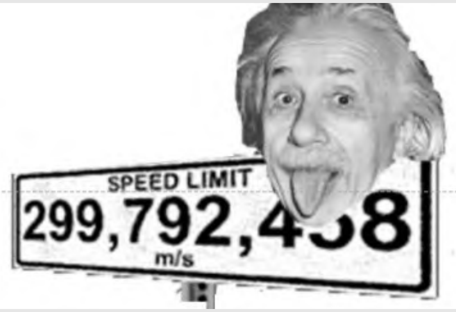
part 1: Antiferromagnetism and antiferromagnetic spintronics

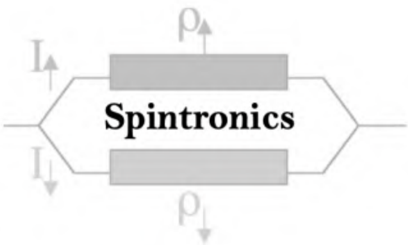
Special relativity theory



part 2: Antiferromagnetic order with spin-polarized bands:

→ Noncollinear Antiferromagnets

→ Altermagnets



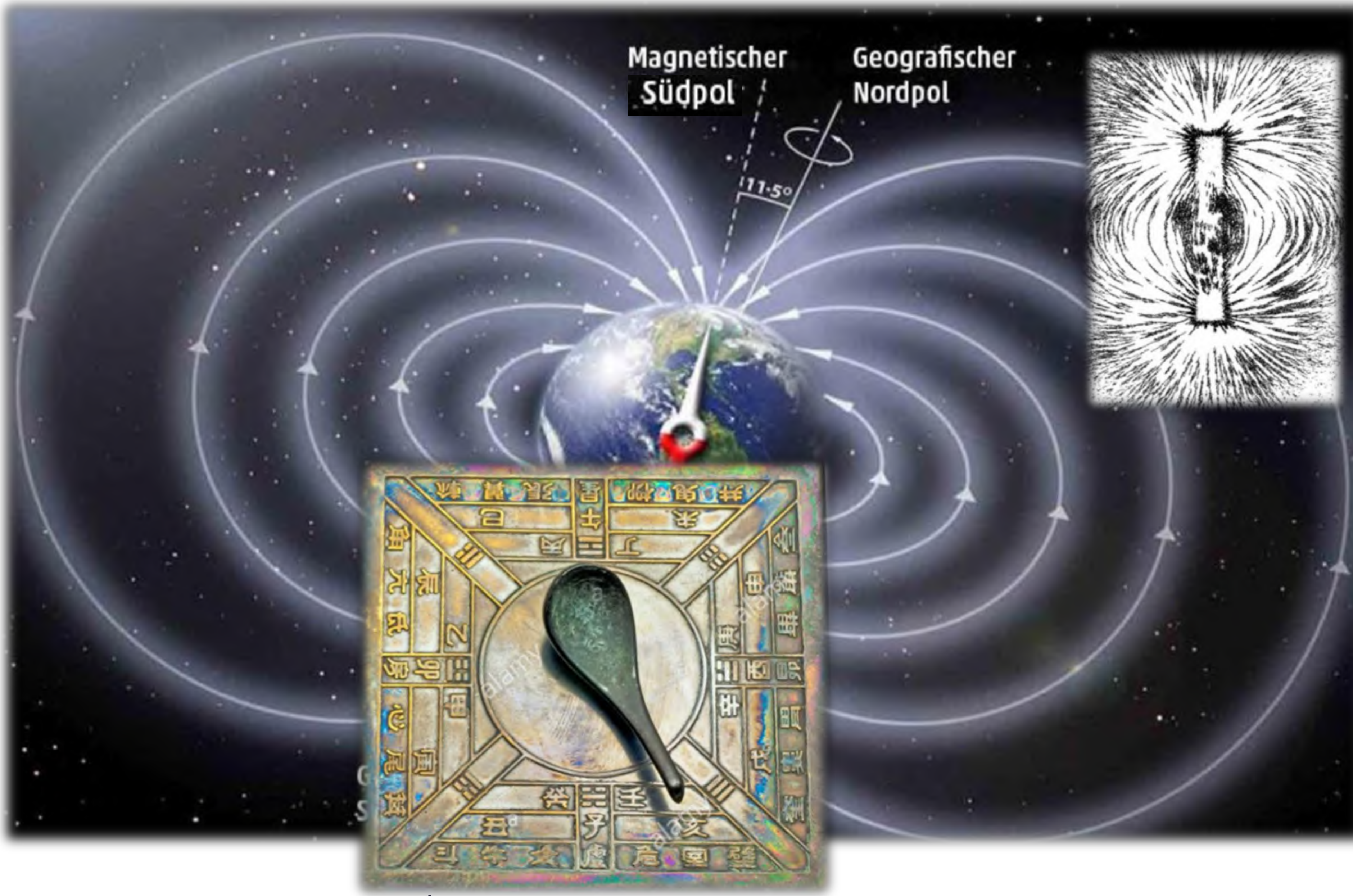
Institute of Physics ASCR
Prague Czech Republic

Jörg Wunderlich

Institute for Experimental and Applied Physics
Universität Regensburg

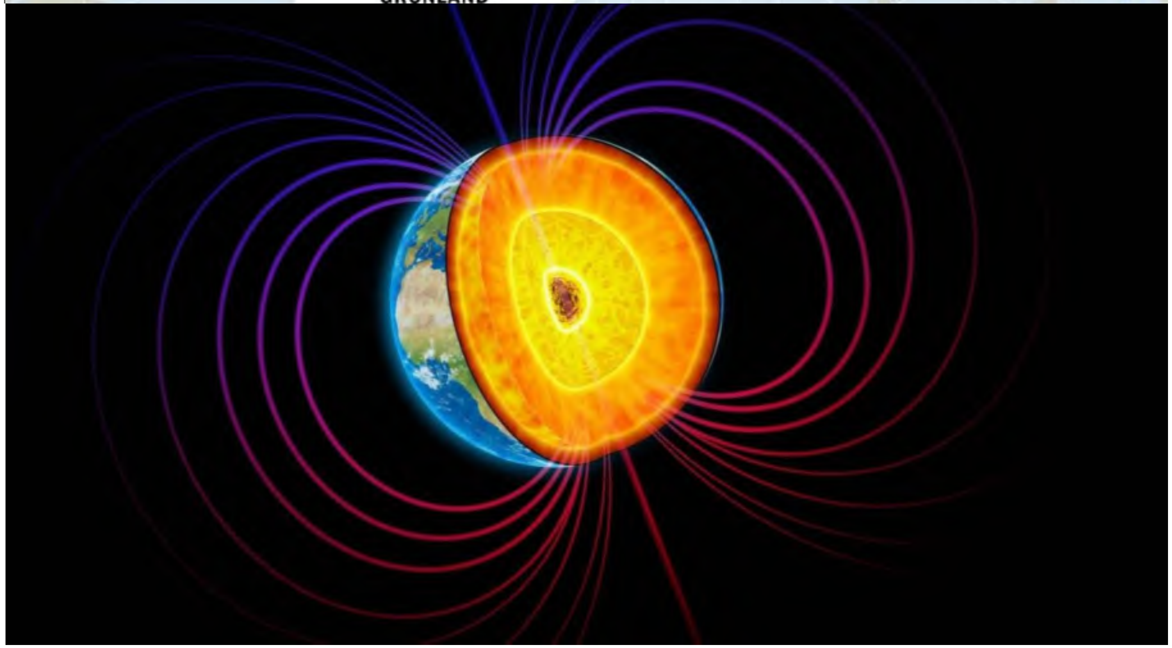
Motivation

Early Applications of Magnetism

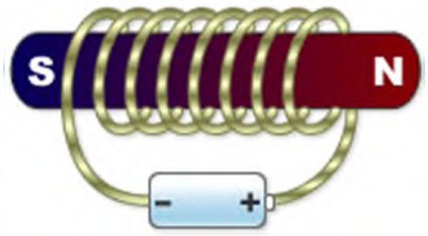


Chinese spoon:

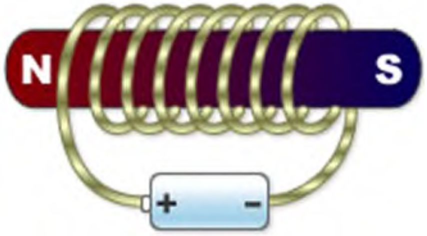
Earth Magnetism

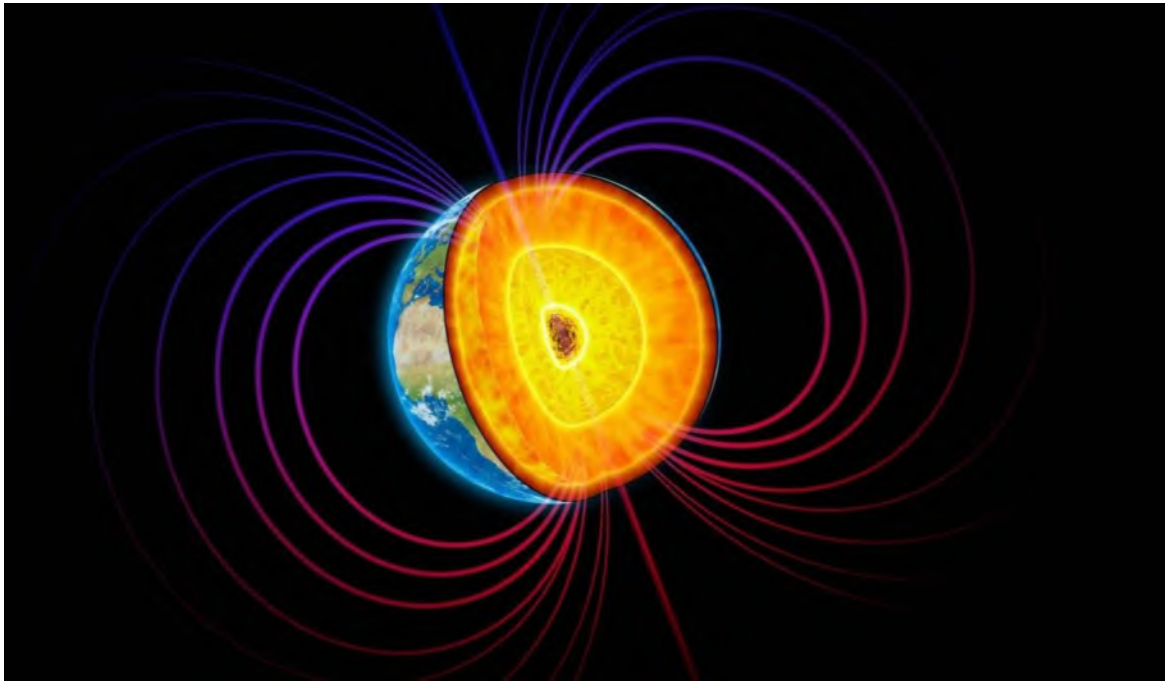


42 thousand years ago: Last reversal of the earth's magnetic field



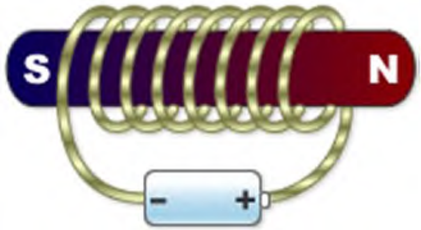
Magnetic Memories

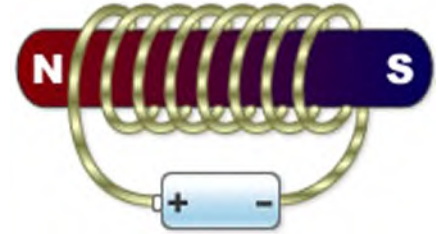




42 thousand years ago: Last reversal of the earth's magnetic field

Magnetic Memories





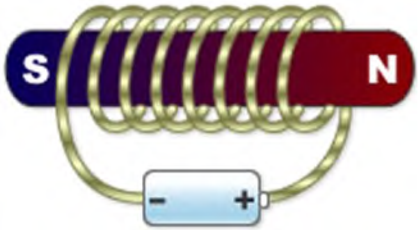
Poulsen’s wire recorder ***1890‘s***

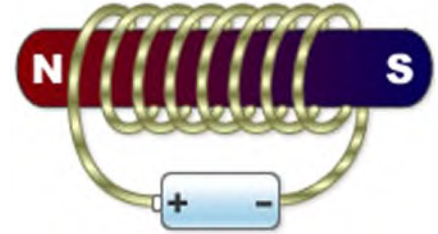
Valdemar Poulsen
(1869 – 1942)

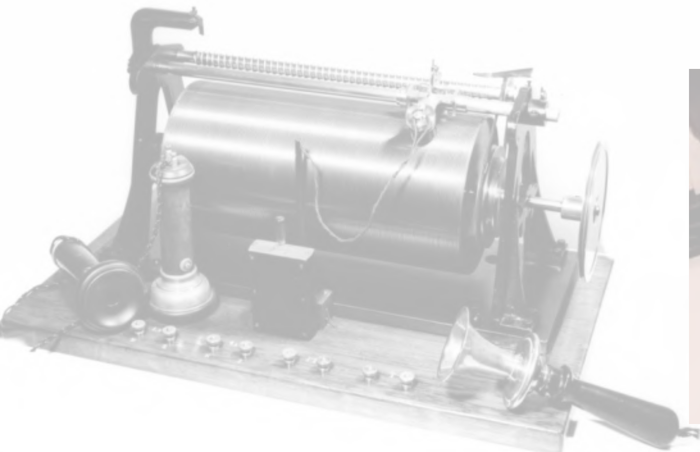
Mechanical gramophone ***1870‘s***

Number 1 application

Magnetic Memories

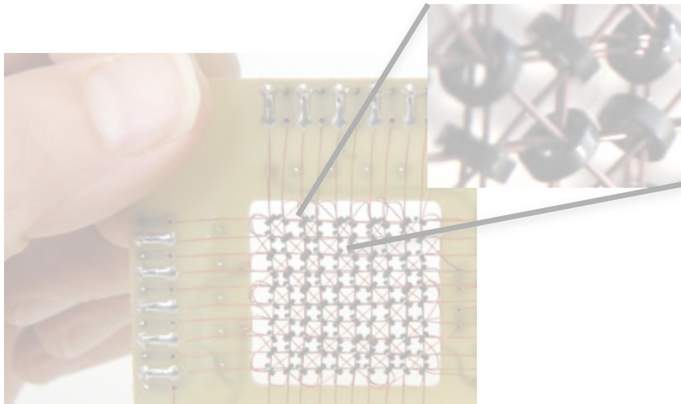






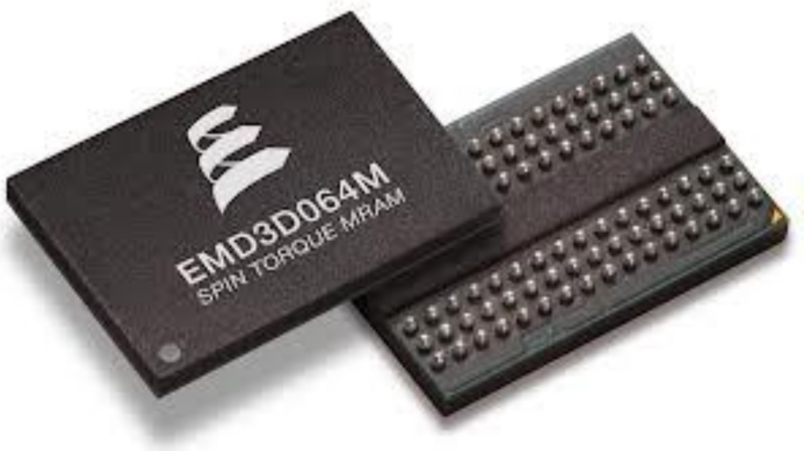
Poulsen’s Wire recorder *1890‘s*

Tape recorder *1930‘s*



Magnetic core memory *1950‘s*

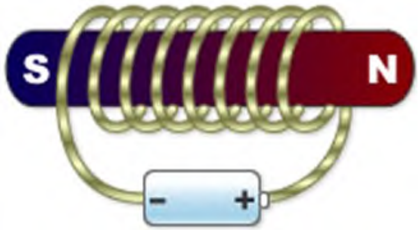
Magnetic Hard Disk Drive (HDD) *1950‘s*

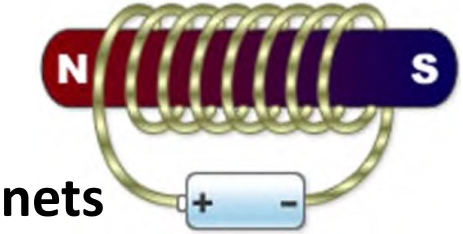


Magnetic RAMS *1980‘s*

Number 1 application

Magnetic Memories



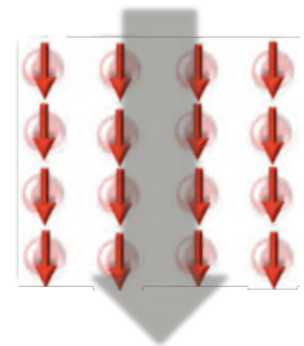


Ferromagnets

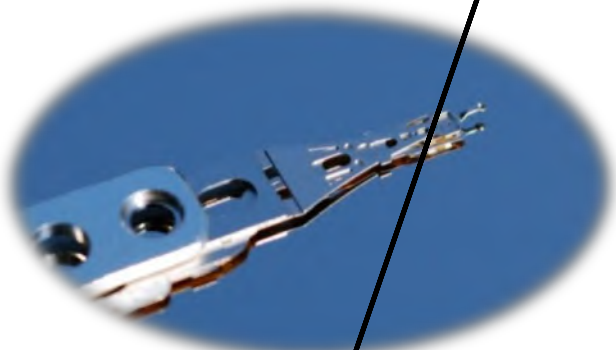
→ $\sim 10 \times 1000\,000 \times 1000\,000$

→ **exhibit Magnetization *M***

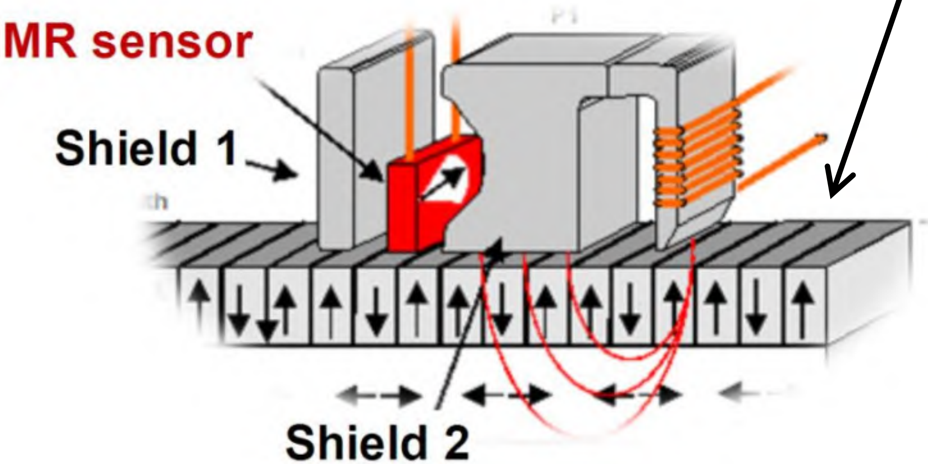
H



HDD

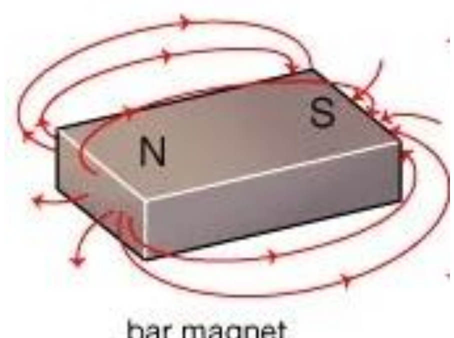


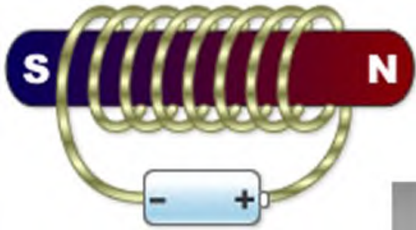
Read / Write head



→ **controllable**

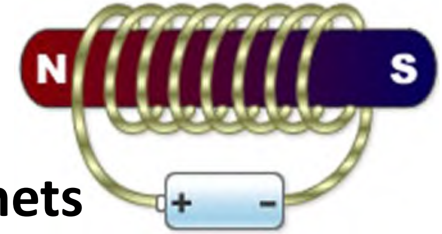
by magnetic fields





Number 1 application

Magnetic Memories



Ferromagnets

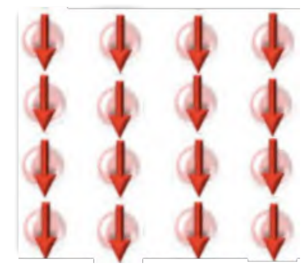
Nobel Prize in Physics 2007

© The Nobel Foundation. Photo: U. Montan
Albert Fert
Prize share: 1/2

© The Nobel Foundation. Photo: U. Montan
Peter Grünberg
Prize share: 1/2

The Nobel Prize in Physics 2007 was awarded jointly to Albert Fert and Peter Grünberg "for the discovery of Giant Magnetoresistance."

→ **exhibit Magnetization**



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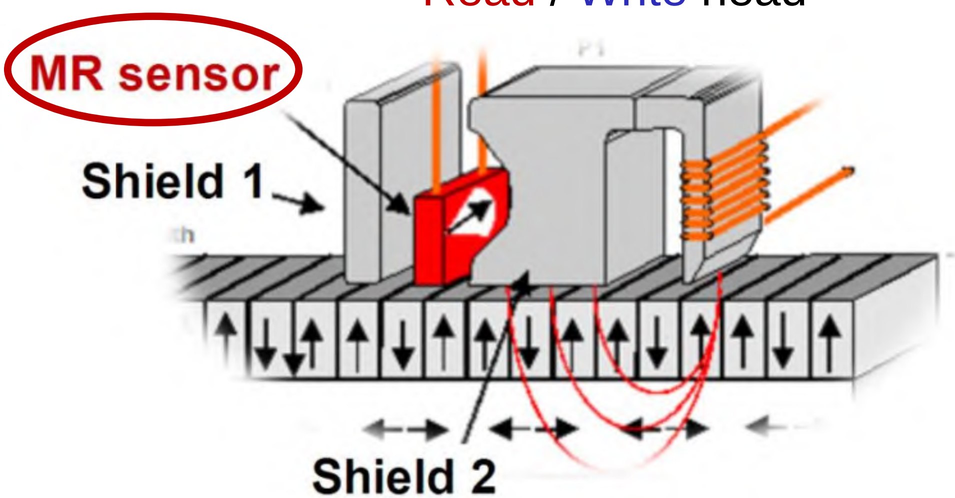
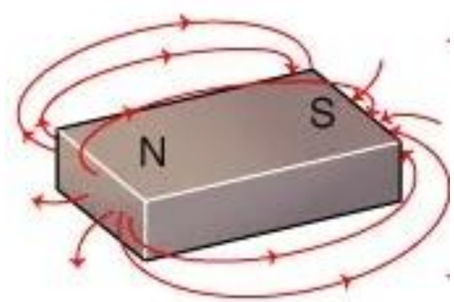
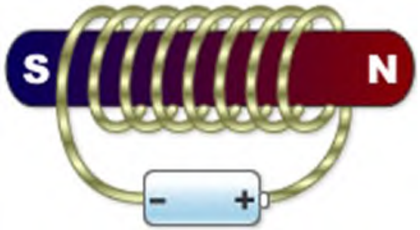


