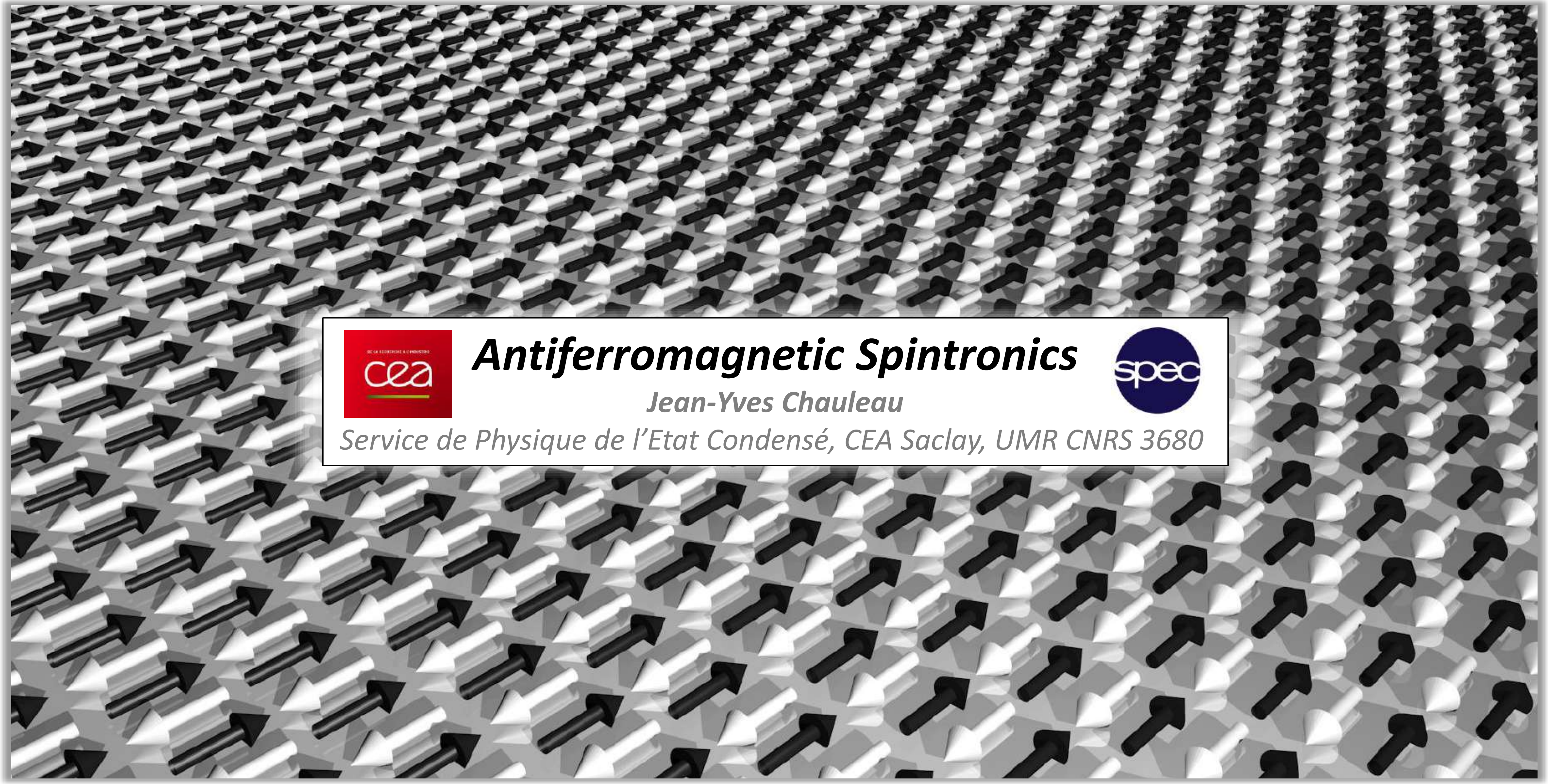
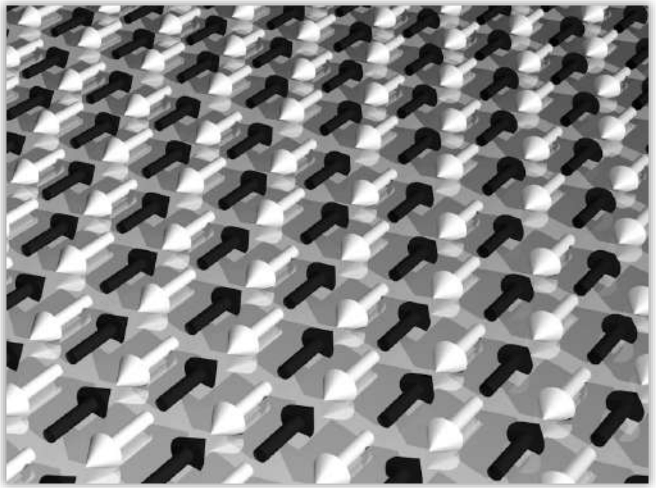


Antiferromagnetic Spintronics

Jean-Yves Chauleau

Service de Physique de l’Etat Condensé, CEA Saclay, UMR CNRS 3680

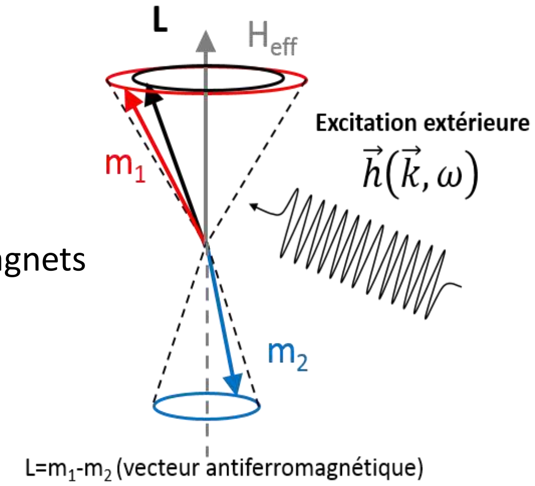
Antiferromagnet



"Antiparallel arrangement of spins"

- ➢ No net magnetization / No magnetic stray field
- ➢ Large majority of magnetic materials are antiferromagnets (metals/ insulators/ with multifunctionnal abilities…)

- ➢ THz magnetic response
- ➢ Picosecond manipulation of the antiferromagnetic order



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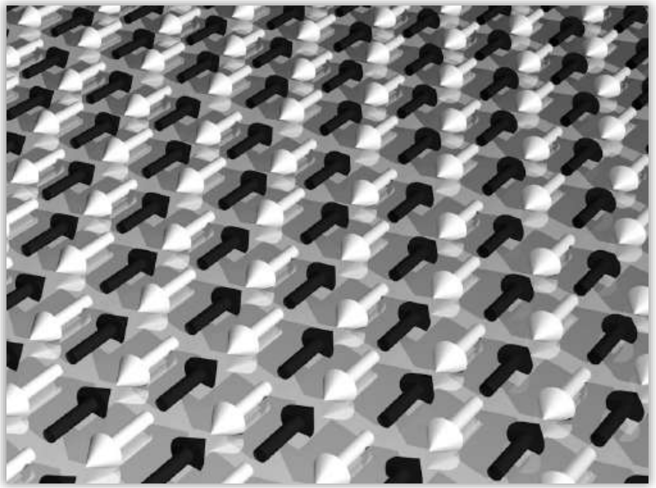

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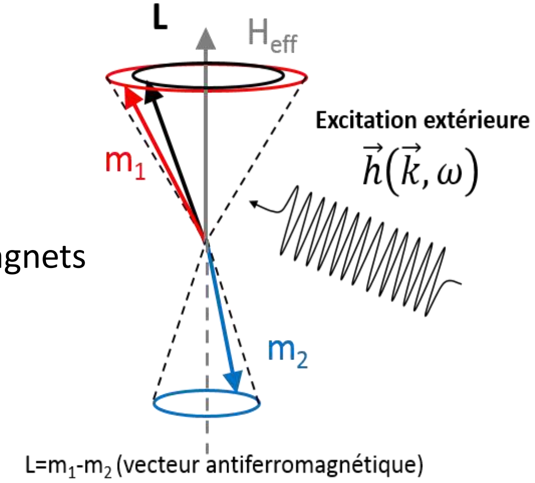
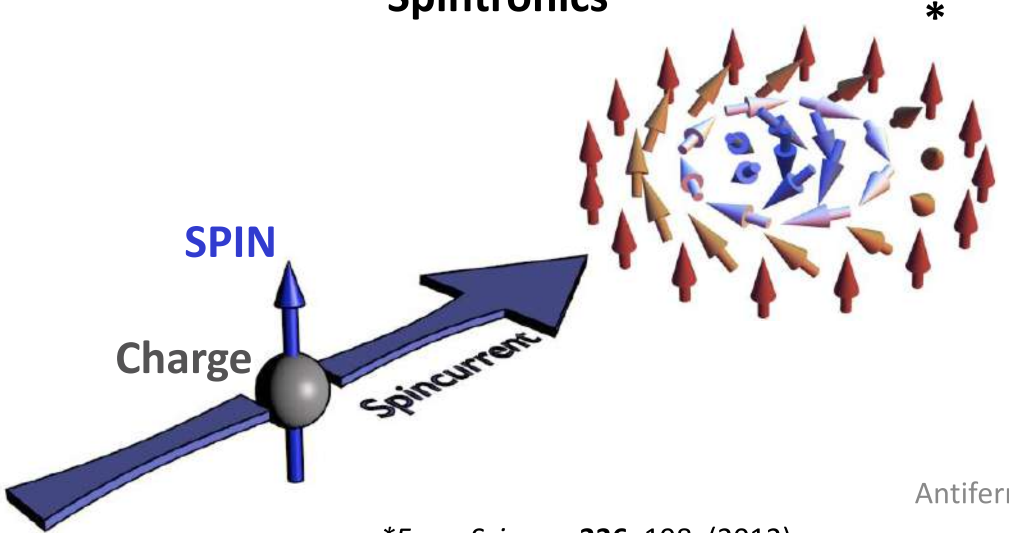


Spintronics



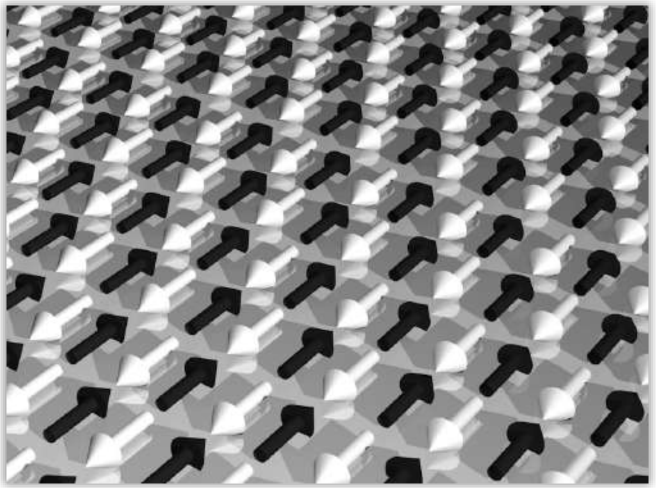
"Interplay between spincurrents and magnetic textures"

- Influence of magnetic textures upon electrical properties
- Generation / Transport / Detection of spincurrents
- Manipulation of magnetic objects using spincurrents (*spin transfer torque, spin-orbit torques…*)

From Science* **336, 198 (2012)

Antiferromagnetic Spintronics

Antiferromagnet



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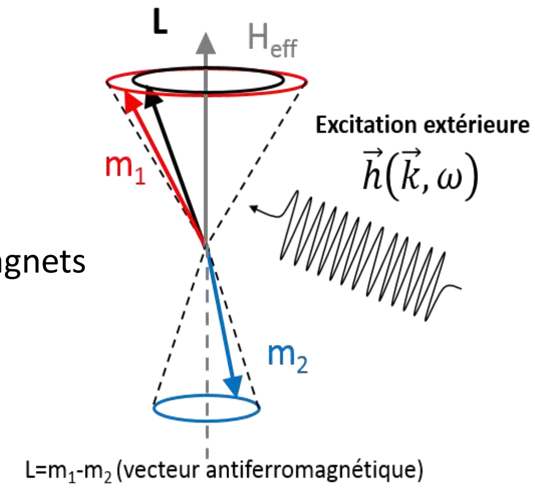

- THz magnetic response
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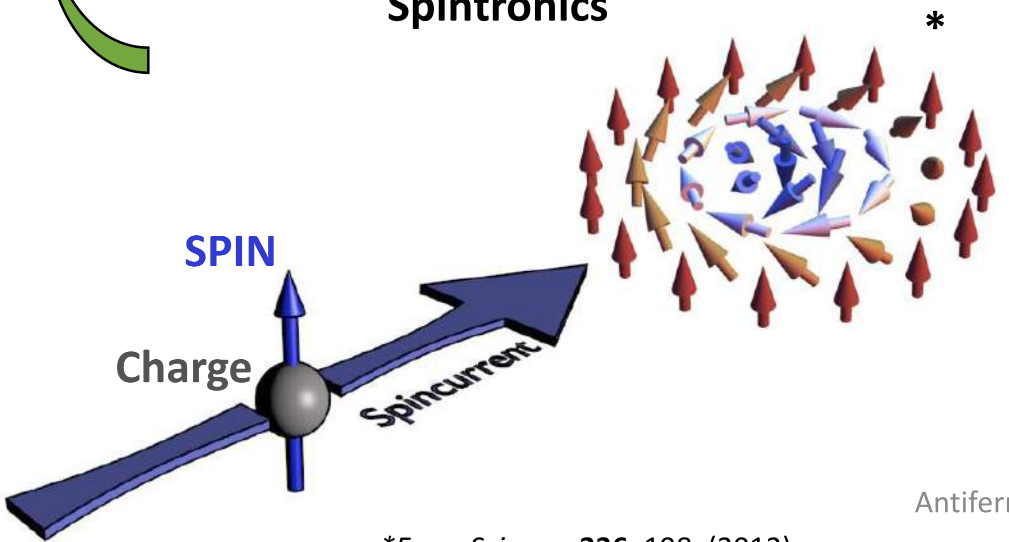
Spintronics



"Interplay between spincurrents and magnetic textures"

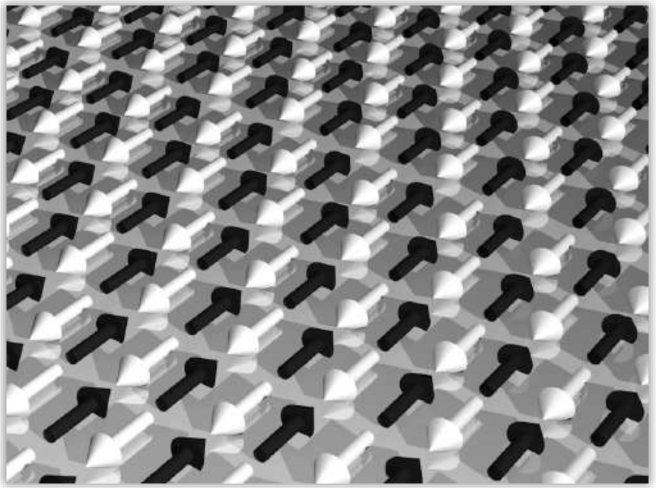
- Influence of magnetic textures upon electrical properties
- Generation / Transport / Detection of spincurrents
- Manipulation of magnetic objects using spincurrents (*spin transfer torque, spin-orbit torques…*)

… Works with/for antiferromagnets !!

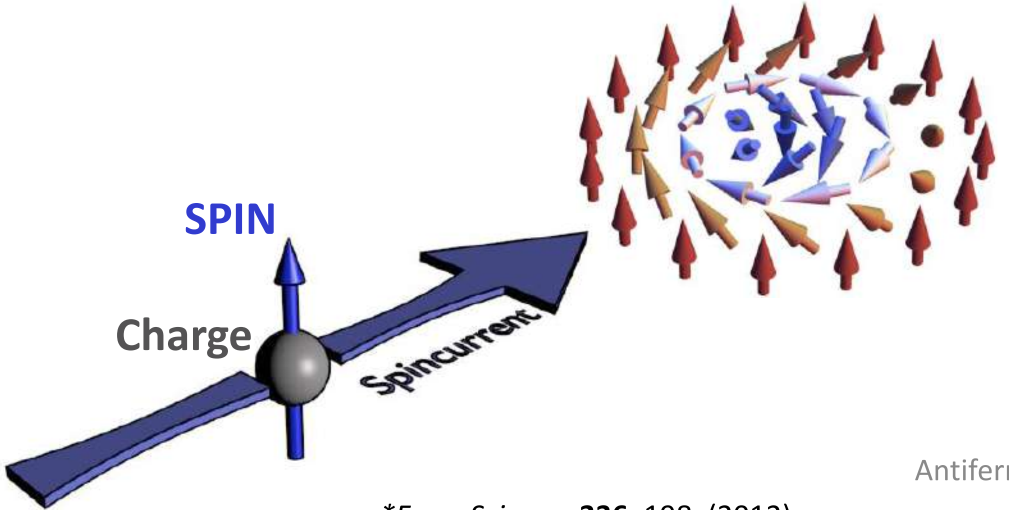
From Science* **336, 198 (2012)

Antiferromagnetic Spintronics

Antiferromagnet



Spintronics *



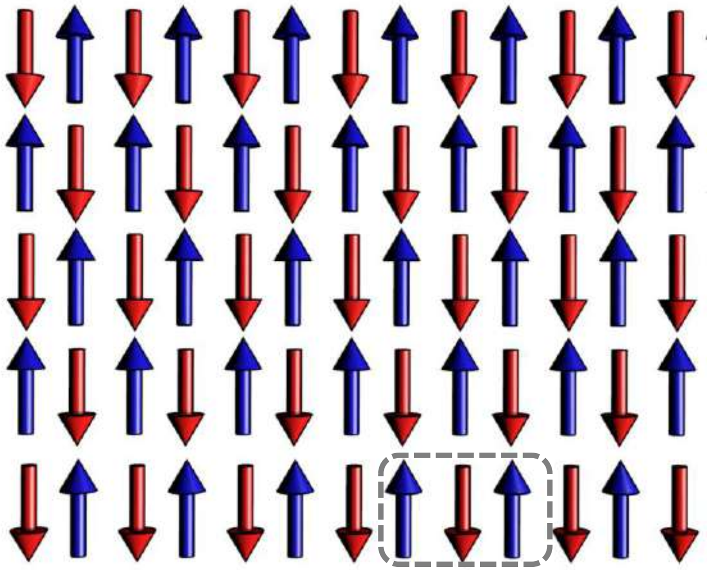
Outline :

1. Generalities about Antiferromagnets
2. Antiferromagnetic dynamics & ultrafast THz capabilities
3. Spincurrents and antiferromagnets
   a) Transport
   b) Manipulation

From Science* **336, 198 (2012)

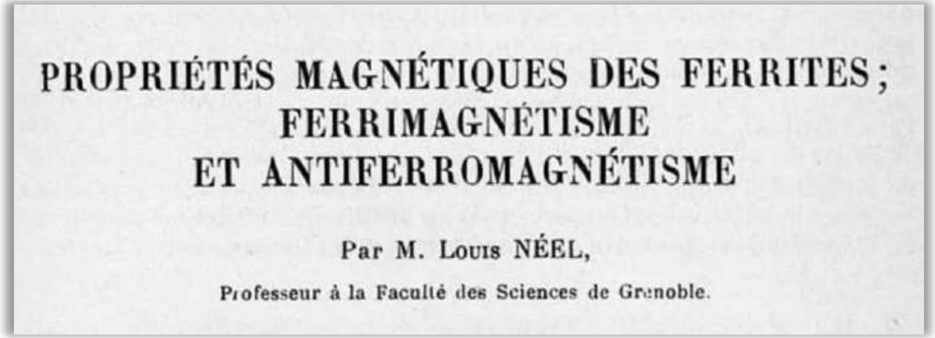
Generalities:

"Antiparallel arrangement of spins"



- Predicated by Louis Néel in 1948

Ann. Phys., **12**, 137 (1948)



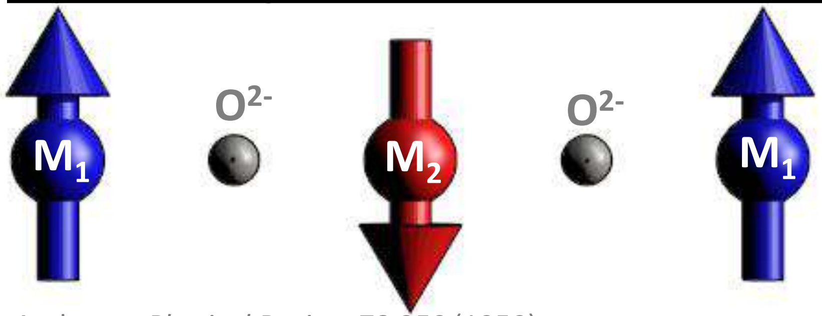
PROPRIÉTÉS MAGNÉTIQUES DES FERRITES ;
FERRIMAGNÉTISME
ET ANTIFERROMAGNÉTISME

Par M. Louis NÉEL,

Professeur à la Faculté des Sciences de Grenoble.

Picture from www.nobelprize.org

Superexchange: main mechanism in oxides



Anderson *Physical Review* ***79*** *350* (1950)
Goodenough *Physical Review* ***100*** *564* (1955)
Kanamori *J. Phys. Chem. Solids* ***10*** *87* (1959)

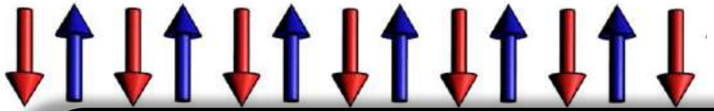
- Negative exchange integral ($\mathfrak{I}_{ij} < 0$), spin antiparallel alignment is favored

$$\mathcal{H}_{ex} = -\sum_{i,j} \mathfrak{I}_{ij} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

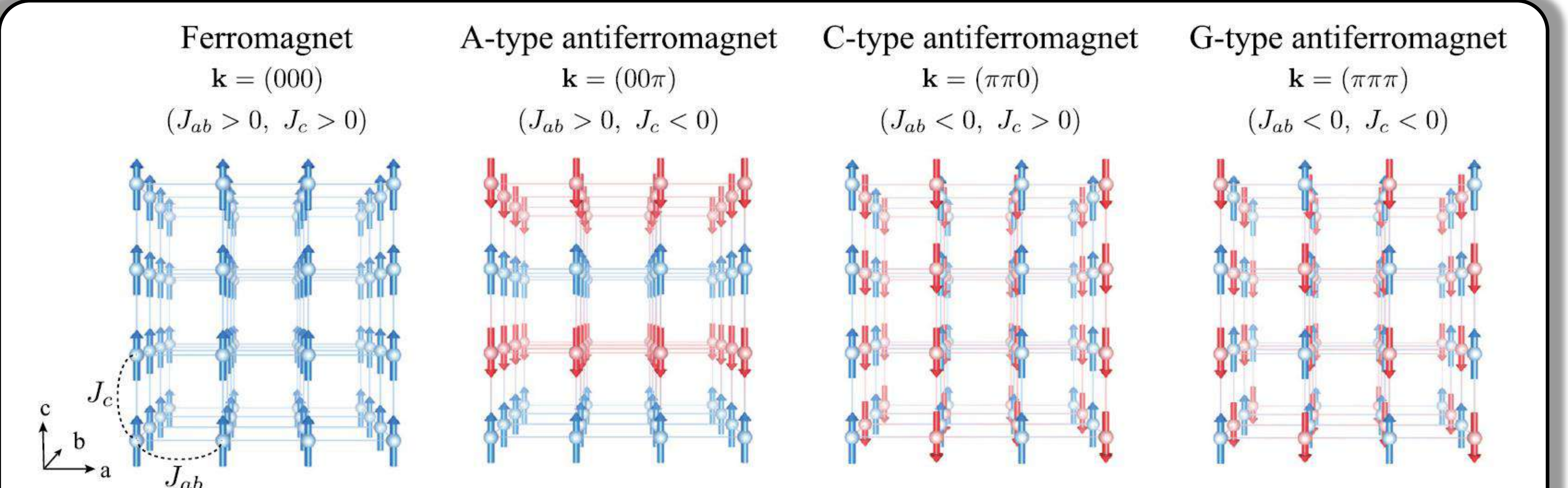
- Antiferromagnets represent a large majority of magnetic materials

Generalities:

"Antiparallel arrangement of spins"



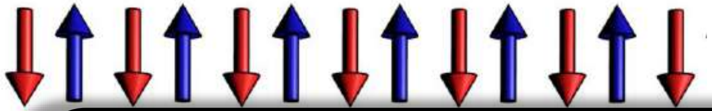
- The various possibilities for spin arrangement of 3D antiferromagnetic textures:

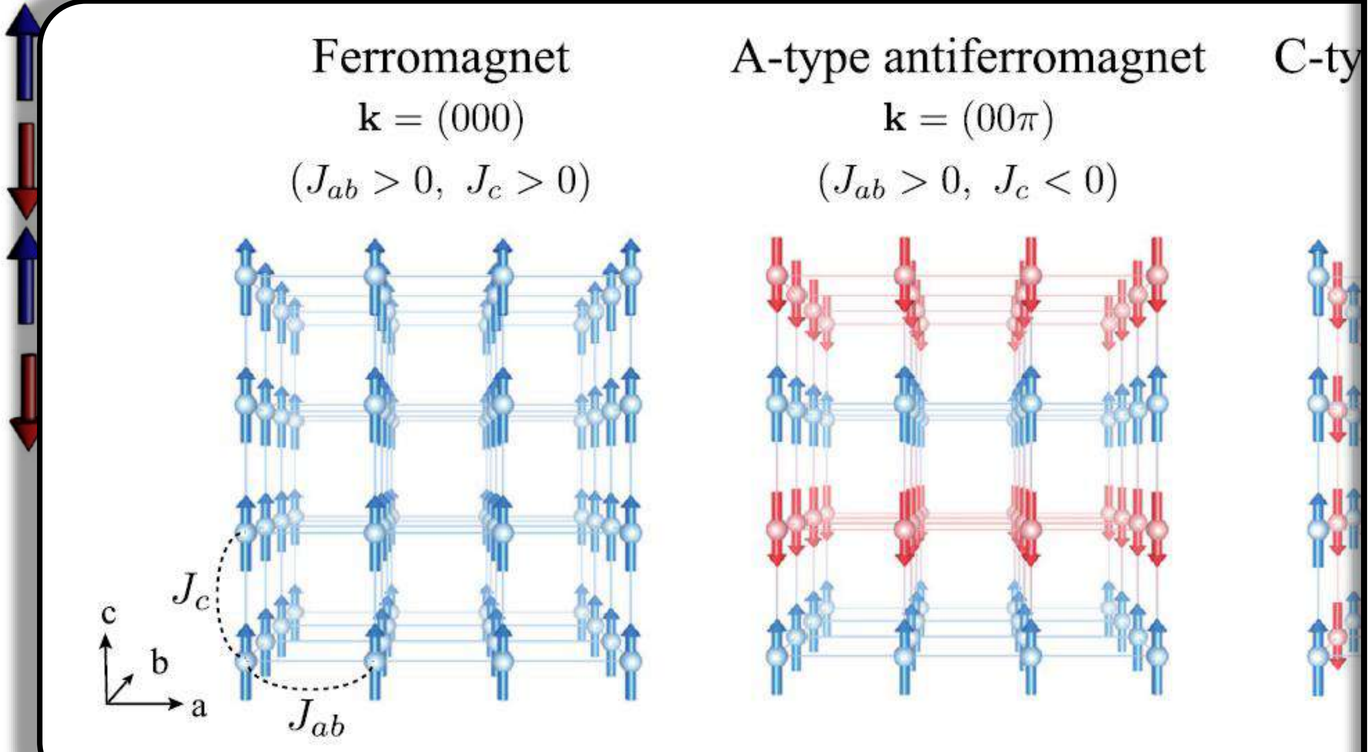


From Tamura et al. *J. Appl. Phys.*, **116**, 053908 (2014)

Generalities:

