Nanoscale Magnetism: Starting with Statics

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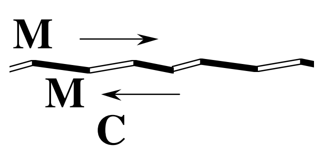
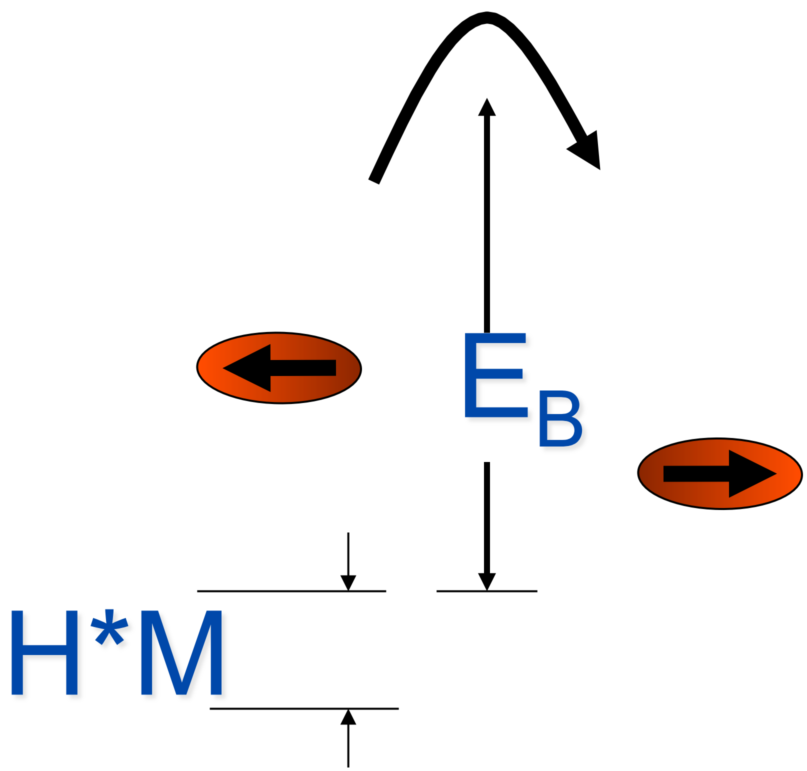
U of M MRSEC

ONR



Ending with dynamics

Magnetic Reversal Dynamics
and
Microscopic Quantum Tunneling



Paul Crowell- psec dynamics

Randy Victora- first principle calculations

Me- statics and statistics (nsec pulses)

Classically $f=f_0\exp(-E_B/k_BT)$

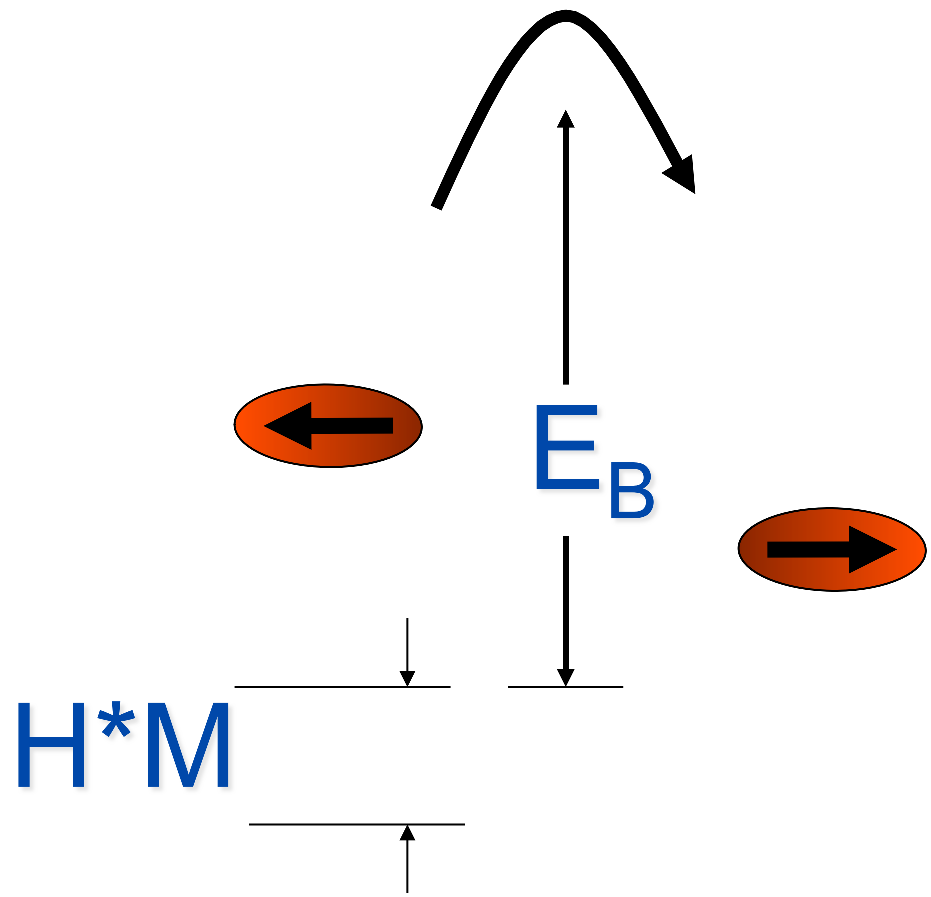
where $E_B = f(K_u v, H)$

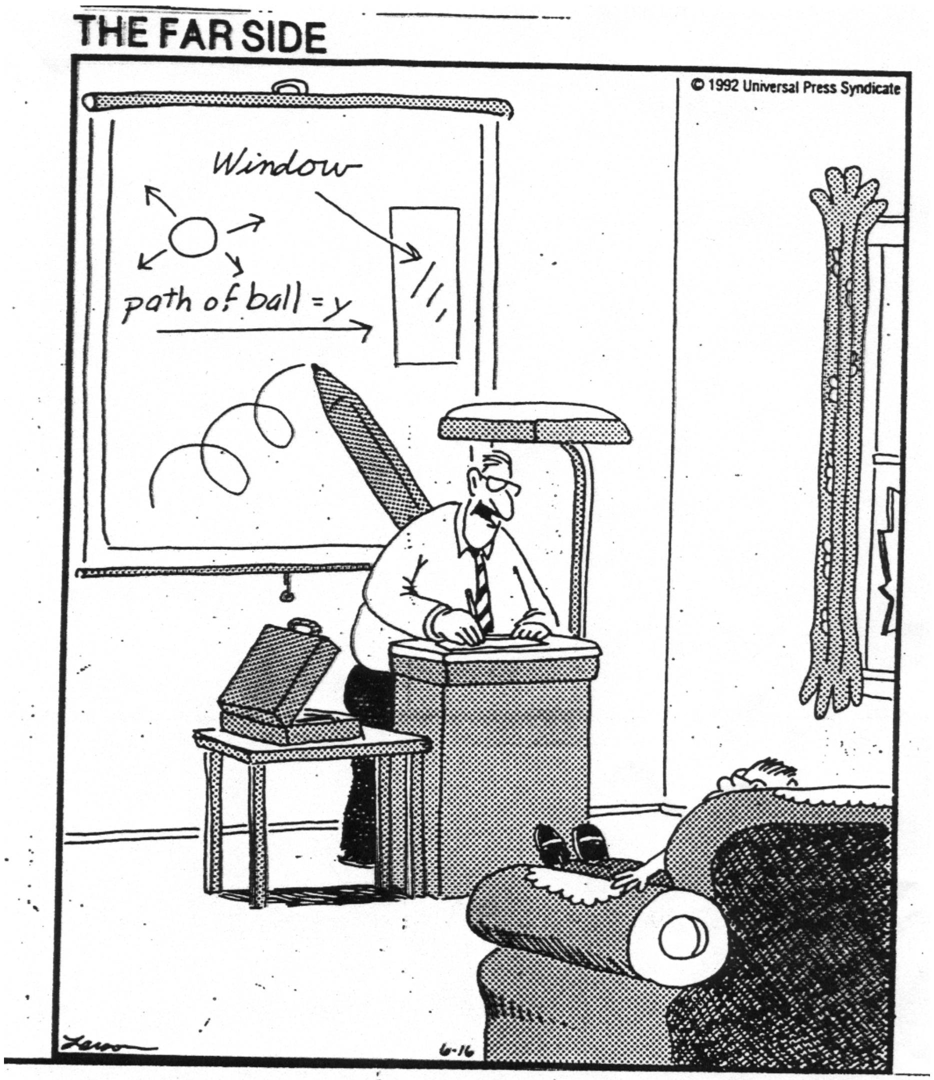
It is $E_B(K_u$, v, and H) we must understand.

To get there

We need to know the magnetic state on an atomic scale.

We need to know the magnetic state in the presence of an applied magnetic field.





Eventually, Billy came to dread his father's lectures over all other forms of punishment.

Micromagnetics- very short

MFM- fun stuff

Two model systems:

Ni particles (cylinders) in zero magnetic field with diameters as small as 40nm.

NiFe stadia with vortices present to measure field dependent state.

