La clase

CURSO DE CHOQUE (BREVE) SOBRE

- **CAMPOS MAGNÉTICOS**
- **NANOPARTICULAS MAGNÉTICAS**
- **NANOMAGNETISMO**

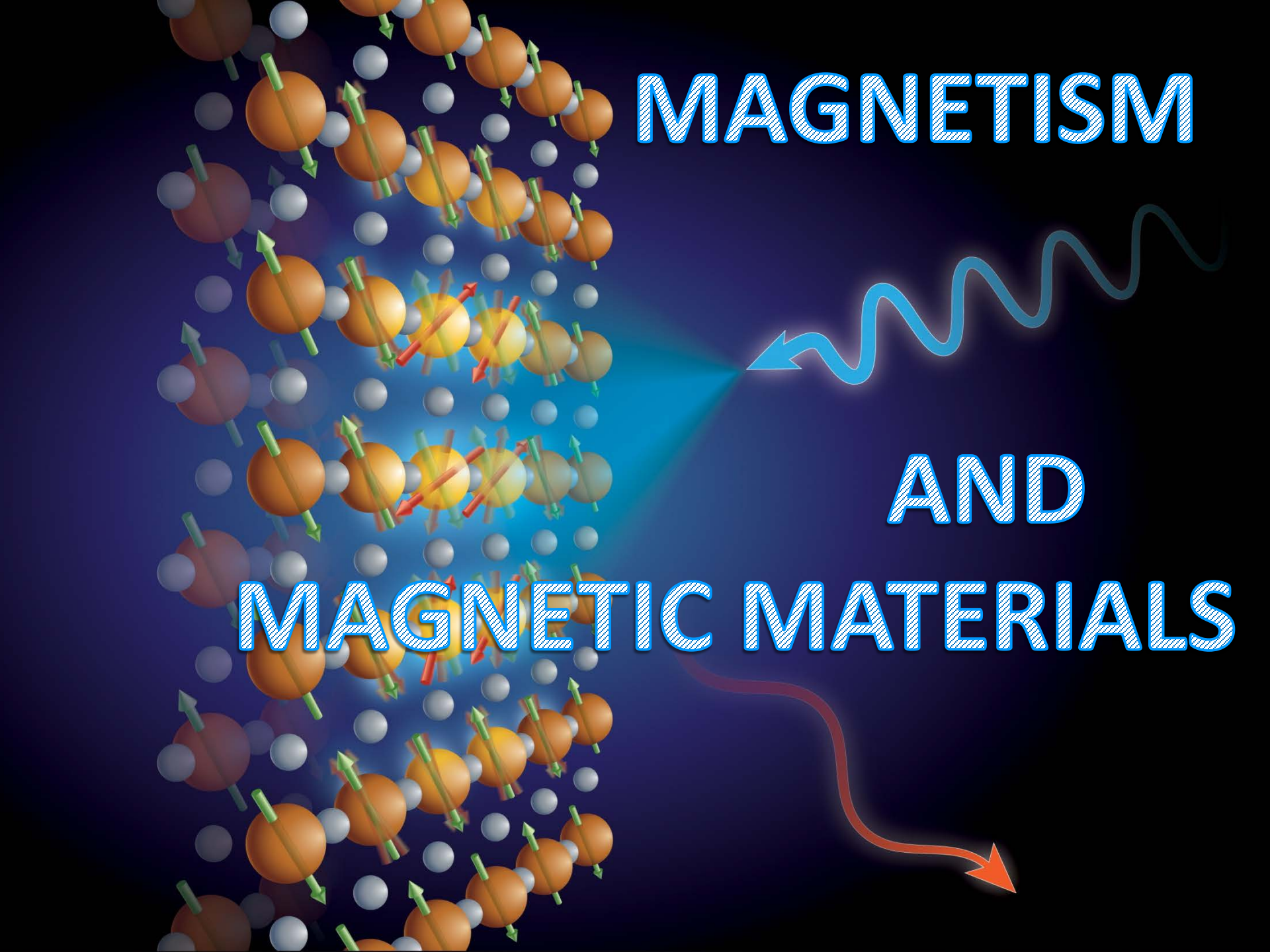
- **HIPERTERMIA MAGNÉTICA**

- **LAS INTERACCIONES**
  - **MAGNETO-BIO**
  - **MAGNETO-BIO-NANO**
- **POSIBILIDADES Y LIMITACIONES**
- **CONCLUSIONES**

- **(AUTO) EVALUACIÓN**

Presentación actualizada

Here


MAGNETISM
AND
MAGNETIC MATERIALS

Pregunta #1

¿De dónde proviene el

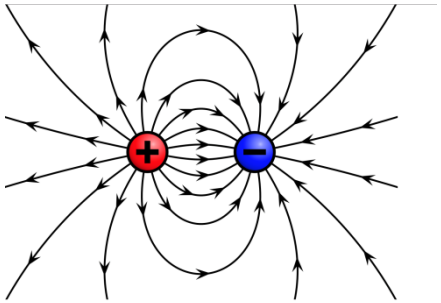
¿Cómo se produce el

¿Cuáles son las fuentes del

} Magnetismo?

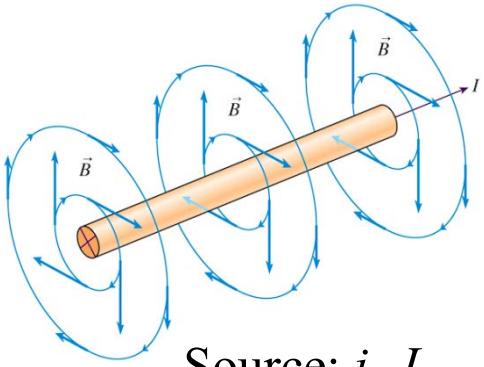
THE ORIGIN OF H AND B

E, D



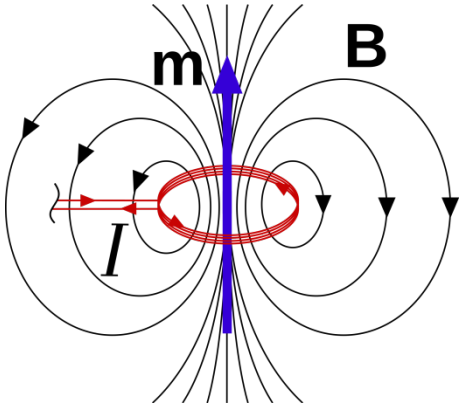
Source: q, ρ

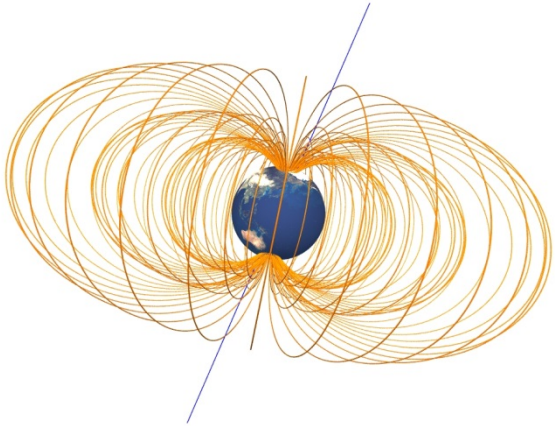
H, B

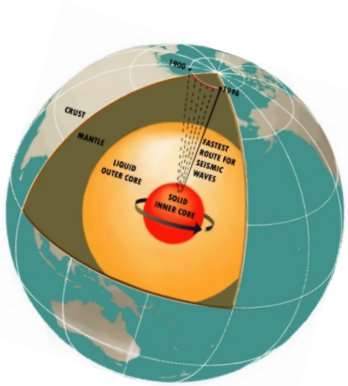


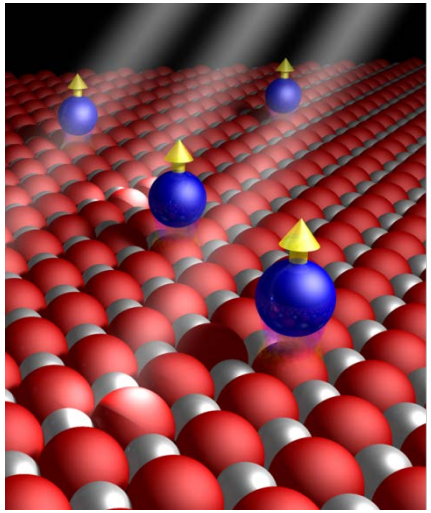
Source: *i*, *J*

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$







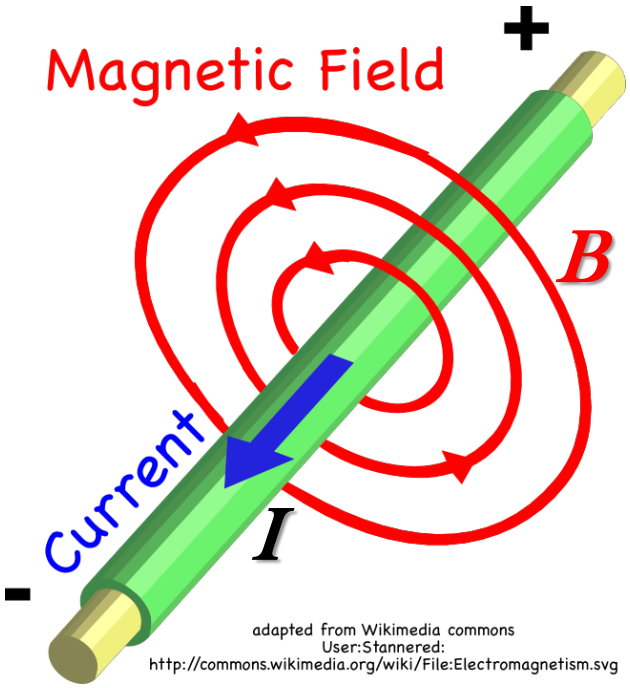


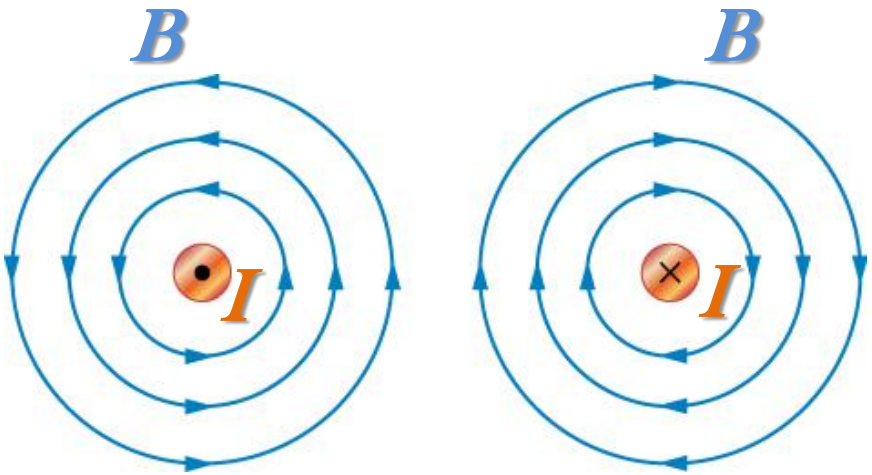
¿De dónde sale H ?

Ley de Ampère

$$\oint B\, dl = \mu_0 I$$

Relaciona campos *B,H*
con la corriente *I* que los produce

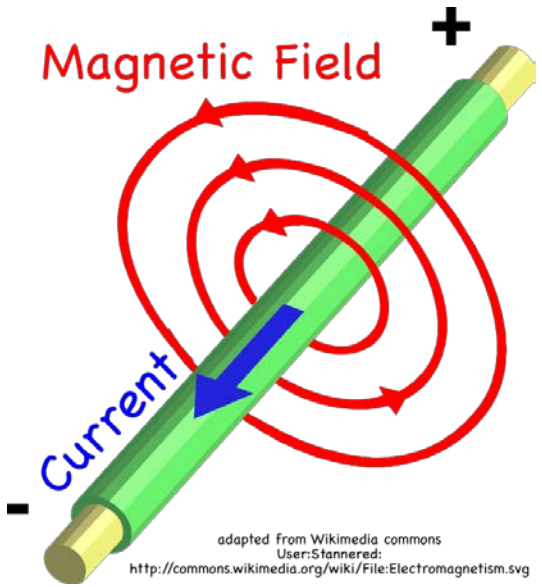


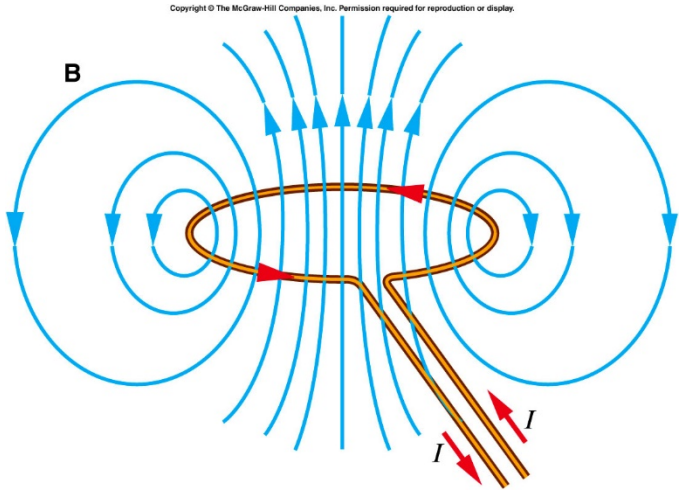


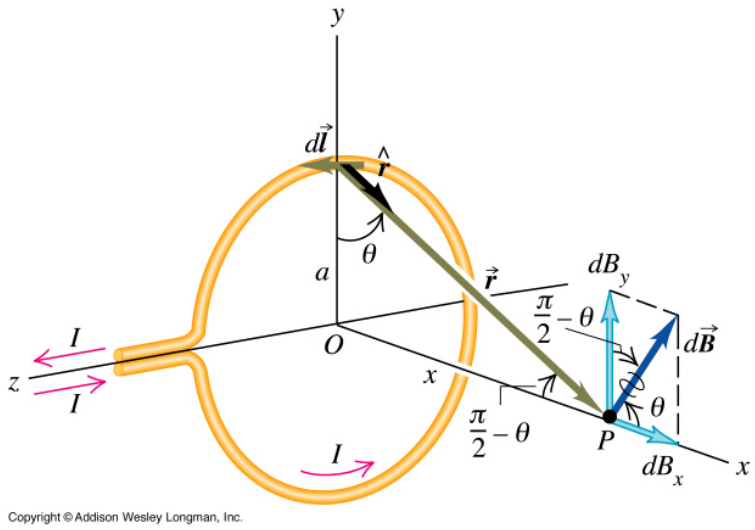
Sources of H

$$\oint B\, dl = \mu_0 I$$

Ampère's circuital law

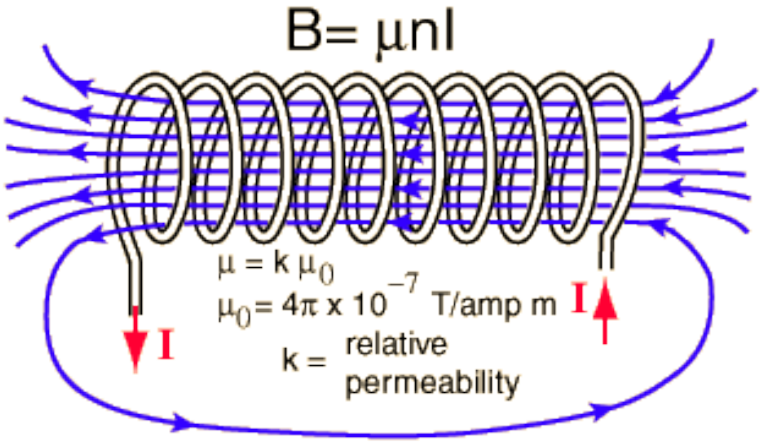


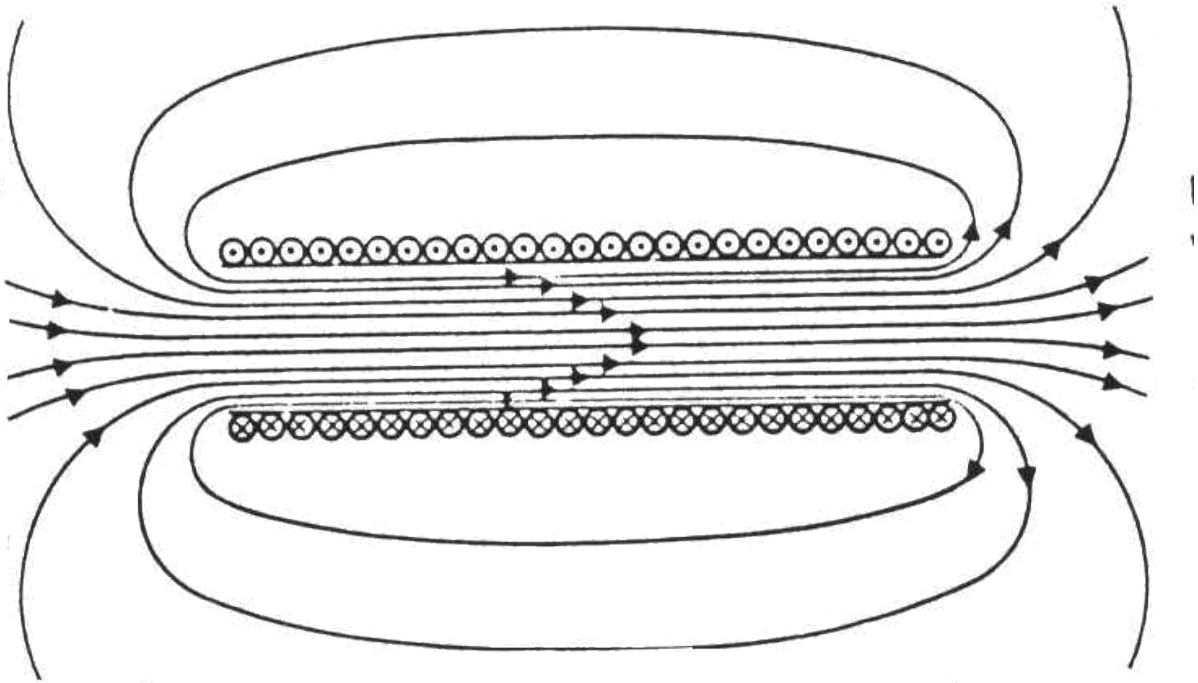




Sources of H

$$\oint B\, dl = \mu_0 I$$





Magnetic Field for a solenoid (a long helical coil)

$$B = \mu_0 \frac{N}{L} I$$

$$B = \mu_0 n\, I$$

Pregunta #2

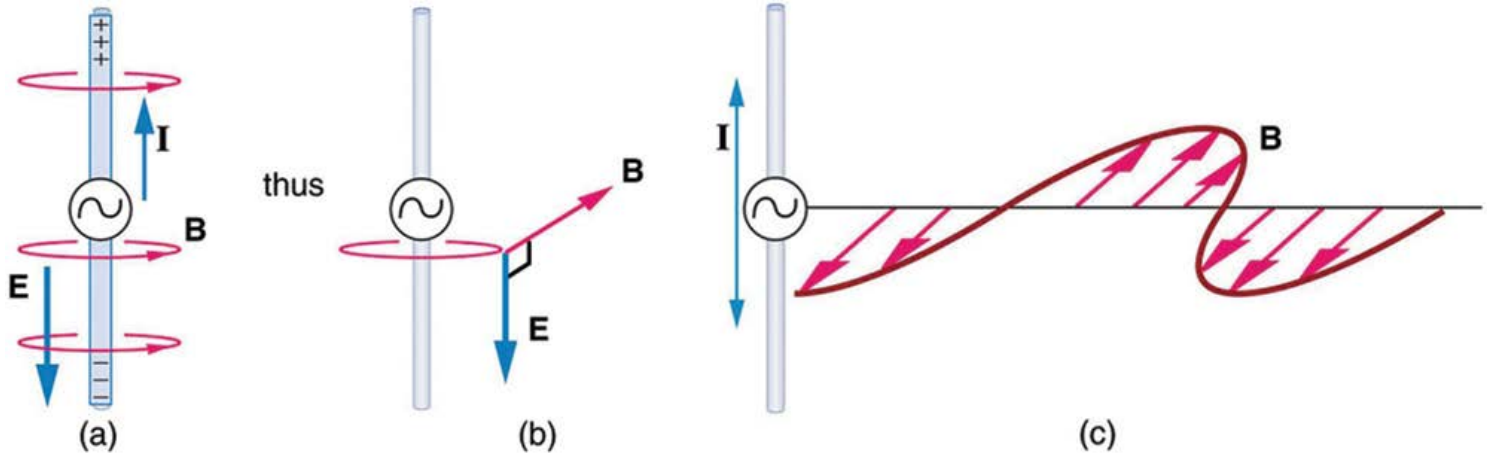
¿De dónde provienen las

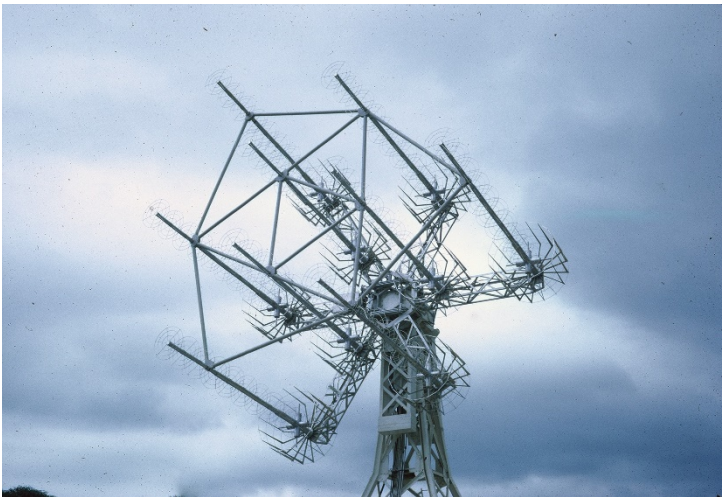
¿Cómo se producen las

¿Cuáles son las fuentes de las

} **Ondas Electromagnéticas?**

With a.c. current…





THE ORIGIN OF H AND B

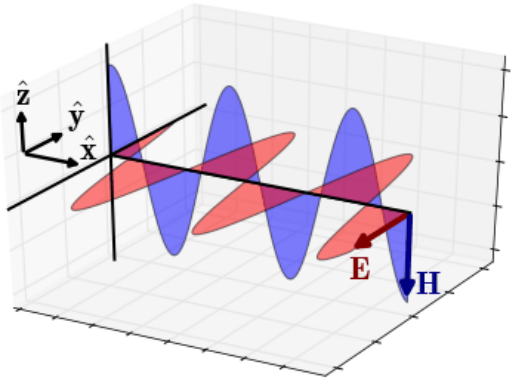
Point Form	Integral Form
$\nabla \times \mathbf{H} = \mathbf{J}_c + \frac{\partial \mathbf{D}}{\partial t}$	$\oint \mathbf{H} \cdot d\mathbf{l} = \int_S \left(\mathbf{J}_c + \frac{\partial \mathbf{D}}{\partial t} \right) \cdot d\mathbf{S}$ (Ampère's law)
$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$	$\oint \mathbf{E} \cdot d\mathbf{l} = \int_S \left(-\frac{\partial \mathbf{B}}{\partial t} \right) \cdot d\mathbf{S}$ (Faraday's law; S fixed)
$\nabla \cdot \mathbf{D} = \rho$	$\oint_S \mathbf{D} \cdot d\mathbf{S} = \int_v \rho \, dv$ (Gauss' law)
$\nabla \cdot \mathbf{B} = 0$	$\oint_S \mathbf{B} \cdot d\mathbf{S} = 0$ (nonexistence of monopole)

https://github.com/phetsims/faradays-law

$$\nabla^2 E - \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} = 0$$

$$\nabla^2 B - \frac{1}{c^2}\frac{\partial^2 B}{\partial t^2} = 0$$

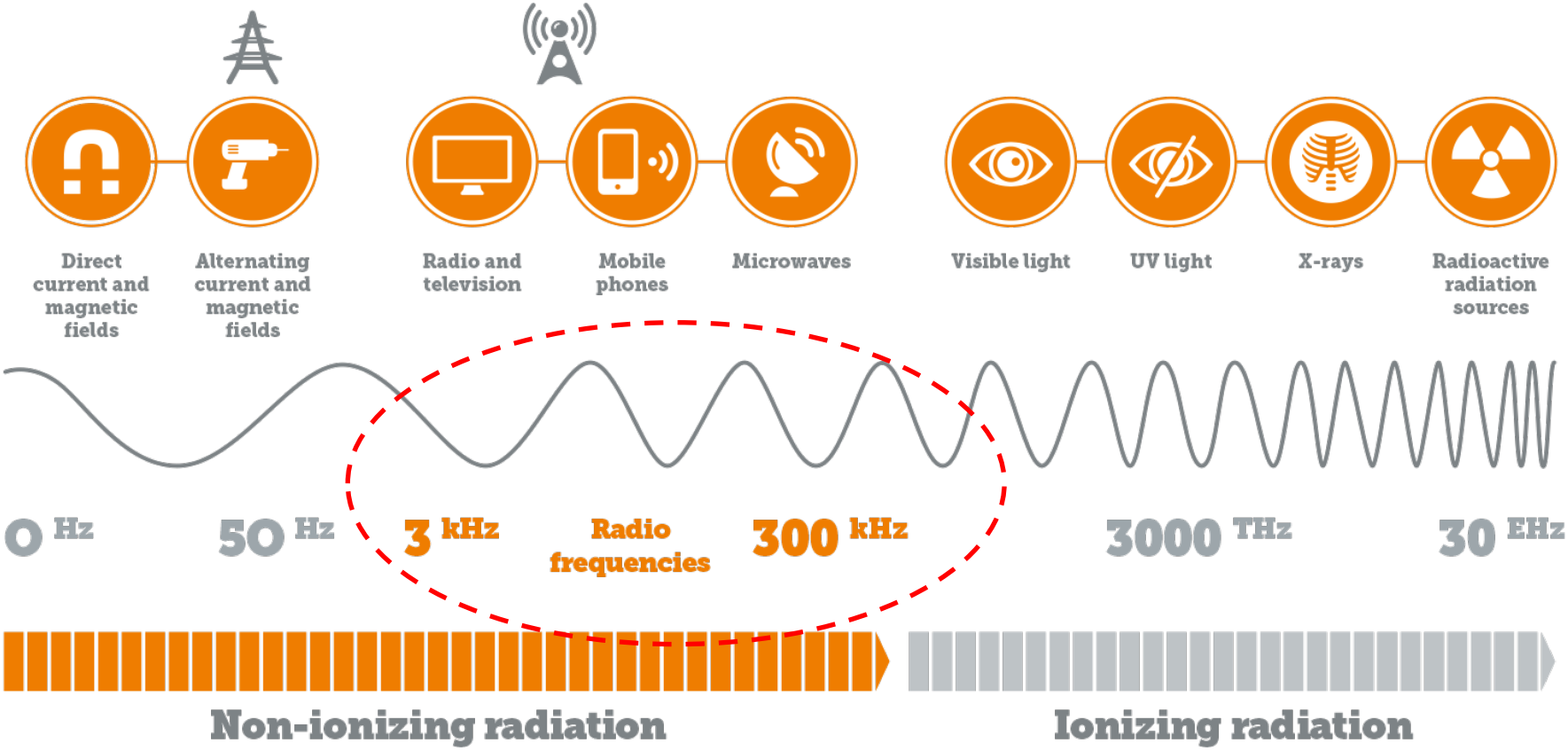
$$c^2 = \frac{1}{\mu\varepsilon}$$



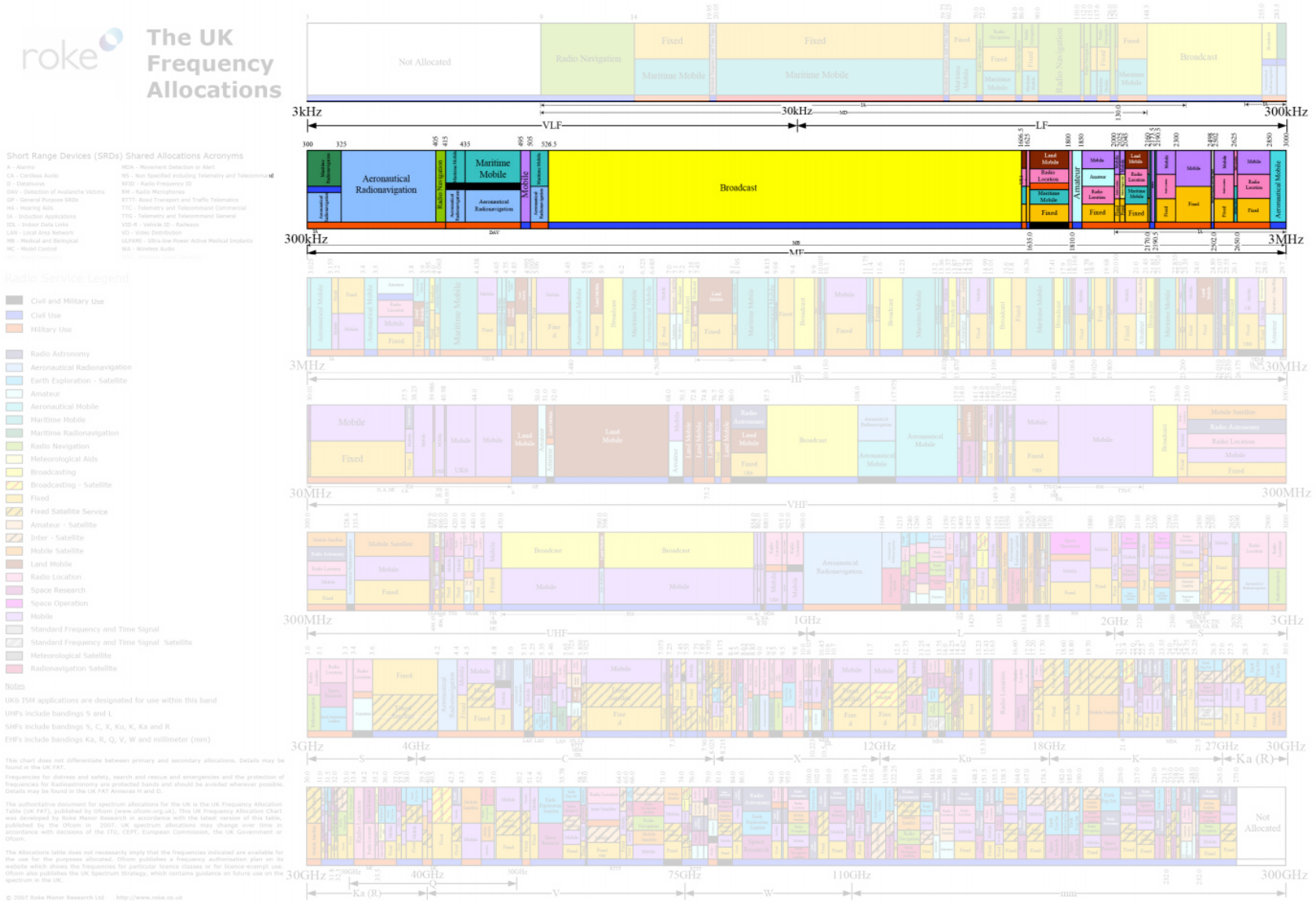
https://em.geosci.xyz/content/maxwell1_fundamentals/harmonic_planewaves_homogeneous/impedancephase.html

Toda onda electromagnetica
que ves/sientes/mides,
proviene de una carga eléctrica
en movimiento,
en algún lugar del Universo.

