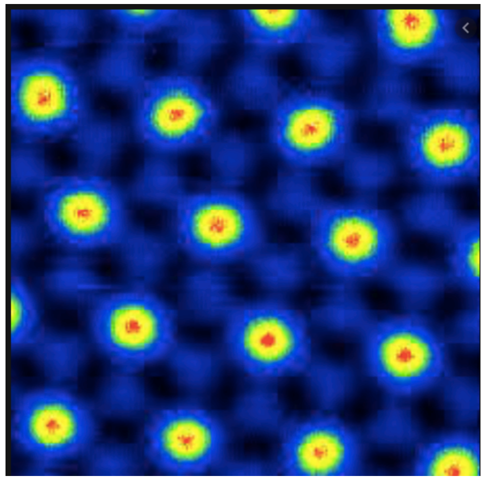
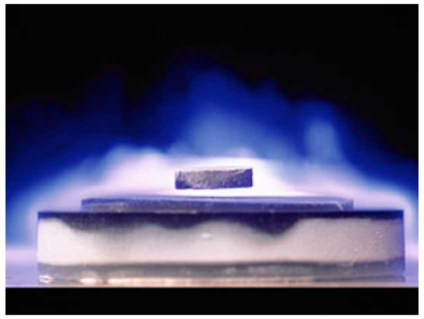
Two-Dimensional Vortex Lattice Melting



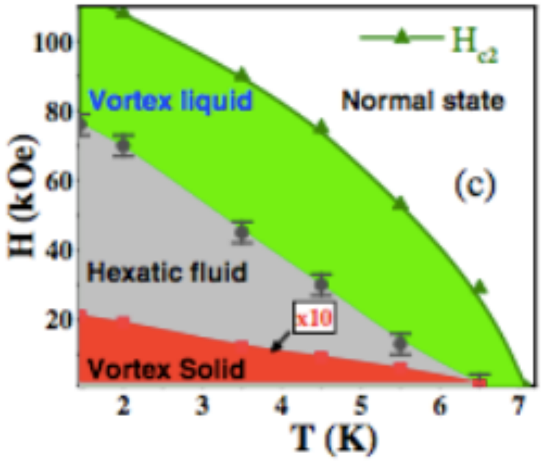
Superconducting Length-Scales and Vortex Lattices

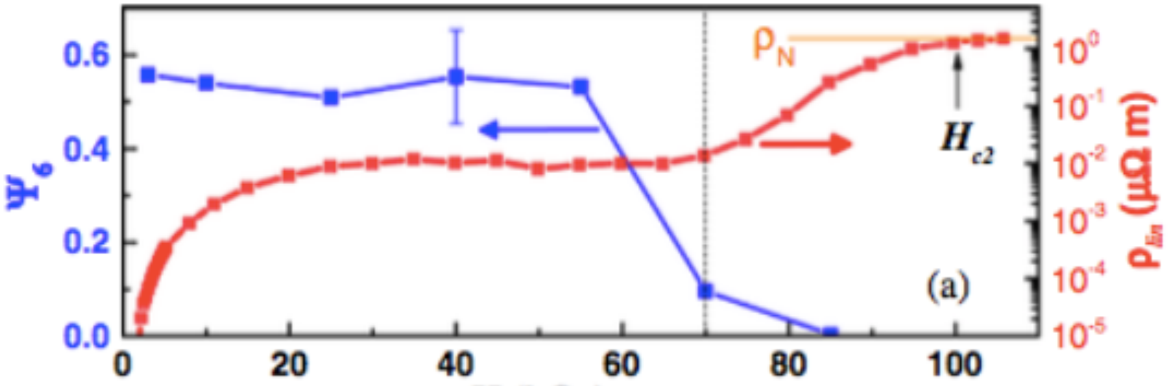


Flux Motion

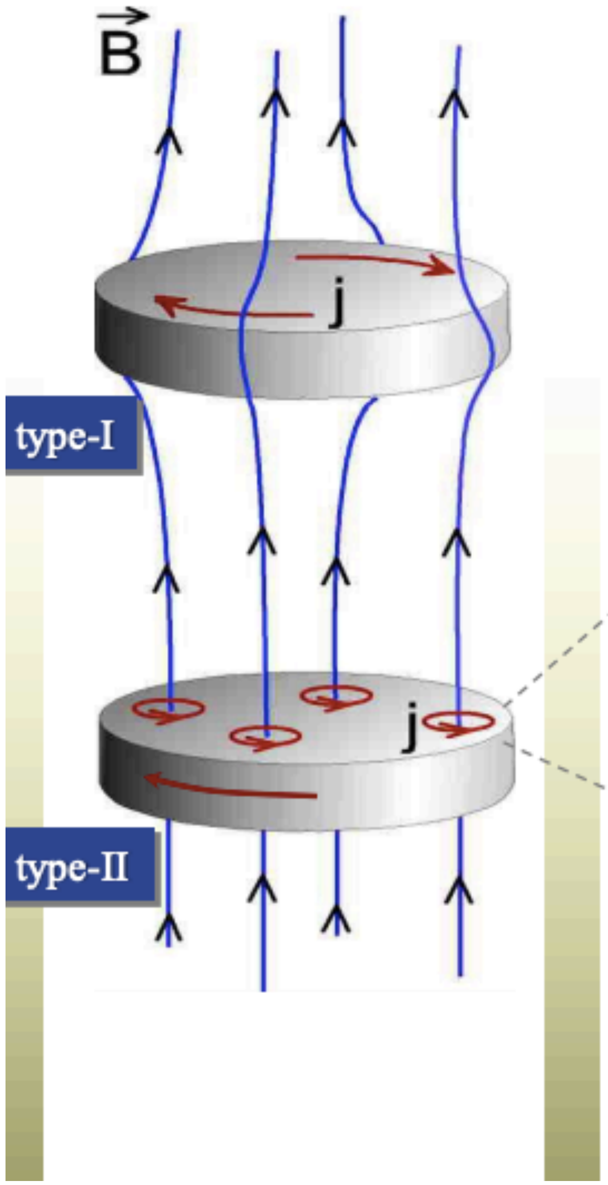
Melting Concepts

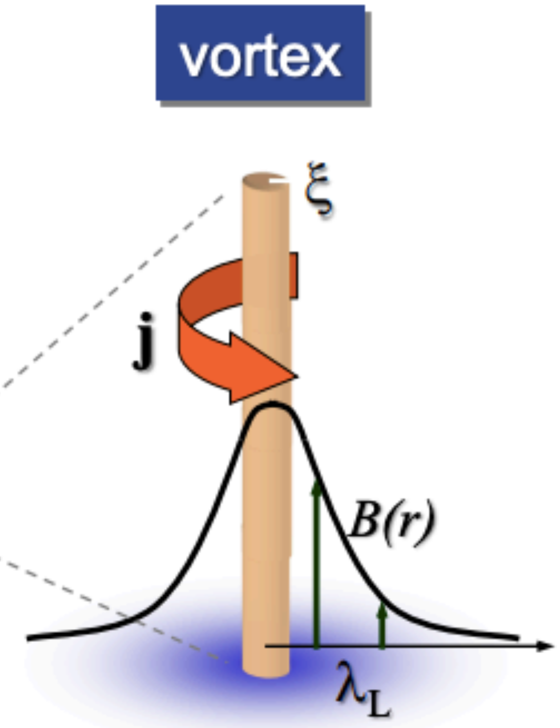
Journal Paper Presentation: “Melting of the Vortex Lattice Through the Hexatic Phase in an MoGe3 Thin Film”





