A Finite Size Kosterlitz-Thouless Transition in Fe/W(001) Ultrathin Films

J. Atchison, A. Bhullar, B. Norman, and D. Venus.

Phys. Rev. B 99, 125425.

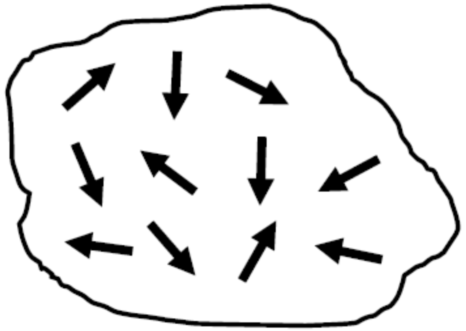
McMaster University

Presentation Outline

1. Kosterlitz Thouless Transition in a Finite 2D XY System
2. Growth and Characterization of Fe/W(001) Films
3. Analysis of Magnetic Susceptibility Signals from Independently Grown Films

Magnetism in Ultrathin Films

- Ultrathin films (a few monolayers thick) are effectively two dimensional
- For 2D systems where anisotropy traps magnetic moments in-plane, the spins can be modeled after the **"2D XY" model**
- Spin configuration energy given by $H = -J\sum_{\langle i,j\rangle}\vec{S}_i \cdot \vec{S}_j$



Square lattice of spins in the 2D XY model.

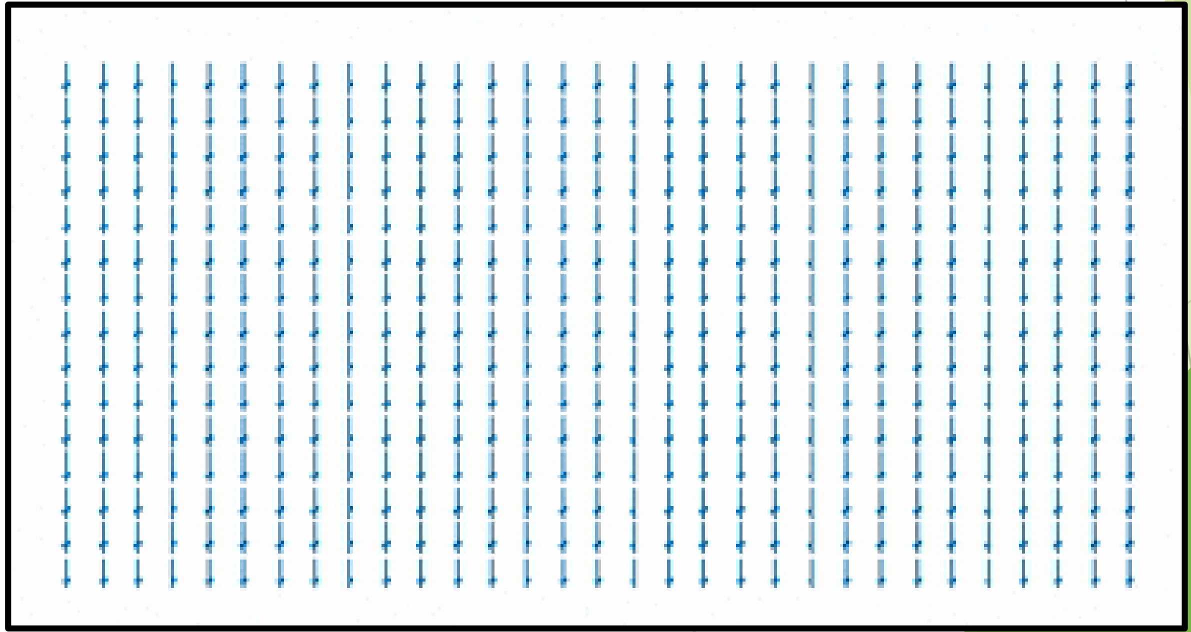
- **Mermin-Wagner Theorem**: *A 2D isotropic array of in-plane spins cannot order at finite temperature.*
  - Spin waves fluctuations prevent ordering at all non-zero temperatures
  - i.e. no 2nd order phase transition

The Kosterlitz-Thouless (KT) Transition

- **Kosterlitz and Thouless (1974):** 2DXY model may have phase transition involving excitations which preserve continuous symmetry
  - Topological phase transition involving vortices and antivortices
  - Above critical temperature T_{KT}, vortex pairs separate into free vortices
  - Above T_{KT}, correlation length and magnetic susceptibility possess unique exponential form

$$\xi(T) \sim \exp\left[\frac{b}{\sqrt{\frac{T}{T_{KT}} - 1}}\right]$$

$$\chi(T) = \chi_0 \exp\left[\frac{B}{\sqrt{\frac{T}{T_{KT}} - 1}}\right]$$



Vortex-Antivortex pair in the 2D XY model.

B. Skinner, (2015). Retrieved from: https://www.ribbonfarm.com/2015/09/24/samuel-becketts-guide-to-particles-and-antiparticles/

Finite-Size Effects and Anisotropy in the KT Transition

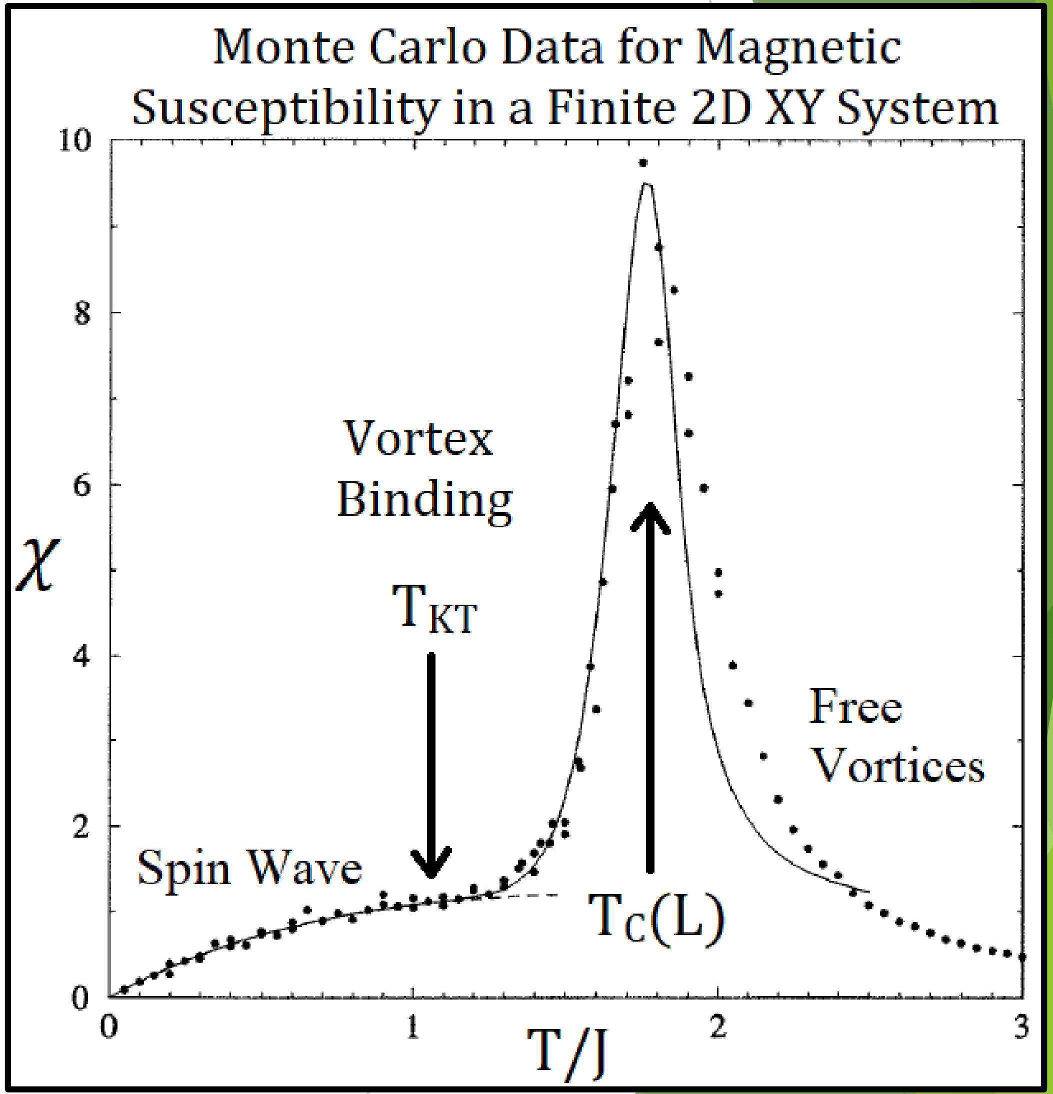
- Diverging correlation length becomes equal to system size at $T_c(L)$

