Instructor Lead

Student Lead

Collaboration

Visual representation of the main activities of this class

Introduce

Suggest Ideas

Brainstorm

Explore Past Work

Propose Idea

Give Idea Feedback

Perform Experiments

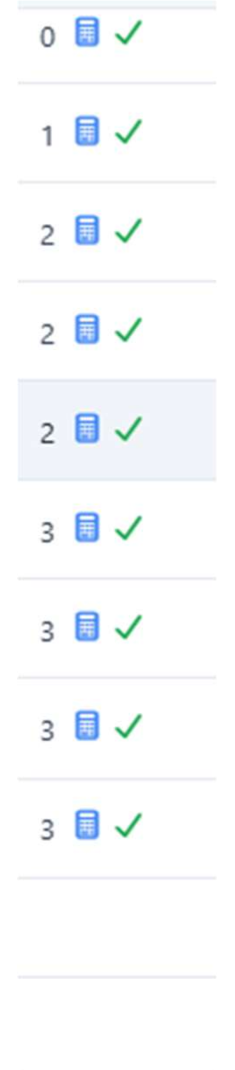
Graph Results

Present Results

Write Up Results

Feedback

Last half of the class



Define Topic ↔ Gather Sources ↔ Experiment ↔ Analyze ↔ Communicate

What's Coming Up?

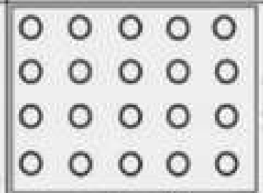
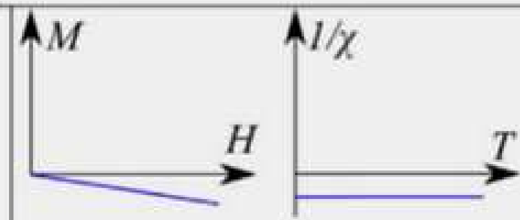
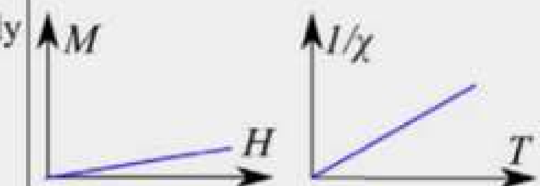
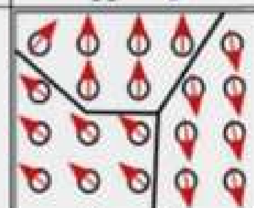
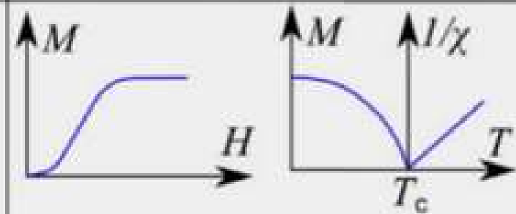
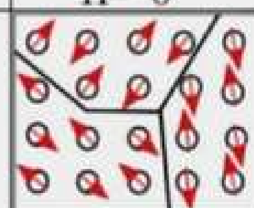
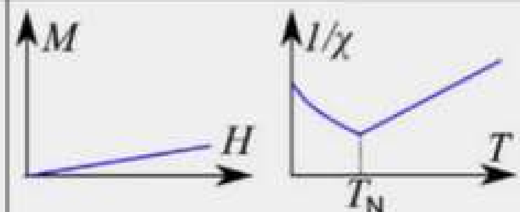
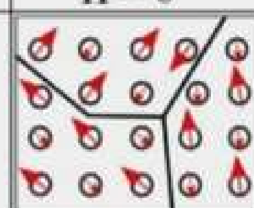
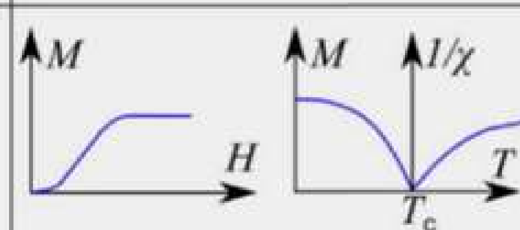
Instructions for safety assignment:
Email me when you email Miranda as in instructions:
[Safety Training | Department of Physics and Astronomy | West Virginia University]

It's not short so get a start when you can!

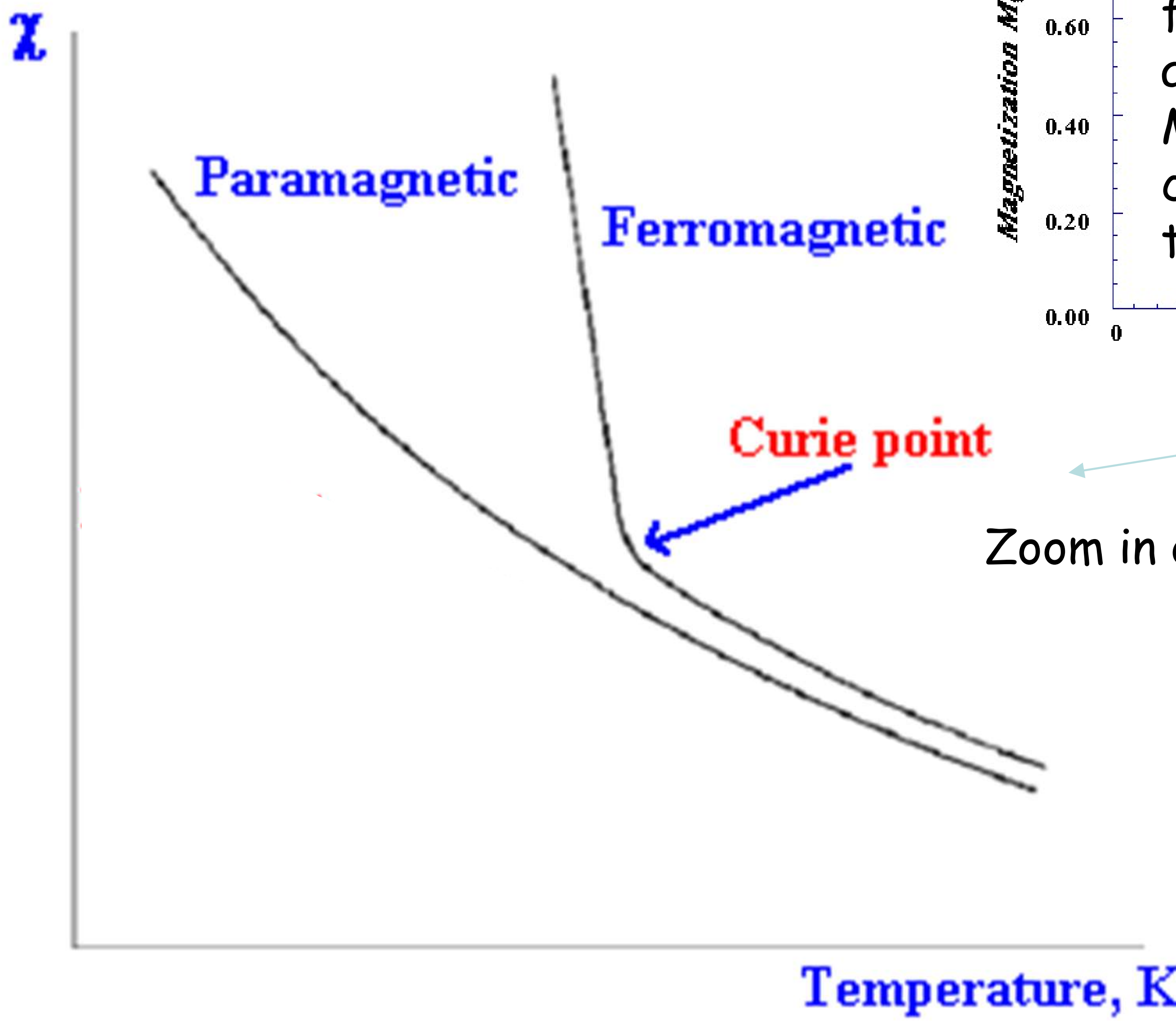
Perusall

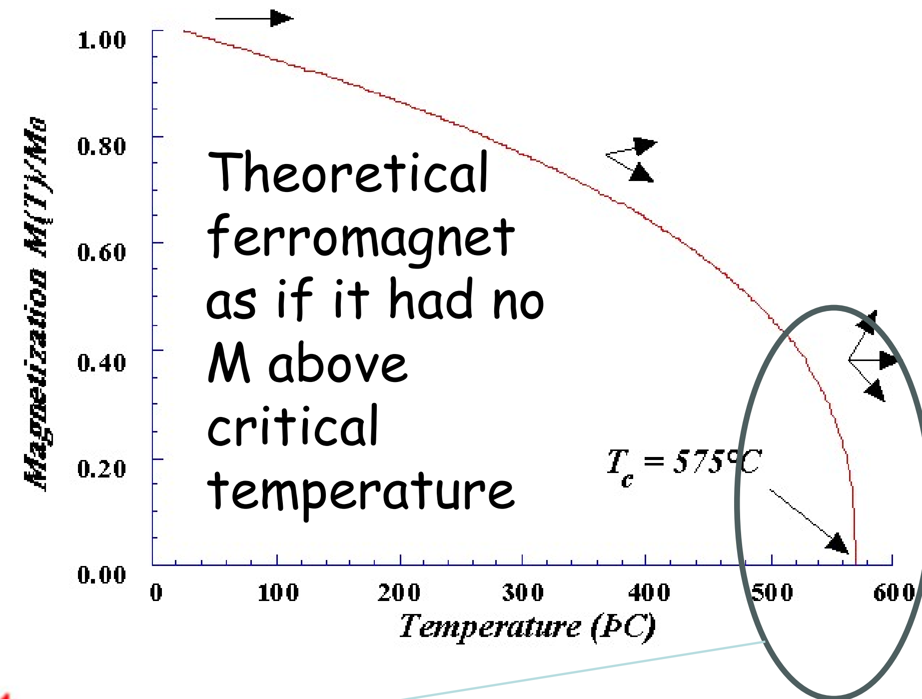
Date	293 Topic	Homework (with goals color)
[illegible]-Aug	Pr[illegible] [illegible]lass Ab[illegible]	[illegible]rtner/S[illegible]
[illegible]-Aug	Dis[illegible] [illegible]netism	[illegible]eading 1 on Perusall
25-Aug	Holcomb Group Discovery	Reading 2 on Perusall
27-Aug	MOKE versus Other Magnetometry	Watch Video on Perusall
1-Sep	Project Planning: What Kinds of Magnetic Measurements	Syllabus Read/Agree
3-Sep	Finding Published Papers Relevant to Your Project	Bring a Related Paper to Class
8-Sep	Reading and Evaluating Papers	
10-Sep	Best Practices with Lab Notebooks	University Safety Requirement
15-Sep	MOKE Hands-On Demonstration	
17-Sep	VSM Hands-On Demonstration	Important Papers. Why? (2-5)
22-Sep	How to Give Peer Feedback and Group Project Planning	
24-Sep	Planning Group Oral Reports and Peer Grading	Mini Reports (in class)
29-Sep	Group Project Planning and Refinement	Quality Reading on Perusall
1-Oct	Assessing the Quality of Materials	Project Proposal
6-Oct	Best Practices with Graphing	Good/Bad Graphs
8-Oct	Fall Break (No Class)	
13-Oct	Introduction to Excel: Spreadsheets, Graphing and Fitting	
15-Oct	Understanding and Processing Your Data	Lab Notebook Check-In
20-Oct	Building a Story with Your Data When It Isn't Obvious	
22-Oct	Check-In and How Are Materials Grown	
27-Oct	How to Give a Good Talk	
29-Oct	Peer Evaluation of Lab Notebooks (Bring Notebooks)	
3-Nov	Election Day (Vote If You Can)	
5-Nov	Project Speed Dating: Share Your Project with Others	Graphs of Your Data
10-Nov	Time for groups to Discuss Presentation/Data Planning	
12-Nov	Eight Minute Group Presentations	Presentations
17-Nov	Eight Minute Group Presentations	Presentations
19-Nov	How to Write a Good Abstract	
1-Dec	Ask Your Final Questions of Instructor, Partners or Class	
3-Dec	Discussion of Research and Scholarship Opportunities	Abstract & Notebook

No need to memorize, but ask if Q’s

Magnetism	Examples	Magnetic behaviour		
Diamagnetism	Bi, Si, Cu, inert gases Susceptibility small and negative (-10^{-6} to -10^{-5})	 H = 0	Atoms have no magnetic moments.	
Paramagnetism	Al, O_2, MnBi Susceptibilty small and positive (10^{-5} to 10^{-3})	 H = 0	Atoms have randomly oriented magnetic moments.	
Ferromagnetism	Fe, Ni, Co, Gd Susceptibility large (generally > 100)	 H = 0	Atoms are organized in domains which have parallel aligned magnetic moments.	
Antiferromagnetism	Cr, MnO, FeO Susceptibilty small and positive (10^{-5} to 10^{-3})	 H = 0	Atoms are organized in domains which have antiparallel aligned moments.	
Ferrimagnetism	Fe_3O_4, $MnFe_2O_4$, $NiFe_2O_4$ Susceptibility large (generally > 100)	 H = 0	Atoms are organized in domains which have a mixture of unequal antiparallel aligned moments.	

