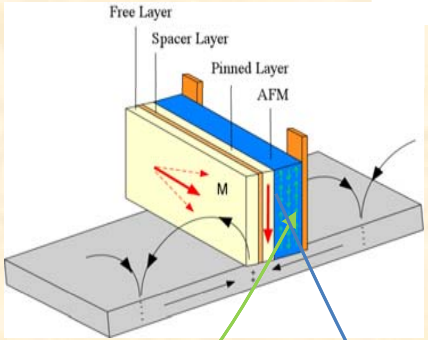
Magnetic recording, and phase transitions in the fcc Kagomé lattice:

A two-part talk.

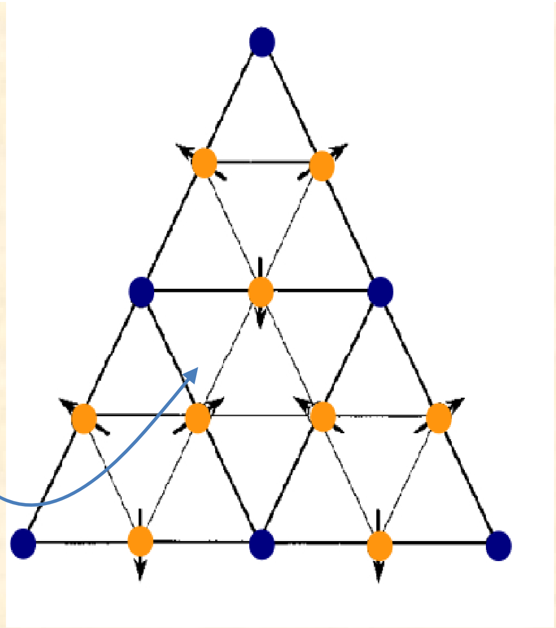
Martin Plumer Memorial University of Newfoundland

Part I.
Magnetic Recording.

Part II.
Geometrically Frustrated Antiferromagnetism

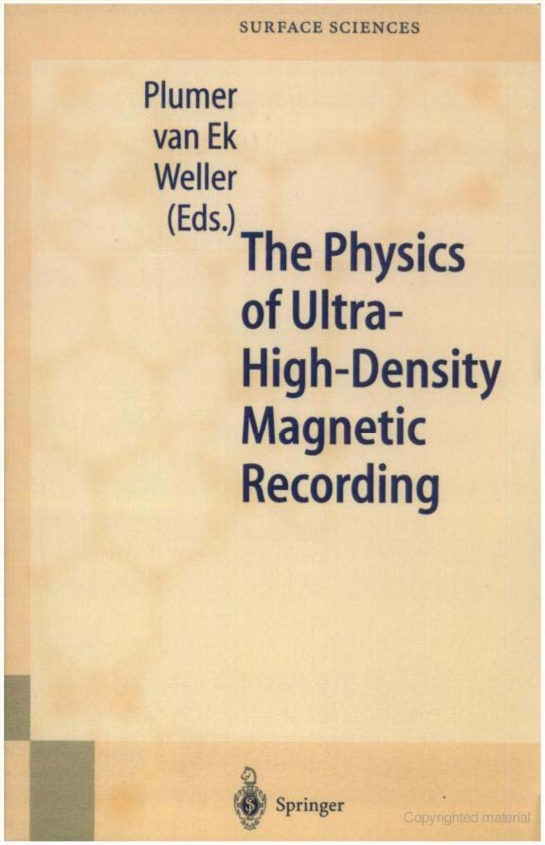


Exchange Pinning



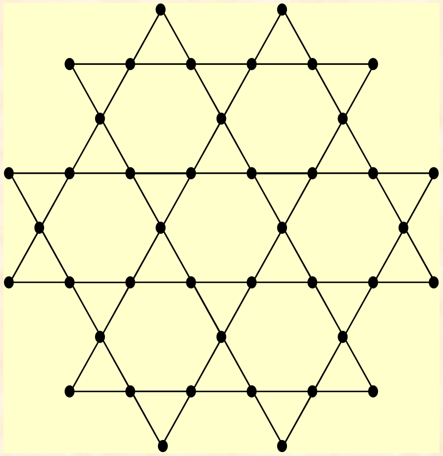
PART I. Review of Old and New Technologies in Magnetic Recording.

- Overview of *The Writer*, *The Reader* (Ir-Mn used for exchange pinning) and *The Media*.



- The Superparamagnetic Trilemma.
- The Recent: Perpendicular Recording and Dual-Layer ECC media.
- The Future (?): Many-layer ECC media, HAMR and BPM.

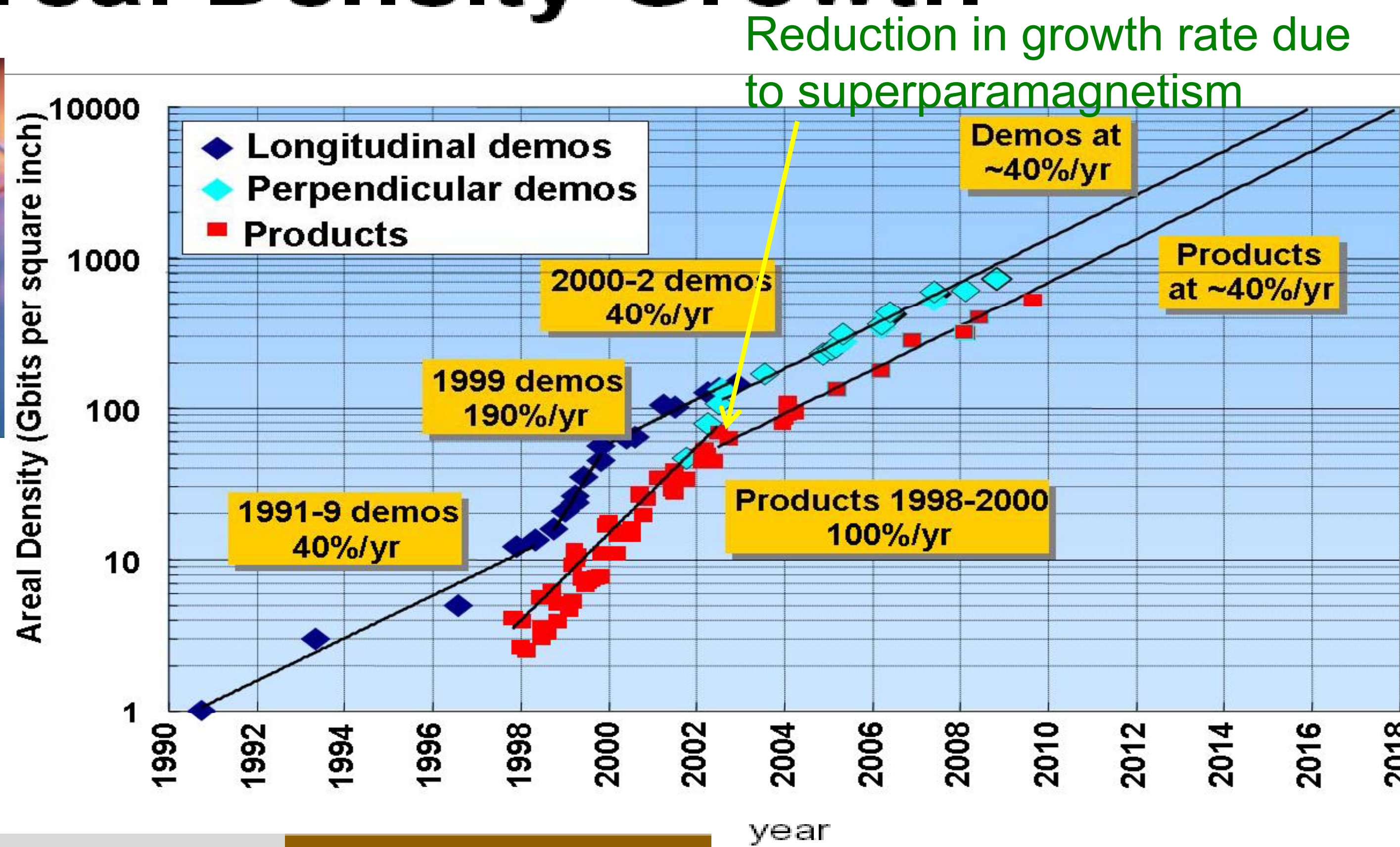
PART II. Monte Carlo Simulations *of ABC* stacked Kagomé planes.



- Review of Exchange Pinning.
- $IrMn_3$ = fcc ABC stacked Kagomé lattice.
- XY and Heisenberg models with NN exchange (8 neighbors).
- Discontinuous transitions to LRO at finite T.
- Impact of spin degeneracies on sub-lattice order parameter.
- Future simulations of exchange bias.

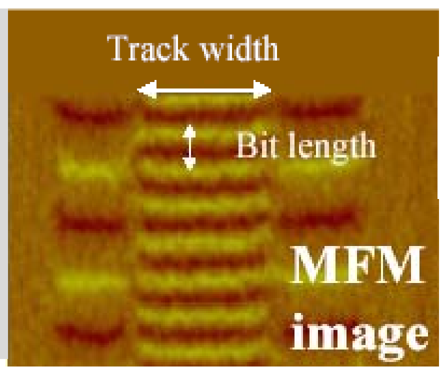
Areal Density Growth

- Additional innovations required at that point
  - heat-assisted recording
  - bit patterned media recording



AD=(1/track width)*(1/bit length)
=(tracks per inch)(bits per inch)

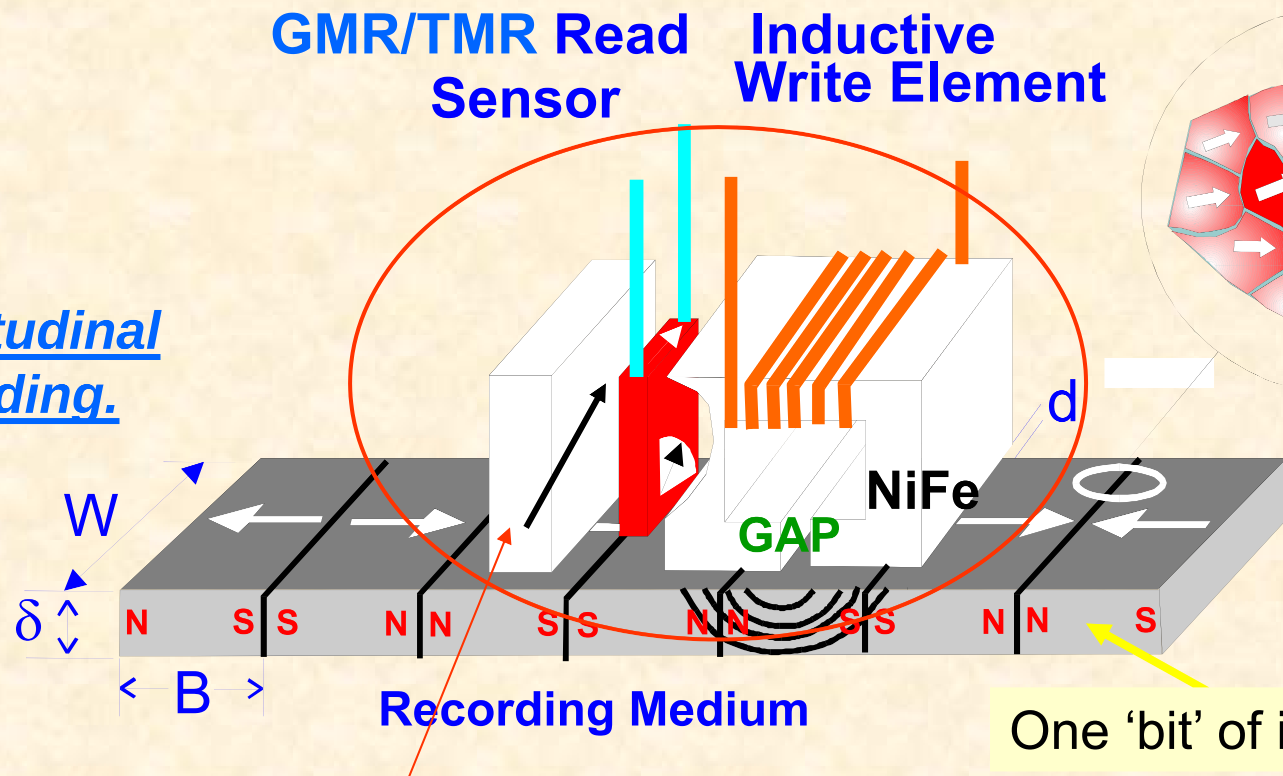
- **Today: AD ~ 500Gb/in^2 Bit length ~ 2 media grains ~ 180 Å**
- **Tomorrow: AD ~ 1000Gb/in^2. Bit length ~ 1 media grain ~ 50 Å**

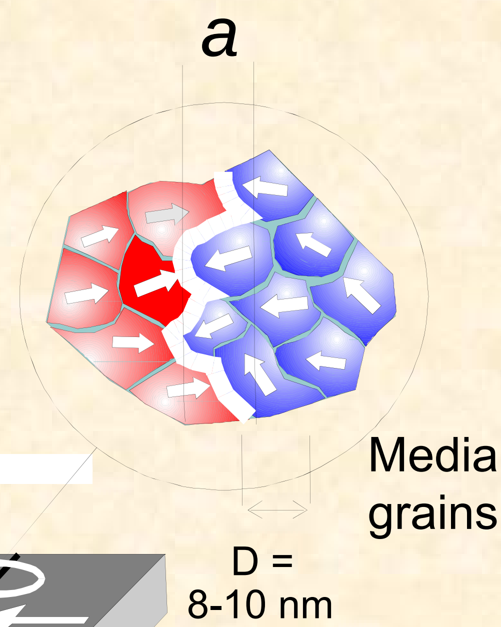


New Paradigms in Magnetic Recording, M.L. Plumer, J. van Ek, and W.C. Cain, Physics in Canada 67, 25 (2011)

The *three* elements of magnetic recording:
The Writer, The Reader, The Media.

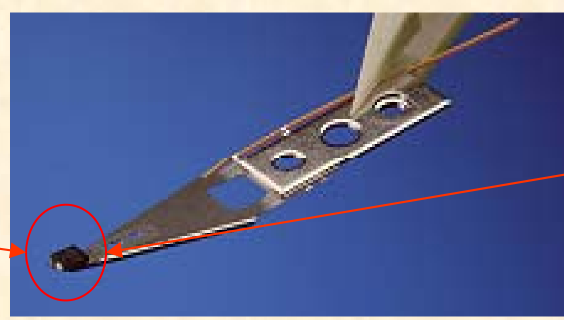
Longitudinal Recording.