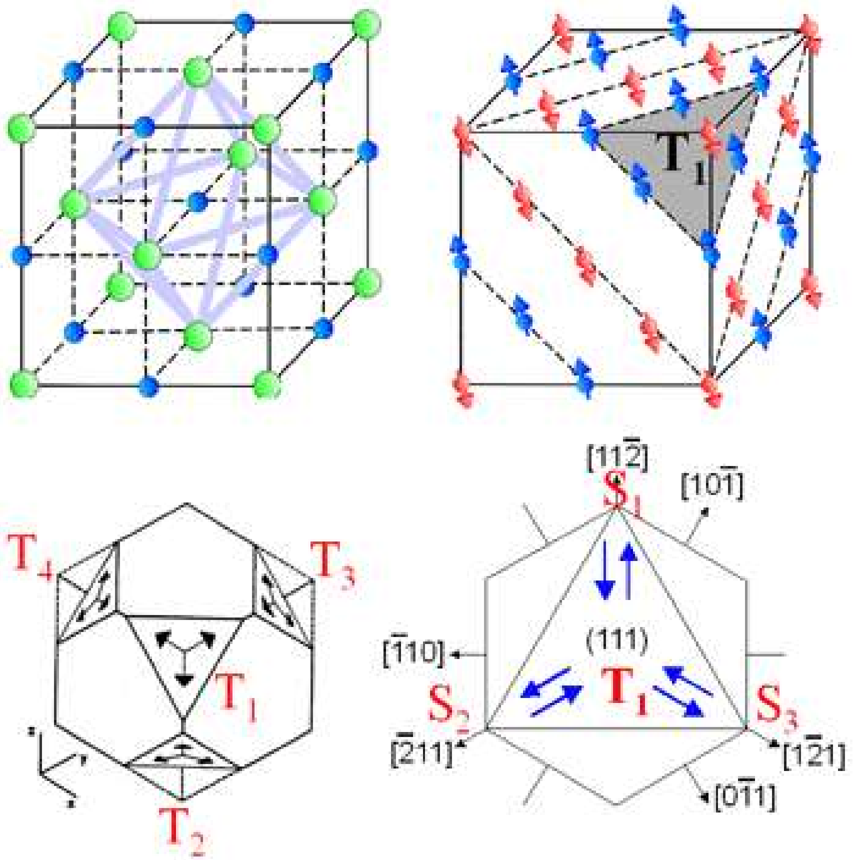
"Antiparallel arrangement of spins"





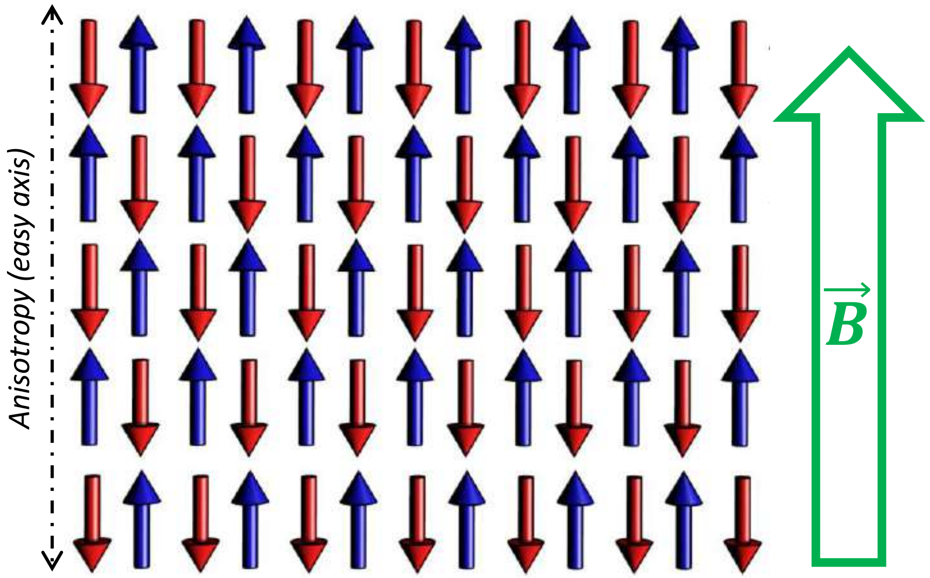
- ➢ The various possibilities for spin arrangement of 3D antiferromagnetic textures:

- ➢ For a G-type antiferromagnet (for ex. NiO)

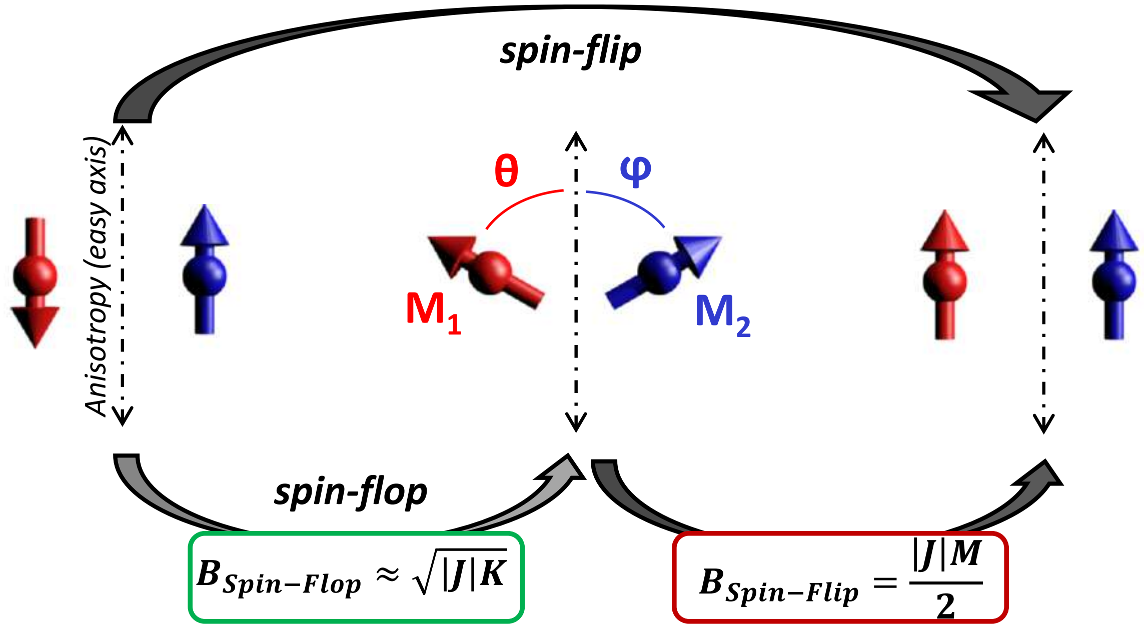


www.hikari.uni-bonn.de/research/multiferroics/

Generalities: Spin-flop (and Spin-flip) transitions



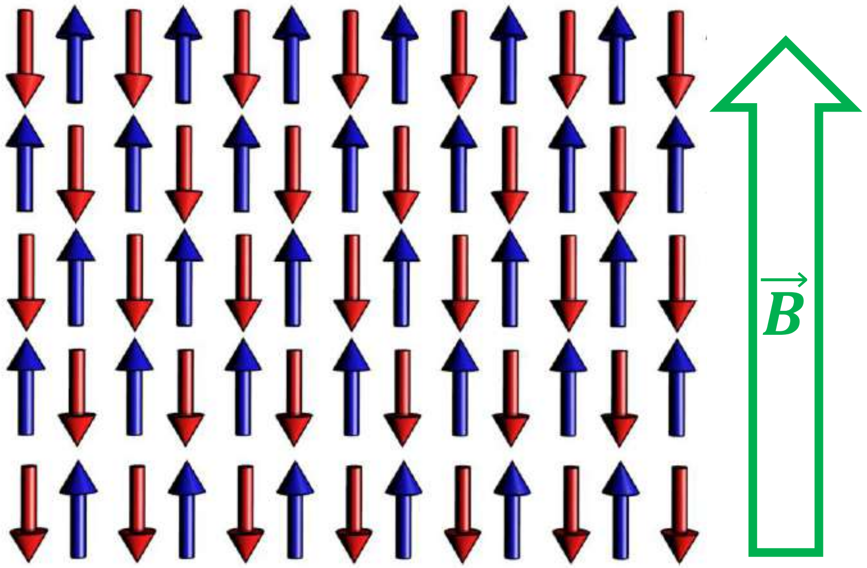
- **Magnetic fields ($\vec{B}$)** : conventional way to act on magnetic textures
- Because of the absence of net magnetization, $\vec{B}$ not "efficient" on AF textures ⟹ ***spin-flop and spin-flip transitions***



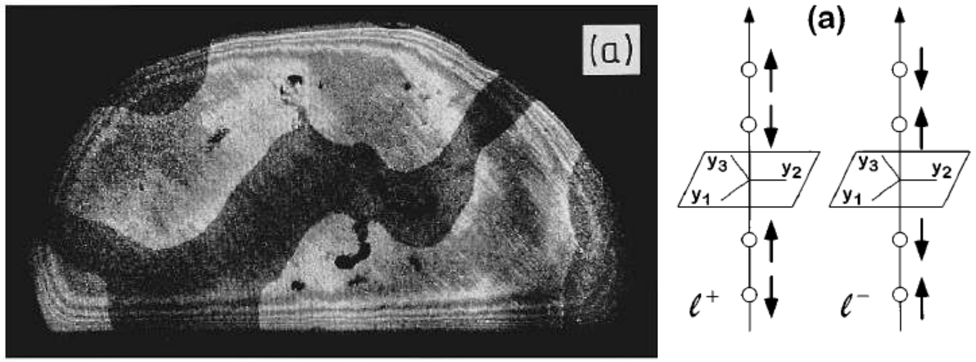
- **Magnetic energy**: E_{mag}

$$E_{mag} = \underbrace{\frac{|J|}{2} M^2 \cos(\theta + \varphi)}_{\textit{Exchange}} - \underbrace{MB(\cos\theta + \cos\varphi)}_{\textit{Zeeman}} + \underbrace{\frac{K}{2}\left(\sin^2\theta + \sin^2\varphi\right)}_{\textit{Anisotropy}}$$

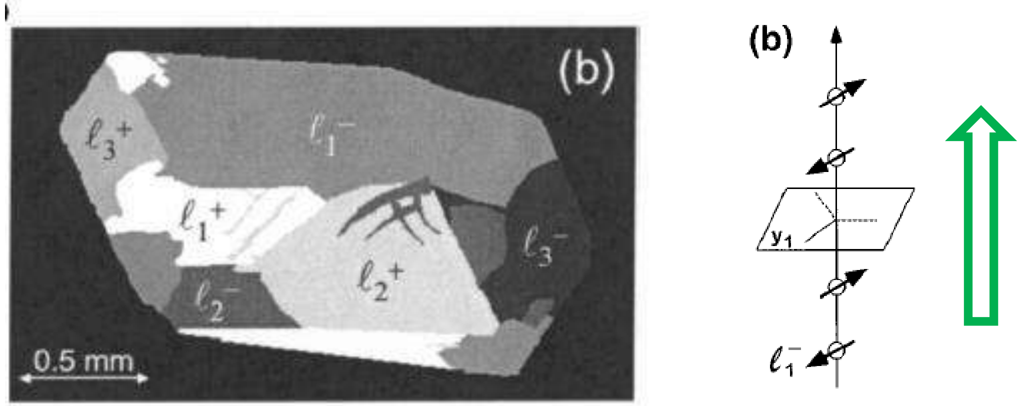
Generalities: Spin-flop (and Spin-flip) transitions



- **Magnetic fields ($\vec{B}$)** : conventional way to act on magnetic textures
- Because of the absence of net magnetization, $\vec{B}$ not "efficient" on AF textures ⟹ ***spin-flop and spin-flip transitions***
- *Example:* **Cr_2O_3**



Fiebig et al. *Appl. Phys. Lett.* ***66*** *2906* (1995)



B= 6.6T at 1.8K

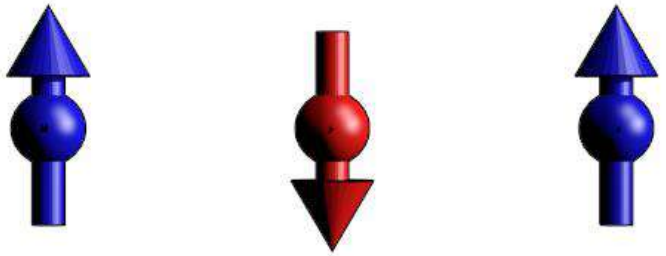
($B_{SF} \approx$ 5.8 T in Cr_2O_3)

Fiebig et al. *J. Opt. Am. B* **22** 96 (2005) *and Phys. Rev. B* ***54*** *12681* (1996)

- *Some other examples:*

B_{SF} in $FeF_2 \approx$ 50 T
B_{SF} in $MnF_2 \approx$ 9 T
B_{SF} in NiO ≈ 7.5 T

Antiferromagnetic dynamics



- Pioneer work by **Kittel and Keffer**

Theory of Antiferromagnetic Resonance

C. Kittel

Bell Telephone Laboratories, Murray Hill, New Jersey

(Received April 2, 1951)

Physical Review ***82*** 565 (1951)

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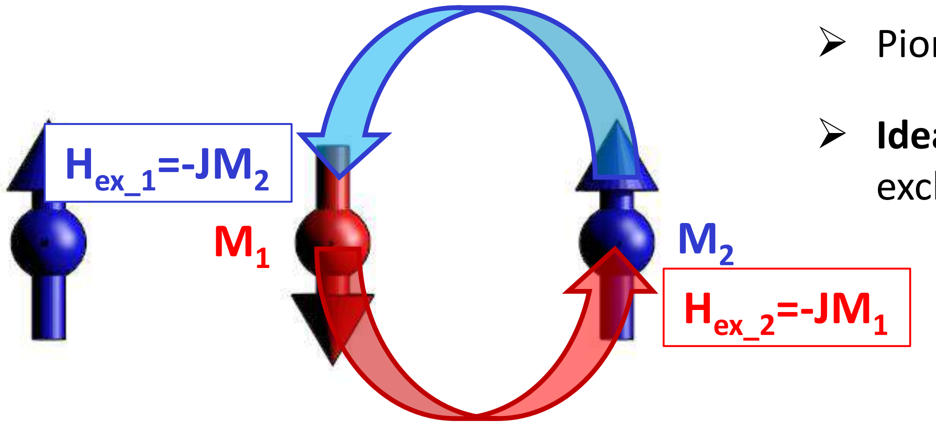

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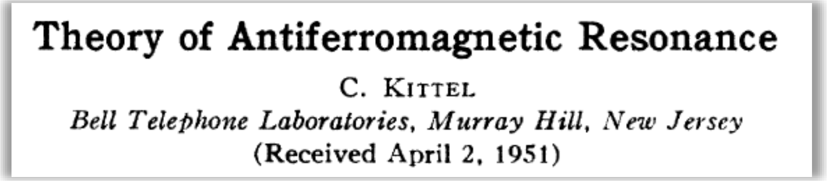
- **Idea:** One sublattice precesses in the exchange field of the other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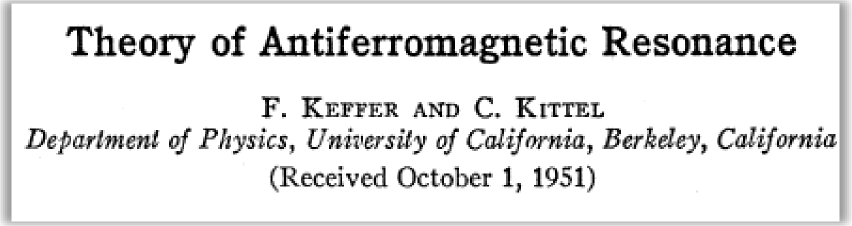
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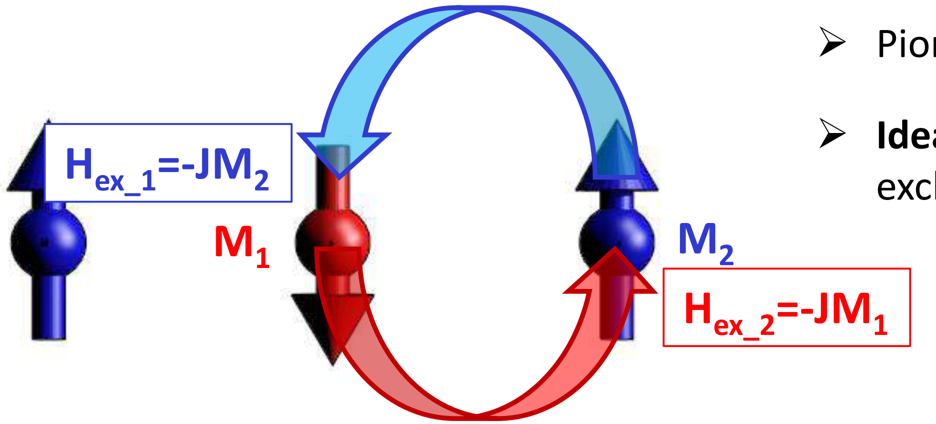

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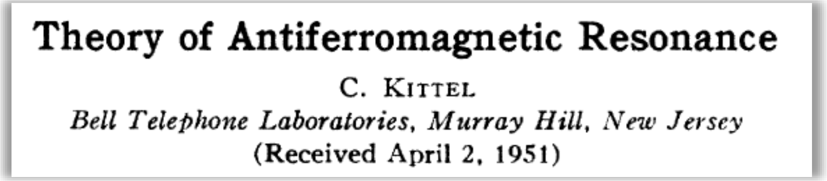

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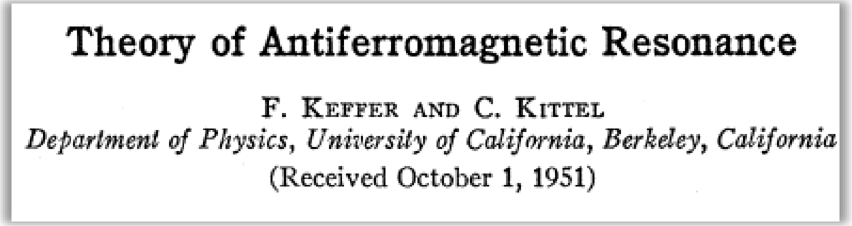

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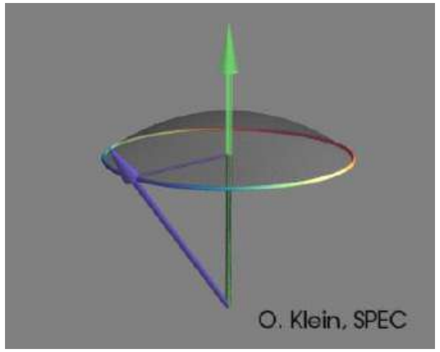
Reminder: magnetization (spin) dynamics & ferromagnetic resonance

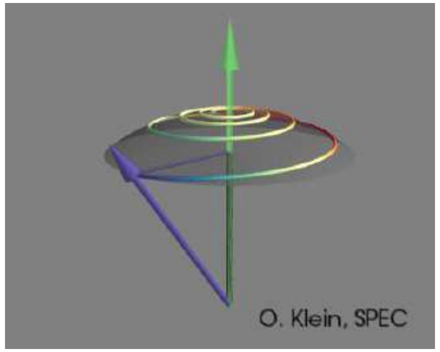
- Governed by the Landau-Lifshitz-Gilbert equation

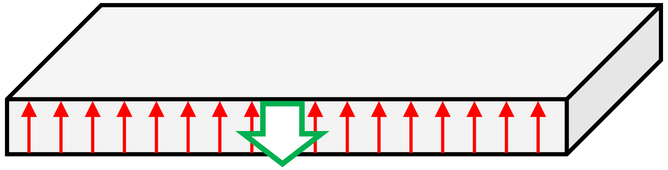
$$\frac{d\boldsymbol{m}}{dt} = \underbrace{-\mu_0\gamma\boldsymbol{m}\times\boldsymbol{H}_{eff}}_{precession} + \underbrace{\alpha\boldsymbol{m}\times\frac{d\boldsymbol{m}}{dt}}_{damping}$$

$\boldsymbol{H}_{eff}$: effective magnetic field / depends on the various magnetic energies *(dipolar, anisotropy, exchange etc…)*

γ : gyromagnetic ratio (≈ 28 GHz/T for electron spin)



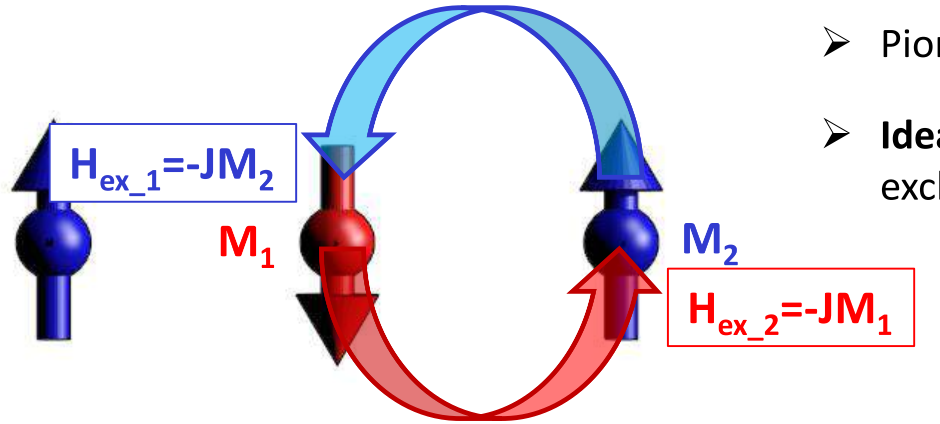




$H_{eff} \approx H_{dipolar} \approx M_S \approx$ 1 Tesla

Ferromagnetic resonance typically in the GHz range

Antiferromagnetic dynamics



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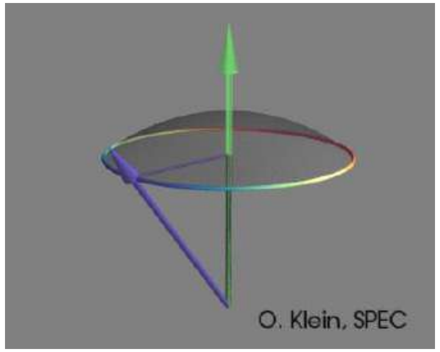
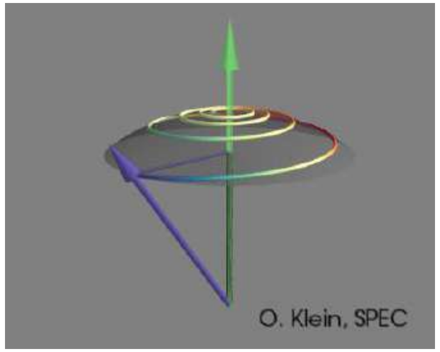
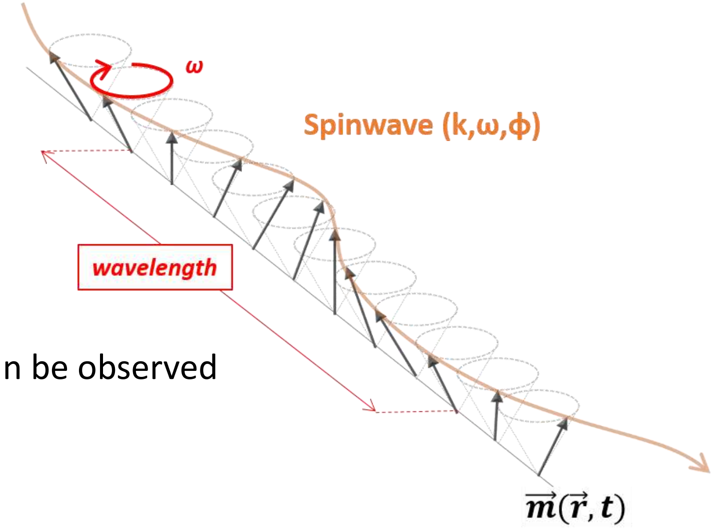




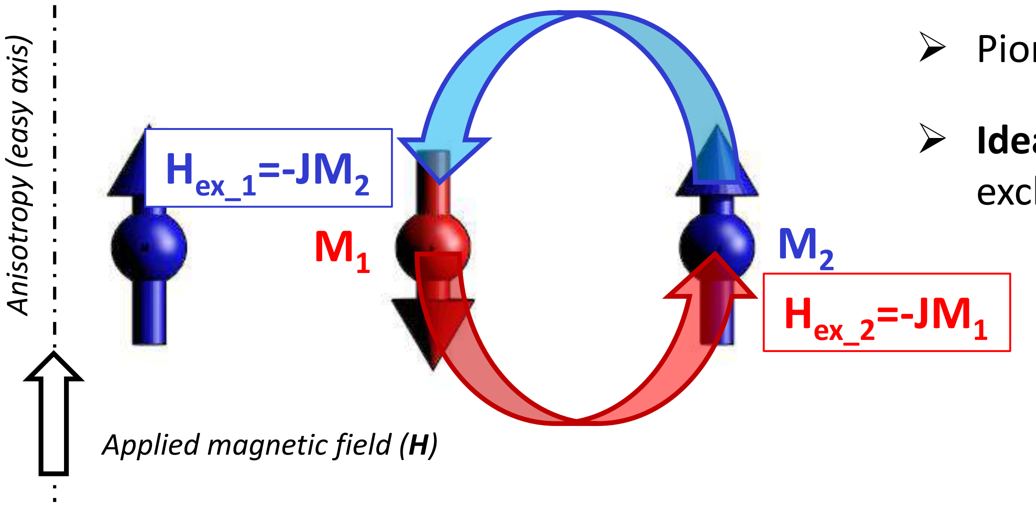
Case of high k-vector spinwaves:

Exchange field plays a role

⟹ higher frequencies can be observed



Antiferromagnetic dynamics



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Antiferromagnetic resonance: two coupled equations

$$\frac{d\boldsymbol{m}_1}{dt} = -\mu_0\gamma\boldsymbol{m}_1 \times (-J\boldsymbol{m}_2 + \boldsymbol{H}_A - \boldsymbol{H})$$

$$\frac{d\boldsymbol{m}_2}{dt} = -\mu_0\gamma\boldsymbol{m}_2 \times (-J\boldsymbol{m}_1 + \boldsymbol{H}_A + \boldsymbol{H})$$

Antiferromagnetic resonance frequency:

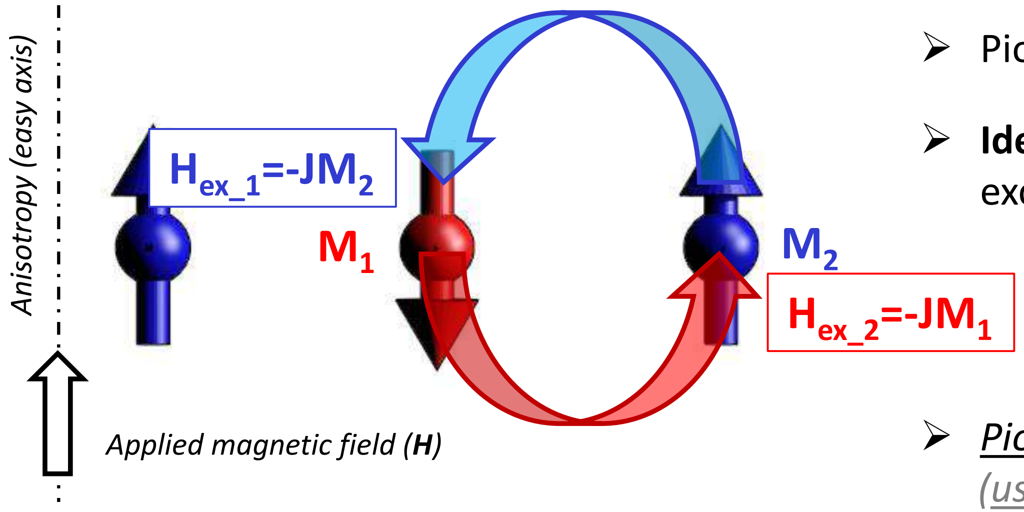
$$\boldsymbol{\omega_{res}} = \boldsymbol{\mu_0\gamma}\left(\sqrt{\boldsymbol{H_A(H_A + 2H_{ex})}} \pm \boldsymbol{H}\right)$$

Usually $\boldsymbol{H_{ex} \gg H_A}$ ⇒ $\boldsymbol{\omega_{res} \approx \mu_0\gamma}\left(\sqrt{\boldsymbol{2H_{ex}H_A}} \pm \boldsymbol{H}\right)$

⇒

- **H_{ex}** from some tens to several hundreds of Tesla
- High resonance frequencies at k=0: **sub-THz and THz ranges**
- Not so easy to assess

Antiferromagnetic dynamics



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*Physical Review **85** 329 (1952)*

- ***Pioneer experimental studies:***
  (using some tricks to decrease the AF resonance into the GHz range)

