university of groningen

University of Groningen Zernike Institute for Advanced Materials

Physics of Nanodevices

NanoLabNL

InSpin

Nonlocal magnon-polaron transport in yttrium iron garnet

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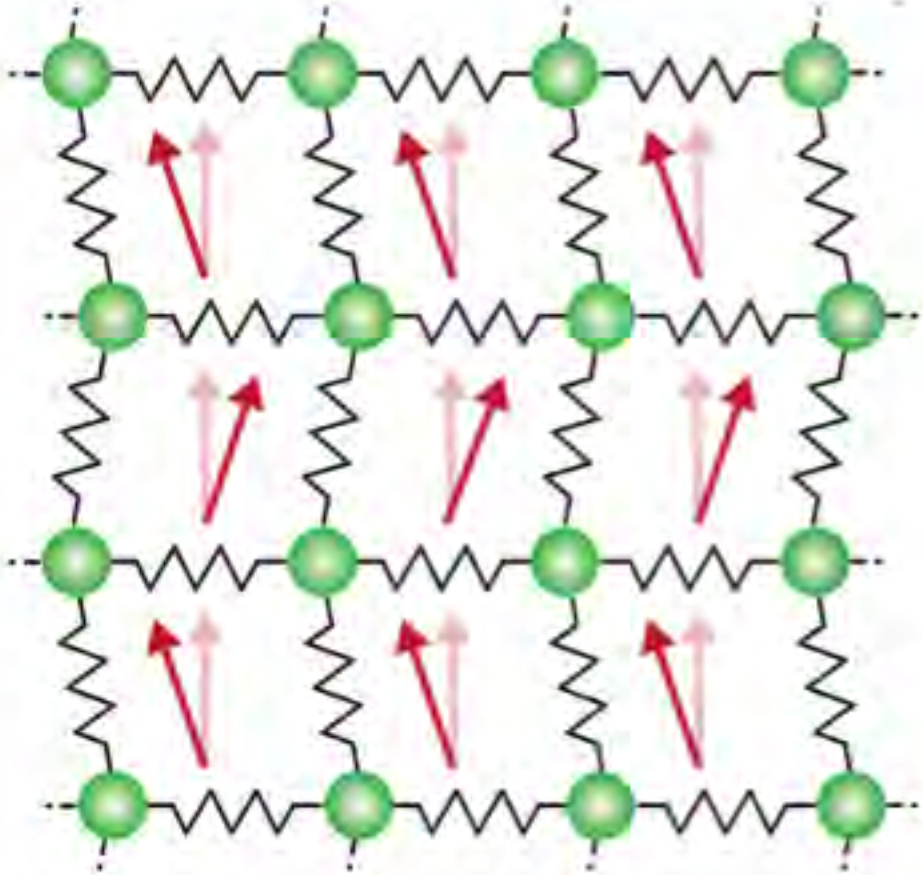
Magnetoelastic coupling[1]



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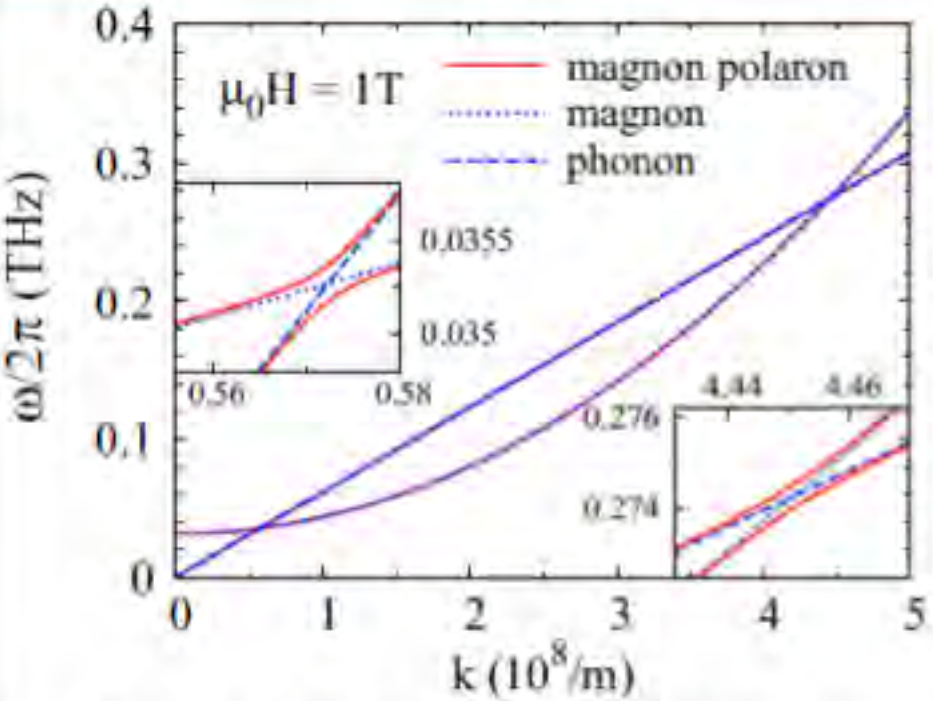
- Local lattice distortions exert torques on the magnetic order
- Conversely, spin waves affect lattice dynamics

1. C. Kittel, Physical Review 110, 836 (1958)

Strong coupling:

Strong coupling?
Magnon-phonon hybridization



At the anticrossings:

Fully mixed quasiparticles aka magnon-polarons

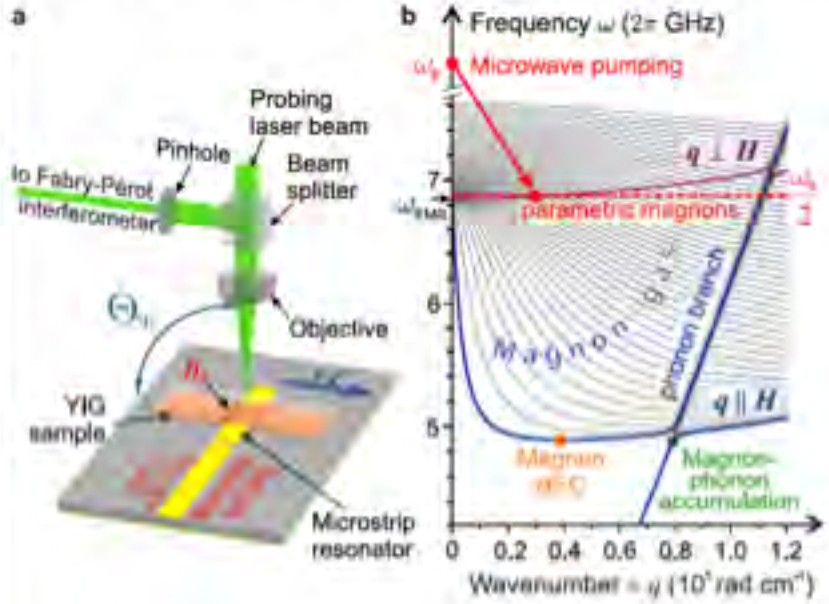
B. Flebus et al., PRB 95, 144420 (2017)
A. Rückriegel et al., PRB 89, 184413 (2014)
A. Kamra et al., PRB 91, 104409 (2015)
S.C. Guerreiro & S.M. Rezende, PRB 92, 214437 (2015)
K. Shen & G.E.W. Bauer, PRL 115, 197201 (2015)
N. Ogawa et al., PNAS 112, 8977 (2015)
D.A. Bohzko et al, PRL 118, 237201 (2017)

Consequences for magnon spin transport?

Consequences for magnon spin transport:

Coherent excitation

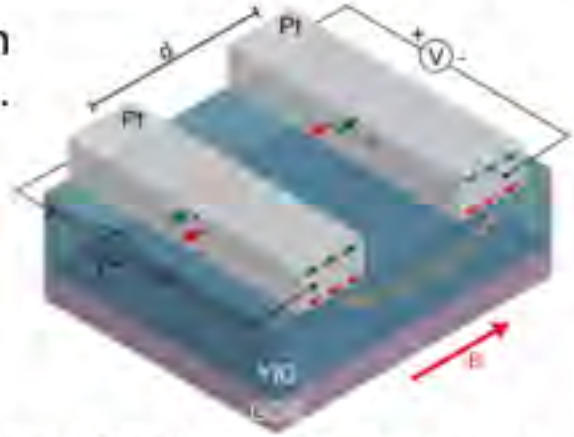
D.A. Bohzko et al, PRL 118, 237201 (2017)



Incoherent excitation

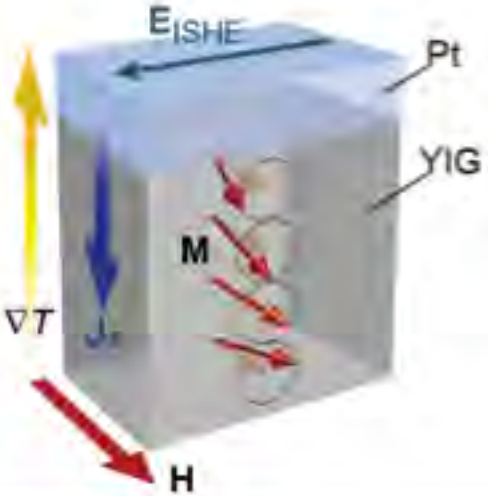
Spin Hall injection - electrically

L.J. Cornelissen et al, Nat. Phys. 11, 1022 (2015)



Spin Seebeck effect - thermally

Uchida et al, APL 97, 172505 (2010)
Kikkawa et al, JPSJ 85, 065003 (2016)



