Nanomagnetism and Spintronics

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μΦ

Experimental Department 1

MAX-PLANCK-GESELLSCHAFT

Nano world

Quantum effects

Quantum confinement

Spin-dependent quantum confinement

Lower symmetry → new effects!

Examples:

1- Spin dependent quantum-well states

2- Spin-dependent quantum interference

3- Magnon Spintronics

Examples:

1- Spin dependent quantum-well states

2- Spin-dependent quantum interference

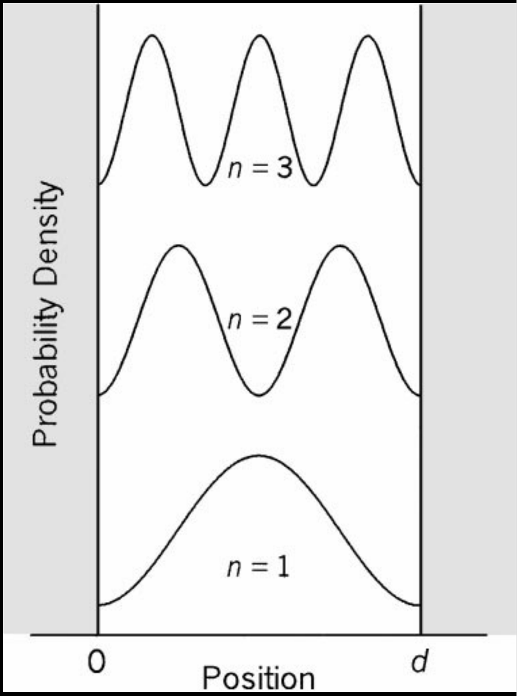
3- Magnon Spintronics

Confinement effects via quantum-well states

quantum well states of a particle confined in a one-dimensional box of size *d*

$$E = \frac{\hbar^2 k^2}{2m} = \frac{\hbar^2}{2m}\left(\frac{n\pi}{d}\right)^2$$

T.-C. Chiang , Surface Science Reports **39** (2000) 181



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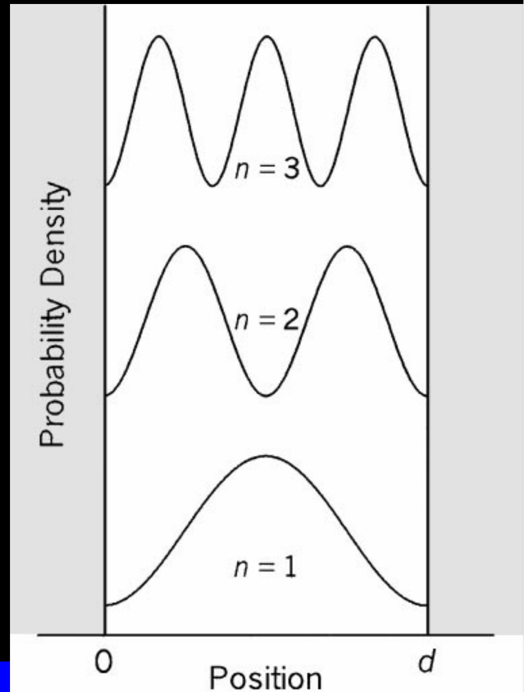
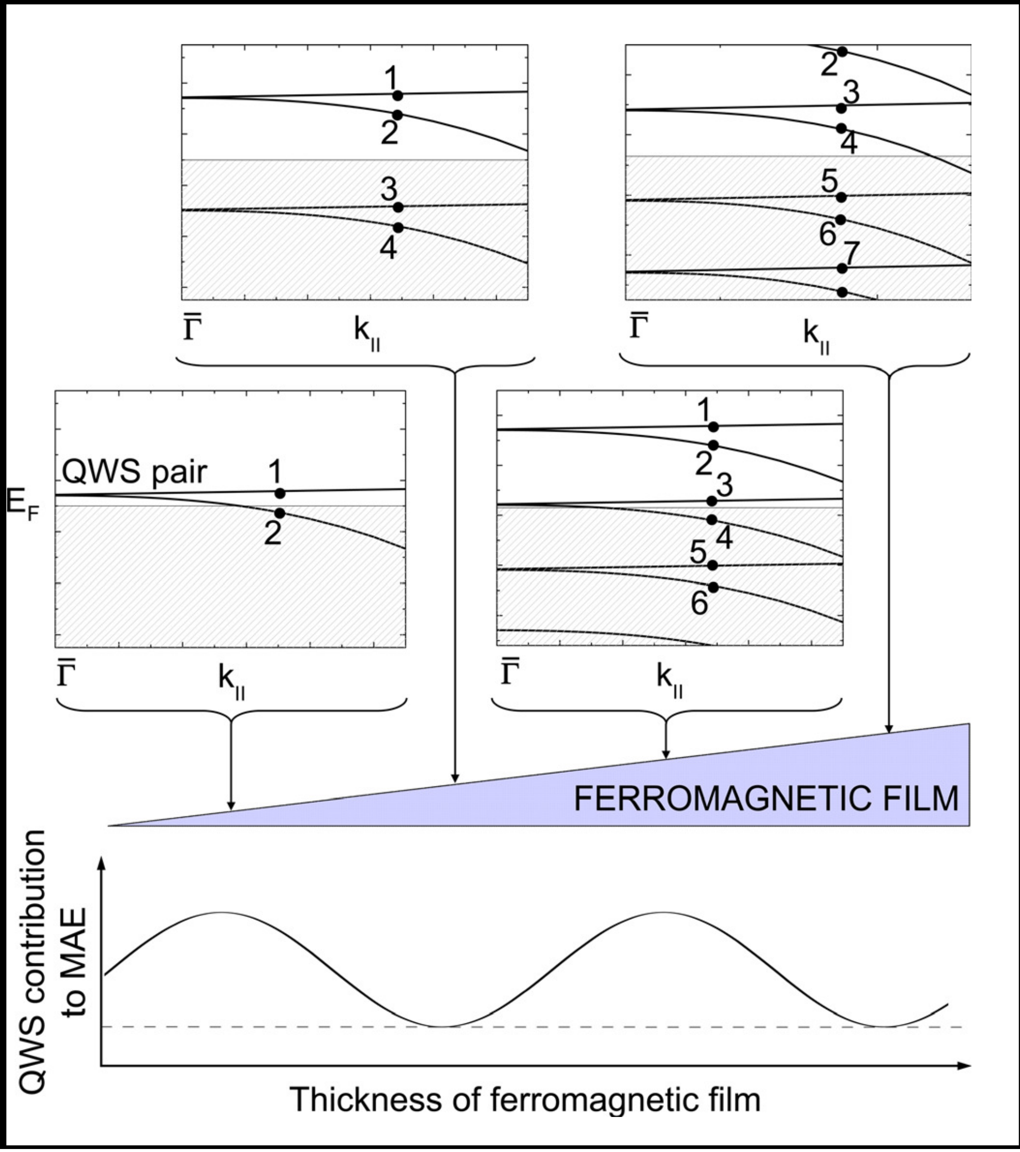


$$\mathrm{MAE}(\theta,\phi) = \sum_{k_{\parallel},n,\sigma,n',\sigma'} \frac{f\left(\varepsilon_{n\sigma}(k_{\parallel})\right) - f\left(\varepsilon_{n'\sigma'}(k_{\parallel})\right)}{\varepsilon_{n\sigma}(k_{\parallel}) - \varepsilon_{n'\sigma'}(k_{\parallel})} \left|\left\langle n\sigma k_{\parallel}\right| H_{SO}(\theta,\phi) \left|n'\sigma' k_{\parallel}\right\rangle\right|^2$$

Significant contributions to MAE due to spin-polarized quantum well states

Przybylski *et al.,* J. Appl. Phys. 111, 07C102 (2012)

Confinement effects via quantum-well states



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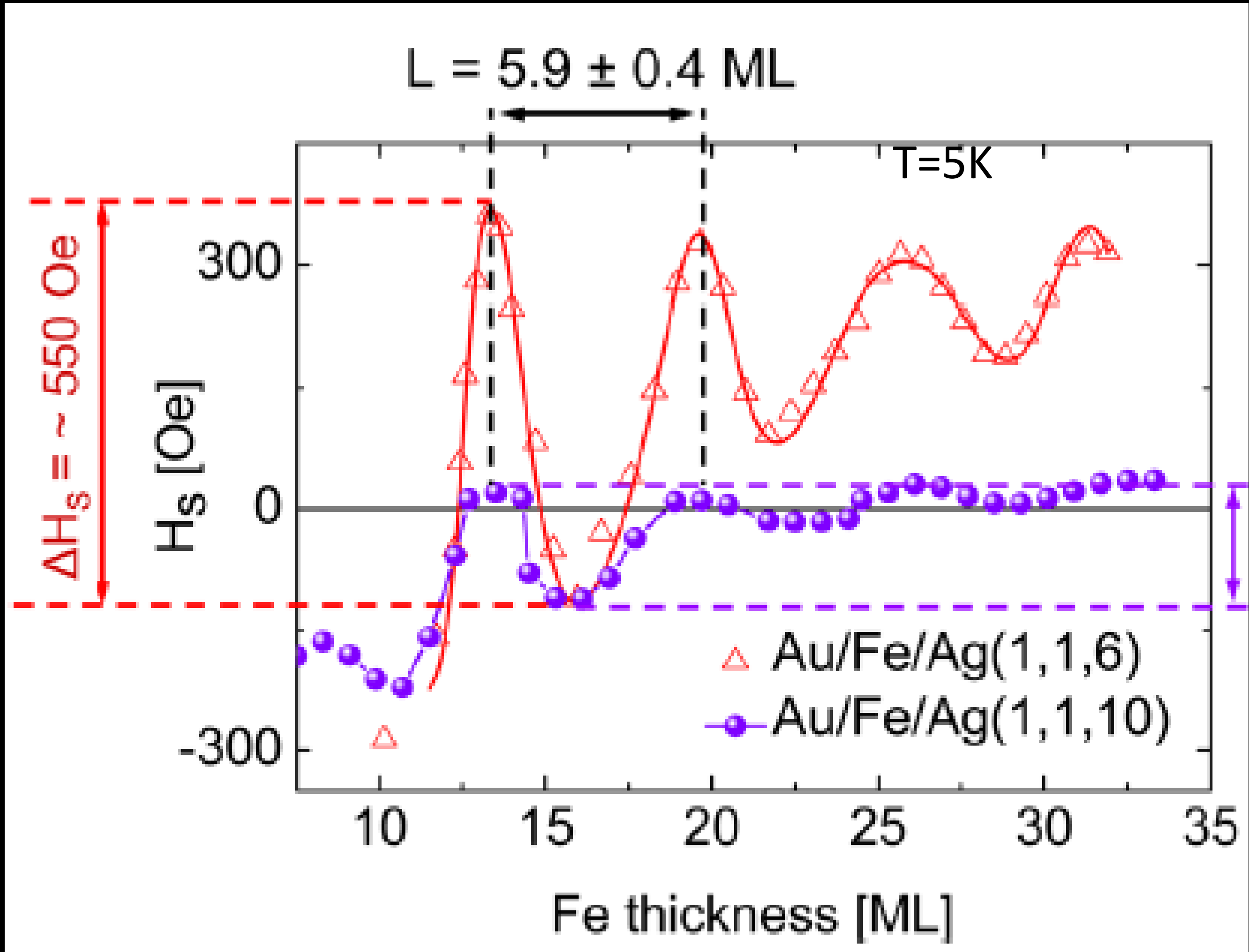
Confinement effects via quantum-well states