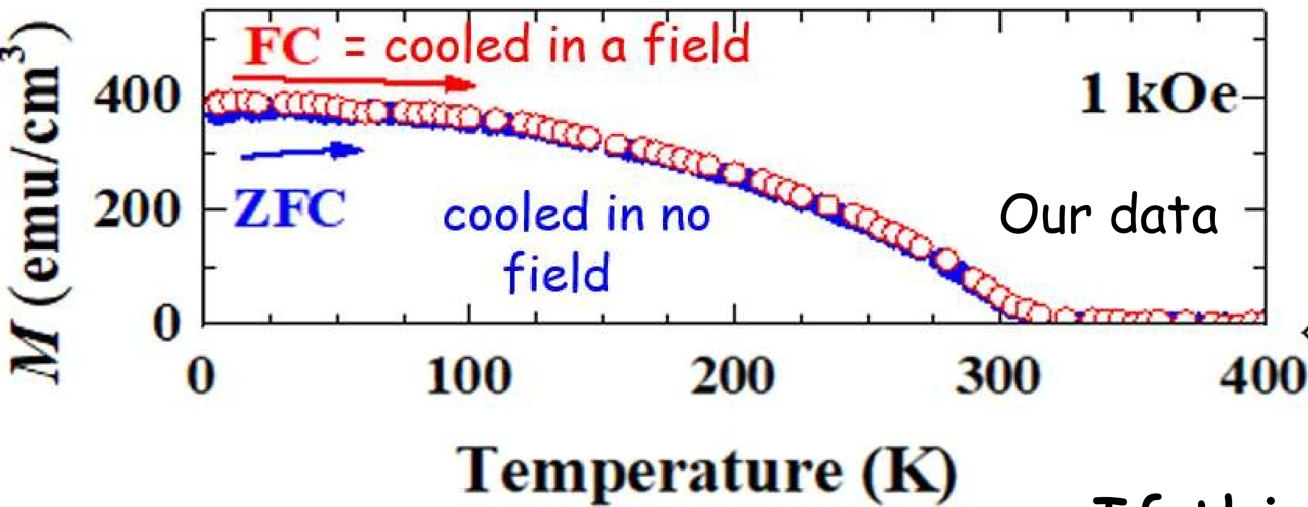
Last time: Ordering temperature (a commonly reported material parameter)





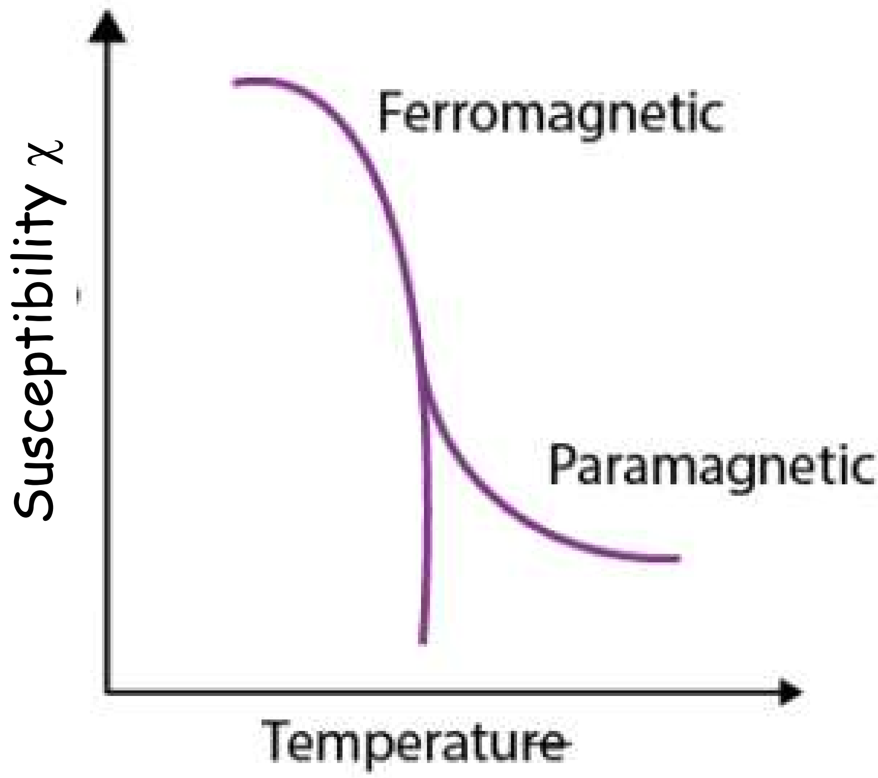
Zoom in on Reality

Real data. Is this sharp?



7.6 nm LSMO on STO

Typical Magnetic Data

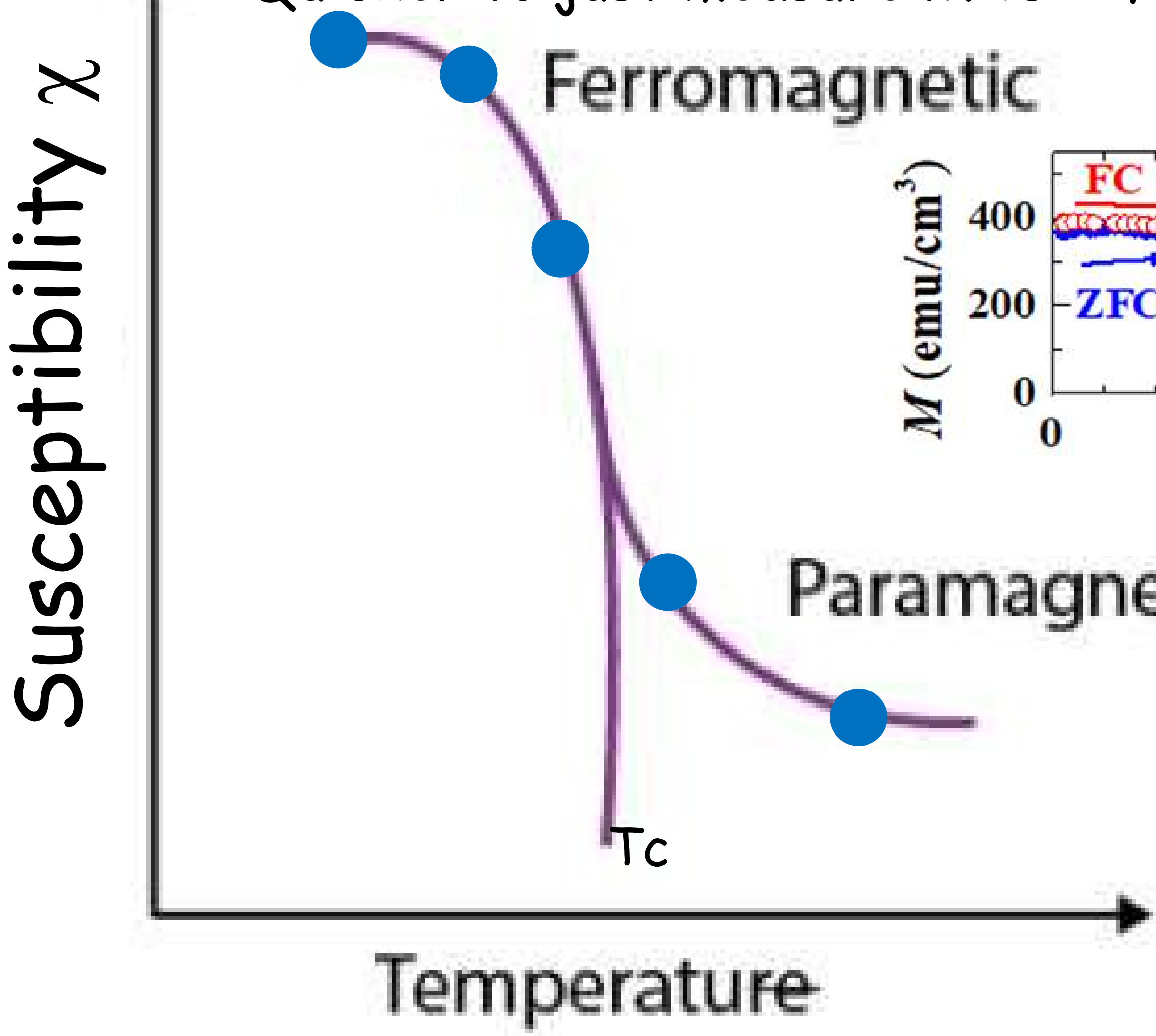


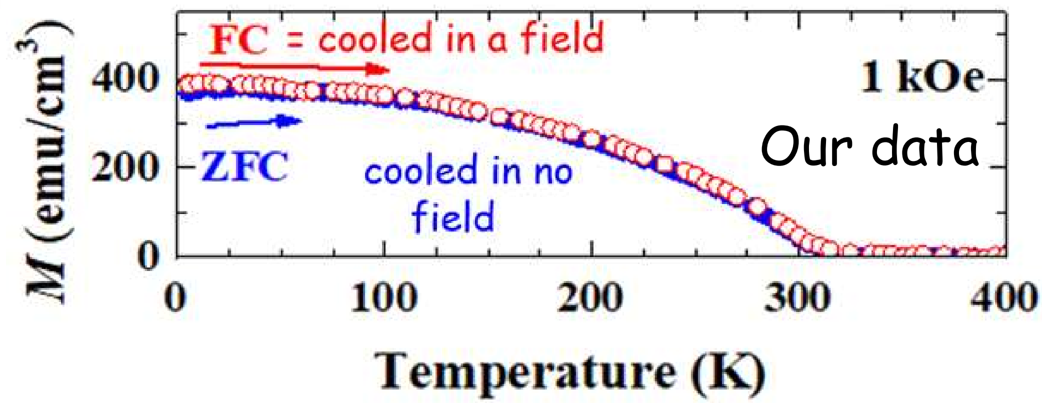
If this were your data, how would you define the critical temperature?

I think we could easily guess within about 10K or so but doing better might be hard.

If you wanted to be more mathematically precise, how do you think you could find the critical temperature?

In the field, the most accepted way is to do multiple M vs H measurements, and see when the behavior switches from FM to PM, but that could be a lot of measurements! Quicker to just measure M vs T for a specific H field.



