超導物理

Complex world of topological solitons. Magnetism and dynamics in type II superconductors

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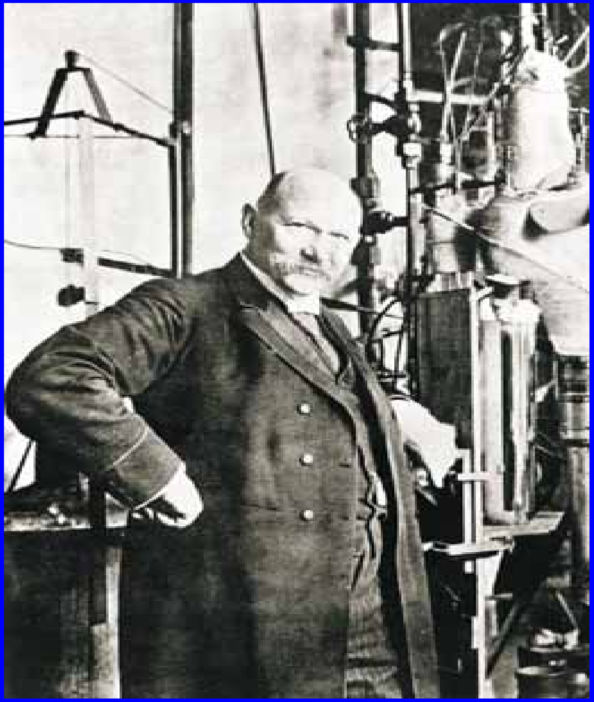
Outline

1. Superconductivity, TC and basic experimental facts.
2. Phenomenological Ginzburg - Landau theory and the Abrikosov vortex solution.
3. A systematic method to obtain the vortex lattice solutions of GL equations.
4. Quantum mechanical analogy and the thermal fluctuations in London approximation.
5. Thermal fluctuations and melting of the vortex lattice (a review).

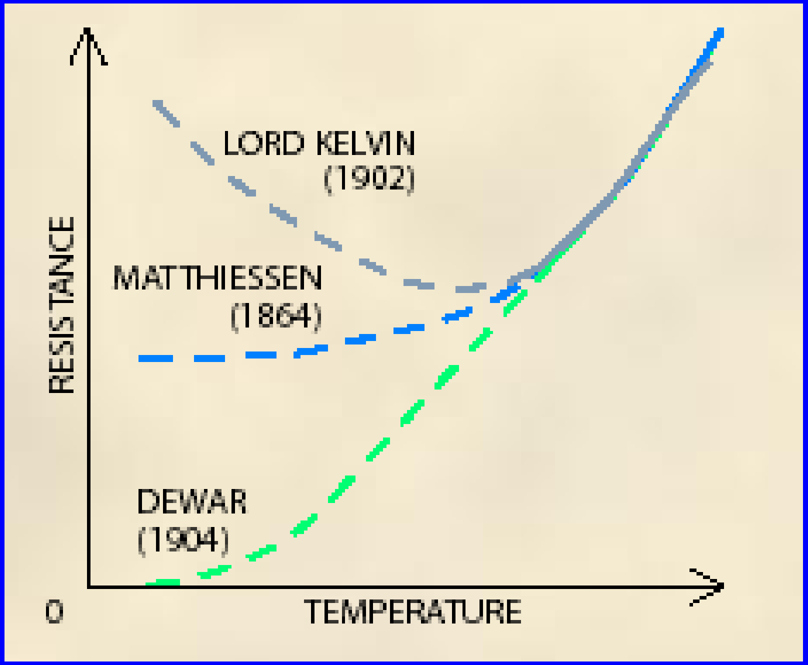
Discovery of dissipationless flow

Low Tc superconductors

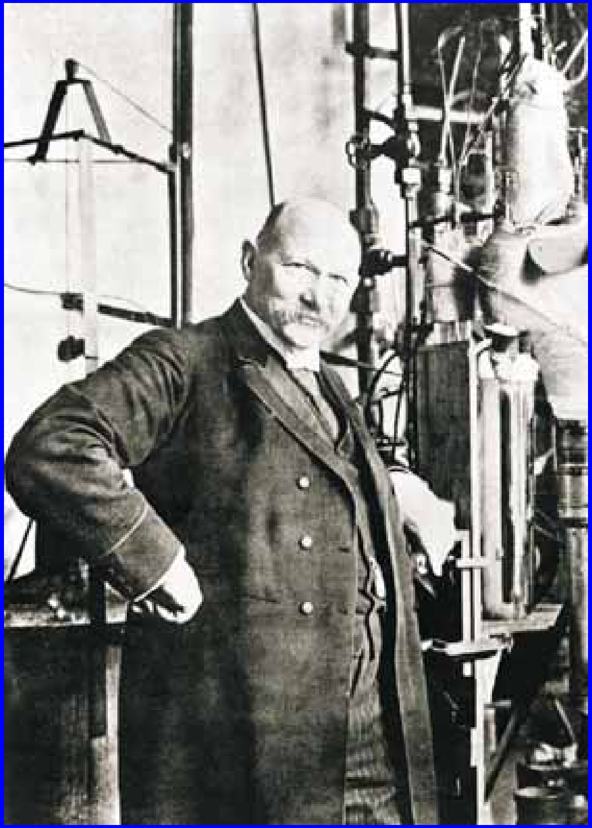
Theoretical predictions of resistivity of metals at low T

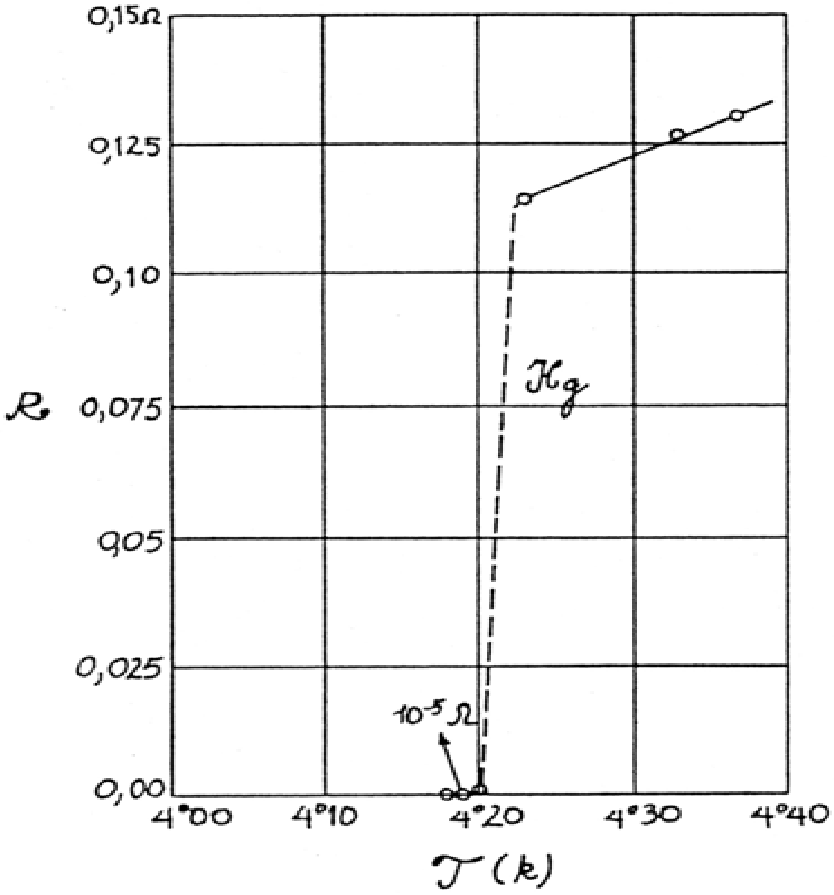


Kamerlingh Onnes (1911)



Experimental results on resistivity of Hg at low T

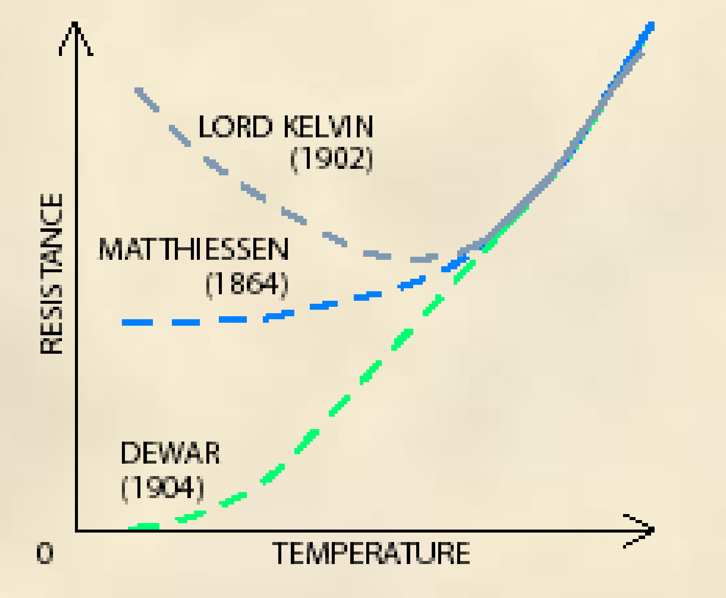




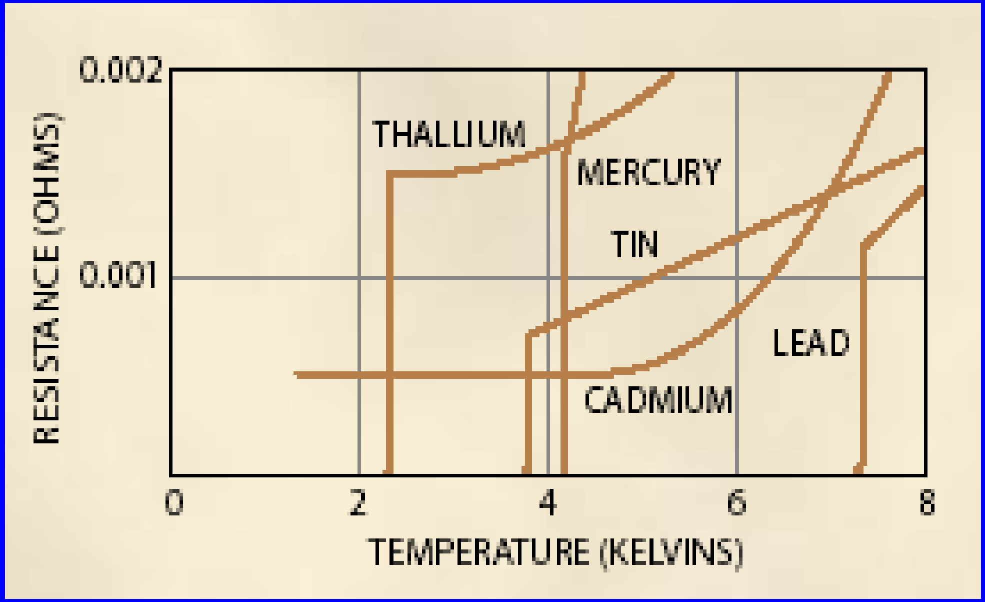
Kamerlingh Onnes (1911)

