University of St. Andrews

Using muons to probe spatial correlations in vortex matter systems of superconductors

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Alan Drew — *Université Fribourg, Switzerland*

IMSS, Tsukuba, Friday 17th October 2008

Overview

- Background to Type II Superconductors
- Muon spin rotation (μSR): what we can learn about superconductivity from the vortex lattice
- Vortex correlations in single crystals of anisotropic superconductors
  - $La_{1.9}Sr_{0.1}CuO_4$ (LSCO)
  - $Bi_{2.15}Sr_{1.85}CaCu_2O_{8+\delta}$ (BSCCO-2212)
  - Irradiated $Bi_{2.15}Sr_{1.85}CaCu_2O_{8+\delta}$ (BSCCO-2212)
- Summary

Background to Type II Superconductors

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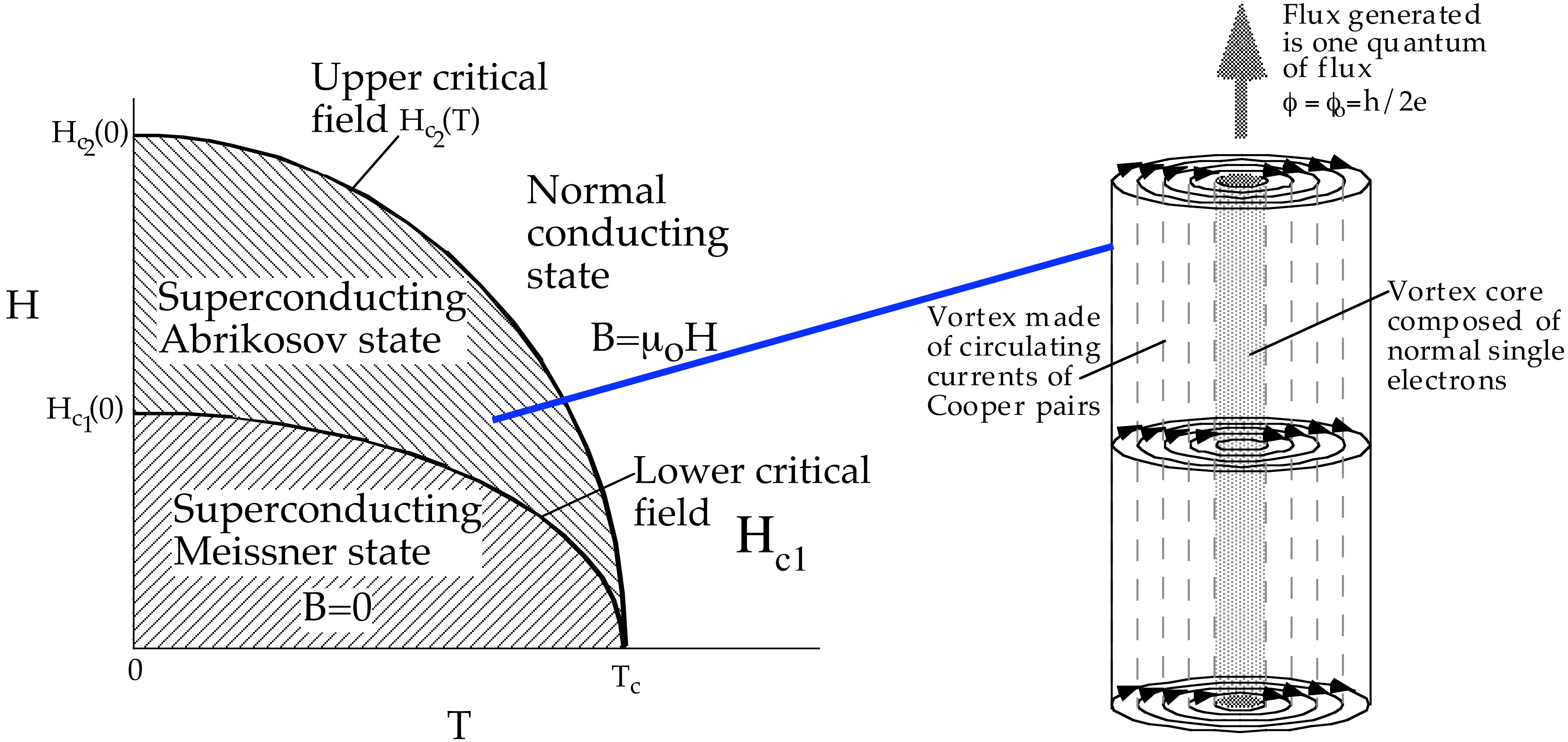
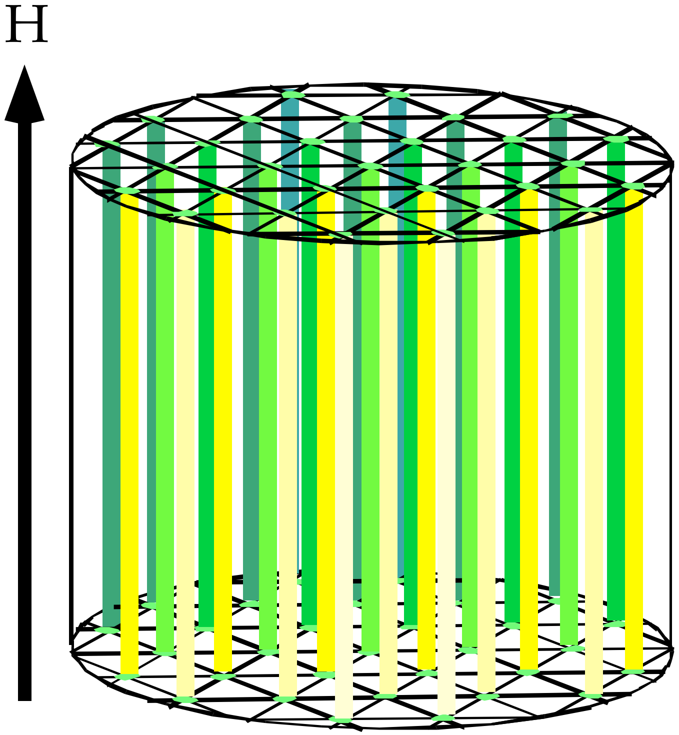
Type II Superconductivity

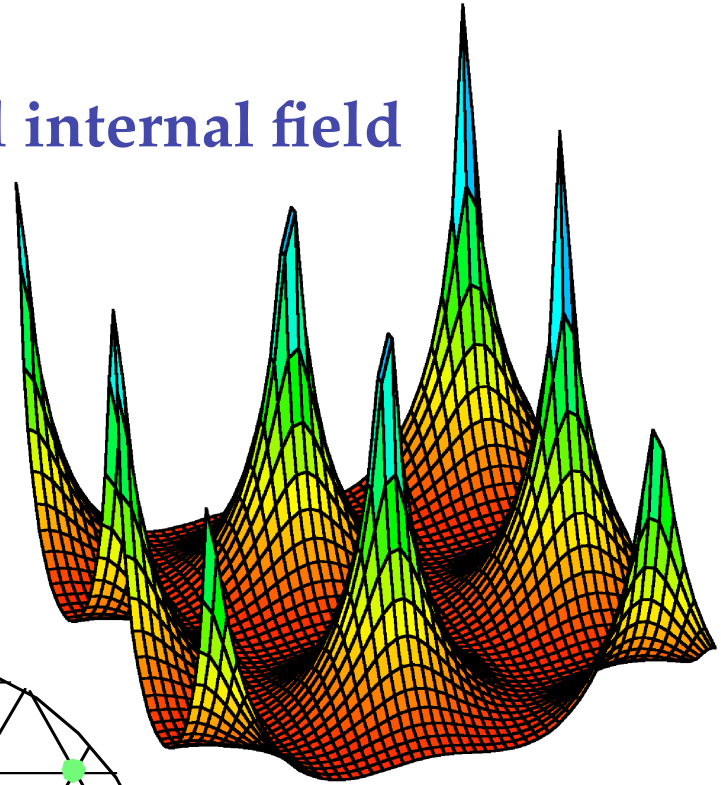


Flux line/vortex

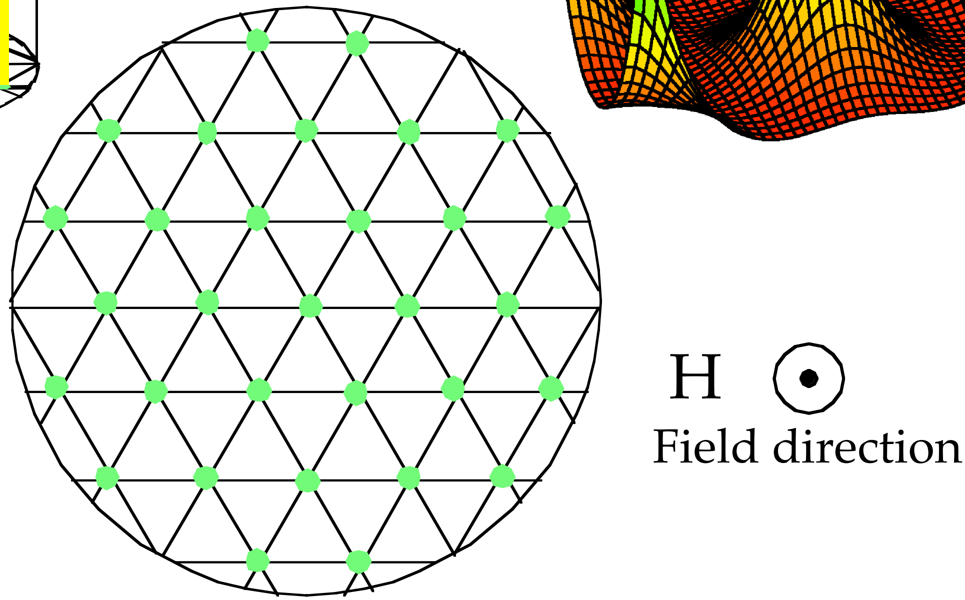
Abrikosov/Mixed State



Local internal field

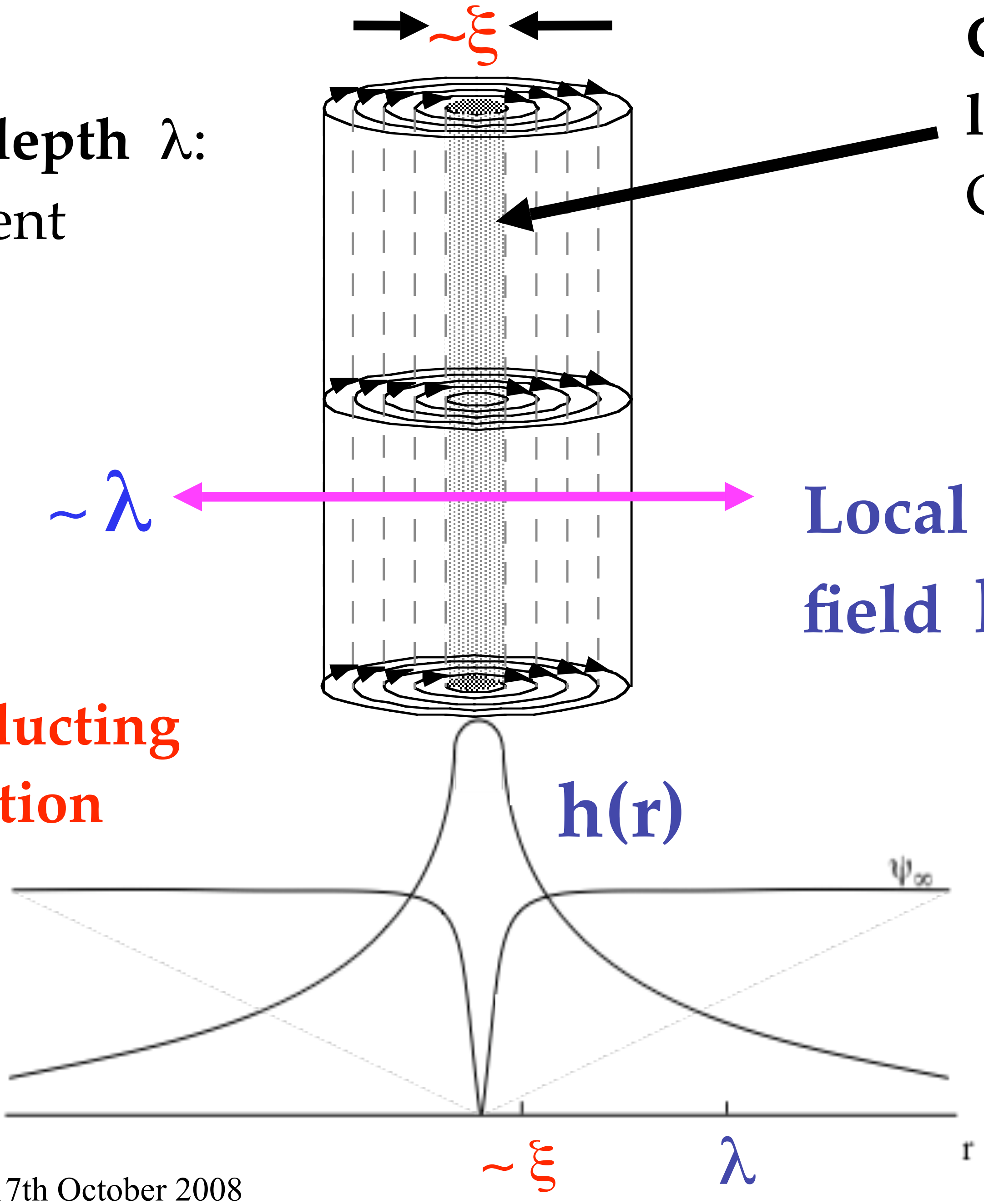


Vortex Lattice



Penetration depth λ:
Magnetic extent
~ λ

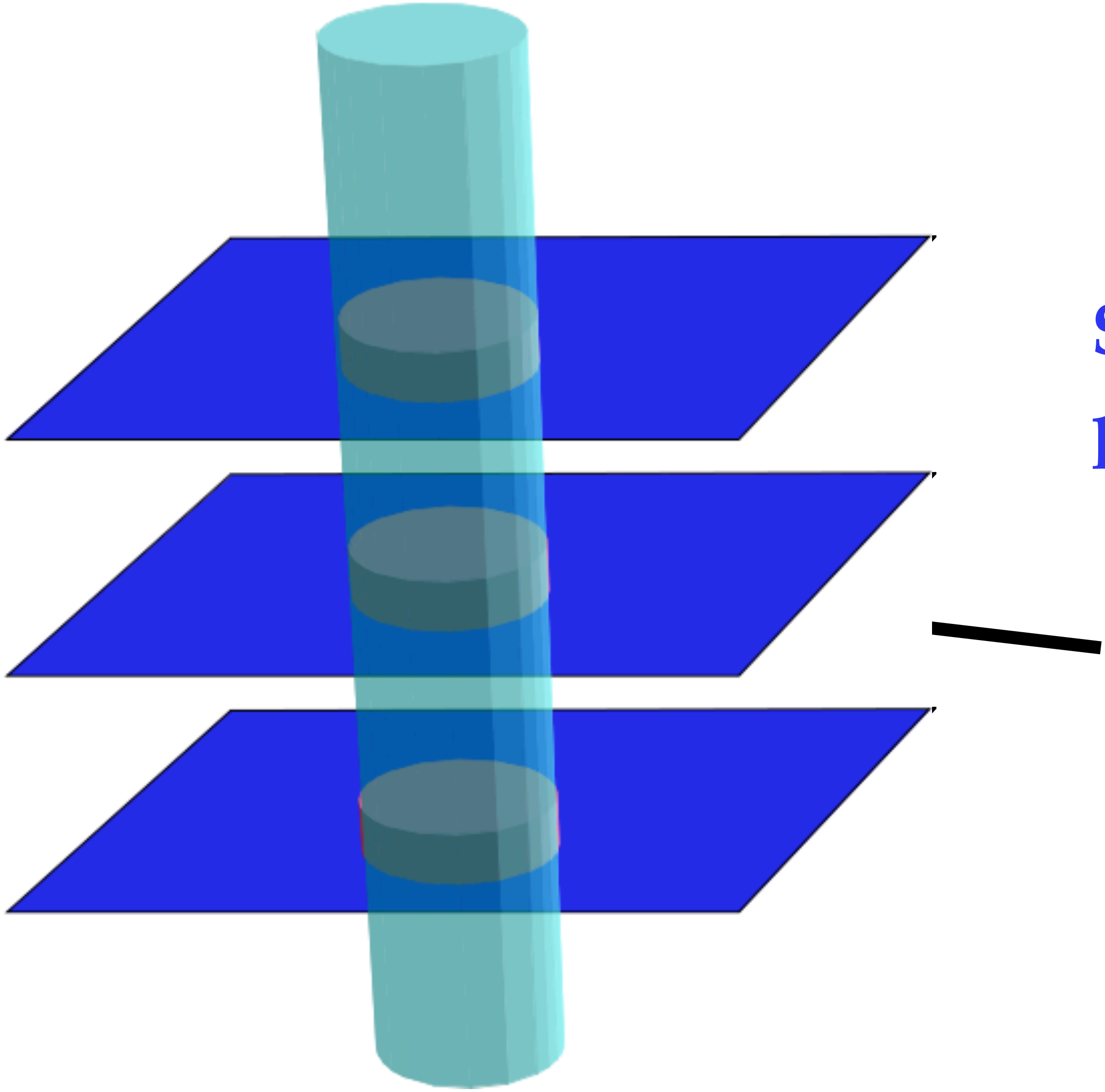
Coherence length ξ:
Core size ~ ξ



Local internal field h(r)

Superconducting wavefunction Ψ(r)