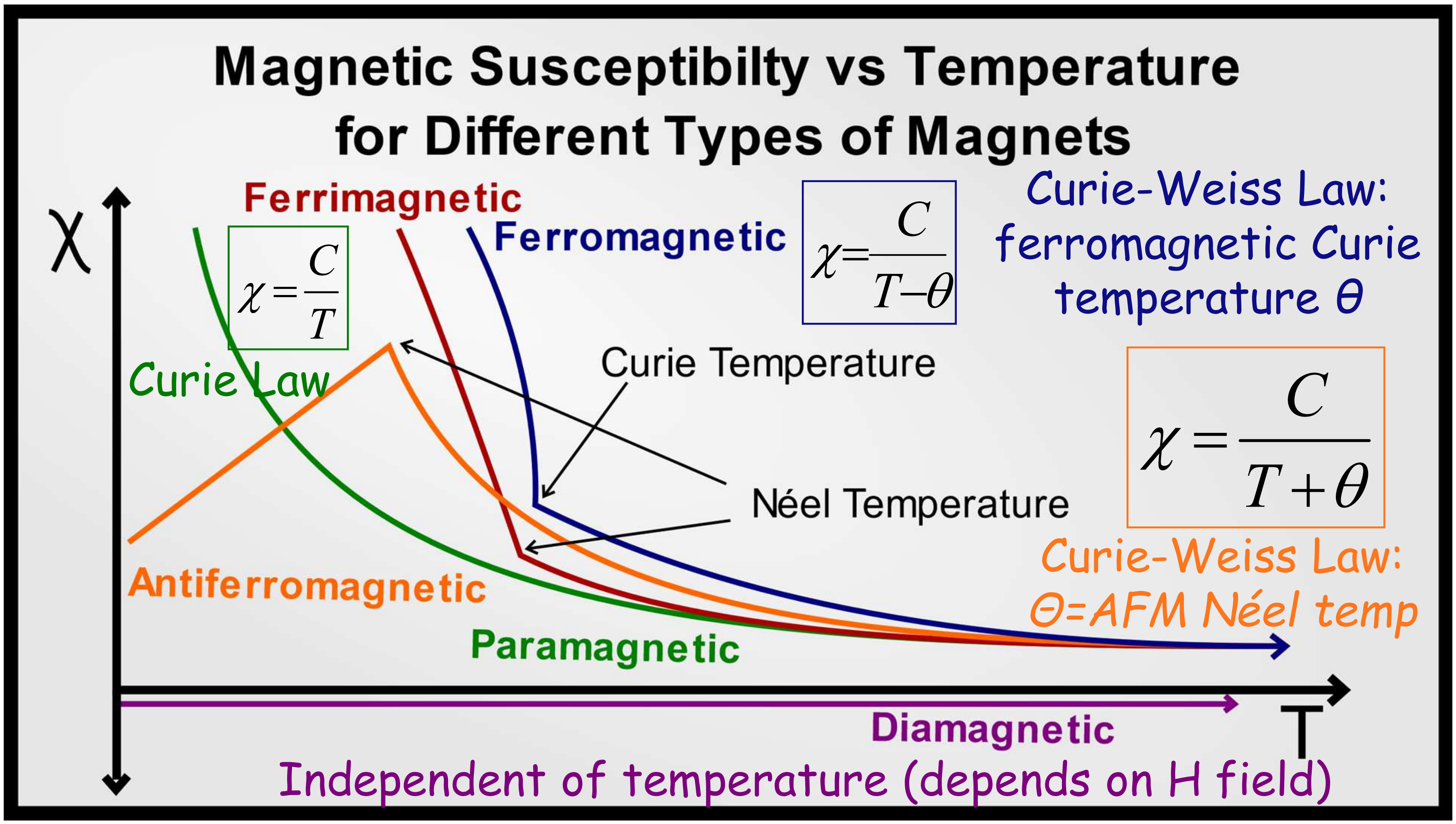


What if you don't have a pretty curve like this and only have a few points along the curve? What should you do?

You could try to fit it (C is a constant)

$M = \chi_m H$

χ_m = Magnetic susceptibility



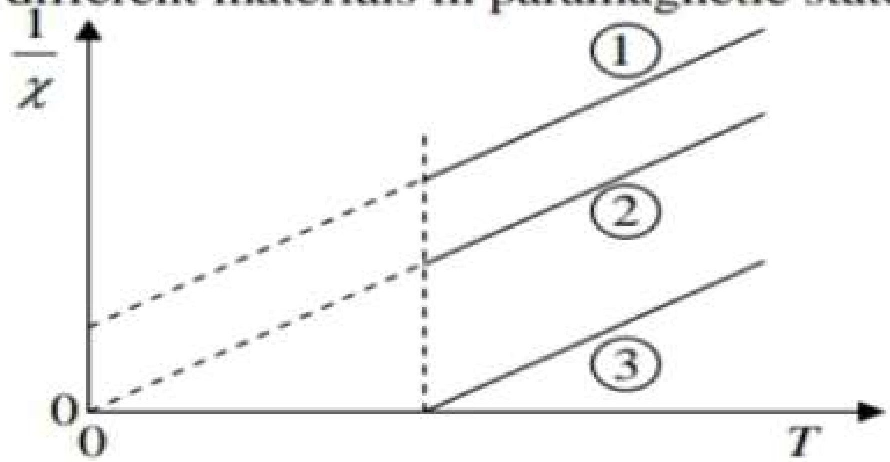
Others (-DM) are paramagnetic above their critical temperature

Plot it a different way (doesn't always work well)

As shown in the figure, inverse magnetic susceptibility ($1/\chi$) is plotted as a function of temperature (T) for three different materials in paramagnetic states.

$$\chi = \frac{C}{T}$$

paramagnet

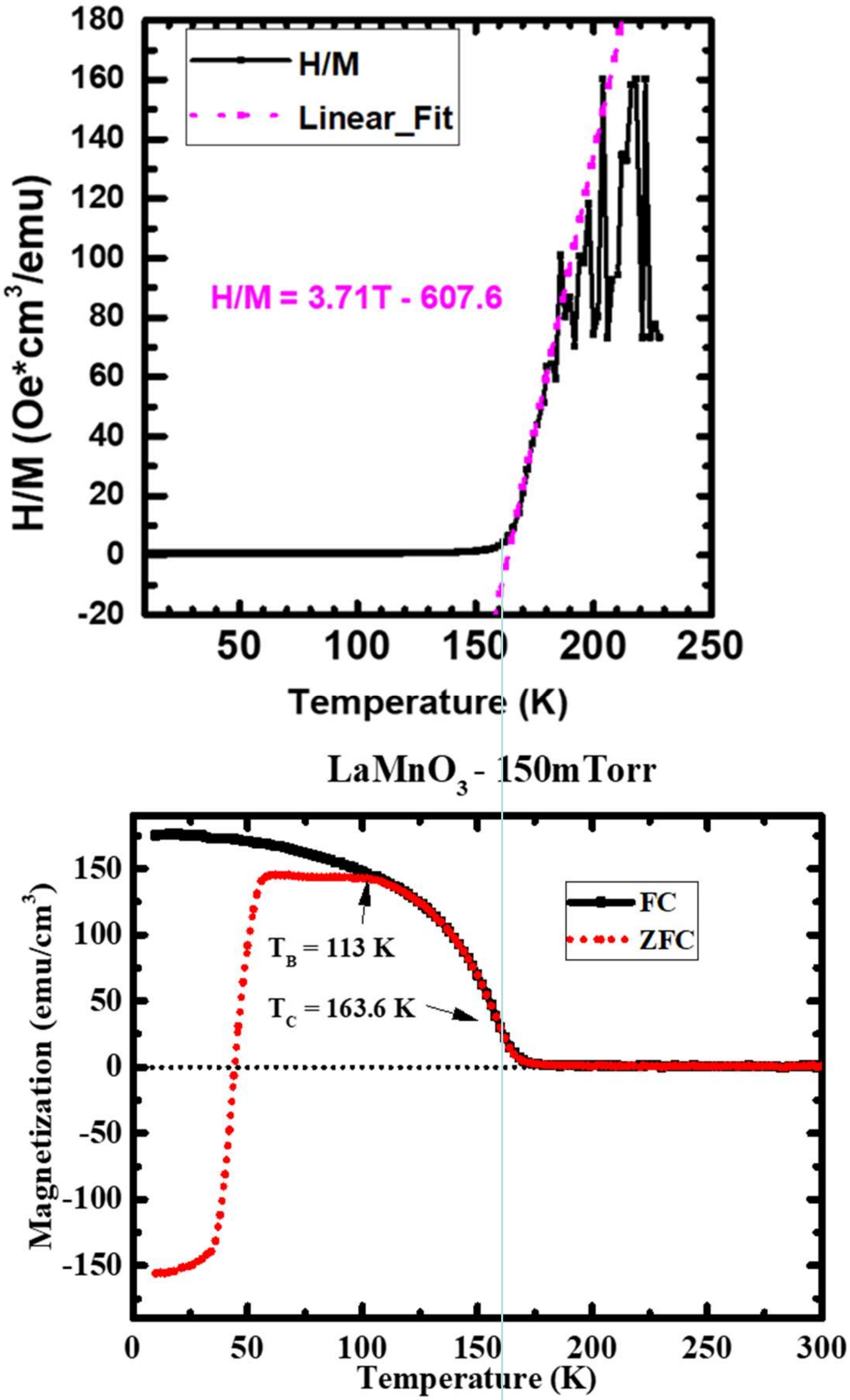


$$\chi = \frac{C}{T-\theta}$$ FM

$$\chi = \frac{C}{T+\theta}$$ AFM

Only the data above the critical temperature should be used to find the trend; should look like a straight line. Fit to a linear line. Where it intercepts on the temperature axis tells you whether it is a/an

1. Antiferromagnet (negative intercept for temperature)
2. Paramagnet (the intercept is at zero)
3. Ferromagnet (positive intercept for temperature)

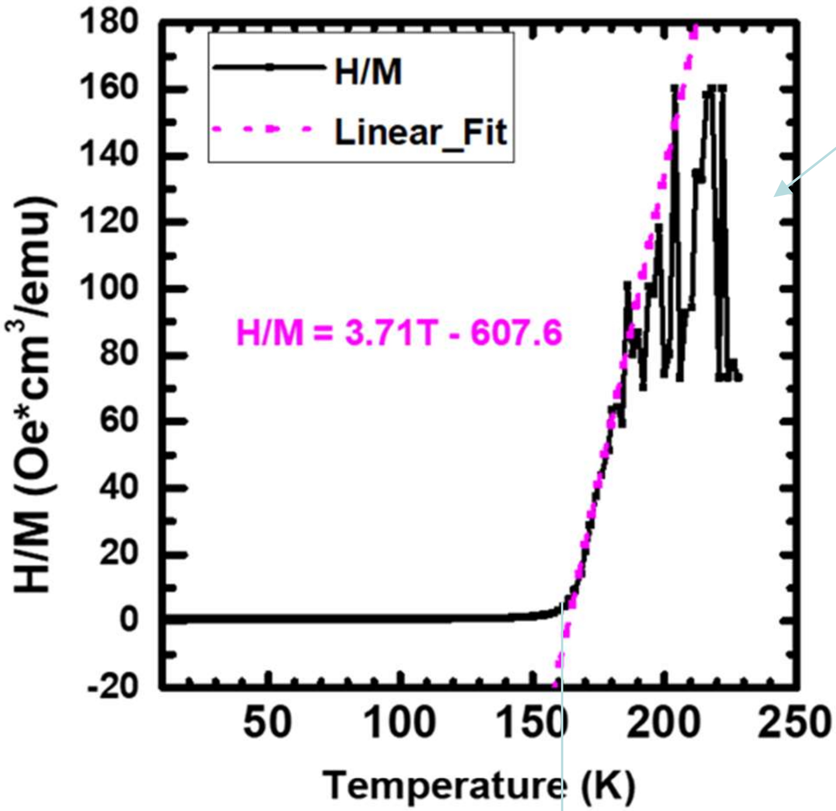


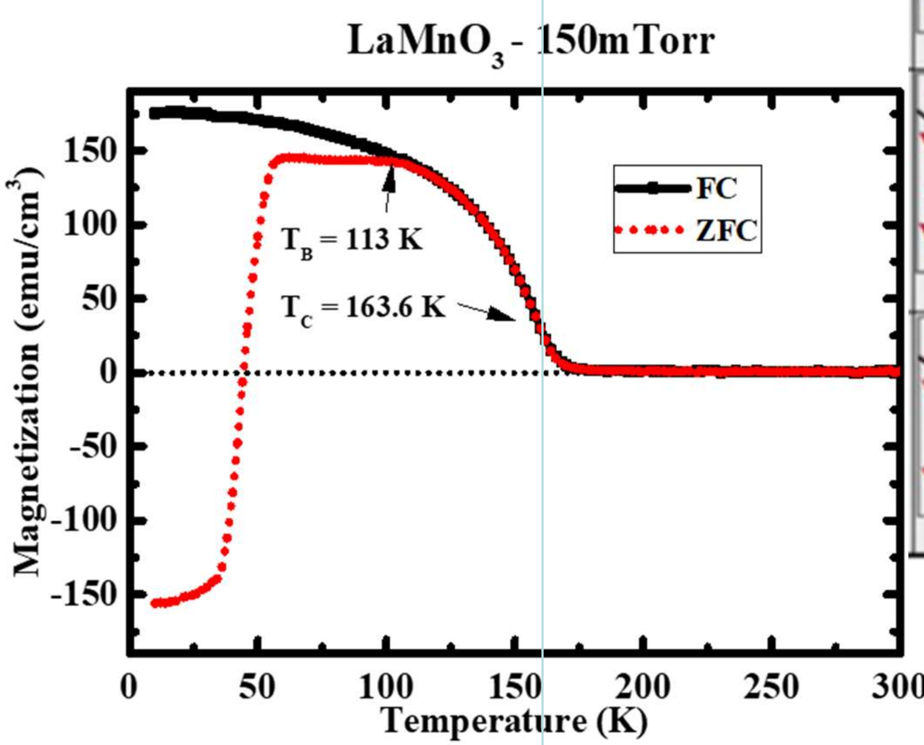
What magnetism is this?
Is it just noisy?

