Bayerische Akademie der Wissenschaften

Technische Universität München

Magneto-Transport

Hans Huebl

Walther-Meißner-Institut
Bayerische Akademie der Wissenschaften

Deutsche Forschungsgemeinschaft DFG

nanosystems initiative munich

WMI

Bayerische Akademie der Wissenschaften

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Surf the Wave & Pump the Charge

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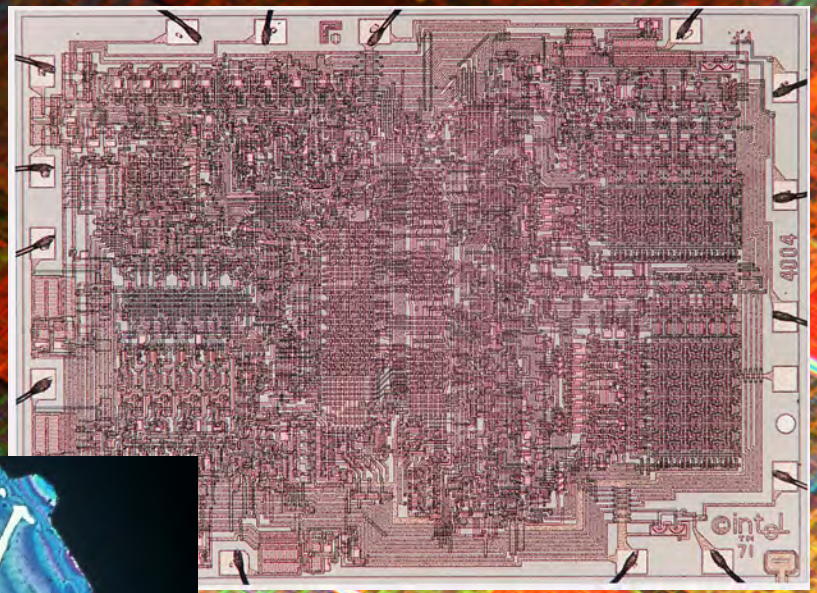
Deutsche Forschungsgemeinschaft DFG

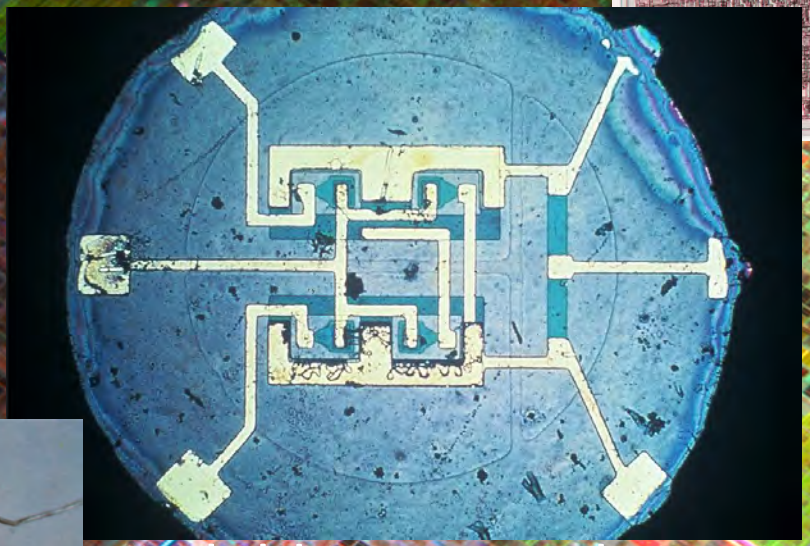
nim nanosystems initiative munich

Electronics

electronics:
only charge degree
of freedom



Intel 4004 CPU

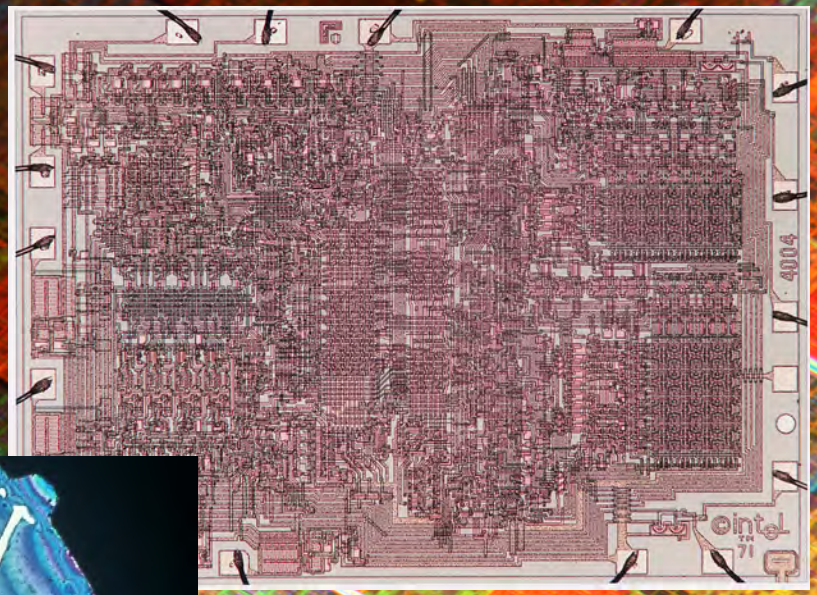


Fairchild integrated circuit

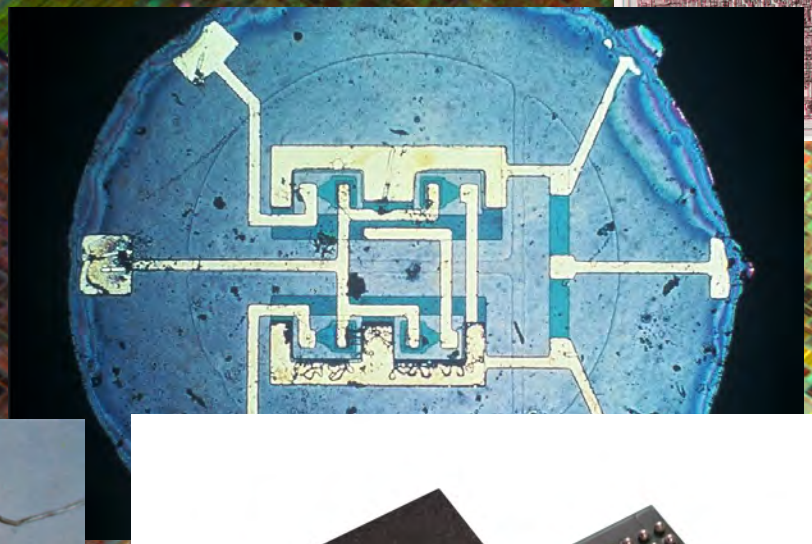
First Transistor

Spintronics / Spincurrents

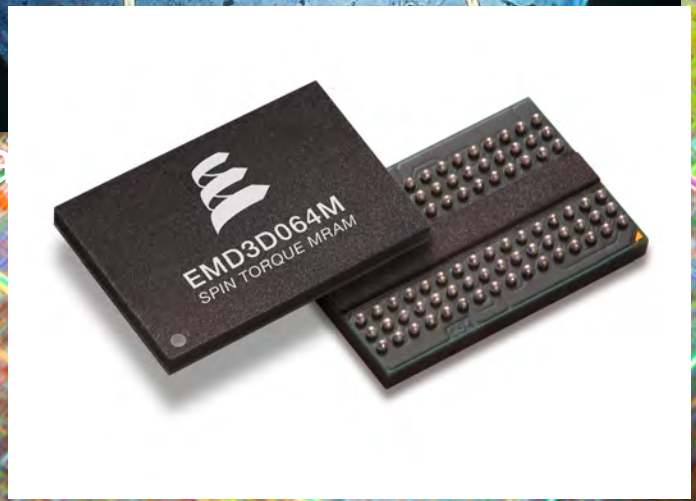
Spin(elec)tronics:
(only) spin degree
of freedom



Intel 4004 CPU



First Transistor

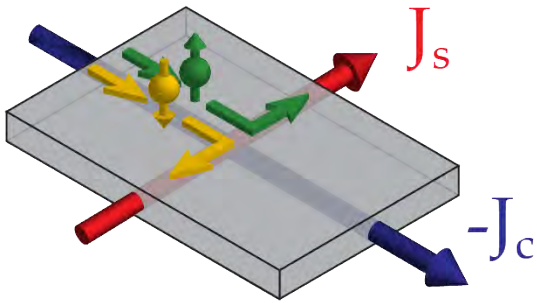


Êverspin

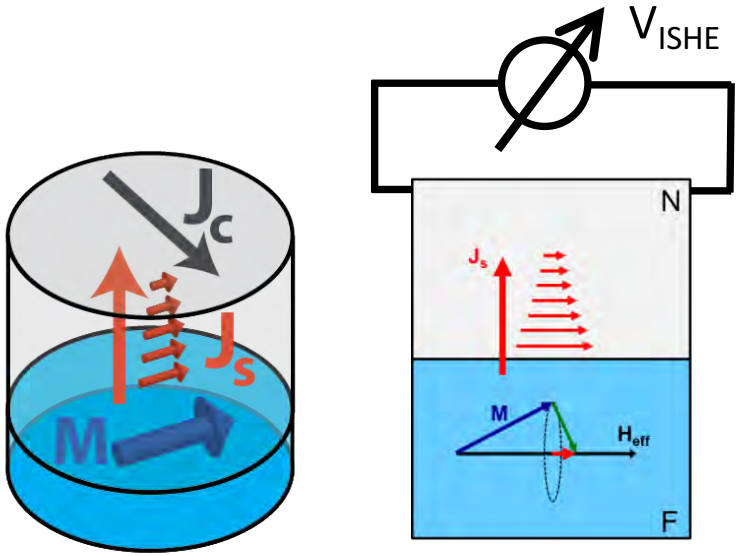
IBM Germany

Outline

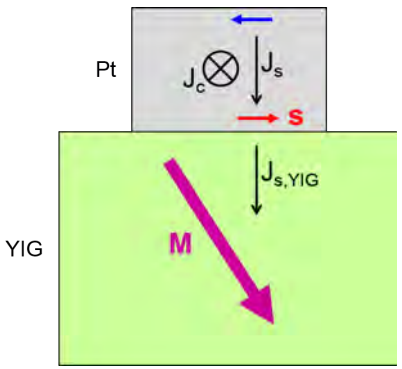
pure spin currents
spin Hall effect



„simple“ spin current circuits
spin pumping



spin Hall magnetoresistance



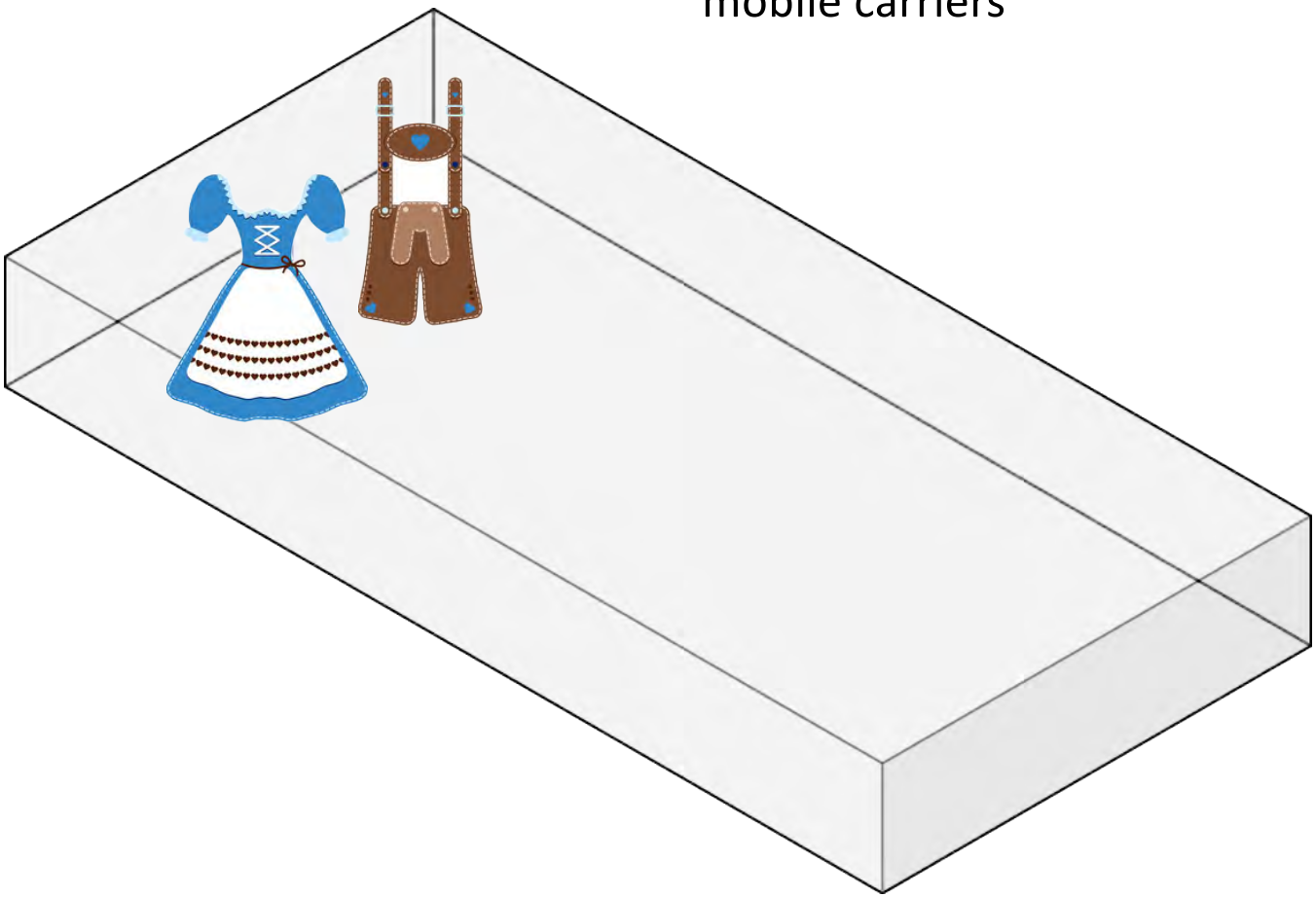
Charge transport in magnetic fields

– Hall effect, magnetoresistance

Literature: O‘Handley, Modern Magnetic Materials (2014)

Hall effect and magneto-resistance

“normal metal”:
no long-range magnetic order
mobile carriers



Hall effect and magneto-resistance

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no long-range magnetic order
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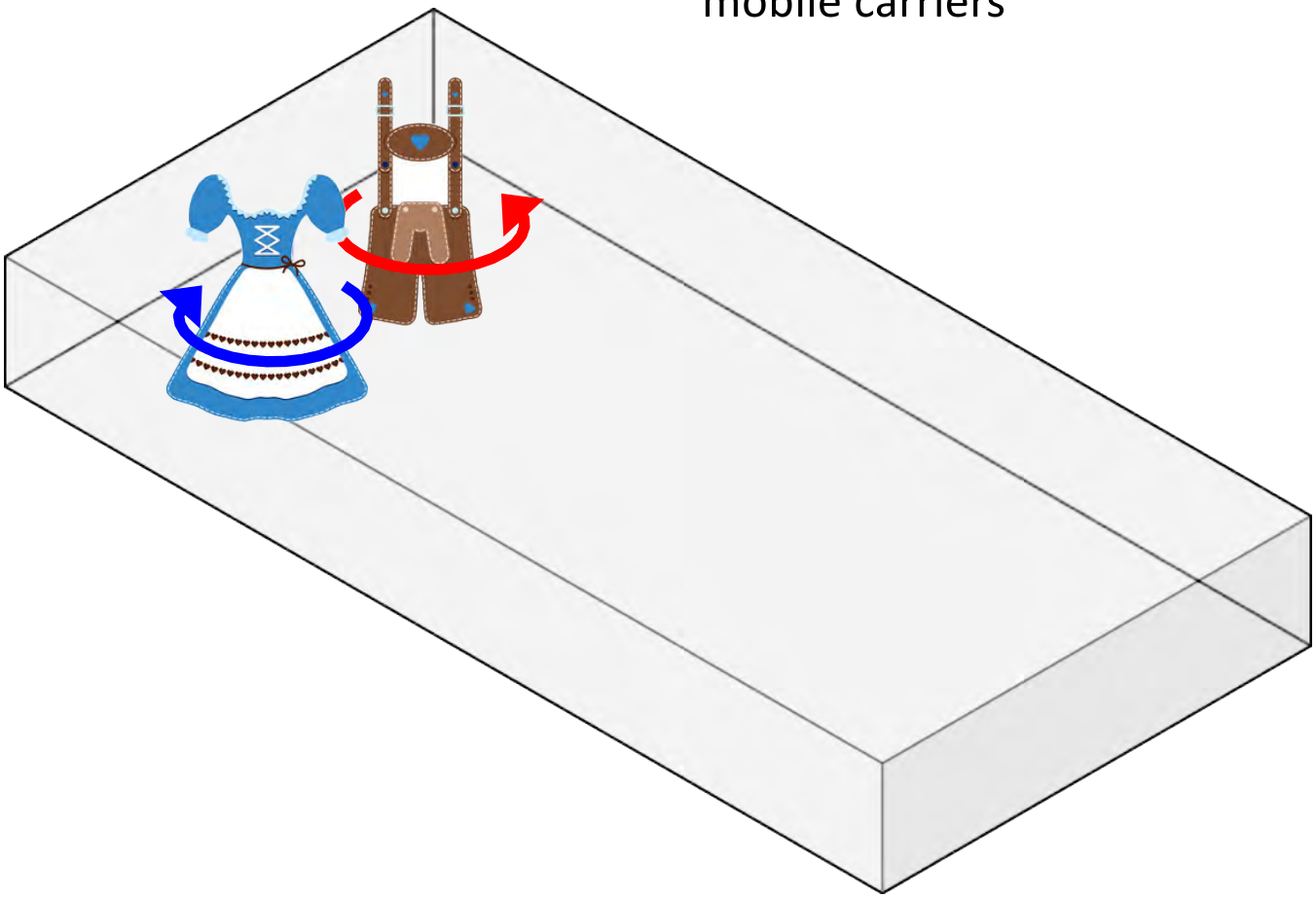
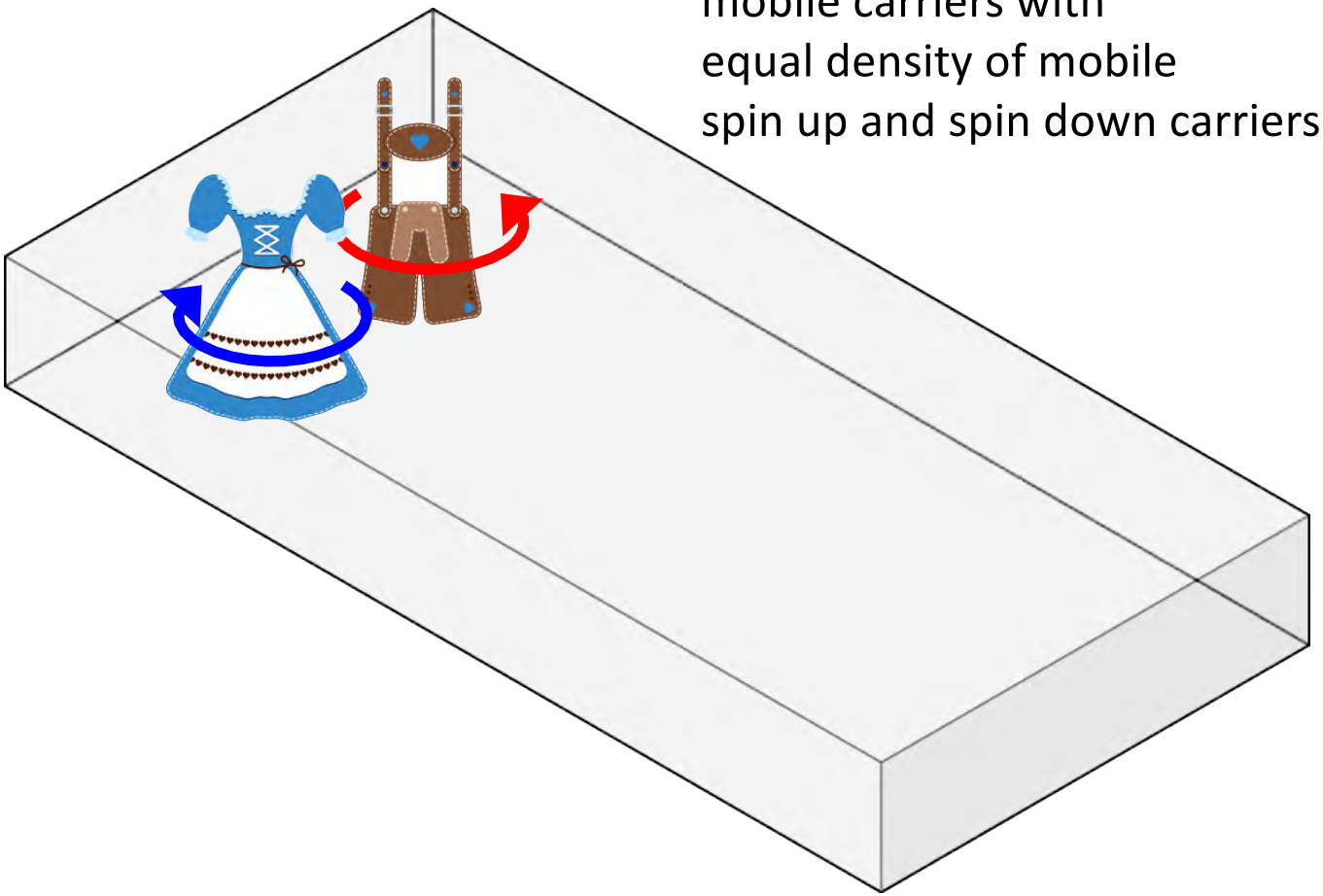


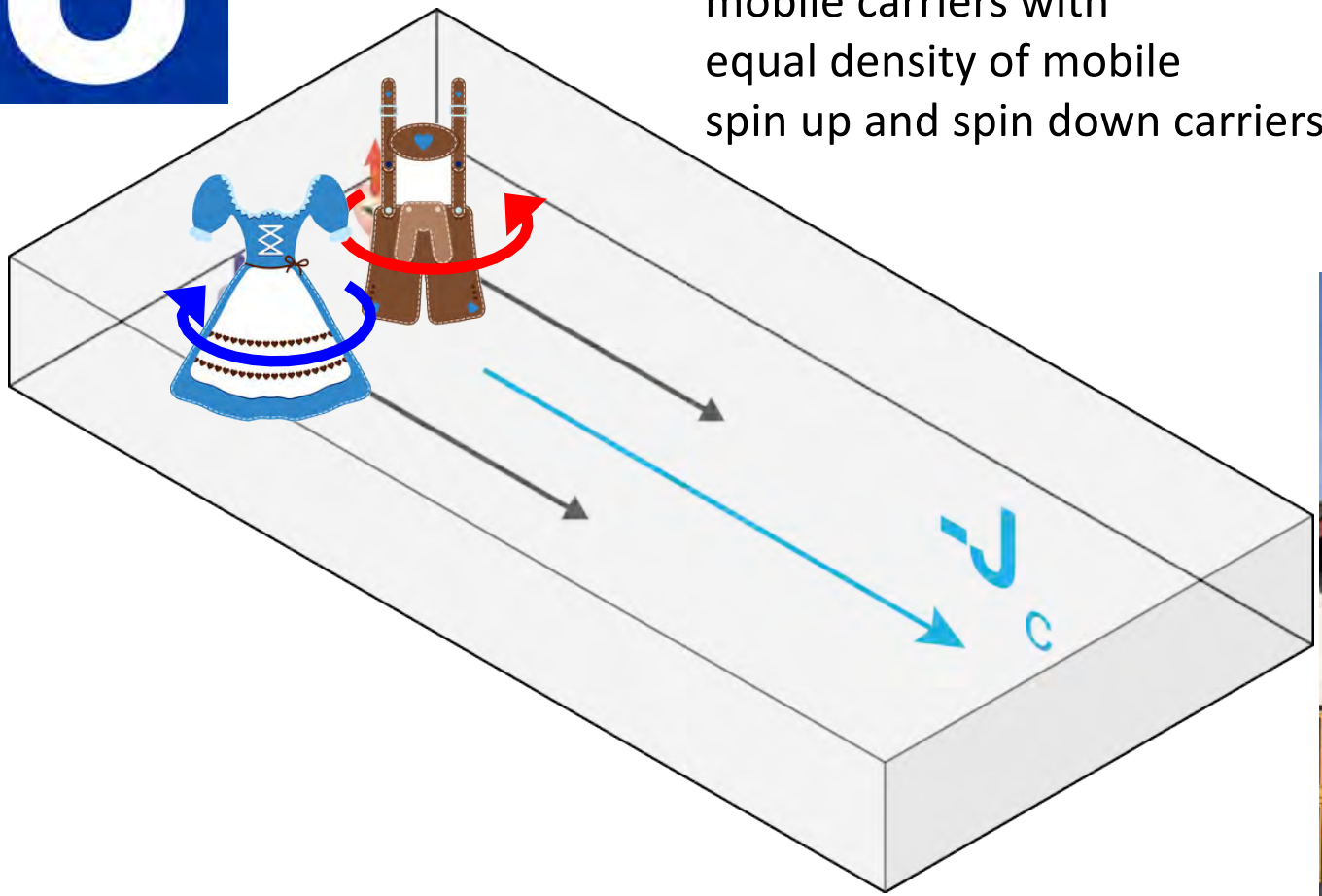
Hall effect and magneto-resistance



“normal metal”:
no long-range magnetic order
mobile carriers with
equal density of mobile
spin up and spin down carriers

