Spintronics with magnetic insulators

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MATERIALS IN MAINZ SCIENCE

erc

SPIN+X SFB/TRR 173 Kaiserslautern • Mainz

- **Magnetic properties of magnetic insulators probed by Spin Cavitronics (I. Boventer, M. Weides)**
- **Lateral spin transport in (anti-) ferromagnetic insulators: Superfluid regime, Diffusive regime (R. Lebrun, A. Ross, S. Bender, R. Duine, A. Brataas, Y. Tserkovnyak)**

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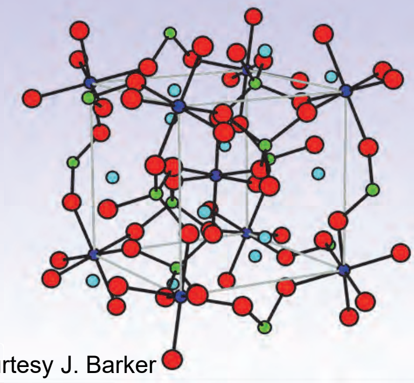
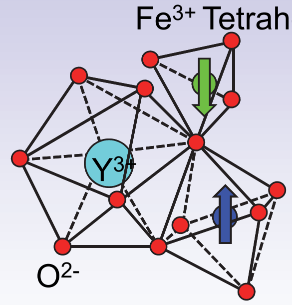
1. Structural Characterization – Garnets

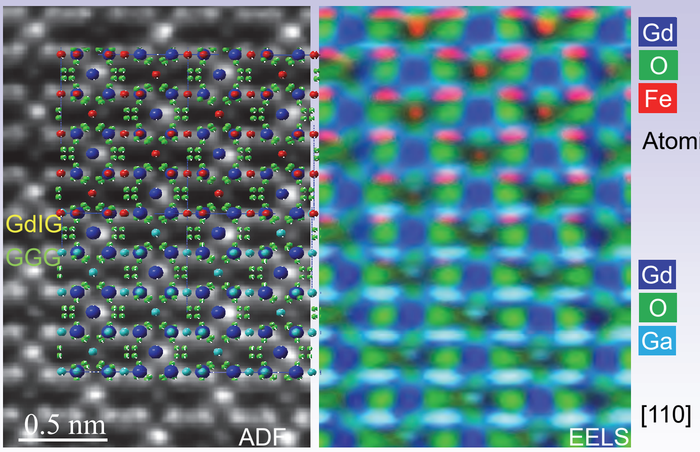
Very large unit cell
20 Fe atoms in primitive cell in two different environments


Courtesy J. Barker



- Yttrium Iron Garnet $Y_3Fe_5O_{12}$ is a complex ferrimagnet with 2 iron sublattices (a and d sites) that are coupled by superexchange.
- Further garnets, such as $Gd_3Fe_5O_{12}$ have an additional third magnetic sub-lattice of the rare-earth element.

1. Structural Characterization – YIG



Atomic resolution EELS

Imaging carried out by Y. Ivanov and J. Kosel (KAUST)

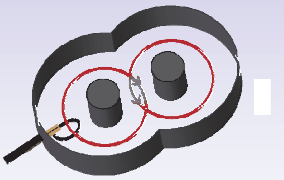
J. Cramer et al., Nano Lett. **17**, 3334 (2017)

- Yttrium Iron Garnet $Y_3Fe_5O_{12}$ is a complex ferrimagnet with 2 iron sublattices (a and d sites) that are coupled by superexchange.
- Further garnets, such as $Gd_3Fe_5O_{12}$ have an additional third magnetic sub-lattice of the rare-earth element.

2. Spin Cavitronics with YIG

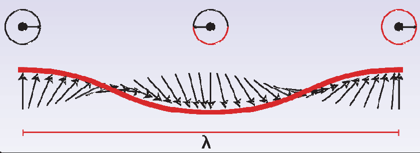
Hybridization of microwave photons with magnons:

Microwave cavity: Photon



g_{eff}

Magnetic sphere : magnon



Strongly coupled systems with new energy eigenstates
Observation of anticrossing at resonance

➢ **cavity-magnon polariton formation**

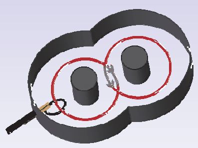
Mathias Kläui SPICE Spin Cavitronics, Mainz, 17.5.2018

2. Spin Cavitronics with YIG

Hybridization of microwave photons with magnons

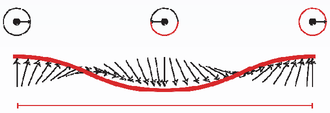
Spectroscopy at room temperature

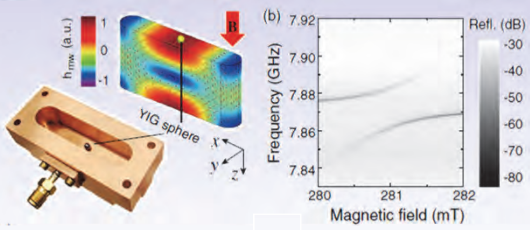
Microwave cavity: Photon



g_{eff}

Magnetic sphere : magnon

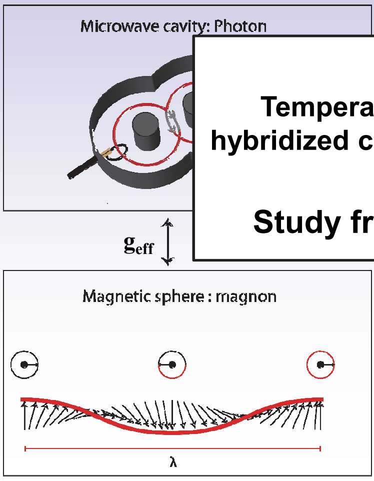




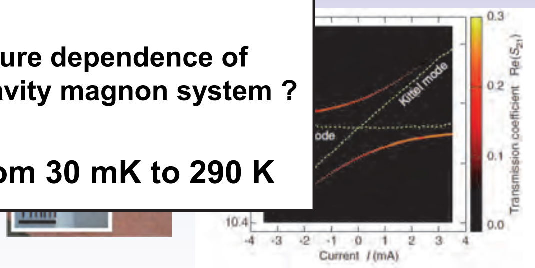
X. Zhang *et al.*, *Phys. Rev. Lett.* **113**, 156401 (2014)

2. Spin Cavitronics with YIG

Hybridization of microwave photons with magnons



Spectroscopy at 20 mK



Temperature dependence of hybridized cavity magnon system ?