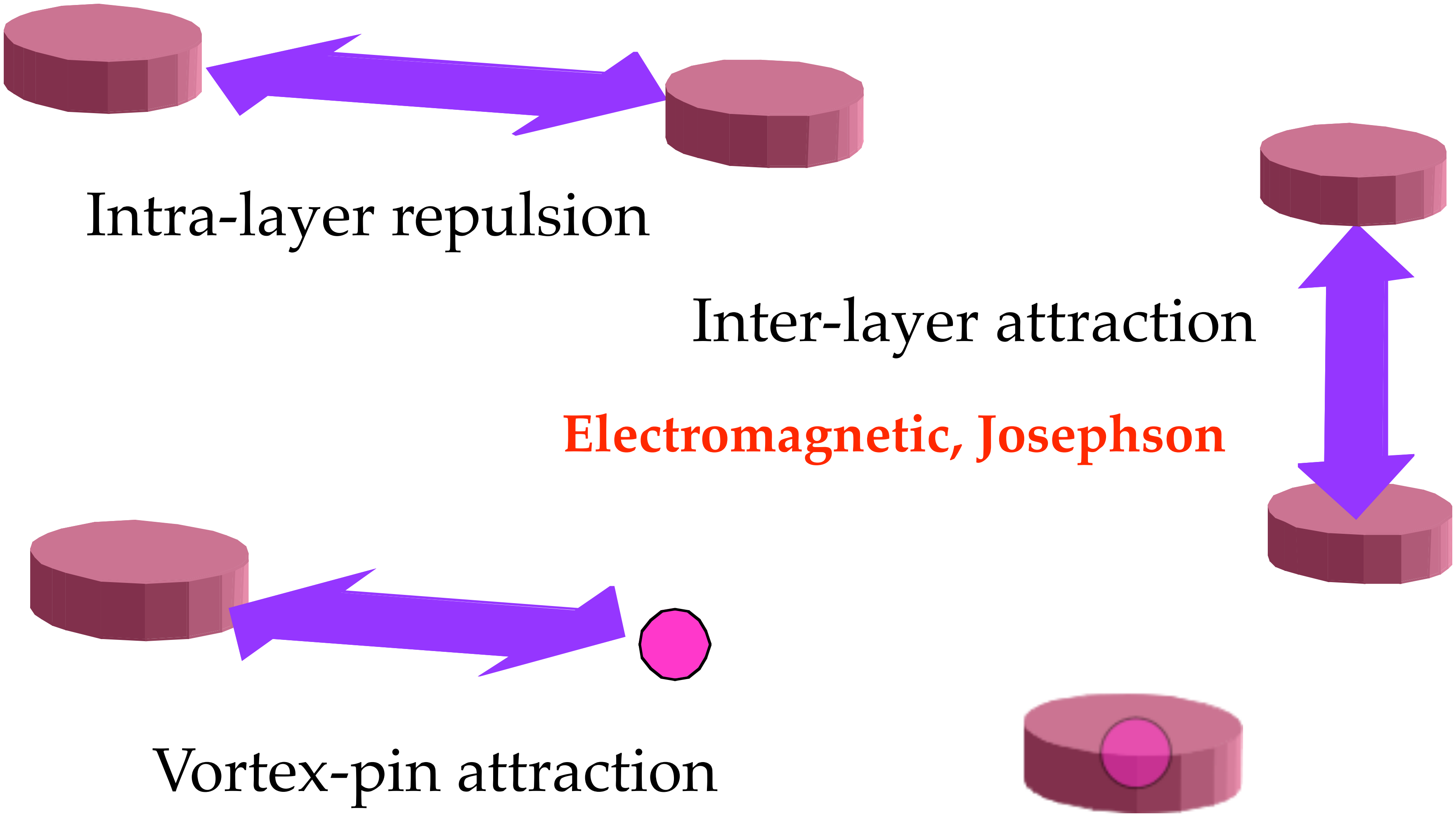
Layered superconductors e.g. High-T_c cuprates



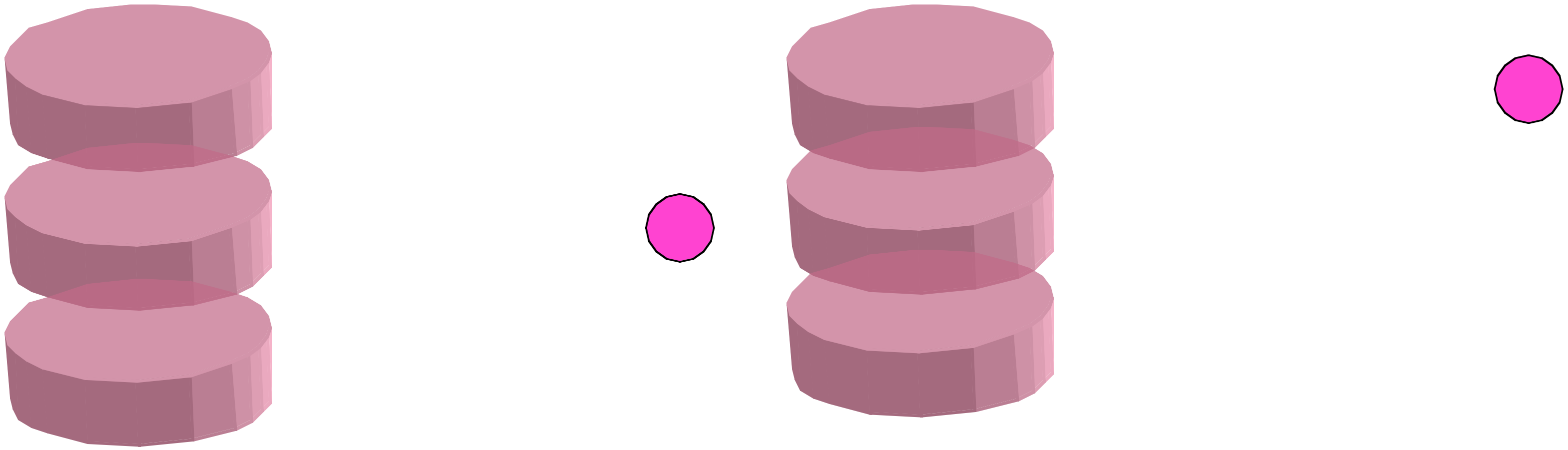
Superconducting planes

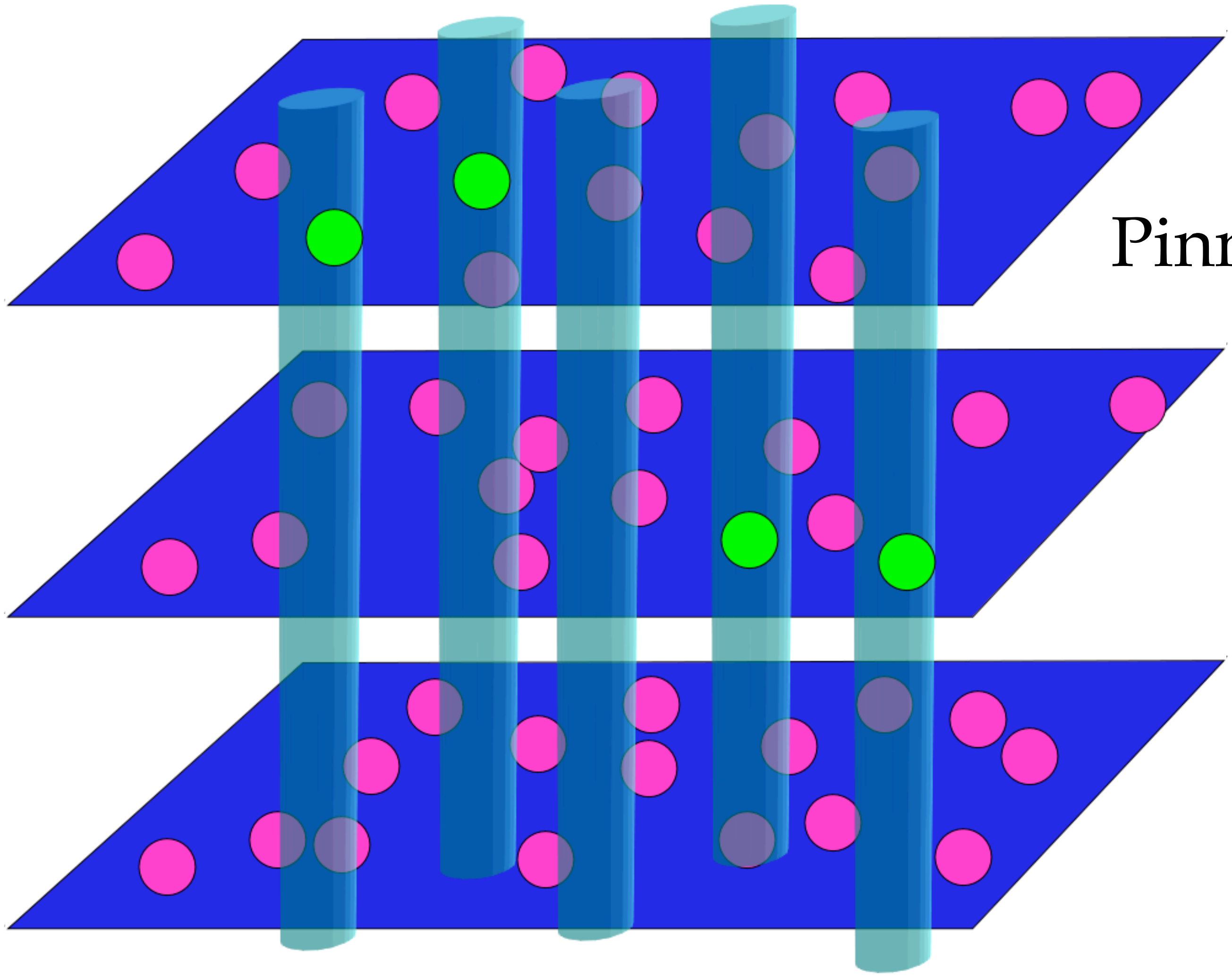
'Pancake' vortices

Vortex Interactions



Vortex Interactions and Pinning lead to **Irreversibility**

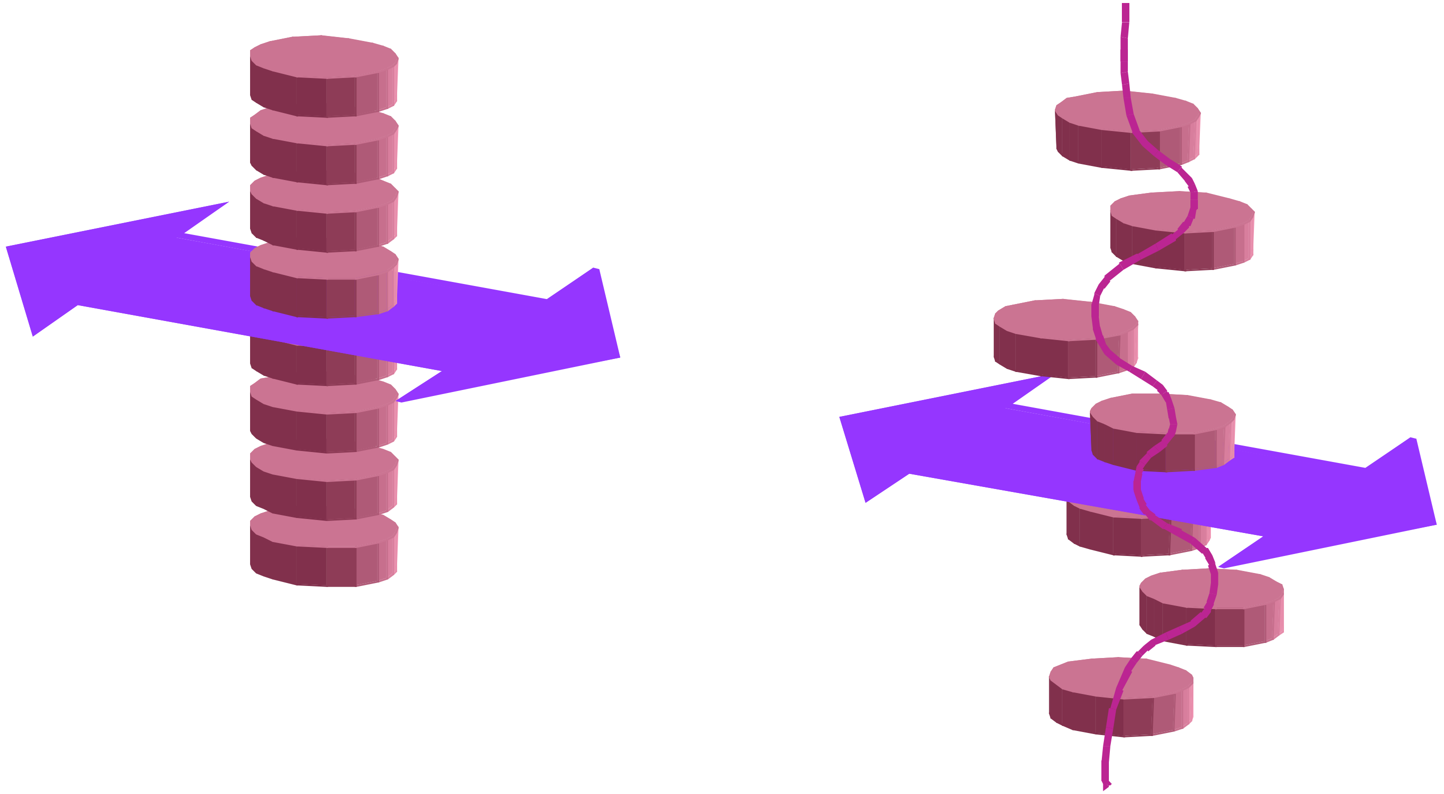




Pinning ‘landscape’

Transition to **glass state** as scale of disorder increases

Thermal disruption and melting



The Vortex Zoo …..

‘Vortex Matter’

Links to soft condensed

matter:

nematics;

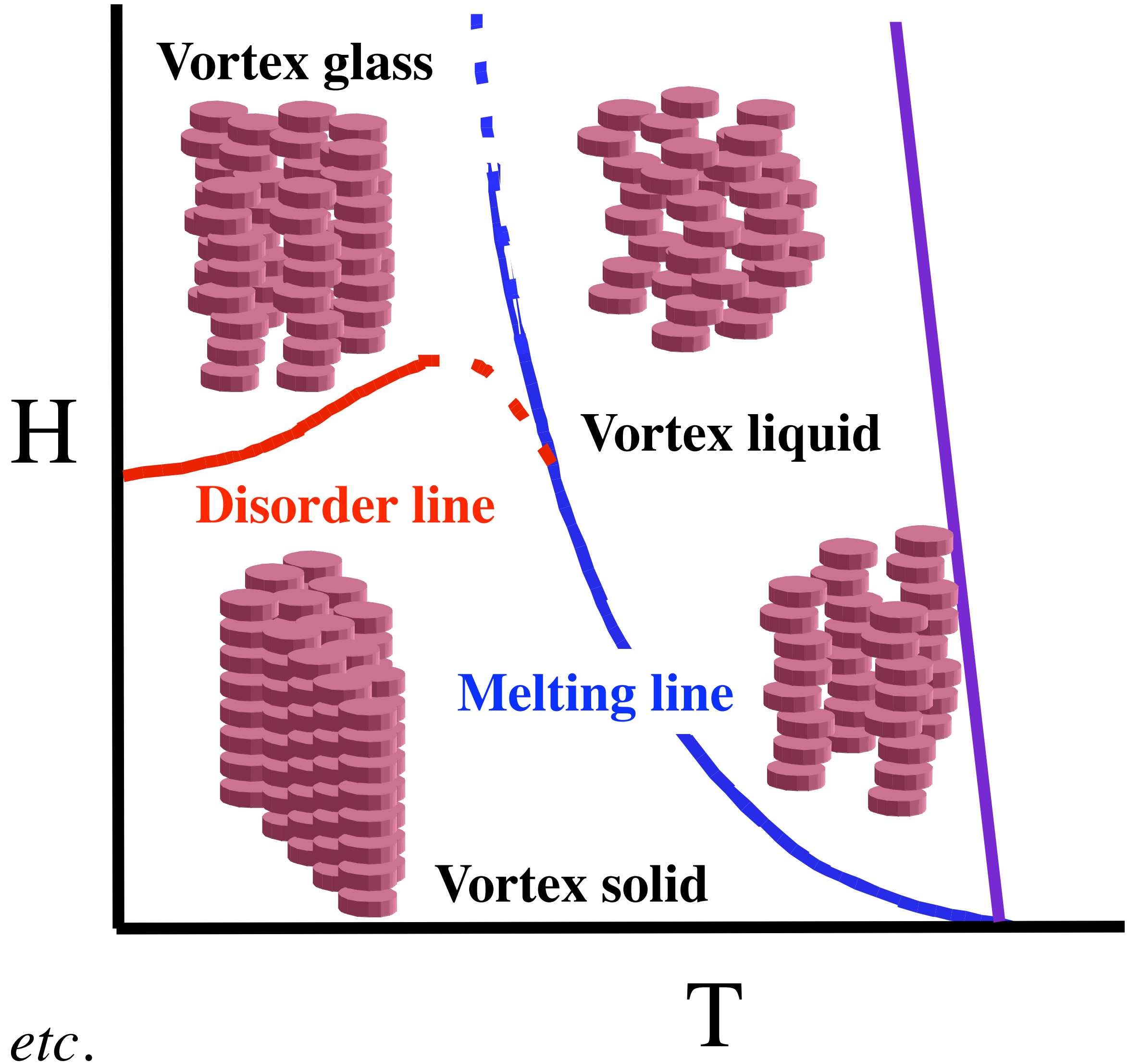
entanglement;

discotics;

glass transitions;

colloids;

higher order correlations etc.



