Mitglied der Helmholtz-Gemeinschaft

Magnetic properties of condensed matter systems probed by magnetometry

O. Petracic

Magnetic moment

The fundamental object in magnetism is the
magnetic moment*, m**, = 'magnetic dipole moment'*,**
(*sometimes:* μ)

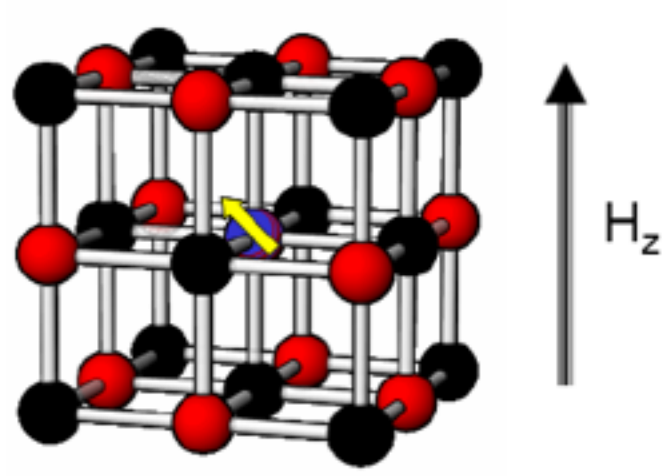
m ↗

Possible origins of **m**:

1. ring current / angular momentum
2. spin

Isolated magnetic moments

Consider **isolated**, **localized** magnetic moments:
↔ no interactions, and no metal



There are two types of magnetic behaviors:

1. **Paramagnetism**: Susceptibility rel. small & positive, $\chi > 0$
   Examples: Al, Ti, Pd, magnetic impurities
2. **Diamagnetism**: Susceptibility small & negative, $\chi < 0$
   Examples: C, Si, Cu

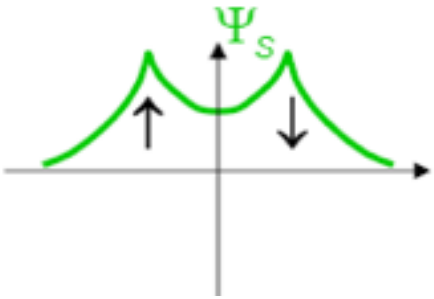
Interactions

With interactions:

dominant in most solids: **exchange interaction**

(i) direct exchange interaction

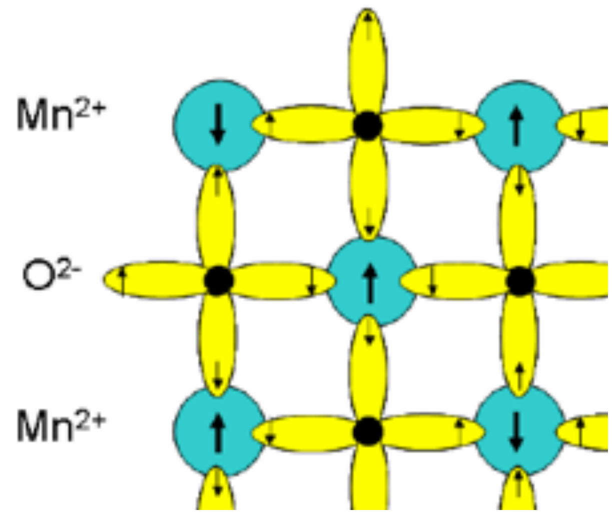
QM effect
↔ spin-spin 'interaction'



→ **3. Ferromagnetism**

(ii) superexchange interaction

QM spin-spin 'interaction' mediated by e.g. Oxygen atoms



→ **4. Antiferromagnetism**

Interactions

Exchange interaction:

Interaction energy can be expressed as:

$$\rightarrow \qquad \hat{H} = -\sum_{<i,j>} J_{ij}\mathbf{S}_i \cdot \mathbf{S}_j$$

Heisenberg Hamiltonian

Magnetic order

Consequences of interaction:

(most important cases)

$$\hat{H} = -\sum_{<i,j>} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j$$

(a)  $J_{ij} > 0$ Ferromagnet (FM, F)

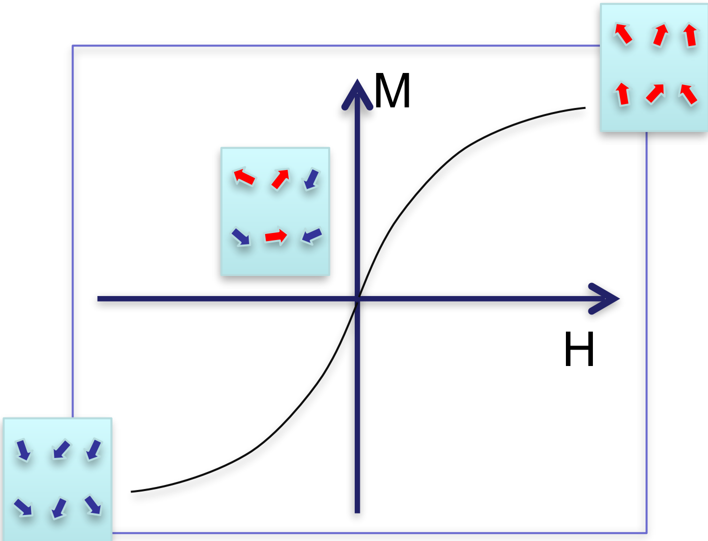
(b)  $J_{ij} < 0$ Antiferromagnet (AFM, AF)

(c)  more J's Ferrimagnet (FiM)

Examples of magnetic properties

M vs. H	M vs. T
χ_{ac} vs. T	H vs. T

1. Paramagnet (Al, Ti, Mn, Nb, Pd, Imp.∈Insul., ...)



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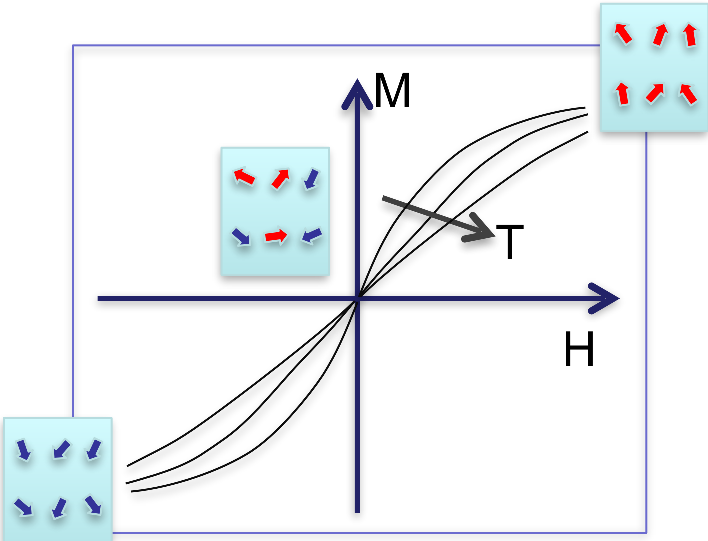

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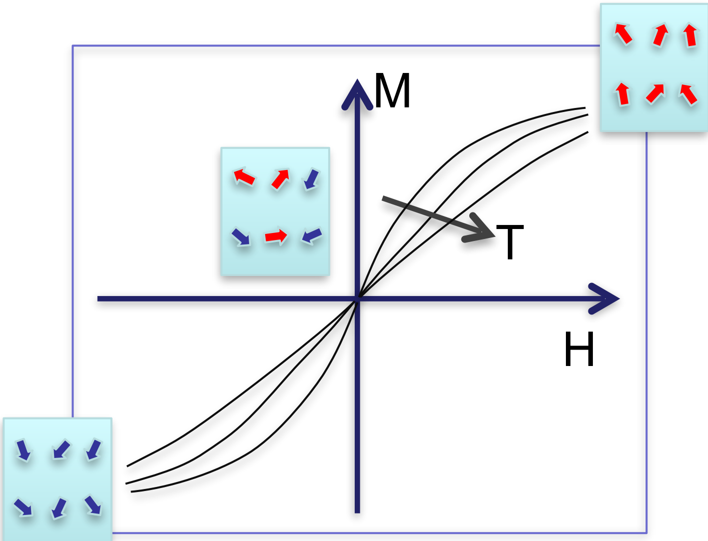

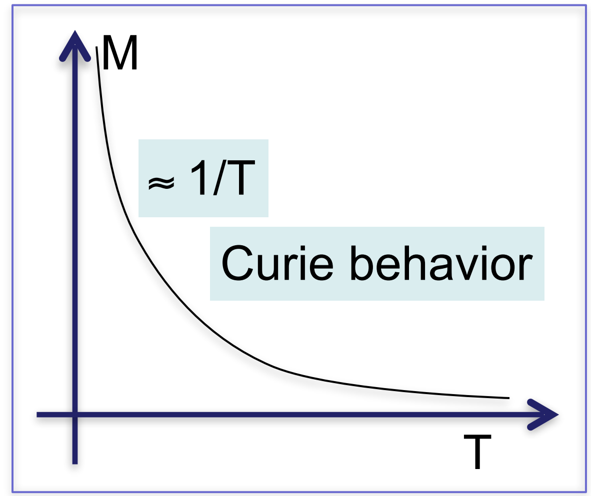

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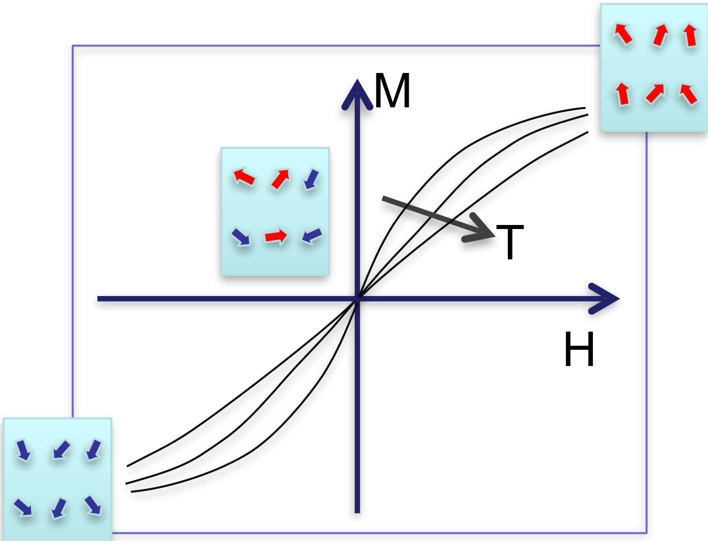