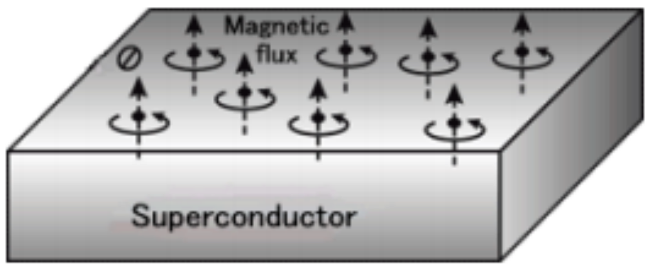
Vortex matter





$$\int B\, dA = h/2e = \Phi_0$$

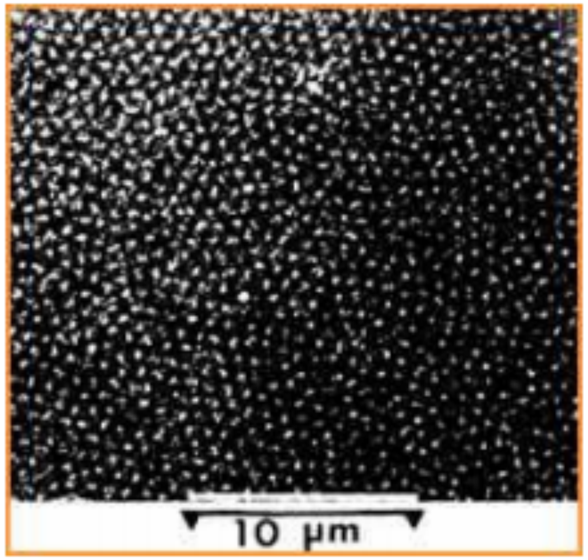
Flux quantum



Repulsive Interaction Between Vortices

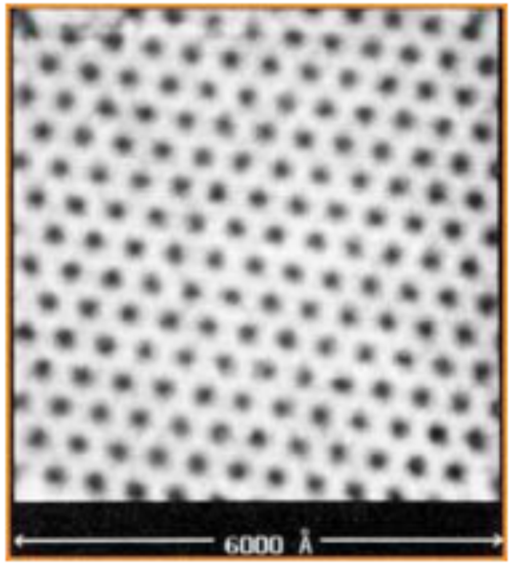
↓

Vortex Lattice



Bitter Decoration
$YBa_2Cu_3O_7$ crystal, 4.2K, 52G

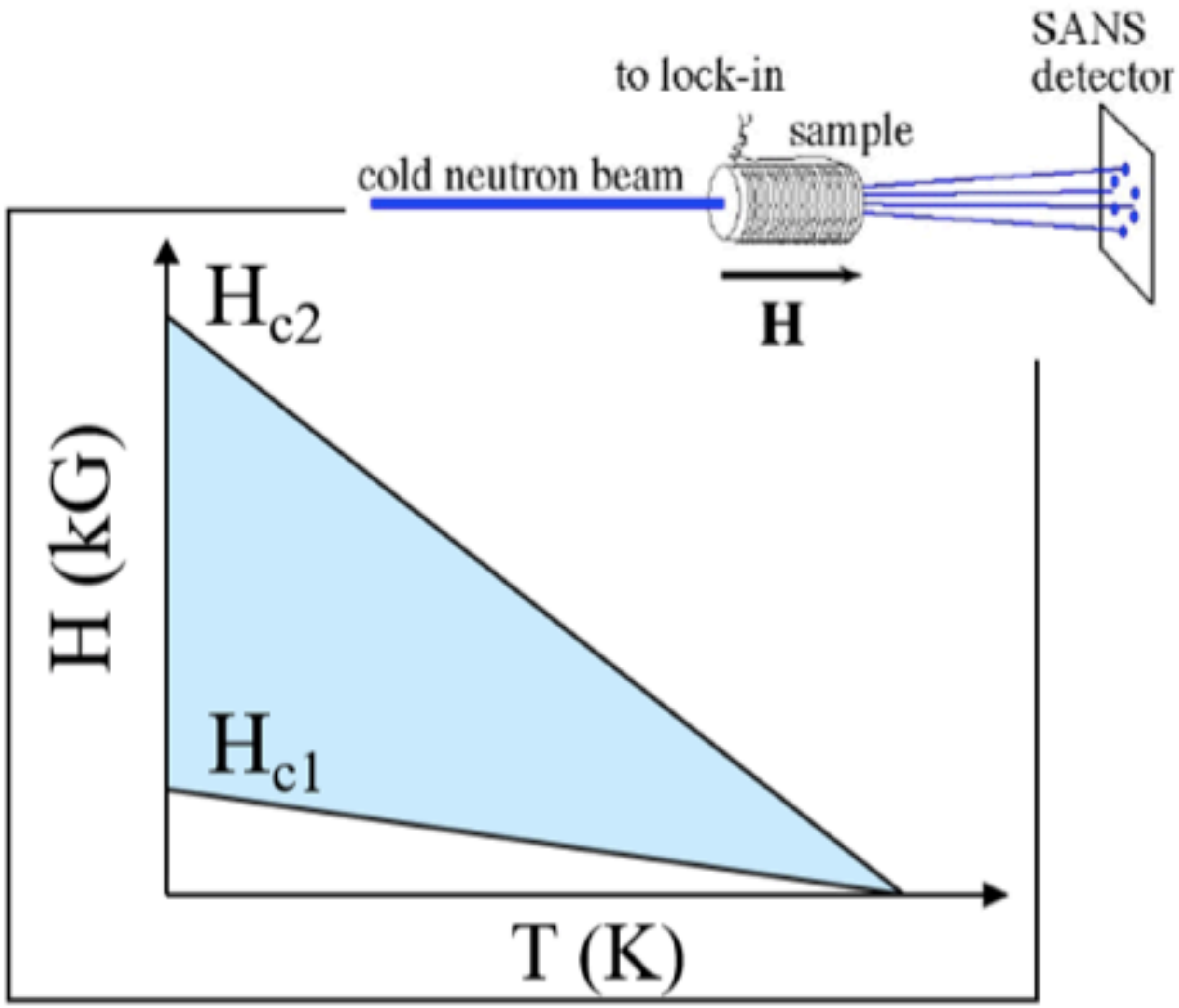
P. L. Gammel et al., Bell Labs



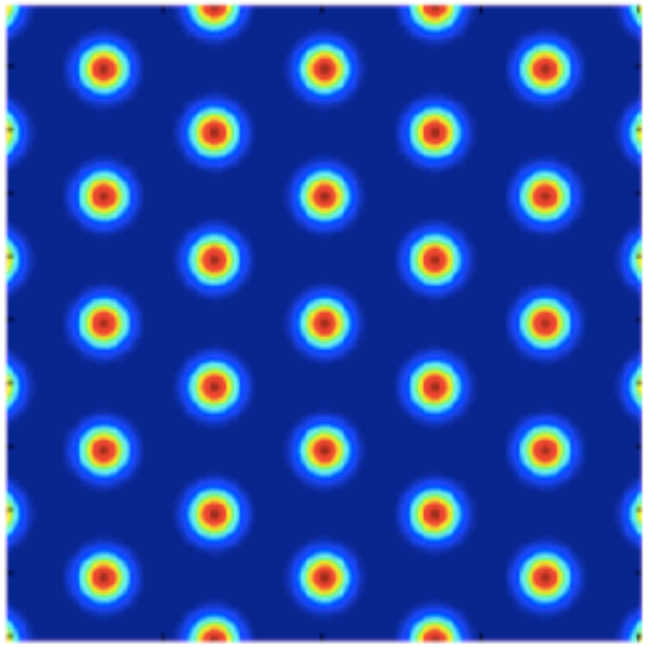
Scanning Tunnel Microscopy
NbSe2, 1T, 1.8K

