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University of Groningen
Zernike Institute
for Advanced Materials

Physics of Nanodevices

Exchange magnon spin transport in the magnetic insulator yttrium iron garnet

Ludo Cornelissen
Jing Liu
Juan Shan
Timo Kuschel
Kevin Peters
Gerrit Bauer
Rembert Duine
Jamal Ben Youssef
Bart van Wees

FOM

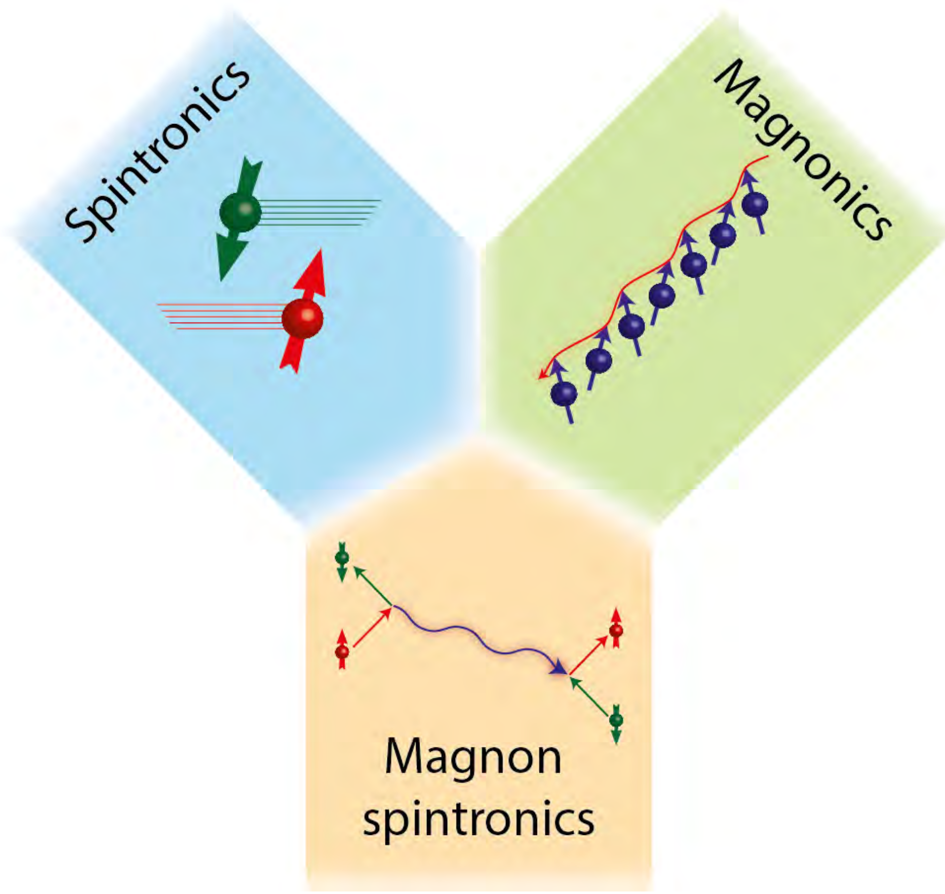
nano LabNL

InSpin

Magnon Spintronics

Magnon spintronics, at GHz frequencies

A. V. Chumak *et al.,* Nat. Phys. **11**, 453 (2015)

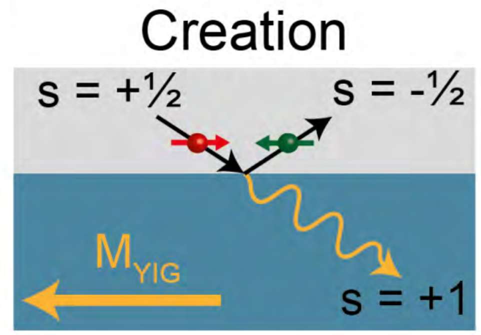


Connecting magnonics and spintronics, without frequency selection

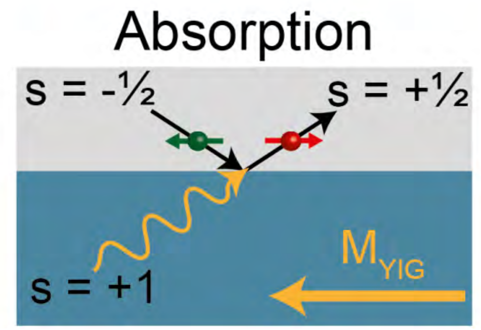
Exciting magnons by spin-flip scattering

- Localized magnon injection (at Metal|YIG interface)
- Spin accumulation generates magnon accumulation
- Linear process

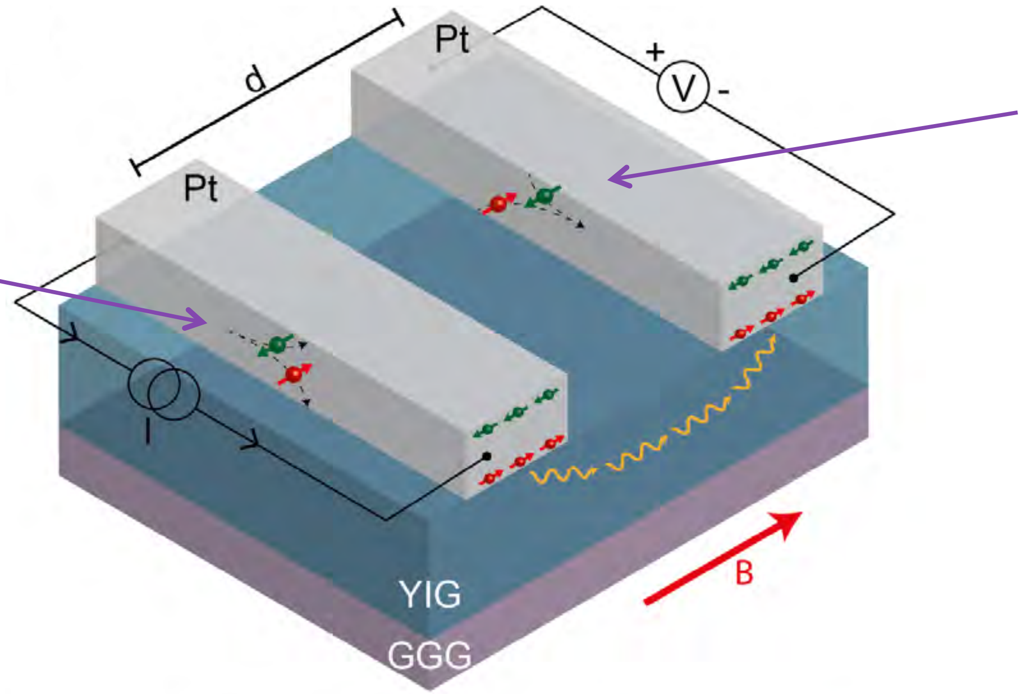
Conduction electron spin-up -> spin-down + magnon



Spin-down + magnon -> spin-up



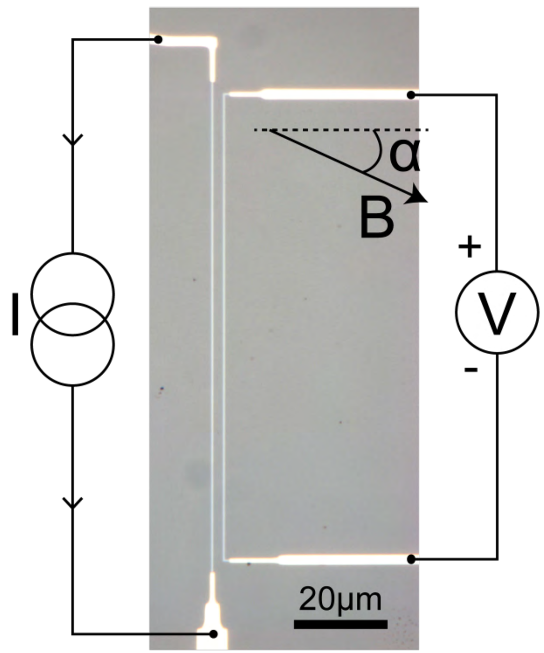
Non-local experiment
Electrical magnon injection



