TECHNISCHE UNIVERSITÄT DRESDEN

DRESDEN concept

Fakultät Mathematik und Naturwissenschaften, Fachrichtung Physik,
Institut für Festkörperphysik (IFP) & Center for Transport and Devices of Emergent Materials (CTD)

Spin Current Transport
in YIG/Pt Heterostructures

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21 September 2016

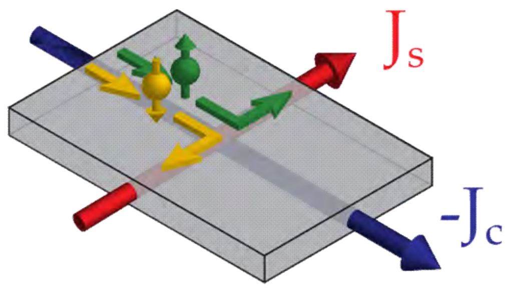
Institut für Festkörperphysik

CENTER FOR TRANSPORT AND DEVICES OF EMERGENT MATERIALS

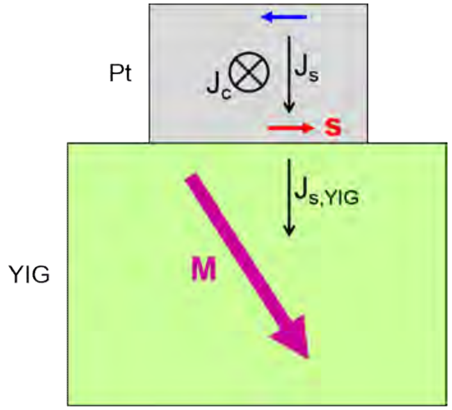
Outline

charge and spin currents

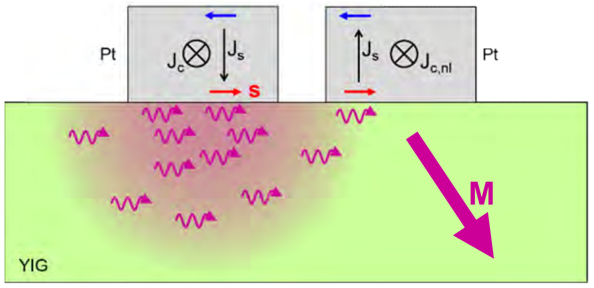
spin Hall effect(s)



SMR = Spin Hall Magnetoresistance
… a spin current-based magnetoresistance
@ magnetic insulator / metal interfaces

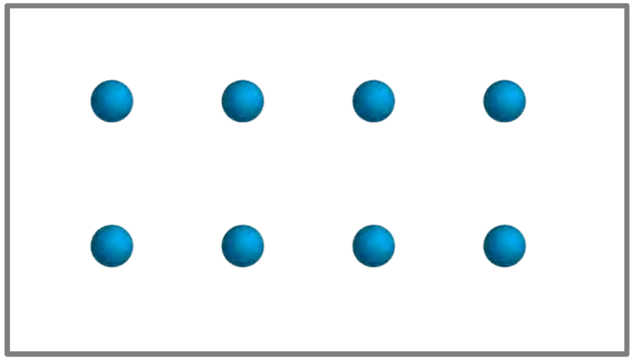


MMR = Magnon-mediated MagnetoResistance
… electrical measurement of magnon diffusion length



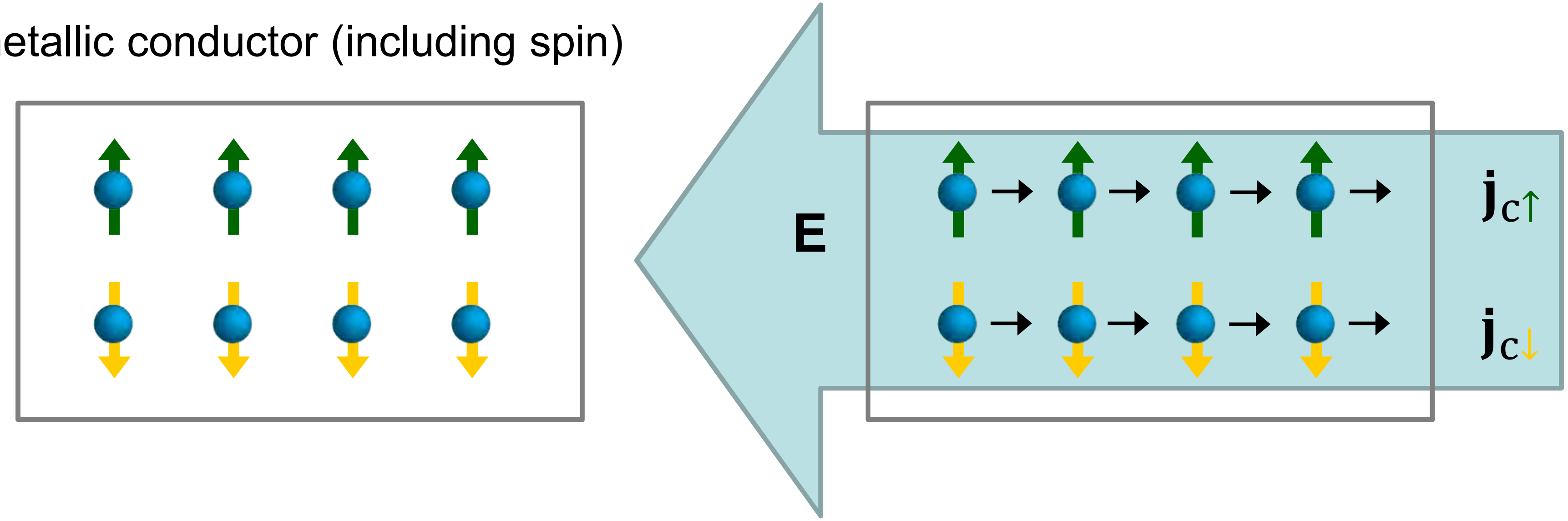
From charge to spin currents

metallic conductor



From charge to spin currents

metallic conductor (including spin)

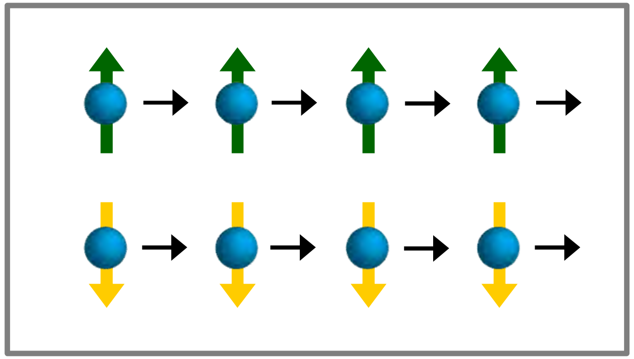


Mott's two spin current model:
charge currents from electrons with different spin are independent and simply add:

$$\left.\begin{aligned} \mathbf{j}_{c\uparrow} &= \sigma_{\uparrow}\mathbf{E} \\ \mathbf{j}_{c\downarrow} &= \sigma_{\downarrow}\mathbf{E} \end{aligned}\right\} \quad \mathbf{j}_{c} = \mathbf{j}_{c\uparrow} + \mathbf{j}_{c\downarrow} = (\sigma_{\uparrow} + \sigma_{\downarrow})\mathbf{E} = \sigma\mathbf{E}$$

R. C. O'Handley, *Modern Magnetic Materials* (John Wiley, New York, 2000).

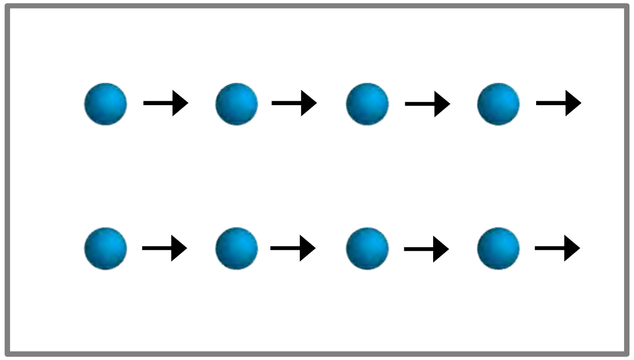
From charge to spin currents



$\mathbf{j}_{c\uparrow}$

$\mathbf{j}_{c\downarrow}$

… charge AND spin transport !?



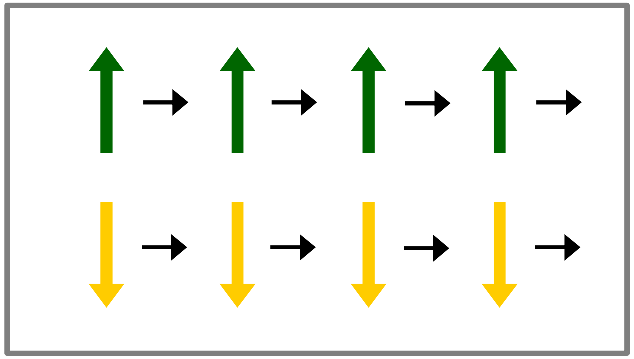
$\mathbf{j}_{c\uparrow}$

$\mathbf{j}_{c\downarrow}$

charge transport:

$$\mathbf{j}_c = \mathbf{j}_{c\uparrow} + \mathbf{j}_{c\downarrow} = (\sigma_\uparrow + \sigma_\downarrow)\mathbf{E} = \sigma\mathbf{E}$$

(in „normal“ metal: $\mathbf{j}_{c\uparrow} = \mathbf{j}_{c\downarrow}$)



$\mathbf{j}_{c\uparrow}$

$\mathbf{j}_{c\downarrow}$

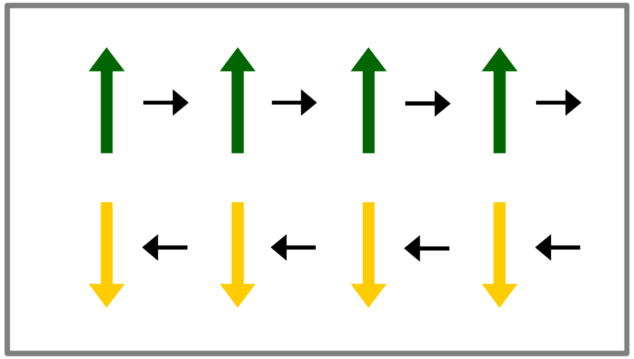
spin transport:

$$\mathbf{j}_s = \frac{+\hbar/2}{e}\,\mathbf{j}_{c\uparrow} + \frac{-\hbar/2}{e}\,\mathbf{j}_{c\downarrow} = 0$$

spin current

(for $\mathbf{j}_{c\uparrow} = \mathbf{j}_{c\downarrow} = \mathbf{j}_c/2$)

Pure spin currents



$\mathbf{j}_{c\uparrow}$

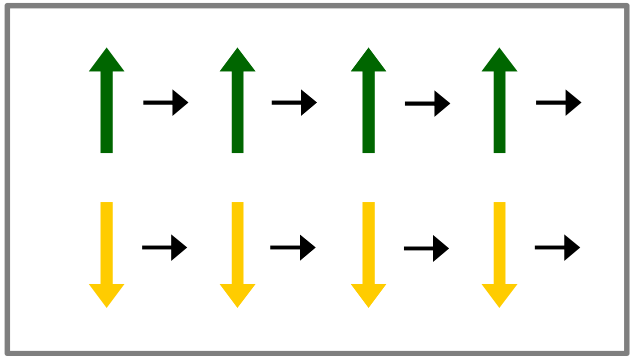
$\mathbf{j}_{c\downarrow}$

interesting: pure spin current

$$\mathbf{j_s} = \frac{+\hbar/2}{e}\,\mathbf{j}_{c\uparrow} - \frac{-\hbar/2}{e}\,\mathbf{j}_{c\downarrow} = 2\frac{\hbar/2}{e}\,\mathbf{j}_{c\uparrow} \neq 0$$

$$(\mathbf{j}_c = \mathbf{j}_{c\uparrow} - \mathbf{j}_{c\downarrow} = 0\ !)$$

… but how can one make electrons move in opposite directions depending on their spin orientation?



$\mathbf{j}_{c\uparrow}$

$\mathbf{j}_{c\downarrow}$

spin transport:

$$\mathbf{j_s} = \frac{+\hbar/2}{e}\,\mathbf{j}_{c\uparrow} + \frac{-\hbar/2}{e}\,\mathbf{j}_{c\downarrow} = 0$$

spin current

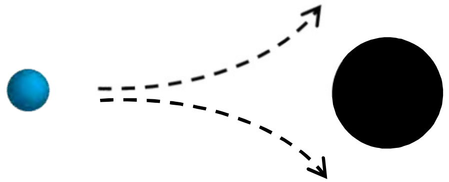
(for $\mathbf{j}_{c\uparrow} = \mathbf{j}_{c\downarrow} = \mathbf{j}_c/2$)

Spin Hall effect

– electrically driven, transverse, pure spin currents

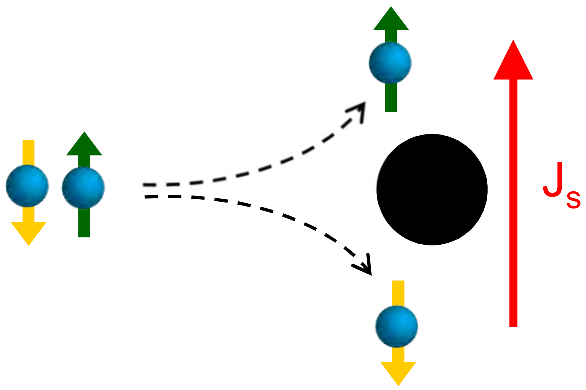
D’yakonov & Perel’, JETP Lett. **13**, 467 (1971).
Hirsch, PRL **83**, 1834 (1999).

The spin Hall effect (an experimental physicist's view)



charge scattering
usually is „symmetric“
(no particular direction preferred)

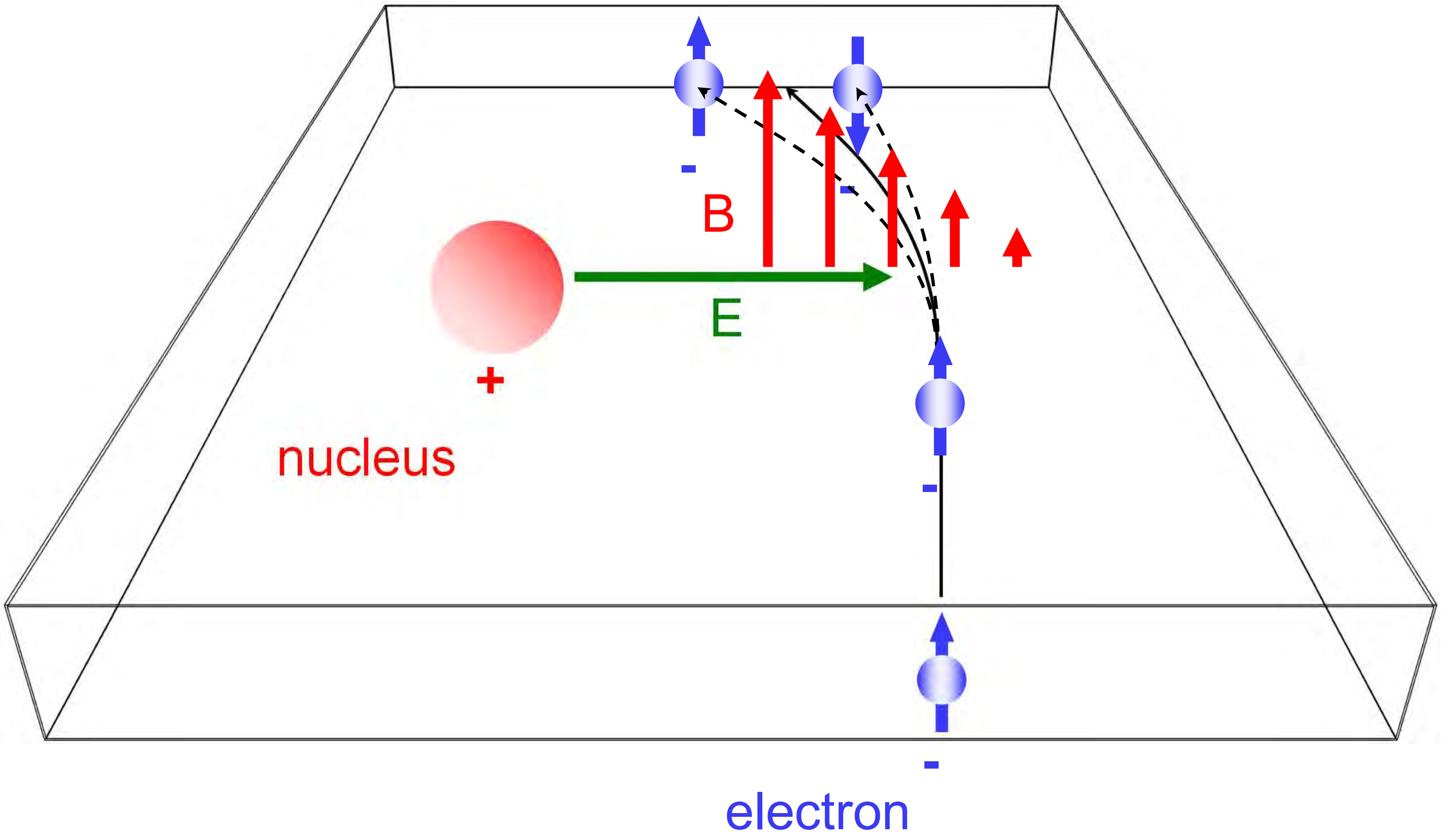
Consider spin-dependent, asymmetric scattering („up→left, down→right“):



spin Hall effect (SHE):
transverse pure spin current

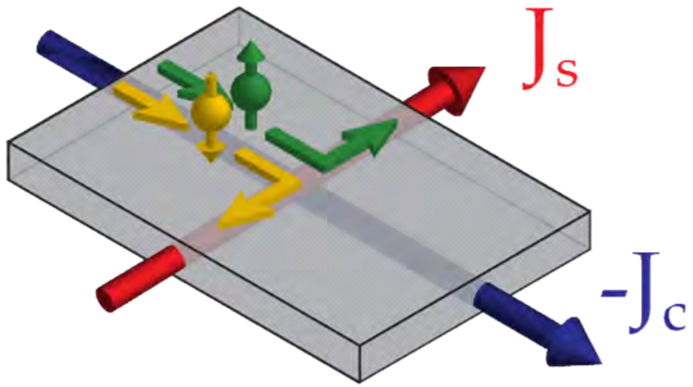
Inoue & Ohno, Science **309**, 2004 (2005).

Spin-Skew Scattering



The spin Hall effect (SHE) : spin – charge current conversion

direct spin Hall effect (SHE)



charge current → spin current

$$\mathbf{J}_s^{\mathrm{SHE}} = \alpha_{\mathrm{SHE}} \frac{\hbar}{2e} \left[\mathbf{J}_c \times \mathbf{s} \right]$$

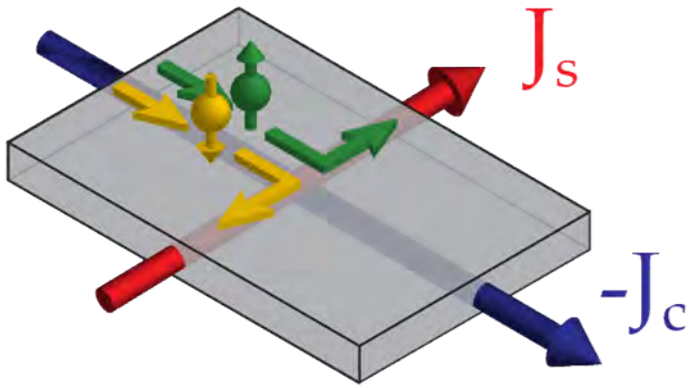
Spin Hall effect

spin-orbit coupling: interaction between spin and charge motion

spin Hall angle α_{SHE} parameterizes charge current ↔ spin current conversion efficiency

The spin Hall effect (SHE) : spin – charge current conversion

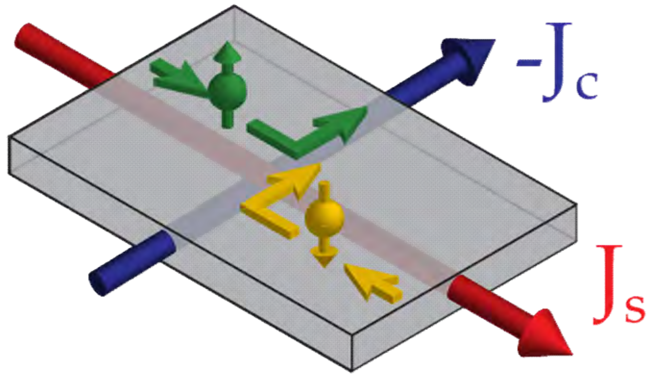
direct spin Hall effect (SHE)



charge current → spin current

$$\mathbf{J}_s^{\mathrm{SHE}} = \alpha_{\mathrm{SHE}} \frac{\hbar}{2e} [\mathbf{J}_c \times \mathbf{s}]$$

inverse spin Hall effect (ISHE)



spin current → charge current

$$\mathbf{J}_c^{\mathrm{ISHE}} = \alpha_{\mathrm{SHE}} \frac{2e}{\hbar} [\mathbf{J}_s \times \mathbf{s}]$$

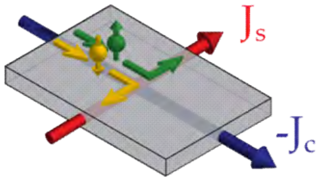
take away: SHE enables “simple” spin current generation & detection

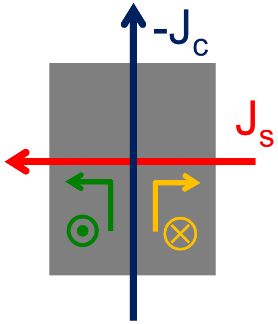
GaAs	$\alpha_{\mathrm{SHE}} \sim 10^{-4}$
Aluminum	$\alpha_{\mathrm{SHE}} \sim 10^{-4}$
Gold	$\alpha_{\mathrm{SHE}} \sim 10^{-3}$
Bi/Ag, Ta, WO_x	$\alpha_{\mathrm{SHE}} \sim 0.1$ ... 0.3

Platinum $\alpha_{\mathrm{SHE}} \sim 0.01$ ... 0.2

Hoffmann, IEEE-TM **49**, 5172 (2013).
Sinova *et al.*, RMP **87**, 1213 (2015).

Direct spin Hall effect in GaAs

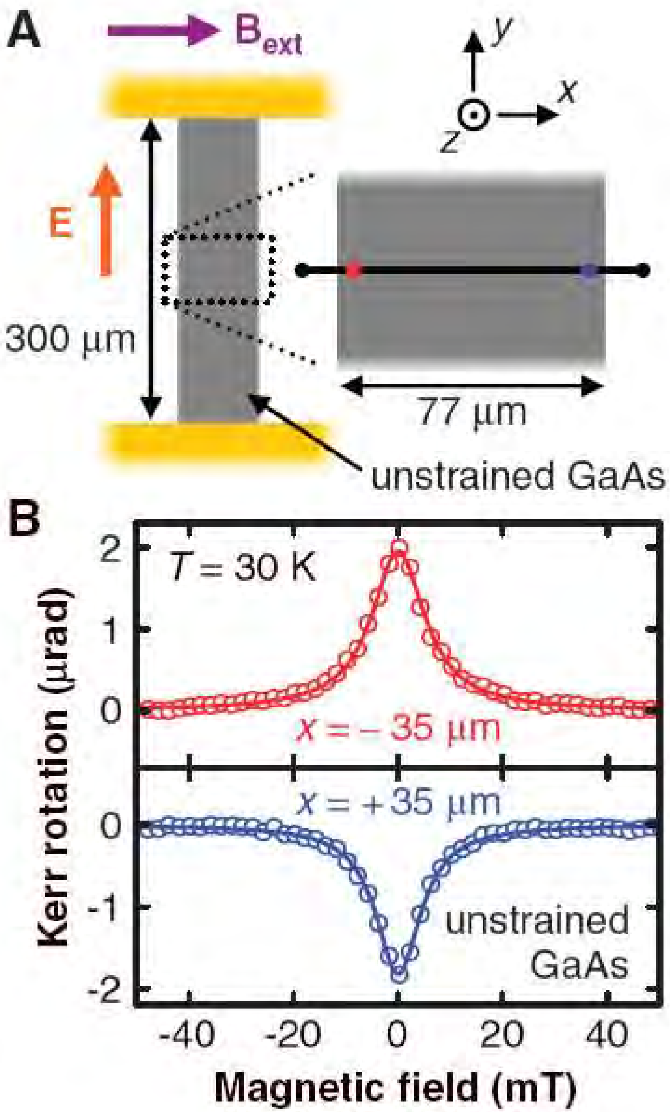




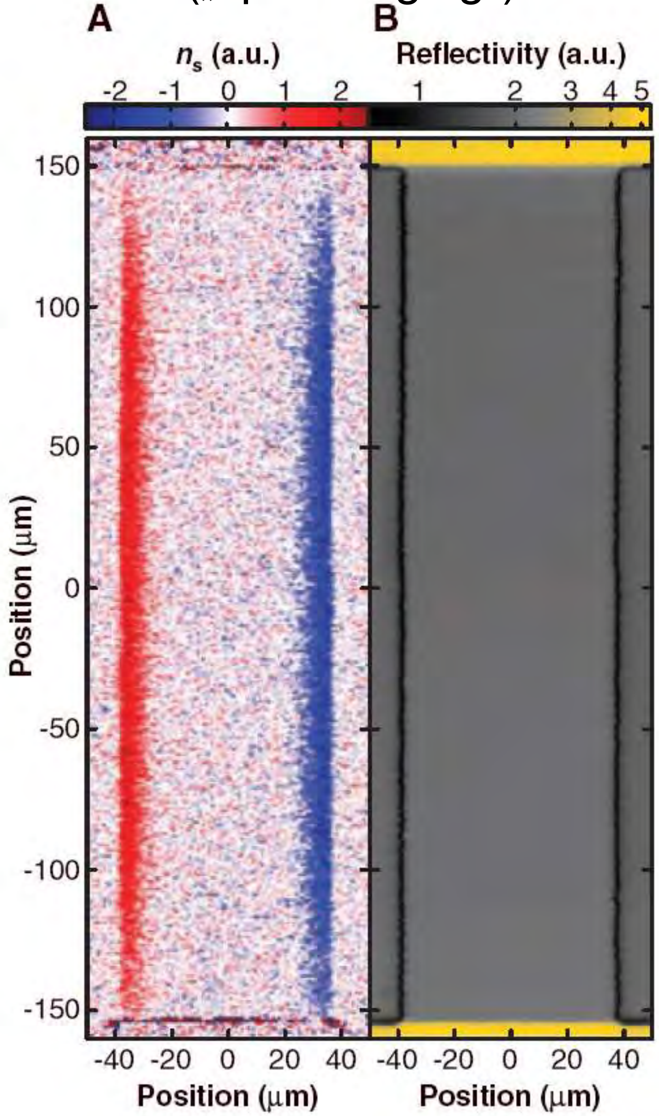
$$\mathbf{J}_S = \alpha_{SHE} \frac{\hbar}{2e} [\mathbf{J}_C \times \mathbf{s}]$$

$$\alpha_{SHE}^{GaAs} \cong 2 \times 10^{-4}$$

Kato *et al.*, Science **306**, 1910 (2004).