Oscillatory magnetic anisotropy due to the spin-polarized quantum-well states

Przybylski *et al.*, J. Appl. Phys. 111, 07C102 (2012)

Examples:

1- Spin dependent quantum-well states

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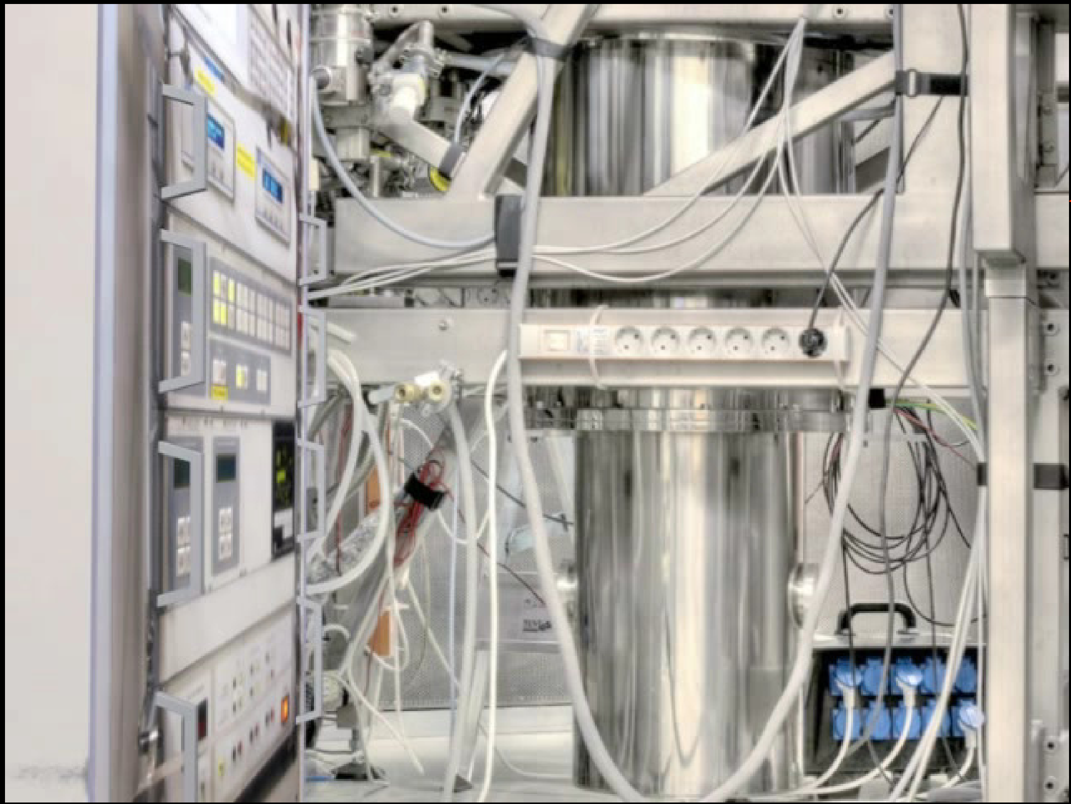
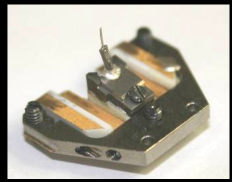
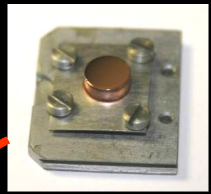
Experimental setup : LT-STM





Bulk Cr or Cr/Co/W Tip



Cu(111) Single Crystal

Lock-in Amplifier

Modulation = 5-20 mV

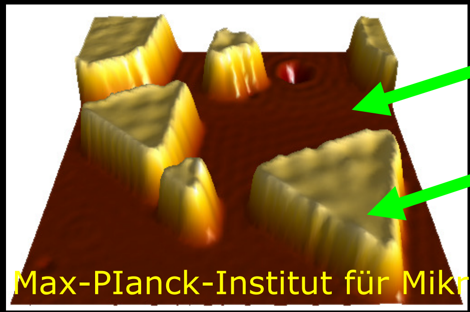
Frequency = 4.8 KHz

$$\left.\frac{dI}{dV}\right|_{V=V_{sample}} \propto LDOS\left(eV_{sample}\right)$$

- Ultra high vacuum → 10^{-11} mbar
- Low temperature → 7 K
- Low noise level → < 1 pm
- High magnetic field → 8 T

Structural and electronic properties

Topography



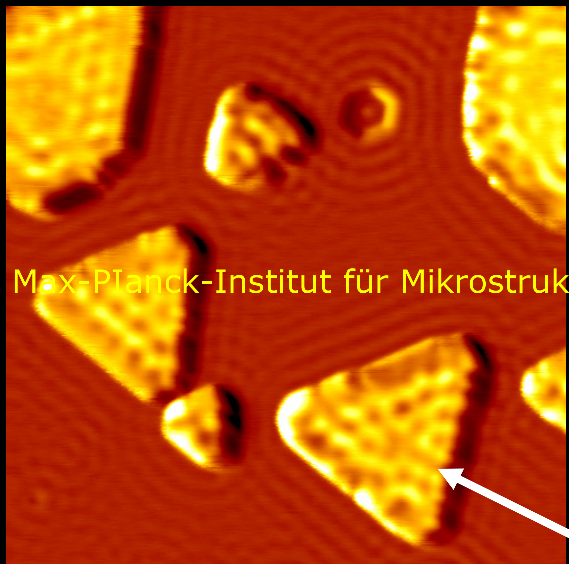
40x40 nm², +0.1 V, 1 nA

Cu(111) substrate

Co islands, double layer high (0.4 nm)

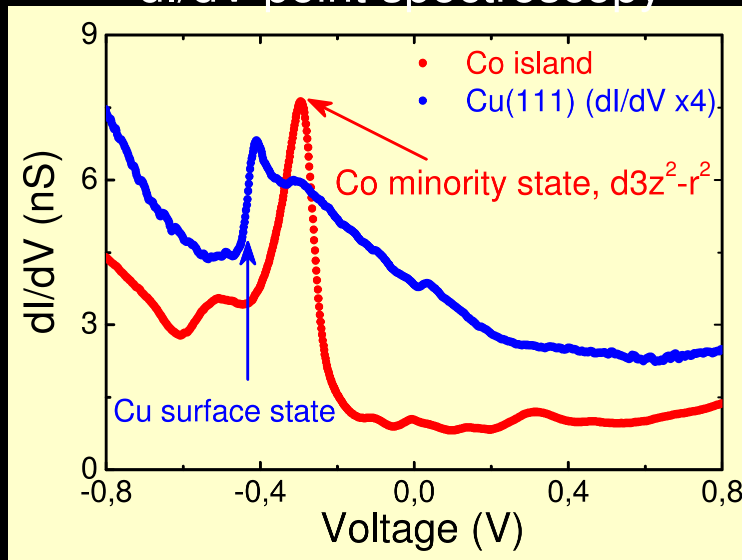
- Co deposition at 300 K
- Measurements at 8 K
- Easy magnetization direction out-of-plane

dI/dV spectroscopy map



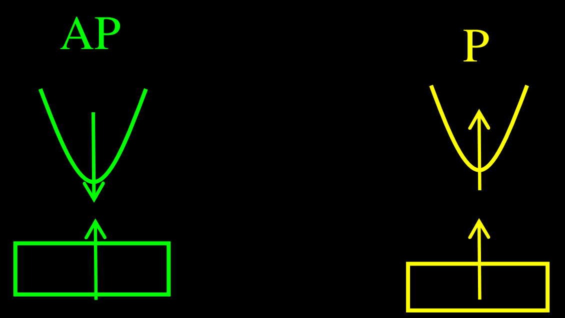
$40x40\ nm^2$, +0.225 V, 1 nA

dI/dV point spectroscopy



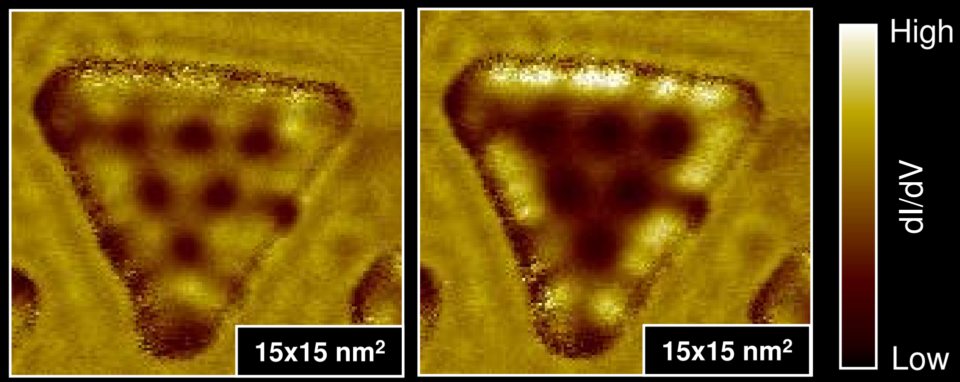
LDOS modulation due to confinement of Co *sp* electrons

dI/dV asymmetry and spin polarization



dI/dV maps at -1.1 T (Cr/Co/W tip)

Anti-parallel state (AP) Parallel state (P)

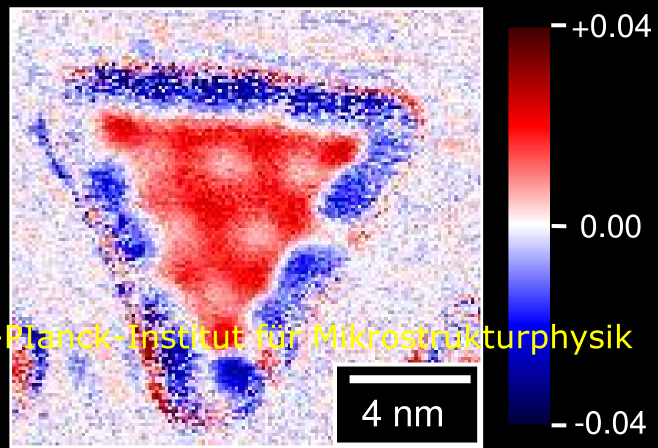


V_s = +0.04 V

dI/dV asymmetry defined by:

$$A_{dI/dV} = \frac{dI/dV\big|_{AP} - dI/dV\big|_{P}}{dI/dV\big|_{AP} + dI/dV\big|_{P}}$$

