Lecture 6

- More on magnetic energies
- Magnetic domains
- Thermal energy
- Magnetic hysteresis

Chapters 4 & 5

Energies we know so far

- Exchange energy (tries to align spins in crystals to keep them parallel or anti-parallel to each other)
- Magnetic anisotropy energy (tries to align spins in certain directions within the crystal)

There are more....

- Energy from external magnetic field (tries to align spins with the external field)
- Thermal energy (tries to misalign everything!)

Energy from external magnetic fields (remember Chapter 1!)

- also called "magnetostatic interaction energy", E_m
- interaction between magnetic lines of flux and the electronic spins.
- in book, there are energies (like E_m) and energy densities (volume normalized), ϵ_m
- $\epsilon_m = -\mathbf{M} \cdot \mathbf{B}$

Magnetic energy & magnetic stability

- Anisotropy energy means that in absence of external field, moment will be parallel to some "easy" axis (lower energy direction)

- Energy will be required to move moment from one axis to another.

- An external field could supply that energy (because magnetic energy = $\mathbf{m} \cdot \mathbf{B}$)

- Definition: field sufficient to flip moment over barrier is the intrinsic coercivity H_k

- For shape anisotropy: $H_k = \Delta N M$

- tiny particles (low M) have almost no stability. called superparamagnetic (SP)

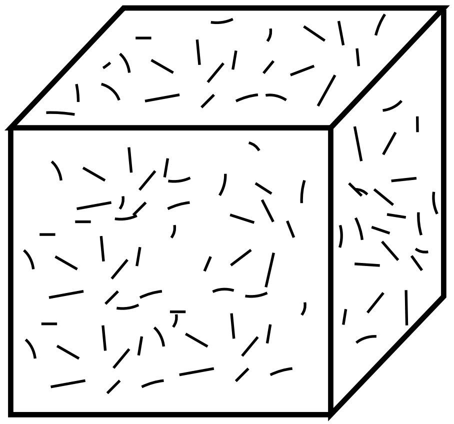
Thermal Energy (remember from Chapter 3)

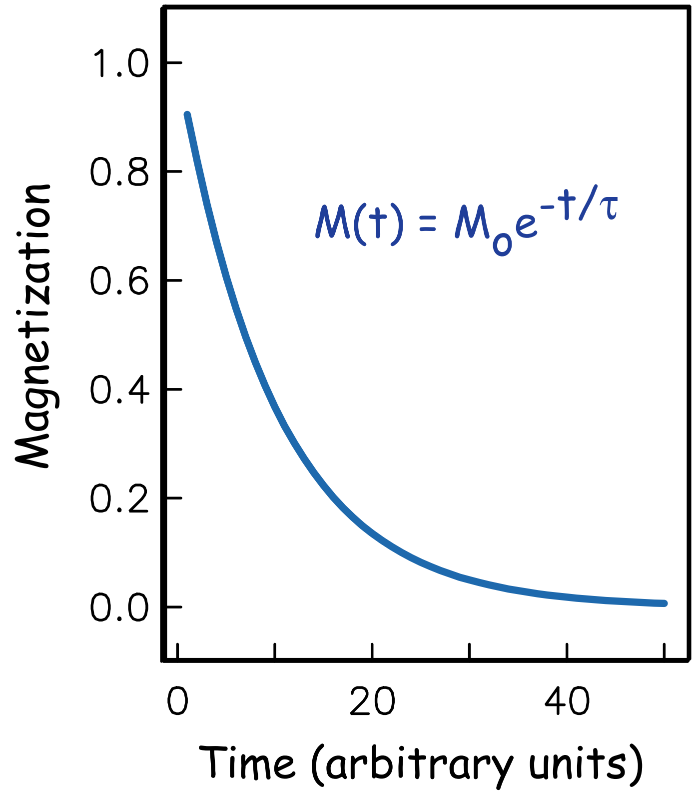
- Boltzmann's constant times absolute temperature (kT)

- So from statistical mechanics, probability of finding particle with sufficient energy to overcome anisotropy energy would be

$$P = \exp(-\frac{E_a}{E_T})$$

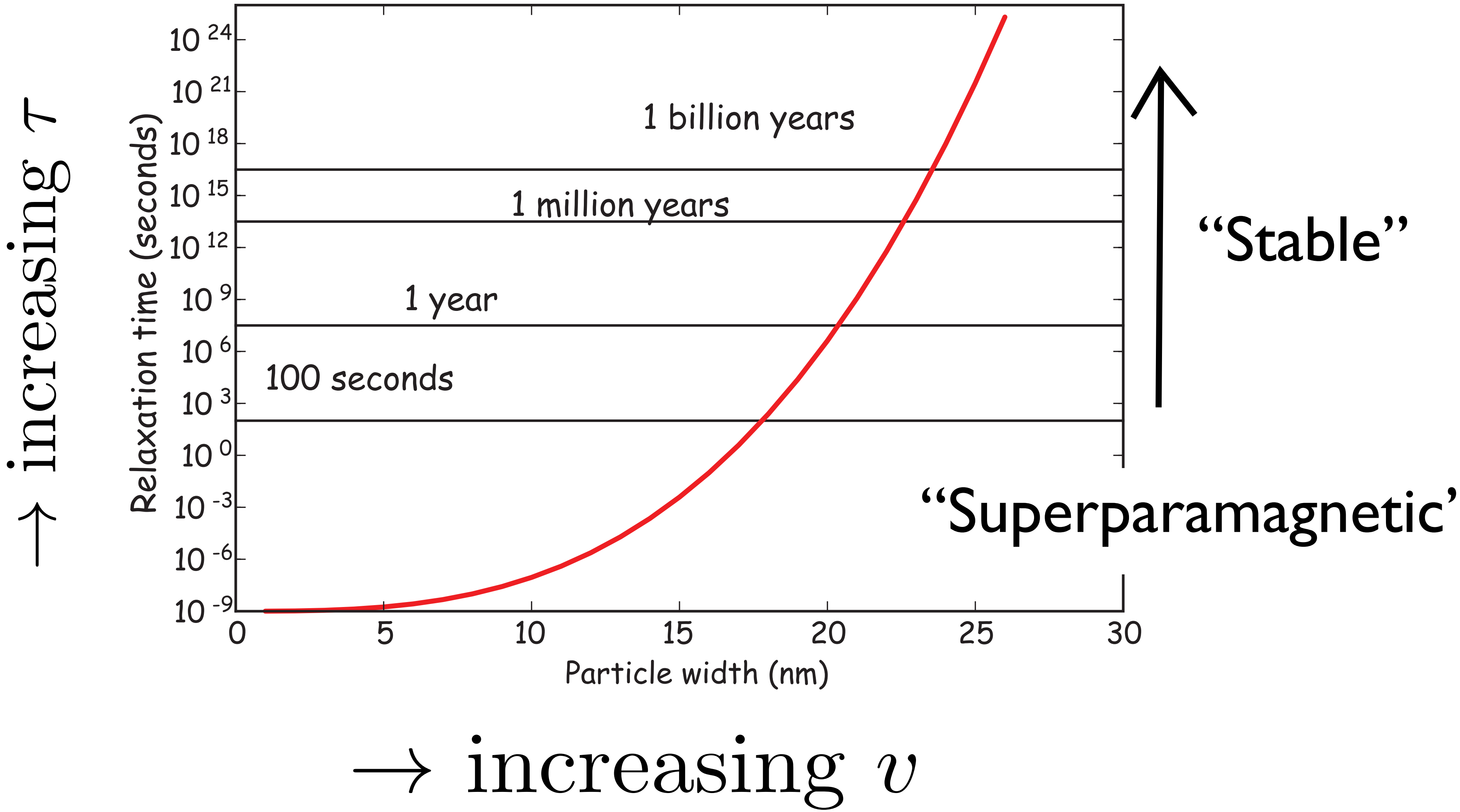
- So if we wait long enough, we will have a particle with sufficient energy to leap over the anisotropy energy barrier