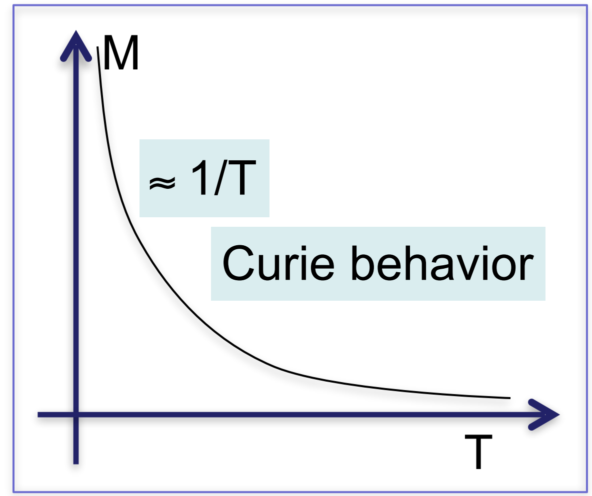

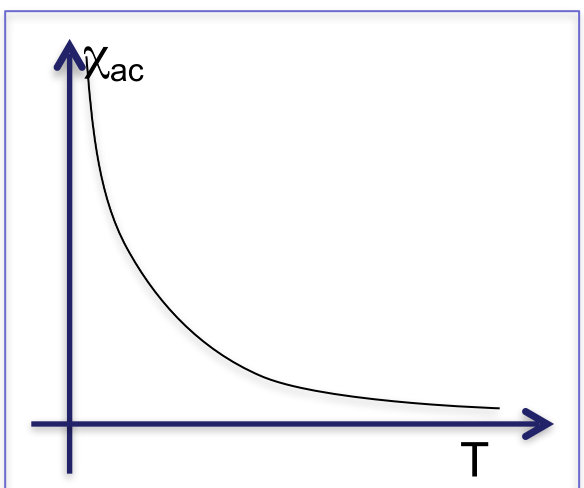

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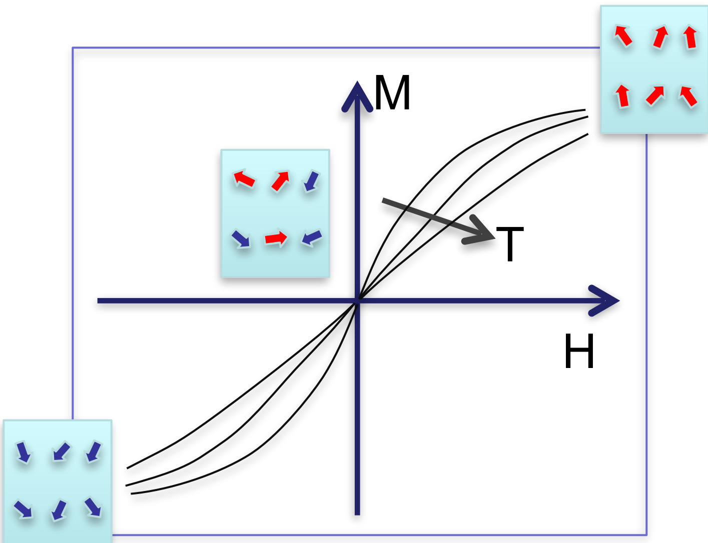
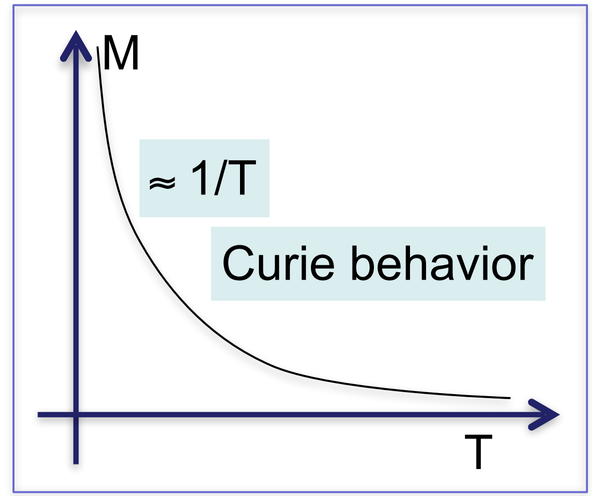
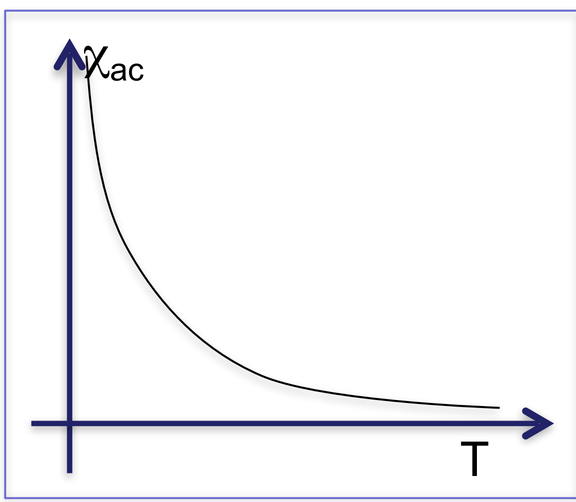
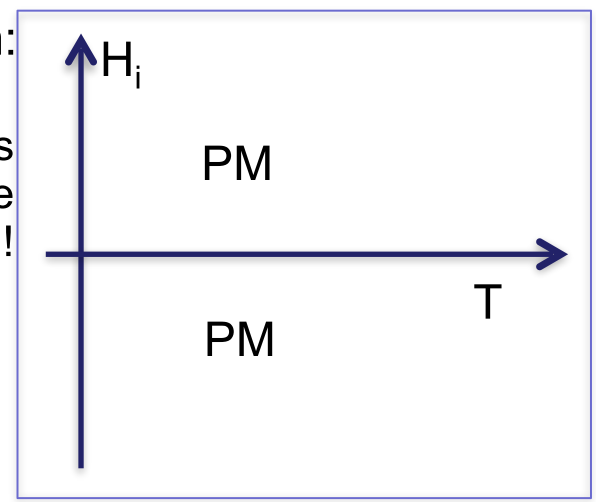




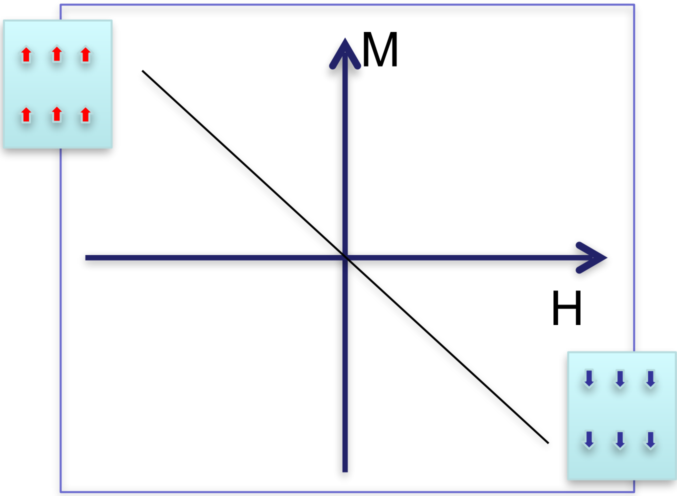


Phase diagram:

there exists
no phase
transition!



2. Diamagnet (C, Si, Cu, Ag, ...)



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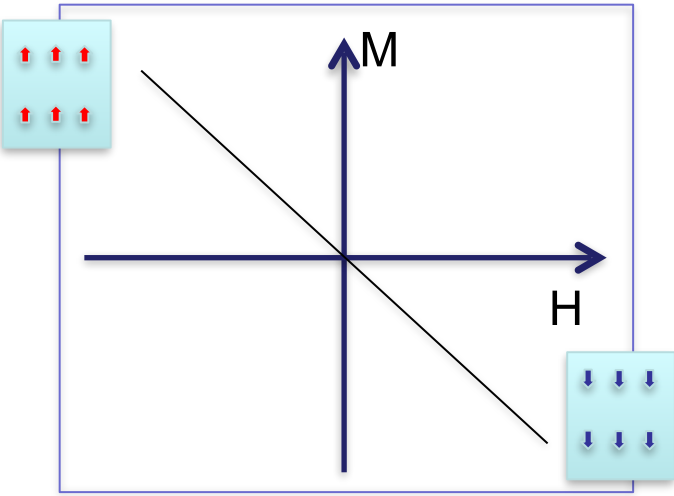

