

# Spin Hall Magnetoresistance in a Canted Ferrimagnet

Sebastian T. B. Goennenwein



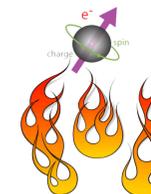
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**S. Meyer, S. Geprägs, H. Huebl, R. Gross**  
& WMI spintronics group  
Walther-Meißner-Institut



Bayerische  
Akademie der Wissenschaften

**J. Barker, G.E.W. Bauer, E. Saitoh** & groups  
Institute for Materials Research, Tohoku U, JPN  
Kavli Institute of NanoScience, TU Delft, NL

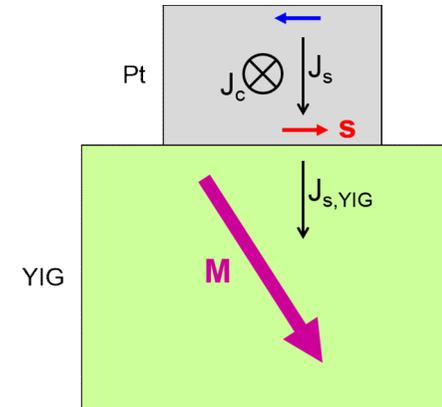
Financial support: Deutsche Forschungsgemeinschaft via  
SPP 1538 “SpinCAT” (GO 944/4) and  
Excellence Cluster NanoSystems Initiative Munich



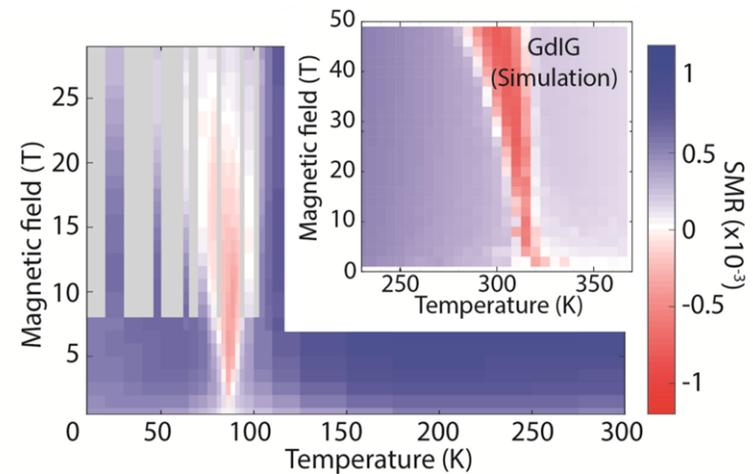
# Outline

## SMR = Spin Hall MagnetoResistance

... a spin current-based magnetoresistance  
@ magnetic insulator / metal interfaces

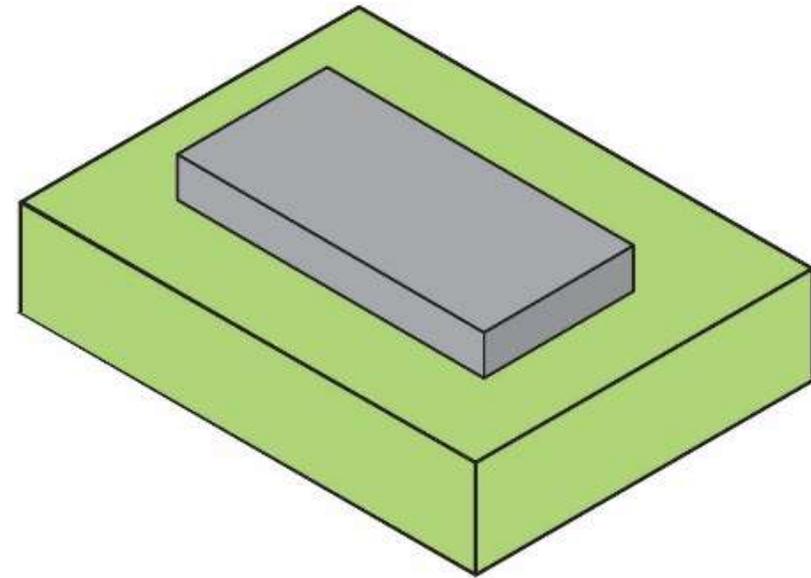
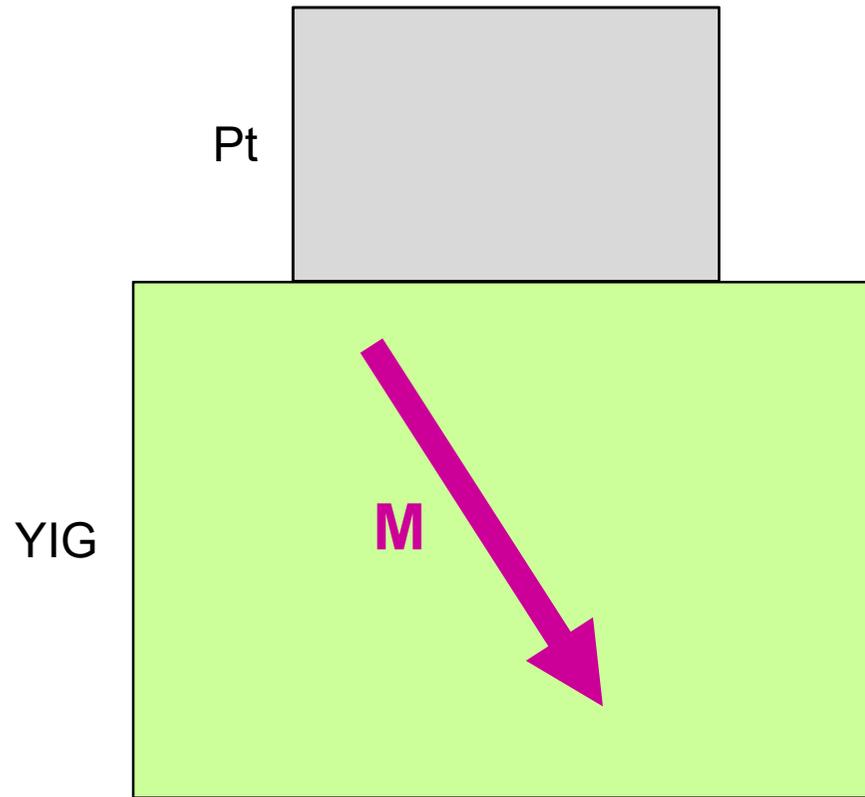


SMR in **non-collinear magnets**



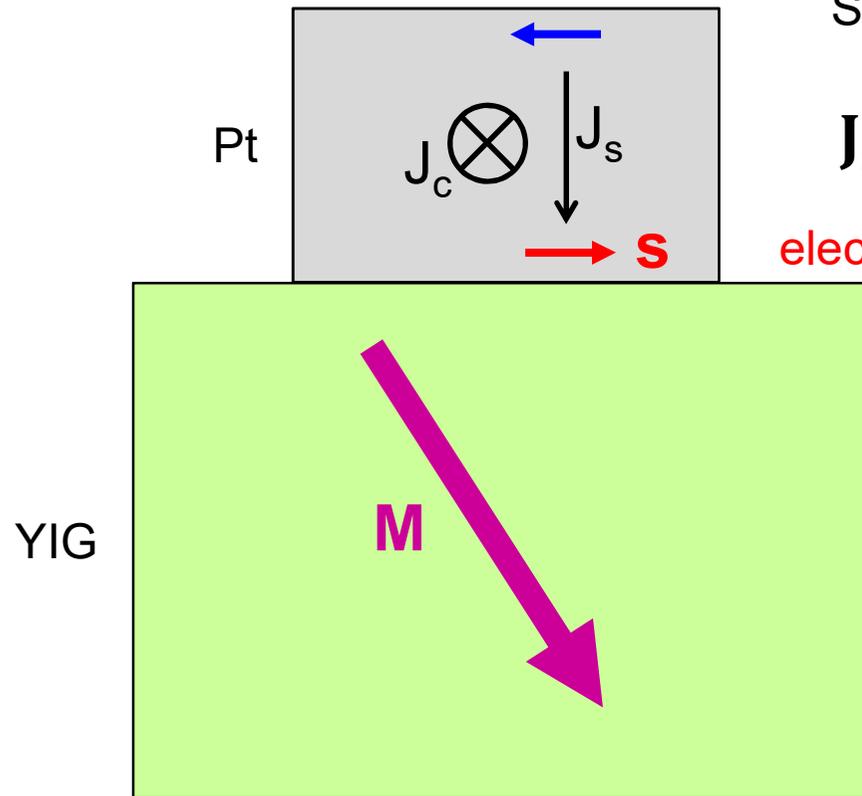
# Spin Hall MR in magnetic insulator / metal bilayers

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YIG:  $\text{Y}_3\text{Fe}_5\text{O}_{12}$   
ferrimagnet  
magnetically ordered  
but electrically insulating

# Spin Hall MR in magnetic insulator / metal bilayers

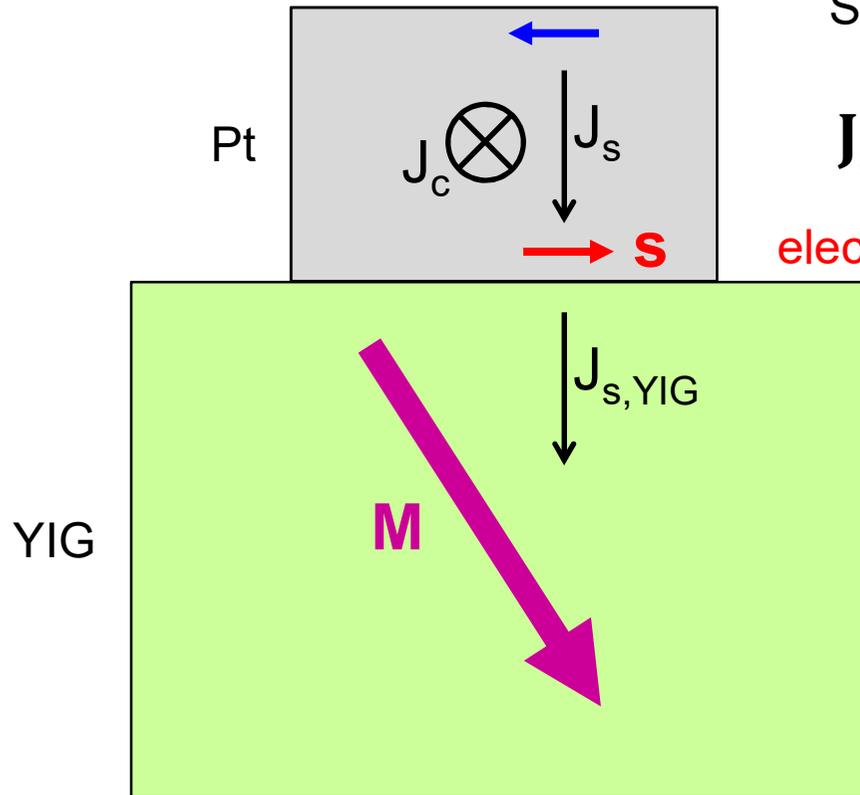


Spin Hall effect (SHE):

$$\mathbf{J}_s = \alpha^{\text{SHE}} \frac{\hbar}{2e} [\mathbf{J}_c \times \mathbf{S}]$$

electron spin accumulation in Pt with spin  $\mathbf{S}$

# Spin Hall MR in magnetic insulator / metal bilayers



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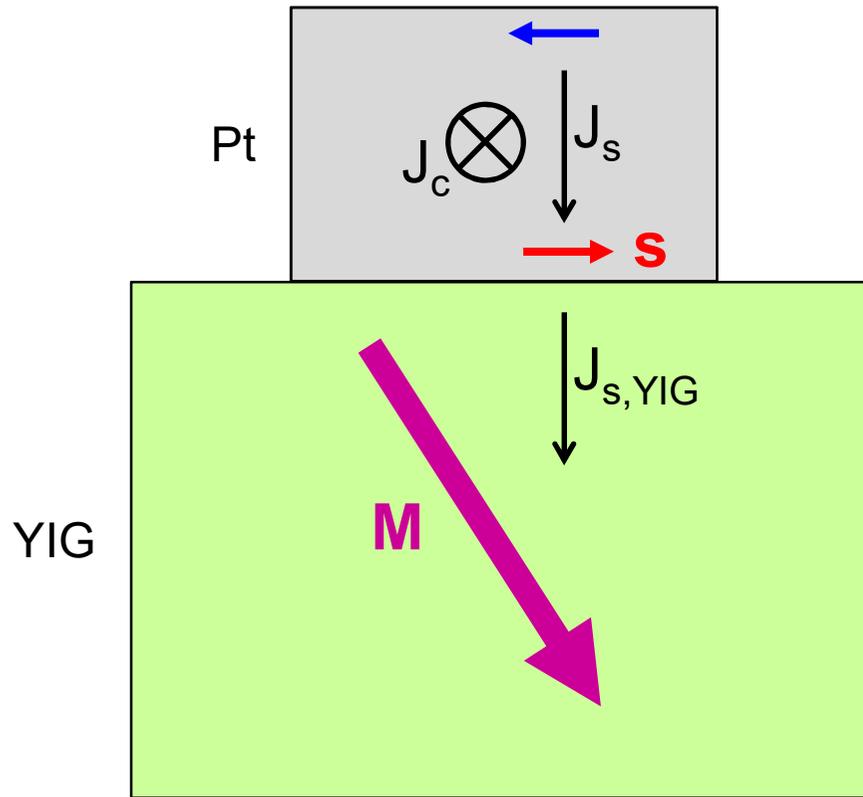
if  $\tau_{\text{STT}} \propto \mathbf{M} \times (\mathbf{M} \times \mathbf{s})$  is finite