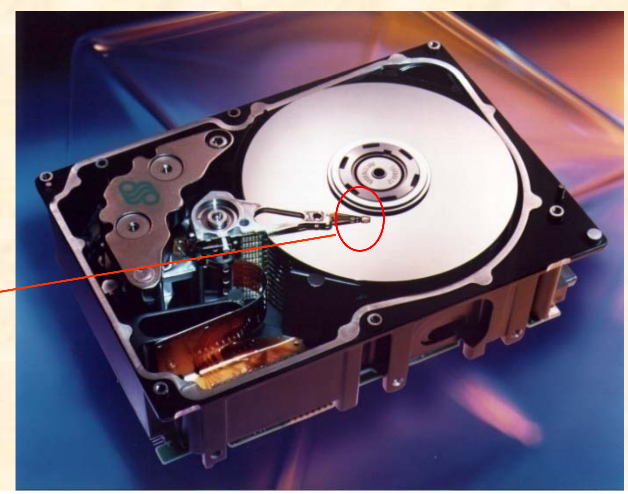




AD=(bpi)(tpi)
bpi ~ 1/B
tpi ~ 1/W

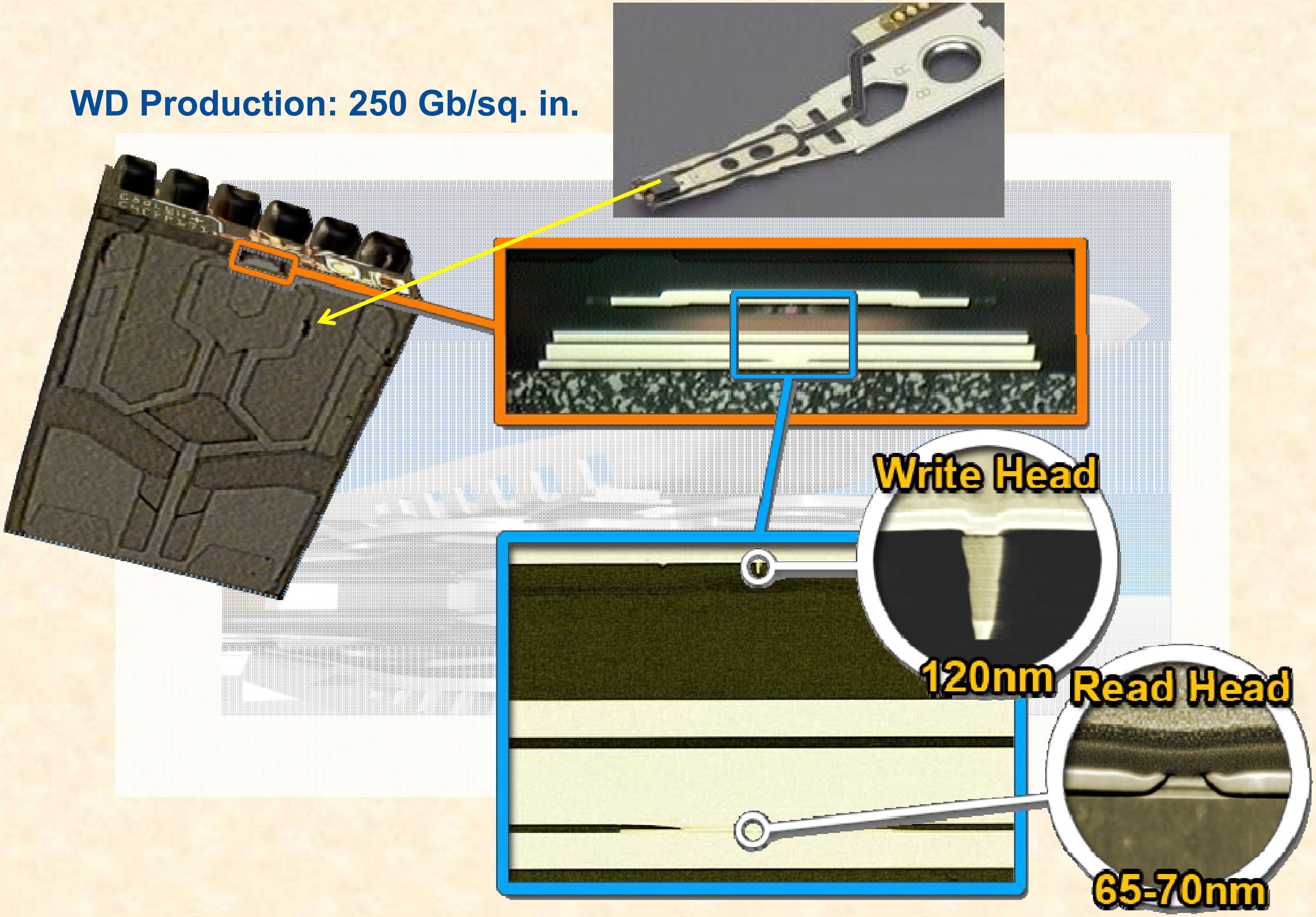
Recording Head



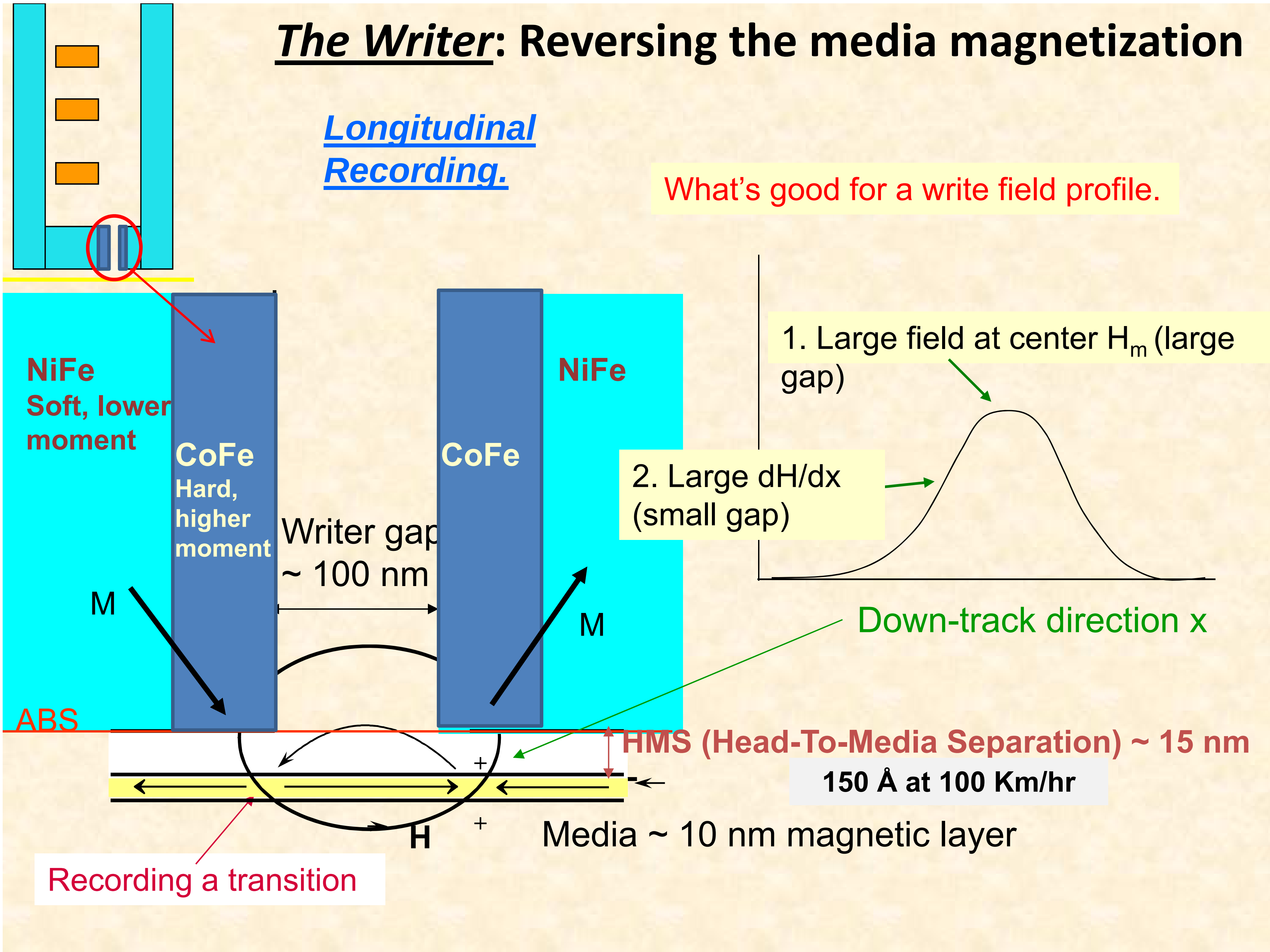


The HDD Head: Extreme Close-up

WD Production: 250 Gb/sq. in.

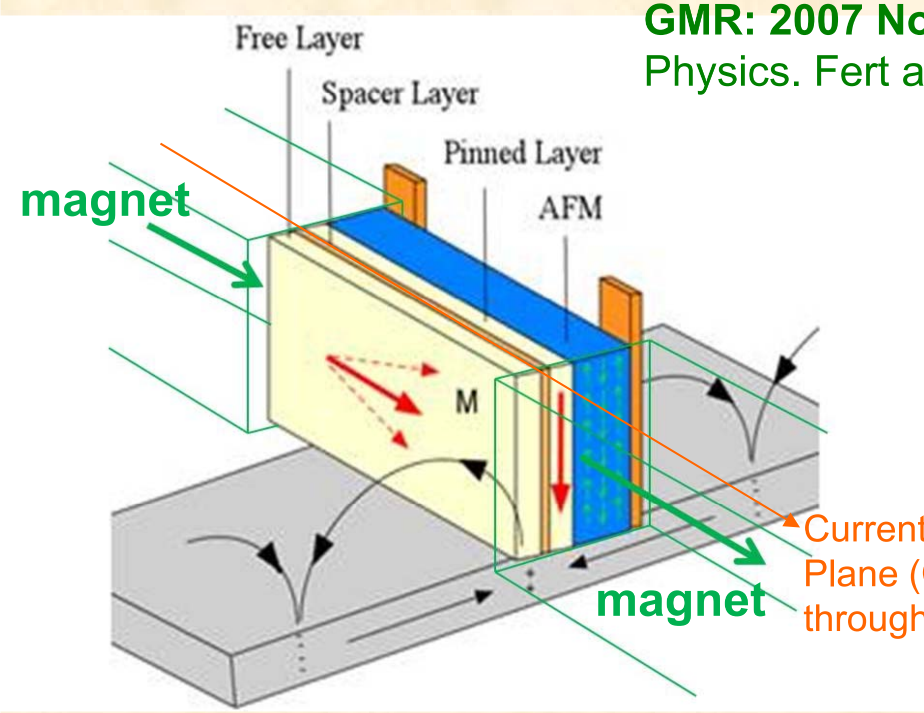


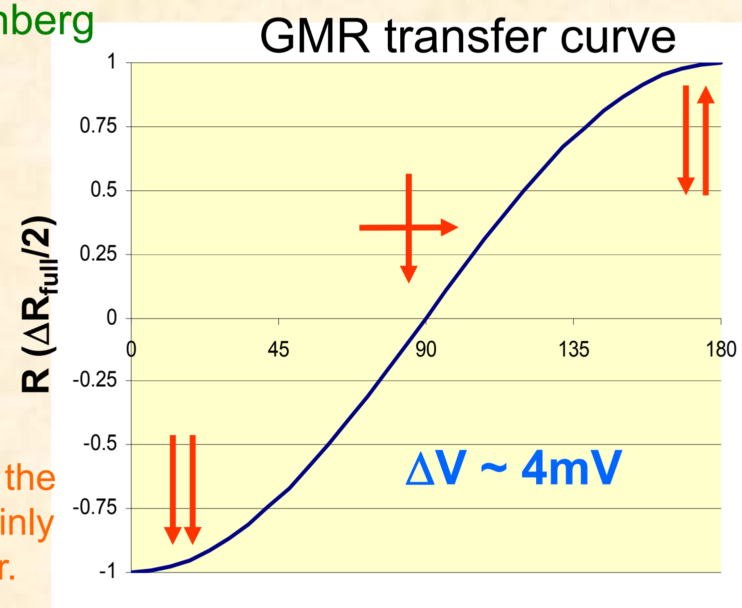
The Writer: Reversing the media magnetization



The Reader: Detection of media magnetization reversal.

GMR: 2007 Nobel Prize in Physics. Fert and Grünberg



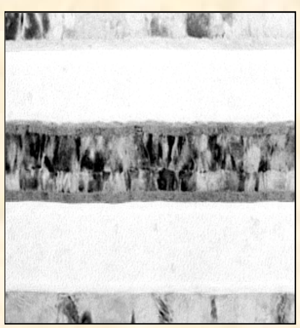


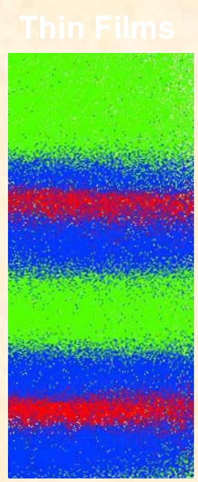
AFM = Ir-Mn (High T_N). 200 Å

media **PL = CoFe (big moment). 25 Å**

FL = $Ni_{80}Fe_{20}$ Permalloy 25 Å

TEM

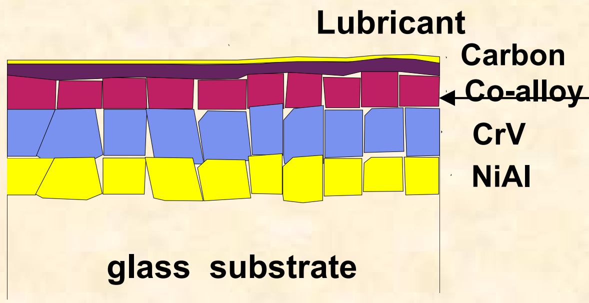




ABS view

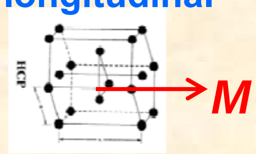
GMR effect involves surface and bulk scattering of spin polarized electrons between the Free Layer and Pinned Layer.

