Neutron Scattering of Nanostructured Magnets

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NEUTRON SCATTERING

Advantages

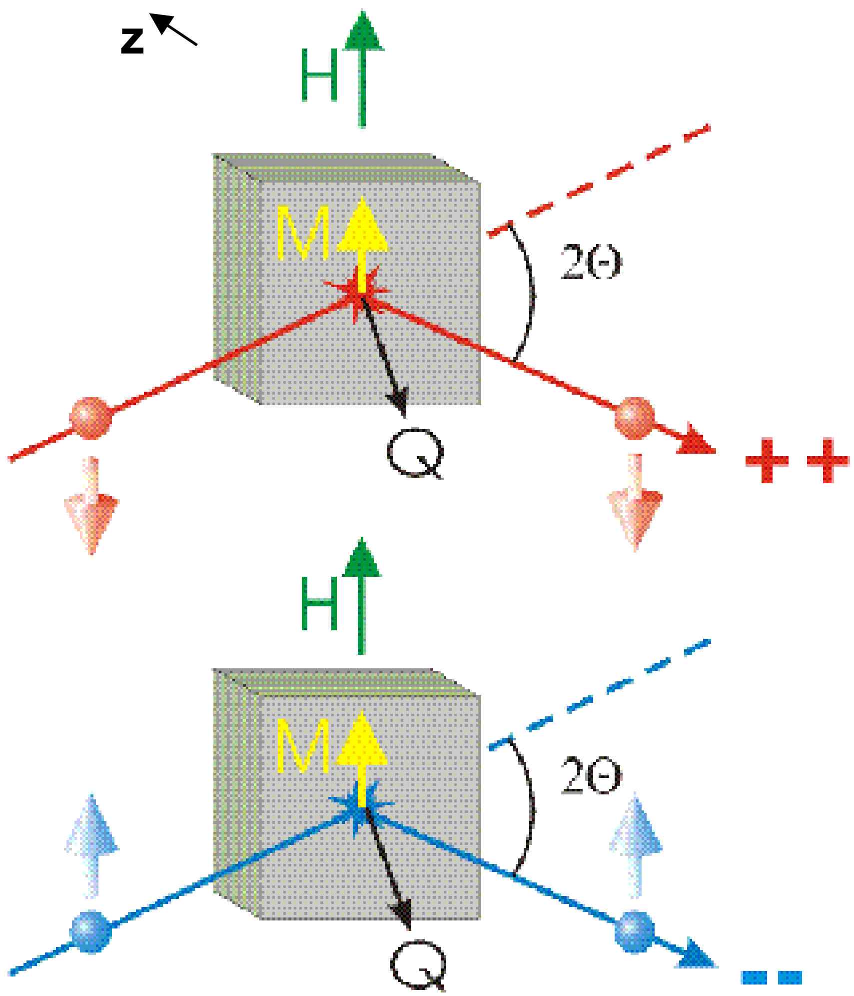
- Old Technique
- Interpretation Straight Forward
- Deep Penetration

Disadvantages

- Low Intensity
- Politics

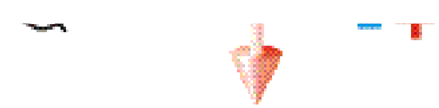
Neutron Scattering
Friends and phones

Polarized Neutron Reflectometry



Non spin-flip cross-sections

- **M||H**
- **vs. Q (vs z).**

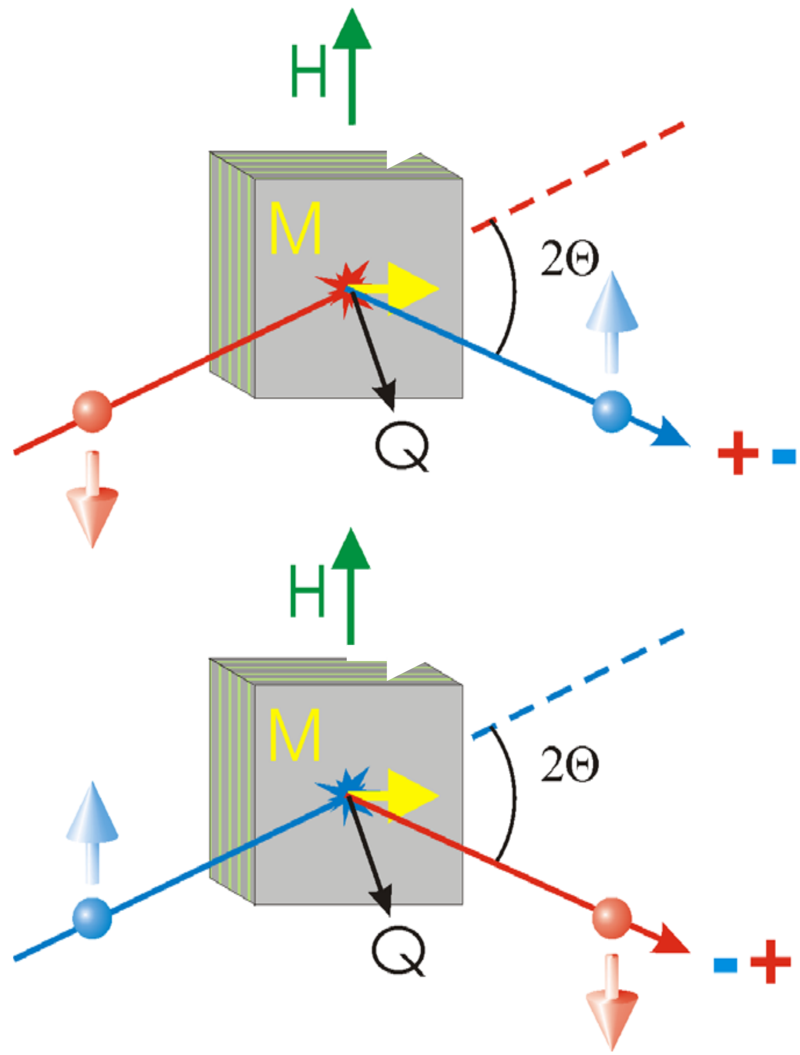


Polarized Neutron Reflectometry

Spin-flip

cross-sections

- **M⊥ H**
- **vs Q (vs z)**



3 cases

1.- Burried Interfaces

(Magnetic and Nonmagnetic)

Roughness in Superlattices

2.- Nanoscopic Magnetic Ordering

Magnetic Orientation in Multilayers

3.- Vector Magnetometry

Exchange Bias in Bilayers

Magnetic & Nonmagnetic Roughness

Mo/Ni Superlattices

Collaborators

ORNL

J. Cable

ANL

M. Khan

G. Felcher

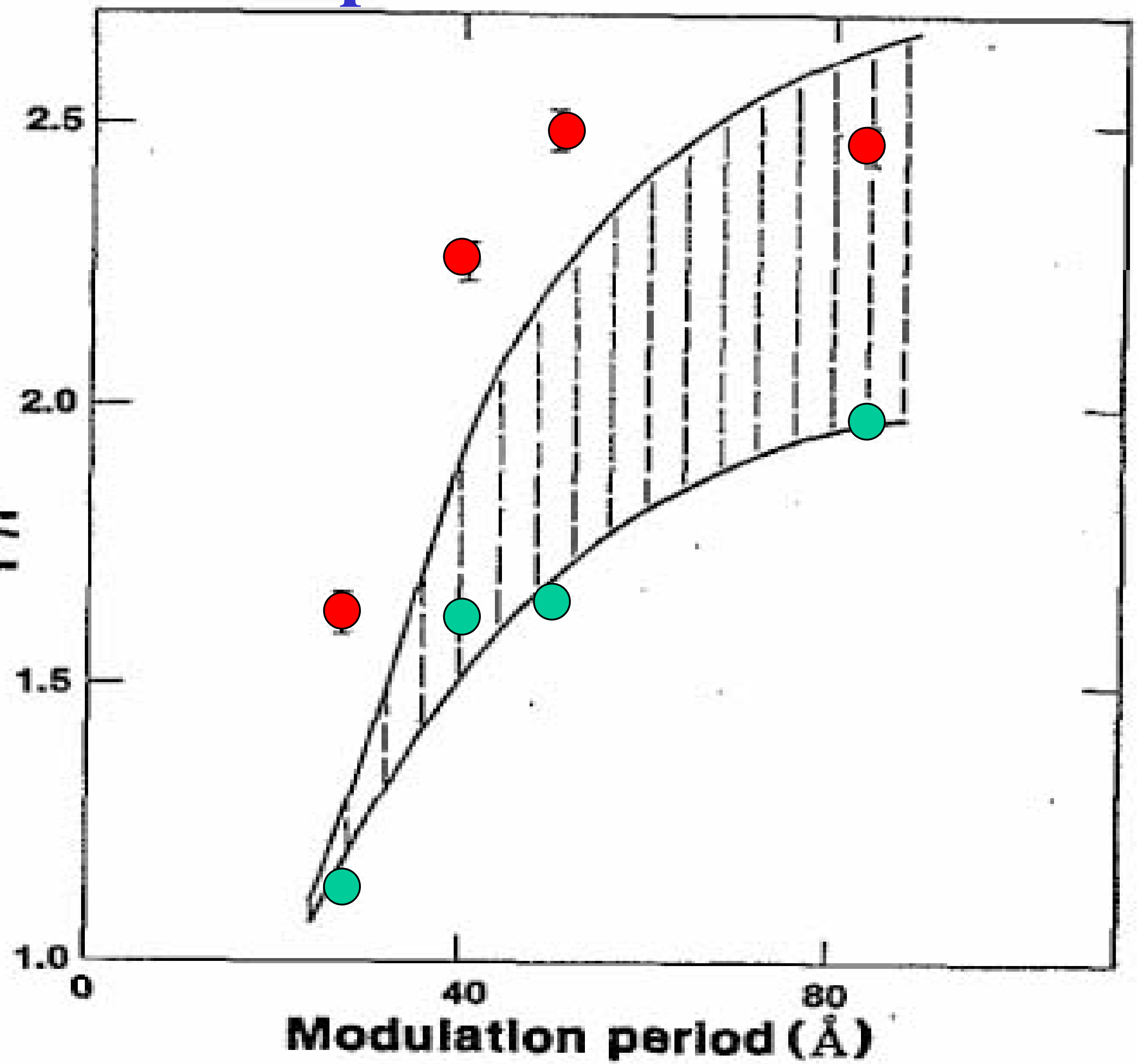
Polarized Neutron Scattering

Mo/Ni Superlattices

Square Modulation

All possible models

Experimental Flipping Ratio



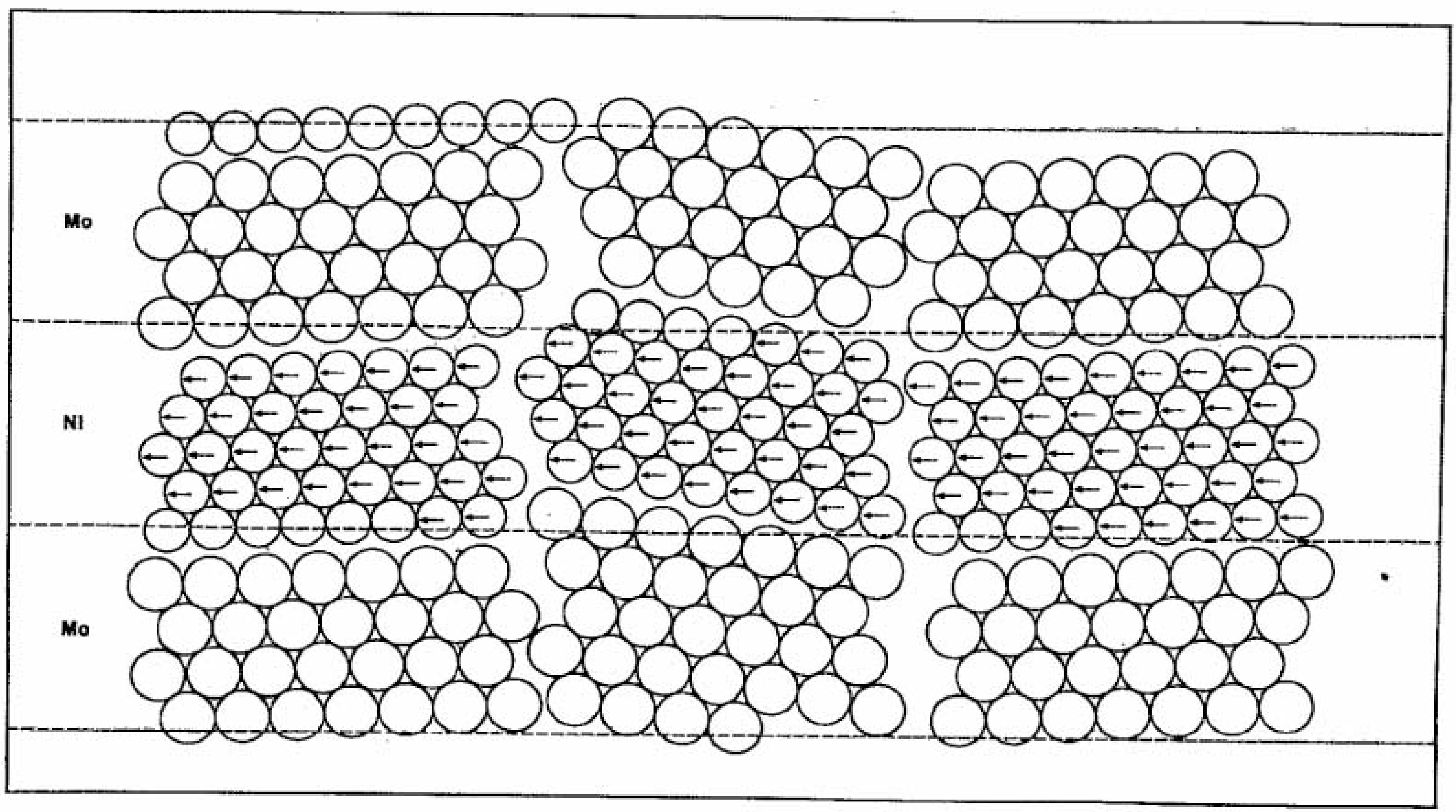
Mo/Ni Superlattices

"A comparison of X-ray and neutron diffraction implies that the magnetic profile in the superlattice is more perfect than the chemical profile."

Mo

Ni

Mo



J. W. Cable, M.R. Khan, G. Felcher, I. K. Schuller, Phys. Rev. B34, 1643(1986)

3 cases

1.- Burried Interfaces(Magnetic-Nonmagnetic)

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Magnetic Orientation-Multilayers

3.- Vector Magnetometry

Exchange Bias in Bilayers

Coupling

Fe/Cr Multilayers

S. teVelthuis et al., In print 2002

Collaborators

ANL

S. te Velthuis

G. Felcher

UCSD

S. Kim

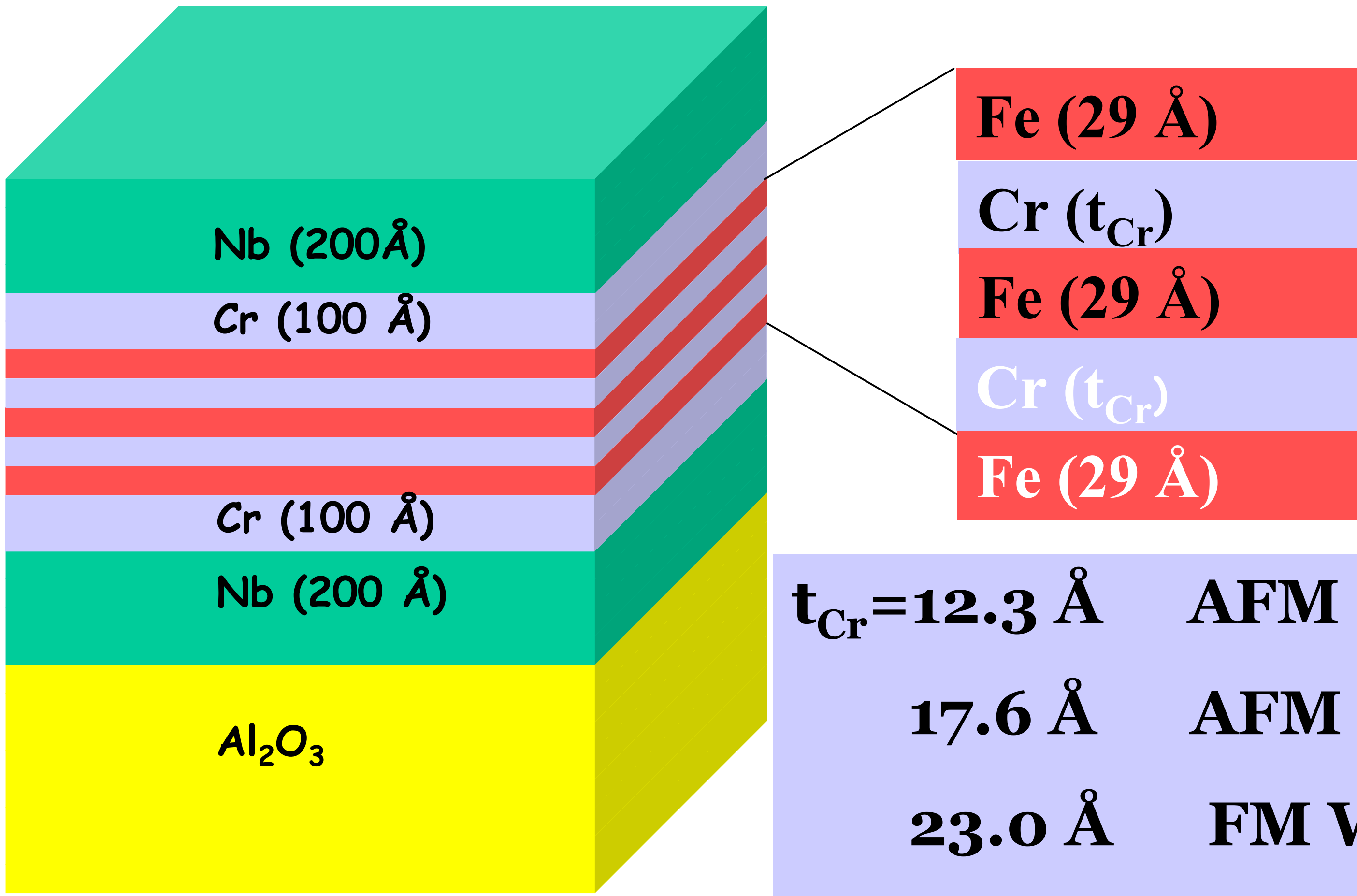
Interlayer exchange coupling

Exchange coupling
F layers
across non-F spacer
is oscillatory

- Long period (≈18Å, Fe/Cr)
- Short period (≈2Å, Fe/Cr)
  Only for very smooth interfaces