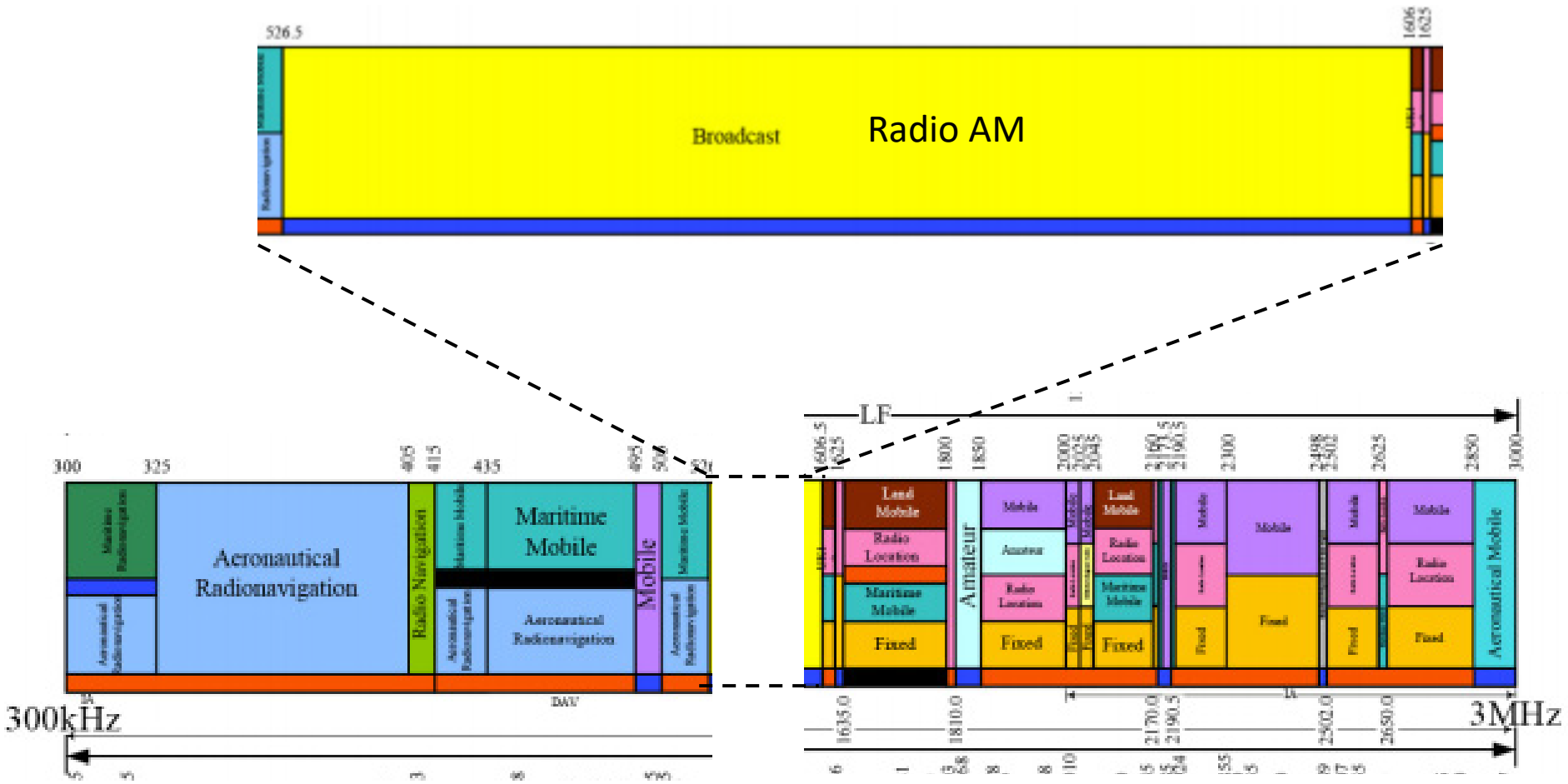
Electromagnetic Field

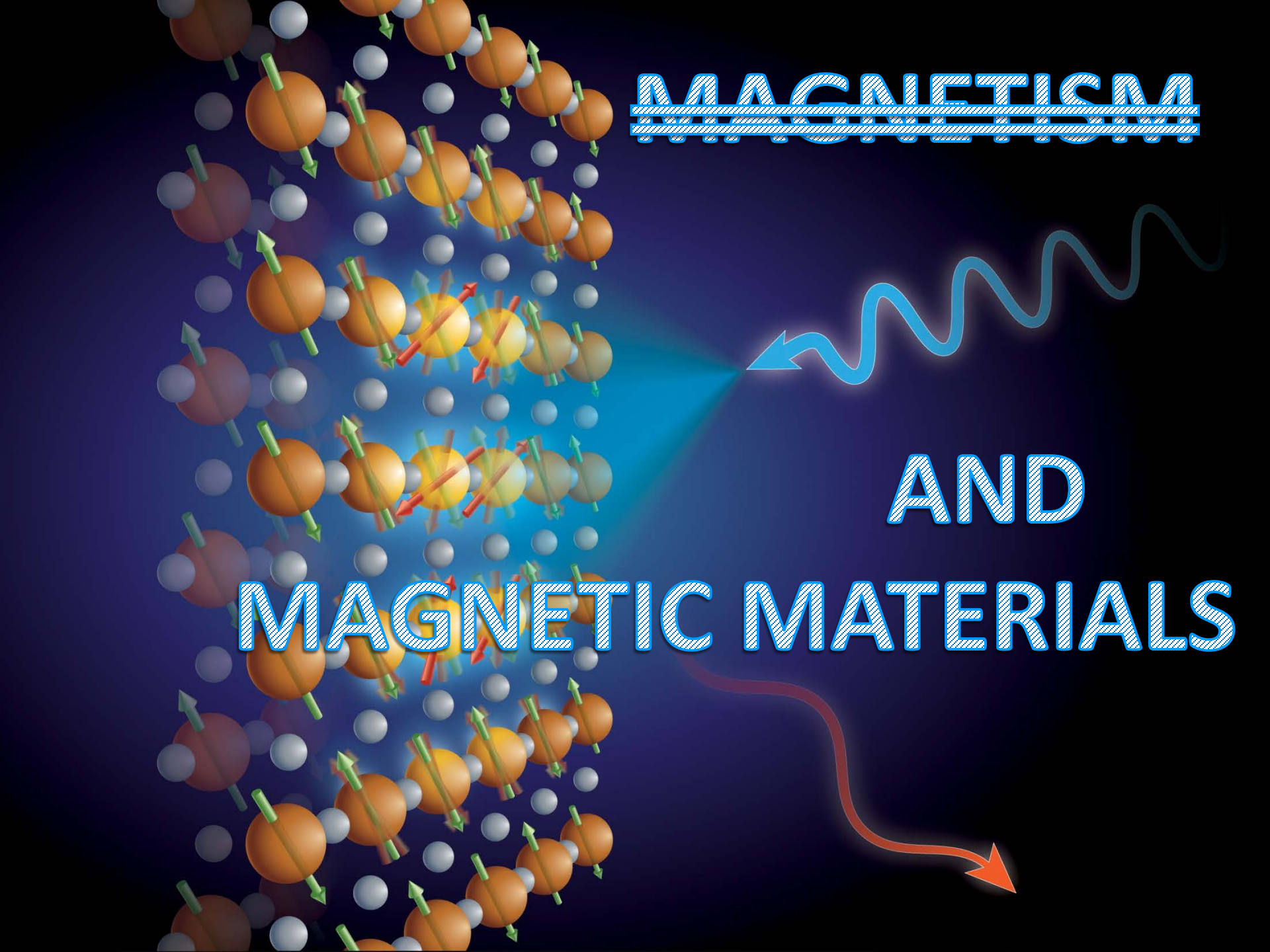


Electromagnetic Field



Ondas usadas en Hipertermia Magnética




MAGNETISM
AND
MAGNETIC MATERIALS

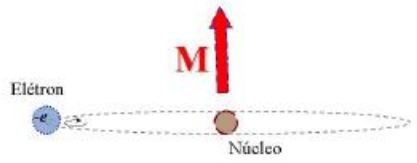
Pregunta #3

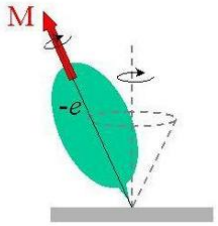
¿Por qué los **Materiales** son **Magnéticos?**

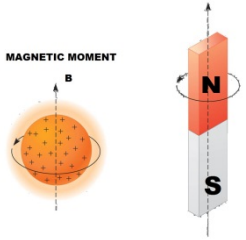
Magnetic materials

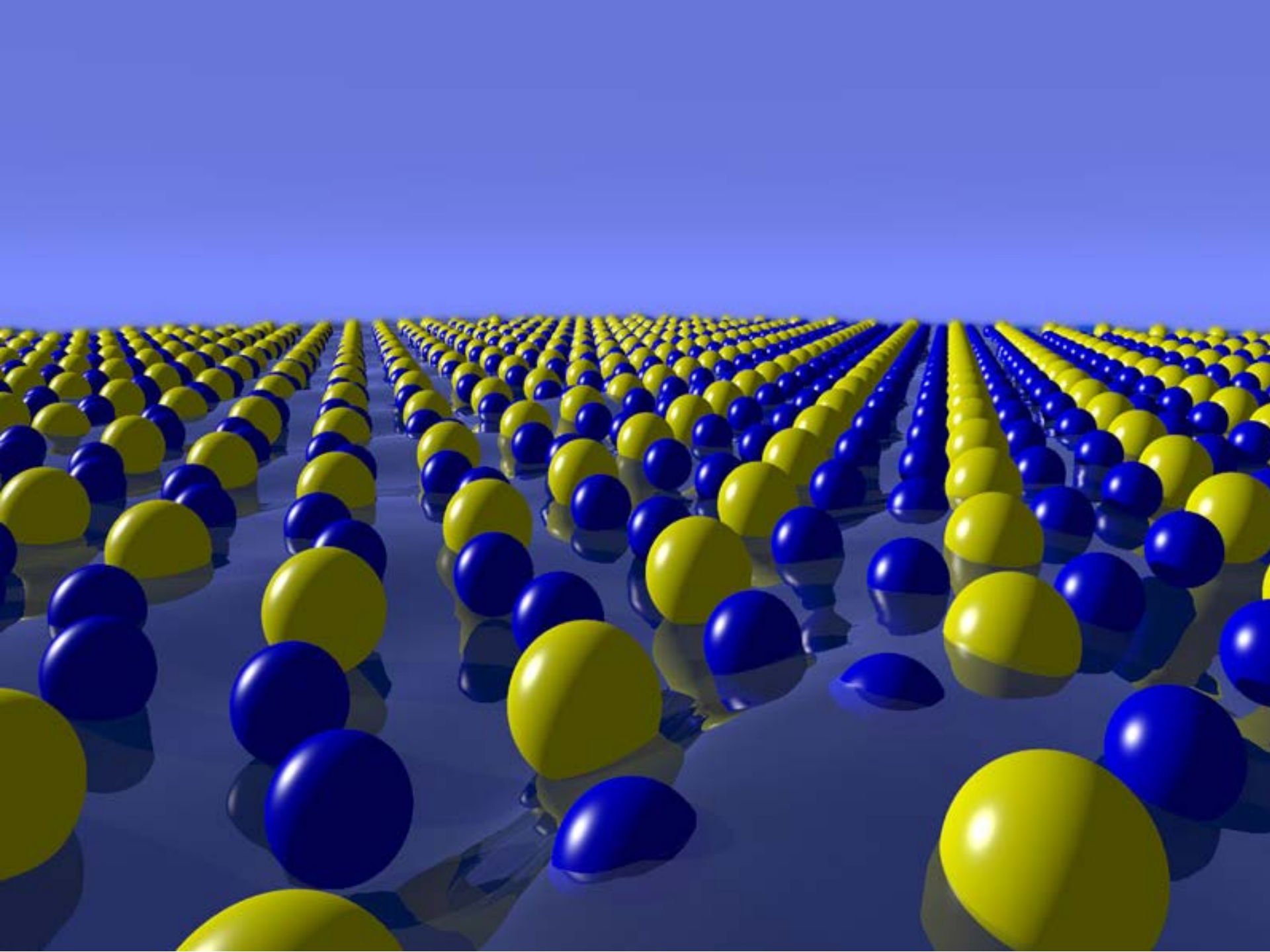
1. Solids are composed by atoms.
2. Atoms have electrons orbiting around the nuclei.
3. Electrons have charge; therefore, the orbitals produce a magnetic field.
4. These atomic fields are represented as atomic magnetic moment M.

So, the origin of magnetism in solids is the moving electron around the nucleus (i.e., atomic orbitals)

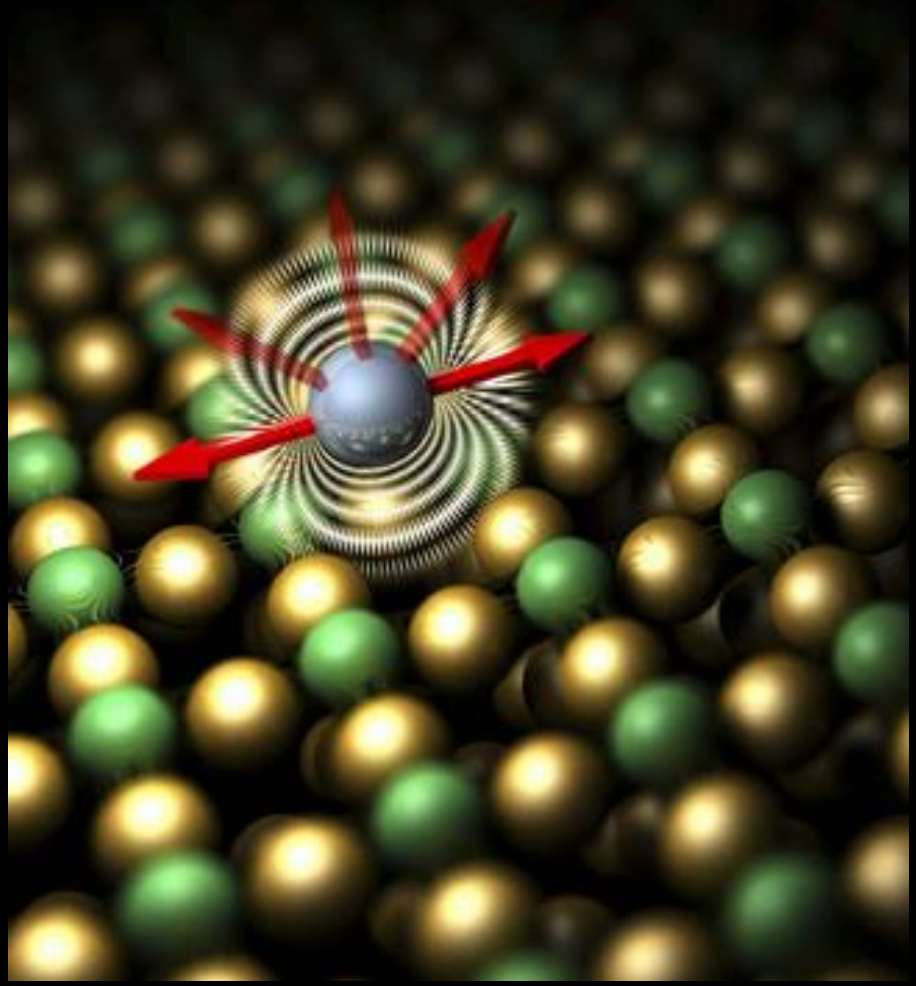




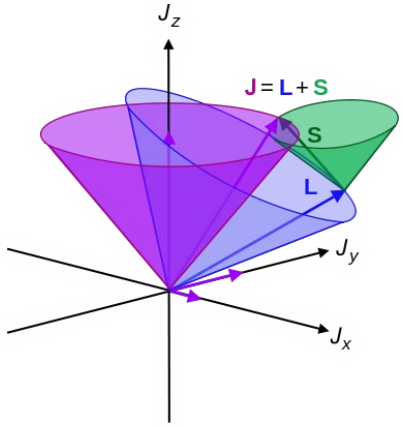


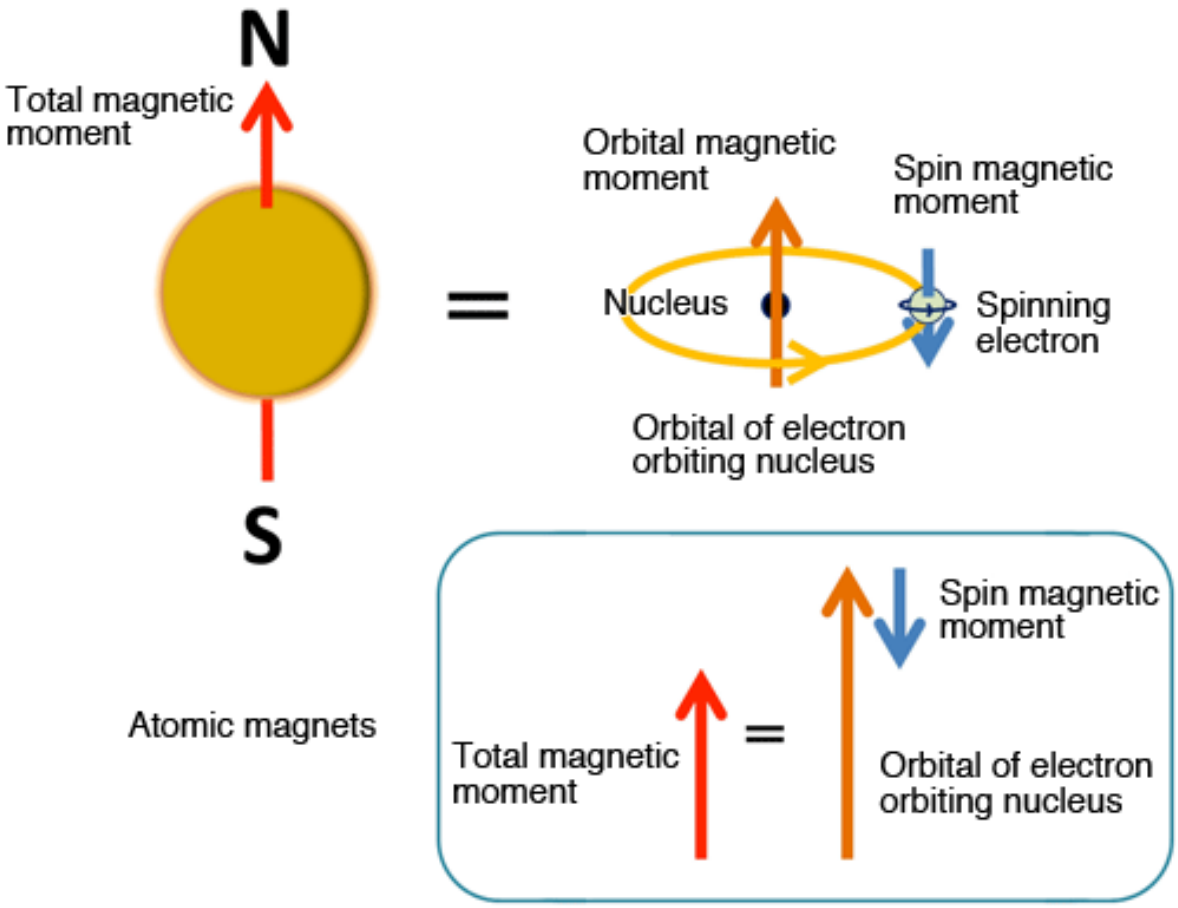


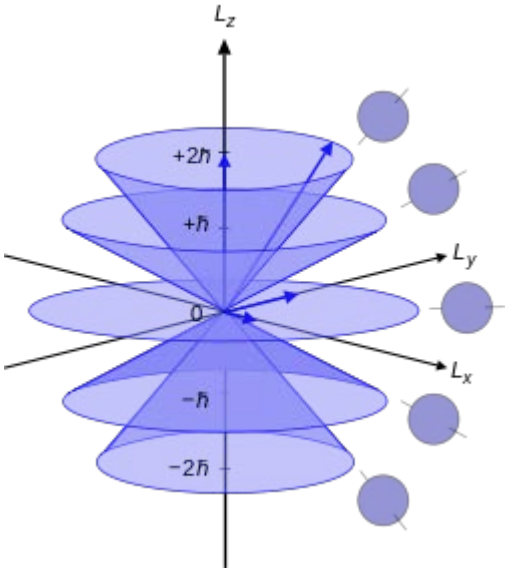
ALL atoms are magnetic…



So, atoms are the origin of magnetism in solids

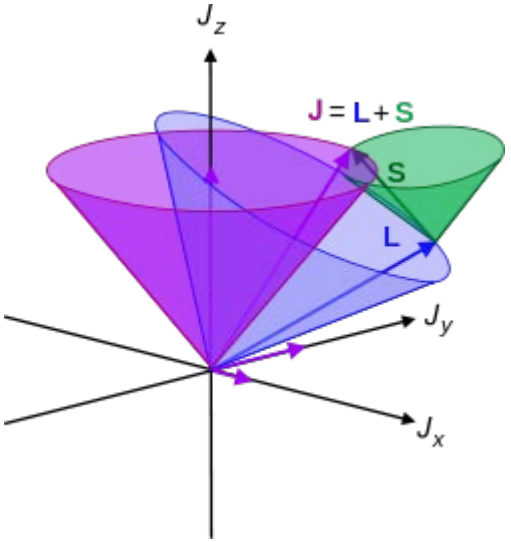




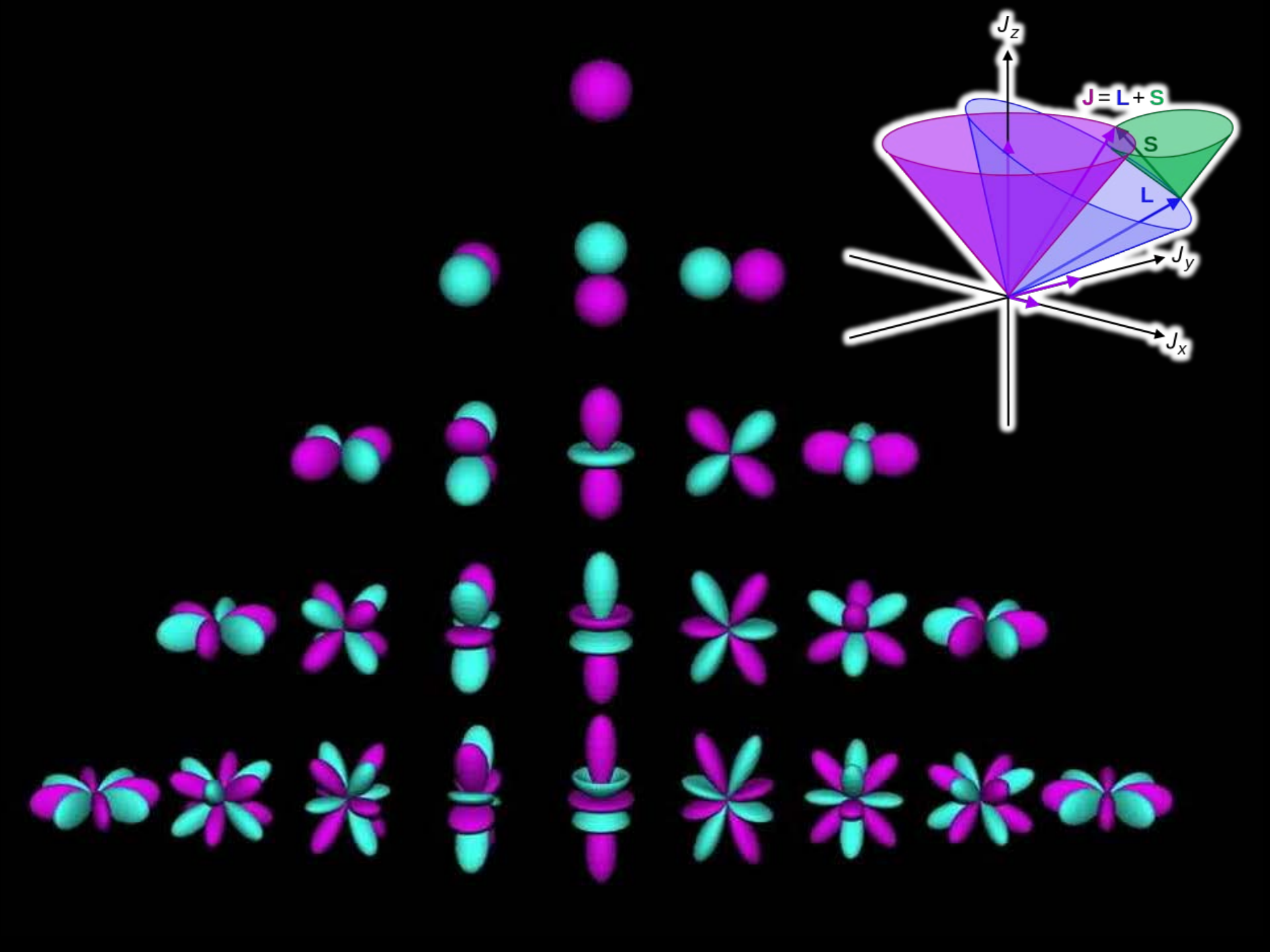


$$L = \sum_i l_i$$

$$\vec{J} = \vec{L} + \vec{S}$$



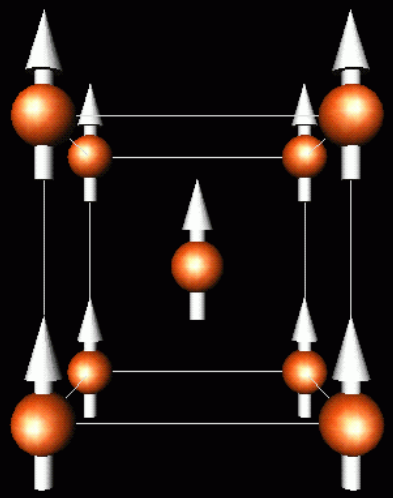
https://en.wikipedia.org/wiki/Angular_momentum_coupling