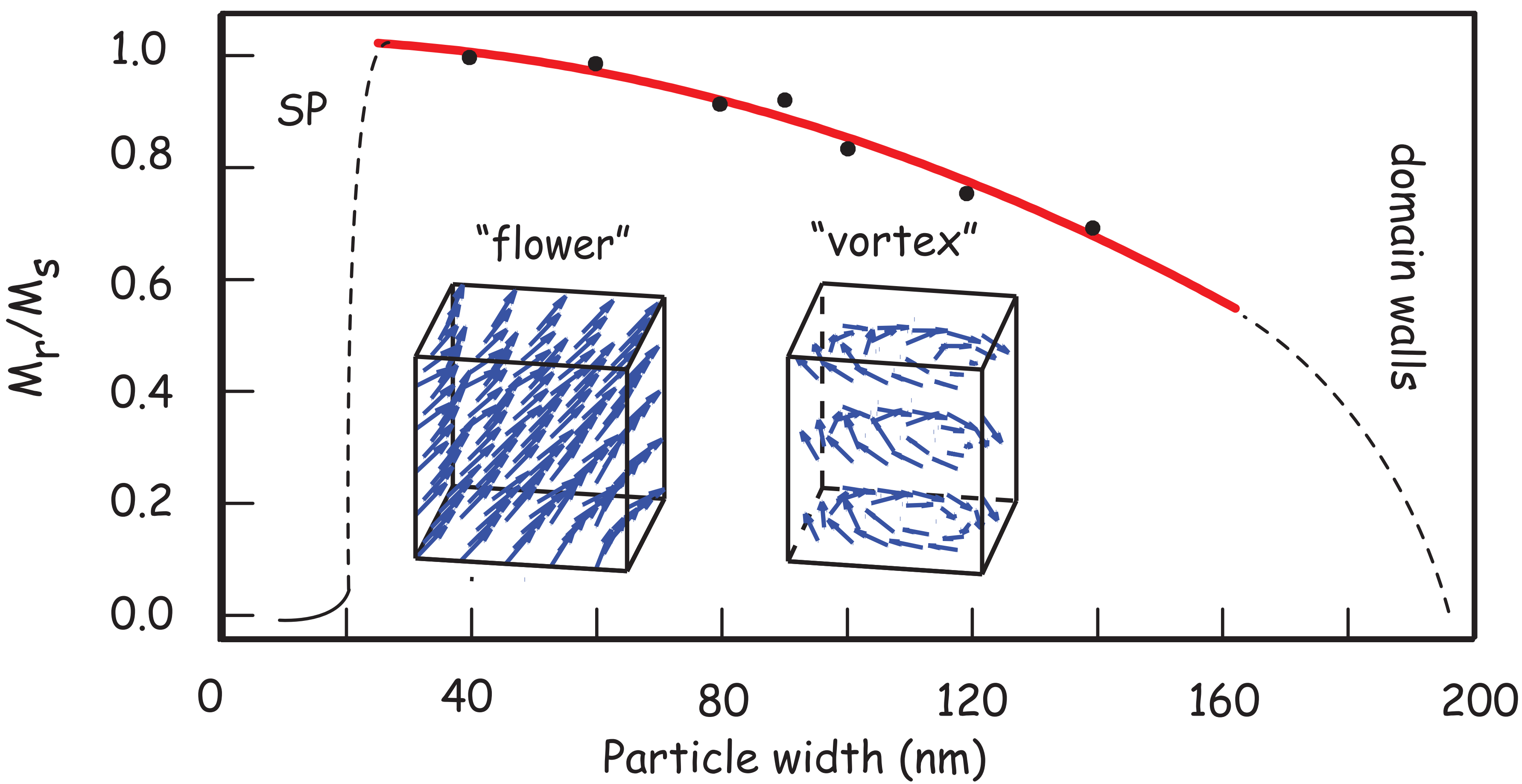
$$\tau = \frac{1}{C}\exp\frac{[\text{anisotropy energy}]}{[\text{thermal energy}]} = \frac{1}{C}\exp\frac{[Kv]}{[kT]}$$

τ is the time constant of decay
for magnetic remanence
- related to P



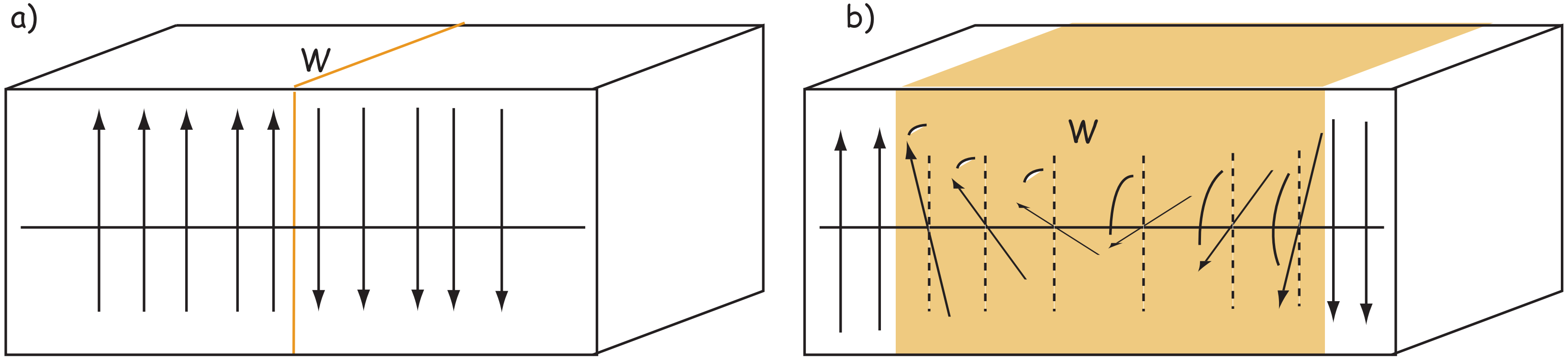
Superparamagnetic grains are in equilibrium with the applied field, so carry no remanence

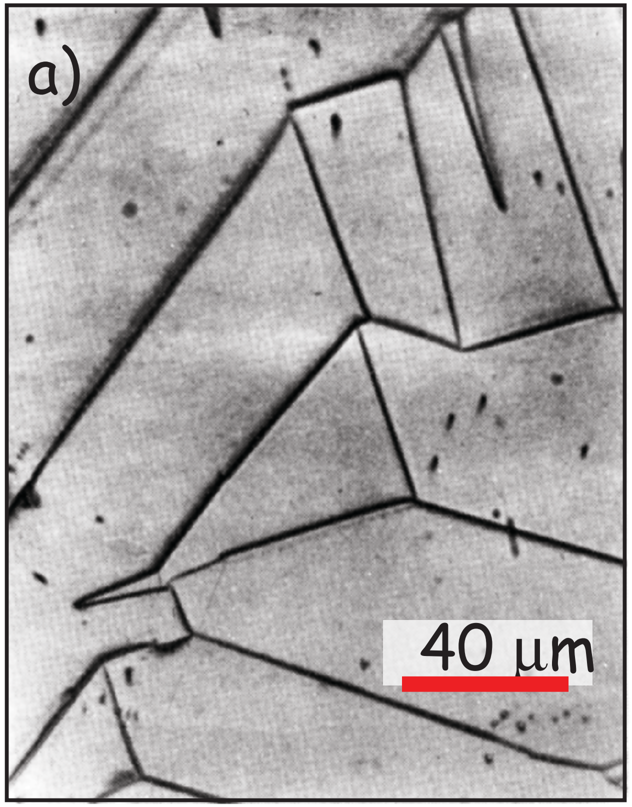
- So far, we have only considered uniformly magnetized particles
- But big particles have BIG self energies
- for highly magnetic particles like magnetite, self energy quickly exceeds other energies keeping things mutually parallel (exchange) or aligned in particular crystal directions (anisotropy)
- so spins in larger particles begin to have more complex structures

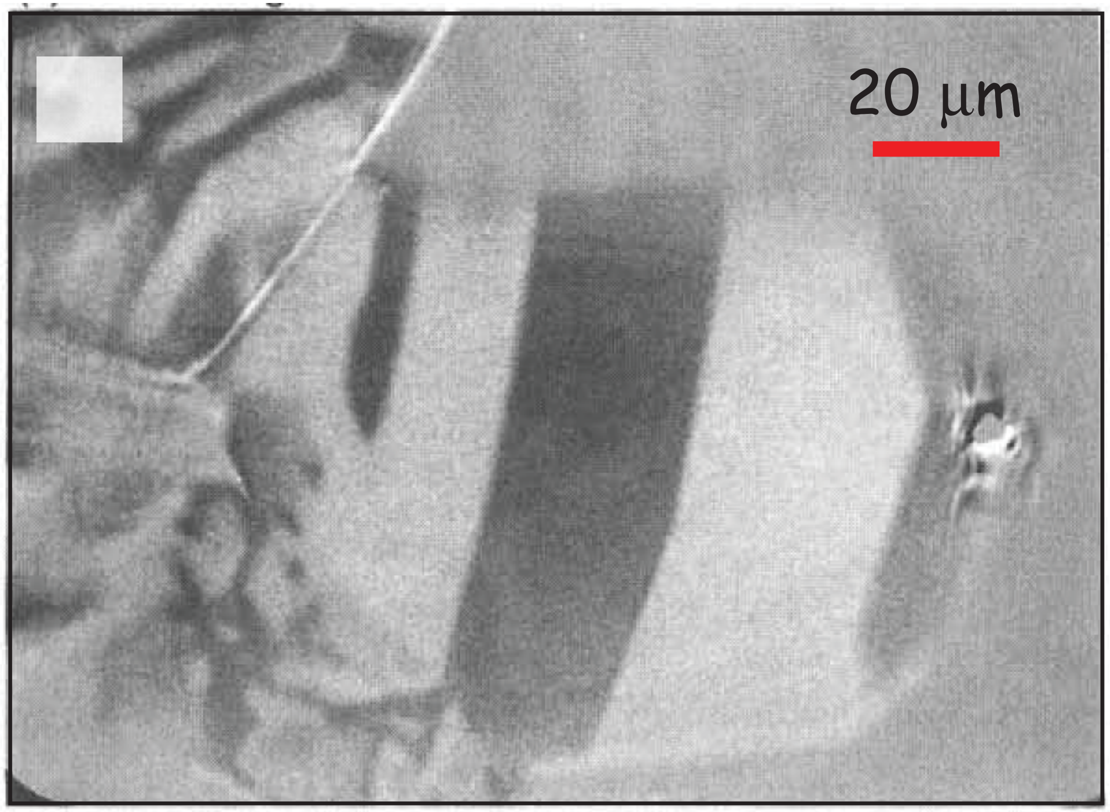


Can model spin alignment - need big computers with lots of memory, called micromagnetic modelling