Review: **M.D. Stiles JMMM 200 (1999) 322**

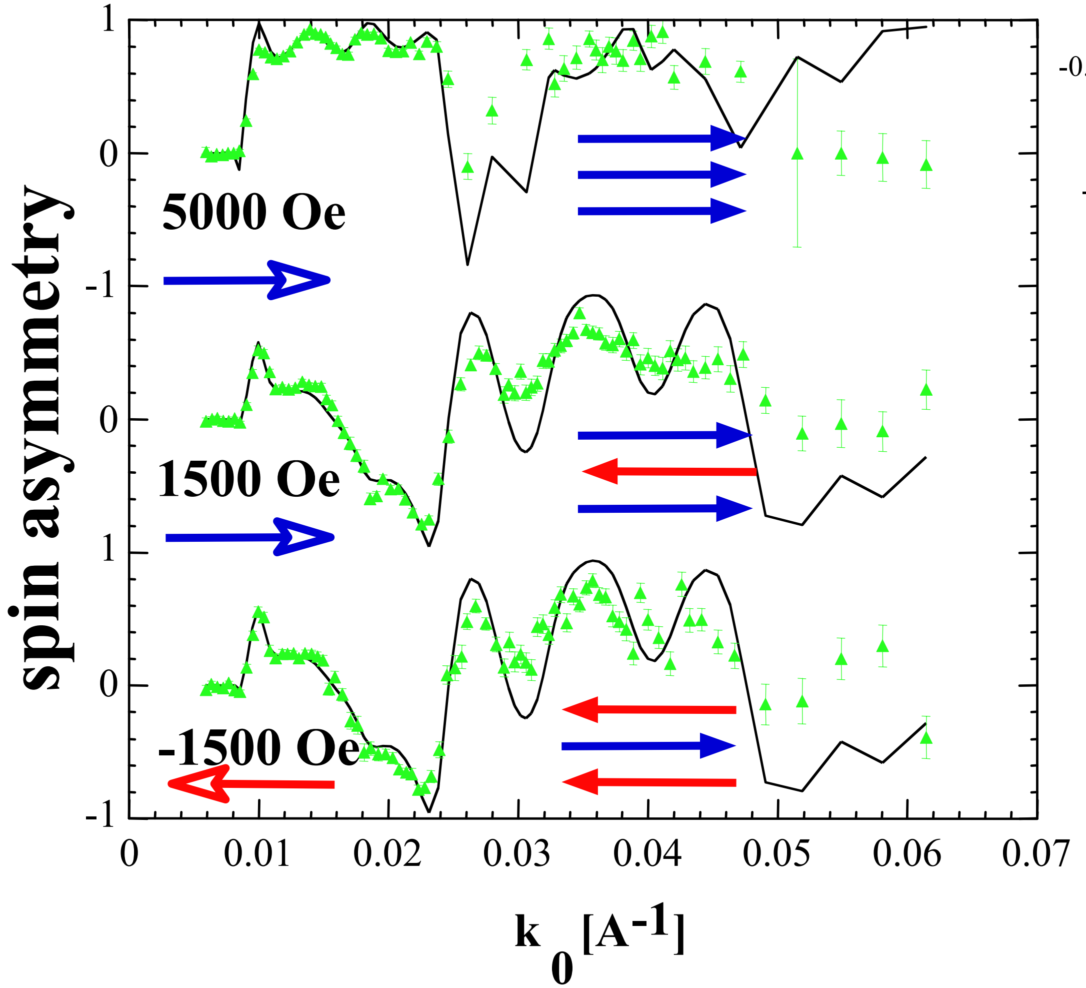
Epitaxial Fe/Cr (110) multilayers

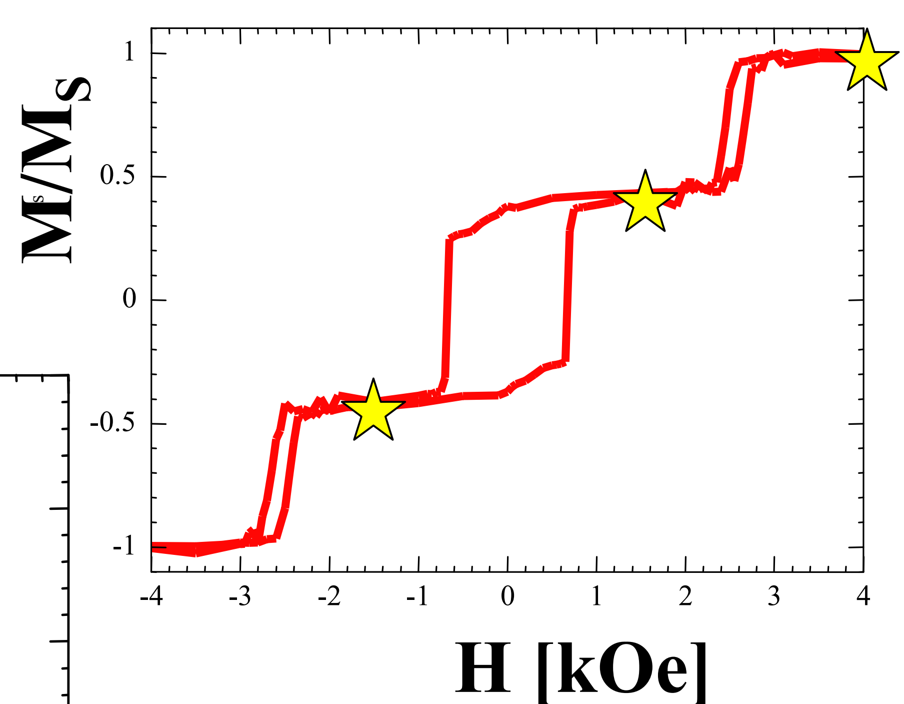


t_{Cr}=12.3 Å	AFM Strong
17.6 Å	AFM Weak
23.0 Å	FM Weak
31.0 Å	FM Strong

$t_{Cr} = 12.3$ Å

Spin asymmetry
$(R^+ - R^-)/(R^+ + R^-)$

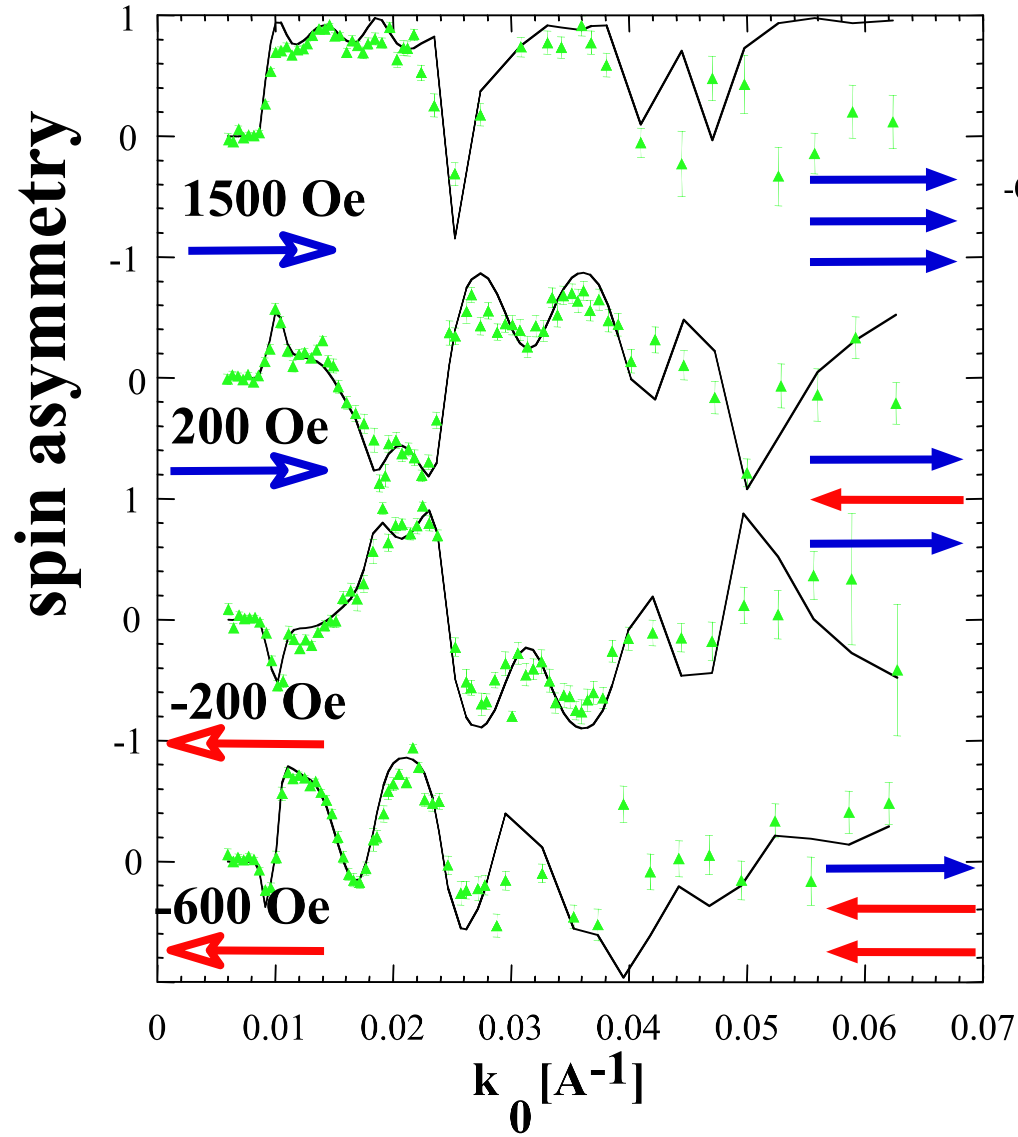


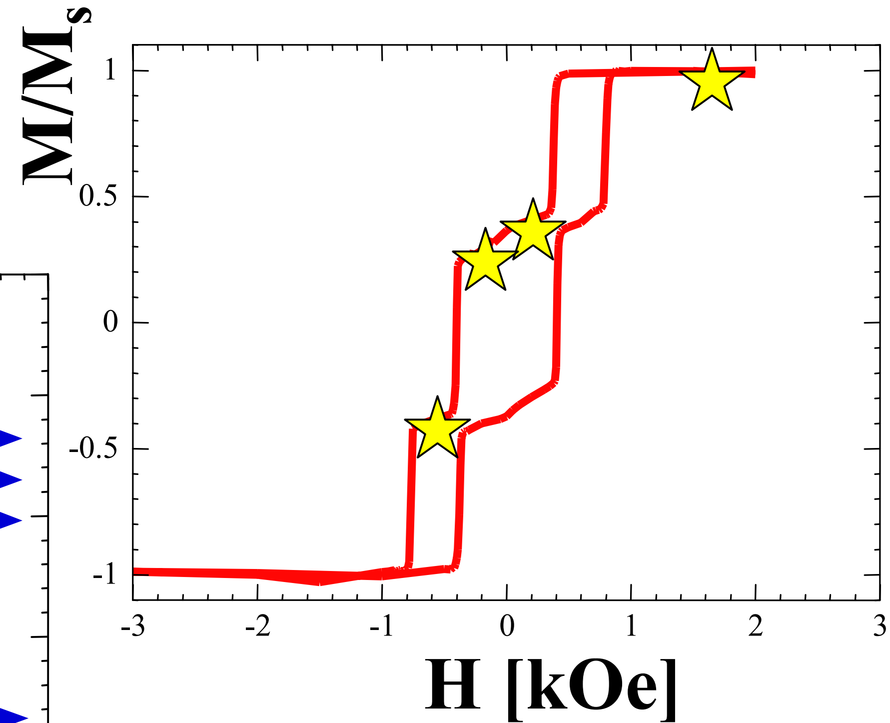


AFM Strong

Top and Bottom Same

t_{Cr} = 17.6 Å

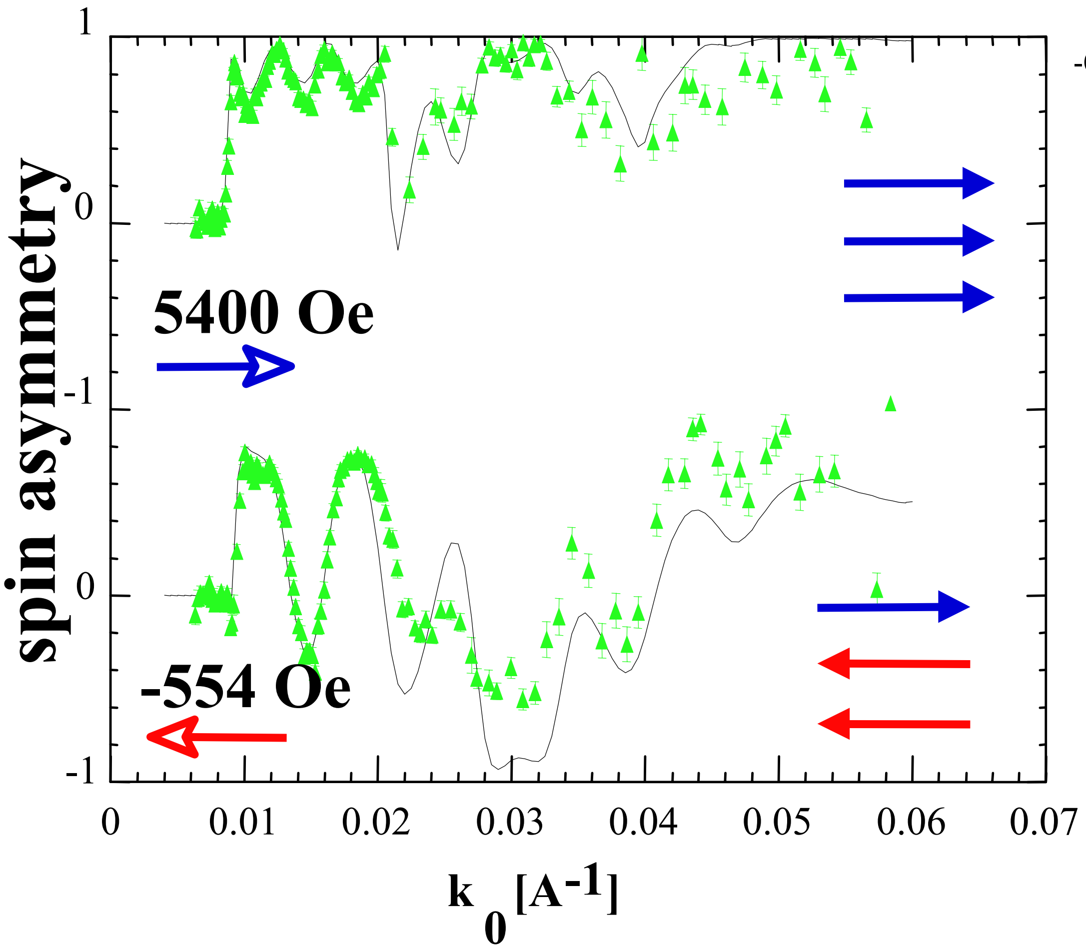


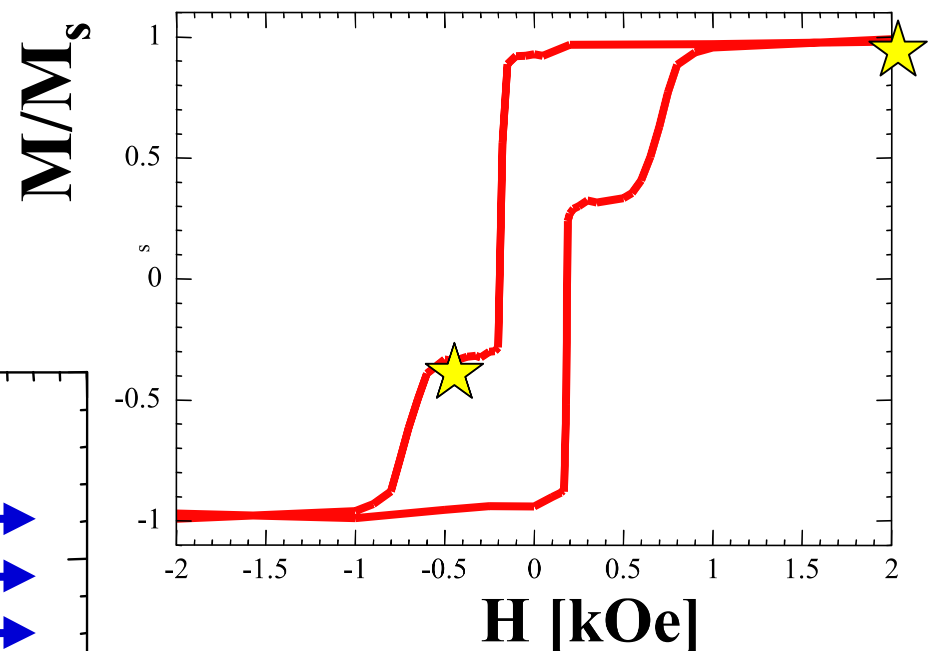


AFM Weak

Top and bottom Different

t_{Cr} = 23 Å



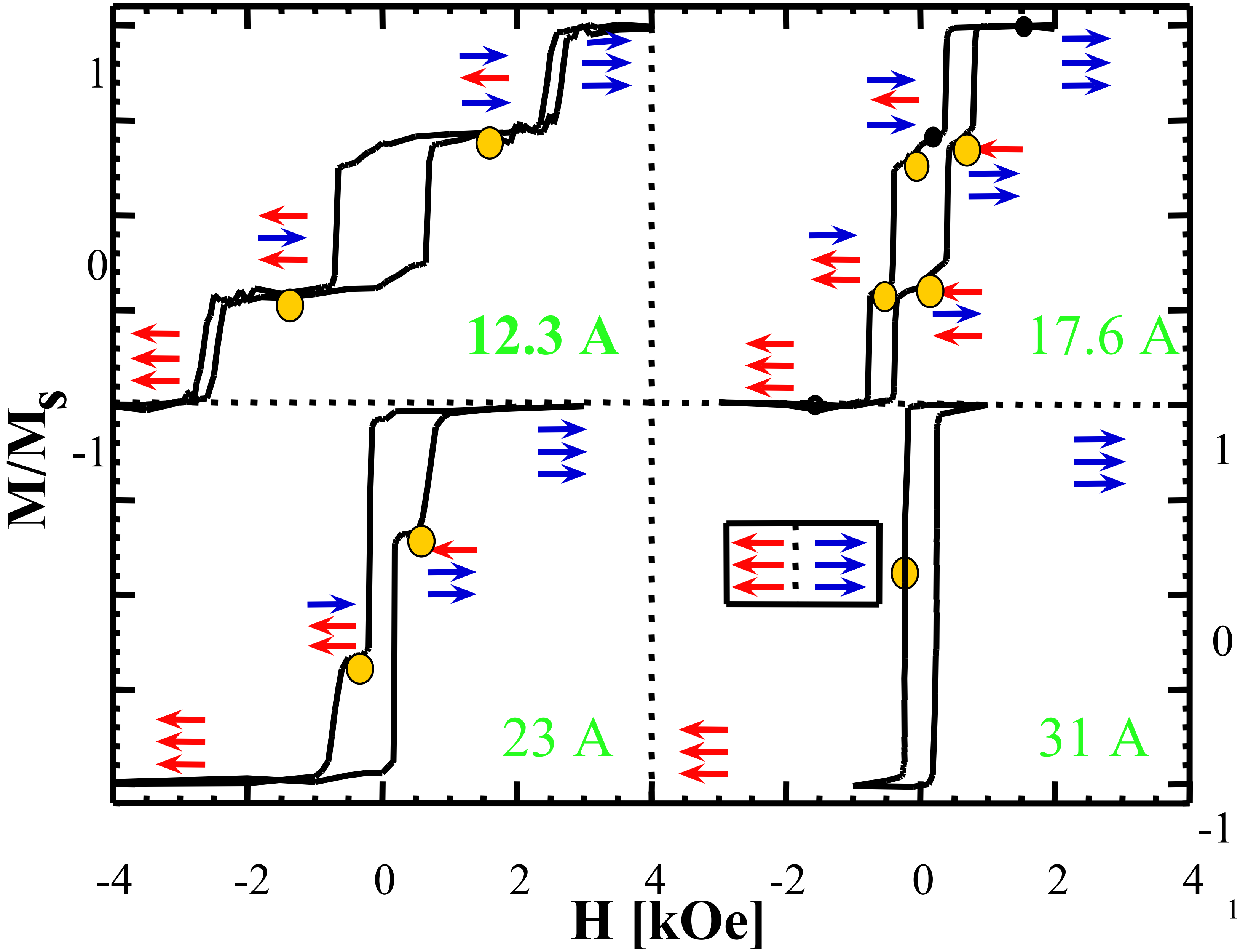


FM Weak

Top and bottom

Different

Summary



3 cases

1.- Burried Interfaces (Magnetic and Nonmagnetic)

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Magnetic Orientation in Multilayers