J_z
J = L + S
S
L
J_y
J_x

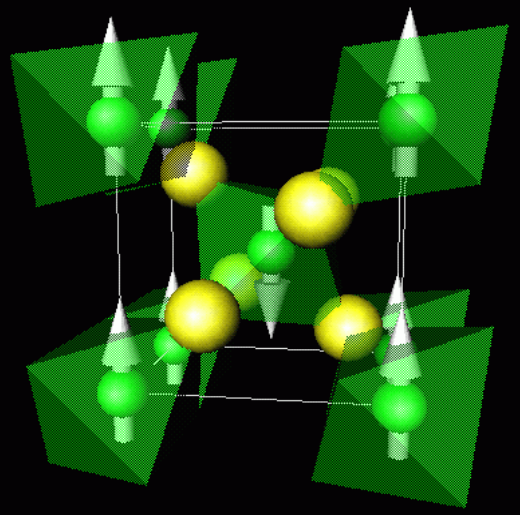
Magnetic Systems

- Paramagnets / Superparamagnets
- Ferromagnets / Antiferromagnets / Ferrimagnets

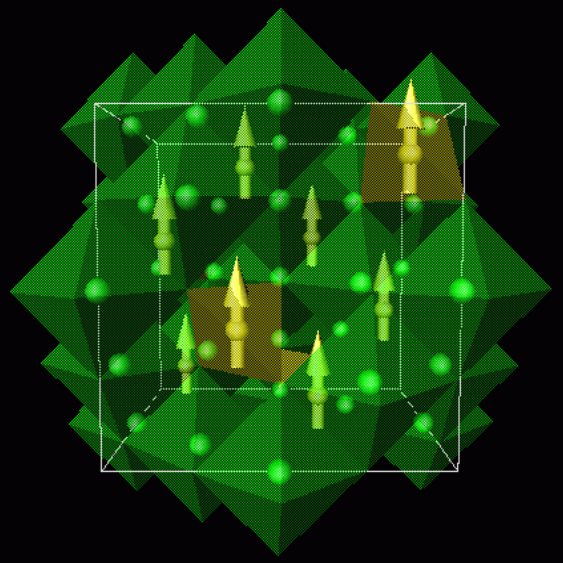
FM: α - Fe



AFM: MnF



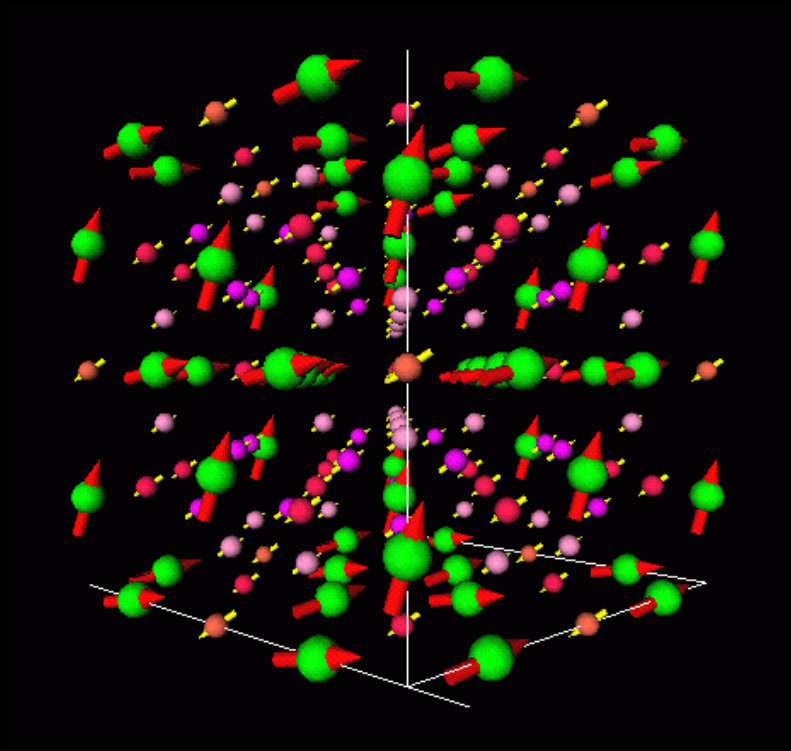
FIM: Fe_3O_4



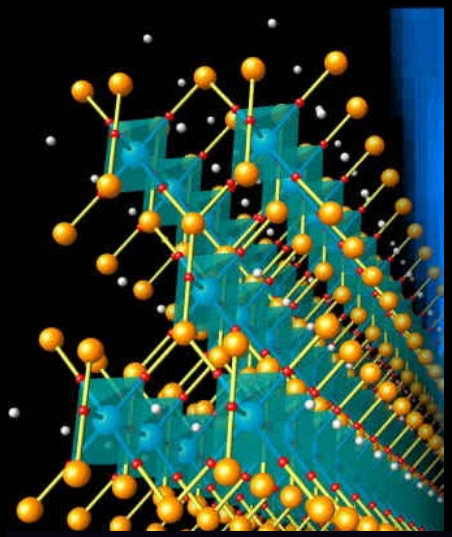
Magnetic Systems

- **Complex helicoidal structures**
- **Low-dimensional structures**

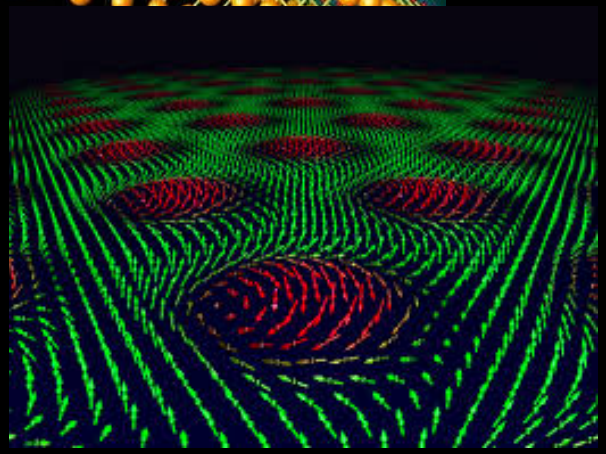
HAFM: Er_6Mn_{23}



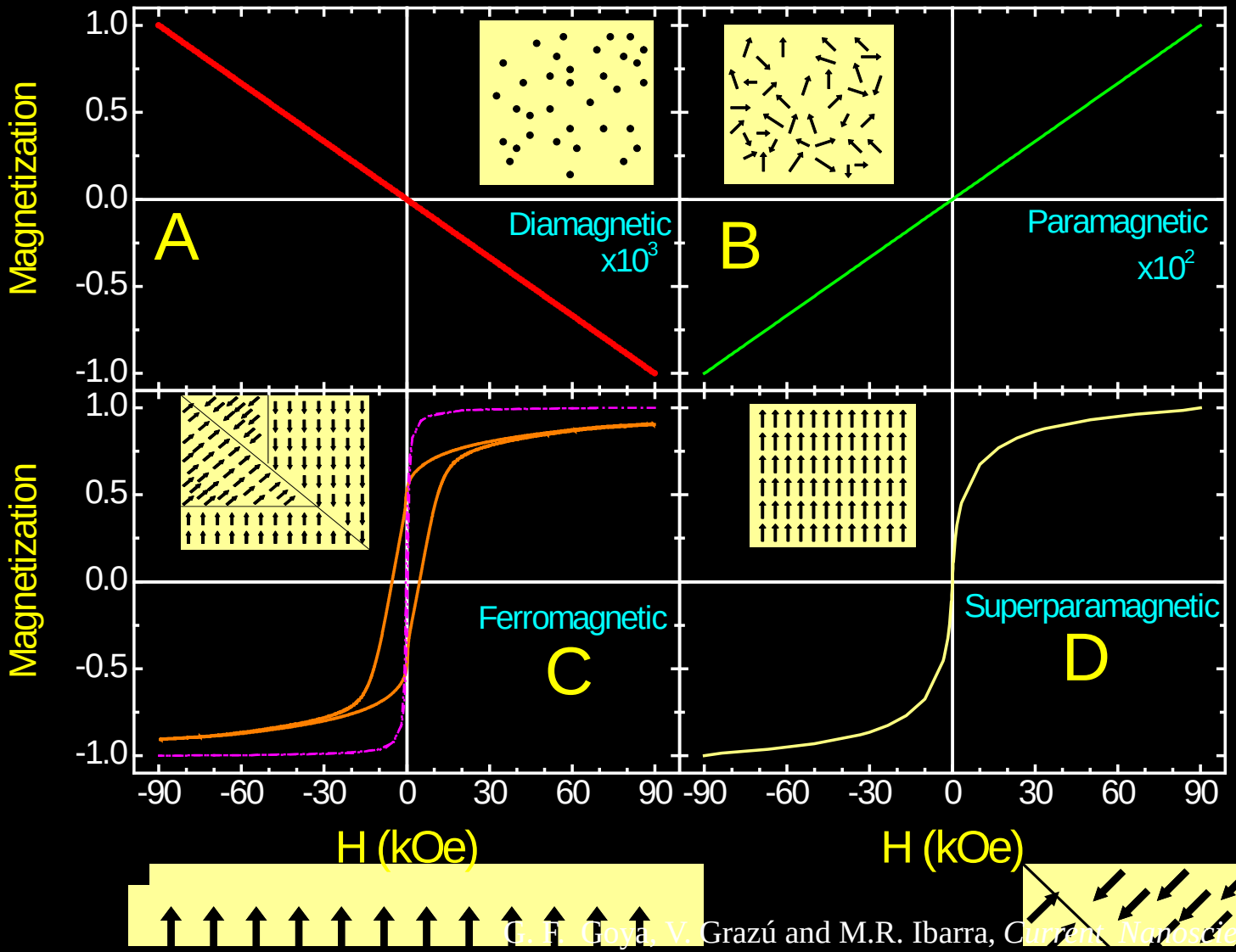
1-D



2-D



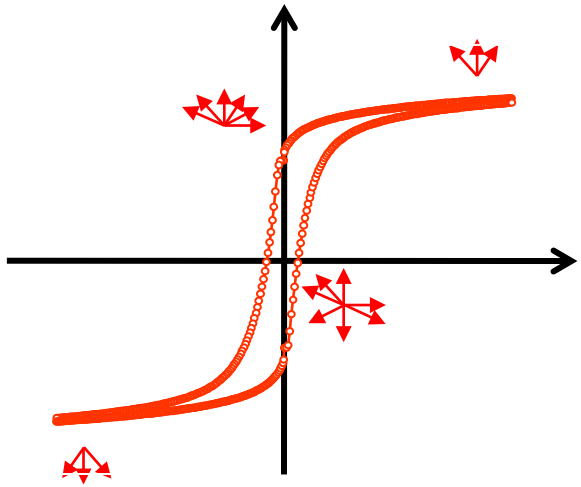
Lo que ves en un VSM

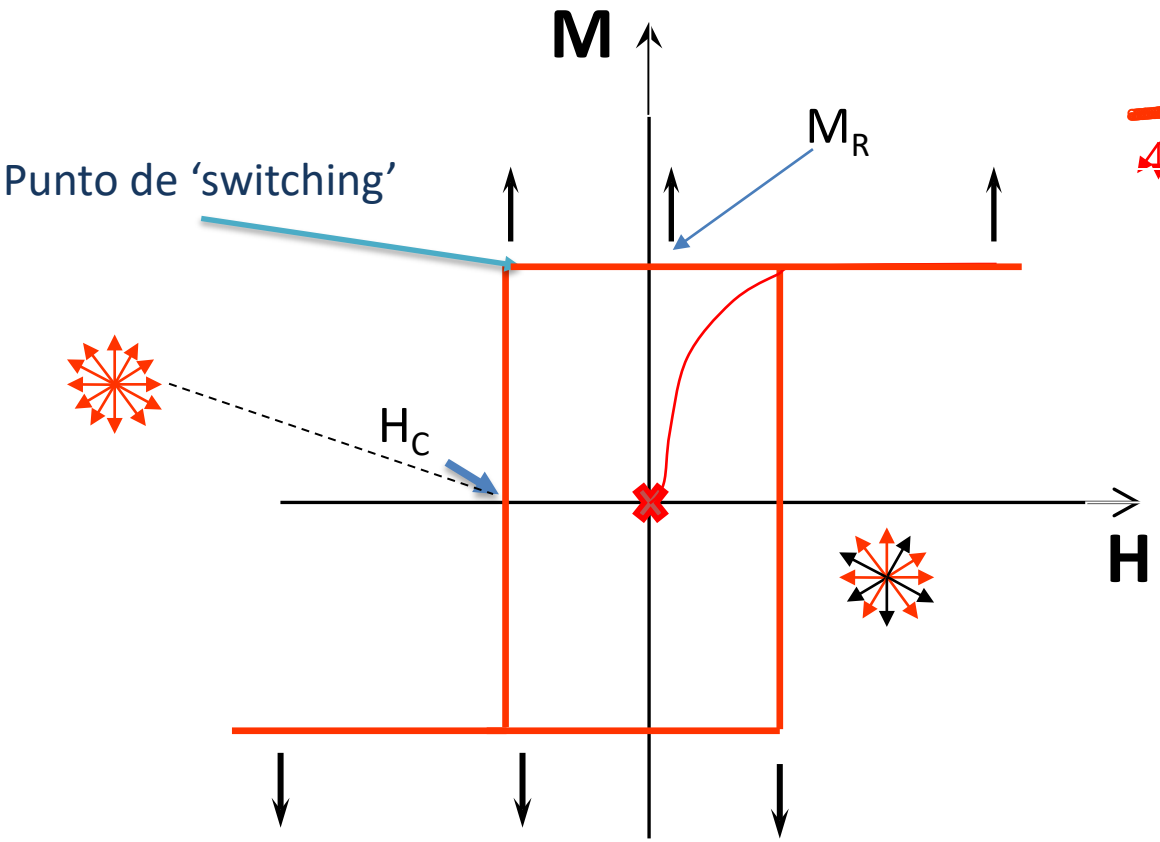


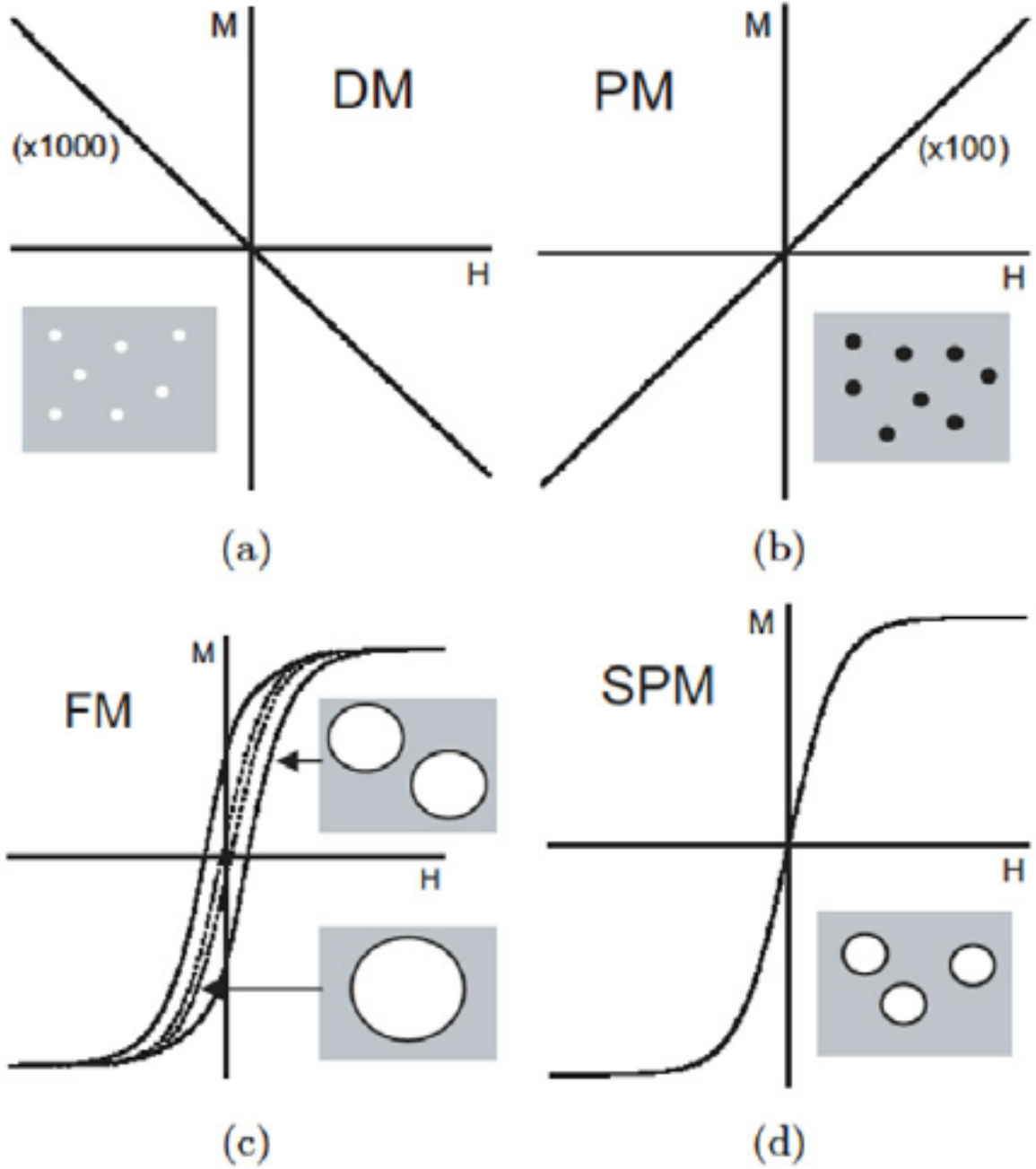
C. F. Goya, V. Grazú and M.R. Ibarra, *Current Nanoscience*, 2007.

Aragon Institute of Nanoscience - INA

Hysteresis cycle






M
DM
(x1000)
H
(a)
M
PM
(x100)
H
(b)
M
FM
H
(c)
M
SPM
H
(d)

Todos los átomos son magnéticos.
Por tanto todos los materiales son magnéticos.

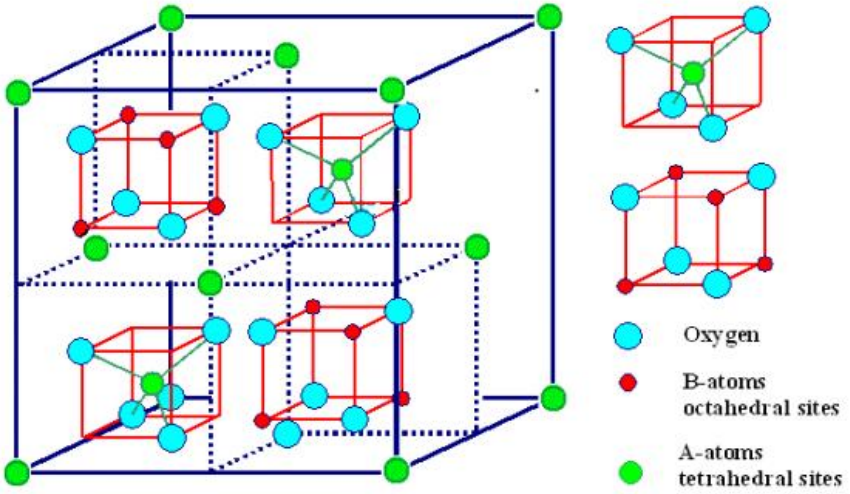
Nos centraremos ahora en los que comúnmente llamamos magnéticos, que en rigor son los

Materiales Ferro/Ferri-magneticos

SPINEL STRUCTURE

AB_2O_4

$[M_\delta Fe_{1-\delta}]^A[M_{1-\delta}Fe_{1+\delta}]^BO_4$



AB_2O_4 **spinel** The red cubes are also contained in the back half of the unit cell

Space Group = Fd3m (227)
a = 5.8 - 8.7
Atomic Positions

A	8a	0, 0, 0	
M	16d	5/8, 5/8, 5/8	
X	32e	x, x, x	x ~ 0.385

Coordination Numbers/Geometry

A	4	Tetrahedral coordination
M	6	Octahedral coordination
X	4	Distorted tetrahedral coordination

http://wwwchem.uwimona.edu.jm/courses/spinel.html

$MgAl_2O_4$ $FeFe_2O_4$ Fe_3O_4

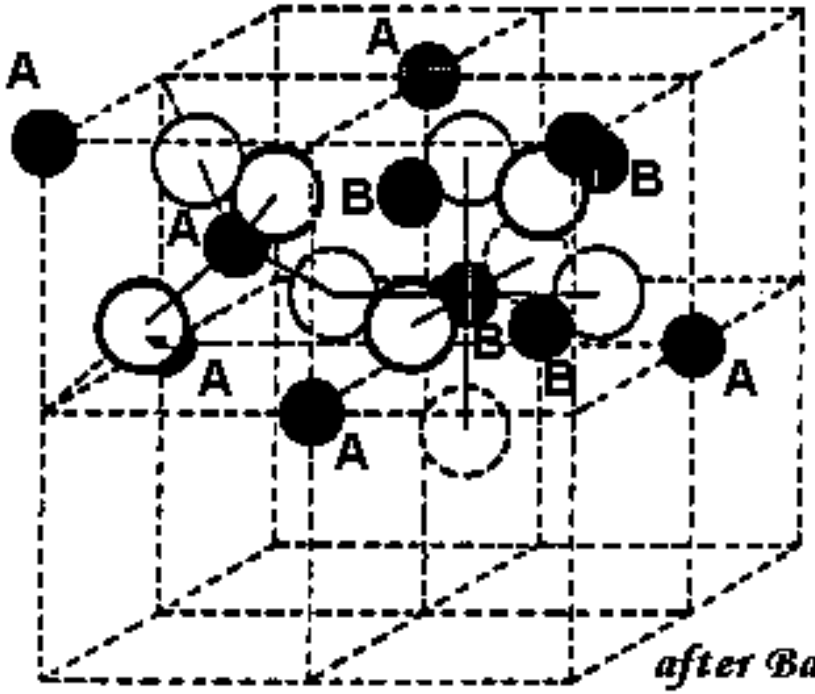
http://beamteam.usask.ca/alumni/sam-leitch.html

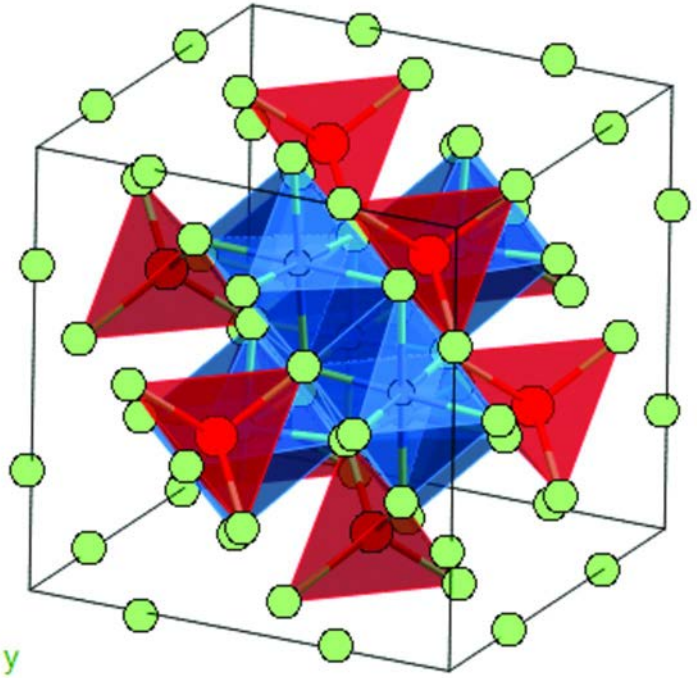
SPINEL STRUCTURE

AB_2O_4

$[M_\delta Fe_{1-\delta}]^A[M_{1-\delta}Fe_{1+\delta}]^B O_4$

1/2 of the 8 octahedral B holes filled
1/8 of the 16 tetrahedral A holes filled





after Banerjee and Moskowitz (1985)

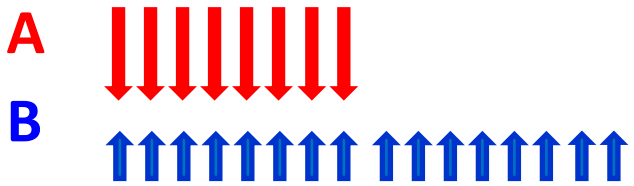
http://cbc-wb01x.chemistry.ohio-state.edu/~woodward/ch754/struct/MgAl2O4.htm

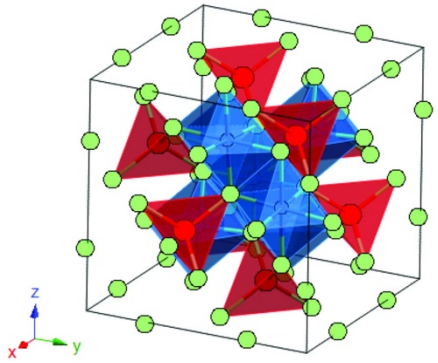
FERRIMAGNETIC SPINEL

AB_2O_4

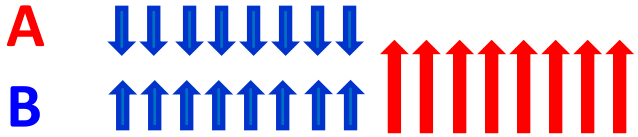
$[M_\delta Fe_{1-\delta}]^A[M_{1-\delta}Fe_{1+\delta}]^BO_4$

$\delta = 1$

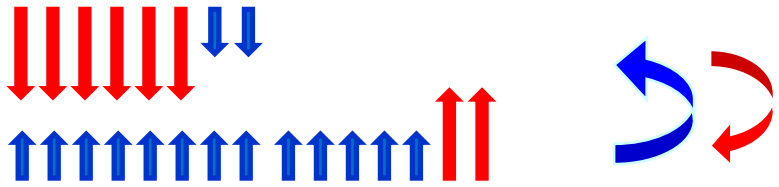




$\delta = 0$



$\delta = 0.25$



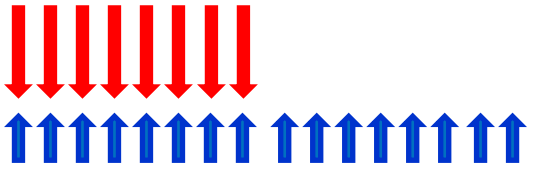
Let's assume

FERRIMAGNETIC SPINEL AB_2O_4

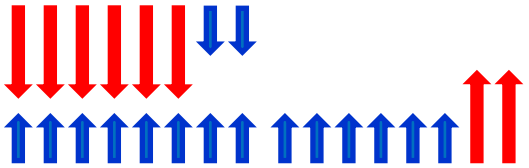
$m_B = 1\ \mu_B$; $m_A = 1.5\ \mu_B$ and normal structure

$m_T = -8x\ 1.5\ \mu_B + 16 \times 1\ \mu_B$

$m_T = (-12 + 16)\ \mu_B = 4\ \mu_B$ /unit cell



Now assume $\delta = 0.25$



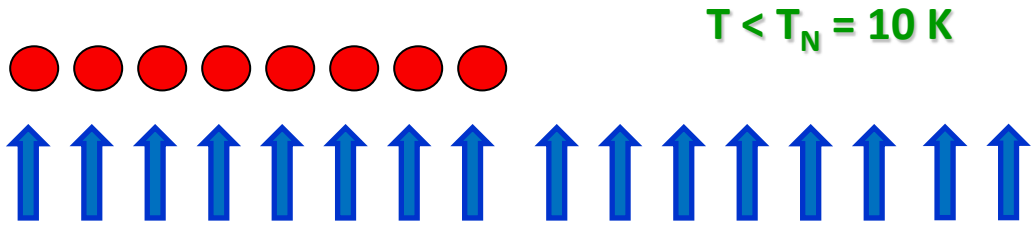
$m_T = -6x\ 1.5\mu_B - 2x\ 1\mu_B + 14x1\mu_B + 2x1.5\mu_B$

$m_T = (-11+17)\ 1\mu_B = 6\ \mu_B$ /unit cell

66% !!!!

