The Vortex Phase Diagram in Superconductors

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NSF Summer School on Superconductivity

July 2000

References

Vortex Phase Diagram

Vortices in high temperature superconductors
Blatter, Feigel'man, Geshkenbein, Larkin, and Vinokur, *Rev. Mod. Phys.* **66**, 1125-1388 (1994)

Resistance in High-Temperature Superconductors
Bishop, Gammel, Huse, *Scientific American* **248** (2) 48 (1993)

Thermodynamic observation of first order vortex-lattice melting transition in BSCCO,
Zeldov, Majer, Konczykowski, Geshkenbein, Vinokur, *Nature (London)* **375**, 373-376 (1995)

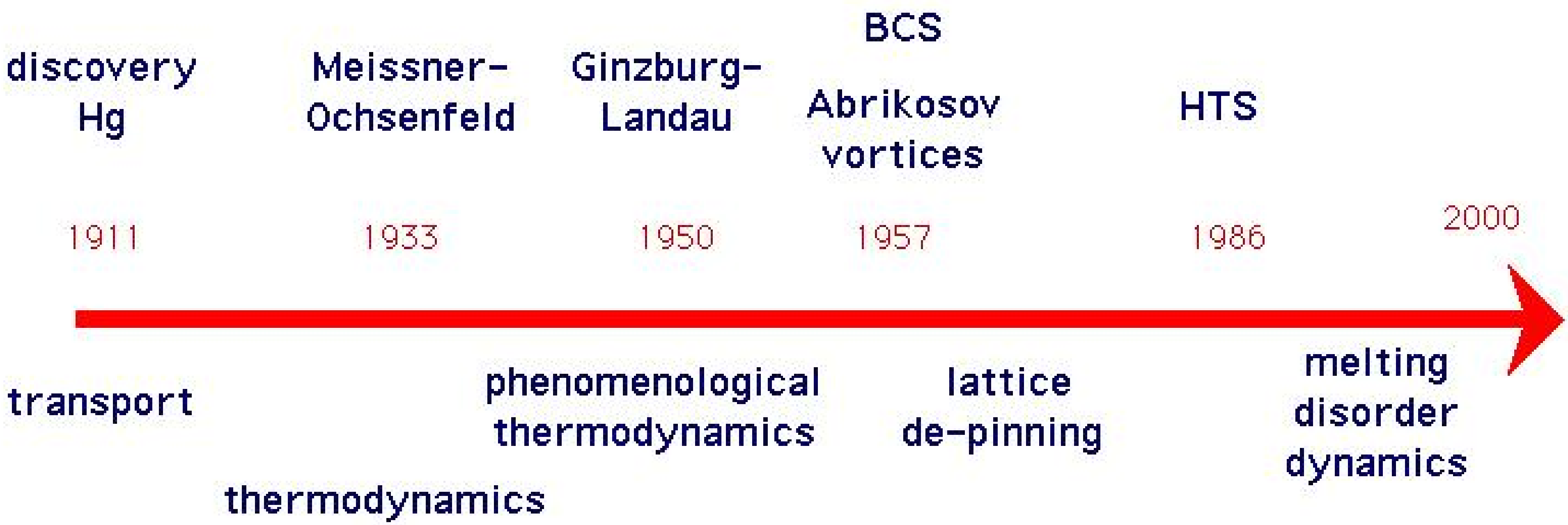
Vortex melitng and the liquid state in YBCO
Crabtree, Kwok, Welp, Lopez, and Fendrich
in *Physics and Materials Science of Vortex States, Flux Pinning, and Dynamics*, R. Kossowsky, S. Bose, V. Pan, and Z. Durusoy, eds. (Kluwer, Dordrecth, 1999) p. 357.
Proceedings of the NATO Advanced Study Institute , Kusadasi, Turkey, July 26-August 8, 1998

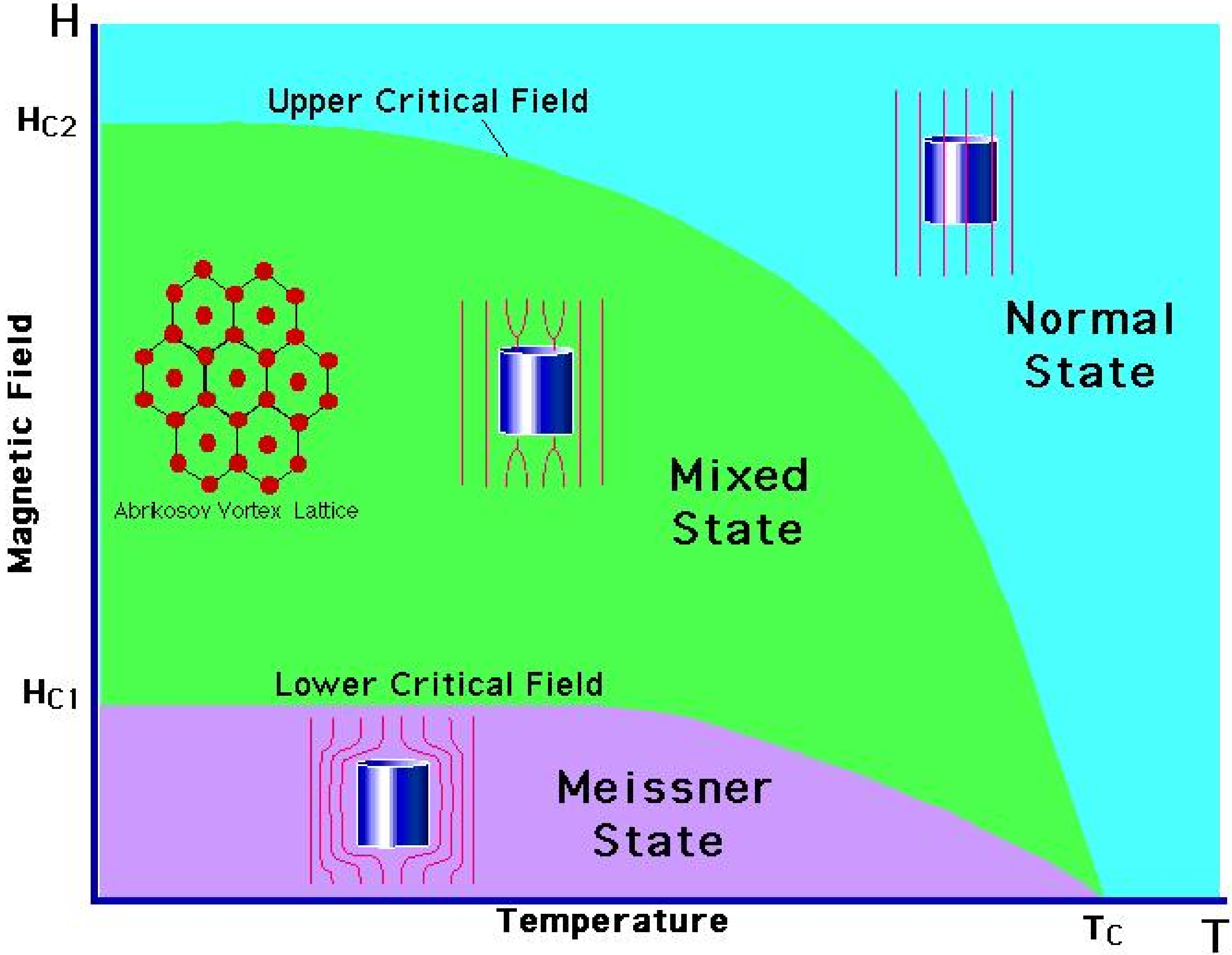
Critical Points in Heavy Ion Irradiated Untwinned YBCO Crystals
W. K. Kwok, R. J. Olsson, G. Karapetrov, L. M. Paulius, W. G. Moulton, D. J. Hofman, and G. W. Crabtree
Phys. Rev. Lett. **84**, 3706 (2000)

Evolution of the vortex phase diagram in YBCO with random point disorder
L. M. Paulius, W.-K. Kwok and R. J. Olsson, A. M. Petrean, V. Tobos, J. A. Fendrich and G. W. Crabtree,
C. A. Burns and S. Ferguson
Phys. Rev. B **61**, 11910 (2000)

Experimental Evidence for the Vortex Glass Phase in Untwinned, Proton Irradiated YBCO
A. M. Petrean and L. M. Paulius, W.-K. Kwok, J. A. Fendrich, and G. W. Crabtree
Phys. Rev. Lett. **84**, 5852 (2000)

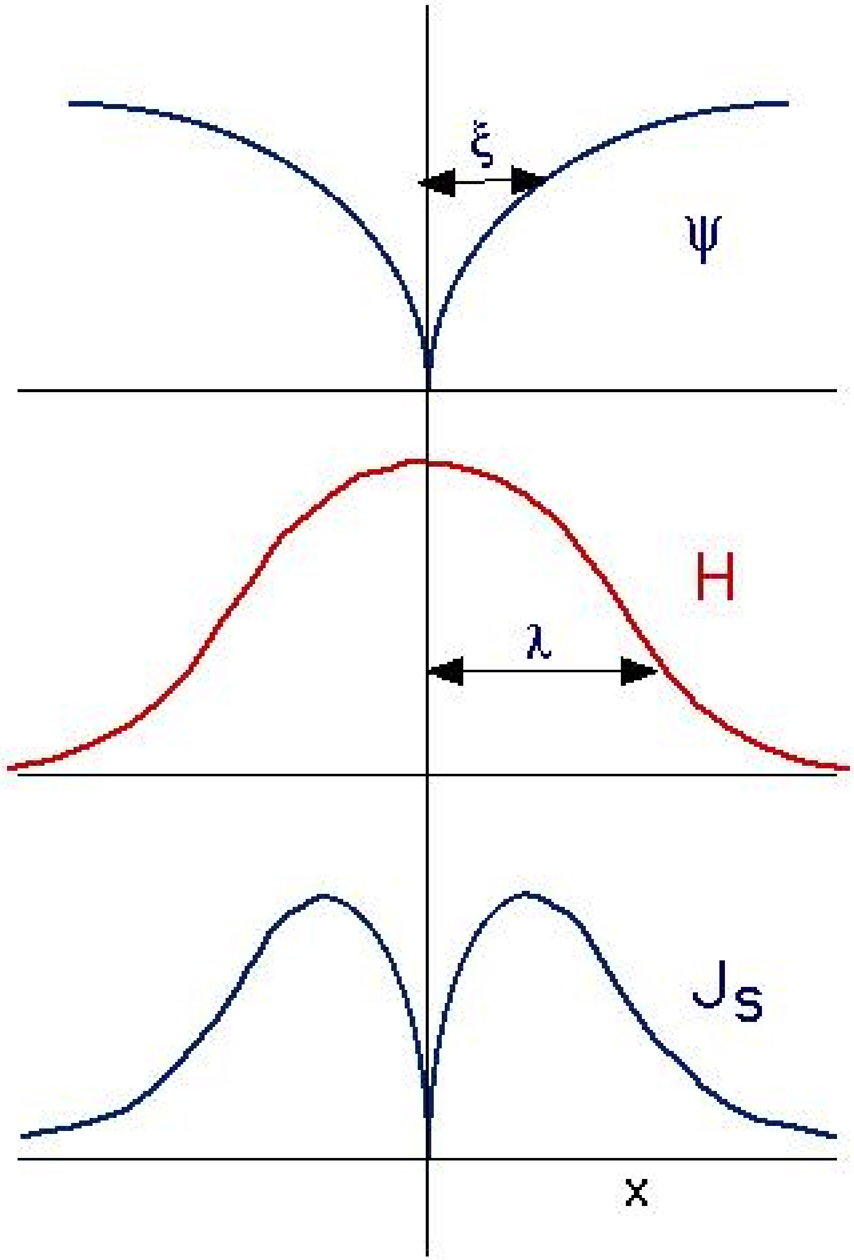
History

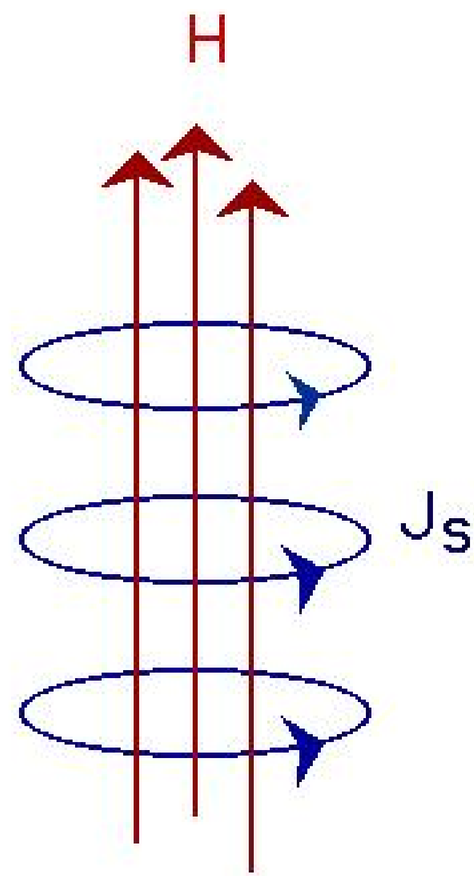

BCS
discovery
Hg
Meissner-
Ochsenfeld
Ginzburg-
Landau
Abrikosov
vortices
HTS
1911
1933
1950
1957
1986
2000
transport
thermodynamics
phenomenological
thermodynamics
lattice
de-pinning
melting
disorder
dynamics



Classical Period before high T_C

What is a Vortex ?