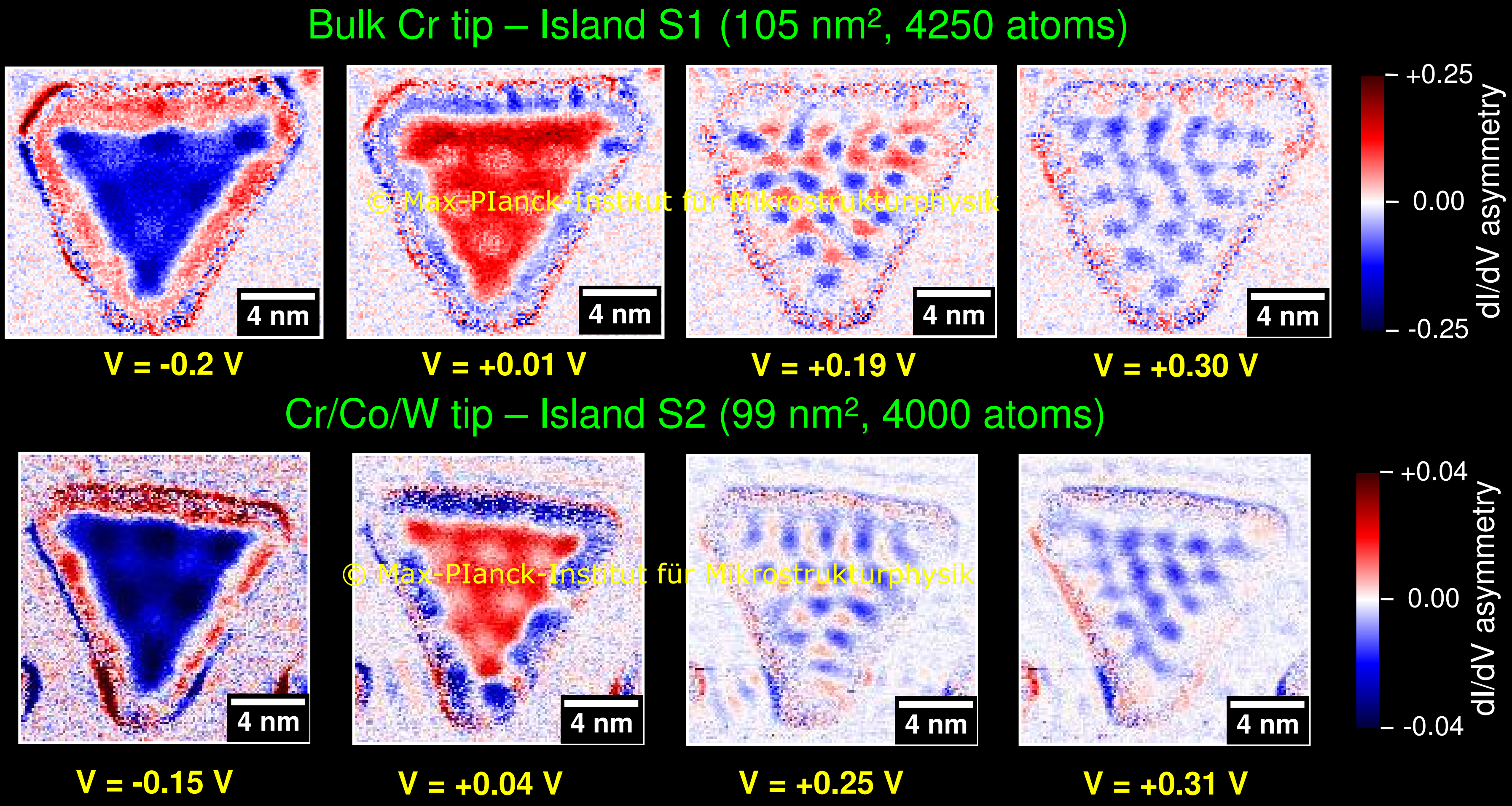
$$A_{dI/dV} = -P_T P_S$$



V_s = +0.04 V

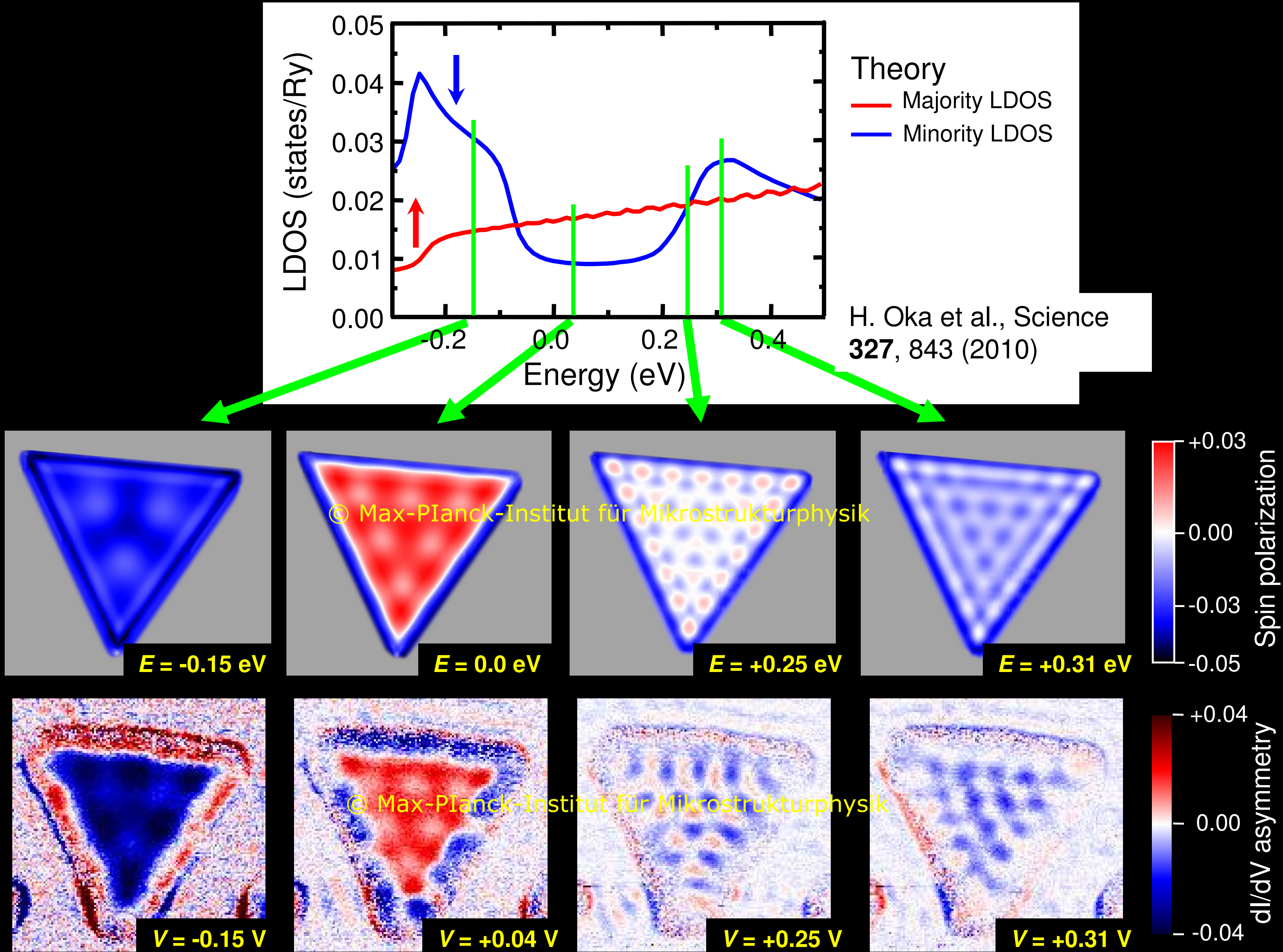
H. Oka *et al.*, Science **327**, 843 (2010)
H. Oka, *et al.*, Proc. of SPIE Vol. 8100 81000O

dI/dV asymmetry and spin polarization

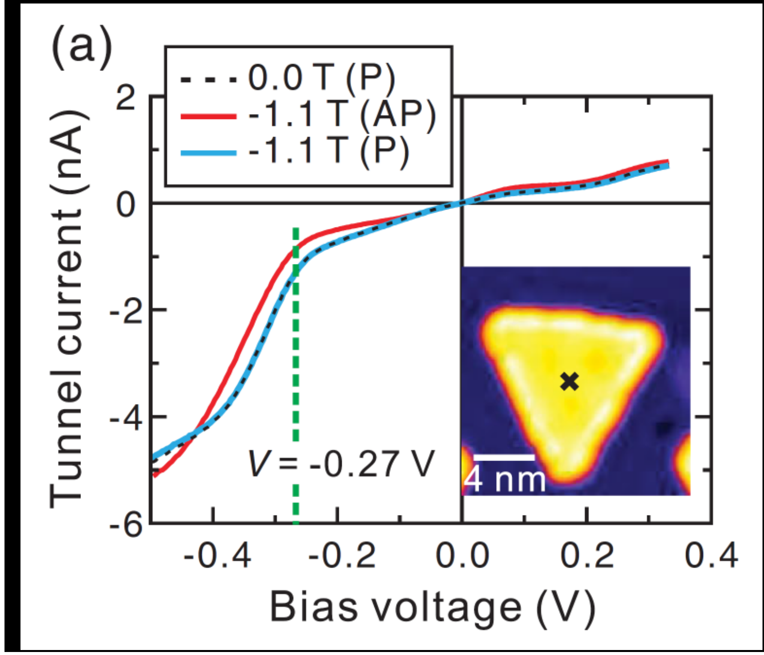


H. Oka *et al.*, Science **327**, 843 (2010)

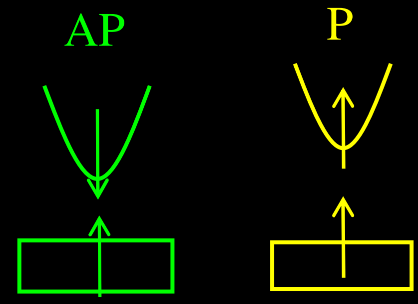
Energy dependence of dI/dV asymmetry and spin polarization

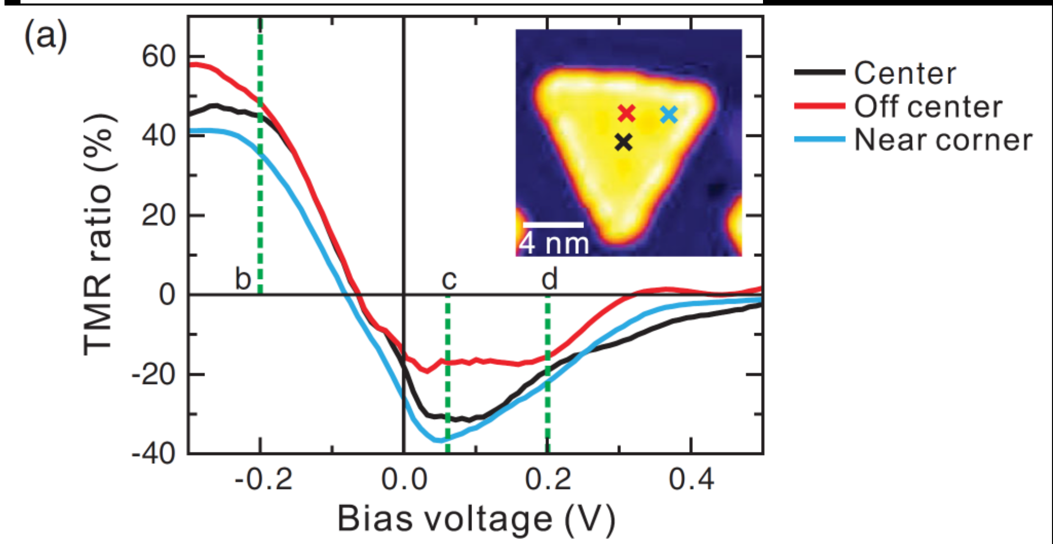


Spatially modulated TMR on the Nanoscale



$$\mathrm{TMR} = \frac{R_{AP} - R_P}{R_P} = \frac{I_P - I_{AP}}{I_{AP}}$$





Oka *et al.*, Phys. Rev. Lett. 107, 187201 (2011)