$$\xi(T_C(L)) = L$$

- Large separation between T_{KT} and $T_C(L)$, creating a broad peak

$$\frac{T_c(L) - T_{KT}}{T_{KT}} = \frac{b^2}{(\ln L)^2}$$

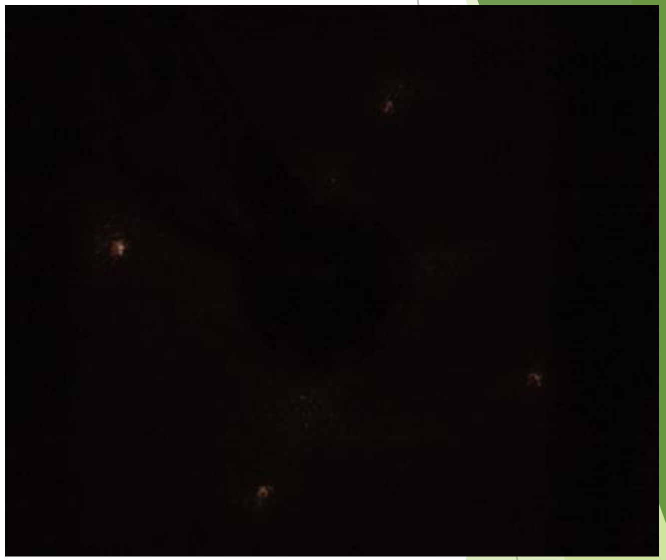
- Anisotropy (not present in figure) leads to formation of magnetic domains/domain walls



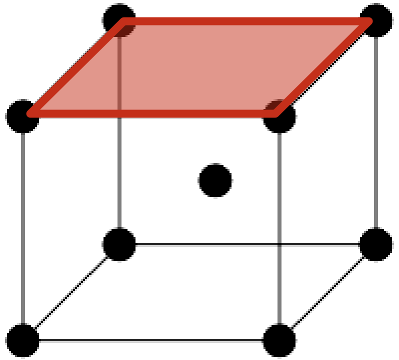
P. Archambault, S. T. Bramwell, P. C. W. Holdsworth, *J. Phys. A.: Math. Gen.* **83**, 7234 (1997).

Ultrathin Fe/W(001) Films

- 3-4 monolayers of iron
- Deposited via molecular beam epitaxy under UHV
- Tungsten (001) substrate as square template
  - 4-fold easy axes
- Confirm epitaxial growth with LEED
- Confirm thickness with AES



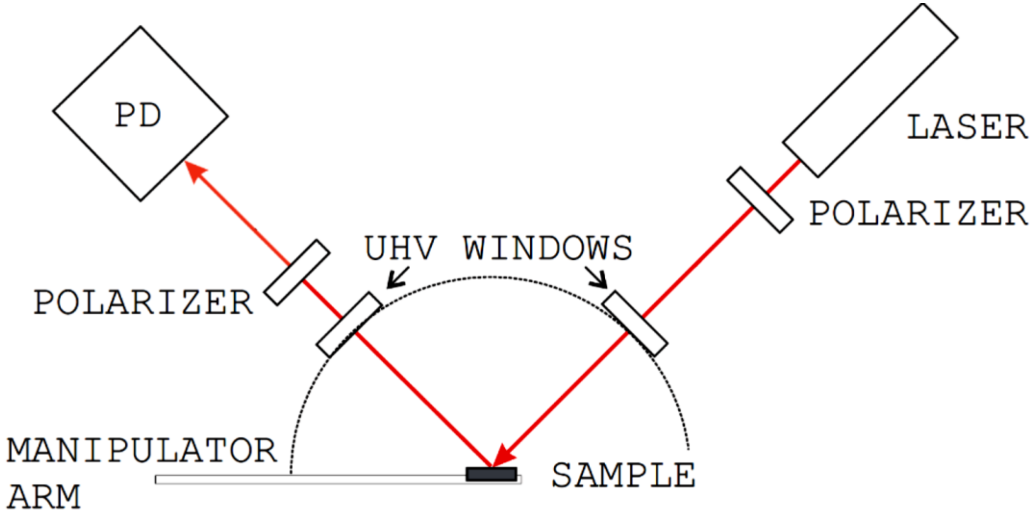
LEED image at 118eV from 3.6ML film



(001) W Crystal Plane

AC Magnetic Susceptibility of Fe/W(100)

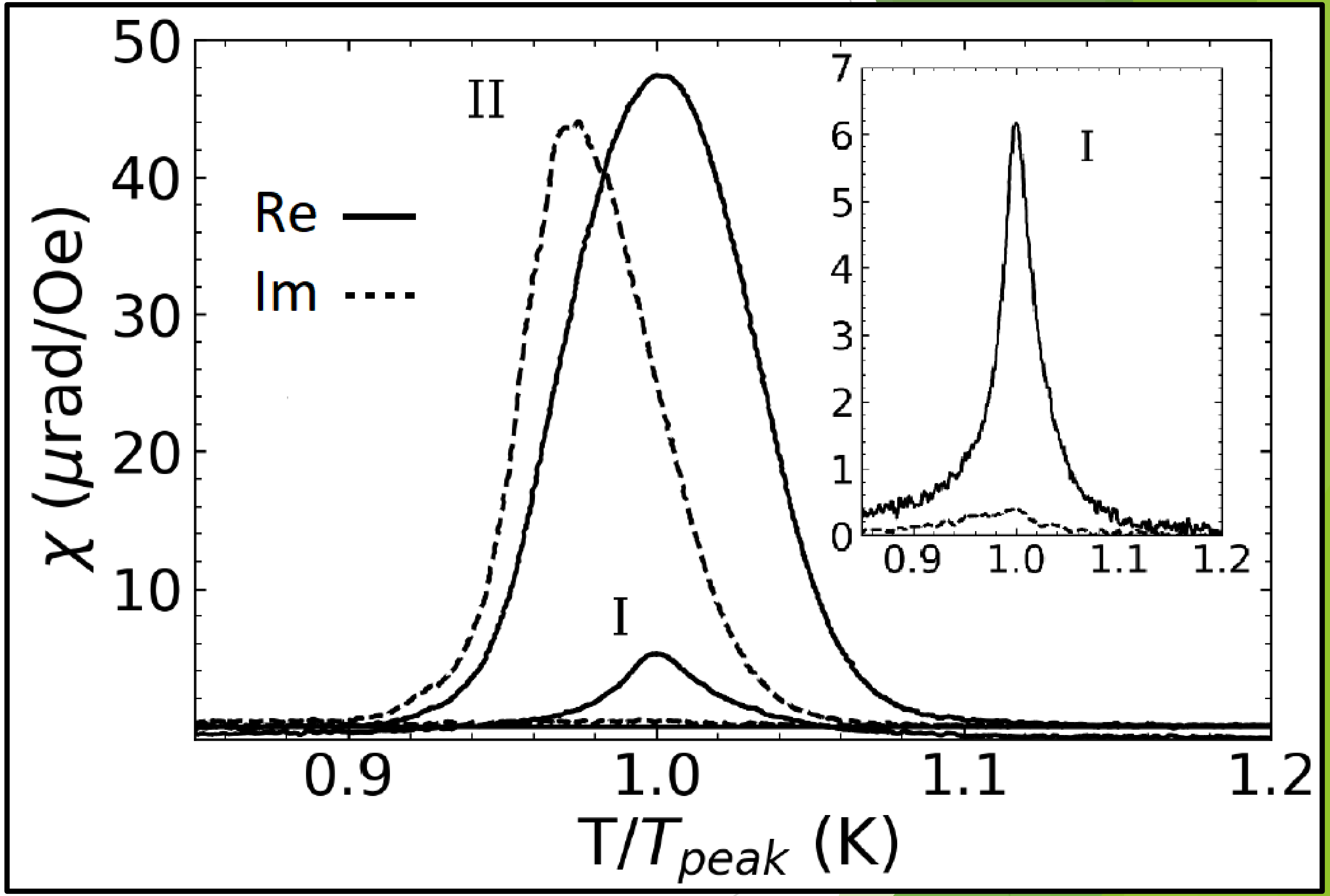
- Measured using Surface Magneto-optic Kerr Effect (SMOKE)
  - Rotation in polarization directly proportional to change in magnetization $\chi \propto \frac{\Phi_K}{H}$
- Use oscillating H to measure AC susceptibility
- AC optical signal collected using lock-in amplifier
  - Imaginary component due to dissipation effects



Schematic diagram of the SMOKE apparatus. The initial polarizer and analyzing polarizer are nearly perpendicular.

