# Tutorial on spin transport in systems with insulating magnets

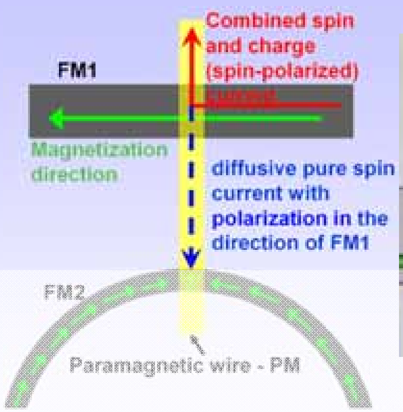
**M. Kläui**
Institut für Physik & Materials Science in Mainz
Johannes Gutenberg-Universität Mainz

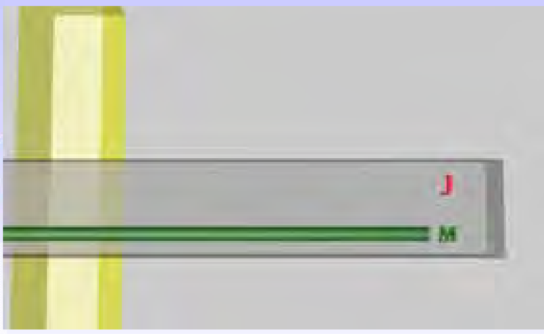
www.klaeui-lab.de

- **Spin transport in magnetic materials**
- **Properties of insulating ferrimagnets**
- **Thermal spin transport in insulators:**
  **-Bulk Effects: temperature dependence of spin currents in ferrimagnets**
  **-Interface Effects: correlation between interface and magnon mode transmission at ferrimagnet-metal interfaces.**
- **Spin transport in antiferromagnets**



## Prologue: Spin Transport – Spin Currents in metallic systems



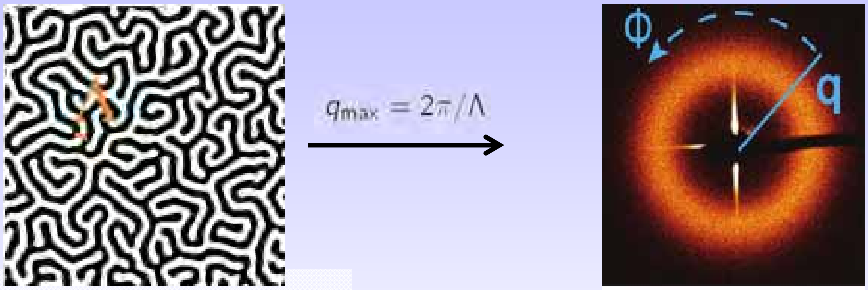



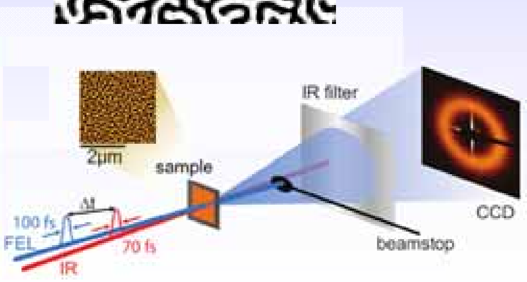

- In a metallic system, spin are carried by spin-polarized charge carriers
- In ferromagnetic metals, electrons with spin parallel to the magnetization are scattered less → spin-polarized current!
- In non-magnetic metals, pure diffusive spin currents transport spin.

M. Johnsonetal., PRB **37**,5326('88); F.Jedema et al., Nature **410**, 345 ('01); D. Ilgaz, MK et al., PRL **105**, 76601 ('10)

Mathias Kläui Mainz, 19.8.2016

## Prologue: Spin Transport – Superdiffusive Spin Currents



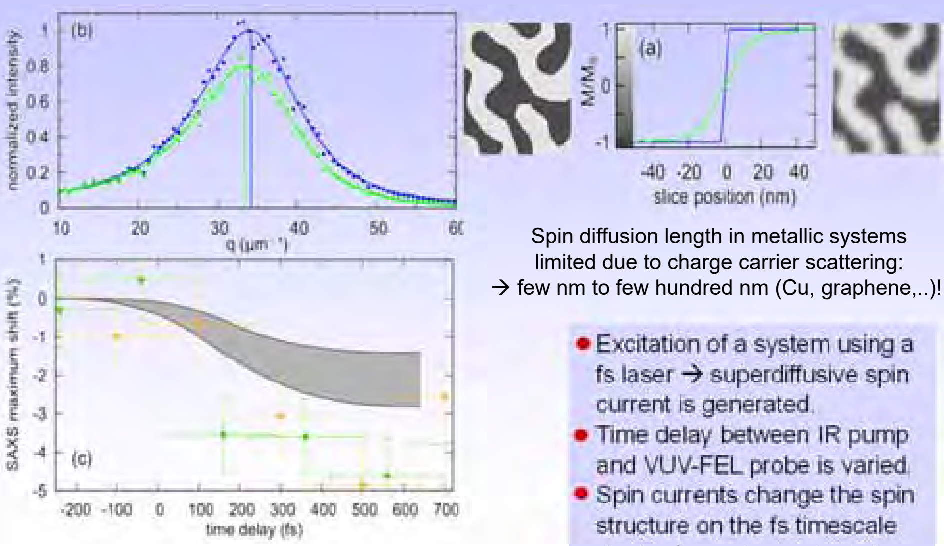




- Excitation of a system using a fs laser → superdiffusive spin current is generated.
- Time delay between IR pump and VUV-FEL probe is varied.

B. Pfau et al., Nature Comm. **3**, 1100 (2012) Collaboration S. Eisebitt, G. Grübel, J. Lüning

Mathias Kläui Mainz, 19.8.2016

## Prologue: Spin Transport – Superdiffusive Spin Currents



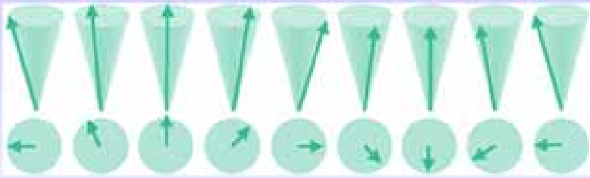

Spin diffusion length in metallic systems limited due to charge carrier scattering:
→ few nm to few hundred nm (Cu, graphene,..)!

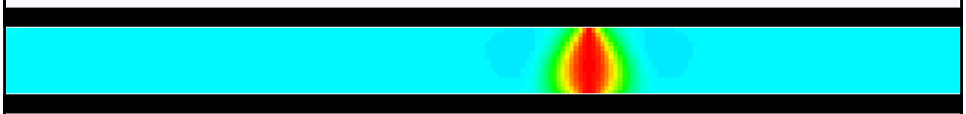
- Excitation of a system using a fs laser → superdiffusive spin current is generated.
- Time delay between IR pump and VUV-FEL probe is varied.
- Spin currents change the spin structure on the fs timescale
  → ultrafast spin manipulation

B. Pfau et al., Nature Comm. **3**, 1100 (2012) Collaboration S. Eisebitt, G. Grübel, J. Lüning

## Prologue: Spin Transport – Insulators

1. Spin Waves – Magnonic spin currents



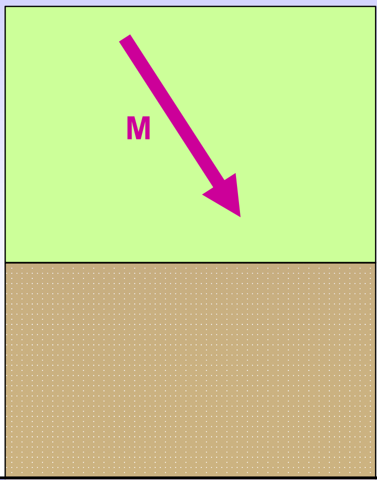


J.-S. Kim, MK et al., PRB **85**, 174428 (2012)



## 1. Interaction between spin currents in metals and insulators

YIG

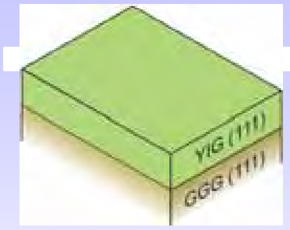



GGG

**electrically insulating ferrimagnet („magnetic insulator")**

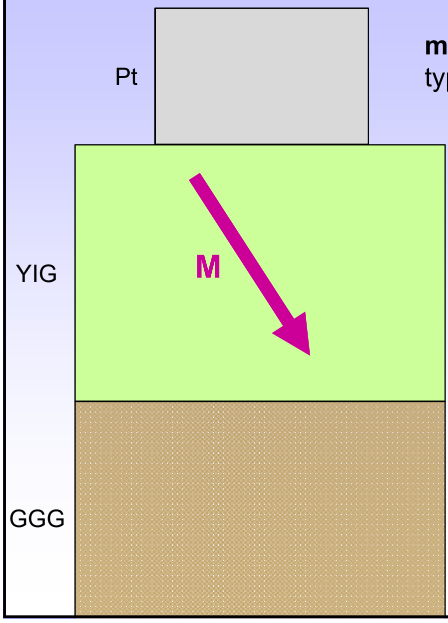
with net magnetization **M**

… we routinely use YIG = $Y_3Fe_5O_{12}$ as the magnetic insulator (later more…)