1/ Low T_N antiferromagnet ⟹ **Small H_{ex}**

Antiferromagnetism and Antiferromagnetic Resonance in $CuBr_2 \cdot 2H_2O$ at 9800 Mc/sec

M. Date
Research Institute for Iron, Steel, and Other Metals, Tôhoku University, Sendai, Japan
(Received June 18, 1956)
*Physical Review **104** 623 (1956)*

2/ Heating up to T_N ⟹ **reducing H_A**

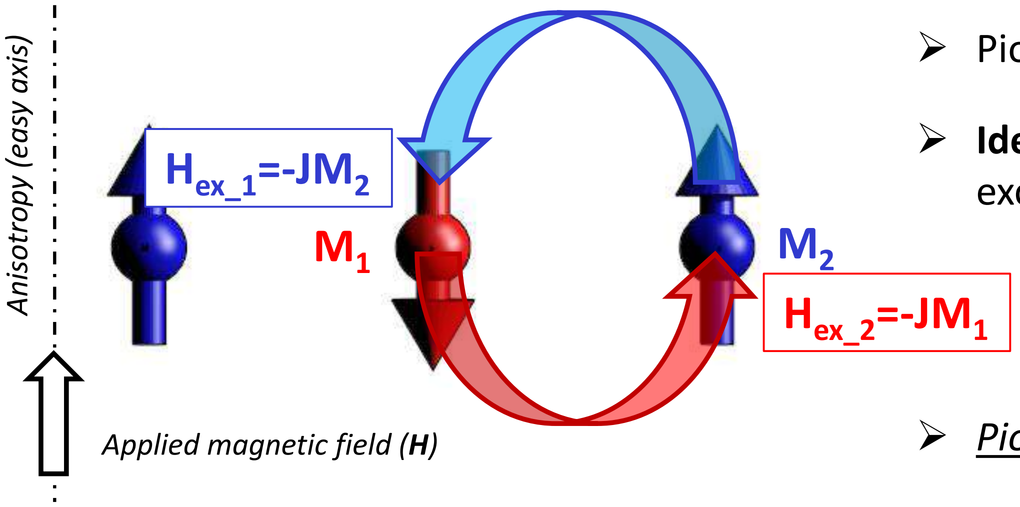
Antiferromagnetic Resonance in Cr_2O_3

Edward S. Dayhoff
United States Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland
(Received February 28, 1957)
*Physical Review **107** 84 (1957)*

Antiferromagnetic resonance frequency:

$$\omega_{res} \approx \mu_0 \gamma \left(\sqrt{2 H_{ex} H_A} \pm H \right)$$

Antiferromagnetic dynamics



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- ***<u>Pioneer experimental studies in sub-THz and THz ranges</u>:***

<u>Antiferromagnetic resonance frequency:</u>

$$\omega_{res} \approx \mu_0\gamma\left(\sqrt{2H_{ex}H_A} \pm H\right)$$

Antiferromagnetic Resonance in MnF_2†

Fred M. Johnson* and Arthur H. Nethercot, Jr.‡
Columbia Radiation Laboratory, Columbia University, New York, New York
(Received November 25, 1958)
Physical Review ***114*** *709* (1959)

f_{res}= 260 GHz

Antiferromagnetic Resonance in FeF_2 at Far-Infrared Frequencies*†

R. C. Ohlmann‡ and M. Tinkham
Department of Physics, University of California, Berkeley, California
(Received March 13, 1961)
Physical Review ***123*** *425* (1961)

f_{res}= 1.5 THz

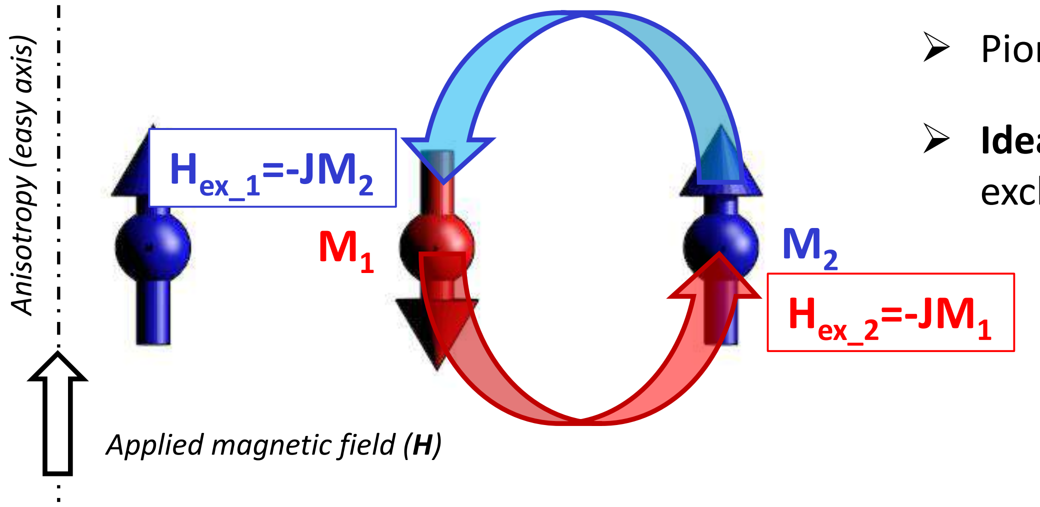
Far Infrared Antiferromagnetic Resonance in MnO and NiO†

A. J. Sievers, III,* and M. Tinkham
Department of Physics, University of California, Berkeley, California
(Received 27 September 1962)
Physical Review ***129*** *1566* (1962)

f_{res_NiO}= 1.1 THz

f_{res_MnO}= 0.82 THz

Antiferromagnetic dynamics



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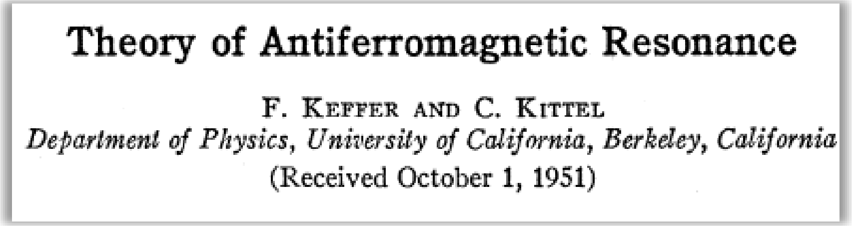

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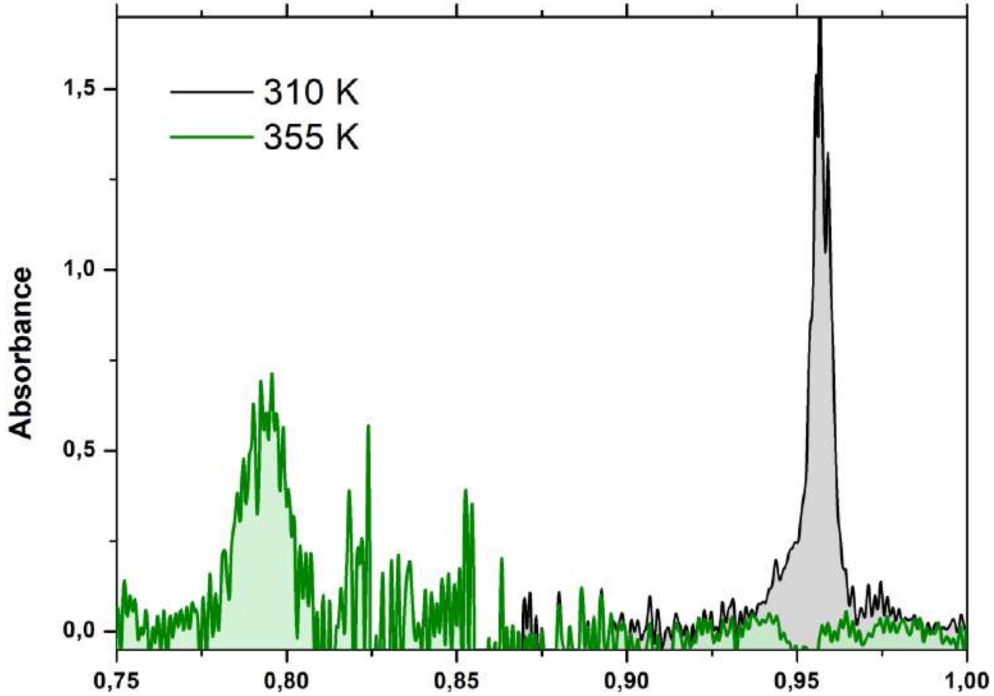
Antiferromagnetic resonance frequency:

$$\omega_{res} \approx \mu_0\gamma\left(\sqrt{2H_{ex}H_A} \pm H\right)$$

THz absorption spectrum of NiO (111) cristal



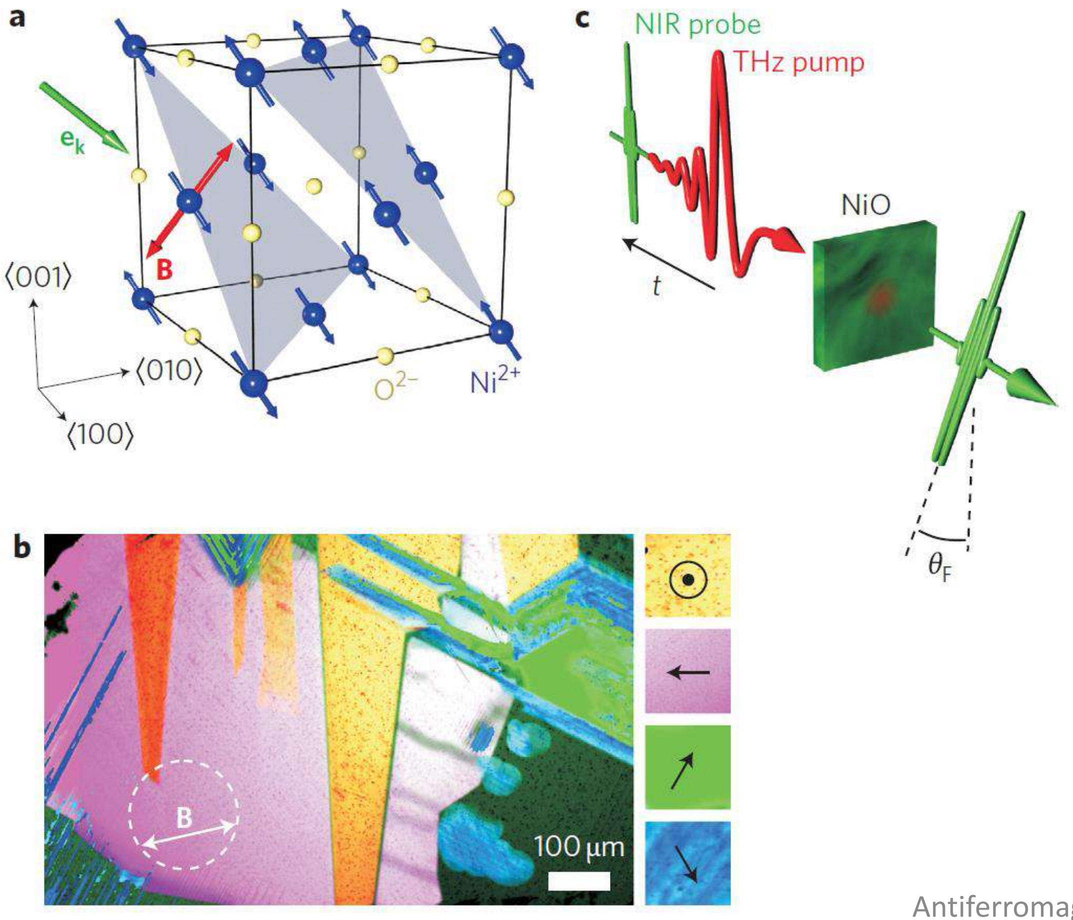
AILES beamline, Synchrotron SOLEIL

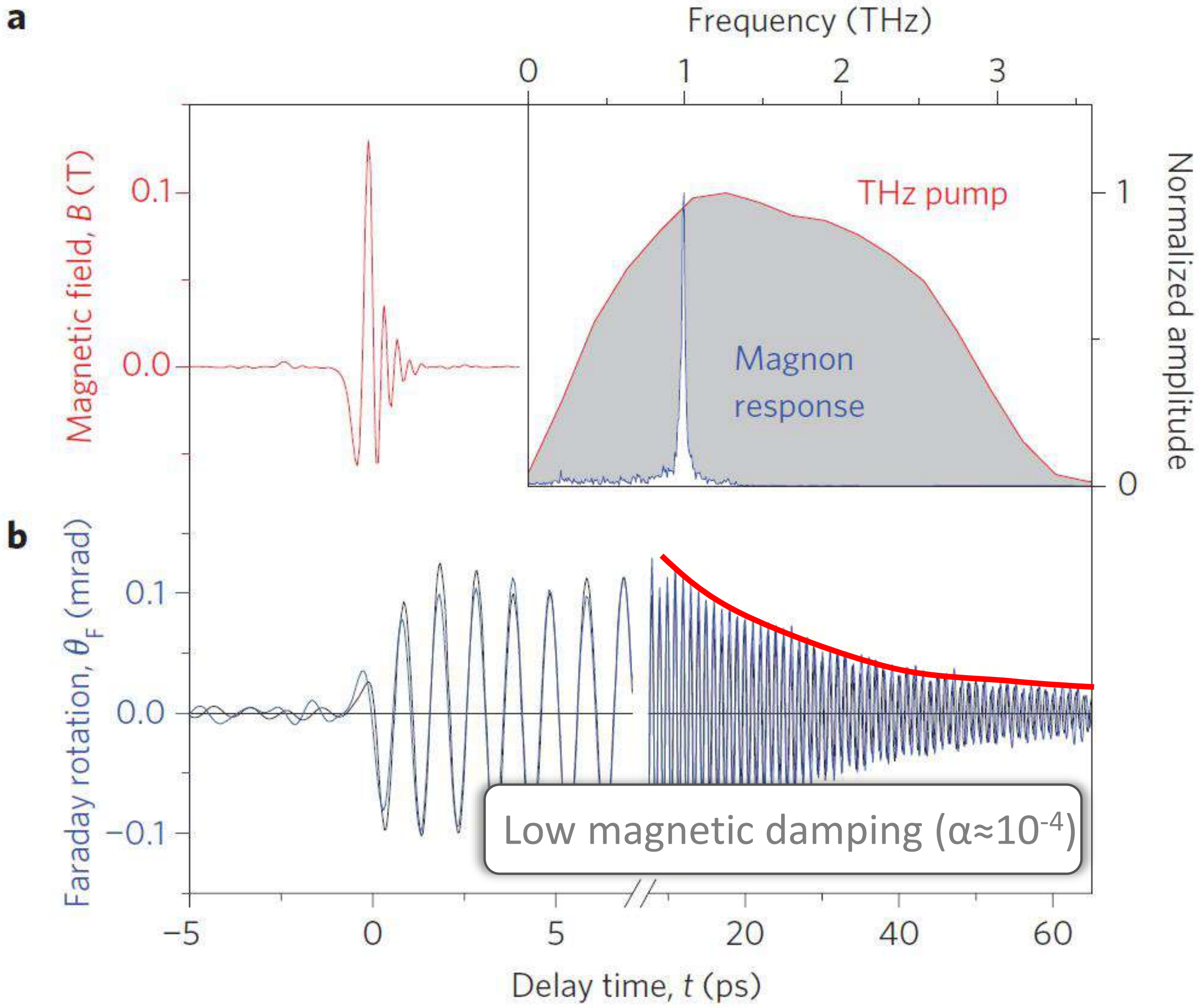
Antiferromagnetic dynamics

nature photonics LETTERS
PUBLISHED ONLINE: 21 NOVEMBER 2010 | DOI: 10.1038/NPHOTON.2010.259

Coherent terahertz control of antiferromagnetic spin waves

Tobias Kampfrath[1,2,3‡]*, Alexander Sell[1‡], Gregor Klatt[1], Alexej Pashkin[1], Sebastian Mährlein[1], Thomas Dekorsy[1], Martin Wolf[2], Manfred Fiebig[4], Alfred Leitenstorfer[1] and Rupert Huber[1‡]*





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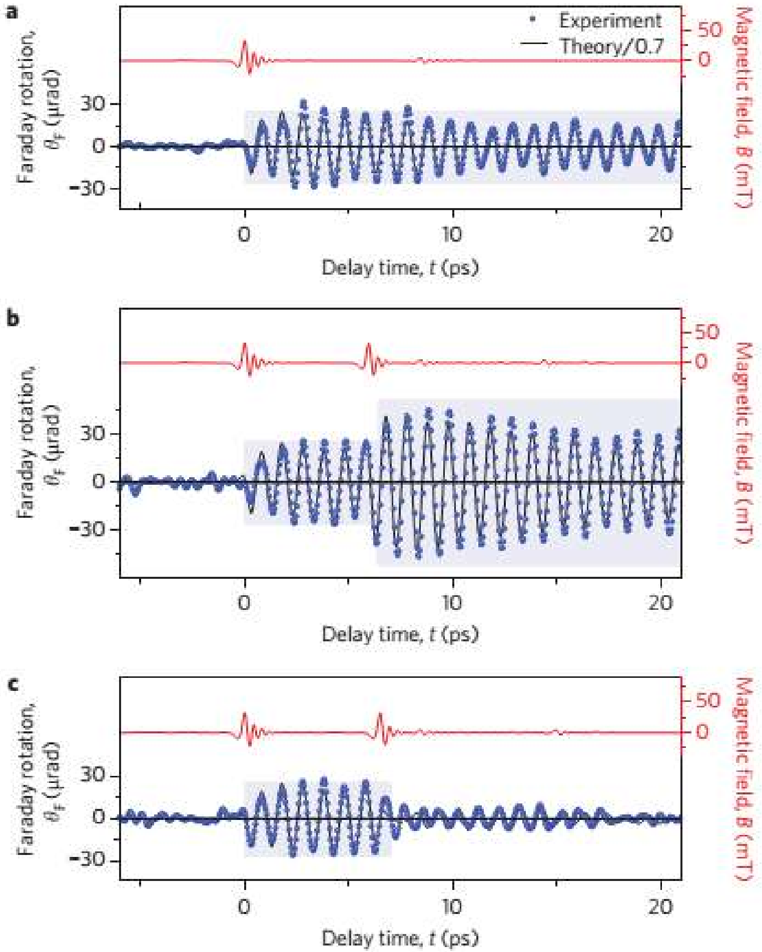
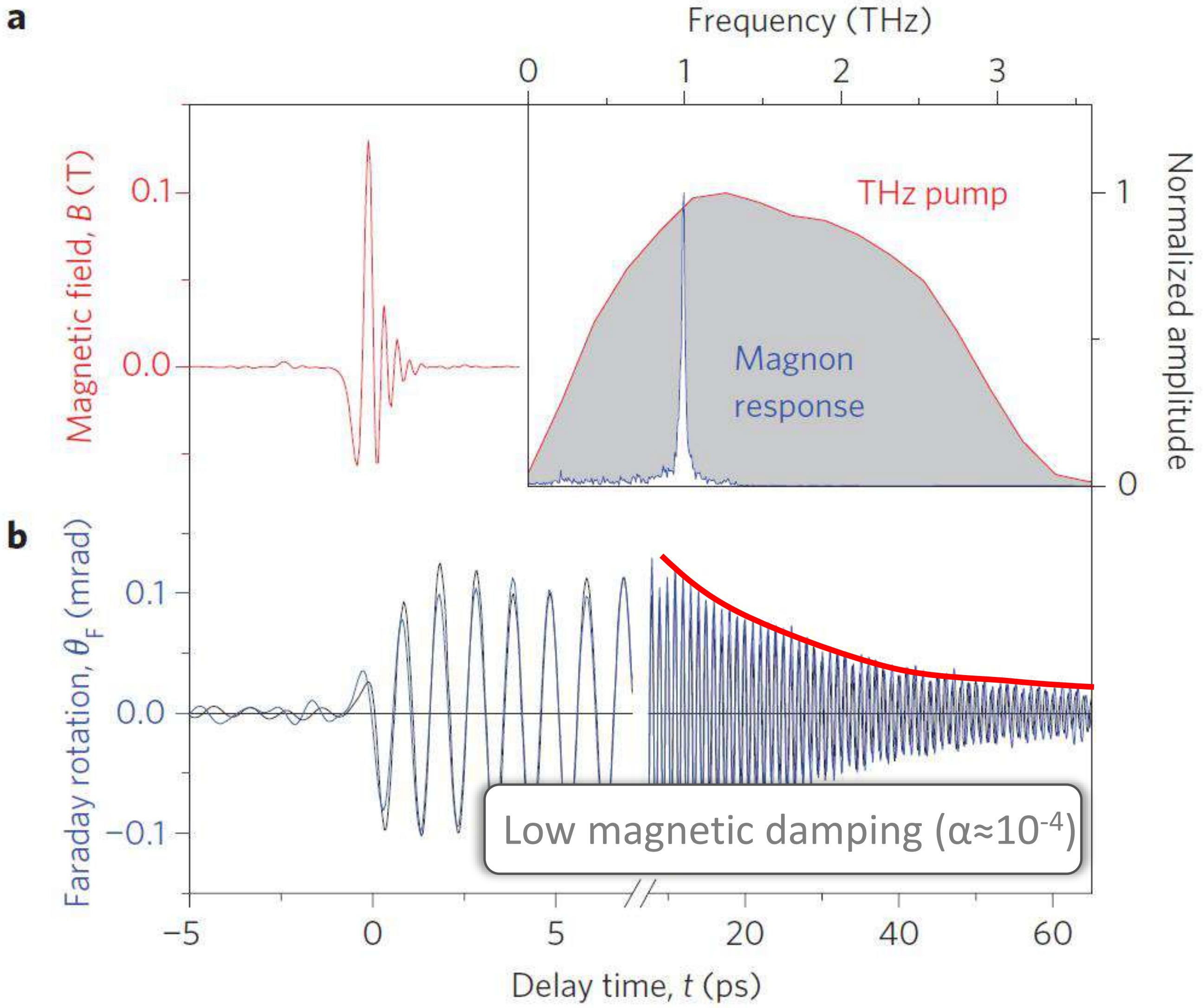


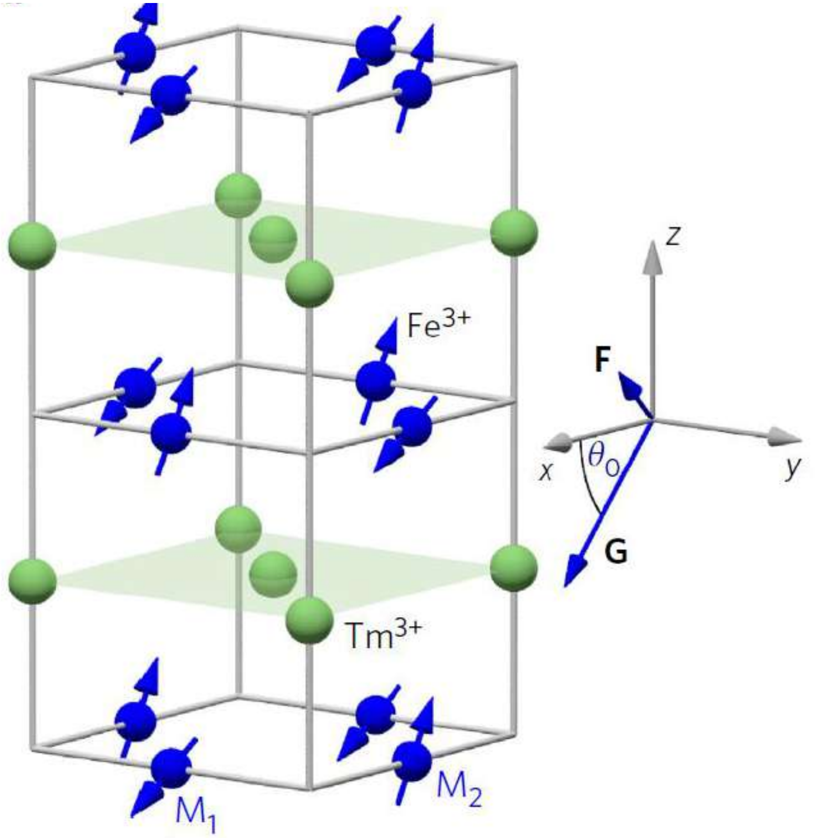


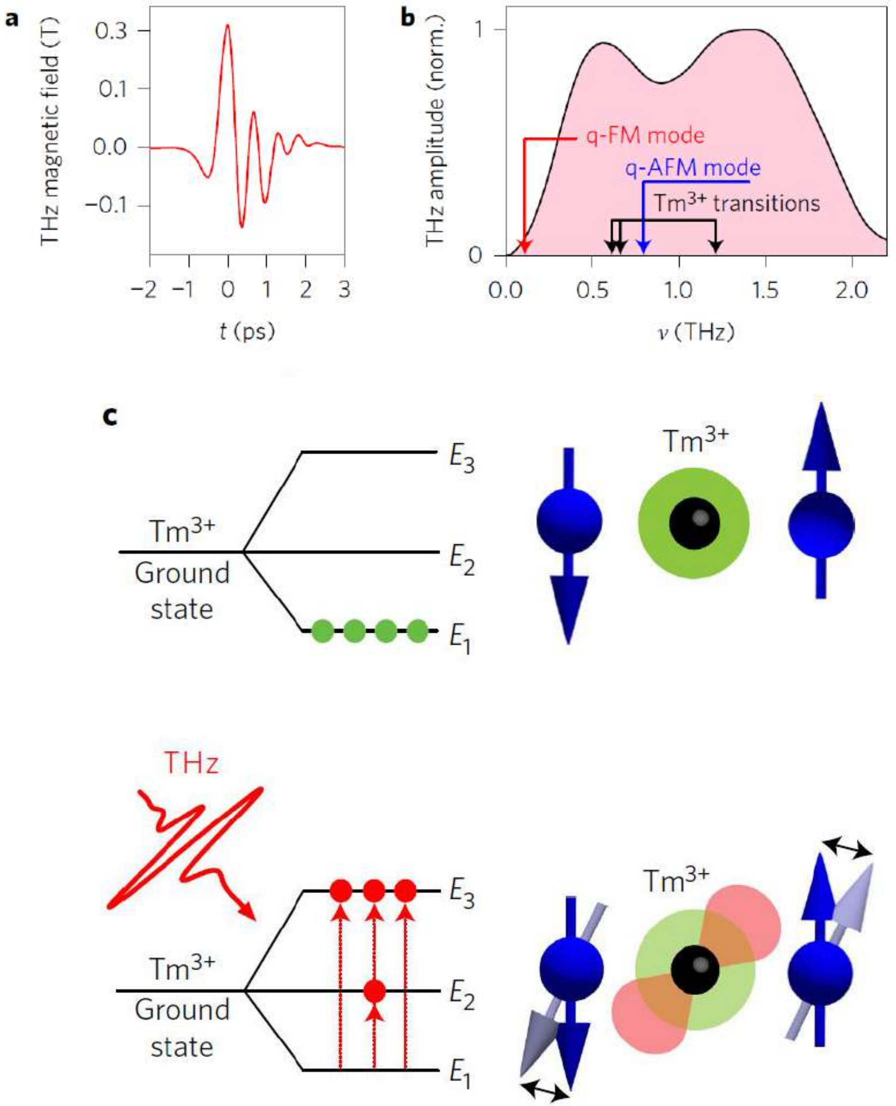
Antiferromagnetic dynamics and ultrafast THz capabilities

nature photonics | LETTERS
PUBLISHED ONLINE: 3 OCTOBER 2016 | DOI: 10.1038/NPHOTON.2016.181

Nonlinear spin control by terahertz-driven anisotropy fields

S. Baierl[1], M. Hohenleutner[1], T. Kampfrath[2], A. K. Zvezdin[3,4,5], A. V. Kimel[4,6], R. Huber[1]* and R. V. Mikhaylovskiy[6]*