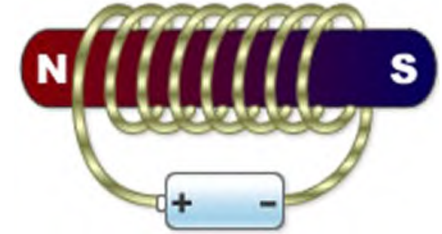
→ **controllable and detectable by magnetic fields**



bar magnet

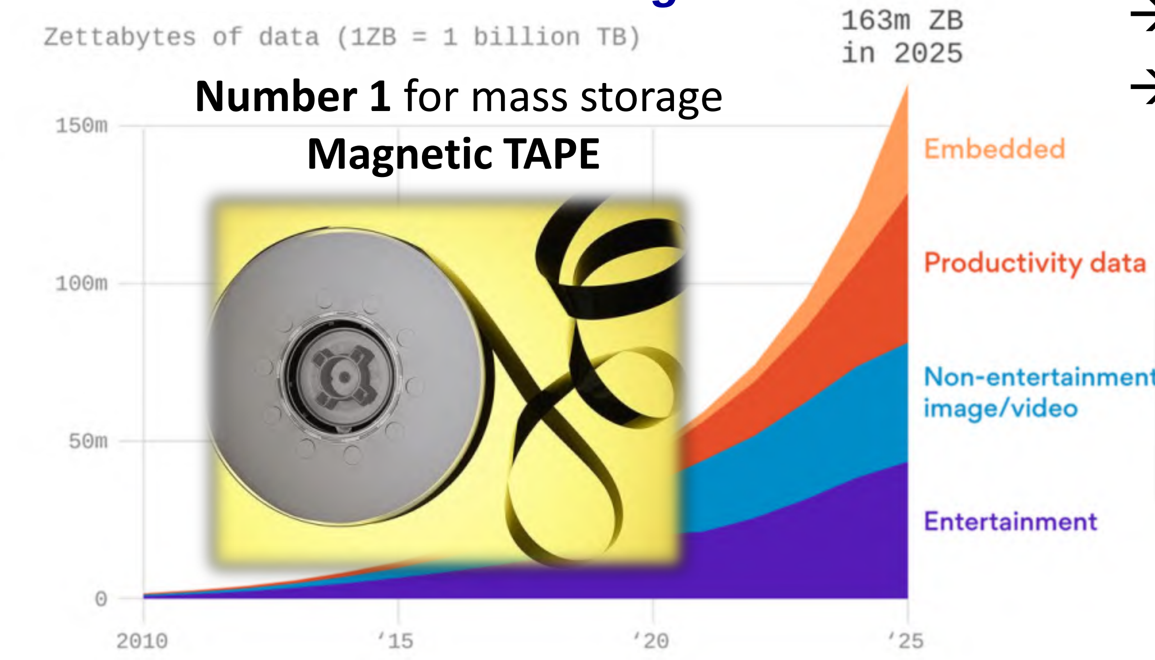
Magnetic Memories





Ferromagnets

HUGE demand on data storage

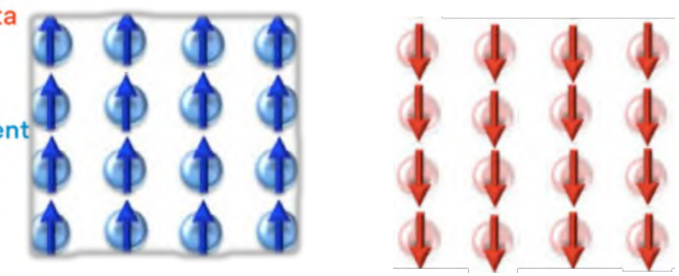


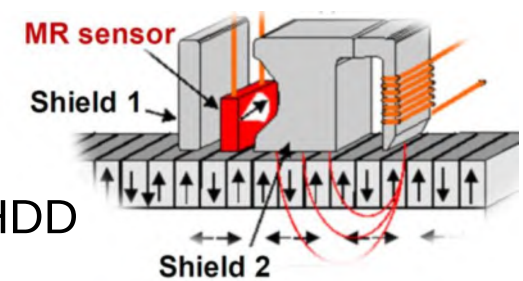
Number 1 for mass storage

Magnetic TAPE

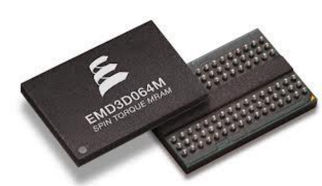
→ **Net-Magnetisation**

→ **easily controllable and detectable by magnetic fields**





HDD



MRAM

Radiation-hard
Spin not charge based

Non-volatile
Magnetic order

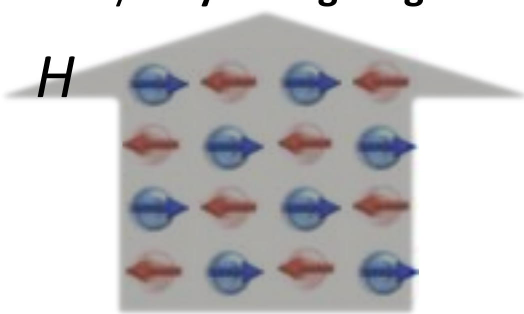
ANTIFERRO versus FERRO

Antiferromagnets

→ **magn. ordered** but **no Net-Magnetisation**

→ **difficult to control**

- by **very strong magnetic fields**



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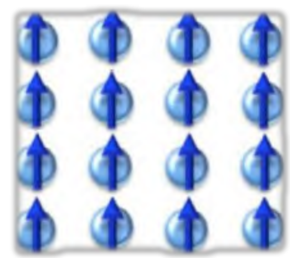
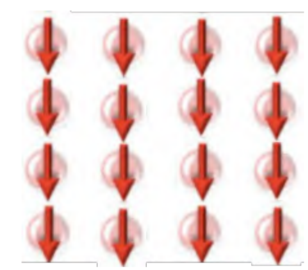
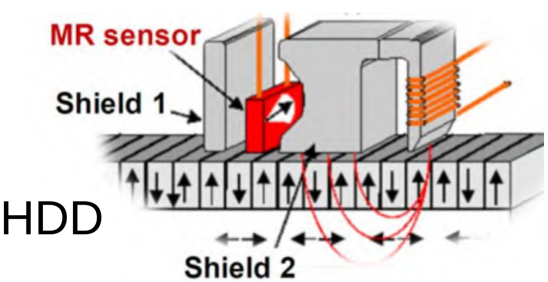
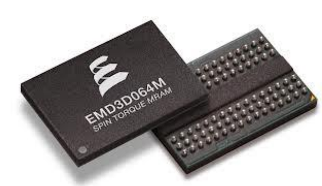






HDD

MRAM



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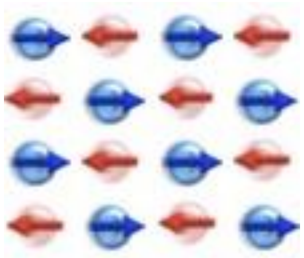

LOUIS NÉEL

Nobel Lecture, December 11, 1970

"Interesting but useless"

Ferromagnets

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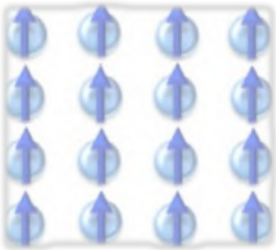

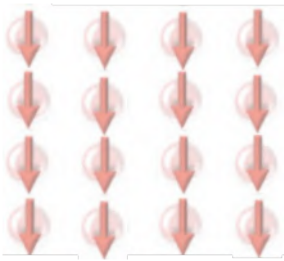

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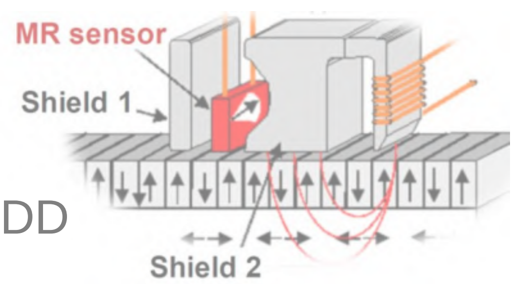
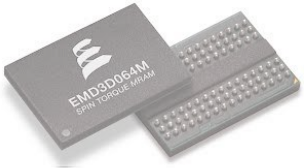
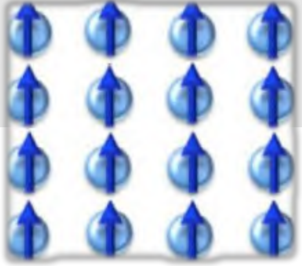
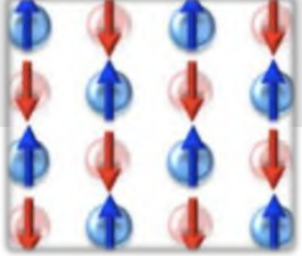


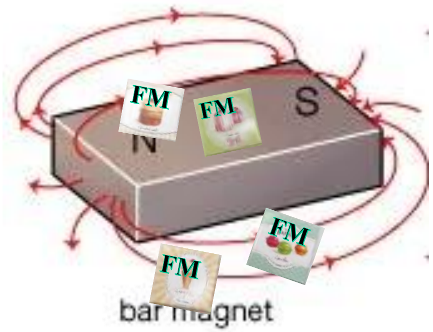
MRAM



ANTIFERRO versus FERRO







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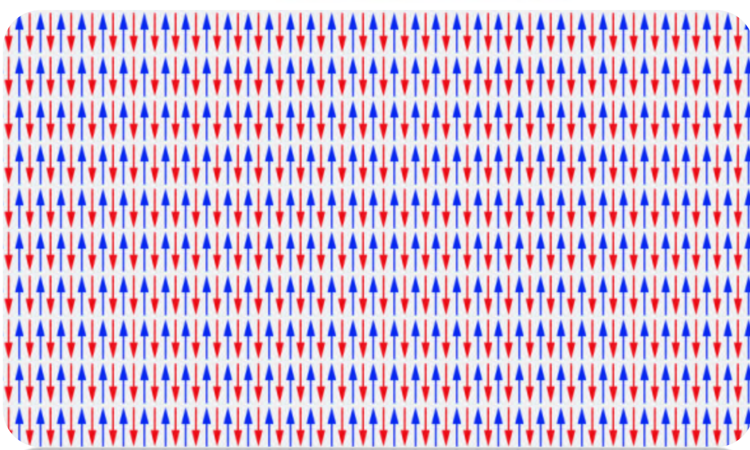
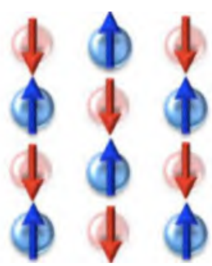


netic fields,

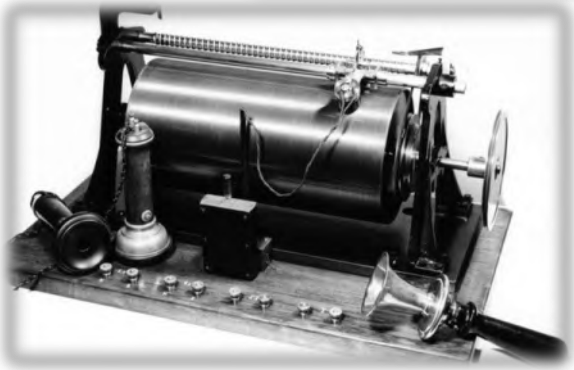
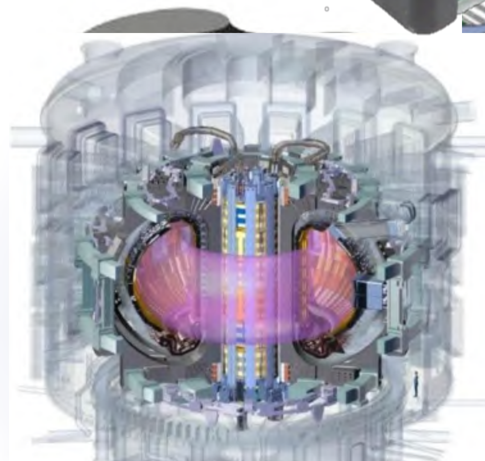
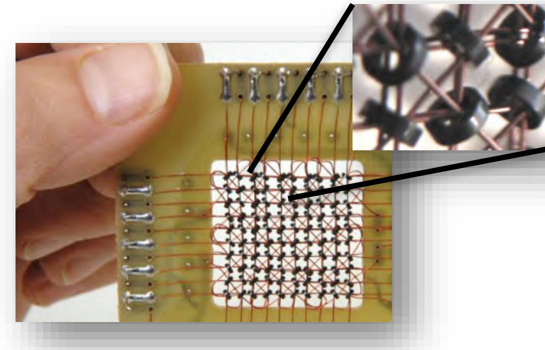


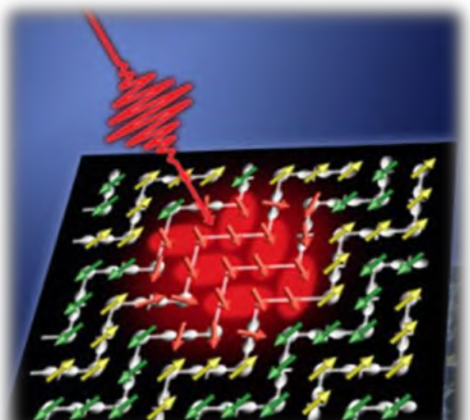
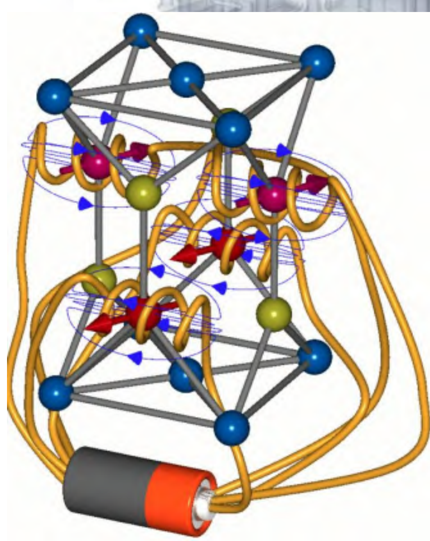
→ How can one generate such alternating fields?

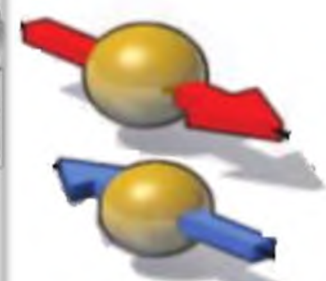
→ How can one distinguish reversed antiferromagn

Magnetism: Application and Science - mesmerizing, but ...



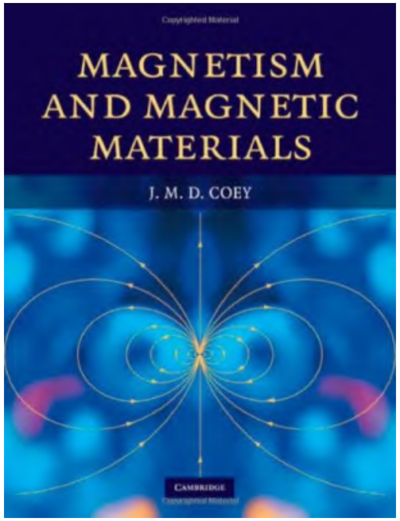




outline of this course:

Antiferromagnetism and antiferromagnetic spintronics

1) **antiferromagnets - basics** (exchange interaction, frustration, critical temperatures and fields: flip and flop)



Michael Coey

outline of this course:

Antiferromagnetism and antiferromagnetic spintronics

1) **antiferromagnets - basics** (exchange interaction, frustration, critical temperatures and fields: flip and flop)

2) **conventional application of antiferromagnetism** (exchange bias: keeping the reference layer fixed …)

3) **AF spintronics** (staggered effective spin-orbit-fields, AF domain wall motion, nonlinear responses, …)

Antiferromagnetic order with spin-polarized bands

Jakub Zelezny (Prague)

Libor Smejkal (Mainz/Prague)

Tomas Jungwirth (Prague)

… could antiferromagnetism become similarly important ?

outline of this course:

Antiferromagnetism and antiferromagnetic spintronics

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Antiferromagnetic order with spin-polarized bands

4) **noncollinear AFMs** (Kagome AFs …)

5) **altermagnets** (crystal and magnetic symmetries → spin-polarized band structure…)

Conclusions

outline of this course:

Antiferromagnetism and antiferromagnetic spintronics

1) **antiferromagnets - basics** (exchange interaction, frustration, critical temperatures and fields: flip and flop)
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Antiferromagnetic order with spin-polarized bands

4) **noncollinear AFM** (Kagome AF …)
5) **altermagnets** (crystal and magnetic symmetries → band structure…)

Conclusions

1.1 Antiferromagnetic Exchange Interaction

Exchange interaction (general remarks)

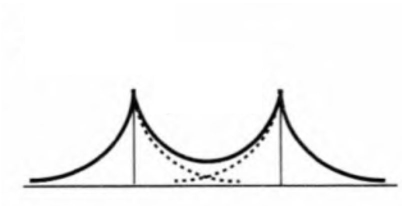
- reflects **Pauli exclusion principle** (two electrons (fermions) are “forbidden” to occupy the same quantum state) combined with the **Coulomb repulsion**

→ $\varepsilon(\langle\uparrow_i\uparrow_j]) \neq \varepsilon(\langle\uparrow_i\downarrow_j])$ neighboring atoms i, j.

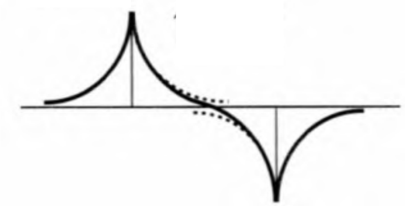
1.1 Antiferromagnetic Exchange Interaction

The world's smallest antiferromagnet: The **Hydrogen molecule**

- 2 molecular orbits: (under exchange) **symmetric bonding orbital** ϕ_s , **antisymmetric antibonding orbital** ϕ_a



$$\phi_s = (1/\sqrt{2})(\psi_1 + \psi_2) \qquad \phi_a = (1/\sqrt{2})(\psi_1 - \psi_2).$$



- 4 wave functions (spinors) with respect to the spin space:

antisymmetric spin singlet state: $S = 0; \quad M_S = 0$, 3 symmetric Spin triplet states: $S = 1; \quad M_S = 1, 0, -1$

$$\chi_a = (1/\sqrt{2})[\uparrow_1, \downarrow_2\rangle - |\downarrow_1, \uparrow_2\rangle] \qquad \chi_s = |\uparrow_1, \uparrow_2\rangle;\ (1/\sqrt{2})[|\uparrow_1, \downarrow_2\rangle + |\downarrow_1, \uparrow_2\rangle];\ |\downarrow_1, \downarrow_2\rangle$$

- total wavefunctions describing the 2 electrons (fermions) must be antisymmetric under exchange:

$$\Psi_I = \phi_s(1,2)\chi_a(1,2),$$
$$\Psi_{II} = \phi_a(1,2)\chi_s(1,2).$$

→ corresponding energies

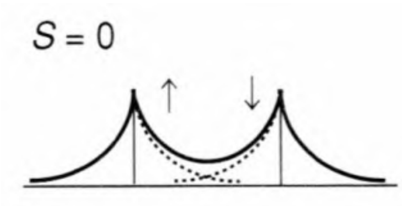
$$\varepsilon_{I,II} = \int \phi^*_{s,a}(\mathbf{r}_1, \mathbf{r}_2)\mathcal{H}(\mathbf{r}_1, \mathbf{r}_2)\phi_{s,a}(\mathbf{r}_1, \mathbf{r}_2)\mathrm{d}r_1^3\mathrm{d}r_2^3.$$

… and ε_I is lower than ε_{II}. Hence the **bounding orbital with the spin-singlet state is the ground state**.

1.1 Antiferromagnetic Exchange Interaction

The world's smallest antiferromagnet: The **Hydrogen molecule**

- 2 molecular orbits: symmetric bonding orbital ϕ_s, and antisymmetric antibonding orbital ϕ_a



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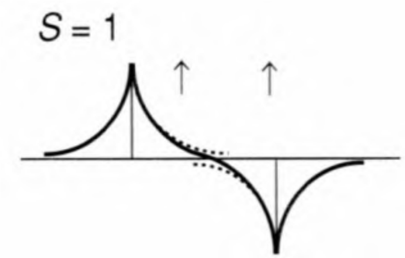
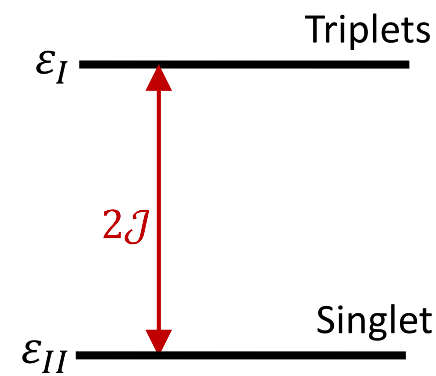


$$\varepsilon_{I,II} = \int \phi^*_{s,a}(\mathbf{r}_1, \mathbf{r}_2)\mathcal{H}(\mathbf{r}_1, \mathbf{r}_2)\phi_{s,a}(\mathbf{r}_1, \mathbf{r}_2)\mathrm{d}r_1^3\mathrm{d}r_2^3.$$



- define exchange integral: $\mathcal{J} = (\varepsilon_I - \varepsilon_{II})/2$,

→ exchange energy : $\varepsilon = -2(\mathcal{J}/\hbar^2)\boldsymbol{s}_1 \cdot \boldsymbol{s}_2$, $\boldsymbol{s}_1 \cdot \boldsymbol{s}_2$ is $\frac{1}{2}[(\boldsymbol{s}_1 + \boldsymbol{s}_2)^2 - \boldsymbol{s}_1^2 - \boldsymbol{s}_2^2]$.

- AF singlet state with $S = s_1 + s_2 = 0$, the eigenvalue is $-\frac{3}{4}\hbar^2$
- triplet states, with quantum number $S = s_1 + s_2 = 1$, the eigenvalue is $+\frac{1}{4}\hbar^2$
- energy splitting between singlet and triplet: $-\frac{3}{2}\mathcal{J} - \frac{1}{2}\mathcal{J} = -2\mathcal{J}$

with the exchange integral: $\mathcal{J} = \int \psi_1^*(\boldsymbol{r}')\psi_2^*(\boldsymbol{r})\mathcal{H}(\boldsymbol{r}, \boldsymbol{r}')\psi_1(\boldsymbol{r})\psi_2(\boldsymbol{r}')\mathrm{d}r^3\mathrm{d}^3r'$.

Heisenberg exchange interaction

- generalization to many-electron atomic spins $\boldsymbol{S}_1$ and $\boldsymbol{S}_2$,

$$\mathcal{H} = -2\mathcal{J}\hat{\boldsymbol{S}}_1 \cdot \hat{\boldsymbol{S}}_2,$$

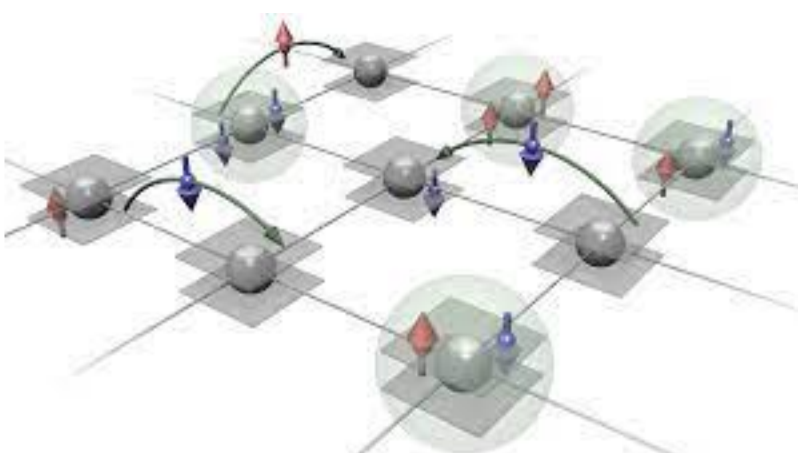
where $\hat{\boldsymbol{S}}_1$ and $\hat{\boldsymbol{S}}_2$ are dimensionless spin operators, like the Pauli spin matrices

- ferromagnetic: $\mathcal{J} > 0$, antiferromagnetic: $\mathcal{J} < 0$

- in general: sum over all pairs of atoms on lattice sites i, j:

$$\mathcal{H} = -2\sum_{i>j} \mathcal{J}_{ij}\boldsymbol{S}_i \cdot \boldsymbol{S}_j.$$

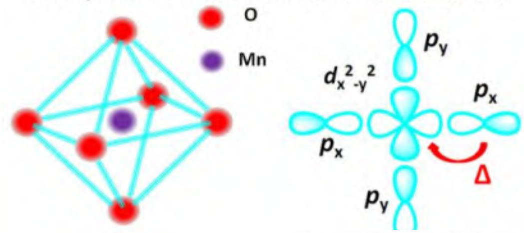
- often simplified to only **nearest neighbor interaction**.