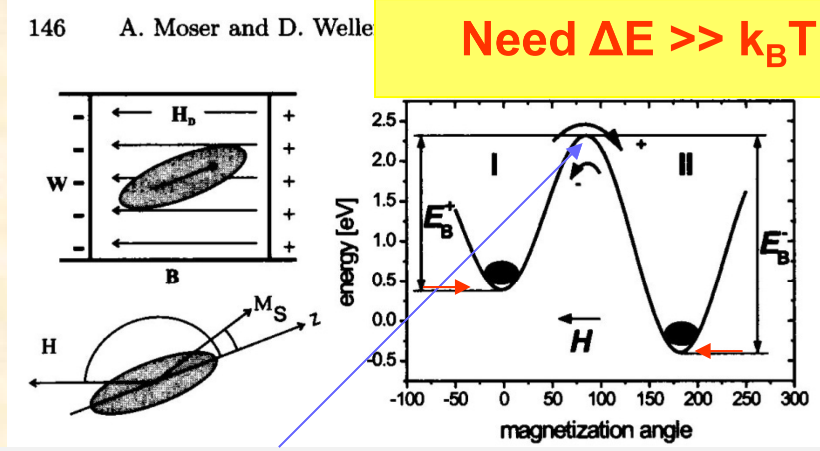
The Media: A “hard” granular magnet



CoCrPt

longitudinal

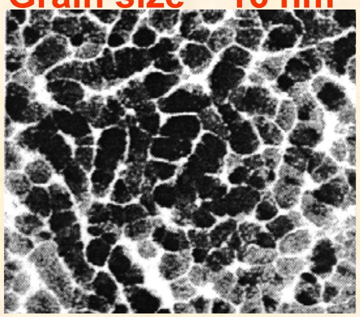




Need $\Delta E \gg k_BT$

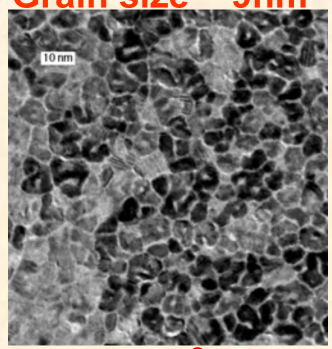
ΔE = (crystal anisotropy)(grain volume = K*V

Grain size ~ 16 nm



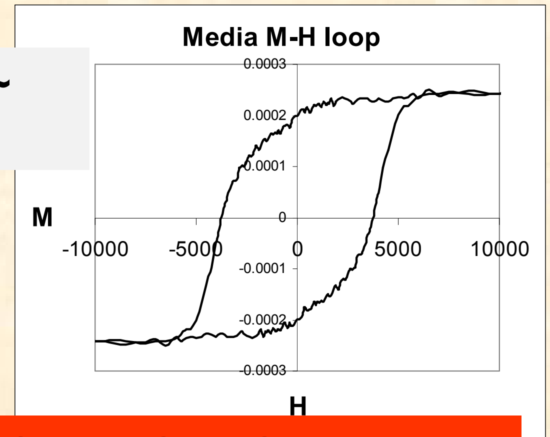
1 Gbit/in^2 media

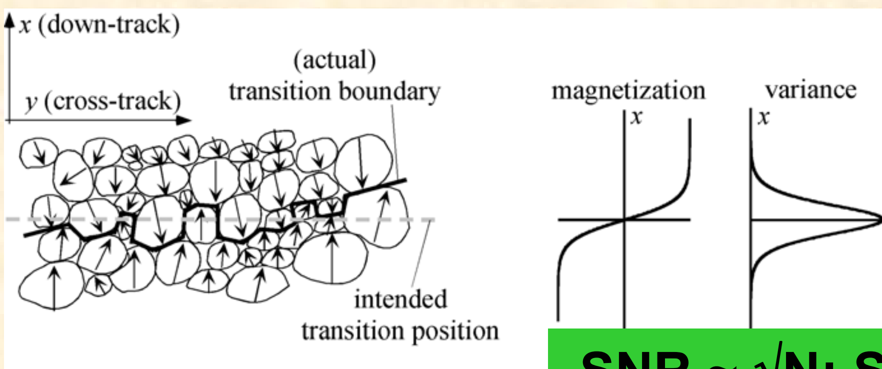
Grain size ~ 9nm



50 Gbit/in^2 media

Switching Field ~ $H_c=2K/M_s$





SUPERPARAMAGNETISM: Smaller grains are *worse* for thermal stability (‘thermal idiots’).

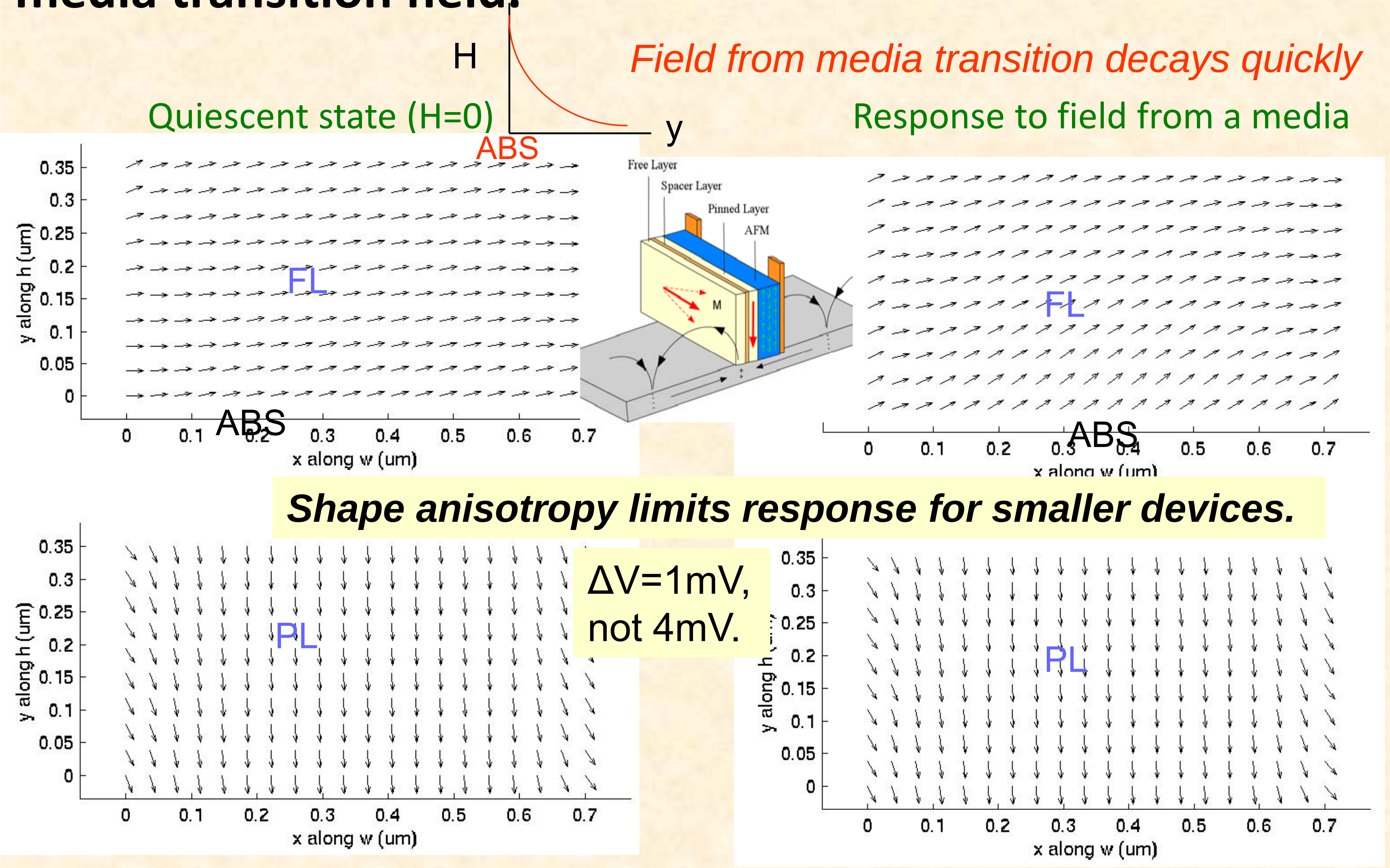
SNR ~ √N: Smaller grains are *better*.

The Trilemma **of shrinking dimensions.**

1. Smaller bits require smaller media grains to maintain SNR.
2. Smaller grains require larger anisotropy (energy barrier) to maintain thermal stability.
3. Larger anisotropy requires larger write fields to switch media transitions.

- Also: Smaller dimensions lead to less responsive read elements (magentically).
- Larger write fields require large moment materials to put at the business end of the write element.
- CoFe at 2.4 Tesla is the largest moment material stable at room temperature ***and has been used since 1999***.

Micromagnetic Modelling of the spin valve response to a media transition field.



Shape anisotropy limits response for smaller devices.

ΔV=1mV, not 4mV.

What then ? *Perpendicular Recording* (even more 'oriented')

From *Yahoo.com Jan. 16, 2006.*

Technology Boosts Hard Drive Capacity (120 GB to 160 GB)

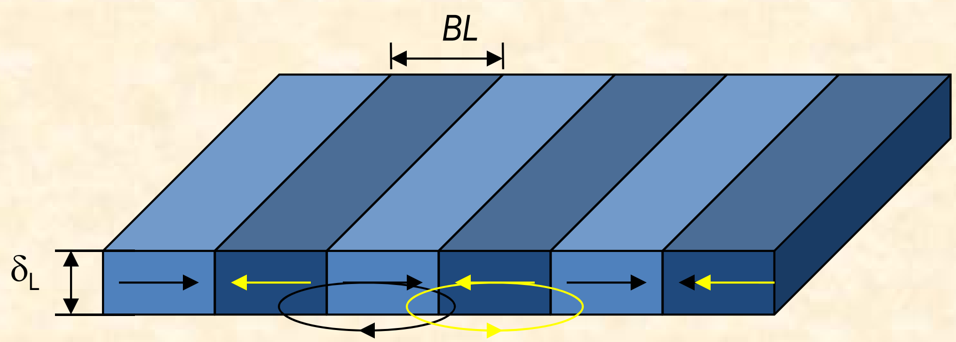
By MATTHEW FORDAHL, AP Technology Writer 1 hour, 8 minutes ago

SAN JOSE, Calif. - **Seagate Technology LLC has started shipping a notebook PC hard drive that overcomes an obstacle many feared would be a major roadblock to the further expansion of disk capacity — and the overall growth of the storage industry.**

The new approach that aligns bits of data vertically rather than horizontally enables Seagate — and other drive vendors — to further boost the density of drives without increasing the risk of scrambling data.

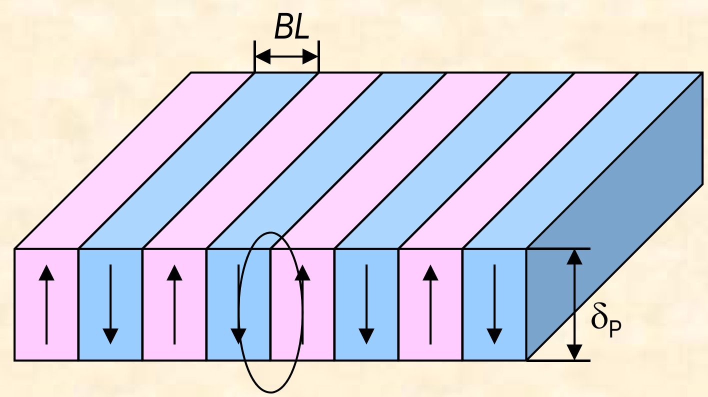
Perpendicular Recording: The ultimate in control of anisotropy-direction distributions

<u>Longitudinal Recording</u>



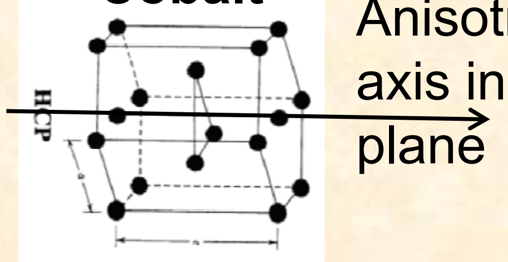
Magnetostatic fields destabilize the transitions (superparamagnetism).

<u>Perpendicular Recording</u>



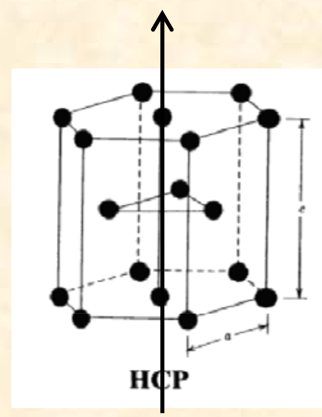
Magnetostatic fields stabilize the transitions.

Cobalt



Anisotropy axis in plane

Hard to control distributions

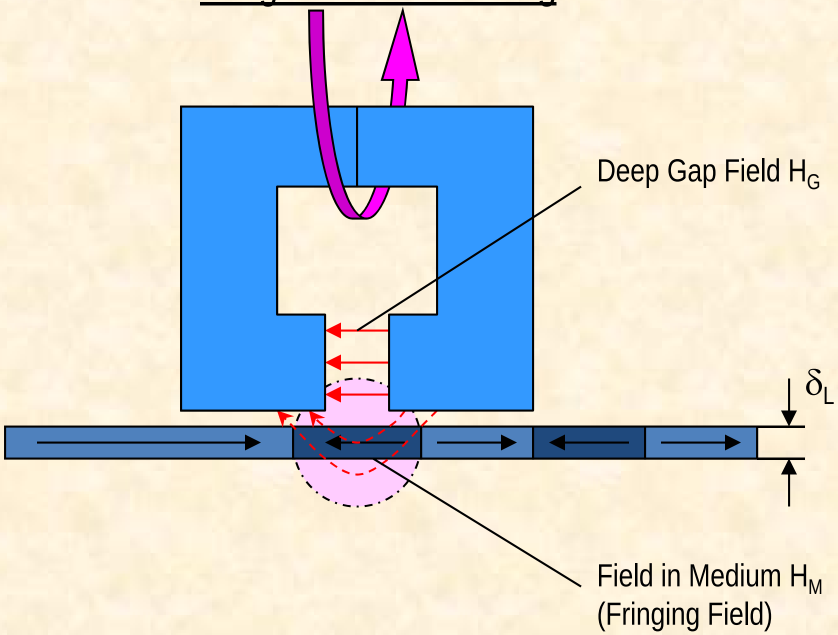


Anisotropy axis out of plane

Easier to control

Larger Write Fields due to media soft underlayer.

