



Torino, Italy, UE

Measuring magnetism in the lab.



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WHAT ARE WE TALKING ABOUT TODAY?

- ▶ SQUID

- ▶ which means we'll spend a few words on VSM as well.

- ▶ Spin-polarised STM

- ▶ which means we'll spend a few words on MFM as well.

- ▶ BLS

- ▶ which means we'll spend very few words on FMR as well.

- ▶ Mössbauer spectroscopy

- ▶ Magneto-optics

SQUID

WHAT DOES IT STAND FOR?

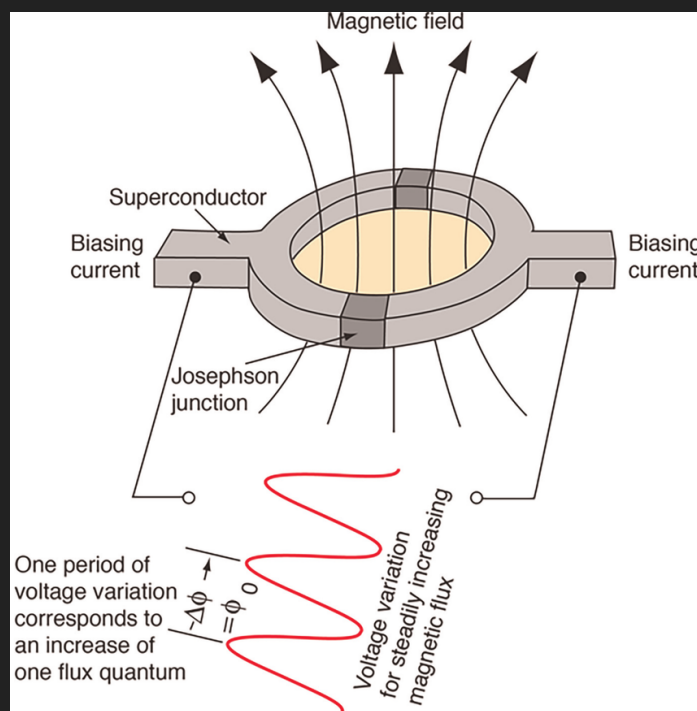
► Squid.



<https://www.antarctica.gov.au/about-antarctica/animals/squid/>
<http://hyperphysics.phy-astr.gsu.edu/hbase/Solids/Squid.html>

WHAT DOES IT STAND FOR?

- ▶ Squid.
- ▶ Or maybe **SQUID**?
- ▶ It's a Superconducting Quantum Interference Device.
- ▶ Seems boring.



<https://www.antarctica.gov.au/about-antarctica/animals/squid/>
<http://hyperphysics.phy-astr.gsu.edu/hbase/Solids/Squid.html>

ONE STEP BACK: MAGNETOMETERS

An instrument that measures the magnetisation of a magnetic sample as a function of H .

ONE STEP BACK: MAGNETOMETERS

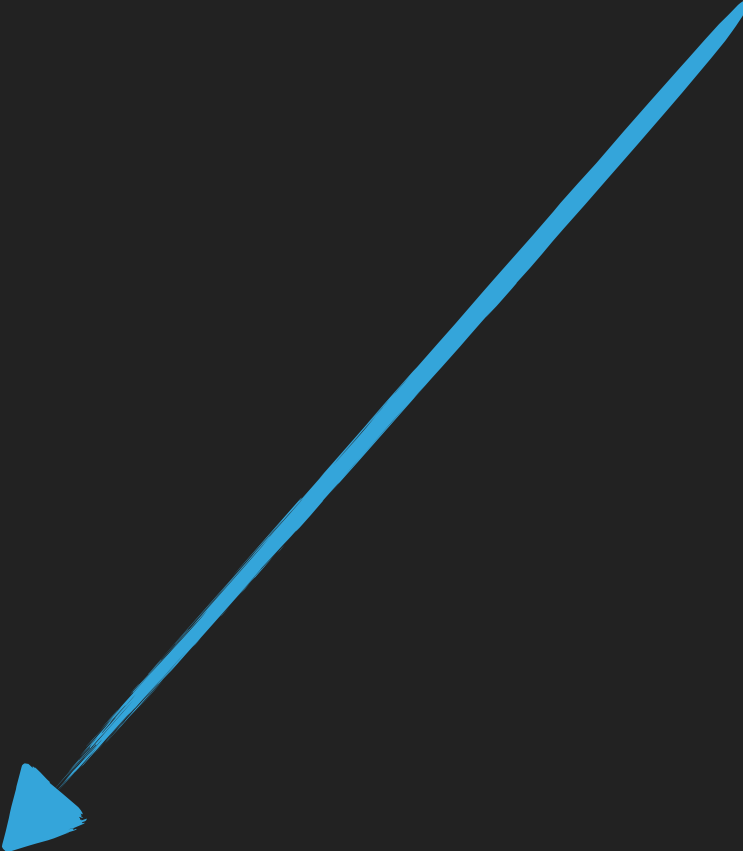
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WRONG on so many levels!

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NO! It measures the magnetic **moment**.

ONE STEP BACK: MAGNETOMETERS

An instrument that measures the magnetisation of a magnetic sample as a function of H .

WRONG on so many levels!

NO! It measures the magnetic **moment**.

- The field is generated by a coil or a magnet: so it's **B**.
- The measurement is in open-circuit: so **$H_d \neq 0$** .
- And normally you don't have the slightest idea on how to calculate **H_d** .
- So what you actually mean is **H_a** , but you assume that **$H \sim H_a$** .
- And then there are magnetic materials everywhere.

BUILDING BLOCKS

- ▶ A means of **generating a magnetic field** of the desired intensity.
- ▶ A means of **measuring the applied magnetic field**.
- ▶ A means of controlling any additional quantity of interest (temperature, orientation of the sample with respect to the applied field, etc.).
- ▶ A means of **measuring the magnetic moment** of the sample (or at least **one of its components**).

TYPICAL WAYS TO GENERATE MAGNETIC FIELDS IN MAGNETOMETERS



Electromagnets

up to 2 – 3 T (20 – 30 kOe)

non-linear (closed-loop feedback required)

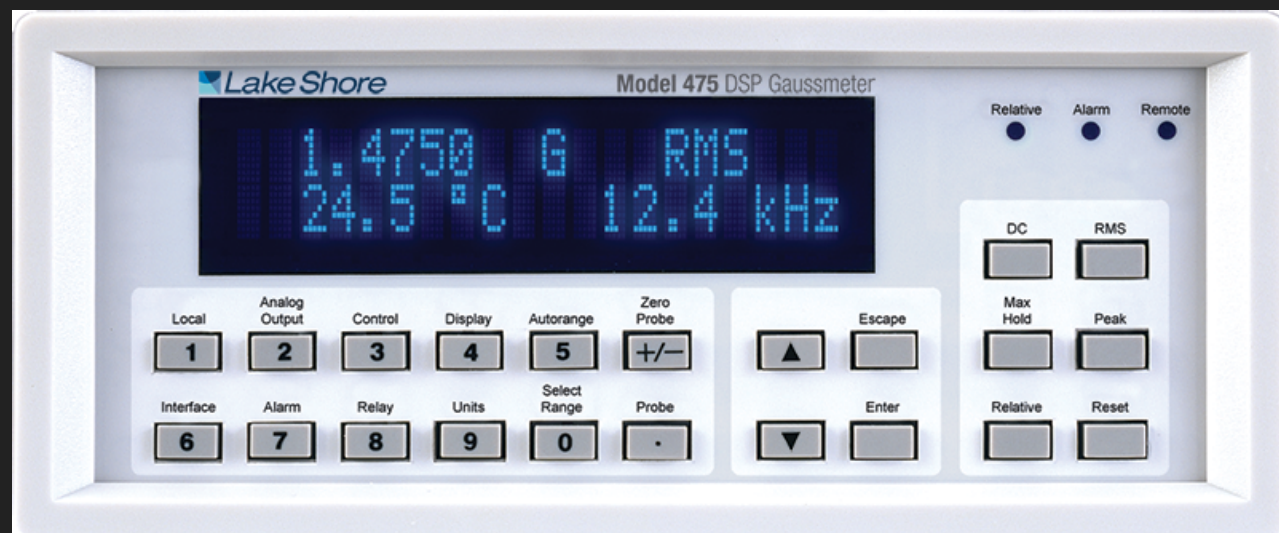
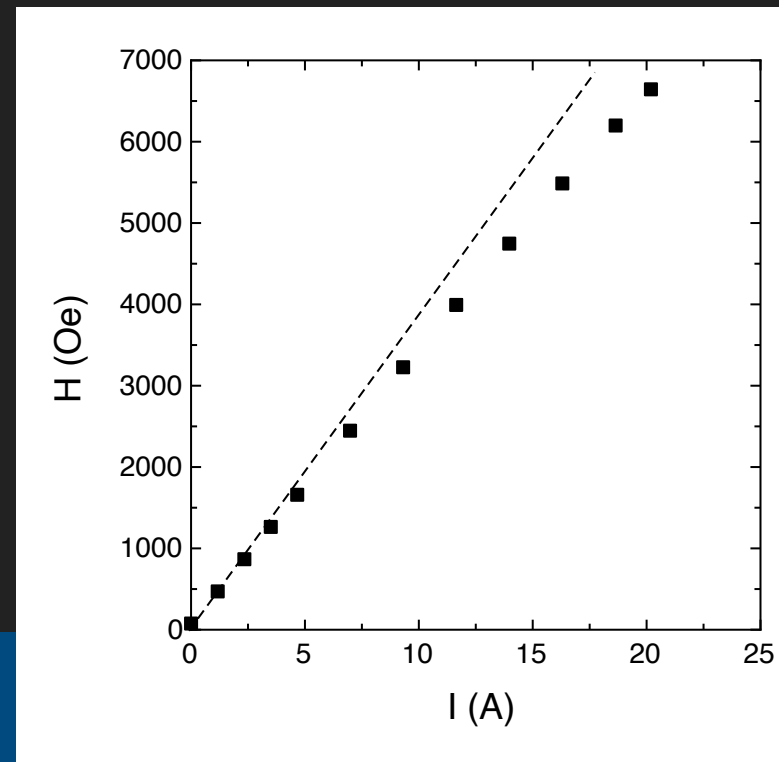
measurement of applied field easy

typically used in VSM

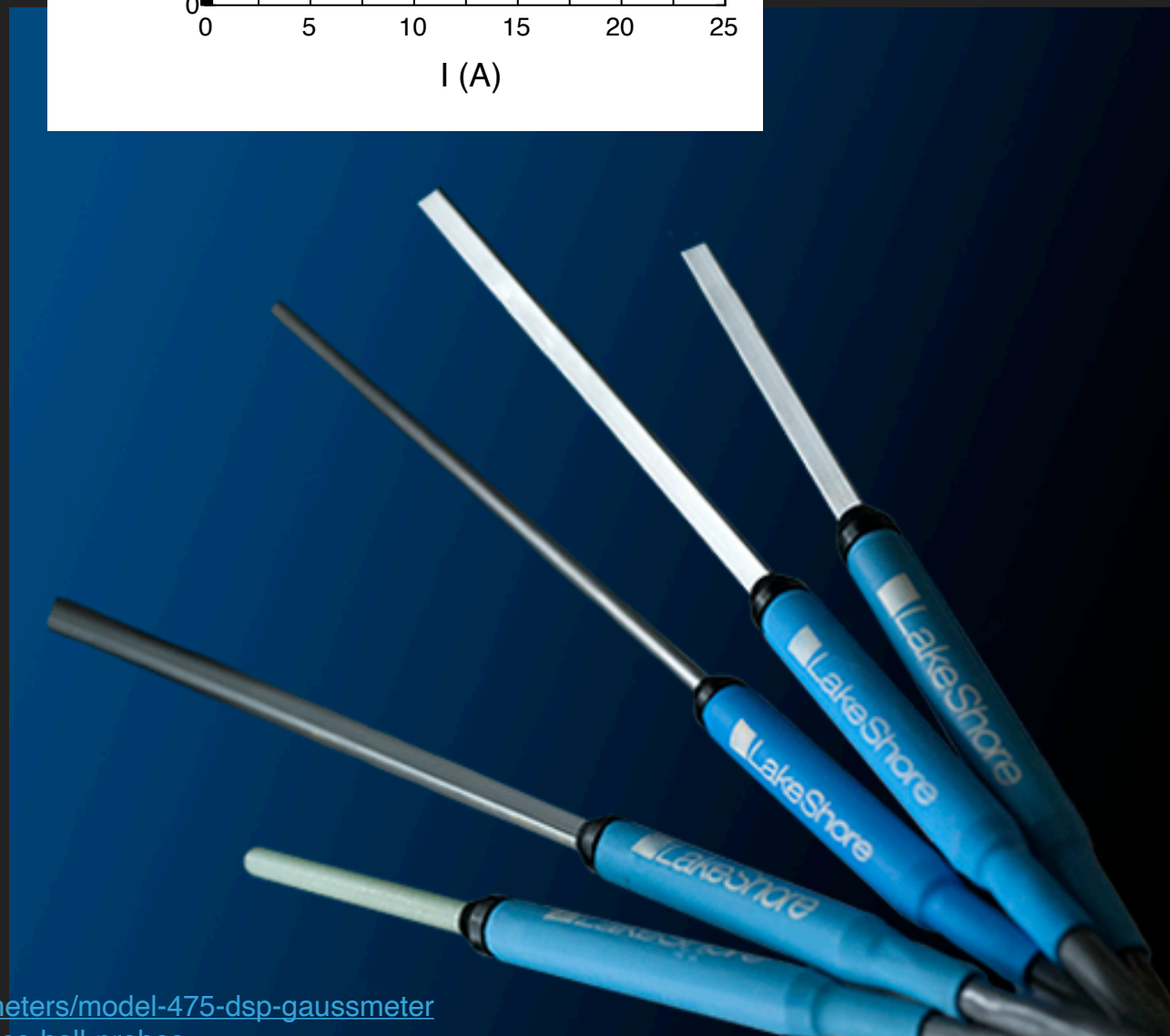
Superconducting solenoids
up to several T (< 20 T, < 200 kOe)
almost linear (one-time calibration
required) but with hysteresis
measurement of applied field hard or
impossible
typically used in SQUID and SQUID/VSM



FIELD MEASUREMENT: ELECTROMAGNETS



A gaussmeter with
transverse and longitudinal
Hall probes

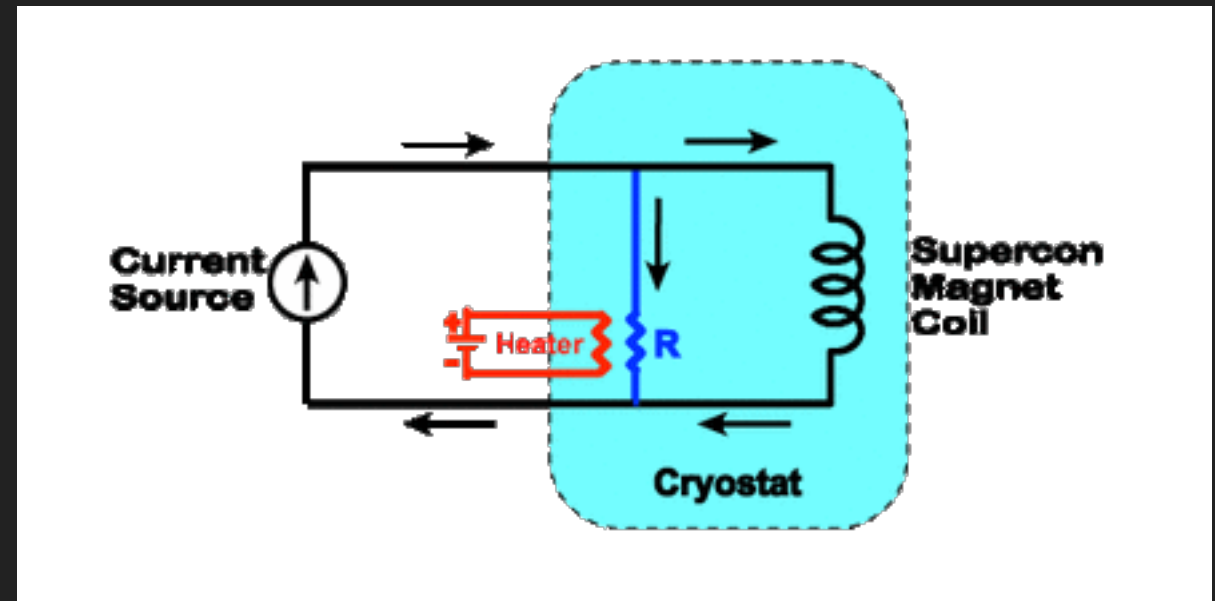


<https://commons.wikimedia.org/wiki/File:AGEM5520.jpg>

<https://www.lakeshore.com/products/categories/overview/magnetic-products/gaussmeters-teslameters/model-475-dsp-gaussmeter>

<https://www.lakeshore.com/products/categories/overview/magnetic-products/hall-probes/400-series-hall-probes>

FIELD MEASUREMENT: SUPERCONDUCTING SOLENOIDS

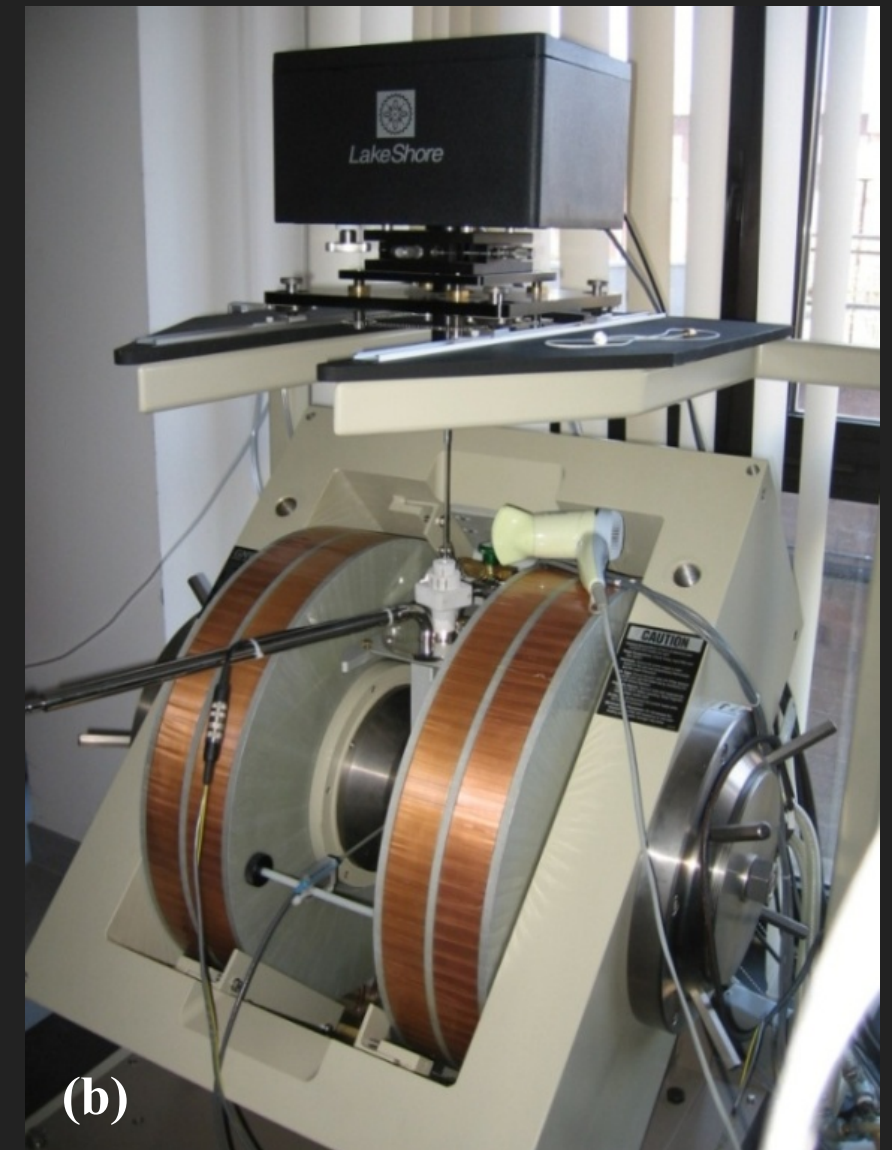
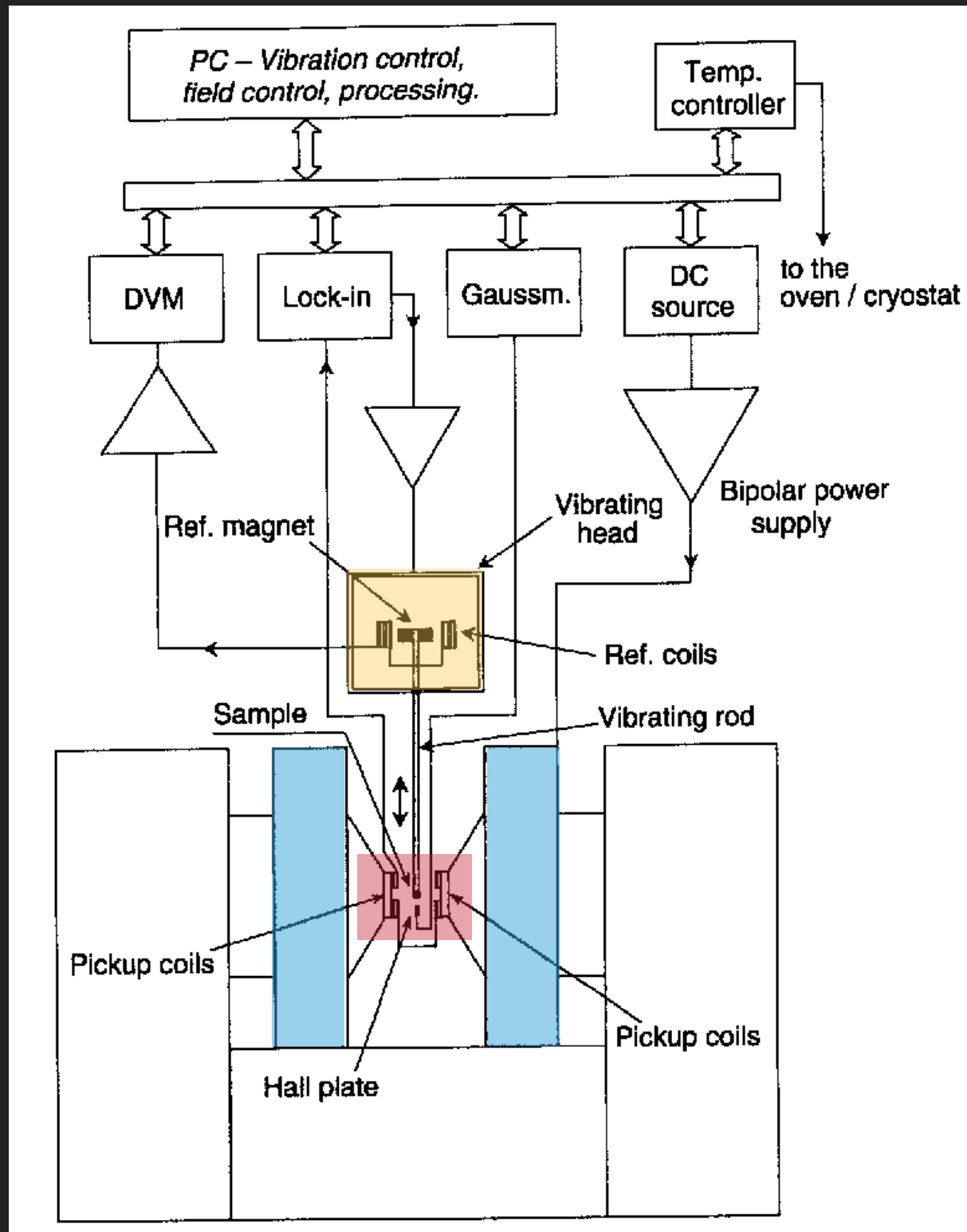


<https://cryomagnetics.com/products/high-field-nb3sn-solenoids/>
<https://mriquestions.com/how-to-ramp.html>
<https://accusrc.com/product-Agilent-HP-3468A-4727>

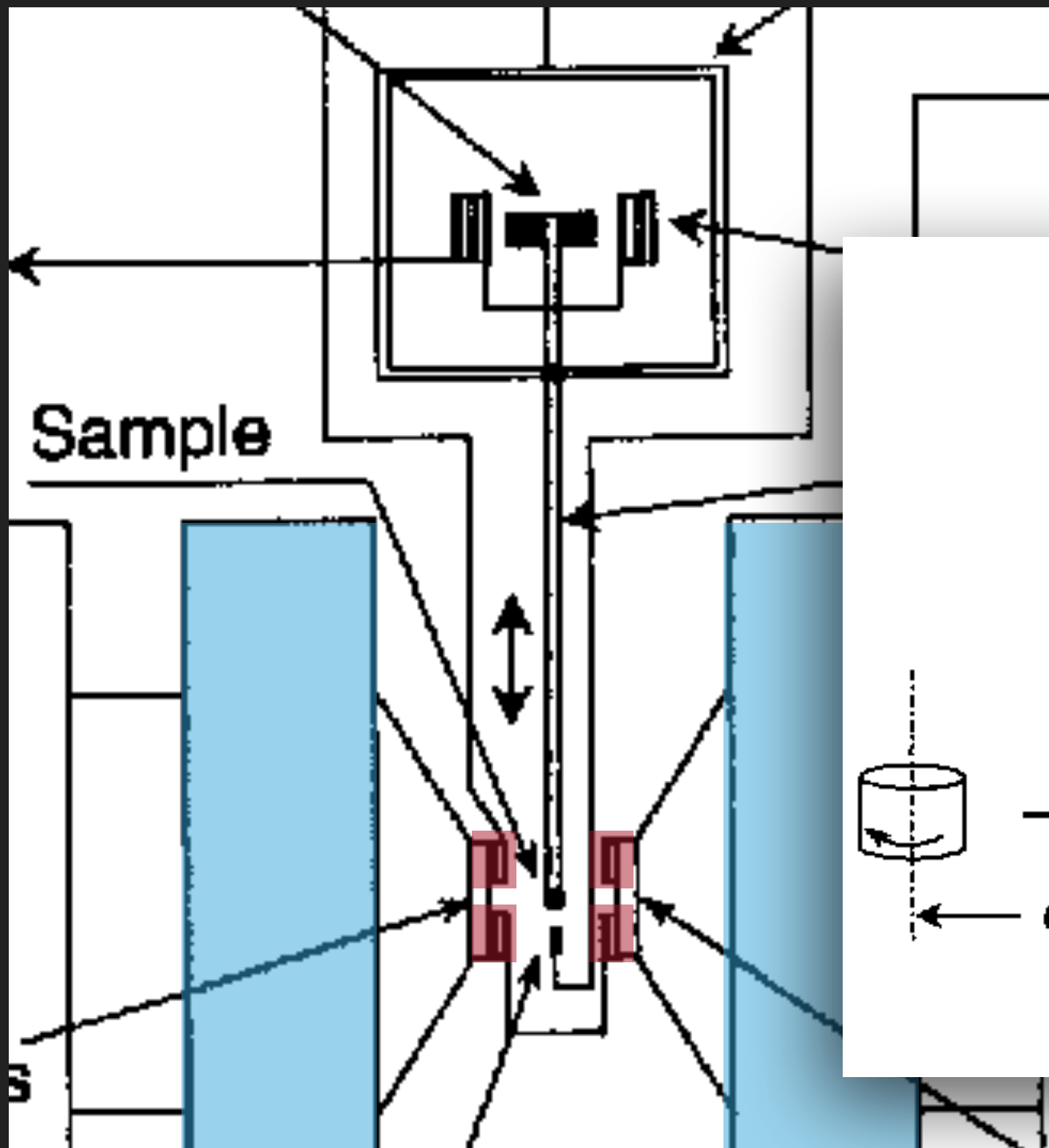
A voltmeter or an ammeter (the calibrated coil factor must be known).
And then there's the coil hysteresis...

MEASURING THE MAGNETIC MOMENT: VSM

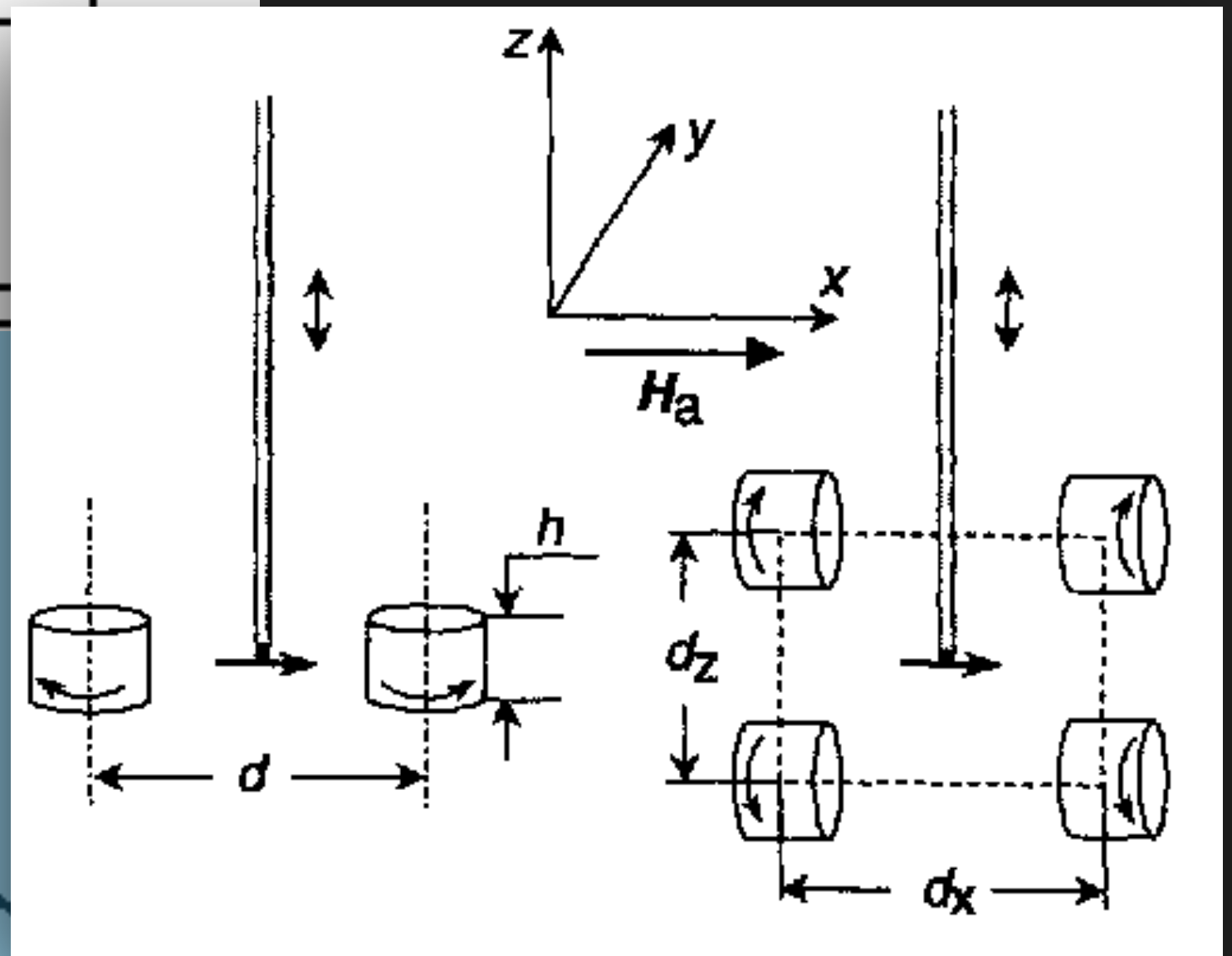
► Vibrating Sample Magnetometer.



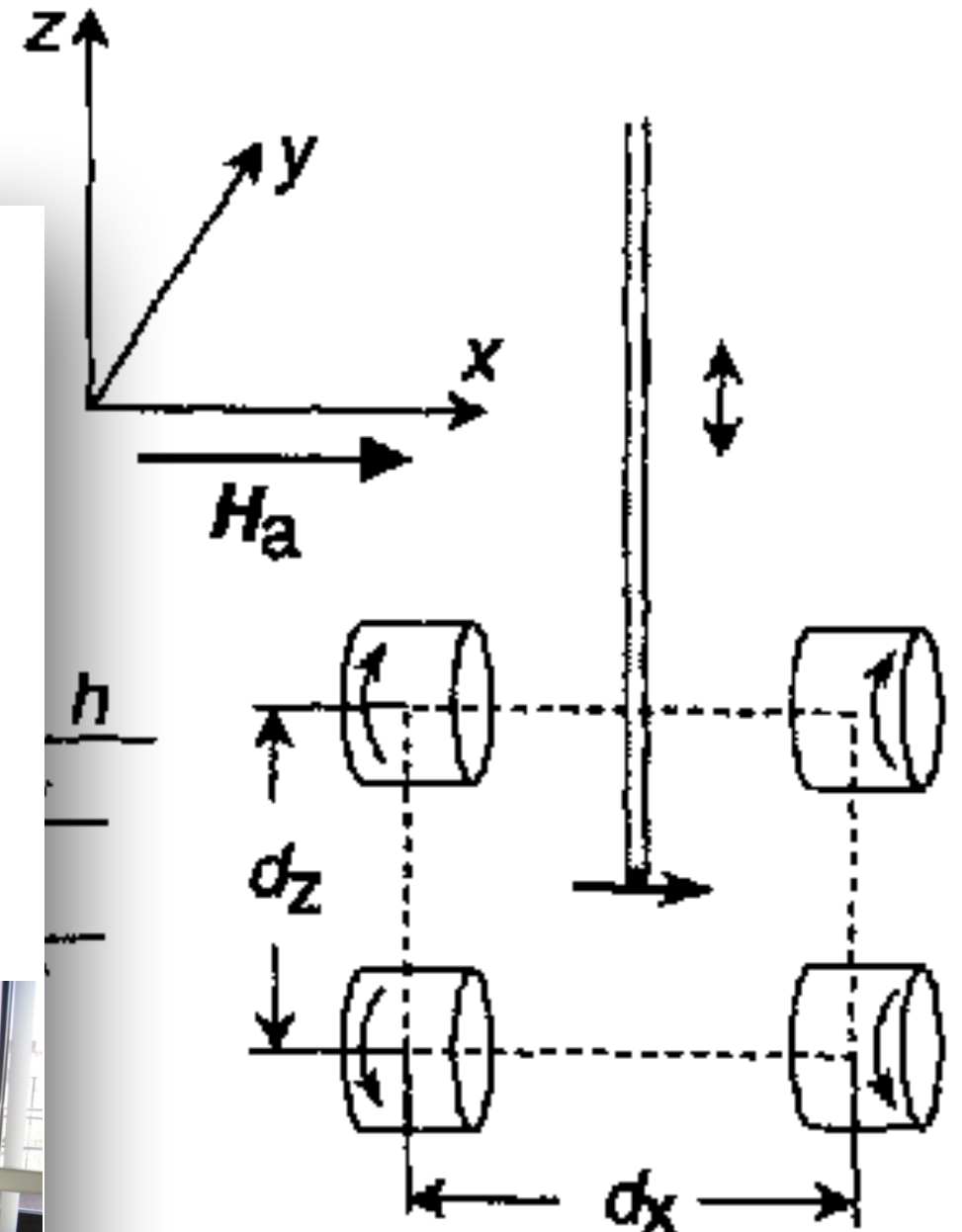
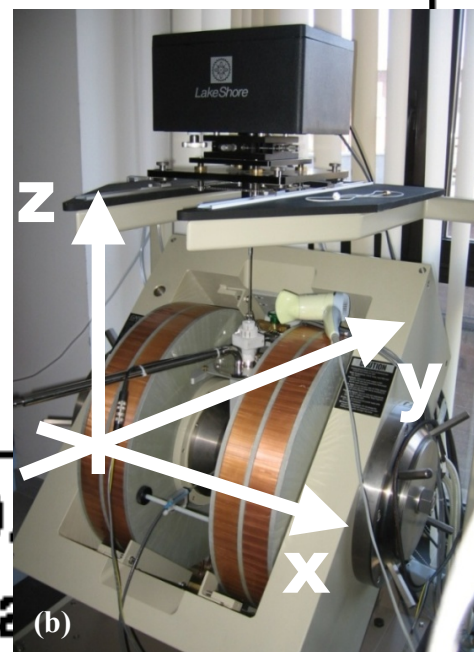
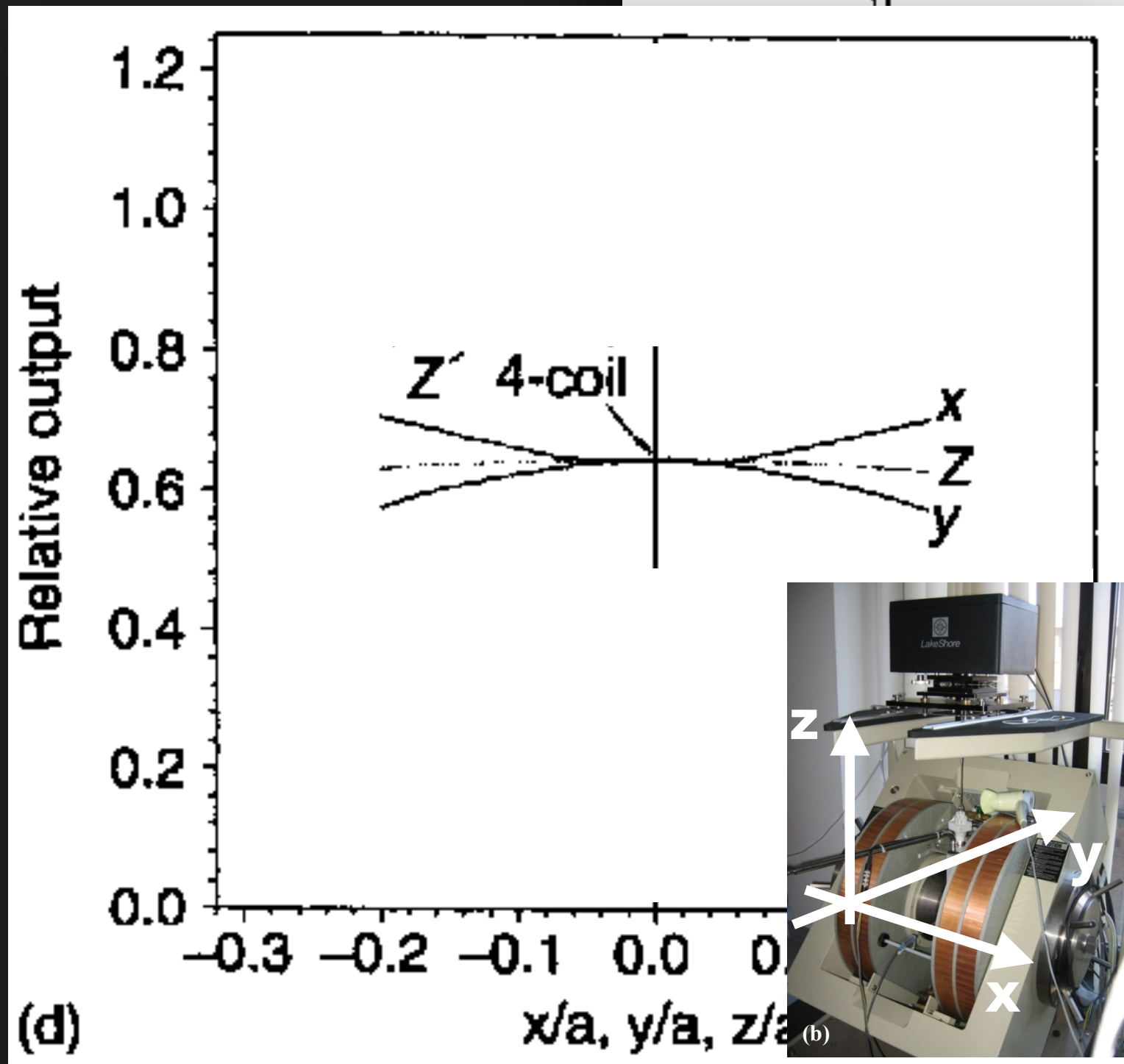
MEASURING THE MAGNETIC MOMENT: VSM



$$output = f(\nu, A, m, x, y, z)$$



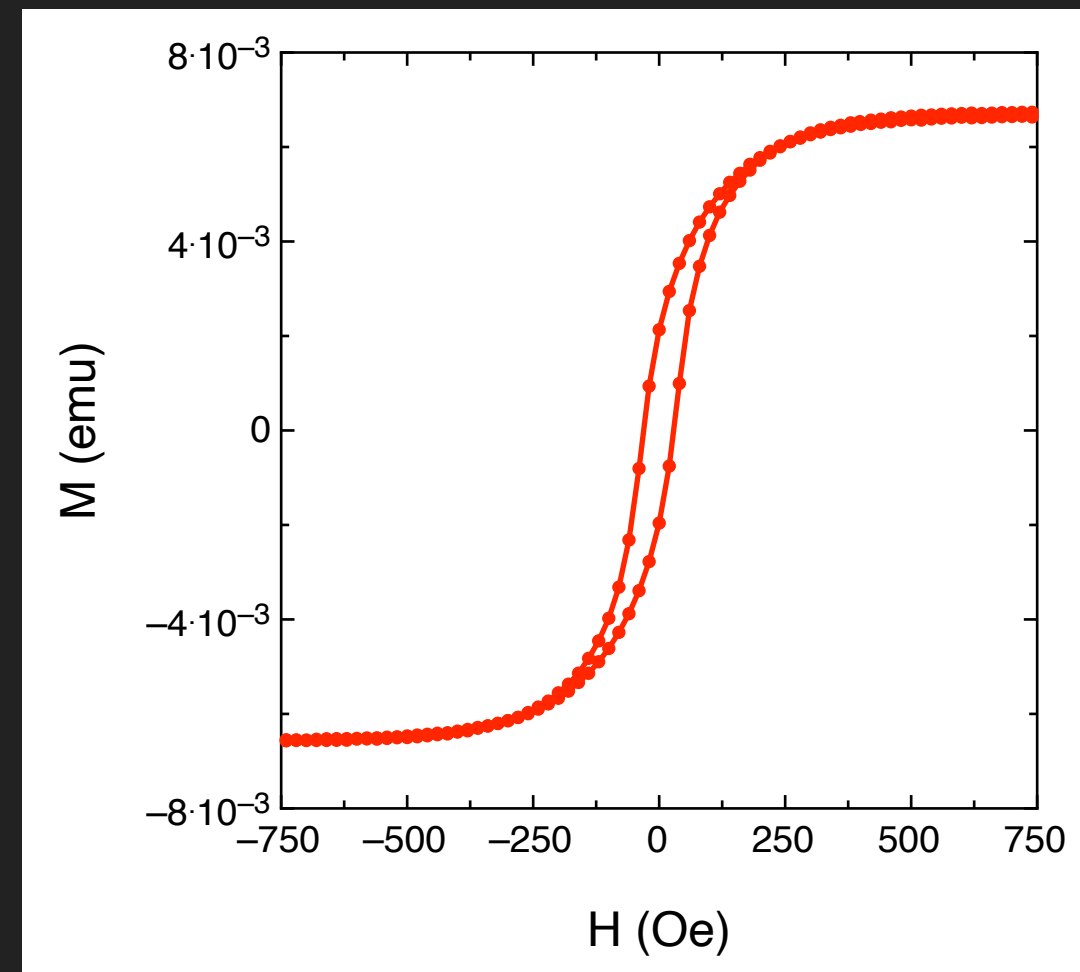
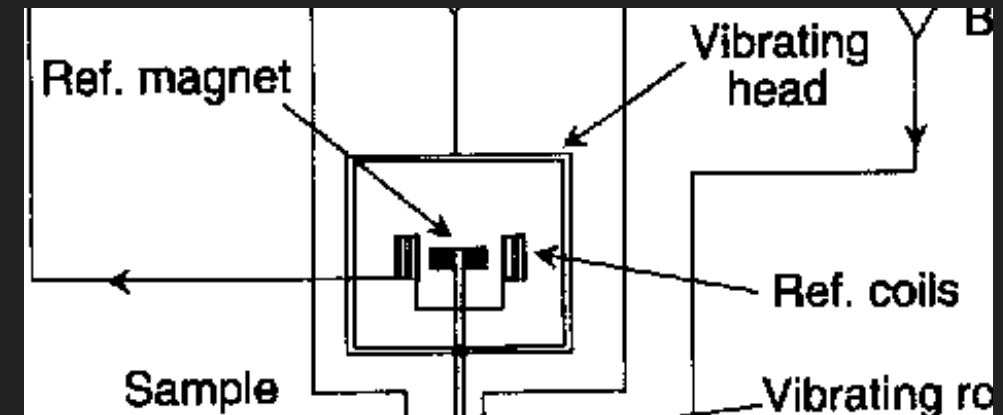
MEASURING THE MAGNETIC MOMENT: VSM



MEASURING THE MAGNETIC MOMENT: VSM

- ▶ ν (vibration frequency): defined and fixed.
- ▶ A (vibration amplitude): defined and fixed (feedback loop on vibrating head).
- ▶ x, y, z : adjusted by user optimising output value.
- ▶ **Calibration**: find output (V) for known m .
- ▶ **Measurement**: use calibration constant for converting V into Am^2 or emu for unknown m , one point (value of H) at a time.

$$\text{output} = f(\nu, A, m, x, y, z)$$



MEASURING THE MAGNETIC MOMENT: SQUID

Indeed, it's a VSM or an extraction magnetometer, where the amplifier connected to the pick-up coils is replaced by a SQUID.