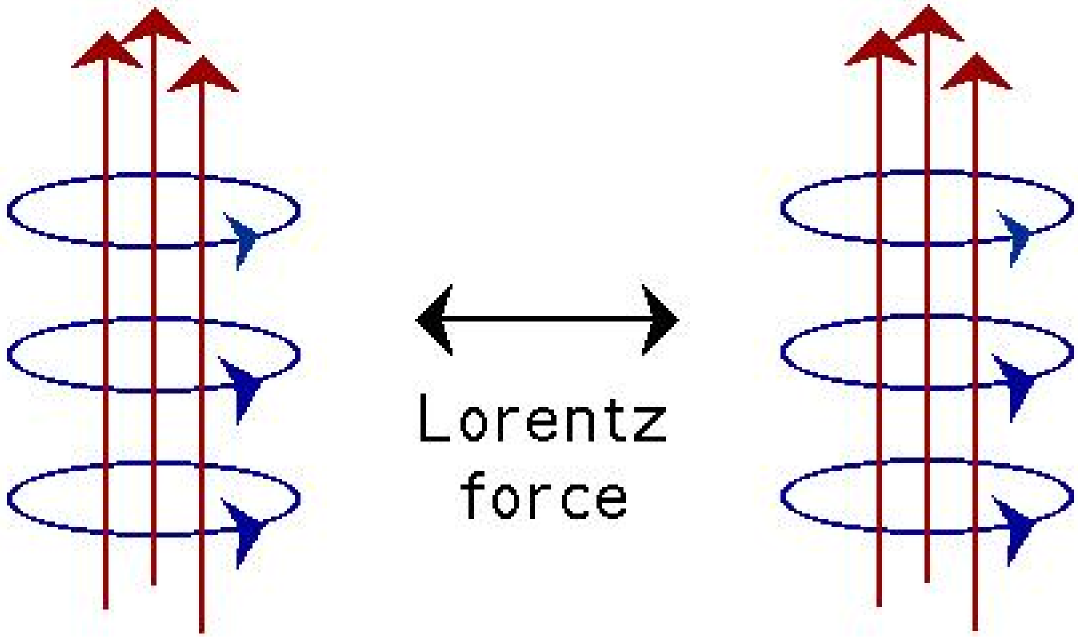


quantum of flux

hc/2e

20.7 Oe-μm^2

Vortex Properties



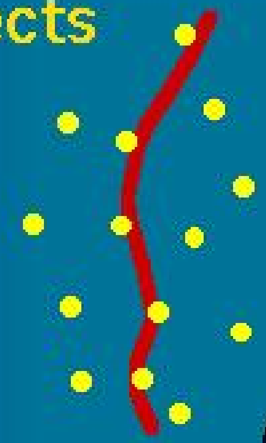
analogy: solenoid

repulsive interaction $\Rightarrow$ Abrikosov lattice

Types of Defects

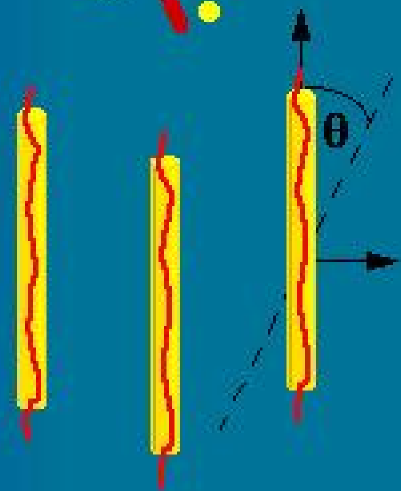
Point Defects

- Oxygen Vacancies
- Electron irradiation induced point defects



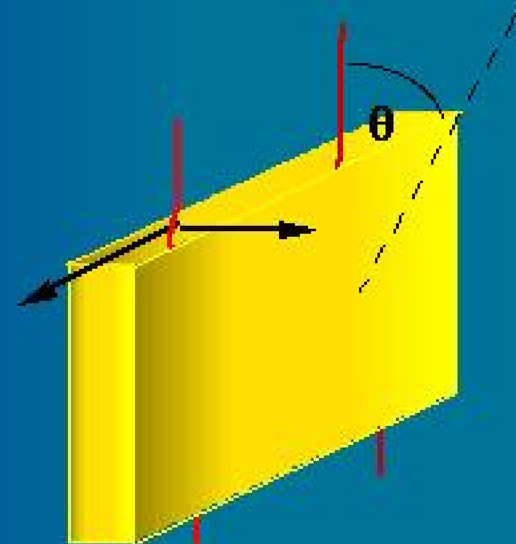
Line Defects

- Heavy ion irradiation induced columnar tracks

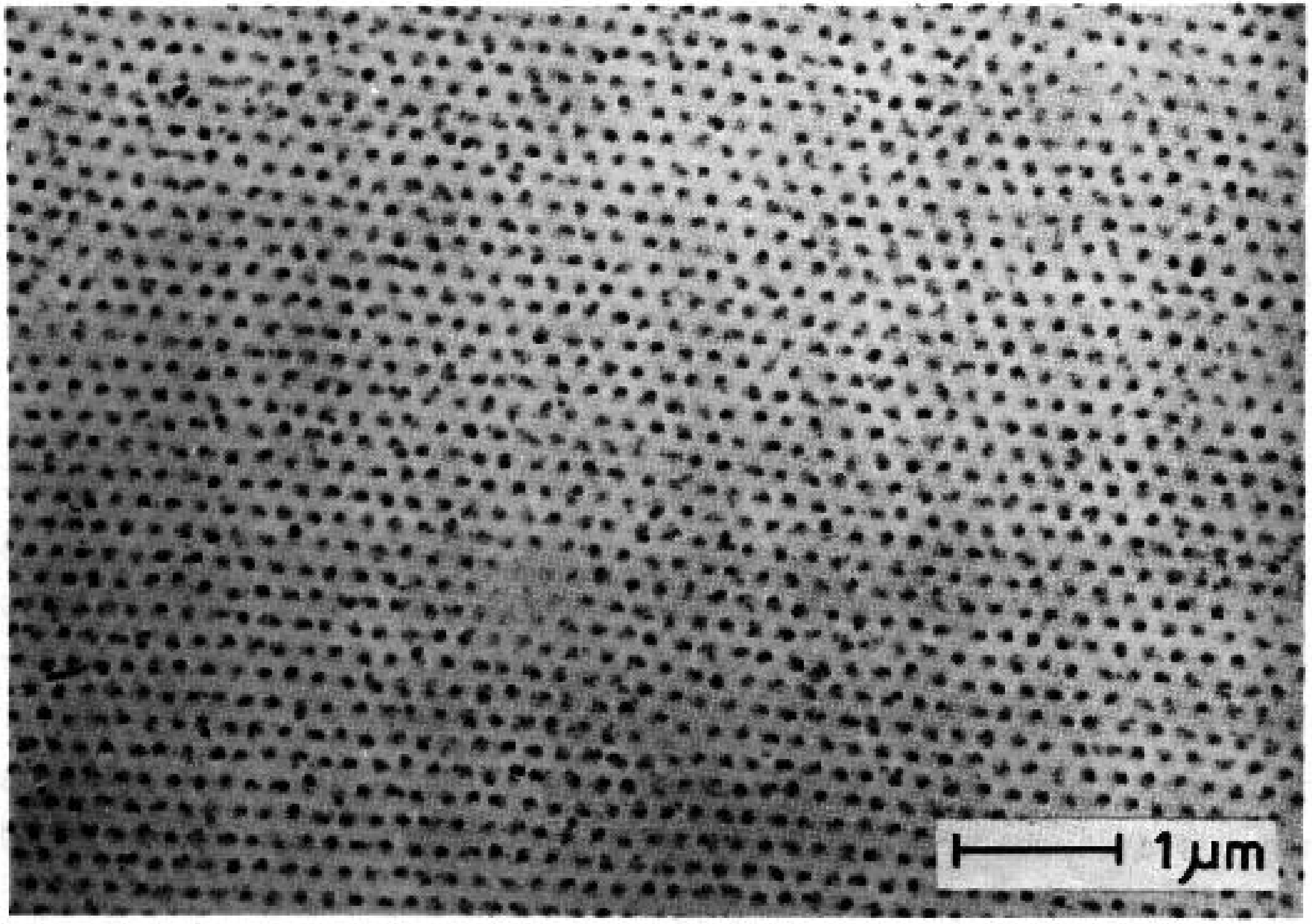


Planar Defects

- Twin boundaries
- Layered structure



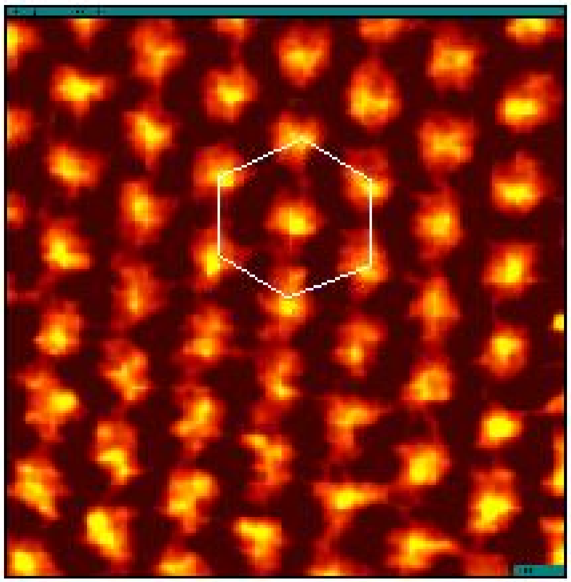
Vortex Decoration



Nb at T= 1.2 K H = 985 G

U. Essmann, H. Träuble, Phys. Lett. **24A**, 526 (1967)

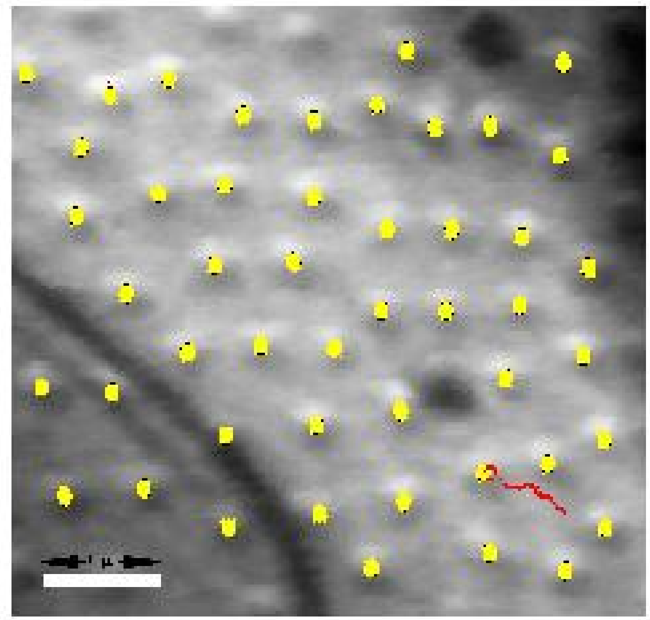
Imaging Vortex Arrays



$NbSe_2$

scanning tunneling microscopy

Y. de Wilde et al



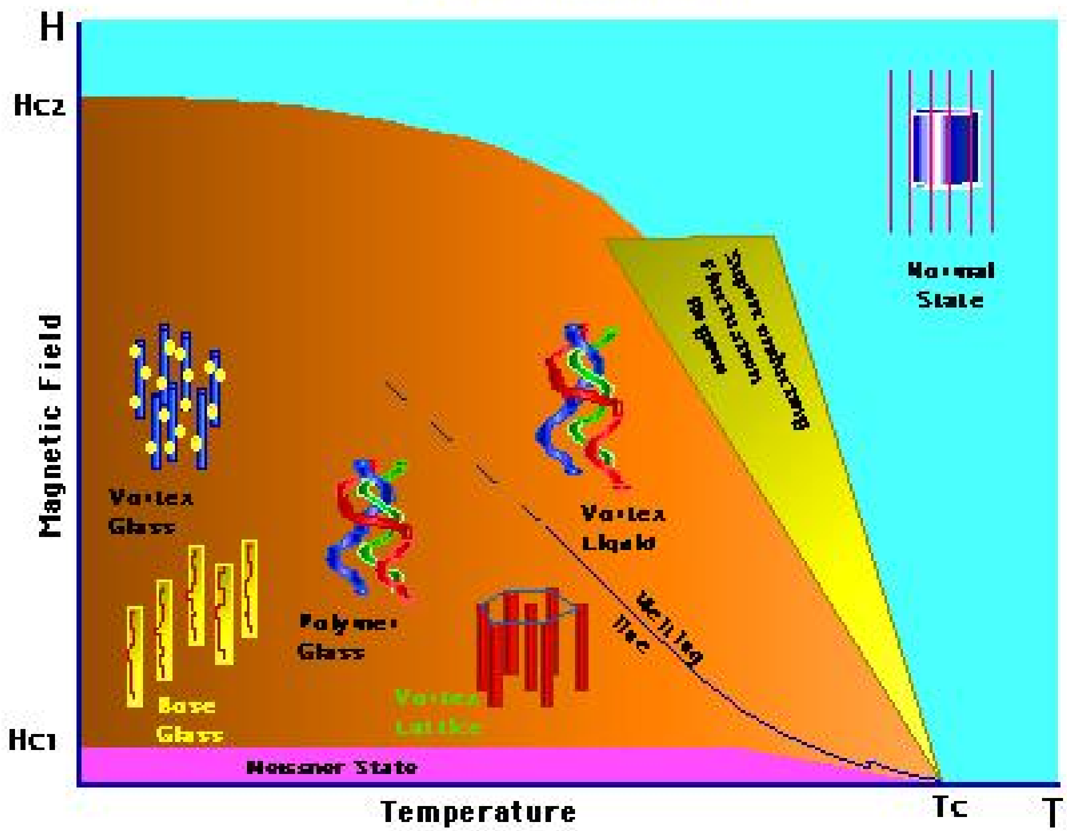
Nb

Lorentz microscopy

A. Tonomura et al

Equilibrium Phases

vortex matter



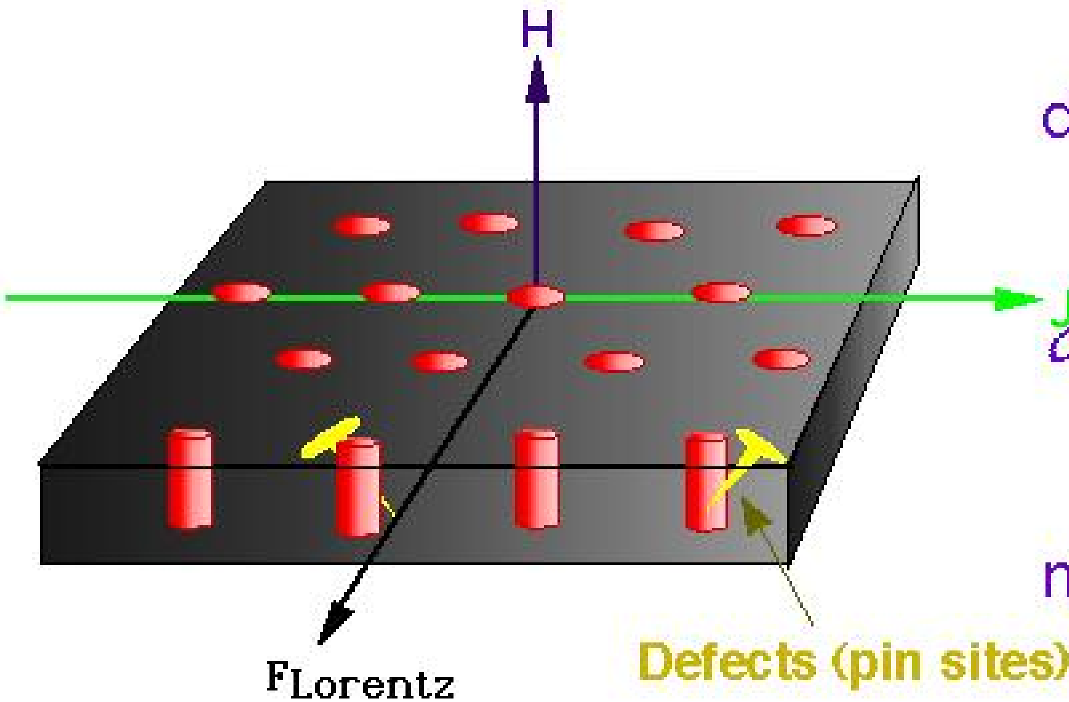
four competing energies

thermal	→	liquid
interaction	→	lattice
pinning	→	glass
coupling	→	3D line

experiment: control all four energies

theory: simple Lorentz force interaction

Dynamic Phases



distinct steady states
plastic/elastic

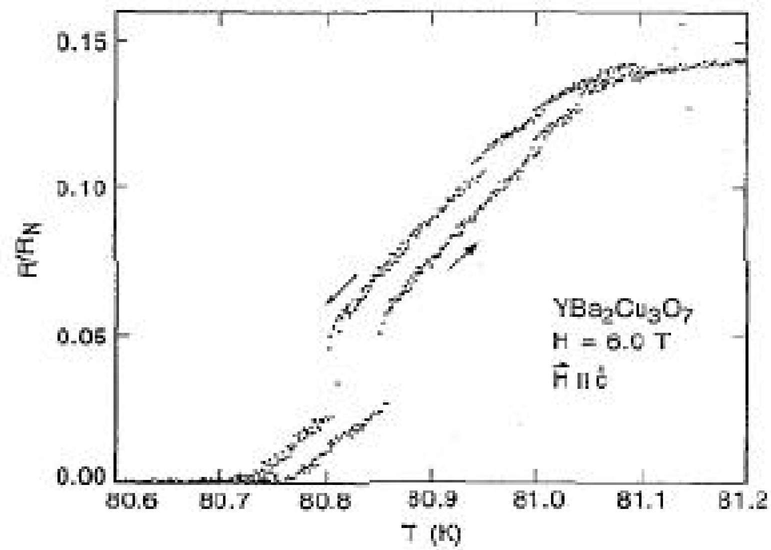
dynamic phase transitions
de-pinning transition

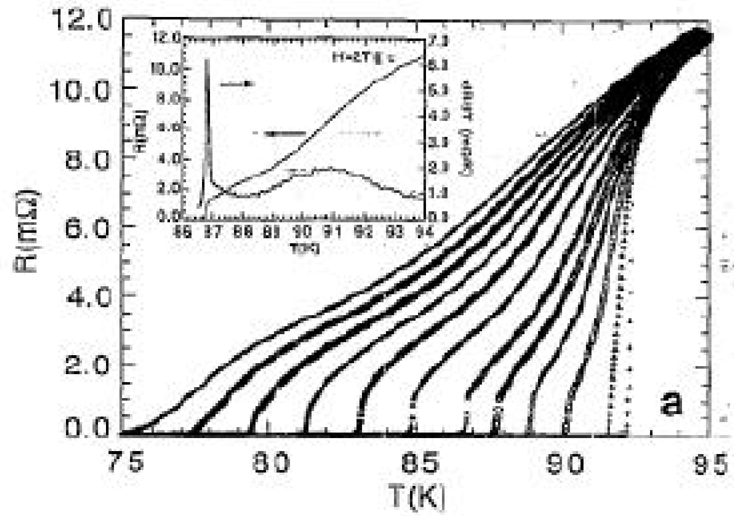
motion → dissipation
no energy conservation
no thermodynamics

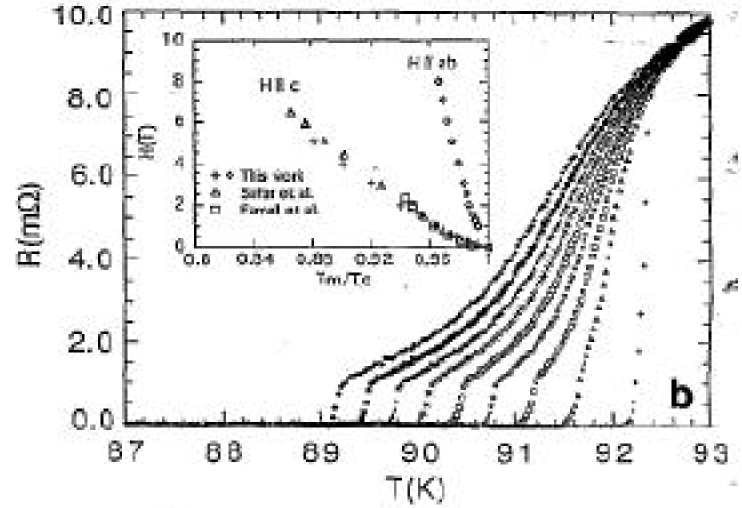
basic science: non-linear dynamics

applications: control vortex motion

First Evidence for Vortex Melting







VOLUME 69, NUMBER 5 PHYSICAL REVIEW LETTERS 3 AUGUST 1992

Experimental Evidence for a First-Order Vortex-Lattice-Melting Transition in Untwinned, Single Crystal $YBa_2Cu_3O_7$

H. Safar, P. L. Gammel, D. A. Huse, and D. J. Bishop
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

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(Received 4 May 1992)

VOLUME 69, NUMBER 23 PHYSICAL REVIEW LETTERS 7 DECEMBER 1992

Vortex Lattice Melting in Untwinned and Twinned Single Crystals of $YBa_2Cu_3O_{7-\delta}$

W. K. Kwok, S. Fleshler, U. Welp, V. M. Vinokur, J. Downey, and G. W. Crabtree
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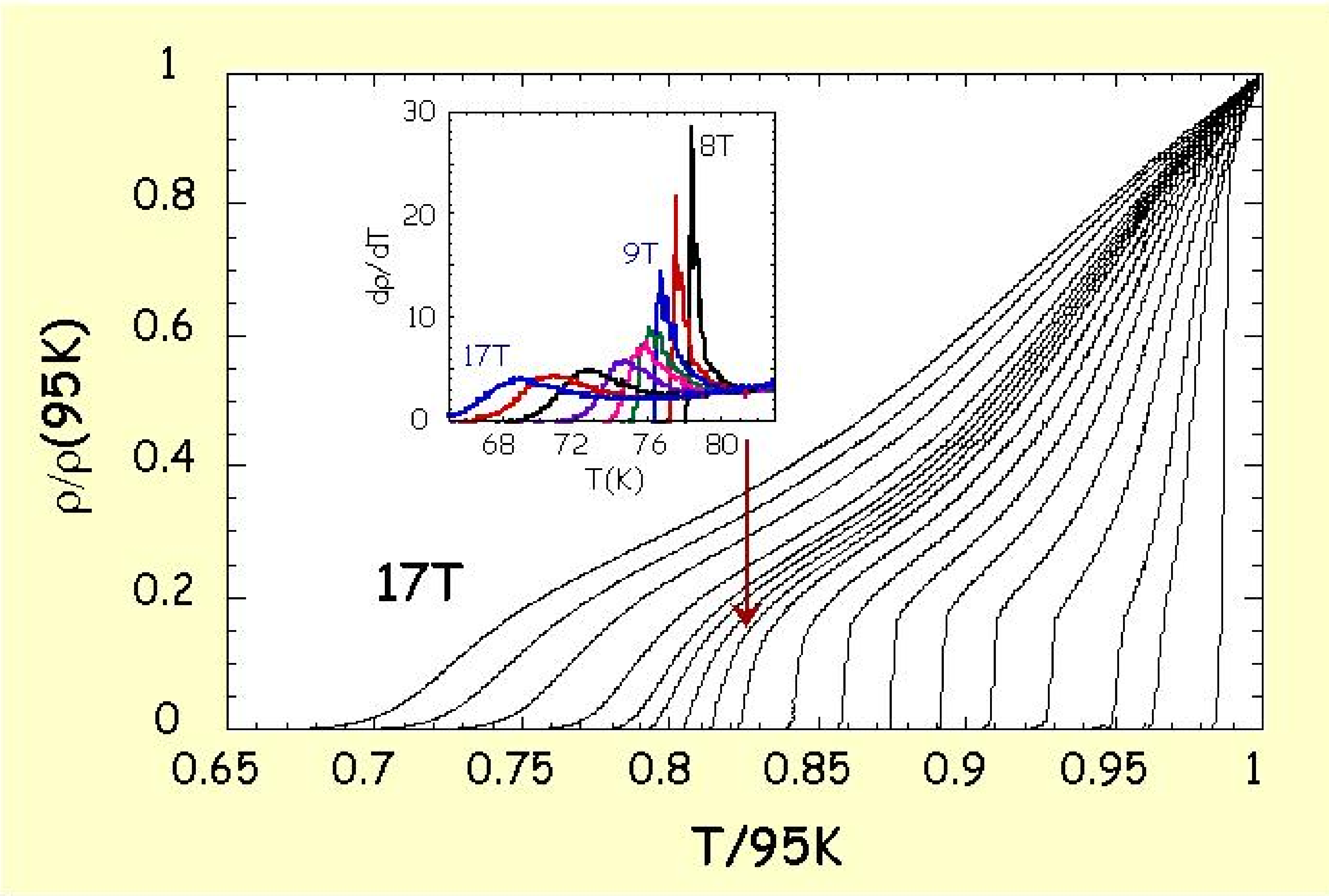
Naval Research Laboratory, Washington, D.C. 20375
(Received 1 October 1992)

