Bragg Glass Superconductivity

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Outline:

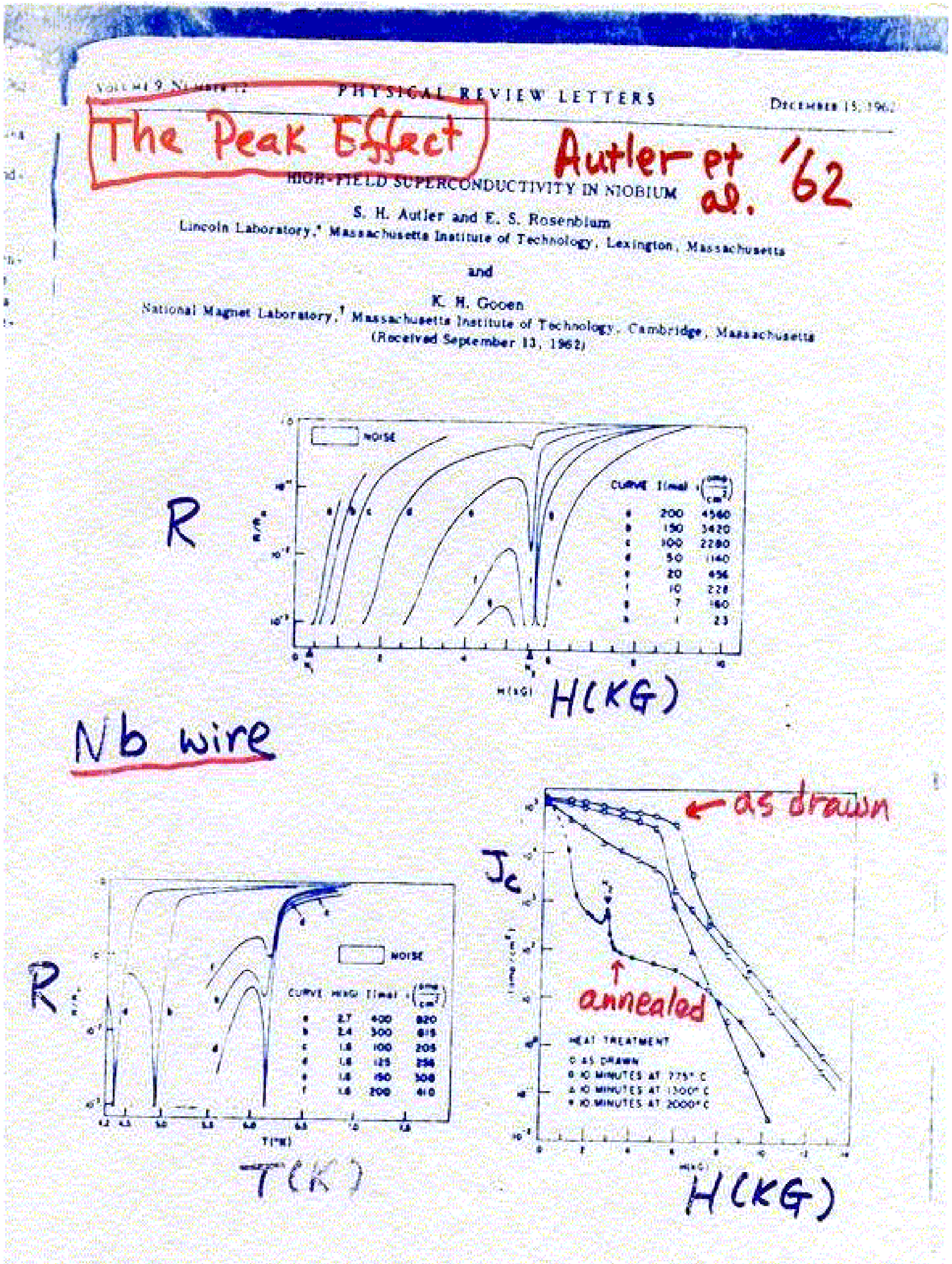
- The peak effect problem (1962-2002):
  observed in most weak-pinning type-II superconductors

- Larkin-Ovchinnikov collective pinning model (1970-1979):
  loss of long-range-order (LRO)
  peak effect = anomalous softening of vortex lattice

- Can there be a real solid-liquid phase transition in vortex matter?
  Bragg glass model (1990-1995): survival of topological LRO
  A true solid-liquid transition should be possible!

- Peak effect = Bragg glass melting transition?
  Brown-NIST experiment: *in-situ* neutron scattering

X.S. Ling, S.R. Park, B.A. McClain, S.M. Choi, D.C. Dender, J.W. Lynn, PRL 86, 712 (2001).
S.R. Park, I. Dimitrov, S.M. Choi, D.C. Dender, J.W. Lynn, X.S. Ling (to be submitted).



The Peak Effect Problem:

Peak effect in high-Tc YBCO:

Ling, Budnick (1991)
D'Anna (1993)
Kwok, Crabtree (1994)
Shi, Ling (1999)

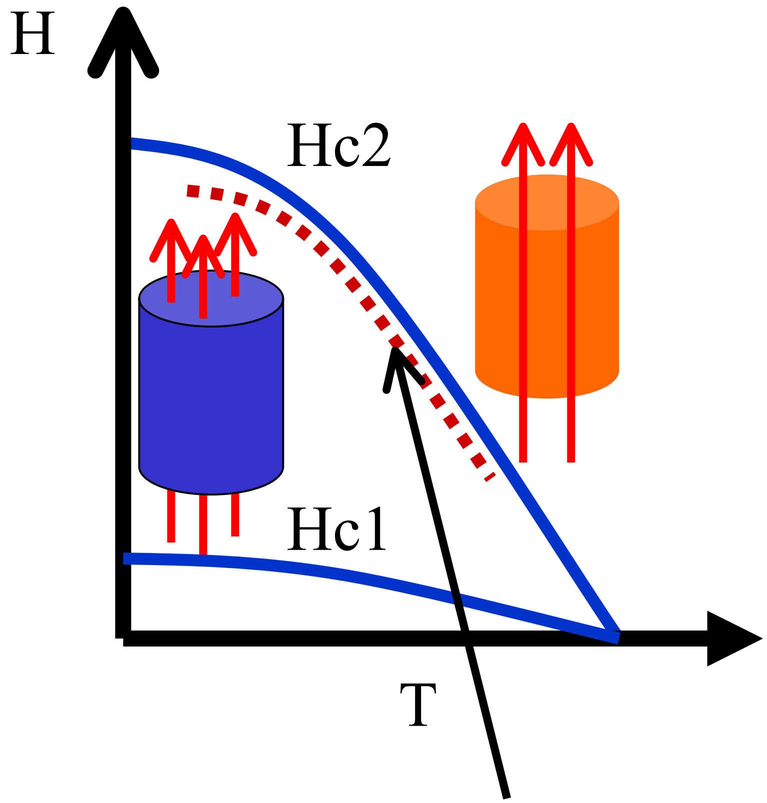
Peak effect in 2H-NbSe2 and other low-Tc systems (1993-):

Bhattacharya, Higgins
Andrei, Xiao
Kes
Ling, Berger
Gammel, Bishop,
Zeldov
Ling, Park, Lynn (2001)

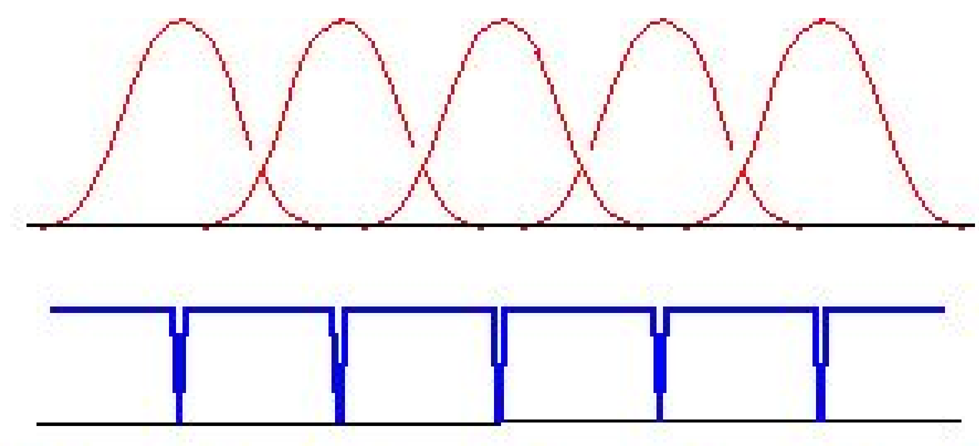
2^{nd}-peak effect in BSCCO may be related to the peak effect:

Konczykowski
Tamegai
Zeldov

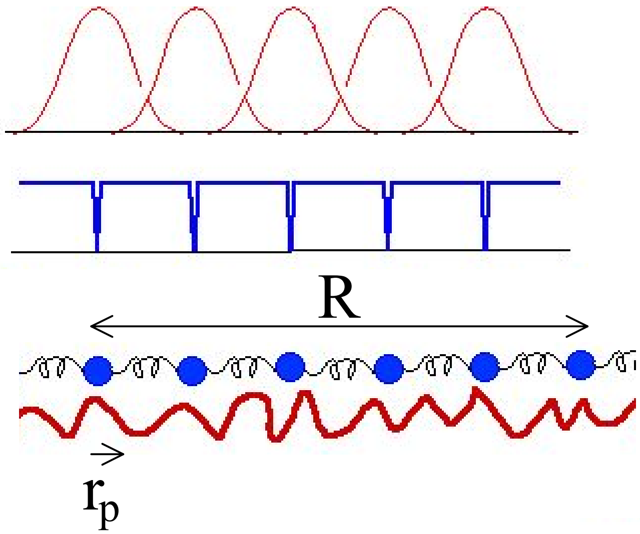
Type-II Superconductors



Abrikosov lattice



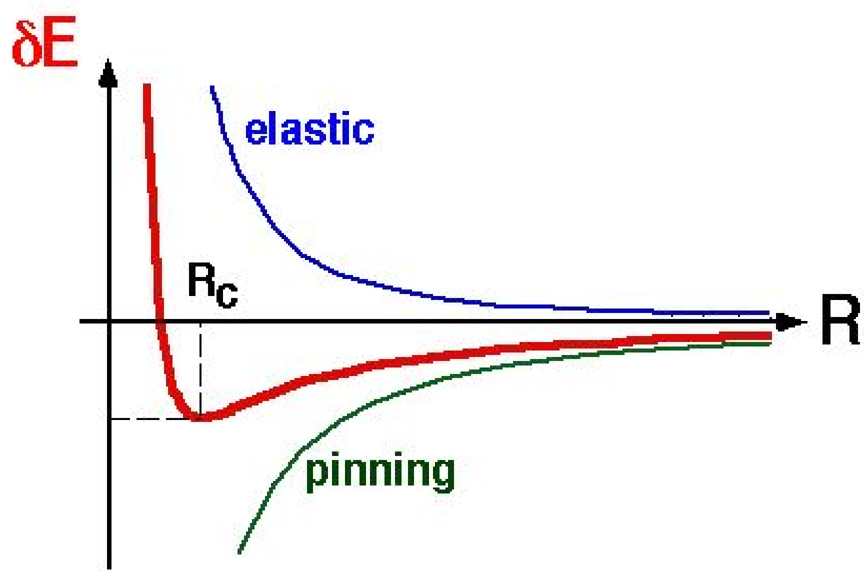
location of the peak effect in low-Tc systems



Random pinning destroys long-range order!