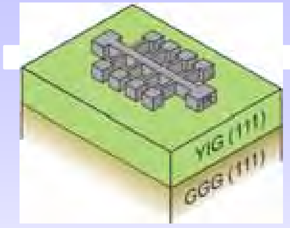



Courtesy S. Gönnenwein

## 1. Interaction between spin currents in metals and insulators




**metal**
typically: platinum




**electrically insulating ferrimagnet („magnetic insulator“)**

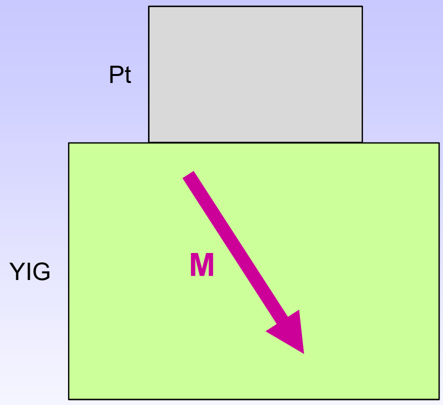
with net magnetization **M**

… we routinely use YIG = $Y_3Fe_5O_{12}$ as the magnetic insulator (later more…)

Courtesy S. Gönnenwein

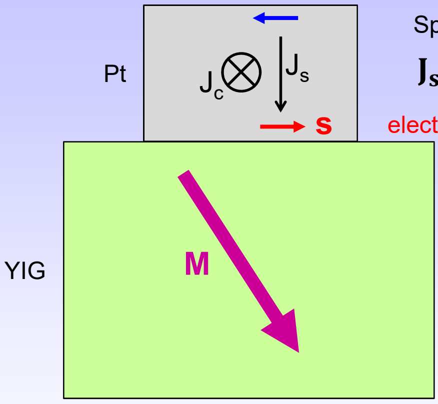


## 1. Interaction between spin currents in metals and insulators




Courtesy S. Gönnenwein

## 1. Interaction between spin currents in metals and insulators




Spin Hall effect (SHE):

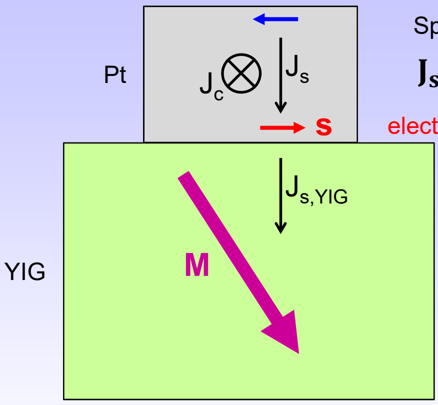
$$\mathbf{J_s} = \alpha^{\mathrm{SHE}} \frac{\hbar}{2e} [\, \mathbf{J_c} \times \mathbf{s} \,]$$

electron spin accumulation in Pt with spin **s**

Courtesy S. Gönnenwein

Mathias Kläui
Mainz, 19.8.2016

## 1. Interaction between spin currents in metals and insulators




Spin Hall effect (SHE):

$$\mathbf{J_s} = \alpha^{\mathrm{SHE}} \frac{\hbar}{2e} [\, \mathbf{J_c} \times \mathbf{s} \,]$$

electron spin accumulation in Pt with spin **s**

if $\tau_{\mathrm{STT}} \propto \mathbf{M} \times (\mathbf{M} \times \mathbf{s})$ is finite

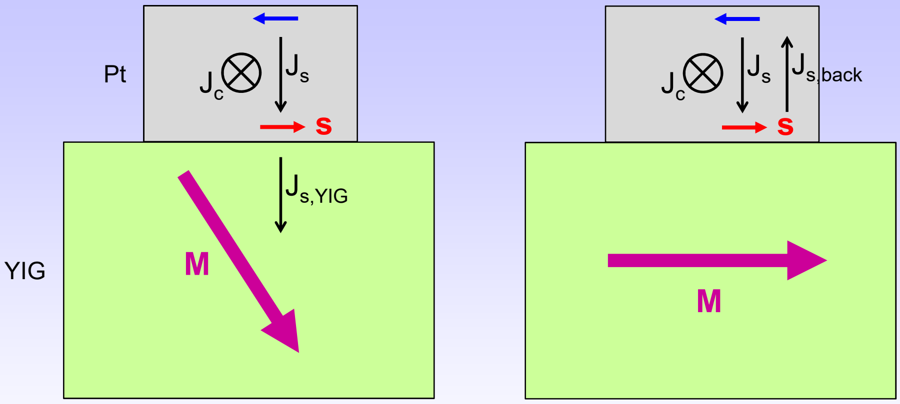
⇒ outflow of $J_s$ into YIG

**enhanced dissipation in Pt**
**⇒ larger Pt resistance**

Courtesy S. Gönnenwein

Mathias Kläui Mainz, 19.8.2016

## 1. Interaction between spin currents in metals and insulators




if $\tau_{STT} \propto \mathbf{M} \times (\mathbf{M} \times \mathbf{s})$ is finite

⇒ outflow of $J_s$ into YIG

**enhanced dissipation in Pt**
**⇒ larger Pt resistance**

$\tau_{STT} \propto \mathbf{M} \times (\mathbf{M} \times \mathbf{s}) = 0$

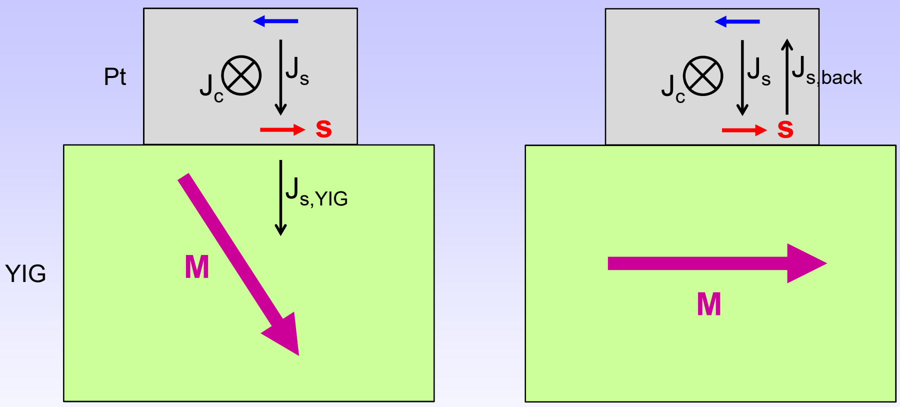
⇒ open boundary conditions for $J_s$

**reduced dissipation**
**⇒ smaller Pt resistance**

Courtesy S. Gönnenwein

Mathias Kläui Mainz, 19.8.2016

1. Interaction between spin currents in metals and insulators



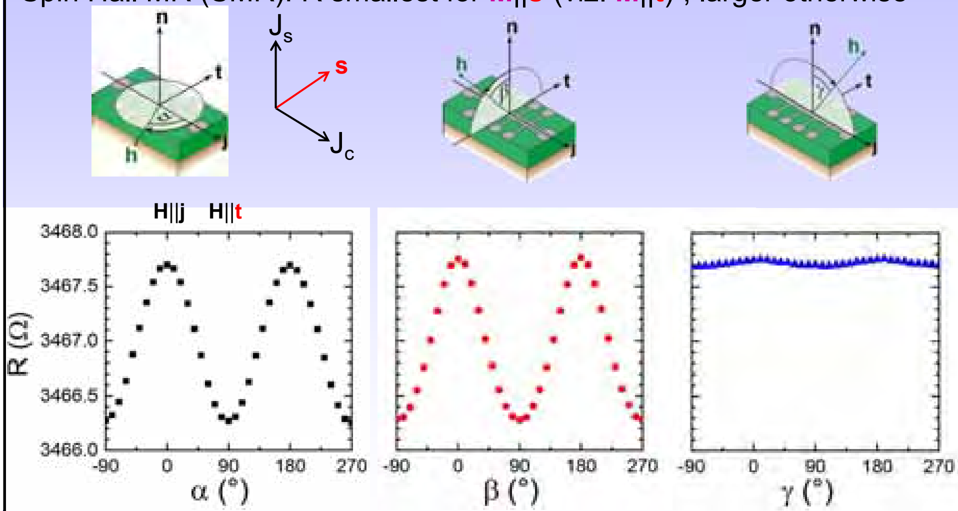

Spin Hall MR (SMR): $R$ smallest for $\mathbf{M} || \mathbf{s}$ , larger otherwise

$$R = R_0 - R_1 (\mathbf{m} \cdot \mathbf{s})^2 = R_0 - R_1 \cos^2(\alpha)$$

References: Nakayama *et al.*, PRL **110**, 206601 (2013); Chen *et al.*, PRB **87**, 144411 (2013); Hahn *et al.*, PRB **87**, 174417 (2013); Vlietstra *et al.*, PRB **87**, 184421 (2013); Althammer *et al.*, PRB **87**, 224401 (2013); Meyer *et al.*, APL **104**, 242411 (2014); Lotze *et al.*, PRB **90**, 174419 (2014).
Review: Chen *et al.*, J. Phys.: Condens. Matter **28**, 103004 (2016).