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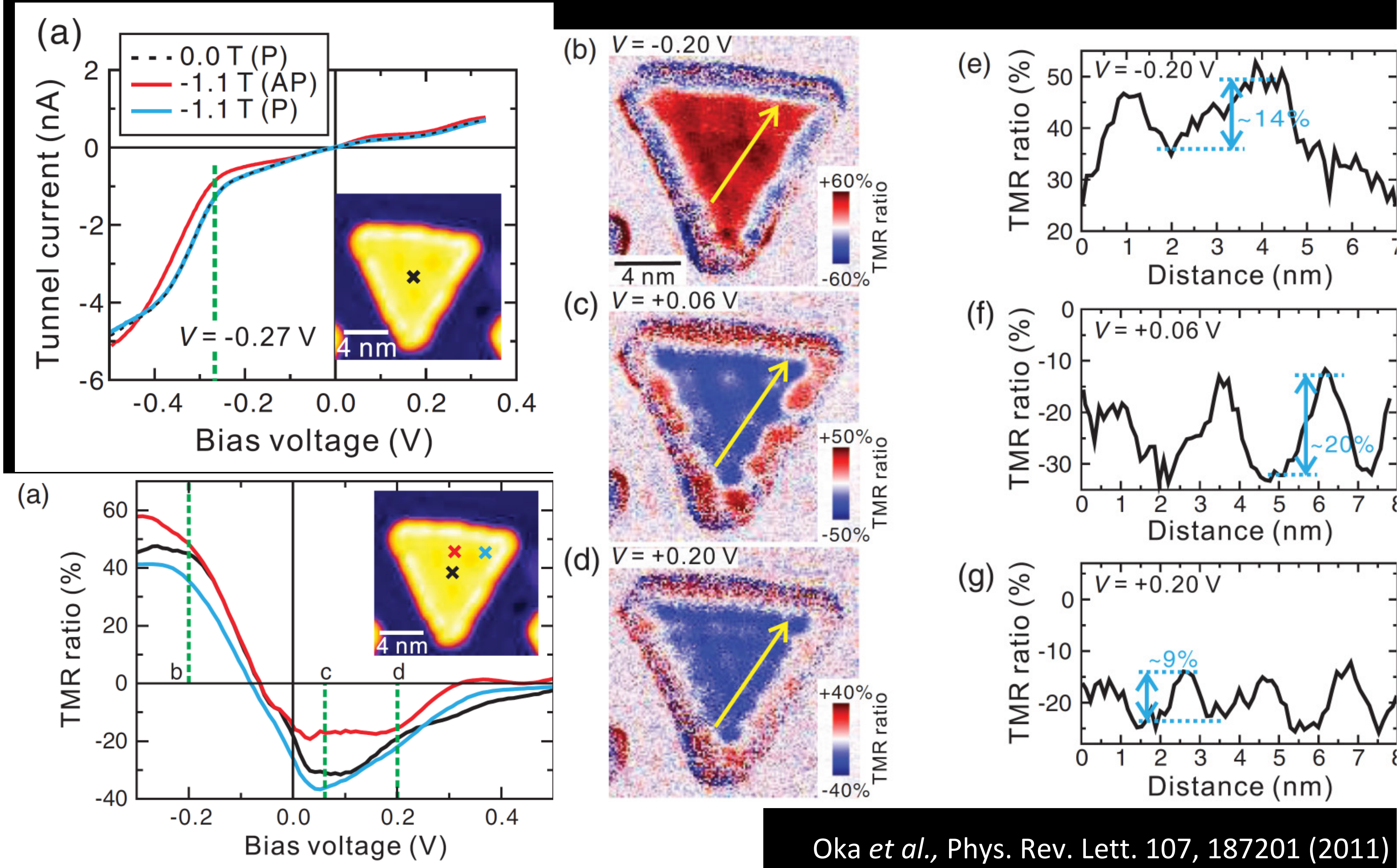


Oka *et al.,* Phys. Rev. Lett. 107, 187201 (2011)

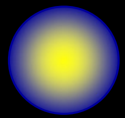
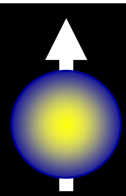
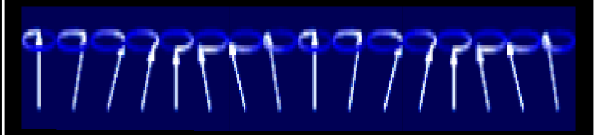
Examples:

1- Spin dependent quantum-well states

2- Spin-dependent quantum interference

3- Magnon Spintronics

Electronics – Spintronics – Magnonics

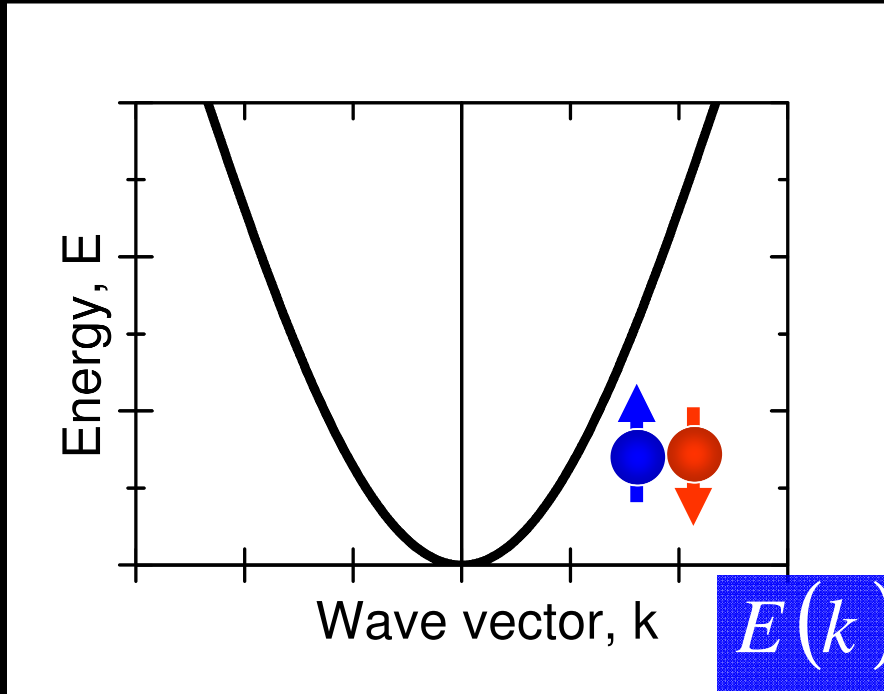
		
Electronics	Spintronics	Magnonics
Information carrier: Charge of electrons	Information carrier: Spin of electrons	Information carrier: Magnon (collective spin excitation)

Conventional Rashba effect

$$H\Psi(\vec{r},\sigma) = E\Psi(\vec{r},\sigma)$$

$$\Psi_{\vec{k}}(\vec{r}) = \frac{1}{\sqrt{V}}\exp\left(i\vec{k}\cdot\vec{r}\right)$$

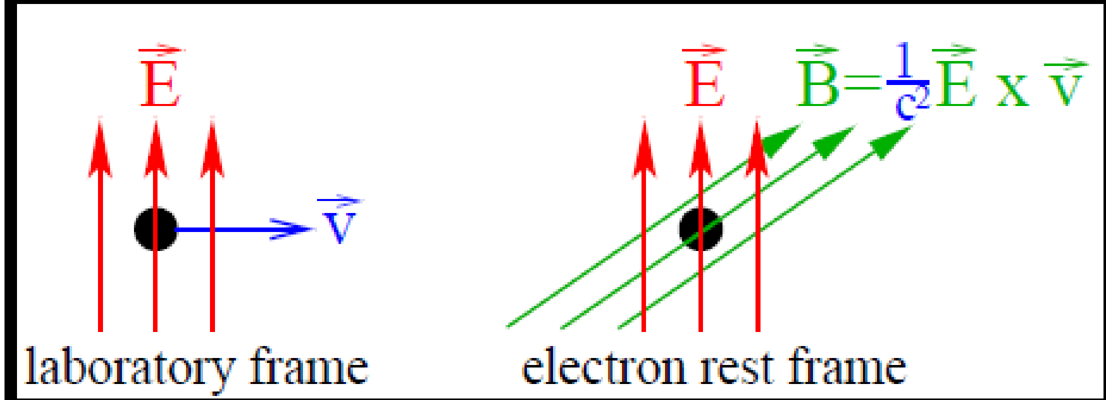
$$E = \frac{\hbar^2 k^2}{2m^*}$$

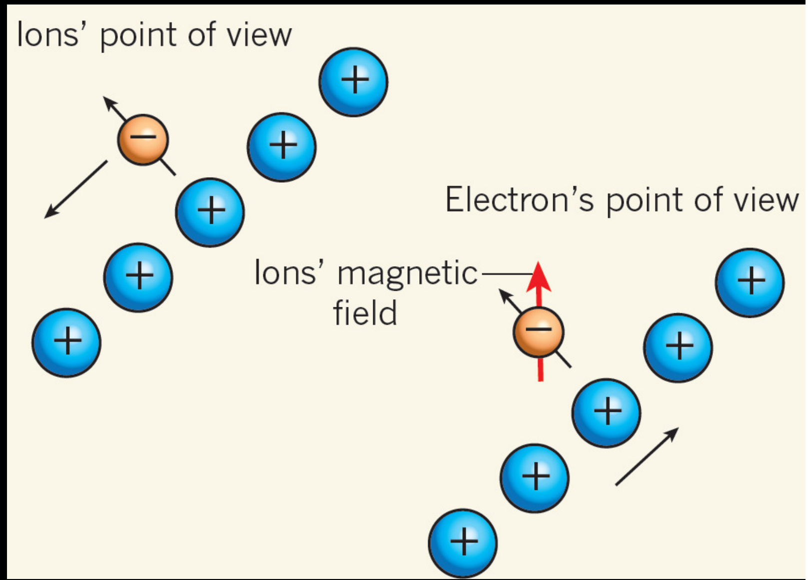


$$E(k) = E(-k)$$

& A. Groß, Theoretical Surface Science, Springer Berlin Heidelberg (2009) ISBN 978-3-540-68966-9