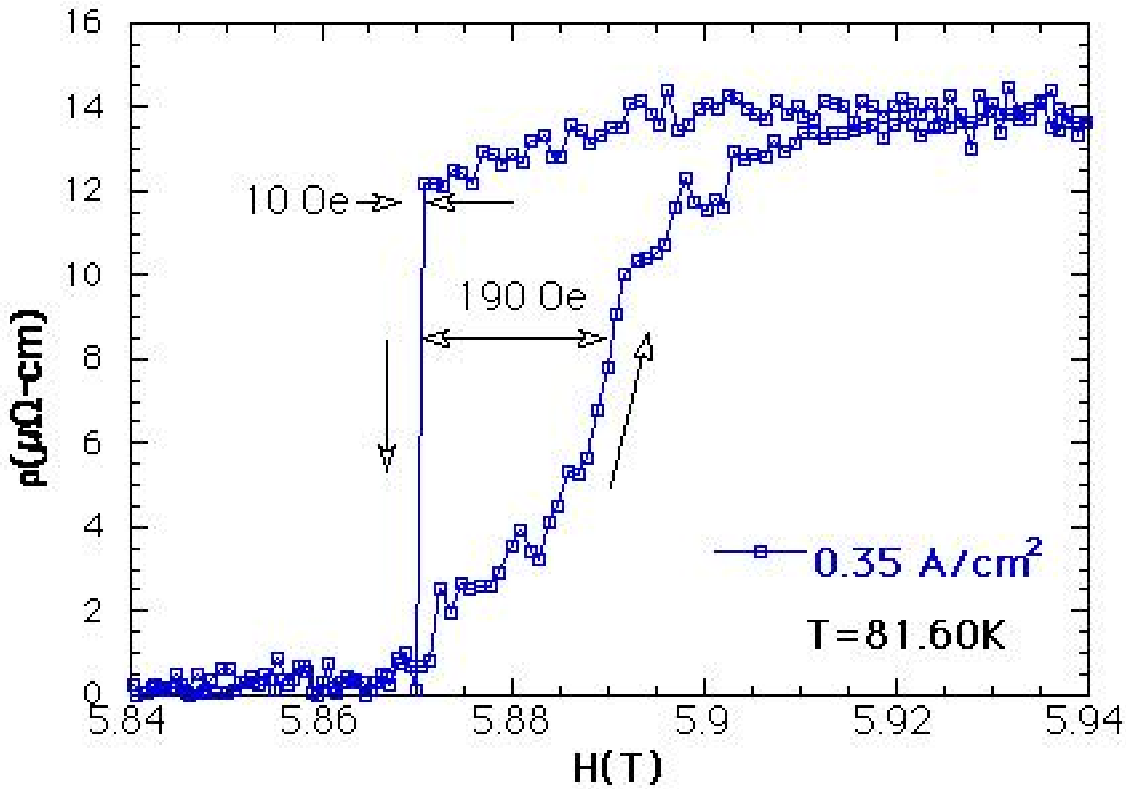
Resistive Melting in Untwinned YBCO



Kwok et al

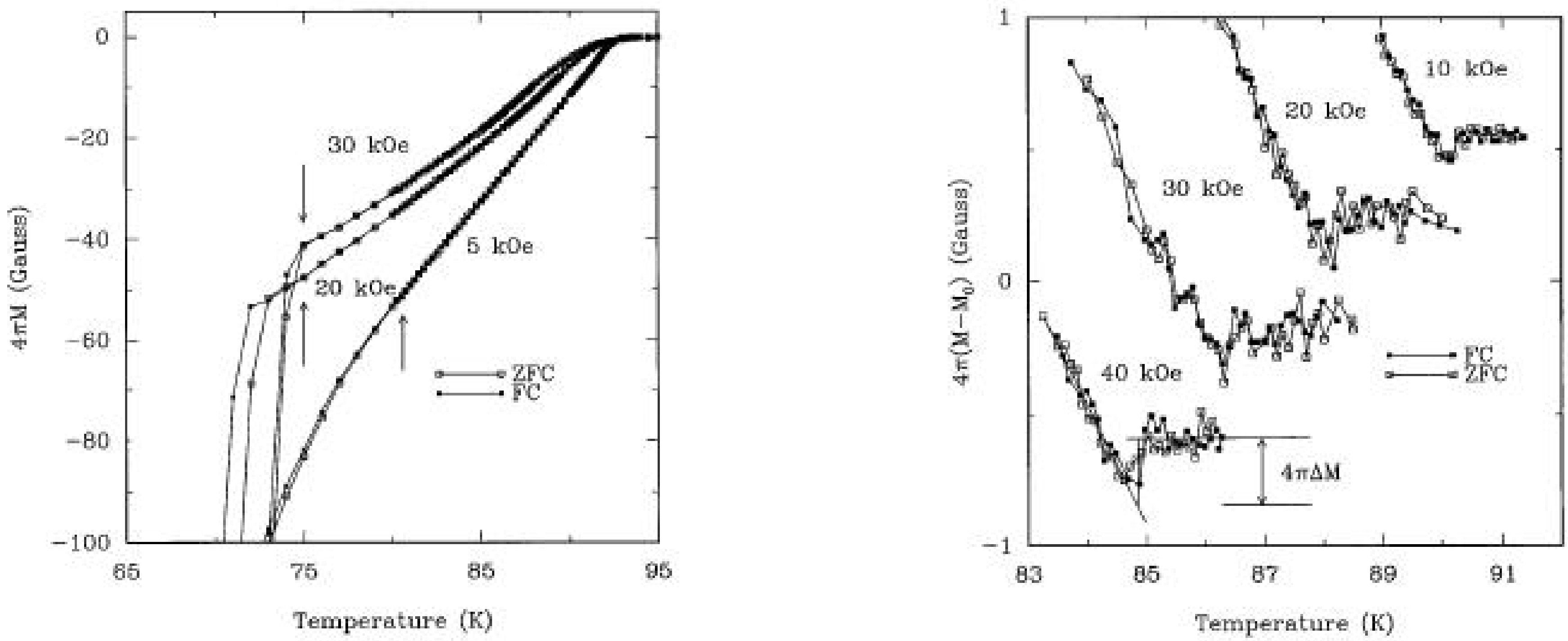
Resistive Hysteresis on Melting

YBCO

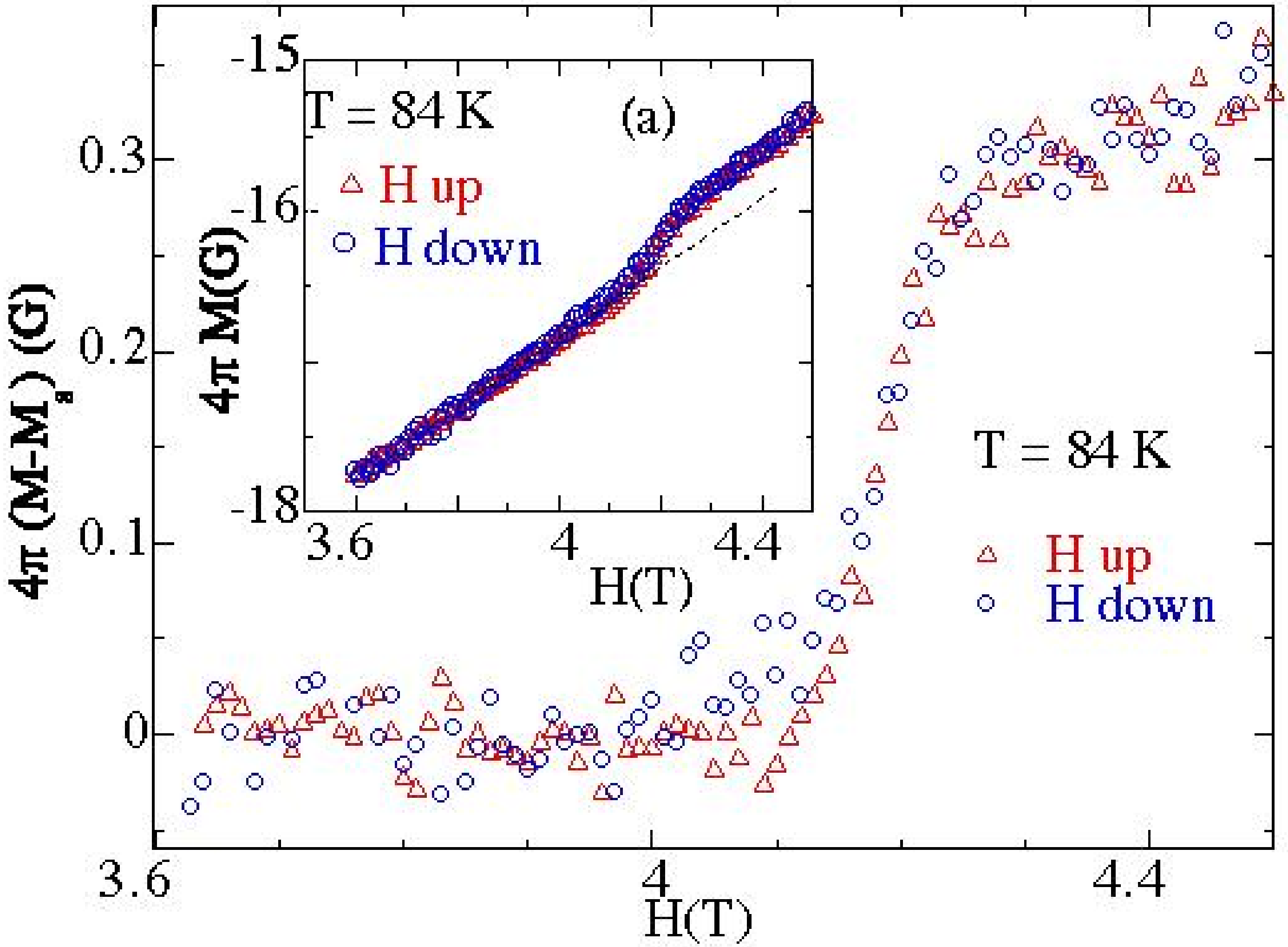


Discontinuity of Reversible Magnetization in Untwinned YBCO Single Crystals at the First Order Vortex Melting Transition

Ruixing Liang, D. A. Bonn, and W. N. Hardy
Department of Physics, The University of British Columbia, 6224 Agricultural Road, Vancouver, British Columbia, Canada V6T 1Z1
(Received 26 June 1995)



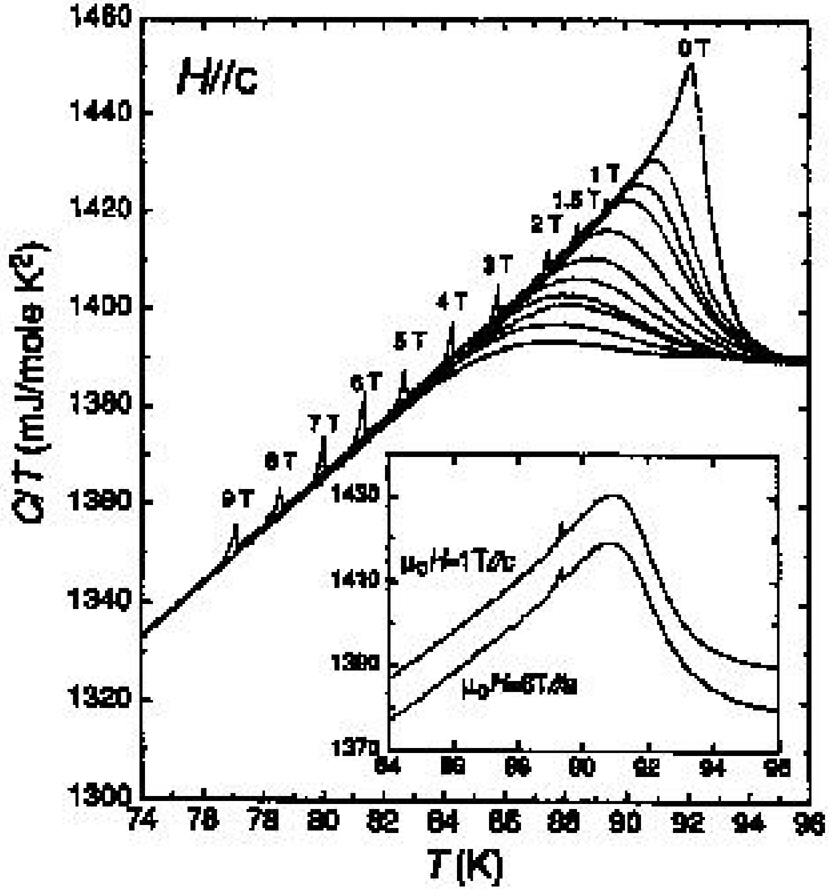
Magnetization Discontinuity on Melting

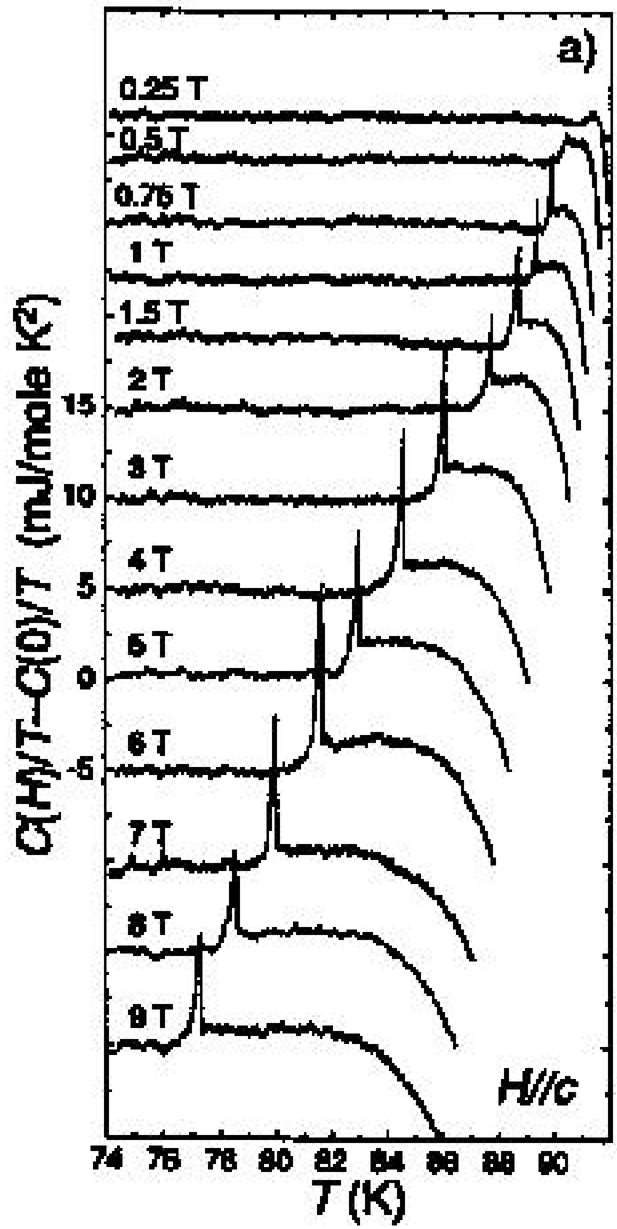


Liang, Bonn, Hardy, PRL **76**, 835 (1996)

Welp, Fendrich, Kwok, Crabtree, Veal, PRL **76**, 4809 (1996)

Heat Capacity YBCO





Schilling, Phillips, Fisher, Welp, Kwok, Crabtree
Nature **382** (1996)
Phys. Rev. Lett. **78** (1997)

Ice-like Melting

Clausius-Clapeyron equation

$$\frac{dH_m}{dT} = -\frac{\Delta S}{\Delta M}$$

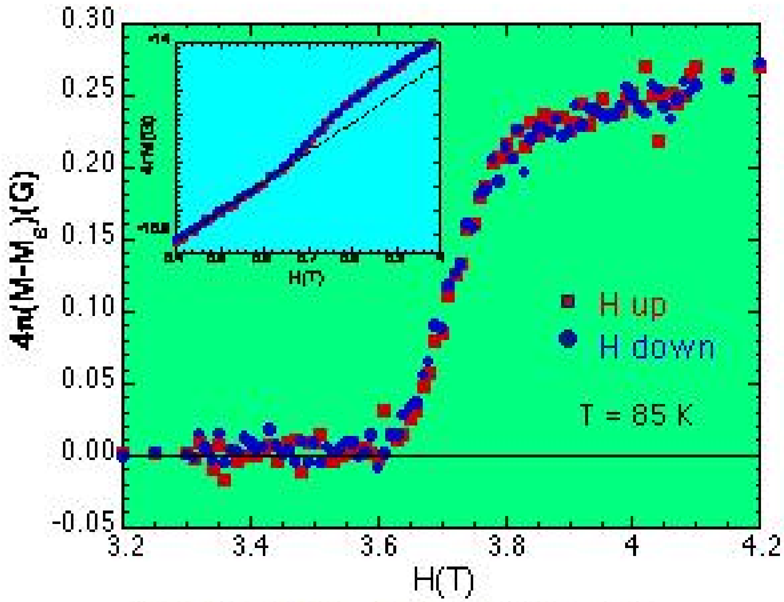
negative melting slope

higher entropy liquid

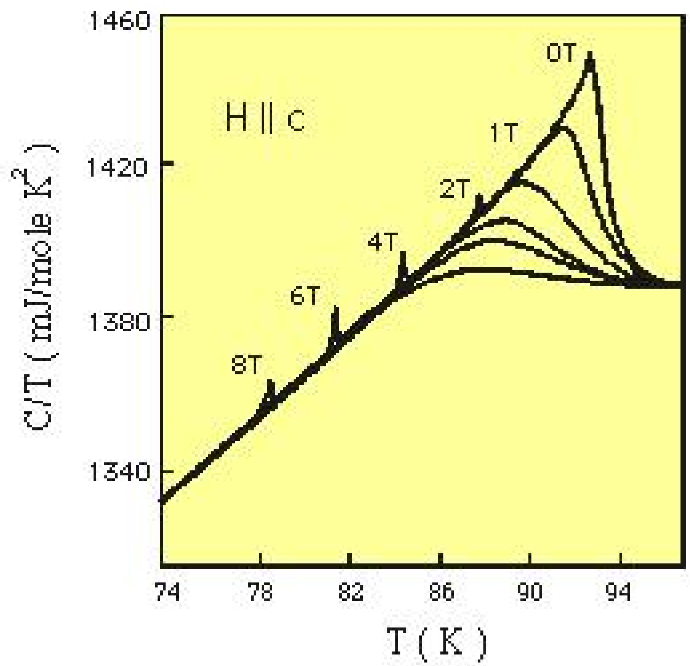
→ denser liquid

origin: weak long range interaction

$$V(r) \sim \ln(\lambda/r)$$



Welp, Fendrich, Kwok, Crabtree, Veal
PRL **76**, 4809 (1996)

