Manipulation of magnetic moments in antiferromagnets

or

spin flop, magnetic anisotropies,
spin-orbit torque and more

K. Vyborny (IoP, Praha)
C.A. Correa (Charles U)
J. Zelezny (IoP, Praha)
T. Jungwirth (Praha+Nottingham)
V. Novak (IoP, Praha)

… and more

Manipulation of magnetic moments in antiferromagnets (AFM)

magnetic moments in AFM are insensitive to magnetic field

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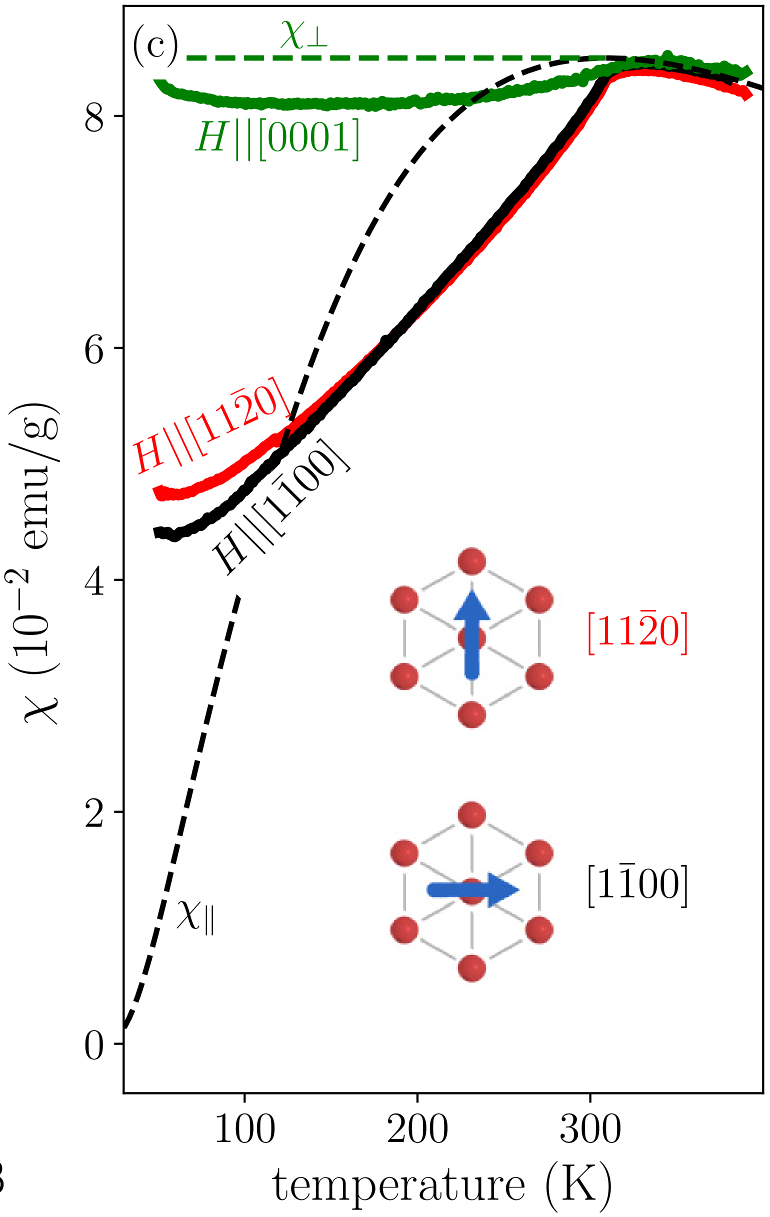
magnetic moments in AFM are insensitive to magnetic field

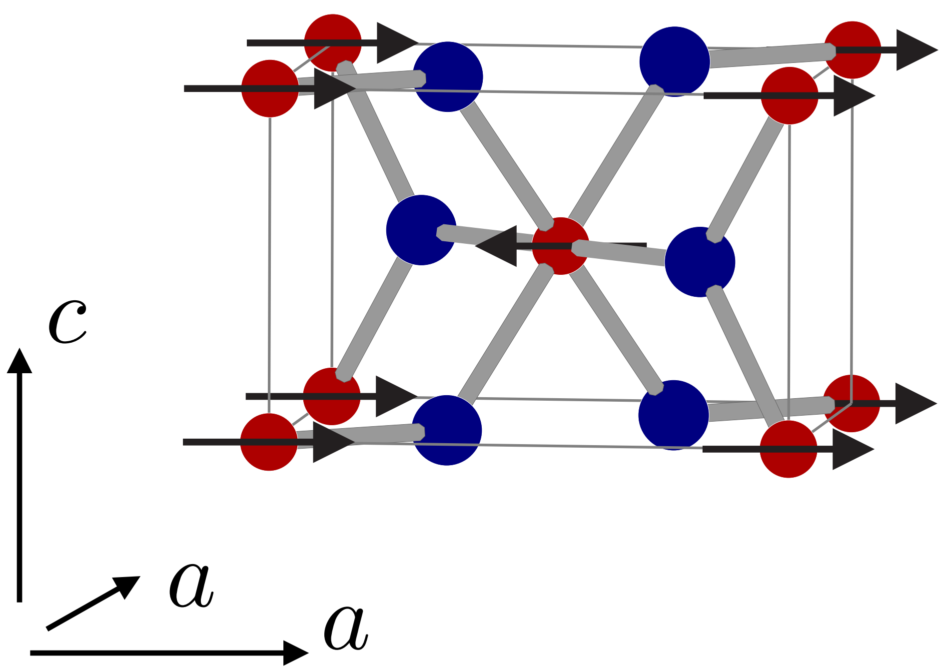
- not completely true, but indeed, the response is typically weak
- example: MnTe (T_N ~ 310 K), magnetic moments in-plane
- weak anisotropy within the easy plane, multiple domains



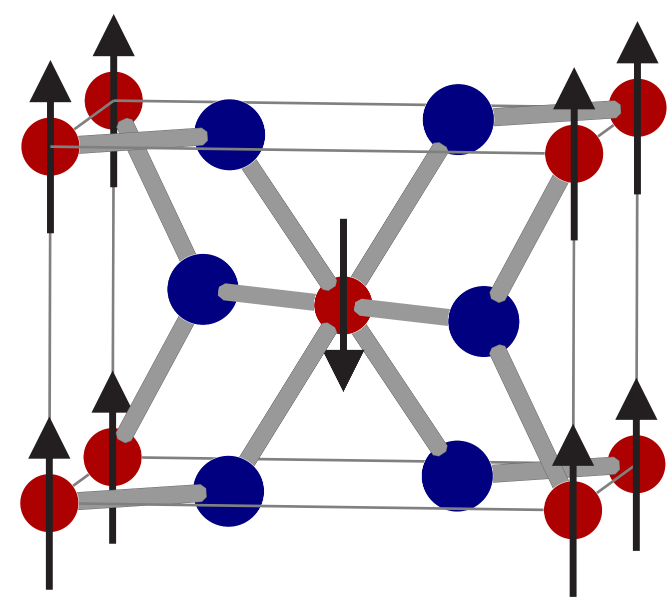
Kriegner et al. ’17
Phys Rev B 96, 214418

Take a simpler example: rutile structure TM difluorides

NiF_2



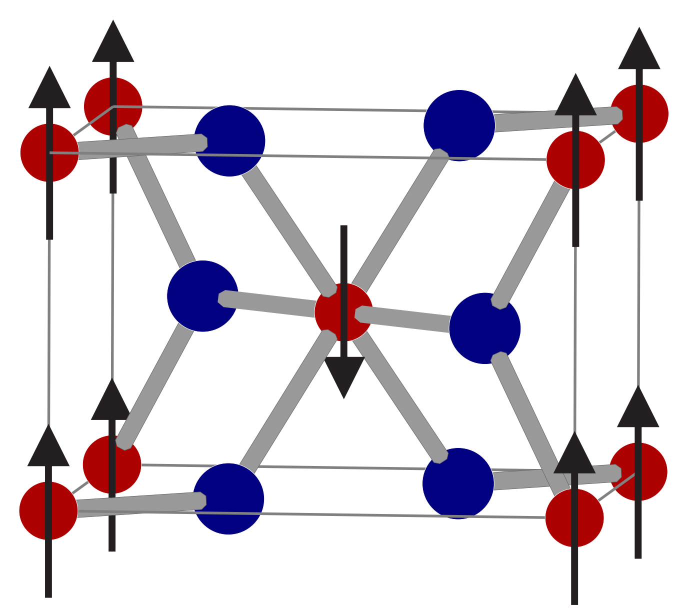
MnF_2



Manipulation of magnetic moments in antiferromagnets (AFM)

Magnetic order in TM difluorides

vanadium	Mn, Fe, Co	nickel	zinc
spiral AFM	AFM	in-plane AFM	diamagnetic
$T_N = 7\ \mathrm{K}$	$T_N \approx 70\ \mathrm{K}$		



Manipulation of magnetic moments in antiferromagnets (AFM)