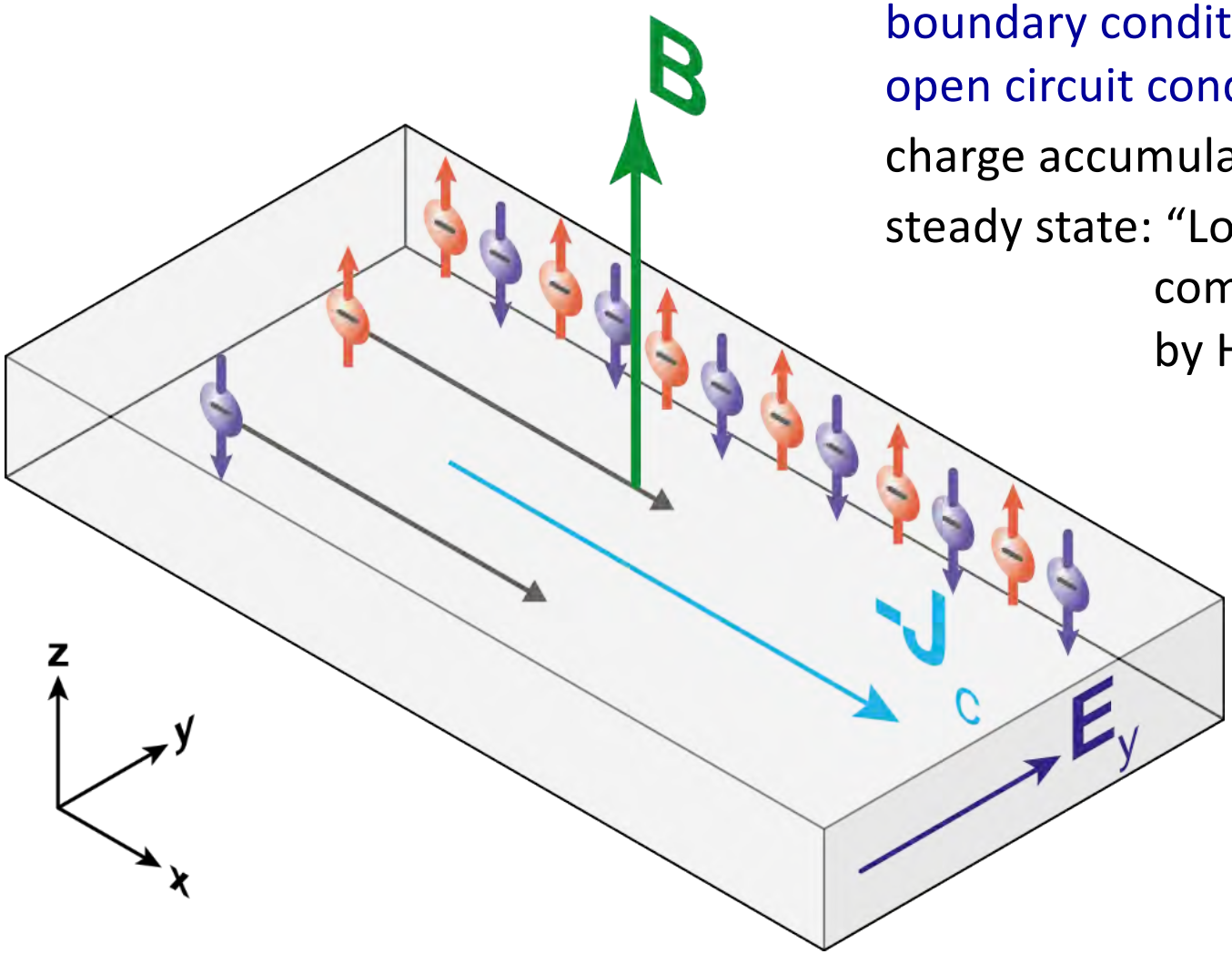
Hall effect and magneto-resistance

“normal metal”:
no long-range magnetic order
mobile carriers with
equal density of mobile
spin up and spin down carriers



Ordinary Hall effect

Ordinary Hall effect



boundary condition 1:

open circuit condition along y: $\mathbf{J}_{c,y}=0$

charge accumulation

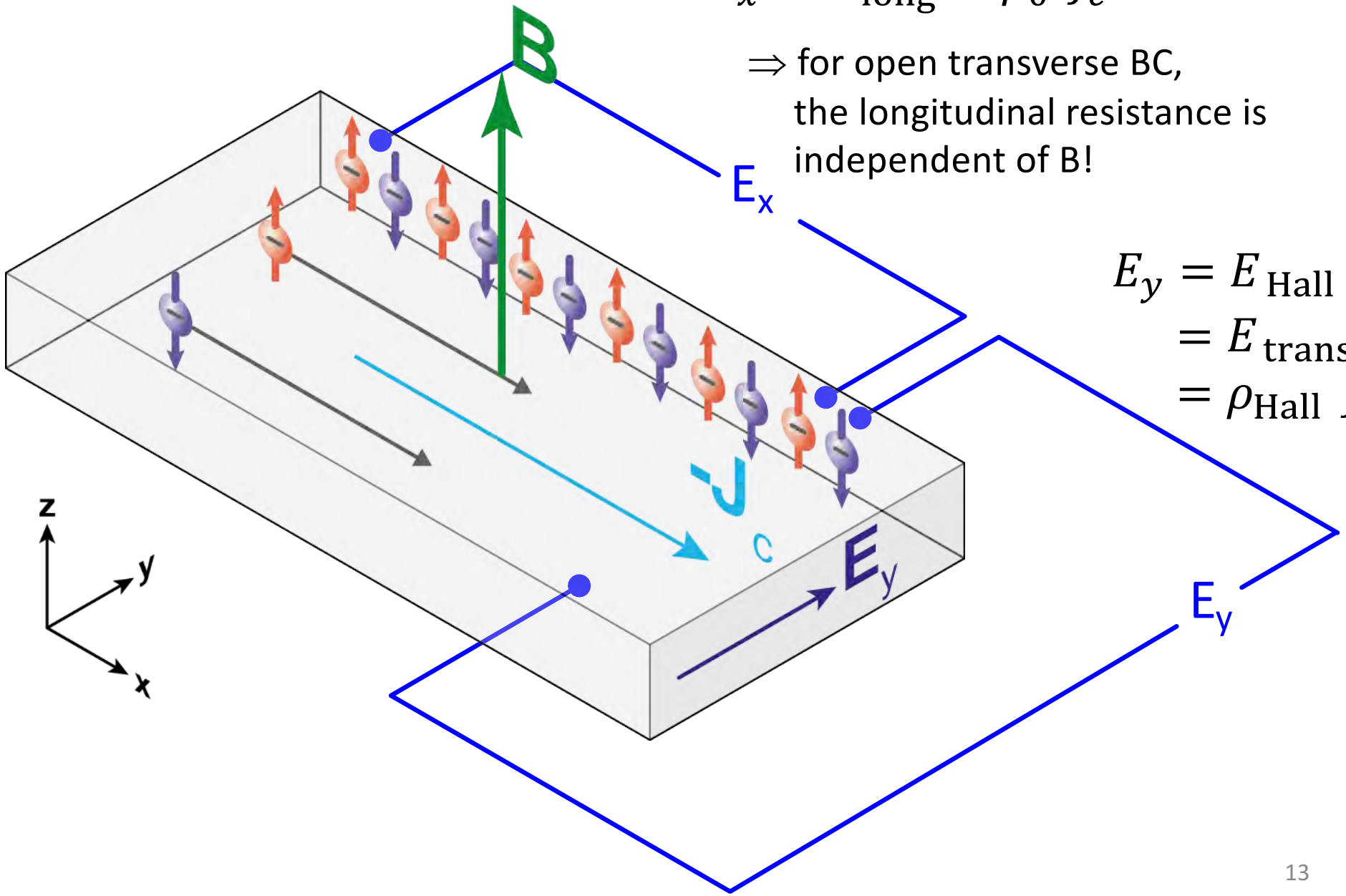
steady state: "Lorentz force compensated by Hall electric field"

Ordinary Hall effect

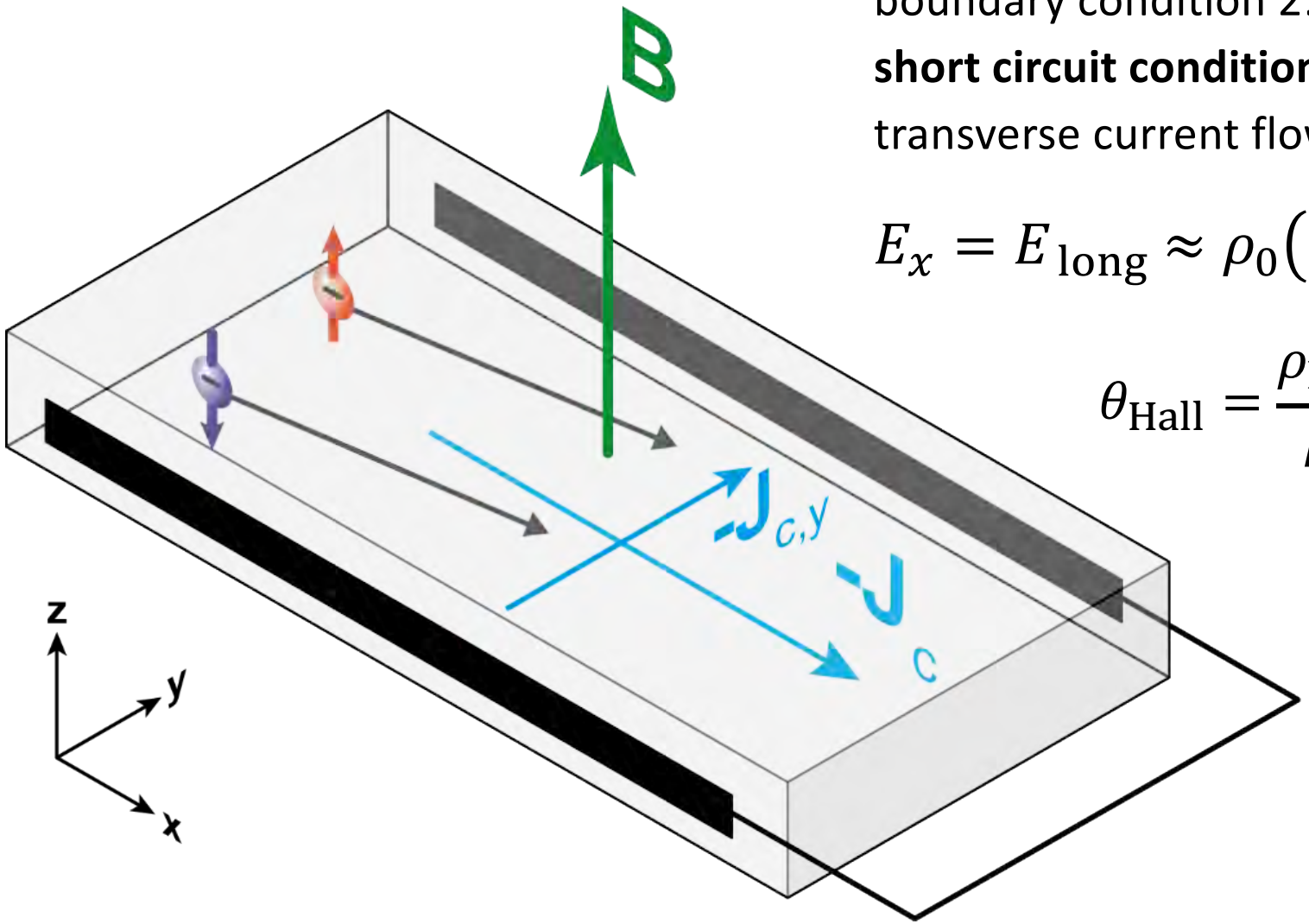
$$E_x = E_{\text{long}} = \rho_0 \; J_c$$

$\Rightarrow$ for open transverse BC, the longitudinal resistance is independent of B!

$$E_y = E_{\text{Hall}} = E_{\text{trans}} = \rho_{\text{Hall}} \; J_c$$



Ordinary Hall effect



boundary condition 2: $E_y=0$

short circuit condition

transverse current flow

$$E_x = E_{\text{long}} \approx \rho_0\left(1+\theta_{\text{Hall}}^2\right)J_c$$

$$\theta_{\text{Hall}} = \frac{\rho_{\text{Hall}}}{\rho_0} = \frac{R_{\text{H}}\,B}{\rho_0}$$

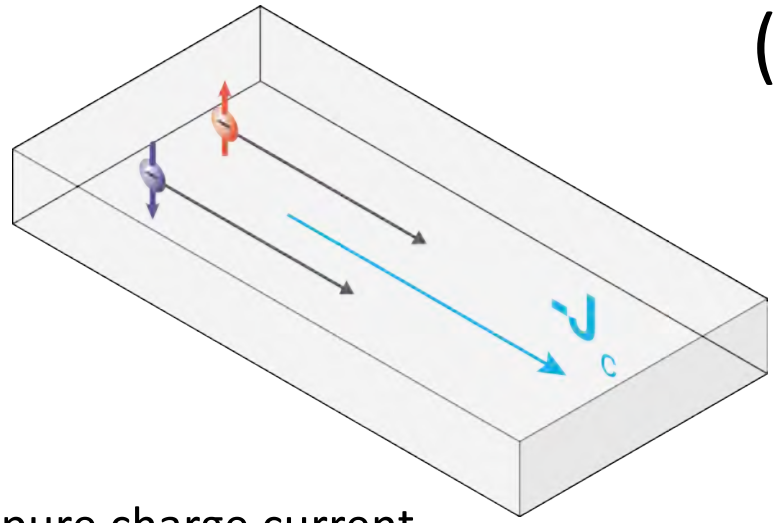
$\Rightarrow$ Hall effect impacts longitudinal resistance

Spin currents

– Spin Hall physics

Literature: Tserkovnyak, Rev. of Mod. Phys. **77**, 1375 (2005)
Sinova, Rev. of Mod. Phys. **87**, 1213 (2015)
M. Wu & A. Hoffmann (eds.),
Recent Advances in Magnetic Insulators - From Spintronics to Microwave Applications (Elsevier, 2014)

Mott's two current model
(two spin channel model)



pure charge current

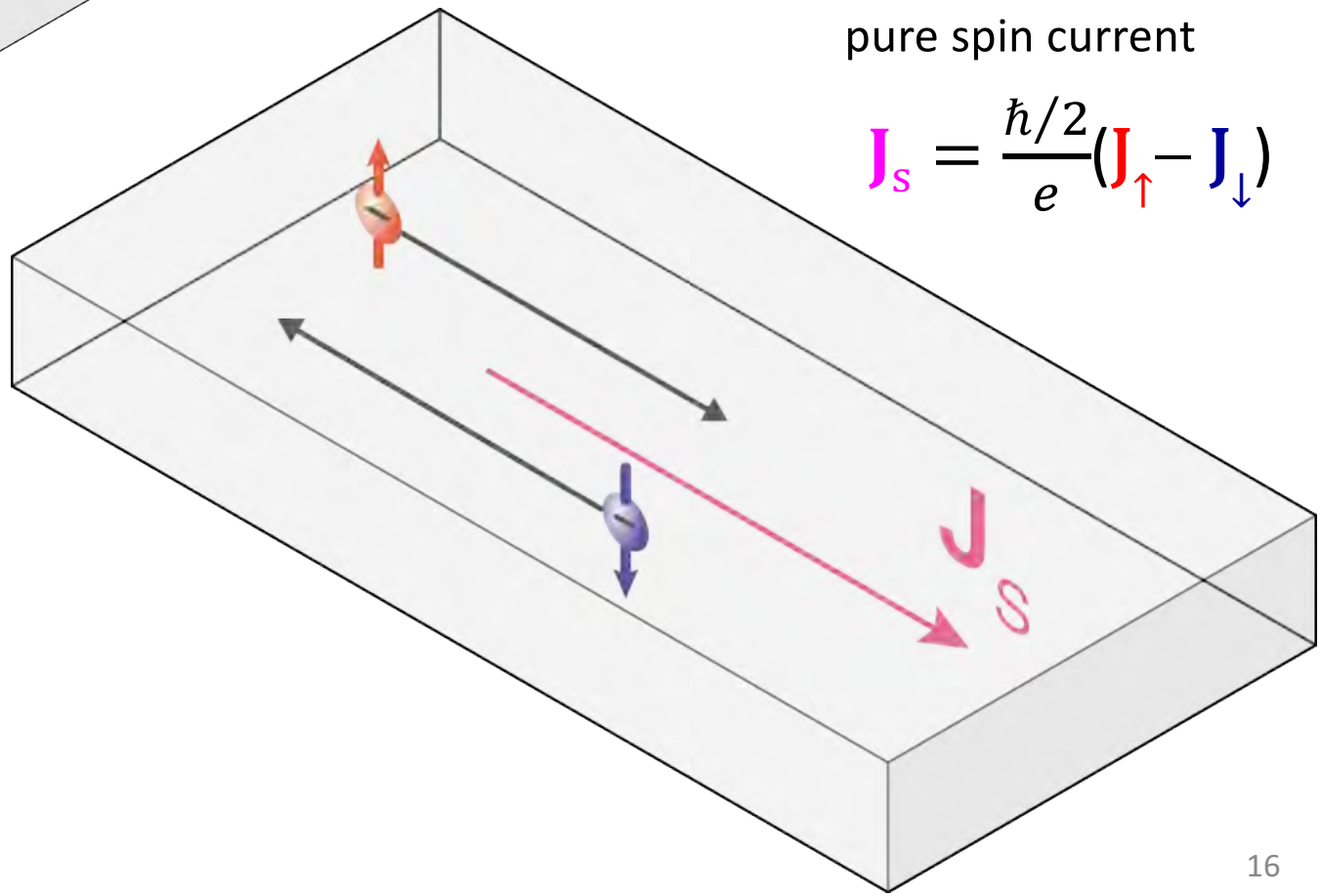
$$-J_c = J_\uparrow + J_\downarrow$$

parallel motion of
↑ and ↓ electrons

anti-parallel motion of
↑ and ↓ electrons

pure spin current

$$J_s = \frac{\hbar/2}{e}(J_\uparrow - J_\downarrow)$$



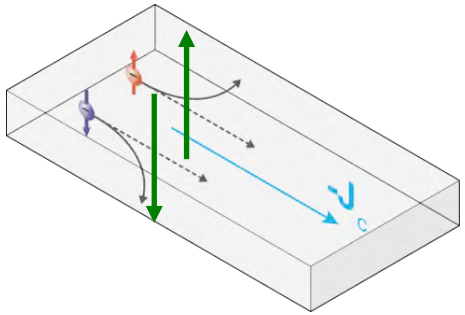
Spin Hall effect (SHE)

spin-orbit coupling: interaction between spin and charge motion

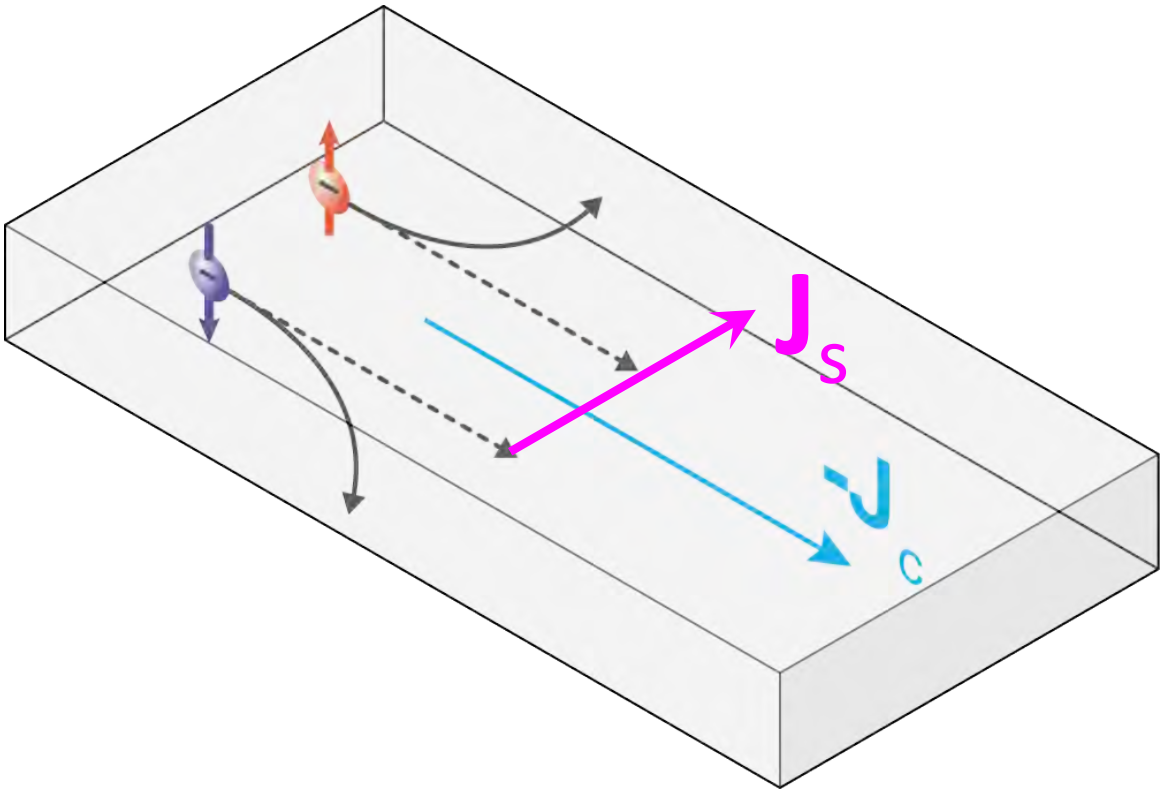
… spin-orientation dependent scattering
(skew / side-jump / intrinsic (Berry phase) mechanisms)

… acts like a spin-orientation dependent Hall magnetic field

⇒ ↑ scattered left, ↓ scattered right



Spin Hall effect: charge current induces transverse spin current



$$\mathbf{J_s} = \alpha_{SH} \left(\frac{\hbar}{2e}\right) \mathbf{J_c} \times \mathbf{s}$$

spin Hall angle $\alpha_{SHE} = \sigma_S / \sigma_C$
parameterizes $J_C \leftrightarrow J_S$ conversion efficiency

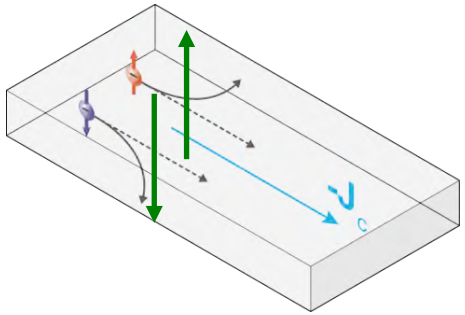
Spin Hall effect (SHE) and inverse spin Hall effect (ISHE)

spin-orbit coupling: interaction between spin and charge motion

… spin-orientation dependent scattering
(skew / side-jump / intrinsic (Berry phase) mechanisms)

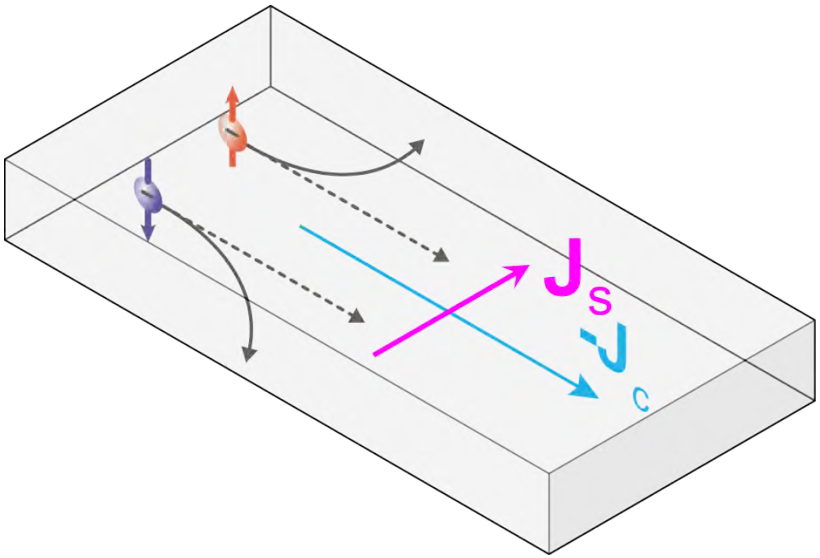
… acts like a spin-orientation dependent Hall magnetic field

⇒ ↑ scattered left, ↓ scattered right



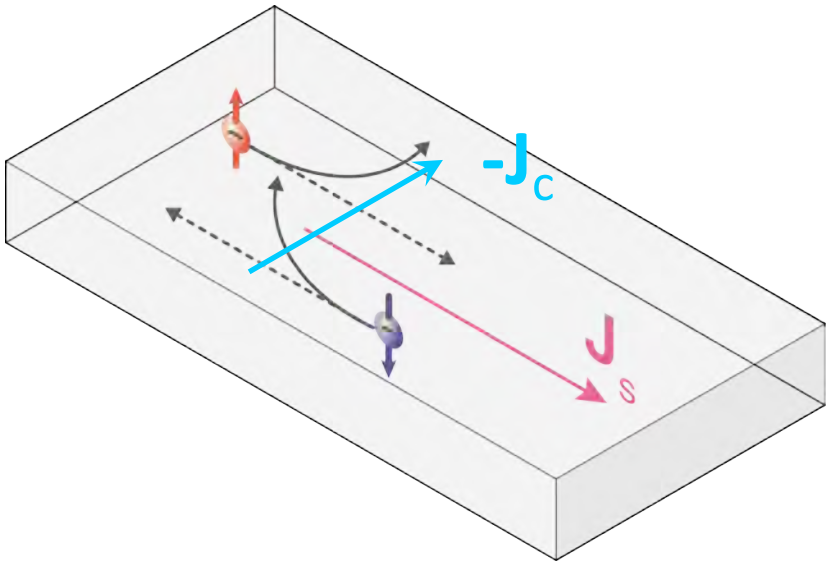
Spin Hall effect (SHE)

$$\mathbf{J_s} = \alpha_{SH}\left(\frac{\hbar}{2e}\right)\mathbf{J_c}\times\mathbf{s}$$



inverse spin Hall effect (ISHE)