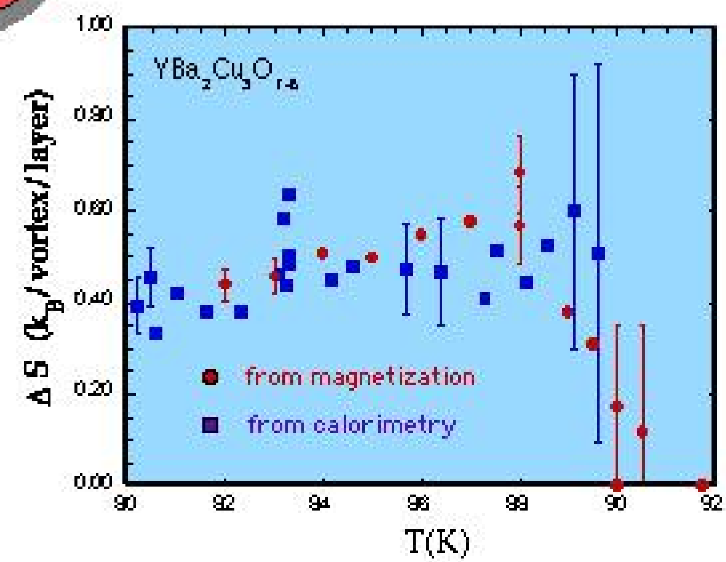


Schilling, Phillips, Fisher, Welp, Kwok, Crabtree,
Nature **382**, 791 (1996)

first order melting

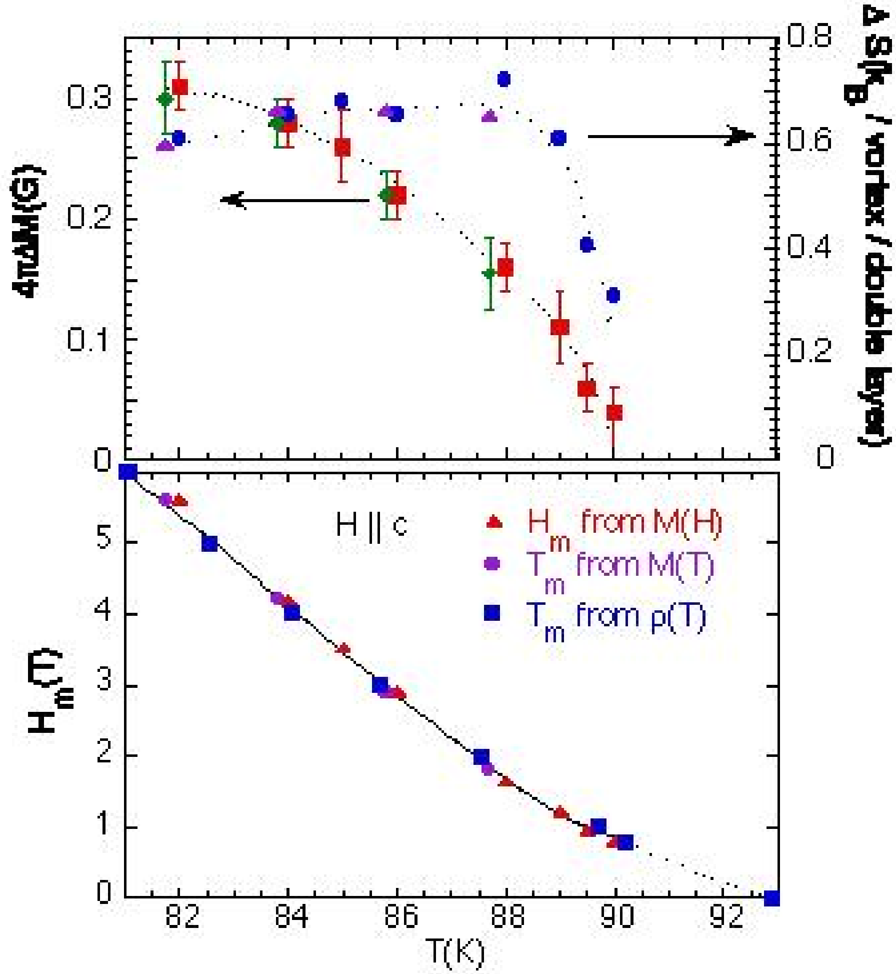
$$\frac{dH_m}{dT} = -\frac{\Delta S}{\Delta M}$$

Clapeyron equation



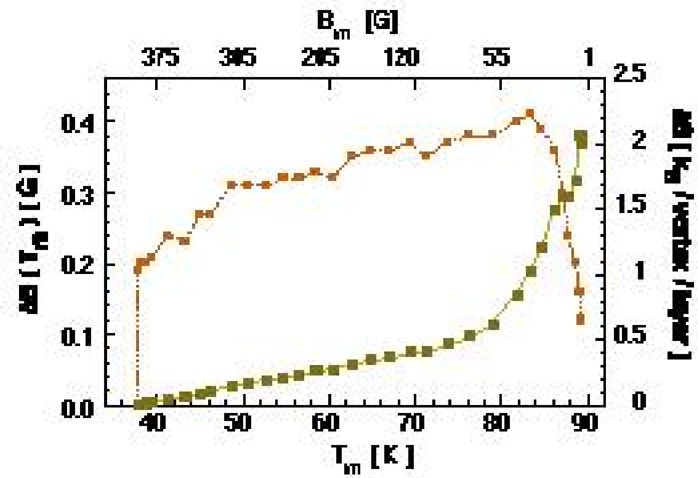
First Order Melting

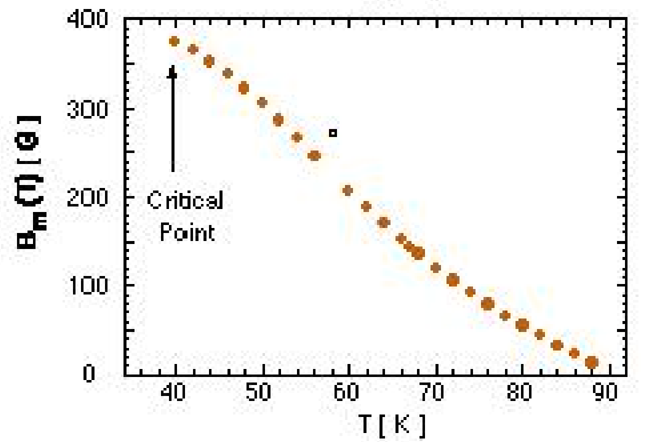
YBCO



Welp, Fendrich, Kwok, Crabtree, Veal, PRL **76**, 4809 (1996)

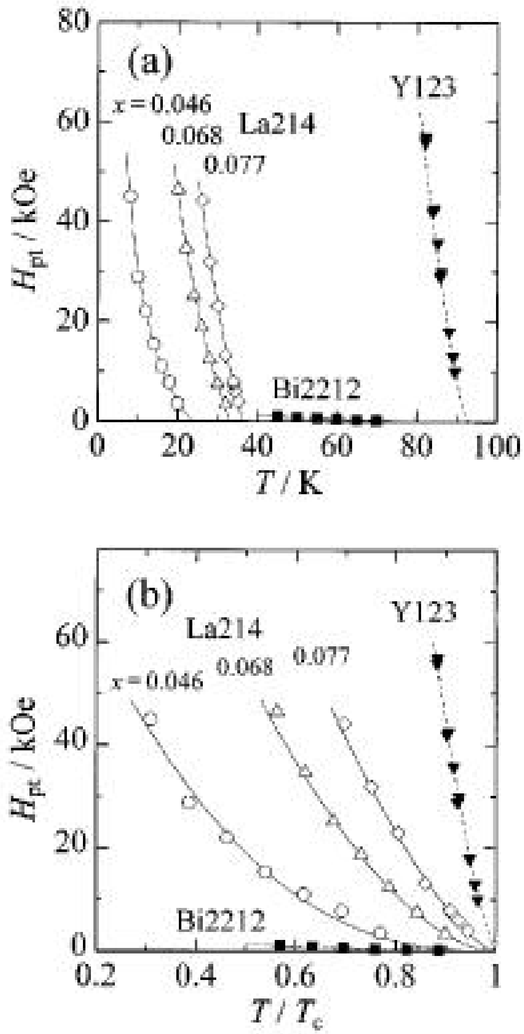
BSCCO

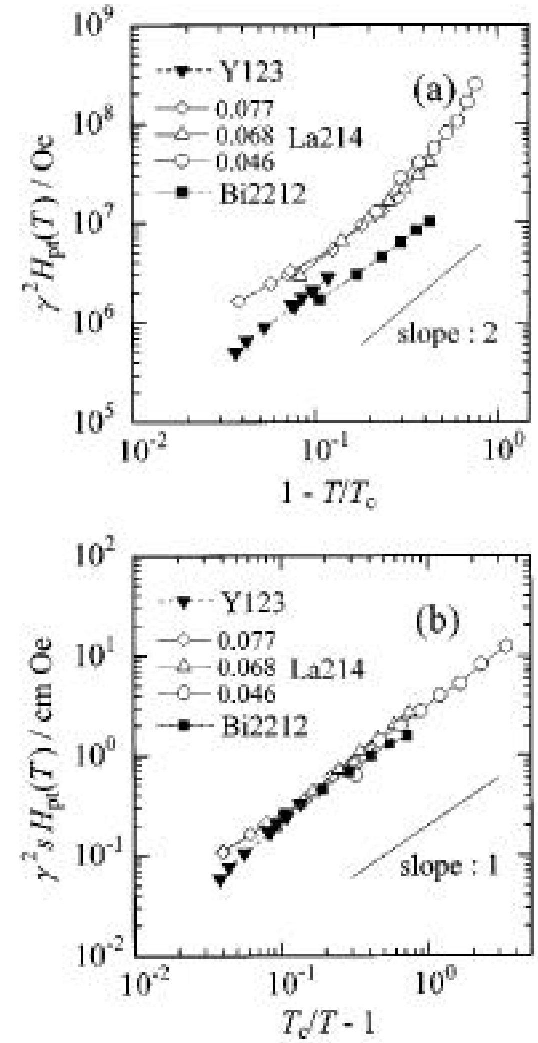




Pastoriza et al, PRL **72**, 2951 (1994)
Zeldov et al, Nature **375**, 373 (1995)
Hanaguri et al, Physica C **256**, 111 (1996)
Ikuta et al Physica C (1996)
Kadowaki et al (1996)

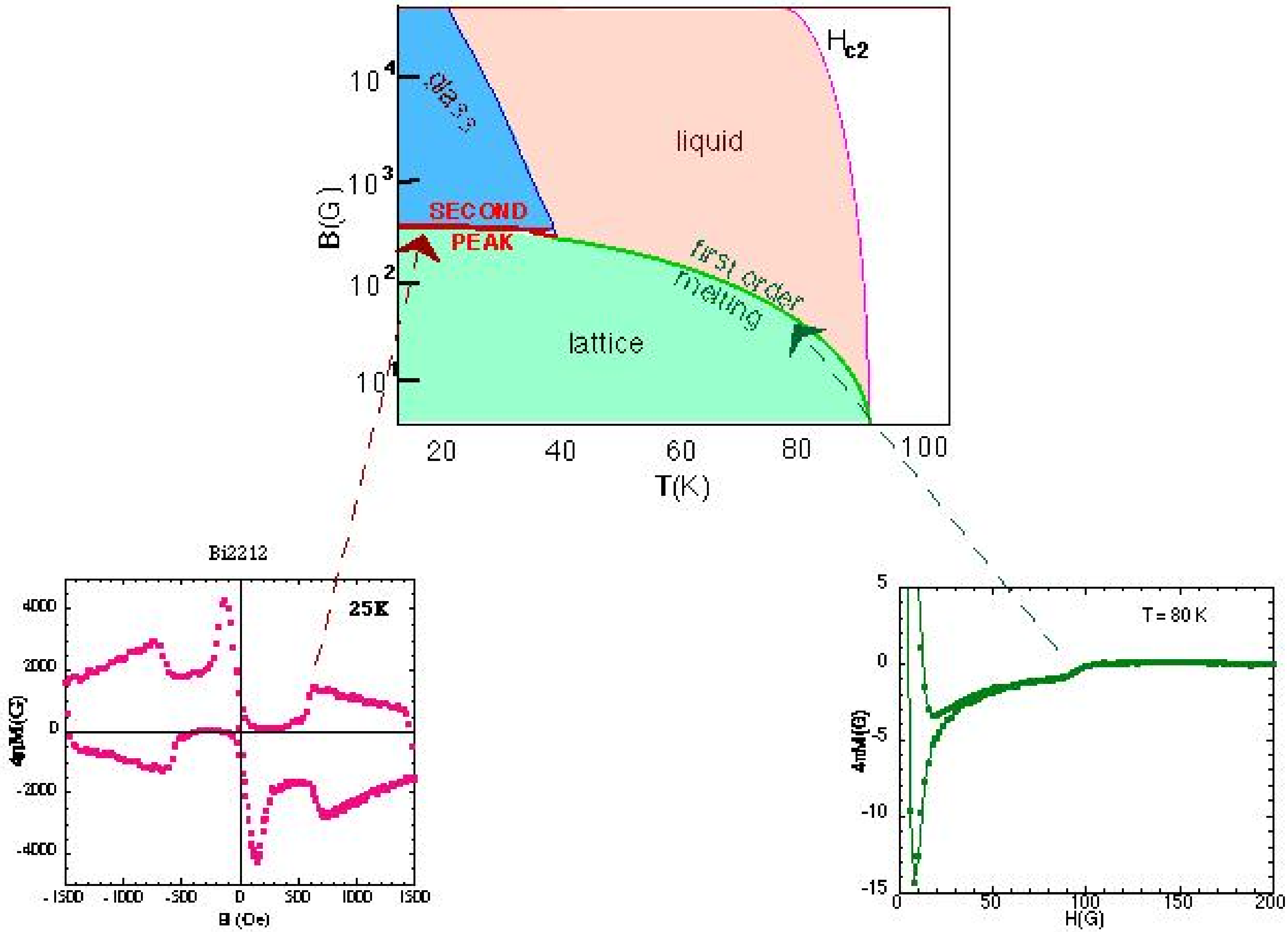
Universal Melting





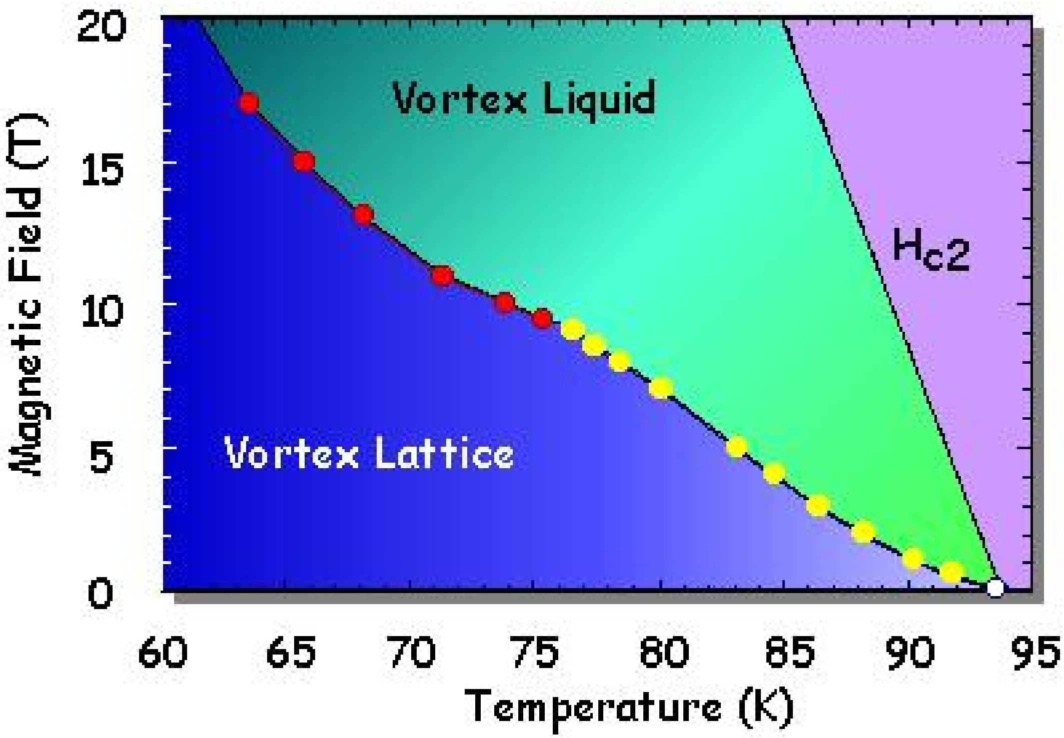
Sasagawa, Kishio, Togawa, Shimoyama, Kitazawa Phys Rev Lett **80**, 4297 (1998)

BSCCO phase diagram



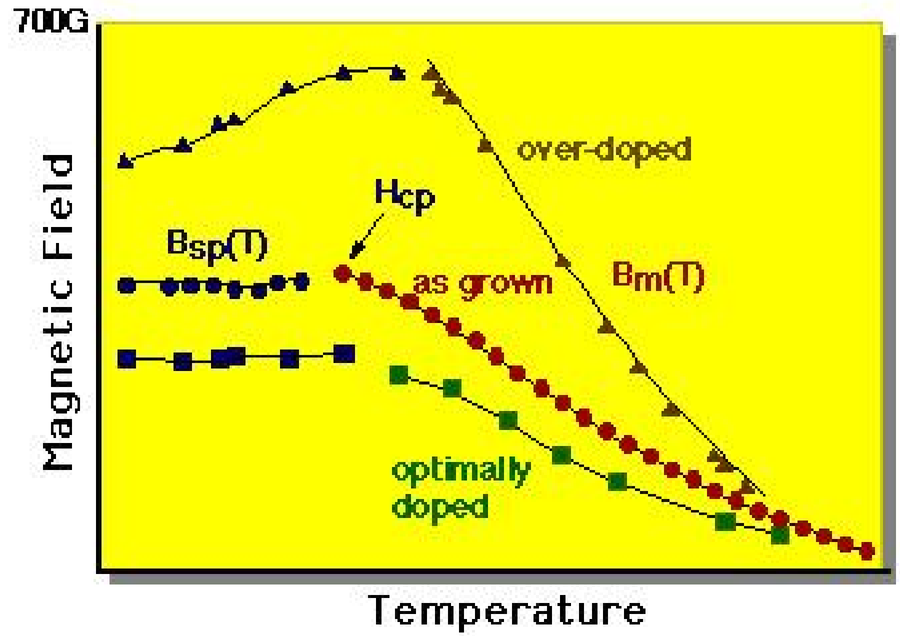
Vortex Melting Phase Diagram

YBCO



H. Safar et al., Phys Rev. Lett. 69,824 (1992)
W. K. Kwok et al.,Phys. Rev. Lett.69, 3370 (1992)
U. Welp et al., Phys. Rev. Lett. 76, 4809 (1996)
A. Schilling et al., Phys. Rev. Lett. 78, 4833 (1998)

BSCCO 2212



Zeldov et al. Nature 375, 373 (1995)
Khaykovich et al., Phys. Rev. Lett. 76, 2555 (1996)

- critical end points
- pinning disorder

Critical Points and Disorder in the Vortex Phase Diagram

W. K. Kwok, L. M. Paulius, A. M. Petrean

G. Karapetrov, R. J. Olsson, V. Tobos,

W. G. Moulton, G. W. Crabtree

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Western Michigan University
Michigan State University
National High Magnetic Field Laboratory