AC Susceptibility Measurements

- Different films exhibit different susceptibility signals
- Type I
  - Small $Re(\chi)$, Very weak $Im(\chi)$
  - Most closely resemble shape predicted by KT theory
- Type II
  - Large $Re(\chi)$ and $Im(\chi)$
  - Regular, symmetric shape



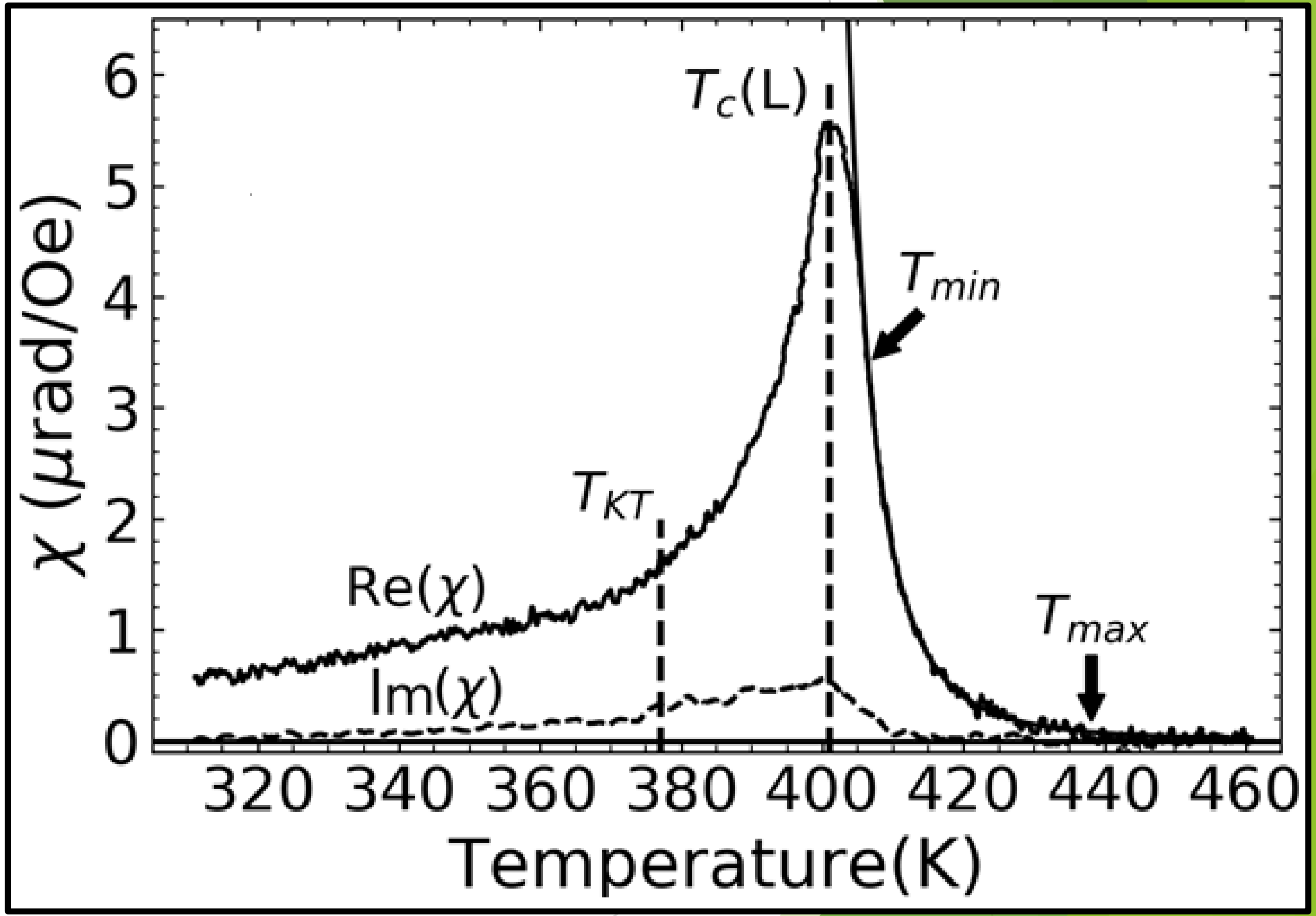
J. Atchison, A. Bhullar, B. Norman, and D. Venus. Phys. Rev. B **99**, 125425.

Type I Signals: Fitting to KT Theory

- High temp tail region fit to:

$$\chi(T) = \chi_0 \exp\left[\frac{B}{\left(\frac{T}{T_{KT}} - 1\right)^a}\right]$$

- Fitting region restricted to where $Im(\chi)$ is small (linear susceptibility)
- 3 parameter fit: find $\boldsymbol{B}$, $\boldsymbol{T_{KT}}$, and $\boldsymbol{\chi_0}$ for a series of $\boldsymbol{a}$ values



