Pillar 2 Quantum control of spins

Pillar Leaders: Bart van Wees, Rembert Duine

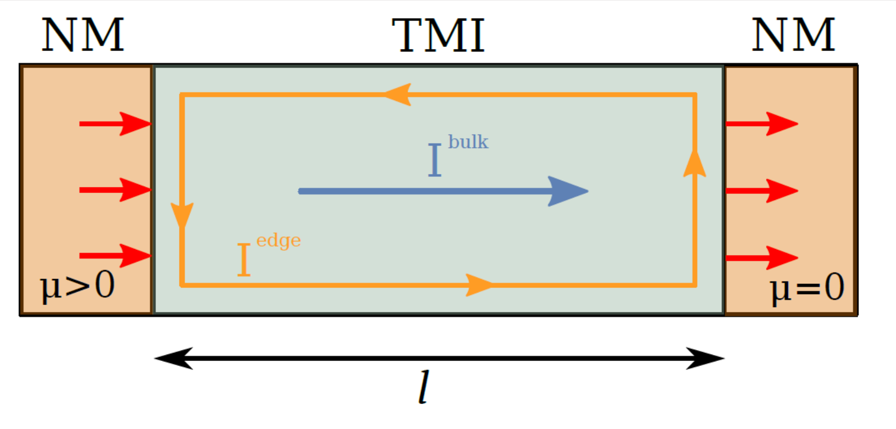
Goal: Obtain full control over spin degree of freedom down to the smallest length scales and shortest times

Applications: Spin information processing and spin transport via topologically protected edge channels for spin excitations

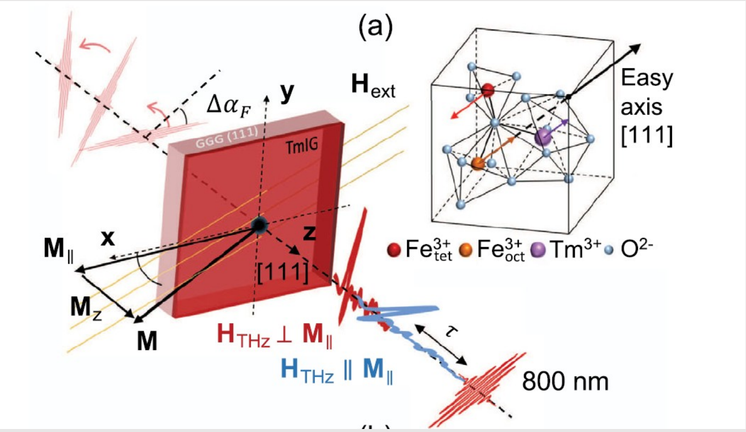
Connection to the other pillars: Pillar 1, Electronic topology
Pillar 4, topological light-matter interfaces

Pillar 2 Quantum control of spins

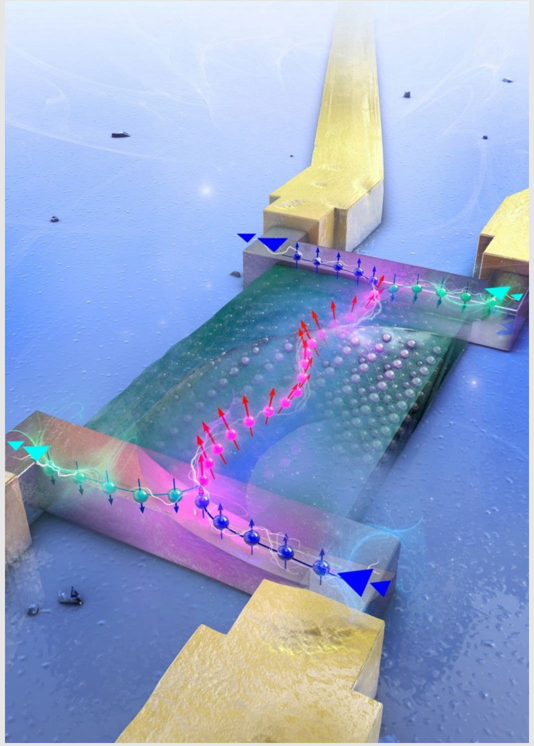
background



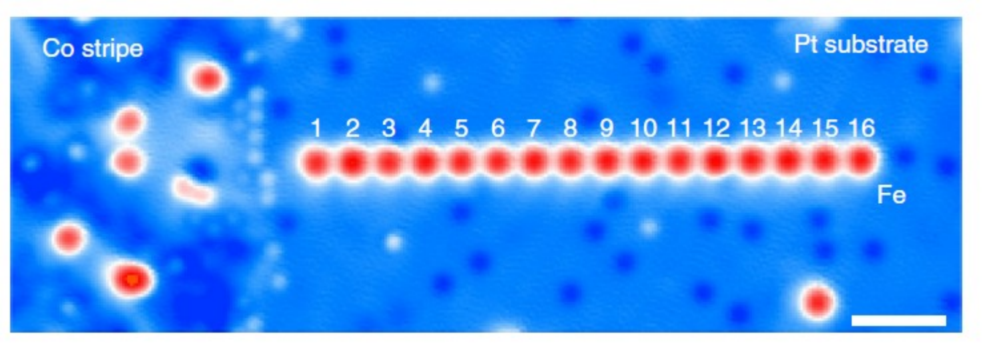
Spin transport via topologically-protected magnonic edge states, A. Ruekriegel, A. Brataas, RD, PRB (2018)



Ultrafast spin dynamics, T. Blank, …, A. Kimel, PRL (2021); also Koopmans group.



Long-distance spin transport through magnetic insulators at room T, L. Cornelissen, …, RD, BvW, Nat. Phys. (2016)



Tailoring magnetic systems and their interactions atom-by-atom, Steinbrecher, …, Khajetoorians, et al., Nat. Comm. (2018); also Otte group.

Pillar 2 Quantum control of spins

open questions/challenges

Topologically-protected magnonic edge channels

- Find/engineer (synthetic) materials, material combinations, that host topologically protected magnon states on their edge and along domain walls
- Demonstrate long-distance spin transport via edge channels
- Utilize non-Hermitian topology to engineer magnetic edge states

Beyond magnons

- Fast dynamics at short length scales
- Excitations of complex magnetic order

Devices

- Interfacing (topological) spin waves/magnons and (magnetic) memory
- Integrate THz magnonics with existing semi-conductors

Pillar 2 : Quantum control of spins

actions and research projects

Theory and design
Duine/Fritz/Katsnelson/Morais Smith/Slawinska

Materials
Guimaraes/Khajetoorians/Otte

Complex and topological spin excitations and transport at short time and length scales

Characterization
Otte/Kimel/Khajetoorians

Devices
Guimaraes/Koopmans/Kuipers/van Wees/

Contributions from …

- Speaker 1: Dennis de Wal (PhD van Wees group, RUG):
  “Magnon transport in the van der Waals antiferromagnet CrPS4”
- Speaker 2: Alex Khajetoorians (PI, RUN): “Probing complex magnetic order and magnetic excitations beyond magnons”
- Speaker 3: Bert Koopmans (PI, TU/e):
  “Magneto-photonic engineering for topological quests”

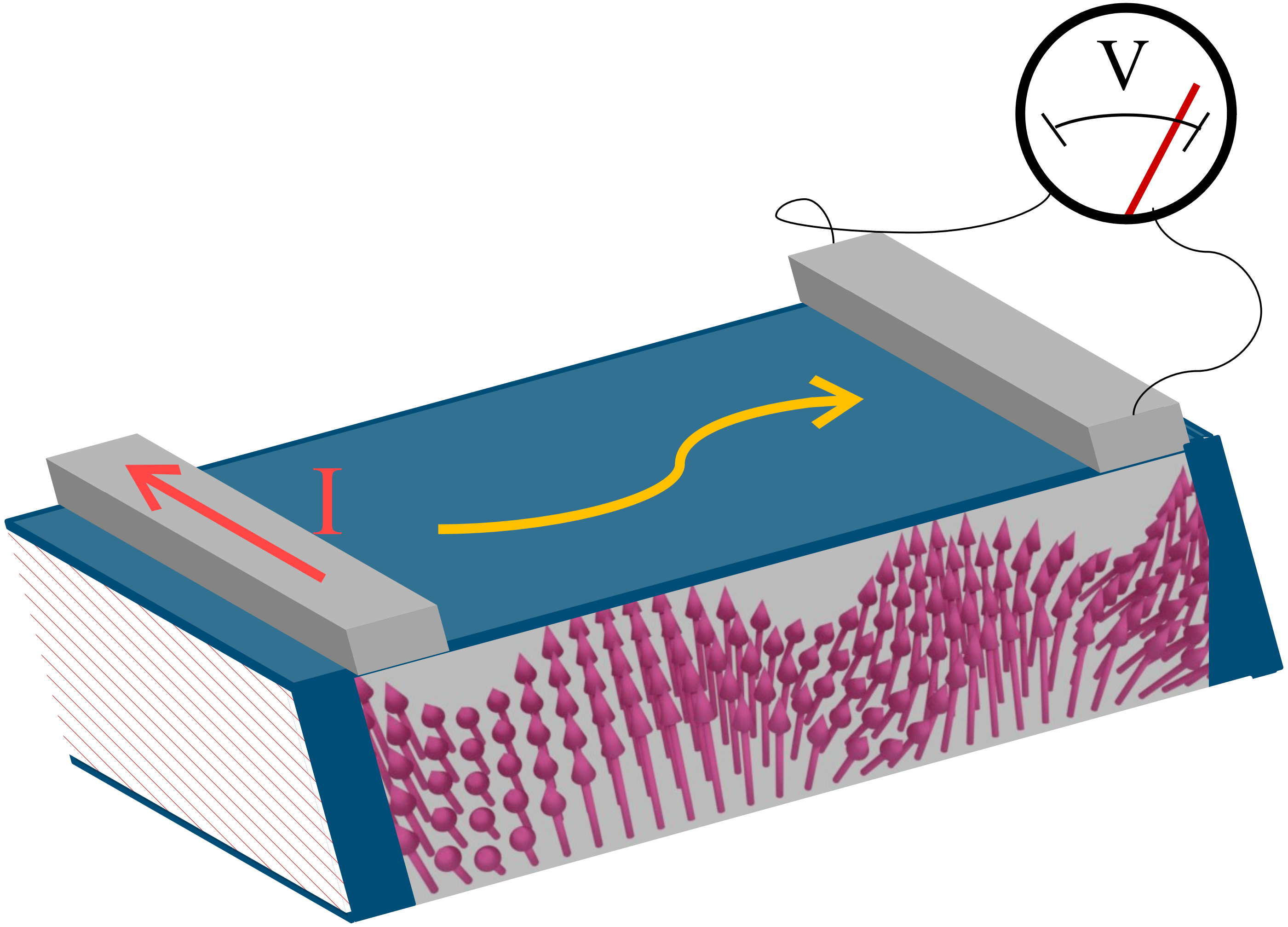
Magnon transport in the van der Waals antiferromagnet CrPS4