$\Rightarrow$  outflow of  $J_s$  into YIG

**enhanced dissipation in Pt**

**$\Rightarrow$  larger Pt resistance**

# Spin Hall MR in magnetic insulator / metal bilayers

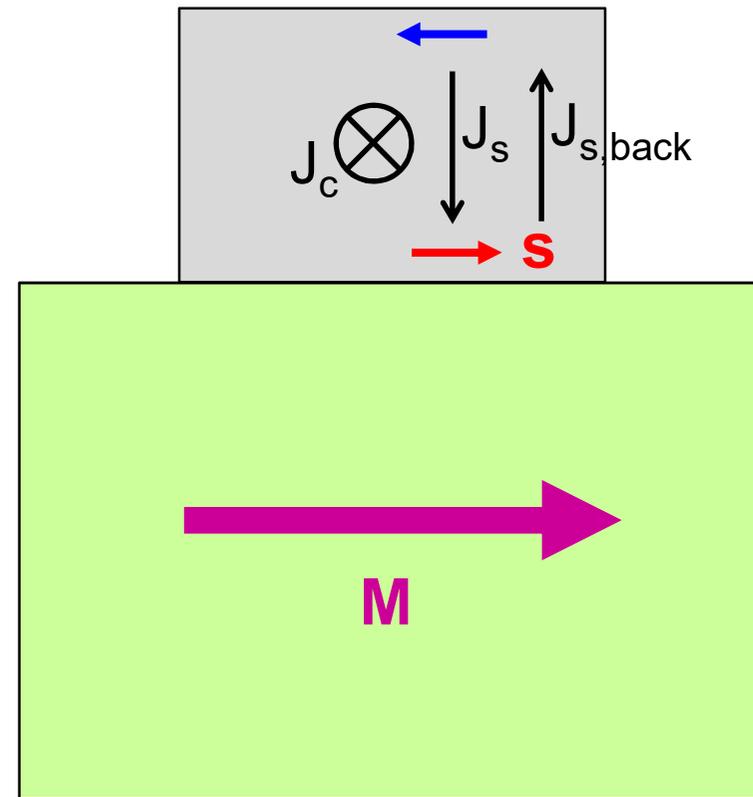


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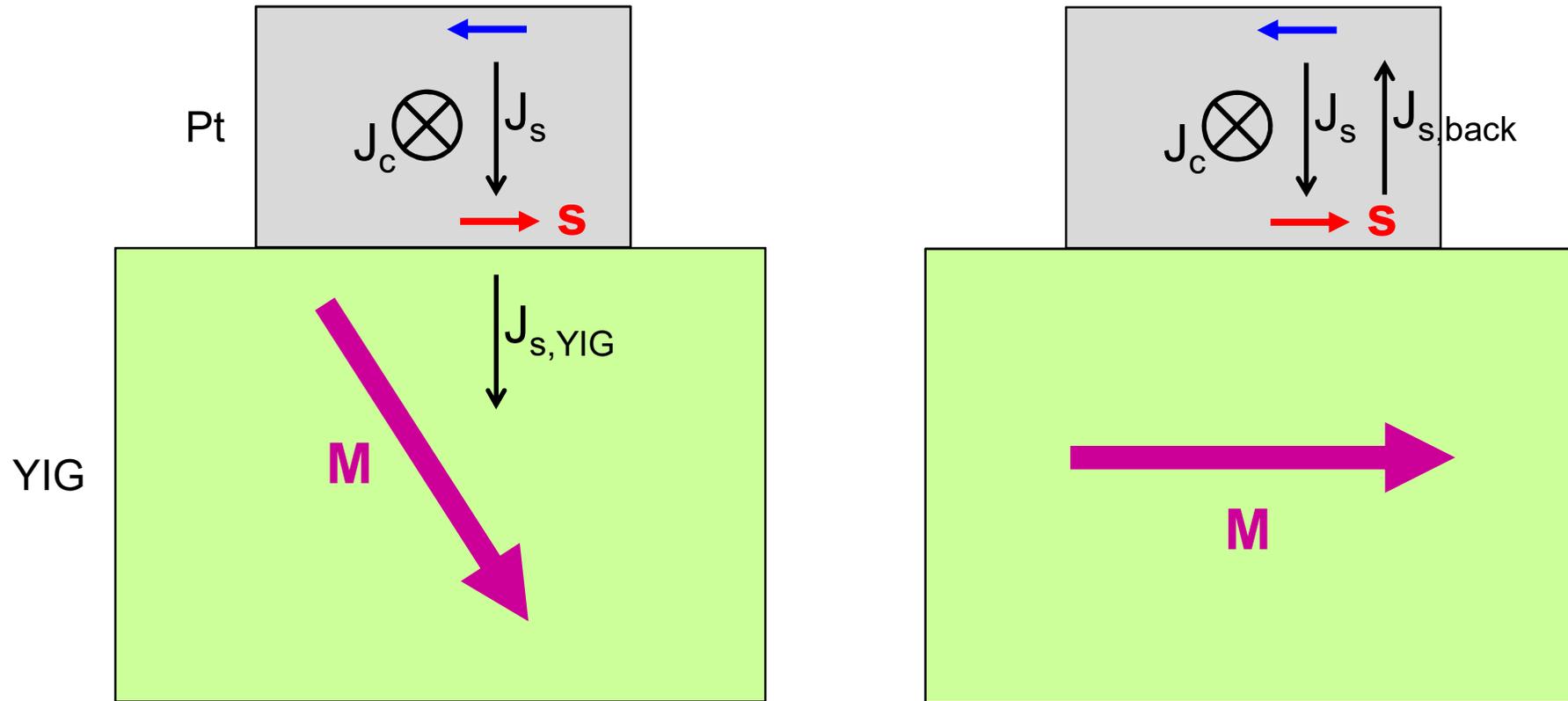
$\tau_{STT} \propto \mathbf{M} \times (\mathbf{M} \times \mathbf{s}) = 0$

$\Rightarrow$  open boundary conditions for  $J_s$

**reduced dissipation**

$\Rightarrow$  **smaller Pt resistance**

# Spin Hall MR in magnetic insulator / metal bilayers

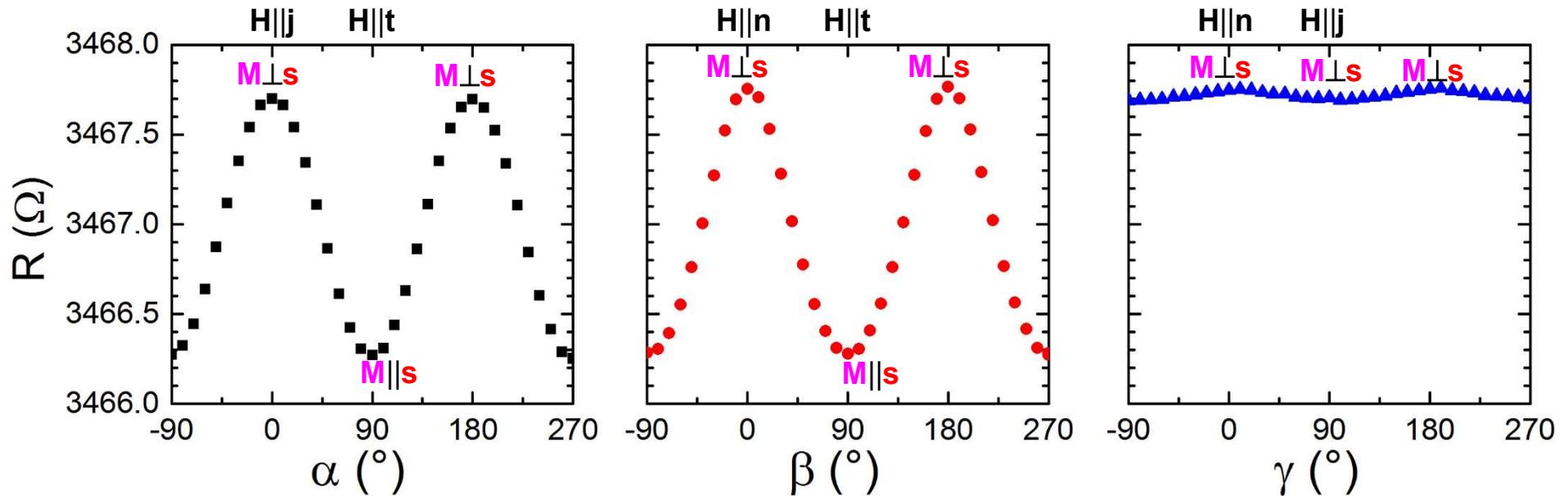
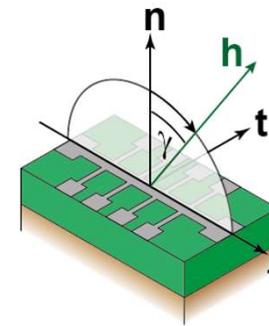
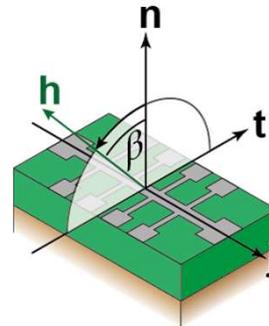
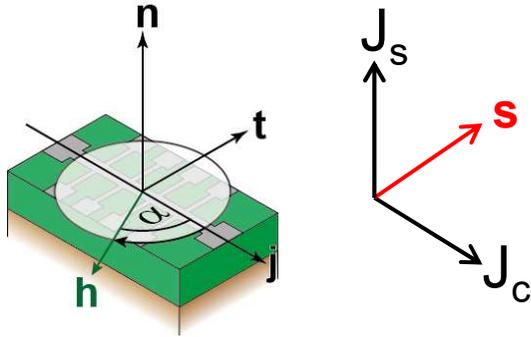


Spin Hall MR (SMR):  $R$  smallest for  $\mathbf{M} \parallel \mathbf{s}$ , larger otherwise

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

# SMR fingerprint

Spin Hall MR (SMR): R smallest for  $\mathbf{M} \parallel \mathbf{s}$  (viz.  $\mathbf{H} \parallel \mathbf{t}$ ), larger otherwise



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

# Outline

## SMR = Spin Hall MagnetoResistance

... a spin current-based magnetoresistance  
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Nakayama *et al.*, PRL **110**, 206601 (2013).

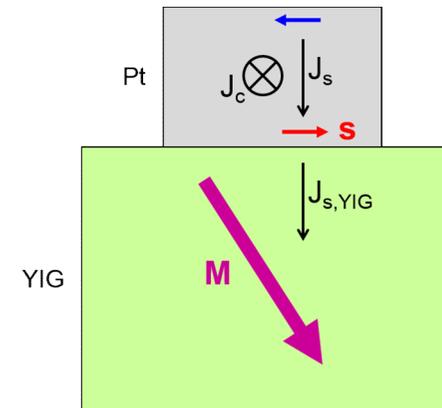
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Hahn *et al.*, PRB **87**, 174417 (2013).

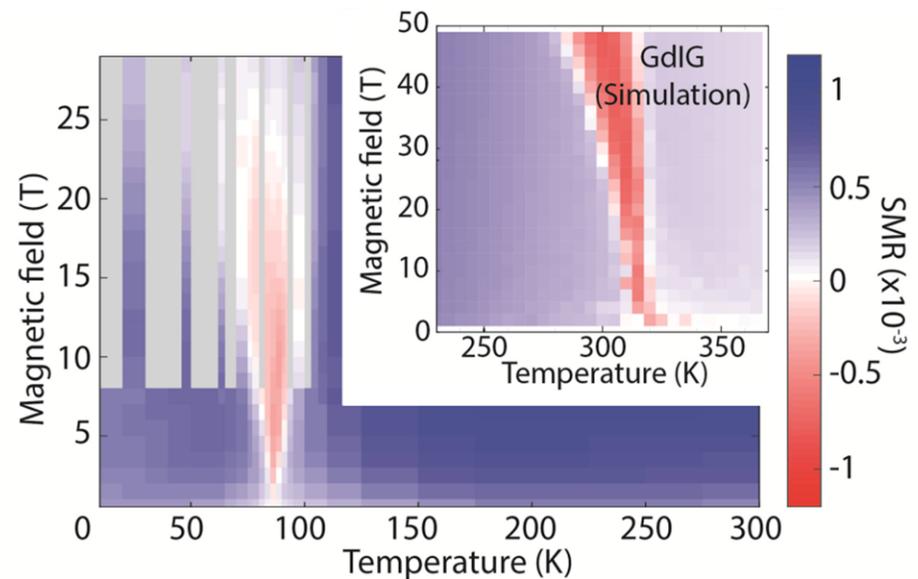
Vlietstra *et al.*, PRB **87**, 184421 (2013).

Althammer *et al.*, PRB **87**, 224401 (2013).

review: Chen *et al.*, J. Phys.: Condens. Matter **28**, 103004 (2016).



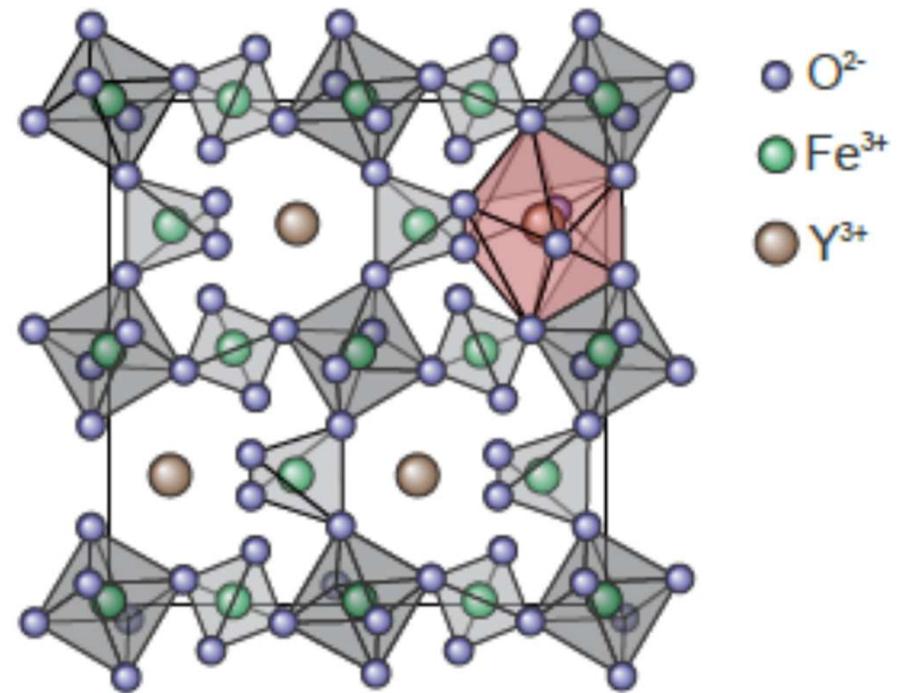
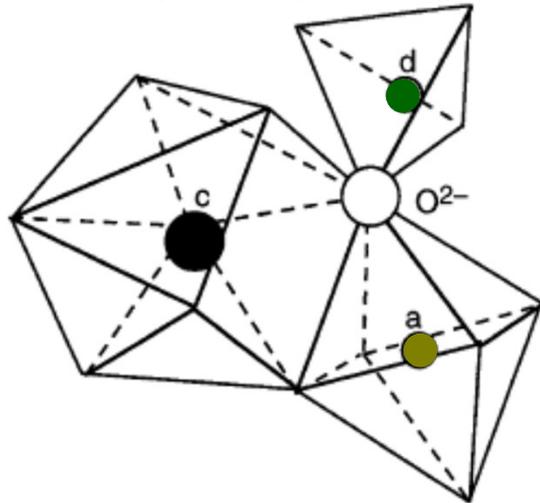
SMR in **non-collinear magnets**