	MnF_2	FeF_2	CoF_2
spin flop [T]	9.3	41.9	14.0

- magnetic field along c-axis (easy direction)
- I.S. Jacobs, JAP 31, 61S

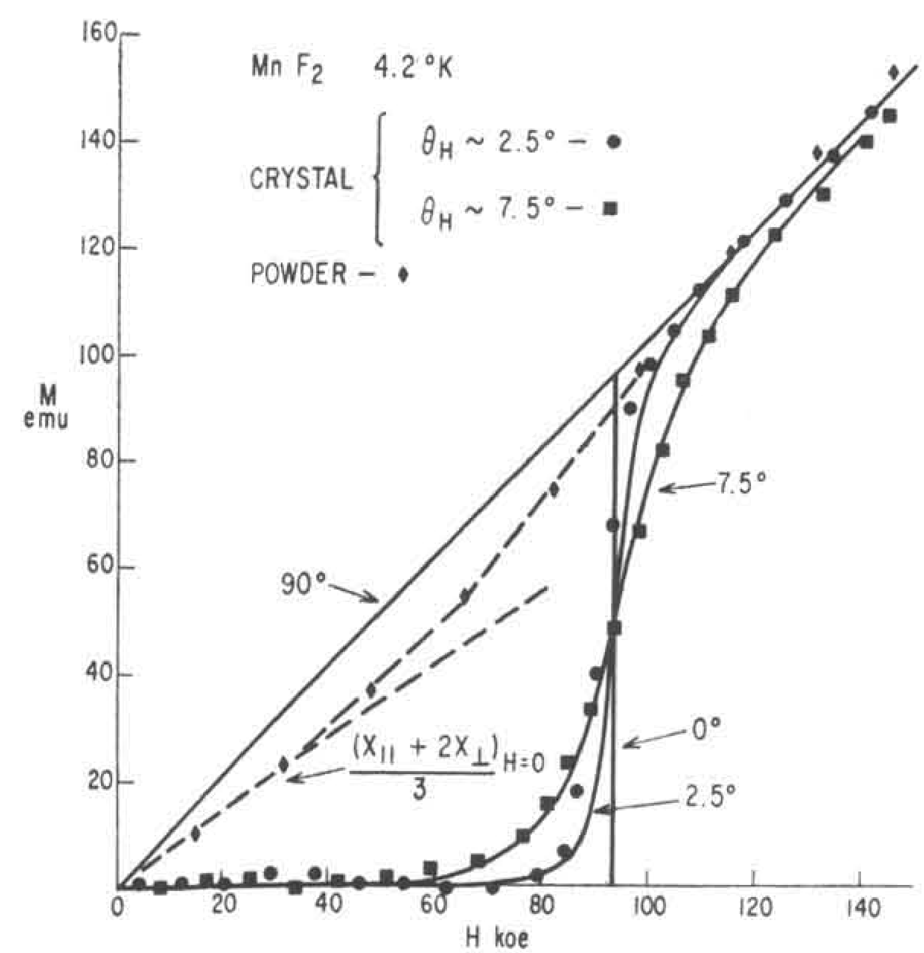
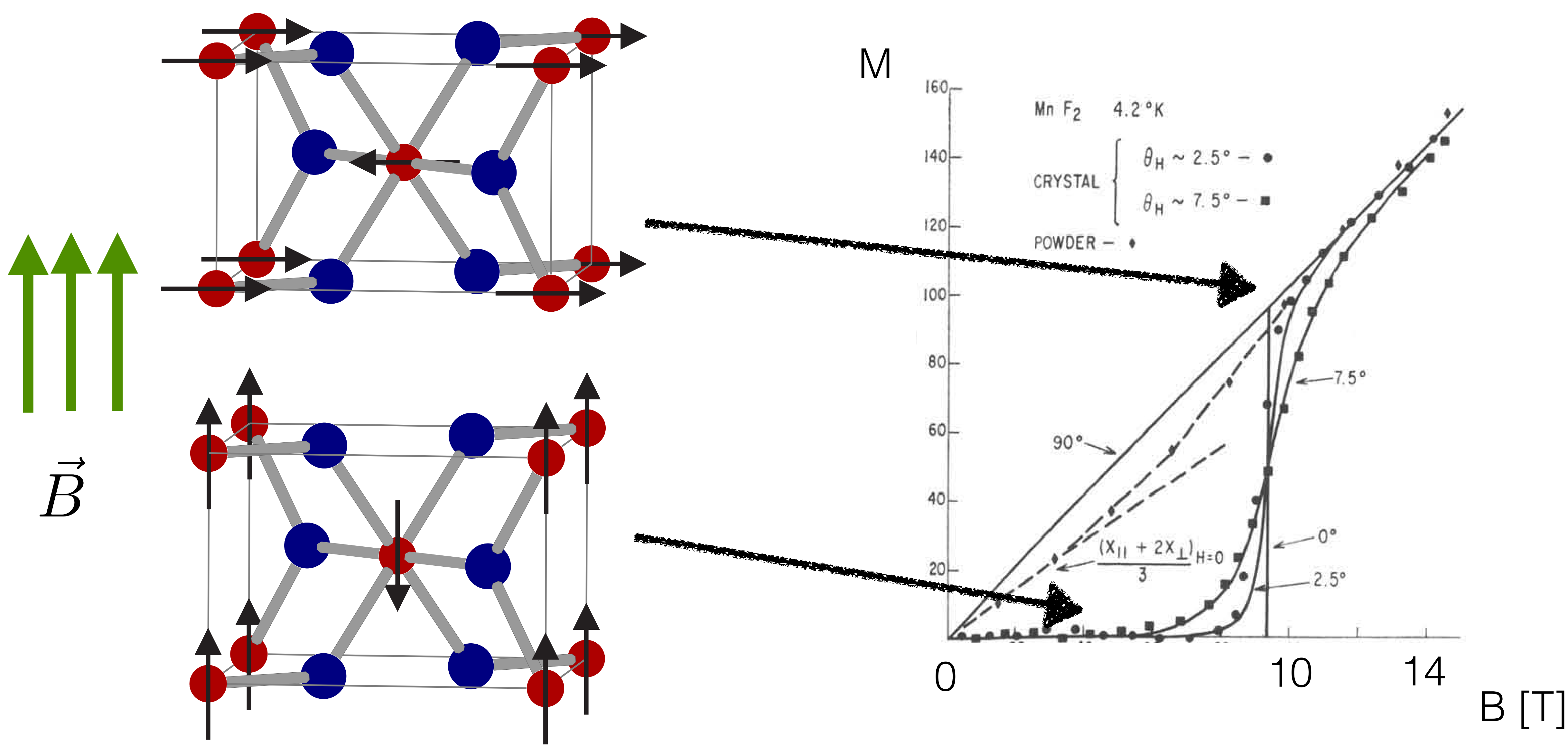


Fig. 1. Magnetization data for powder and various crystal orientations. Solid curves calculated from simplified theory.

How does this work?

	MnF_2	FeF_2	CoF_2
spin flop [T]	9.3	41.9	14.0



Manipulation of magnetic moments in antiferromagnets (AFM)

Any other option?

Manipulation of magnetic moments in antiferromagnets (AFM)

Any other option?

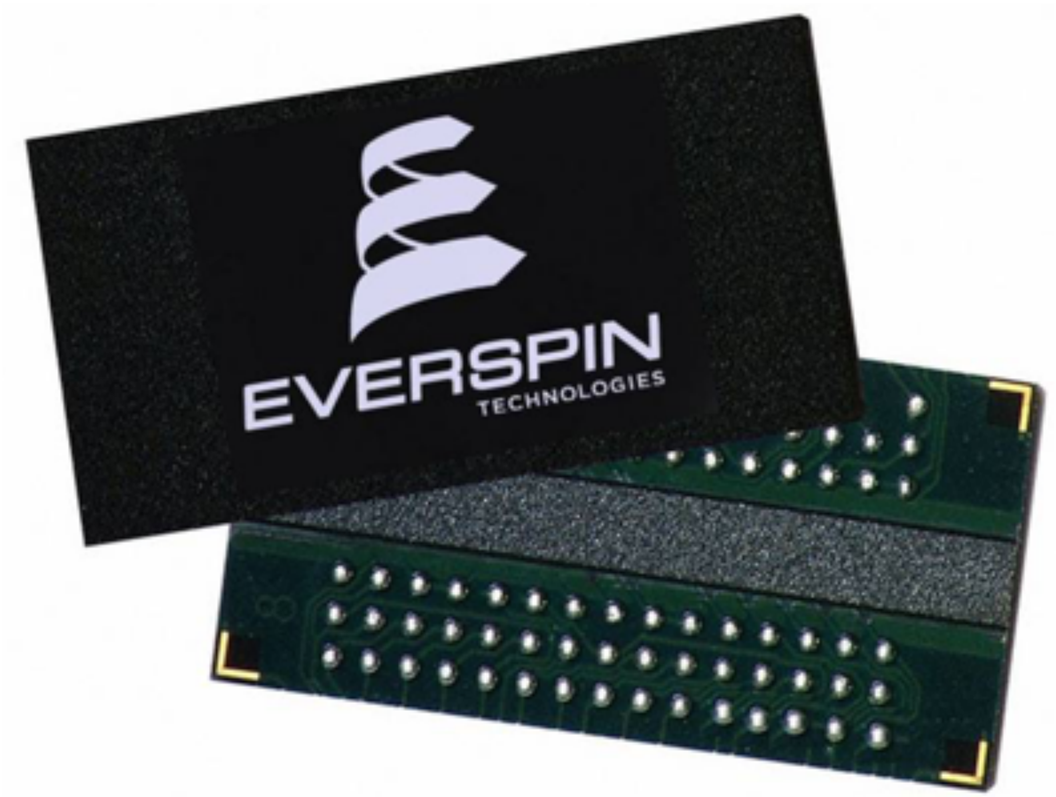
… spin-orbit torques

originate from

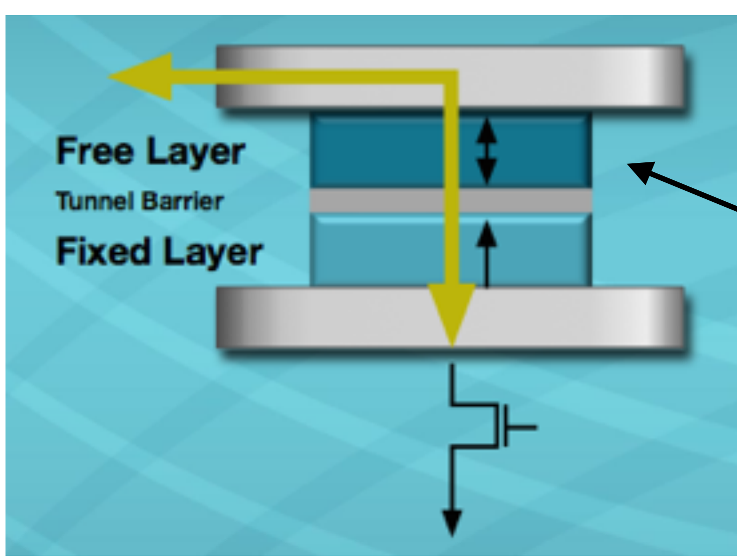
current-induced spin polarisation *S*, i.e. linear response of *S* to applied electric field

Magnetic memories: beyond HDD

ferromagnets:



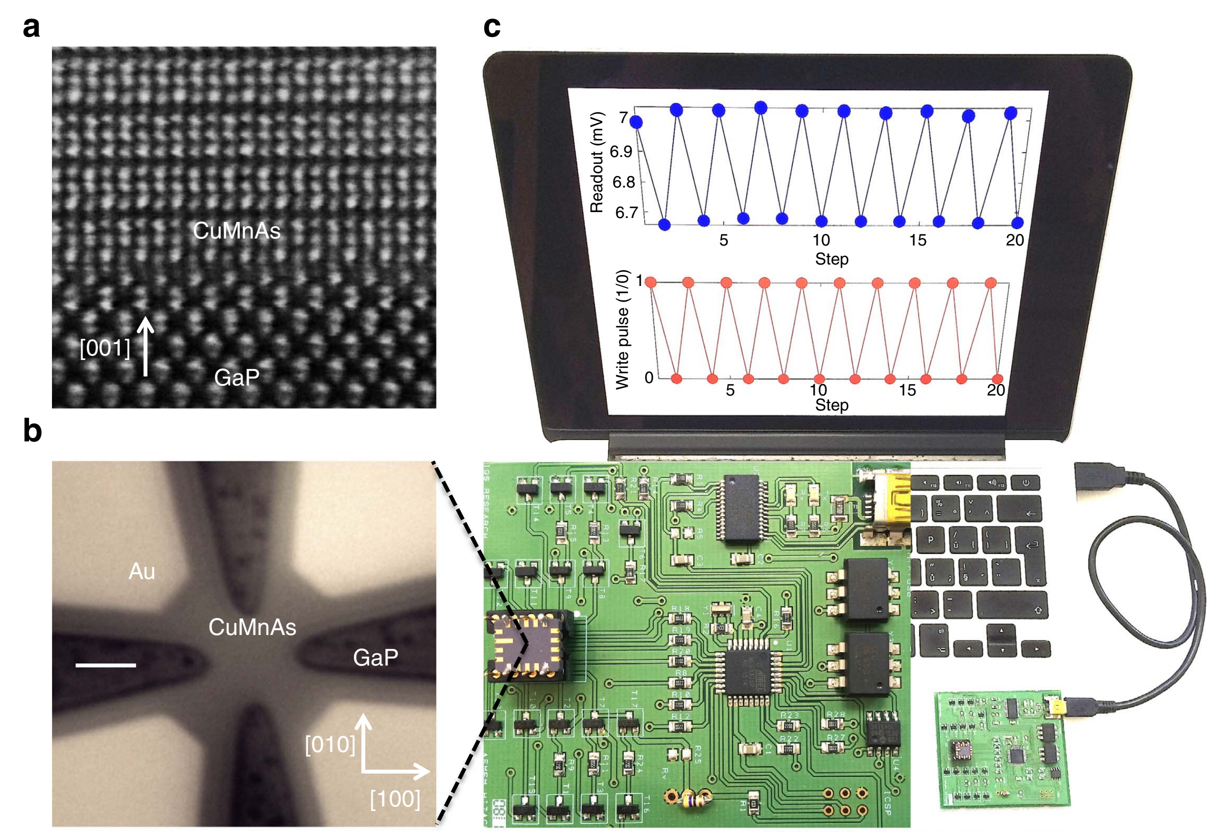
MTJ-based MRAM



0 or 1: free layer magnetisation direction

any new ideas? Yes!

