**2004 Annual Meeting of The Minerals Metals Materials Society (TMS), Charlotte N.C.**
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Symposium on Challenges in Advanced Thin Films: Microstructures, Interfaces, and Reactions

# Fluxon Pinning in the Nodeless Pairing State of Superconducting $YBa_2Cu_3O_7$

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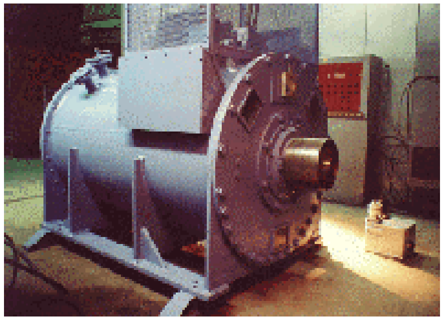
# High $T_c$ / High $J_c$ Type II Superconductors

Magnetic Levitation

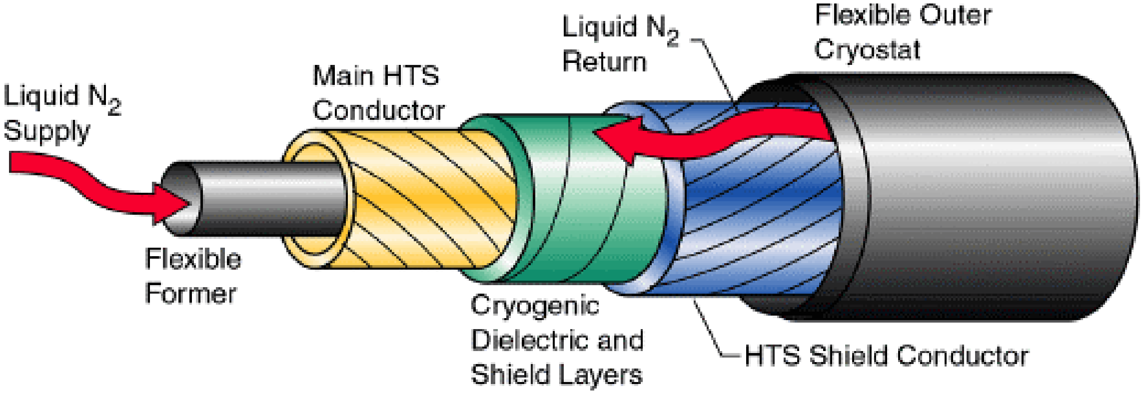
www.fys.uio.no/super/ gallery.html

Power Control



www.powersuper.com

Power Transmission

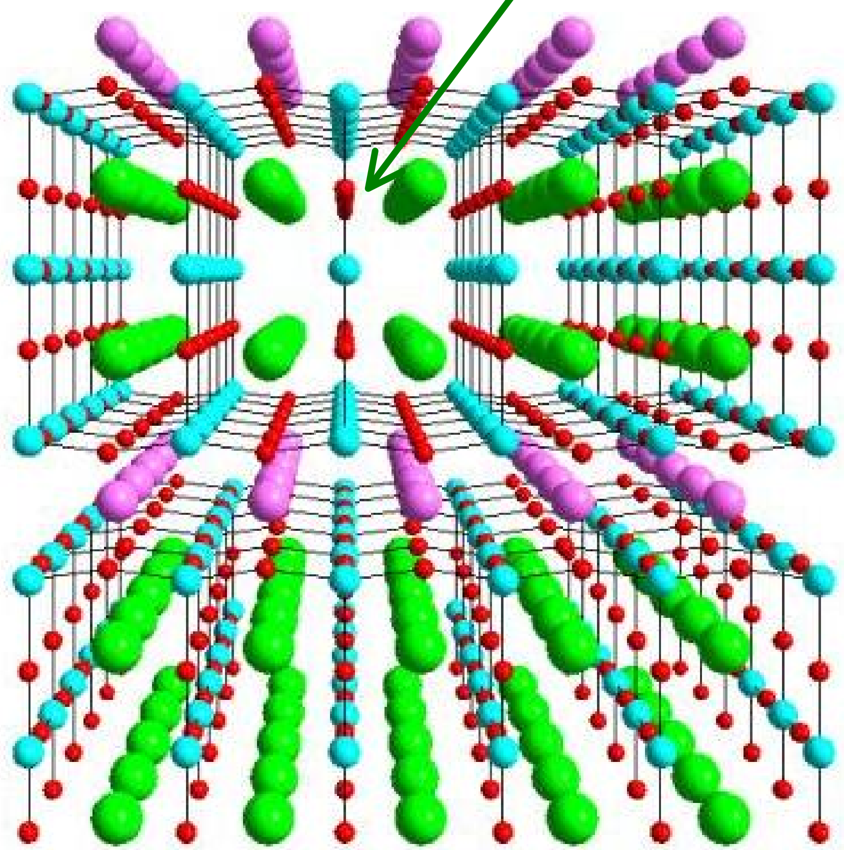



Southwire Co. / Oak Ridge N L

# Anisotropic Superconductivity in $YBa_2Cu_3O_7$

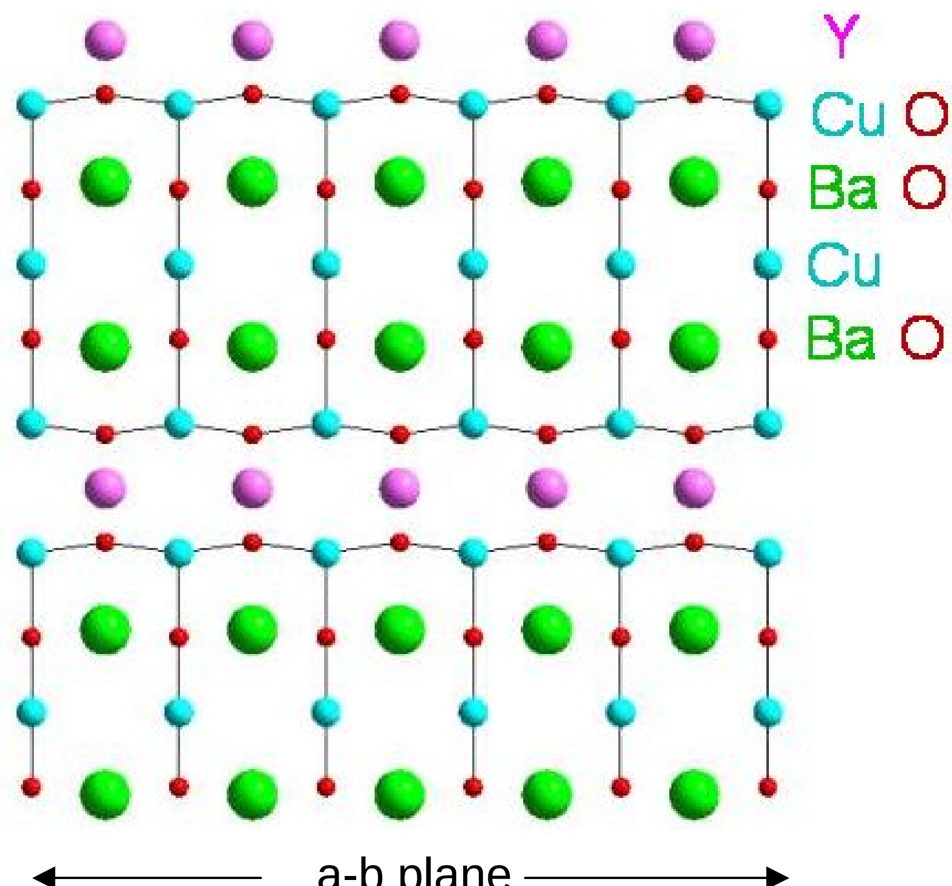
## Stacked 2D Ba-O Superconducting Layers / Cu-O layers provide hole doping

Ba-O Superconducting layer



Artwork : www.liv.ac.uk

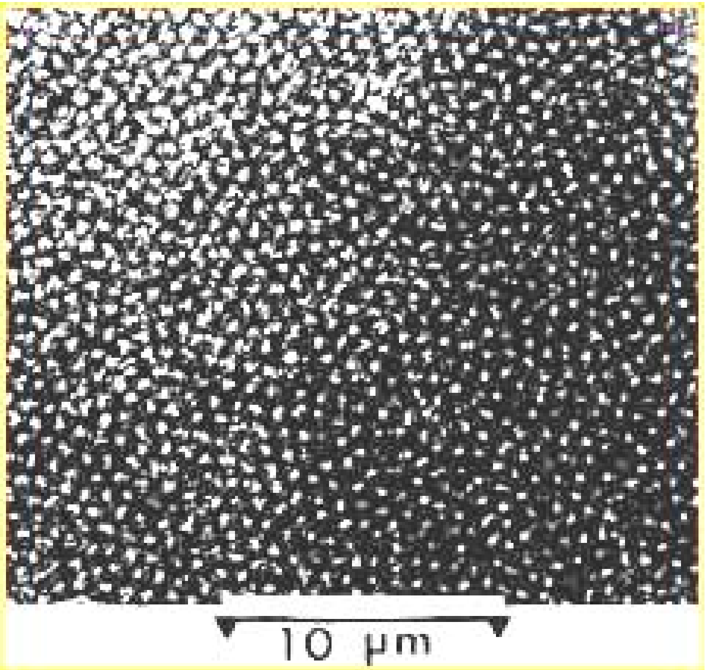
Nodeless s-wave hole pairing
J. D. Dow and D. R. Harshman (2003)



# Magnetic Field Penetration • Array of Fluxons

## Equilibrium Configuration: 2 Dimensional Triangular Lattice

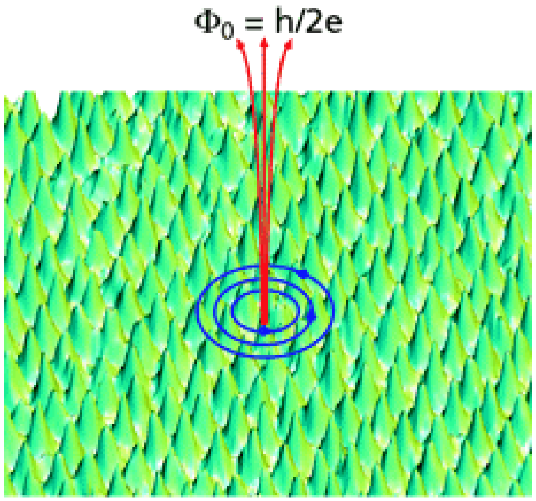
**A. A. Abrikosov** • Soviet Physics JETP 5, 1174 (1957) • **Nobel Prize in Physics (2003)**




Bitter Decoration $YBa_2Cu_3O_7$

T = 4.2K B = 52 G

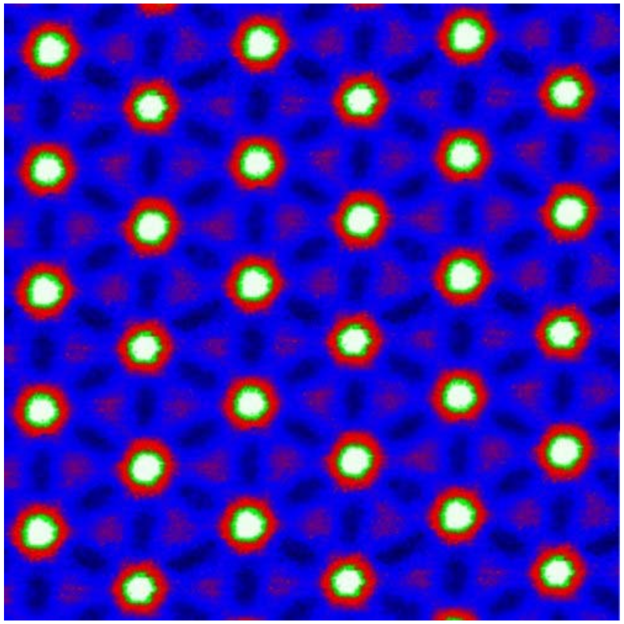
Bell Labs, P. L. Gammel (1987)




STEM $V_3Si$

T = 2.3K H = 3T

NIST (2002)