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Outline

- Introduction
- Magnon-polarons in the local spin Seebeck effect
- Nonlocal magnon spin transport in YIG
- Nonlocal magnon-polaron transport
- Conclusions

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Magnon-polarons in the local SSE

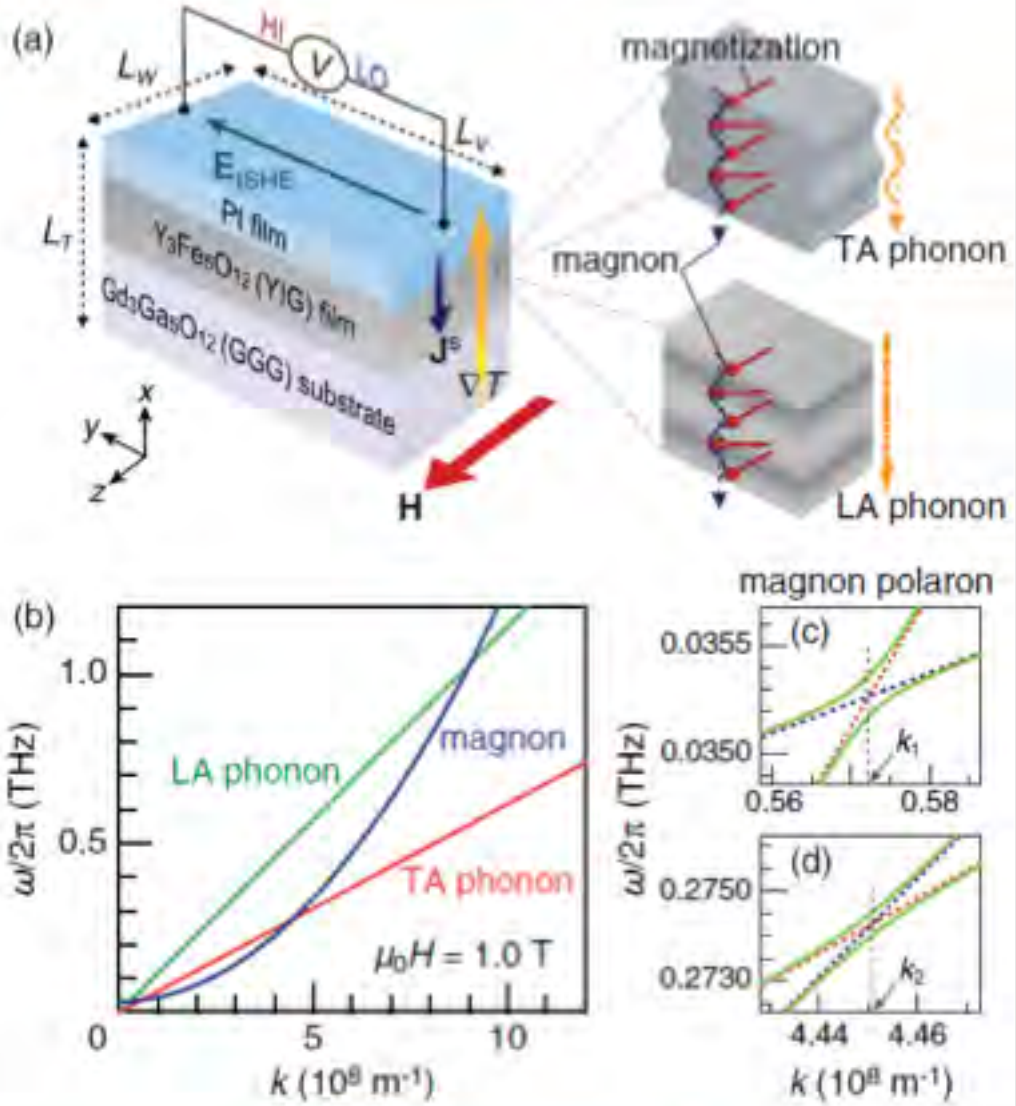
- Heater-induced longitudinal spin Seebeck effect

- Magnon dispersion:

$$\omega_k = \sqrt{Dk^2 + \gamma\mu_0 H} \cdot \sqrt{Dk^2 + \gamma\mu_0 (H + M_s \sin^2\theta)}$$

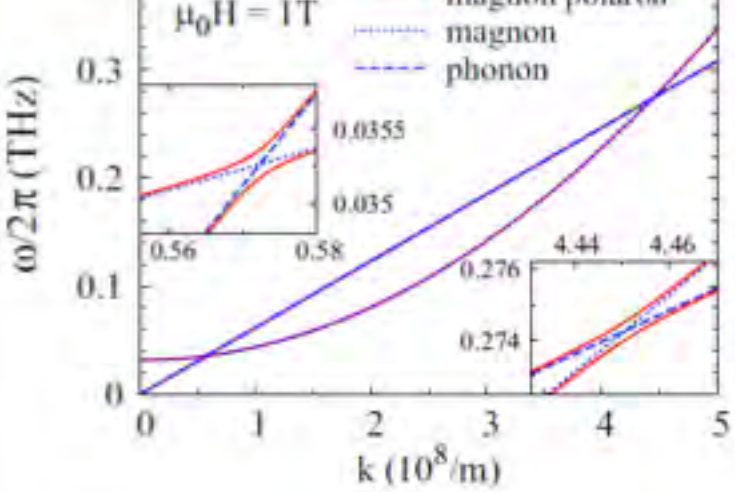
- Phonon dispersion:

$\omega_p = ck \quad (c_{TA}$ or $c_{LA})$

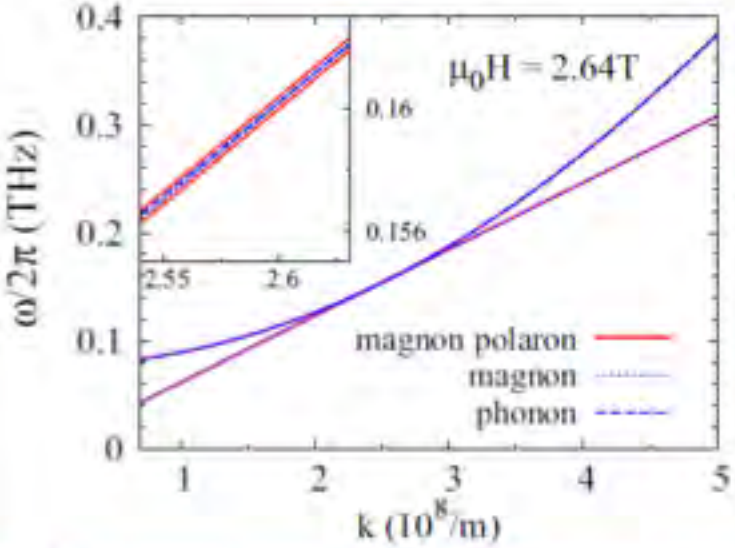


1. T. Kikkawa *et al.*, PRL. **117**, 207203 (2016)

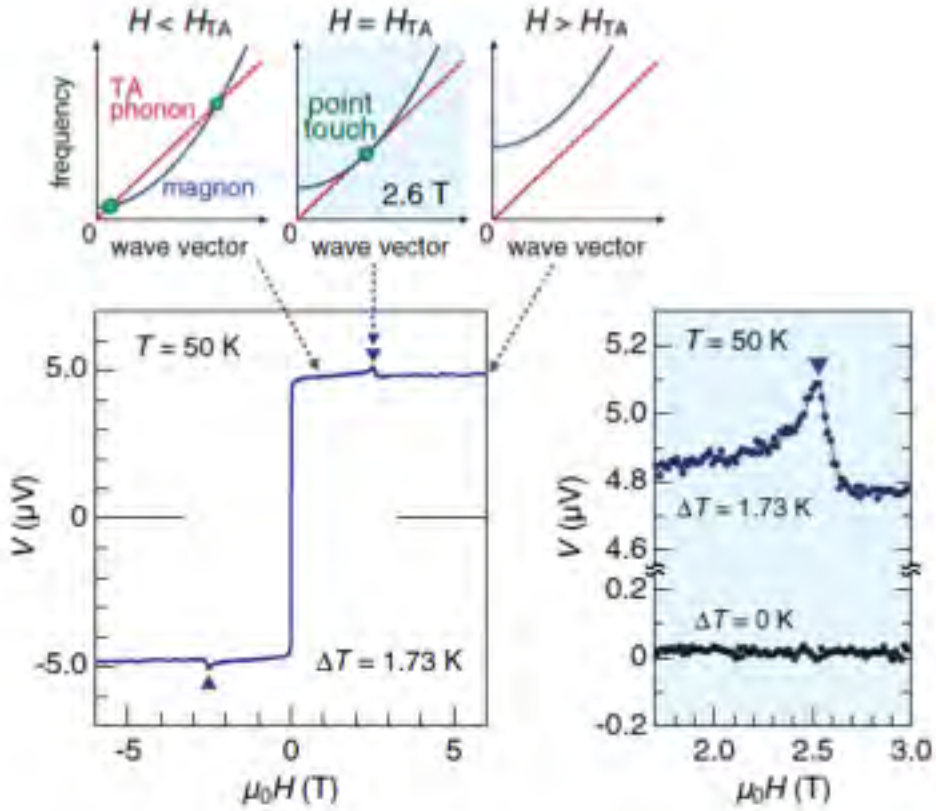
Magnon-polarons in the local SSE



H>H^TA



H=H^TA



1. B. Flebus et al., PRB 95, 144420 (2017)
2. T. Kikkawa et al., PRL 117, 207203 (2016)

Magnon and phonon lifetime

› Scattering potentials v_{mag} and v_{ph}

› SSE shows a **peak** when $|v_{mag}/v_{ph}| > 1$, $\tau_m < \tau_p$

› SSE shows a **dip** when $|v_{mag}/v_{ph}| < 1$, $\tau_m > \tau_p$

› In this sample, magnons are scattered more strongly than phonons.