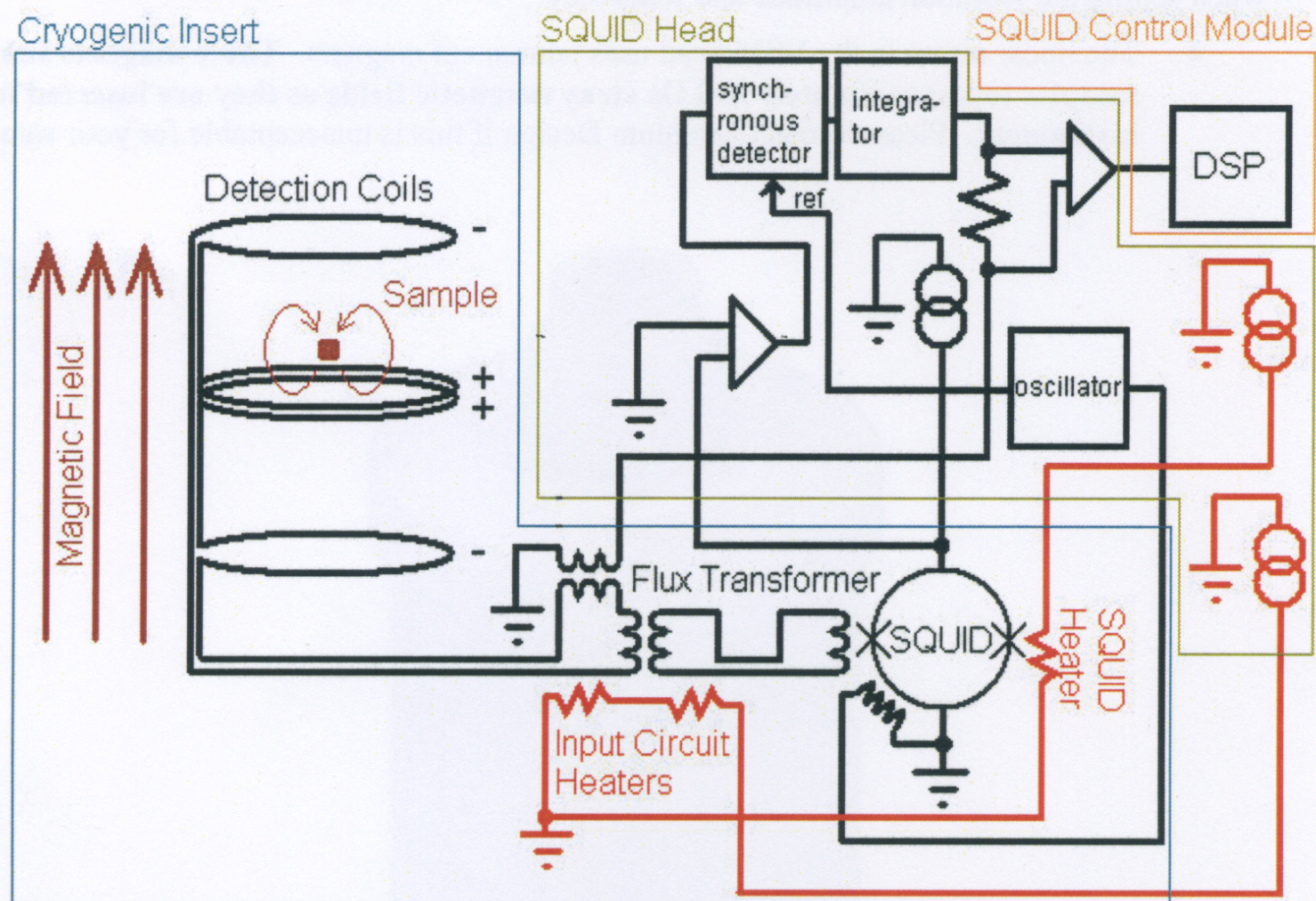
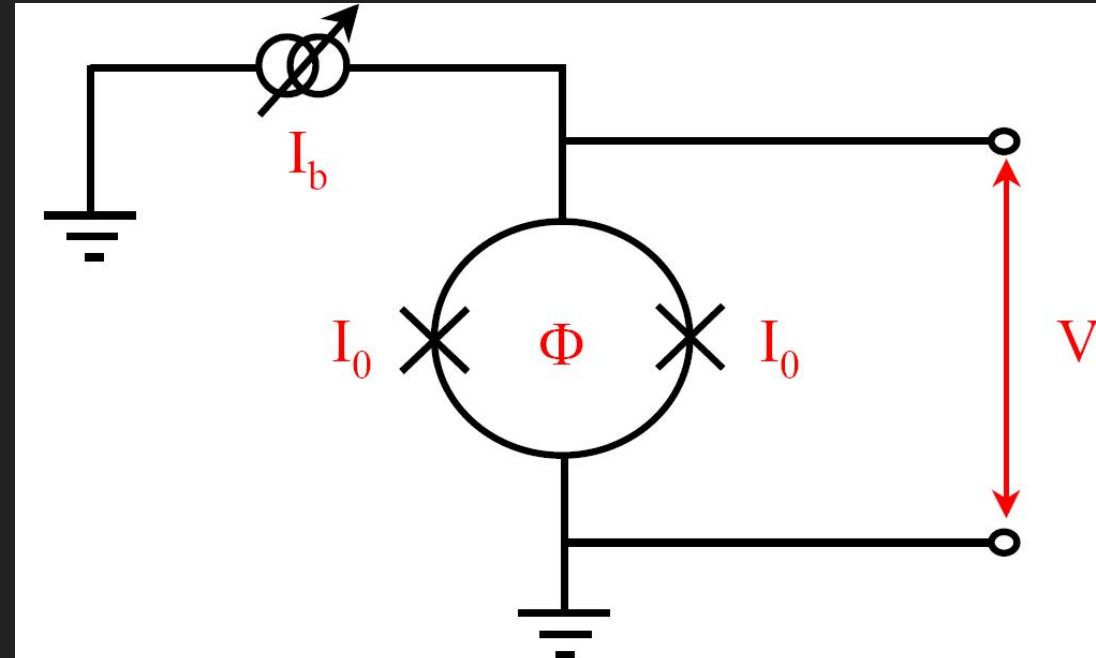
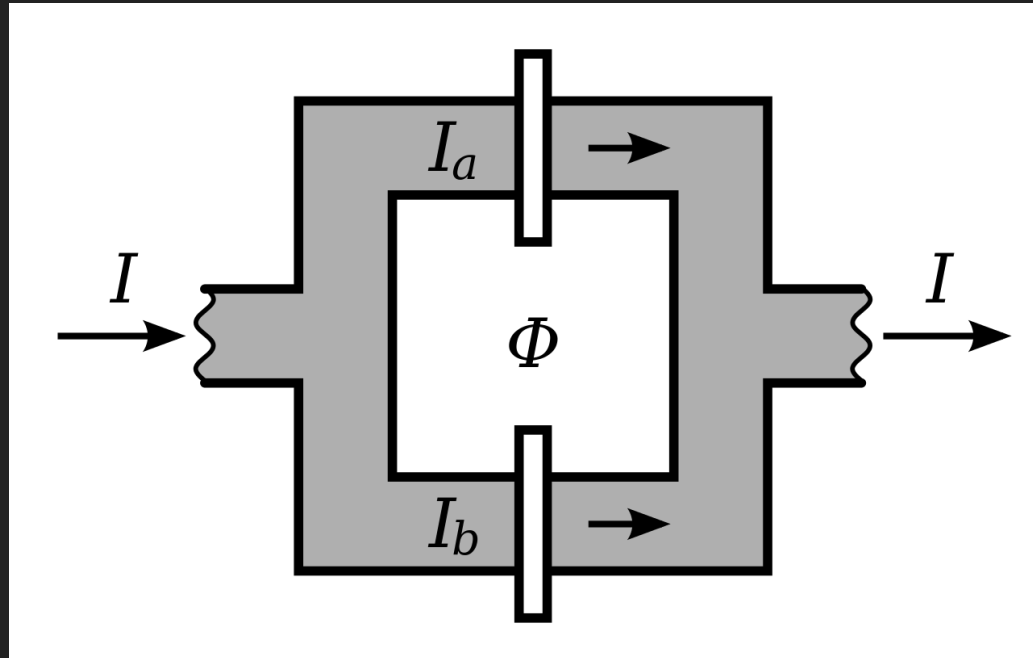


Figure 3-9. SQUID detection diagram.

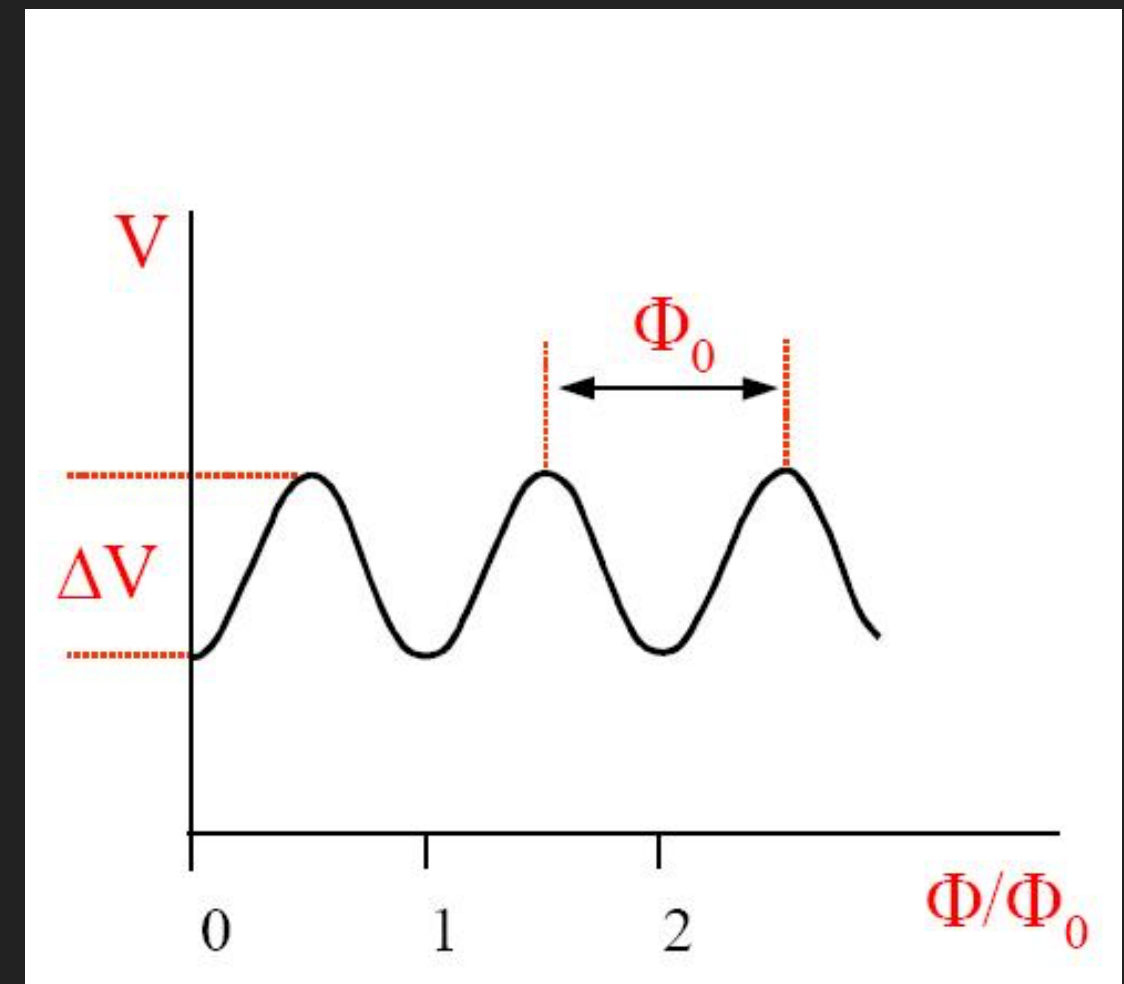


[QD MPMS III SQUID-VSM manual]

MEASURING THE MAGNETIC MOMENT: SQUID

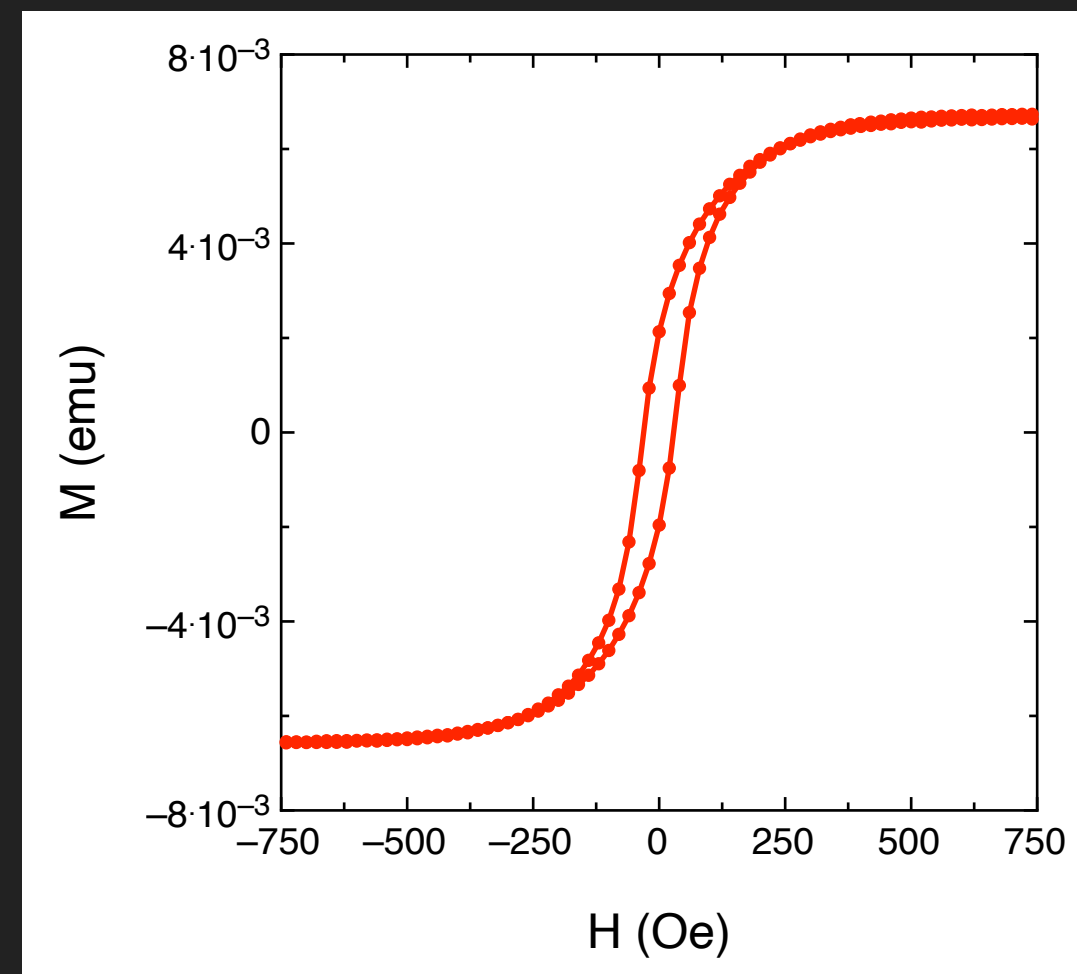
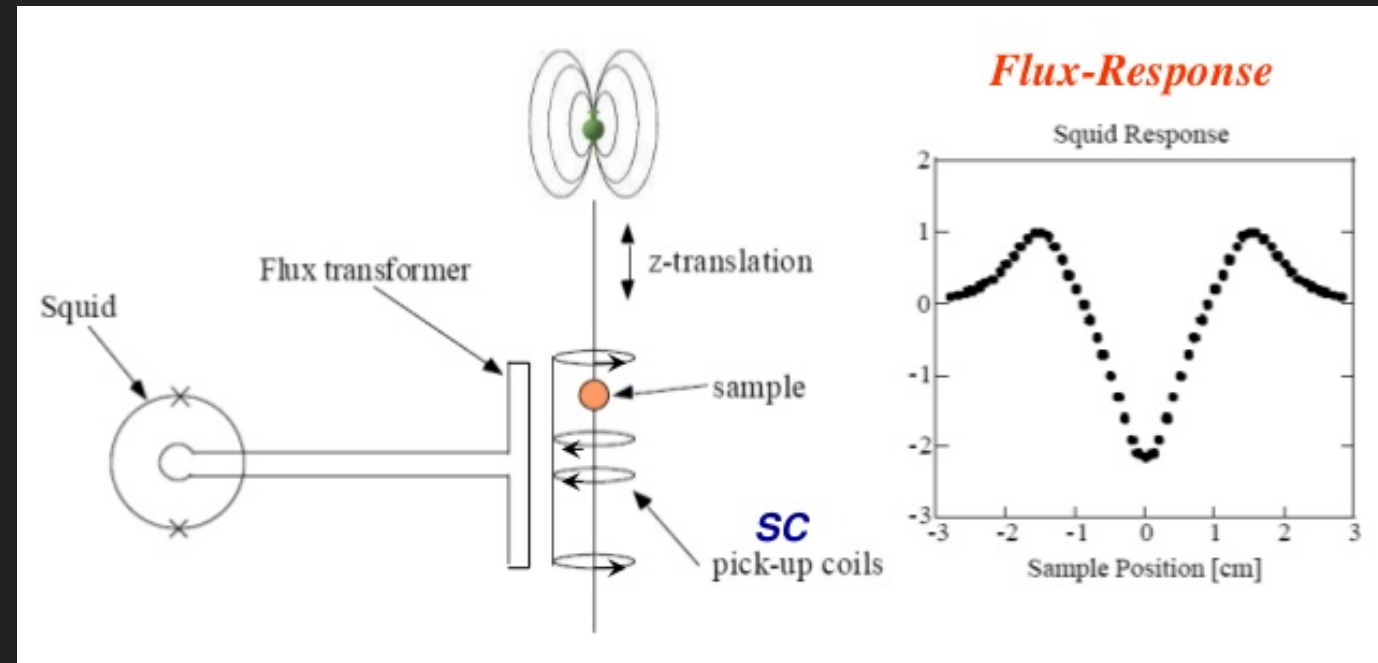


$$\Phi_0 = \frac{h}{2e} = 2.068 \times 10^{-15} \text{ Wb}$$



MEASURING THE MAGNETIC MOMENT: SQUID

- ▶ Extraction: direct measurement of $V(t)$ or $V(x)$ and subsequent integration.
- ▶ VSM: direct measurement of V_{rms} through a lock-in amplifier.
- ▶ Comparison with calibration standard for determining the magnetic moment.
- ▶ Acquisition of the measured curve one point at a time.



EVENTUALLY YOU HAVE THE MAGNETIC MOMENT. NOW WHAT?

- ▶ Maybe you would like to obtain a magnetisation...

this is what you'd like to know

$$\text{magnetisation} = \frac{\text{moment}}{\text{volume}}$$

this is what you measure

this is your nightmare

The diagram shows the equation $\text{magnetisation} = \frac{\text{moment}}{\text{volume}}$ in yellow italicized font. Three blue arrows point to different parts of the equation: one from the text 'this is what you'd like to know' to the word 'magnetisation', one from 'this is what you measure' to the word 'moment', and one from 'this is your nightmare' to the word 'volume'.

EVENTUALLY YOU HAVE THE MAGNETIC MOMENT. NOW WHAT?

- ▶ Maybe you would like to obtain a magnetisation...

The diagram illustrates the equation for magnetisation, $\text{magnetisation} = \frac{\text{moment}}{\text{volume}}$, with several annotations and a large red 'X' over the 'moment' term.

- A blue arrow points from the text "this is what you'd like to know" to the word "magnetisation".
- A blue arrow points from the text "this is your nightmare" to the word "volume".
- A blue arrow points from the text "this is what you measure" to the word "moment".
- A large red 'X' is drawn over the word "moment", indicating it is the unknown quantity to be determined.

EVENTUALLY YOU HAVE THE MAGNETIC MOMENT. NOW WHAT?

- ▶ Maybe you would like to obtain a magnetisation...

Diagram illustrating the relationship between magnetisation, magnetic moment, and volume:

$$\text{magnetisation} = \frac{\text{moment}}{\text{volume}}$$

Annotations:

- Blue arrow pointing to "magnetisation": this is what you'd like to know
- Blue arrow pointing to "moment": this is what you measure
- Blue arrow pointing to "volume": this is your nightmare

The entire equation is crossed out with a large red X.

This is what you measure:

$$M_{\text{measured}} = M_{\text{sample}} + M_{\text{support}} + M_{\text{holder}}$$

EVENTUALLY YOU HAVE THE MAGNETIC MOMENT. NOW WHAT?

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This is what you measure:

$$M_{\text{measured}} = M_{\text{sample}} + M_{\text{support}} + M_{\text{holder}}$$

The terms M_{measured} and M_{sample} are circled in blue.

GETTING RID OF ALL THE REST

- ▶ $M_{measured}$: what comes out of your magnetometer.
- ▶ M_{holder} : the rod (SQUID, VSM), the straw (SQUID) + anything used to fix the sample (grease, varnish, PTFE tape, ...). Let's say that you can measure it.
- ▶ $M_{support}$: the substrate (thin film), the container (powders, liquids), ... You can measure it too! Somehow.

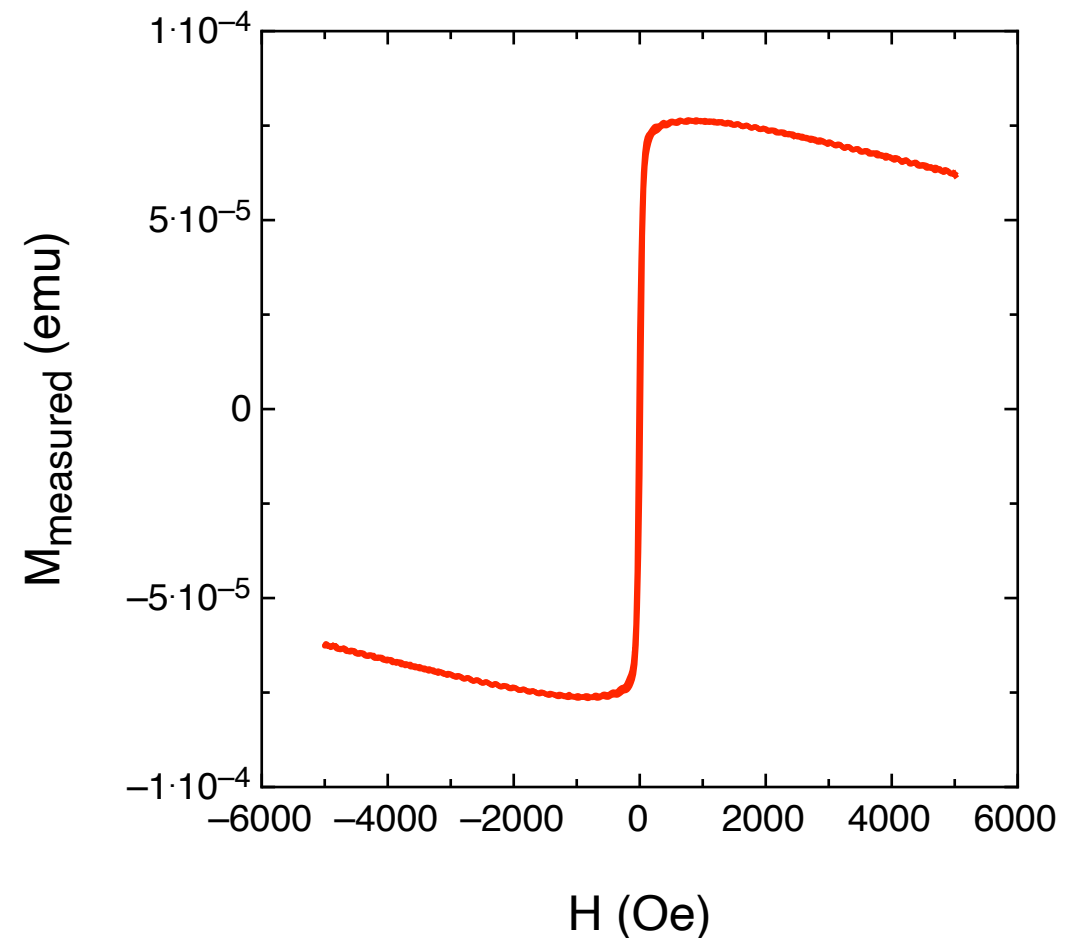
$$M_{measured} = M_{sample} + M_{support} + M_{holder}$$

OBTAINING M_{SAMPLE}

This is a thin film.

We are measuring:

- the **film**,
- the **substrate** (SiO_2),
- the **PTFE tape** holding the sample on the quartz rod,
- the quartz **rod**.



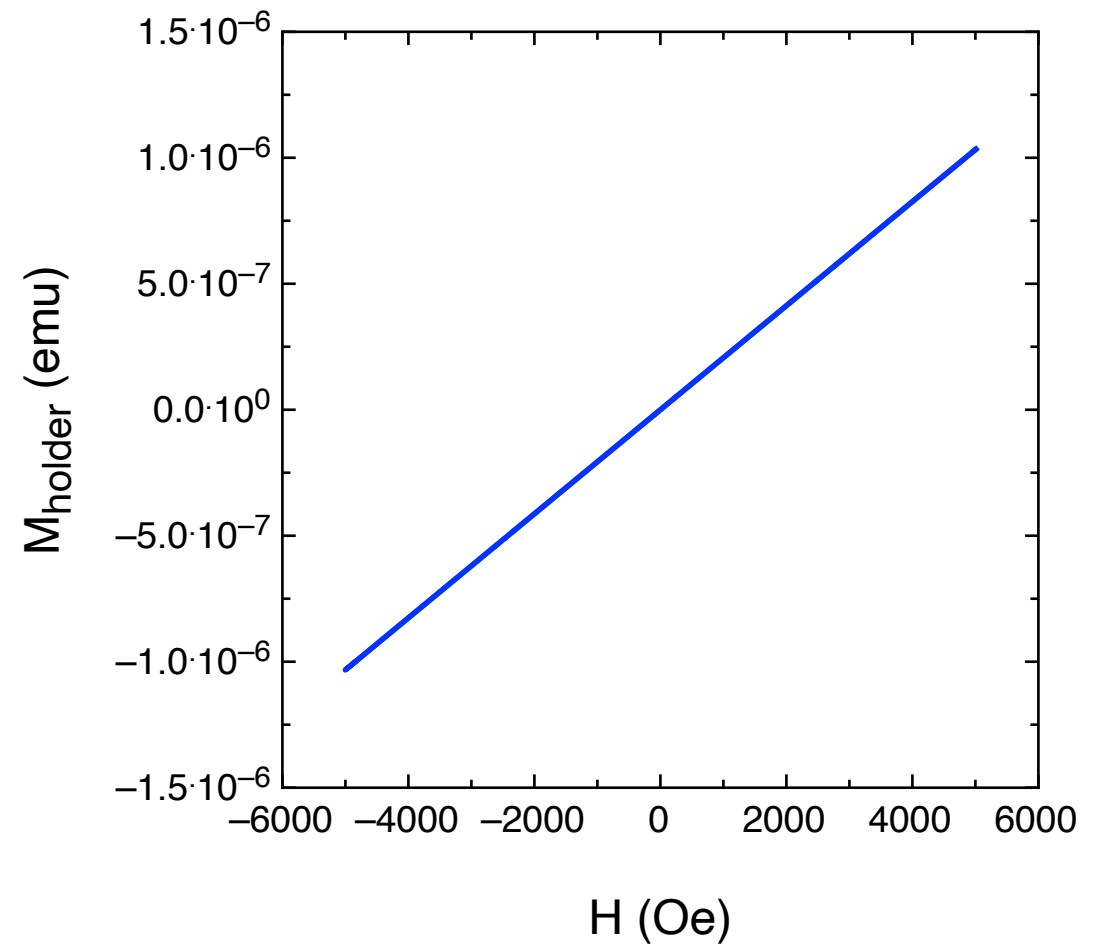
$$\underline{M_{\text{measured}}} = M_{\text{sample}} + M_{\text{support}} + M_{\text{holder}}$$

OBTAINING M_{SAMPLE}

Let's begin with the holder.

We are measuring:

- the **PTFE tape**
(approximately the same amount that we used to hold the sample on the quartz rod),
- the quartz **rod**.



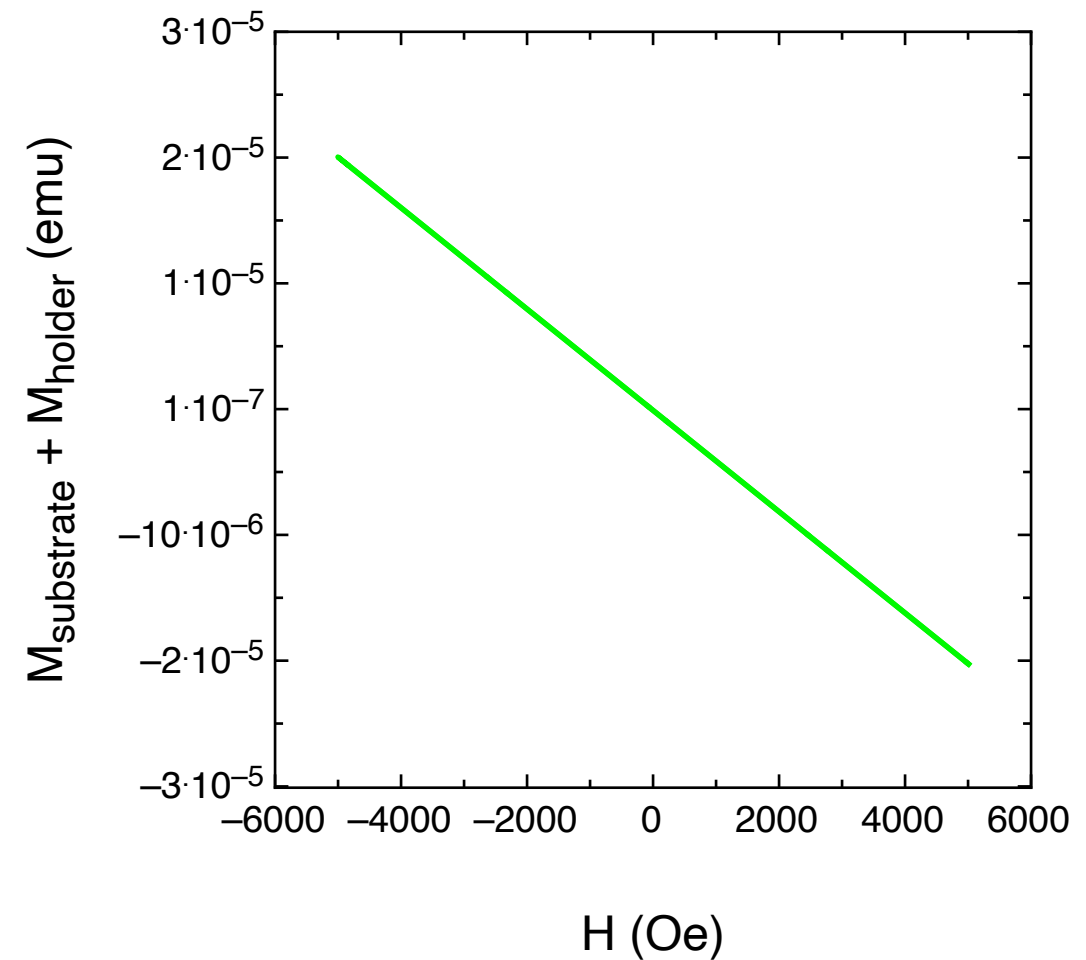
$$\underline{M_{\text{measured}}} = M_{\text{sample}} + M_{\text{support}} + \underline{M_{\text{holder}}}$$

OBTAINING M_{SAMPLE}

Let's go with the support.

We are measuring:

- the **substrate** (but another piece, with a different volume!)
- the **PTFE tape** (approximately the same amount that we used to hold the sample on the quartz rod),
- the quartz **rod**.



$$\underline{M_{\text{measured}}} = M_{\text{sample}} + M_{\text{support}} + \underline{M_{\text{holder}}}$$

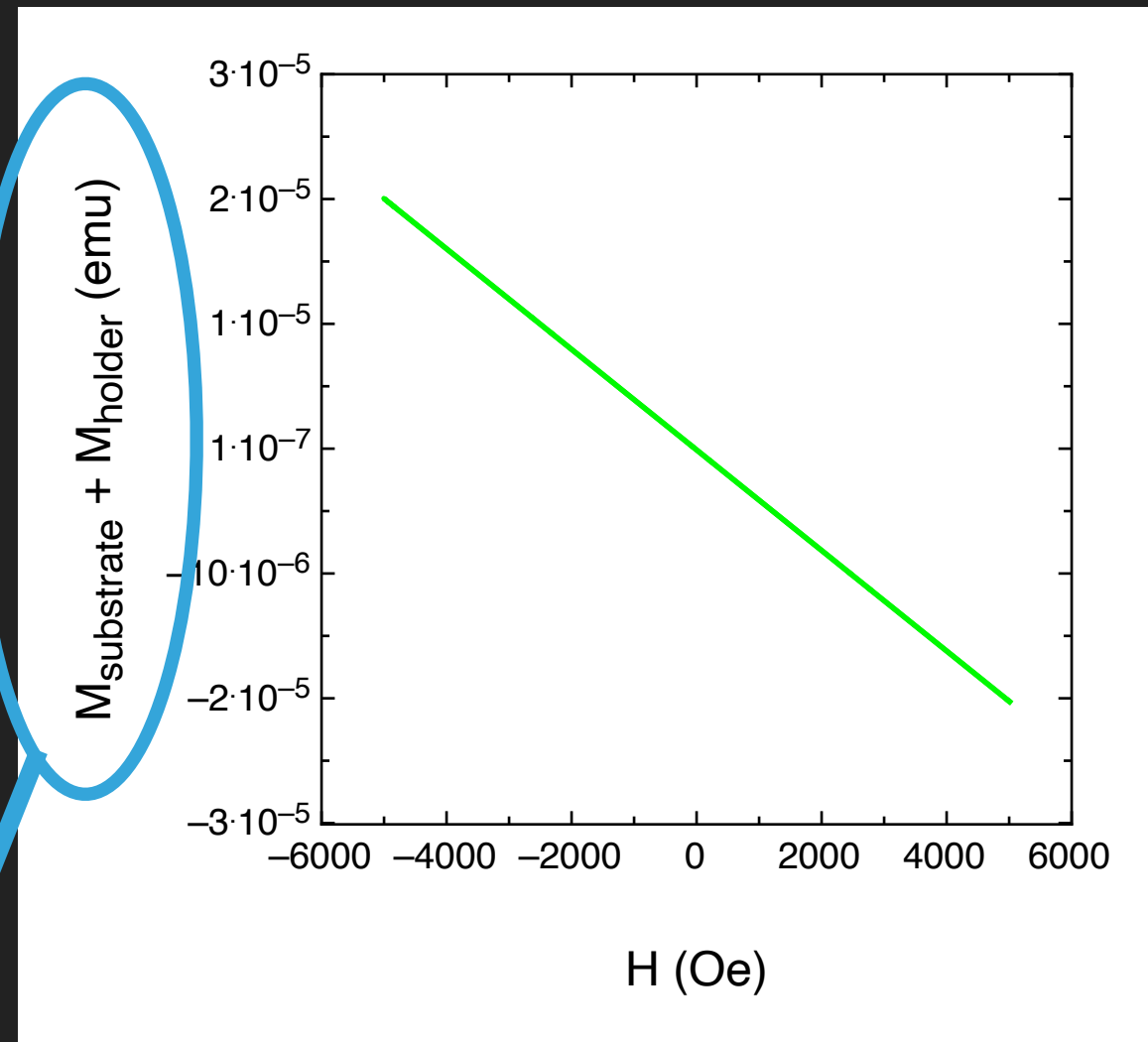
OBTAINING M_{SAMPLE}

Let's go with the support.

We are measuring:

- the **substrate** (but another piece, with a different volume!)
- the **PTFE tape** (approximately the same amount that we used to hold the sample on the quartz rod),
- the quartz **rod**.

M_2



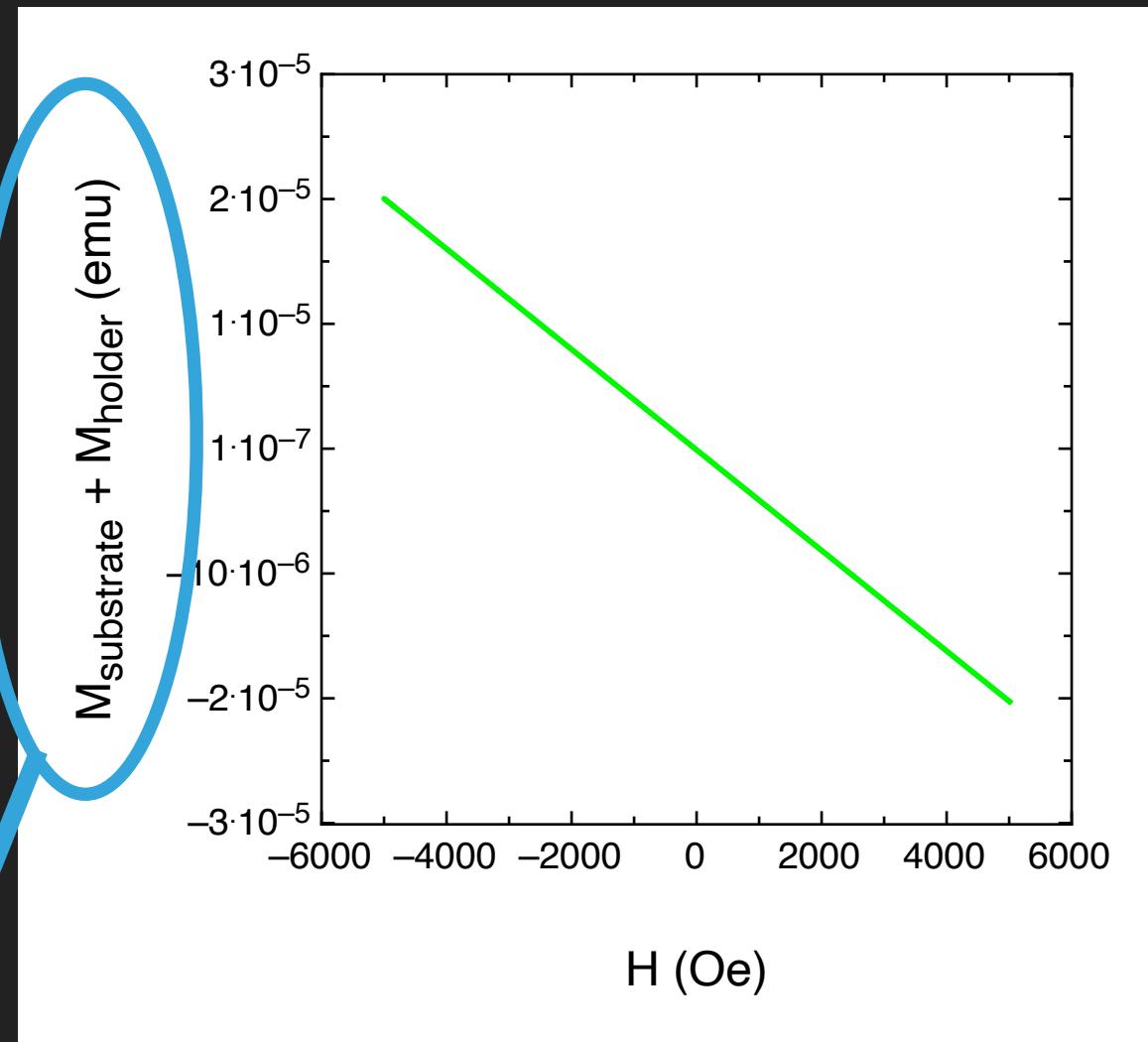
$$\underline{M_{\text{measured}}} = M_{\text{sample}} + M_{\text{support}} + \underline{M_{\text{holder}}}$$

OBTAINING M_{SAMPLE}

Let's go with the support.

We are measuring:

- the **substrate** (but another piece, with a different volume!)
- the **PTFE tape** (approximately the same amount that we used to hold the sample on the quartz rod),
- the quartz **rod**.



$$M_2 \rightarrow M_{\text{substrate},2} = M_2 - M_{\text{holder}}$$

$$\underline{M_{\text{measured}}} = M_{\text{sample}} + M_{\text{support}} + \underline{M_{\text{holder}}}$$

OBTAINING M_{SAMPLE}

Let's continue with the support.

We must rescale the magnetic moment of the substrate just measured, to the one of the substrate on top of which our film has been grown.

