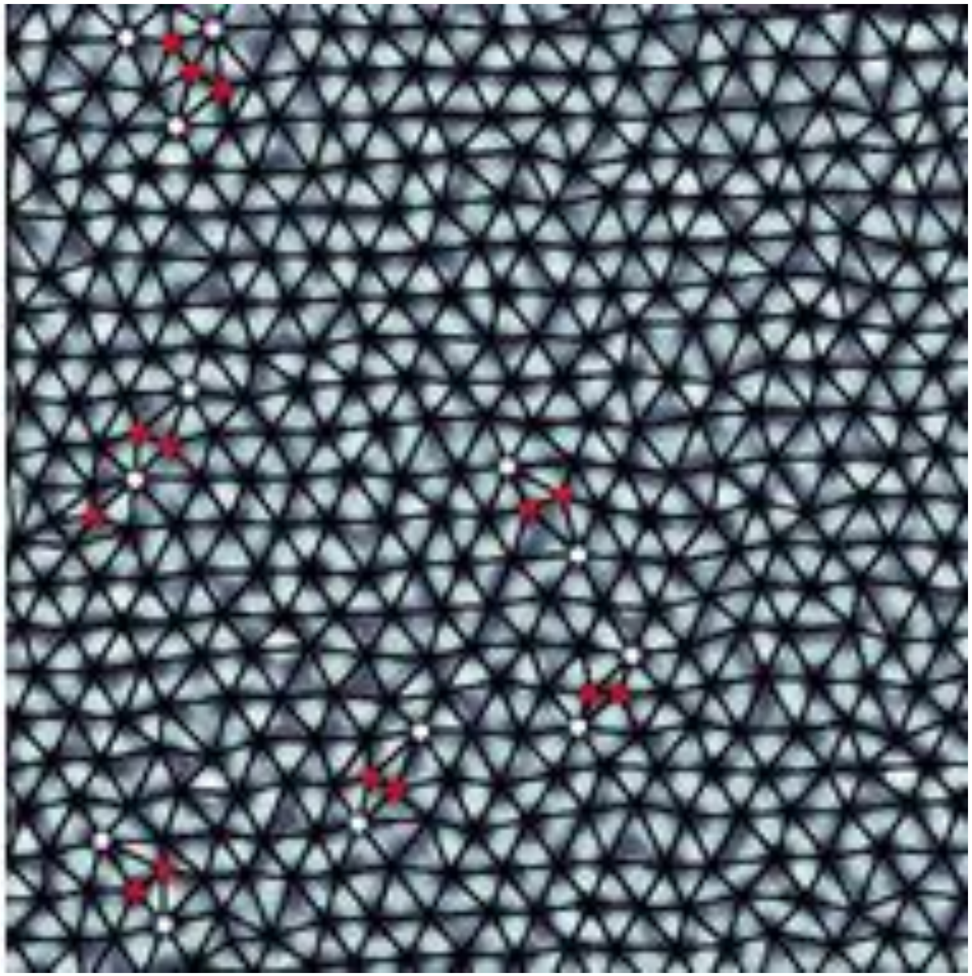
4.14 K



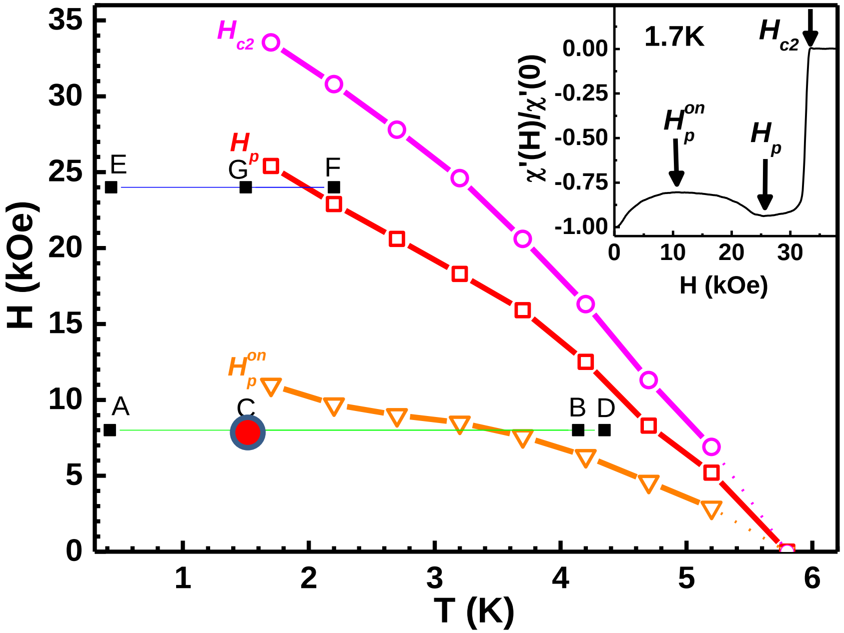
(Metastable) Ordered State



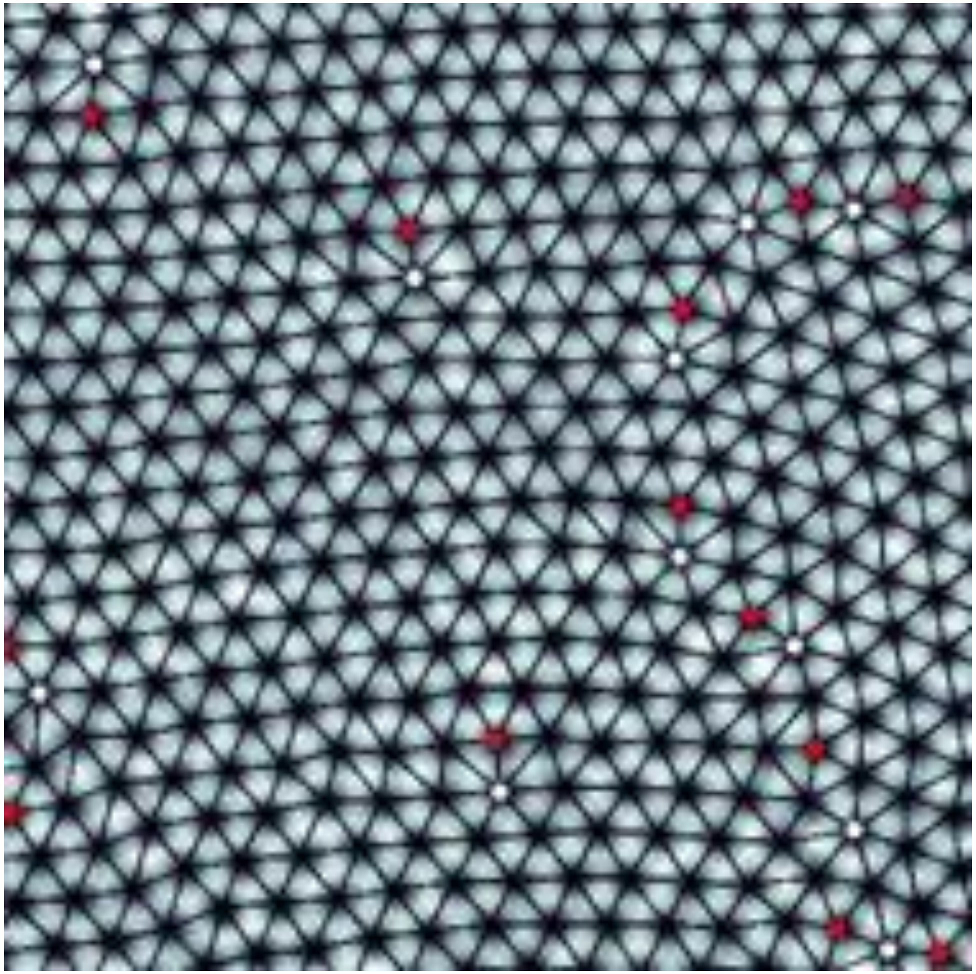
4.14 K + pulse



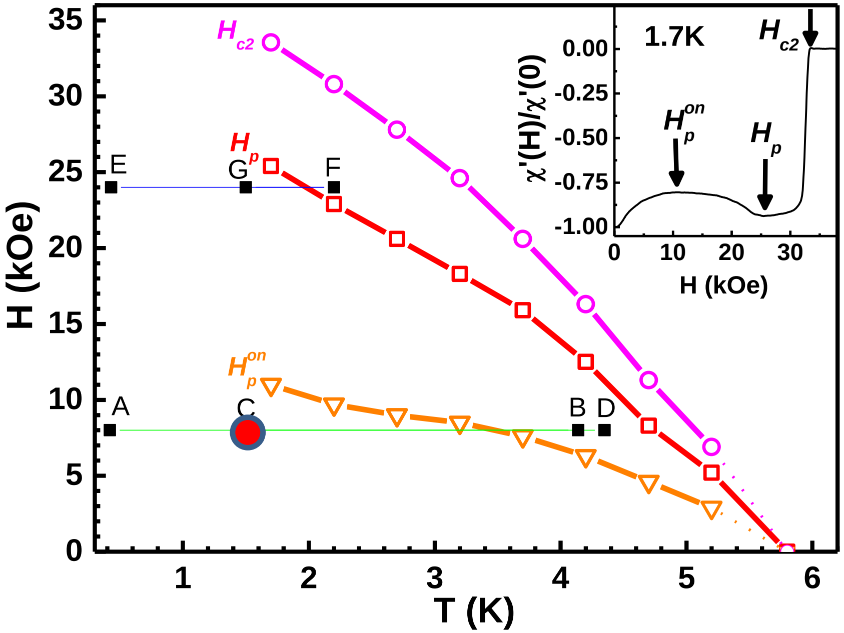
Orientational Glass



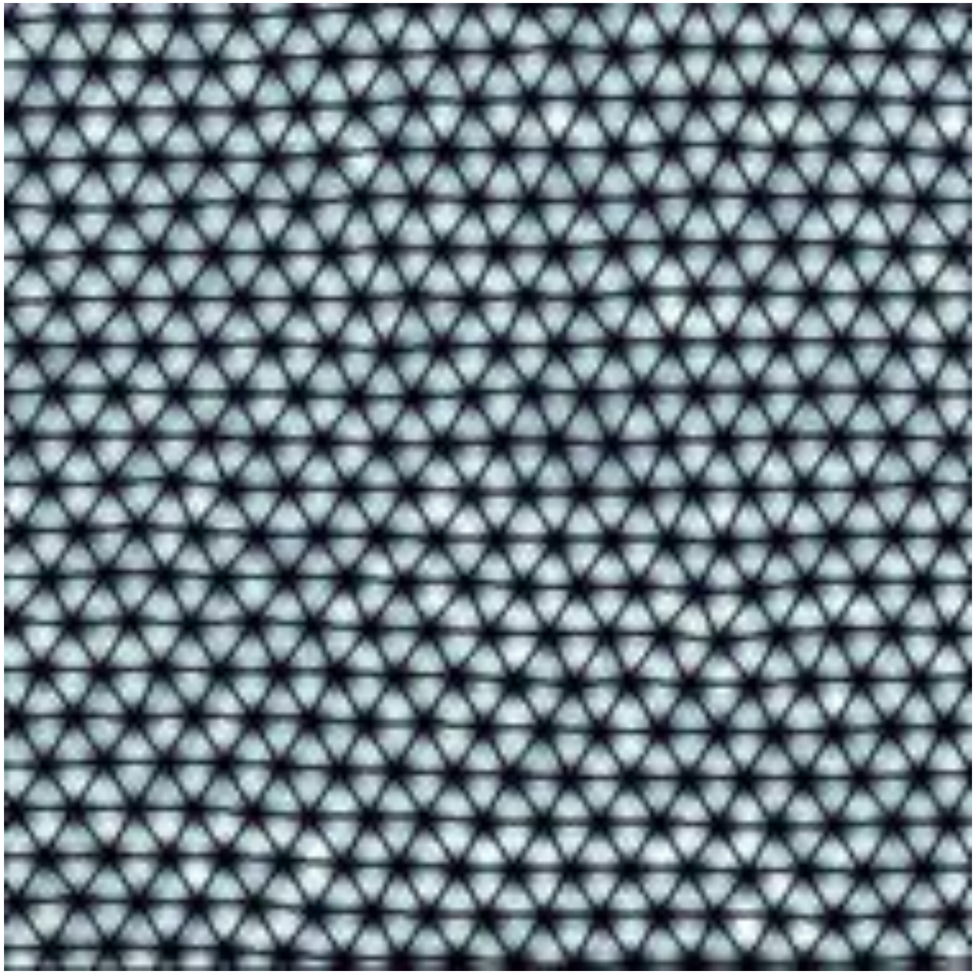
Cooled to 1.6 K



(metastable) Orientational Glass



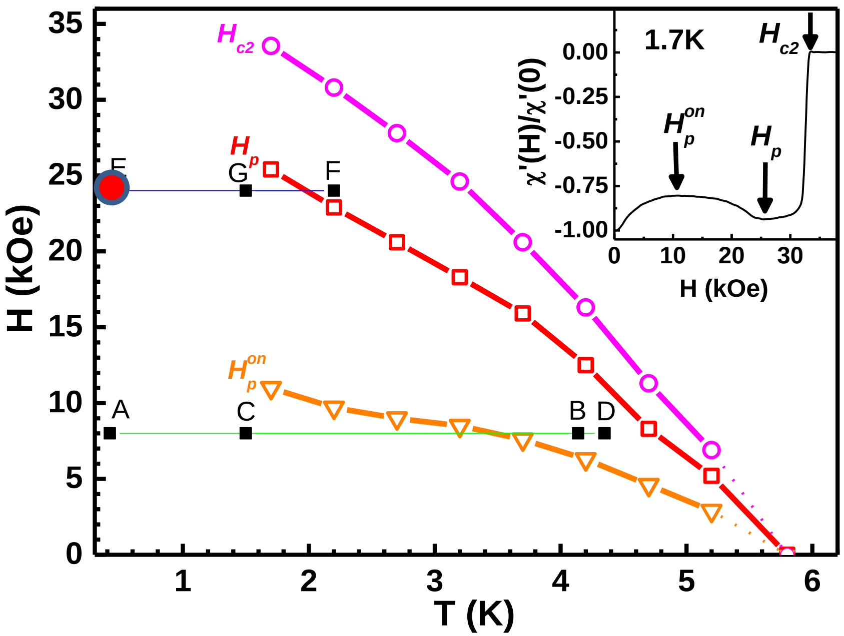
1.6 K + pulse

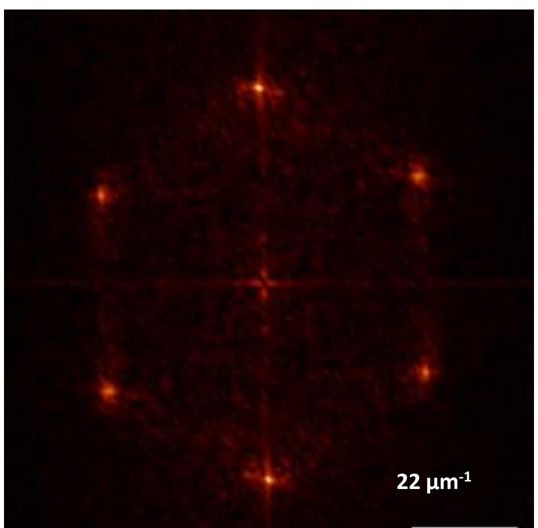


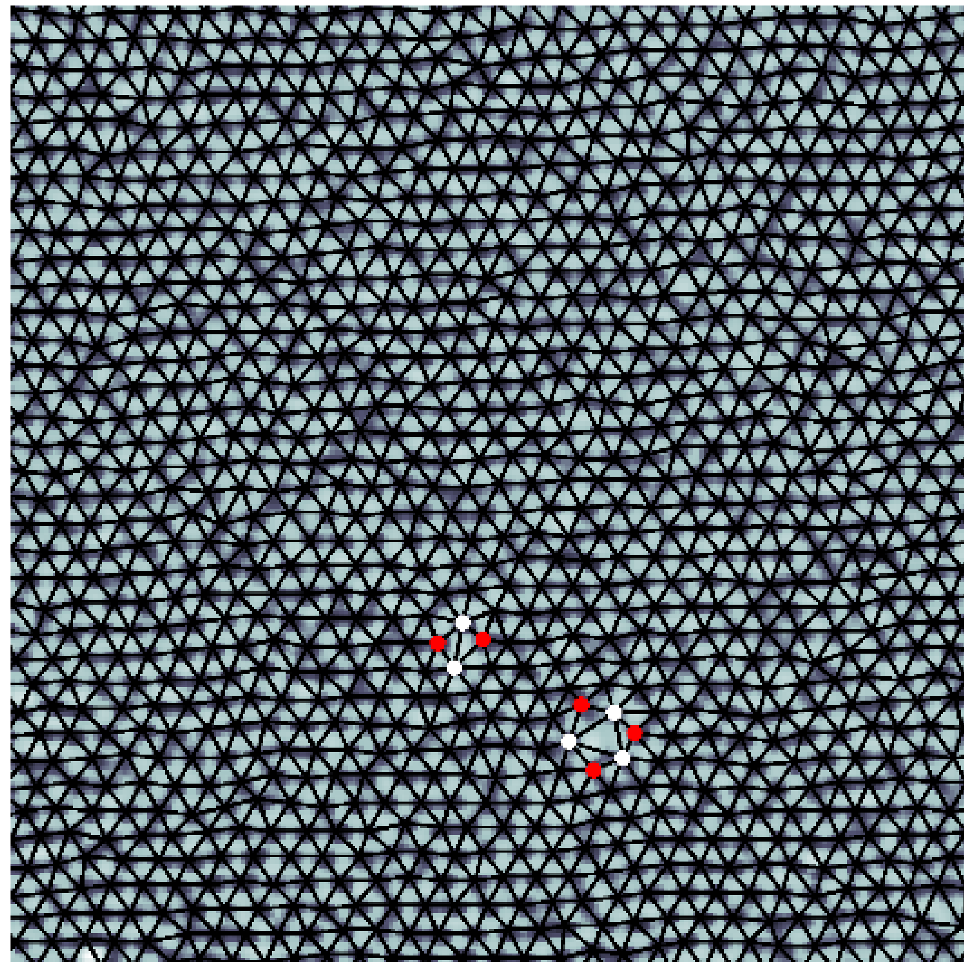
Ordered State

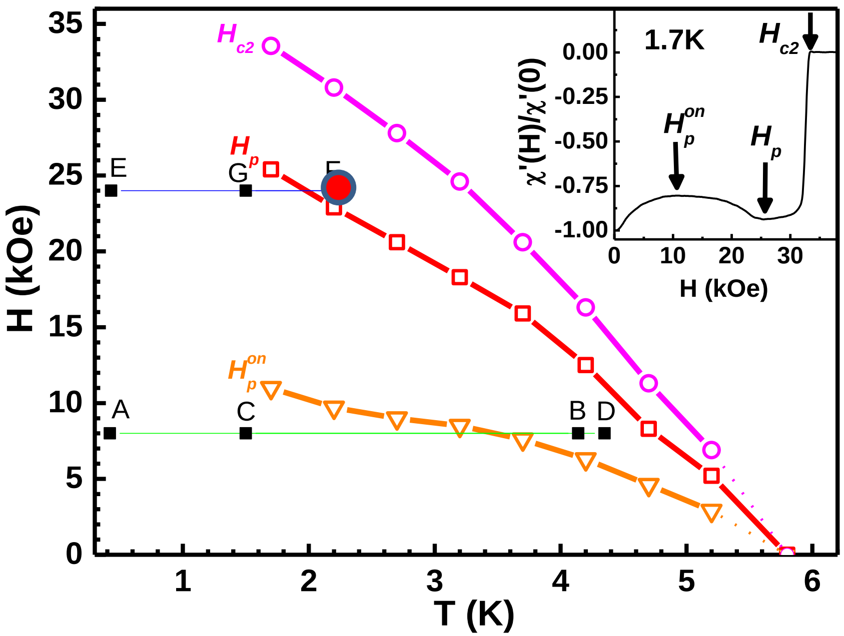
Orientational Glass

ZFC (420 mK) at 24 kOe