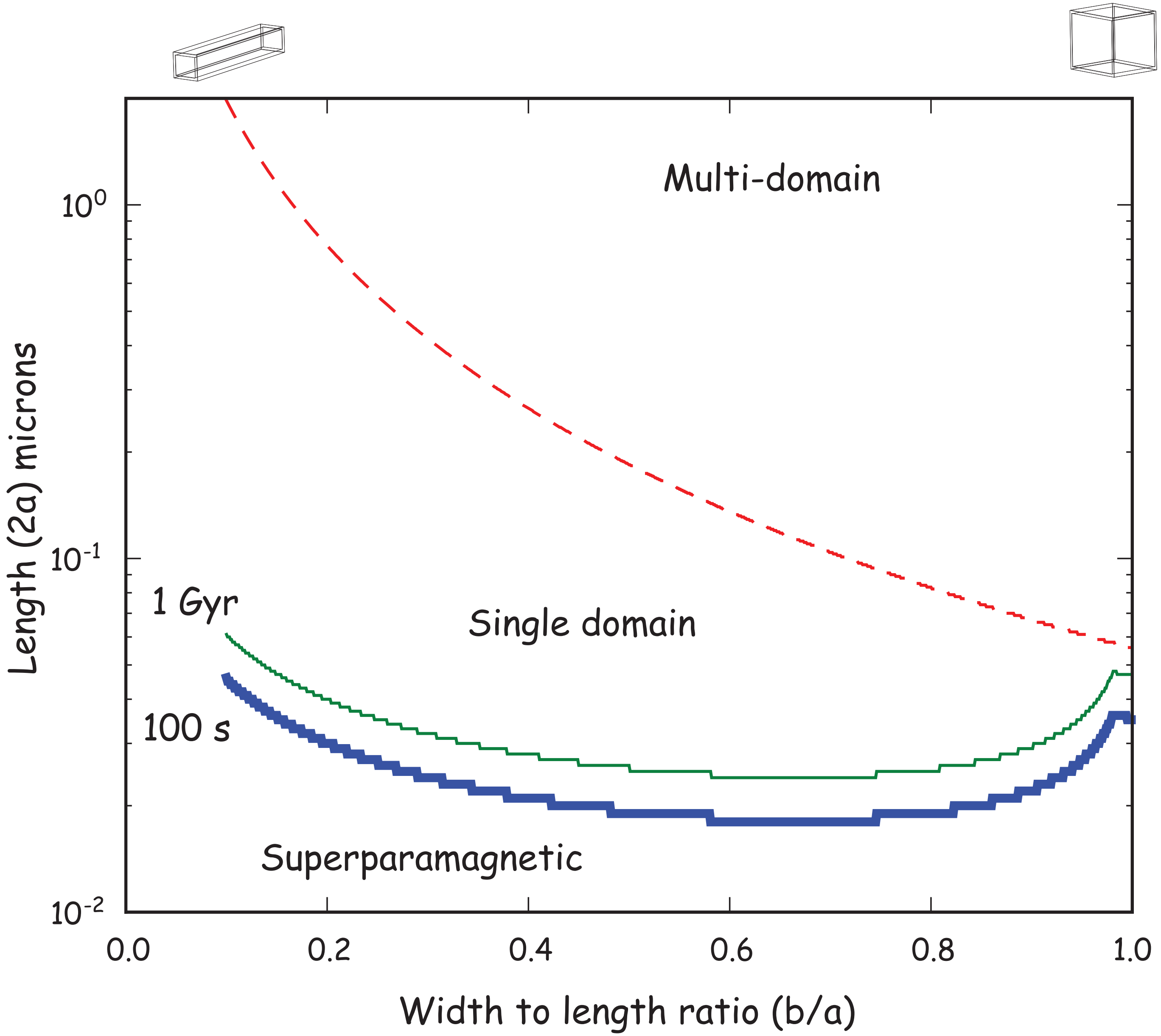
- Even bigger particles develop regions of uniform magnetization separated by "domain walls"







domains can be imaged



Putting shape versus stability together

- longevity of magnetization has to do with energy barriers (how high are they), how much energy is around to jump over them (e.g., thermal or magnetic), and how long you wait around

- Now let' talk about coercivity, a.k.a. flipping field. Flipping field is the field with enough umph to flip a moment over an energy barrier to another stable state.

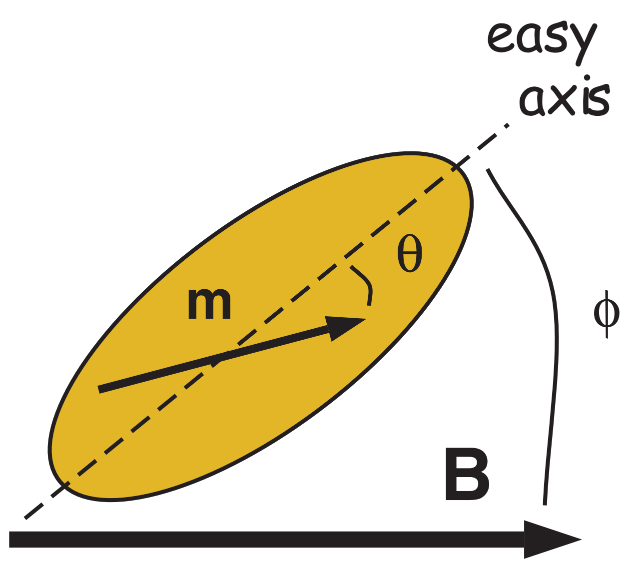
- Depends on the height of the energy barrier (anisotropy energy) and angle of moment wrt field.

Two parts to this:

anisotropy energy (from shape, crystal structure, stress) - just consider shape (it is easier) $\epsilon_a = K_u \sin^2\theta$

and energy from external field (magnetic energy)

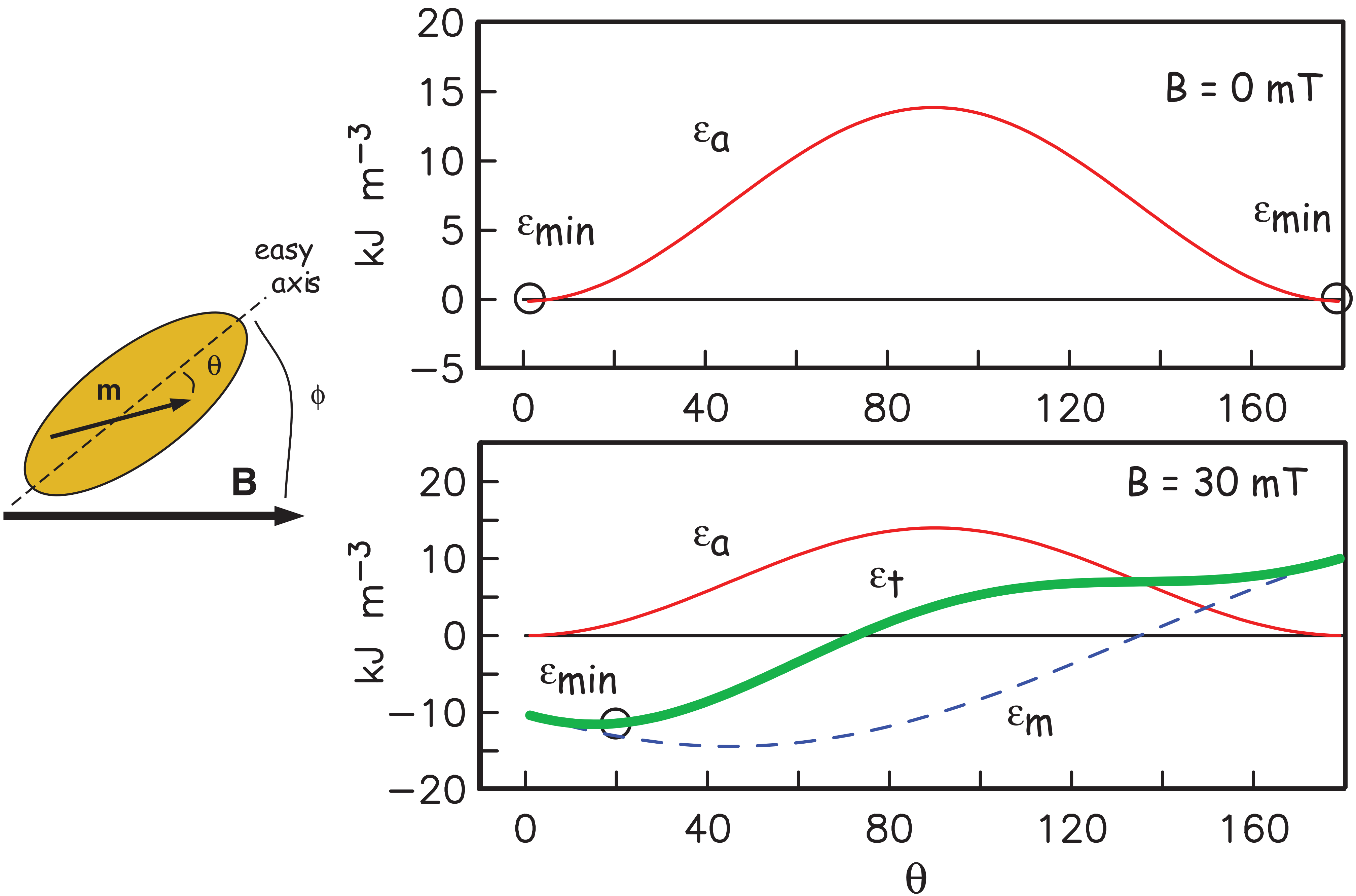
$$\epsilon_m = -\mathbf{M}\cdot\mathbf{B} = -MB\cos(\phi-\theta)$$