3.- Vector Magnetometry

Exchange Bias in Bilayers

Exchange Bias

Fe-*X*F_2 Bilayers

X=Fe,Mn,Zr,Co

Collaborators

LANL:
M Fitzsimmons
J.R. Groves
P. Arendt
R. Springer
A. Hoffmann
P.C. Yashar

NIST:
C.F. Majkrzak
J.A. Dura
B. Shull

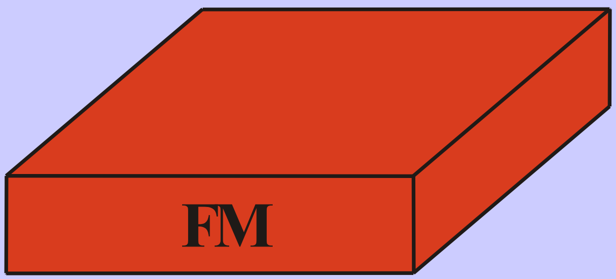
HMI:
H. Fritzsche

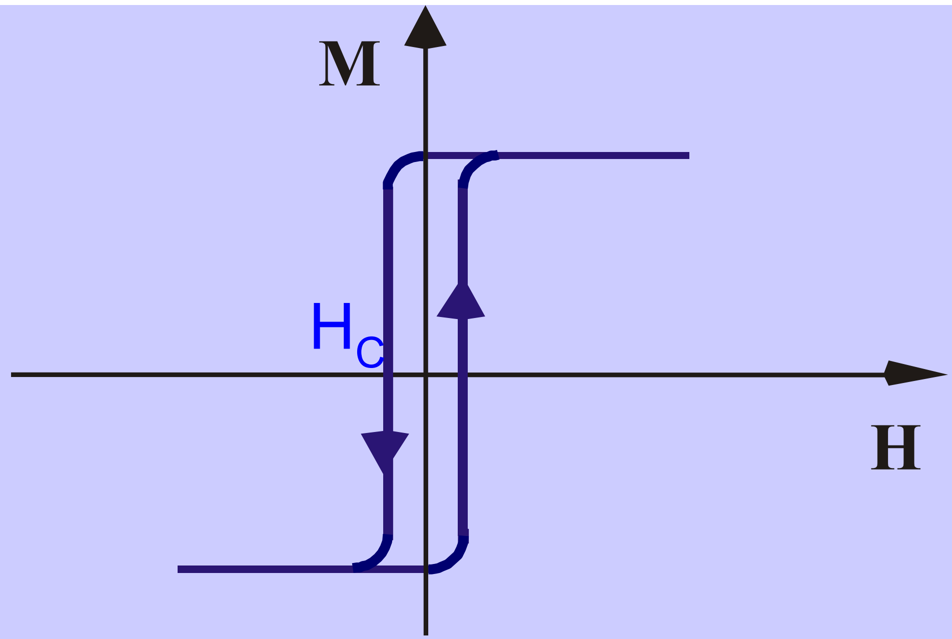
U. A. Barcelona:
J. Nogues

ILL:
Vincent Leiner
Hans Lauter

UCSD:
C. Leighton
K. Liu

EVERYTHING YOU WANTED TO KNOW ABOUT FERROMAGNETISM…….but …were afraid to ask





Free FM

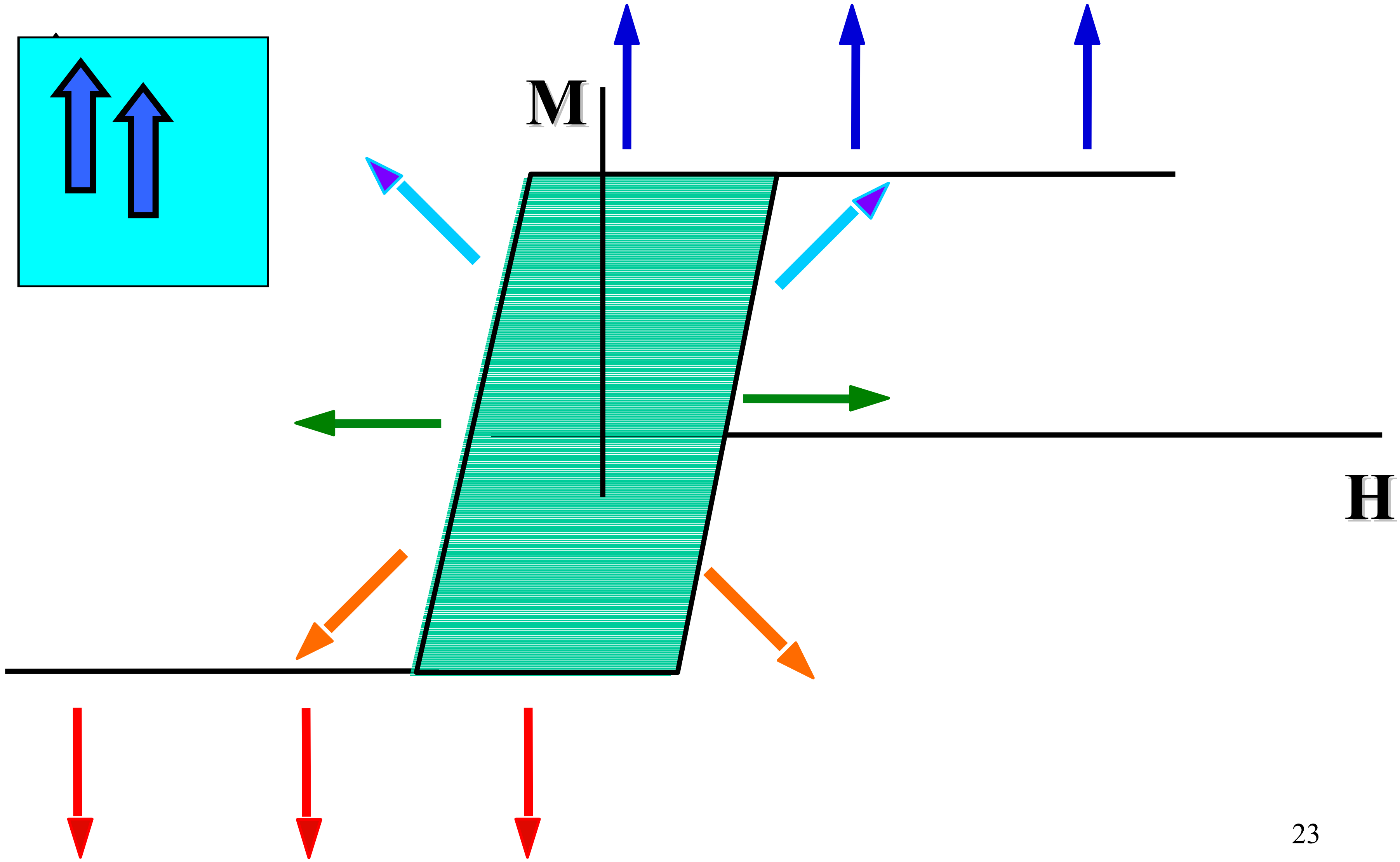
Small coercivity H_C

Exchange field H_E=0

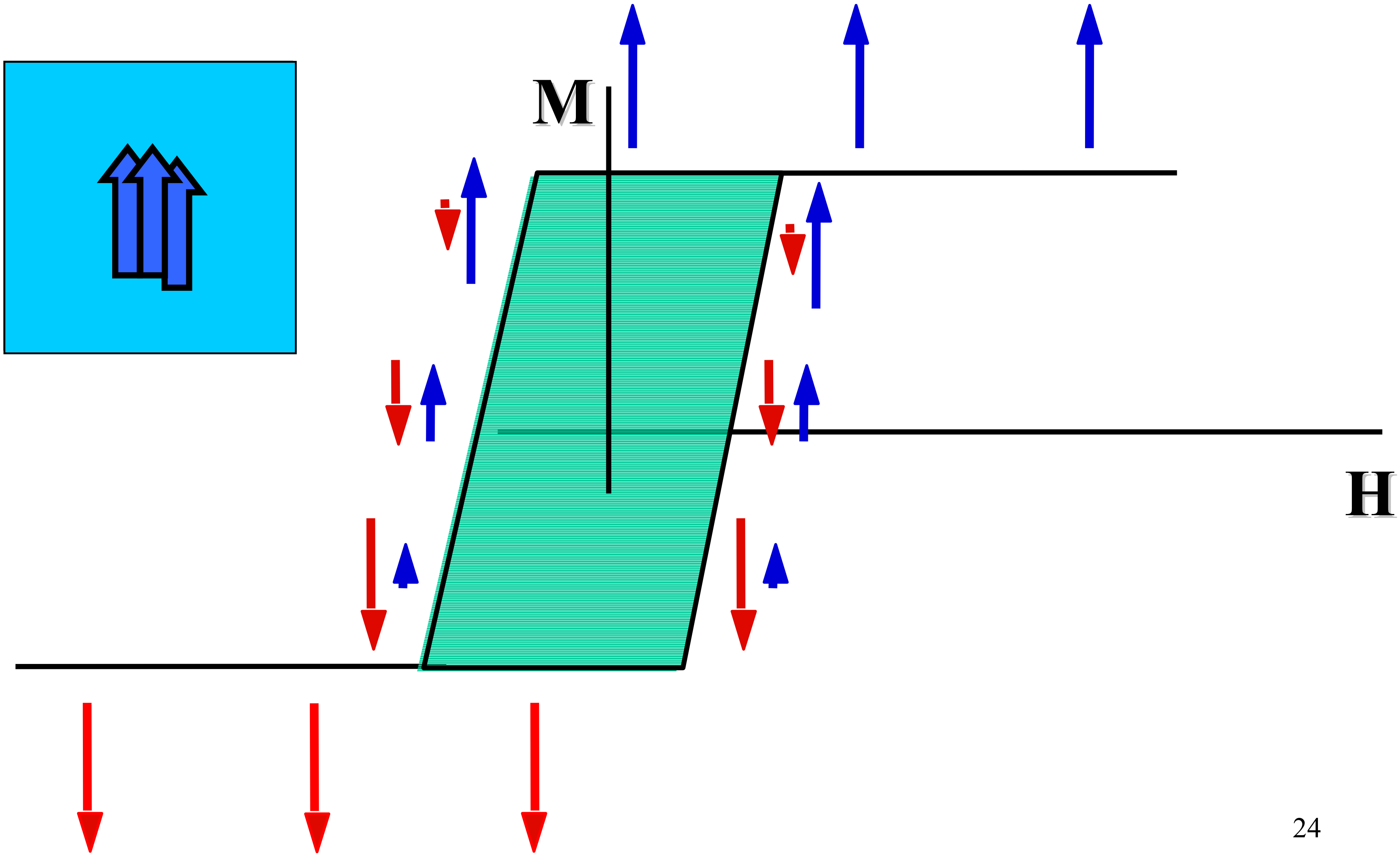
(centered at H=0)

WHAT IS THE REVERSAL MODE ?

ROTATION



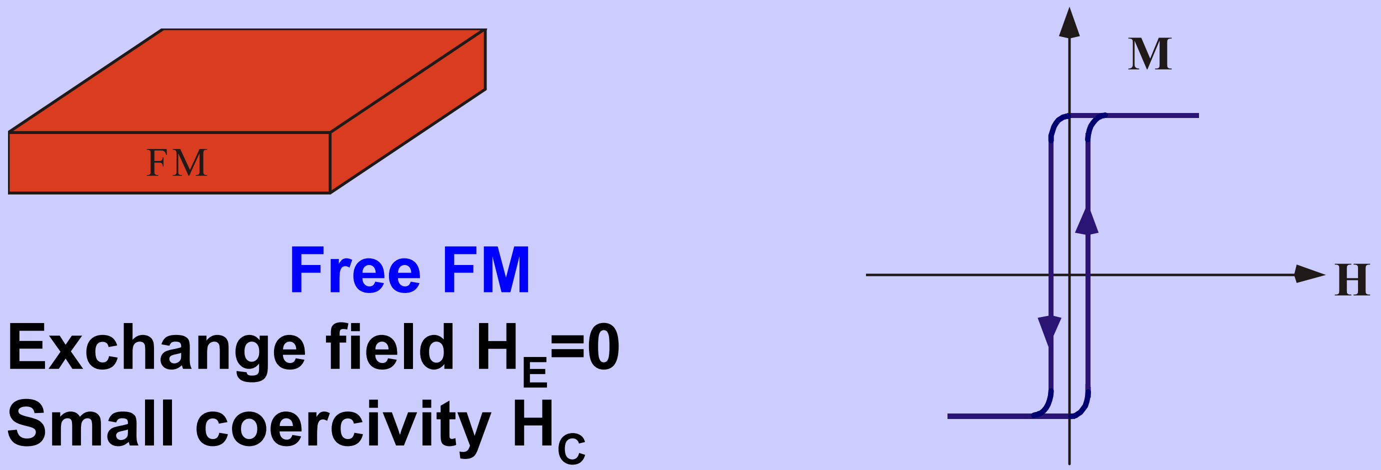
NUCLEATION & WALL MOTION



Reversal Mode is the Same in Both Sides of the Hysteresis Loop

In all materials systems
known to man

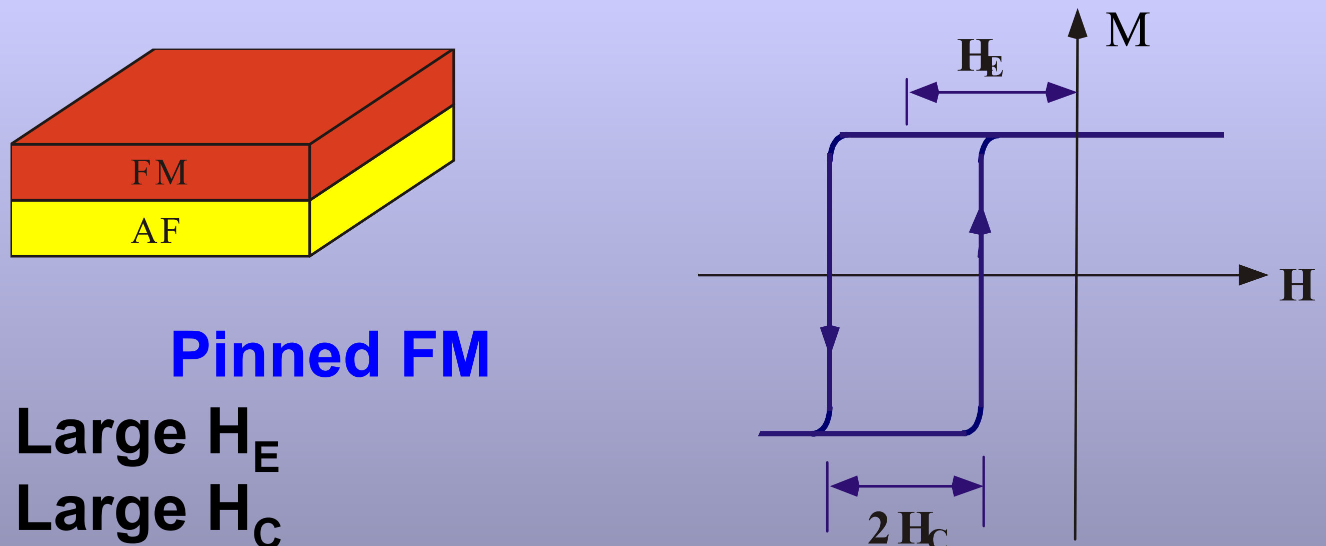
Exchange Bias



Free FM

Exchange field H_E=0

Small coercivity H_C



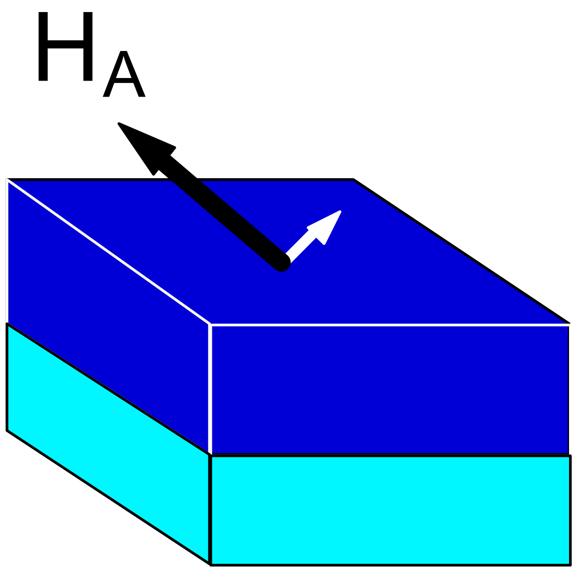
Pinned FM

Large H_E

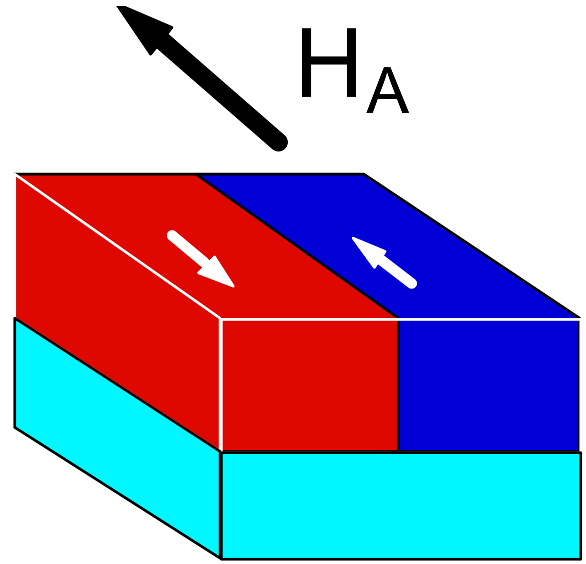
Large H_C

Some Neutron Related Issues

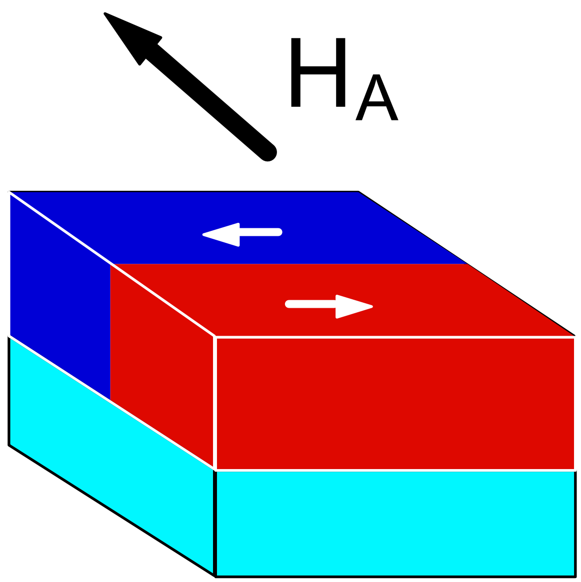
- Reversal Mode
- Domains in the F or AF
- Moments in the AF
- Interfacial magnetic structure



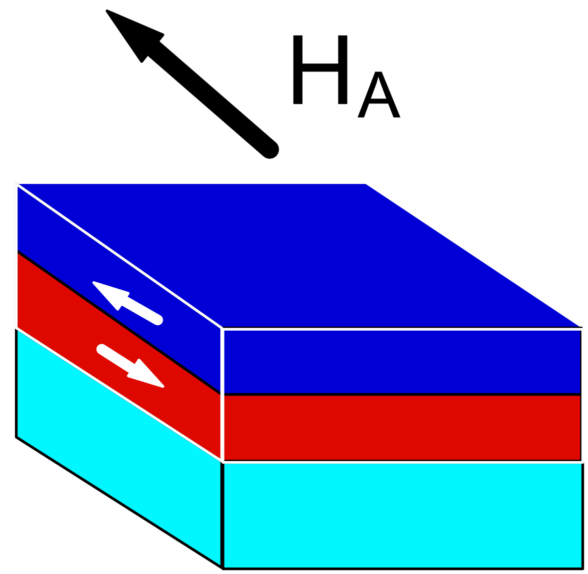
Coherent Rotation



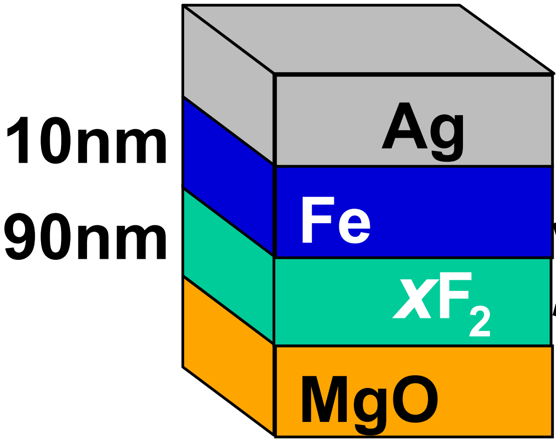
Opposed Domains

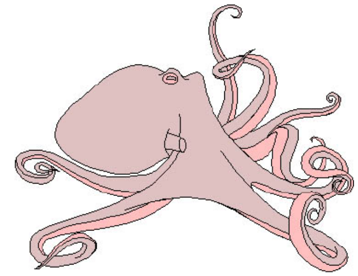


Opposed Domains + Rotation

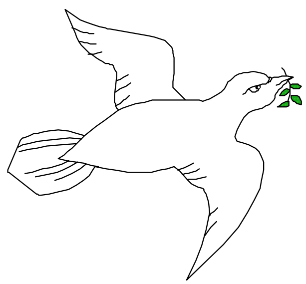


Layered Domains

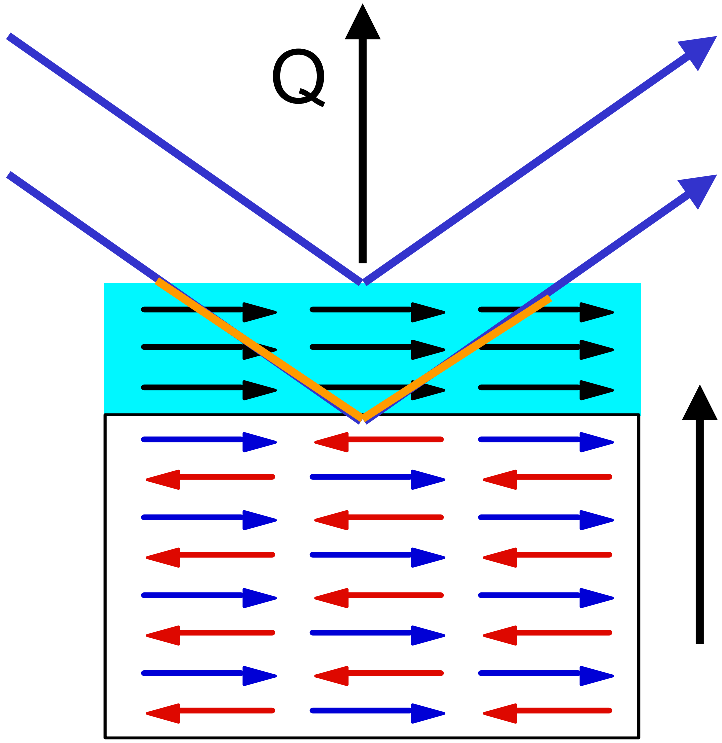


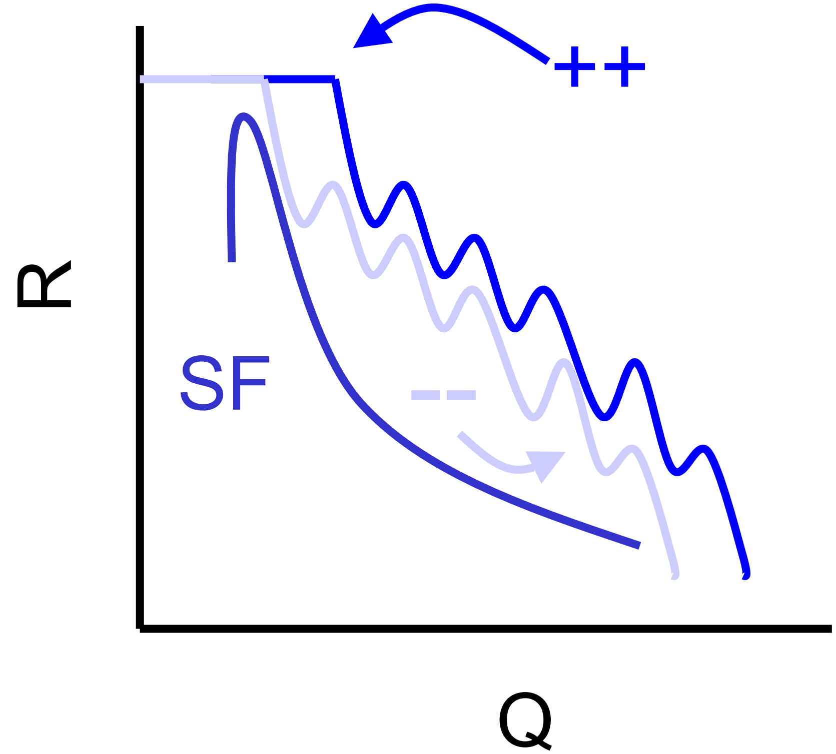


X= Fe, Mn, Co, Zn



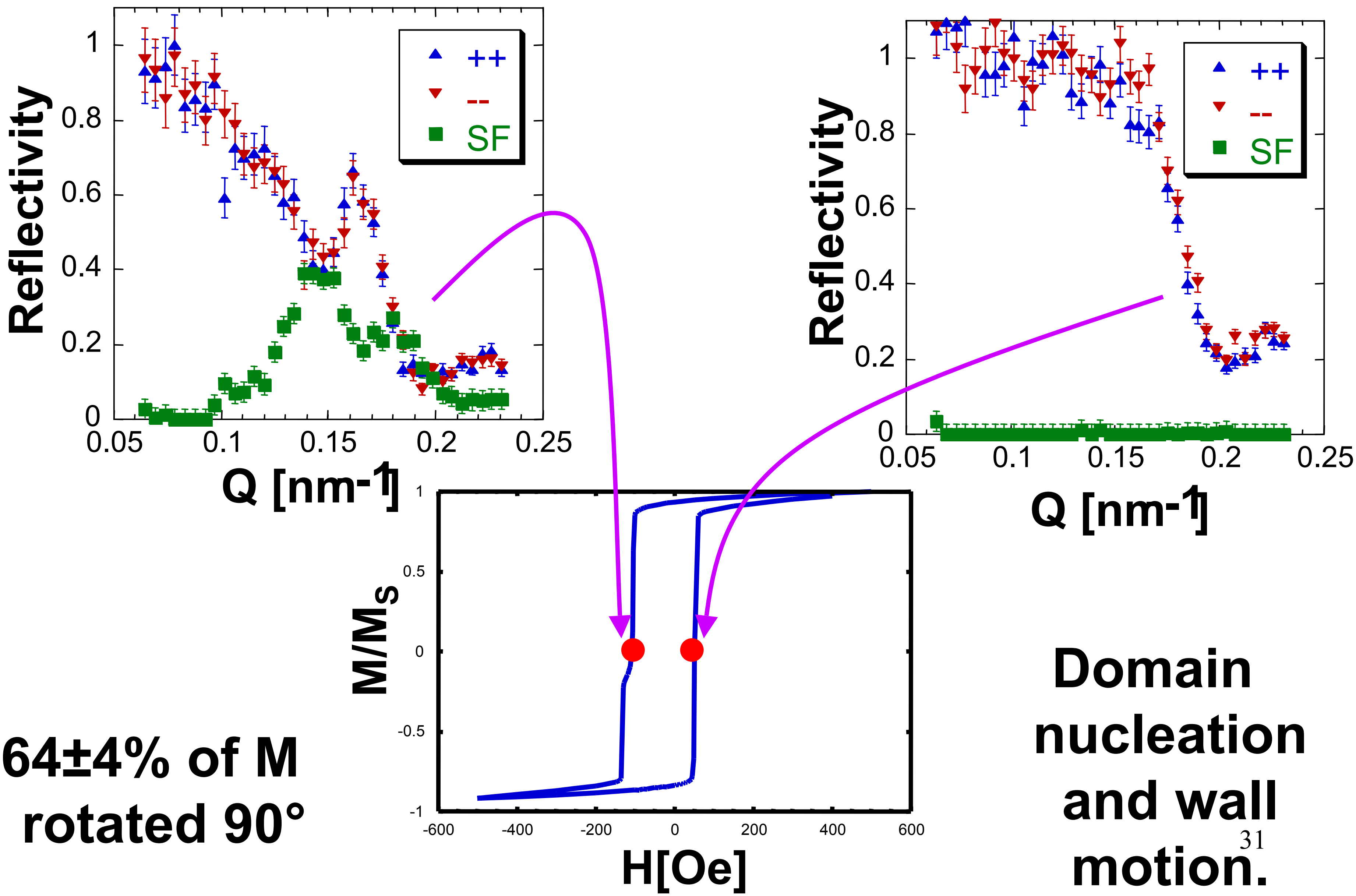
Neutron scattering— essential!