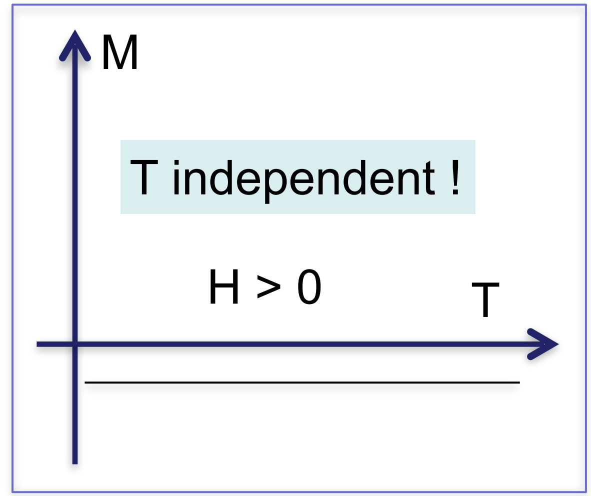

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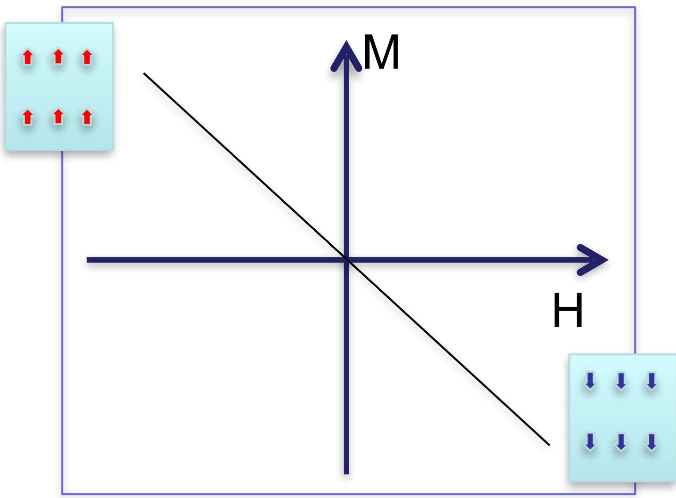

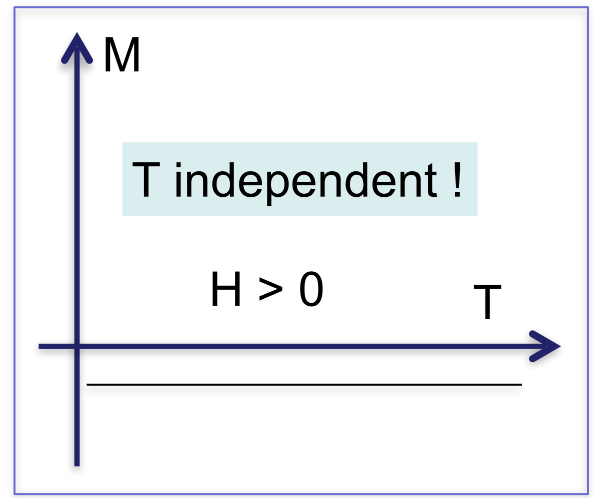

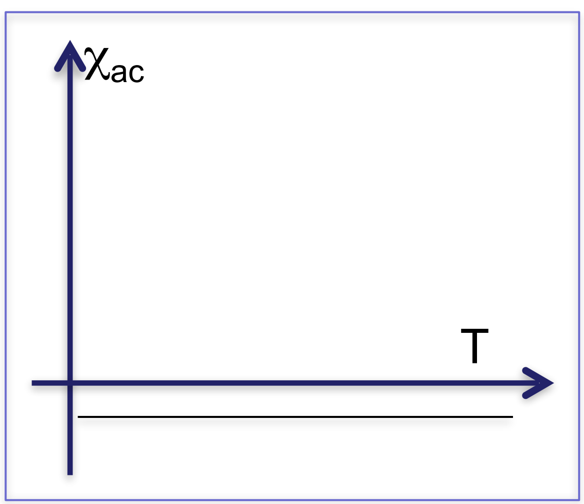

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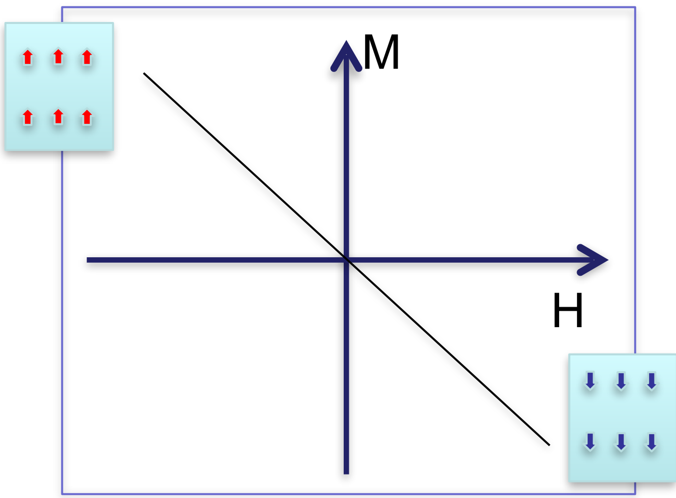

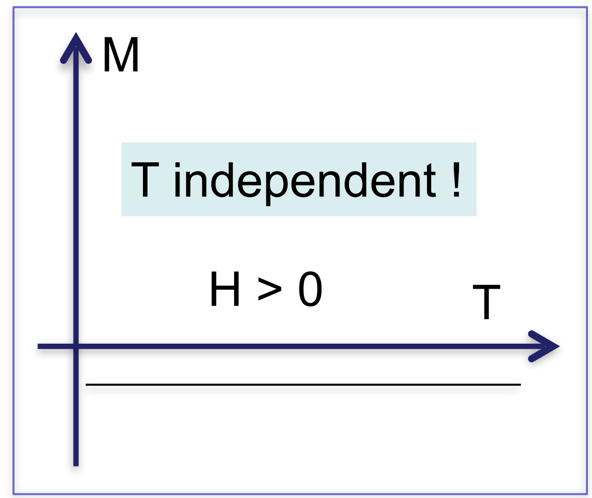

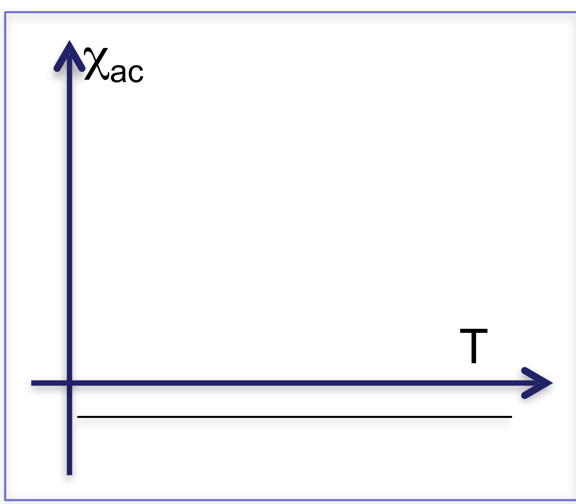

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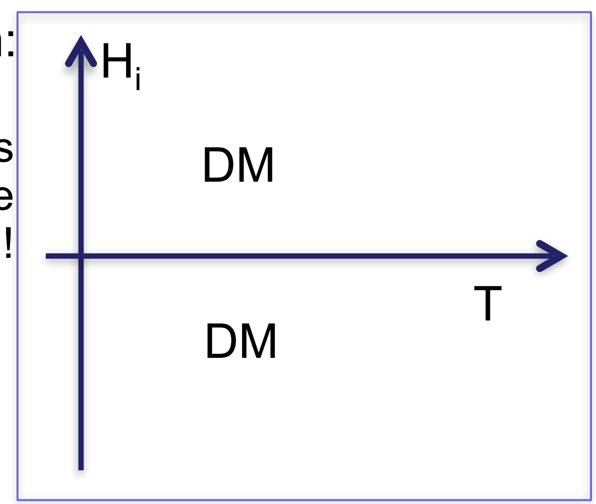
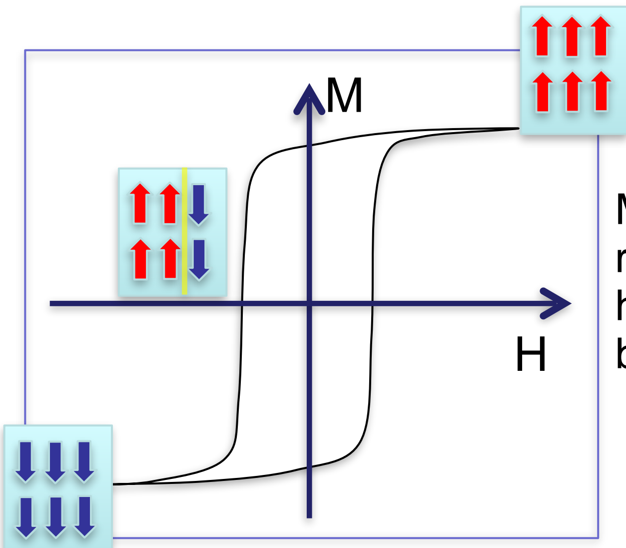