Study from 30 mK to 290 K

Y. Tabuchi *et al.*, *Phys. Rev. Lett.* **113**, 083603 (2014)

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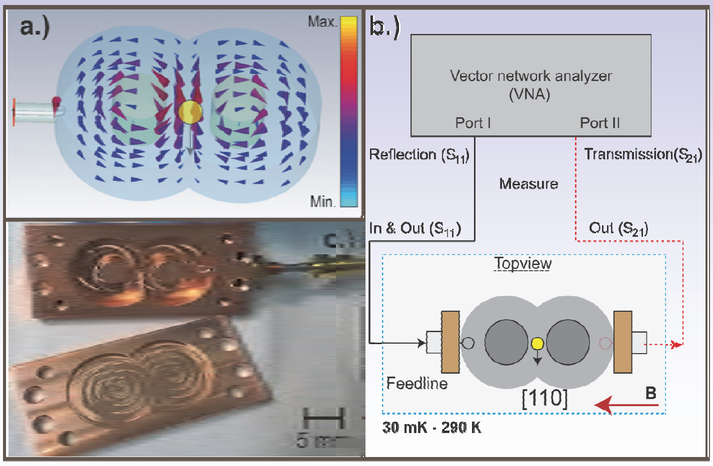
SPICE Spin Cavitronics, Mainz, 17.5.2018

2. Spin Cavitronics with YIG – Experimental Setup



Reentrant cavity:M. Goryachev *et al.*, *Phys. Rev. Appl.* **2,** 054002 (2014)

2. Spin Cavitronics with YIG – Avoided Crossing

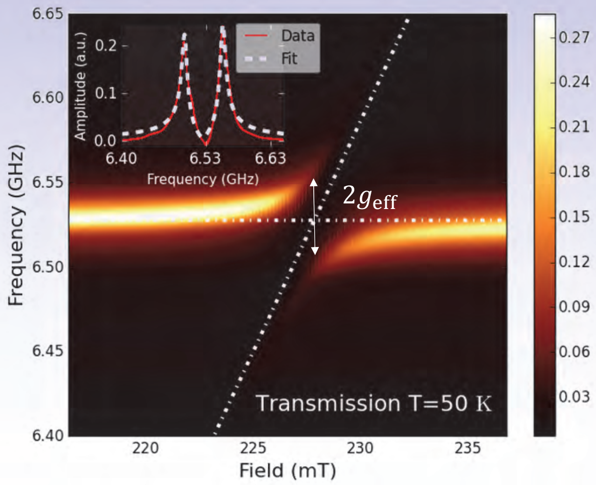
Consider coupling to Kittel mode only

- **Cavity:**
  field independent

- **YIG :**
  field dependent

Sphere: $\omega_{res} = \gamma\mu_0 \overrightarrow{H_{eff}}$

- **At resonance:**
  $\omega_{res} = \omega_r = \omega_m$



I. Boventer et al., PRB **97**, 184420 (2018)

2. Spin Cavitronics with YIG – Determination of properties

Scattering parameter S_{11} from Input-Output theory:

$$S_{11} = -1 + \frac{2\kappa_e}{i(\omega_r - \omega) + \kappa_r + \frac{g_{eff}^2}{i(\omega_m - \omega) + \kappa_m}}$$

κ_e : External coupling losses
$\kappa_r = \kappa_e + \kappa_c$:Total losses
$g_{eff} = g_s\sqrt{2Ns}$: Coupling strength
κ_m: Magnon losses

Temperature dependence?

I. Boventer et al., PRB **97**, 184420 (2018)

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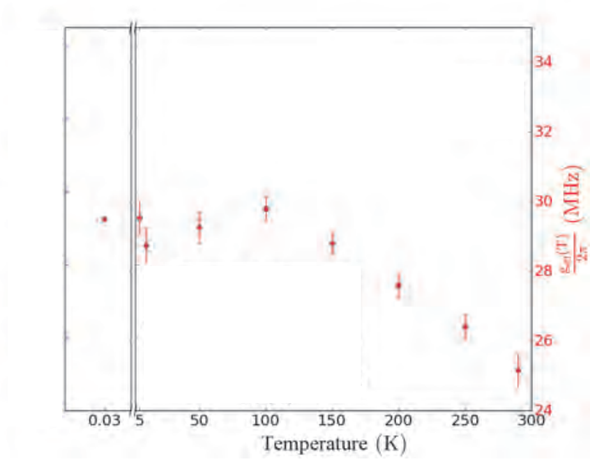
2. Spin Cavitronics with YIG – Determination of properties