Small changes in δ may produce large changes in M

For $[Zn_\delta Fe_{1-\delta}]^A[Zn_{1-\delta}Fe_{1+\delta}]^BO_4$

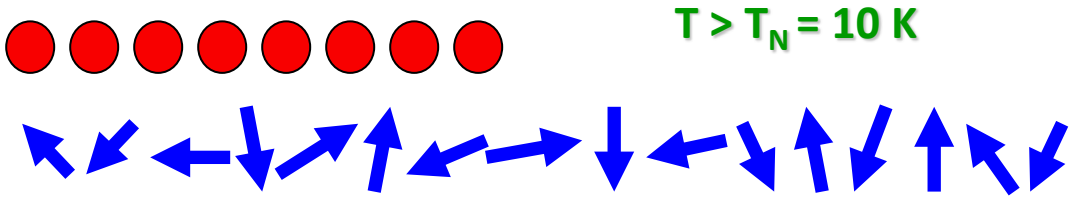


$Zn^AFe_2{}^BO_4$

$m_T = 16 \times 1\ \mu_B = 16\ \mu_B$ /unit cell

BUT....

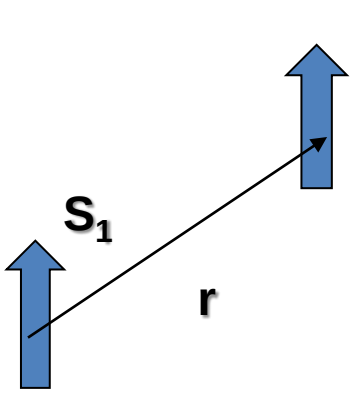
$ZnFe_2O_4$



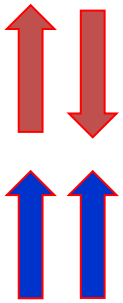
Pregunta #4

¿Por qué algunas cosas se pegan a mi nevera y otras no?

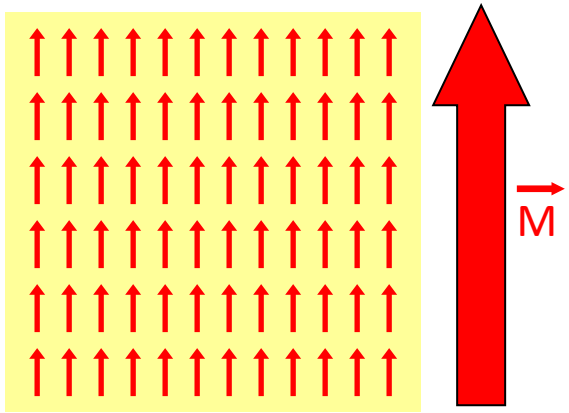

Print
STOP
Pehchaan
wkręt



$$H_{SE} = J_{AF} \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j$$



(1 cm^3)

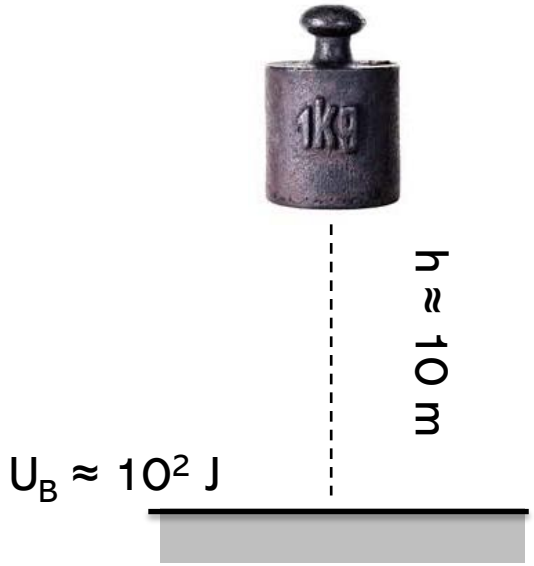


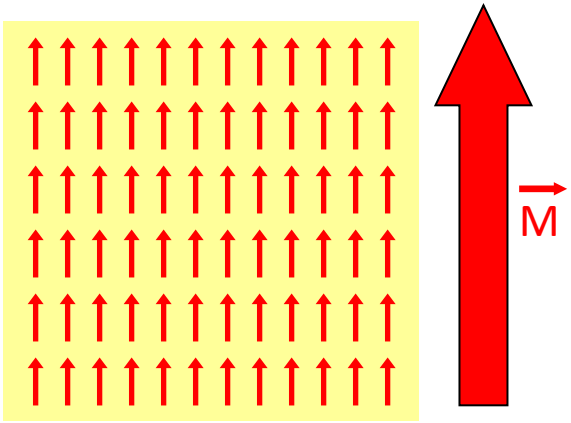
$U_B \approx 10^2$ J !!!

$$E \propto |\overrightarrow{\mu_1}| \cdot |\overrightarrow{\mu_2}| \cos\theta$$

$$E \propto N \propto V$$

$$U_B \propto \iiint_{all\ space} M^2 \, dV$$

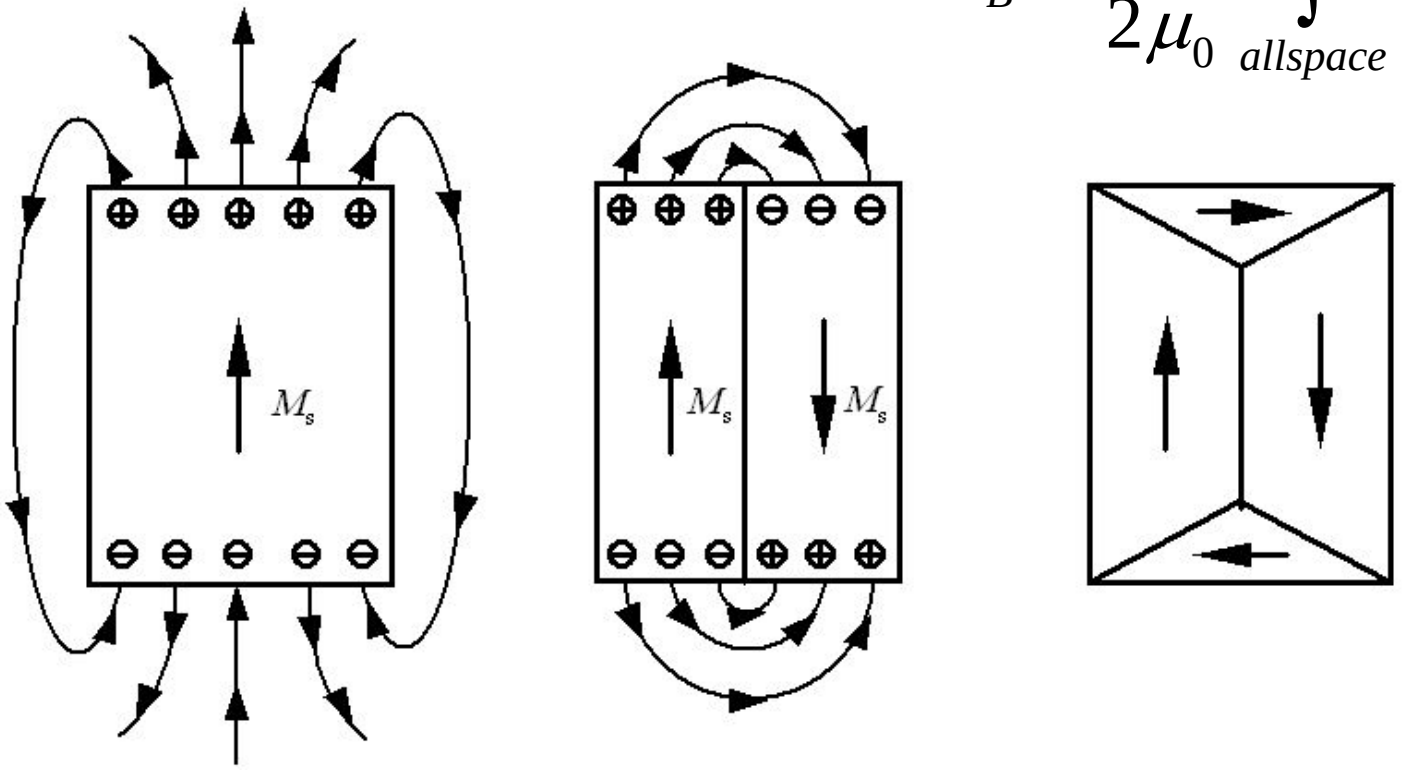




$$H_{SE} = J_{AF} \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j$$

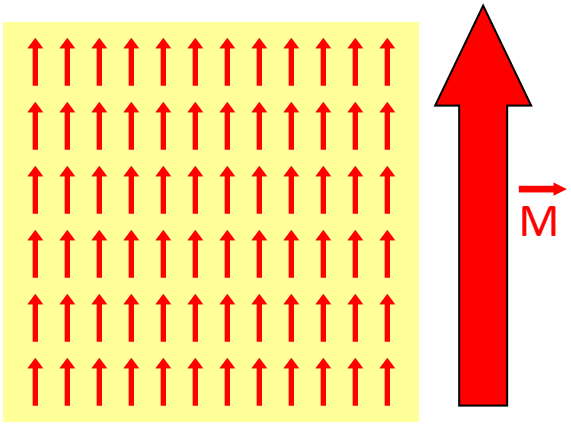
Magnetic Domain

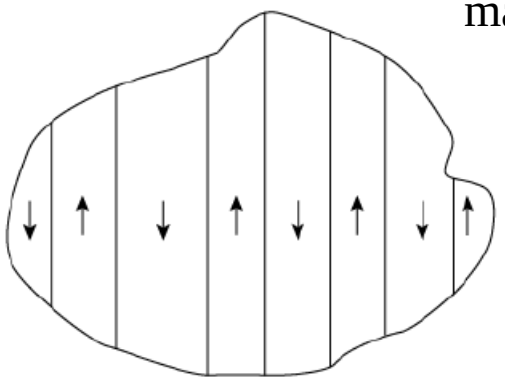
$$U_B = \frac{1}{2\mu_0} \int_{allspace} B^2 d\tau$$



(a) A single-domain sample with a large stray field. (b) A sample split into two domains in order to reduce the magnetostatic energy. (c) A sample divided into four domains. The closure domains at the ends of the sample make the magnetostatic energy zero.

Magnetic Domains

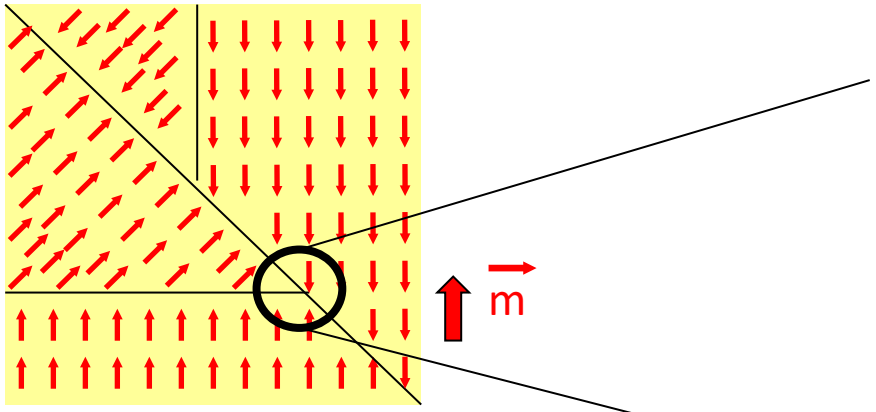


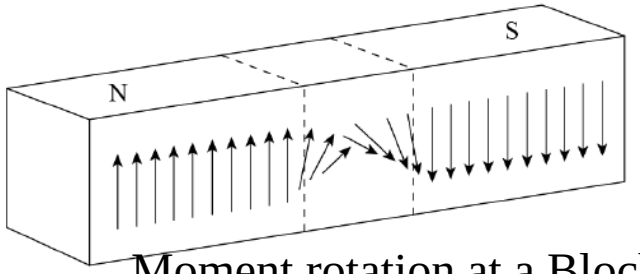


Minimization of magnetostatic energy

$$U_B = \frac{1}{2\mu_0} \int_{allspace} B^2 d\tau$$

leads to domain wall formation





Moment rotation at a Bloch Wall

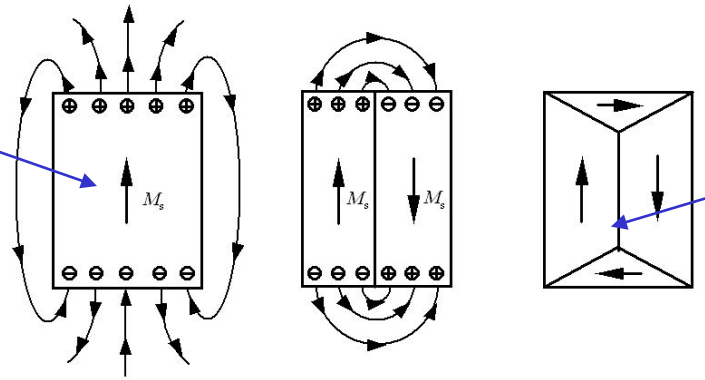
$$\sigma_{BW} = \pi\sqrt{AK} \quad \text{where} \quad A = \frac{2J_{ex}S^2}{a}$$

Magnetostatic Energy and Domain Structure

$$E = E_{ms} + E_{wall} = 1.7M_S^2 D + \gamma L/D$$

Where γ is the domain wall energy per unit area of wall, L is the thickness of the crystal and D is the thickness of the slab-like domains.

$$E_{ms} = N_d M_S^2/2 = 2\pi M_S^2 L$$



$$E = 2\sqrt{1.7M_S^2 \gamma L}$$

$$\frac{dE}{dD} = 1.7M_S^2 - \frac{\gamma L}{D^2} = 0$$

$$D = \sqrt{\frac{\gamma L}{1.7M_S^2}}$$

For Cobalt, γ=7.6 ergs/cm^2, L=1 cm

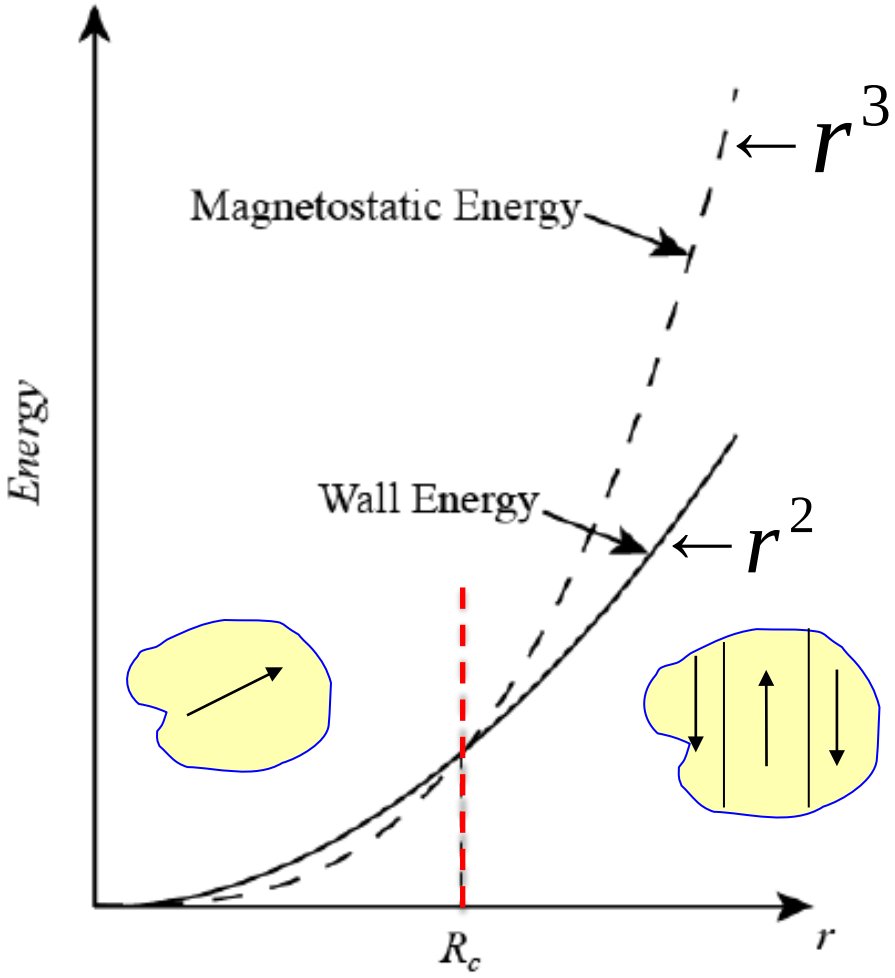
D=1.5×10^{-3}cm, i.e.,

700 domains in a 1 cm cube crystal

Cullity. Introduction to Magnetic Materials

Critical size for single-domain particles

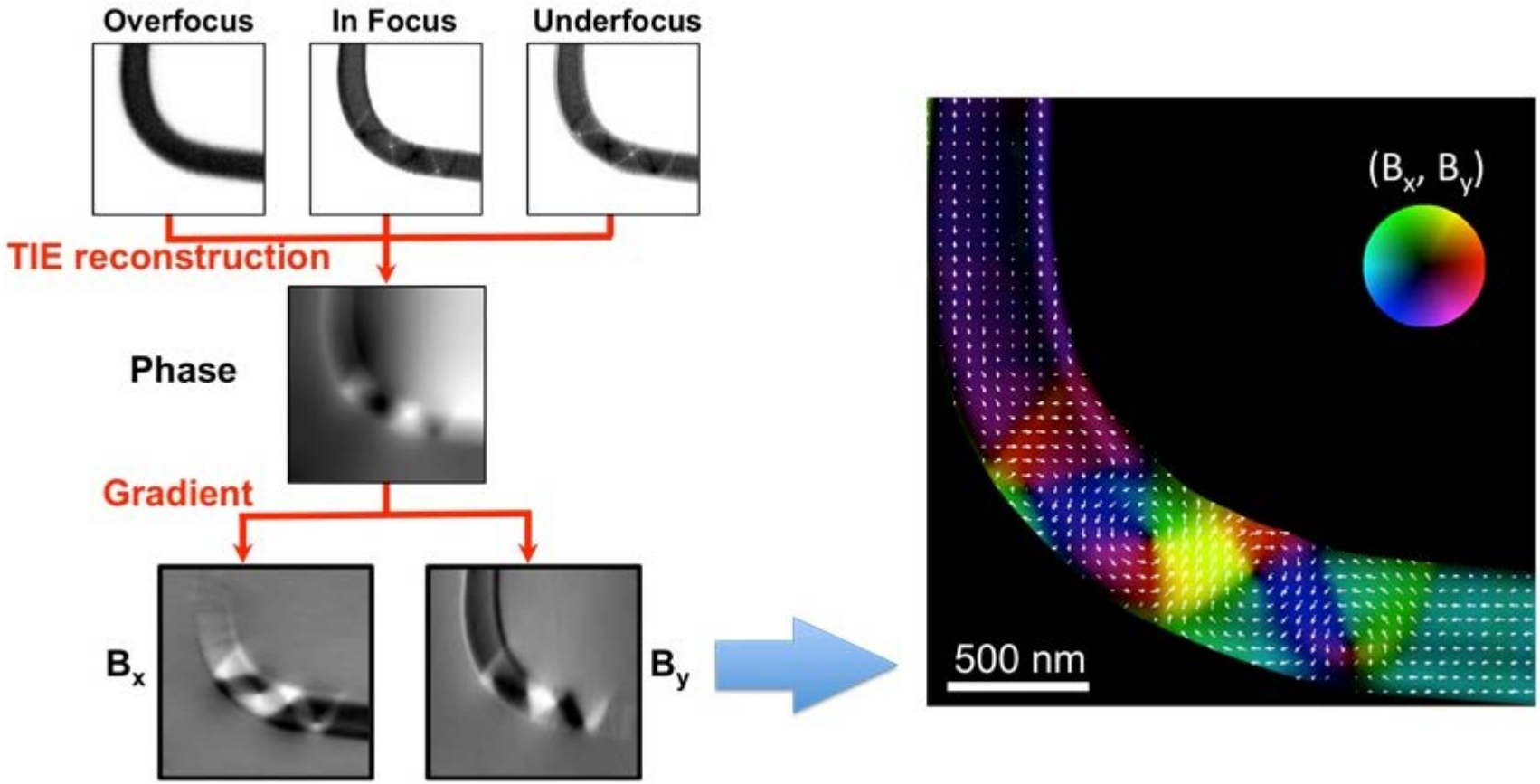
Magnetostatic *vs.* wall energy as a function of particle size for a spherical particle of radius *r*



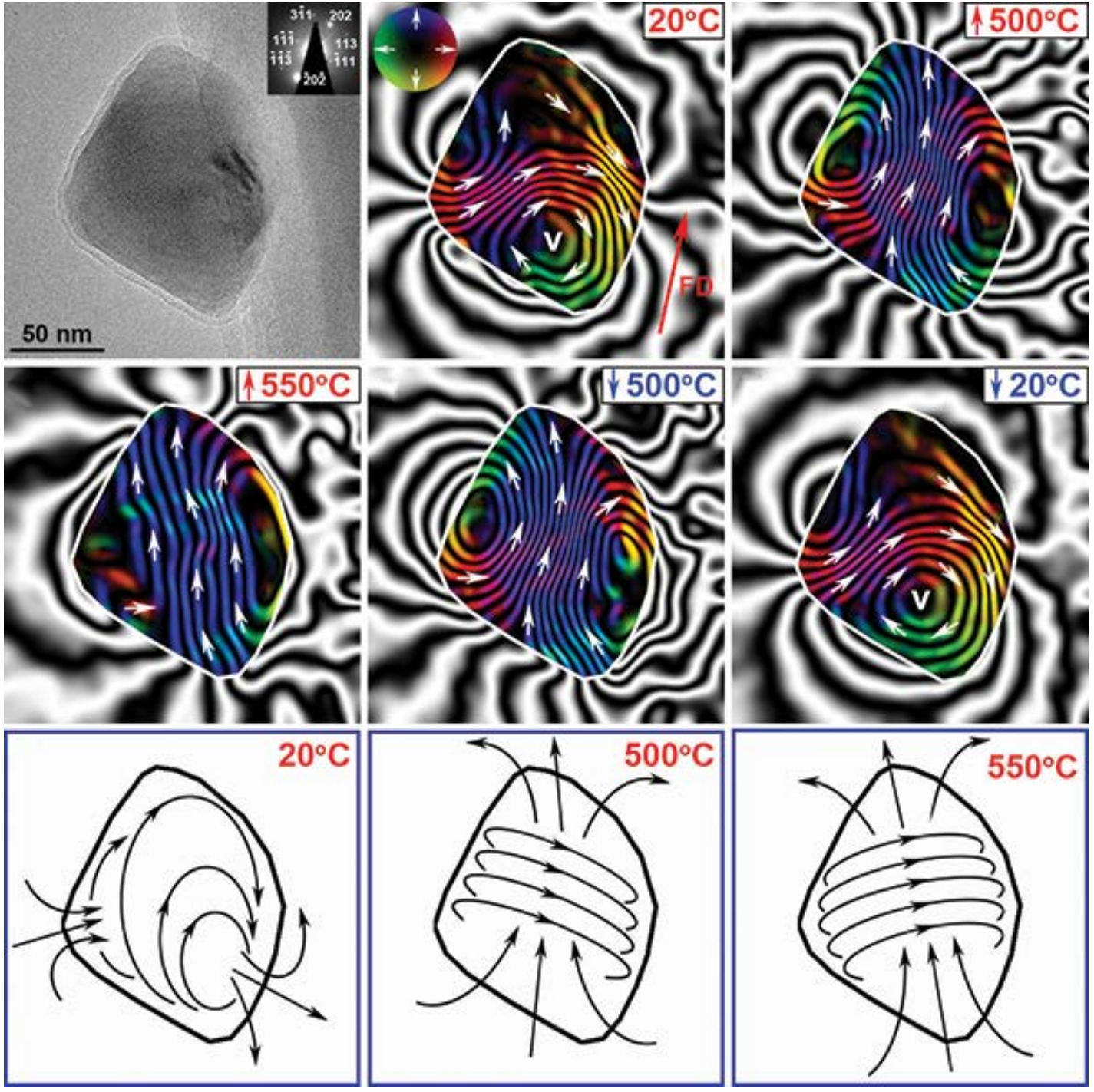
$$R_C = R_{SMD} = \frac{6\sqrt{AK}}{\mu_0 M_s^2}$$

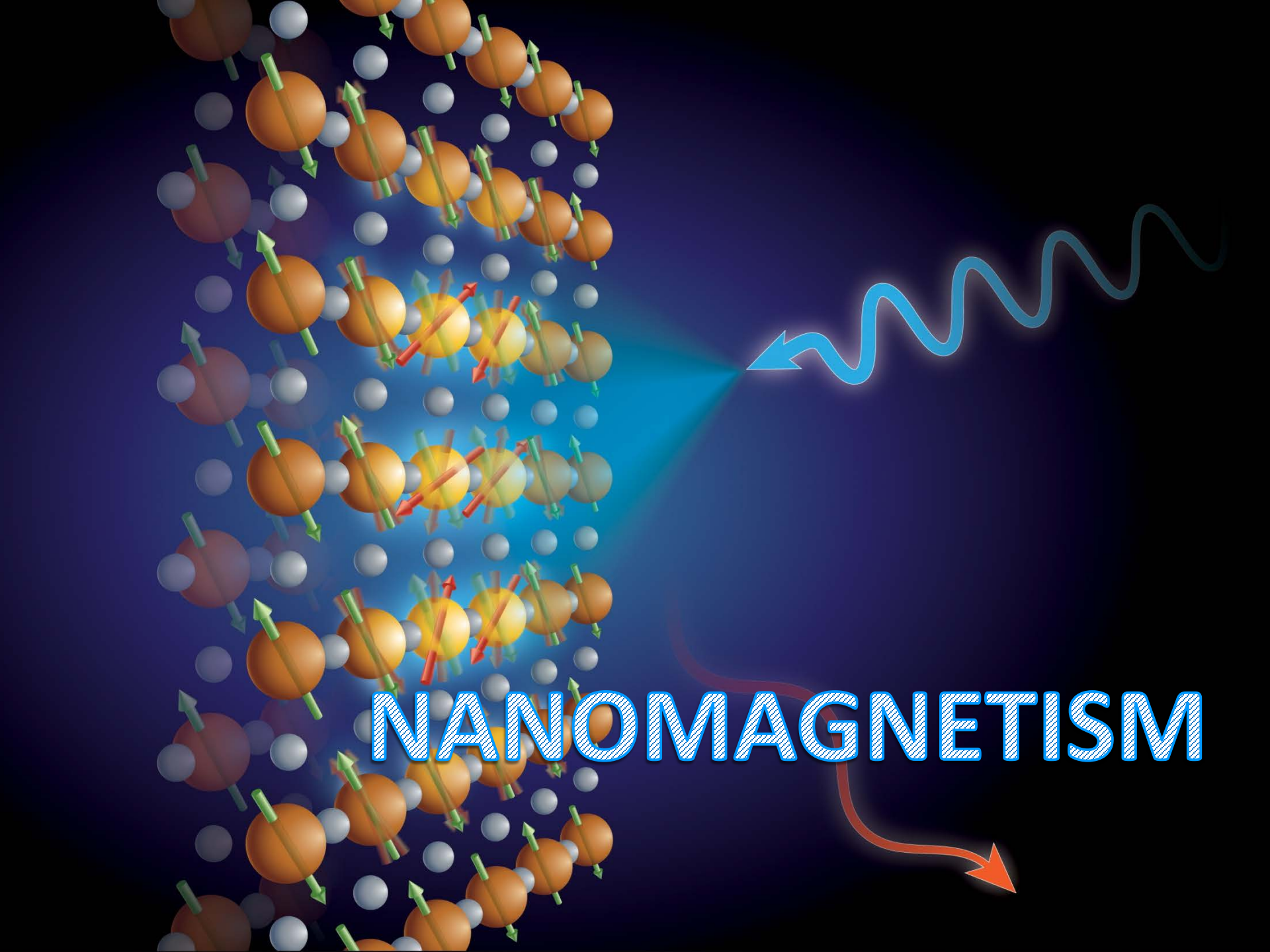
Below R_c the particle is a Single Magnetic Domain, and thus permanently magnetized. The demagnetized state cannot be formed.