3. Ferromagnet (Fe, Co, Ni, Gd ...)



Magnetization reversal, here: by DWM

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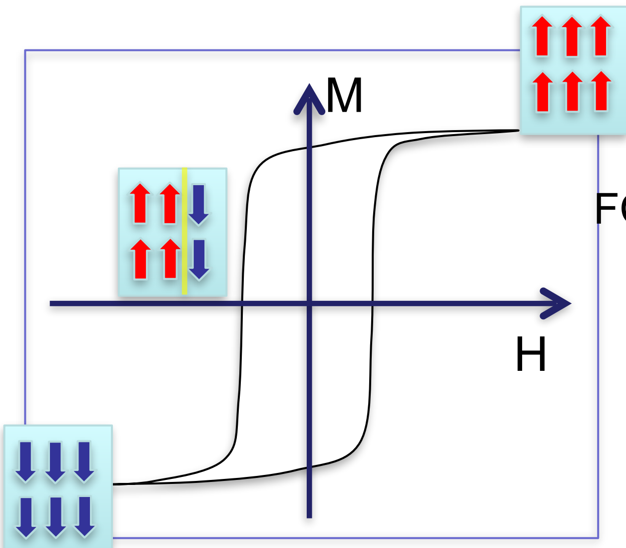
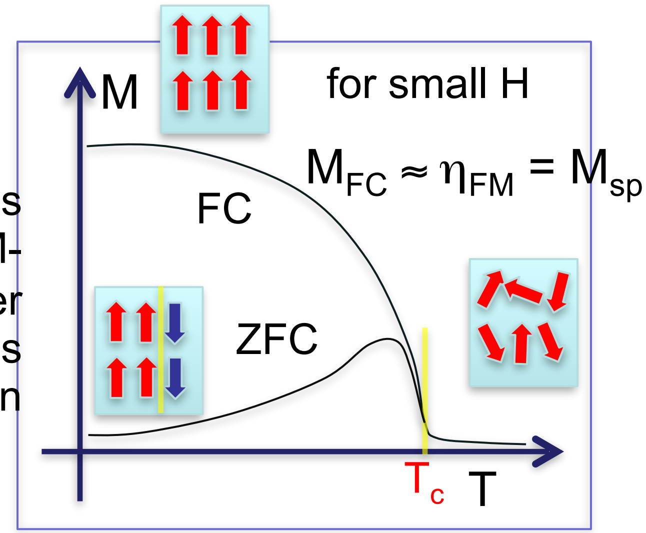


FC for small fields
≈ FM-
order parameter
= Spontaneous
magnetization



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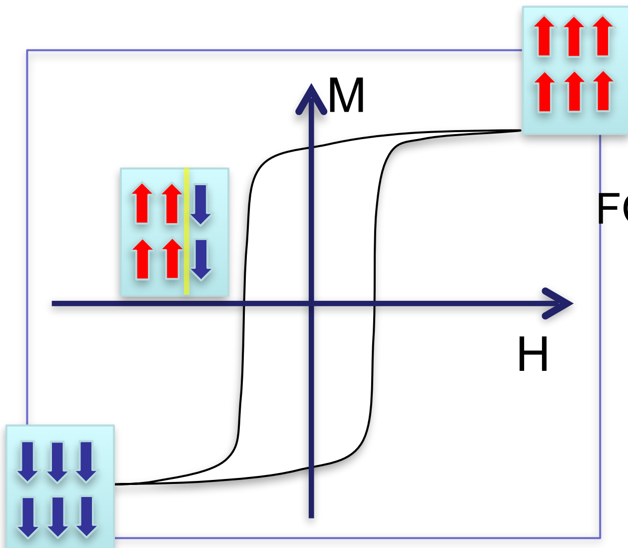

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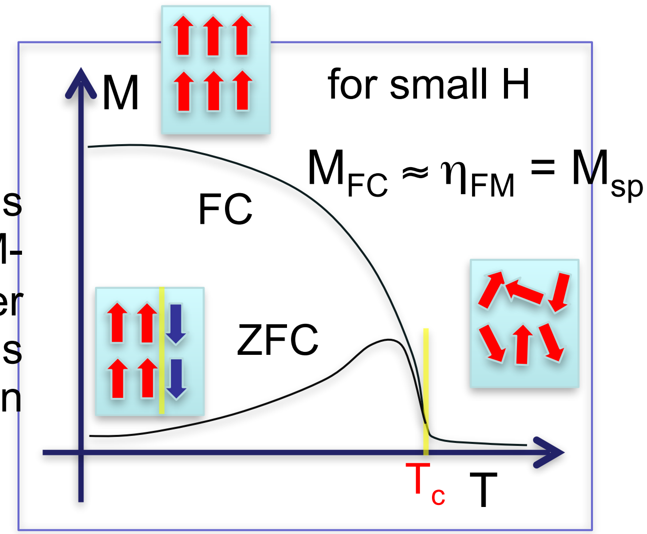

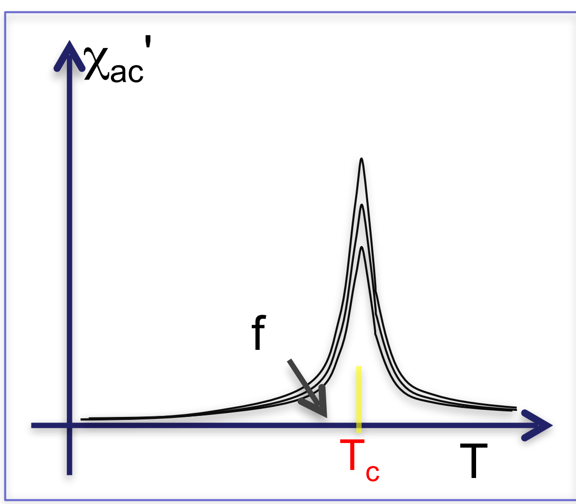

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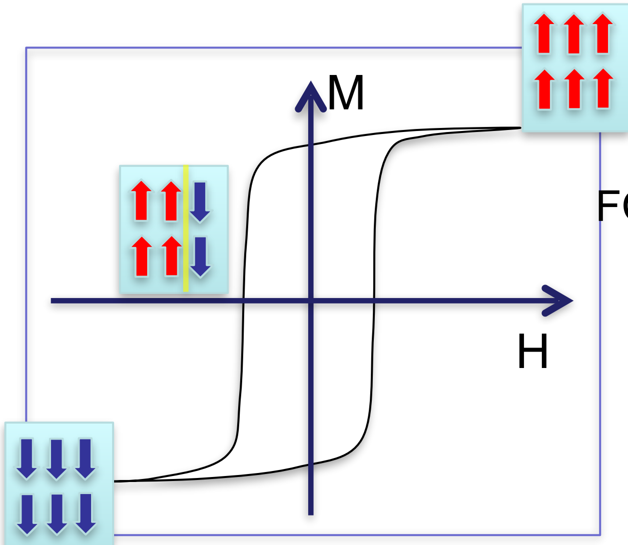

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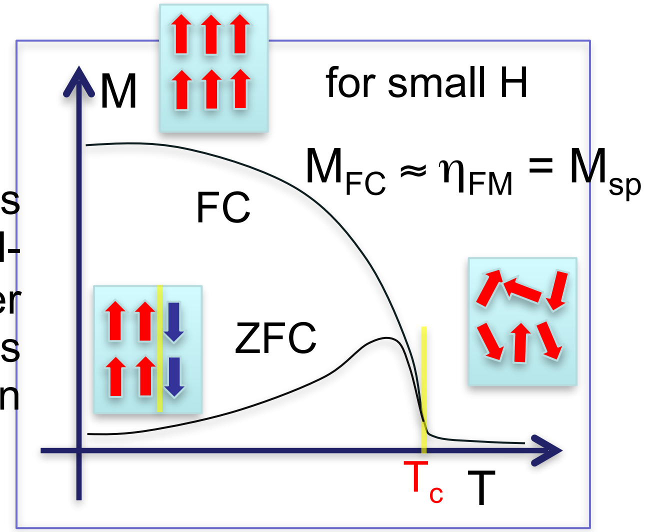
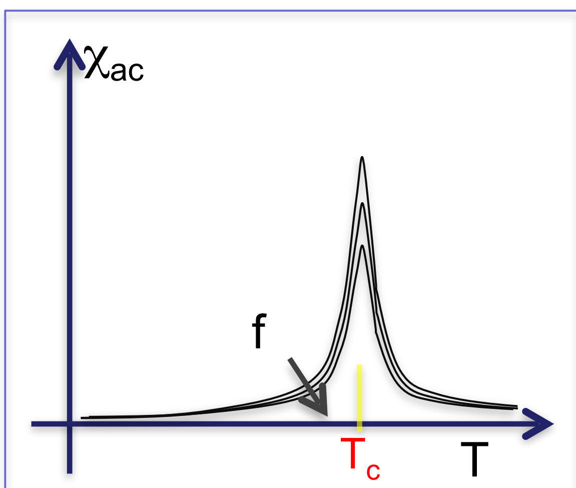
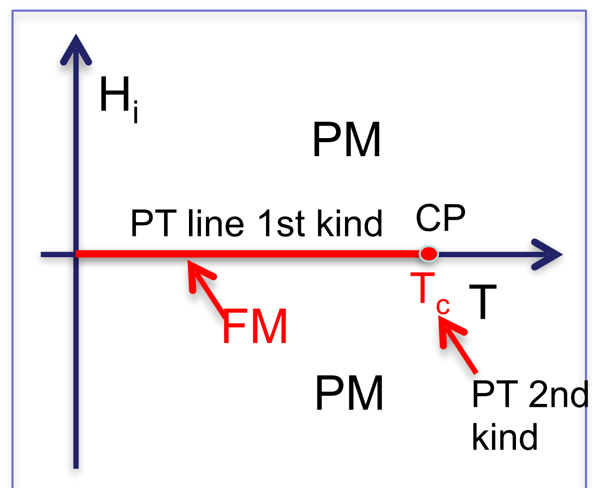




Phase diagram

inner field:

$\mathbf{H_i = H_a - N.M}$



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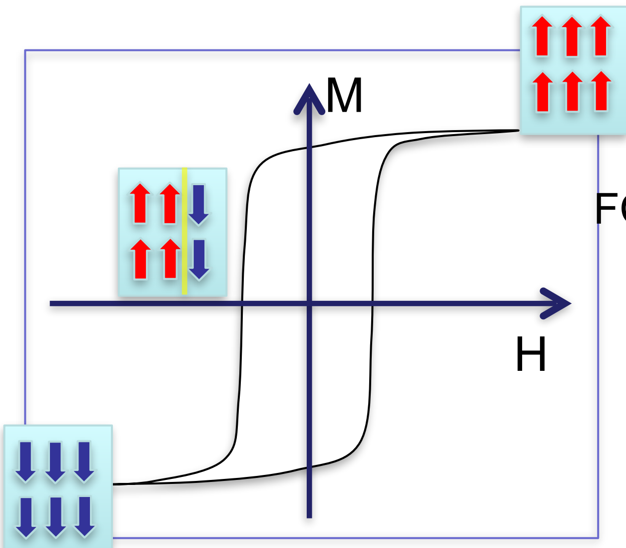