› Acoustic quality is larger than magnetic one.

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- Nonlocal magnon-polaron transport
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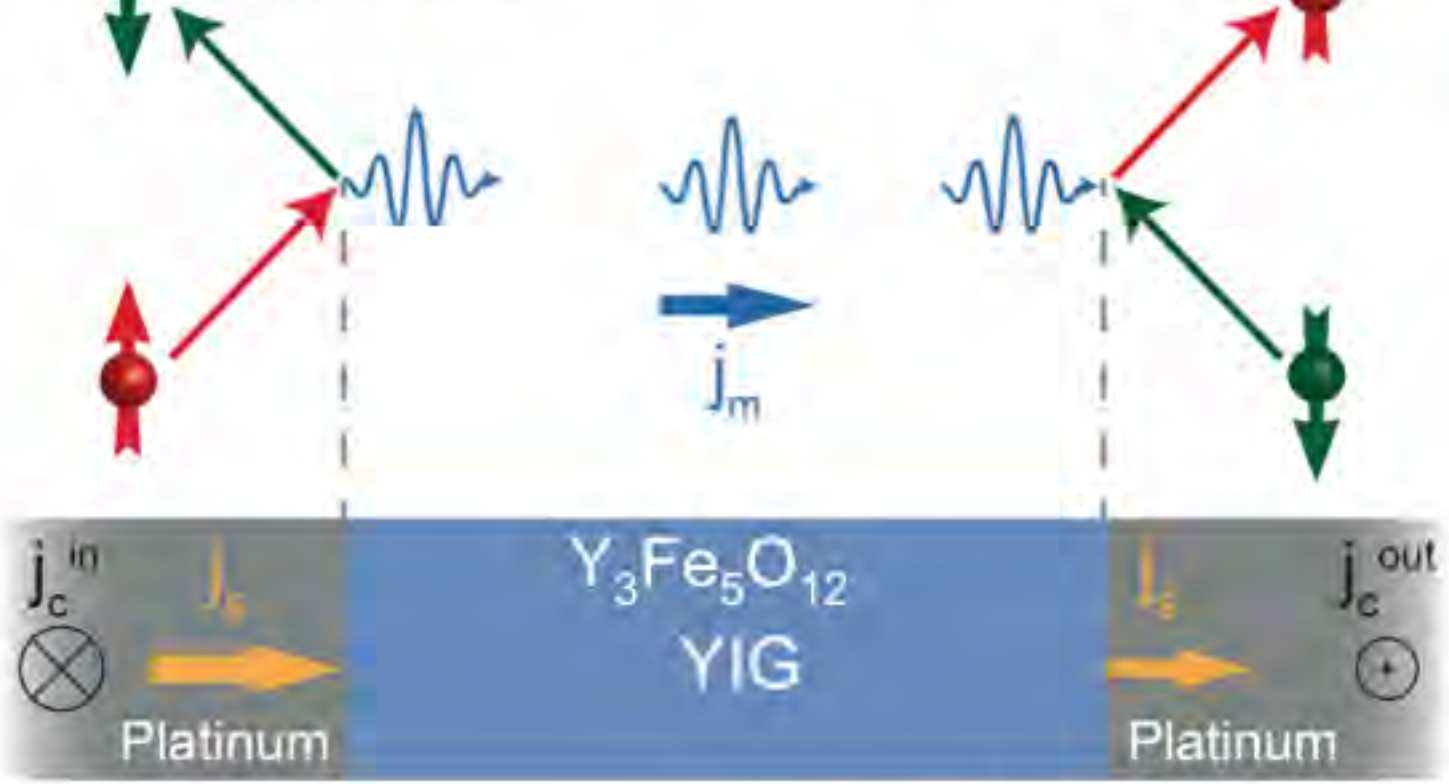
Magnon generation and detection



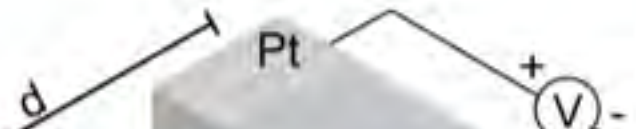
Spin Hall effect

Inverse spin Hall effect

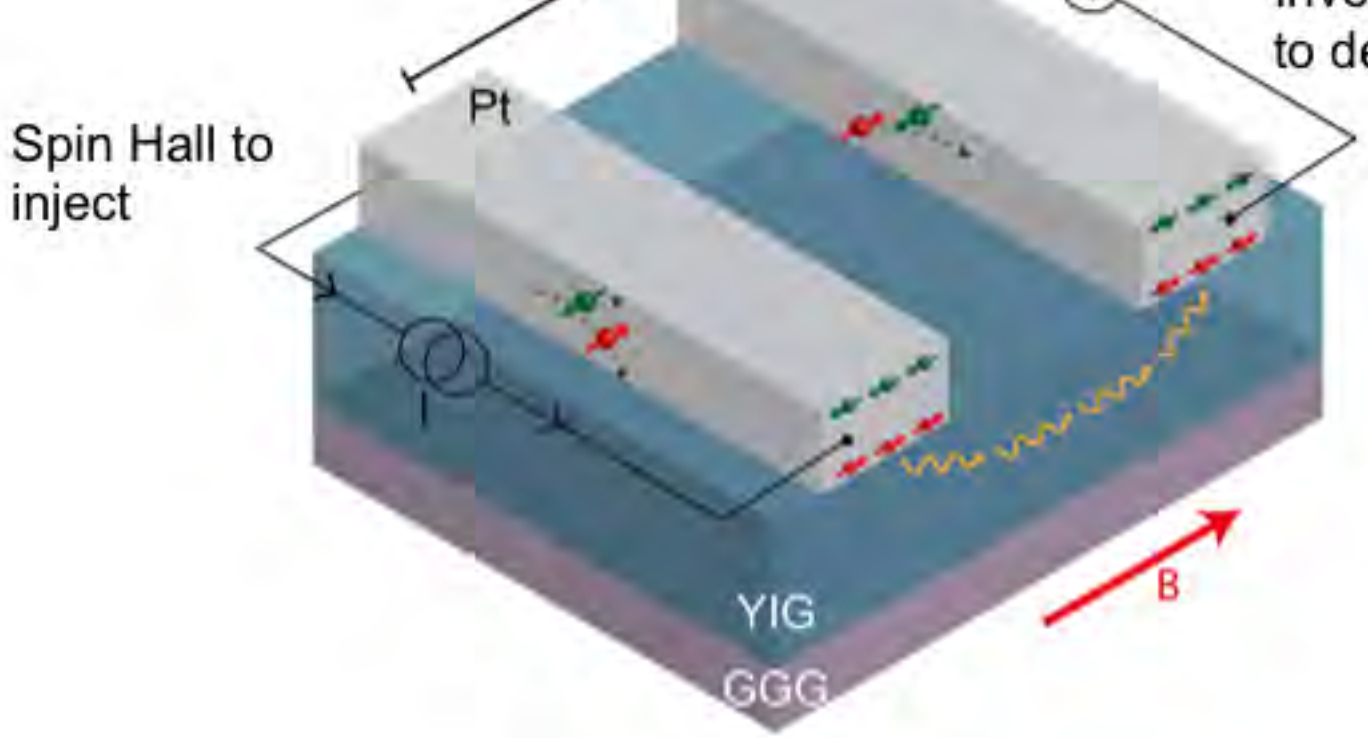
1. L.J. Cornelissen *et al.*, PRB 94, 014412 (2016)