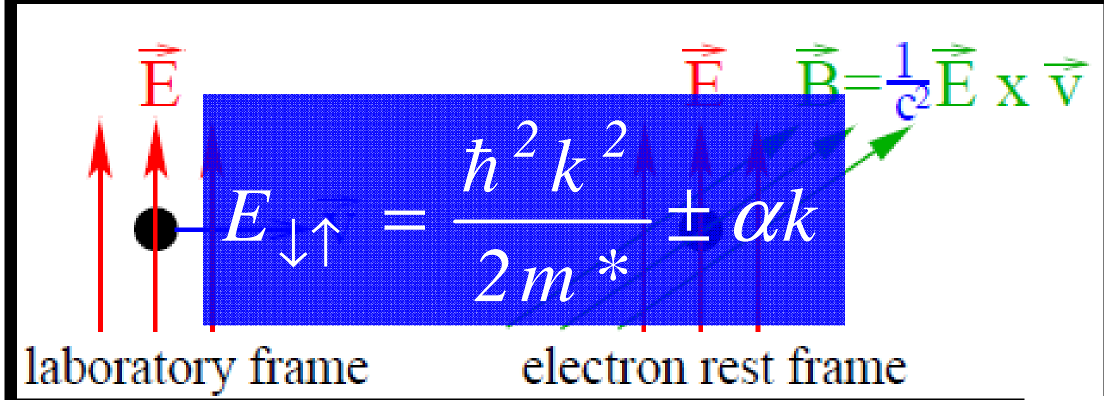
Conventional Rashba effect



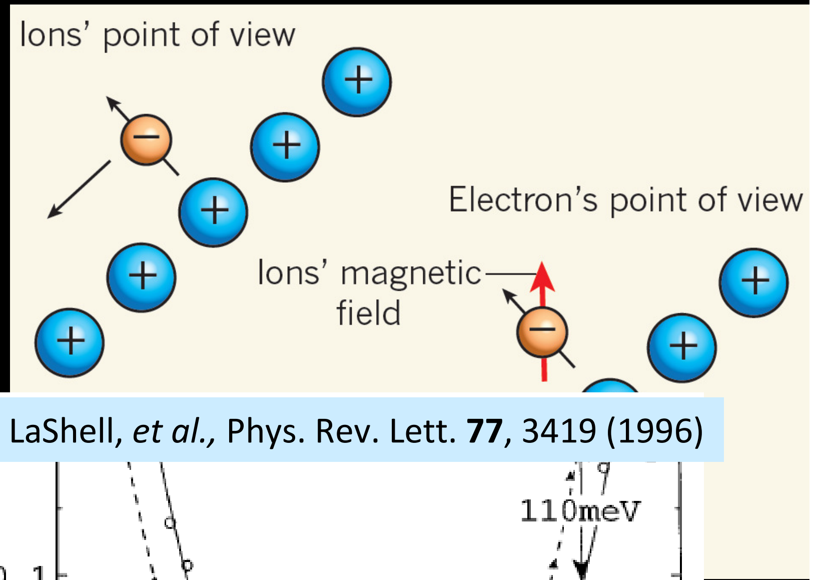


& M. Chapman & C. de Melo, Nature **471**, 41 (2011)

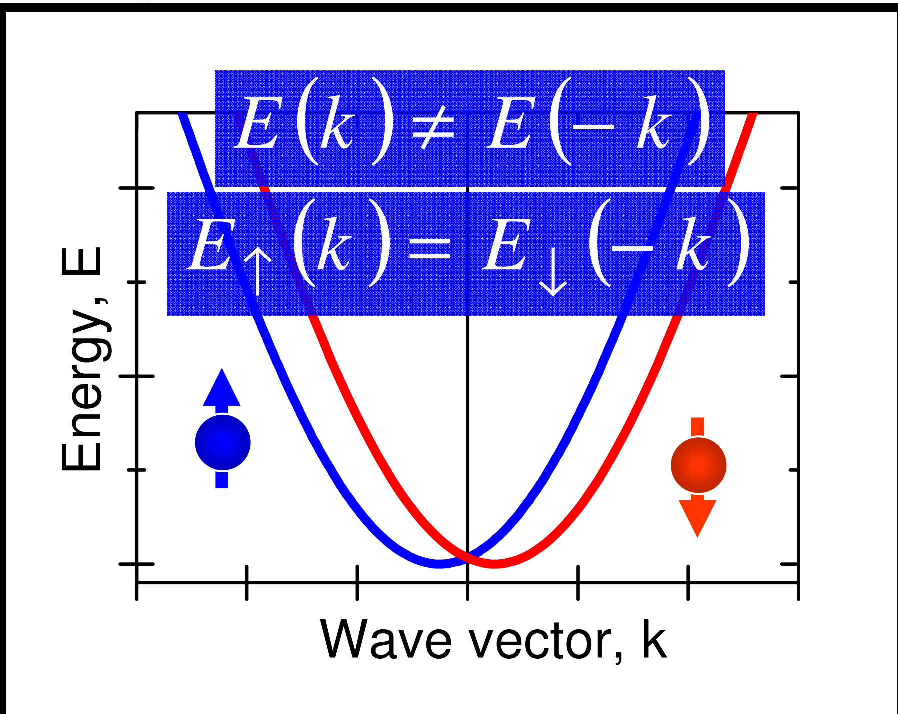
Conventional Rashba effect



$$E_{\downarrow\uparrow} = \frac{\hbar^2 k^2}{2m^*} \pm \alpha k$$



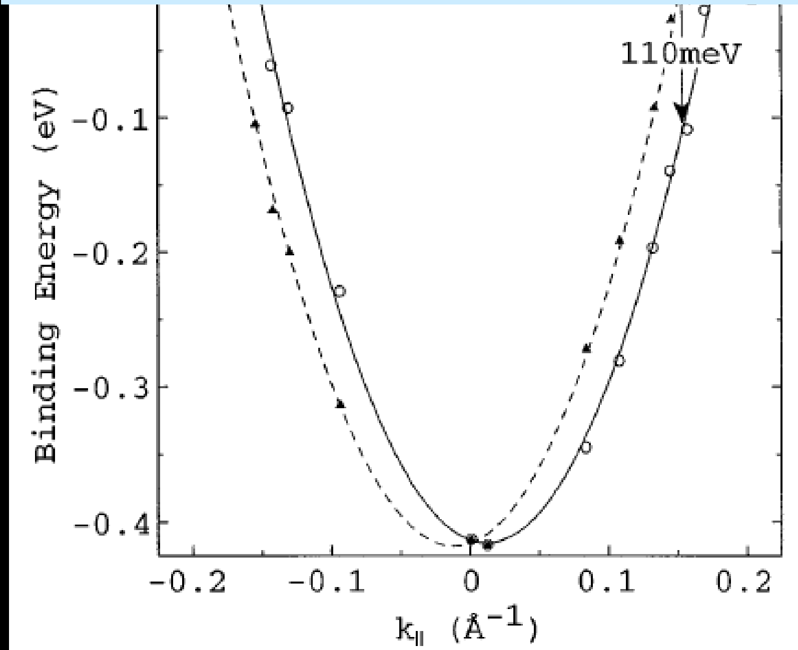
(2011)



$$E(k) \neq E(-k)$$

$$E_{\uparrow}(k) = E_{\downarrow}(-k)$$

& S. LaShell, *et al.*, Phys. Rev. Lett. **77**, 3419 (1996)



The influence of the spin-orbit coupling on electrons (fermions) is rather well-known (Rashba effect) !

- E. I. Rashba, Sov. Phys. Solid State **2**, 1109 (1960).
- Yu.A. Bychkov and E. I. Rashba, JETP Lett. **39**, 78 (1984).
- S. Datta and B. Das, Appl. Phys. Lett. **56**, 665 (1990).
- R. Winkler, *Spin-Orbit Coupling Effects in Two-Dimensional Electron and Hole Systems* (Springer, New York, 2003).

- S. LaShell, *et al.*, Phys. Rev. Lett. **77**, 3419 (1996).
- J. Henk, A. Ernst, and P. Bruno, Phys. Rev. B **68**, 165416 (2003).
- O. Krupin, *et al.*, Phys. Rev. B **71**, 201403(R) (2005).
- G. Bihlmayer,*et al.*, Surf. Sci. **600**, 3888 (2006).
- M. Heide, G. Bihlmayer, and S. Blügel, Phys. Rev. B **78**, 140403(R) (2008); Physica **404B**, 2678 (2009).

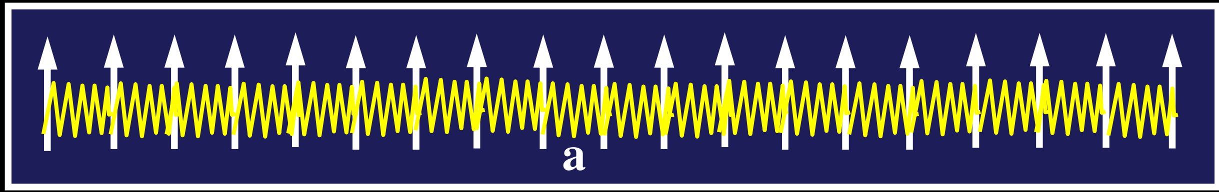
- C. R. Ast, *et al.*, Phys. Rev. Lett. **98**, 186807 (2007).

Can the spin-orbit coupling affect the bosonic quasi-particles?!

YES!!!

Zakeri *et al.*, Phys. Rev. Lett. **104**, 137203 (2010)
Zakeri *et al.*, Phys. Rev. Lett. **108**, 197205 (2012)

Elementary spin excitations (magnons)



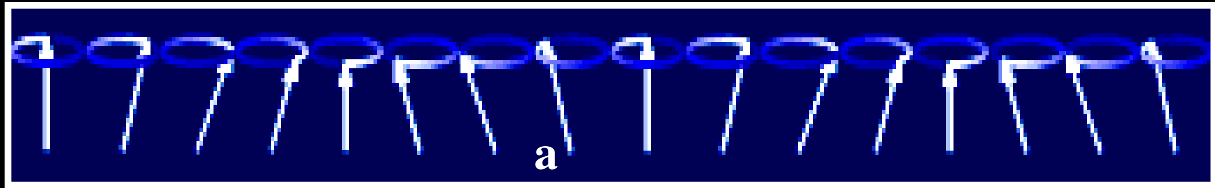
Heisenberg Hamiltonian

$$H_s = -\sum_{i \neq j} J_{ij} \vec{S} \cdot \vec{S}$$

J exchange coupling constant
S magnitude of the spin

Werner Heisenberg
1928

Elementary spin excitations (magnons)