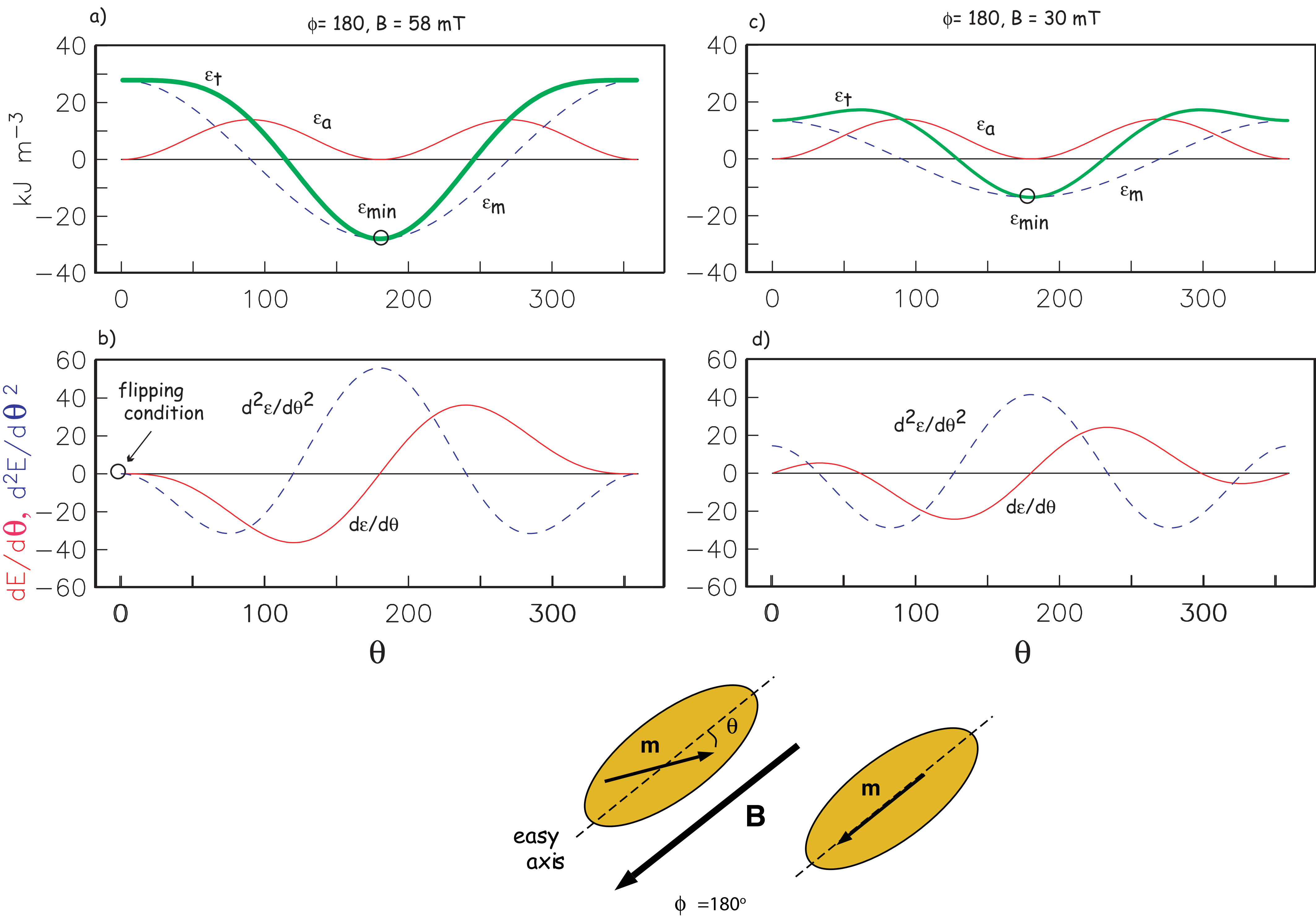
total energy (ϵ_t) balances these two

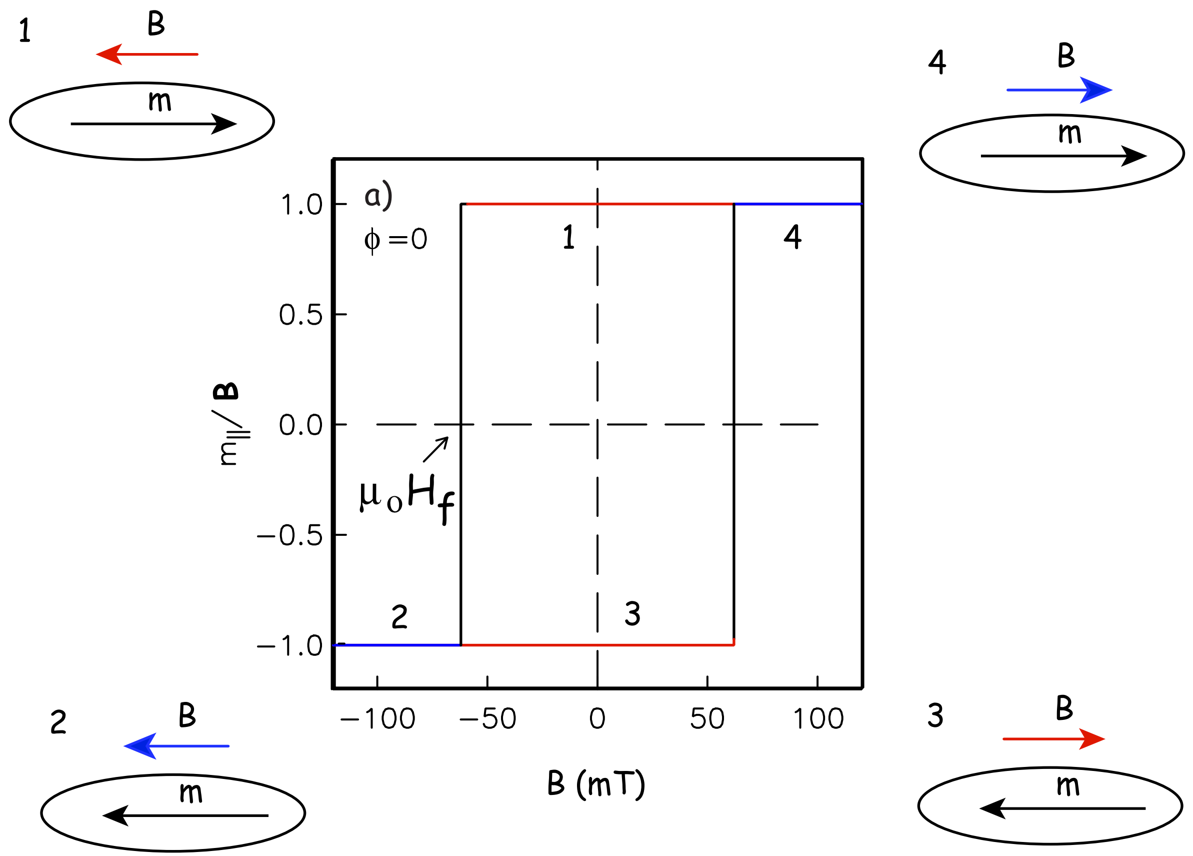
ϵ_a ϵ_m

$$\epsilon_t = K_u \sin^2\theta - M_s B \cos(\phi - \theta)$$

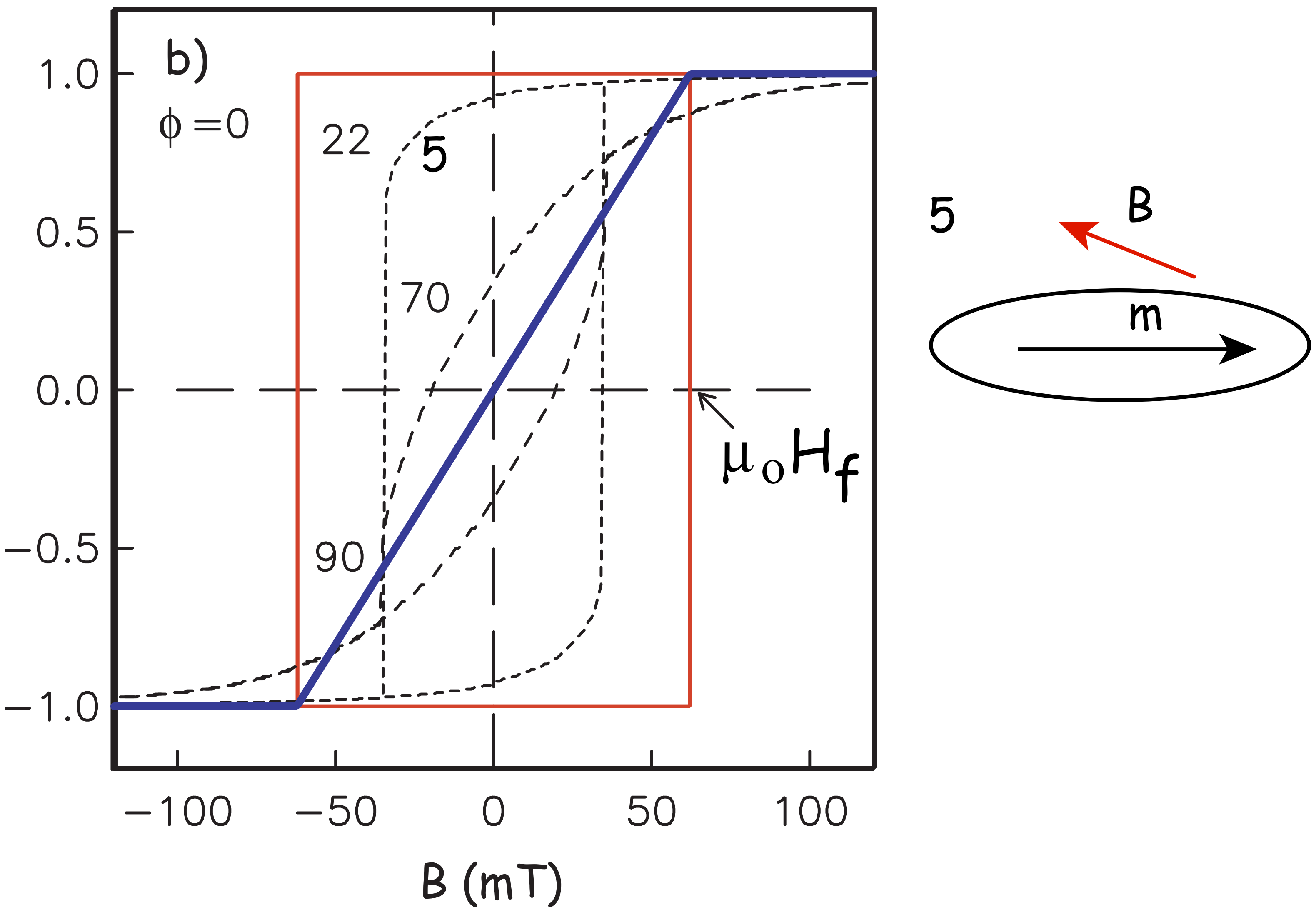


- Lots of math in Chapter 5 shows that there will be a field of sufficient energy to flip the moment of a particle with easy axis aligned at an arbitrary angle to the applied field.
- called the flipping field. the maximum flipping field is the intrinsic coercivity discussed before


a)
ϕ= 180, B = 58 mT
c)
ϕ= 180, B = 30 mT
kJ m−3
εt
εa
εm
εmin
b)
d)
flipping condition
d2ε/dθ2
dε/dθ
dE/dθ, d2E/dθ 2
θ
m
θ
B
easy axis
ϕ =180°