Nonlocal devices

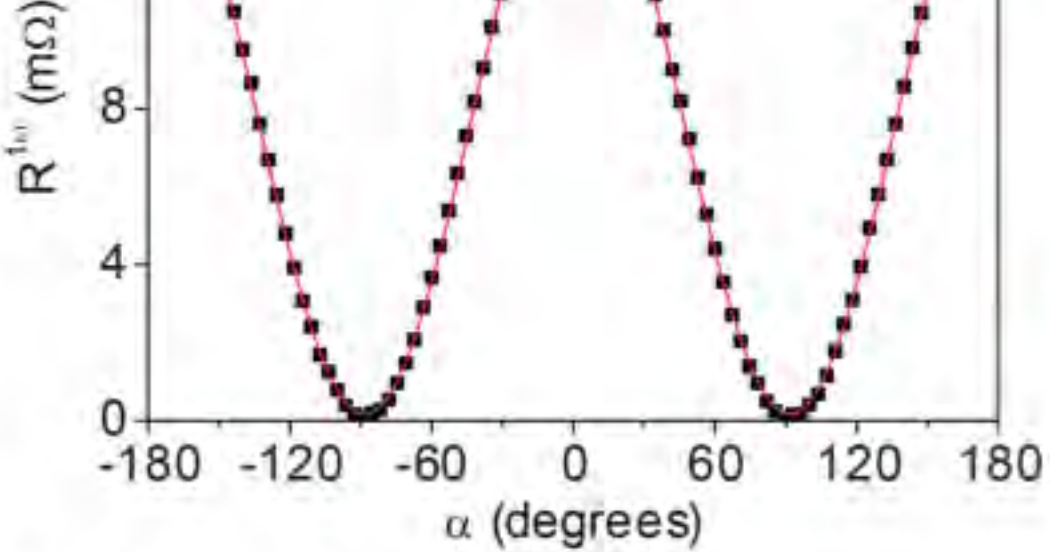
Electrical magnon injection

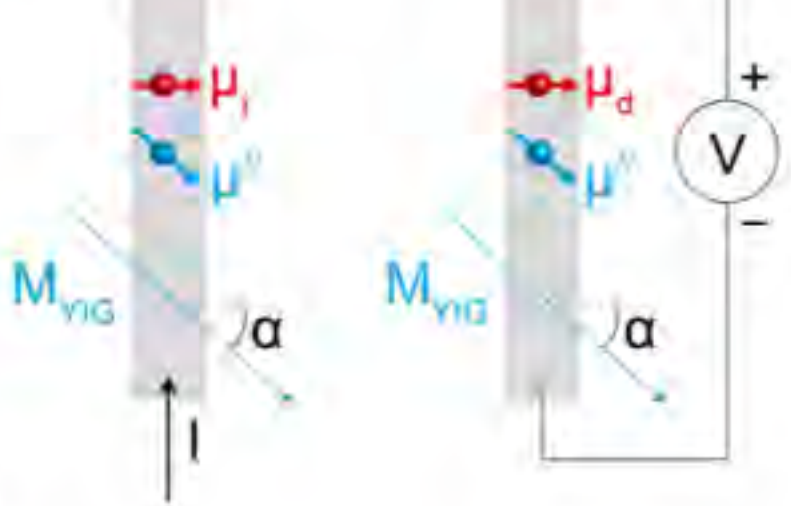


Inverse spin Hall



Angle dependent measurements





- Injector: $\mu^{\parallel}$ generates magnons -> $\cos\alpha$
- Detector: μ_d contributes to V_c -> $\cos\alpha$
- Nonlocal signal is product of the two: $\cos^2\alpha$

1. L.J. Cornelissen et al., Nat. Phys. **11**, 1022 (2015)

Nonlocal magnon spin transport
Electrical generation

Lateral geometry, YIG

- S.T.B. Goennenwein et al, APL 107, 172405 (2015)
- S. Velez et al, PRB 94, 174405 (2016)

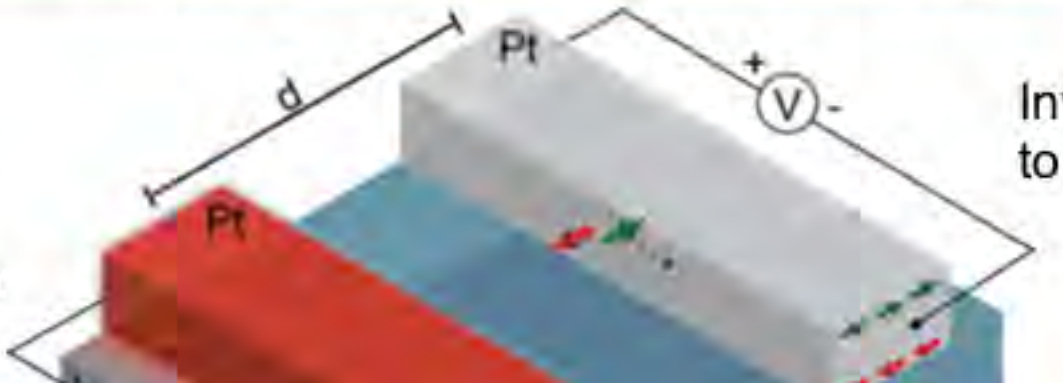
› K. Ganzhorn et al, APL 109, 022405 (2016)

› Other materials:
› K. Ganzhorn et al, arXiv:1705.02871 (2017) (**GdIG**)
› J. Shan et al, APL 110, 132406 (2017) (**NFO**)

Sandwich geometry, YIG
› J. Li et al., Nat. Comm. 7, 10858 (2016)
› H. Wu et al., PRB 93, 060403 (2016)

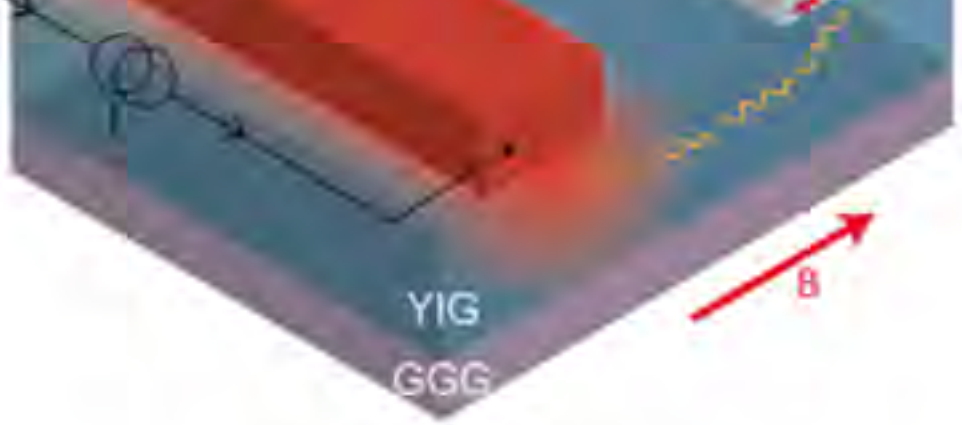
Nonlocal devices

Thermal magnon injection



Joule heating to inject

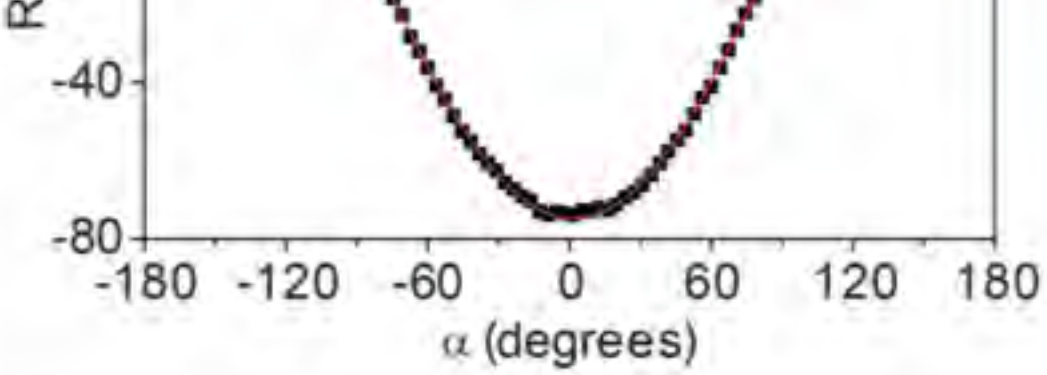
Inverse spin Hall to detect



Injection relies on spin Seebeck effect:

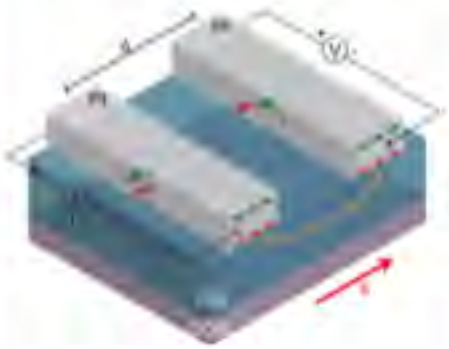
$$\frac{2e}{\hbar}\mathbf{j}_m = -S_S \nabla T \quad \text{, with } \nabla T \propto I^2$$

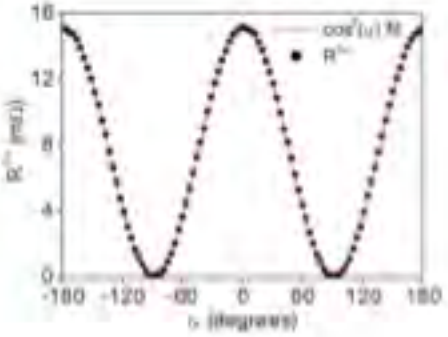
Angle dependent measurements

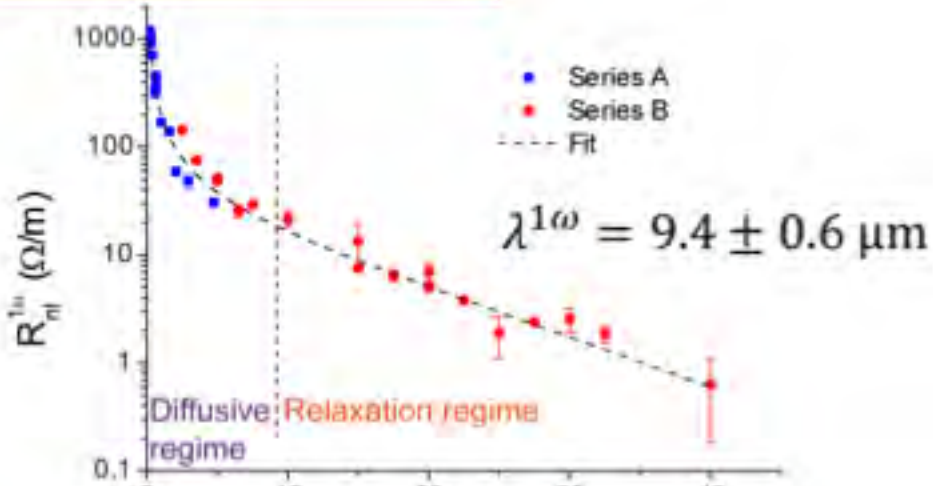


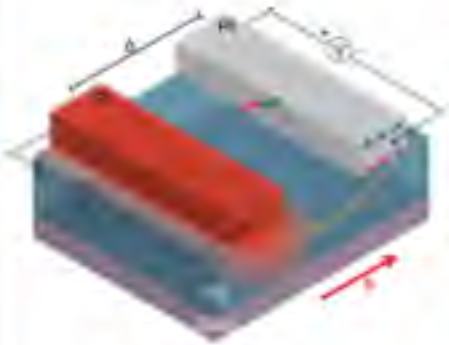
- Injector: I^2 generates heat -> const.
- Detector: μ_d contributes to V_c -> $\cos\alpha$
- Thermal nonlocal signal -> $\cos\alpha$