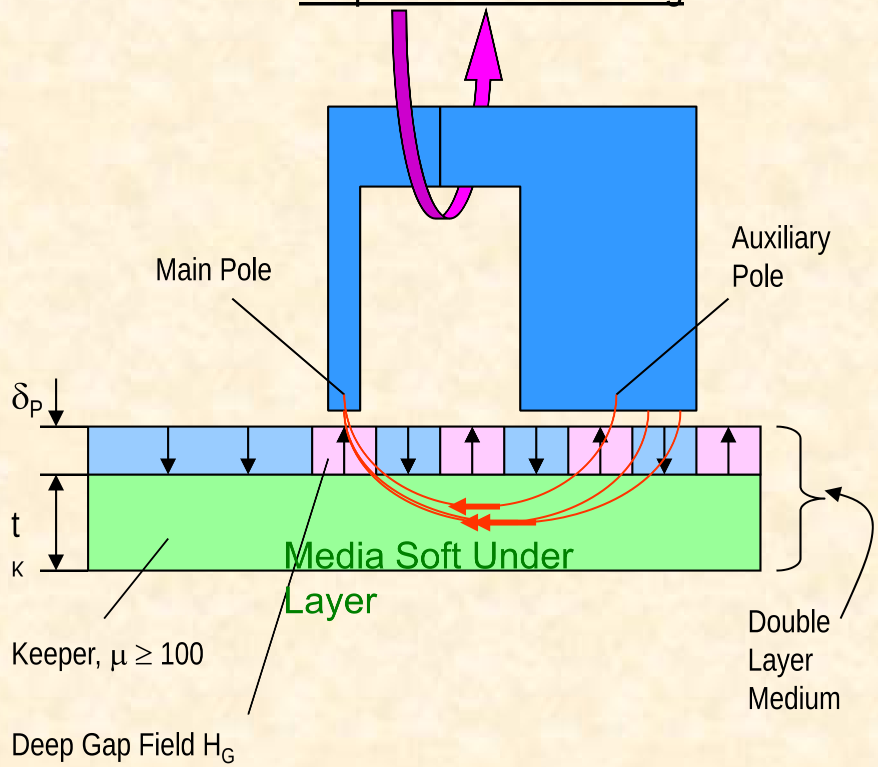
Longitudinal Recording



Single layer medium (longitudinal or perpendicular):

- *Transition is recorded by fringing field*

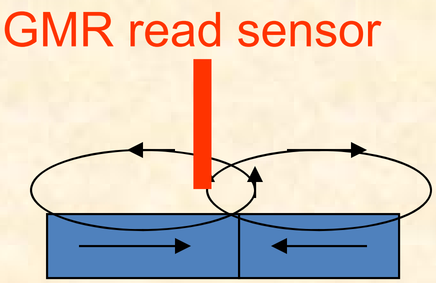
Perpendicular Recording

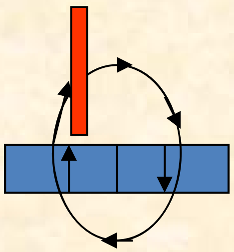


Double layer perpendicular media with soft magnetic Underlayer: media becomes part of the write element

- *Transition is recorded by deep gap field: 50 % boost.*

…and more field emanating from media transitions





Stronger fields from perpendicular bits = larger play-back amplitude.

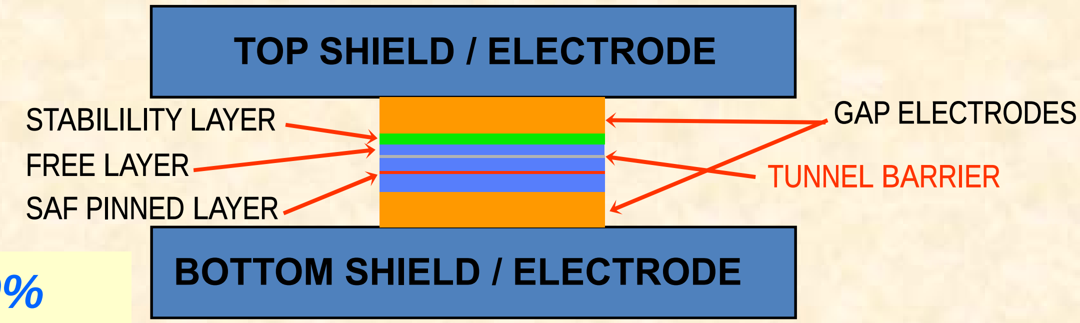
Another ~50% boost.

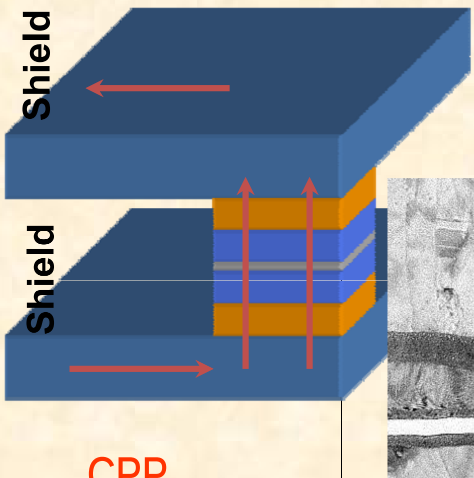
And TMR…Tunneling GMR Heads:

Double the read-sensor amplitude.

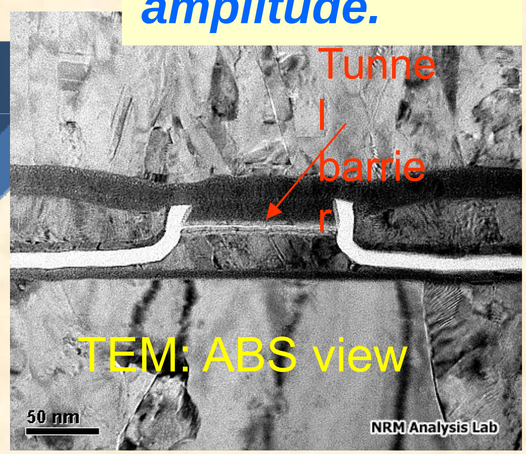
- **New Structure**
- **New materials**
- **New physics**

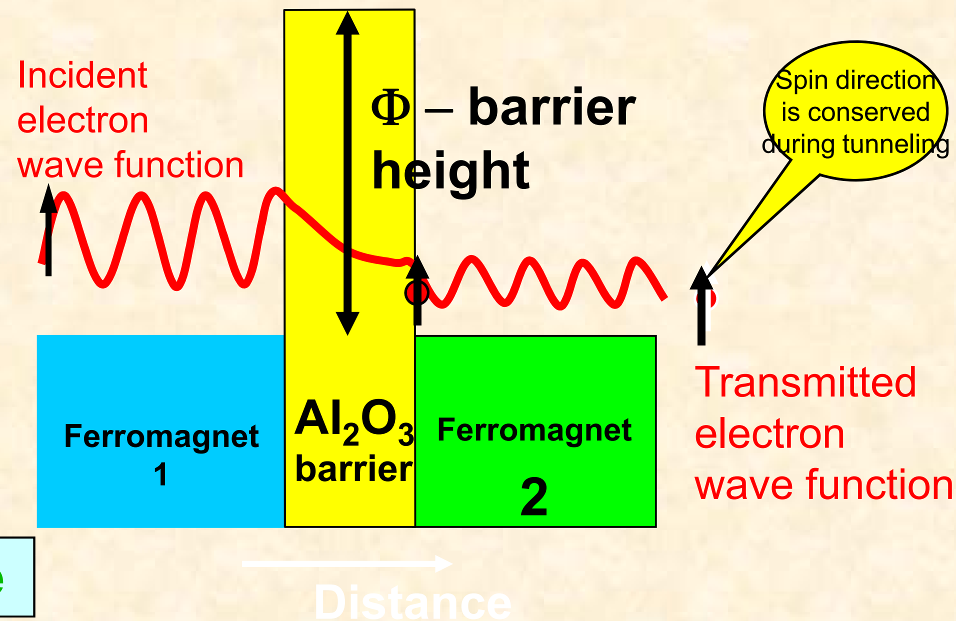
(aka: MTJ, SDJ, Tunnel valve, spin tunneling head)





Another 50% boost in amplitude.



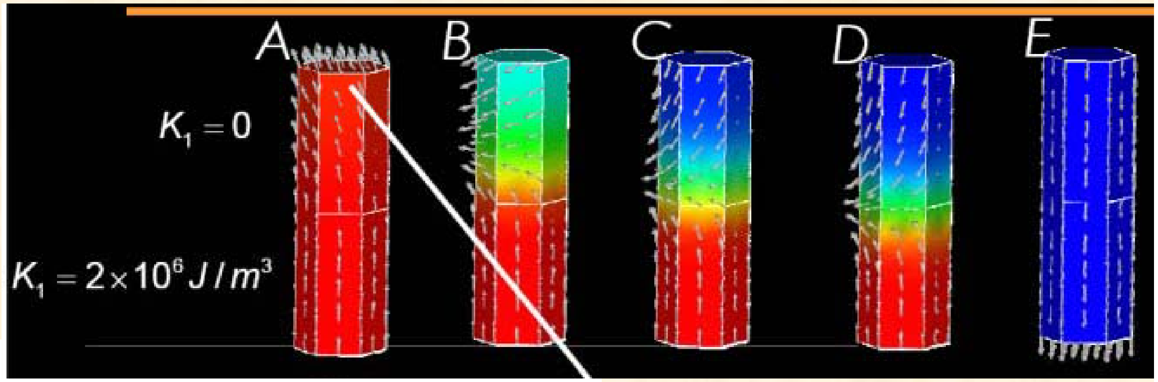


CPP = Current Perpendicular to Plane

Exchange-Coupled-Composite Media:

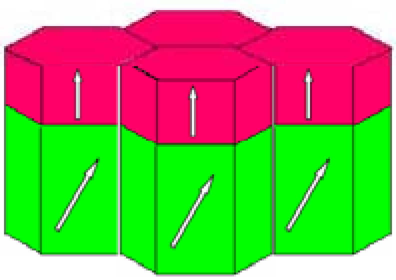
Easier to reverse with same thermal stability.

Gerardo BERTERO Western Digital Corporation



Introduction to ECC media

Material with extremely high anisotropy Ku and volume V_{hard}. Store information. Provide thermal stability



Soft material with volume V_{soft}. Facilitate switching of the grain.

$K_u x V_{hard}$

$$\xi = \frac{2\Delta E}{M_s H_s V}$$

$V_{hard} + V_{soft}$

$$\frac{(M_{hard}V_{hard} + M_{soft}V_{soft})}{V_{hard} + V_{soft}}$$

This term can be used to compare the switching fields of different kind of media with the same thermal barrier, volume and magnetization

UNIVERSITY OF MINNESOTA

R.H. Victora and X. Shen, *IEEE Magnetics* ***41,*** *537-542 (2005).*

D. Suess *et al., J. Magn. Magn. Mat.* ***551,*** *290-291 (2005).*

Figure of merit:

Ratio of thermal energy barrier to switching energy.