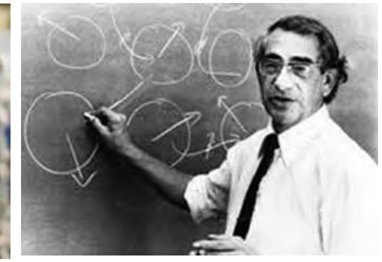
1.1 Antiferromagnetic Exchange Interaction

AF Exchange in Insulators

(localized electrons)



John B. Goodenough
1922-2023

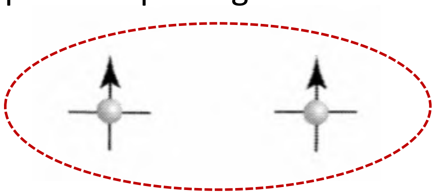


Junjro Kanamori
1930 -2012

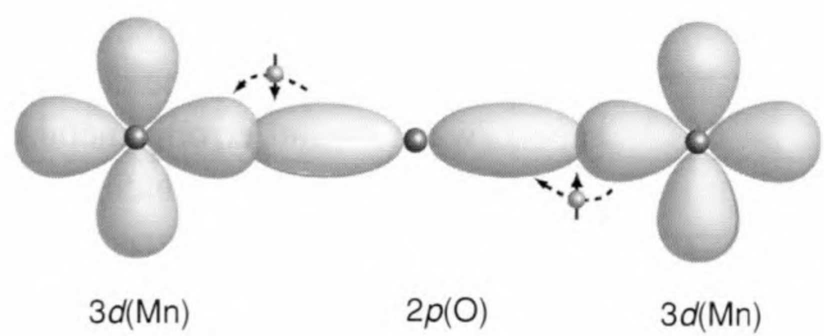
- Superexchange

- 3*d* TM orbitals **hybridize** with the oxygen 2*d* orbit $\phi_{3d} = \alpha\psi_{3d} + \beta\psi_{2p}$
  (“oxygen bridges” transmit the superexchange interaction)
- for singly occupied 3*d* orbitals: **AFM coupling**

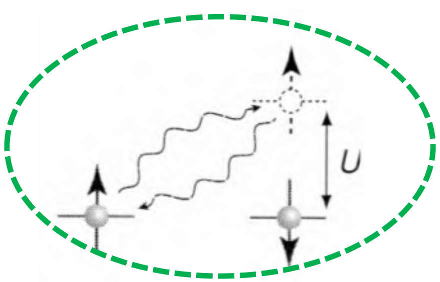
parallel spin alignment:



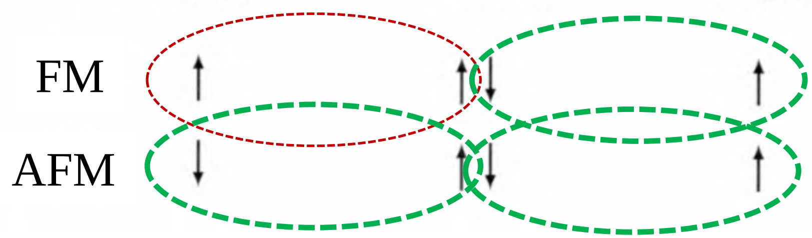
hopping forbidden
because of Pauli principle



antiparallel spin alignment:



energy gain due to virtual
hopping

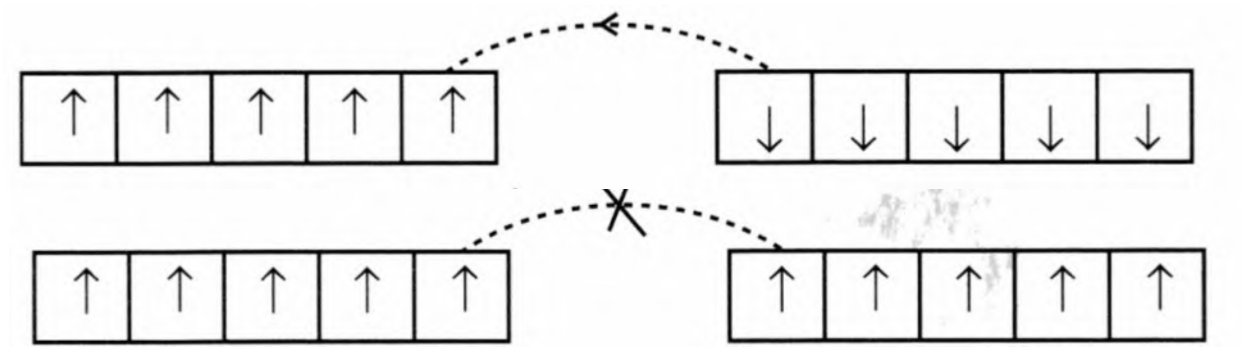


→ AFM configuration is lower in energy than the FM configuration if 3*d* TM orbitals are occupied with 1 electron each

1.1 Antiferromagnetic Exchange Interaction

Direct Exchange interactions in metals involves overlap of partly localized atomic orbitals

- **antiferromagnetic exchange** for half-filled *d*-bands

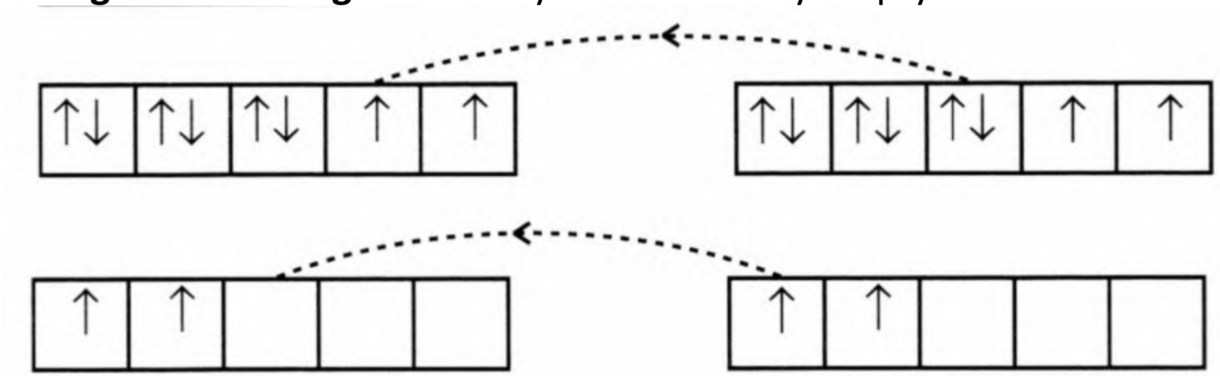


Cr: [Ar] $3d^5\ 4s^1$

Mn: [Ar] $3d^5\ 4s^2$

(electrons can only hop into already with 1 electron occupied orbitals)

- **ferromagnetic exchange** for nearly filled or nearly empty *d*-bands



Fe: [Ar] $3d^6\ 4s^2$

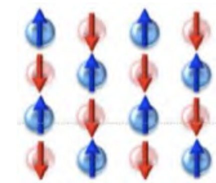
Co: [Ar] $3d^7\ 4s^2$

Ni: [Ar] $3d^8\ 4s^2$

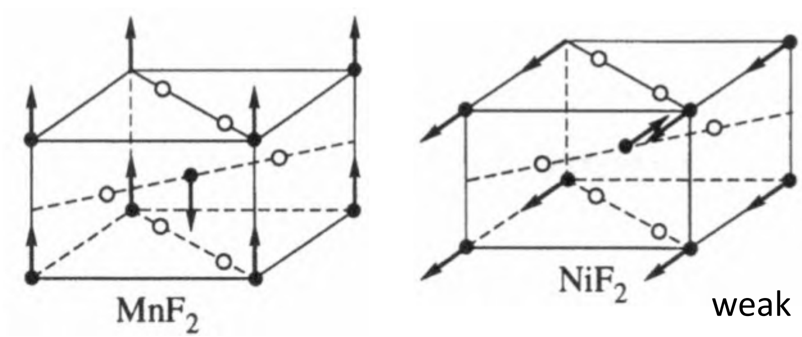
1.2 Crystal and magnetic structures

- idea of antiferromagnetic order was proposed simultaneously both by Luis Néel and by Lev Landau

- ***Néel AF***: nearest neighbour moments are reversed



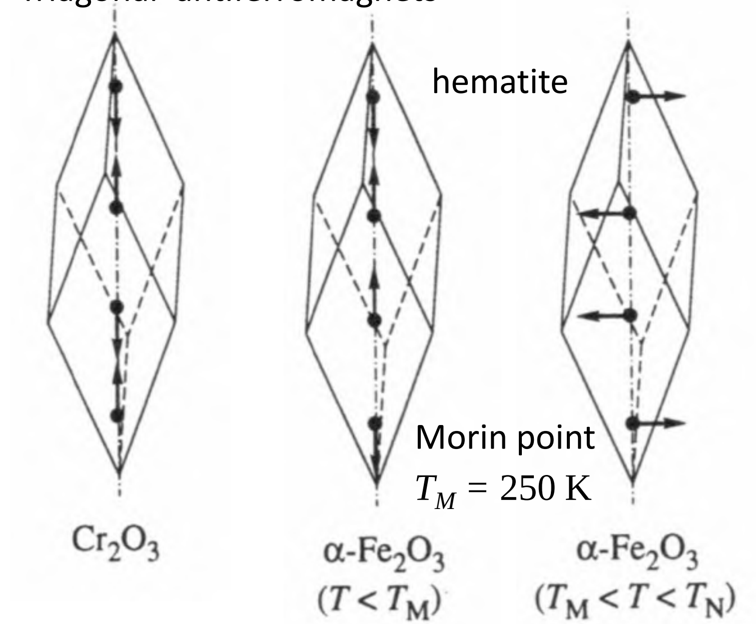
Tetragonal antiferromagnets



weak FM

(not perfectly collinear AF ordered magnetic Ni moments)

Triagonal antiferromagnets



hematite

Morin point $T_M = 250$ K

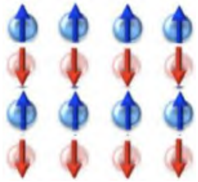
→ crystallographic unit cell equal to the magnetic unit cell

1.2 Crystal and magnetic structures

- idea of antiferromagnetic order was proposed simultaneously both by Lev Landau and by Luis Néel

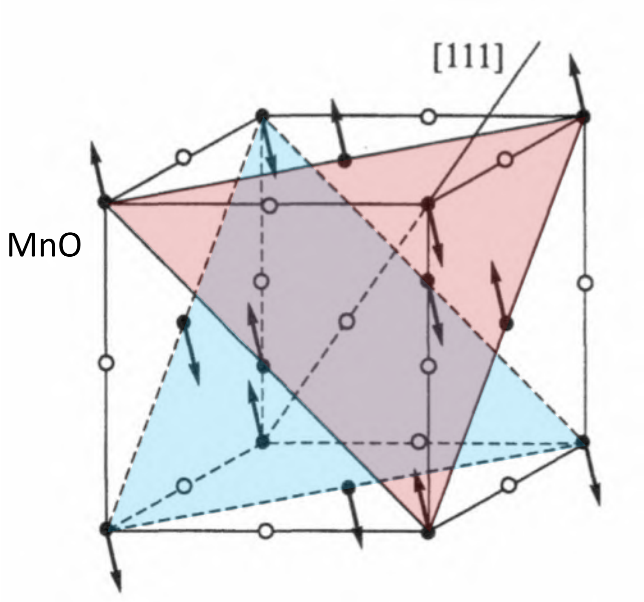
- ***Néel AF***: nearest neighbour moments are reversed

- ***Landau AF***: ferromagnetic atomic layers are antiferromagnetically coupled



Cubic AF

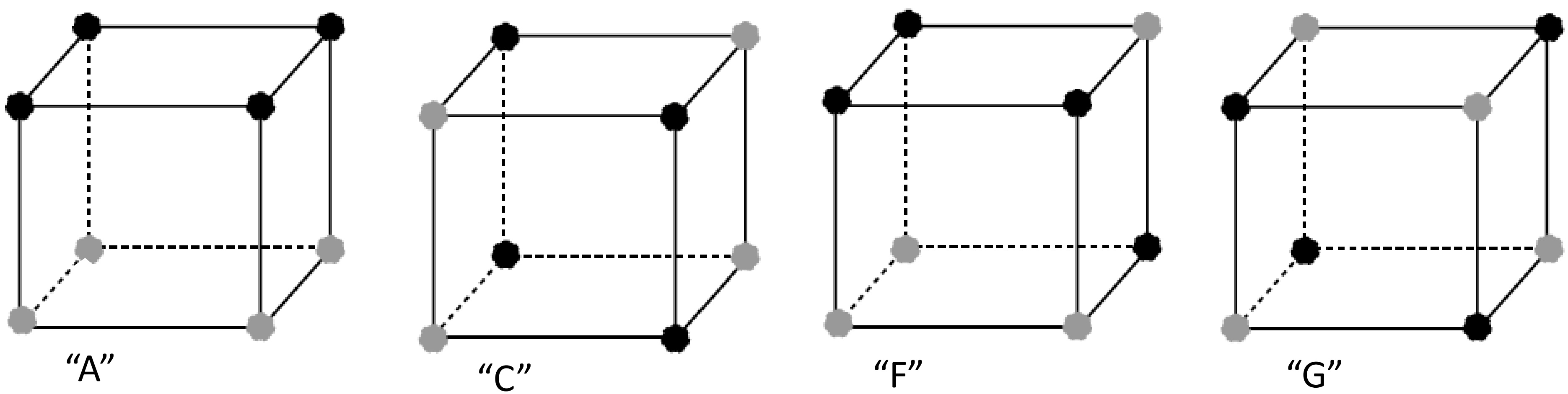
MnO



→ doubling of the magnetic unit cell with respect to the crystallographic unit cell

- antiferromagn. order for given crystal structure can often be realized in many different ways: → **Frustration**

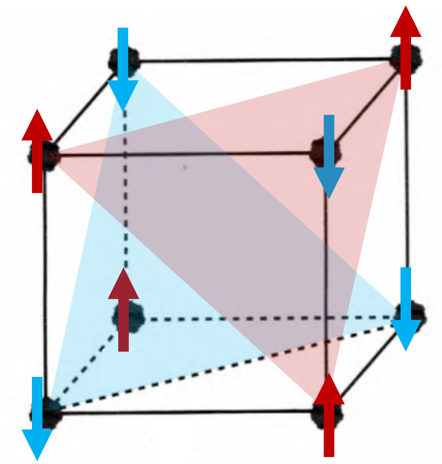
Simple cubic lattice: 4 possible antiferromagnetic modes for 2 magn. sublattices with $\mathbf{M}_1 = -\mathbf{M}_2$



1.2 Crystal and magnetic structures

- antiferromagn. order for given crystal structure can often be realized in many different ways: → **Frustration**

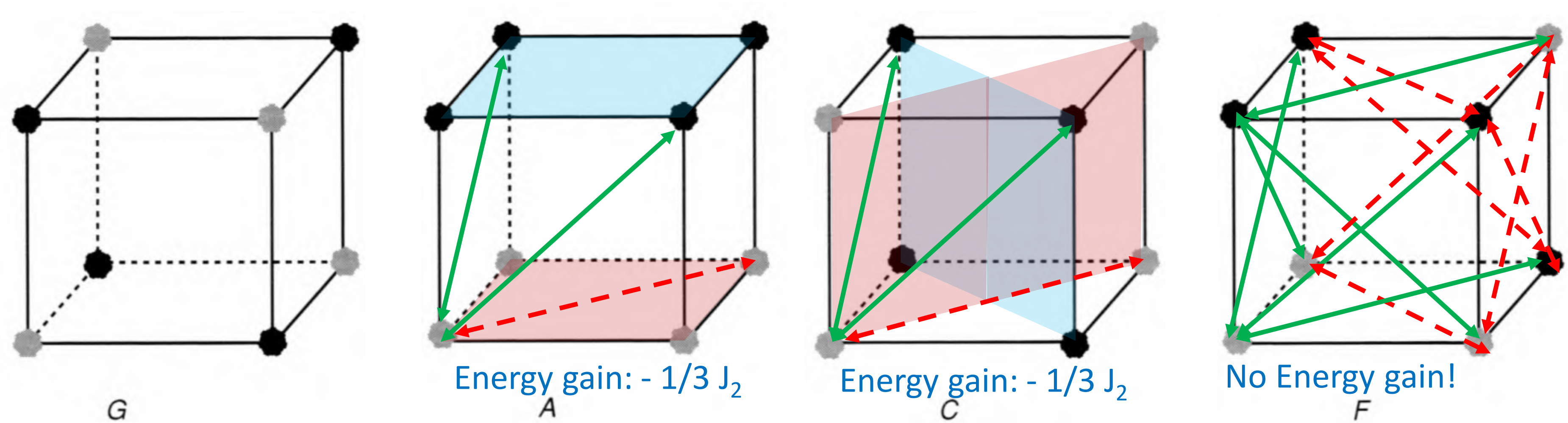
Simple cubic lattice: - two possible exchange interactions, nearest and next nearest neighbor $\mathcal{J}_1$ and $\mathcal{J}_2$



- for af nearest neighbor $\mathcal{J}_1$ interaction only – no frustration – *G* - mode
- If $\mathcal{J}_2$ is the only antiferromagnetic interaction, it becomes impossible to satisfy all *twelve* next-nearest neighbors simultaneously

→ the "less frustrated " solutions have eight of them on the opposite sublattice and 4 of them on the same sublattice, as in the A and C modes

- the final F mode is not antiferromagnetic



1.2 Crystal and magnetic structures

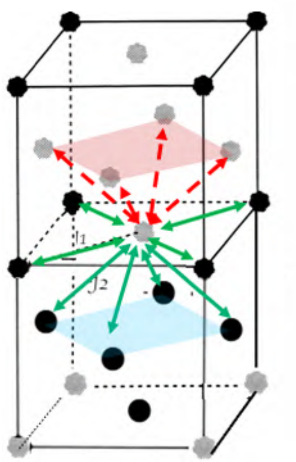
- antiferromagn. order for given crystal structure can often be realized in many different ways: → **Frustration**

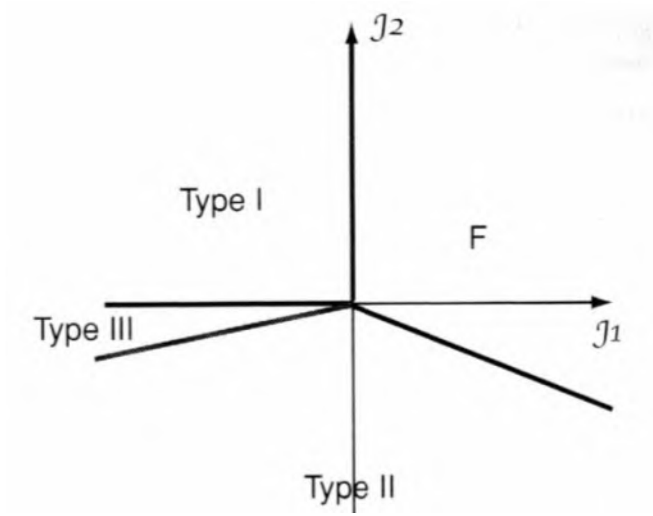
Face centered cubic lattice (important one, because many AF oxides have fcc crystal structure)

- 3 possible magnetic modes for the fcc lattice:

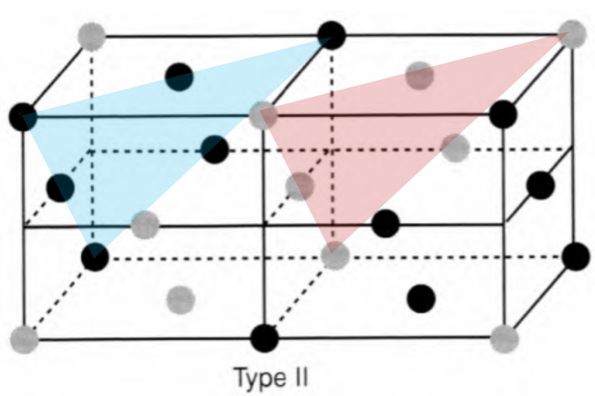
→ type 1

$MnTe_2$



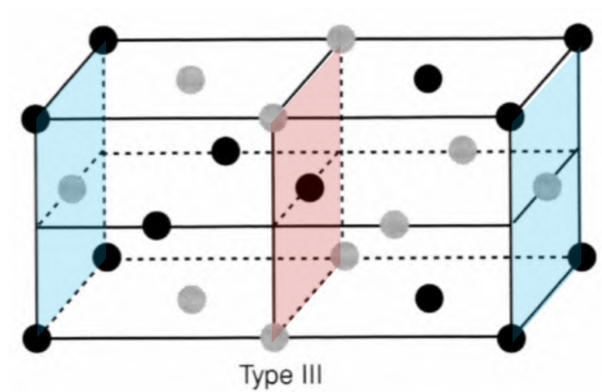


→ type 2 with alternating fm [111] planes:



MnO, FeO,
CoO and NiO

→ type 3 with alternating af [001] planes:



MnS_2

Pierre Ernest Weiss
(1865 - 1940)

Molecular field theory (most simple description of magnetic order)

- **for ferromagnets**: assume an internal *molecular field,* which is **proportional to the spontaneous magnetization** of the ferromagnet: $\boldsymbol{H}^i = n_W \boldsymbol{M} + \boldsymbol{H}$. ($\boldsymbol{H}$ ais an applied magnetic field)

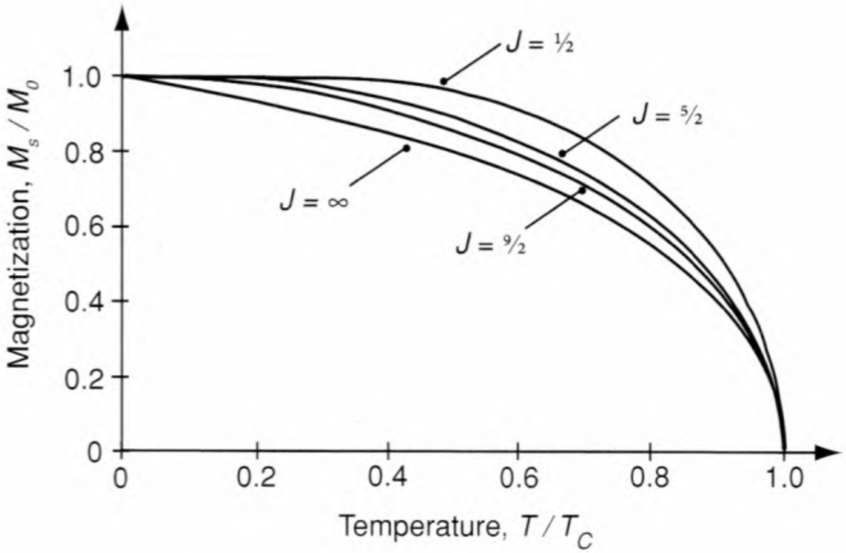
- **magnetization described by Brillouin function** with $M = M_0 \mathcal{B}_J(x), \quad M_0 = n\mathfrak{m}_0 = n g \mu_B J,$

n is the density of magnetic atoms.

$$\mathcal{B}_J(x) = \left\{ \frac{2J+1}{2J} \coth \frac{2J+1}{2J} x - \frac{1}{2J} \coth \frac{x}{2J} \right\}$$

, and $x = \mu_0 \mathfrak{m}_0 (n_W M + H)/k_B T.$

→



Molecular field theory (most simple description of magnetic order)

- **for antiferromagnets**: two oppositely oriented magnetic sublattices 'A' and 'B' with $\mathbf{M}_A = -\mathbf{M}_B$
- **antiferromagnetic exchange field** is represented by a **negative Weiss coefficient** $n_{AB} < 0$
- **intra-sublattice ferromagnetic** expressed by $n_{AA} > 0$

→ molecular (net) field acting on each sublattice:

$$\boldsymbol{H}^i_A = n_{AA}\boldsymbol{M}_A + n_{AB}\boldsymbol{M}_B + \boldsymbol{H},$$
$$\boldsymbol{H}^i_B = n_{BA}\boldsymbol{M}_A + n_{BB}\boldsymbol{M}_B + \boldsymbol{H},$$

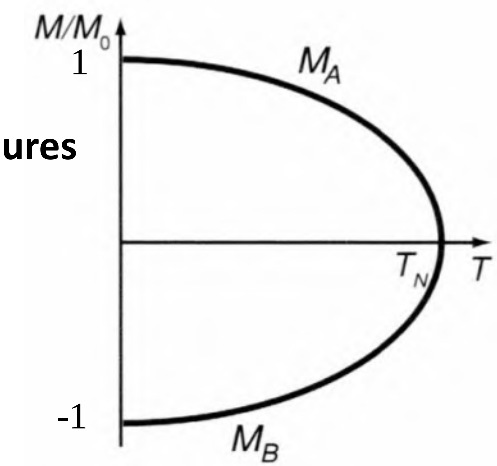
where $n_{AA} = n_{BB}$, $n_{AB} = n_{BA}$ and $\boldsymbol{H}$ is the contribution from an externally applied field.

→ no net-magnetization $\boldsymbol{M} = \boldsymbol{M}_A + \boldsymbol{M}_B = 0$ for $\boldsymbol{H} = 0$.

… however, the **sublattice magnetization at non-zero temperatures follows each s Brillouin function** $M_\alpha = M_{\alpha 0}\mathcal{B}_J(x_\alpha)$,

where $\alpha = A, B$ and $x_\alpha = \mu_0 \mathrm{m}|H^i_\alpha|/k_B T$.

$$M_{A0} = -M_{B0} = (n/2)g\mu_B J = (n/2)\mathrm{m}.$$



Sublattice magnetization of an antiferromagnet. T_N is the Néel temperature.

Molecular field theory: Néel- and paramagnetic Curie temperature

- Curie law: $M_\alpha = \chi H_\alpha^i$, where $\chi = C'/T$ with $C' = \mu_0(n/2)\mathrm{m}_{eff}^2/3k_B$, hence

$$\boldsymbol{M}_A = (C'/T)(n_{AA}\boldsymbol{M}_A + n_{AB}\boldsymbol{M}_B + \boldsymbol{H}),$$
$$\boldsymbol{M}_B = (C'/T)(n_{BA}\boldsymbol{M}_A + n_{BB}\boldsymbol{M}_B + \boldsymbol{H}).$$

- condition for the appearance of spontaneous **sub-lattice magnetization** for $\boldsymbol{H} = 0$:

$$[(C'/T)n_{AA} - 1]\boldsymbol{M}_A + (C'/T)n_{AB}\boldsymbol{M}_B = 0,$$
$$(C'/T)n_{BA}\boldsymbol{M}_A + [(C'/T)n_{BB} - 1]\boldsymbol{M}_B = 0.$$

→ determinant of the coefficients of M_A and M_B must be zero,

hence $[(C'/T)n_{AA} - 1]^2 - [(C'/T)n_{AB}]^2 = 0,$ so that the Néel temperature is

$$T_N = C'(n_{AA} - n_{AB}).$$

→ antiferromagnetic exchange coupling ($n_{AB} < 0$)

but also intra-sublattice ferromagnetic exchange coupling ($n_{AA} > 0$) enhance T_N.

Molecular field theory: **Néel- and paramagnetic Curie temperature**

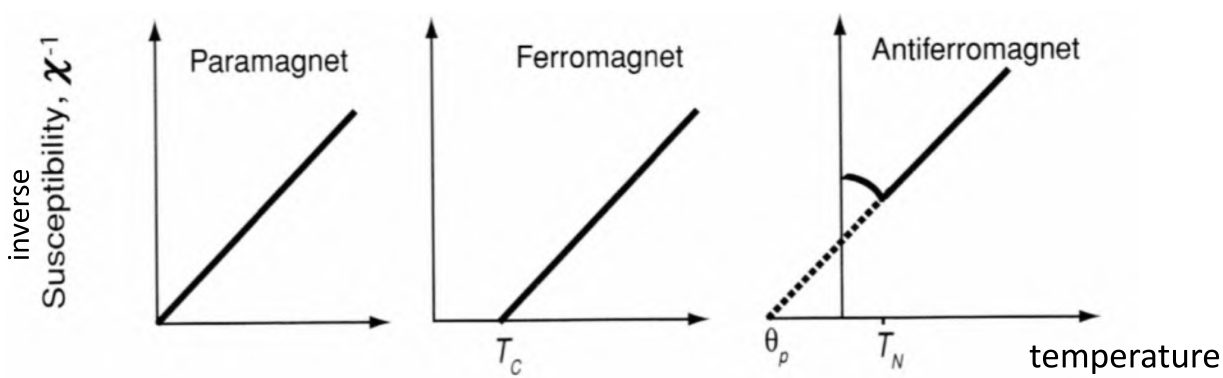
- **above** T_N → **total nonzero magnetization** $M_A + M_B = \chi H.$

$$(C'/T)(n_{AA}\boldsymbol{M}_A + n_{AB}\boldsymbol{M}_B + \boldsymbol{H} + n_{BA}\boldsymbol{M}_A + n_{BB}\boldsymbol{M}_B + \boldsymbol{H}) = \chi H.$$

→ susceptibility : $\chi = C/(T - \theta_p),$

where $C = 2C'$ and the paramagnetic Curie temperature is given by

$$\theta_p = C'(n_{AA} + n_{AB}).$$



- inverse susceptibility vs temperature gives the paramagnetic Curie temperature (typically negative) θ_p

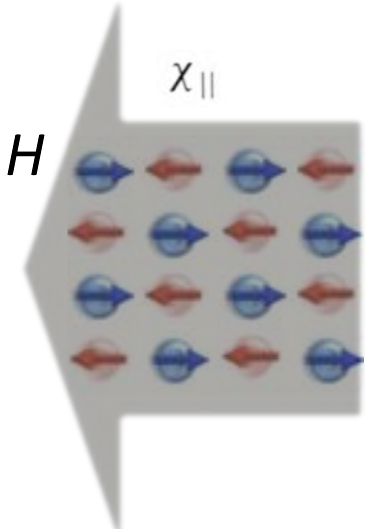
- minima (or small cusp) of inverse susceptibility vs temperature marks the Néel temperature T_N

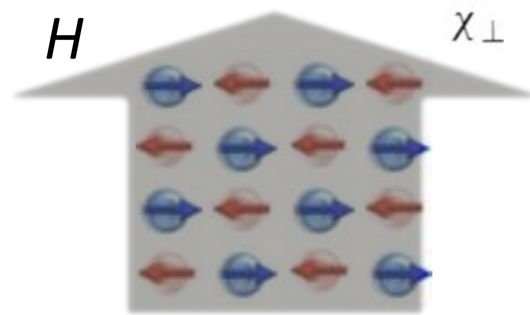
- from difference and sum of T_N and θ_p one can evaluate both n_{AB} and n_{AA}.