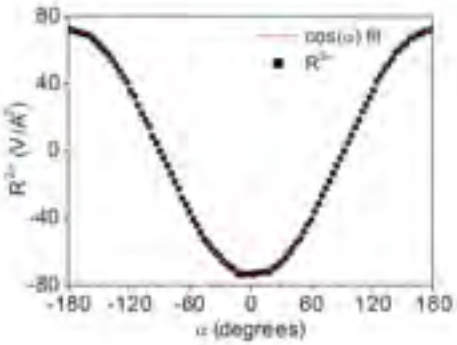
Magnon generation: electrical and thermal

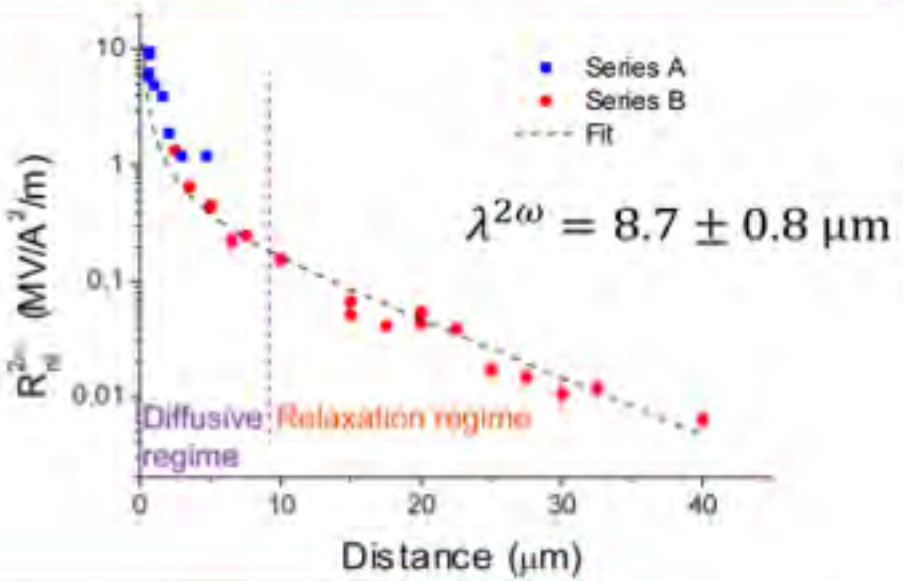






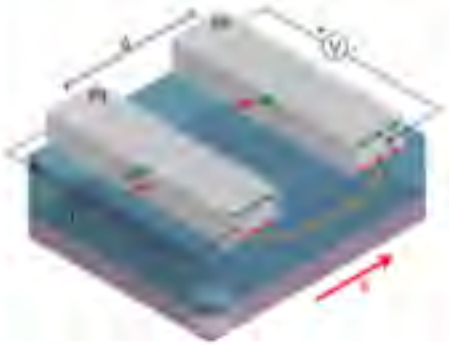


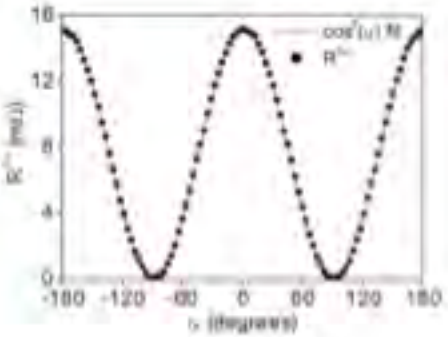


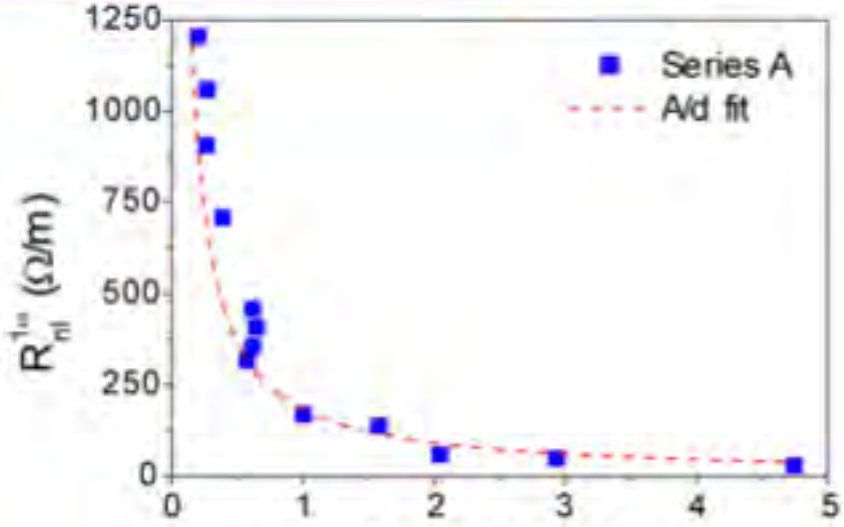


1. L.J. Cornelissen et al., Nat. Phys. **11**, 1022 (2015)

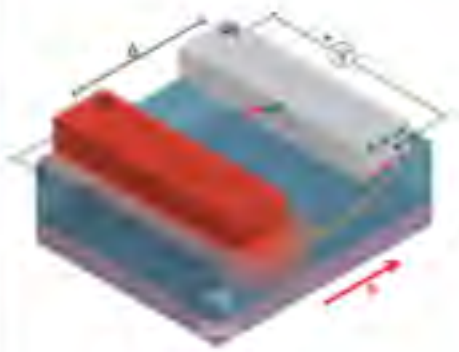
Magnon generation: electrical and thermal

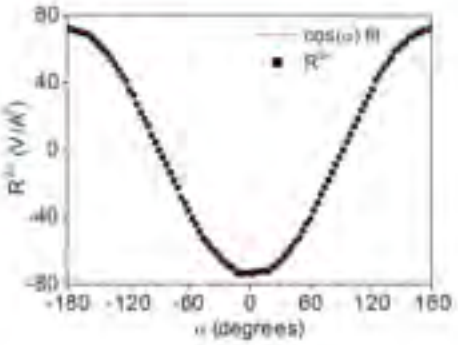


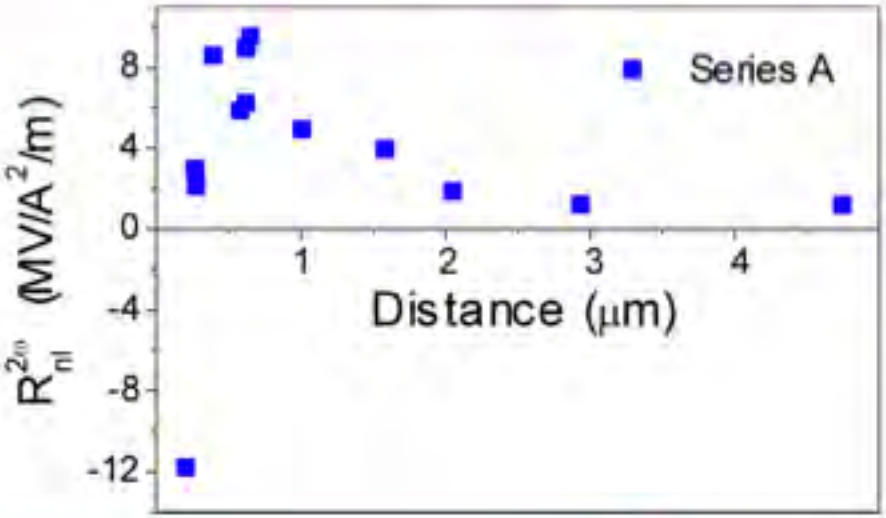




Distance (μm)