Micromagnetics- A (very) brief introduction

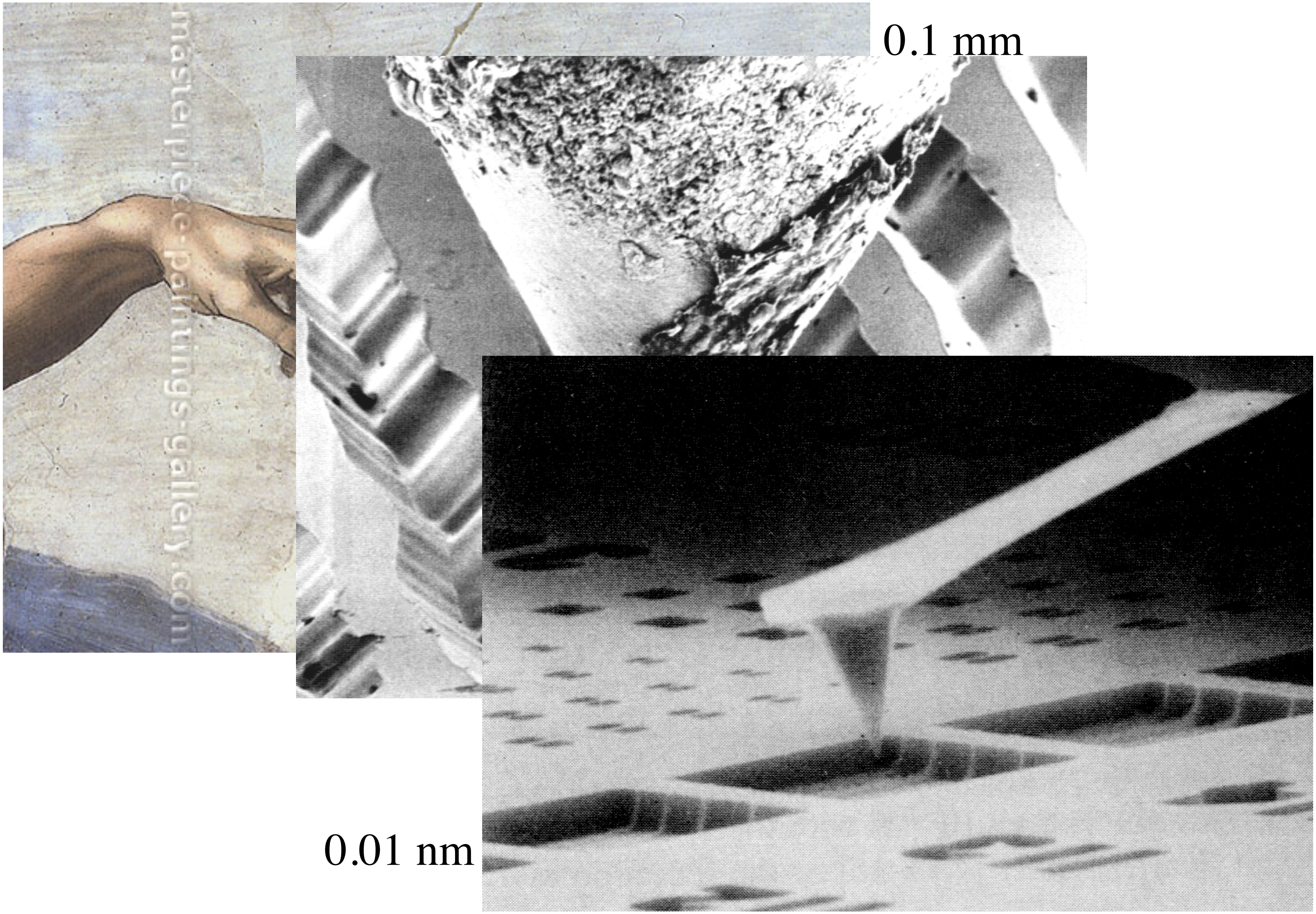
$$E = E_{zeeman} + E_{exchange} + E_{anisotropy} + E_{magnetostatic}$$

E_{zeeman}	=Energy due to external field
$E_{exchange}$	=Exchange energy magnetic moments
$E_{anisotropy}$	= Energy coupling the magnetization to the lattice
$E_{magnetostatic}$	=Dipolar coupling

$$\mathbf{H} = -\frac{\partial E}{\partial \mathbf{M}}$$

$$\frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M} \times \mathbf{H} - \frac{\lambda}{M} \mathbf{M} \times \mathbf{M} \times \mathbf{H}$$

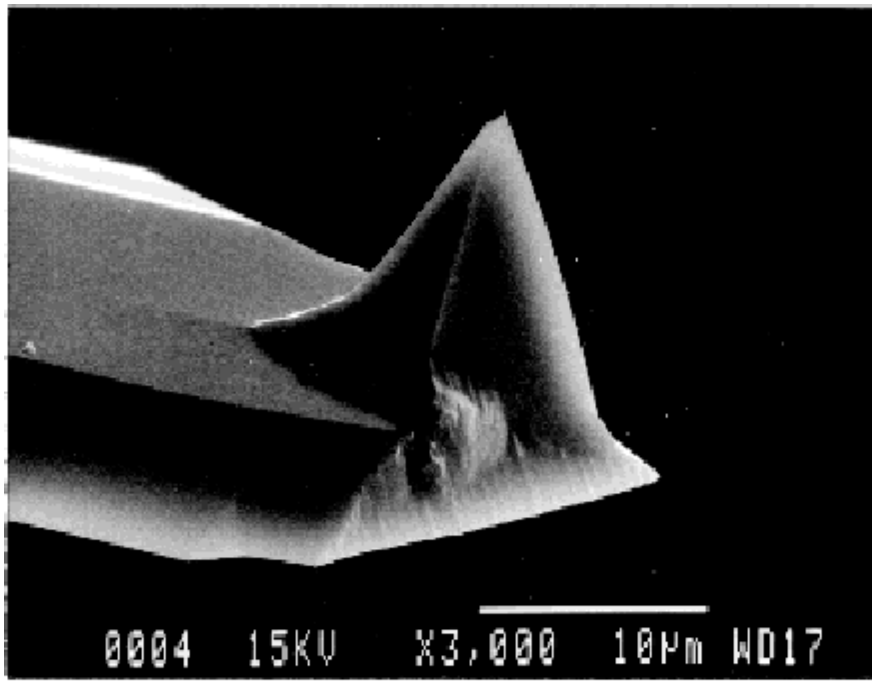
Scanning Force Microscopes . . . a brief history