Coupling strength

$g_{eff} \propto g_s \cdot \sqrt{N}$

Saturation magnetization

$M_s = \sum_i^N m_i \propto N$

Relation between quantities

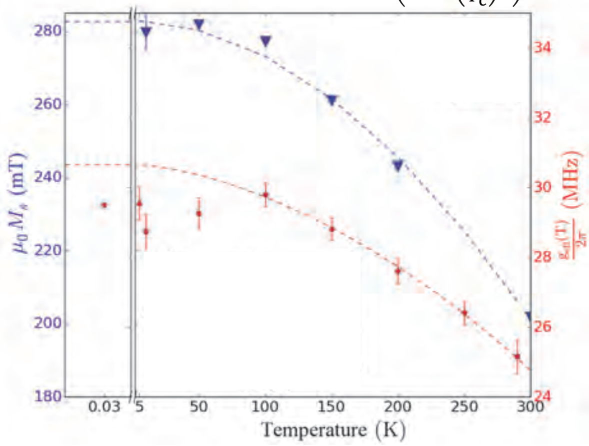
$g_{eff} \propto \sqrt{M_s}$

I. Boventer et al., PRB **97**, 184420 (2018)

Mathias Kläui SPICE Spin Cavitronics, Mainz, 17.5.2018

2. Spin Cavitronics with YIG – Determination of properties

Bloch's $T^{\frac{3}{2}}$ law : $M_s = M_s(0) \cdot \left(1 - \left(\frac{T}{T_c}\right)^{\frac{3}{2}}\right)$



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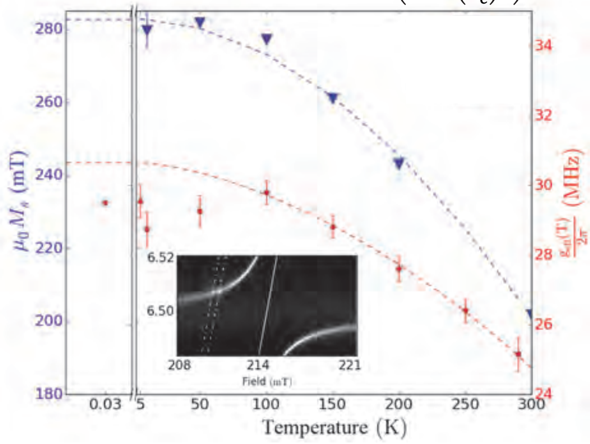
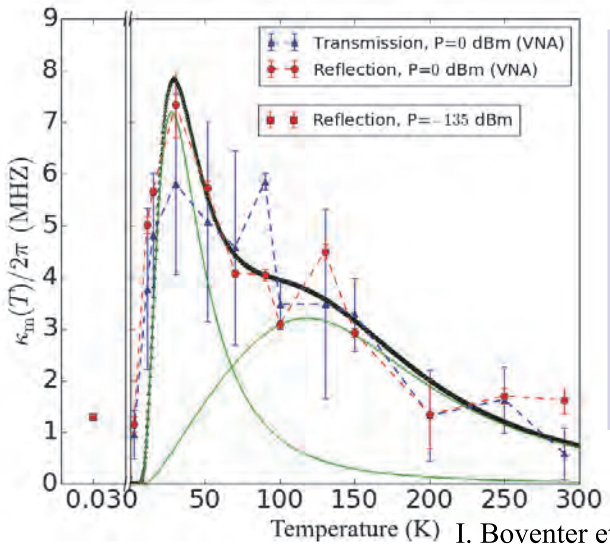


- Agreement T ≥100 K
- T < 100 K : Deviations

Additional coupling to higher order magnetostatic modes

- **Conservation of spin number N : Coupling strength g_{eff} to Kittel mode lowered**

2. Spin Cavitronics with YIG – Determination of properties

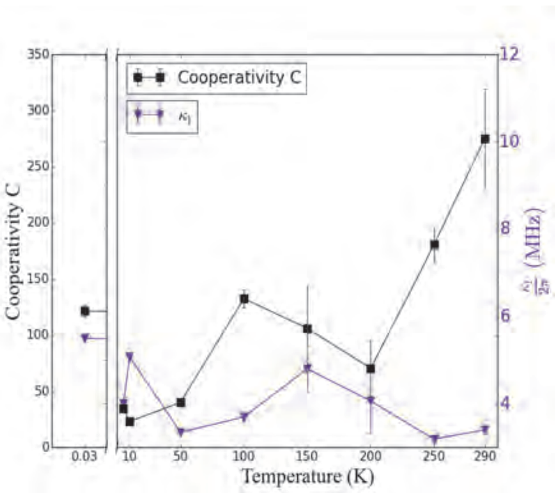


Rare earth impurity scattering
- Dominant peak at 43 K
- ‚Broad shoulder' at 90 K
- Offset of ~1 MHz from intrinsic damping & surface scattering

Model well the temperature behaviour of our system

I. Boventer et al., PRB **97**, 184420 (2018)

2. Spin Cavitronics with YIG – Determination of properties



I. Boventer et al., PRB **97**, 184420 (2018)

$$C = \frac{g_{eff}^2}{\kappa_l \kappa_m}$$

- Cavity dissipation (κ_l) does not change much
- Strong coupling regime for all temperatures
- C governed by changes in magnon dissipation
- Coherent information exchange between sub-systems robust.

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- **Lateral spin transport in (anti-) ferromagnetic insulators: Superfluid regime, Diffusive regime (R. Lebrun, A. Ross, S. Bender, R. Duine, A. Brataas, Y. Tserkovnyak)**