Muon Spin Rotation (μSR):
What we can learn about
superconductivity from the vortex lattice

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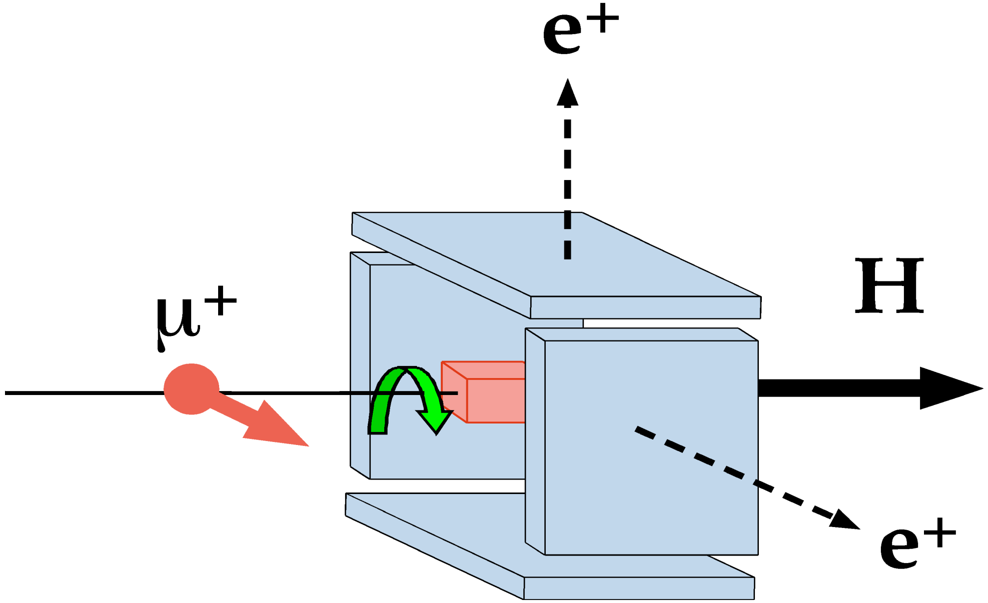
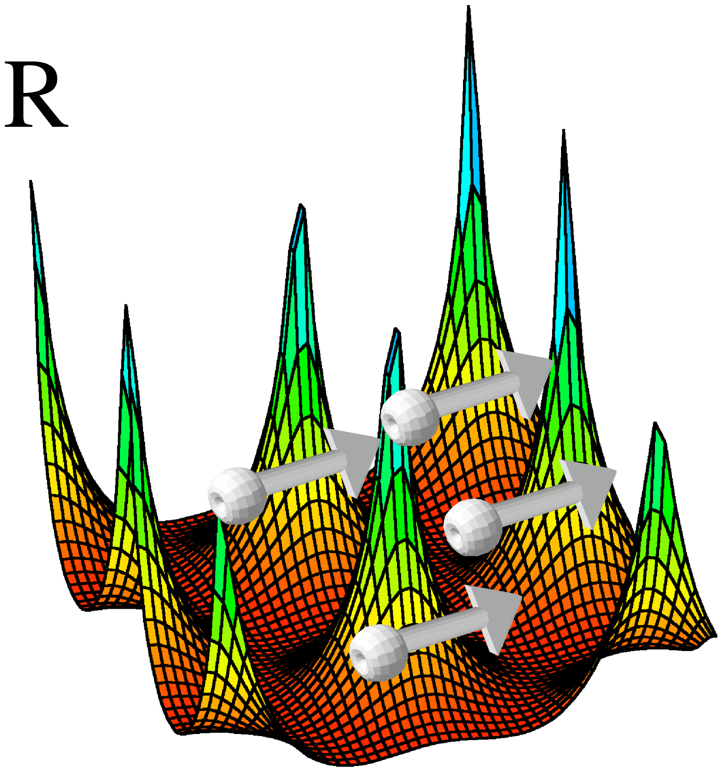
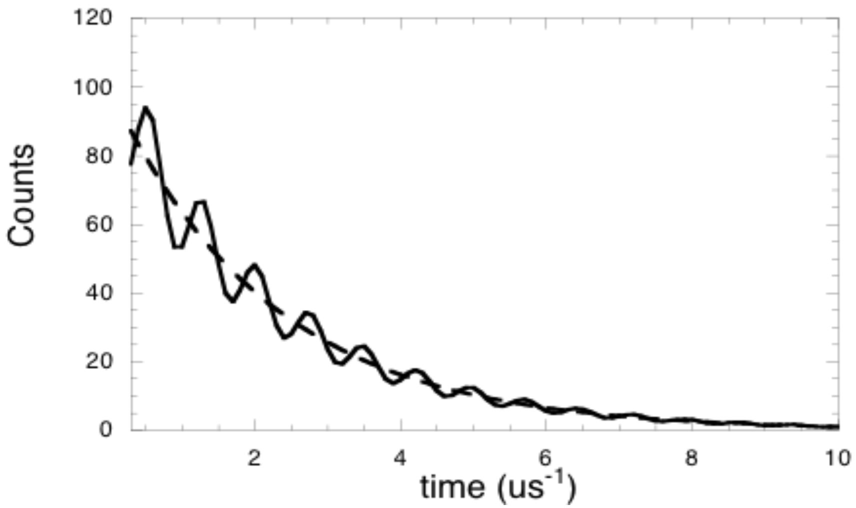
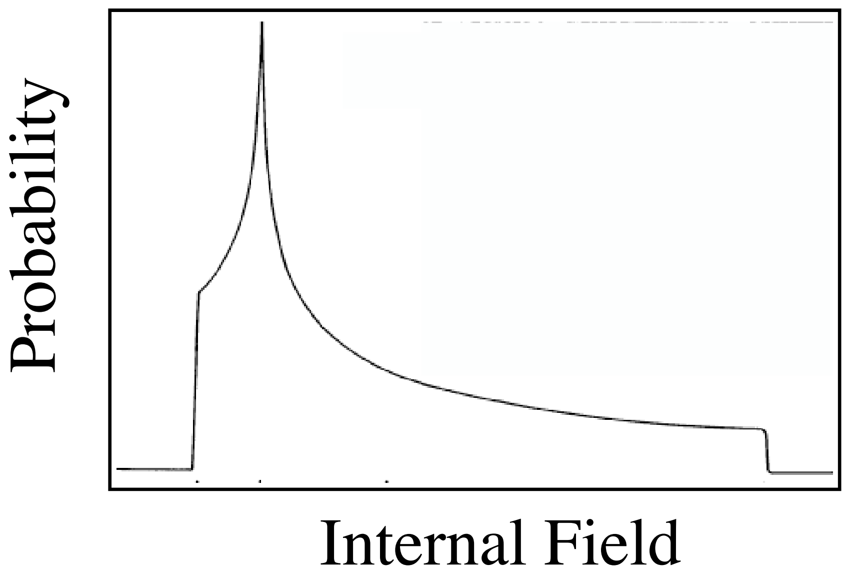
Muon spin rotation μSR



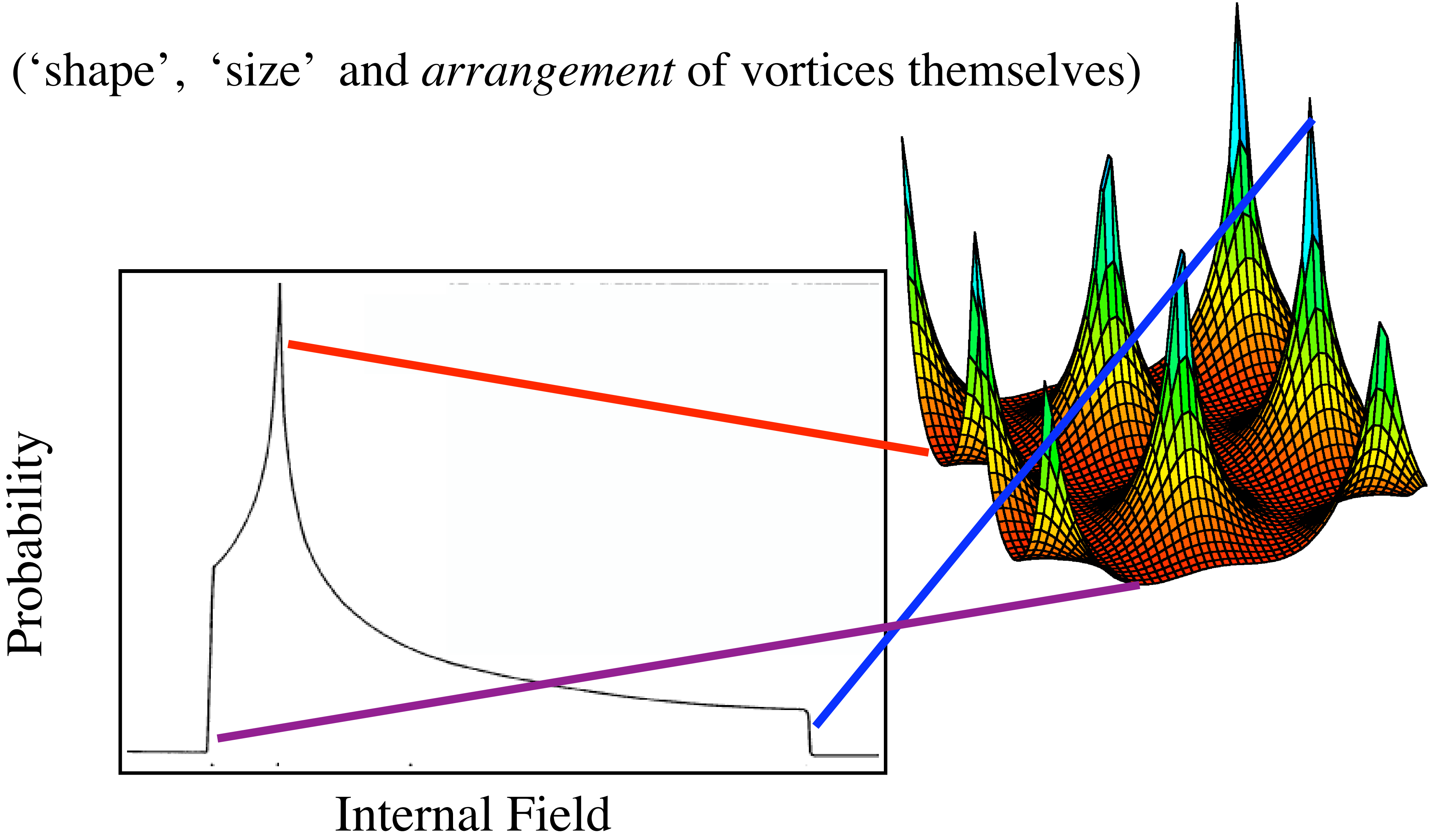




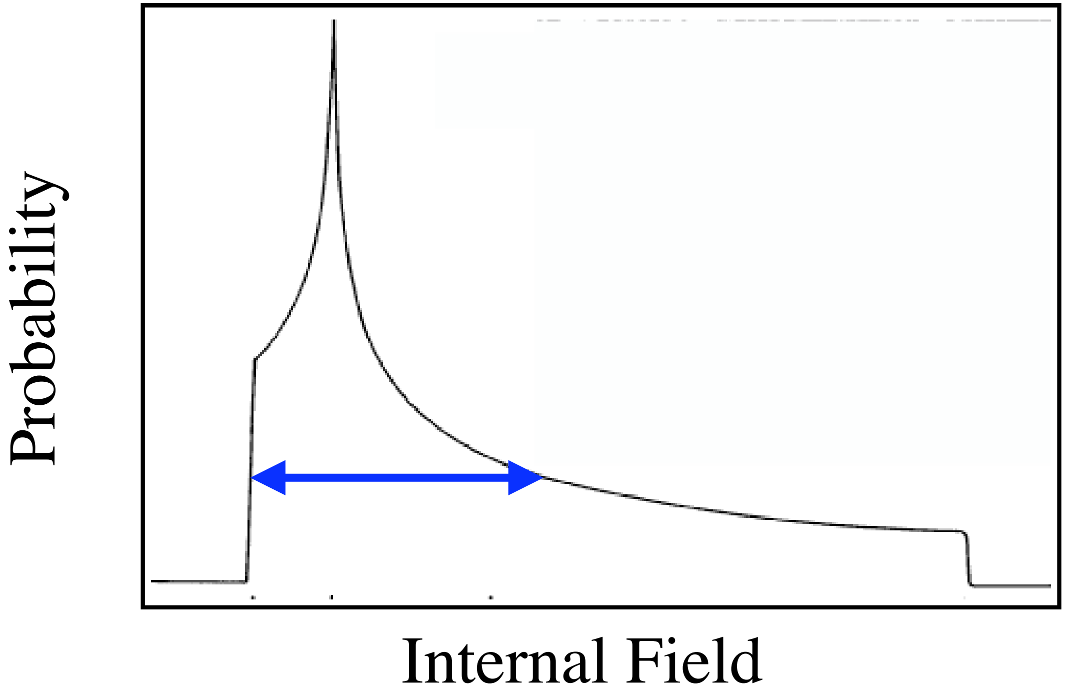


Shape of μSR signal is closely related to **spatial distribution** of vortices

('shape', 'size' and *arrangement* of vortices themselves)



If we assume that the vortex lattice is *ideal* (perfectly ordered), we can extract characteristic length scales such as the magnetic penetration depth $\lambda(T,B)$ and the superconducting coherence length $\xi(T,B)$

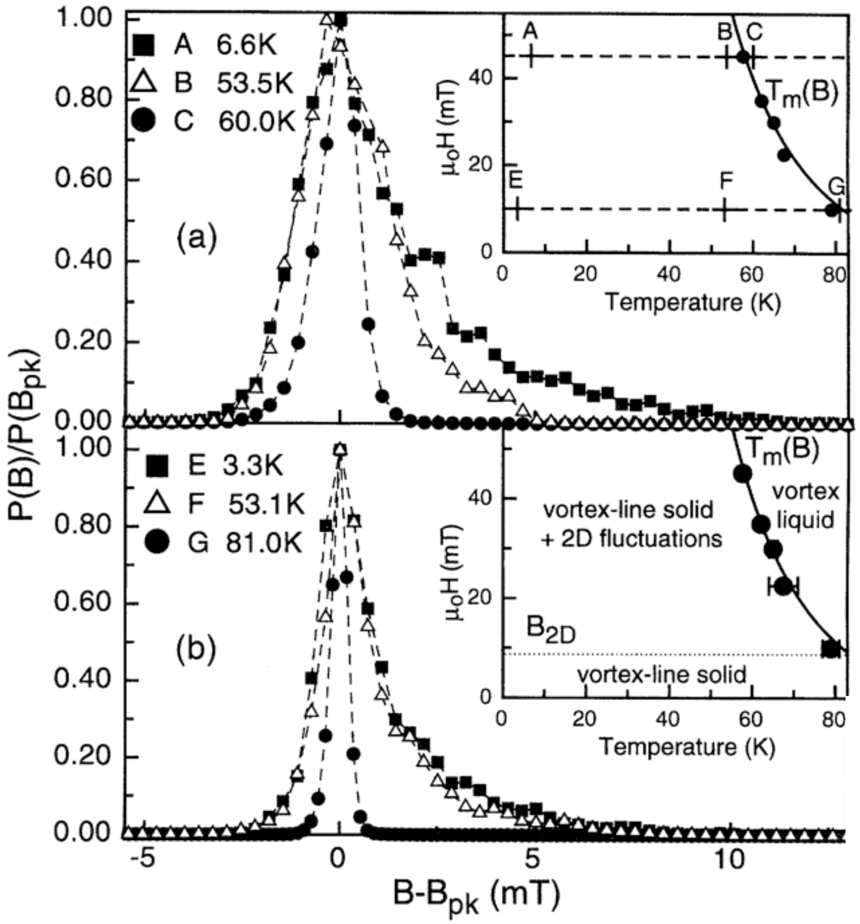


e.g. width (second moment)

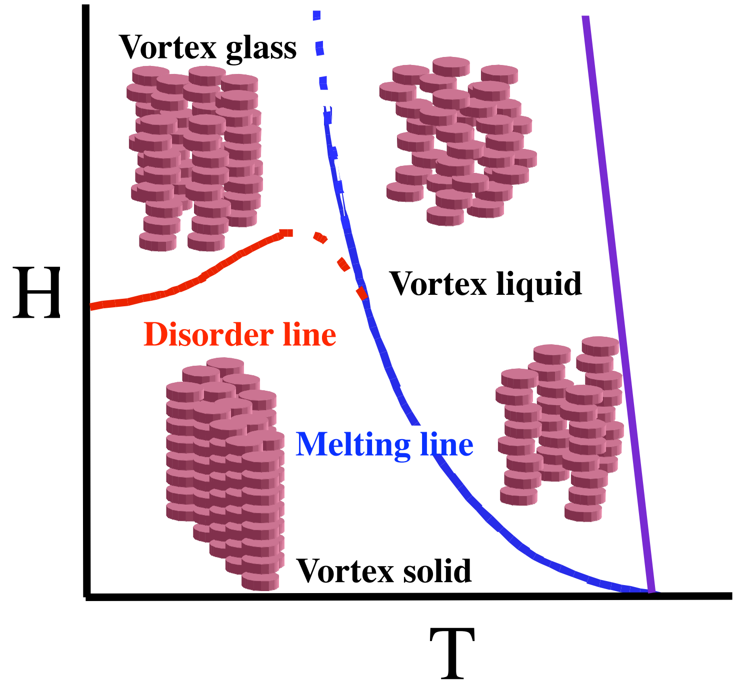
$$\langle \Delta B^2 \rangle^{1/2}(T) \propto \lambda^{-2}(T)$$

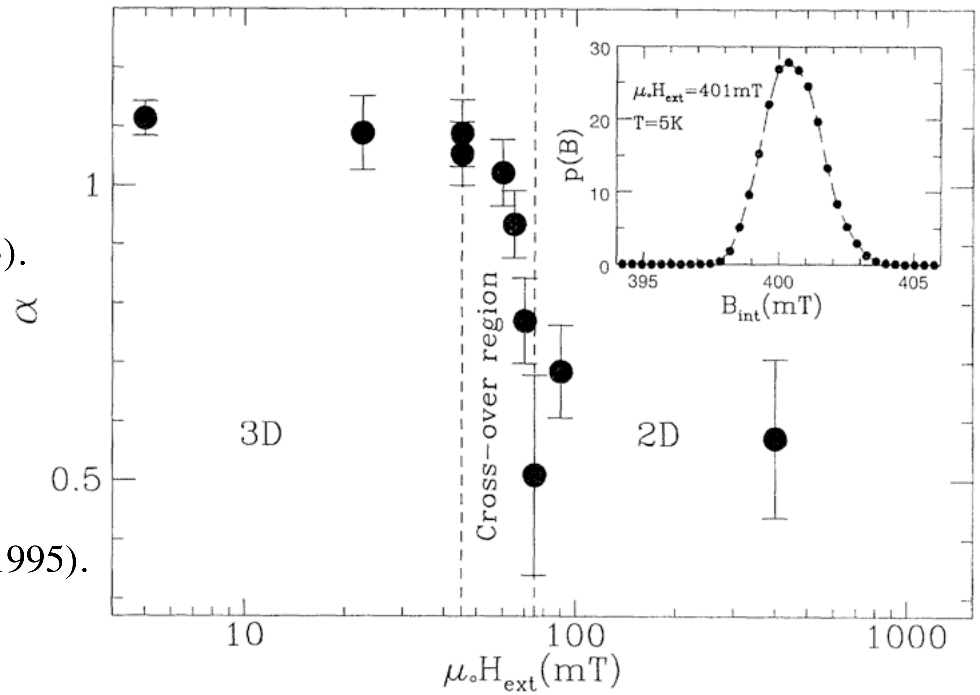
$$\lambda^{-2}(T) \propto n_s(T)/m^*$$

However, vortex lattice may be far from ideal............