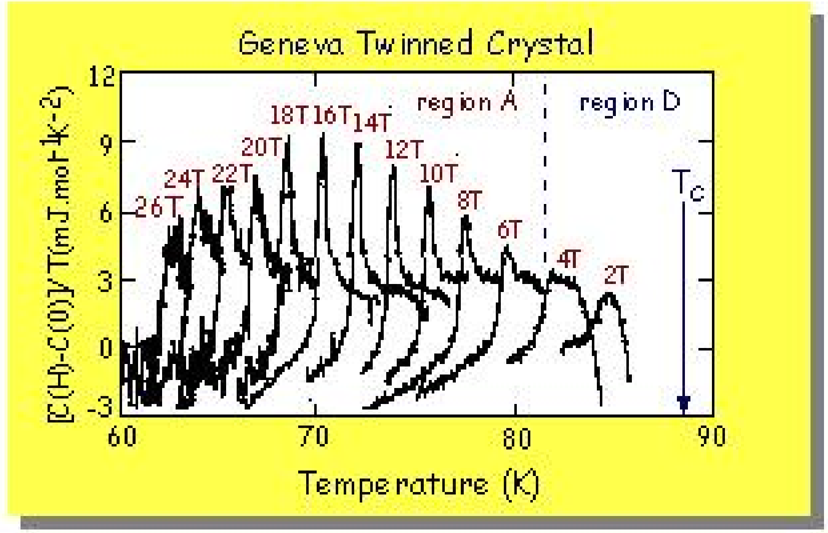
outline

upper/lower critical points ⇔ line/point disorder

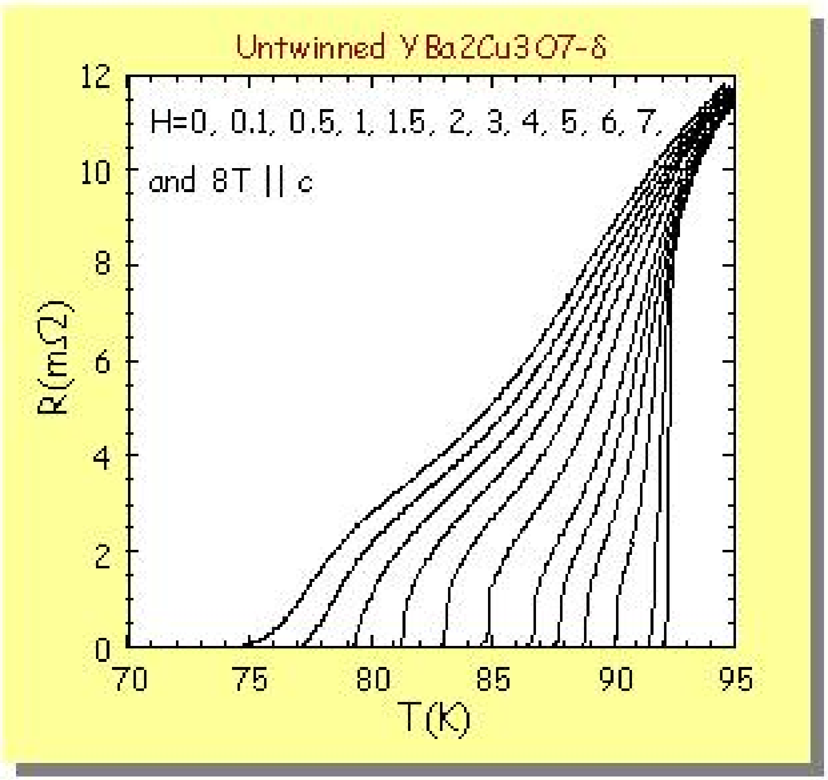
Bose glass < lower critical point

longitudinal entanglement / transverse randomization

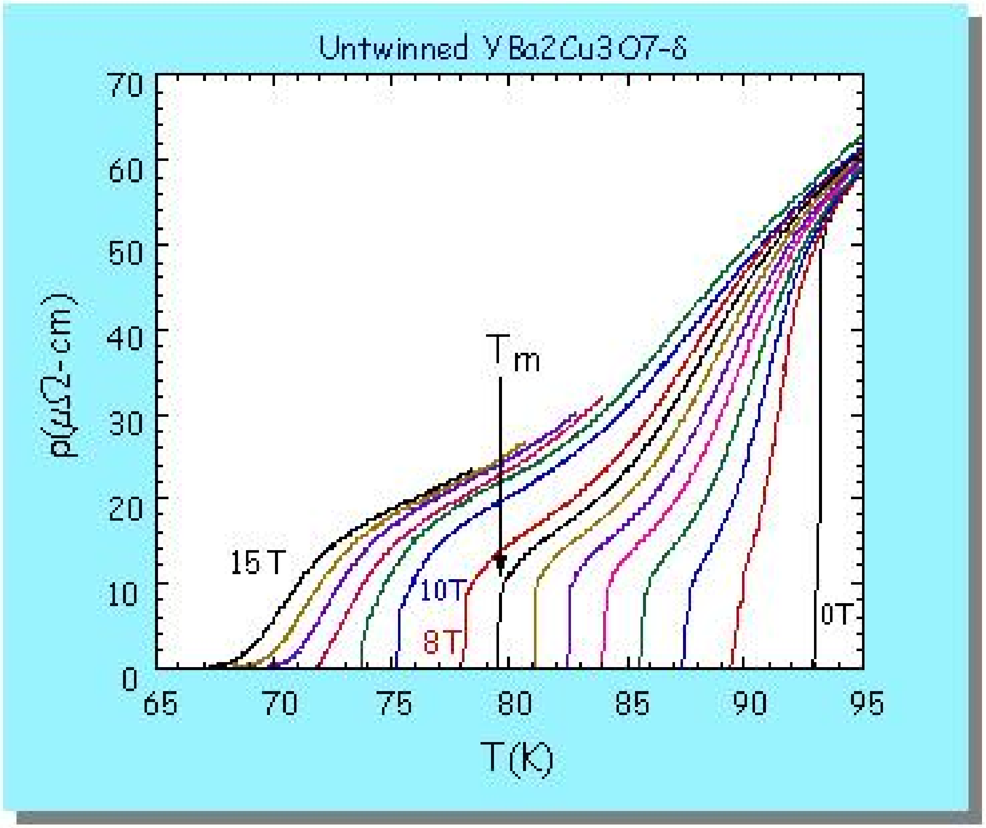
Upper Critical Point



F. Bouquet & C. Marcenat et al, Proceed. of the NATO Adv. Study Inst, Kusadasi, Turkey, 1998

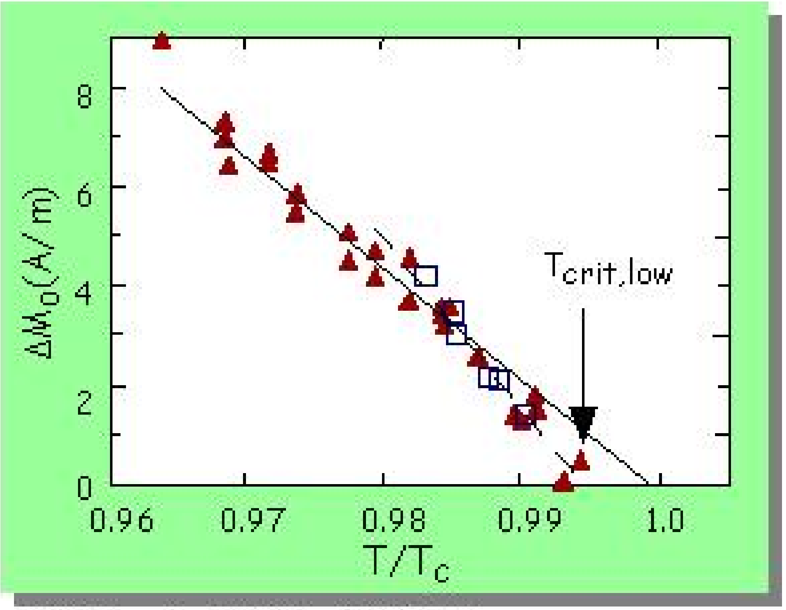


W. Kwok et al, Phys. Rev. Lett. 69, 3370 (1992)

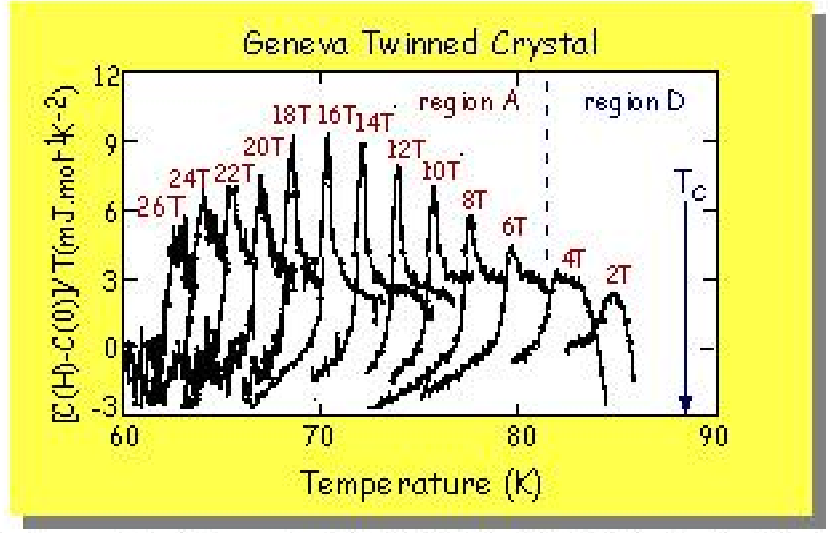


W. Kwok et al, (1999)

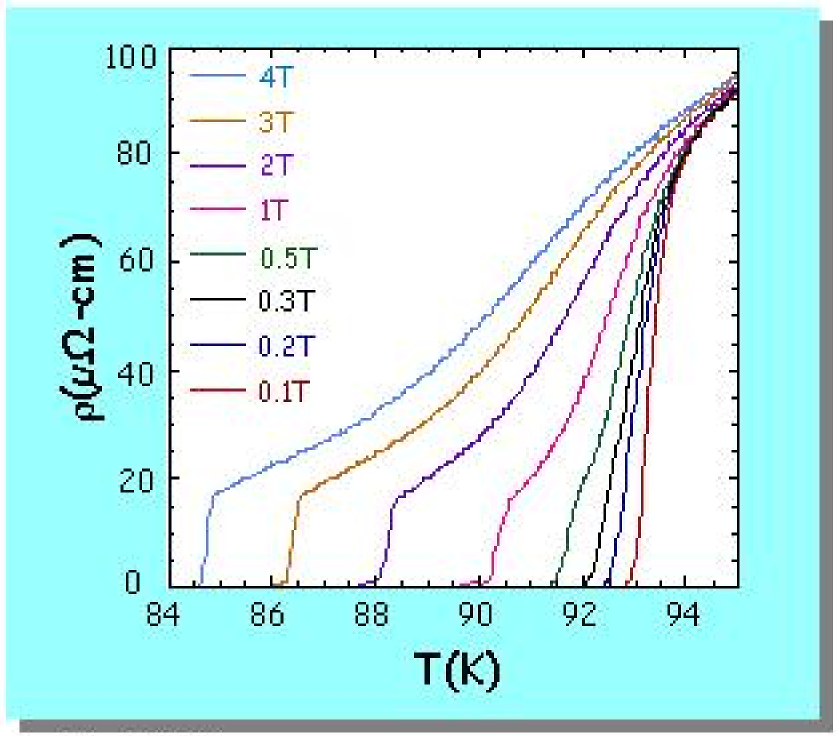
Lower Critical Point



A. Schilling et al., PRB 61, 3192, 2000



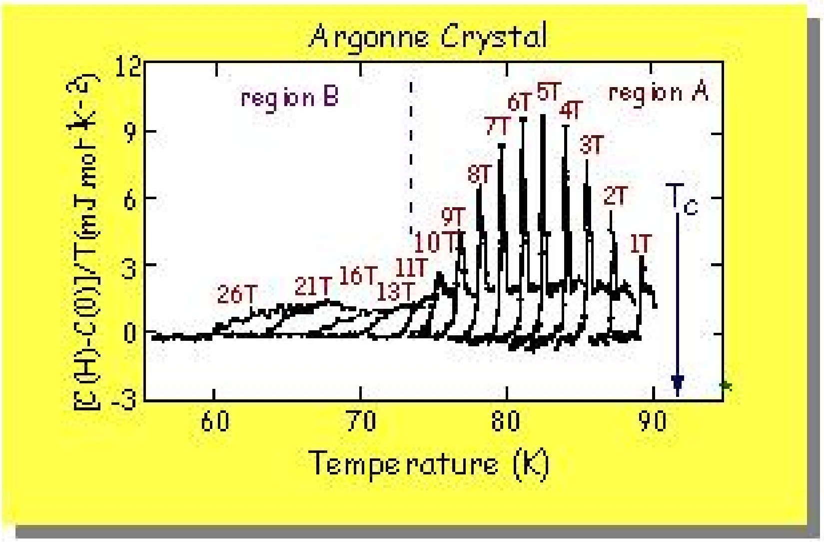
F. Bouquet & C. Marcenat et al., Proceed. of the NATO Adv. Study Inst., Kusadasi, Turkey, 1998

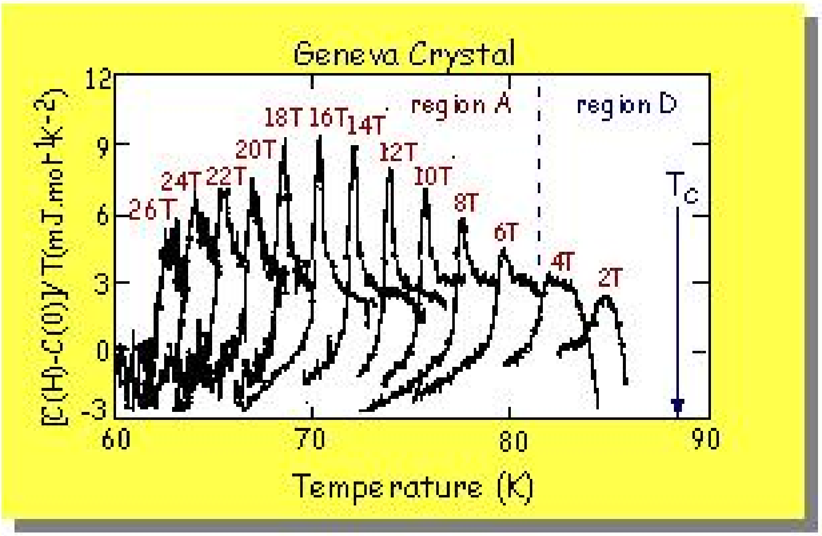


Kwok et al., (1999)

Thermodynamic Lower and Upper Critical Points

heat capacity of $YBa_2Cu_3O_7$





untwinned, x ~ 6.93 point pinning

upper critical point ~ 12 T

twinned, x ~ 7.0 planar pinning

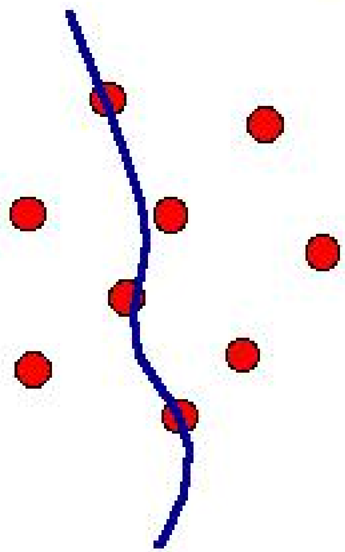
upper critical point > 26 T

lower critical point ~ 4 T

F. Bouquet and C. Marcenat et al
in *Physics and Materials Science of Vortex States, Flux Pinning and Dynamics*, R. Kossowsky, S. Bose, V. Pan, and Z. Durusoy, eds. (Kluwer, Dordrecth, 1999) p. 743.
Proceedings of the NATO Advanced Study Institute , Kusadasi, Turkey, July 26-August 8, 1998

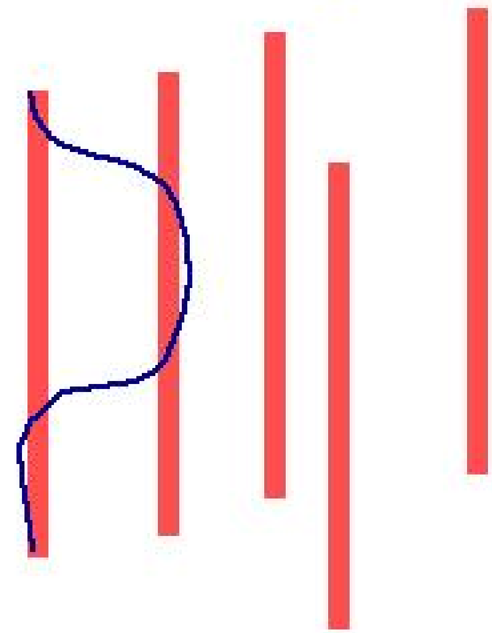
Thermodynamic Glassy States

vortex glass



D. S. Fisher, M. P. A. Fisher, and D. A. Huse
Phys. Rev. B **43,** 130-159 (1991)

Bose glass



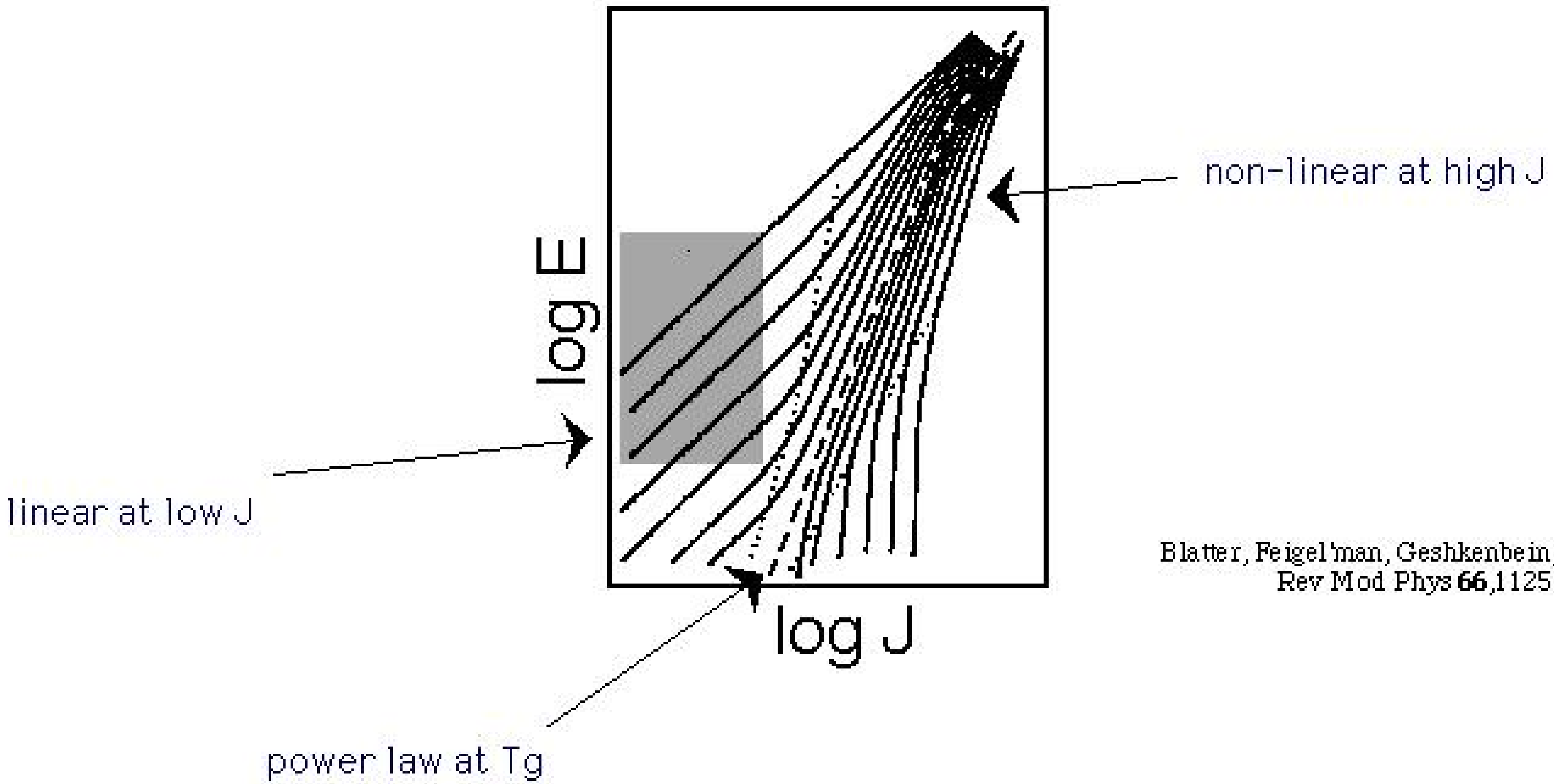
D. R. Nelson and V. M. Vinokur
Phys. Rev. B **48**, 13060-13097 (1993)