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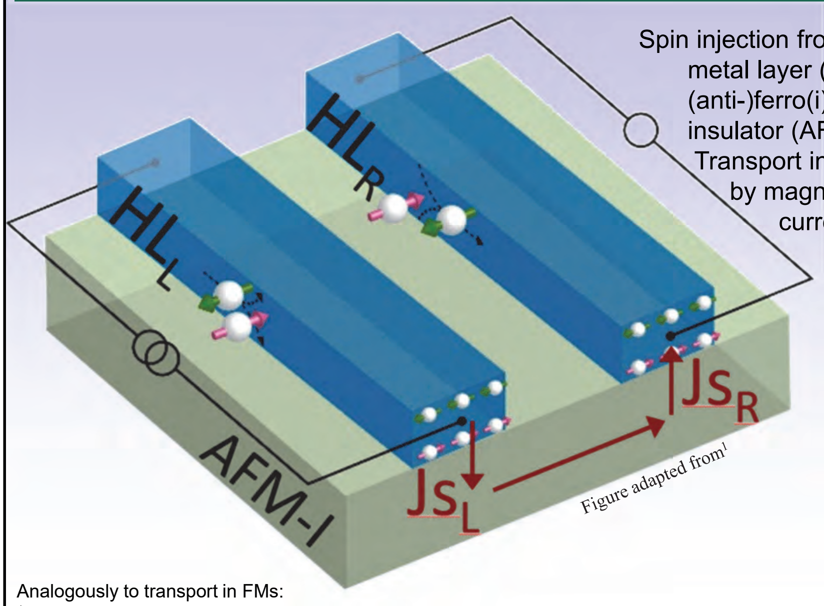
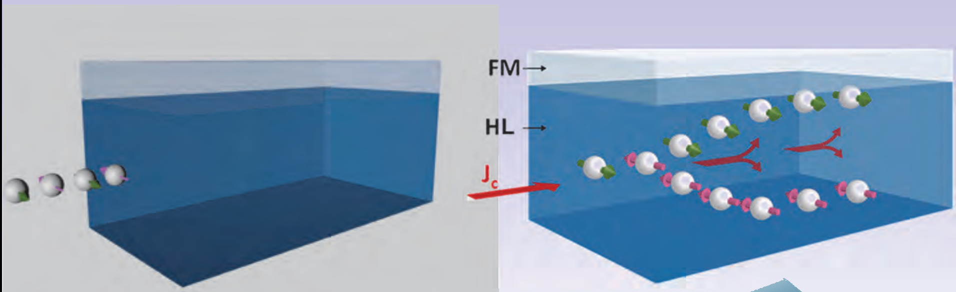
3. Lateral spin transport in (anti-)ferromagnetic insulators



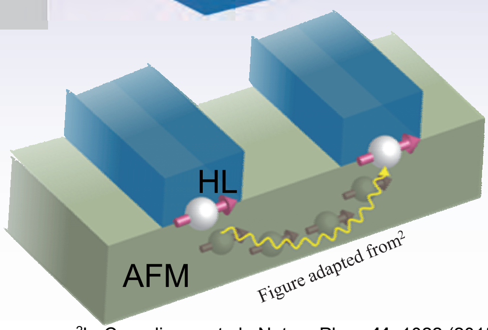
Spin injection from a heavy metal layer (HM) into a (anti-)ferro(i)magnetic insulator (AFM-I)[1,2]. Transport in the AFMI-I by magnonic spin currents.

Analogously to transport in FMs:
[1]L. Cornelissen et al., Nature Phys. **11**, 1022 (2015); K. Ganzhorn, MK et al., AIP Adv. **7**, 085102 (2017)

3. Lateral spin transport in ferro(i)magnetic insulators

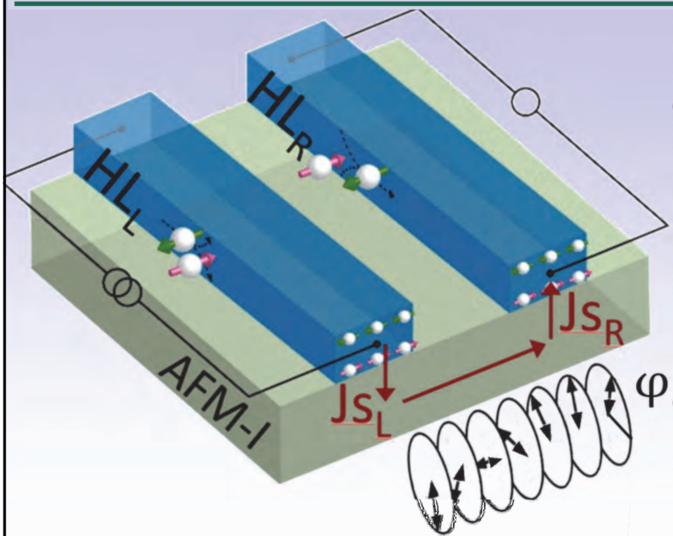


- Spin Hall efffect[1] generates a spin current that leads to a spin accumulations and manipulates the adjacent magnetization.
- The spin accumulation at the interfaces polarizes the magnons → magnonic spin current in the antiferromagnet.



[1]J. Sinova et al., Rev. Mod. Phys. **87**, 1213 (2015) [2]L. Cornelissen et al., Nature Phys. **11**, 1022 (2015)

3. Superfluid lateral spin transport in AFM insulators



Bosonic nature of magnons lends itself to condensation instabilities

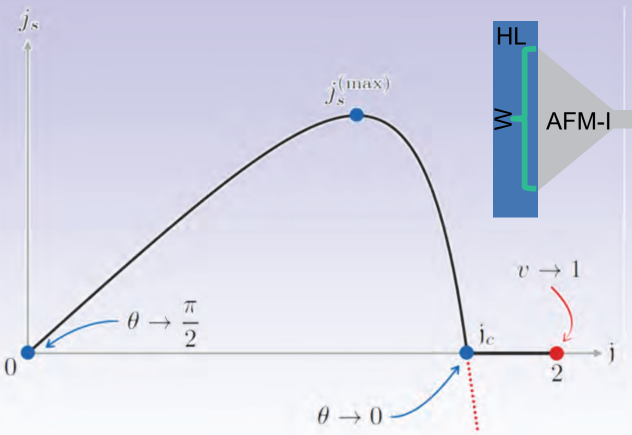
(i) BEC of quasiparticle magnons can be produced via external DC spin injection.