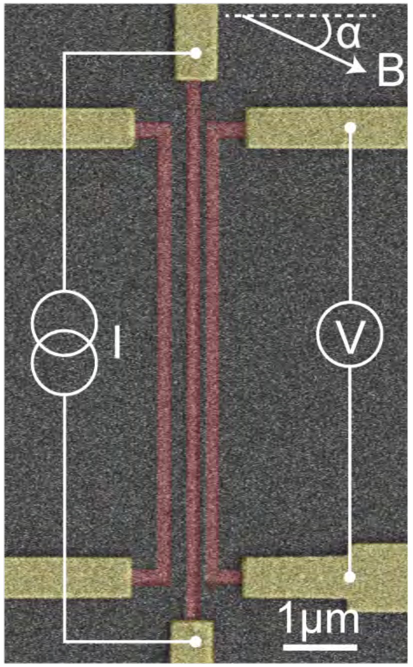
Current I is AC	:	$I(\omega) = A \sin \omega t$
Measure V(ω)	:	1st harmonic V(1ω) $\propto I$
	:	2nd harmonic V(2ω) $\propto I^2$
Linear regime	:	$V \propto I$
Non-local resistance	:	$R_{nl} = \frac{V}{I}$

Devices

Long distances
2.5um < d < 160um
Device length 100um



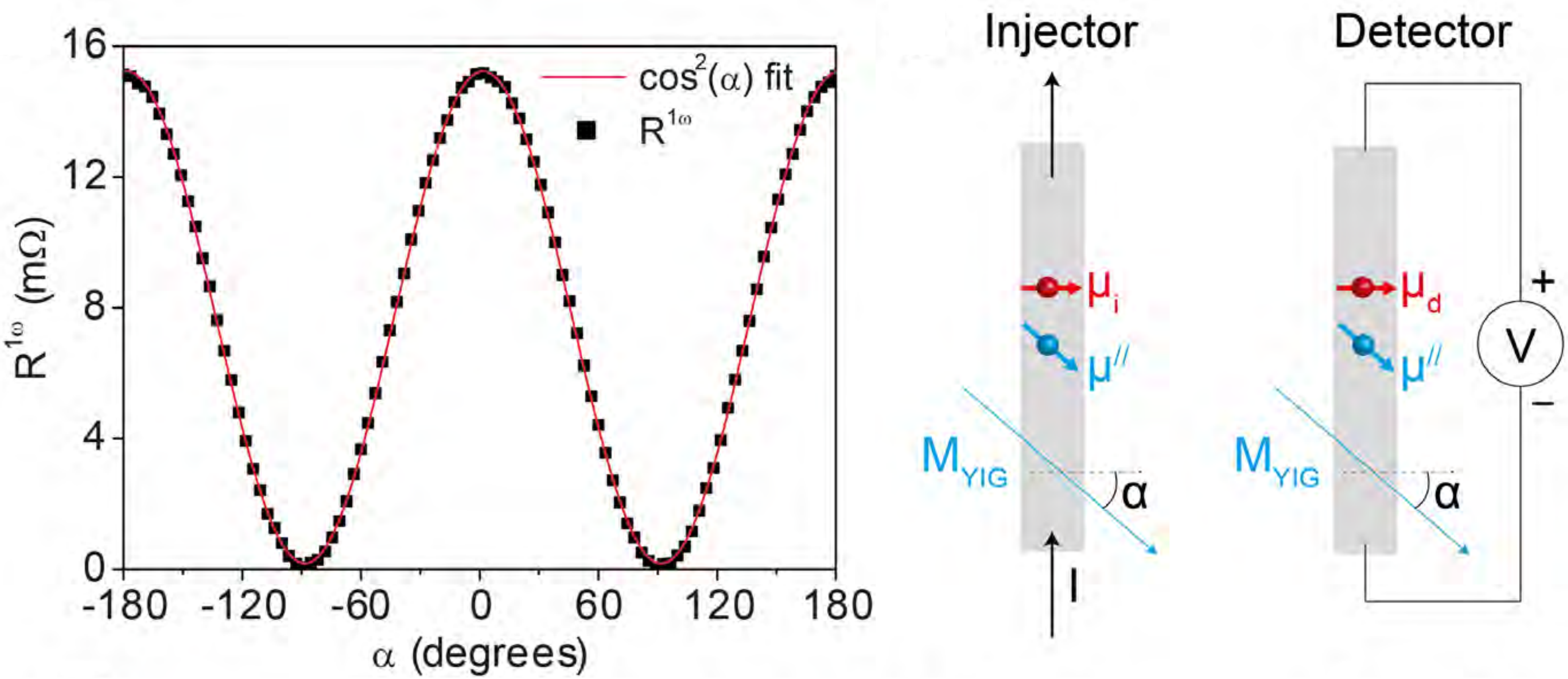
Short distances
200nm < d < 5um
Device length 12.5um



Pt

Ti/Au

Electrical magnon generation

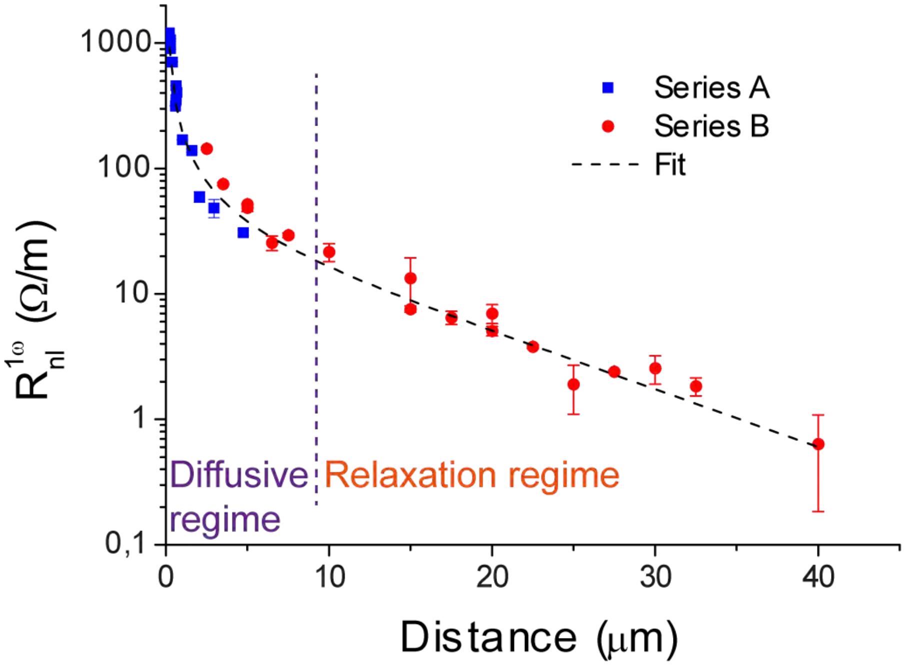


Injector: $\mu^{\parallel}$ generates magnons -> $\cos\alpha$

Detector: μ_d contributes to V_c -> $\cos\alpha$

1ω signal is product of the two: $\cos^2\alpha$

Distance dependence



1D spin diffusion equation:

$$\frac{d^2 n_m}{dx^2} = \frac{n_m}{\lambda^2}$$

+ B.C. yields:

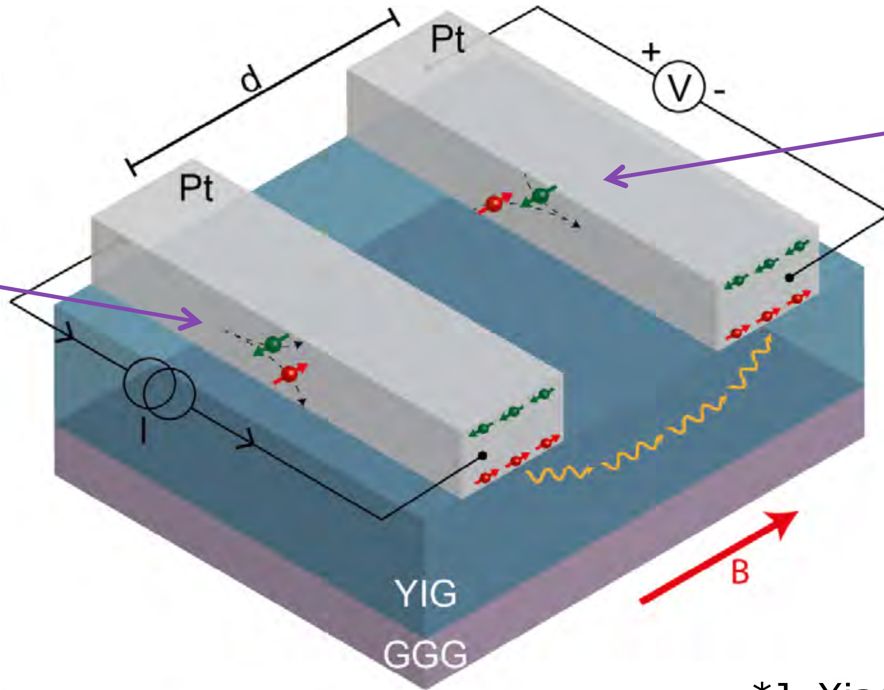
$$R_{\text{non-local}}(d) = \frac{A}{\lambda} \cdot \frac{\exp(d/\lambda)}{1-\exp(2d/\lambda)}$$

$$\lambda = 9.4 \pm 0.6 \ \mu m$$

Relaxation regime -> exponential decay
Diffusive regime -> 1/d decay

Parameters of the magnon system

Interfacial SPE here?



Interfacial SSE* here?

*J. Xiao *et al.*, PRB **81,** 214418 (2010)

- Does not work!
  - κ_m several orders of magnitude too small
  - λ_{m-ph} several orders of magnitude too small

Magnon chemical potential

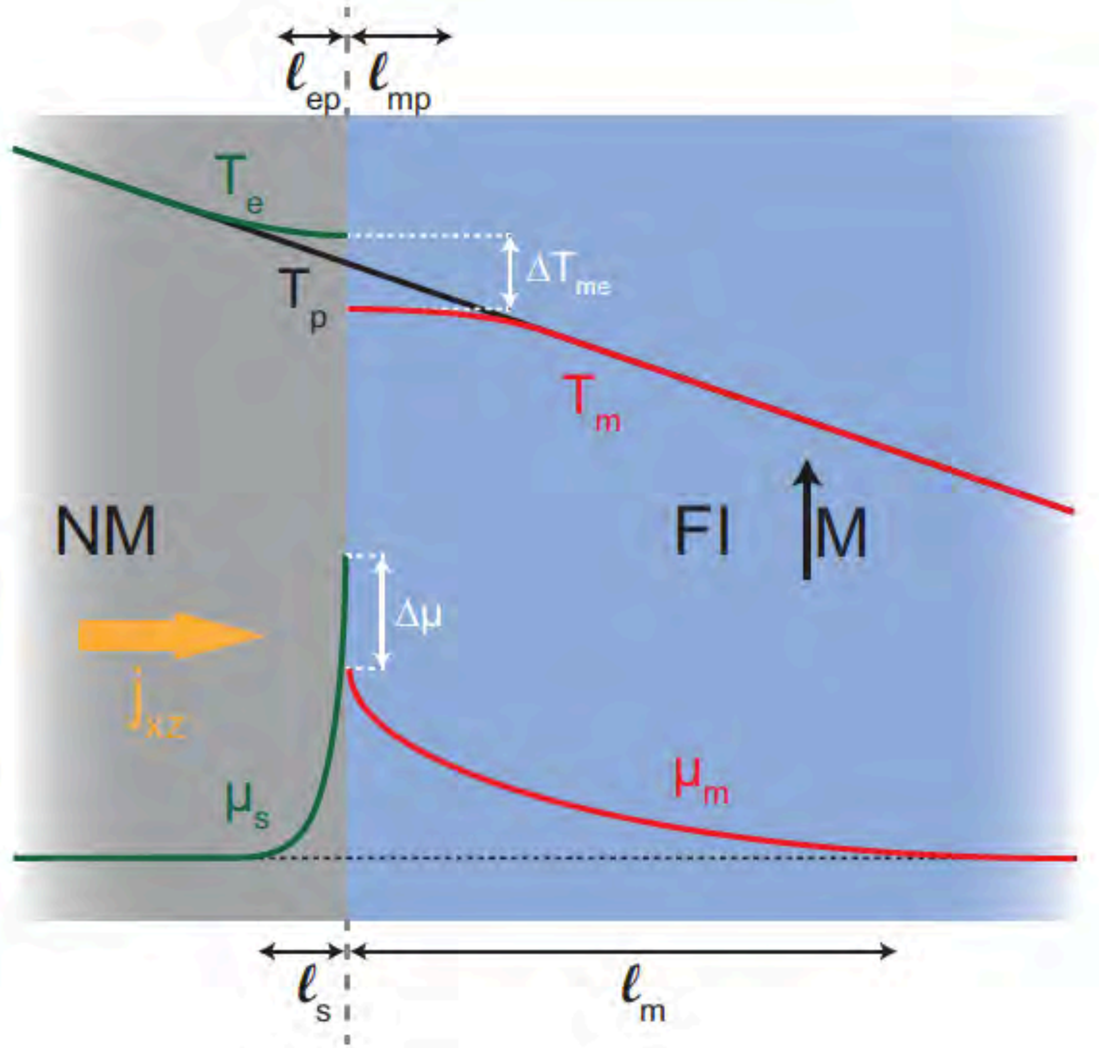
- Out of equilibrium parameters for the system
  - μ_m
  - T_m

- Conservation of magnon number (μ_m)
  - Timescale limited by magnon-relaxation

- Conservation of energy (T_m)
  - Timescale limited by magnon-relaxation and magnon-phonon scattering

1. L.J. Cornelissen, K.J.H. Peters, G.E.W. Bauer, R.A. Duine and B.J. van Wees, *PRB* **94**, 014412 (2016)

Magnon chemical potential



1. L.J. Cornelissen, K.J.H. Peters, G.E.W. Bauer, R.A. Duine and B.J. van Wees, *PRB* **94**, 014412 (2016)

Modeling the experiments

- **Linear response transport theory**[1]

spin Seebeck

$$\begin{pmatrix} \frac{2e}{\hbar}\mathbf{j}_m \\ \mathbf{j}_{\mathrm{Q,m}} \end{pmatrix} = -\begin{pmatrix} \sigma_m & L/T \\ \hbar L/2e & \kappa_m \end{pmatrix} \begin{pmatrix} \nabla \mu_m \\ \nabla T_m \end{pmatrix}$$

spin Peltier

- $\mathbf{j}_m$ **Magnon spin current density,**
- σ_m **Magnon spin conductivity,**
- L **Bulk spin Seebeck coefficient,**
- μ_m **Magnon chemical potential,**