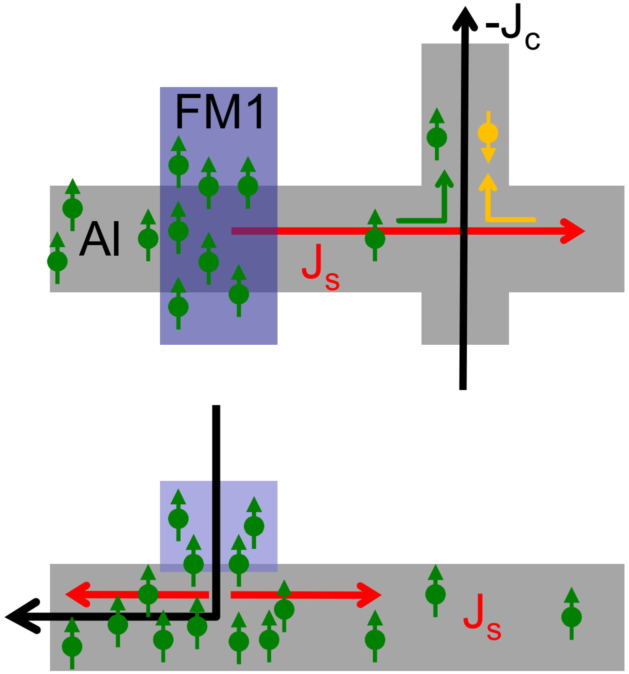
Kerr microscopy („spin imaging“)

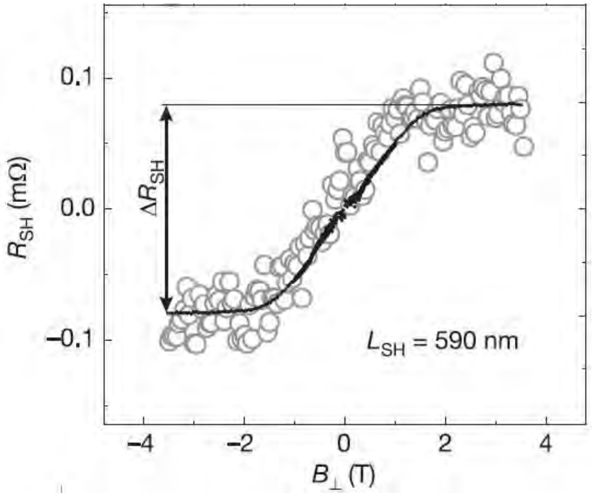


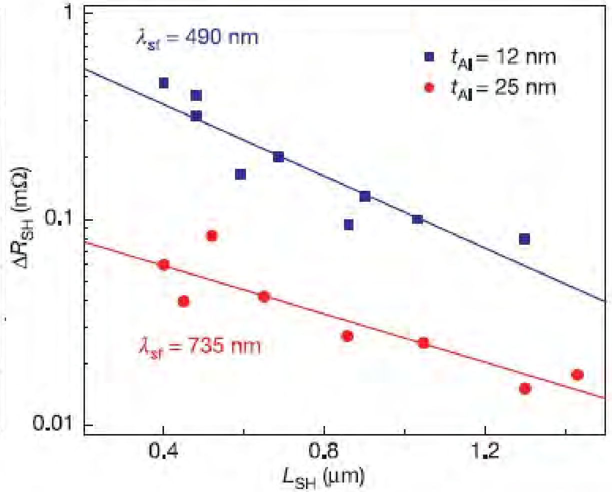
iSHE in Metallic F/N Nanostructures

Valenzuela & Tinkham, Nature **442**, 176 (2006).

$$\mathbf{J}_c^{\mathrm{ISHE}} = \alpha_{\mathrm{SHE}} \frac{2e}{\hbar}[\mathbf{J}_s \times \mathbf{s}]$$







$$\Delta R_{\mathrm{SHE}} \propto \alpha_{\mathrm{SHE}} \exp\left(-L_{\mathrm{SH}} / \lambda_{\mathrm{SF}}\right)$$

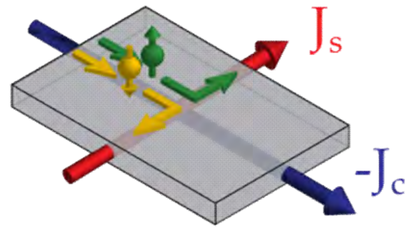
detection of diffusive spin current via inverse spin Hall effect

Aluminium: $\alpha_{\mathrm{SHE}} = \dfrac{\sigma_{\mathrm{SHE}}}{\sigma_{\mathrm{C}}} \cong 1 \times 10^{-4}$

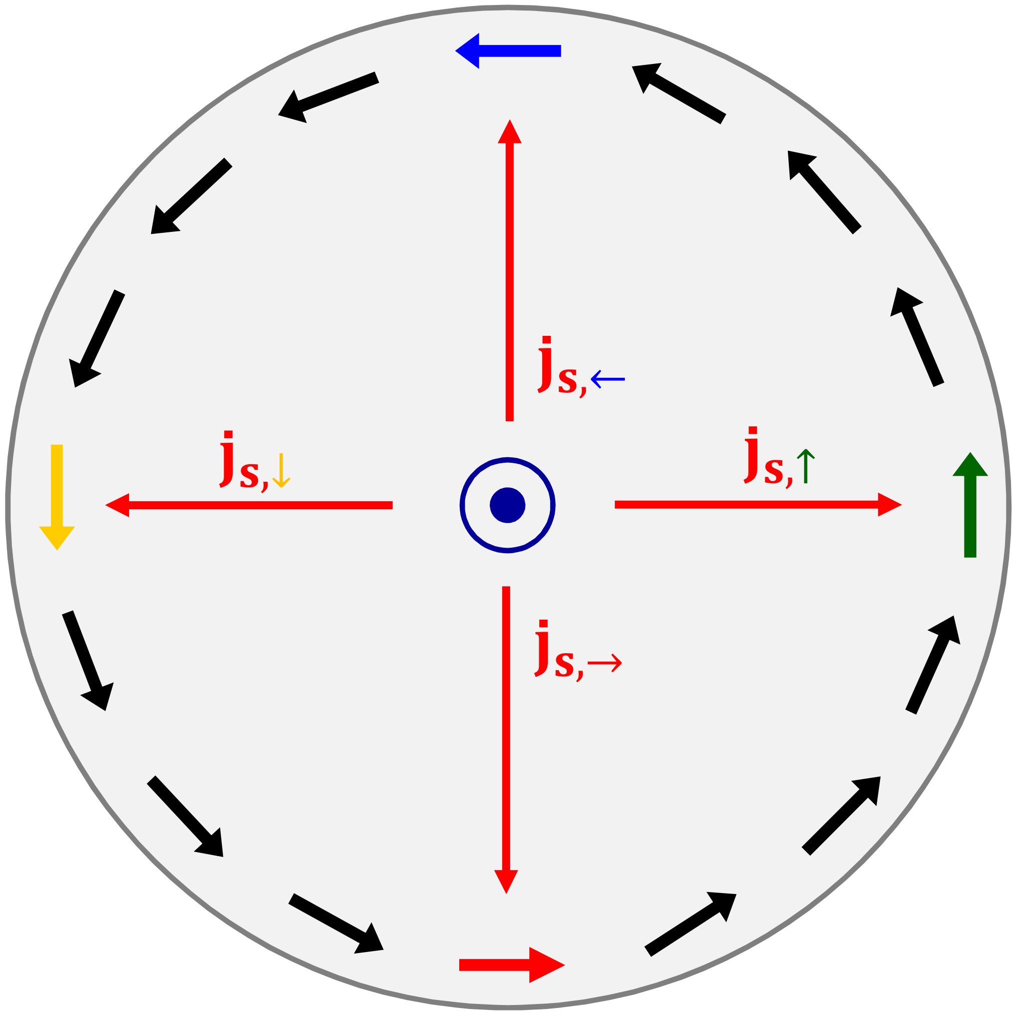
Saitoh *et al.*, APL **88**, 182509 (2006).
Mosendz *et al.*, Phys. Rev. Lett. **104**, 046601 (2010).
Liu *et al.*, Science **336**, 555 (2012).
Niimi *et al.*, Phys. Rev. Lett. **109**, 156602 (2012).
…and many more …
→review: Hoffmann, IEEE-TM **49**, 5172 (2013).
Sinova *et al.*, RMP **87**, 1213 (2015).

Gold : α_{SHE}=0.0016
Platinum : α_{SHE}=0.013 … **0.11** (0.16)
Bi, Bi/Ag, Ta : α_{SHE}=0.1 … **0.3**

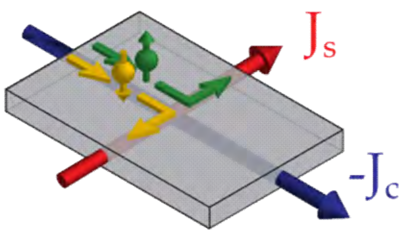
spin Hall effect



Nota bene:
spin currents have a direction of propagation $\mathbf{j_s}$
AND a spin orientation $\mathbf{s}$



spin Hall effect



Nota bene:
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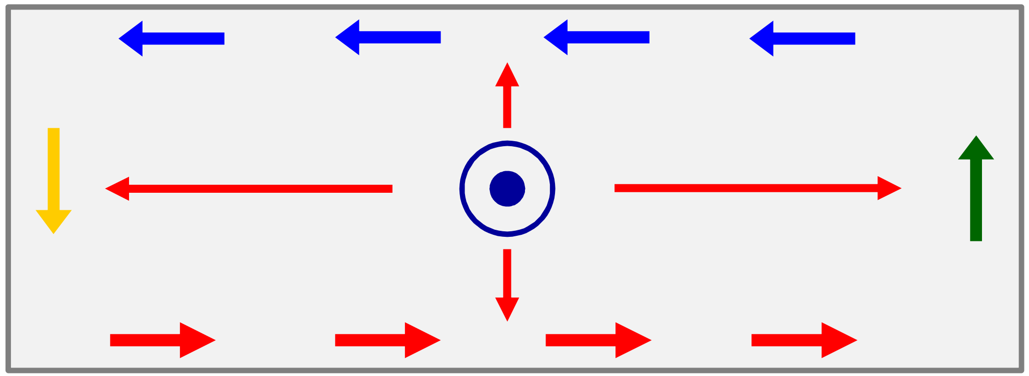
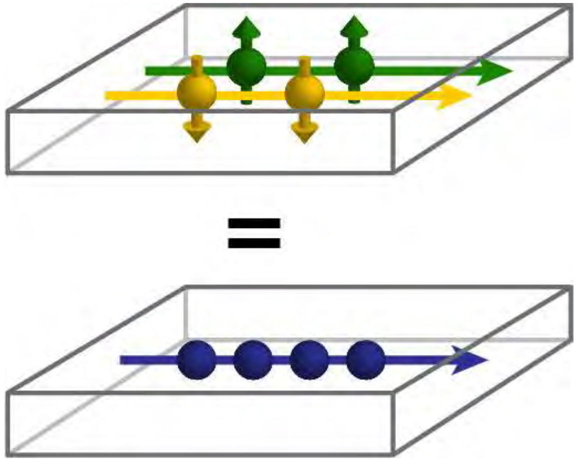


Charge vs. spin currents

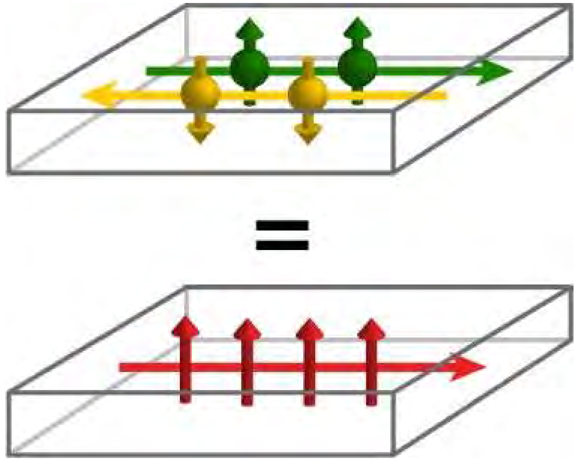
wrap-up: pure charge current



j_c *finite*

j_s *zero*

pure spin current

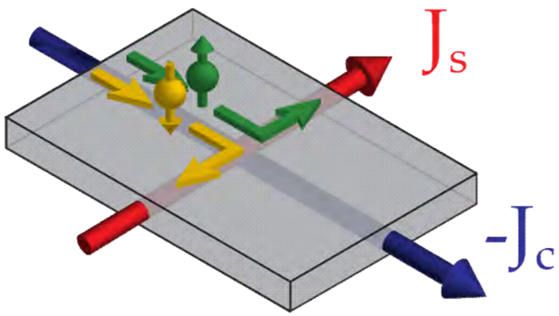


j_c *zero*

j_s *finite*

ISHE:

$j_s \rightarrow j_c$



SHE:

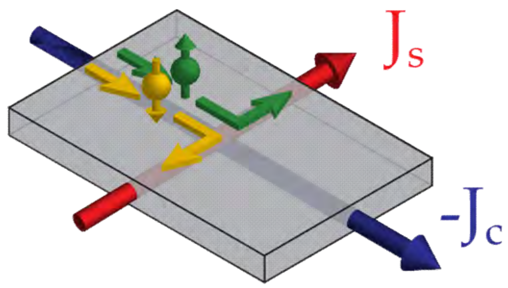
$j_c \rightarrow j_s$

Outline

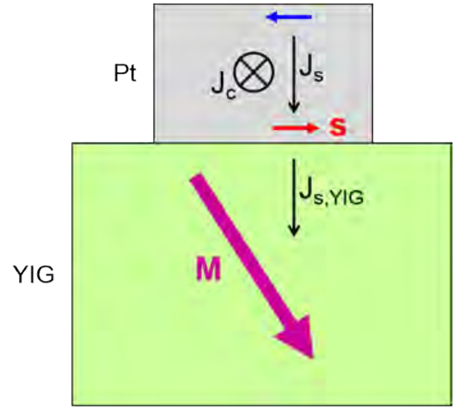
pure spin currents
spin Hall effect

Hoffmann, IEEE-TM **49**, 5172 (2013).
Sinova *et al.*, RMP **87**, 1213 (2015).

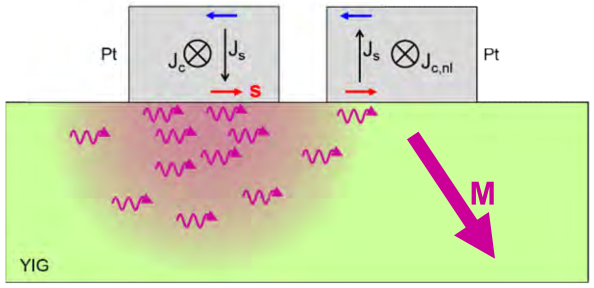
$g^{\uparrow\downarrow} \cong 10^{19}\mathrm{m}^{-2}$
$\alpha_{\mathrm{SHE,Pt}} = 0.1$
$\lambda_{\mathrm{SD,Pt}} = 1.5\mathrm{nm}$



SMR = Spin Hall Magnetoresistance
… a spin current-based magnetoresistance
@ magnetic insulator / metal interfaces

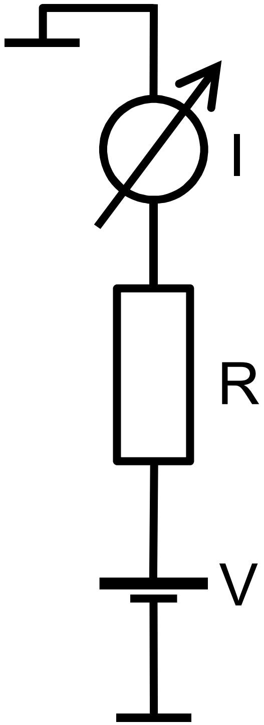


MMR = Magnon-mediated MagnetoResistance

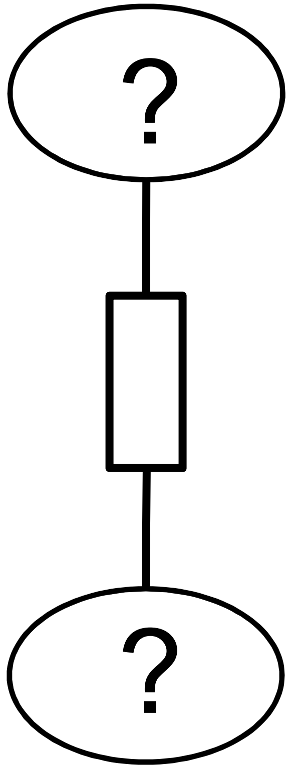


spin current circuits

charge-tronic circuit



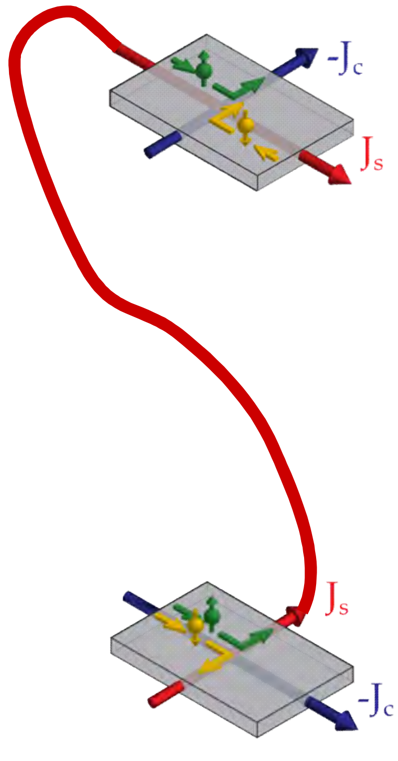
spin-tronic circuit



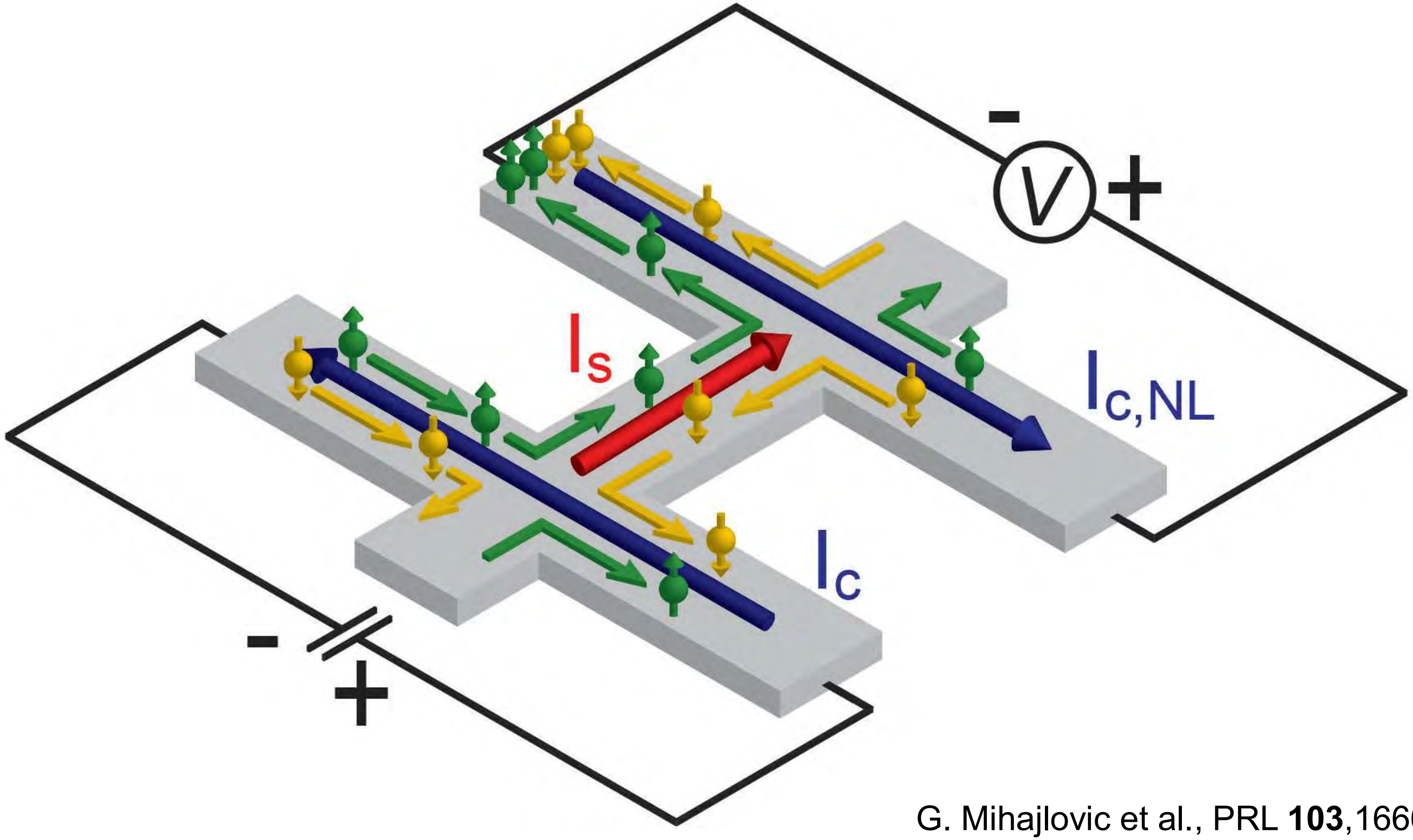
spin current detector

spin current conductor

spin battery (spin current source)

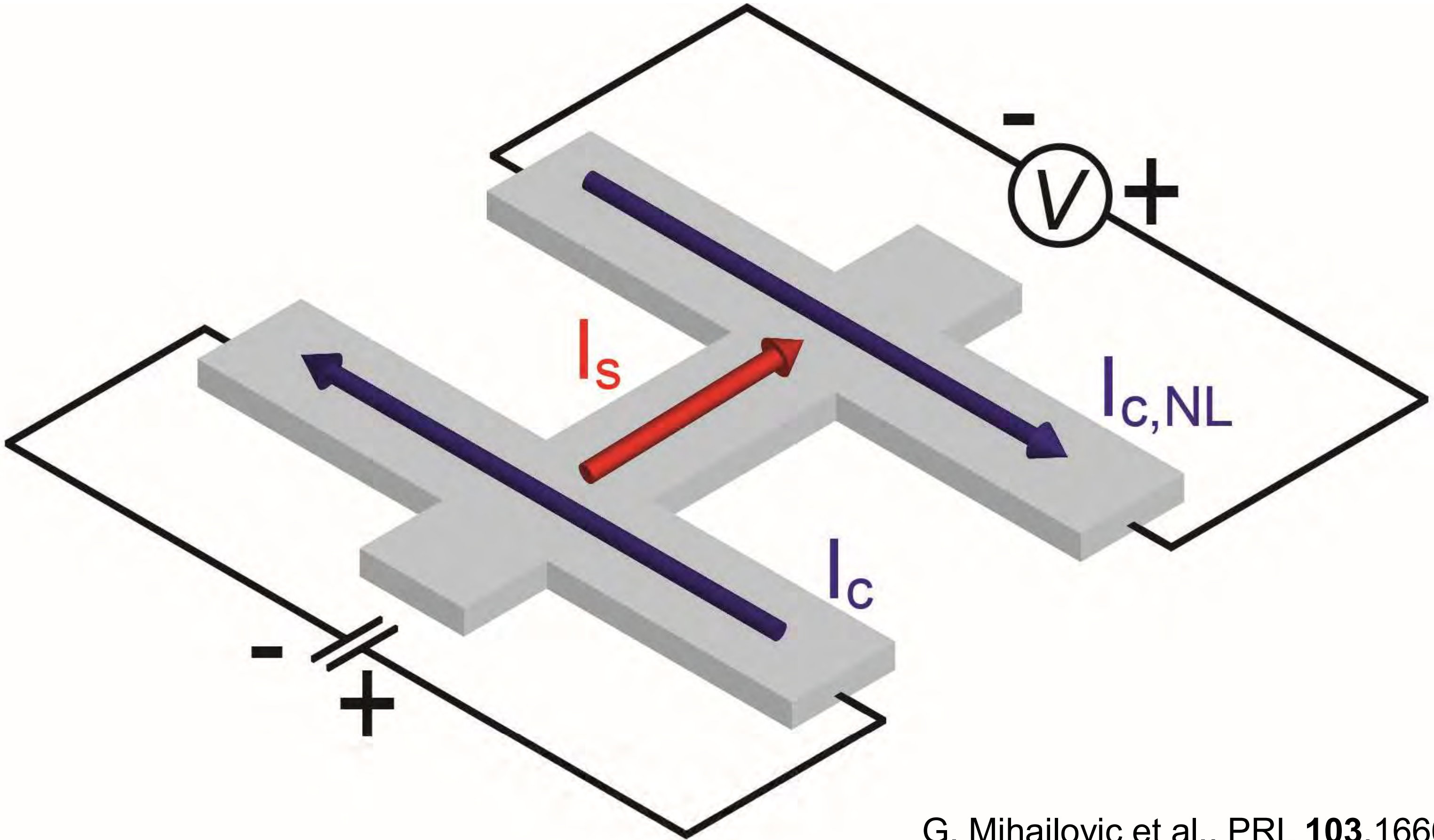


SHE & iSHE in a single metallic nanostructure



G. Mihajlovic et al., PRL **103**,166601 (2009).
F. Czeschka, PhD Thesis, TUM (2011).

SHE & iSHE in a single metallic nanostructure



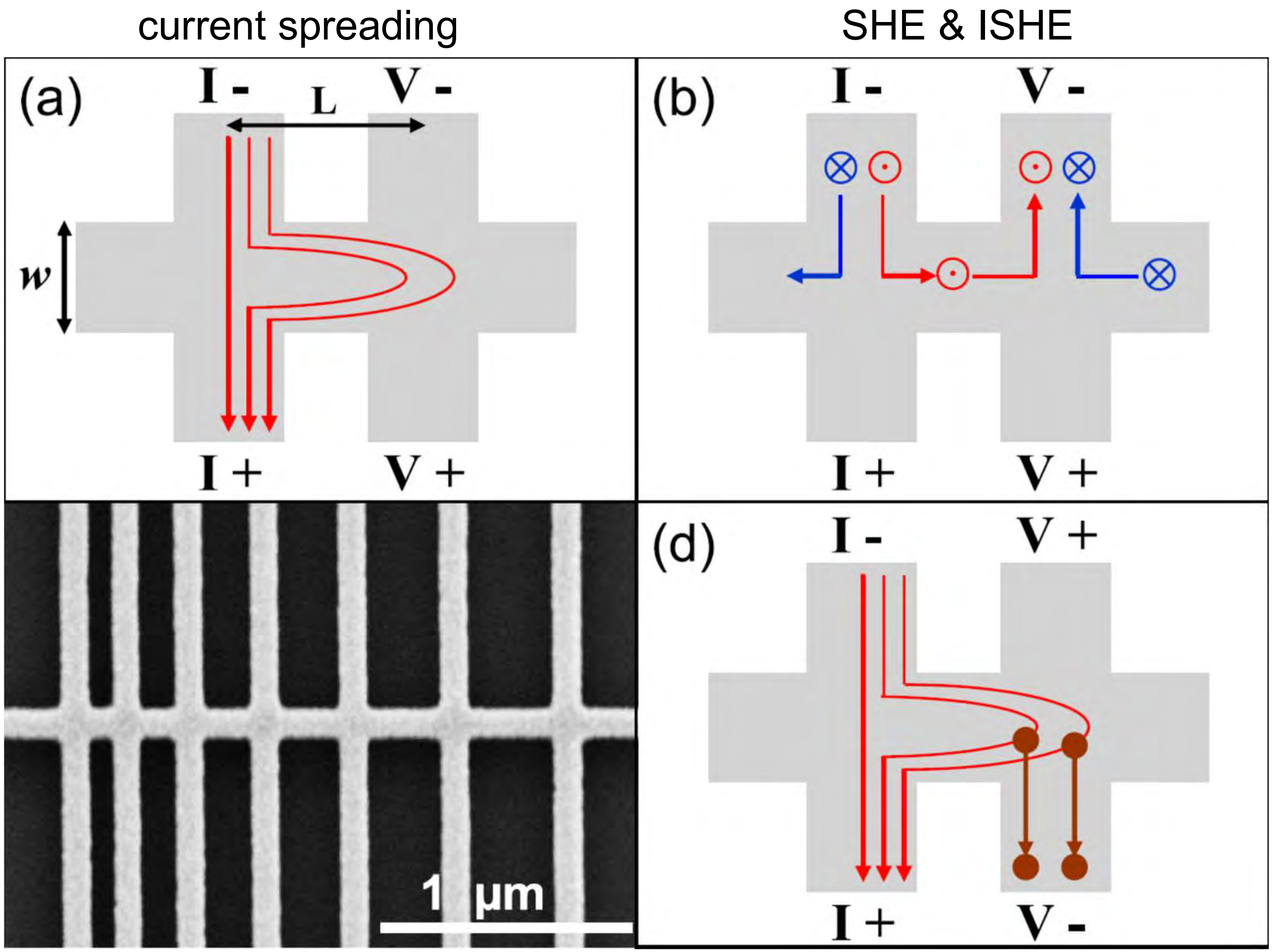
G. Mihajlovic et al., PRL **103**,166601 (2009).
F. Czeschka, PhD Thesis, TUM (2011).