## 1. Interaction between spin currents in metals and insulators

Spin Hall MR (SMR): R smallest for **M||s** (viz. **M||t**) , larger otherwise

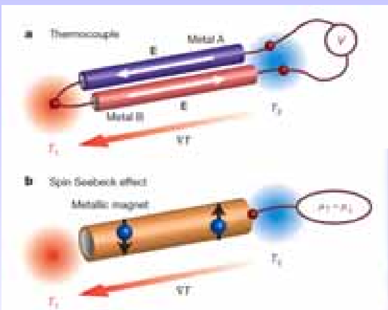



SMR amplitude in YIG/Pt: $\frac{\Delta R}{R} \leq 2 \times 10^{-3}$ , ideally $\frac{\Delta R}{R} \leq \left(\alpha_{Pt}^{SHE}\right)^2 \approx 0.01$

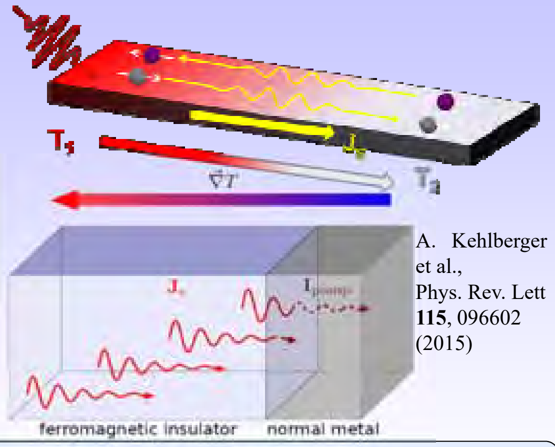
Courtesy S. Gönnenwein

Mathias Kläui Mainz, 19.8.2016

## 2. Generation of Spin Currents by thermal gradients




K. Uchida et al., Nature 455, 778 (2008)




A. Kehlberger et al., Phys. Rev. Lett **115**, 096602 (2015)

- Simplest pictures: „boiling of spins“ leading to more magnon generation in the „hot“ part that propagate to the cold part.[1]
- Theory based on magnon temperature[2] and magnon chemical potential[3] termed Spin Seebeck Effect → Presentation by G. Bauer

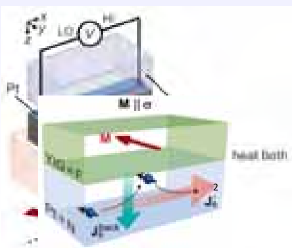
[1]G. Bauer et al., Nat. Mater. **11**, 391 (2012); [2]J. Xiao, Phys. Rev. B **81**, 214418 (2010); [3]L. Cornelissen et al., arxiv: 1604.03706

## 2. The Spin Seebeck Effect – Experimental Work

| Key findings | |
|---|---|
| 2008 - 10 Measurement of spin signals generated by thermal gradients in conductors and insulators (YIG) | K. Uchida *et al.* Nature **455**, 778 (2008)<br>K. Uchida *et al.* Appl. Phys. Lett. **97**, 172505 ('10) |
| 2011 - Investigation of the YIG/Pt interface and coupling-induced magnetoresistance effects | H. Nakayama *et al.* Phys. Rev. Lett. **110**, 206601 ('13)<br>N. Vlietstra *et al.* Phys. Rev. B **87**, 184421 ('13) |
| 2012 - New materials are being investigated | C. M. Jaworski et al., Nature 487, 201 (2012), many.. |

Many active groups (Sendai, JAEA, WMI, Ohio State, Konstanz, Johns Hopkins, Kaiserslautern, Trondheim, Groningen, Greifswald, Utrecht, Riken, Bielfeld, Recife, Berlin, Almaden, Regensburg, Beijing, Mainz, etc.)!

1



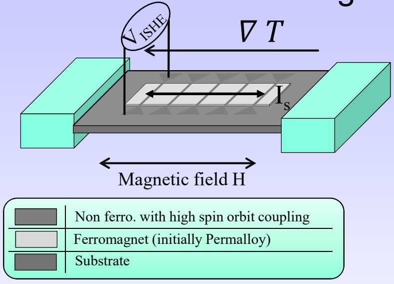

**Challenges**

- Transverse Spin Seebeck Effect with poorly controlled temperature gradients (Problem 1).
- Origin of the measured signals in ferromagnetic conductors: spin-caloric or charge-caloric effects (Problem 2)?
- Contributions of parasitic interface effects to the measured signal (Problem 3)?
- Dependence of SSE on magnon spectrum
- Interface effects (proximity induced magnetization, spin mixing conductance, etc.)
- SSE in ferrimagnets and antiferromagnets
- Can we make the SSE useful? N.I.T.T.



## 2. The Spin Seebeck Effect – Experimental Work

SSE in the transverse configuration [1]

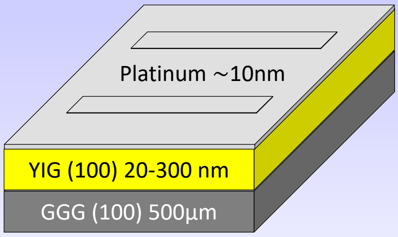



$$V_{ISHE} \propto D_{ISHE} I_S \times \sigma \rightarrow \propto \sin(\theta)$$

[1] K. Uchida et al., Nature **455**, 778 (2008); M. Schmid et al., PRL **111**, 187201 (2013); A. Kehlberger, PhD ('15)

Mathias Kläui — Mainz, 19.8.2016

## 2. Obervation of the SSE in the longitudinal geometry




**Fabrication process:**

- $Y_3Fe_5O_{12}$ (100) grown by Pulsed Laser Deposition on $Gd_3Ga_5O_{12}$ (20-300 nm)
- XRD, XRR and profilometer characterization
- In-situ surface cleaning
- Sputtering of Platinum ~10nm
- Optical Lithography and Ion-etching
- 2 x 4mm x 100µm Stripes per sample

- Longitudinal geometry provides well-defined temperature gradient (solves Problem 1)!
- YIG is a very good insulator (high band gap)
  → no thermoelectric effects (solves Problem 2, but proximity induced magnetization in Pt could lead to charge – based thermoelectric effects – Problem 3)
- Thick $Y_3Fe_5O_{12}$ is grown by Liquid Phase Epitaxy on $Gd_3Ga_5O_{12}$ (100)
- Lowest damping is observed for >1 µm thick LPE grown YIG.
- → in the following use always longitudinal geometry and a ferromagnetic insulator!

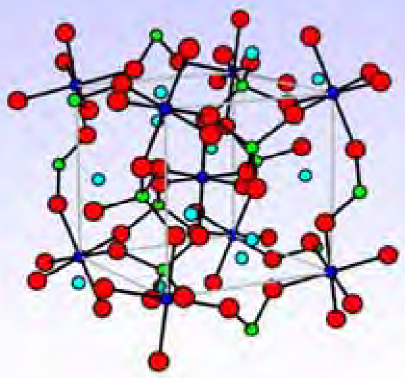
Growth details, see: M. Onbasli et al., APL Materials **2**, 106102 (2014).

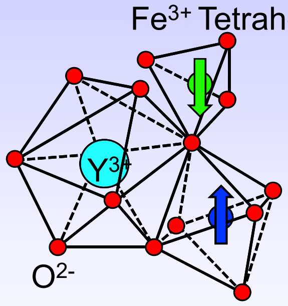
Mathias Kläui — Mainz, 19.8.2016

## 2. Structural Characterization – YIG

Very large unit cell

20 Fe atoms in primitive cell in two different environments

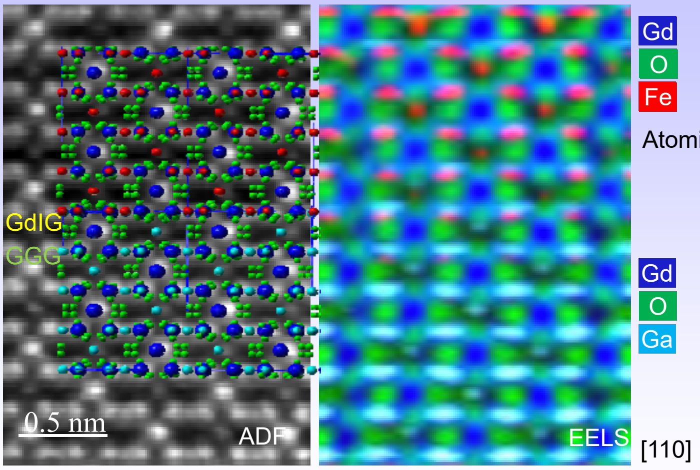





Courtesy J. Barker

- Yttrium Iron Garnet $Y_3Fe_5O_{12}$ is a complex ferrimagnet with 2 iron sublattices (a and d sites) that are coupled by superexchange.

## 2. Structural Characterization – TEM measurements



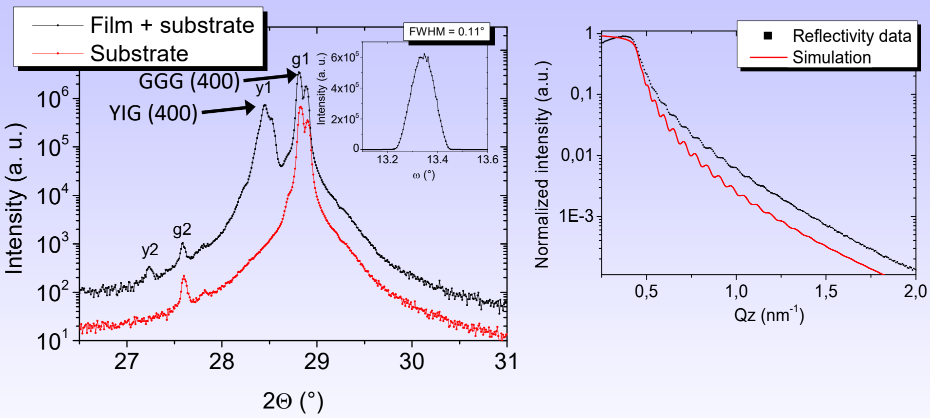

Atomic resolution EELS

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

- High resolution STEM imaging of GGG/YIG and GGG/GdIG interfaces grown by PLD
- Very abrupt interface between GGG and GdIG is found.