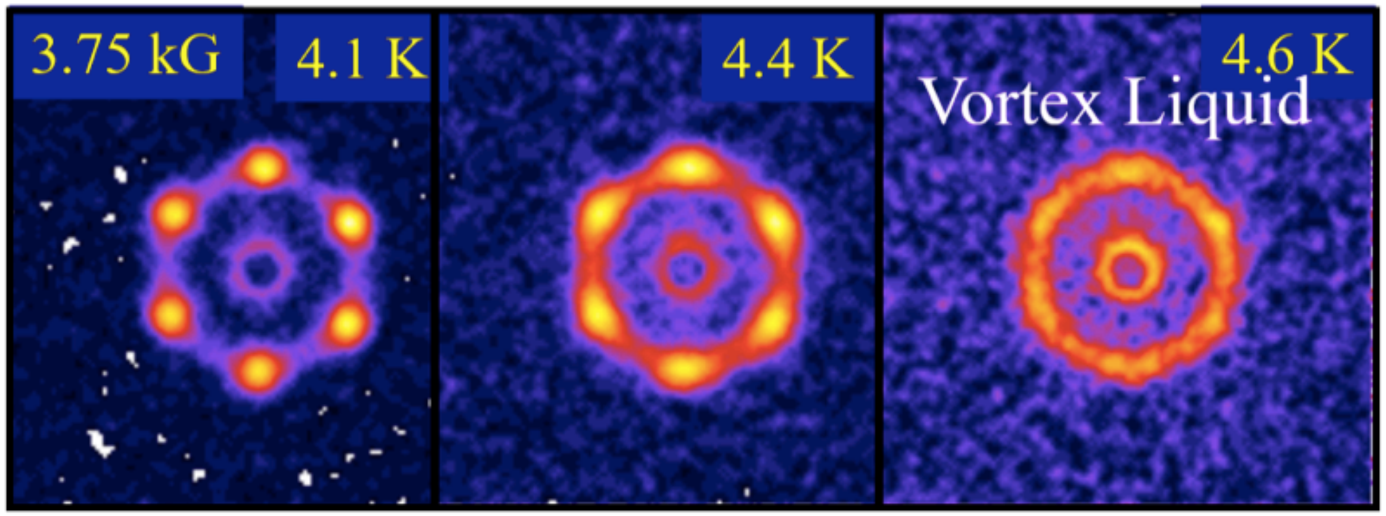
H. F. Hess et al., Bell Labs

Vortex Melting in Superconducting Nb

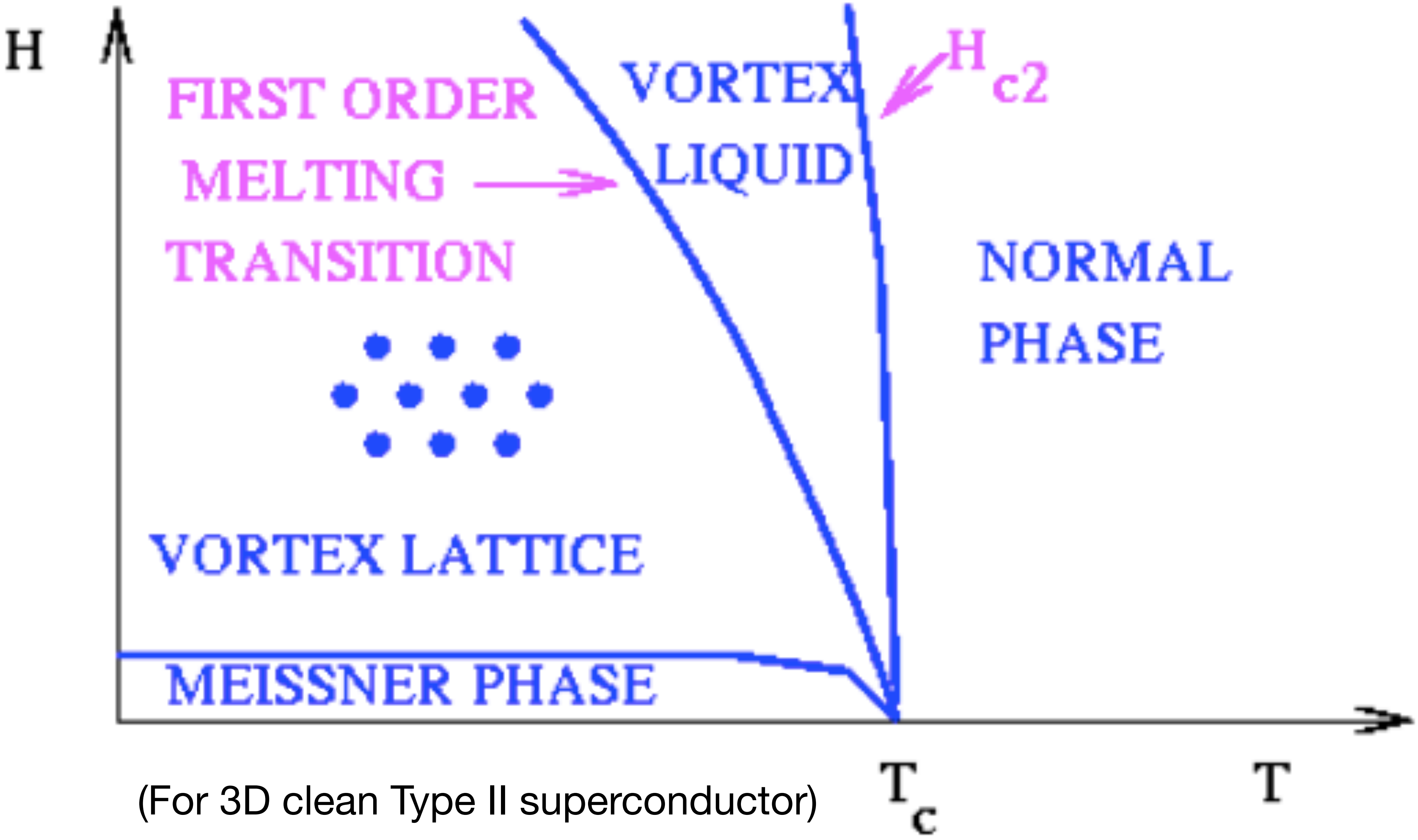


Real space depiction of vortex lattice





Phase Diagram

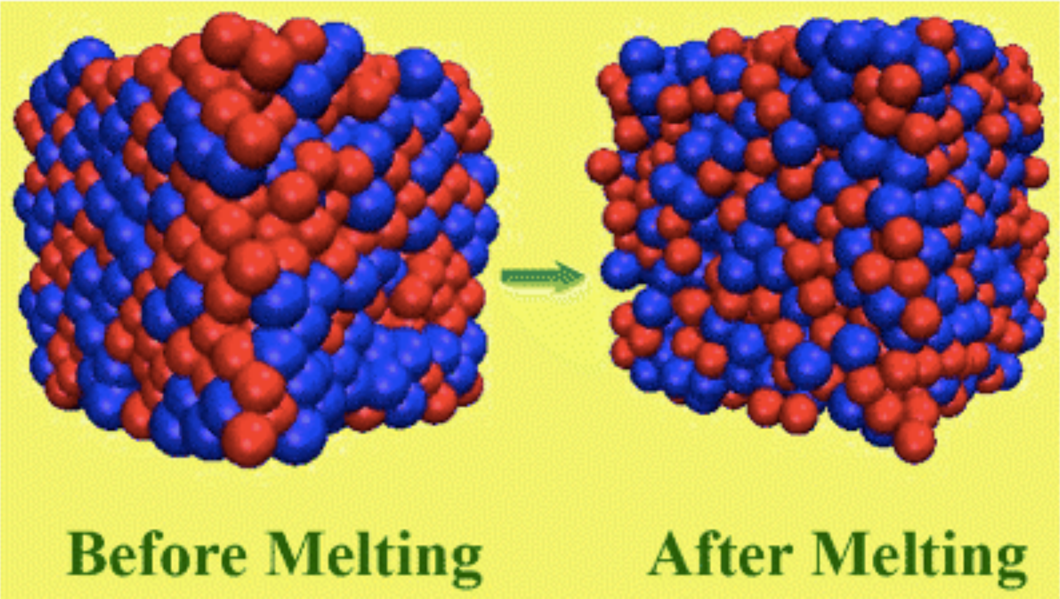


(For 3D clean Type II superconductor)

Vortex Lattice Expands on Freezing (Like Ice) ⟶ Jump in the Magnetization

Melting Concepts

3D

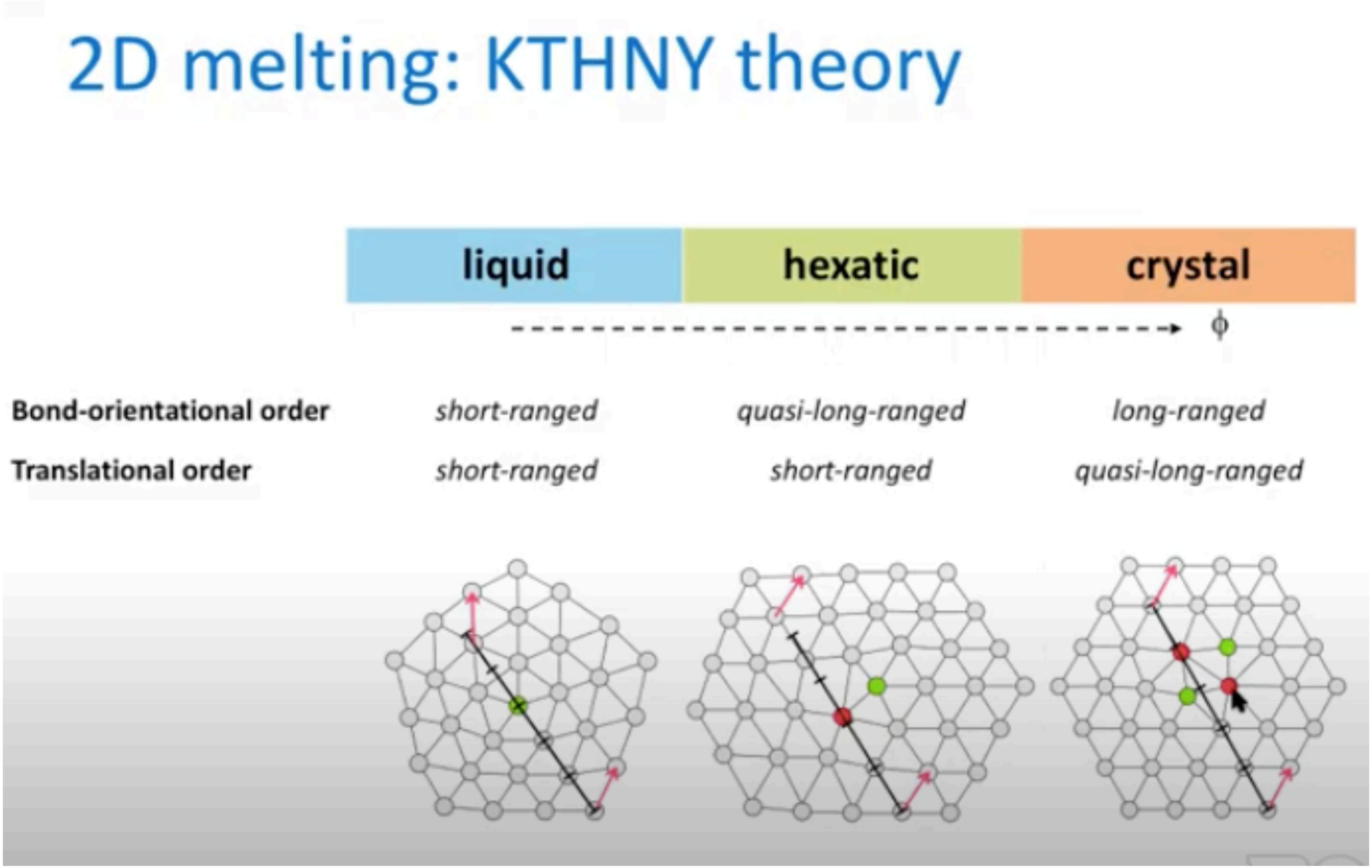


Solid Liquid

Lindemann Criterion

$$\sqrt{(\Delta r)^2} \approx \alpha a$$

1st Order Transition



2D melting: KTHNY theory

	liquid	**hexatic**	**crystal**
Bond-orientational order	*short-ranged*	*quasi-long-ranged*	*long-ranged*
Translational order	*short-ranged*	*short-ranged*	*quasi-long-ranged*

ϕ

Journal Presentation

Motivation/Context

Results

Interpretation

Questions/Ideas for Future Work

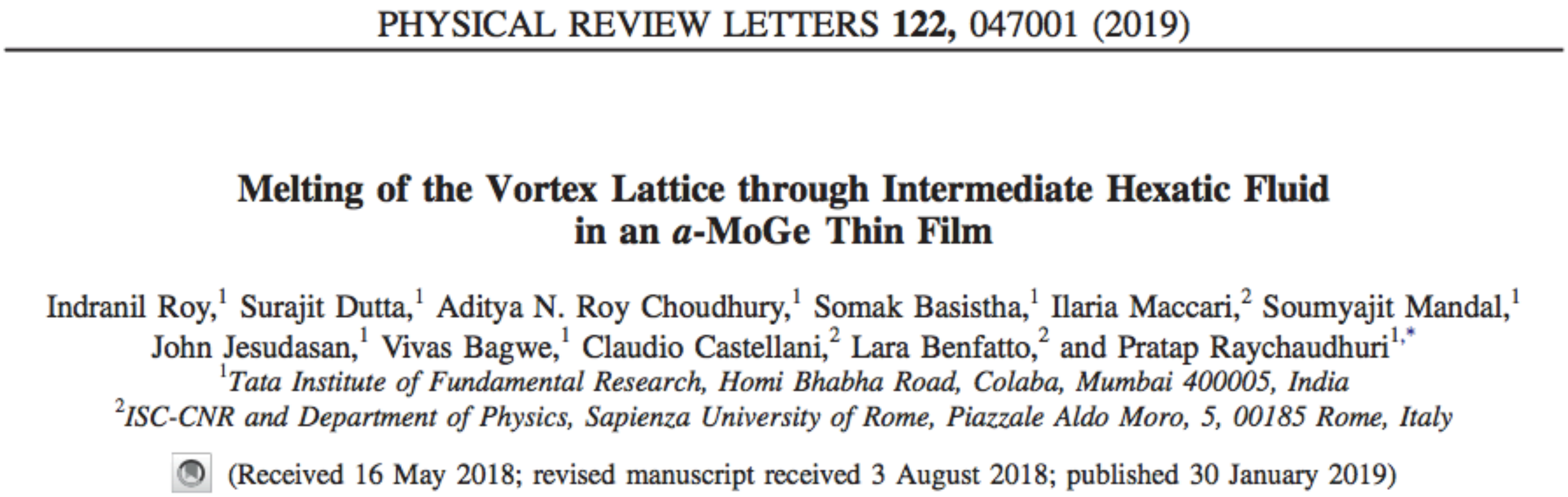
(aim for 30-45 mins)

Please check the course site about the presentation schedule

No class on The April 8, 15

Make-Ups on Ms April 12, 19

(Weekly Discussion to be Rescheduled)

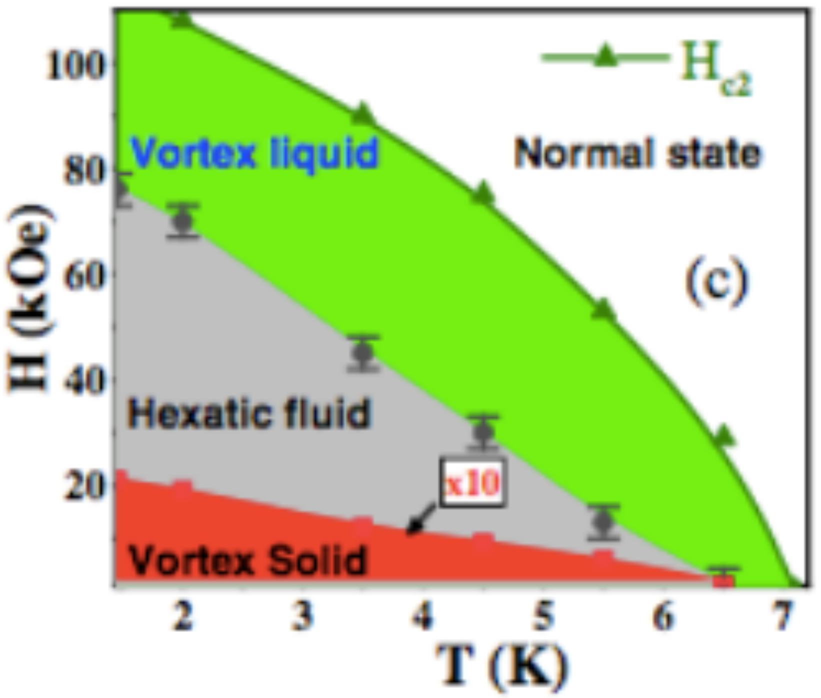


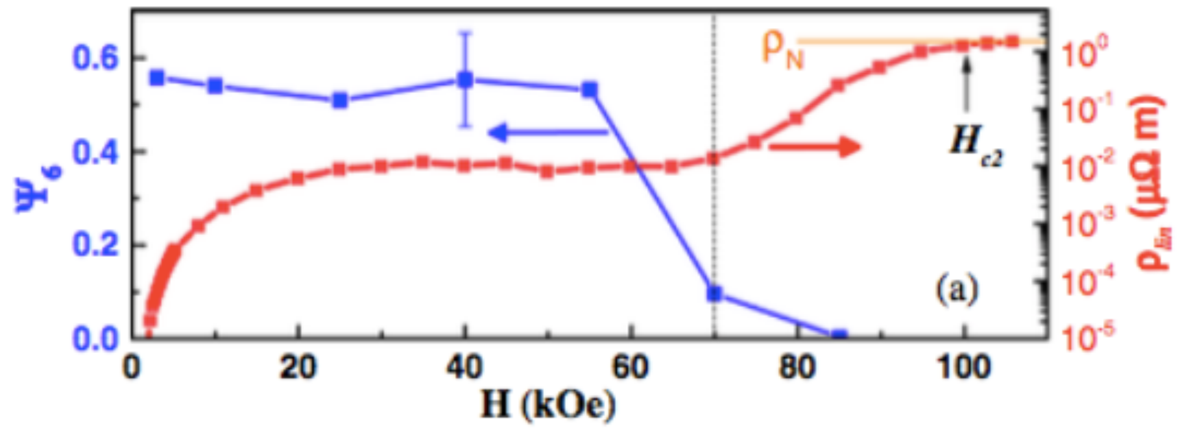
PHYSICAL REVIEW LETTERS **122,** 047001 (2019)