Molecular field theory: Antiferromagnetic susceptibility

How does a simple Antiferromagnet react to an external magnetic field?

- simple antiferromagnet with two sublattices and uniaxial magnetic anisotropy (easy magnetic axis)





→ above T_N (paramagnetic susceptibility): $\chi_{\|} = \chi_{\perp} = [M_A(H) + M_B(H)]/H$

→ at T_N (max. susceptibility): $M_\alpha = 0$ and $\mathcal{B}'_J(0) = (J+1)/3J$ → $\chi_{\|(\perp)} = -1/n_{AB}$

→ below T_N: $\chi_{\|} \longrightarrow 0,$ since no field induced canting (no Zeeman energy gain)

$\chi_{\perp} = -1/n_{AB}$, since in equilibrium, the torque on each $\boldsymbol{M}_i$ is compensated by the exchange field torque $M_A H = M_A n_{AB} M_B \sin 2\delta$ and the resulting magnetization do to canting is $M_{\perp} = 2M_\alpha \sin\delta$.

Molecular field theory: Antiferromagnetic susceptibility

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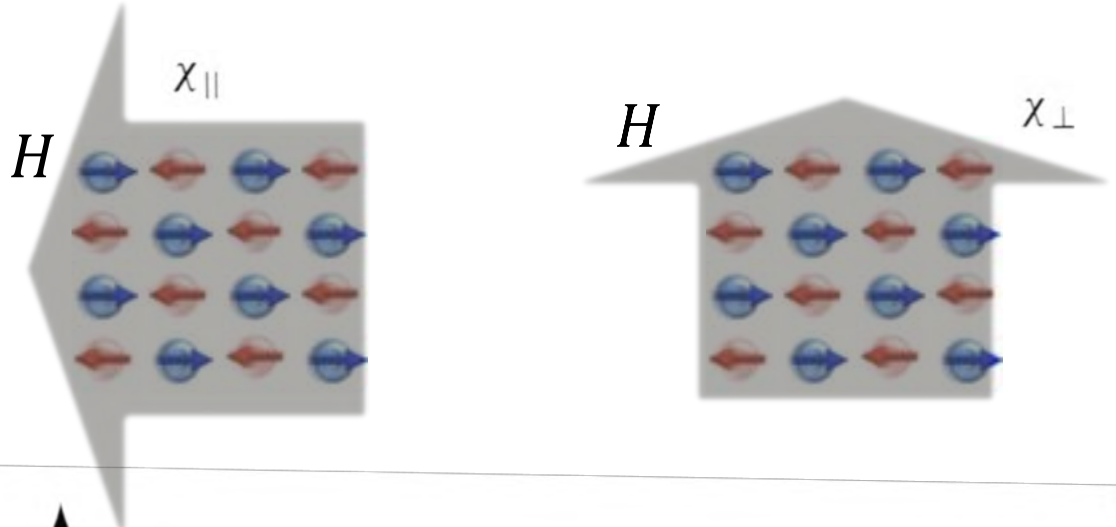
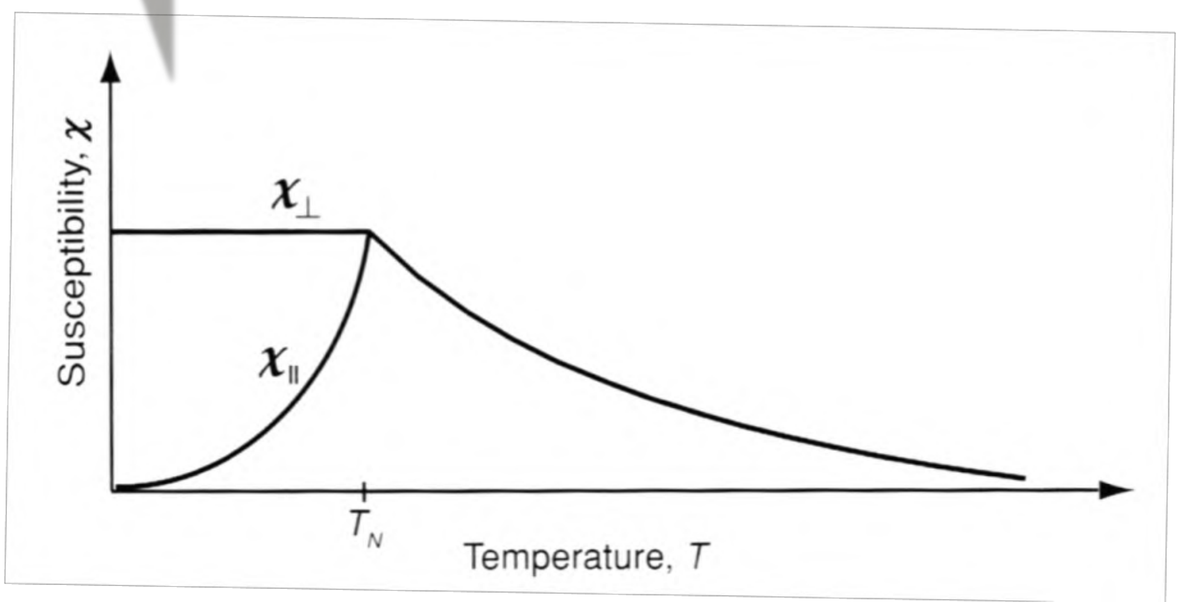


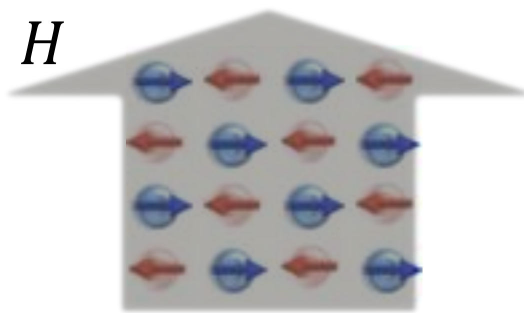


Molecular field theory: Antiferromagnetic susceptibility

How does a simple Antiferromagnet react to an external magnetic field?

- since $\chi_\perp > \chi_{||}$ for $T < T_N$, **"spin flop" transition at applied field H_{sf}** when Zeeman energy overcomes the effective anisotropy barrier $-2M_\alpha H_a - \frac{1}{2}\chi_{||}H_{sf}^2 = -\frac{1}{2}\chi_\perp H_{sf}^2$

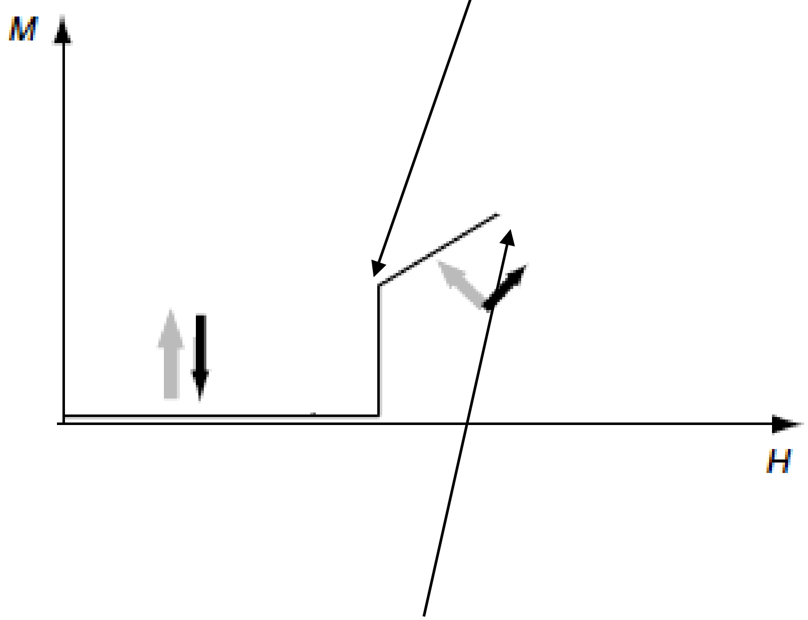
$$\rightarrow \quad H_{sf} = [4M_\alpha H_a/(\chi_\perp - \chi_{||})]^{\frac{1}{2}}.$$



$\rightarrow$ $H_{sf} = 2(H_a H_\alpha^i)^{\frac{1}{2}}$ for $T << T_N$

Molecular field theory: spin-flop and spin flip

- for $H \rightarrow$ $H_{sf} = 2(H_a H_\alpha^i)^{\frac{1}{2}}$: Spin Flop transition



- for $H \rightarrow H_\alpha^i$: Spin Flip transition

outline of this course:

Antiferromagnetism and antiferromagnetic spintronics

1) **antiferromagnets - basics** (exchange interaction, frustration, critical temperatures and fields: flip and flop)
2) **conventional application of antiferromagnetism** (exchange bias: keeping the reference layer fixed …)
3) **AF spintronics** (staggered effective spin-orbit-fields, AF domain wall motion, nonlinear responses, …)

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Antiferromagnetic order with spin-polarized bands

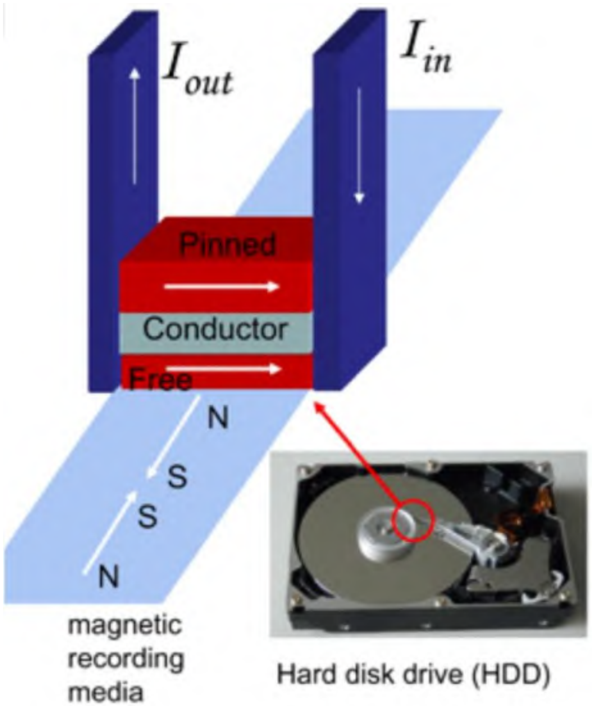
4) **noncollinear AFM** (Kagome AF …)

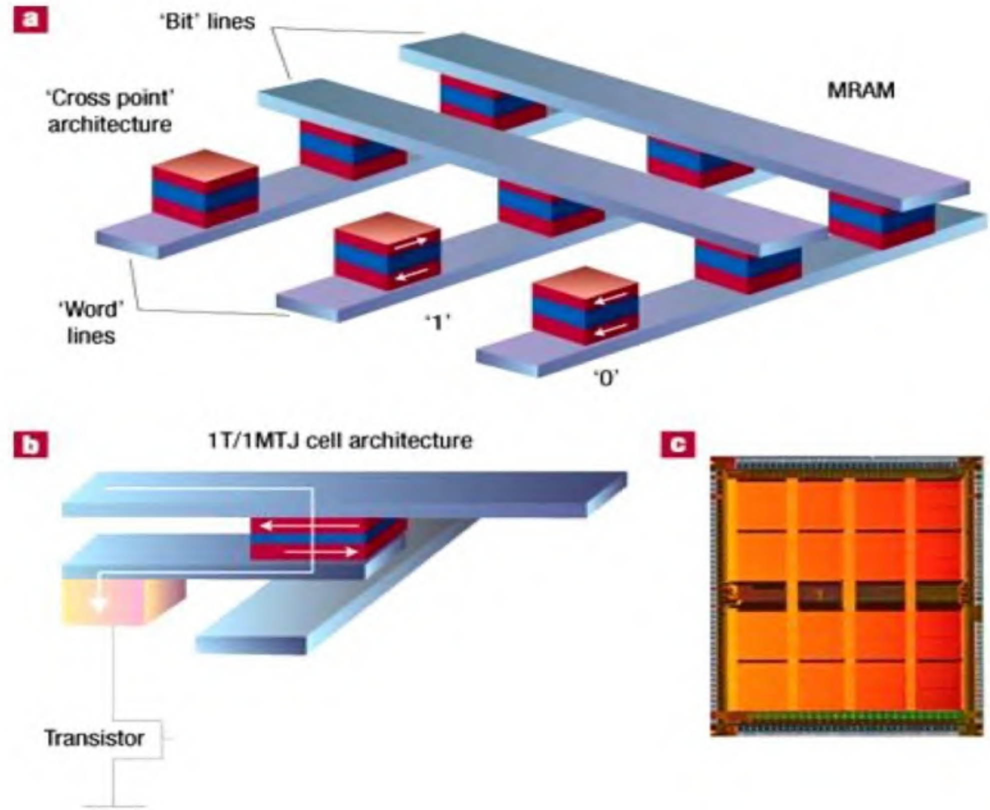
5) **altermagnets** (crystal and magnetic symmetries → band structure…)

Conclusions

2. Exchange bias effect

application for nonvolatile magnetic storage (HDD, MRAM): **GMR and TMR** - effects





Seagate

Western Digital

TOSHIBA

EVERSPIN TECHNOLOGIES

SAMSUNG

TDK

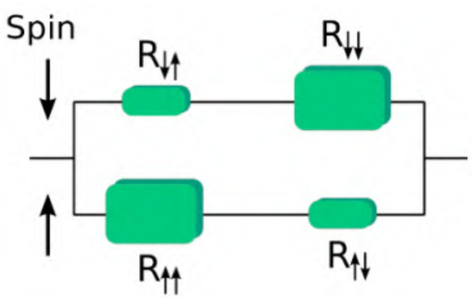
GRANDIS

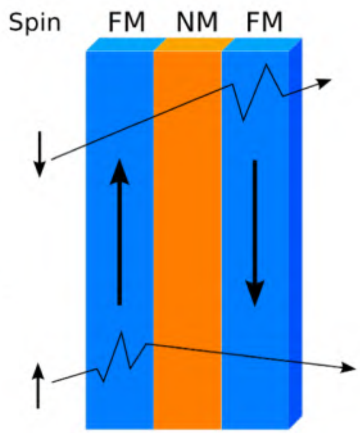
infineon

2. Exchange bias effect

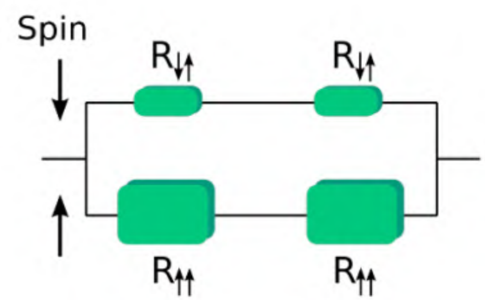
application for nonvolatile magnetic storage (HDD, MRAM): **GMR** and TMR - effects

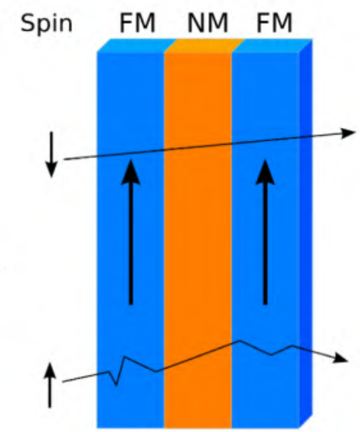
- Simple 2-channel resistor model





high total resistance





low total resistance

$$\text{GMR ratio} = \frac{R_{AP} - R_P}{R_{AP}} = \frac{\left(R_{\uparrow\downarrow} - R_{\uparrow\uparrow}\right)^2}{\left(R_{\uparrow\downarrow} + R_{\uparrow\uparrow}\right)^2}$$

Details: Valet-Fert model (CPP configuration)

T. Valet and A. Fert, Physical Review B **48**, 7099 (1993)

2. Exchange bias effect

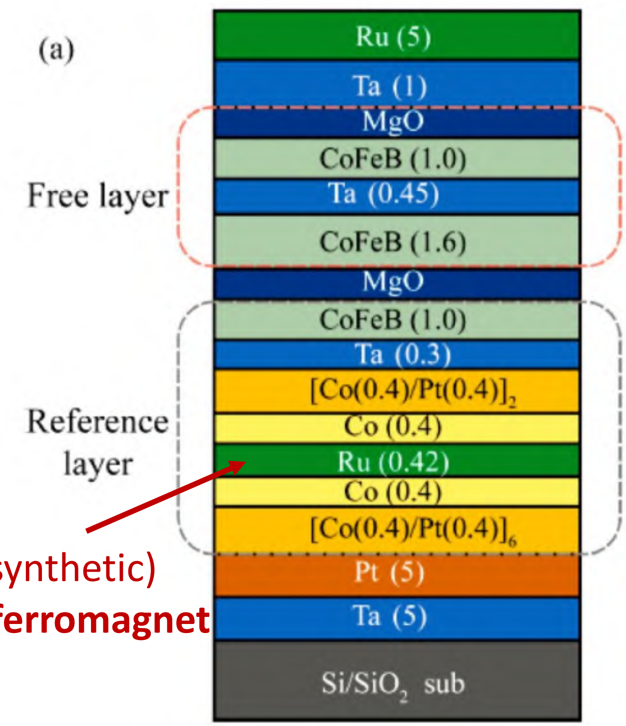
application for nonvolatile magnetic storage (HDD, MRAM): GMR and **TMR** - effects

Breakthrough 2004: Large TMR > 100% at RT due to highly spin-polarized tunneling transport in CoFeB/MgO/CoFeB MTJ

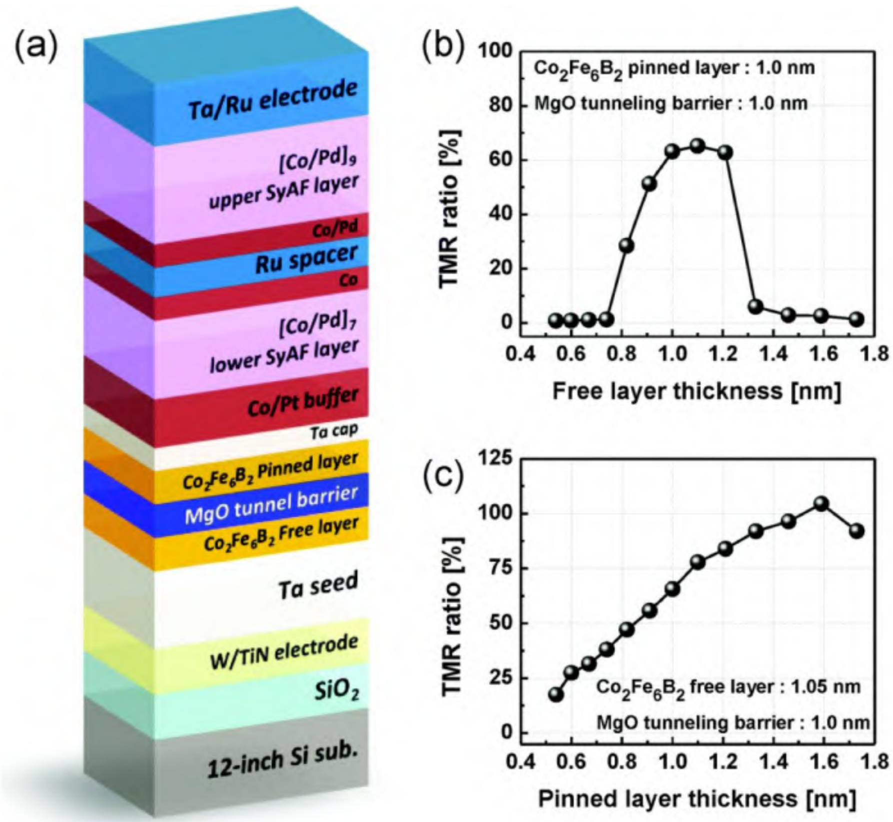
(epitaxial growth of MgO barrier: spin-polarizing transport through tunneling barrier at)

Magnetic random access memory (MRAM)

– Contemporary structures



(synthetic) **antiferromagnet**



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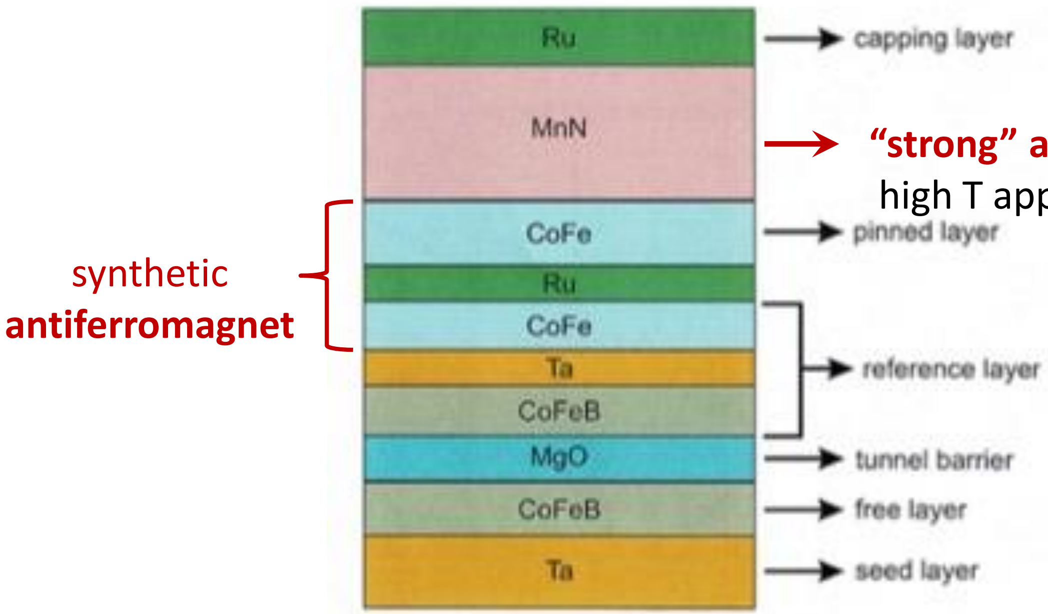
Breakthrough 2004: Large TMR > 100% at RT due to highly spin-polarized tunneling transport in CoFeB/MgO/CoFeB MTJ

(epitaxial growth of MgO barrier: spin-polarizing transport through tunneling barrier at)

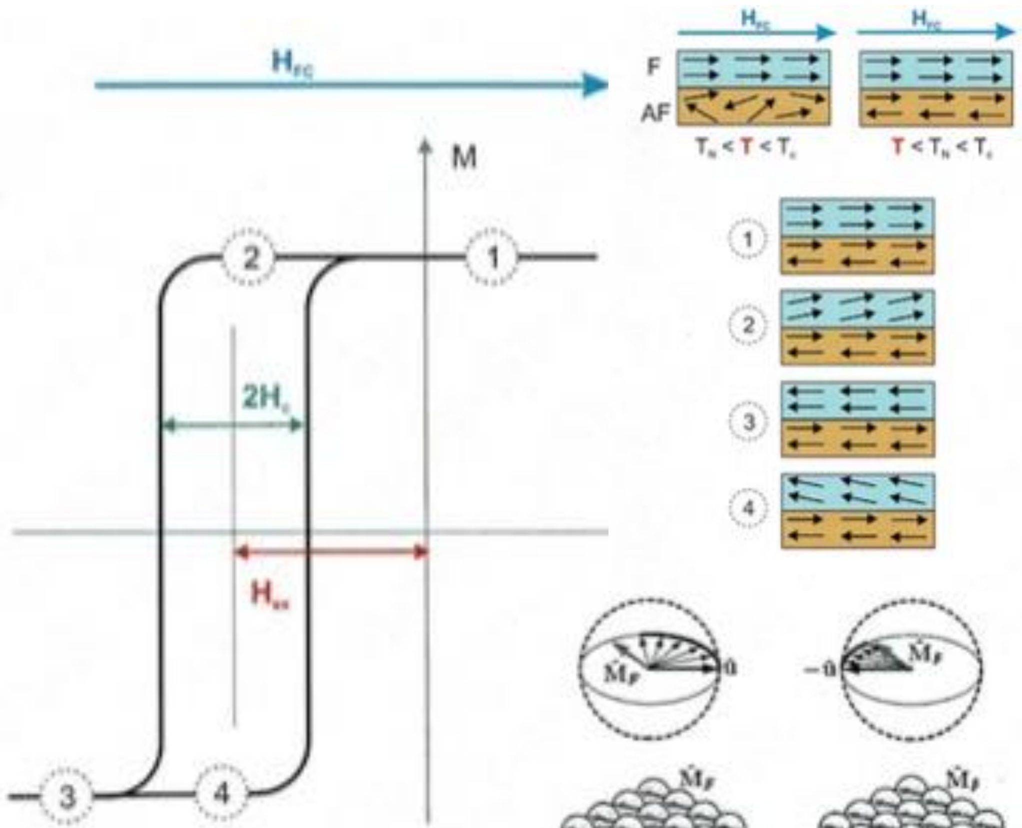
exchanged biased from top TMR structure



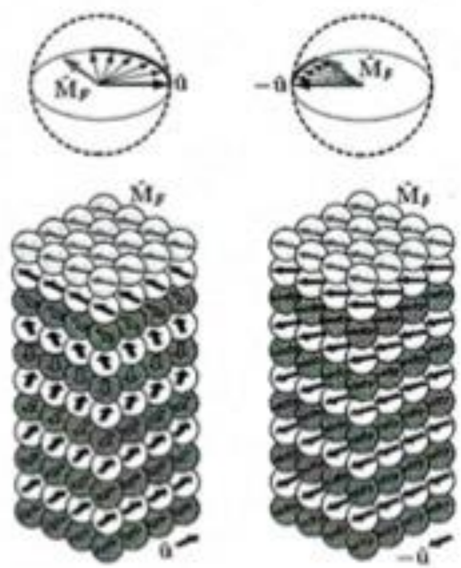
"strong" antiferromagnet (IrMn, PtMn) for high T applications (e.g. automotive appl.)