Provided that the two substrates are equal except for their volume, then:

$$M_{\text{support}} = M_{\text{substrate},2} \frac{V_{\text{support}}}{V_{\text{substrate},2}}$$

And since their thickness is the same, what really counts is their surface area:

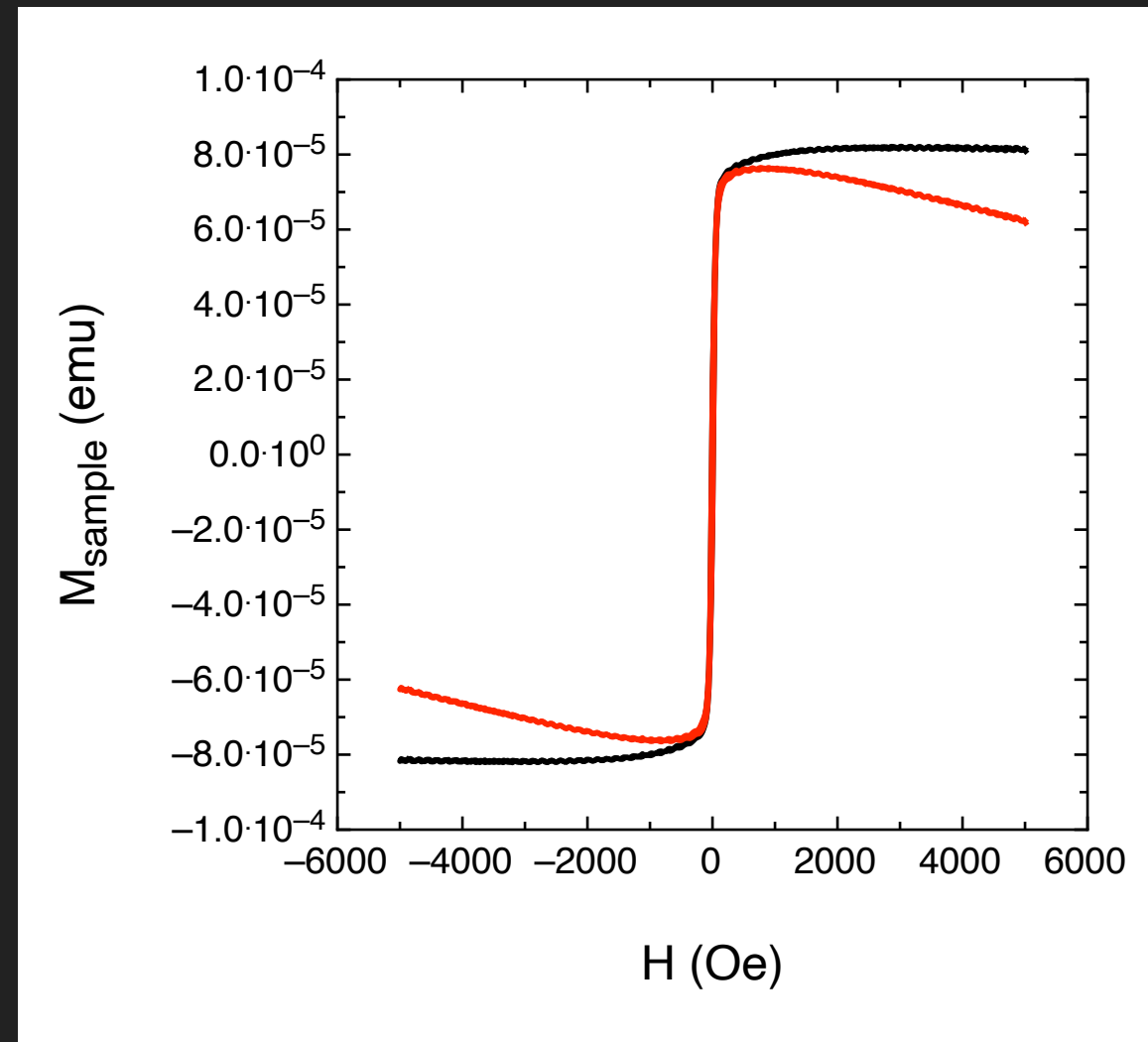
$$M_{\text{support}} = M_{\text{substrate},2} \frac{S_{\text{support}}}{S_{\text{substrate},2}}$$

$$\underline{M_{\text{measured}}} = M_{\text{sample}} + \underline{M_{\text{support}}} + \underline{M_{\text{holder}}}$$

OBTAINING M_{SAMPLE}

Therefore, 3 measurements:

1. M_{measured} : film + substrate + holder
2. M_2 : substrate2 (without film) + holder
3. M_{holder}



$$M_{\text{sample}} = M_{\text{measured}} - (M_2 - M_{\text{holder}}) \frac{S_{\text{support}}}{S_{\text{substrate},2}} - M_{\text{holder}}$$

OBTAINING A MAGNETISATION

- ▶ Once you have M_{sample} , you have a chance of determining the magnetisation from the measurement of the magnetic moment.

$$\text{magnetisation} = \frac{\text{moment}}{\text{volume}}$$

Diagram illustrating the formula for magnetisation:

- magnetisation : this is what you'd like to know
- moment : this is what you have just obtained
- volume : this is your next headache

To obtain the sample volume: directly, mass and density, surface area and thickness, any other relevant means, depending on sample type (films, powders, etc.).

OBTAINING A MAGNETISATION: CAVEATS

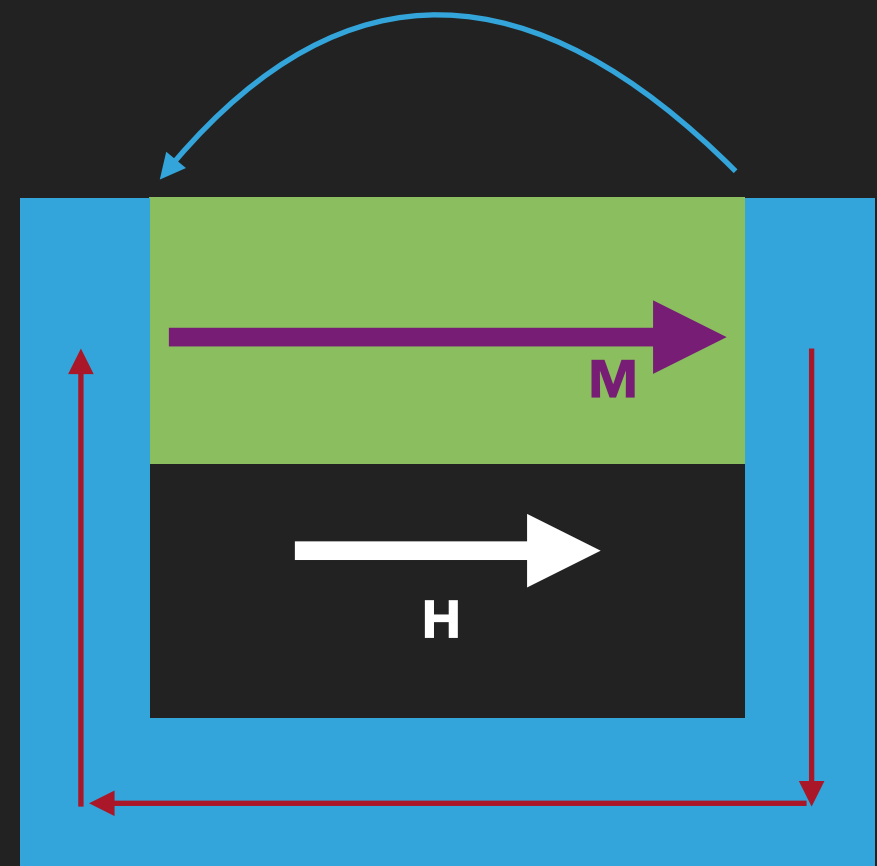
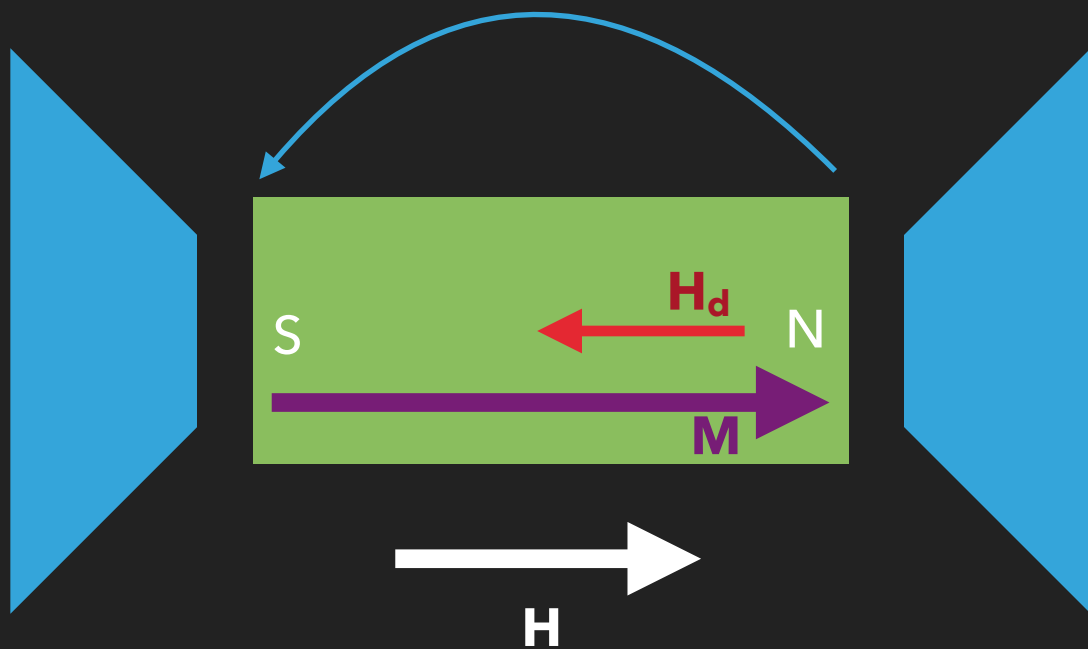
- ▶ Thin films: surface area is rather easy to measure (optical microscopy, photos, ...), thickness should be known. But keep in mind that a film density might not be the same as the bulk's.
- ▶ Thin films: in some cases you can weight the substrate before and after the deposition. You don't have the volume, but at least you have a mass.
- ▶ Patterned media: a covering ratio must be defined, the surface must be homogeneously covered.
- ▶ Powders: determining the mass is usually the easiest approach.

OBTAINING A MAGNETISATION: CAVEATS

- ▶ In any case: properly define the material the magnetisation refers to.
- ▶ Example: Fe_3O_4 nanoparticles coated with SiO_2 . The mass (volume) refers to the Fe_3O_4 component, or to the whole $\text{Fe}_3\text{O}_4@\text{SiO}_2$ core@shell system?
- ▶ Example: a multilayer system Ta/CoFeB/Ta. The volume (mass) is that of the trilayer, or of the CoFeB layer only? That depends on what you have measured, and if you have a way for subtracting the contribution of the non-magnetic layers from the total measured magnetic moment.

OPEN MAGNETIC CIRCUIT MEASUREMENTS

- ▶ These magnetometers measure the magnetic moment in the open magnetic circuit configuration.
- ▶ Free poles, no flux closure.



$$H_{internal} = H_{applied} - H_d$$

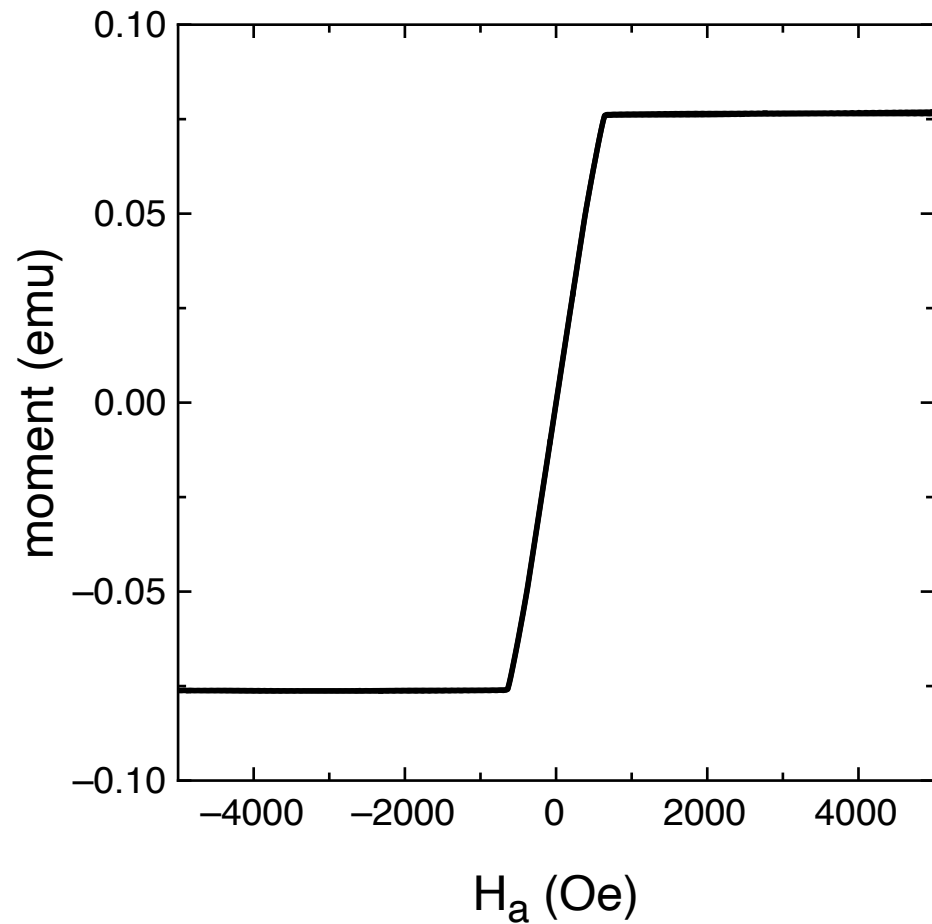
DEMAGNETISING FIELD

- ▶ H_d proportional to M , through three coefficients: N_x, N_y, N_z .
- ▶ $N_x + N_y + N_z = 1$ (in SI).
- ▶ N_i larger along directions where the sample is shorter.
- ▶ Spheres: $N_x = N_y = N_z = 1/3$.
- ▶ Thin films ($t \ll$ lateral dimensions): $N_z = 1, N_x = N_y = 0$.
- ▶ Nanoparticles:
$$N_p \simeq \frac{1}{3} + f \left(N - \frac{1}{3} \right)$$

demagnetising factor of spherical particles with packing factor f in a sample holder having a shape with demagnetising factor N

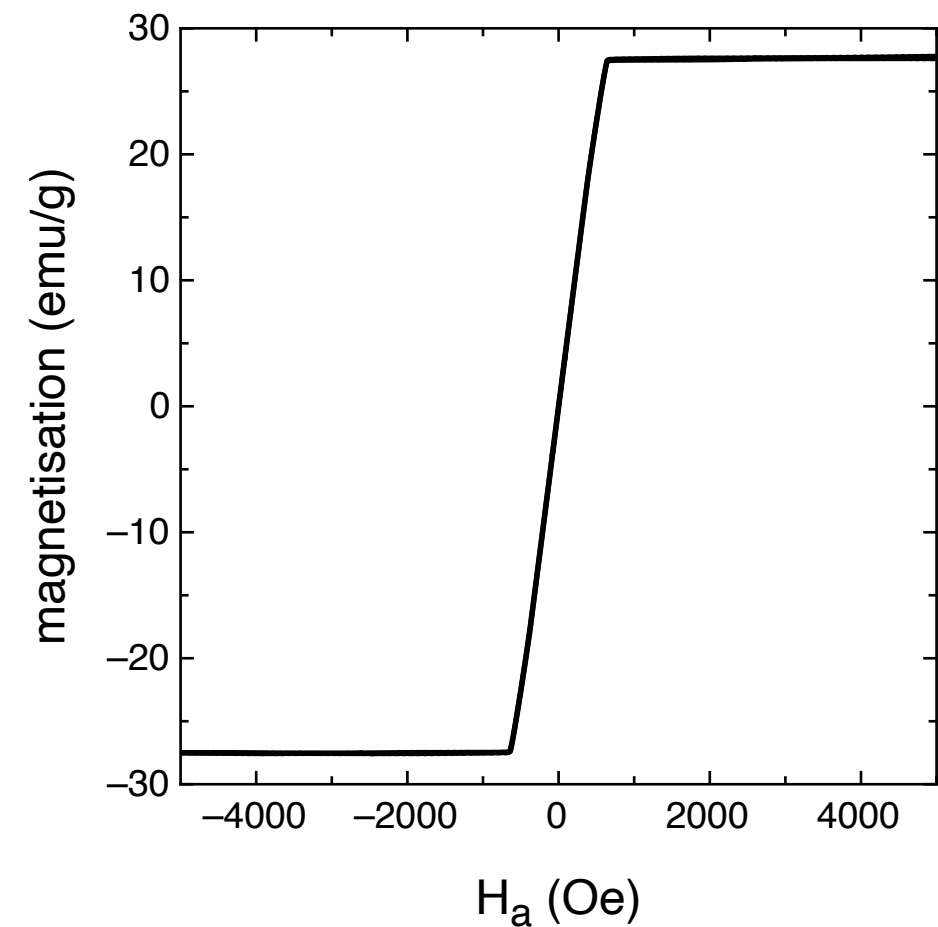
DEMAGNETISING FIELD CORRECTION FOR A SPHERE

- Let's take a YIG calibration sphere.



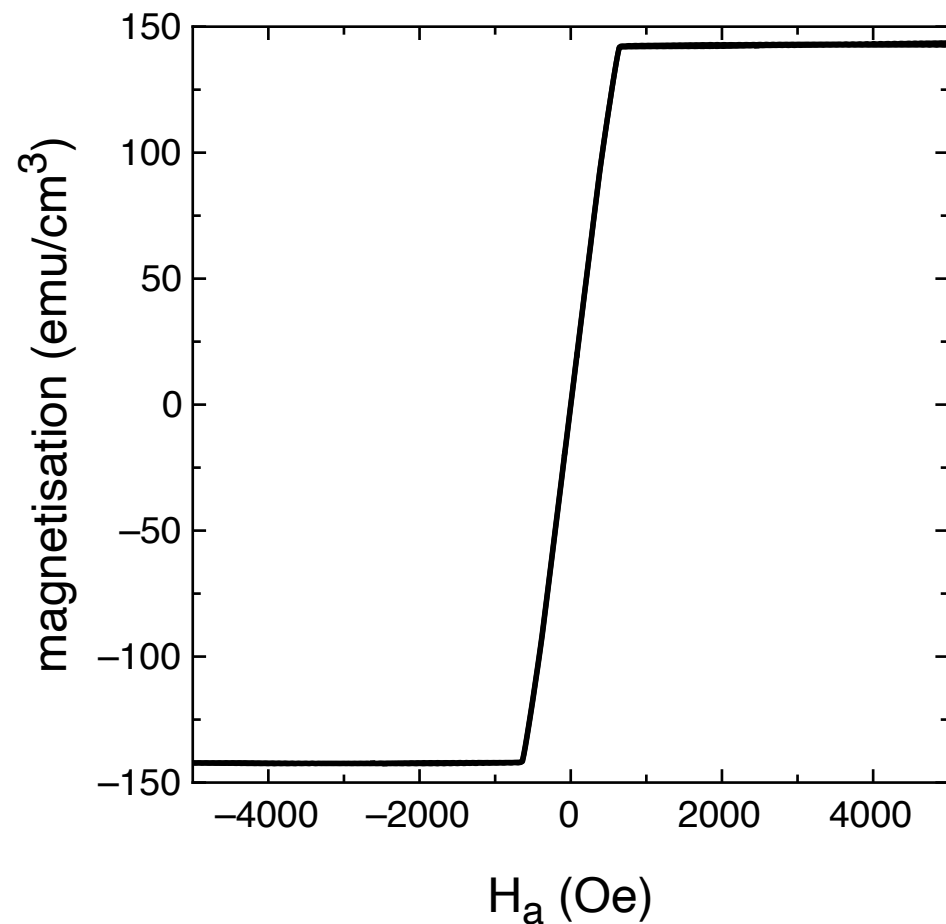
as-measured data

mass magnetisation of the sample
(after holder subtraction)

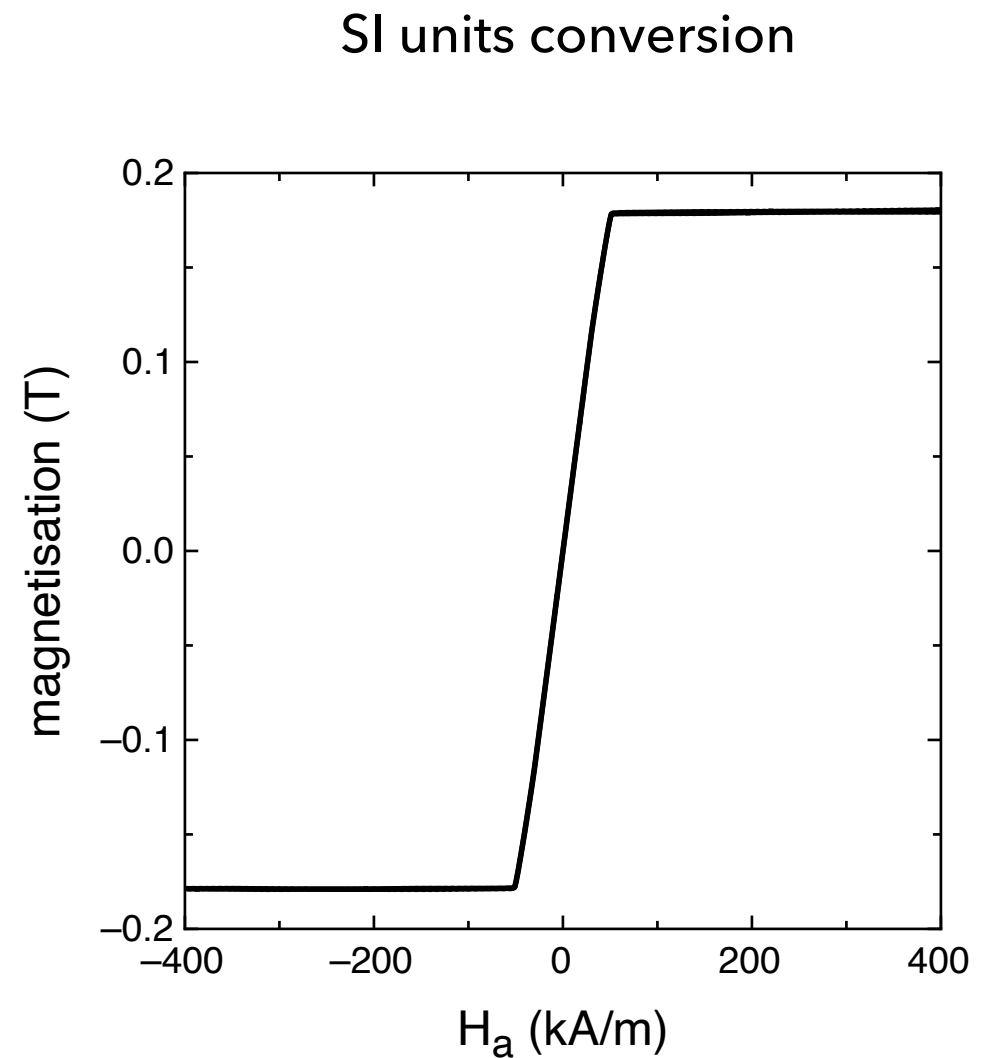


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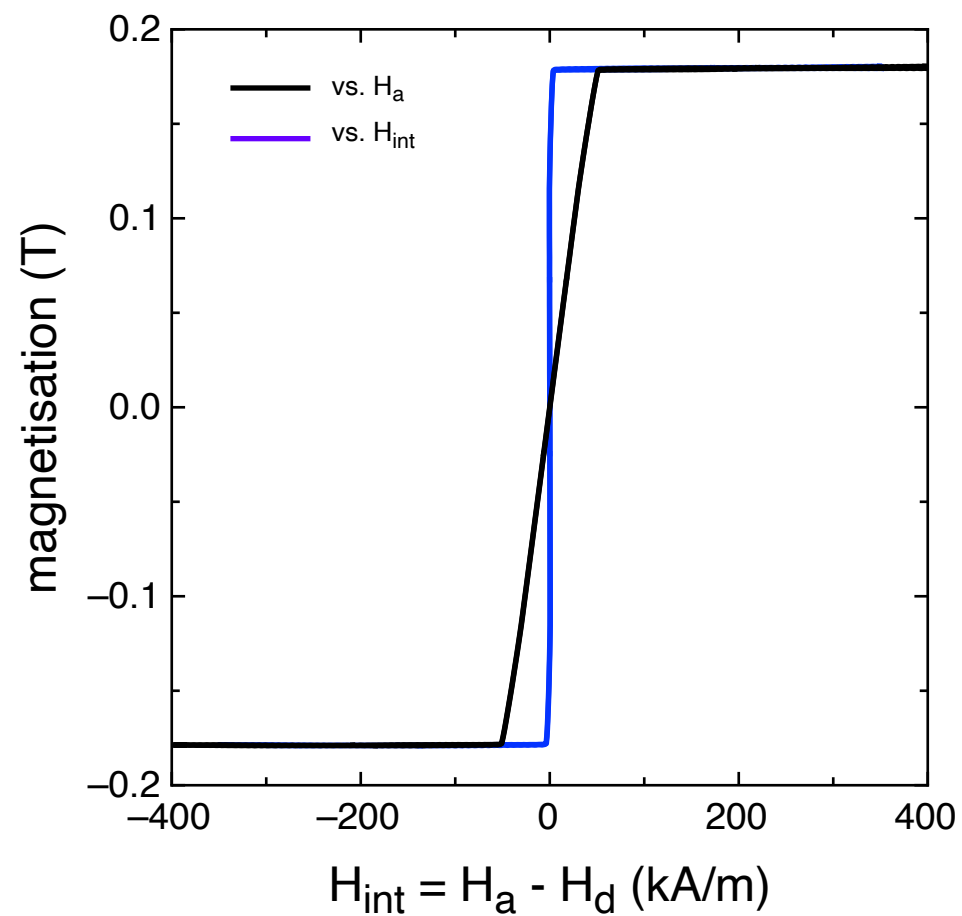


volume magnetisation of the sample
using nominal YIG density



DEMAGNETISING FIELD CORRECTION FOR A SPHERE

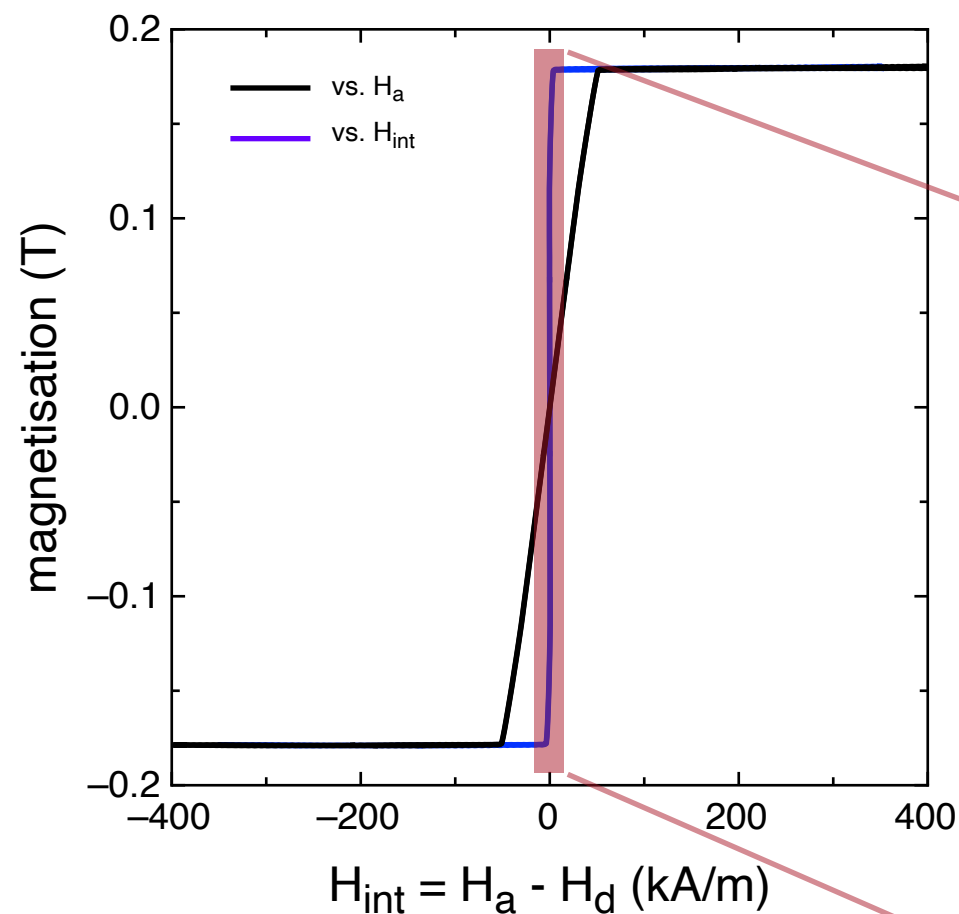
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calculation of $H_d = 1/3 M$
and plot against H_{int}

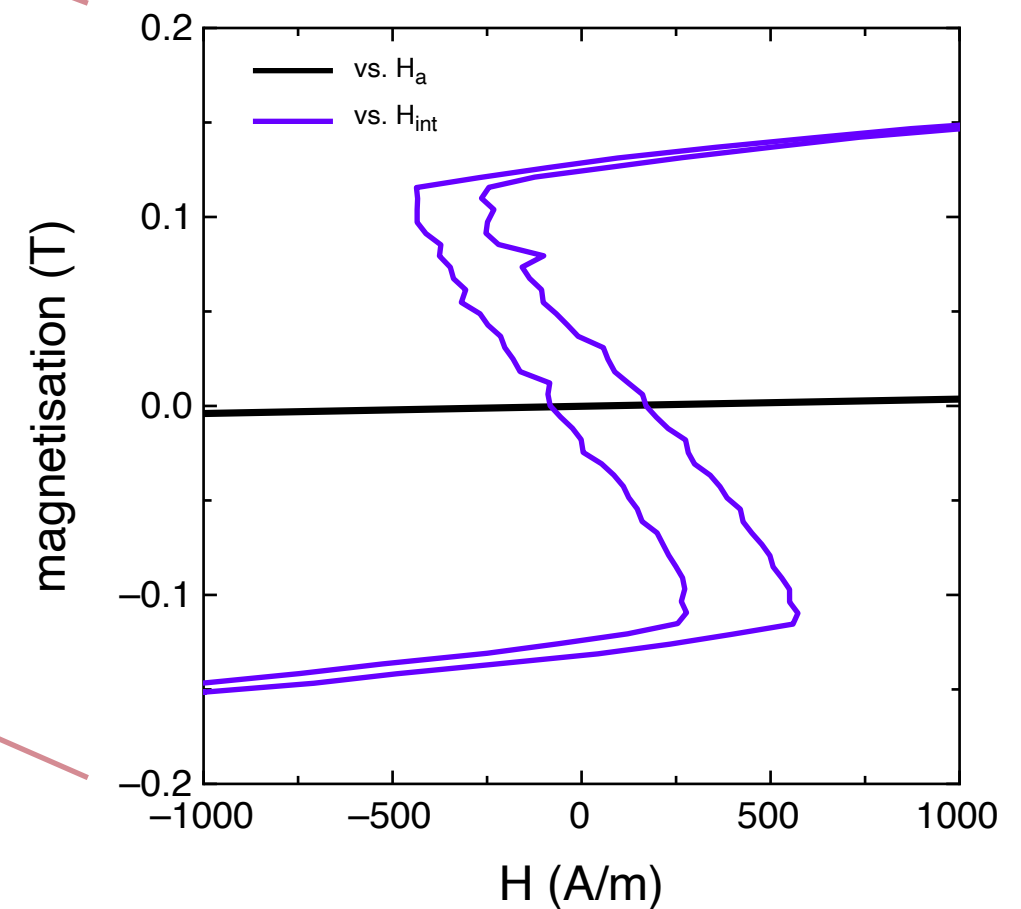
DEMAGNETISING FIELD CORRECTION FOR A SPHERE

- ▶ Let's take a YIG calibration sphere.



calculation of $H_d = 1/3 M$
and plot against H_{int}

Note the very different
horizontal scale!



WHY MEASURING THE FIELD IS SO IMPORTANT

- ▶ Magnetometer with an electromagnet: non linearity and hysteresis, but H is directly measured with a Hall probe.
- ▶ Magnetometer with coils: linearity and no hysteresis, H is indirectly measured with a voltmeter / ammeter.
- ▶ Magnetometer with superconducting solenoid: quasi-linearity and hysteresis, H is indirectly measured with an ammeter!

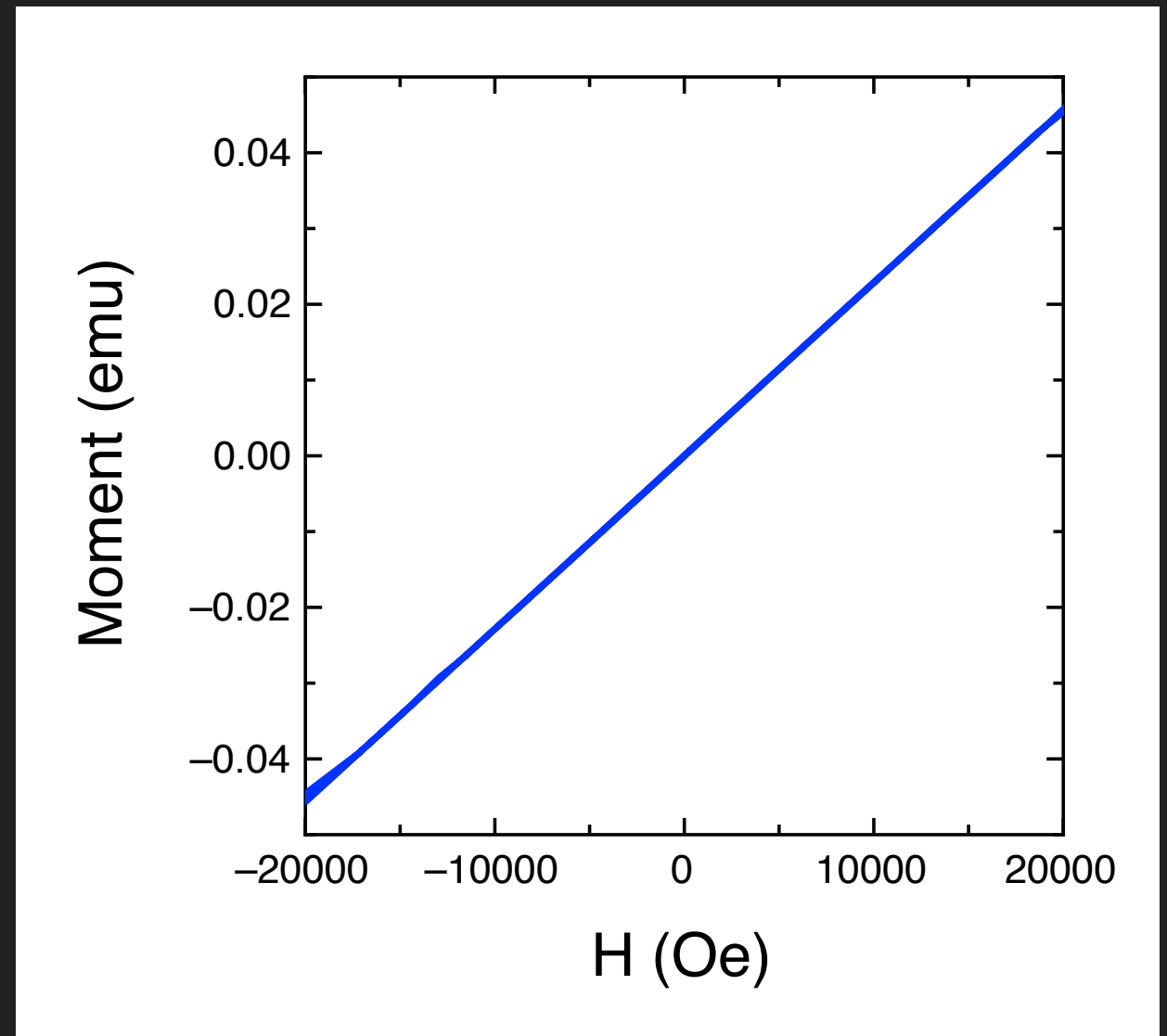


WHY MEASURING THE FIELD IS SO IMPORTANT

- ▶ SQUID magnetometer, with superconducting solenoid.
- ▶ Pd sample: it's paramagnetic, the expected magnetisation curve is a straight line (should be a Langevin curve, but up to a few tesla it's still a straight line).

WHY MEASURING THE FIELD IS SO IMPORTANT

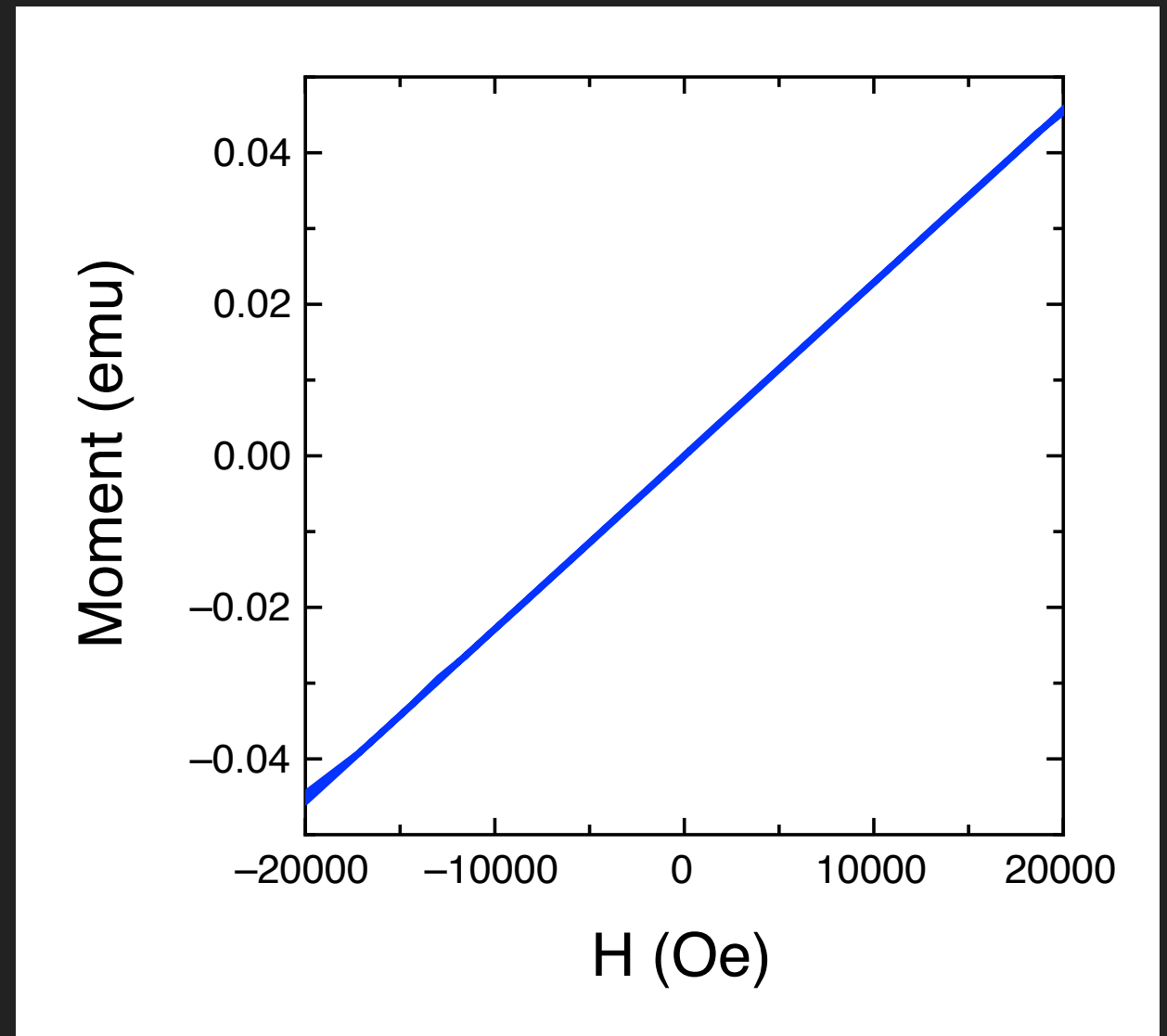
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It is.