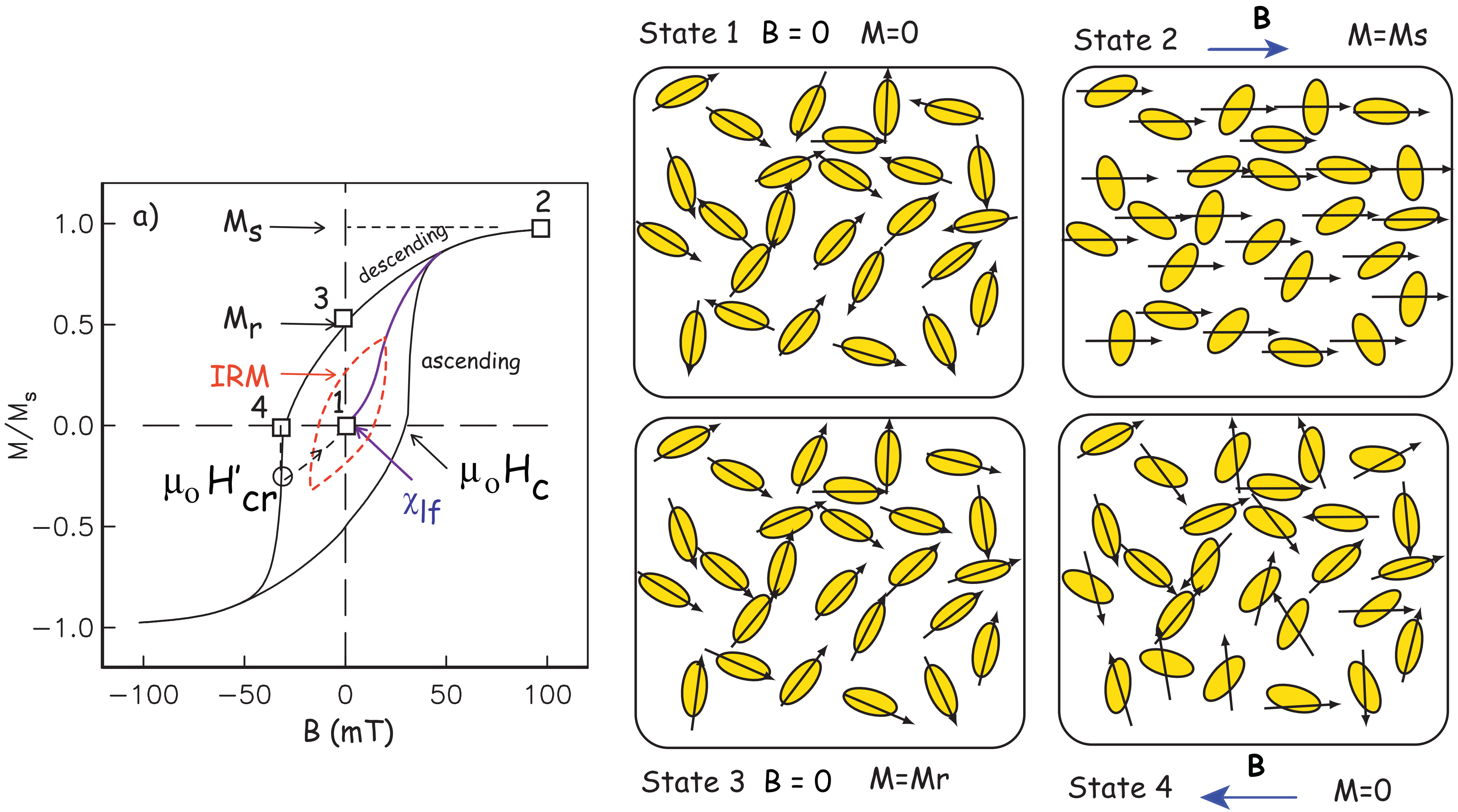


1
B
m
4
B
m
a)
ϕ =0
1.0
0.5
0.0
−0.5
−1.0
1
4
2
3
$\mu_o H_f$
$m_{\parallel}/$B
−100
−50
0
50
100
B (mT)
2
B
m
3
B
m



b)
ϕ =0
22
5
70
90
μ₀H_f
1.0
0.5
0.0
−0.5
−1.0
−100
−50
0
50
100
B (mT)
5
B
m

Assemblages of (SD) particles



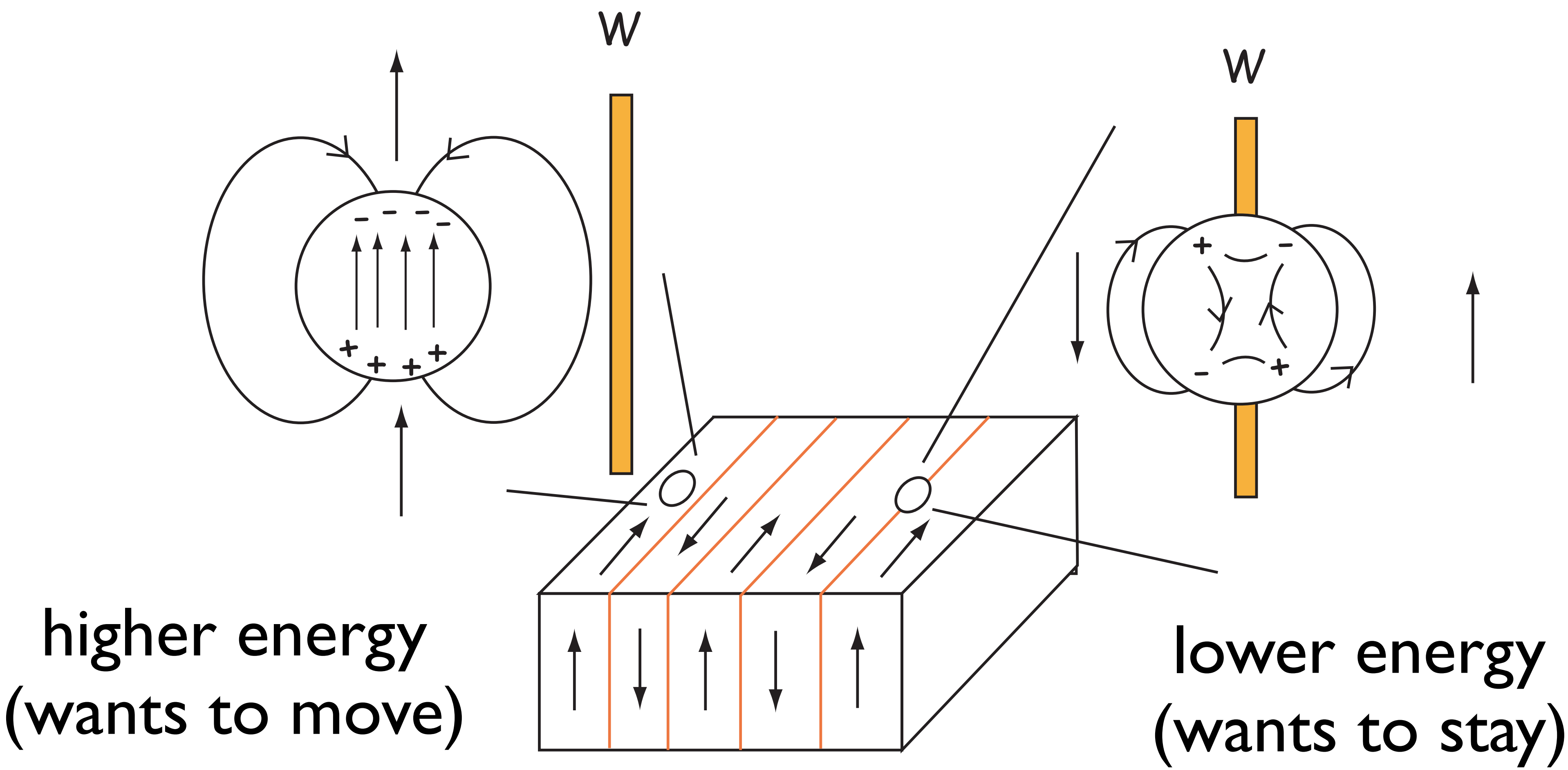
Note - figure in printed book is wrong
- see online version