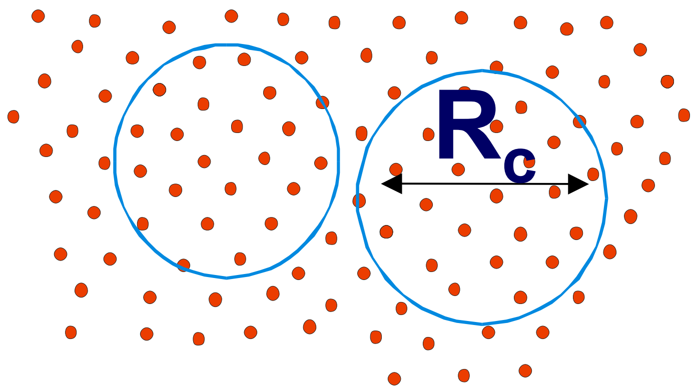
A.I. Larkin (1970)
Y. Imry, S.-k. Ma (1975)
P.A. Lee, T.M. Rice (1980)

$$\delta E = C_{66}\left(\frac{r_p}{R}\right)^2 + C_{44}\left(\frac{r_p}{L}\right)^2 - f r_p\left(\frac{n}{R^2 L}\right)^{1/2}$$



Collective Pinning Model

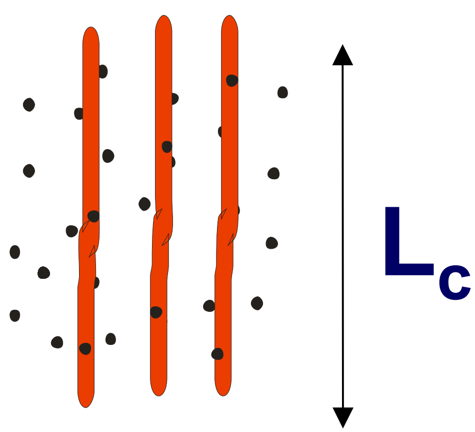
A.I. Larkin, Yu. Ovchinnikov (1979)



$$F_p = \frac{\sqrt{N} f}{V_c} = \sqrt{\frac{n f^2}{V_c}} = J_c B = \frac{n^2 f^4}{C_{66}^2 C_{44} r_p^3} \qquad \text{3D}$$

$$= \frac{n f^2}{C_{66} r_p d} \qquad \text{2D}$$

$$R_c \cong \frac{C_{66}^{3/2} C_{44}^{1/2} r_p^2}{n f^2} \qquad \frac{L_c}{R_c} = \sqrt{\frac{C_{44}}{C_{66}}}$$

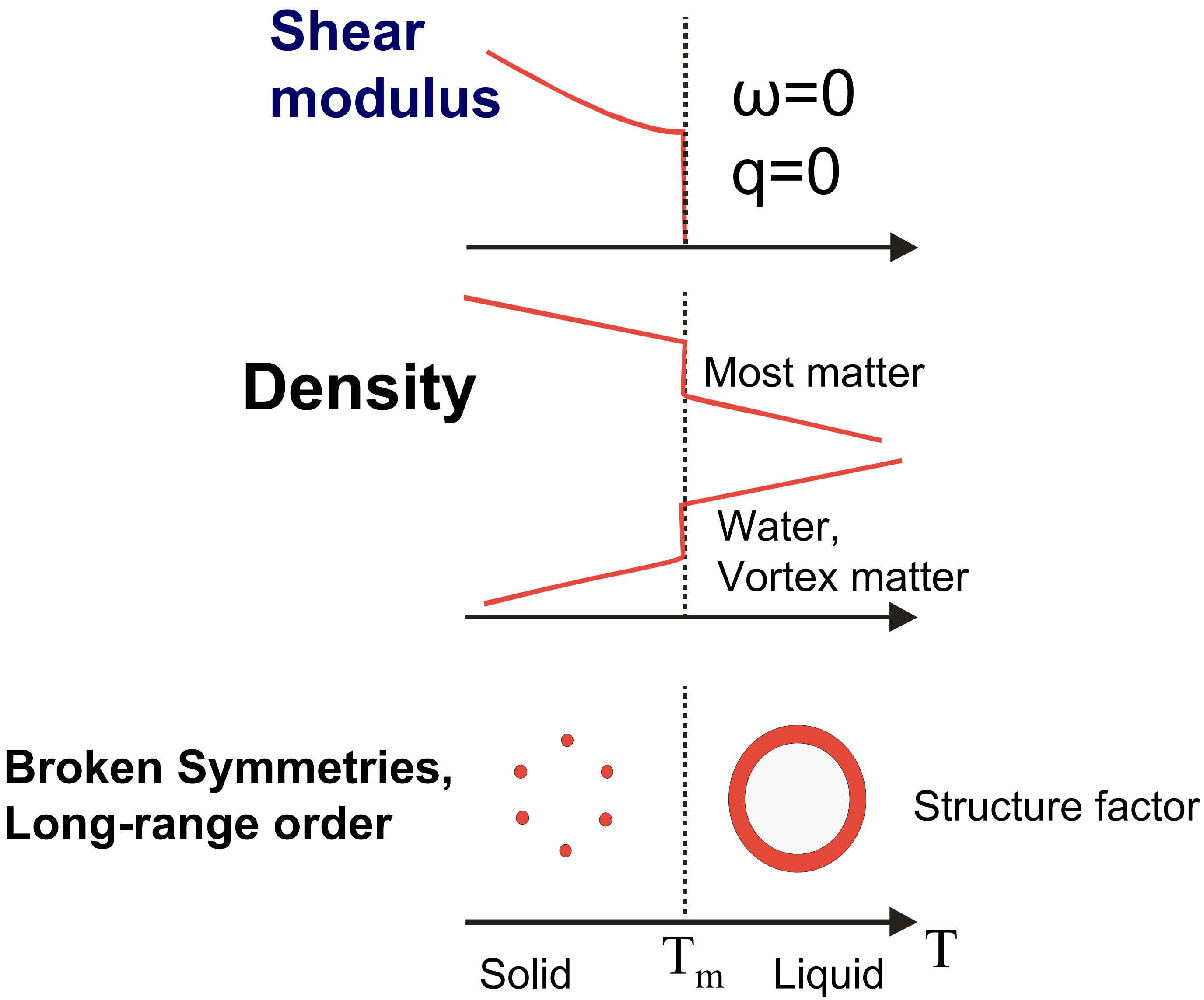


In the Larkin model, the peak effect is caused by a sudden softening of the vortex lattice.

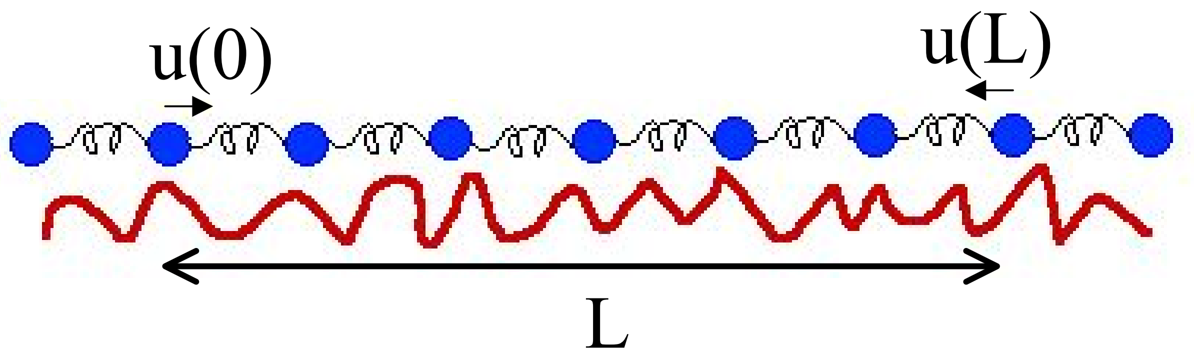
Is it a phase transition?

Signatures of conventional solid-liquid transitions:

1st order phase transitions



weak random pinning systems



$$\langle \overline{[u(L)-u(0)]^2} \rangle = A \log L$$

Quasi-long-range-order can survive in 3D weak pinning systems!

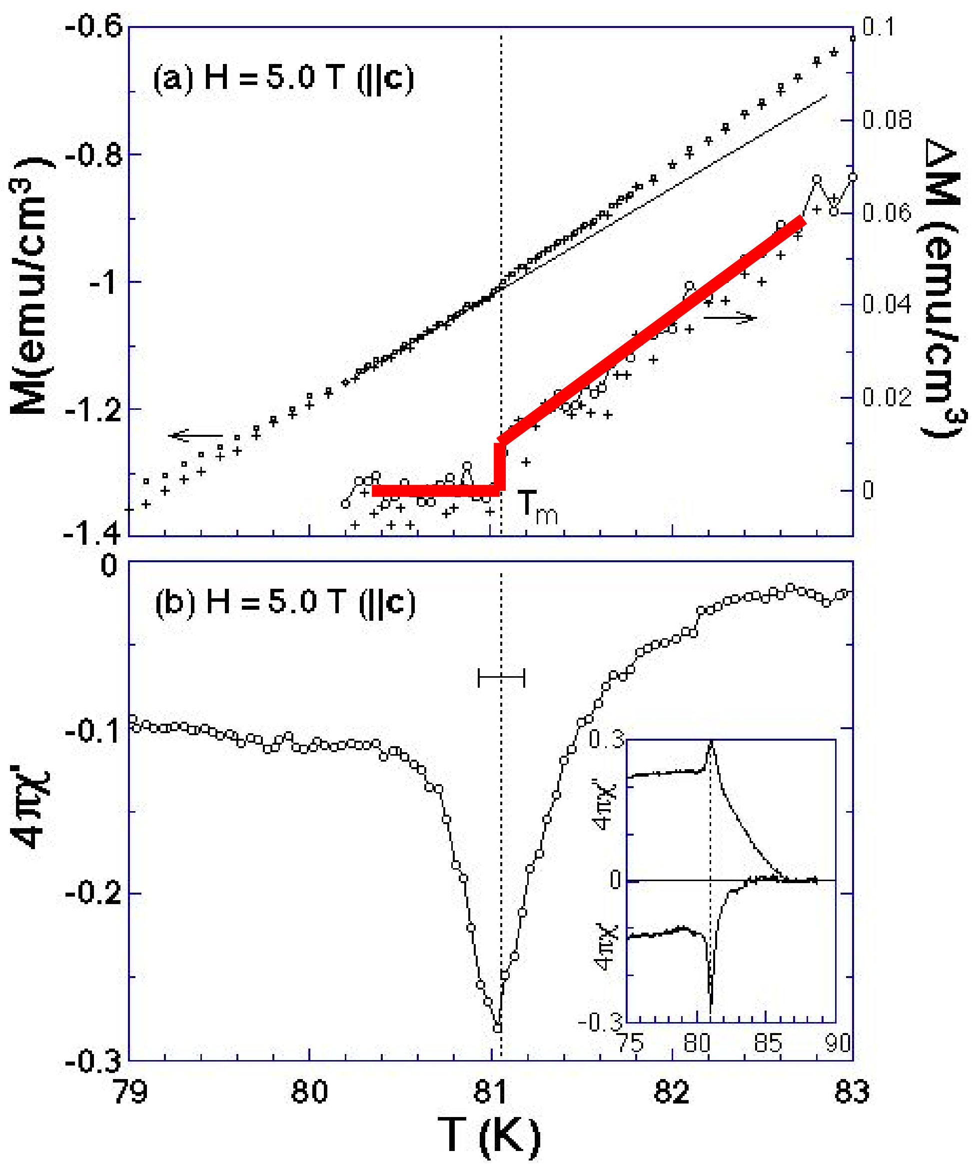
T. Nattermann (1992)
T. Giamarchi,
P. le Doussal (1995)

It's a Bragg glass!

A real solid-liquid transition is possible.