Melting of the Vortex Lattice through Intermediate Hexatic Fluid in an *a*-MoGe Thin Film

Indranil Roy,[1] Surajit Dutta,[1] Aditya N. Roy Choudhury,[1] Somak Basistha,[1] Ilaria Maccari,[2] Soumyajit Mandal,[1]
John Jesudasan,[1] Vivas Bagwe,[1] Claudio Castellani,[2] Lara Benfatto,[2] and Pratap Raychaudhuri[1,*]
[1]*Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai 400005, India*
[2]*ISC-CNR and Department of Physics, Sapienza University of Rome, Piazzale Aldo Moro, 5, 00185 Rome, Italy*

(Received 16 May 2018; revised manuscript received 3 August 2018; published 30 January 2019)

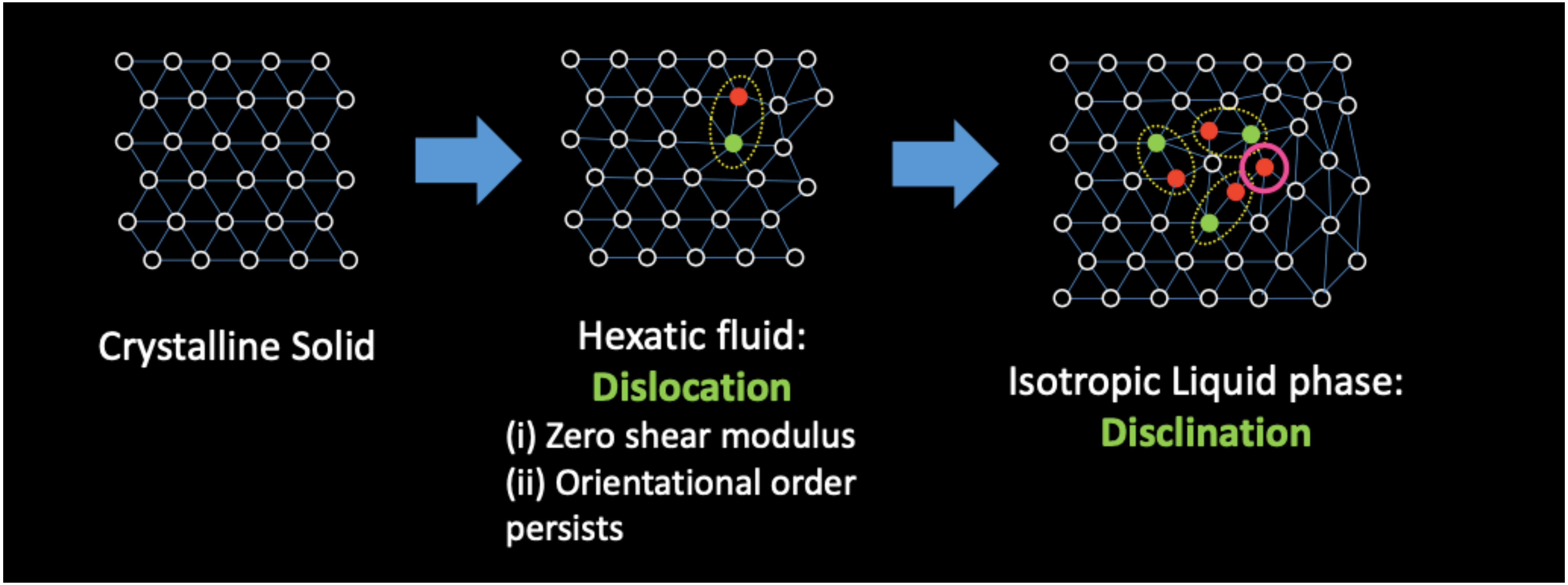




First Definitive Observation of the Hexatic Phase in a Superconducting Film

(with thanks to Indranil Roy and Pratap Raychaudhuri)

Two Dimensional Melting (BKT + HNY theory)



Crystalline Solid

Hexatic fluid:

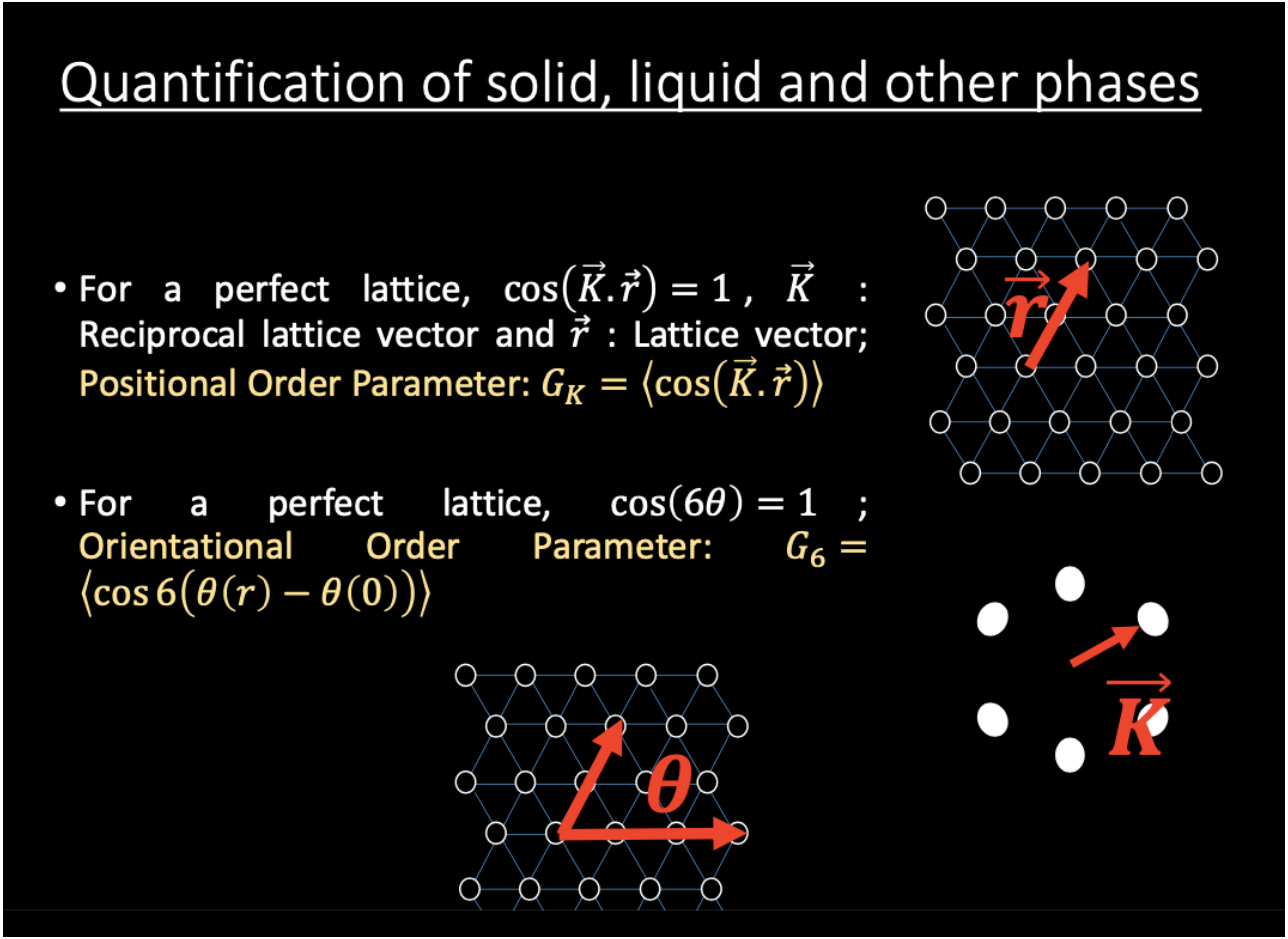
Dislocation

(i) Zero shear modulus

(ii) Orientational order persists

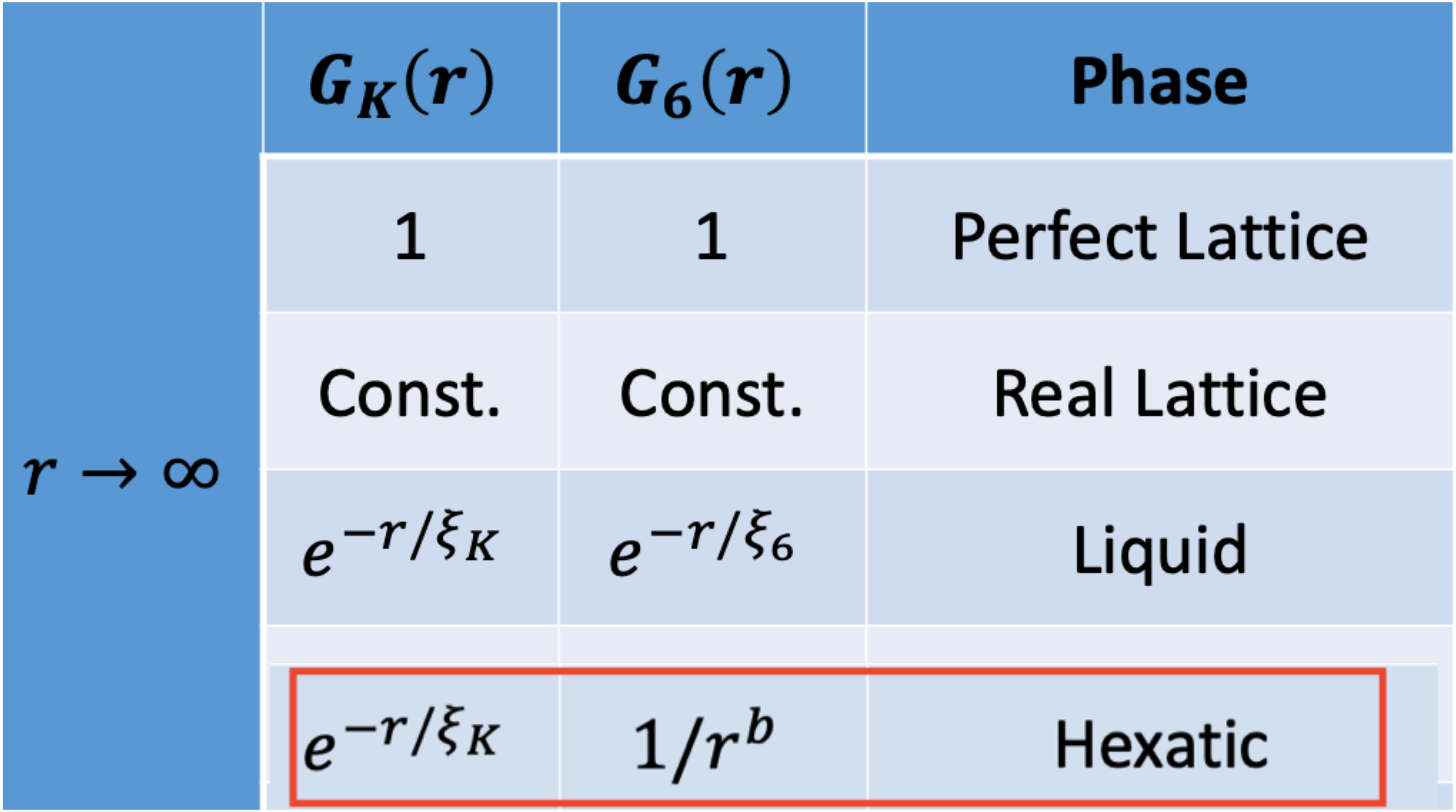
Isotropic Liquid phase:

Disclination



Quantification of solid, liquid and other phases

- For a perfect lattice, $\cos(\vec{K}.\vec{r}) = 1$, $\vec{K}$: Reciprocal lattice vector and $\vec{r}$: Lattice vector; Positional Order Parameter: $G_K = \langle \cos(\vec{K}.\vec{r}) \rangle$
- For a perfect lattice, $\cos(6\theta) = 1$; Orientational Order Parameter: $G_6 = \langle \cos 6(\theta(r) - \theta(0)) \rangle$



	$G_K(r)$	$G_6(r)$	Phase
$r \to \infty$	1	1	Perfect Lattice
	Const.	Const.	Real Lattice
	e^{-r/ξ_K}	e^{-r/ξ_6}	Liquid
	e^{-r/ξ_K}	$1/r^b$	Hexatic

Hexatics have been observed in 2D colloidal systems

Why not in the Melting of the Vortex Phase of Superconducting Films ??

Quest for the Hexatic Liquid Phase in $\alpha - MoGe$

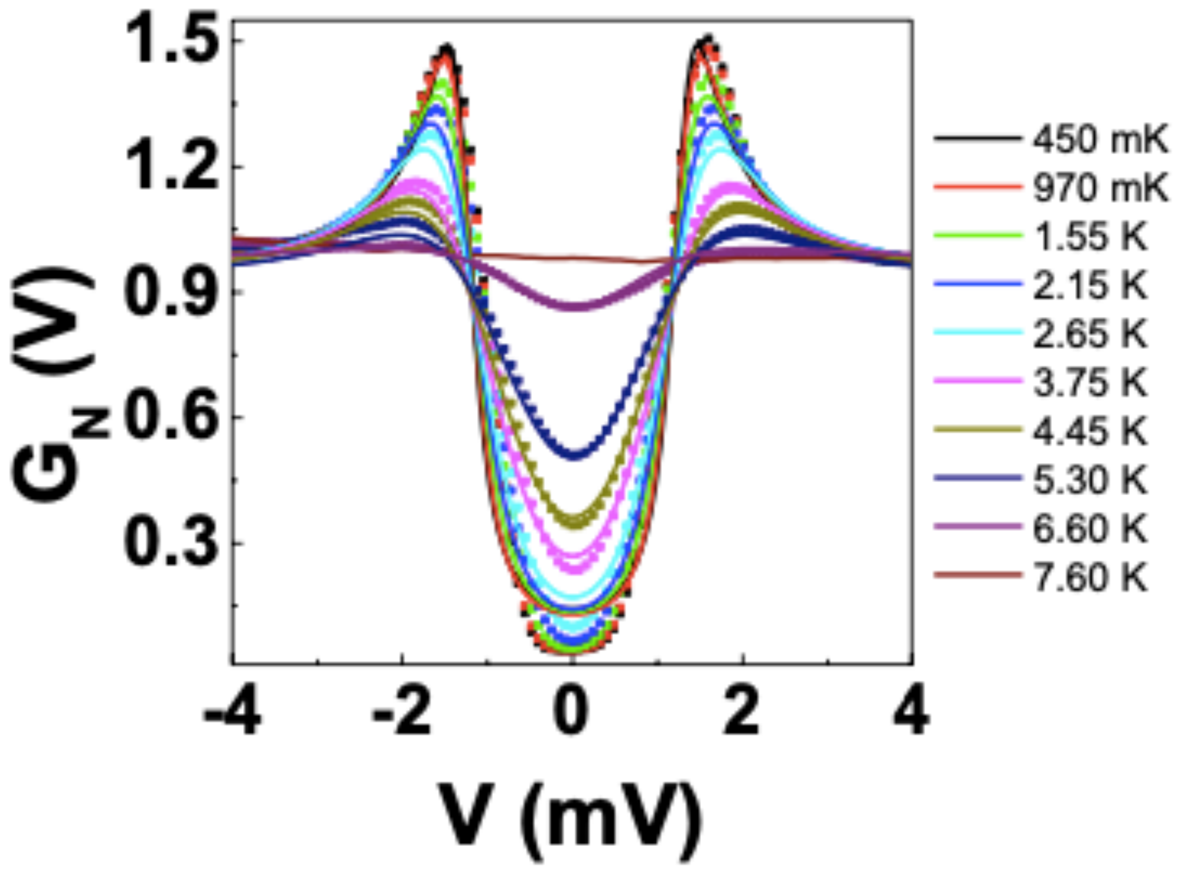
Why Not Before ??

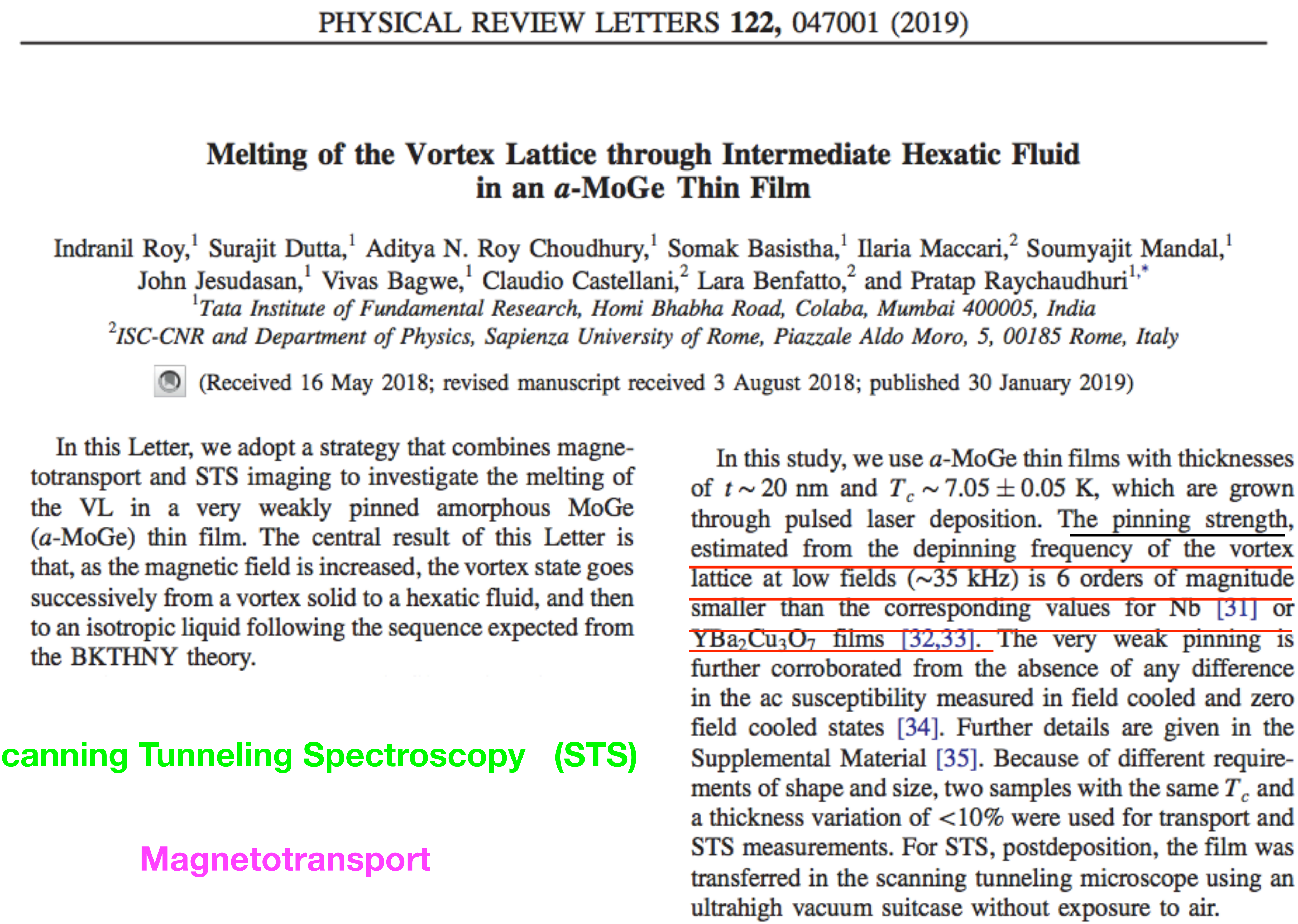
Orientational Coupling between Atomic and Vortex Lattices → Hexatic Glass !!

Solution: Amorphous Superconductor (no lattice effect)

Very Weak Pinning

BCS-Type Superconductor





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(Received 16 May 2018; revised manuscript received 3 August 2018; published 30 January 2019)

In this Letter, we adopt a strategy that combines magnetotransport and STS imaging to investigate the melting of the VL in a very weakly pinned amorphous MoGe (*a*-MoGe) thin film. The central result of this Letter is that, as the magnetic field is increased, the vortex state goes successively from a vortex solid to a hexatic fluid, and then to an isotropic liquid following the sequence expected from the BKTHNY theory.