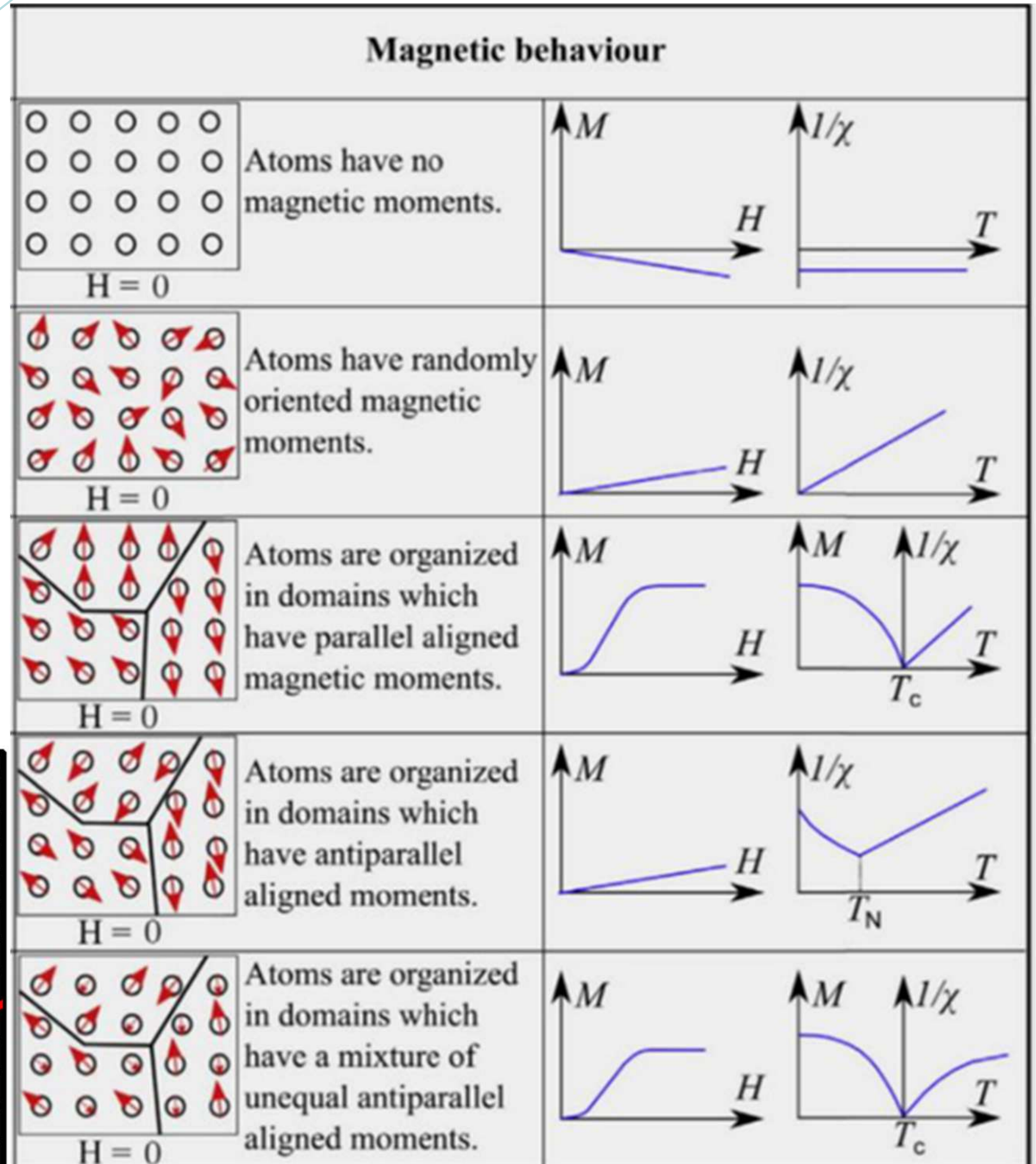
If you use this method to find Tc, stop before the data gets noisy

I wanted to show this other way because it's commonly in the literature, but I think the <u>curvature method</u> is typically the closest. Best method is a bunch of M vs H at different temperatures. But takes more time.

What do you think is a good match?





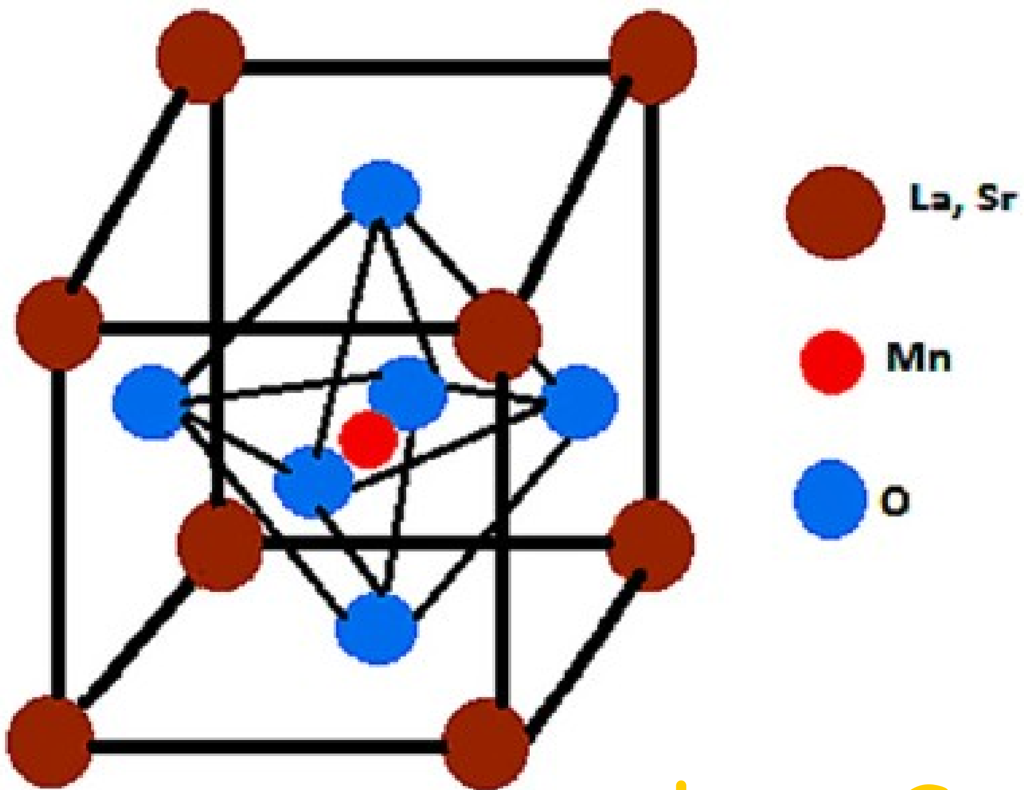


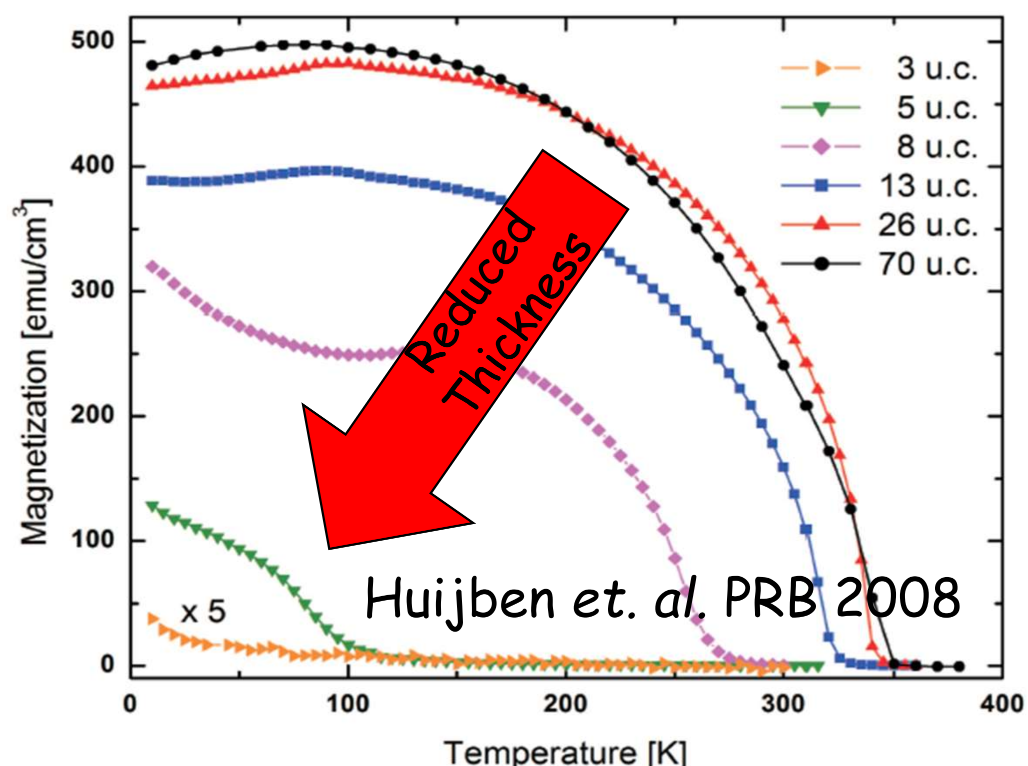
The Holcomb group found some very weird behavior.

Don't be surprised if you don't understand everything, because I can't confidently say I do either. I have some good guesses. ←Science is testing good guesses.

You don't have to study this if it doesn't appeal to you!

We solved: Why do magnetic thin films lose their magnetism?





$La_{0.7}Sr_{0.3}MnO_3$

Ferromagnetic, T_C ~ 360 K for t > 10nm

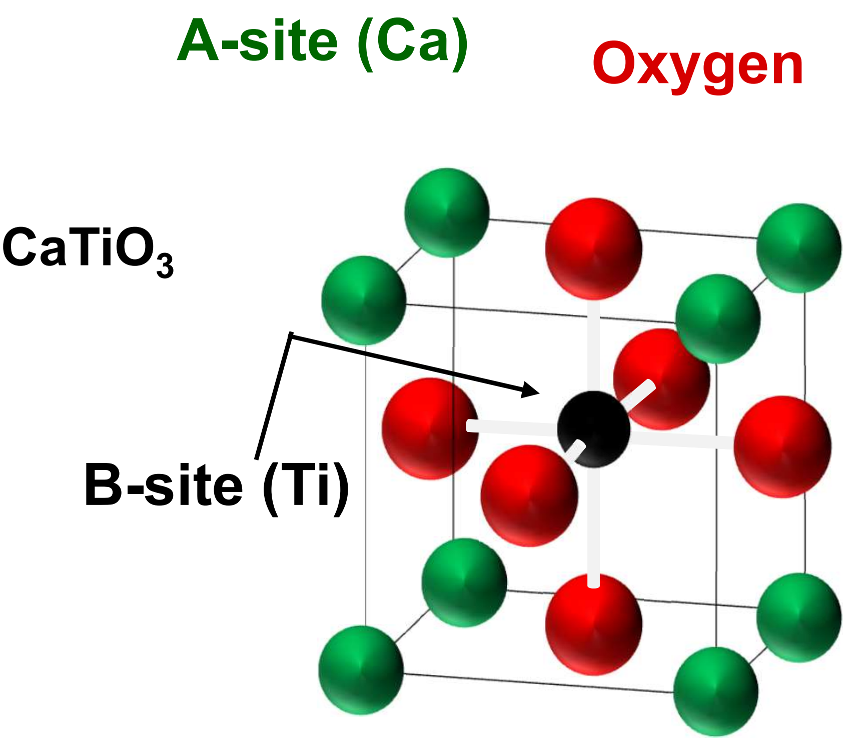
Used by companies like Intel & Applied Materials

LSMO behaves like a half-metal, good for spintronics.