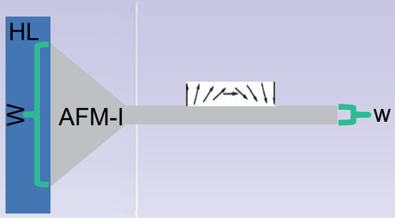
(ii) Superfluid phase[1] in U(1) symmetry system (easy plane, high density limit of magnons) can be described by a two-fluid model: Condensed and itinerant magnons

Signatures: threshold current density & non-linear spacing dependence

[1] S. Takei et al., PRL **112**, 227201 ('15); H. Skarsvag et al., PRL **115**, 237201 ('15); H. Chen et al., arxiv:1604.02429 B. Flebus et al., Phys. Rev. Lett. **116**, 117201 (2016); PRL **118**, 173201 (2017), W. Yuan et al., Sci. Adv. 4, 1098,...

3. Maximizing the superfluid spin current

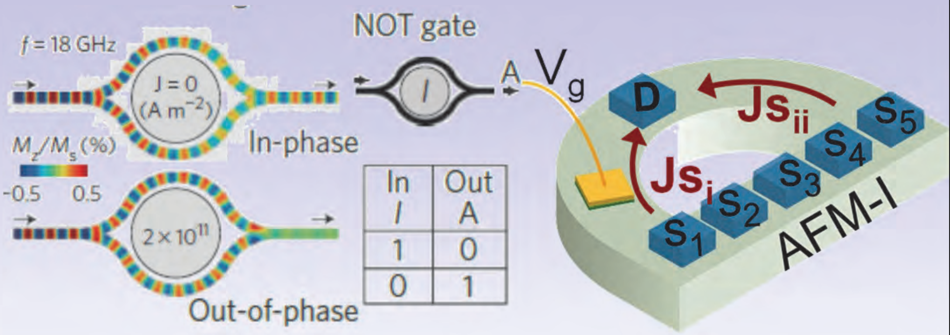




- Increasing injected spin current, the Néel vector that initially curls in the plane ($\Theta=\pi/2$) starts to turn out of plane ($\Theta=0$) reducing the carried spin current → maximum exists
- Geometric hydrodynamic scaling leads to increase by W/w for tapered spin conduit!

[1] Y. Tserkovnyak and M. Kläui, Phys. Rev. Lett. **119**, 187705 (2017)

3. Coherent superfluid spin current interference – NOT gate



K.-S. Lee et al., J. Appl. Phys. **104**, 053909 (2008).
A. Chumak et al., Nature Phys. **11**, 453 (2015)

- NOT gate using phase-coherent magnonic spin currents proposed.
- Within healing length thermal magnons can become superfluid
  → DC generation coherent magnonic spin currents with phase coherence.
- Interference device: in non-linear regime, 2 spin currents (Js_i and Js_{ii}) with phase-coherent propagation interfere. Gate manipulates Js_i phase → NOT/NAND gate!

[1] Y. Tserkovnyak and M. Kläui, Phys. Rev. Lett. **119**, 187705 (2017)

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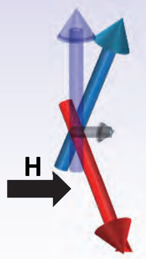
4. Diffusive lateral spin transport in AFM insulators

1. Generation of angular momentum in easy-axis insulating antiferromagnets

Angular momentum **L** induced by Neel order **n** dynamics

Field conditions :
H small or along H_A (H < Hc)

Angular momentum **L** induced by field induced magnetisation **m** dynamics (or "canted state")



Field conditions :
H "large" along H_A (H >> Hc) or perp. to H_A (H >> H_A)

R. Lebrun, A. Ross, S. Bender, A. Qaiumzadeh, J. Cramer, A. Brataas, R. A. Duine, and M. Kläui, arxiv:1805.02451

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AFM angular momentum is small but exists and can have two contributions

R. Lebrun, A. Ross, S. Bender, A. Qaiumzadeh, J. Cramer, A. Brataas, R. A. Duine, and M. Kläui, arxiv:1805.02451

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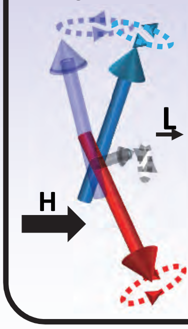

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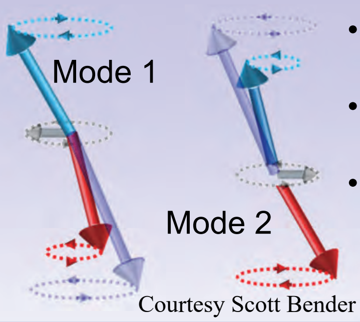
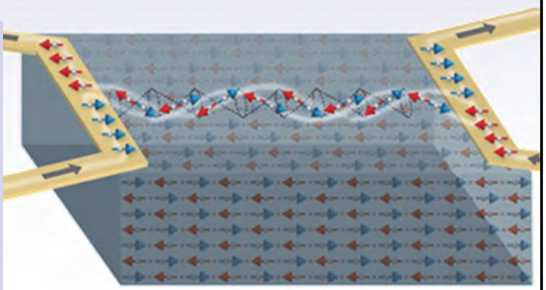


- Two energetically degenerate magnon modes!
- The two modes carry opposite angular momentum → total spin transport = 0!
- Spin biasing due to spin accumulation favours one mode → spin transport!

- Spin Hall efffect[1] generates a spin current that leads to a spin accumulations and manipulates the adjacent magnetization.
- The spin accumulation at the interfaces polarizes the magnons → magnonic spin current in the antiferromagnet.