Antiferromagnetic memory based on CuMnAs



Olejník et al. '17
[10.1038/ncomms15434]

Torques acting on magnetic moments

Basics:

mechanical torque: $$\vec{T} = \frac{d\vec{L}}{dt}$$

magnetic field acting on a dipole: $$\vec{T} = \vec{\mu} \times \vec{B}$$

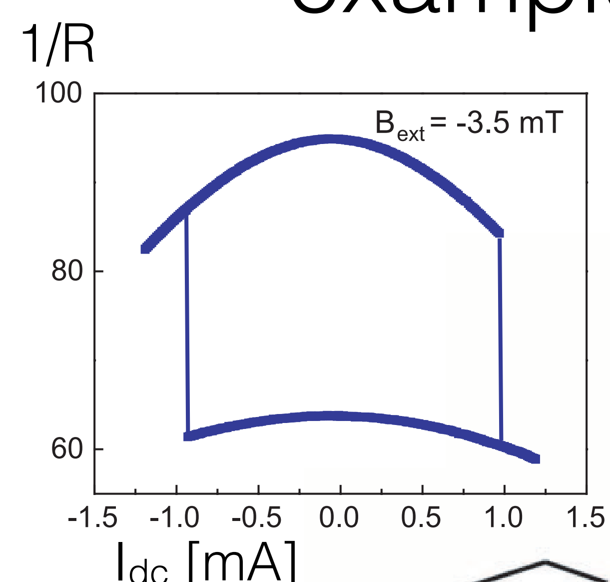
gyromagnetic ratio: $$\vec{\mu} = \gamma \vec{L}$$

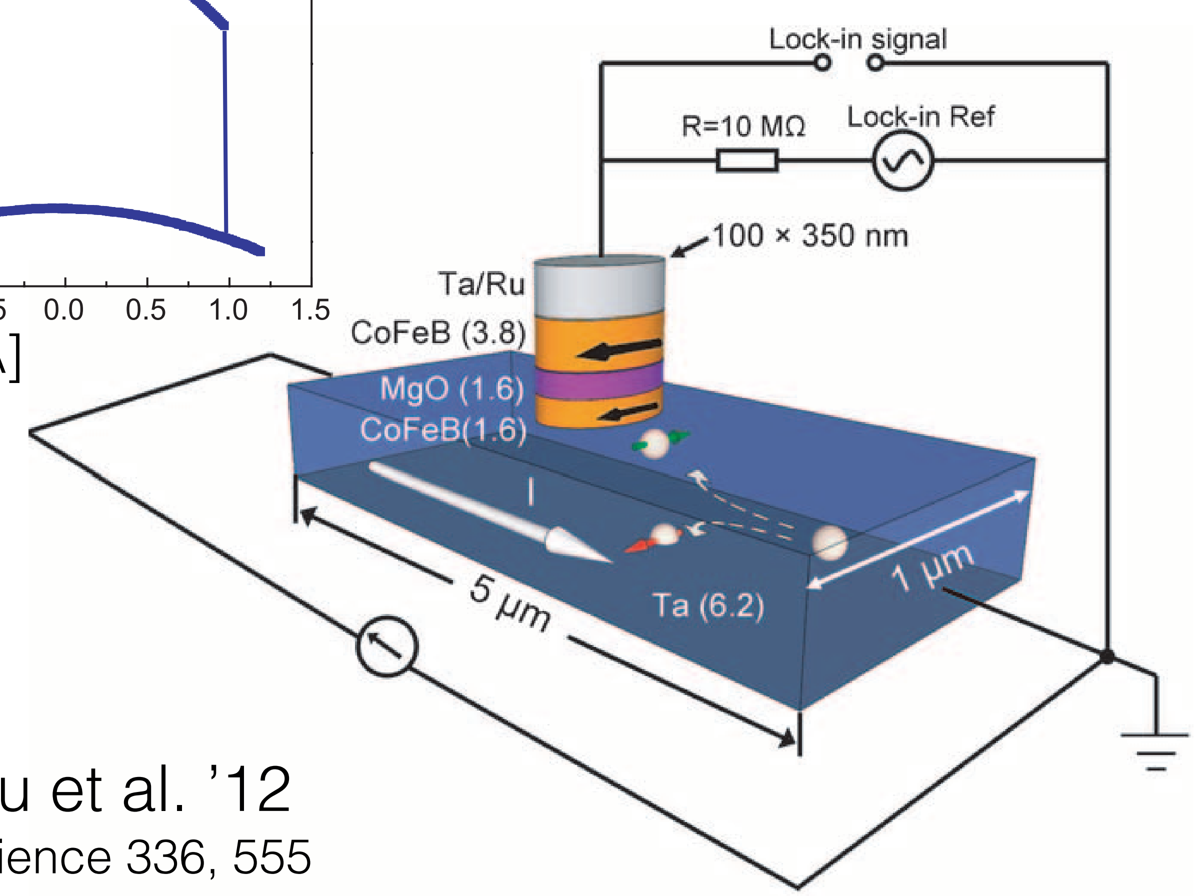
total magnetisation: $$\vec{M} = \frac{1}{V} \sum_i \vec{\mu}_i$$

Solid state:

$$\frac{d\vec{M}}{dt} = \gamma \vec{M} \times \vec{B}$$

example: SHE-SOT





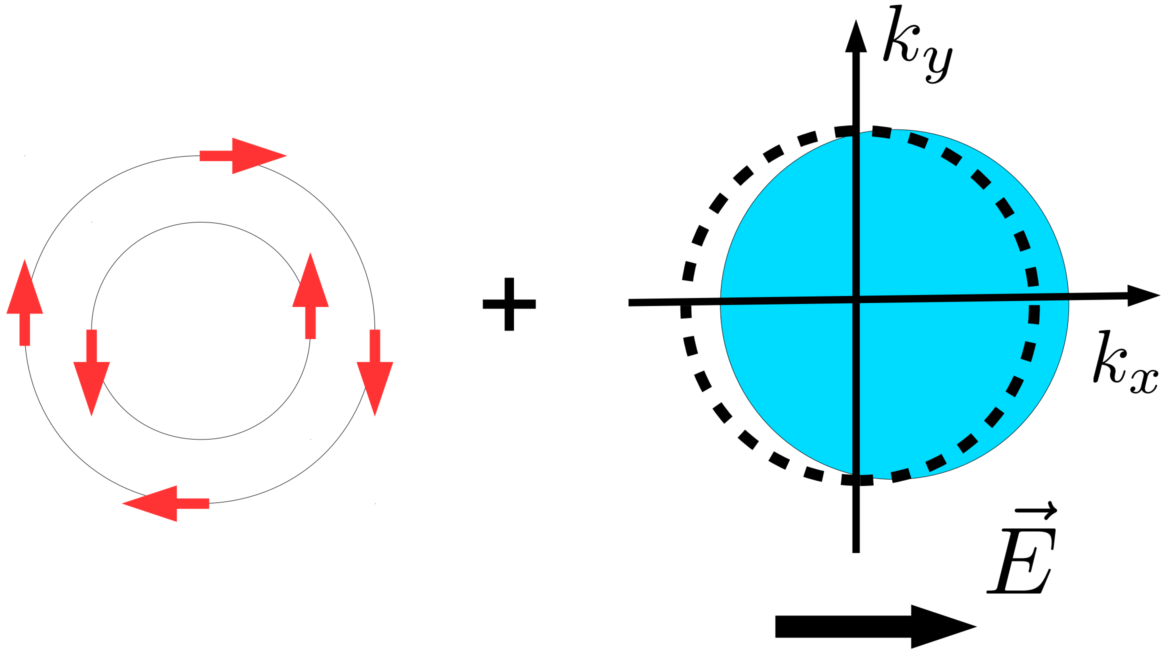
Liu et al. '12
Science 336, 555

Current-induced spin-orbit torque - for ferromagnets

Edelstein effect…

$$\delta \mathbf{S} = \chi \, \mathbf{E}$$

simplest example: Rashba-Bychkov spin-orbit int. (sol. st. comm. 73, 233)



$$\delta \mathbf{S} = \int S \delta f \; dk + \int f \delta S \; dk$$

… action on magnetic moments

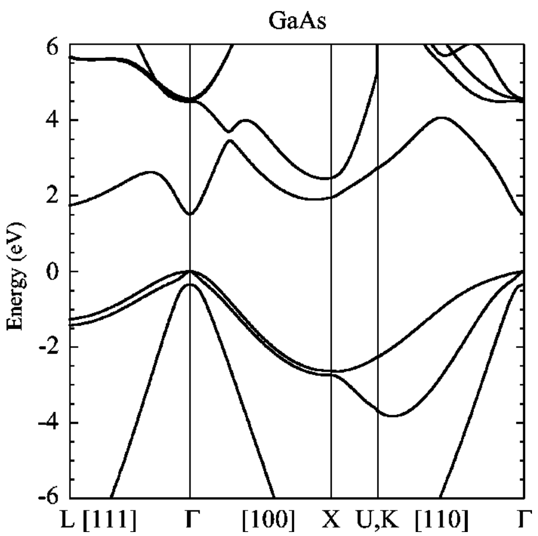
Phil. Tr. R. Soc. London A 369, 3175

$$\vec{T} = \frac{J_{pd}}{M} \delta \vec{S} \times \vec{M}$$

in the context of p-d type Hamiltonian

$$H = H_{KL} + h\hat{e}_M \cdot \mathbf{s}$$

… applicable to (Ga,Mn)As



- ferromagnetism ind. by carriers
- Mn d-states coupled to hole p-states (carrier)

$$H = H_{KL} + J_{pd} \sum_{i,I} \vec{S}_I \cdot \vec{s}_i \delta(\vec{r}_i - \vec{R}_I)$$

Current-induced spin-orbit torque - ferromagnetic (Ga,Mn)As

$$\delta\mathbf{S} = \chi\,\mathbf{E}$$

$$S_i = \chi_{ij} E_j$$

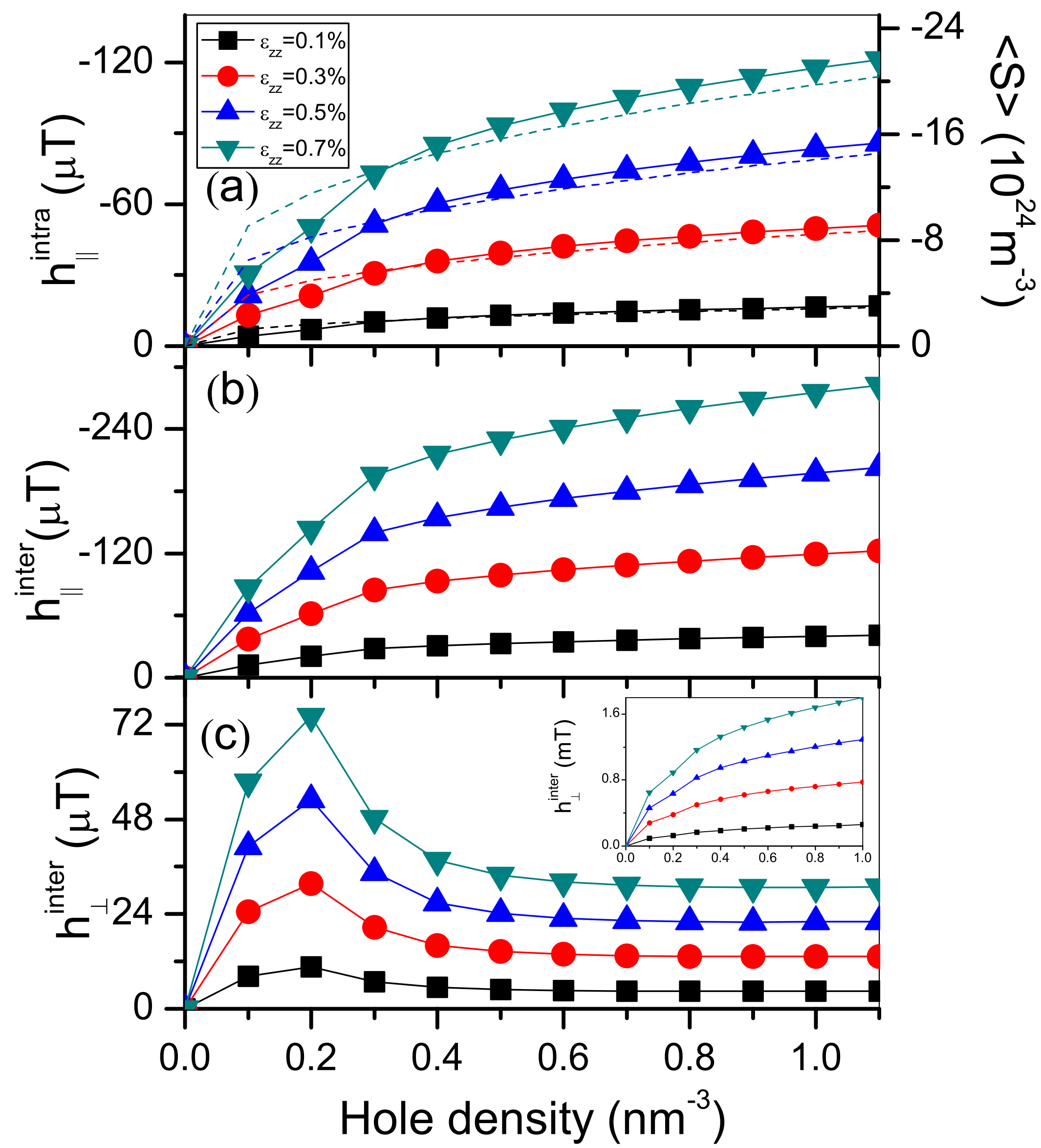
CISP - in linear response

$$\delta\mathbf{S} = \delta\mathbf{S}^{\rm intra} + \delta\mathbf{S}_1^{\rm inter} + \delta\mathbf{S}_2^{\rm inter}$$