Heisenberg Hamiltonian

$$H_s = -\sum_{i \neq j} J_{ij} \vec{S} \cdot \vec{S}$$

J exchange coupling constant
S magnitude of the spin

Dispersion relation:

nearest neighbor interaction (NNH)

$$E = \hbar\omega = 4JS(1-\cos Qa)$$
$$\approx 2JSa^2Q^2 = DQ^2 = \frac{\hbar^2}{2m^*}Q^2$$

$$E(Q) = E(-Q)$$

Spin-waves

Many-body collective excitations

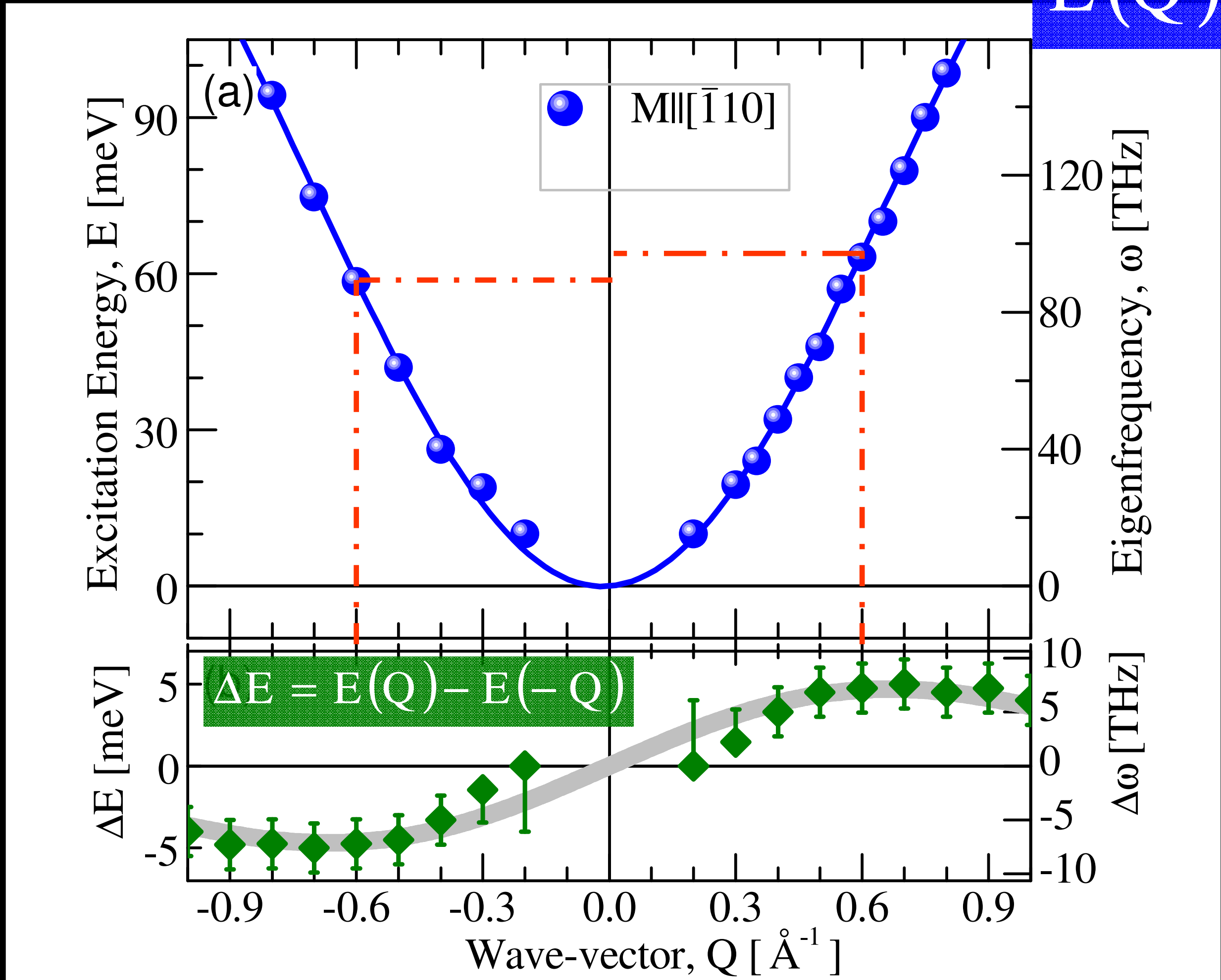
Magnon carries

Energy: $\hbar\omega$, Momentum: Q, Spin: $1\hbar$

Werner Heisenberg
1928

The magnon Rashba effect

$E(Q) \neq E(-Q)$



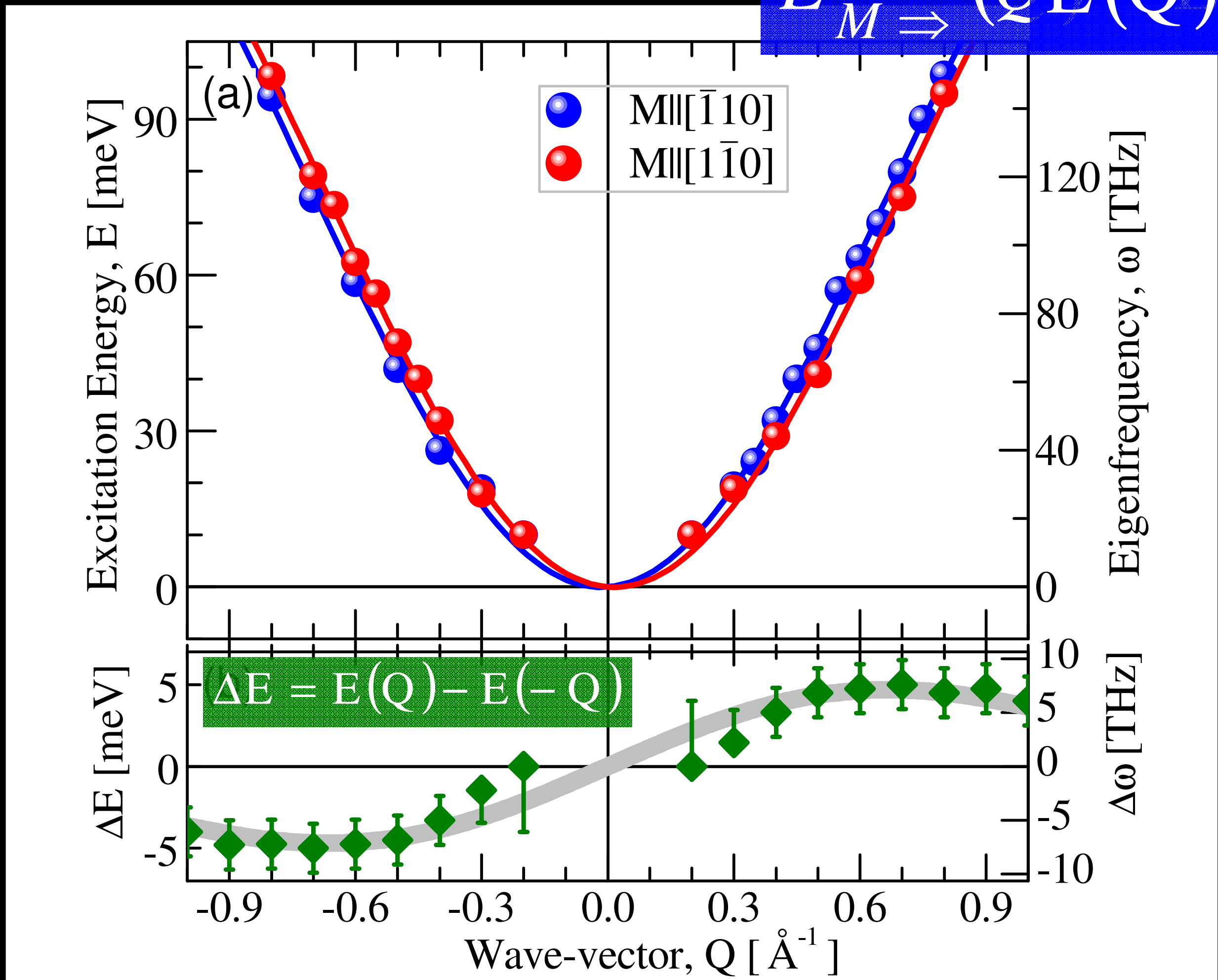
Example: Two atomic layers of Fe on W(110)

& Udvardi & L. Szunyogh, Phys. Rev. Lett. **102**, 207204 (2009)

& A. T. Costa, *et al.*, Phys. Rev. B **82**, 014428 (2010)

The magnon Rashba effect

$E_{\vec{M}} \Rightarrow (\mathcal{Q}) \quad E(Q) \neq E(-Q)$



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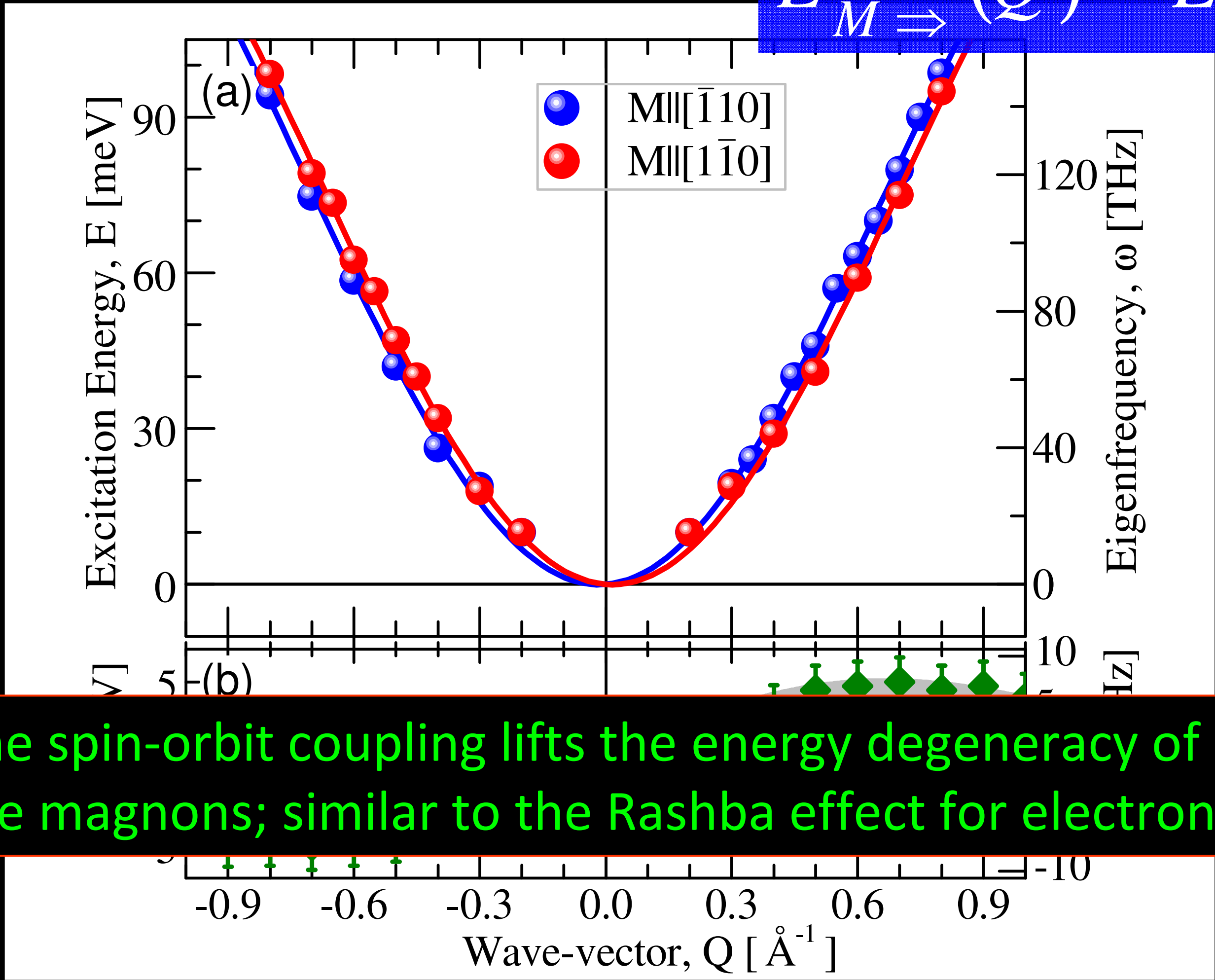
- Udvardi & L. Szunyogh, Phys. Rev. Lett. **102**, 207204 (2009)
- A. T. Costa, *et al.*, Phys. Rev. B **82**, 014428 (2010)