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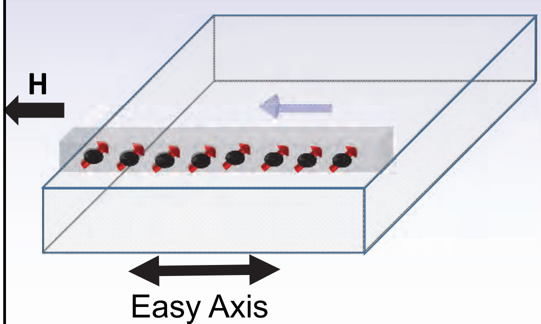
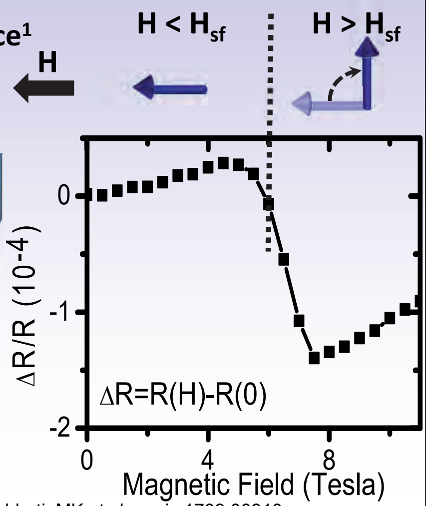
4. Detection of spin-flop field in an easy-axis AFM insulator

2. Spin transport in the easy-axis AFI α-Fe_2O_3
(can be grown by PLD on a- or r-plane sapphire)

Preparatory spin-Hall magnetoresistance[1]

- Abrupt spin-flop reorientation detected





[1] H. Nakayama et al., Phys. Rev. Lett. 110, 206601 (2013); L. Baldrati, MK et al., arxiv:1709.00910

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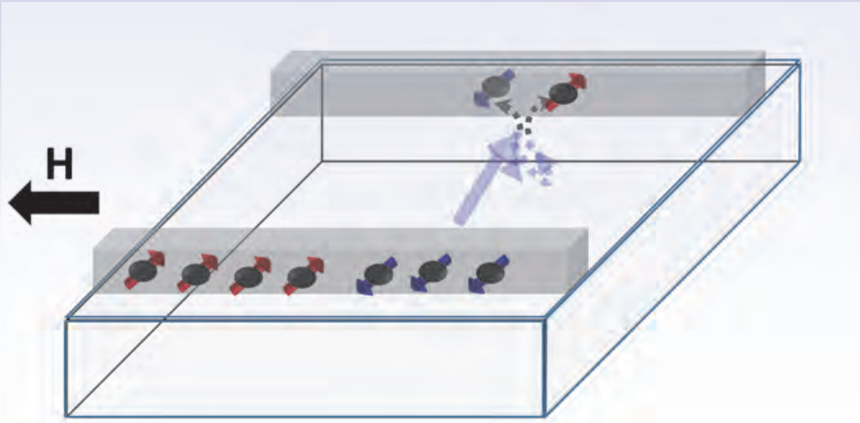
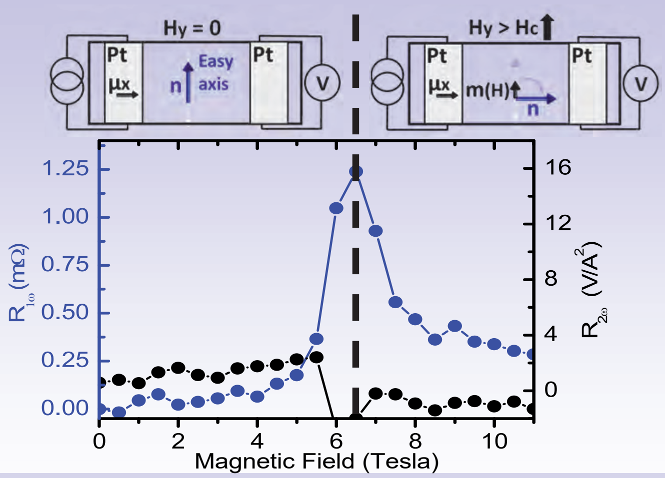
Geometry for detecting spin-bias spin transport: detecting spin-flop



R. Lebrun, A. Ross, S. Bender, A. Qaiumzadeh, J. Cramer, A. Brataas, R. A. Duine, and M. Kläui, arxiv:1805.02451

4. Measuring the spin conductivity

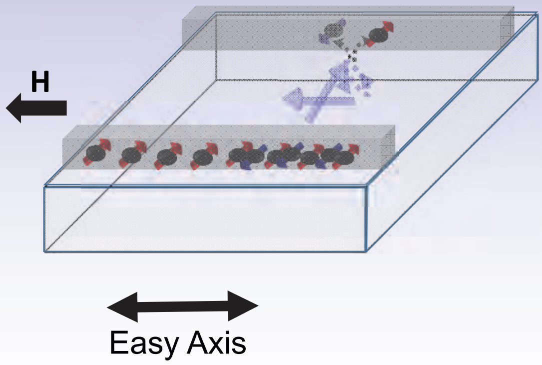


- The Spin Seebeck transport signal stays zero over the whole field range (R_{2w})
- The Spin bias transport signal goes up at the spin-flop transition and exhibits a peak and then falls off but stays finite at larger fields → explanation?

[1] S. Bender, H. Skarsvag, Arne Brataas and Rembert Duine, Phys. Rev. Lett. **119**, 056804 (2017)

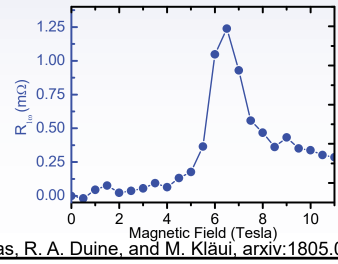
4. Measuring the spin conductivity

Platinum stripes along the easy-axis
H parallel to easy axis / stripes



- At zero field, the Néel vector is pointing along the easy axis.
- At a sufficiently large field (above the so-called spin-flop field), the Néel vector rotates perpendicular to the applied field → angular momentum can be transported by spin bias.