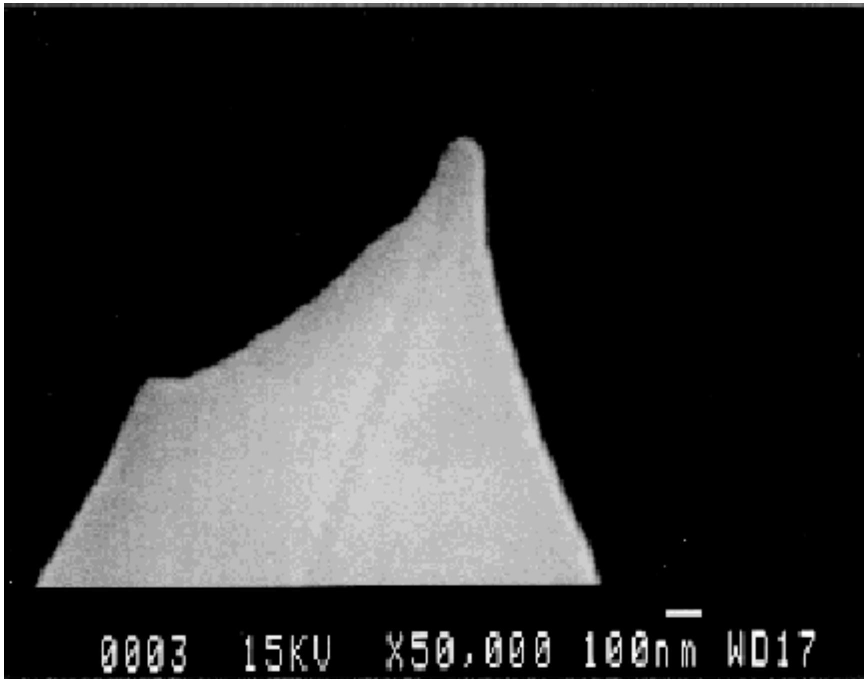
0.1 mm

0.01 nm

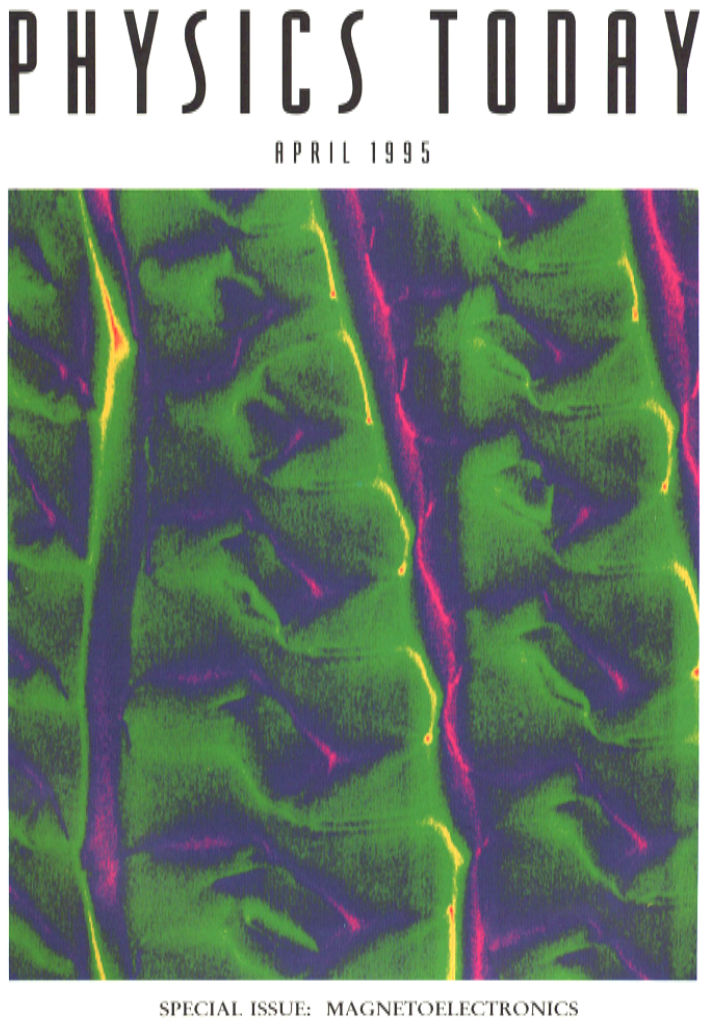
SEM Images of an MFM Cantilever Tip



Tip coated with a thin film of CoCr alloy



You are now expert in force microscopy including MFM!



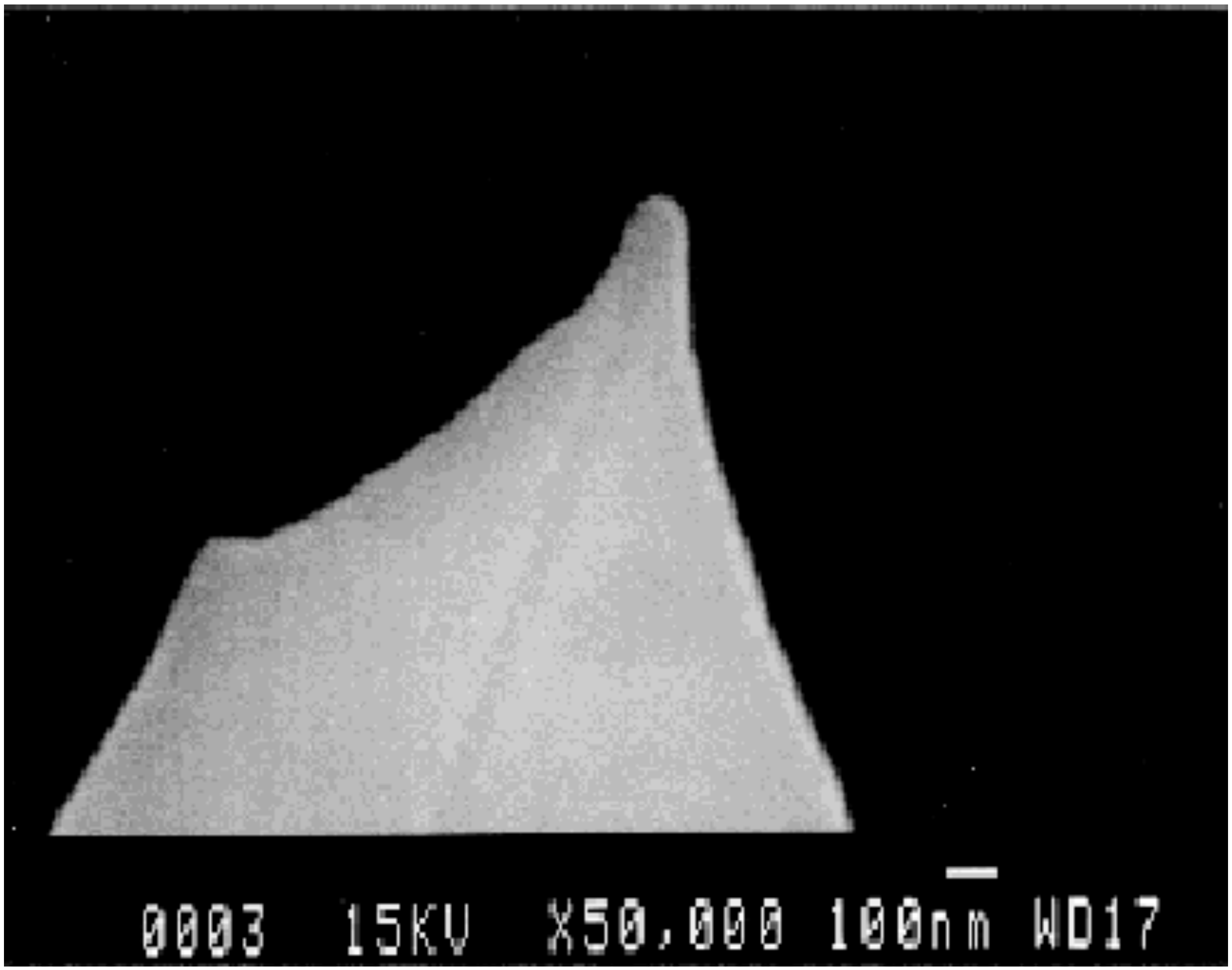
MFM 101 Homework

What is separation between magnetic poles?

What is magnetization pattern in the card?

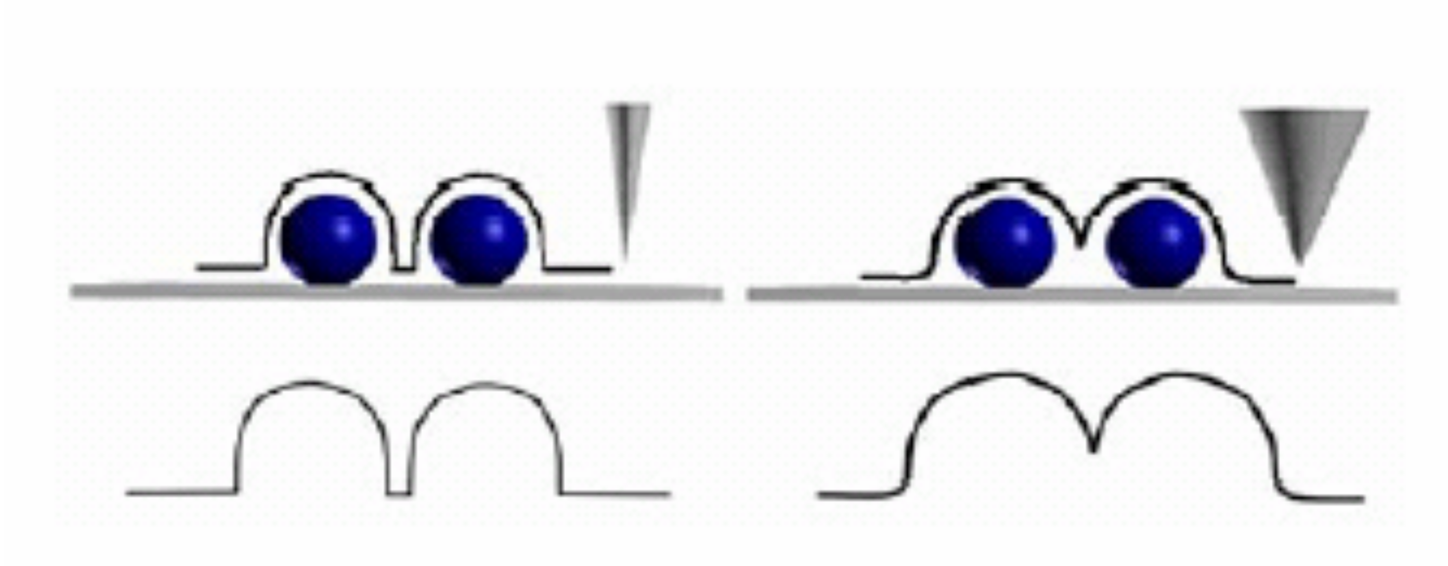
Was the finger cut from the refrig magnet co-linear or perpendicular to the stripes?