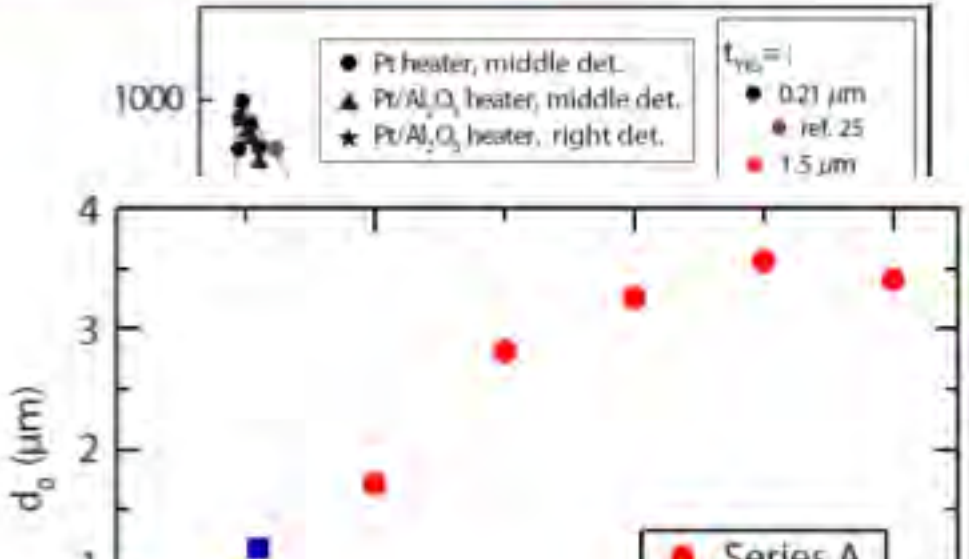




1. L.J. Cornelissen et al., Nat. Phys. **11**, 1022 (2015)

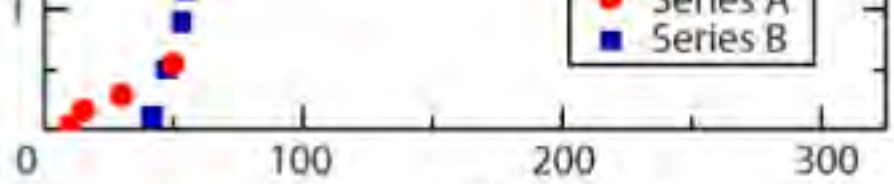
Thermal magnon generation: the nonlocal SSE

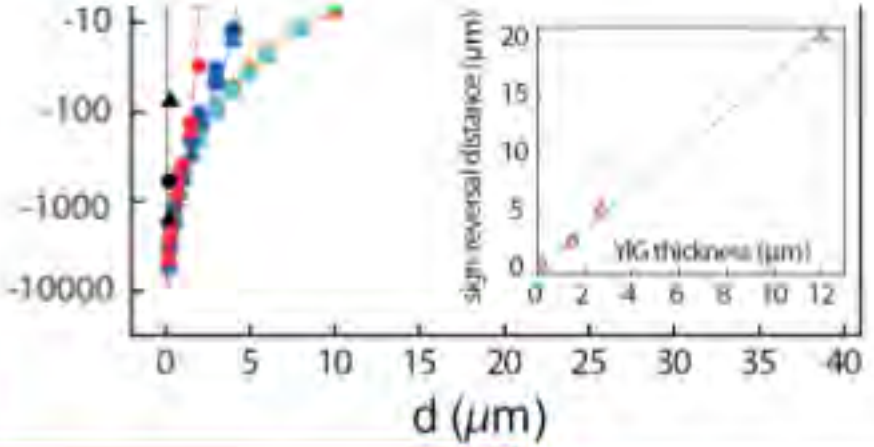
- Changes sign for short distances[1]
- At room temperature[2]: $d_0 \approx 1.6 t_{YIG}$



$d_{sc} \approx 1.6 l_{YIG}$

› $d_{sc} \downarrow$ as $T \downarrow$ [3, 4]





1. L.J. Cornelissen et al., Nat. Phys. 11, 1022 (2015)
2. J. Shan, L.J. Cornelissen et al., PRB 94, 174437 (2016)
3. K. Ganzhorn et al., arXiv:1701.02635 (2017)
4. X.J. Zhou et al., APL 110, 062407 (2017)

Modeling the nlSSE

$d_{sc} \approx t_{YIG}$

spin Seebeck

Magnon spin current

Magnon heat current

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

spin Peltier

1. L.J. Cornelissen *et al.*, arXiv:1706.04373 (2017)
2. L.J. Cornelissen *et al.*, PRB 93, 014412 (2016)

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- Introduction
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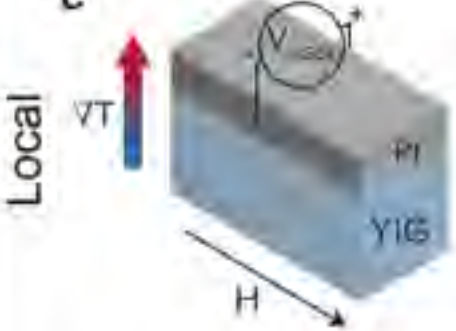
› Nonlocal magnon-polaron transport

› Conclusions

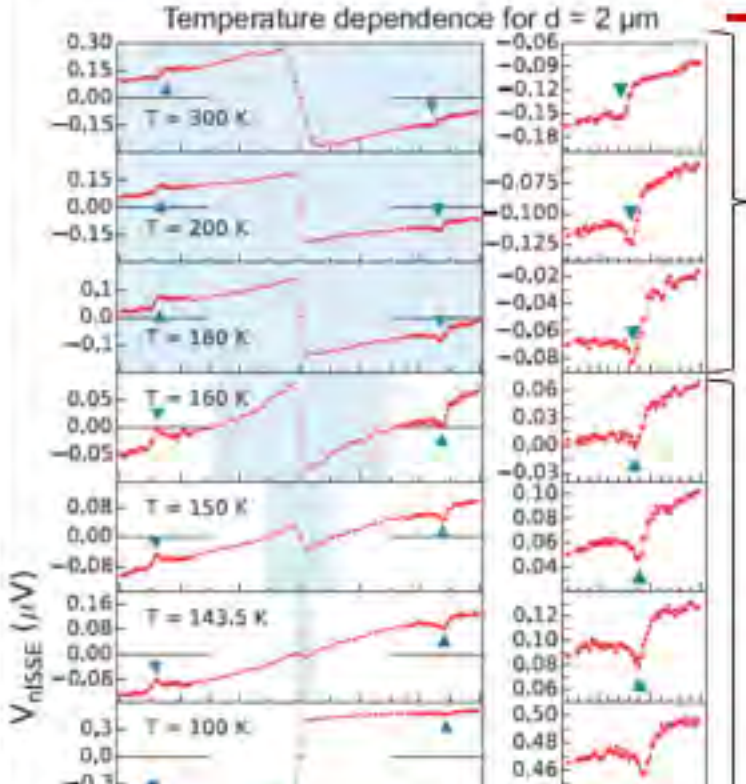
Nonlocal magnon-polaron transport: local SSE vs nonlocal SSE



$T = 200\ K, t_{YIG} = 2.5\ \mu m$

1. L.J. Cornelissen *et al.*, arXiv:1706.04373 (2017)

Temperature dependence



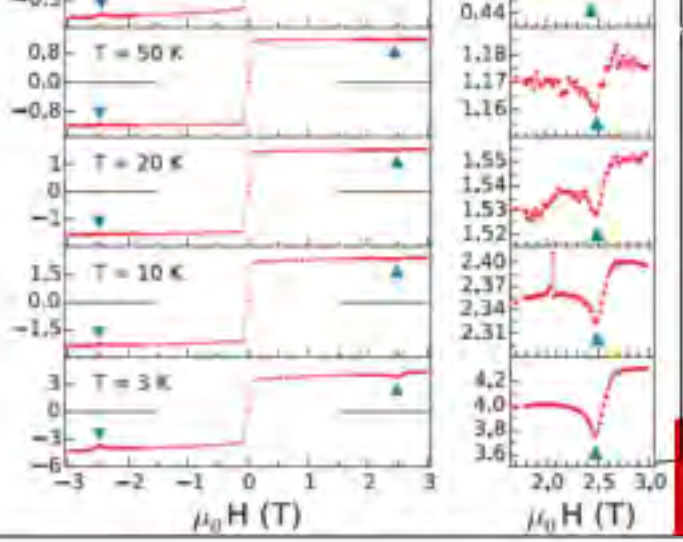
Resonant SSE enhancement (**peaks**)

Resonant SSE

Magnitude of the resonance:
$V_{TA} = V(H_{TA} + 0.2) - V(H_{TA})$

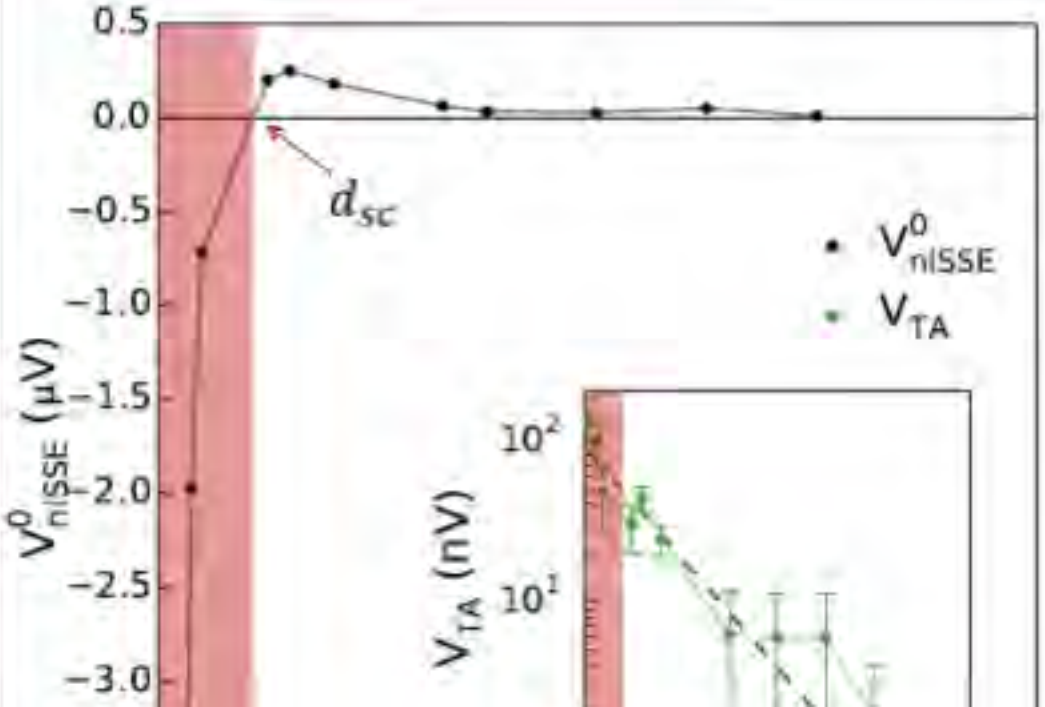
V_{TA} is positive for all temperatures and distances!