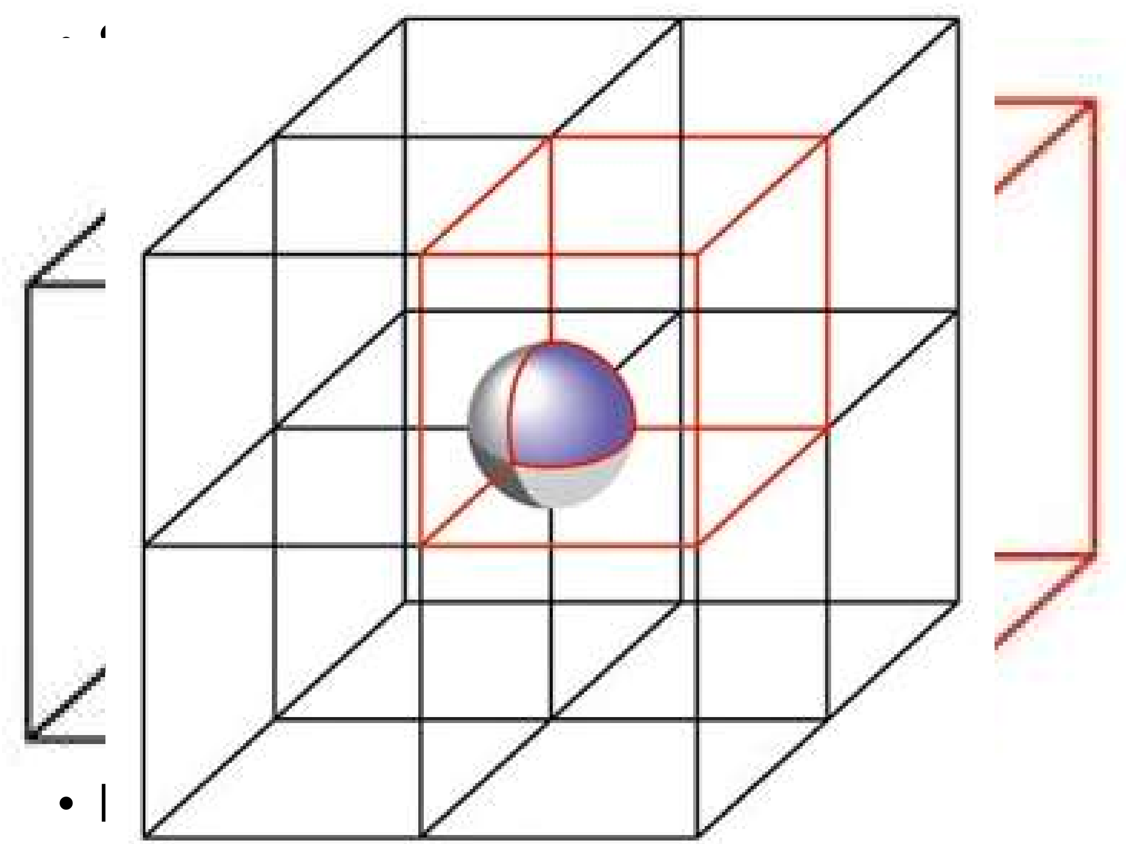
Oxides are already oxidized, unlike many other materials.

Quick Aside on the Crystal Structure

Depending on A and B, different properties



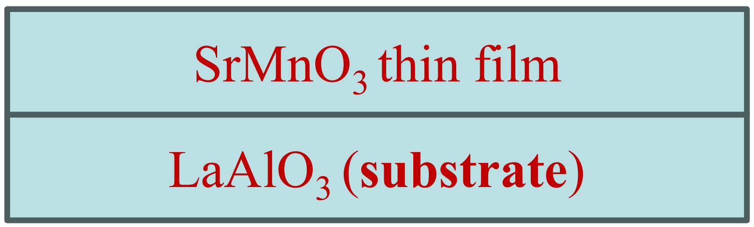
Perovskite



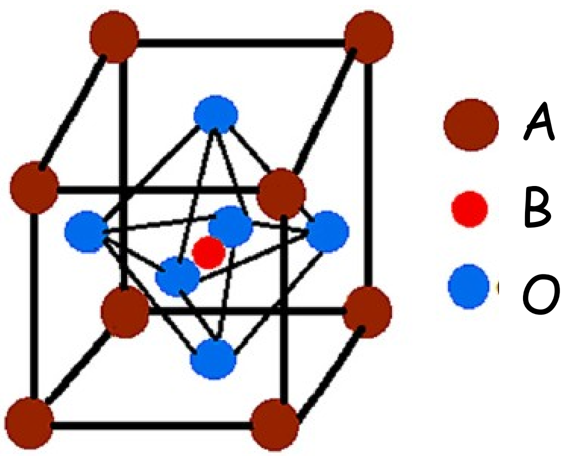
- Formula unit – ABO_3 <u>Why do you think it has this formula?</u>
- A atoms at the corners
- B atoms (smaller) at the body-center
- O atoms at the face centers

What Are These Structures

$SrMnO_3/LaAlO_3$



The **substrate** is what you grow on. To grow a good film, your substrate should be smooth and of similar spacing between atoms of your thin film.



ABO_3 is the perovskite crystal structure

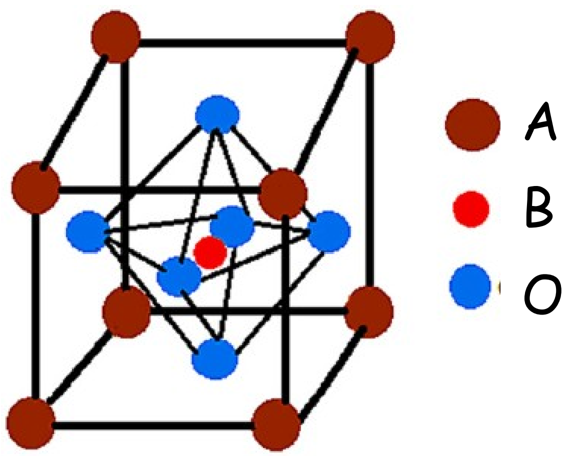
In $SrMnO_3$, A=Sr and B=Mn

The first discovered perovskite was $CaTiO_3$ (calcium titanate), a mineral first discovered by German mineralogist Gustav Rose in 1839 and was named **in honor of the Russian mineralogist Lev Perovski** (1792-1856)

What Are These Structures

$(La,Sr)MnO_3/SrTiO_3$

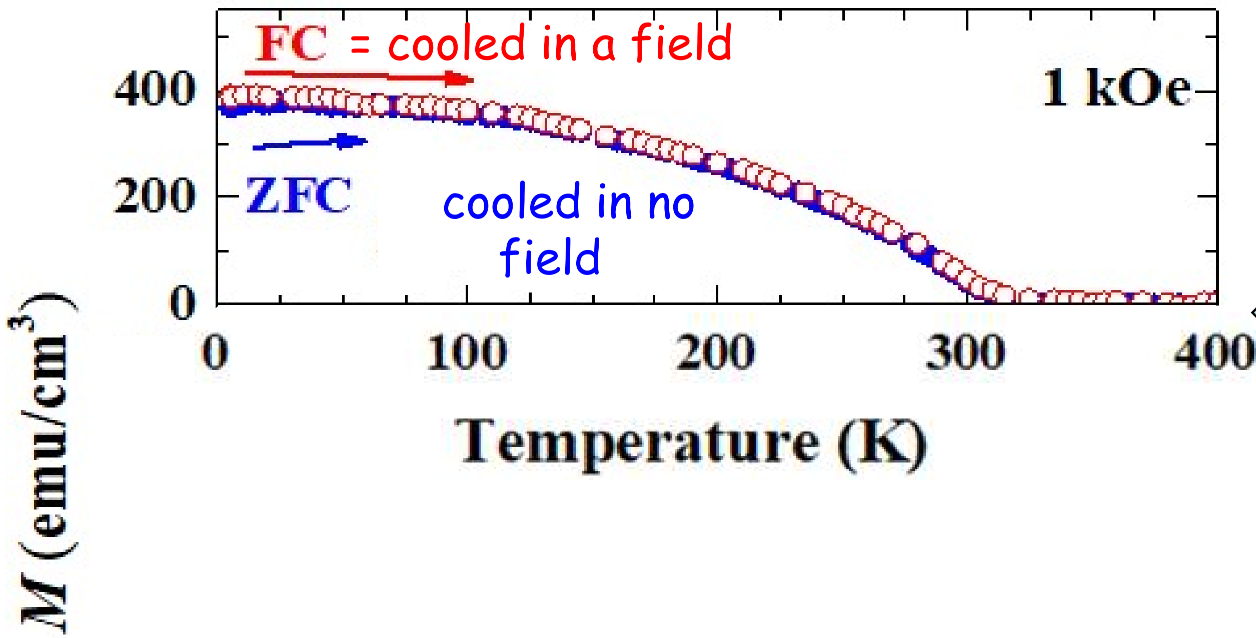
$LaSrMnO_3$ thin film (LSMO)
$SrTiO_3$ (STO **substrate**)



ABO_3 is the perovskite crystal structure

In $LaSrMnO_3$, A=La and Sr and B=Mn

Bigger Considered Better



7.6 nm LSMO on STO

Typical Magnetic Data

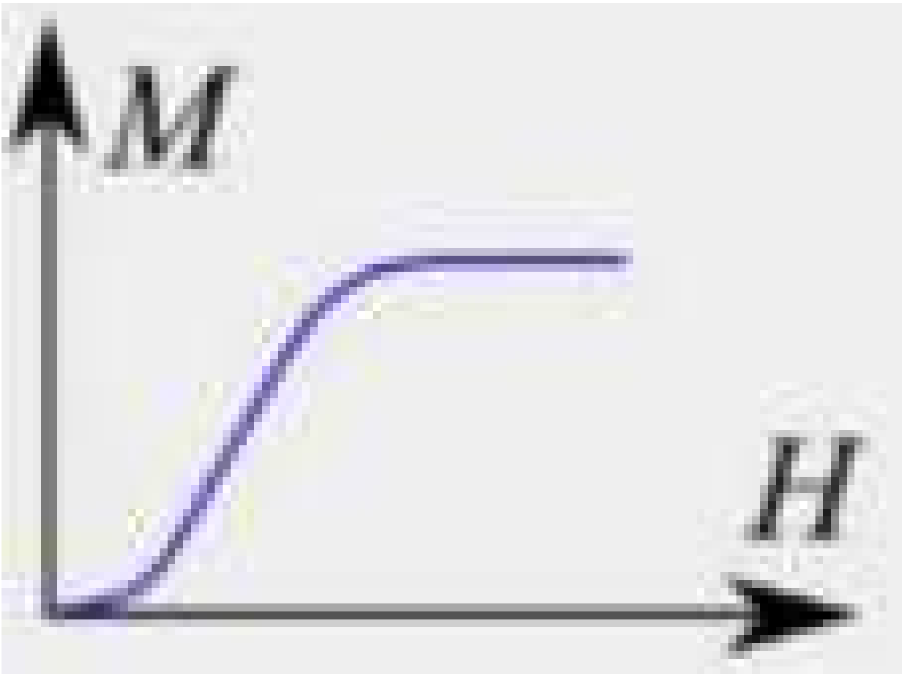
Negative magnetization at low fields, which is what we would be applying in real world applications.