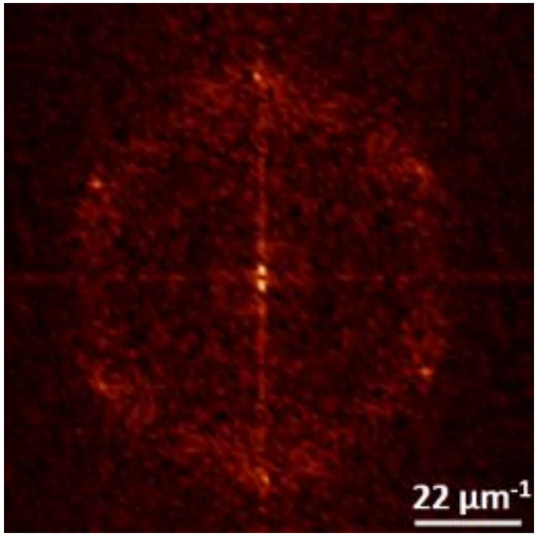


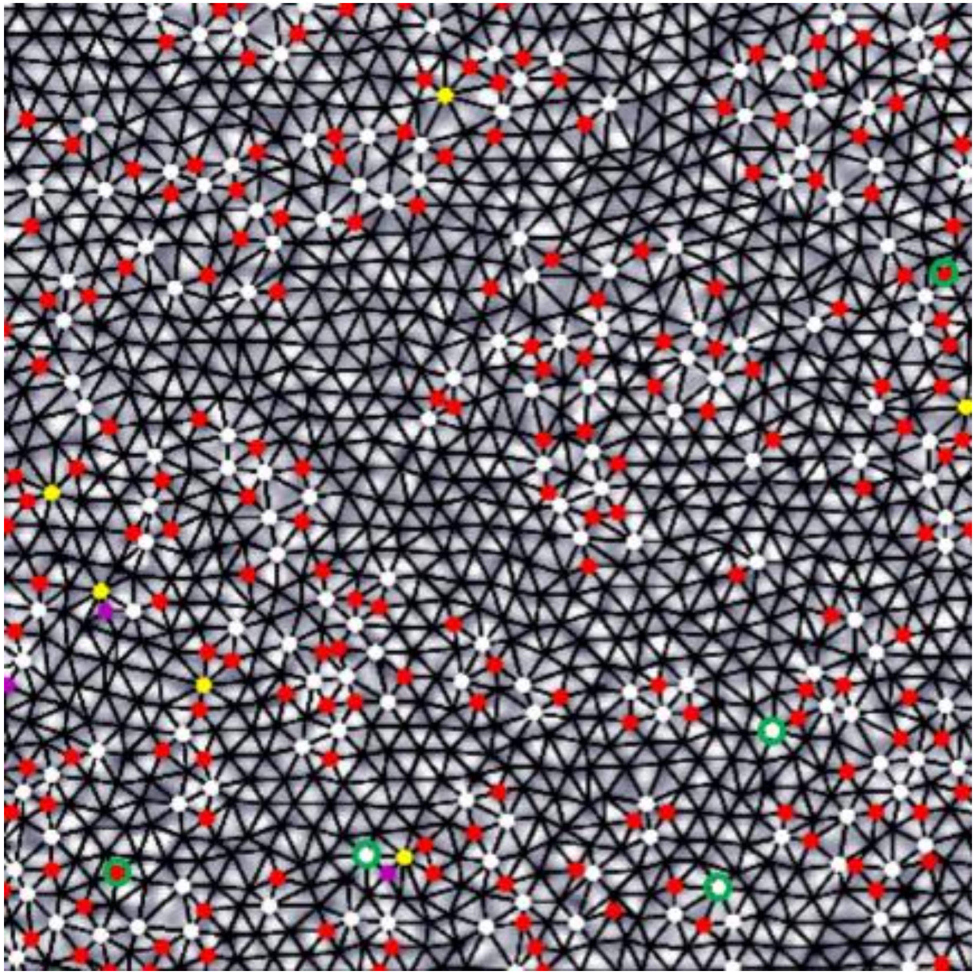




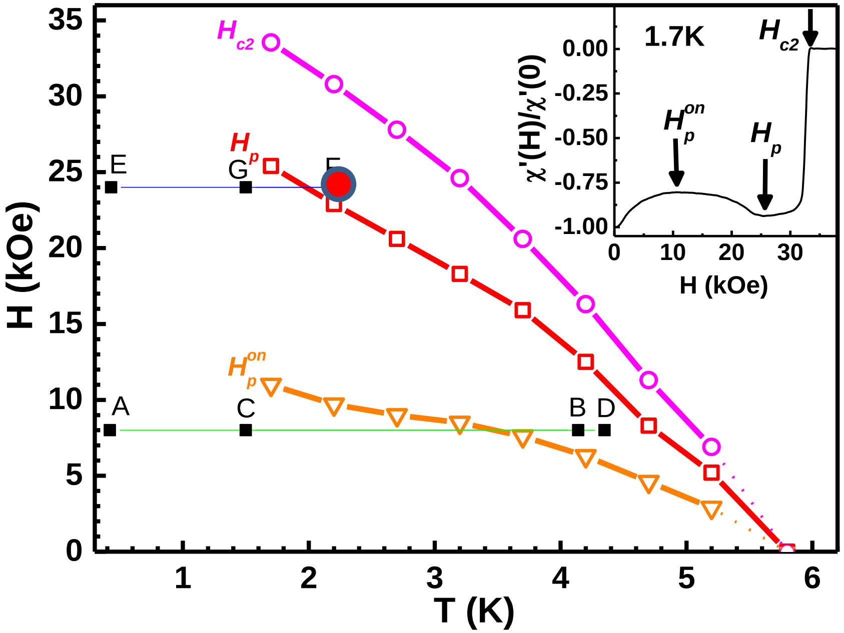
(metastable)
Orientational Glass

2.2 K

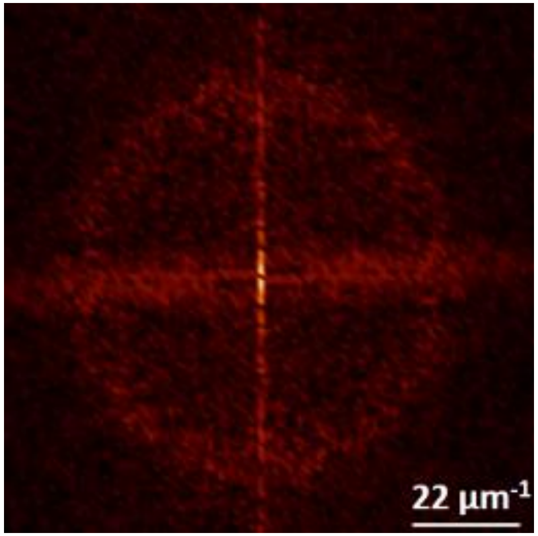


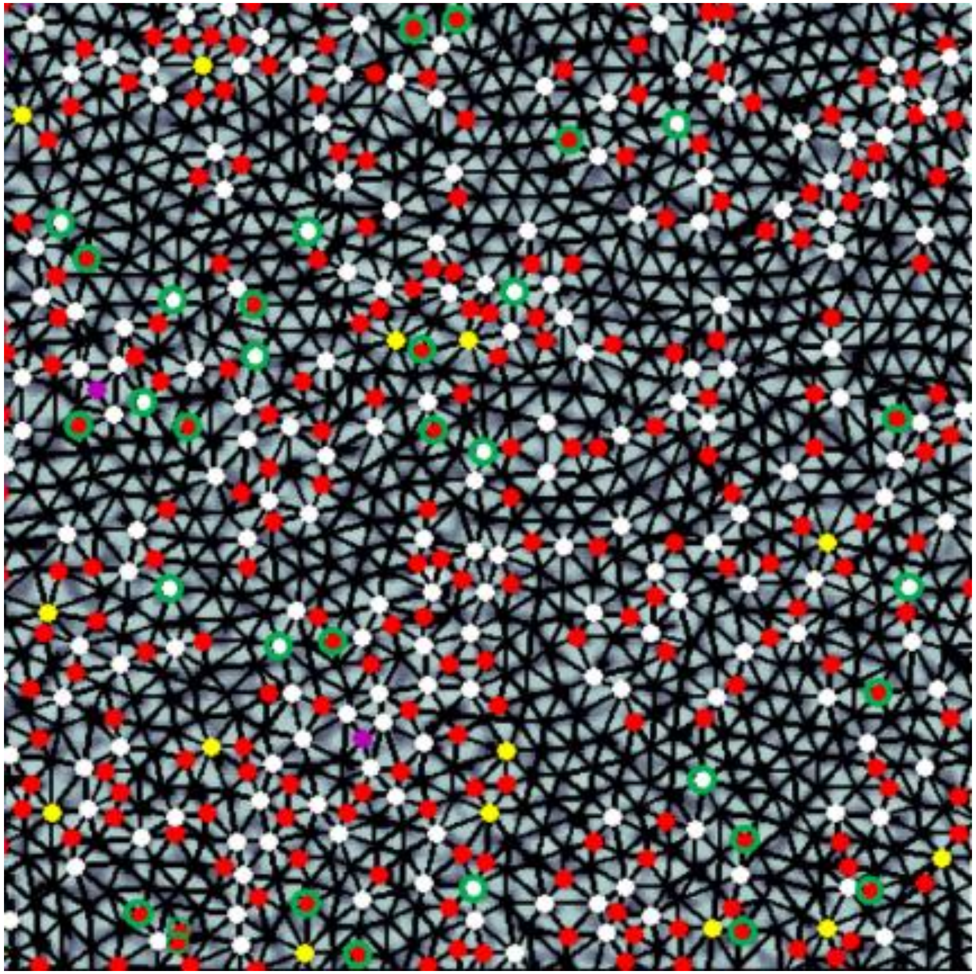


Vortex Glass

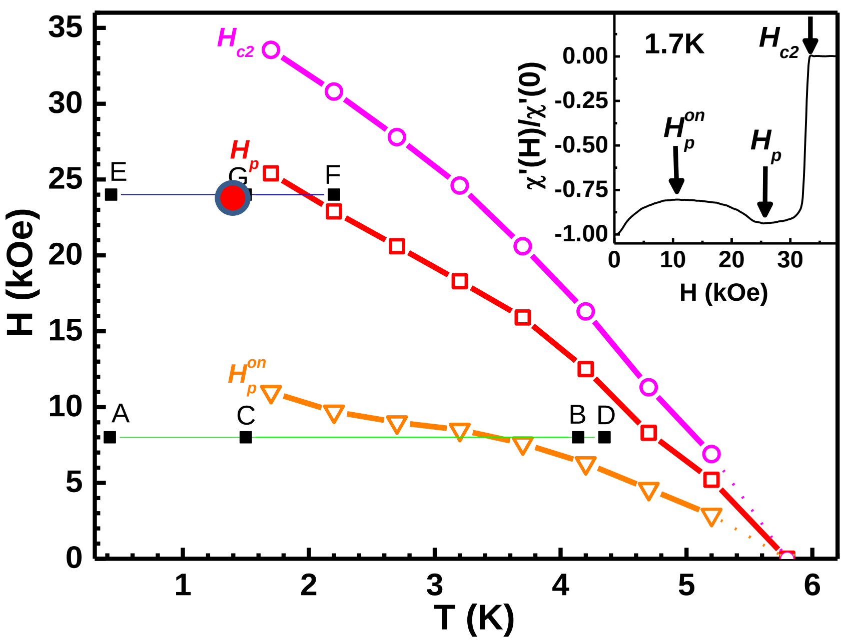


2.2 K + pulse

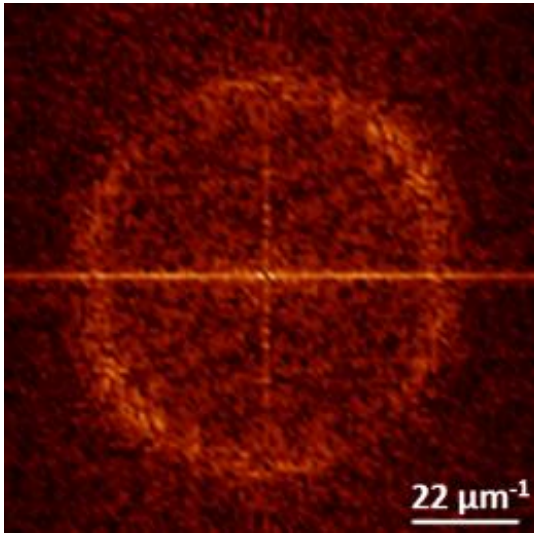


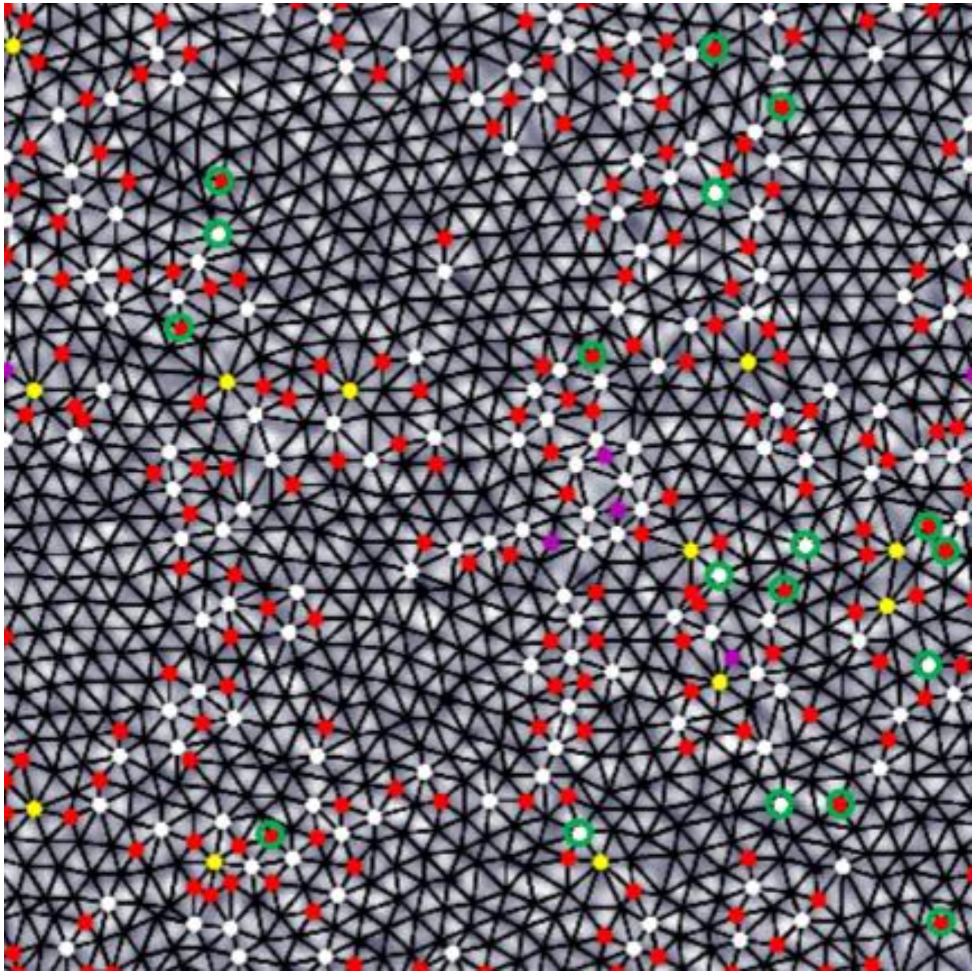


Vortex Glass

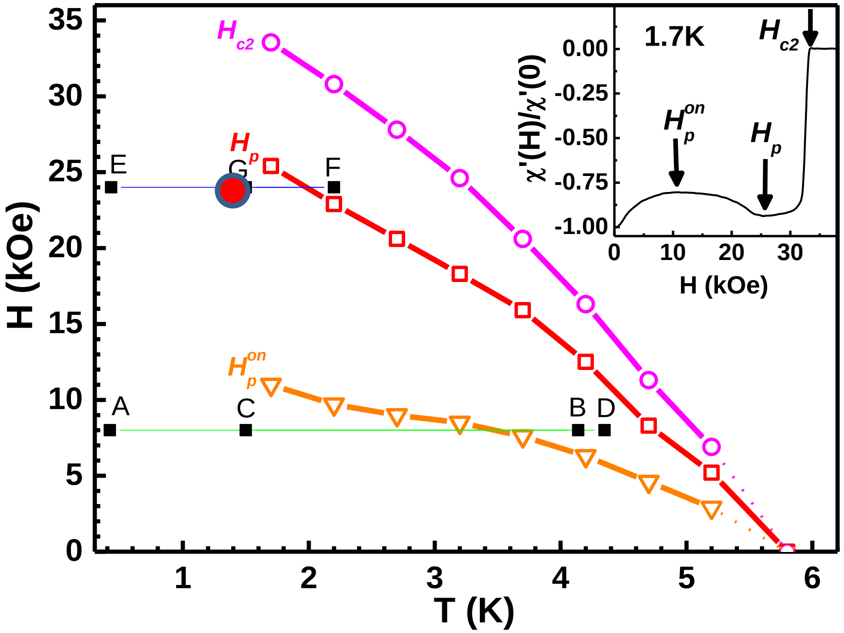


1.6 K

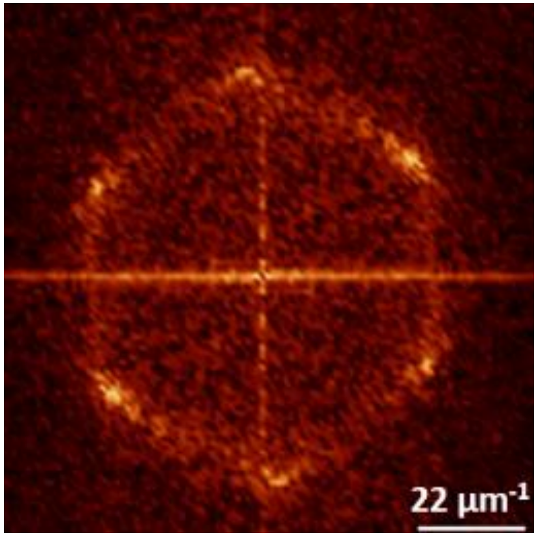


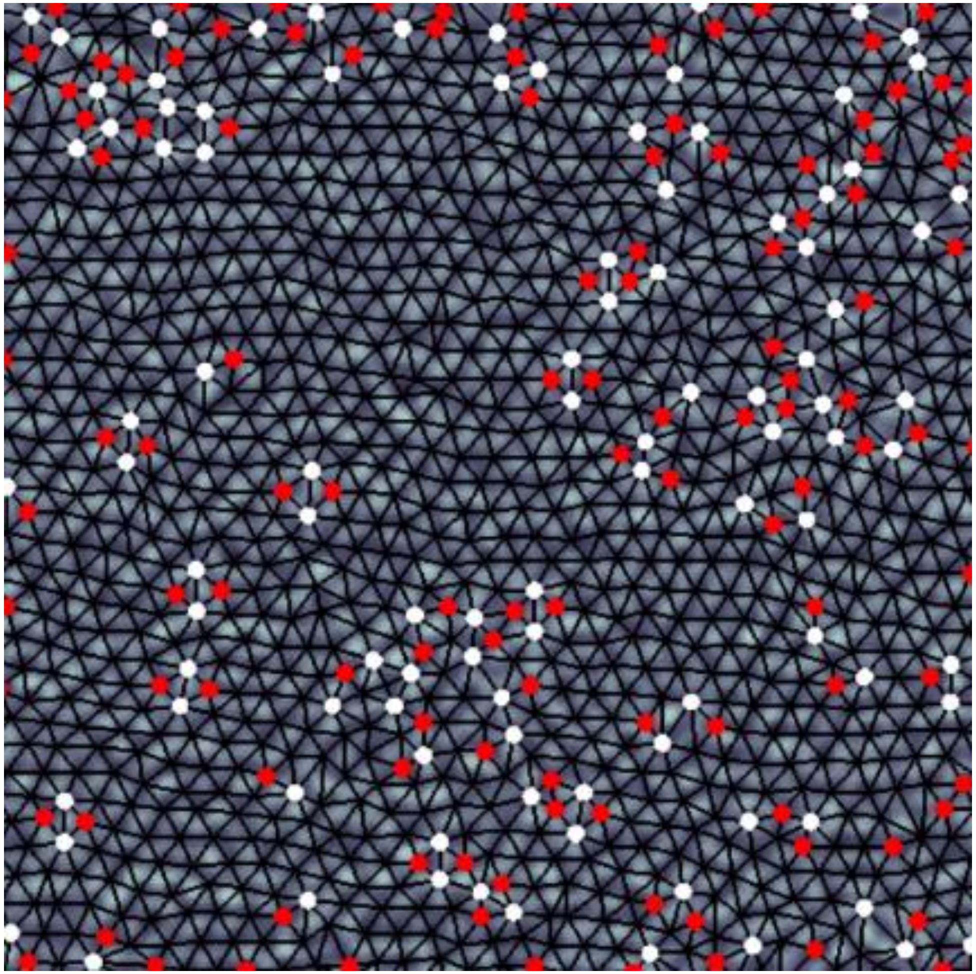