2^{nd} order transition to liquid

scaling

vortex glass		Bose glass
$\rho \sim (T - T_g)^{\nu(z-1)}$	*linear regime*	$\rho \sim (T - T_{BG})^{\nu(z-2)}$
$E/J(T-Tg)^{\nu(z-1)} \sim F_{\pm}(J/(T-Tg)^{2\nu})$	*non-linear regime*	$E/J(T-T_{BG})^{\nu(z-2)} \sim F_{\pm}(J/(T-Tg)^{3\nu})$
$E \sim J^{(z+1)/2}$	*at T_g*	$E \sim J^{(z+1)/3}$

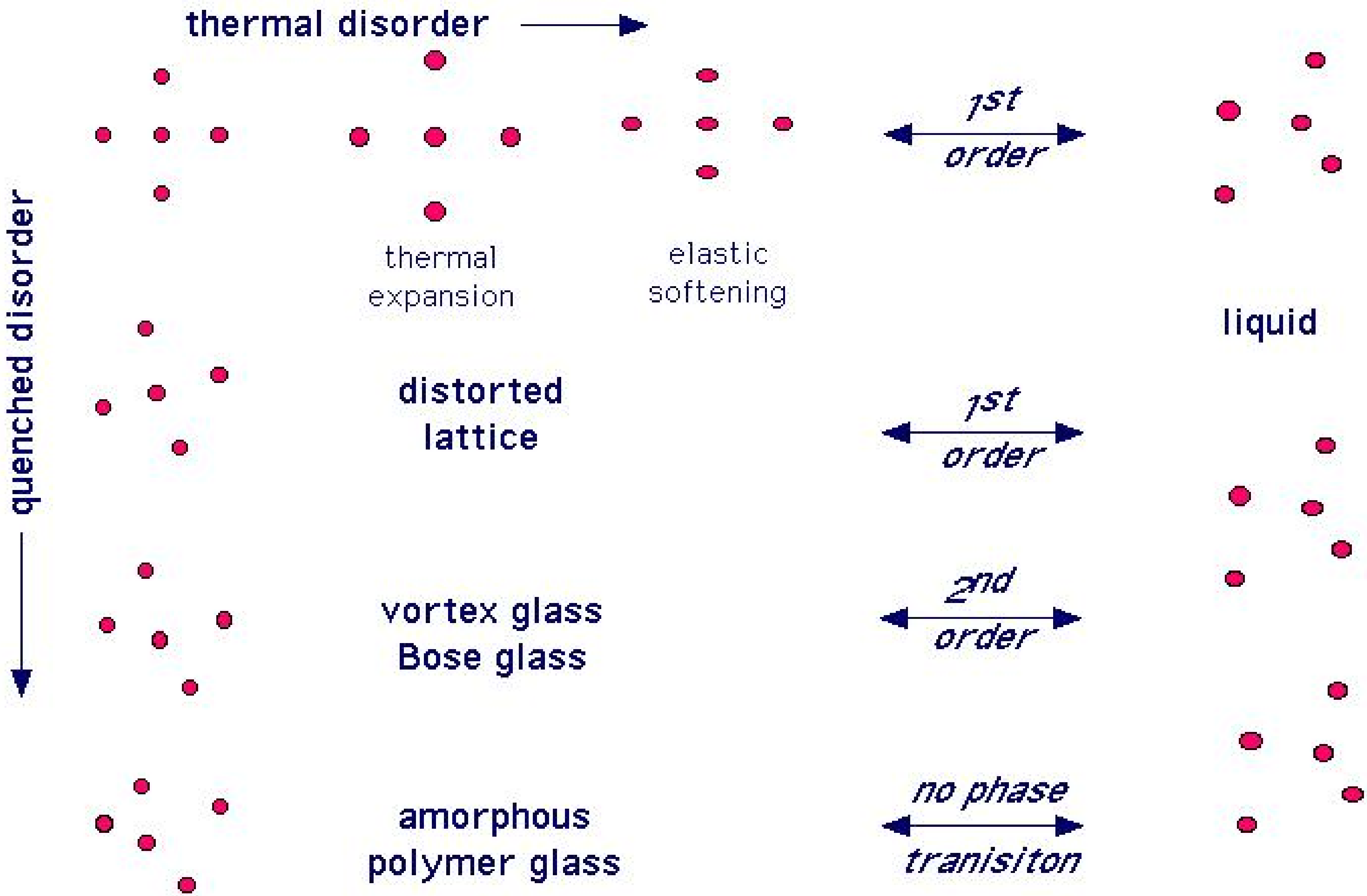
2^{nd} Order Glass – Liquid Scaling



Blatter, Feigel'man, Geshkenbein, Larkin, Vinokur
Rev Mod Phys **66**,1125 (1994)

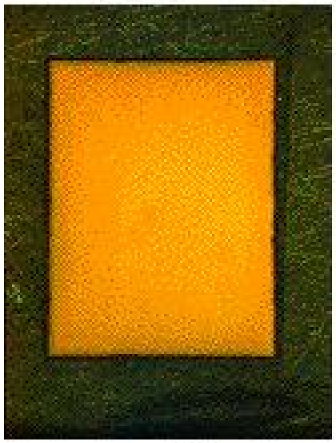
$\rho \sim (T-T_g)^{\nu(z-1)}$	*linear regime*	$\rho \sim (T-T_{BG})^{\nu(z-2)}$
$E/J(T-Tg)^{\nu(z-1)} \sim F_{\pm}(J/(T-Tg)^{2\nu})$	*non-linear regime*	$E/J(T-T_{BG})^{\nu(z-2)} \sim F_{\pm}(J/(T-Tg)^{3\nu})$
$E \sim J^{(z+1)/2}$	*at T_g*	$E \sim J^{(z+1)/3}$

Effects of Disorder

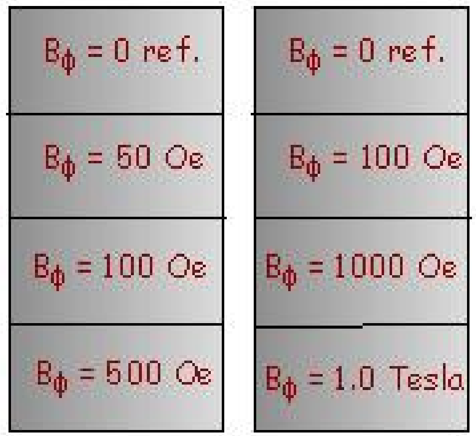


Experiment: Line Disorder and the Critical Points

Experimental Design



untwinned YBCO



cleave into several pieces

heavy ion irradiation

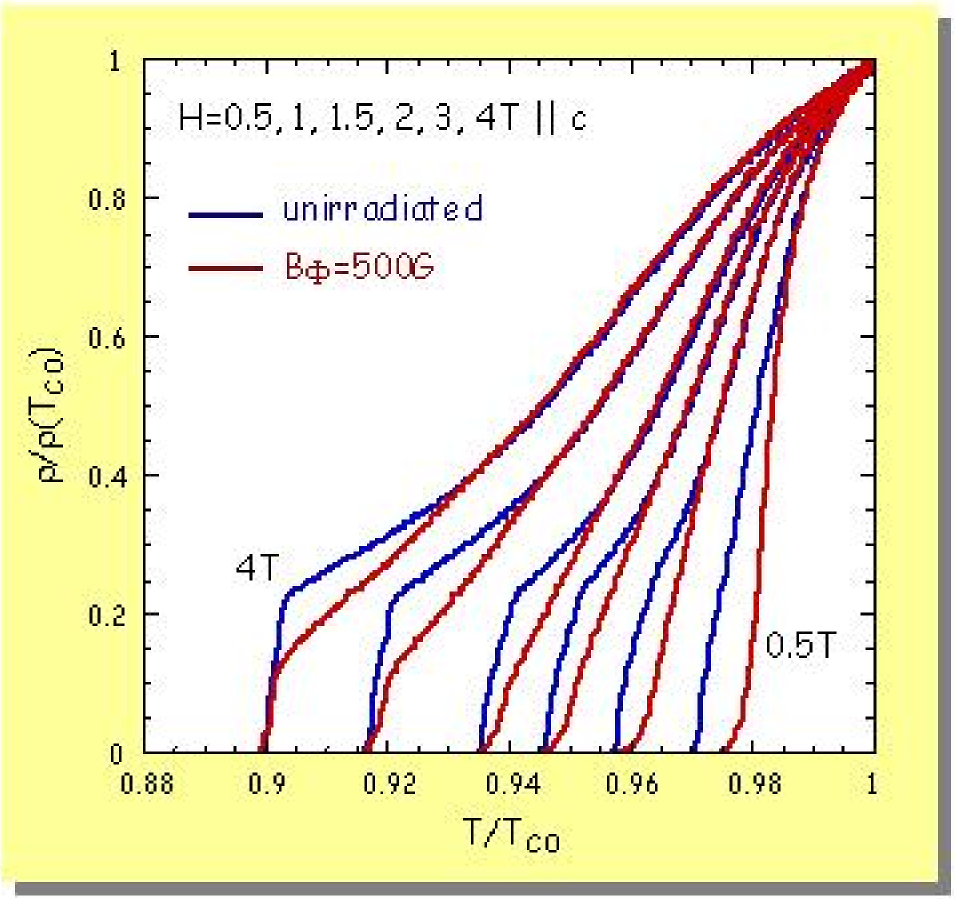
1.4 GeV ^{208}Pb^{56+}

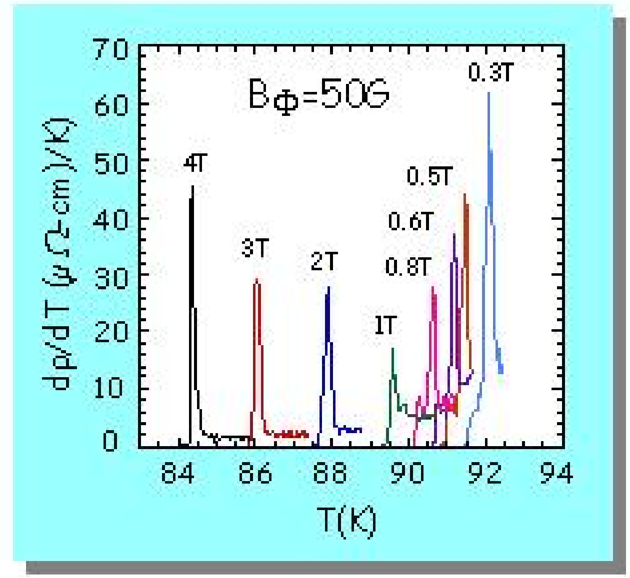
B_ϕ = matching field

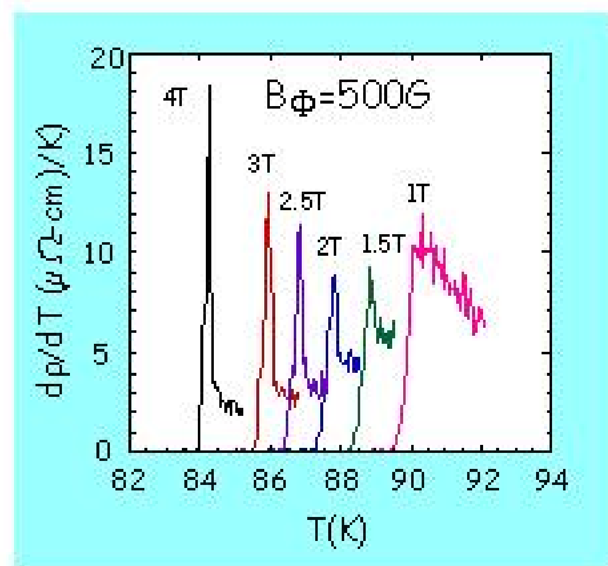
vortex density = column density

- untwinned crystal/sharp first order melting → no competing disorder
- cleave from one crystal → identical initial states
- systematic variation of defect density B_ϕ