$\mathbf{j}_{\mathrm{Q,m}}$ **Magnon heat current density**

κ_m **Magnon heat conductivity**

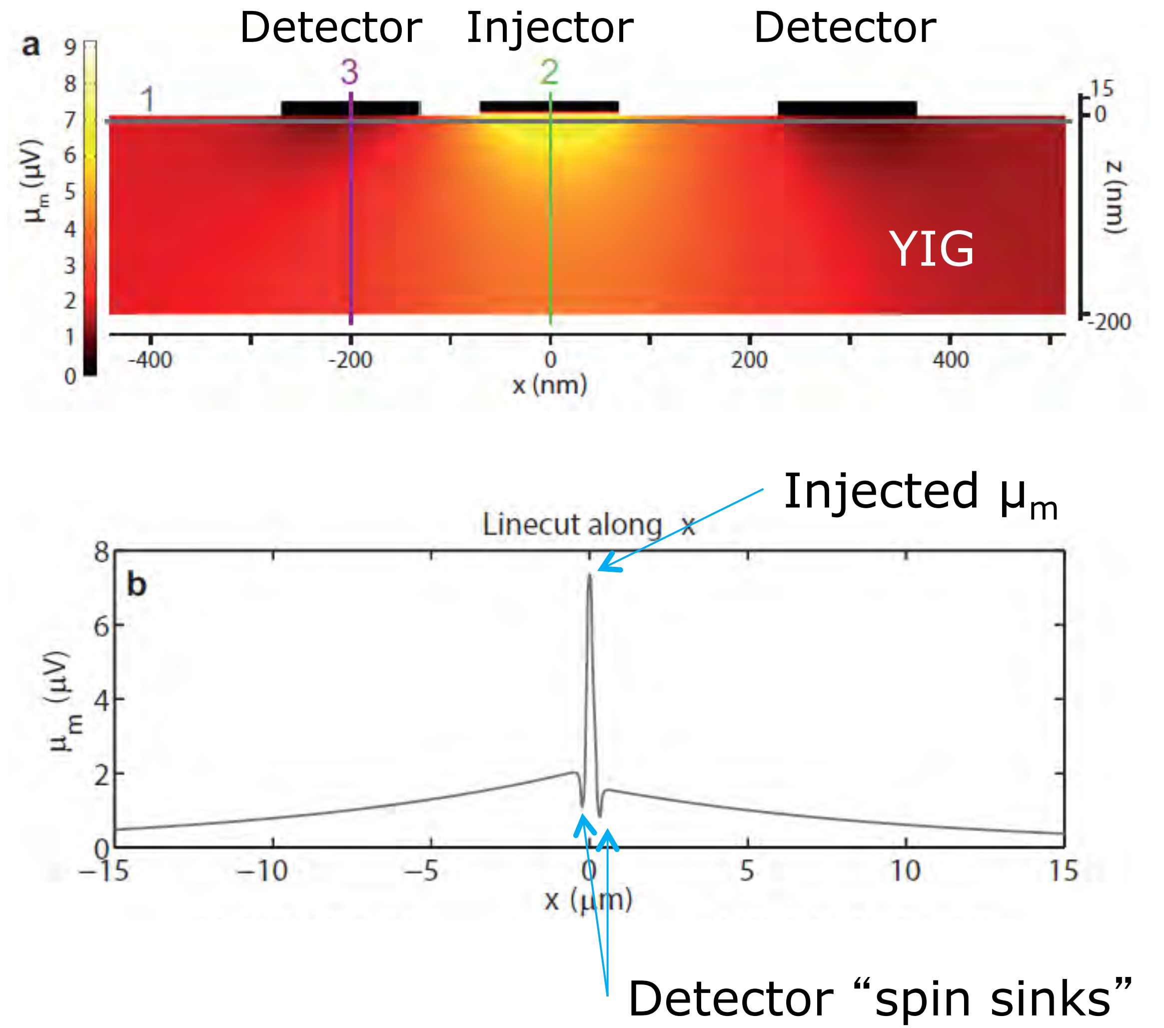
T **Ambient temperature**

T_m **Magnon temperature**

1. L.J. Cornelissen, K.J.H. Peters, G.E.W. Bauer, R.A. Duine and B.J. van Wees, *PRB* **94**, 014412 (2016)

Finite element model

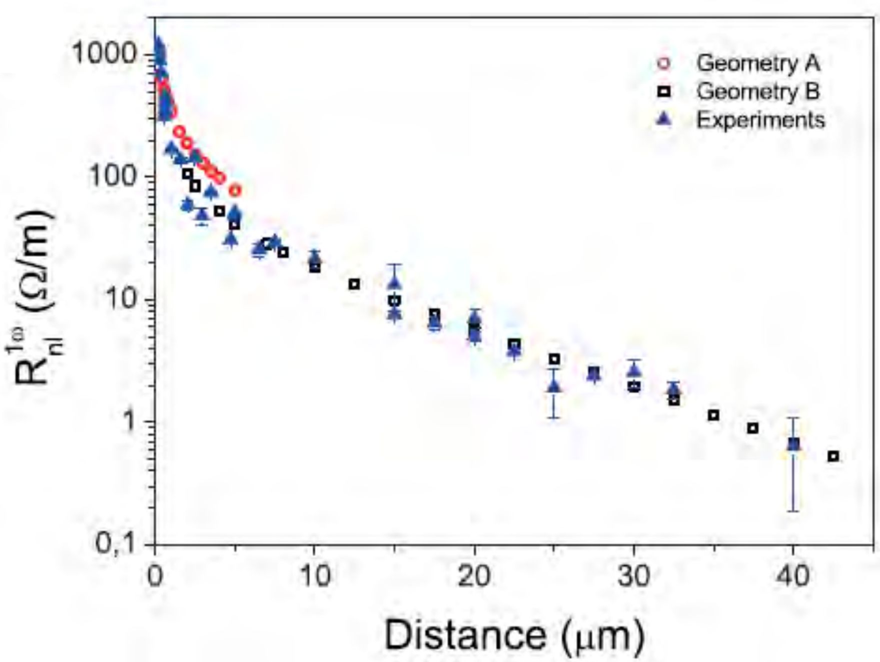
- FEM gives the magnon chemical potential profile
- Find the spin current into the contacts:
  $j_s^{int} = g_s(\mu_m - \mu_s)$



L.J. Cornelissen, K.J.H. Peters, G.E.W. Bauer, R.A. Duine and B.J. van Wees, *PRB* **94**, 014412 (2016)

FEM results

Good agreement with experiments, for electrical generation



However, does not predict YIG thickness dependence of the signal correctly

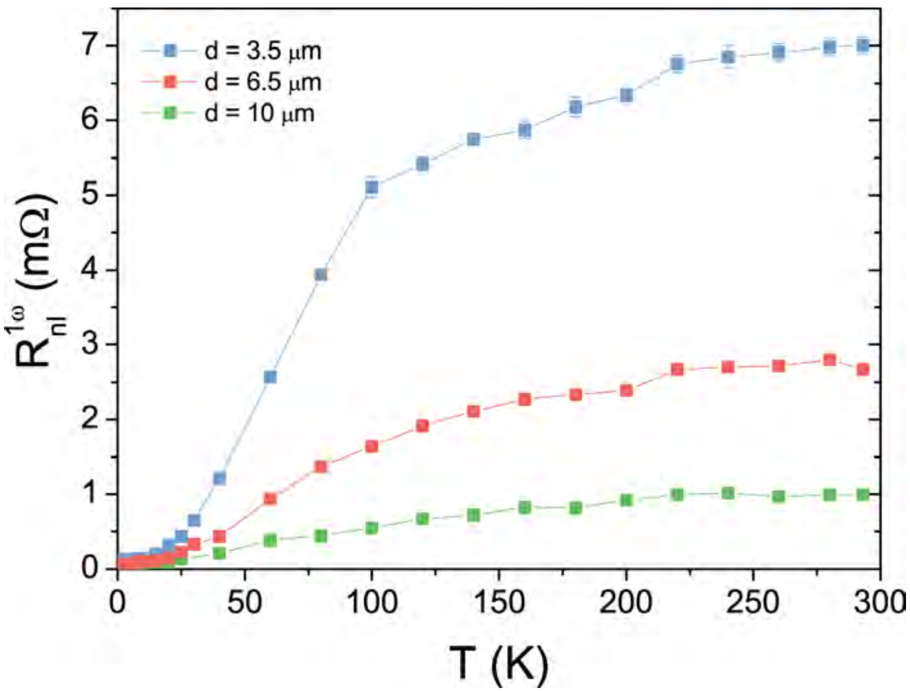
J. Shan, L.J. Cornelissen *et al.*, arXiv:1608.01178 (2016)

We extract:

› $\sigma_m = 5 \times 10^5$ S/m

› $g_s = 0.96 \times 10^{13}$ S/m^2

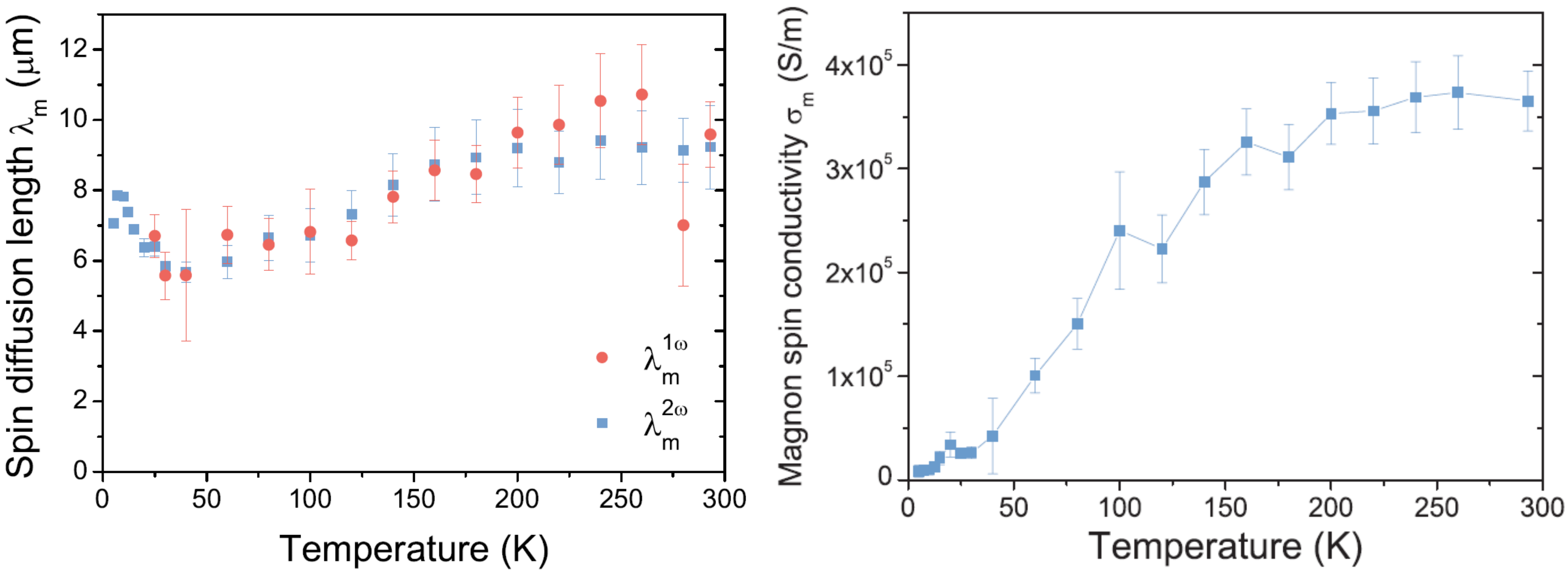
Effect of temperature
Electrical magnon injection



- T-dependence agrees qualitatively with other observations*
- Distance dependence and FEM can be used to find:
  - $\lambda_m(T)$
  - $\sigma_m(T)$

*S.T.B. Goennenwein *et al.*, *APL* **107,** 172405 (2015)
J. Li *et al, Nat. Commun.* **7:**10858 (2016)
Vélez *et al.*, arxiv:1606.02968 *(*2016*)*
Wu *et al.*, PRB **93** 060403(R) (2016)

λ_m (T) and σ_m (T)



L.J. Cornelissen and B.J. van Wees, *arXiv:1607.01506* (2016)

Thermal magnon generation

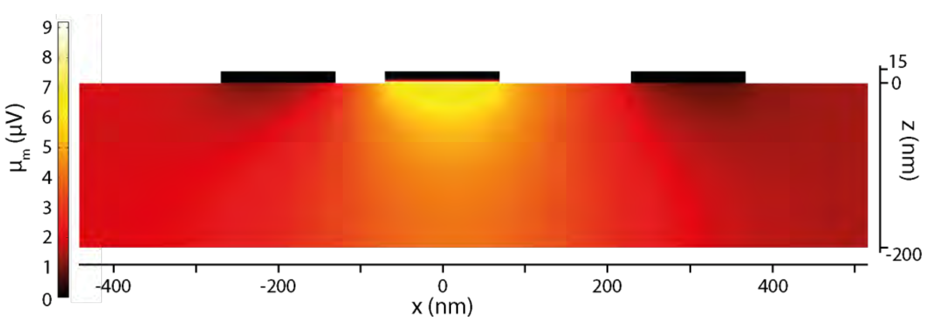
› Temperature gradient causes magnon spin current

spin Seebeck

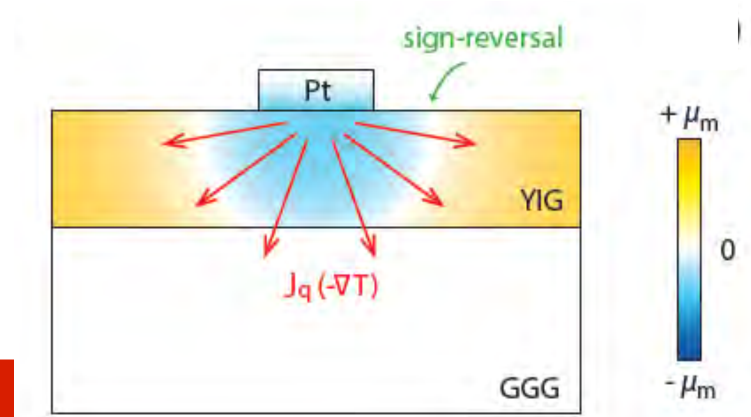
$$\begin{pmatrix} \frac{2e}{\hbar}\mathbf{j}_m \\ \mathbf{j}_{\mathrm{Q,m}} \end{pmatrix} = -\begin{pmatrix} \sigma_m & \boxed{L/T} \\ \hbar L/2e & \kappa_m \end{pmatrix} \begin{pmatrix} \nabla \mu_m \\ \nabla T_m \end{pmatrix}$$