Dennis de Wal, Tian Liu, Arnaud Iwens, Bart van Wees

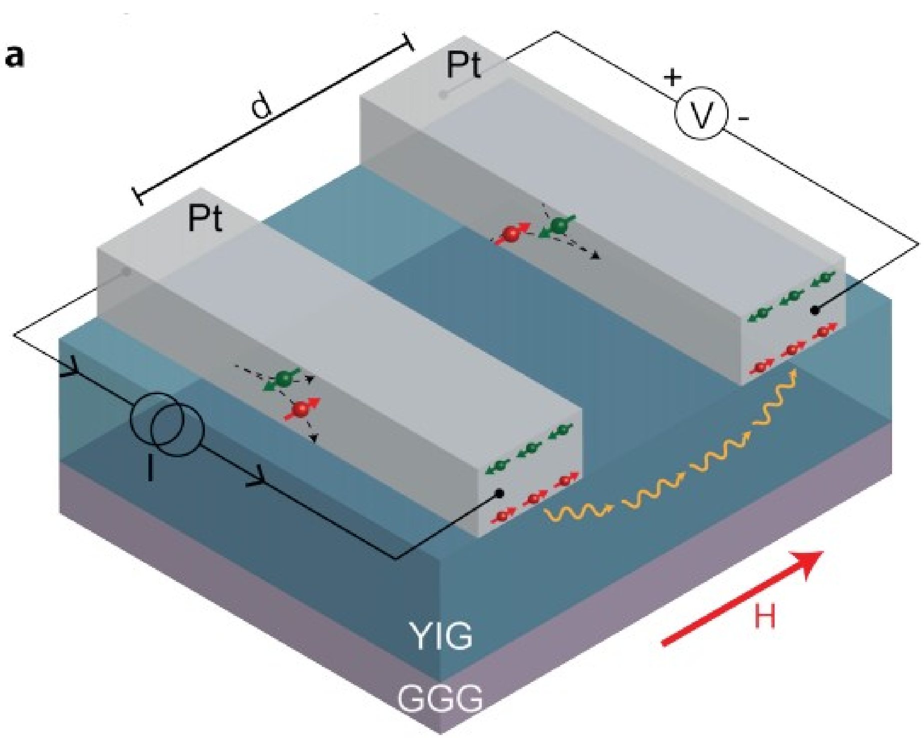
Direct information transport through MI

<u>Information carried purely by spin</u>

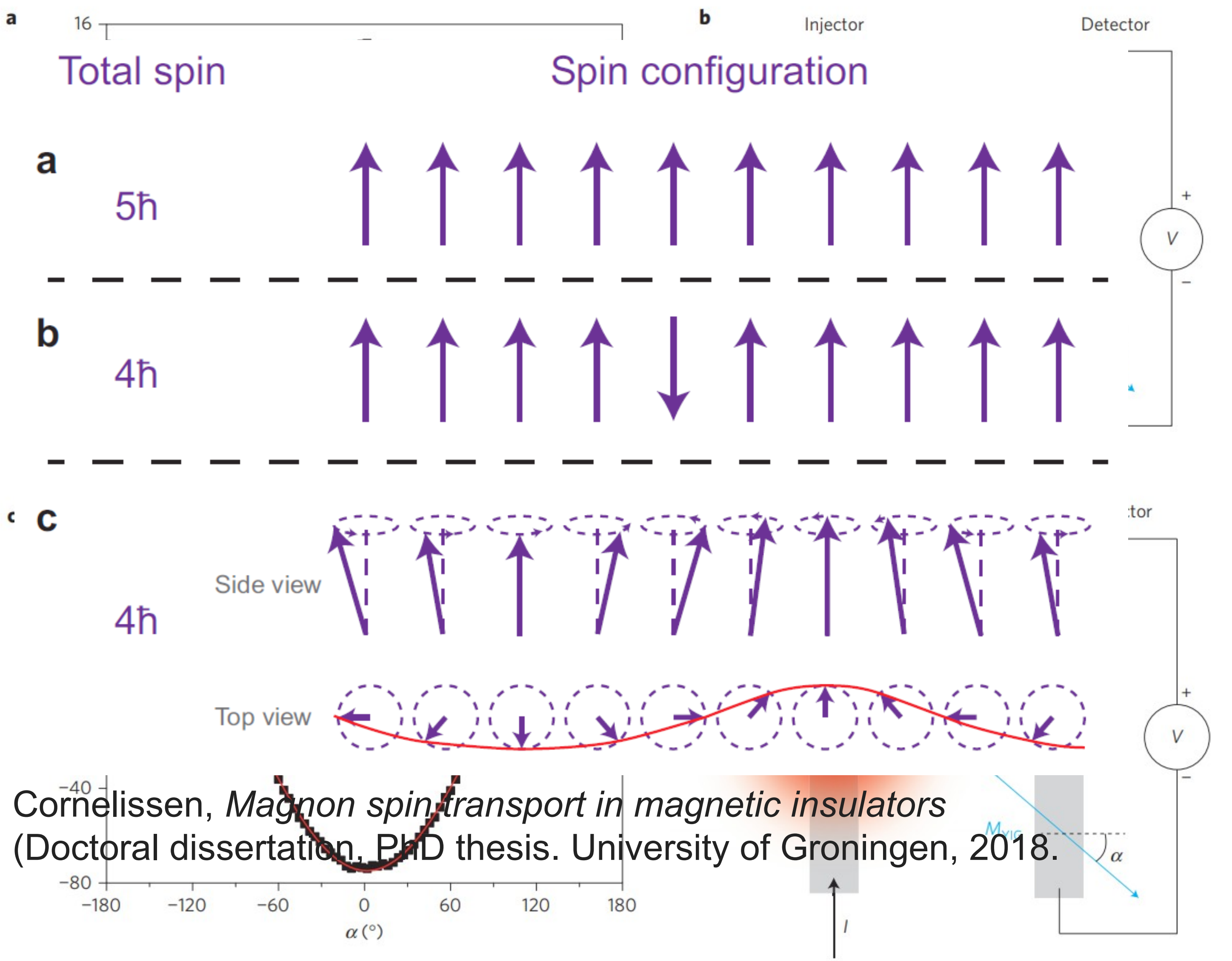
- **Charge** → ***Spin***
- Transport by ***Spin-waves***
  - Fast dynamics
- ***Spin*** → **Charge**



Magnon spin transport



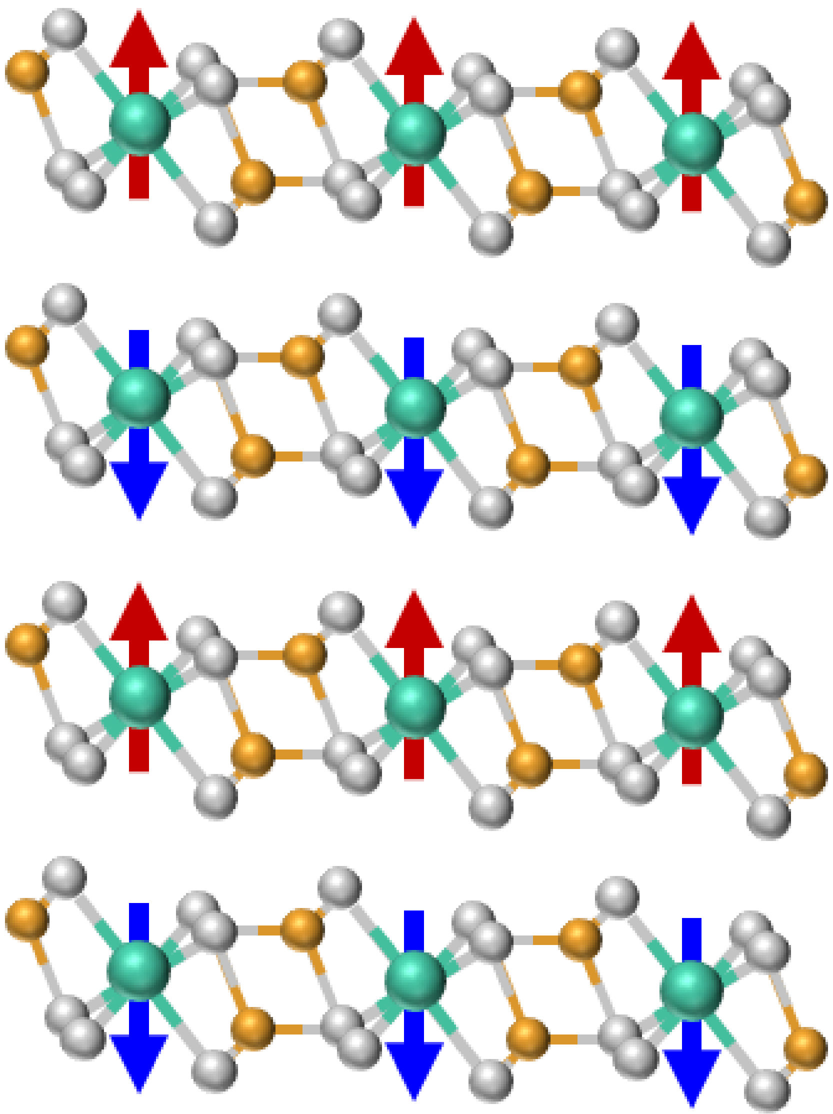
Cornelissen, et al. *Nat. Phys,*, ***11*(12)**, 1022-1026, 2015



Cornelissen, *Magnon spin transport in magnetic insulators* (Doctoral dissertation, PhD thesis. University of Groningen, 2018.

Chromium Thiophosphate

- A-Type Anti FerroMagnet (AFM)
  - In-plane FM (Intralayer)
  - Interlayer AFM
  - Critical temperature $T_N \approx 40K$
- Electrically insulating
- Air stable