$$\vec{M}\left(\vec{H_A}\ \vec{H}_{fc},\ T,\ P, z \ldots\right)$$

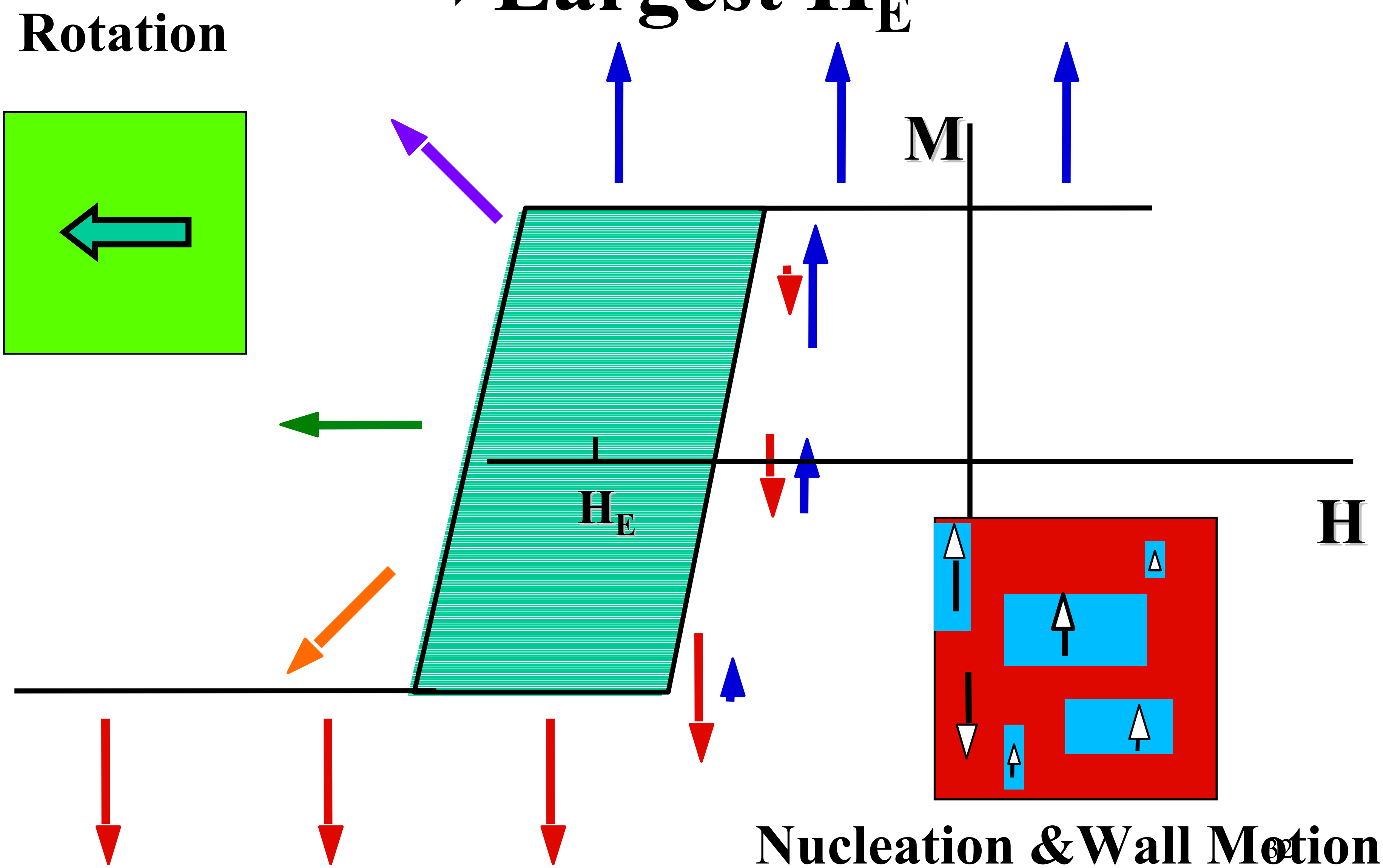
Asymmetric reversal



64±4% of M rotated 90°

Domain nucleation and wall motion.

Asymmetric reversal
⇒ Largest H_E



Fe on *twinned* single crystal AF

- **Asymmetric magnetization reversal**
- **Asymmetry correlated with H_E.**
  - **Cooling field**
  - **Temperature**
- **Frustration of perpendicular exchange**

M.R. Fitzsimmons *et. al.,* Phys. Rev. Lett., 84, 3986 (2000)

SUMMARY

- **Burried Interfaces**

M and Non-M Roughness-*Different*

- **Nanoscopic Magnetic Ordering**

Magnetic Orientation in Multilayers-*Delicate*

- **Vector Magnetometry**

Exchange Bias in Bilayers-*Complex*

Do this with synchrotrons, Watson !!!

Sherlock Holmes

Future

Neutron

- Diffuse
- Inelastic
- Time dependence
- Pump-Probe

Systems

- Burried interfaces
- Multilayers
- Superlattices
- Nanostructures

Sample environment

•H field

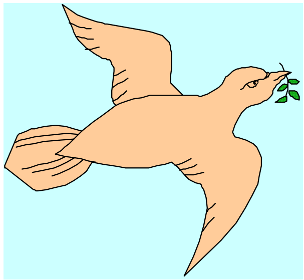
•Low temperature

•High pressure

BEYOND PROOF OF CONCEPT

LESSONS

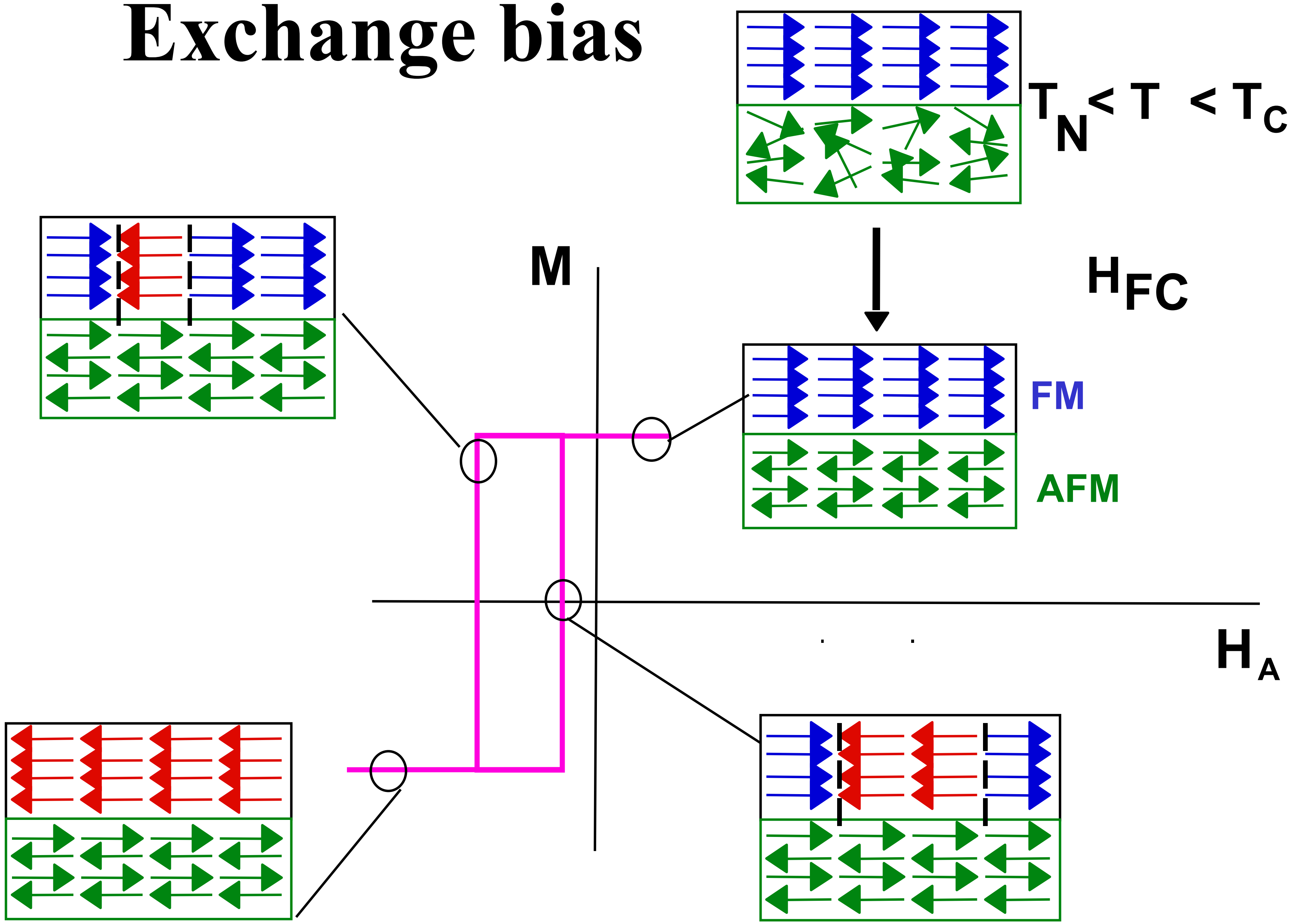
- Interpretation of neutron scattering straight forward
- Penetration Large
- Physical structure doesn’t have all the information
- Magnetic structure subtle
- Need interesting materials and physics



Is OK

Fini-End-Fin-Ende

Exchange bias



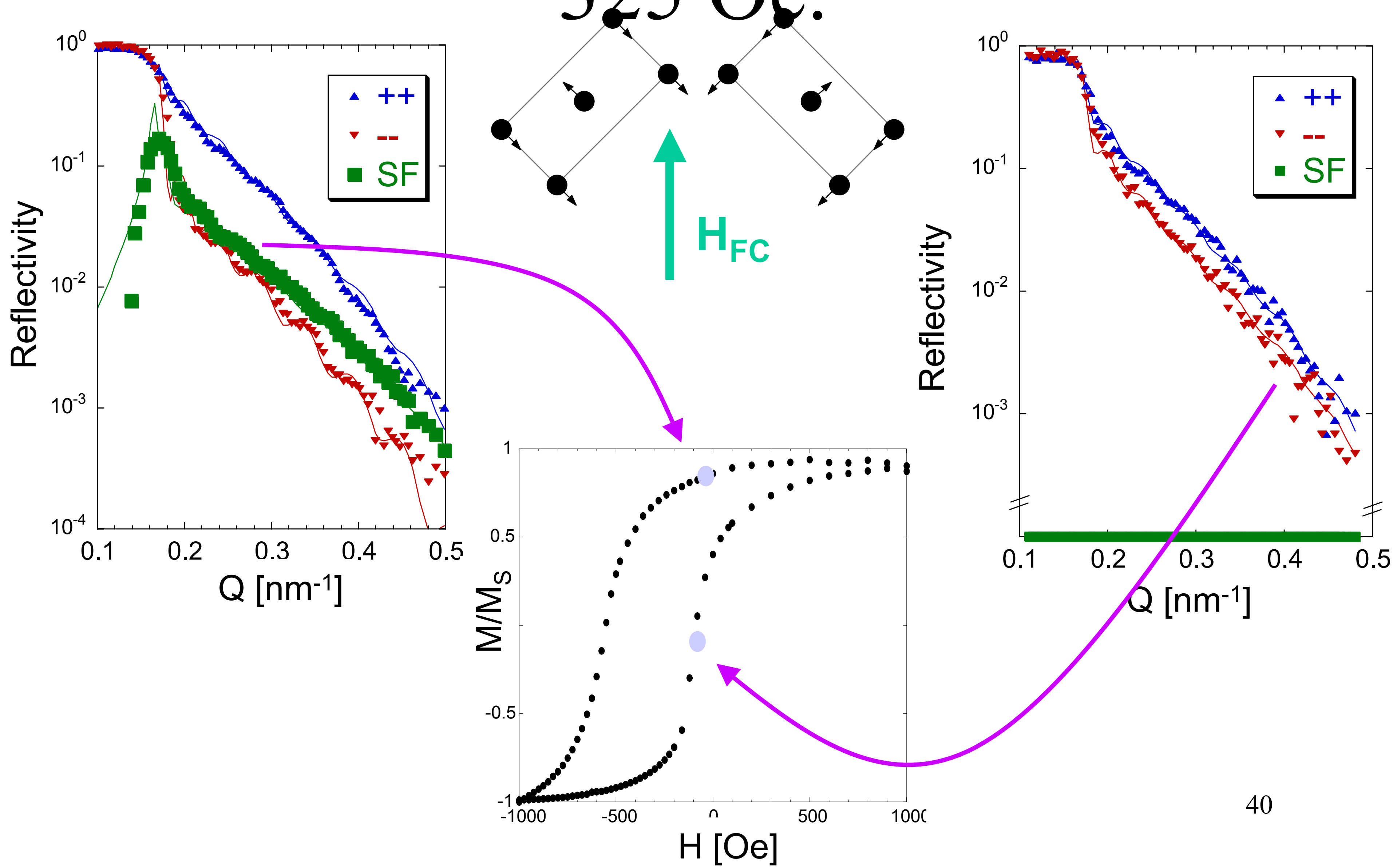
W.H. Meiklejohn, C.P. Bean, Phys. Rev., 105, 904 (1957).

Approach

- **Model systems**
  - Controlled conditions.
  - Tailored epitaxy (crystallography).
  - Tailored chemistry (pure and doped films).
  - Tailored microstructure (interface roughness, twinning)
- **Experimental Tools**
  - SQUID
  - X-ray diffraction (high and low angle)
  - Ferromagnetic resonance
  - Magnetoresistance

Large collaborative team effort

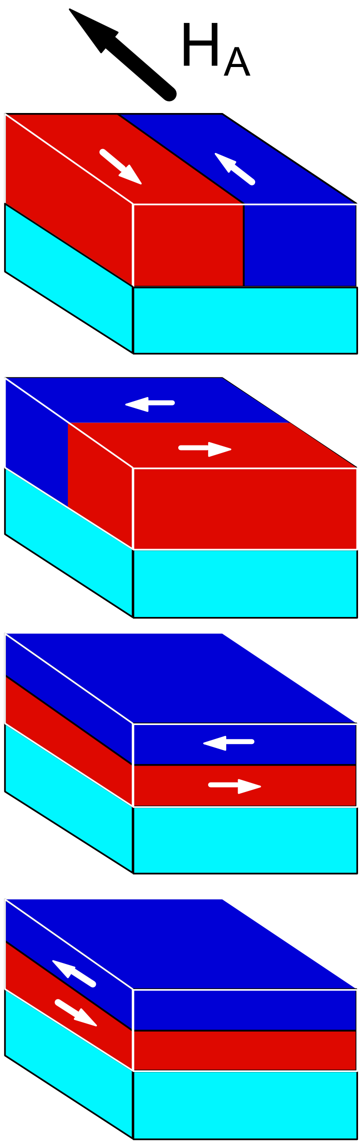
Fe- *twinned* FeF_2, case for H_E = -325 Oe.

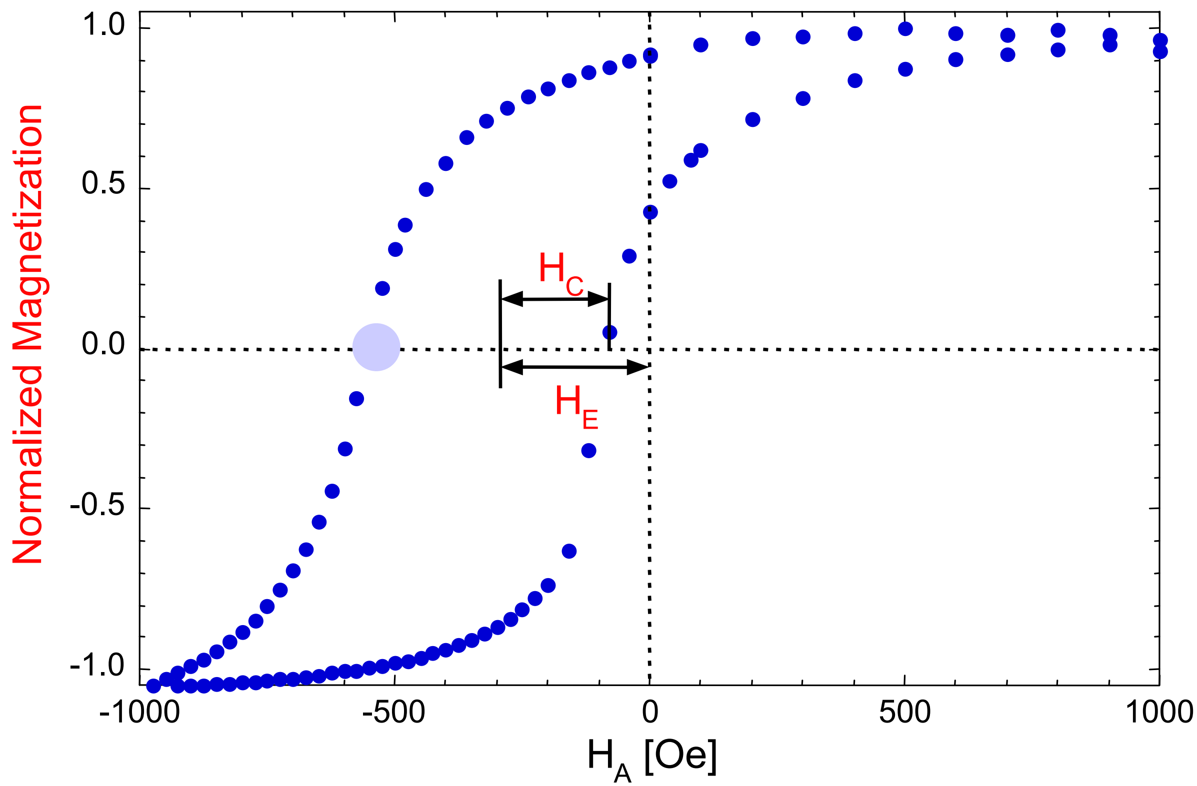


Conclusions

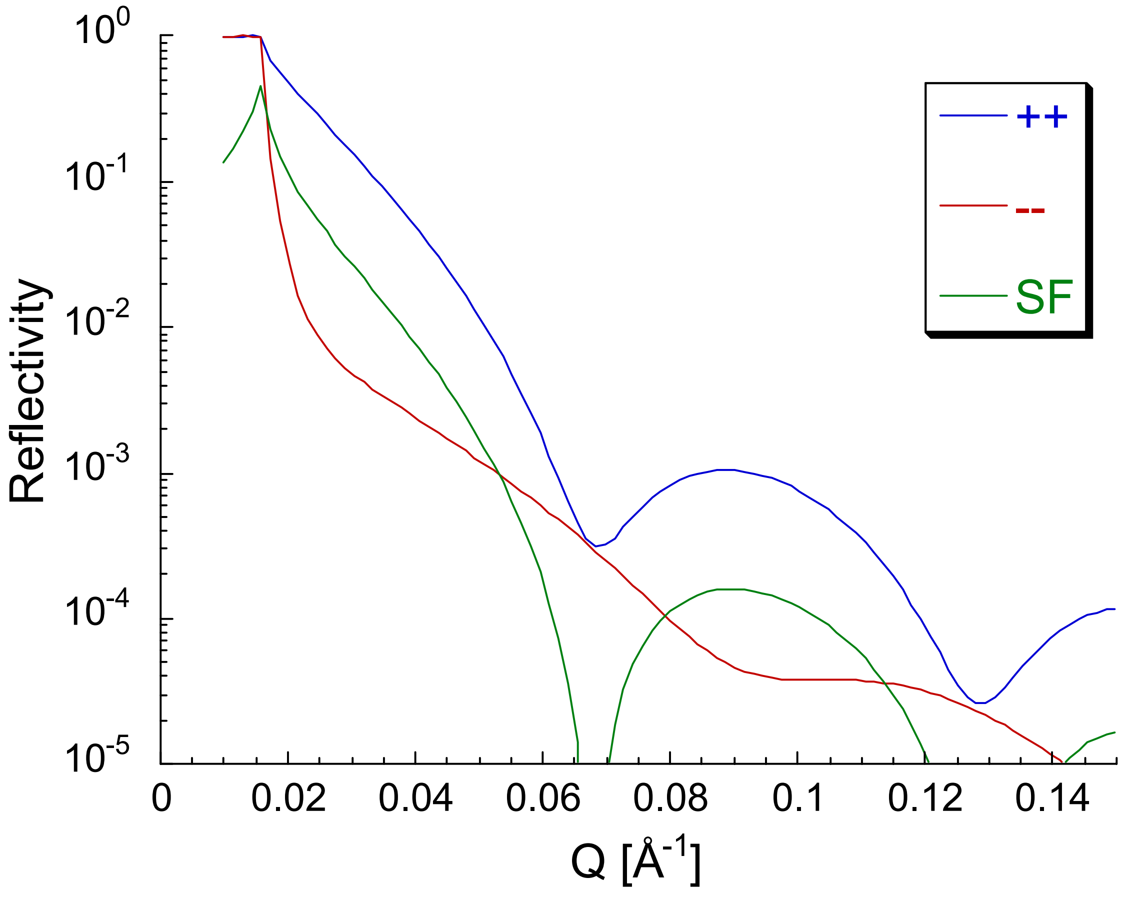
- To enhance exchange bias:
  - Choose $\sum_{domains}\left|\vec{S}_F \bullet \vec{S}_{AF}\right| \neq 0$ while field cooling.
  - Promote multiple well-defined anisotropy axes in FM.
  - Promote asymmetric magnetization reversal.