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LETTERS

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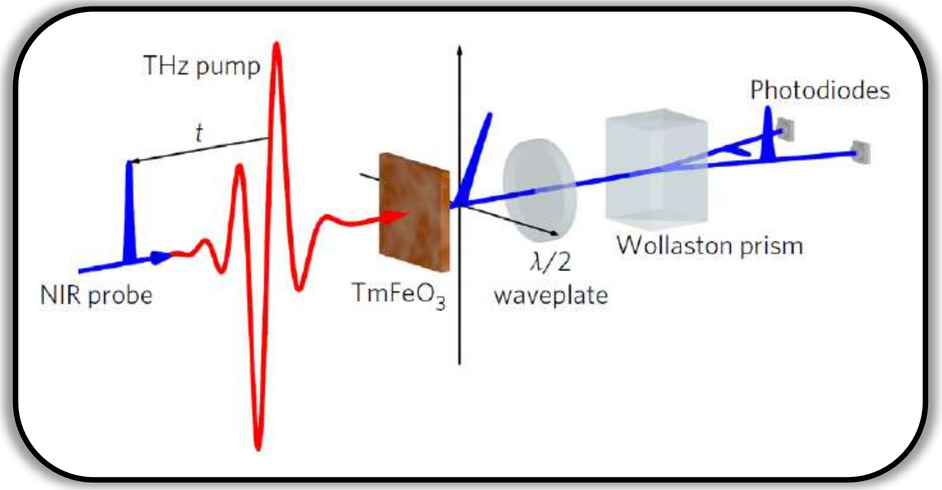
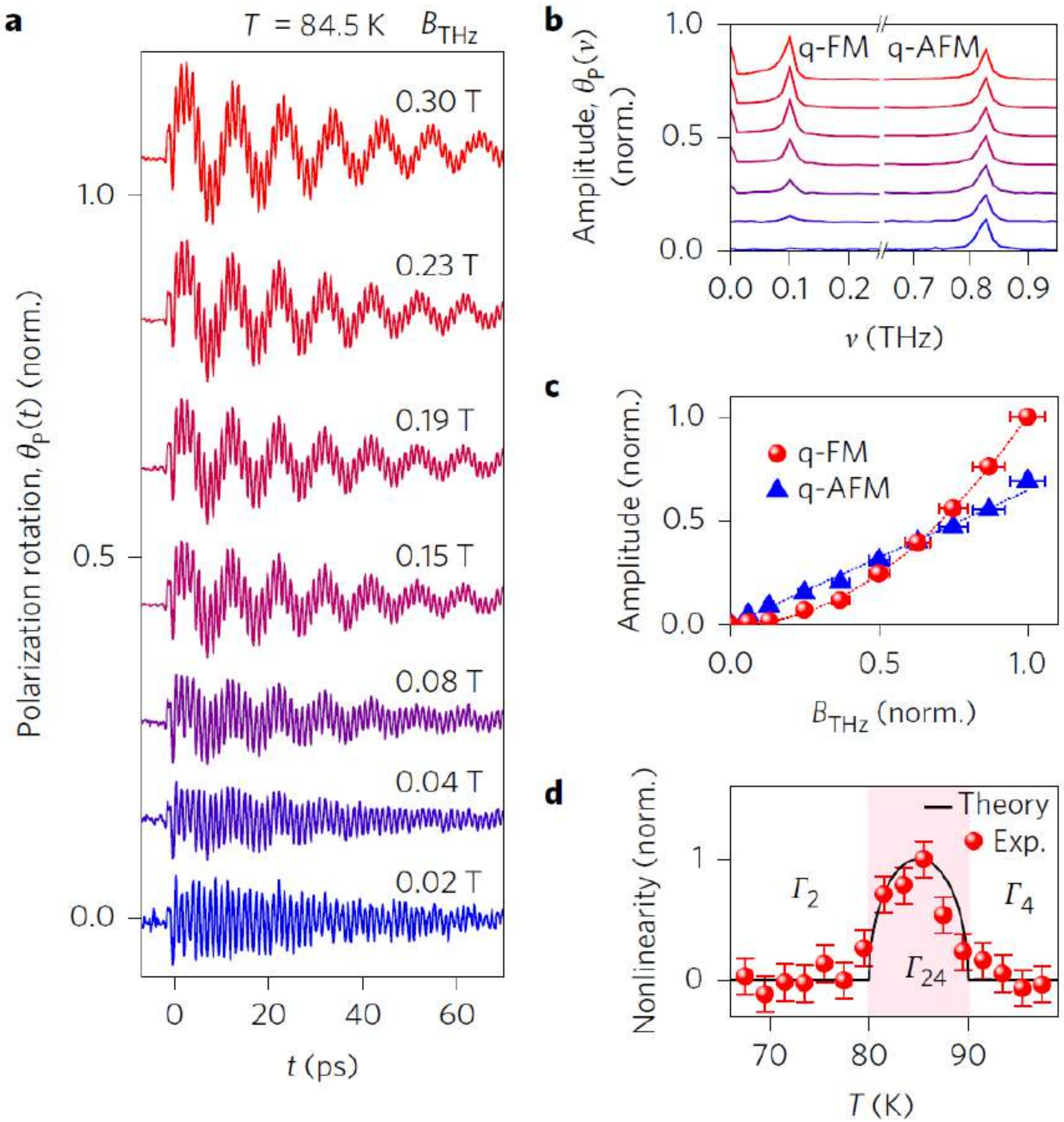
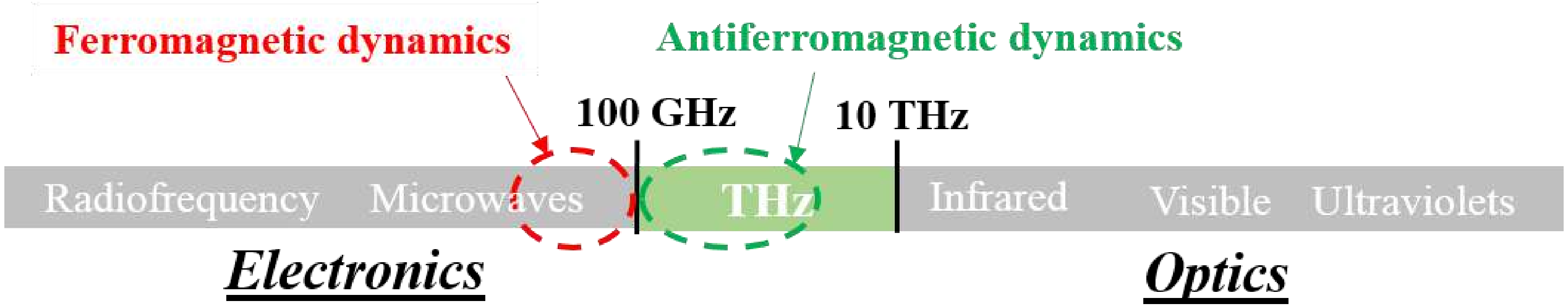
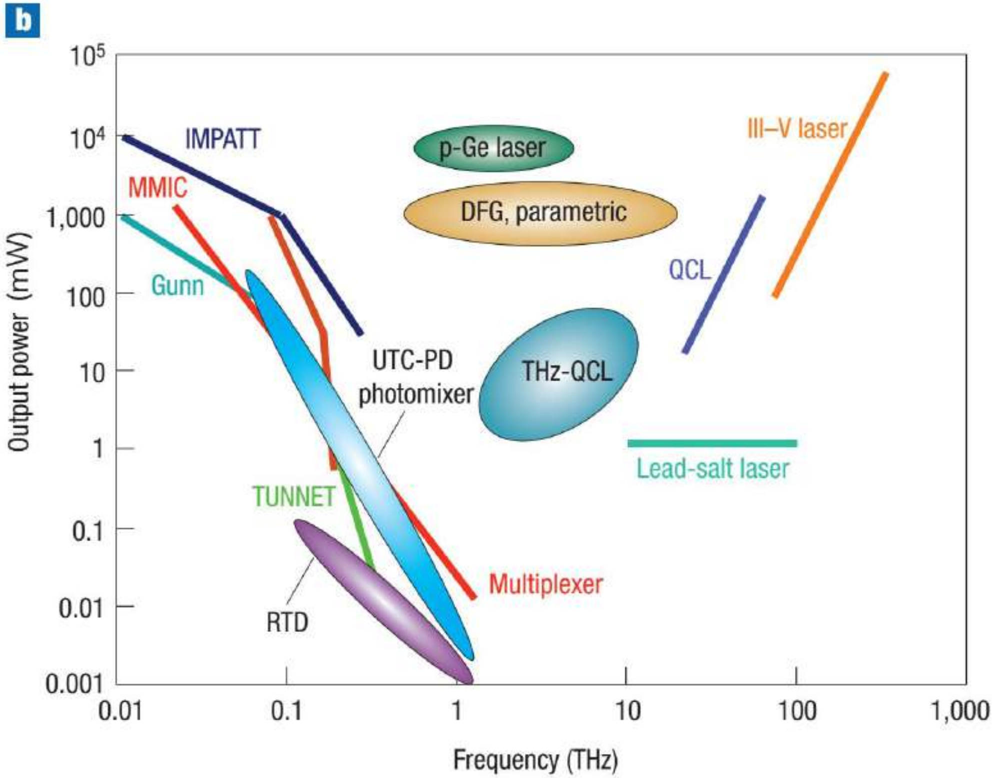




Antiferromagnetic dynamics





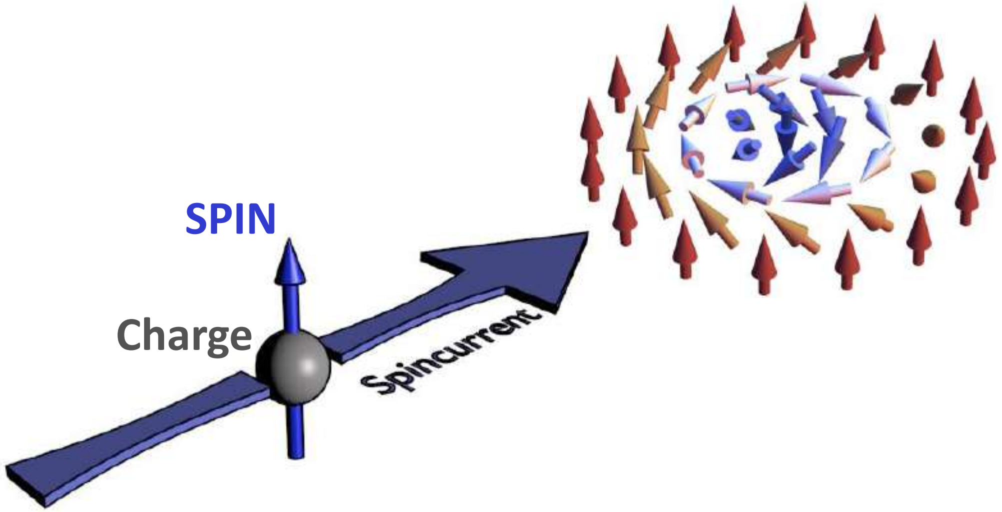
- Antiferromagnetic dynamics : in the THz range
- AF could play a role in future ultrafast devices

However:

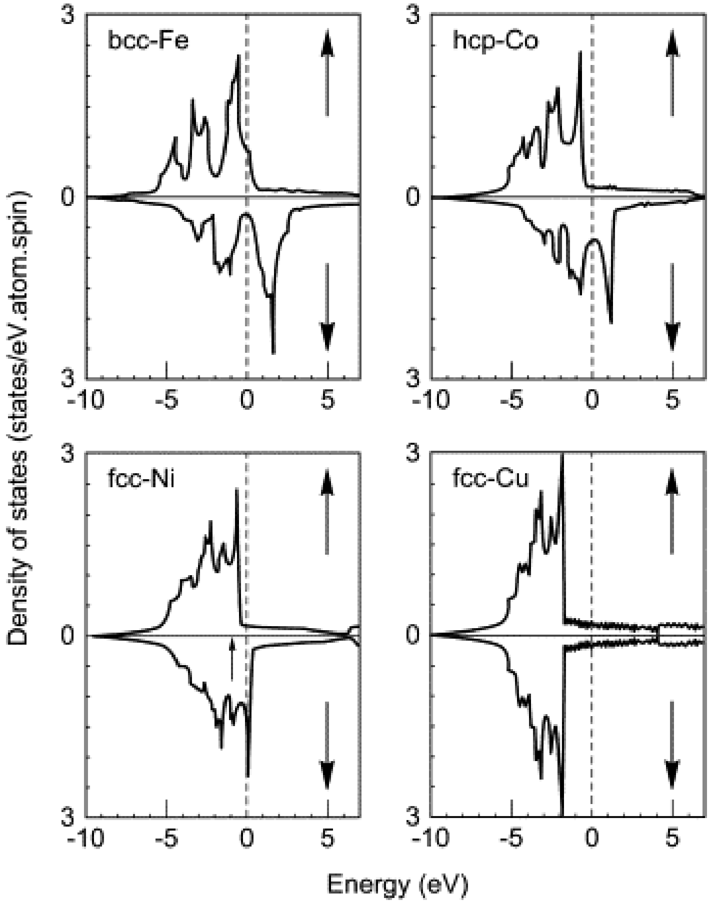
- Their efficient actuation remains a challenge

⟹ *Role of spincurrents?*

<u>Spintronics:</u> Interplay between *spincurrents* and *magnetic textures*



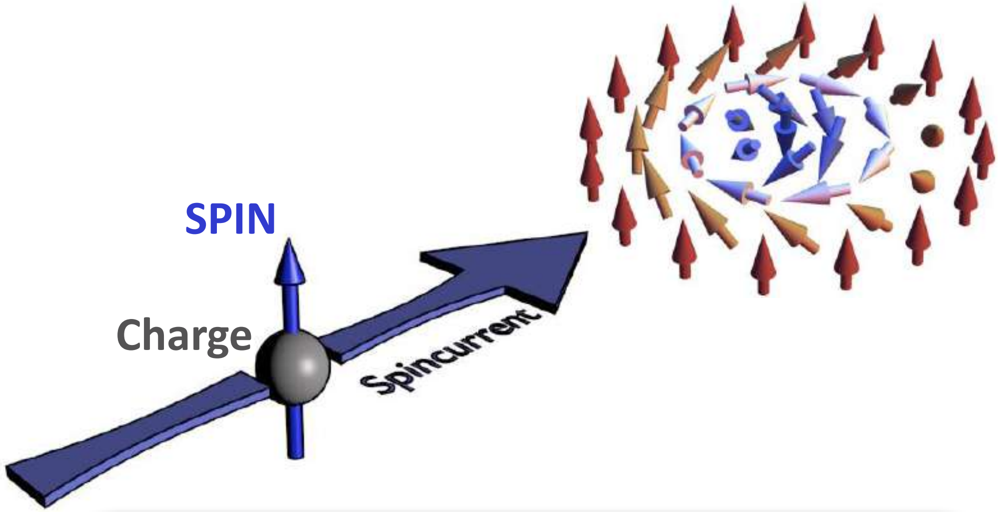
- **1/ Spin-polarized electrical currents** *(… in ferromagnetic metals)*



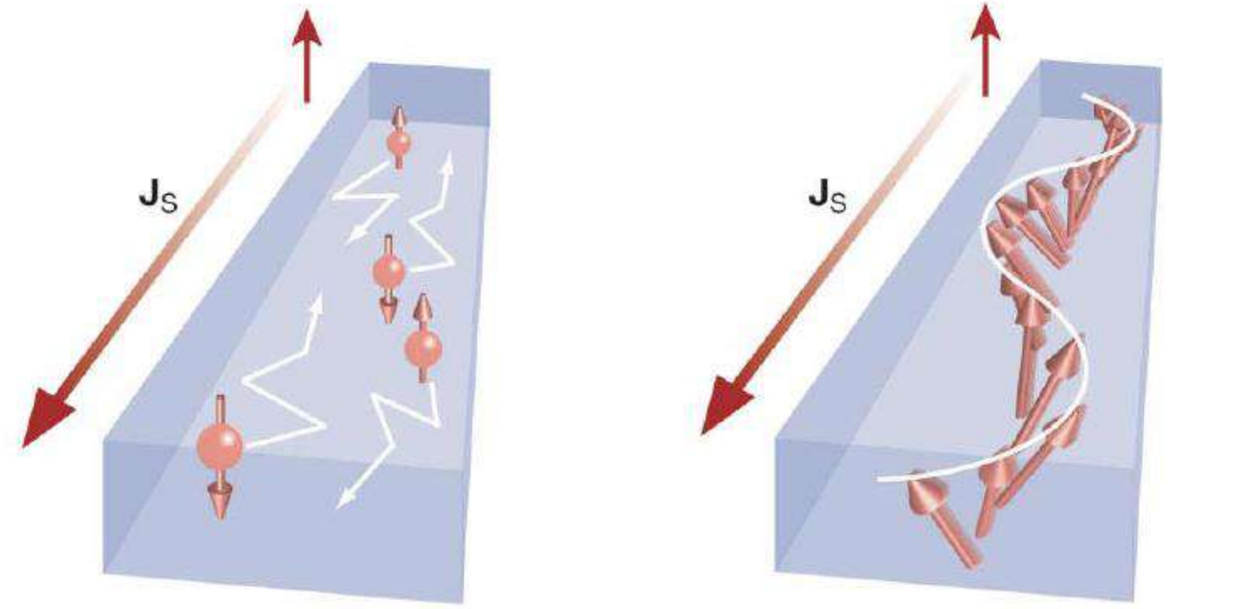
Unbalanced spin density of state at the fermi energy

Spincurrents and Antiferromagnets

Spintronics: Interplay between *spincurrents* and *magnetic textures*

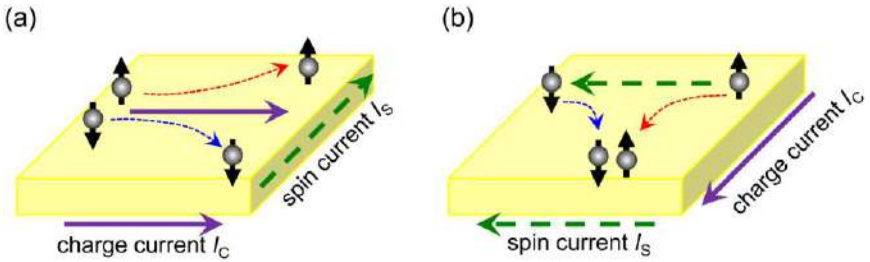


- **2/ Pure spincurrents**



Kajiwara et al. *Nature* ***464*** 262 (2010)

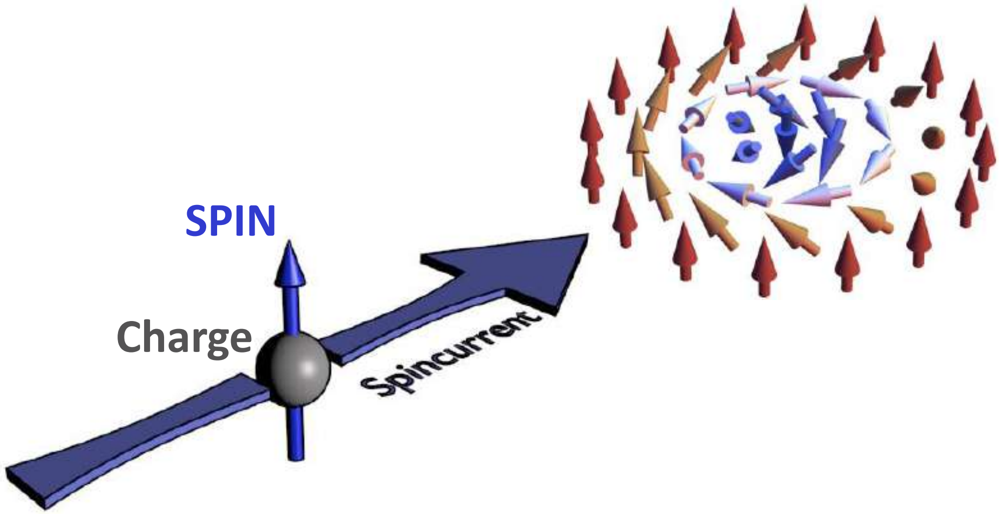
Spin Hall effect



from Niimi et al. *Rep. Prog. Phys.* **78** 124501 (2015)

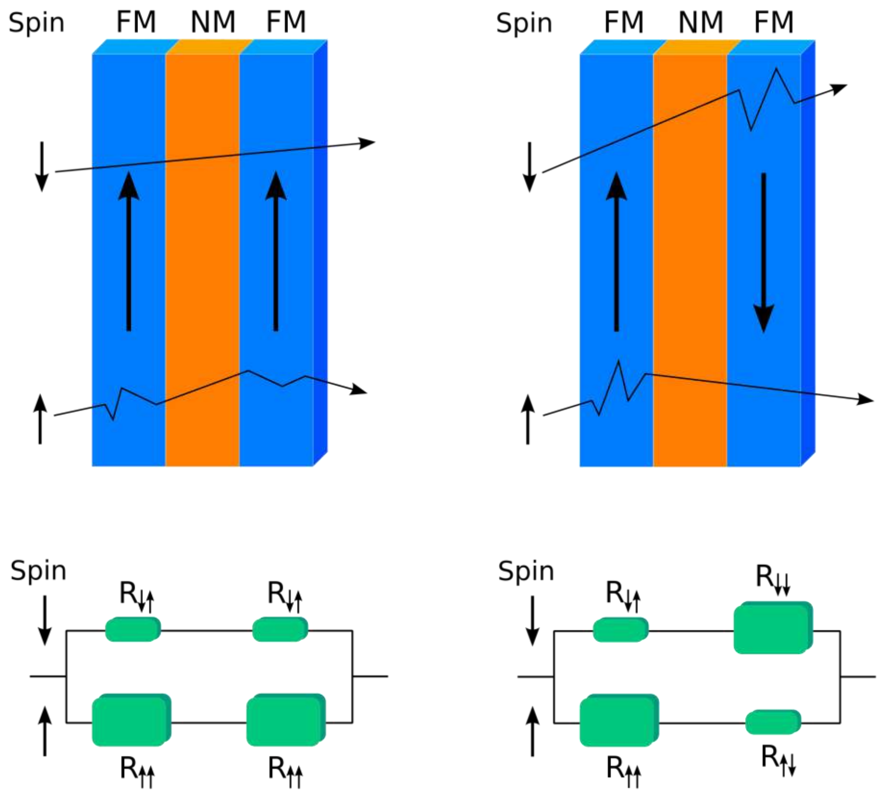
Also at Rashba-splitted interfaces: ***Rashba-Edelstein effect***

<u>Spintronics:</u> Interplay between *spincurrents* and *magnetic textures*



Spincurrents and Antiferromagnets

Spintronics: Interplay between *spincurrents* and *magnetic textures*



- *The "origins" of spintronics*: **Giant Magneto-Resistance (GMR)**

  Baibich et al. *Phys. Rev. Lett.* **61** 2472 (1988)

  Binasch et al. *Phys. Rev. B.* **39** 4828 (1989)

- *Its reciprocal effect*: **Spin-Transfer Torque"s" (STT)**

  Ralph et al. *J. Magn. Magn. Mater.* **320**, 1190 (2008) (review article)

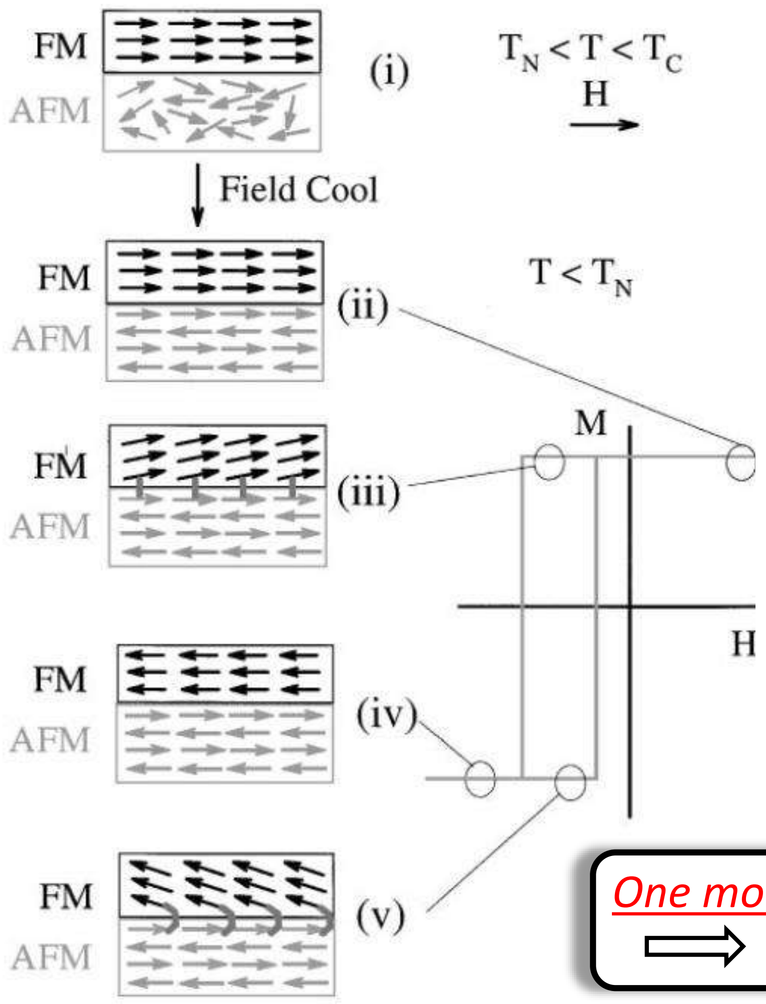
1997: 1st introduction of GMR in HDD

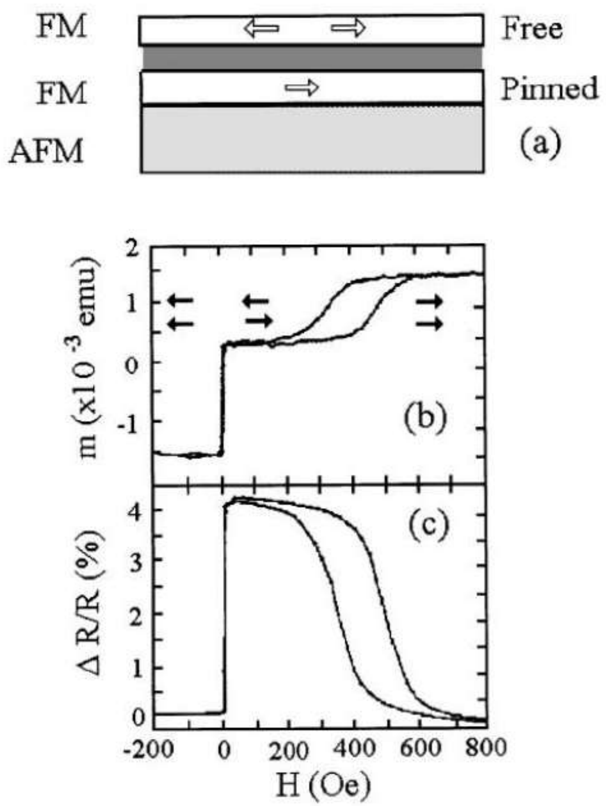
Antiferromagnets have already been integrated in spintronics devices for decades only as … **passive elements…**

Spincurrents and Antiferromagnets

Antiferromagnets have already integrated in spintronics devices for decades only as … **passive elements…**

- **Exchange coupling & exchange bias:**





One motivation behind ***AF spintronics:***

⟹ **AF as active element in spintronic devices : use of their interesting properties**