# Magnetic garnets



is the prototype magnetic garnet

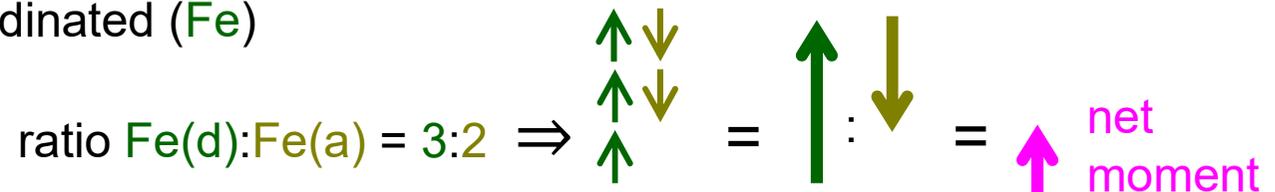


c site: dodecahedrally coordinated ( $Y^{3+}$ )

a site: octahedrally coordinated (Fe)

d site: tetrahedrally coordinated (Fe)

YIG is a ferrimagnet :

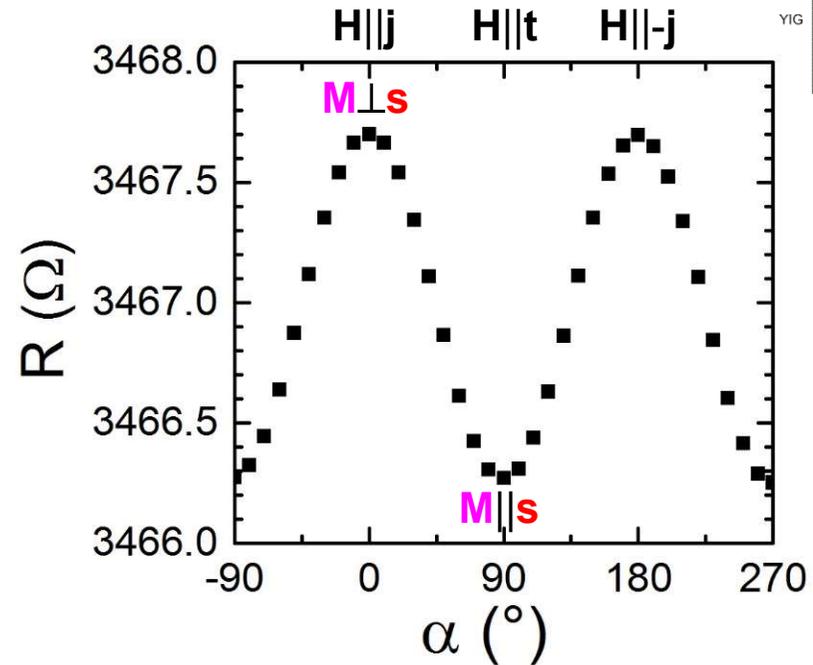
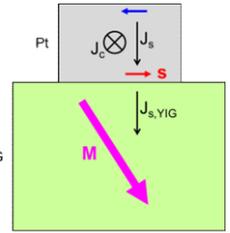
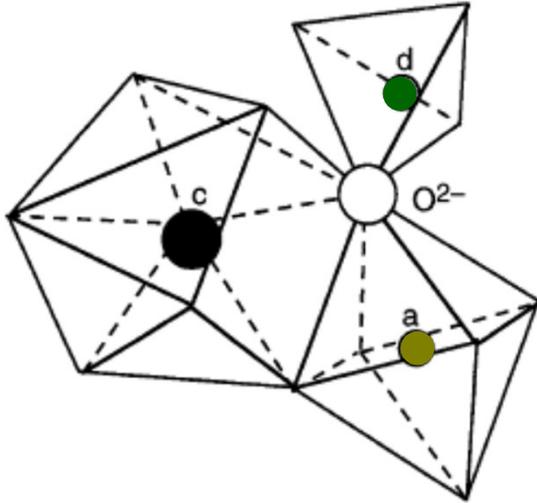


... and an electrical insulator with a gap of  $\sim 3eV$

# SMR in magnetic garnets



is the prototype magnetic garnet



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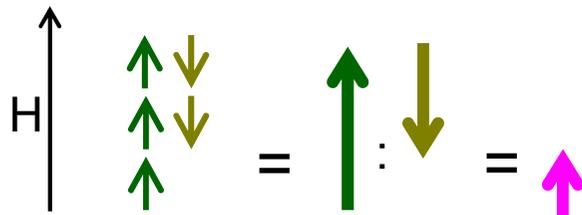
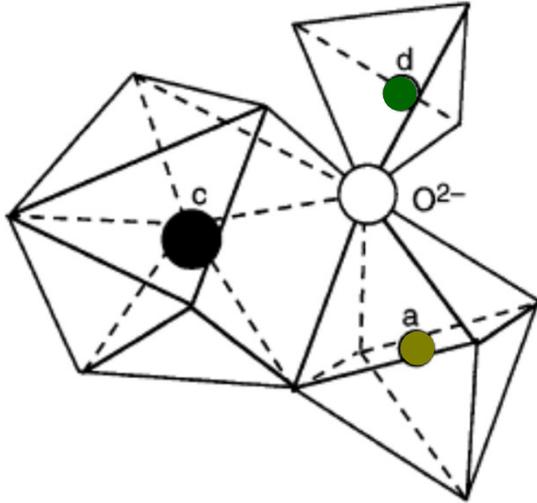
YIG is a ferrimagnet : ratio  $Fe(d):Fe(a) = 3:2 \Rightarrow$  = net moment

... and an electrical insulator with a gap of  $\sim 3eV$

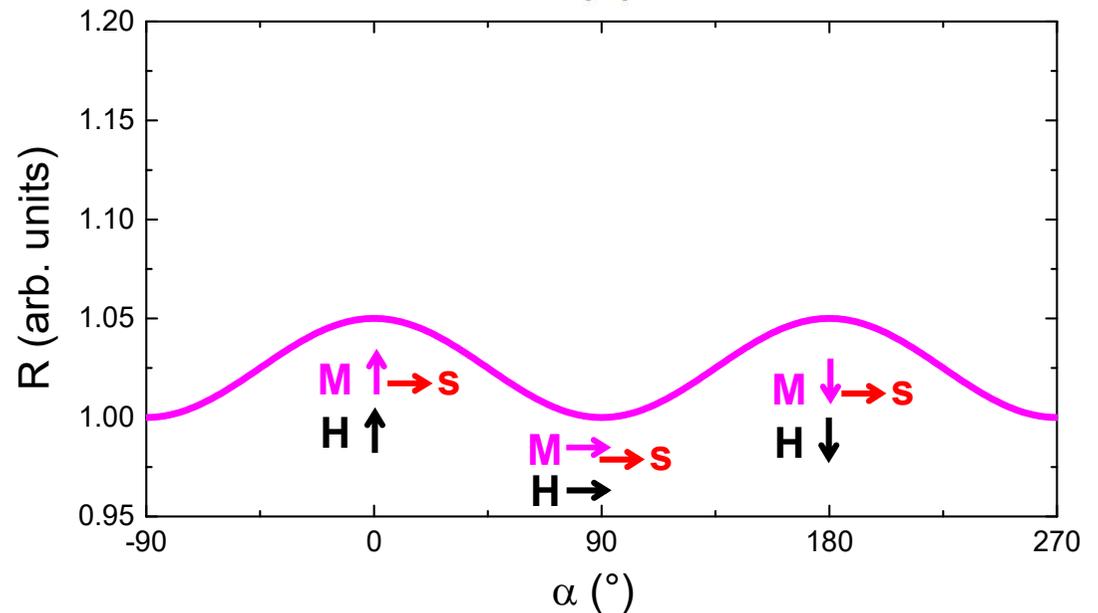
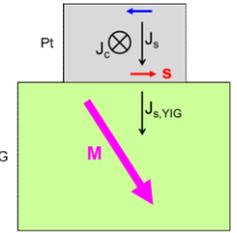
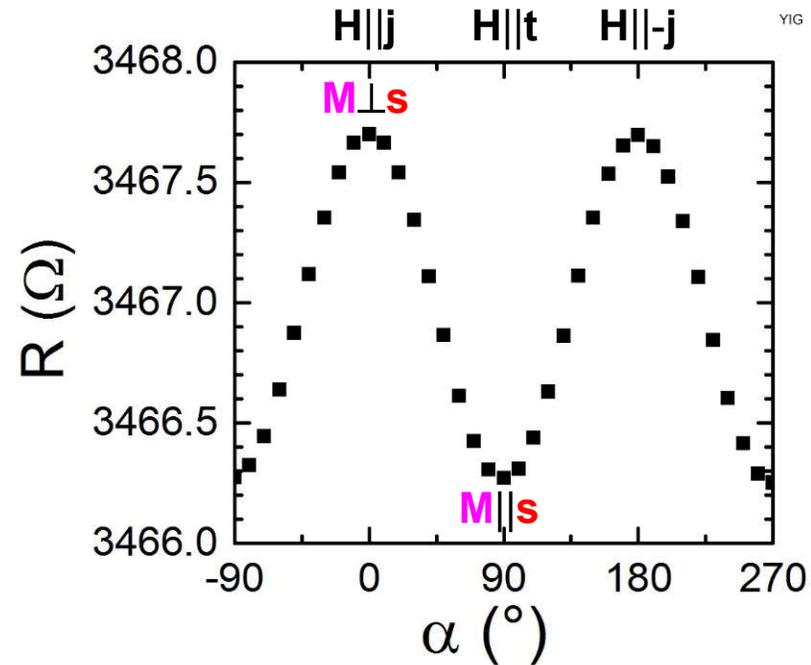
# SMR in magnetic garnets



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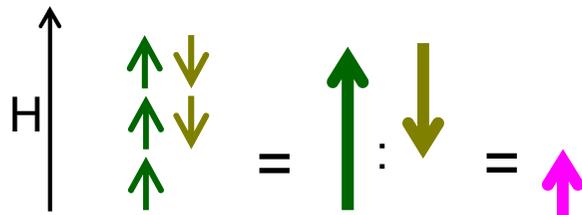
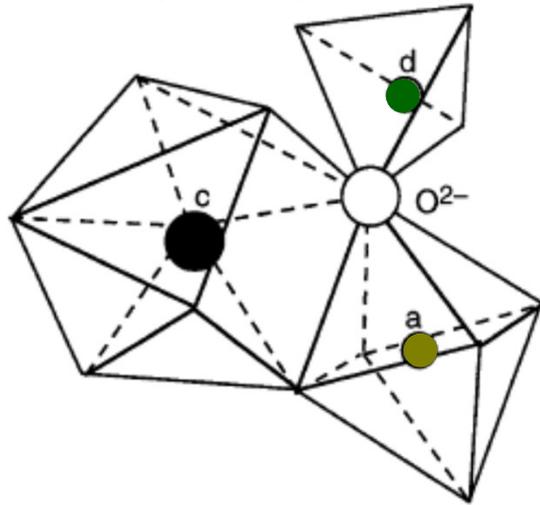
$$R = R_0 + R_1 \cos^2(\alpha)$$



# SMR in magnetic garnets

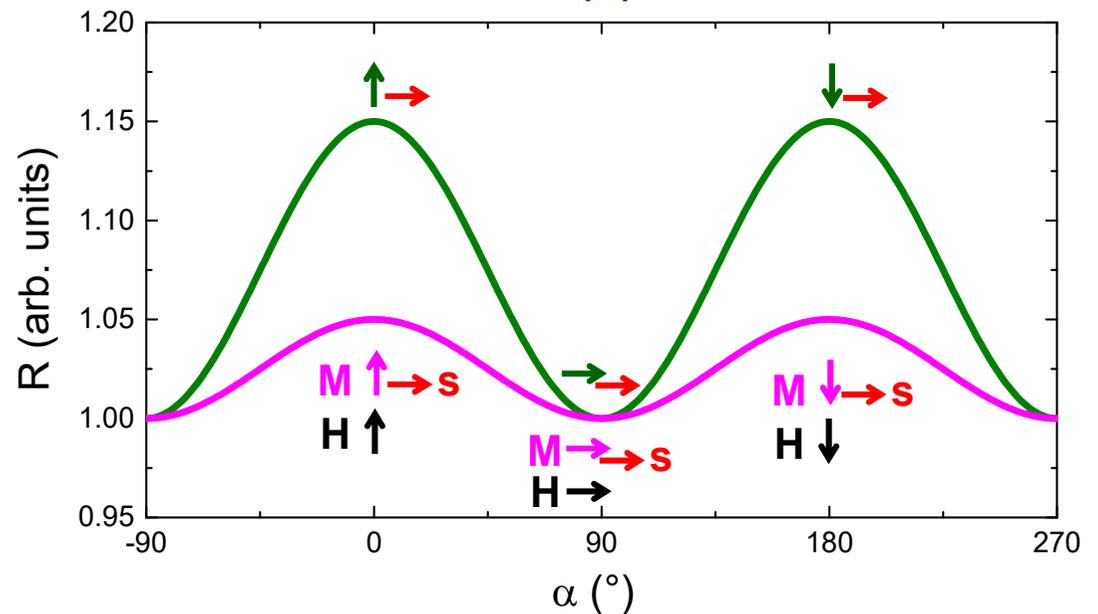
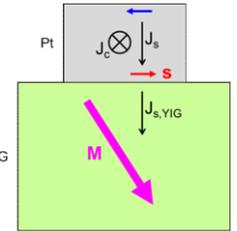
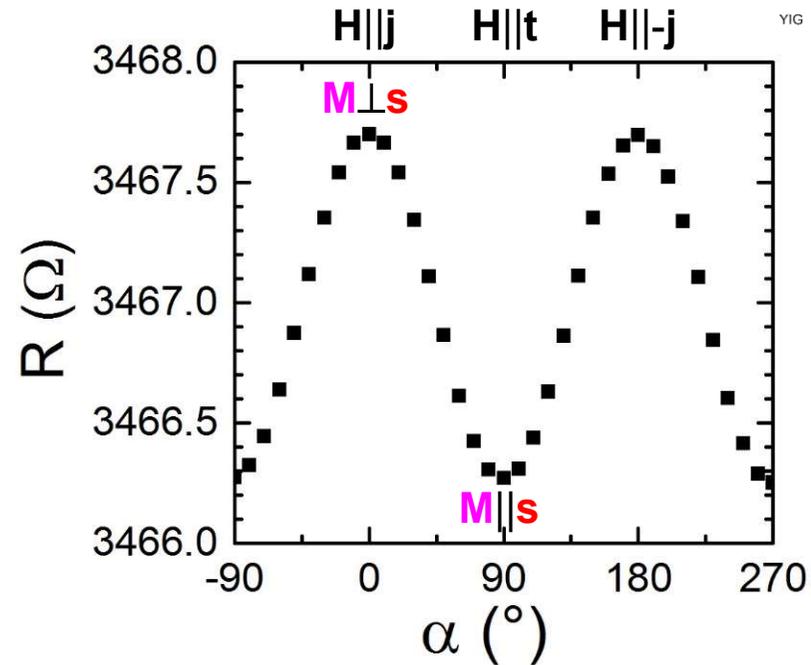