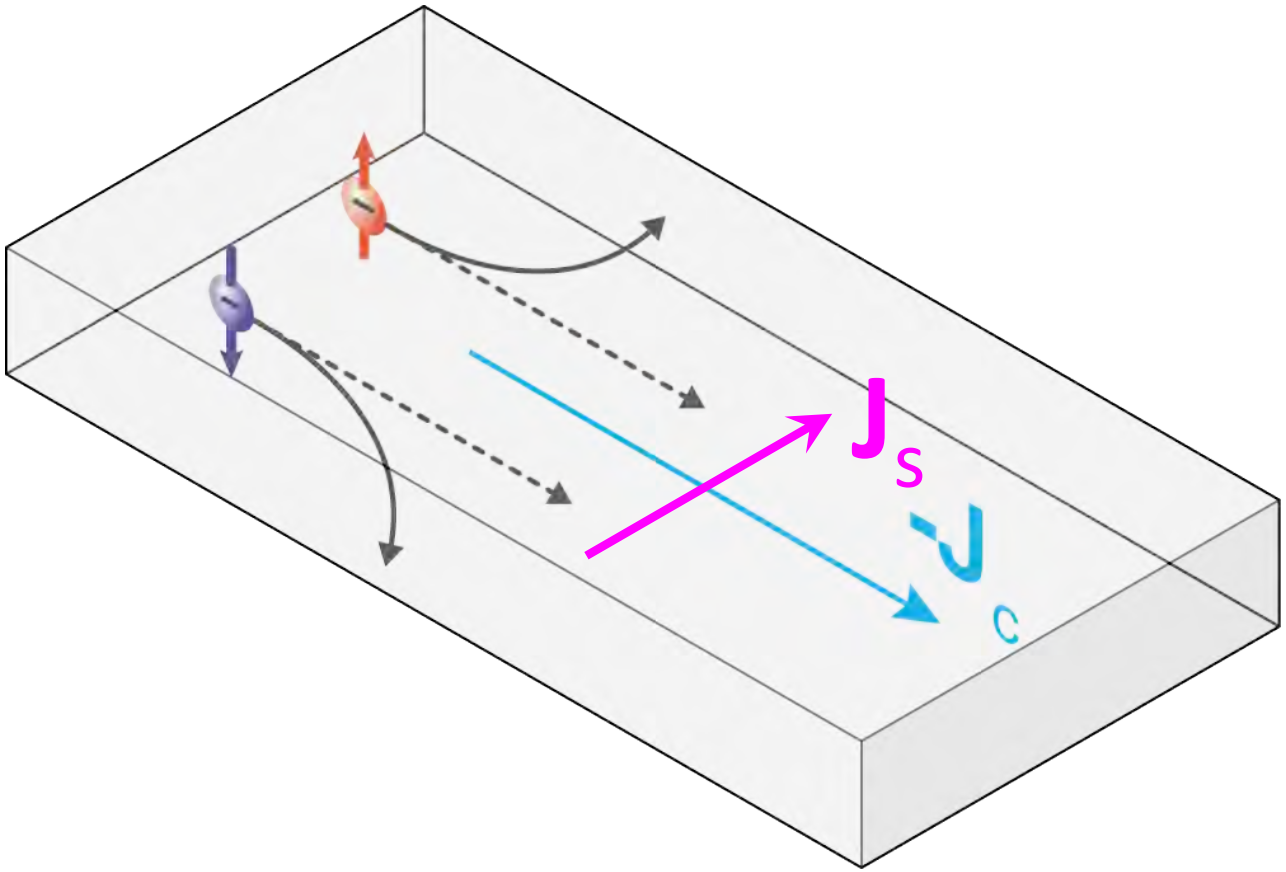
$$\mathbf{J_c} = \alpha_{SH}\left(\frac{2e}{\hbar}\right)\mathbf{J_s}\times\mathbf{s}$$

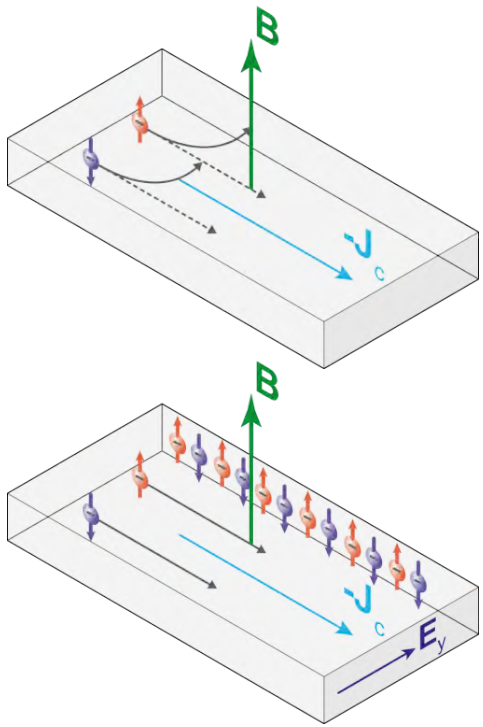


Spin Hall effect & boundary conditions

Spin Hall effect:

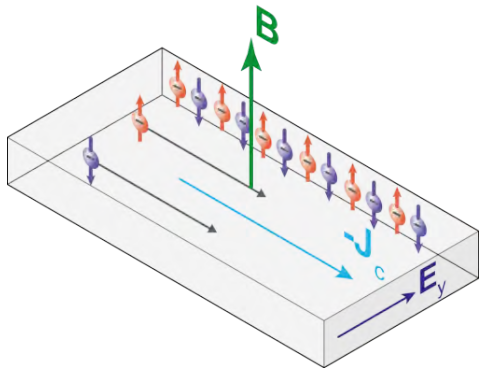
charge current induces transverse spin current via SOC





$$\mathbf{J_s} = \alpha_{SH} \left(\frac{\hbar}{2e}\right) \mathbf{J_c} \times \mathbf{s}$$

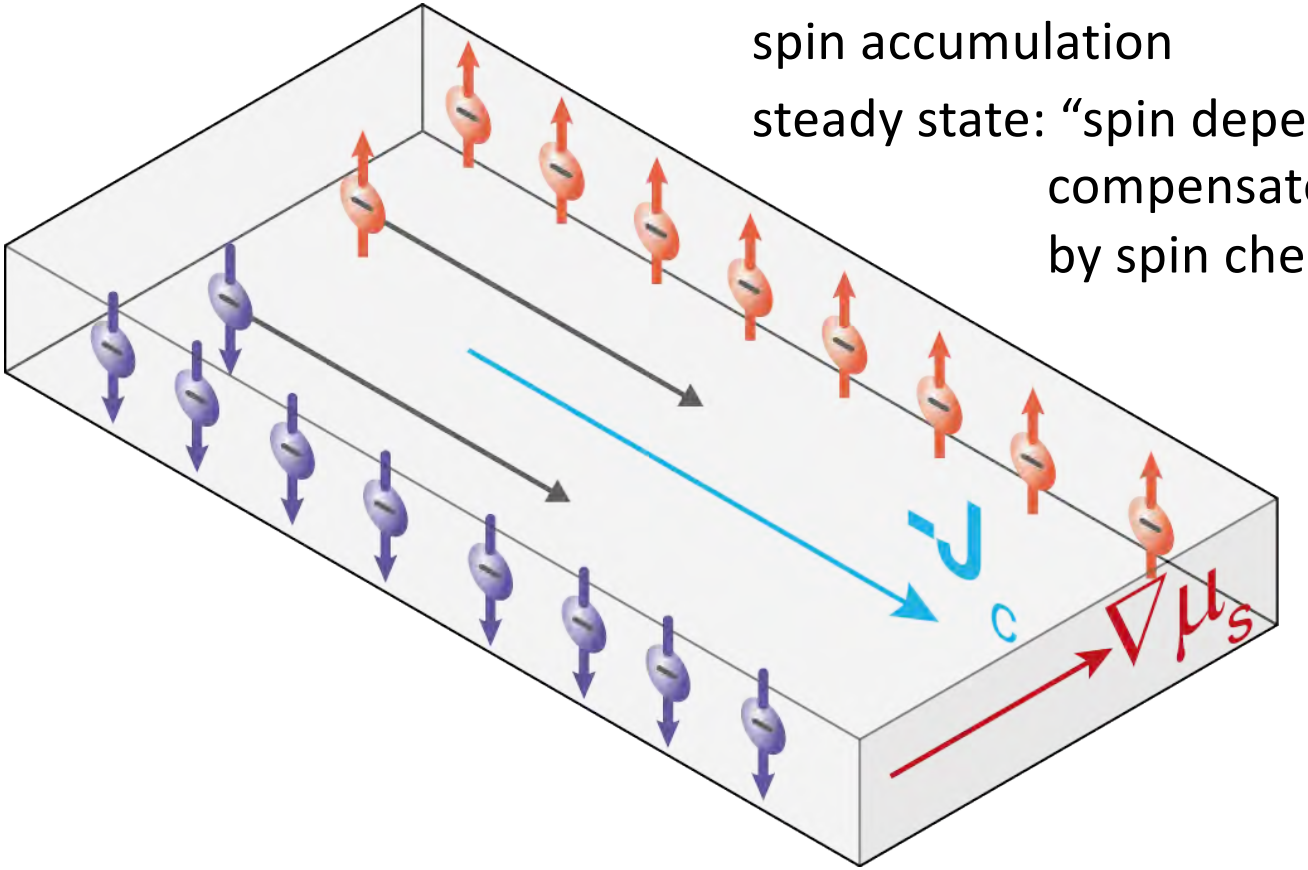
Spin Hall effect & boundary conditions



spin boundary condition 1:
open spin circuit along y: $\mathbf{J}_{s,y}=0$

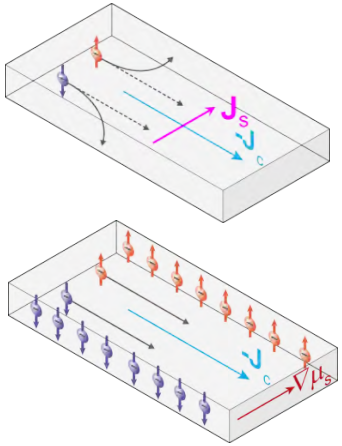
spin accumulation

steady state: "spin dependent scattering compensated by spin chemical potential"



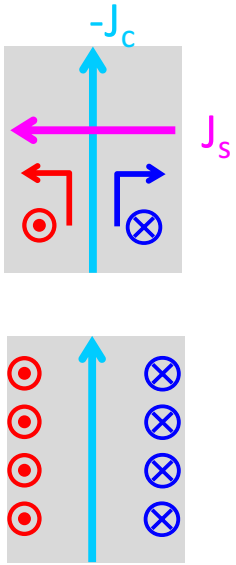
$$\mathbf{J_s} = \alpha_{SH}\left(\frac{\hbar}{2e}\right)\mathbf{J_c}\times\mathbf{s}$$

Direct spin Hall effect in GaAs

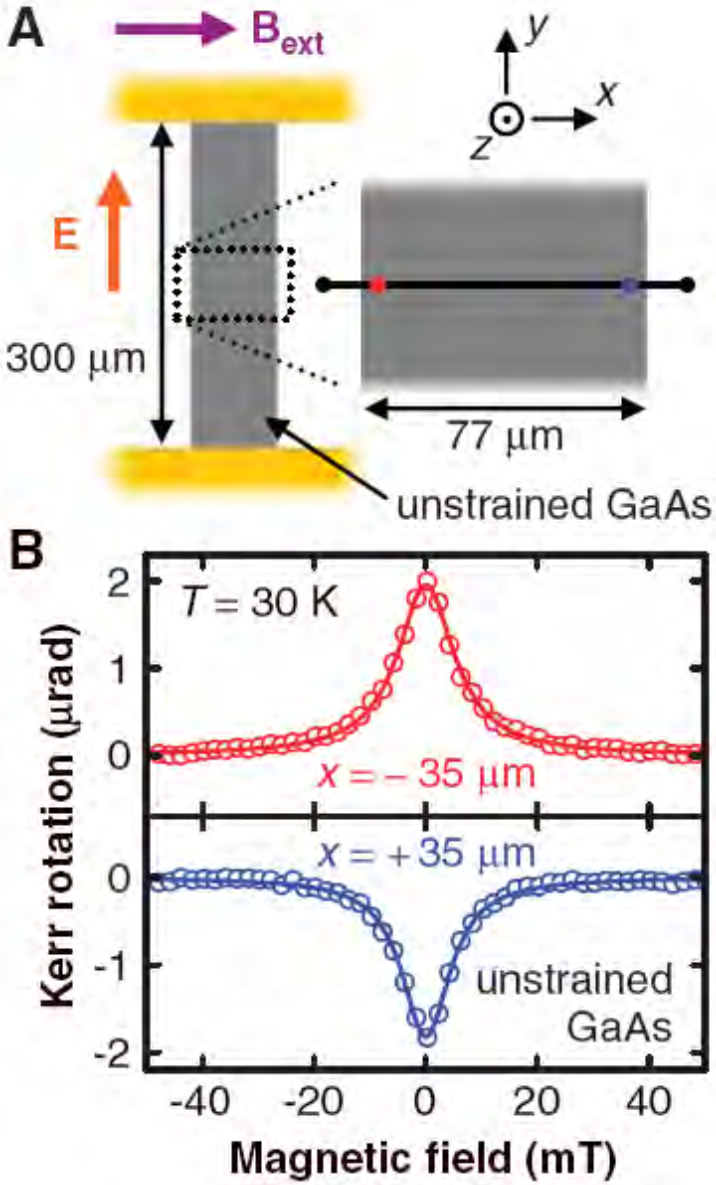


$$\mathbf{J}_S = \alpha_{SHE} \frac{\hbar}{2e} [\mathbf{J}_C \times \mathbf{s}]$$

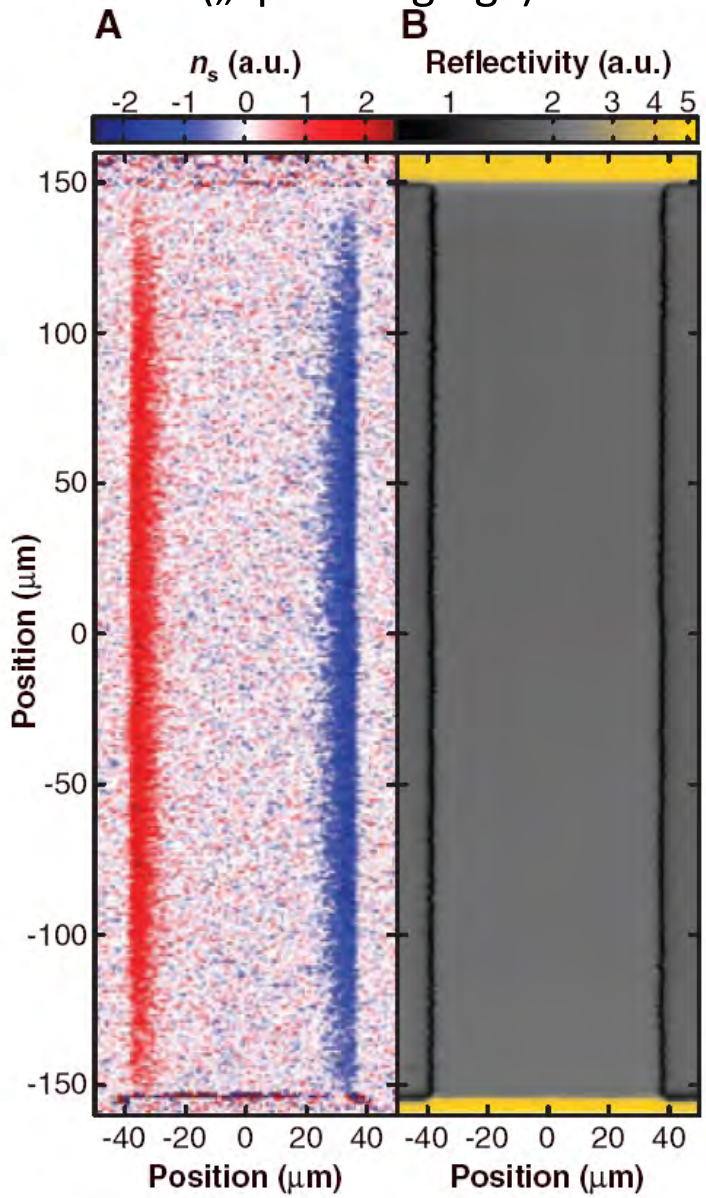
$$\alpha_{SHE}^{GaAs} \cong 2 \times 10^{-4}$$



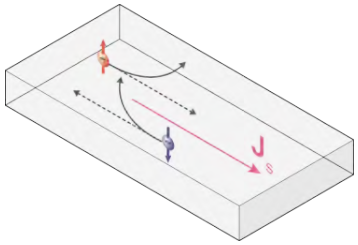
Kato *et al.*, Science **306**, 1910 (2004).



Kerr microscopy („spin imaging“)

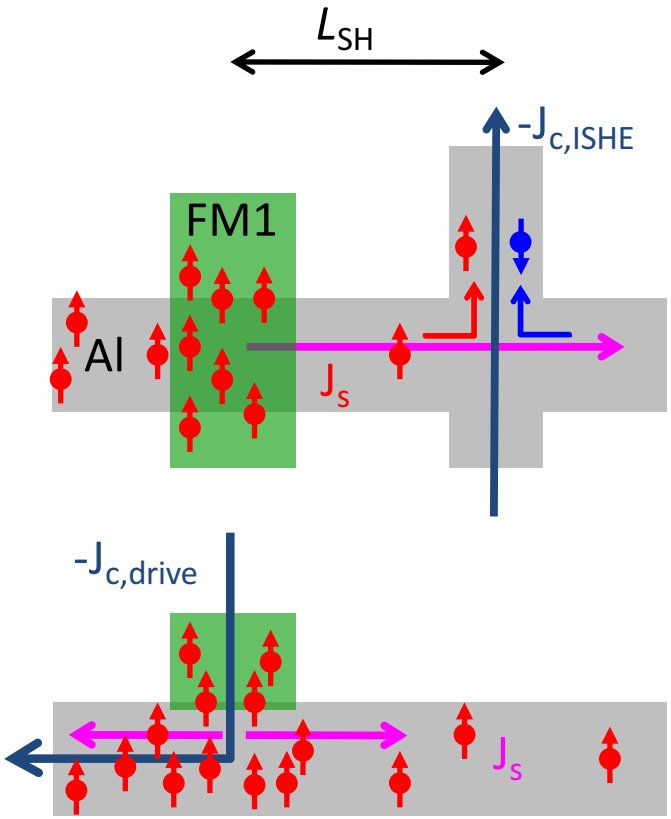


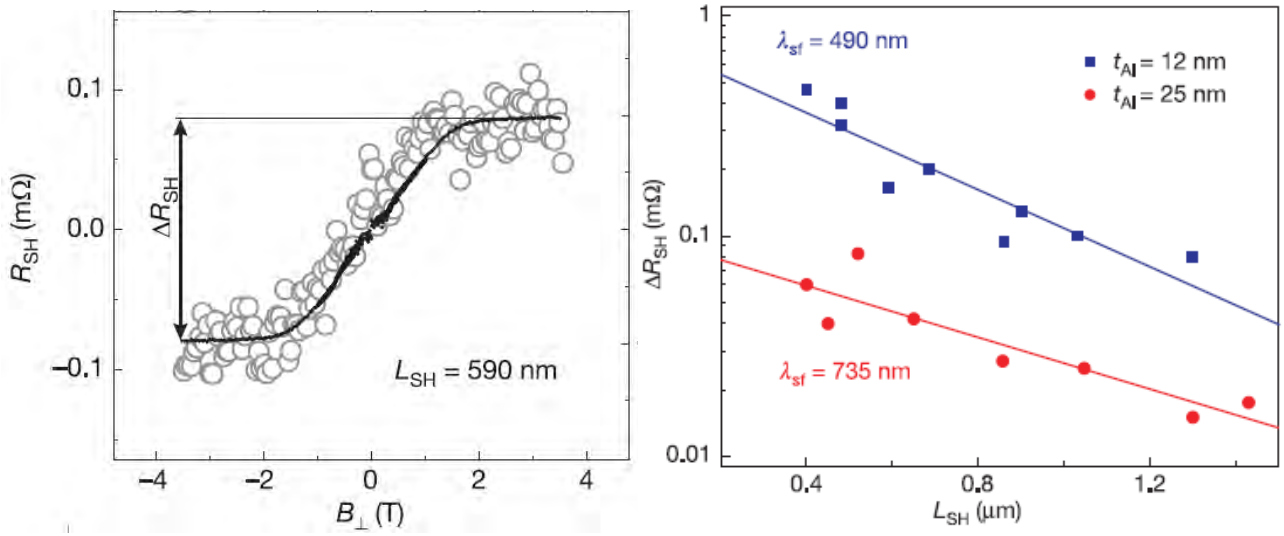
iSHE in Metallic F/N Nanostructures



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

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





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

detection of diffusive spin current via inverse spin Hall effect

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

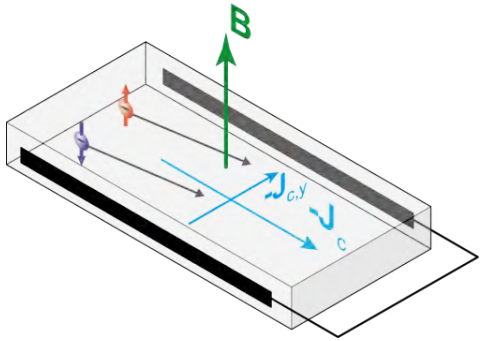
Gold : α_{SHE}=0.0016

Platinum : α_{SHE}=0.013 … **0.11** (0.16)

Bi, Bi/Ag, Ta : α_{SHE}=0.1 … **0.3**

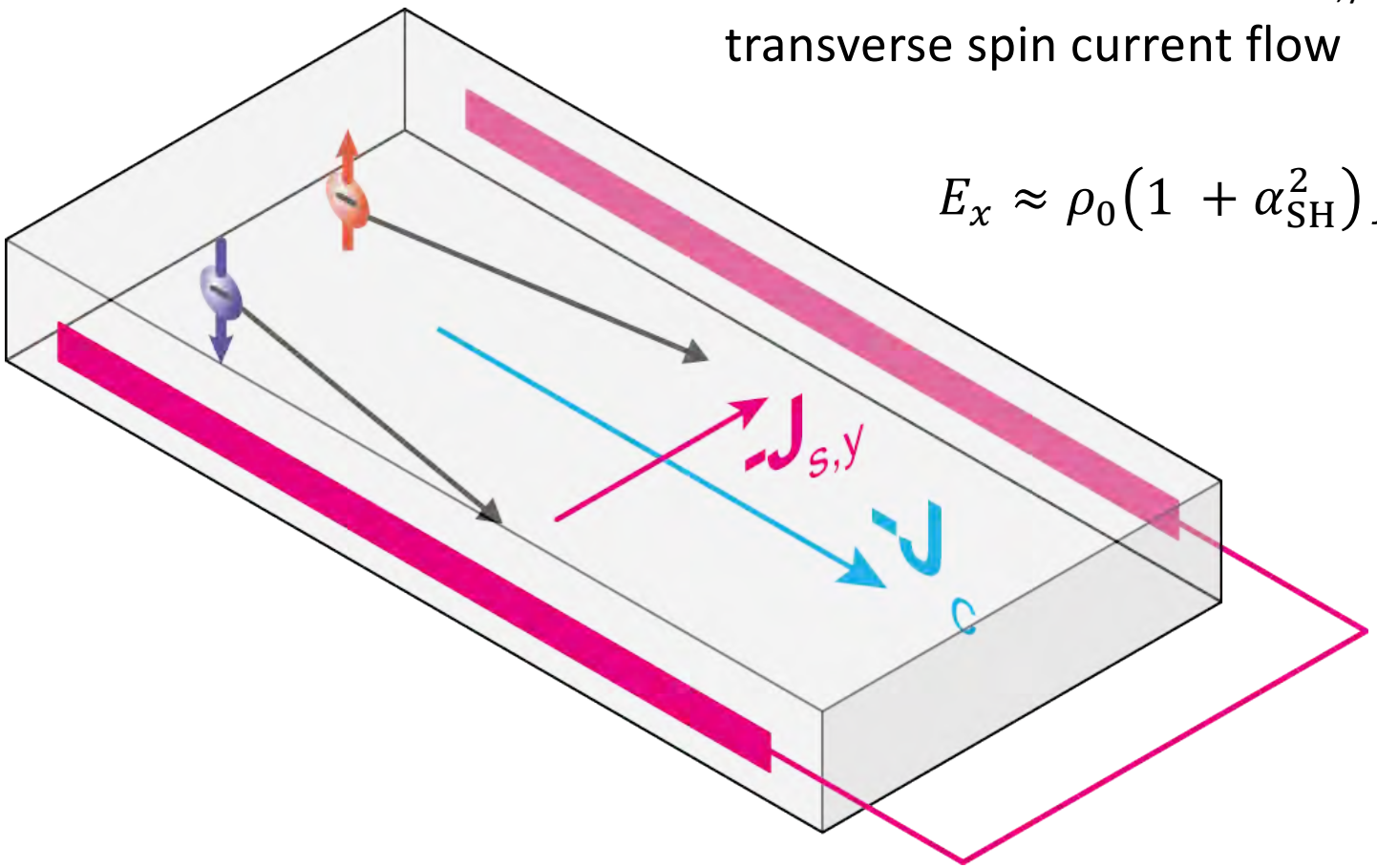
Valenzuela & Tinkham, Nature **442**, 176 (2006).
Mosendz *et al.*, Phys. Rev. Lett. **104**, 046601 (2010).
Liu *et al.*, Science **336**, 555 (2012).
Niimi *et al.*, Phys. Rev. Lett. **109**, 156602 (2012).
…and many more …
M. Wu & A. Hoffmann (eds.), *Recent Advances in Magnetic Insulators - From Spintronics to Microwave Applications* (Elsevier, 2014)

Spin Hall effect & boundary conditions



spin boundary condition 2:
short spin circuit along y: $\mu_{s,y}=0$
transverse spin current flow

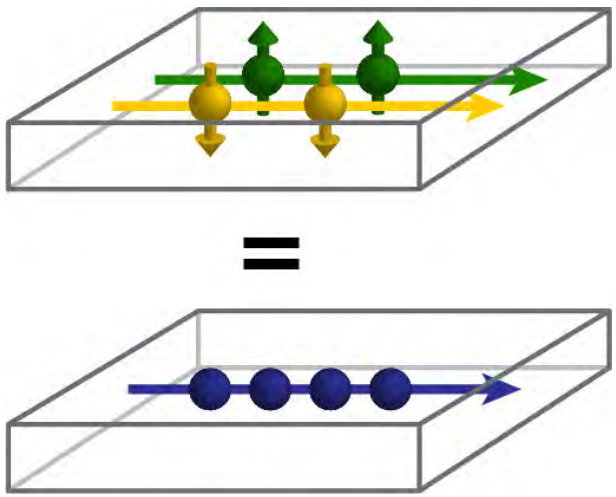
$$E_x \approx \rho_0 \left(1 + \alpha_{\mathrm{SH}}^2\right) J_c$$

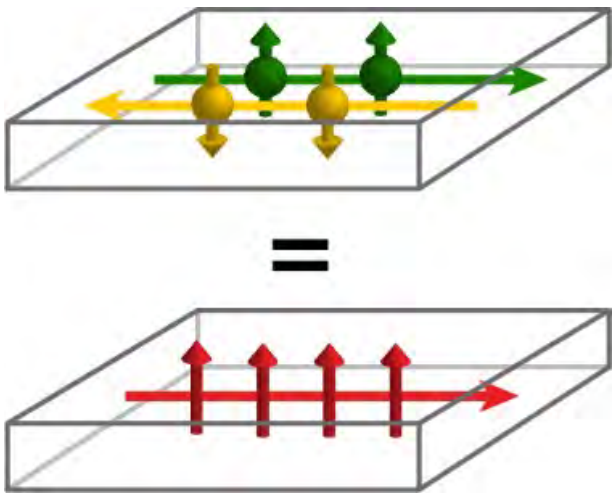


⇒ spin Hall effect impacts longitudinal resistance (= SMR) !