SEM Images of an MFM Cantilever Tip



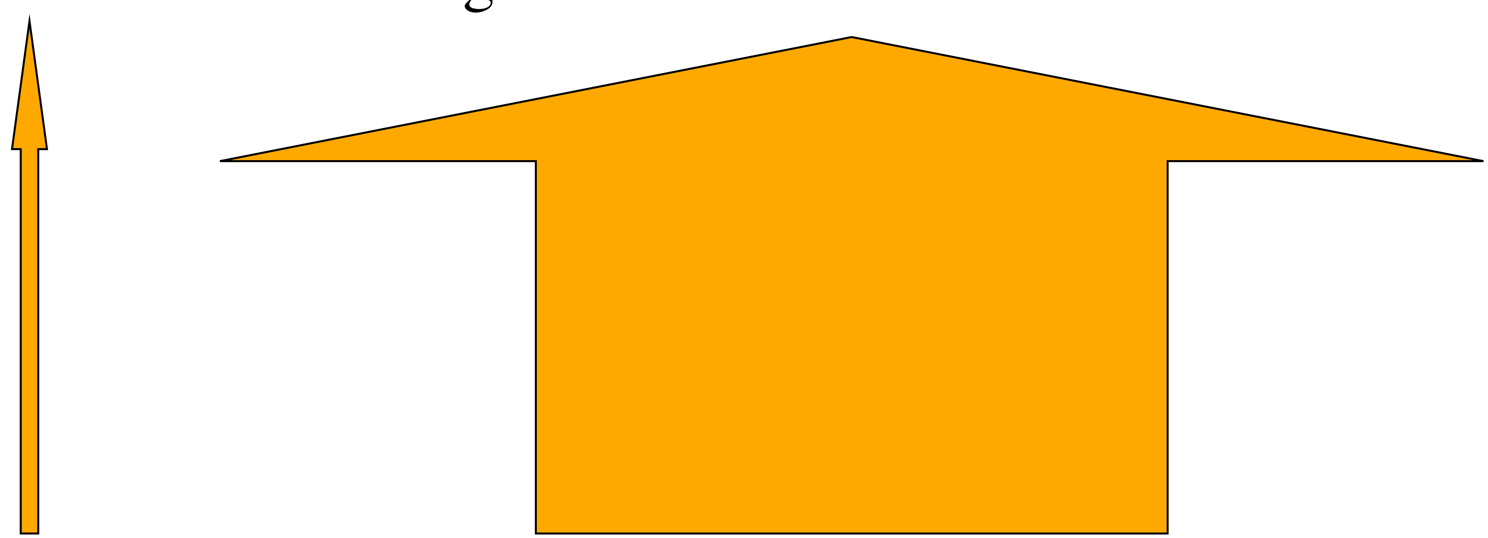
Standard MFM tip resolution ≈ 100-200nm

100nm



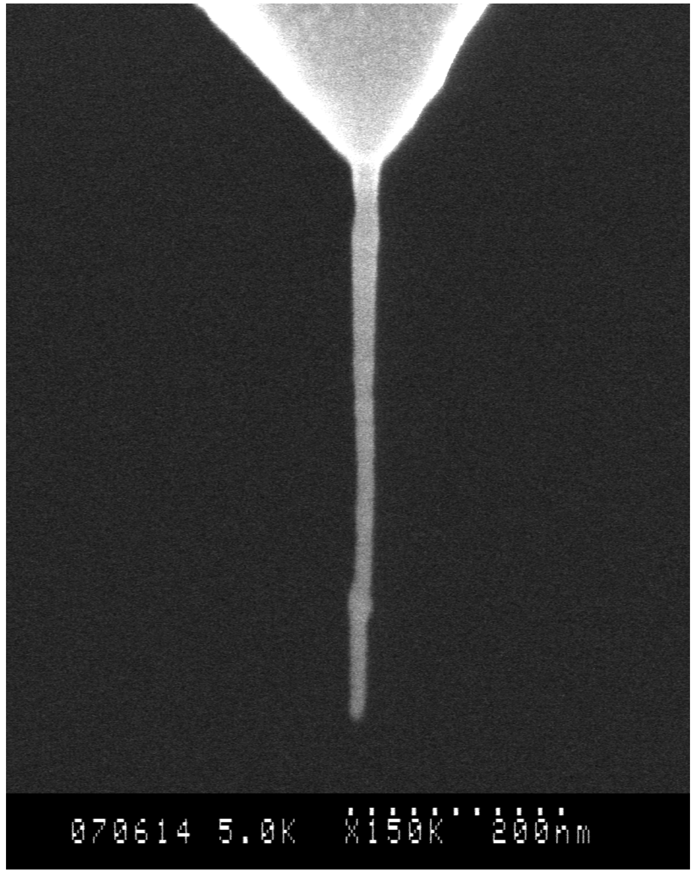
To distinguish between ↑ and ↑ ↓ ↑

which finger do I use?



EBD MFM tips (electron beam "contamination" deposition)

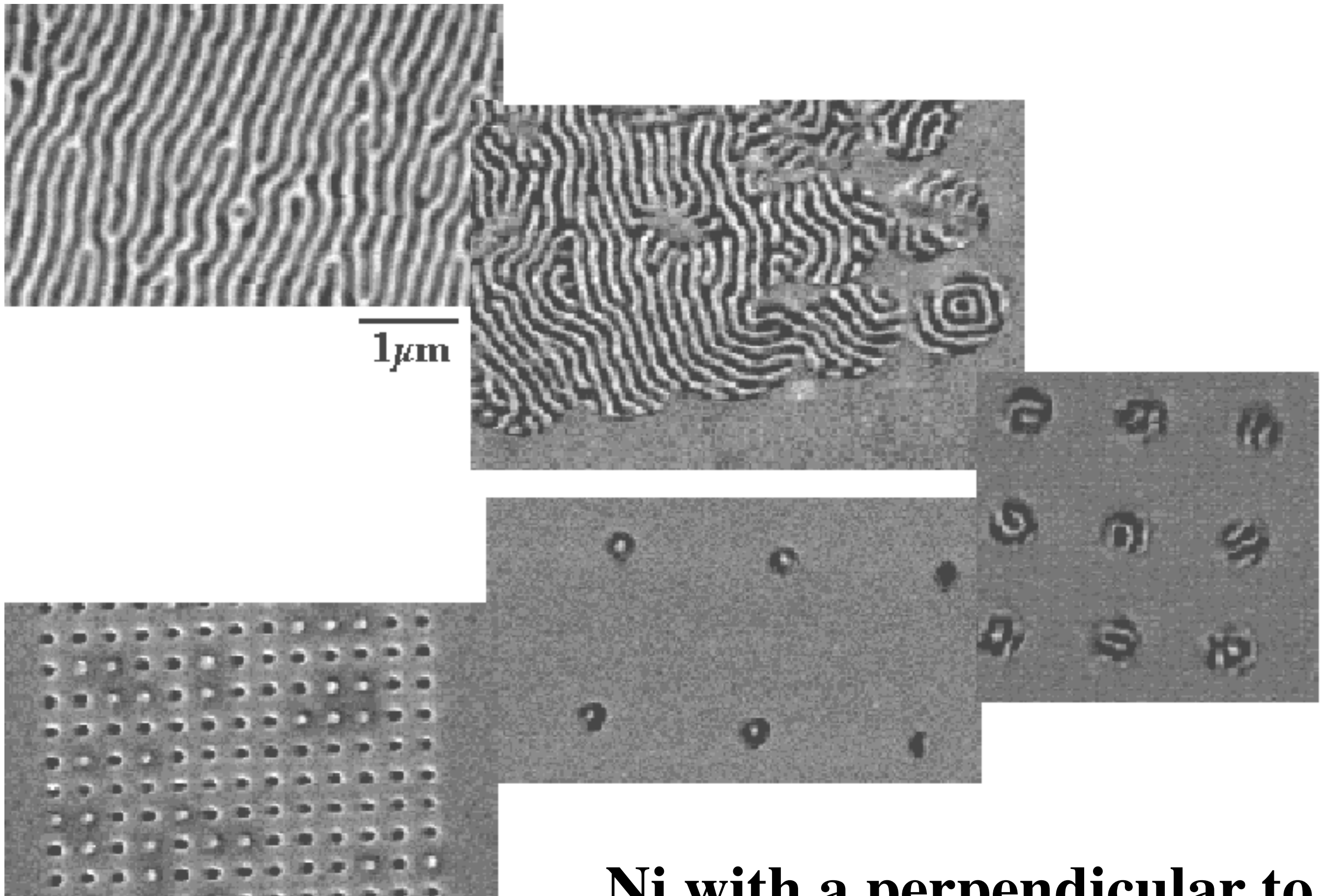
Following Ruhrig, Porthun, and Lodder, RSI **65**, 3224 (1994)



200 nm

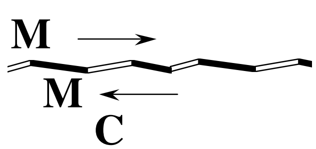
MFM resolution on order of 30nm

Nanoscale Magnetism: First Statics, H=0



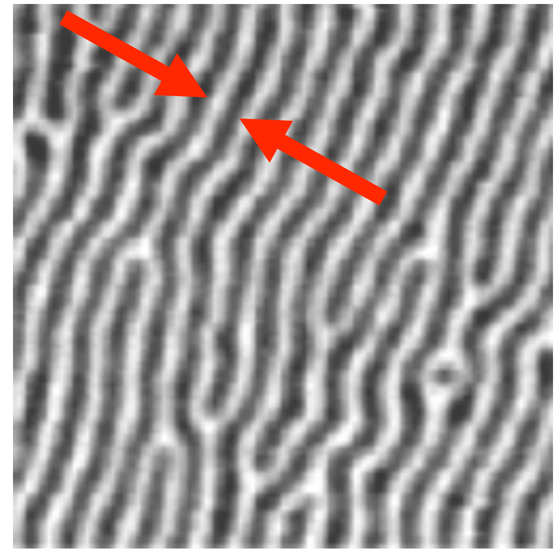
Ni with a perpendicular to the plane anisotropy. Diameters 40nm and larger, thicknesses varied around 150nm

ONR



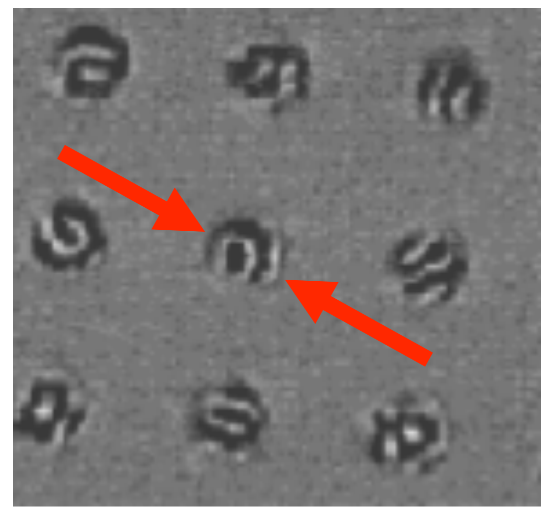
Over 3000 images have been made in dots with sizes from 40 nm to 300 nm.