Issues:
- current spreading (spurious signals)
- large $\alpha_{\mathrm{SHE}} \leftrightarrow$ small spin diffusion length

$\alpha_{\mathrm{SHE,Pt}} = 0.1 \leftrightarrow \lambda_{\mathrm{SD,Pt}} = 1.5\mathrm{nm}$

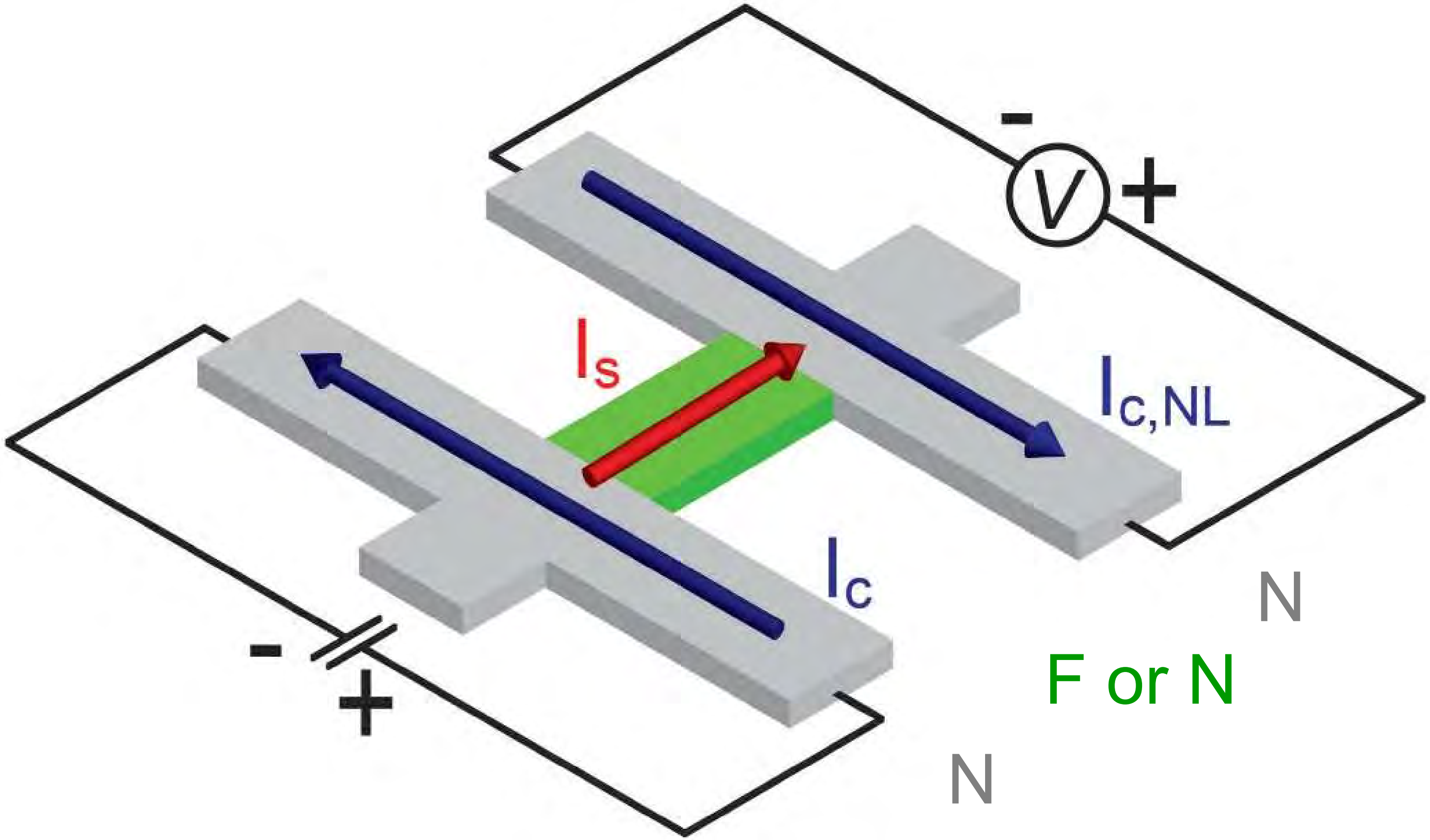
$\rightarrow$ heterostructures !!

SHE & iSHE in a Single Metallic Nanostructure

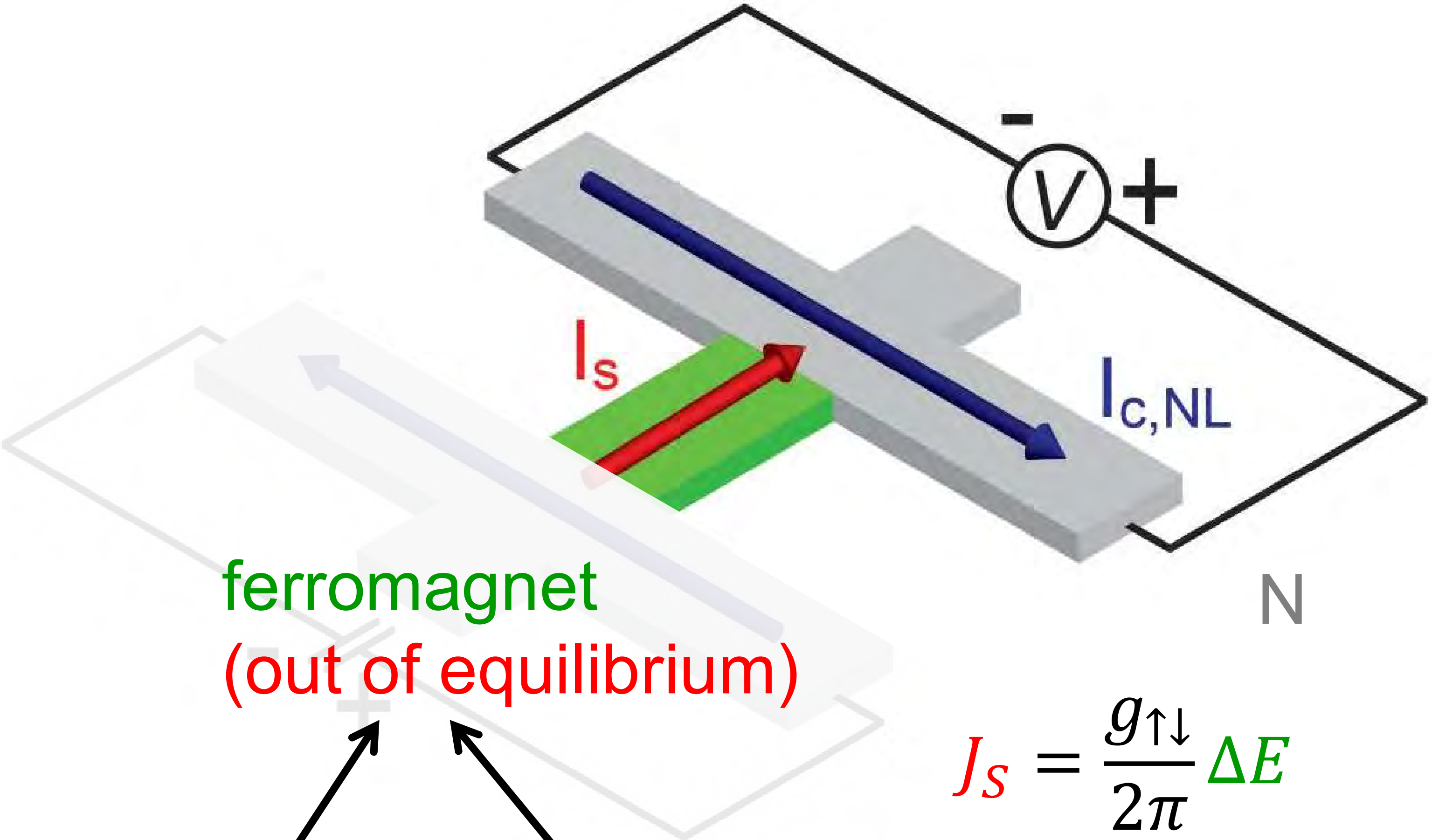


G. Mihajlovic et al., PRL **103**,166601 (2009). F. Czeschka, PhD Thesis, TUM (2011).

Spin current circuits



Spin current circuits



ferromagnet
(out of equilibrium)

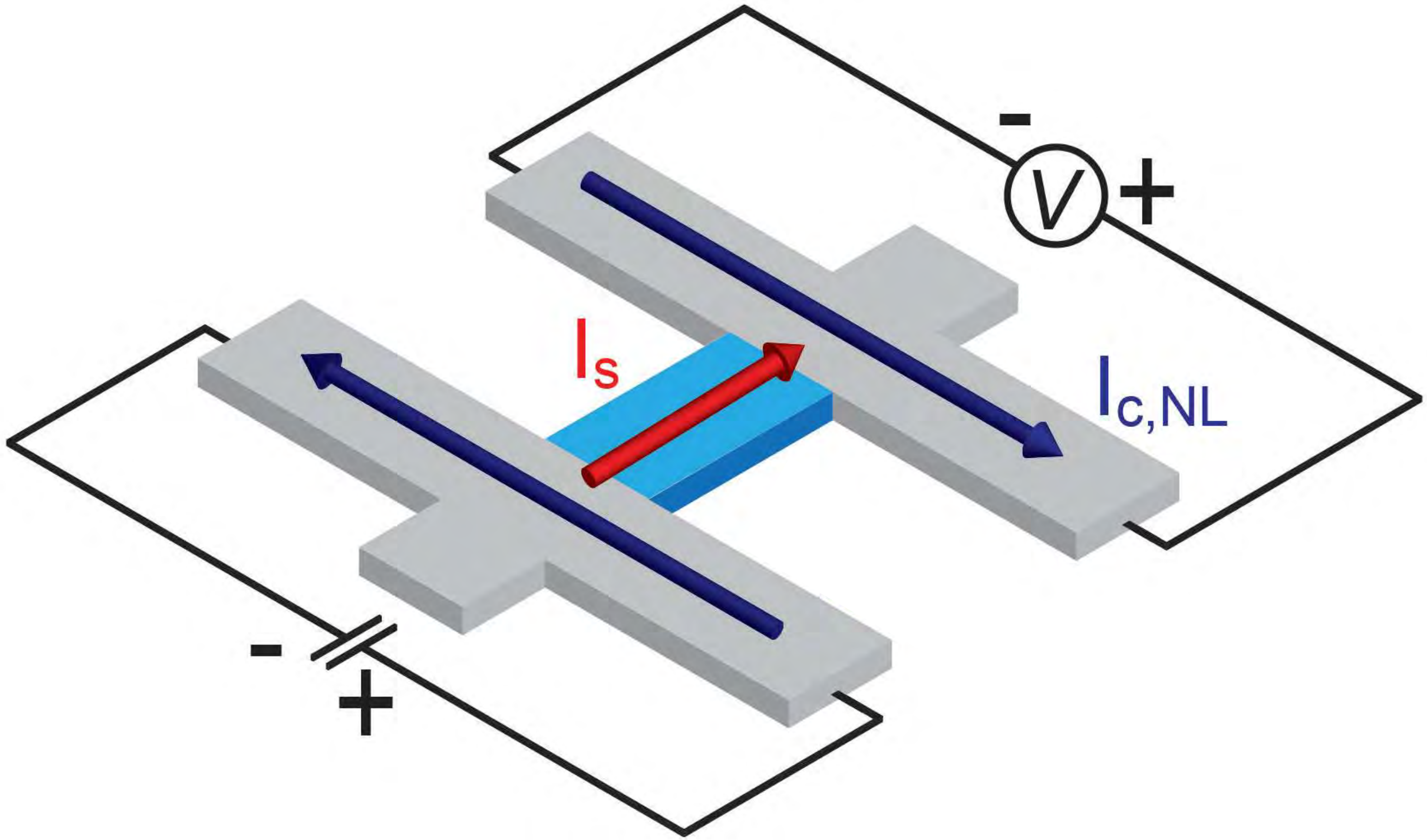
$$J_S = \frac{g_{\uparrow\downarrow}}{2\pi}\Delta E$$

Tserkovnyak *et al.*, PRL **88**, 117601 (2002).
Weiler *et al.*, PRL **111**, 176601 (2013).

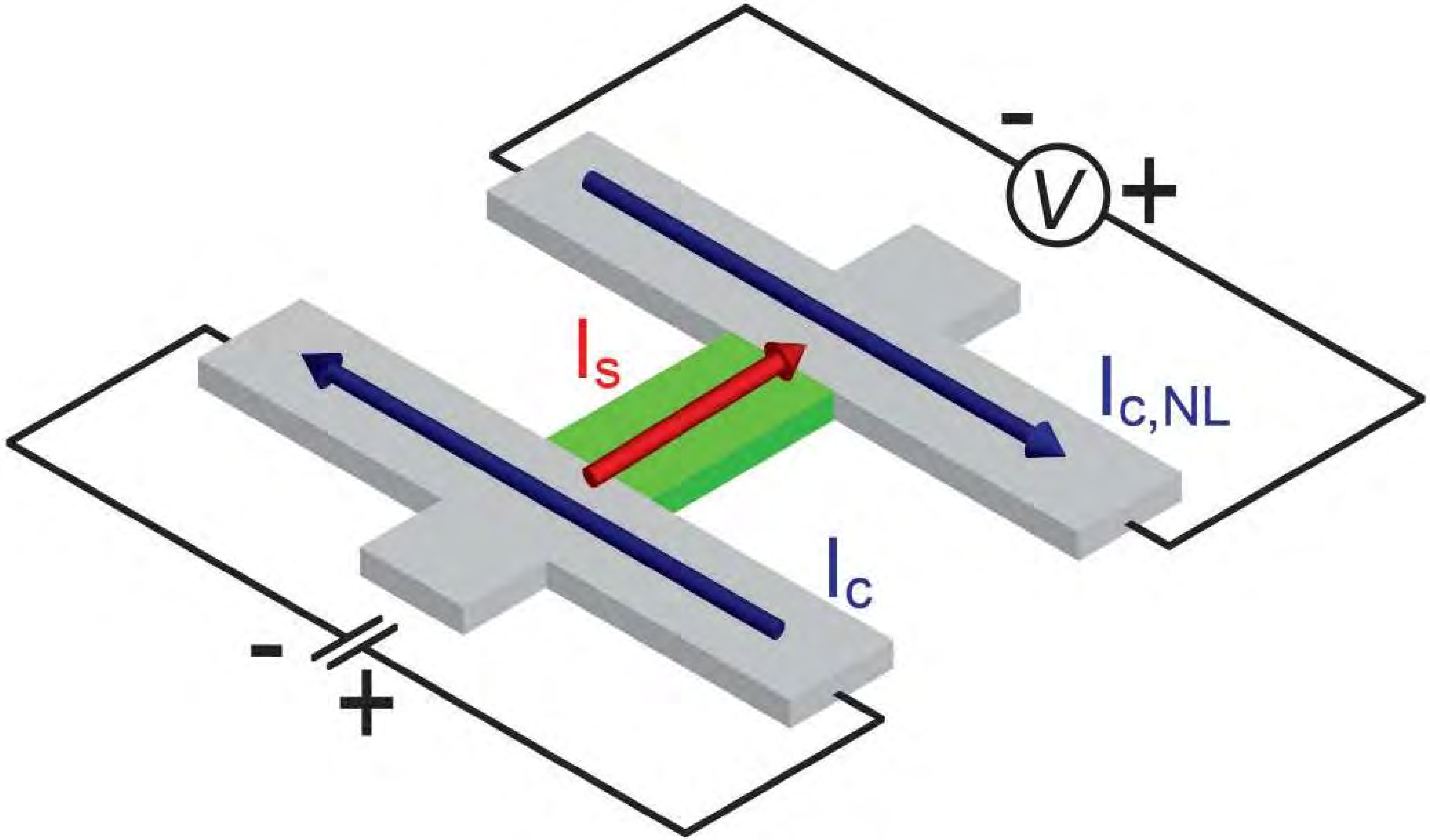
thermal excitation:
spin Seebeck effect

resonant excitation:
spin pumping

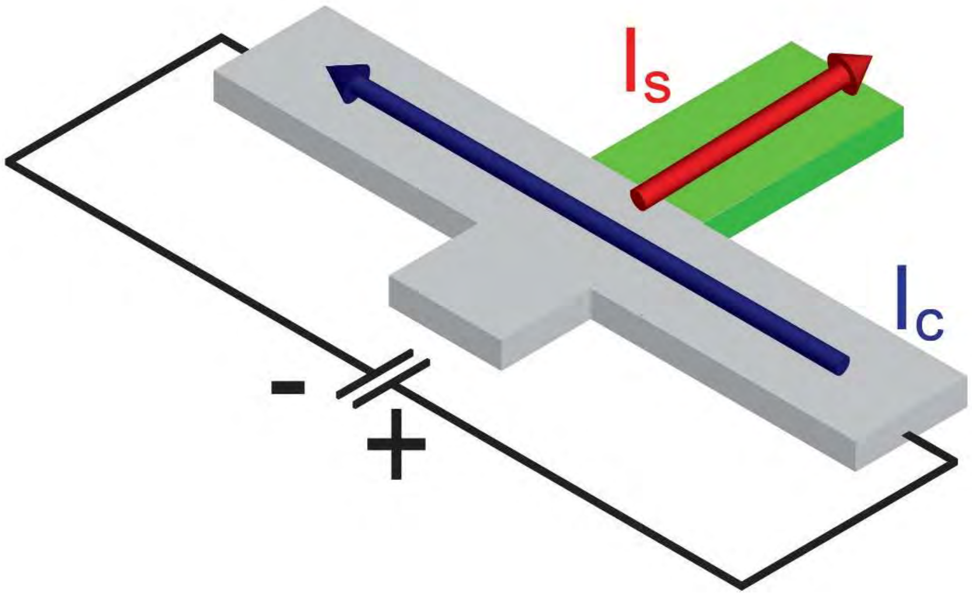
Spin current circuits

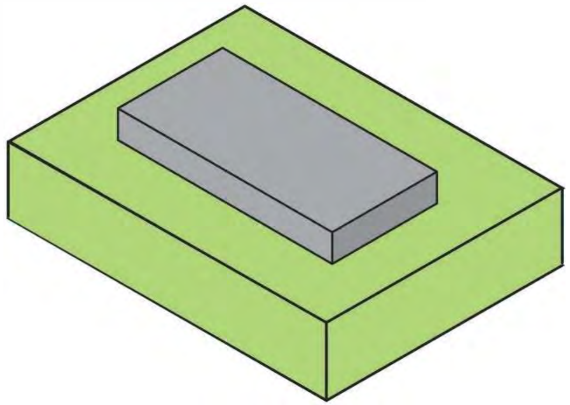


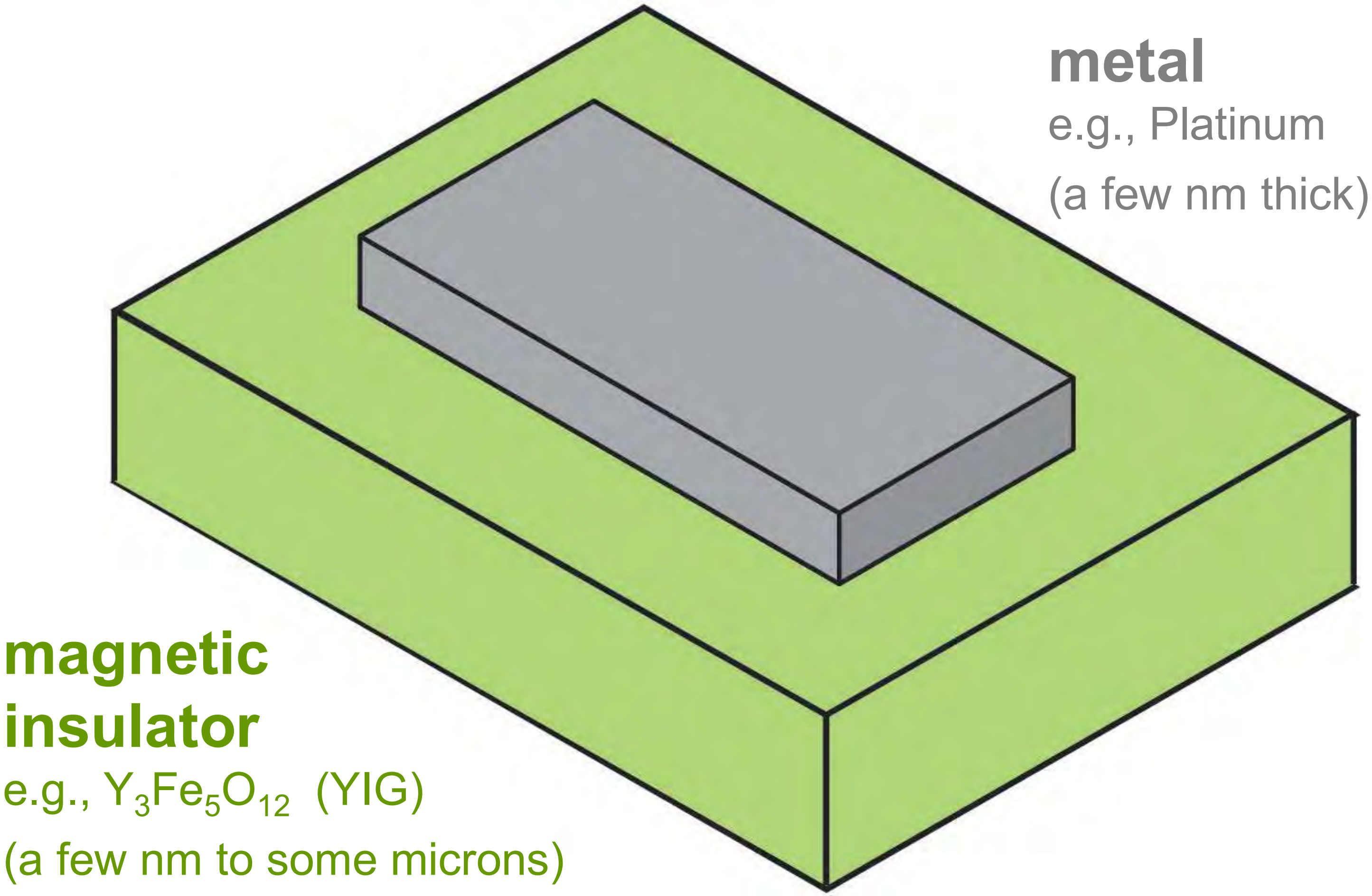
Spin current circuits



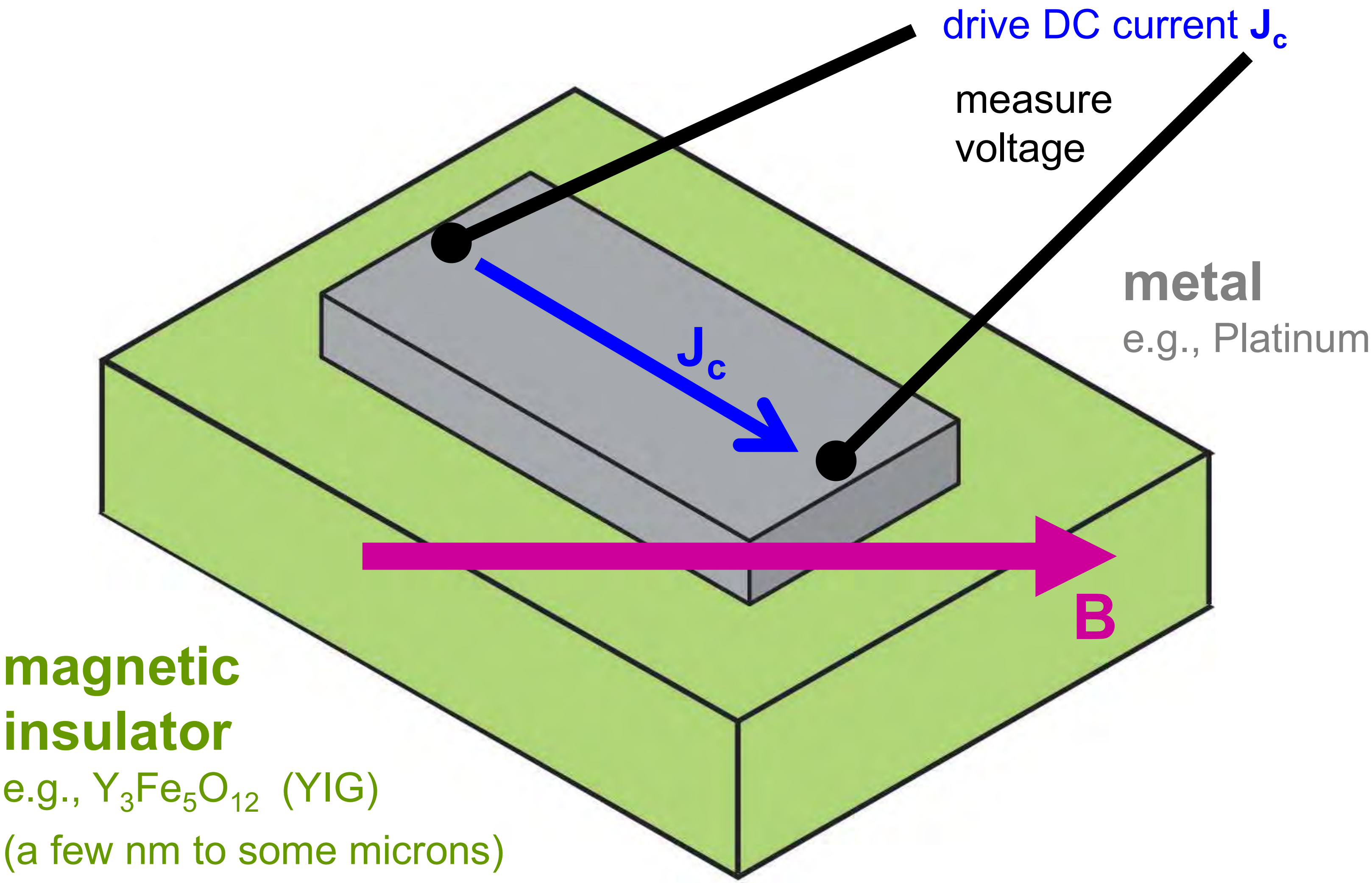
Spin current circuits





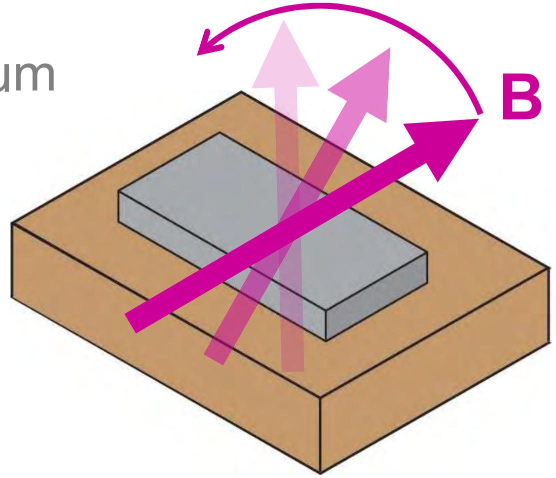


metal
e.g., Platinum
(a few nm thick)
magnetic insulator
e.g., $Y_3Fe_5O_{12}$ (YIG)
(a few nm to some microns)