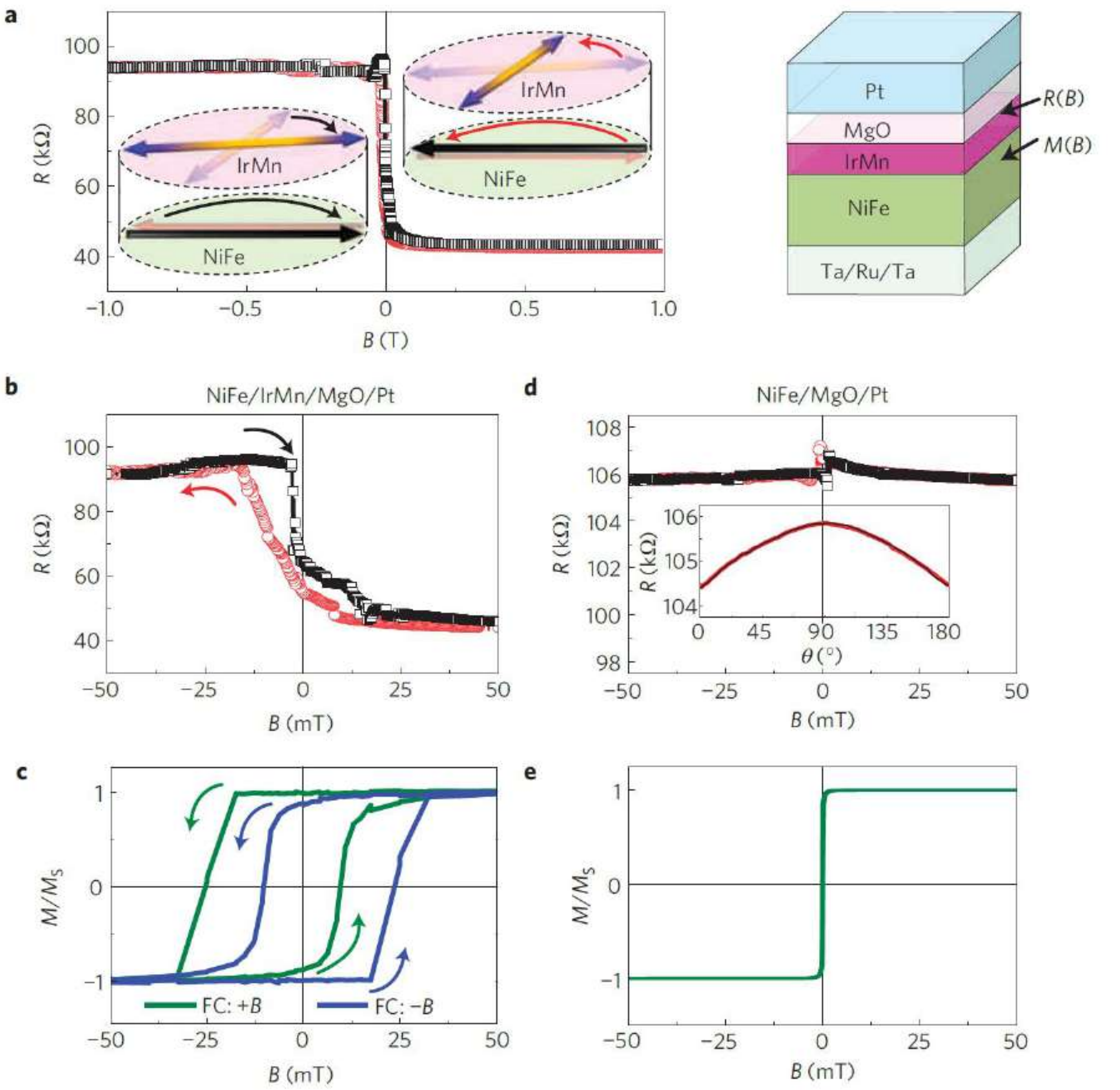
From Noguès et al. *JMMM* ***192*** 203 (1999)

➢ AF as active element in spintronic devices :

nature materials | LETTERS
PUBLISHED ONLINE: 13 MARCH 2011 | DOI: 10.1038/NMAT2983

A spin-valve-like magnetoresistance of an antiferromagnet-based tunnel junction

B. G. Park[1]*, J. Wunderlich[1,2], X. Martí[3], V. Holý[3], Y. Kurosaki[4], M. Yamada[4], H. Yamamoto[4], A. Nishide[4], J. Hayakawa[4], H. Takahashi[1,4], A. B. Shick[5] and T. Jungwirth[2,6]*



- ➢ Antiferromagnetic tunneling anisotropic magnetoresistance (AFM-TAMR)
- ➢ Large spin-valve like signal
- ➢ **First demonstrations with metallic AF.**

➢ **What about insulating AF oxides? :**

epl A LETTERS JOURNAL EXPLORING THE FRONTIERS OF PHYSICS

December 2014

EPL, **108** (2014) 57005 www.epljournal.org

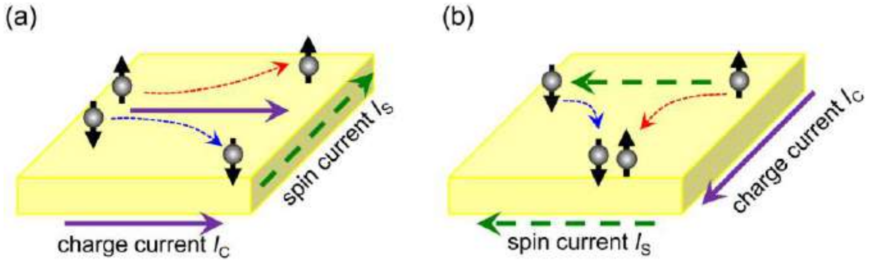
doi: 10.1209/0295-5075/108/57005

Conduction of spin currents through insulating antiferromagnetic oxides

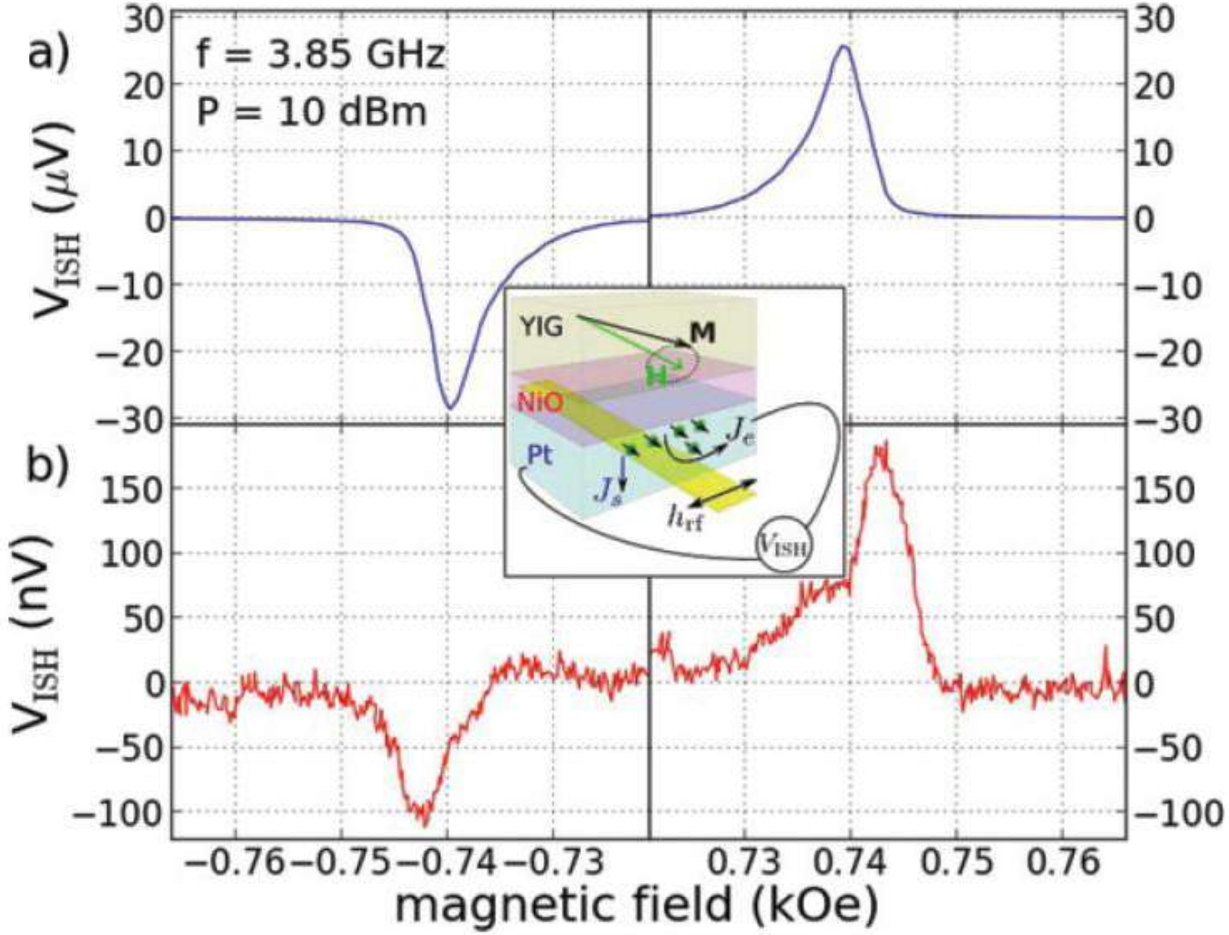
CHRISTIAN HAHN[1], GRÉGOIRE DE LOUBENS[1], VLADIMIR V. NALETOV[1,2], JAMAL BEN YOUSSEF[3], OLIVIER KLEIN[1] and MICHEL VIRET[1(a)]

[1] *Service de Physique de l'État Condensé (CNRS URA 2464), CEA Saclay - 91191 Gif-sur-Yvette, France*
[2] *Institute of Physics, Kazan Federal University - Kazan 420008, Russian Federation*
[3] *Université de Bretagne Occidentale, Laboratoire de Magnétisme de Bretagne CNRS - 6 Avenue Le Gorgeu, 29285 Brest, France*

Spin Hall effect



from Niimi et al. *Rep. Prog. Phys.* **78** 124501 (2015)



➢ **What about insulating AF oxides? :**

epl A Letters Journal Exploring the Frontiers of Physics

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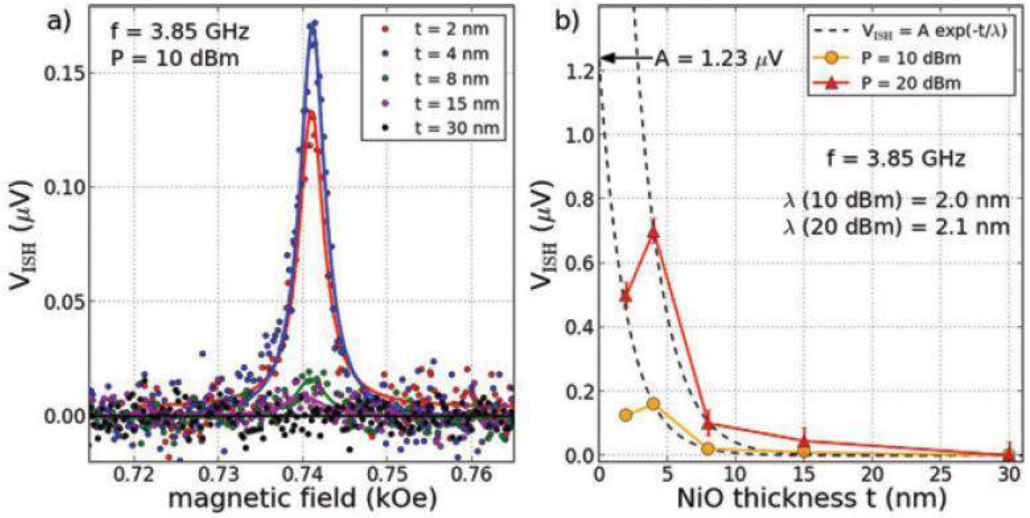

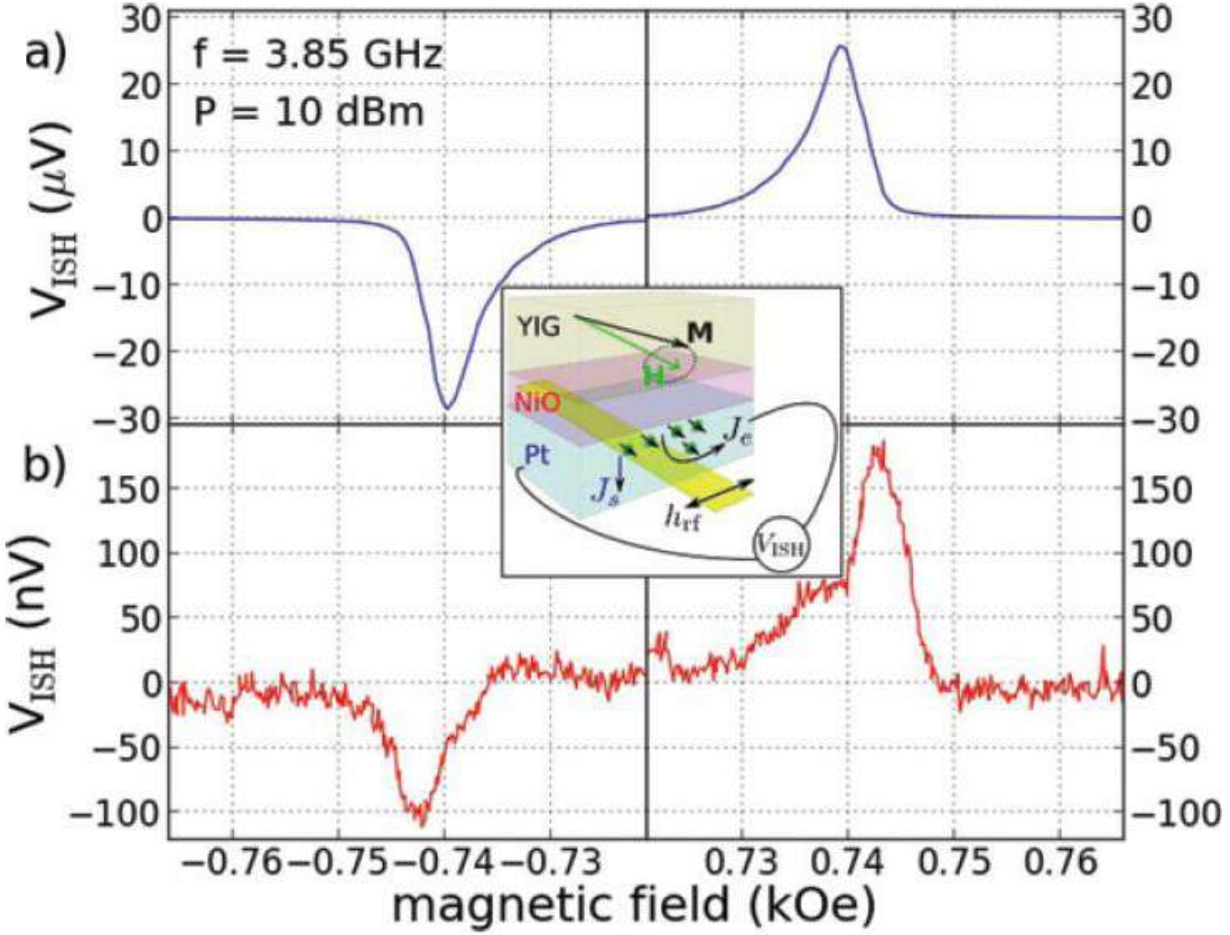

- **What about insulating AF oxides? :**

epl A LETTERS JOURNAL EXPLORING THE FRONTIERS OF PHYSICS

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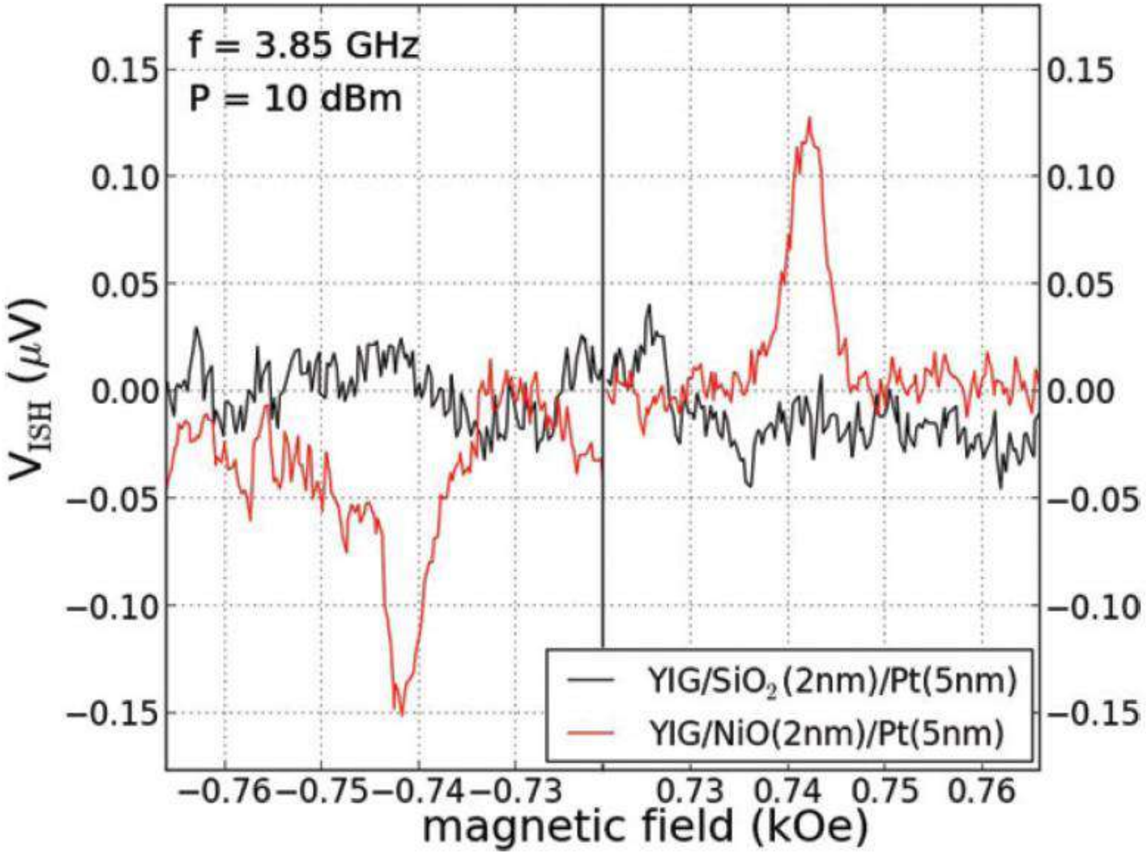
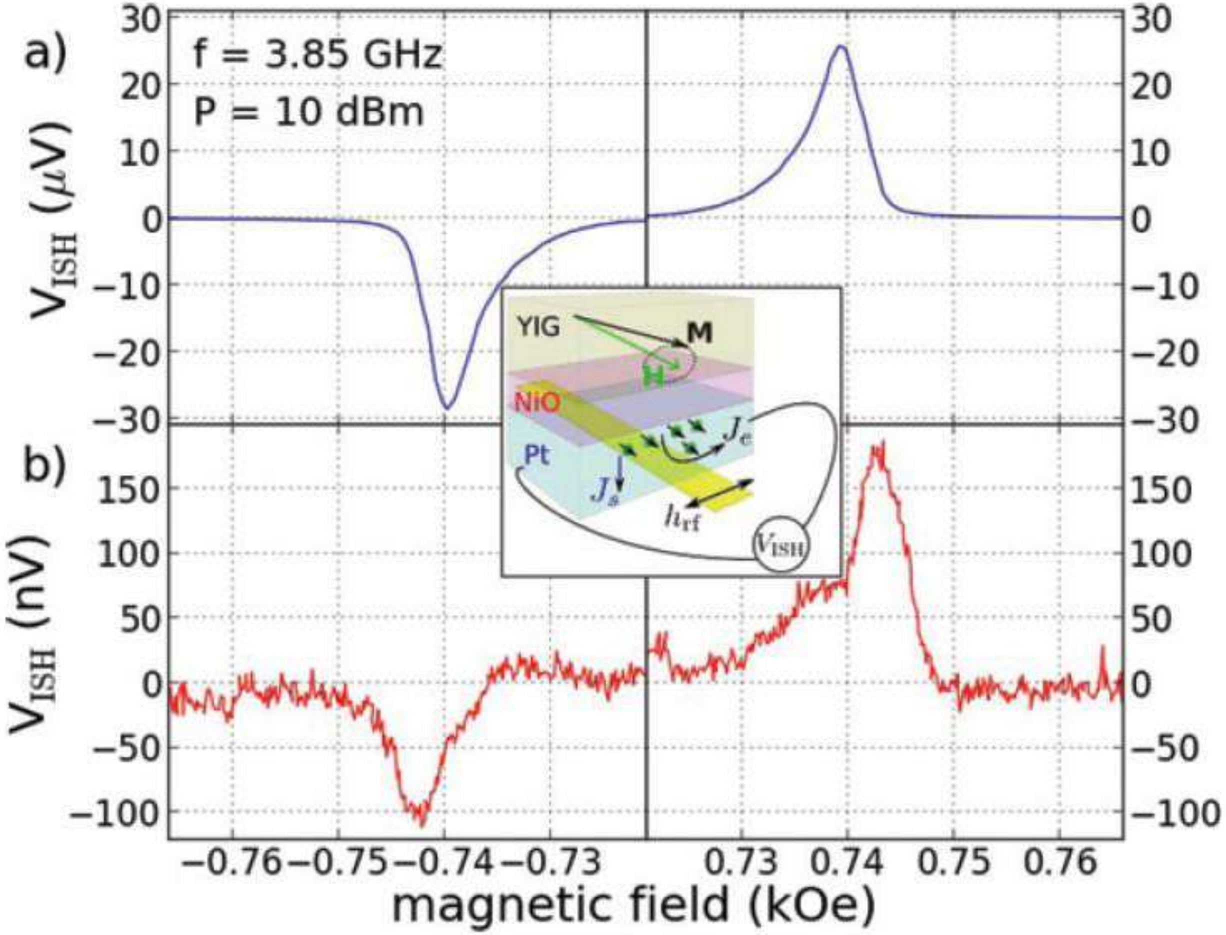


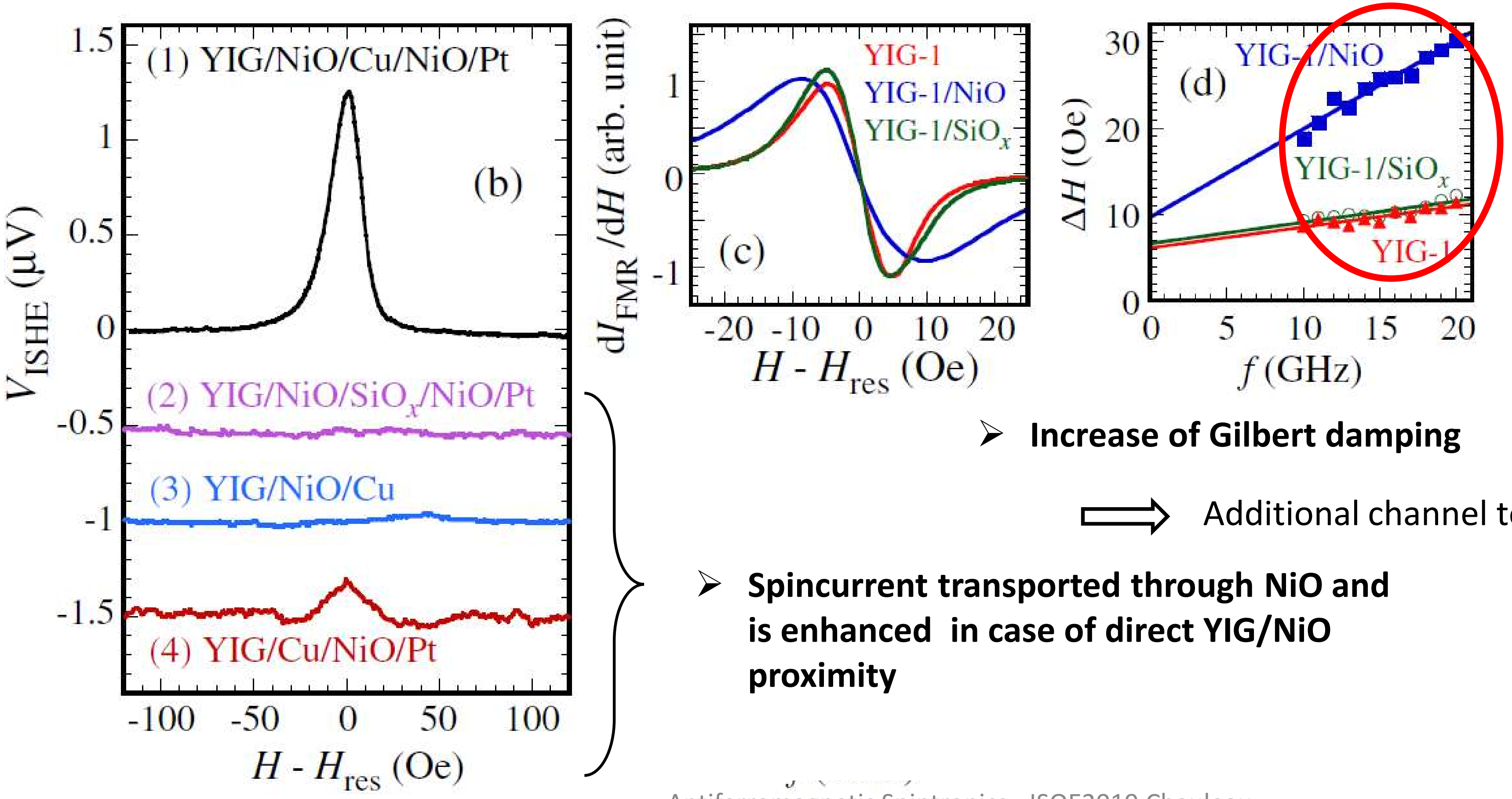


Spincurrents and Antiferromagnets : Transport

PRL **113**, 097202 (2014) PHYSICAL REVIEW LETTERS week ending 29 AUGUST 2014

Antiferromagnonic Spin Transport from $Y_3Fe_5O_{12}$ into NiO

Hailong Wang, Chunhui Du, P. Chris Hammel,* and Fengyuan Yang†
Department of Physics, The Ohio State University, Columbus, Ohio 43210, USA
(Received 21 March 2014; revised manuscript received 21 May 2014; published 29 August 2014)



- **Increase of Gilbert damping** $\left(\mu_0 \Delta H = \frac{\alpha}{\gamma} 2\pi f\right)$

⟹ Additional channel to carry away angular momentum

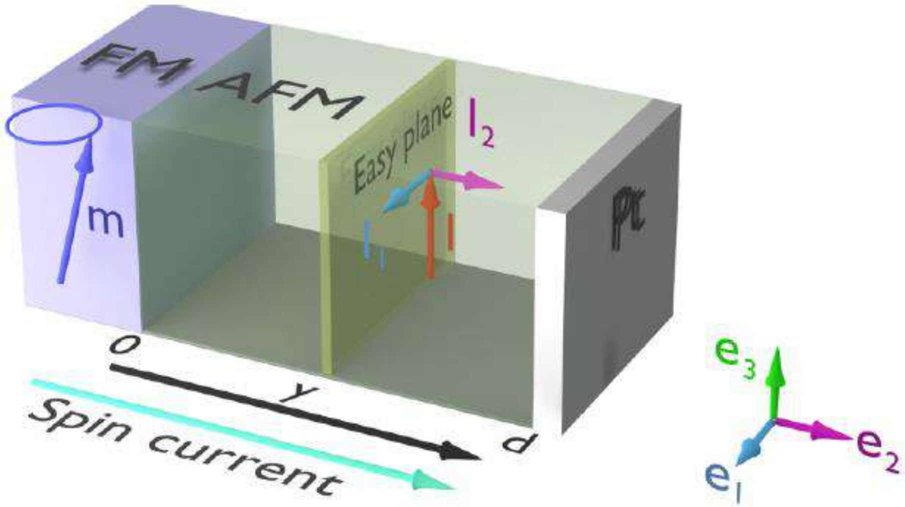
- **Spincurrent transported through NiO and is enhanced in case of direct YIG/NiO proximity**

Spincurrents and Antiferromagnets : Transport

PHYSICAL REVIEW B **93**, 224421 (2016)

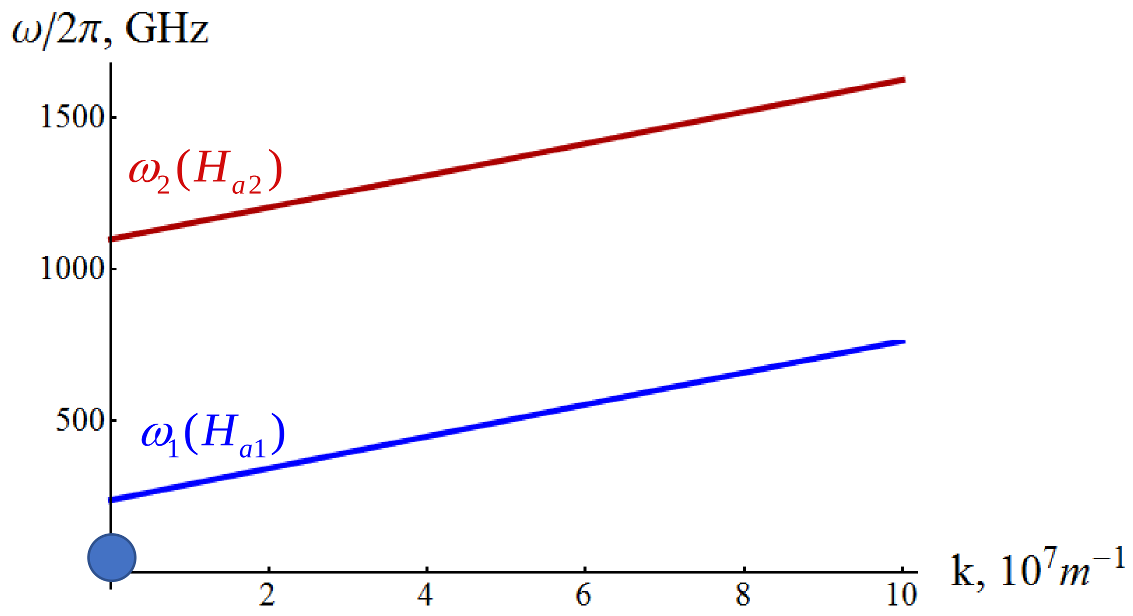
Transformation of spin current by antiferromagnetic insulators