Line Disorder and Lower Critical Point

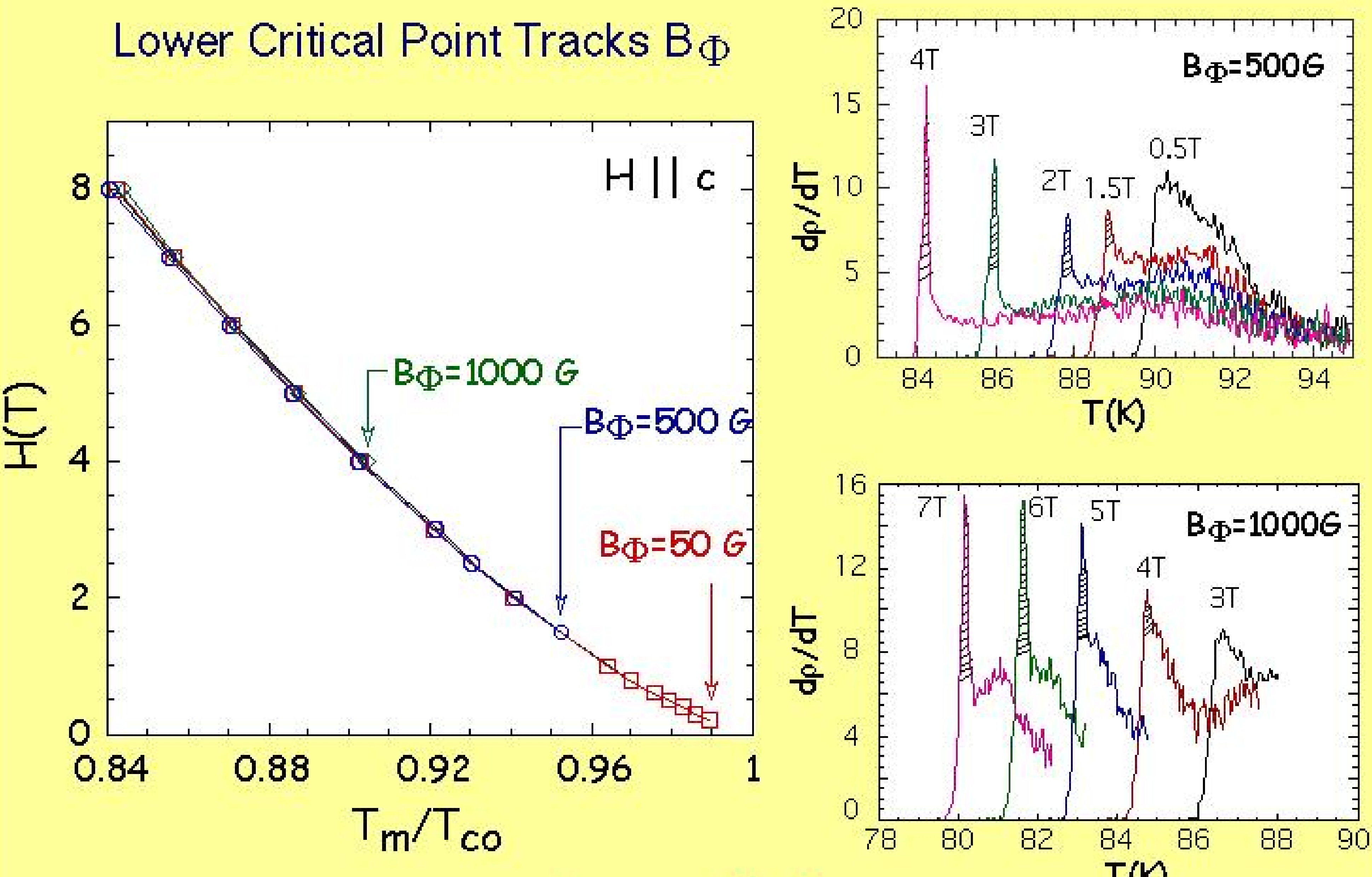




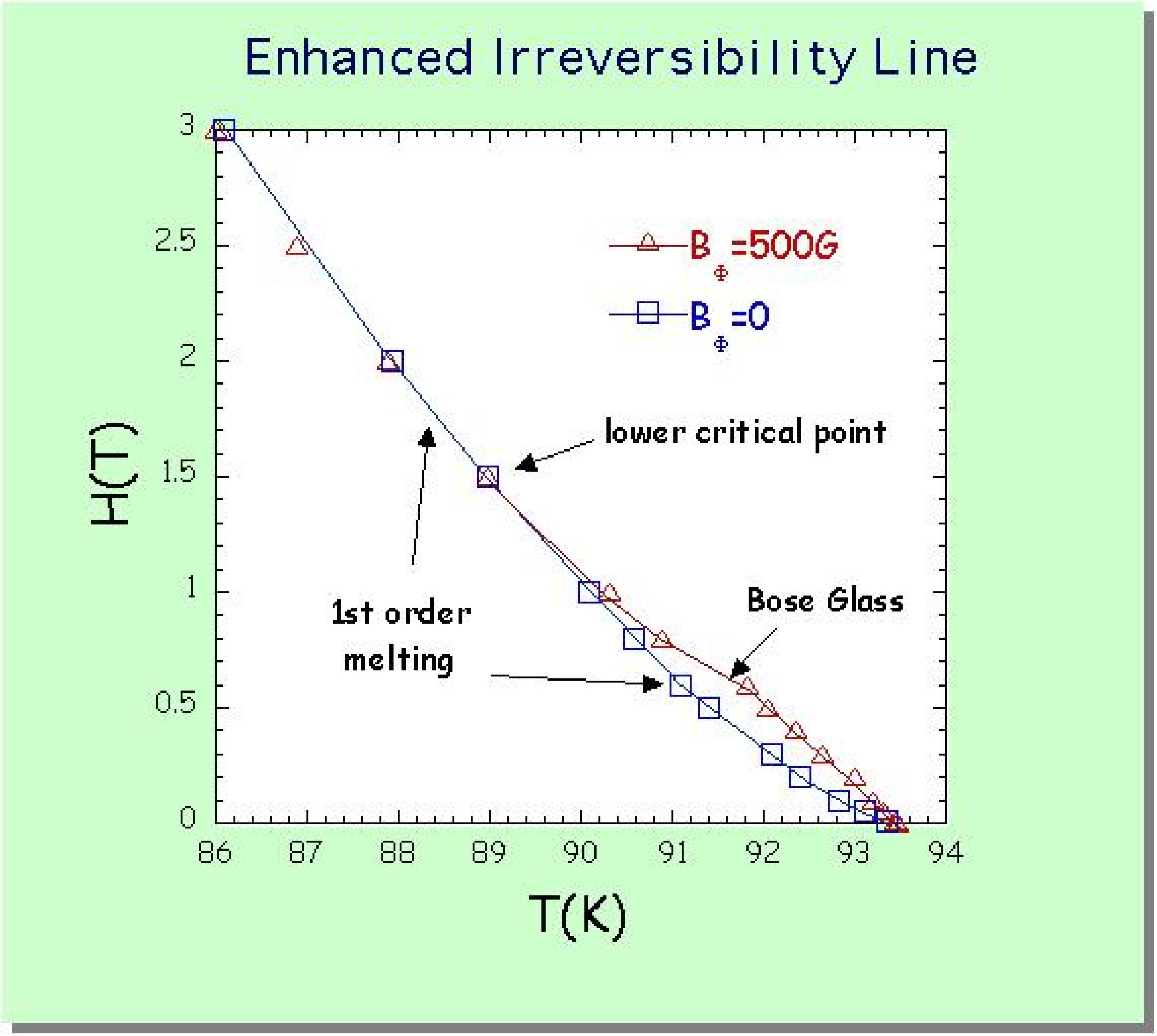


Line Disorder

Lower Critical Point Tracks B_Φ

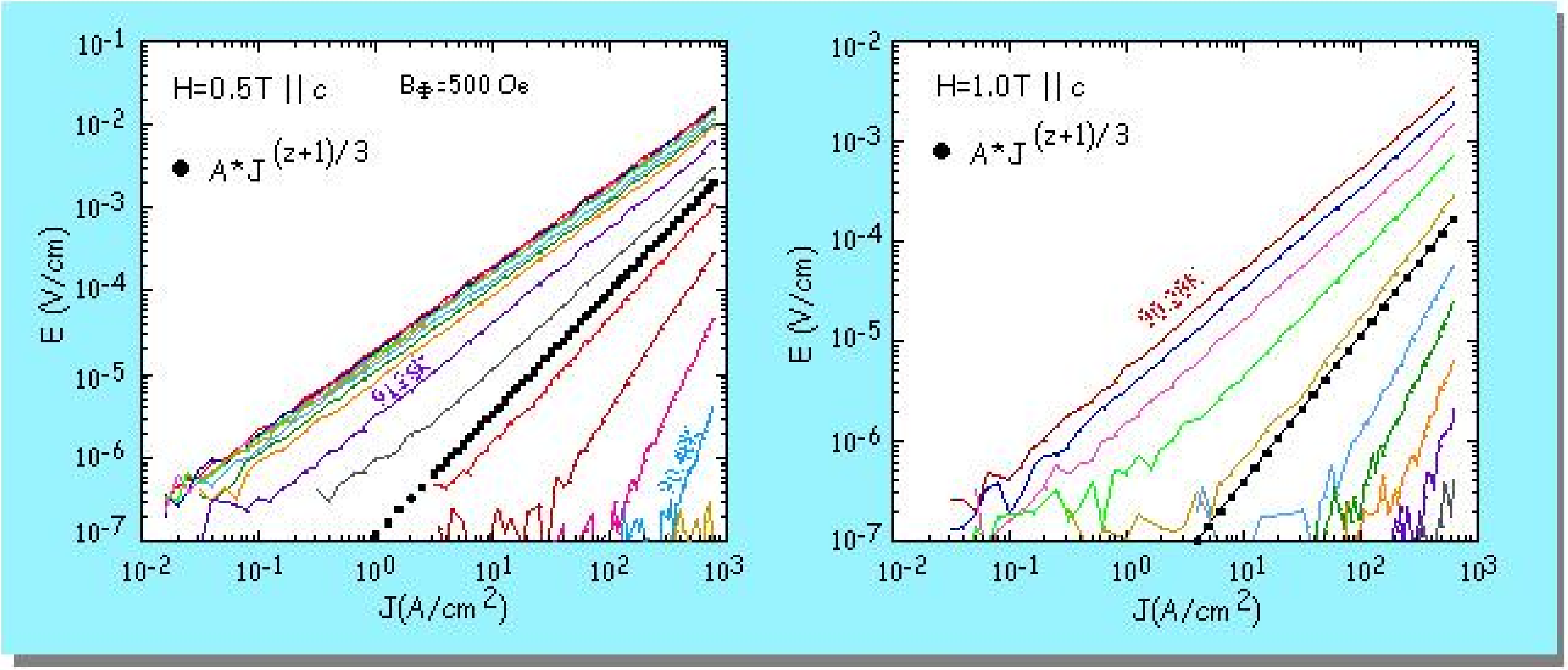


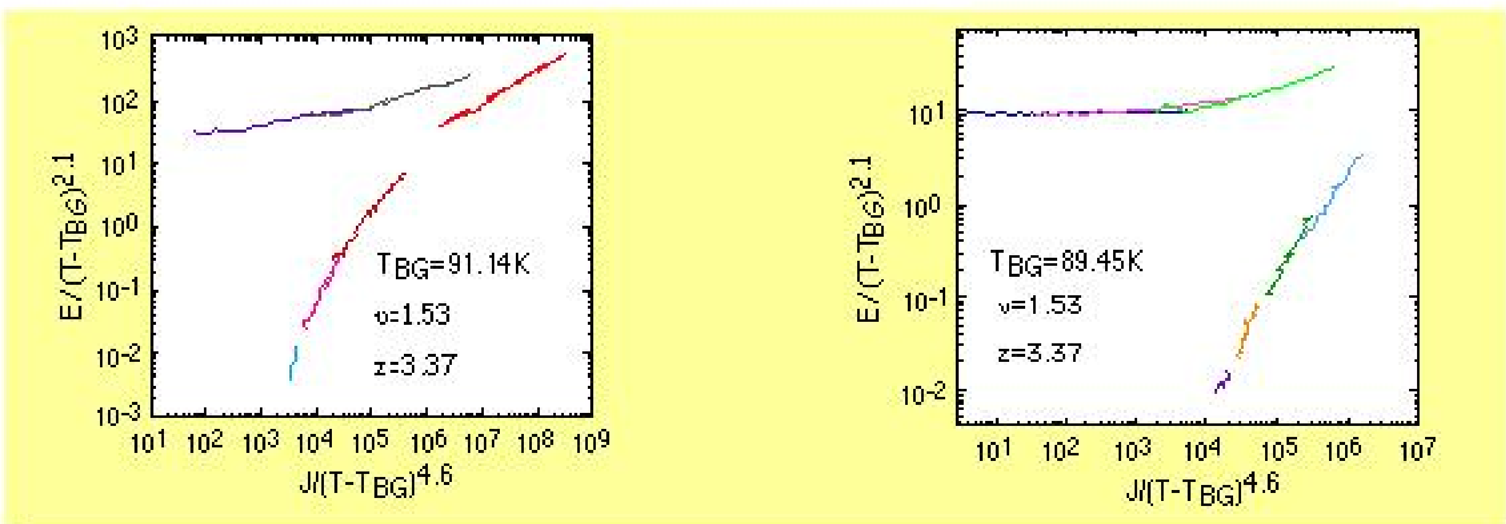
$H_{lcp} \sim 40\ B_\Phi$



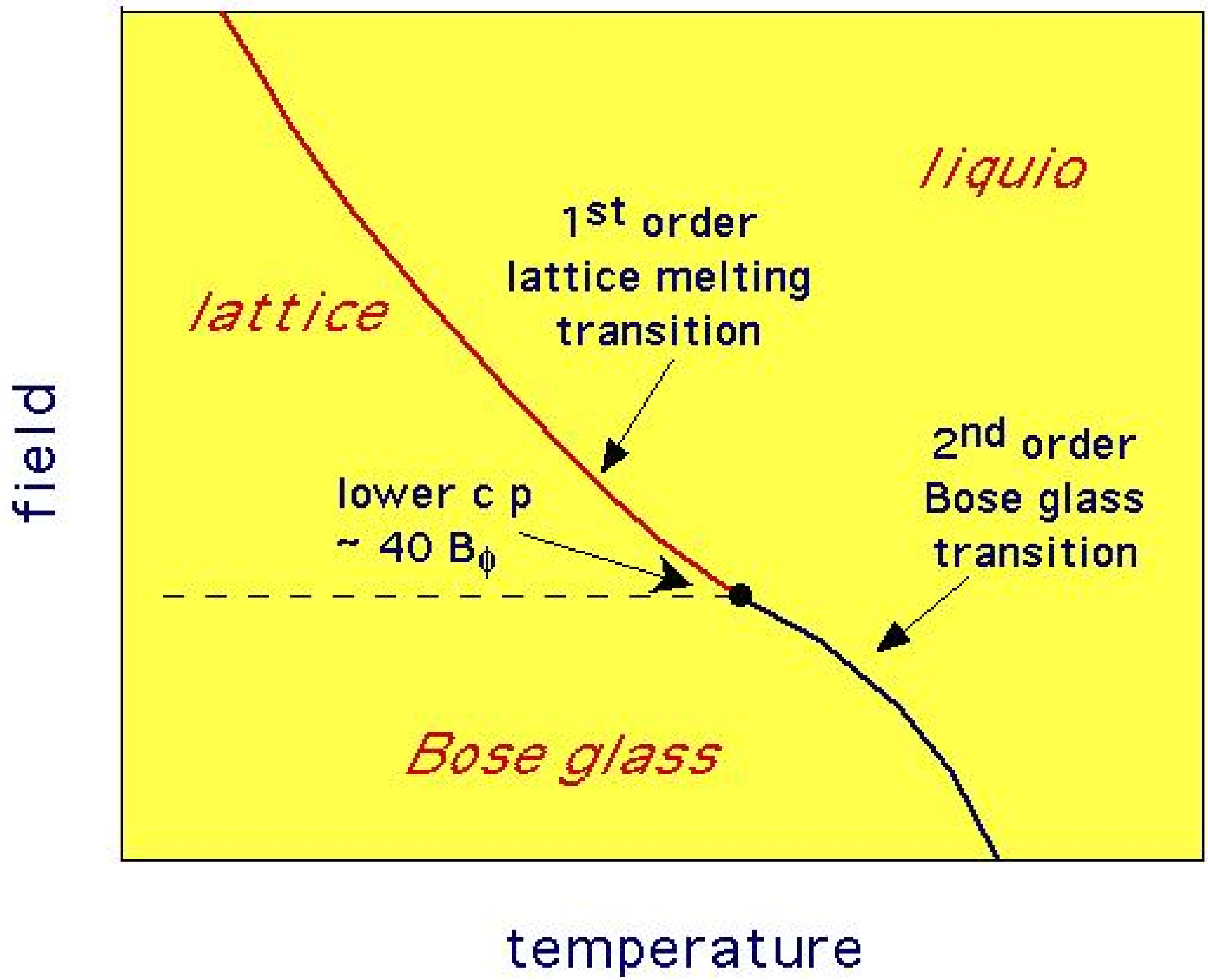
Enhanced Irreversibility Line
H(T)
T(K)
3
2.5
2
1.5
1
0.5
0
86
87
88
89
90
91
92
93
94
B Φ =500G
B Φ =0
lower critical point
1st order
melting
Bose Glass

Bose Glass Scaling Below the Lower H_{cp}

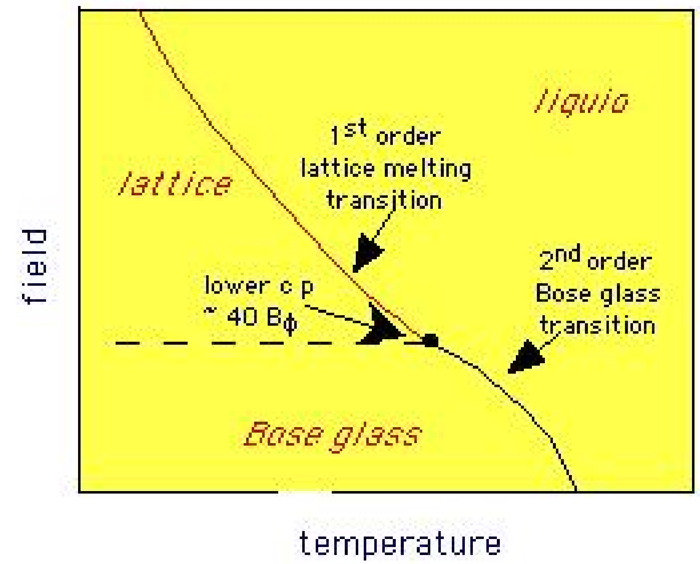


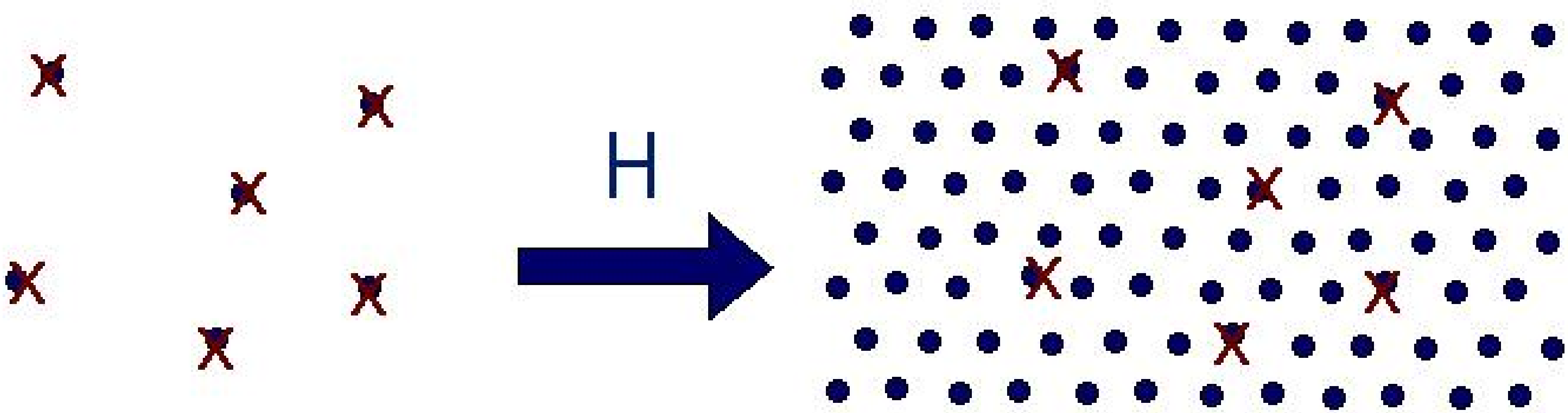


New Phase Diagram
with
Line Disorder



Bose Glass → Lattice





$B \leq B_\phi$

pinning energy >> interaction energy

Bose glass

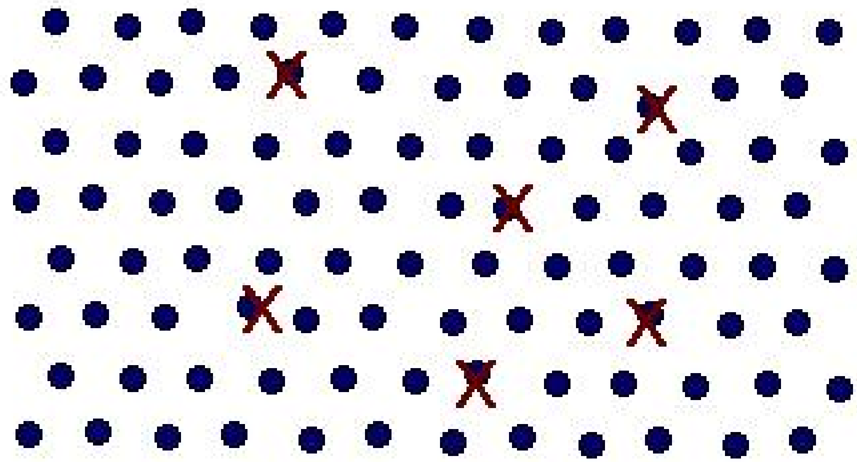
$B >> B_\phi$

interaction energy >> pinning energy

lattice

Triggering the Lower Critical Point

$B/B_\Phi \sim 40$



degree of disorder

$1/40 = 2.5\ \%$

of vortices displaced

degree of order

$\sqrt{40} \sim 6$

lattice constants

correlation length

Lindemann criteria

interstitial vortices: $\langle u^2 \rangle = 0$

pinned vortices: $\langle u^2 \rangle = a_0^2/2$

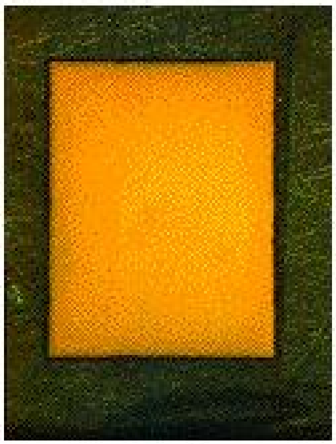
(random displacement)