$$\delta\mathbf{S}^{\rm intra} = \frac{1}{V}\frac{e\hbar}{2\Gamma}\sum_{\mathbf{k},a}\langle\psi_{\mathbf{k}a}|\hat{\mathbf{s}}|\psi_{\mathbf{k}a}\rangle\langle\psi_{\mathbf{k}a}|\mathbf{E}\cdot\hat{\mathbf{v}}|\psi_{\mathbf{k}a}\rangle \times \delta(E_{\mathbf{k}a} - E_F), \quad (3)$$

$$\delta\mathbf{S}_1^{\rm inter} = -\frac{e\hbar}{V}\sum_{\mathbf{k},a\neq b} 2{\rm Re}[\langle\psi_{a\boldsymbol{k}}|\hat{\mathbf{s}}|\psi_{b\boldsymbol{k}}\rangle\langle\psi_{b\boldsymbol{k}}|\mathbf{E}\cdot\hat{\mathbf{v}}|\psi_{a\boldsymbol{k}}\rangle] \times \frac{\Gamma(E_{\mathbf{k}a} - E_{\mathbf{k}b})}{[(E_{\mathbf{k}a} - E_{\mathbf{k}b})^2 + \Gamma^2]^2}(f_{\mathbf{k}a} - f_{\mathbf{k}b}), \quad (4)$$

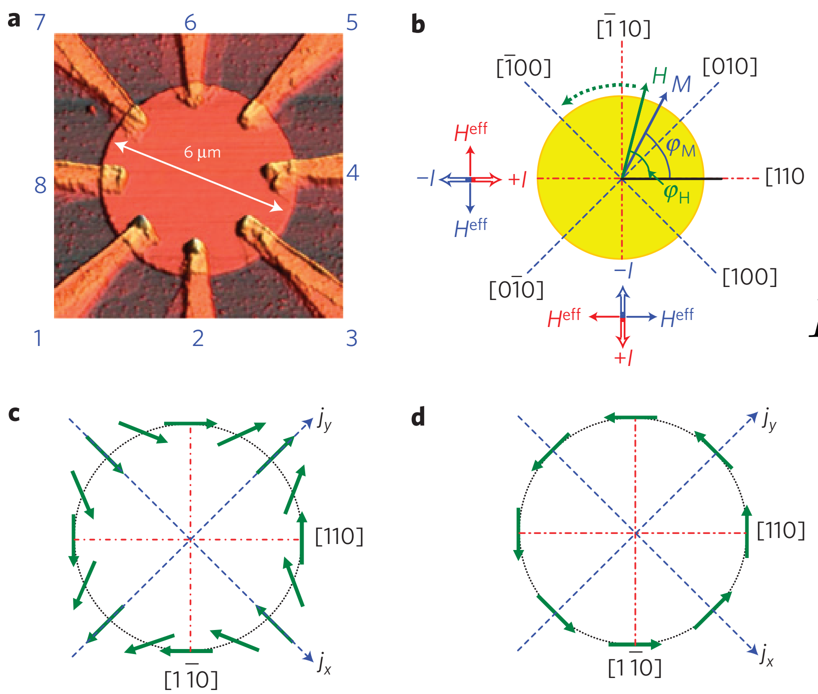
$$\delta\mathbf{S}_2^{\rm inter} = -\frac{e\hbar}{V}\sum_{\mathbf{k},a\neq b} {\rm Im}[\langle\psi_{\mathbf{k}a}|\hat{\mathbf{s}}|\psi_{\mathbf{k}b}\rangle\langle\psi_{\mathbf{k}b}|\mathbf{E}\cdot\hat{\mathbf{v}}|\psi_{\mathbf{k}a}\rangle] \times \frac{\Gamma^2 - (E_{\mathbf{k}a} - E_{\mathbf{k}b})^2}{[(E_{\mathbf{k}a} - E_{\mathbf{k}b})^2 + \Gamma^2]^2}(f_{\mathbf{k}a} - f_{\mathbf{k}b}). \quad (5)$$



Li et al. '15
Phys Rev B 91, 134402

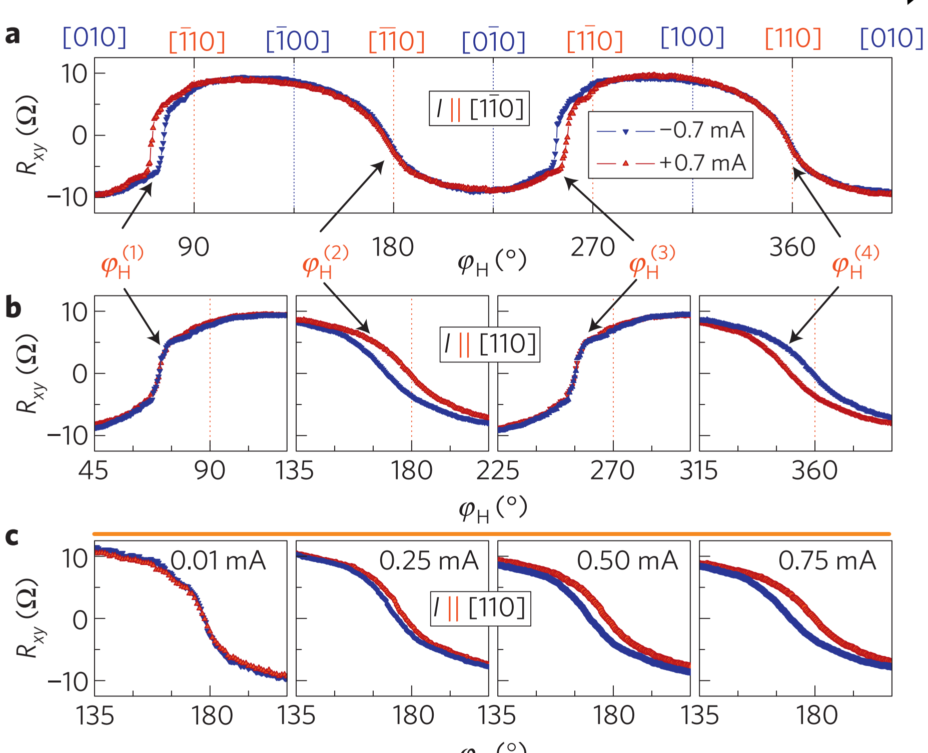
Current-induced field - experiment in (Ga,Mn)As

static case



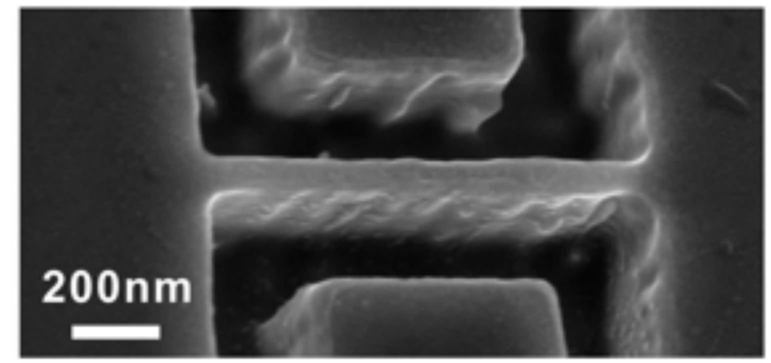
transversal AMR (planar Hall effect)

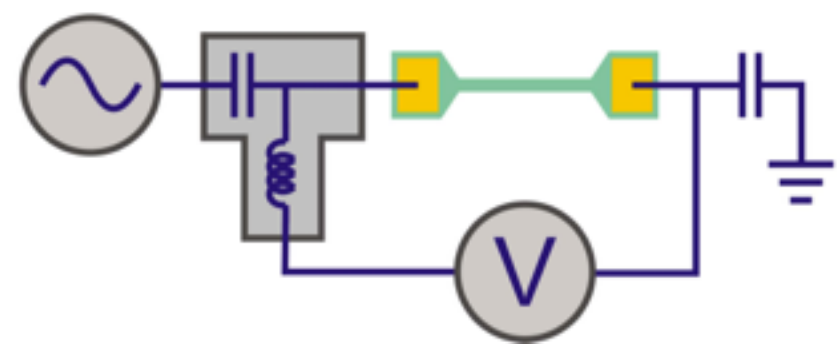
$$R_{xy} = (R_{||} - R_{\perp})\sin 2\varphi_M$$

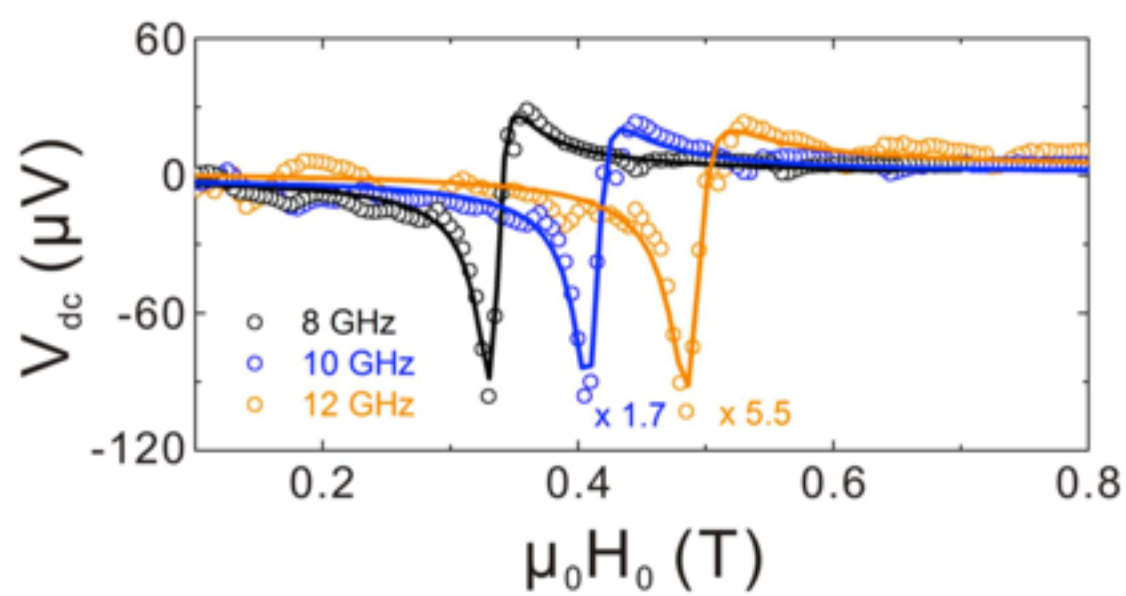


Chernyshev et al., Nat Phys (2009)

dynamic case







Fang et al., Nat Nano (2011)

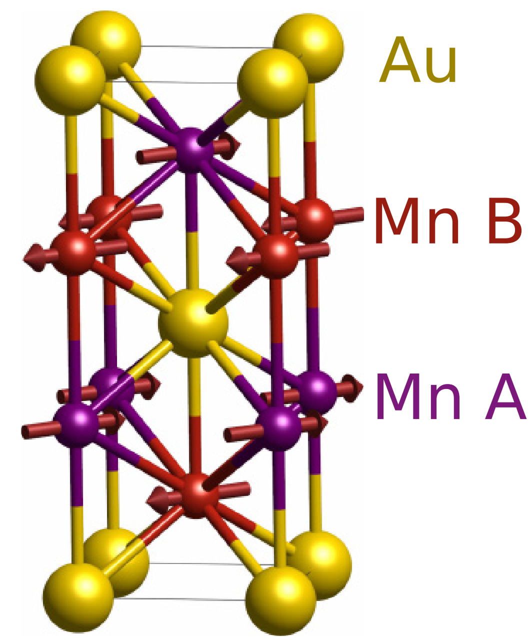
Current-induced spin-orbit torque - for antiferromagnets