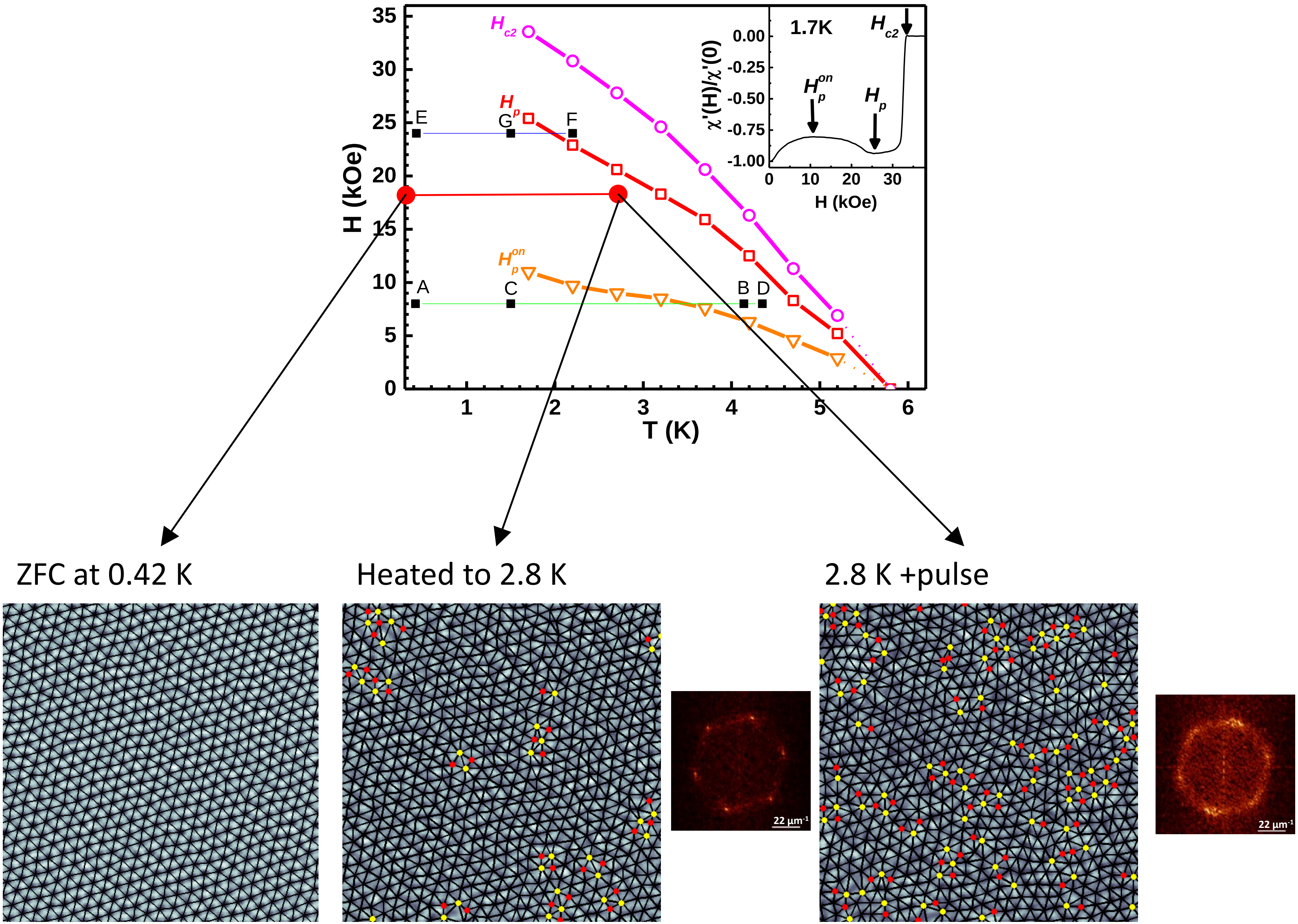
Vortex Glass



1.6 K + pulse

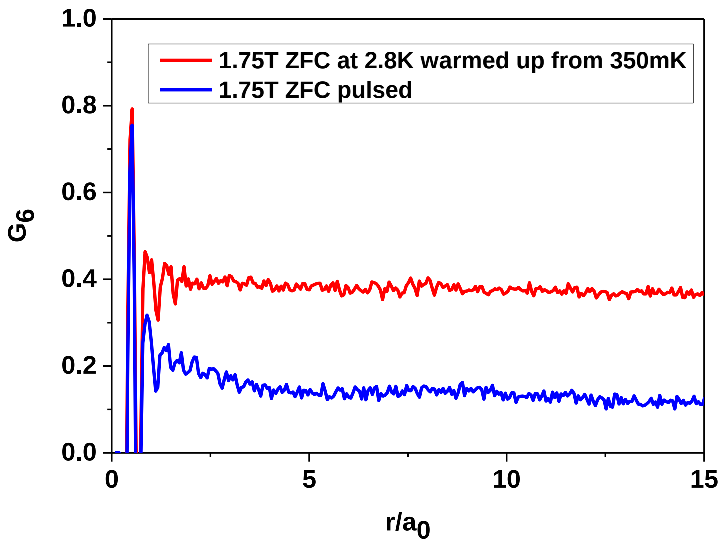




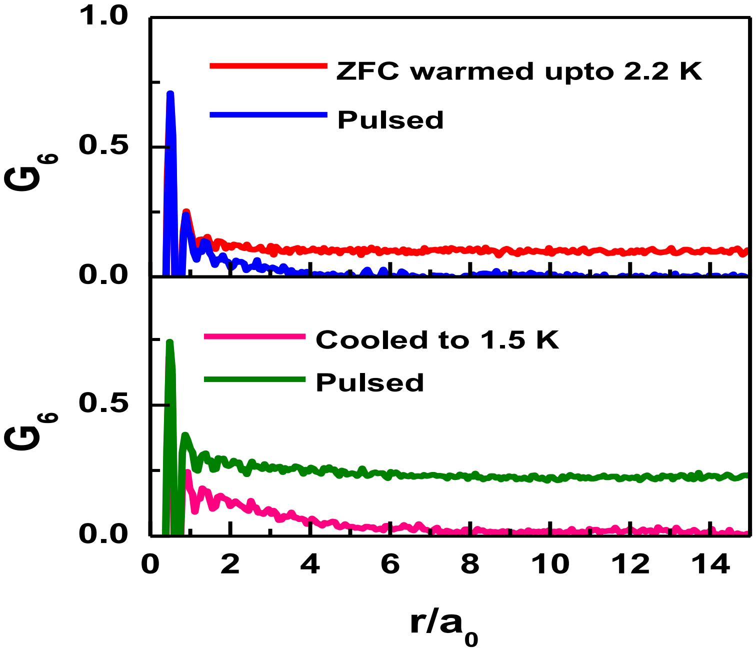


H (kOe)
T (K)
H_{c2}
H_p
H_p^{on}
A
B
C
D
E
F
G
1.7K
$\chi'(H)/\chi'(0)$
H (kOe)
ZFC at 0.42 K
Heated to 2.8 K
2.8 K +pulse
22 μm⁻¹
22 μm⁻¹

Orientational Correlation function G_6 before and after pulsing **without crossing a phase boundary.**



Orientational Correlation function G_6 before and after pulsing **for the superheated and supercooled state.**



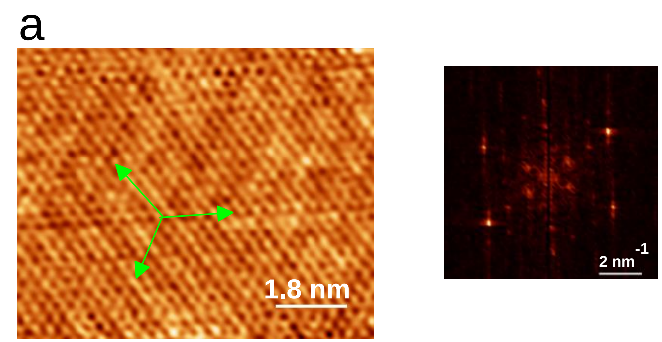
Summary

- The nature of order-disorder fundamentally changes in the presence of a random pinning potential.
- The 3-D vortex lattice in weakly pinned $NbSe_2$ disorders through successive proliferation of dislocations and disclinations.
- The orientational order of the vortex persists well above the onset of the peak effect and even above the peak of the peak effect is weakly pinned crystals.
- It would be interesting to probe other systems, such as colloidal crystals and magnetic arrays to explore if this scenario is generic to order-disorder transitions in the presence of random pinning.