average $\langle u^2 \rangle = 0.025\ a_0^2/2$

$c_L = \left(\langle u^2 \rangle / a_0^2\right)^{1/2} \sim 0.11$

Experiment: Point Disorder and the Critical Points

Experimental Design



Untwinned YBCO

→

proton irradiation

9 MeV
Western Michigan U
tandem accelerator

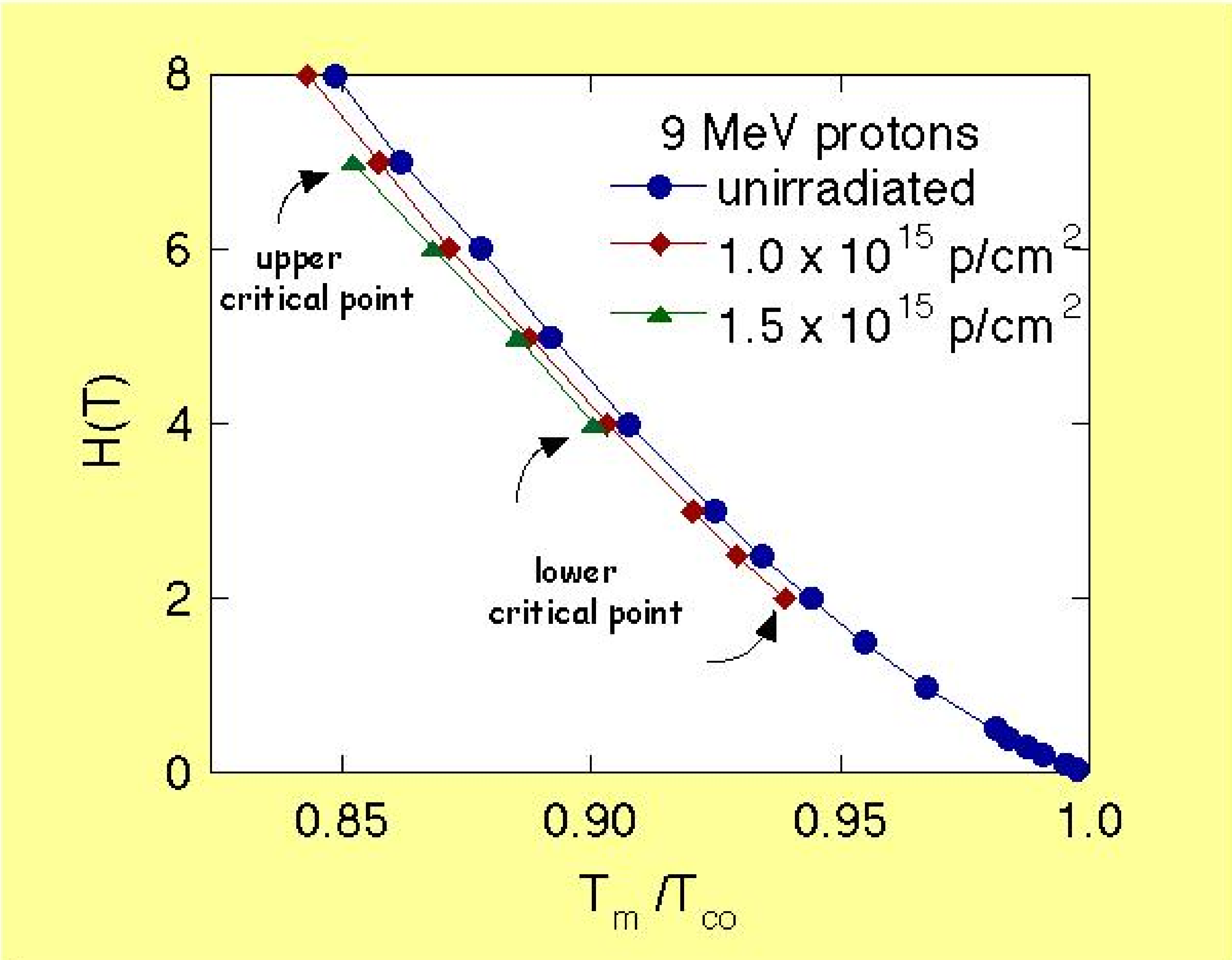
→

successive doses

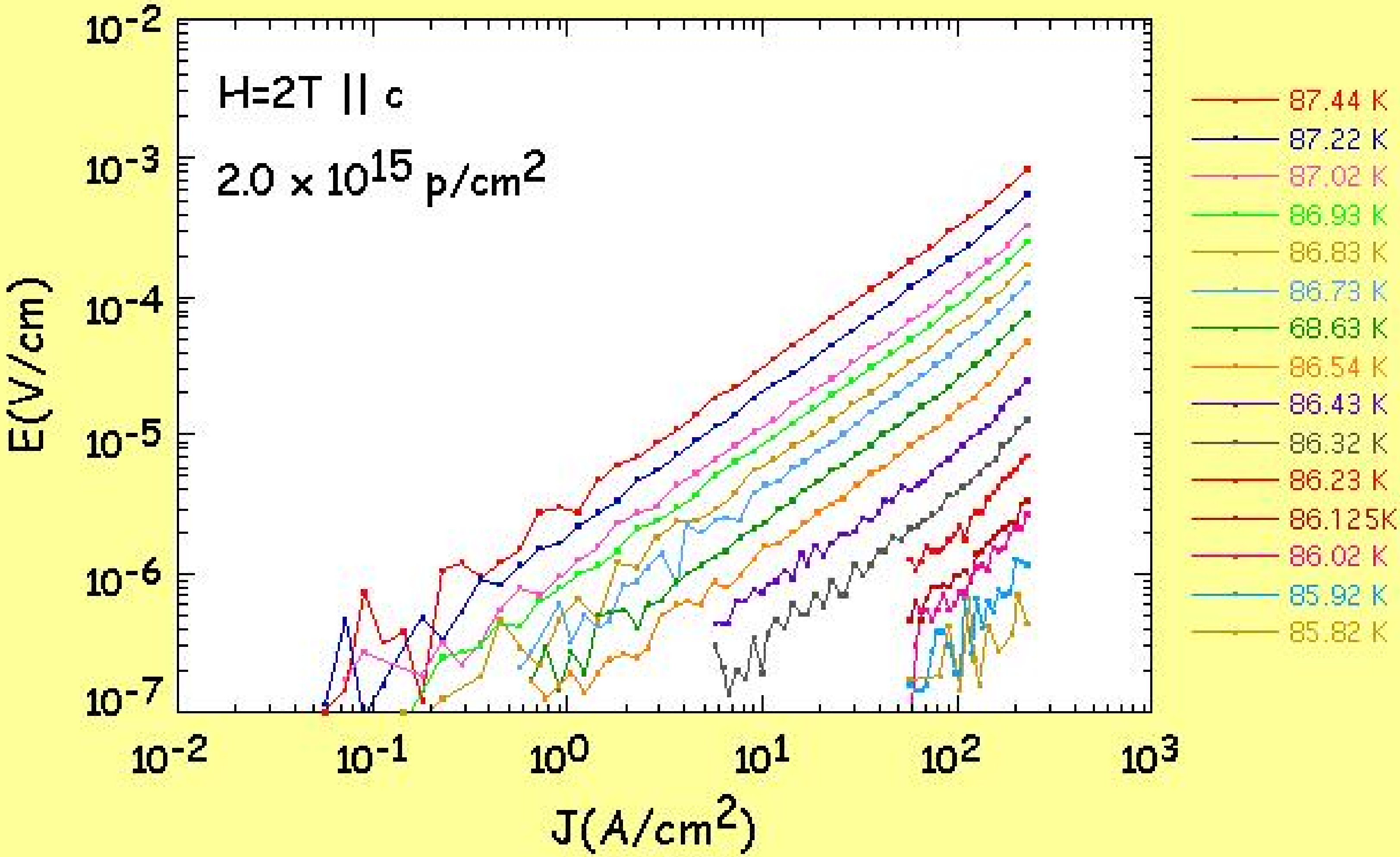
0.5×10^{15} p/cm^2
1.0×10^{15} p/cm^2
1.5×10^{15} p/cm^2
2.0×10^{15} p/cm^2

- untwinned crystal/sharp first order melting $\rightarrow$ no competing disorder
- successive irradiation of same crystal
- systematic variation of defect density B_ϕ

Point Disorder Phase Diagram

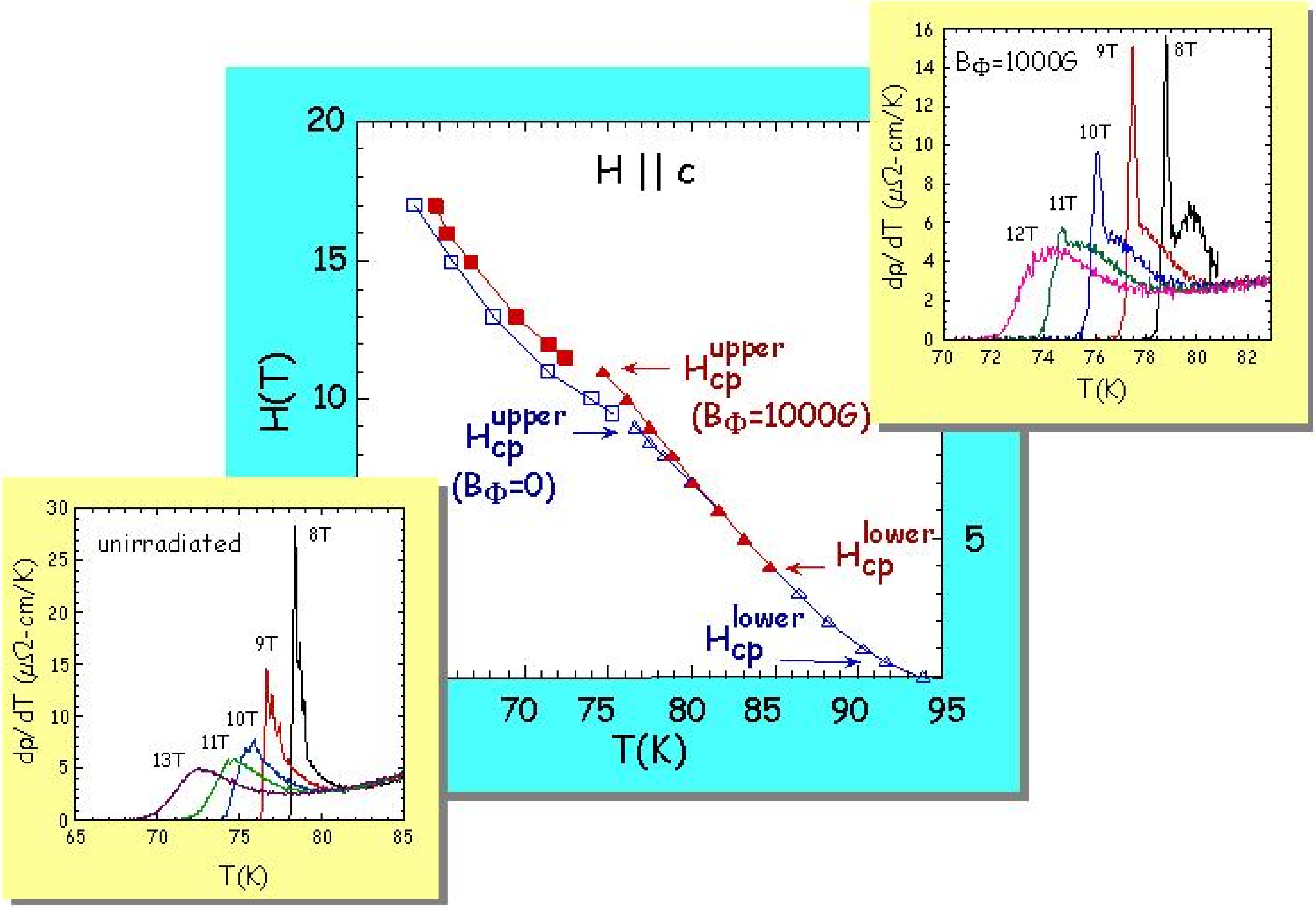


Point Disorder: Linear I-V



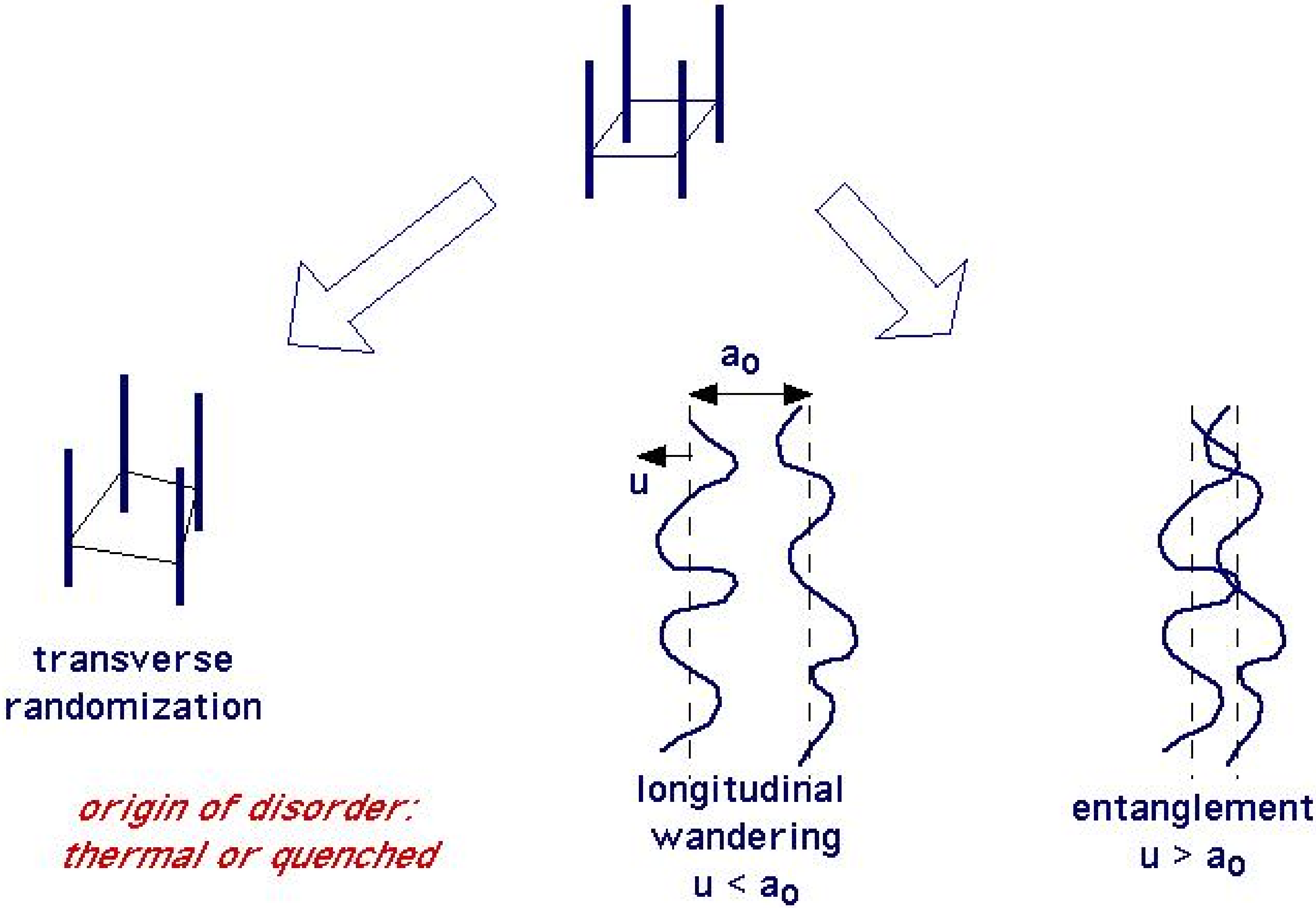
No Glassy Behavior

Line Disorder Phase Diagram

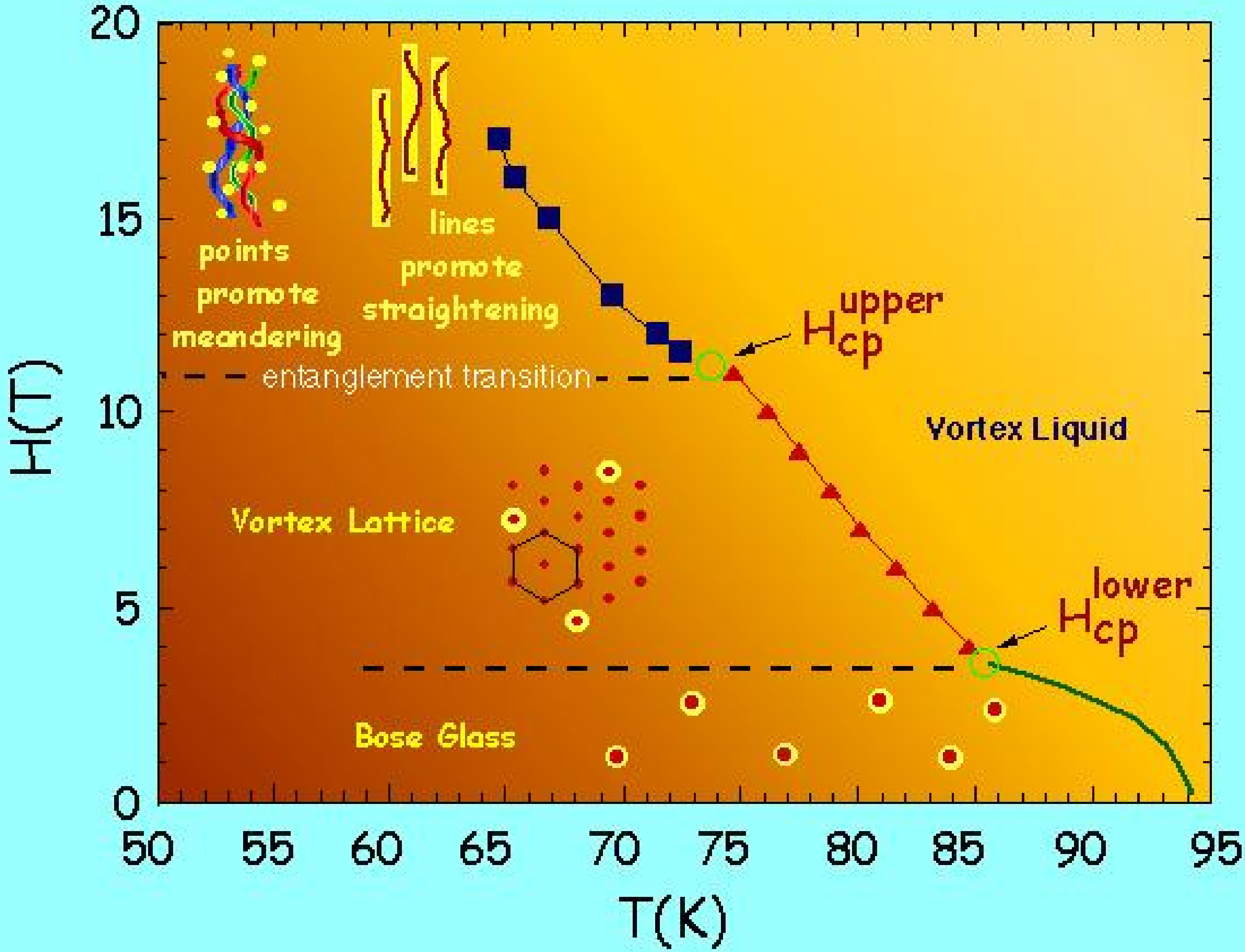


Disorder in Line Systems

polymers, liquid crystals, vortices

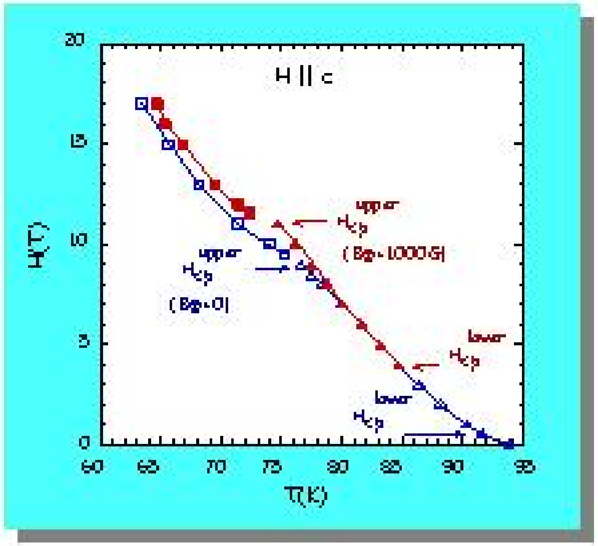


Phase Diagram of Vortex Matter

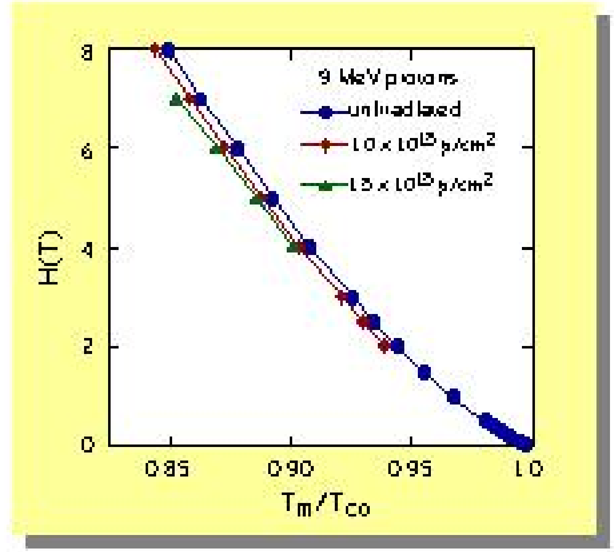


W. K. Kwok, R. J. Olsson, G. Karapetrov, L. M. Paulius, W. G. Moulton, D. J. Hofman , G. W. Crabtree (1999)

Summary



line disorder



point disorder

critical points controlled by disorder

- line defects: Bose glass < lower critical point $H_{lcp} \sim 40\ B_\phi$
- point defects: disordered phases not identified
- upper phase - longitudinal wandering & entanglement
- lower phase - transverse randomization