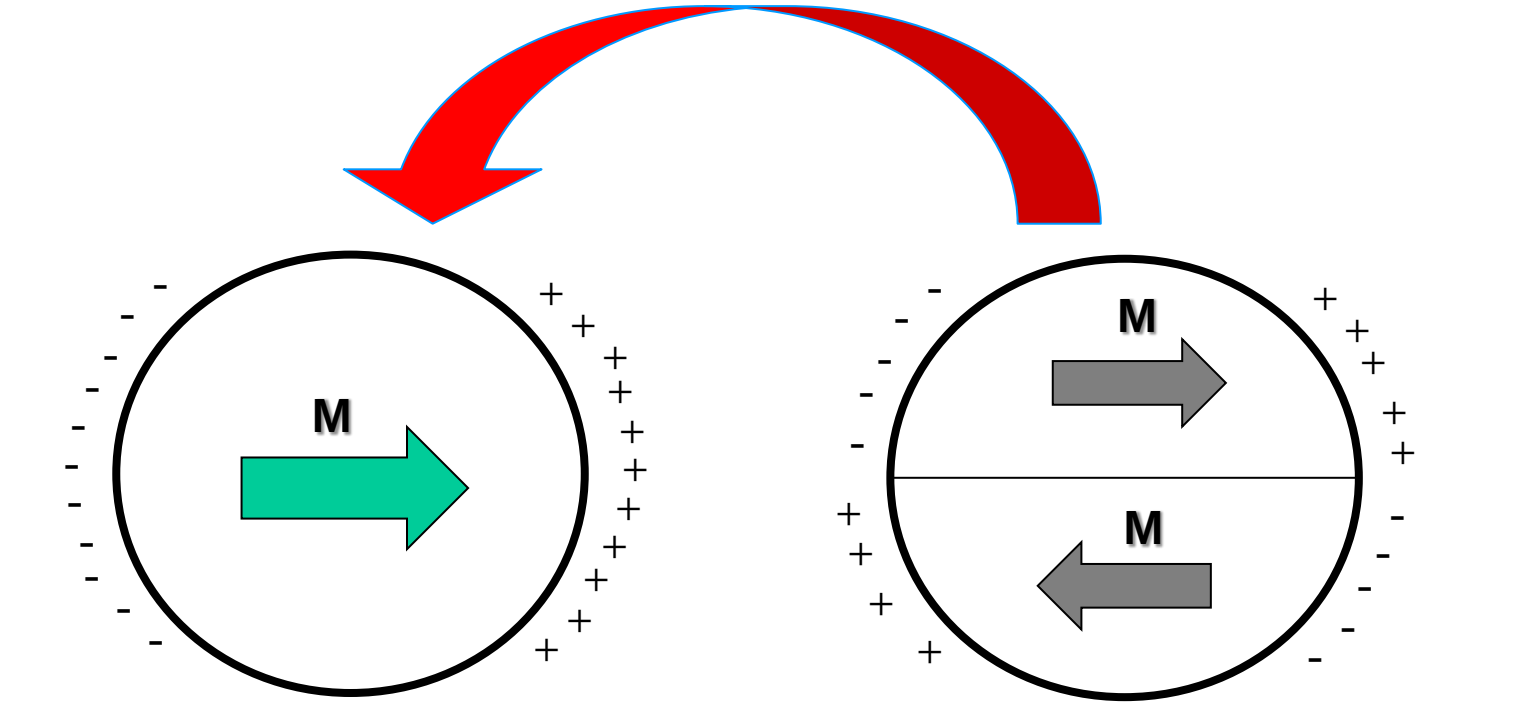
$R_c \sim 10$-100 nm



http://lma.unizar.es/research/transmission-electron-microscopy-tem/tem-magnetic-materials


50 nm
20°C
V
FD
500°C
550°C
500°C
20°C
V
20°C
500°C
550°C


NANOMAGNETISM



$Single - Domain$

$multi - domain$

$$R \leq \approx 10 - 100\ nm$$

Below a critical size, domain wall energy exceeds magnetostatics and Single-domain configuration is the fundamental state.

Magnetic Moment

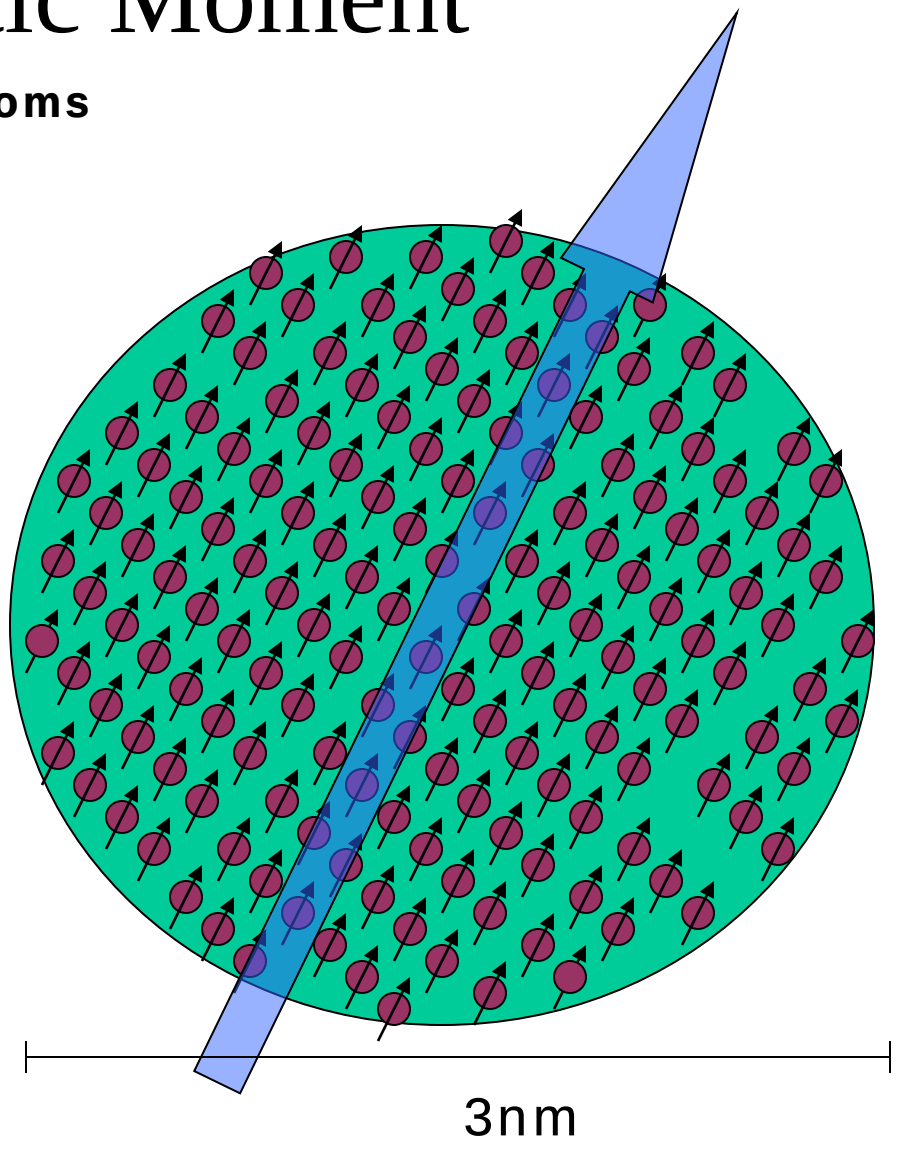
Case of Co atoms

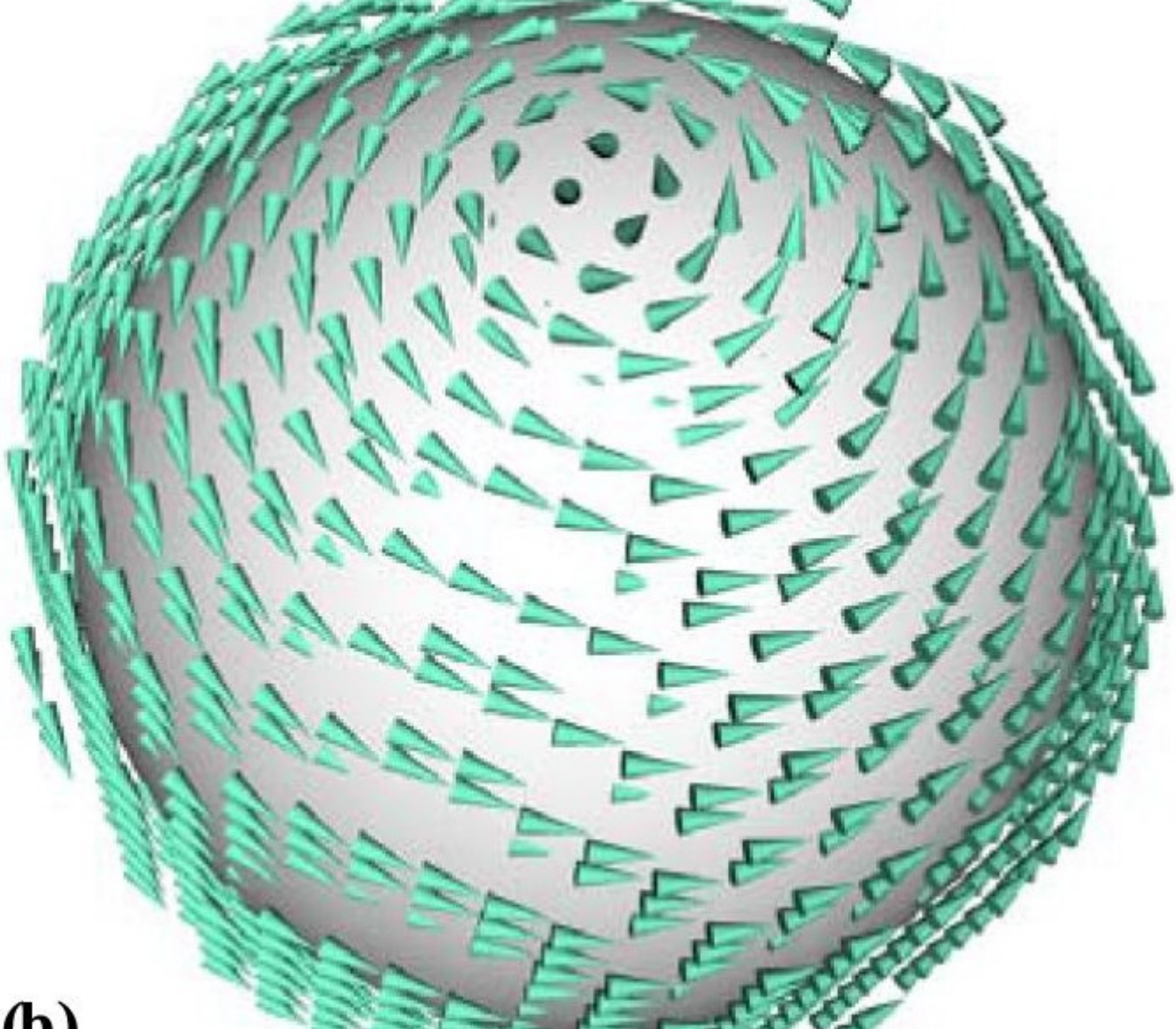
$$\vec{\mathbf{M}} = N \times 1.64\mu_B$$

N is of the order of 1000 atoms.

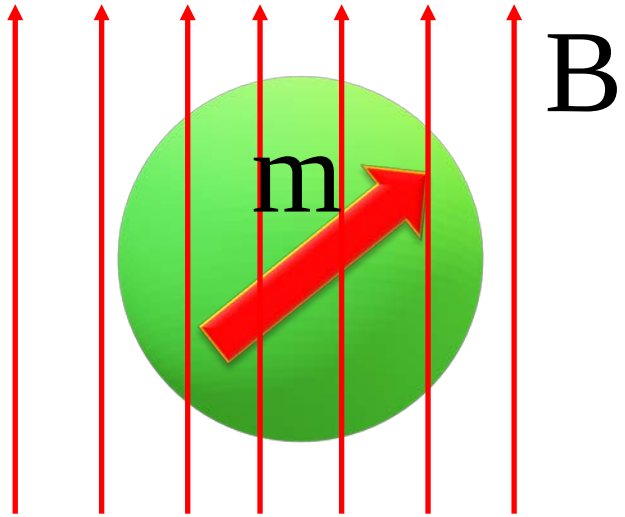
The grain is a big magnetic moment which produces a magnetic field (magnetic field of a big dipole)

One magnetic grain (spherical nanomagnet) is a ferromagnetic monodomain of N atoms.

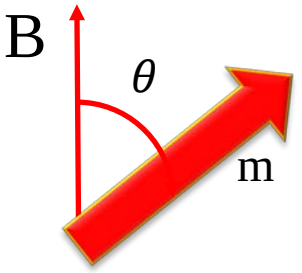




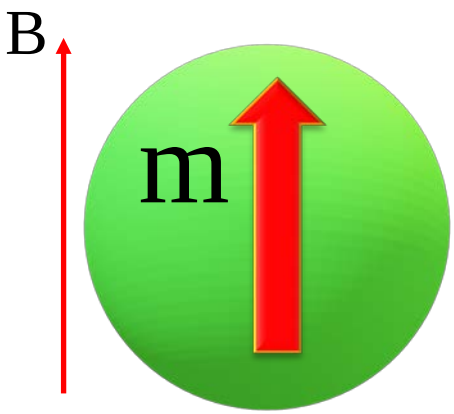
(b)

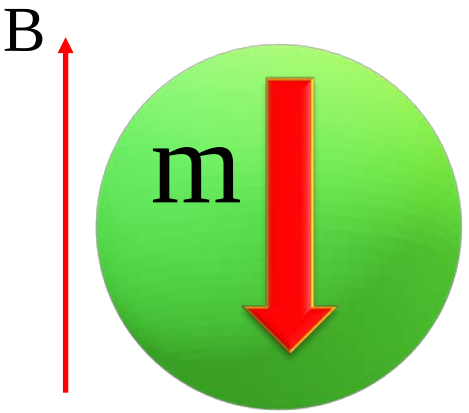


$$U = -\vec{m} \cdot \vec{B}$$



$$U = -|\vec{m}| \cdot |\vec{B}| \, cos\theta \begin{cases} \theta = 0 \\ \theta = 180 \end{cases}$$

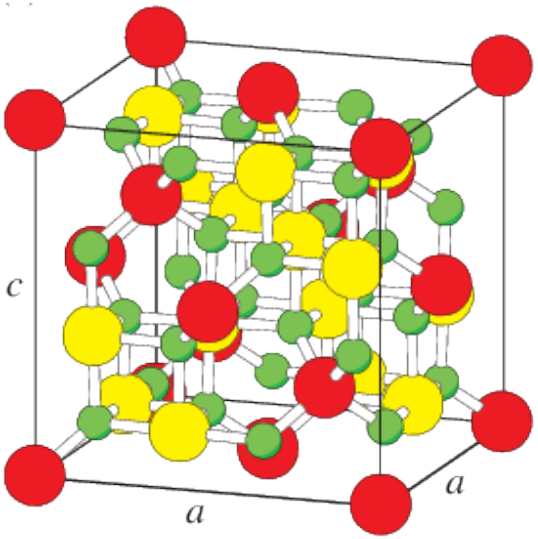


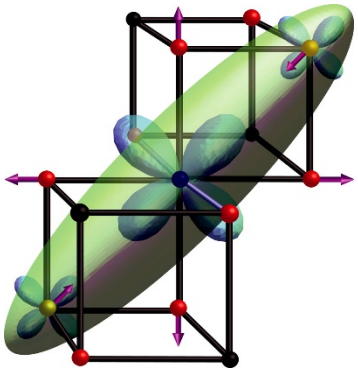


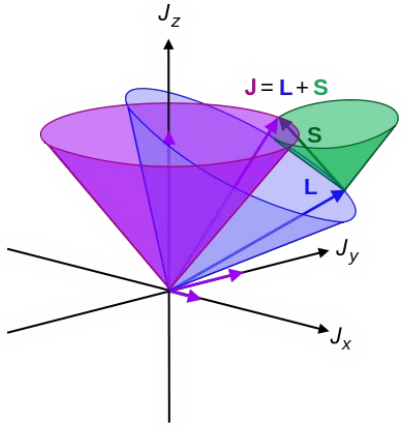
$$U_{min} = -|\vec{m}| \cdot |\vec{B}| \qquad U_{max} = +|\vec{m}| \cdot |\vec{B}|$$

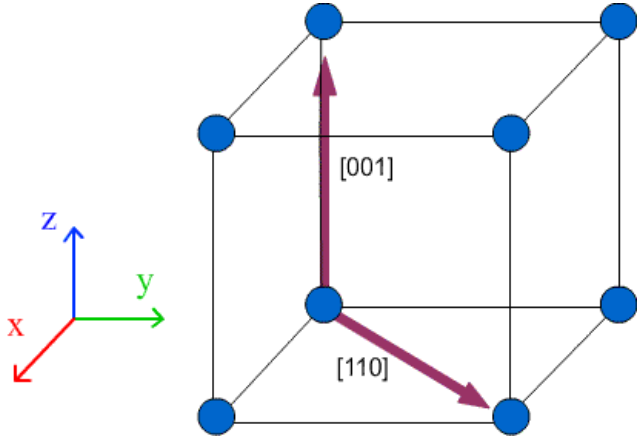
Magnetic Anisotropy

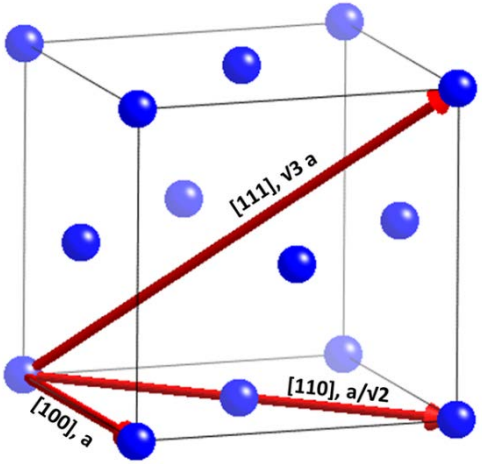
Magnetic Anisotropy



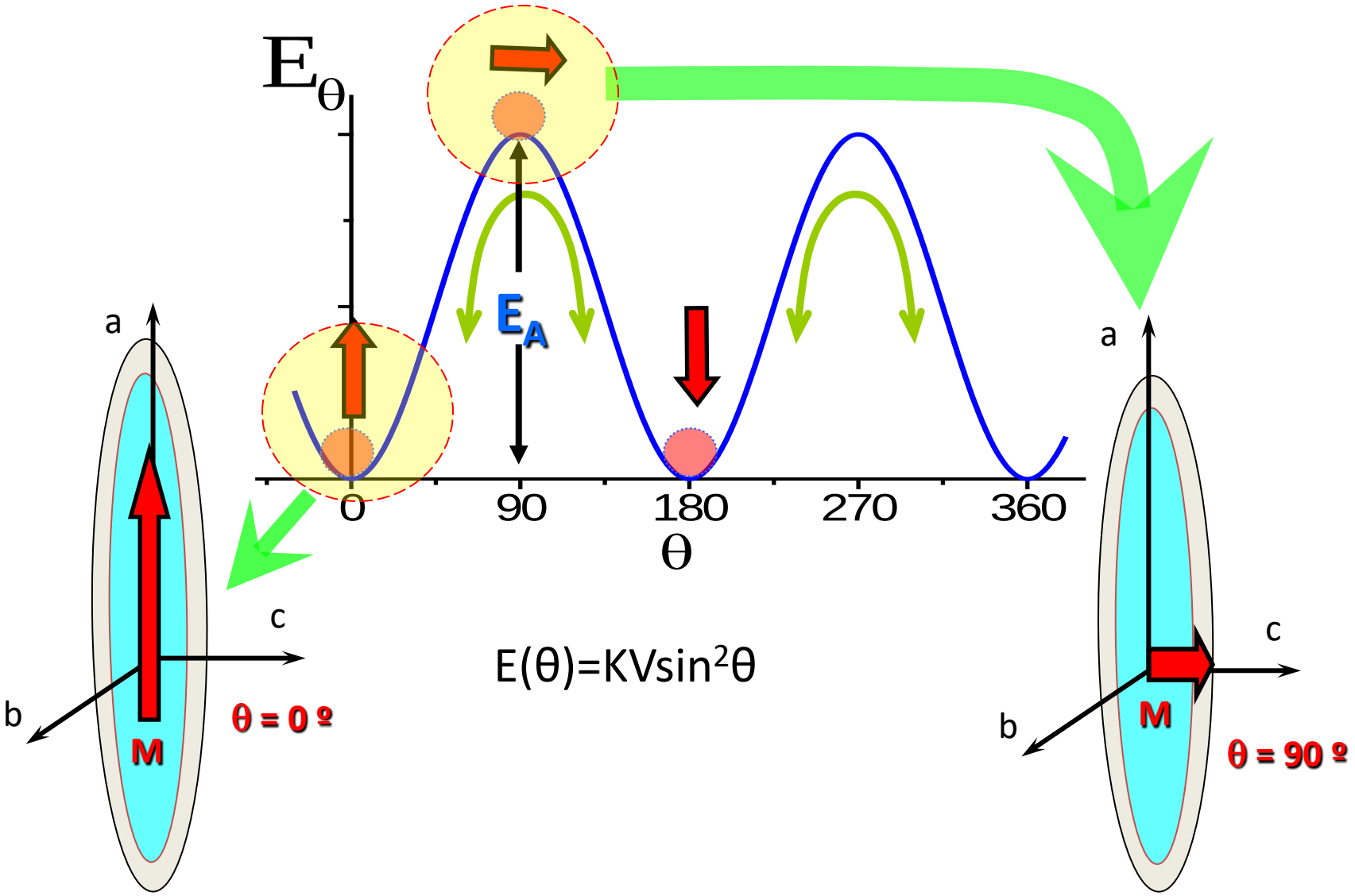








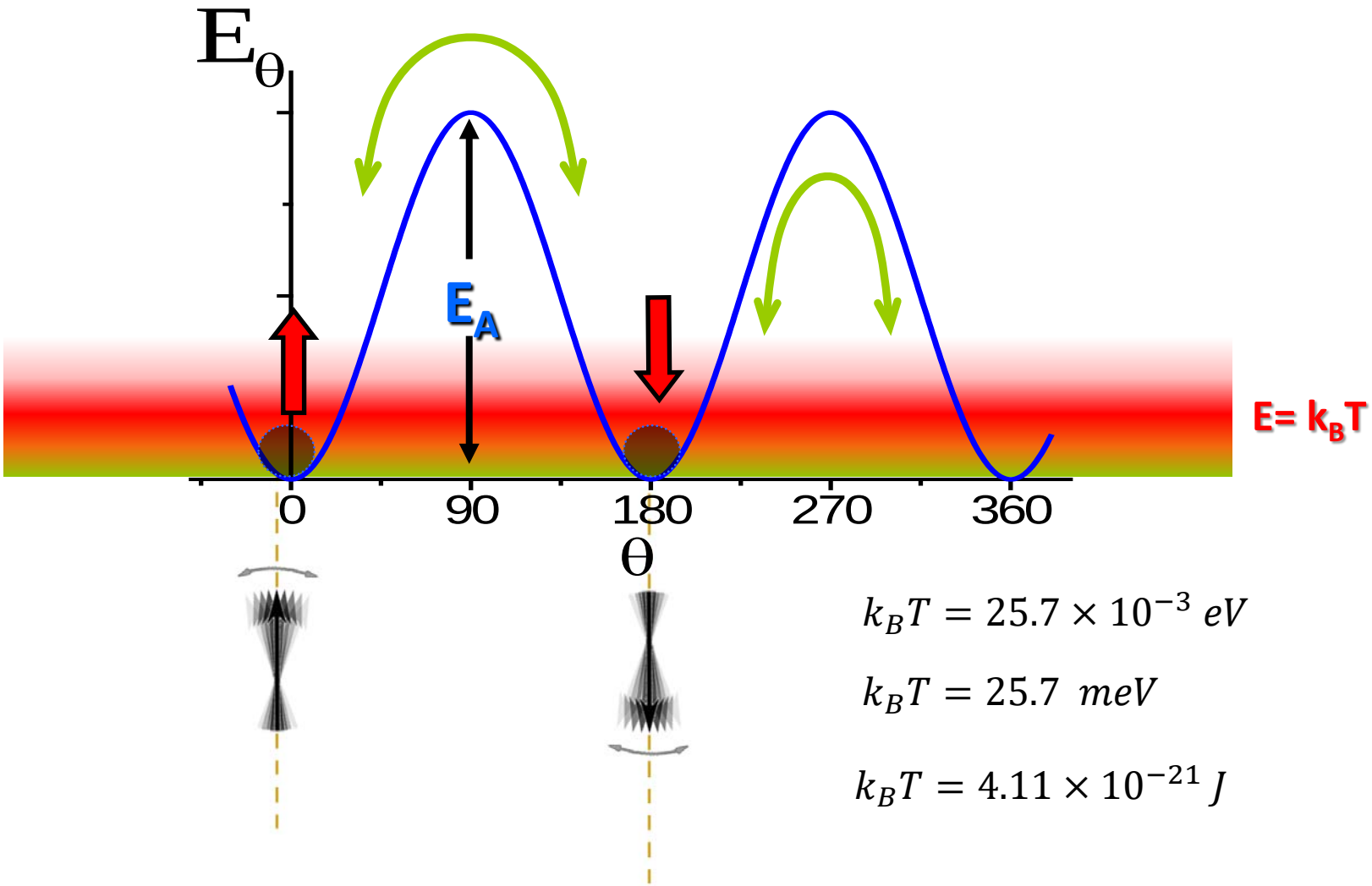
MODEL OF A SINGLE-DOMAIN PARTICLE



$E(\theta)=KV\sin^2\theta$

Superparamagnetism: Low T

$$E(\theta) = KVsin^2\theta$$



$$k_B T = 25.7 \times 10^{-3}\ eV$$

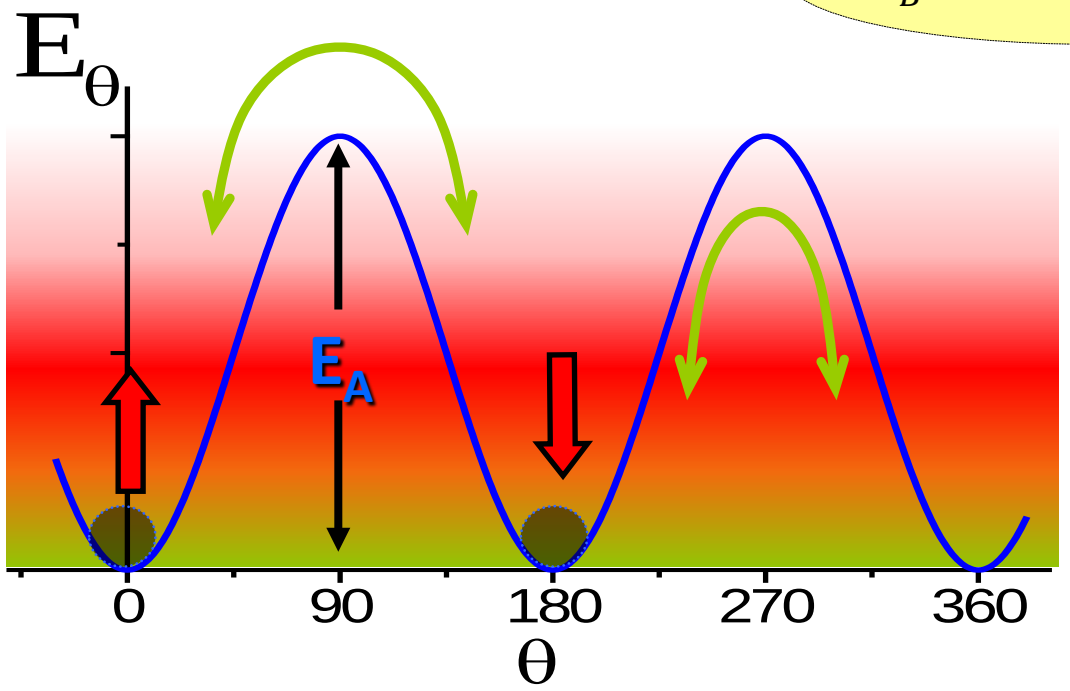
$$k_B T = 25.7\ meV$$

$$k_B T = 4.11 \times 10^{-21}\ J$$

Superparamagnetism: Room Temperature

$k_B T = 25.7\ meV$

$k_B T = 4.11 \times 10^{-21}\ J$



$R = 5\ nm$

$K = 2 \times 10^3 \frac{J}{m^3}$

E= k_BT

$E(\theta) = KV \sin^2\theta$

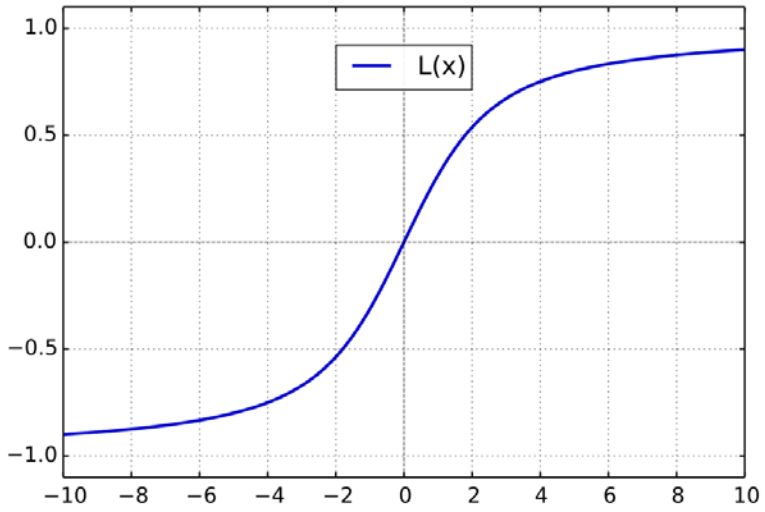
$KV = 2 \times 10^3 \frac{J}{m^3} \times 524 \times 10^{-27}\ m^3 = 1.05 \times 10^{-21} J$