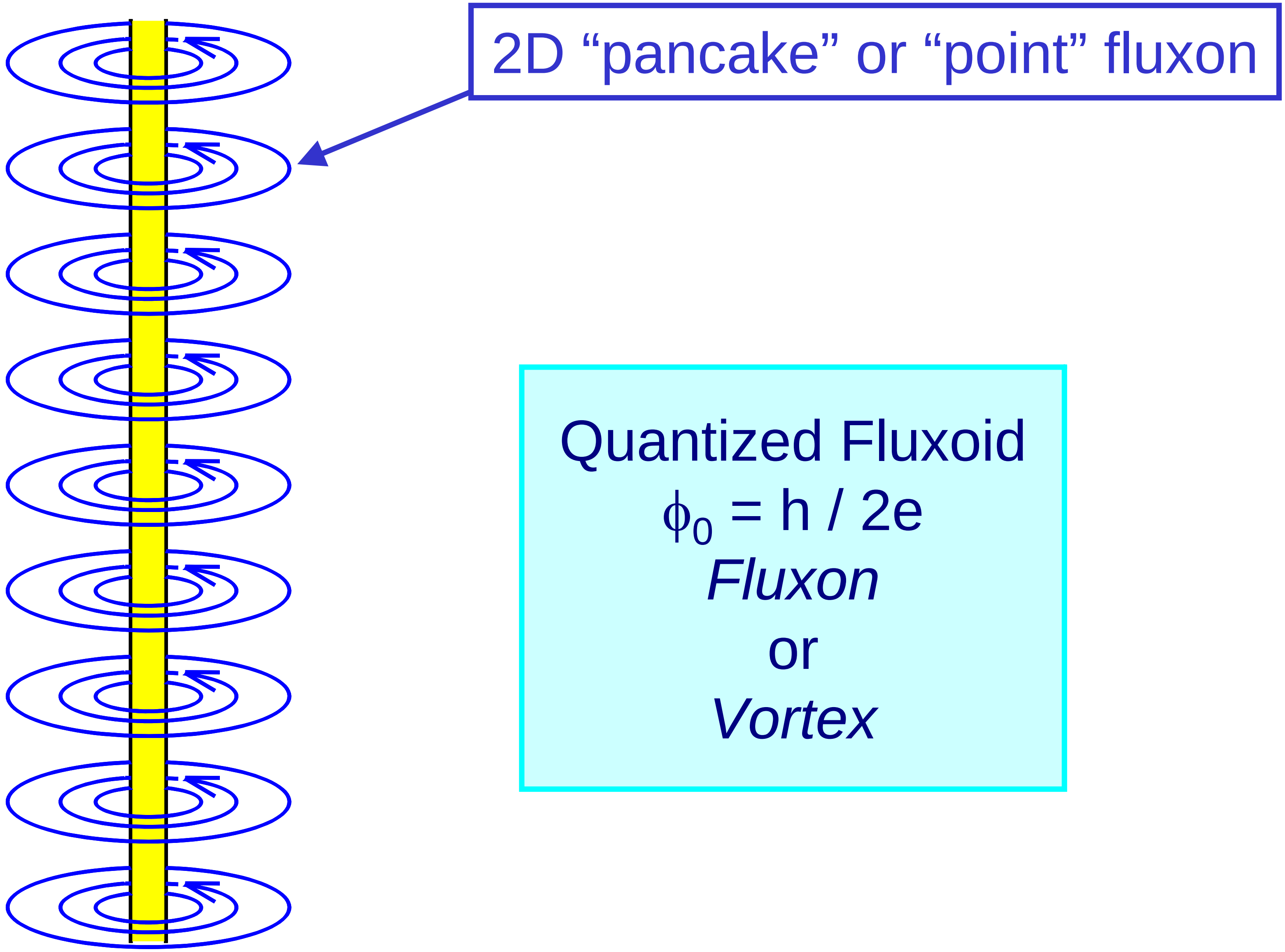
STEM $NbSe_2$

T = 0.3K H = 1T

J.C. Davis, Cornell (2003).

# Anisotropic Fluxon in $YBa_2Cu_3O_7$

## 2-Dimensional Fluxons in Layers • Aligned by Magnetic and Josephson Coupling




Quantized Fluxoid

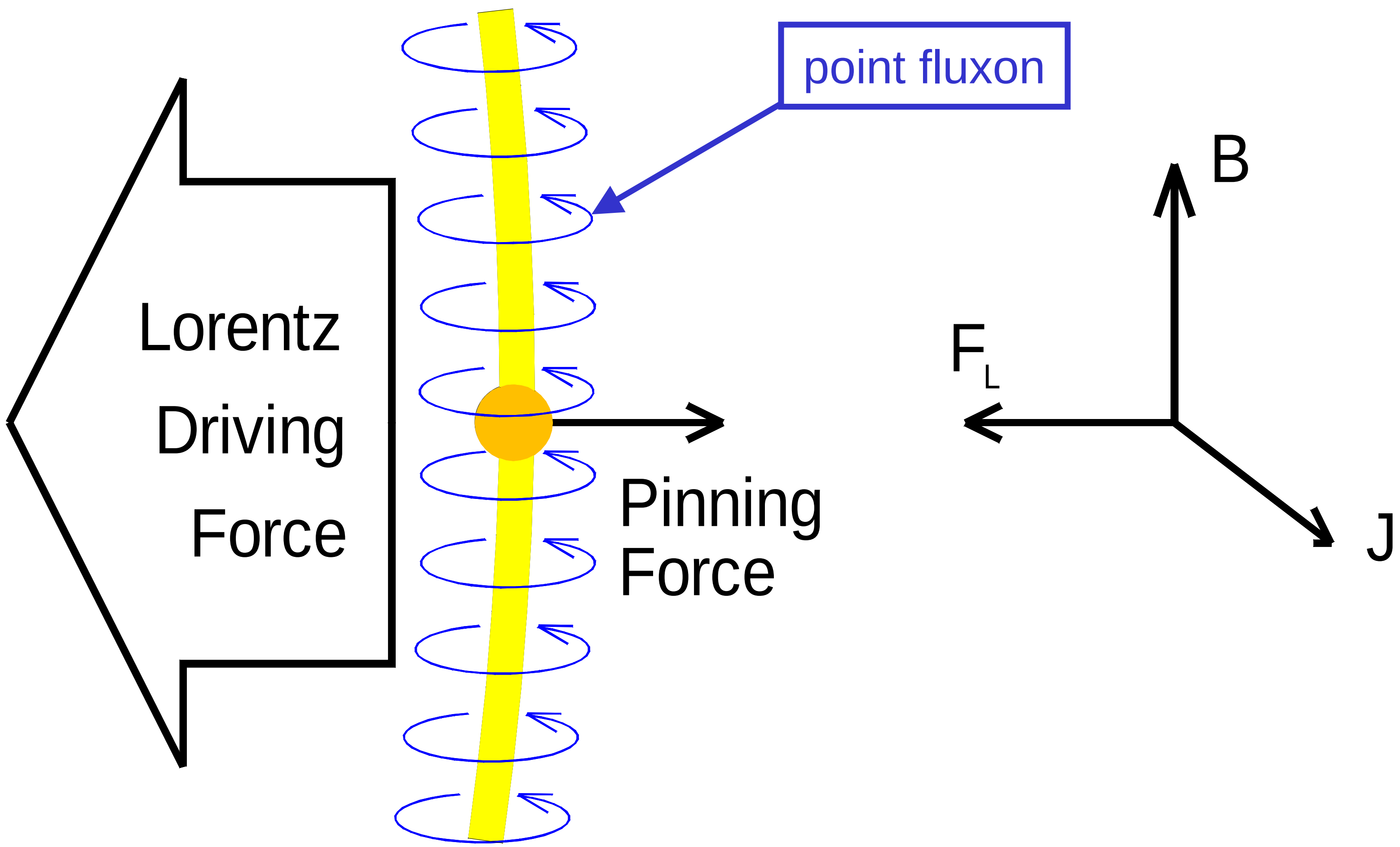
$\phi_0 = h / 2e$

*Fluxon*

or

*Vortex*

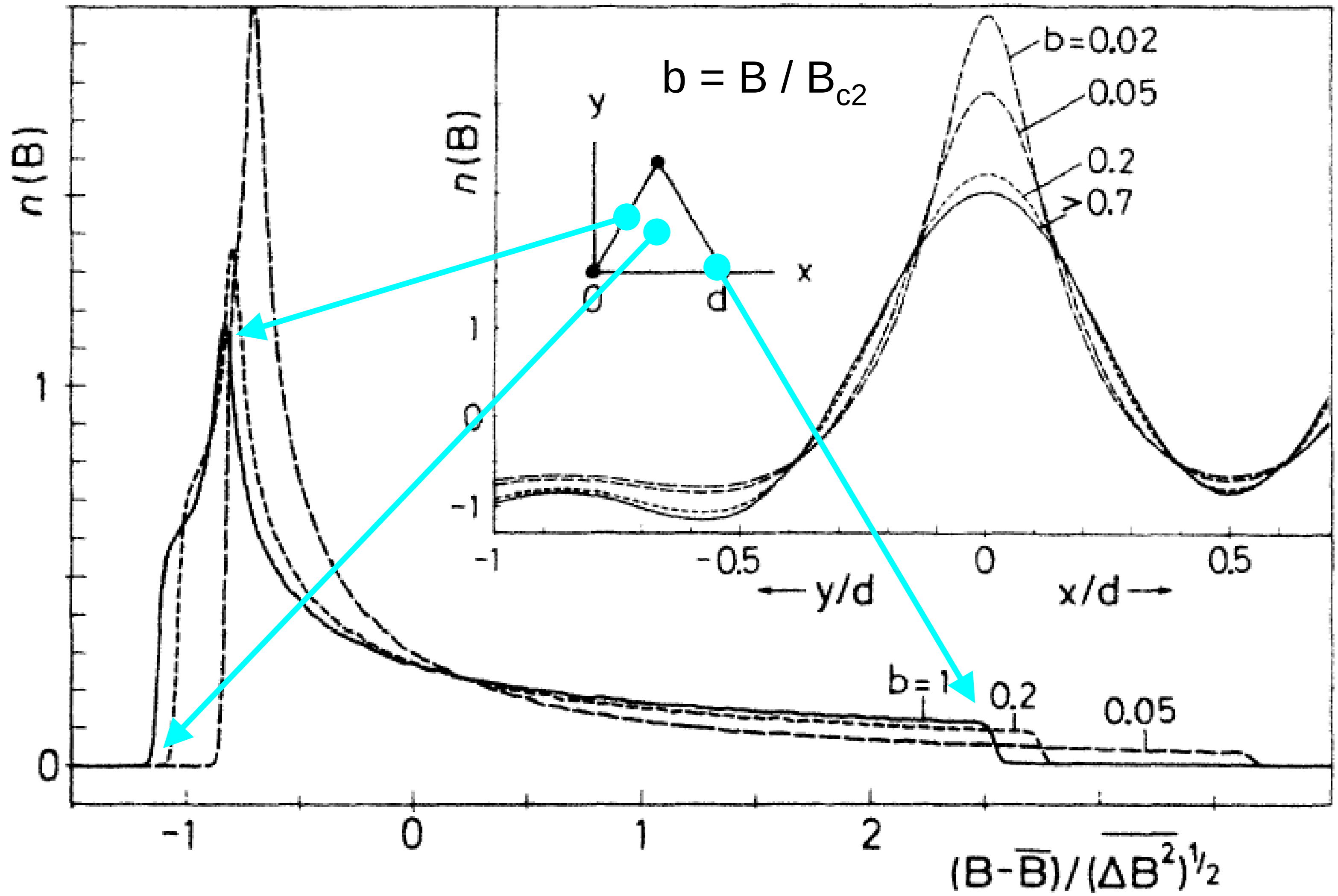
# Pinned Superconducting Fluxon




Critical Current Density $J_c \propto$ Maximum Pinning Force

# Local Magnetic Field Distribution • Theoretical Fluxon Lattice

Local Field Width $\Delta B = 0.0609\ \phi_0/\lambda^2$ • Magnetic Penetration Depth $\lambda^2 = m^* c^2 / 4\pi n_S e^2$