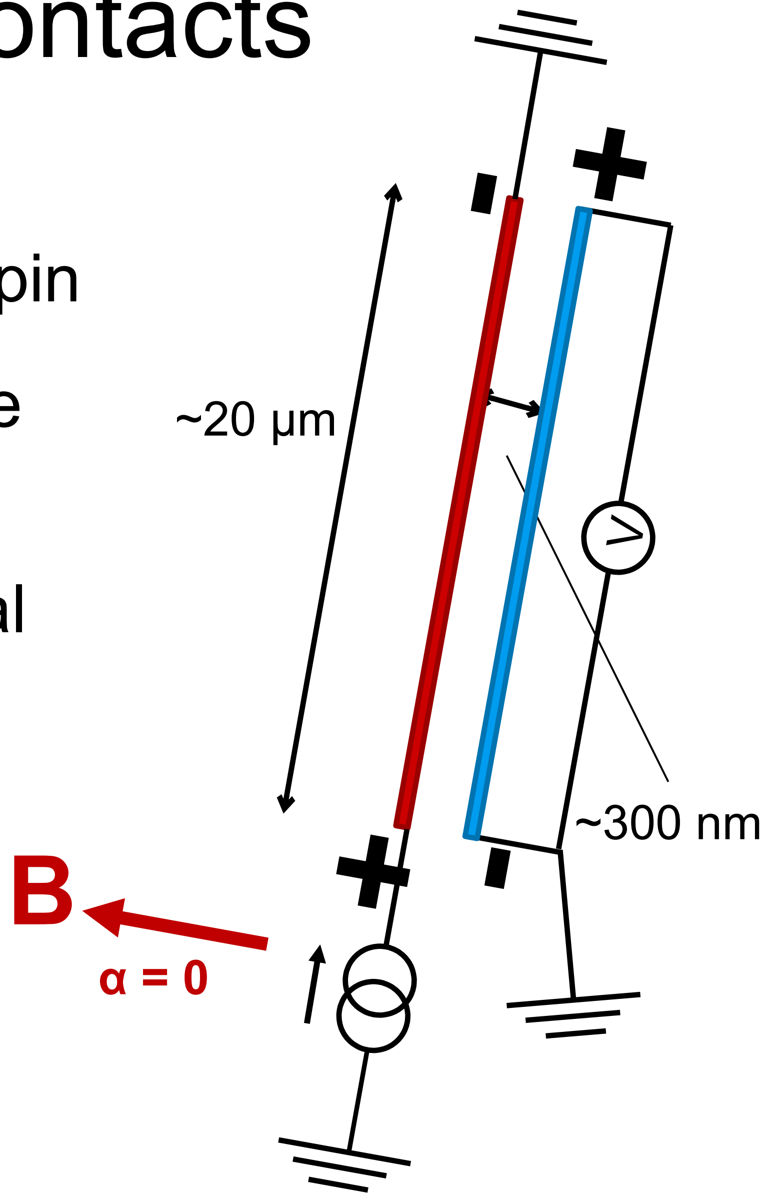


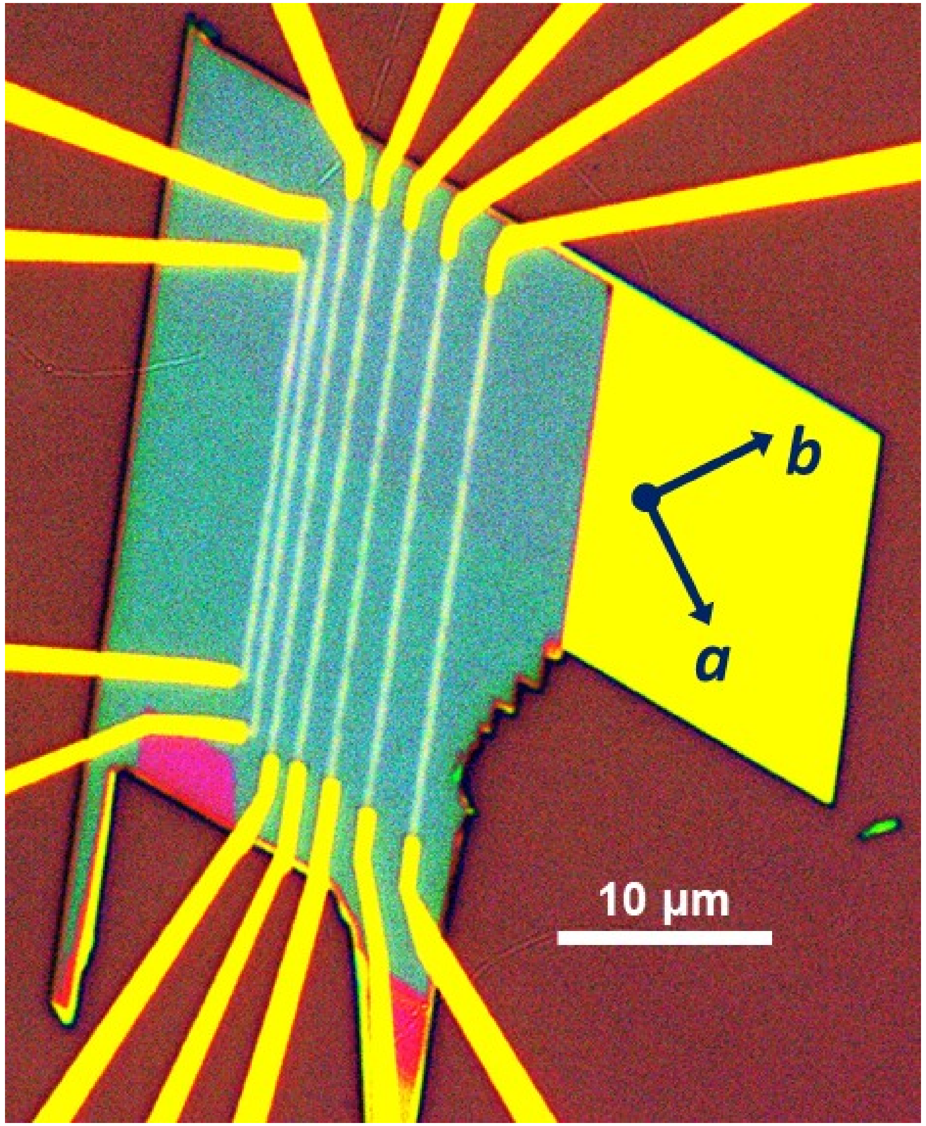
Device and contacts

› Electrically inject spin

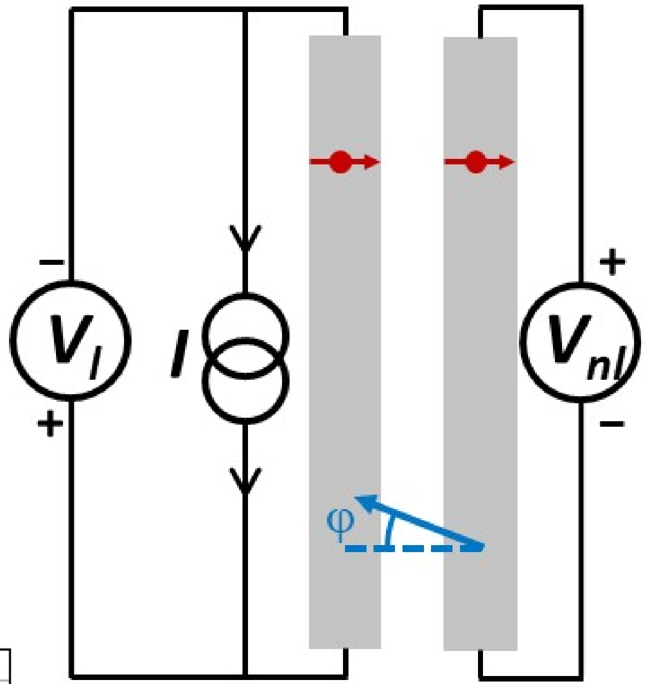
› Thermally generate magnons

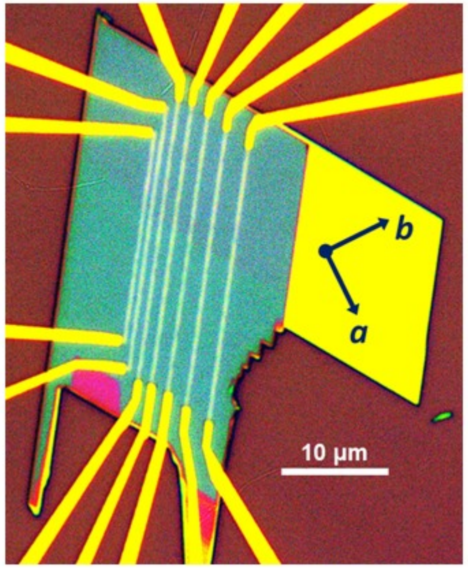
› Local and non-local detection

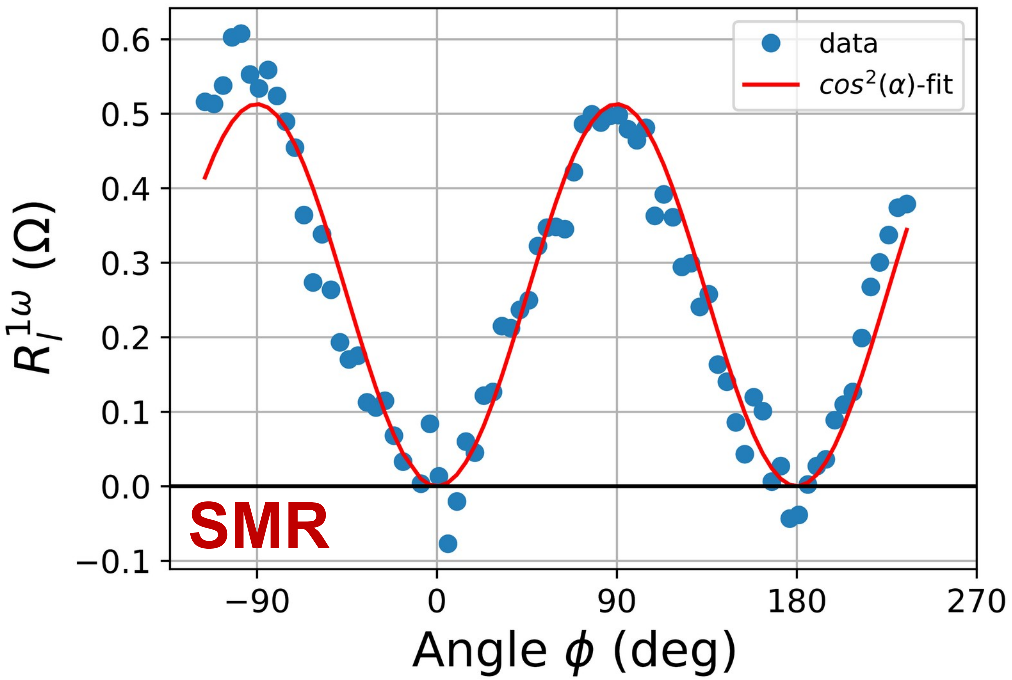


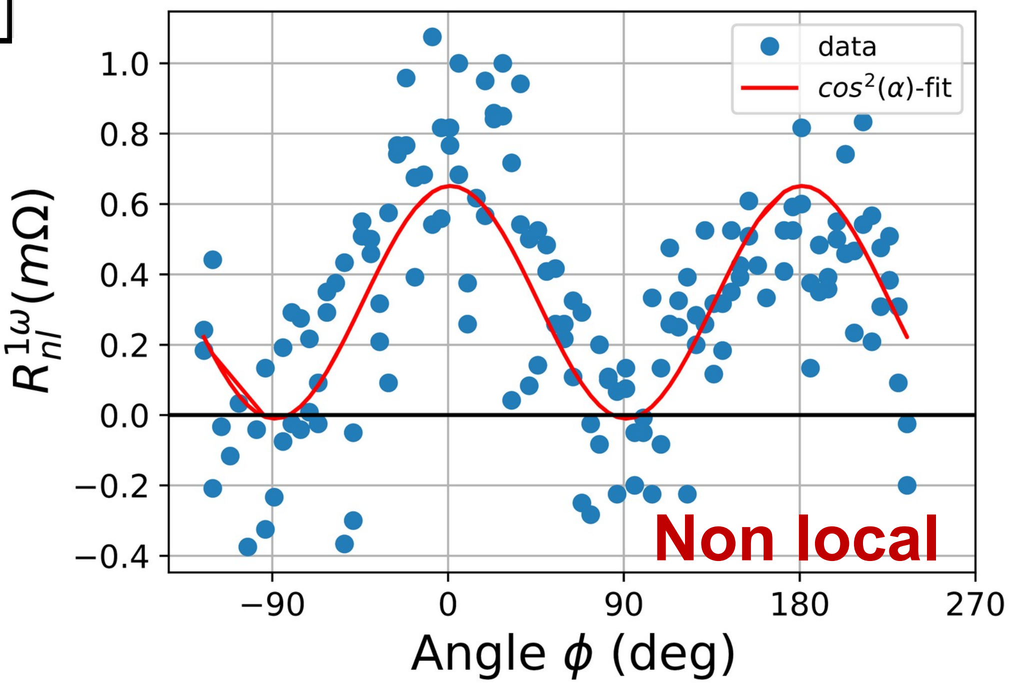


Results