› Joule heating in device causes magnon accumulation

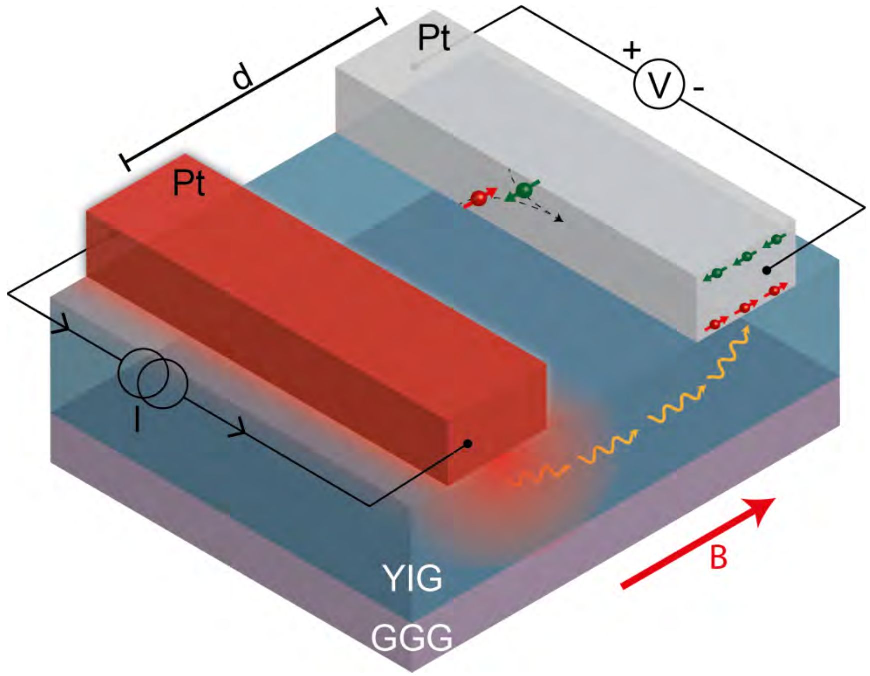
Electrical



Thermal



Non-local experiment
Thermal magnon injection



Injection relies on spin Seebeck effect

$$\frac{2e}{\hbar}\mathbf{j}_m = -\frac{L_m}{T}\nabla T_m$$

And

$$\nabla T_m \propto I^2$$

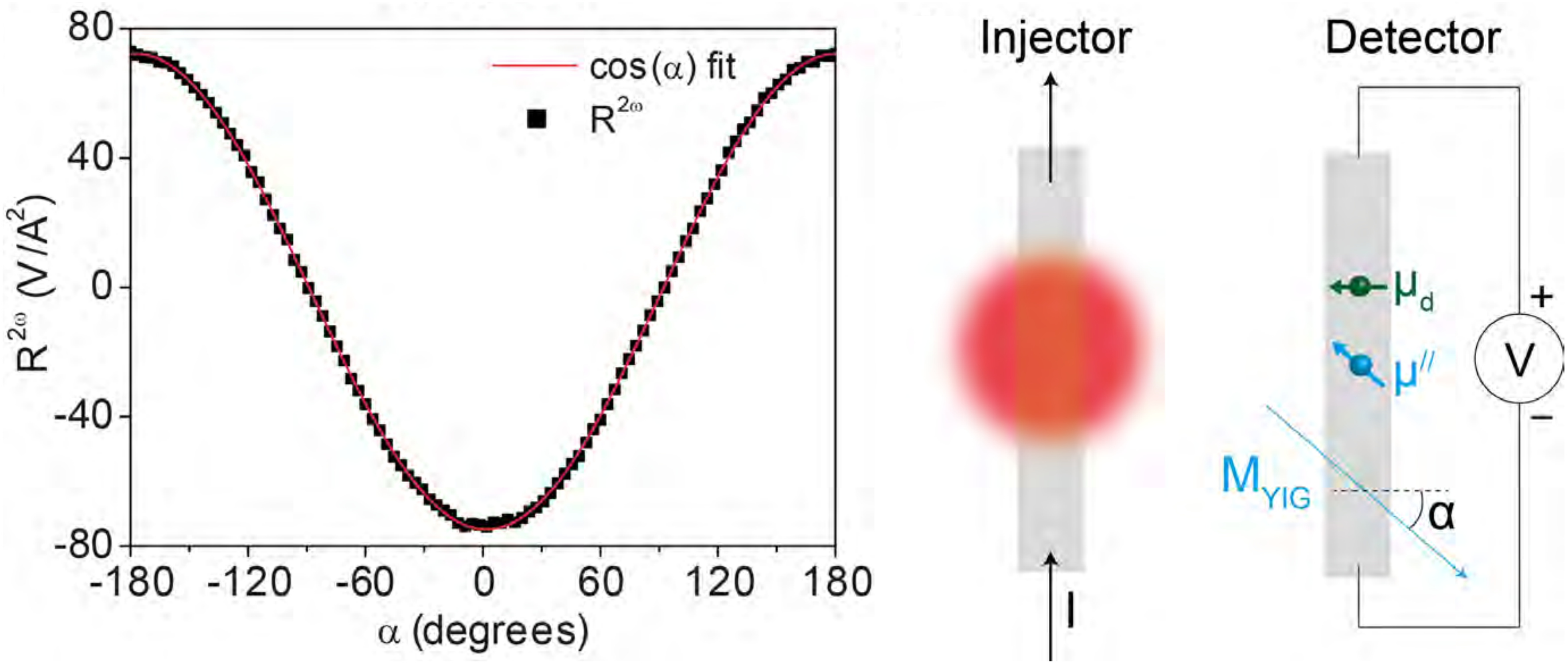
With:

L_m bulk spin Seebeck coefficient

T_m magnon temperature

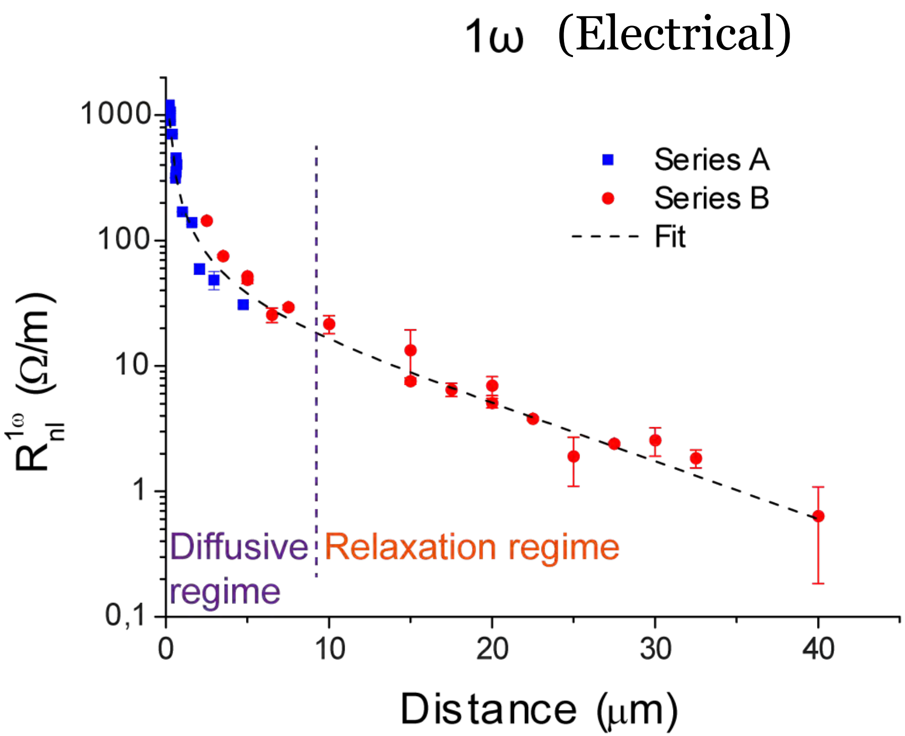
$\mathbf{j}_m$ magnon spin current

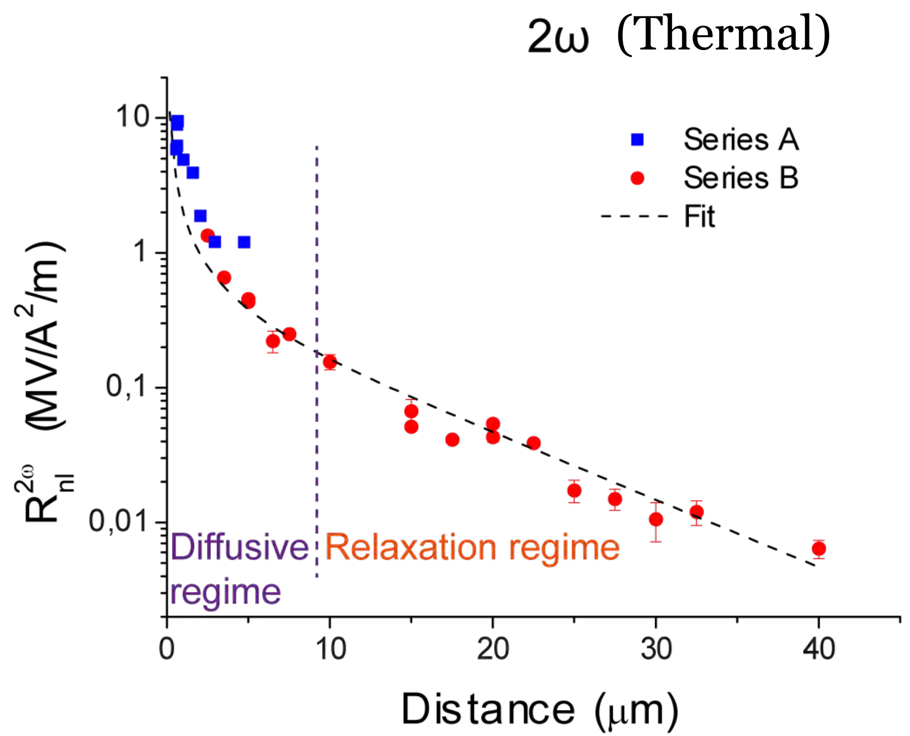
Angle dependent measurements: 2ω



- Injector: I^2 generates heat -> const.
- Detector: μ_d contributes to V_c -> $\cos\alpha$
- 2ω signal -> $\cos\alpha$