Stripe period, **λ** determined in the bulk films.

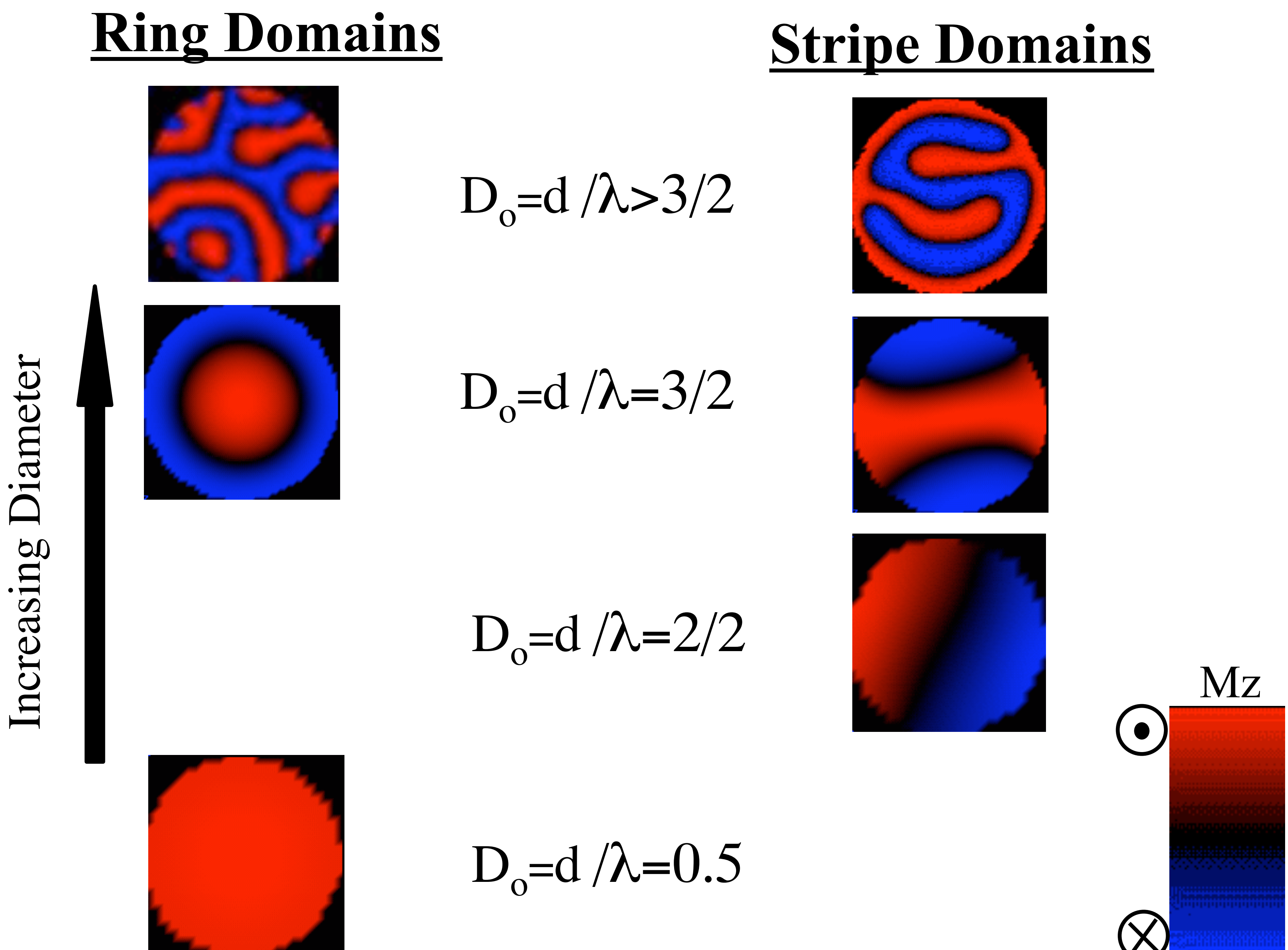


We find a single scaling parameter determines the evolution of the micromagnetic states. This parameter is $Do=d/\lambda$

Dot diameter, **d** determined by the lithography

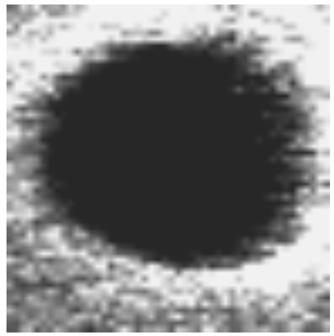


$$E = E_{exchange} + E_{anisotropy} + E_{dipole} \quad (no\ E_{zeeman})$$


Ring Domains
Stripe Domains
$D_o = d/\lambda > 3/2$
$D_o = d/\lambda = 3/2$
$D_o = d/\lambda = 2/2$
$D_o = d/\lambda = 0.5$
Increasing Diameter
Mz