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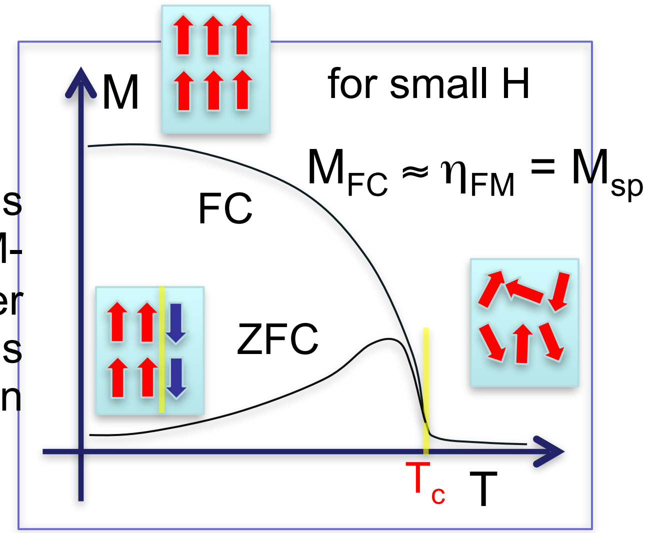
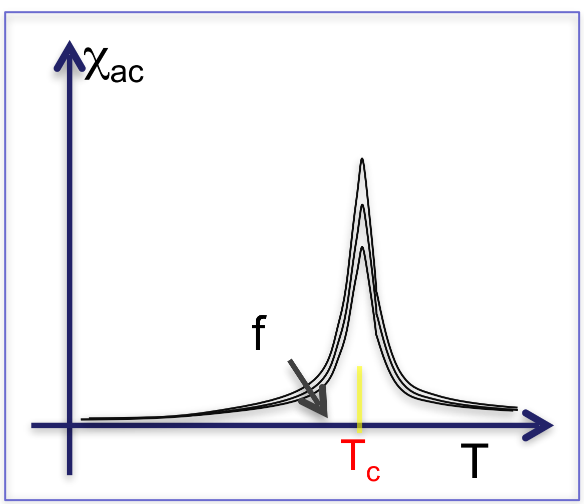
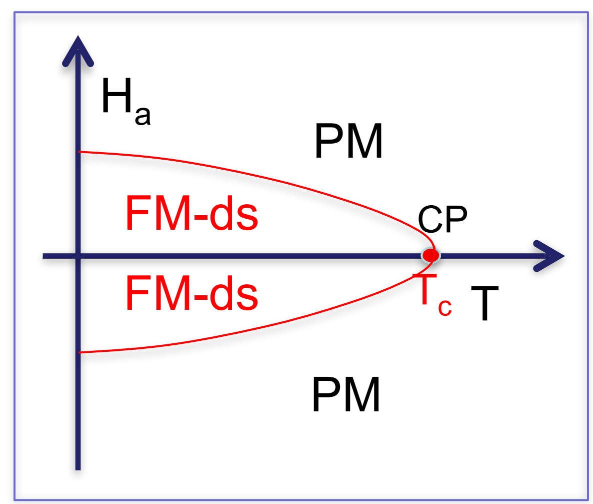
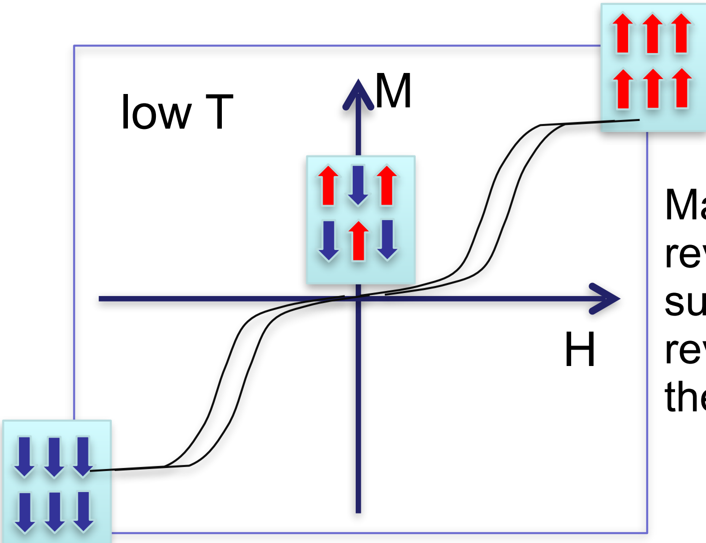




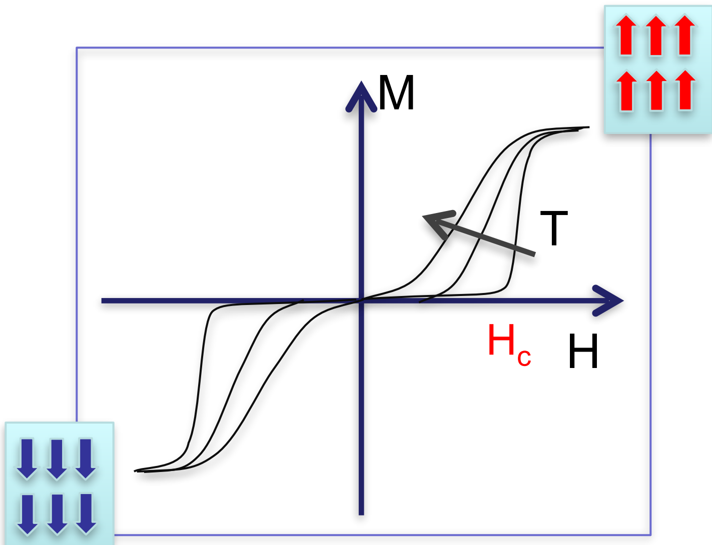


4. Antiferromagnet (MnO, CoO, NiO, ...)



Magnetization reversal by sublattice reversal and thermal fluct.

4. Antiferromagnet



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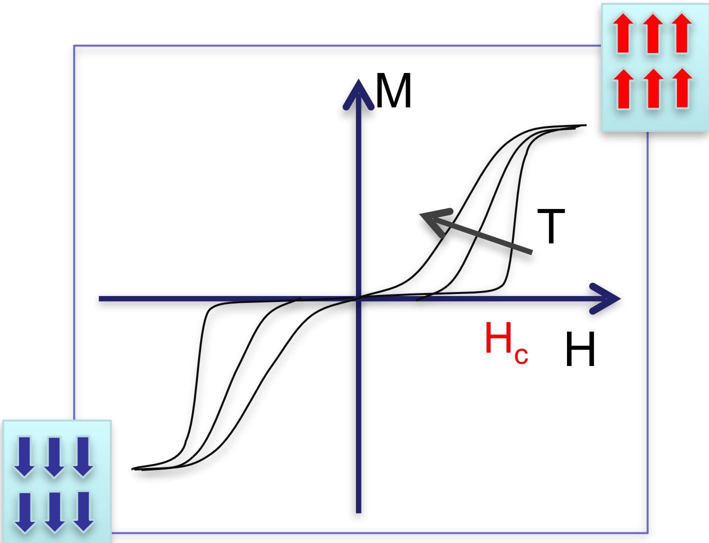

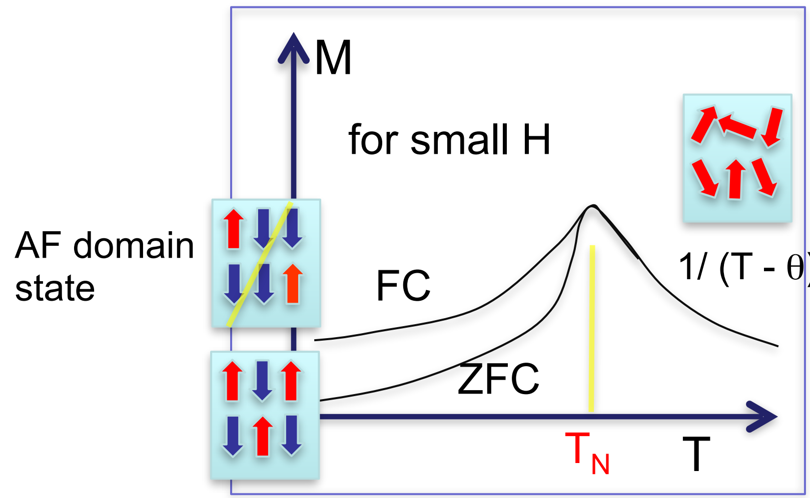

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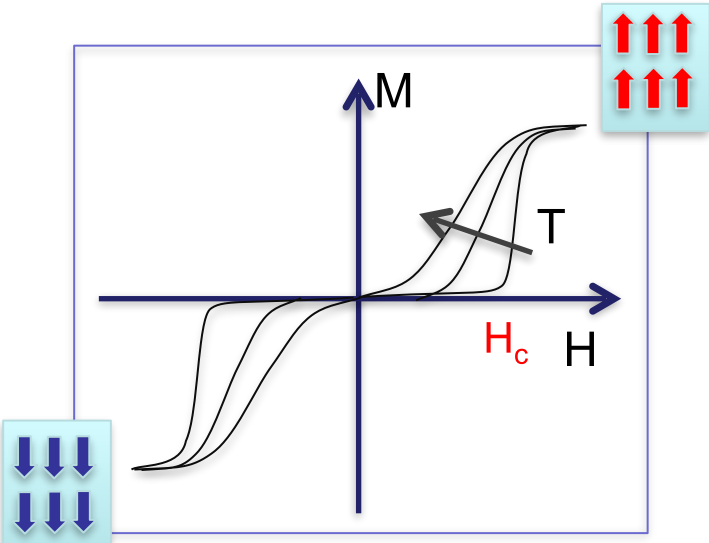
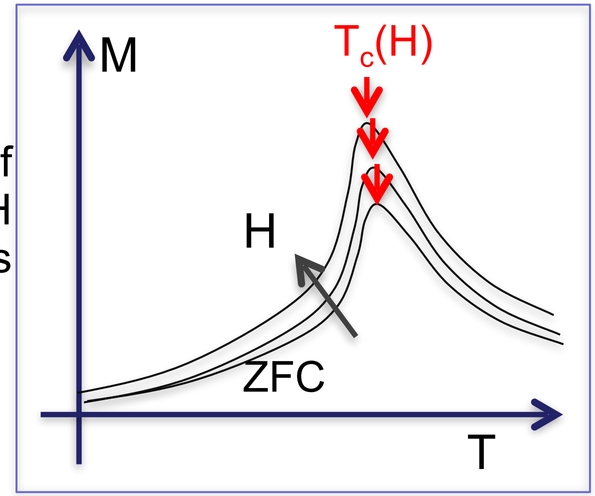