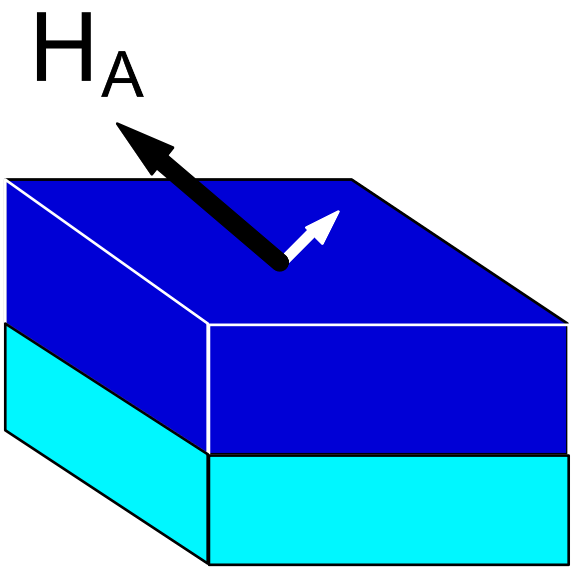
Reversal process?



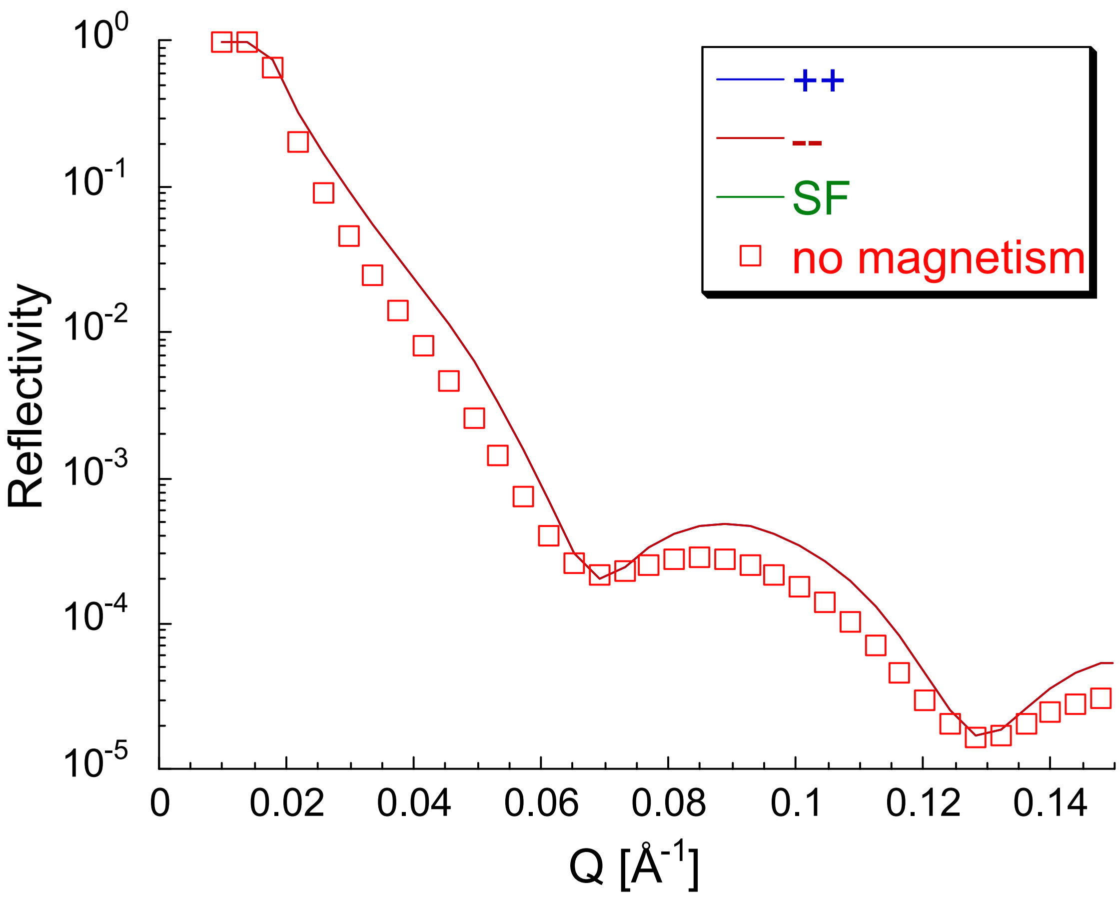


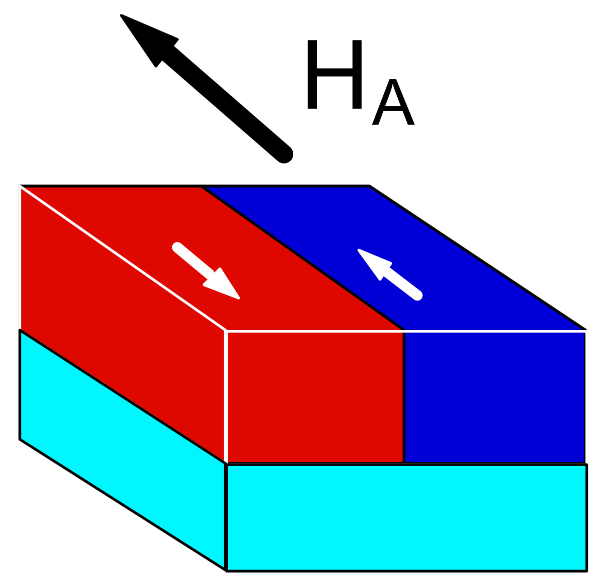
Simple example for coherent rotation



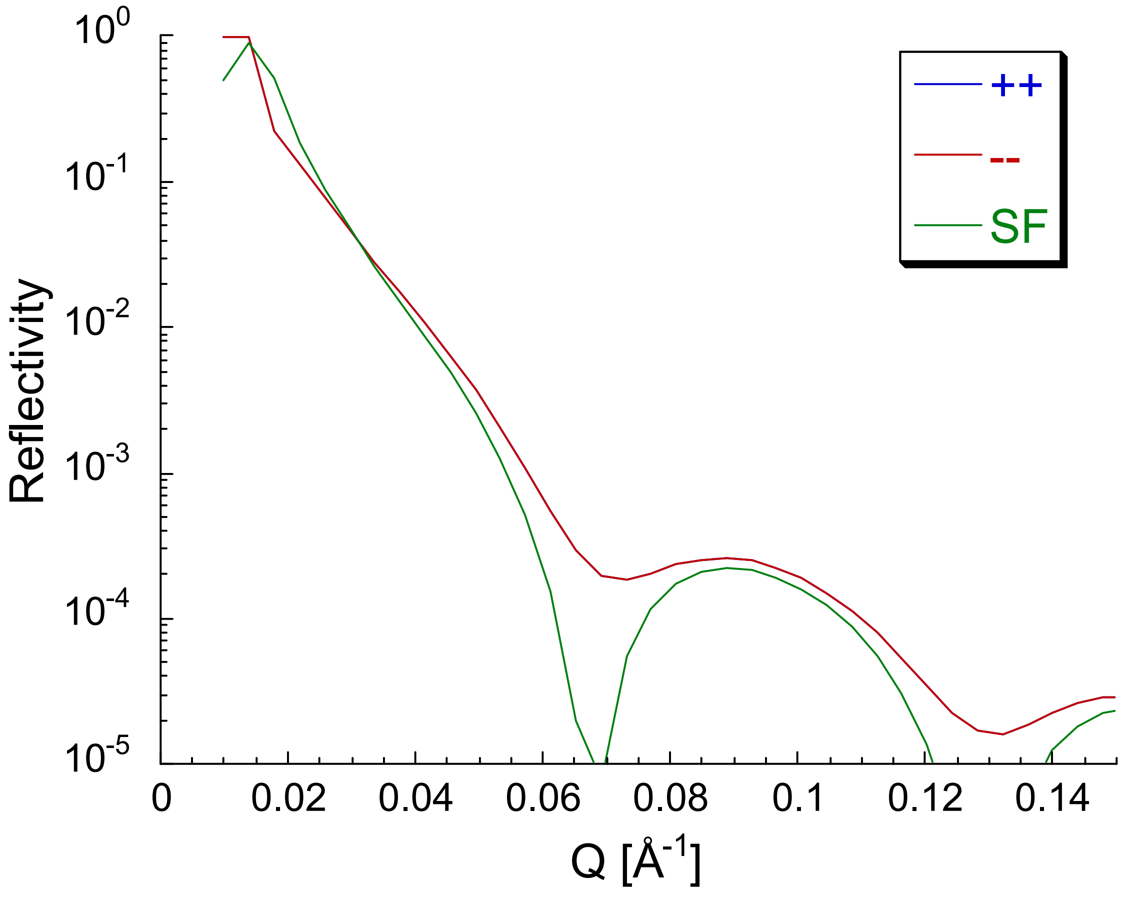


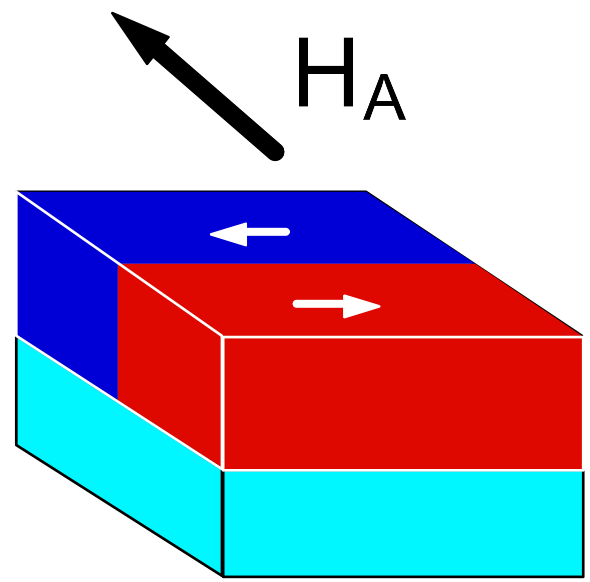
Example 1: Opposed domains



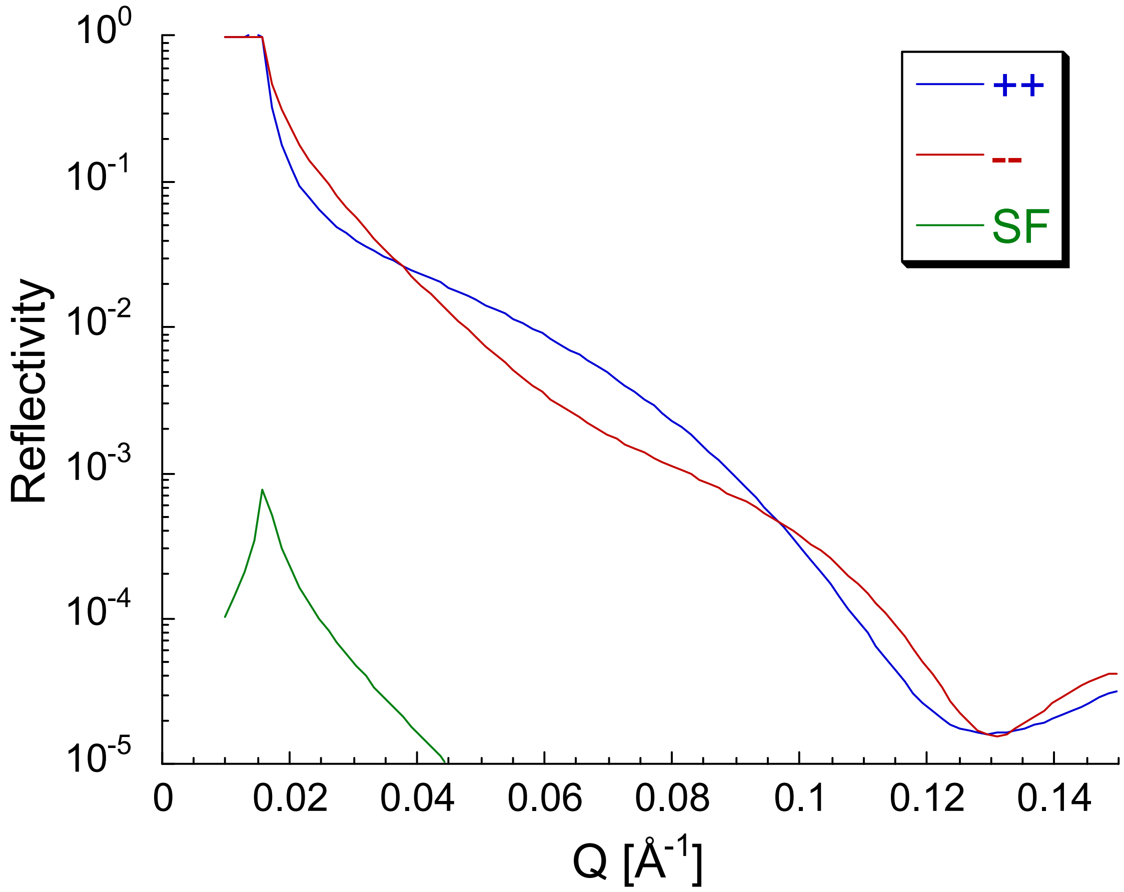


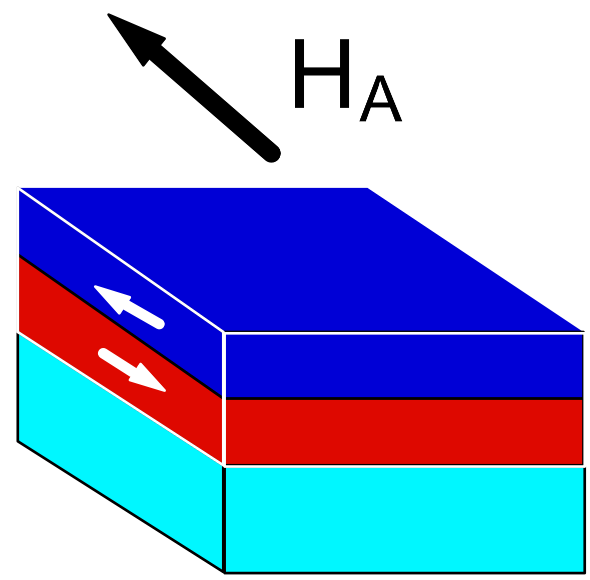
Example 2: Opposed domains + rotation



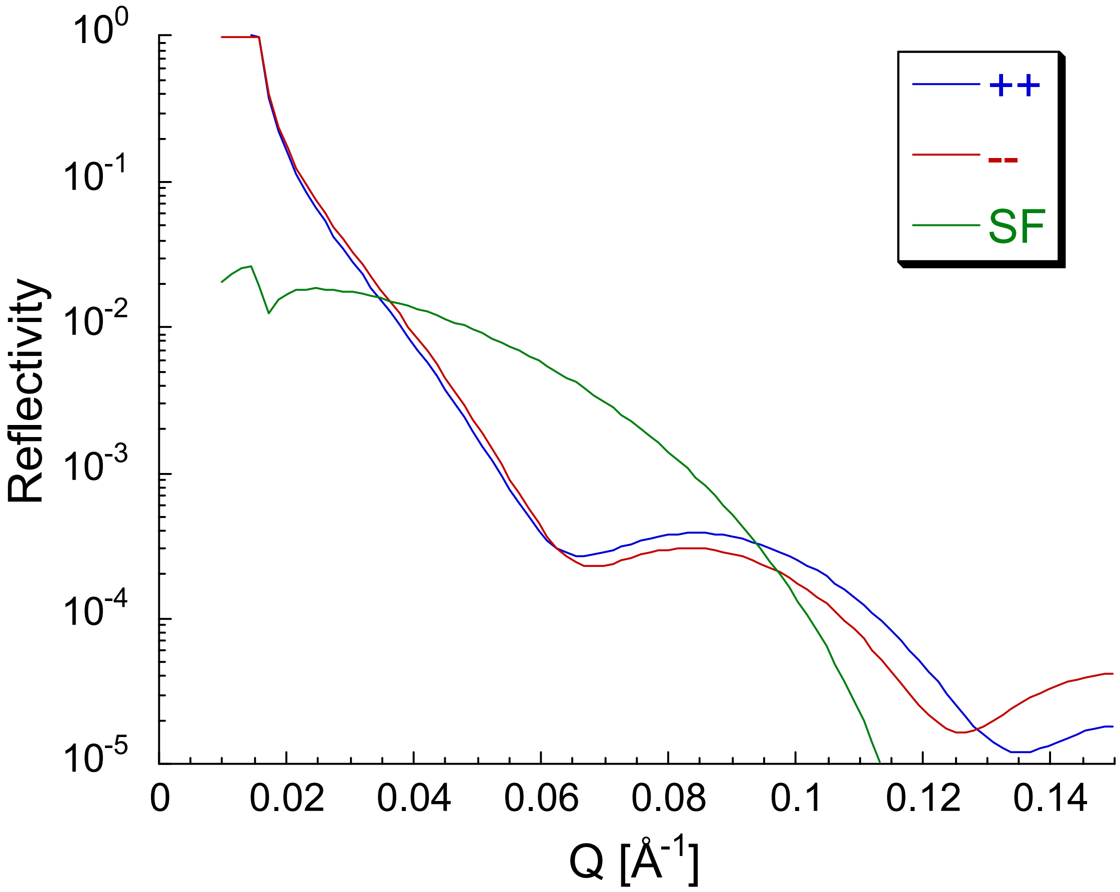


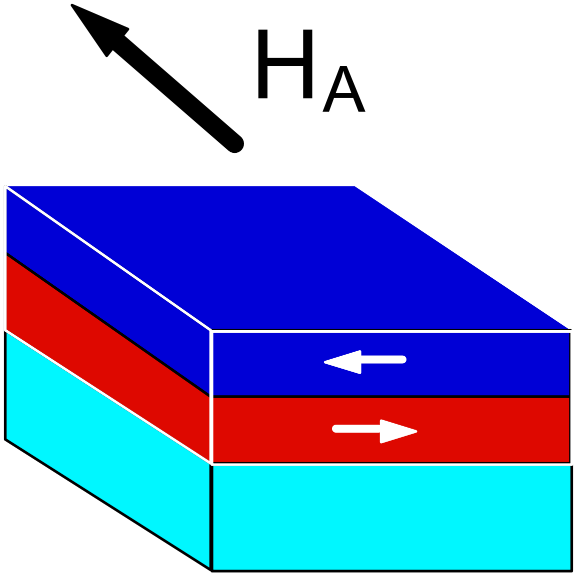
Example 3: Layered domains



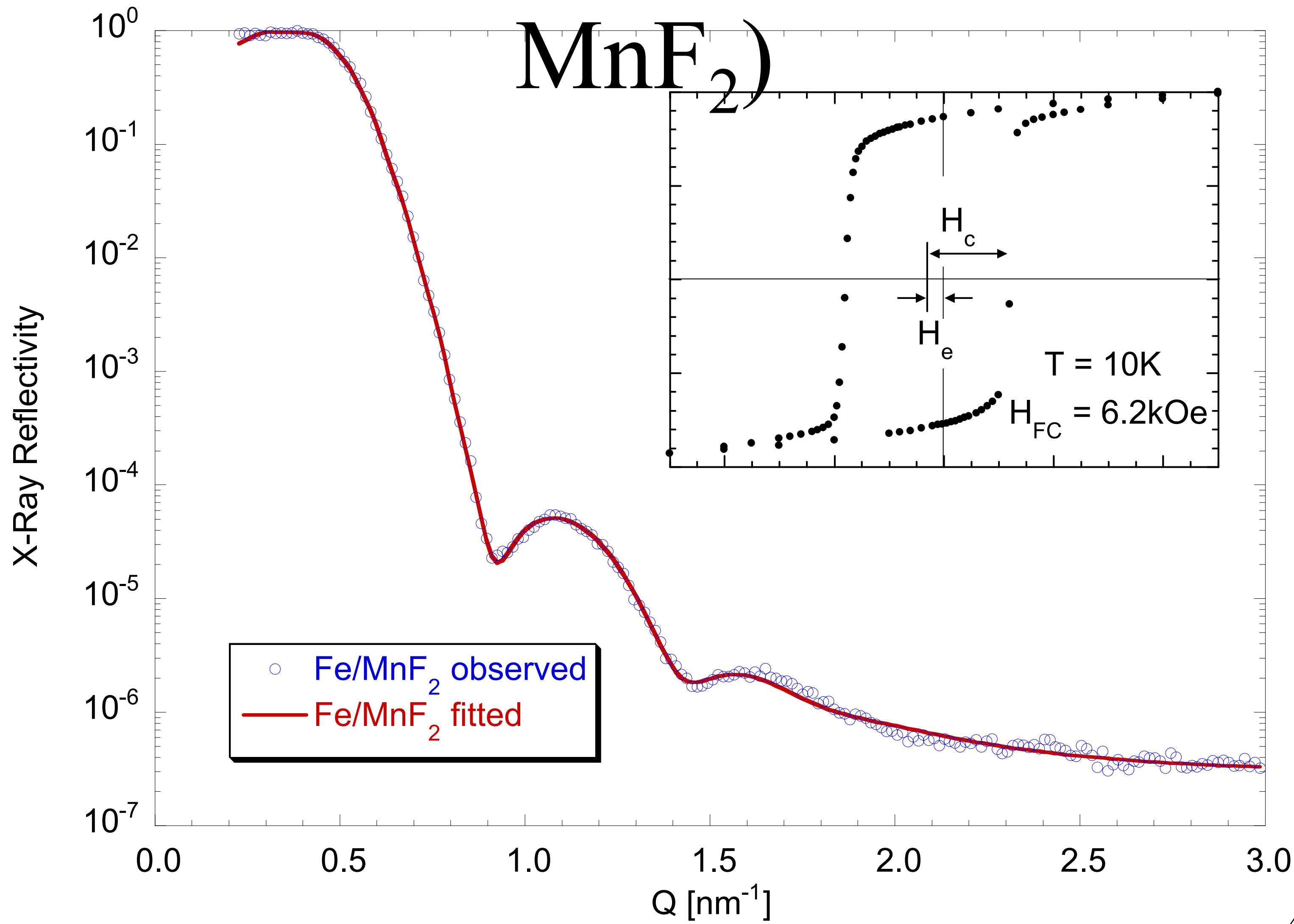


Example 4: Layered domains + rotation

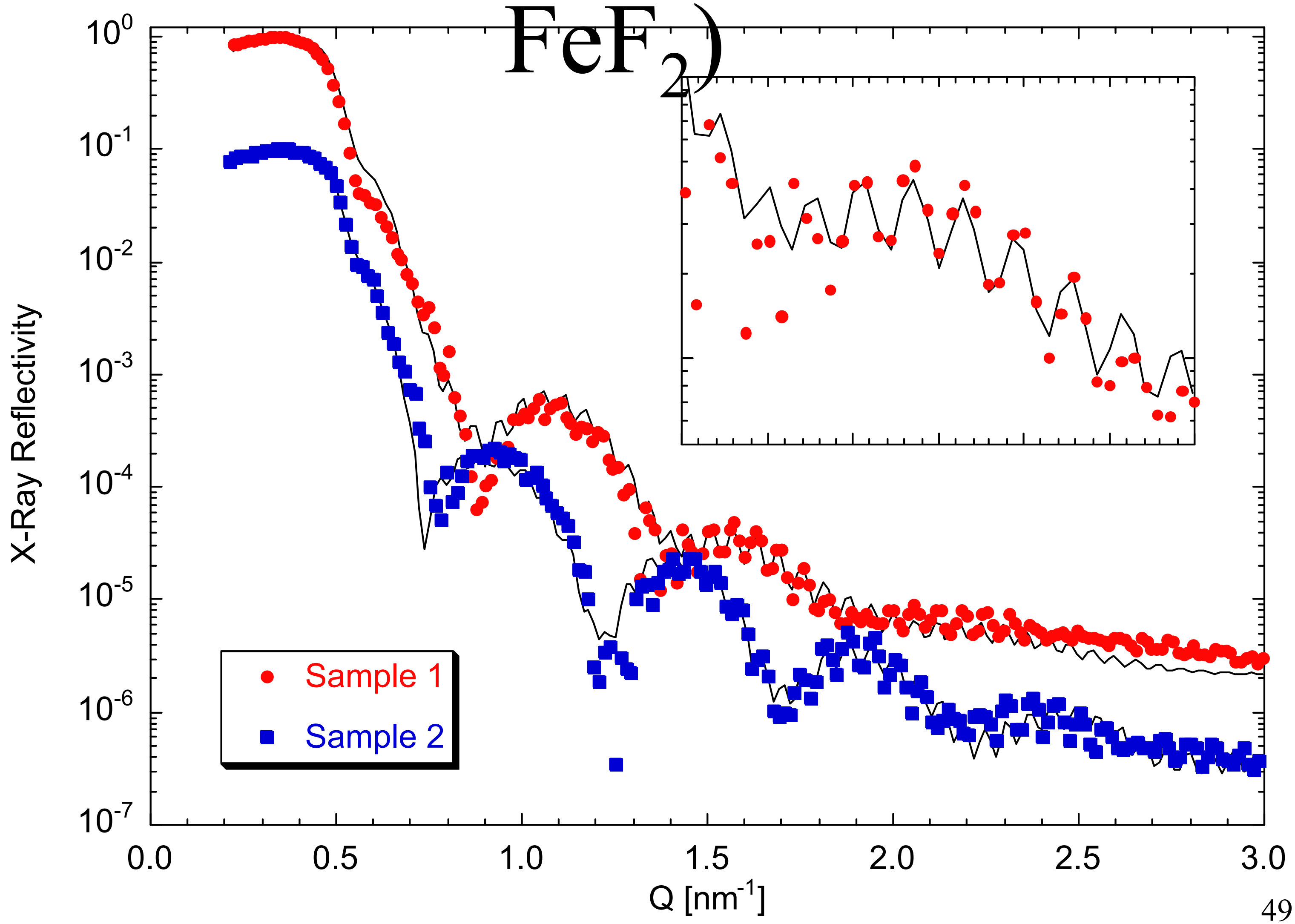




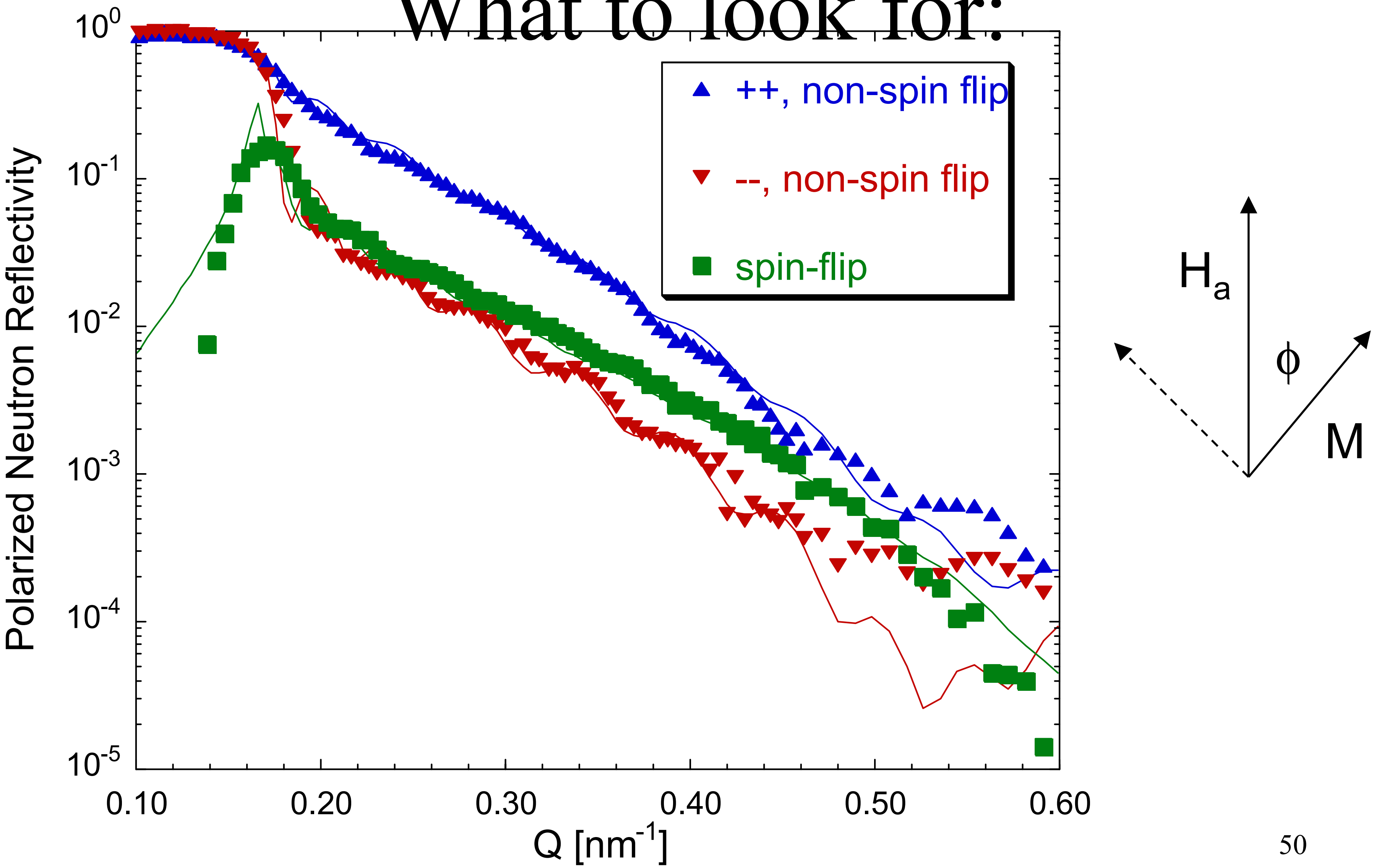
X-ray reflectometry (Fe on MnF_2)



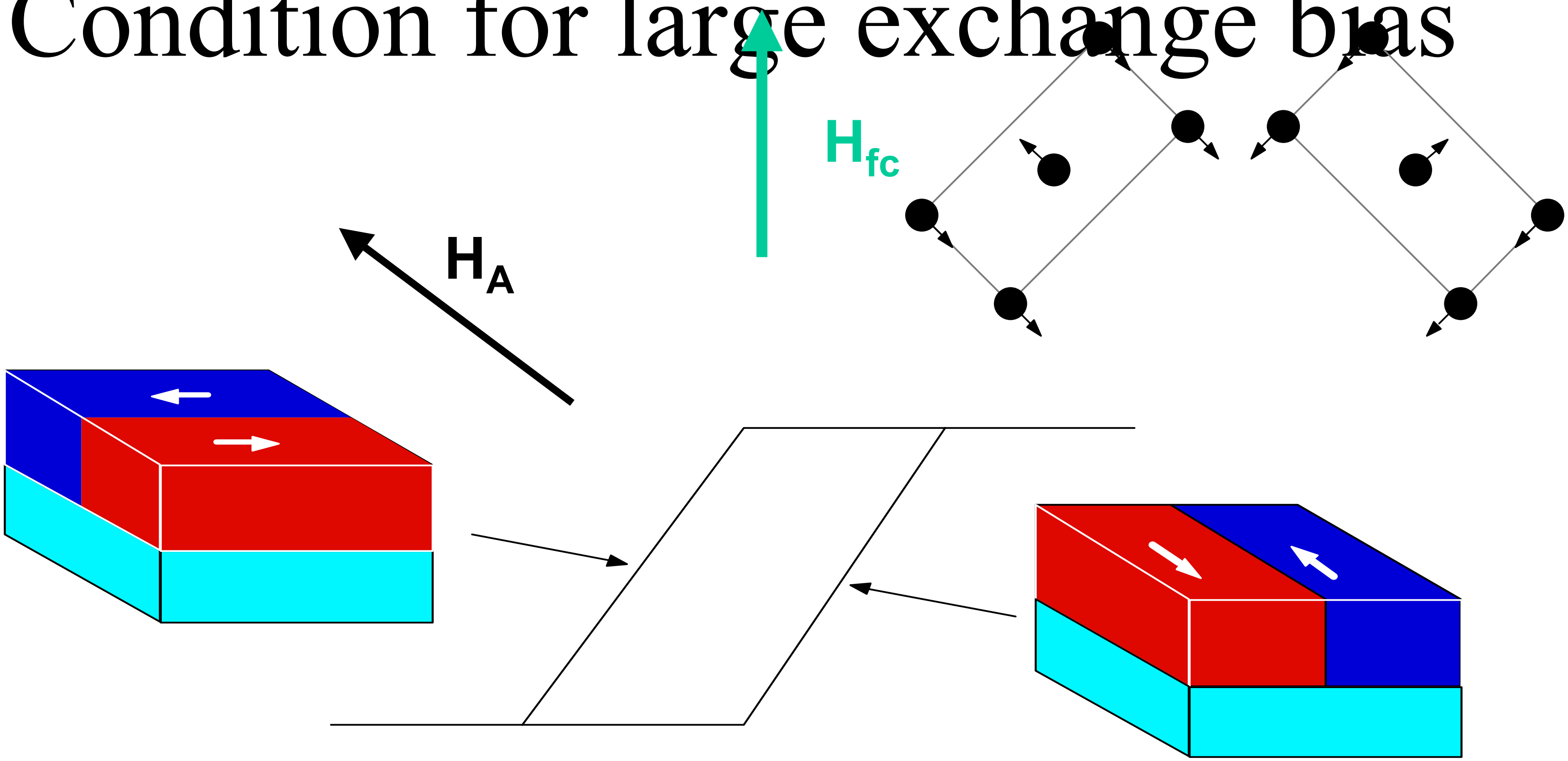
More X-ray reflectometry (Fe on FeF_2)