Charge vs. Spin Currents

wrap-up: pure charge current | pure spin current





$$j_c = j_{c\uparrow} + j_{c\downarrow} \neq 0$$

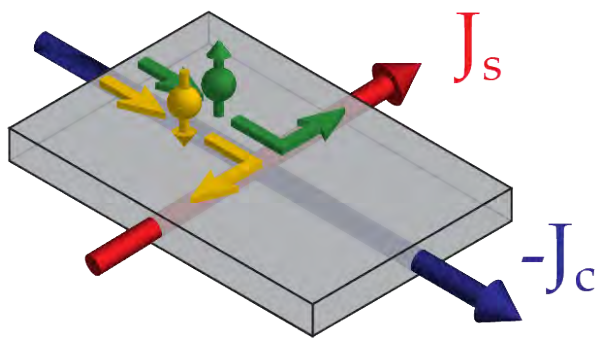
$$j_s = \frac{+\hbar/2}{e} j_{c\uparrow} + \frac{-\hbar/2}{e} j_{c\downarrow} = 0$$

$$j_c = j_{c\uparrow} + j_{c\downarrow} = 0$$

$$j_s = \frac{+\hbar/2}{e} j_{c\uparrow} + \frac{-\hbar/2}{e} j_{c\downarrow} \neq 0$$

ISHE:

$j_s \rightarrow j_c$

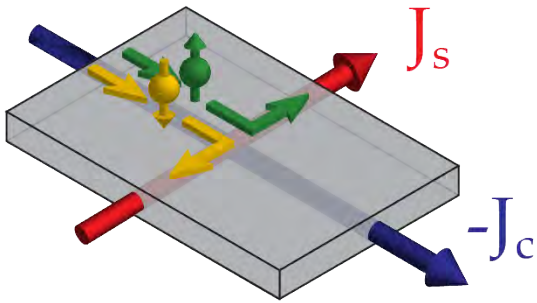


SHE:

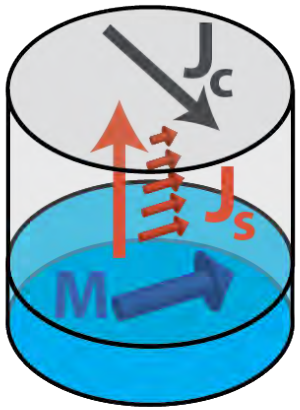
$j_c \rightarrow j_s$

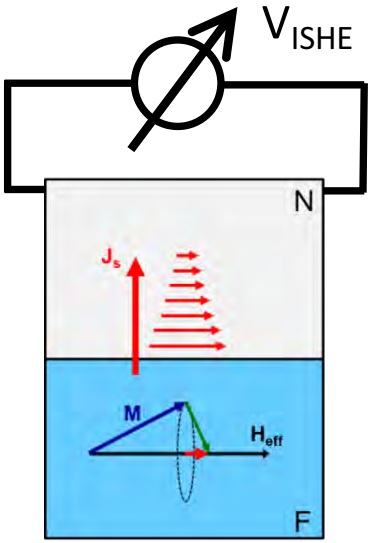
Outline

pure spin currents
spin Hall effect

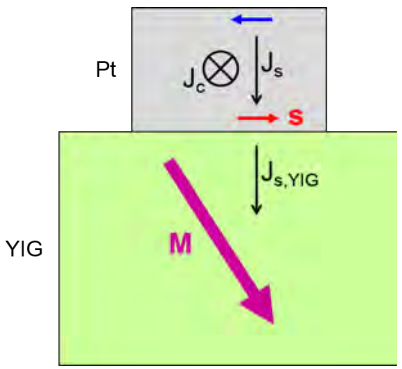


„simple“ spin current circuits
spin pumping





spin Hall magnetoresistance

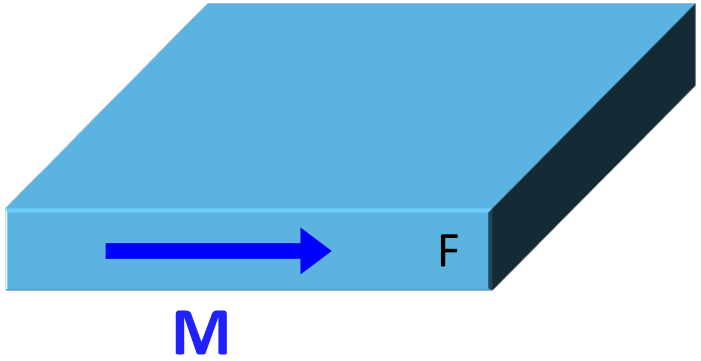


Coherent magnetization dynamics

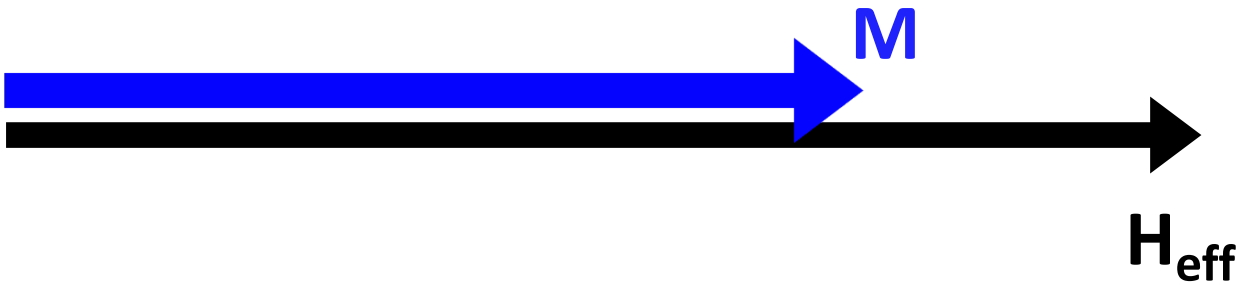
- (Anti-)ferromagnetic Resonance
- Spin pumping (damping)
- Spin pumping (electrically detected)

Literature: Vonsovskii, Ferromagnetic Resonance (1964)
Tserkovnyak, Rev. of Mod. Phys. **77**, 1375 (2005)
Sinova, Rev. of Mod. Phys. **87**, 1213 (2015)
M. Wu & A. Hoffmann (eds.),
Recent Advances in Magnetic Insulators - From Spintronics to Microwave Applications (Elsevier, 2014)

Coherent magnetization dynamics



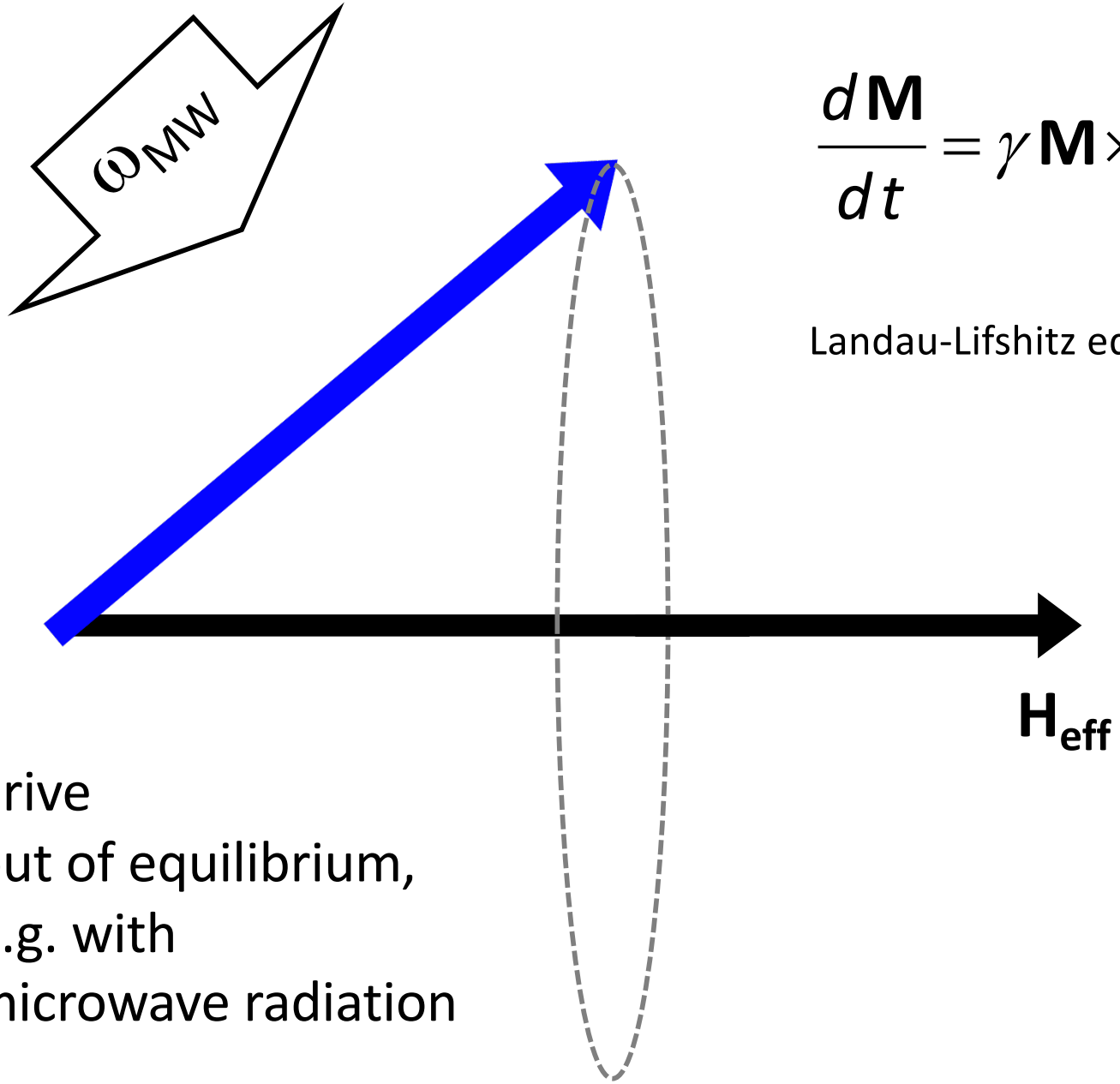
ferromagnet (F) with
macroscopic moment **M**



$$\mathbf{H}_{\text{eff}} = \mathbf{H}_0 + \mathbf{H}_{\text{demag.}} + \mathbf{H}_{\text{anistropy}} + \mathbf{H}_{\text{exchange}} + \mathbf{H}_{\text{RF}} + \ldots$$

Magnetization dynamics

Magnetization dynamics

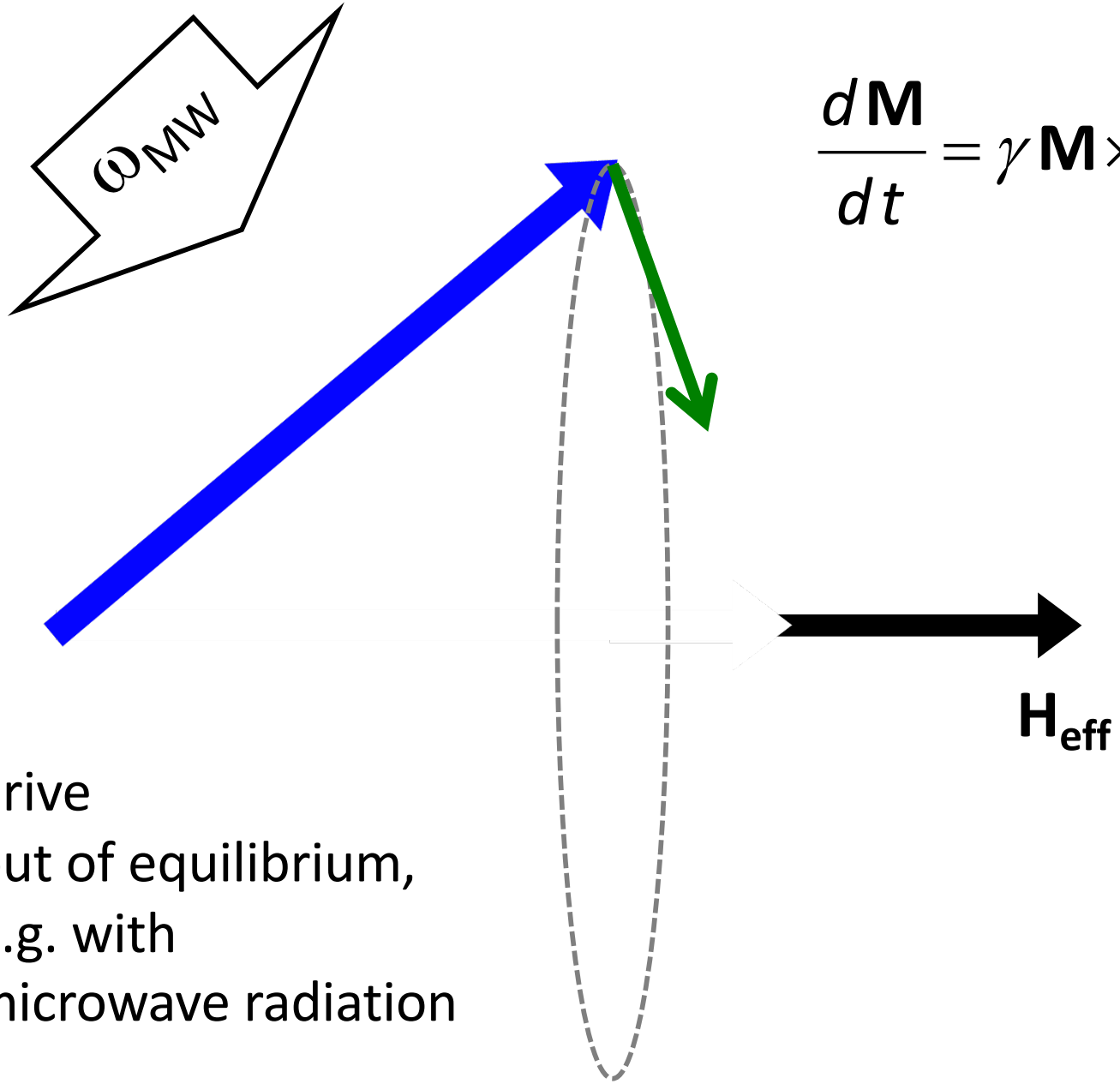


$$\frac{d\mathbf{M}}{dt} = \gamma \mathbf{M} \times \mu_0 \mathbf{H}_{\text{eff}}$$

Landau-Lifshitz equation (LL)

drive
out of equilibrium,
e.g. with
microwave radiation

Magnetization dynamics



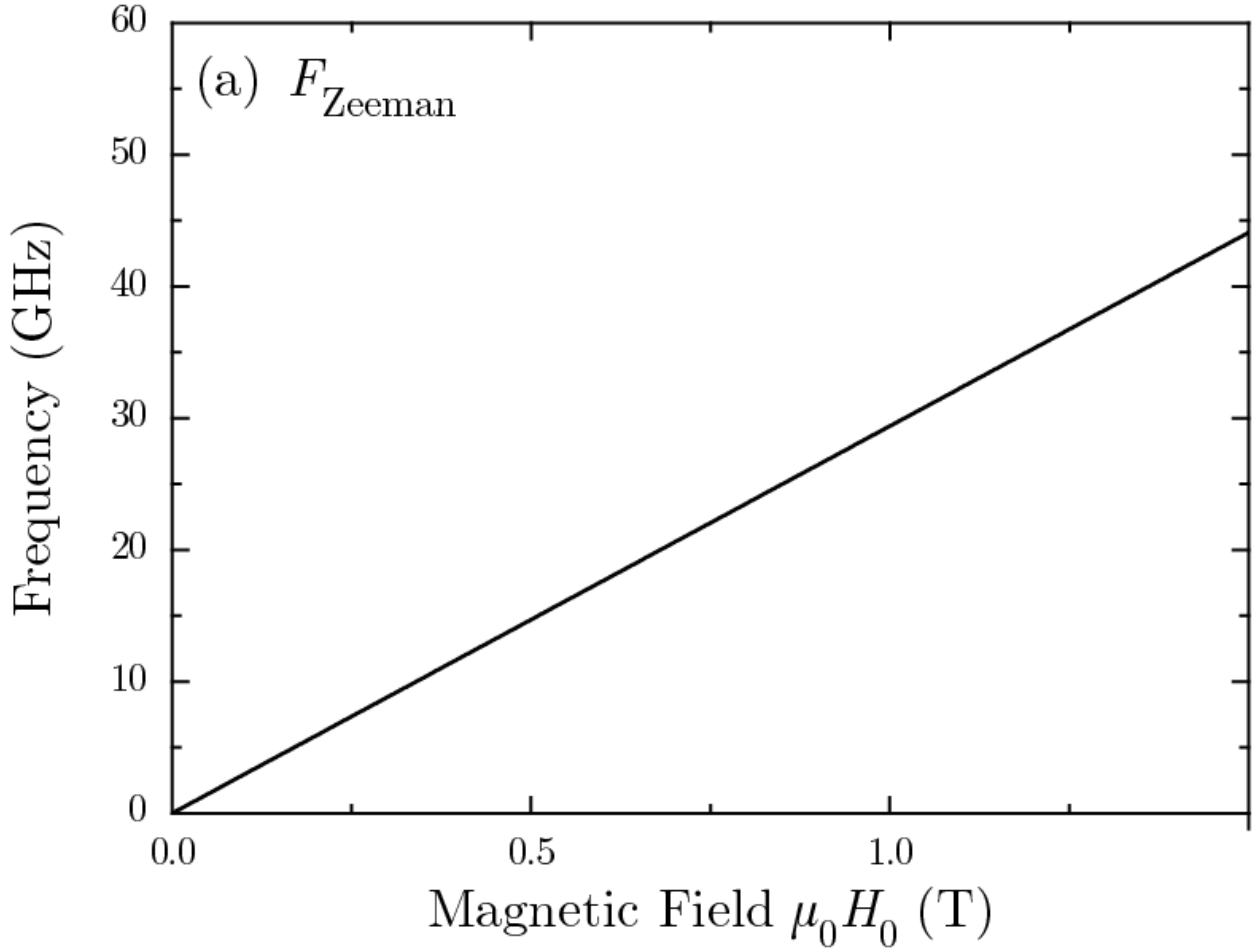
$$\frac{d\mathbf{M}}{dt} = \gamma \mathbf{M} \times \mu_0 \mathbf{H}_{\mathrm{eff}} + \alpha \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t}$$

Gilbert damping

drive
out of equilibrium,
e.g. with
microwave radiation

Resonance Frequency

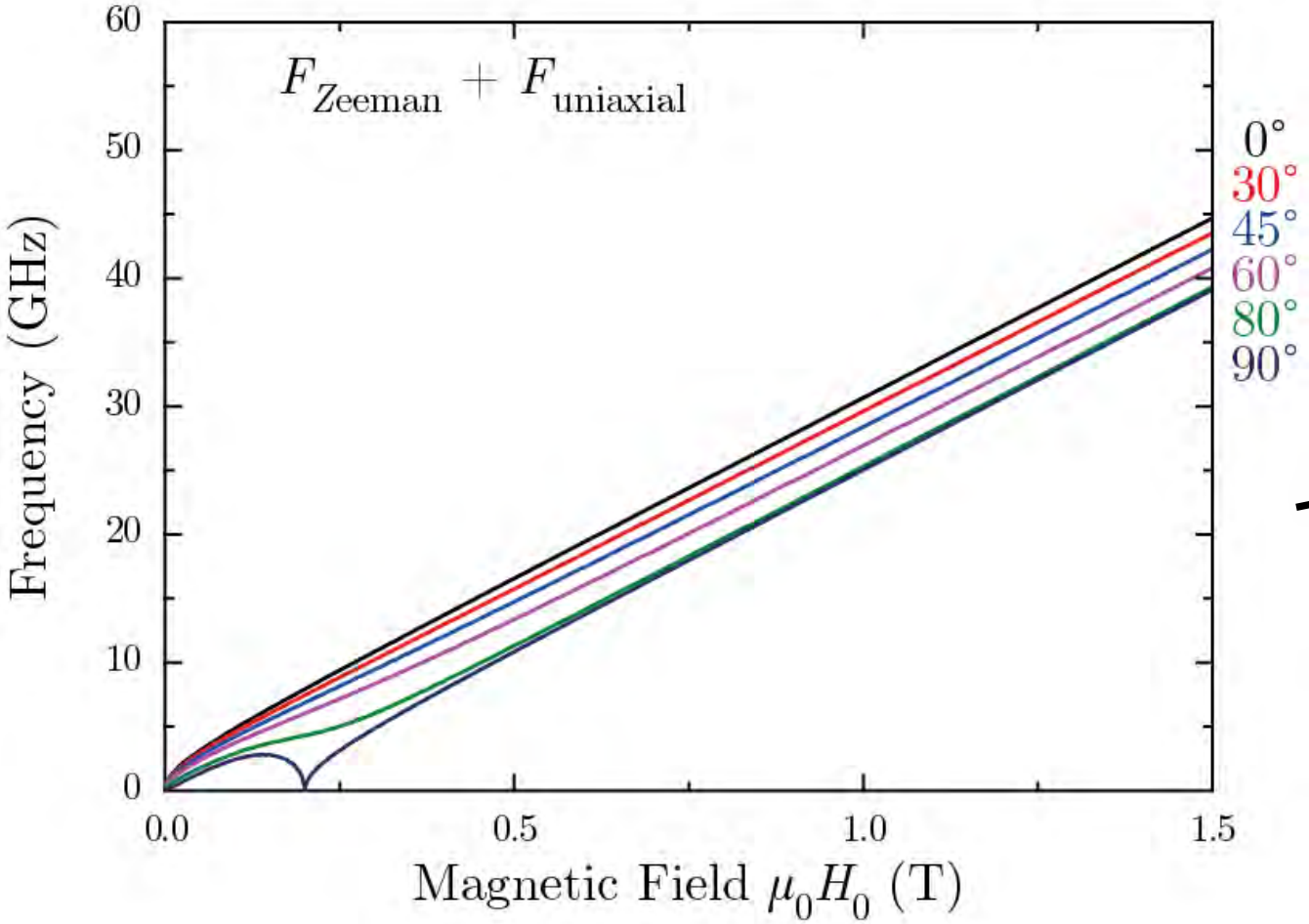
example: no anisotropy, external magnetic field only