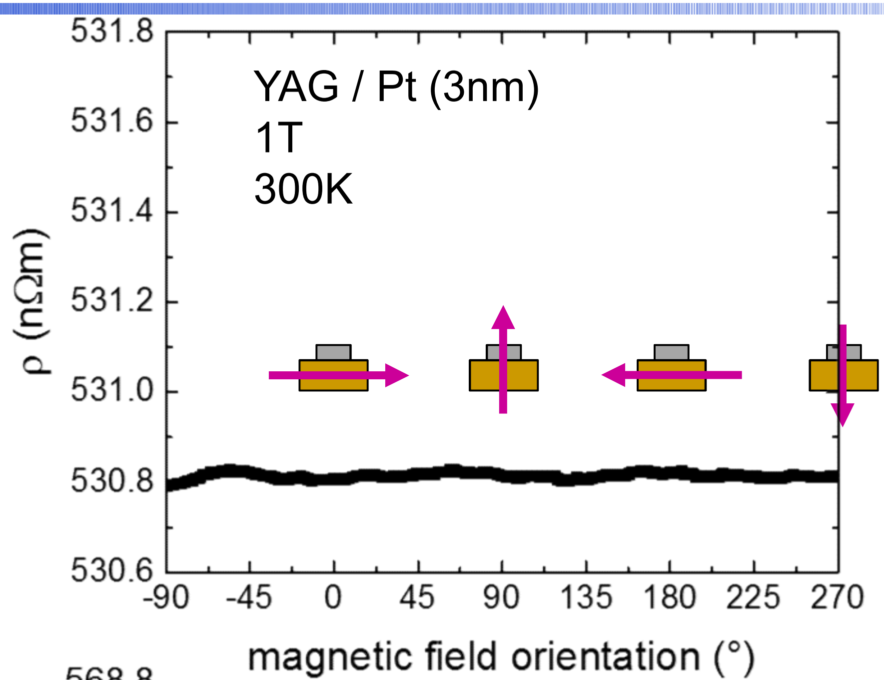


measure resistance R of the metal … as a function of the applied magnetic field **B**
(via current-bias, 4-point voltage measurements)

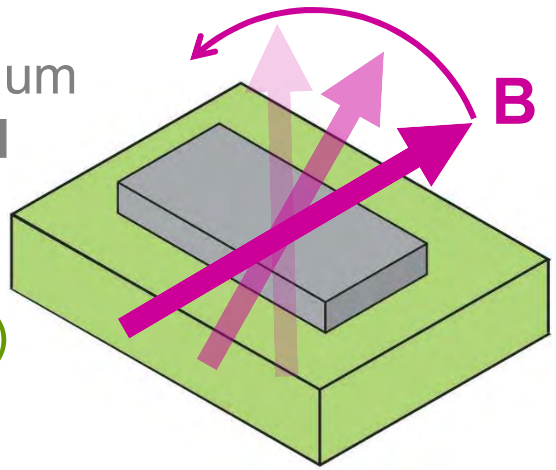
Platinum
metal



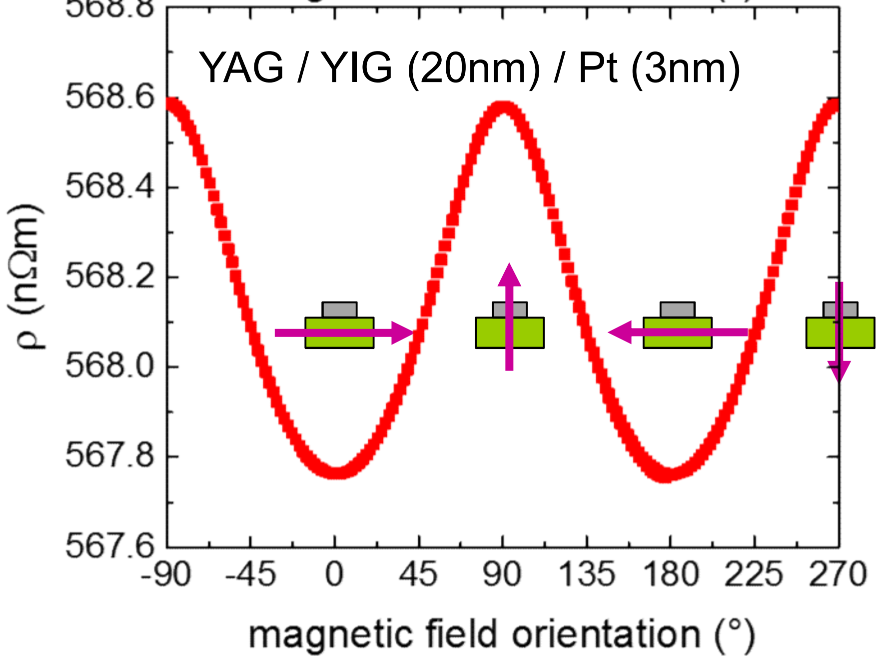
$Y_3Al_5O_{12}$ (YAG)
non-magnetic insulator



Platinum
metal



$Y_3Fe_5O_{12}$ (YIG)
magnetic insulator

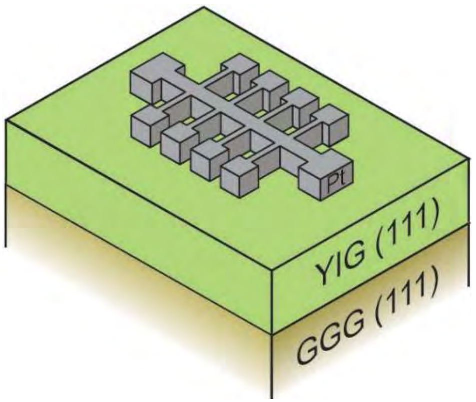


SMR = Spin-Hall magnetoresistance

$$\frac{\Delta\rho}{\rho} = 1.5 \times 10^{-3}$$

spin Hall magnetoresistance

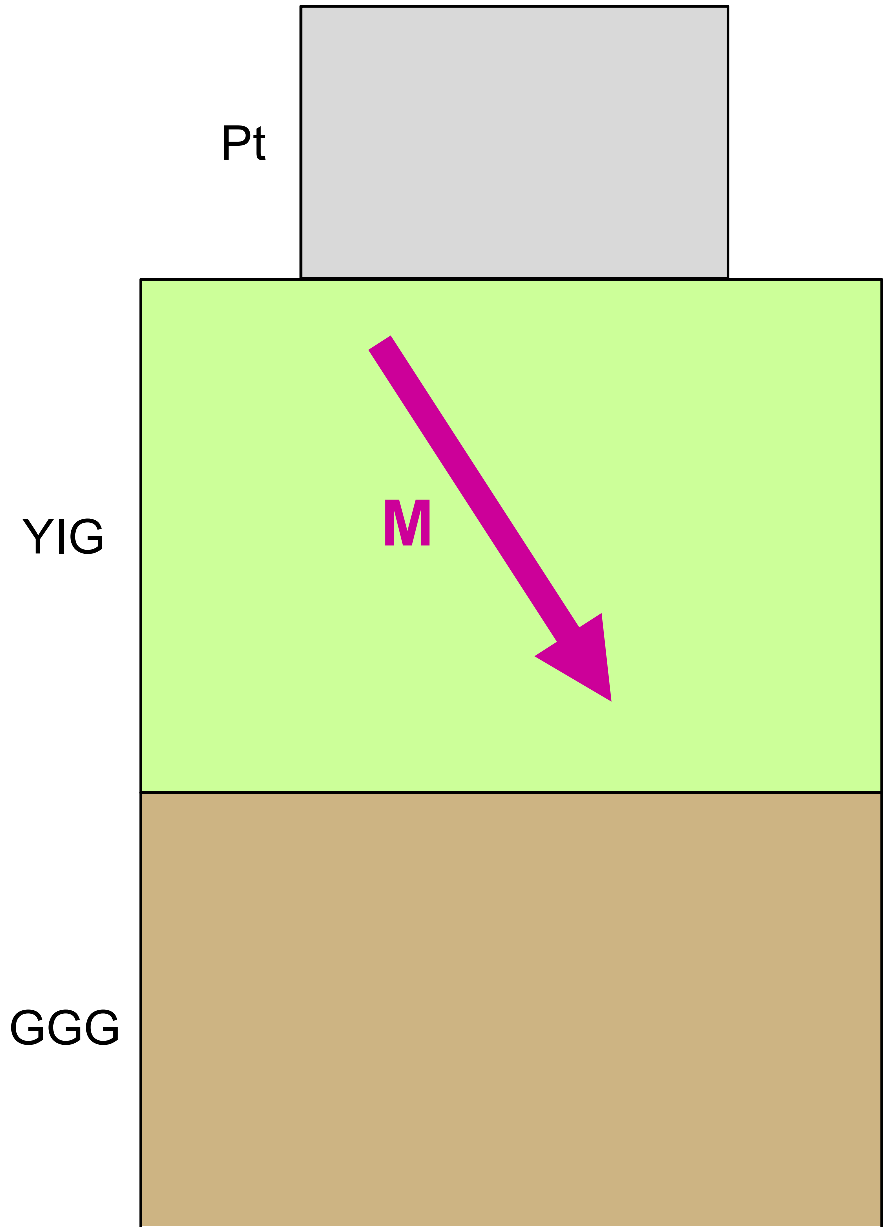
(a spin current MR @ FMI / N interfaces)

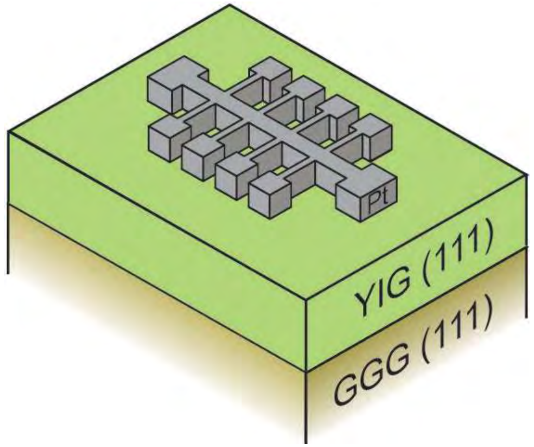


Nakayama *et al.*, PRL **110**, 206601 (2013).
Chen *et al.*, PRB **87**, 144411 (2013).
Hahn *et al.*, PRB **87**, 174417 (2013).
Vlietstra *et al.*, PRB **87**, 184421 (2013).
Althammer *et al.*, PRB **87**, 224401 (2013).
Meyer *et al.*, APL **104**, 242411 (2014).
Lotze *et al.*, PRB **90**, 174419 (2014).

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

YIG/Pt bilayer sample





Platinum
here: ~10nm

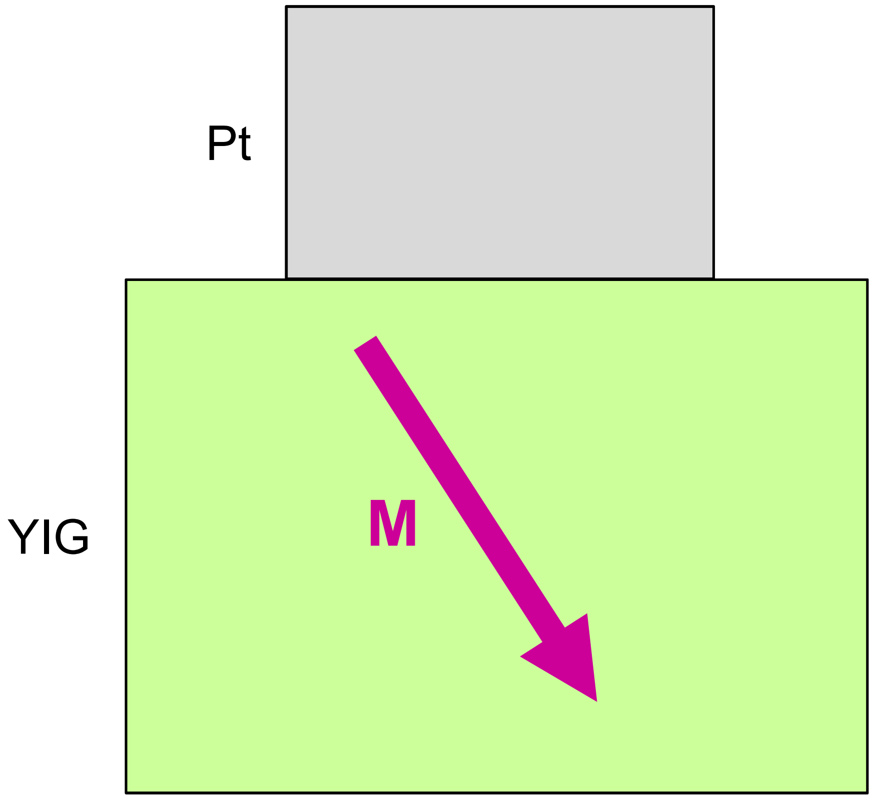
YIG = $Y_3Fe_5O_{12}$

electrically insulating ferrimagnet
(„magnetic insulator“)
with net magnetization **M**

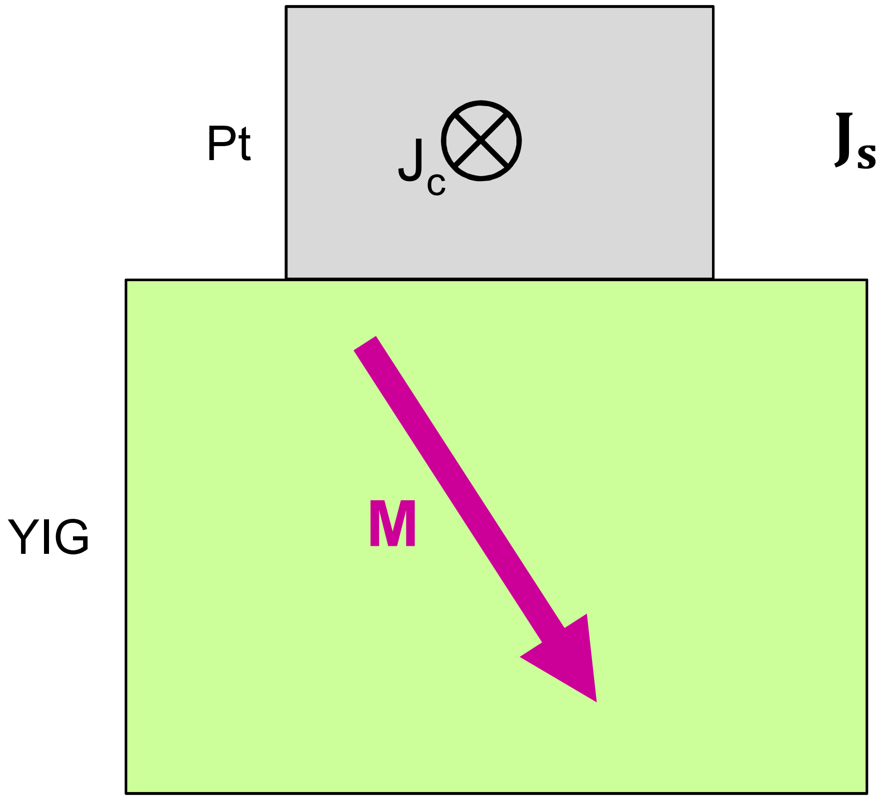
here: 3µm thick YIG film

grown onto 500µm of GGG = $Gd_3Ga_5O_{12}$
via liquid phase epitaxy (LPE)

SMR mechanism

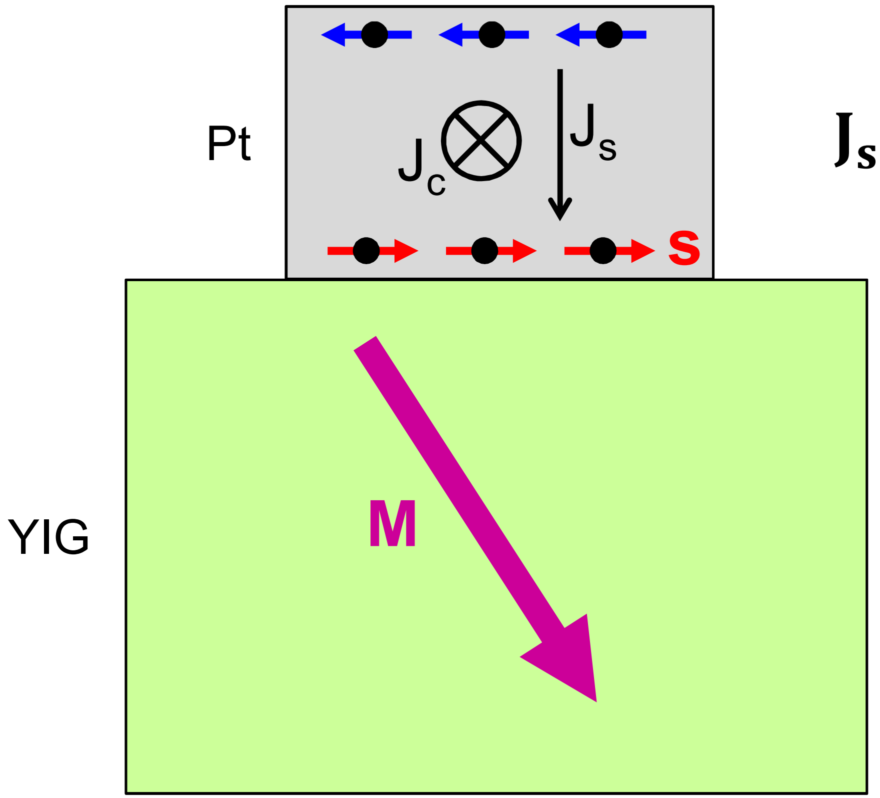


SMR mechanism



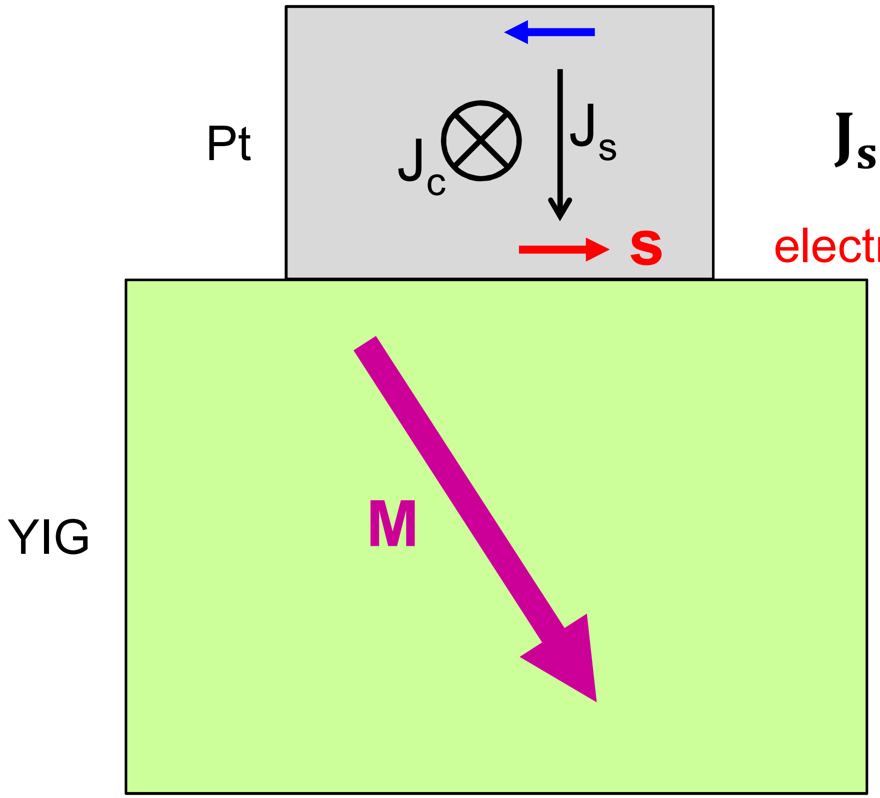
$$\mathbf{J_s} = \alpha^{\mathrm{SHE}} \frac{\hbar}{2e} [\, \mathbf{J_c} \times \mathbf{s} \,]$$

SMR mechanism



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

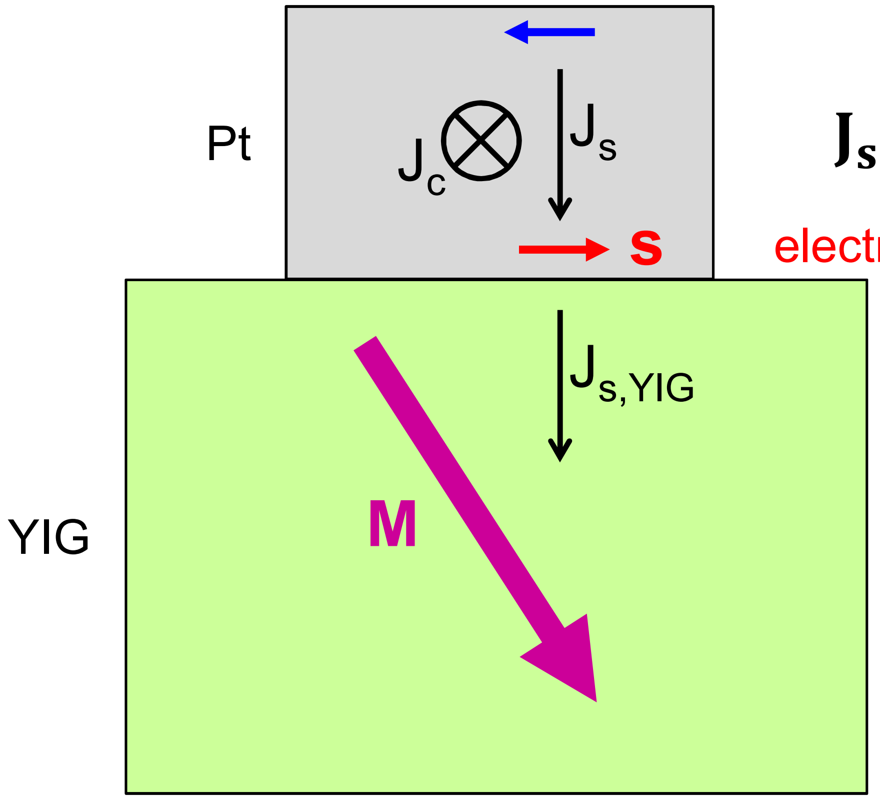
SMR mechanism



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

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

SMR mechanism



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

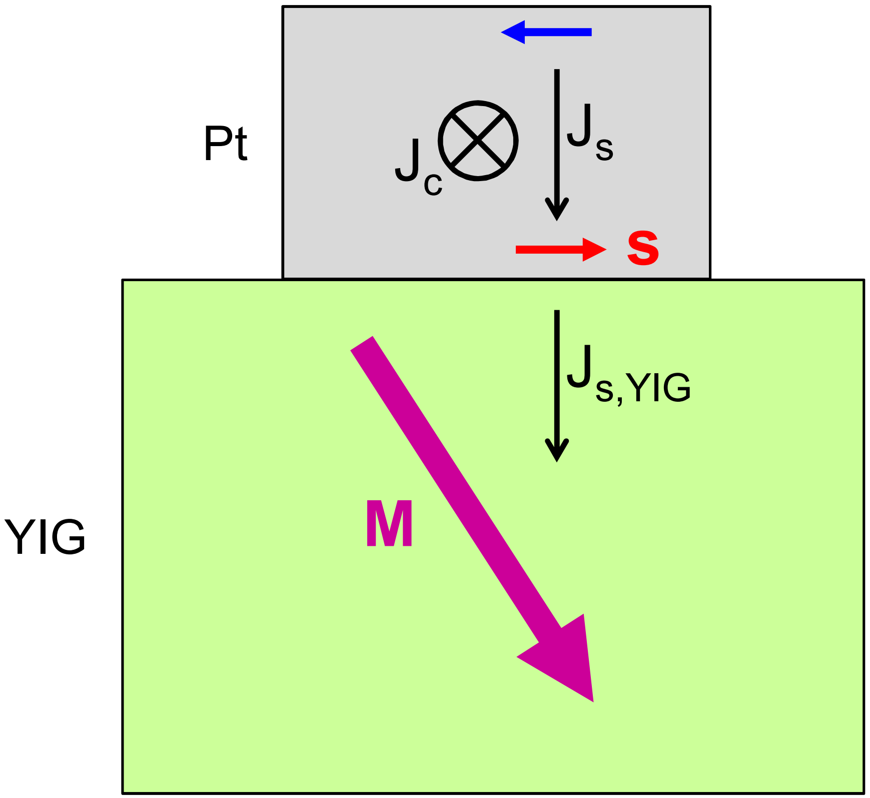
electron spin accumulation in Pt with spin **s**