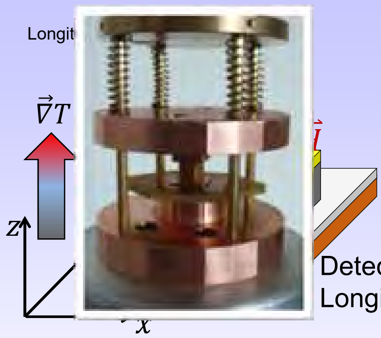
## 2. Structural Characterization - XRD/XRR measurements




- X-ray diffraction using a X-Pert PW3040 diffractometer with a Cu K α source.
- Determined lattice constants (YIG = 1,235 nm) fit the literature value (YIG = 1,2376 nm).[1]
- Peaks from the 2Θ/ω scan show epitaxial growth and the FWHM a good crystallographic orientation of our films.
- Analysis of XRR data is used to determine the thickness (here shown for an 80 nm film).

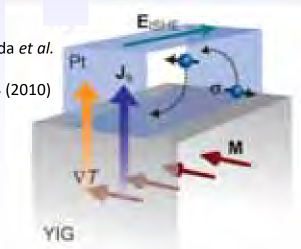
[1]S. Geller et al., J. Appl. Cryst. **2**, 86 (1969); Y. Krockenberger et al., Appl. Phys. Lett. **93**, 092505 (2008)

## 2. Generation and detection of the SSE signal




| Colorcode | Material | Thickness |
|---|---|---|
| Non.ferro. metal | Pt (Platinum) | 8-11nm |
| Ferrimag. film | YIG (Yttrium Iron Garnet) | 20-300nm |
| Substrate | GGG (Gadolinium Gallium Garnet) | 500µm |
| Isolation & Thermal Connection | $Al_2O_3$ & thermal conduction tape | ~800µm |
| Heat bath | Copper | |

Detection of $j_s$ using the inverse Spin Hall Effect
Longitudinal → no parasitic temperature gradient

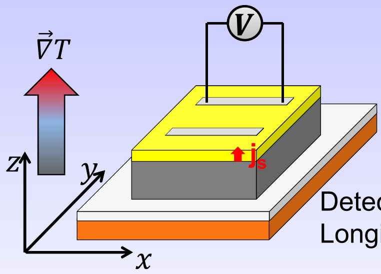



K. Uchida *et al.* APL **97**, 262504 (2010)

[1]A. Kehlberger et al., J. Appl. Phys. **115**, 17C731 (2014); M. Onbasli et al., APL Materials **2**, 106102 (2014).

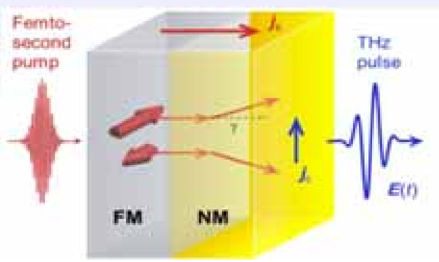
Mathias Kläui Mainz, 19.8.2016

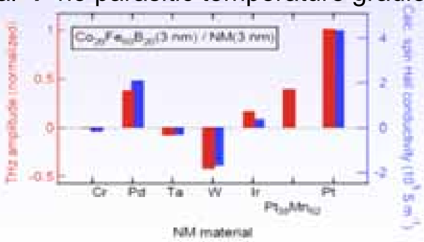
## 2. Detection of the SSE signal – optimizing the ISHE




| Colorcode | Material | Thickness |
|---|---|---|
| Non.ferro. metal | Pt (Platinum) | 8-11nm |
| Ferrimag. film | YIG (Yttrium Iron Garnet) | 20-300nm |
| Substrate | GGG (Gadolinium Gallium Garnet) | 500µm |
| Isolation & Thermal Connection | $Al_2O_3$ & thermal conduction tape | ~800µm |
| Heat bath | Copper | |

Detection of $j_s$ using the inverse Spin Hall Effect
Longitudinal → no parasitic temperature gradient

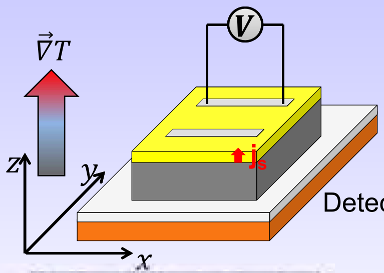



T. Seifert, T. Kampfrath, M. Kläui et al., Nature Photon. **10**, 483 (2016)

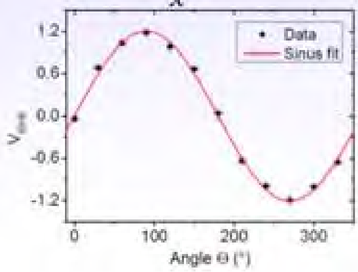
## 2. Angular dependence of the SSE signal

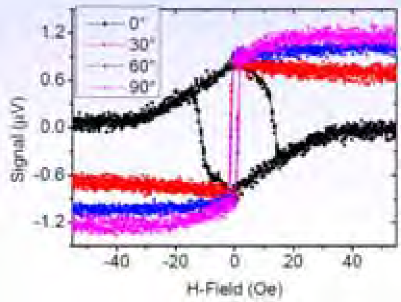
Longitudinal configuration




| Colorcode | Material | Thickness |
|---|---|---|
| Non.ferro. metal | Pt (Platinum) | 8-11nm |
| Ferrimag. film | YIG (Yttrium Iron Garnet) | 20-300nm |
| Substrate | GGG (Gadolinium Gallium Garnet) | 500µm |
| Isolation & Thermal Connection | $Al_2O_3$ & thermal conduction tape | ~800µm |
| Heat bath | Copper | |

Detection of $j_s$ using the inverse Spin Hall Effect

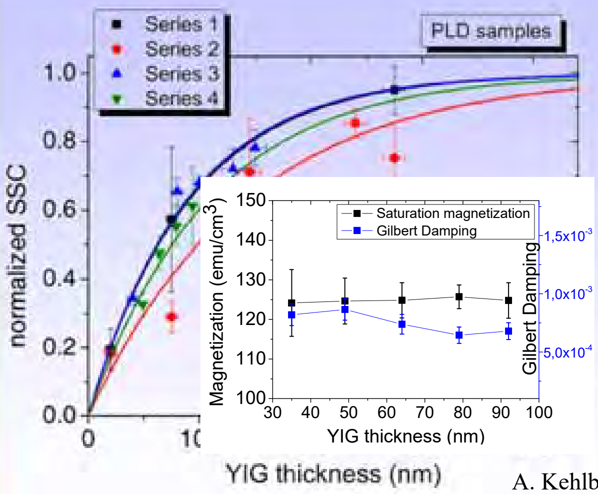



[1]A. Kehlberger et al., J. Appl. Phys. **115**, 17C731 (2014); M. Onbasli et al., APL Materials **2**, 106102 (2014).

Mathias Kläui Mainz, 19.8.2016

## 3. Thickness dependence of the SSE signal




- Signal increases and then saturates with increasing thickness
- → thickness dependence demonstrates that observed signal originates from bulk!
- Materials parameters (saturation magnetization & damping are constant).

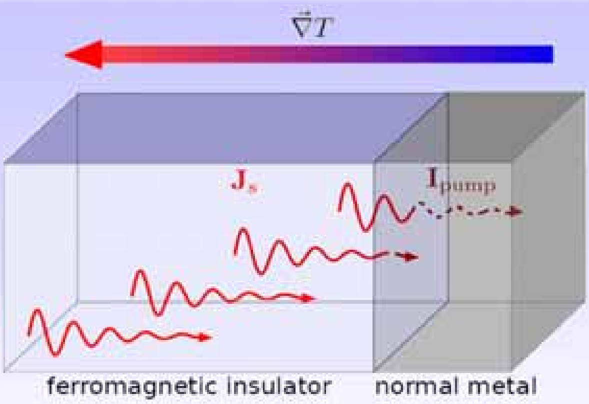
→Intrinsic Spin Seebeck Effect effect exists in longitudinal geometry of YIG/Pt!