is the prototype magnetic garnet



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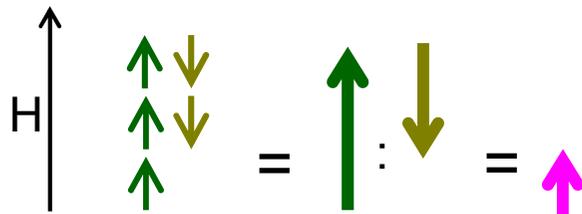
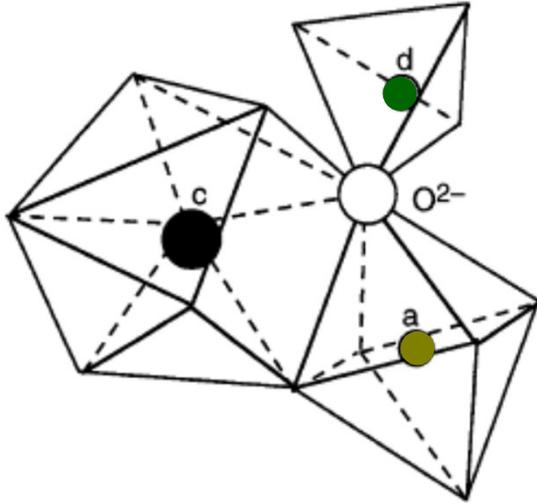
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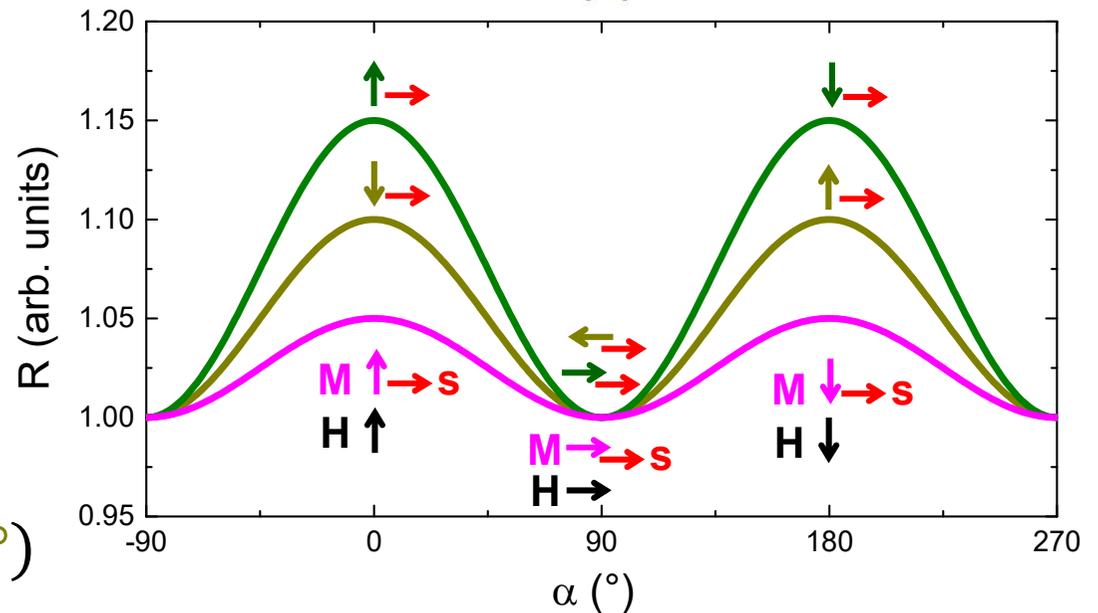
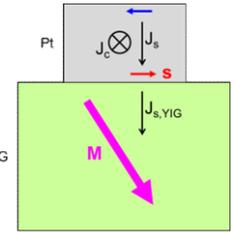
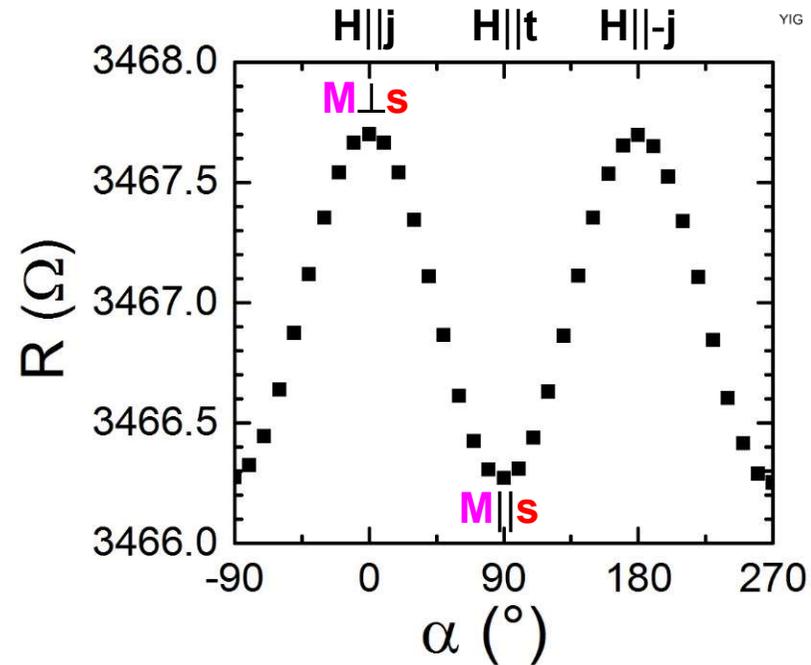
# SMR in magnetic garnets



is the prototype magnetic garnet

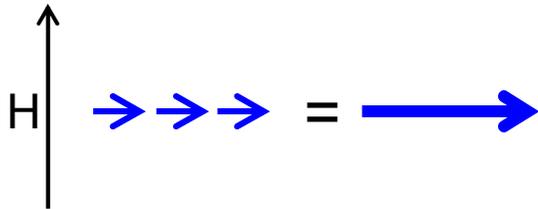


$$\begin{aligned}
 R &= R_0 + R_1 \cos^2(\alpha) \\
 &= R_0 + R_1 \cos^2(\alpha) \\
 &= R_0 + R_1 \cos^2(\alpha + 180^\circ)
 \end{aligned}$$



# SMR in non-collinear magnets

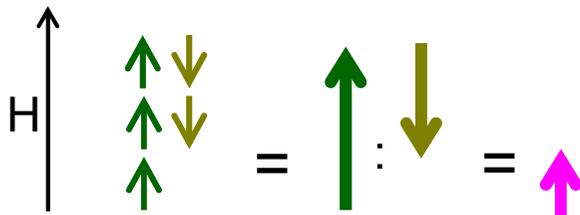
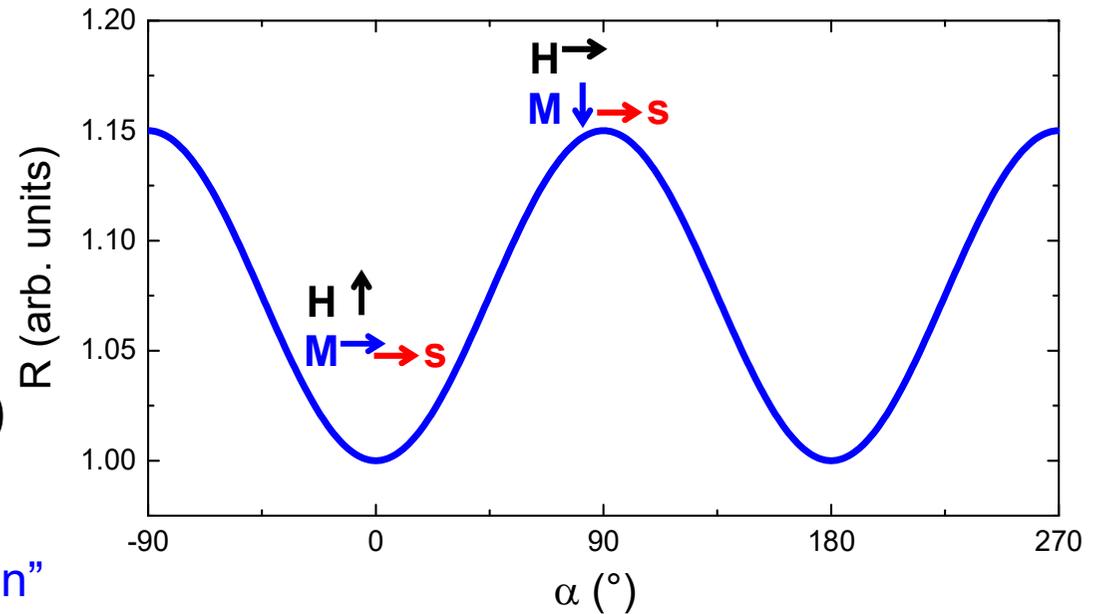
What about this:



$$R = R_0 + R_1 \cos^2(\alpha + 90^\circ)$$

$$= \widetilde{R}_0 - R_1 \cos^2(\alpha)$$

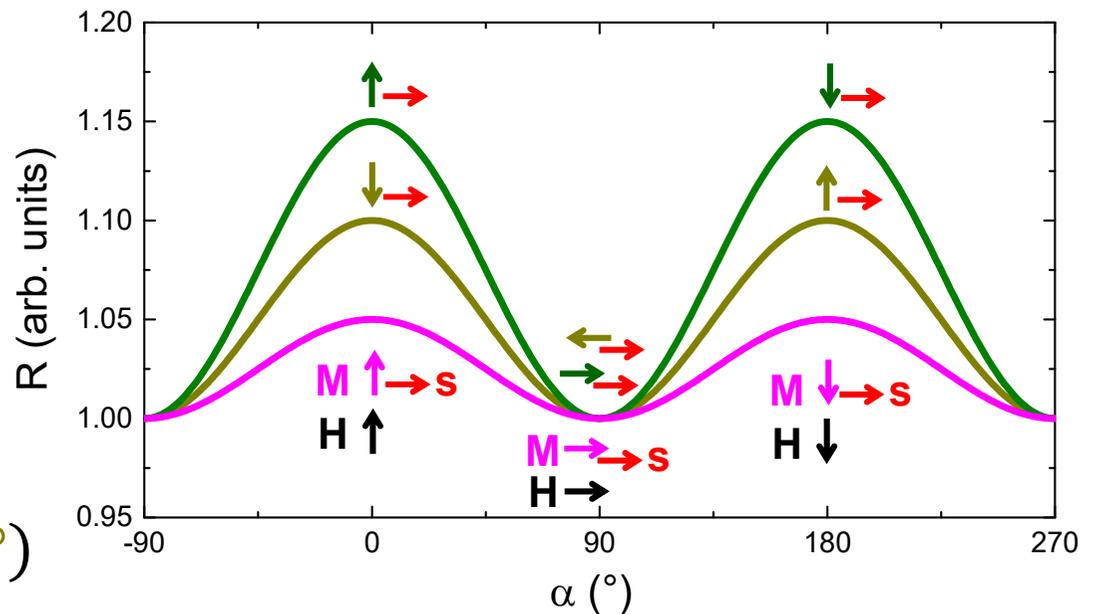
“90° phase shift / SMR sign inversion”



$$R = R_0 + R_1 \cos^2(\alpha)$$

$$= R_0 + R_1 \cos^2(\alpha)$$

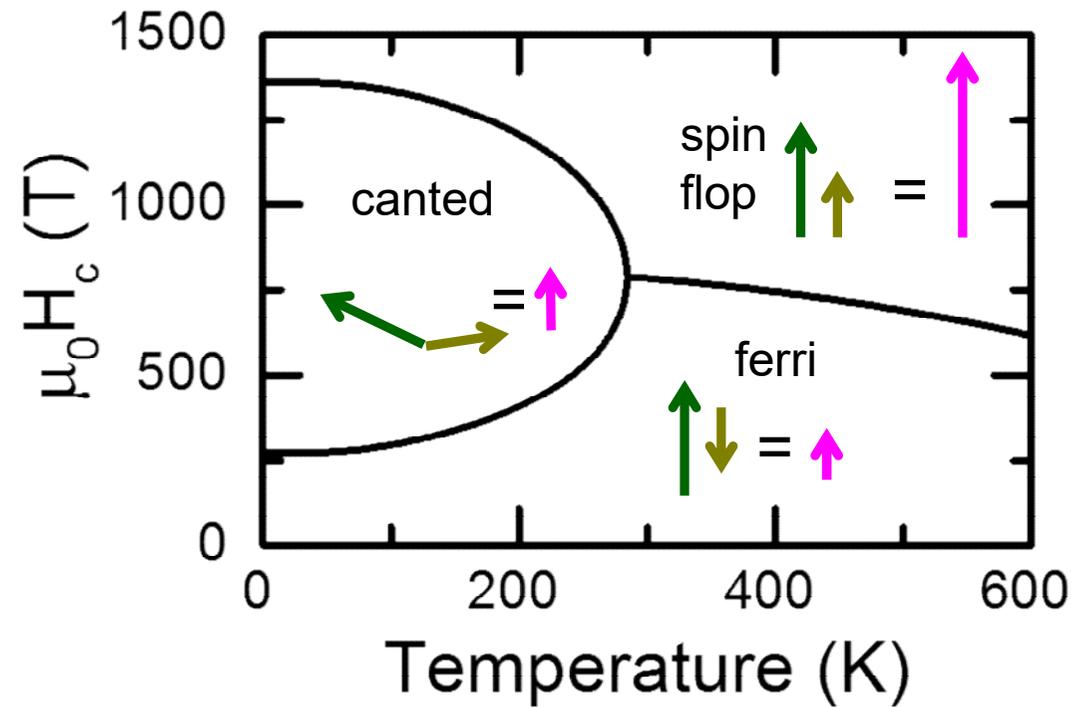
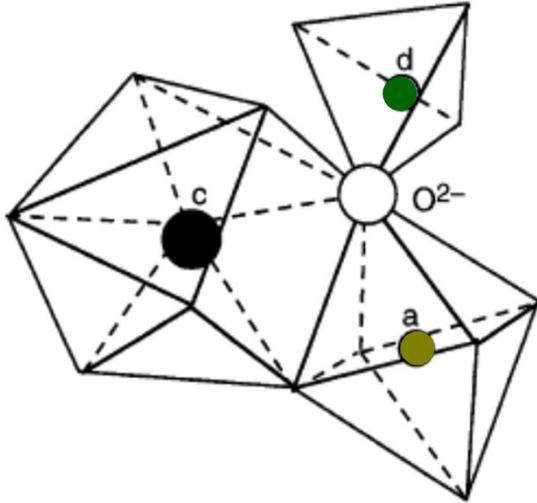
$$= R_0 + R_1 \cos^2(\alpha + 180^\circ)$$