Electrical vs thermal injection
Long distances

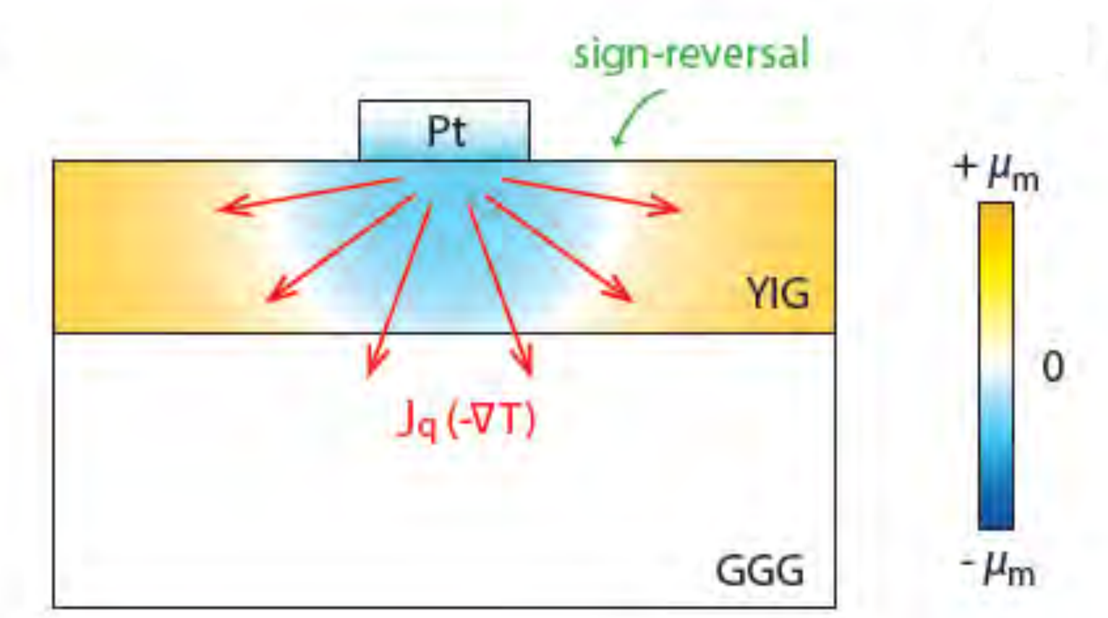




- $\lambda^{1\omega} = 9.4 \pm 0.6$ μm
- $\lambda^{2\omega} = 8.7 \pm 0.8$ μm

Model for thermal generation

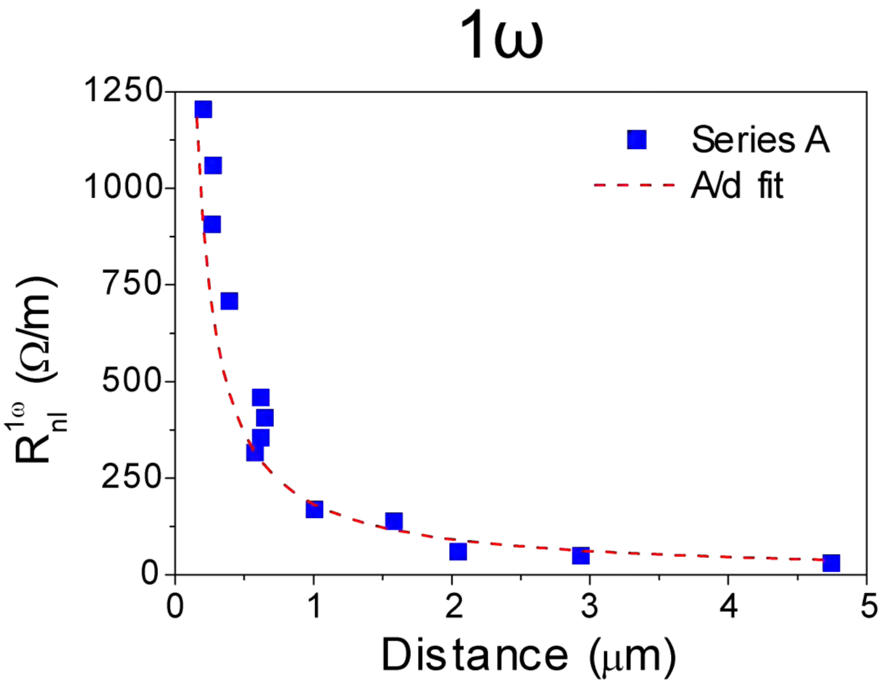
- Heat current flows outward from detector
- SSE generates magnon spin current
- Magnon current cannot enter GGG
- Magnon accumulation at interface

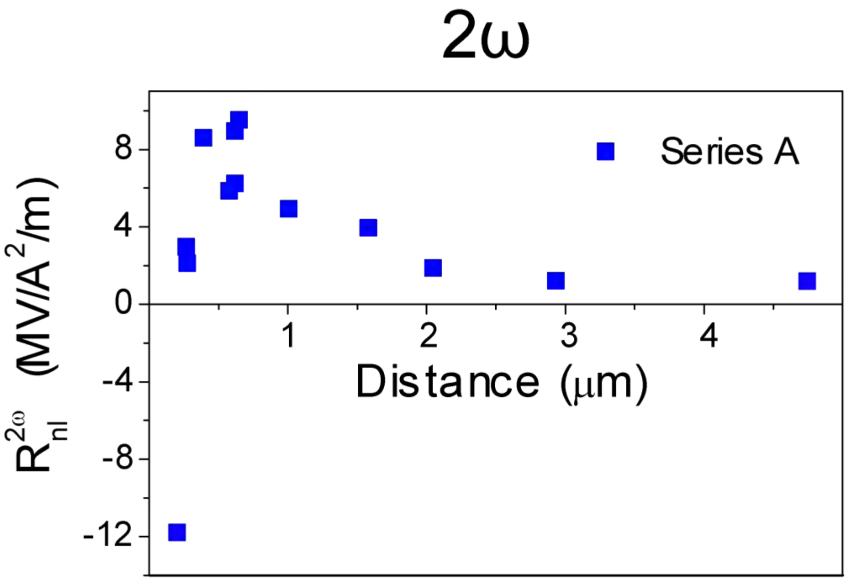


J. Shan, L.J. Cornelissen, N. Vlietstra, J. Ben Youssef, T. Kuschel, R.A. Duine and B.J. van Wees, arXiv:1608.01178 (2016)