Local SSE shows **peaks** in all samples

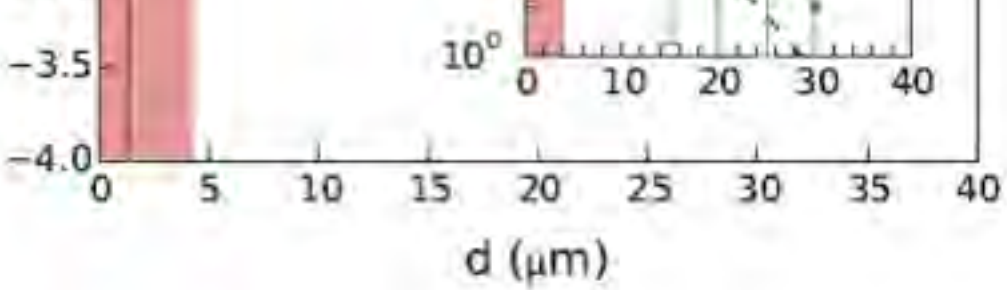


suppression
(**dips**)

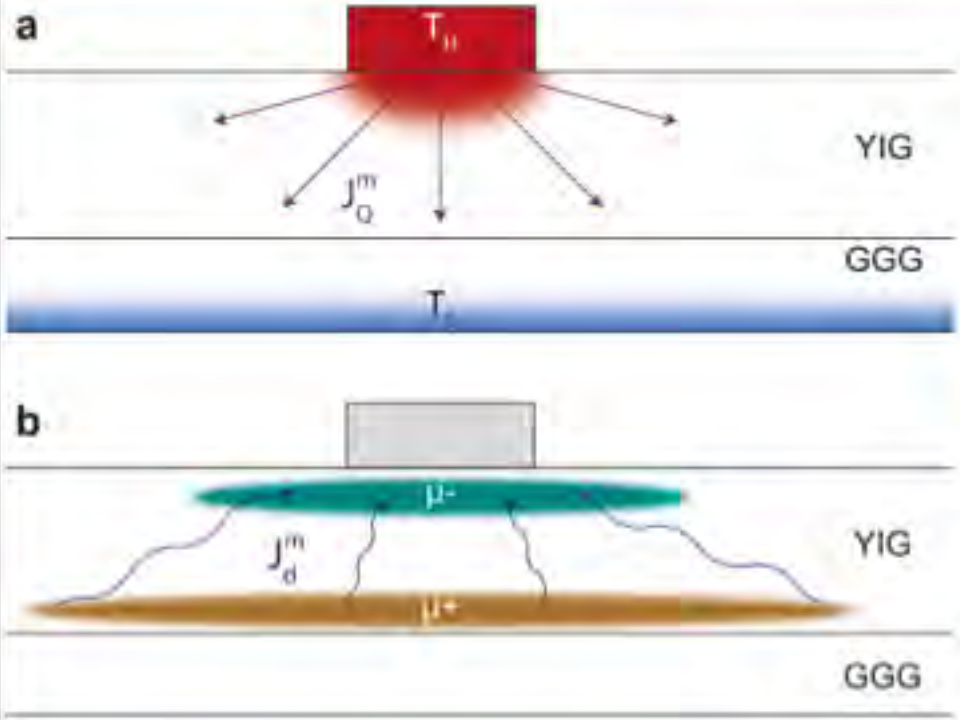
Distance dependence: V_{nlSSE} vs V_{TA}

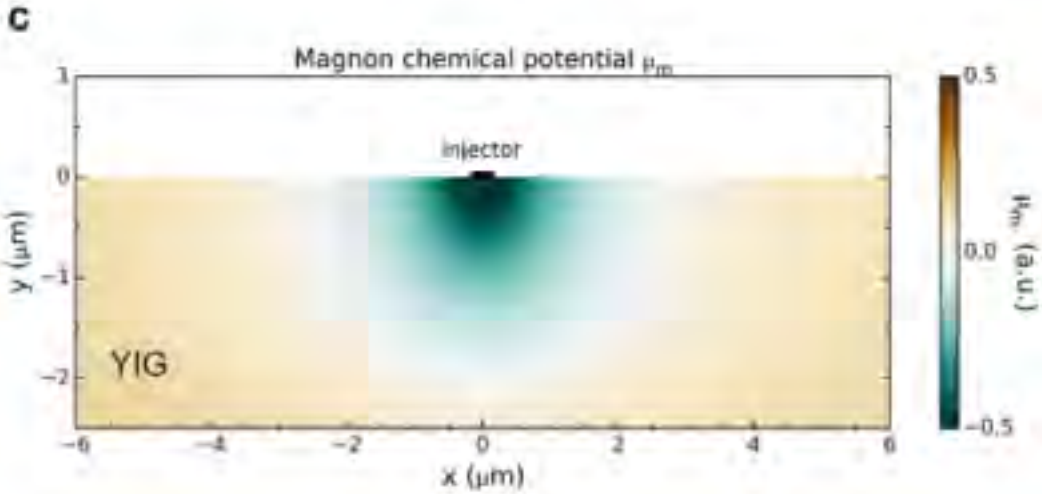


- Short distance: **peaks**
- Long distance: **dips**
- Measured on same YIG sample -> acoustic and magnetic quality do not change! We have $|v_{mag}/v_{ph}| > 1$



Modeling magnon-polaron transport





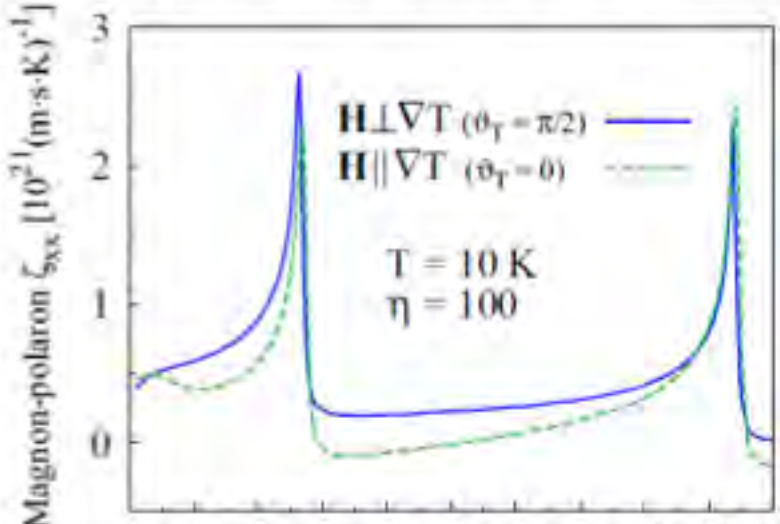
$$\begin{pmatrix} \frac{2e}{\hbar}\mathbf{j}_m \\ \mathbf{j}_{Q,m} \end{pmatrix} = - \begin{pmatrix} \sigma_m & L/T \\ \hbar L/2e & \kappa_m \end{pmatrix} \begin{pmatrix} \nabla\mu_m \\ \nabla T_m \end{pmatrix}$$

- Kikkawa et al.: increase in spin Seebeck coefficient
- Does not explain dips in nlSSE!

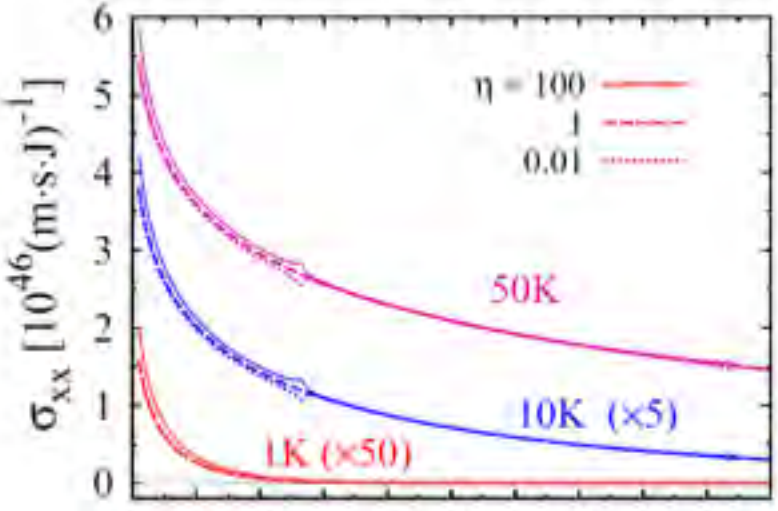
Relevant transport parameters

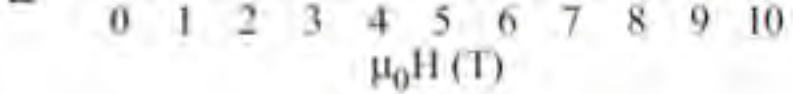
- Flebus et al. calculated magnon-polaron contribution to spin Seebeck coefficient and magnon spin and heat conductivity[1]