A. Kehlberger et al., PRL **115**, 096602 (2015)

Problem 1: uncontrolled temperature gradients solved by using longitudinal geometry
Problem 2: charge caloric effects in ferromagnetic metals solved by insulating magnet
Problem 3: no proximity induced interface effects as shown by thickness dependence

Mathias Kläui Mainz, 19.8.2016

## 3. Theoretical model for thickness dependence of SSE



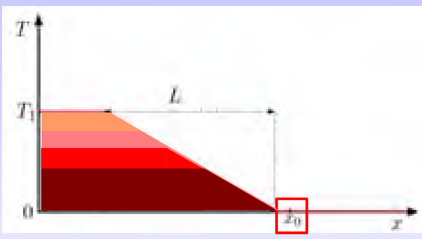

A. Kehlberger et al., Phys. Rev. Lett. **115**, 096602 (2015)

Further theoretical predictions:
J. Xiao, G. Bauer et al., Phys. Rev. B 81, 214418 (2010);
S. Hoffman et al., Phys. Rev. B 88, 064408 (2013).
L. Cornelissen et al., arxiv:1604.03706

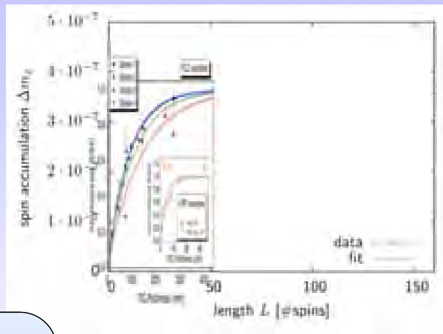
- Bulk origin of SSE signal → magnonic spin current (insulator!).
- Excited magnons have a finite effective propagation length (reach).
- Increased thickness → more generated magnons reach the interface
- As film thickness reaches the propagations length of the magnons → number of magnons reaching the interface becomes constant

Mathias Kläui Mainz, 19.8.2016

## 3. Theoretical model for the thickness dependence of SSE




A. Kehlberger et al., Phys. Rev. Lett. **115**, 096602 (2015)




**Simulation system:**

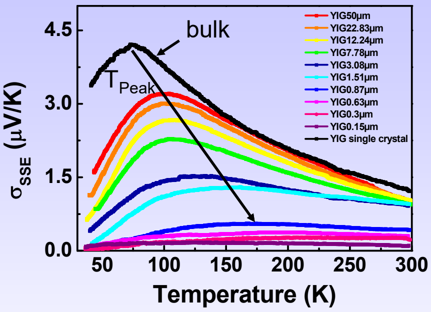
- Atomistic simulations based on the Landau Lifschitz equation
- Anisotropie constant $d_x = 0.1\, J$
- Length of the temperature gradient $L$
- Gilbert damping constant $\alpha = 0.1$
- Spin accumulation $\Delta m_x$ at position $x_0$ ($T = 0\, K$)
- We derive $\Delta m_x$ for a constant temperature gradient $dT/dx$ but different lengths $L$

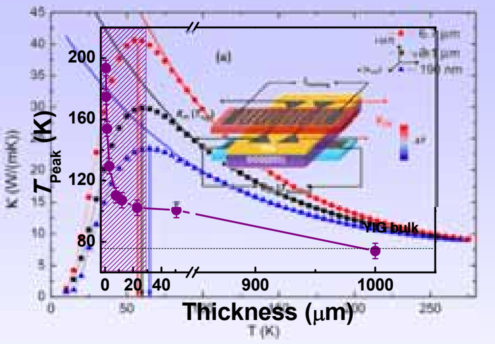
- The spin accumulation $\Delta m_x$ show a saturation signal, which can be approximated by a geometric series:

$$\Delta m_x \propto \left(1 - e^{(-L/\xi)}\right)$$

L: Length of the temperature gradient = sample thickness
$\xi$: Magnon propagation length

# 4. Temperature dependence of the SSE signal – role of bulk



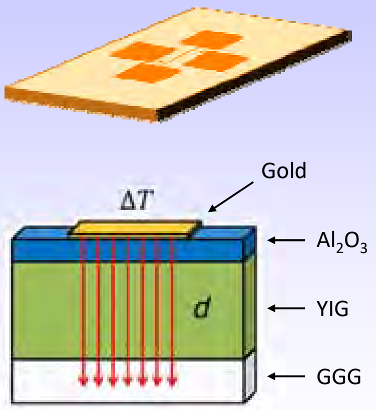

E.-J. Guo et al., PRX (2016) arXiv:1506.06037  C. Euler et al., Phys. Rev. B **92**, 094406 (2015)

- Signal enhancement at low T (see also K. Uchida et al. APL 97, 252506 (2010))
- Peak position increases with decreasing film thickness
  - Decreasing number of magnons ↔ Increasir
- Peak position of $\sigma_{SSE}$ and κ do not coincide
- No pronounced thickness dependence for the pe

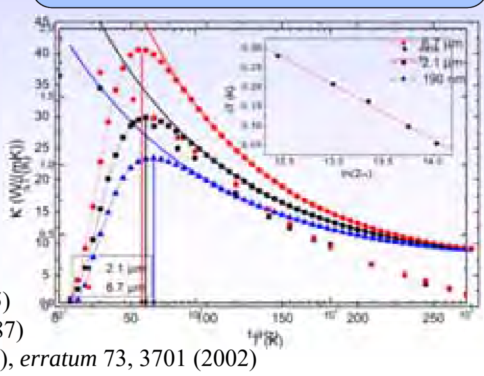
Magnon-phonon coupling not dominating low T SSE enhancement

Mathias Kläui Mainz, 19.8.2016

# 4. Determination of thermal conductivity by 3ω method

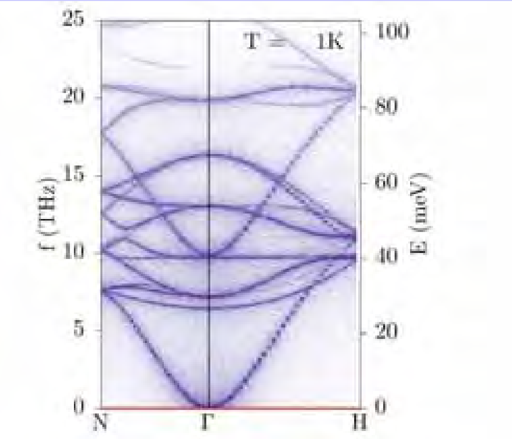


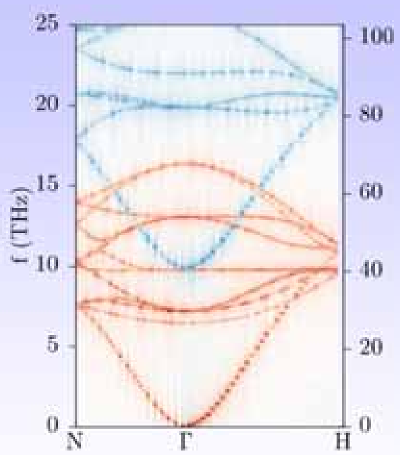

- 2ω heating by AC signal
- Simultaneous resistance detection
  → $U_{3\omega}$ contribution (slope yields κ)
- Signal influenced by heat transport in material
- YIG: Bayesian statistics required



C. Euler et al., Phys. Rev. B **92**, 094406 (2015)
D. G. Cahill et al., Phys. Rev. B **35**, 4067 (1987)
D. G. Cahill, Rev. Sci. Instrum. **61**, 802 (1990), *erratum* 73, 3701 (2002)

## 4. YIG Temperature dependence of the SSE – role of bulk



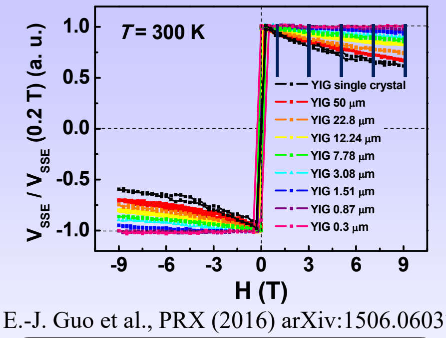

Two types of magnons: + decreases magnetization
- increases magnetization

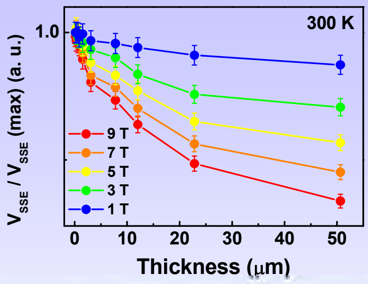
Calculation by J. Barker and G. Bauer (Tohoku)

- Temperature dependence of the magnon dispersion relation leads to temperature dependent spin current → quantitative comparison?



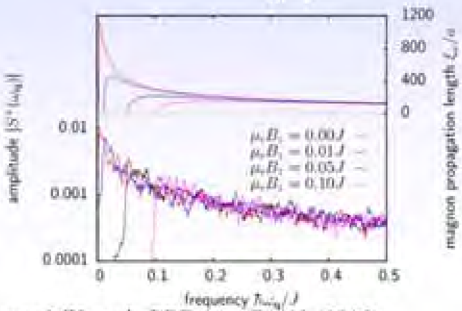
## 5. Field suppression of the SSE signal



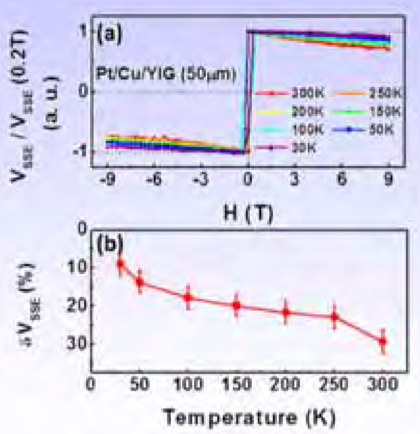

E.-J. Guo et al., PRX (2016) arXiv:1506.06037

- Signal suppression for high magnetic fields
- Higher field suppression for thick films
- Low energy magnons suppressed
→ mean propagation length reduction




T. Kikkawa et al., PRB **92**, 64413 (2015) U. Ritzmann, MK et al., PRB **92**, 174411 (2015)

## 5. Field suppression of the SSE signal



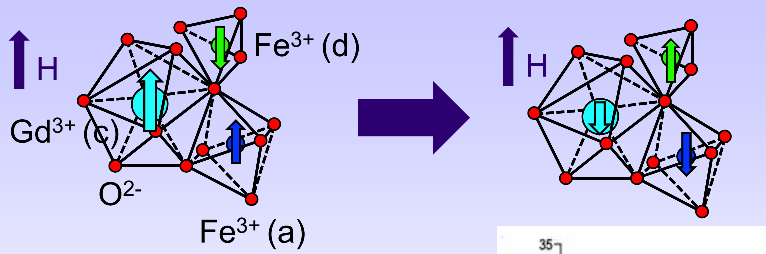

- Reduced suppression at low temperatures
- Increased propagation length counteracts field suppression
- Strong suppression expected at further decreased temperatures (opening Zeeman gap)