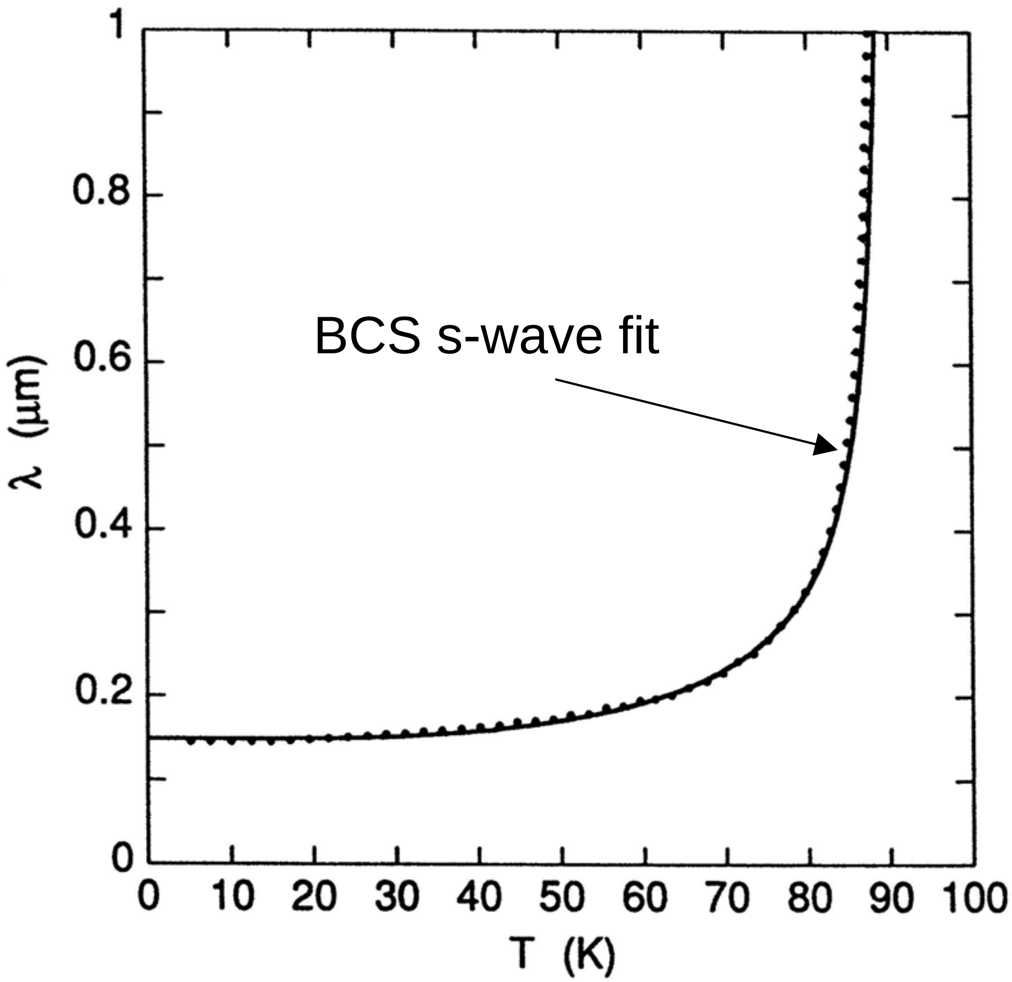


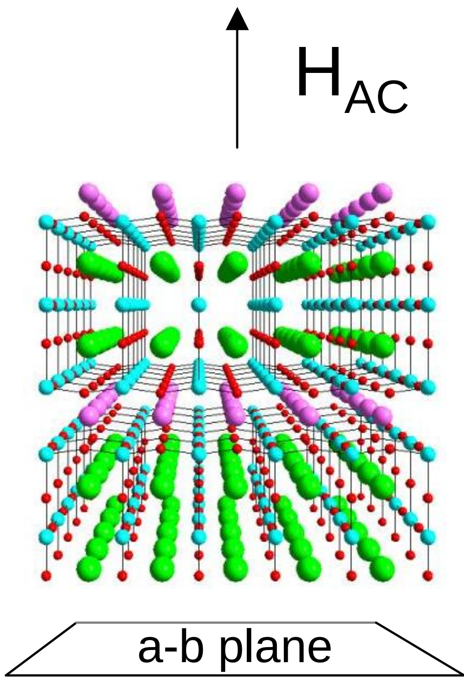

**LOCAL MAGNETIC FIELD (NORMALIZED)**

Source: E. H. Brandt, Phys. Rev. B **37**, 2349 (1988).

# Magnetic Penetration Depth • 50-nm $YBa_2Cu_3O_7$ Film

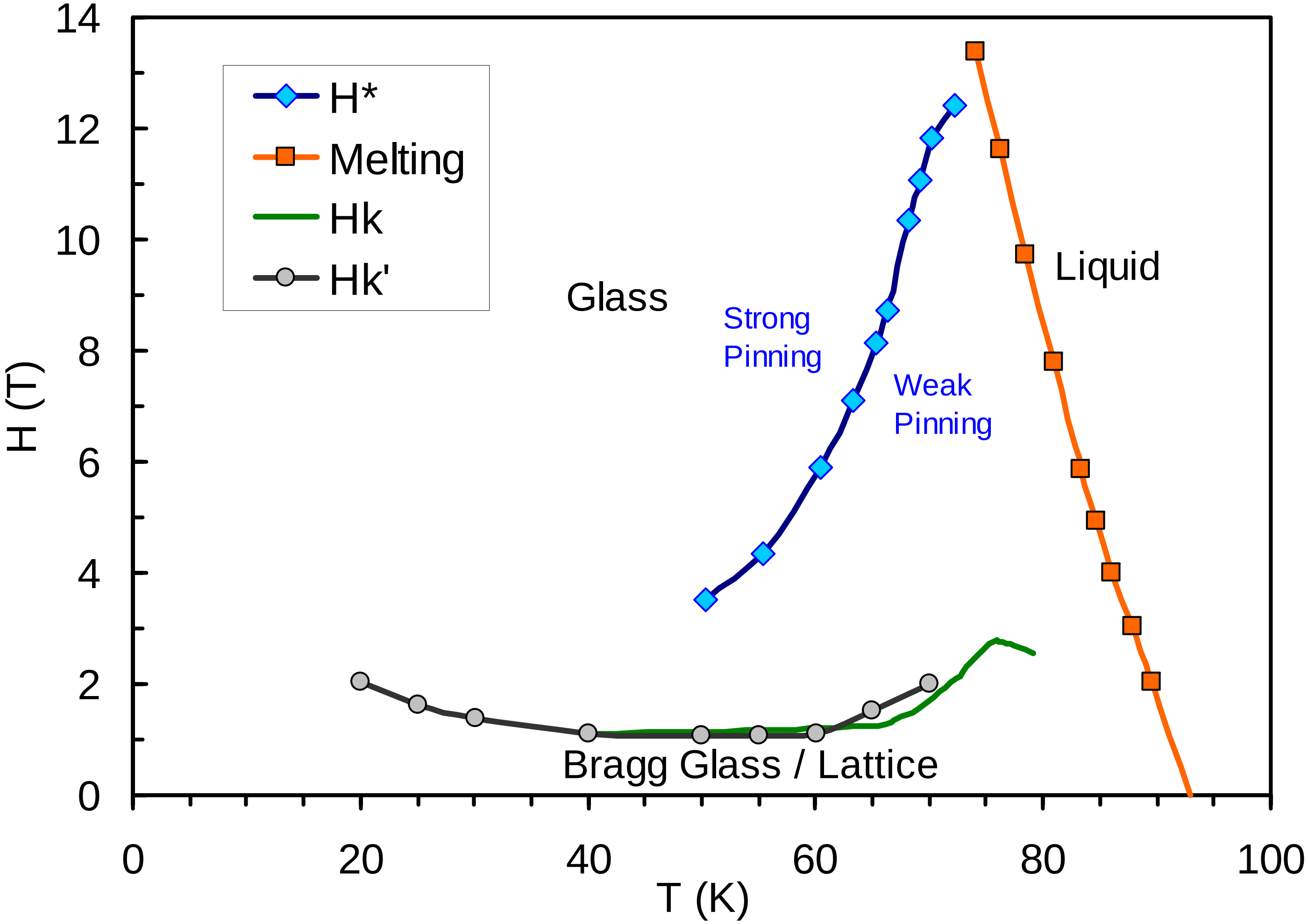
$\lambda$ in a-b basal plane of crystal • Weak ac field screening method



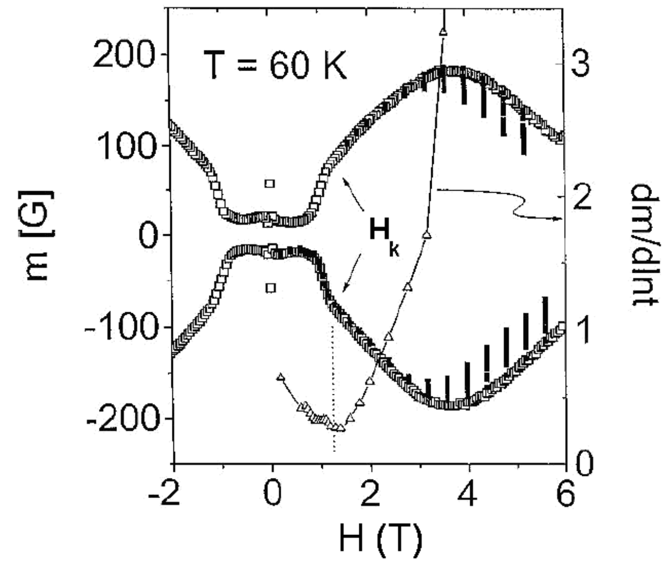



# Fluxon Phase Diagram for $YBa_2Cu_3O_7$

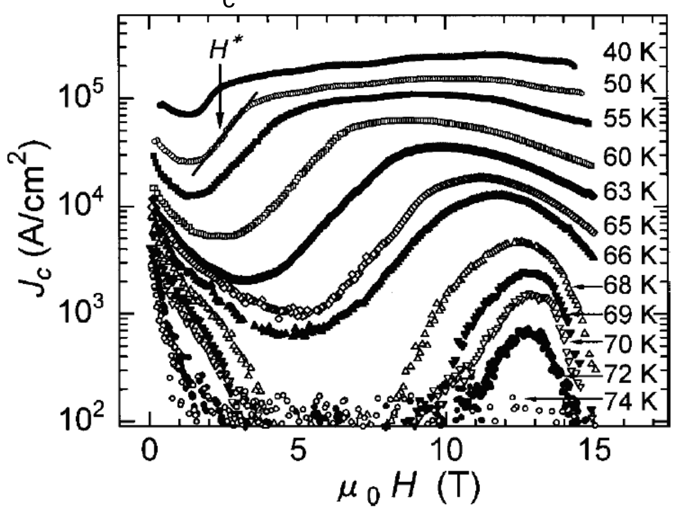
## Phase Boundaries from M *vs* H Dynamics




M-H hysteresis




$J_c$ critical state model




Sources: H*, $J_c$, Melting: Nishizaki (1998); m-H, Hk: Giller (1999); Hk': Radyner (2000).