# Magnetic Garnets



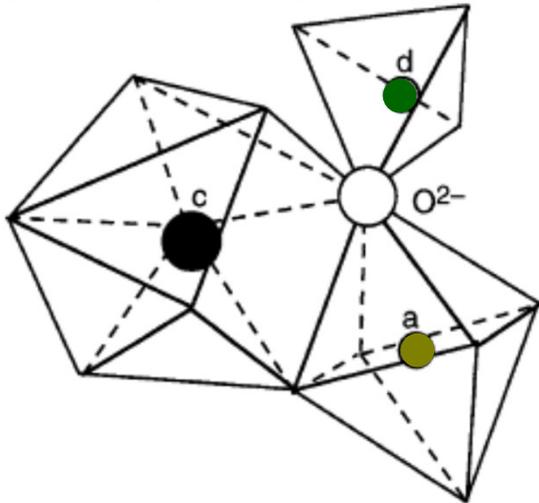
is the prototype magnetic garnet



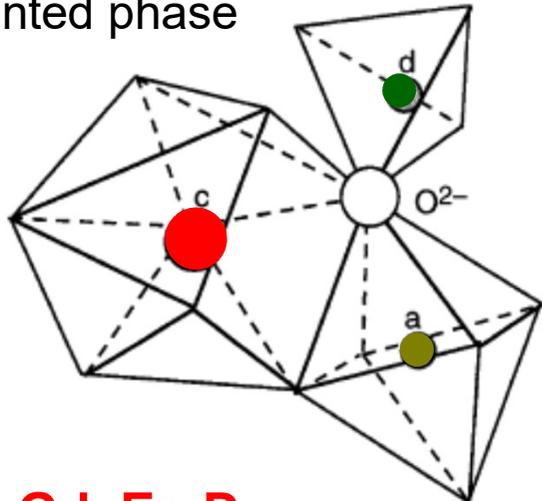
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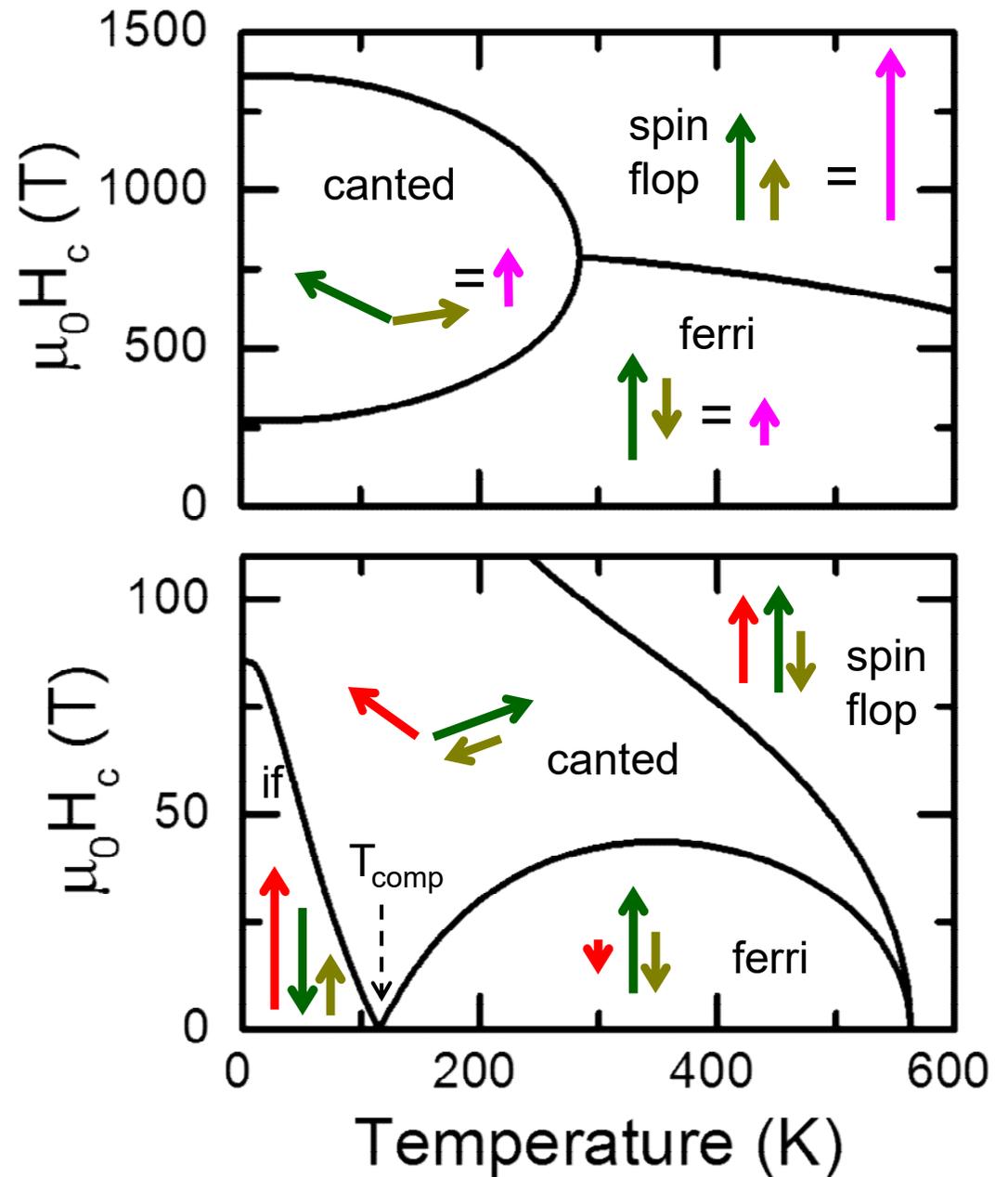
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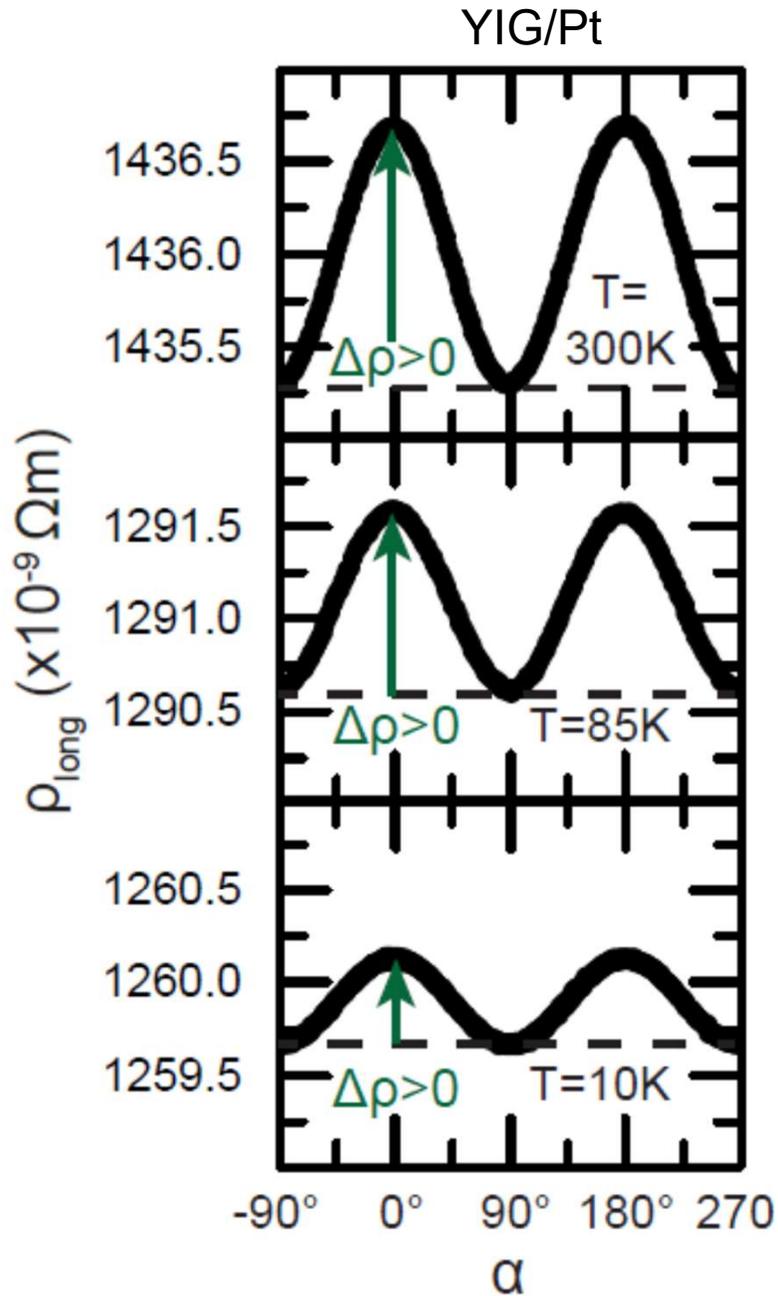
with canted phase



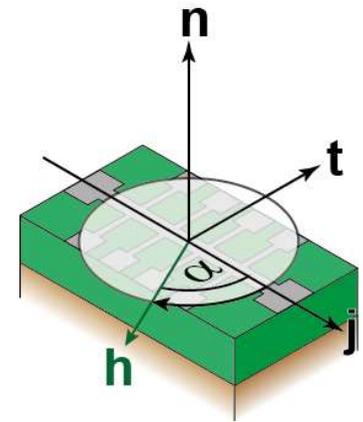
**Re = Gd, Er, Dy, ...**



# SMR in compensated garnet/Pt hybrids

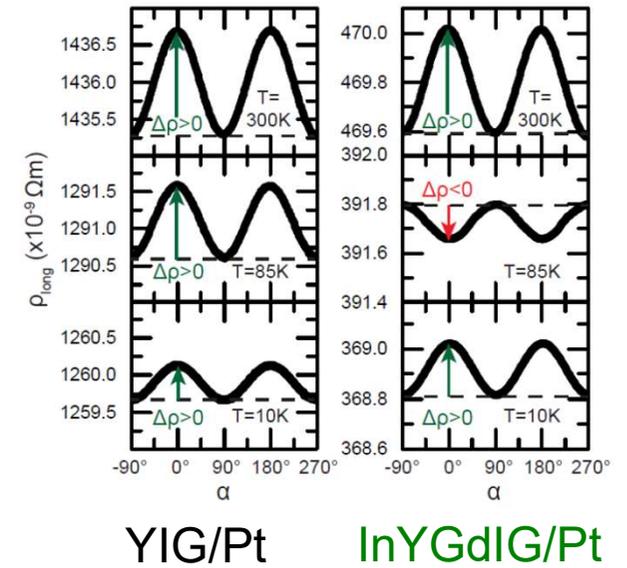
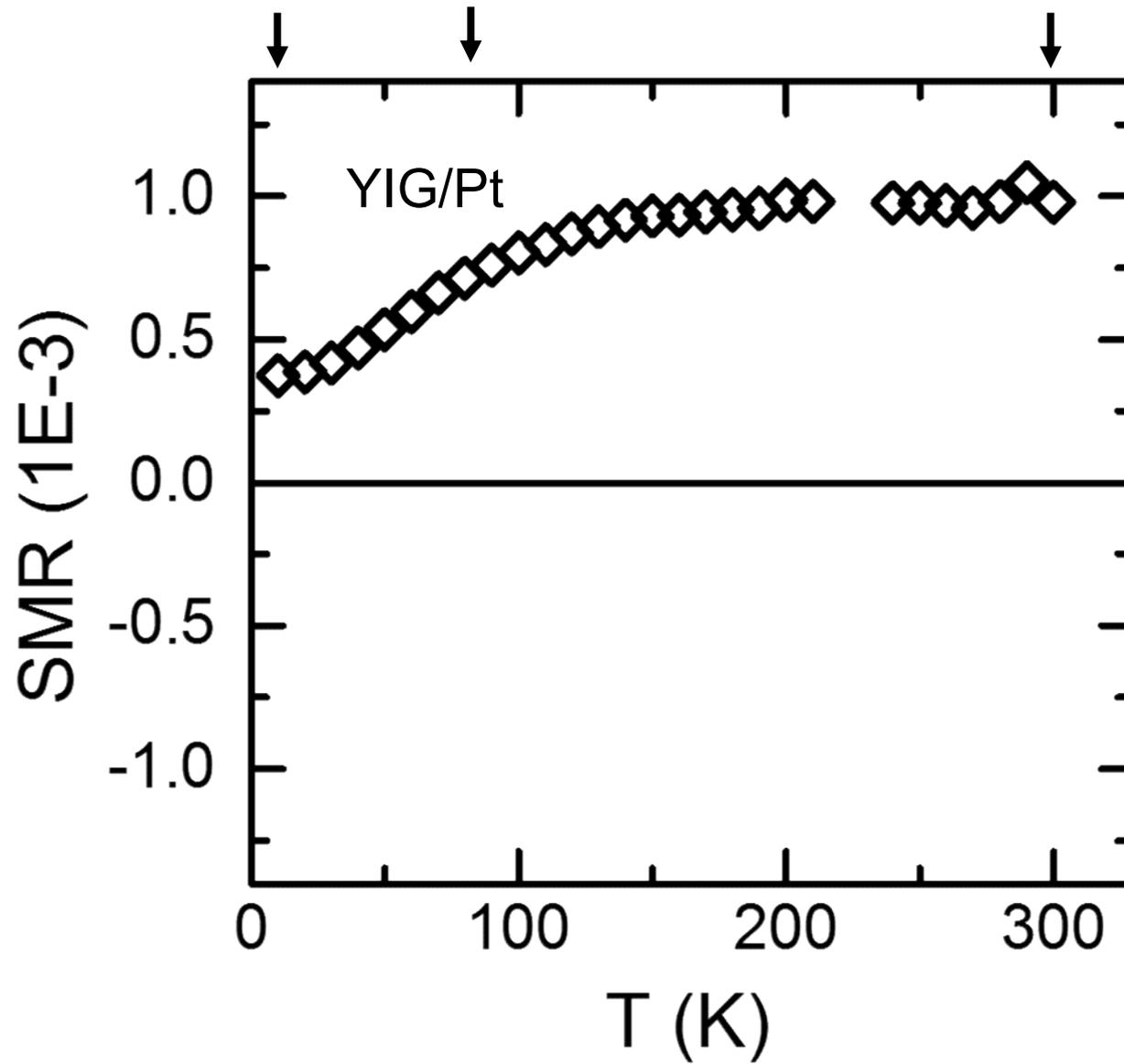


$$\begin{aligned} \rho_{\text{long}} &= \rho_0 - \rho_1 \mathbf{m}_t^2 \\ &= \rho_0 + \Delta\rho \cos^2 \alpha \end{aligned}$$