J. Atchison, A. Bhullar, B. Norman, and D. Venus. Phys. Rev. B **99**, 125425.

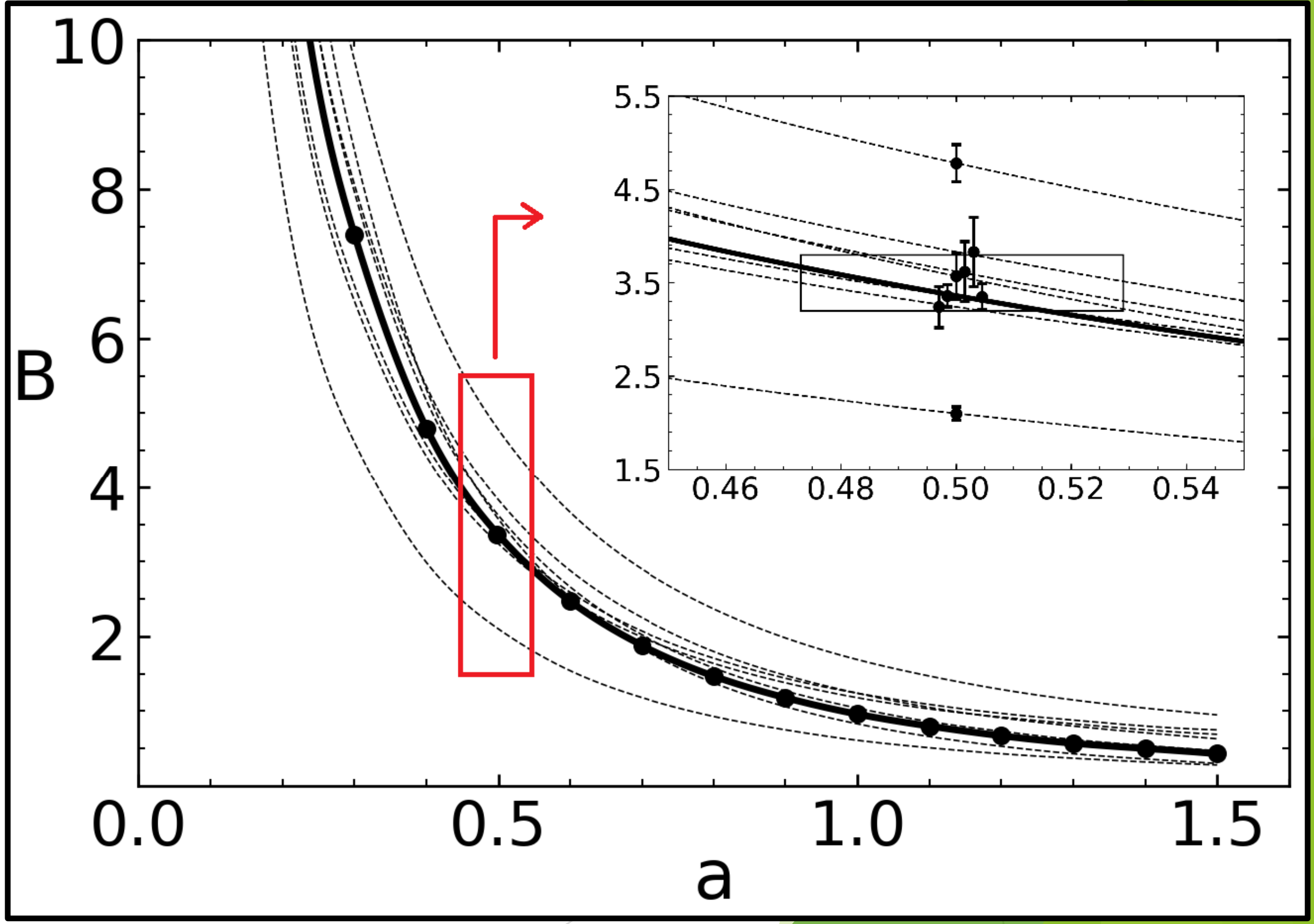
Type I Fitting Summary

- Fitted values of B for different chosen values of a
- KT theory independently predicts $a = 1/2$ and $3.2 < B < 3.8$
- For 6 curves in the box:
  - When $a = 1/2$, $\boldsymbol{B = 3.5 \pm 0.2}$
  - For $3.2 < B < 3.8$, $\boldsymbol{a = 0.50 \pm 0.03}$

$$\xi(T_C(L)) = L = \exp\left[\frac{b}{\sqrt{\frac{T_C(L)}{T_{KT}} - 1}}\right]$$

- $L \sim \mu m$, approx. size of mag. domains

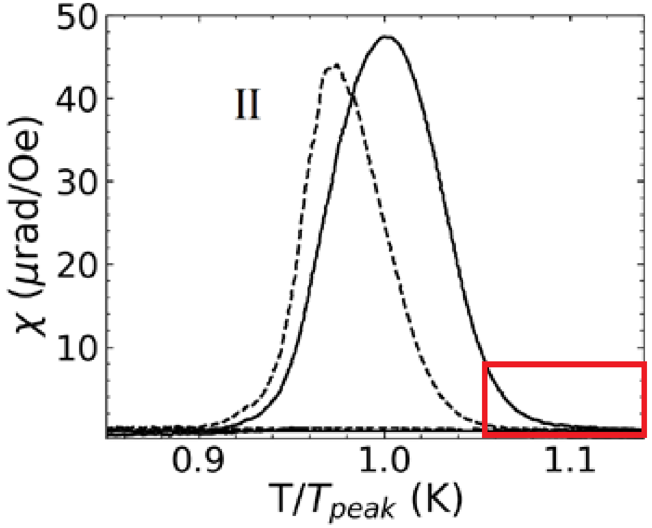
Interpolation Curves of B(a) for Type I Signals from 8 Different Films



J. Atchison, A. Bhullar, B. Norman, and D. Venus. Phys. Rev. B **99**, 125425.

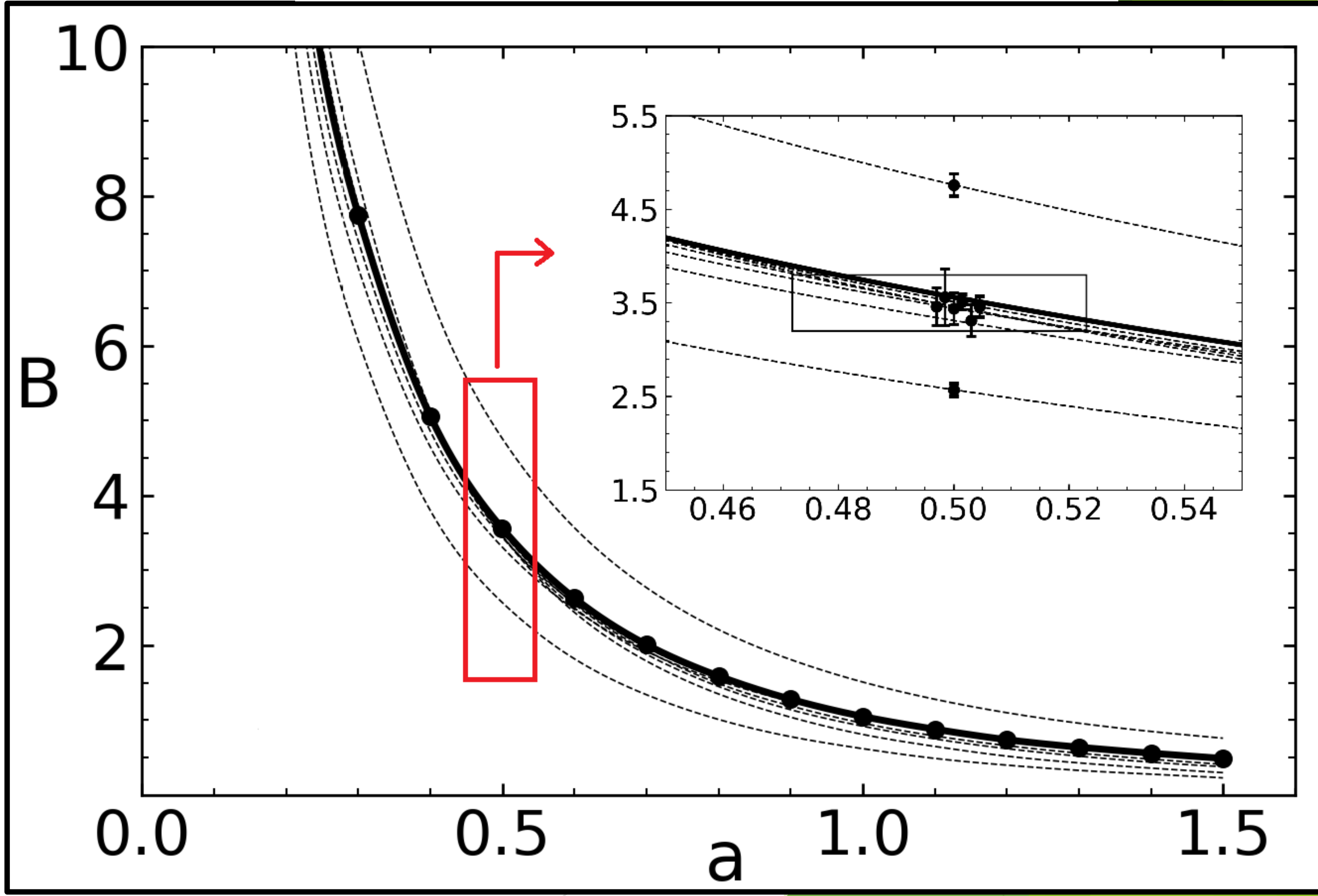
Type II Fitting Summary

- The high temperature tail of Type II signals can be analyzed as well
- Fitting region restricted to where $Im(\chi)$ is small (linear susceptibility)



- For 6 curves in the box:
  - When $a = 1/2$, $\boldsymbol{B = 3.46 \pm 0.08}$
  - For $3.2 < B < 3.8$, $\boldsymbol{a = 0.50 \pm 0.03}$