First Hint from YBaCuO:
coincidence of peak effect and magnetization jump



T. Ishida (1997)
J. Shi, X.S. Ling, R. Liang, D. Bonn, W. Hardy (1999).

Also in BSCCO:

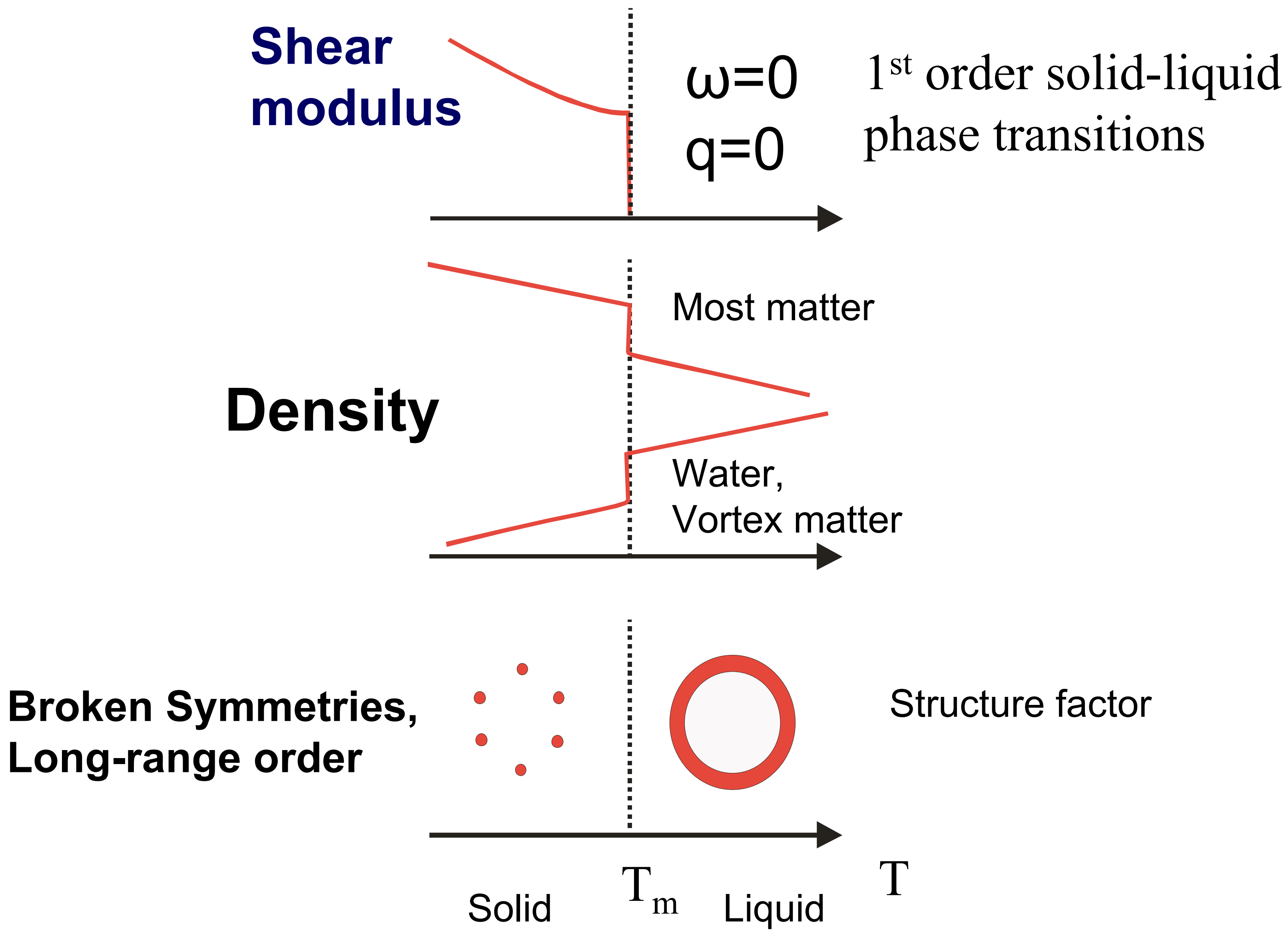
N. Avraham, E. Zeldov et al. (2002)