slight shift of
peak with H
for most AFs



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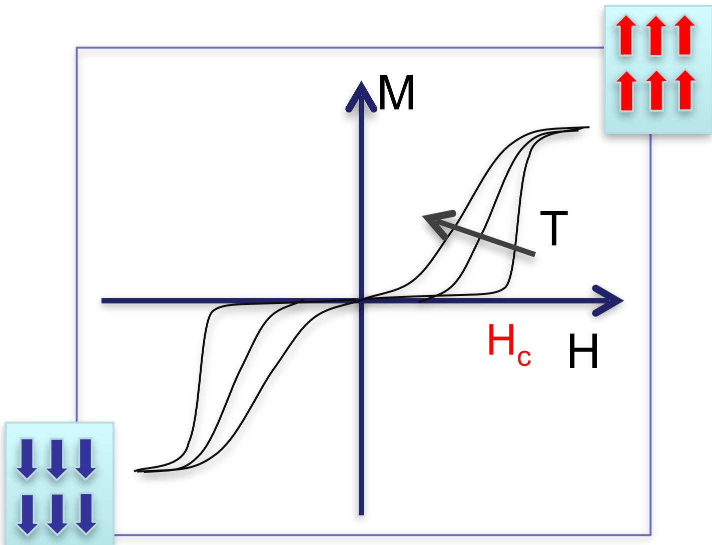

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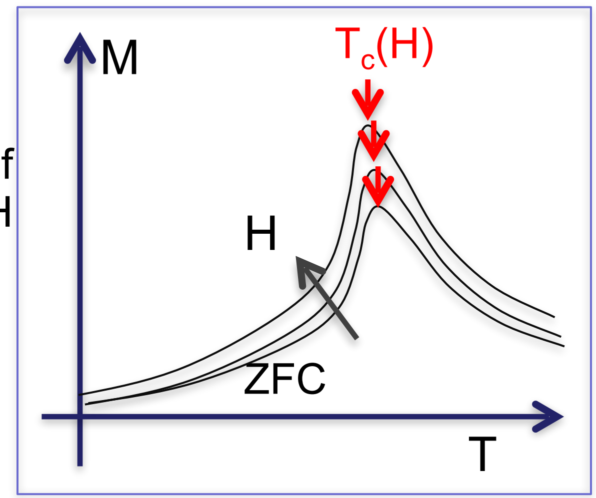

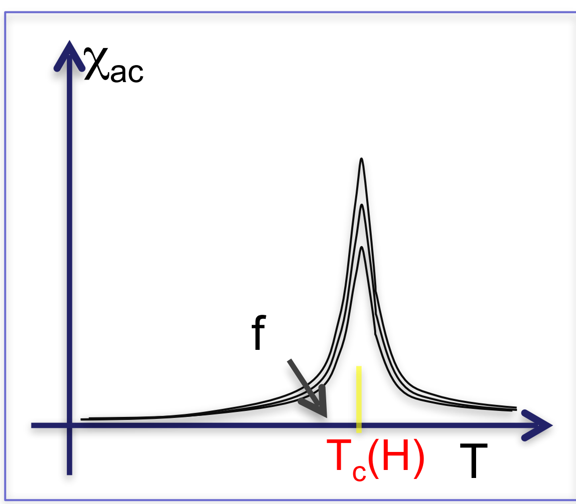

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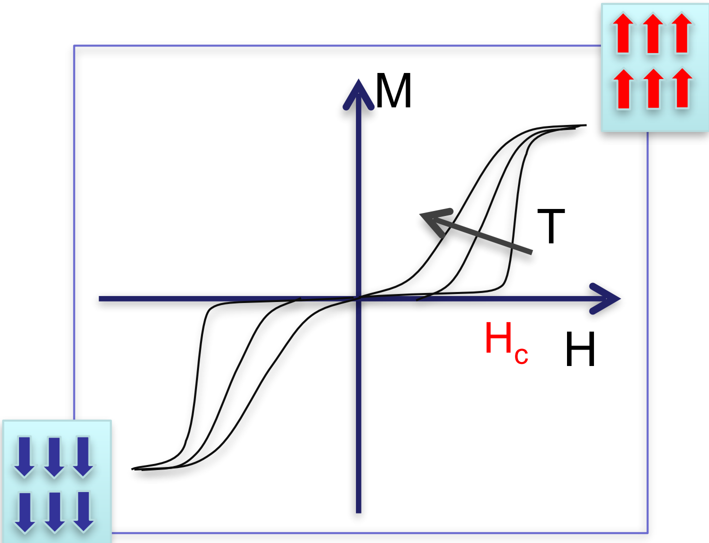

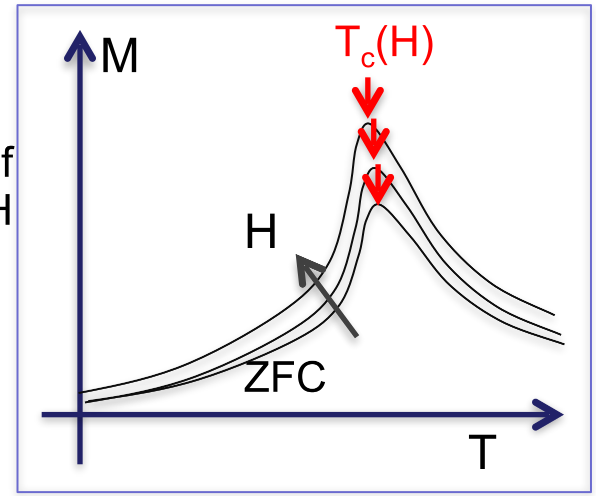

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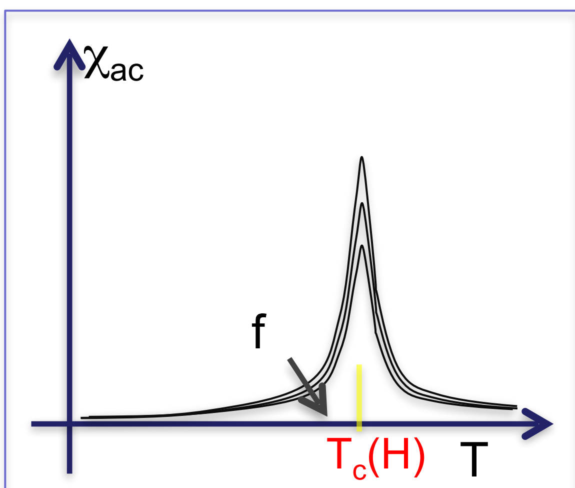
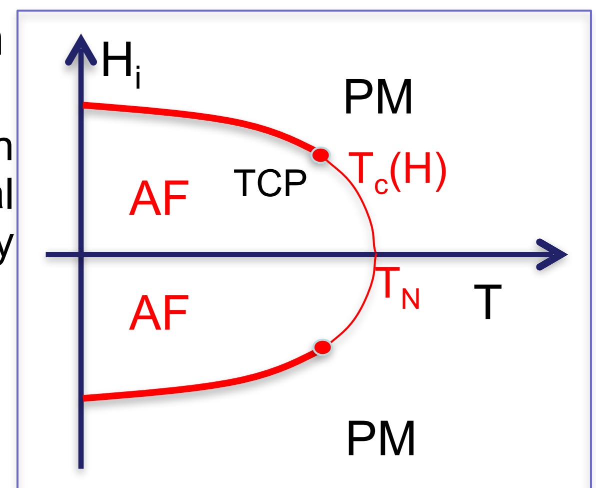