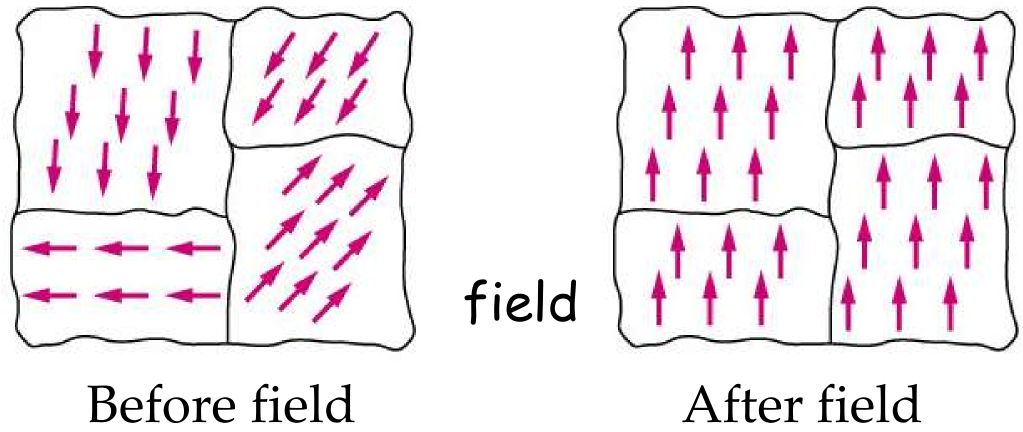
Aligning opposite the applied field!

Navid Mottaghi, *et. al.* JPCM 2018

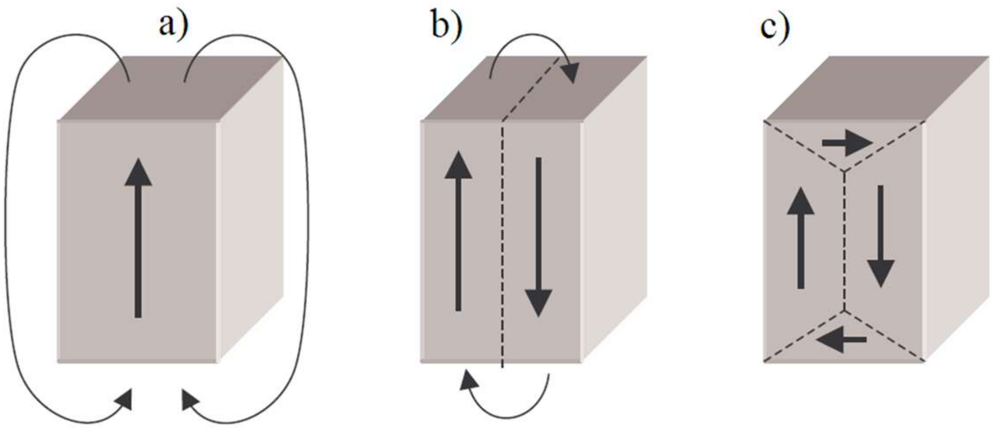
Magnetization vs H Field

Ferromagnet

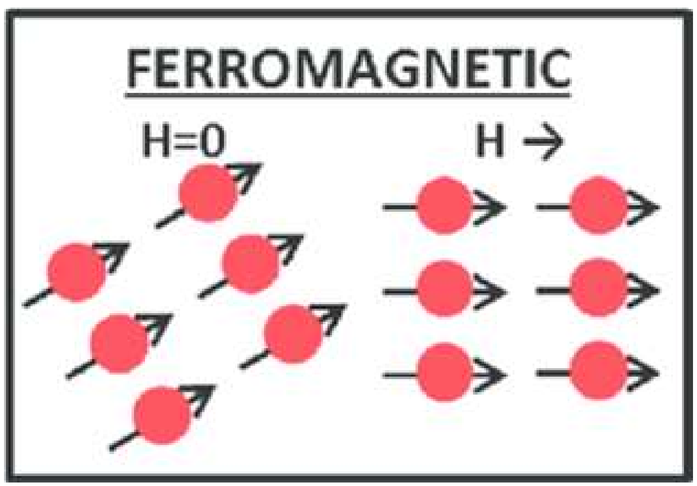


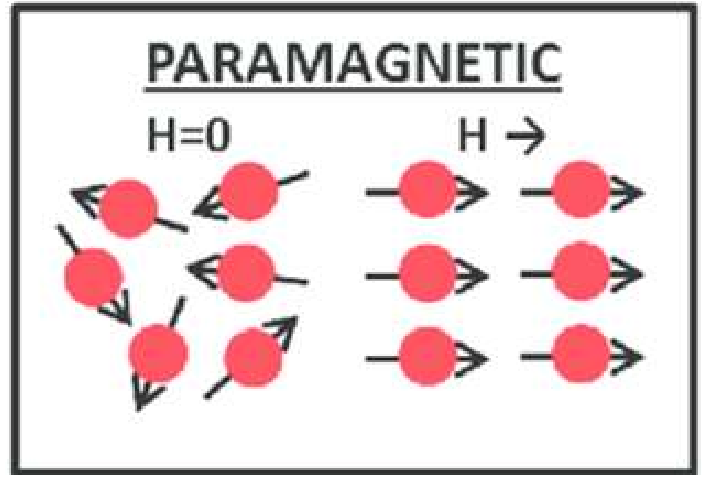


This result will look different once the material is saturated with a field. How do you think?



What is different about a ferromagnet though?





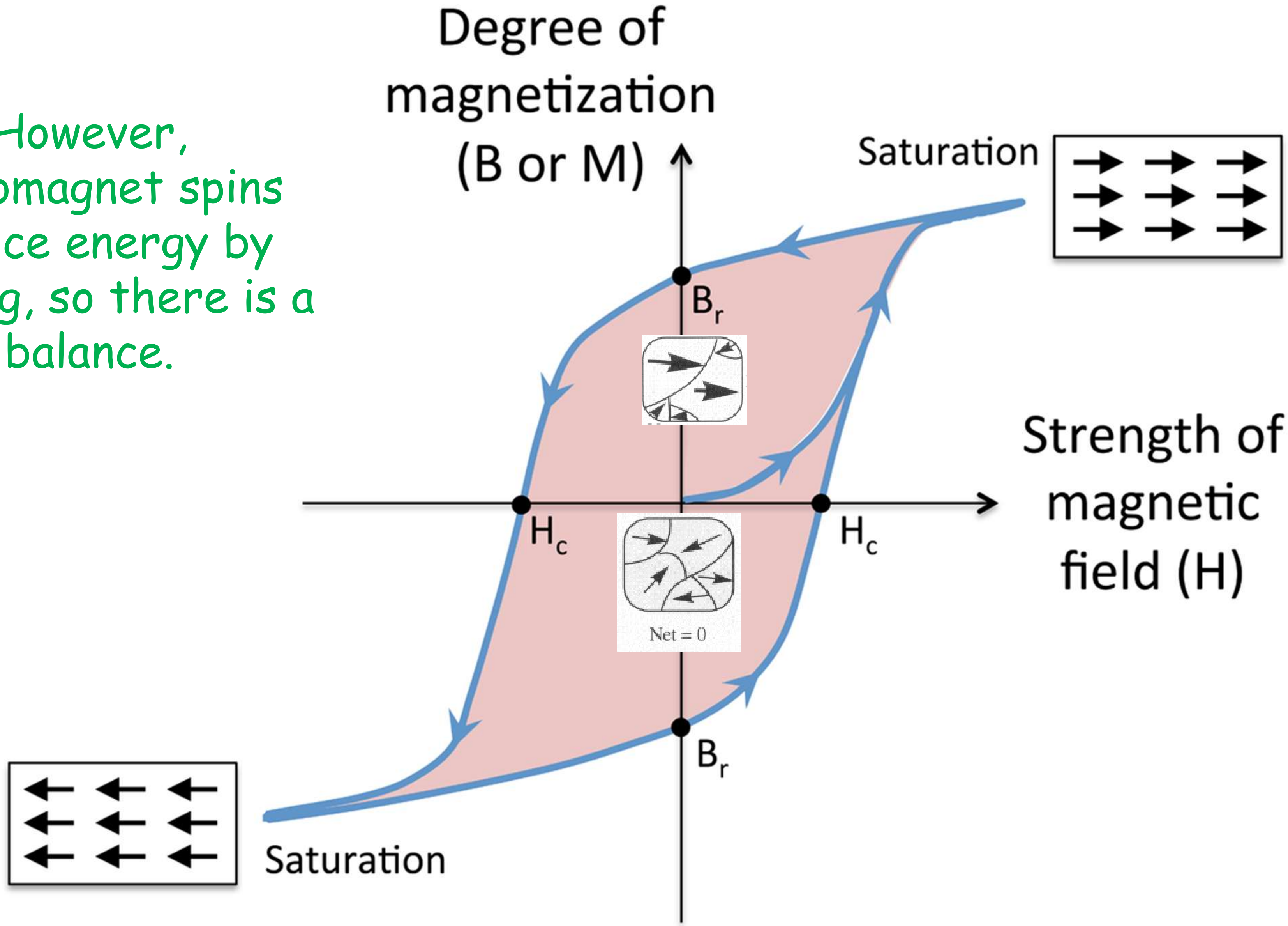
Nearly immediately demagnetizes when field removed.

When a material is magnetized, it creates its own magnetic field. That field stores energy, and the system would rather not 'pay' that energy cost.

Domains During Hysteresis

Typical Hysteresis Loop of a Ferromagnet

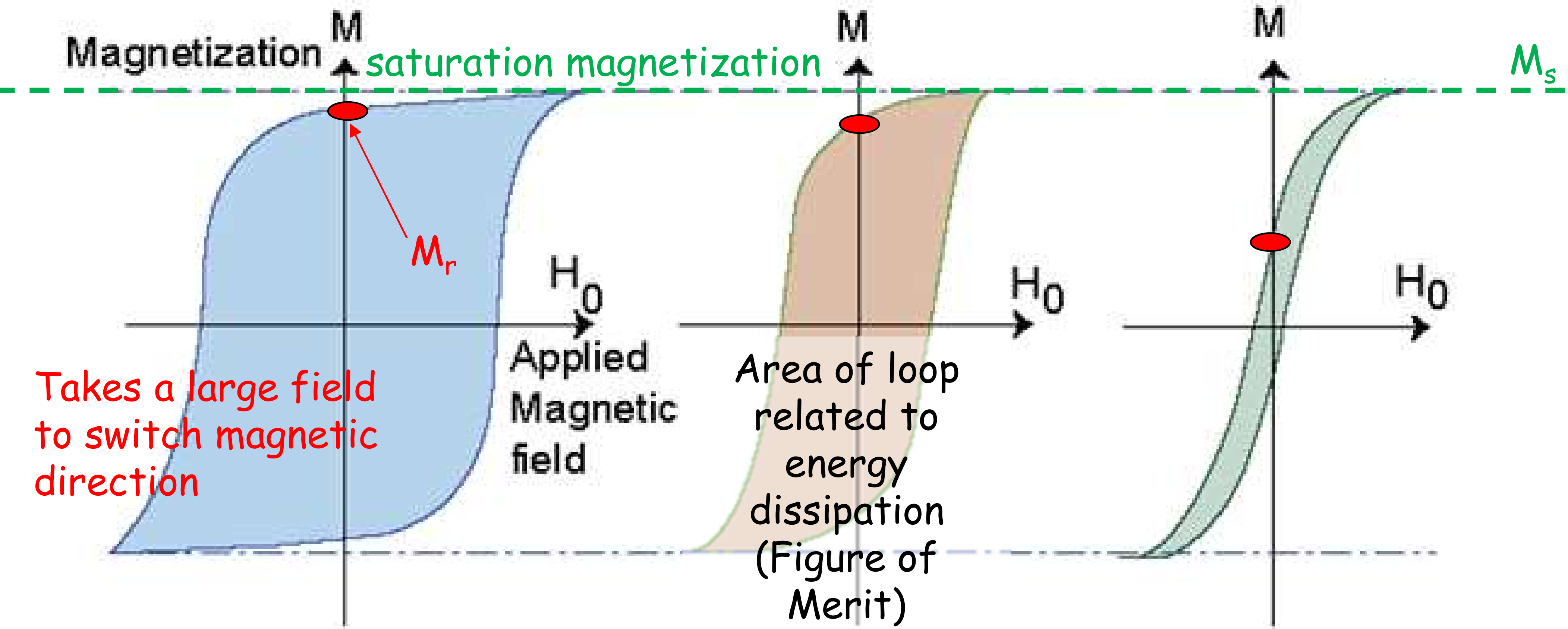
However, ferromagnet spins reduce energy by aligning, so there is a balance.