WHY MEASURING THE FIELD IS SO IMPORTANT

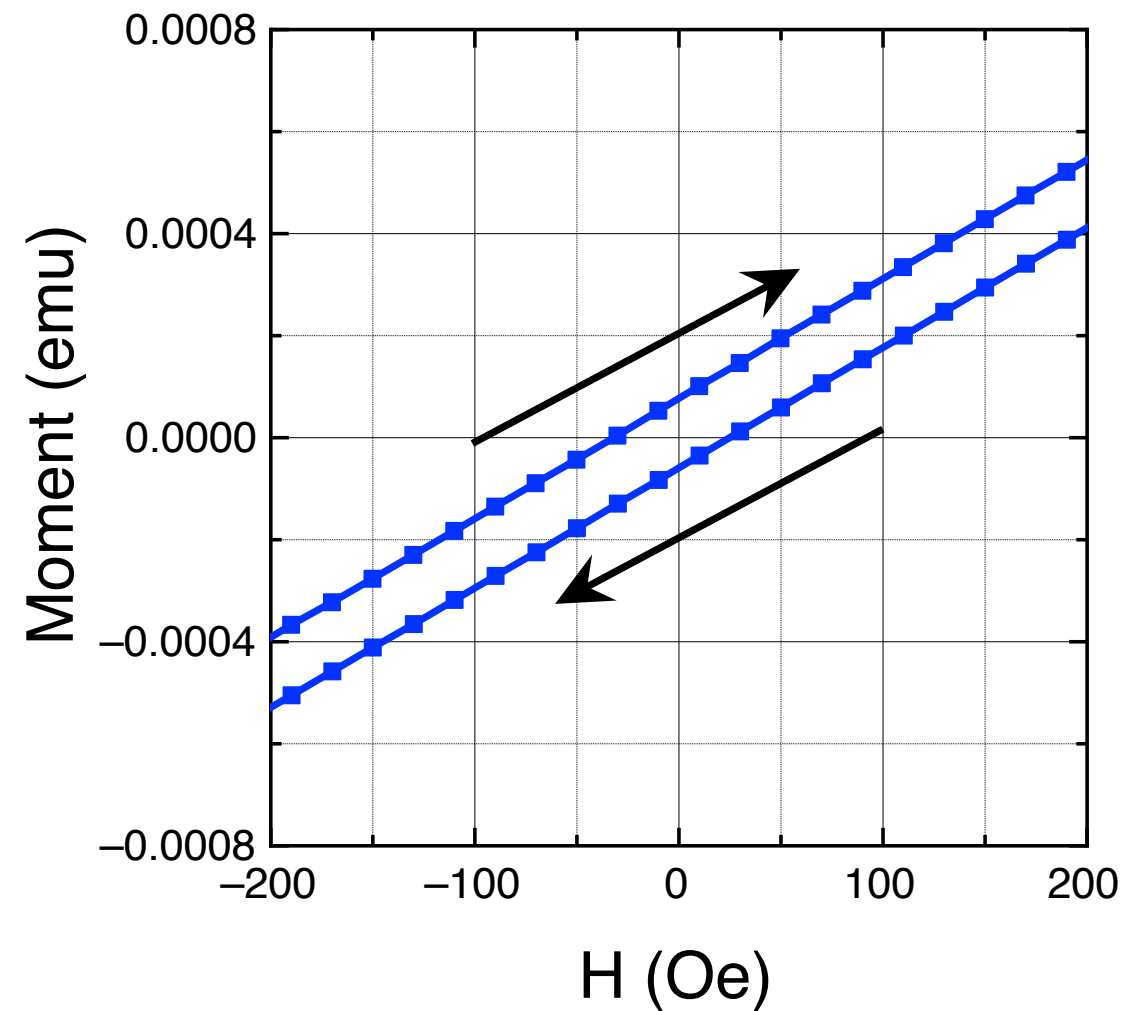
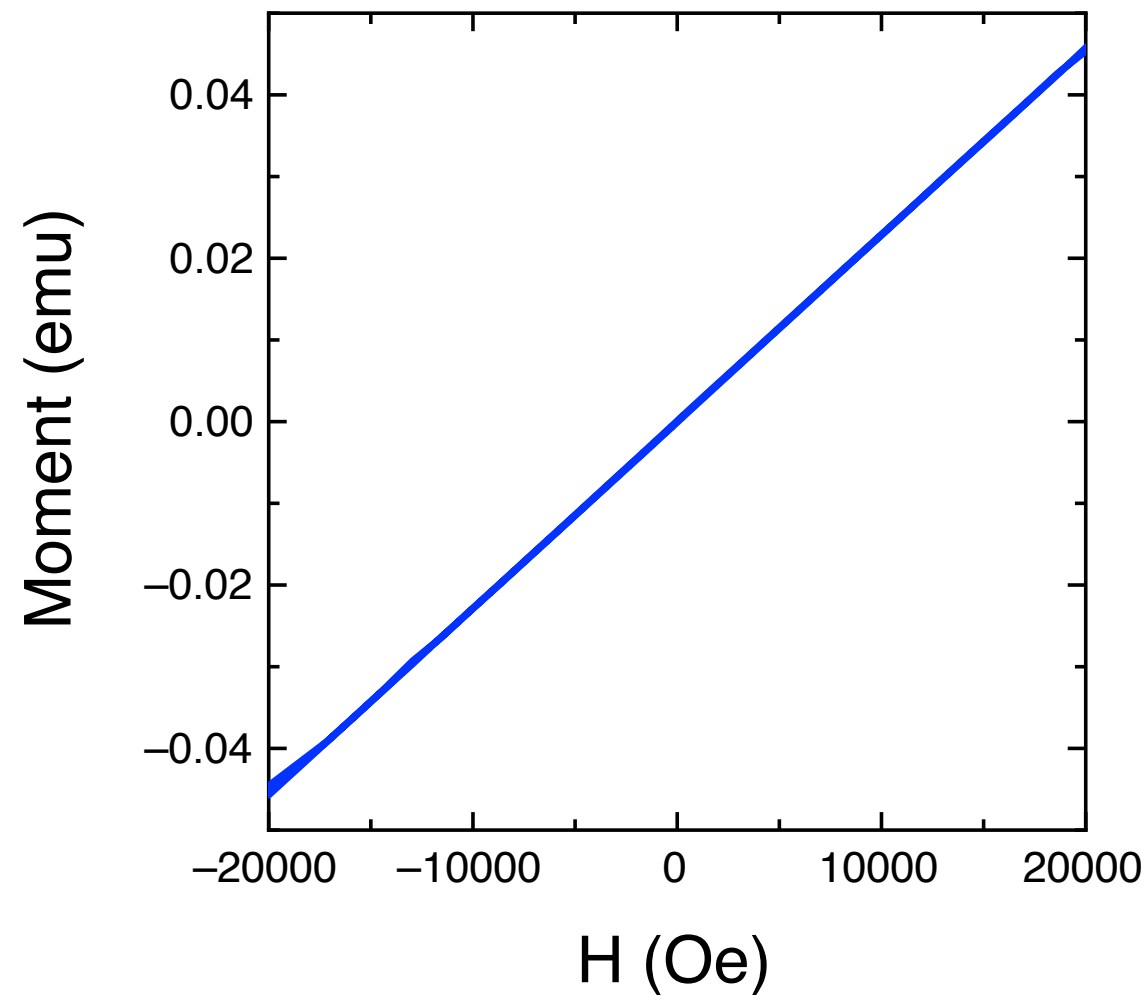
- ▶ SQUID magnetometer, with superconducting solenoid.
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It is.

Or is it?

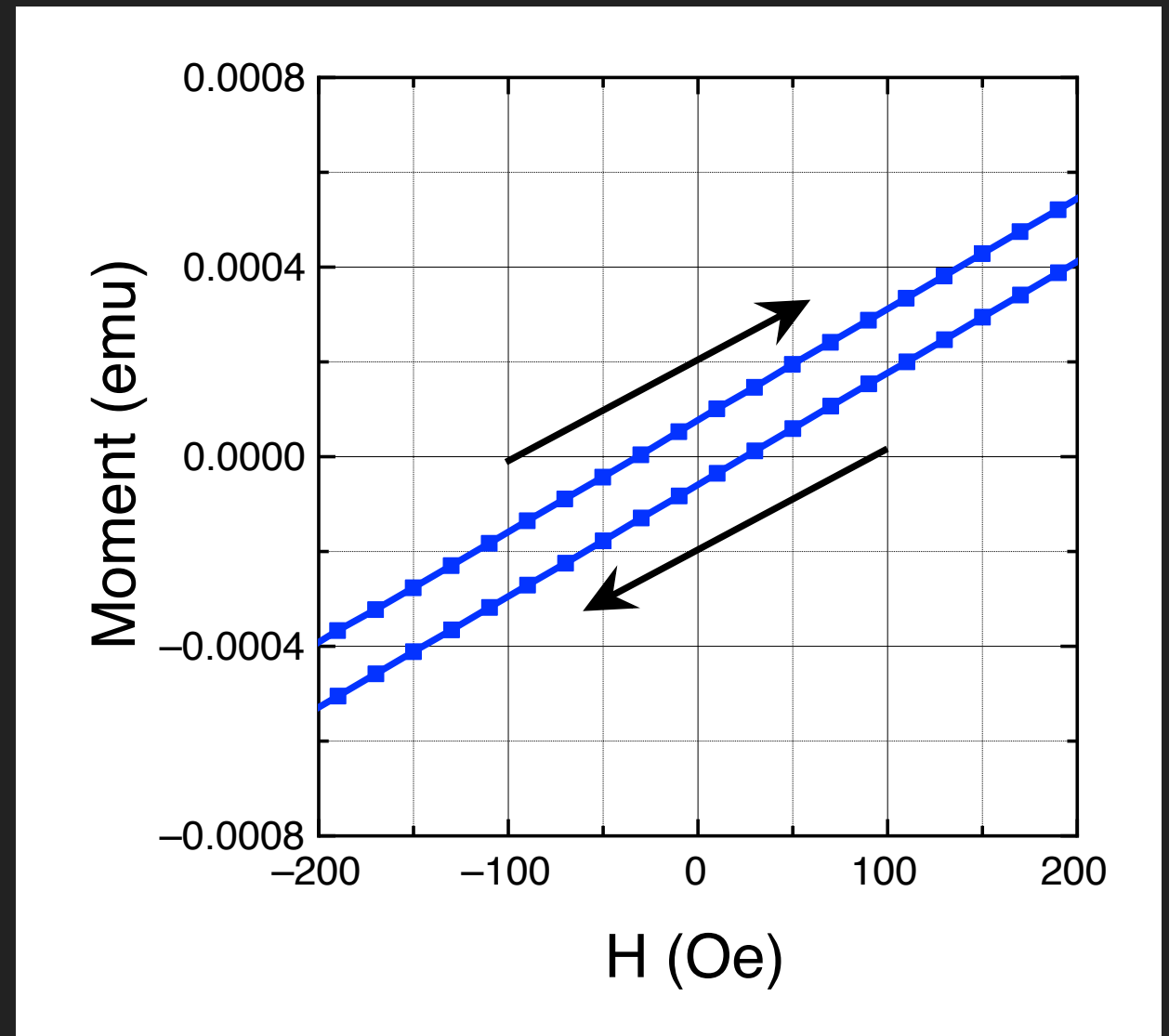
WHY MEASURING THE FIELD IS SO IMPORTANT



Hysteresis! With a reversed hysteresis loop!

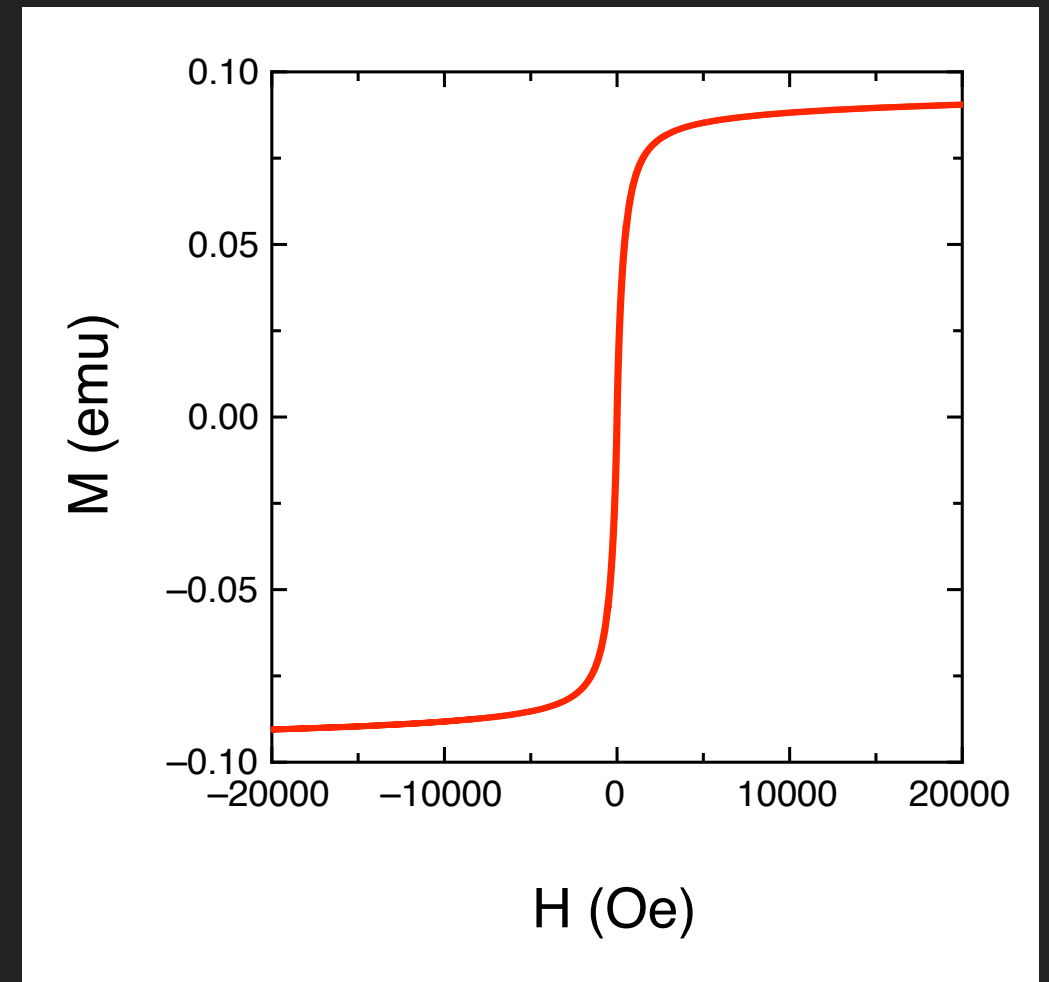
WHY MEASURING THE FIELD IS SO IMPORTANT

- ▶ The superconducting coil traps some flux: hysteresis.
- ▶ The trapped flux opposes the applied field.
- ▶ The actual field is actually that due to the current circulating in the solenoid, **minus** the (opposing) trapped flux.
- ▶ You cannot trust the reading of the ammeter!



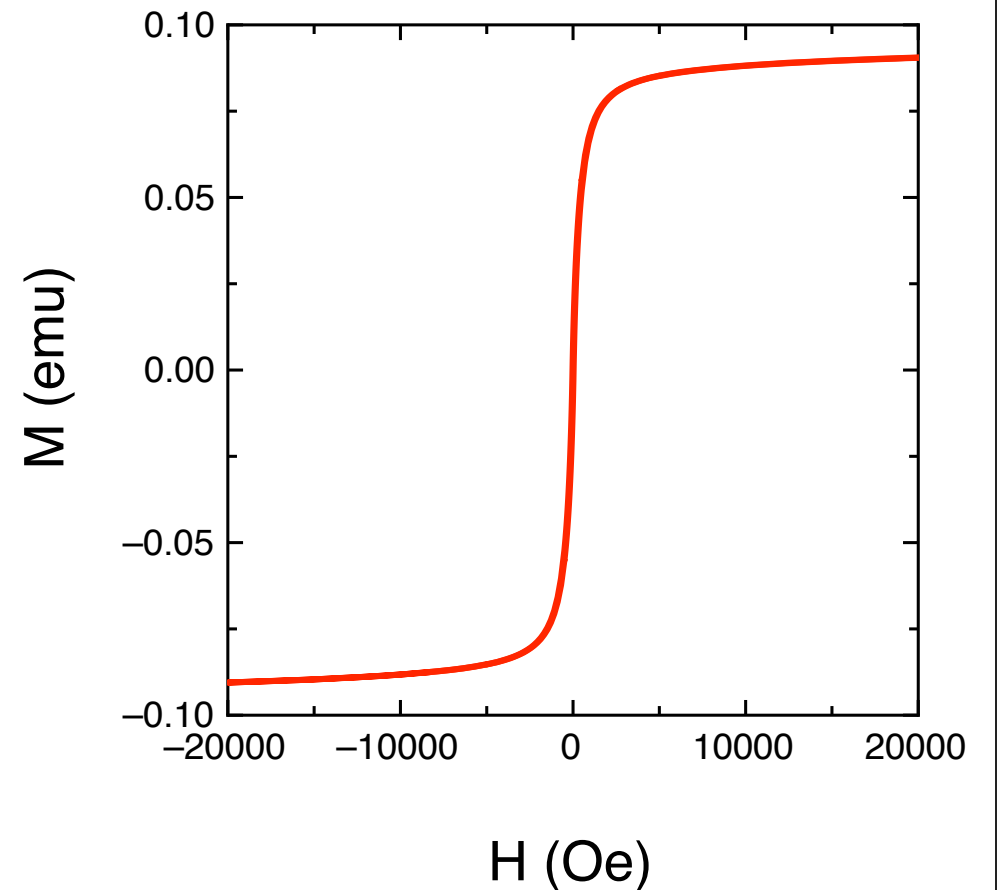
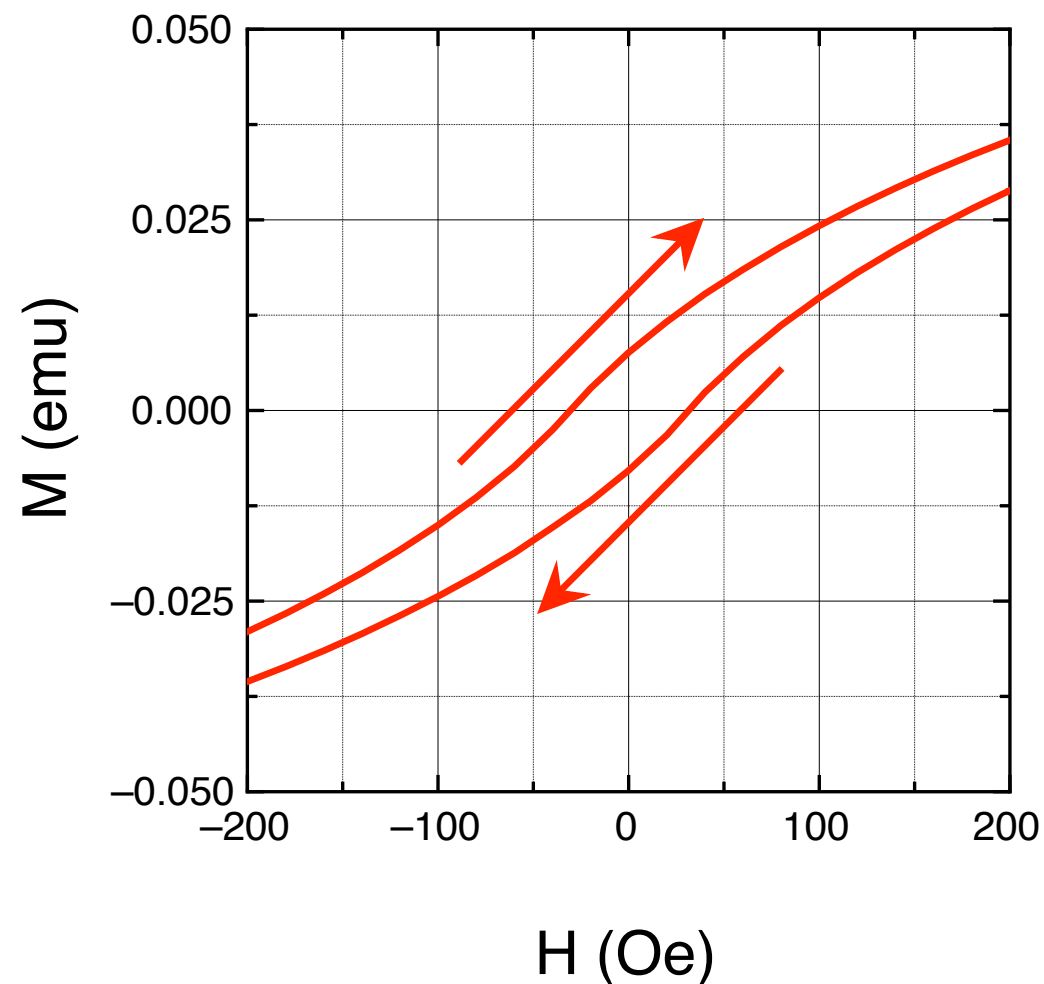
WHY MEASURING THE FIELD IS SO IMPORTANT

- ▶ Fe_3O_4 nanoparticles.
- ▶ So nicely superparamagnetic!



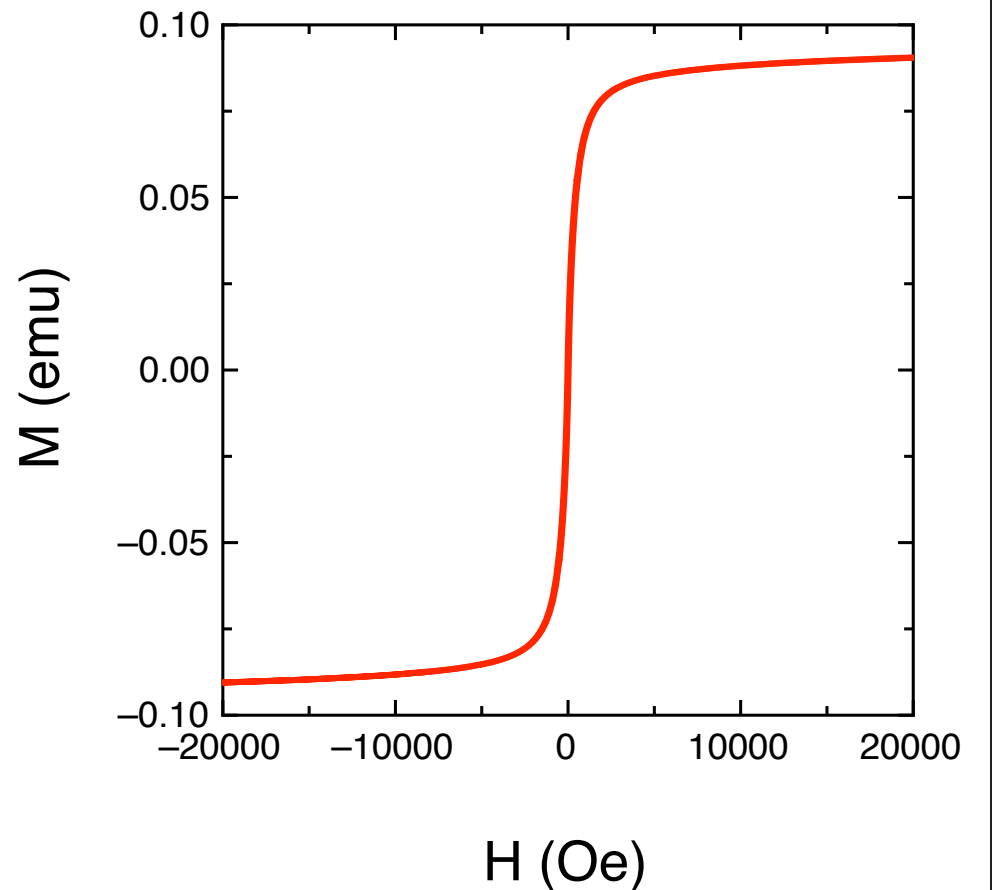
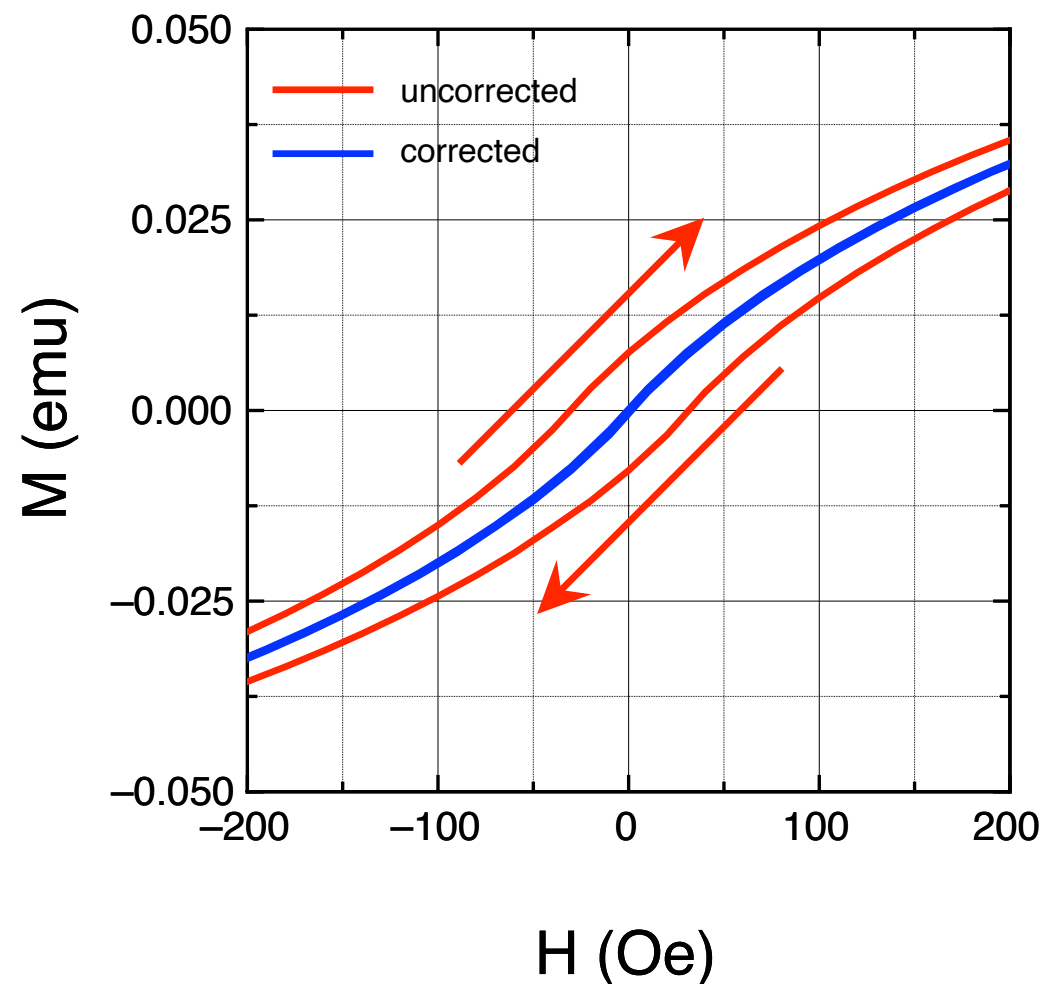
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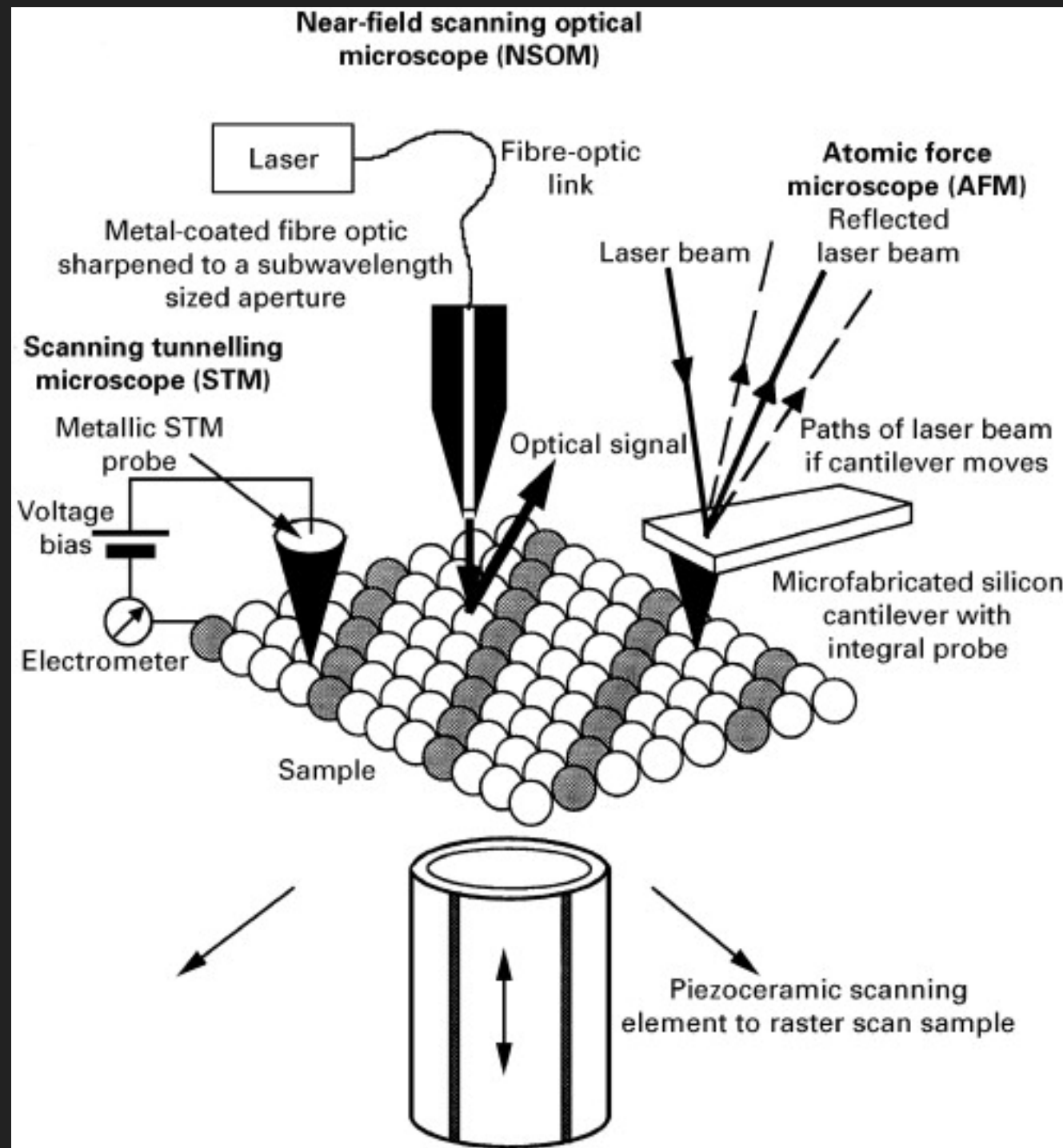
SPIN-POLARISED STM

ONE BIG FAMILY

- ▶ Scanning Probe Microscopy (SPM).
 - ▶ Scanning Tunnel Microscopy (STM).
 - ▶ Field-Polarised STM.
 - ▶ Atomic Force Microscopy (AFM).
 - ▶ Magnetic Force Microscopy (MFM).