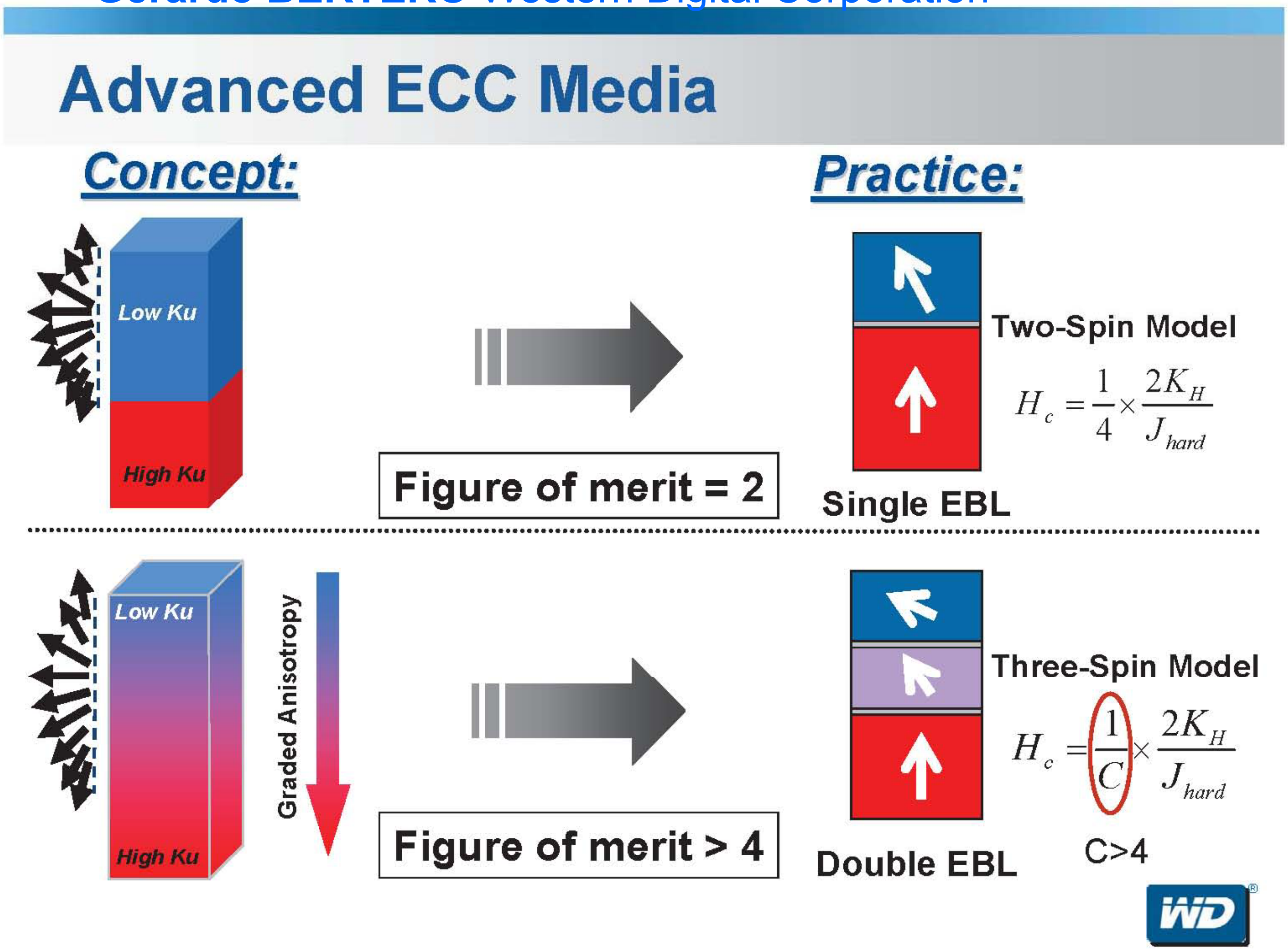
ξ= 1 for single-layer

ξ = 2 for dual-layer

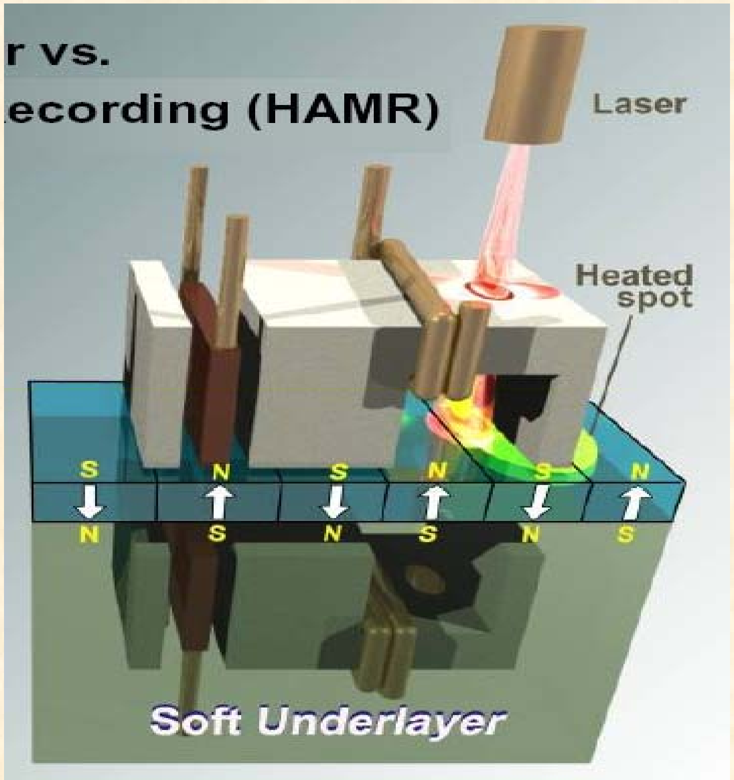
Now What ?

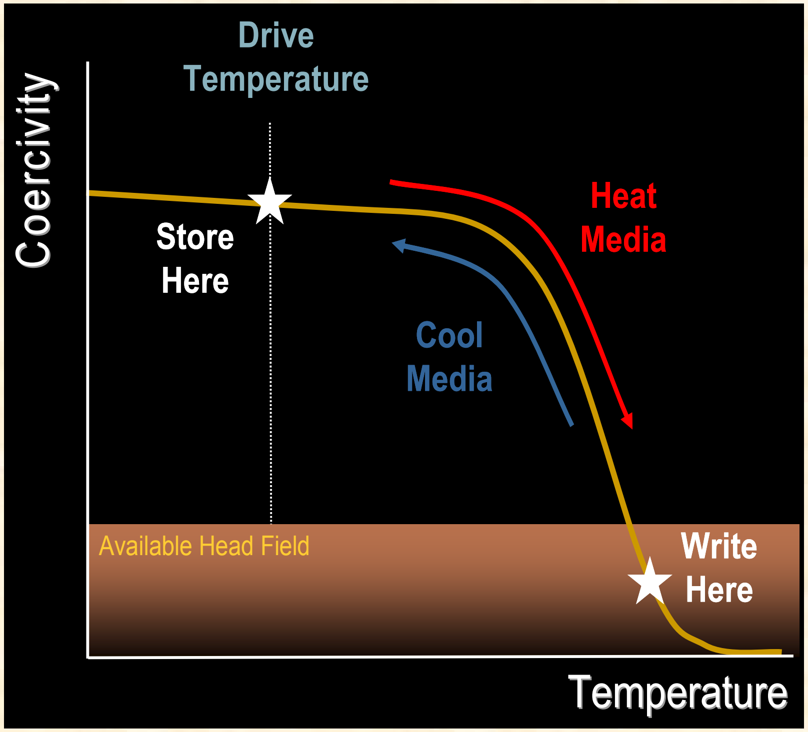
Try more: Multi-Layer ECC Media

Gerardo BERTERO Western Digital Corporation



Try exotic. HAMR – Heat Assisted Magnetic Recording



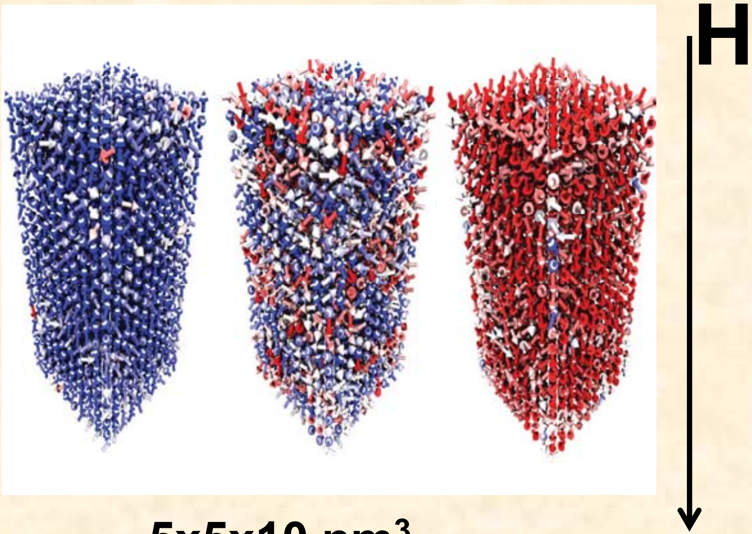


• The challenge in making HAMR work is in creating sufficiently small spatial thermal gradients that will prevent interference between adjacent bits.

Modeling HAMR at the atomic scale using LLG.

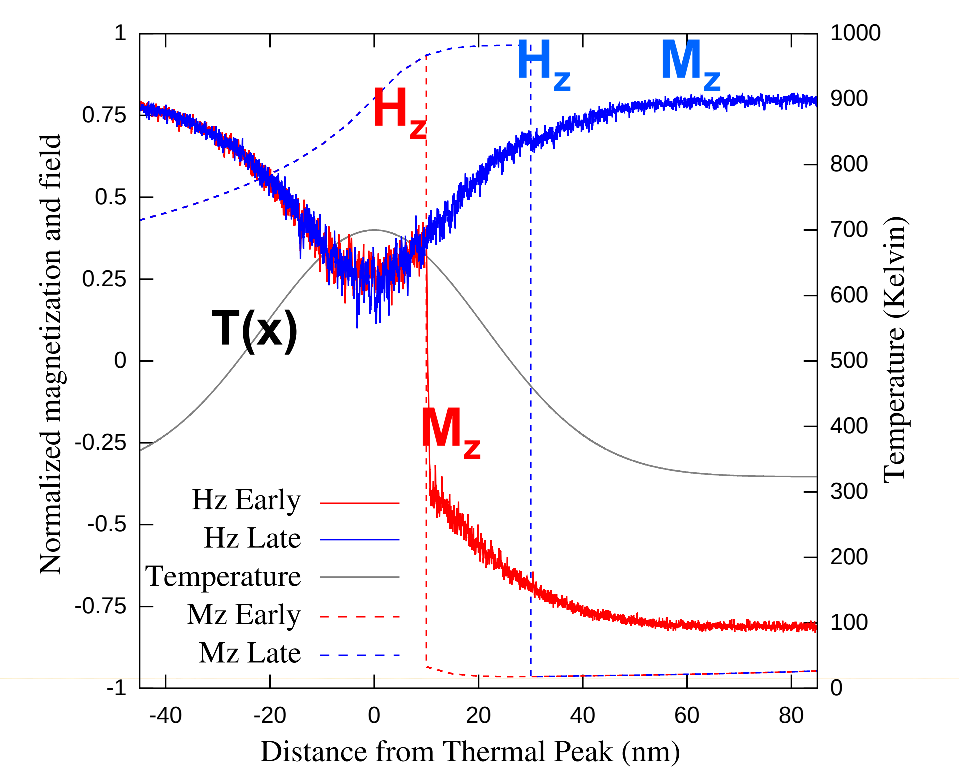
J.I. Mercer, M.L. Plumer, J.P. Whitehead, and J. Van Ek, Appl. Phys. Letts. 98, 192508 (2011).

Each grain = 2000 'spins'



5x5x10 nm³

Grain reversal is highly non-uniform.



X = Down track direction

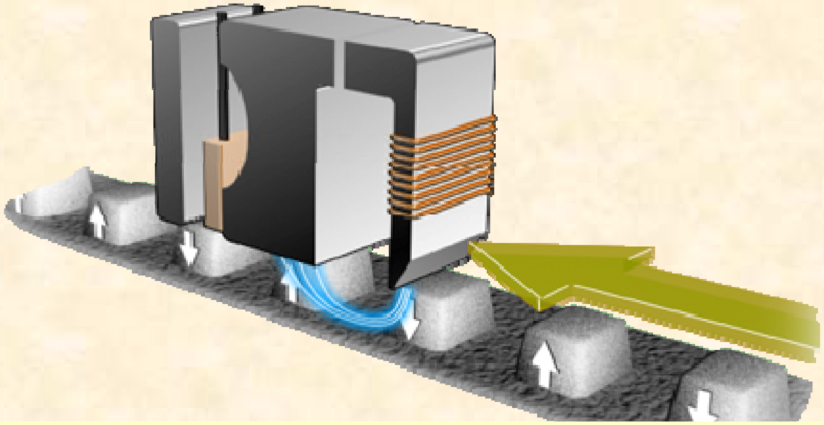
Position of temperature pulse relative to head field maximum is crucial.

Challenges.
- **Control of thermal spot size.**

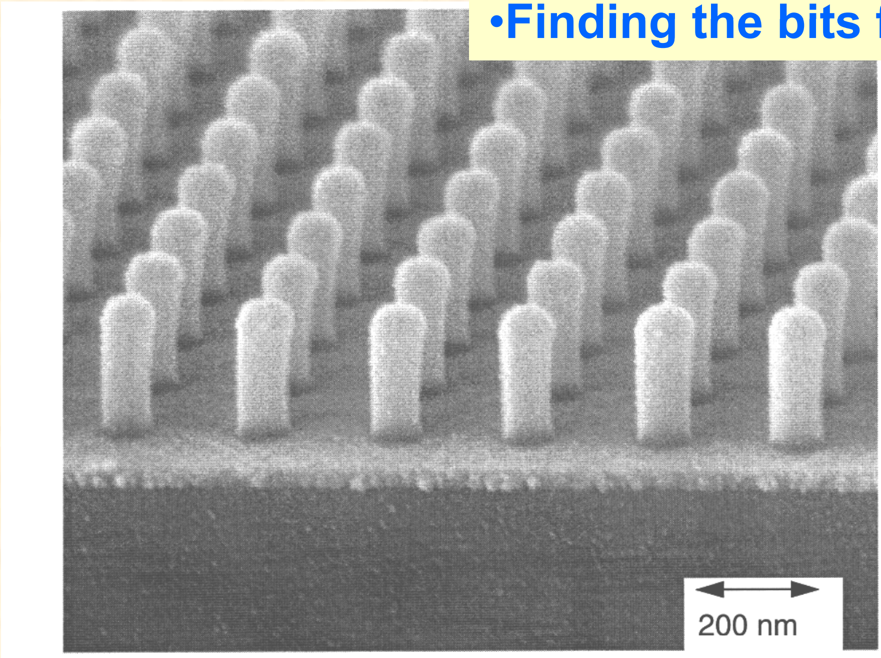
Try more control:

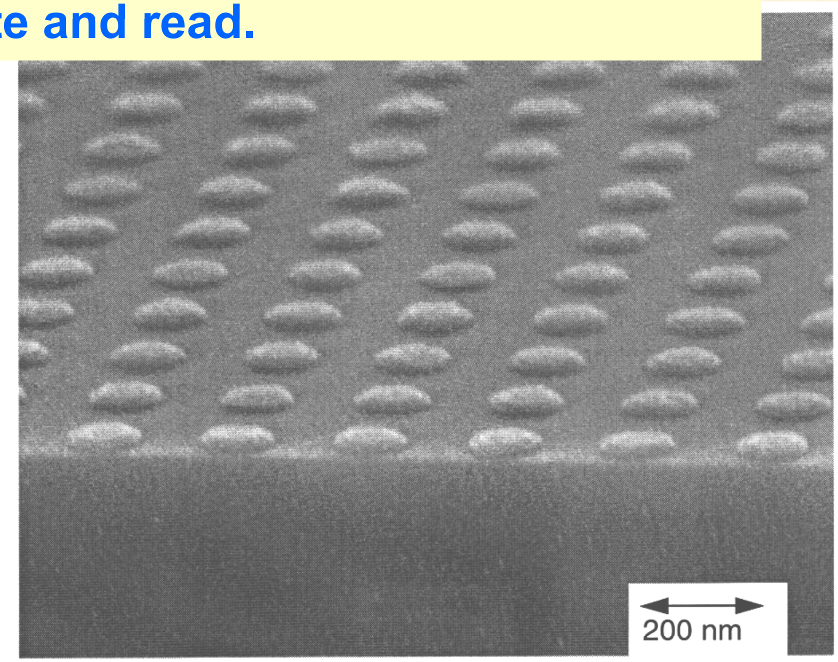
Bit Patterned Media

Lithographically Patterned Bits:
One bit = one magnetic grain to decrease transition jitter and increase SNR.



Challenges.
- **Making them small enough (1 Tb/in^2 $\Longrightarrow$ 13 nm bits).**
- **Finding the bits for write and read.**





100 nm diameter Co/Cu bilayer dots with 200 nm period

Conclusions (Part I)

- Large number of new technologies introduced into magnetic recording over the past decade: GMR, Perpendicular, TMR, ECC,…

- New paradigms such as HAMR or BPM will be very challenging to implement effectively.

- Most likely advances in *Areal Density* in the near future will come from materials science and increased understanding of the underlying physics through numerical simulations.

Seagate HAMRs hard drives to 1Tb per square inch

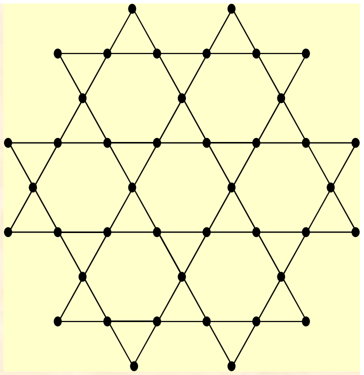
Published on 20th March 2012 by Gareth Halfacree

Seagate's HAMR-based hard drives could, it claims, store up to 60TB of data before the technology reaches its upper limit.