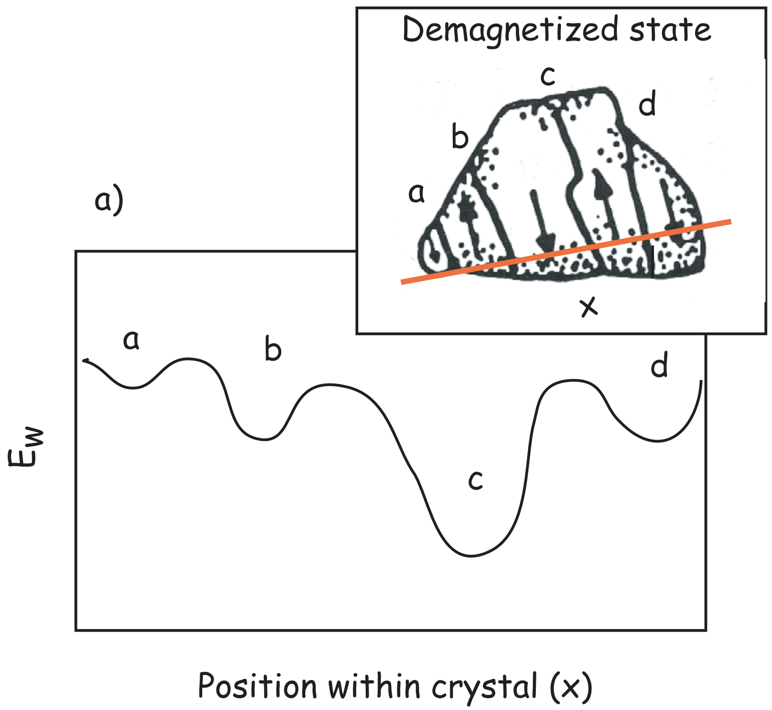
But life is not simple: things that affect hysteresis loops

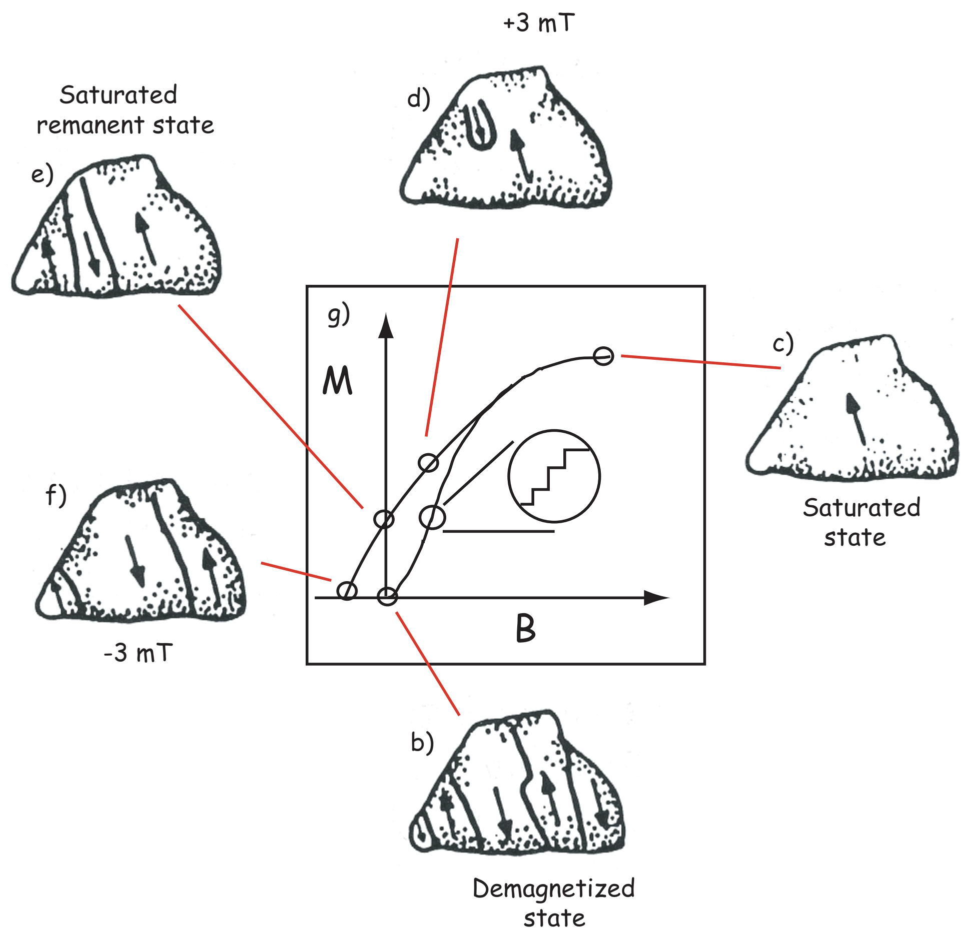
- Larger grain sizes try to minimize Mr (domain walls, flower/vortex strucures), so they depress the Mr/Ms ratio
- Larger grain sizes have lower coercivities (because domain walls are easier to move than flipping easy axes in SD particles)
- and SMALLER grain sizes are super paramagnetic (Mr/Ms= 0, Hc=0)

- Let’s start with domain walls

bigger particles (multi-domain) are not so simple - energy function of position of domain wall