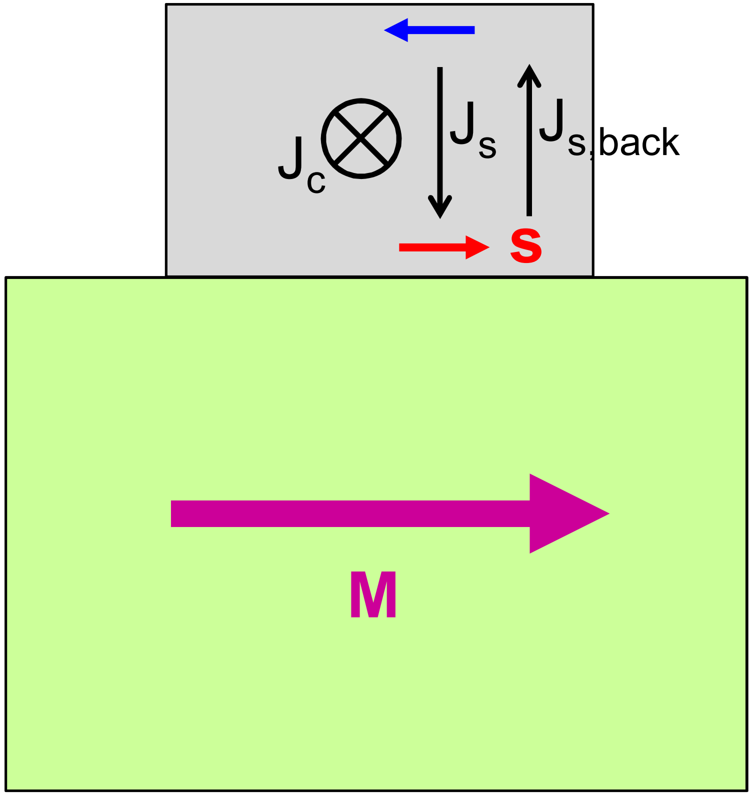
if $\tau_{\mathrm{STT}} \propto \mathbf{M} \times (\mathbf{M} \times \mathbf{s})$ is finite

⇒ outflow of J_s into YIG

enhanced dissipation in Pt
⇒ larger Pt resistance

SMR mechanism





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

$\Rightarrow$ outflow of J_s into YIG

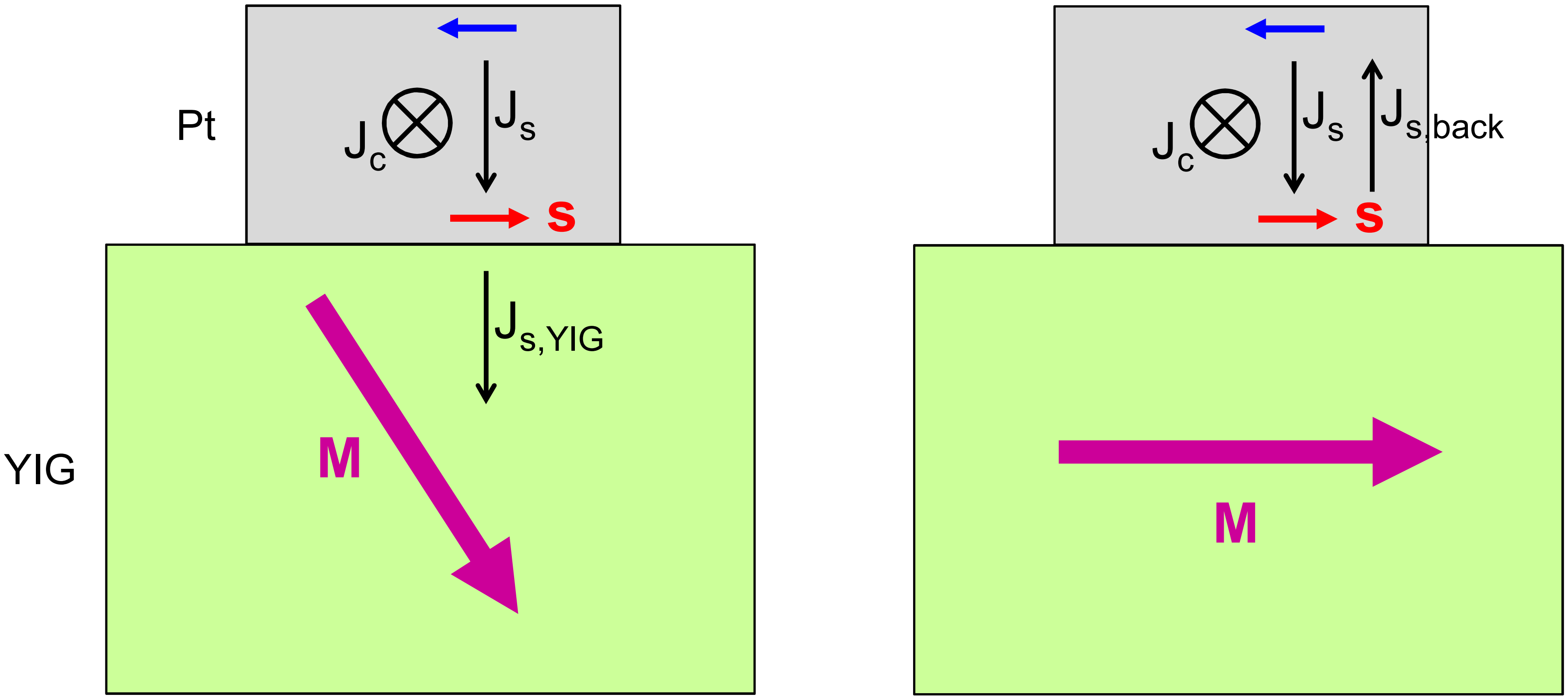
enhanced dissipation in Pt
$\Rightarrow$ larger Pt resistance

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

$\Rightarrow$ open boundary conditions for J_s

reduced dissipation
$\Rightarrow$ smaller Pt resistance

SMR mechanism



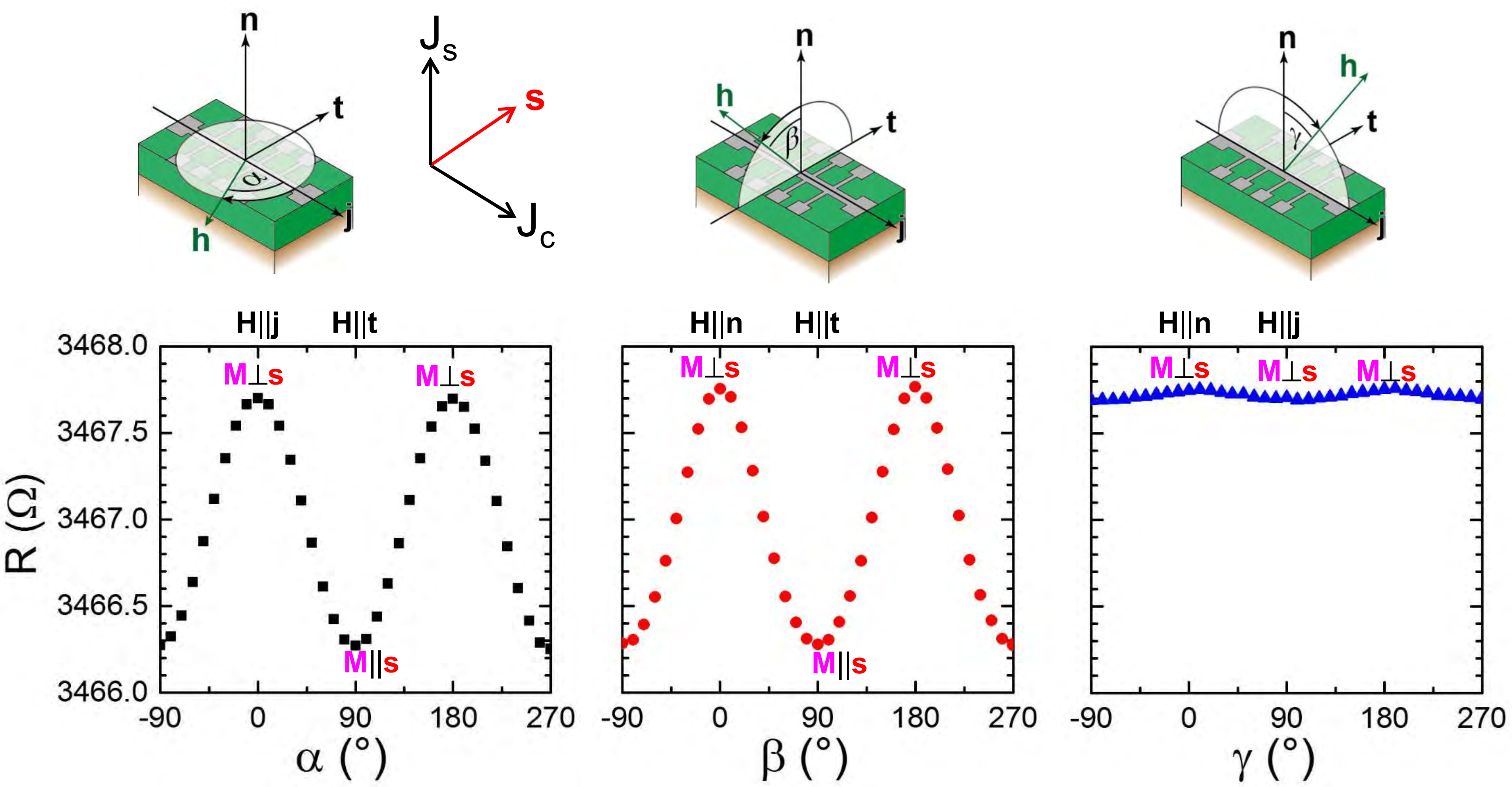
Spin Hall MR (SMR): *R* smallest for **M**||**s** , larger otherwise

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

PRL **110**, 206601 (2013)

SMR fingerprint

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

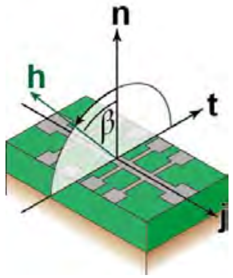


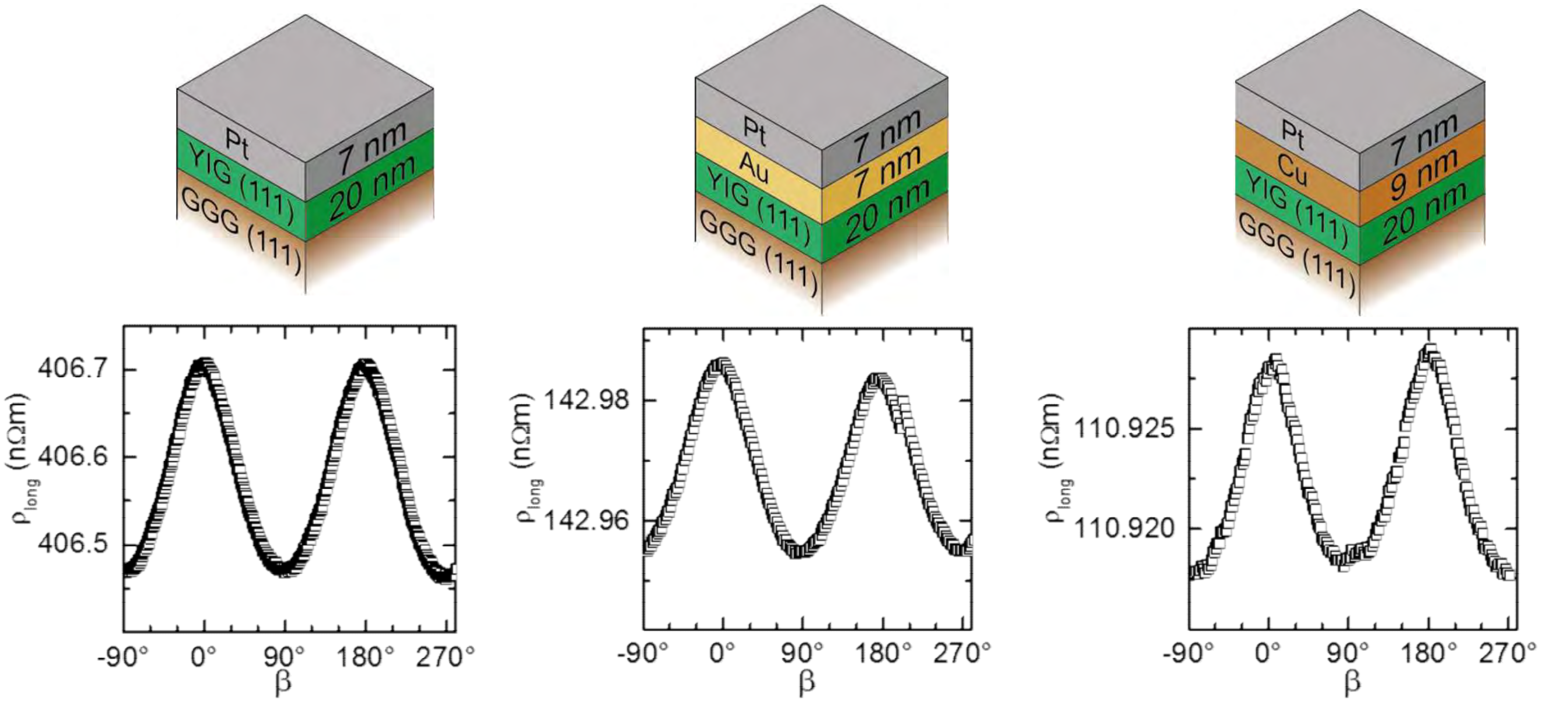
SMR amplitude in YIG/Pt: $\frac{\Delta R}{R} \leq 2 \times 10^{-3}$, ideally $\frac{\Delta R}{R} \leq \left(\alpha_{Pt}^{SHE}\right)^2 \approx 0.01$

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

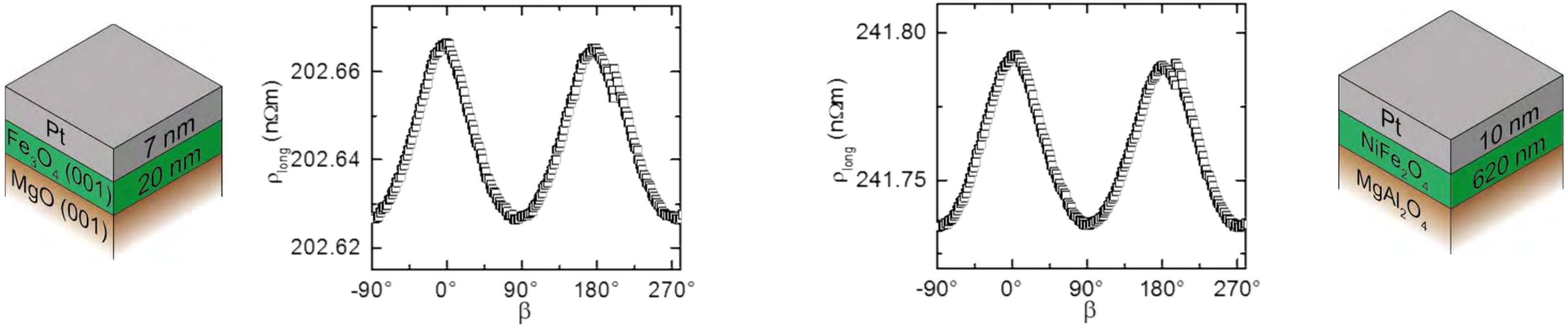
SMR in YIG/NM/Pt hybrids

300 K, 1 T





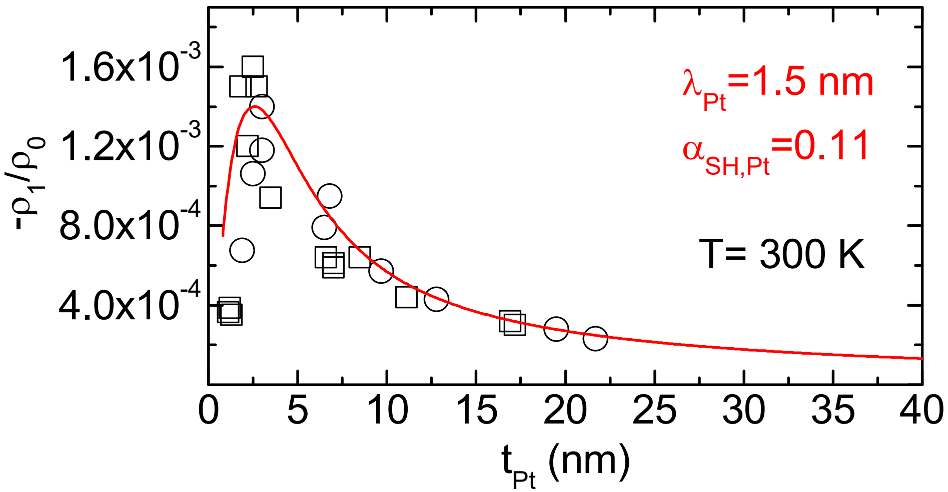
⇒ **spin current physics !** (NOT static proximity effect as in Huang *et al.*, PRL **109**, 107204 (2012).)



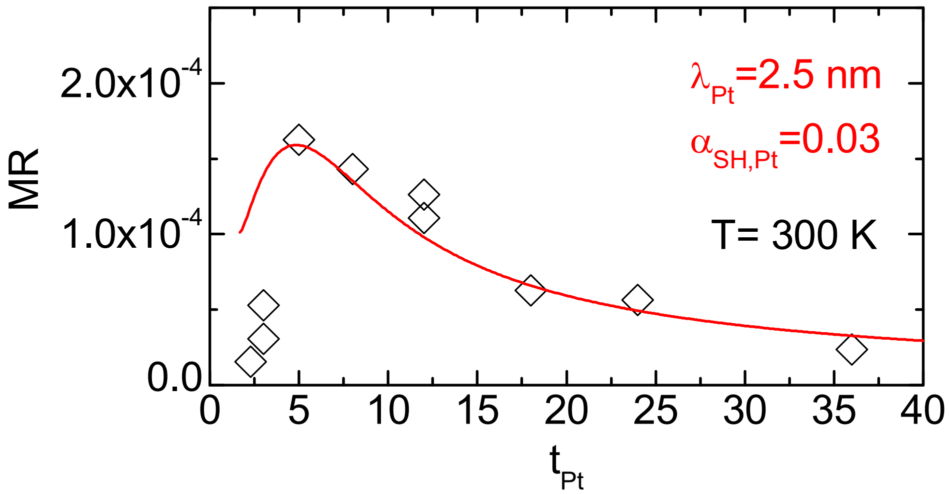
NFO thin film samples: A. Gupta, University of Alabama, and T. Kuschel, Universität Bielefeld

Extraction of spin Hall angle from SMR

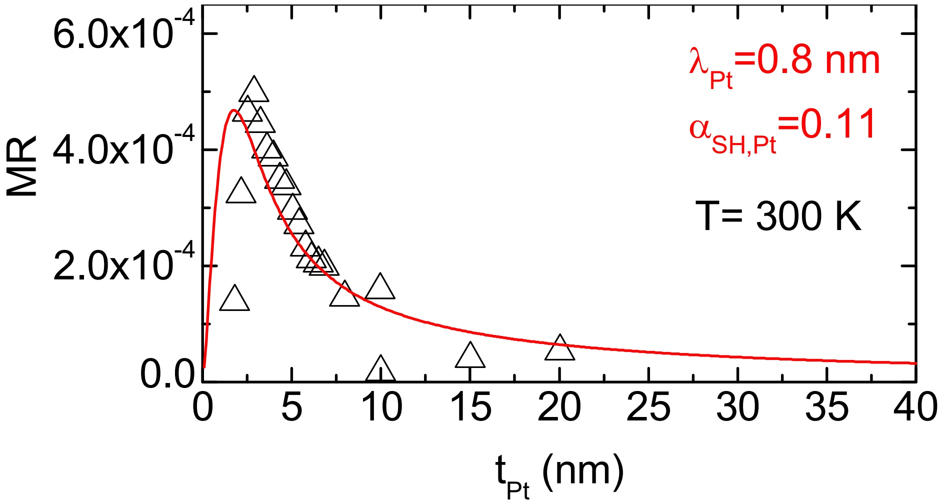
YIG/Pt @ WMI



YIG/Pt @ IMR



YIG/Pt @ Huang *et al.*, PRL, **109**, 107204 (2012)

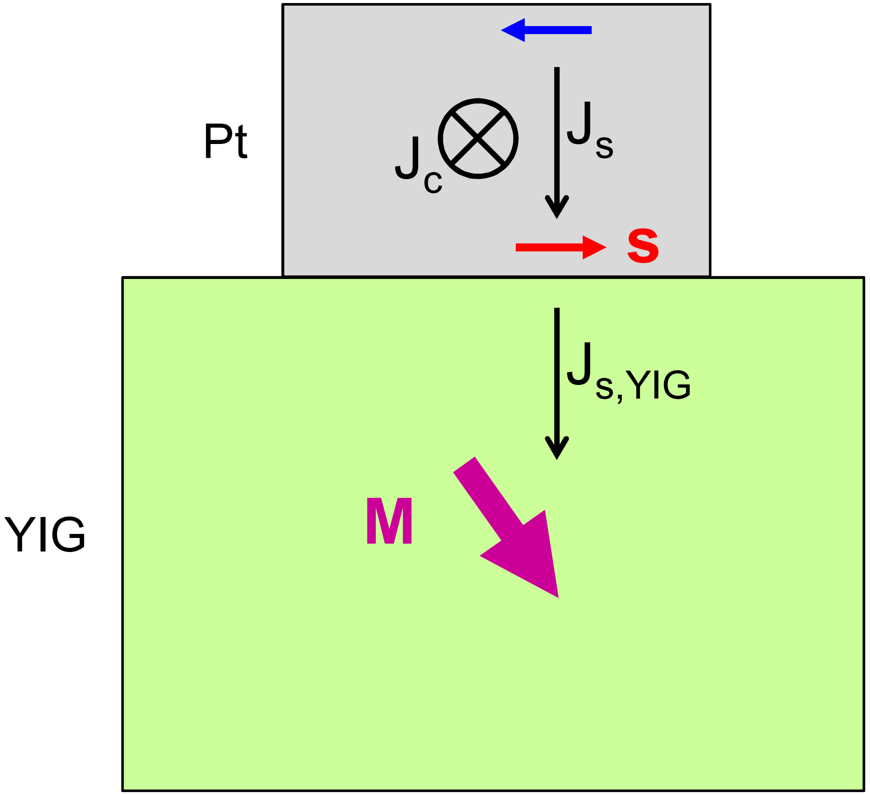


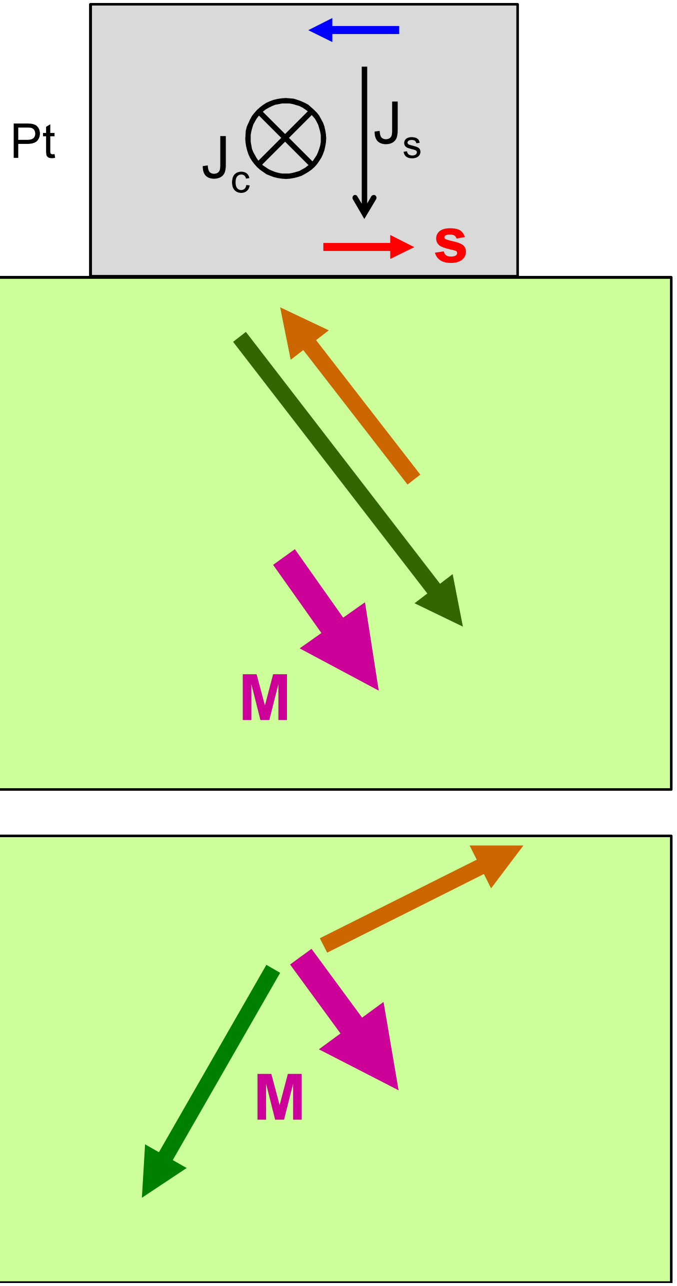
Spin Hall magneto-resistance:

- ✓ MR in (nonmagnetic) Pt, governed by **M** in insulating YIG
- ✓ "simple" measurement of spin Hall transport parameters
- ✓ electrical detection of **M** in FMI