$$B = H + 4\pi M$$

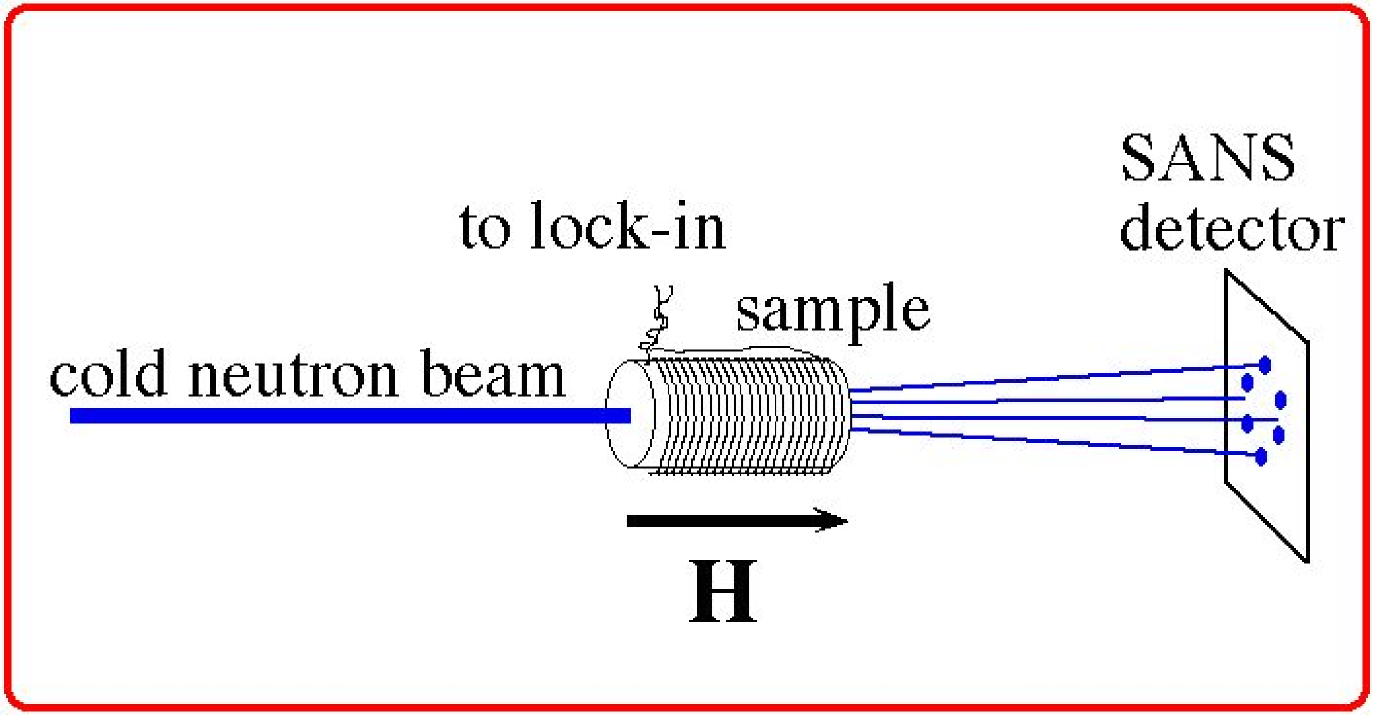
$$B = \mathbf{n}\ \phi_o$$

Vortex density

Now, we still need structural evidence



Experimental Configuration

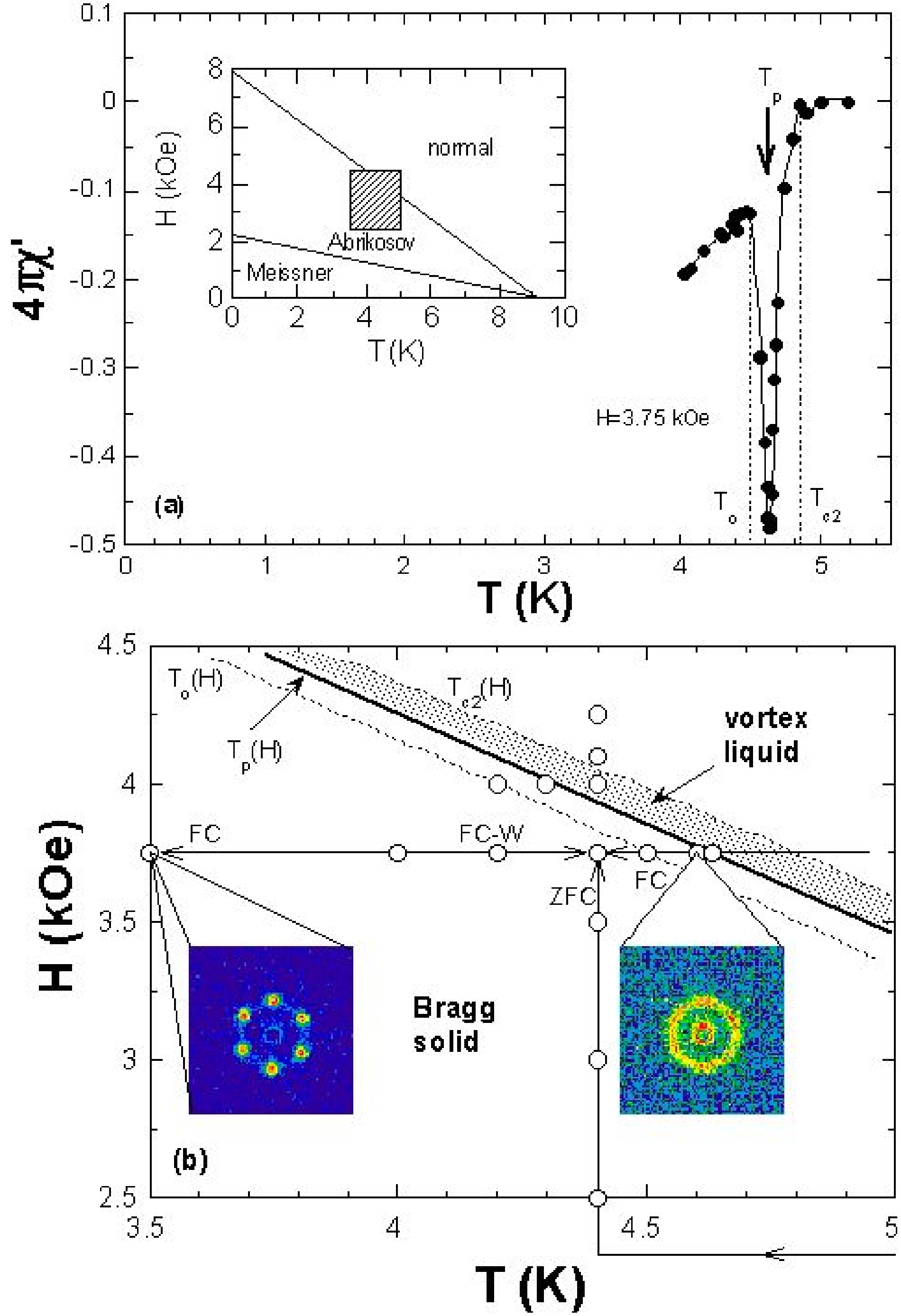


Nb single crystal 99.998%

λ=0.6nm, $\Delta\lambda/\lambda$=0.11, H || <111>


NIST Center for Neutron Research

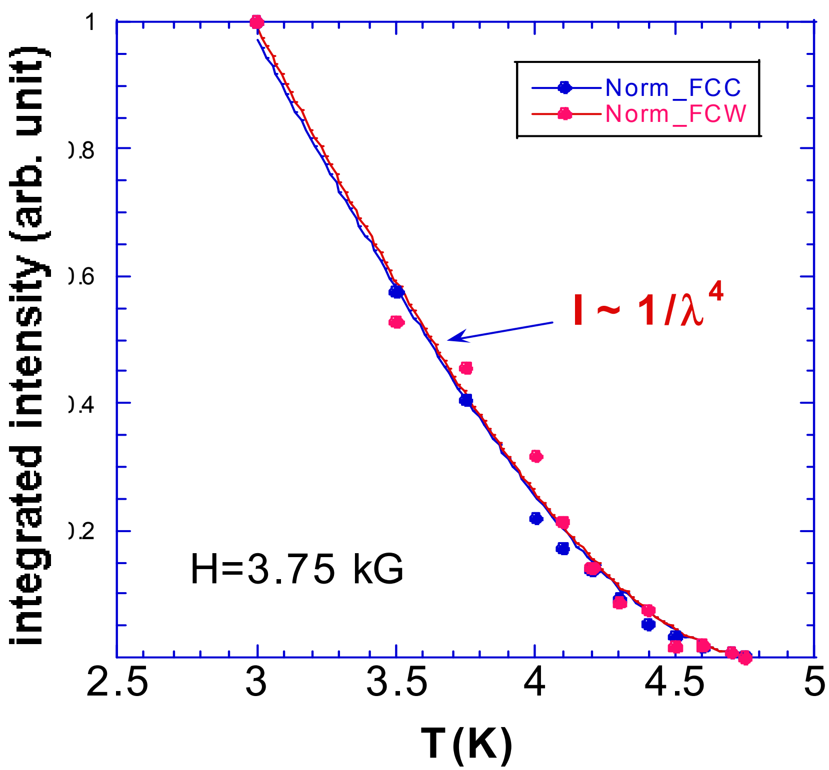
Phase Diagram of Nb

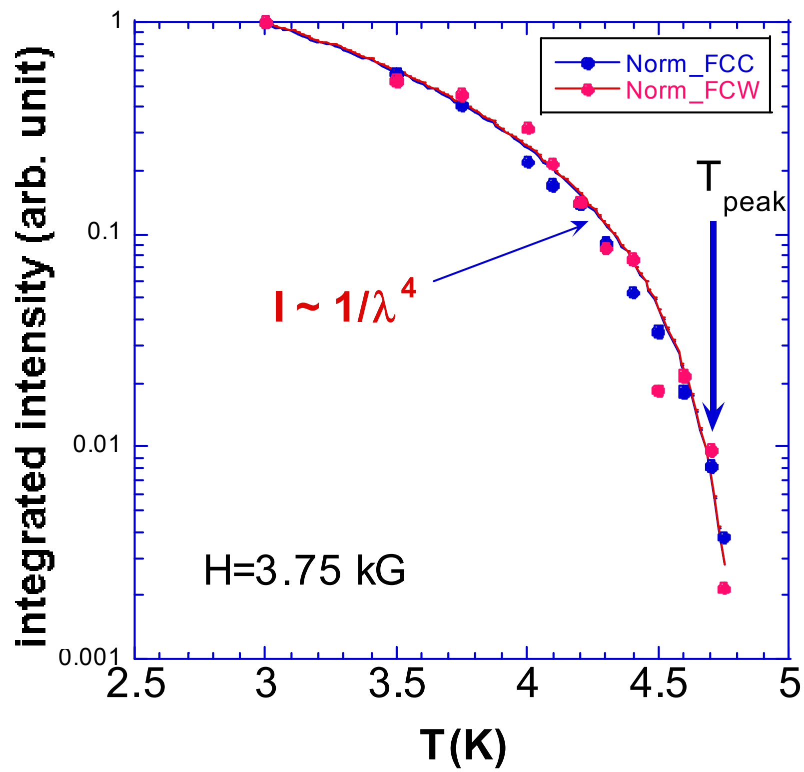


Integrated Intensity

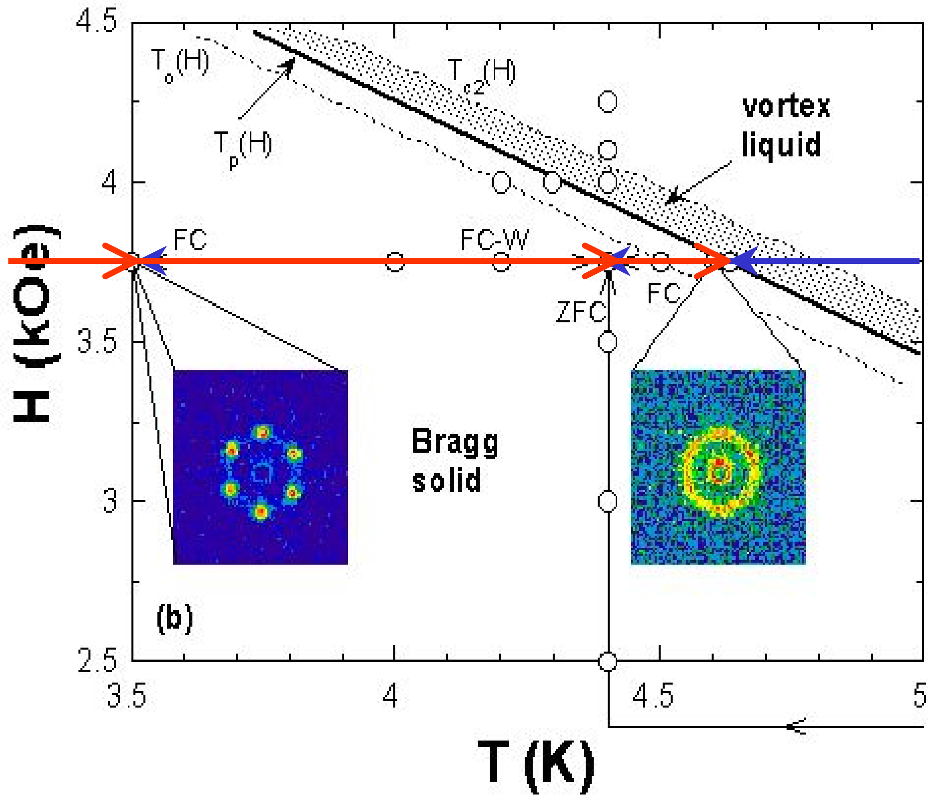
$$I_{hk} = 2\pi\phi \left(\frac{\gamma}{4}\right)^2 \frac{\lambda_n^2}{\Phi_o^2 q_{hk}} \left|F_{hk}\right|^2 \qquad F_{hk} = \frac{B}{1+\lambda^2 q_{hk}^2}$$

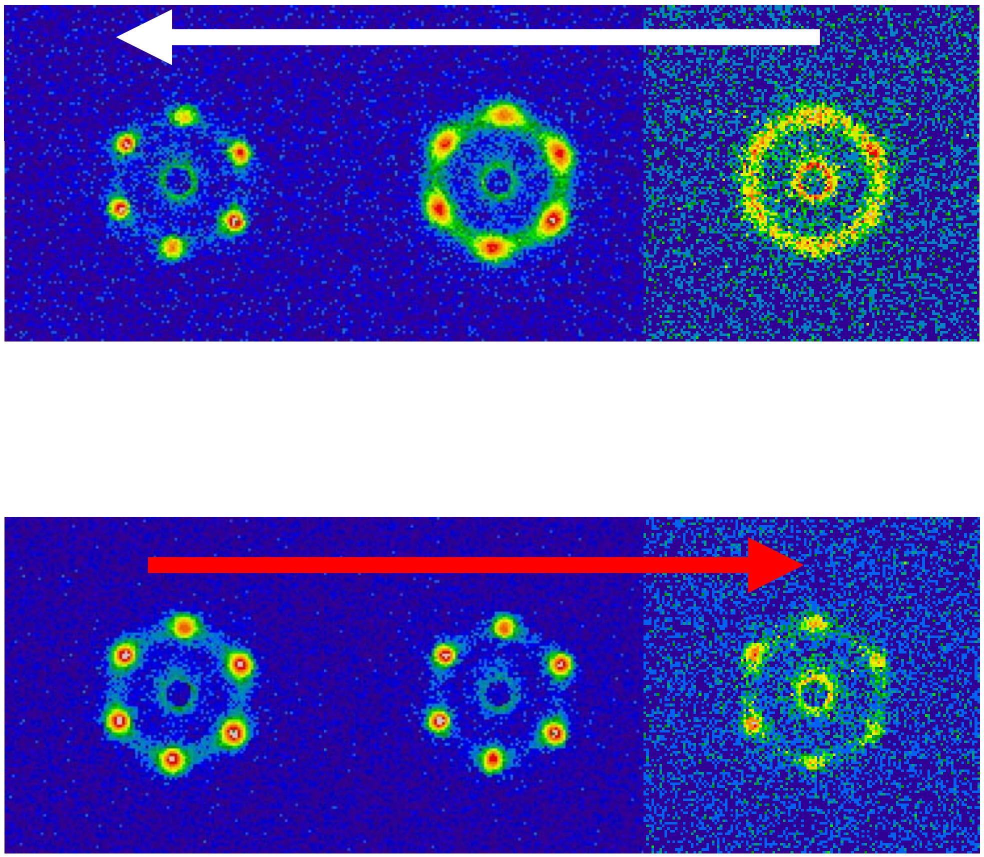
D.K.Christen,F.Tasset,
S.Spooner,H.A.Mook(1977)