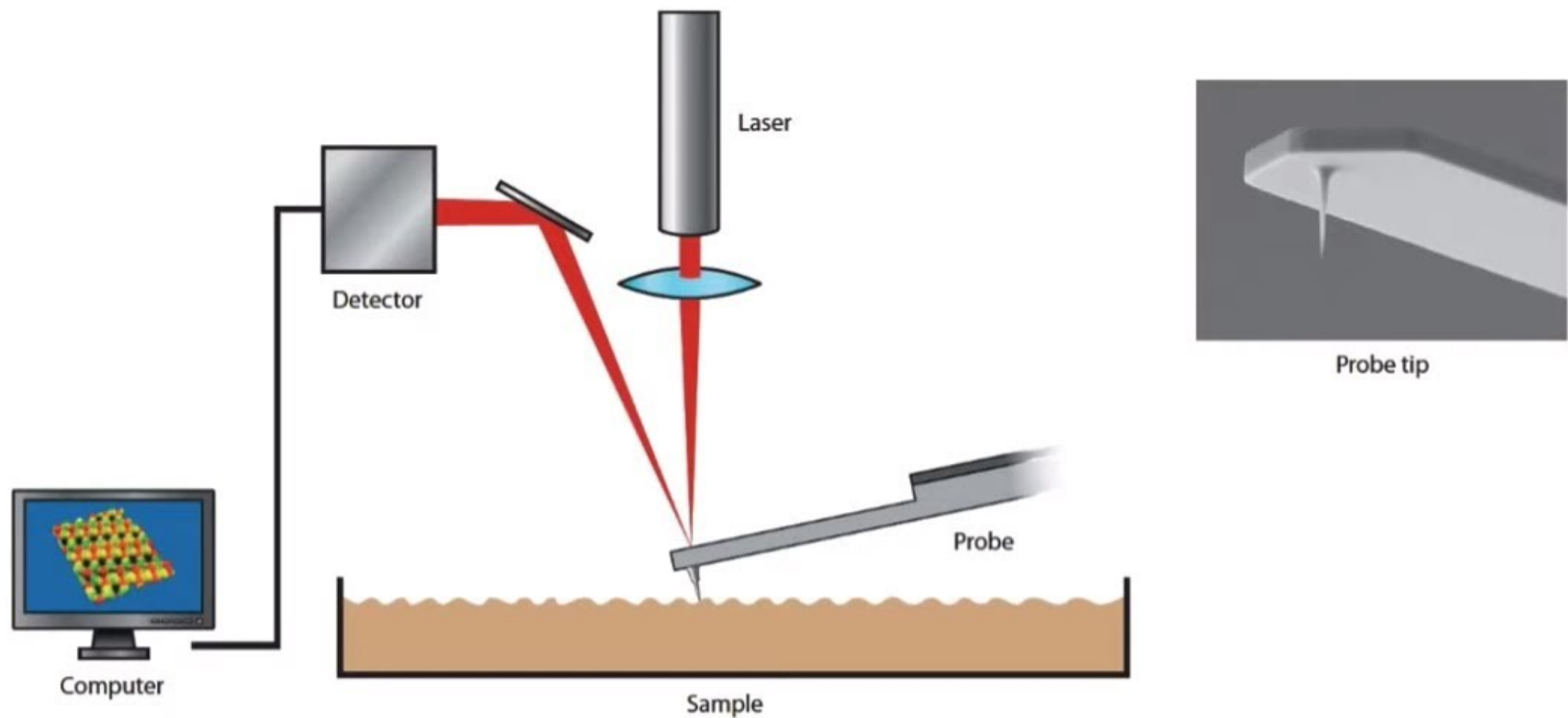
And many many others

BASIC PRINCIPLES OF A SCANNING PROBE MICROSCOPE

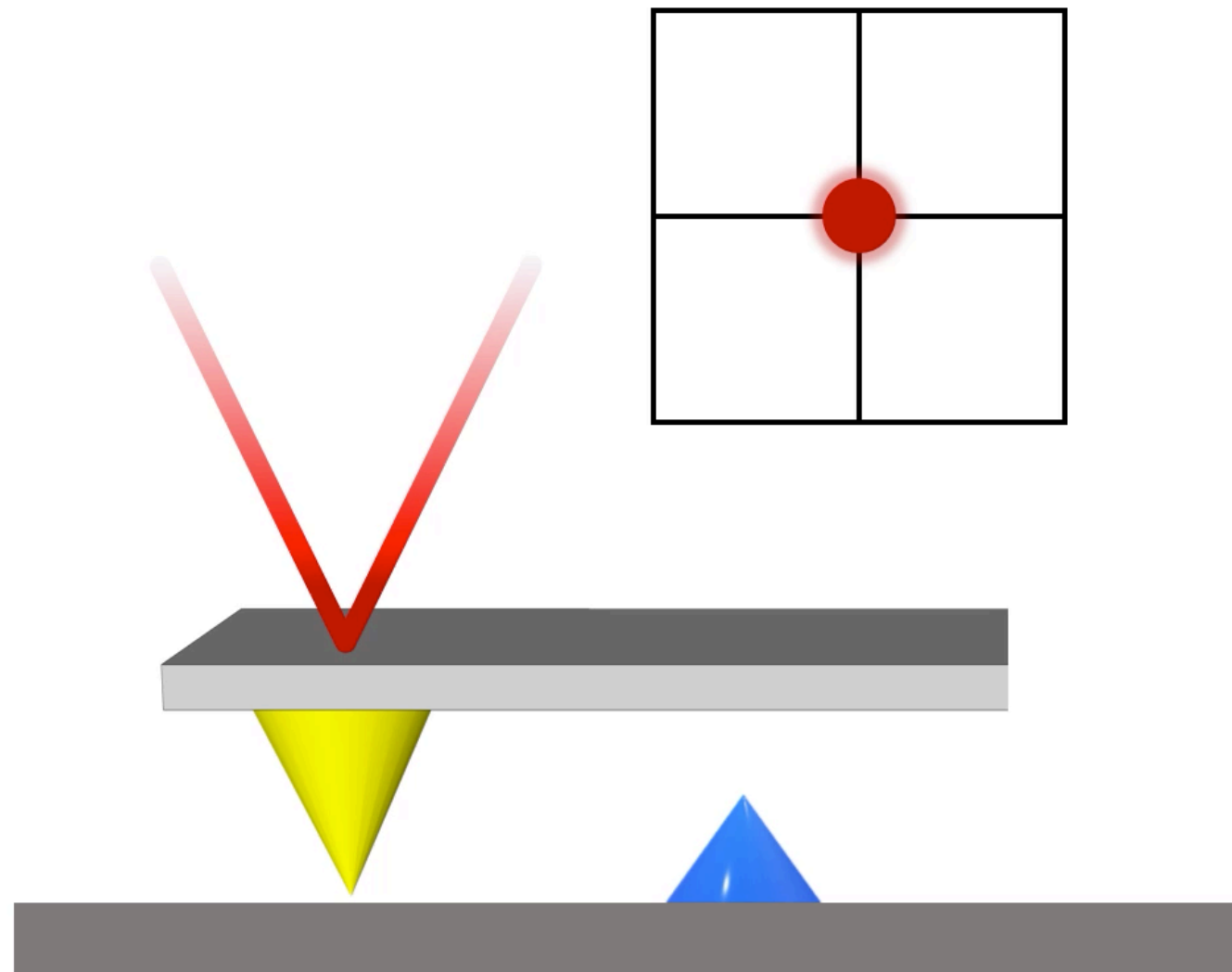


MEASURING SAMPLE MORPHOLOGY: AFM

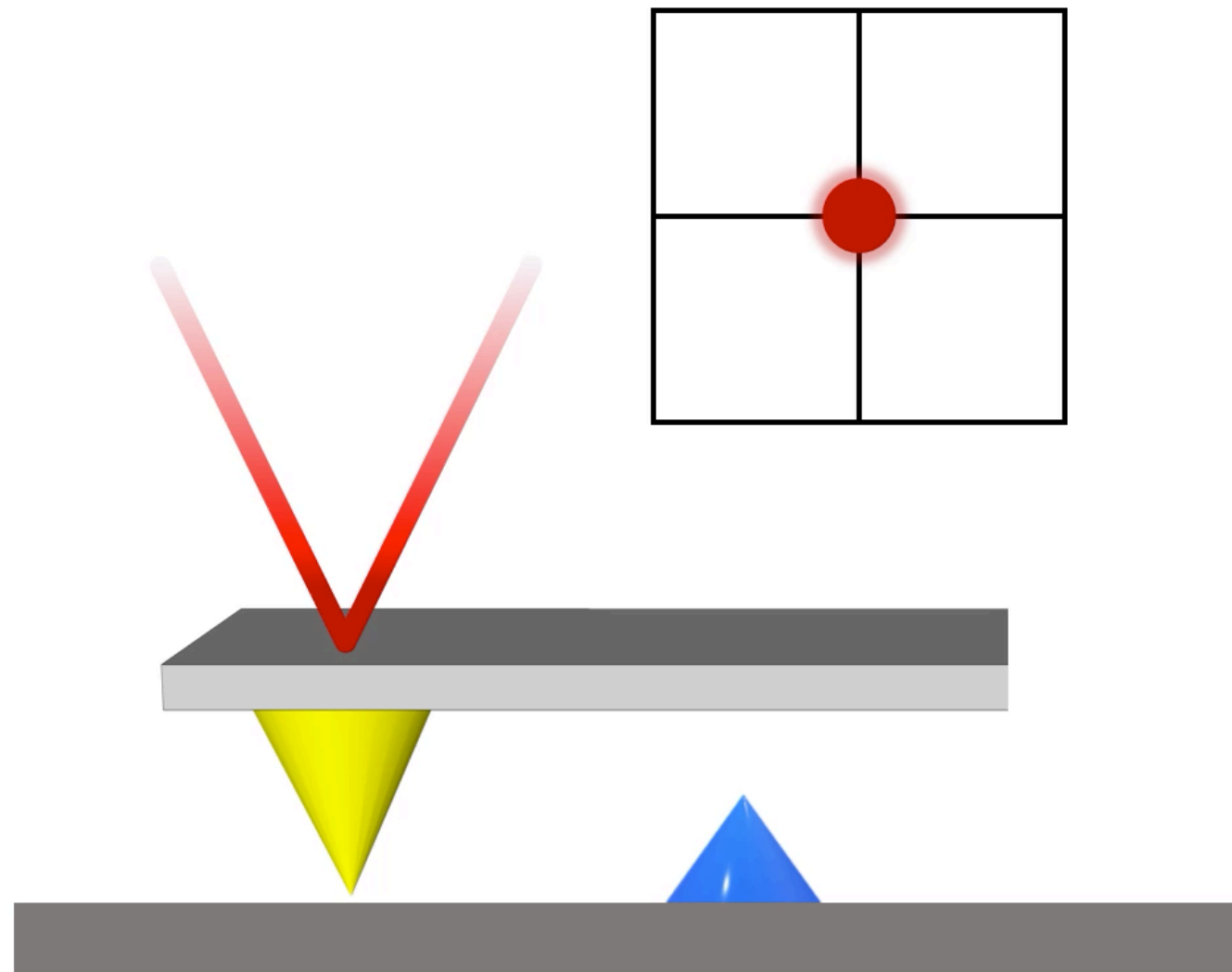
Scanning Probe Microscope



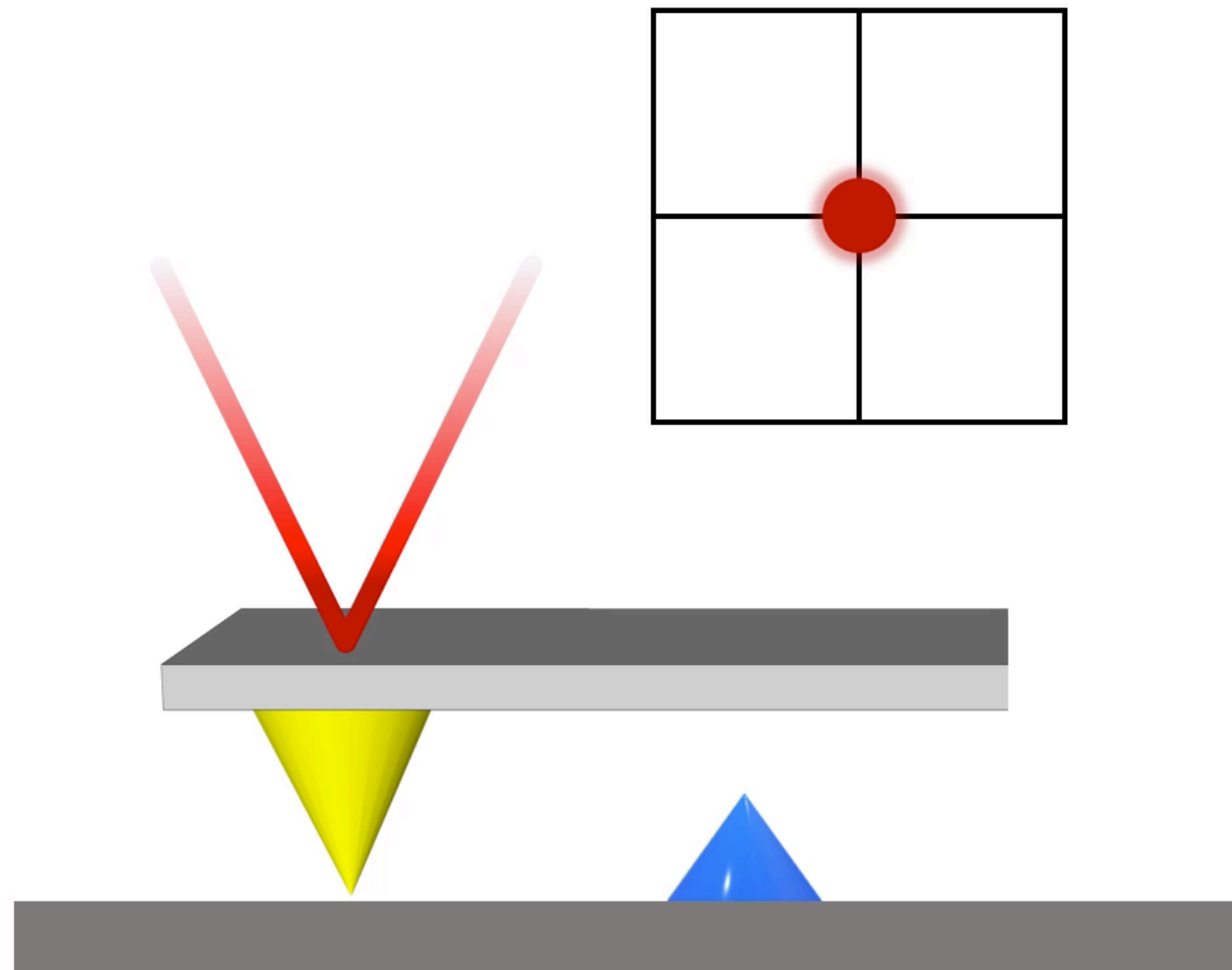
THE WAY AN AFM DOES NOT WORK



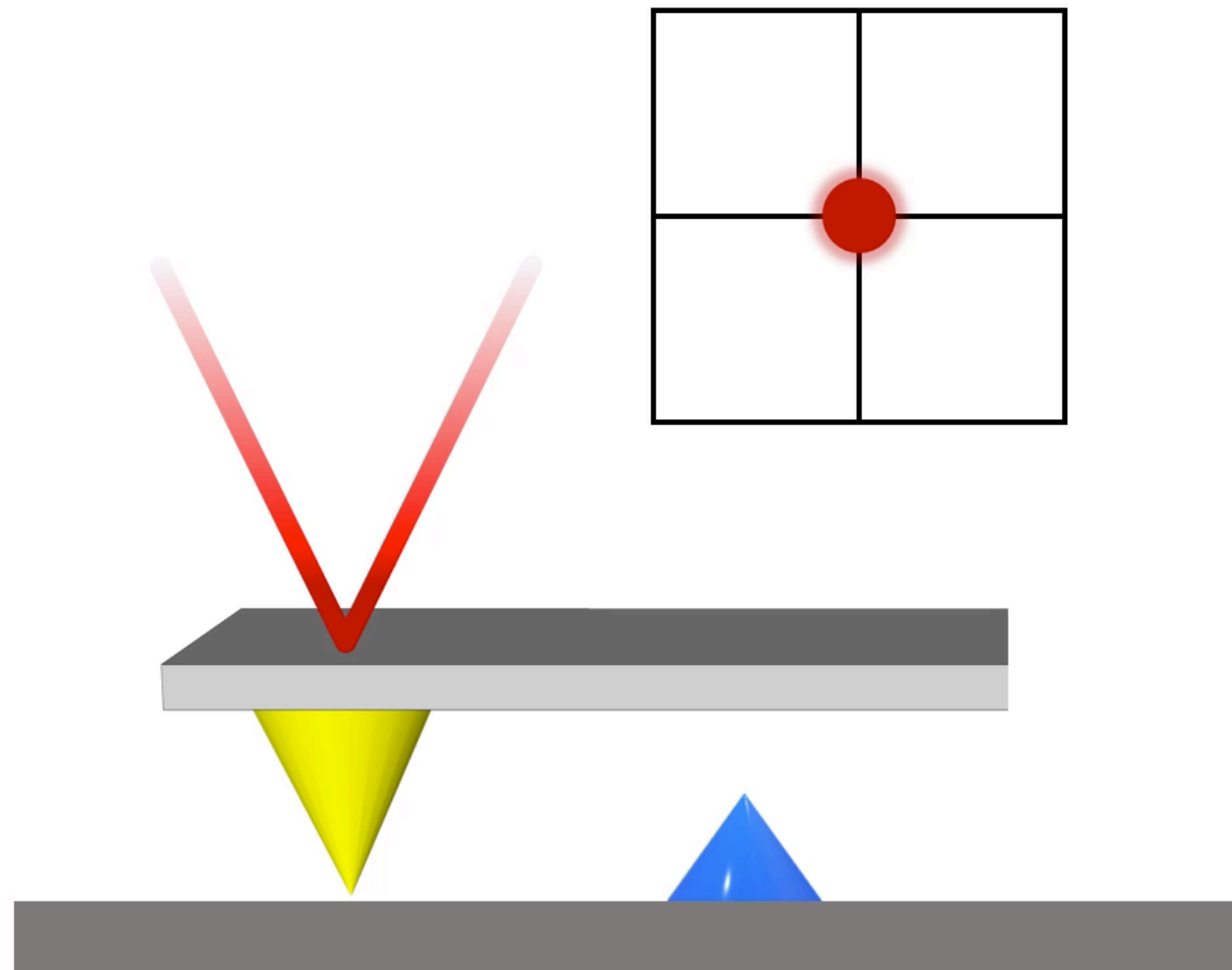
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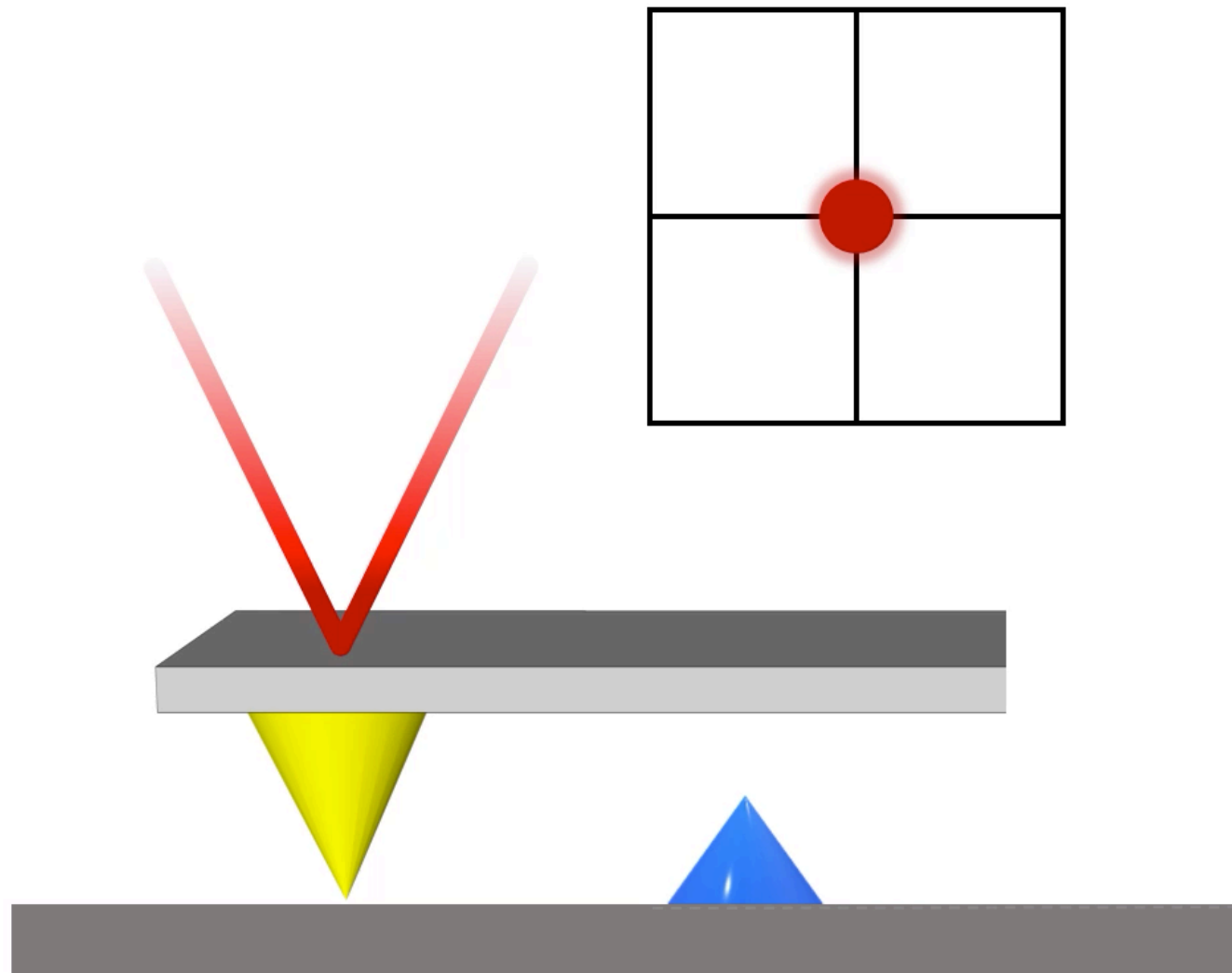
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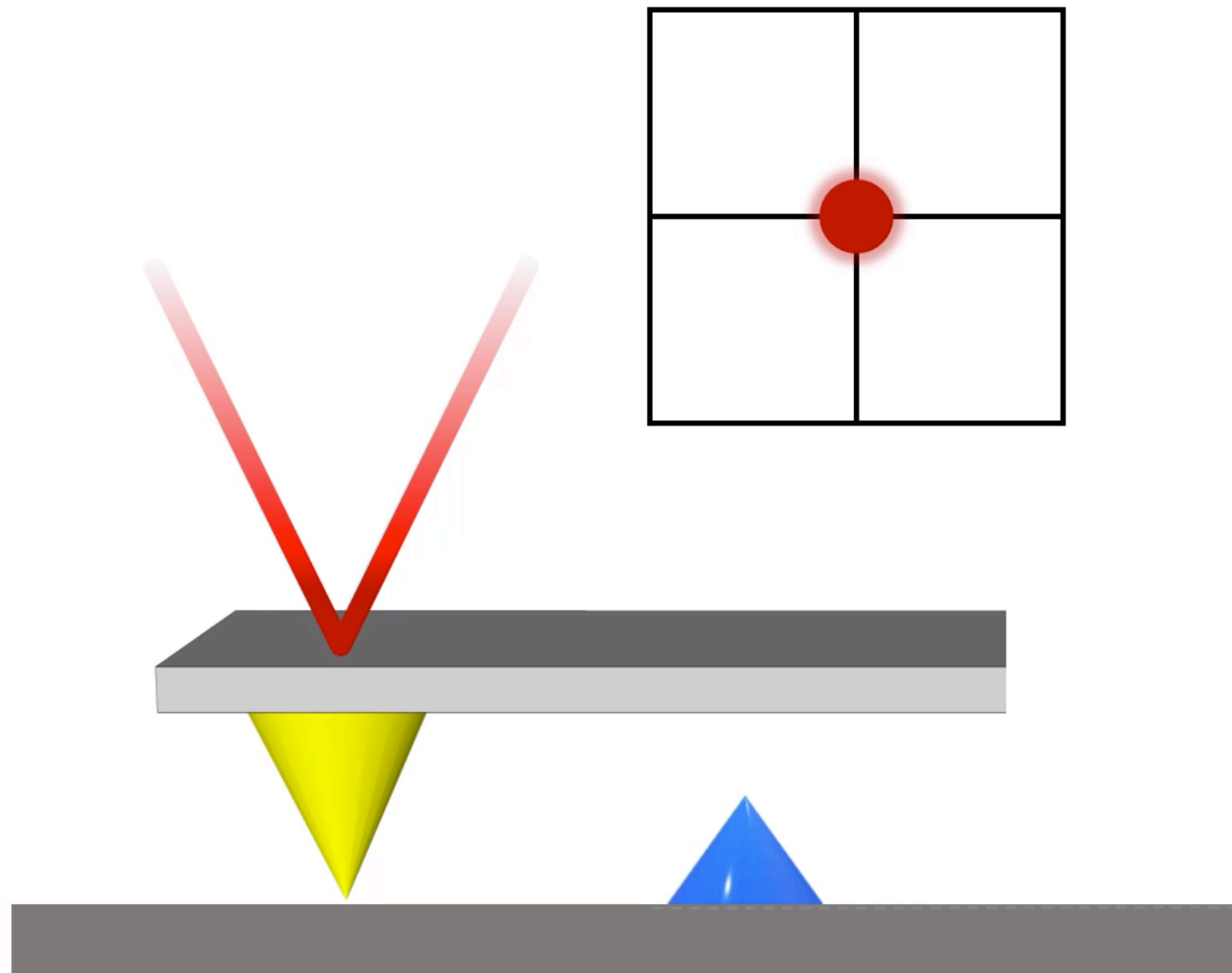
THE WAY AN AFM DOES WORK



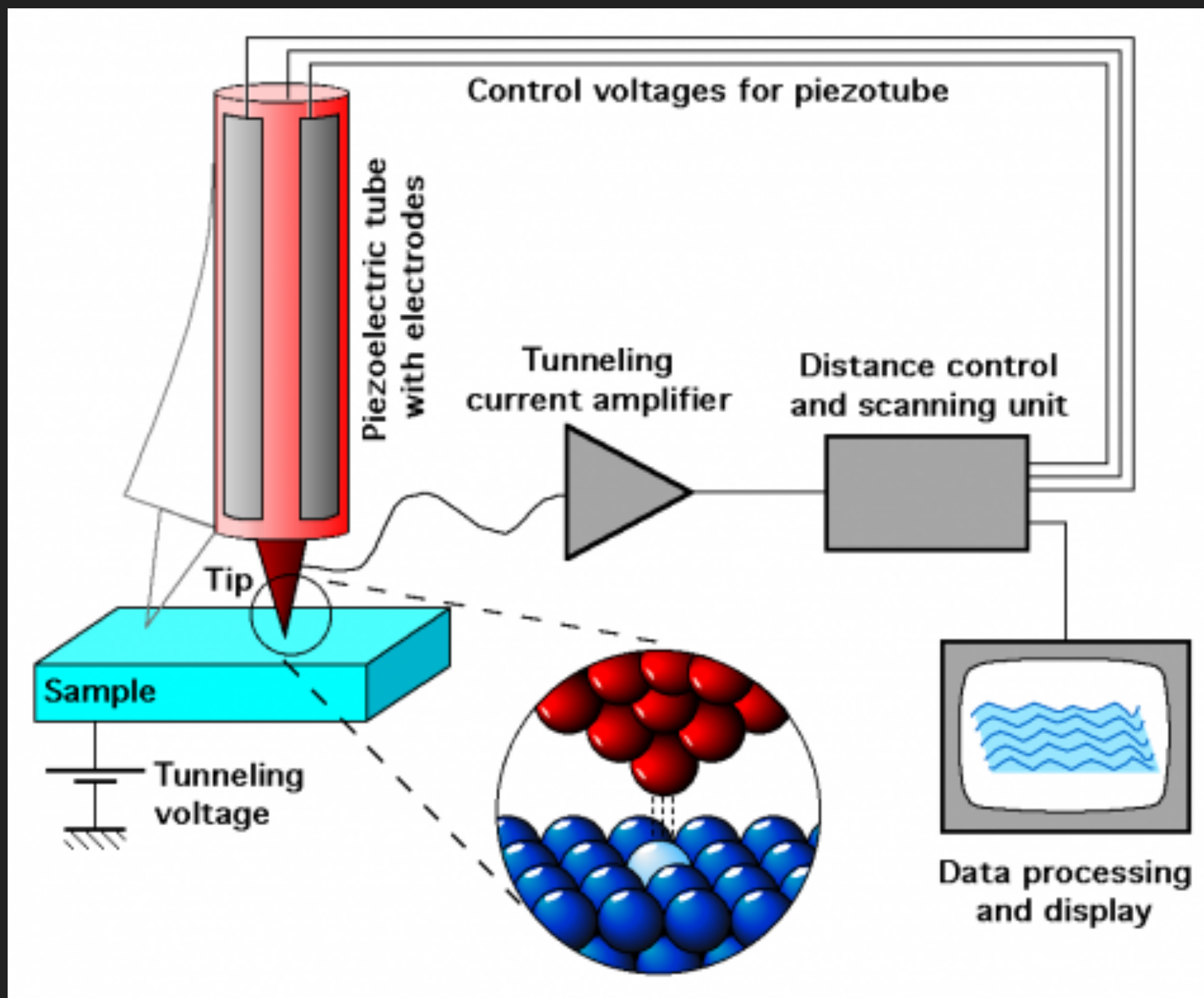
WHAT AN AFM REALLY MEASURES



WHAT AN AFM REALLY MEASURES



MEASURING SAMPLE MORPHOLOGY: STM



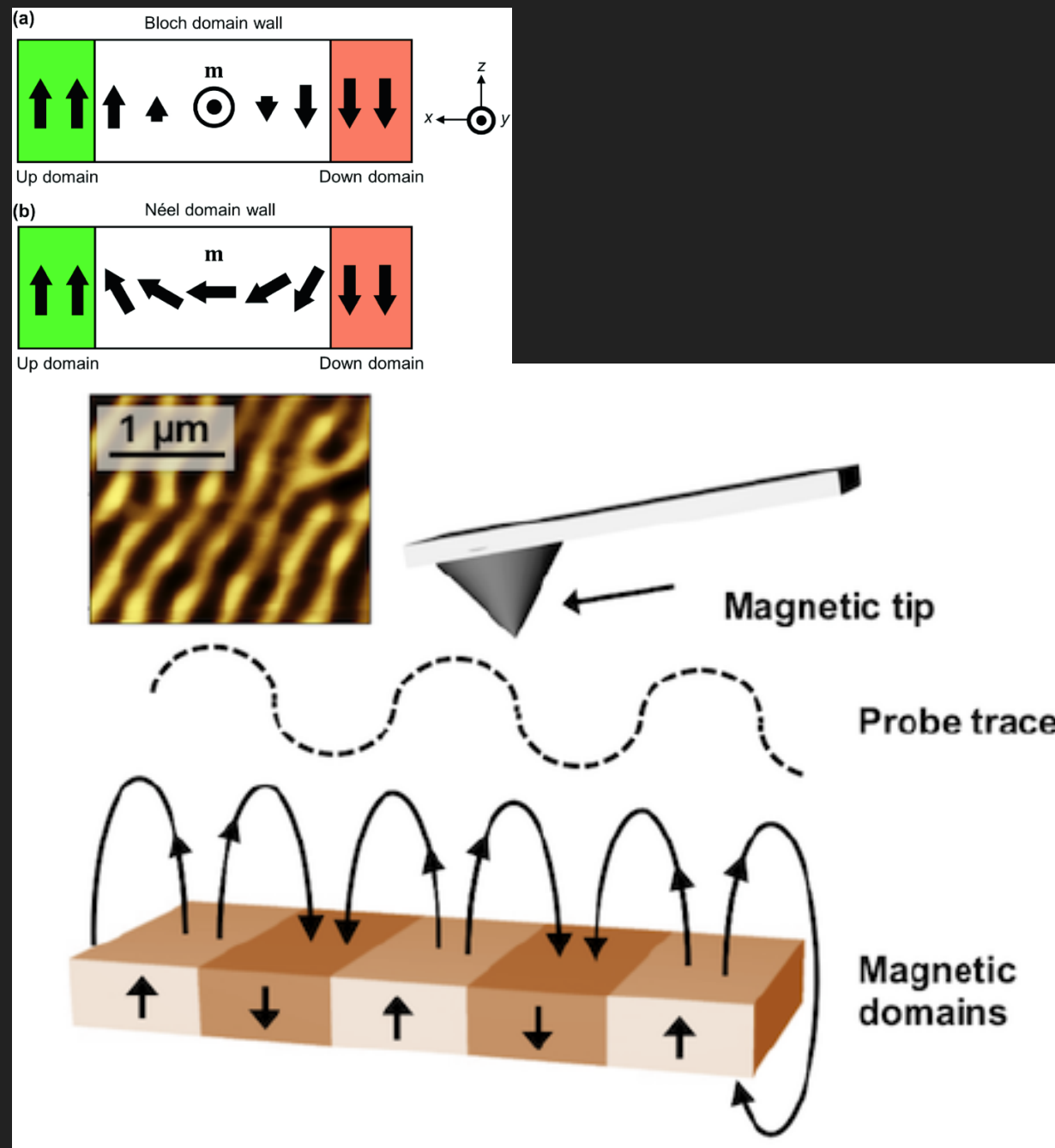
NOW WE HAVE THE MORPHOLOGY. AND THEN?

- ▶ Density of states (STM).
- ▶ Mechanical properties (AFM).
- ▶ Electric properties (STM, AFM).
- ▶ ...
- ▶ **Magnetic properties.**

MAGNETIC PROPERTIES: MFM

https://link.springer.com/chapter/10.1007/978-981-15-9176-1_1

<https://www.degruyterbrill.com/document/doi/10.2478/nanofab-2014-0003/html>



$$\nabla \cdot \vec{H} = -\nabla \cdot \vec{M}$$

$$\vec{H} = \frac{q_m \vec{r}}{4\pi r^3} \quad \text{charges}$$

$$\sigma_m = \vec{M} \cdot \vec{e}_n$$

charge density at each point of surface

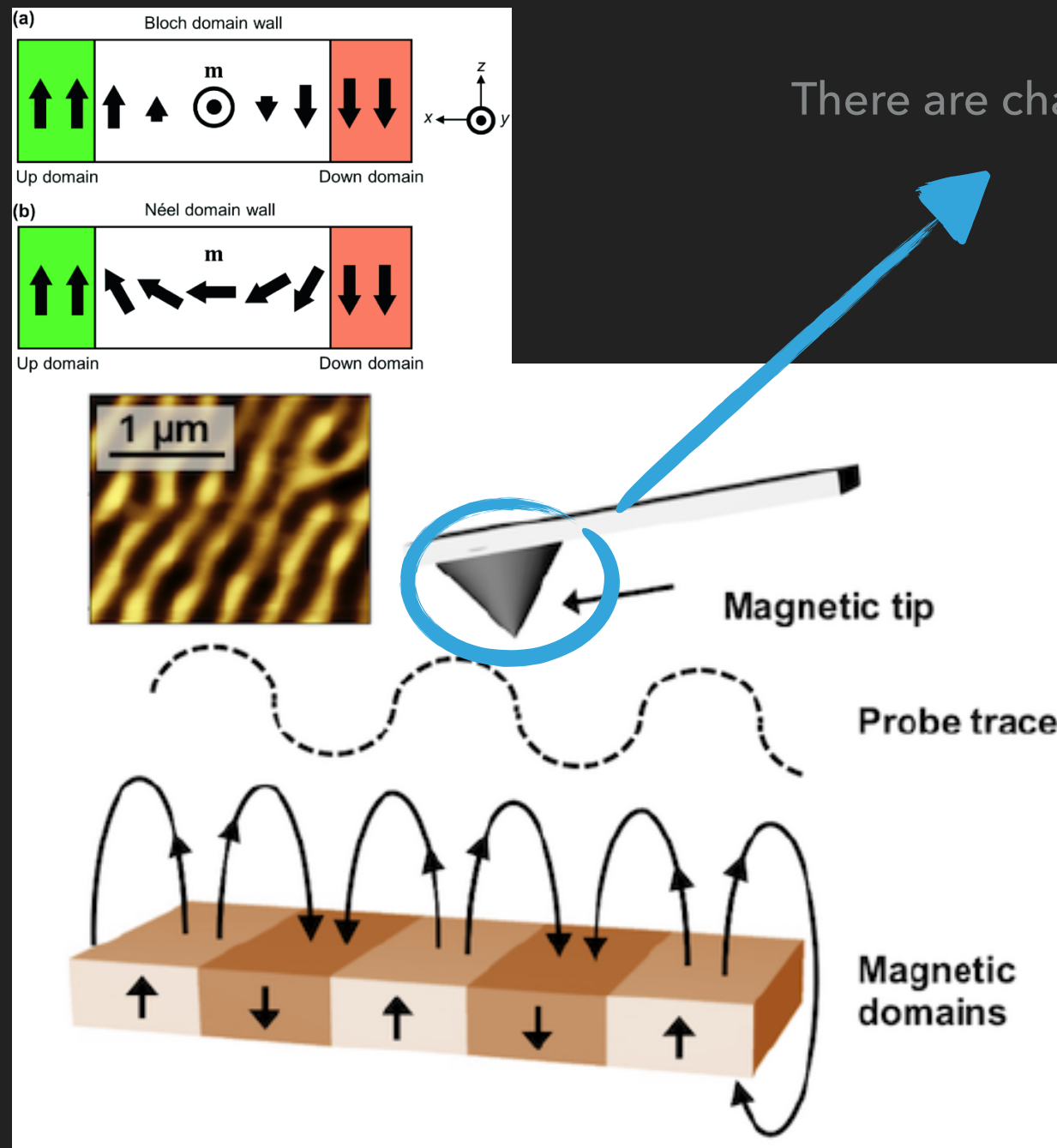
$$\vec{f}_m = \mu_0 q_m \vec{H}$$

force exerted on charges by field

MAGNETIC PROPERTIES: MFM

https://link.springer.com/chapter/10.1007/978-981-15-9176-1_1

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There are charges also at the tip!

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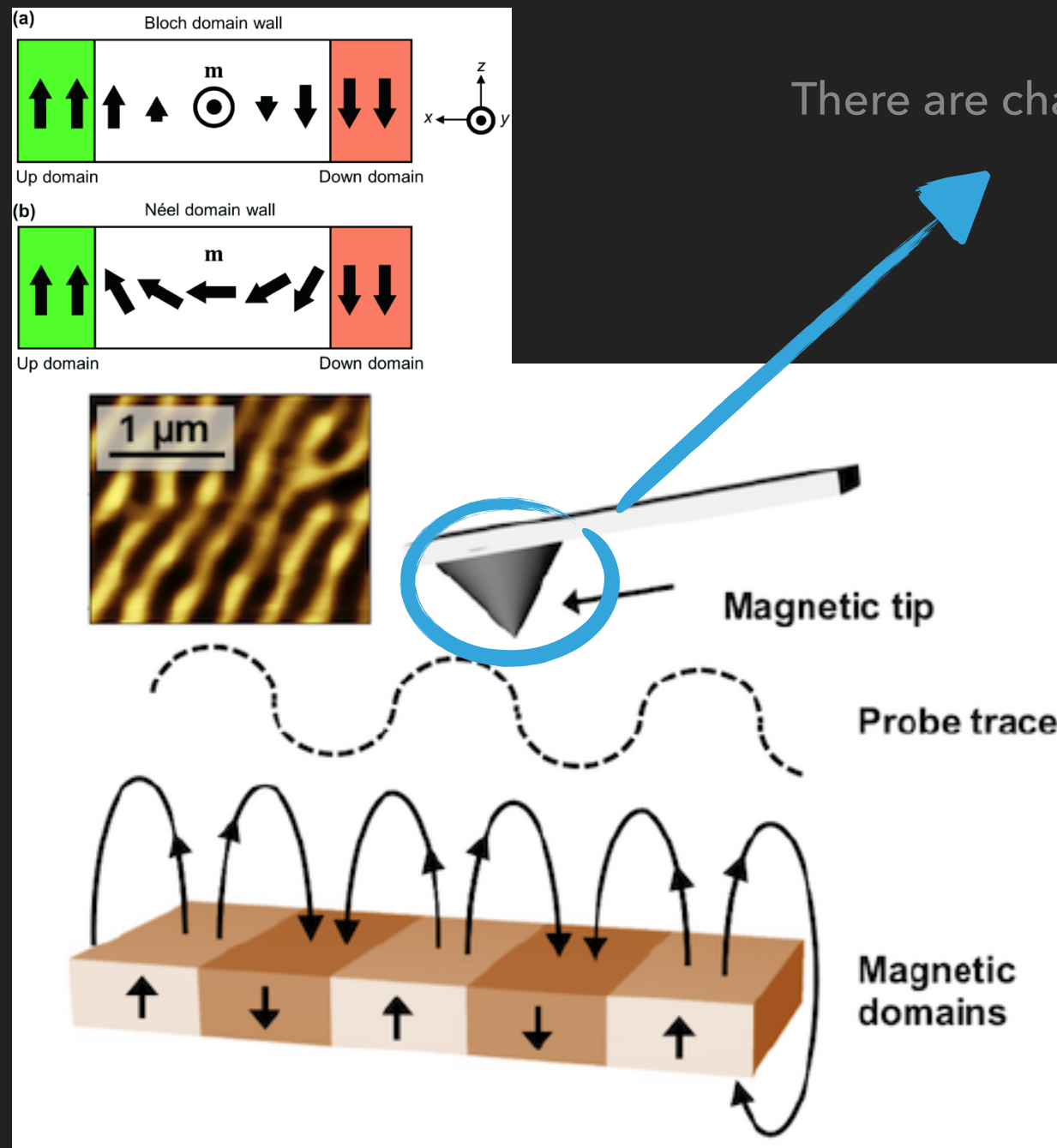
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charge density at each point of surface

$$\vec{f}_m = \mu_0 q_m \vec{H}$$

force exerted on charges by field

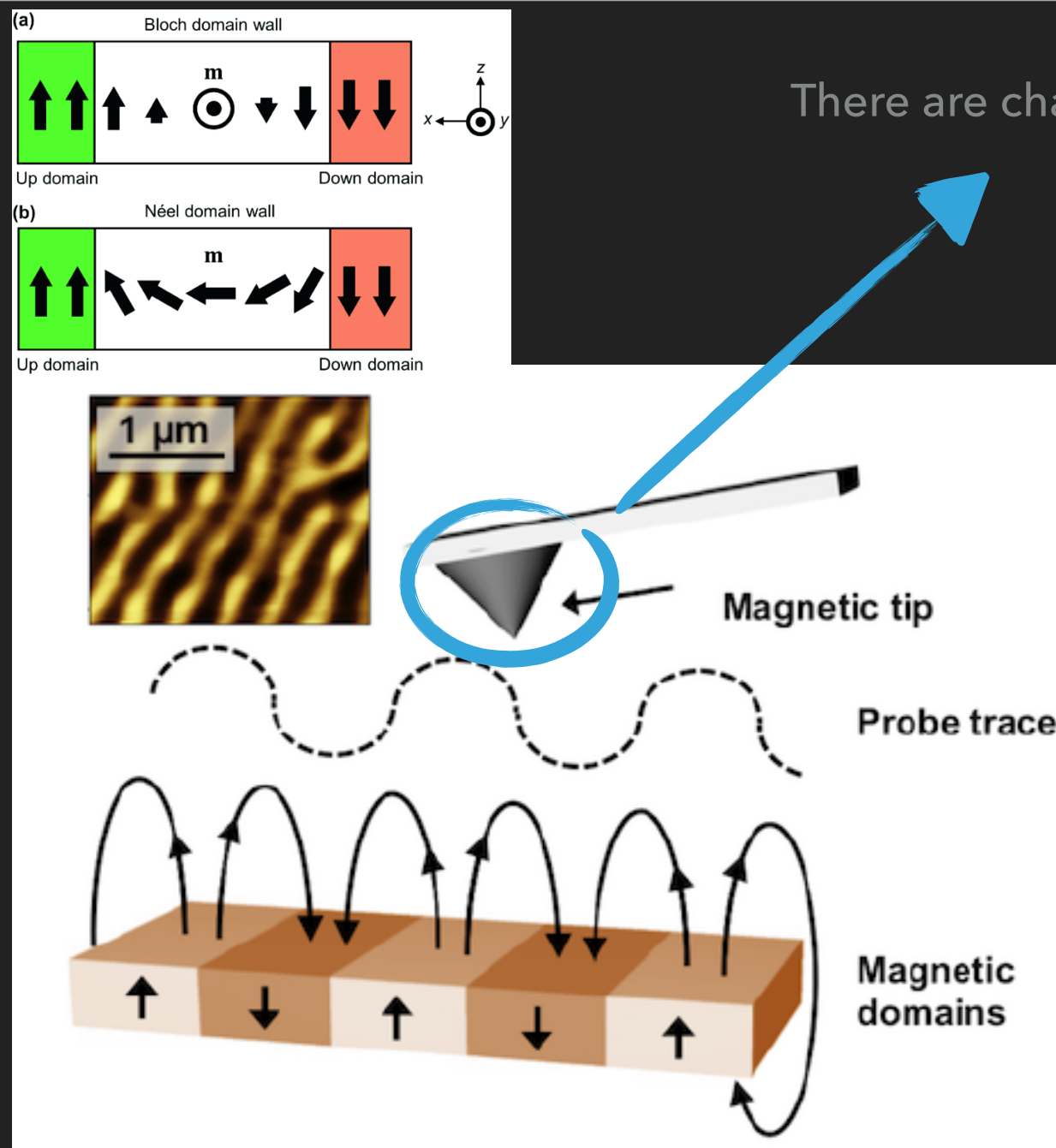
You can measure the deflection of the cantilever, or the shift of its resonance frequency, or the dephasing of its oscillations with respect to the excitation: all these quantities are proportional to:

$$\frac{\partial^2 H_z}{\partial z^2}$$

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force exerted on charges by field

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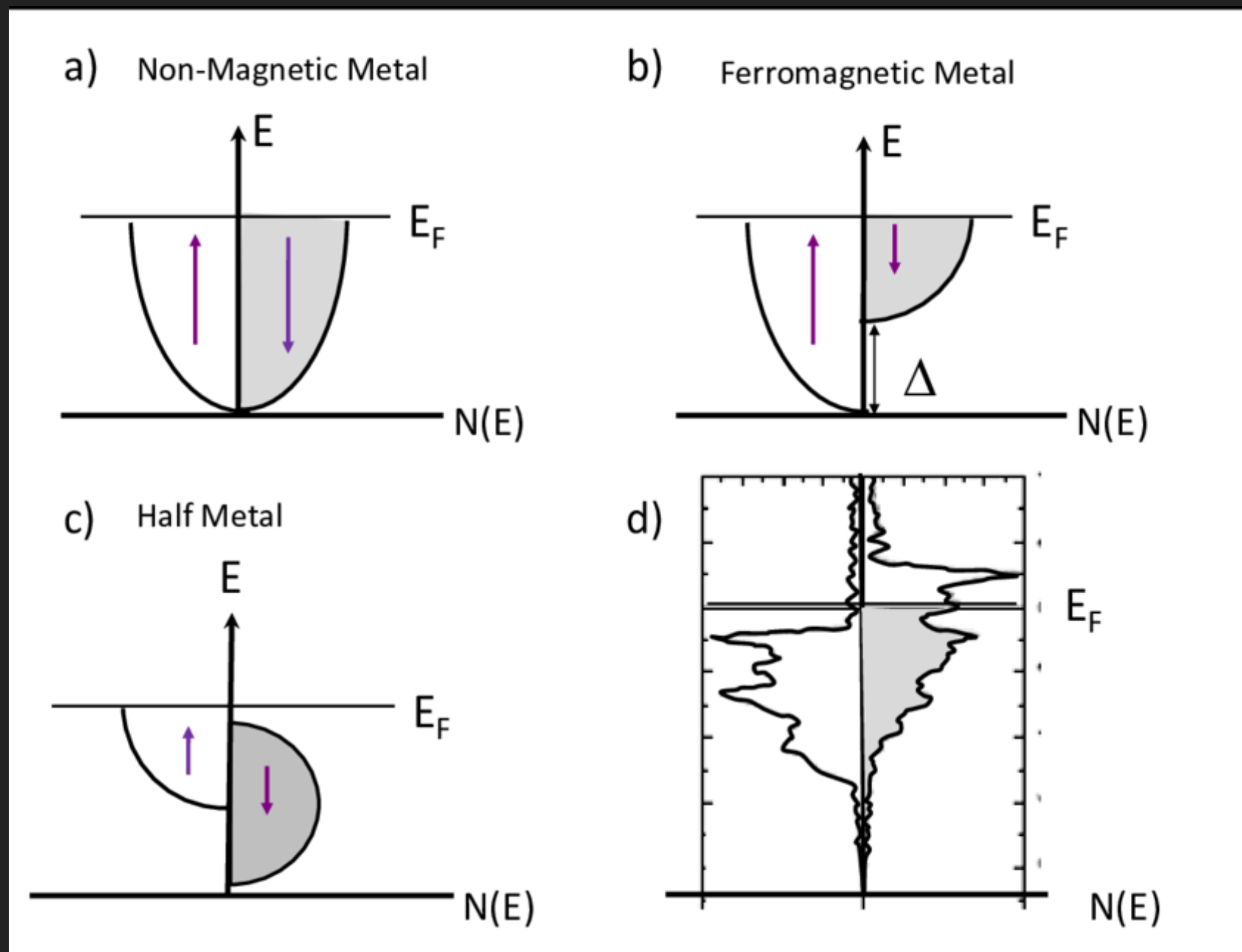
Generated by the charges on sample surface.

IS IT QUANTITATIVE?

- ▶ No. Unless complex calibration protocols are used, which require reference samples.
- ▶ In principle NV centres can give quantitative measurements of the magnetic field.
- ▶ Still, from the fringing field you must calculate the magnetic charge density on the sample surface and from that you can try to infer the magnetisation of the sample.

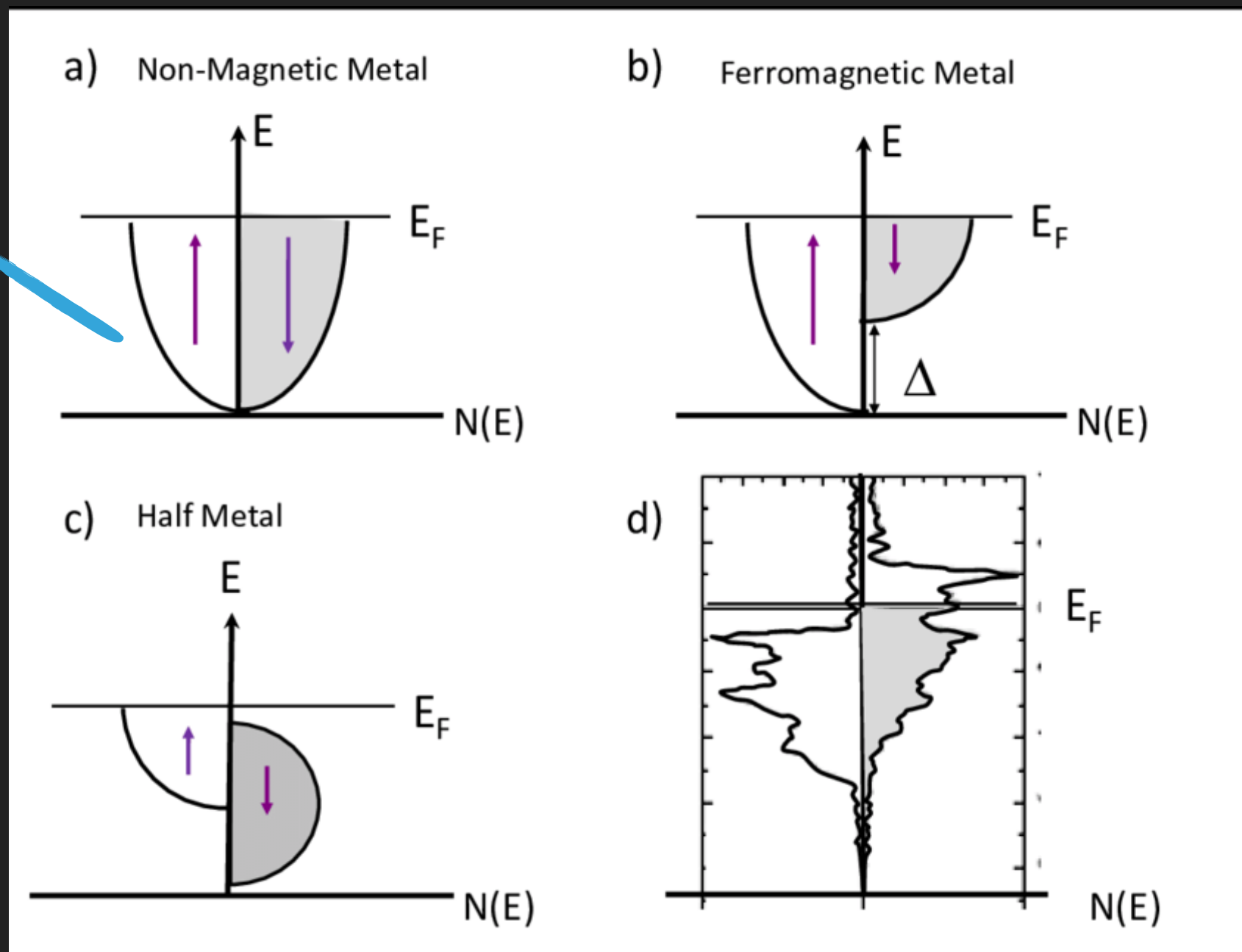
AND SPIN-POLARISED STM?

- ▶ An interesting principle: asymmetry of the spin up and down density of states in a magnetic material.