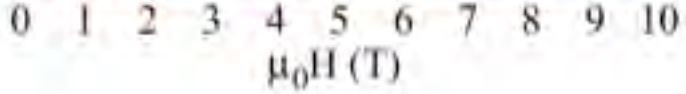
Spin Seebeck coefficient



Magnon spin conductivity



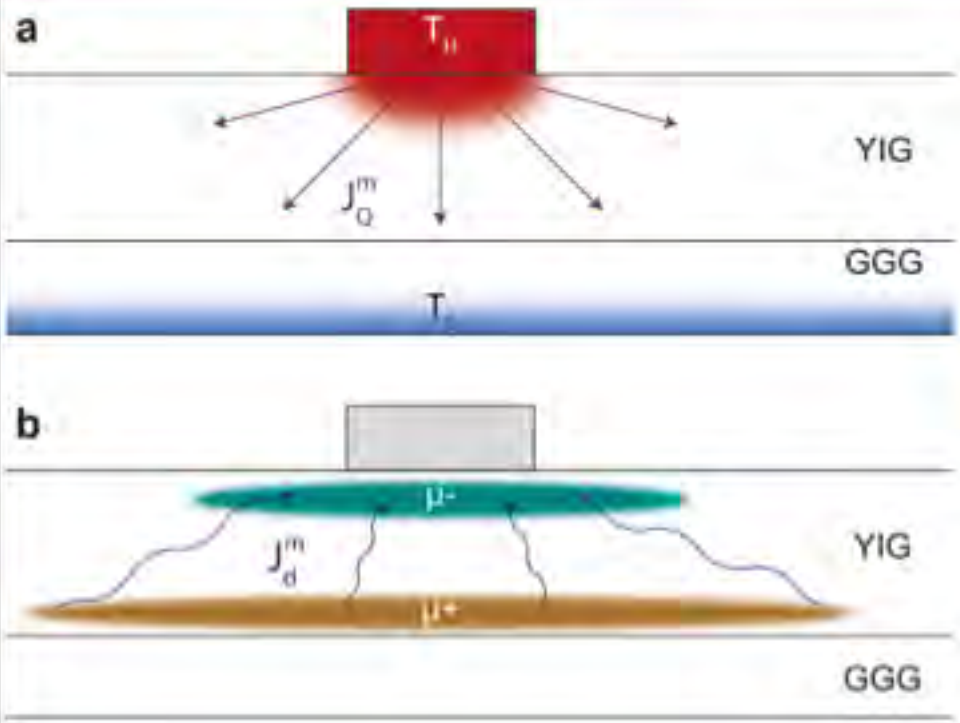


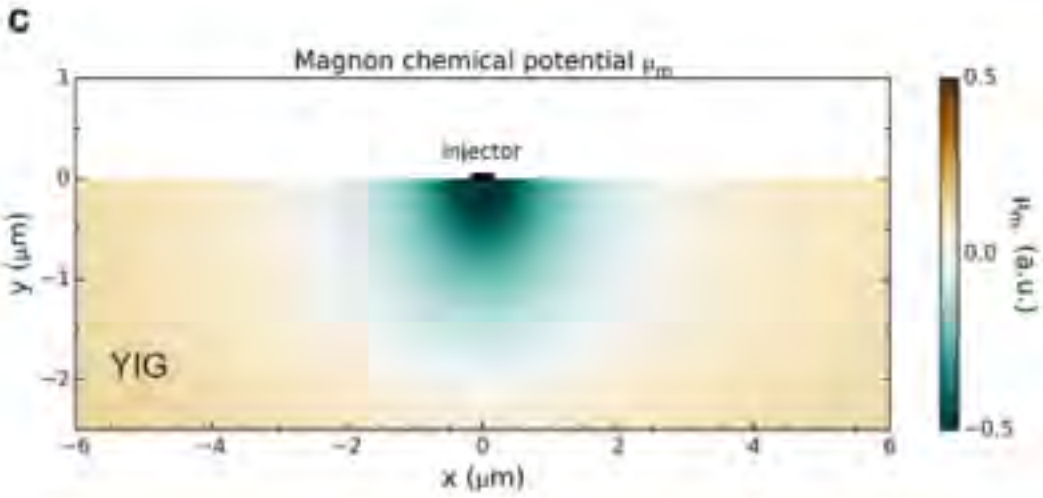


$$\eta = \left|v_{mag}/v_{ph}\right|^2$$

1. B. Flebus et al., PRB 95, 144420 (2017)

Modeling magnon-polaron transport





$$\begin{pmatrix} \frac{2e}{\hbar}\mathbf{j}_m \\ \mathbf{j}_Q \end{pmatrix} = \begin{pmatrix} \sigma_m & L/T \\ \cdots & \cdots \end{pmatrix} \begin{pmatrix} \nabla\mu_m \\ \cdots \end{pmatrix}$$

› Resonant enhancement in σ_m increases backflow current $\mathbf{j}_Q^m$

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

current $\mathbf{j}_d$

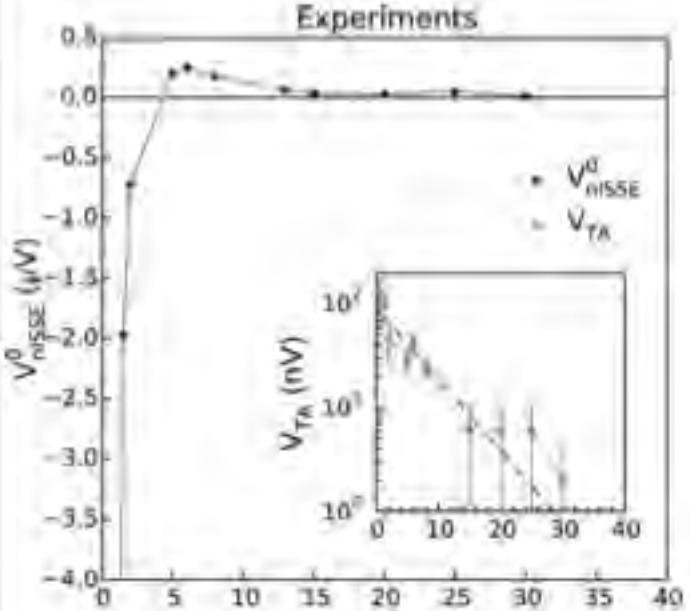
› Can cause dips at large distance

Comparison between model and experiment

› › We include enhancement of ζ and σ_m in the model

› Vary the enhancement ratio between them:

$\delta = f_\zeta / f_\sigma$, with $f_\zeta = \zeta(H_{TA})/\zeta^0$ and $f_\sigma = \sigma_m(H_{TA})/\sigma_m^0$

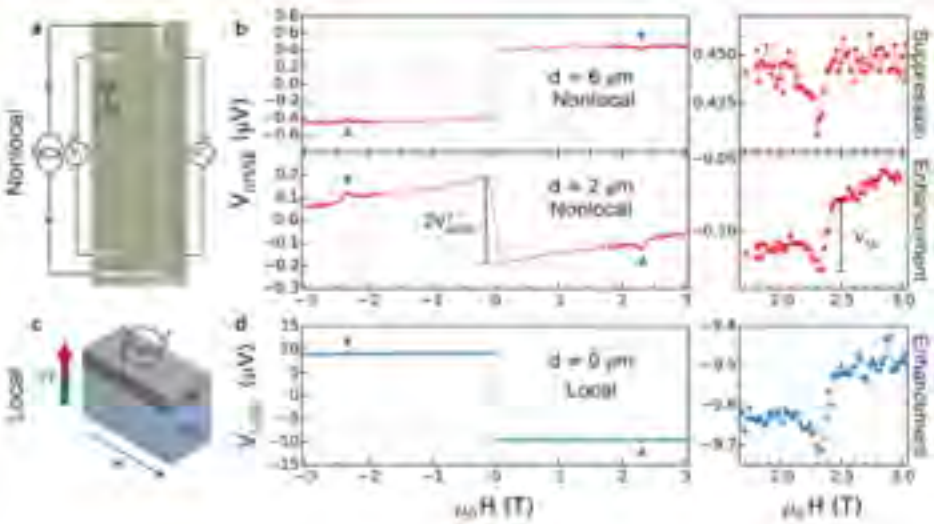


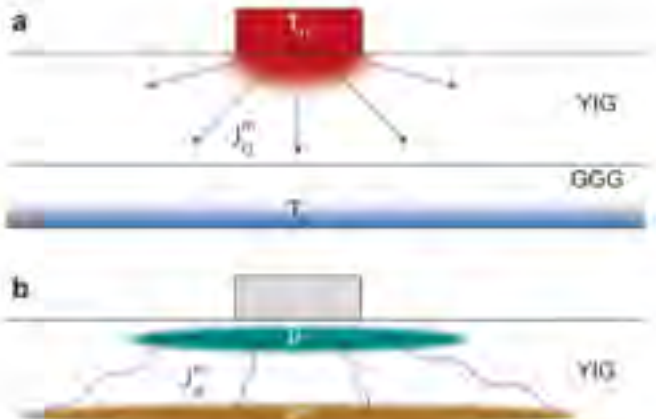
d (μm)

› Qualitative agreement for $1 < \delta < 0.5$, i.e. $f_\sigma > f_\zeta$

Conclusions

- Magnon-polaron transport can be detected both locally and nonlocally
- Sign change in the nlSSE can be explained qualitatively using a bulk magnon spin current model
- Including magnon-polaron contribution in both ζ and σ_m can explain peak/dip cross-over
- Details: arXiv:1706.04373





Thank you for your attention!

Physics of Nanodevices group

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