Summary of R(T) at low temperatures

Theoretical predictions



Experiment



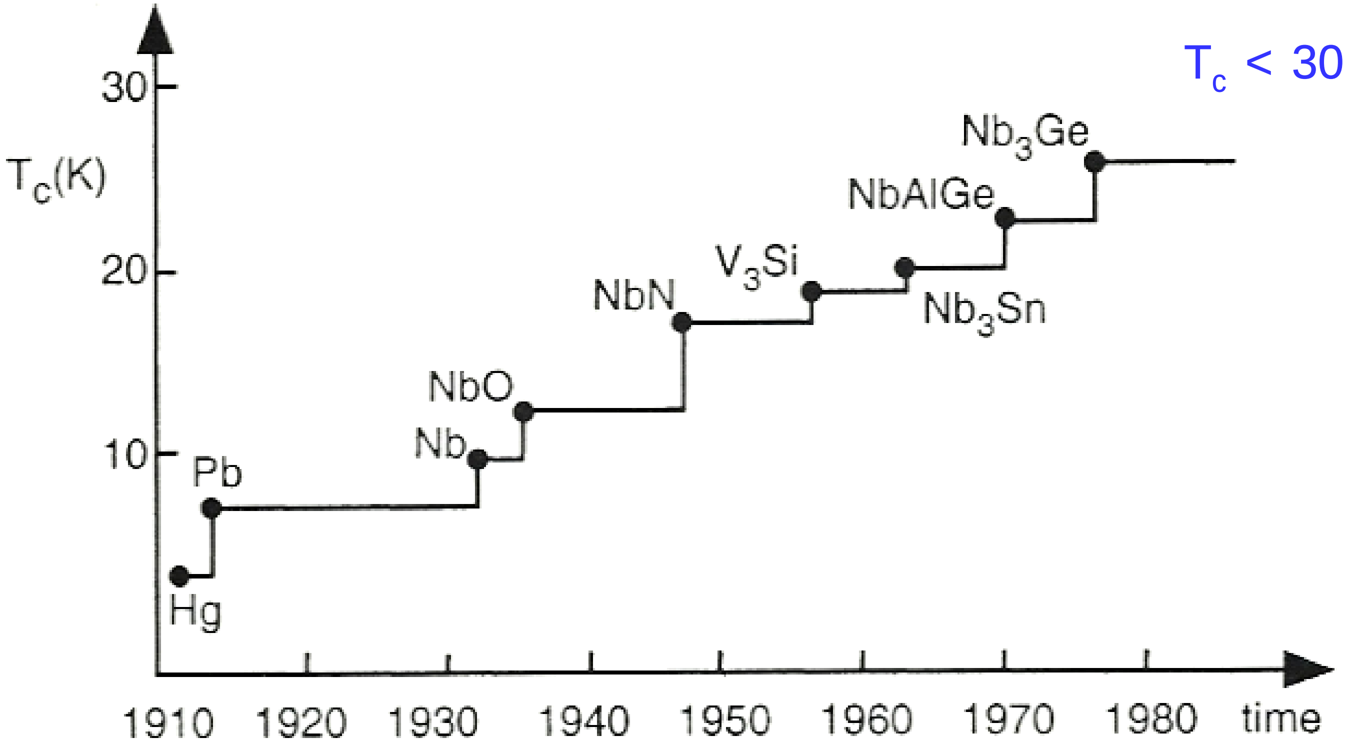
First basic property of superconductors:

perfect conductivity

Metals and their Tc

	Be 0.026																
												Al 1.140	Si* 7	P* 5			
			Ti 0.39	V 5.38							Zn 0.875	Ga 1.091	Ge* 5	As* 0.5	Se* 7		
			Zr 0.546	Nb 9.50	Mo 0.90	Tc 7.77	Ru 0.51	Rh 0.0003			Cd 0.56	In 3.4035	Sn 3.722	Sb* 3.5	Te* 4		
Cs* 1.5	Ba* 5	La(fcc) 6.00	Hf 0.12	Ta 4.483	W 0.012	Re 1.4	Os 0.655	Ir 0.14			Hg 4.153	Tl 2.39	Pb 7.193	Bi* 8			
			Ce* 2													Lu 0.1	
			Th 1.368	Pa 1.4	U* 2												

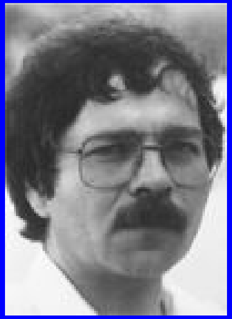
Critical temperature of superconductors

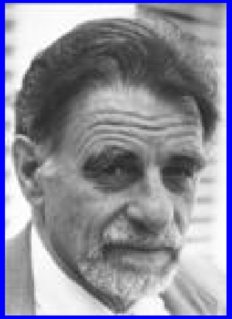


$T_c < 30$ K

“conventional” superconductors: metals and alloys

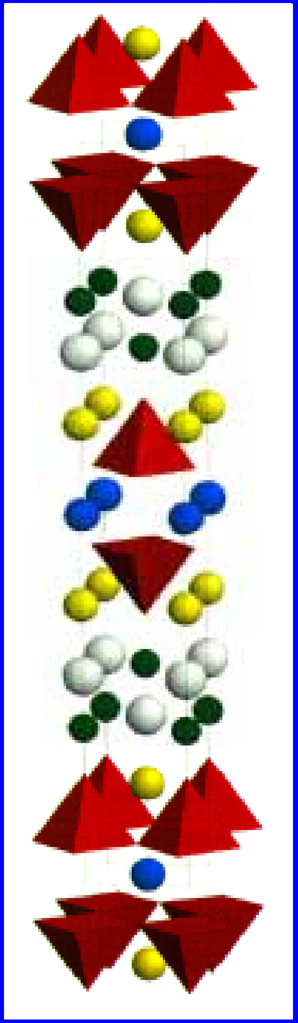
2.High Tc superconductors



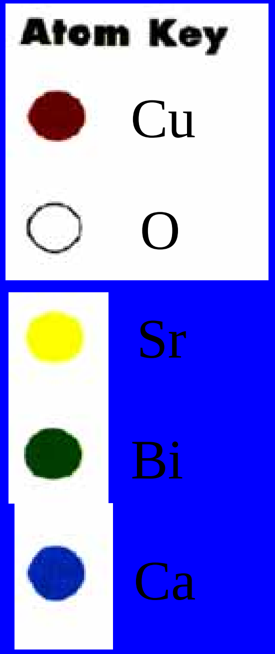


J. Georg Bednorz K. Alexander Müller

$(La_{1.85}Ba_{.15})CuO_4$
$YBa_2Cu_3O_7$
$Bi_2Sr_2CaCu_2O_8$
$Bi_2Sr_2Ca_2Cu_3O_{10}$
$Tl_2Ba_2Ca_2Cu_3O_{10}$
$Hg_{0.8}Tl_{0.2}Ba_2Ca_2Cu_3O_{8.33}$