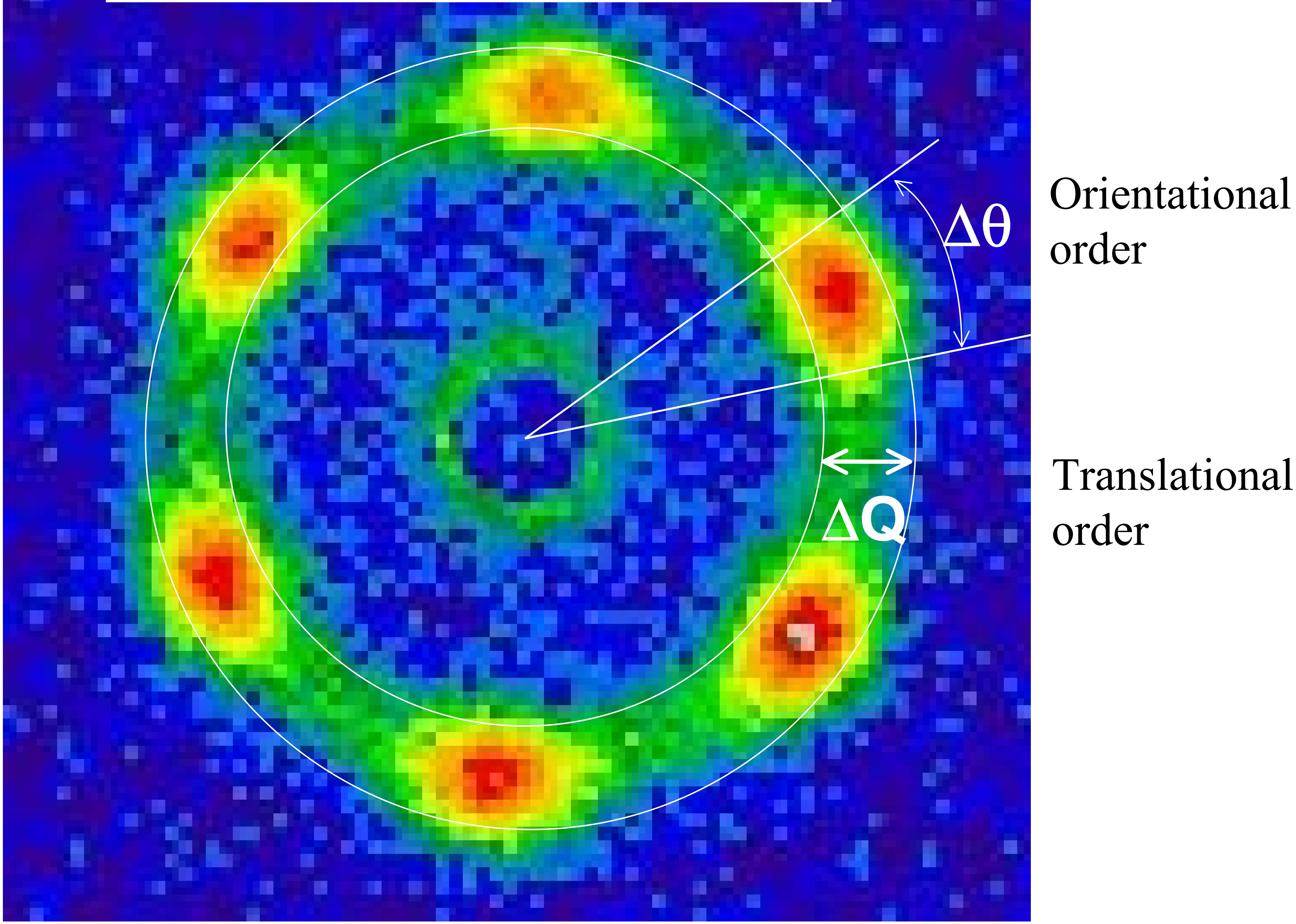


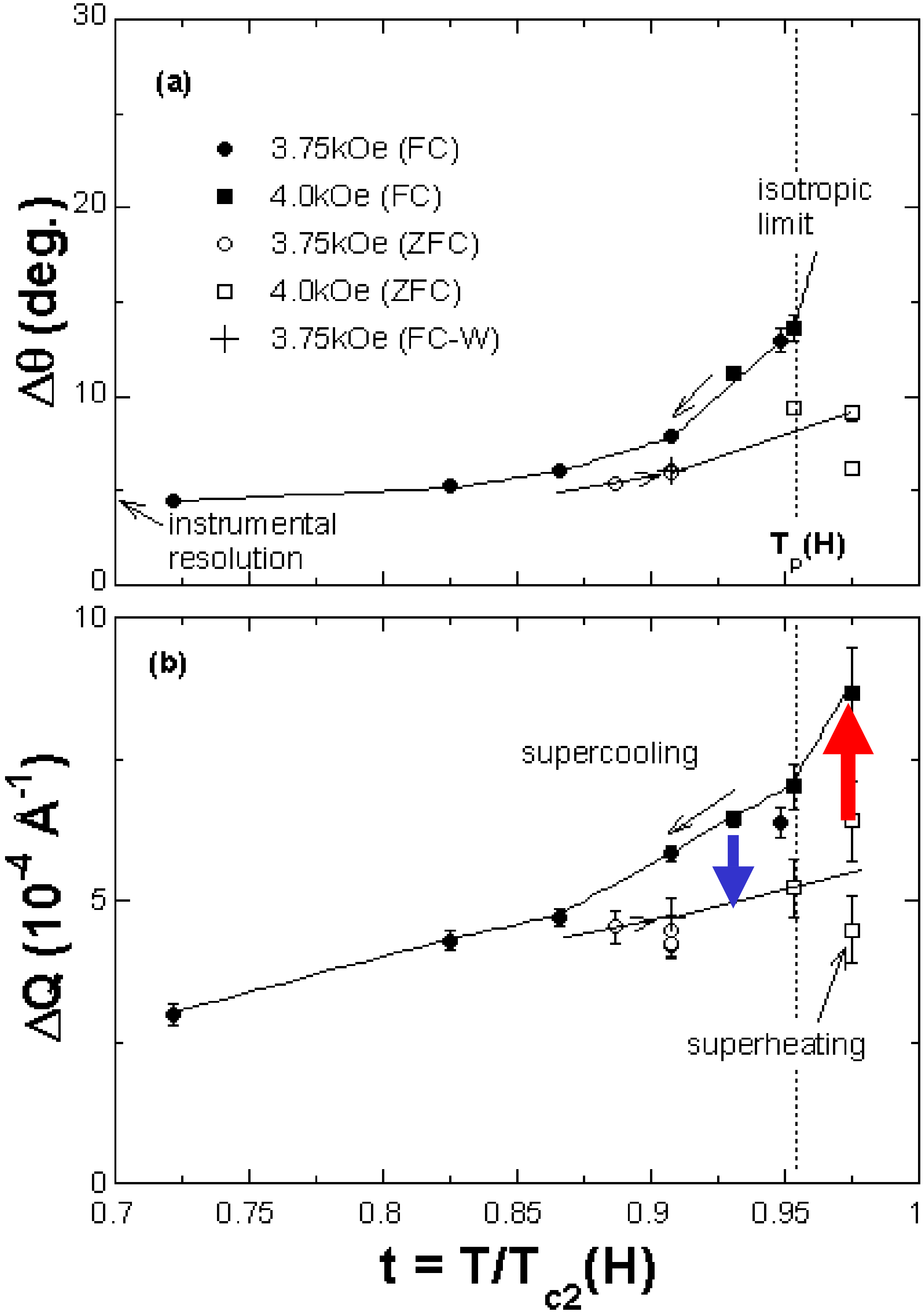
Thermal Hysteresis in S(Q)





Measurements of order



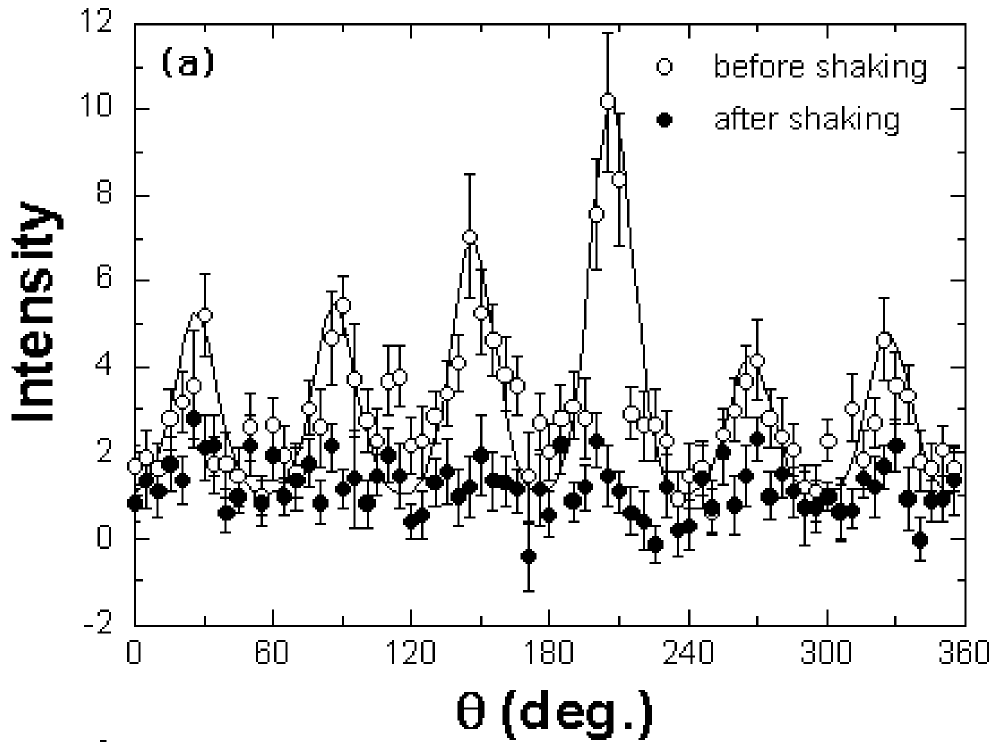


Direct evidence of a solid-liquid transition:

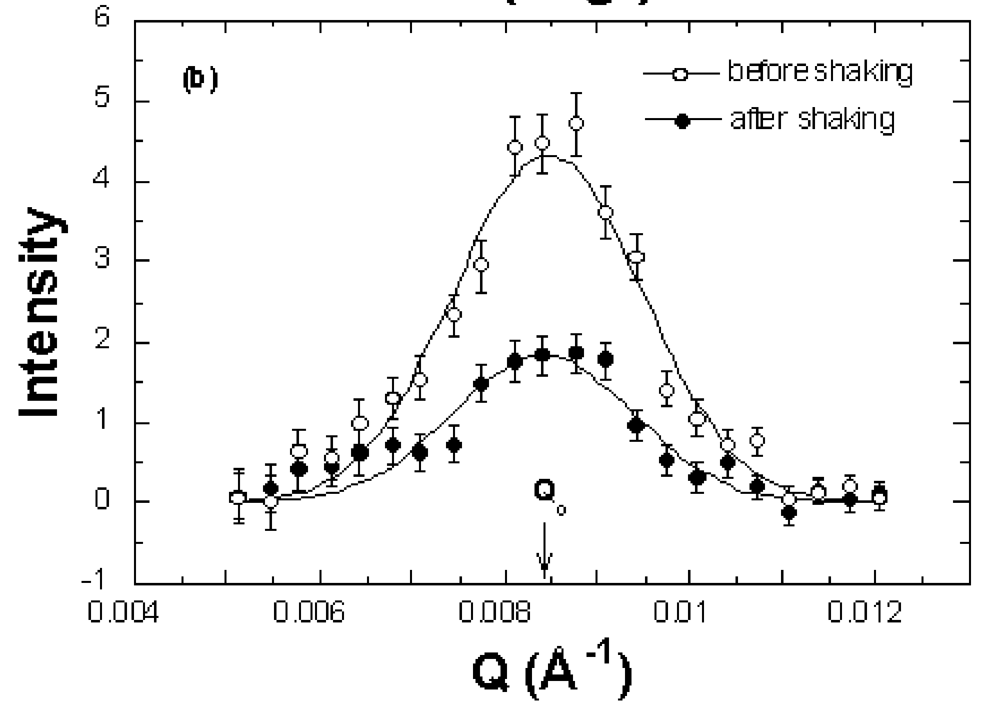
Simultaneous broadening of Bragg peaks in azimuthal and radial widths

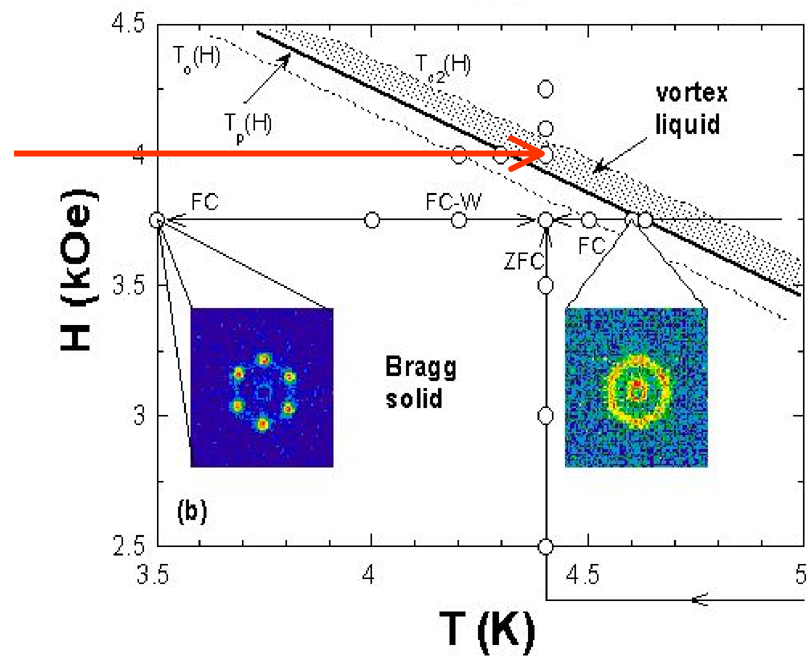
Annealing effects

X.S. Ling et al. PRL 86, 712(2001)



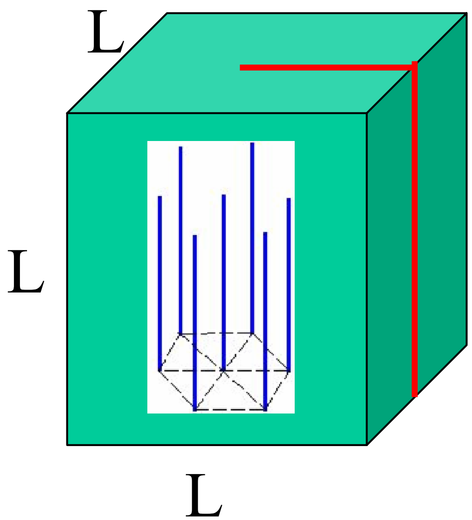
Bragg glass can be superheated, melts upon shaking.