Magnon distribution manipulation by magnetic fields possible

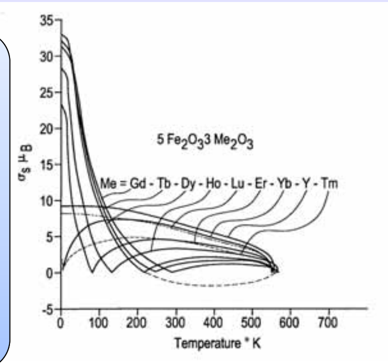
E.-J. Guo et al., PRX (2016) arXiv:1506.06037



## 6. SSE signal in GIG (Gd Iron Garnet)



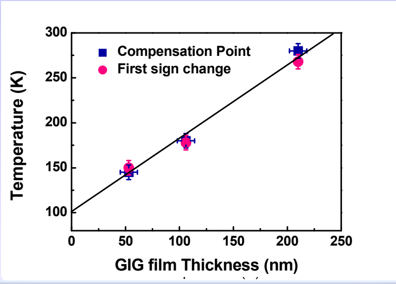

- Gadolinium Iron Garnet (GIG): Ferrimagnet with 3 sublattices:
  a-site Fe, d-site Fe, c-site Gd.
  a-site Fe and d-site Fe: AFM coupling
  d-site Fe and c-site Gd AFM coupling
- Depending on temperature different sites dominate: low temperature c-site Gd with a-site Fe; high temperature d-site Fe
- Compensation temperature: ~285 K

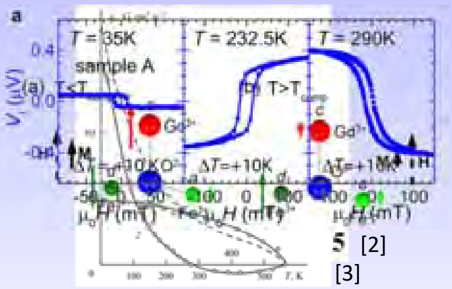



K. P. Belov, Phys. Usp. **39** 623 (1996)

Mathias Kläui Mainz, 19.8.2016

## 6. SSE signal in GIG (Gd Iron Garnet)




[2]

[3]

**Gadolinium Iron Garnet (GIG):**

- Magnetic compensation point at ~285 K

**First SSE sign change at high temp close to magnetic compensation point:**

- **Fe** on **a** site and **d** site couple antiferromagnetially; **c** site **Gd** weakly coupled to **a** site → compensation of magnetic moment → sign change

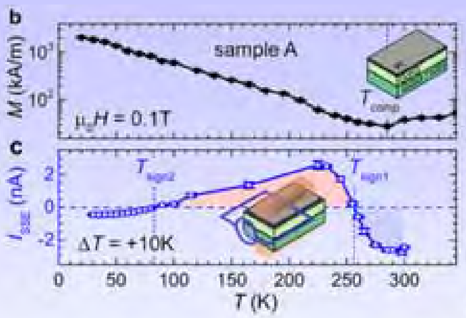
**Second sign change at low temp ~80K:**

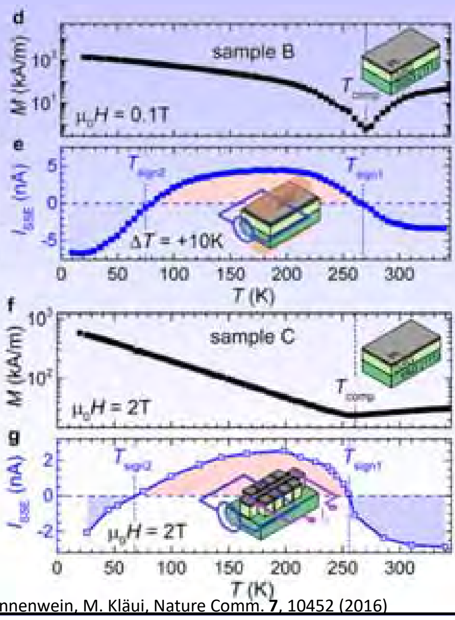
- **Gd** moment strongly increases at with temperatures → at low temperatures **Gd** dominates the spin current signal → sign change

[1]S. Geprägs et al., Nature Comm. **7**, 10452 (2016) [2]Y. Ohnuma et al., Phys. Rev. B **87**, 014423 (2013) [3]K. P. Belov, Phys. Usp. **39** 623 (1996)

Mathias Kläui Mainz, 19.8.2016

## 6. SSE signal in GIG (Gd Iron Garnet)




**Gadolinium Iron Garnet (GIG)**

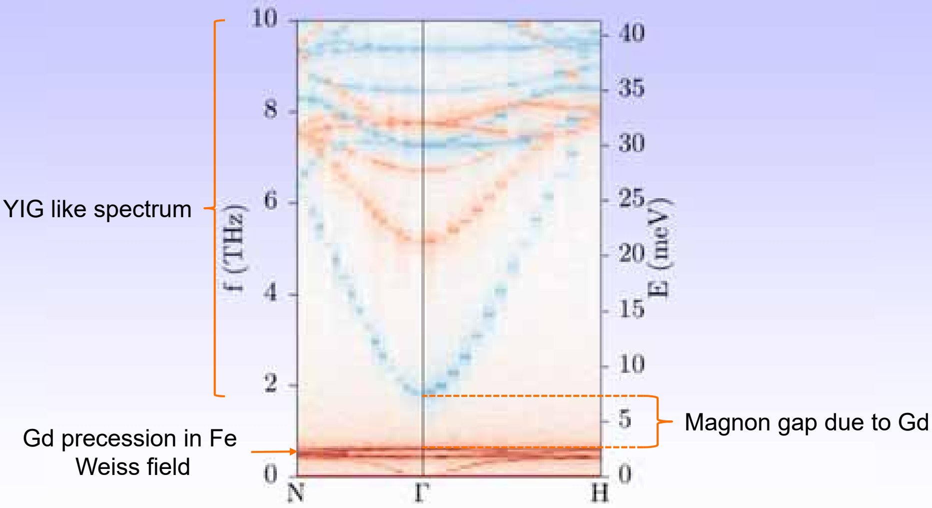
- Sign Changes are reproducible for samples grown by different groups on different substrates!

A: Johannes Gutenberg University Mainz
B: IMR, Tohoku University
C: WMI, TU Munich

[1]S. Geprägs, …, J. Barker, G. Bauer, S. Maekawa, E. Saitoh, S. Gönnenwein, M. Kläui, Nature Comm. **7**, 10452 (2016)

Mathias Kläui Mainz, 19.8.2016

## 6. Magnon spectrum in GdIG

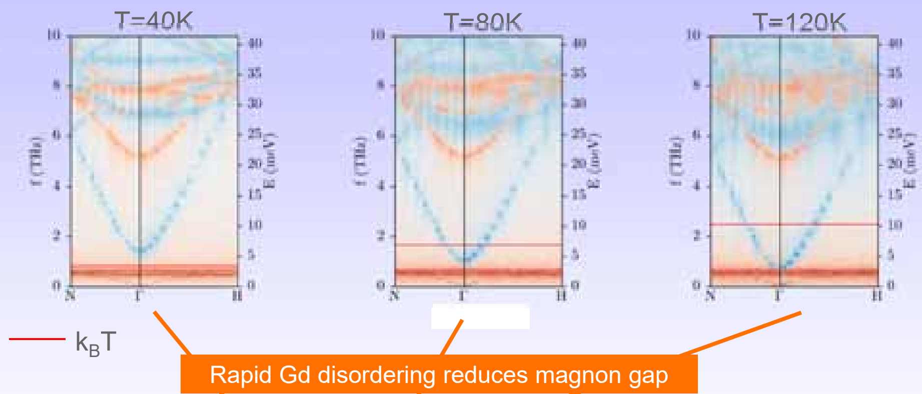


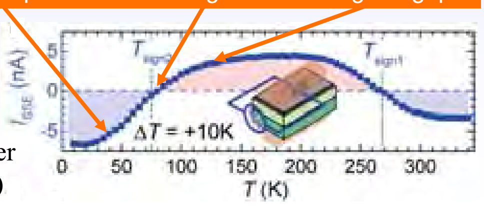

Calculation by J. Barker and G. Bauer (Tohoku)

S. Geprägs, …, J. Barker, G. Bauer, S. Maekawa, E. Saitoh, S. Gönnenwein, M. Kläui, Nature Comm. **7**, 10452 (2016)

Mathias Kläui Mainz, 19.8.2016

## 6. SSE sign change in GdIG due to bulk effects

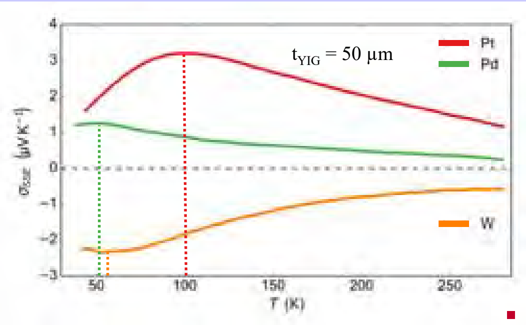



Calculation by J. Barker and G. Bauer (Tohoku)