2. Exchange bias effect

after field cooling above Néel temperture → shift of ferromagnetic hysteresis of the FM reference layer by exchange bias field $\boldsymbol{H_{ex}}$ opposite to the direction of the applied cooling field $\boldsymbol{H_{FC}}$



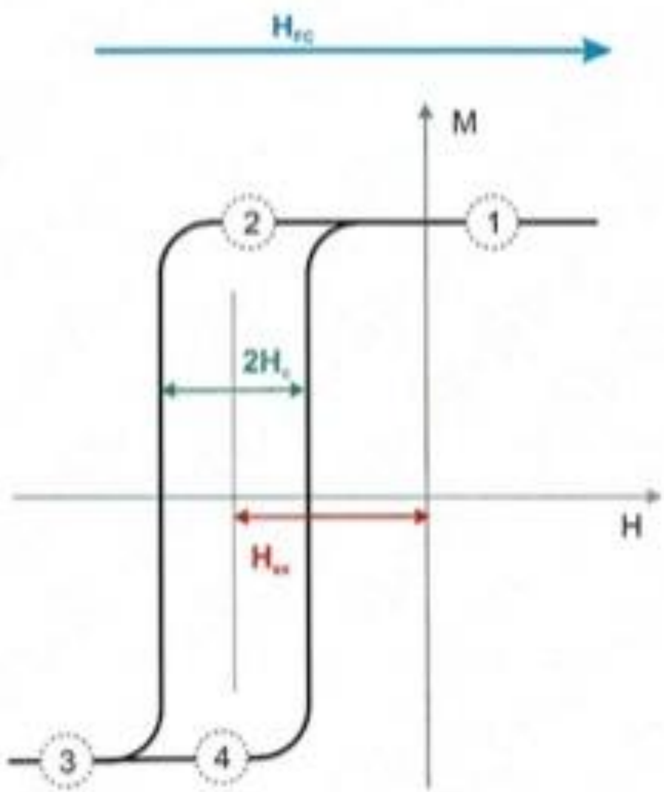
- **Meiklejohn-Bean model**:
  - ferromagn. exchange coupling between a.f.- and and f.m.- layer
  - $|H_C|$ depends on the a.f. magn. anisotropy and the strength of the interfacial exchange interaction J_{ex}



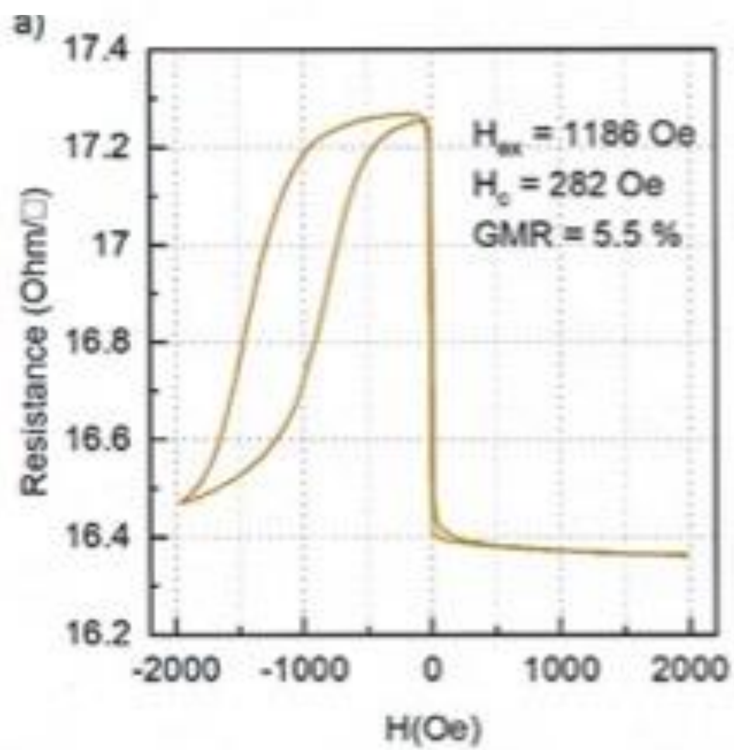
- **AF domain wall model**:
  - coupling to a planar domain wall in the antiferromagnet
  - $|H_C|$ depends on the a.f. domain wall energy $\sim\sqrt{A_{AF}K_{AF}}$ and on J_{ex}
- ...

Ferromagnetic hysteresis

of the exchange biased reference layer



Magnetoresistance
of an exchange biased GMR stack



Magnetic field angle sensor from exchange biased GMR sensor Wheatstone bridges

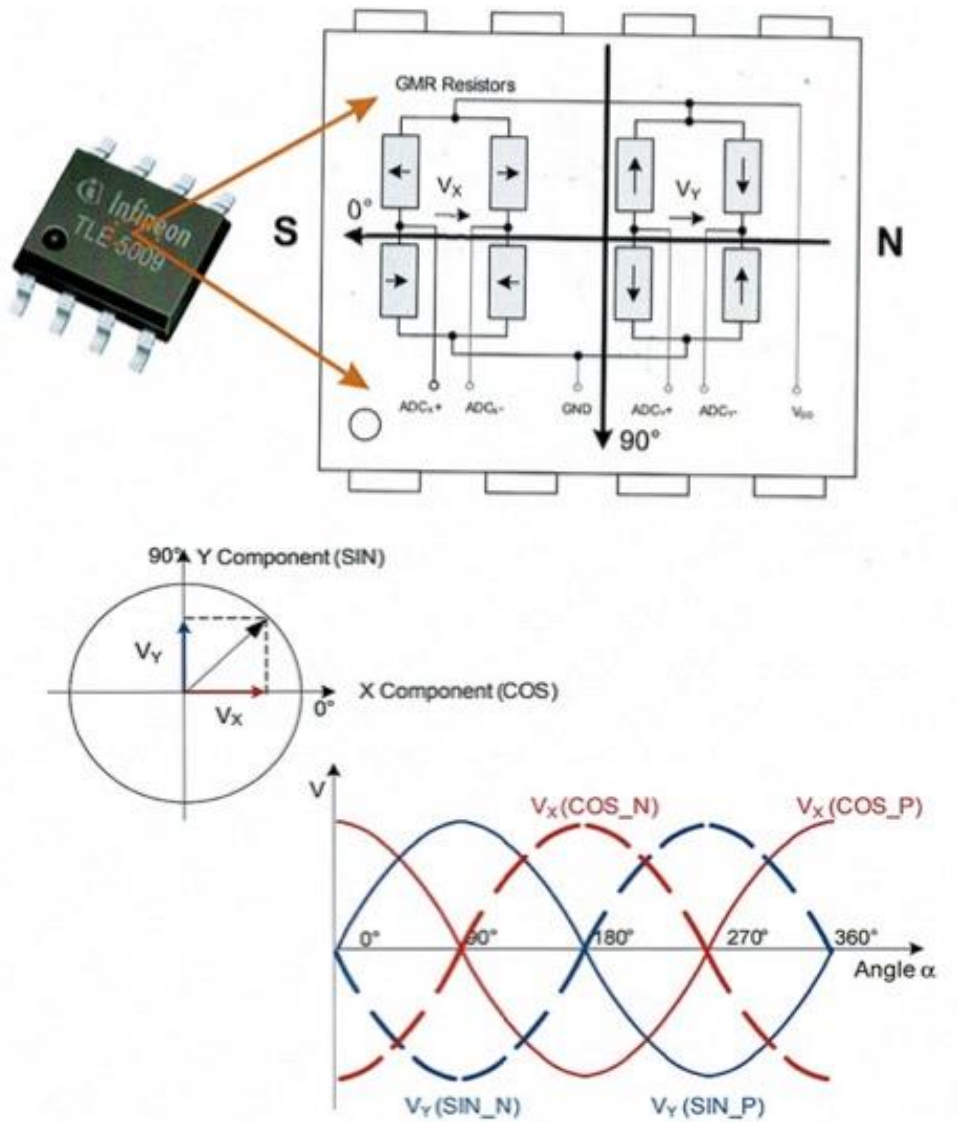


Figure 4.34 | Ideal output of the GMR sensor bridges which enables precise measurement of the magnetic field direction from 0°-360°, figures from [59].

outline of this course:

Antiferromagnetism and antiferromagnetic spintronics

1) **antiferromagnets - basics** (exchange interaction, frustration, critical temperatures and fields: flip and flop)

2) **conventional application of antiferromagnetism** (exchange bias: keeping the reference layer fixed …)

outline of this course:

Antiferromagnetism and antiferromagnetic spintronics

1) **antiferromagnets - basics** (exchange interaction, frustration, critical temperatures and fields: flip and flop)

2) **conventional application of antiferromagnetism** (exchange bias: keeping the reference layer fixed …)

3) **AF spintronics** (staggered effective spin-orbit-fields, AF domain wall motion, nonlinear responses, …)

Antiferromagnetic order with spin-polarized bands

4) **noncollinear AFM** (Kagome AF …)

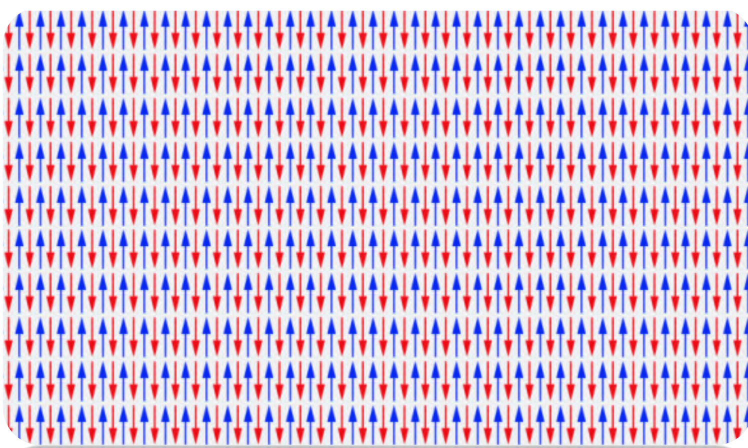
5) **altermagnets** (crystal and magnetic symmetries → band structure…)

Outlook and Conclusions

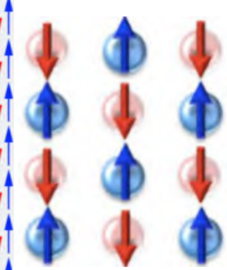
6) **Neuromorphic computing with AF**

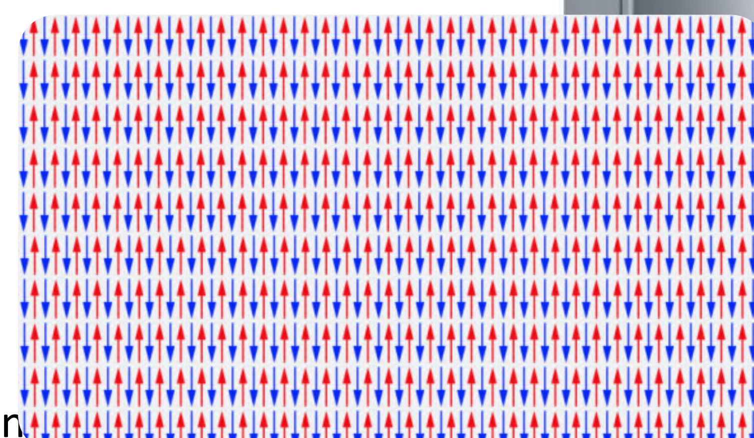
Antiferromagnets

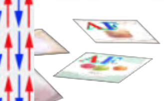
→ **magn. ordered** but **no Net-Magnetisation**



…etic fields,





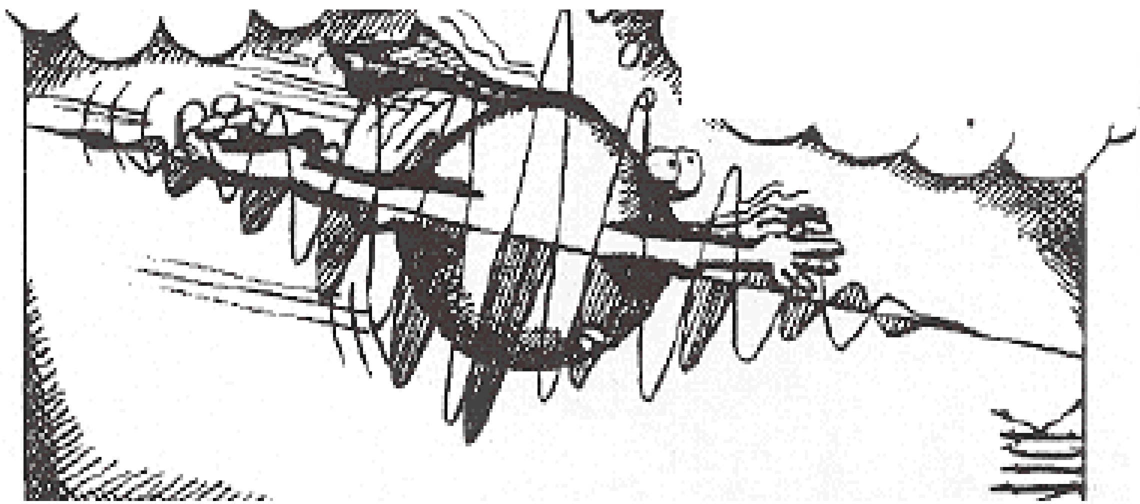


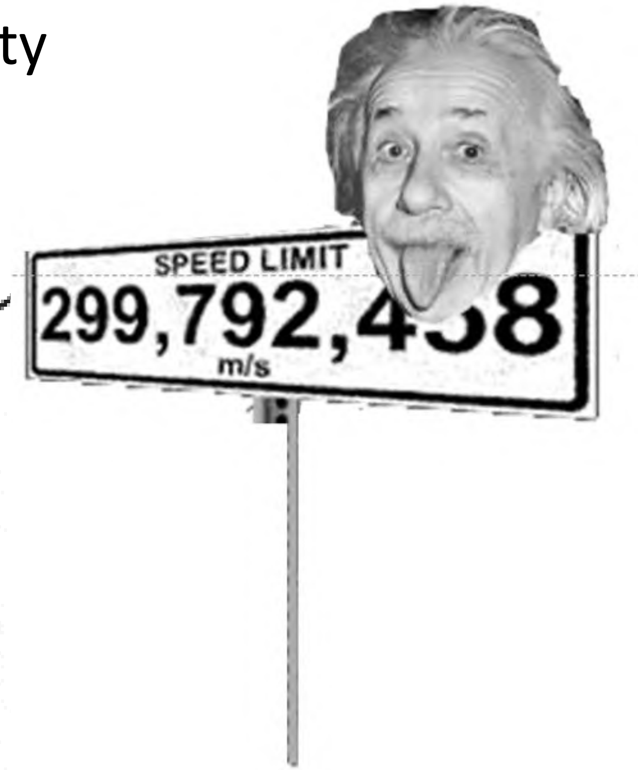
→ How can one generate such alternating fields?

→ How can one distinguish reversed antiferromagn…

→ Generation of **locally alternating magnetic fields** $H_{Néel}$

Special Theory of Relativity

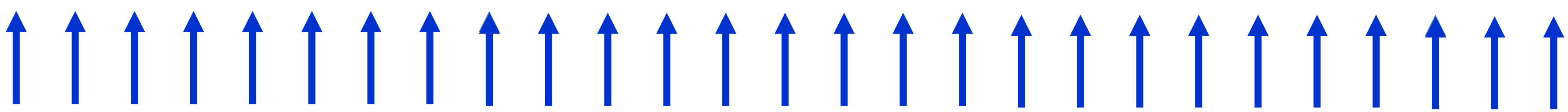




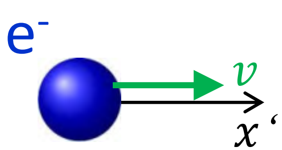
3.1 staggered effective spin-orbit-fields

→ Generation of **locally alternating magnetic fields $H_{Néel}$**

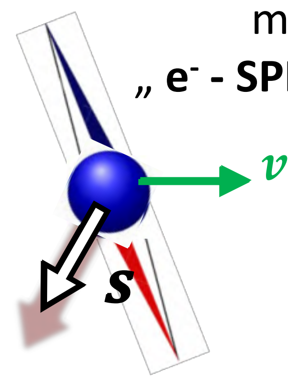
eletric field E_z (in the laboratory)



Electric current (many electrons) becomes „ **SPIN-polarised** “



magnetic „ **e- - SPIN** “ moment



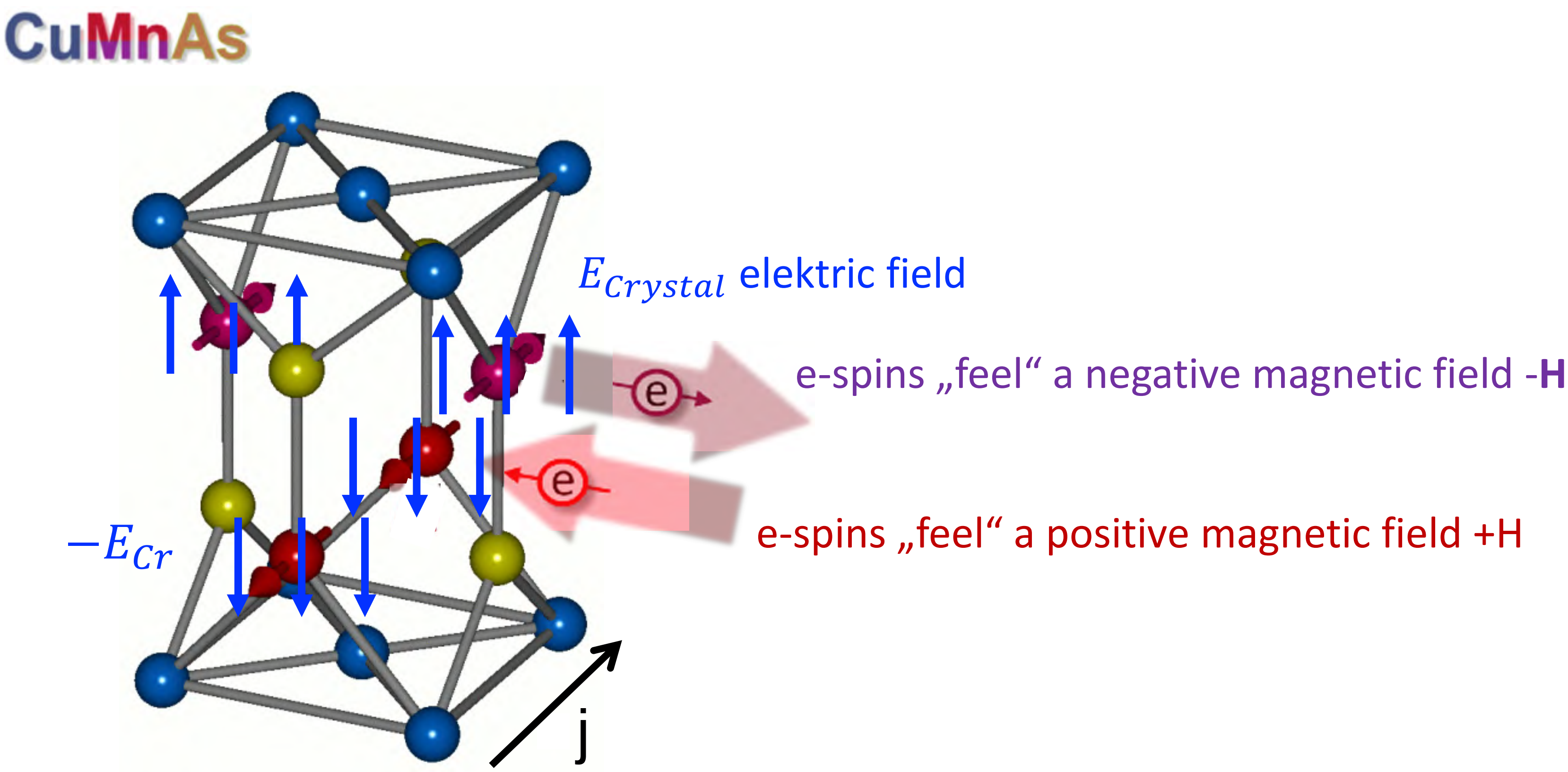
Magnetic field: $H_{y'} = \gamma / c^2 \, v \, E_z$

(at the moving electron) $\left(\gamma = 1/\sqrt{1 - v^2/c^2}\right)$

3.1 staggered effective spin-orbit-fields

can be generated in antiferromagnets (AF) with lokally broken inversion symmetry

J. Železný, et al., Phys. Rev. Lett. 113, 157201 (2014).



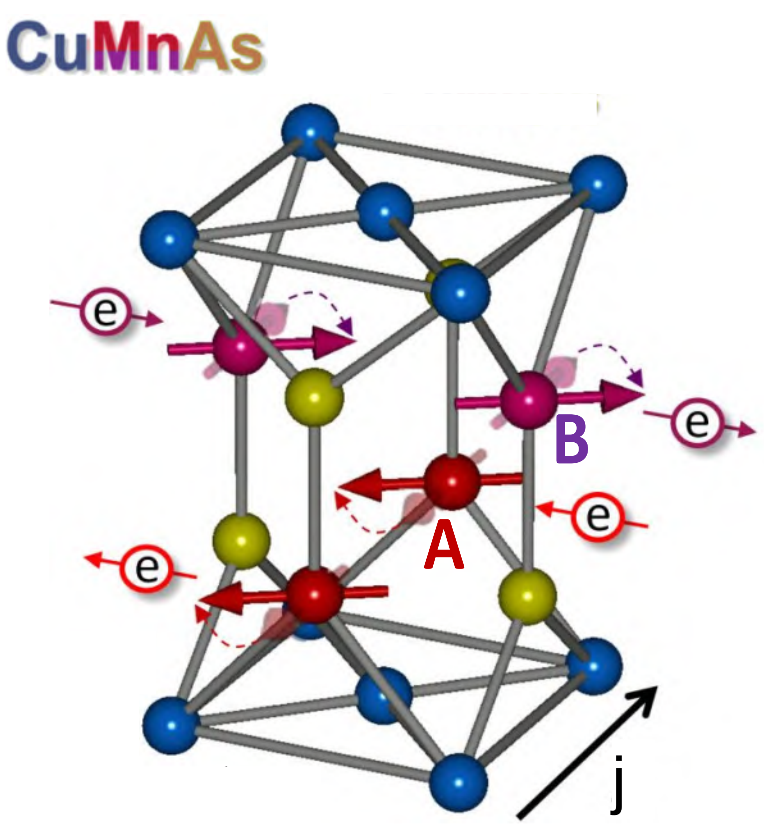
electron current j

(through the entire crystal)

3.1 staggered effective spin-orbit-fields

can be generated in antiferromagnets (AF) with lokally broken inversion symmetry

J. Železný, et al., Phys. Rev. Lett. 113, 157201 (2014).



Interaction

between

spinpolarized electrons

and

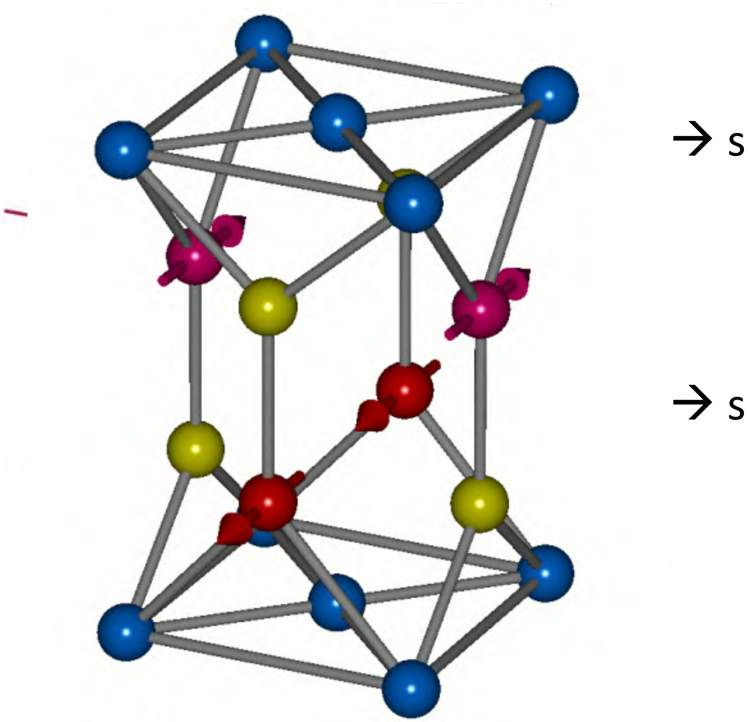
magnetic Mn-Atomen in the crystal

3.1 staggered effective spin-orbit-fields

can be generated in antiferromagnets (AF) with lokally broken inversion symmetry

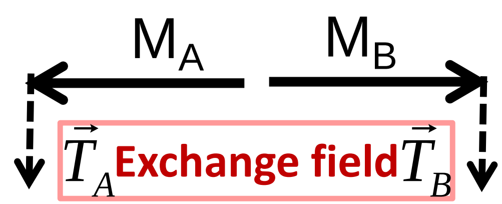
J. Železný, et al., Phys. Rev. Lett. 113, 157201 (2014).