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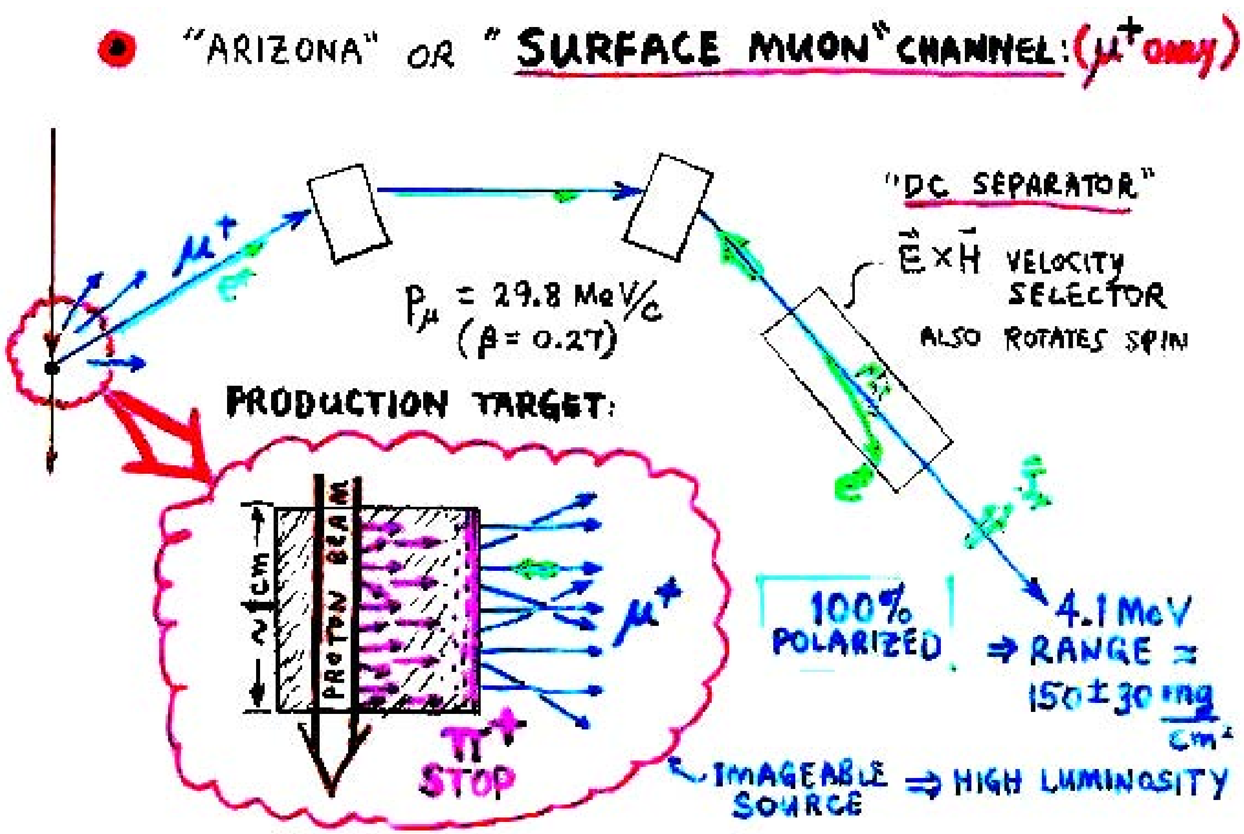
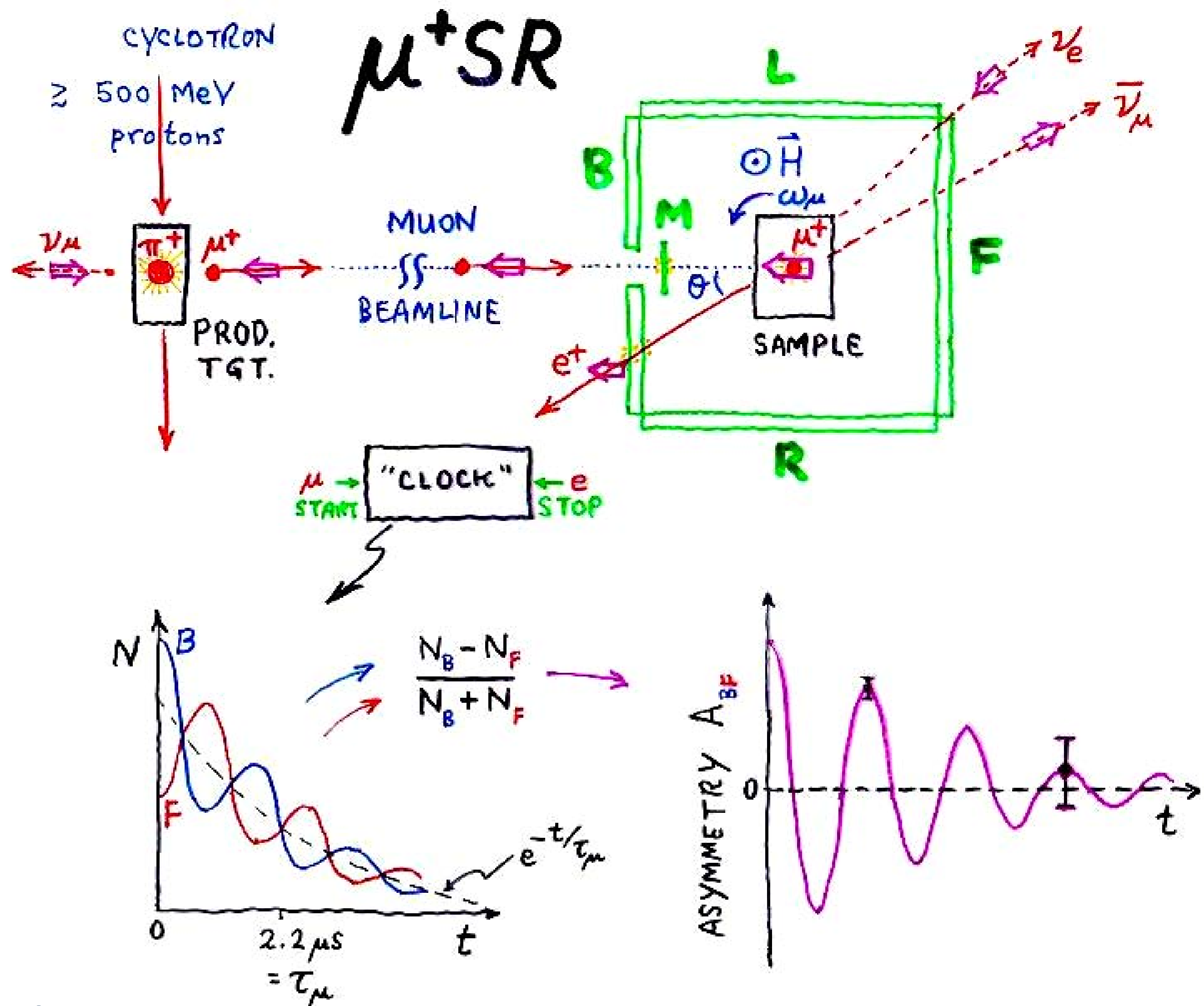
# Production of spin polarized muon beam (TRIUMF Cyclotron)