S.L. Lee *et al*., Phys. Rev. Lett. **71** 3862-3865 (1993).





S.L. Lee *et al*., Phys. Rev. Lett. **75** 922 (1995).

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Vortex Correlations in Single Crystals of Anisotropic Superconductors

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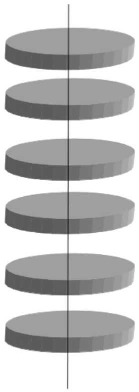
Example: $La_{1.9}Sr_{0.1}CuO_4$ (LSCO)

Increasing anisotropy



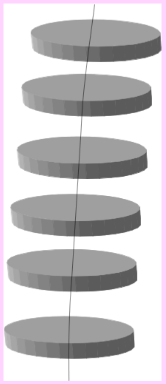
YBCO (T_c=93 K)

λ~1400 Å

γ~ 4

$\lambda_J = s\,\gamma \sim 50$Å

$\lambda_J << \lambda_{ab}$



LSCO (x=0.1) (T_c=29 K)

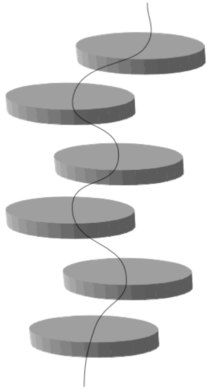
λ~3000 Å

γ>~ 40

$\lambda_J = s\,\gamma \sim 260$ Å

$\lambda_J << \lambda_{ab}$

Long λ, modest γ



BSCCO-2212 (T_c=85 K)

λ~1800 Å

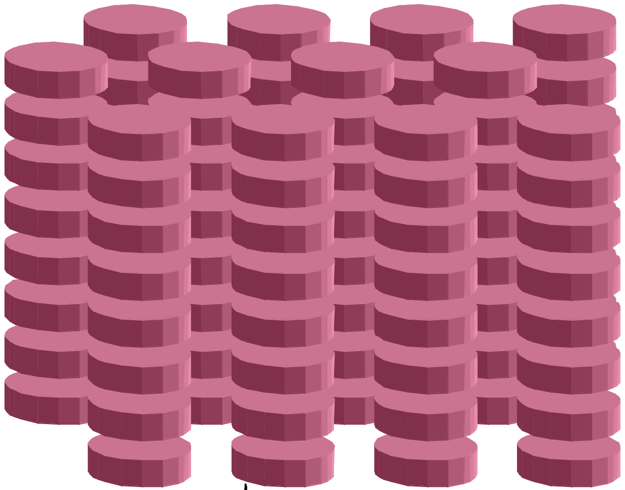
γ>~ 150

$\lambda_J = s\,\gamma \sim 2300$ Å

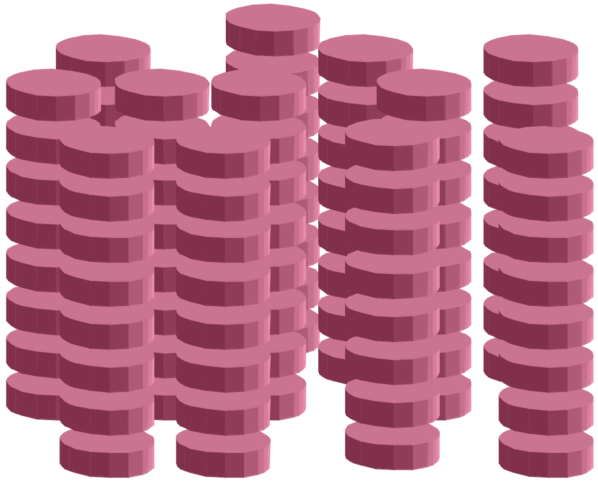
$\lambda_J \sim \lambda_{ab}$

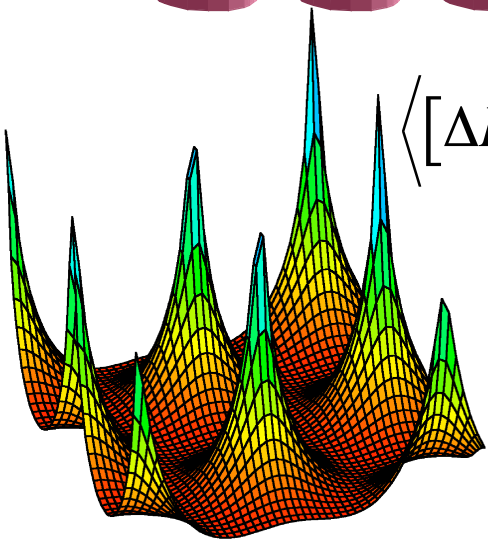
Interpretation of second moment (line width)

Disorder of **rigid** vortices always leads to **increase in width** of distribution



Disorder →

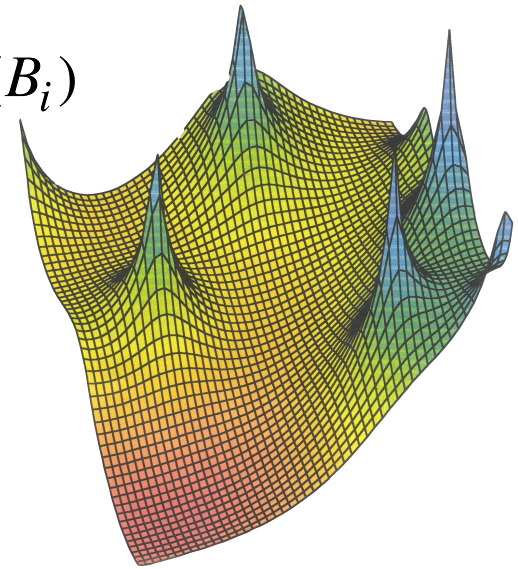




$$\left\langle [\Delta B]^2 \right\rangle = \sum p(B_i)(B_i - \langle B \rangle)^2 \Big/ \sum p(B_i)$$

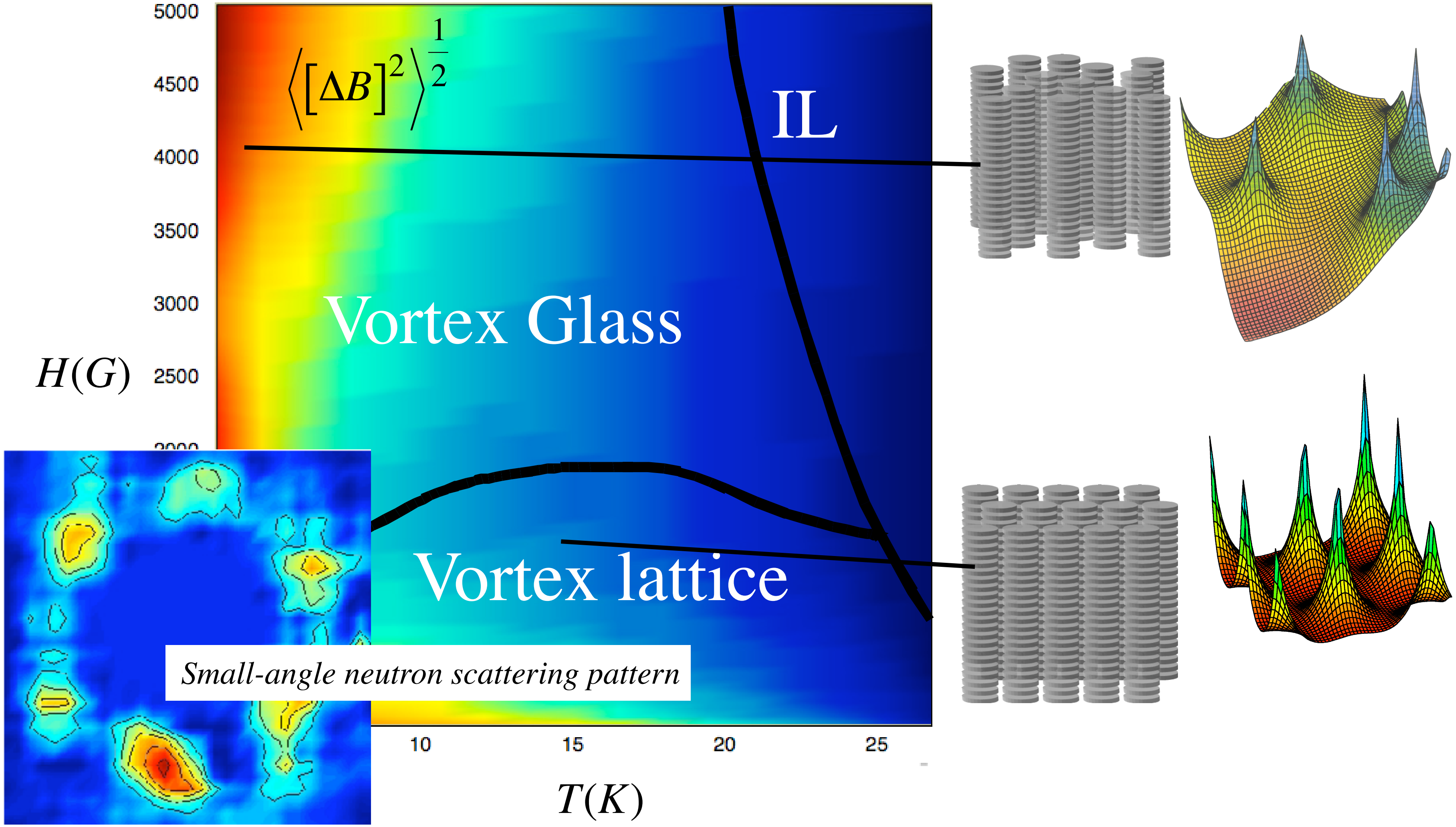
Line width →

λ>>a



LSCO: line width

$$\left\langle [\Delta B]^2 \right\rangle = \sum p(B_i)(B_i - \langle B \rangle)^2 \Big/ \sum p(B_i)$$



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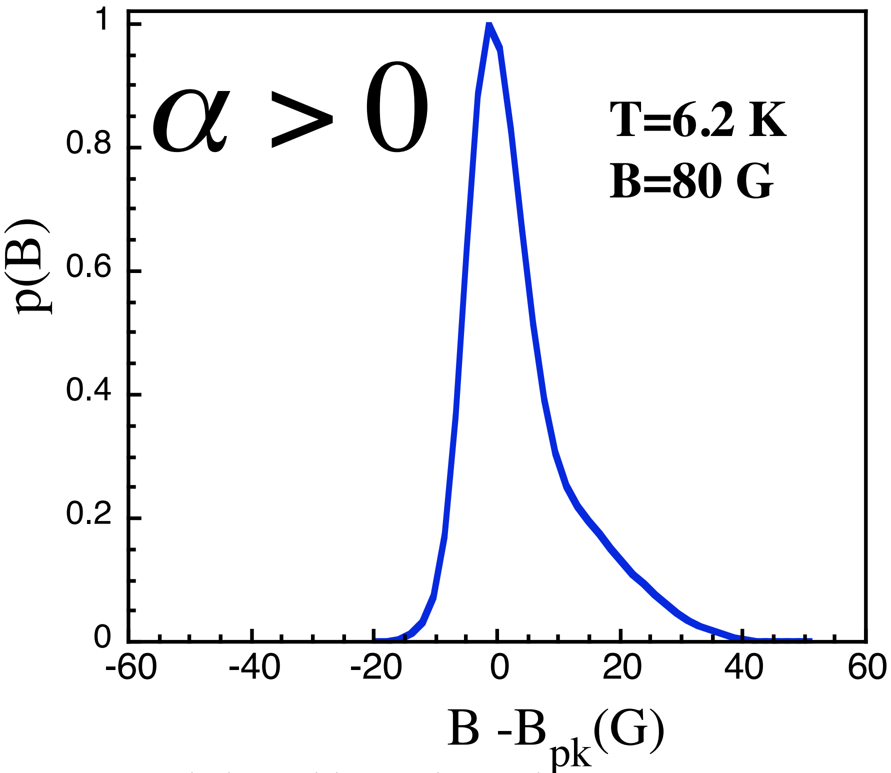
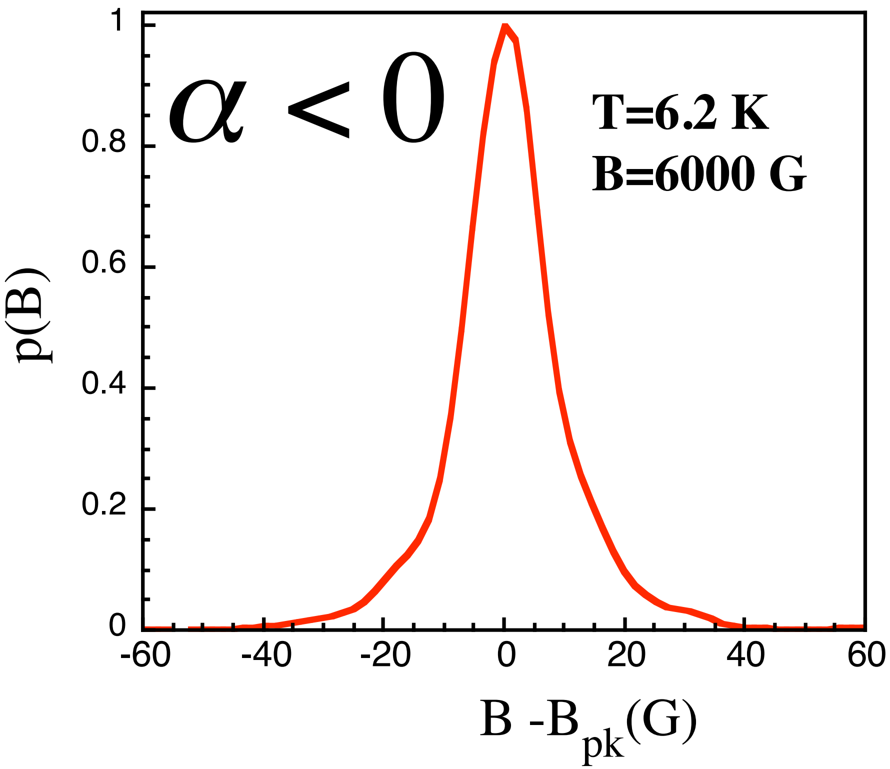
Divakar *et al.*, Phys. Rev. Lett. **92**(23) 237004 (2004)

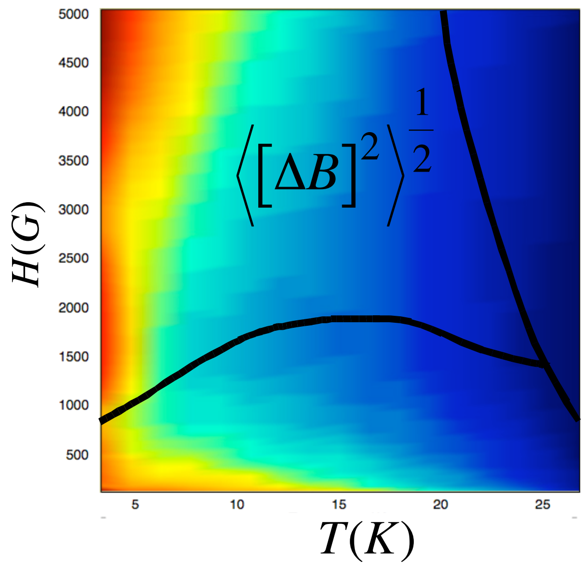
μSR 'Skewness'

$$\alpha = \left\langle [\Delta B]^3 \right\rangle^{\frac{1}{3}} \Big/ \left\langle [\Delta B]^2 \right\rangle^{\frac{1}{2}}$$

$$\left\langle [\Delta B]^3 \right\rangle = \sum p(B_i)(B_i - \langle B \rangle)^3 \Big/ \sum p(B_i)$$