Interpolation Curves of B(a) for Type II Signals from 8 Different Films

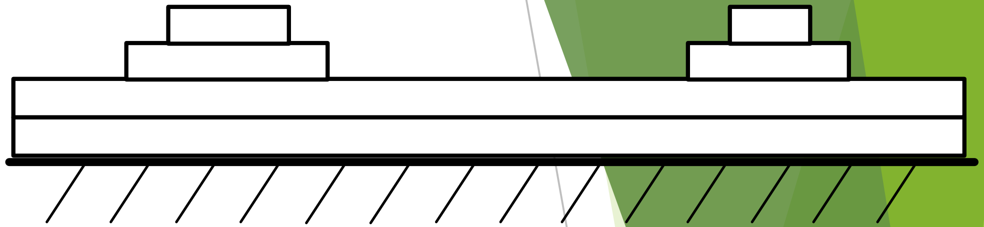


J. Atchison, A. Bhullar, B. Norman, and D. Venus. Phys. Rev. B **99**, 125425.

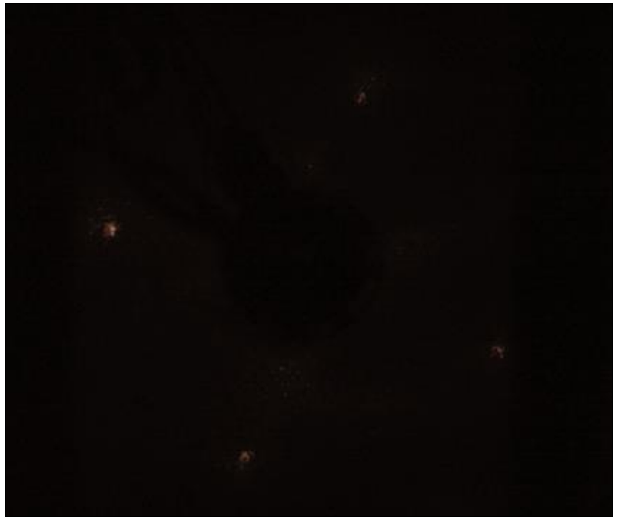
Conclusions

- First demonstration of the exponential behaviour of the magnetic susceptibility in a real system
- Magnetic susceptibility measurements on Fe/W(001) films provide persuasive evidence of a finite size KT transition
  - Agreement between fitted values and KT theory
  - The fitted T_{KT} is substantially below the peak, which is in agreement with finite size KT theory
  - The separation between T_{KT} and $T_C(L)$ gives an effective size of L~μm, consistent with domain size

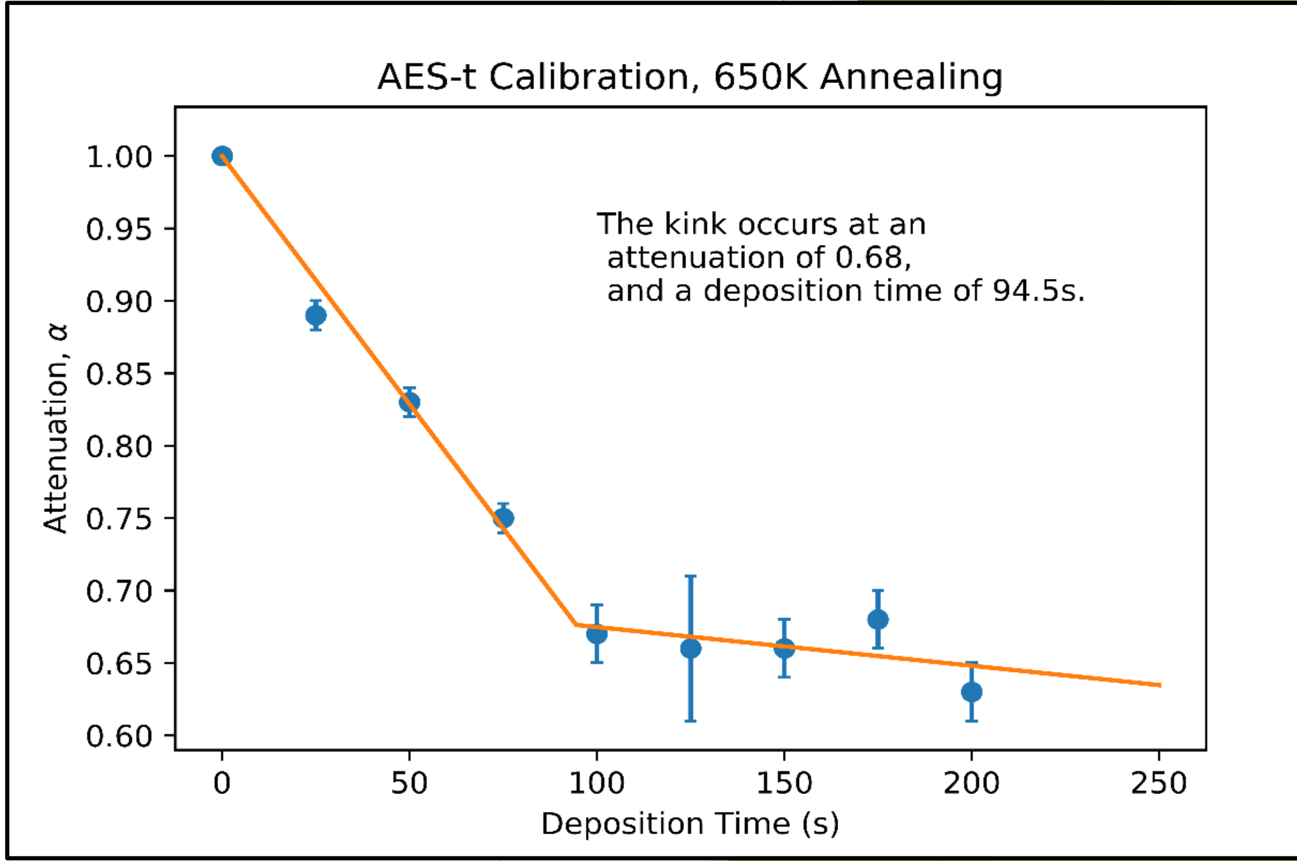
Fe/W(001) Film Growth



- Substrate is a square lattice (W(001) surface)
- Only the first 2ML are stable at 600K+
  - Allows for film thickness calibration using Auger Electron Spectroscopy (AES)
  - “Kink” due to islands covering less area



LEED image at 118eV from 3.6ML film



Calculation of System Size

$$\xi(T) \sim \exp\left[\frac{b}{\sqrt{\frac{T}{T_{KT}} - 1}}\right]$$

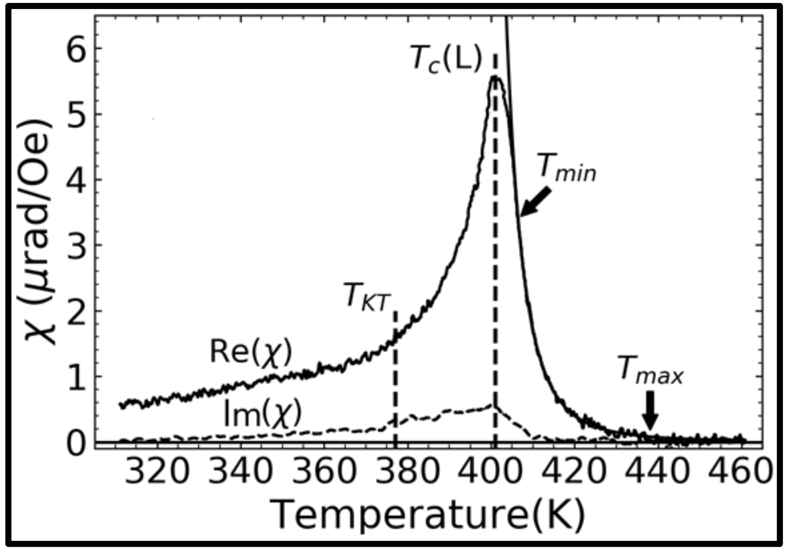
$$\chi(T) \sim \xi^{2-\eta}$$

$$\chi(T) = \chi_0 \exp\left[\frac{B}{\left(\frac{T}{T_{KT}} - 1\right)^a}\right]$$