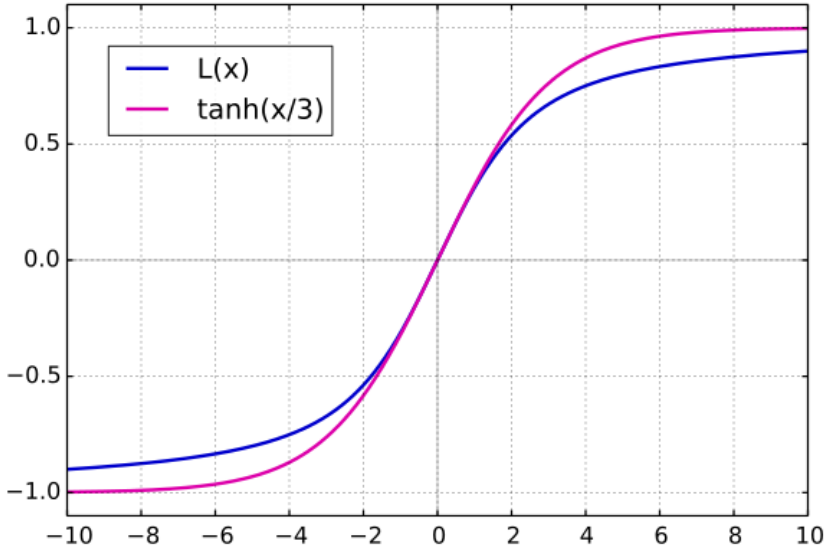
$KV \approx k_B T$

The theory of (Super)paramagnetism states that

$$M = n\,\mu\,\mathcal{L}\left(\frac{\mu H}{k_B T}\right)$$

$$\mathcal{L}(x) = \coth(x) - \frac{1}{x}$$

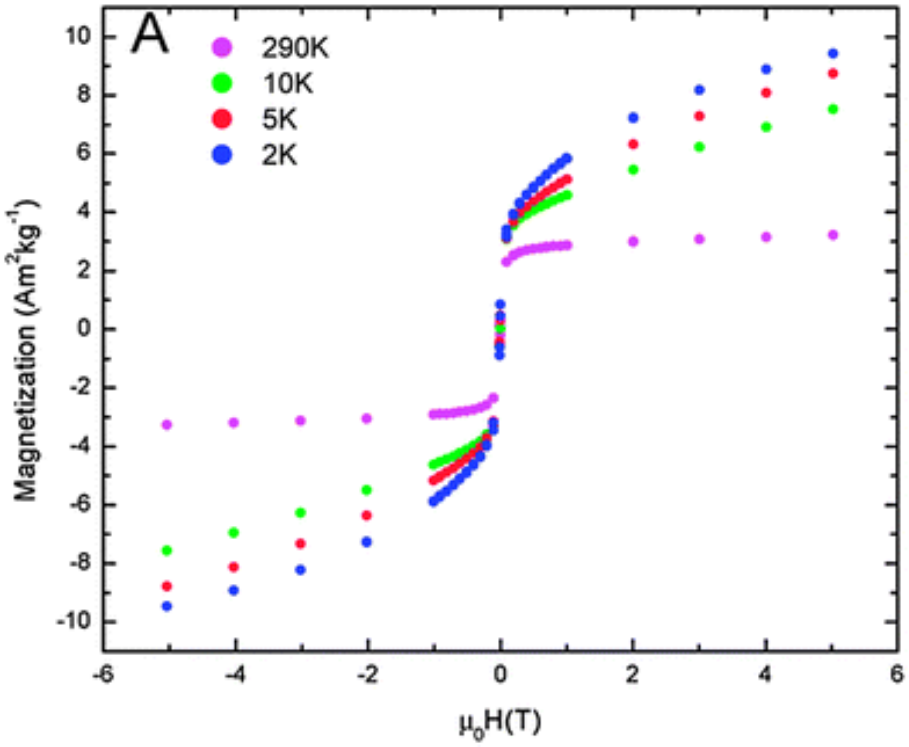


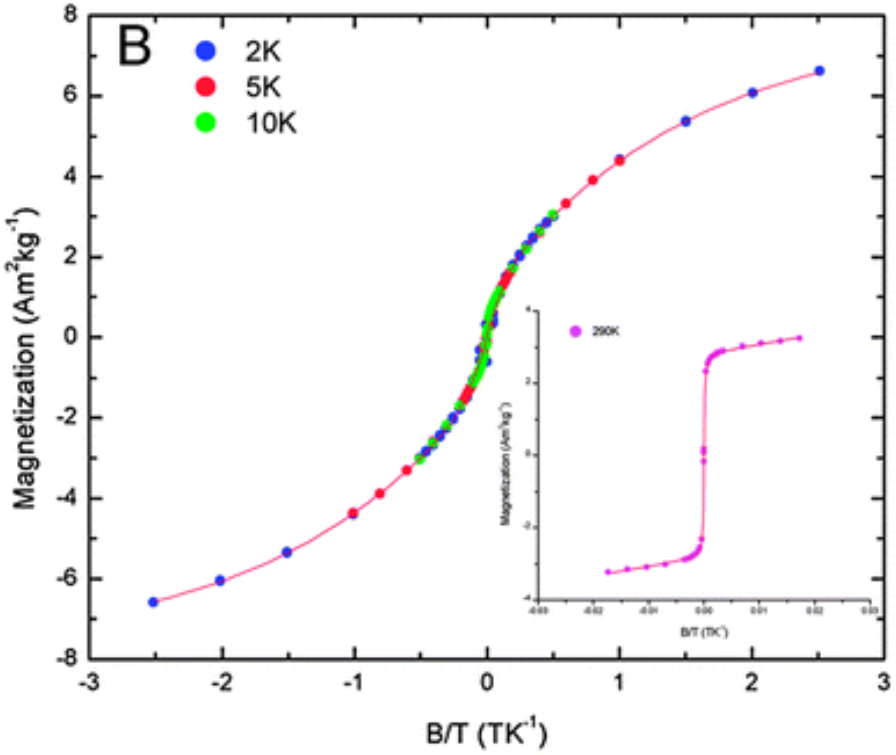


C. P. Bean and J. M. Livingston [J. Appl. Phys., 30 (1959) p. 120S].

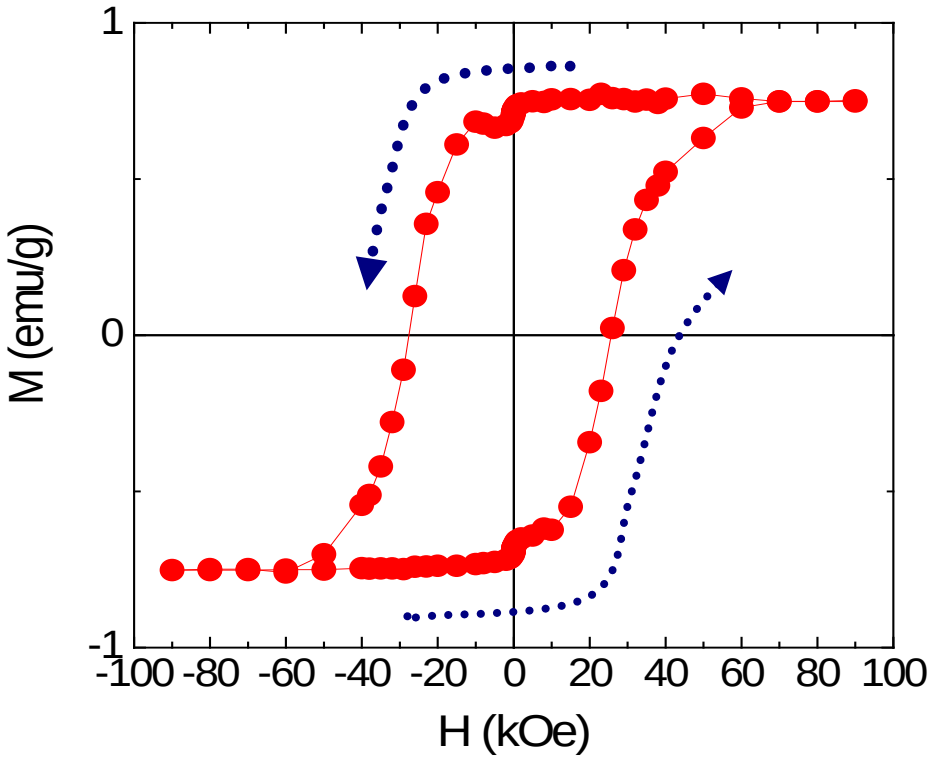
Scaling of the L(x) function

$$M = n\,\mu\,\mathcal{L}\left(\frac{\mu H}{k_B T}\right)$$





$$\Delta U = -\mu_0 \oint M \; dH$$



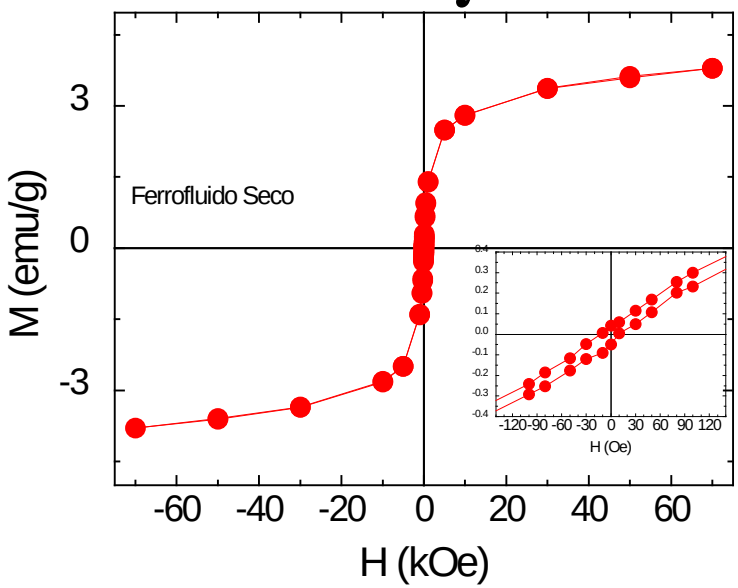
$P = f \Delta U$

R.E.Rosensweig *JMMM 252- 2002*

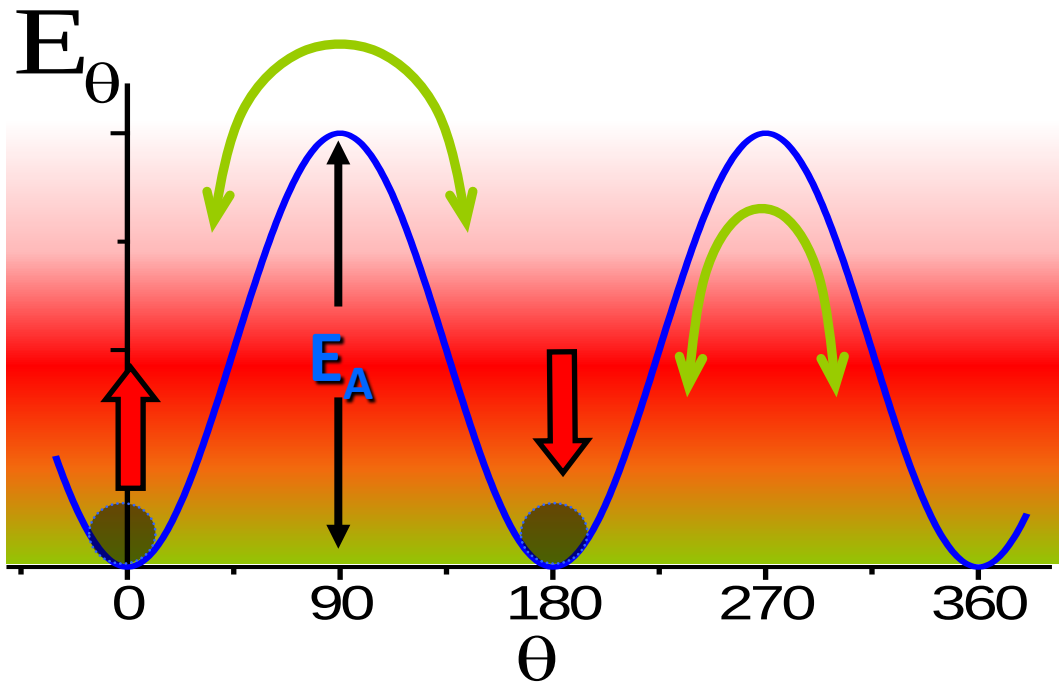
Pregunta #5

Por qué medimos SAR en una muestra SUPERPARAMAGNETICA, si Hc=0??

$$P = \mu_0 f \oint H dM$$



Superparamagnetismo: todo es cuestión de tiempo



$E = k_B T$

Temperatura o tiempo

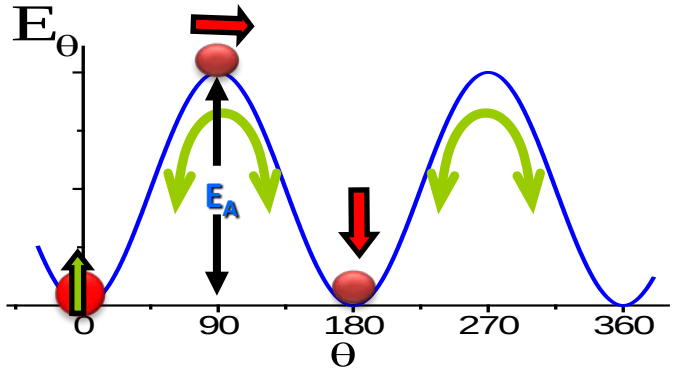
The TIME factor

$$\tau_{\mathrm{N}} = \tau_0 \exp\left(\frac{KV}{k_{\mathrm{B}}T}\right)$$

Svante August Arrhenius

A transition between superparamagnetism and the blocked state occurs when $\tau_m = \tau_N$. In several experiments, the measurement time is kept constant but the temperature is varied, so the transition between superparamagnetism and blocked state is a function of the temperature. The temperature for which $\tau_m = \tau_N$ is called the *blocking temperature*:

$$T_{\mathrm{B}} = \frac{KV}{k_{\mathrm{B}} \ln(\tau_{\mathrm{m}}/\tau_0)}$$



$$\tau = \tau_0 \, e^{KV/k_B T}$$

$\tau = 100 \; s$

$100 = 10^{-9} \, e^{KV/k_B T}$

$\frac{KV}{k_B T} = \ln 10^{11} = 25$

$\tau = 10^{-8} s$

$10^{-8} = 10^{-9} \, e^{KV/k_B T}$

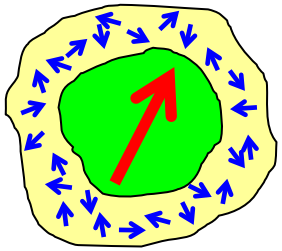
$\frac{KV}{k_B T} = \ln 10^{1} = 2.3$

$T_{B1} = \frac{KV}{25 \, k_B}$ $\qquad$ $T_{B2} = \frac{KV}{2.3 \, k_B}$

$\frac{T_{B2}}{T_{B1}} \approx 11$

$\tau = 10^{-6} s$ $\qquad$ $T_{B2} = \frac{KV}{6.9 \, k_B}$ $\qquad$ $\frac{T_{B2}}{T_{B1}} \approx 3.6 \; - 2.8$

Ventana de tiempo de medida



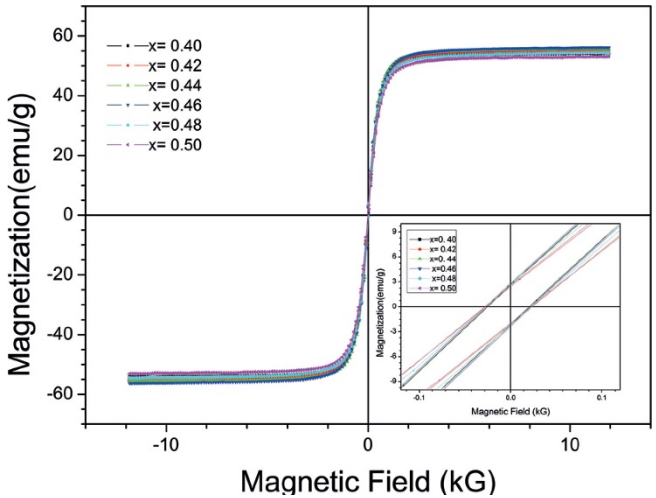
$\tau = 100\ s$

$\tau = 10^{-6} s$

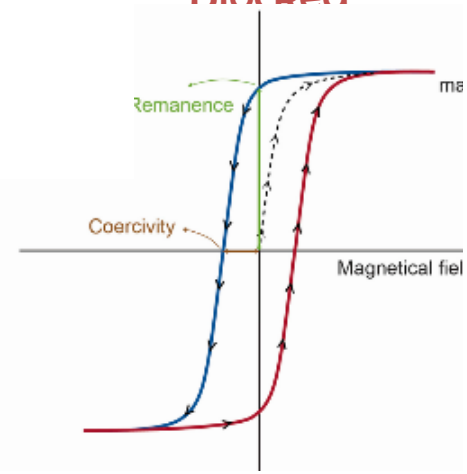
D fijo

T fija

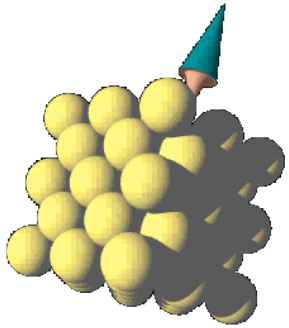
Superparamagnetic



Blocked



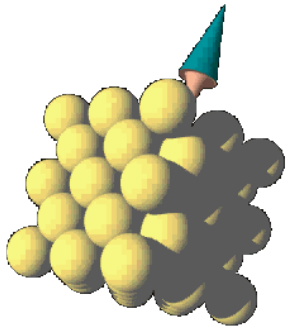
Néel Relaxation (τ_N)



Changes of direction in atomic magnetic moments

$$\tau_N = \tau_0 \frac{e^{\xi}}{\sqrt{\xi}} \quad ; \quad \xi = \frac{K_{eff} V_M}{k_B T}$$

Brown Relaxation (τ_B)



Rotation of the particle

$$\tau_B = \frac{3\eta\, V_H}{k_B T}$$

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_B} + \frac{1}{\tau_N} = \frac{(\tau_N + \tau_B)}{\tau_N \tau_B}$$

Animación del Dr. Viktor Chikan, Kansas State University, USA.
http://www.k-state.edu/chem/people/grad-faculty/chikan/

MAGNETIC HYPERTHERMIA

En medicina y biología, el término **hipertermia** se define como una temperatura corporal anormalmente alta.

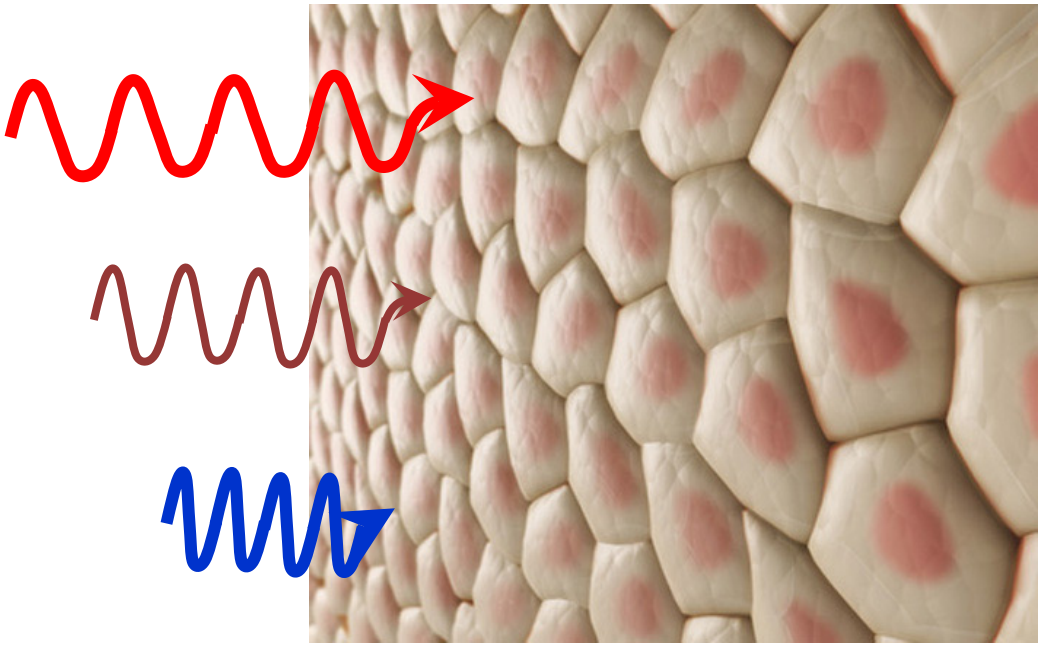
Para algunos autores hipertermia es un sinónimo de hiperpirexia, la hiperpirexia es una temperatura corporal muy alta que supera los 41 ºC y se acerca al máximo tolerado por el cuerpo humano, sin embargo, no existe acuerdo en esta definición, otros textos consideran como hipertermia cualquier elevación de la temperatura corporal por encima de la normalidad.

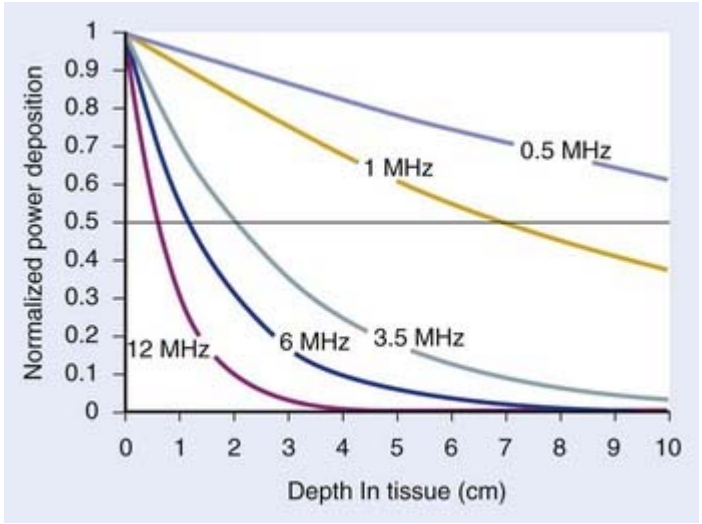
En la hipertermia oncológica se eleva de forma intencionada la temperatura de una parte del cuerpo como método terapéutico (termoterapia) para el tratamiento del cáncer, en este caso se define hipertermia como la elevación artificial y controlada de la temperatura en el interior de un tumor, sin superar los límites de tolerancia de los tejidos sanos vecinos.