First harmonic response



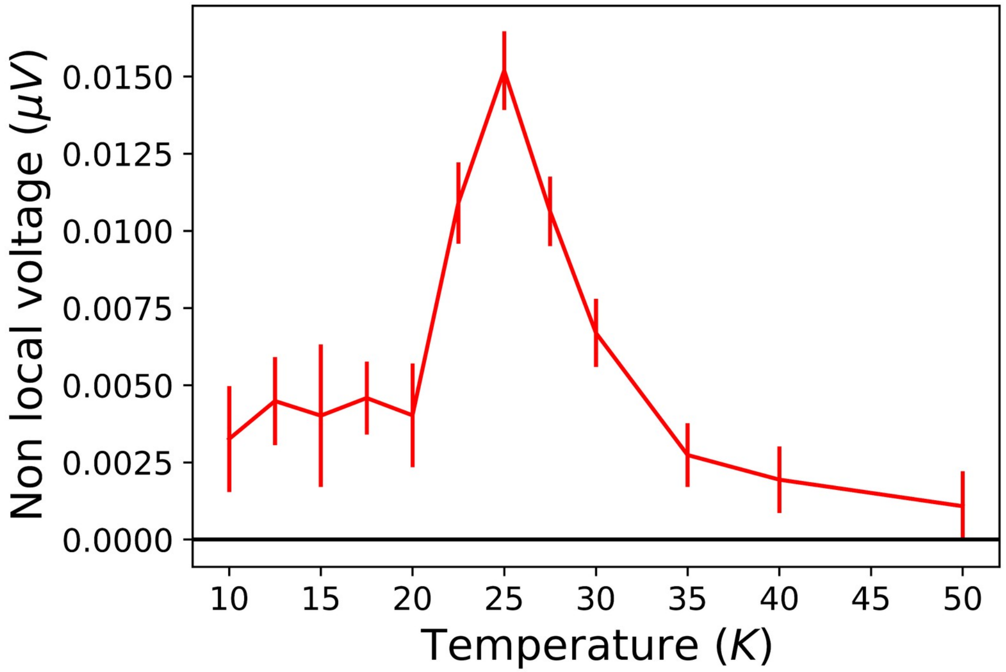






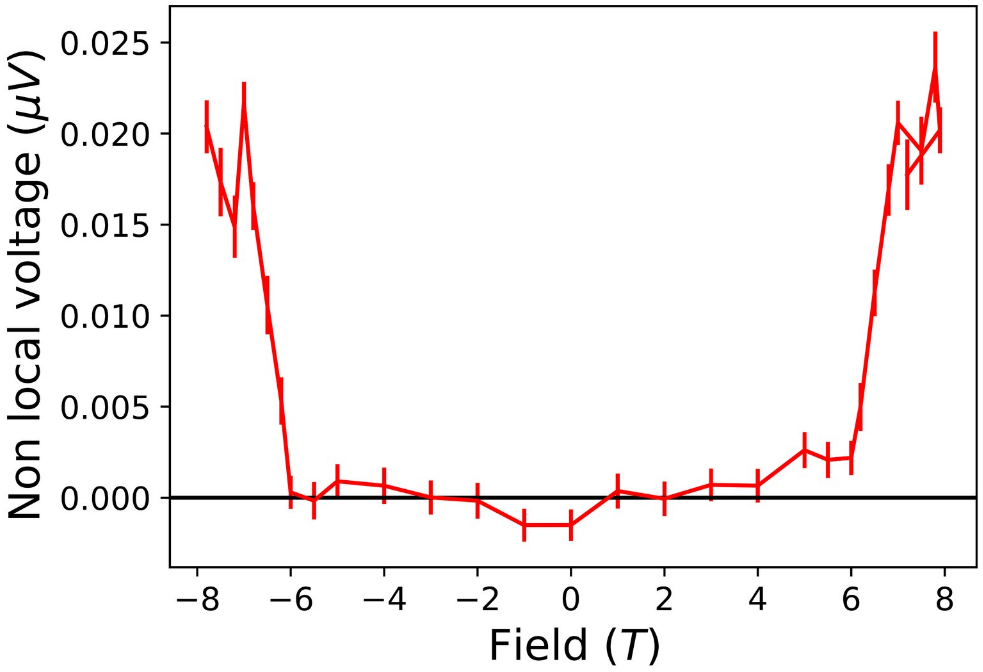
Results

Temperature dependence



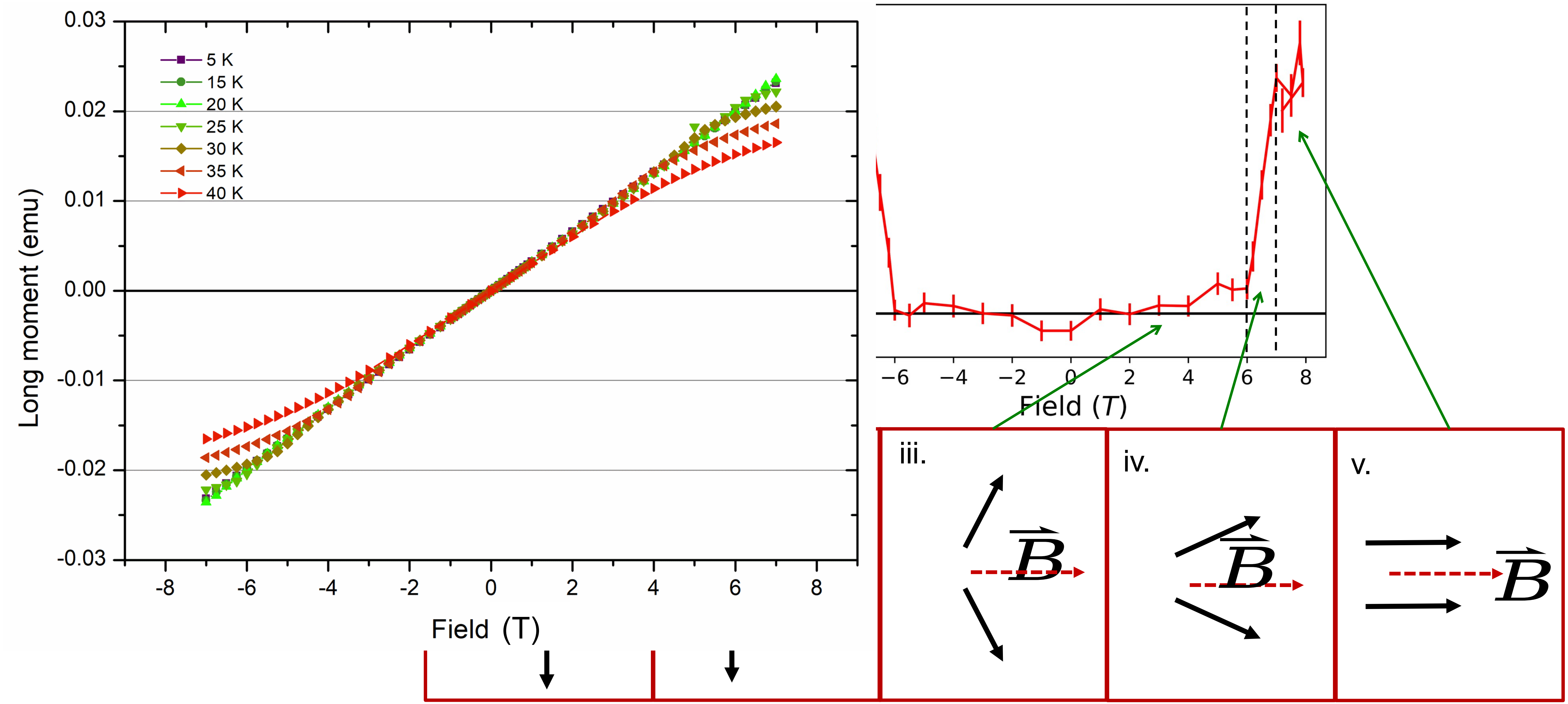
Bias: 40 μA; Field: 7 T

Field dependence

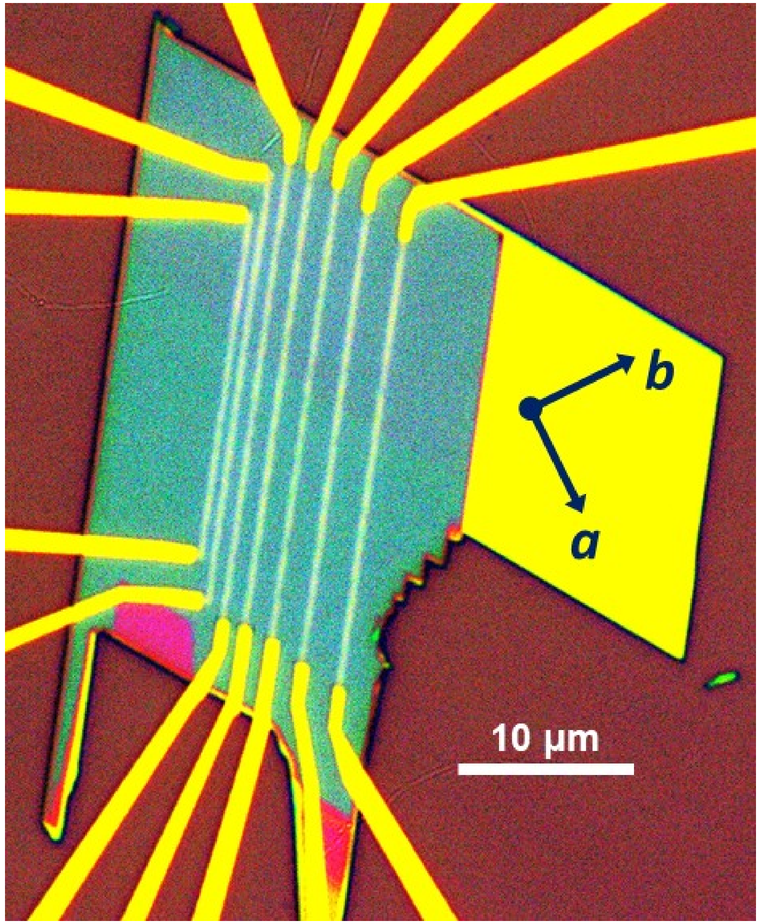


Bias: 60 μA; Temperature: 25K

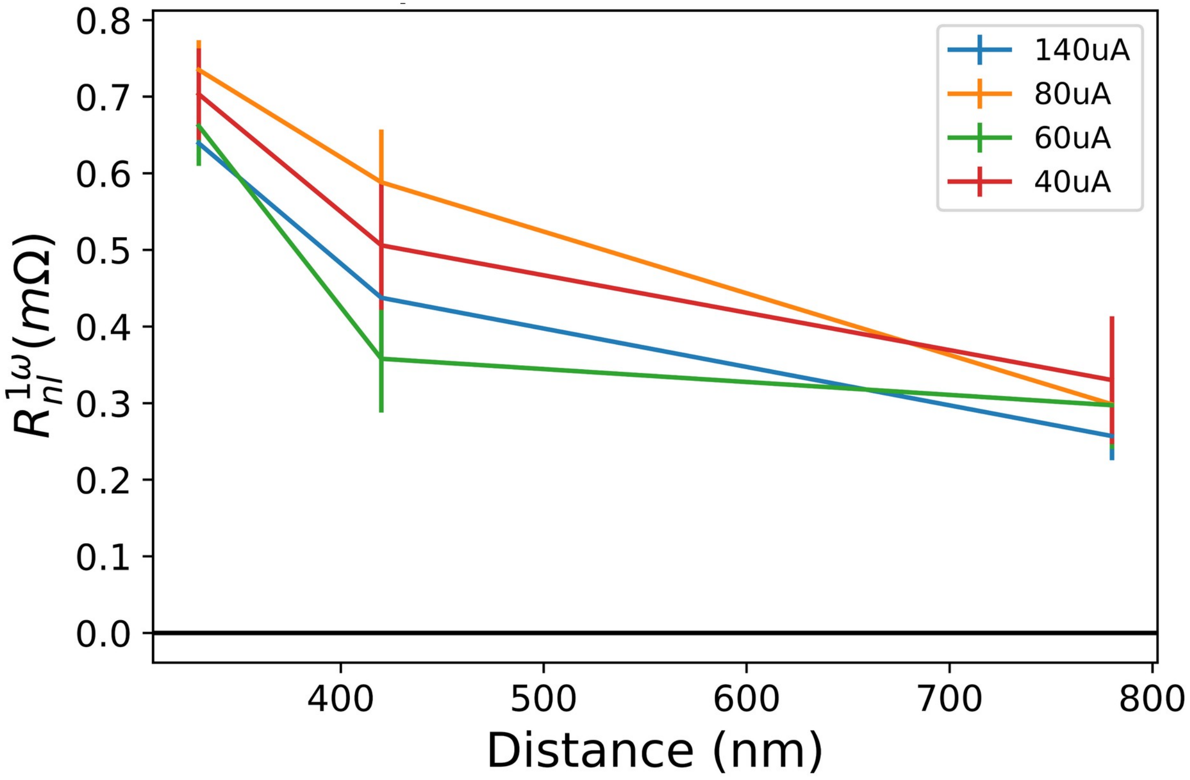
Saturation of two sublattices?