CuMnAs



→ spatially alternating effect spin-orbit field "Néel-Feld"

→ spin-orbit torques on **M_A** and **M_B** are equal

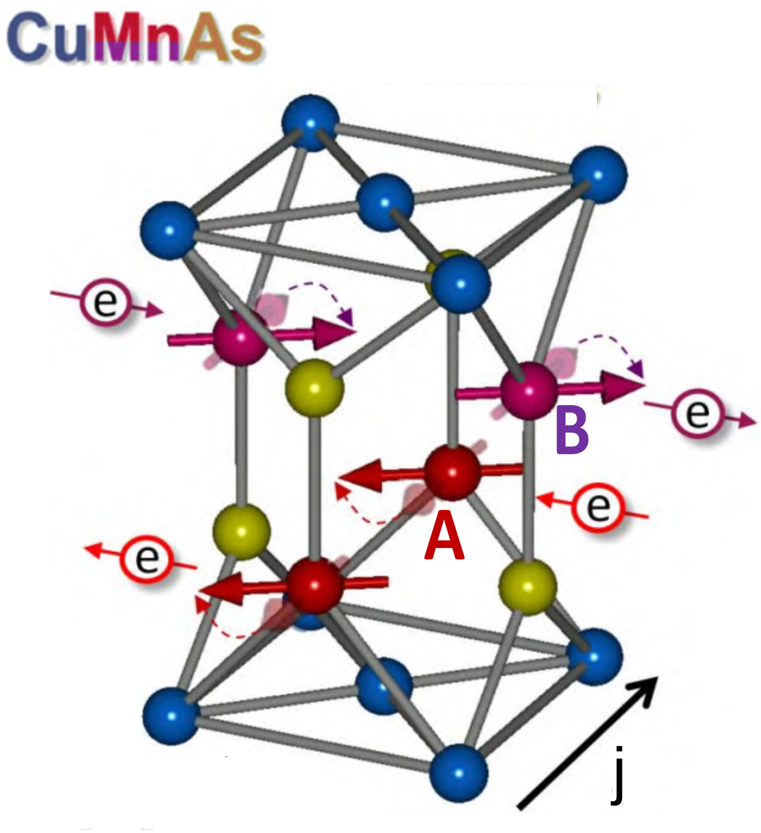


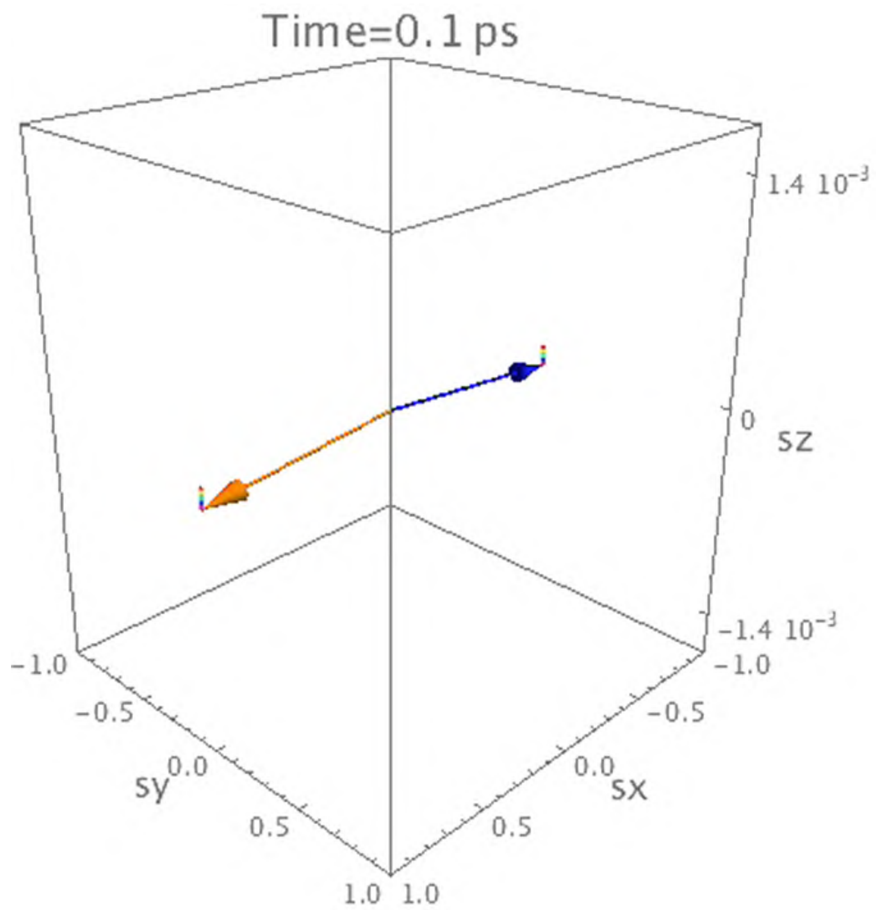
→extremely fast precession

3.1 a) **orthogonal switching** with staggered effective spin-orbit-fields

can be generated in antiferromagnets (AF) with lokally broken inversion symmetry

J. Železný, et al., Phys. Rev. Lett. 113, 157201 (2014).





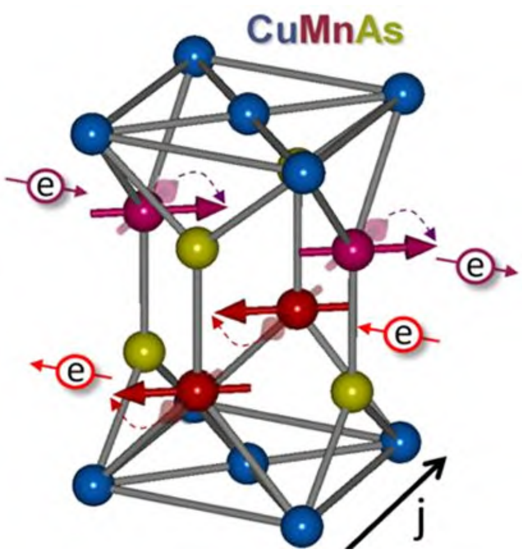
3.1 b) **orthogonal switching** with staggered effective spin-orbit-fields

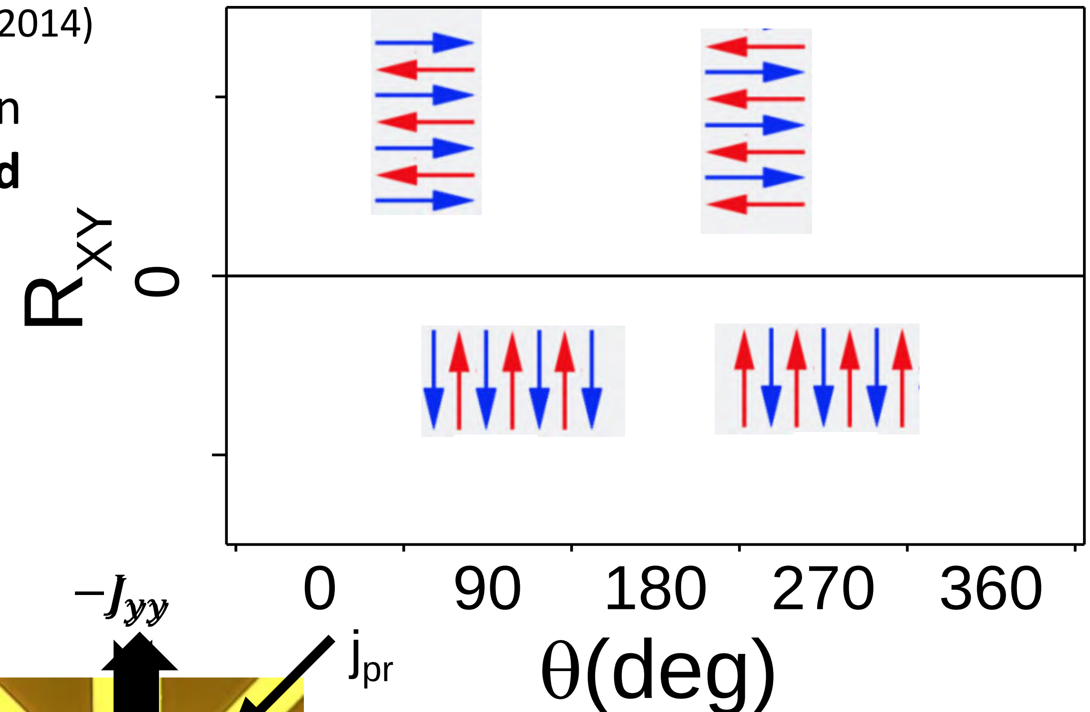
Electrical Writing
by Spin-Orbit Torque

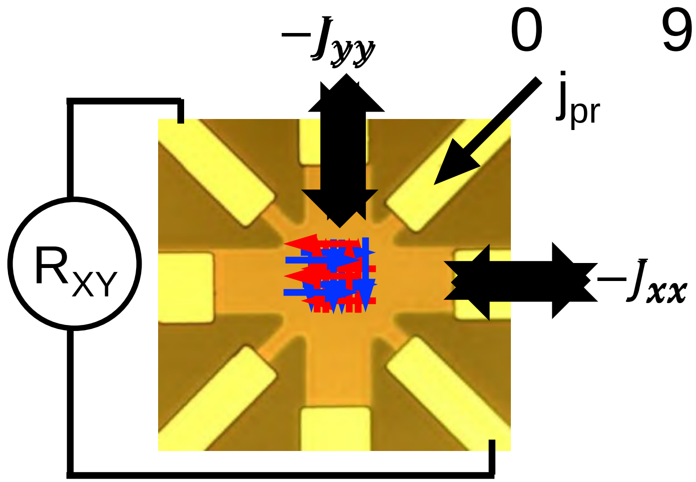
Reading
by Anisotropic Magnetoresistance

J. Železný, et al., PRL 113, 157201 (2014)

in AFs with locally broken inversion symmetry → **"staggered" SO-field**



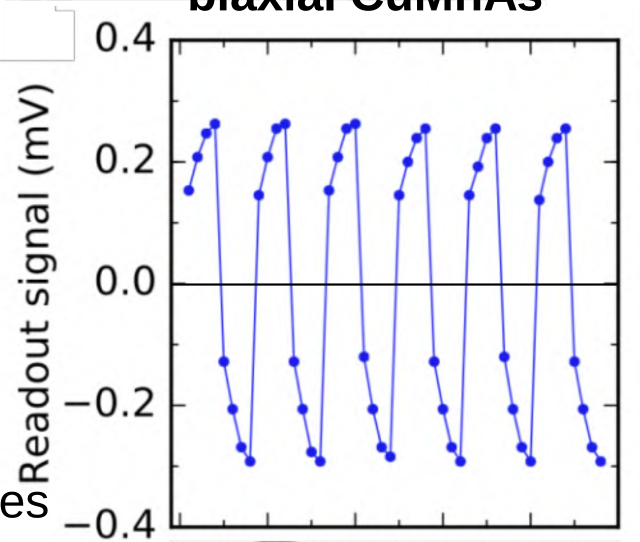




orthogonal states can be distinguished by linear AMR response

3.1 a) **orthogonal switching** with staggered effective spin-orbit-fields

→ **Electrical pulse experiment in biaxial CuMnAs**



Small

'ti-magnetic domain states

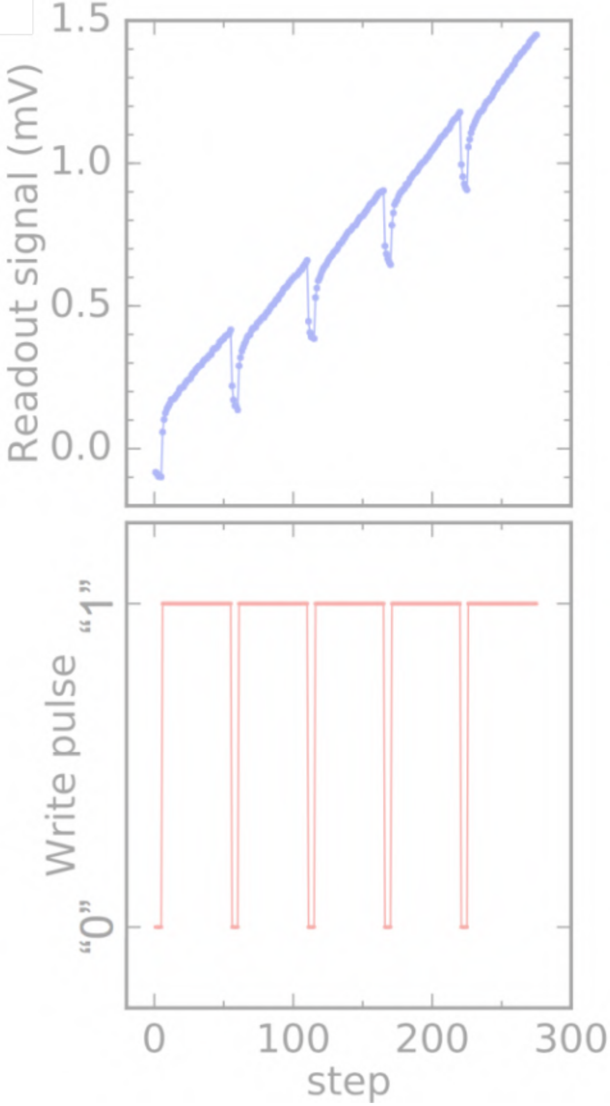
→ PEEM - XMLD

Synchrotron Light sources

EXPERIMENT: K. Olejnik, et al., Nat. Comm. 8, 15434 (2017)

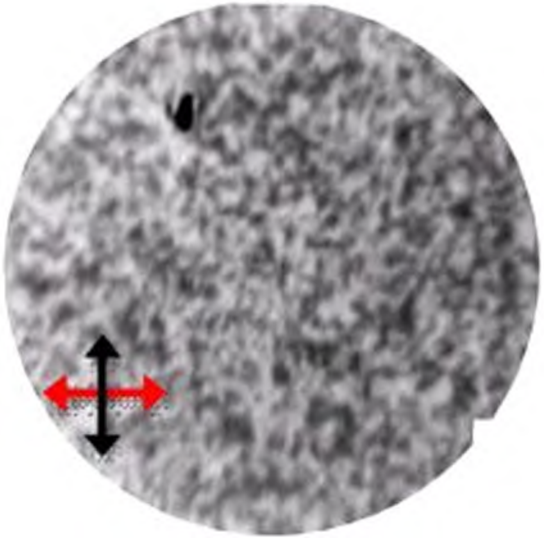
3.1 a) **orthogonal switching** with staggered effective spin-orbit-fields

→ **Short electrical pulses**
(down to τ_P ~250ps)

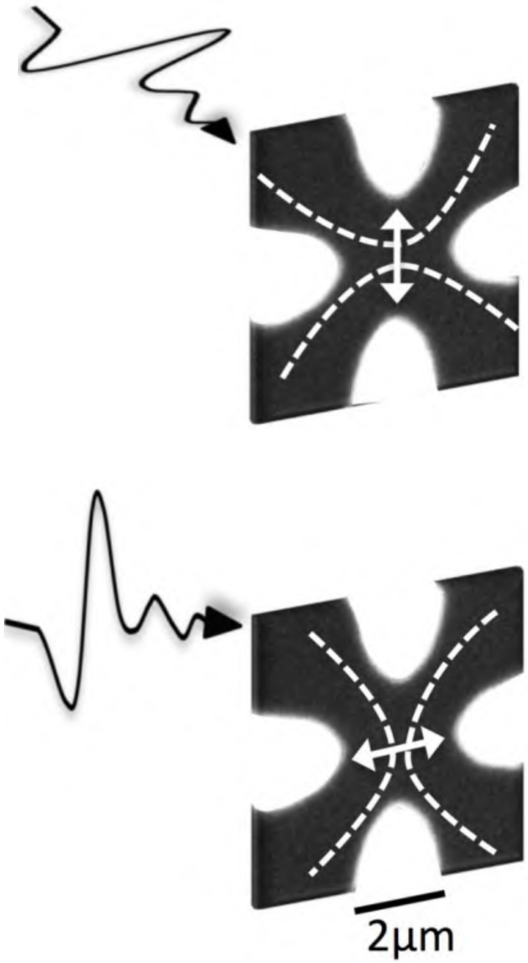


(K. Olejnik, et al., Nat. Comm. 2017)

biaxial CuMnAs

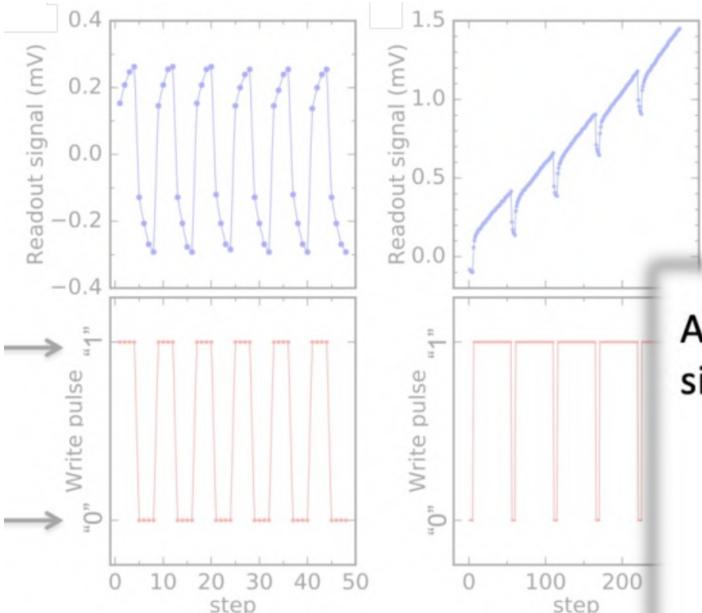


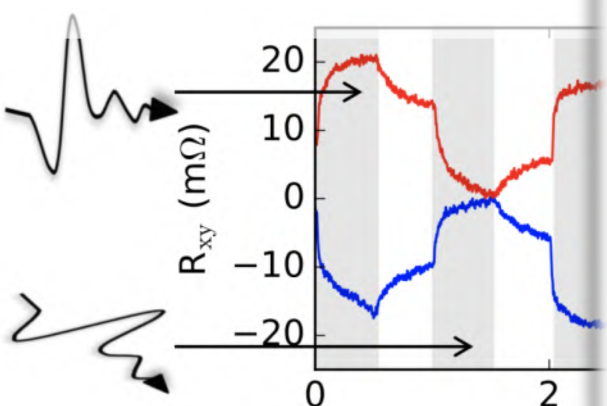
→ **Polarized THz Laser Pulses**
(τ_P ~1ps)



(K. Olejnik, et al., Sci. Adv. 2018;4:eaar356)

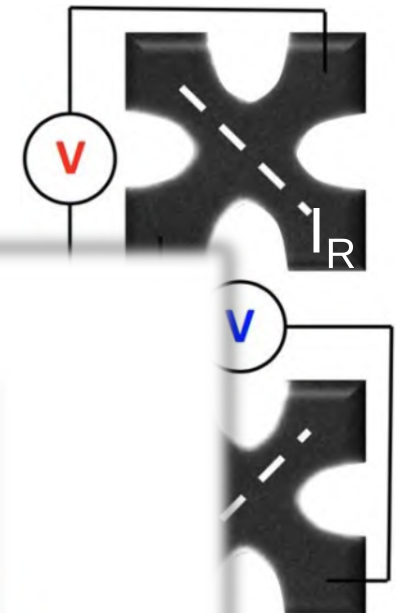
→ **Electrical pulses**
(down to τ_P ~250ps)

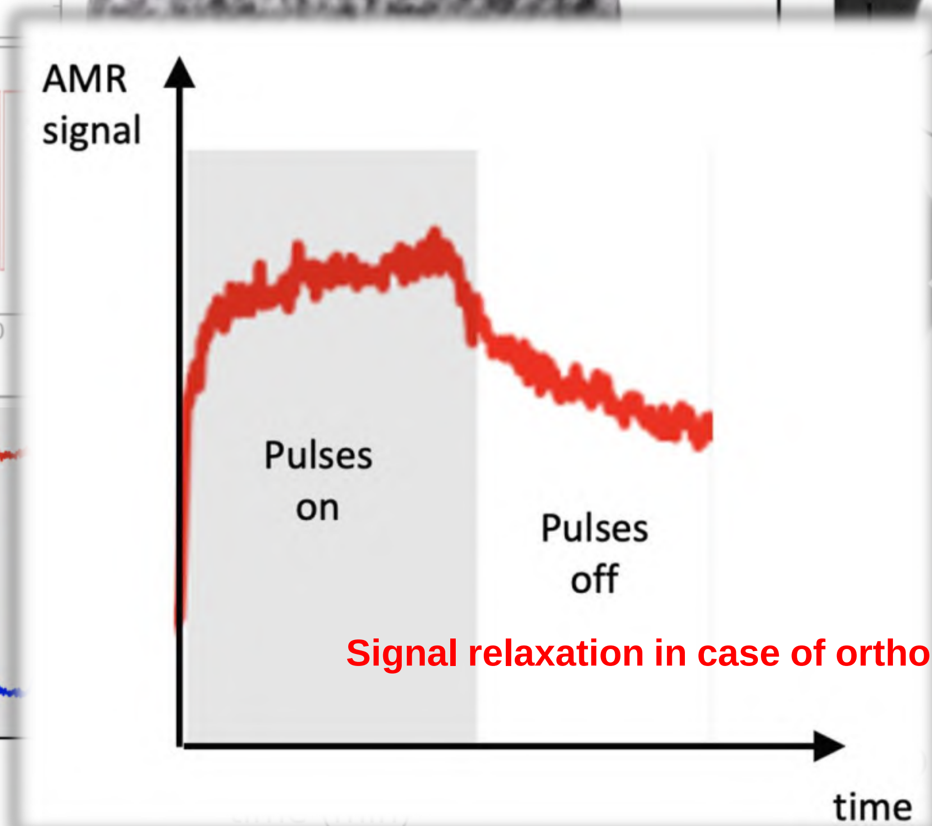




biaxial CuMnAs

→ **Polarized THz Laser Pulses**
(τ_P ~1ps)





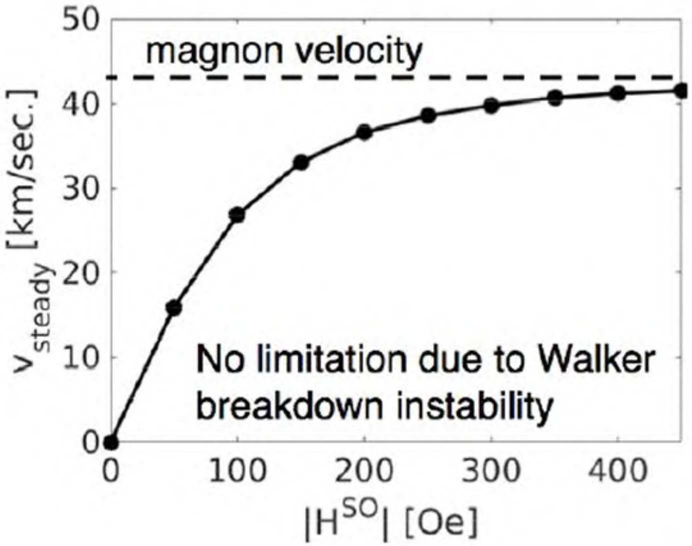
Signal relaxation in case of orthogonal switching

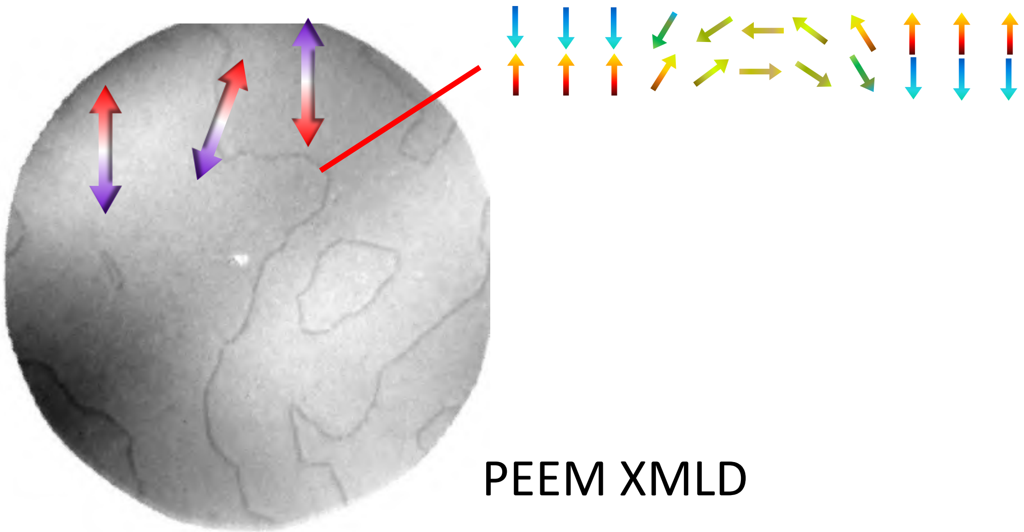
(K. Olejnik, et al., Sci. Adv. 2018;4:eaar3566)

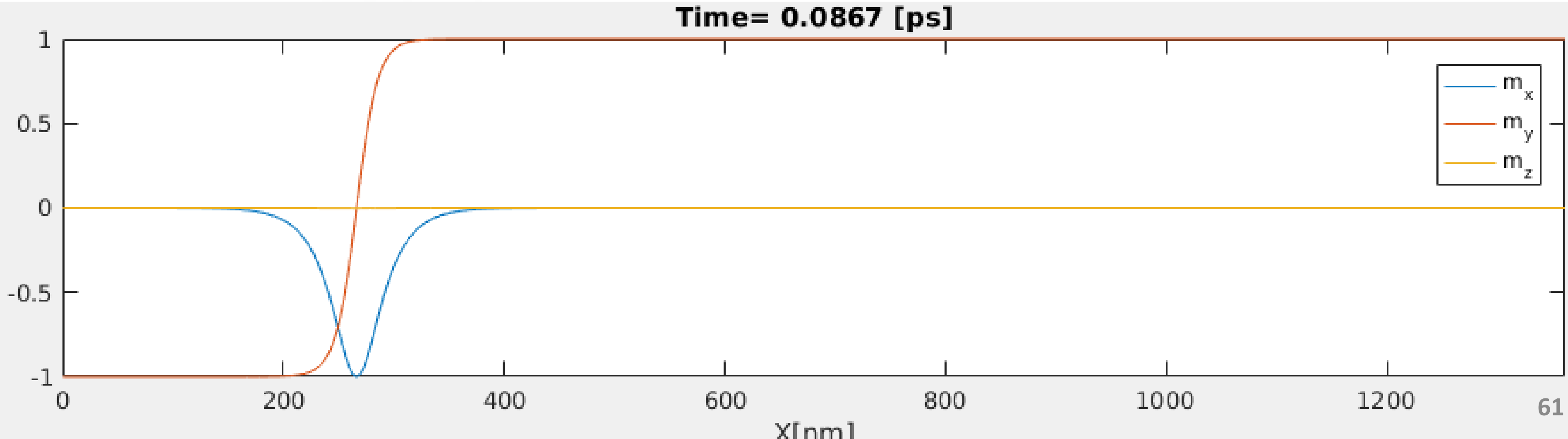
3.1 b) **Néel vector reversal** with staggered effective spin-orbit-fields