Hysteresis Loop Goals

Obvious Goal: Want large M_s at application temperature

(Left) Retains a large fraction of the saturation field when field removed

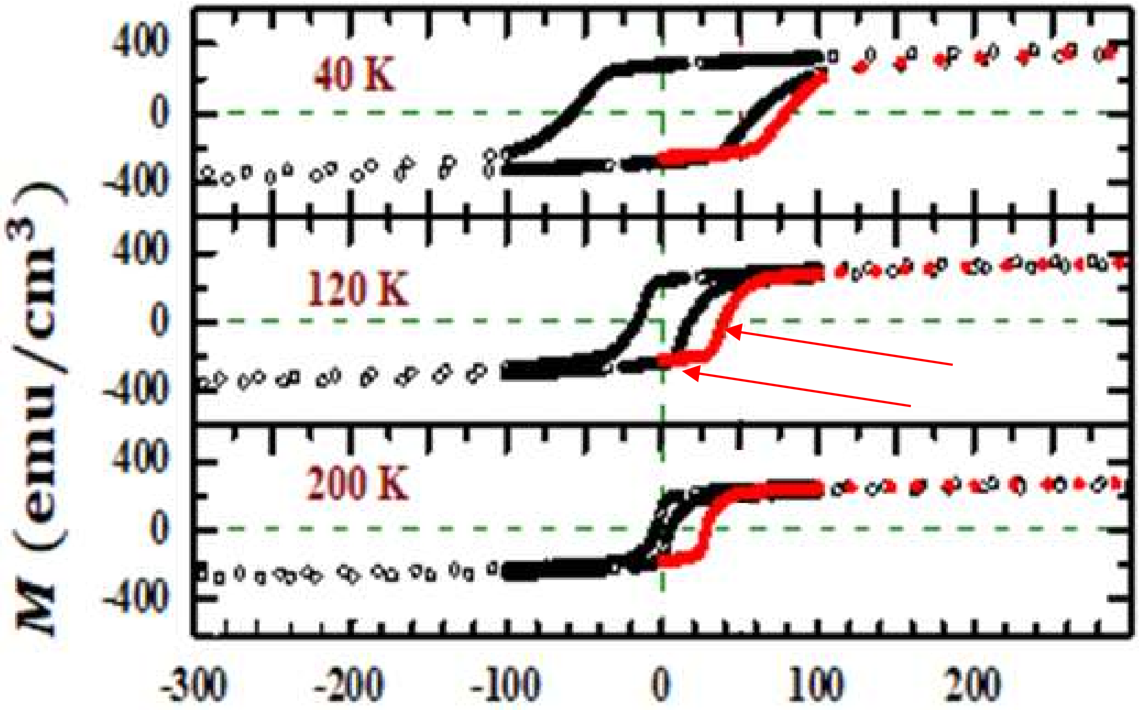


Goal for M_r and loop width depends on application

Desirable for permanent magnets and magnetic recording and memory devices

Desirable for transformer and motors to minimize energy dissipation due to alternating fields

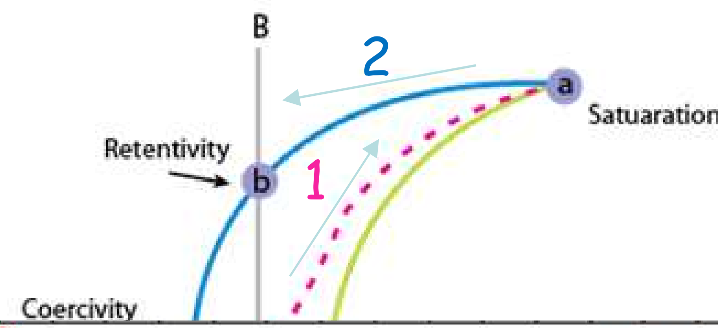
Other Interesting Results



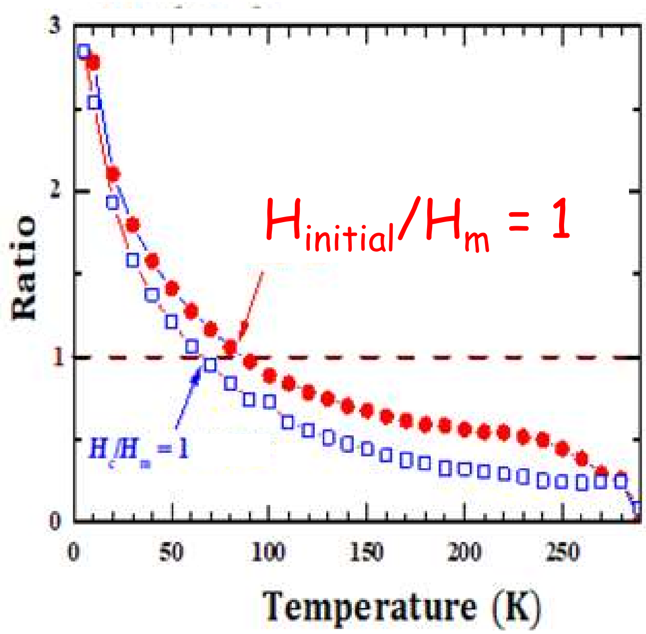
Larger field needed initially (Hi).

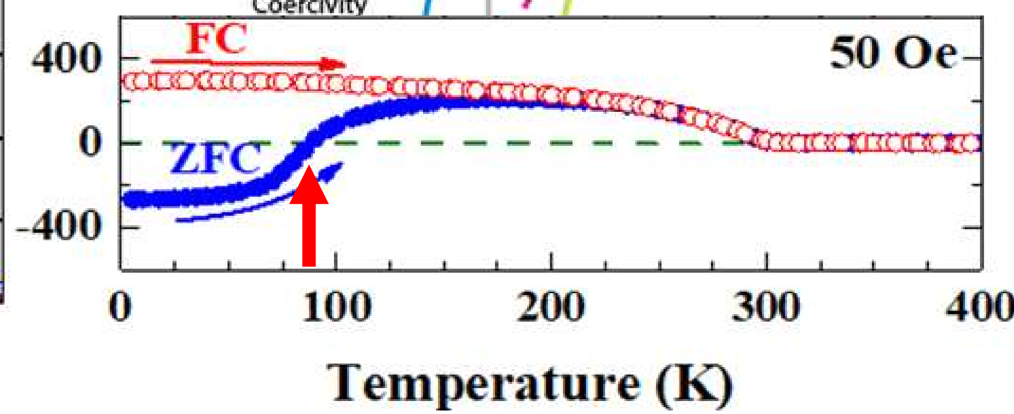
But not just the first time it sees a field!

Typical hysteresis loops

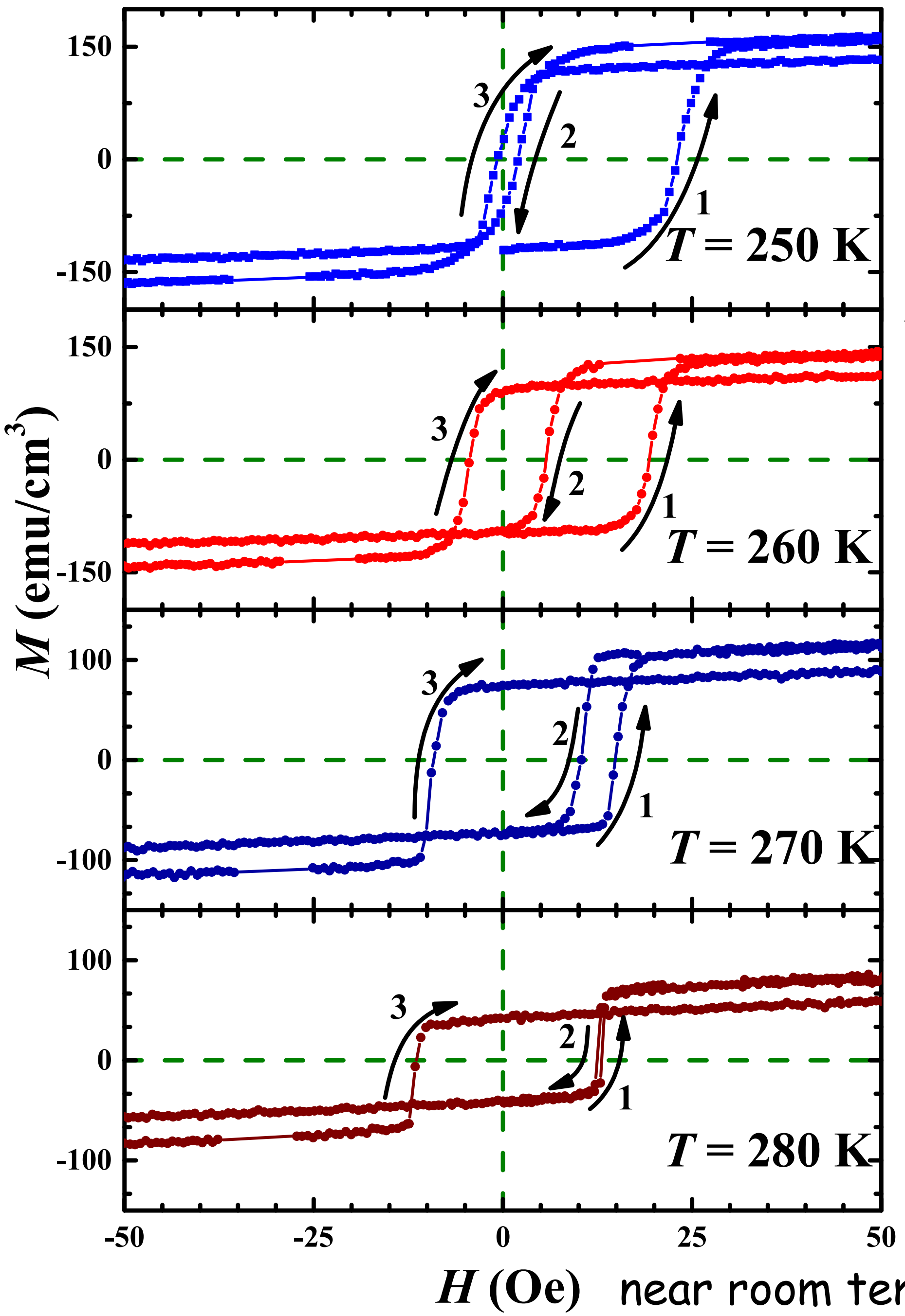


As soon as the measurement field is larger than the initial coercive field, this negative effect is lost temporarily.