Roman Khymyn,[1,*] Ivan Lisenkov,[1,2] Vasil S. Tiberkevich,[1] Andrei N. Slavin,[1] and Boris A. Ivanov[3,4]
[1]*Department of Physics, Oakland University, Rochester, Michigan 48309, USA*
[2]*Institute of Radio-engineering and Electronics of RAS, Moscow 125009, Russia*
[3]*Institute of Magnetism, NASU and MESYSU, Kiev 03142, Ukraine*
[4]*Taras Shevchenko National University of Kiev, 01601 Kiev, Ukraine*
(Received 29 November 2015; revised manuscript received 19 May 2016; published 22 June 2016)



Driven magnetization dynamics in the GHz: far below AF dynamics

- Spin current transfer cannot be explained by the excitation of AF propagating spinwaves



Courtesy A. Slavin

PHYSICAL REVIEW B **93**, 224421 (2016)

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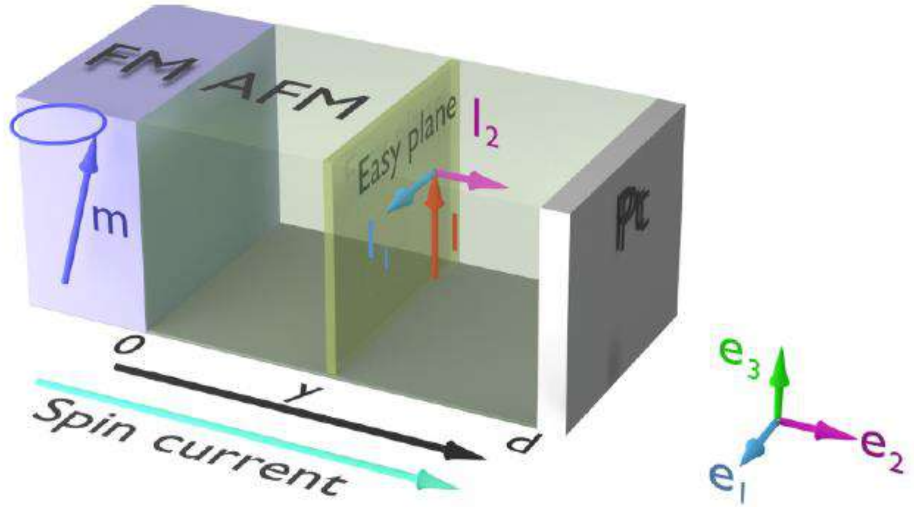
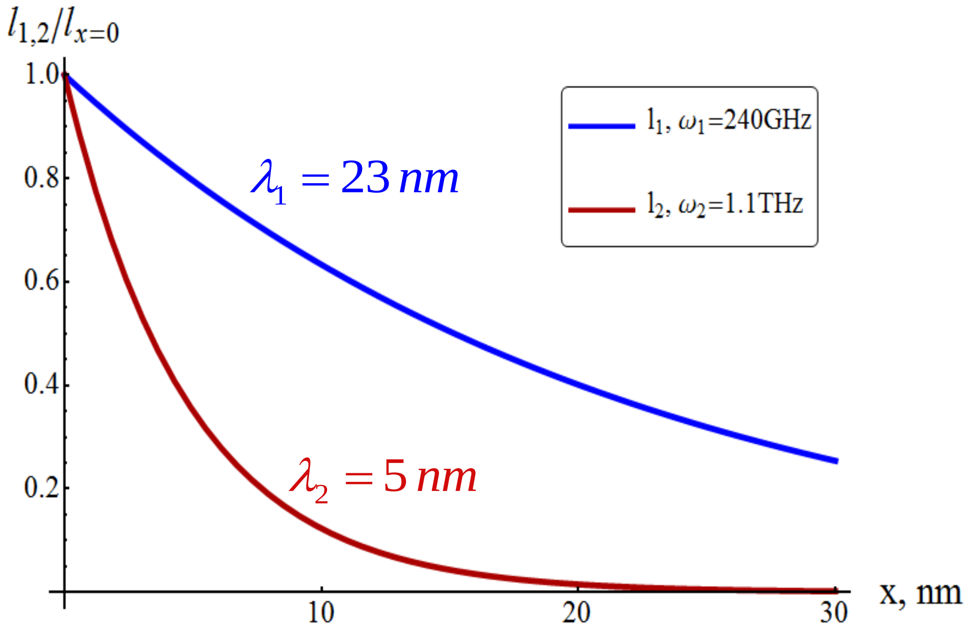


Driven magnetization dynamics in the GHz: far below AF dynamics

- Spin current transfer cannot be explained by the excitation of AF propagating spinwaves
- Ferromagnetic dynamics generates evanescent modes in the AF layer

Penetration depth:

$$\lambda_j = c/\sqrt{\omega_j^2 - \omega^2}$$



Courtesy A. Slavin

Spincurrents and Antiferromagnets : Transport

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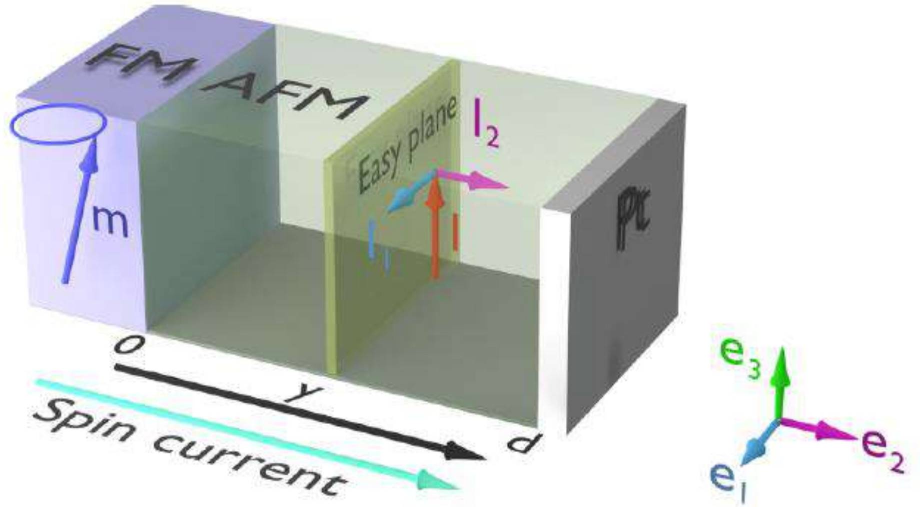
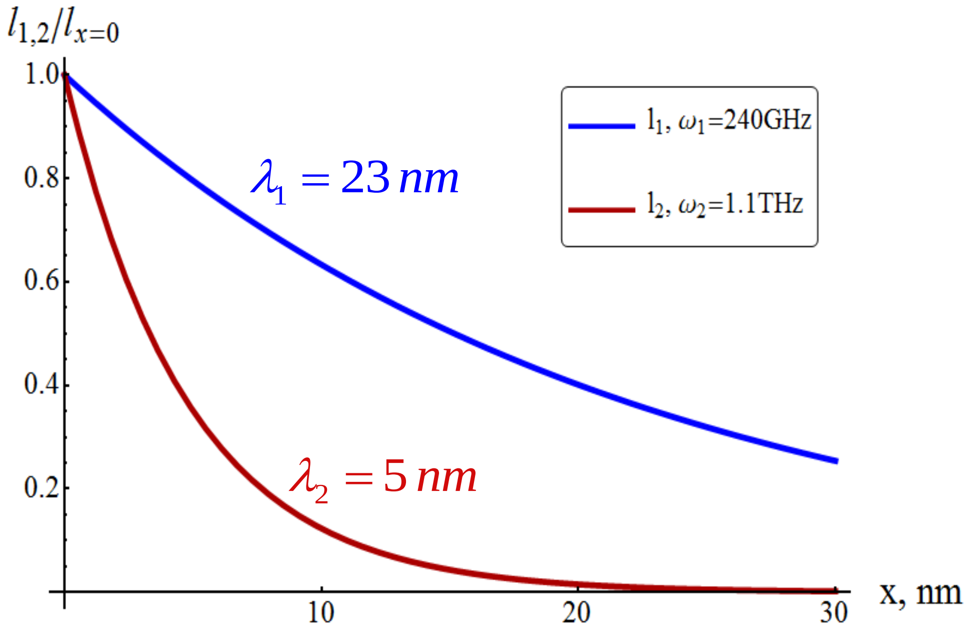


<u>Driven magnetization dynamics in the GHz: far below AF dynamics</u>

- Spin current transfer cannot be explained by the excitation of AF propagating spinwaves
- Ferromagnetic dynamics generates evanescent modes in the AF layer
- Linearly polarized evanescent modes



Courtesy A. Slavin

Spincurrents and Antiferromagnets : Transport

PHYSICAL REVIEW B **93**, 224421 (2016)

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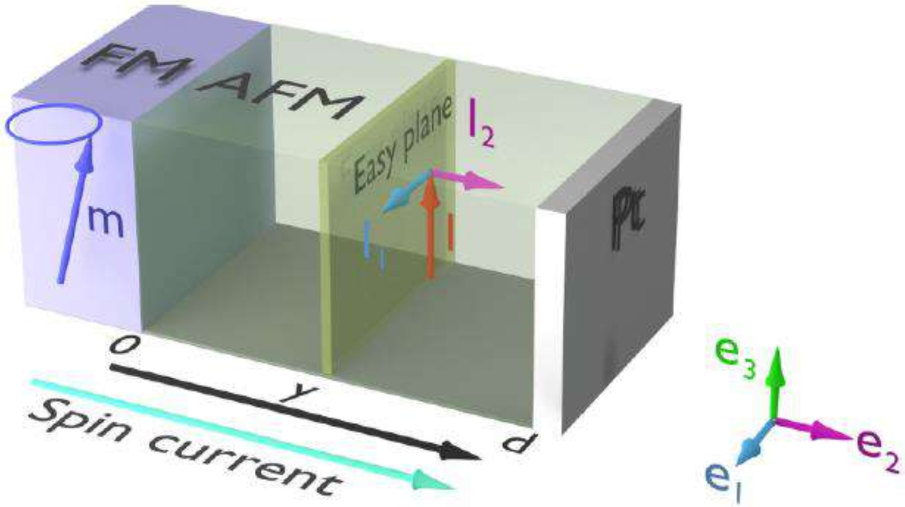
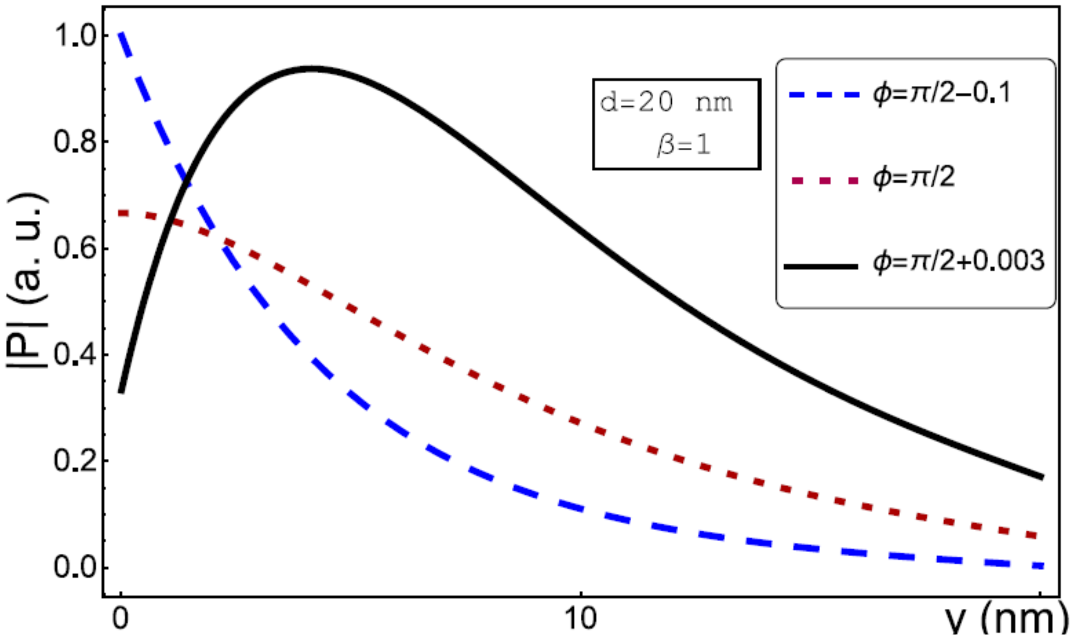


Driven magnetization dynamics in the GHz: far below AF dynamics

- Spin current transfer cannot be explained by the excitation of AF propagating spinwaves
- Ferromagnetic dynamics generates evanescent modes in the AF layer
- Linearly polarized evanescent modes
- 2 modes have to be both excited in order to support the angular momentum transport

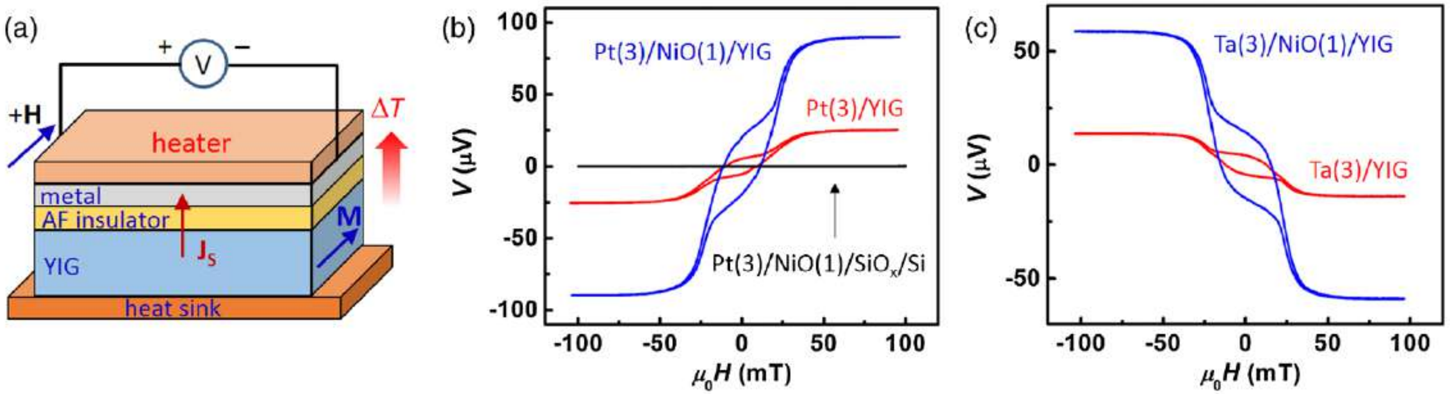


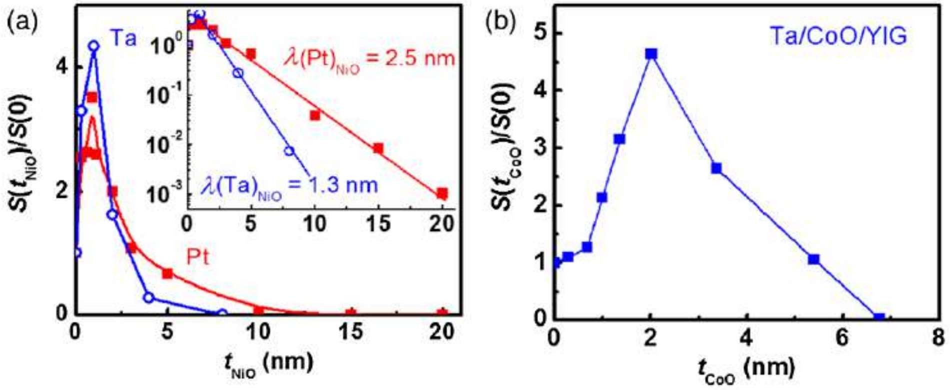
Spincurrents and Antiferromagnets : Transport

PRL 116, 186601 (2016) PHYSICAL REVIEW LETTERS week ending 6 MAY 2016

Enhancement of Thermally Injected Spin Current through an Antiferromagnetic Insulator

Weiwei Lin,[1,*] Kai Chen,[2] Shufeng Zhang,[2] and C. L. Chien[1,†]
[1]Department of Physics and Astronomy, Johns Hopkins University, Baltimore, Maryland 21218, USA
[2]Department of Physics, University of Arizona, Tucson, Arizona 85721, USA
(Received 15 October 2015; revised manuscript received 8 February 2016; published 5 May 2016)





- Spincurrent driven by spin Seebeck effect
- Unlike FMR spin pumping: DC spincurrent, no coherent resonance
- Broad spectrum distribution of non-equilibrium thermal magnons

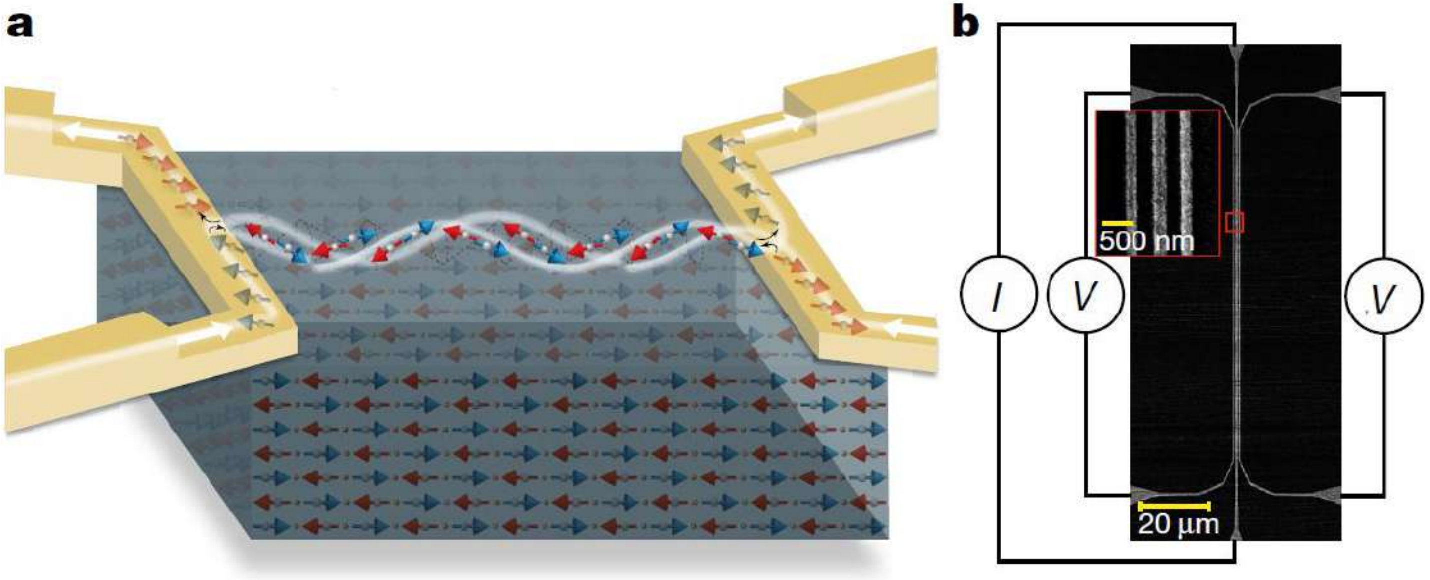
LETTER

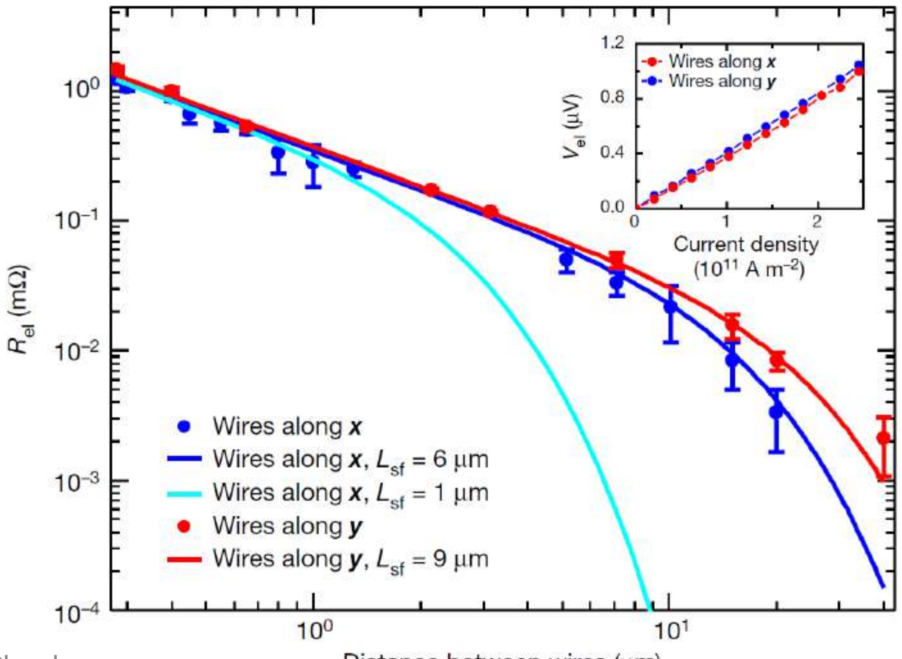
https://doi.org/10.1038/s41586-018-0490-7

Tunable long-distance spin transport in a crystalline antiferromagnetic iron oxide

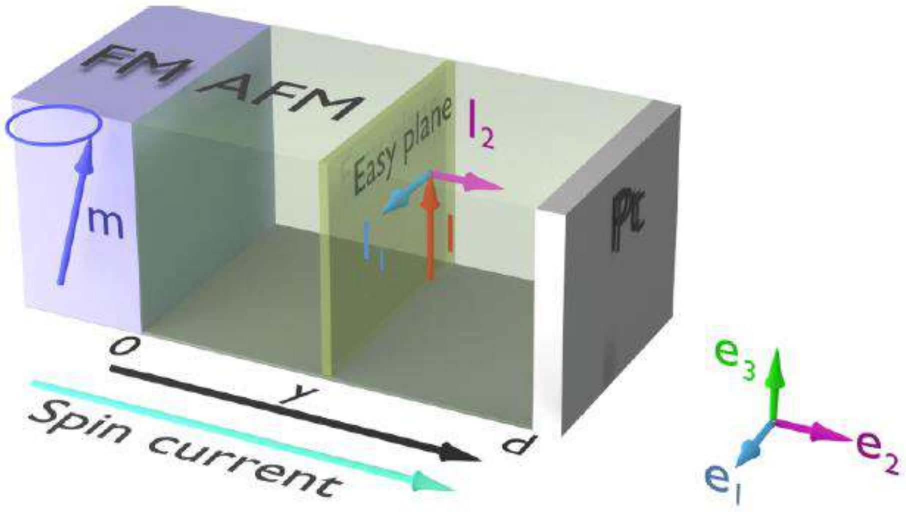
R. Lebrun[1,6]*, A. Ross[1,2,6], S. A. Bender[3], A. Qaiumzadeh[4], L. Baldrati[1], J. Cramer[1,2], A. Brataas[4], R. A. Duine[3,4,5] & M. Kläui[1,2,4]*

- Spincurrent in AF induced by 2 effects:
  - ✓ spin-Seebeck effect
  - ✓ spin accumulation at the Pt/AF interface
- Unlike previous studies: long-distance spincurrent transport in AF (α-Fe_2O_3)





Spincurrents and Antiferromagnets : Transport



Antiferromagnetic insulators ⟹ **Low dissipation spincurrent conductors**

What about manipulating AF distributions using spincurrents?

Spincurrents and Antiferromagnets : AF manipulation

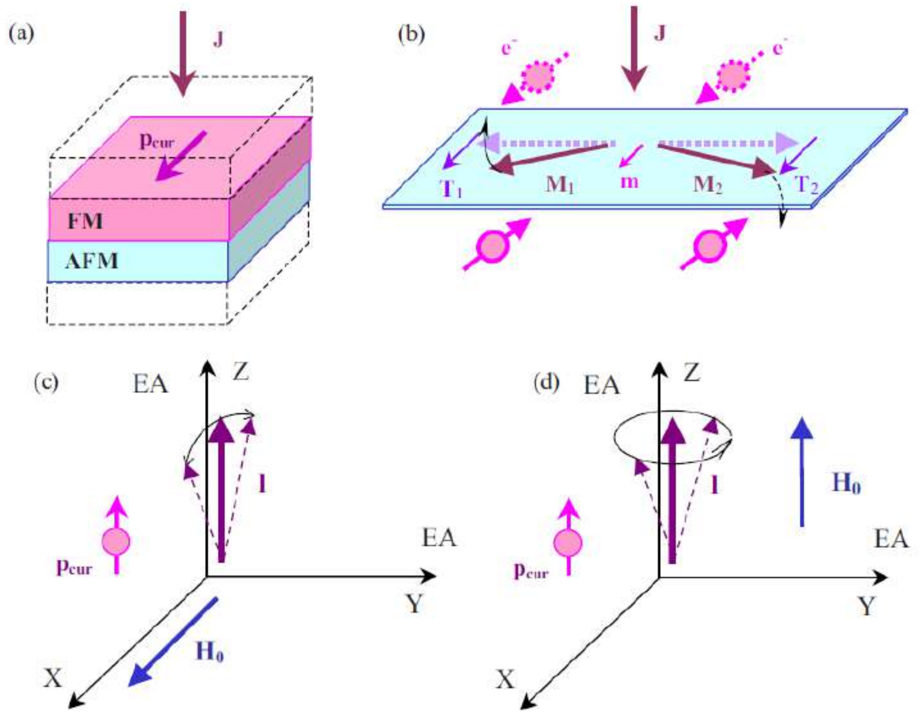
PHYSICAL REVIEW B **81**, 144427 (2010)

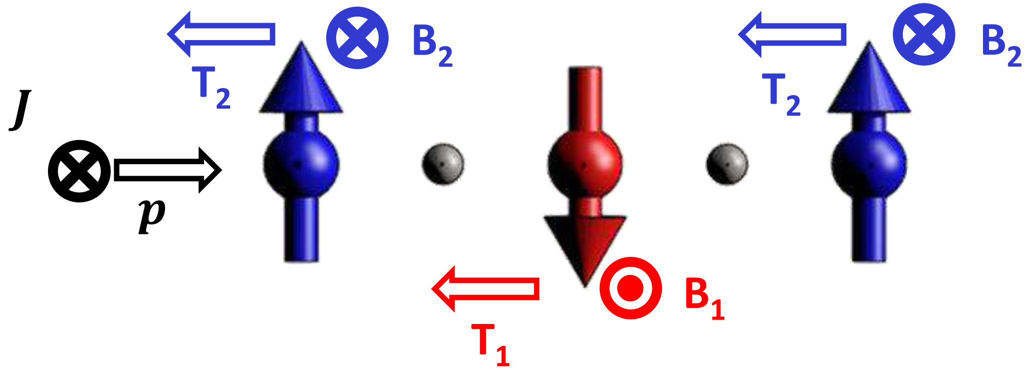
Spin transfer and current-induced switching in antiferromagnets

Helen V. Gomonay
National Technical University of Ukraine "KPI," 37 Peremogy Avenue, 03056 Kyiv, Ukraine

Vadim M. Loktev
Bogolyubov Institute for Theoretical Physics, NAS of Ukraine, Metrologichna Street 14-b, 03143 Kyiv, Ukraine

(Received 21 September 2009; revised manuscript received 17 December 2009; published 27 April 2010)