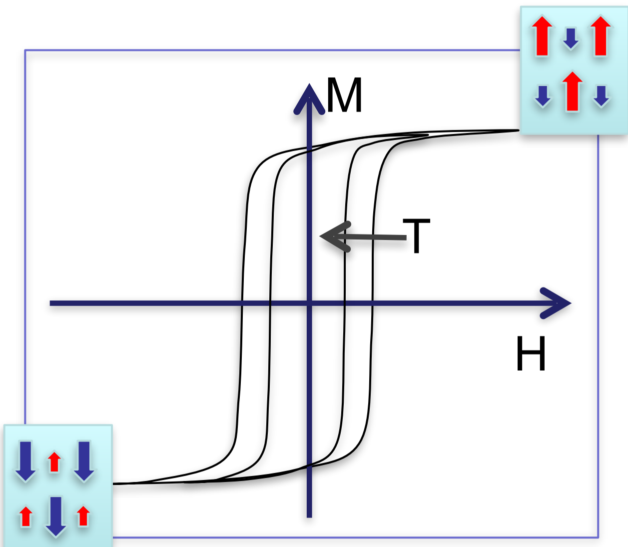
Phase diagram

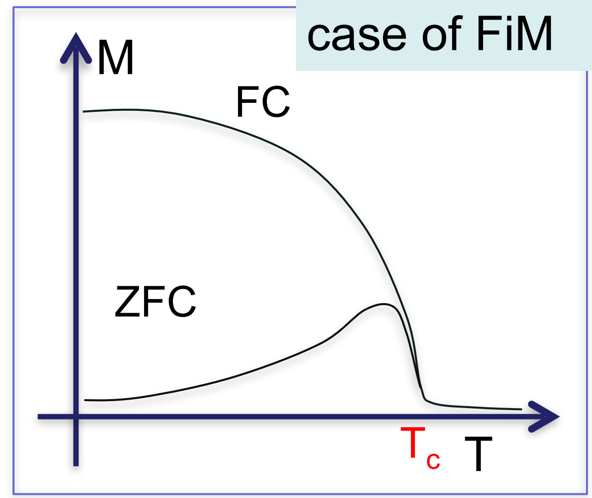
for AFs with high uniaxial anisotropy

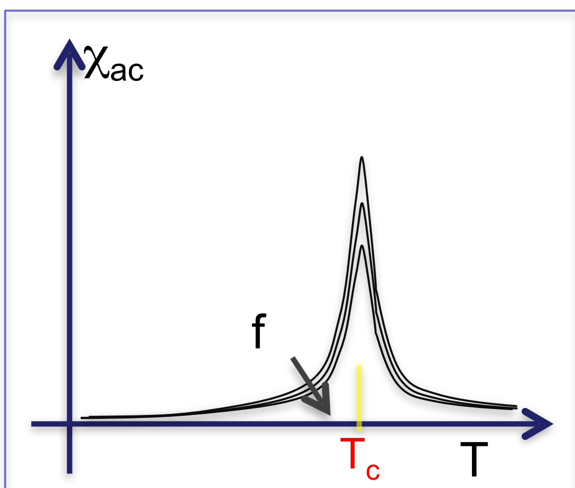


5. Ferrimagnet (γ-Fe_2O_3, ...) ≈ Ferromagnet

valid for the "simplest" case of FiM

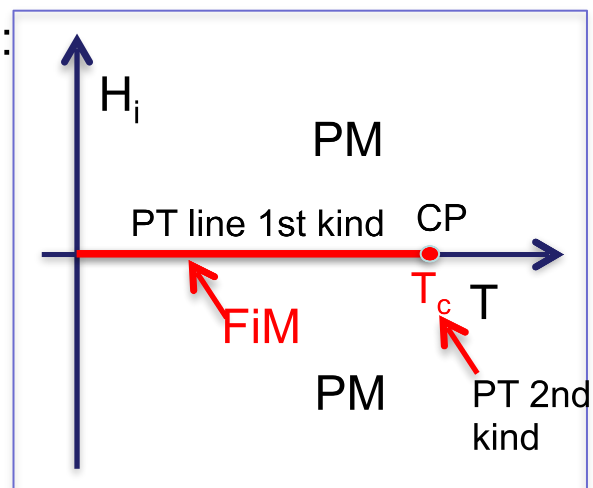






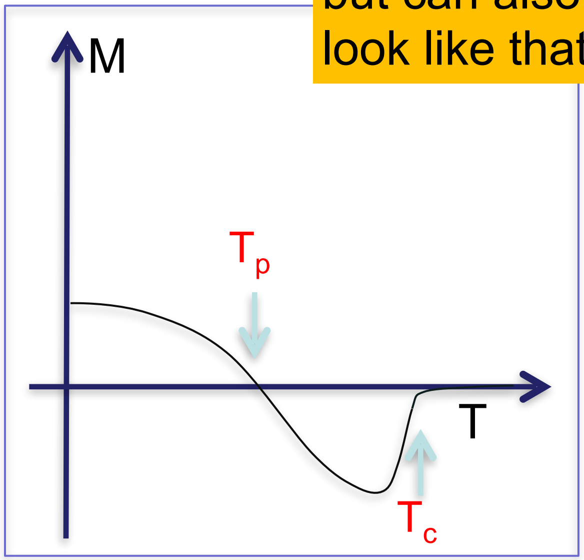
Phase diagram:

inner field:
$\mathbf{H_i = H_a - N.M}$



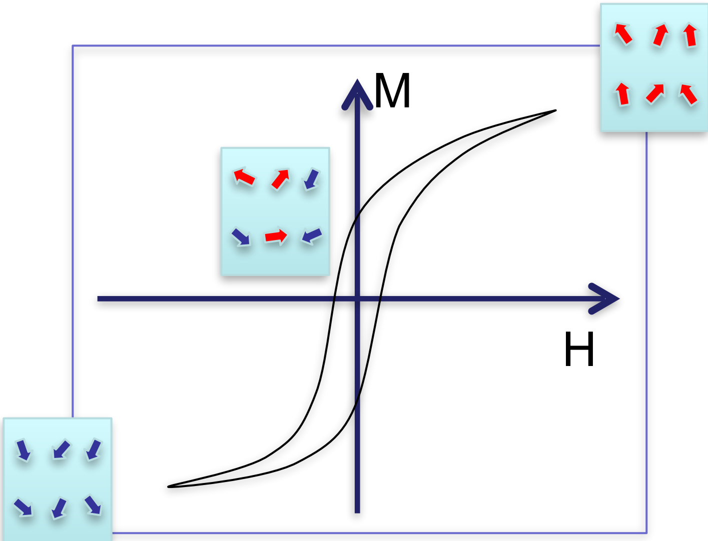
5. Ferrimagnet

but can also look like that:



T_p: compensation point due to differing sublattice behaviors vs. temperature

6. Spin glass (AuFe, ...)



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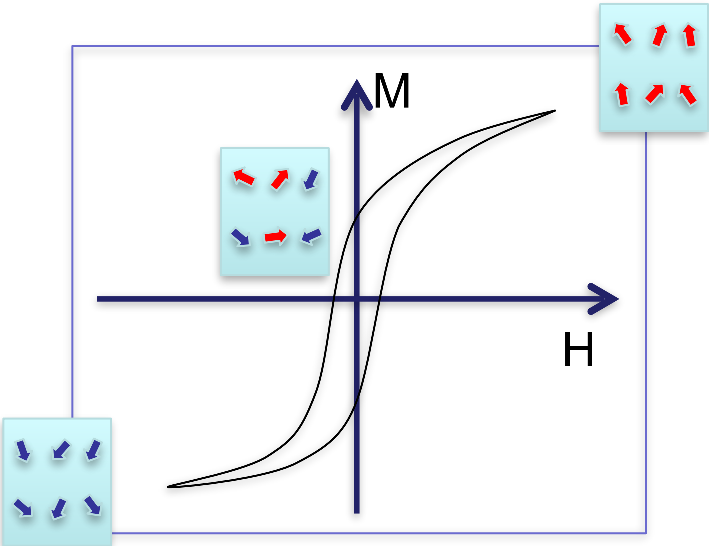

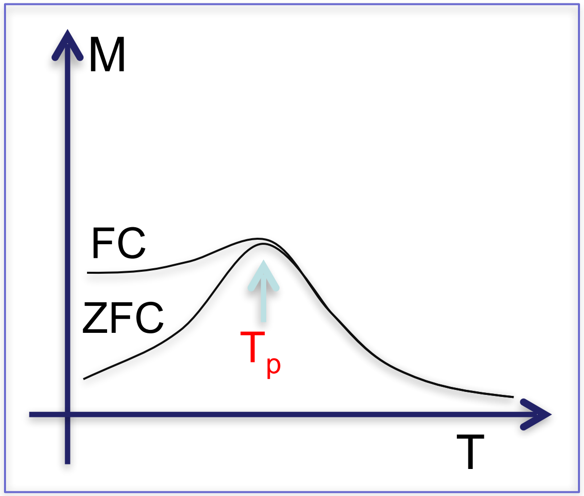

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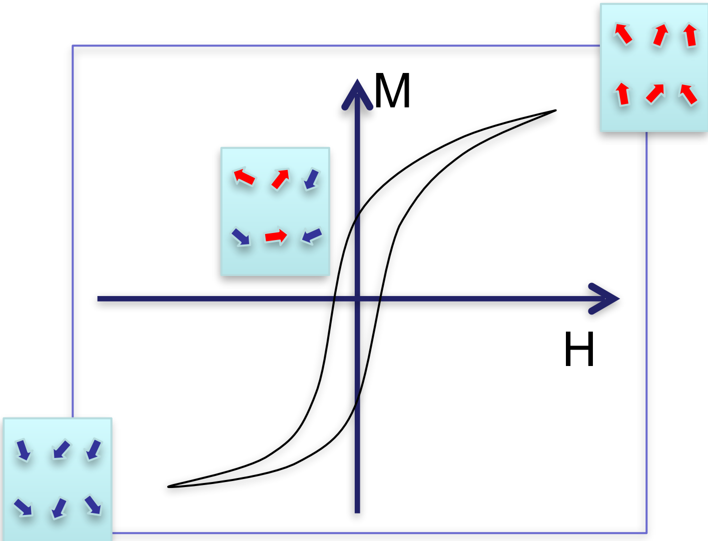