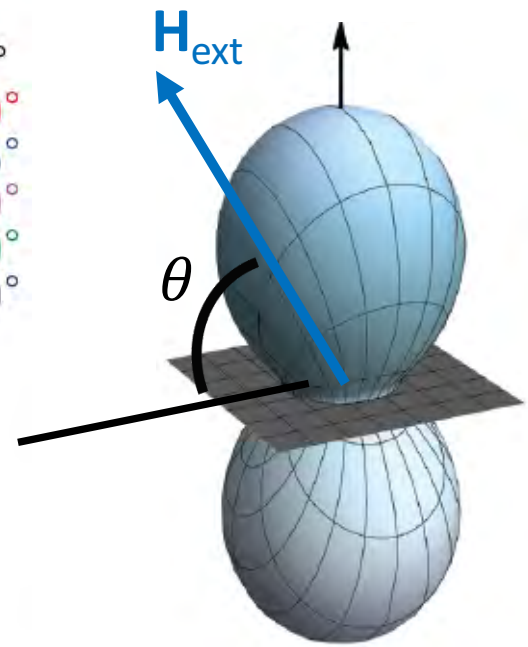


$$\mathbf{H}_{\text{eff}} = \mathbf{H}_{\text{ext}}$$

Resonance Frequency: Effects of Anisotropy

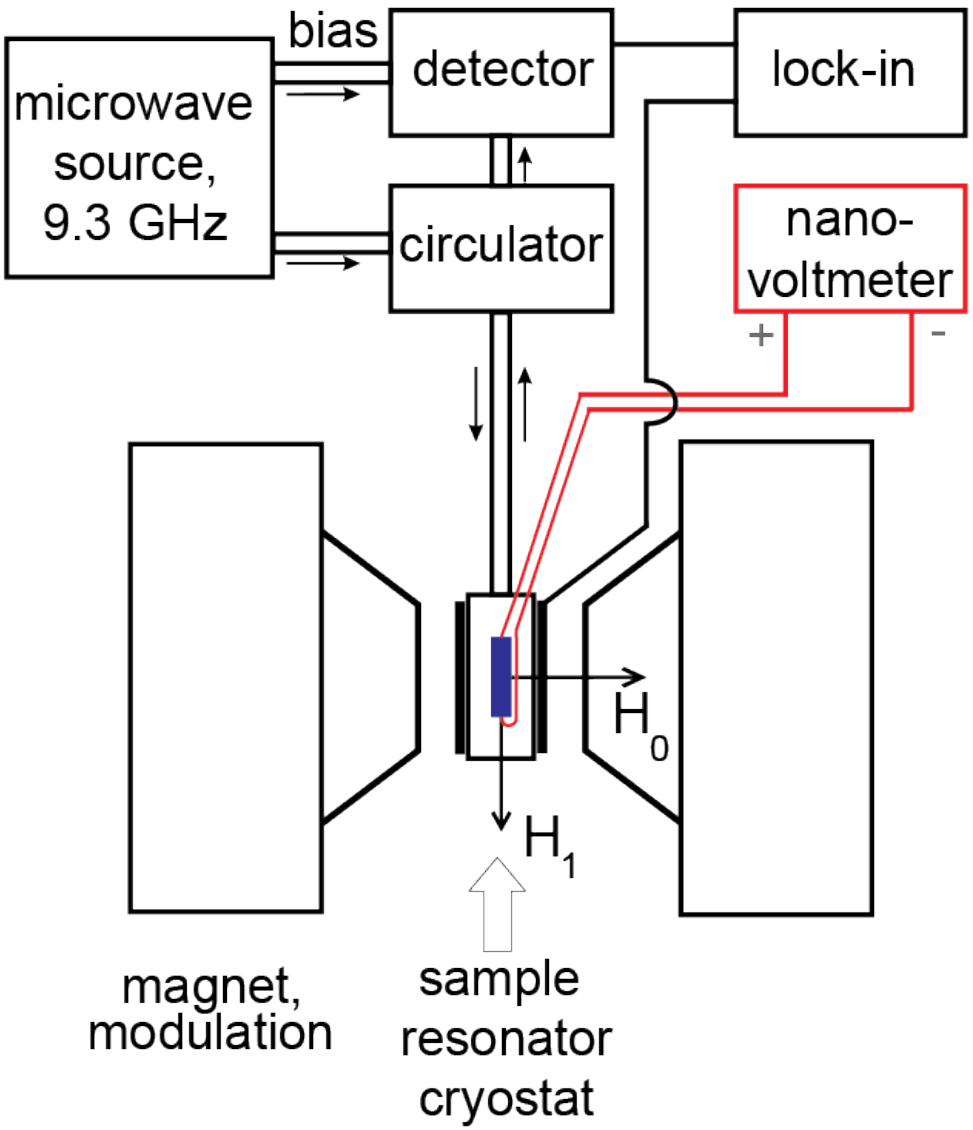
example: easy plane anisotropy, calculate resonance frequencies

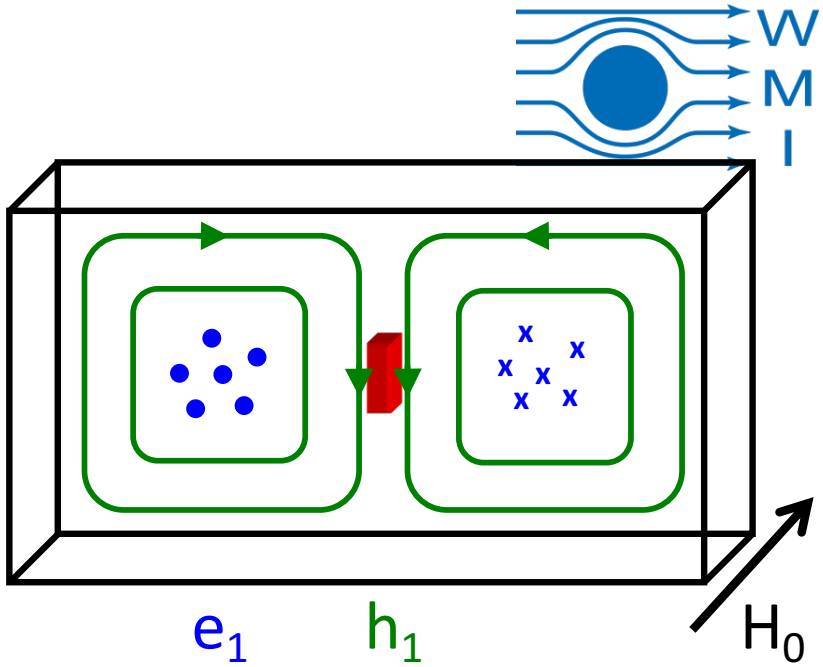




resonator-based CW FMR

$$\frac{\partial \mathbf{M}}{\partial t} = \gamma \mathbf{M} \times \mu_0 \left(\mathbf{H}_0 + \mathbf{h}_1 + \ldots \right)$$





resonator dimensions = $n\ \lambda_{MW} / 2$
resonator determines MW frequency
resonator quality Q > 1000

→ experiments @ fixed MW frequency
→ e_1 and h_1 spatially separated

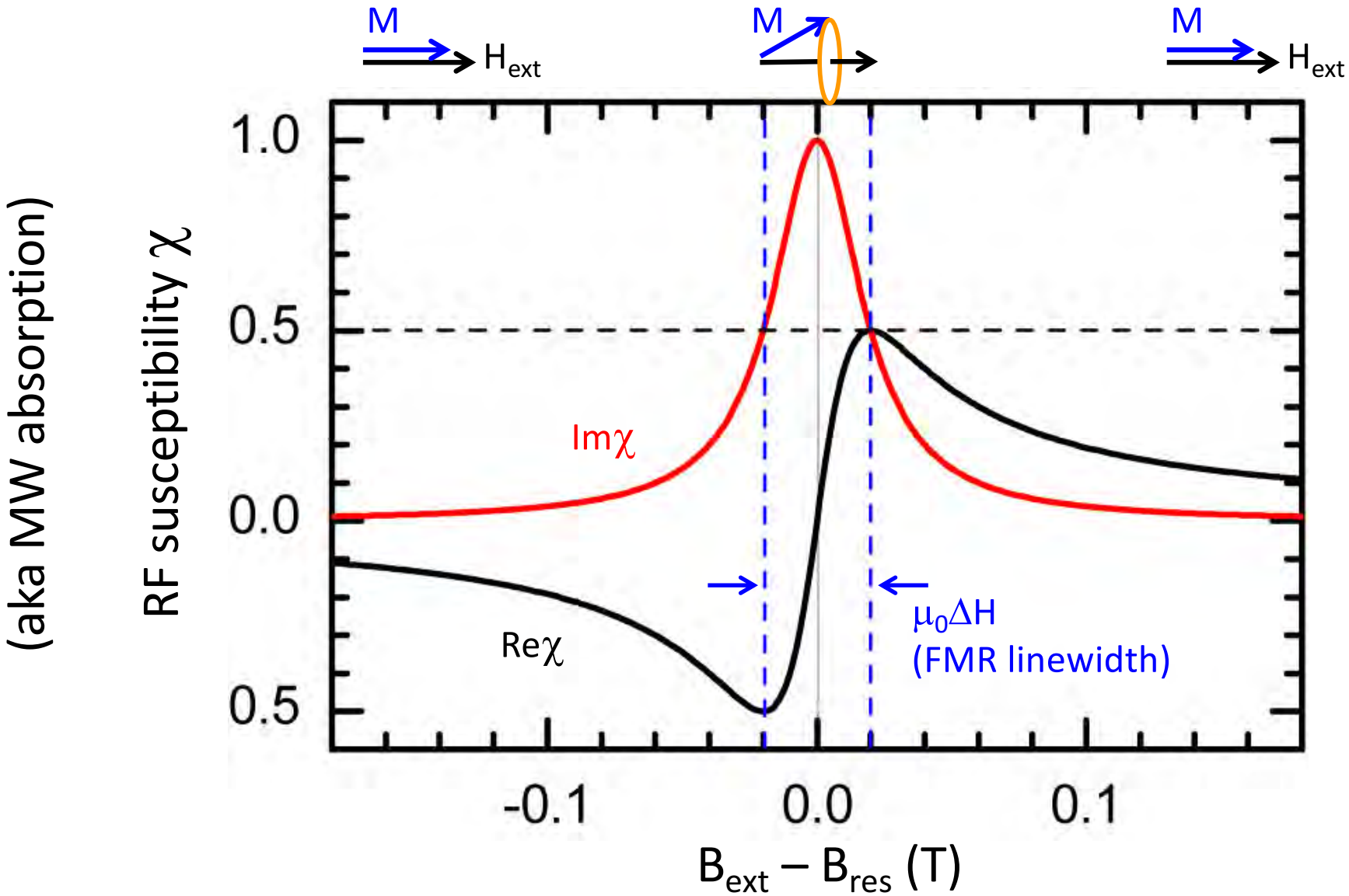
Bruker biospin

FMR signal

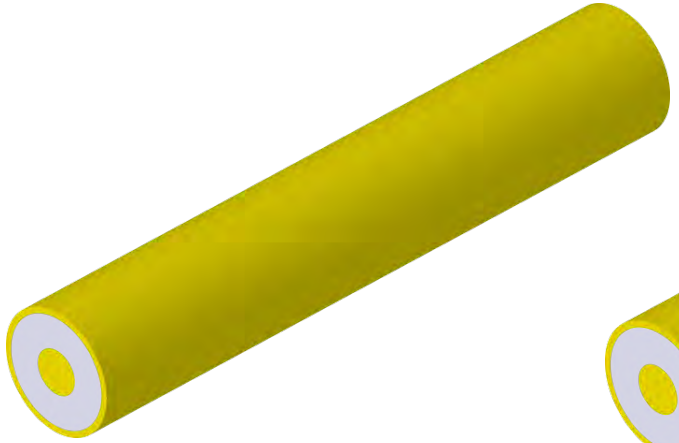
$$\frac{\partial \mathbf{M}}{\partial t} = \gamma \mathbf{M} \times \mu_0 \left(\mathbf{H}_{\text{ext}} + \mathbf{h}_1 + \ldots \right)$$

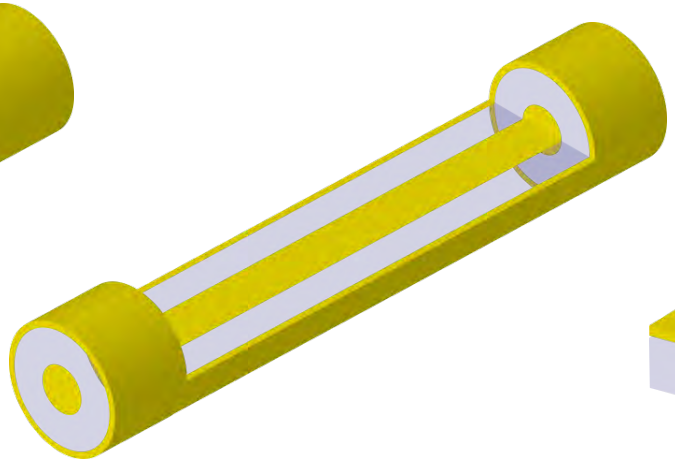
→ FMR resonance condition: $2\pi \nu_{MW} = \gamma B_{res}$

→ real and imaginary part of RF susceptibility

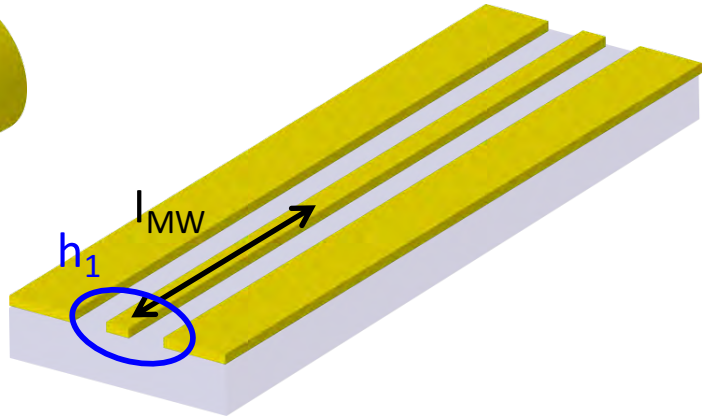


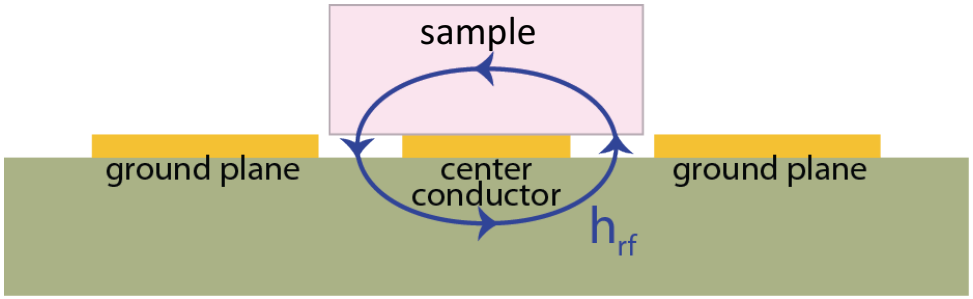
Broadband FMR

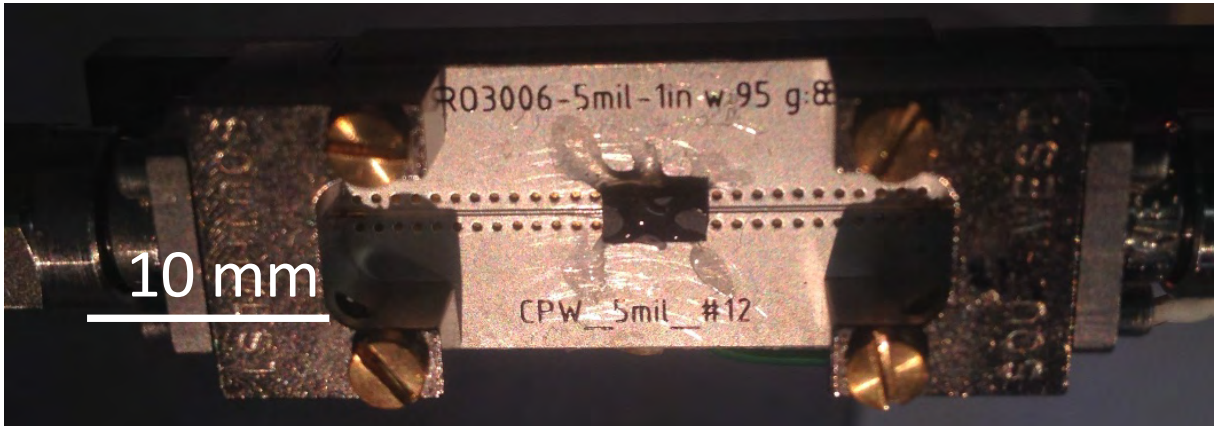


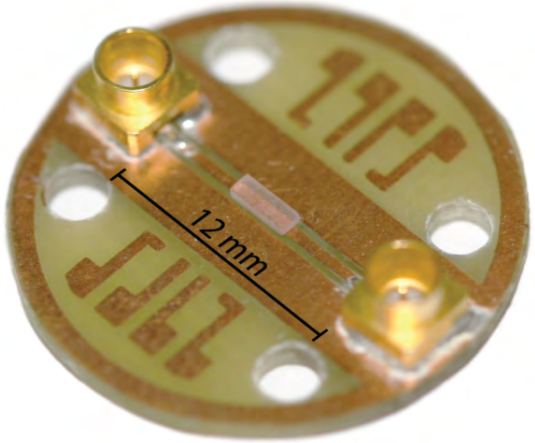


coplanar waveguide (CPW)



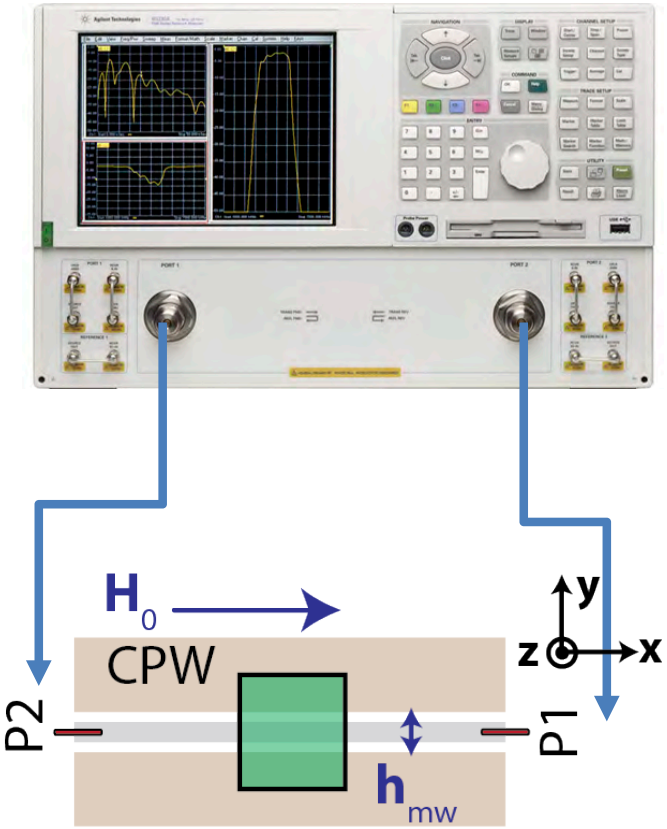




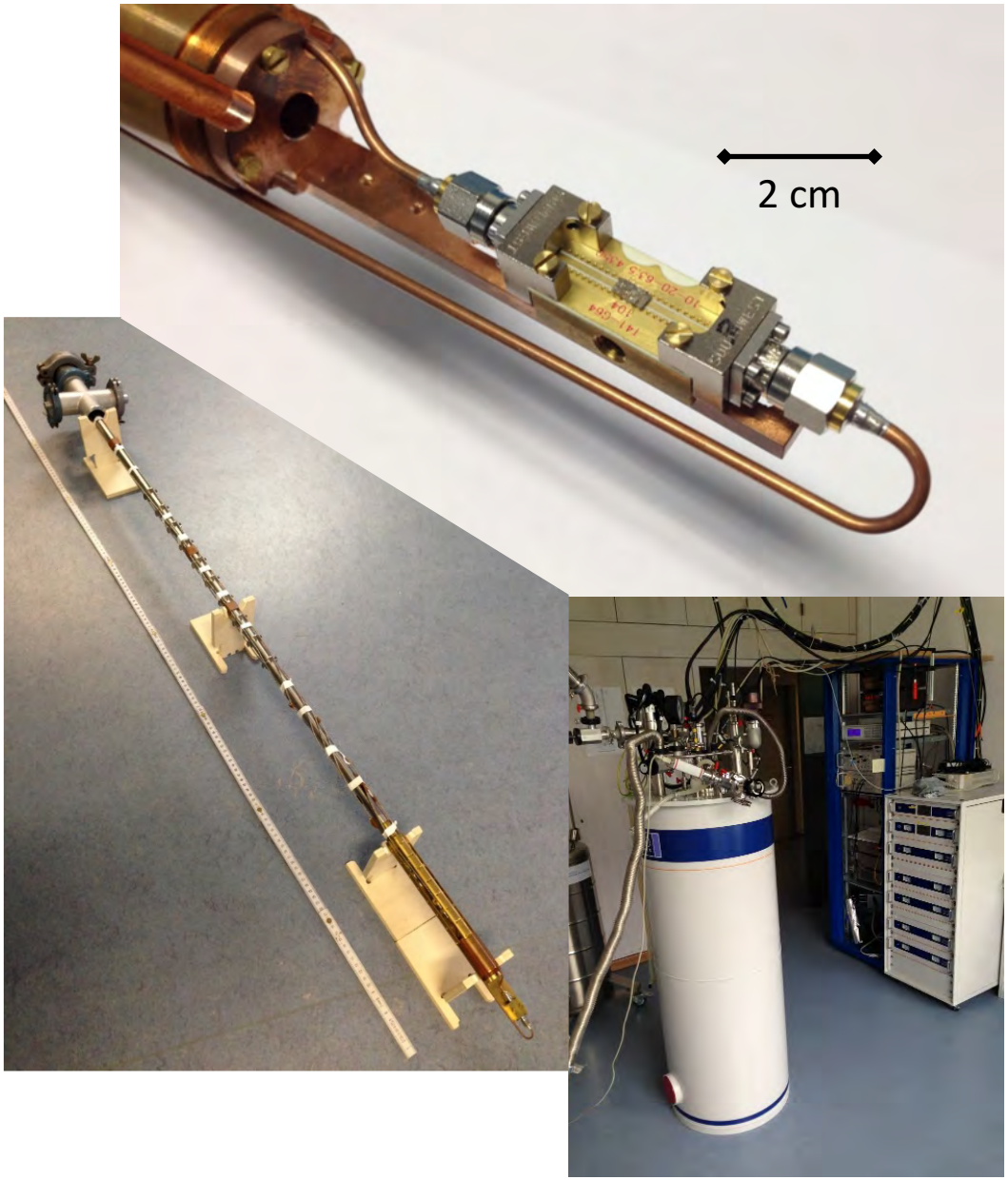


Broadband magnetic resonance setup

Vector Network Analyzer

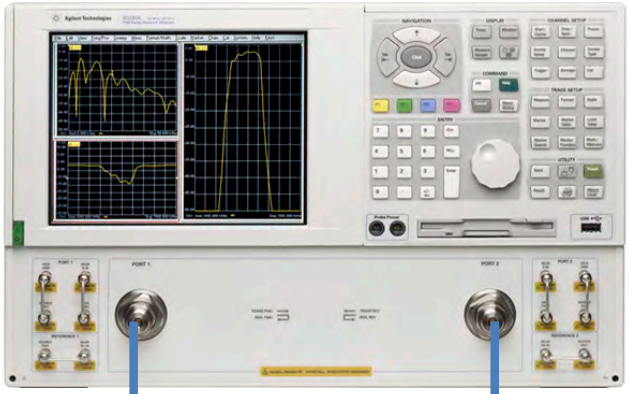


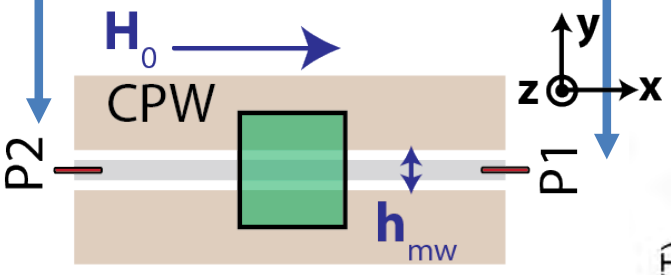
$$S_{21} = \frac{V_2}{V_1}$$

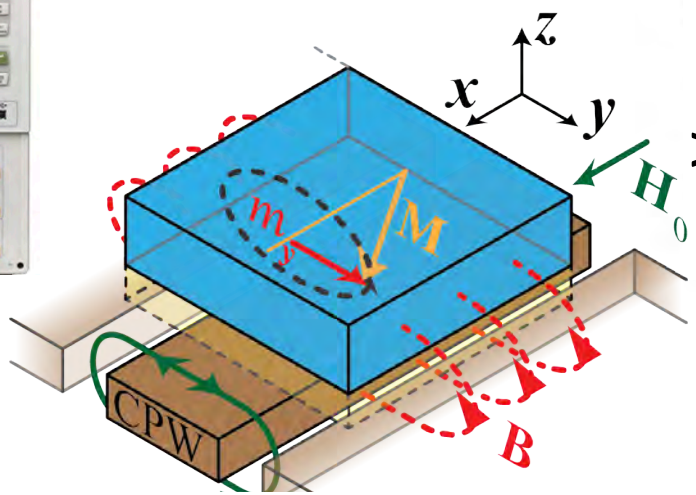


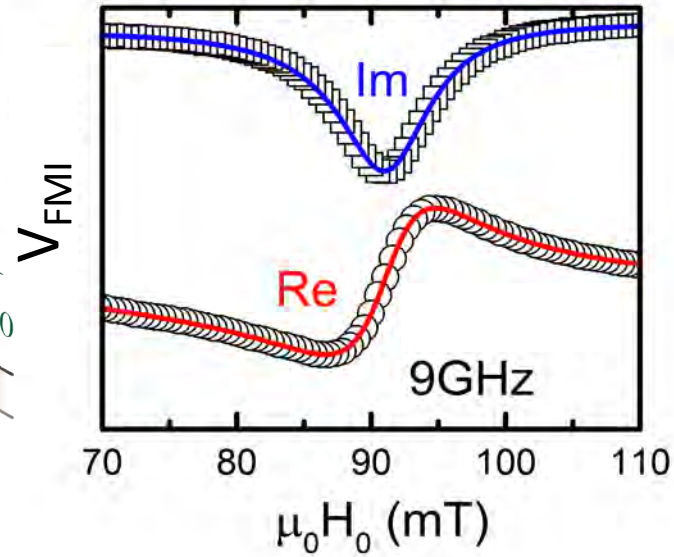
Spectra

Vector Network Analyzer







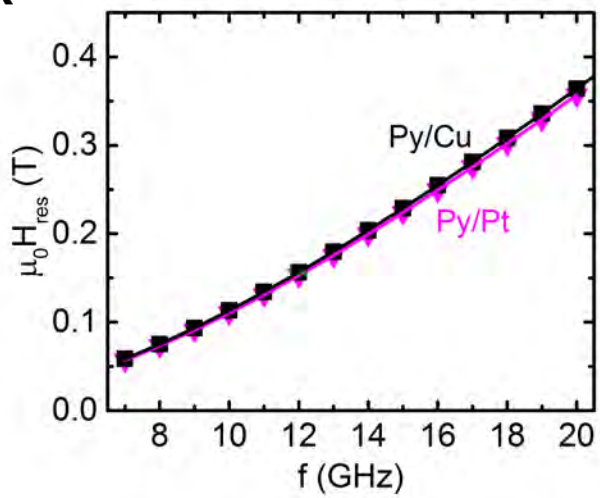


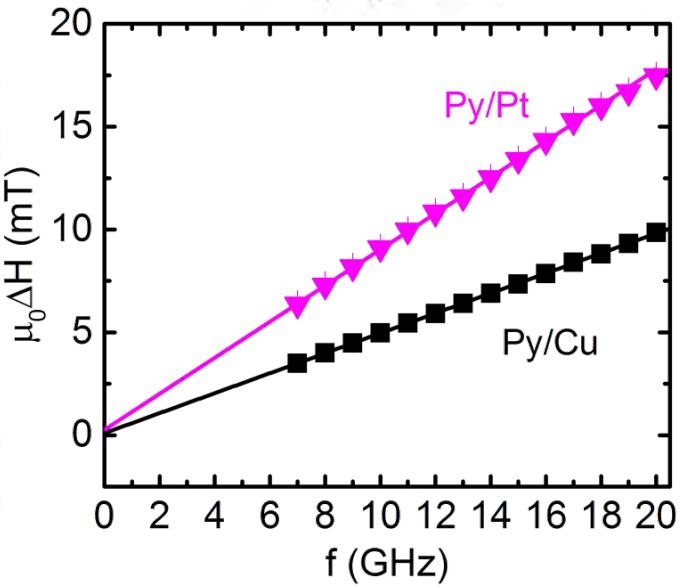
$$S_{21} = \frac{V_2}{V_1}$$

Quantitative analysis

→ mag. hf-susceptibility

$$S_{21} = S_{21}^0 \left[1 - i\,\omega\,\mu_0 \frac{1}{16 w Z_0}\,\delta\, l\, \chi_{xx} \right]$$