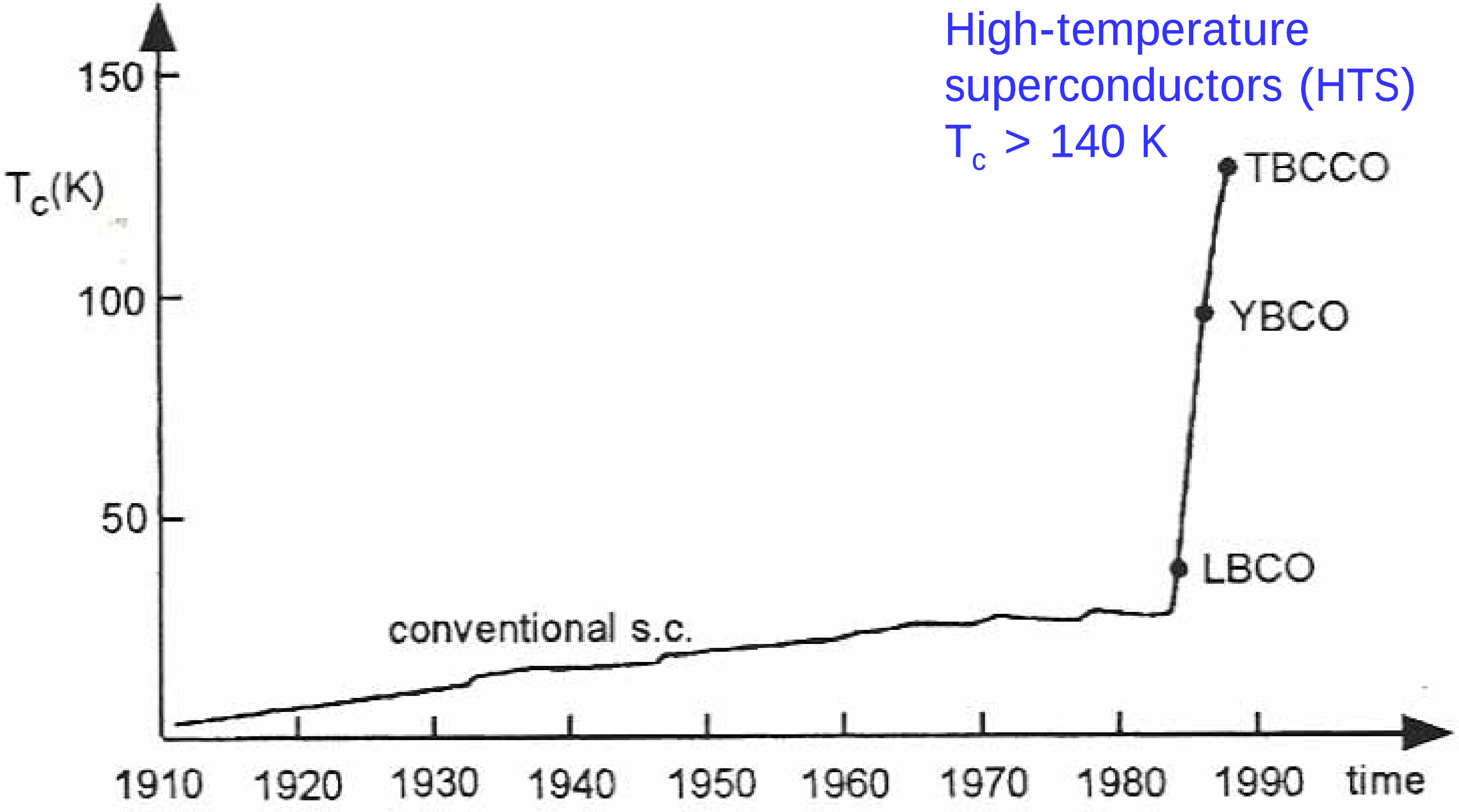


$Bi_2Sr_2CaCu_2O_8$



CuO_2 double layer

Critical temperature of superconductors



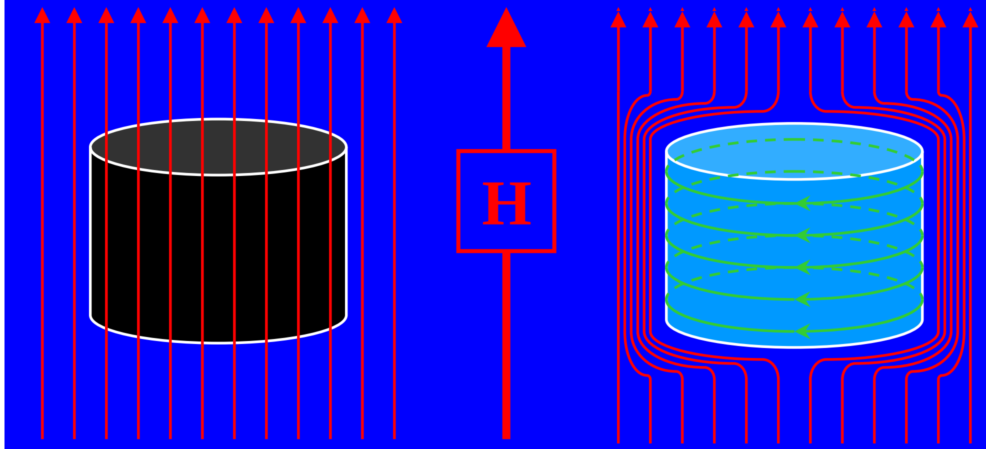
High-temperature superconductors (HTS)
$T_c > 140$ K

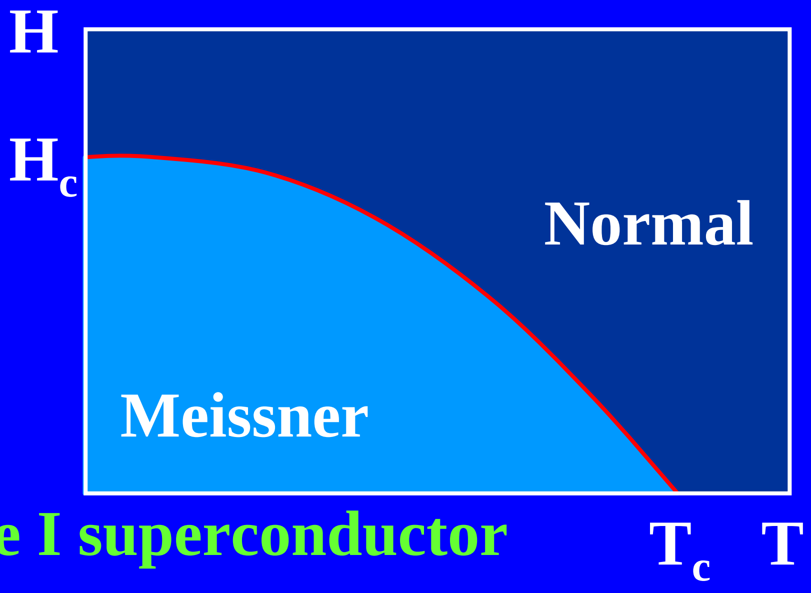
Magnetism in type II superconductors

Two defining electromagnetic properties of superconductor:

1. Zero resistivity

2. Perfect diamagnetism

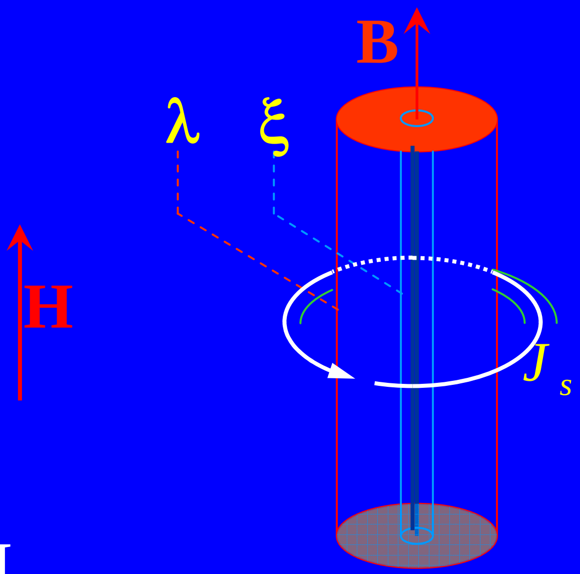




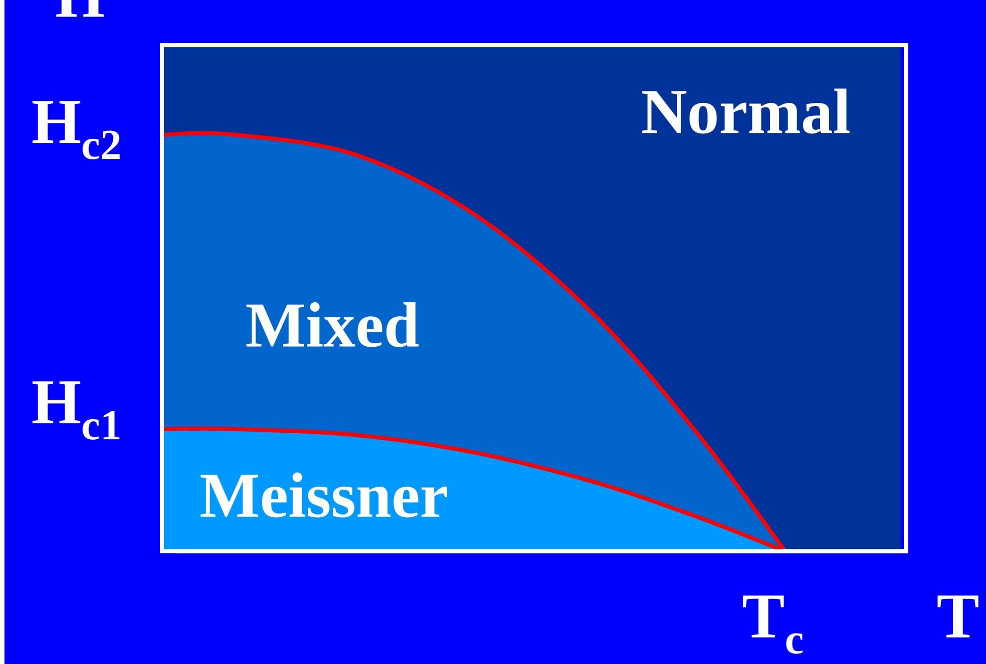
Magnetic flux is expelled from a Type I superconductor

However the situation in the Type II superconductors (including all the high Tc) is much more complex: a strong enough magnetic field does penetrates in the form of an array of magnetic “vortices”.

Magnetic (Abrikosov) vortices in a type II superconductor



$\lambda >> \xi$



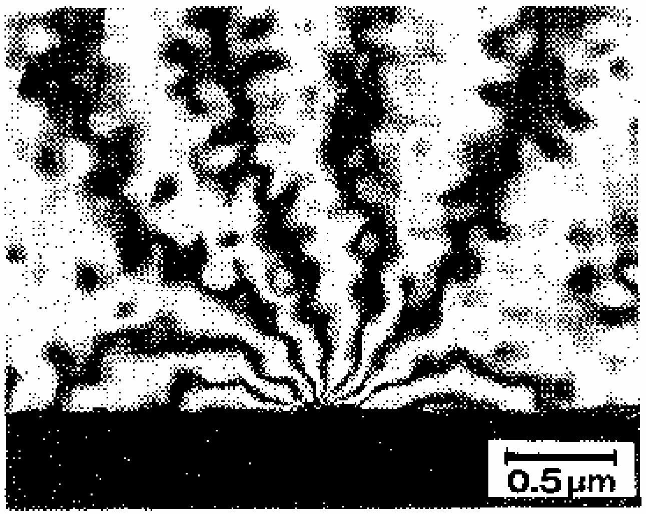


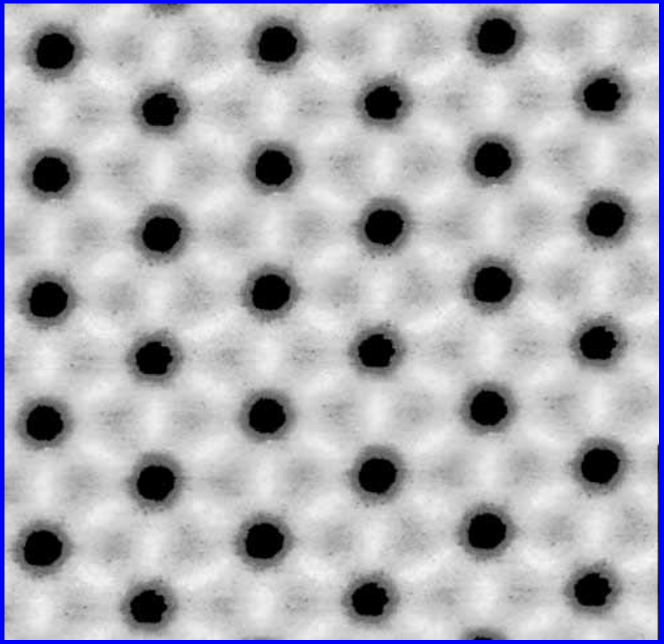
FIG. 2. 16-times phase-amplified interference micrograph of a single fluxon (film thickness =0.2 μm and sample temperature =4.5 K).