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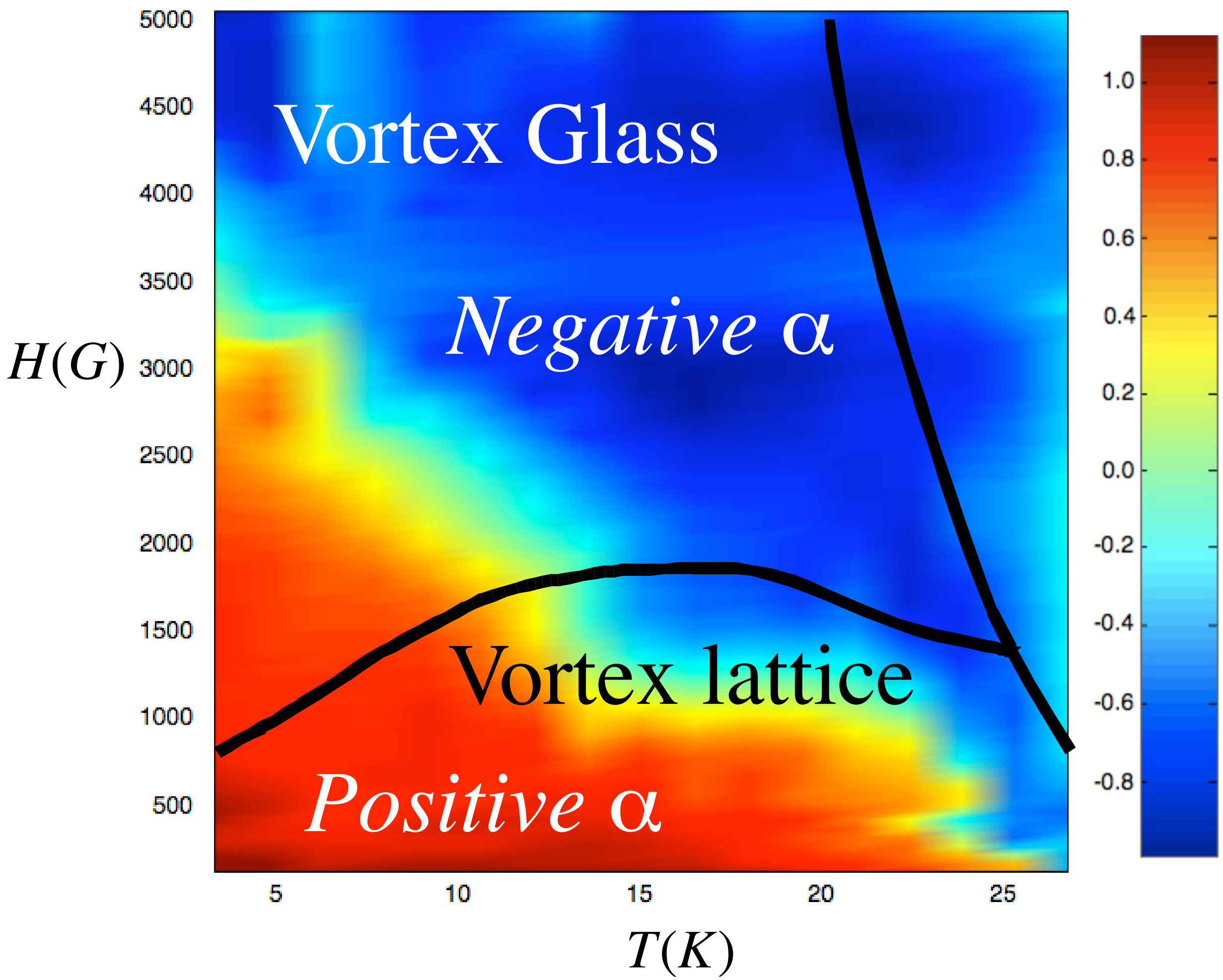
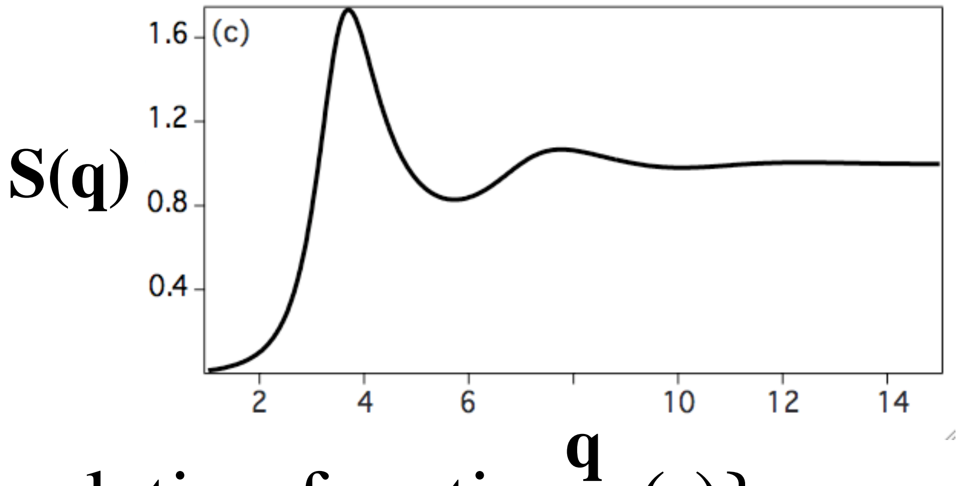


Conventional 'two body' structure factor S(q)

Second Moment (width)

$$\left\langle [\Delta B]^2 \right\rangle \propto \int d^2 q S(\mathbf{q}) b^2(\mathbf{q})$$



S(q)=F.T{pair density correlation function g(r)}

$b(q)$=F.T{Flux line local field **h**(**r**)} $=1/(1+q^2\lambda^2)$

Third Moment (skewness)

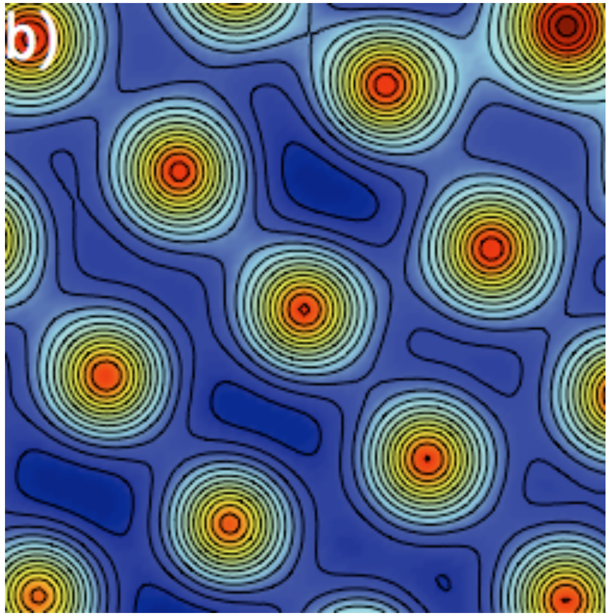
$$\left\langle [\Delta B]^3 \right\rangle \propto \iint d\mathbf{q}_1 d\mathbf{q}_2 S^{(3)}(\mathbf{q}_1,\mathbf{q}_2) b(\mathbf{q}_1) b(\mathbf{q}_2) b(-\mathbf{q}_1 - \mathbf{q}_2)$$

$$S^{(3)}(\mathbf{q}_1,\mathbf{q}_2) = \frac{1}{N}\left\langle \delta\rho(\mathbf{q}_1)\delta\rho(\mathbf{q}_2)\delta\rho(-\mathbf{q}_1 - \mathbf{q}_2)\right\rangle$$

Triplet Structure Factor

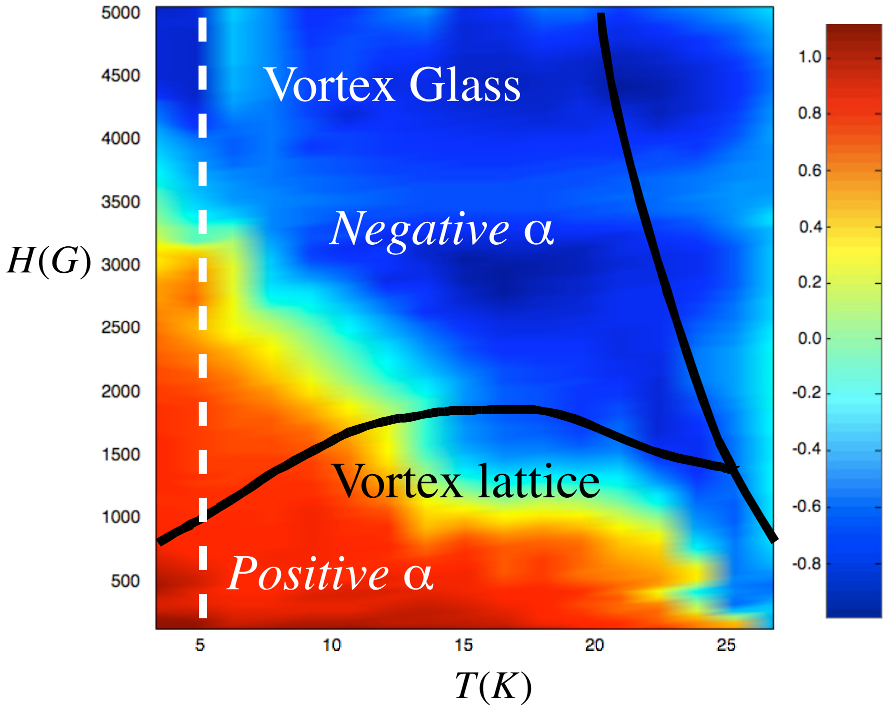
Triplet Structure Factor

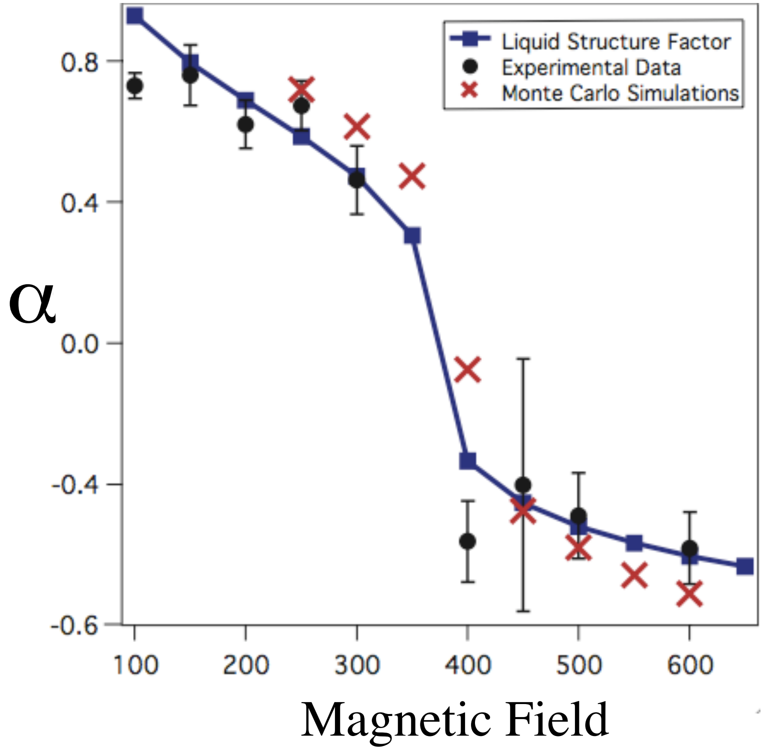
$$S^{(3)}(\mathbf{q}_1,\mathbf{q}_2) = \frac{1}{N}\left\langle \delta\rho(\mathbf{q}_1)\delta\rho(\mathbf{q}_2)\delta\rho(-\mathbf{q}_1-\mathbf{q}_2)\right\rangle$$



-information on *orientational* correlations

$$\alpha = \left\langle [\Delta B]^2 \right\rangle^{\frac{1}{3}} \Big/ \left\langle [\Delta B]^2 \right\rangle^{\frac{1}{2}}$$





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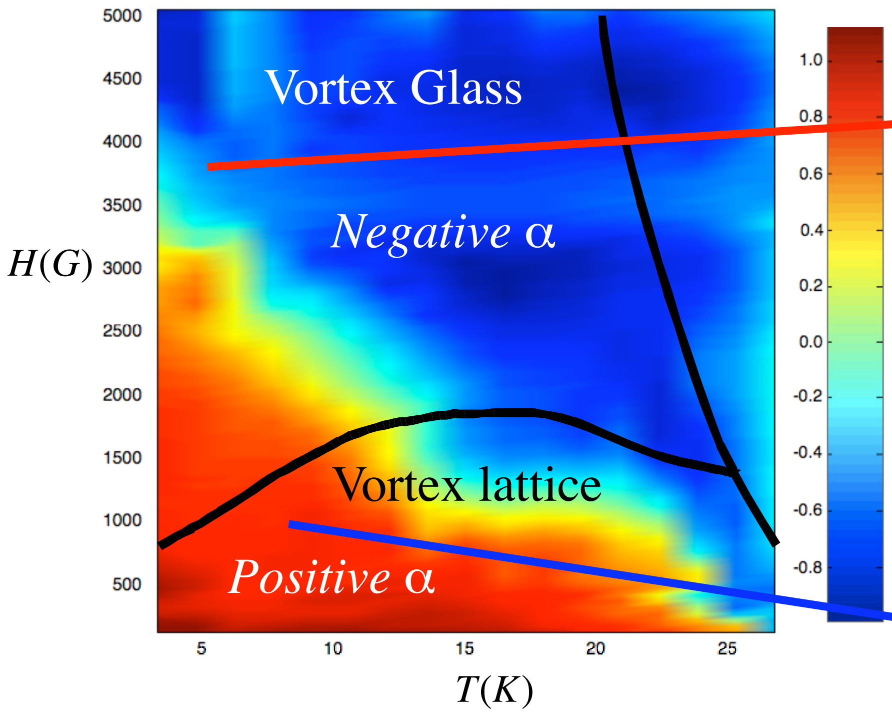
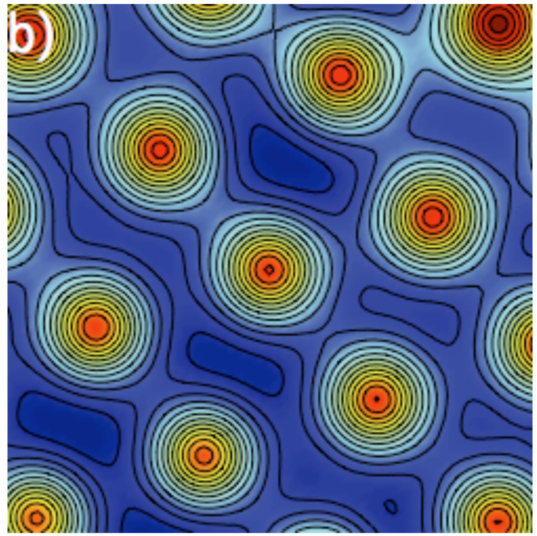
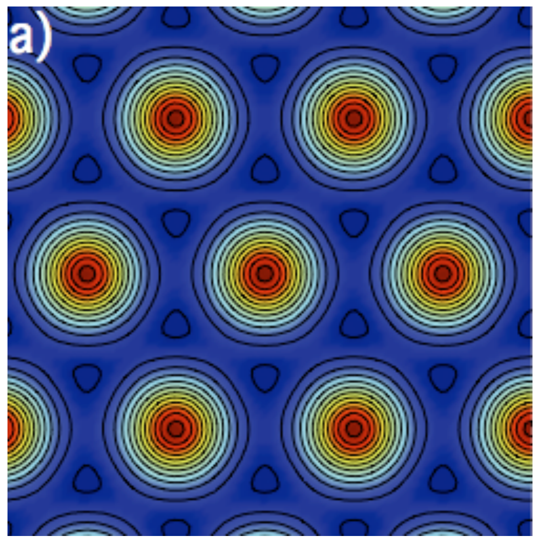
Menon *et al.*, Phys. Rev. Lett. **97** 177004 (2006)

$$\alpha = \left\langle [\Delta B]^2 \right\rangle^{\frac{1}{3}} \Big/ \left\langle [\Delta B]^2 \right\rangle^{\frac{1}{2}}$$

High field: glassy order including *non-trivial triangular coordination* extending several lattice spacings



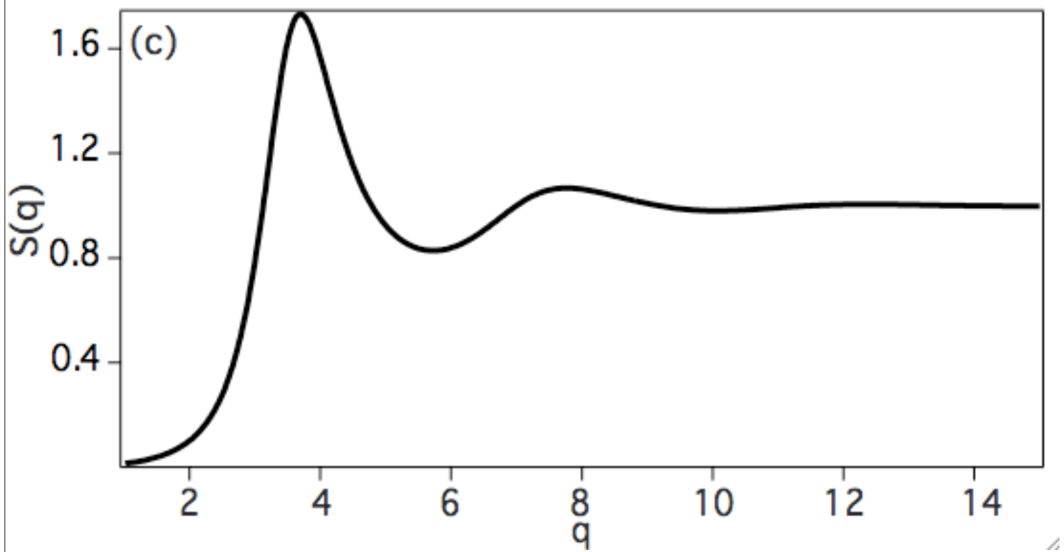


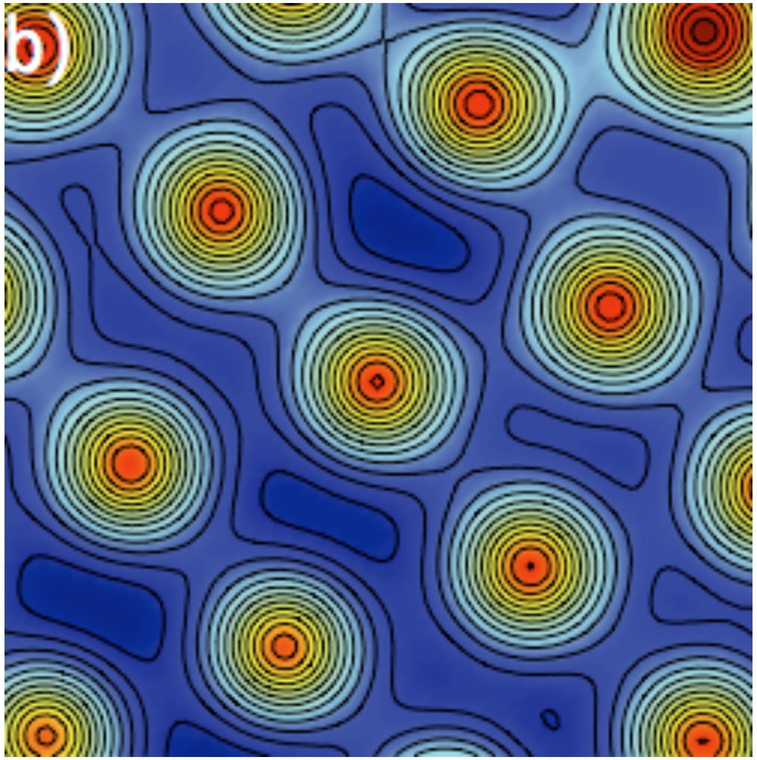


Low field: 'trivial' triangular coordination
Vortex lattice/Bragg glass

Typically **alpha is positive** (α>0) for either highly-ordered or highly-disordered systems (although disorder reduces value of α)

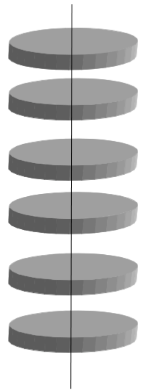
Theoretically, **negative alpha (α<0)** occurs only for a very *particular combination* of **2-body (S(q))** and **3-body ($S^{(3)}$) correlations**





Example: $Bi_{2.15}Sr_{1.85}CaCu_2O_{8+\delta}$ (BSCCO-2212)

Increasing anisotropy →



YBCO (T_c=93 K)