- Spin-polarized current can efficiently manipulate the AF order
- Spin-torque ($\boldsymbol{T}_{1(2)}$) on each individual sublattices

$$\frac{d\boldsymbol{m}_1}{dt} = -\mu_0\gamma\boldsymbol{m}_1 \times (-J\boldsymbol{m}_2 + \boldsymbol{H}_A - \boldsymbol{H}) + \boldsymbol{T}_1$$

$$\frac{d\boldsymbol{m}_2}{dt} = -\mu_0\gamma\boldsymbol{m}_2 \times (-J\boldsymbol{m}_1 + \boldsymbol{H}_A + \boldsymbol{H}) + \boldsymbol{T}_2$$

with $\boldsymbol{T}_{1(2)} \propto \boldsymbol{m}_{1(2)} \times \left(\boldsymbol{m}_{1(2)} \times \boldsymbol{p}\right)$

Eq. to a staggered "field", $B_{1(2)}$

See also:

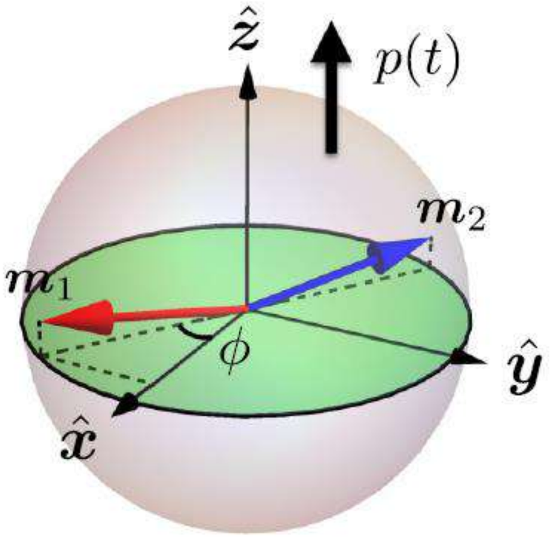
- Gomonay et al. *Phys. Rev. B* ***85*** 134446 (2012)
- Cheng et al. *Phys. Rev. Lett.* **113**, 057601 (2014)
- Cheng et al. *Phys. Rev. B* **113**, 064423 (2015)

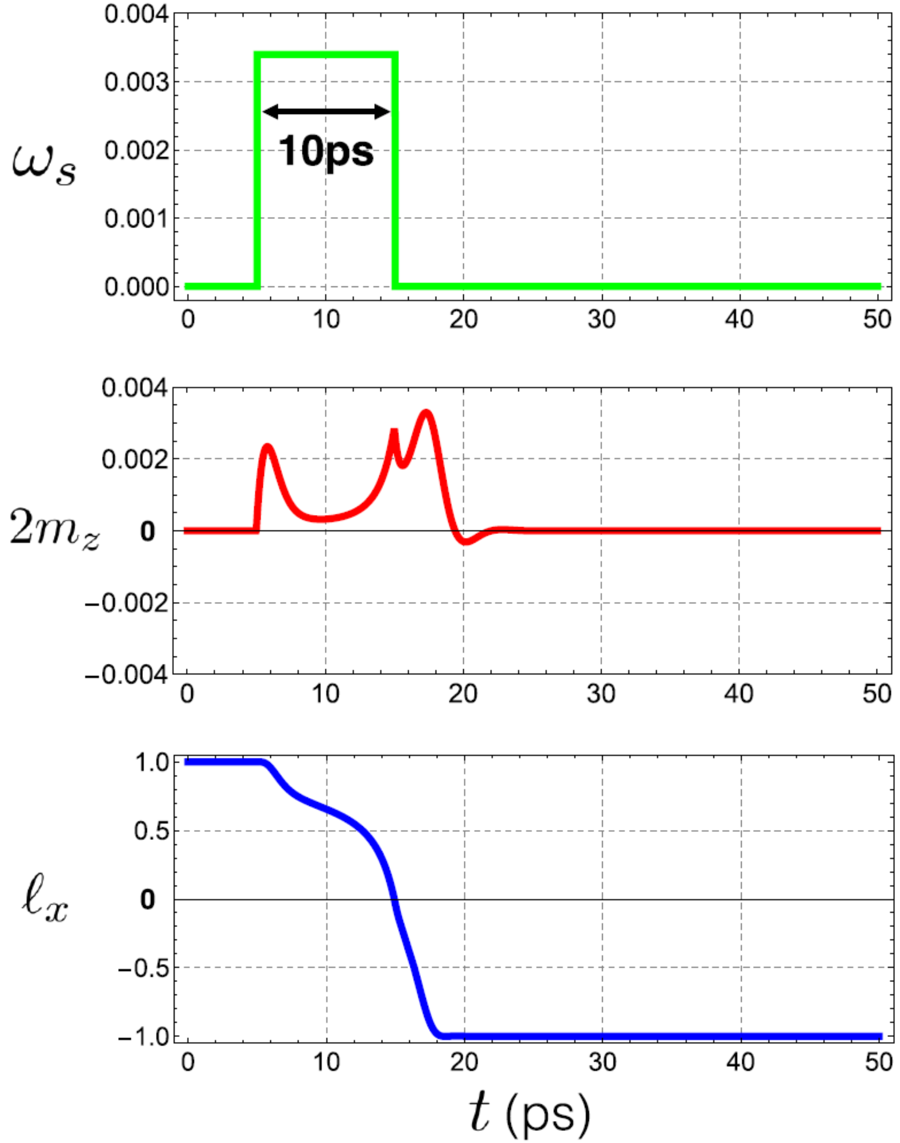
Spincurrents and Antiferromagnets : AF manipulation

PHYSICAL REVIEW B **91**, 064423 (2015)

Ultrafast switching of antiferromagnets via spin-transfer torque

Ran Cheng,[1] Matthew W. Daniels,[1] Jian-Gang Zhu,[2] and Di Xiao[1]
[1]*Department of Physics, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, Pennsylvania 15213, USA*
[2]*Department of Electrical and Computer Engineering, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, Pennsylvania 15213, USA*
(Received 10 December 2014; published 27 February 2015)





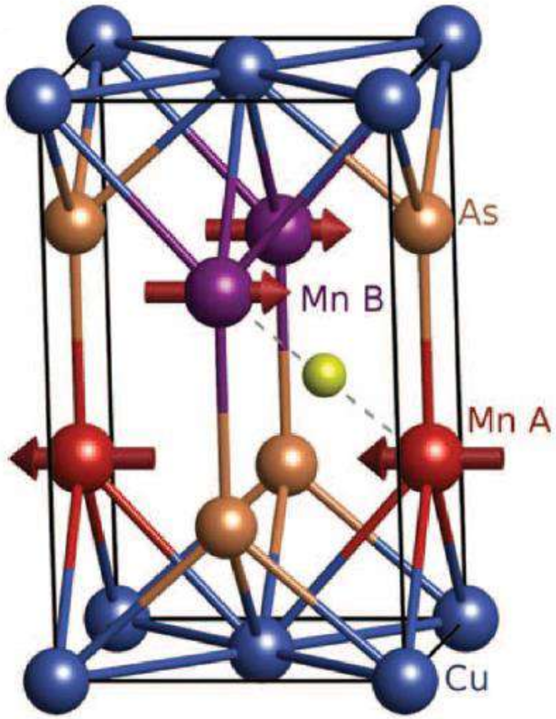
Spincurrents and Antiferromagnets : AF manipulation

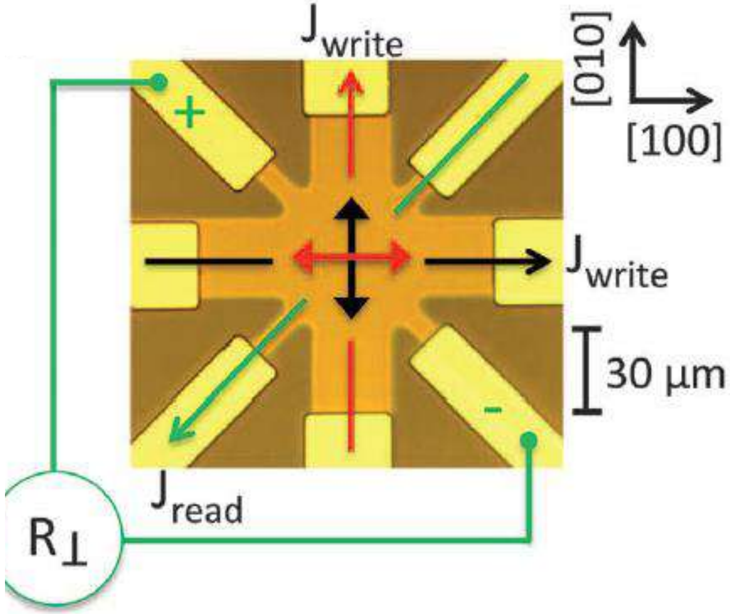
SPINTRONICS

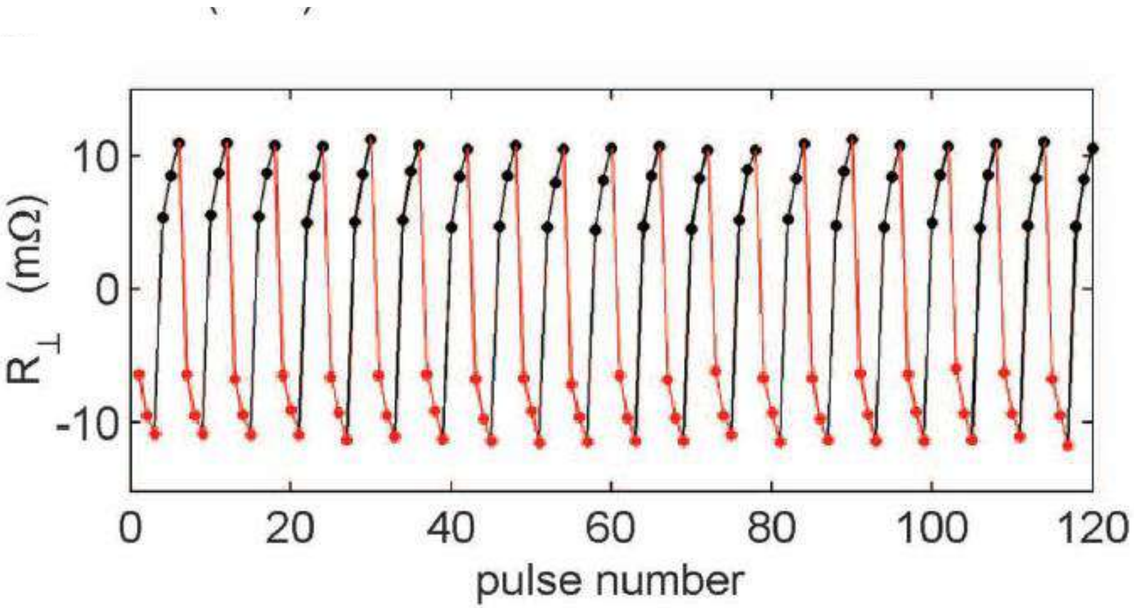
Electrical switching of an antiferromagnet

P. Wadley,[1*†] B. Howells,[1*] J. Železný,[2,3] C. Andrews,[1] V. Hills,[1] R. P. Campion,[1]
V. Novák,[2] K. Olejník,[2] F. Maccherozzi,[4] S. S. Dhesi,[4] S. Y. Martin,[5] T. Wagner,[5,6]
J. Wunderlich,[2,5] F. Freimuth,[7] Y. Mokrousov,[7] J. Kuneš,[8] J. S. Chauhan,[1]
M. J. Grzybowski,[1,9] A. W. Rushforth,[1] K. W. Edmonds,[1] B. L. Gallagher,[1] T. Jungwirth[2,1]

- First experimental demonstration in **CuMnAs** by Wadley at al. *SCIENCE* **351** 587 (2016)
- Local Broken inversion symmetry: electrical current generates a non-equilibrium spin-polarization with opposite polarities on sites A and B







Spincurrents and Antiferromagnets : *AF manipulation*

SPINTRONICS

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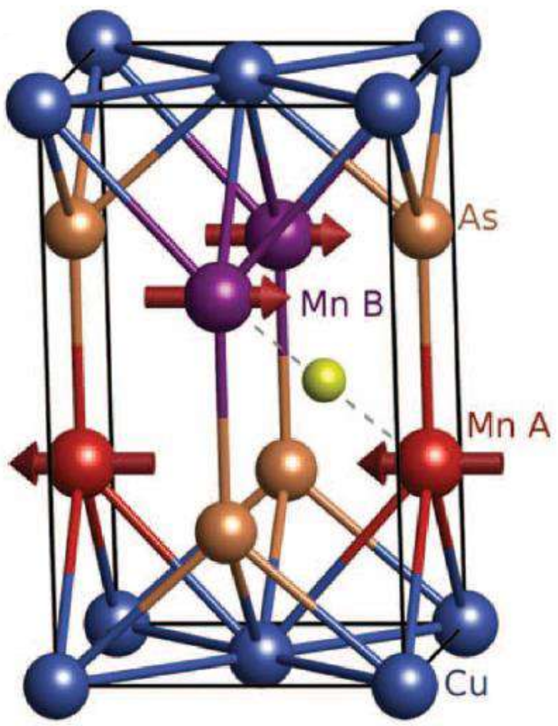
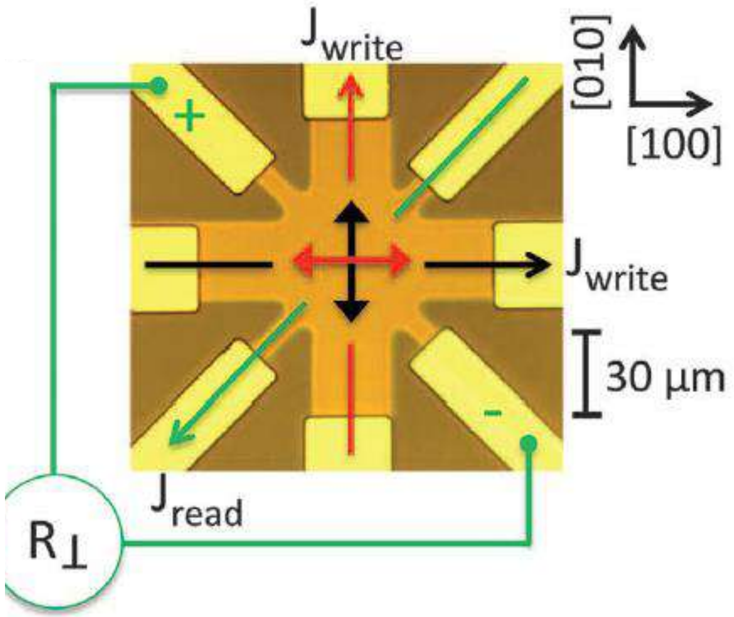
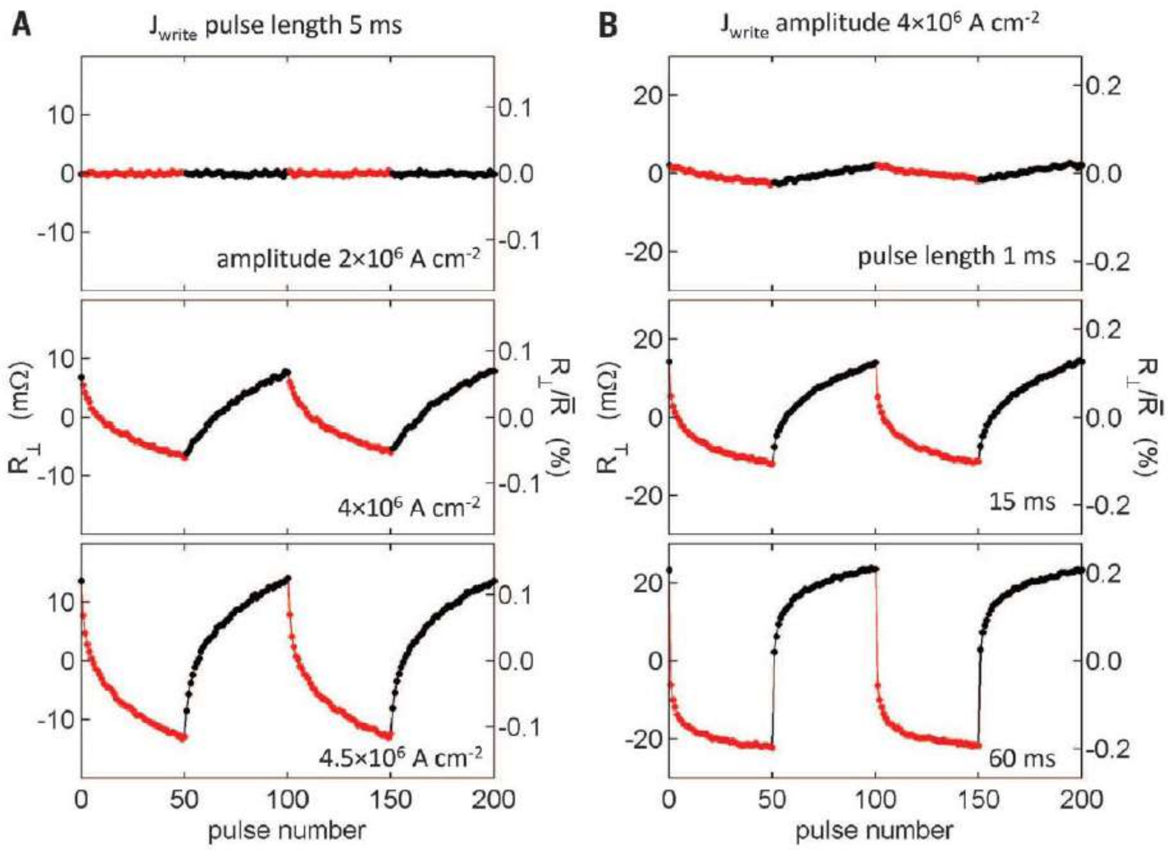






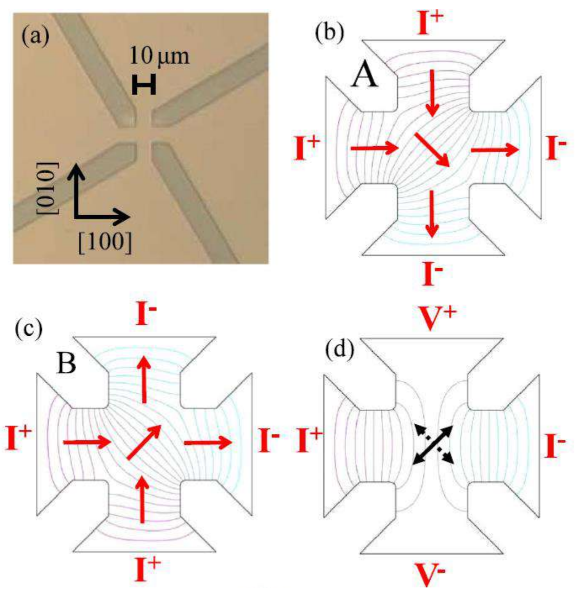
Spincurrents and Antiferromagnets : AF manipulation

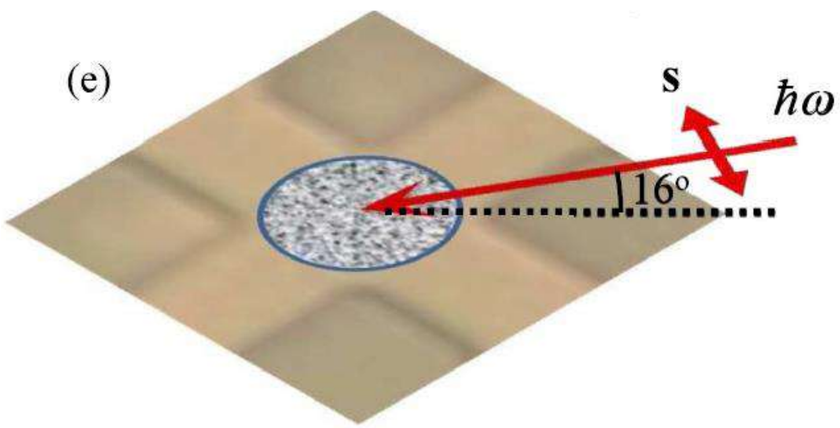
PRL 118, 057701 (2017) PHYSICAL REVIEW LETTERS week ending 3 FEBRUARY 2017

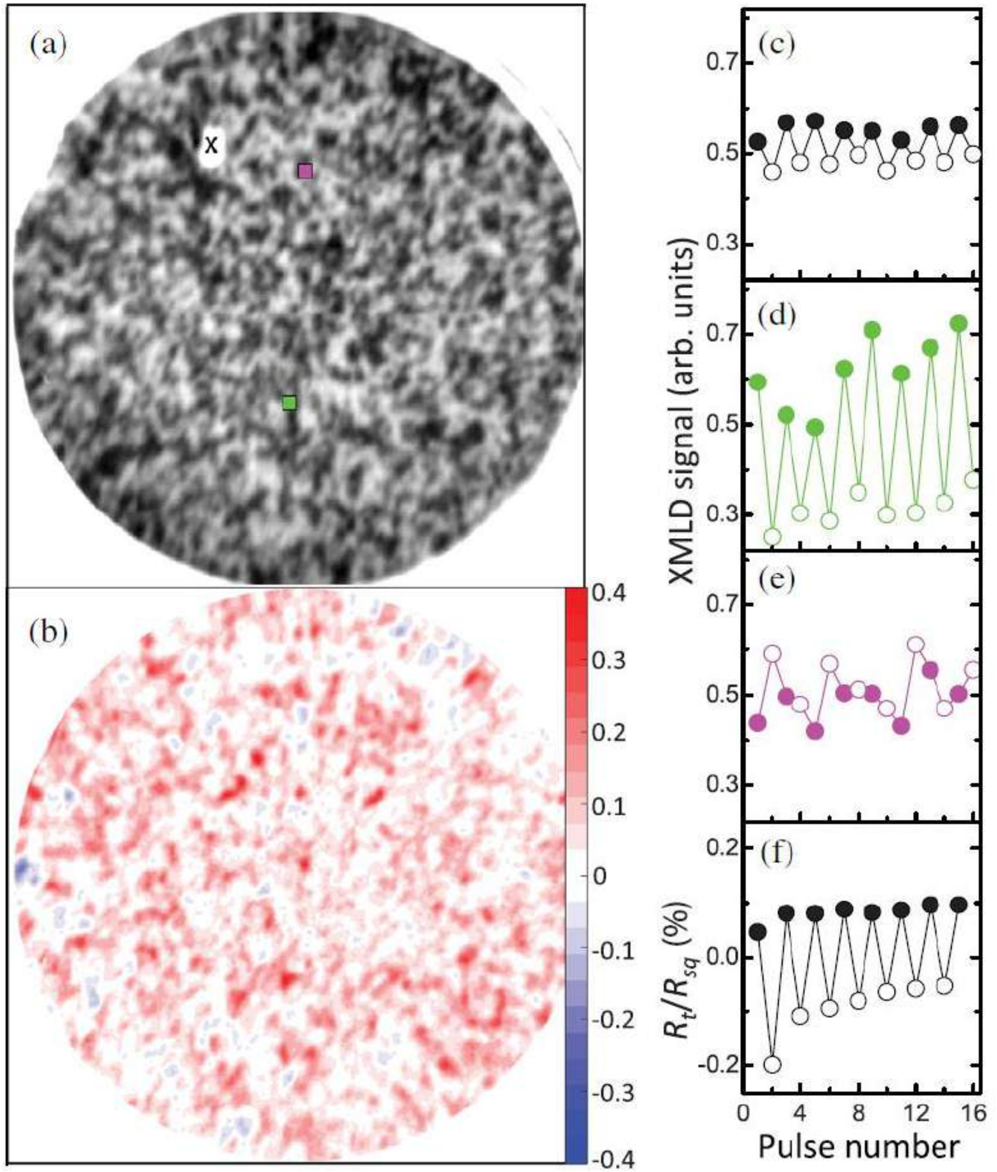
Imaging Current-Induced Switching of Antiferromagnetic Domains in CuMnAs

M. J. Grzybowski,[1,2] P. Wadley,[1] K. W. Edmonds,[1] R. Beardsley,[1] V. Hills,[1] R. P. Campion,[1] B. L. Gallagher,[1] J. S. Chauhan,[1] V. Novak,[3] T. Jungwirth,[3,1] F. Maccherozzi,[4] and S. S. Dhesi[4]
[1]*School of Physics and Astronomy, University of Nottingham, University Park, Nottingham NG7 2RD, United Kingdom*
[2]*Institute of Physics, Polish Academy of Sciences, Aleja Lotnikow 32/46, PL-02668 Warsaw, Poland*
[3]*Institute of Physics, Academy of Sciences of the Czech Republic, Cukrovarnicka 10, 162 00 Praha 6, Czech Republic*
[4]*Diamond Light Source, Chilton, Didcot, Oxfordshire OX11 0DE, United Kingdom*
(Received 4 August 2016; published 31 January 2017)

- XLMD-PEEM imaging: synchrotron-based technique sensitive to the Néel vector







Spincurrents and Antiferromagnets : AF manipulation

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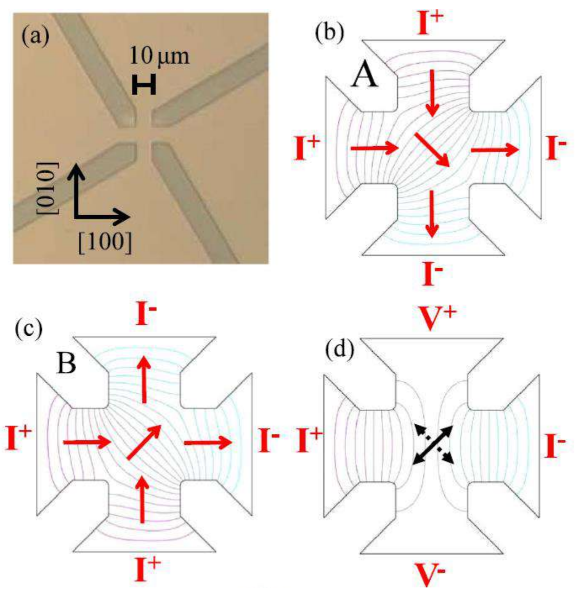
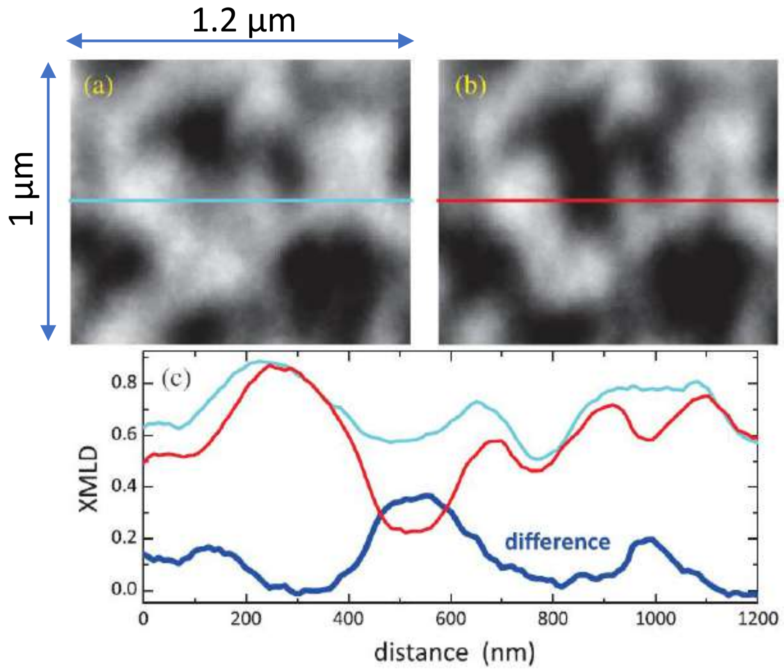
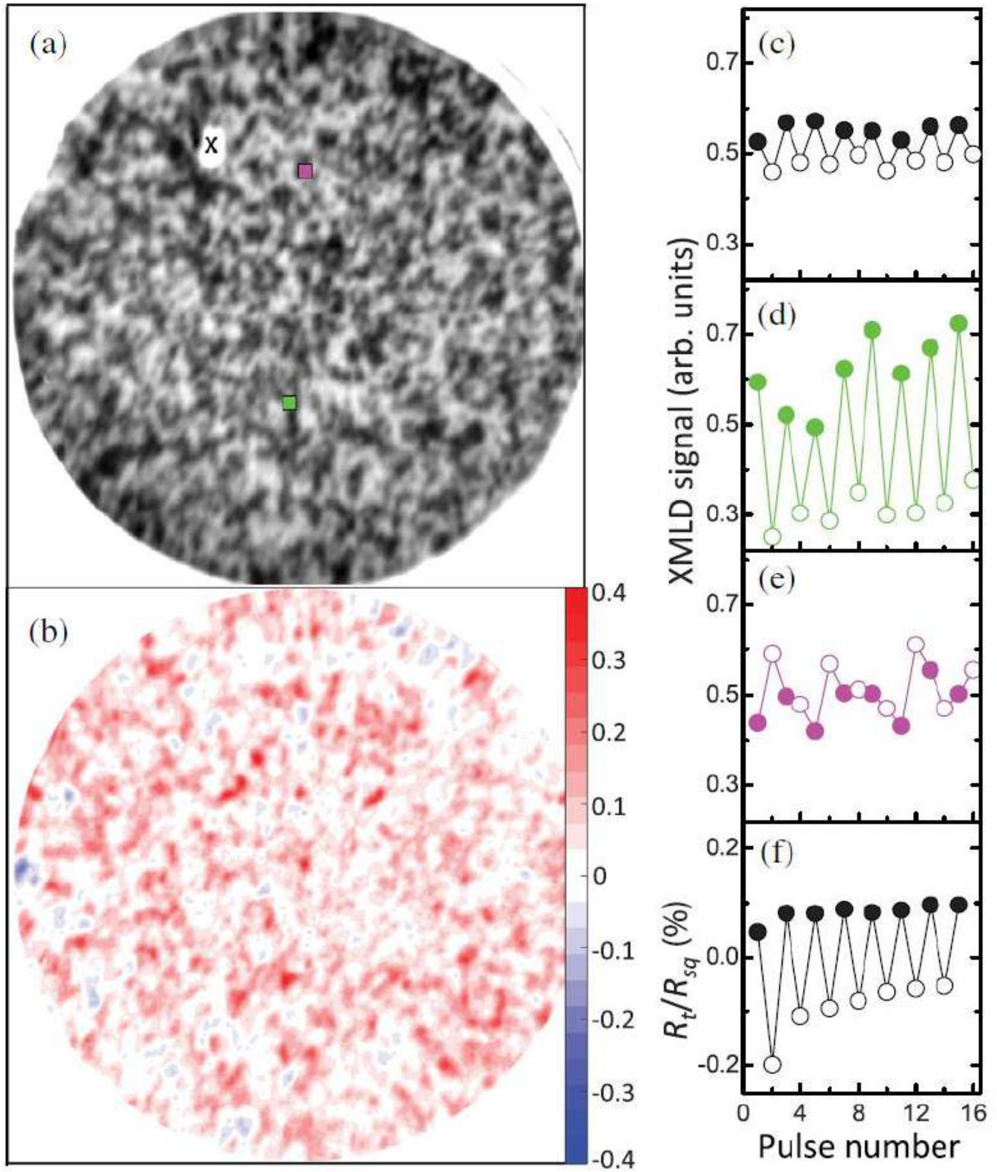