Source: musr.triumf.ca

# Muon Spin Rotation • Local Magnetic Field Spectroscopy

## Stopped muon precesses in local field • Decay positron emitted

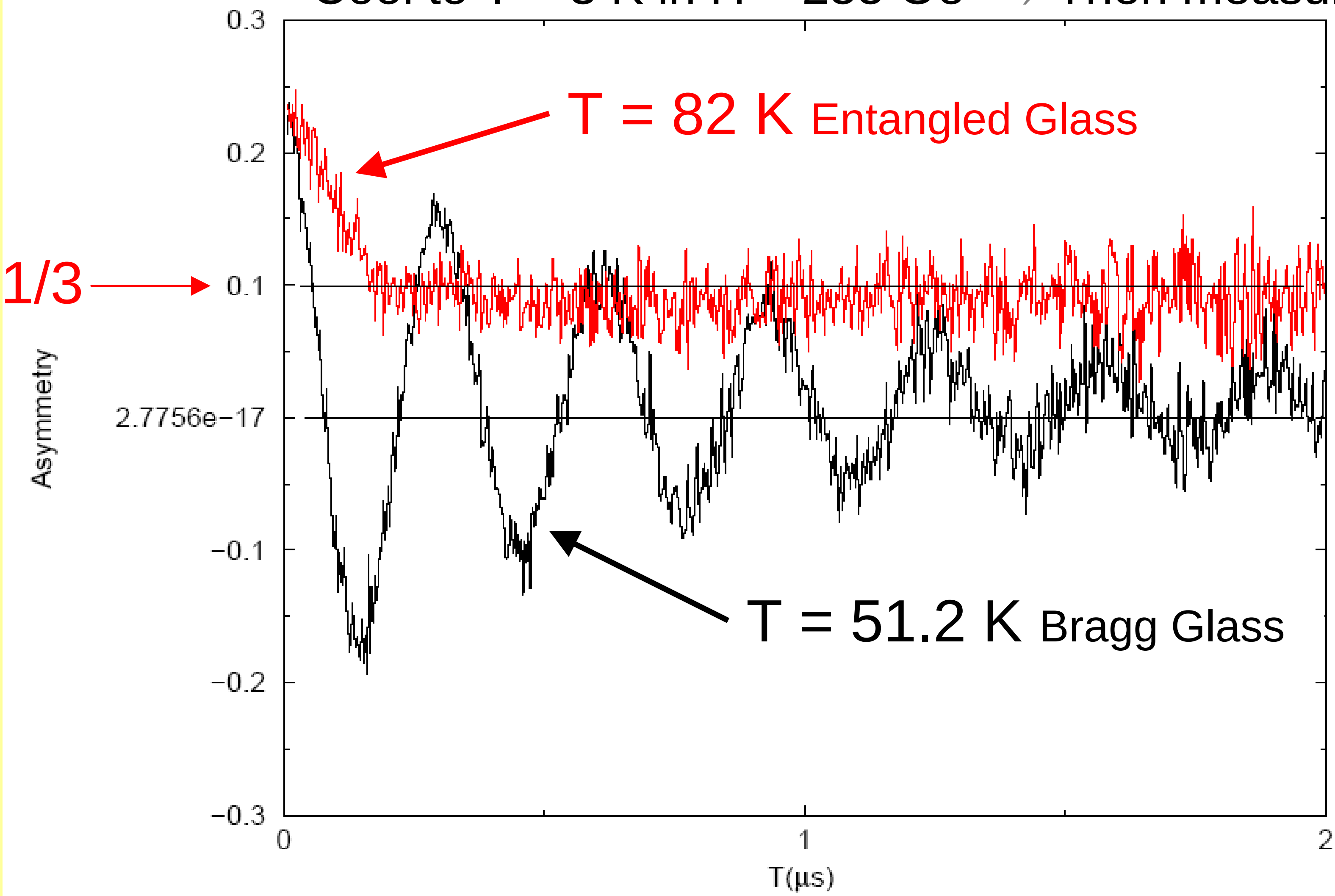


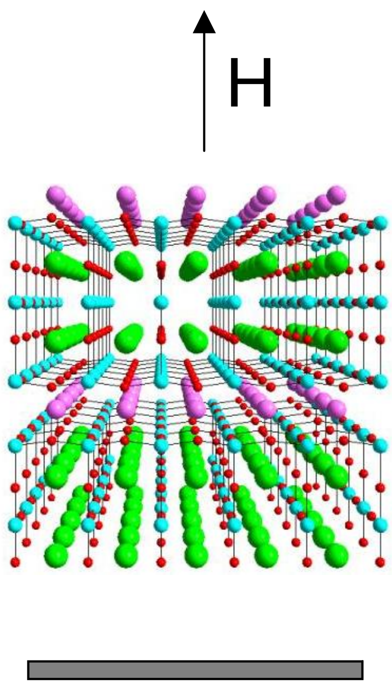

Source: musr.triumf.ca

# Persistence of Pinned Fluxon States in $YBa_2Cu_3O_7$ Crystal

## Oscillation and Depolarization of μSR Asymmetry

Cool to T = 3 K in H = 255 Oe ⇒ Then measure at H = 0




Crystal is a thin plate
a-b plane ⊥ **H**



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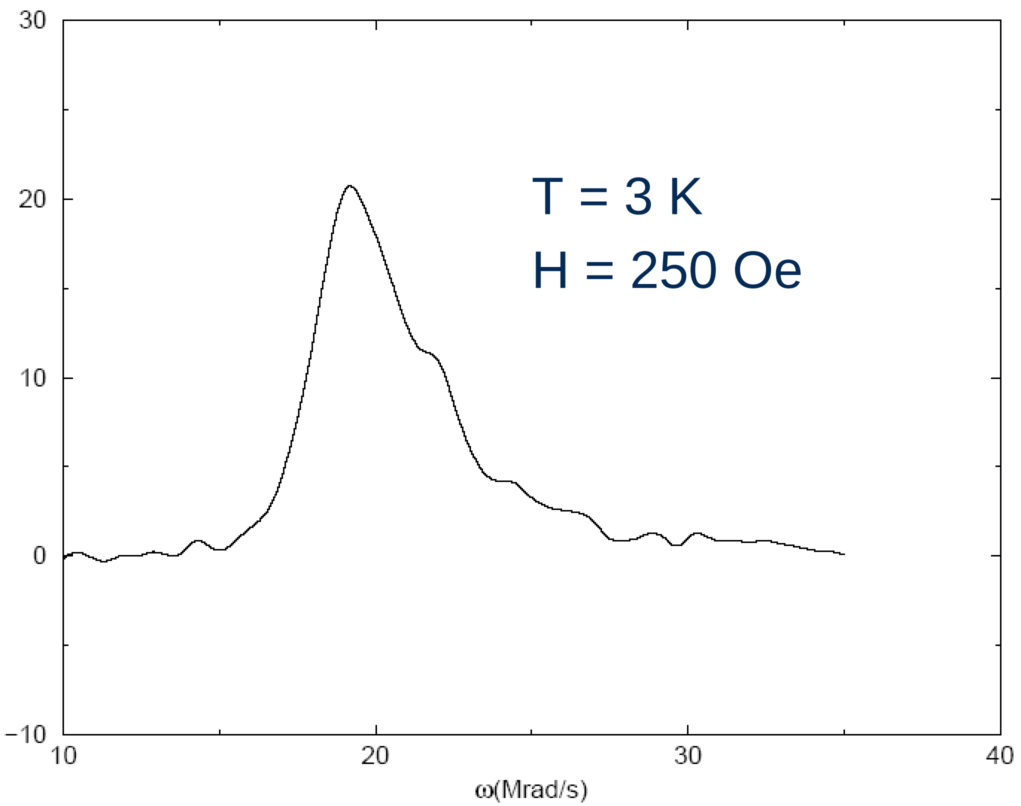
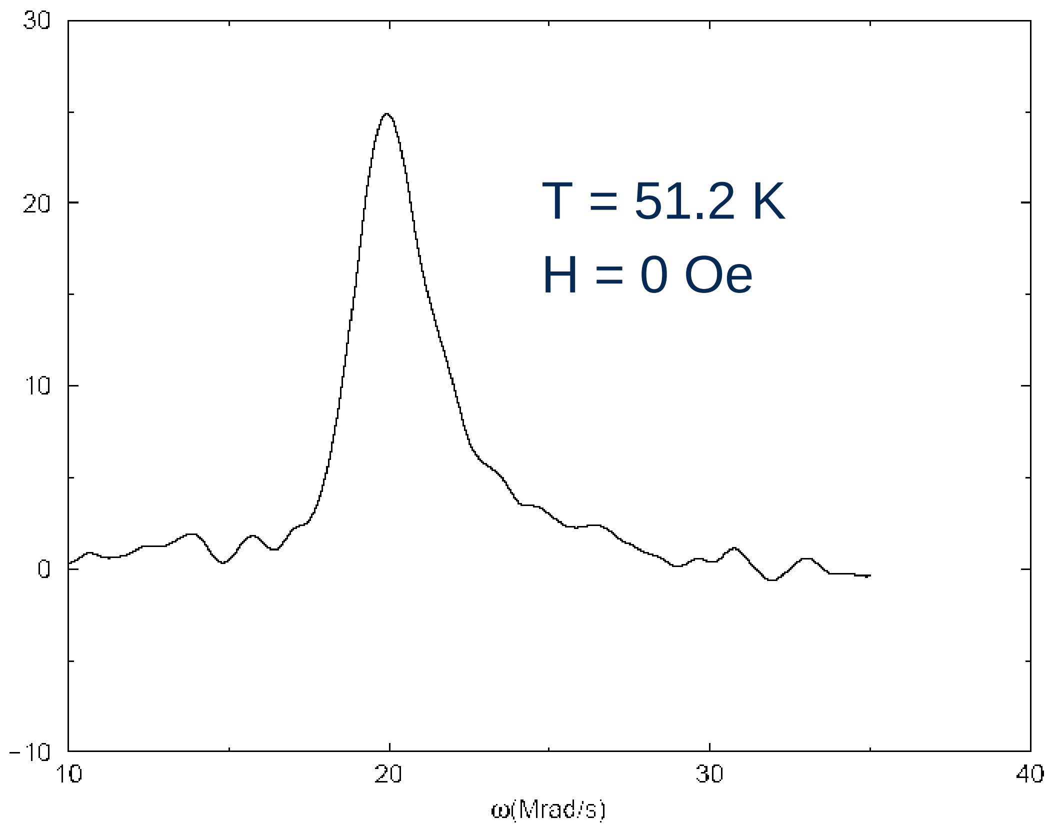
# Persistence of Pinned Fluxon States in $YBa_2Cu_3O_7$ Crystal

Fourier transform of μSR time spectra yields local magnetic field distribution

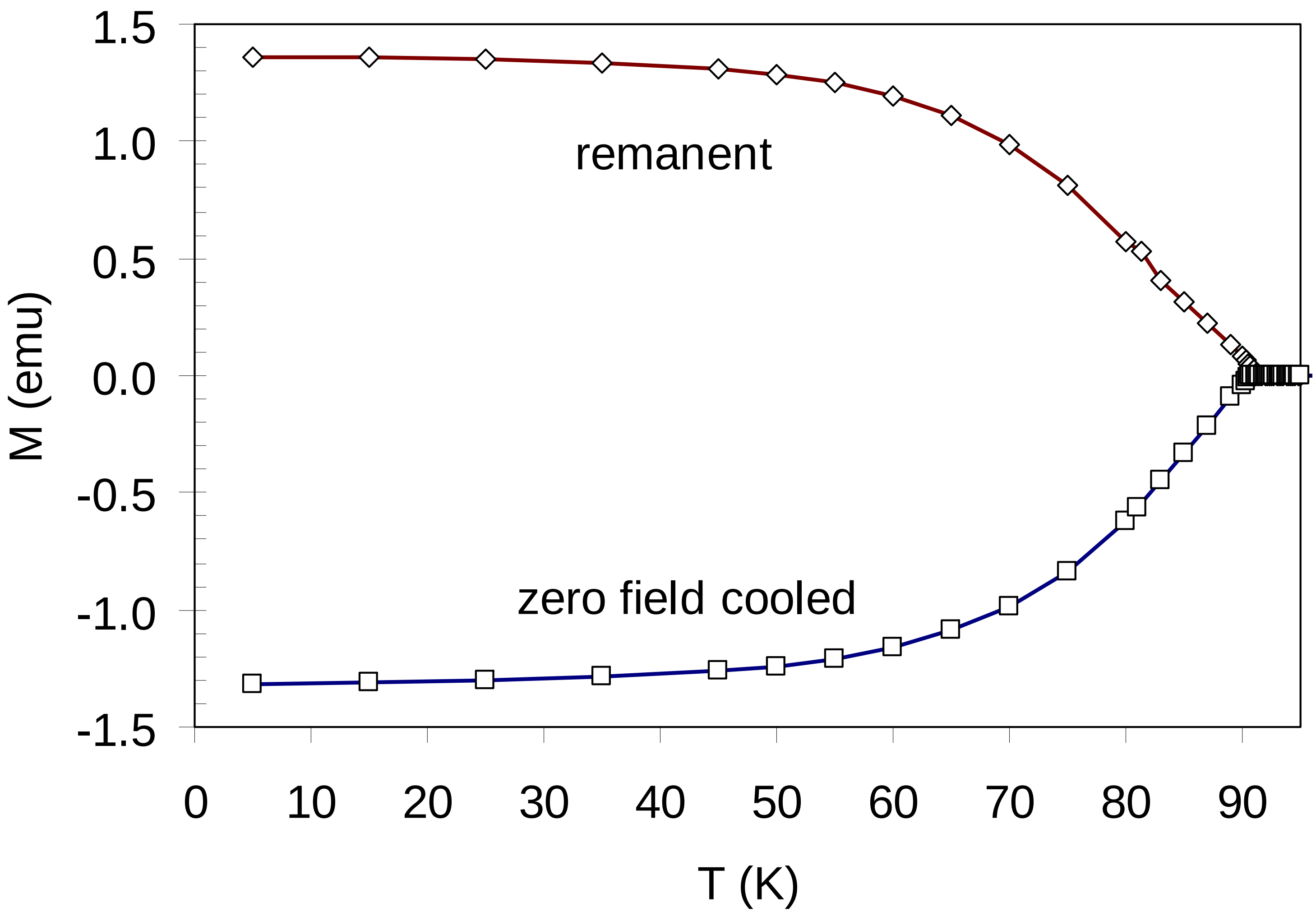



Theory: Fluxons form “Bragg glass” → pinned quasi-ordered lattice

# Magnetization of $YBa_2Cu_3O_7$ Crystal

Remanant Bragg Glass • Cooled at H = 250 Oe → Warmed at H=0
Meissner Shielding • Zero field cooled → Warmed at H = 250 Oe



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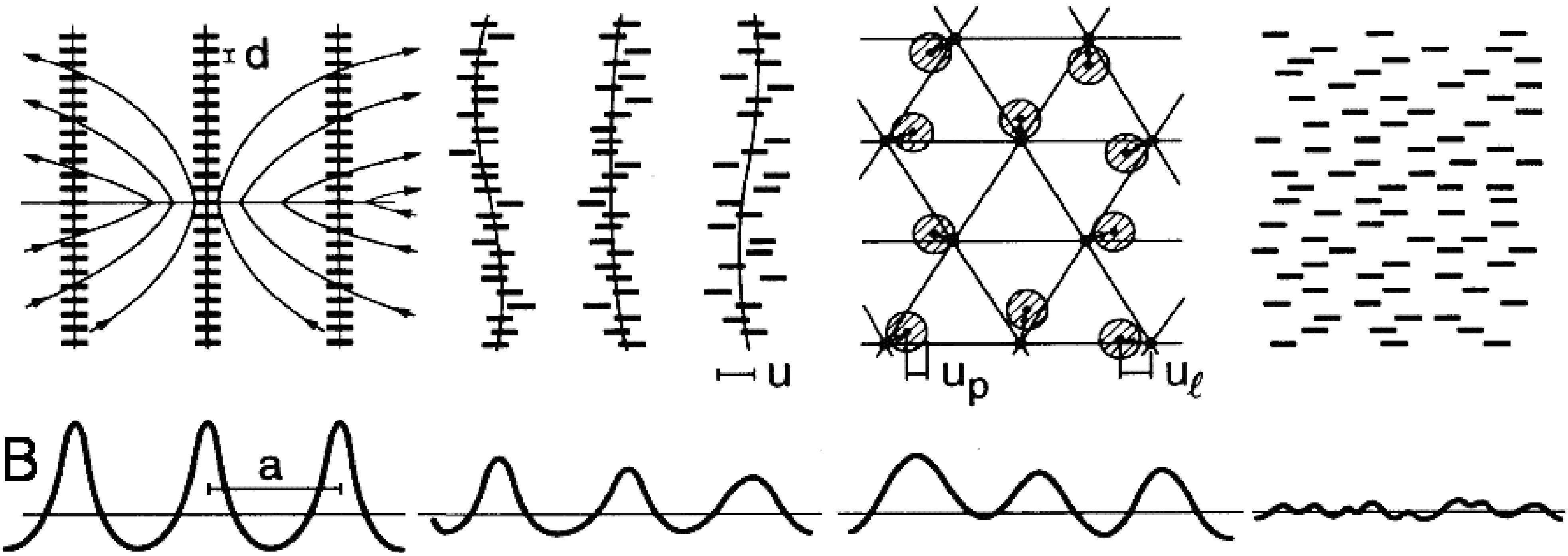
# Local Disorder • 2D Fluxons in Superconducting Layers

$u_p$ shift of point fluxons from smooth line position • “fuzzy core”
$u_l$ shift of smooth line position from lattice site




Fluxon lattice | Disordered point fluxons | Random

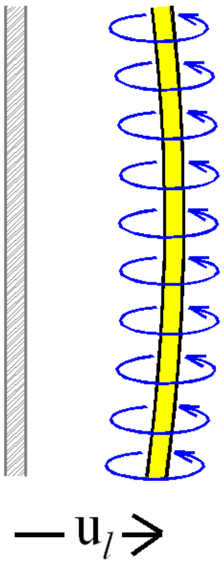
Source: E. H. Brandt, Phys. Rev. Lett. **66**, 3213 (1991).