Electron tomography

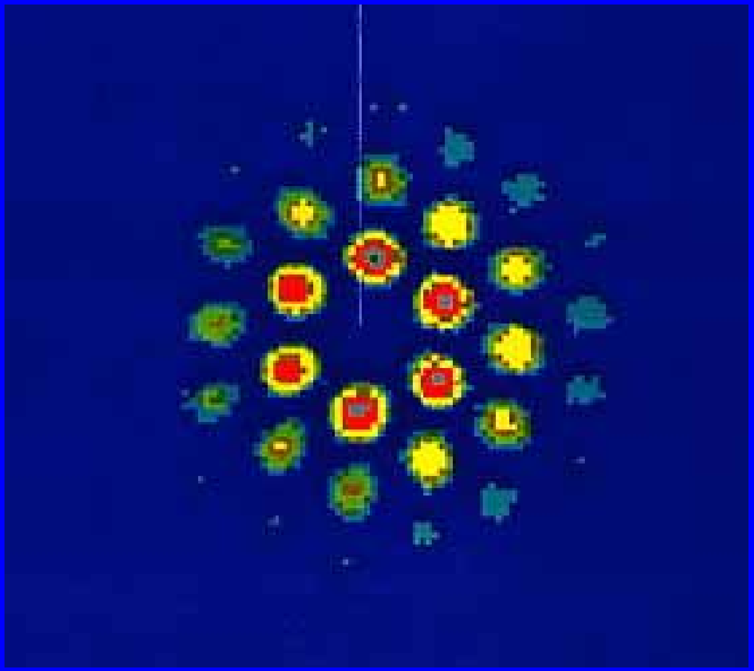
Tonomura et al, PRL66,2519 (1993)

The first defining property, perfect diamagnetism, is lost

Vortex line repel each other forming highly ordered structures like flux line lattice (as seen by STM and neutron scattering)



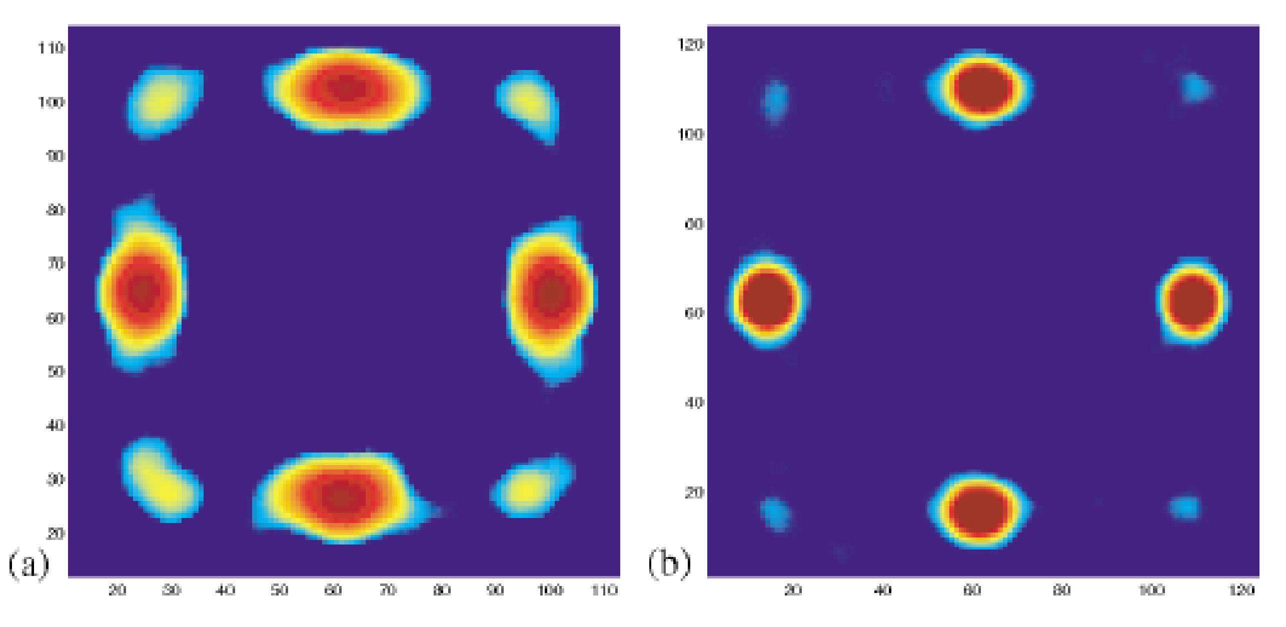
**Pan et al
(02)**

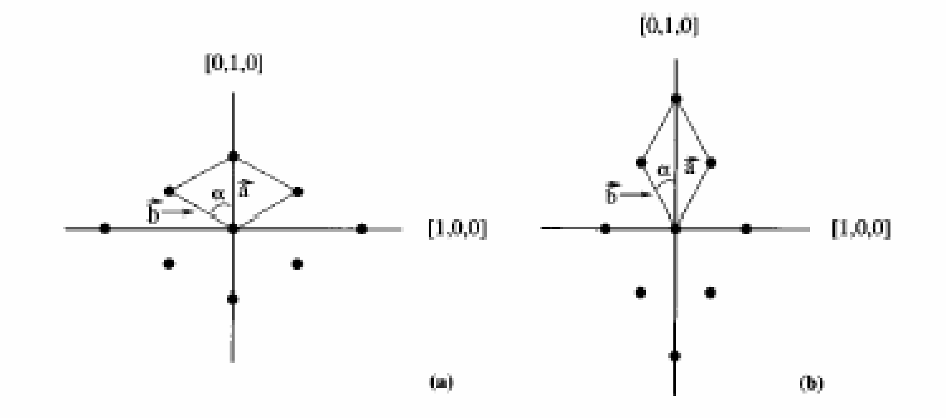


**Park et al
(00)**

Sometimes one directly observes phenomena familiar from (atomic) solids. Example: structural transition between two lattices

High Tc superconductors (YBCO is shown) have a fourfold symmetry, which is spontaneously broken in the rhombic phase of the vortex lattice





Brown et al, PRL92,067002 (04)

Increased role of thermal fluctuations in new type II materials or high magnetic fields leads to qualitatively new effects like melting of the lattice into a liquid

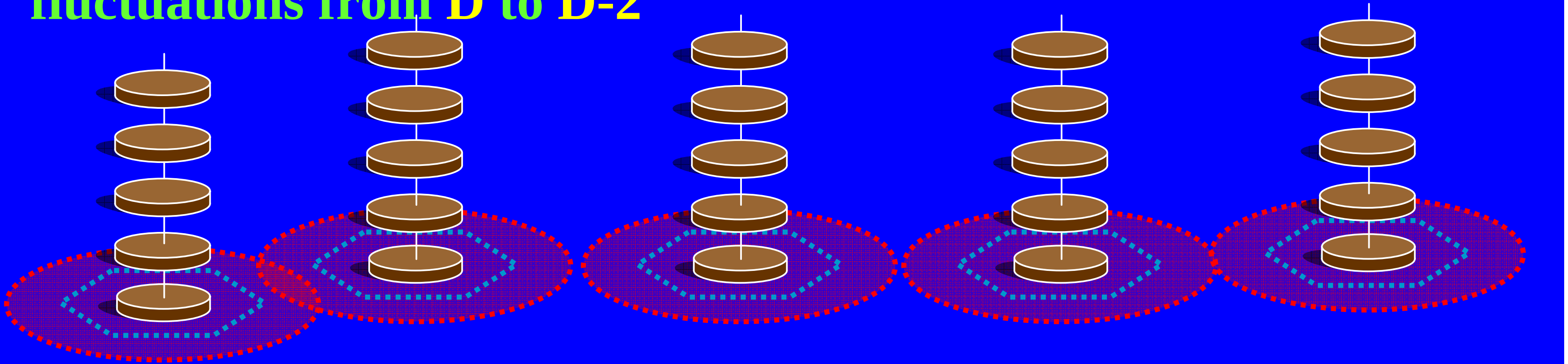
1. Ginzburg number characterizing the strength of thermal fluctuations is much larger for high Tc

$$Gi \equiv \frac{1}{2}\left(\frac{T_c}{H_c{}^2 \xi^3}\right)^2$$

Metals, low Tc:: $Gi \approx 10^{-8} - 10^{-6}$

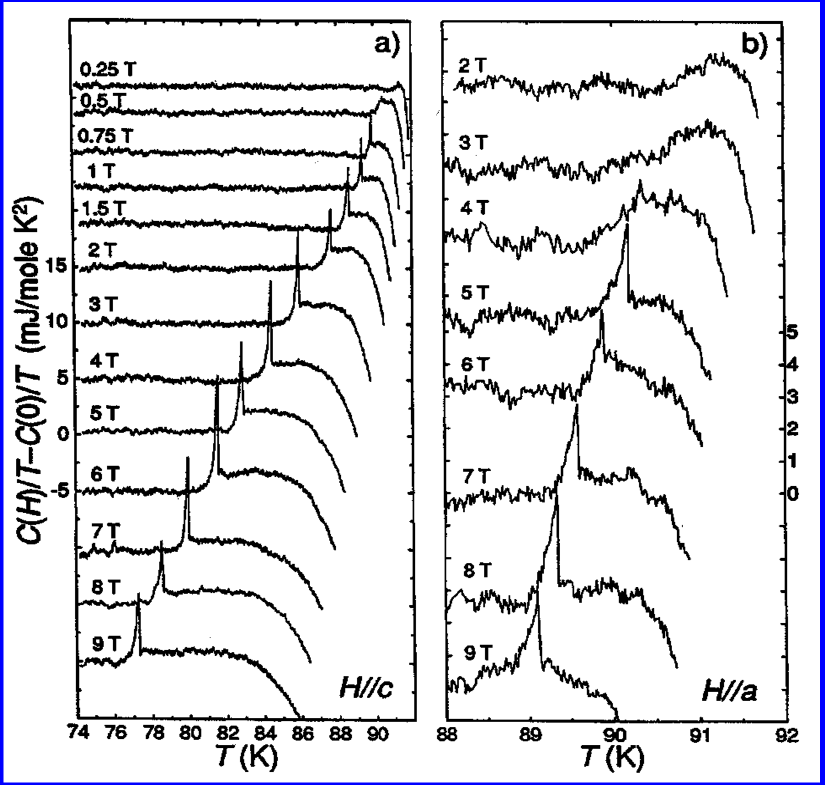
High Tc: $Gi \approx 10^{-4} \to 0.1$

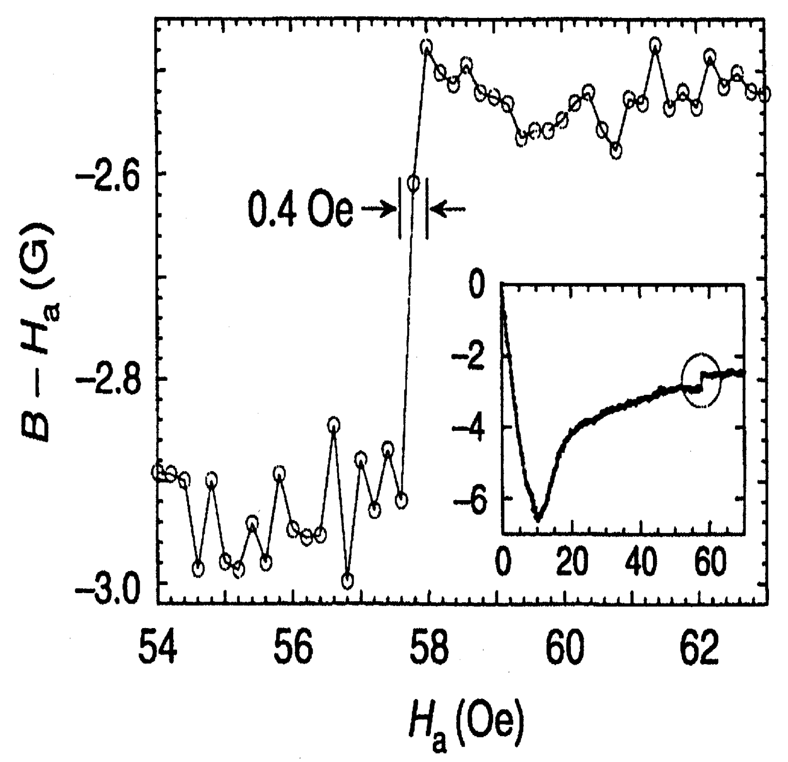
2. Strong magnetic field effectively reduces dimensionality of fluctuations from D to D-2