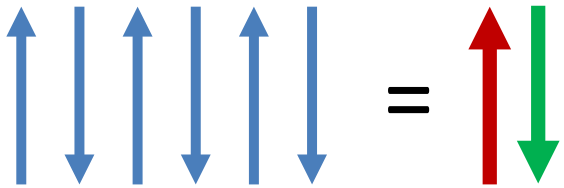




Shaw, Appl. Phys. Lett. **105**, 062406 (2014)

Antiferromagnets

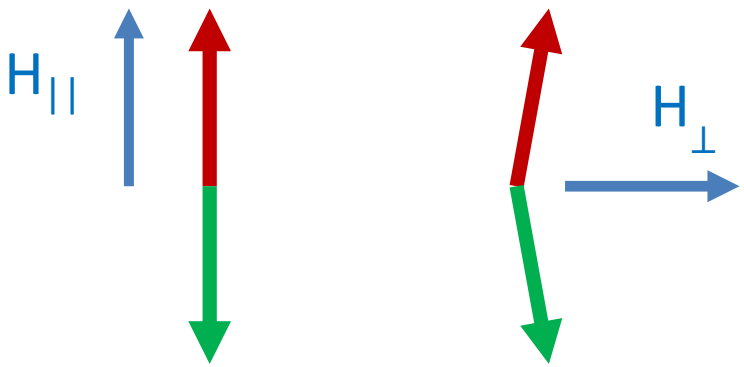
antiferromagnet

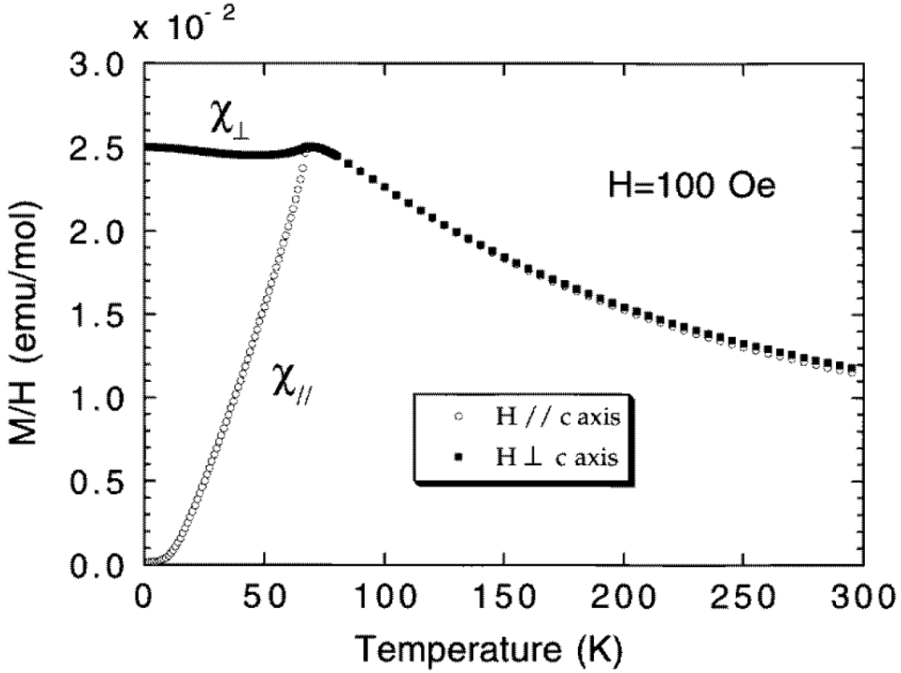


two compensating sublattices

common antiferromagnets:

- Cr
- NiO
- Fe_2O_3
- MnF_2

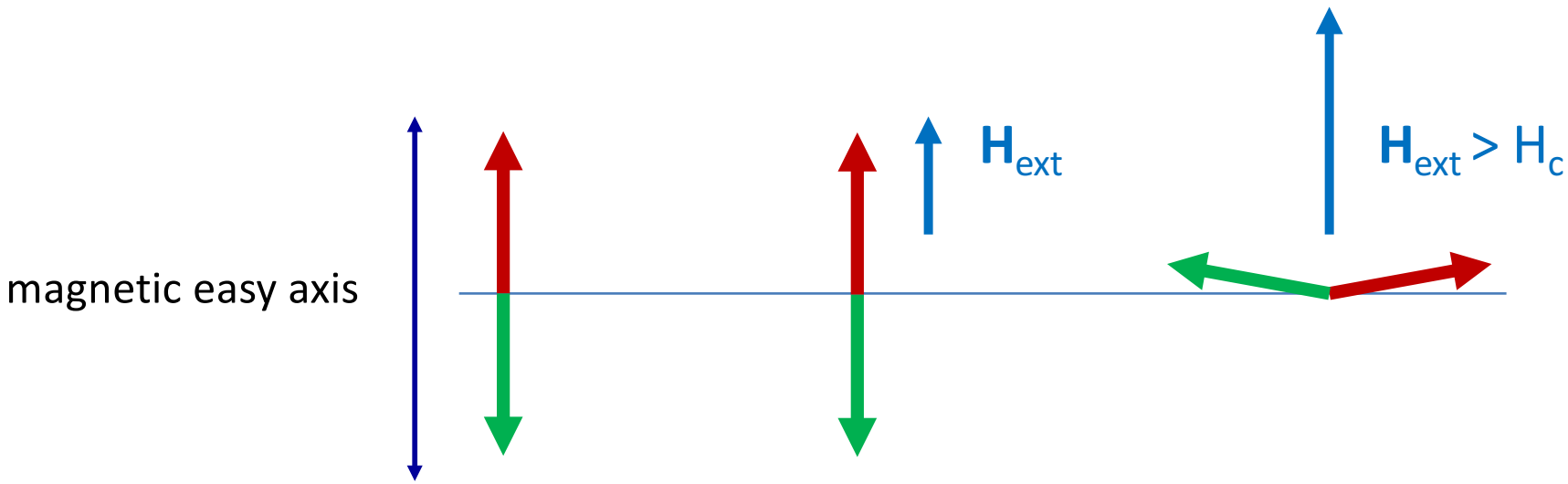




antiferromagnetic below T_N ,
Néel Temperature

Hagiwara et. al., J. Phys.: Condens. Matter **8** (1996) 7349–7354

The Spin Flop Transition

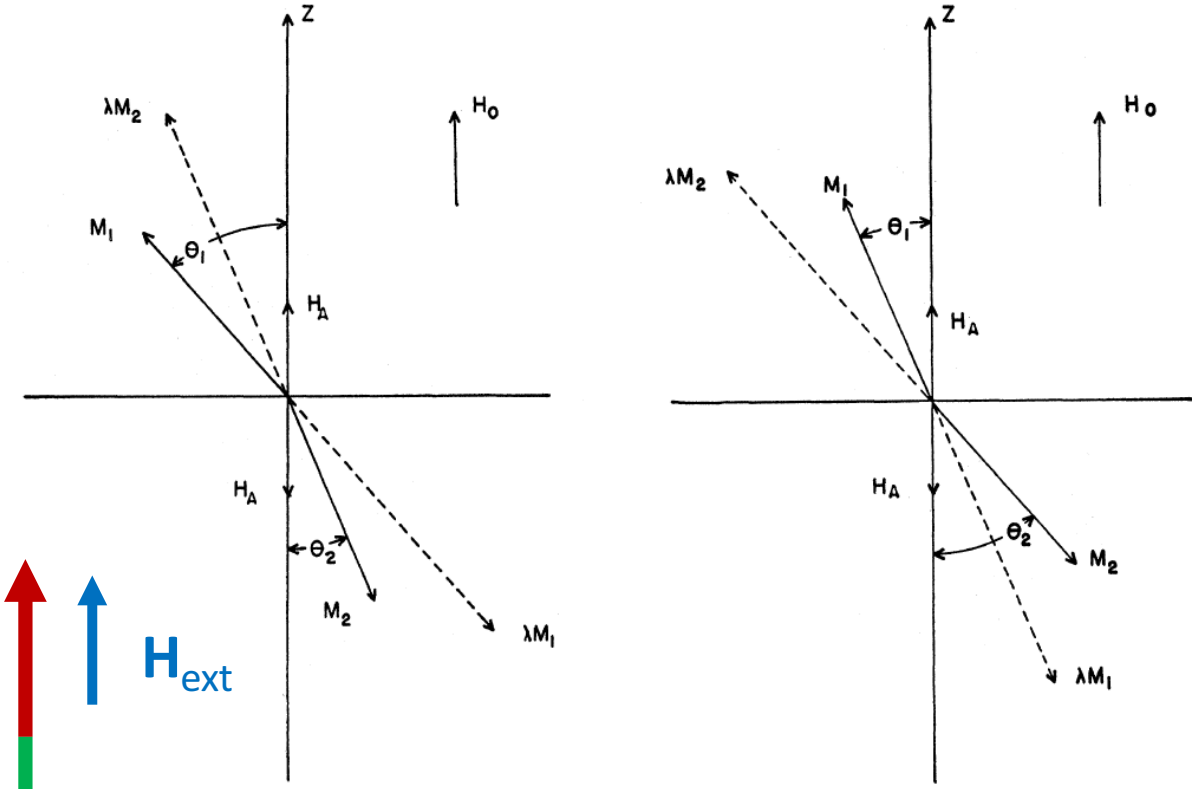


$$H_C = (H_A^2 + 2H_A H_E)^{1/2}$$

gain in Zeeman energy > loss in anisotropy energy

Antiferromagnetic Resonance

two sublattices
$\Rightarrow$ two resonance frequencies

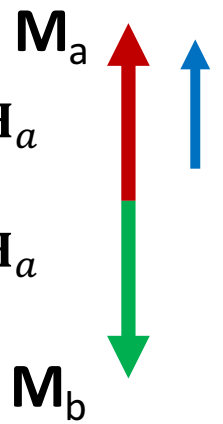


Keffer and Kittel, Physical Review **85**, 329 (1952)

effective field:

$$\mathbf{H}_{eff,a} = \lambda \mathbf{M}_b + \mathbf{H}_{ext} + \mathbf{H}_a$$

$$\mathbf{H}_{eff,b} = \lambda \mathbf{M}_a + \mathbf{H}_{ext} + \mathbf{H}_a$$



very high effective fields, $\lambda M > 100$ T possible $\Rightarrow$ high frequencies

simultaneous precession of magnetisation of both sublattices

MnF_2: A prototypical antiferromagnet

Only easy axis anisotropy

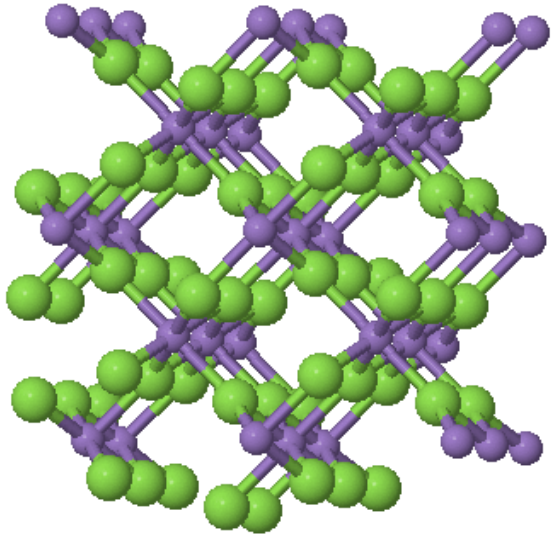
$B_{anisoptropy}$ = 0.8 T

$B_{exchange}$= 52 T

T_N= 67 K

Mn^{2+}

F^-



http://wwwchem.uwimona.edu.jm:1104/courses/mnf2J.html

mini SMP connector

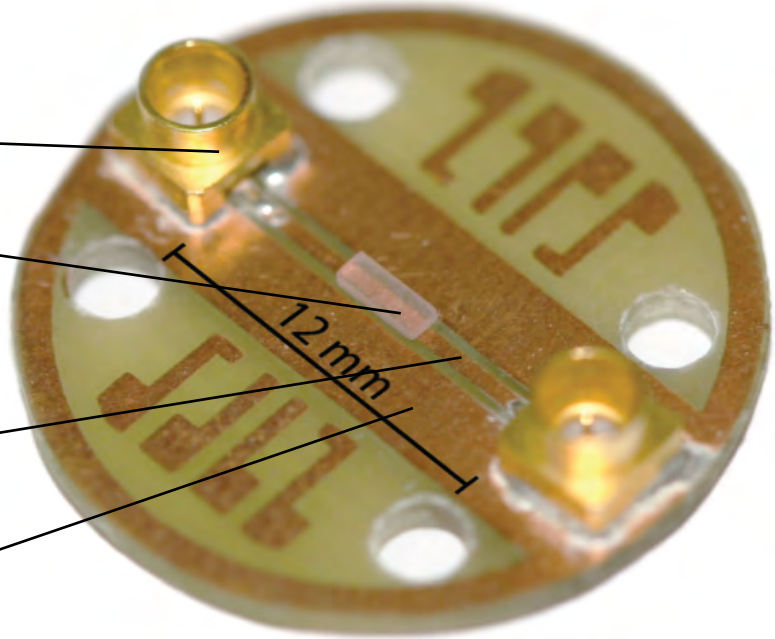
MnF_2 crystal

coplanar waveguide:

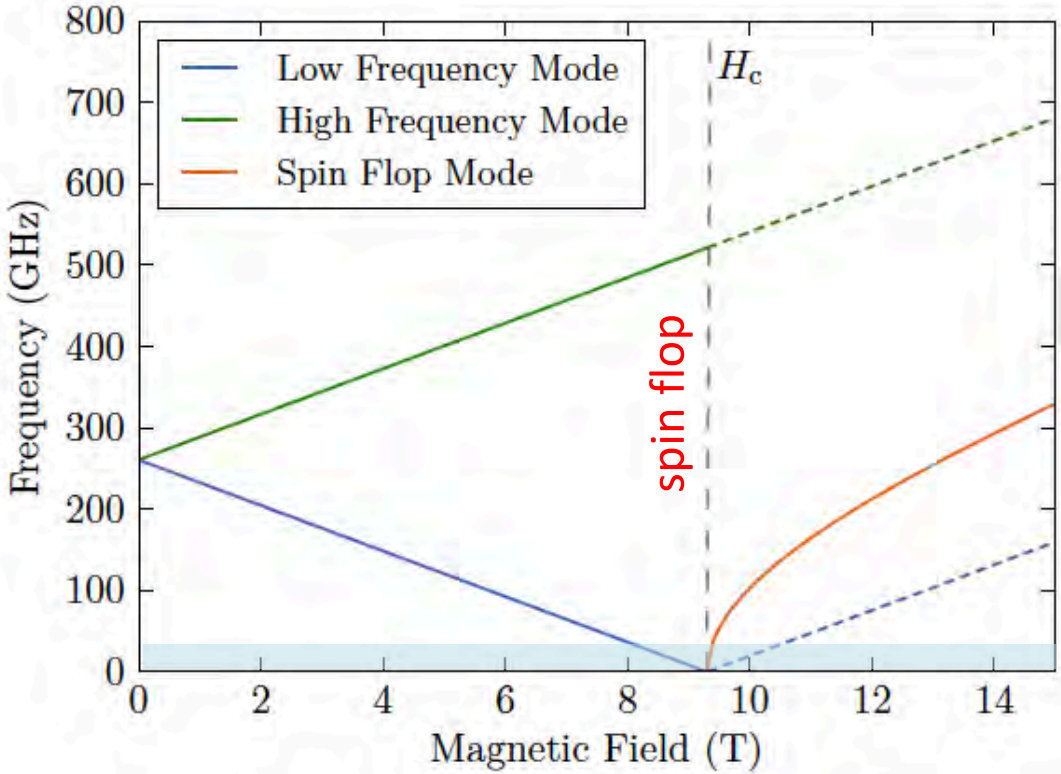
center line

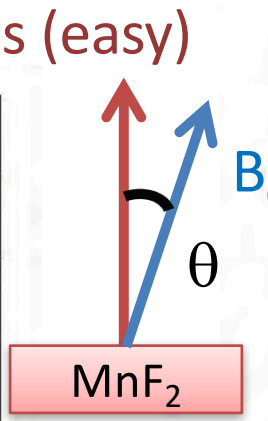
and

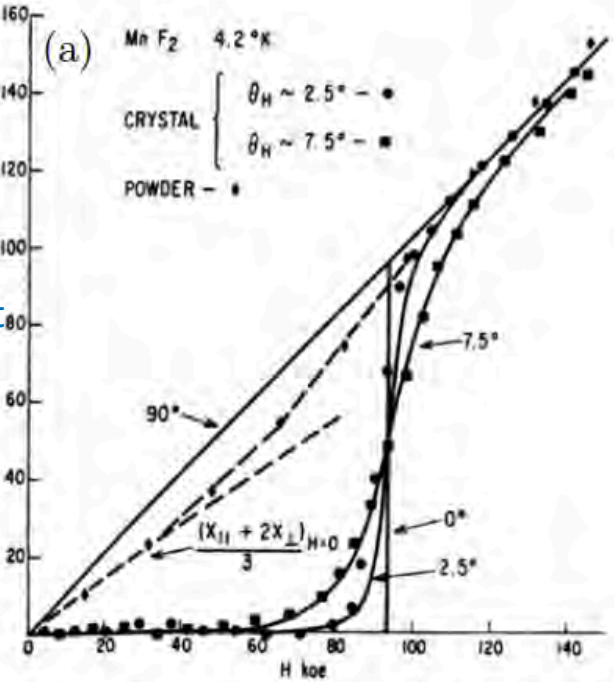
ground plane



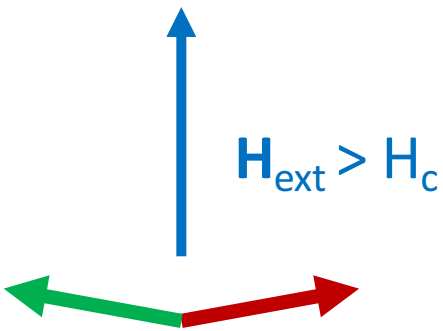
Simulated Resonance Frequency

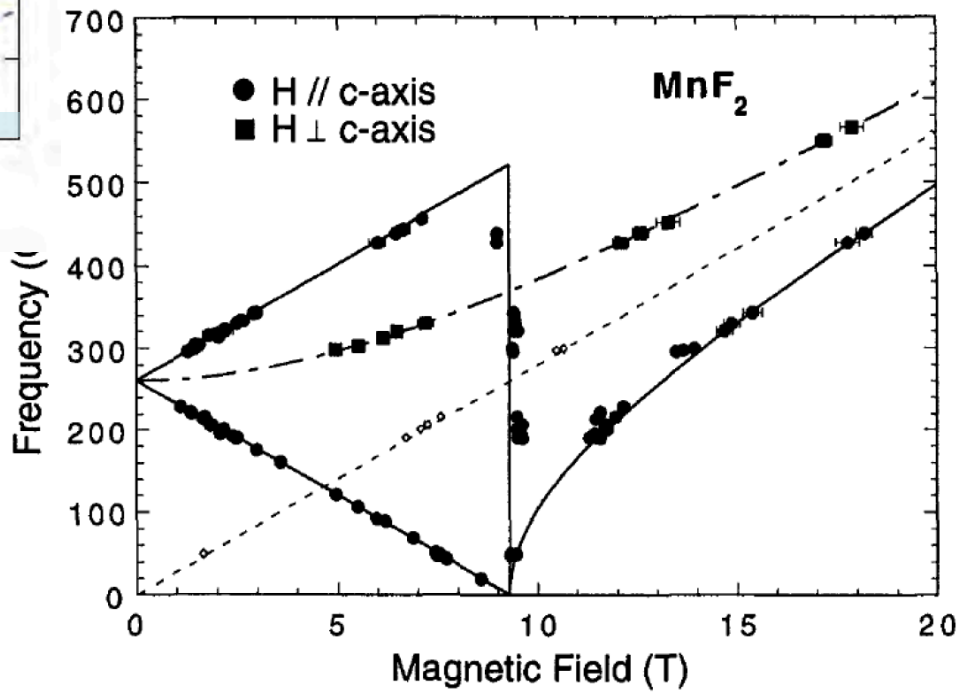






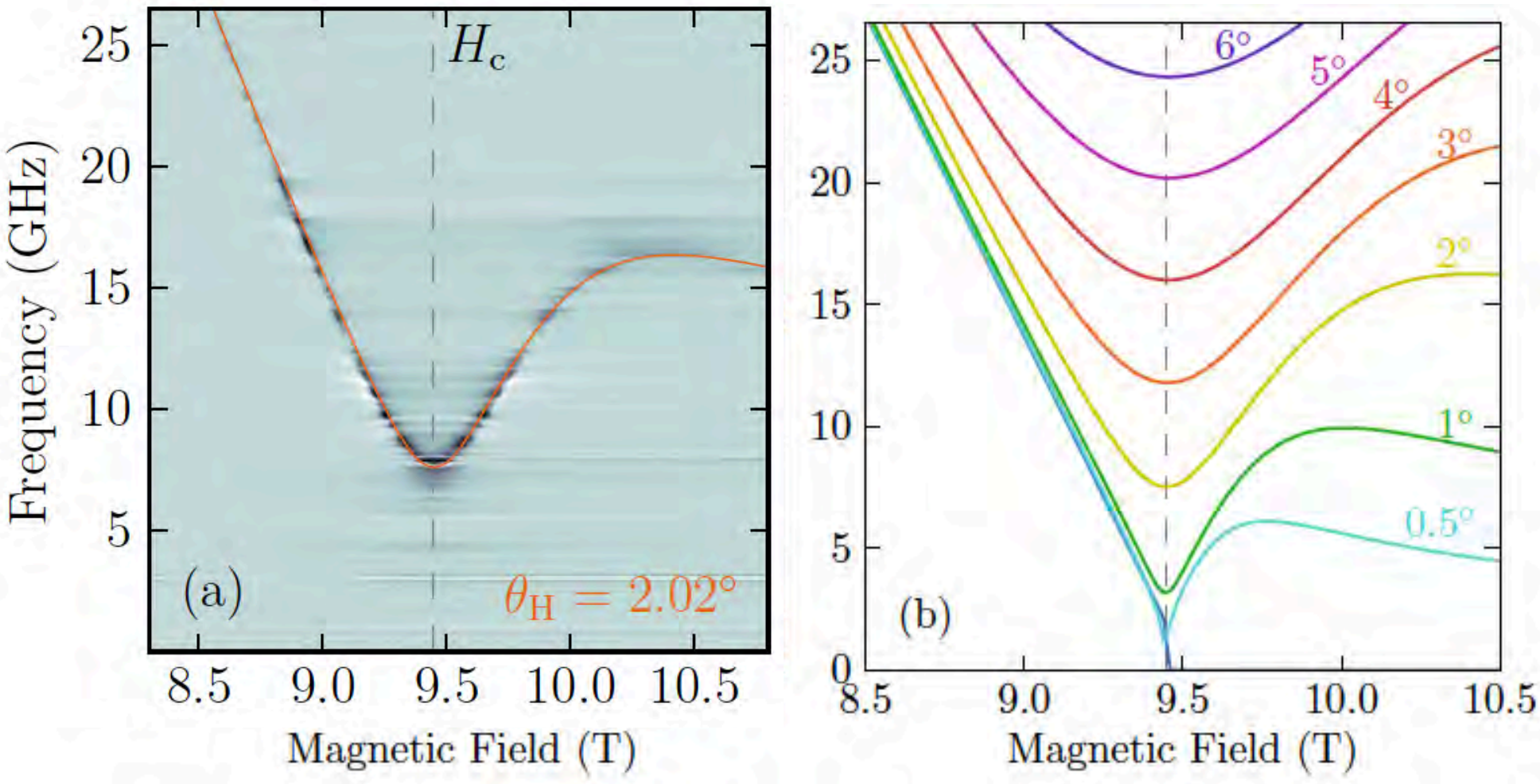
I. S. Jacobs, J. Appl. Phys. **32**, S61 (1961).