Edelstein effect…

$$\delta \mathbf{S}_a = \chi_a \mathbf{E} \qquad \text{(CISP)}$$

(sublattice-resolved)

… staggered CISP



Mn_2Au

$$\chi_A^{\text{even}} = -\chi_B^{\text{even}}$$
$$\chi_A^{\text{odd}} = \chi_B^{\text{odd}},$$

Symmetry considerations:

$$\chi_{a,ij}(\hat{\mathbf{n}}) = \chi^{(0)}_{a,ij} + \chi^{(1)}_{a,ij,k}\hat{n}_k + \chi^{(2)}_{a,ij,kl}\hat{n}_k\hat{n}_l + \cdots$$

where n is the Néel vector, $\mathbf{L} = L\hat{\mathbf{n}} = \mathbf{M}_1 - \mathbf{M}_2$

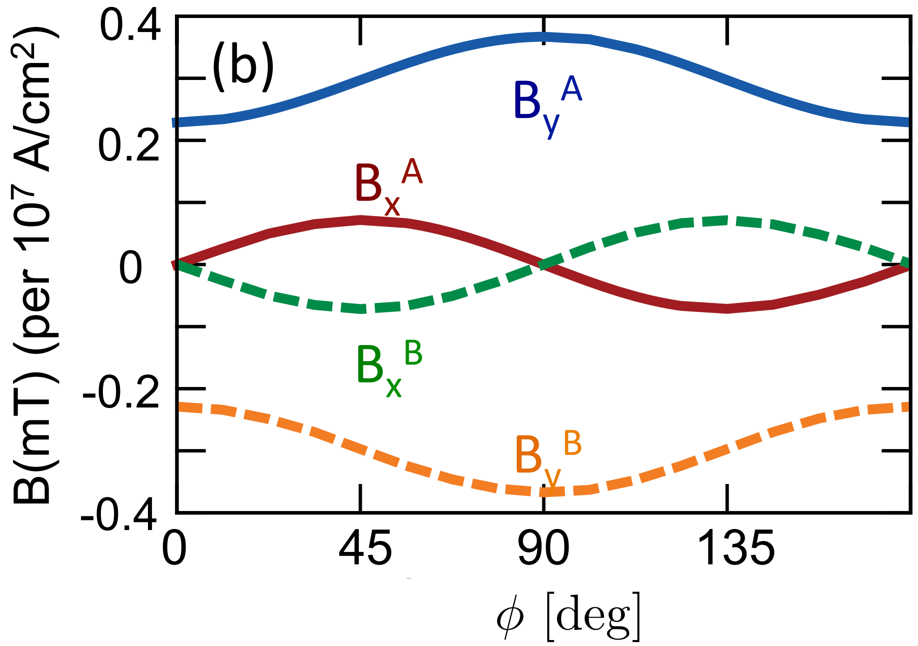
Železný et al. '17
Phys Rev B 95, 014403

Crystal system	Point group	$\chi^{(0)}$	$\chi^{(1)}$
tetragonal	4	$\begin{pmatrix} x_{11} & -x_{21} & 0 \\ x_{21} & x_{11} & 0 \\ 0 & 0 & x_{33} \end{pmatrix}$	$\begin{pmatrix} \hat{n}_z x_6 & -\hat{n}_z x_2 & \hat{n}_x x_5 - \hat{n}_y x_7 \\ \hat{n}_z x_2 & \hat{n}_z x_6 & \hat{n}_x x_7 + \hat{n}_y x_5 \\ \hat{n}_x x_4 - \hat{n}_y x_3 & \hat{n}_x x_3 + \hat{n}_y x_4 & \hat{n}_z x_1 \end{pmatrix}$

…

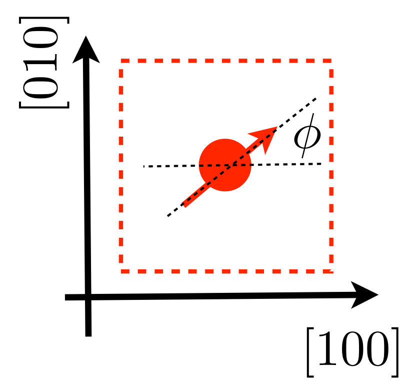
Spin-orbit torque in model systems

Železný et al. ’14
Phys Rev Lett 113, 157201



	intra	inter
Mn_2Au	staggered field-like	normal anti-damping
Rashba	normal field-like	staggered antidamping

- **intraband non-equilibrium spin polarization**
- **projected to sublattice A/B**



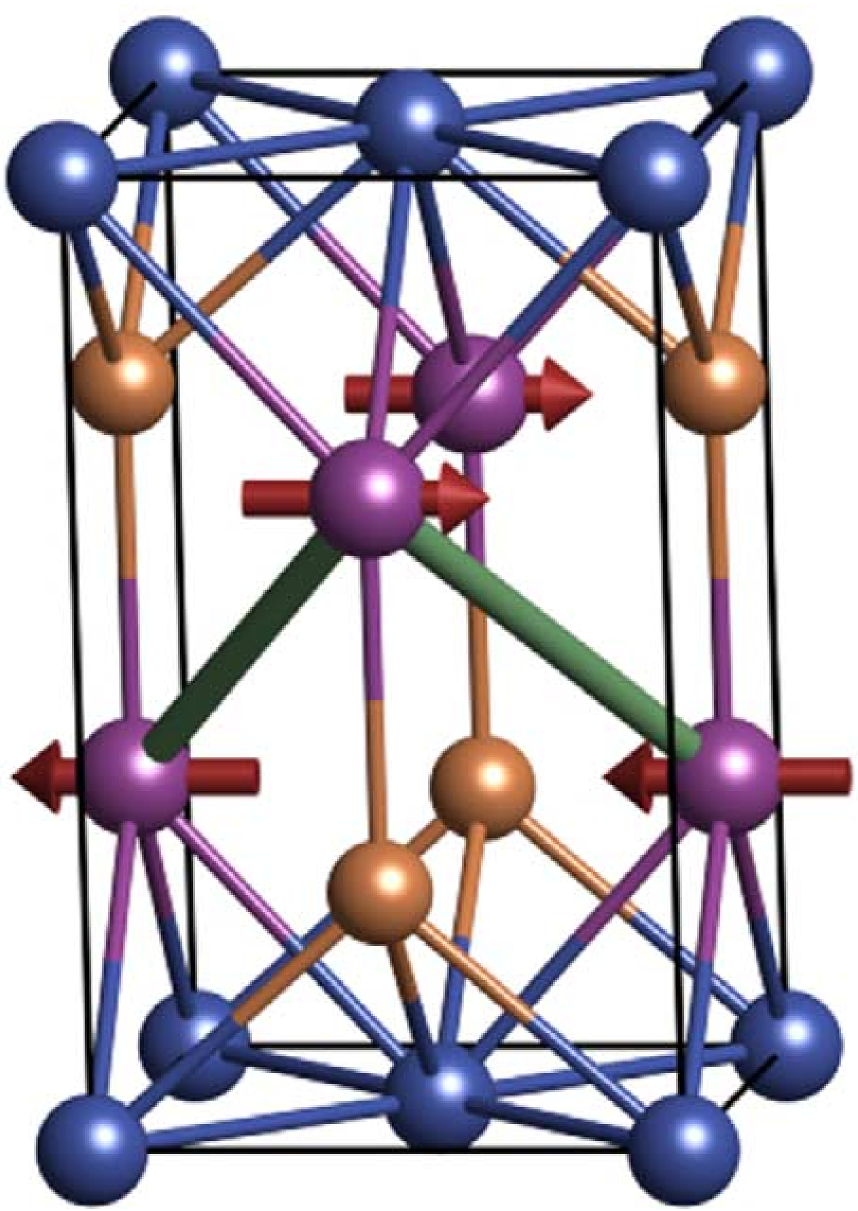
- interband part
- both extrinsic and intrinsic contributions, e.g.

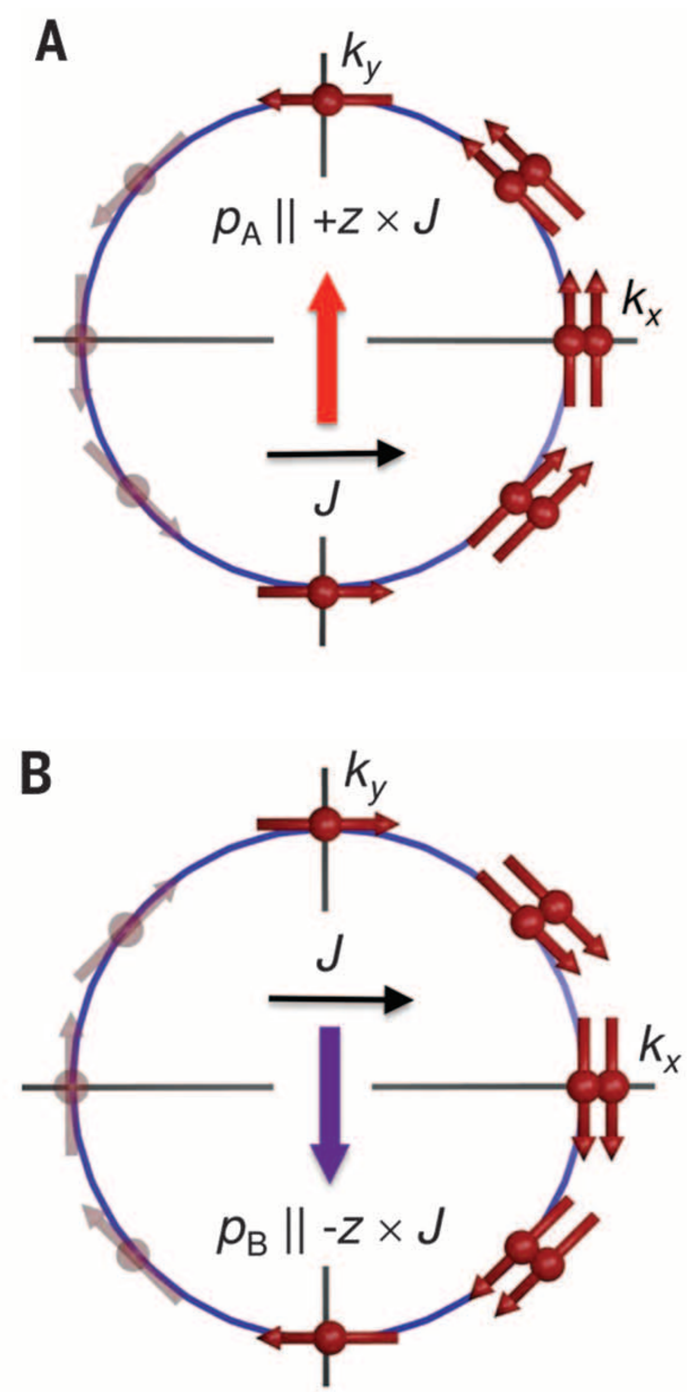
$$\delta\vec{s}^{\text{intra}} = \frac{eE\hbar}{2\Gamma}\int\frac{d^3k}{(2\pi)^3}\sum_\alpha(\vec{s})^{\text{A}}_{\vec{k}\alpha}(v_I)_{\vec{k}\alpha}\delta(E_{\vec{k}\alpha}-E_F)$$