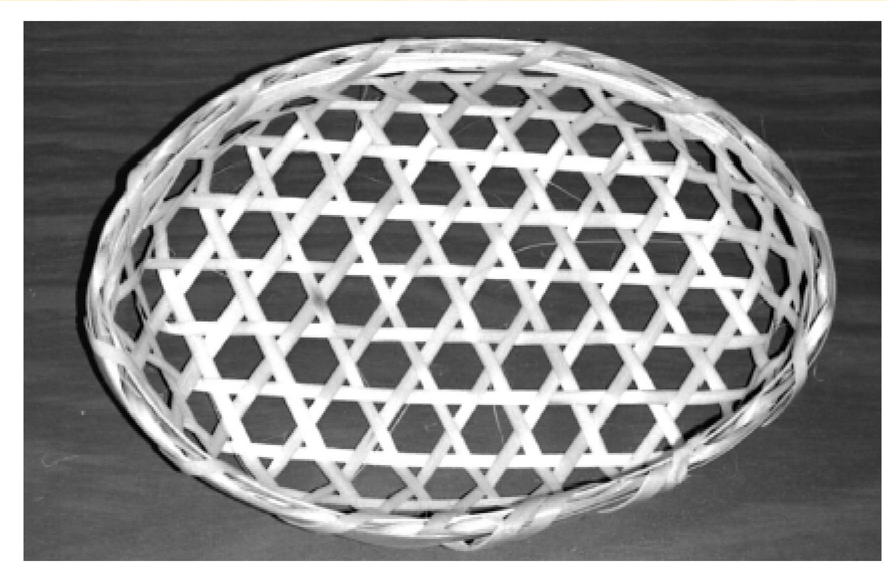
Storage giant Seagate has become the first hard drive manufacturer to reach the dizzy heights of one terabit per square inch areal density, using a technology known as heat-assisted magnetic recording (HAMR.)

Designed as a next-generation replacement for perpendicular magnetic recording as used in today's hard drives, HAMR holds the potential for 3.5in hard drives holding as much as 60TB. That, Seagate is quick to point out, would mean more bits in a square inch of hard drive platter than stars in the Milky Way.

PART II.



Monte Carlo Simulations of *ABC* stacked Kagomé planes.



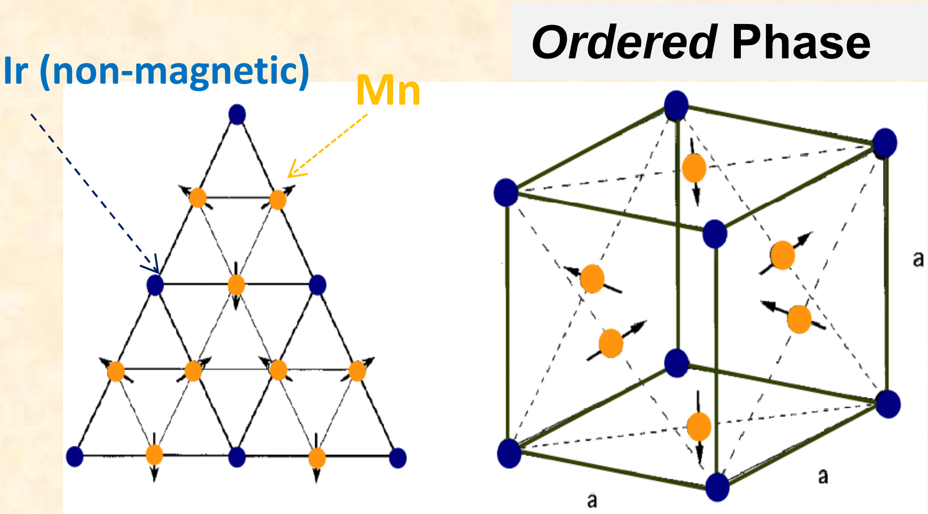
Kagome: The Story of the Basketweave Lattice. M. Mekata, Physics Today Feb. 2003.

First study of magnetic properties: I. Syozi, Prog. Theor. Phys. (1951).

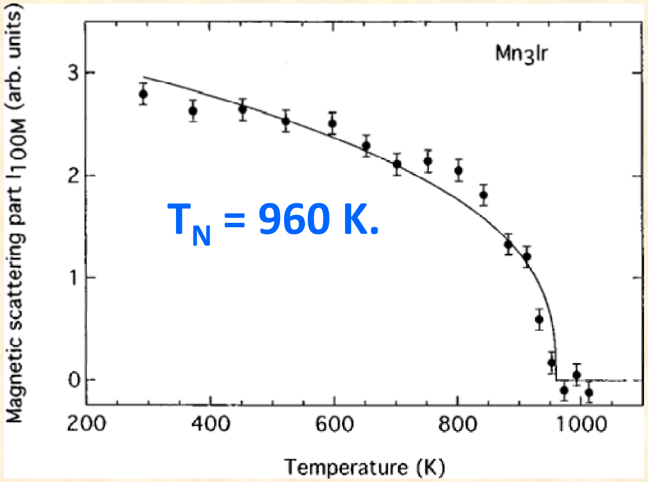
Ir-Mn ($IrMn_3$) most popular AF material in spin valves.

$IrMn_3$ = fcc $AuCu_3$ crystal structure. Also: $RhMn_3$ and $PtMn_3$

I. Tomeno et al J. Appl. Phys. 86, 3853 (1999).



Neutron diffraction on bulk single crystals.



'T1' ⇒ 2D spin structure

Very large T_N.

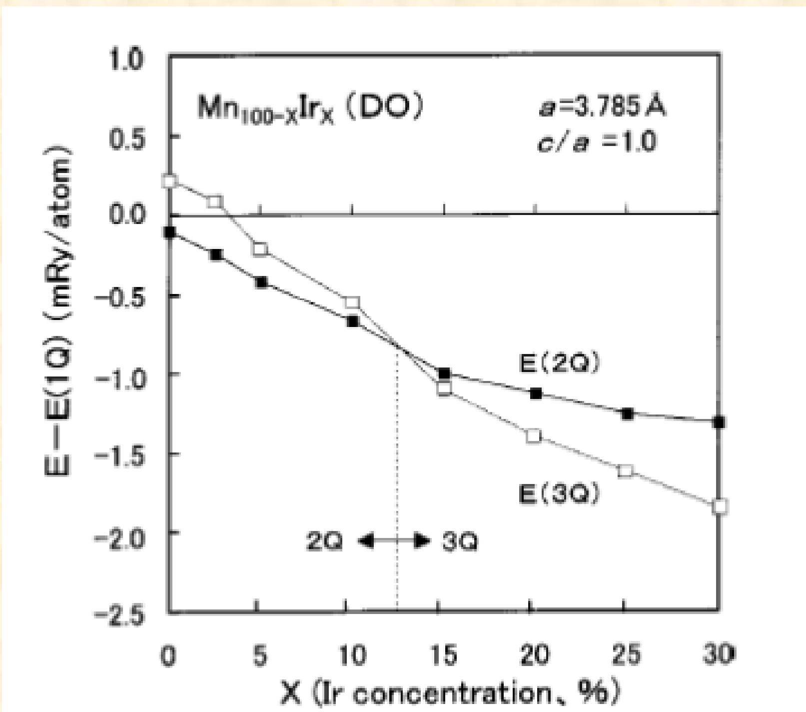
fcc lattice = *ABC* stacked triangular layers ⊥ <111>

It comes in other forms...

Relevant for sputtered thin films.

1. Disordered $IrMn_3$: 3Q SDW: $\theta = 54.7^0$

2. Disordered Ir_xMn_{100-x}: 2Q SDW: $\theta = 90^0$



Sakuma *et al*, PRB 67, 024420 (2003).
"First-principles study of the magnetic structures of ordered and disordered Mn-Ir alloys."

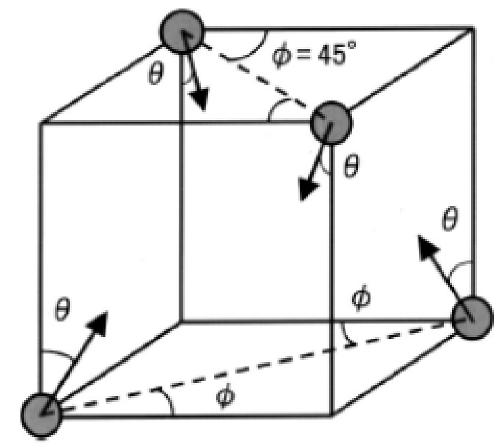
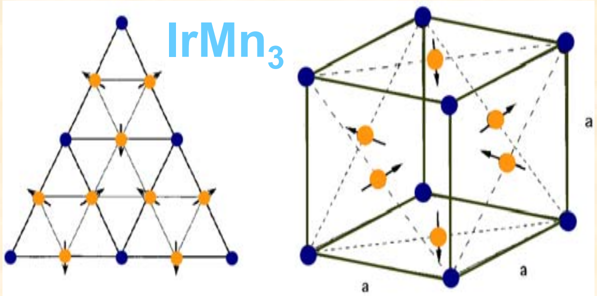


FIG. 3. Multiple-Q spin density wave (MQSDW) structures in the magnetic primitive cell of an fcc lattice.

Ordered $IrMn_3$

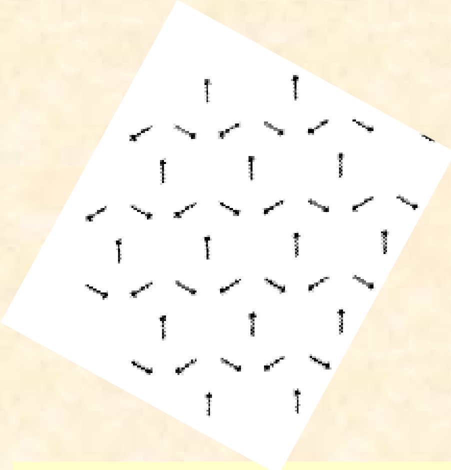


Applied Physics: 'T1' spin structure (no mention of Kagomé).

E. Krén et al, Phys. Lets. 20, 331 (1966).
I. Tomeno et al J. Appl. Phys. 86, 3853 (1999).

Thin films of $IrMn_3$ form <111> planes.

fcc Kagomé lattice = *ABC* stacked
Kagomé layers ⊥ <111>



2D Kagomé: Highly Frustrated AF

Basic Physics: 'q=0' spin structure (no mention of 'T1').

A.B. Harris et al, PRB 45, 2899 (1992).

- **2D Heisenberg model exhibits coplanar spin structure.**
- **Macroscopic spin degeneracy at T=0**

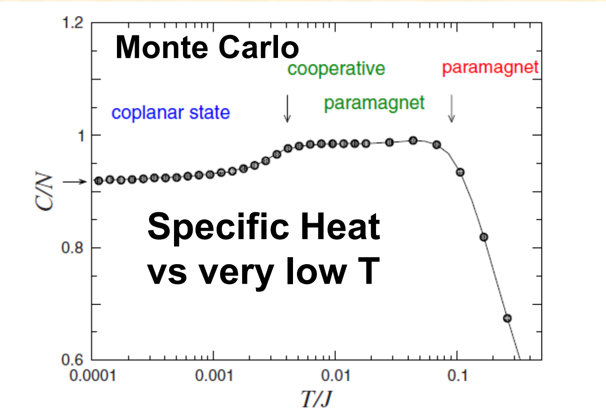


FIG. 3. (Color online) Temperature dependence of the specific heat for a kagome lattice cluster with $L=36$. The horizontal arrow denotes the value $C/N=\frac{11}{12}$. The two vertical arrows indicate boundaries between three different regimes.

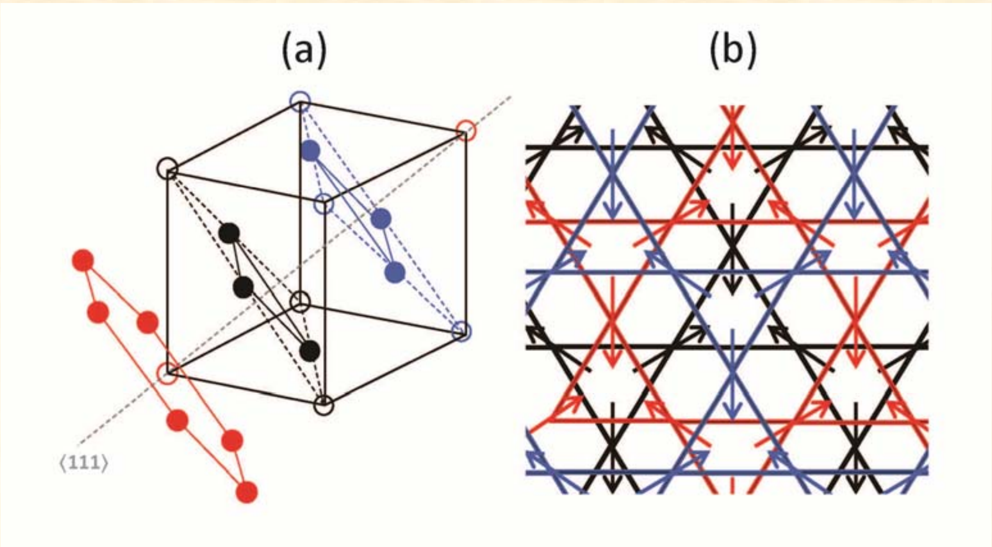
M. Zhitomirsky, PRB 78, 094423 (2008).

Monte Carlo simulations of the fcc Kagomé lattice.

Heisenberg and XY Models with NN Exchange J Only.

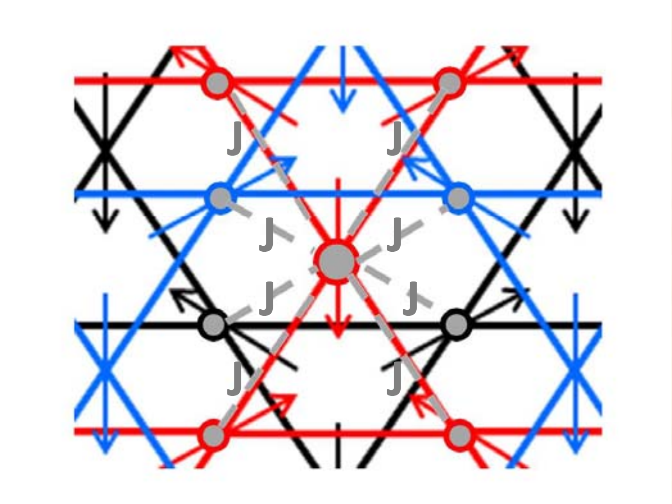
V. Hemmati, M.L. Plumer, J.P. Whitehead, and B.W. Southern, PRB submitted (2012).