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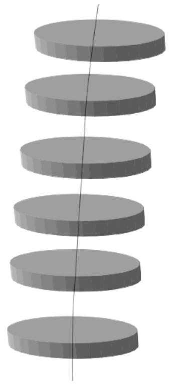

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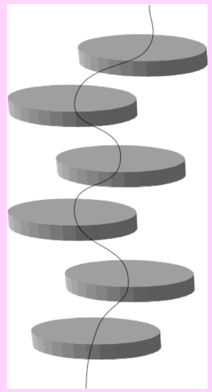
Long λ, modest γ



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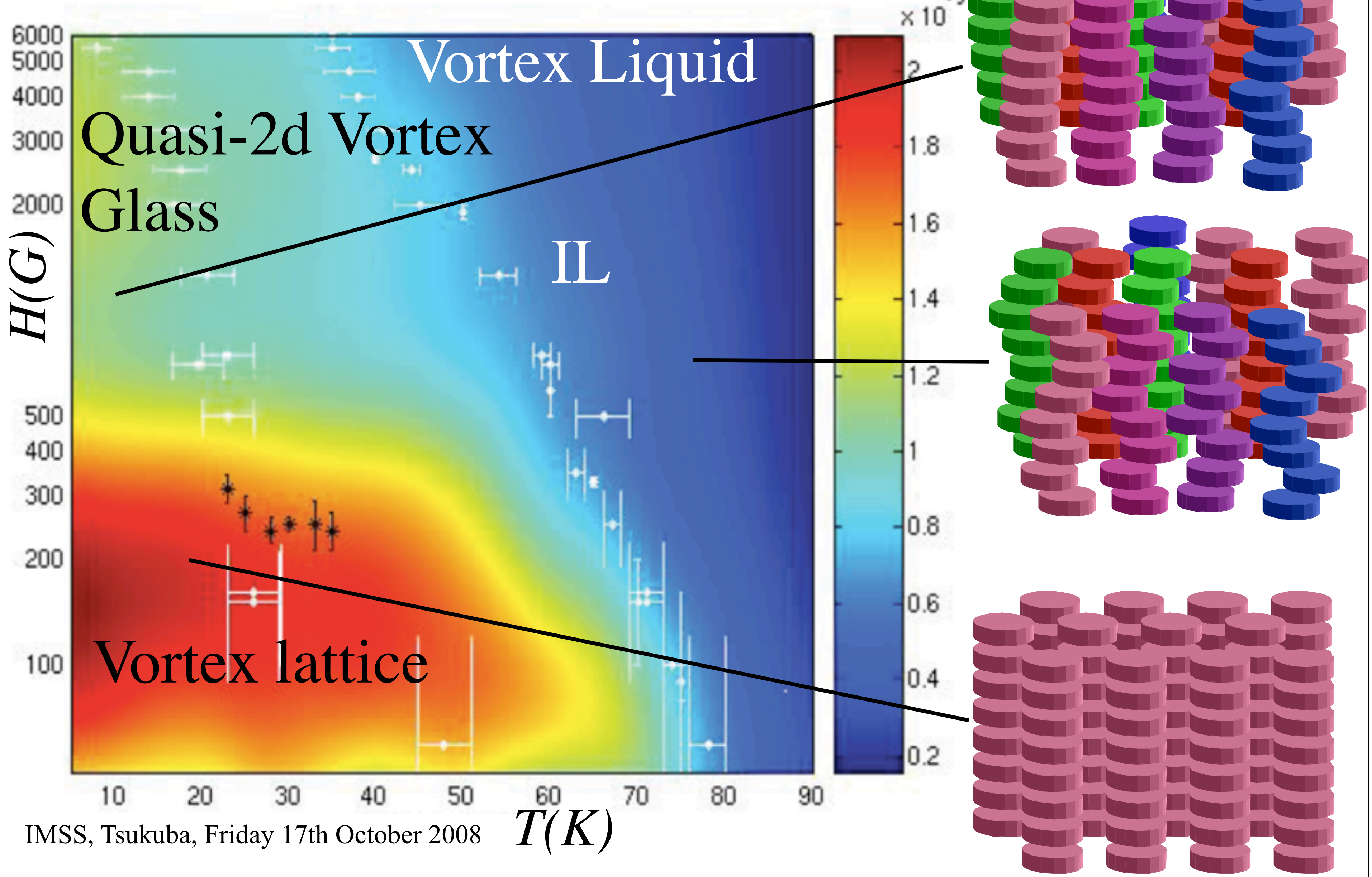
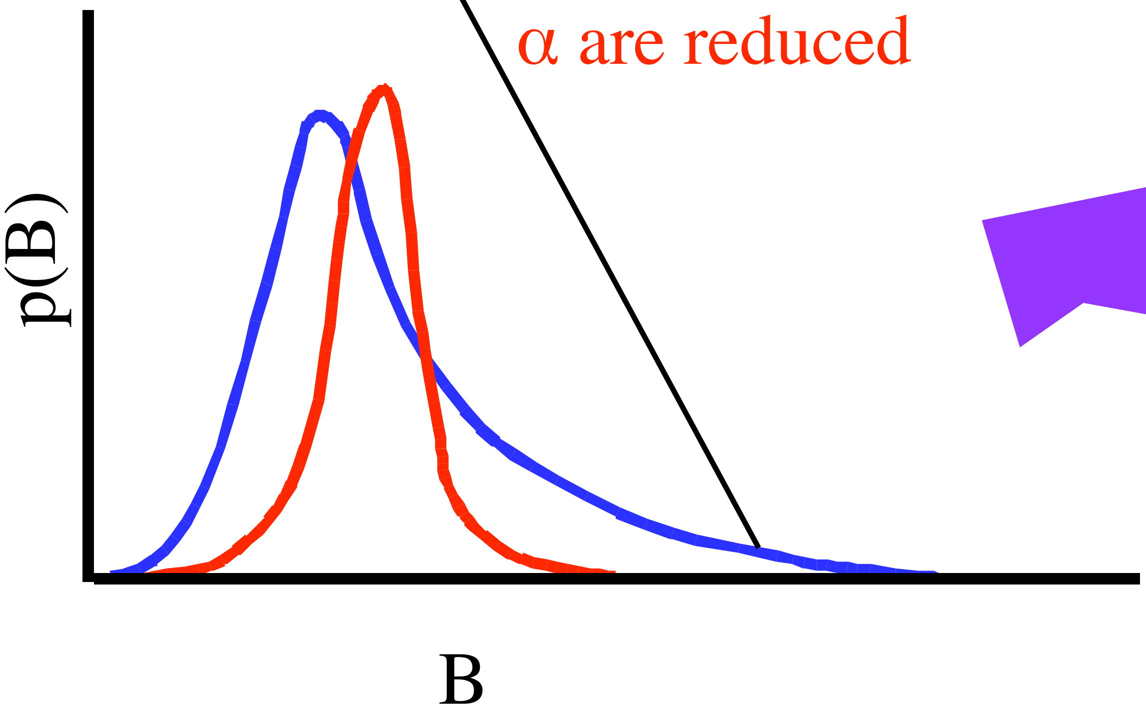
$$\left\langle [\Delta B]^2 \right\rangle^{\frac{1}{2}}$$

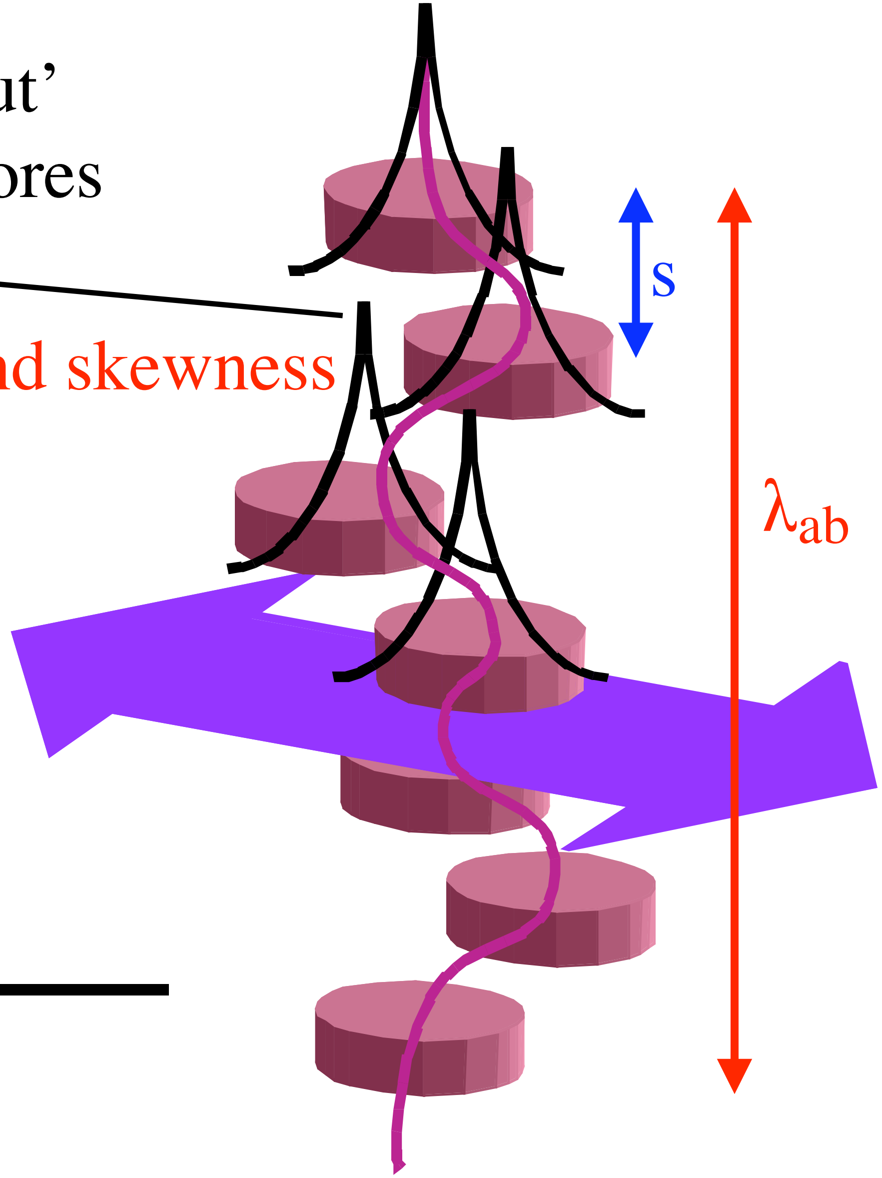


Field perpendicular to the planes in only screened on a length scale ~λ_{ab} >> s (plane spacing)

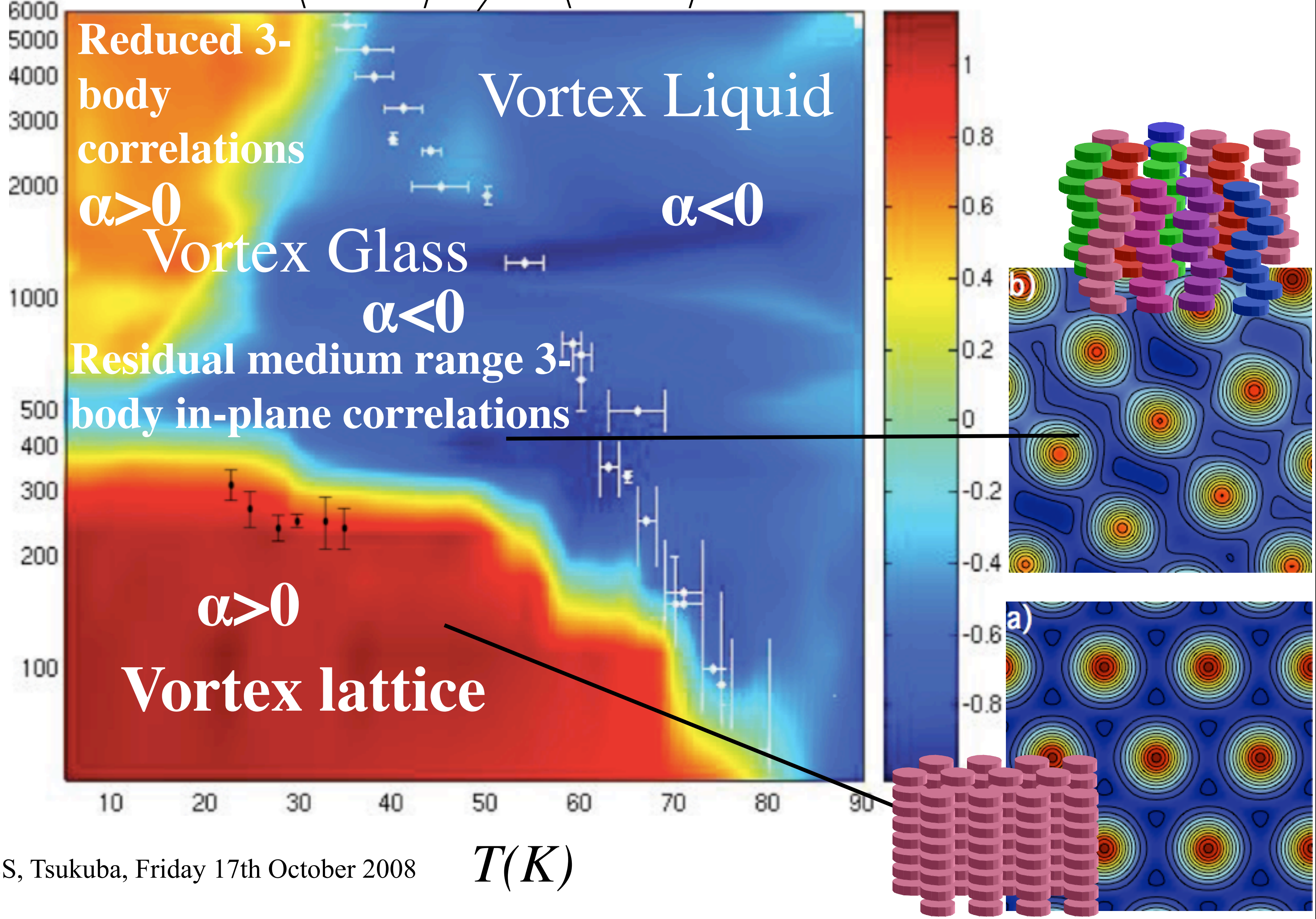
Longitudinal fluctuations 'wash out' the high fields originating in the cores

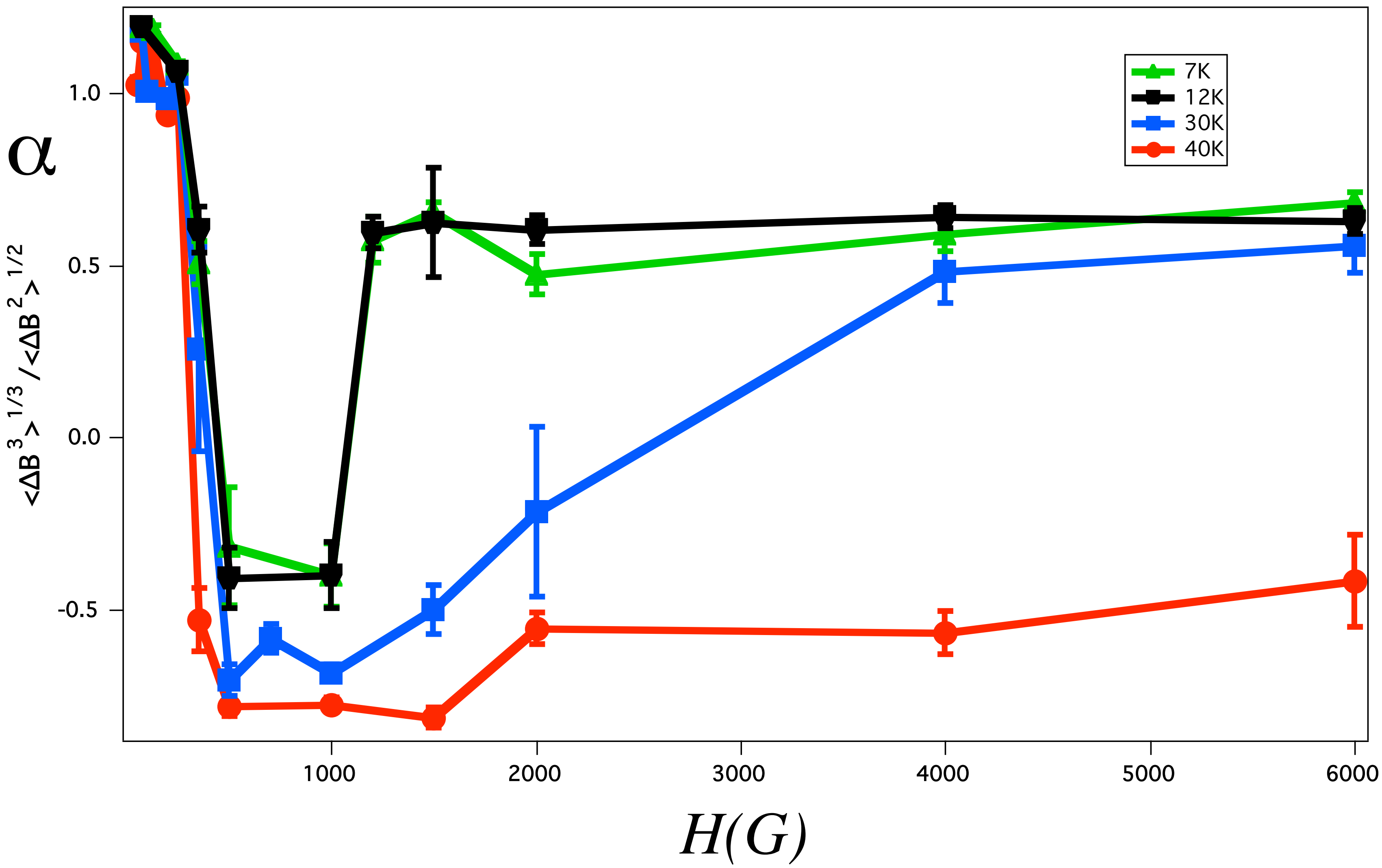
Both width σ and skewness α are reduced





$$\alpha = \left\langle [\Delta B]^2 \right\rangle^{\frac{1}{3}} \Big/ \left\langle [\Delta B]^2 \right\rangle^{\frac{1}{2}}$$