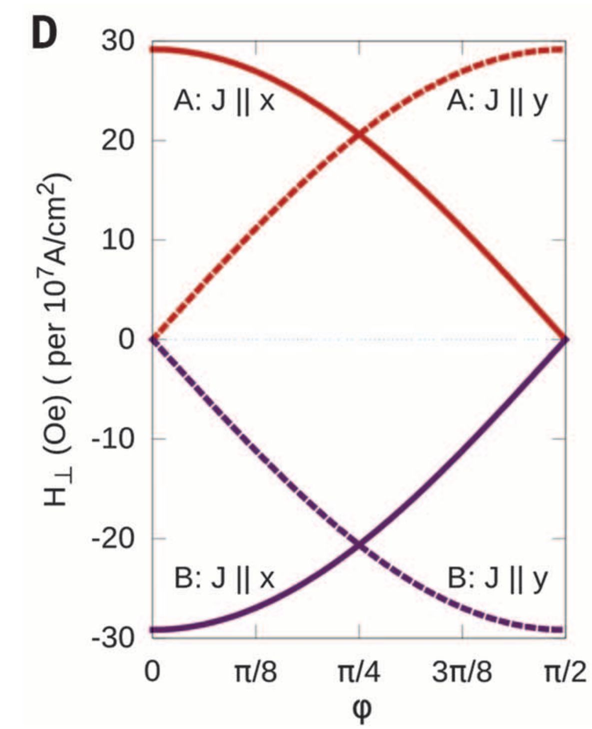
$$\delta\vec{s}^{\text{inter}} = \frac{\hbar}{L^2}\sum_{\vec{k}\alpha\neq\beta}(f_{\vec{k}\alpha}-f_{\vec{k}\beta})\frac{\text{Im}[(\vec{s})^{\text{A}}_{\alpha\beta}(e\vec{E}\cdot\vec{v})_{\beta\alpha}]}{(E_{\vec{k}\alpha}-E_{\vec{k}\beta})^2}$$

Spin-orbit torque in CuMnAs

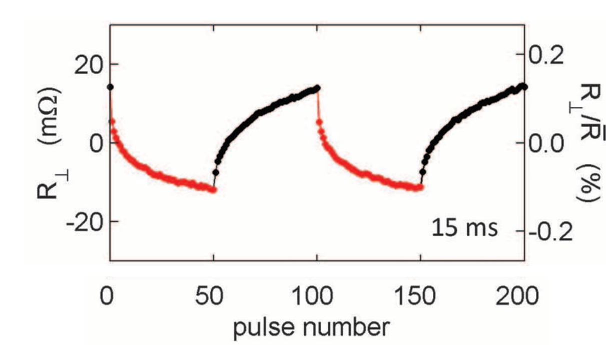
CuMnAs tetragonal





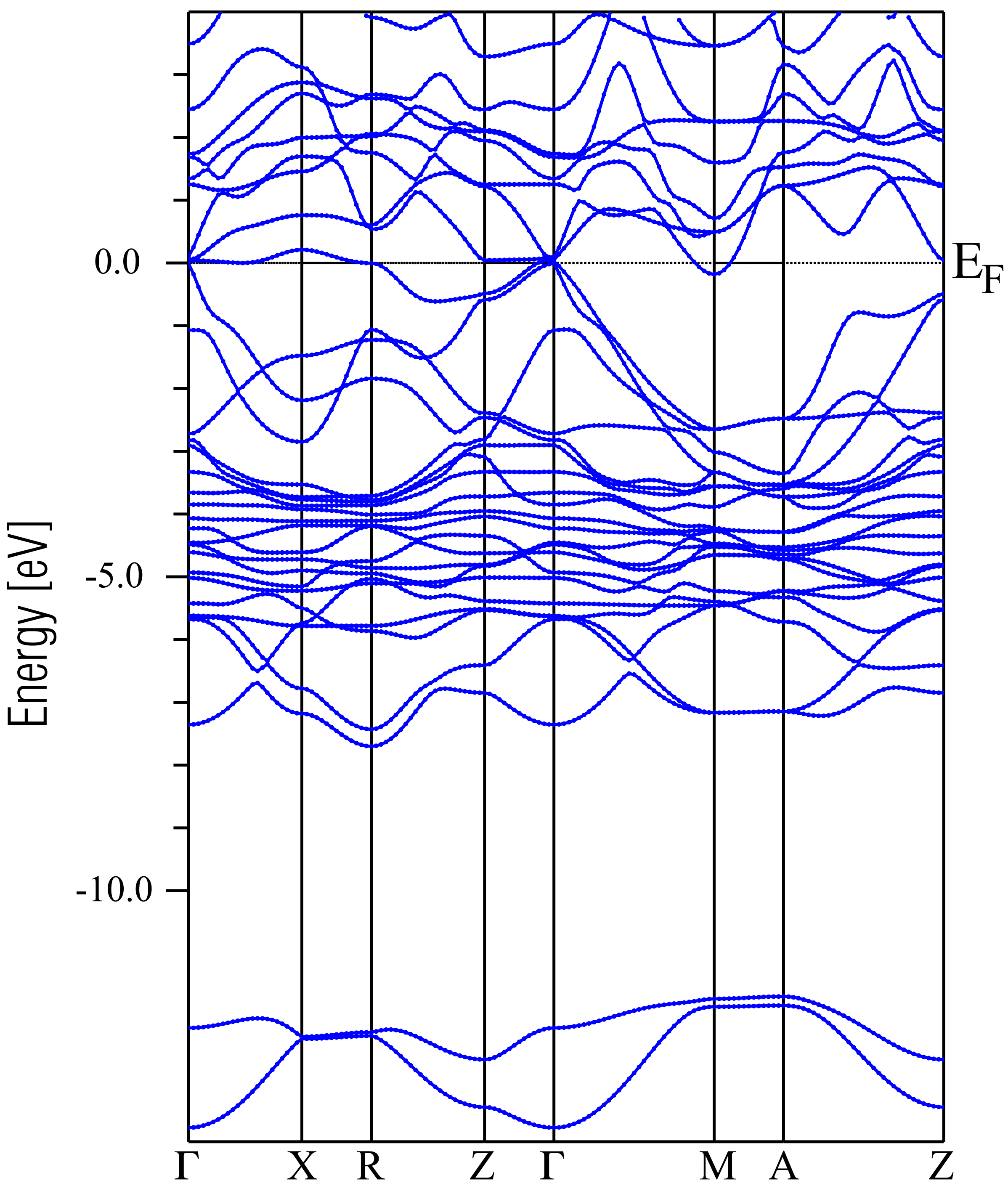


train of ‘write’ pulses:



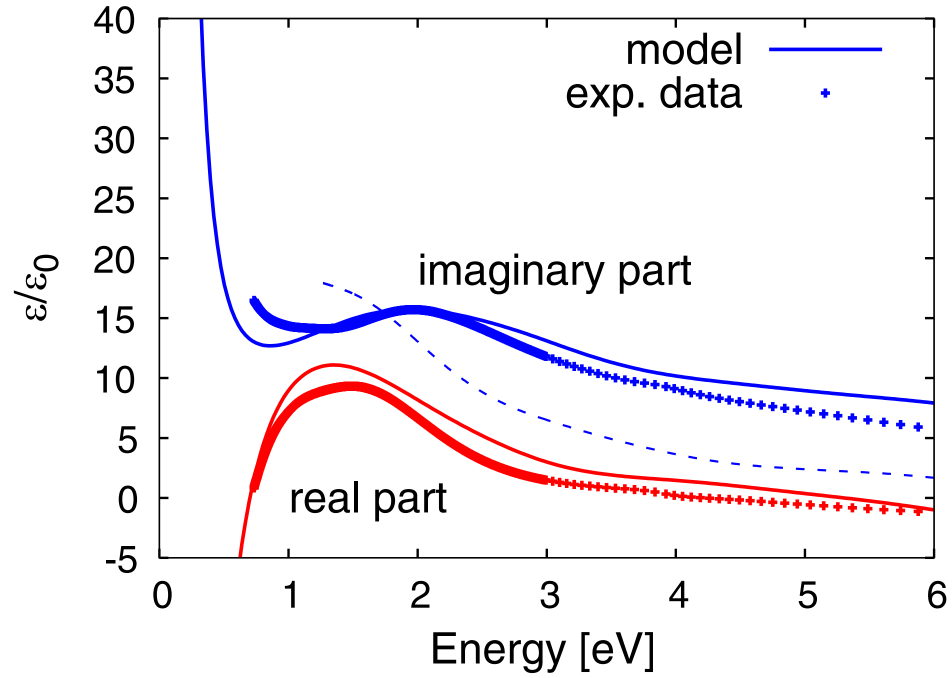
Wadley et al. ’16
Science 351, 587

ab initio modelling - CuMnAs

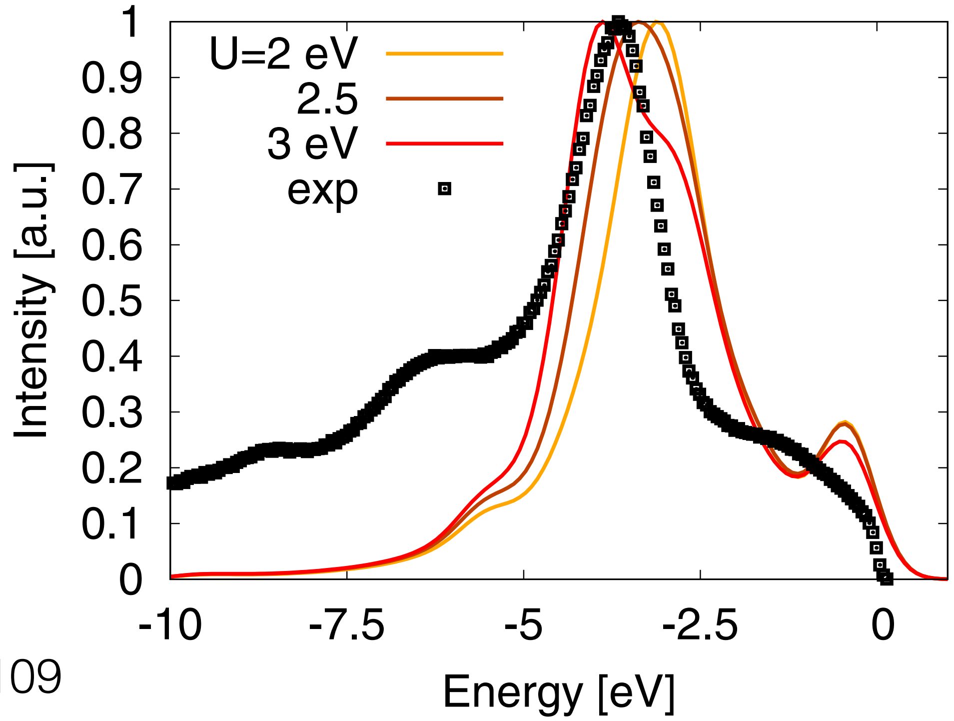


Veis et al. '18
Phys Rev B 97, 125109

ellipsometry



photoemission



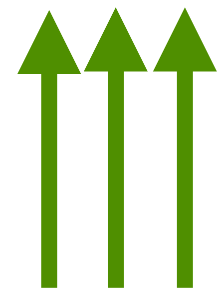
Barrier to spin switching: magnetic anisotropy

… back to spin flop

$$B_{sf} = 2\sqrt{B_a B_e}$$

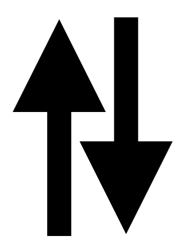
Why spin flop?