***ABC* stacked** **View along <111>**



J ⇒ **4 NN in-plane**

+ 2 NN above + 2 NN below



- Recall fcc = ABC stacked triangular layers with 12 NN^s.
- Regular fcc AF with NN Heisenberg exchange shows first order transition to a collinear state.

Ground State from simulations:

- Each layer has q=0 spin structure.
- 120^0 between all 8 NNs.

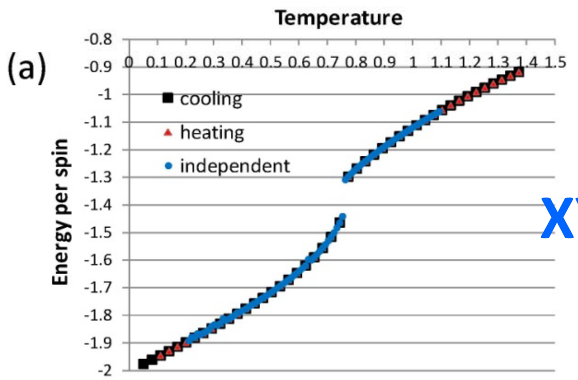
Monte Carlo simulations of the fcc Kagomé lattice.

Energy and Specific Heat.

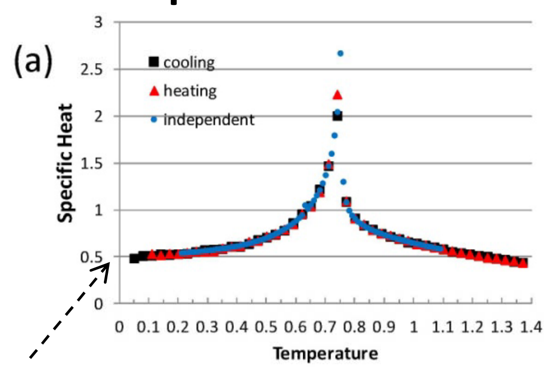
- *Standard Metropolis MC.*
- *L* layers of ABC stacked *LxL* Kagomé planes with PBC.
- *L* = 12, 18, 24, 30, 36, 60 with MCS = $10^6 - 10^7$
- *Cooling, Heating and Independent* temperature runs.

L=24

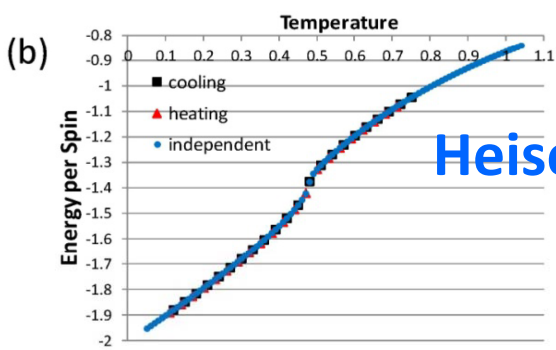
Energy **Specific Heat**



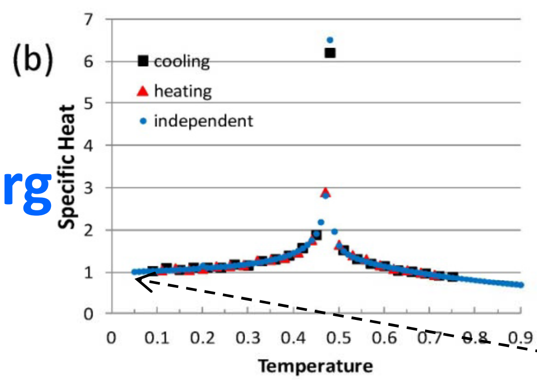
XY



C(T=0) = 5/12 k_B.



Heisenberg



C(T=0) = 11/12 k_B.

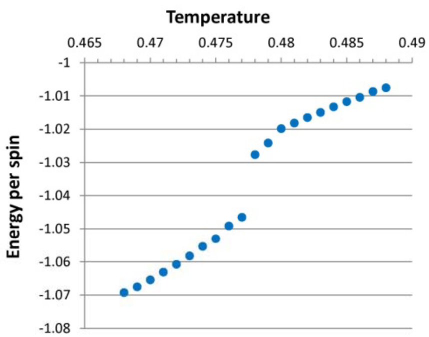
- **All three types of simulations yield equivalent results.**
- **For XY model, T_N = 0.760 and appears to be strongly first order.**
- **For Heisenberg model, T_N = 0.476 and could be first order.**

Monte Carlo simulations of the fcc Kagomé lattice.

Order of the Transitions.

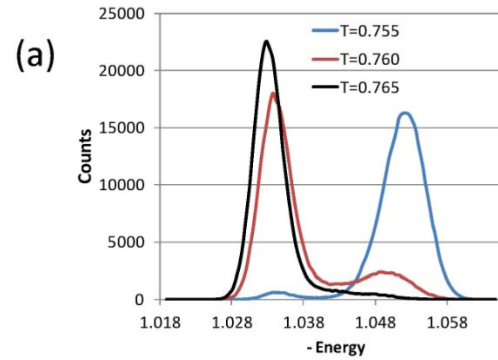
Heisenberg Energy.

L=36.

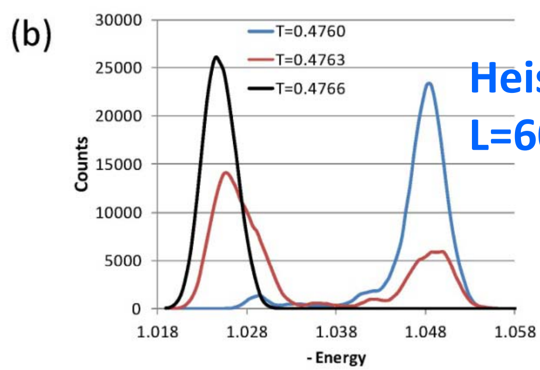


Discontinuity in Heisenberg energy clearer at L=36.

Energy Histograms near T_N



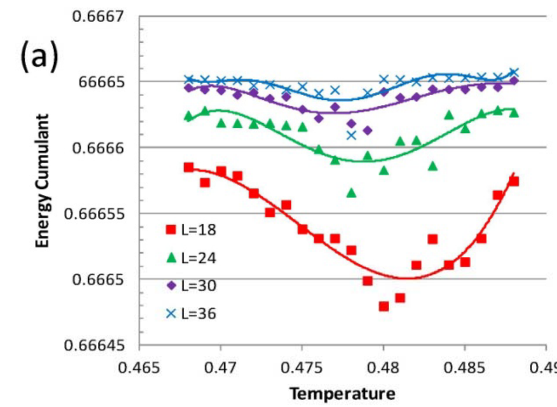
XY. L=24.

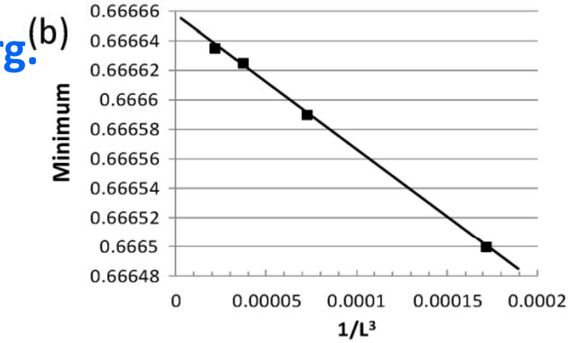


Heisenberg. L=60.

Indicate energy gap between disordered and ordered phases for *both* models.

Binder *Heisenberg* Energy Cumulant near T_N.





Inconclusive: Could be 2/3, or just close.

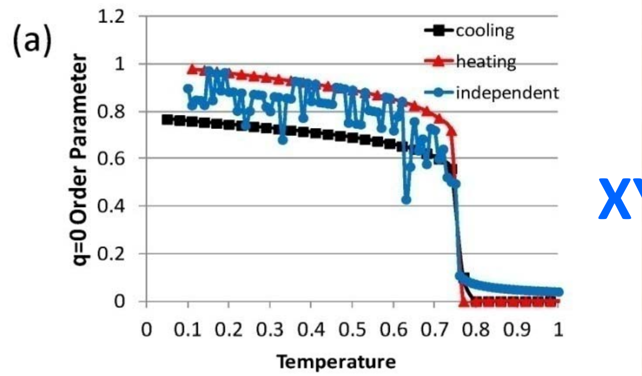
Monte Carlo simulations of the fcc Kagomé lattice.

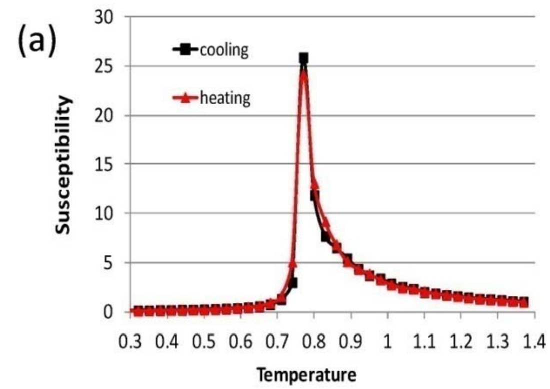
q=0 Order Parameter and Susceptibility.

L=24

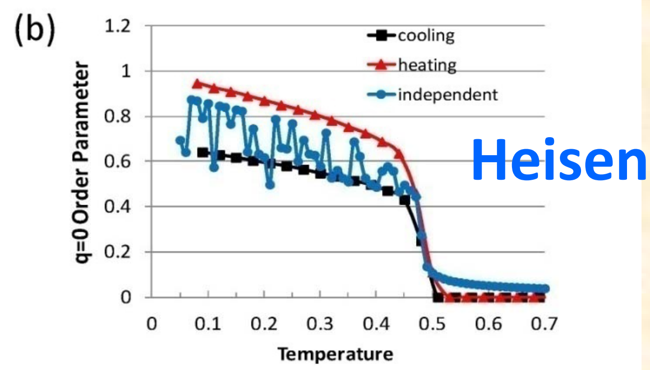
Order Parameter | **Susceptibility**

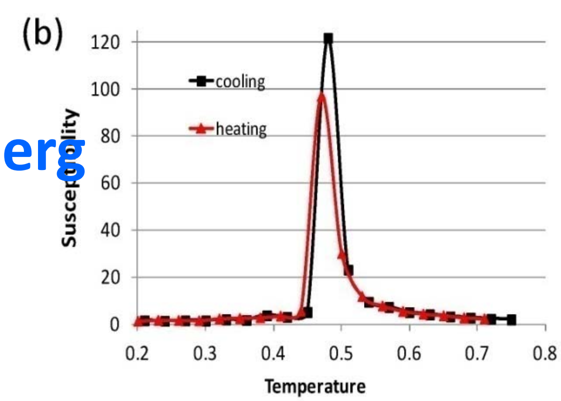
XY





Heisenberg





- •Heating runs start at T=0 from fully order q=0 state.

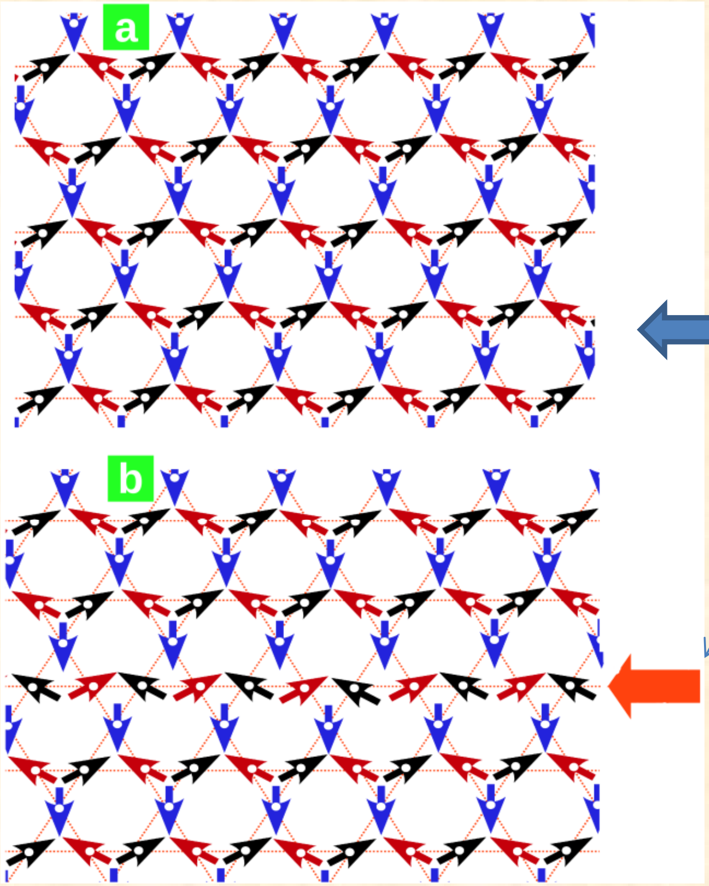
- •Order Parameter and Susceptibility show strong dependence on simulation mode (heating, cooling or independent temperature) and fluctuates between values, *in contrast with energy and specific heat.*

- •This feature is due to Kagomé-lattice spin degeneracies

Monte Carlo simulations of the fcc Kagomé lattice.

Spin Degeneracies.

Define 3 ferromagnetic sub-lattice magnetization vectors: black, blue red.



‘q=0’ magnetic structure ⇒ 3 spins around each triangle at 120^0

In 2D, can switch direction of two of the sub-lattices vectors in a row (e.g., **black** $\longleftrightarrow$ **red**) with no change in energy.