Melting of the vortex lattice

with a magnetization (entropy) jump and a spike on top of the jump in specific heat



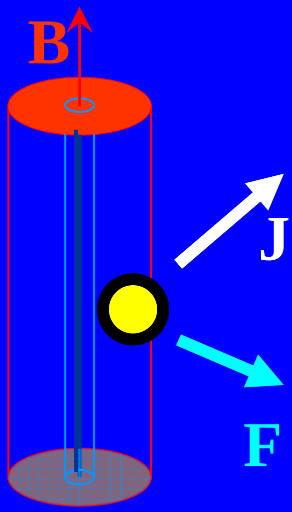


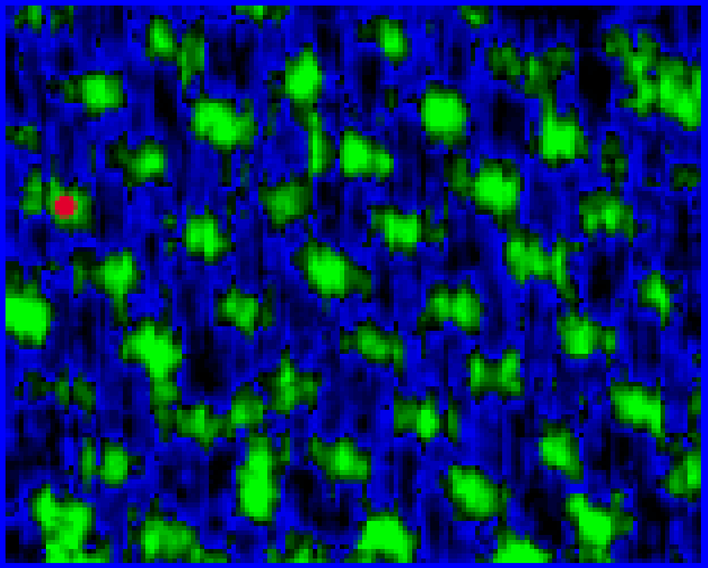
Schilling et al
Nature 382, 791 (1996)

Zeldov et al
Nature 375, 373, (1995)

Fast dynamics on the mesoscopic scale

Fluxons are light and move. The motion is generally a friction dominated one with energy dissipated in the vortex cores. An external current "induces" the flux flow, causing voltage.

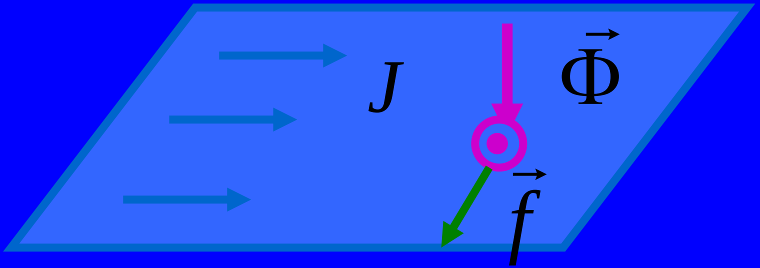


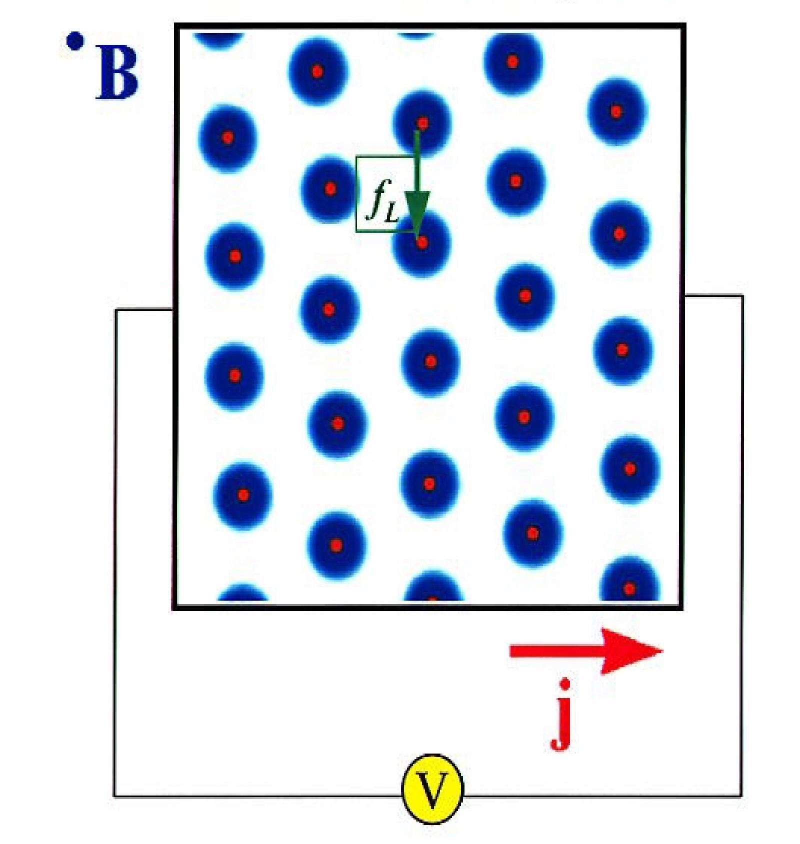


Troyanovsky et al (04)

Field driven flux motion probed by STM on NbSe2

The current “induces” flux flow, causing voltage via “phase slips”.



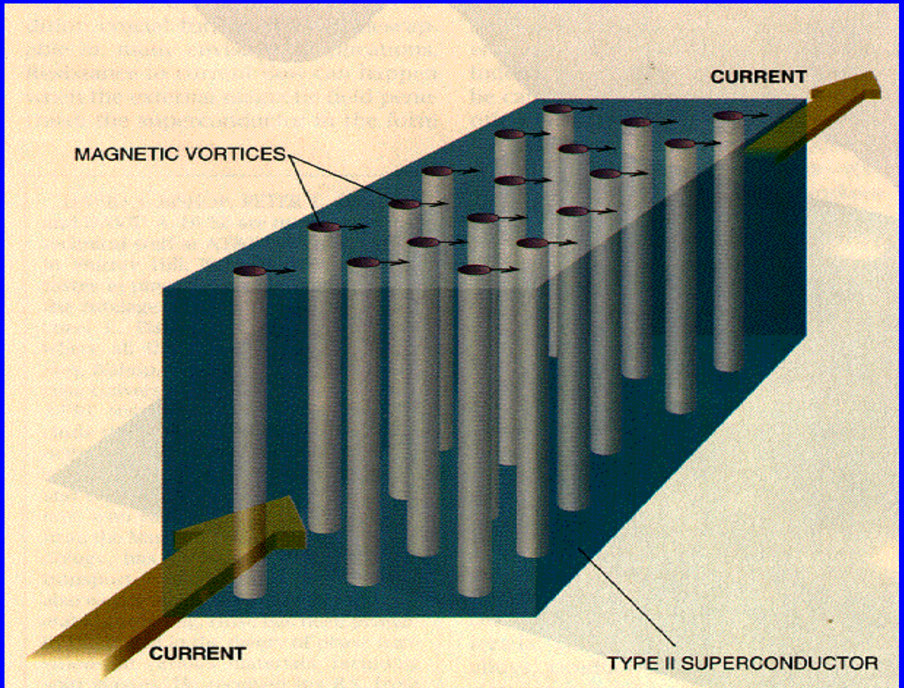


Phenomenologically the friction force is described (in 2D) by:

$$f_{dissipation} = \eta \frac{d}{dt}\vec{x} \equiv \eta v$$

The second defining property, zero resistivity, is lost in magnetic field just above Hc1

This however is not end of the story

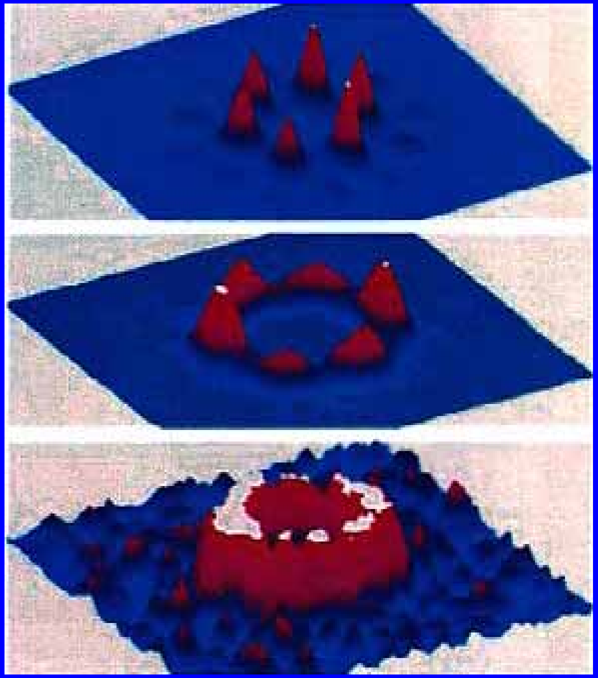


CURRENT FLOW through a superconductor (*blue rectangular box*) can be disrupted by vortices (*cylinders*). Each vortex consists of a ring of circulating current induced by an external magnetic field (*not shown*). The applied current adds to the circulating current on one side of the vortex but subtracts from the other. The net result is a force that pushes the vortices at right angles to the current flow; the movement dissipates energy and produces resistance.