S. Geprägs, …, J. Barker, G. Bauer, S. Maekawa, E. Saitoh, S. Gönnenwein, M. Kläui, Nature Comm. **7**, 10452 (2016)

## 7. Spin current transmission across YIG/NM interfaces




- SSE as a function of temperature for Pt, Pd, and W capping layer

| $T_{Pt}$ | $T_W$ | $T_{Pd}$ |
|---|---|---|
| ≈ 101 K | ≈ 59 K | ≈ 51 K |

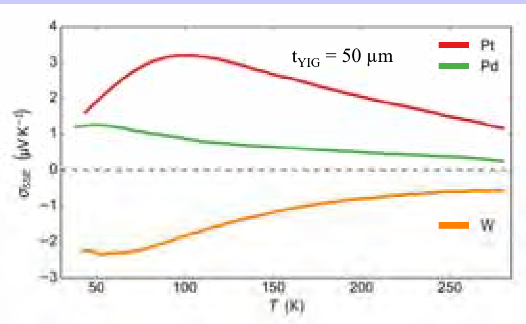
- **Low temperature signal peak shifts for varying capping layers**
- No differences due to bulk YIG properties
  - Same YIG thickness
  - Samples cut from one wafer

- Different sign for Pt/Pd and W
  - Spin Hall angle (pos/neg)
- Change of signal amplitude
  - Sheet resistance
  - Spin mixing conductance

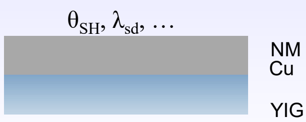
T. Seifert, T. Kampfrath, M. Kläui et al., Nature Photon. **10**, 483 (2016).



## 7. Spin current transmission across YIG/NM interfaces




- ~~Shift due to intrinsic NM properties:~~
  - ~~Temperature dependence of spin Hall angle $\theta_{SH}$~~
  - ~~Temperature dependence of spin diffusion length $\lambda_{sd}$~~
  - ~~…~~

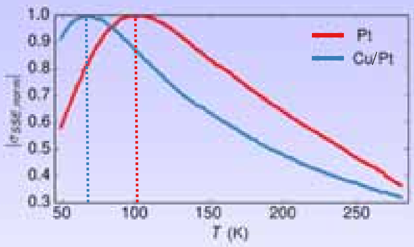


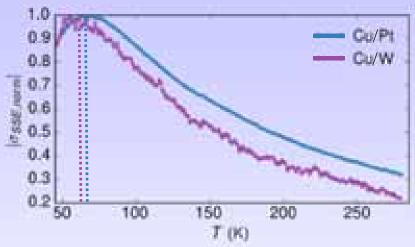

- Insertion of Cu (2 nm) spacer layer
  - Large spin diffusion length (several 100 nm[1])
  - Large spin transmission at Cu/NM interface
  - → No change of $T_{peak}$ expected
- Reduction of $\sigma_{SSE}$, shift of signal peak

[1] Villamor *et al.*, Phys. Rev. B **88**, 184411 (2013)

Mathias Kläui Mainz, 19.8.2016

## 7. Influence of interface condition on SSE




- Comparison of spin transmission in YIG/Pt and YIG/Cu/Pt
- Large shift of $\Delta T_{peak} \approx 35$ K in case of YIG/Pt and YIG/Cu/Pt

  → $\Delta T_{peak}$ not due to intrinsic properties of detection layer

- Comparison of spin transmission in YIG/Cu/Pt and YIG/Cu/W
- Amplitude different, but $T_{peak}$ is the same

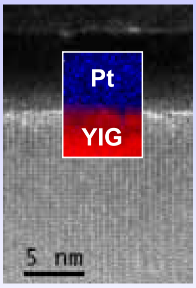
  → Direct YIG/NM interface gives dominating effect

Guo, MK *et al.*, PRX 6, 031012 (2016)

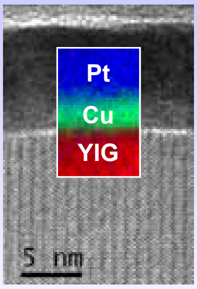
Mathias Kläui Mainz, 19.8.2016

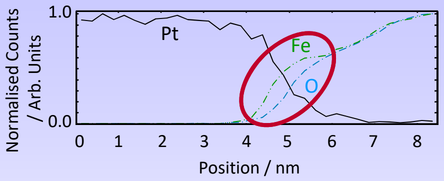
## 7. Analysis of atomistic interface structure

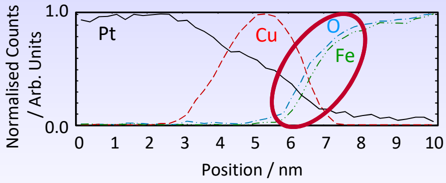
YIG/Pt




YIG/Cu/Pt




- Transmission electron microscopy
  - High
  - Well-defined interface
- Electron energy loss spectroscopy
  - → O termination for YIG/Cu/Pt

**Mode dependent interface transmission affected by interface condition (capping layer → YIG termination)**

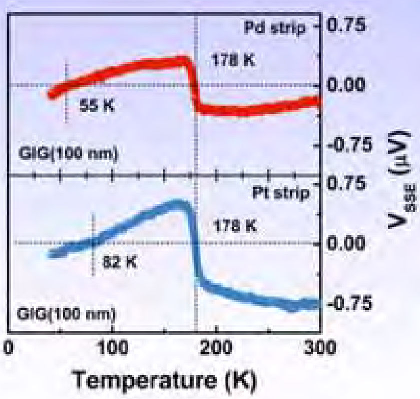
Measurements performed by D. MacLaren, University of Glasgow

Guo, MK *et al.*, PRX 6, 031012 (2016)

## 7. Interface effect in GIG (Gd Iron Garnet)/NM

**SSE in GdIG (100 nm) / Pd (Pt) bilayer**

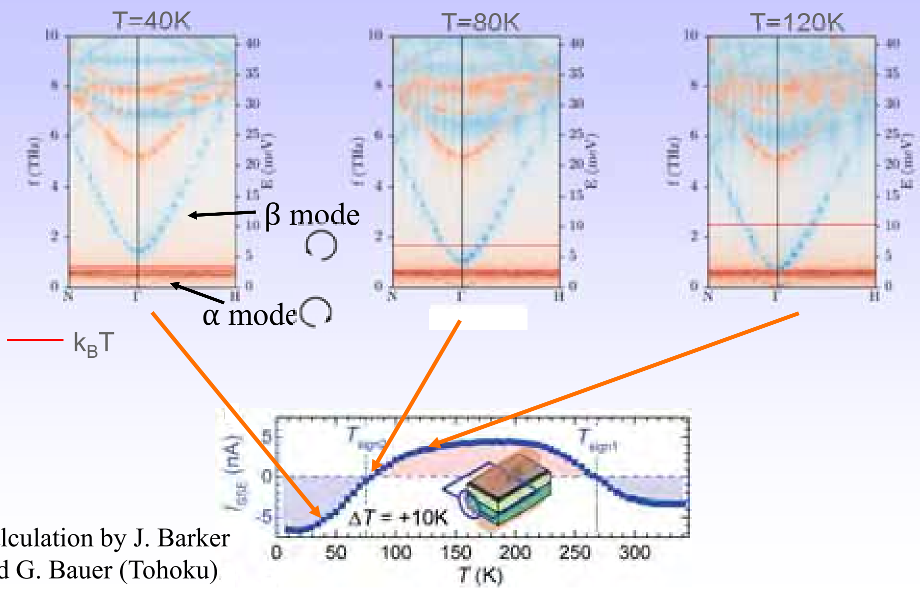
- GdIG / Pt vs. GdIG / Pd
  - Reduced amplitude for Pd
  - $T_{sign1}$ remains unchanged
  - $T_{sign2}$ at higher temperatures for Pt
- Identical bulk system → shift of $T_{sign2}$ due to changed interface exchange coupling




[3]Y. Ohnuma et al., Phys. Rev. B **87**, 014423 (2013)

Mathias Kläui Mainz, 19.8.2016

## 7. SSE sign change in GdIG due to bulk effects




Calculation by J. Barker and G. Bauer (Tohoku)

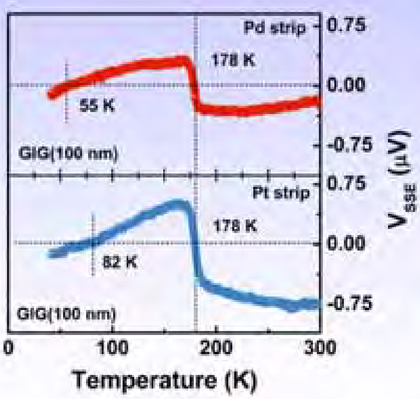
S. Geprägs, ..., J. Barker, G. Bauer, S. Maekawa, E. Saitoh, S. Gönnenwein, M. Kläui, Nature Comm. **7**, 10452 (2016)

Mathias Kläui Mainz, 19.8.2016

## 7. Interface effect in GIG (Gd Iron Garnet)/NM

**SSE in GdIG (100 nm) / Pd (Pt) bilayer**

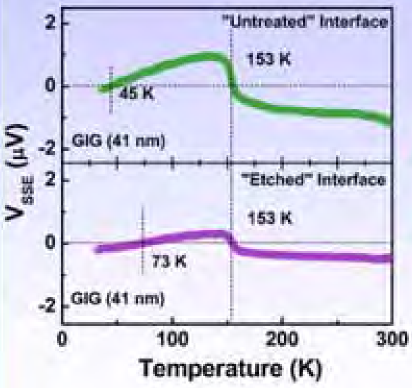
- GdIG / Pt vs. GdIG / Pd
  - Reduced amplitude for Pd
  - $T_{sign1}$ remains unchanged
  - $T_{sign2}$ at higher temperatures for Pt
- Identical bulk system → shift of $T_{sign2}$ due to changed interface exchange coupling
- Possible explanation
  - Weaker interface exchange coupling of $\alpha$ mode in Pd
  - 4f Gd – Pt coupling more effective than 4f Gd – Pd coupling