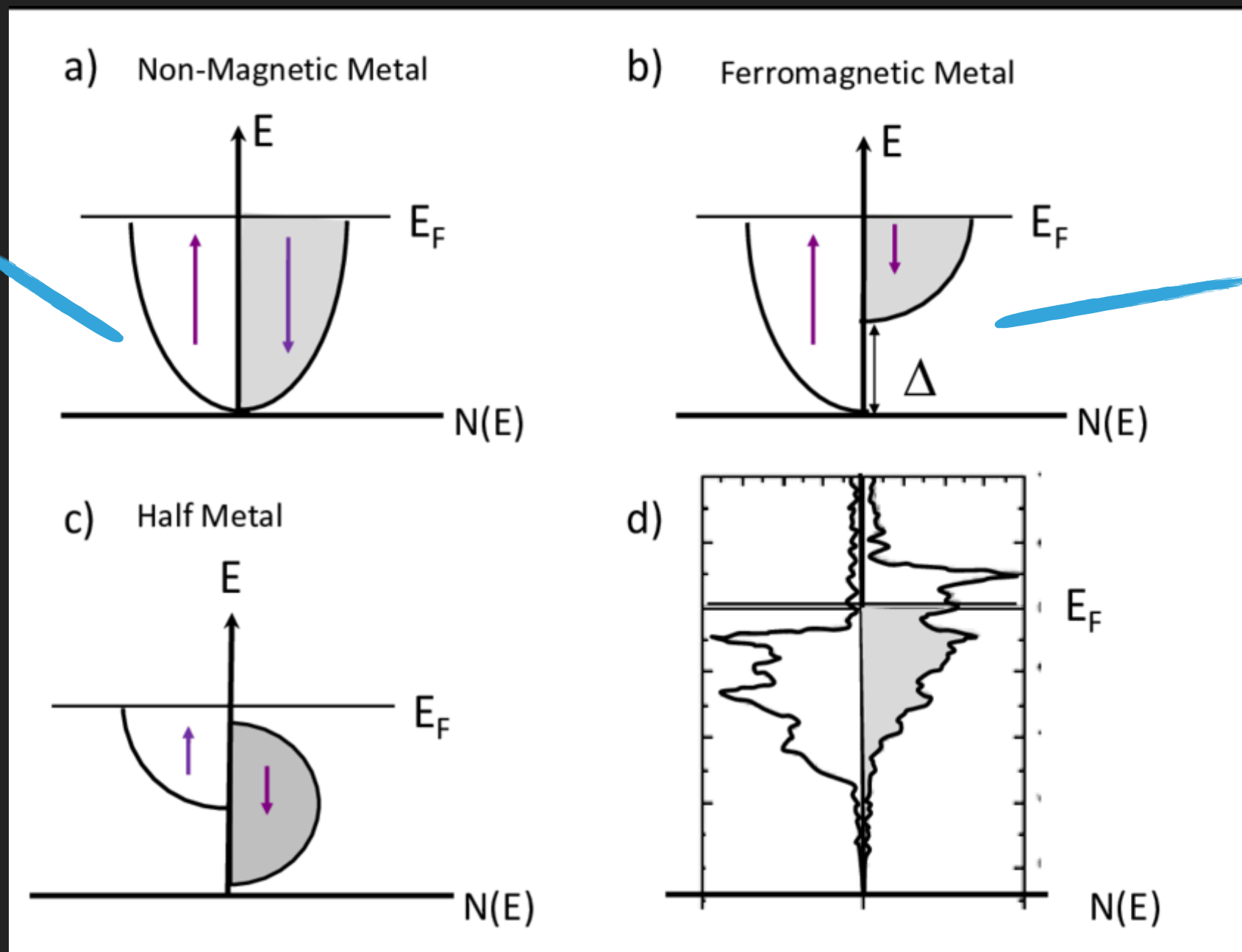
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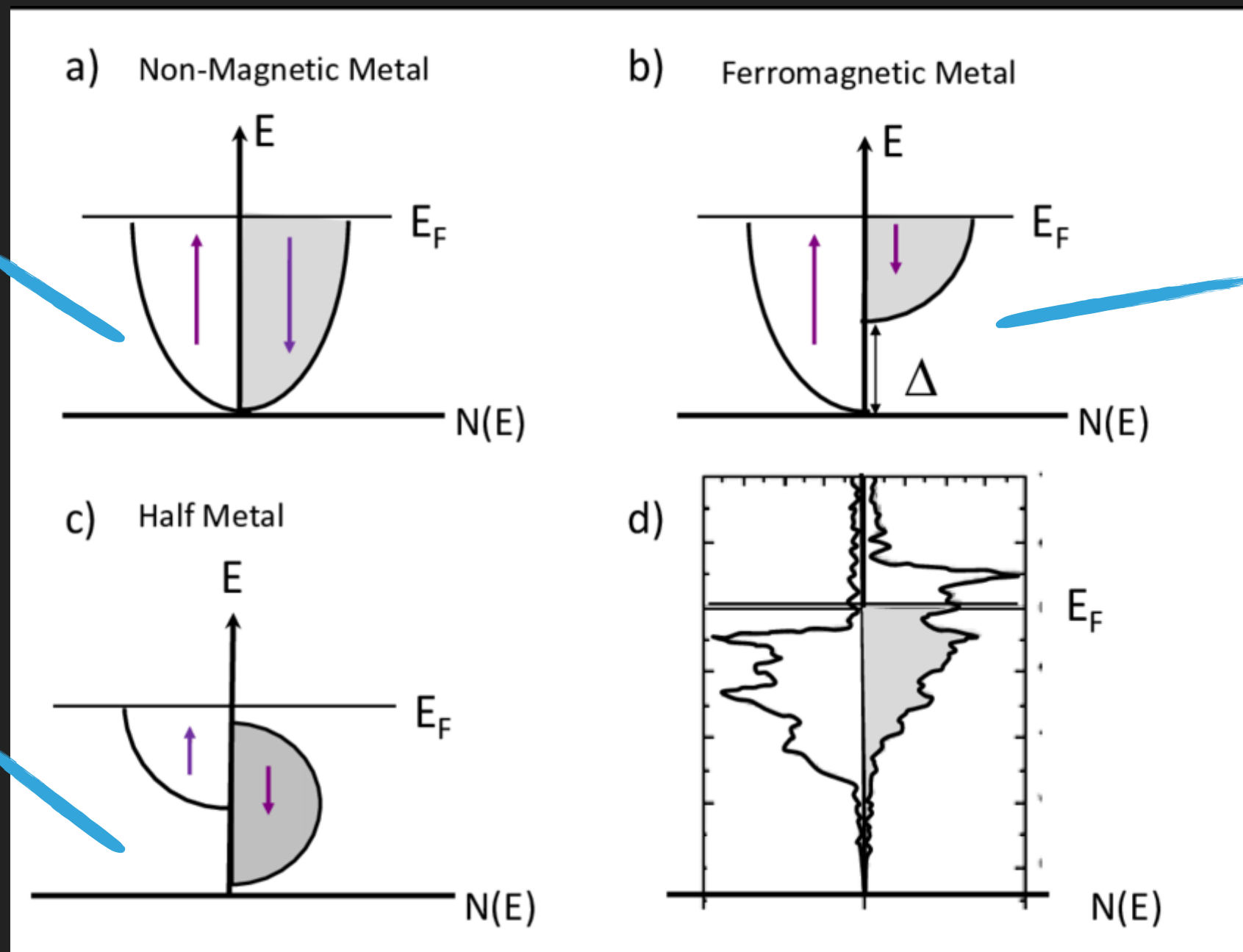
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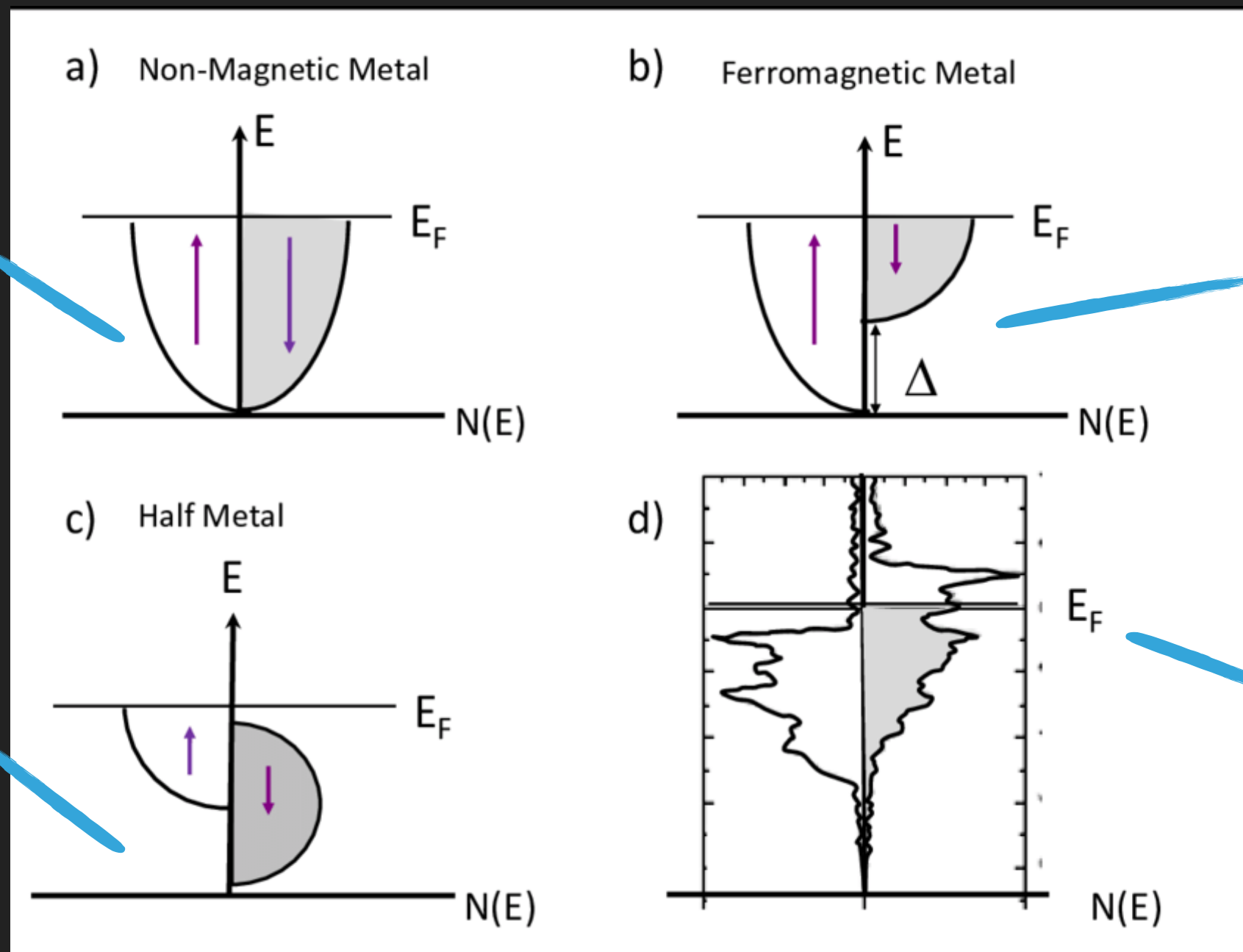
Spin up and down have different density of states.

Oh boring metals.

Interesting things happen at the Fermi level.

AND SPIN-POLARISED STM?

- ▶ An interesting principle: asymmetry of the spin up and down density of states in a magnetic material.

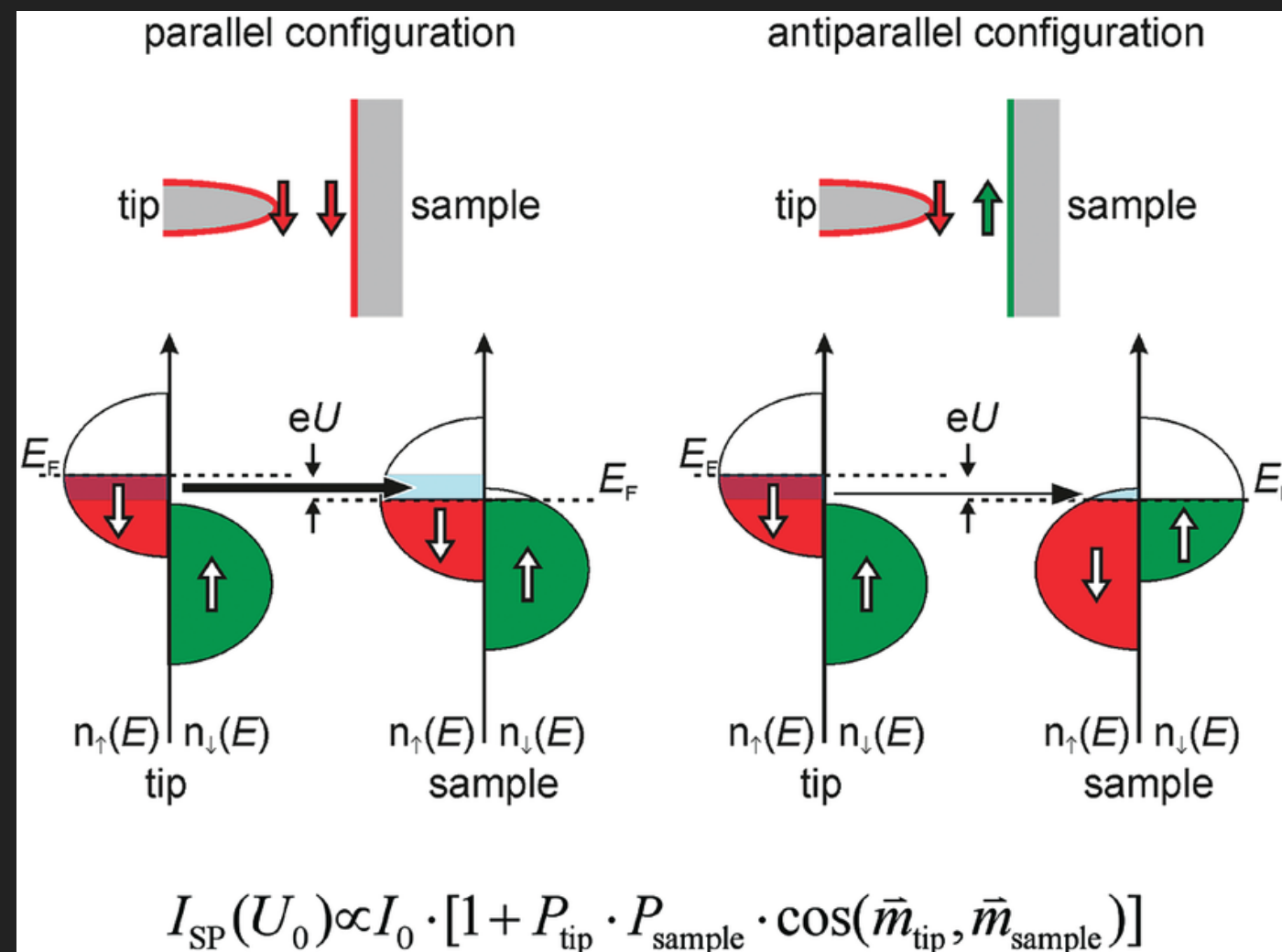


Spin up and down have different density of states.

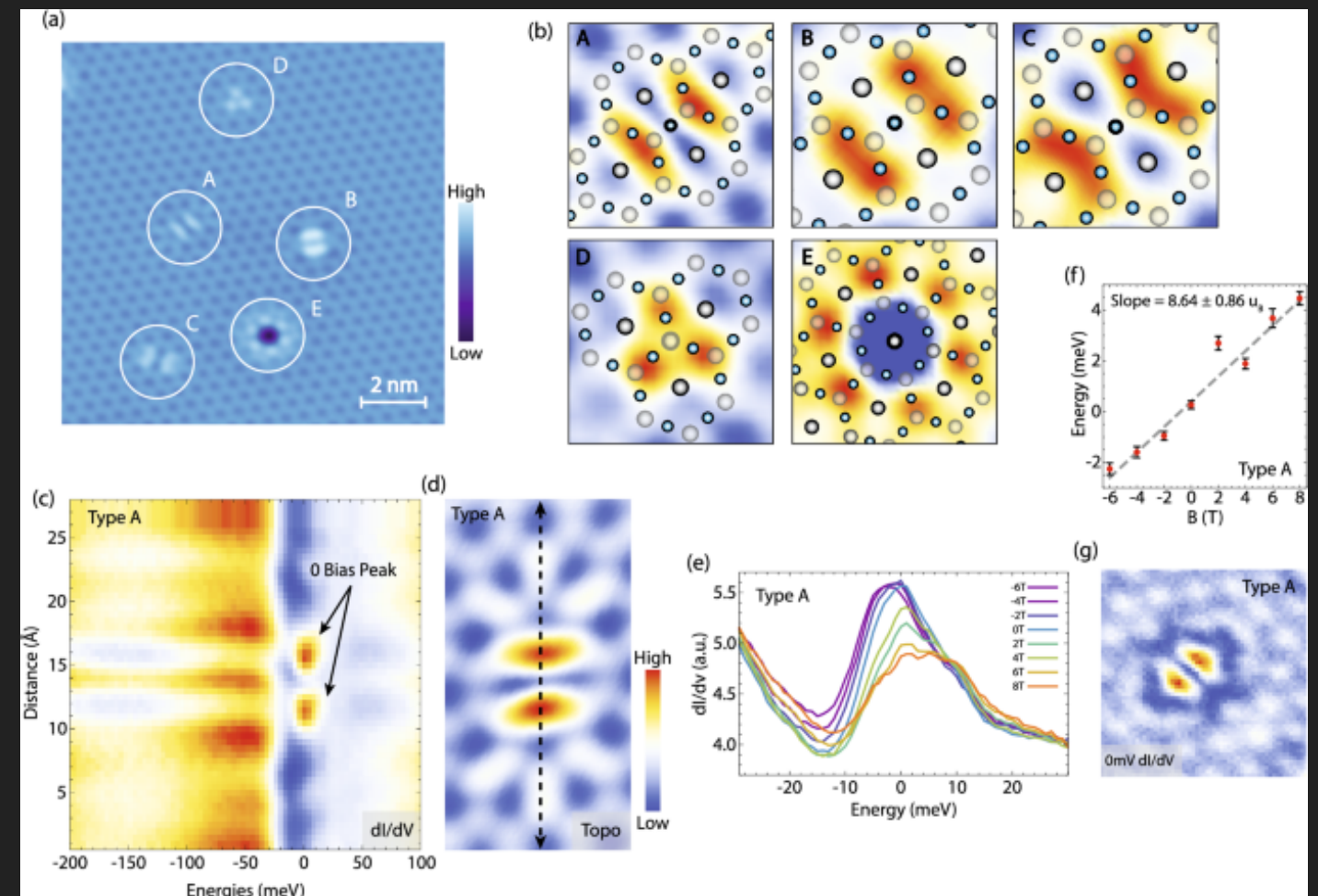
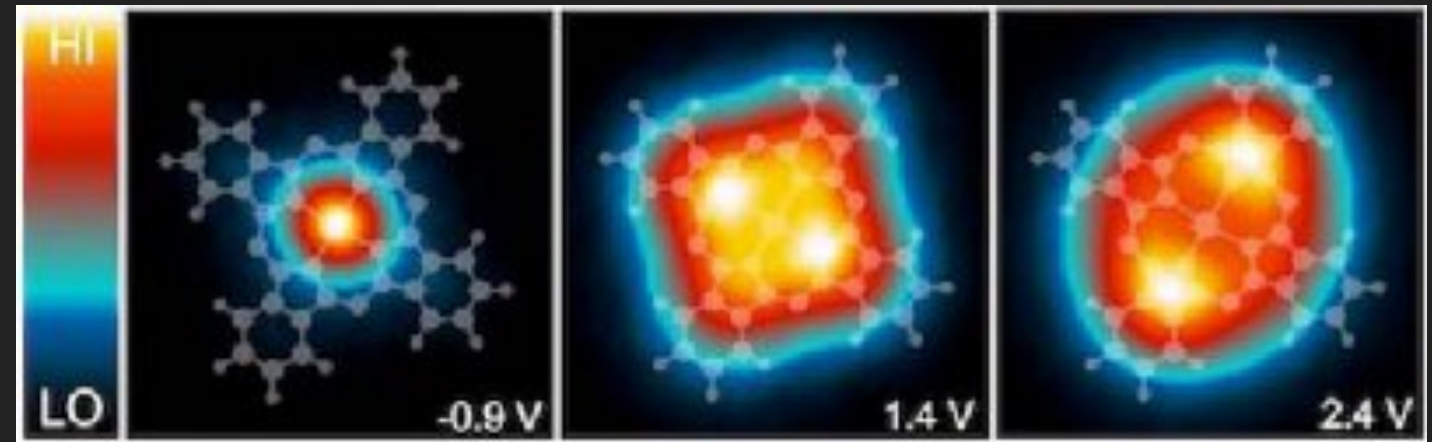
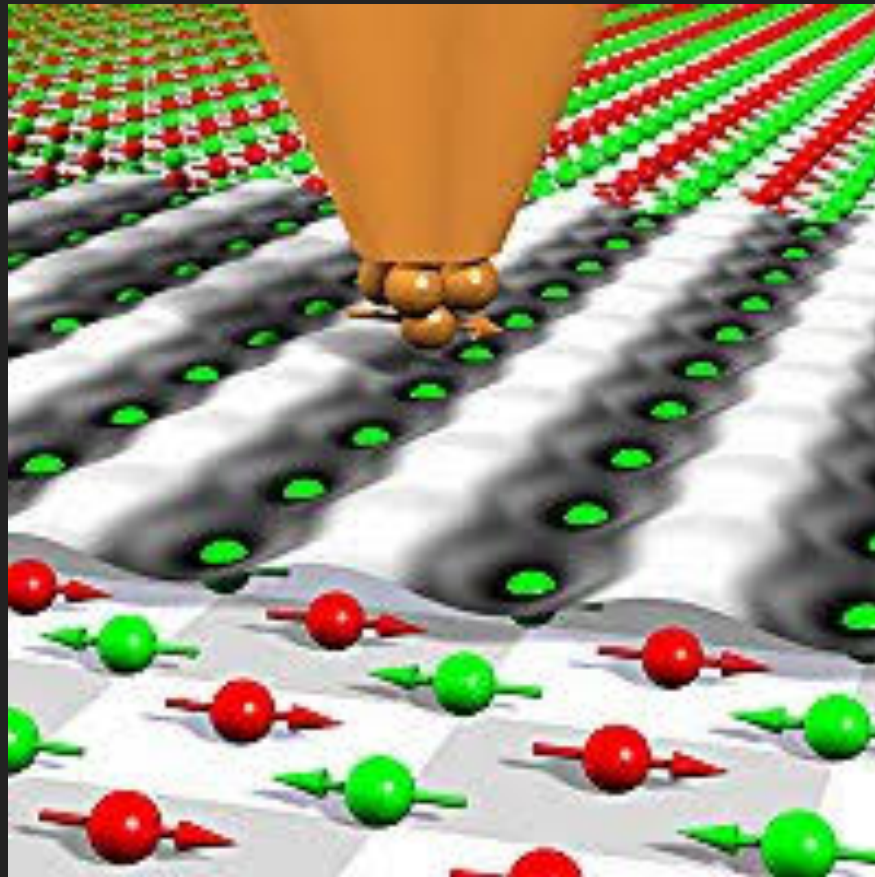
Fully polarised magnetic materials.

AND SPINS-POLARISED STM?

- ▶ Spin polarisation at the tip and at the sample Fermi level.
- ▶ Exclusion principle: only electrons with spins compatible with empty levels at the Fermi energy of the material receiving them can tunnel, the others are blocked.



FOR ATOMS, NOT FOR DOMAINS



http://www.nanoscience.de/group_r/stm-spstm/

<https://www.ipcms.fr/en/jean-pierre-bucher-2/research-jp-bucher/spin-polarized-stm-spectroscopy-on-single-objects/>

<https://www.nature.com/articles/s41598-022-18678-8>

BLS

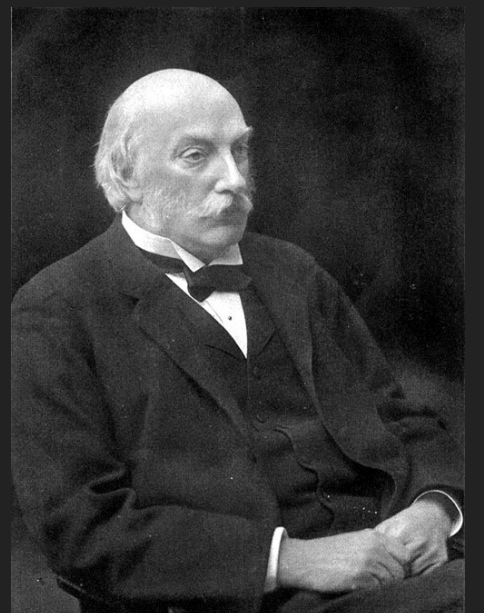
BRILLOUIN LIGHT SCATTERING



- ▶ Named after Léon Nicolas Brillouin.
- ▶ A **spectroscopy** technique.
- ▶ Traditionally, interaction between optical and acoustic fields in optical waveguides.
- ▶ More generally, interaction between photons and quasiparticles of the solid state (**phonons, polarons, magnons**).
- ▶ Gives information on **spin-transfer** phenomena and **spin-wave** propagation.

BRILLOUIN VS. RAMAN VS. RAYLEIGH

- ▶ **Brillouin:** scattering of photons with large-scale, low-frequency phonons, fluctuations are periodic and correlated.
- ▶ **Raman:** inelastic process where photons are scattered by vibrational and rotational transitions of neighbouring atoms.
- ▶ **Rayleigh:** elastic, involves only random, incoherent fluctuations.



https://commons.wikimedia.org/wiki/File:Léon_Brillouin_Solvay_conference_1927.jpg

https://commons.wikimedia.org/wiki/File:Sir_CV_Raman.JPG

https://commons.wikimedia.org/wiki/File:John_William_Strutt.jpg

BRILLOUIN VS. RAMAN VS. RAYLEIGH

Light and small particles or inhomogeneities, elastic

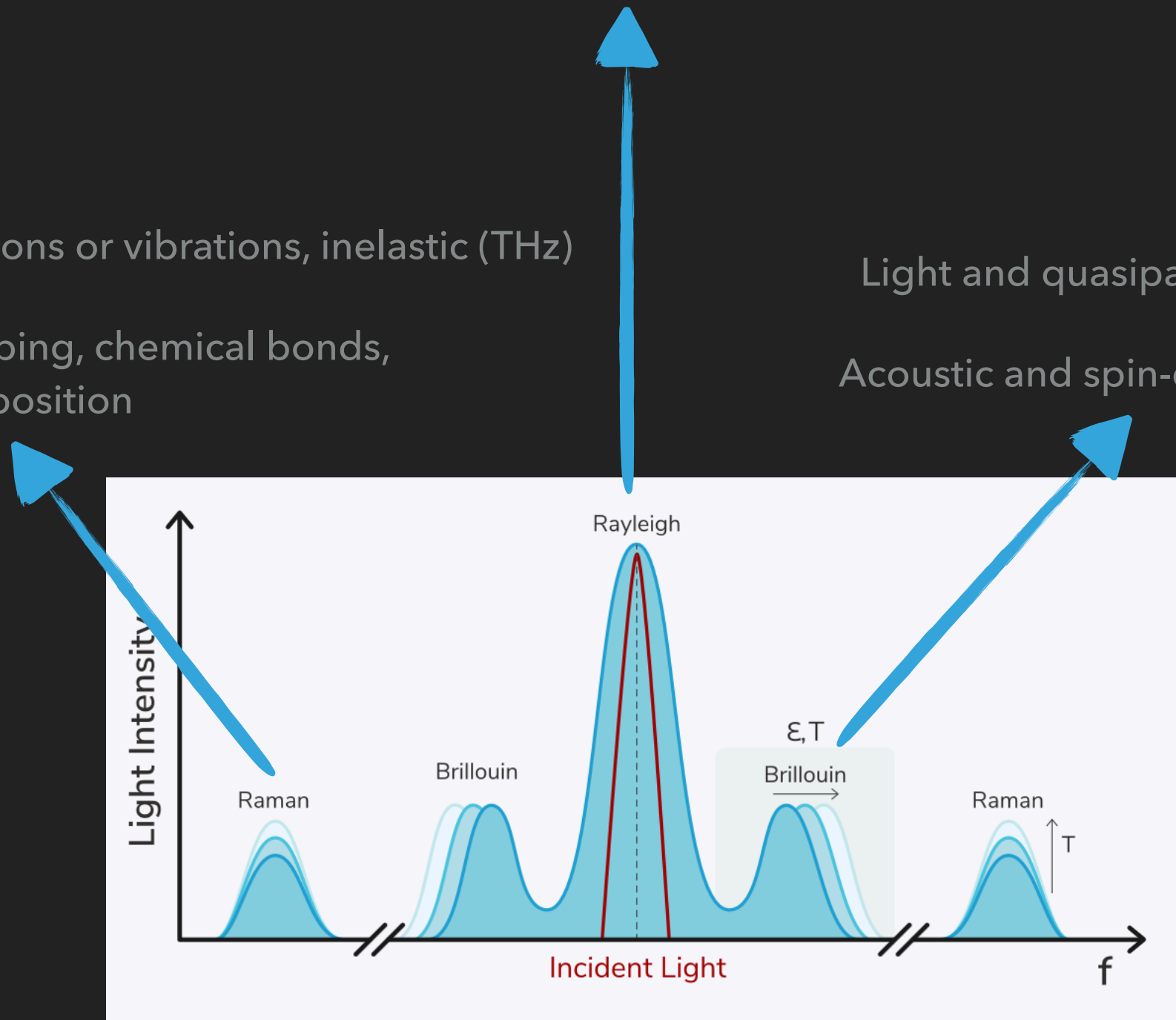
Particle size and shape analysis, LiDAR

Light with phonons or vibrations, inelastic (THz)

Label-free mapping, chemical bonds,
molecular composition

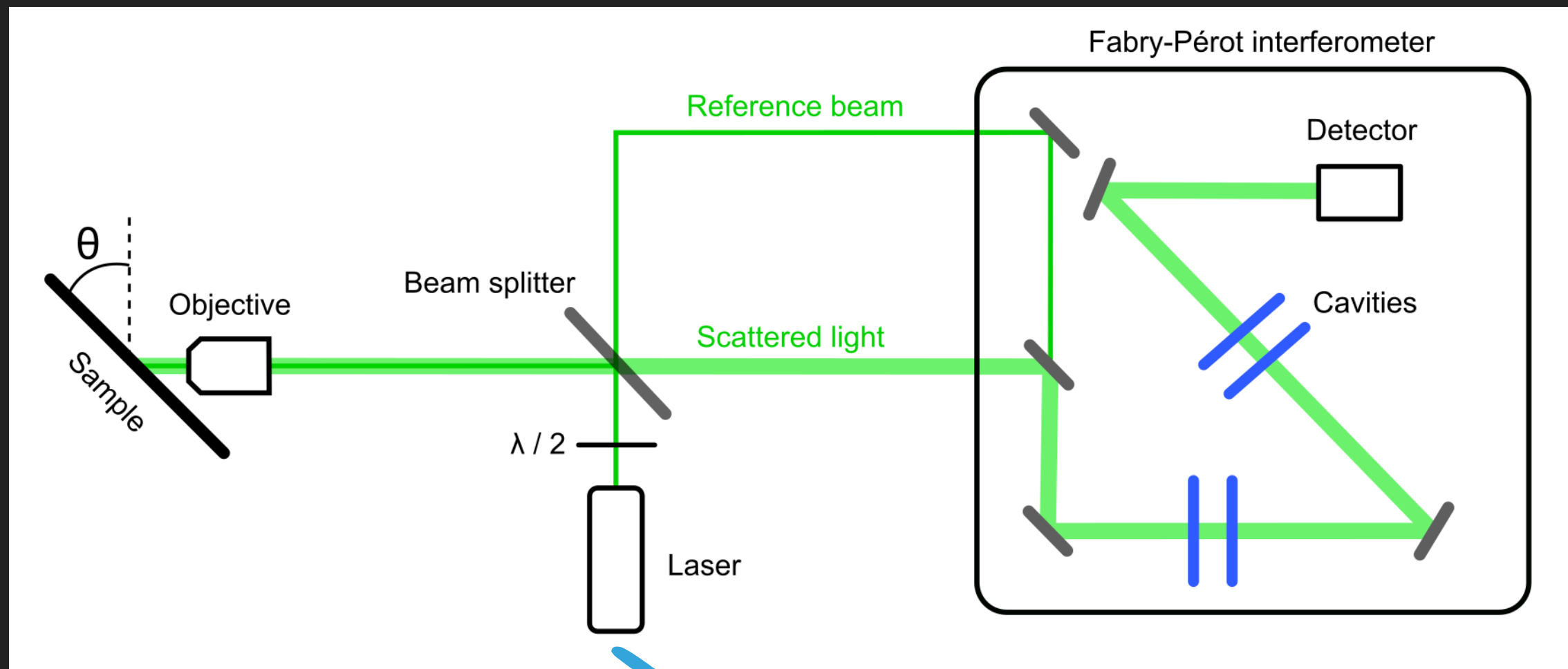
Light and quasiparticles, inelastic (GHz)

Acoustic and spin-dependent properties



BLS IN A NUTSHELL

optical filter to analyse the frequency shifts resulting from photon-magnon and photon-phonon interactions



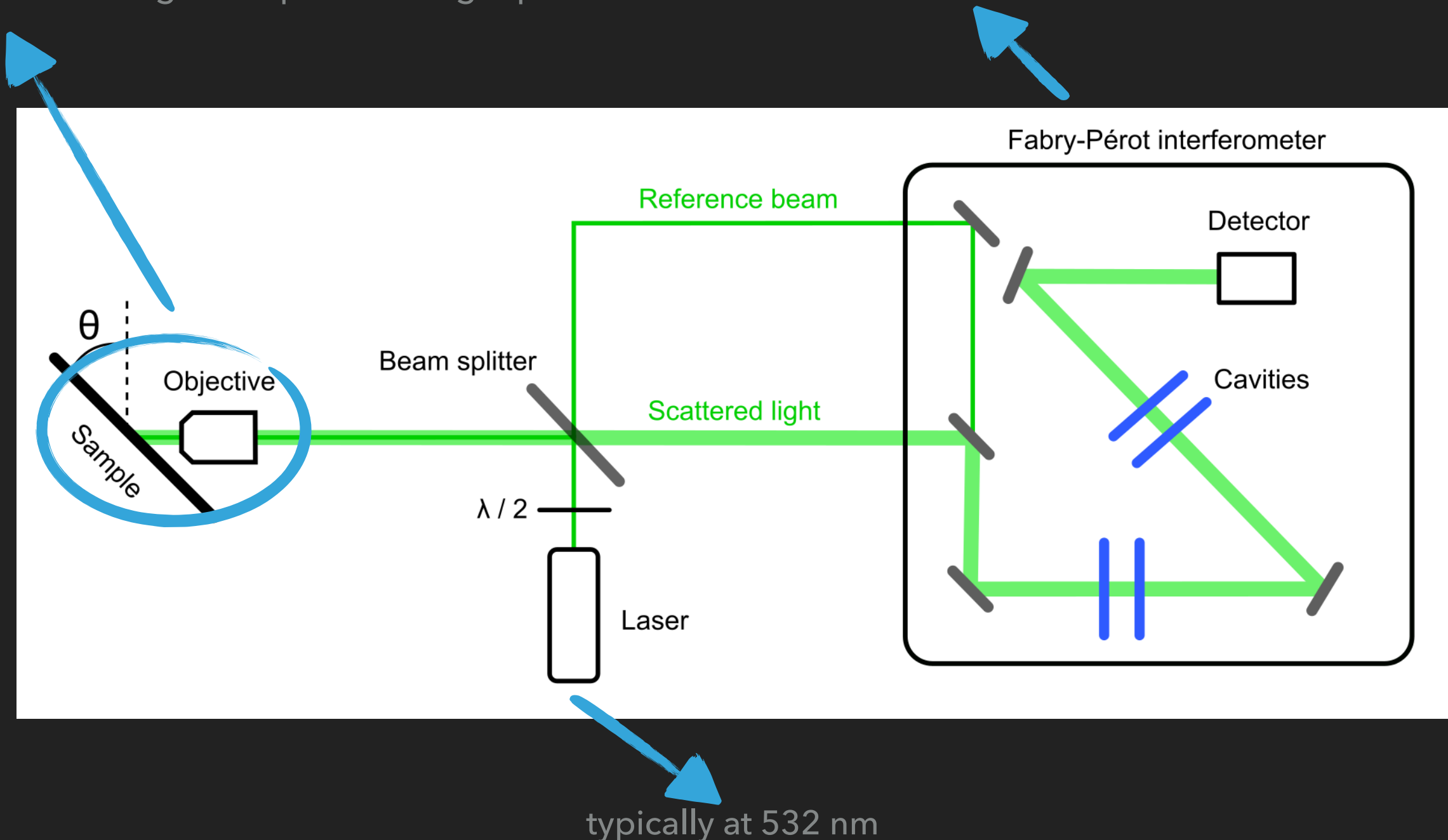
typically at 532 nm

Time stamps are assigned to laser pulses, detected photons and internal state of the interferometer. The temporal evolution of the spectra is then reconstructed.

BLS IN A NUTSHELL

Narrow focussing + sample scanning = μ BLS

optical filter to analyse the frequency shifts resulting from photon-magnon and photon-phonon interactions



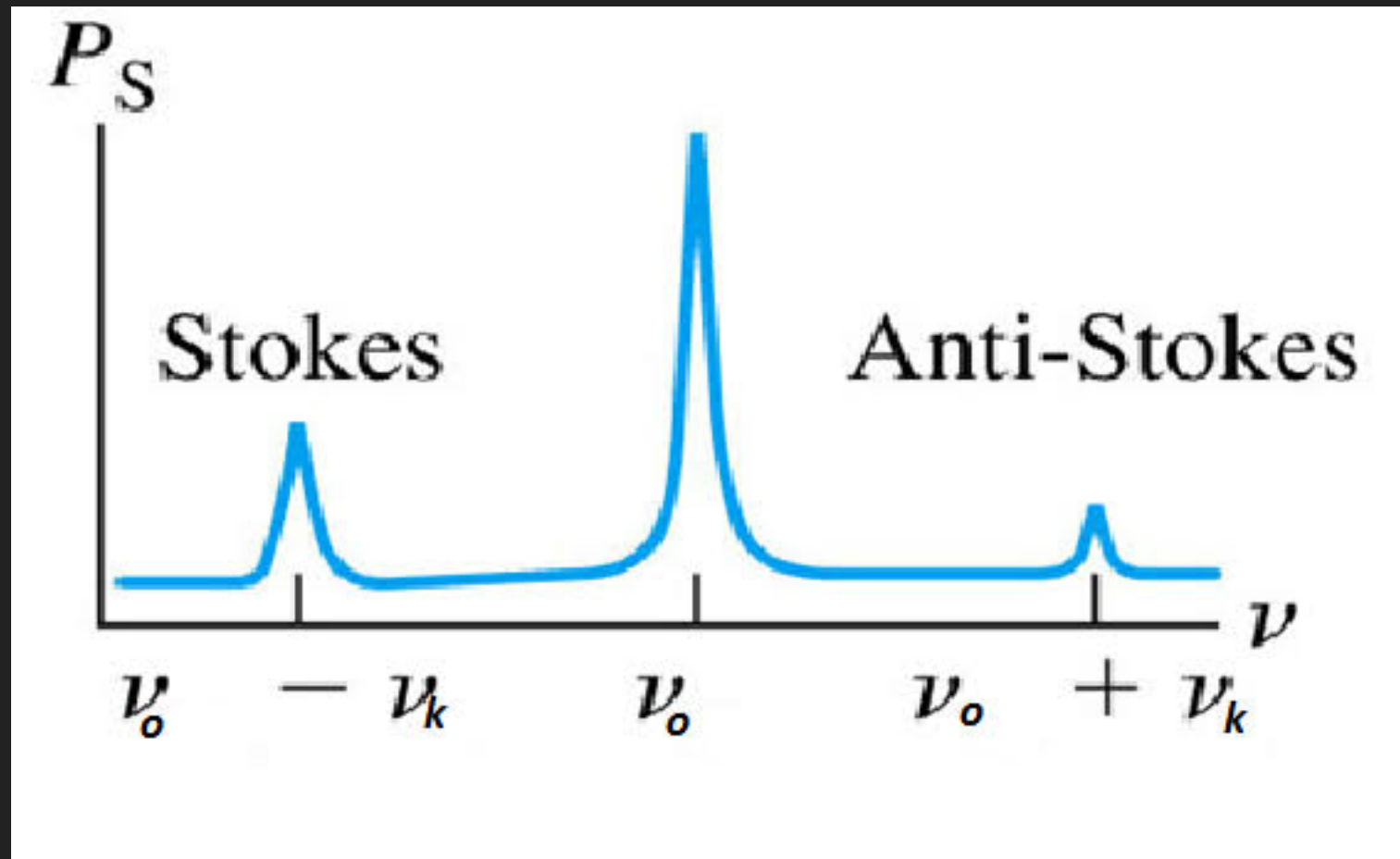
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STOKES AND ANTI-STOKES

<https://commons.wikimedia.org/wiki/File:Ggstokes.jpg>

https://www.researchgate.net/publication/336747033_Development_of_methods_based_on_NIR_and_Raman_spectroscopies_together_with_chemometric_tools_for_the_qualitative_and_quantitative_analysis_of_gasoline

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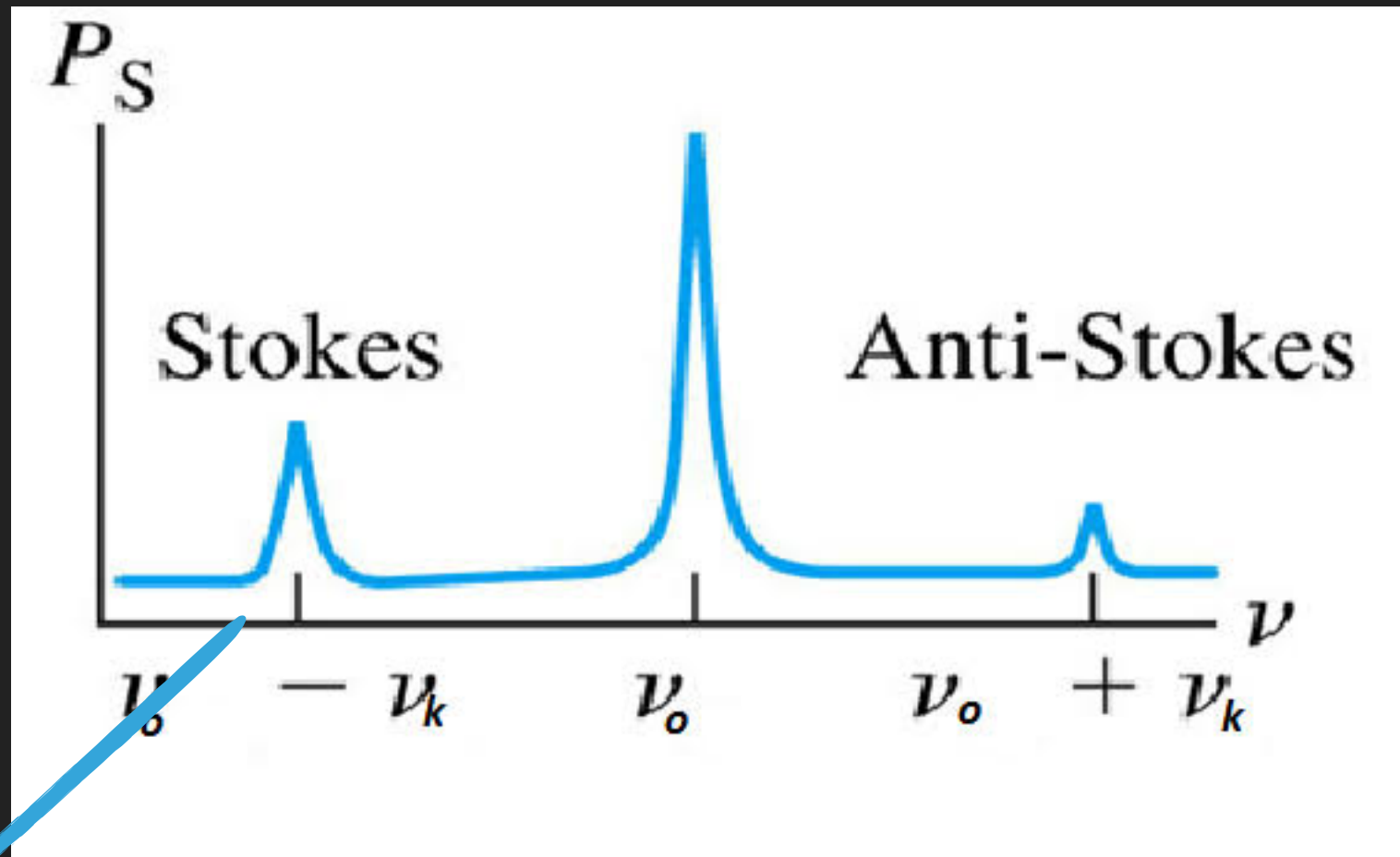


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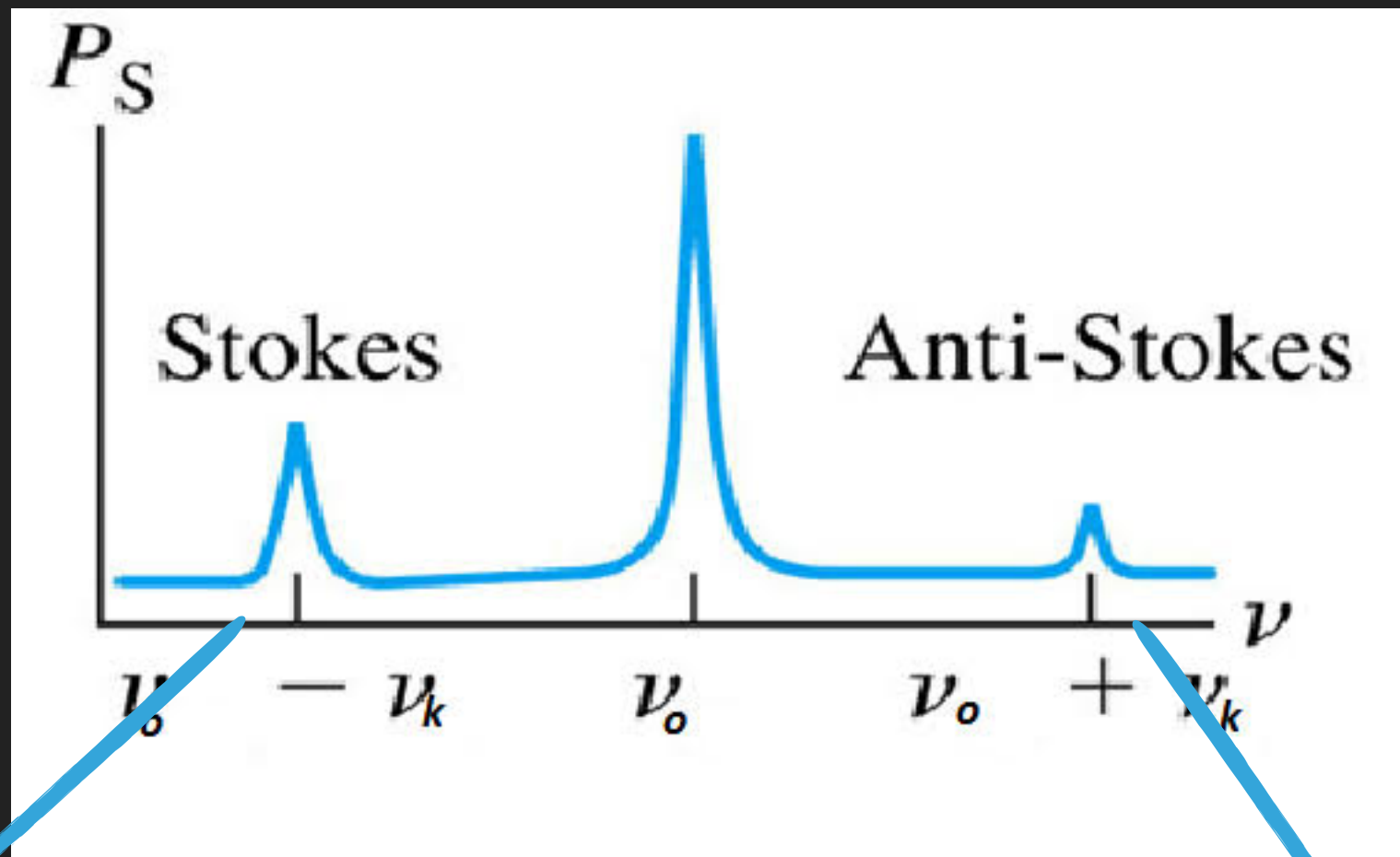
high freq. photon $\Rightarrow$ low freq. Stokes photon + magnon

STOKES AND ANTI-STOKES

<https://commons.wikimedia.org/wiki/File:Ggstokes.jpg>

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336747033_Development_of_methods_based_on_NIR_and_Raman_spectroscopies_together_with_chemometric_tools_for_the_qualitative_and_quantitative_analysis_of_gasoline



high freq. photon $\Rightarrow$ low freq. Stokes photon + magnon

low freq. photon + magnon $\Rightarrow$ high freq. anti-Stokes photon

CONSERVATION

$$q = k_2 - k_1$$

$$\Omega = \omega_2 - \omega_1$$

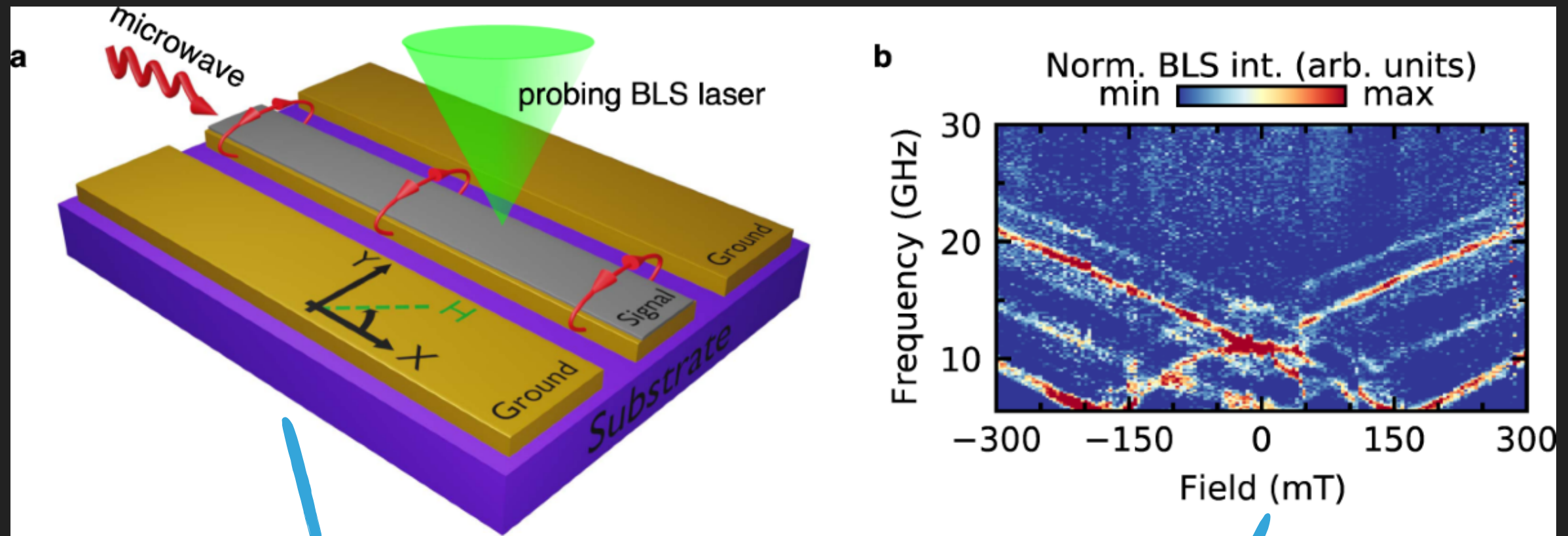
You need a medium (sample) where magnons can propagate (spin-waves).