Flower

Opposite Tip MFM Images

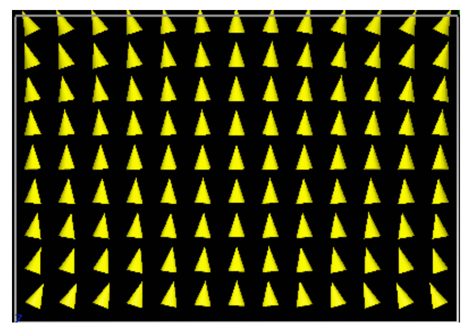


70 nm

LLG Simulation Results

70 nm

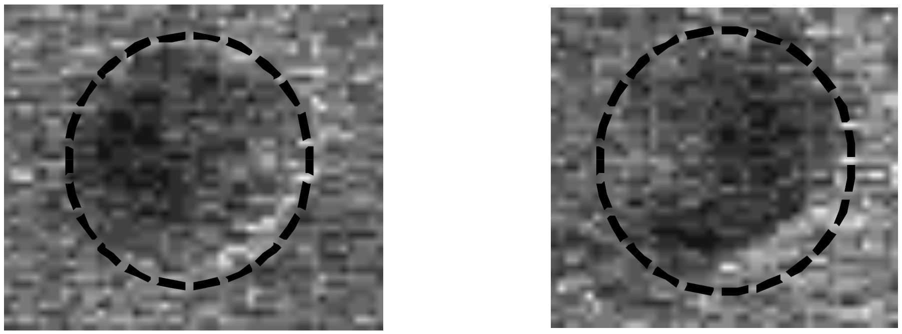
Vertical Slice



D_o: < 1/2 1/2 2/2 3/2 > 3/2

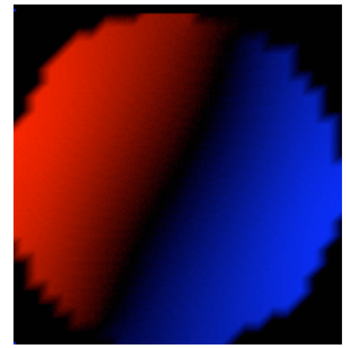
In-Plane Vortex

Opposite Tip MFM Images



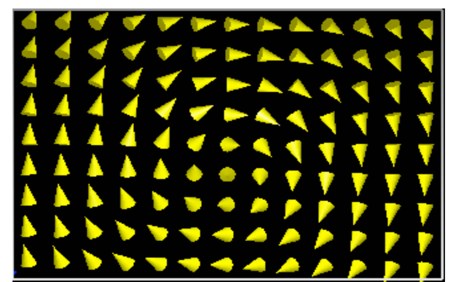
70 nm

LLG Simulation Results



70 nm

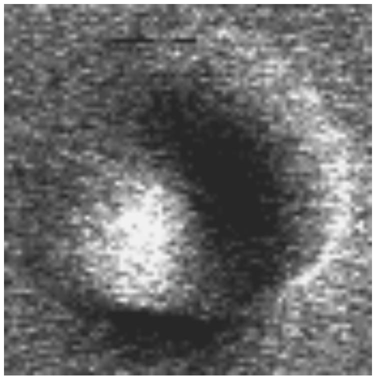
Vertical Slice

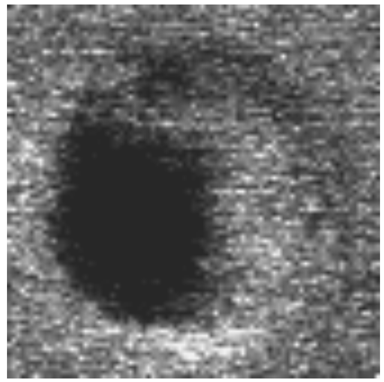


D_o: $< 1/2$ $1/2$ $2/2$ $3/2$ $> 3/2$

Crescent

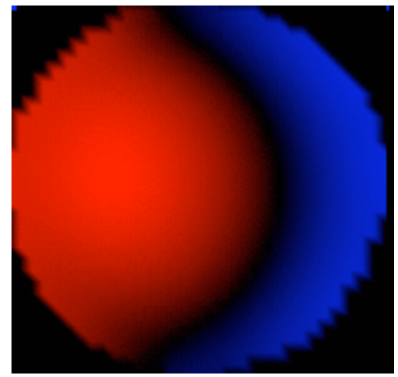
Opposite Tip MFM Images





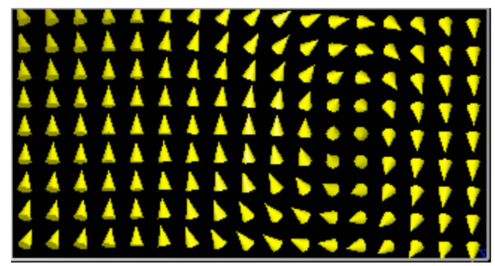
100 nm

LLG Simulation Results



100 nm

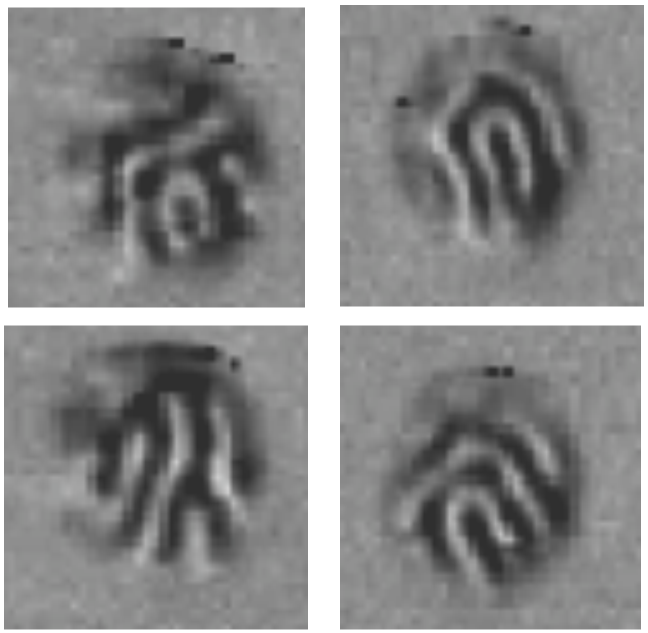
Vertical Slice



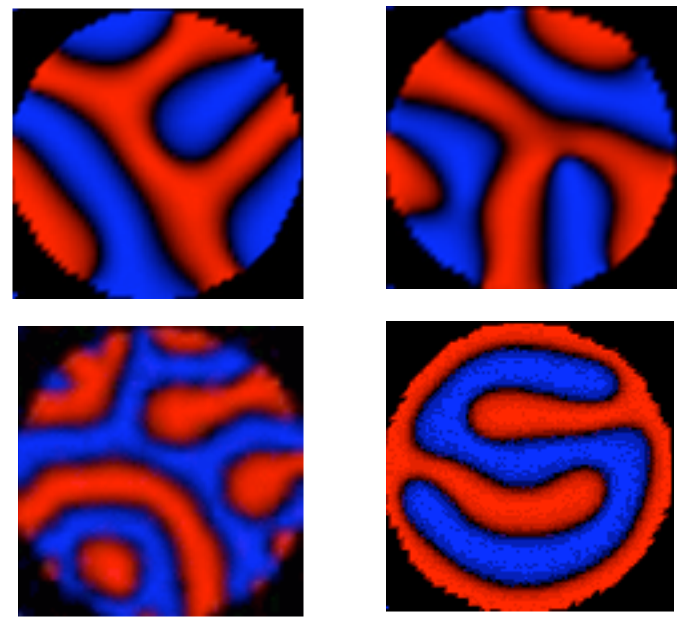
D_o: < 1/2 1/2 2/2 3/2 > 3/2

Unclassified

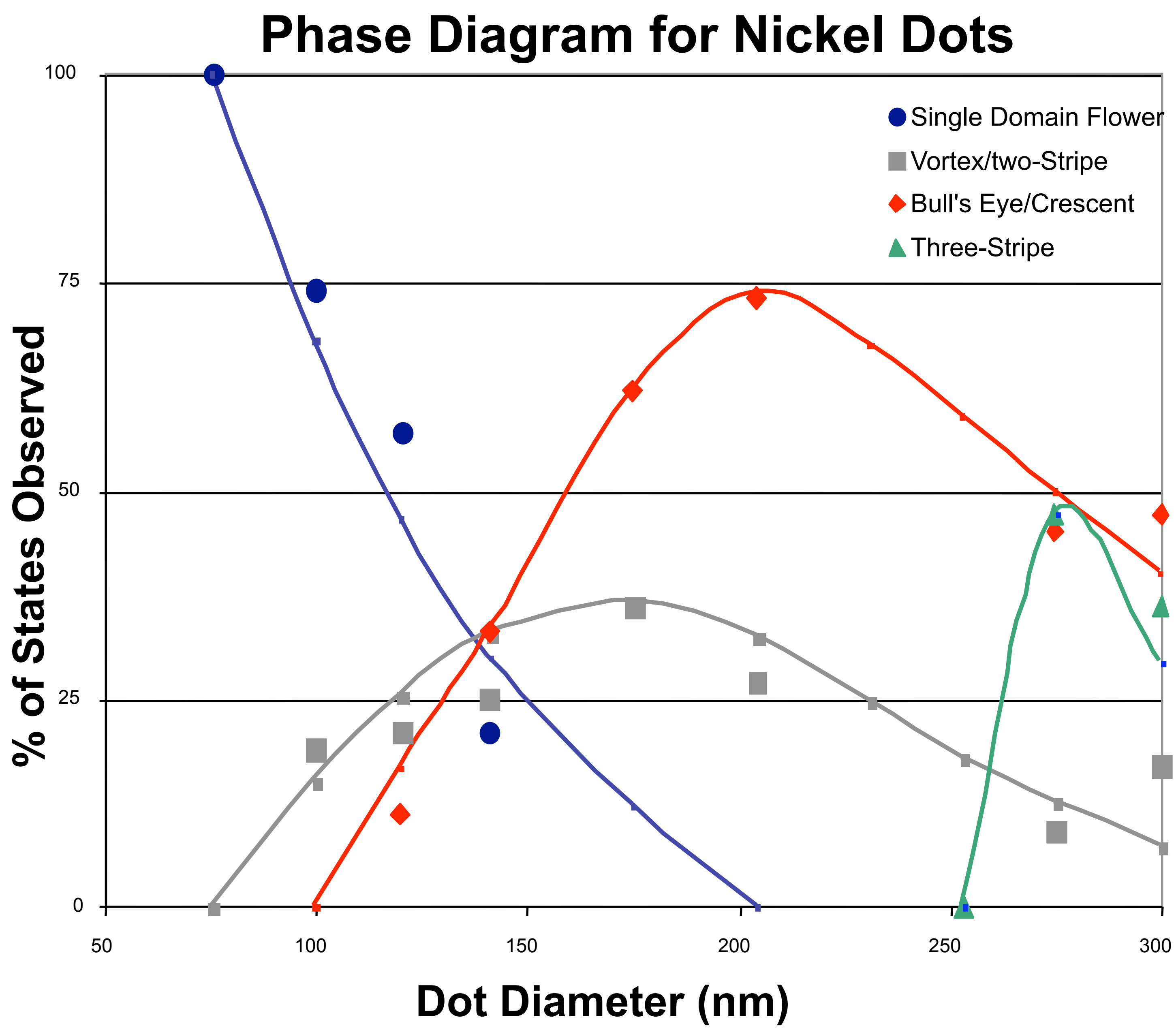