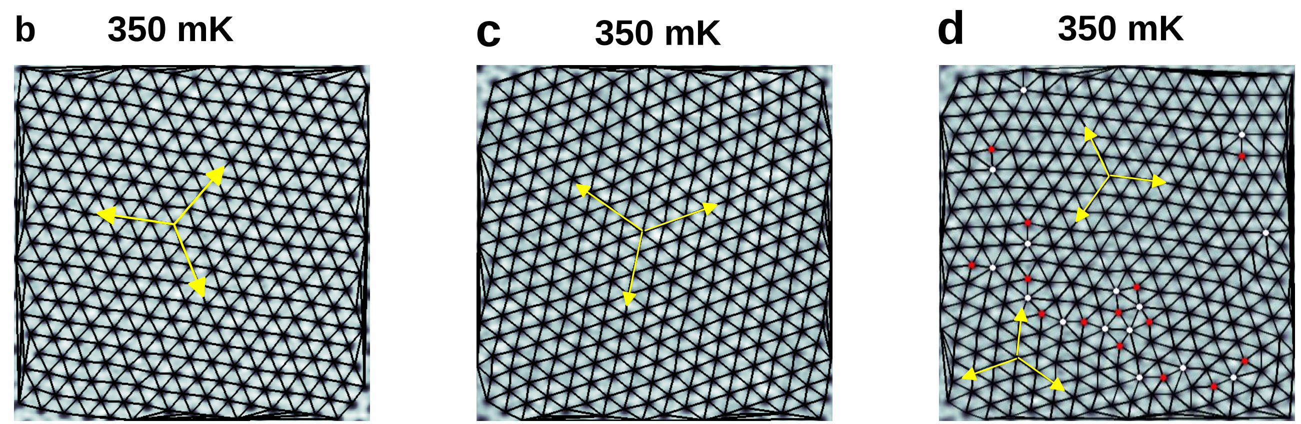
Thank you

Orientation order of the VL: The role lattice symmetry

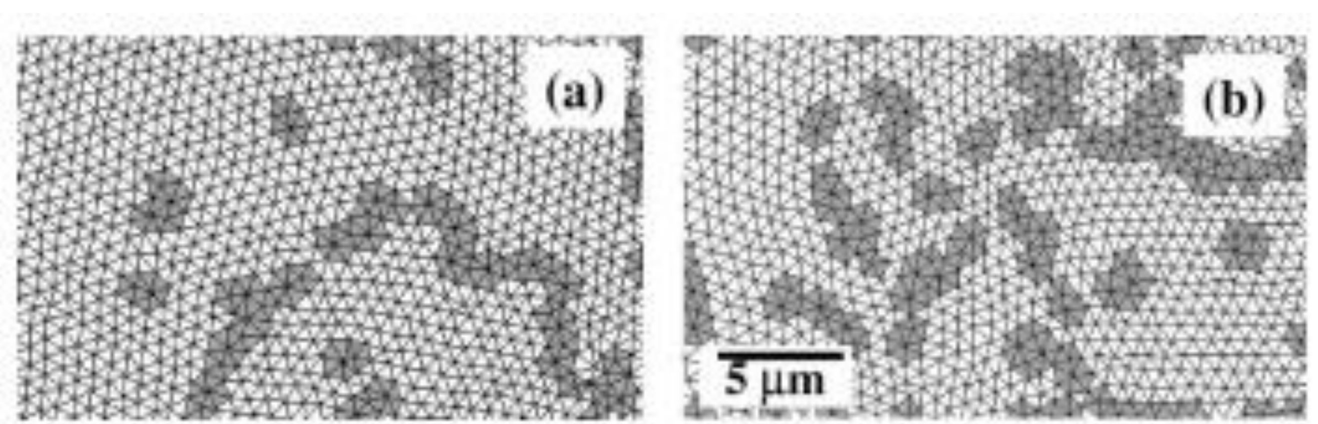
Atomic lattice →



ZFC state at 2.5 kOe →

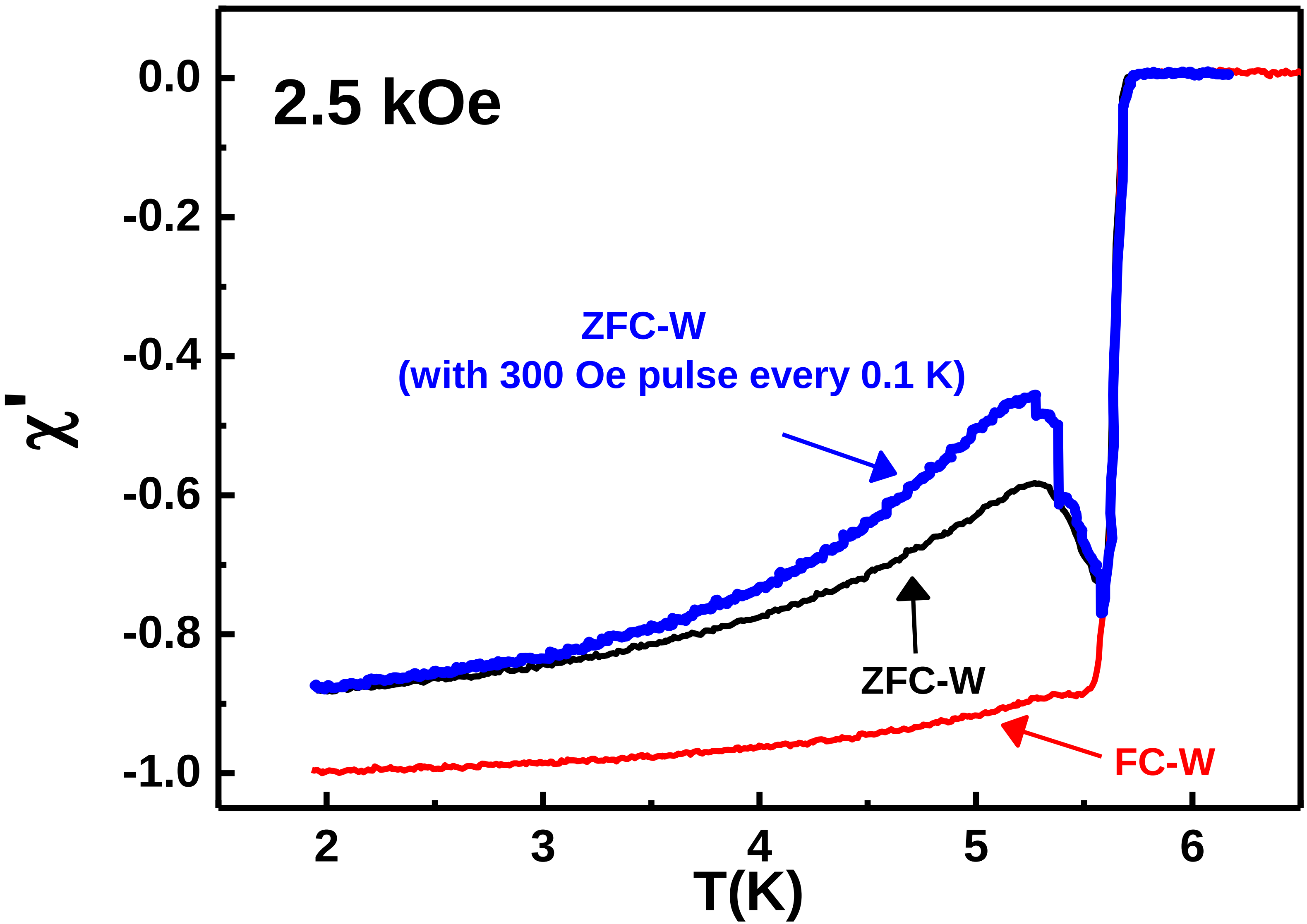


After heating and applying a pulse of 0.3 kOe →

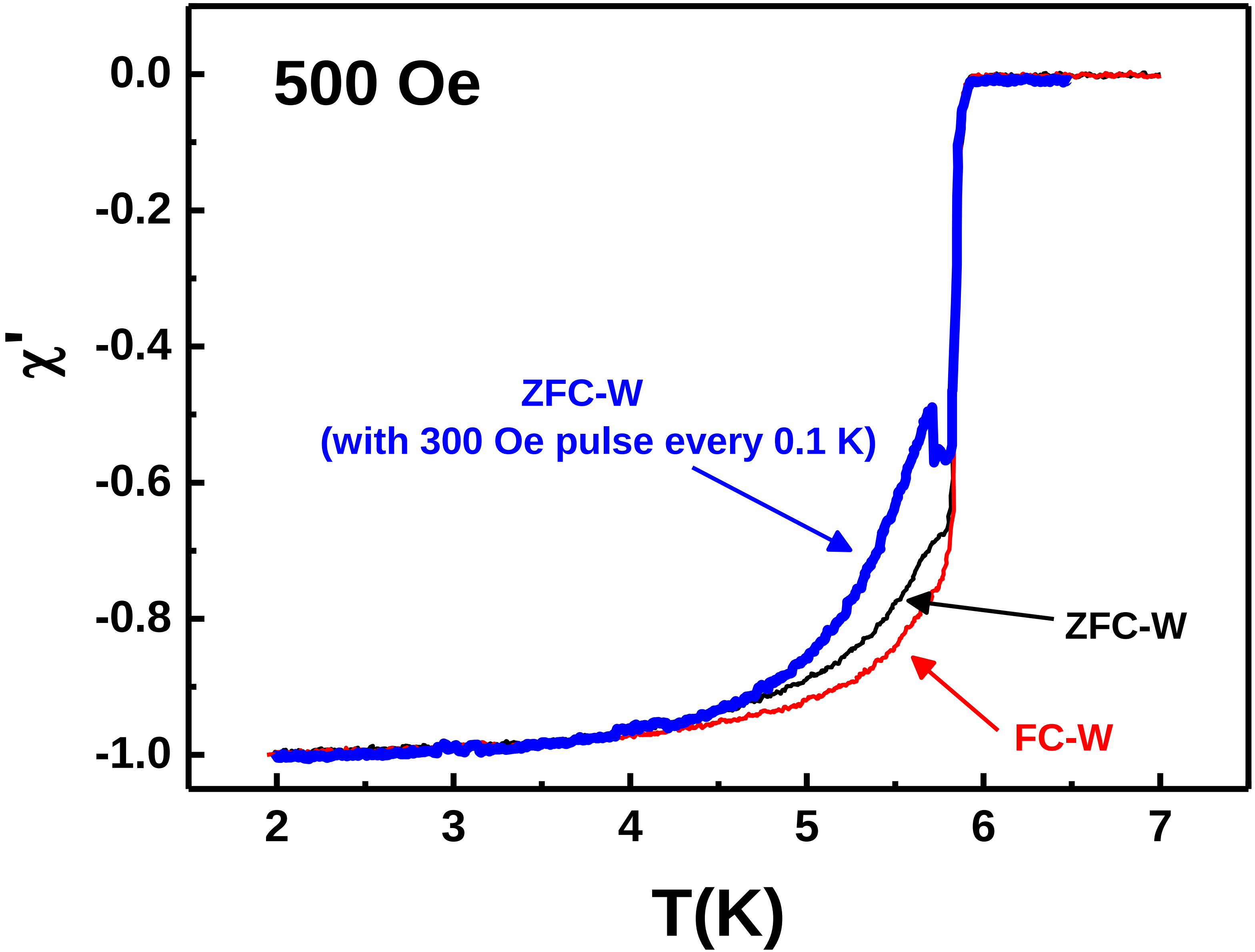