A vortex line solid-liquid transition must be accompanied by a disentanglement-entanglement transition.

D.R. Nelson (1988)
D.R. Nelson, M.C. Marchetti (1990)



Consider the free energy of an edge dislocation in a solid of rigid lines

$$\text{Cost } U = aL \log(L)$$

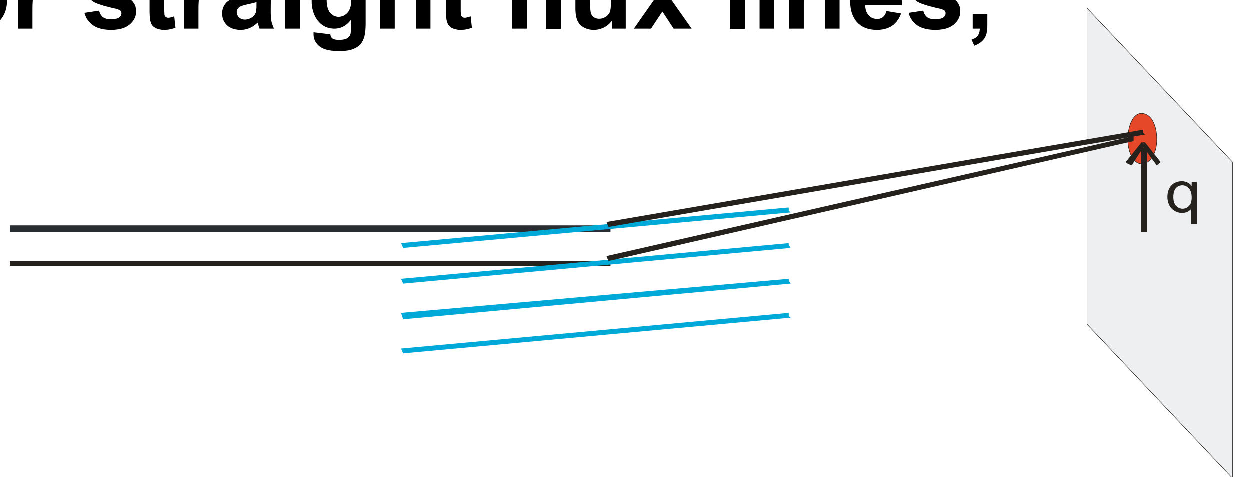
$$\text{Gain } S = k_B \log(L^2)$$

$$F = U - TS = (aL - 2k_B T)\log(L)$$

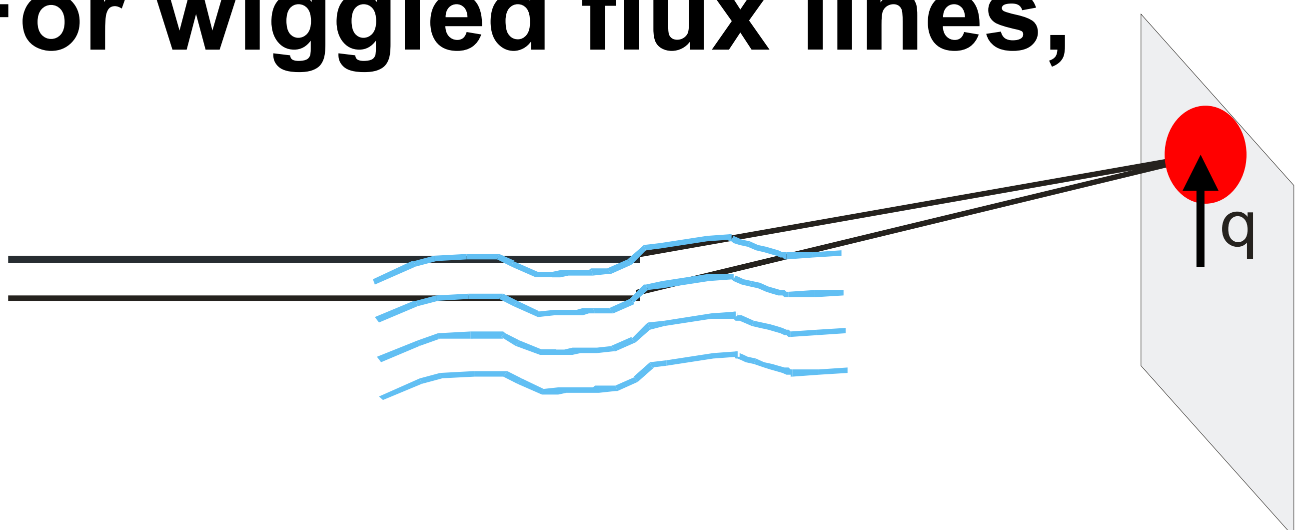
In thermodynamic limit, large L, edge dislocations are forbidden.
Rigid-line solids cannot melt.
Vortex-line solid melting must have entanglement effects.

Search for the Nelson-Marchetti effect:

For straight flux lines,

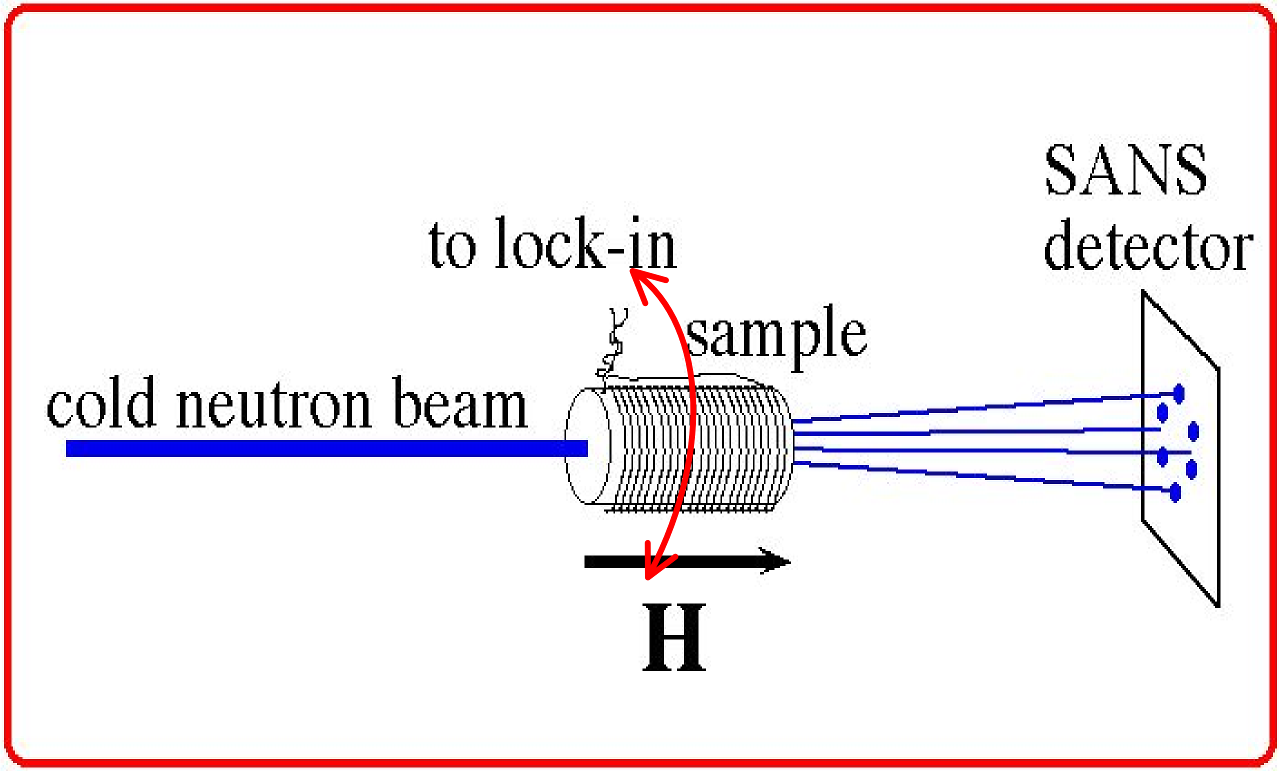


For wiggled flux lines,



Rocking curve widths:

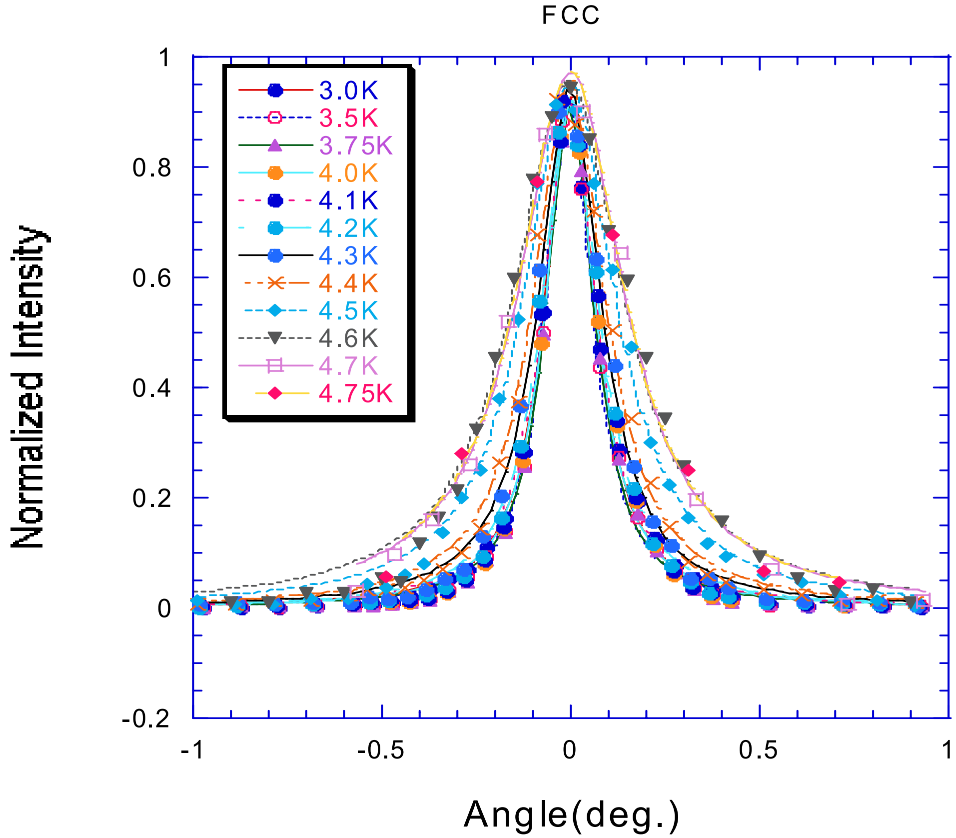
straightness of vortex lines

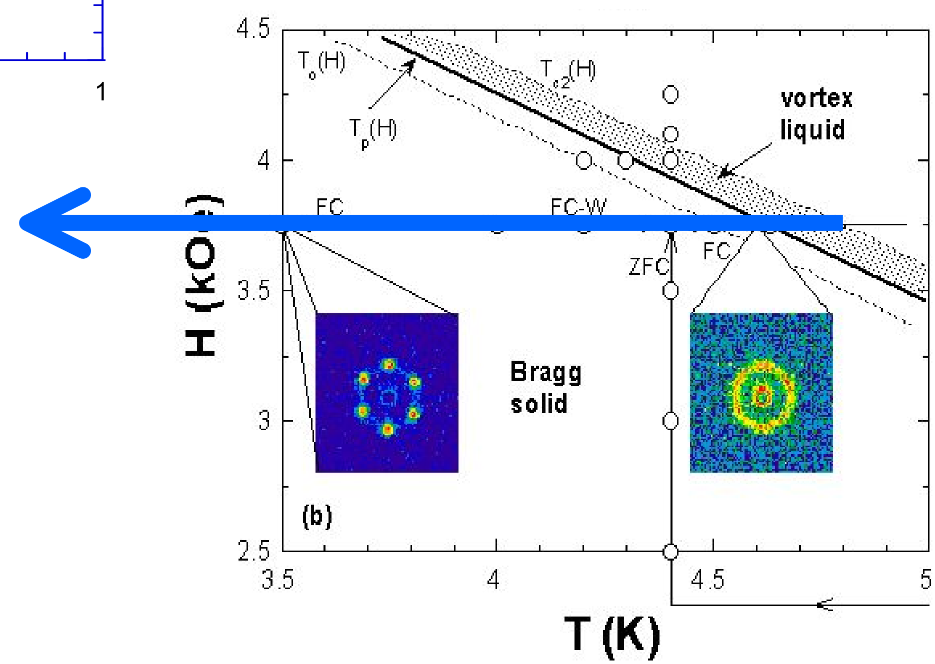


Cooling in field:

Gradual sharpening of rocking curves:

supercooled phase is made of entangled vortex lines

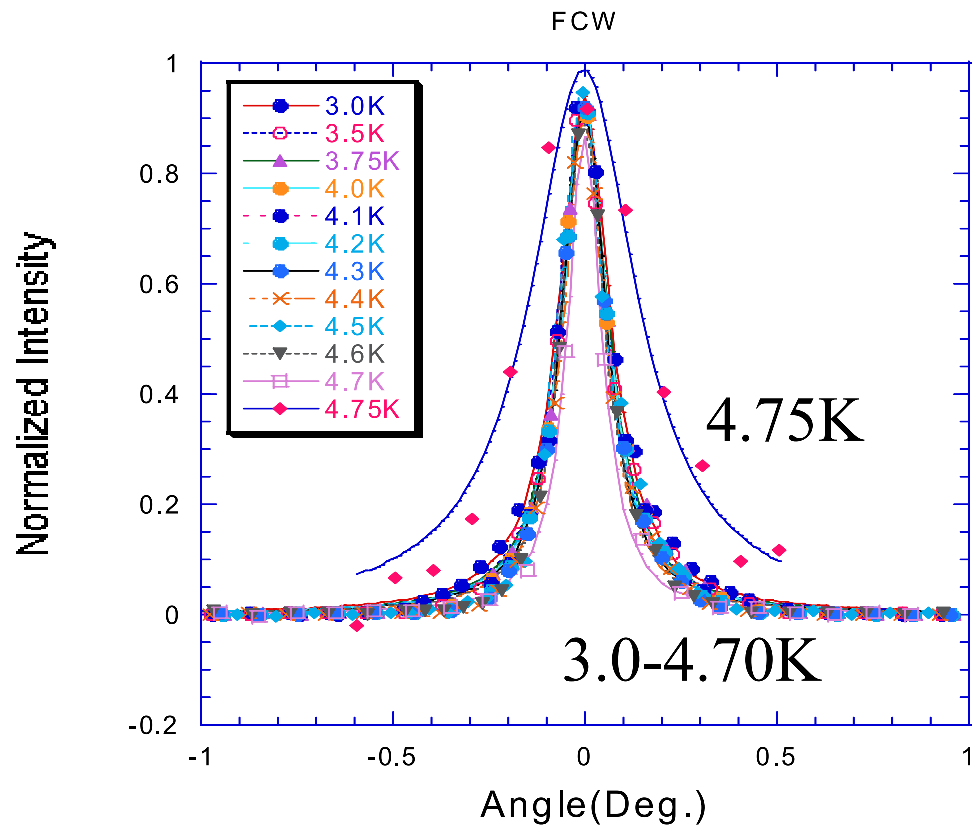




Such supercooling effects were observed in transport:

Xiao, Andrei et al.

Kes et al.

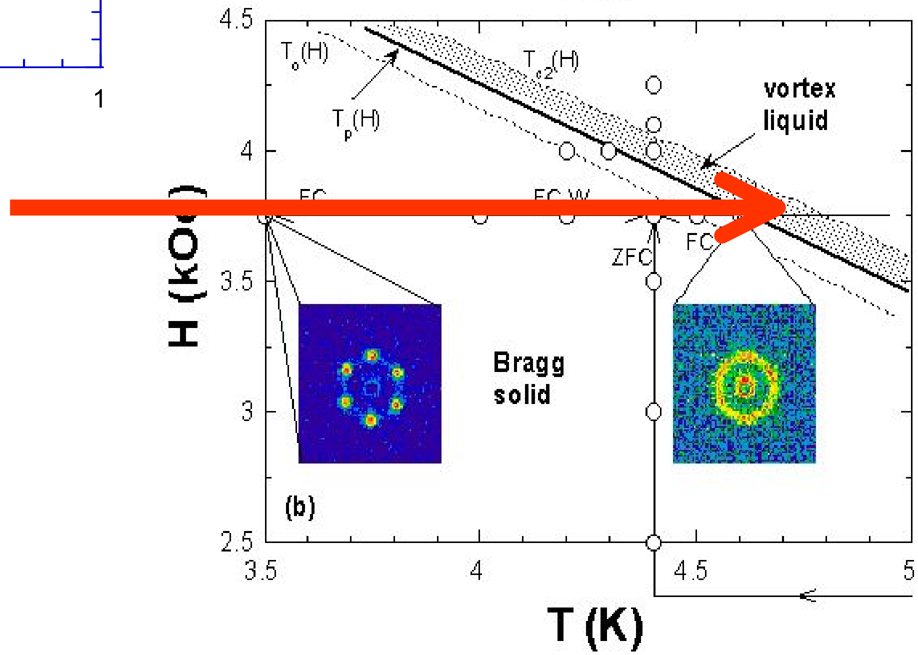


Warming in field:

Sudden broadening of rocking curves:

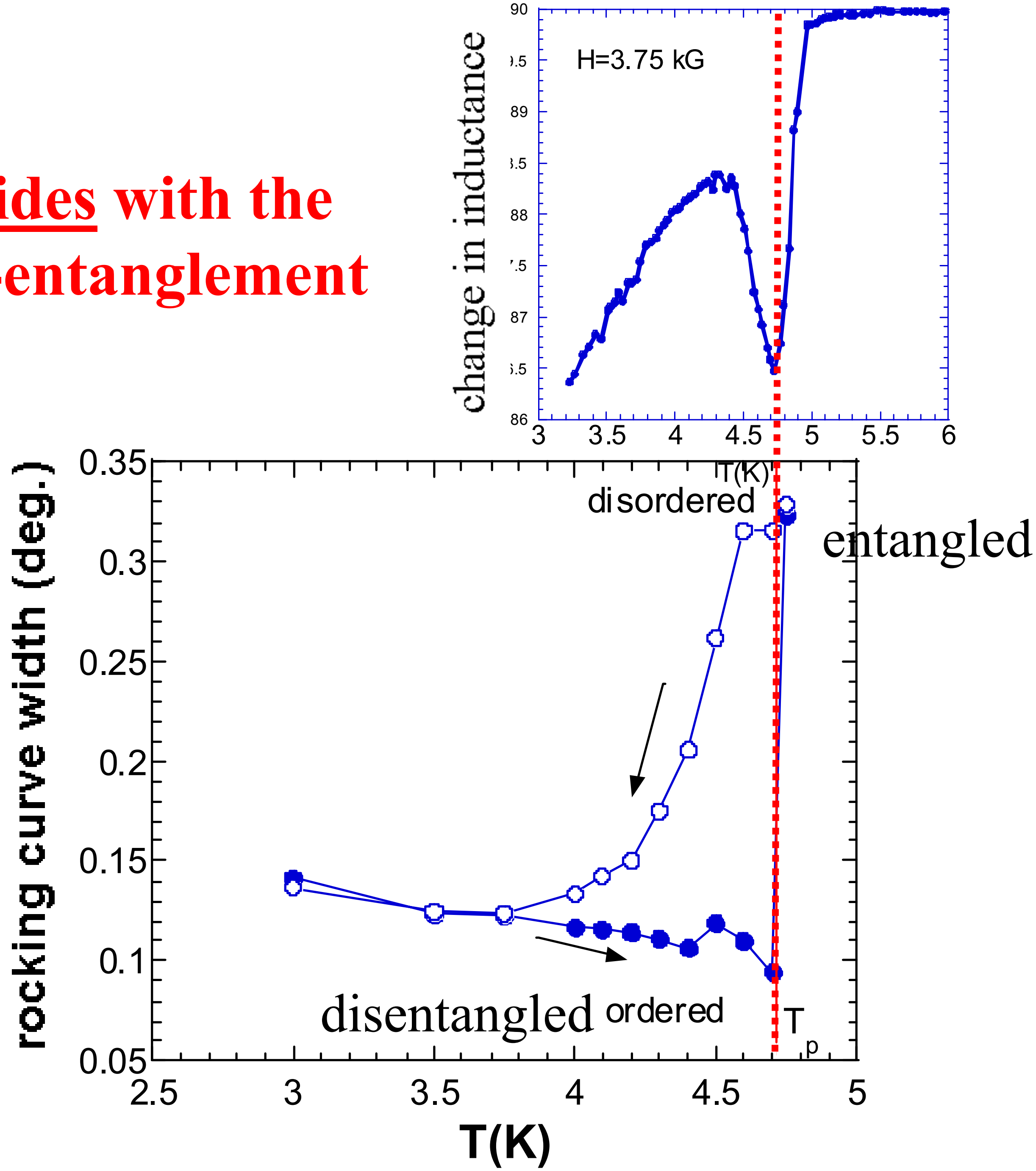
Vortex lines remain straight up to $T_p(H)$.

Melting occurs by entanglement.



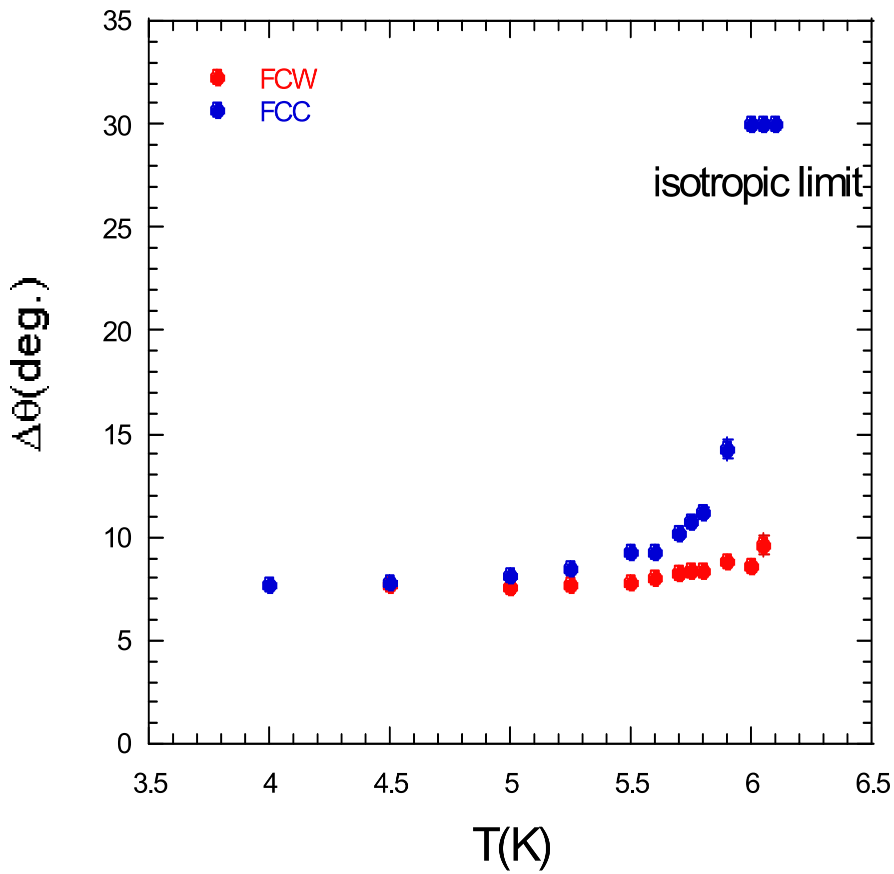
Recent numerical simulations also suggested this effect:
Nonomura, Hu (2001)
Teitel (2001)
Reichhardt (2001)
Kosterlitz (2002)

Peak effect coincides with the disentanglement-entanglement transition.