In 3D, can switch direction of two of the sub-lattices vectors in a plane with no change in energy

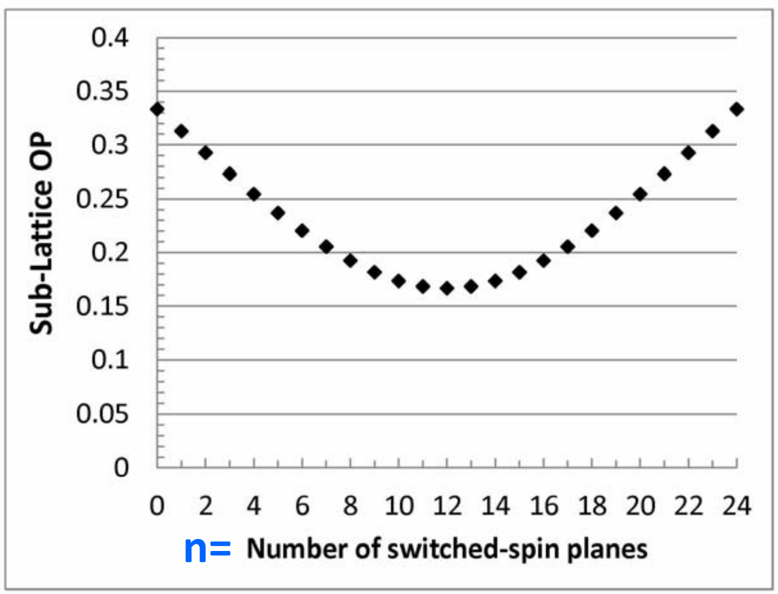
Monte Carlo simulations of the fcc Kagomé lattice.

Spin Degeneracies.

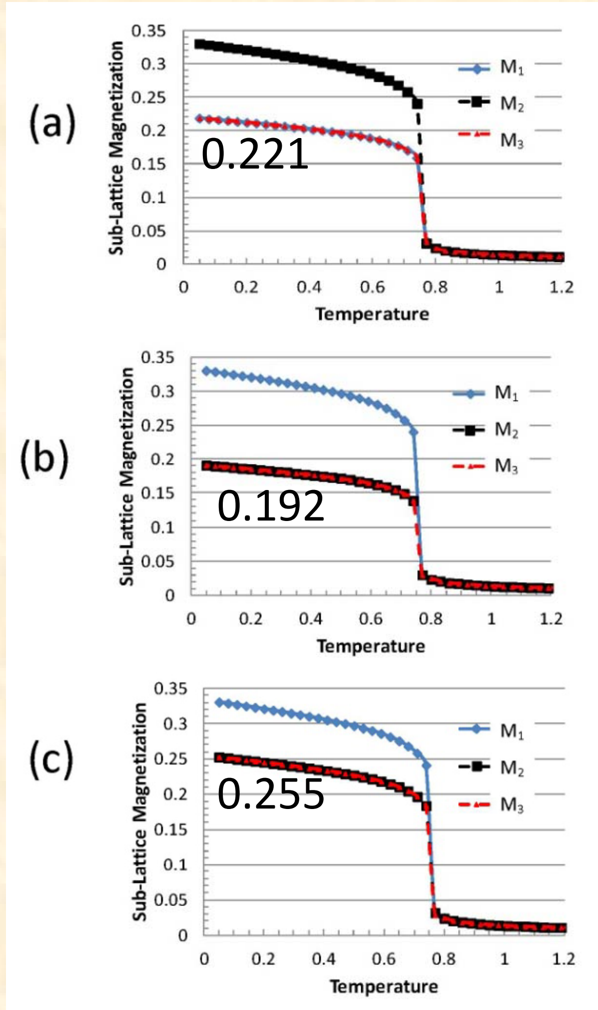
Enumerate all possible switches for L=24 and determine size of ground-state sub-lattice moment:

$$M_\eta = \frac{\sqrt{\left(\frac{1}{4}\,L^3 - \frac{3}{2}\,n\right)^2 + \left(\frac{\sqrt{3}}{2}\,n\right)^2}}{\frac{3}{4}\,L^3}$$

$L^3/8 < n < L/2$



Three different MC cooling runs (different random initial configuration).



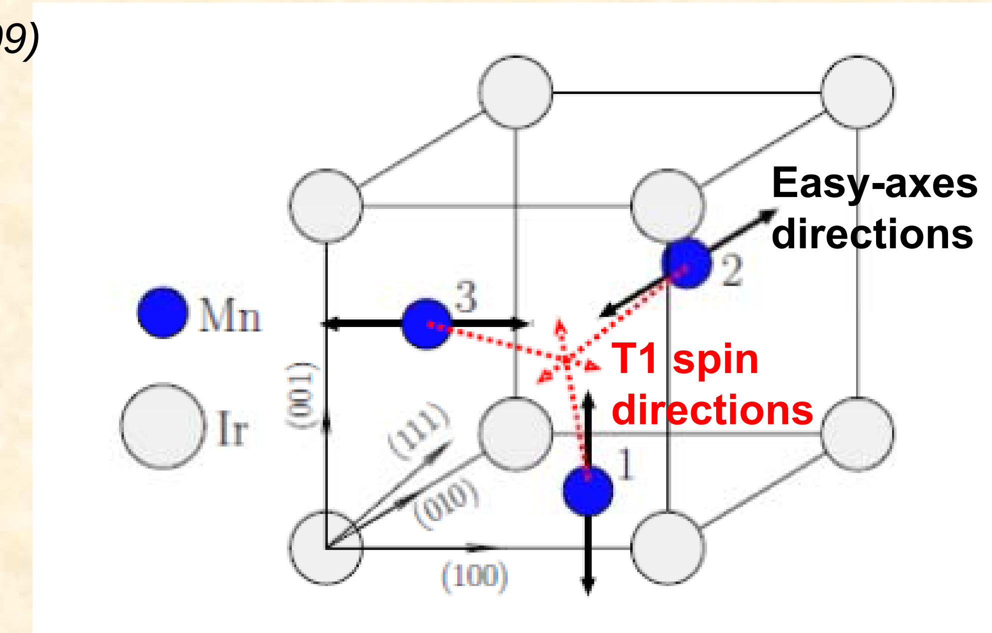
- **One sub-lattice is always fully saturated.**
- **The other two randomly approach (T=0) predicted values.**

Monte Carlo simulations of the fcc Kagomé lattice.

Add anisotropy

L. Szunyogh et al PRB 79, 020403 (2009)

$$H = -\frac{1}{2}\sum_{i\neq j} J_{ij}\vec{S}_i\vec{S}_j - \frac{K_{\mathrm{eff}}}{2}\sum_i (\vec{S}_i \cdot \vec{n}_i)^2,$$



Effective local anisotropy axes (similar to spin-ice pyrochlore tetrahedrons).

Mn moments are *not* aligned in the easy-axes directions for the coplanar T1 spin structure.

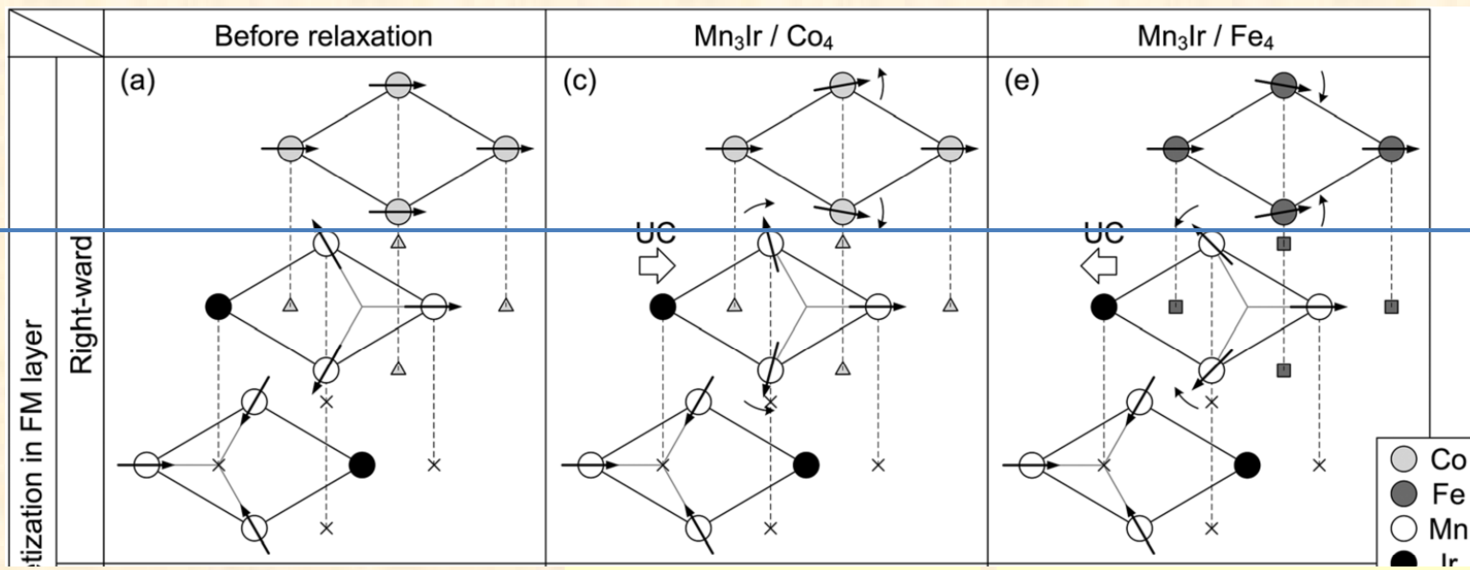
Work in progress.

Relation to Exchange Pinning.

DFT calculations of $IrMn_3/CO_4$ and $IrMn_3/Fe_4$ interface spin structures. *H. Takahashi et al, J. Appl. Phys. 110, 123920 (2011)*

Interaction with ferromagnetic layer induces a net moment in surface Mn spins

Interface



Mn moments rotate toward Co-moments

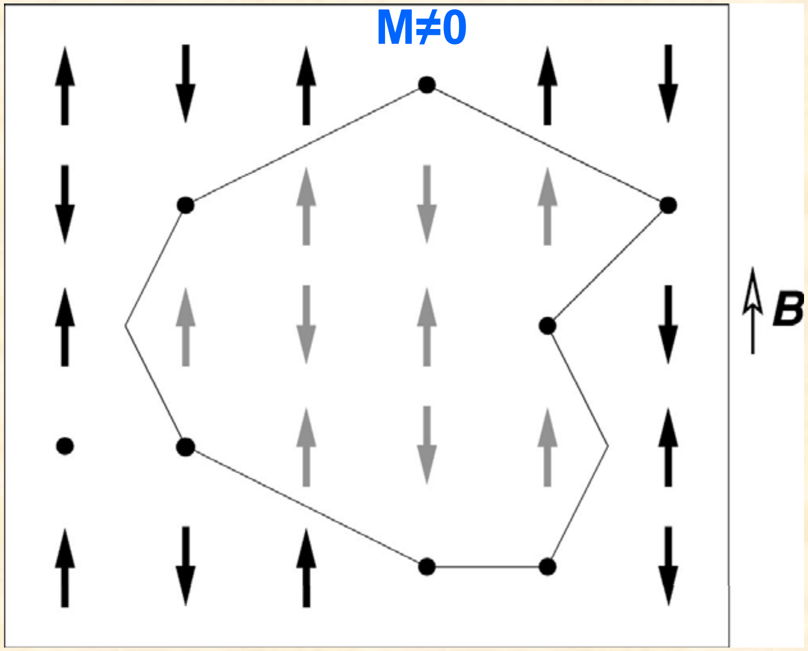
Mn moments rotate away from Fe-moments

Relation to exchange pinning?

A Model of Exchange Pinning

Domains involving non-magnetic surface sites.

Relevant for $IrMn_3$?



U. Nowak et al PRB 66, 014430 (2002).

M. R. Fitzsimmons et al, PRB 77, 224406 (2008).

"After more than 50 years there is still no definitive theory that can account for the observed effects."
K. O'Grady et al., JMMM 322, 883 (2010).

Phase transitions in the fcc Kagomé lattice

Summary and Conclusions

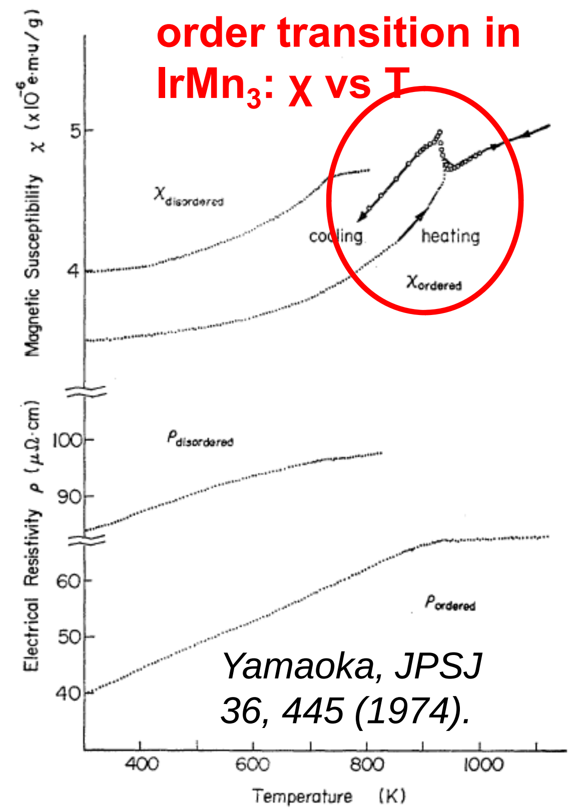
• 3D fcc Kagomé lattice with NN exchange only shows LRO transitions of the 'q=0' type at T_N=0.760 J for the XY model and T_N = 0.476 J for the Heisenberg model.

• XY model ⇒ Strongly first order.
• Heisenberg model ⇒ Probably weakly first order.
• Mean field theory ⇒ Continuous transition in both cases.

• Spin degeneracies of the 2D model persist in the 3D case ⇒ Order-by-disorder?

Future work:
- effects of anisotropy.
- thin films and surface effects
- add a ferromagnetic layer and dipole interactions.
- ⇒ ***Exchange Pinning?***

Evidence for first-order transition in $IrMn_3$: χ vs T



Yamaoka, JPSJ 36, 445 (1974).

Fig. 5. Temperature dependences of magnetic susceptibility χ and electrical resistivity ρ of the partially ordered (S=0.83) alloy compared with those of the disordered (S<0.08) alloy with x=0.256. Open circles indicate the cooling process.

Magnetic recording, and phase transitions in the fcc Kagomé lattice:

Collaborations and Support: Who's doing the work and who's paying for it.

- **Vahid Hemmati (MSc graduate)** Memorial
- **Jason Mercer (PhD student)** Memorial
- **Martin Leblanc (PhD student)** Memorial
- **Tim Fal (postdoc)** Memorial
- **John Whitehead (professor)** Memorial
- **Byron Southern (professor)** U. of Manitoba
- **Johannes Van Ek (physicist)** Western Digital Corporation

- **Natural Sciences and Engineering Council of Canada**
- **Western Digital Corporation**
- **Canada Foundation for Innovation**
- **Atlantic Centre of Excellence Network**