Pt thickness dependence → spin Hall angle and spin diffusion length in Pt

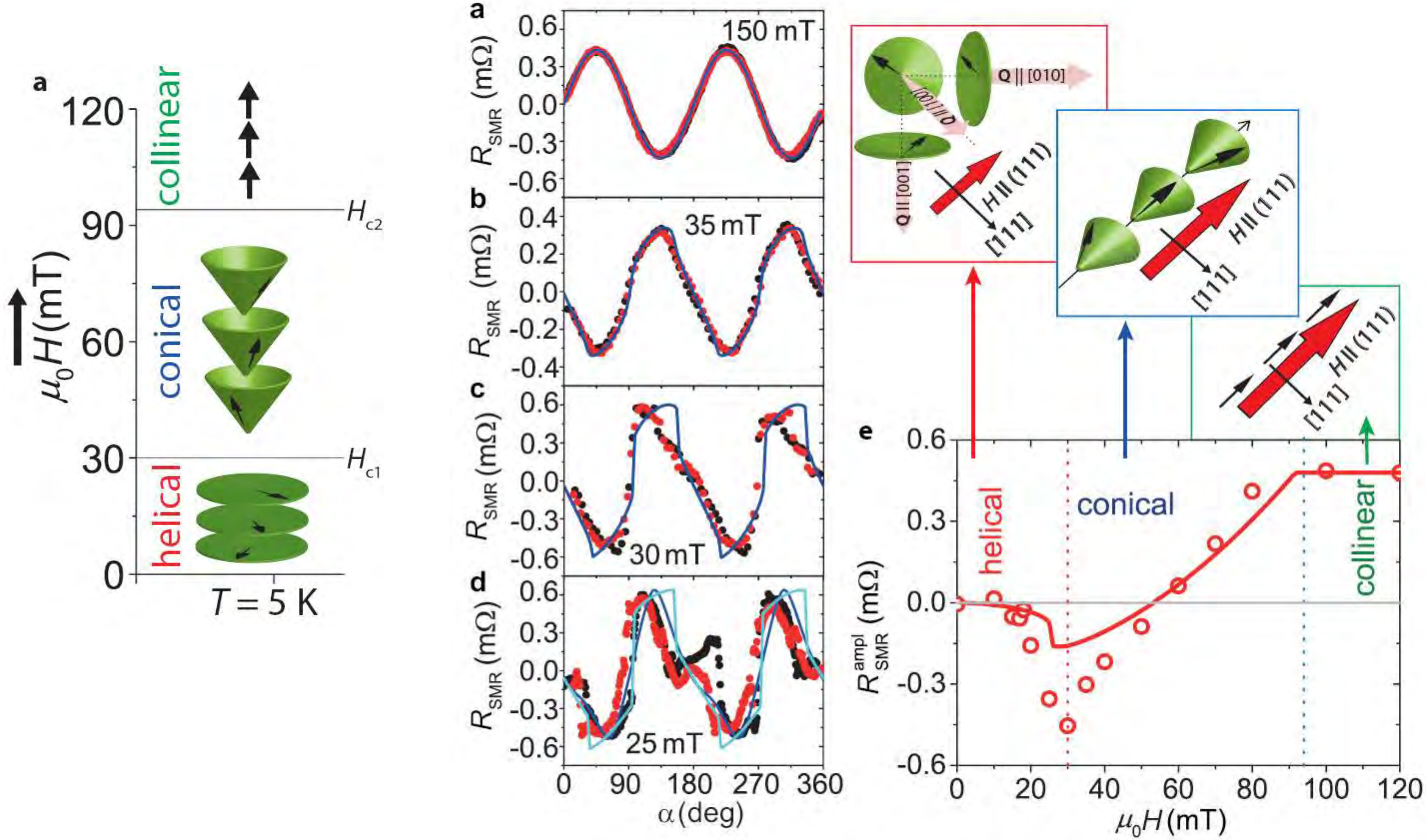
(open) issues …





SMR in Cu_2OSeO_3 / Pt heterostructures

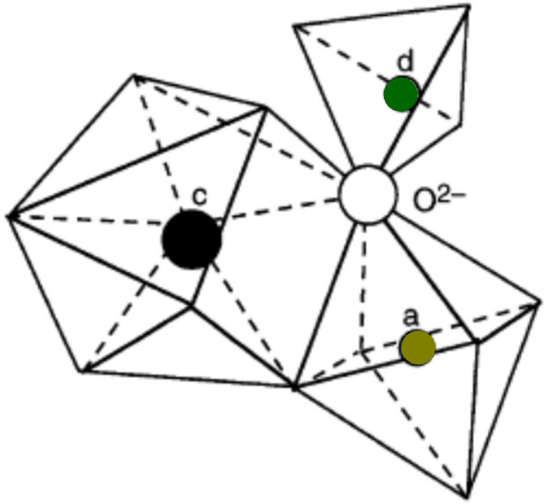
Aqeel *et al.*, arXiv 1607:056301

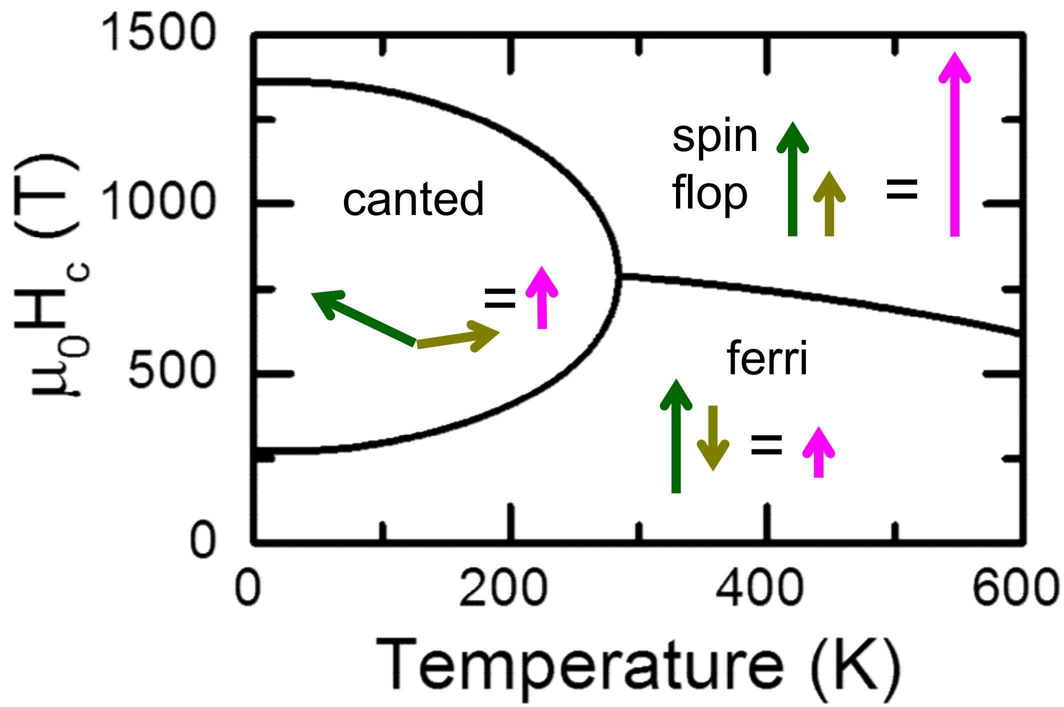


SMR Outlook - Magnetic Garnets

YIG = $Y_3Fe_5O_{12}$

is the prototype magnetic garnet





SMR Outlook - Magnetic Garnets

YIG = $Y_3Fe_5O_{12}$
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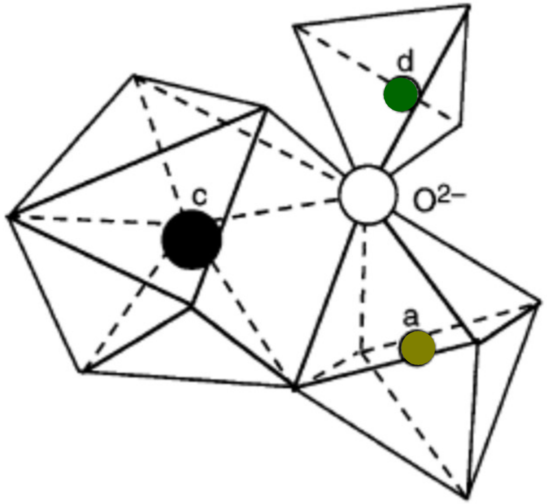
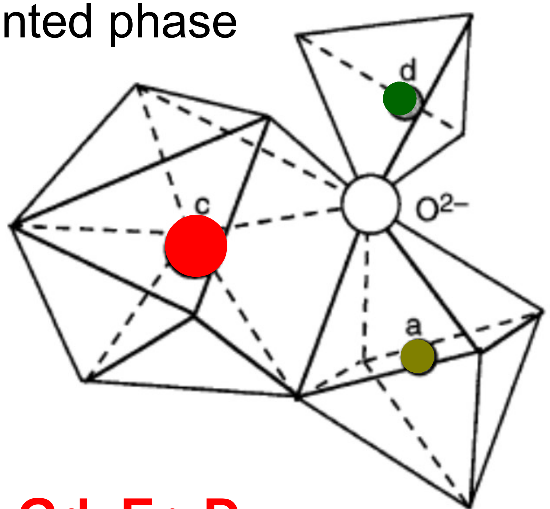
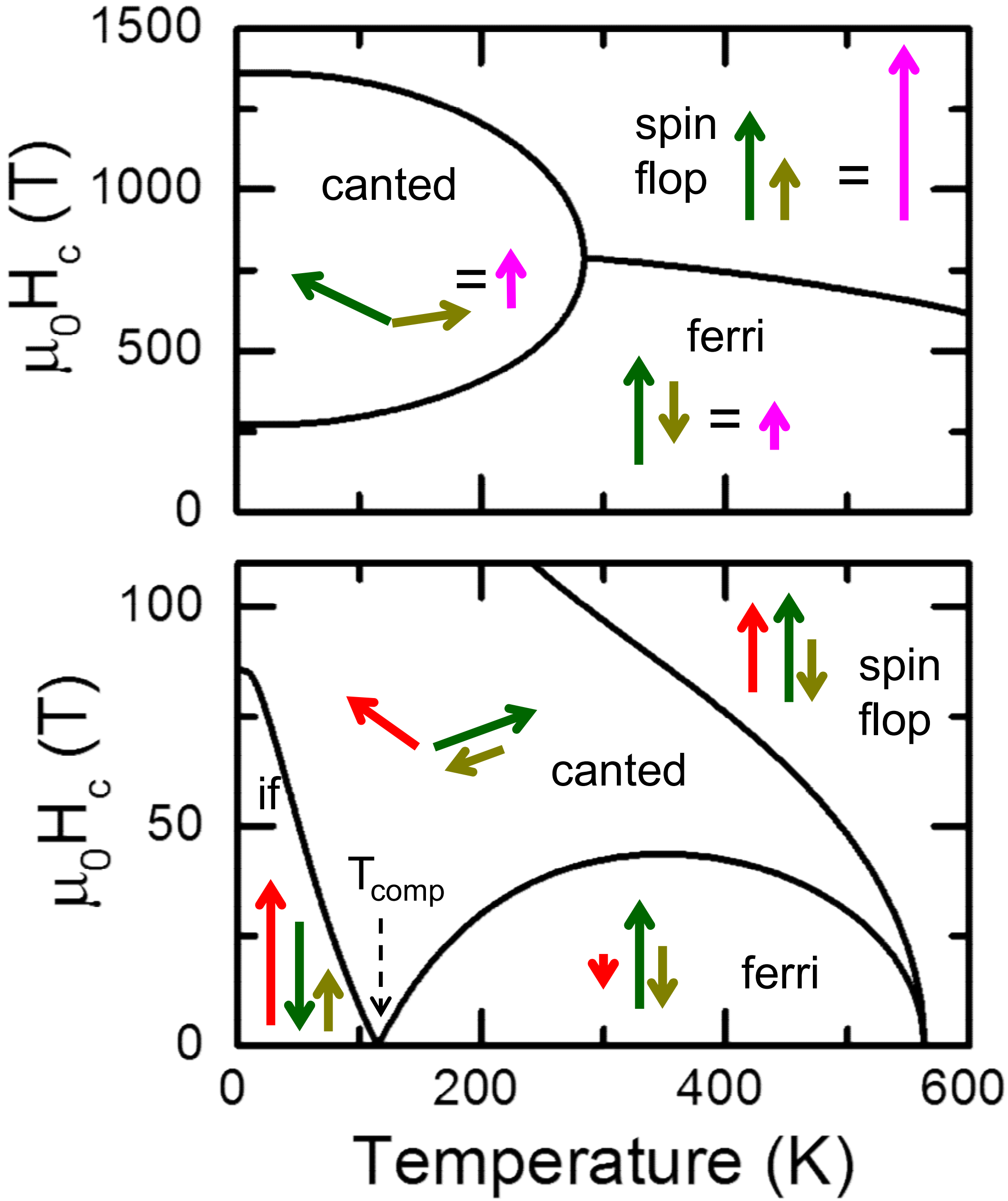


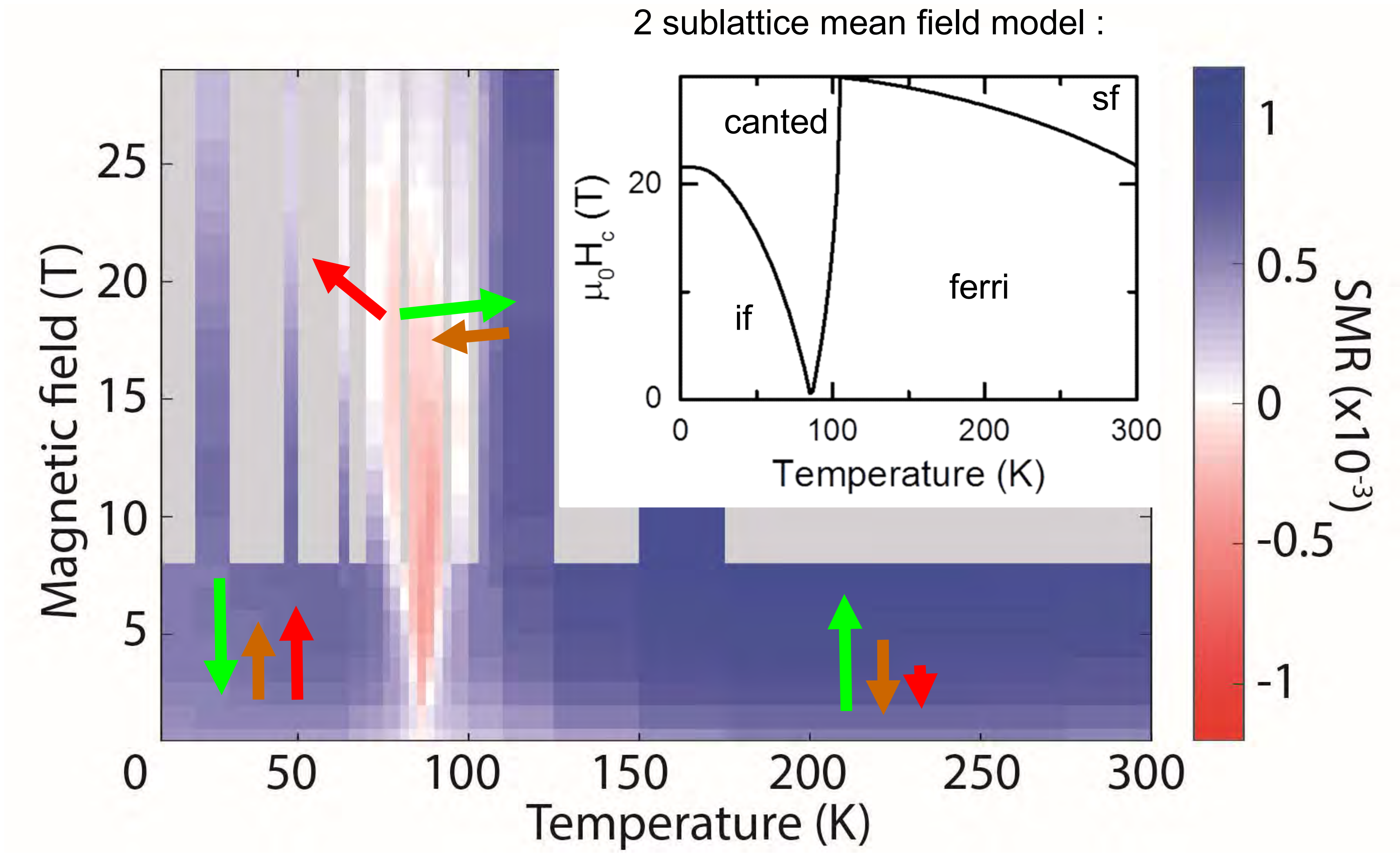
***Re*IG = *Re*$_3$$Fe_5O_{12}$**
with canted phase



***Re* = Gd, Er, Dy, …**



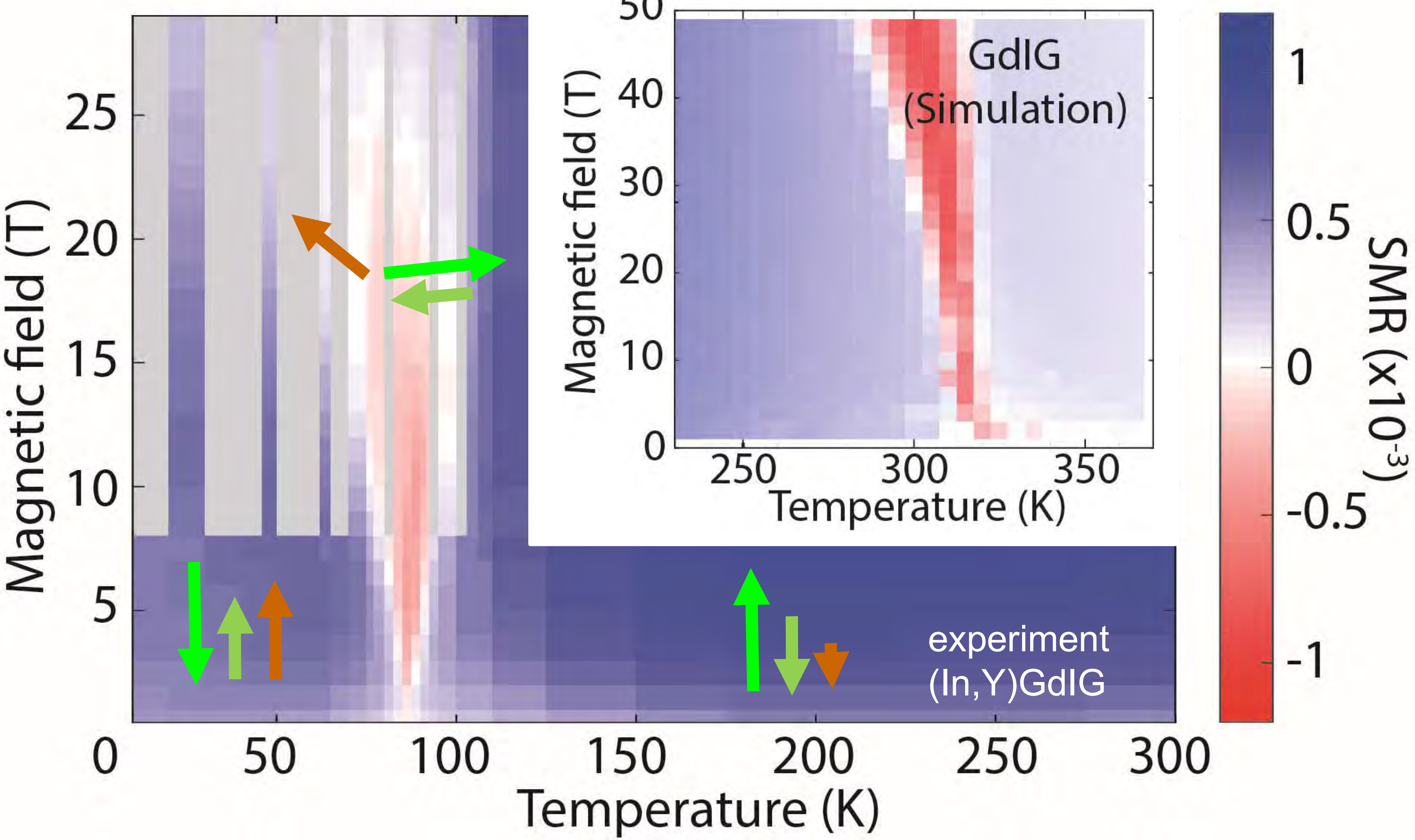
SMR in compensated garnet/Pt hybrids



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

SMR in compensated garnet/Pt hybrids

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

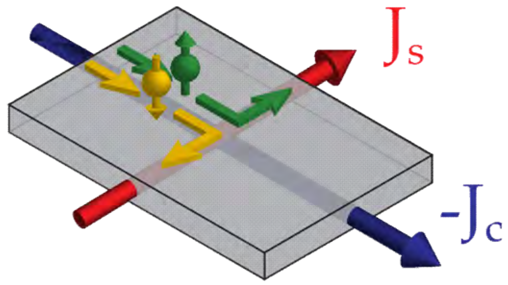


Ganzhorn *et al.*, PRB **94**, 094401 (2016).

Conclusions

pure spin currents
spin Hall effect(s)

Hoffmann, IEEE-TM **49**, 5172 (2013).
Sinova *et al.*, RMP **87**, 1213 (2015).

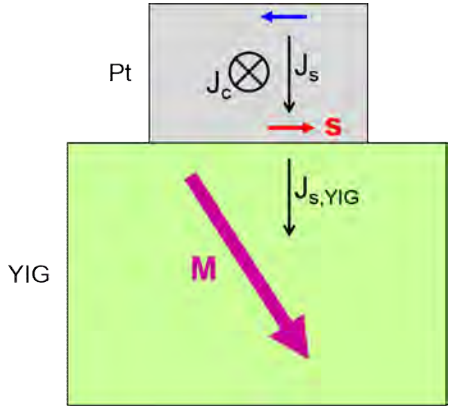


SMR = Spin Hall Magnetoresistance
… a spin current-based magnetoresistance
@ magnetic insulator / metal interfaces

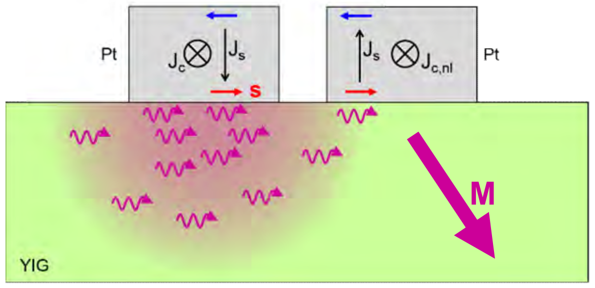
Nakayama *et al.*, PRL **110**, 206601 (2013).
Chen *et al.*, PRB **87**, 144411 (2013).
Hahn *et al.*, PRB **87**, 174417 (2013).
Vlietstra *et al.*, PRB **87**, 184421 (2013).
Althammer *et al.*, PRB **87**, 224401 (2013).
Meyer *et al.*, APL **104**, 242411 (2014).
Lotze *et al.*, PRB **90**, 174419 (2014).

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

Ganzhorn et al., PRB **94**, 094401 (2016).
Aqeel *et al.*, PRB **92**, 224410 (2015) & arXiv 1607:056301



MMR = Magnon-mediated MagnetoResistance
… electrical measurement of magnon diffusion length

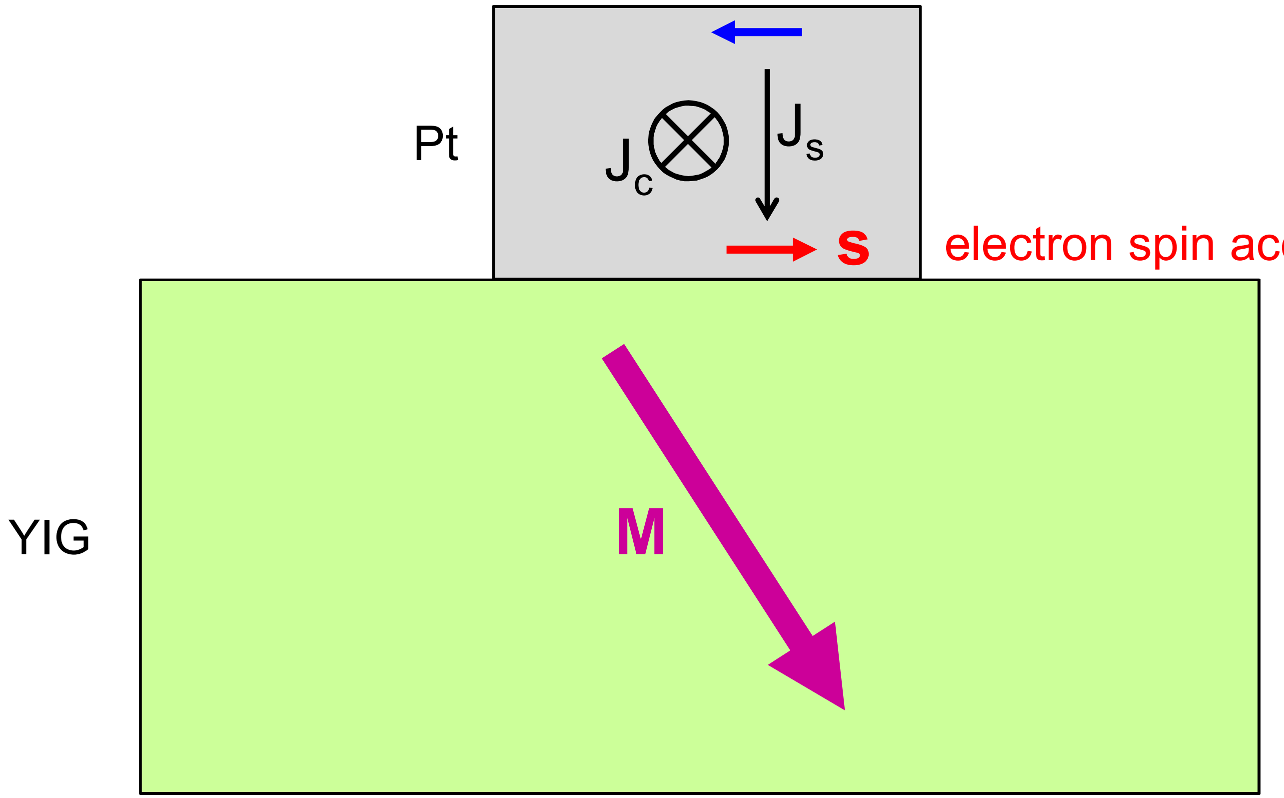


Magnon-Mediated Magnetoresistance (MMR)

a non-local, magnon-based MR
@ FMI / N interfaces

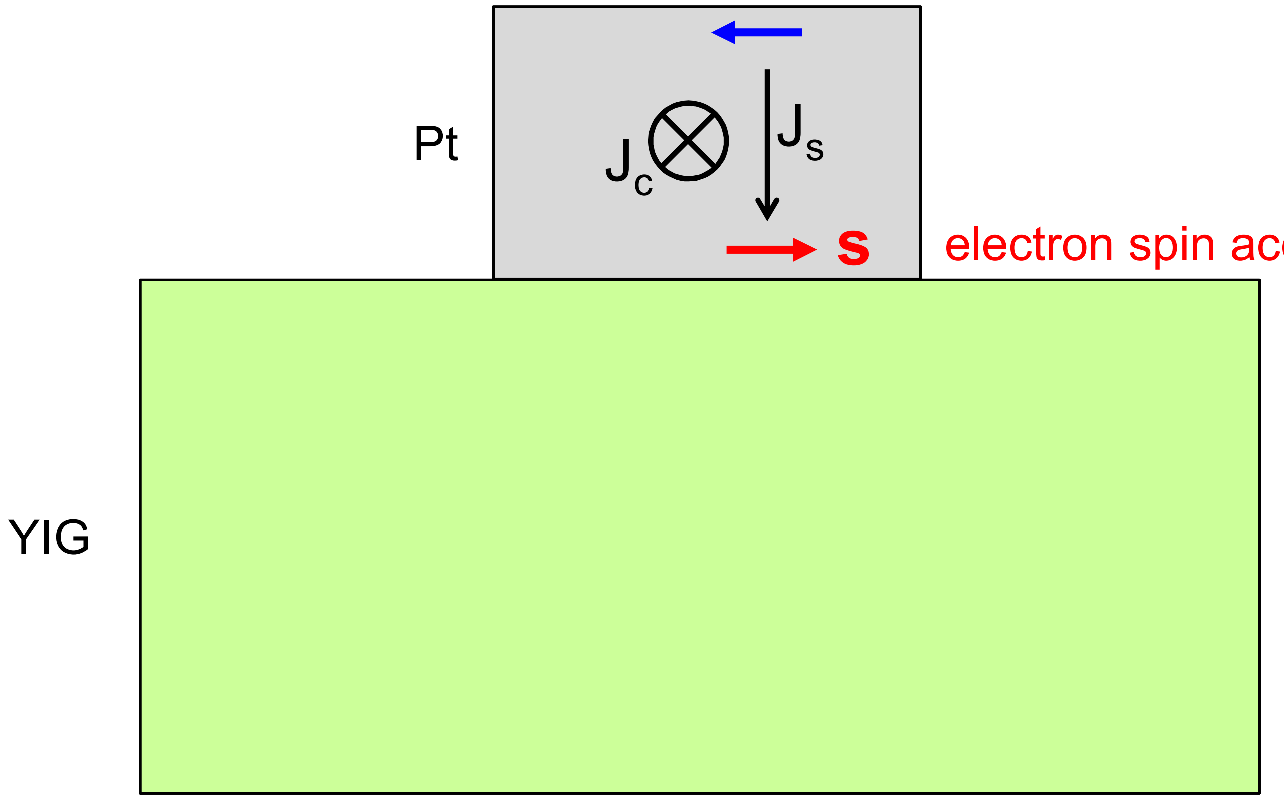
Zhang & Zhang, PRB **86**, 214424 (2012).
Cornelissen *et al.*, Nature Phys. **11**, 1022 (2015).
Goennenwein *et al.*, APL **107**, 172405 (2015).