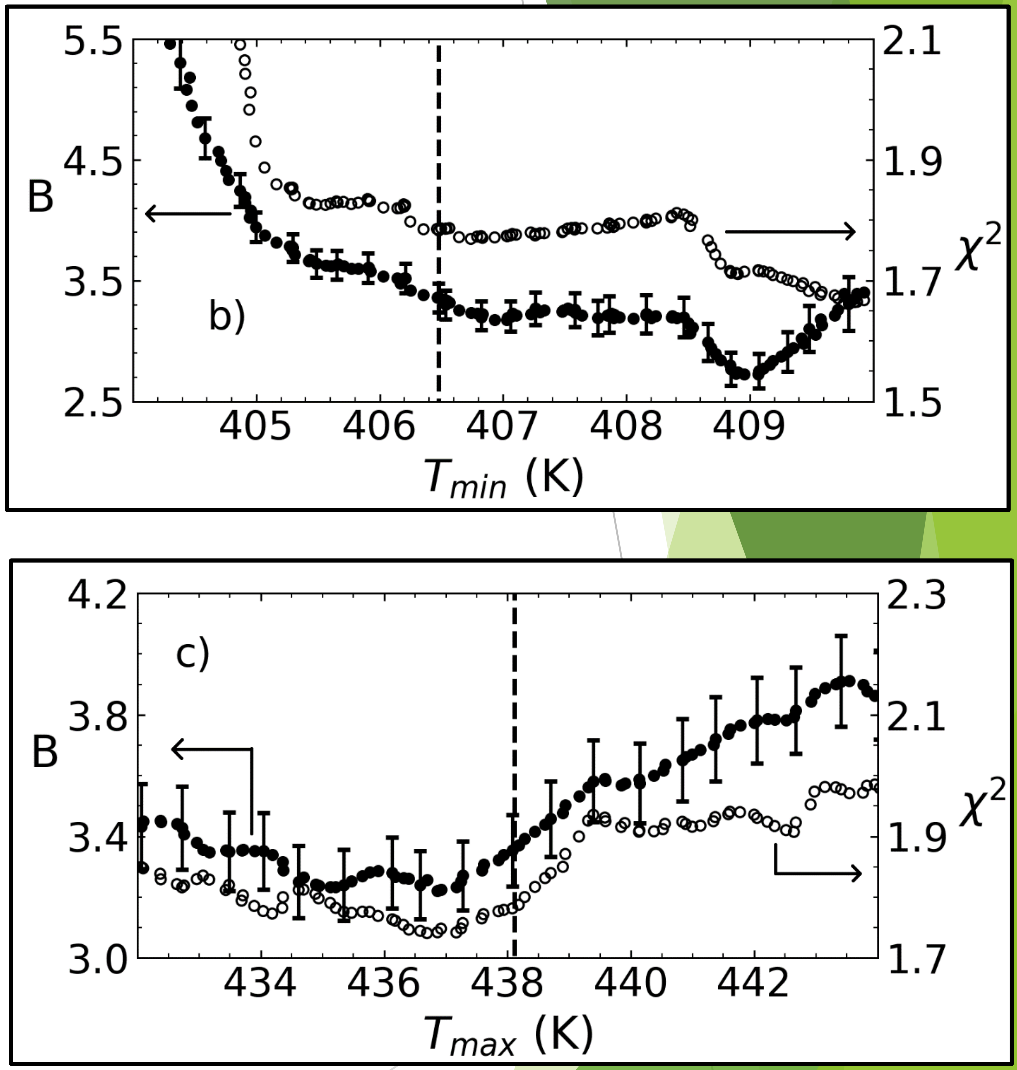
$$B = (2 - \eta)b$$

$\eta = 1\backslash 4$ at T_{KT}

Type I Signals: Fitting Region



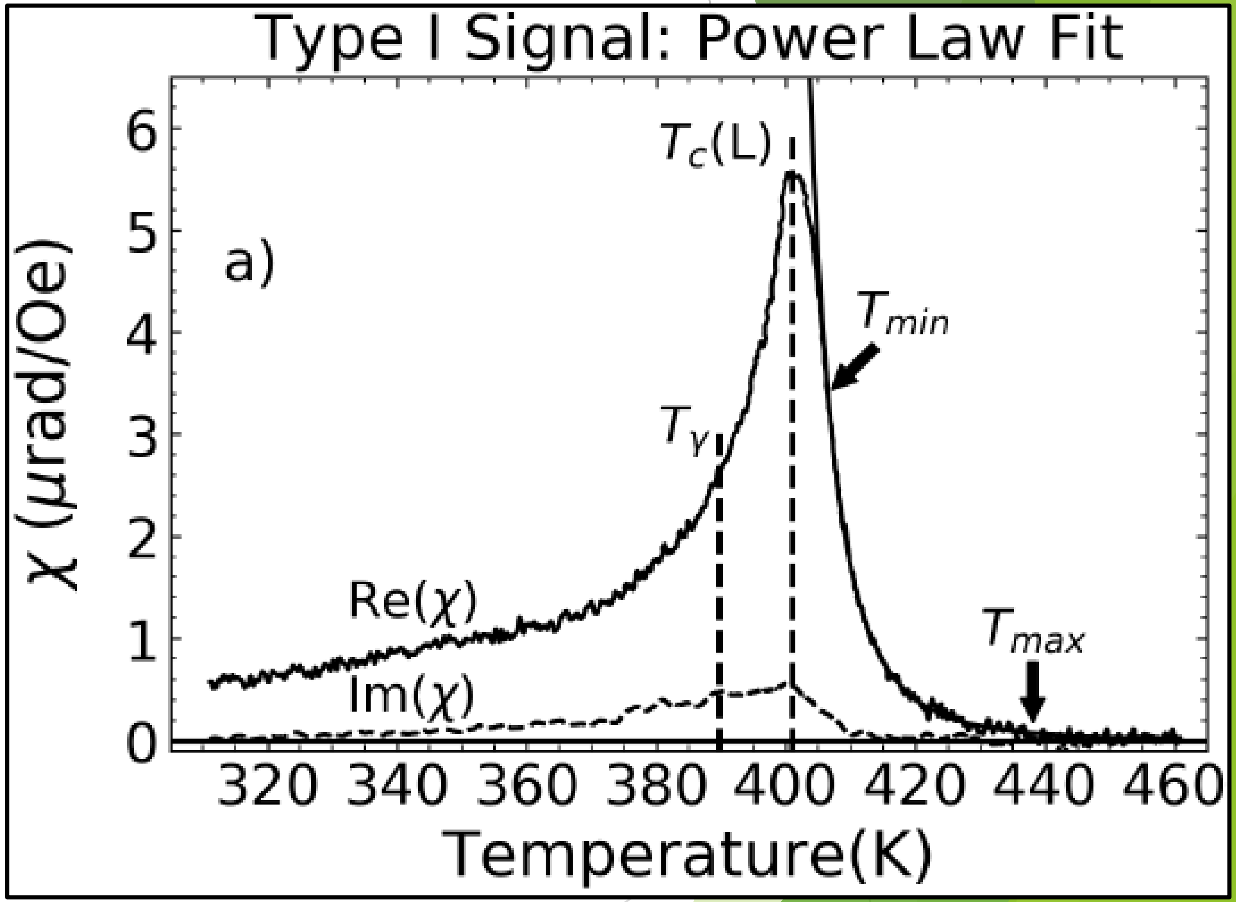
- Look at parameter B and the "goodness of fit" χ^2 as a function of T_{min} and T_{max}
- T_{min} and T_{max} should fall in region where fitted parameters don't depend on them
- Choose largest reasonable region to maximize number of data points
- T_{min} exists due to finite size effects stopping divergence
- T_{max} exists due to limits in signal-to-noise