Pinning restores loss-free current

Point - like disorder

Defects are pinning centers of vortices

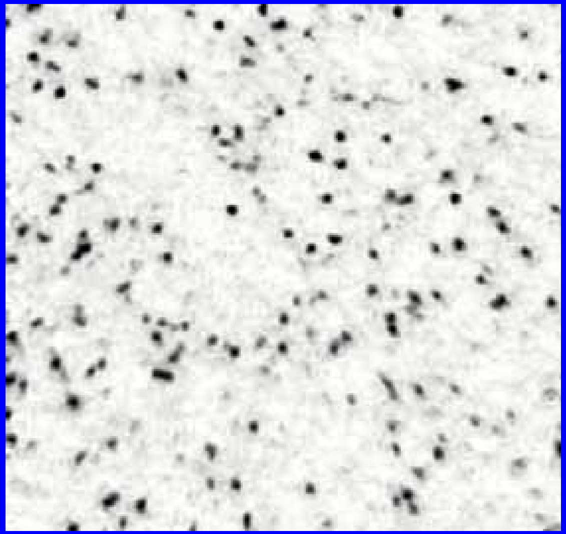


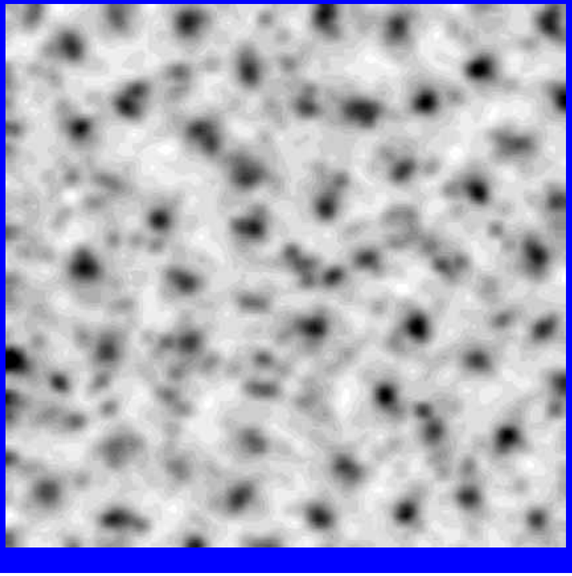
Disappearance of Bragg peaks as disorder increases

Gammel et al PRL 80,833 (1998)

STM of both the pinning centers (top) and the vortices (bottom)

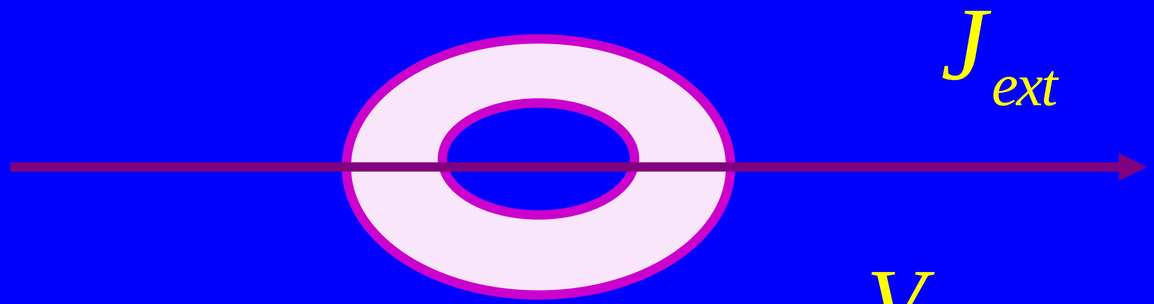
Pan et al PRL 85, 1536 (00)





Vortex loops, KT pairs and avalanches

Current produces expanding vortex loops even in the Meissner phase leading to non-ohmic "broadening" of I-V curves

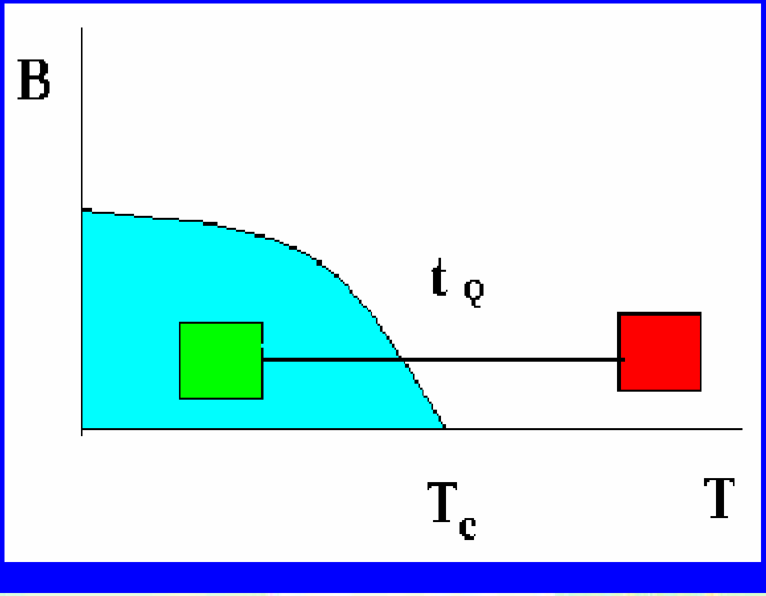


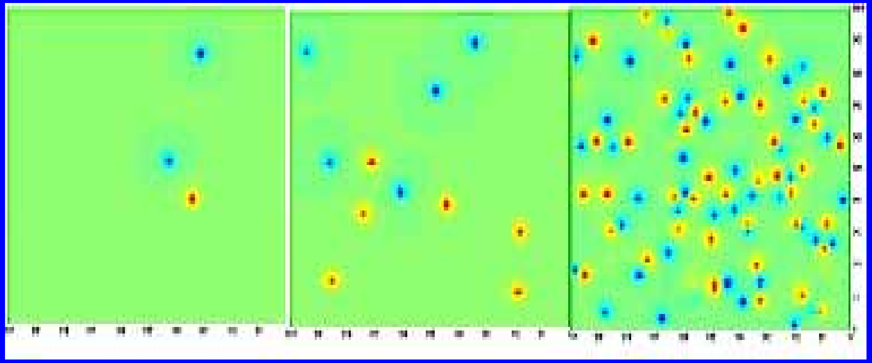
$$\rho \equiv \frac{V}{I} \propto e^{-const/(T\,I)}$$

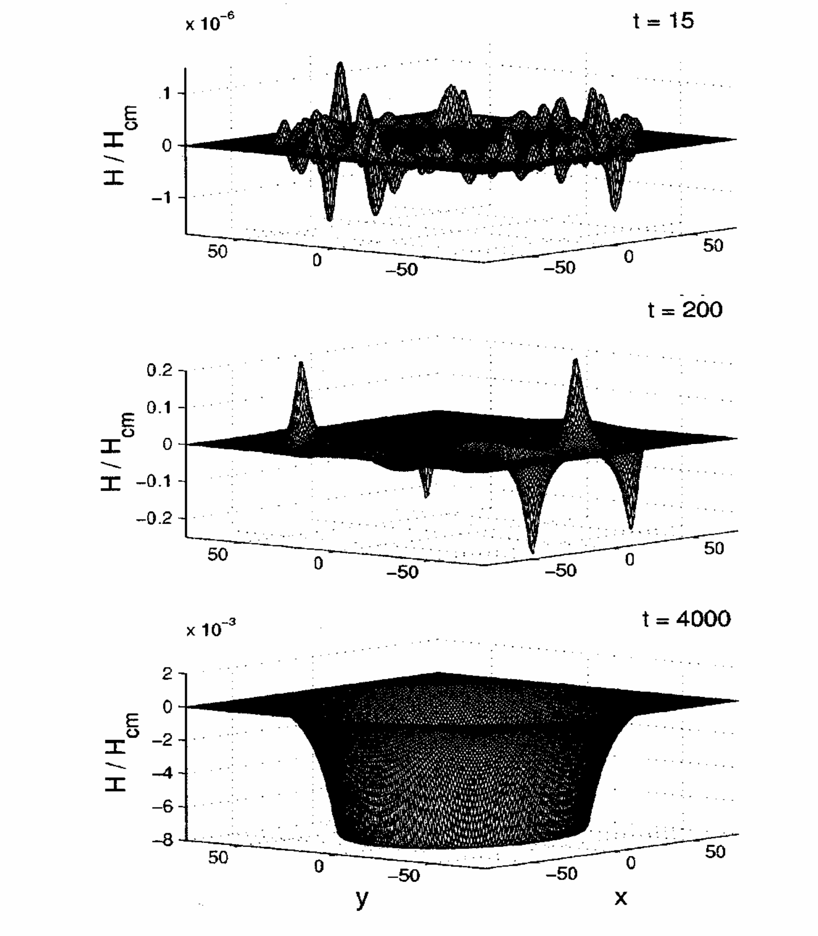
In 2D thermal fluctuations generate a curious Kosterlitz – Thouless vortex plasma exhibiting many unique features well understood theoretically

Unstable normal domain under homogeneous quench splits into vortex-antivortex (KT) plasma

Kirtley,Tsuei and Tafuri (2003)







Polturak, Maniv (2004)

Scanning SQUID magnetometer

Spontaneous flux in rings

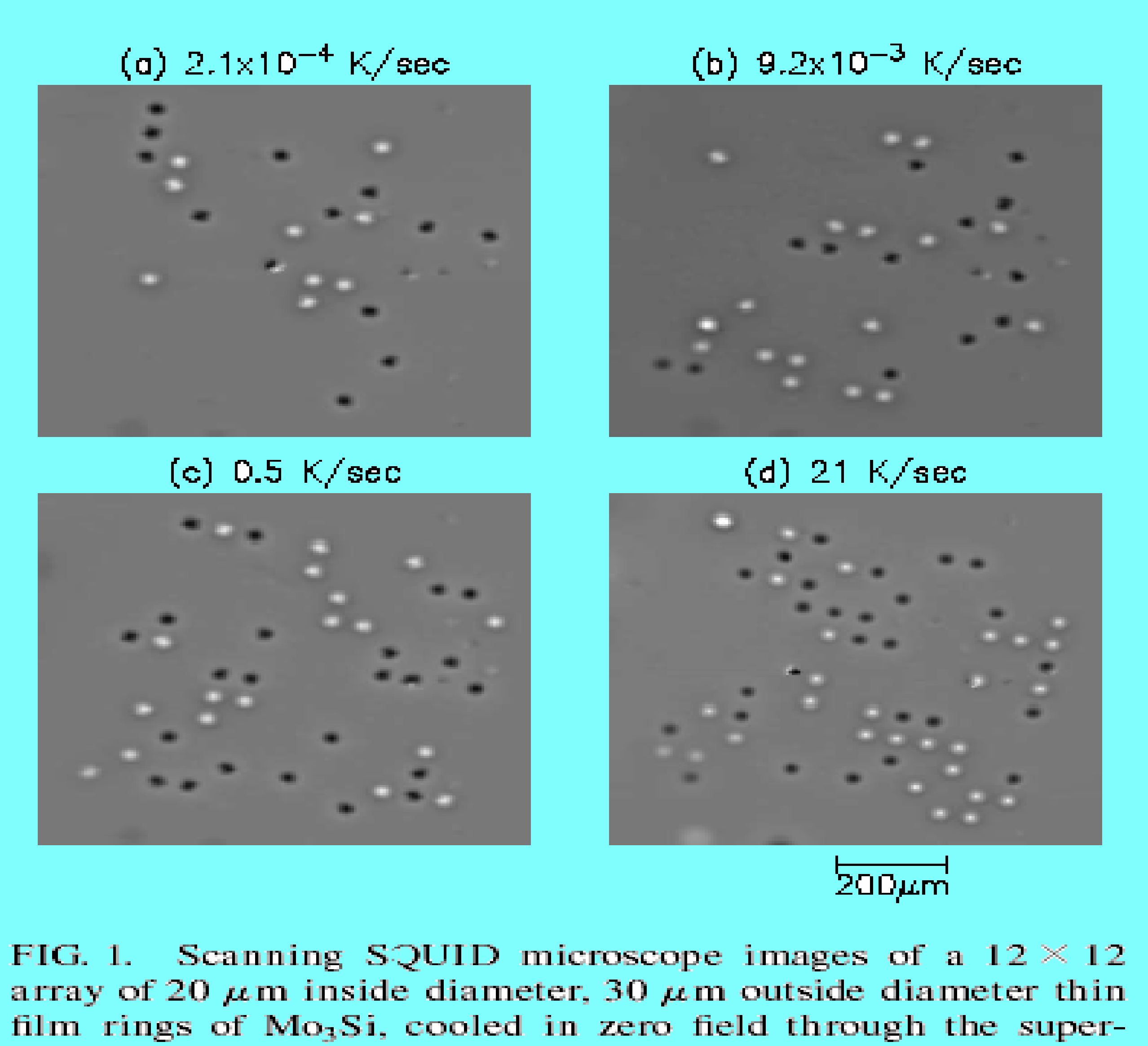


FIG. 1. Scanning SQUID microscope images of a 12 × 12 array of 20 μm inside diameter, 30 μm outside diameter thin film rings of Mo_3Si, cooled in zero field through the super-