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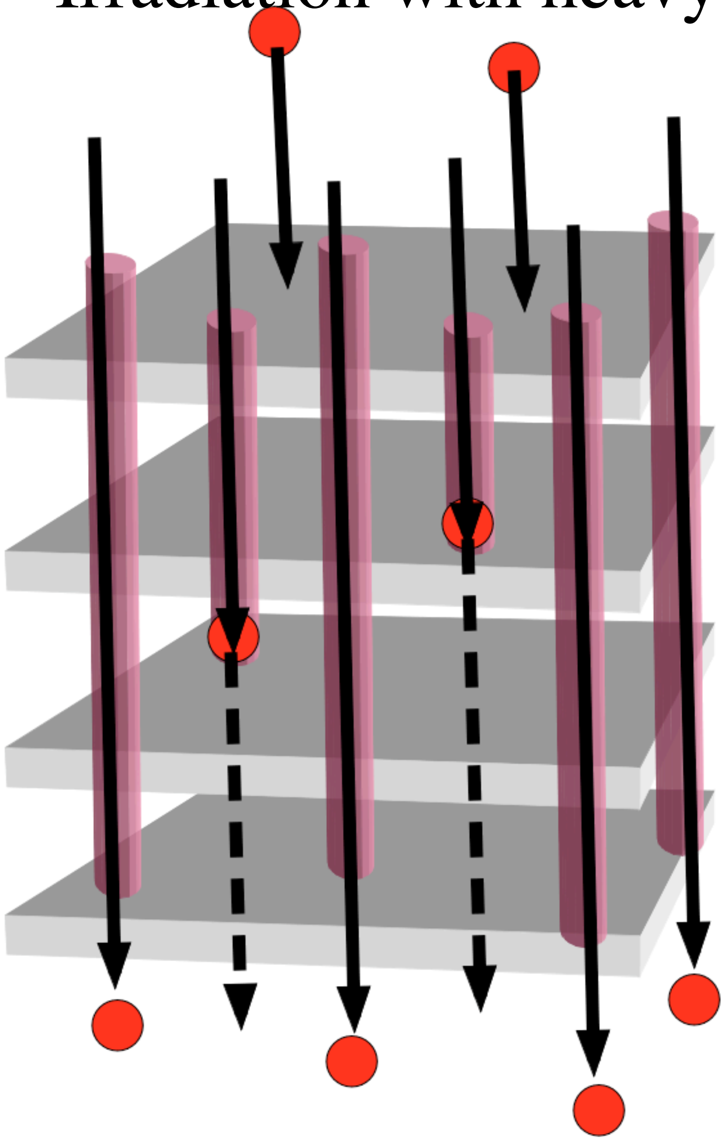
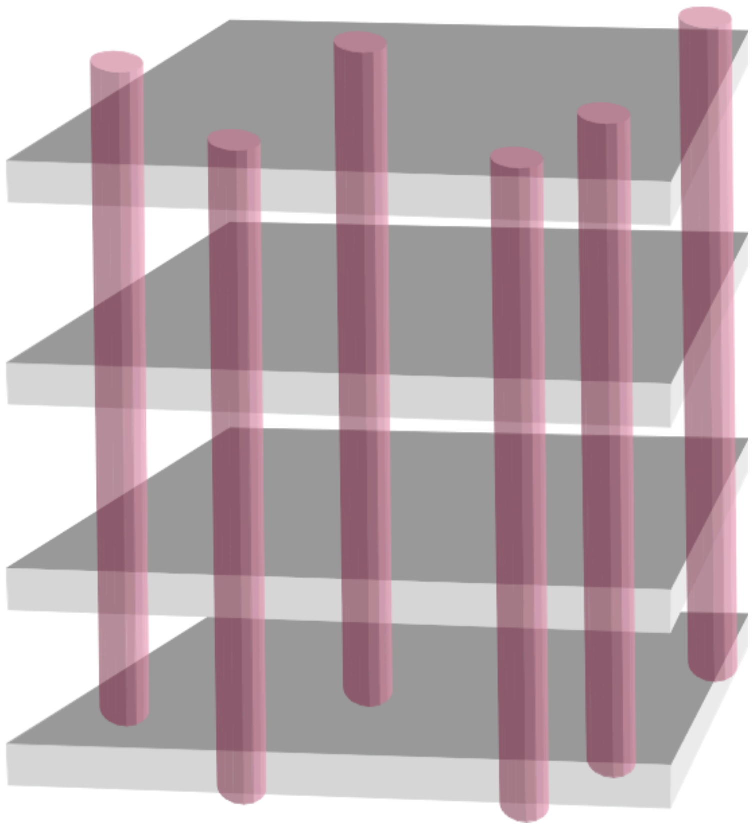
BSCCO with Columnar Defects $B_\phi = 2000$ G

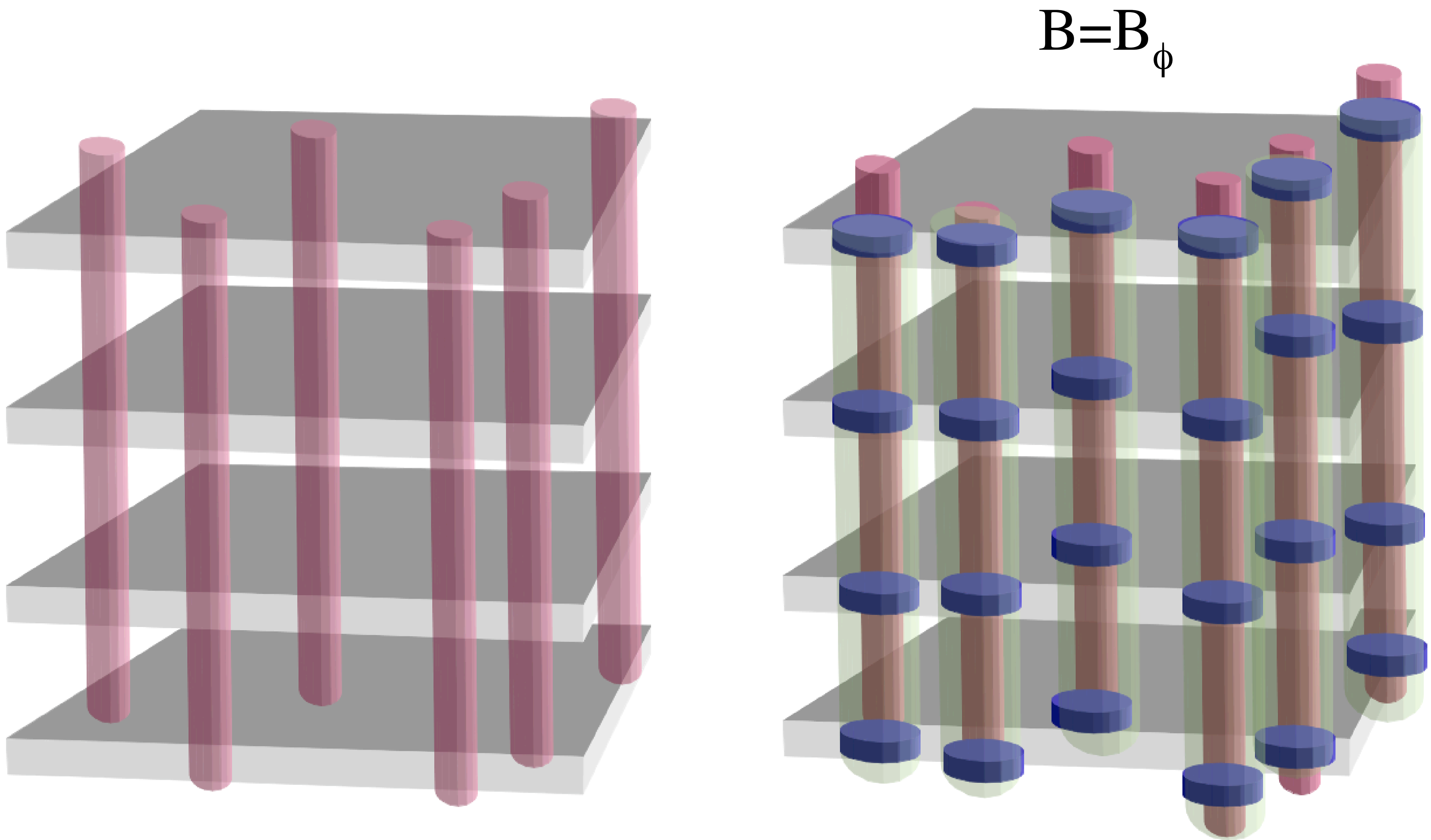
Irradiation with heavy ions (17.7 GeV U ions)



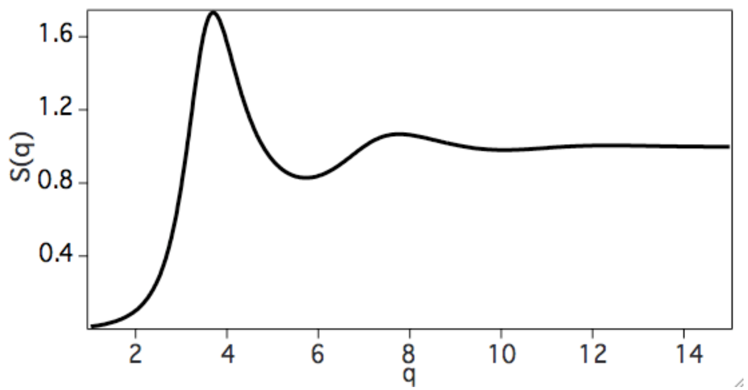
Columnar Defects

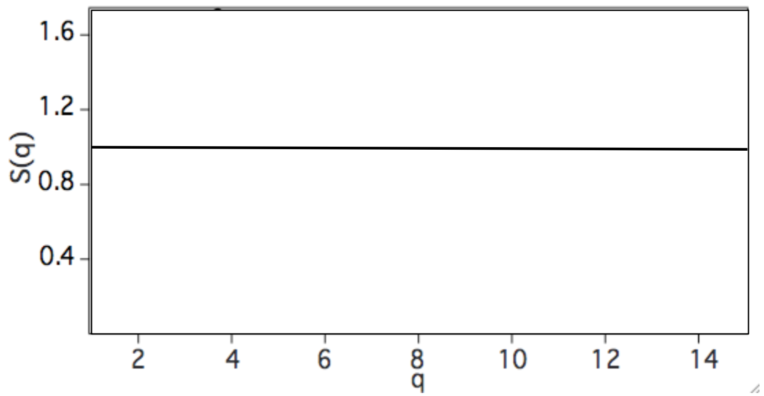


The **Matching Field** B_ϕ : Applied for for which the areal density of vortex lines = density of 'columnar defects'



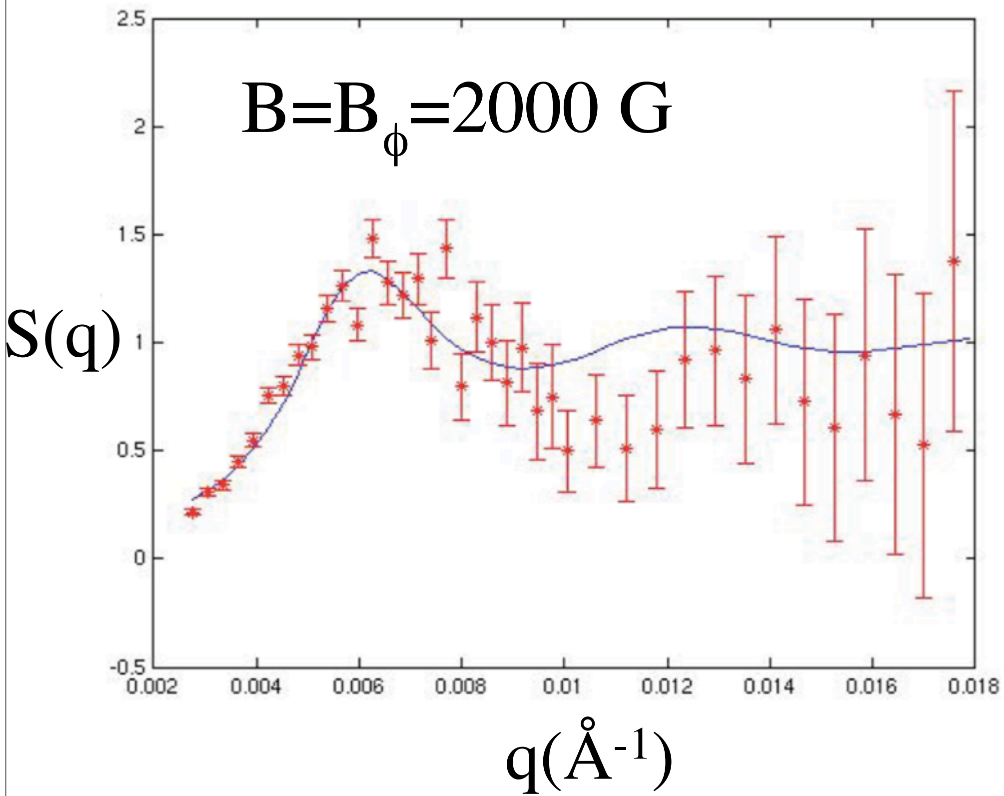
If positions of vortices were truly random at B= B_ϕ, μSR line width would *extremely large*, and S(q) would be trivial.

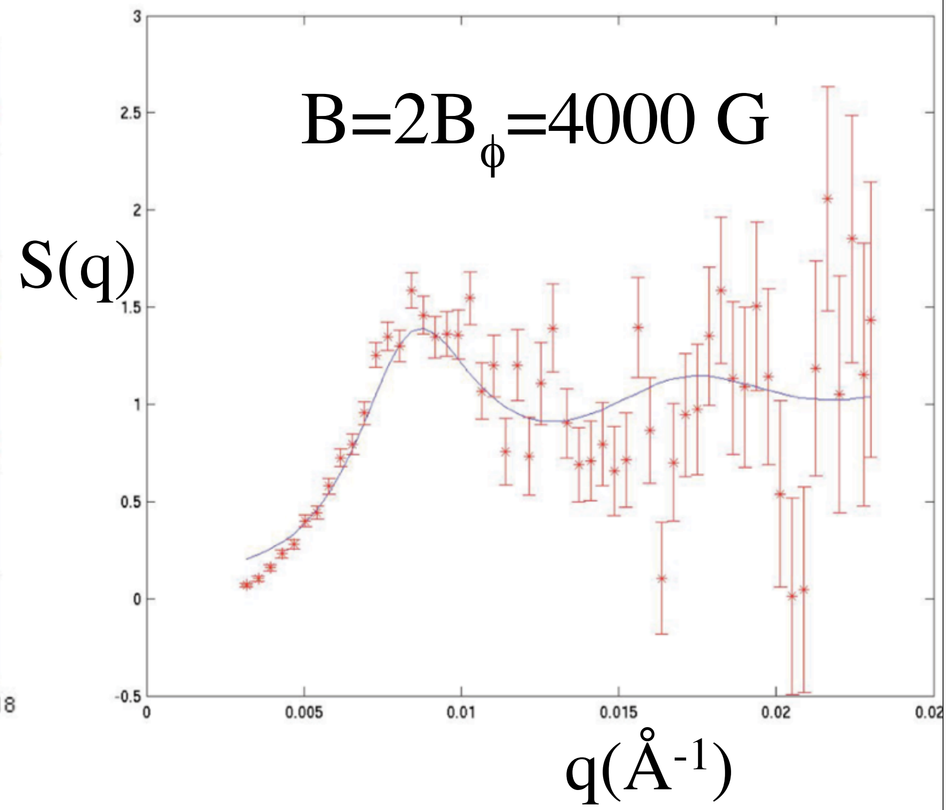




In reality there are always some 2-body correlations even at B_ϕ

see e.g. S.L. Lee *et al.*, a Phys. Rev. Lett. **81** 5209 (1998).