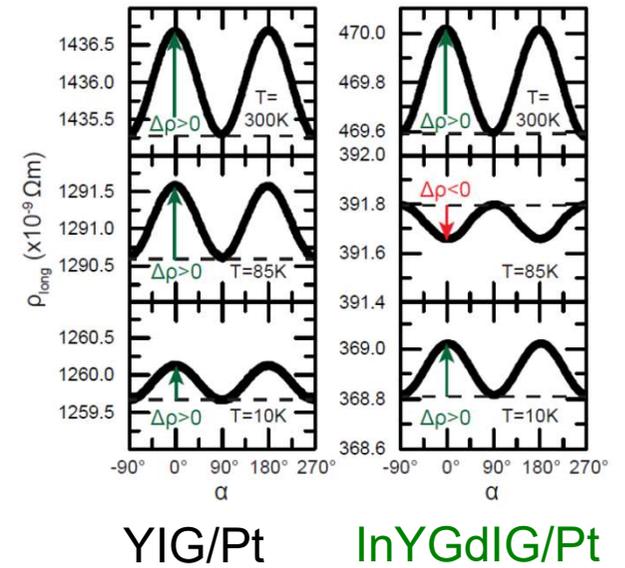
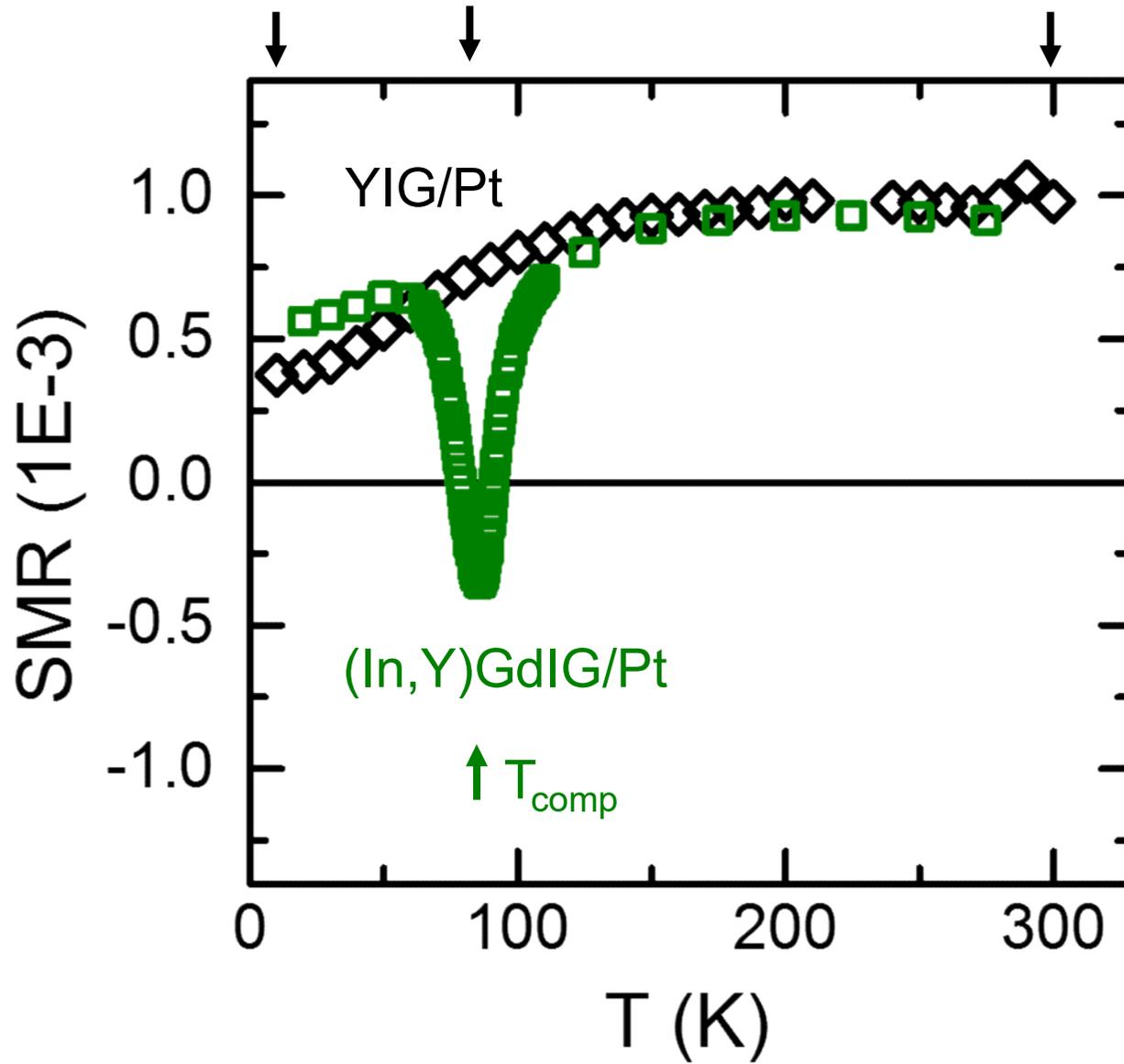


o

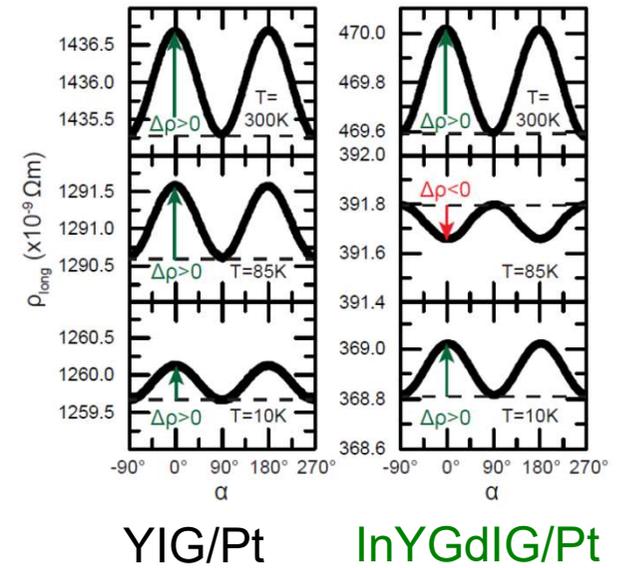
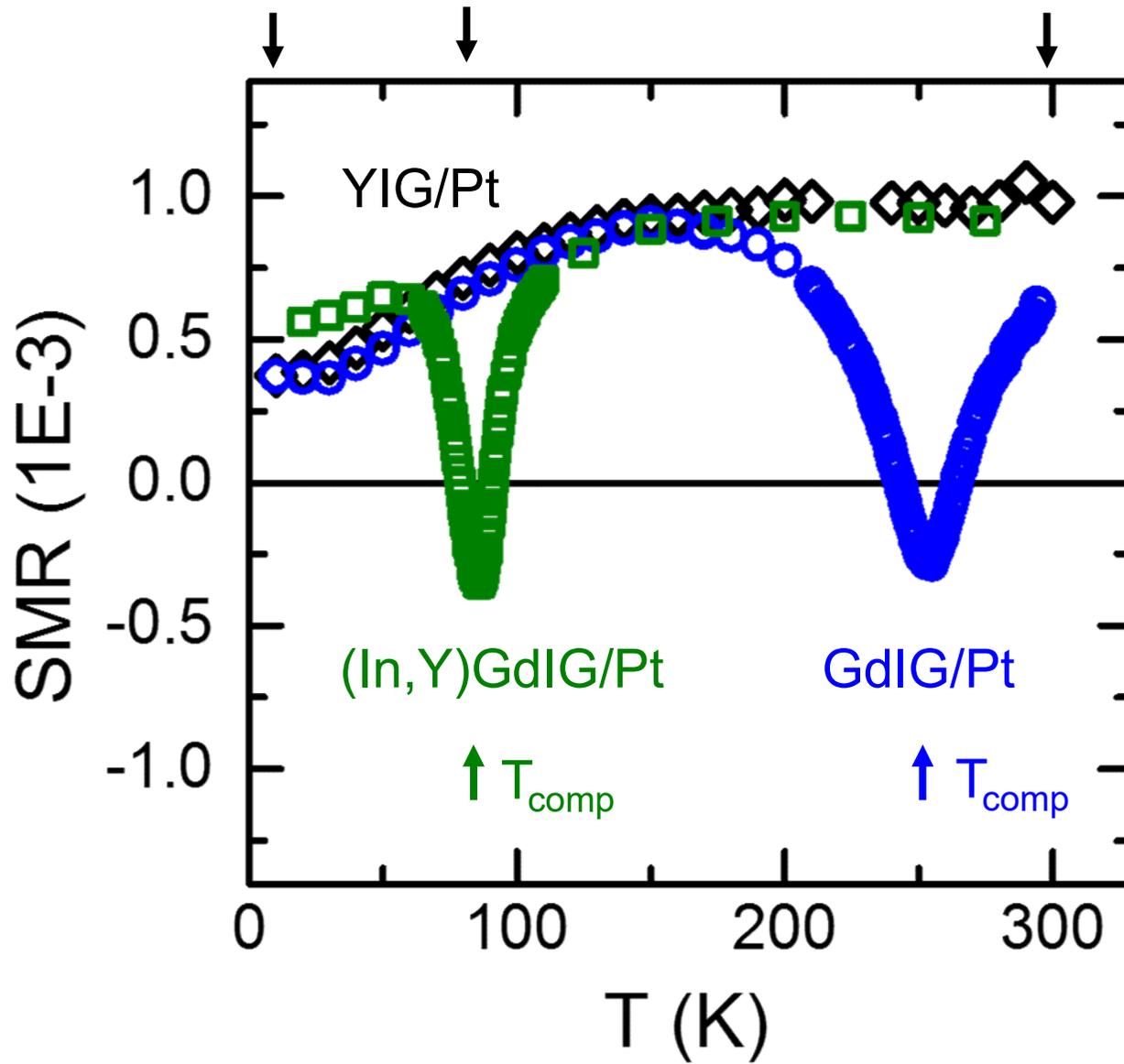
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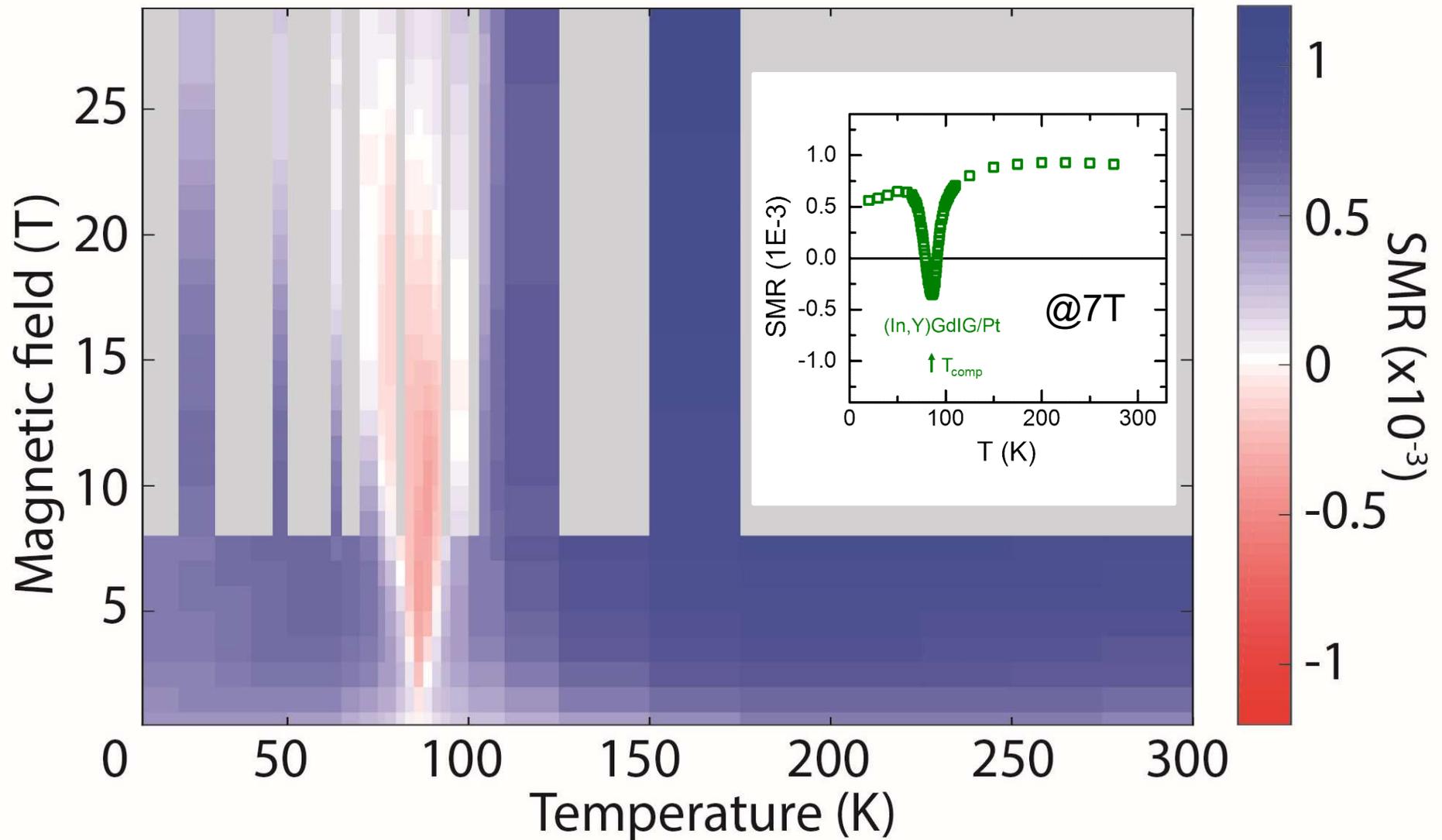
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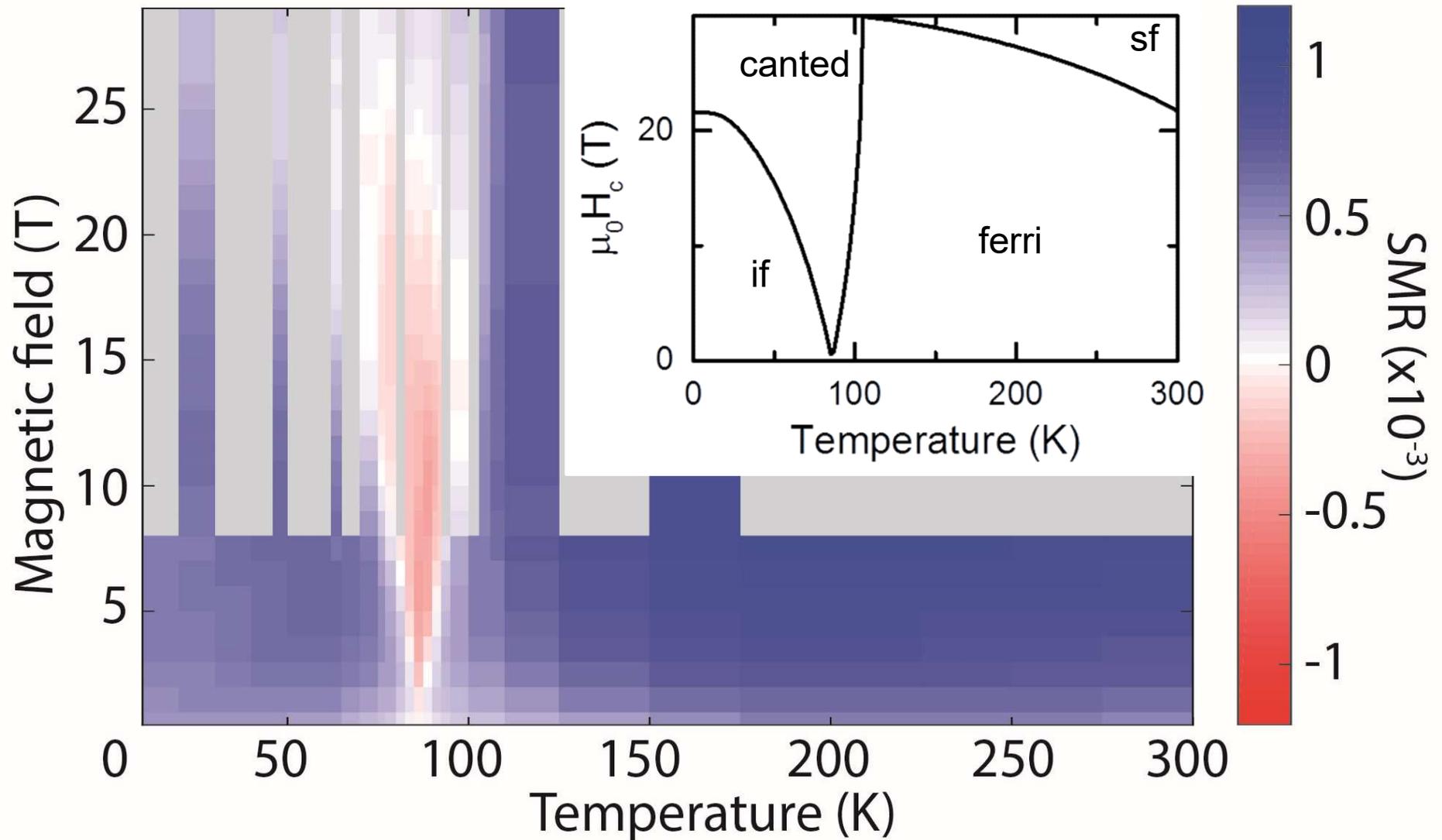
# SMR in compensated garnet/Pt hybrids