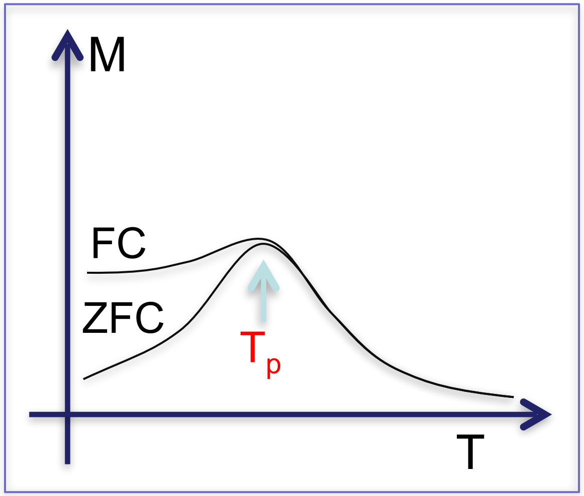

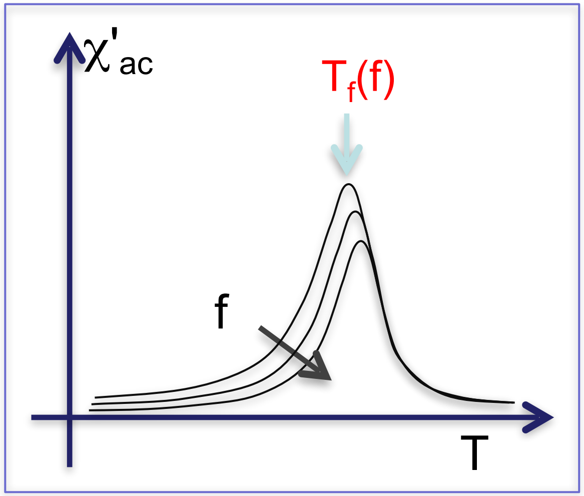

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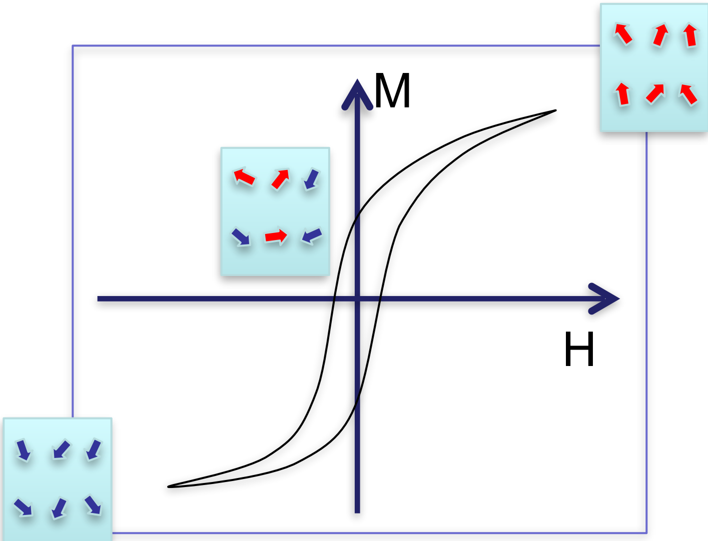
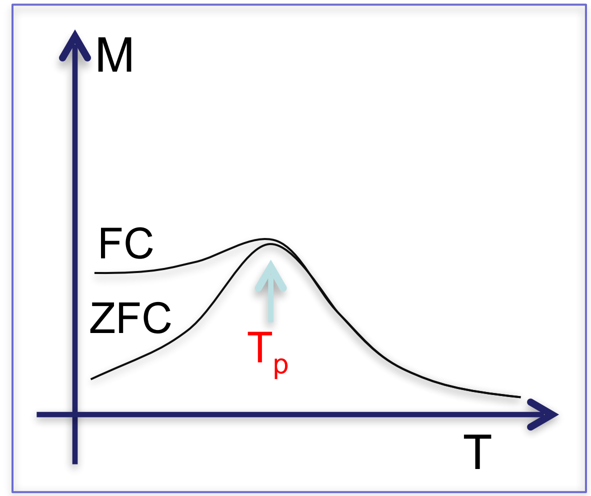
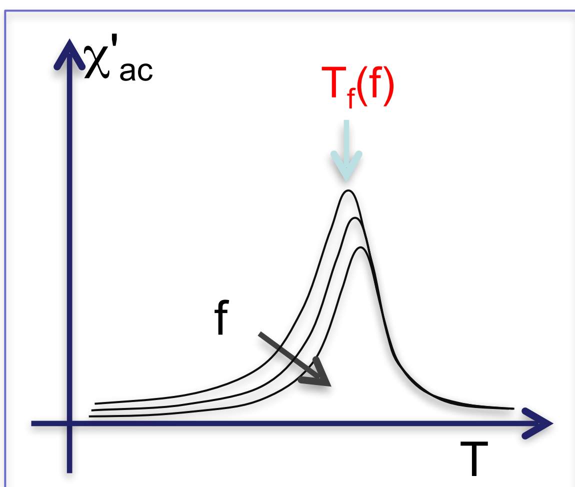
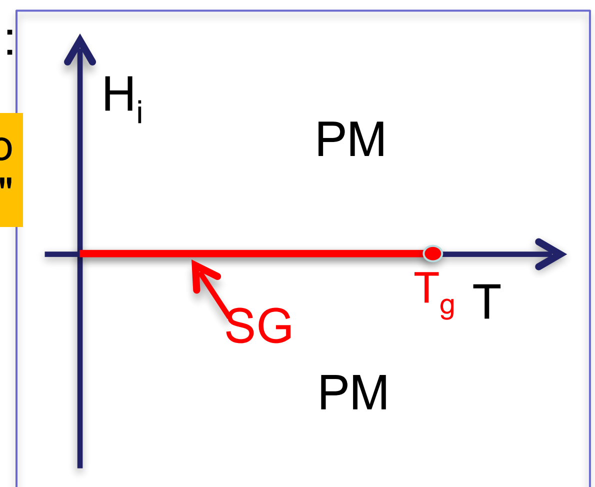




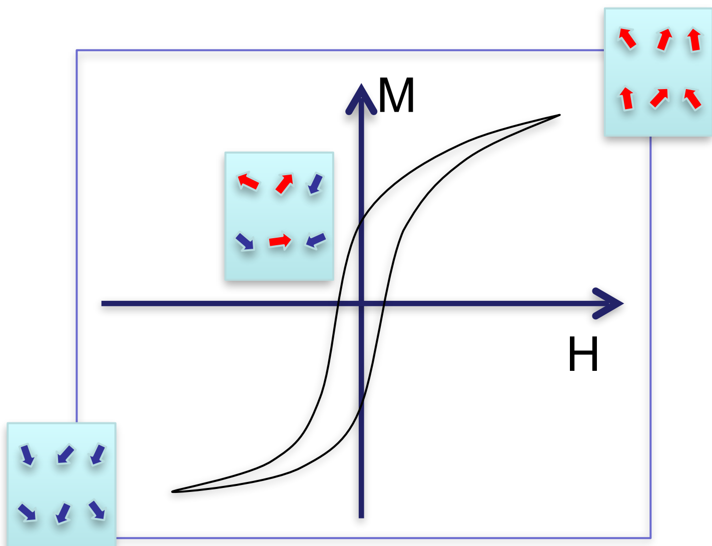


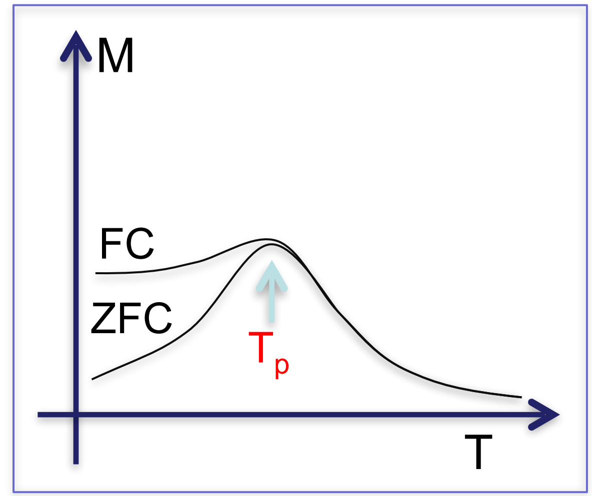
Phase diagram:

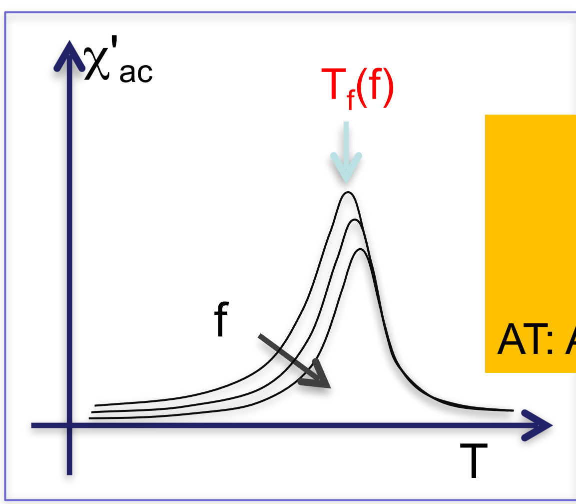
according to "droplet model"



6. Spin glass (AuFe, ...)



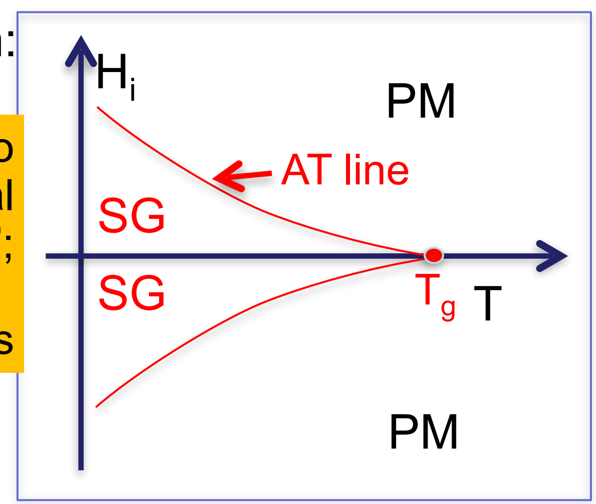




Phase diagram:

according to "hierarchical model";

AT: Almeida-Thouless



Thank you.