MFM Images



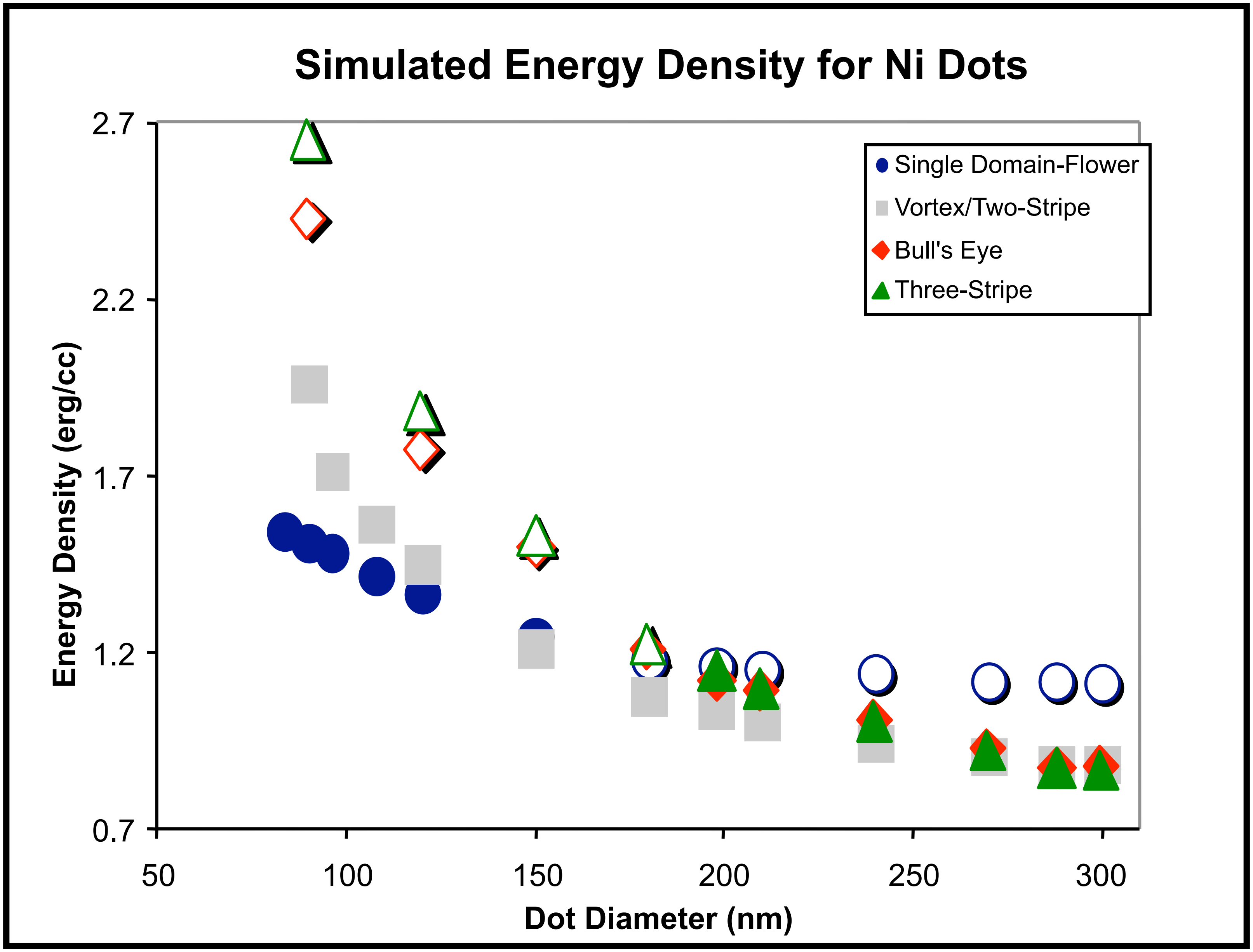
LLG Simulation Results



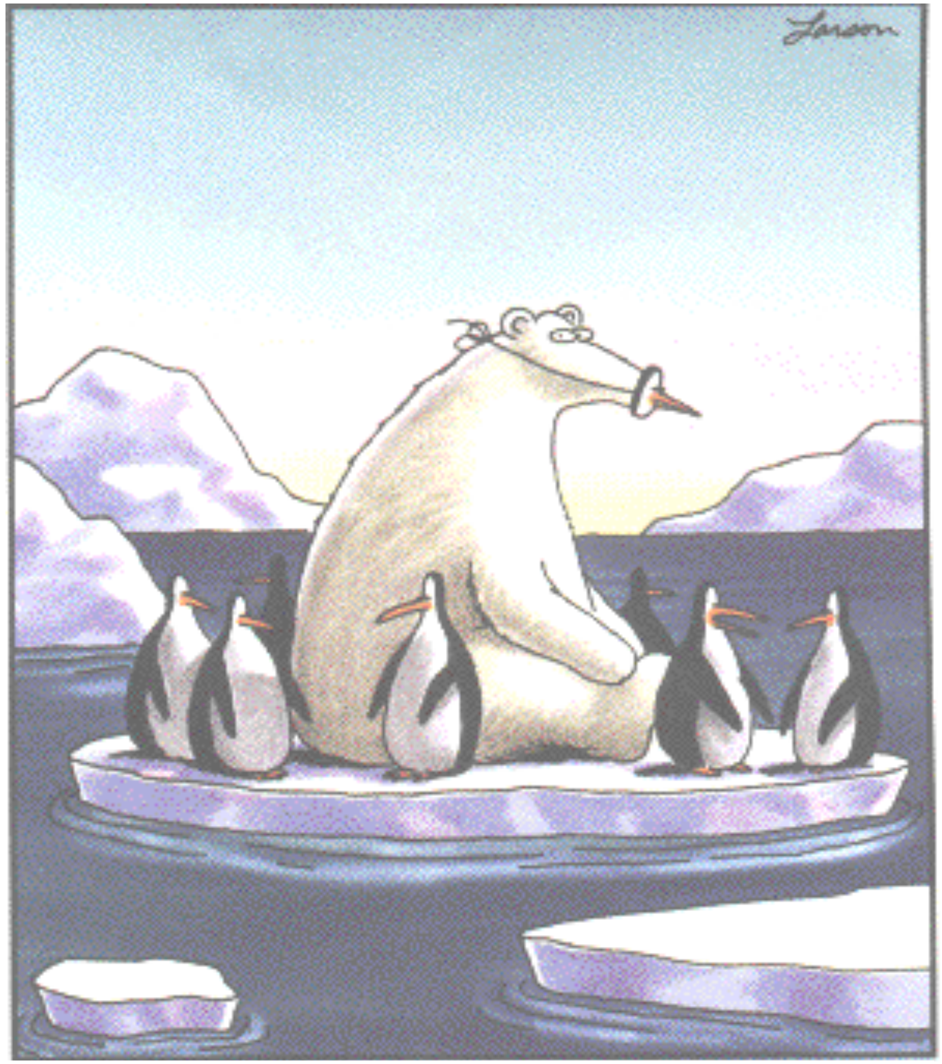
D_o: < 1/2   1/2   2/2   3/2   > 3/2



Phase Diagram for Nickel Dots
100
75
50
25
0
50
100
150
200
250
300
% of States Observed
Dot Diameter (nm)
Single Domain Flower
Vortex/two-Stripe
Bull's Eye/Crescent
Three-Stripe

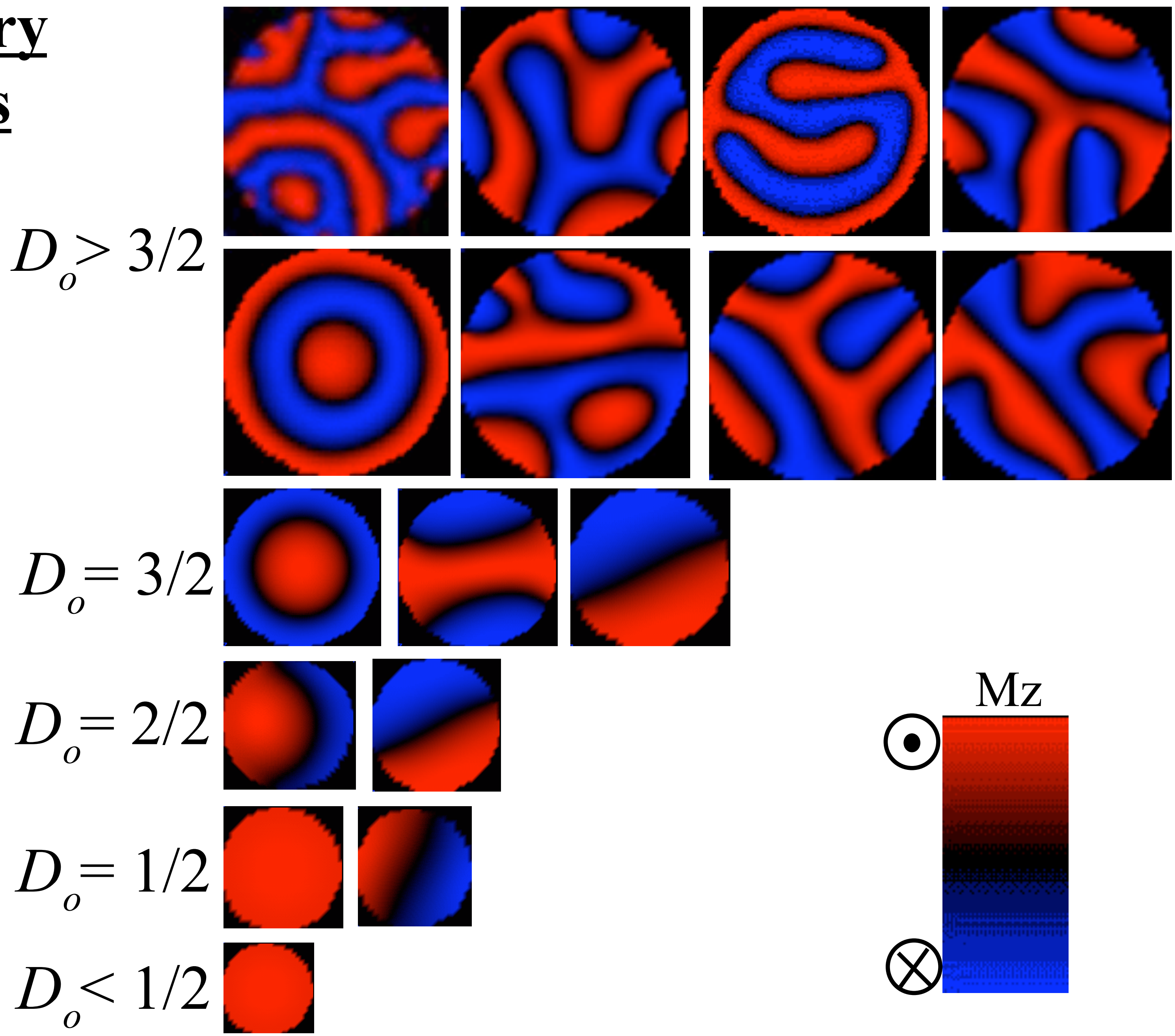

Simulated Energy Density for Ni Dots
Single Domain-Flower
Vortex/Two-Stripe
Bull's Eye
Three-Stripe
Energy Density (erg/cc)
2.7
2.2
1.7
1.2
0.7
50
100
150
200
250
300
Dot Diameter (nm)

Do the LLG energies predict the probability of occurance? **NO!**



"And now Jolene is gone….
Something's going on around here

Summary of States



Nanoscale Magnetism: Statics but H not 0

"Dan, may I be excused? My brain is full"

"But Tannner, this is even more interesting!"