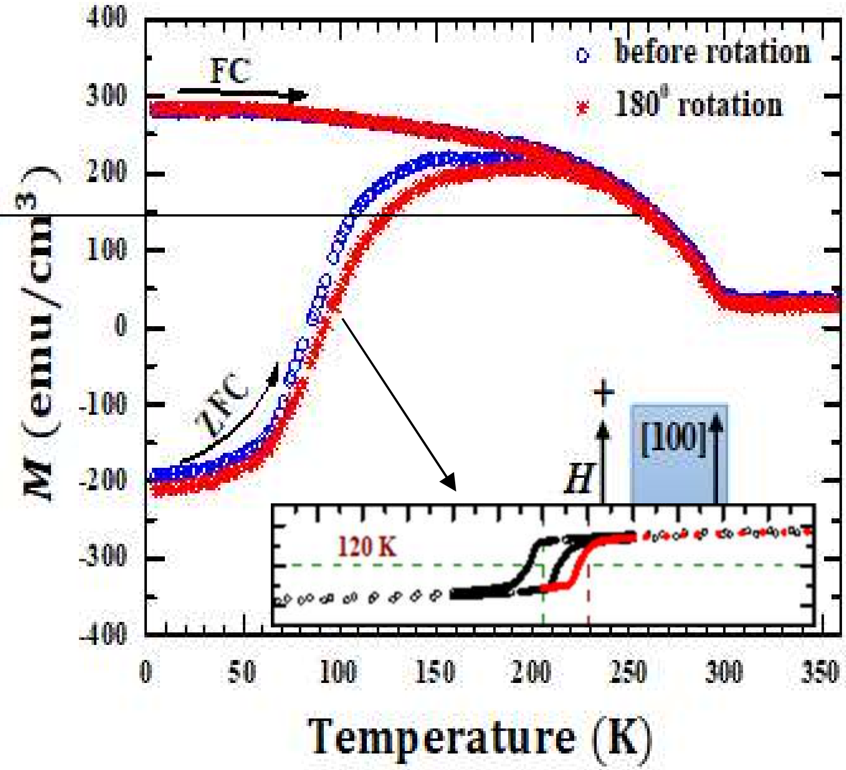


Inverted Loops at Higher Temps



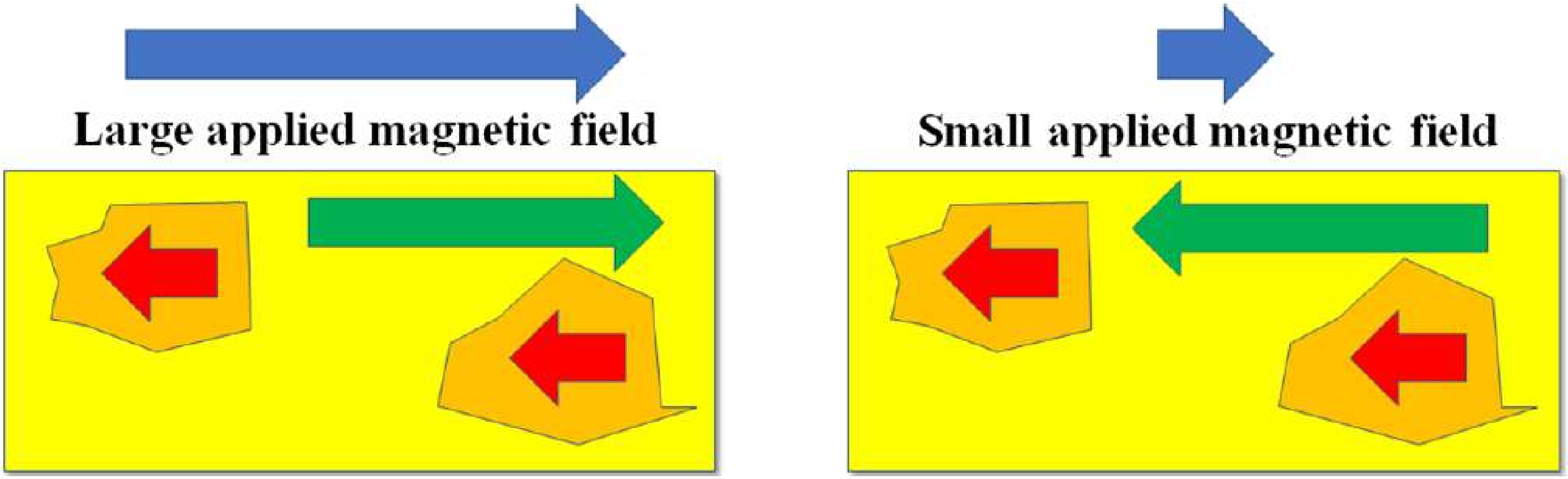
near room temperature

Navid Mottaghi, *et. al.* JPCM 2018



Above the bifurcation temperature (where FC and ZFC meet), the hysteresis loops invert, meaning the magnetization switches direction when the field becomes small!

The Simplified Analogy

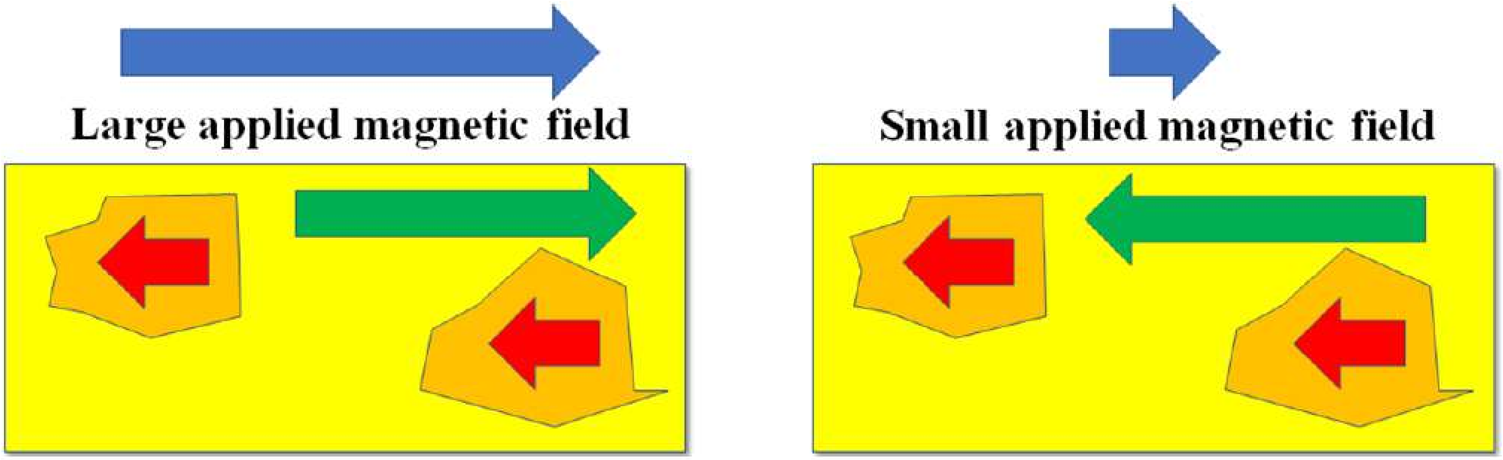


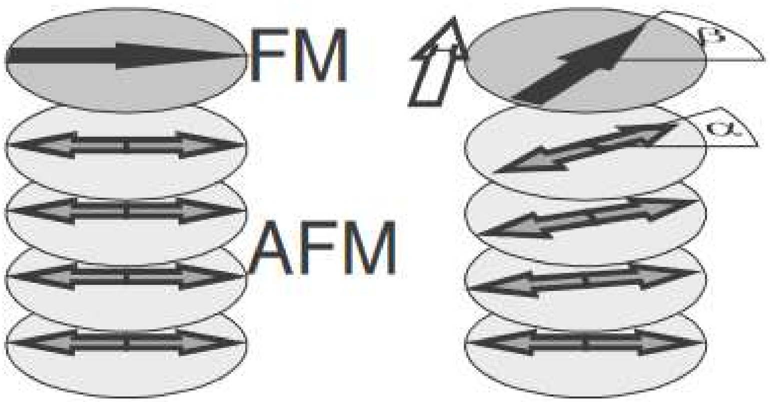
The green arrow indicates the ferromagnetic moments which are normally aligned in the direction of the field.

We have a diamagnetic-like phase that aligns counter to the applied field.

As long as the applied magnetic field is small enough, the field from the diamagnetic-like phase dominates the applied field. Leads to a rapid switch when limit is overcome.

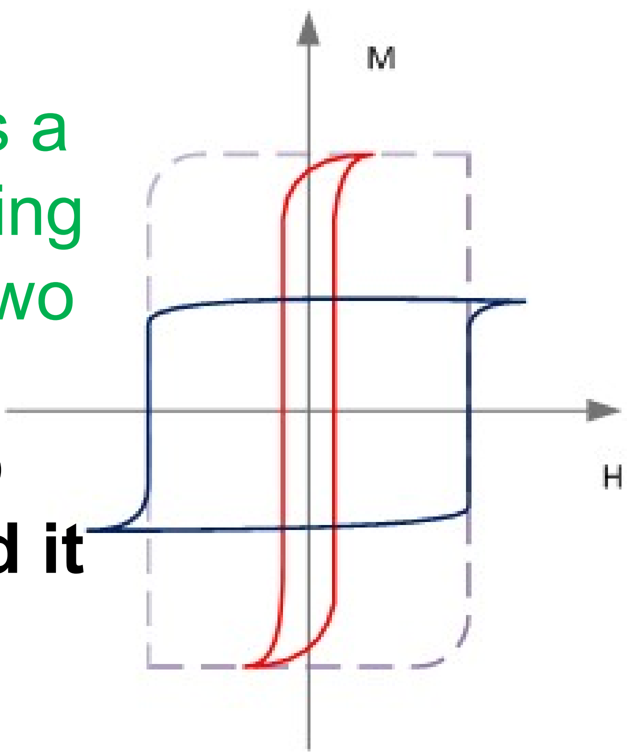
The Simplified Analogy





In reality, it is probably something more complicated, such as a canted exchange spring (the combination of two magnetic phases)

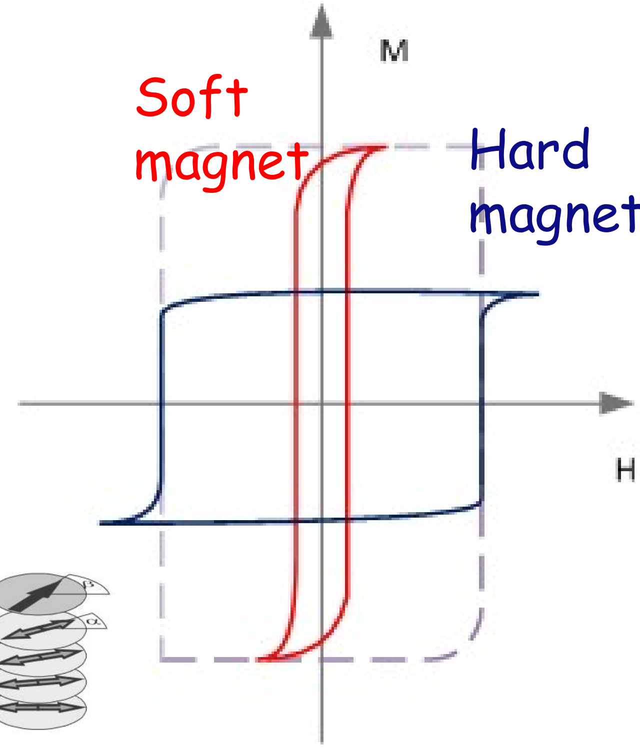
and we need help trying to understand it better!

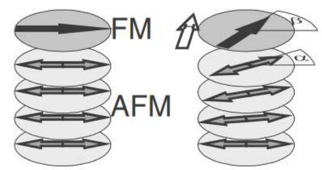


I had another recent idea, but easier to explain next time. Need one more concept first.

A Typical Exchange Spring

An exchange spring is a permanent magnet made from two materials at the nanoscale: a "hard" and a "soft" magnetic material. The hard material resists demagnetization, while the soft material produces a strong magnetic field. The coupling between them works like a coiled spring to create a magnet with both exceptional strength and resilience.





The "spring" effect:

- When an external magnetic field is applied in the opposite direction, the magnetic moments of the soft material begin to twist and bend away from the hard material.
- The strong exchange coupling with the hard material pulls back on the soft material, similar to how a coiled spring would be compressed or stretched. The soft material's magnetic moments twist but don't completely flip.
- When the opposing external magnetic field is removed, the "exchange spring" recoils, forcing the soft material's magnetic moments to snap back into alignment with the hard material.

Possible Applications

Flipping at low field could be interesting for:

- **Magnetic sensors** – detecting when a field crosses through zero.
- **Magnetic logic or memory devices** – where sharp switching thresholds are useful.
- **Magnetic ratchets or neuromorphic circuits** – where unusual hysteresis responses can encode information.

Meet Your Group

Times are not expected regularly.

Groups (do any of these not work?):

- Friday 5pm: Melissa, Shelby, Leeam
- Tuesday 10:30am: Evan, Jeffrey, Austin
- Monday 5pm: Ryan, Gavin, Alp
- Tuesday 4pm: Bryce and Tyler
- Monday/Friday 5pm: Nickolai and Durham

Meet your partner(s) and discuss any ideas you currently are thinking about for your projects. Take some notes to remember.

Many of you have other overlap too, fyi.