Mathias Kläui Mainz, 19.8.2016

## 7. Interface effect in GIG (Gd Iron Garnet)/NM

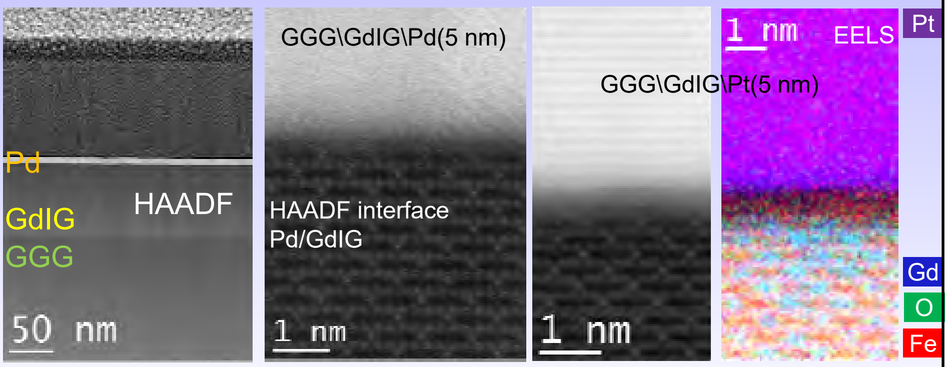
**SSE in GdIG (41 nm) / Pt bilayer**




- Unaltered interface vs. in-situ oxygen etching
  - Reduced amplitude
  - $T_{sign1}$ remains unchanged
  - $T_{sign2}$ shifted to higher temperatures
- Identical bulk system → shift of $T_{sign2}$ due to changed interface exchange coupling
- Possible explanation
  - Increased damping/ reduced transmissivity of $\beta$ mode
  - Less effective coupling of 3d Fe spins to Pt conduction electrons at etched interface

**Correlation between interface structure and transmissivity of particular magnon modes**

## 7. Interface structure analysis of GIG (Gd Iron Garnet)/NM

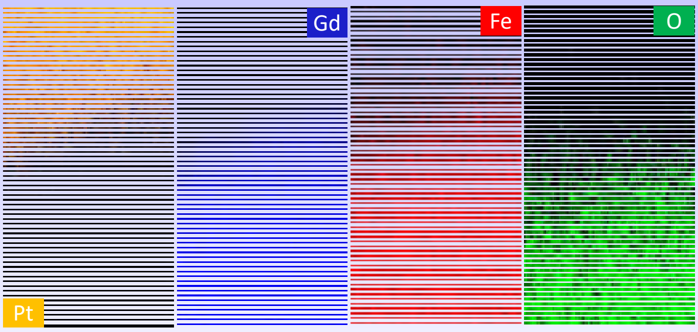



- HAADF microscopy shows smooth growth of GdIG on GGG and of Pd on a smooth GdIG surface.
- EELS shows some Pd and Pt intermixing at the interface.

GGG\GdIG\Pt(5 nm) and GGG\GdIG\Pd(5 nm) Imaging by Y. Ivanov and J. Kosel (KAUST)



## 7. Interface structure analysis of GIG (Gd Iron Garnet)/NM



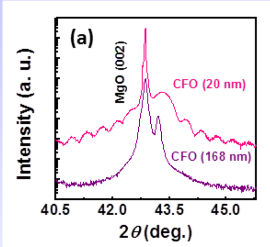

GGG\GdIG\Pt(7.5 nm)

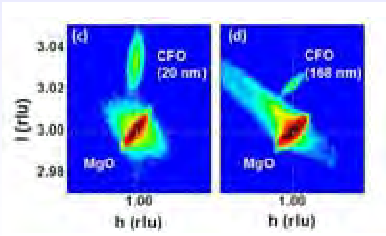
Imaging by Y. Ivanov and J. Kosel (KAUST)

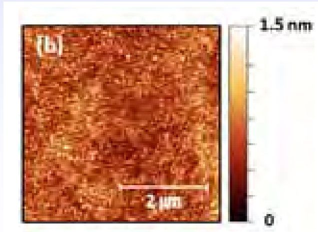
- HAADF microscopy shows smooth growth of GdIG on GGG and of Pd on a smooth GdIG surface.
- EELS shows some intermixing at the interface.
- For GdIG/Pt a clear Fe-Gd termination is visible.
- Analysis ongoing (theoretical input welcome!)

## 8. Spin Seebeck effect in Cobalt Ferrite (CFO)

- $CoFe_2O_4$ (CFO)
  - $T_c \approx 790$ K
  - Insulating (band gap ≈ 1.4 eV)
- Simple structure compared to YIG (spinel ferrite)
- High anisotropy and magnetostriction[1]
- Here: Smooth surface/in-plane tensile strain[2]



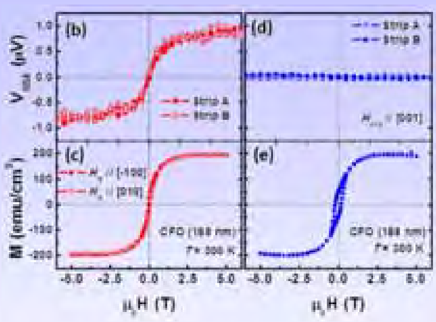



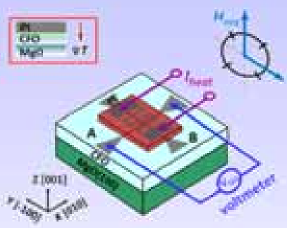



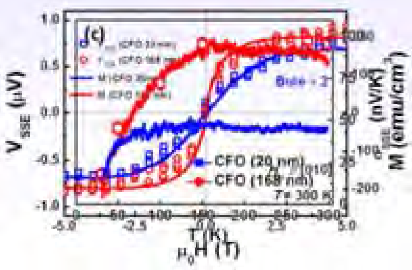

[1]Bozorth et al., Phys. Rev. B **99**, 1788 (1955) [2]E.-J. Guo et al., APL 108, 022403 (2016)

Mathias Kläui
Mainz, 19.8.2016

## 8. Spin Seebeck effect in Cobalt Ferrite (CFO)






E.-J. Guo et al., APL **108**, 022403 (2016)

- LSSE for Strip A/B in [100]/[010] direction
- SSE follows magnetization
  → Appropriate tool for sample characterization
- No low T enhancement observed

# Thanks!

## 1. Great group members:

A. Kehlberger, J .Cramer, B. Dong, E Guo
K. Litzius, K. Lee, I. Boventer, M. Braatz
D. Schönke, G. Karnad, P. Krautscheid,
B. Borie, M. Filianina, F. Musseau, F. Mu
A. di Lucia, R. Reeve, J. Cramer, H. Wan
P. Bassirian, B. Krüger, S. Jaiswal,, M. Weides, **H. Zabel, M. Jourdan, G. Jakob…**

## 2. Great support & collaborations:

U. Nowak, Konstanz; D. MacLaren, Glasgow;
M. Onbasli, C. Ross, MIT; T. Kuschel, Bielefeld;
S. Gönnenwein, WMI-TUD; Y. Ivanov, KAUST;
Y. Ohnuma, J. Barker, G. Bauer, E. Saitoh, S. Maekawa,…

## 3. Funding

European Research Council Grants MASPIC & MultiRev
DFG (SPP SpinCaT, SFB TRR173, MAINZ, KL1811/19), DAAD
EU (ITN Wall, STREP InSpin & MoQuS, IP IFOX), Zeiss Stiftung
Stanford-Tohoku-Mainz SpinNet, AvH Stiftung, BMBF, Samsung

MASPIC & MultiRev

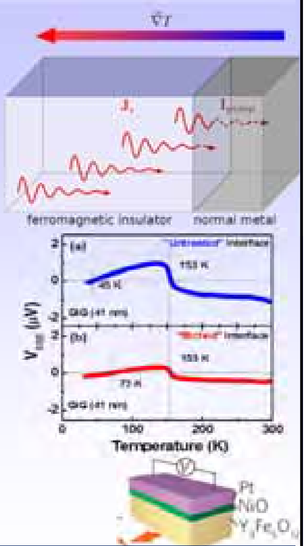
**Review on Ferrimagnetic Garnets: V. Cherepanov et al., Phys. Rep. 229, 81 (1993)**
**Review on SSE: G. Bauer et al., Nature Mater. 11, 391 (2012)**

www.klaeui-lab.de

Mathias Kläui Mainz, 19.8.2016

## Summary:

- Spin Seebeck Effect:
  The origin of the measured signals are thermal magnonic spin currents generated by the longitudinal SSE in the bulk ferrimagnet.
- Both the bulk properties (film thickness) and the interface (ISHE detector) govern the temperature dependence.
- SSE in GdIG is found to exhibit 2 sign changes: at the magnetization compensation point and at lower temperature. Different interfaces transmit the different magnon modes differently.
- Spin transport by magnons occurs in ferro- and antiferromagnets with an amplification at $T_{Néel}$




**References:** Phys. Rev. Lett. **115**, 096602 (2015); Phys. Rev. X **6**, 031012 (2016); Nature Commun. **7**, 10452 (2016); Nature Photon. **10**, 483 (2016)