J. Atchison, A. Bhullar, B. Norman, and D. Venus.
Phys. Rev. B **99**, 125425.

Type I Signals: Power Law Fit

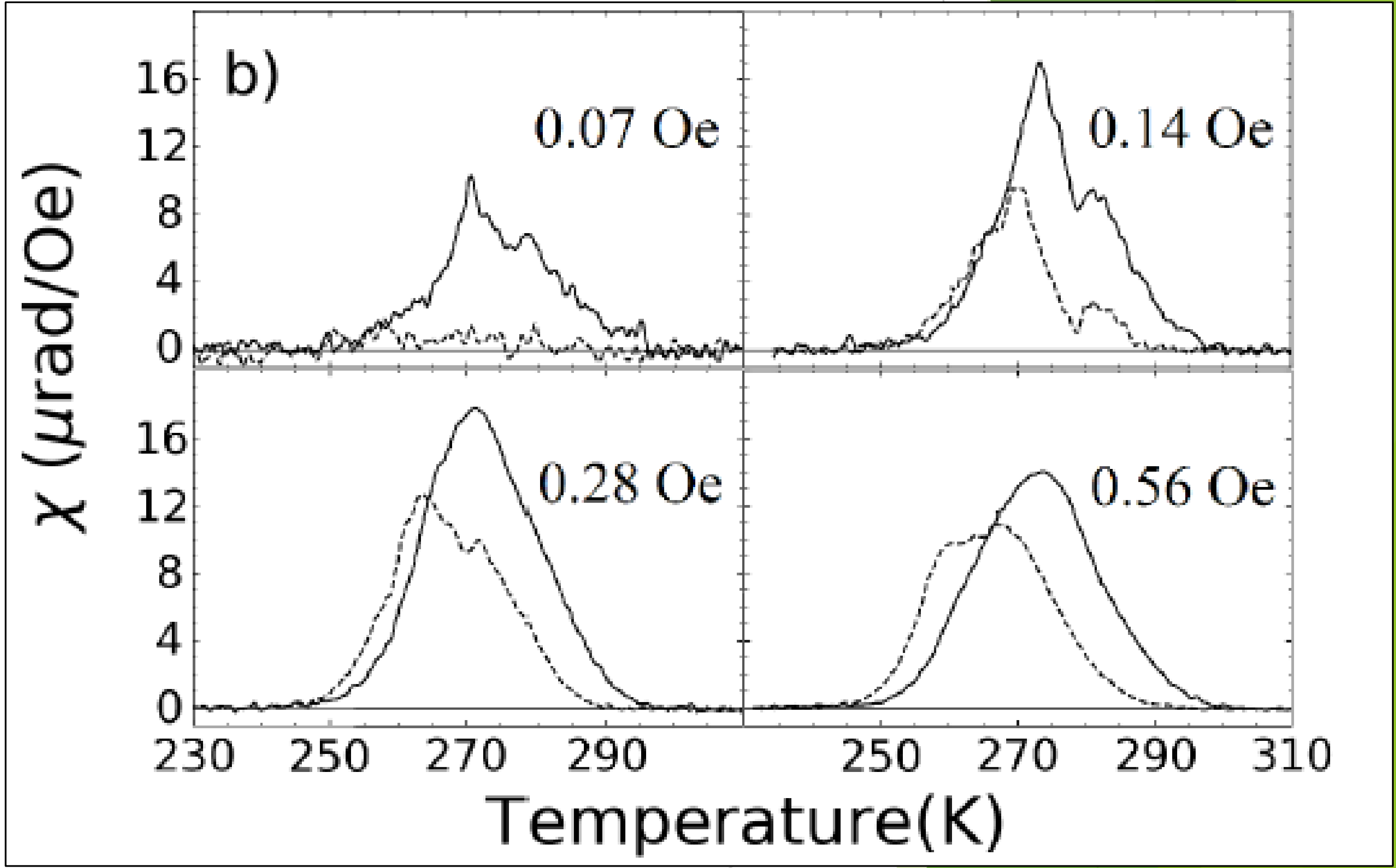
- Data fit to a power law
- $\chi(T) = \chi_0 \left(\frac{T}{T_\gamma} - 1\right)^{-\gamma}$
- Statistical χ^2 is no better or worse
- Fitted parameters are unphysical
  - $\gamma = 3.61 \pm 0.08$
    - does not match any known universality class
  - $T_\gamma = 389.7 \pm 0.5\text{K}$
    - 12K below the peak here, compared to ~2K below in 2D Ising system Fe/W(110)
- Above parameters are representative of a larger data set



J. Atchison, A. Bhullar, B. Norman, and D. Venus. Phys. Rev. B **99**, 125425.

Type II Signals: Low Field Strength

- Separation of a Type II peak into two peaks at low field
  - Separated by ~10K
- We speculate that high T peak is vortex transition, low T peak is domain wall transition
- Type II signals could be a Type I signal plus domain wall contributions

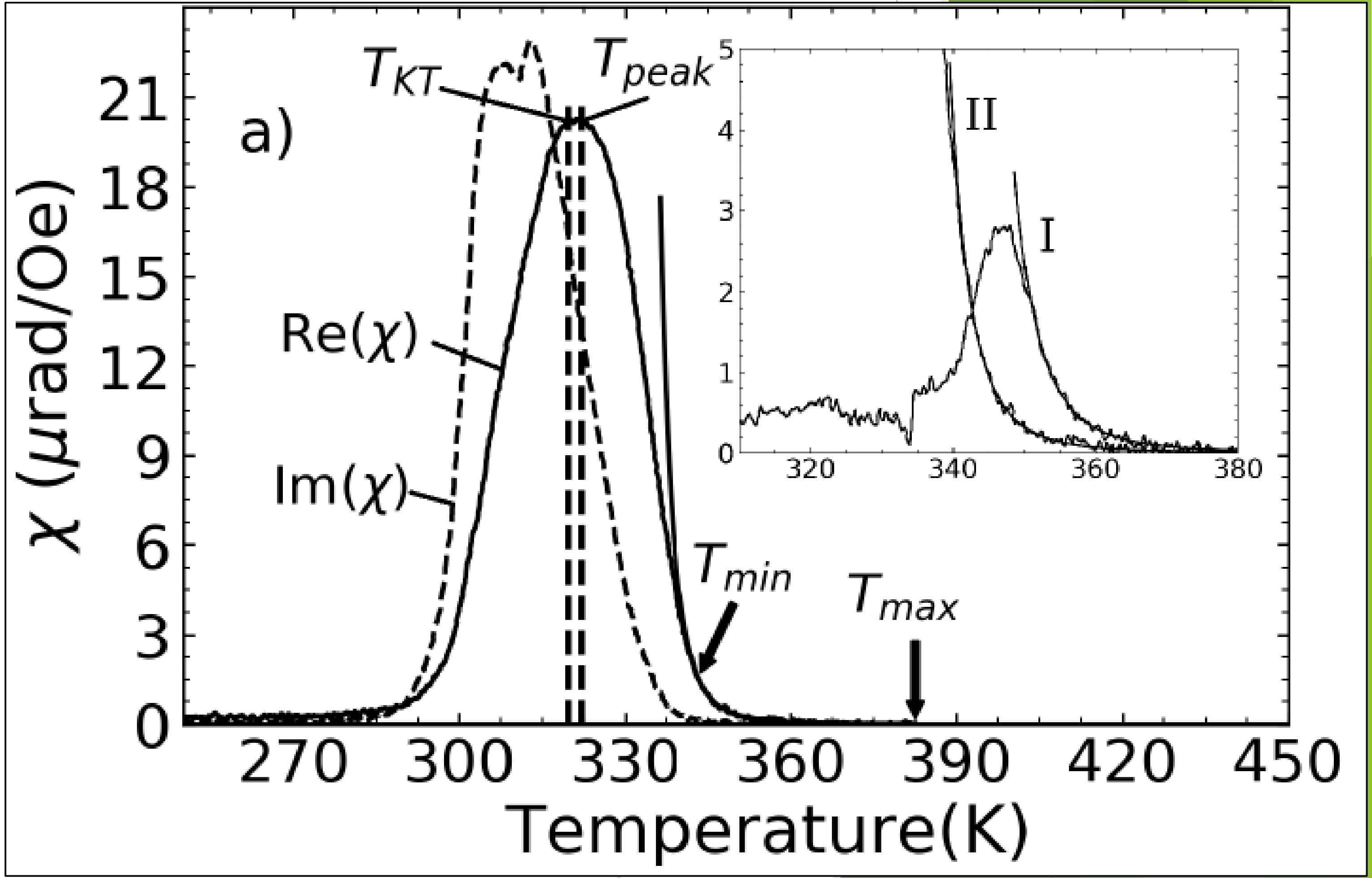


J. Atchison, A. Bhullar, B. Norman, and D. Venus. Phys. Rev. B **99**, 125425.

Type II Signals: High Temperature Behaviour

- From a single film, we've observed Type II -> Type I signal after strong field pulse
- Curve fitting to high T tail resulted in consistent values