Kirtley, Tsuei and Tafuri (2003)

Vortex front propagation is normally shock wave like, but occasionally creates avalanches

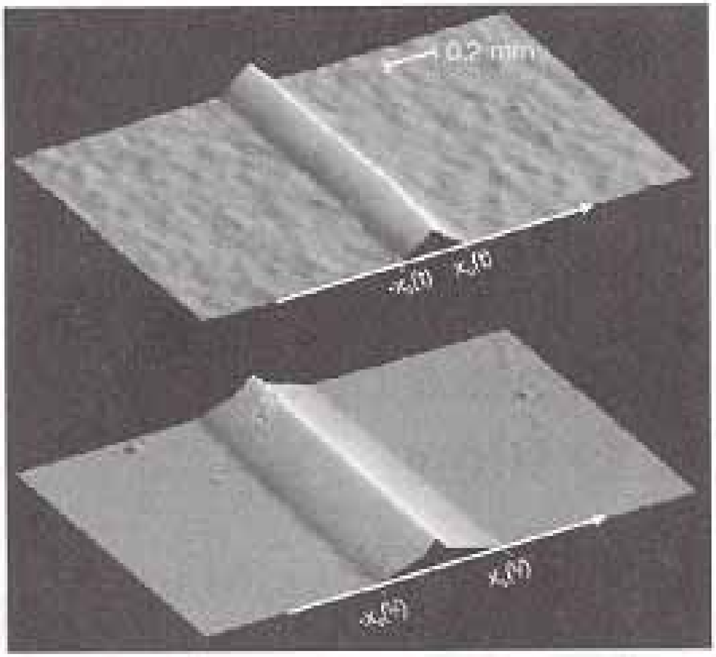
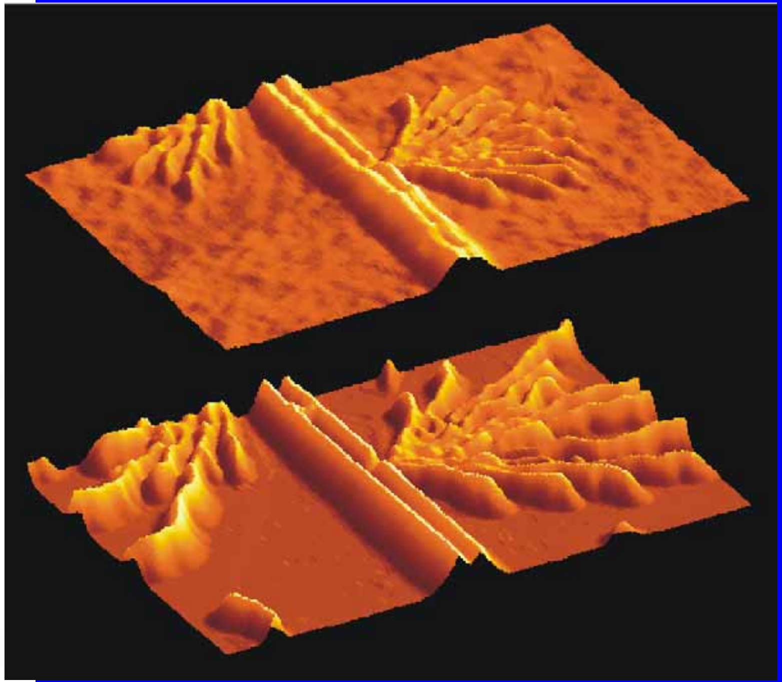


Fig. 1. Magnetic flux profiles after a time delay of 67.8 ns and of the final state ($T = 30$ K, $B_a = 15.2$ mT).



after
50 ns

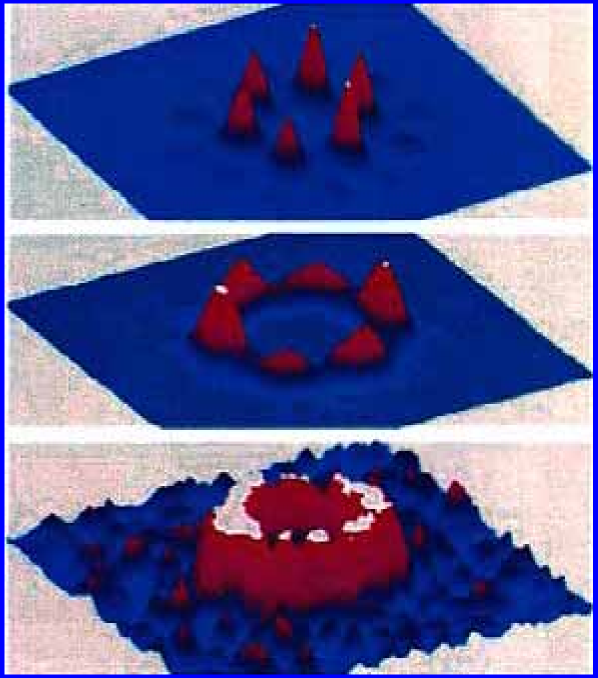
after
10 s

Boltz et al (2003)

Magneto-optics in YBCO films, 10K, B=30mT, size 2.3x1.5 mm

Point - like disorder

Defects are pinning centers of vortices



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Gammel et al PRL 80,833 (1998)

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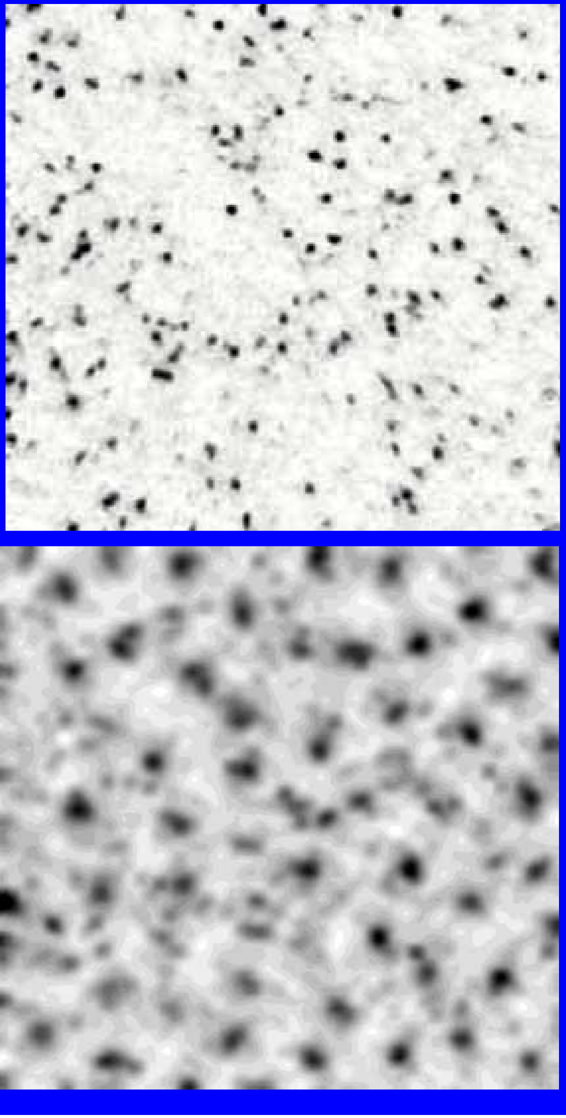
Pan et al PRL 85, 1536 (00)

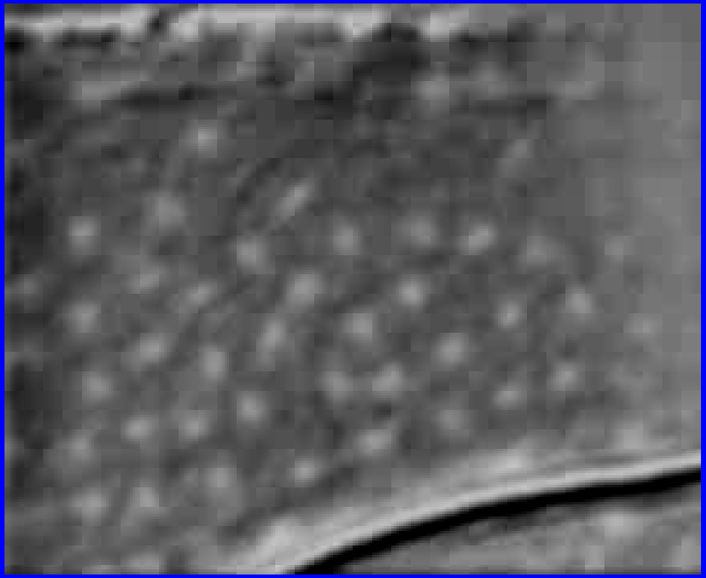


Vortex dynamics in the presence of disorder

Disorder profoundly affects dynamics leading to the truly superconducting vortex glass state in which exhibits irreversible and memory dependent phenomena (like hyatwresis, aging…).