Useful for investigating exchange interaction, anisotropy fields, DMI interactions.

You can achieve resolutions $< \mu\text{m}$ and $< \text{ns}$.



SPIN-WAVES



Generate spin-waves through a coplanar waveguide and a microwave.

Probe spin-waves properties through BLS as a function of applied field.

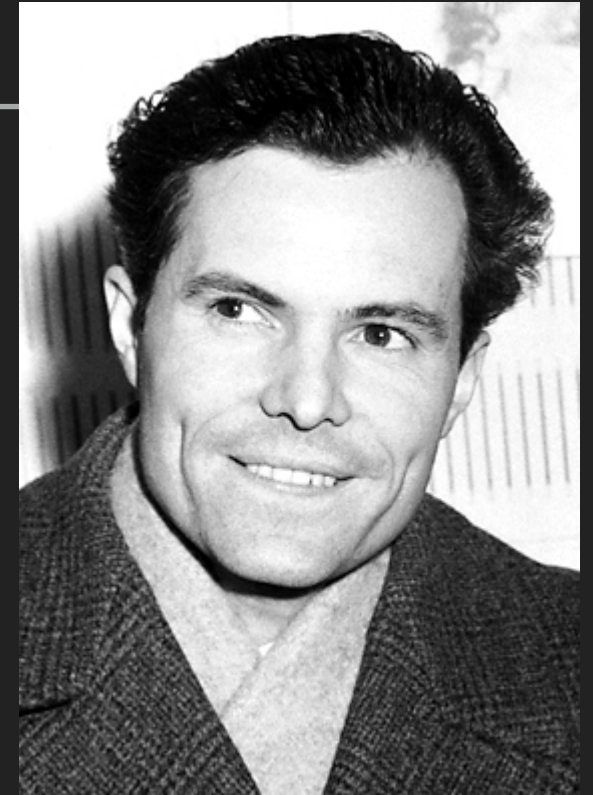
BLS VS. FERROMAGNETIC RESONANCE (FMR)

- ▶ Same kind of samples.
- ▶ Same preparation (cpw + sample on top, or cpw patterned on sample).
- ▶ **BLS:** dynamic conditions, propagating spin-waves.
- ▶ **FMR:** standing waves.

MÖSSBAUER SPECTROSCOPY

A NUCLEAR TECHNIQUE

- ▶ Two (in principle identical) nuclei.
- ▶ One emits a γ photon.
- ▶ Another (in the sample) absorbs it.
- ▶ Both nuclei are embedded in solids, and the photons have relatively low energy, so both emission and absorption are **without recoil**. Why is this important?
- ▶ Source and target are in relative motion, to exploit **Doppler effect**. Why would you care?



WHICH NUCLEI?

- ▶ Magnetic materials usually contain significant amounts of Fe.
- ▶ So if you want to detect Fe (and study some of its properties), the source must be of Fe as well.
- ▶ Fe isotopes:
 - ▶ ^{54}Fe (5.8%), ^{56}Fe (91.8%), ^{57}Fe (2.1%), ^{58}Fe (0.3%).
- ▶ All stable, but: ^{57}Co is a relatively stable Co isotope with a half-life of ~ 272 d which decays into ^{57}Fe .

AN INTERESTING PATH

- ▶ Start with ^{57}Co (obtained by proton irradiation of Ni or Fe or by other kinds of ion irradiation).
- ▶ ^{57}Co decays by **electron capture**: an inner electron (K or L shells) is captured and a proton is converted into a neutron, with emission of a neutrino.




7 VIIB	8 VIIB	9 VIIB	10 VIII	11 IB	12 IIB
25 Mn Manganese 54.938044 2-8-13-2	26 Fe Iron 55.845 2-8-14-2	27 Co Cobalt 58.933 2-8-15-2	28 Ni Nickel 58.693 2-8-16-2	29 Cu Copper 63.546 2-8-18-1	30 Zn Zinc 65.38 2-8-18-2
43 Tc Technetium (98) 2-8-18-13-2	44 Ru Ruthenium 101.07 2-8-18-15-1	45 Rh Rhodium 102.91 2-8-18-16-1	46 Pd Palladium 106.42 2-8-18-18	47 Ag Silver 107.87 2-8-18-18-1	48 Cd Cadmium 112.41 2-8-18-18-2
75 Re Rhenium 186.21 2-8-18-32-13-2	76 Os Osmium 190.23 2-8-18-32-14-2	77 Ir Iridium 192.22 2-8-18-32-15-2	78 Pt Platinum 195.08 2-8-18-32-17-1	79 Au Gold 196.97 2-8-18-32-18-1	80 Hg Mercury 200.59 2-8-18-32-18-2

- ▶ ^{57}Fe is in an **excited nuclear state**.
- ▶ ^{57}Fe decays into its **fundamental state** by emitting **γ photons** (14.4 keV).



ENERGY CONSERVATION

- ▶ In free nuclei, **resonant emission and absorption** of photons is never observed, because both effects involve recoil.
- ▶ In solids, recoil is quantised in phonons, and at **low emission energies** recoil-free processes are permitted.
- ▶ Resonant emission and absorption are then possible!
- ▶ γ photons have very narrow line width. Small changes in the energies of nuclear transitions may prevent resonant absorption.
- ▶ **Doppler effect** provides the small energy variations necessary to match the energy conservation requirements taking into account the **interactions** of the absorbing nucleus with its electrons and those of the nearby nuclei.

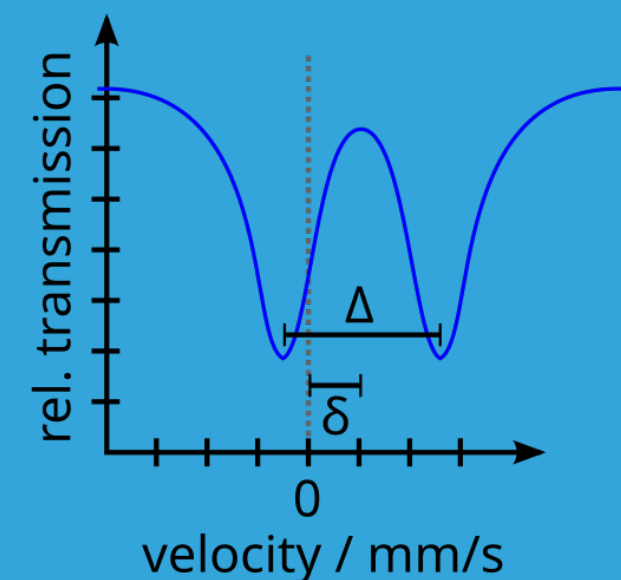
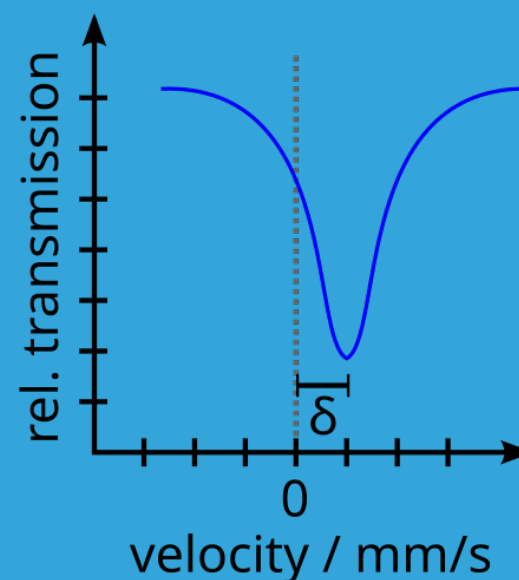
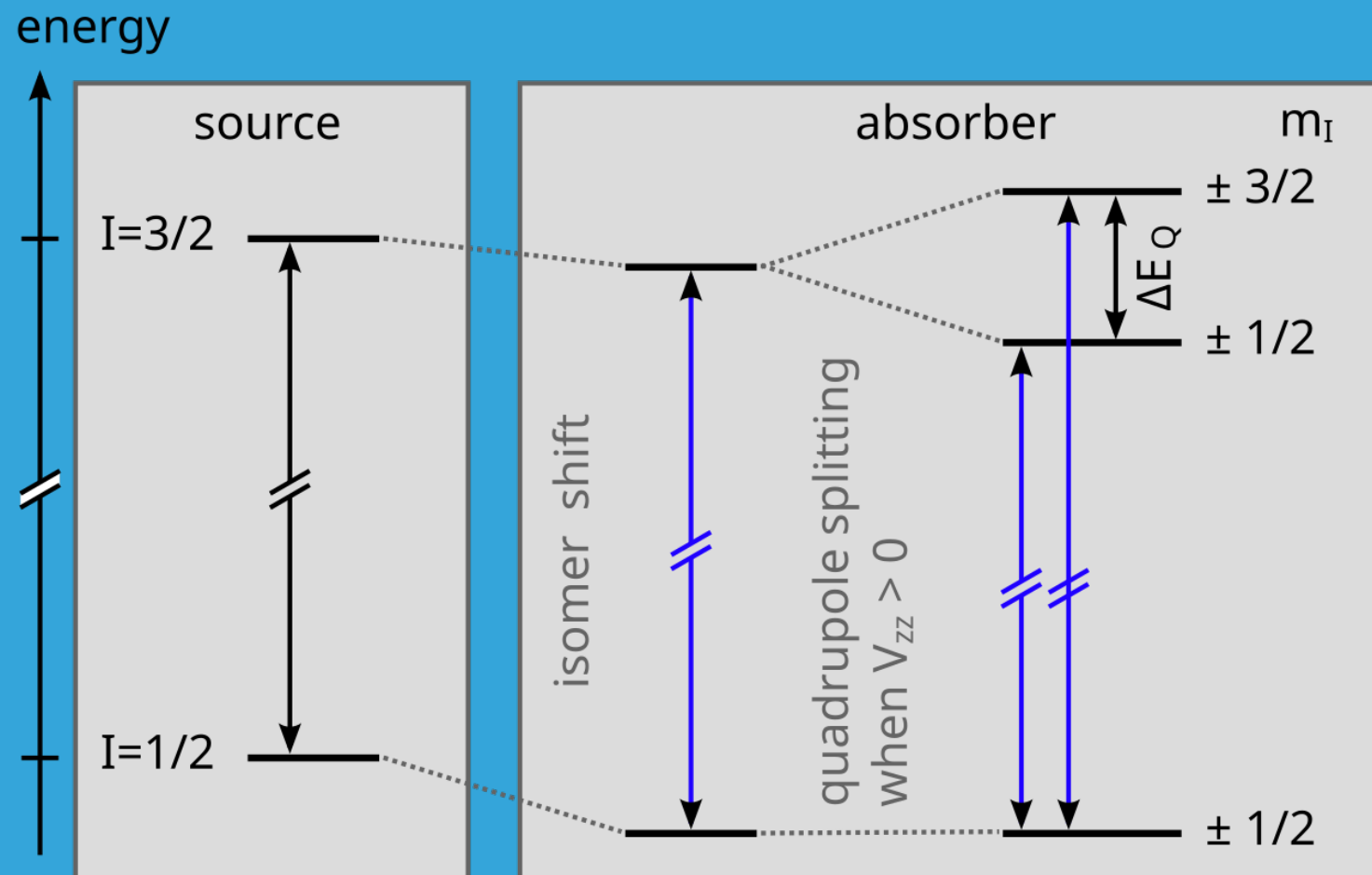
MÖSSBAUER SPECTROSCOPY

- ▶ Mössbauer spectroscopy is therefore a technique that explores the **electron environment of a set of absorbing nuclei**.
- ▶ If the target is ^{57}Fe , the electron environment of ^{57}Fe is explored.
- ▶ And the electron environment of ^{57}Fe contains energy contributions due to **ferromagnetic interactions!**

ISOMER SHIFT AND QUADRUPOLE SPLITTING

Isomer shift: interaction with S electrons.

Quadrupole splitting: interaction with electric field gradients.

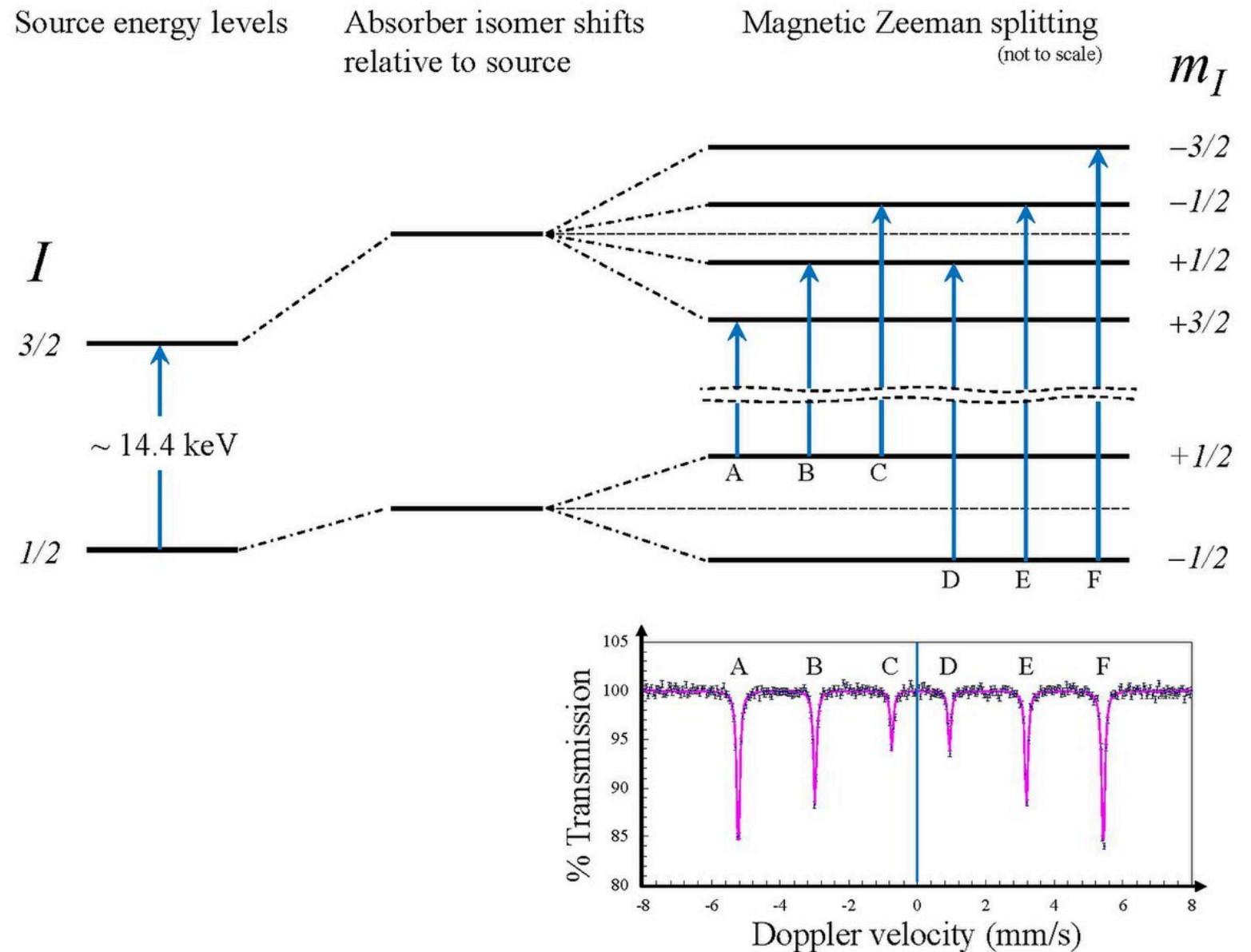


MAGNETIC HYPERFINE SPLITTING

Hyperfine splitting:

interaction with surrounding magnetic field (e.g. due to the natural internal magnetic fields in ferromagnetic materials).

The intensity of the magnetic field can be inferred from the spacing of the peaks, provided that the g-factors of the nuclear states are known.

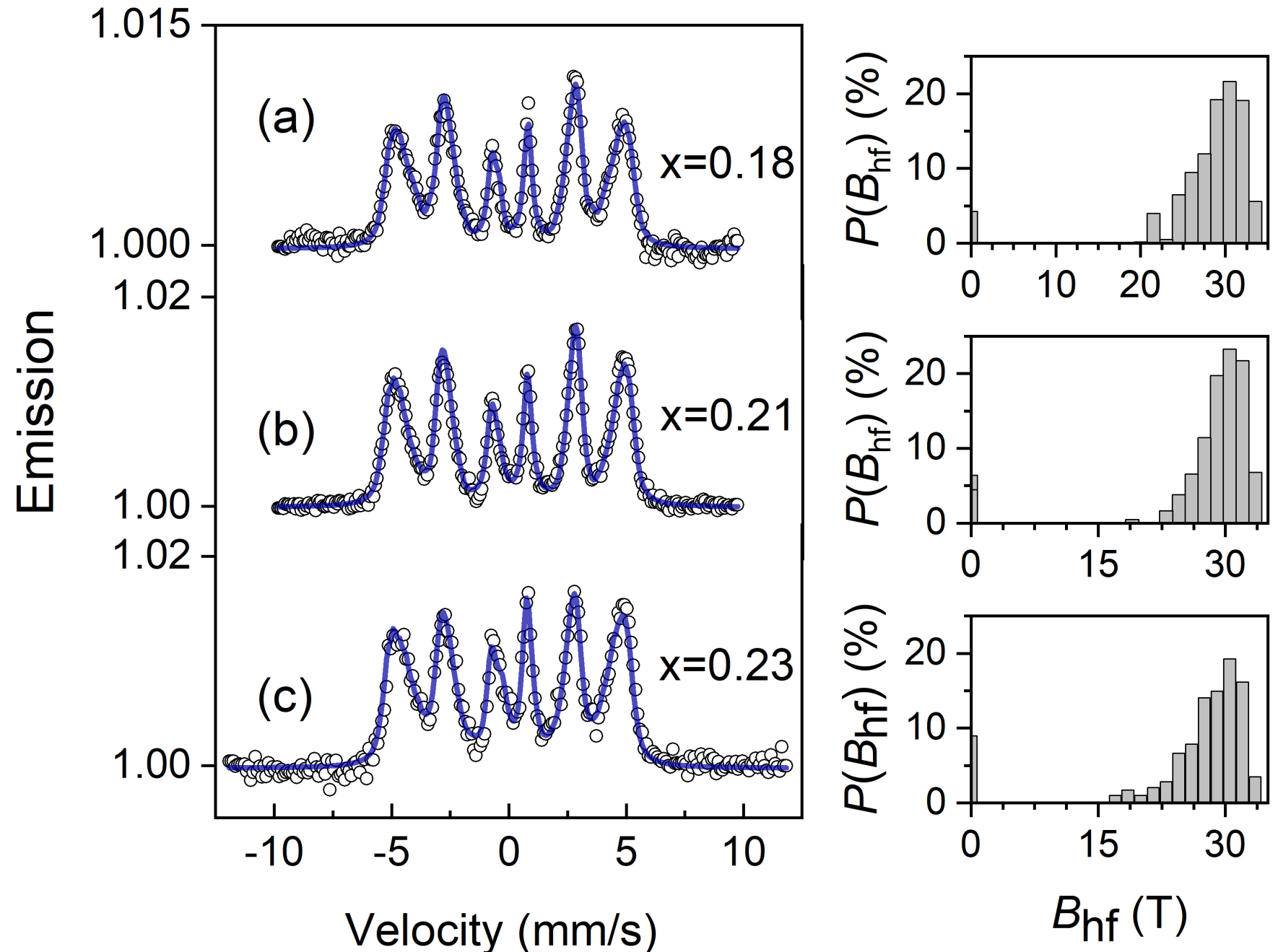


ANALYSIS

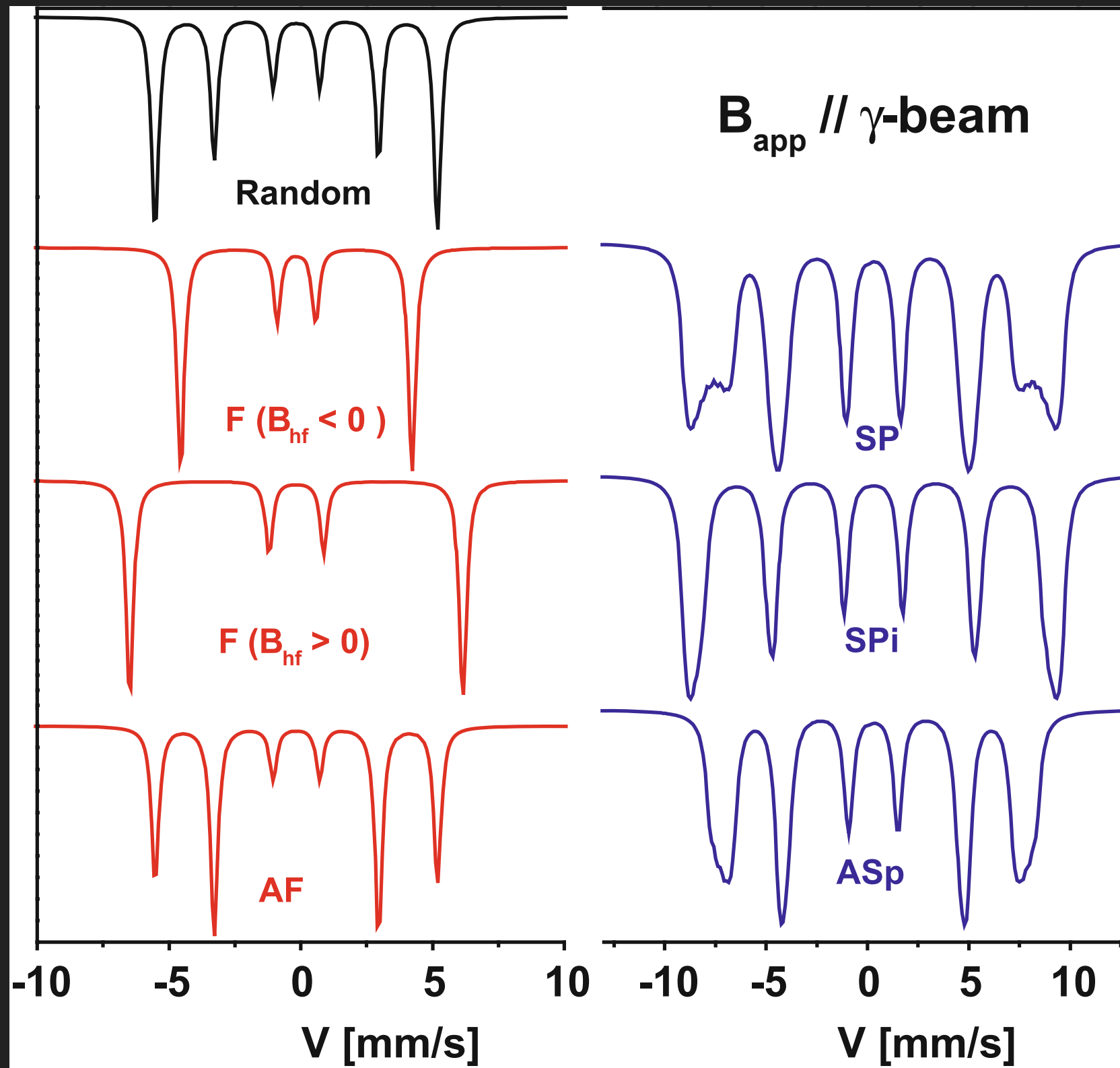
The Mössbauer spectra are **fitted**, with isomer shift, quadrupole splitting and hyperfine splitting as free parameters / distributions.

Comparison with reference standards allows **identification of compounds** in sample, or identification of sites of Fe atoms in a crystal (e.g. ferrites).

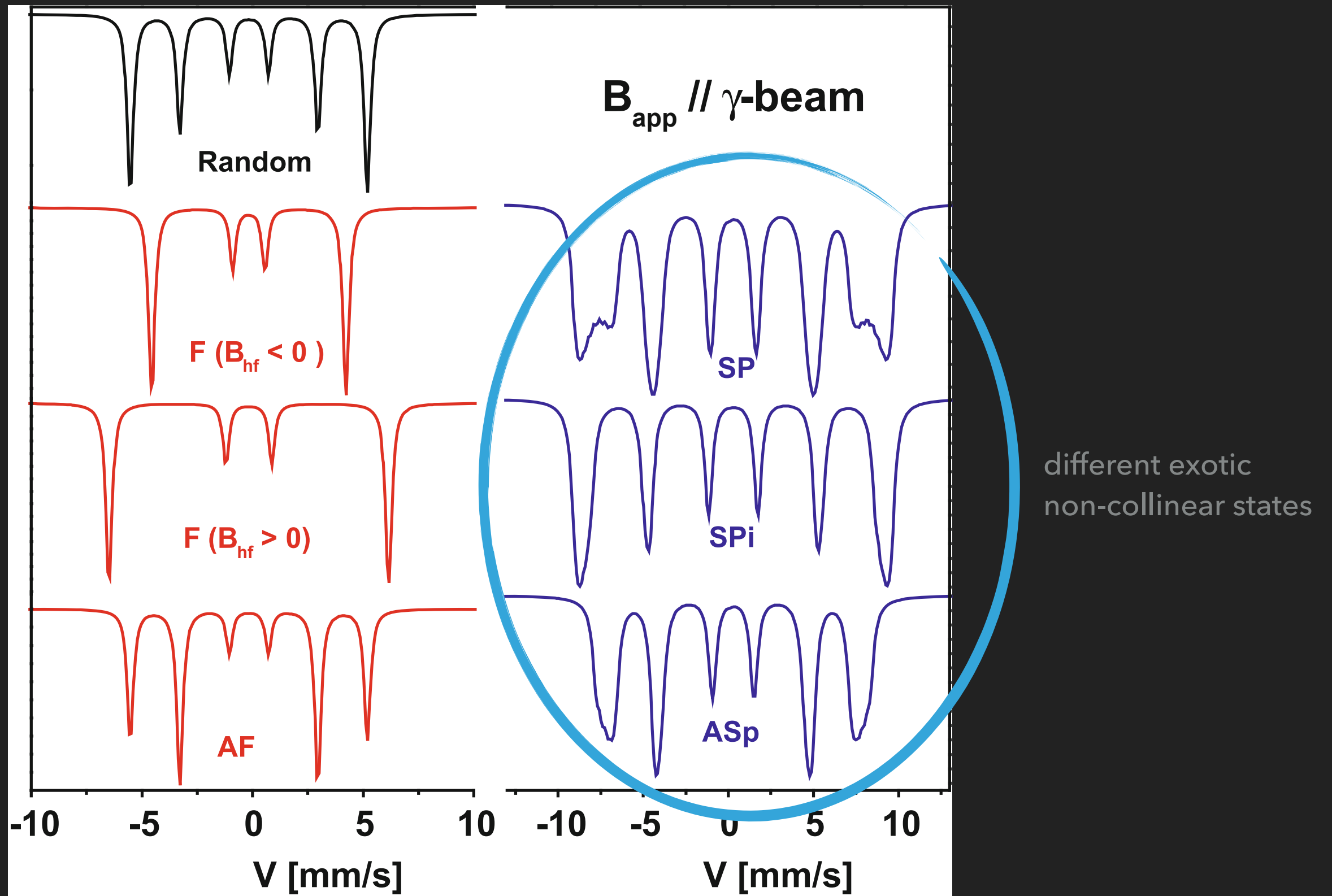
Peaks relative intensity provide a **semi-quantitative analysis of composition**.



TO GIVE AN IDEA



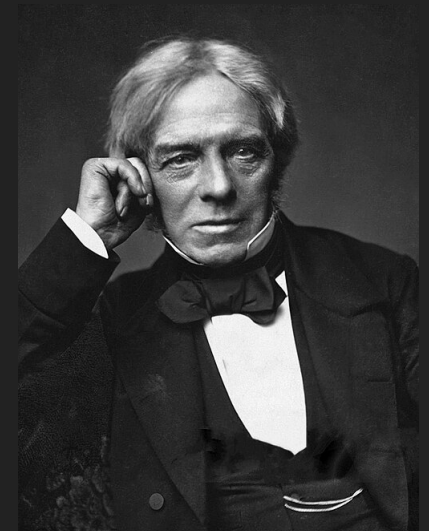
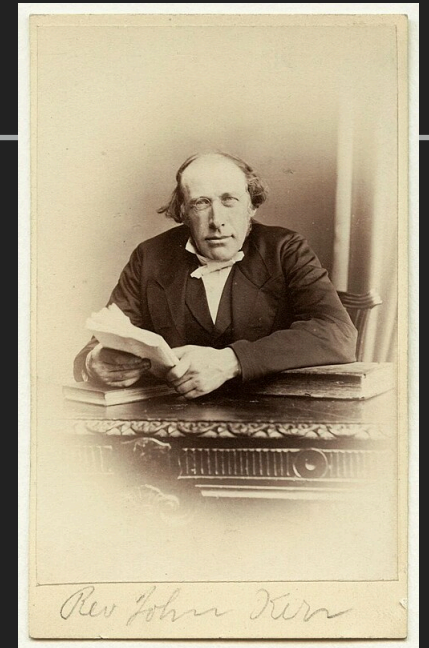
TO GIVE AN IDEA



MAGNETO-OPTICS

KERR AND FARADAY EFFECTS

- ▶ Two similar effects: **small rotation of the plane of polarisation of light** reflected by (Kerr) or transmitted through (Faraday) a magnetic material.
- ▶ **Weak intensity:** in practice, digital subtraction of background (saturated state) is the only viable solution to obtain good results.
- ▶ An additional Voigt effect adds second-order corrections and is even weaker.



[https://commons.wikimedia.org/wiki/File:John_Kerr_\(physicist\).jpg](https://commons.wikimedia.org/wiki/File:John_Kerr_(physicist).jpg)

https://commons.wikimedia.org/wiki/File:Michael_Faraday_sitting_crop.jpg

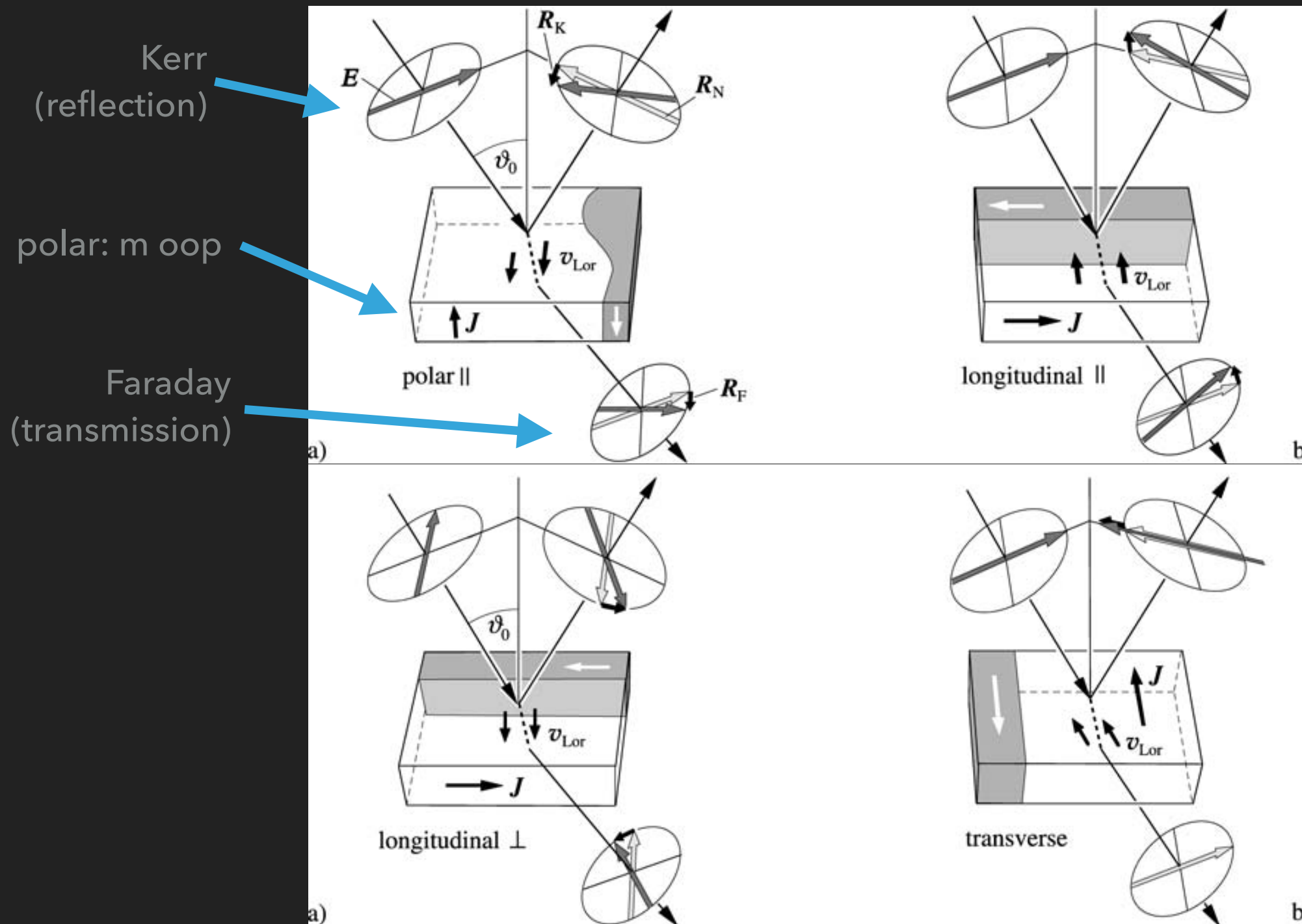
https://commons.wikimedia.org/wiki/File:Woldemar_Voigt,_c._1908.jpg

MOSTLY A MATTER OF ELECTRICAL PERMITTIVITY

$$\epsilon' + i\epsilon'' = \epsilon \begin{bmatrix} 1 & -iQ_V m_3 & iQ_V m_2 \\ iQ_V m_3 & 1 & -iQ_V m_1 \\ -iQ_V m_2 & iQ_V m_1 & 1 \end{bmatrix} + \begin{bmatrix} B_1 m_1^2 & B_2 m_1 m_2 & B_2 m_1 m_3 \\ B_2 m_1 m_2 & B_1 m_2^2 & B_2 m_2 m_3 \\ B_2 m_1 m_3 & B_2 m_2 m_3 & B_1 m_3^2 \end{bmatrix}$$

- ▶ Q_V : Voigt material constant describing the **magneto-optical rotation** of the plane of polarisation of the light (Faraday in transmission, Kerr in reflection).
- ▶ B_1 and B_2 : Voigt constants.
- ▶ m_i : components of the **unit vector of magnetisation** along the cubic axes.
- ▶ All constants are frequency dependent and complex, even though their real parts dominate over the imaginary parts.
- ▶ A similar principle applies to the tensor of magnetic permeability, but it is much weaker ($\sim 10^{-2}$) than electrical permittivity.

YOU SPIN ME RIGHT ROUND...

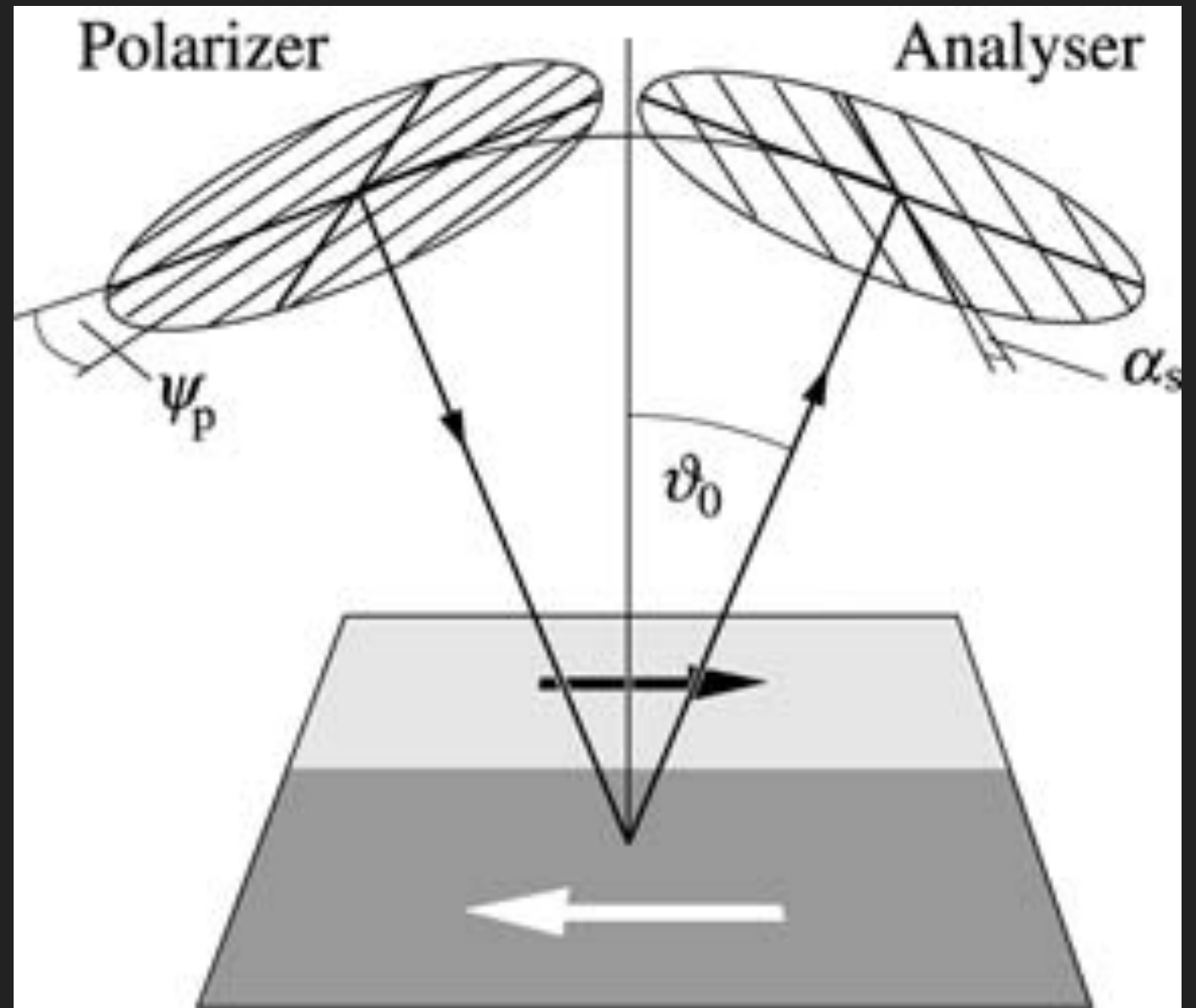


The incident light induces **oscillations of electrons** parallel to the plane of polarisation (direction of E).

A **Lorentz force**, driven by the magnetisation of the material, acts on the oscillating electrons inducing a **small rotation of the plane of polarisation** of the light.