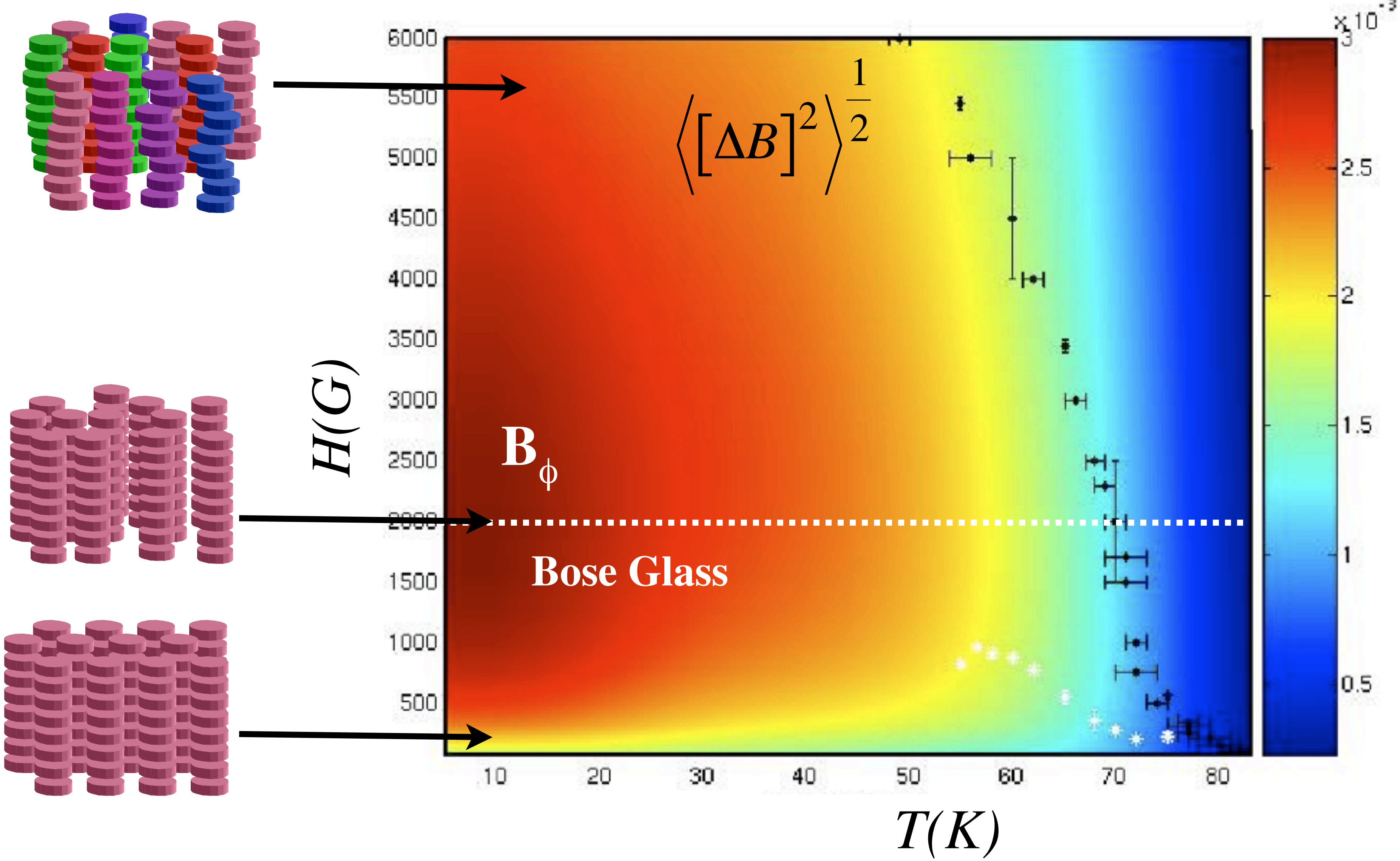


Structure Factors

-Measured by Small-angle neutron scattering (SANS)

$$\langle [\Delta B]^2 \rangle \propto \int d^2q S(\mathbf{q}) b^2(\mathbf{q})$$

Related to 2-body correlations



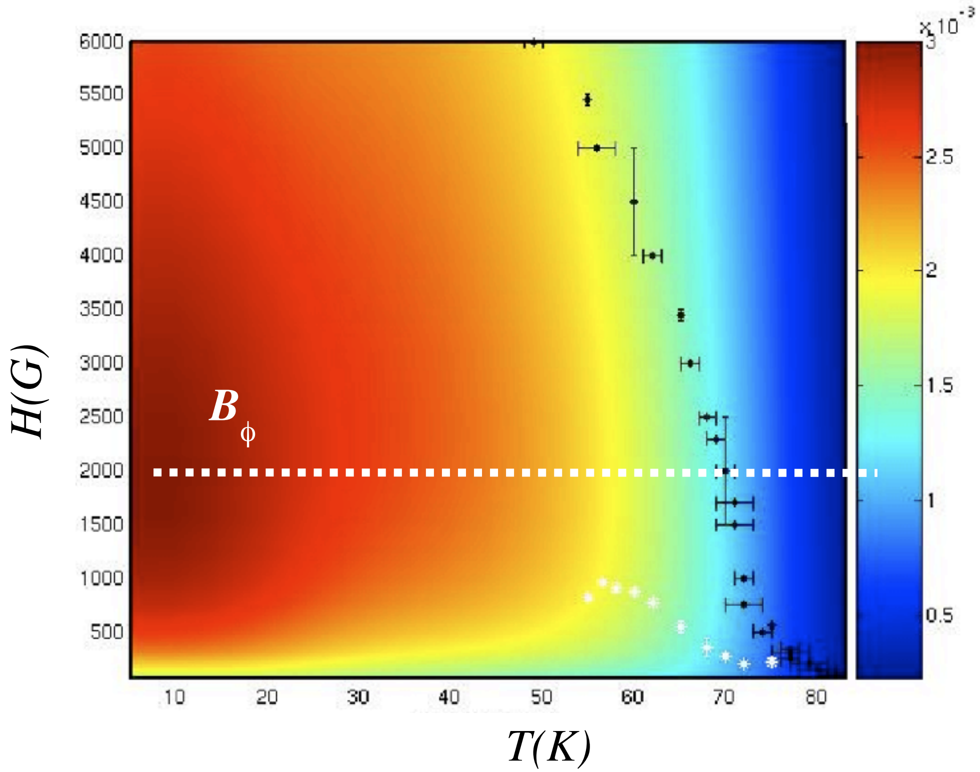
At low temperature optimal disruption to in-plane order at $B=B_\phi$

Width is always large in irradiated sample:

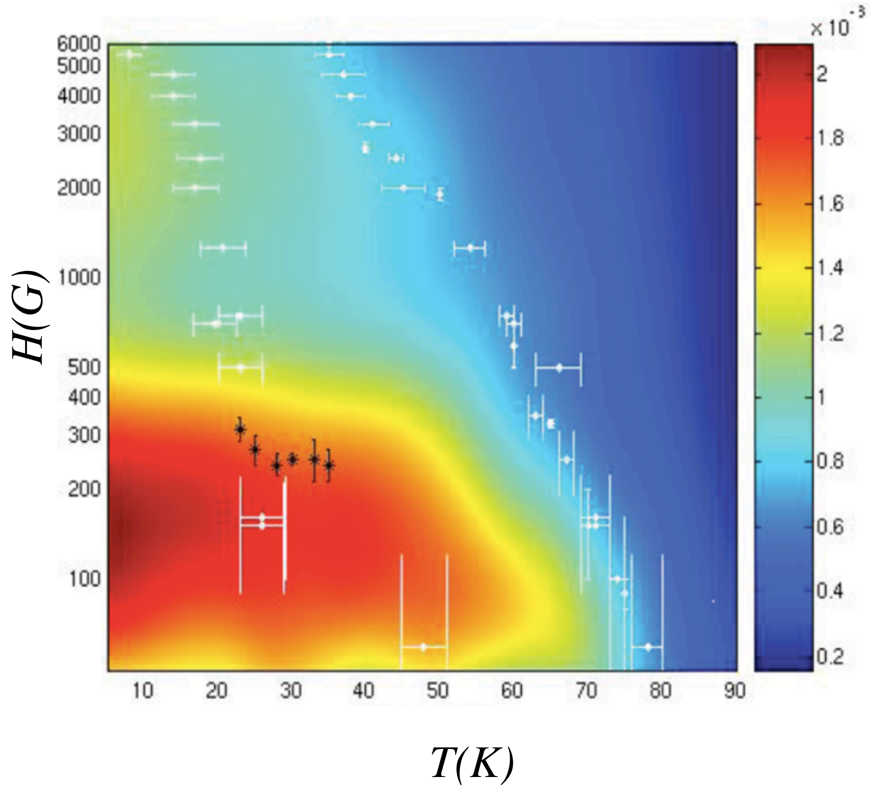
Defects keep the vortices 'rigid'

$$\left\langle [\Delta B]^2 \right\rangle^{\frac{1}{2}}$$

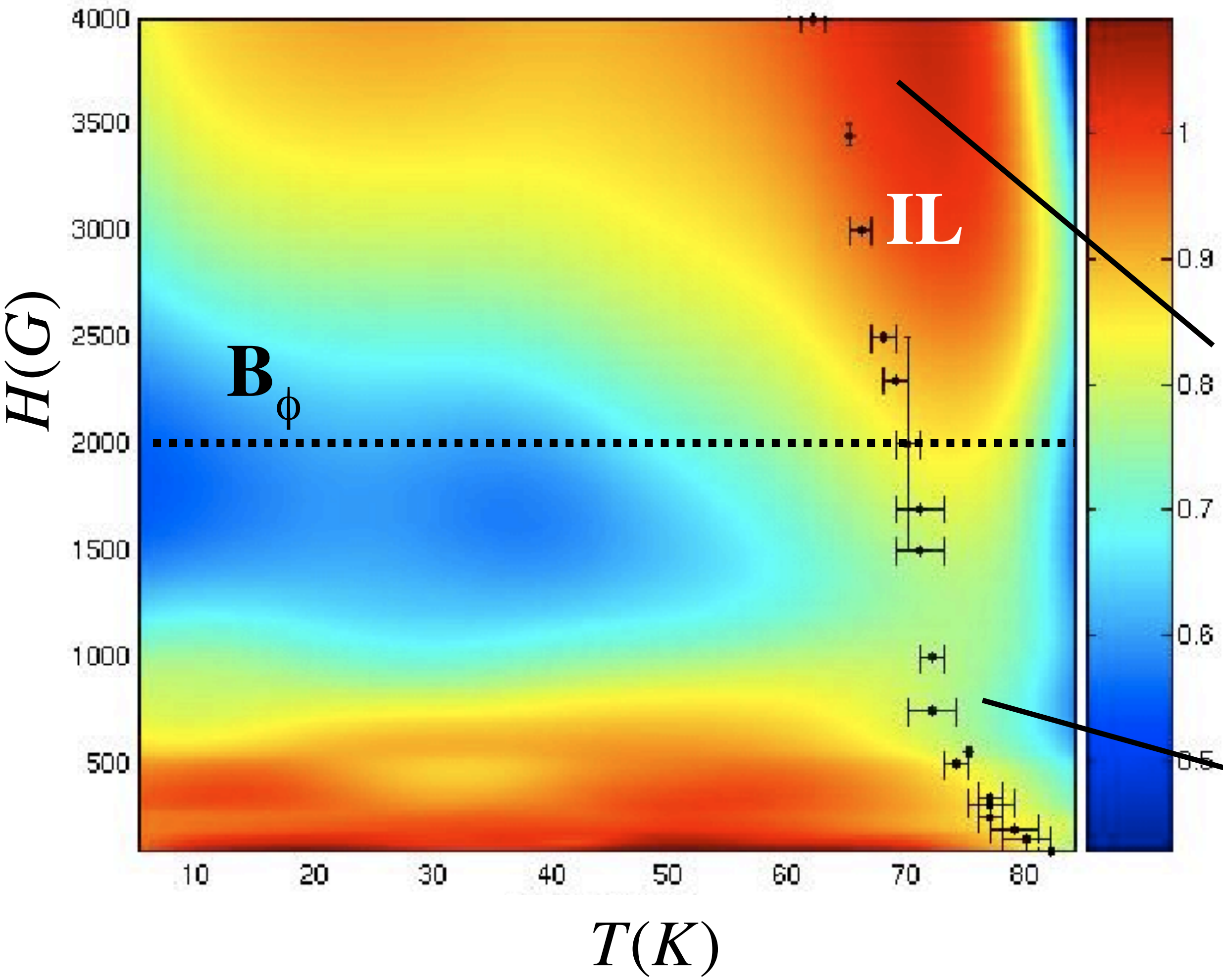
Irradiated



Pristine (unirradiated)



$$\alpha = \left\langle [\Delta B]^2 \right\rangle^{\frac{1}{3}} \Big/ \left\langle [\Delta B]^2 \right\rangle^{\frac{1}{2}}$$



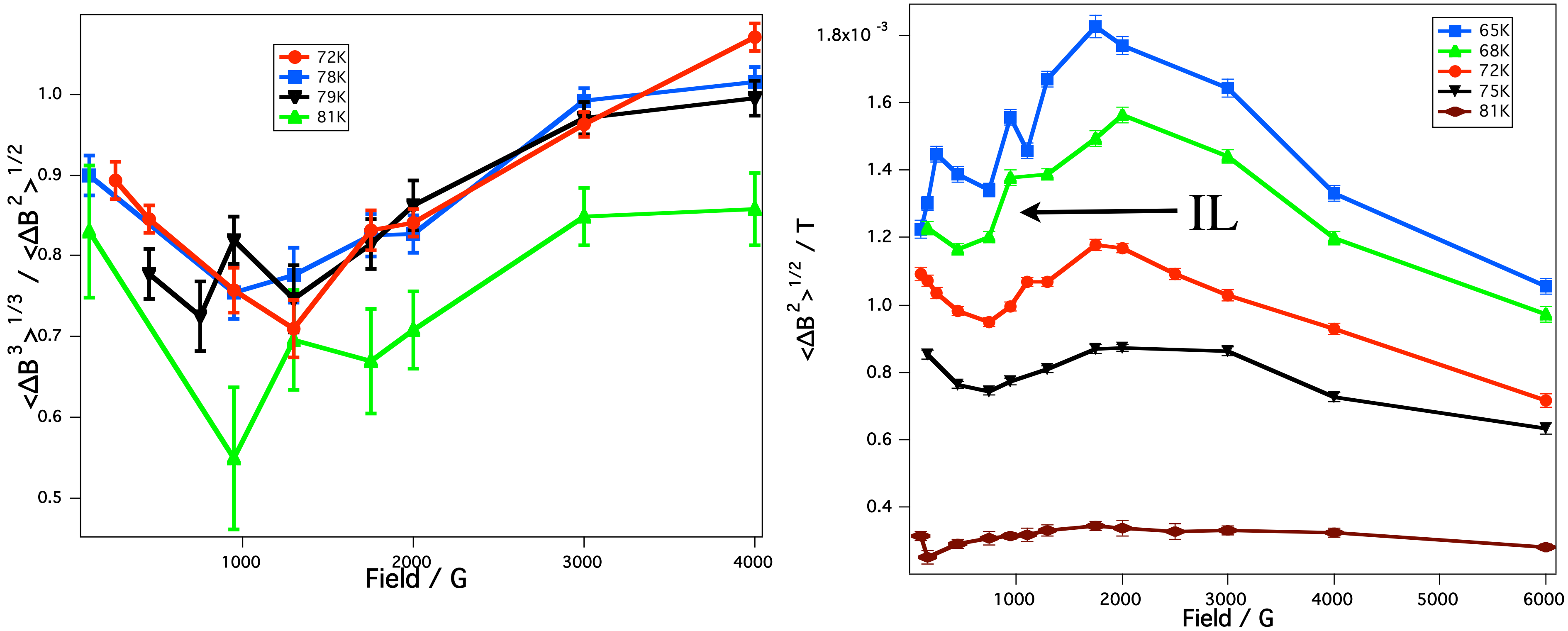
1. α>0 everywhere

2. At *low T*, α has minimum at B_ϕ: implies 3-body correlations also strongly suppressed

3. At *high T* and B, 3-body correlations seem well-developed above irreversibility line: ***new phase***??

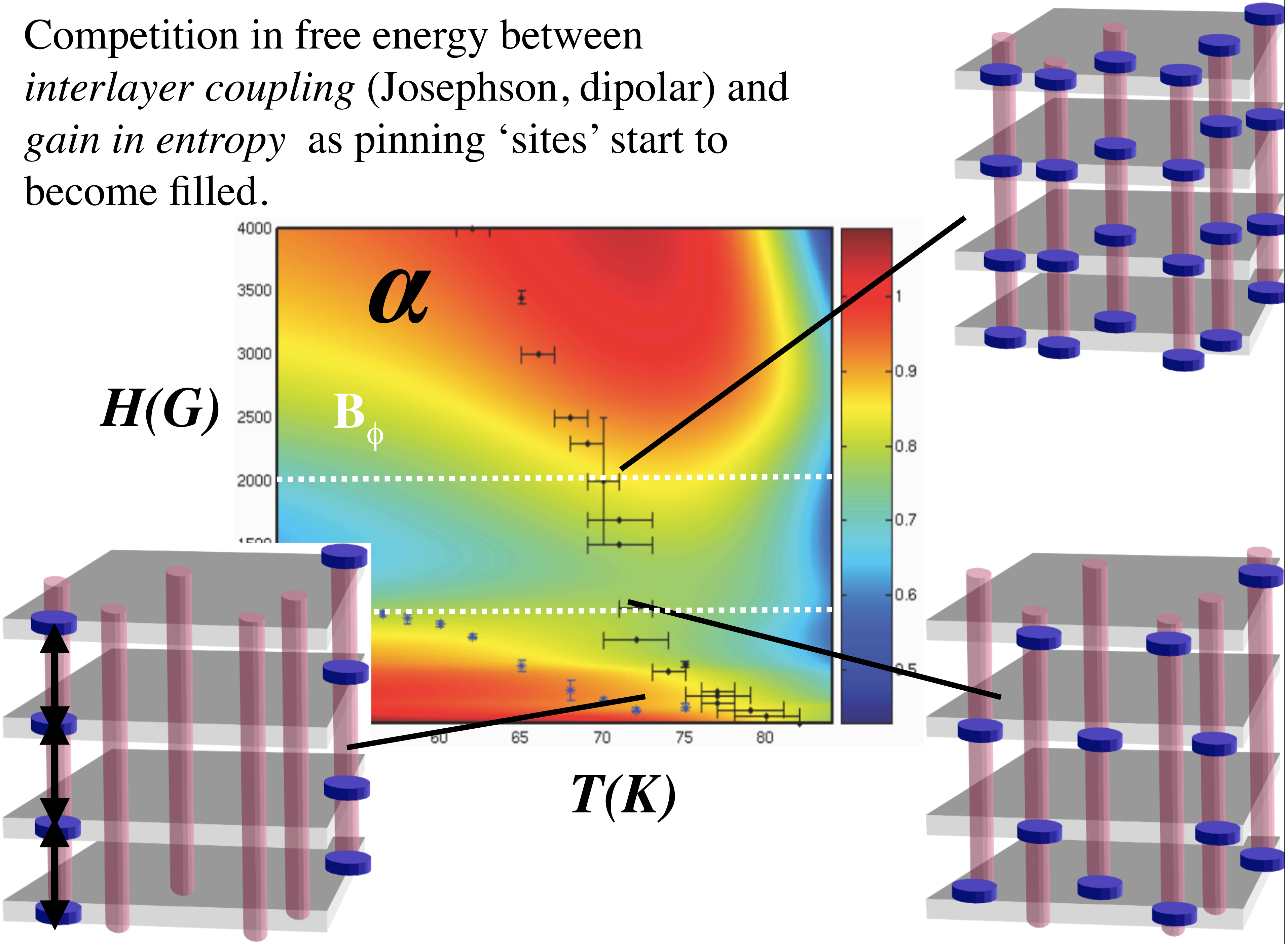
4. At *high T* and low B, minimum in α and width at B~ $B_\phi/3$ - $B_\phi/2$: entropically driven disorder?

$$\alpha = \left\langle [\Delta B]^2 \right\rangle^{\frac{1}{3}} \Big/ \left\langle [\Delta B]^2 \right\rangle^{\frac{1}{2}} \qquad \left\langle [\Delta B]^2 \right\rangle^{\frac{1}{2}}$$



Mimima develop at temperatures *above the irreversbility line* (IL) where the vortices become much *more mobile*

Competition in free energy between *interlayer coupling* (Josephson, dipolar) and *gain in entropy* as pinning 'sites' start to become filled.



Summary

Bulk μSR is useful for probing the vortex state in single crystals of superconducting materials.

μSR may even yield information on classical three body correlations in disordered vortex systems, which are hard to measure by other methods.

Characteristic length scales (ξ, λ) can be extract *if* one fully undertands the vortex state and how to model it. The *state of order* of the vortex system has a profound influence on the *moments* of the μSR line shapes and quantitative interpretation of these moments must be carefully considered.