Magneto-optics in Nb

Johansson et al (04)



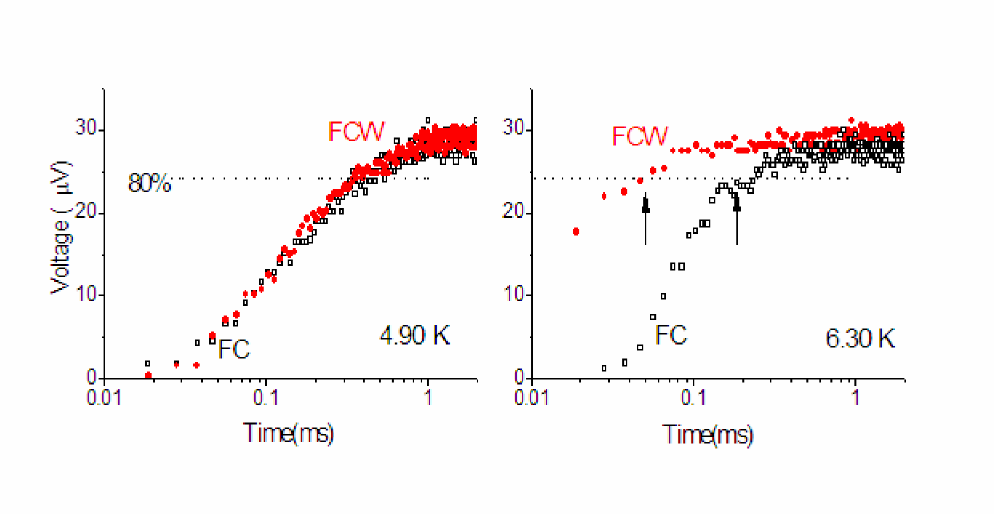
It became perhaps the most convenient playground to study the glass dynamics

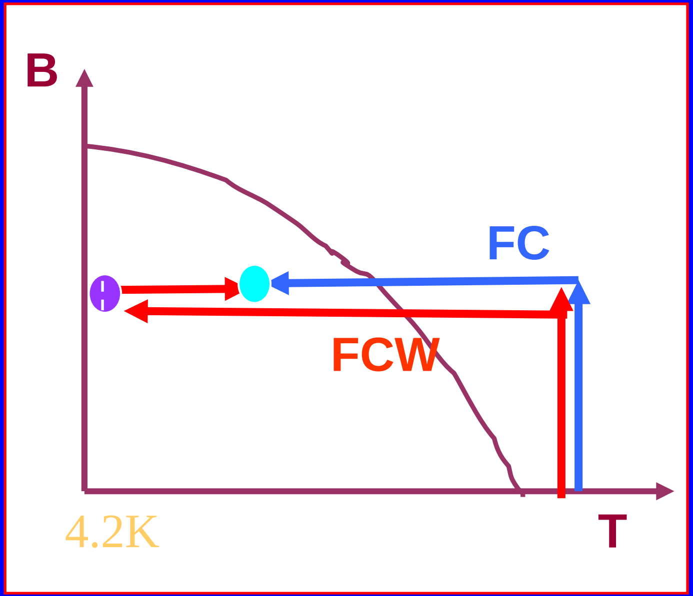
Dependence on magnetic history: the field cooled and the field cooled with return protocols result in different states.

Transport in Nb

Reversible region

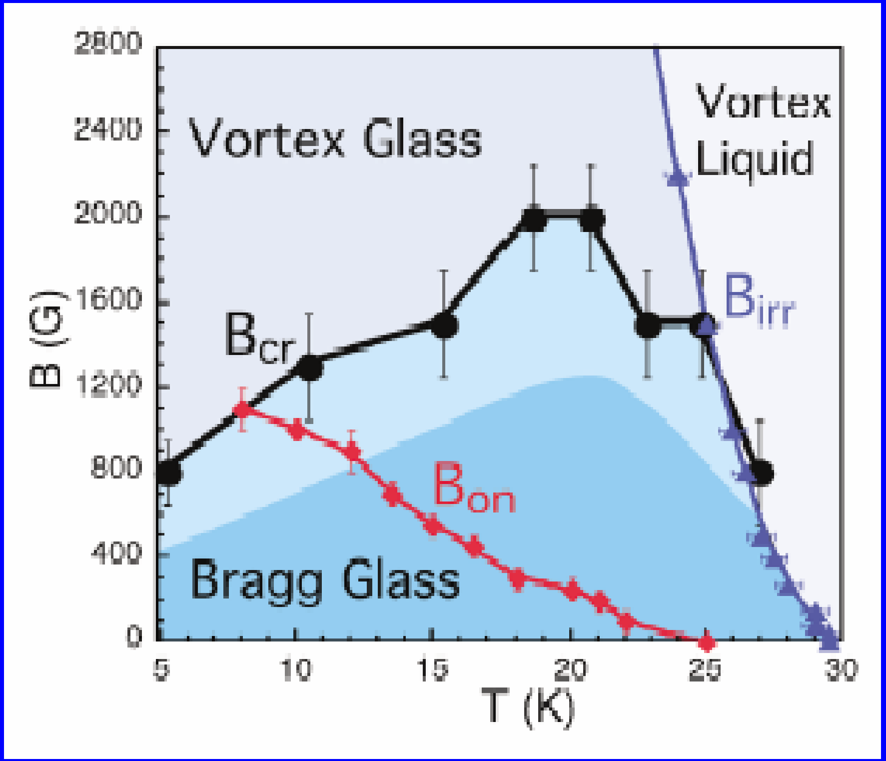
Irreversible region

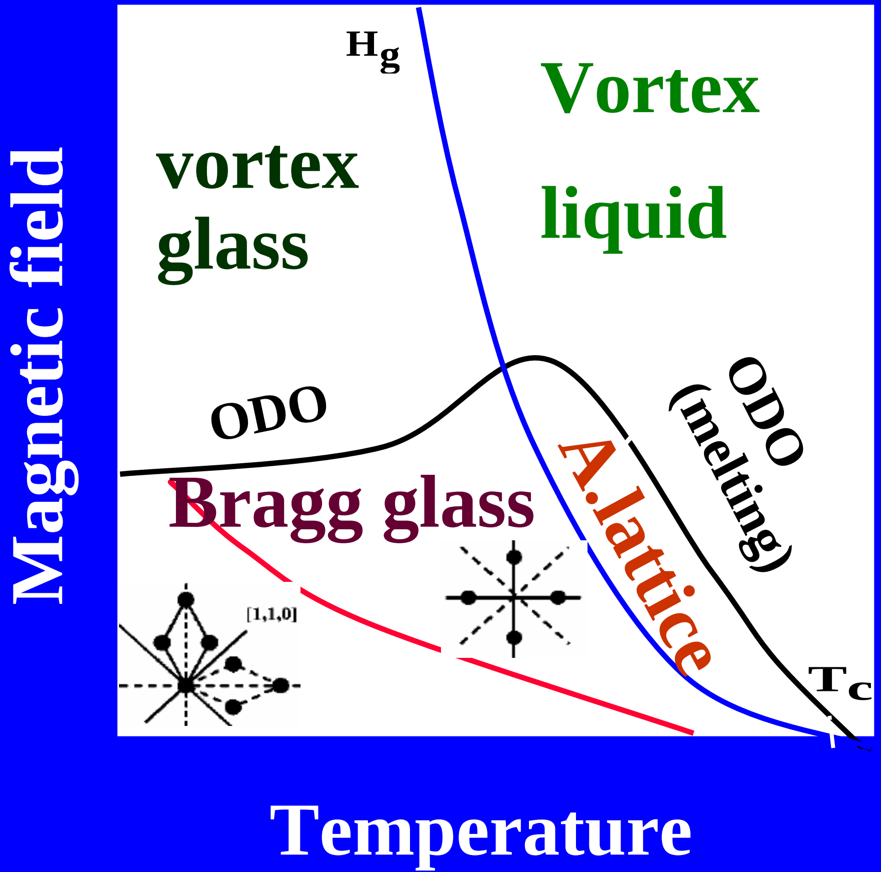




Andrei et al (2004)

Generic vortex matter phase diagram of a HTSC

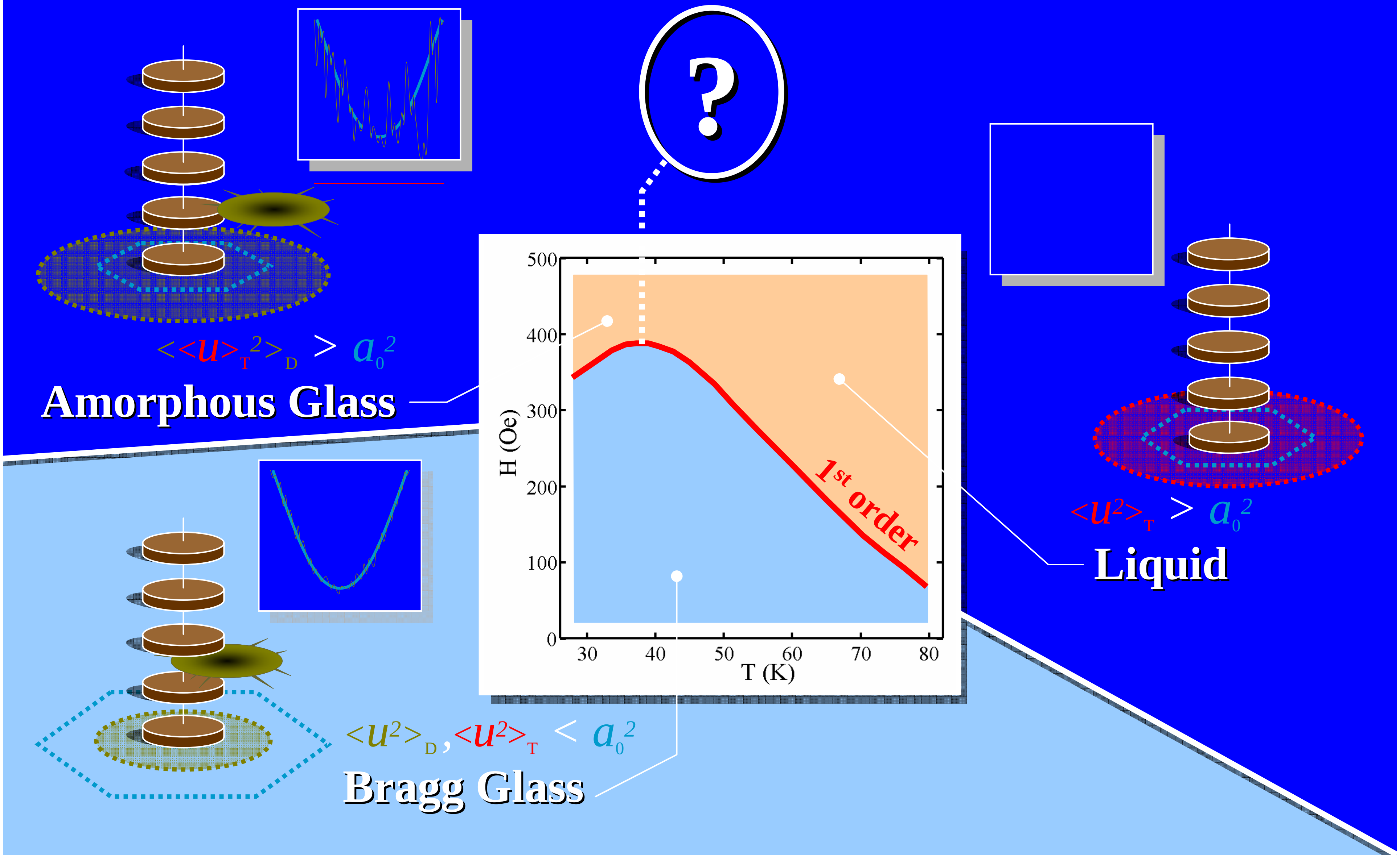




LaSCO

Divakar et al, PRL92,237004 (04)

First-order Melting transition



$<<u>_T^2>_D > a_0^2$

Amorphous Glass

$<u^2>_T > a_0^2$

Liquid

$<u^2>_D, <u^2>_T < a_0^2$

Bragg Glass