The magnon Rashba effect

$$E_{\vec{M} \Rightarrow}(Q) = E_{\vec{M} \Leftarrow}(-Q)$$



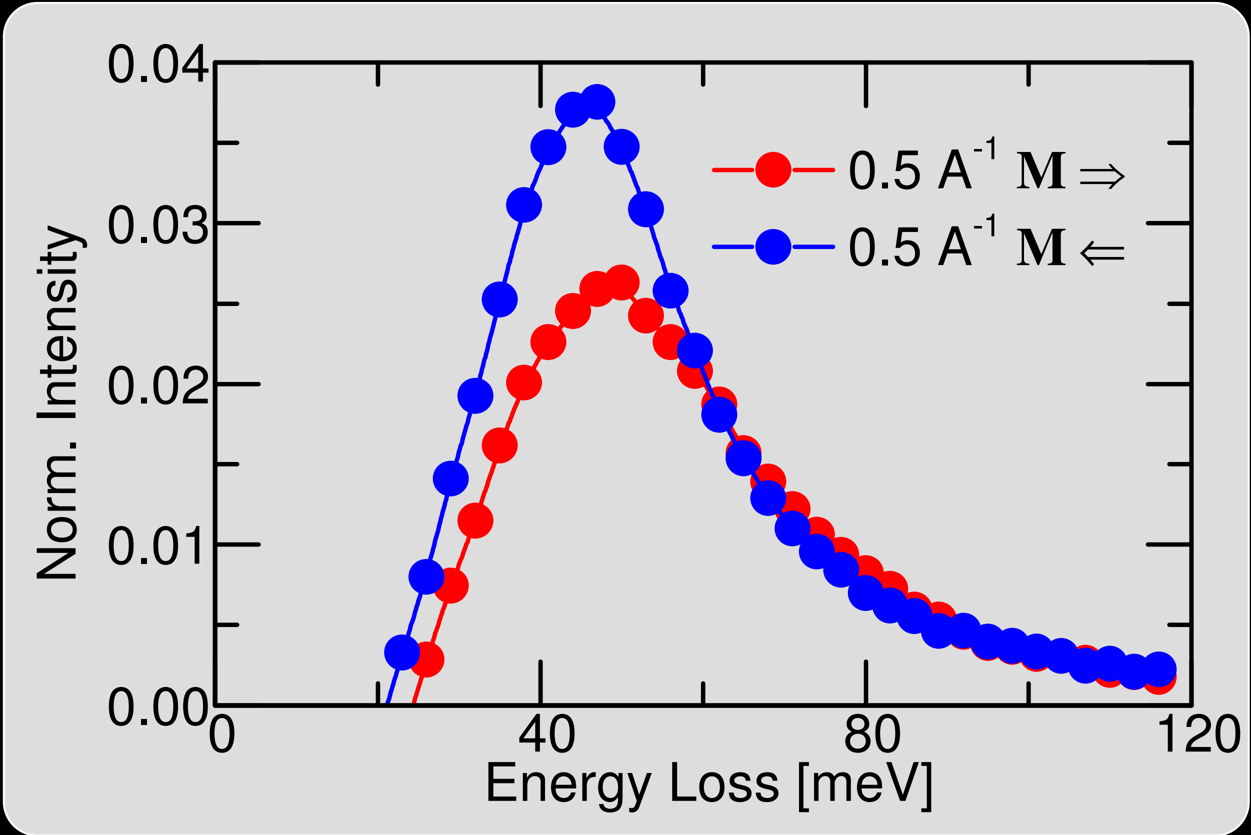
The spin-orbit coupling lifts the energy degeneracy of the magnons; similar to the Rashba effect for electrons.

Example: Two atomic layers of Fe on W(110)

& Udvardi & L. Szunyogh, Phys. Rev. Lett. **102**, 207204 (2009)

& A. T. Costa, *et al.*, Phys. Rev. B **82**, 014428 (2010)

What about the lifetime?



$$\tau = \frac{2\hbar}{\Delta}$$

Δ: Intrinsic linewidth

$\tau_- = 45 \pm 5$ fs

$\tau_+ = 37 \pm 5$ fs

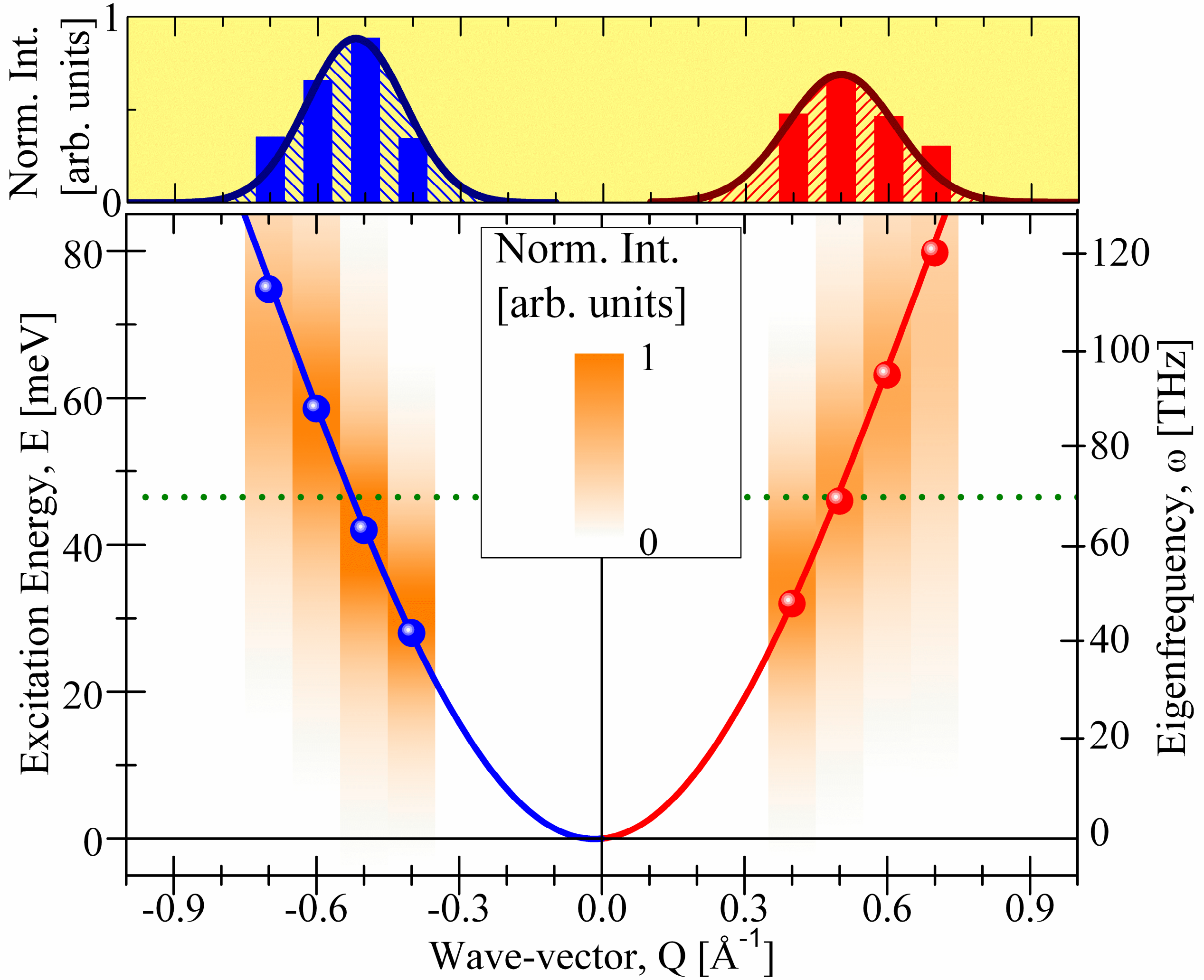
The spin-orbit coupling influences the magnons' lifetime.

Zakeri *et al.*, Phys. Rev. Lett. **104**, 137203 (2010)

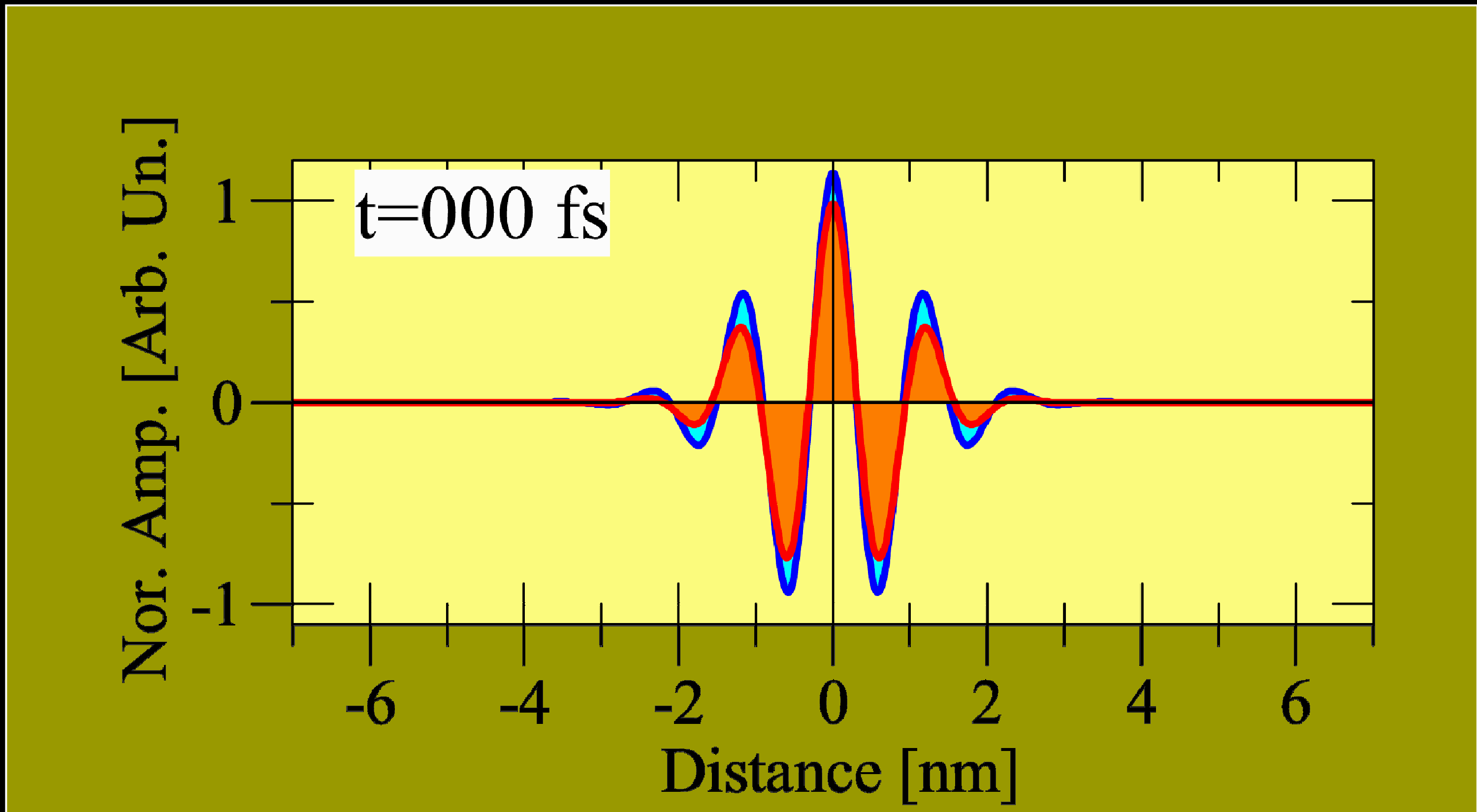
Zakeri *et al.*, Phys. Rev. Lett. **108**, 197205 (2012)