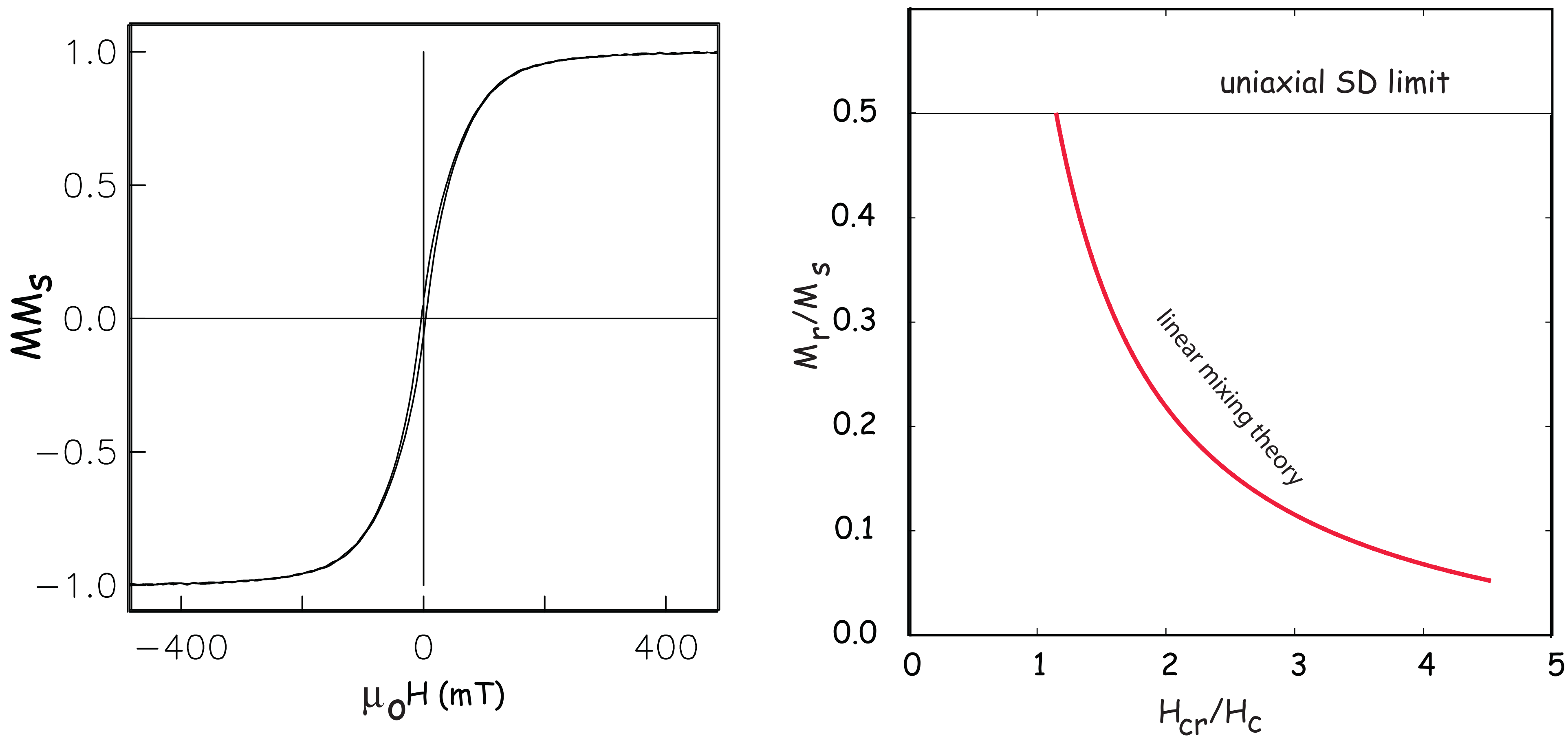




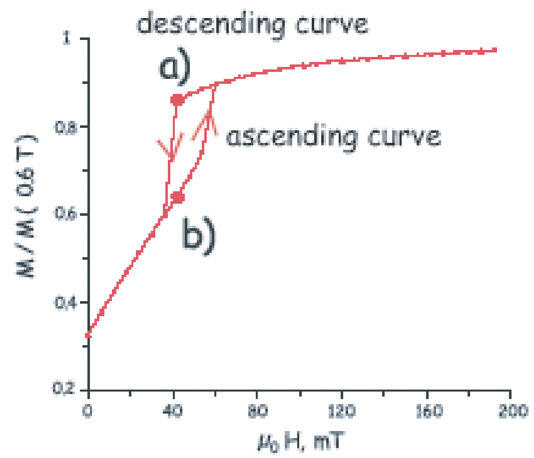


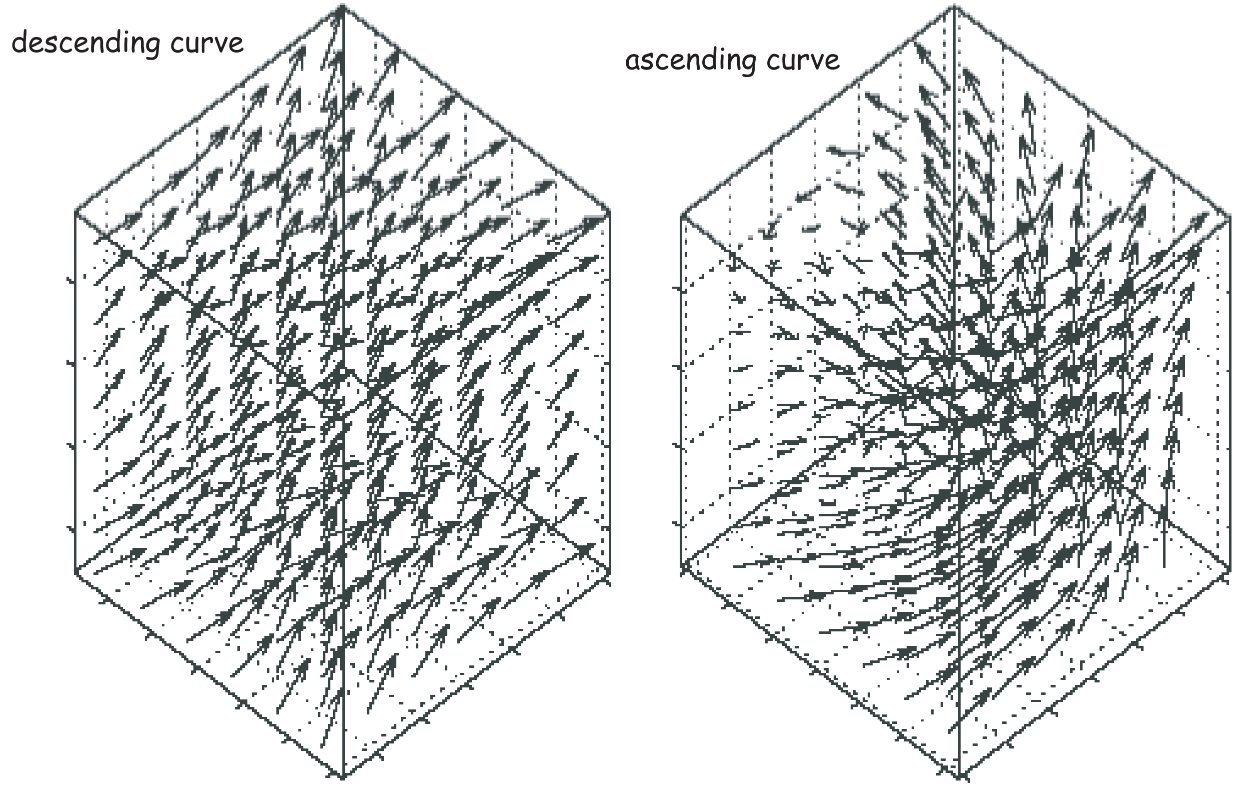
Note depression of Mr/Ms

Typical "MD" loop



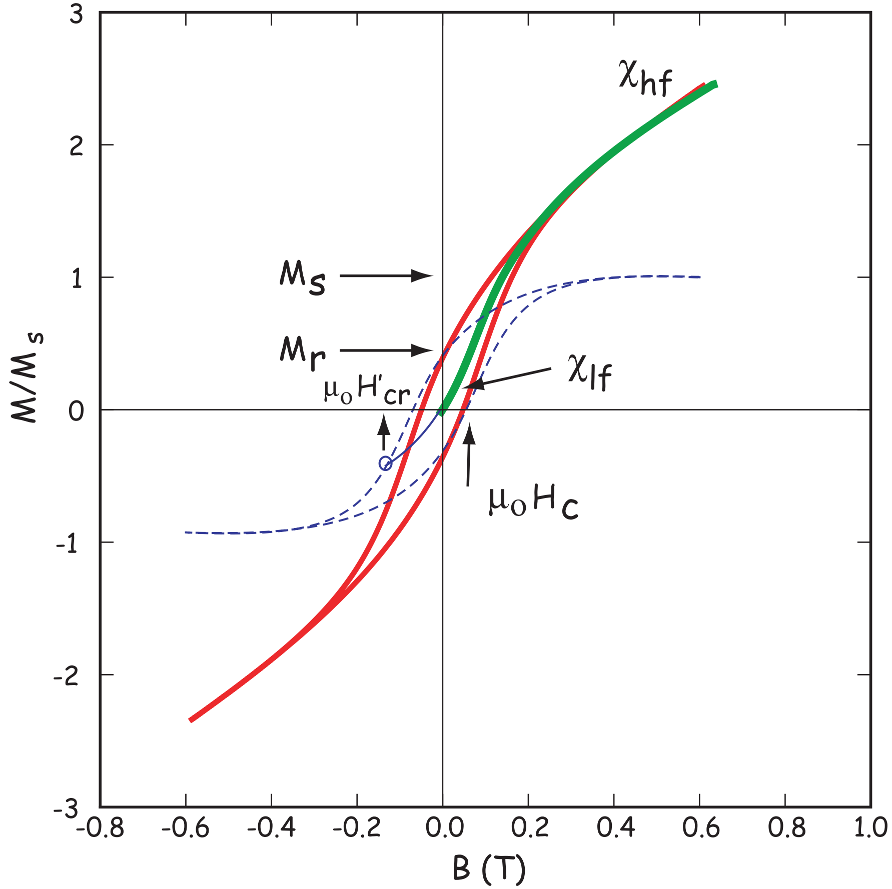
- Now what about vortex structures?