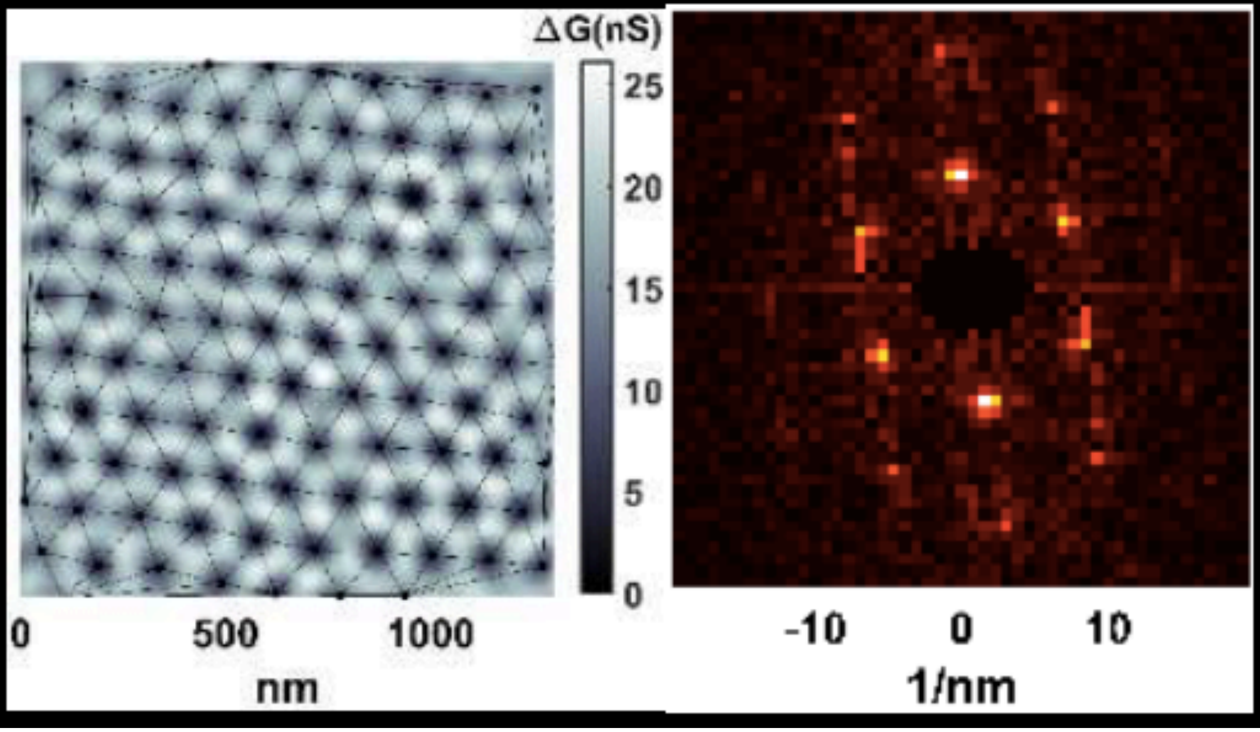
In this study, we use *a*-MoGe thin films with thicknesses of $t \sim 20$ nm and $T_c \sim 7.05 \pm 0.05$ K, which are grown through pulsed laser deposition. The pinning strength, estimated from the depinning frequency of the vortex lattice at low fields (~35 kHz) is 6 orders of magnitude smaller than the corresponding values for Nb [31] or $YBa_2Cu_3O_7$ films [32,33]. The very weak pinning is further corroborated from the absence of any difference in the ac susceptibility measured in field cooled and zero field cooled states [34]. Further details are given in the Supplemental Material [35]. Because of different requirements of shape and size, two samples with the same T_c and a thickness variation of <10% were used for transport and STS measurements. For STS, postdeposition, the film was transferred in the scanning tunneling microscope using an ultrahigh vacuum suitcase without exposure to air.

Scanning Tunneling Spectroscopy (STS)