# Thermally Activated Fluxon Pinning Model

Pinning energy varies with fluxon displacement $E = \beta u_l^2$

Pinning distortion is thermally activated $u_l^2 = u_{l0}^2 [1 - \exp(-E/k_B T)]$

Expressed in dimensionless form $y = 1 - \exp(-y/x)$

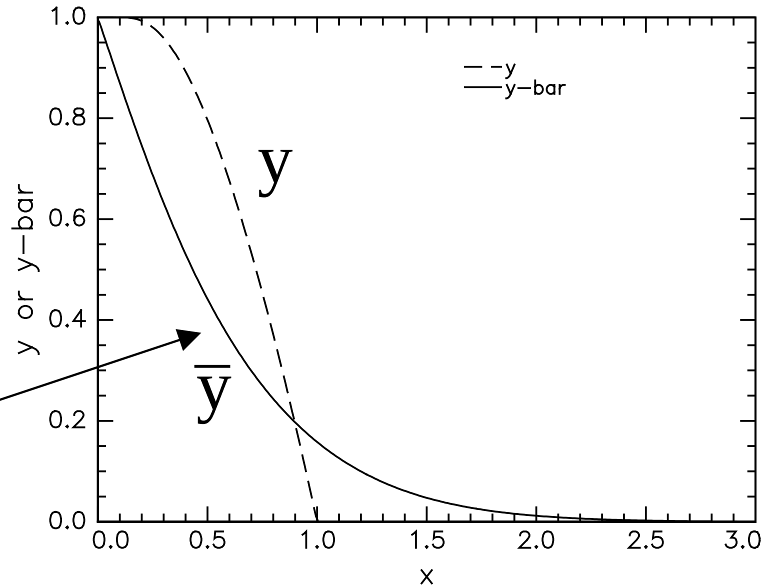



Introduce randomness through Gaussian convolution of unit width

$$\bar{y}(x) = \pi^{-1/2} \int_0^\infty \exp(-z^2/2)\, y(x/z)\, dz$$

**Result**: Model function for pinning contributions to $u_l$ fluctuations

$$u_l^2 = \bar{y}(k_B T\, \lambda(0)^2 / E_P\, \lambda^2)$$



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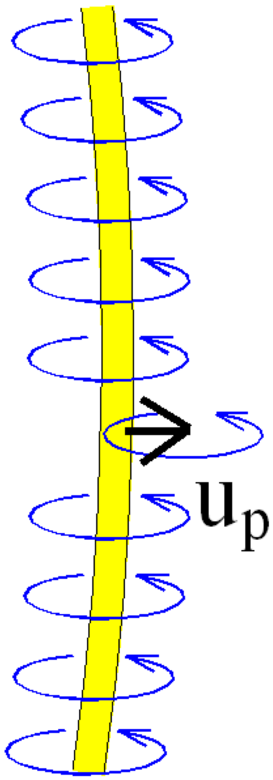
# Point Fluxon Displacement Model

Model variation of point 2D fluxons from smooth line position
Mean square variation is proportional to $k_B T$:

$$u_p^{\,2} = u_{p0}^{\,2} + u_{p1}^{\,2}\, T / T_c$$



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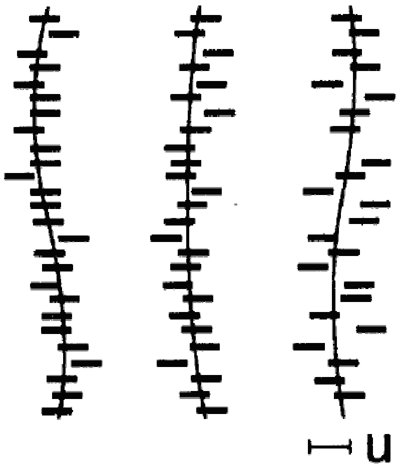
# Influence of Fluxon Pinning on μSR Linewidth

Pinning changes the μSR linewidth (root second moment of local field)

$$\Delta B \equiv \sigma = \sigma_L \ [\ \exp(-26.4\ u^2 / a^2) + 24.8\ (u_l^2 / a^2) \ln(\kappa') \ ]^{1/2}$$




$$u^2 = u_l^2 + u_p^2$$

$$\kappa' = [(u_l^2 + 2\lambda^2)/(u^2 + 4\xi^2)]^{1/2}$$

$u_p$ shift of point fluxons from smooth line position – decreases σ ↓

$u_l$ shift of smooth line position from lattice site – increases σ ↑

$\sigma_L$ linewidth in absence of pinning

$\xi$ coherence distance (fluxon core size)

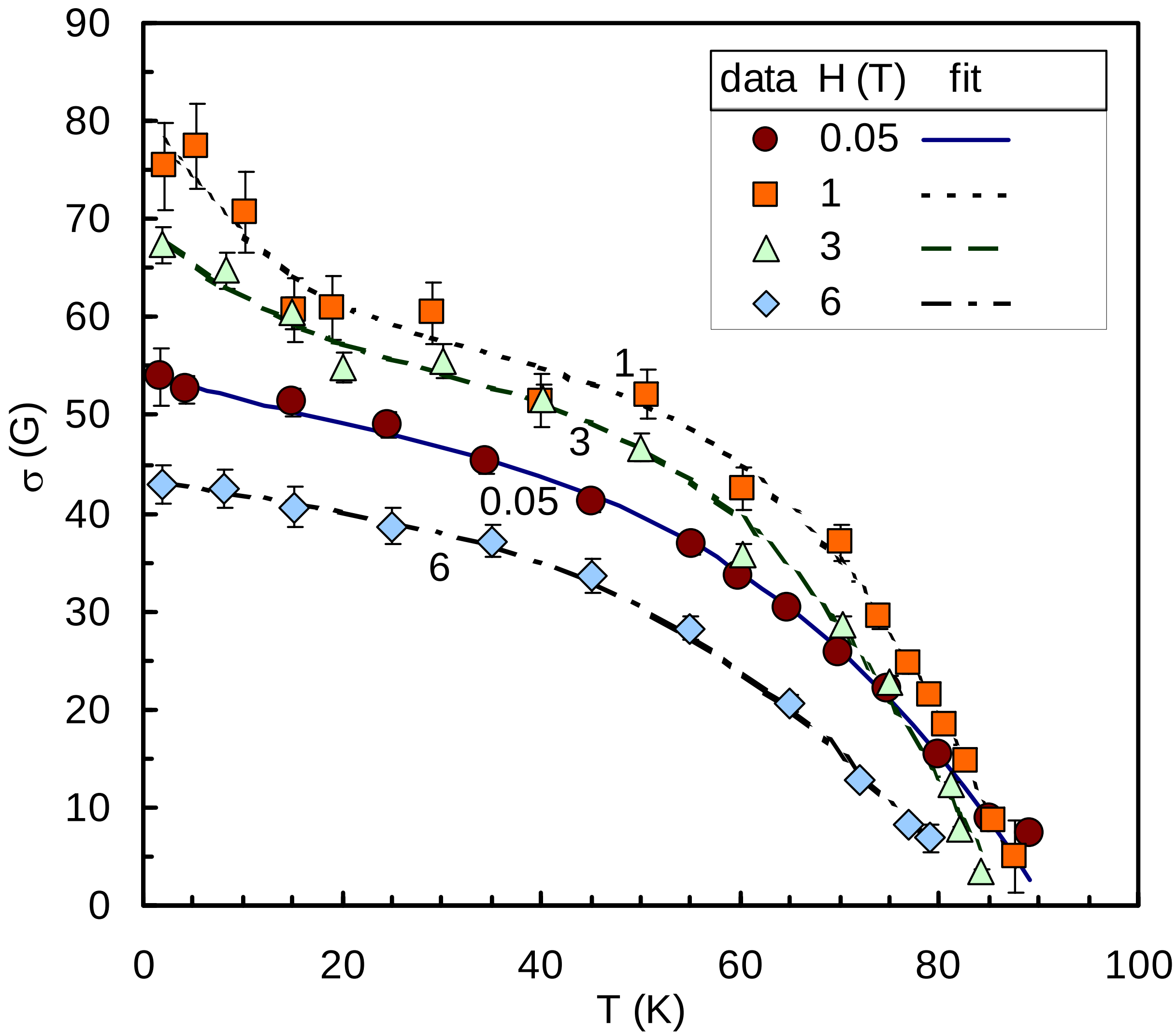
$\lambda$ magnetic penetration depth

$a$ fluxon lattice spacing $\propto B^{-1/2}$

Source: E. H. Brandt, Phys. Rev. Lett. **66**, 3213 (1991).

# μSR Linewidth in $YBa_2Cu_3O_7$ Crystal

## Field and temperature dependence includes fluxon pinning




If no pinning:
$\sigma \propto \lambda^{-2}$
and would be ***monotonic*** function of H

Bragg glass / glass phase boundary lies near H = 1T

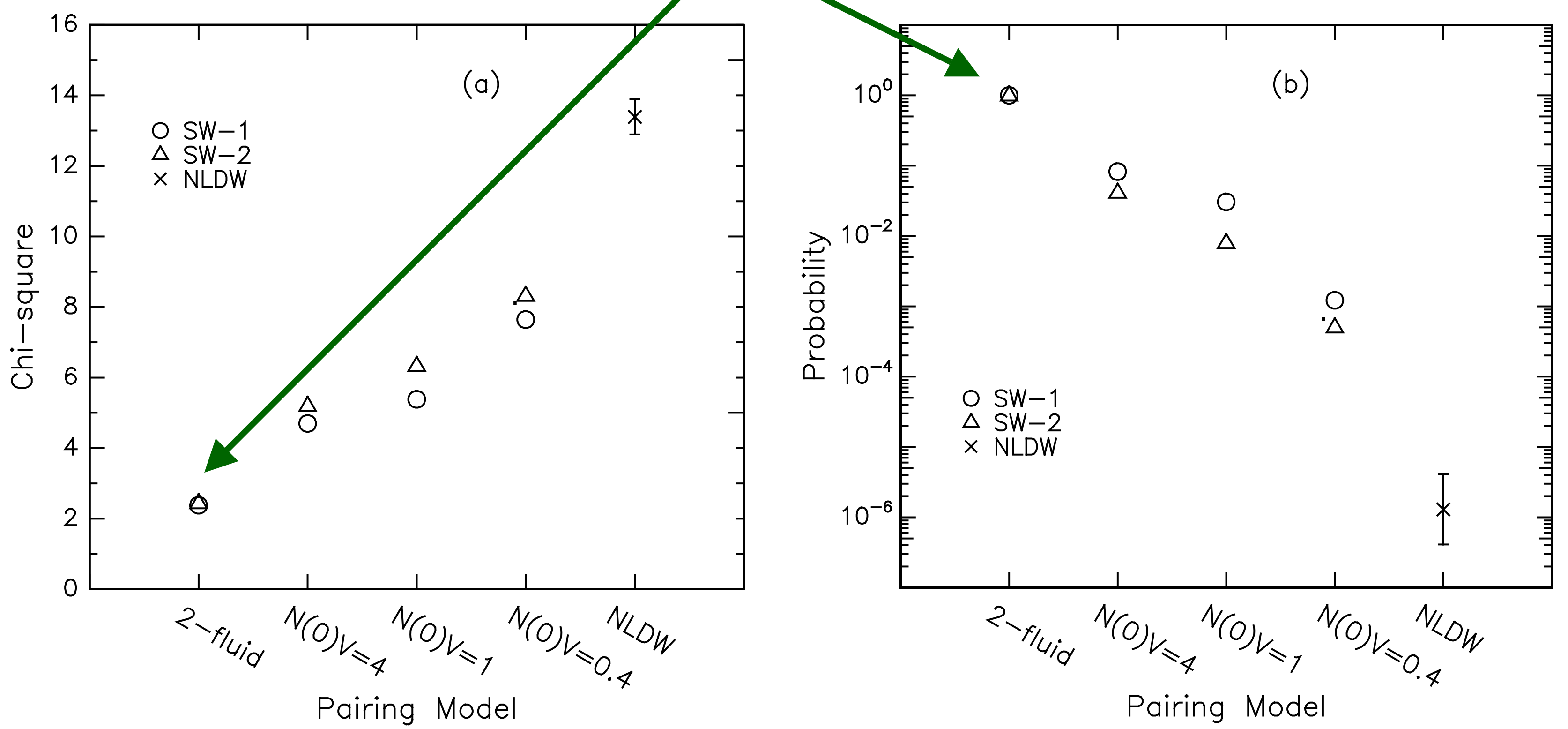
# Penetration Depth Theory & Pinning Model ⇒ Fitted Data