LIGHT IS POLARISED AND THEN ANALYSED

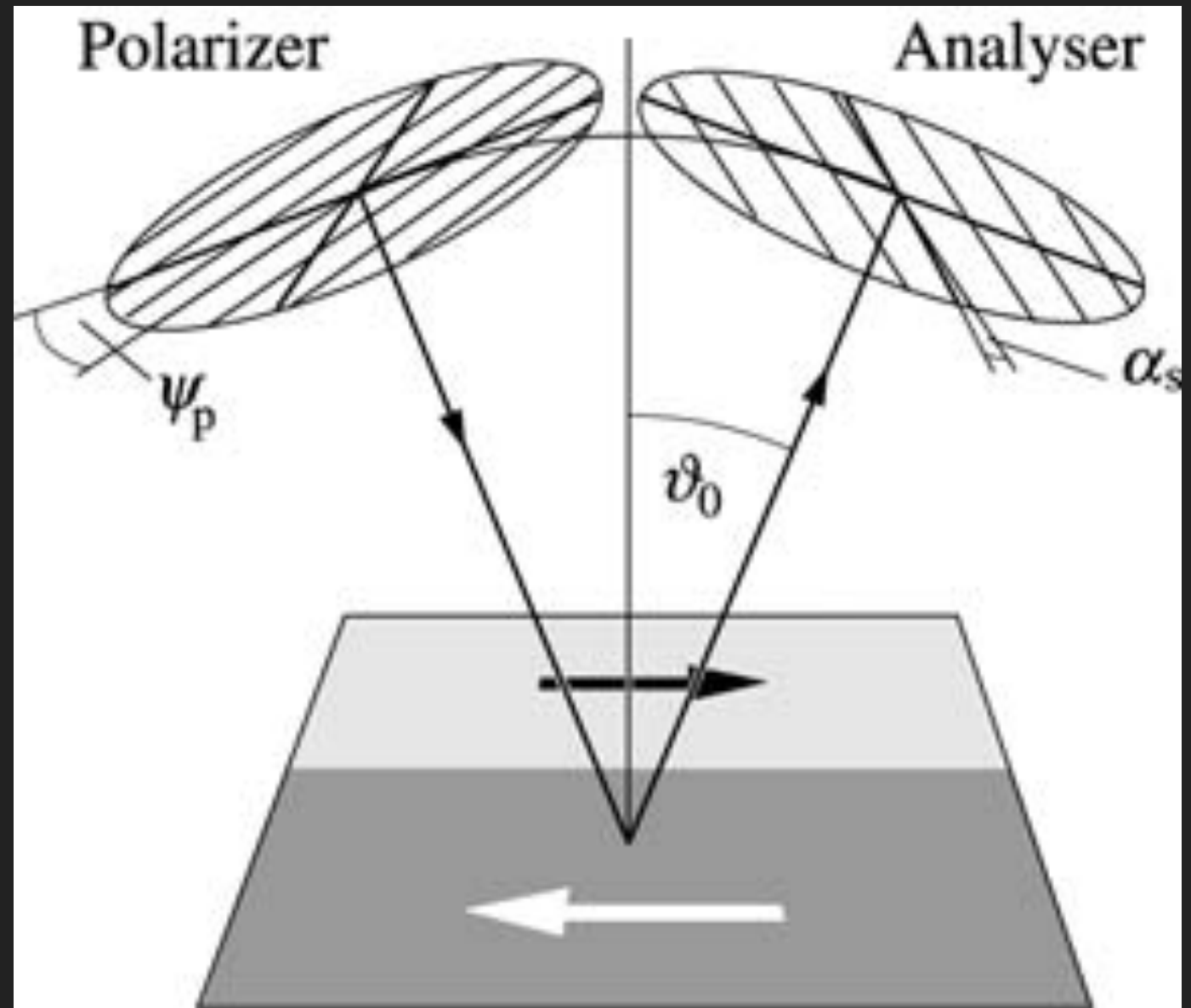
$$\begin{aligned} A_{tot} = & -R_p \cos \Psi_p \sin \alpha_s \\ & + R_s \sin \Psi_p \cos \alpha_s \\ & + R_K^{pol} \cos(\alpha_s - \Psi_p) m_{pol} \\ & + R_K^{lon} \cos(\alpha_s + \Psi_p) m_{lon} \\ & - R_K^{tra} \cos \Psi_p \sin \alpha_s m_{tra} \end{aligned}$$



LIGHT IS POLARISED AND THEN ANALYSED

amplitude relative to incident amplitude

$$\begin{aligned}
 A_{tot} = & -R_p \cos \Psi_p \sin \alpha_s \\
 & + R_s \sin \Psi_p \cos \alpha_s \\
 & + R_K^{pol} \cos(\alpha_s - \Psi_p) m_{pol} \\
 & + R_K^{lon} \cos(\alpha_s + \Psi_p) m_{lon} \\
 & - R_K^{tra} \cos \Psi_p \sin \alpha_s m_{tra}
 \end{aligned}$$

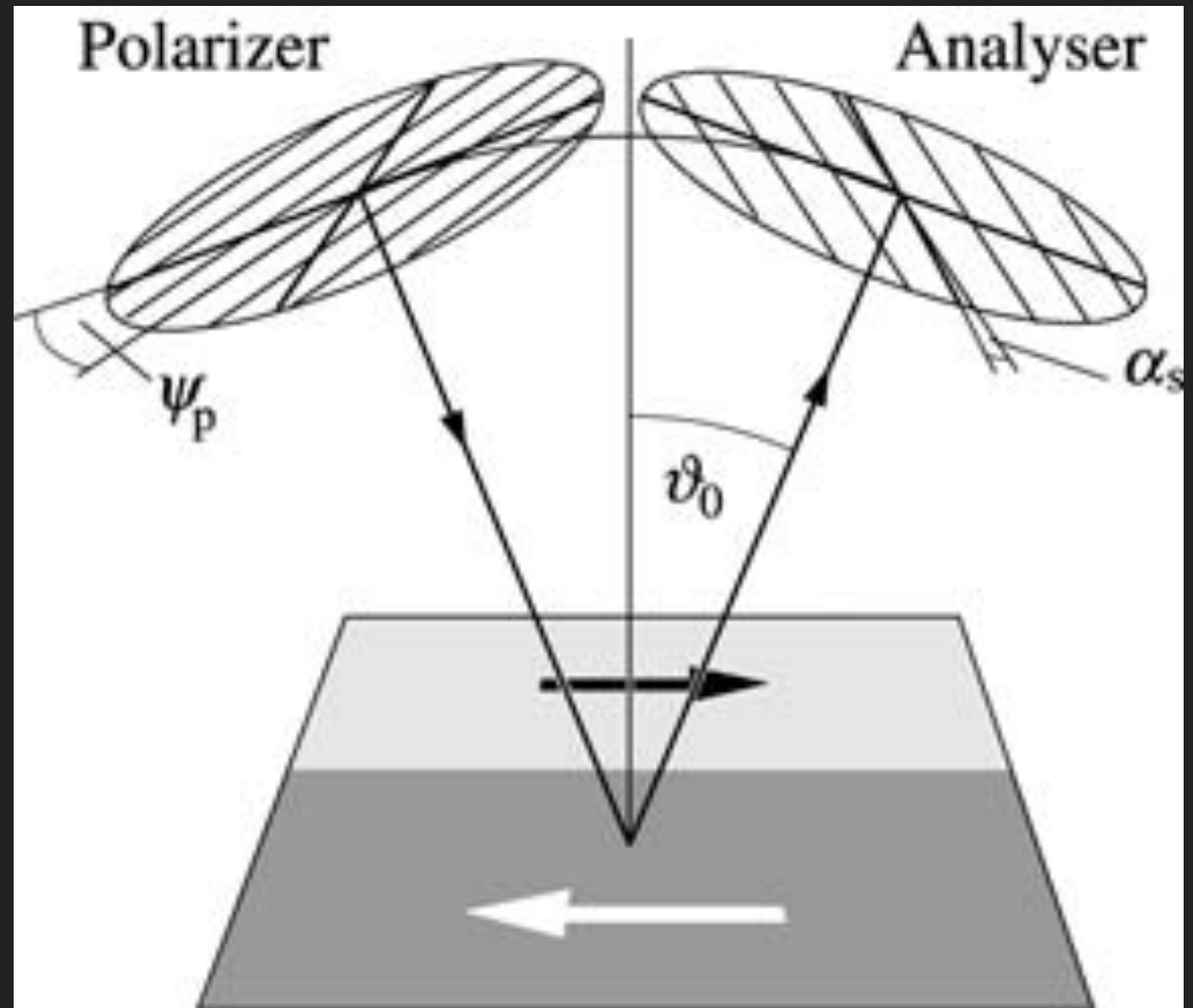


LIGHT IS POLARISED AND THEN ANALYSED

amplitude relative to incident amplitude

reflection coefficients

$$A_{tot} = -R_p \cos \Psi_p \sin \alpha_s + R_s \sin \Psi_p \cos \alpha_s + R_K^{pol} \cos(\alpha_s - \Psi_p) m_{pol} + R_K^{lon} \cos(\alpha_s + \Psi_p) m_{lon} - R_K^{tra} \cos \Psi_p \sin \alpha_s m_{tra}$$



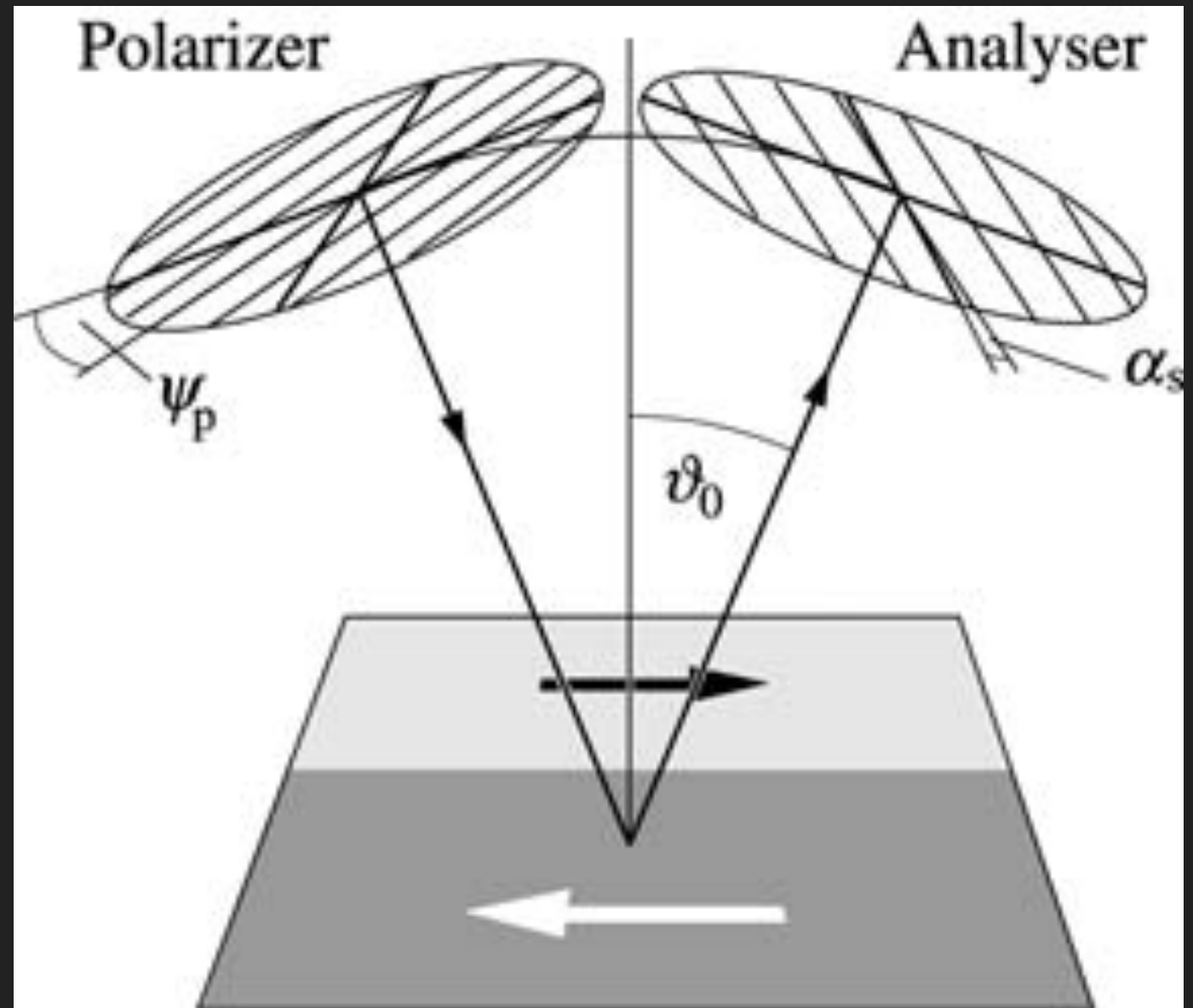
LIGHT IS POLARISED AND THEN ANALYSED

amplitude relative to incident amplitude

reflection coefficients

$$A_{tot} = -R_p \cos \Psi_p \sin \alpha_s + R_s \sin \Psi_p \cos \alpha_s + R_K^{pol} \cos(\alpha_s - \Psi_p) m_{pol} + R_K^{lon} \cos(\alpha_s + \Psi_p) m_{lon} - R_K^{tra} \cos \Psi_p \sin \alpha_s m_{tra}$$

Kerr amplitudes



LIGHT IS POLARISED AND THEN ANALYSED

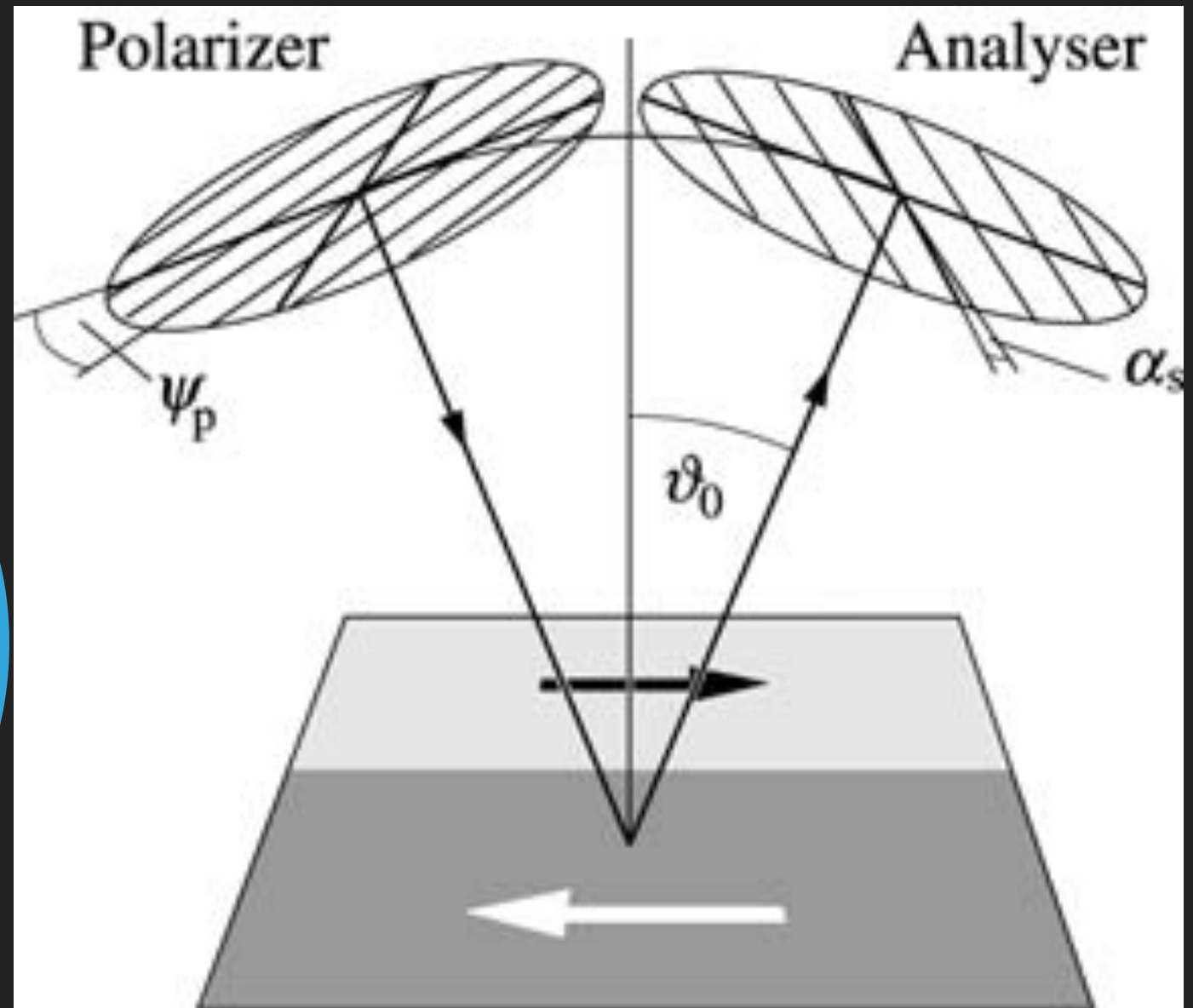
amplitude relative to incident amplitude

reflection coefficients

$$A_{tot} = -R_p \cos \Psi_p \sin \alpha_s + R_s \sin \Psi_p \cos \alpha_s + R_K^{pol} \cos(\alpha_s - \Psi_p) m_{pol} + R_K^{lon} \cos(\alpha_s + \Psi_p) m_{lon} - R_K^{tra} \cos \Psi_p \sin \alpha_s m_{tra}$$

Kerr amplitudes

magnetisation components

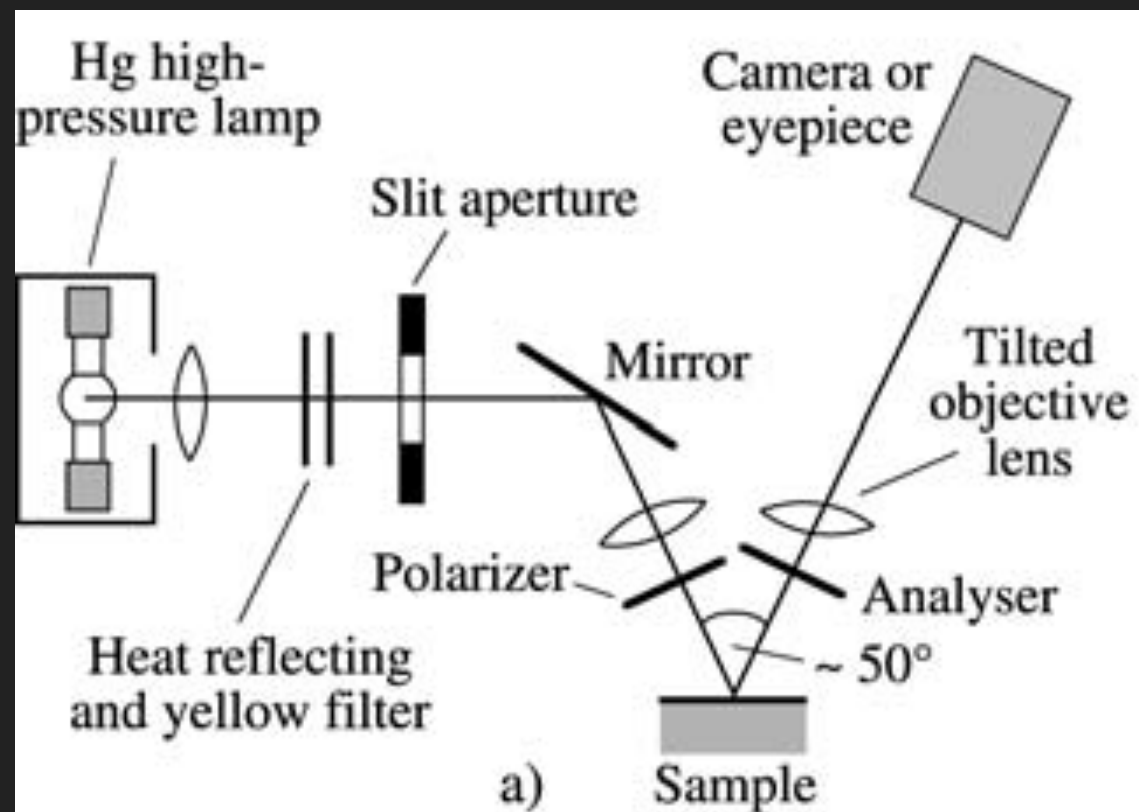


OPERATION

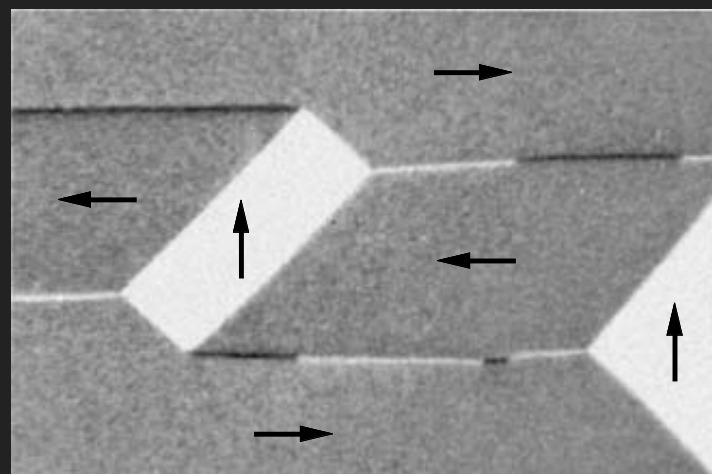
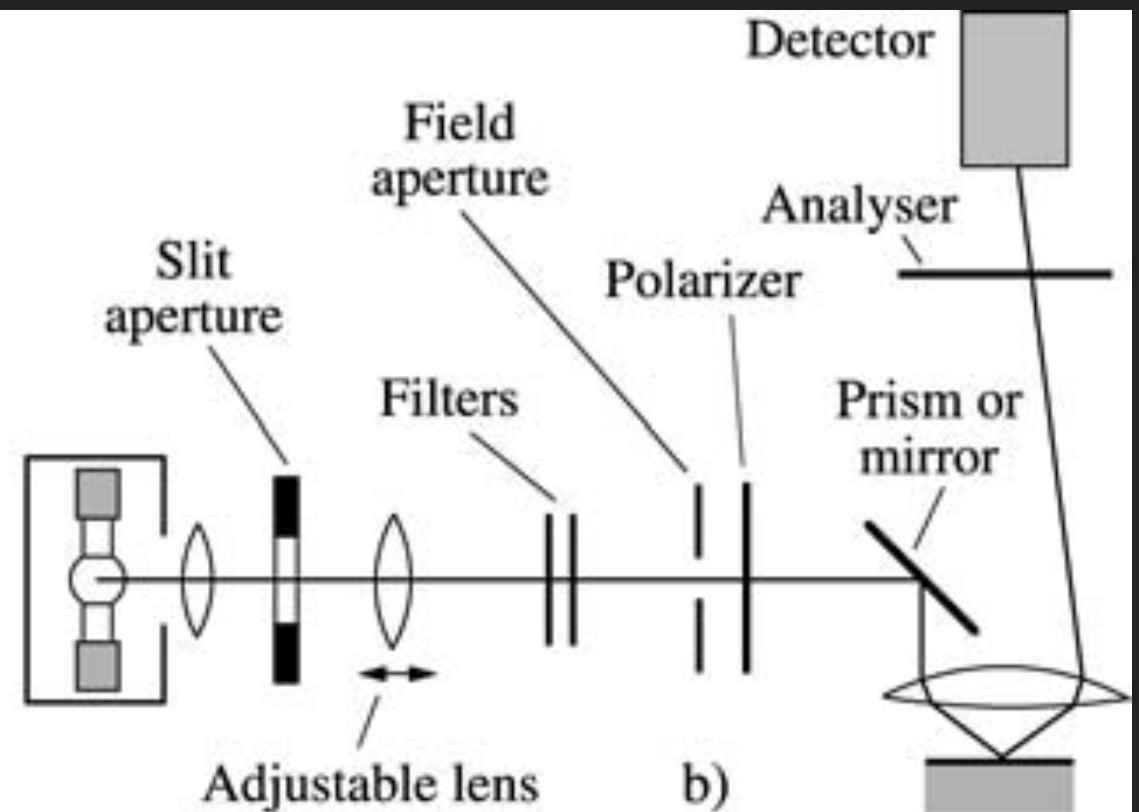
- ▶ Polariser is oriented along the desired saturation direction.
- ▶ Analyser is adjusted so that domains along the saturation are completely dark.
- ▶ Analyser angle is fine-tuned to optimise contrast or sensitivity or in general to achieve better results.

EXPERIMENTAL SETUP

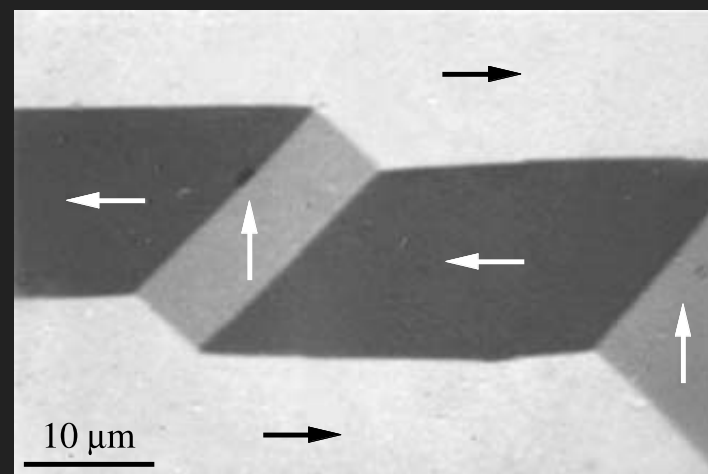
low resolution, high sensitivity



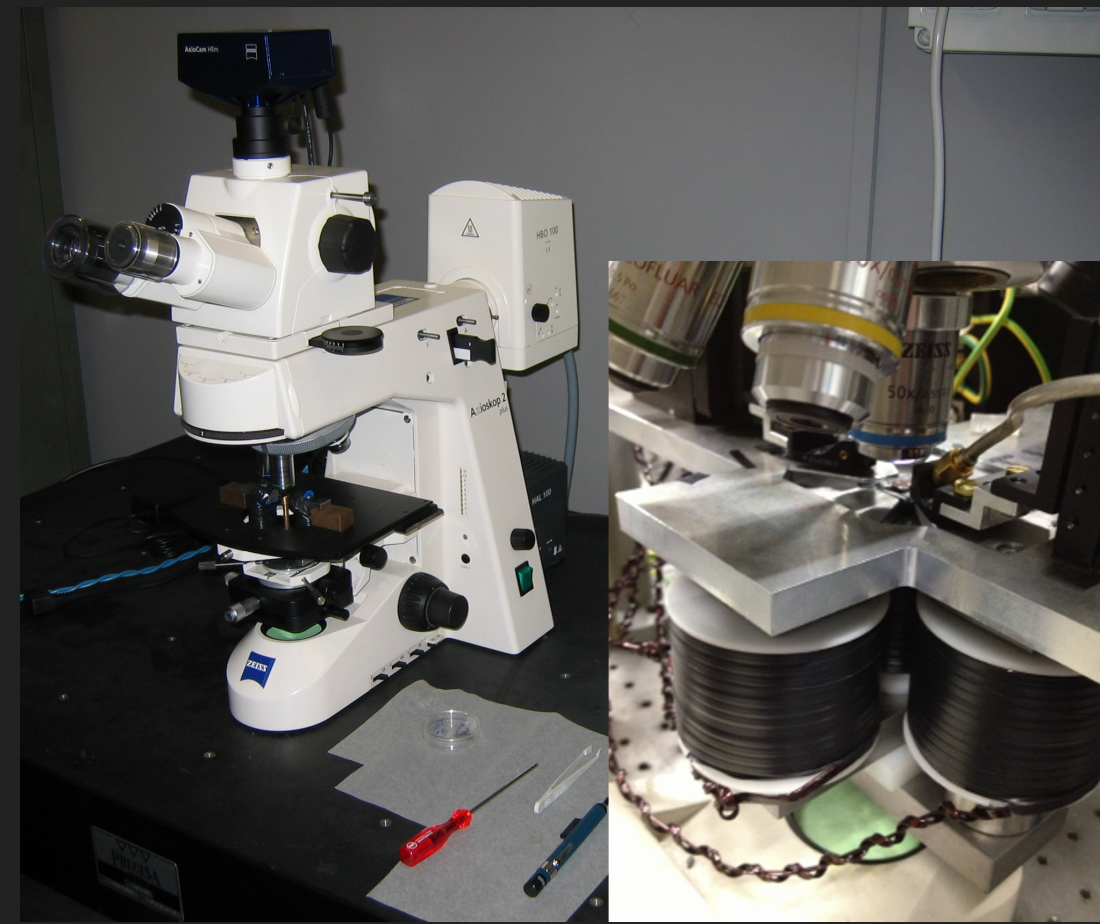
high resolution



a)



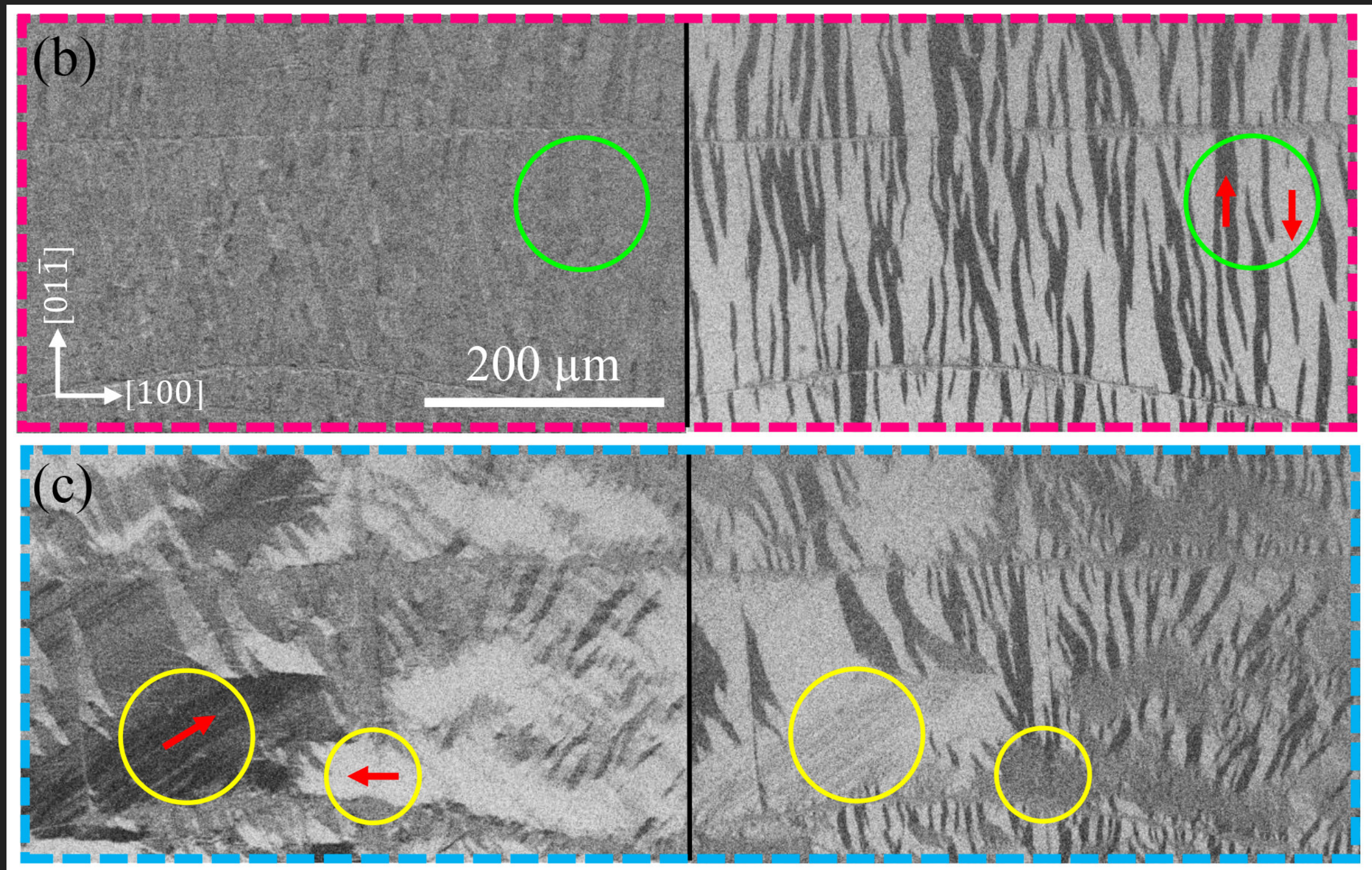
b)



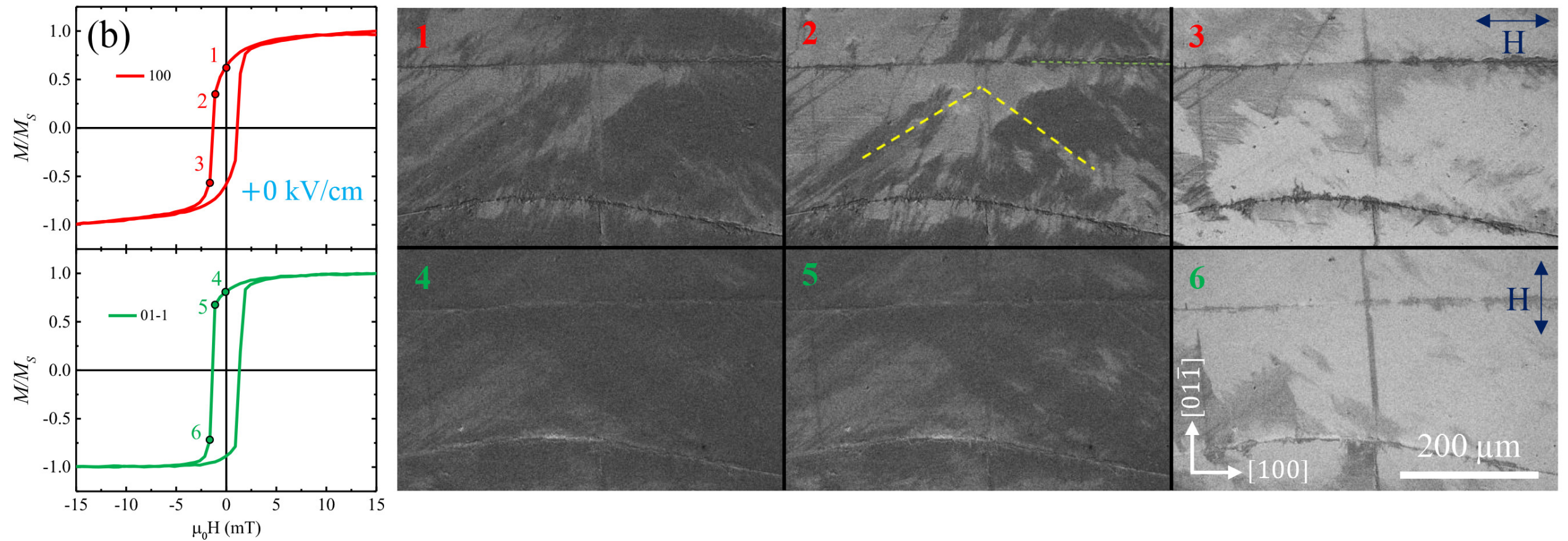
INFORMATION ACQUIRED

- ▶ Magnetic domains configuration.
- ▶ Evolution of magnetisation with applied magnetic field.
- ▶ Evolution of magnetisation over time.
- ▶ Ultrafast magnetisation dynamics (periodic processes).

MAGNETIC DOMAINS CONFIGURATION



M VS. H

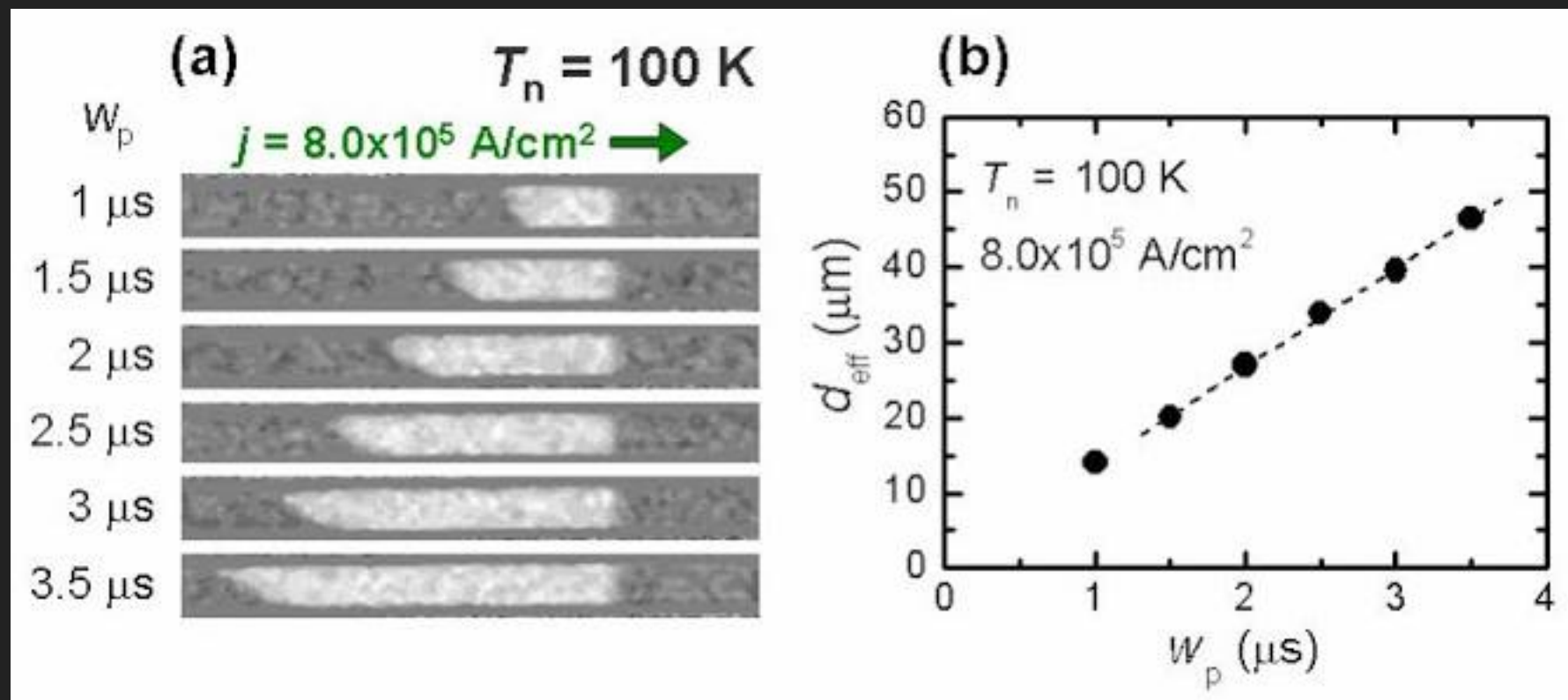
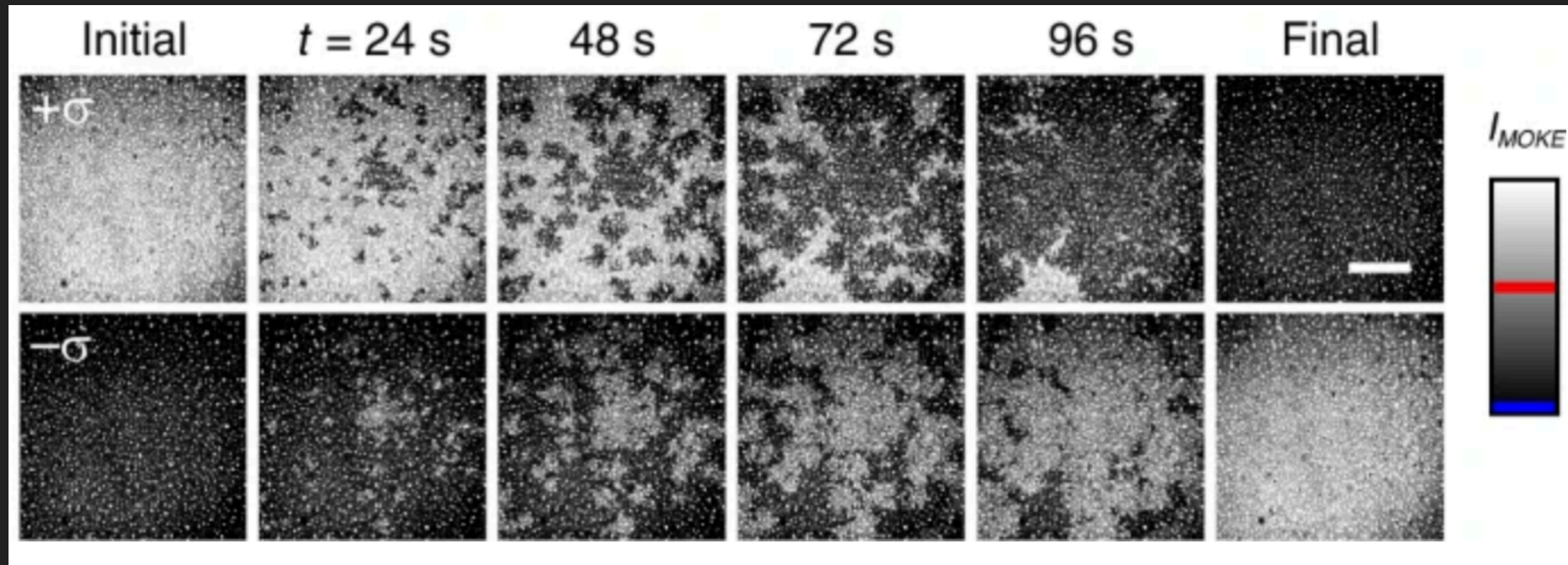


Each image corresponds to a different applied field.

For each applied field, an average value (level of grey) is calculated.

That is the normalised MOKE magnetisation.

M VS. TIME



ULTRAFAST MAGNETISATION DYNAMICS

- ▶ A stroboscopic variant.
- ▶ Repetitive phenomena necessary.
- ▶ The phenomenon is excited, and the response acquired (several times to increase signal) at different delays from the excitation.
- ▶ Subsequent analysis and reconstruction gives the time-resolved evolution of the periodic phenomenon, with a very high time resolution.

THAT'S ALL (PHEW!)

THAT'S WHY YOU NEED SCHOOLS AND BOOKS

- ▶ **J.M.D. Coey**, *Magnetism and Magnetic Materials*, Cambridge University Press 2009, ISBN-13 978-0-511-67743-4 (eBook) and 978-0-521-81614-4 (hardback).
- ▶ **F. Fiorillo**, *Measurement and Characterisation of Magnetic Materials*, Elsevier Academic Press 2004, ISBN-13 978-0-12-257251-7.
- ▶ **B.D. Cullity, C.D. Graham**, *Introduction to Magnetic Materials (Second Edition)*, Wiley 2009, ISBN-13 978-0-471-47741-9.
- ▶ **G. Bertotti**, *Hysteresis in magnetism*, Academic Press 1998, ISBN 0-12-093270-9.
- ▶ **A. Hubert, R. Schäfer**, *Magnetic Domains*, Springer 1998, ISBN-13 978-3-540-64108-7.

THANK YOU!



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