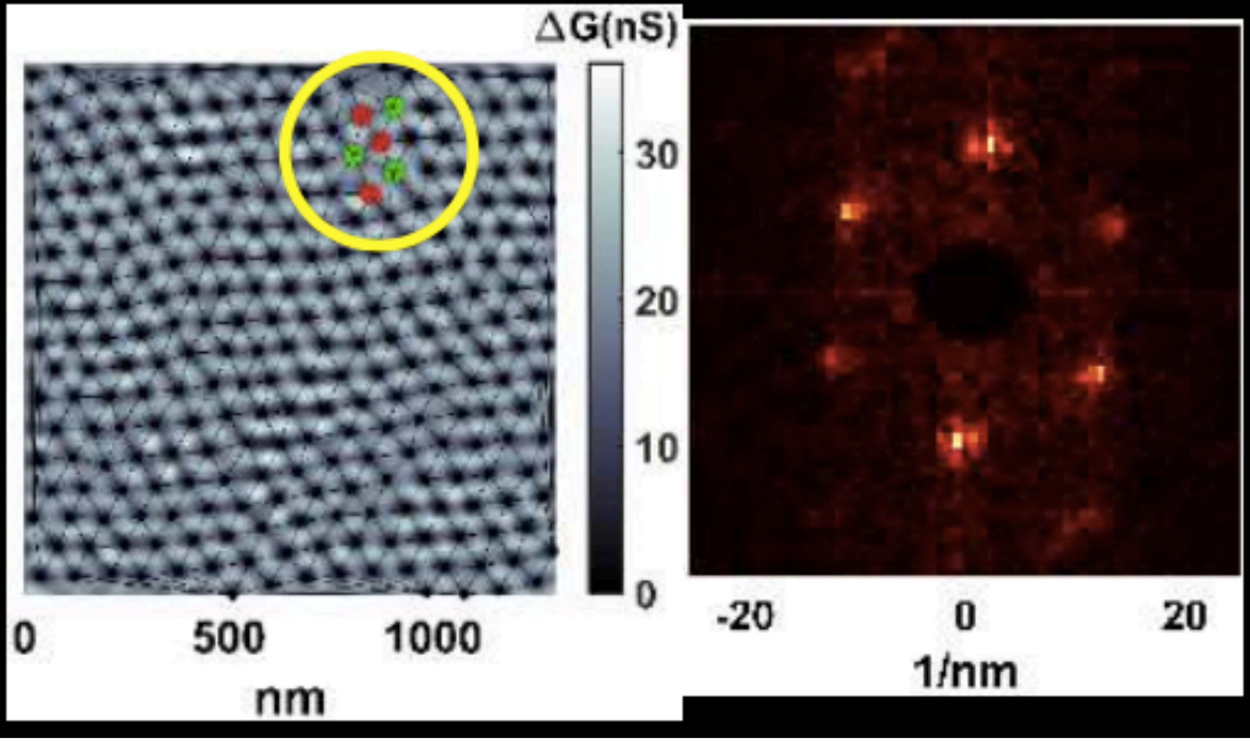
Magnetotransport

Real space evolution of vortex lattice as a function of magnetic field at 2 K

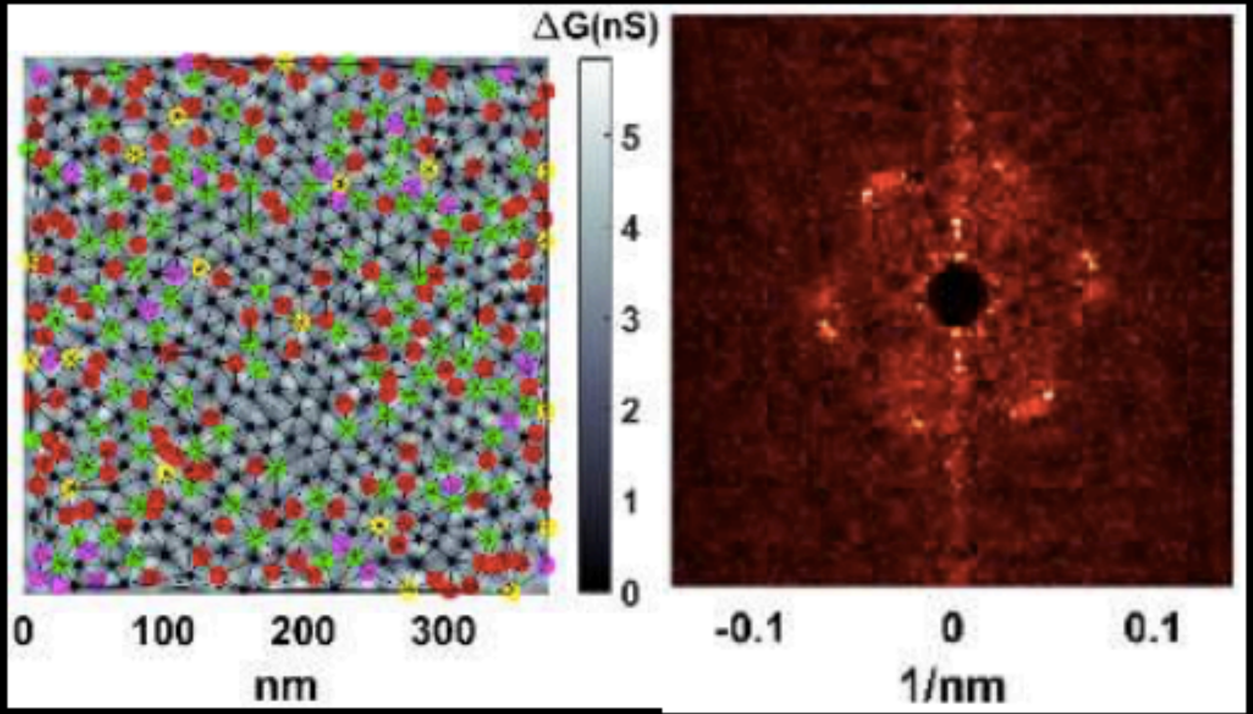
1 kOe



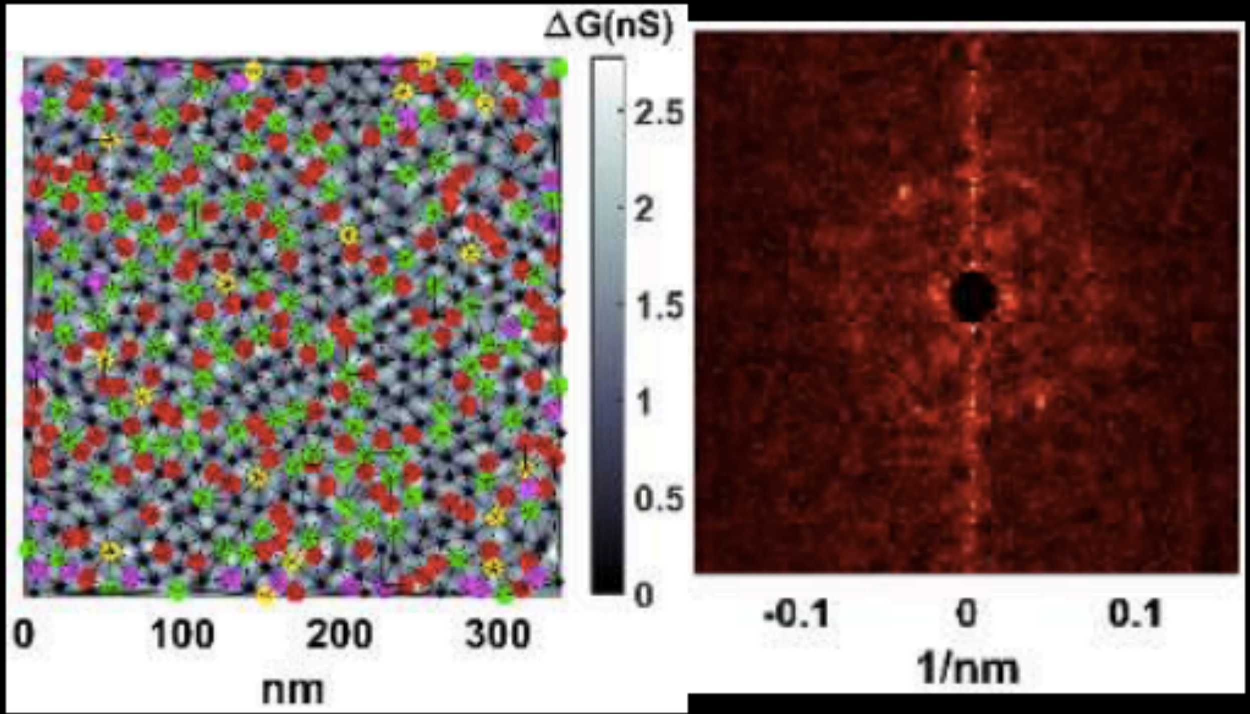
3 kOe



70 kOe



85 kOe



Melting observed using bulk measurements

Thermally Activated Flux Flow (TAFF)

TAFF Resistance: R_{TAFF} is slope of linear region of V-I curves, for $I < 100\ \mu A \ll I_c$

For $I \ll I_c$, due to Thermally Activated Flux Flow, R_{TAFF} $V/I = R_{ff}\exp(-U/kT)$

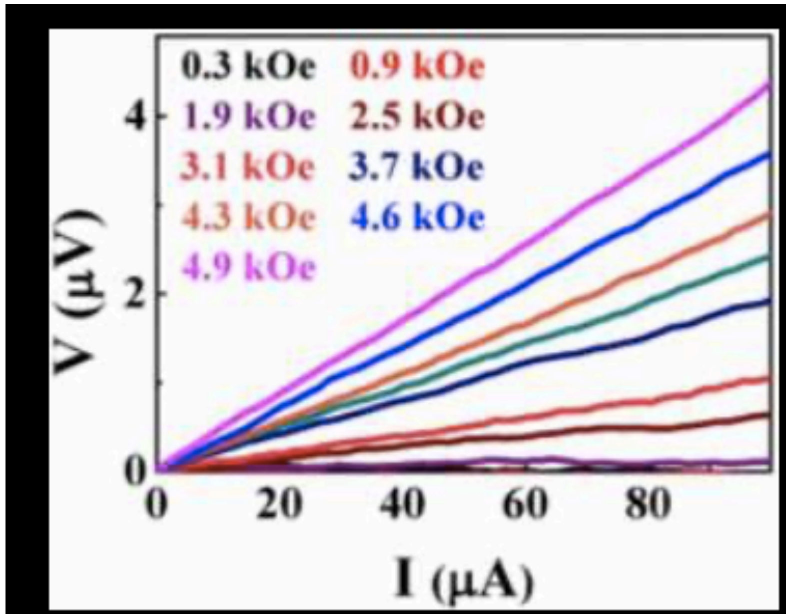
Activated nature for Solid

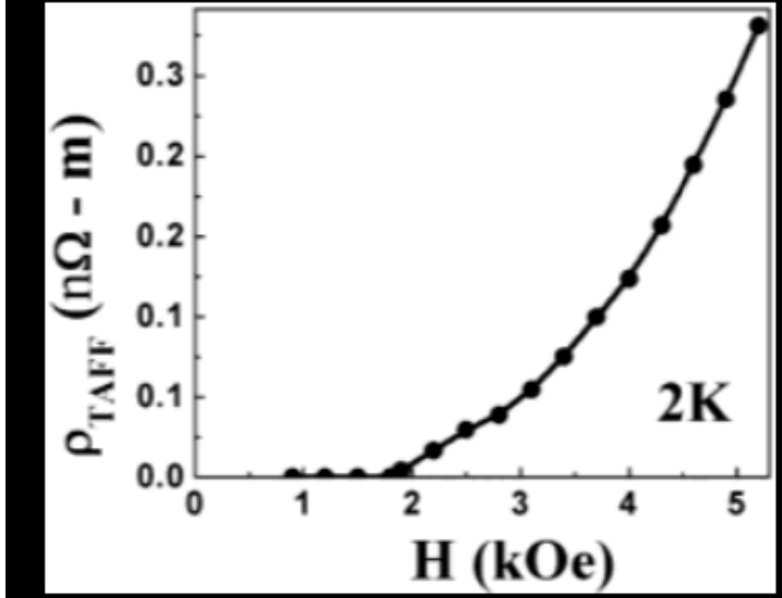
For Vortex Solid, $U(I) = U_0(I_c/I)^\alpha$

Hence, for $I \to 0$, $R_{TAFF} \to 0$

Background Potential independent liquid

For Vortex Liquid, U and R_{TAFF} is independent of I.





Below 1.9 kOe, R_{TAFF} is zero.

Ref: M. V. Feigel'man et al, Theory of collective flux creep, Phys. Rev. Lett. 63, 2303 (1989)

Differentiating solid from hexatic liquid

$$V/I = R_{ff} \exp(-U/kT)$$

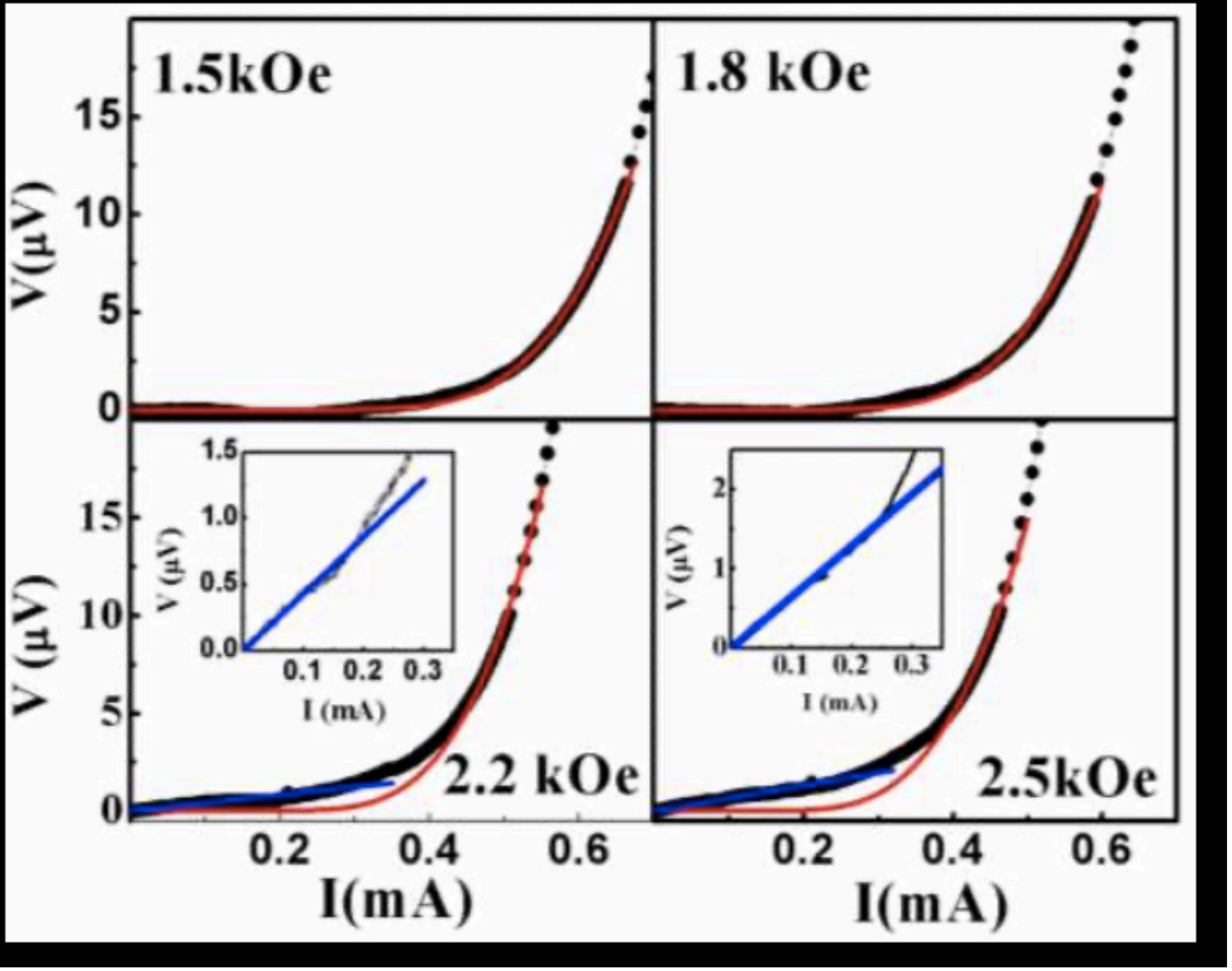
Solid: $U(I) = U_0(I_c/I)^{\alpha}$

Below H=1.9 kOe,
V-I curves are well fitted,
taking α=1

Liquid: U is independent of I

Above H=1.9 kOe,
V-I curves deviate from
the exponential form;
rather becomes linear.