→ Current induced antiferromagnetic domain wall motion

→ extremely fast Domain Wall motion (Gomonay, et al., PRL 2016)







→ Current induced antiferromagnetic domain wall motion

COMMUNICATIONS PHYSICS

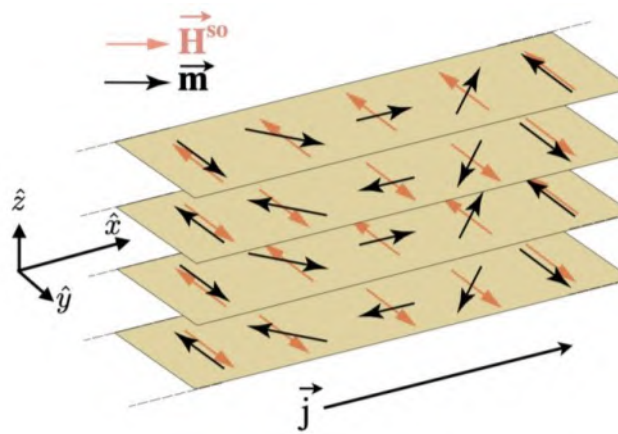
ARTICLE

https://doi.org/10.1038/s42005-020-00456-5 OPEN

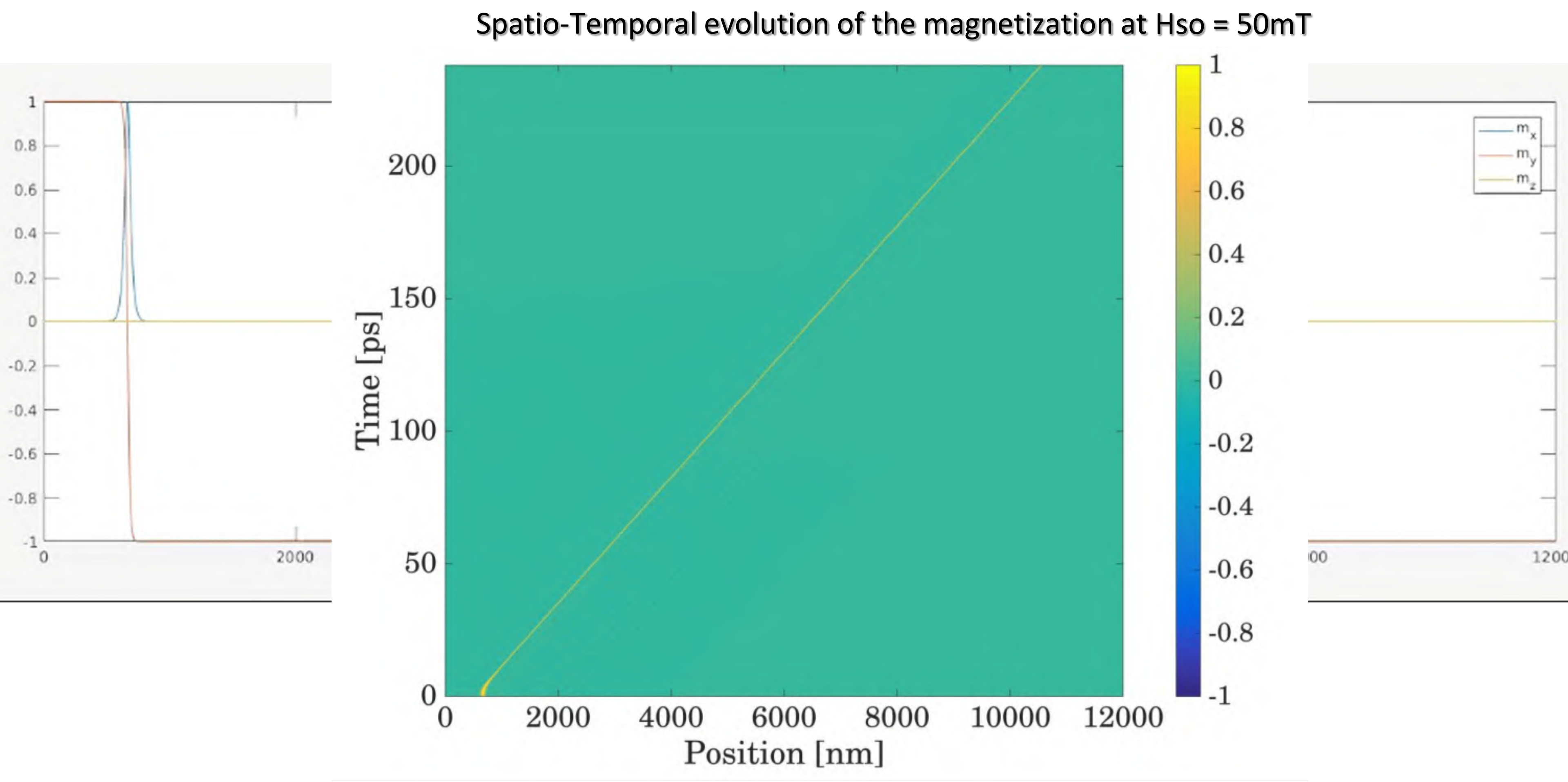
Walker-like domain wall breakdown in layered antiferromagnets driven by staggered spin-orbit fields

Rubén M. Otxoa[1,2✉], P. E. Roy[1], R. Rama-Eiroa[2,3], J. Godinho[4,5], K. Y. Guslienko[3,6] & J. Wunderlich[1,4,7]

Within linear continuum theory, no magnetic texture can propagate faster than the maximum group velocity of the spin waves. Here, by atomistic spin dynamics simulations and supported by analytical theory, we report that a strongly non-linear transient regime due to the appearance of additional magnetic textures results in the breaking of the Lorentz translational invariance. This dynamical regime is akin to domain wall Walker-breakdown in ferromagnets and involves the nucleation of an antiferromagnetic domain wall pair. While one of the nucleated domain walls is accelerated beyond the magnonic limit, the remaining pair remains static. Under large spin-orbit fields, a cascade of multiple generation and recombination of domain walls are obtained. This result may clarify recent experiments on current pulse induced shattering of large domain structures into small fragmented domains and the subsequent slow recreation of large-scale domains.

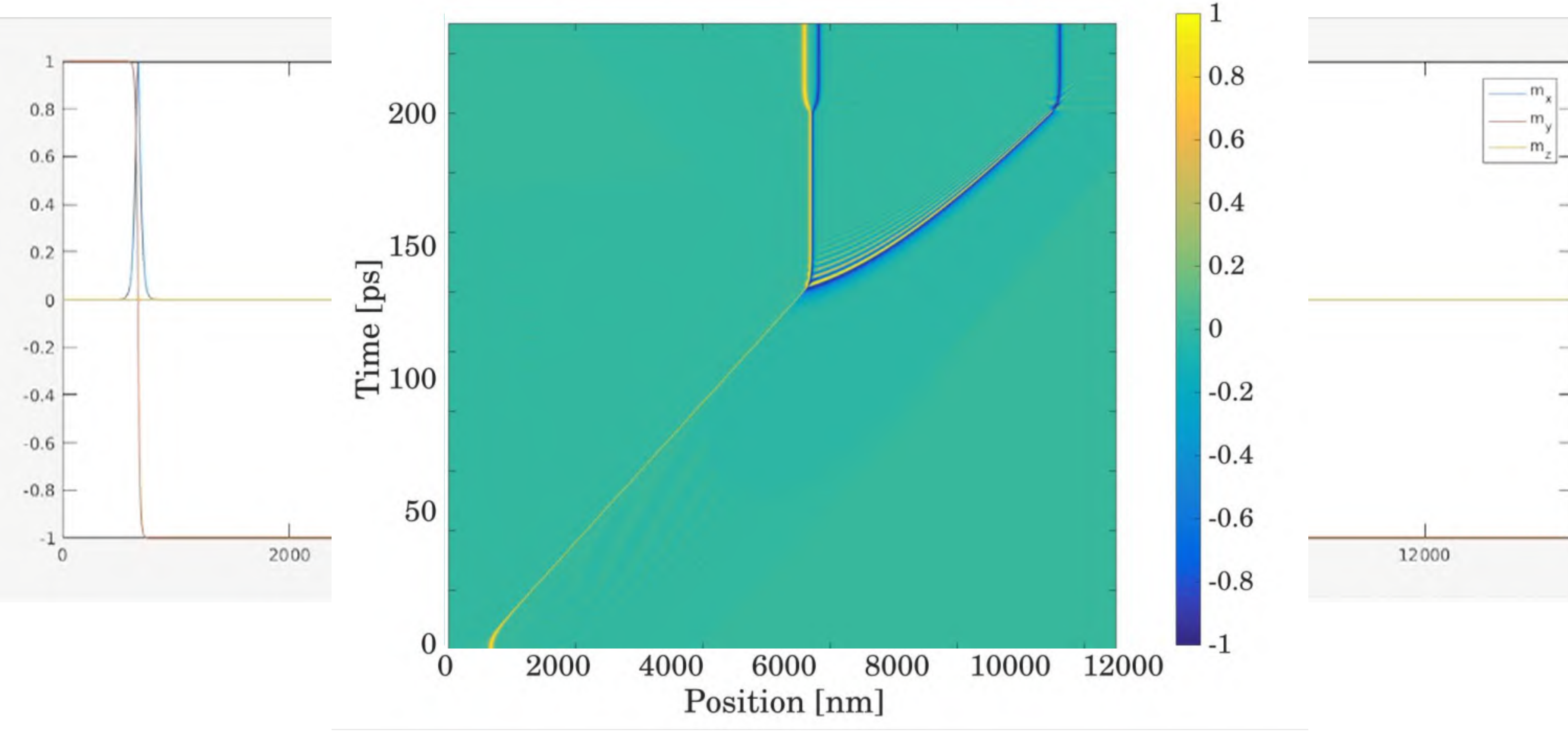


3.2 **AF domain wall motion** with staggered effective spin-orbit-fields



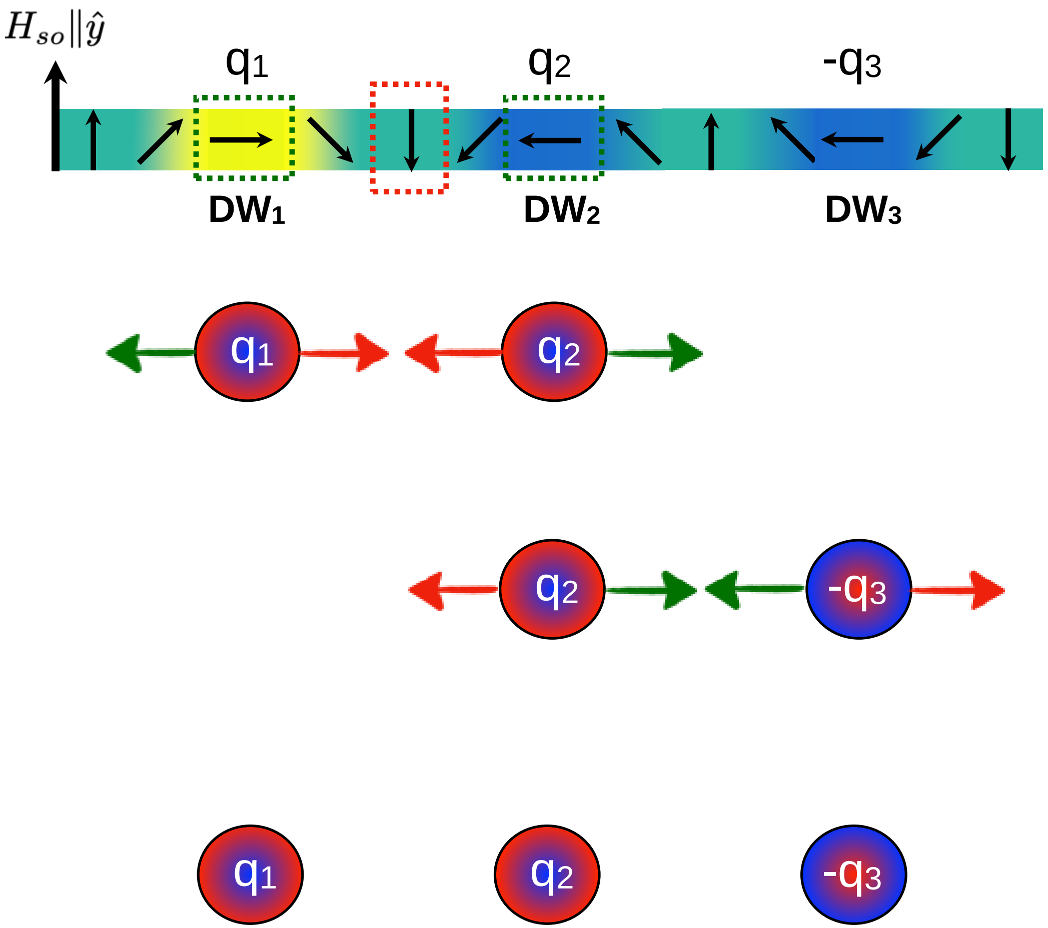
3.2 **AF domain wall motion** with staggered effective spin-orbit-fields

Spatio-Temporal evolution of the magnetization at Hso = 65mT



3.2 **AF domain wall motion** with staggered effective spin-orbit-fields

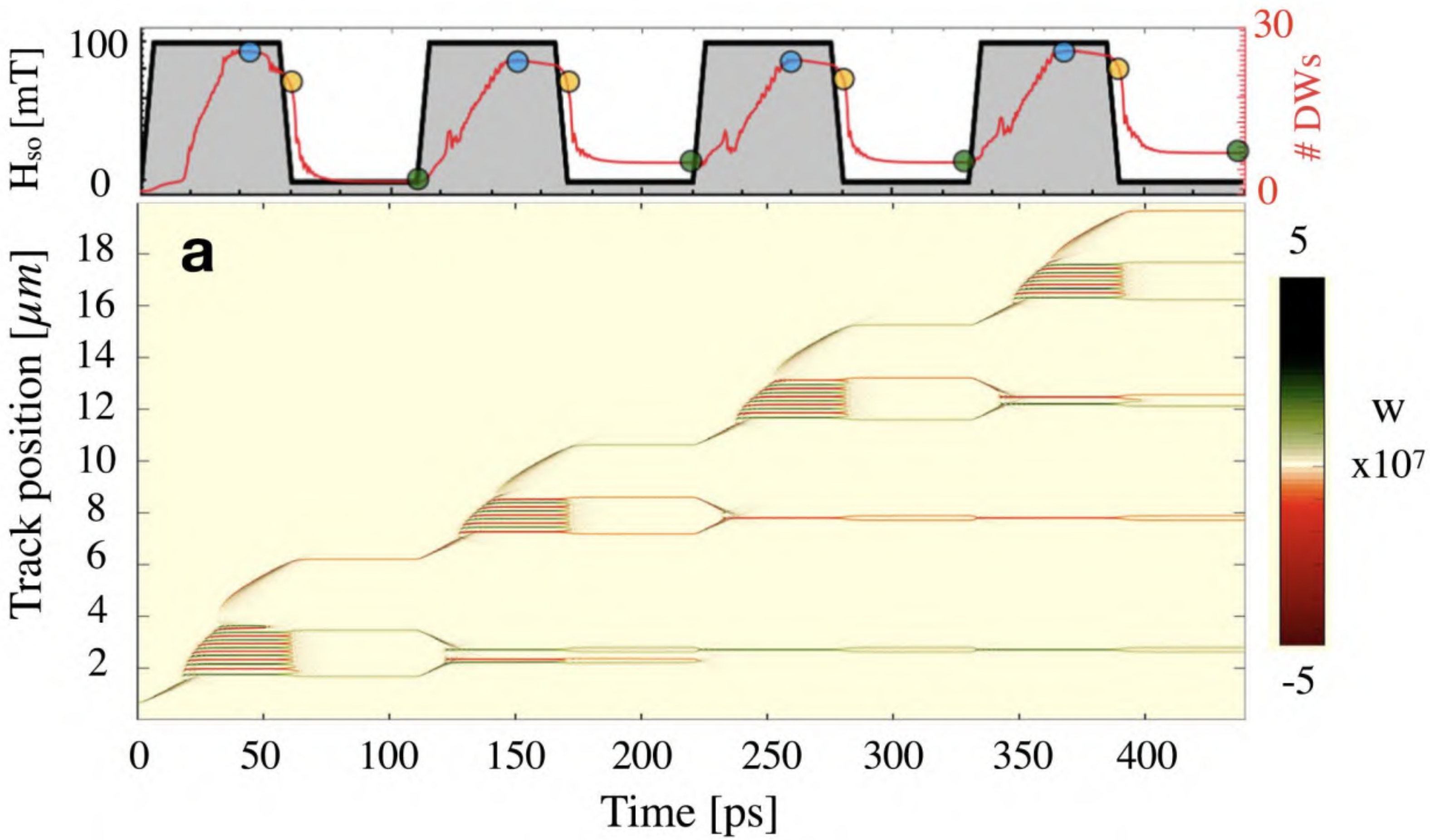
Domain wall dynamical properties



Exchange Energy

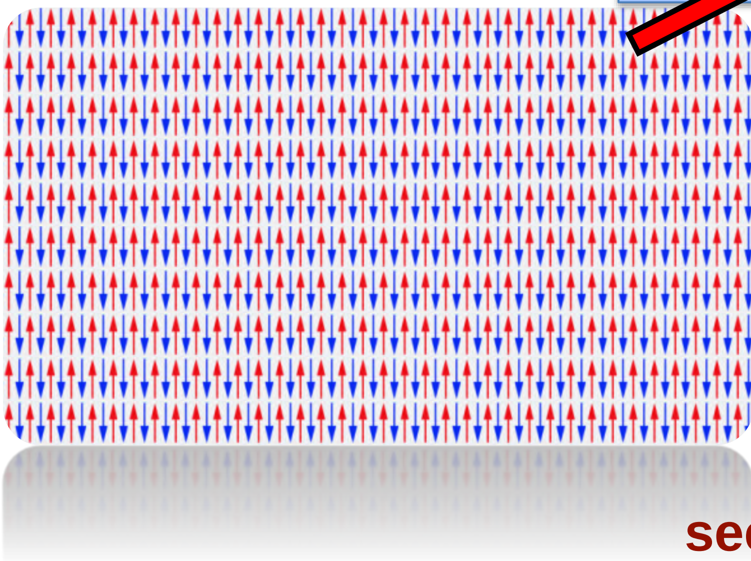
Zeeman Energy

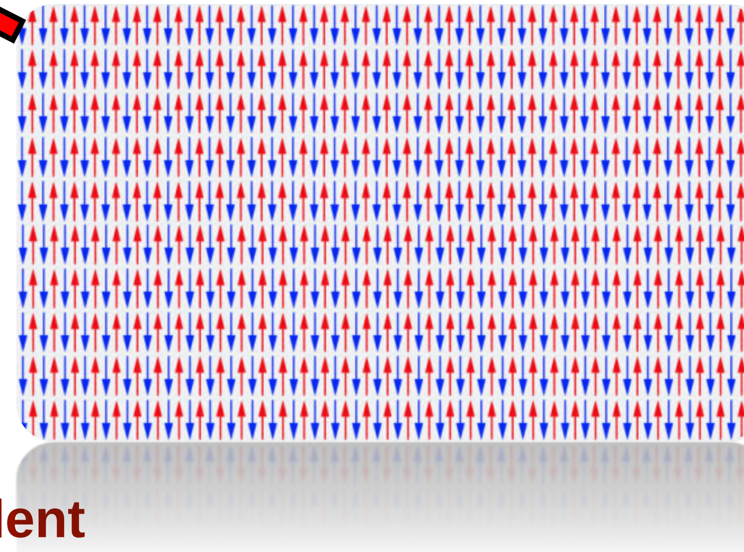
Domain wall nucleation and annihilation



3.3 Detecting reversed anitferromagnetic states

~~**Anisotropic Magnetoresistance**~~
~~**linear response**~~



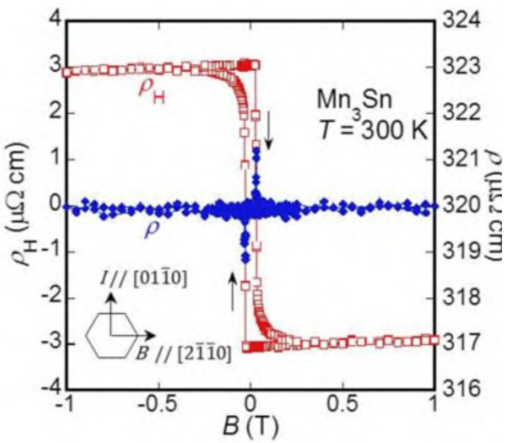


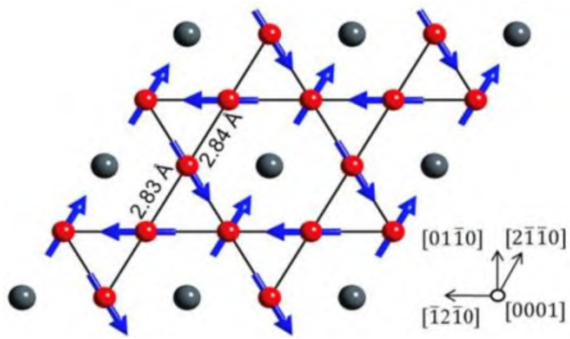
Electrical
DETECTION
of
seemingly equivalent
reversed antiferromagnetic STATES
?

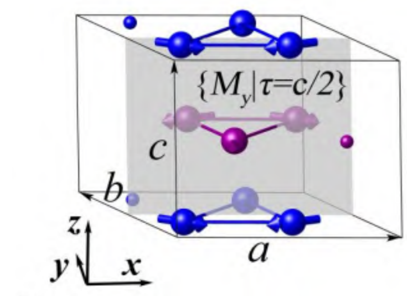
3.3 Detecting reversed anitferromagnetic states

Anomalous Hall effect (AHE) in **non-collinear Kagome AFs** (Mn_3Ir, Mn_3Ge, Mn_3Sn, …)

(section 4)

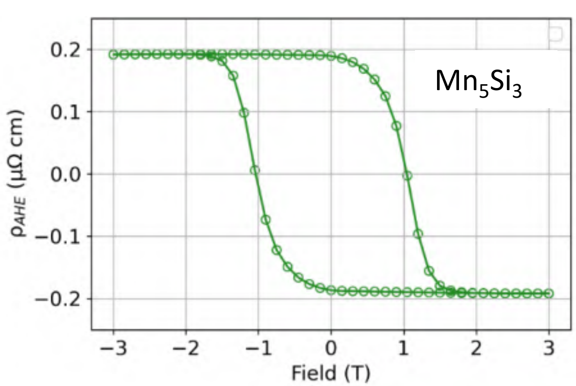


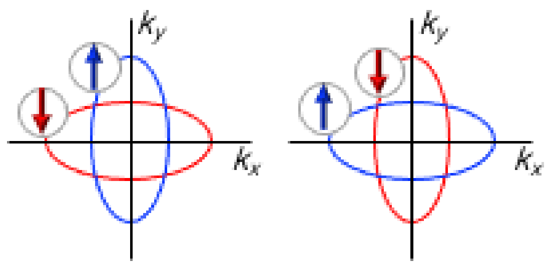




Chen et al., PRL 112, 017205 (2014)
Nakatsuji, et al., Nature 527, 212 (2015)
Nayak, et al., Sci. Adv. 2, e1501870 (2016)
…

… in **Altermagnets** (RuO_2, MnTe, Mn_5Si_3 …) (section 5)





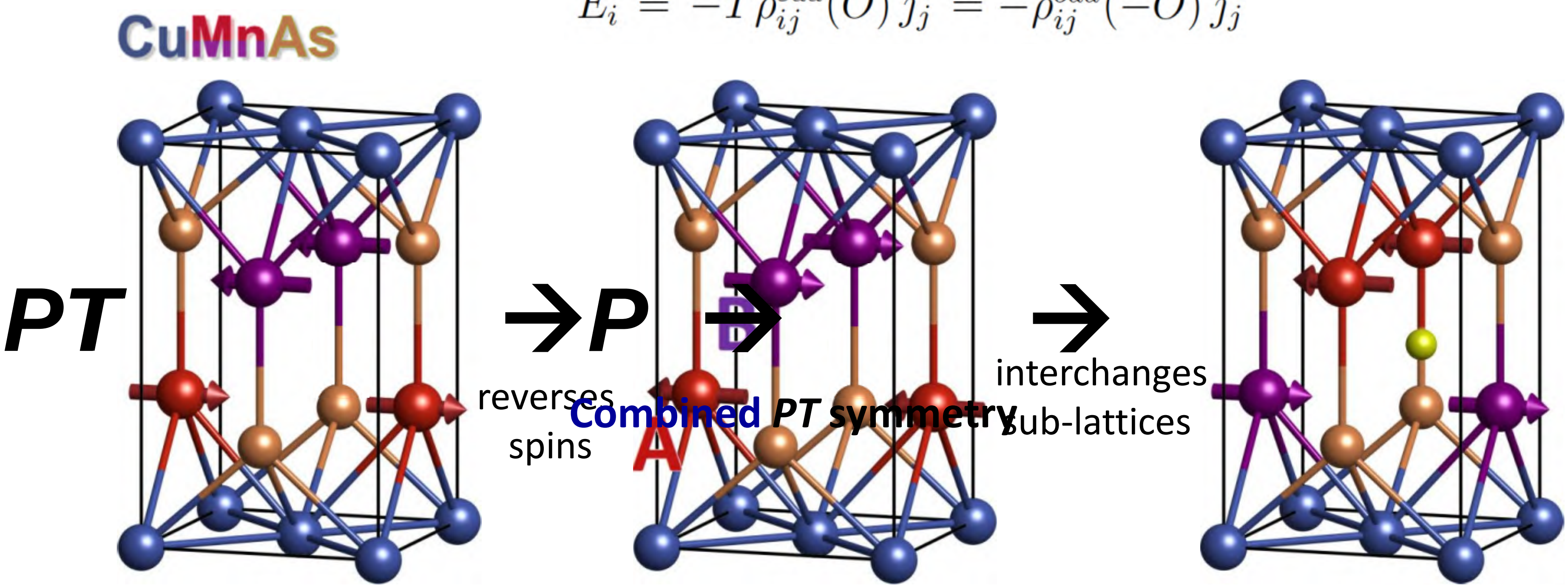
Šmejkal, et al., Sci. Adv. 6, eaaz8809 (2020); Nat. Rev. Mater. 7, 482 (2022)
Feng, et al., Nat. Elec. 11, 735 (2022); Betancourt, et al., PRL 130, 036702 (2023),
Reichlová, et al., arXiv:2012.15651

3.3 Detecting reversed anitferromagnetic states

Anomalous Hall effect (AHE) linear response: **E** = (ρ + ξj + ...) **j**

AHE (odd under time reversal): $E_i = \rho_{ij}^{odd}(\vec{O})\, j_j$;

$$E_i = -T\rho_{ij}^{odd}(\vec{O})\, j_j = -\rho_{ij}^{odd}(-\vec{O})\, j_j$$



broken time reversal symmetry broken space-inversion symmetry

PT symmetry of the CuMnAs crystal: $\rho_{ij}^{\mathrm{odd}} = PT\rho_{ij}^{\mathrm{odd}}$ (even under time reversal + space inv.)