Fasano et al. (2002)

Effect on bulk properties

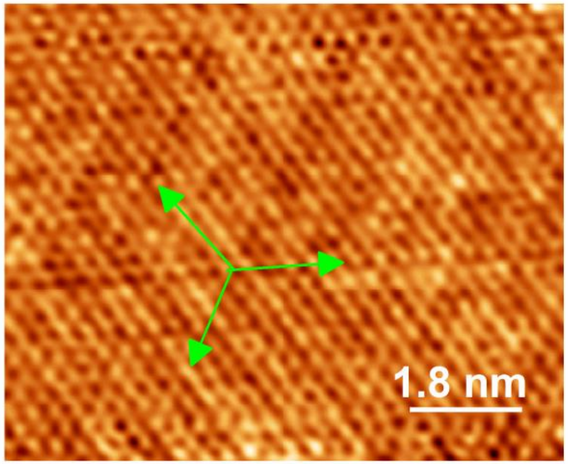


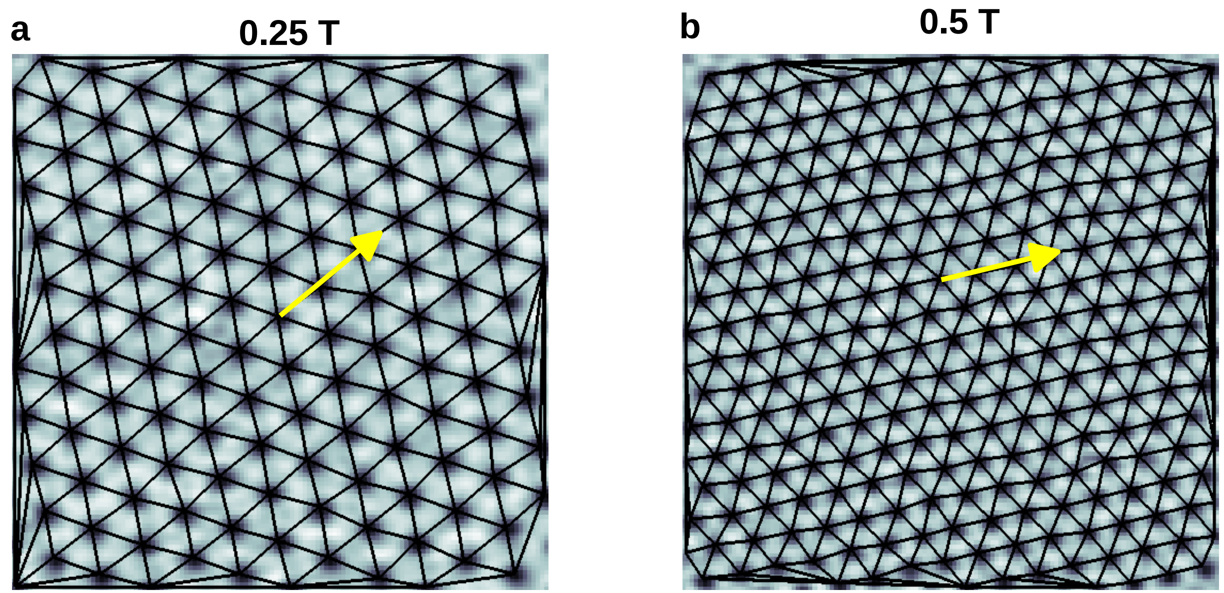
Effect on bulk properties

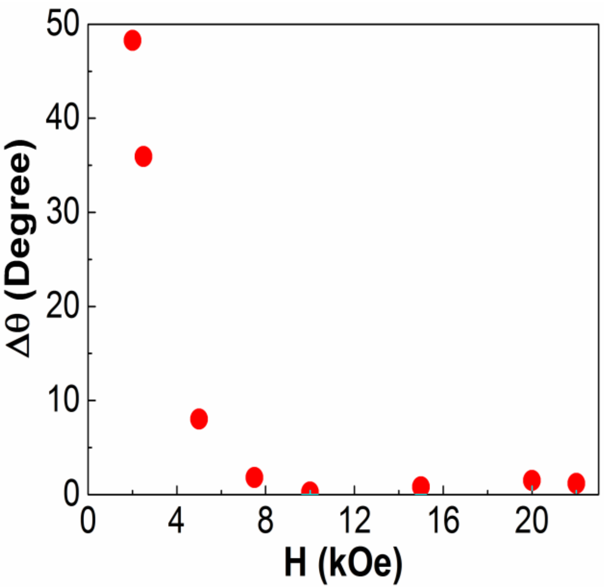


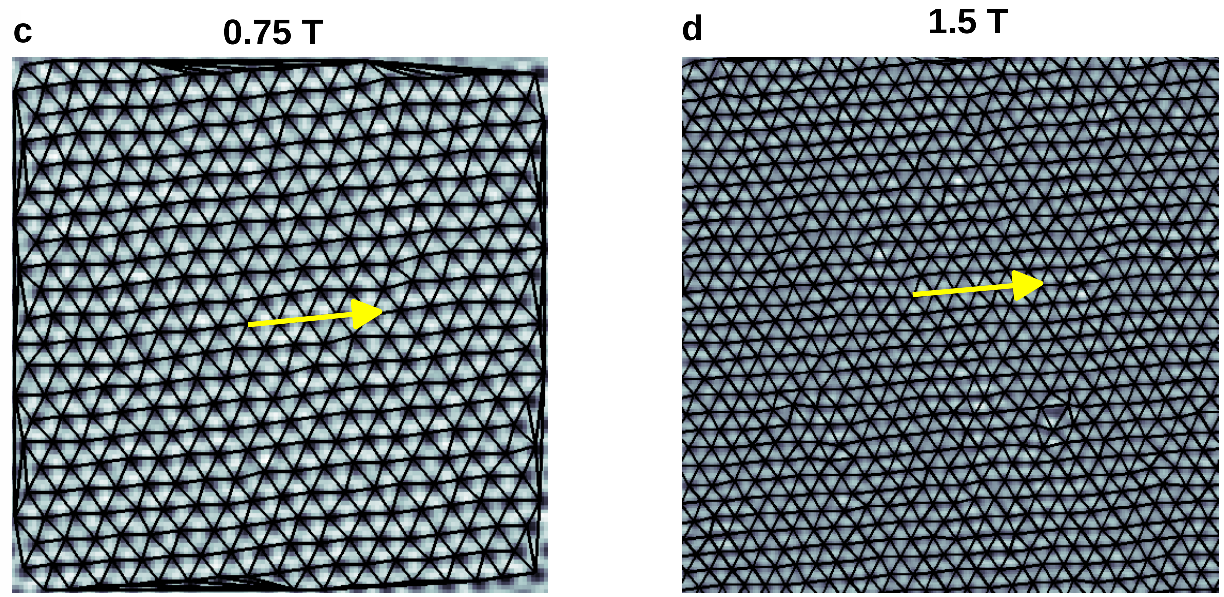
Alignment of the vortex lattice with magnetic field