WIKIPEDIA
La enciclopedia libre

EM – BIO

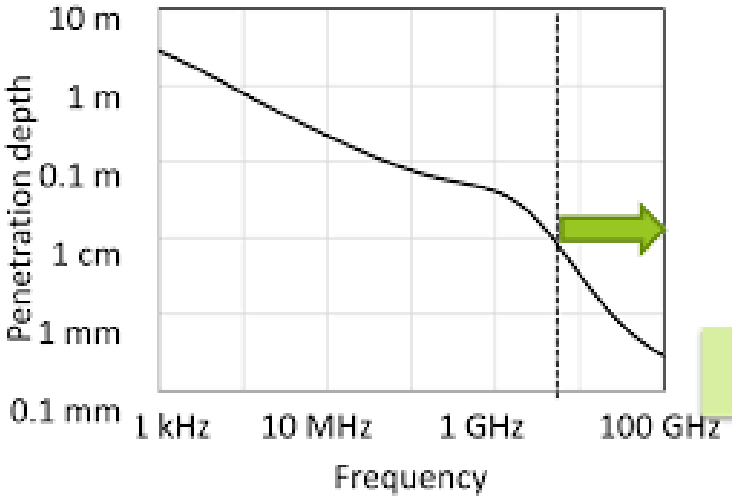
INTERACTION



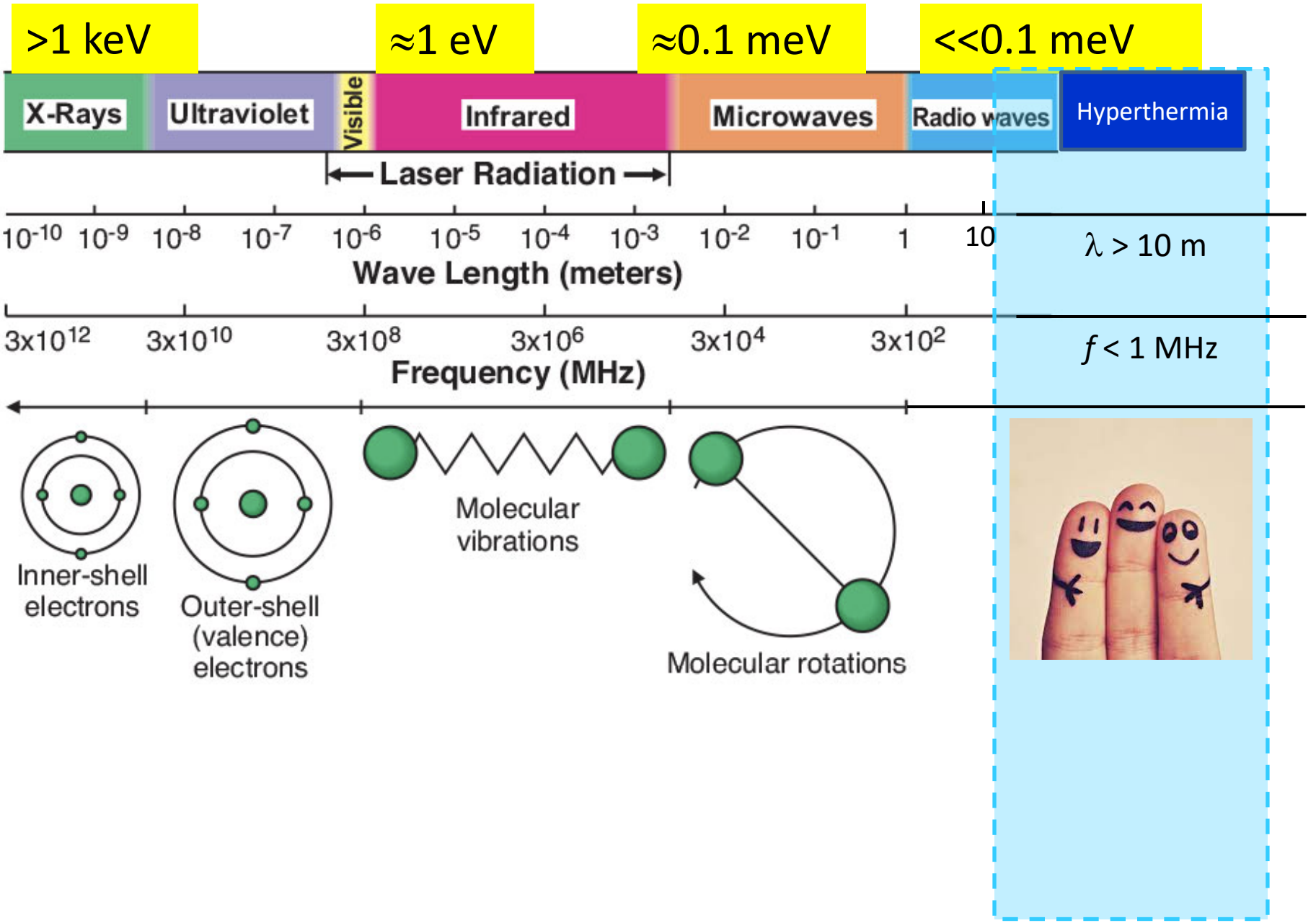


International Telecommunication Union (ITU)

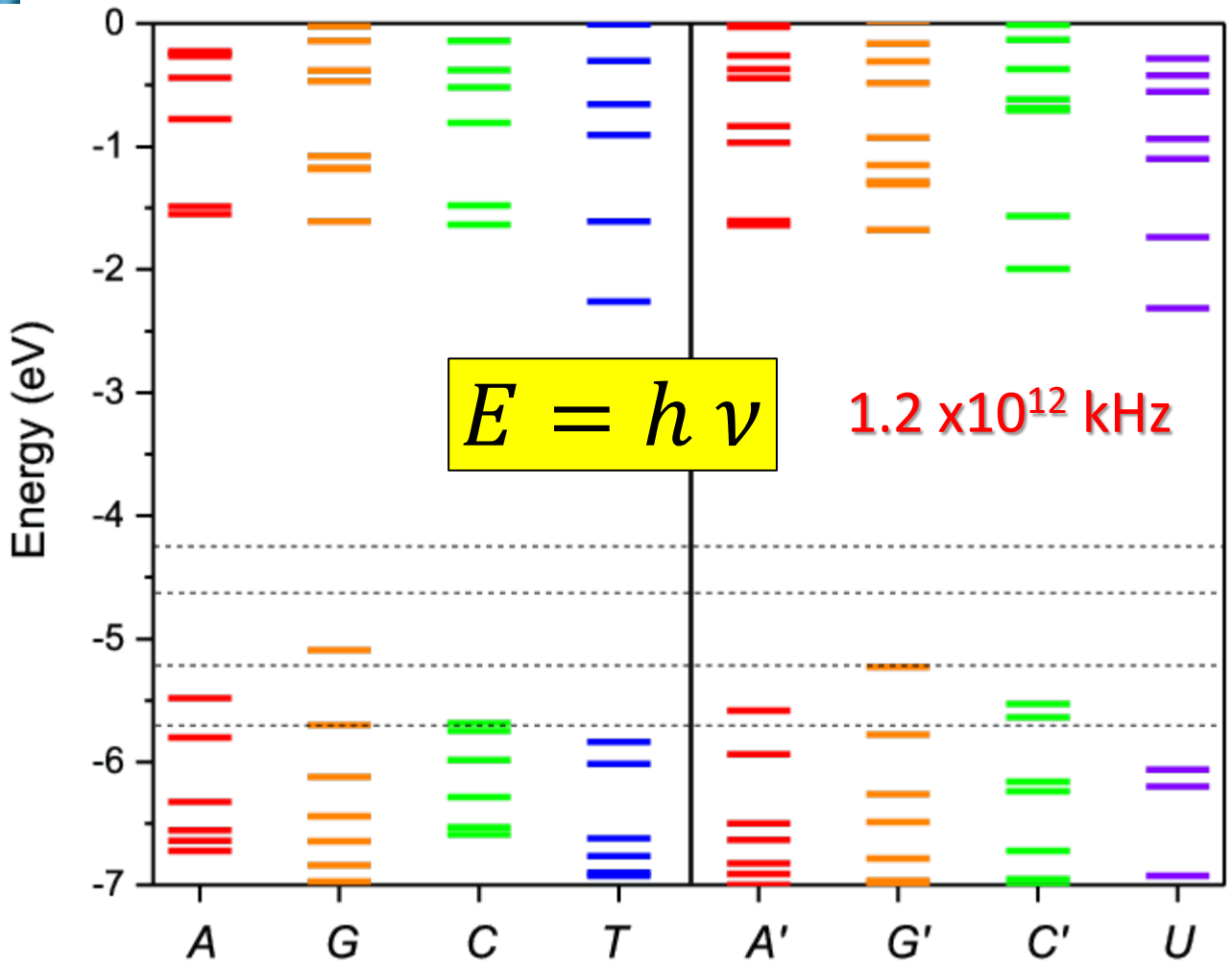
ITU REGIONAL FORUM
FOR EUROPE 5G

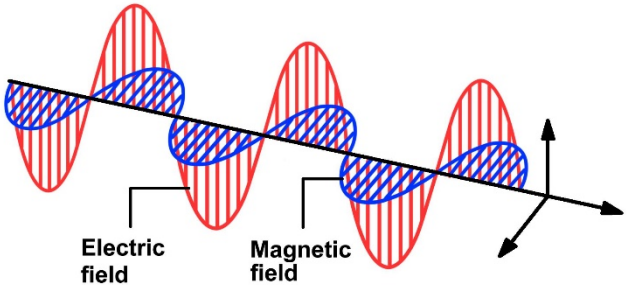


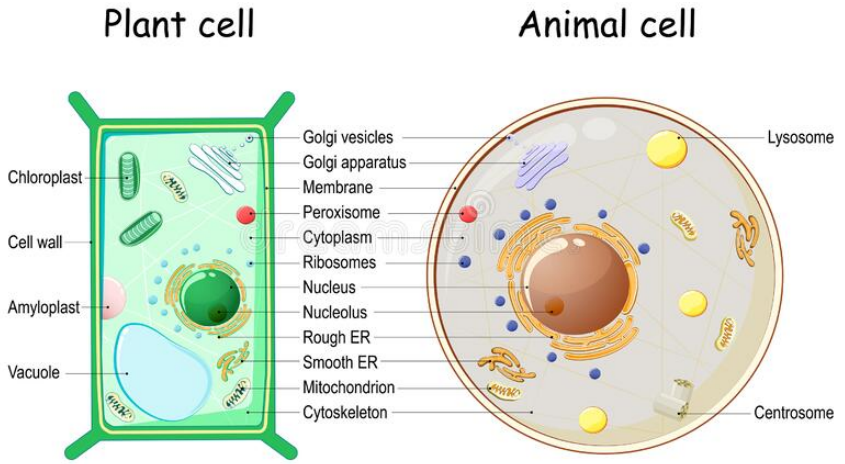
https://www.itu.int/en/about/Pages/default.aspx


>1 keV
≈1 eV
≈0.1 meV
<<0.1 meV
X-Rays
Ultraviolet
Visible
Infrared
Microwaves
Radio waves
Hyperthermia
Laser Radiation
10-10 10-9 10-8 10-7 10-6 10-5 10-4 10-3 10-2 10-1 1 10
Wave Length (meters)
λ > 10 m
3x10^12 3x10^10 3x10^8 3x10^6 3x10^4 3x10^2
Frequency (MHz)
f < 1 MHz
Inner-shell electrons
Outer-shell (valence) electrons
Molecular vibrations
Molecular rotations

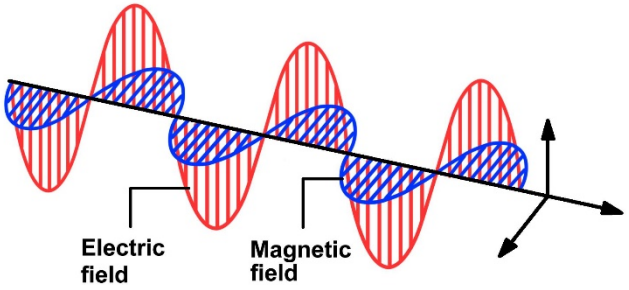
Niveles de Energia de bases ADN

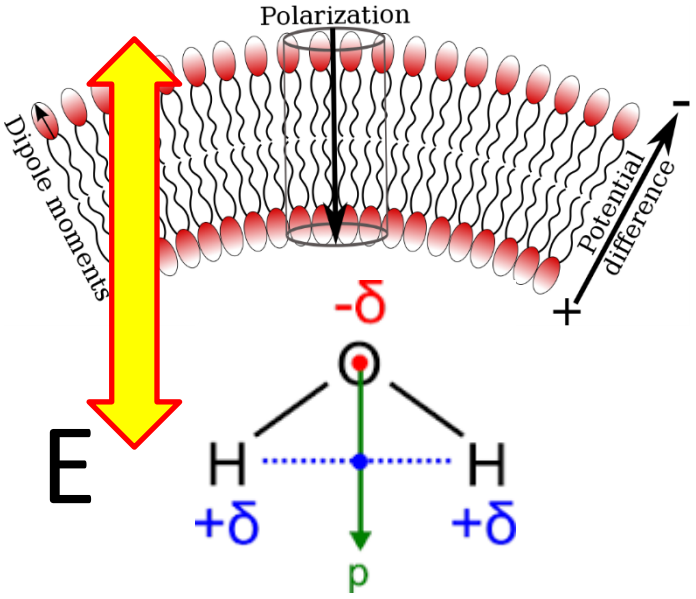




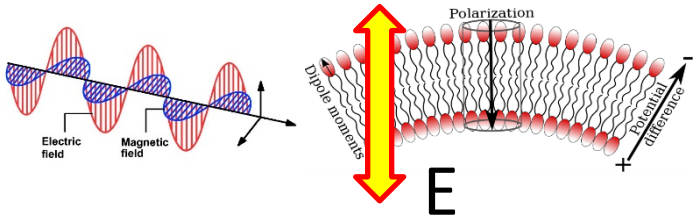


COMPONENTE ELECTRICO

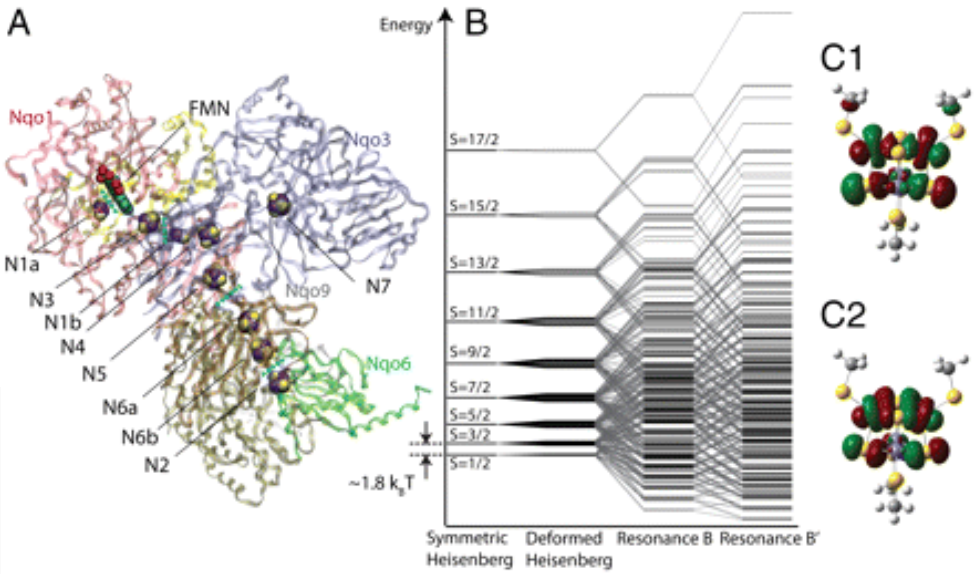




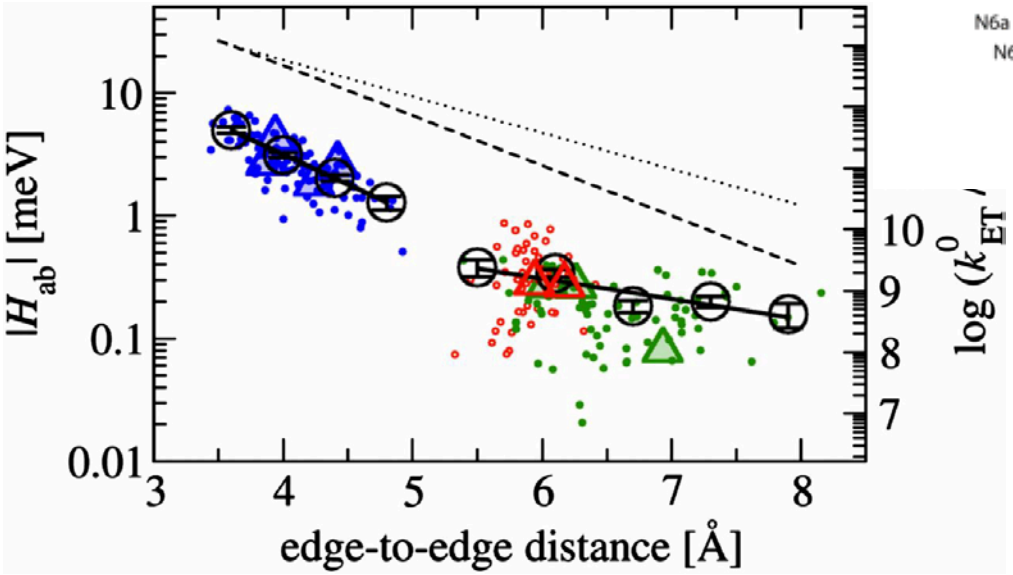
Niveles de energia em sistemas biológicos



Electron tunneling in respiratory complex I



Electron flow in multiheme bacterial cytochromes



EM - BIO - MNP

INTERACTION

For single-domain Magnetic Nanoparticles (MNPs)

- The coupling between MNPs and an alternating magnetic field is related to the single-domain magnetic structure of MNPs below a critical particle size.

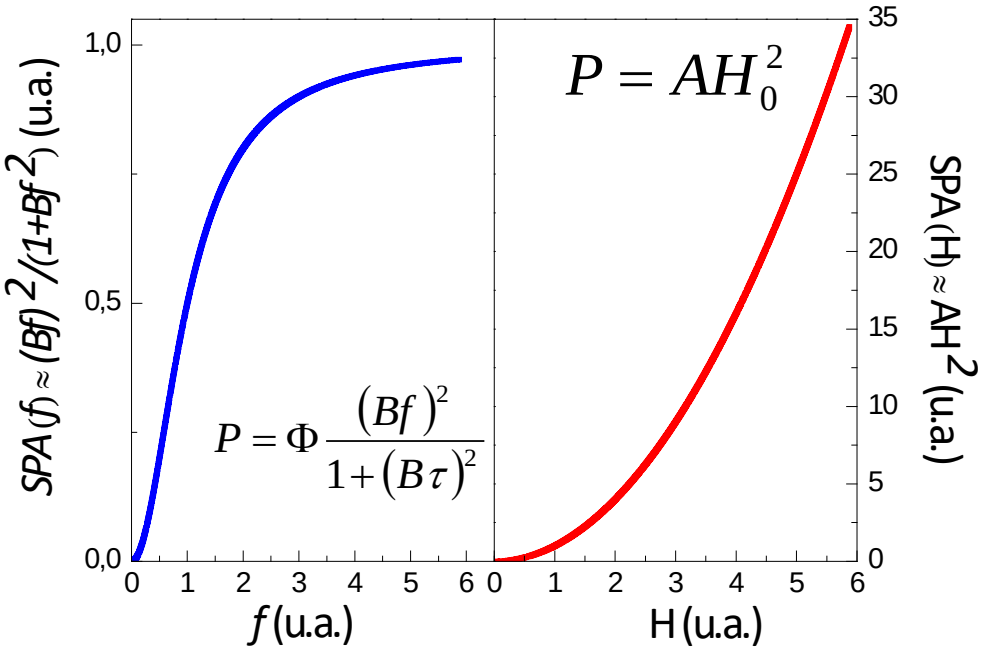
Pregunta #6

Quiero calentar a saco.
Es mejor subir la frecuencia *f* o el campo H?

SPA model

$$SPA = \pi\mu_0\chi_0 H_0^2 f \frac{2\pi f\tau}{1+(2\pi f\tau)^2}$$

$$SPA = AH_0^2 \frac{(Bf)^2}{1+(Bf)^2}$$



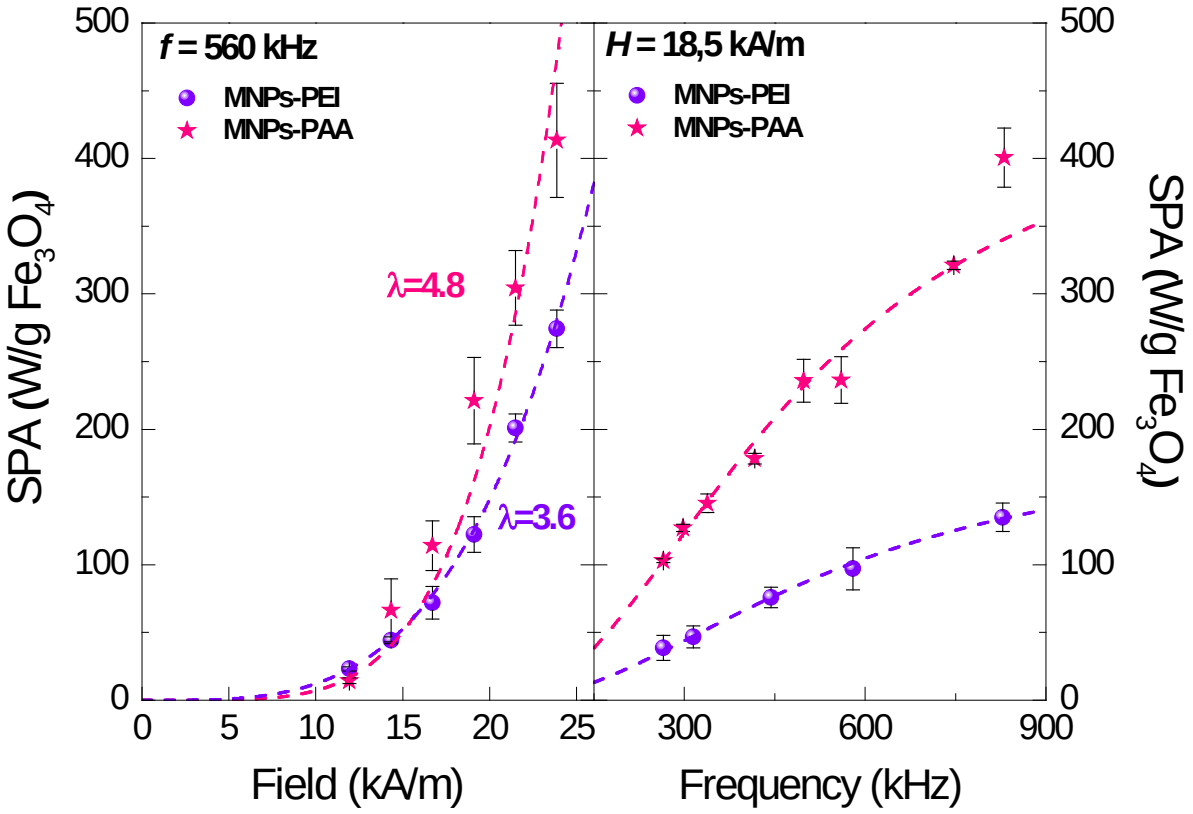
R.E.Rosensweig *JMMM 252- 2002*

SPA in water

$$H_k = \frac{2k_1}{M_s} = 45\ kA/m \qquad H_o \ll H_k \qquad 23{,}9kA/m < 45\ kA/m$$

$$SPA = H^{\lambda}$$

λ(MNPs-PEI) = 3.6
λ(MNPs-PAA) = 4.8



λ≠2

$$SPA = AH_0^2 \frac{(Bf)^2}{1+(Bf)^2}$$

$$SPA = AH_0^{\lambda} \frac{(Bf)^2}{1+(Bf)^2}$$

Magnetic hyperthermia

The calorimetric side of heating

$$Q = \left(m_{np}\, c_{np} + m_l c_l + m_d c_d\right)(\Delta T)$$

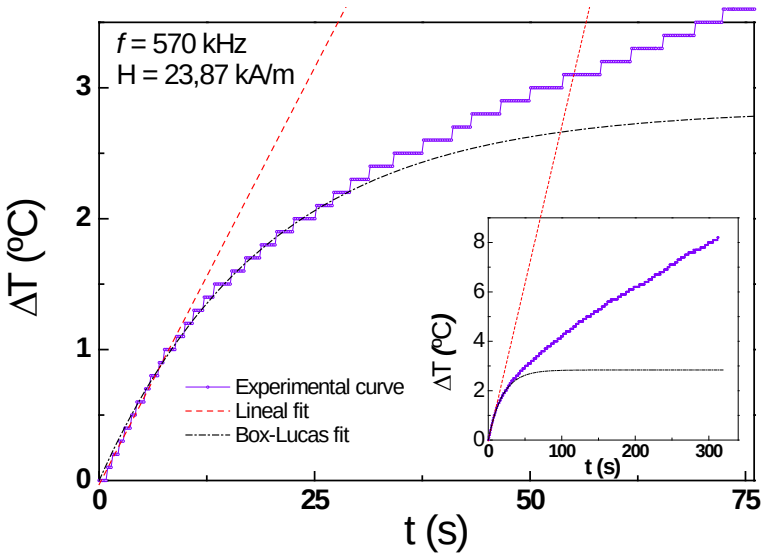
$$Power = \frac{Q}{\Delta t} = \left(m_{np}\, c_{np} + m_l c_l + m_d c_d\right)\left(\frac{\Delta T}{\Delta t}\right)$$

$$SPA = \frac{1}{m_{np}}\frac{Q}{\Delta t} = \frac{P}{m_{np}}$$

$$SPA = \frac{\left(m_{np}\, c_{np} + m_l c_l\right)}{m_{np}}\left(\frac{dT}{dt}\right)_{max}$$

Calorimetric concepts

Calorimetric device. Quase-adiabatic measurements



Sanz, B. et al., European Journal of Inorganic Chemistry (2015)

$$SPA = \frac{\delta_l \cdot c_l}{\varphi_{np}} \cdot \left(\frac{\partial T}{\partial t}\right)_{max}$$

Non-linear fit:
Modified Box-Lucas function

$$T(t) = A \cdot (1 - e^{-Bt}) + C$$

$$\left(\frac{dT}{dt}\right)_{max} = A \cdot B = (T_{eq} - T_o)\frac{1}{\tau}$$

$$SPA = \frac{\delta_l \cdot c_l}{\varphi_{np}} \cdot A \cdot B$$

Diference ≤ 8%

Pregunta #6943

¿Cómo mido la relación causa-efecto?

¿Cómo cuantifico el ‘efecto hipertermia’?

¿Temperatura?

¿Tiempo?

¿Ambos?

Qué es más eficaz:

Aplicar 45ºC por 20 minutos?

Aplicar 48ºC por 30 segundos?

International Commission on Radiological Protection **(ICRP)**
International Commission on Radiation Units and Measurements **(ICRU)**

A Word about units

Sievert	**Sv** $= J/kg$	**SI**
Grey	**Gy** $= J/kg$	**SI**
Roentgen Equivanelt man	rem $= 100\ erg/g$	Non-SI

1 Sv = 100 rem

Dose equivalent *H*

$$H = Q \times D$$

D = absorbed dose of ionizing radiation
Q = quality factor *Q* (dimensionless) defined as a function of linear energy transfer by ICRU

The value of Q is not defined further, but it requires the use of the relevant ICRU recommendations to provide this value.

The gray - quantity "D"
1 Gy = 1 joule/kilogram - a physical quantity. 1 Gy is the deposit of a joule of radiation energy in a kg of matter or tissue.
The sievert - quantity "H"
1 Sv = 1 joule/kilogram - a biological effect. The sievert represents the equivalent biological effect of the deposit of a joule of radiation energy in a kilogram of human tissue. The equivalence to absorbed dose is denoted by Q.