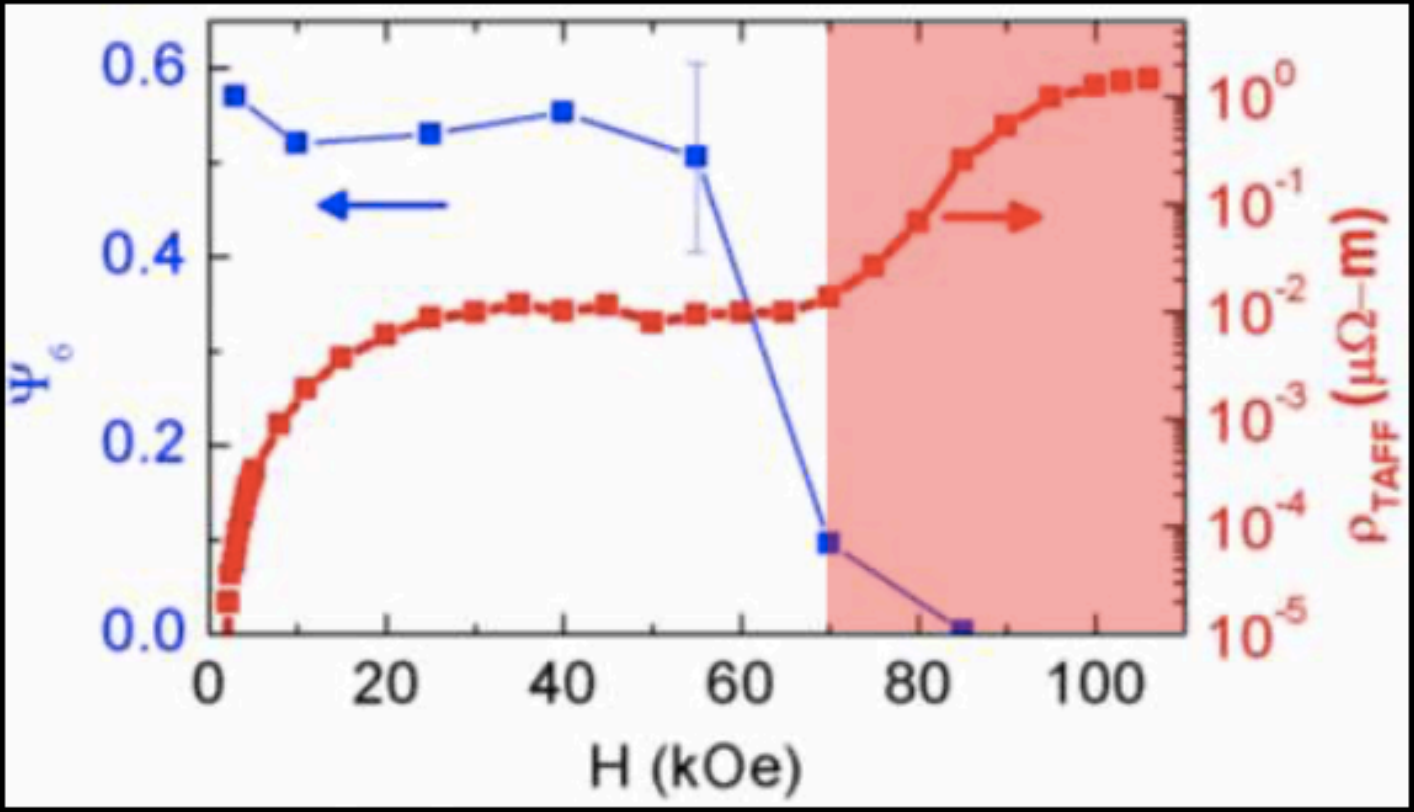
2 K

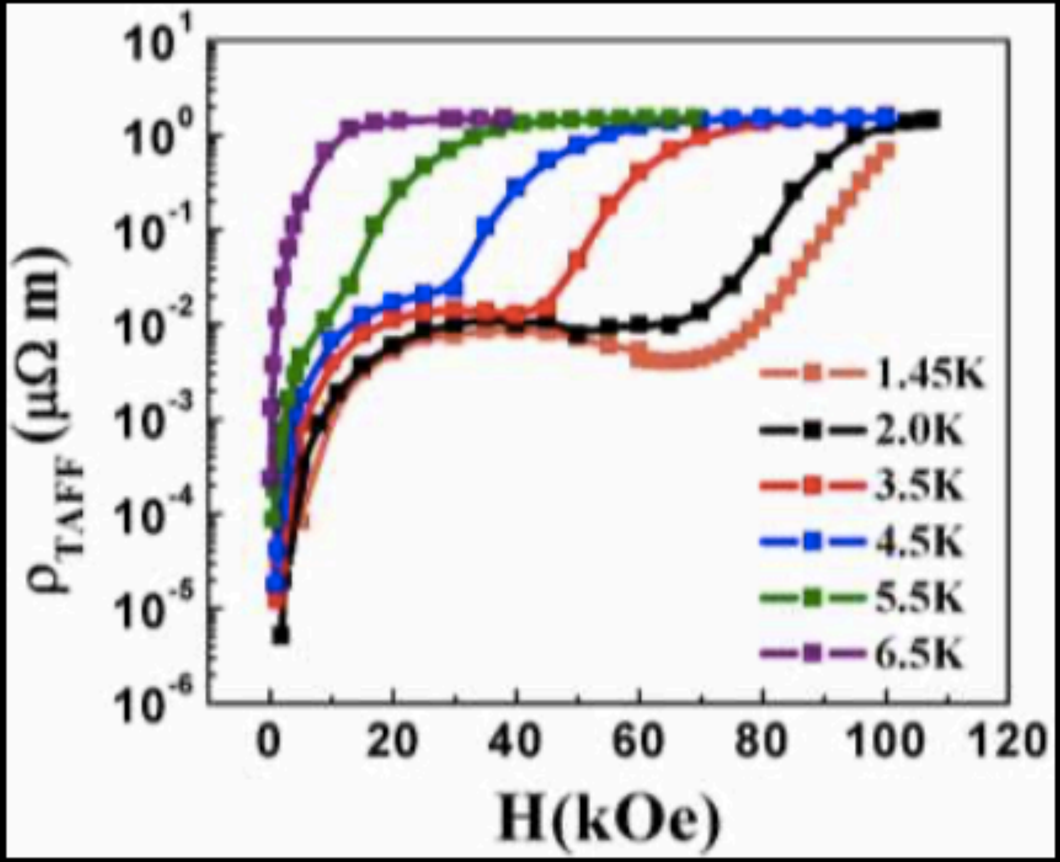


At 2 K, H=1.9 kOe is the transition point from Vortex solid to Hexatic fluid.

Hexatic to vortex liquid transition

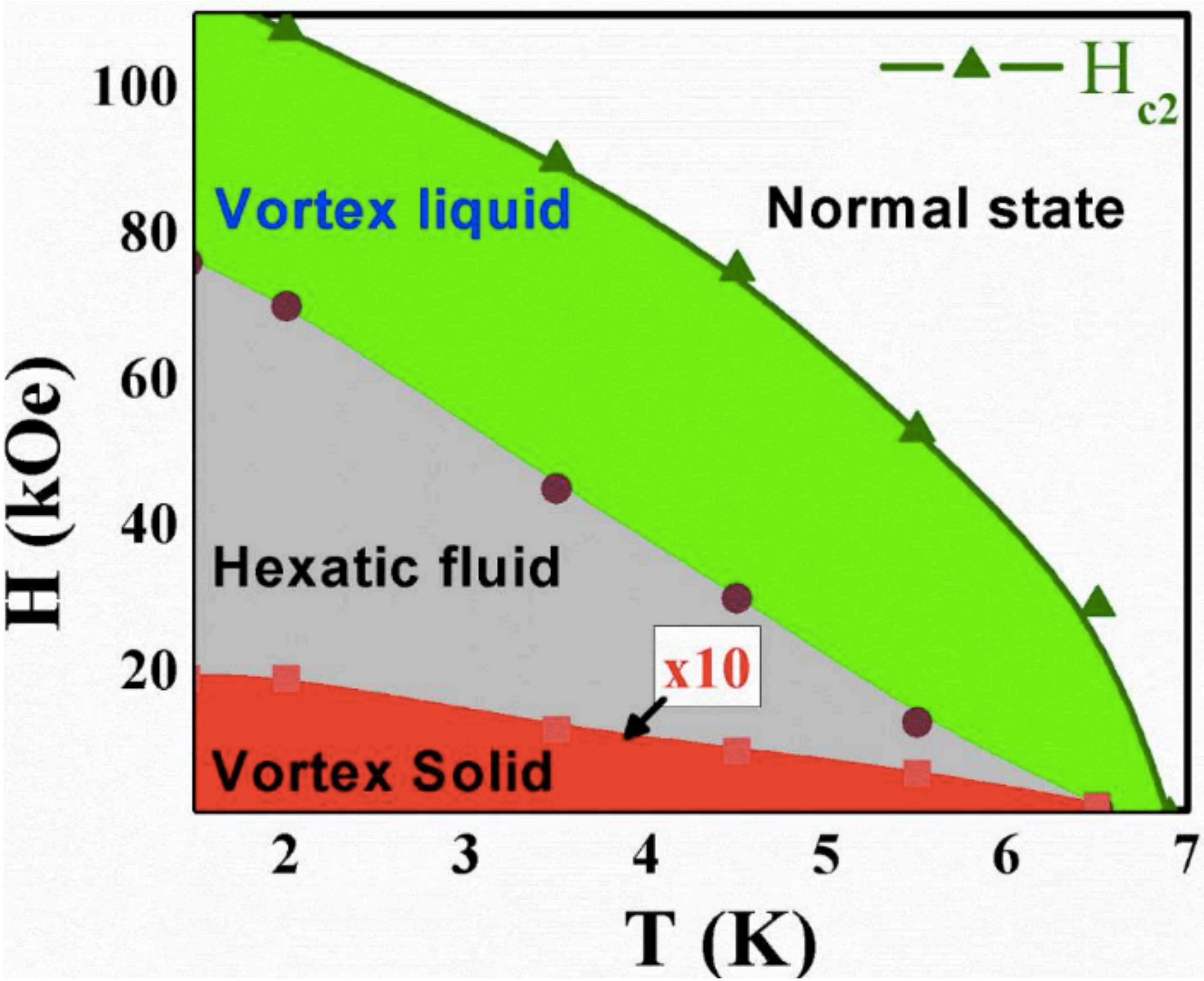
- Six-fold Orientational Order Parameter:
  $\Psi_6 = \frac{1}{N}\langle \sum_{k,l} e^{[6i(\phi_k - \phi_l)]} \rangle$
  (For perfect hexagonal lattice, $\Psi_6 = 1$)





- Hexatic liquid to Isotropic liquid transition point is identified.
- H_{c2} is determined.

The Resulting Phase Diagram



Summary

First Observation of Hexatic Fluid Phase in a 2D Superconducting Film

Pinning Significantly Weaker than in Previous Studies

STS (imaging)
Magnetotransport ("shear")

Questions/Ideas for the Future

Size-Dependence of Hexatic Order Parameter ??

Low T limit of the Hexatic Fluid: Quantum Vortex Fluid ??

What happens in Layered Films ??


рахмат
danke
謝謝
ngiyabonga
teşekkür ederim
Баярлалаа
spas
mersi
kia ora
barka
welalin
tack
mahalo
спасибо
faafetai lava
vinaka
спасибі
blagodaram
dank je
misaotra
matondo
paldies
grazzi
tapadh leat
kiitos
dankie
nanni
nandri
dhanyavad
thank you
gracias
хвала
asante
manana
obrigada
tenki
bedankt
bayarlalaa
gracie
hvala
mauruuru
köszönöm
akun
dankon
aciu
djiere dieuf
tau
mochchakkeram
murakoze
enkosi
dziękuję
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sulpay
go raibh maith agat
sobodi
dėkuji
sagolun
sukriya
kop khun krap
taiku
obrigado
mesi
ありがとう
arigatô
takk
dakujem
trugarez
didi madloba
najis tuke
tanemirt
grazie
kam sah hamnida
rahmat
terima kasih
rahmet
diolch
dhanyavadagalu
shukriya
merce
мерси
তোমাকে ধন্যবাদ
감사합니다
xiexie
ευχαριστώ
merci