w/ B. A. Piot, Laboratoire National des Champs Magnetiques Intenses, Grenoble

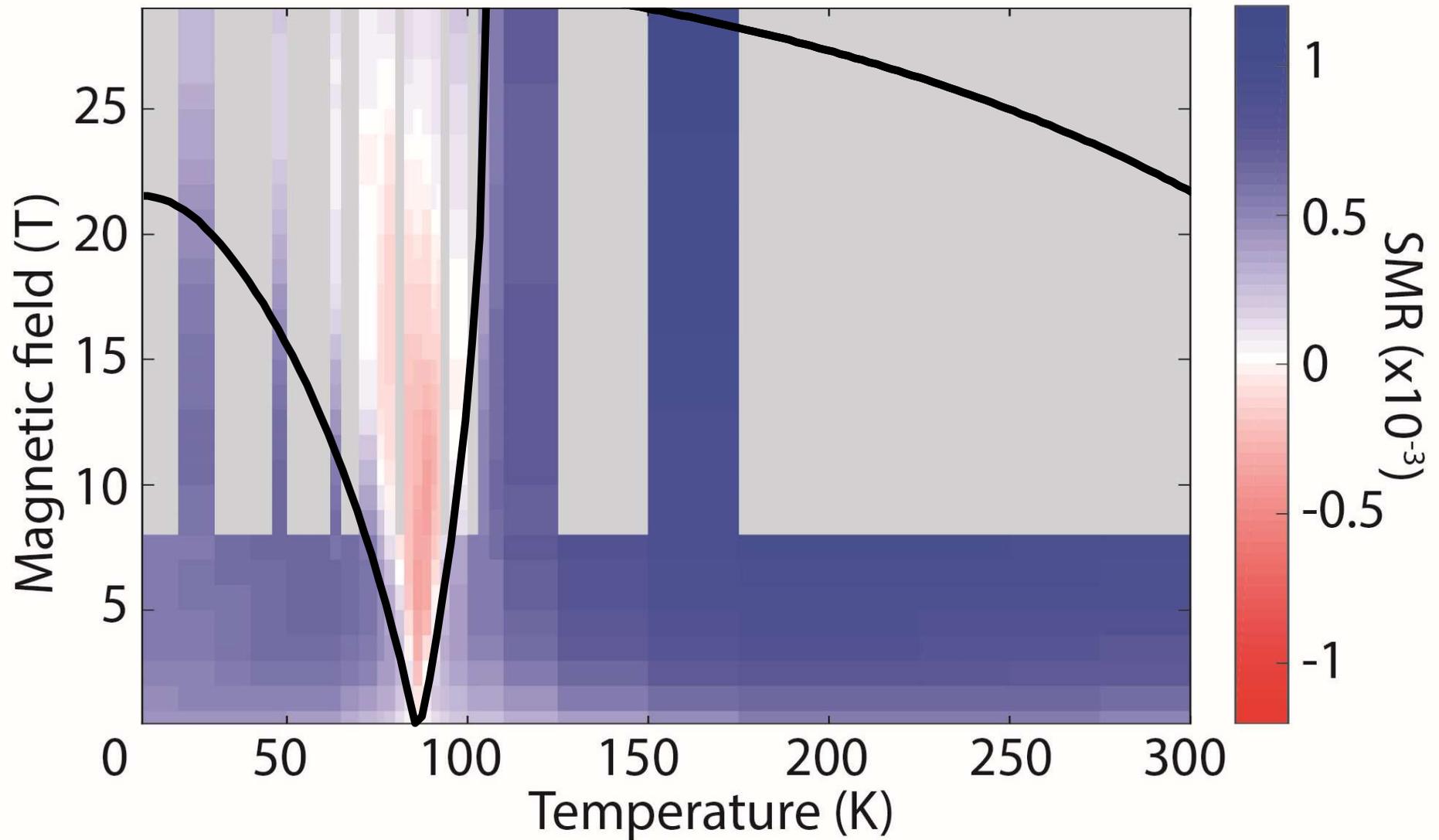
# SMR in compensated garnet/Pt hybrids

2 sublattice mean field model :



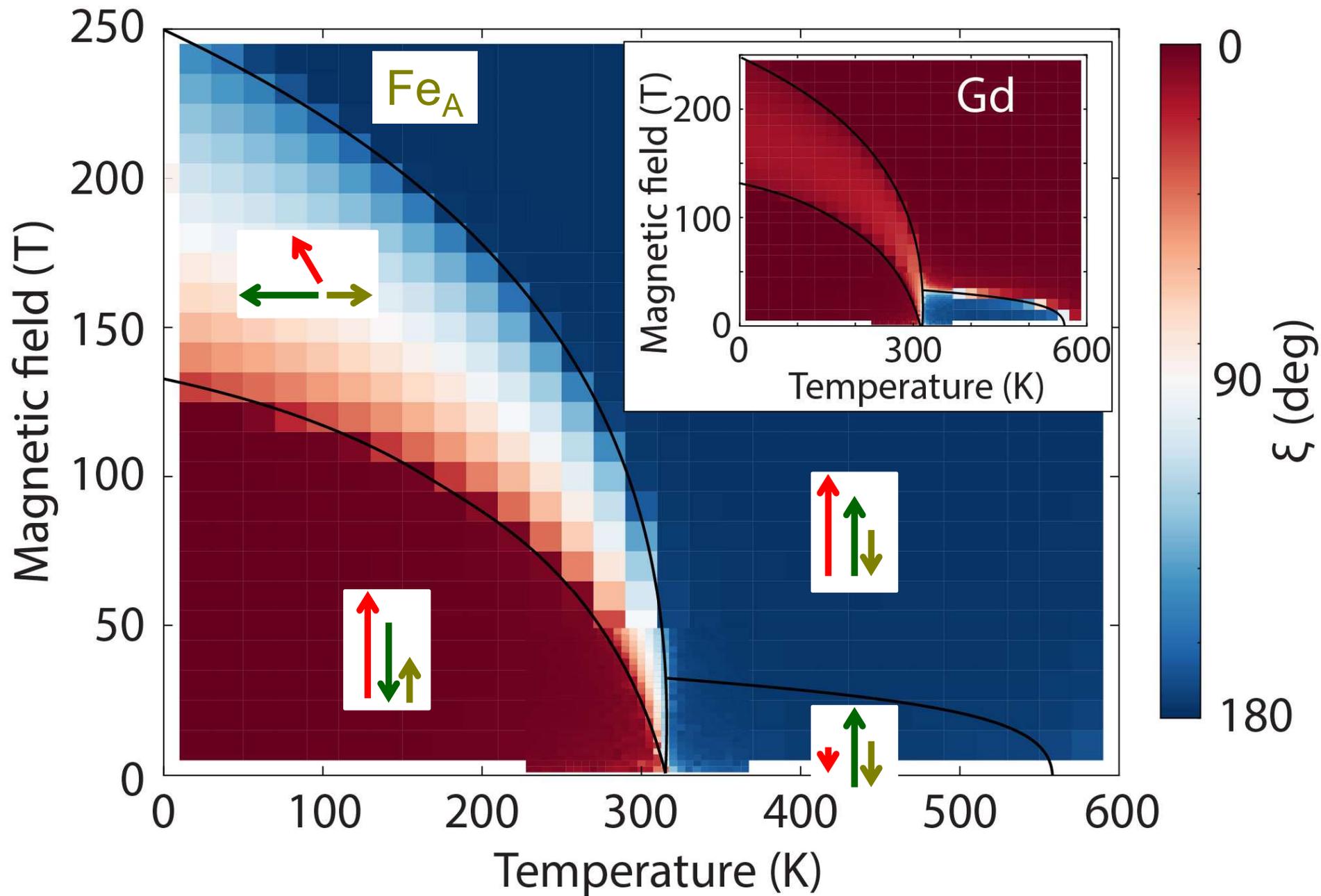
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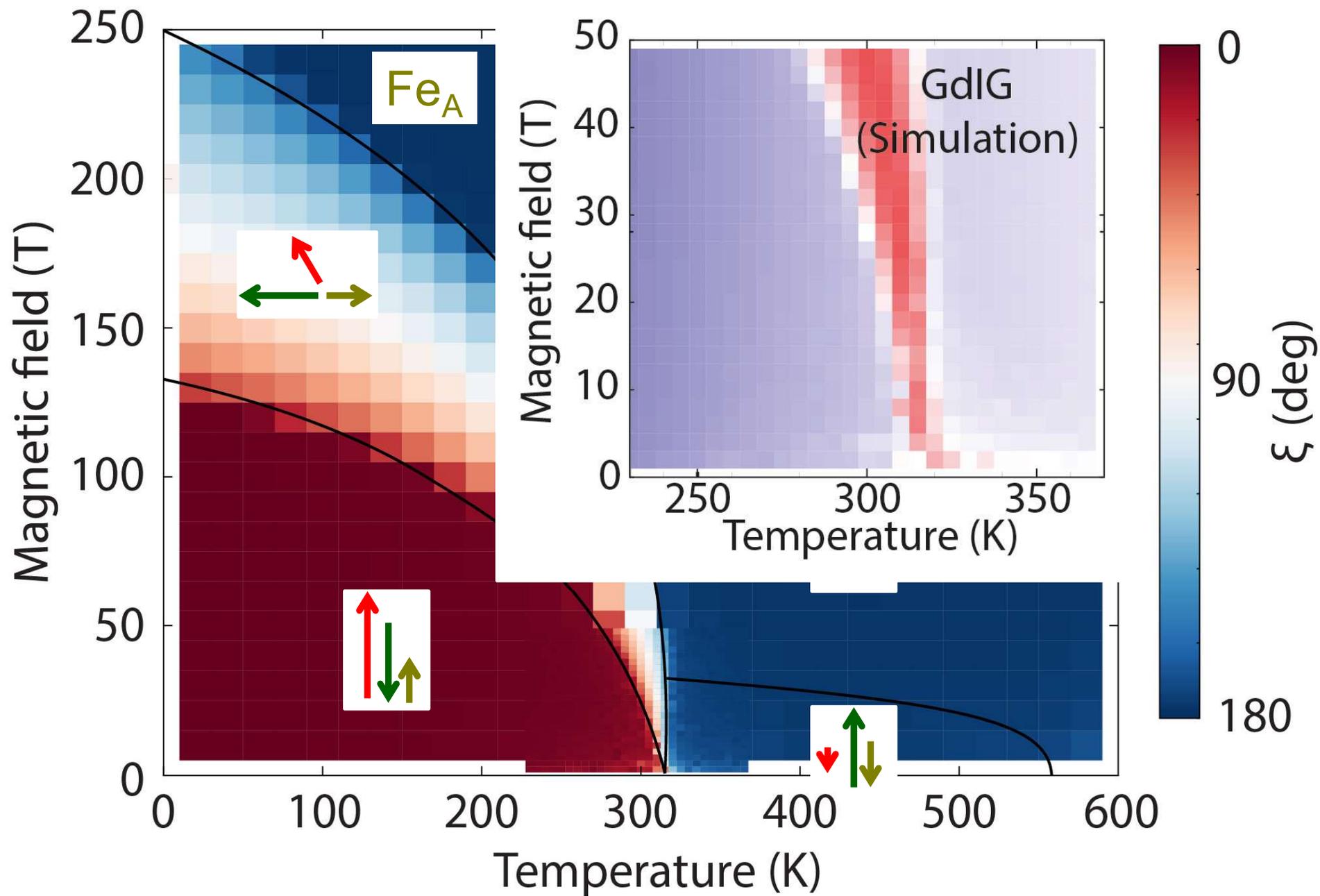