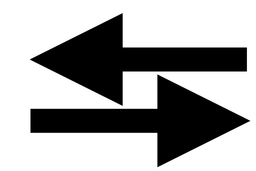
- consider only AFM exchange & “Zeeman”
- no energy gain possible

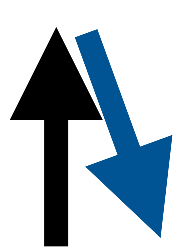


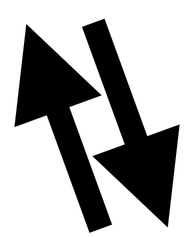
$\vec{B}$

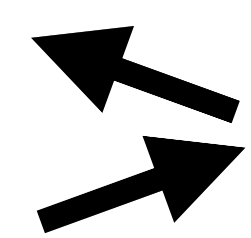
- rotate & cant
  loss in exchange energy
- compensated by “Zeeman”











$\Delta E \propto 1 - \cos\alpha$

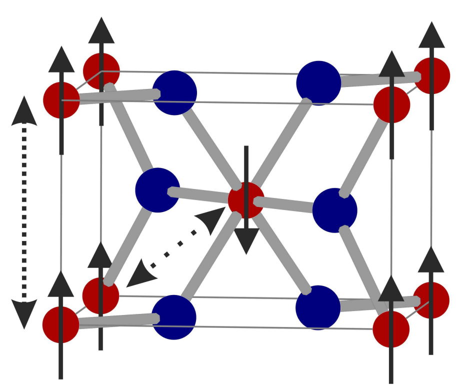
+: $\Delta E \propto 1 - \cos\alpha$

- : $\Delta E \propto \sin\alpha$

Comparison between experiment and model

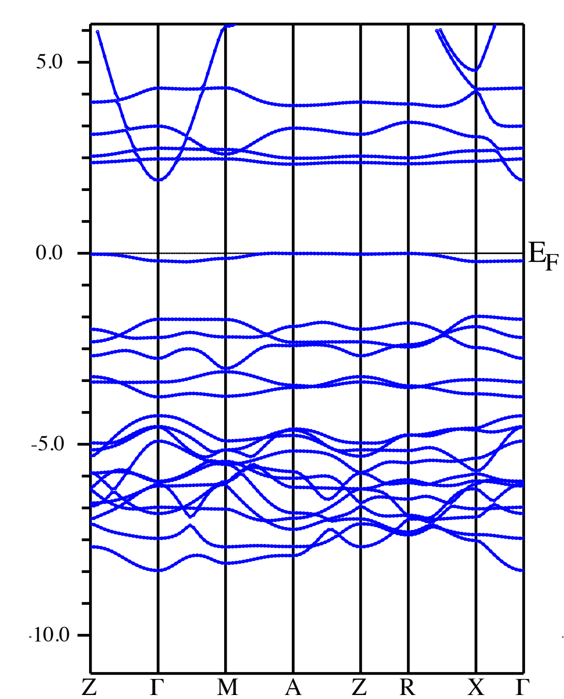
- let's make a theoretical estimate of B_{sf}
- microscopic origin of magnetic anisotropy in an antiferromagnet

dipole-dipole int.



$$\vec{B}_j = \frac{\mu_0}{4\pi} \sum_i \frac{3(\hat{\mu}_i \cdot \hat{r}_{ij})\vec{r}_{ij} - \vec{\mu}_i}{|\vec{r}_{ij}|^3}$$

magnetocrystalline anisotropy (MCA)



The three fluorides

	MnF_2	FeF_2	CoF_2
spin flop [T]	9.3	41.9	14.0
mag. anisotropy [T]	0.7	14.9	3.2
dominant source	dipolar	MCA	MCA

$$B_{sf} = 2\sqrt{B_a B_e}$$

The three fluorides

	MnF_2	FeF_2	CoF_2
spin flop [T]	9.3	41.9	14.0
mag. anisotropy [T]	0.7	14.9	3.2
dominant source	dipolar	MCA	MCA

Beware of the definition!

$$\frac{E}{MV} = B_e \vec{m}_1 \cdot \vec{m}_2 - B\vec{b} \cdot (\vec{m}_1 + \vec{m}_2) + B_a[(\vec{m}_1 \cdot \hat{z})^2 + (\vec{m}_2 \cdot \hat{z})^2].$$

(Stoner-Wohlfarth)

spin flop field: $B_{sf} = 2\sqrt{B_a B_e}$

The path to B_a

- measured: B_{sf} & T_N
- mean-field mapping of SW to spin model:

$$\frac{kT_N}{J} = \frac{1}{3}S(S+1)$$

- spin-lattice Hamiltonian: $H = J\sum_{\langle i,j\rangle} \vec{S}_i \cdot \vec{S}_j$
- effective field

$$B_e = NJS^2/MV$$

- combine B_{sf} and B_e

MA: quantitative summary

TABLE I. Parameters of MnF_2, FeF_2, CoF_2 and NiF_2 related to magnetism. Note that definitions of B_e and B_a vary through literature.

	MnF_2		FeF_2		CoF_2		NiF_2	
	exp	calc	exp	calc	exp	calc	exp	calc
mag.mom. [μ_B]	5.04[5]	4.4	3.93,[5] 3.75[6]	3.6	2.21[5]	2.6	1.96[5]	1.63
ideal S	2.5		2		1.5		1	
B_e [T]	46.5[7], 57.5[3]	85.5	43.4[7], 62[3]	116.7	32.4[7]	67.4		163.5
B_a [T]	0.697[7], 0.8[3]	0.42	14.9[7], 19.2[3]	2.6	3.2[7]	0.73*		−0.50
$B_a^{(1)}$ [T]		$0.2\cdot10^{-3}$		2.3		0.52*		−0.71
dipolar term		418 mT		317 mT		211 mT		203 mT
B_{sf} [T]	9.27[8]	12.0	41.9[9]	34.8	14.0[7]	***		
T_N [K]	67.7[5]		75.8[5]		37.7[10]		74.1[5]	

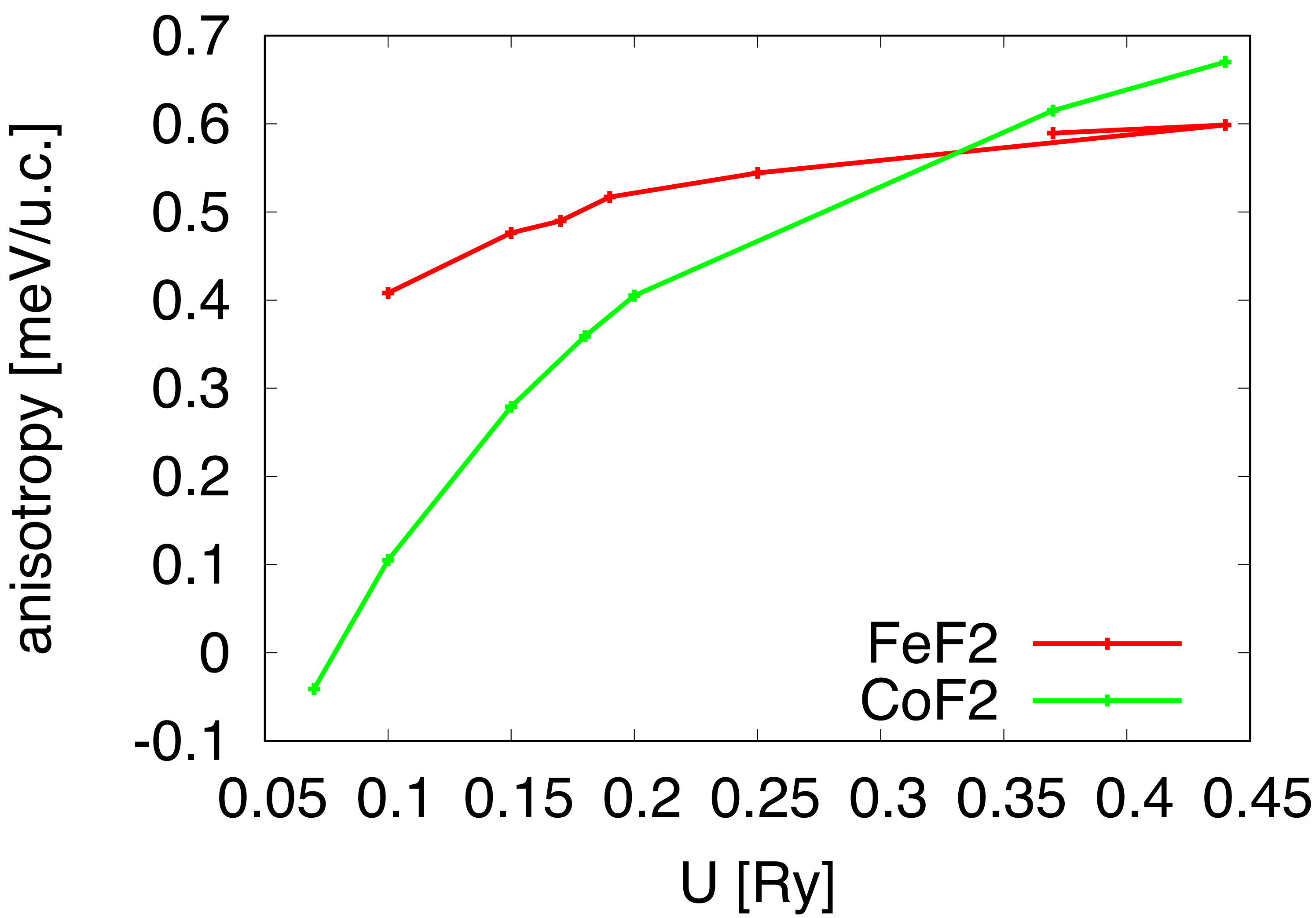
electronic config.:

$3d^5$ $3d^6$ $3d^7$ $3d^8$

Correa et al. '18

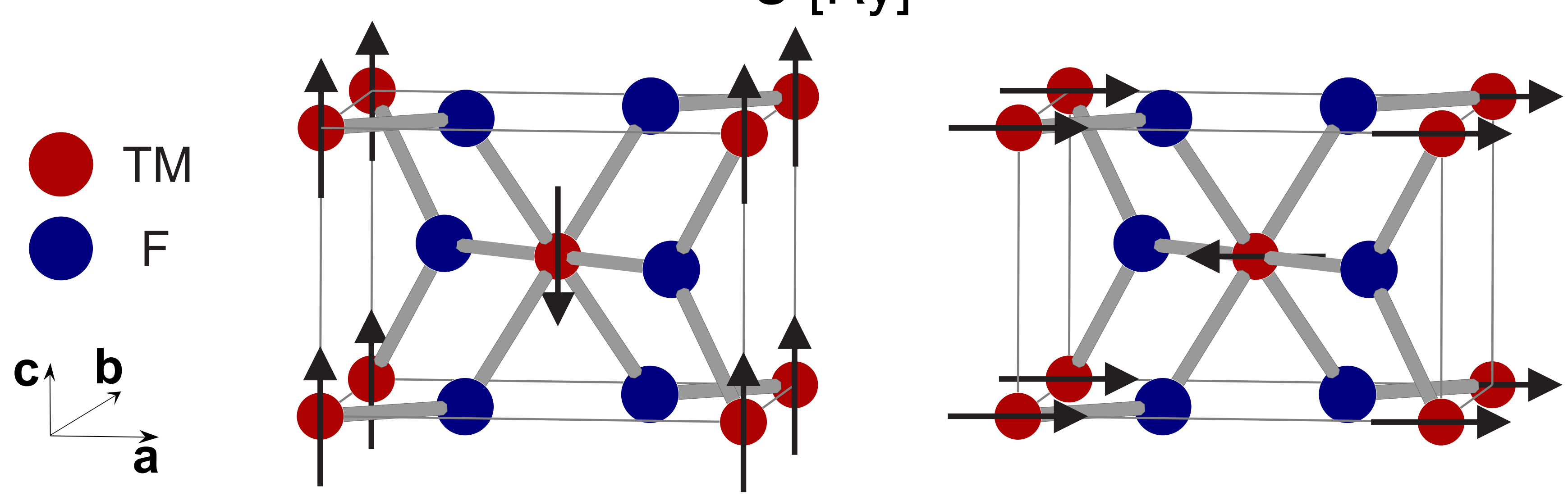
Phys Rev B 97, 235111

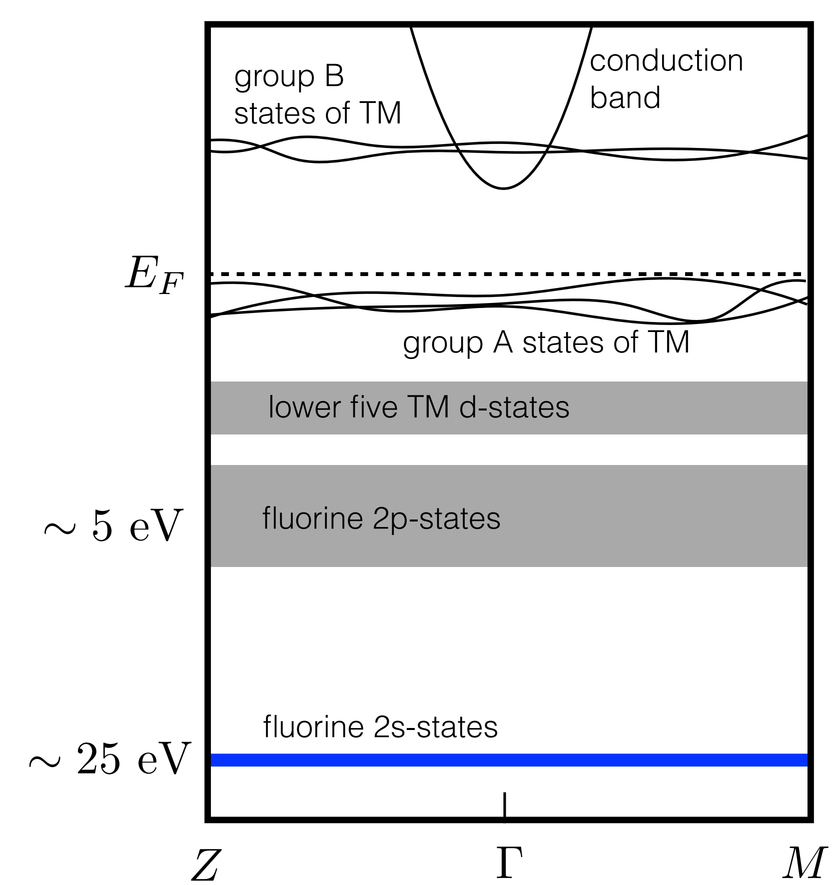
MA: magnetocrystalline contribution (MCA)



effect of Hubbard U:

- pushing d-states
- size of optical gap





Theoretical estimates

	MnF_2	FeF_2	CoF_2
mag. anisotropy	0.42 T	2.6 T	n/a
MCA	< 1 mT	2.3 T	~1 T

Manipulation of magnetic moments - dynamics

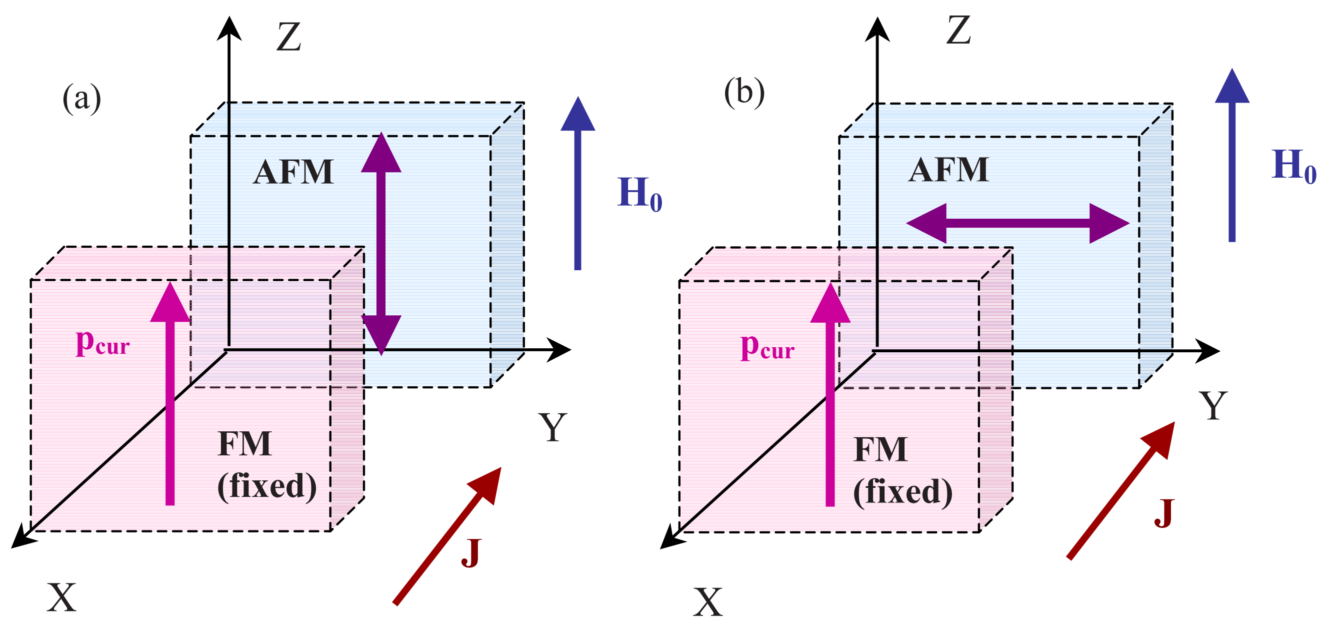
$$\frac{\partial \mathbf{m}}{\partial t} = \gamma \mathbf{m} \times \mathbf{H}^{\text{eff}} + \frac{\alpha}{|\mathbf{m}|} \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t}$$

for ferromagnets:
Landau-Lifshitz-Gilbert eq.

Manipulation of magnetic moments - dynamics

$$\frac{\partial \mathbf{m}}{\partial t} = \gamma \mathbf{m} \times \mathbf{H}^{\text{eff}} + \frac{\alpha}{|\mathbf{m}|} \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t}$$

(Landau-Lifshitz-Gilbert eq.)



Switching AFM in a multilayer
by current pulses … extend LLG

Gomonay & Loktev, '10
Phys Rev B 81, 144427

Manipulation of magnetic moments - dynamics

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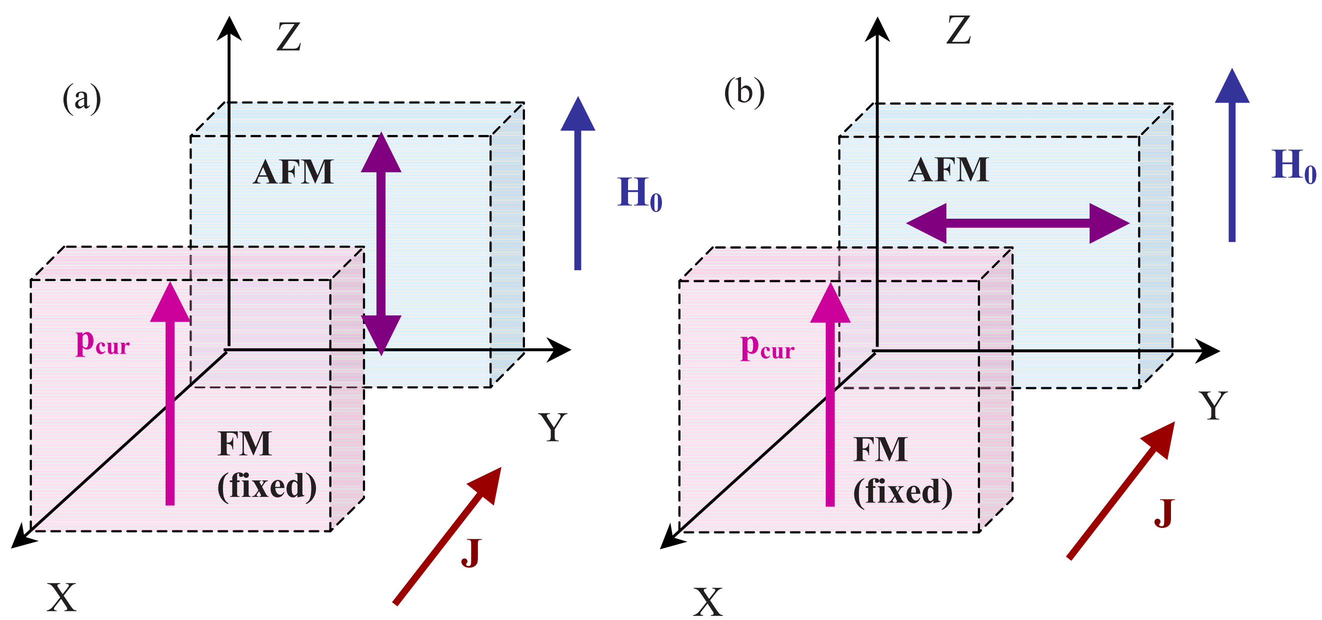
$$\dot{\mathbf{M}}_j = -\gamma(\mathbf{M}_j \times \mathbf{H}_j) + \frac{\alpha_G}{M_{0j}}(\mathbf{M}_j \times \dot{\mathbf{M}}_j) + \frac{\sigma_j J}{M_{0j}}[\mathbf{M}_j \times (\mathbf{M}_j \times \mathbf{p}_{\text{cur}})],$$



introduce the Néel vector

$$\vec{m} = \vec{M}_1 + \vec{M}_2$$

$$\vec{l} = \vec{M}_1 - \vec{M}_2$$

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Manipulation of magnetic moments - dynamics

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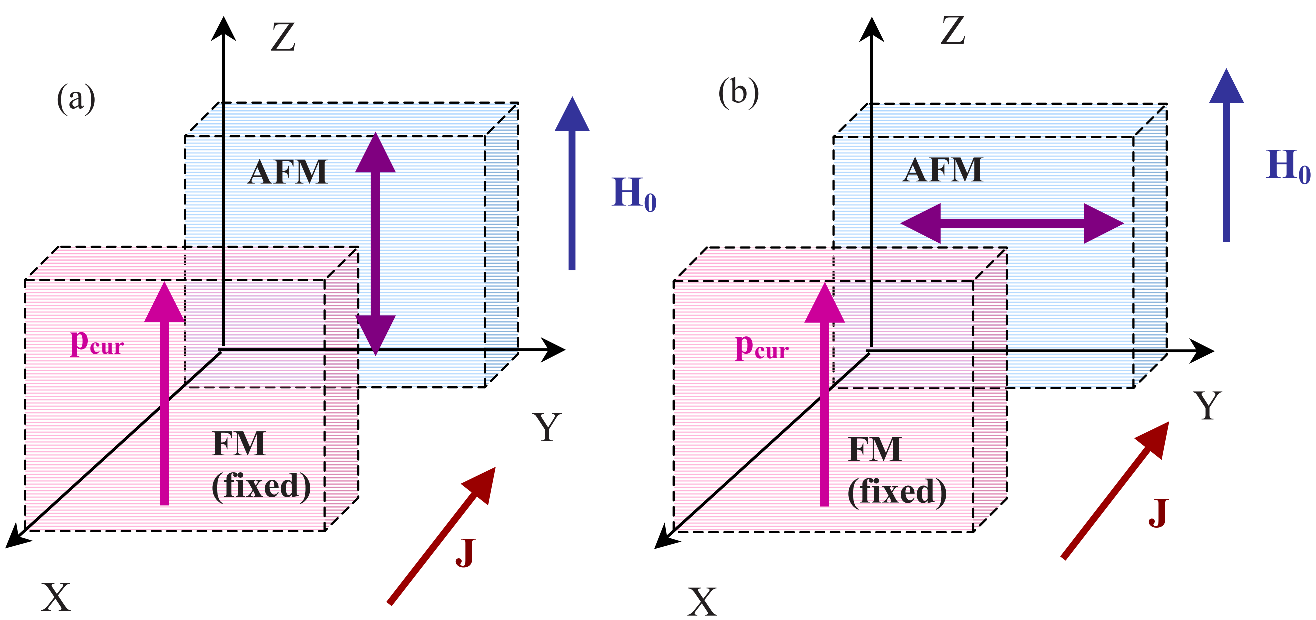
$$\vec{l} = \vec{M}_1 - \vec{M}_2$$

$$\ddot{l}_X + 2\gamma_{\mathrm{AFM}}\dot{l}_X + (\omega_X^2 + \omega_H^2)l_X + \gamma H_E \sigma J l_Y = 0,$$

$$\ddot{l}_Y + 2\gamma_{\mathrm{AFM}}\dot{l}_Y + \omega_Y^2 l_Y - \gamma H_E \sigma J l_X = 0.$$



Switching AFM: critical current

$$|J| \le J_{\mathrm{cr}}^{(1)} \equiv \frac{1}{2\gamma H_E \sigma}|\omega_X^2 - \omega_Y^2 + \omega_H^2|$$

$$\omega_X = 2\gamma\sqrt{(H_{\mathrm{an}\perp} + H_{\mathrm{an}\parallel})H_E}, \quad \omega_Y = 2\gamma\sqrt{H_{\mathrm{an}\parallel}H_E}$$

Switching AFM in a multilayer by current pulses

$$w_{\mathrm{an}} = \frac{H_{\mathrm{an}\perp}}{M_0}l_X^2 - \frac{H_{\mathrm{an}\parallel}}{8M_0^3}(l_X^4 + l_Y^4 + l_Z^4)$$

Gomonay & Loktev, '10

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Summary

- antiferromagnets do respond to magnetic fields
- … but spin-orbit torques are much more efficient
- barrier to “free manipulation” = magnetic anisotropy
    - magnetocrystalline (spin-orbit)
    - dipolar interaction
- dynamics: generalised LLG (and beyond…)