& A. T. Costa, *et al.*, Phys. Rev. B **82**, 014428 (2010)

Magnons in real time and space

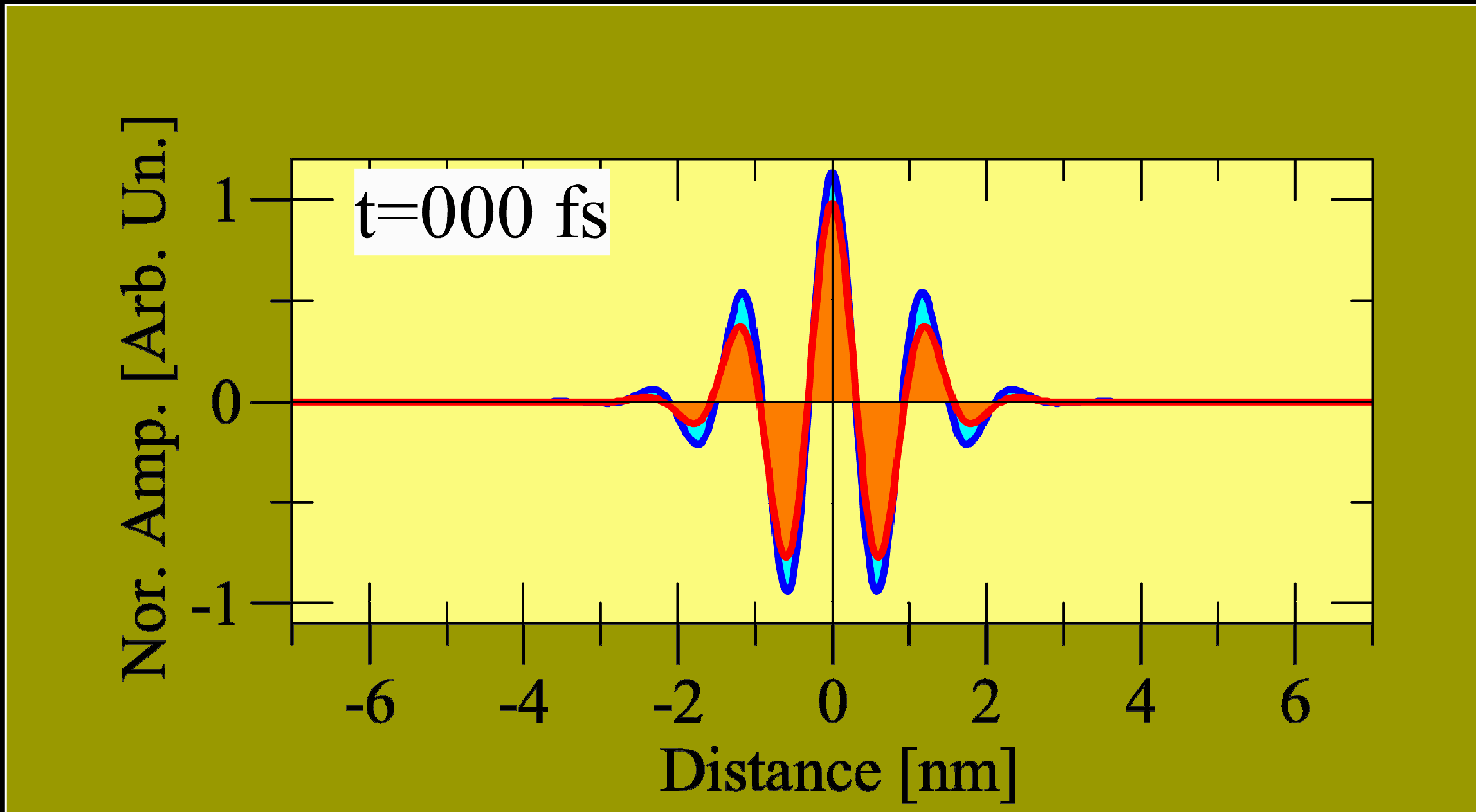


Magnons in real time and space



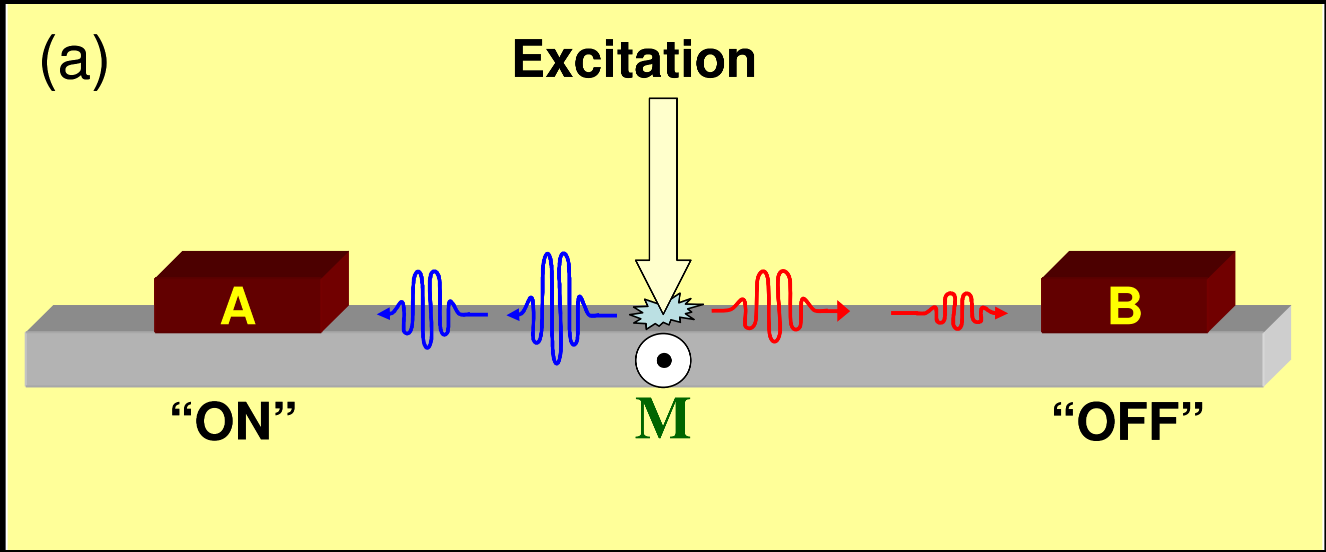
Zakeri *et al.*, Phys. Rev. Lett. **108**, 197205 (2012)

Magnons in real time and space

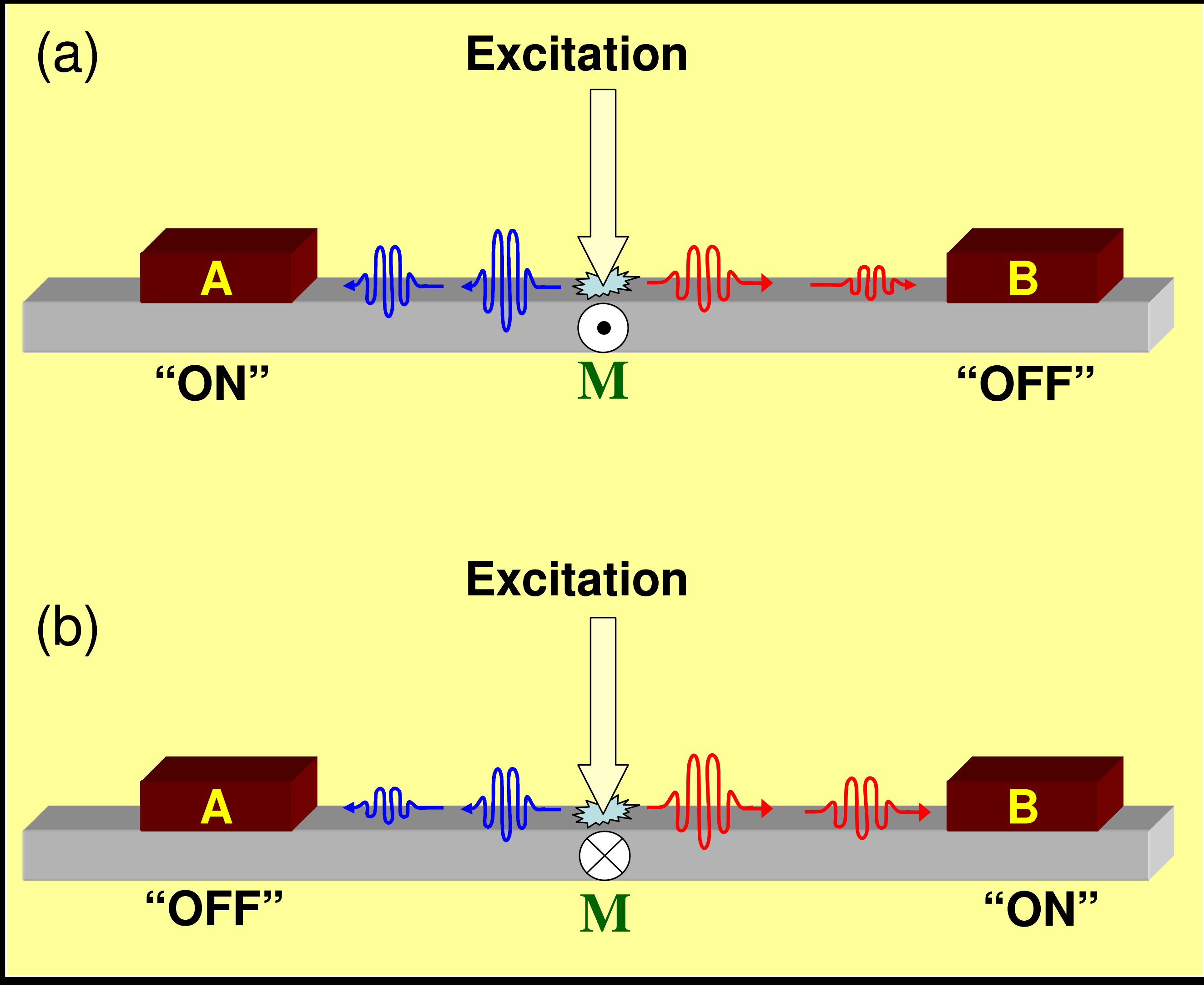


Zakeri *et al.*, Phys. Rev. Lett. **108**, 197205 (2012)

A magnon-based device



A magnon-based device



Summary

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Quantum effects

Quantum confinement

Spin-dependent quantum confinement

Lower symmetry

new effects!