Distance dependence

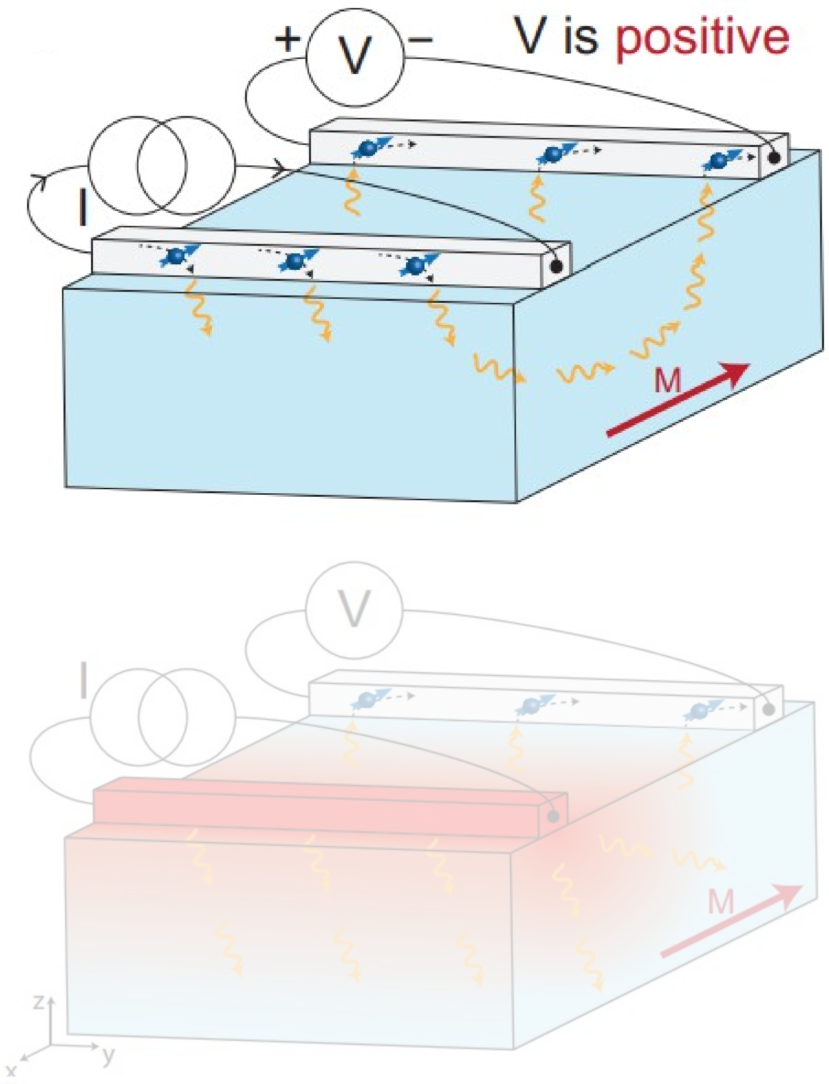


$$R_{nl} = \frac{C}{\lambda} \frac{\exp\left(d/\lambda\right)}{1 - \exp(2d/\lambda)}$$



Conclusions

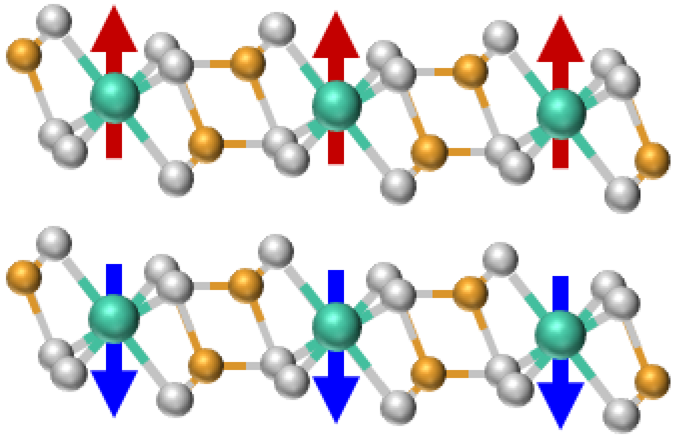
- First time *direct* magnon transport in 2D antiferromagnet
  - Up to distances of at least 1 μm
- Transition from AFM to FM state
  - Only observe transport in FM state
- Magnonics in antiferromagnets?

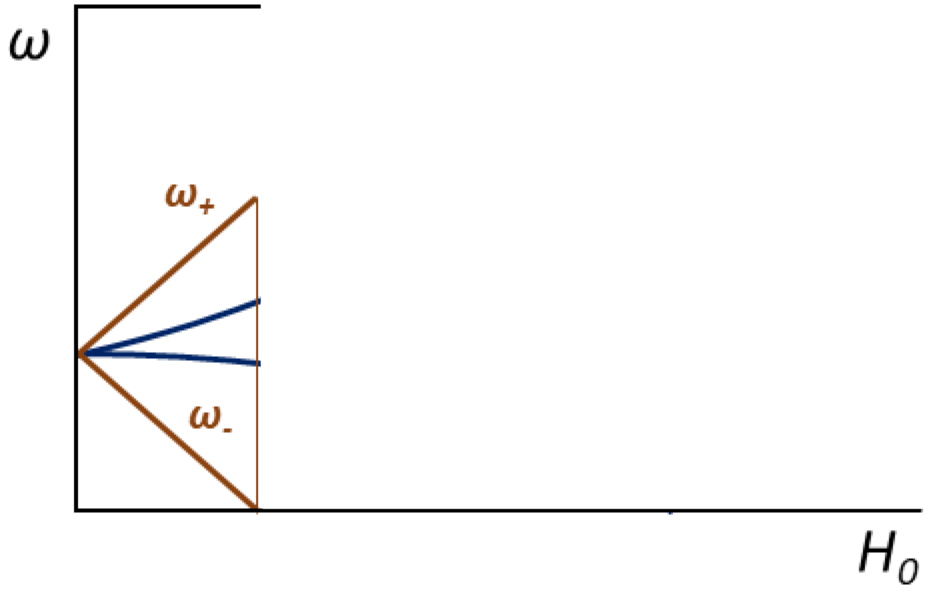


Cornelissen, Doctoral dissertation, PhD thesis

Magnon modes at IP fields

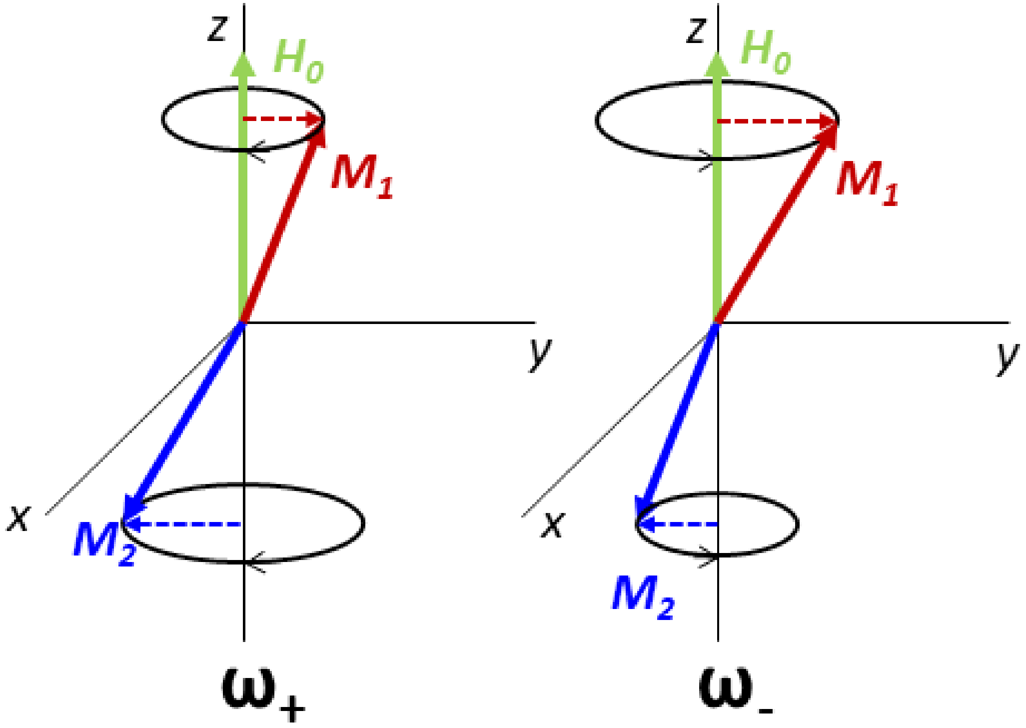
(a)



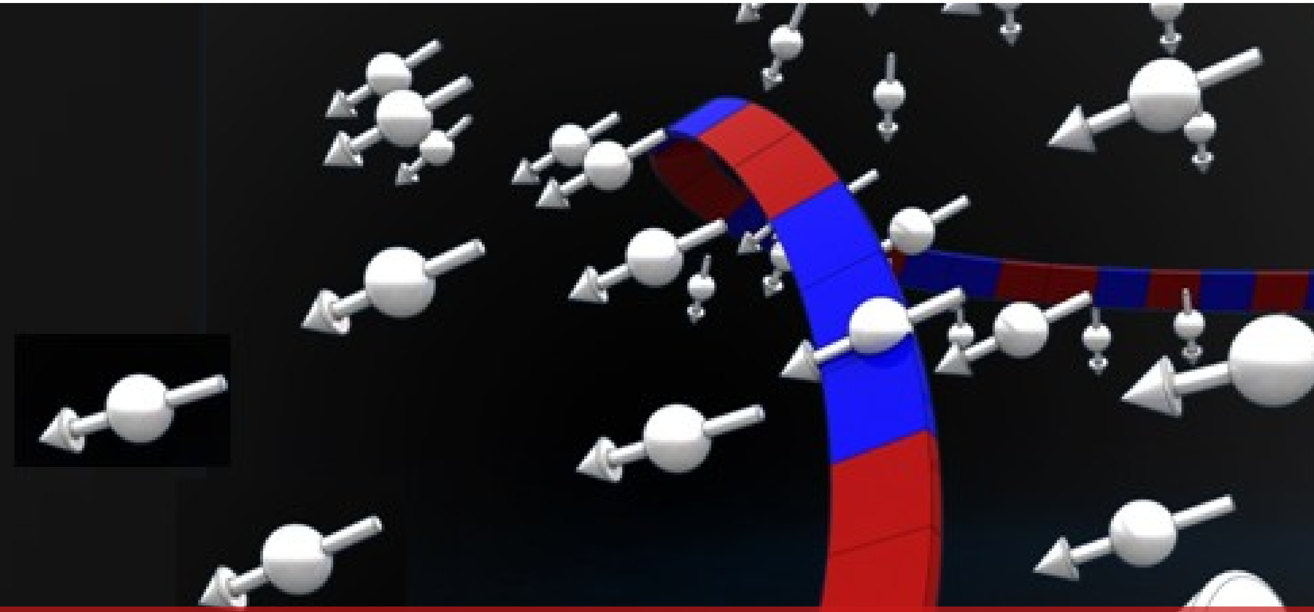


(b)

(c)



Magnetic (MagnetoPhotonic) nano-engineering for topological quests



Input Pillar 2 (and 4)

Bert Koopmans, Marcos Guimaraes, Kobus Kuipers, Reinoud Lavrijsen, Alexey Kimel, Erik Bakkers, Rembert Duine, Reinoud Lavrijsen, Diana leitao…