Atomic Lattice

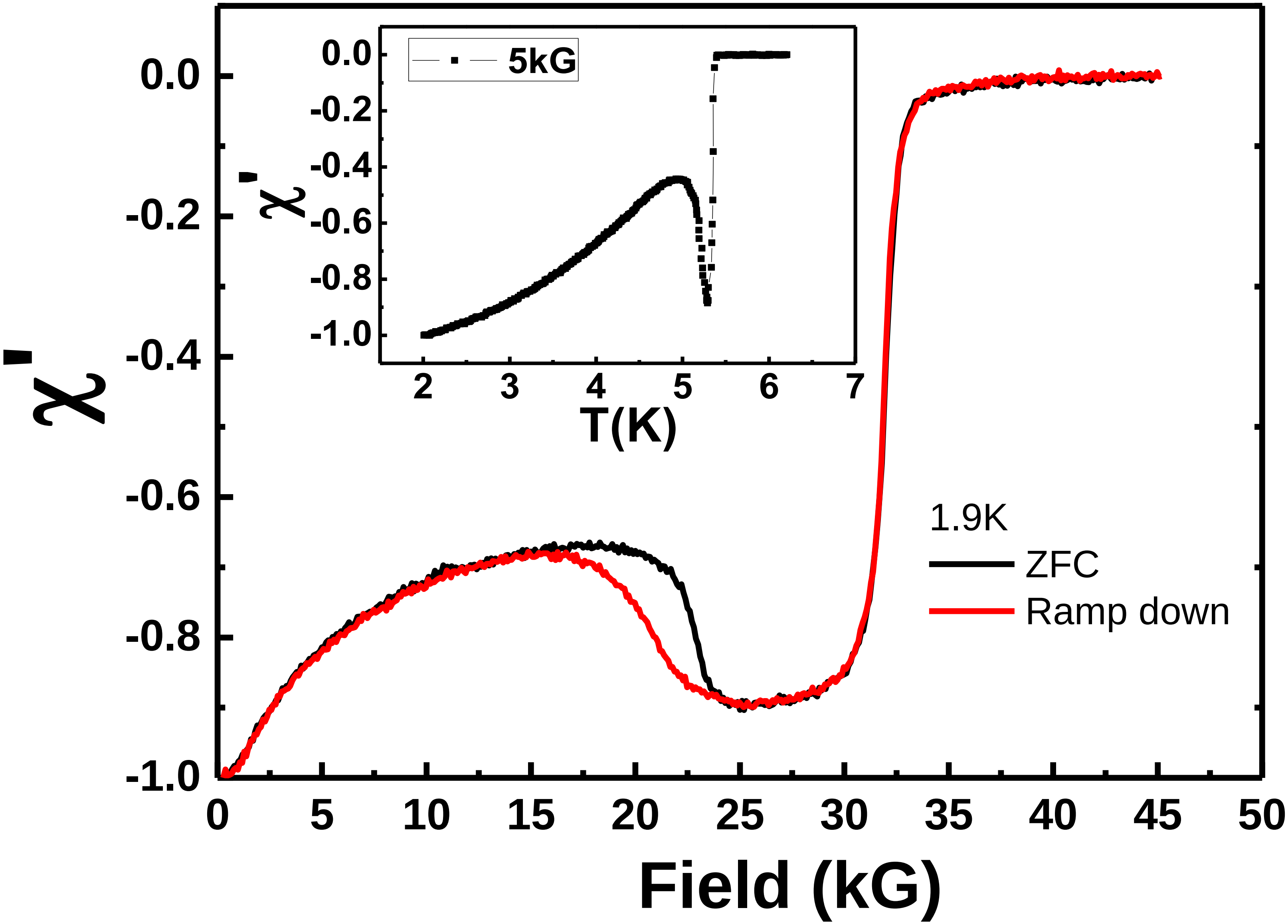








$Co_{0.0075}NbSe_2$ ($T_c \sim 5.9K$)

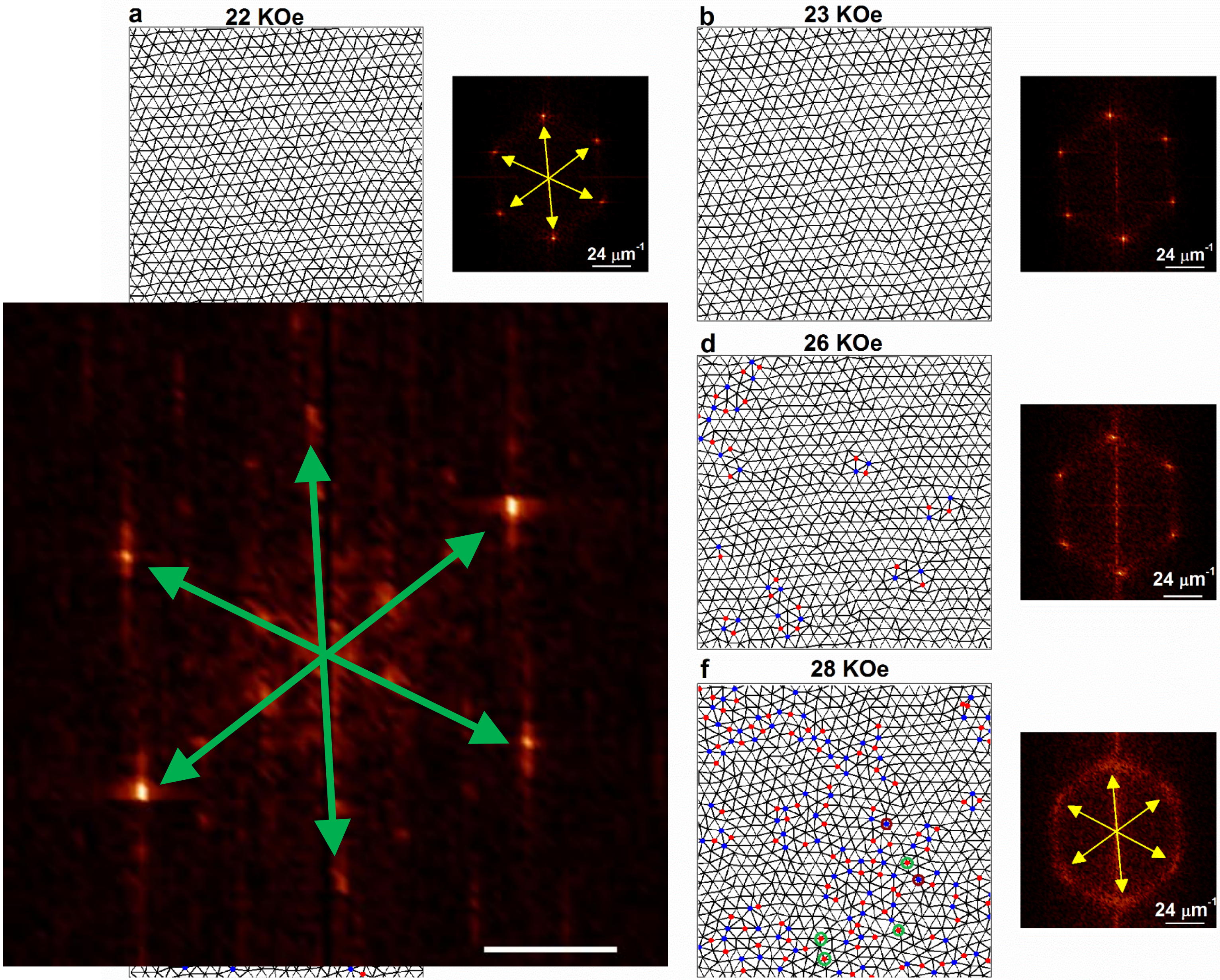


$Co_{0.0075}NbSe_2$ (T_c ~ 5.9K)

Ordered VL

Dislocations

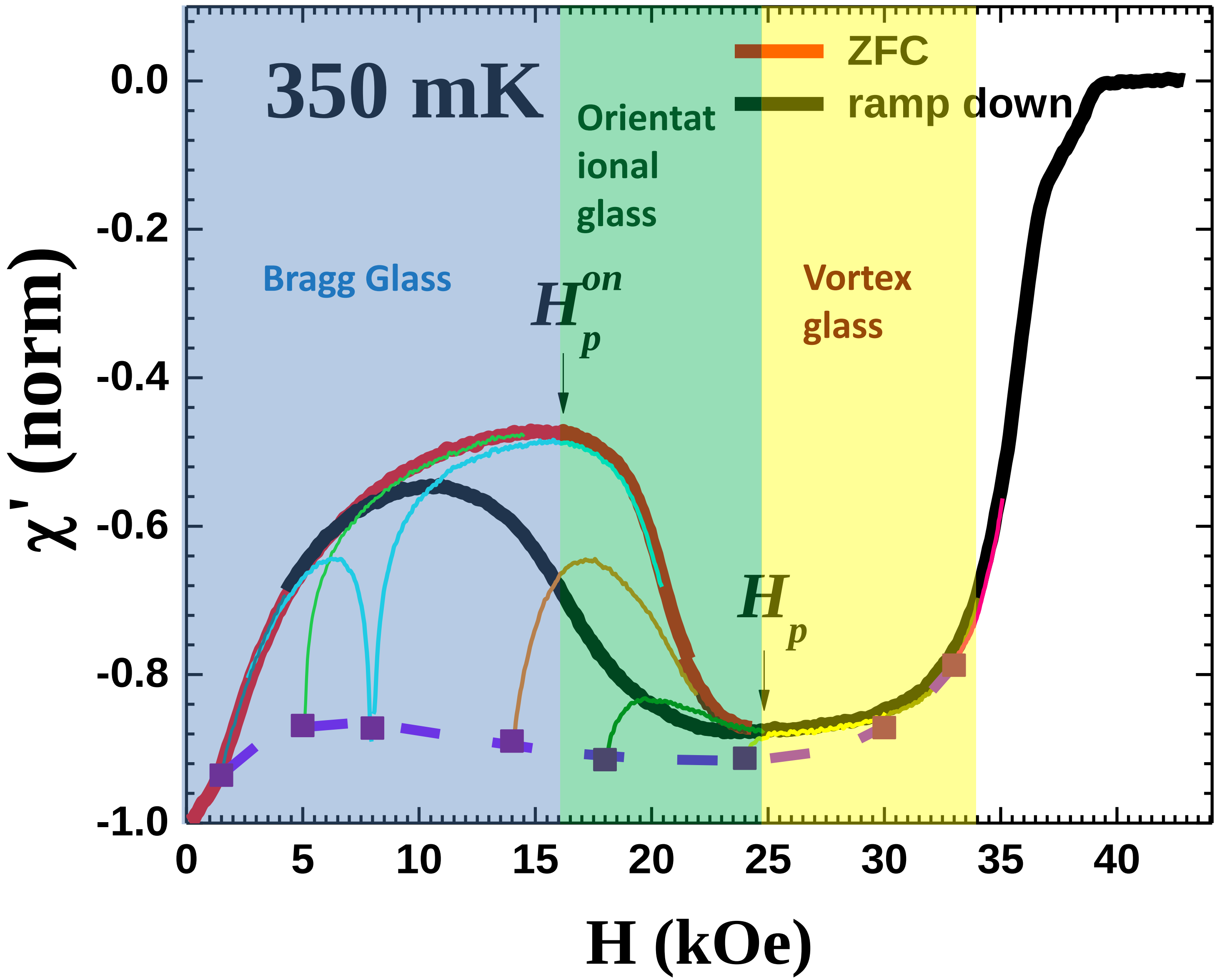
Disclinations



Summary

- The vortex lattice in weakly pinned $NbSe_2$ disorders through successive proliferation of dislocations and disclinations.
- The orientational order of the vortex persists well above the onset of the peak effect and even above the peak of the peak effect is weakly pinned crystals.
- We observe a strong orientational pinning of the vortex lattice with the crystalline lattice.