Two-fluid pairing model for temperature dependence

S-wave model • Like BCS theory with strong coupling

Ginzburg-Landau model for field dependence

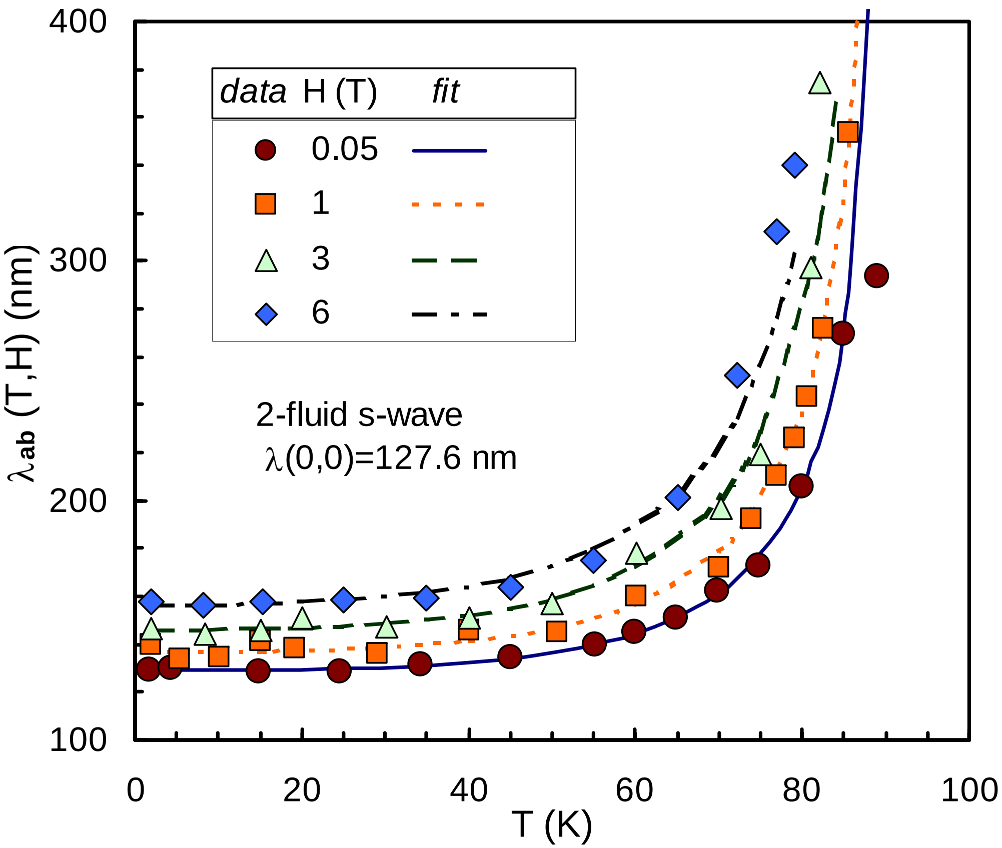
$$\lambda(T,H)^{-2} = \lambda(0,0)^{-2} f\,(H / H_{c2}(T))\,[1 - (T/T_c)^4]$$



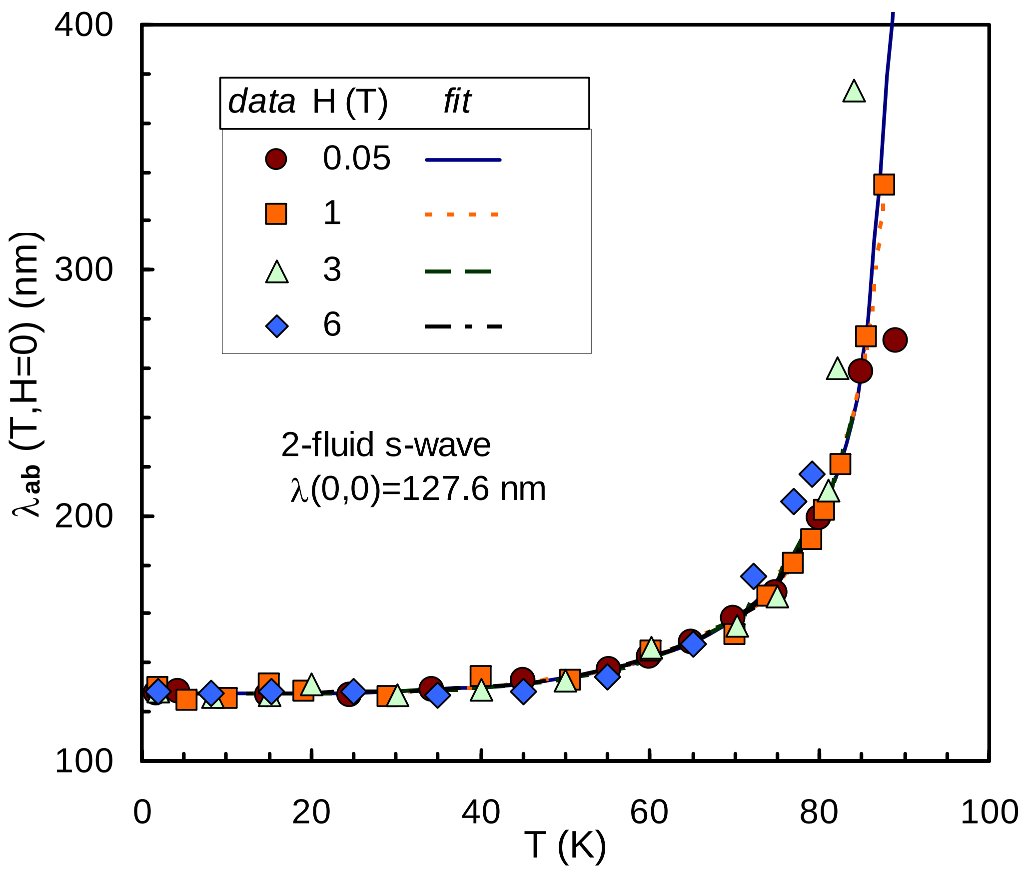
# Penetration Depth a-b Basal Plane $YBa_2Cu_3O_7$ Crystal

*After effects of fluxon pinning are removed*

## T and H dependence




## T dependence, H=0 limit




No nodes in gap function: λ(T) has zero slope at T=0



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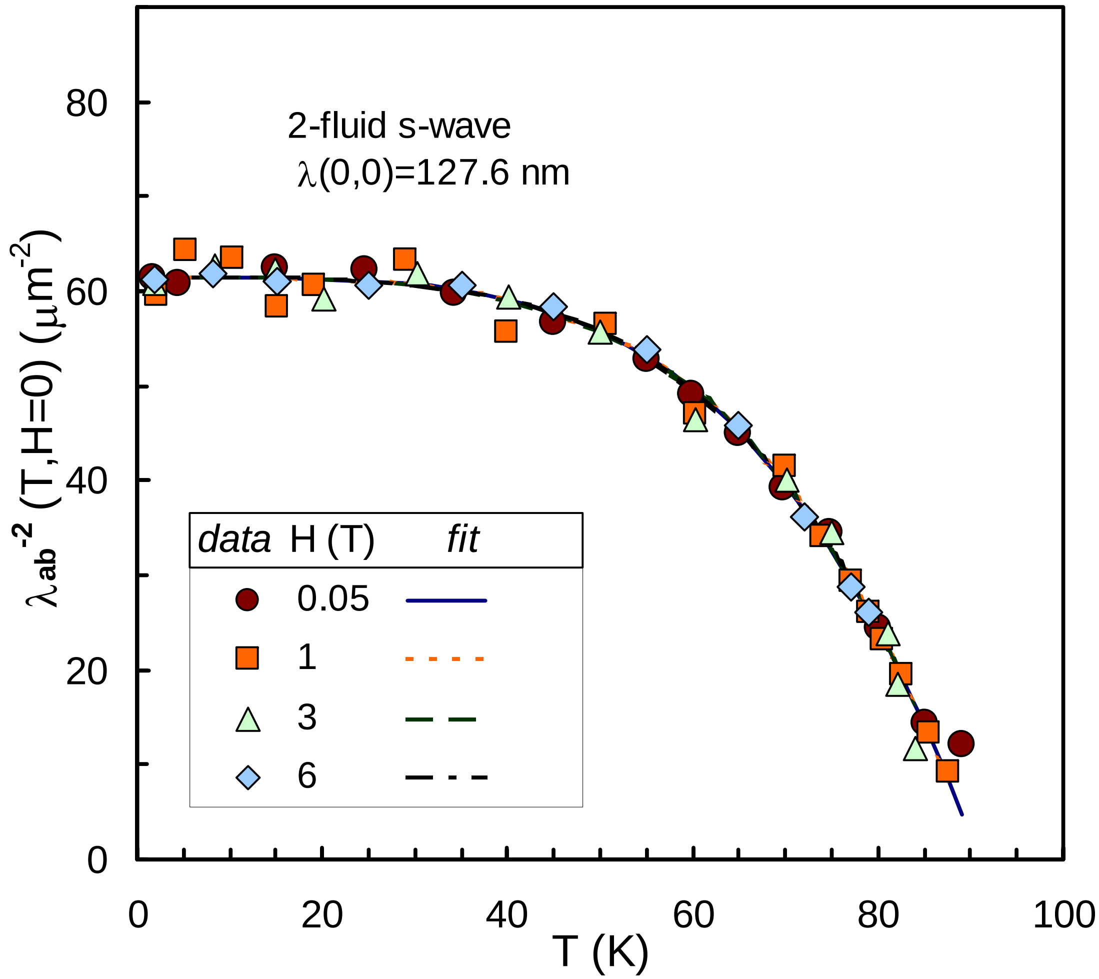
# Penetration Depth $YBa_2Cu_3O_7$ Crystal