Look at the magnetization processes with the application of external magnetic fields.

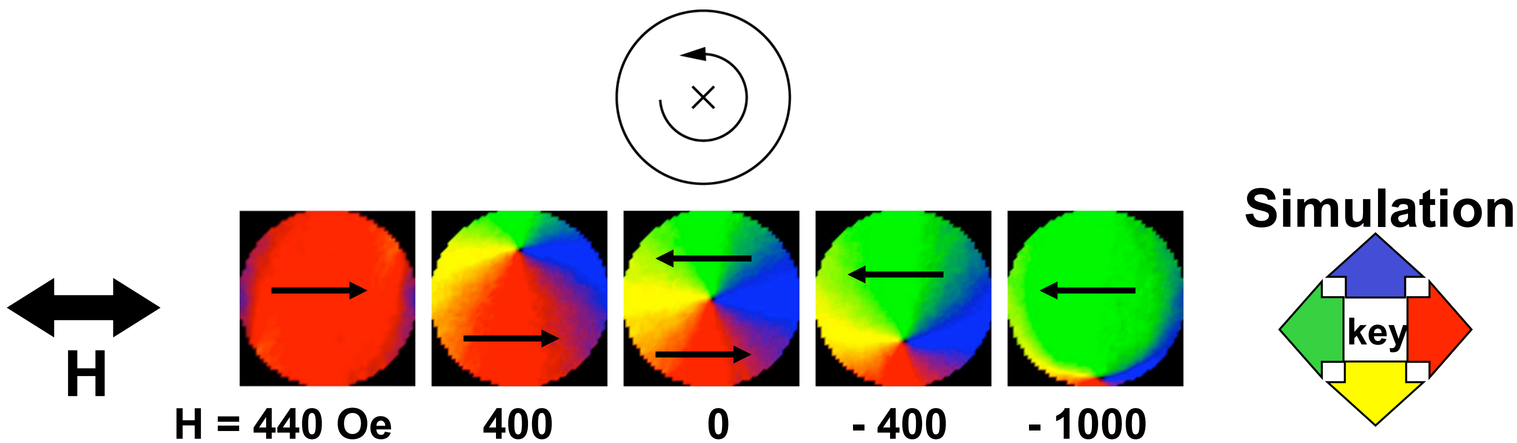
Soft magnetic particles with small in-plane or no anisotropy in a circular geometry have vortices in their ground state.

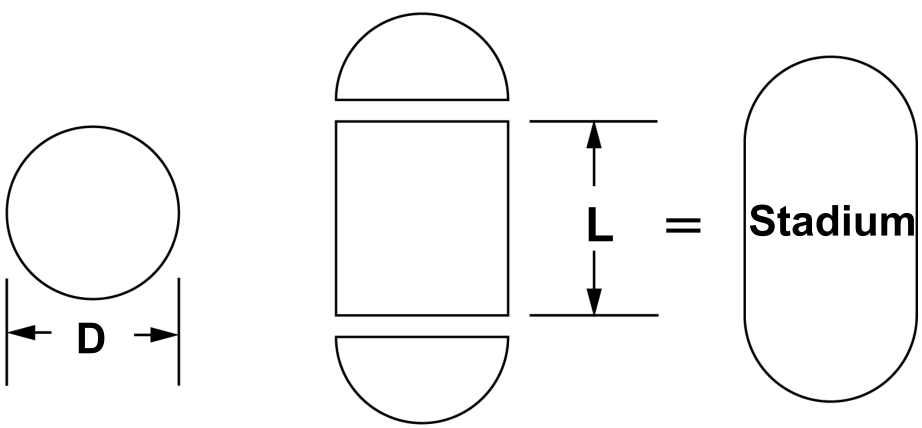
We have found that stadia shaped particles (circle with a rectangle in the middle) have multiple vortices and we can study their properties in a field, including vortex-vortex interactions.

$$E = E_{zeeman} + E_{exchange} + E_{dipole} \text{ (no } E_{anisotropy} \text{)}$$

Vortex-Antivortex Interactions in Submicron Permalloy Stadia

Pete Eames

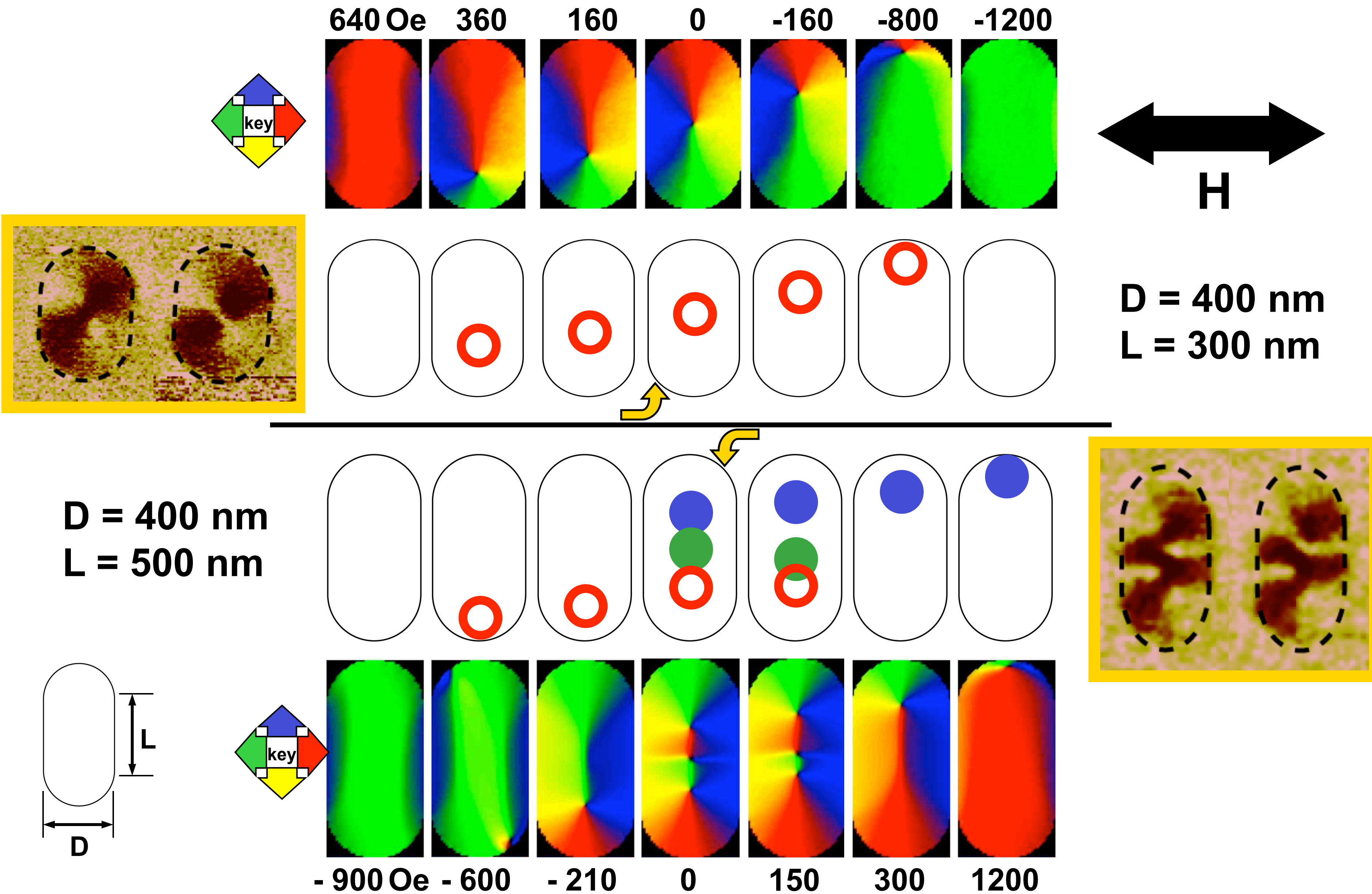




D = 400 nm
L = 300 nm

- Structures
- Nucleation
- Interactions

Virtual Particles



Summary: Ni dots

The use of the parameter $Do=d/\lambda$ is useful to describe the evolution of the domain structure in the nanodots.

As the particle diameter increases the number of metastable domain states increases rapidly, but at small diameters the magnetization state is relatively simple.

The dicotomy of the evolution is a trade off between the bulk stripes and the confining circular geometry.

LLG micromagnetic simulations agree with the MFM results and expand on the experiments by giving a detailed picture of the magnetic domain structure states.

Summary: NiFe stadia

Using geometry and applied magnetic fields we can create vortex states for model systems.

Understanding the vortex-antivortex nucleation process and the associated energies and dynamics is in progress.