Spincurrents and Antiferromagnets : AF manipulation

Feb, 2016

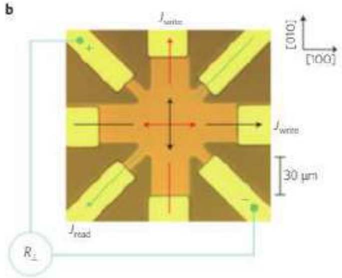
October, 2016

Science paper

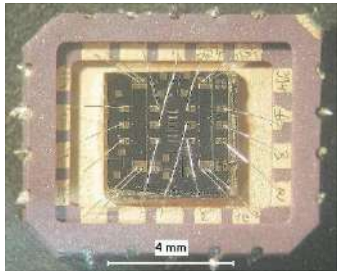

Science

Electrical switching of an antiferromagnet

P. Wadley, B. Howells, J. Železný, C. Andrews, V. Hills, R. P. Campion, V. Novák, K. Olejník, F. Maccherozzi, S. S. Dhesi, S. Y. Martin, T. Wagner, J. Wunderlich, F. Freimuth, Y. Mokrousov, J. Kuneš, J. S. Chauhan, M. J. Grzybowski, A. W. Rushforth, K. W. Edmonds, B. L. Gallagher, T. Jungwirth

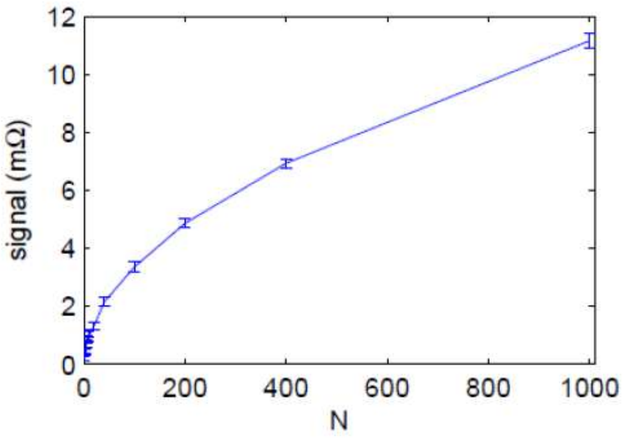


2 cells wire bonded



Packaged prototype

Passive traffic flow monitoring



One AFM cell is an incremental counter

8 pin chip carrier: could contain 2 AFMEM counters

\+

Transistors, USB comms, voltmeter, programming

Spincurrents and Antiferromagnets : *AF "**ultrafast**" manipulation?*

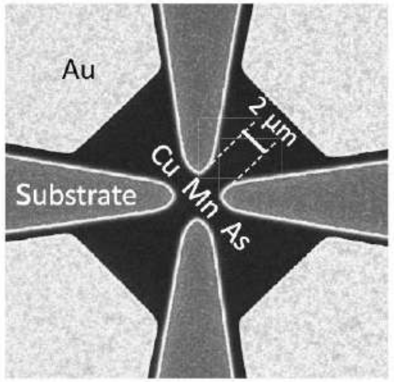
SCIENCE ADVANCES | RESEARCH ARTICLE   Sci. Adv. 2018;4: eaar3566 (2018)

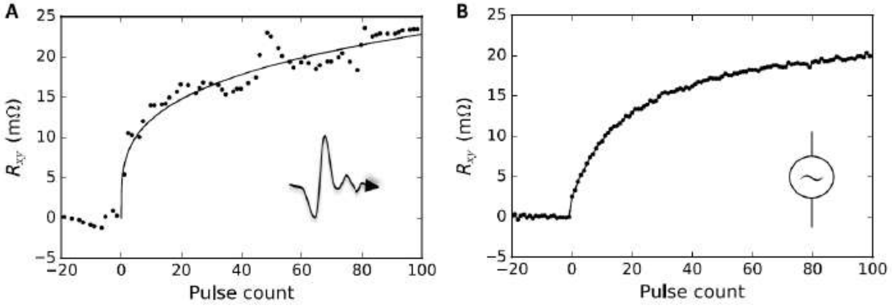
APPLIED SCIENCES AND ENGINEERING

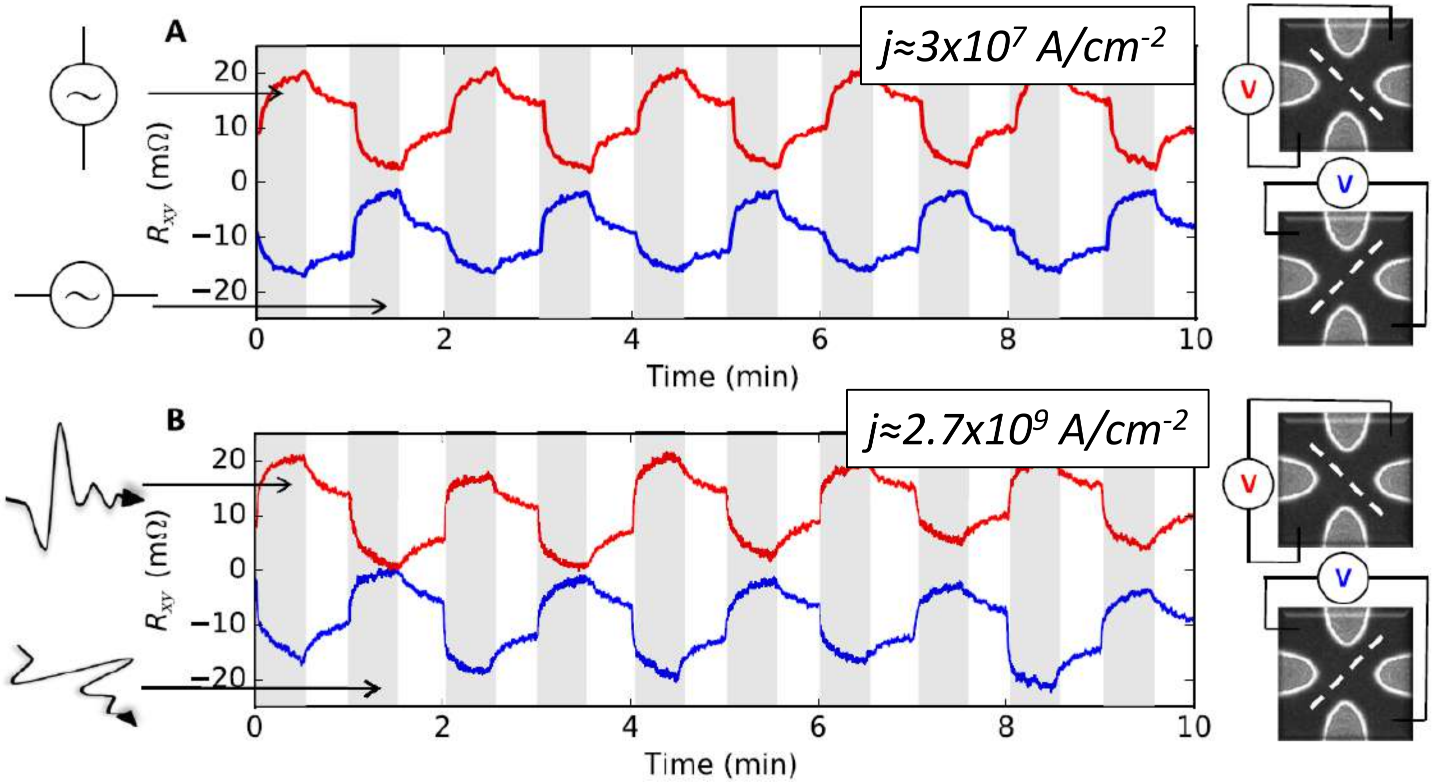
Terahertz electrical writing speed in an antiferromagnetic memory

Kamil Olejník,[1]* Tom Seifert,[2] Zdeněk Kašpar,[1,3] Vít Novák,[1] Peter Wadley,[4] Richard P. Campion,[4] Manuel Baumgartner,[5] Pietro Gambardella,[5] Petr Němec,[3] Joerg Wunderlich,[1,6] Jairo Sinova,[1,7] Petr Kužel,[8] Melanie Müller,[2] Tobias Kampfrath,[2,9] Tomas Jungwirth[1,4]

- AF system responds similarly to "DC" and THz stimuli
- *DC reading:* no information about a possible ultra actual







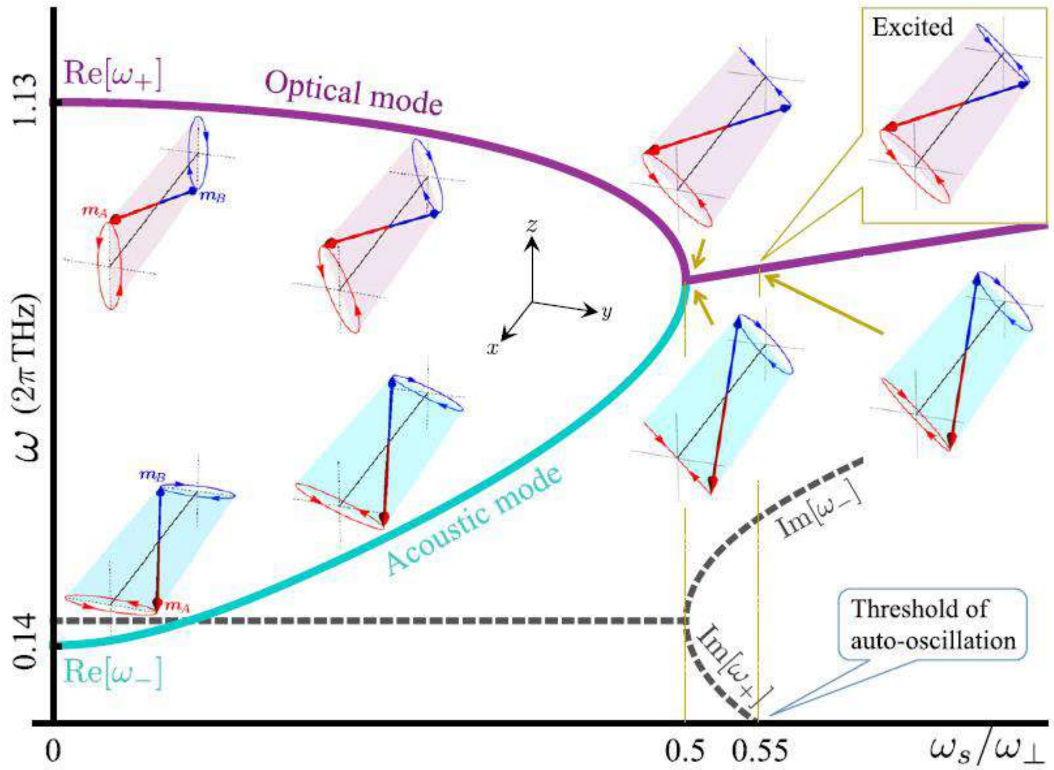
Spincurrents and Antiferromagnets : THz generation

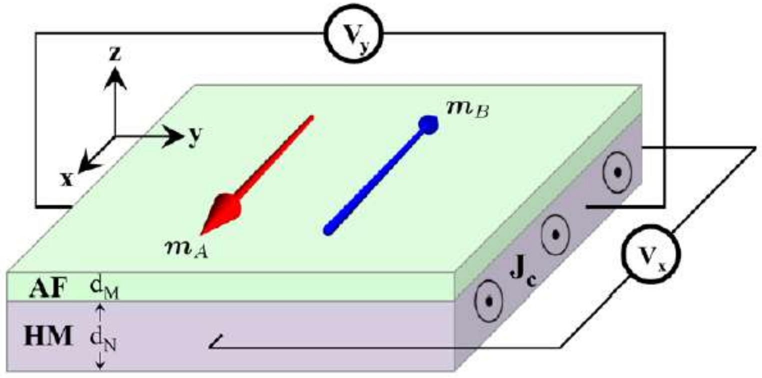
PRL **116**, 207603 (2016) PHYSICAL REVIEW LETTERS week ending 20 MAY 2016

Terahertz Antiferromagnetic Spin Hall Nano-Oscillator

Ran Cheng* and Di Xiao
Department of Physics, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA

Arne Brataas
Department of Physics, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway
(Received 30 September 2015; published 20 May 2016)

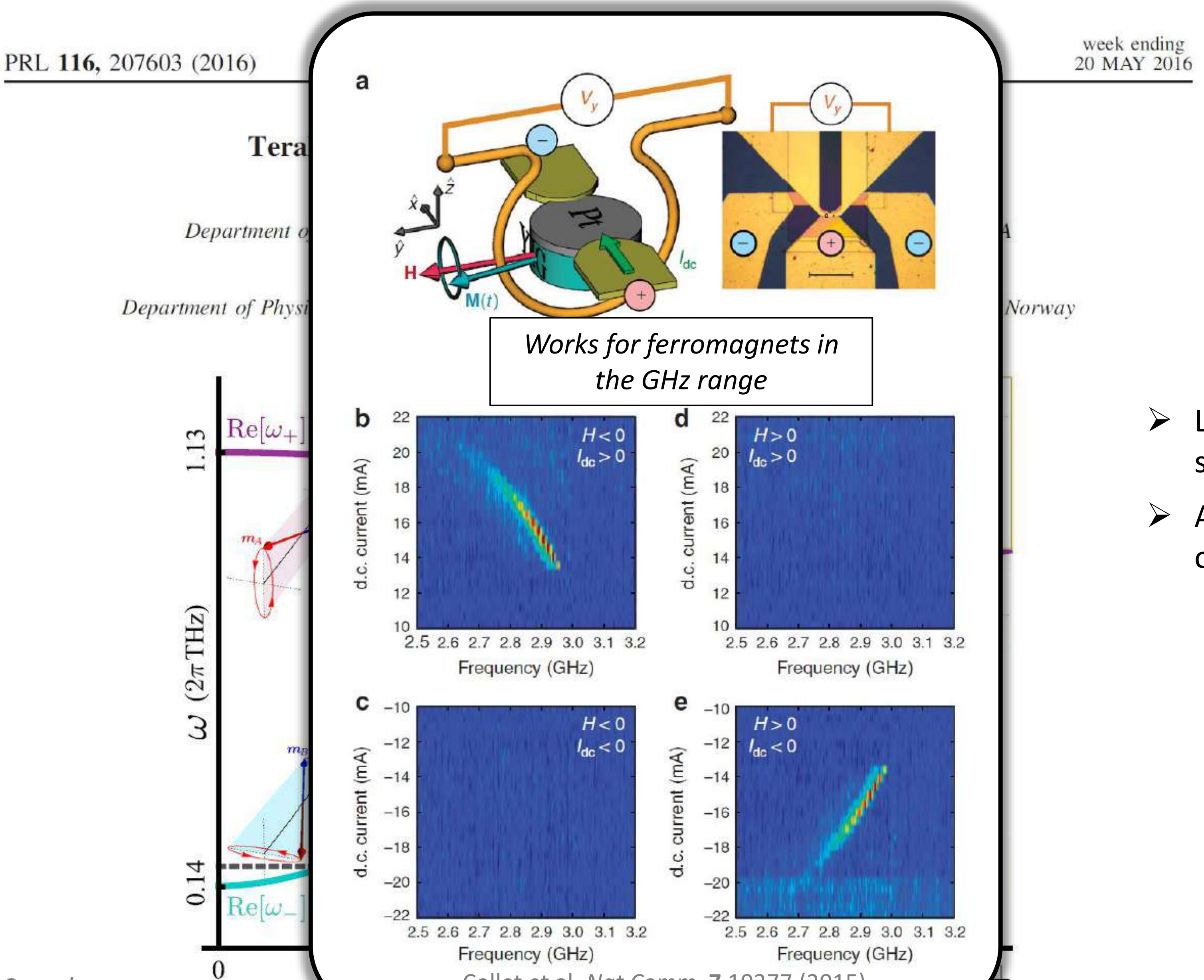




- Linear response of the AF eigenmodes as function of a DC spin-transfer torque
- At a threshold value, the STT compensate, leading to the onset of spontaneous oscillations: ***auto-oscillations***

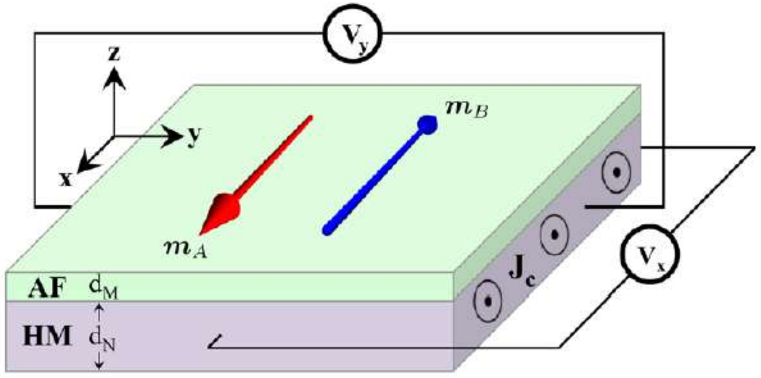
See also:
- Khymyn et al. Scientific report (2016)

Spincurrents and Antiferromagnets : *THz generation*



Works for ferromagnets in the GHz range

Collet et al. *Nat Comm.* **7** 10377 (2015)



- ➢ Linear response of the AF eigenmodes as function of a DC spin-transfer torque
- ➢ At a threshold value, the STT compensate, leading to the onset of spontaneous oscillations: ***auto-oscillations***

See also:

- ➢ Khymyn et al. Scientific report (2016)

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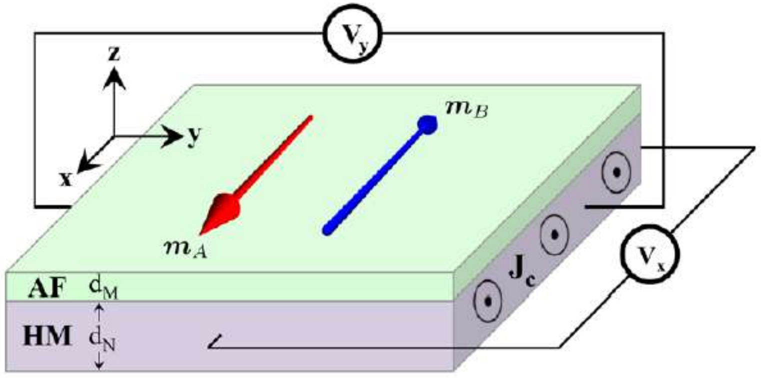
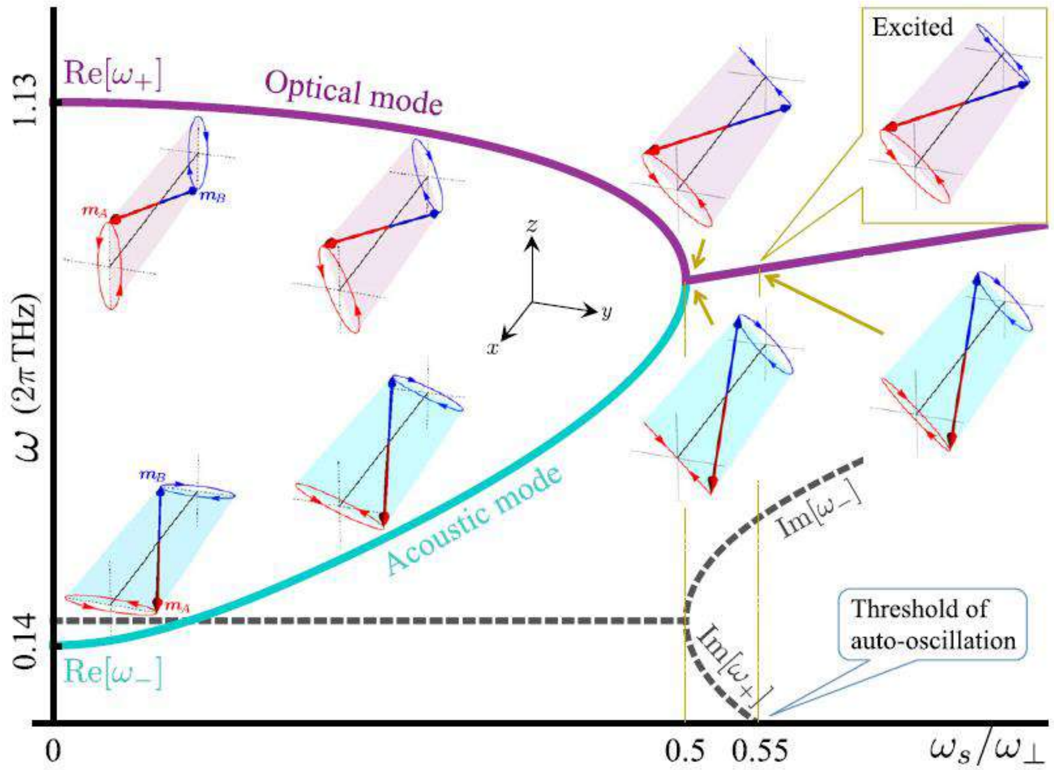




- Linear response of the AF eigenmodes as function of a DC spin-transfer torque
- At a threshold value, the STT compensate, leading to the onset of spontaneous oscillations: ***auto-oscillations***
- Estimation of threshold current density for NiO/Pt systems: j_c=2.9x10^8 A/cm^{-2}
- Need to consider the "backflow"

See also:

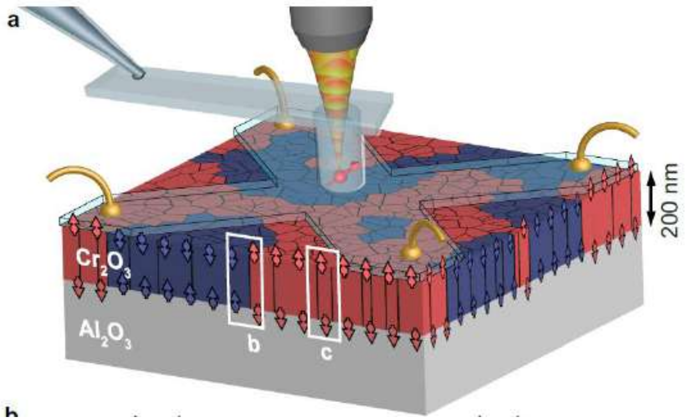
- Khymyn et al. Scientific report (2016)

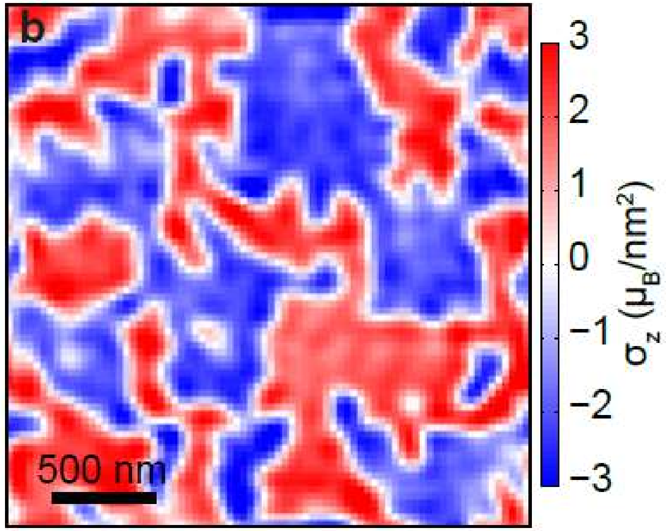
Antiferromagnetic spintronics:

One of the main challenges:

- ✓ Antiferromagnetic domains in thin layer are small
- ✓ Difficulty to prepare monodomain states

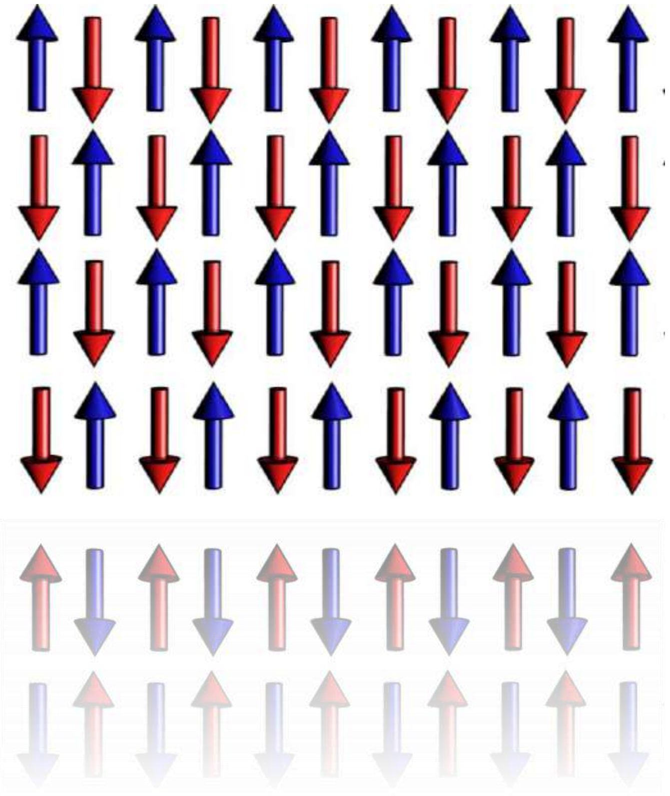
Example in Cr_2O_3
imaged by NV magnetometry





Appel et al. *Nano lett.* (2019)

Antiferromagnetic spintronics: Conclusion



- Antiferromagnets :
  - ✓ Large majority on the magnetic materials
  - ✓ Robust against external magnetic perturbation
  - ✓ THz intrinsic dynamics
- Magnonic spincurrents can be transported through AF insulating oxides
  - ✓ Demonstrated for DC and GHz regimes
  - ✓ On long distances for bulk AF crystals
- AF order can be manipulated using spincurrents
  - ✓ Demonstrated in the peculiar case of CuMnAs
  - ✓ Several interesting theoretical works
  - ✓ Still experimentally challenging to study