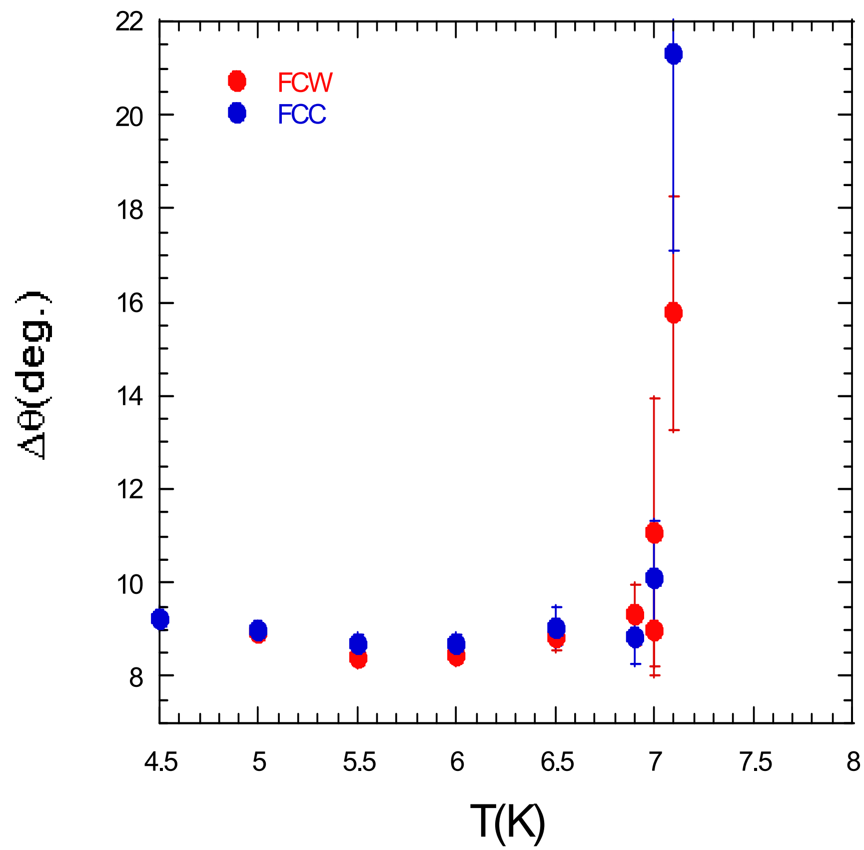


S(Q) hysteresis effect disappears at low H

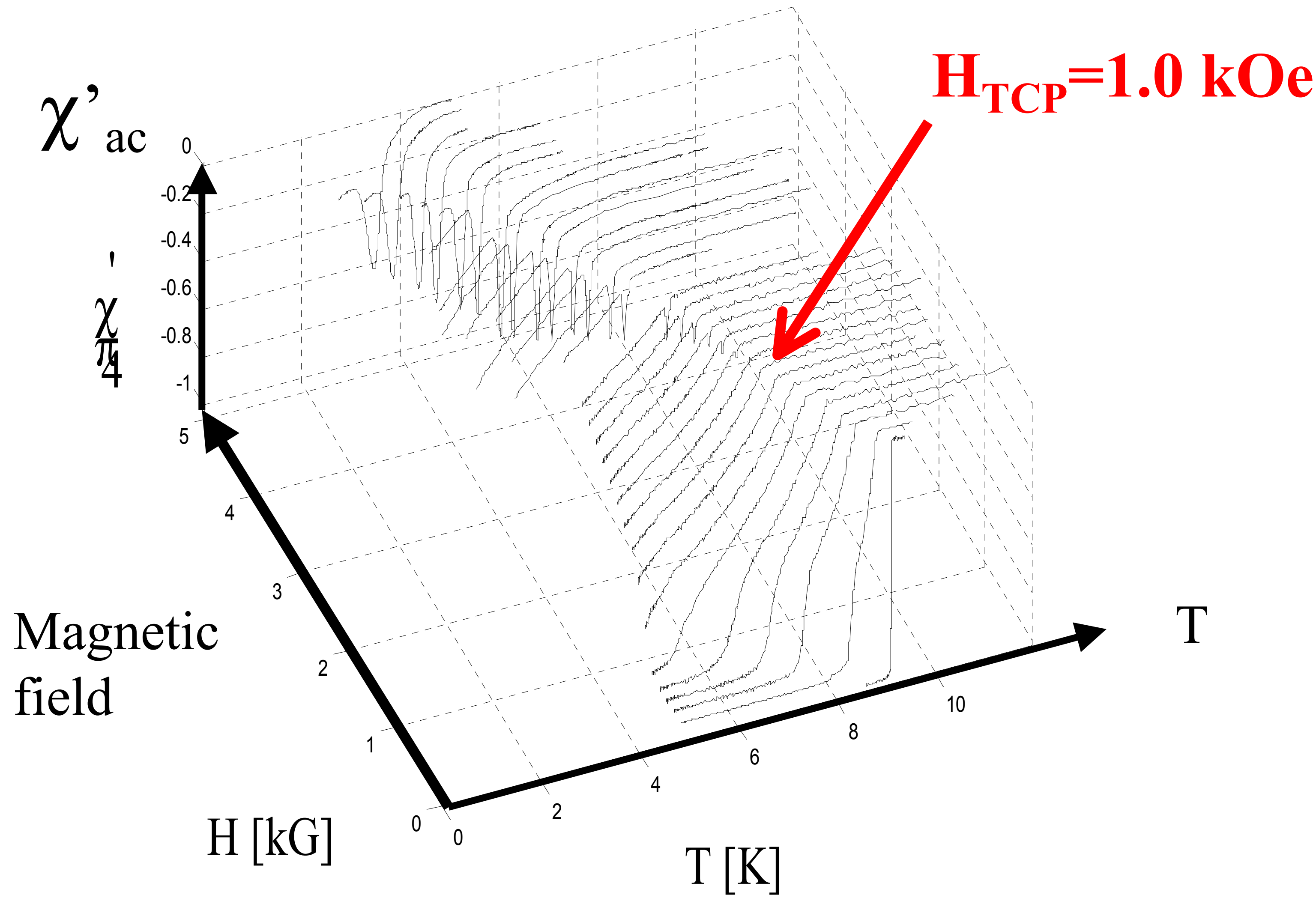
H = 3kG

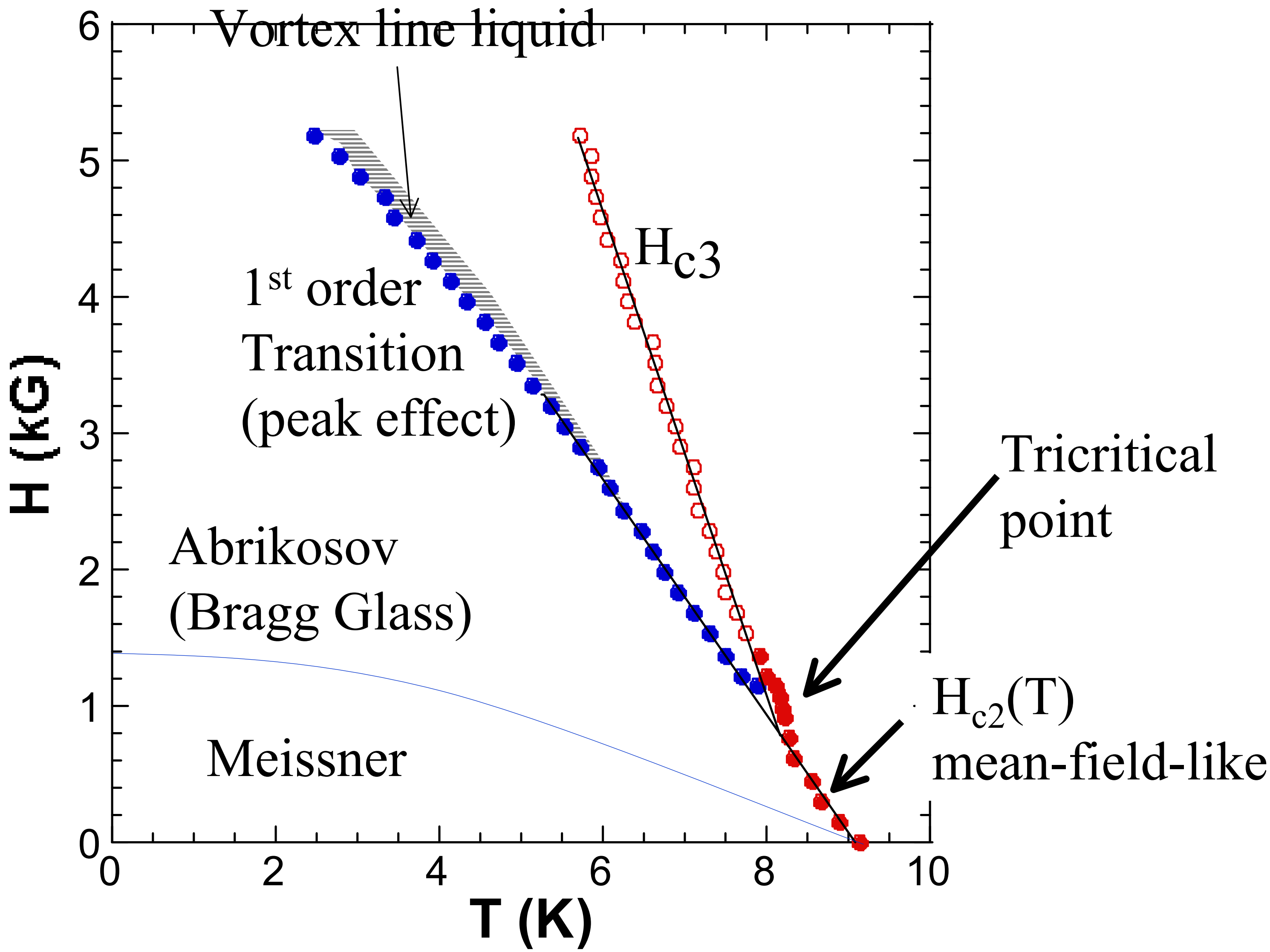


H = 2kG



The peak effect has an end point at low H!





Vortex line liquid
1st order
Transition
(peak effect)
Hc3
Tricritical
point
Abrikosov
(Bragg Glass)
Hc2(T)
mean-field-like
Meissner
H (kG)
T (K)
0
1
2
3
4
5
6
0
2
4
6
8
10

Conclusions:

1. We observed the first direct evidence of a first-order vortex solid-liquid transition at the peak effect, using *in-situ* neutron scattering and ac susceptibility measurements.

2. At low field, the hysteresis of vortex-matter structure factor becomes negligible and correspondingly the peak effect disappears, suggesting the existence of a tri-critical point on the solid-liquid phase boundary.

3. The vortex solid-liquid transition is indeed accompanied by entanglement-disentanglement transition, as predicted by theory (Nelson, 1988).

Sang Ryul Park Bridget McClain