Electrical vs thermal injection

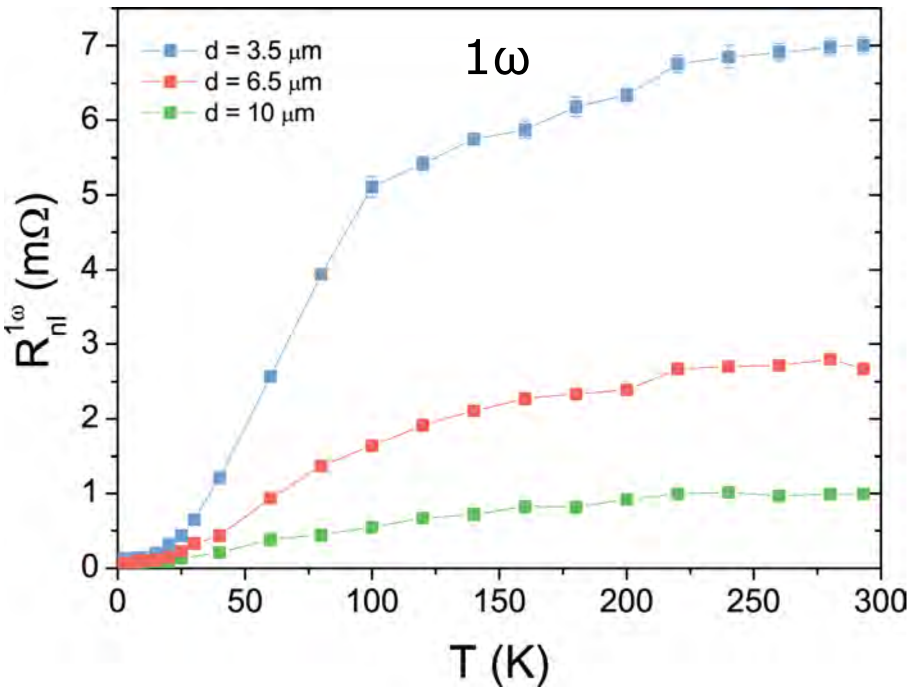
Short distances

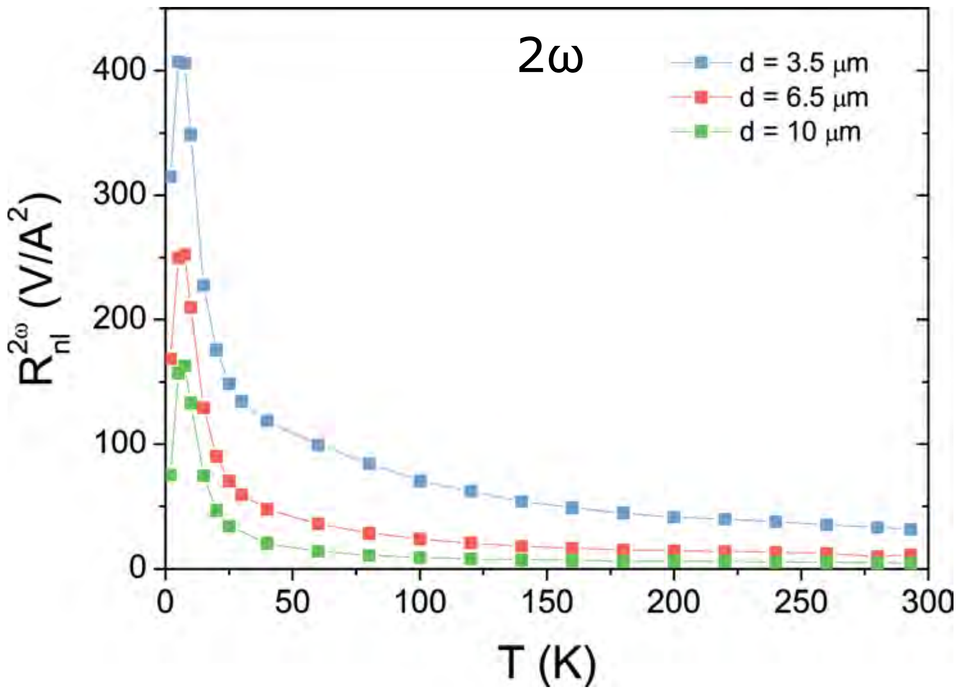




- 1/d decay indicates diffusive transport, for $d < \lambda$
- Thermally excited magnons behave differently for $d \approx t_{YIG}$ -> injector not a localized source for thermal magnons.

Effect of temperature
Electrical vs thermal magnon injection



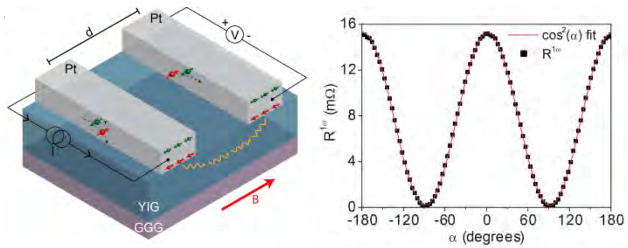


› Complex T-dependence of 2ω is not yet understood

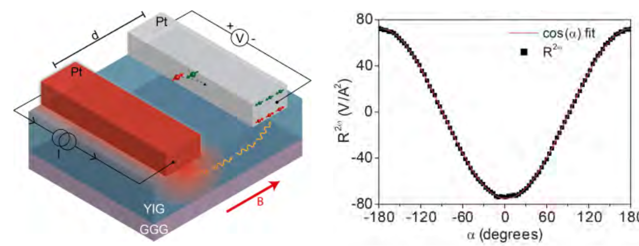
Summary (I)

- Conversion between charge, electronic spin and magnonic spin currents

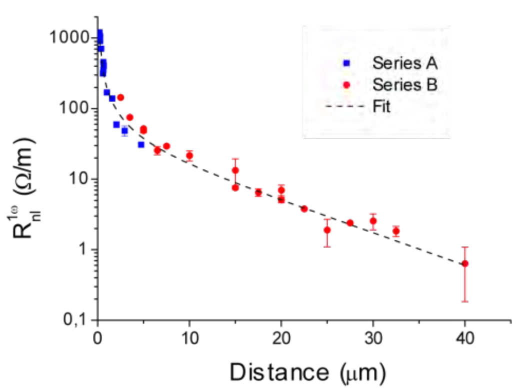
Electrical magnon injection

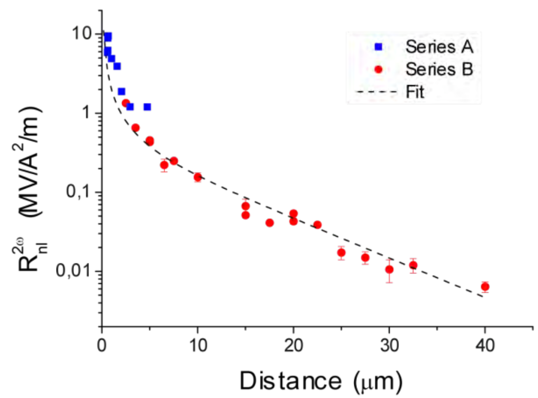


Thermal magnon injection



- YIG is a good conductor for diffuse spin currents, long spin diffusion length $\lambda_m = 9.4 \pm 0.6$ μm at low fields and RT





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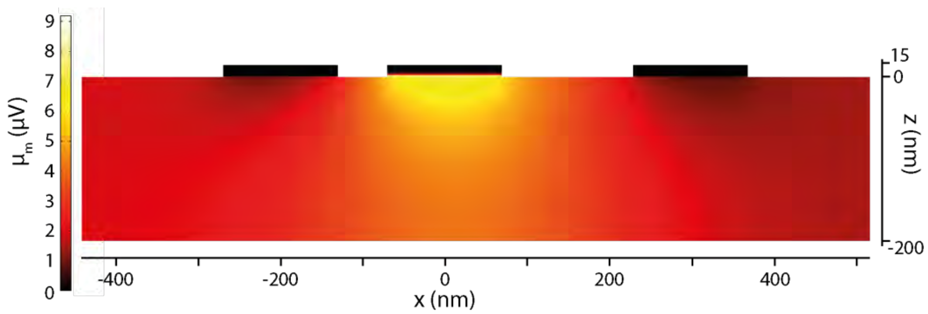
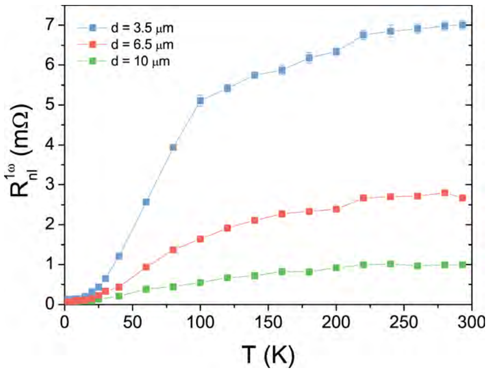
Summary (II)

› Magnon chemical potential is an essential parameter in describing the magnon spin transport

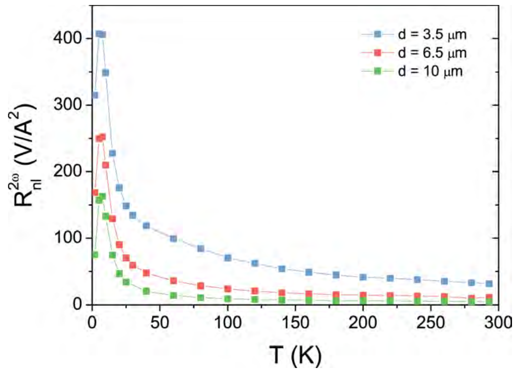


› Temperature dependencies for electrical and thermal injection are completely different, but spin diffusion lengths agree

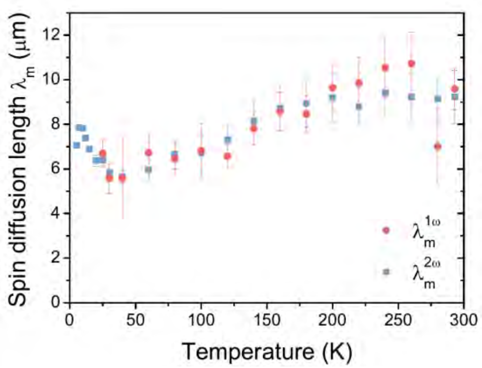
1ω



2ω



λ



Thank you!

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Kevin Peters
Rembert Duine
Gerrit Bauer
Jamal Ben Youssef
Technical staff @ PND group

Physics of Nanodevices group

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