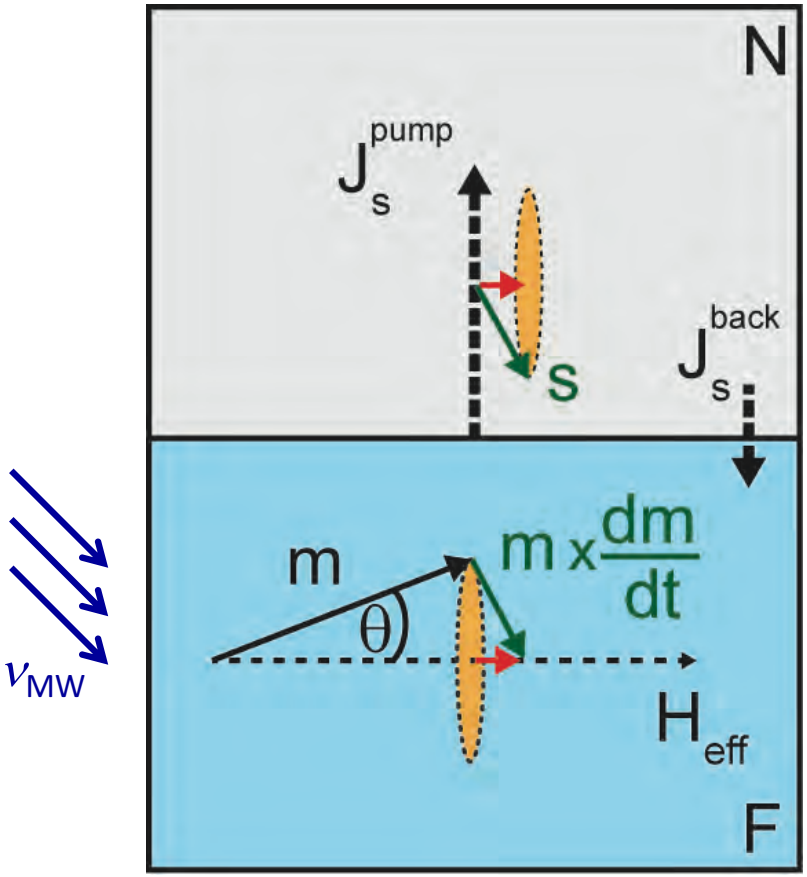
Hagiwara et. al., J. Phys.: Condens. Matter **8** (1996) 7349–7354

Antiferromagnetic resonance MnF_2



F/N + microwave photons = spin battery

suggested by Tserkovnyak, Brataas & Bauer, PRL (2002)



resonantly driven magnetization in F relaxes via the **emission of a spin current** into the adjacent N layer

spin pumping

$$\mathbf{J}_S = \frac{\mathbf{I}_S}{A} = \frac{\hbar}{4\pi} G_r \left(\mathbf{m} \times \frac{d\mathbf{m}}{dt} \right)$$

G_r: spin mixing conductance, units $1/m^2$

in F:
additional damping

$$\alpha_{SP} = G_r \frac{\gamma \hbar}{4\pi M_{sat}} \frac{1}{t_F} \eta$$

in N:
DC spin current

$$J_S^{circ} = \frac{\hbar}{2} \nu_{MW} G_r \sin^2 \Theta$$

and
AC spin current ... see D. Wei et al., Nature Comm. **5**, 1 (2014)

Tserkovnyak, Phys. Rev. Lett. **88**, 117601 (2002).
Brataas, Phys. Rev. B **66**, 060404 (2002).
Tserkovnyak, Phys. Rev. B **66**, 224403 (2002).

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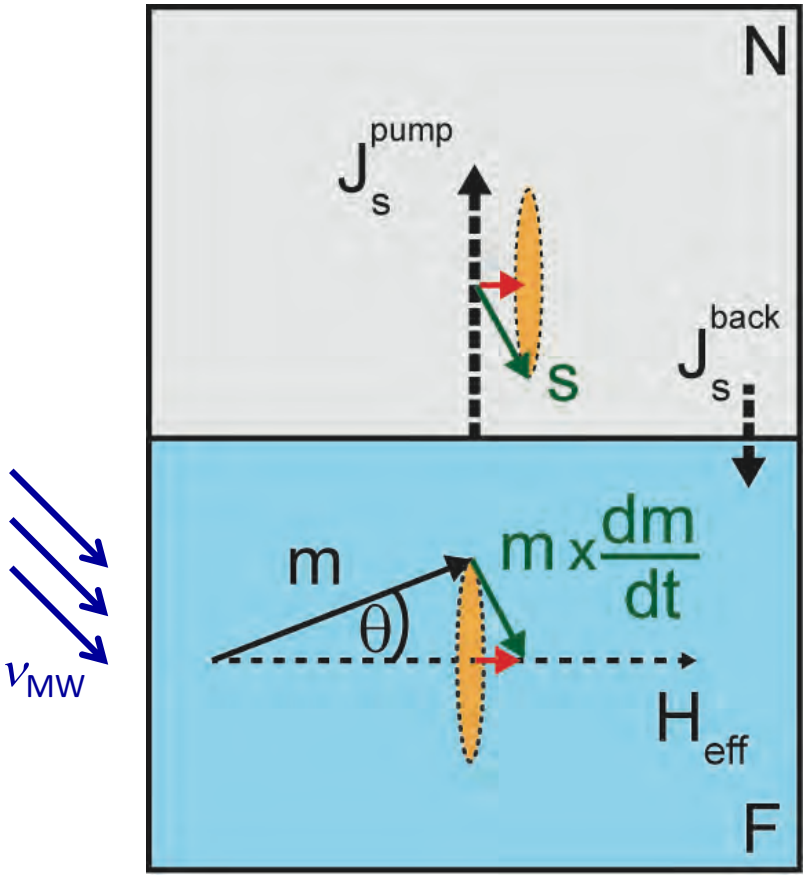

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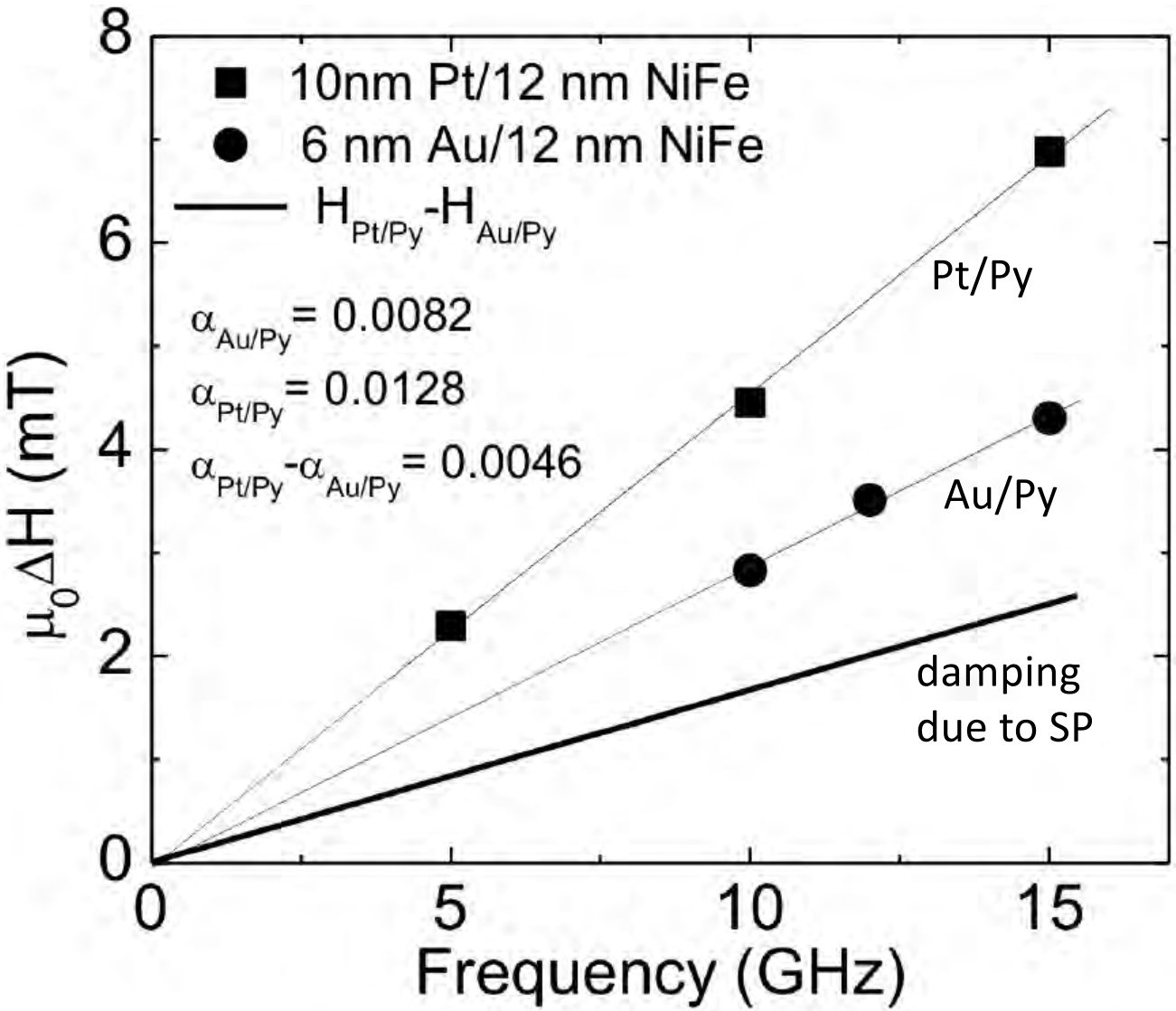
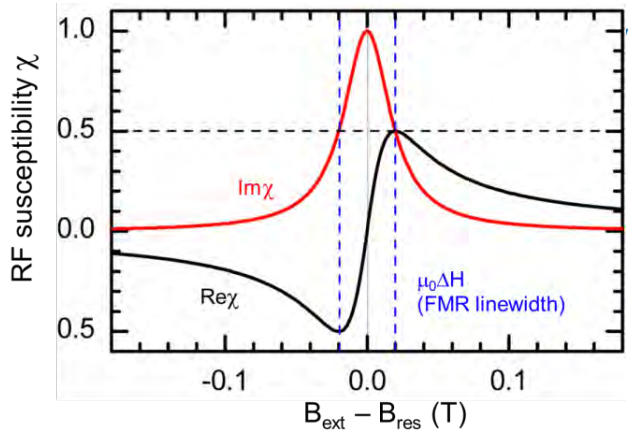
Tserkovnyak, Phys. Rev. B **66**, 224403 (2002).

Spin pumping as a damping mechanism

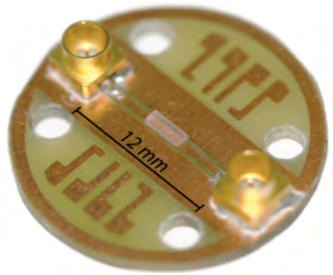




$$\alpha_{SP} = \alpha_{Pt/Py} - \alpha_{Au/Py}$$

$$= G_r \frac{1}{t_{Py}} \frac{\gamma \hbar \eta}{4\pi M_{sat,Py}}$$

$$G_r = 2.5 \times 10^{19}\ \mathrm{m}^{-2}$$



M. Wu & A. Hoffmann (eds.), *Recent Advances in Magnetic Insulators - From Spintronics to Microwave Applications* (Elsevier, 2014)

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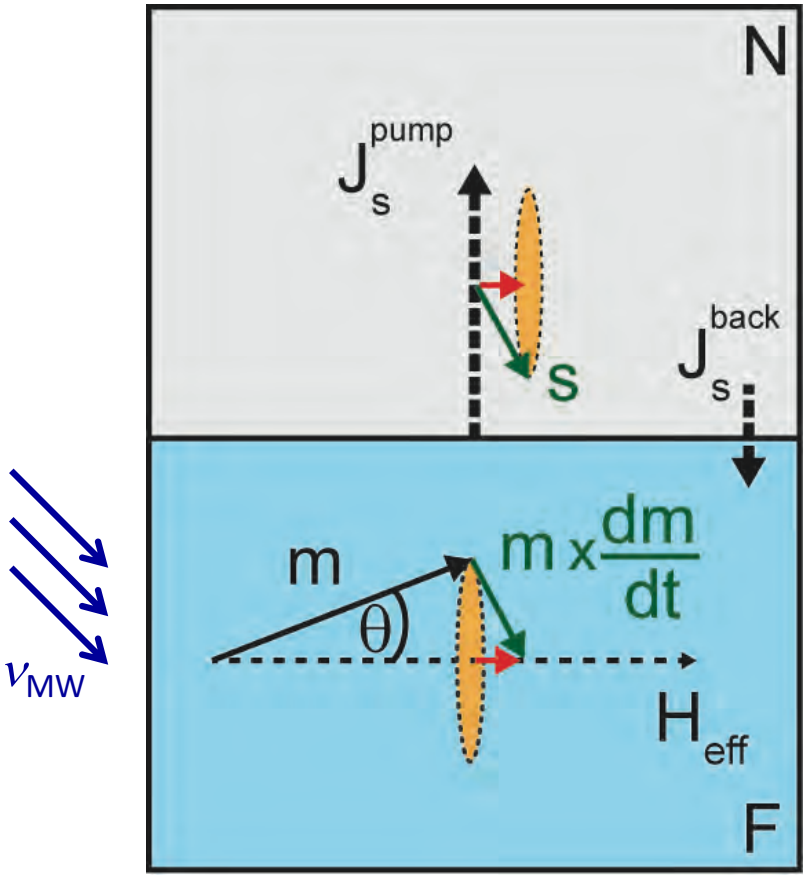

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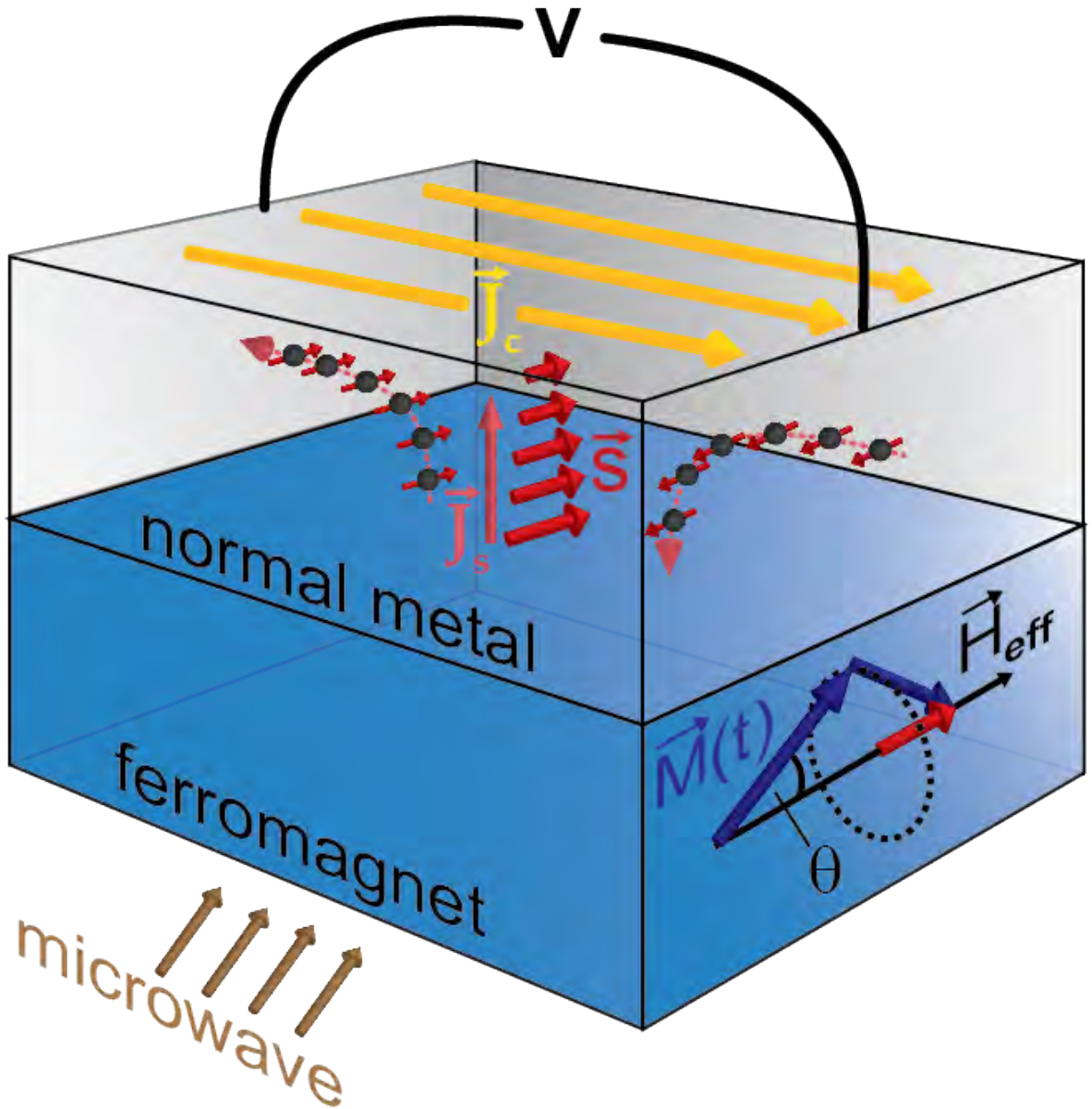
Tserkovnyak, Phys. Rev. Lett. **88**, 117601 (2002).
Brataas, Phys. Rev. B **66**, 060404 (2002).
Tserkovnyak, Phys. Rev. B **66**, 224403 (2002).

Spin pumping with spin current detection



microwave + DC magnetic field

↓ FMR

magnetization precession

↓ spin pumping

DC spin current

$$J_S = \frac{\hbar}{2}\nu_{MW}\,\mathrm{Re}\left(g^{\uparrow\downarrow}\right)\sin^2\Theta$$

↓ inverse spin Hall effect

DC charge current J_c

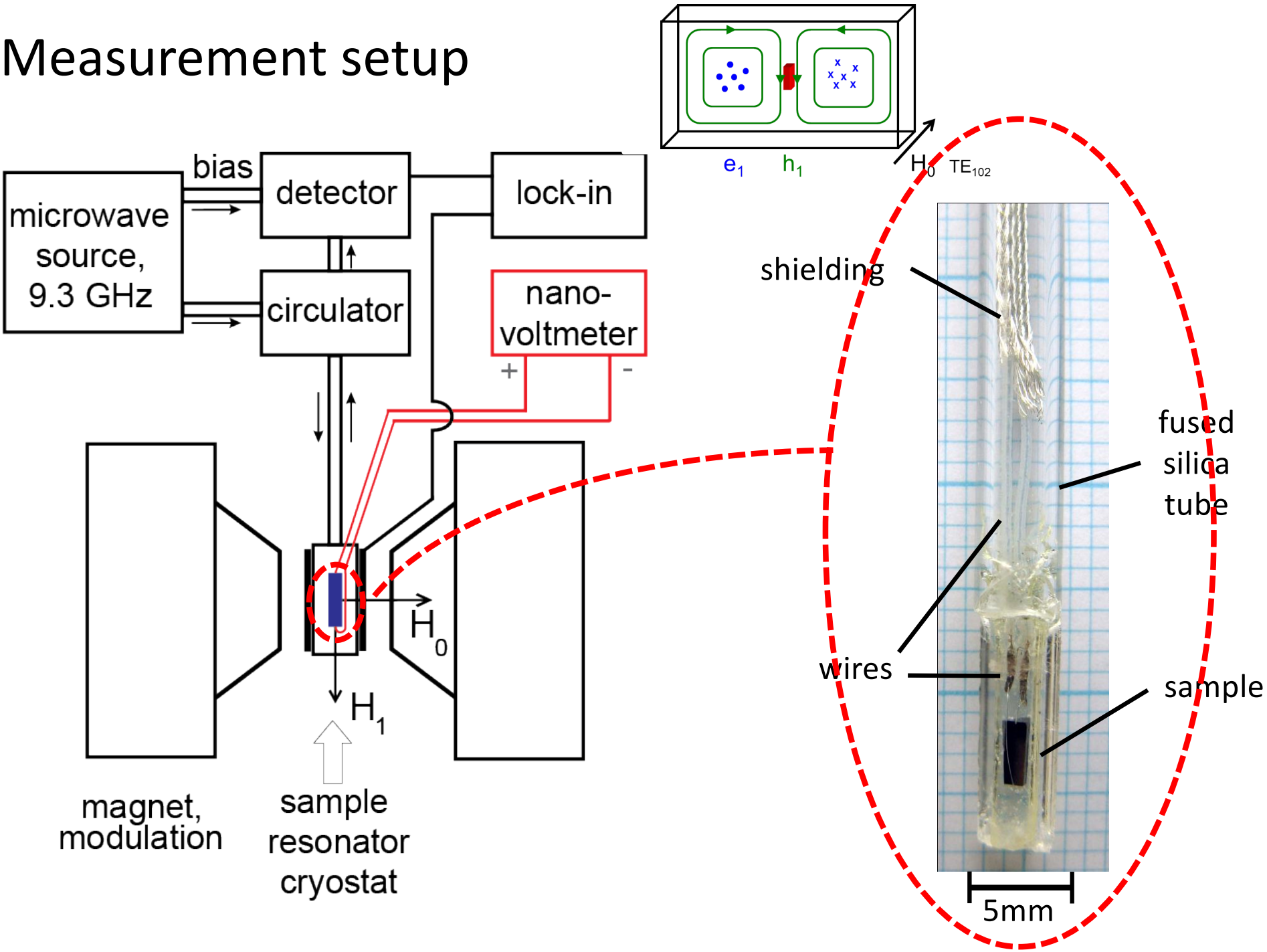
$$\vec{J}_C^{ISHE} = \alpha_{SH}\left(2e/\hbar\right)\left[\vec{J}_S \times \hat{s}\right]$$

↓ open circuit

DC voltage drop V

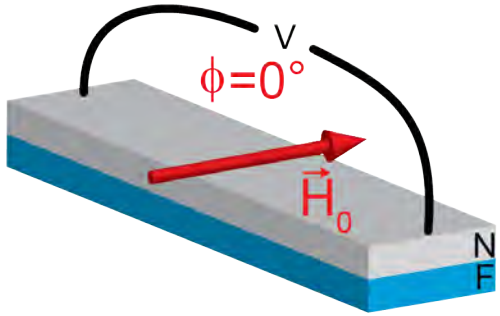
Tserkovnyak *et al.*, Phys. Rev. Lett. **88**, 117601 (2002). Saitoh *et al.*, Appl. Phys. Lett. **88**, 182509 (2006)

Measurement setup

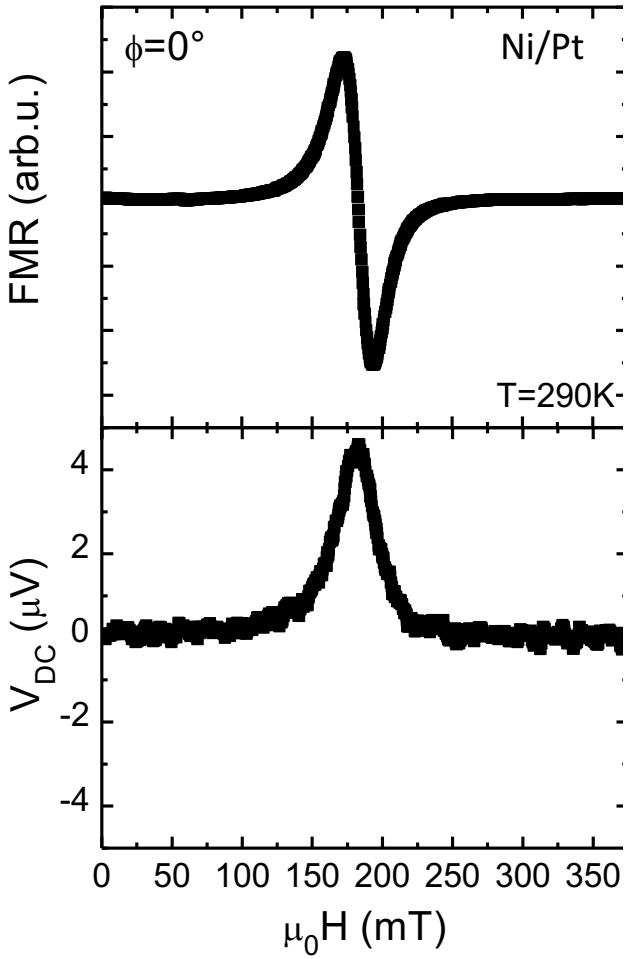


Typical sample dimensions L × W × t = 3mm × 1mm × (10nm/10nm)