QuMat Kick-Off, October 2022

Outline

Expertise @ TU/e

- Magnetic NanoEngineering @ NanoAccess
- Fs laser-induced control & Integrated MagnetoPhotonics

'Our' position in the program

Pillar 2

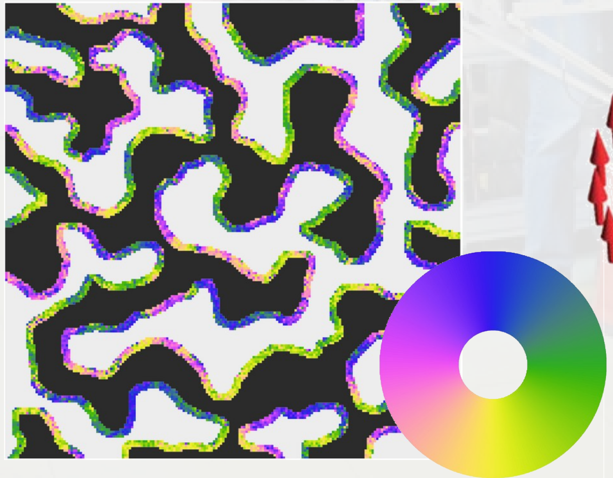
- Controlling synthetic spin-orbit coupling by nanomagnetic engineering
- Topological spin-waves / magnons ✉ Synthetic nanomagnetic systems

Pillar 4

- Towards devices: Integrated MagnetoPhotonics

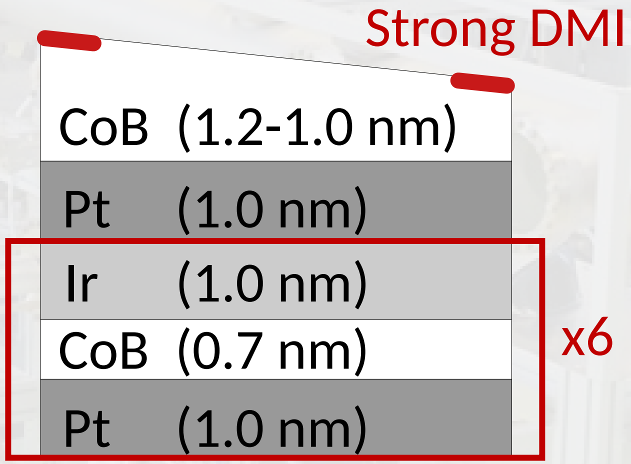
Magnetic NanoEngineering @NanoAccess

DMI – chirality – topological skyrmions



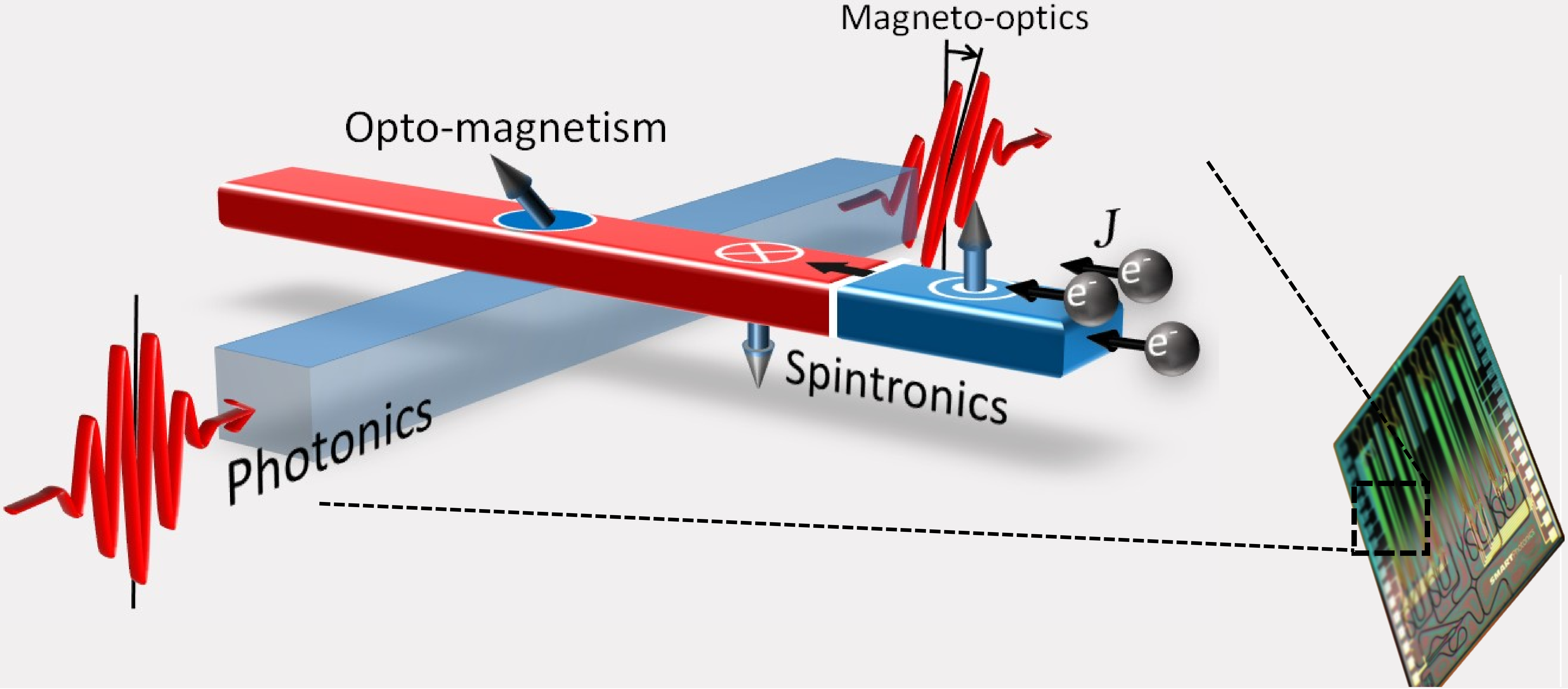
Lucassen, RL *et al.*, PRL 2019
Meijer, RL *et al.*, PRL 2020

Deposition



TU/e

Fs & Integrated Magneto-Photonics



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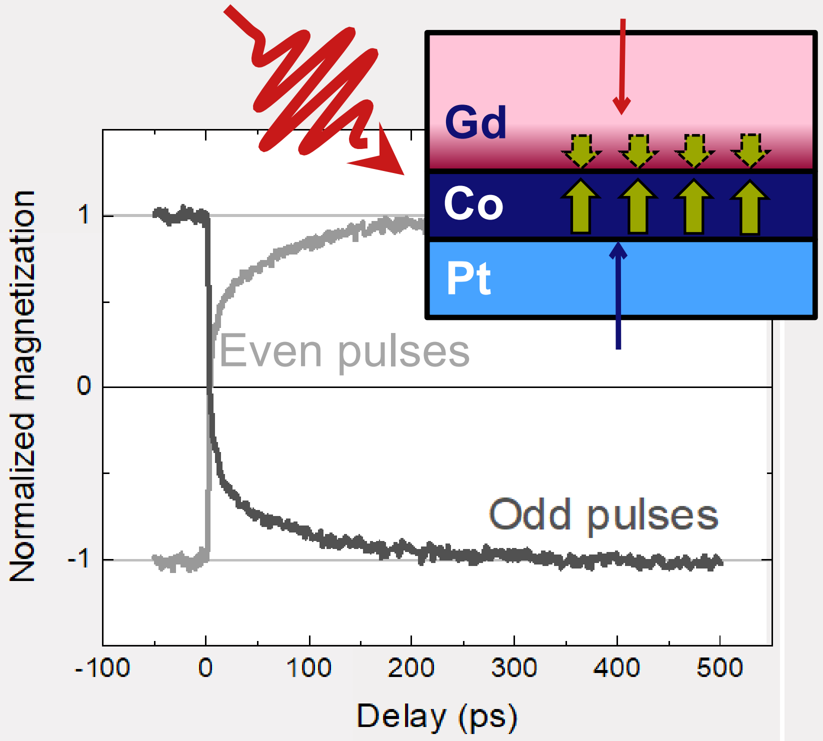
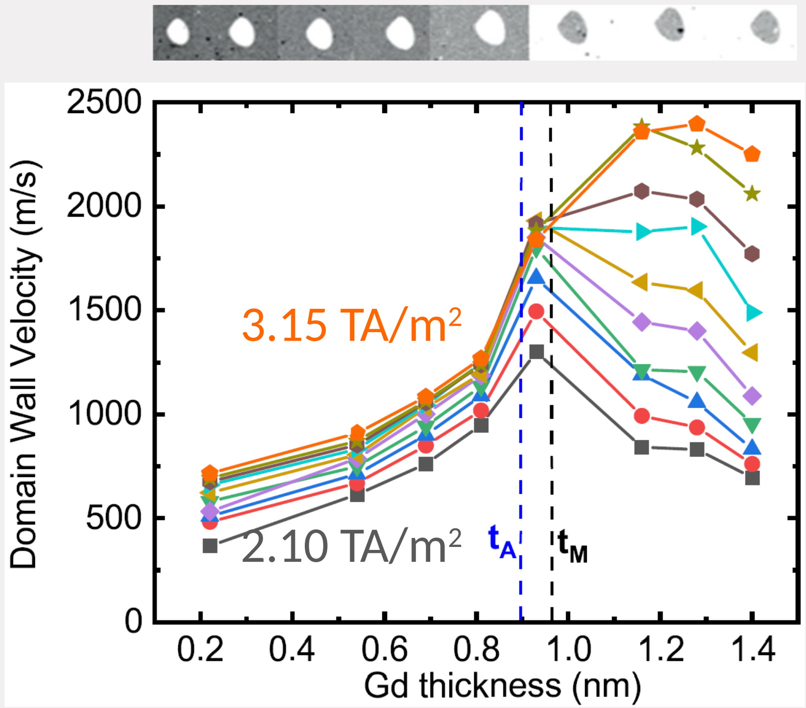
Fs & Integrated Magneto-Photonics

All-optical writing



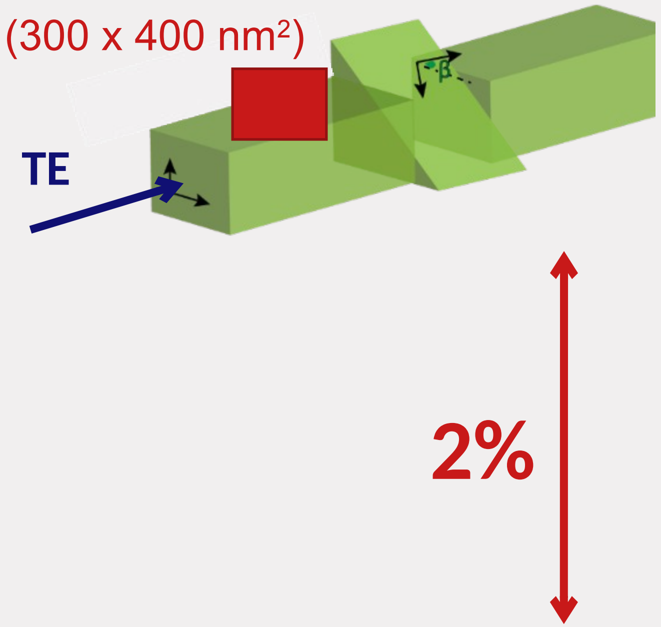
Lalieu *et al.*, Nature Comms. 2019
Peeters *et al.*, PRB 2022