Spin bias (R_{1w}) transport possible ✓



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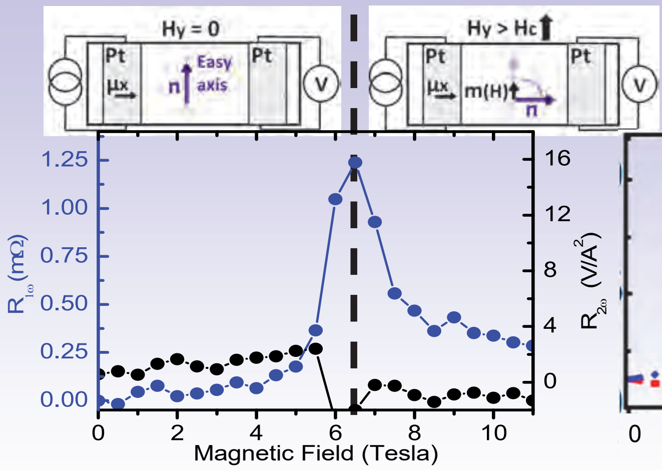
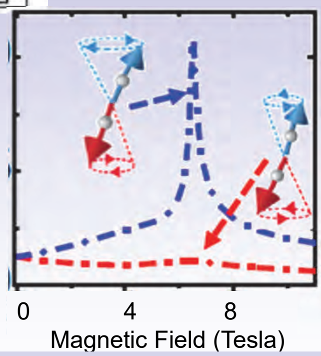


Calculations[1]: Scott Bender & Rembert Duine



- Increasing injected spin current, the Néel vector that initially curls in the plane ($\Theta=\pi/2$)
- Measurement shows huge amplification at spin flop transition! Closing spin wave gap → one mode exhibits enhancement → good agreement with spin transport theory

[1] S. Bender, H. Skarsvag, Arne Brataas and Rembert Duine, Phys. Rev. Lett. **119**, 056804 (2017)

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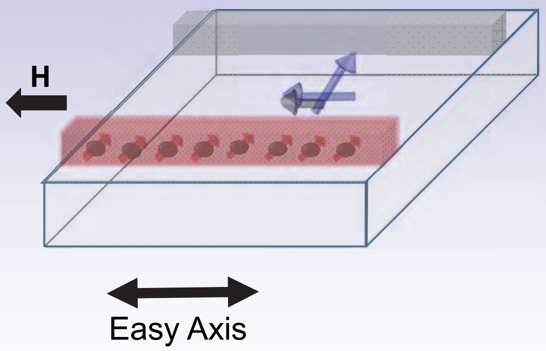
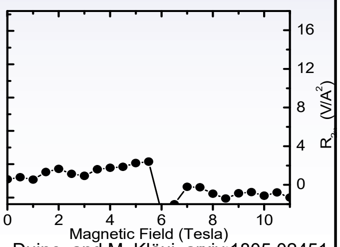
H parallel to easy axis / stripes



- At zero field, the Néel vector is pointing along the easy axis.
- At a sufficiently large field (above the so-called spin-flop field), the Néel vector rotates perpendicular to the applied field and a small magnetic moment is formed.



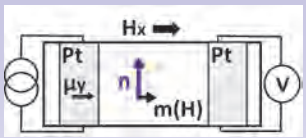
Spin-Seebeck (R_{2w}) transport not possible ☒

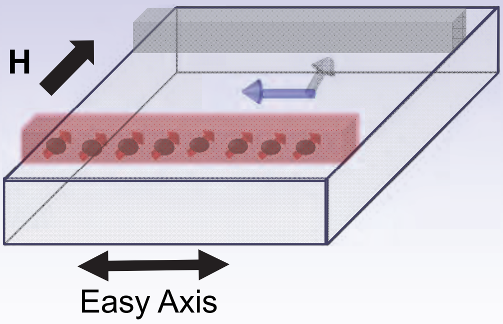
R. Lebrun, A. Ross, S. Bender, A. Qaiumzadeh, J. Cramer, A. Brataas, R. A. Duine, and M. Kläui, arxiv:1805.02451

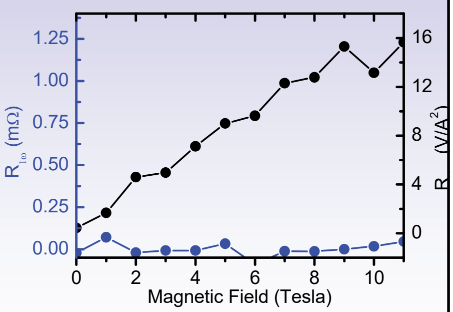
Mathias Kläui
SPICE Spin Cavitronics, Mainz, 17.5.2018

4. Measuring the spin conductivity

Platinum stripes along the easy-axis
H perpendicular to easy axis / stripes





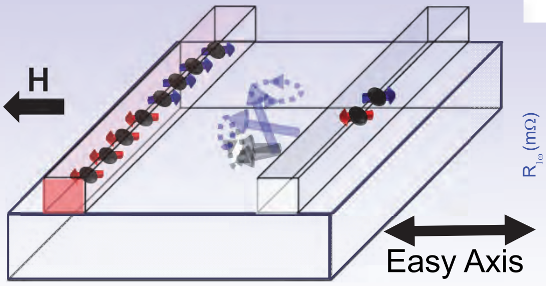


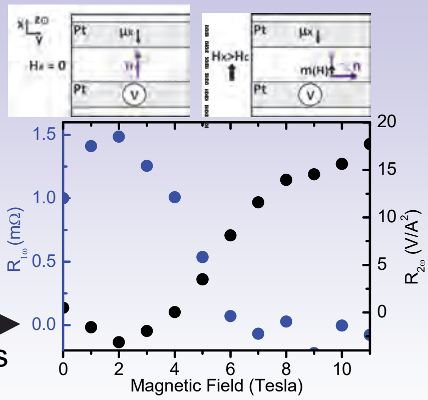
Spin bias transport (R_{1w}) not possible ☒
Spin-Seebeck (R_{2w}) transport possible ✓

R. Lebrun, A. Ross, S. Bender, A. Qaiumzadeh, J. Cramer, A. Brataas, R. A. Duine, and M. Kläui, arxiv:1805.02451

4. Measuring the spin conductivity

Platinum stripes perpendicular to easy-axis
H parallel to easy-axis and
thus perpendicular to stripes