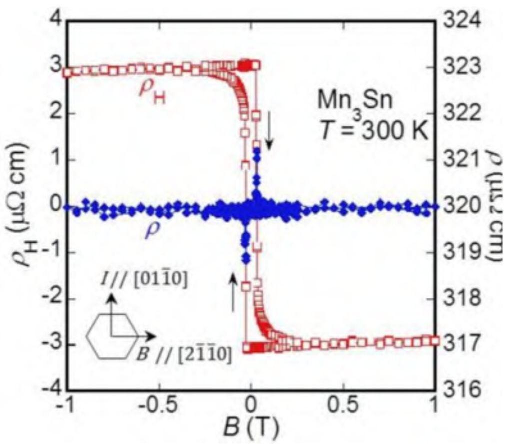
Space inversion flips sign of both electric field E_i and current j_j ⟹ $\rho_{ij}^{\mathrm{odd}} = 0$ (**no AHE**)

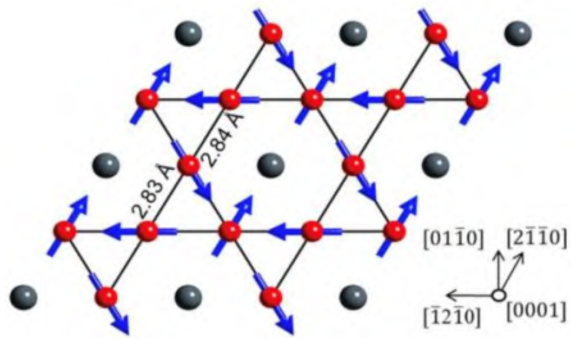
Time rev. symmetry flips only the sign of the current j_j: $\rho_{ij}^{\mathrm{odd}} = -PT\rho_{ij}^{\mathrm{odd}}$

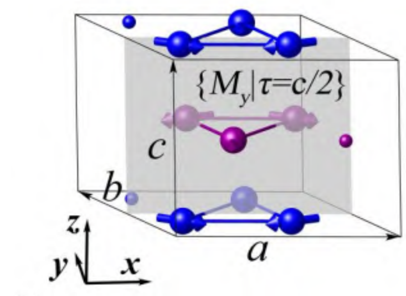
3.3 Detecting reversed anitferromagnetic states

Anomalous Hall effect (AHE) in **non-collinear AFs**

which crystallize in ferromagn. symmetry groups, able to develope a magnetic moment (**Mn_3Ir**, **Mn_3Ge**, **Mn_3Sn**, **…**)







Chen et al., PRL 112, 017205 (2014)
Nakatsuji, et al., Nature 527, 212 (2015)
Nayak, et al., Sci. Adv. 2, e1501870 (2016)
…

Higher order Magnetoresistance (J. Godhino, JW et al. Nat Comm. 9, 4686 (2018))

$$\mathbf{E} = (\rho + \xi \mathbf{j} + \dots)\,\mathbf{j}$$ (second order response)

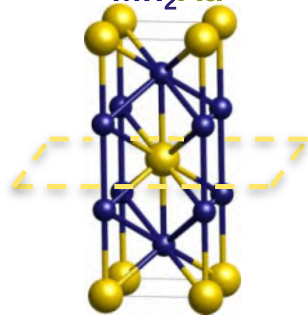
- allows detection of spin-reversal in AF with combined **broken *T*** and broken ***P* symmetry**

[39] D.-F. Shao, S.-H. Zhang, G. Gurung, W. Yang, and E. Y. Tsymbal, "Non-linear anomalous hall effect for néel vector detection," Physical Review Letters **124**, 067203 (2020).

Photocurrents in Mn_2Au (M. Merte, Y. et all, APL Mater. 11, 071106 (2023))

3.3 Detecting reversed anitferromagnetic states

PT symmetric Antiferromagnets (CuMnAs, Mn_2Au, …)

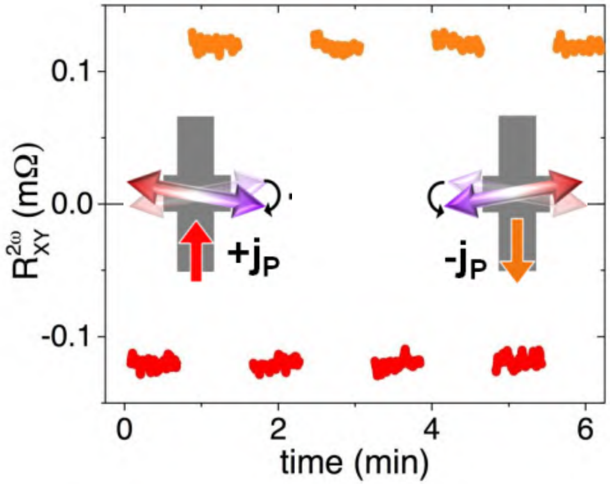


Centro-symmetric nonmagnetic lattice

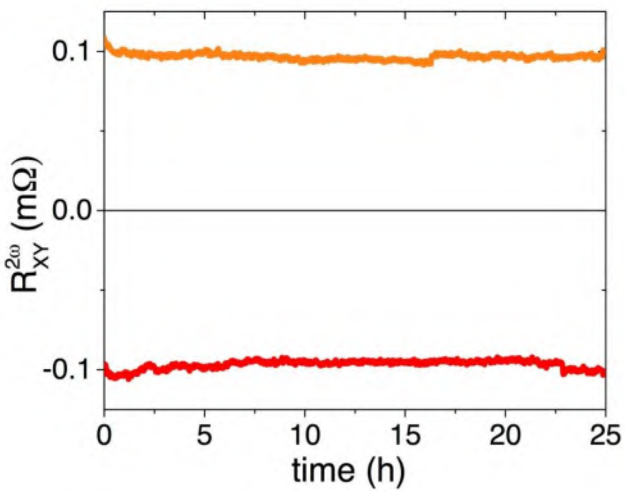
3.3 Detecting reversed anitferromagnetic states

at $\omega \rightarrow 0$

- 180 deg switching

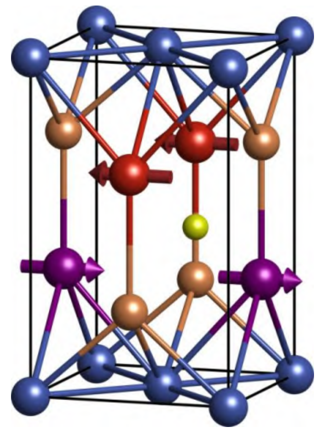


- after a single pulse:

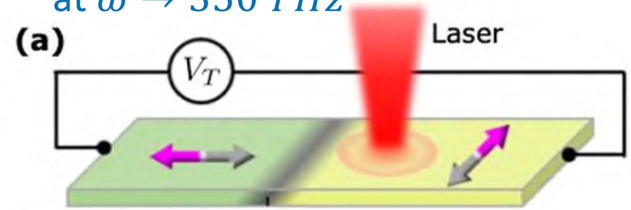


J. Godinho, JW, et al., Nat Commun 9, 4686 (2018).

CuMnAs

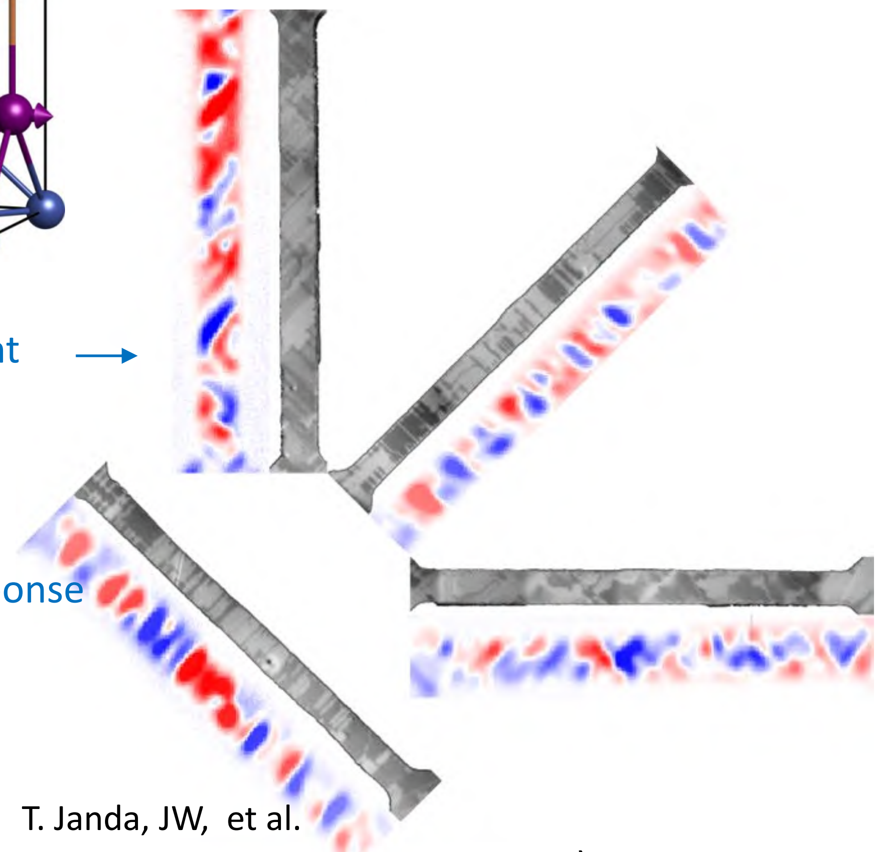


at $\omega \rightarrow 350\ THz$



Photocurrent response →

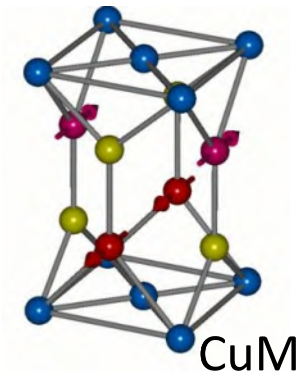
2nd order AMR response

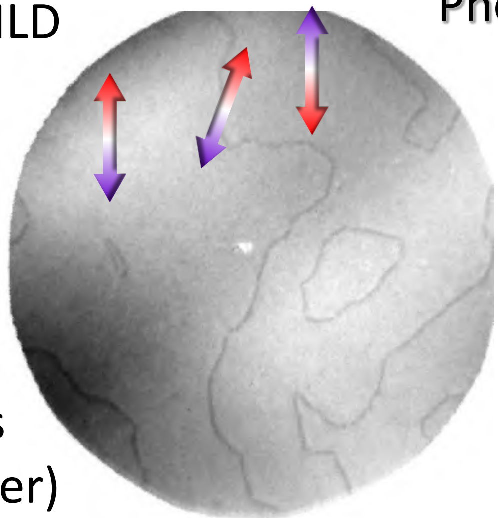


T. Janda, JW, et al.
Phys. Rev. Materials 4, 094413 (2020)

3.3 Detecting reversed anitferromagnetic states

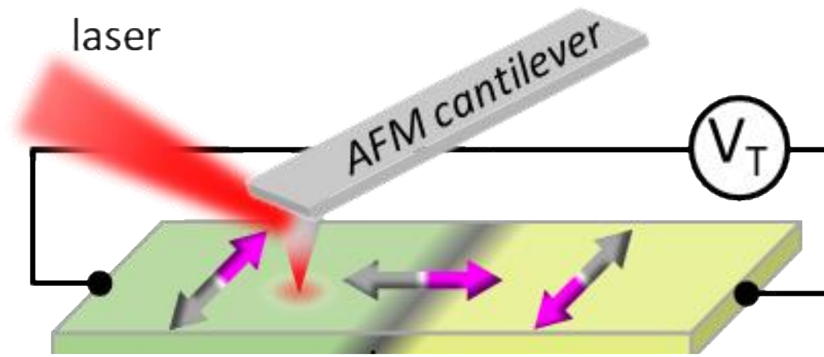
PEEM XMLD





CuMnAs
(thin layer)

Photocurrent

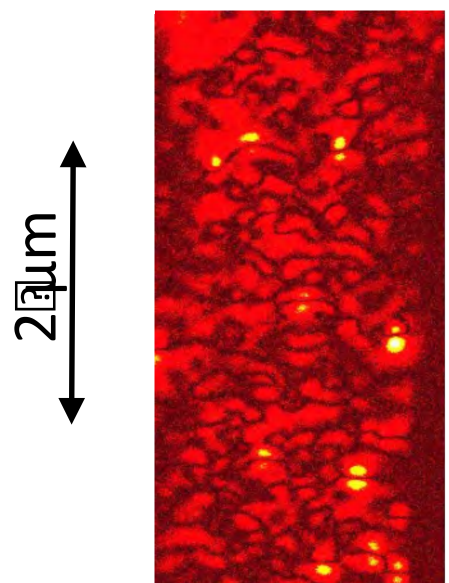


Near-field Nanoscopy:
AFM + thermal voltage

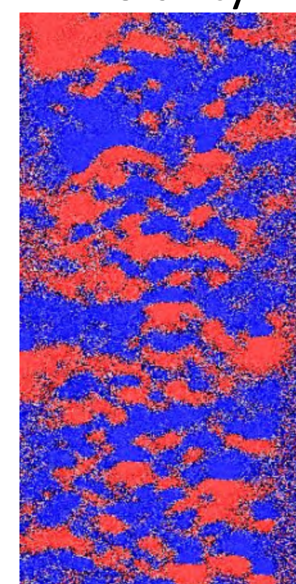
thin 20nm CuMnAs

AFM (~1nm res.)
(2 µm wide stripe)

Photocurrent
Magnitude

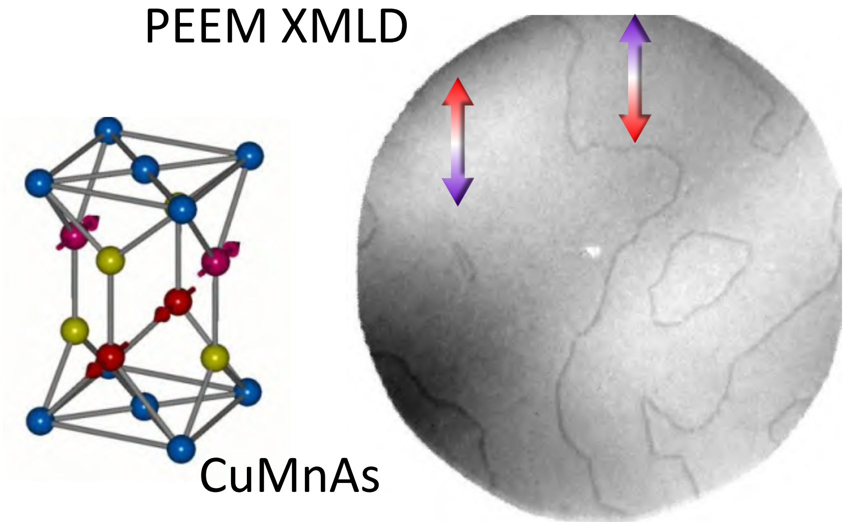


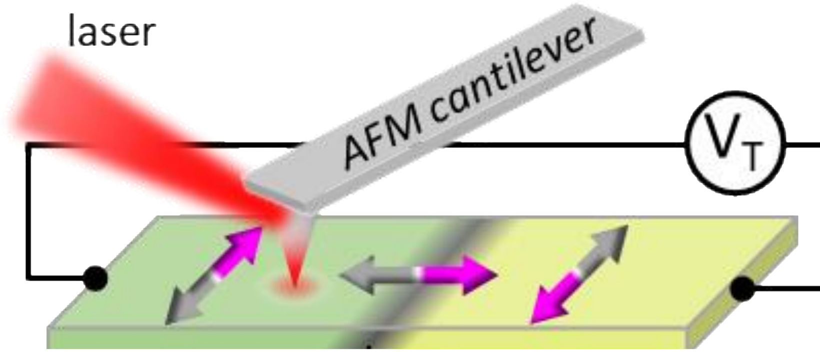
Photocurrent
Polarity

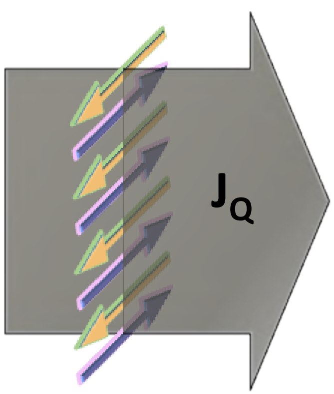


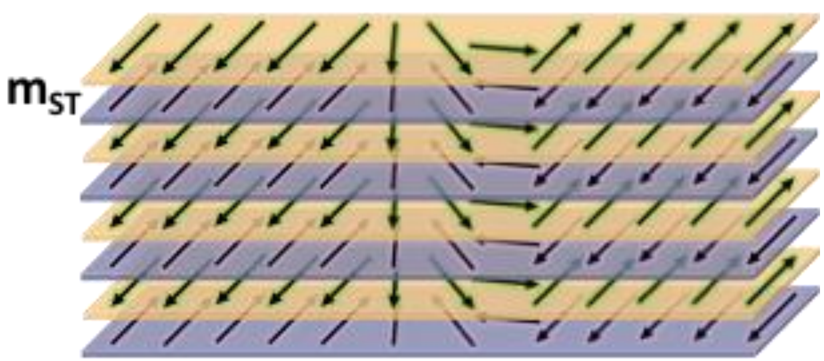
T. Janda et al, Phys. Rev. Materials 4, 094413 (2020)

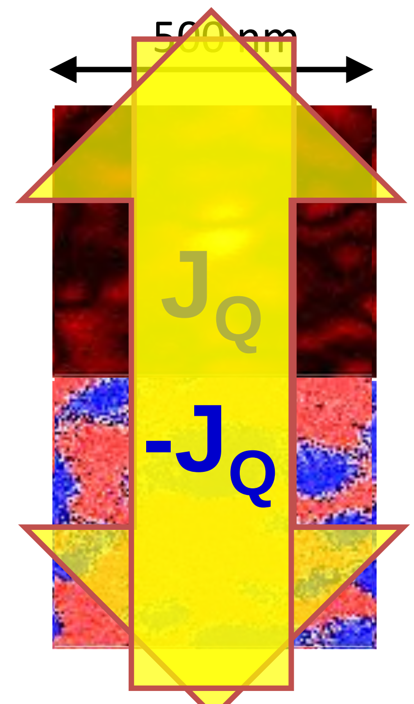
3.3 Detecting reversed anitferromagnetic states





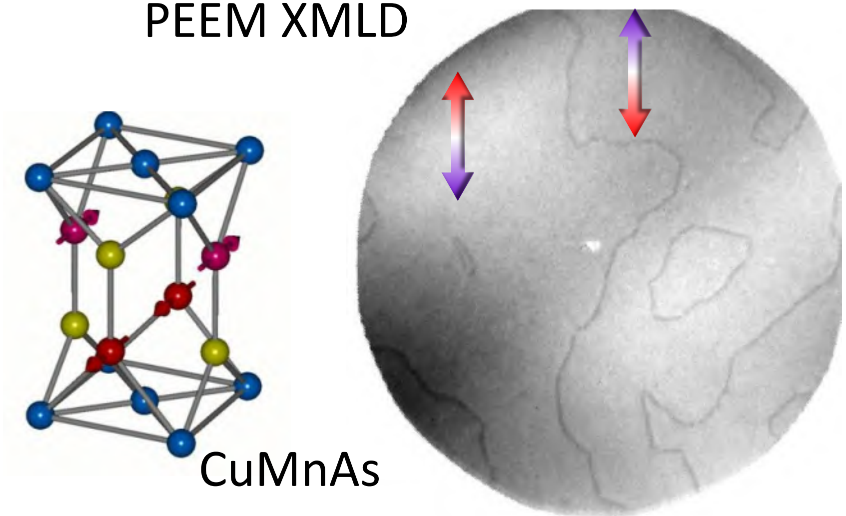




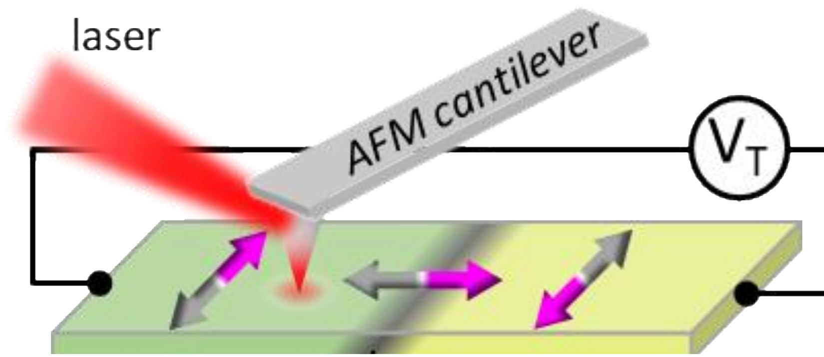


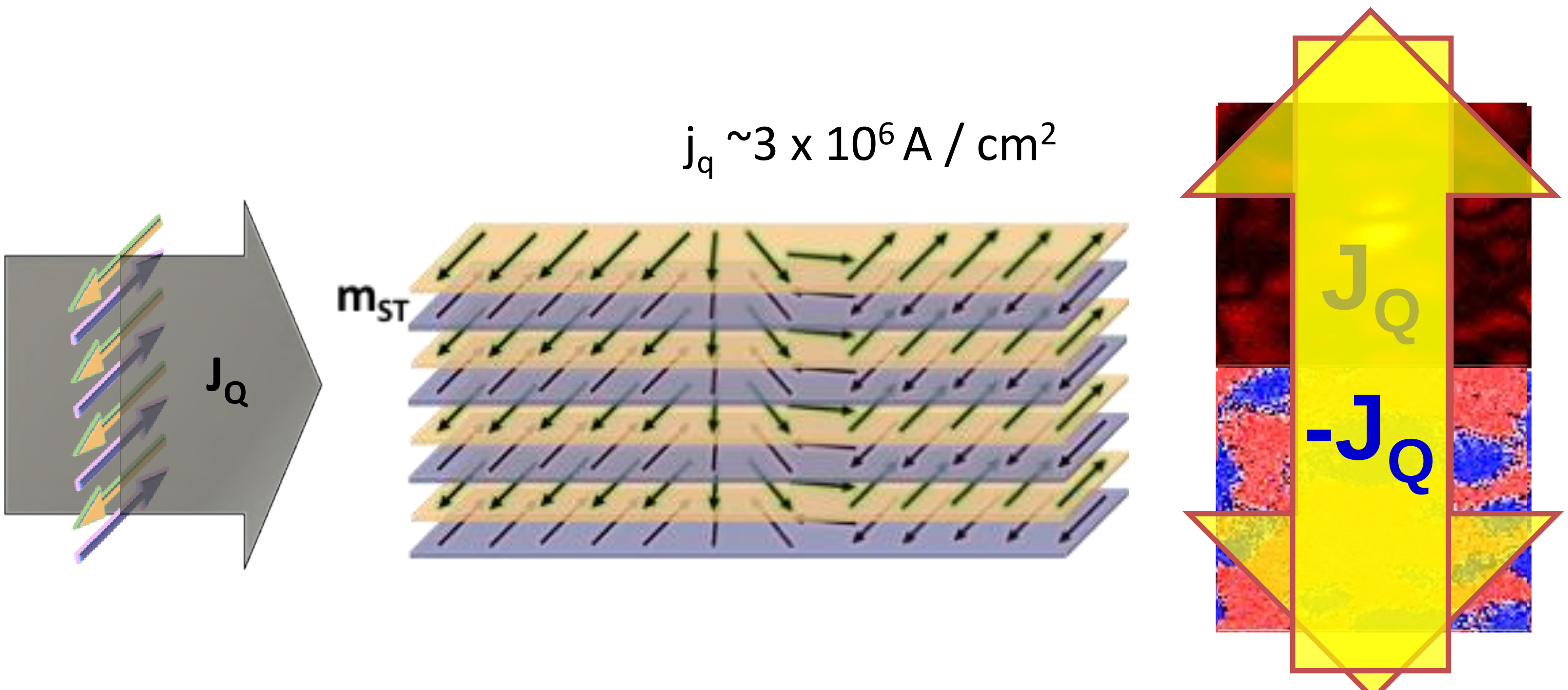
(~50 nV amplitude, 0.01 GW/m^2 power density)

3.3 Detecting reversed anitferromagnetic states



Anisotropic Magneto-Seebeck Effect





Antiferromagnetism and antiferromagnetic spintronics

1) **antiferromagnets - basics** (exchange interaction, frustration, critical temperatures and fields: flip and flop)

2) **conventional application of antiferromagnetism** (exchange bias: keeping the reference layer fixed …)

3) **AF spintronics** (staggered effective spin-orbit-fields, AF domain wall motion, nonlinear responses, …)