SHE spin current in YIG/Pt revisited



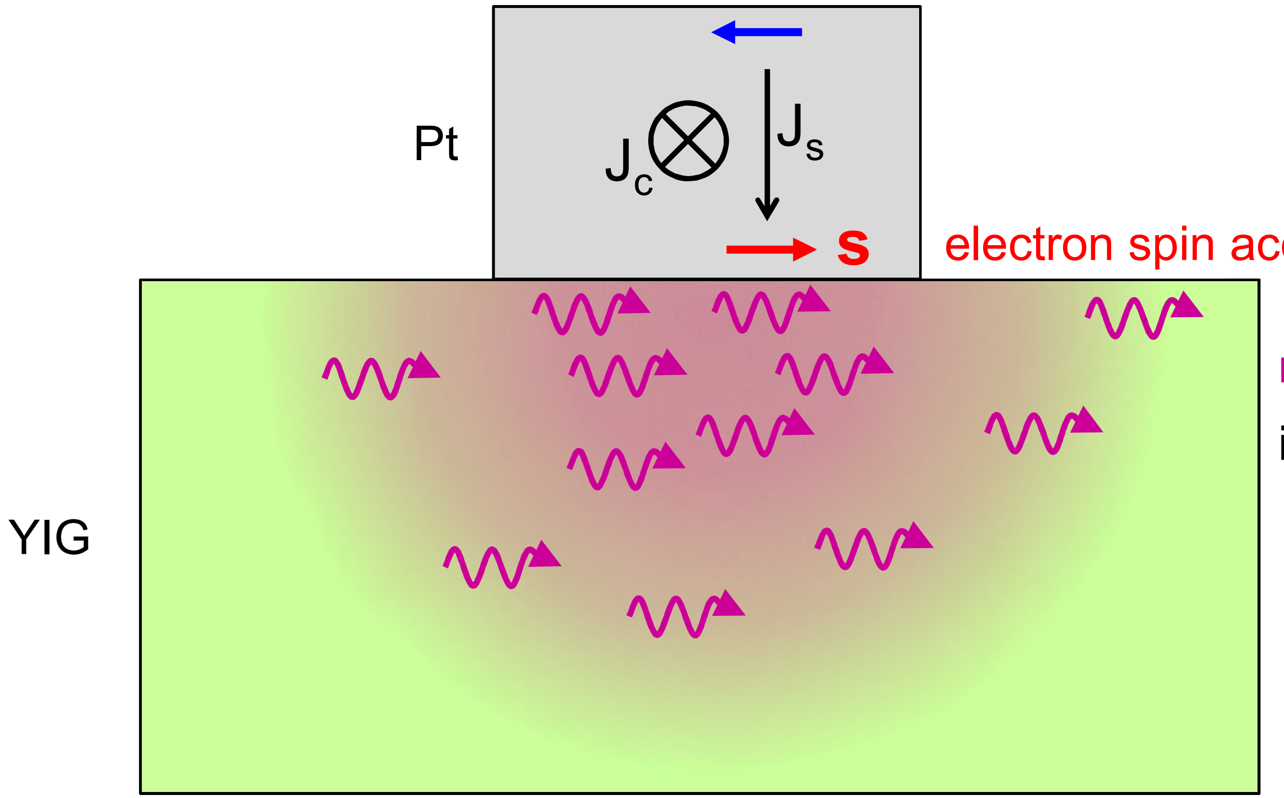
electron spin accumulation in Pt with spin **s**

SHE spin current in YIG/Pt revisited



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

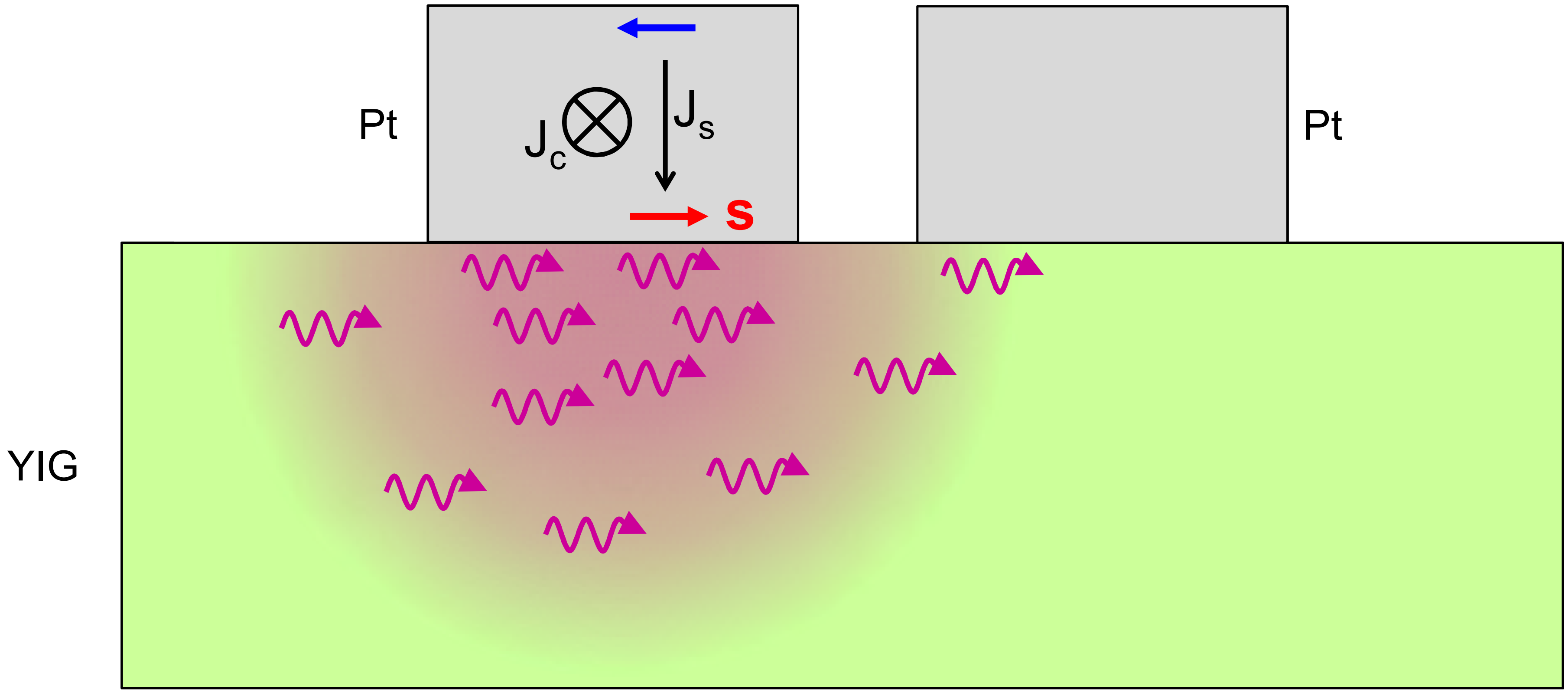
SHE-induced magnon accumulation



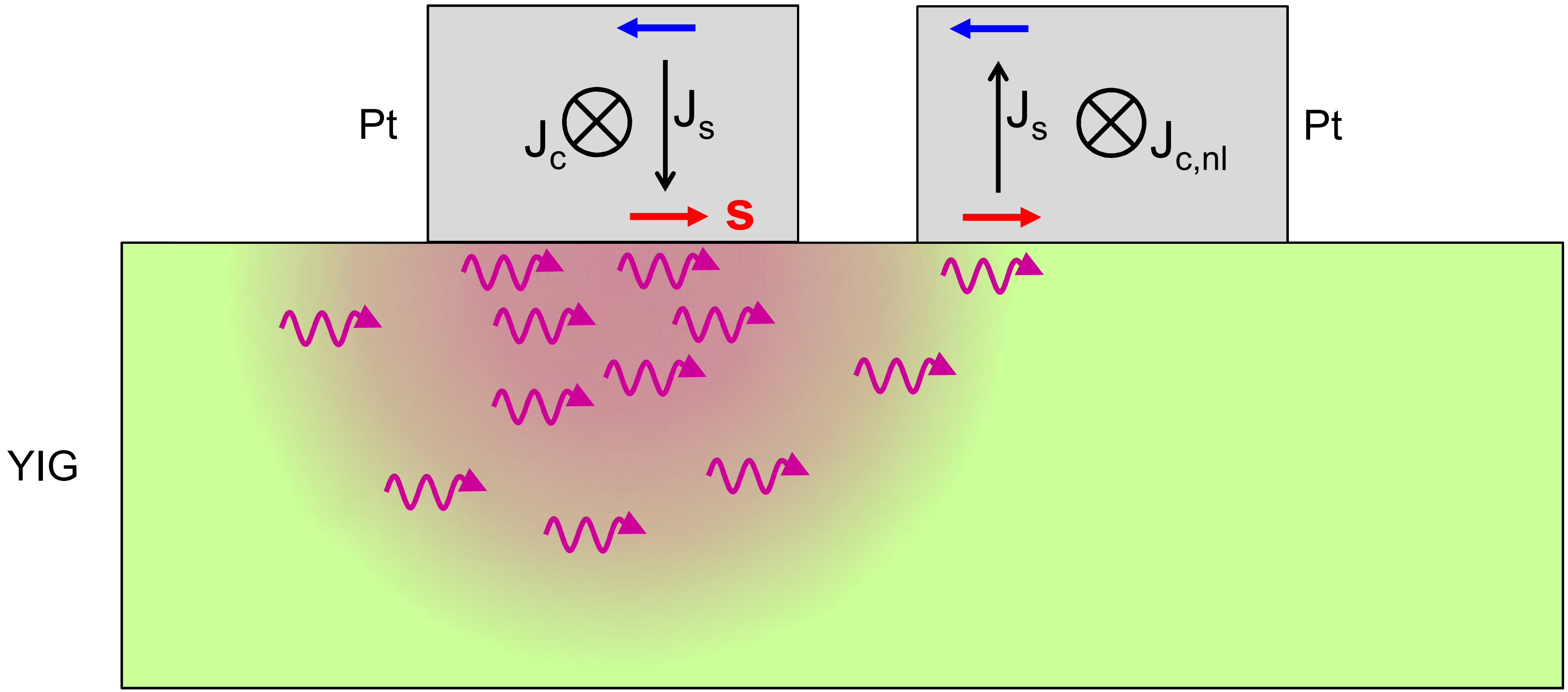
electron spin accumulation in Pt with spin **s**

magnon spin accumulation in YIG

SHE-induced magnon accumulation



MMR: a non-local, magnon-driven analogon of the SMR



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Zhang & Zhang, PRB **86**, 214424 (2012).
Cornelissen *et al.*, Nature Phys. **11**, 1022 (2015).
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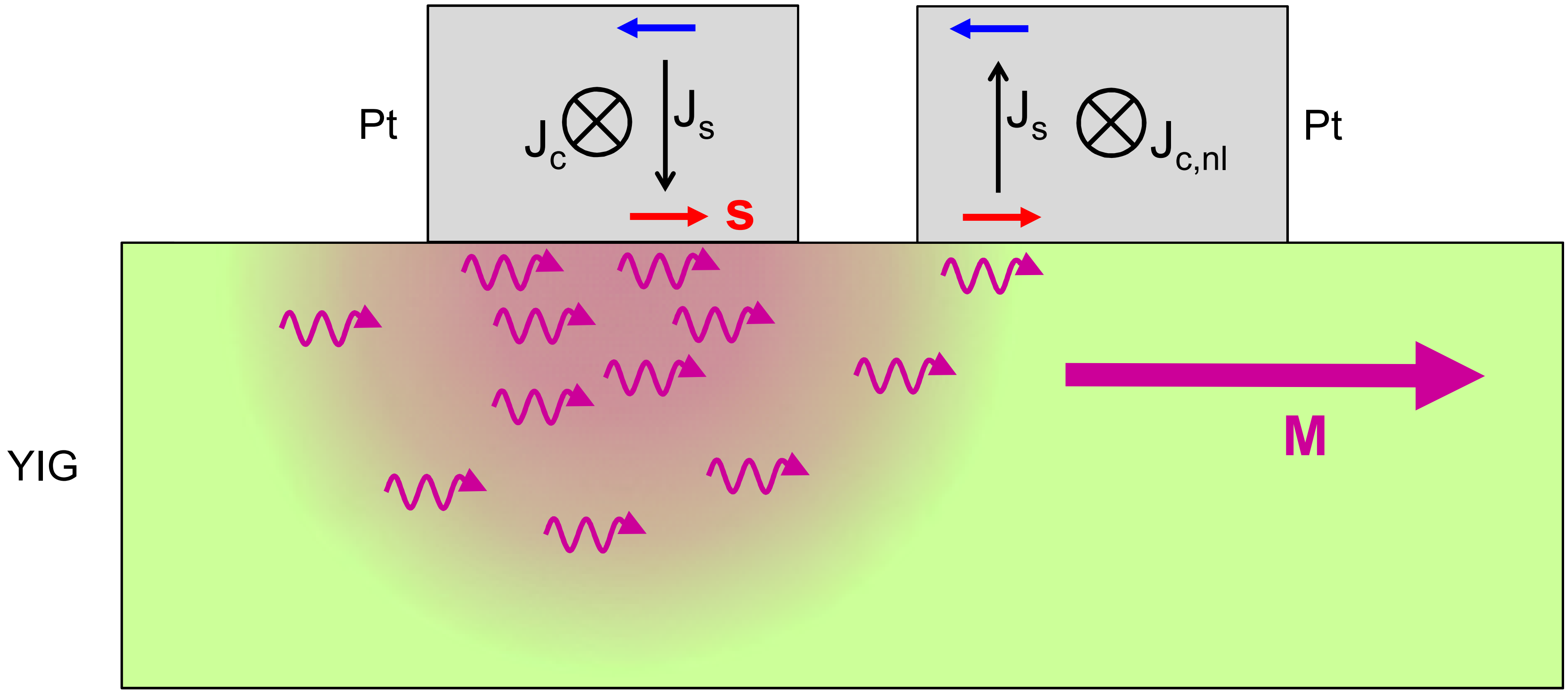

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Cornelissen *et al.*, Nature Phys. **11**, 1022 (2015).
Goennenwein *et al.*, APL **107**, 172405 (2015).

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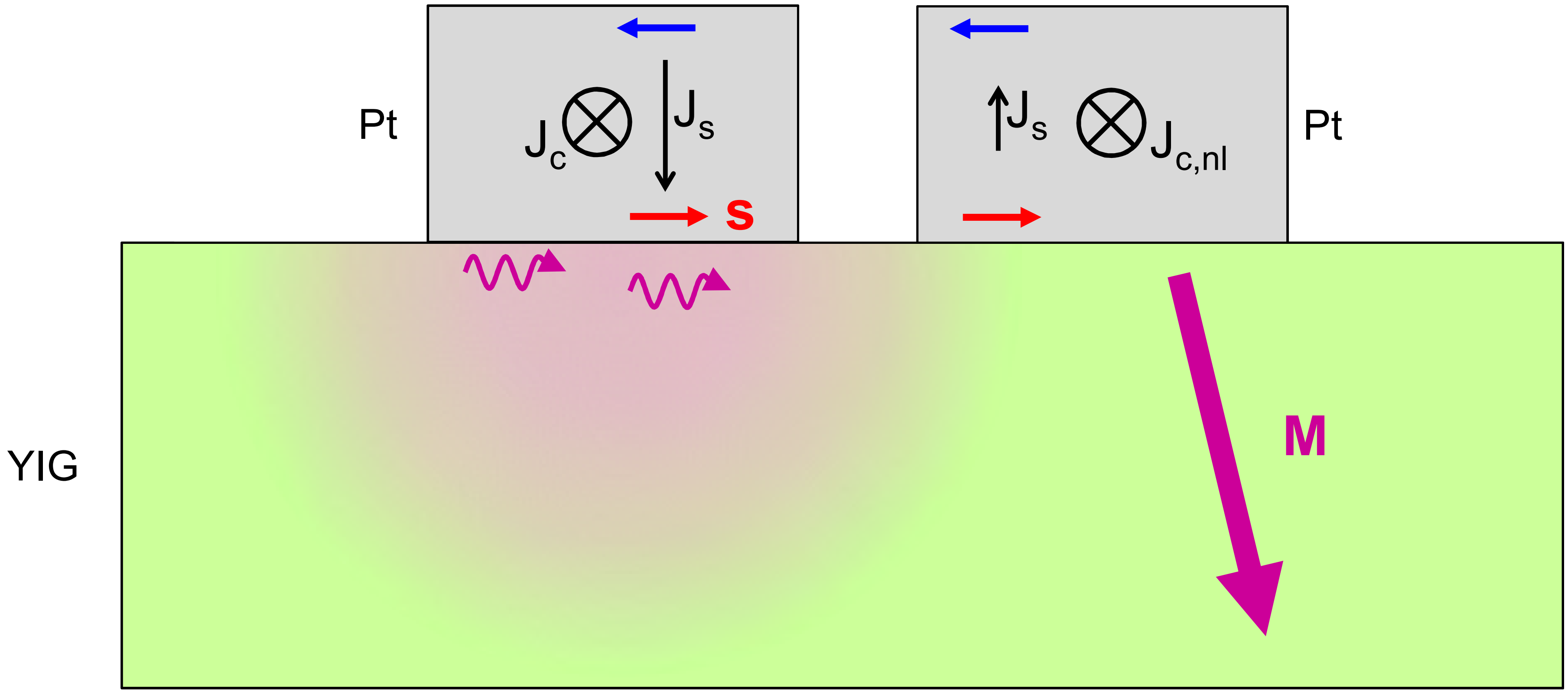

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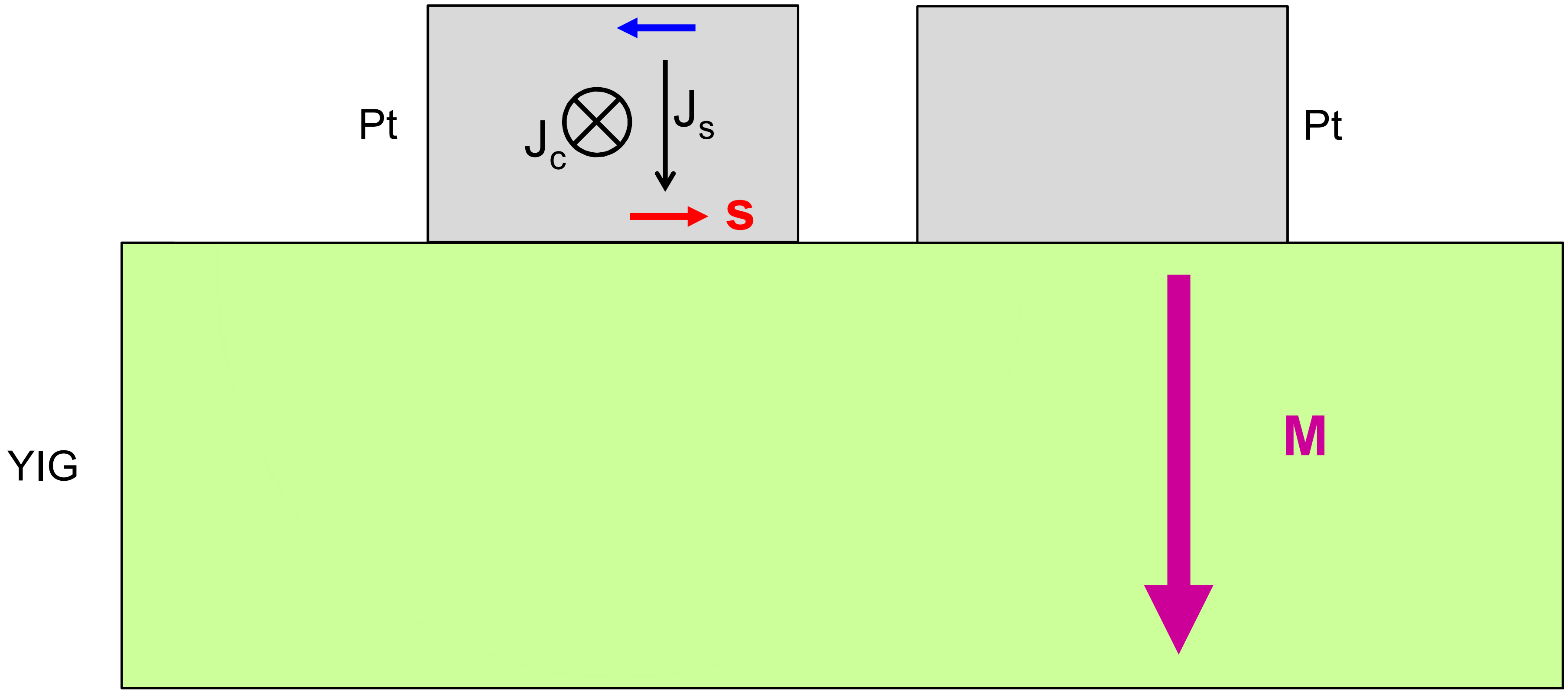

MMR = magnon-mediated magnetoresistance

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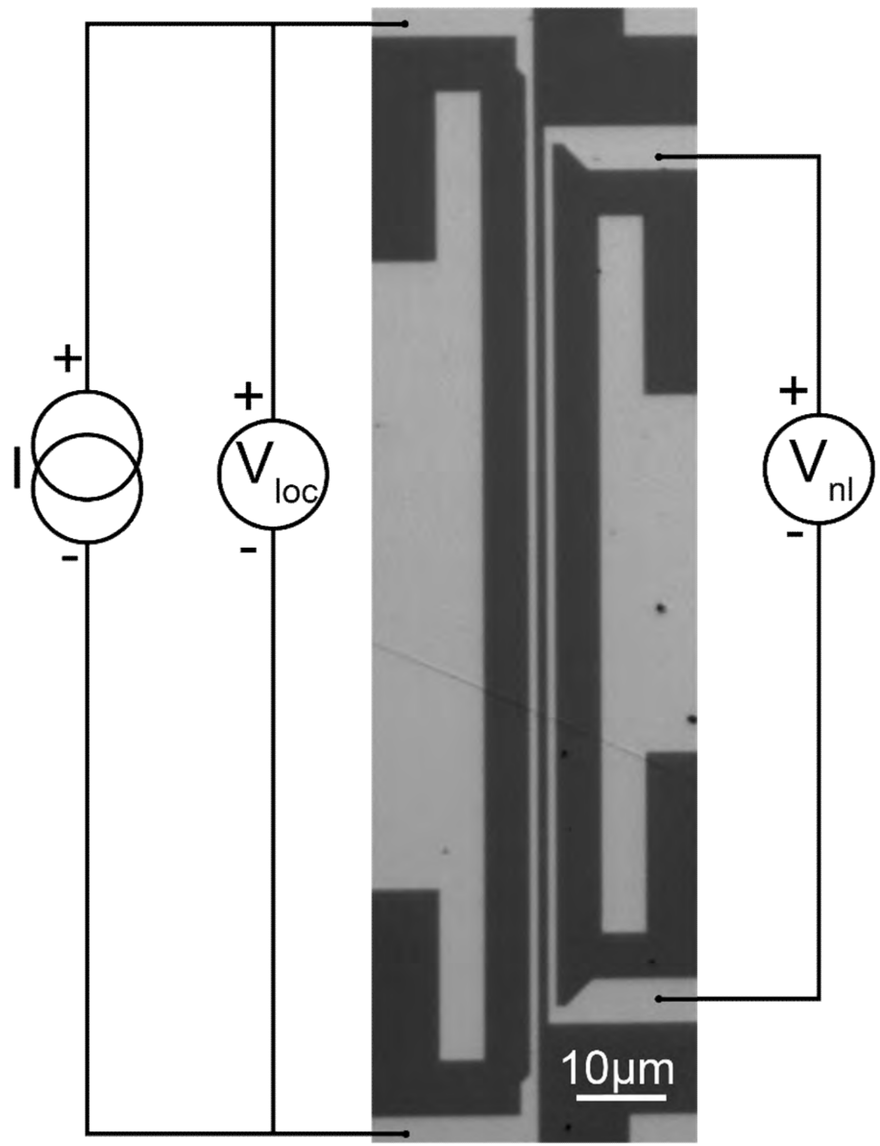
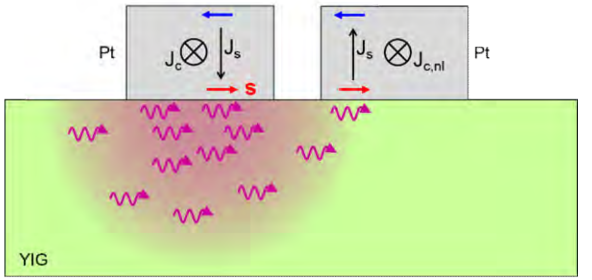
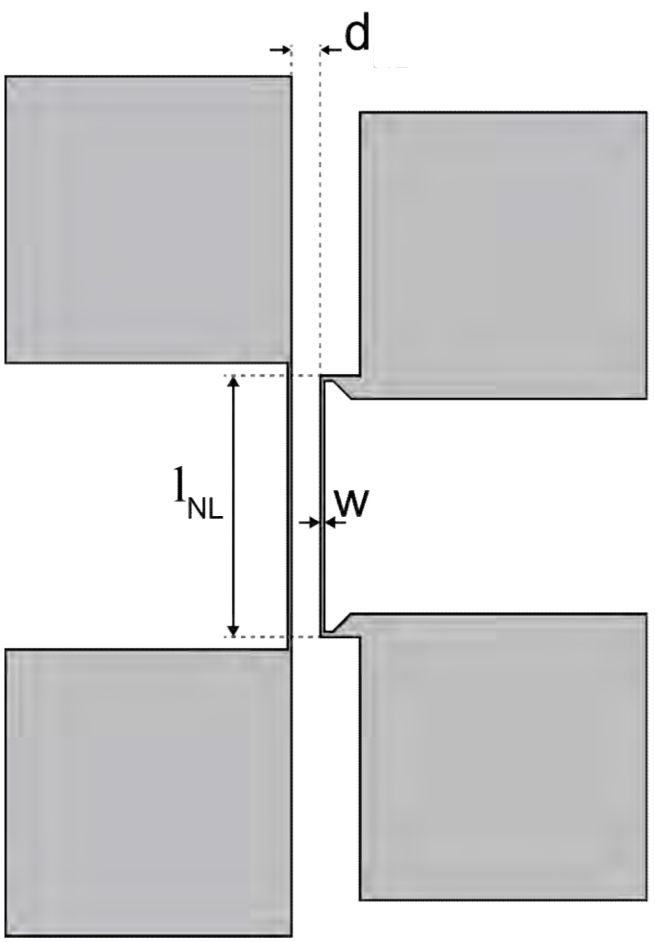
Cornelissen *et al.*, Nature Phys. **11**, 1022 (2015).
Goennenwein *et al.*, APL **107**, 172405 (2015).