Thank you



350 mK
ZFC
ramp down
Bragg Glass
Orientat
ional
glass
Vortex
glass
H_p^{on}
H_p
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
χ' (norm)
0
5
10
15
20
25
30
35
40
H (kOe)

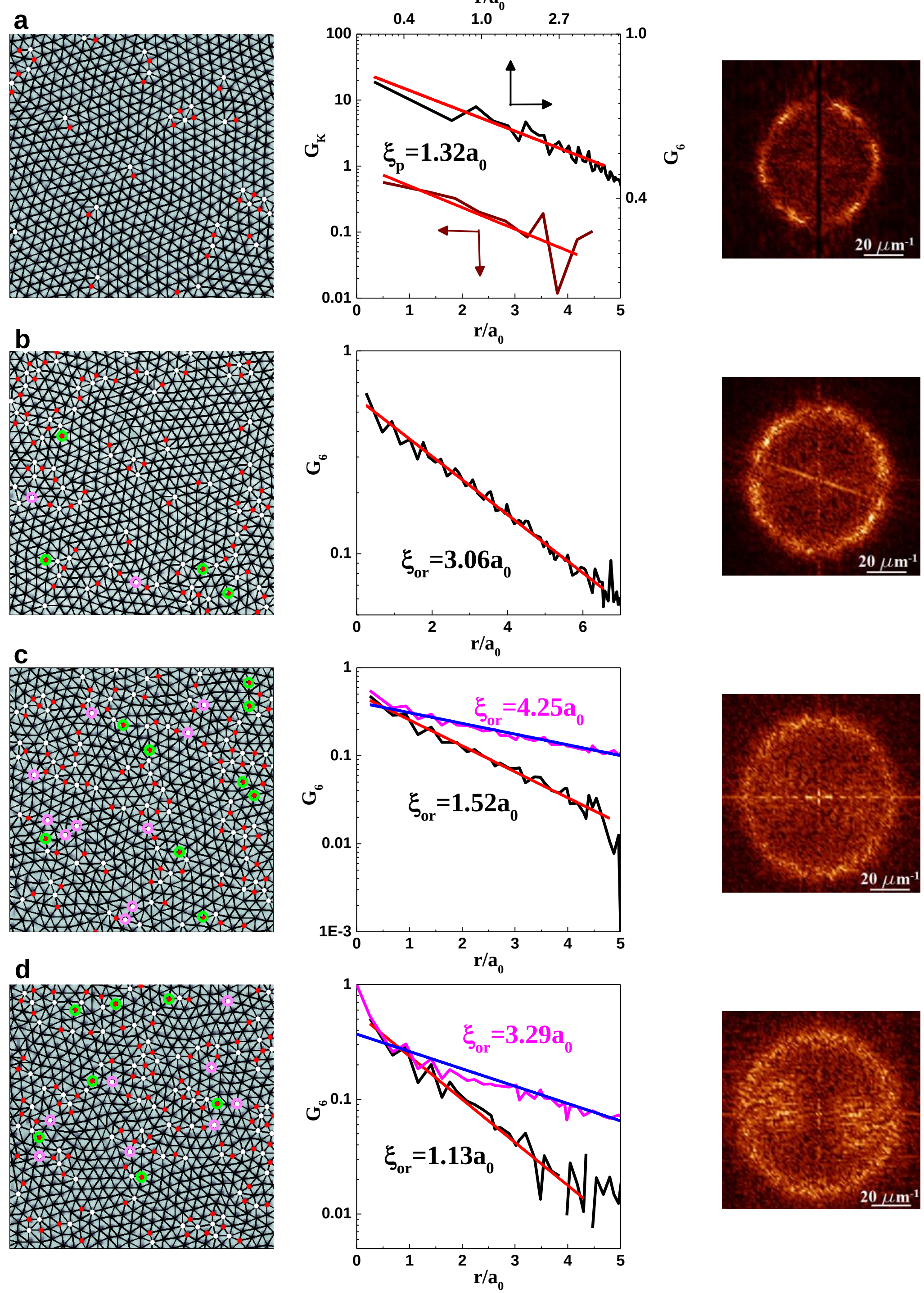
Non-equilibrium states

FC at 15 kOe
Hexatic Glass

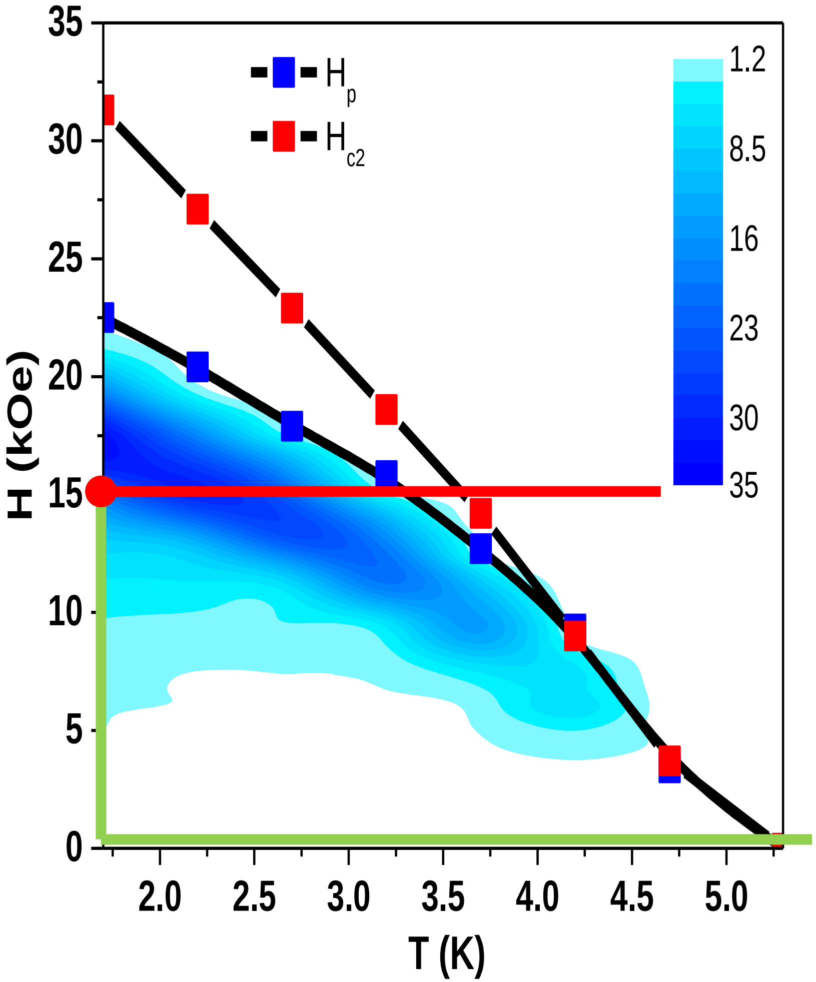
FC at 20 kOe
Vortex Glass

FC at 26 kOe
Vortex Glass

FC at 28 kOe
Vortex Glass



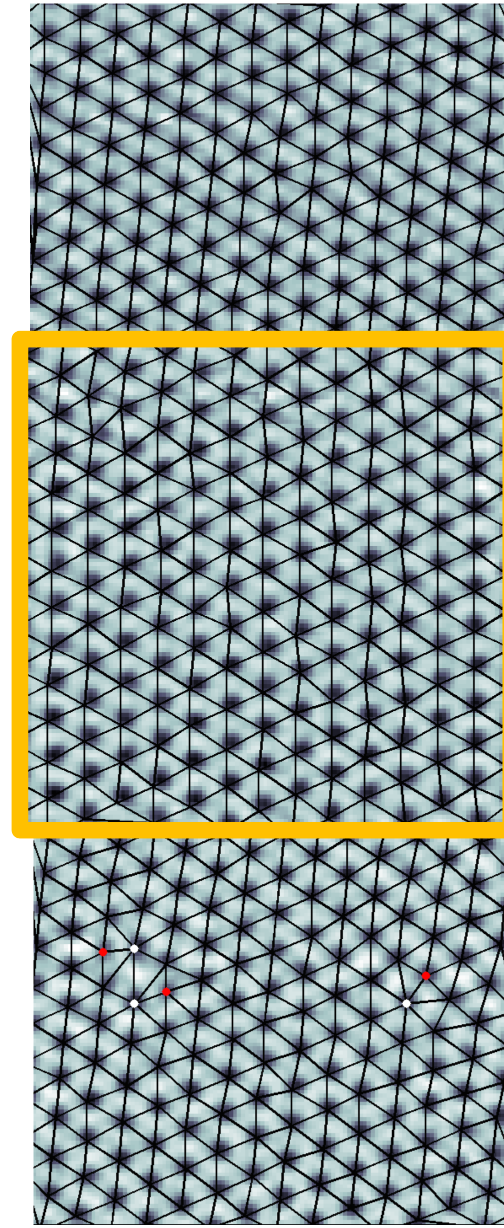
Metastability of the pinned vortex lattice

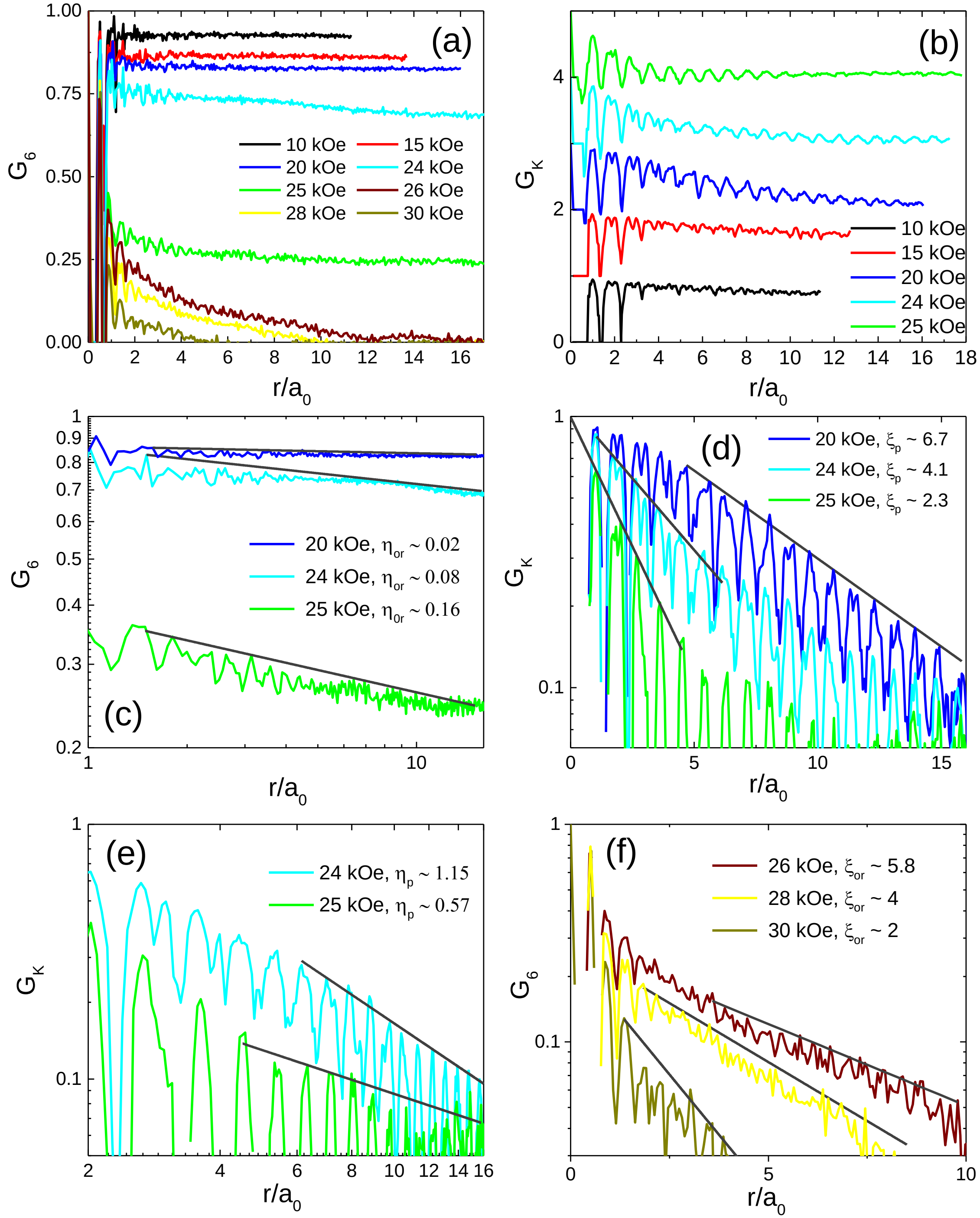


Zero field Cooled
Ordered State

Field Cooled
Then magnetic field pulse of 0.13 kOe

Field Cooled
Ordered State





Orientational Glass

$G_6(r) \sim 1/r^n$

$G_K(r) \sim e^{-r/\xi}$ at short distance
but power-law tail at larger.

Vortex Glass

$G_6(r)$ and $G_K(r)$ decay exponentially.

Summary

We show that the vortex lattice in a 3D superconductor follows the same route to disordering as that of a 2D hexagonal crystal.

The presence of pinning give rise to a variety of additional non-equilibrium states which can be accessed through thermomagnetic cycling.

Outstanding Question

Theoretically the possibility of a single first order transition is not precluded in a 2D system.

Is weak pinning essential to observe the two step melting?

Does the transition transform into a single first order transition below a critical value of disorder?

Thank you