Maximum permissible exposure values of EMF:

as determined by the *Federal Communications Commission (FCC).*

♣ *Valid for 100 kHz to 6 GHz range.*

Exposure	*Freq.*	H (A/m)	S (mW/cm²)	Partial-body SAR ♣	Whole-body SAR ♣
Controlled §	300 kHz to 3 MHz	1.63	100	< 8 W/kg	< 400 mW/kg
Uncontrolled § §	300 kHz to 1340 kHz	1.63	100	< 1.6 W/kg	< 80 mW/kg

§ *Controlled limits apply to persons exposed as a consequence of their employment provided those persons are fully aware of the potential for, and can exercise control over, the exposure.*

§ § *Uncontrolled exposures apply in situations in which the general public may be exposed, that are not fully aware of the potential for, or can not exercise control over, the exposure.*

Sievert: Sv $\mathrm{Sv} = J/kg$

ICRP definition: "The **sievert** is the special name for the SI unit of equivalent dose, effective dose, and operational dose quantities. The unit is joule per kilogram".[5]

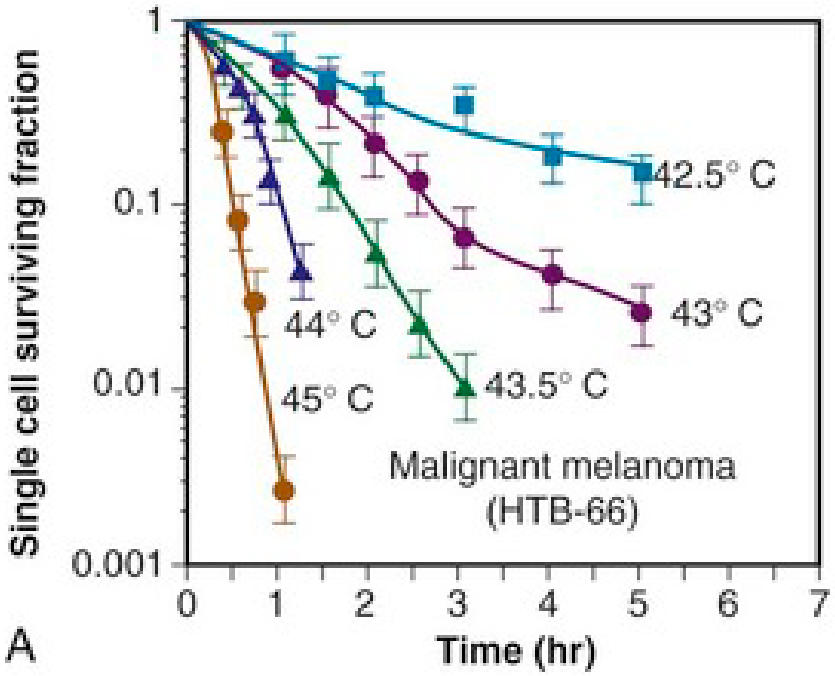
Standardization using thermal dose as a common unit

Cumulative Equivalent Minutes

$$CEM_{43} = \sum_{i=1}^{n} t_i \times R^{(43-T_i)}$$

R=1/4; T<43ºC
R=1/2; T>43ºC

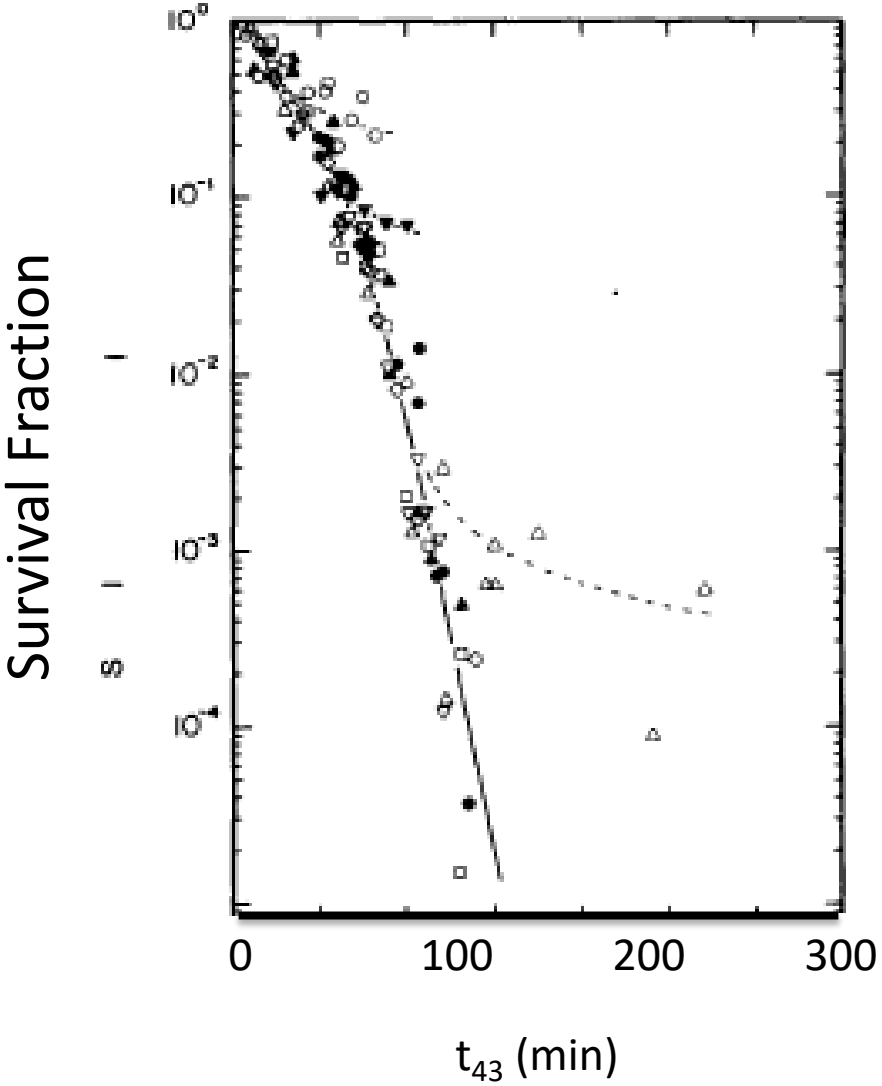
Thermal dose determination in cancer therapy.Sapareto SA, Dewey WC
Int J Radiat Oncol Biol Phys. 1984 Jun; 10(6):787-800.



$$CEM_{43} = t_1 \times R^{(43-T_1)}$$

Cumulative Equivalent Minutes

$$CEM_{43} = \sum_{i=1}^{n} t_i \times R^{(43-T_i)}$$



The dose survival response for asynchronous Chinese hamster ovary cells at various temperatures plotted as a function of equivalent-minutes at 43'C. Error bars have been omitted for clarity.

The data at 4 1.5,42.0, and 42.5 deviate from a single line, as shown by the dashed lines, due to the development of thermotolerance.

Pregunta #8545643

¿Puedo calentar una única célula usando MNPs y campos magnéticos?

Heat as therapeutic tool

- Hyperthermia has been used to treat cancer for thousands of years.
- Although biological effects of heat remained the same along the time, the challenge of heating only malignant cells, related to the sources of heating, remains elusive.
- Magnetic hyperthermia aims to heat from within the cells, and only targeted ones, using MNPs as nanoheaters under external a.c. magnetic fields.
- Cell killing efficiency of intracellular hyperthermia has been compared to extracellular (i.e., waterbath) heating.

Heat as therapeutic tool

GORDON'S SUGGESTION

Medical Hypotheses
Volume 5, Issue 1, January 1979, Pages 83–102

Hypothesis: intracellular hyperthermia is a more destructive approach than macroscopic heat sources, because it allows intracellular space to reach higher temperatures than cell environment.

R.T Gordon, J.R Hines, D Gordon

RABIN'S THEORETICAL MODEL

Heat generation can only be produced in a large group of cells, in volumes of at least 1 mm.

"It is argued in this report that there is no reason to believe that intracellular hyperthermia is superior to extracellular hyperthermia in the thermal sense.!

Y.Rabin, *Int J. Hyperthermia* 18, 194 (2002).

Experimental evidence

- "Our results are…..in agreement with the theoretical rejection by Rabin of the Gordon's postulate that a labeled cell could be heated independently of neighboring unlabelled cells."

Claire Wilhelm, Jean-Paul Fortin, and Florence Gazeau

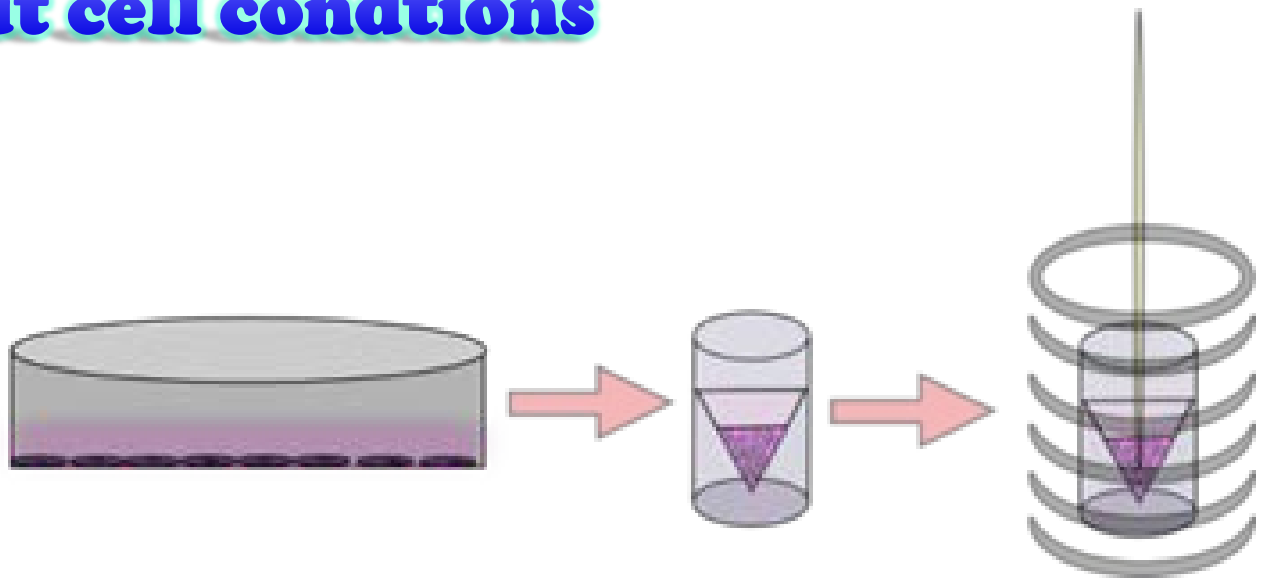
J. Nanosci. Nanotech., 7, 1–5, 2007

- "These results suggest a minimum tumor volume threshold of approximately 1 mm^3, below which nanoparticle-mediated heating is unlikely to be effective as the sole cytotoxic agent."

Hedayati M, Thomas O, Abubaker-Sharif B, Zhou H, Cornejo C, Zhang Y, Wabler M, Mihalic J, Gruettner C, Westphal F, Geyh A, Deweese TL, Ivkov R.

Nanomedicine (Lond). 2013 Jan;8(1):29-41

About cell condtions



‘micro-tumour’ environment: dense mass of cells (**$6x10^6$ cells**) immersed in **50 µl** of protein-rich culture media

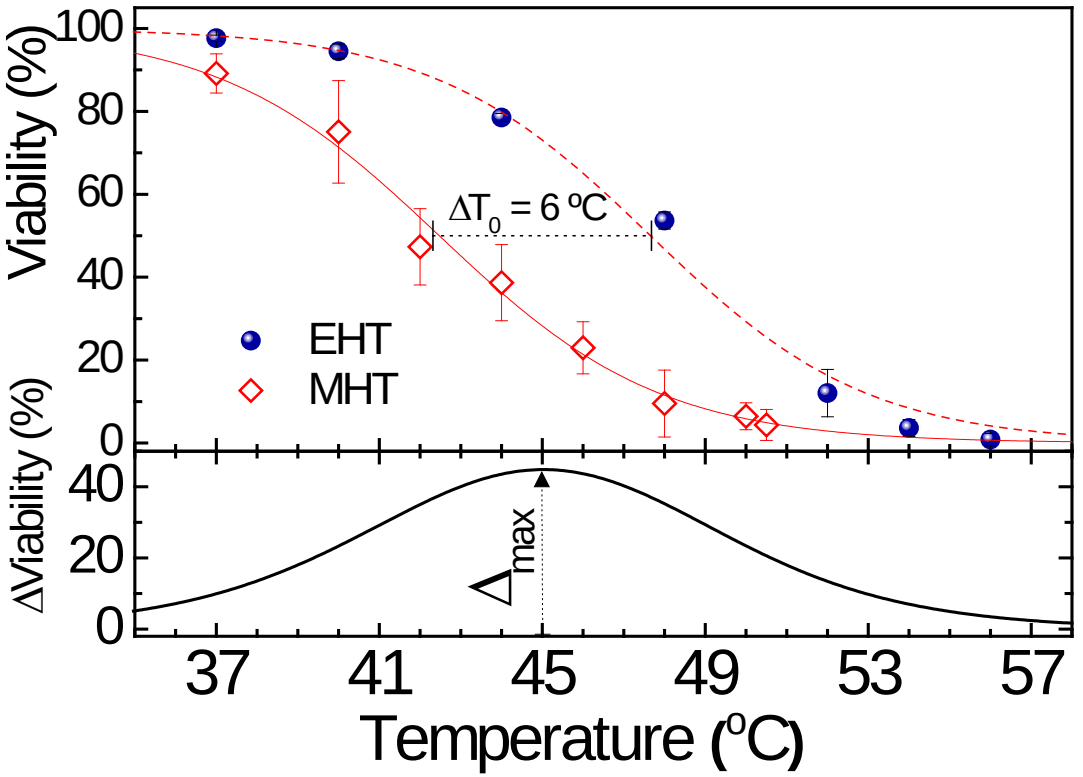
V_{BV2} (50 µl)

V_{BV2} (50 µl) = 50 mm^3

Hipertermia SH-SY5Y

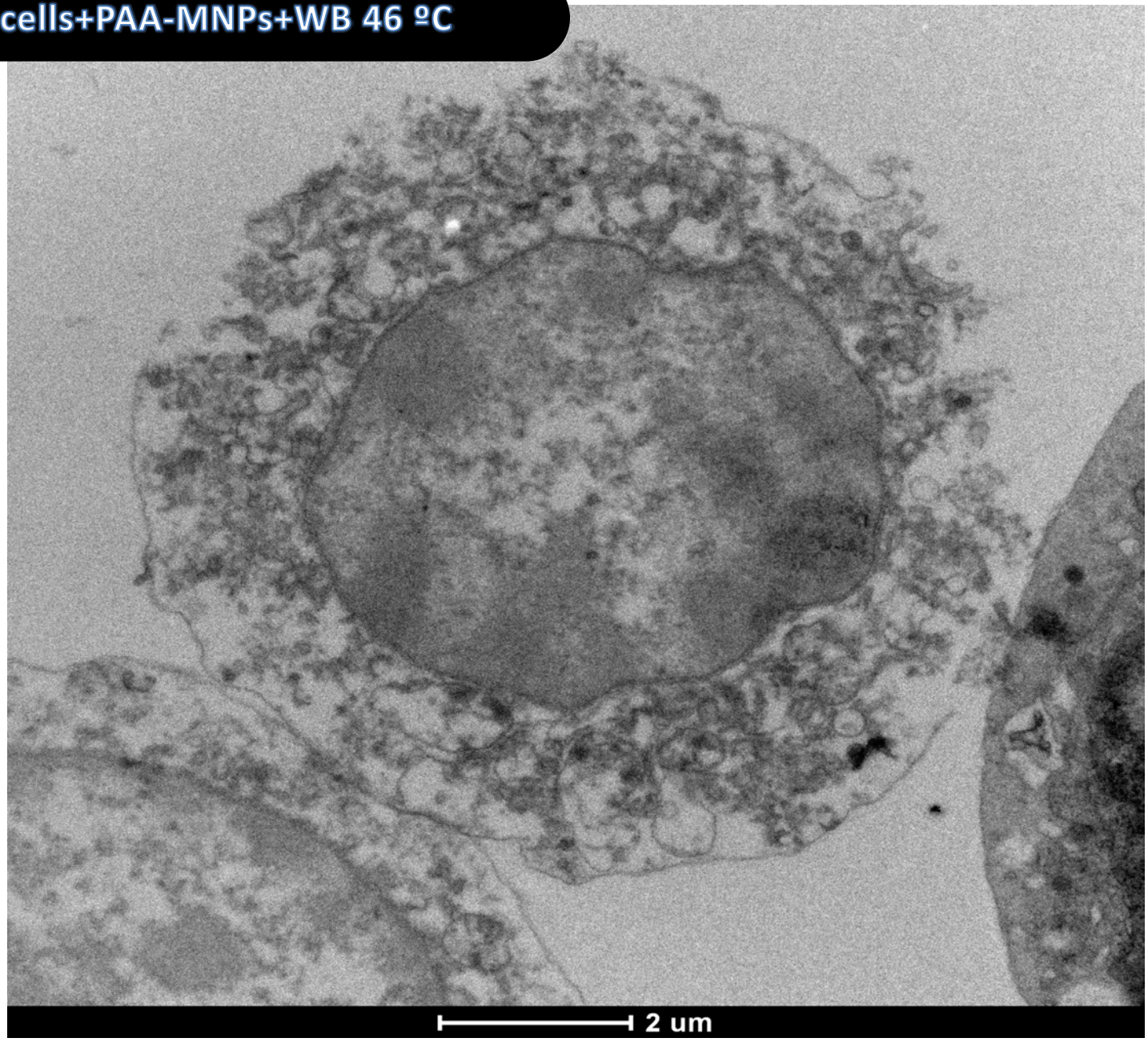
WATER BATH
vs.
MHT

$$y = \frac{A}{1 + e^{B \cdot (x - x_0)}}$$



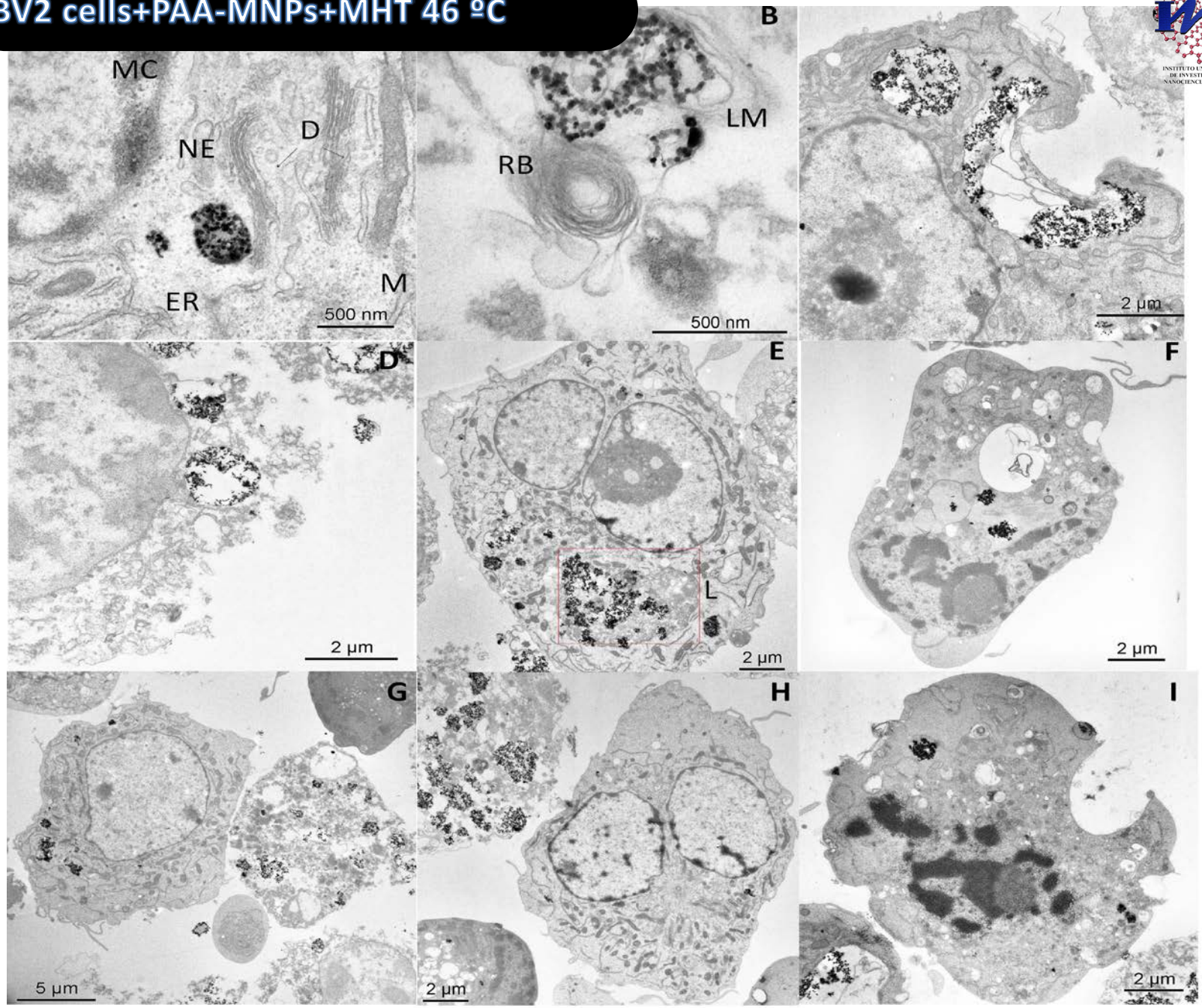
Treatment	$T_{50\%}$@ t_0	$T_{50\%}$@ t_{6h}
WB	50.3 ºC	47.7 ºC
MHT	44 ºC	42.1 ºC
ΔT_{50} (ºC)	6.3 ºC	5.6 ºC

BV2 cells+PAA-MNPs+WB 46 ºC

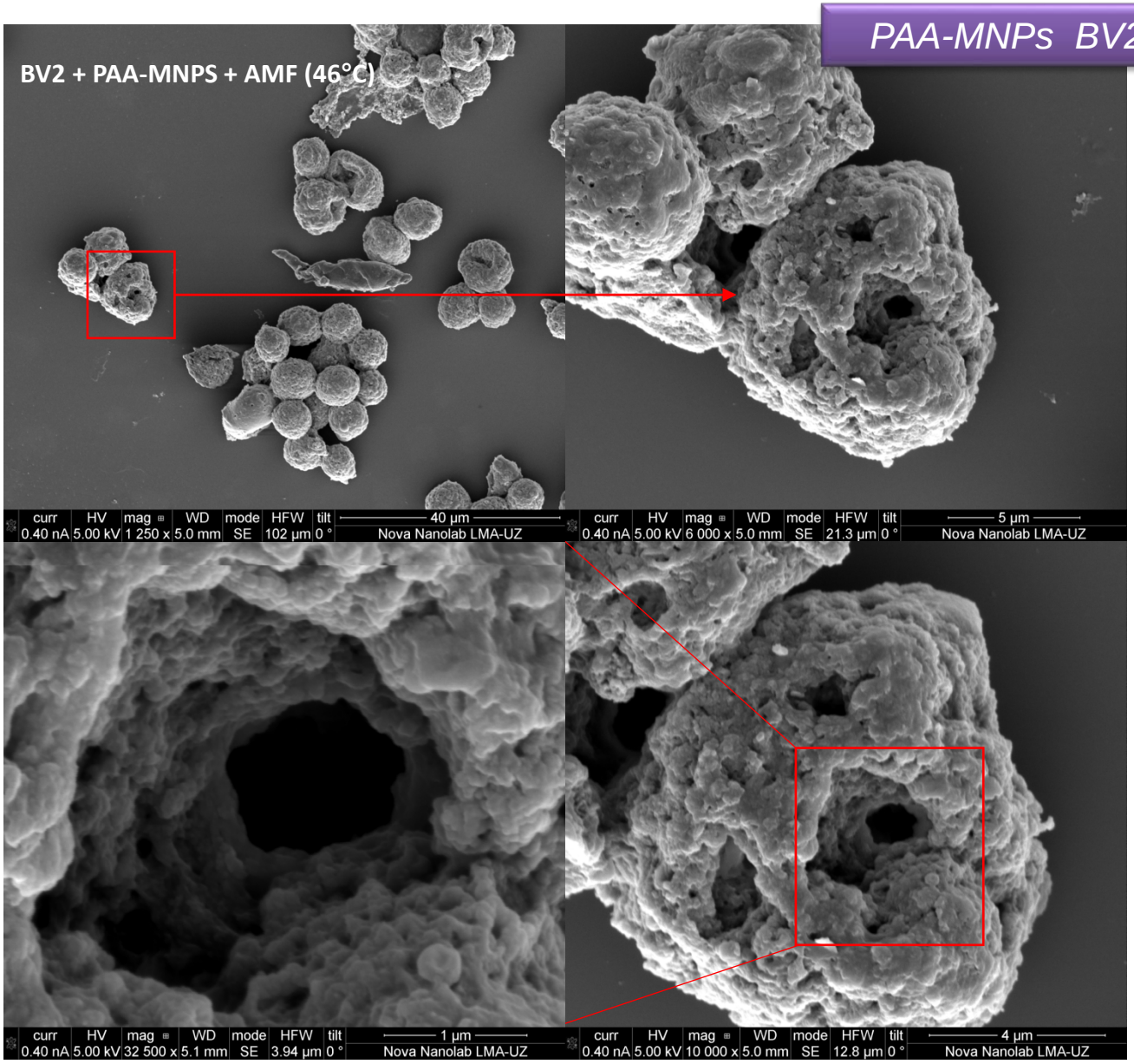


INSTITUTO UNIVERSITARIO DE INVESTIGACIÓN EN NANOCIENCIA DE ARAGÓN

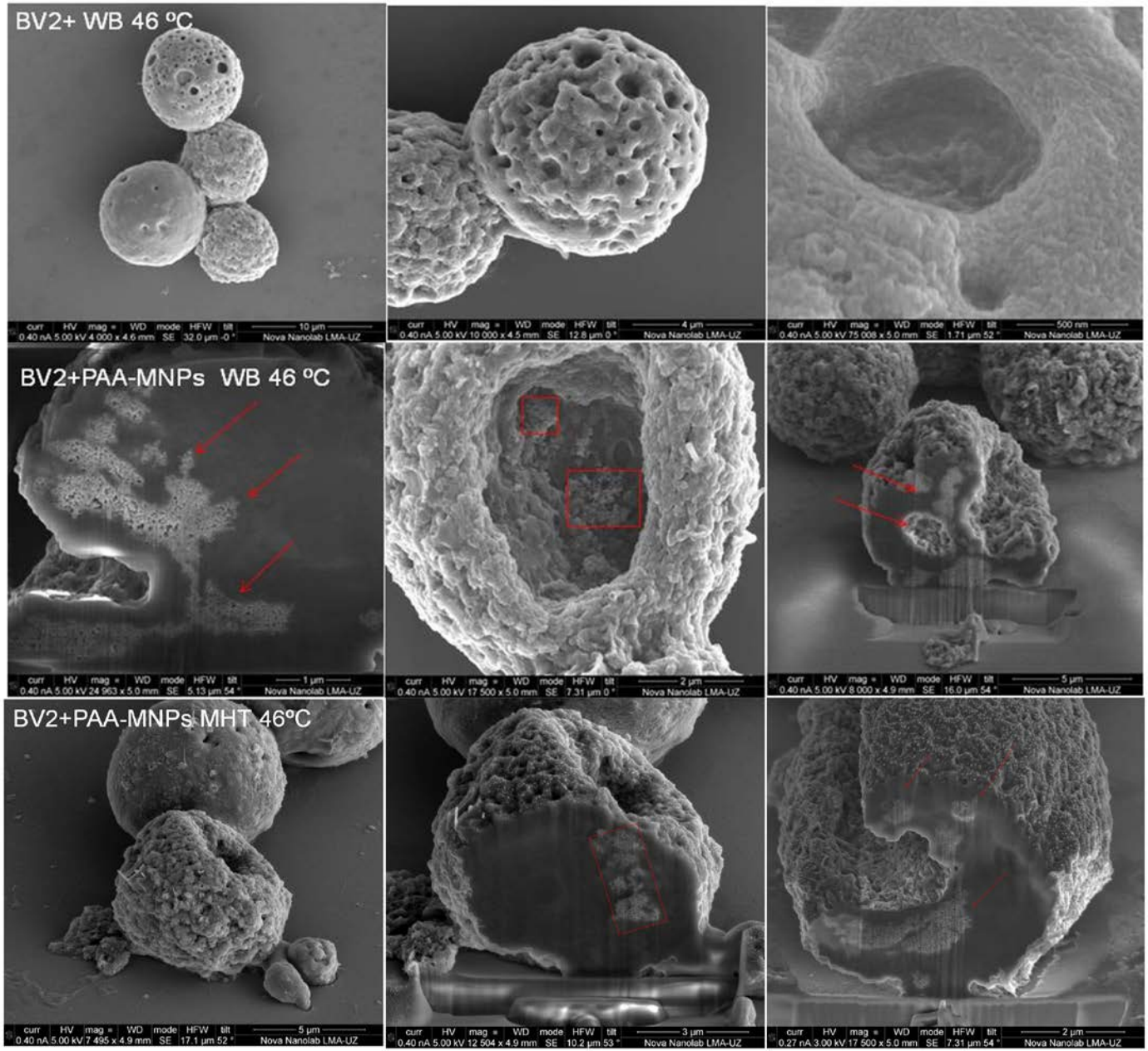
BV2 cells+PAA-MNPs+MHT 46 ºC



Membrane damage



MNPs



CONCLUSIONS

WHAT WE KNOW:

- We can design efficient MNPs. We know the physical mechanisms and we can do materials engineering.
- There is no local effects in the thermal sense (applies to MHT).
- It seems possible to surpass the suggested ower limit of 1 mm^3 if better nanoparticles are manufactured.
- Killing efficiency for WB is quite similar to MHT in the thermal sense.
- However, MNPs perform better that WB in damaging cell structures. (Non-thermal effects cannot be ignored).

END