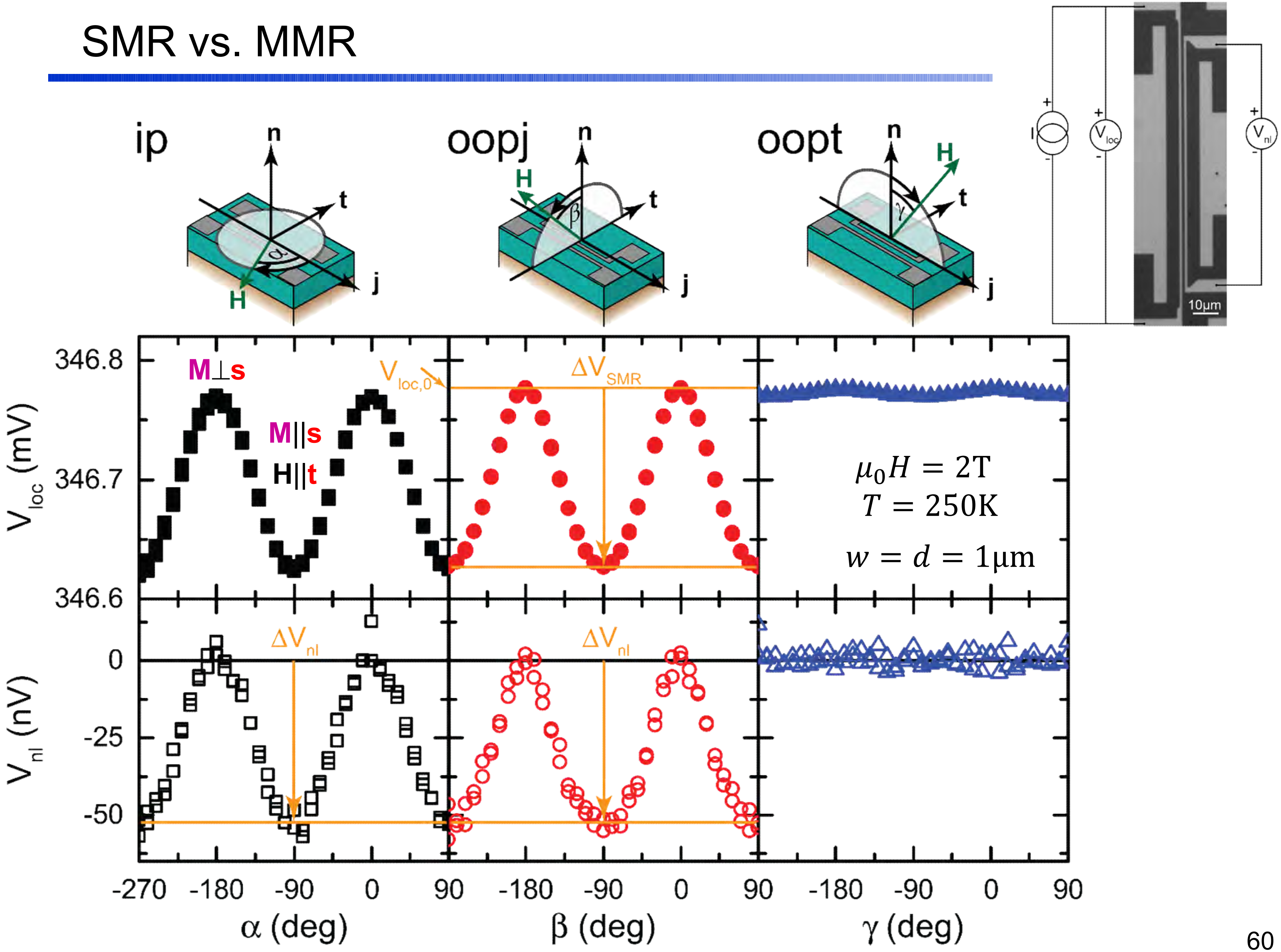
YIG/Pt nanostructures





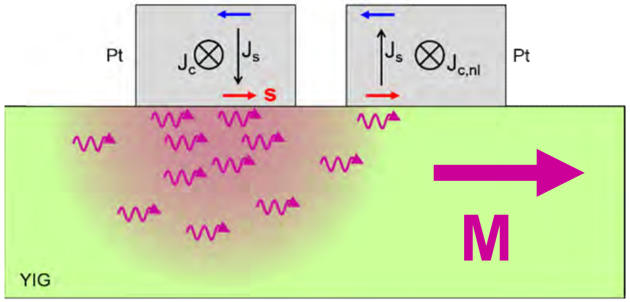


SMR vs. MMR



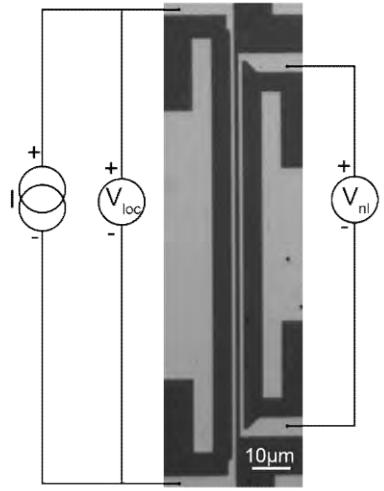
ip
n
t
j
H
α
oopj
n
H
β
t
j
oopt
n
H
γ
t
j
I
+
-
V_loc
V_nl
10μm
V_loc (mV)
346.8
346.7
346.6
M⊥s
M||s
H||t
V_loc,0
ΔV_SMR
μ_0H = 2T
T = 250K
w = d = 1μm
V_nl (nV)
0
-25
-50
ΔV_nl
ΔV_nl
-270
-180
-90
0
90
α (deg)
β (deg)
γ (deg)

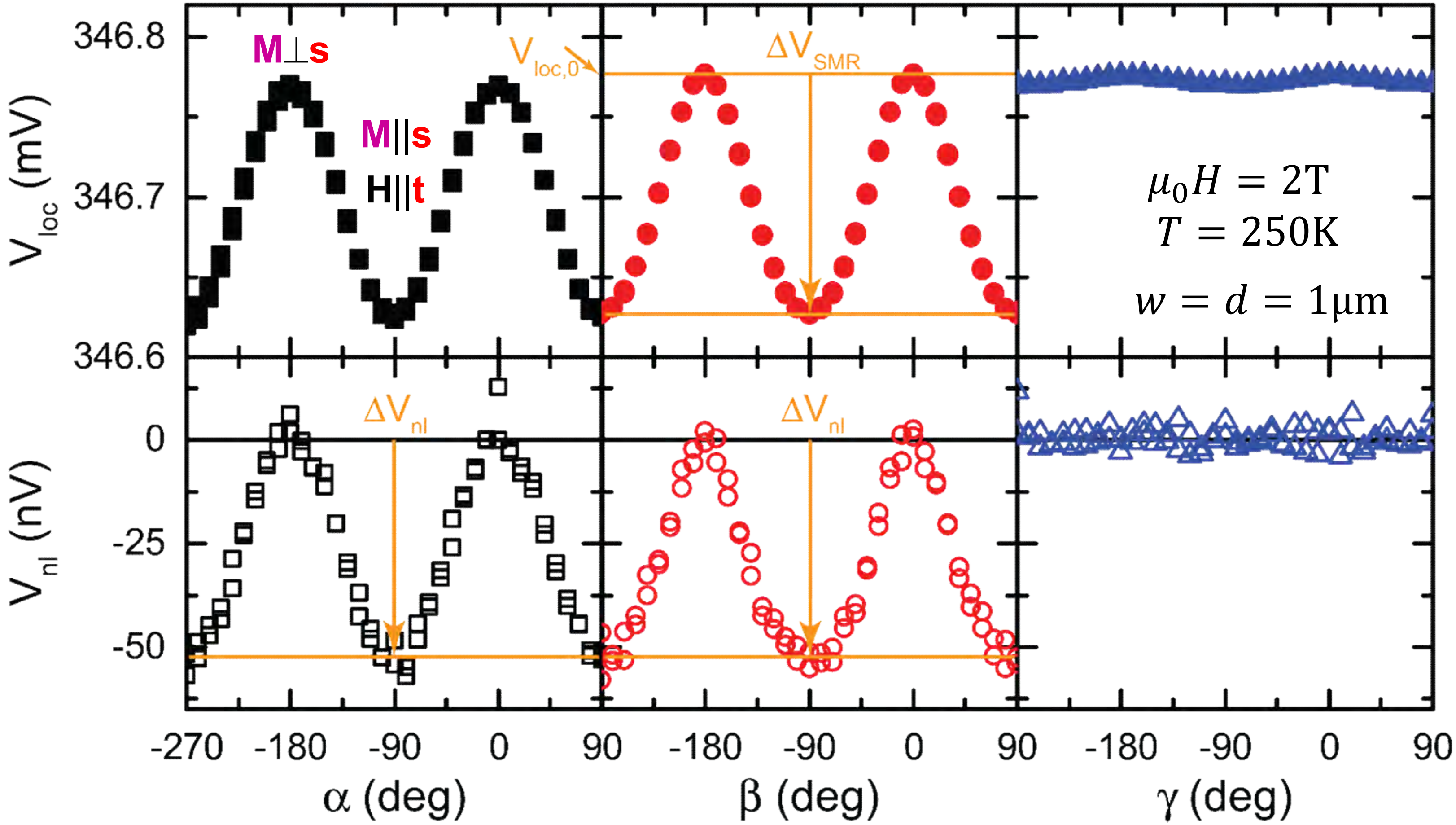
SMR vs. MMR



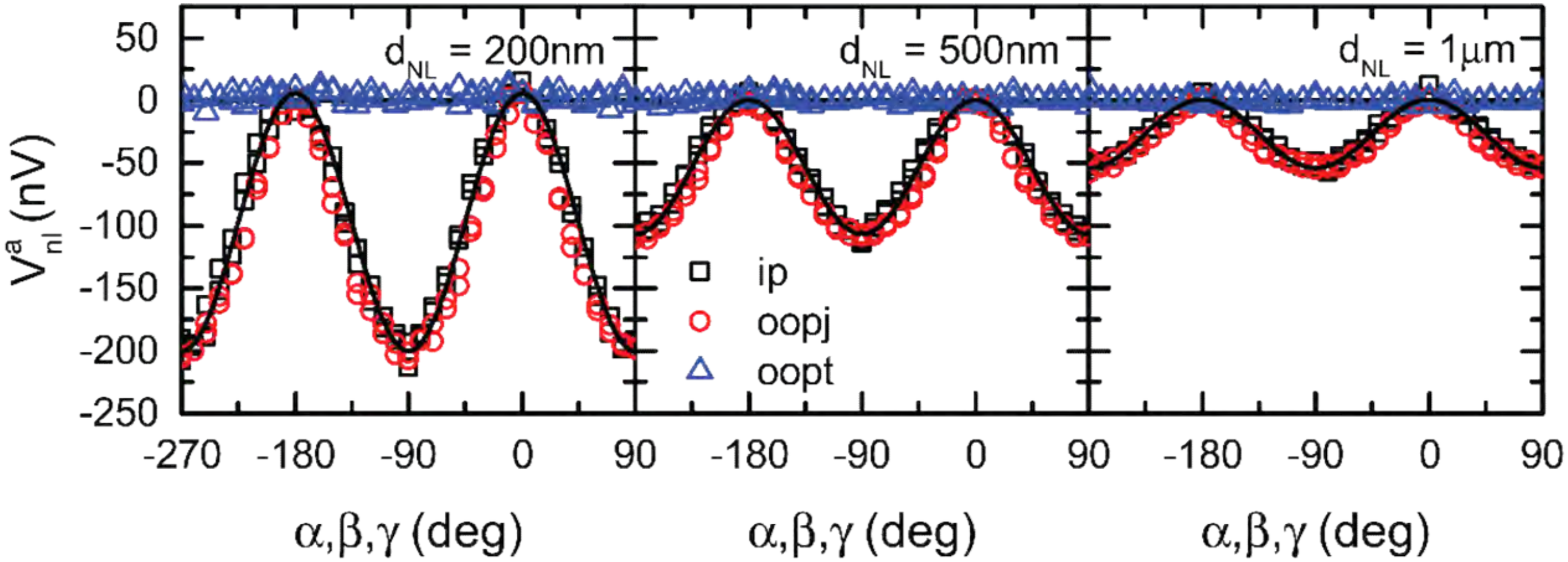
V_{nl} large (<0!) for **M||s** (viz. **M||t**)

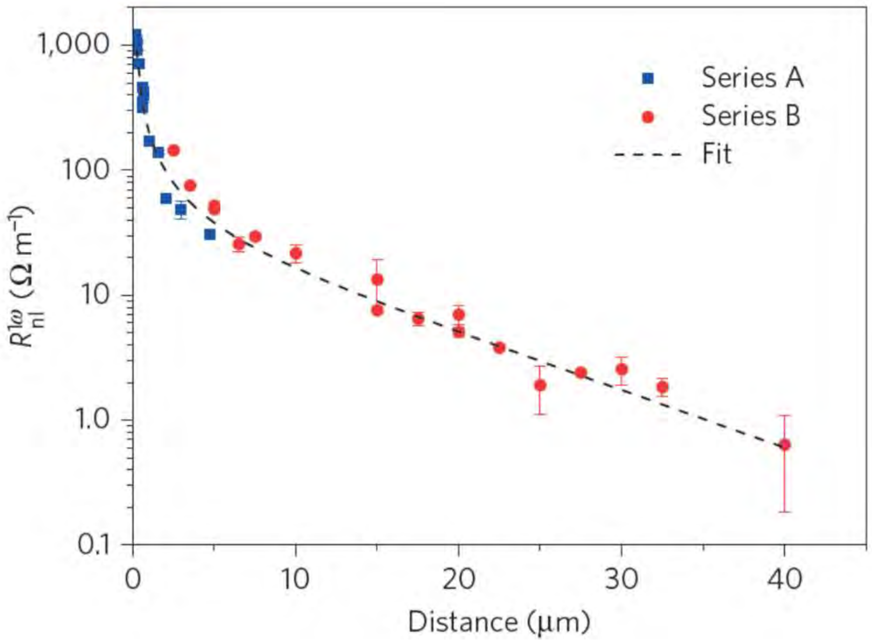
V_{nl} vanishes for for **M⊥s** (viz. **M⊥t**)

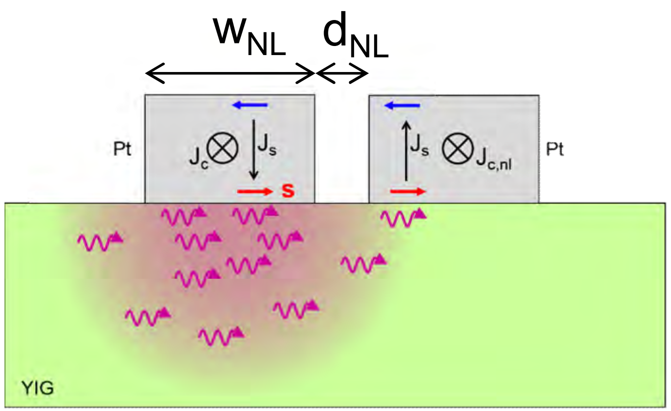




Gap dependence



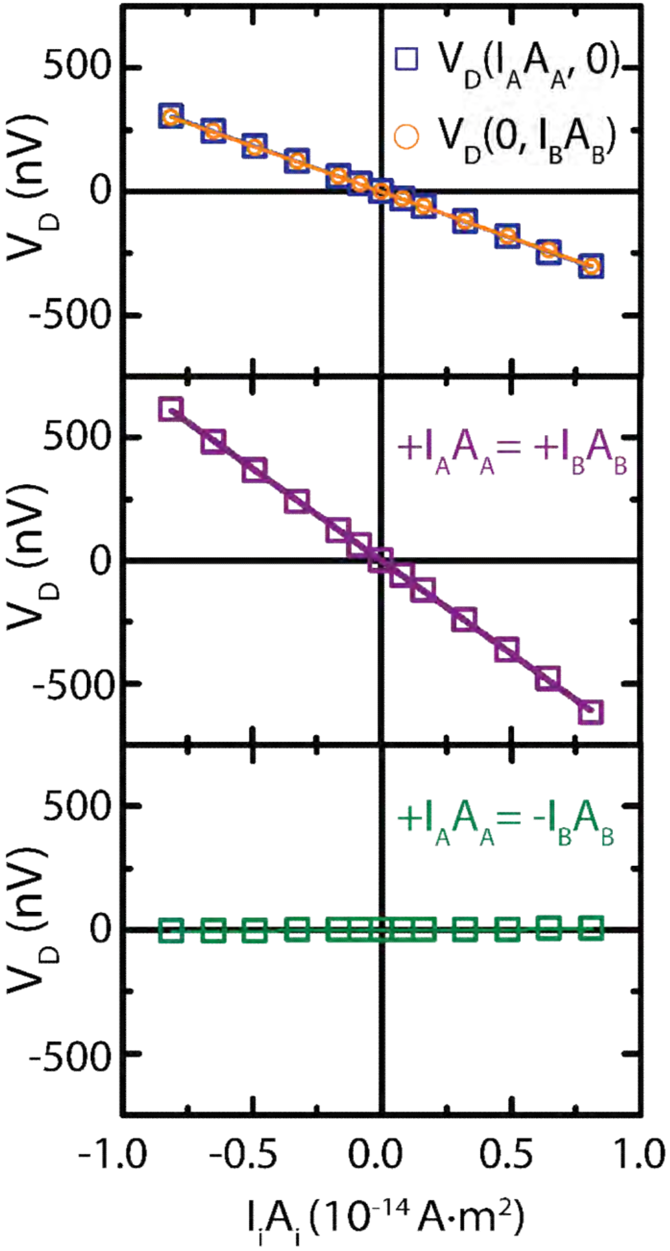


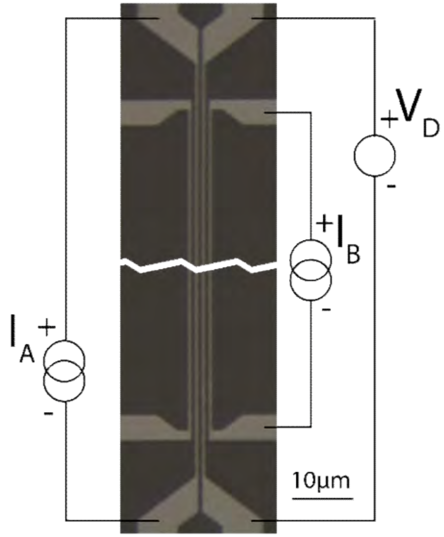


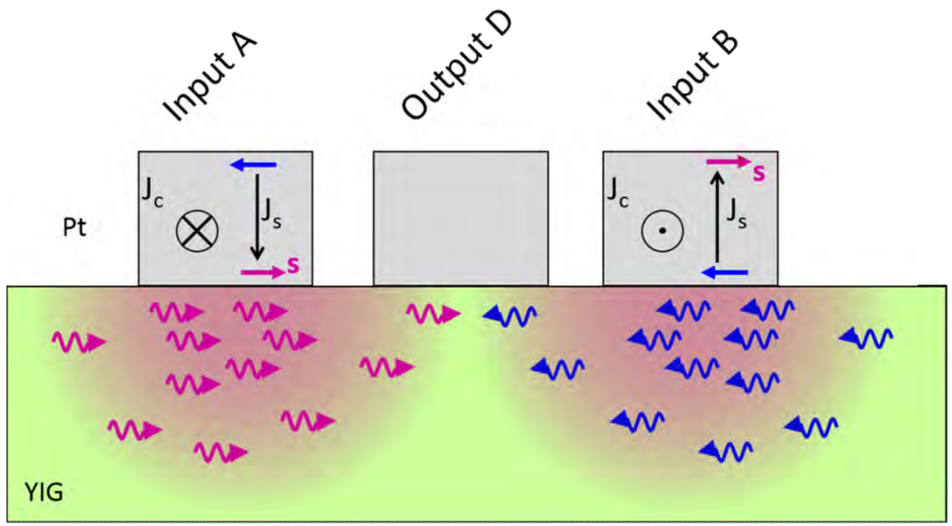
magnon propagation over μm distances

Cornelissen *et al.*, Nature Phys. **11**, 1022 (2015).

Incoherent Superposition of Magnons



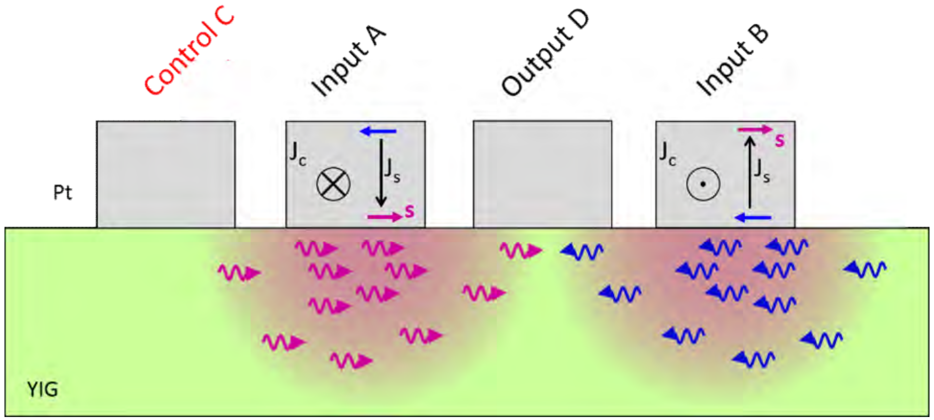


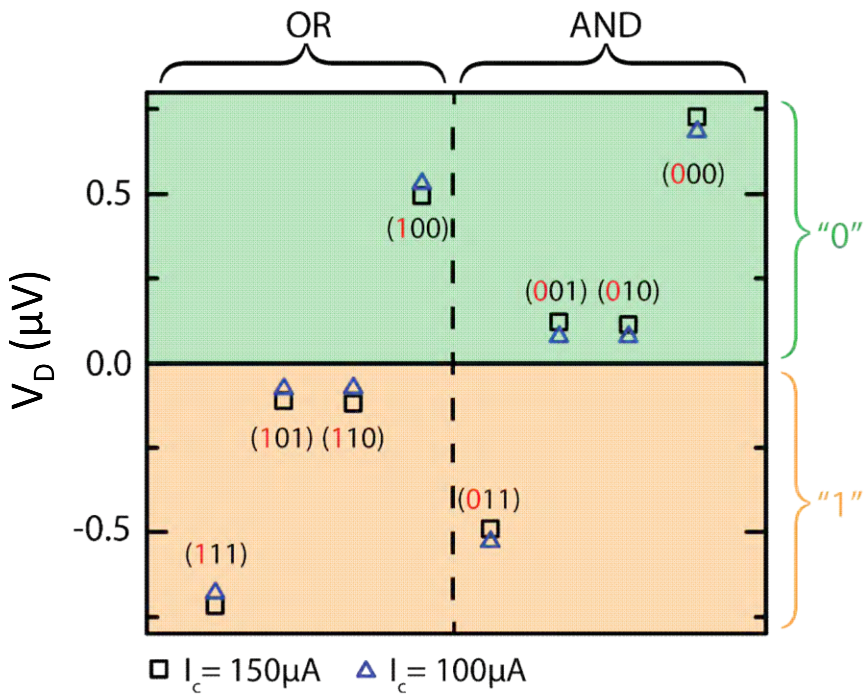


Ganzhorn *et al.*, Appl. Phys. Lett. **109**, 022405 (2016)

Magnon Majority Gate

C	A	B	D		I_C	I_A	I_B	V_D	
0	0	0	0		–	–	–	+	AND
0	0	1	0		–	–	+	+	AND
0	1	0	0		–	+	–	+	AND
0	1	1	1		–	+	+	–	AND
1	0	0	0		+	–	–	+	OR
1	0	1	1		+	–	+	–	OR
1	1	0	1		+	+	–	–	OR
1	1	1	1		+	+	+	–	OR

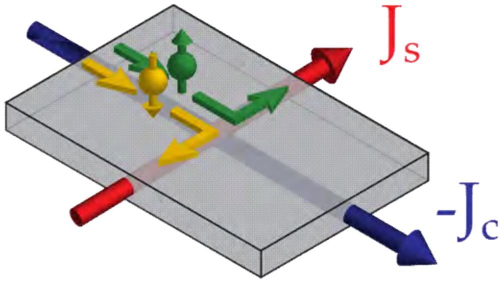




GHz frequencies,
straightforward downscaling

Ganzhorn *et al.*, Appl. Phys. Lett. **109**, 022405 (2016)

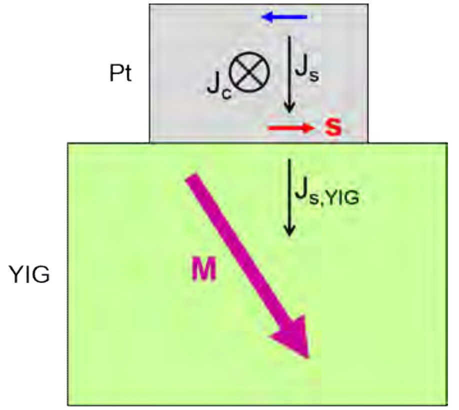
Conclusions



pure spin currents
spin Hall effect(s)

Hoffmann, IEEE-TM **49**, 5172 (2013).
Sinova *et al.*, RMP **87**, 1213 (2015).

SMR = Spin Hall Magnetoresistance
… a spin current-based magnetoresistance
@ magnetic insulator / metal interfaces



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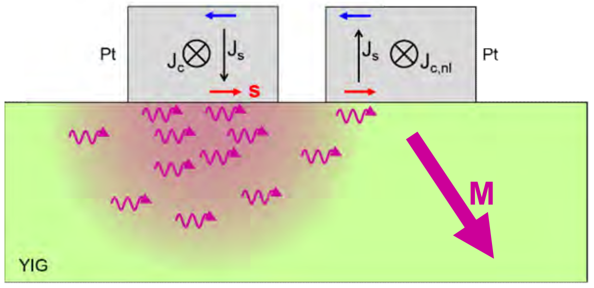
Ganzhorn et al., PRB **94**, 094401 (2016).
Aqeel *et al.*, PRB **92**, 224410 (2015) & arXiv 1607:056301

MMR = Magnon-mediated MagnetoResistance
… electrical measurement of magnon diffusion length



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