What to look for:

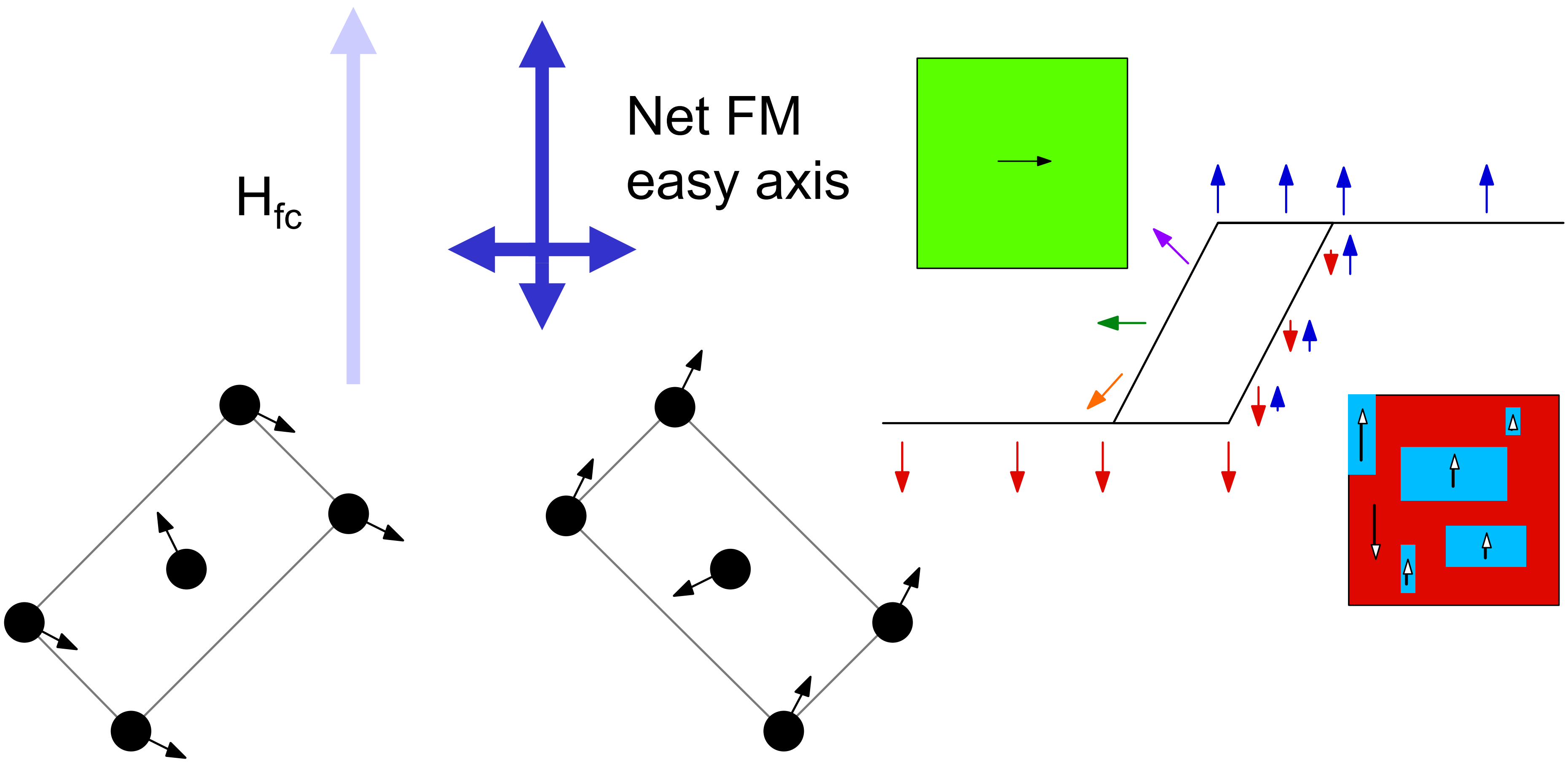


Condition for large exchange bias



Why does the asymmetric reversal process occur?

Large exchange bias



More conclusions

- Spin-flip neutron scattering is a quantitative measure of magnetization rotation away from applied field.
- SF scattering for $T<T_N$ varies as $B_{5/2}(T)$ for a smooth sample, but not for a rough sample.
- T-dependence of SF scattering (and asymmetric magnetization reversal) correlates with H_E.
- Uniaxial anisotropy axis perpendicular to the unidirectional anisotropy axis is an important

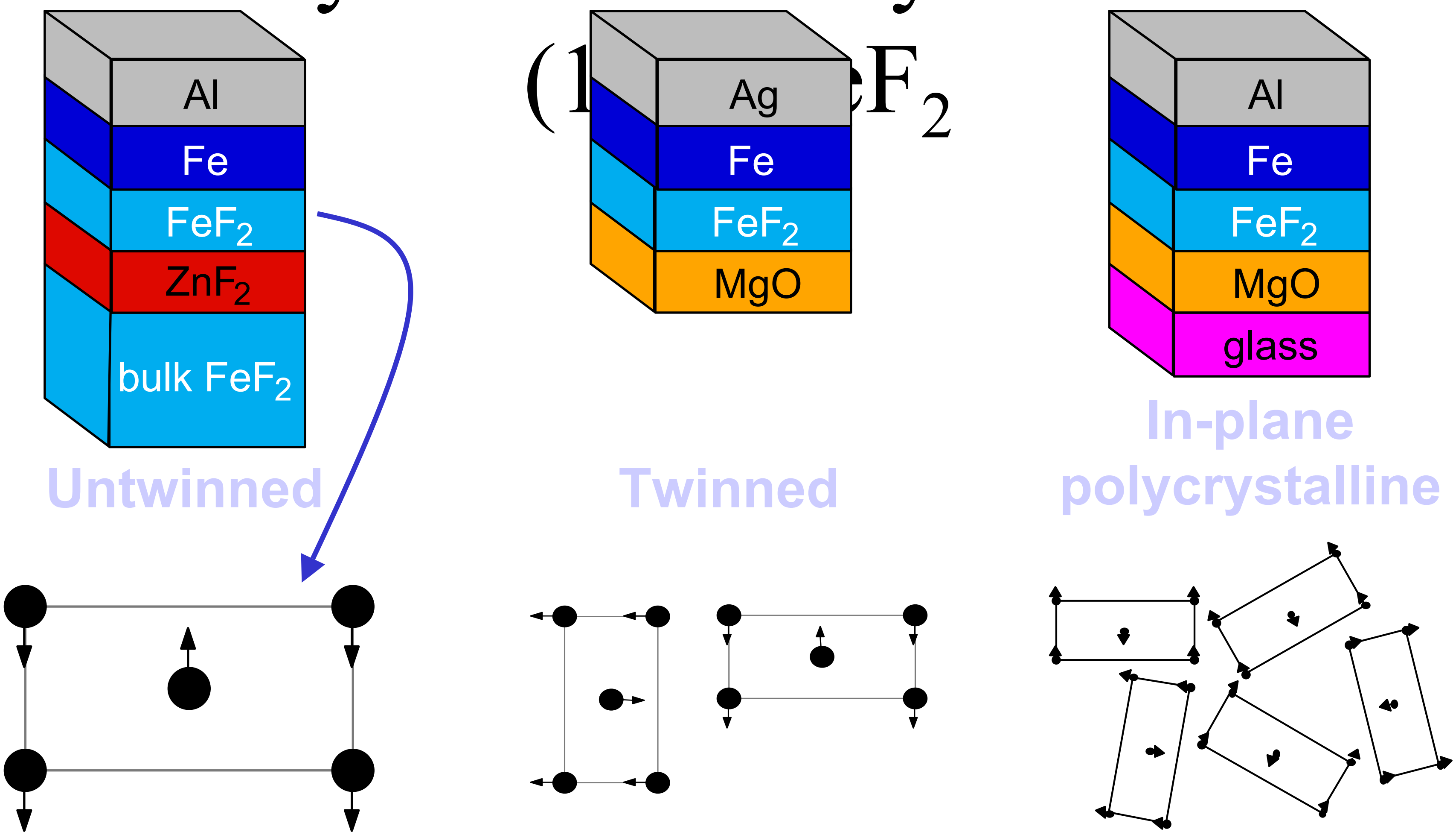
Yet more conclusions

- Large asymmetry in reversal process is correlated with large H_E.
  - Cooling field (orientation) dependence.
  - Temperature dependence.
  - Cooling field (strength) dependence.