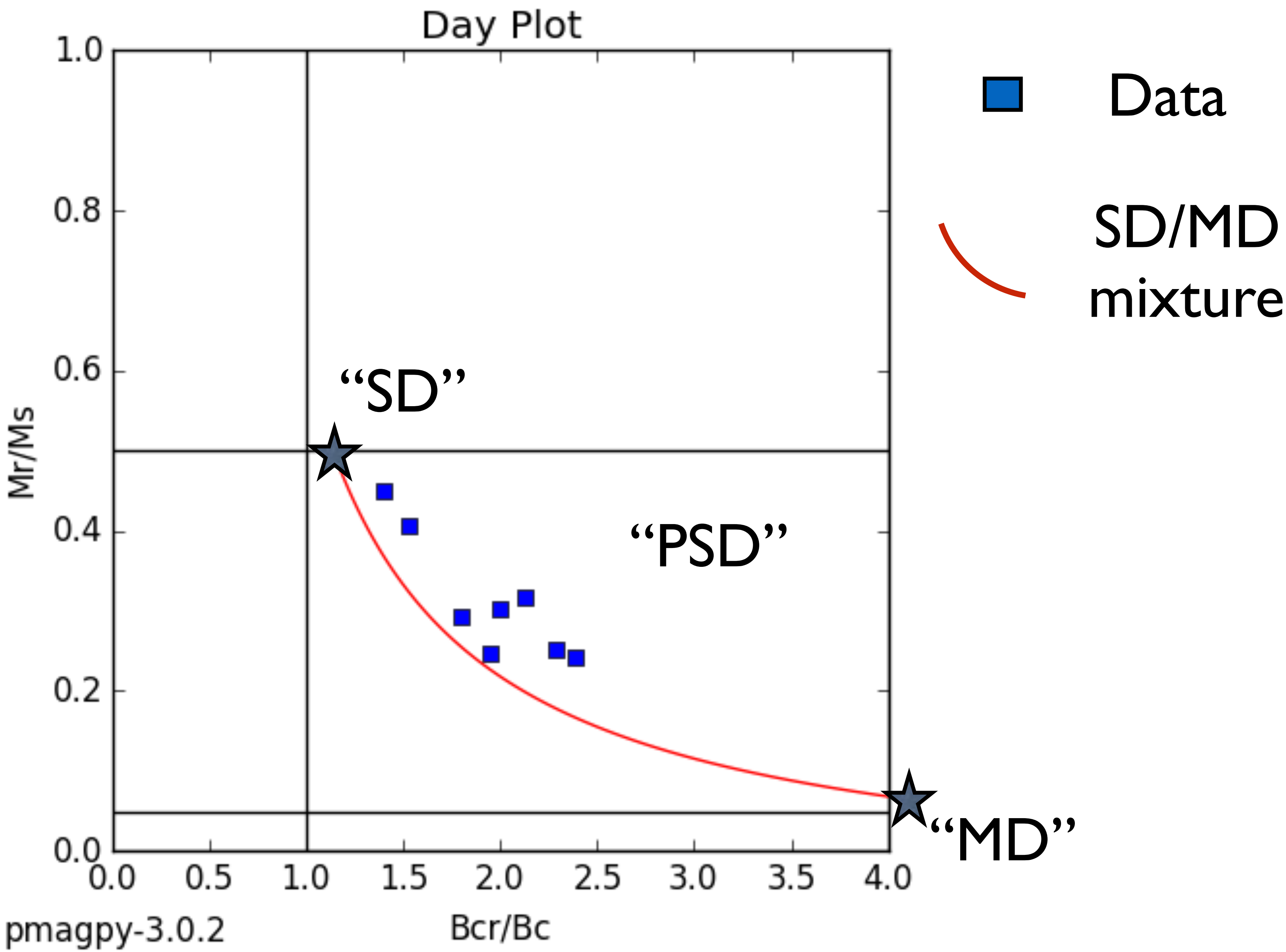




Also lowers Mr/Ms and raises Hcr/Hc

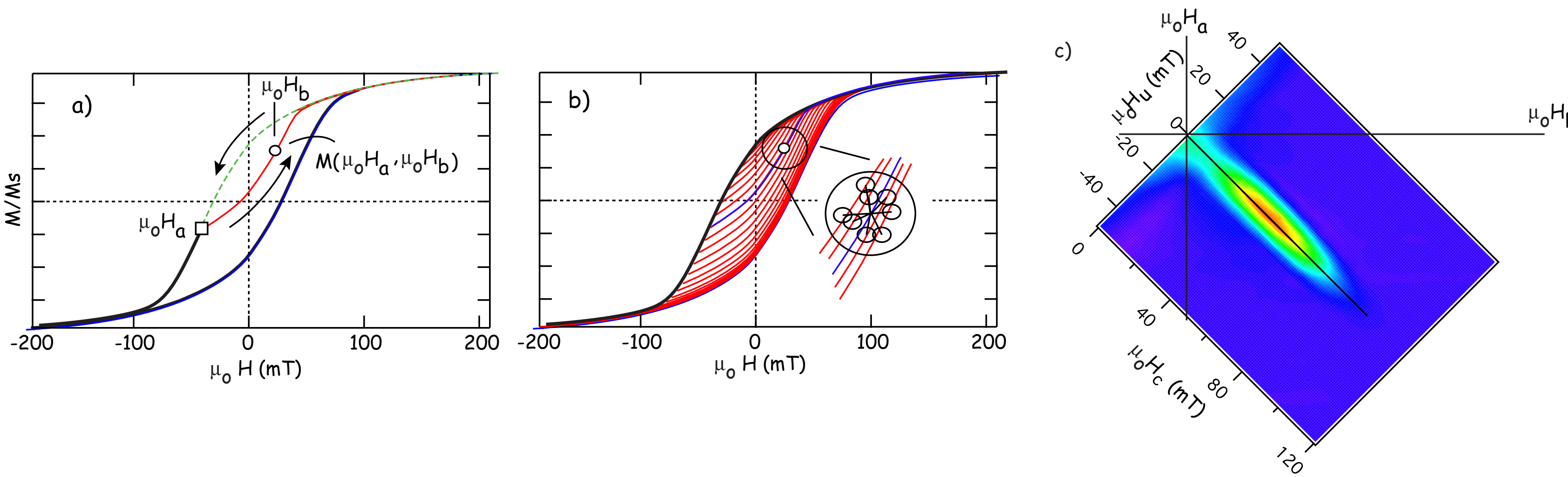
Typical loop vortex state loop (called pseudo-single domain) or “PSD”





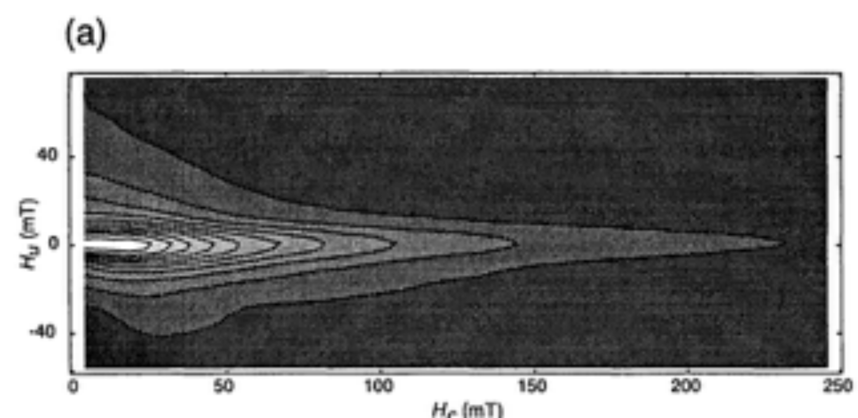
Day Plot
1.0
0.8
0.6
0.4
0.2
0.0
Mr/Ms
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Bcr/Bc
pmagpy-3.0.2
“SD”
“PSD”
“MD”
Data
SD/MD mixture

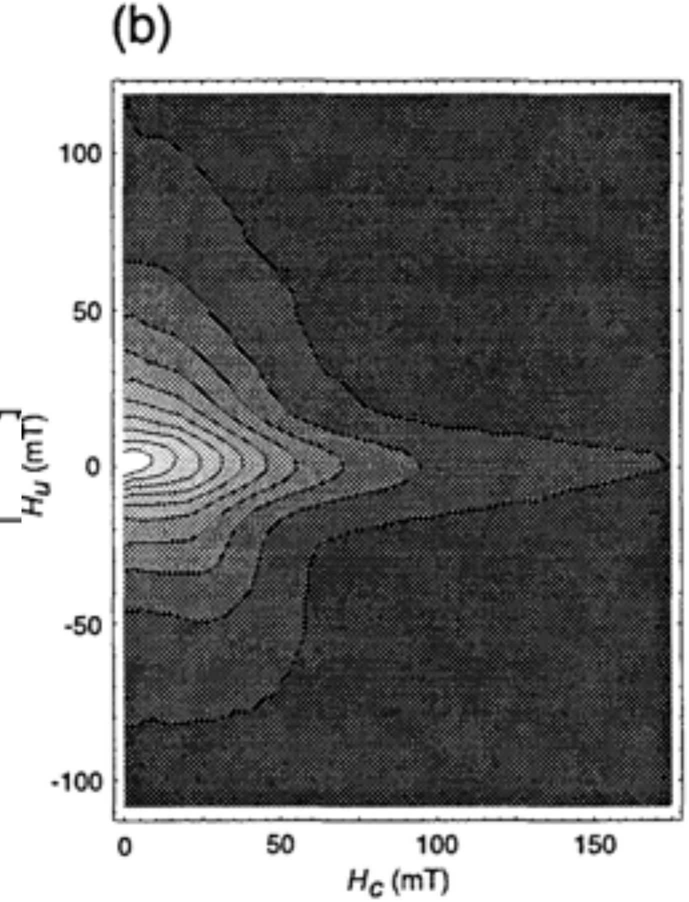
- First Order Reversal Curves (FORCs)

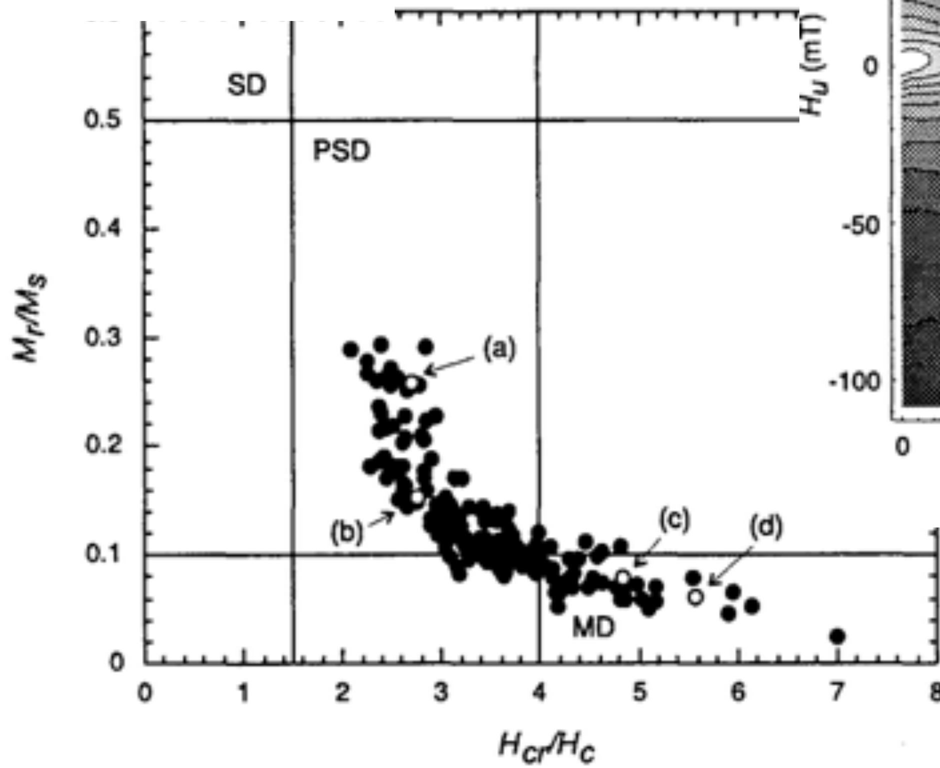


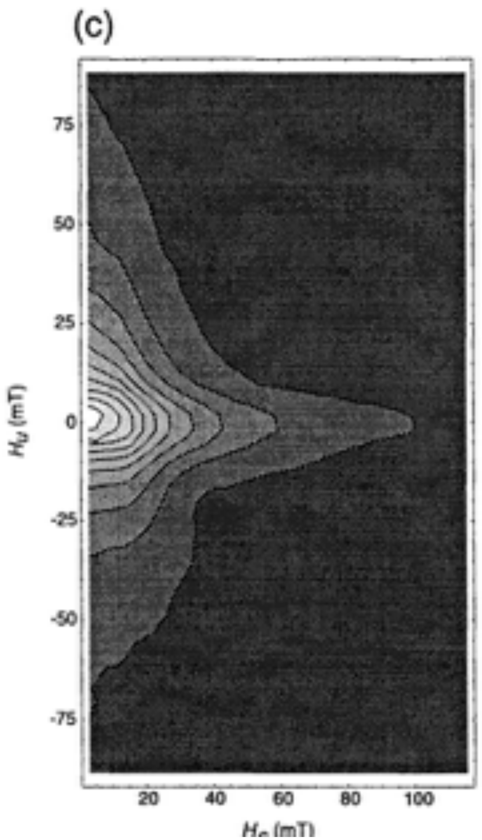
a)
b)
c)
M/Ms
μoHb
μoHa
M(μoHa, μoHb)
-200
-100
0
100
200
μo H (mT)
μoHa
μoHu (mT)
μoHb
μoHc (mT)
40
20
0
-20
-40
0
40
80
120

FORC examples









Roberts et al. (2000)

Assignment

- Problems 4.2 and 5.2 in online textbook