*After effects of fluxon pinning are removed, H=0 limit*

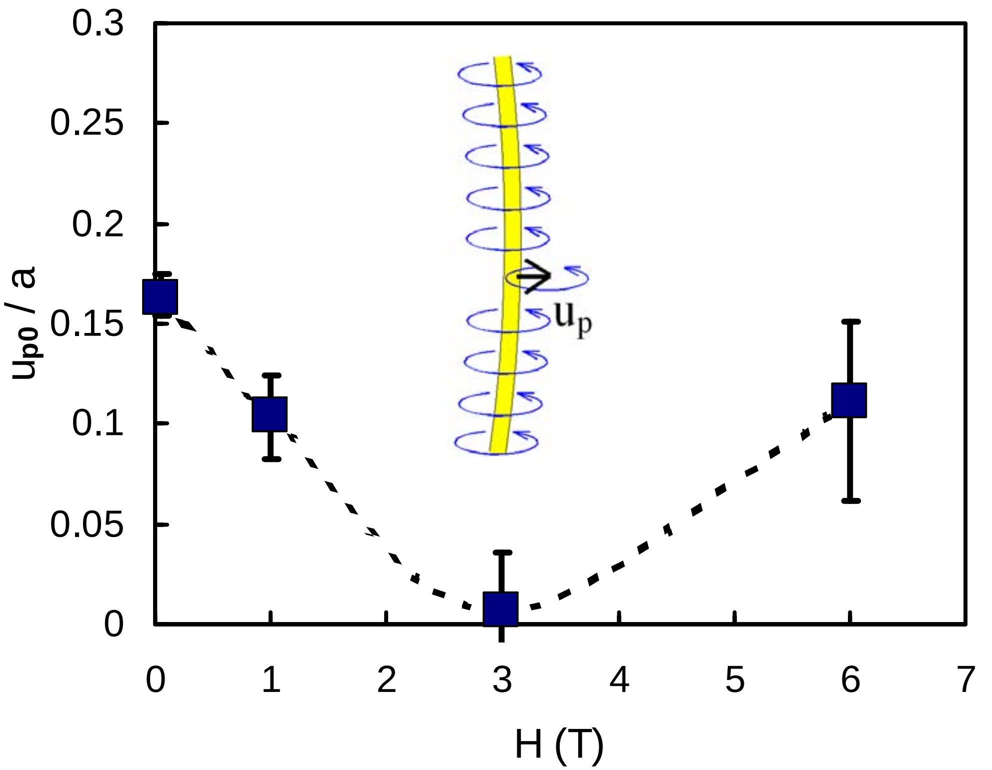
Superfluid Density

$n_s = m^*c^2 / 4\pi \lambda_{ab}^2$

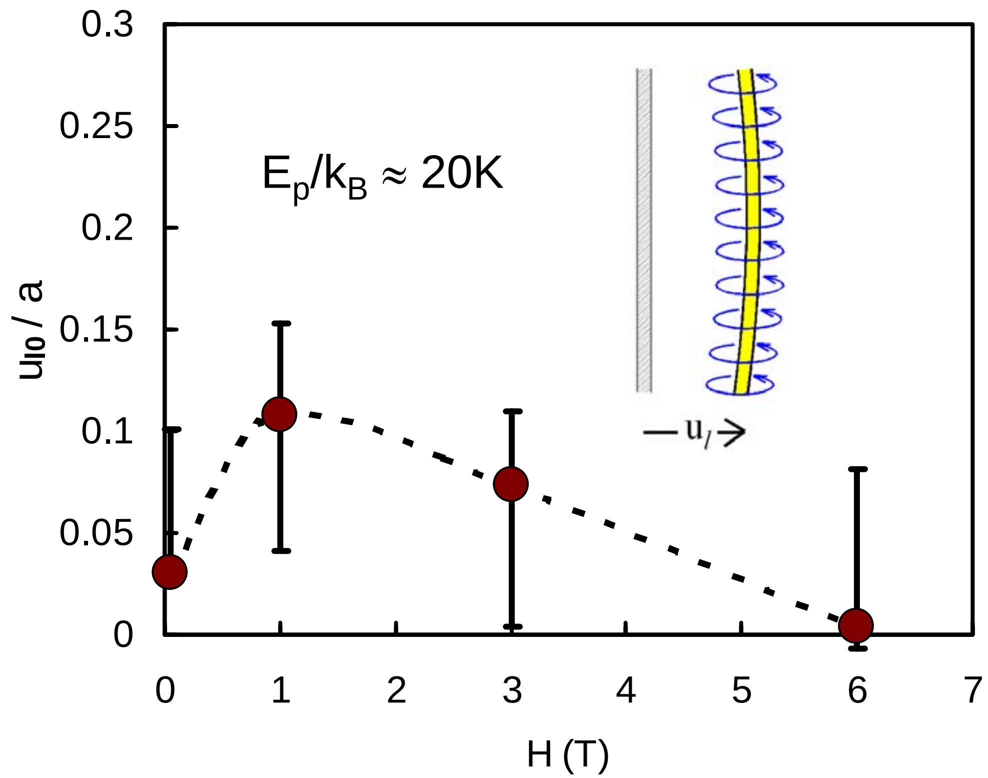


# Variation of Fluxon Pinning with Magnetic Field

$u_p$ Mean shift of point fluxons from smooth line position




$u_l$ Shift of smooth line position from lattice site




T = 0 Limit



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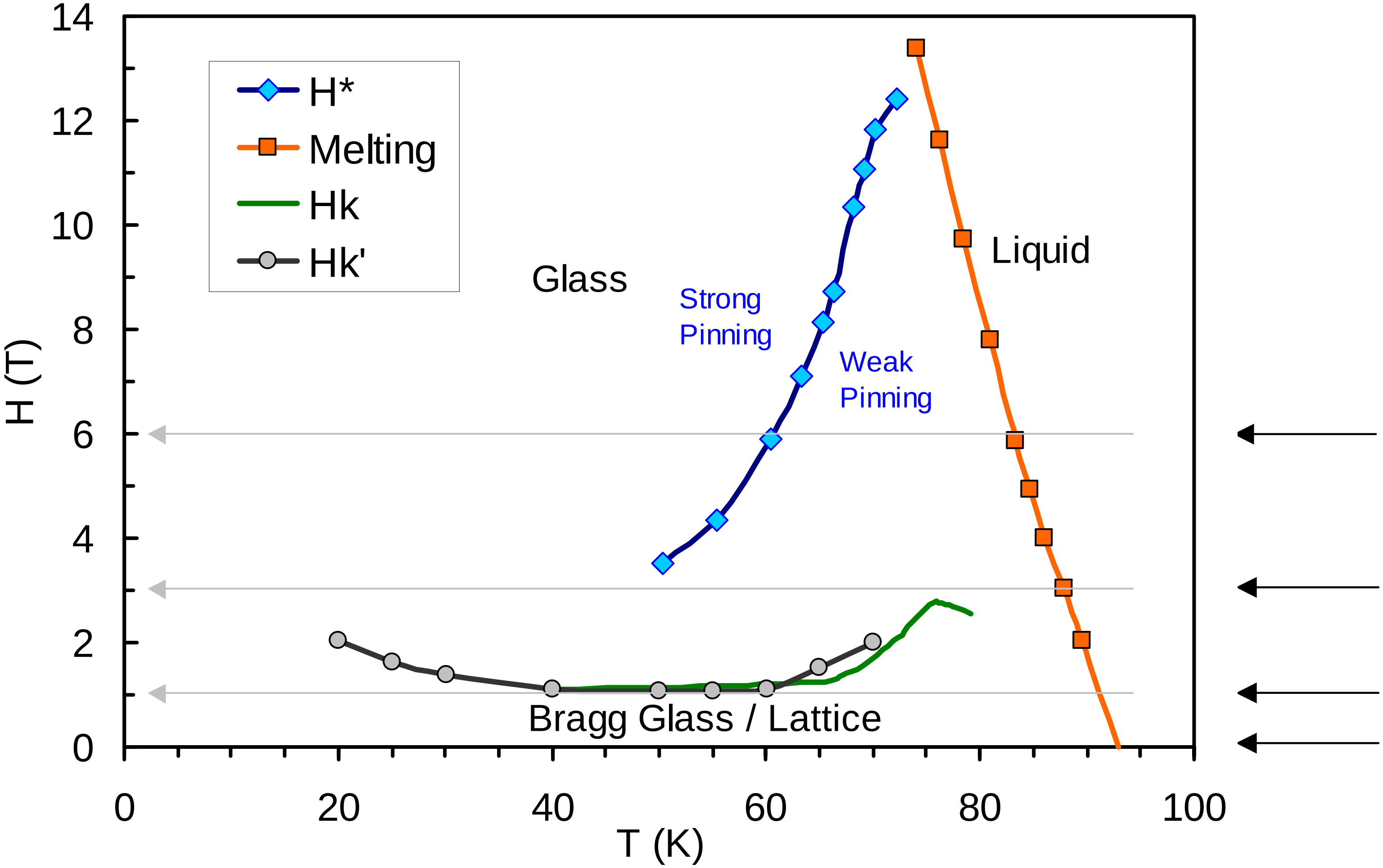
# Fluxon Phase Diagram for $YBa_2Cu_3O_7$

Diagram: Conventional Probes H ≠ Constant

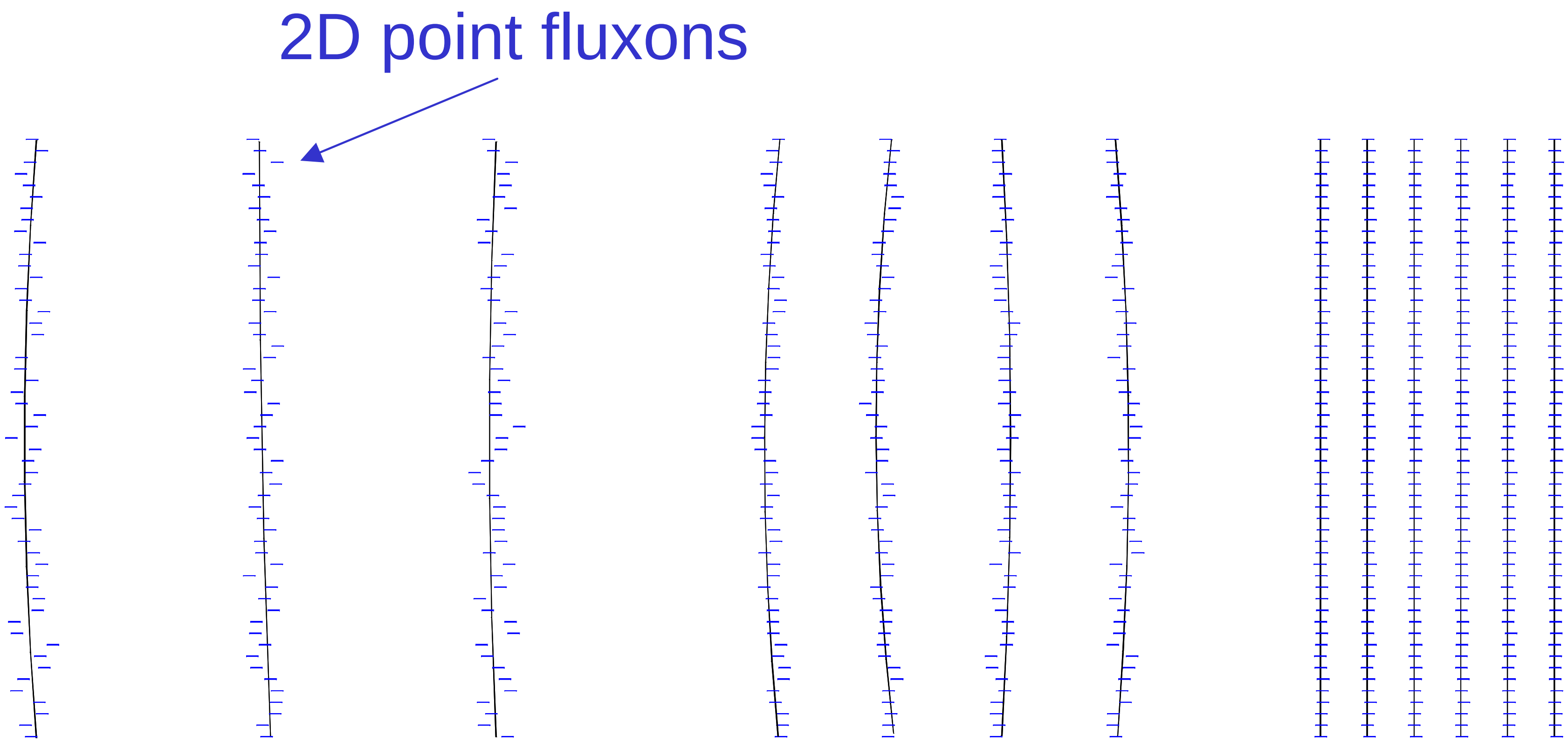



Muon Probe

Experiments

H = Constant

# Schematic Summary • Pinned Fluxons




| H | 0.05 T | 1 T | 6 T |
|---|---|---|---|
| $u_{p0}$ /a | 0.16 | 0.10 | 0.11 |
| $u_{l0}$ /a | 0.03 | 0.11 | 0.004 |
| | Bragg Glass | (Boundary) | Glass |

# Conclusions

Temperature and field dependence of fluxon pinning

- Fluxon configuration varies with temperature • Cooling in constant H

Pinning causes distortions in fluxon lattice

- Misalignment of point fluxons among layers
  - "Fuzzy core" • *Reduce* $\Delta$B
- Displacement of fluxons from triangular lattice sites
  - Lattice distortion / Line defects • *Increase* $\Delta$B

Model reveals underlying penetration depth $\lambda_{ab}(T)$

- S-wave pairing and superconductivity in BaO layers confirmed

Field-cooled demonstration of fluxons trapped by pinning

- Remanent magnetization
- Persistent fluxon states • Bragg glass $\Rightarrow$ Entangled glass

# Acknowledgements

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Garching, Bavaria, Germany