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atomistic spin simulations for  $\text{Gd}_3\text{Fe}_5\text{O}_{12}$  by Joe Barker, Tohoku U, Sendai

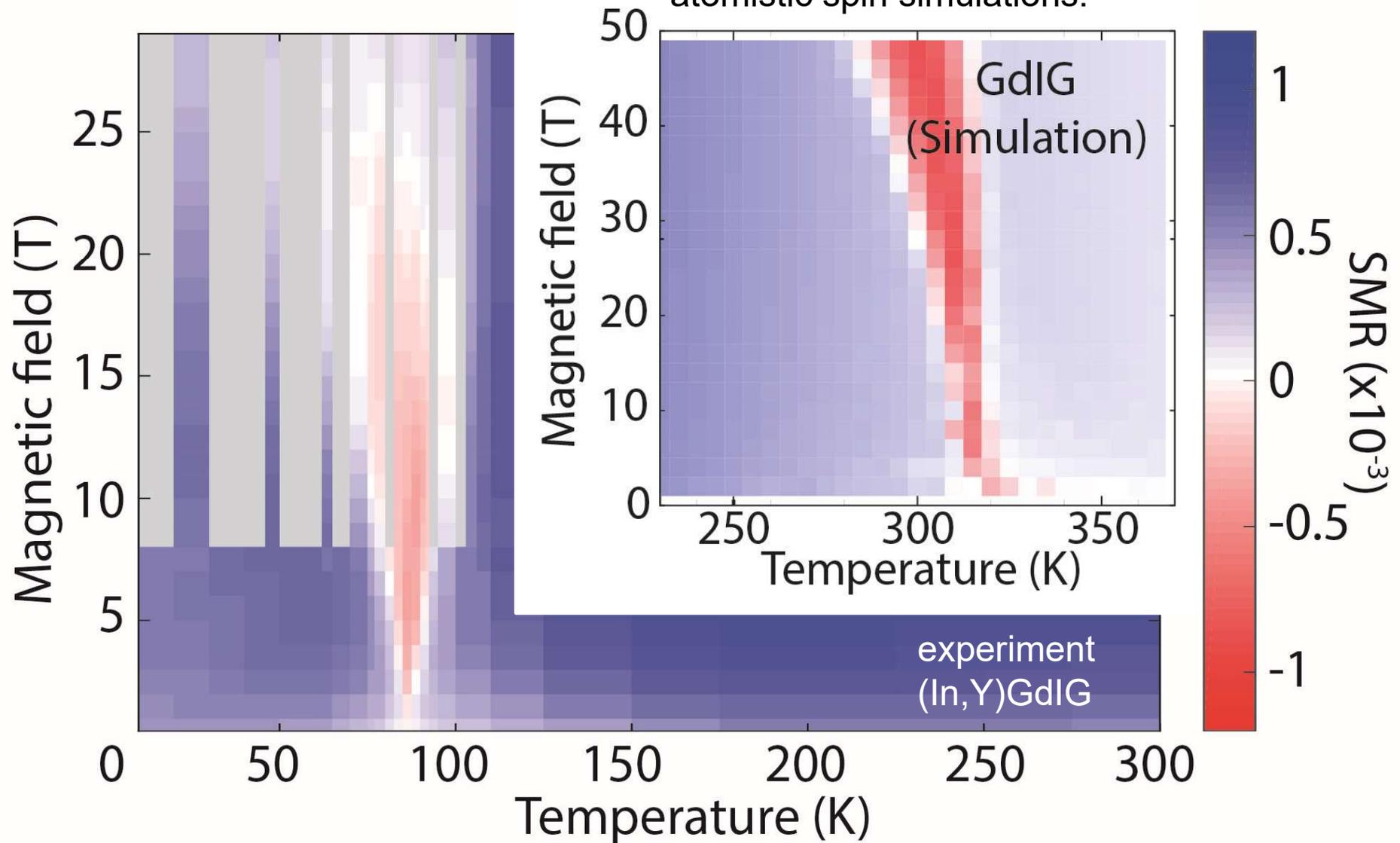


atomistic spin simulations for  $\text{Gd}_3\text{Fe}_5\text{O}_{12}$  by Joe Barker, Tohoku U, Sendai



⇒ SMR is sensitive to the **local moment configuration**

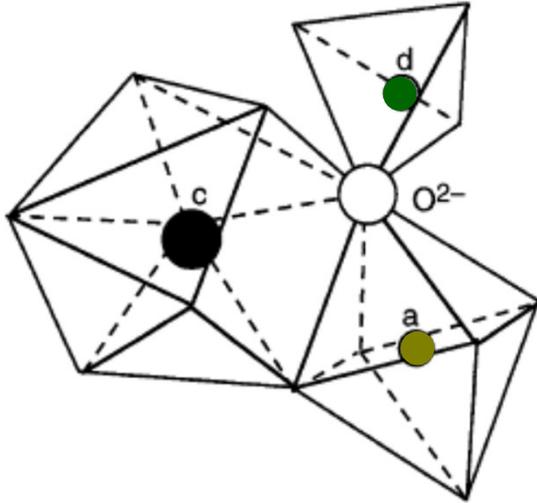
SMR of Fe SL in GdIG calculated via atomistic spin simulations:



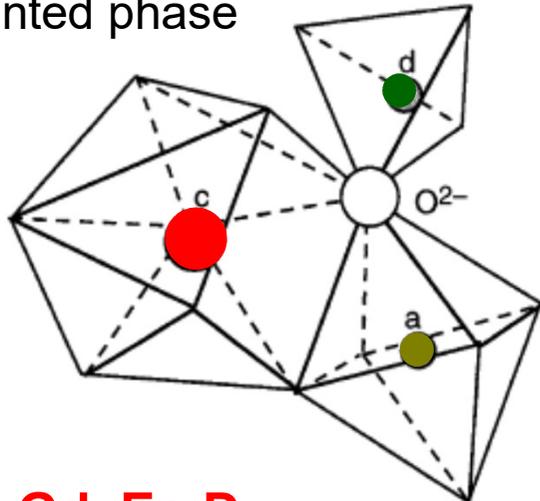
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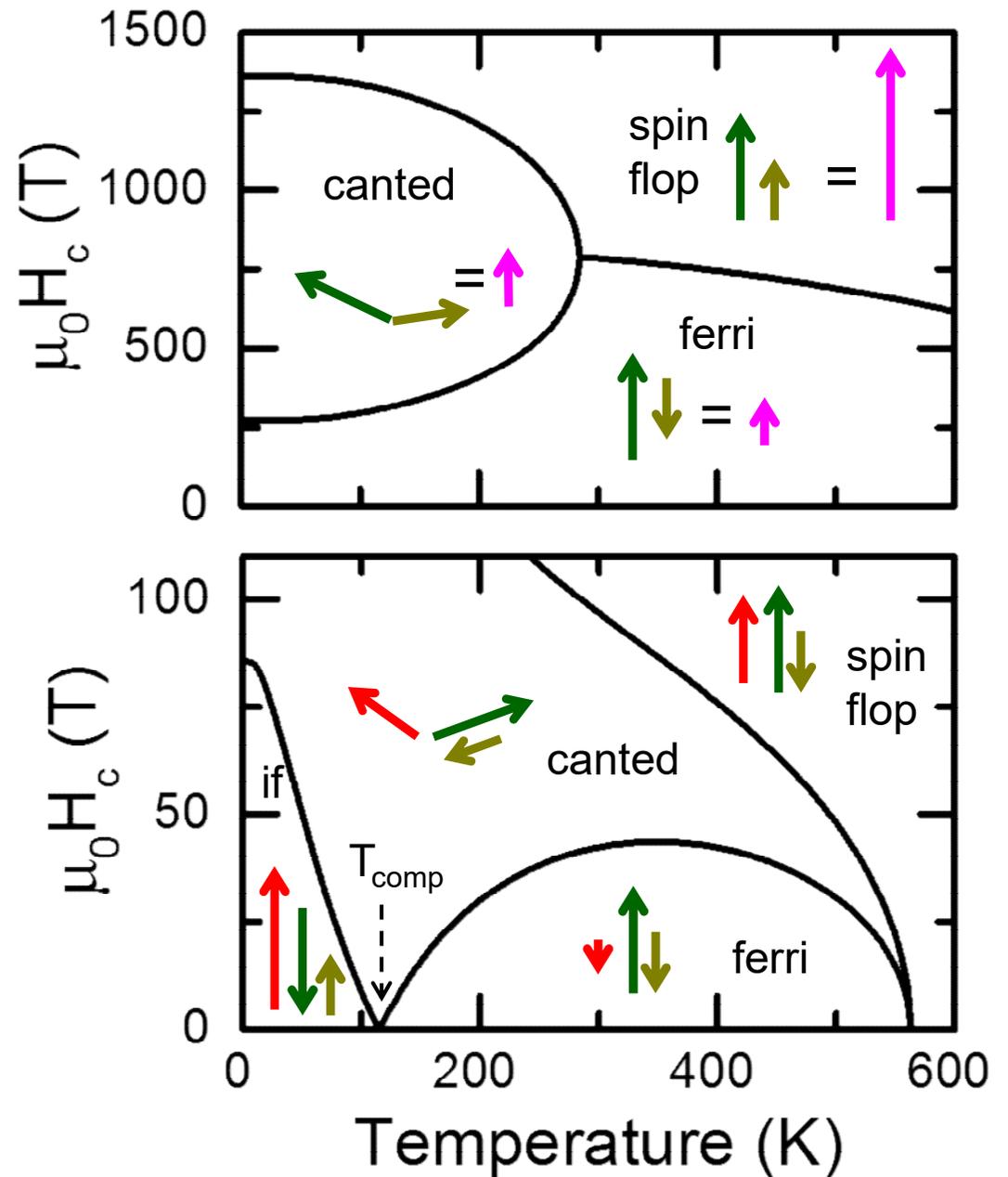
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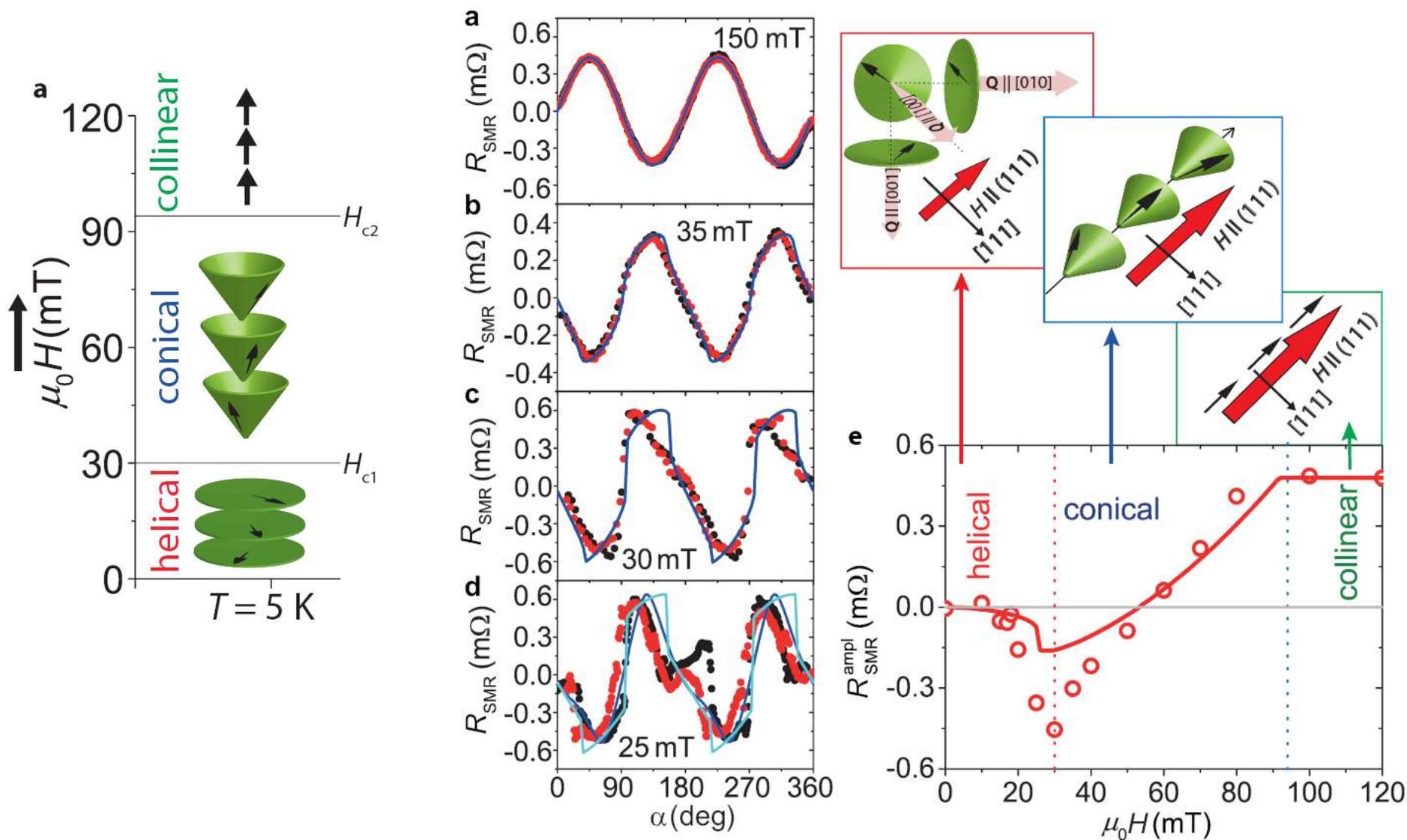


**Re = Gd, Er, Dy, ...**



# SMR in $\text{Cu}_2\text{OSeO}_3$ / Pt heterostructures

Aqeel *et al.*, arXiv 1607:056301



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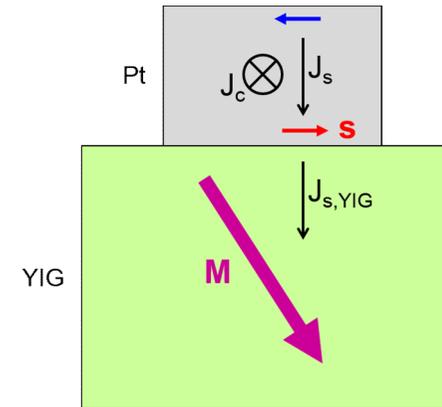
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Althammer *et al.*, PRB **87**, 224401 (2013).

review: Chen *et al.*, J. Phys.: Condens. Matter **28**, 103004 (2016).



## SMR in non-collinear magnets

... governed by sublattice moment orientations  
(NOT the net magnetization)

Ganzhorn *et al.*, PRB **94**, 094401 (2016).

Aqeel *et al.*, arXiv 1607:056301

Aqeel *et al.*, PRB **92**, 224410 (2015).