Future directions

- Non-uniformity in magnetic heterostructures
  - Incomplete domain walls in exchange bias and exchange spring systems
  - Influence of chemical doping and/or geometrical frustration on FM & AFM
  - Confinement, e.g. suppression of domains in thin films
  - Incomplete domain walls and reorientation transitions, e.g. Fe(110)/W(110)

A systematic study of Fe on (1 eF$_2$



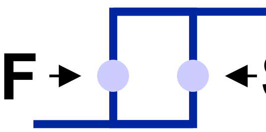
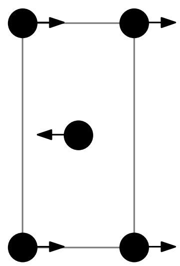
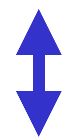
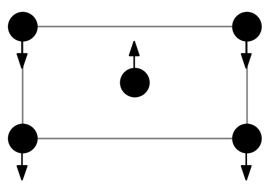
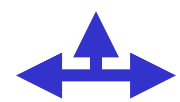
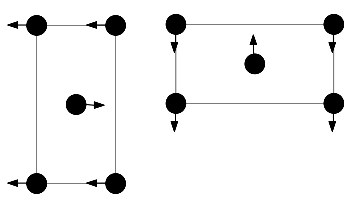
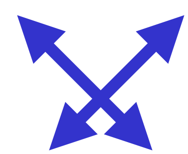
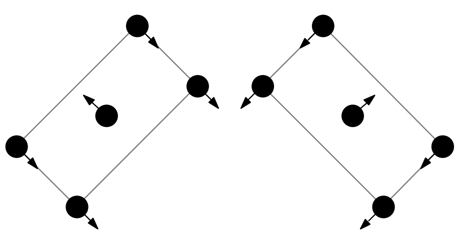
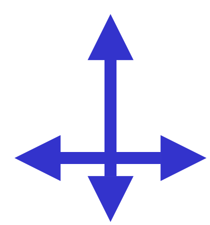
⊥- coupling not sufficient

Asymmetrical reversal

⊥- coupling not required

Summary


H_{FC}

	H_E	$\sum_{domains}\left\|\vec{S}_F \bullet \vec{S}_{AF}\right\|$	K_F's	SF →	 ← SF
	**0**	0		No	No
	**-32**	1		**Yes**	**Yes**
	**-76**	0.5		**Yes**	**Yes**
	**-325**	0.7		**Yes**	No

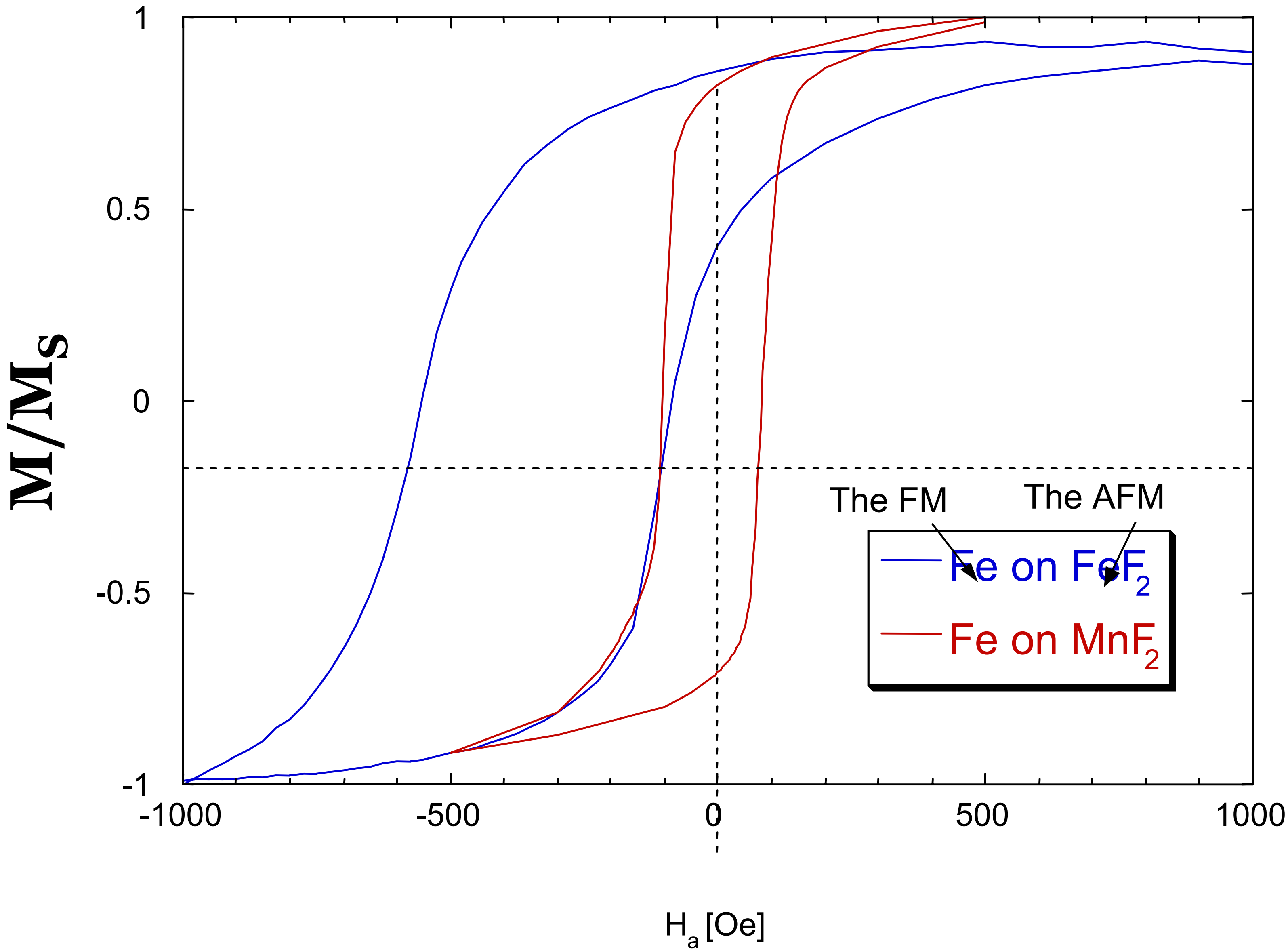
Future

- Phonons….anomalous elastic constants
- Magnons……unusual in thin films
- Modification by strain
- Burried interfaces
- Time Dependence
- Magnetic reversal
- Anisotropy
- Interfacial Magnetic Structure
- Diffuse Scattering (structure and magnetism)

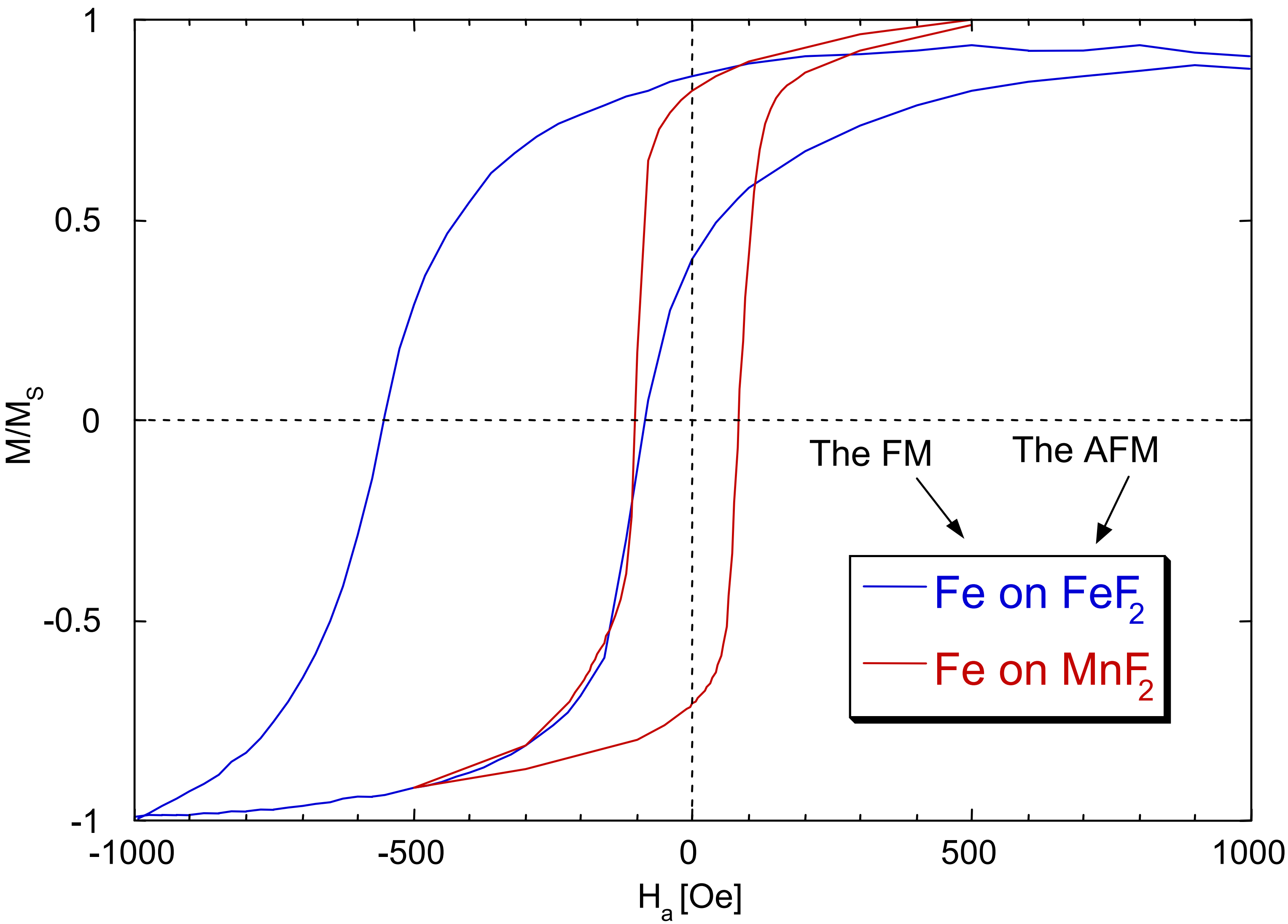
What are some issues?

- Simple models incorrectly predict H_E.
- H_E for *compensated* antiferromagnetic interfaces
- Positive H_E
- T-dependence of H_E and H_C
- H_E and domains in ferromagnet or antiferromagnet
- Ferromagnetic moment in the antiferromagnet

What is exchange bias?



What is exchange bias?

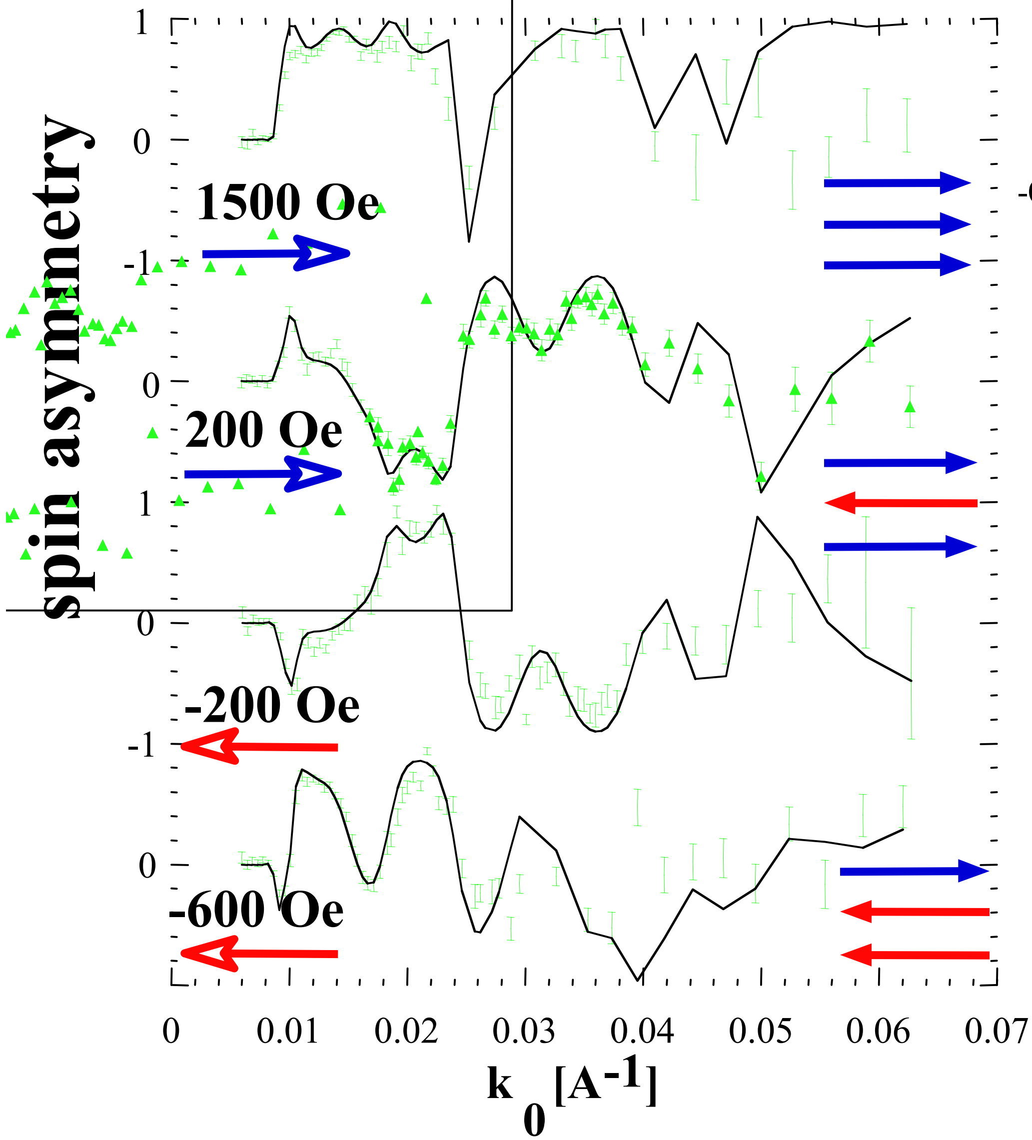


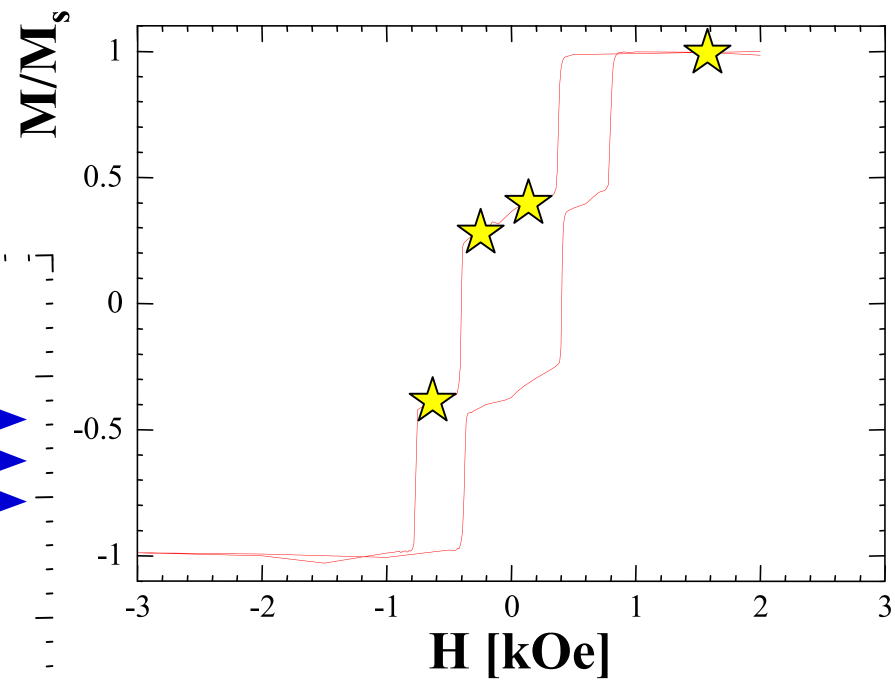
What's our approach?

- Study model systems
  - Bilayers grown under controlled conditions.
  - Tailored epitaxy (crystallography).
  - Tailored chemistry (pure and doped films fabricated).
  - Tailored microstructure (interface roughness, twinning).
- Bring many investigative tools to bear
  - SQUID
  - Wide angle X-ray diffraction
  - Glancing incidence (in-plane) diffraction
  - X-ray reflectometry
  - Ferromagnetic resonance
  - Magnetoresistance
  - Magnetic interferometric optical imaging
  - SHMOKE