SOT-DW motion



Pingzhi Li et al., Electr. Func. Mat. 2022
arXiv:2204.11595

On-chip reading

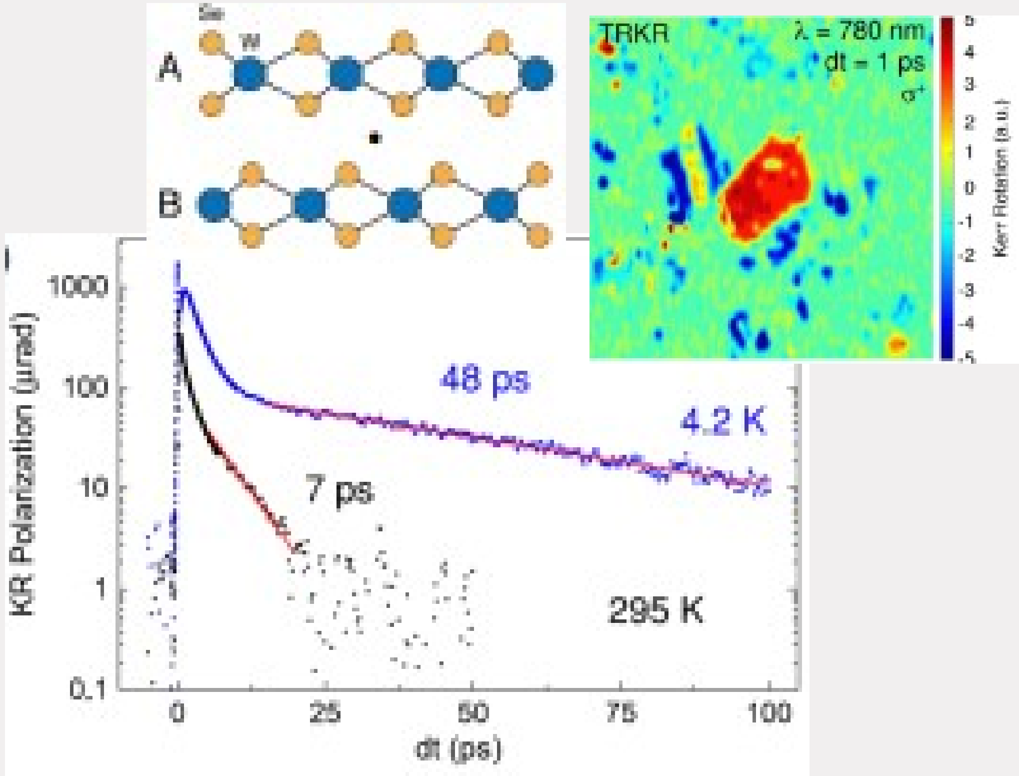


Demirer, BK *et al.*, Nanophot. 2022

TU/e

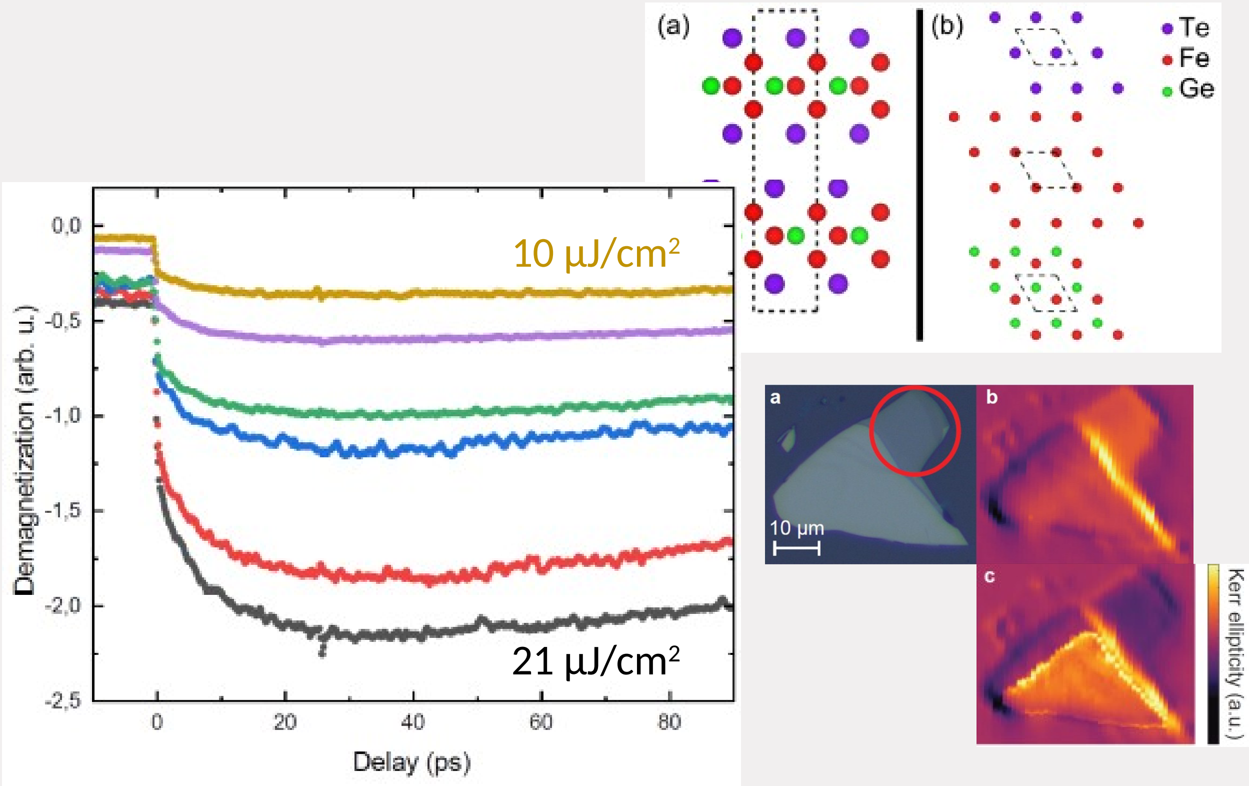
Spin & M dynamics in 2D materials

ps dynamics of optically-induced hidden spin polarization in WSe_2



Guimaraes & BK, Phys. Rev. Lett. 2018

Ultrafast laser-induced magnetization dynamics in Fe_3GeTe_2



Lichtenberg, MG & BK, 2D materials (2022), accepted

'Our' position in the program

2.1 Topological magnonics

D	*Spin-orbit-matter based devices* - 1 PhD; TT TU/e, Koopmans (TU/e). We will integrate magnonics with semiconductor technology and develop devices that can effectively transfer magnetic into electrical signals and vice versa based on effects at interfaces between semiconductors with a large spin-orbit interaction and magnets.

2.2 Controlling spins …

D	*Opto-magnonic devices* – PhD (0.5 FTE)#; Koopmans (TU/e), Guimarães (RUG), Kuipers (TUD). We will design and demonstrate scalable, nearly non-dissipative spin-wave devices and circuits, such as logic gates, filters, waveguides, diodes, and multiplexors. In these devices, topological exchange spin waves are used as information carriers that do not suffer from conventional problems of magnonic devices but benefit from the advantages of the nanoscale wavelength and THz frequency.

4.2 Spin-orbit opto-matter

C	*Optical sensing and control of topologically protected states* – PhD (0.5 FTE)*; Kimel (RU), Koopmans (TU/e). We will study the emergence of complex magnetic order in rare-earth materials and ascertain the role of spin orbit coupling and magnetic exchange. We will aim at manipulating this order, with laser fields, in order to quantify how we can utilize these materials for magnetic memory and low-energy spin transfer. Moreover, we will explore the presence of topological magnons as well as fundamentally new types of quasiparticle excitations, like fractons, in these material systems.
SD	*On-chip coupling of light to spin and pseudo-spin* – PhD (0.5 FTE)#; Koopmans (TU/e), Guimarães (RUG), Kuipers (TUD) We will develop hybrid magnet/waveguide devices for selective on-chip, optical near-field initiation of spins and pseudospins in 2D magnets at room temperature. The degree of preservation of spin or pseudo-spin in the light/matter interconversion will be studied by nanowire optics.

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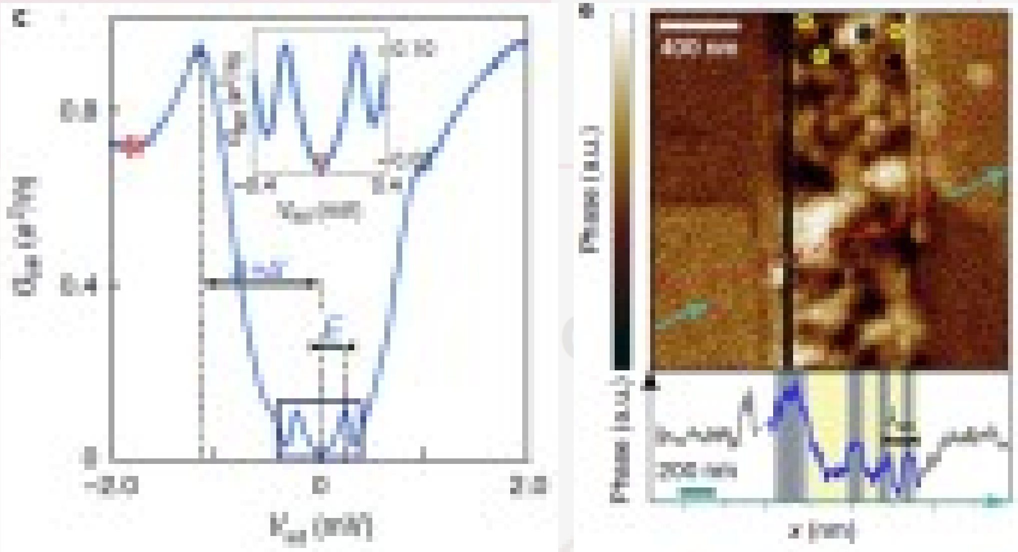
1. Synthetic spin-orbit interaction

- E_{so} ~ 1.1 meV
- Revealed through oscillations of s.c.-induced subgap states
- Robust zero-energy state



LETTERS

https://doi.org/10.1038/s41563-019-0457-6

Synthetic spin-orbit interaction ... devices

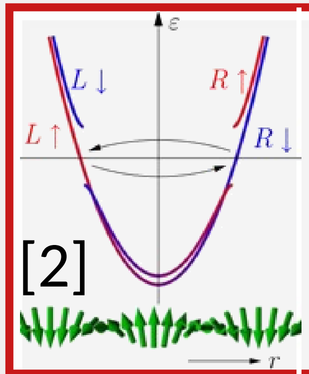
M. M. Desjardins[1,4], L. C. Contamin[1,4], M. R. Delbecq[1], M. C. ... J. J. Viennot[1,2], F. Mallet[1], S. Rohart[3], A. Thiaville[3], A. Cottet[1] ...

The interplay of superconductivity with non-trivial spin textures is promising for the engineering of non-Abelian Majorana quasiparticles. Spin-orbit coupling is crucial for the topological protection of Majorana modes as it forbids other trivial excitations at low energy but is typically intrinsic to the ...

A magnet... lent to a Ra... tive constan... λ sets the sp... tude of the ...