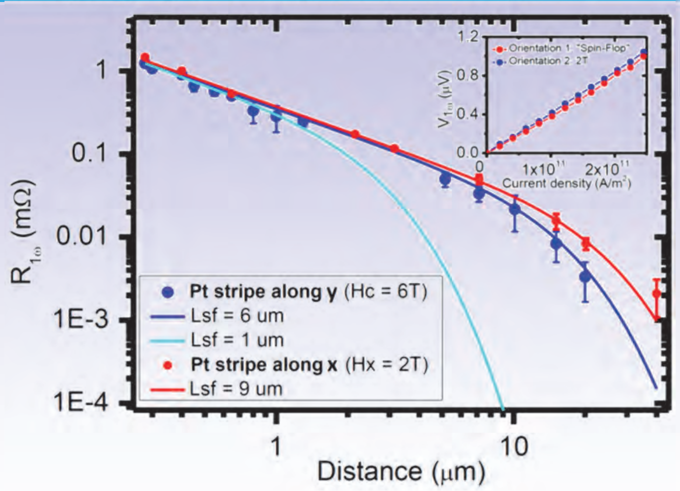
- Spin-bias transport (R_{1w}) at zero applied field (< H_c) ✓
- Spin-Seebeck transport (R_{2w}) (> H_c) ✓

→ Spin-bias depends on **n** and Spin-Seebeck on **m(H)**

R. Lebrun, A. Ross, S. Bender, A. Qaiumzadeh, J. Cramer, A. Brataas, R. A. Duine, and M. Kläui, arxiv:1805.02451

Mathias Kläui
SPICE Spin Cavitronics, Mainz, 17.5.2018

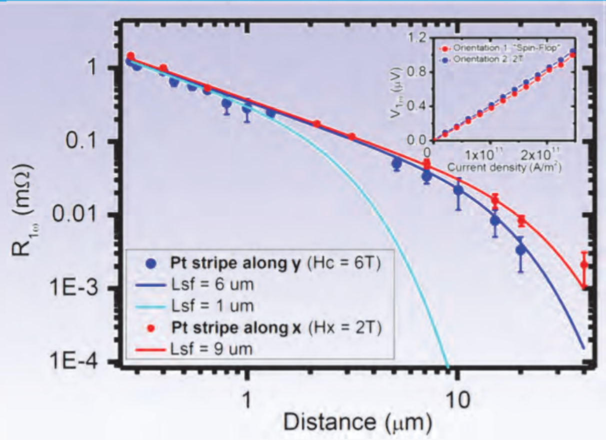
4. Quantifying spin transport and dissipation



- Distance dependence: exponential decay → diffusive spin transport
- Largest ever reported spin diffusion lengths for a magnetic insulator: 5-10 μm depending on applied field and transport over 40 μm observed!

R. Lebrun, A. Ross, S. Bender, A. Qaiumzadeh, J. Cramer, A. Brataas, R. A. Duine, and M. Kläui, arxiv:1805.02451

4. Quantifying spin transport and dissipation



- No threshold
- Visible at high temperature
- Exponential decay
  → Diffusive transport over tens of microns in easy axis AFM!
- Previous transport in insulator AFMs only over few nm![1]

R. Lebrun, A. Ross, S. Bender, A. Brataas, R. A. Duine, and M. Kläui arxiv:1805.02451
[1]PRL 113, 97202 (2014); Nat. Comm. **9**, 1089; arxiv:1802.01844

	Experiments	Spin superfluid	Diffusive transport
Threshold	No	X	✓
Temperature	200 K	X	✓
Decay	Exponential (visible for large D)	X	✓

Thanks!

1. Great people@JGU

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B. Dong, E. Guo, N. Richter, K. Litzius
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A. Pfeiffer, P. Bassirian, M. Filianina, R. Weber, **M. Weides, H. Zabel, M. Jourdan, G. Jakob…**

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H. Gomonay, L. Smejkal, J. Sinova, JGU; I. Turek, T. Jungwirth, Prague
S. Gönnenwein, H. Hübl, R. Gross, WMI/TUM/TUD
A. Qaiumzadeh, H. Skarsvag, A. Brataas, NTNU
S. Bender, R. Duine, Utrecht
Y. Tserkovnyak, UCLA

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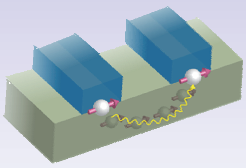
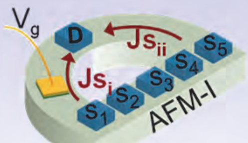
Stanford-Tohoku-Mainz SpinNet, AvH Stiftung, BMBF, Samsung

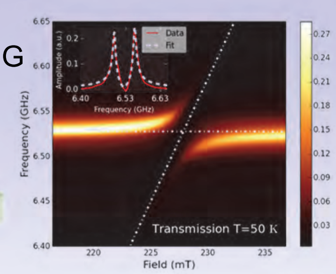
MASPIC & MultiRev

Summary:

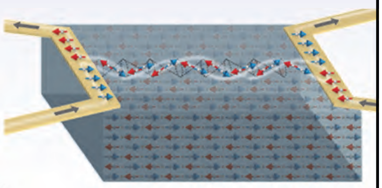
- -Determination of coupling strength and dissipation temperature dependence of YIG
  I. Boventer et al., PRB **97**, 184420 (2018)







- -Superdiffusive transport in easy-plane AFM
  Y. Tserkovnyak&MK PRL **119**, 187705 (2017)



- -Diffusive transport (40µm!) in easy-axis AFM with low damping
  -Need to probe length scales >> λ_{sd} to identify superfluid vs. diffusive transport
  R. Lebrun, A. Ross, S. Bender et al., arXiv:1805.02451 (Nature in press (2018))