- Requires large collaborative team effort

t_{Cr} = 17.6 Å

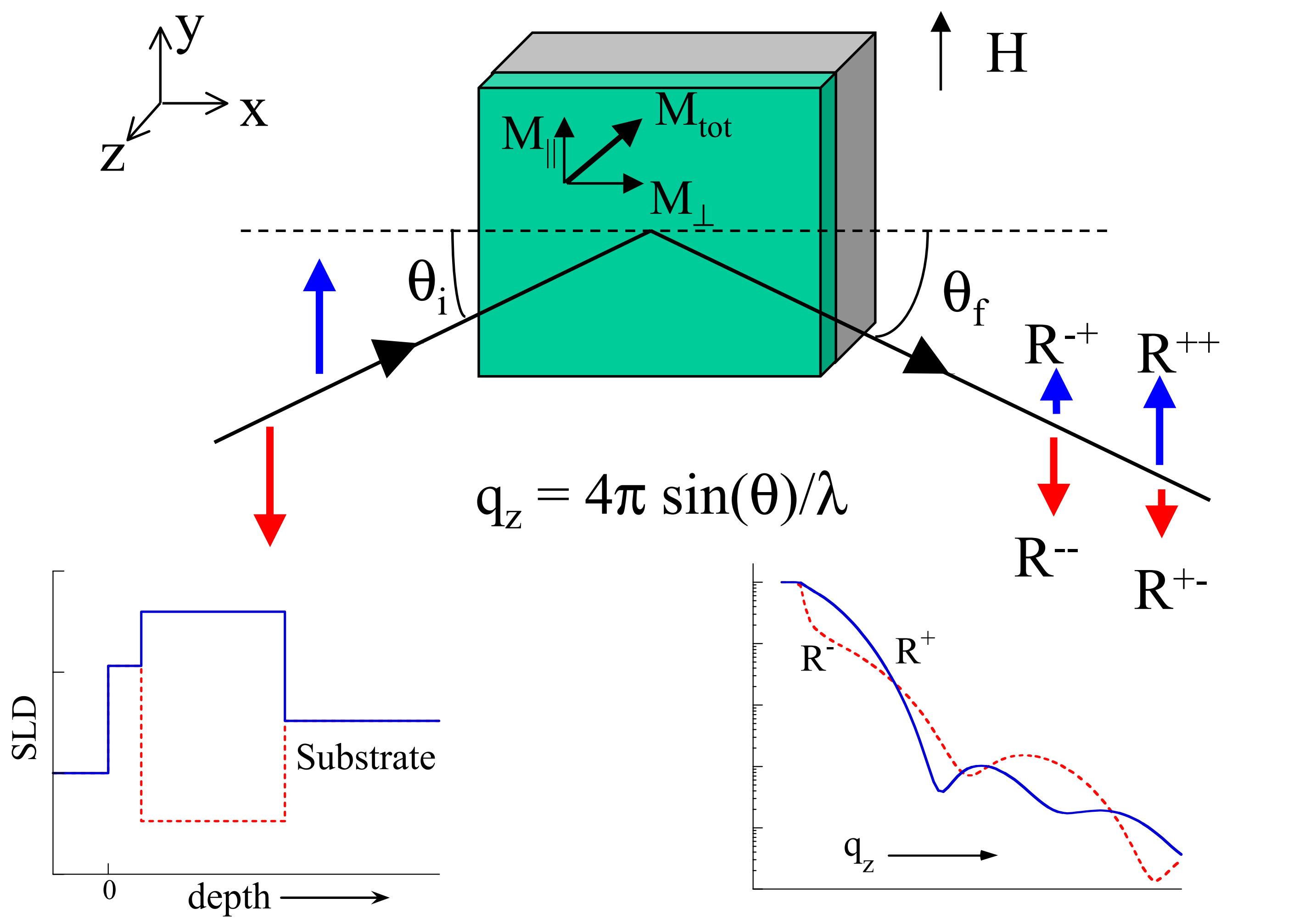




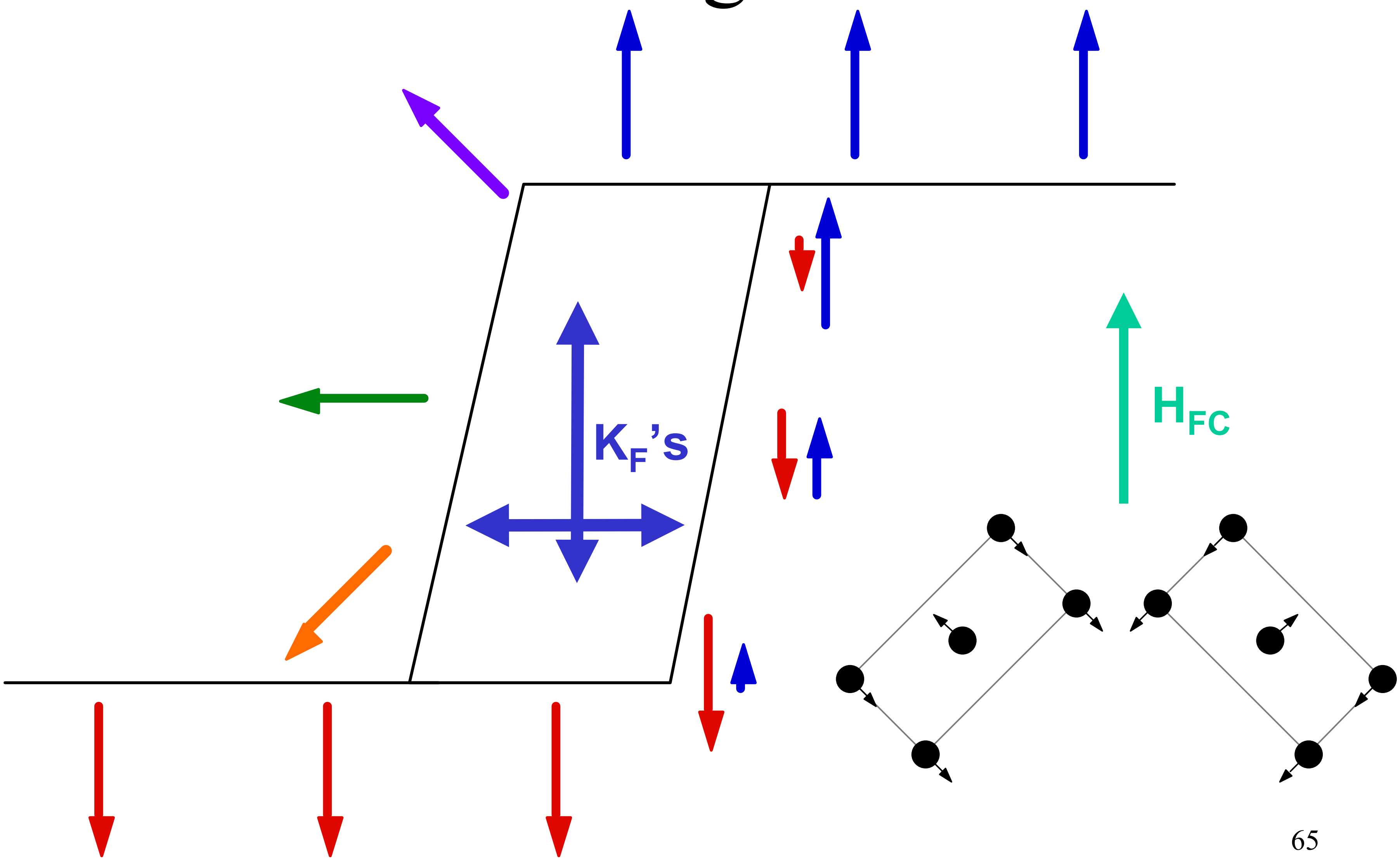
AFM coupling

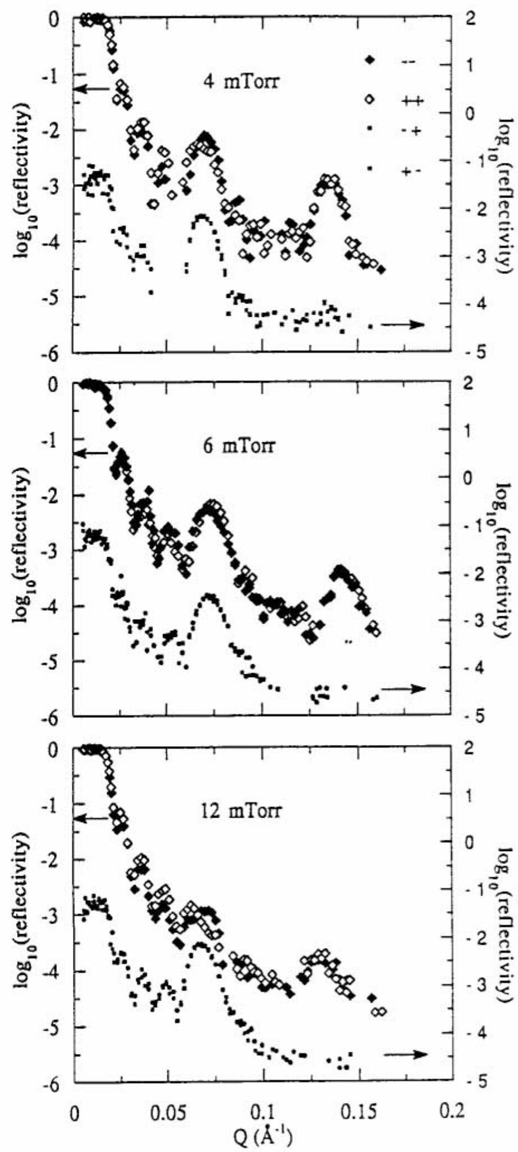
Top and bottom Different

Polarized Neutron Reflectivity



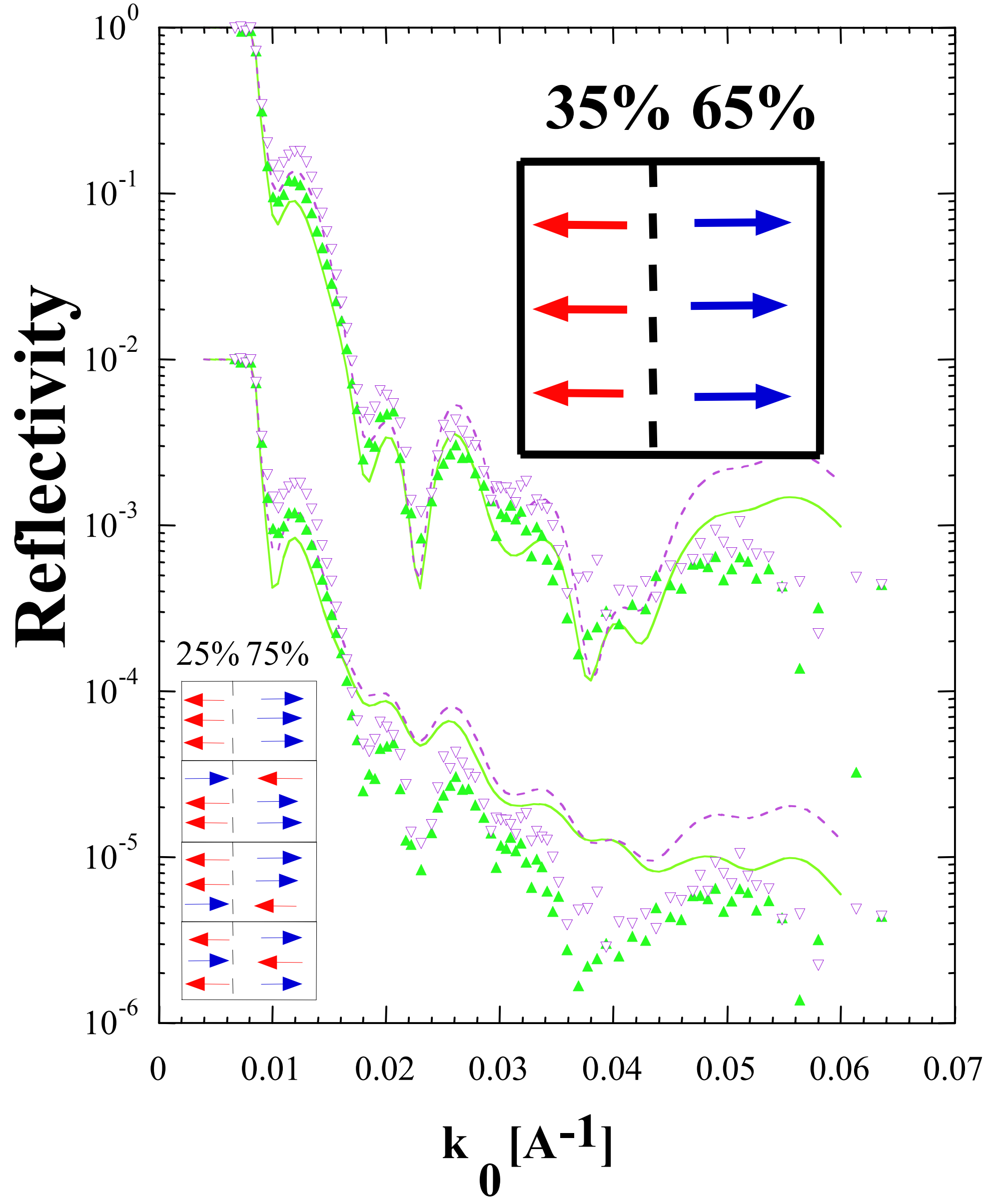
Asymmetric reversal = largest exchange bias

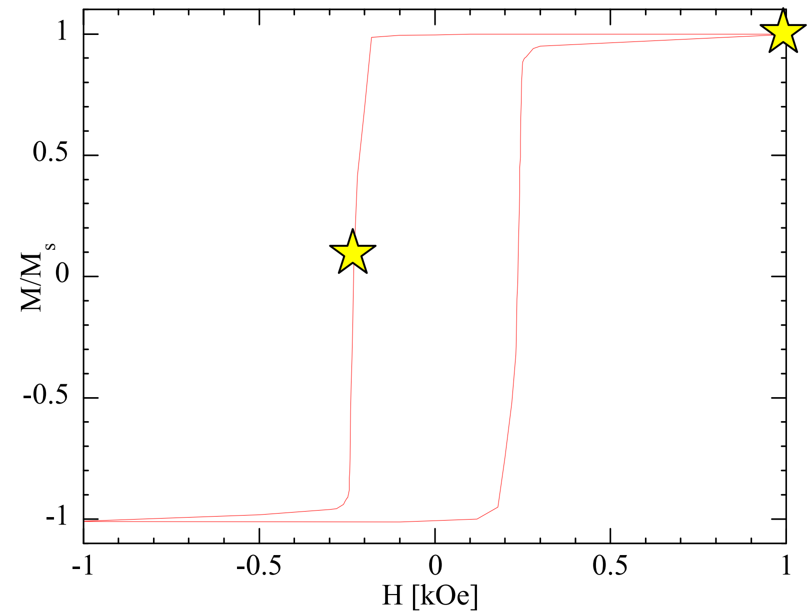




4 mTorr
6 mTorr
12 mTorr
--
++
-+
+-
log10(reflectivity)
Q (Å-1)
0
-1
-2
-3
-4
-5
-6
2
1
0
-1
-2
-3
-4
-5
0.05
0.1
0.15
0.2

t_{Cr} = 31 Å, H//easy axis

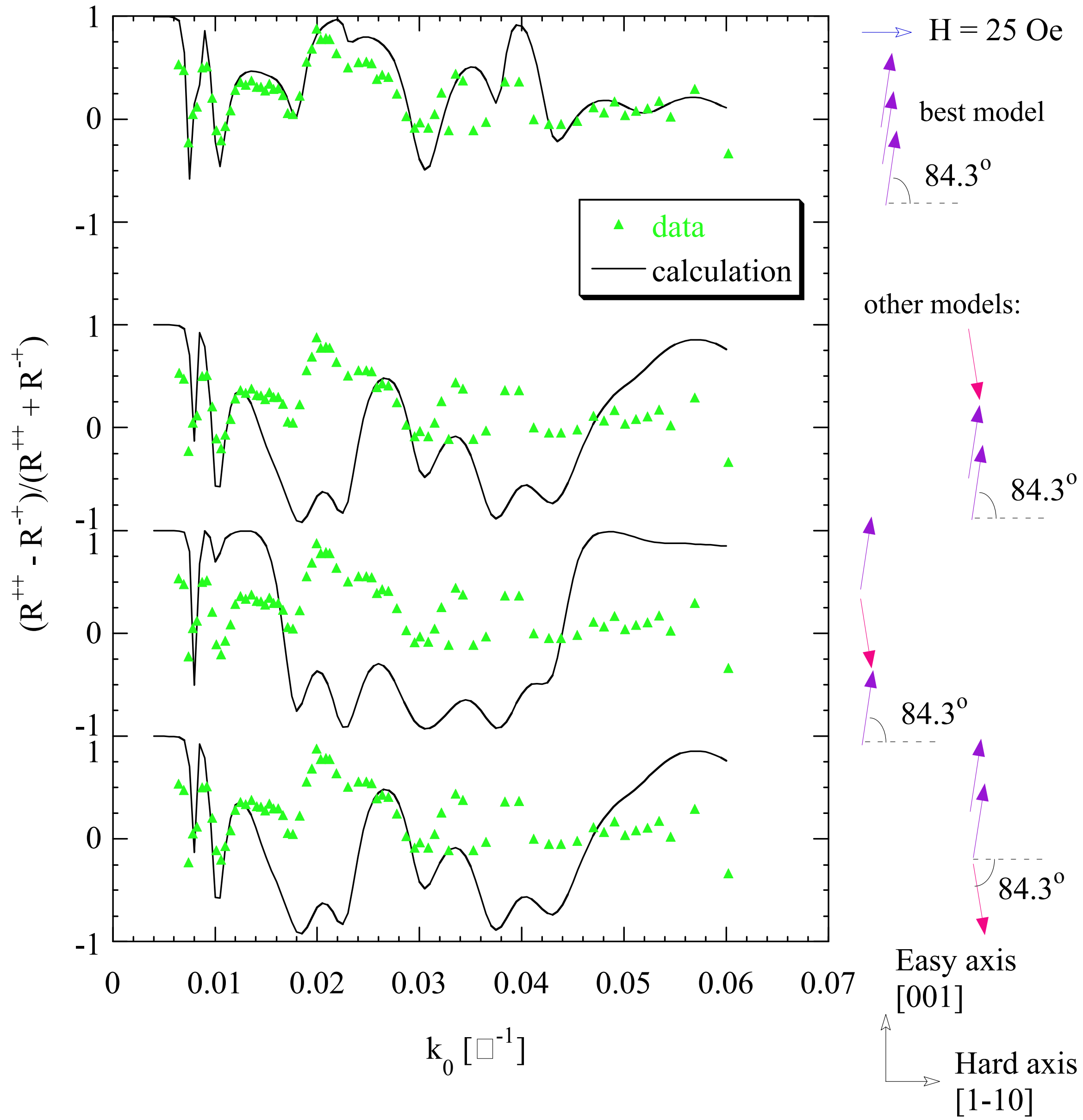




Only two types of domains with all three moments parallel

Indication of FM coupling

t_{Cr} = 31 Å, H// hard axis

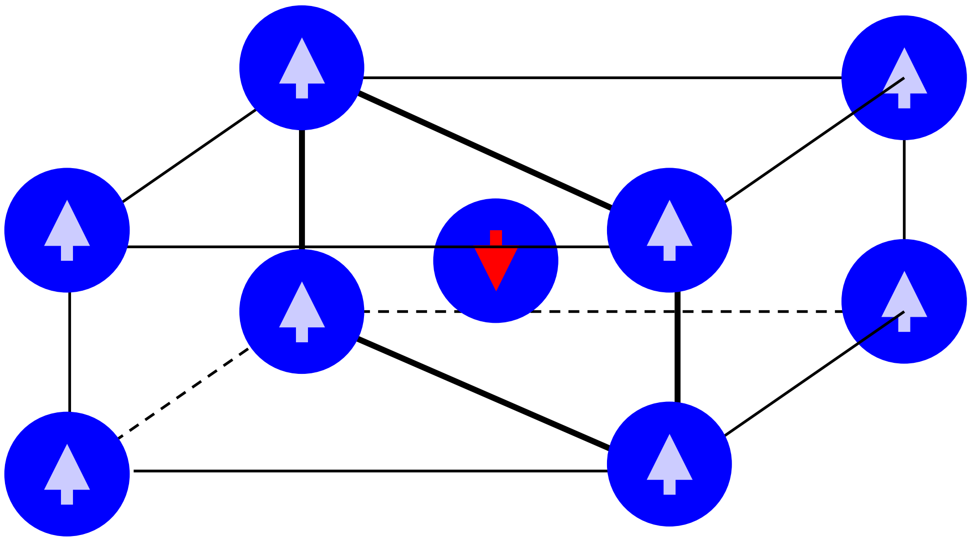


- Saturated along the hard axis
- Measured in small residual field of 25 Oe

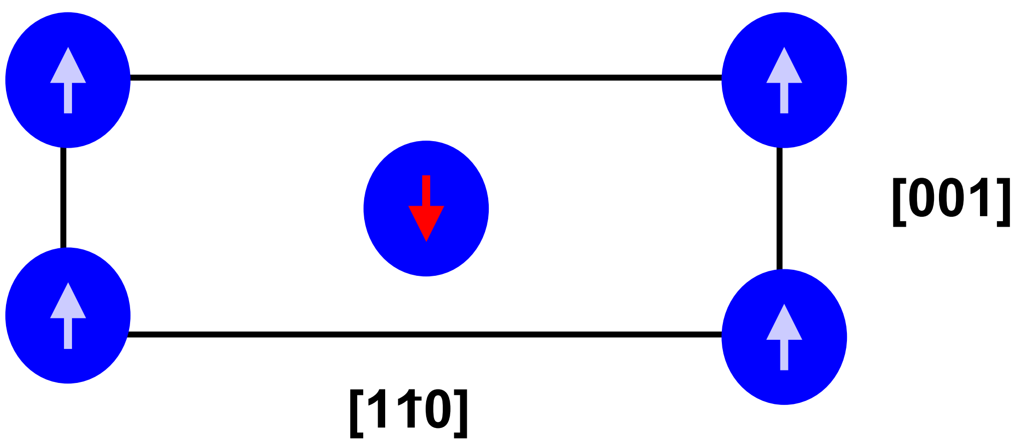
All three moments are parallel

Indication of FM coupling

FeF_2, MnF_2, CoF_2, ZnF_2

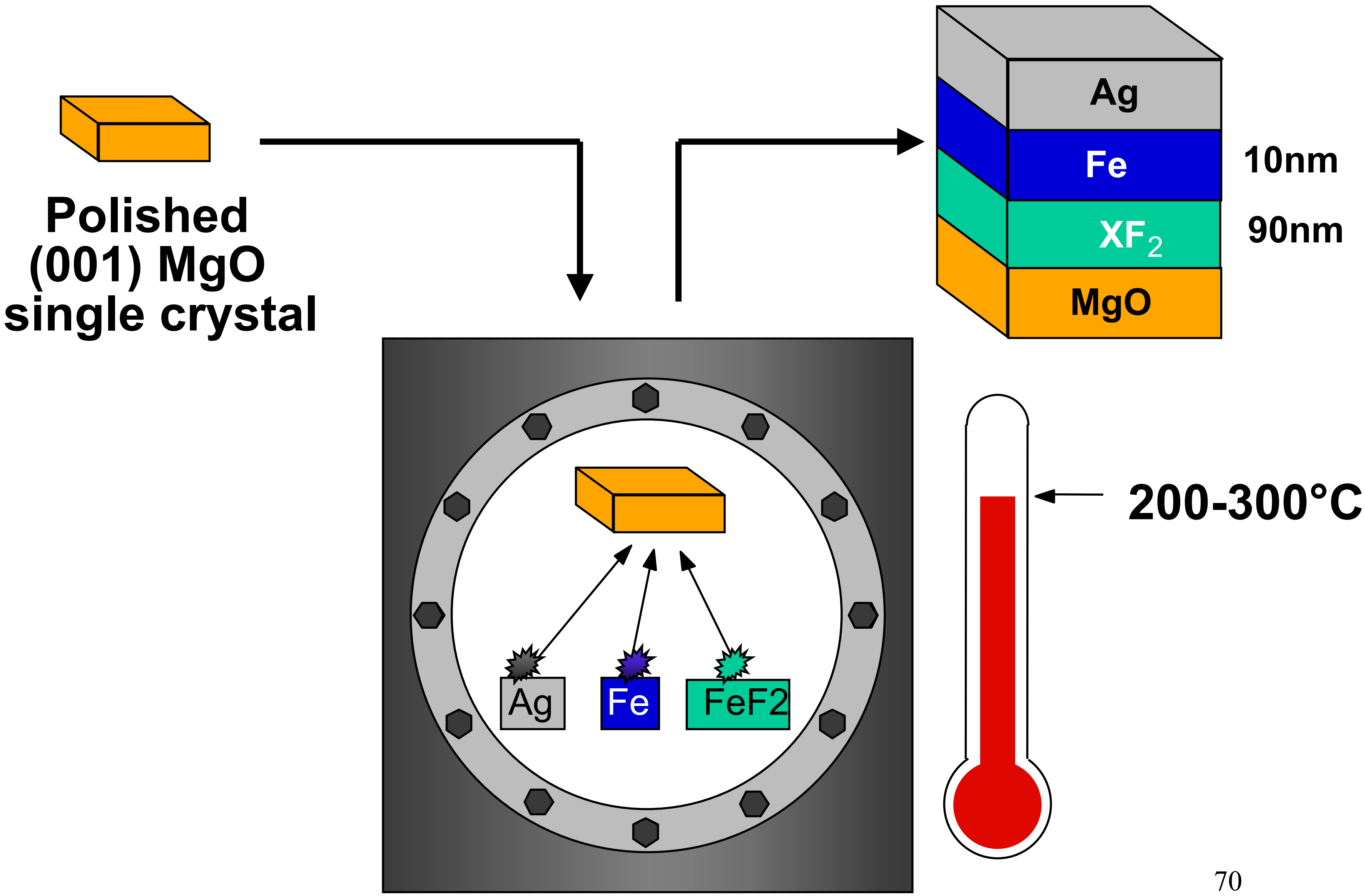


110 Interface



- **Compensated AF surface.**
- **Simple spin structure.**

Fe- *twinned* *X* F_2



Interlayer exchange coupling

The exchange coupling *J* between ferromagnetic layers across a non-ferromagnetic spacer is oscillatory.

- Ferromagnetic coupling
- Antiferromagnetic coupling
  - AFM alignment at zero field
  - Spin flop transition at high field
- Biquadratic coupling
  - 90° or non-collinear alignment

- Long period (≈18Å, Fe/Cr)
- Short period (≈2Å, Fe/Cr)
  - Only observed for very smooth interfaces

Review: M.D. Stiles JMMM 200 (1999) 322