TU/e

Research ideas



[2]

400 nm in [1]

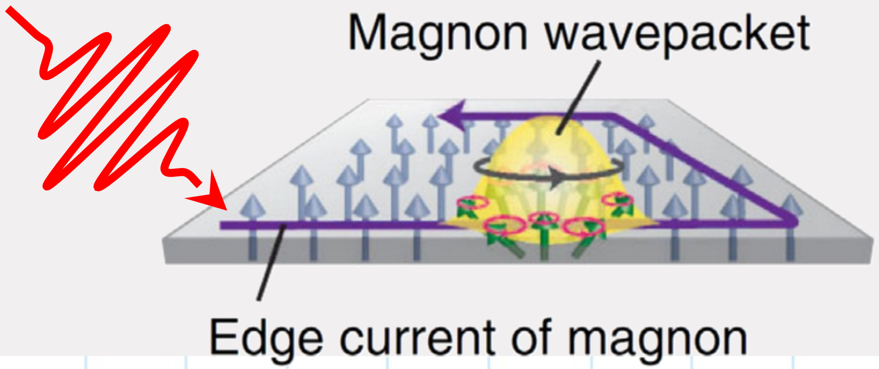
[1] Desjardin *et al.*, [2] Braunecker *et al.*

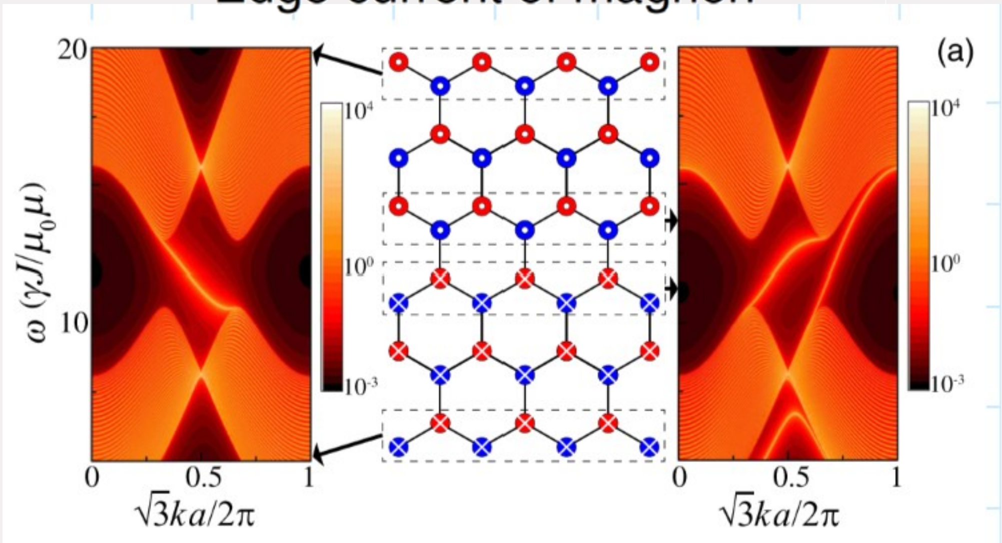
- **Induce synthetic s.o. in low-Z materials**
- **Tune s.o. in large-s.o. materials like InSb NWs**
- **Boost (switchable) s.o. using engineered multilayers, chiral strip domains, exploiting FIB manipulation, etc.**
- **Wild idea: use cross section of synthetic AF?**
- **Challenge: Ultrafast all-optically switchable synthetic s.o.**

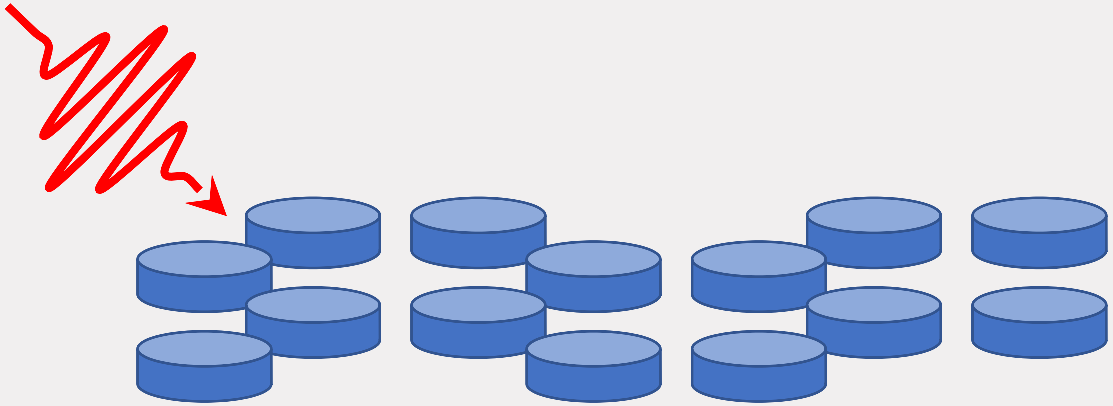
Collaboration: Guimaraes, Bakkers, …

Link to next theme

Topological magnons ✉ Synthetic?







Synthetic systems

Li *et al*., Physics Reports. 2021
Wang *et al*., Phys. Rev. Applied 2018

Guimaraes & Koopmans

Lavrijsen, Leitao, Duine & Koopmans

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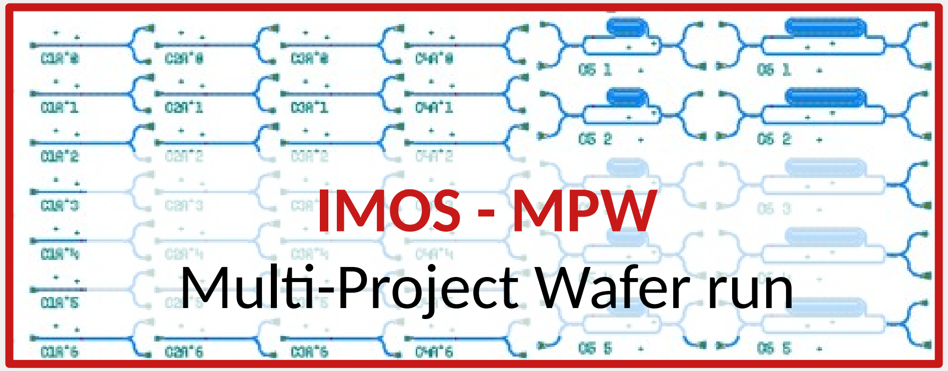
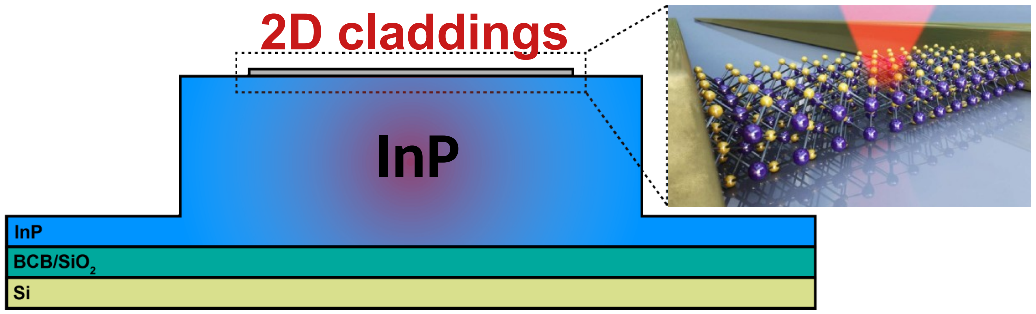
On-chip hybrid 2D (magnetic) devices

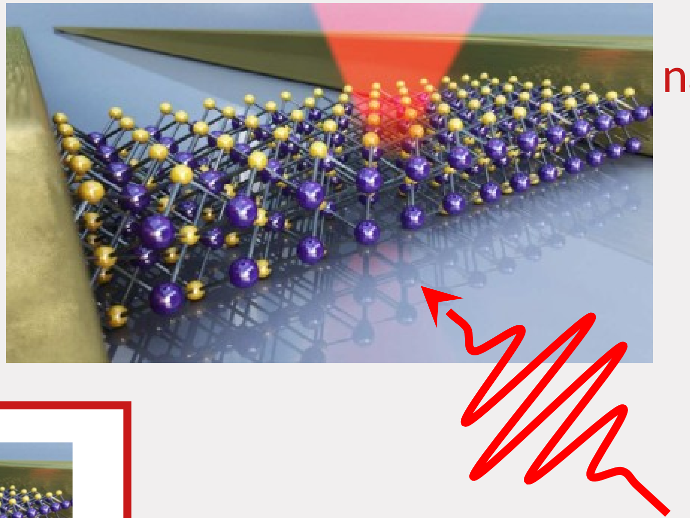
Photonic Integrated Circuits



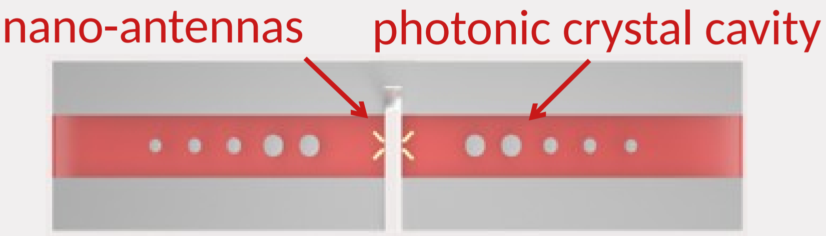


Demirer, BK *et al.*, Nanophot. 2022

2D (Magnets)



Near-field / Plasmonics

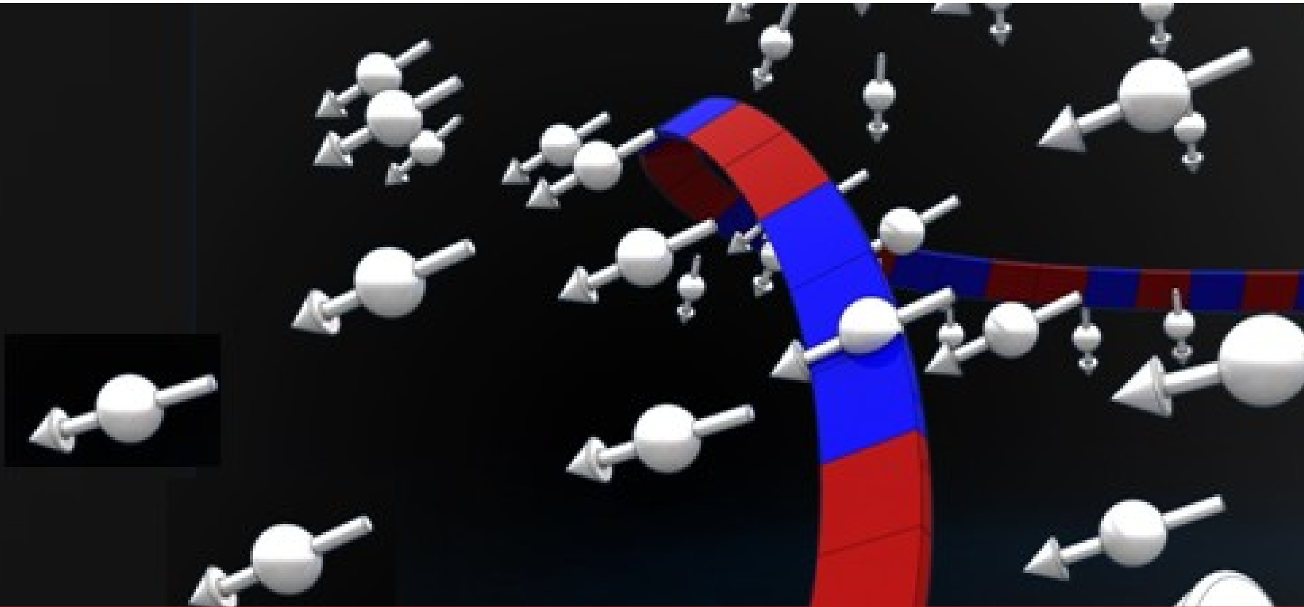


IEEE J. Quantum Electronics, Pezshki, BK *et al.*, accepted

"focus on (coherent) photonic circuits with spins/magnetism and the combination with quantum materials"

Guimaraes & Koopmans

TU/e



Magnetic (MagnetoPhotonic) nano-engineering for topological quests

Input Pillar 2 (and 4)

Bert Koopmans, Marcos Guimaraes, Kobus Kuipers, Reinoud Lavrijsen, Alexey Kimel, Erik Bakkers, Rembert Duine, Reinoud Lavrijsen, Diana leitao…

QuMat Kick-Off, October 2022