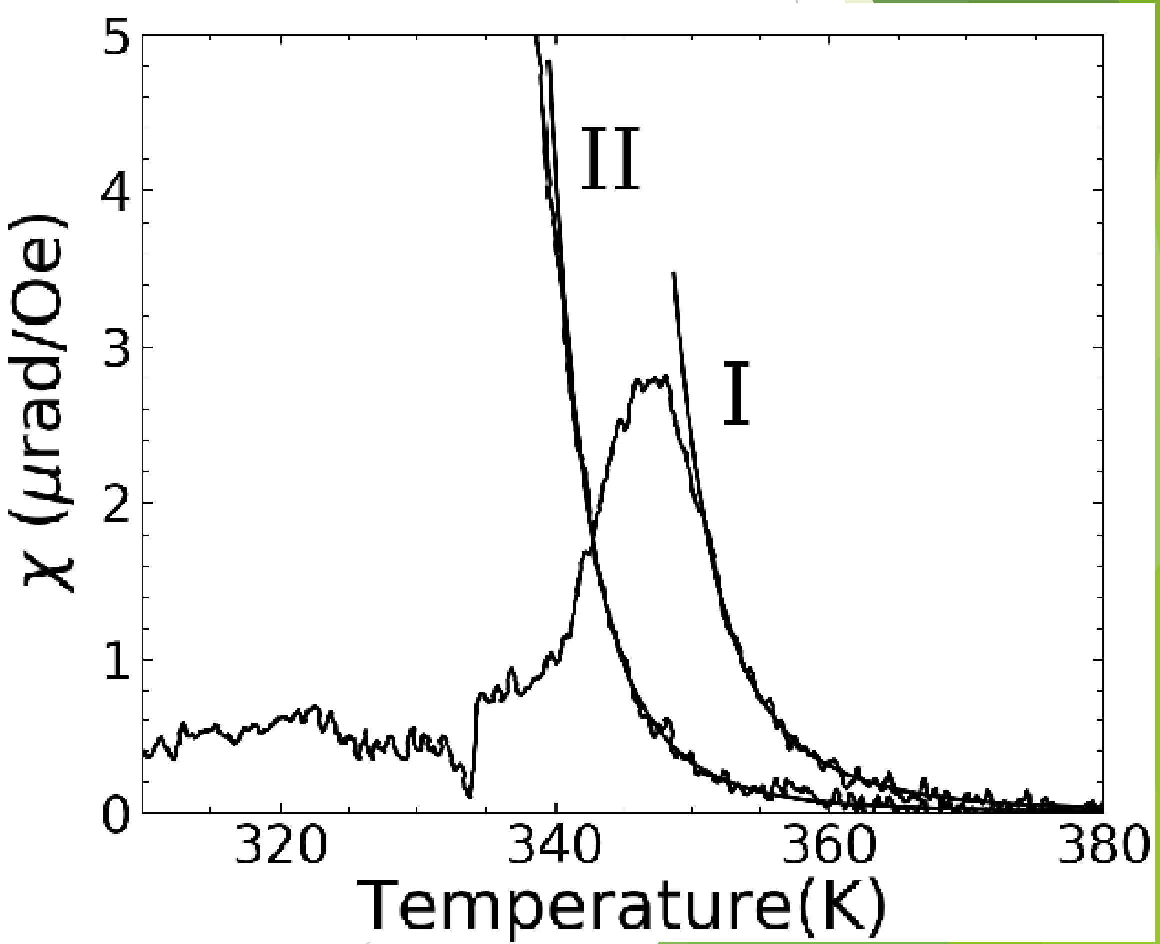
	B	T_{KT} (K)
Type I	3.6 ± 0.3	325 ± 2
Type II	3.6 ± 0.3	320 ± 2



J. Atchison, A. Bhullar, B. Norman, and D. Venus. Phys. Rev. B **99**, 125425.

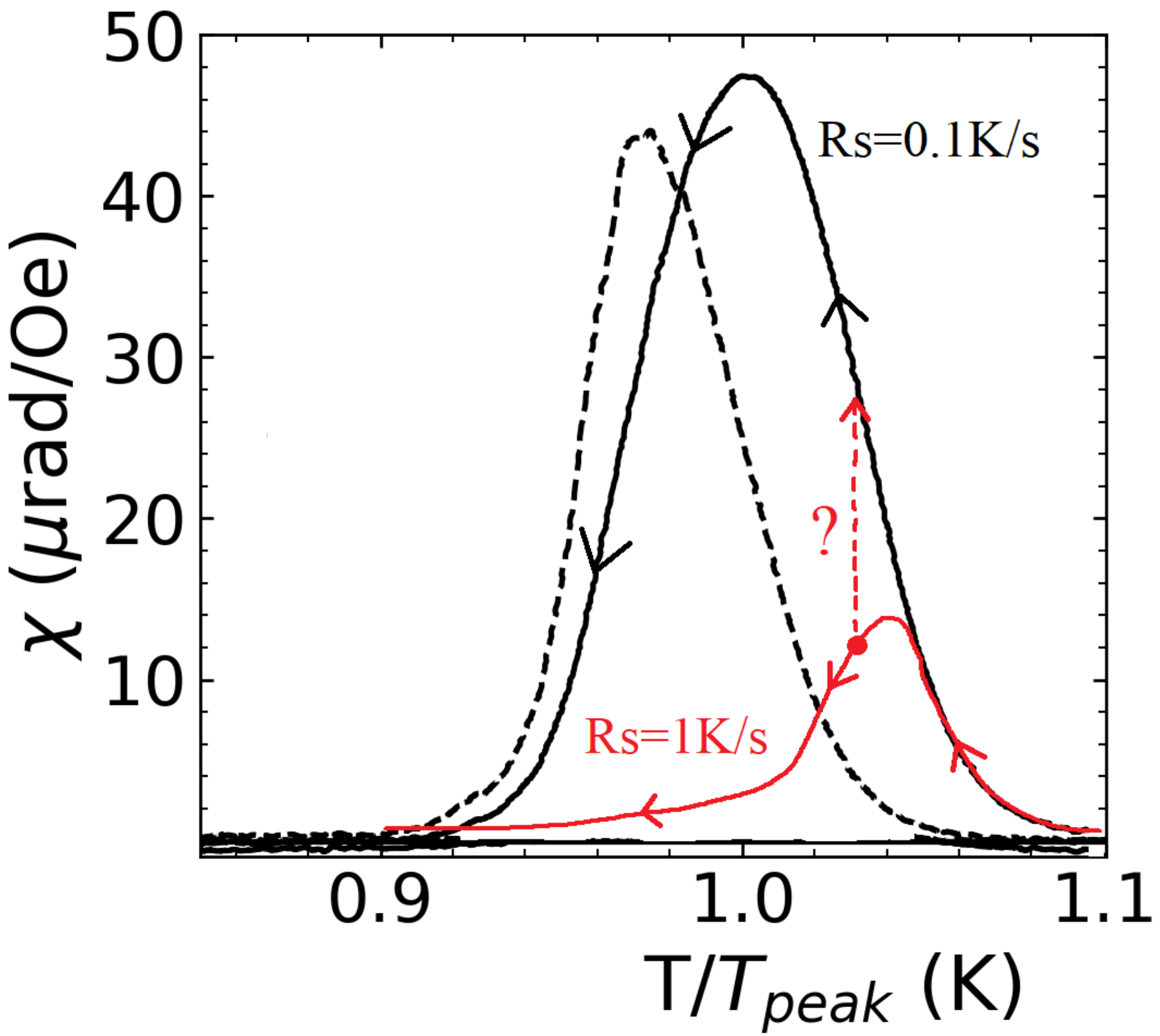
Research Idea II: Domain Component

- Type II signals have large Re and Im components
  - Domain wall motion could be responsible
- Domain structure can be controlled
  - Film thickness
  - Film orientation (azimuthal rotation)
  - Strong field pulse
- Look for change to low T behaviour but same high T behaviour
  - We've observed Type II -> Type I signal after strong field pulse



Research Idea III: System Relaxation

- In 2DXY model, approach to equilibrium near critical point may depend on initial state
  - Free vortices and bound pairs have different relaxation
- Investigate system relaxation in various ways
  - Heat to different points near critical temp and observe relaxation
  - Heating vs cooling, heating/cooling rate, different field strengths



Finite-Size Effects and Anisotropy

- Logarithmic divergence of 2D spin wave fluctuations with system size, N

$$\langle|\boldsymbol{M}|\rangle \propto \left(\frac{1}{2N}\right)^{\frac{k_B T}{8\pi J}} = \left(\frac{1}{2N}\right)^{\frac{1}{16}}$$

  - spin-waves only disrupt long range order for systems much larger than are experimentally feasible
  - Allows for a finite magnetization, but with no fixed direction

$$\langle\boldsymbol{M}\rangle = 0$$

- Anisotropy can trap the finite magnetization along a specific direction
  - Allows for measurement of finite magnetization at non-zero temperatures

$$\langle|\boldsymbol{M}|\rangle \neq 0$$

Research Idea I: Nature of Double Peaks

- **Double peak** observed in Type II signals at low field
  - What is the physical origin?
- High T peak is vortex binding/unbinding?
- Low T peak is melting of domain walls?
- Find fitted parameters T^*, T_{KT}
  - Compare to peak locations

$$\chi(T) = \chi_0 \exp\left[\frac{B}{\left(\frac{T}{T_{KT}} - 1\right)^a}\right]$$

$$\frac{T^* - T_{KT}}{T_{KT}} = \frac{b^2}{4(\ln L)^2} \qquad B = (2-\eta)b$$

$$(T_C(L) - T_{KT}) = 4(T^* - T_{KT})$$