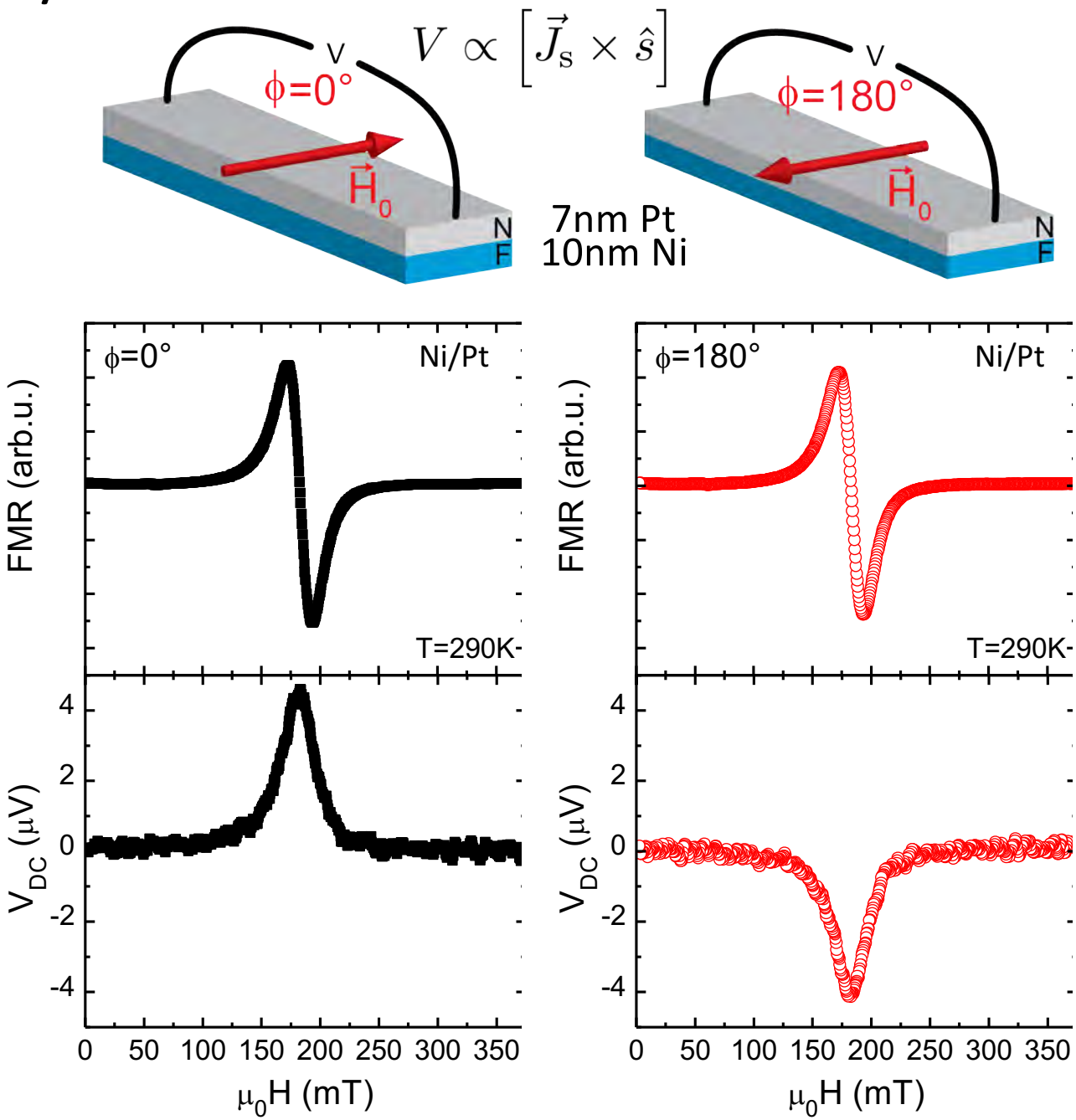
Ni/Pt



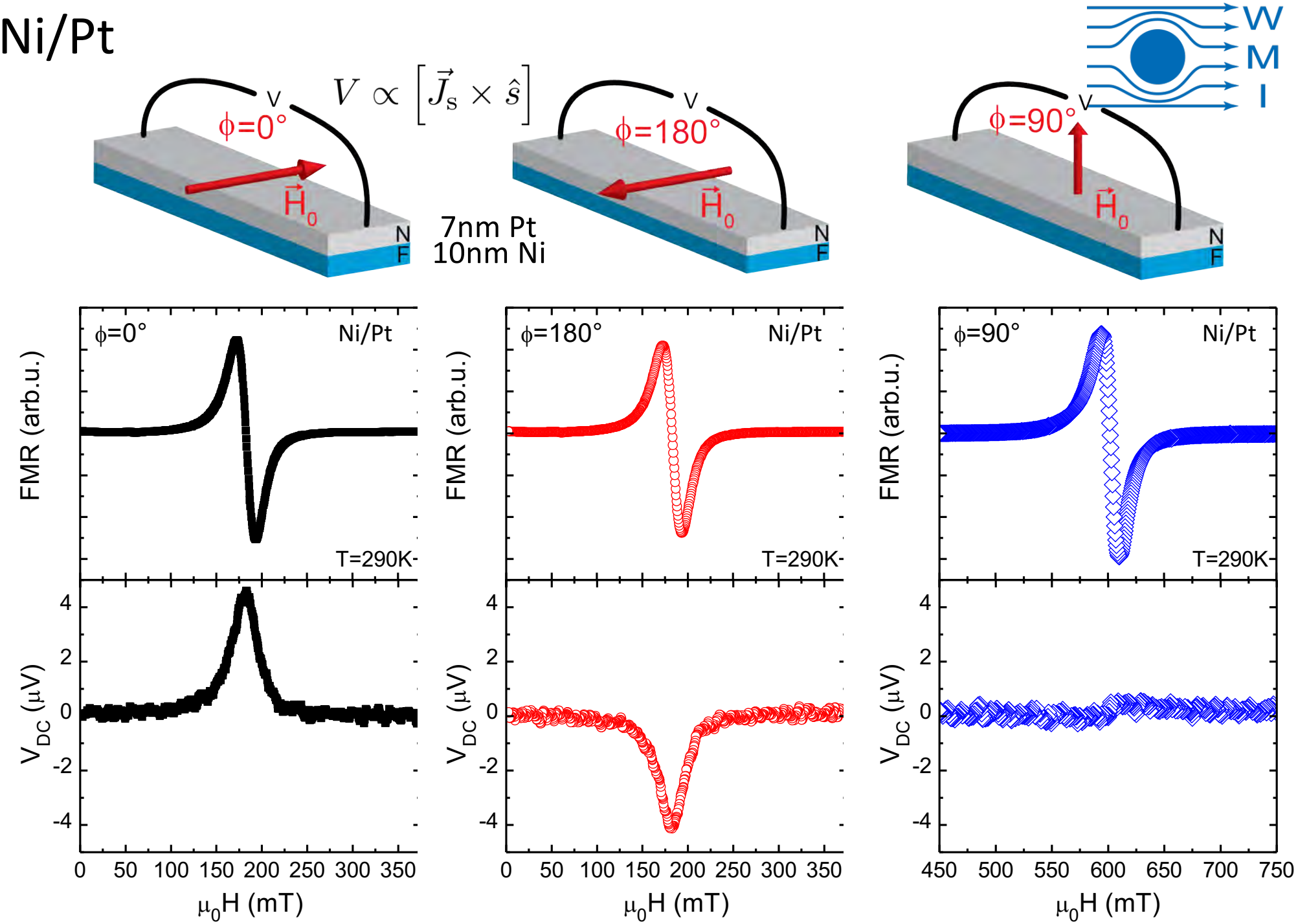
7nm Pt
10nm Ni



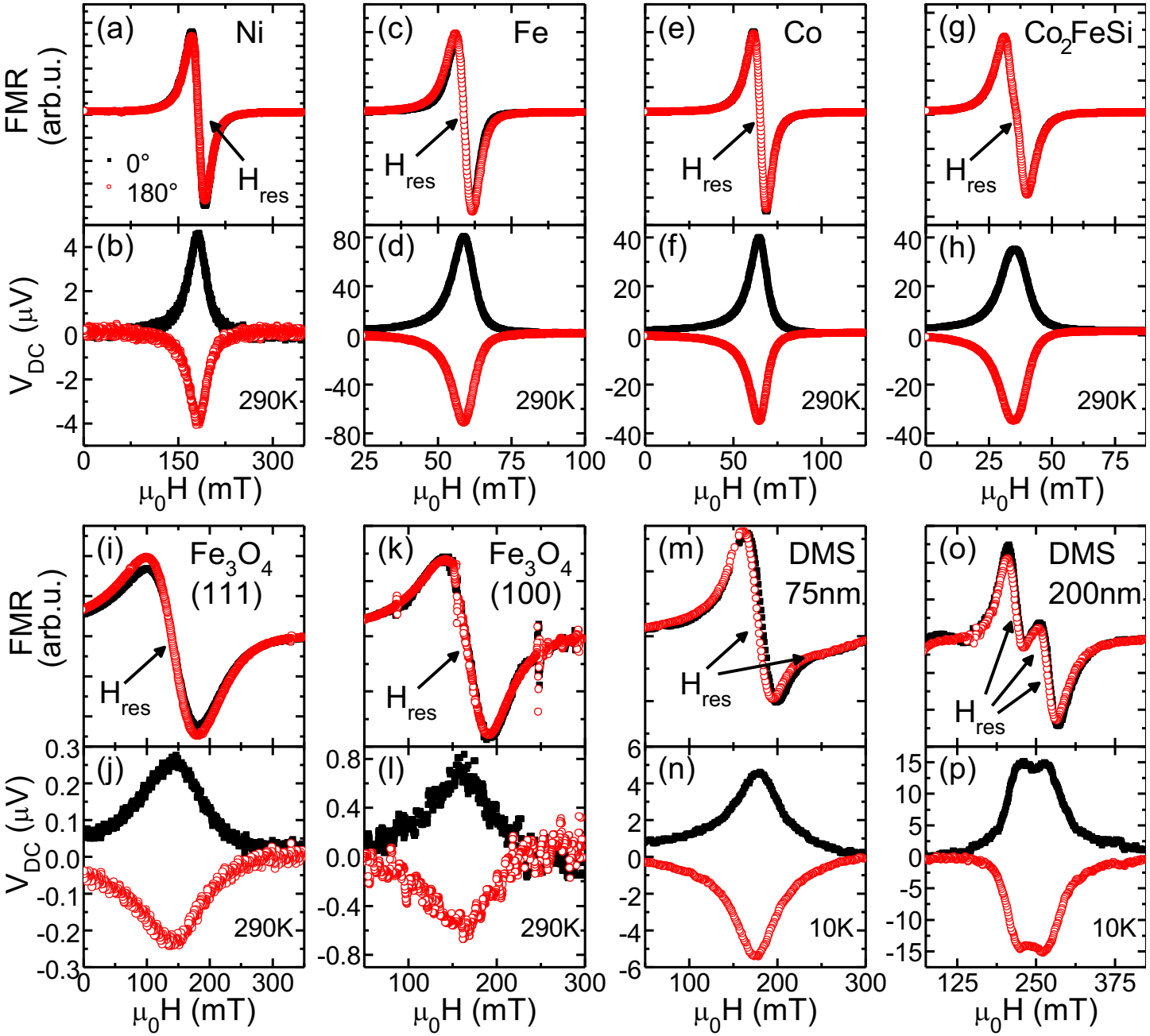
Ni/Pt

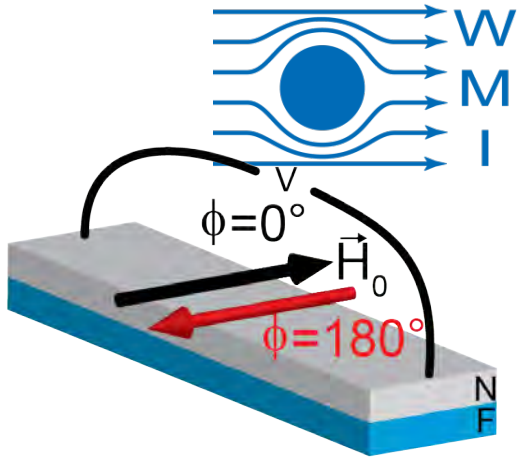

$V \propto \left[\vec{J}_s \times \hat{s}\right]$
V
ϕ=0°
$\vec{H}_0$
N
F
7nm Pt
10nm Ni
V
ϕ=180°
$\vec{H}_0$
N
F
ϕ=0°
Ni/Pt
T=290K
FMR (arb.u.)
ϕ=180°
Ni/Pt
T=290K
FMR (arb.u.)
V_{DC} (μV)
4
2
0
-2
-4
0 50 100 150 200 250 300 350
μ_0H (mT)
V_{DC} (μV)
4
2
0
-2
-4
0 50 100 150 200 250 300 350
μ_0H (mT)

Ni/Pt


$V \propto \left[\vec{J}_s \times \hat{s}\right]$
V
ϕ=0°
$\vec{H}_0$
N
F
7nm Pt
10nm Ni
V
ϕ=180°
$\vec{H}_0$
N
F
V
ϕ=90°
$\vec{H}_0$
N
F
W
M
I
ϕ=0°
Ni/Pt
T=290K
ϕ=180°
Ni/Pt
T=290K
ϕ=90°
Ni/Pt
T=290K
FMR (arb.u.)
V_{DC} (μV)
4
2
0
-2
-4
0 50 100 150 200 250 300 350
450 500 550 600 650 700 750
μ_0H (mT)

Different materials

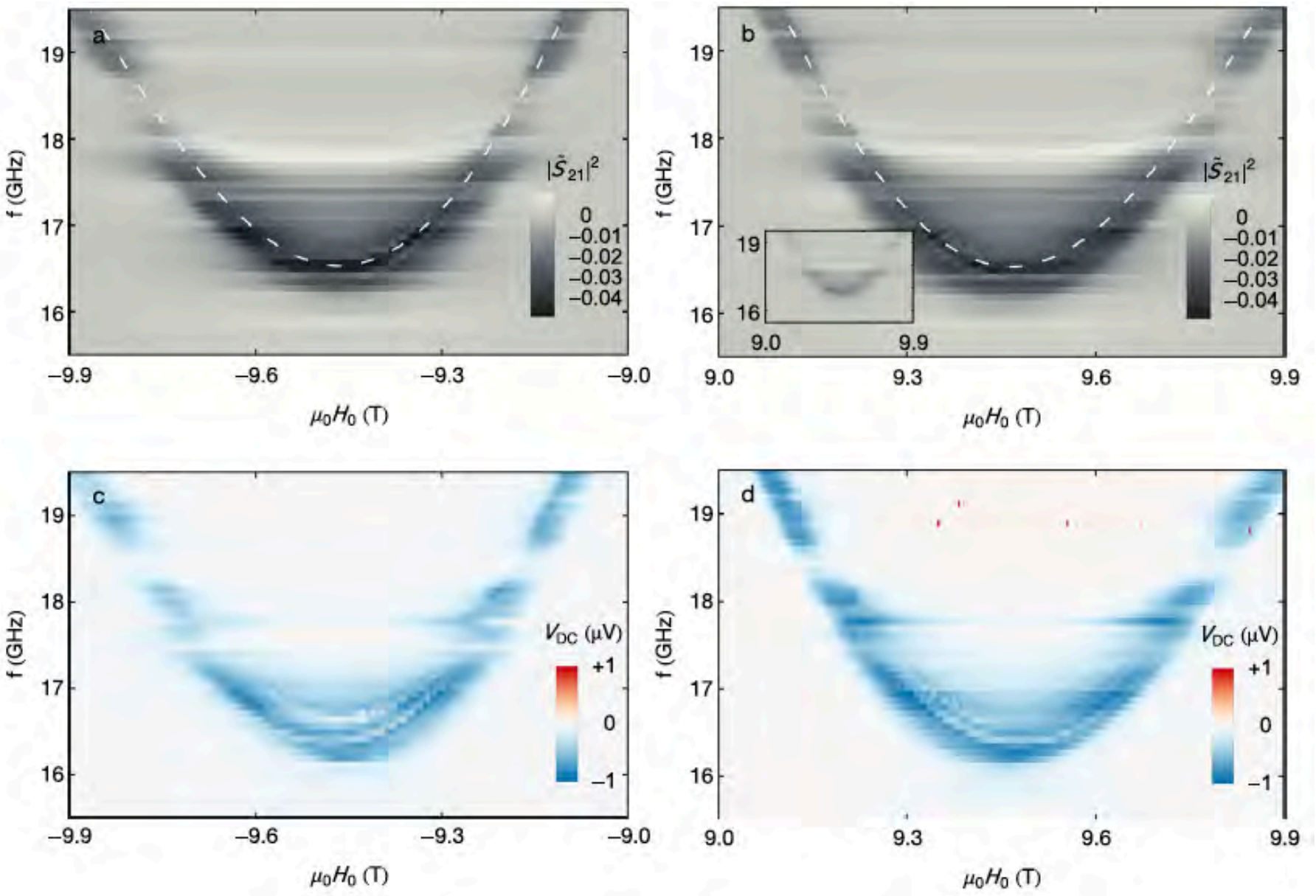




- works for many different F/platinum bilayers
- same sign of V_{DC} for $\phi=0°$ for all bilayers
- not MW rectification [MW-induced $J_c(t) \times m(t) \rightarrow V_{DC}$] but **spin pumping**!
- Similar spin-mixing conductance for all systems

Czeschka, Phys. Rev. Lett **107**, 046601 (2011)

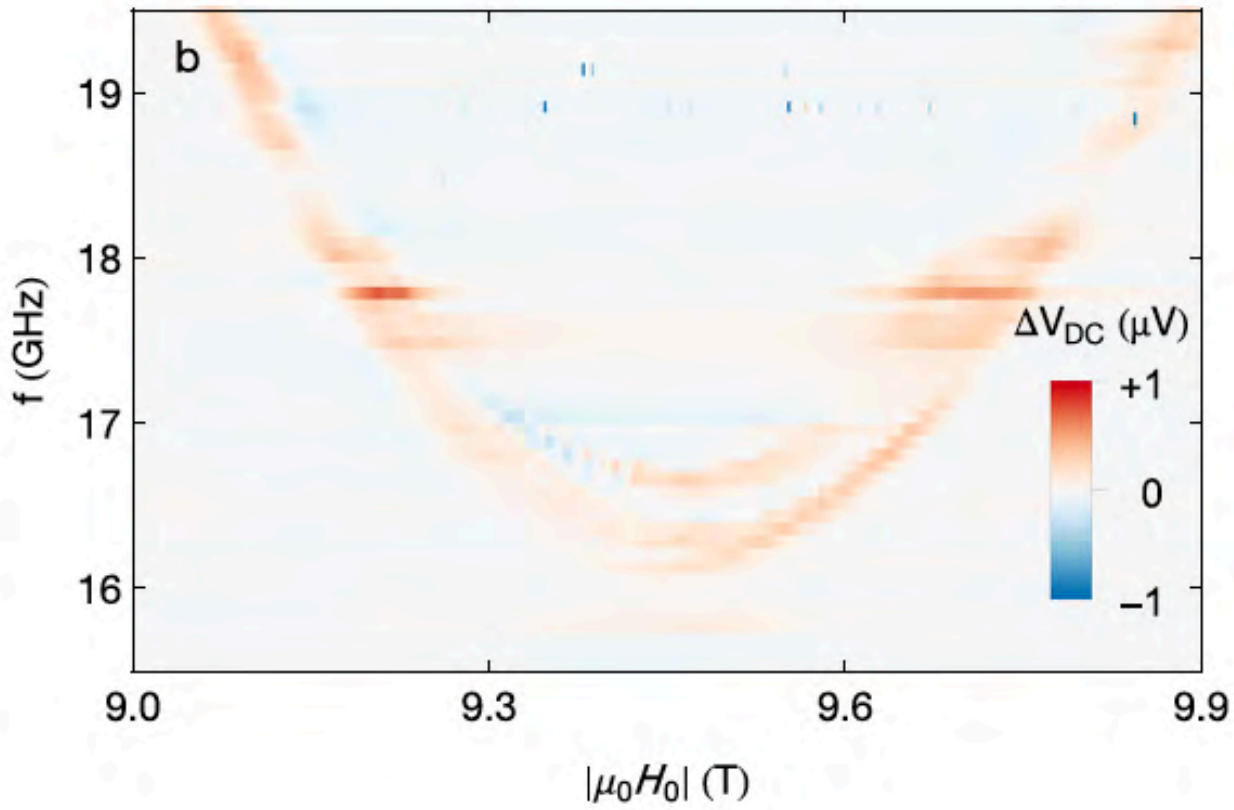
AFMR vs ED spin pumping MnF_2



Ross, J. Appl. Phys., **118** 233907 (2015)

Spin pumping in MnF_2

difference signal under field inversion



Main spin pumping signal not due to spin pumping

Small difference signal indicates spin current injected into Pt

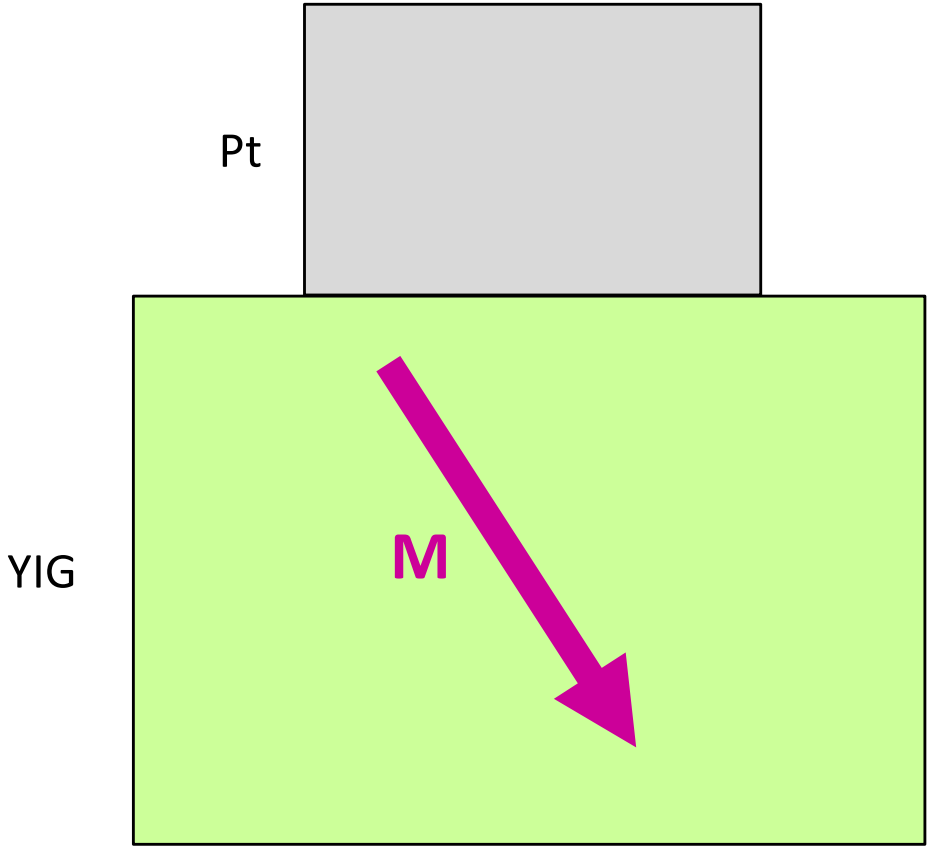
Ross, J. Appl. Phys., **118** 233907 (2015)

Spin Hall magnetoresistance

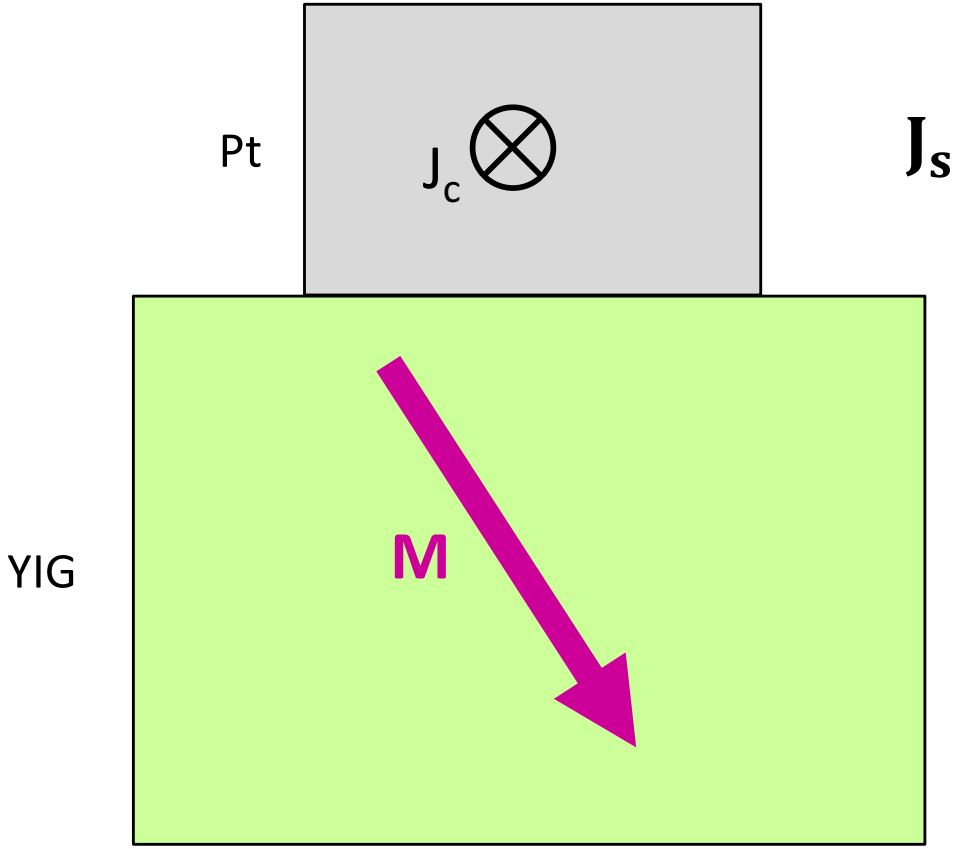
– Spin Hall magnetoresistance

Literature: Sinova, Rev. of Mod. Phys. **87**, 1213 (2015)
Nakayama, Phys. Rev. Lett. **110**, 206601 (2013)
Althammer, Phys. Rev. B **87**, 224401 (2013)
Chen, Phys. Rev. B **87**, 144411 (2013)
Vlietstra Phys. Rev. B **87**, 184421 (2013)
....

SMR mechanism

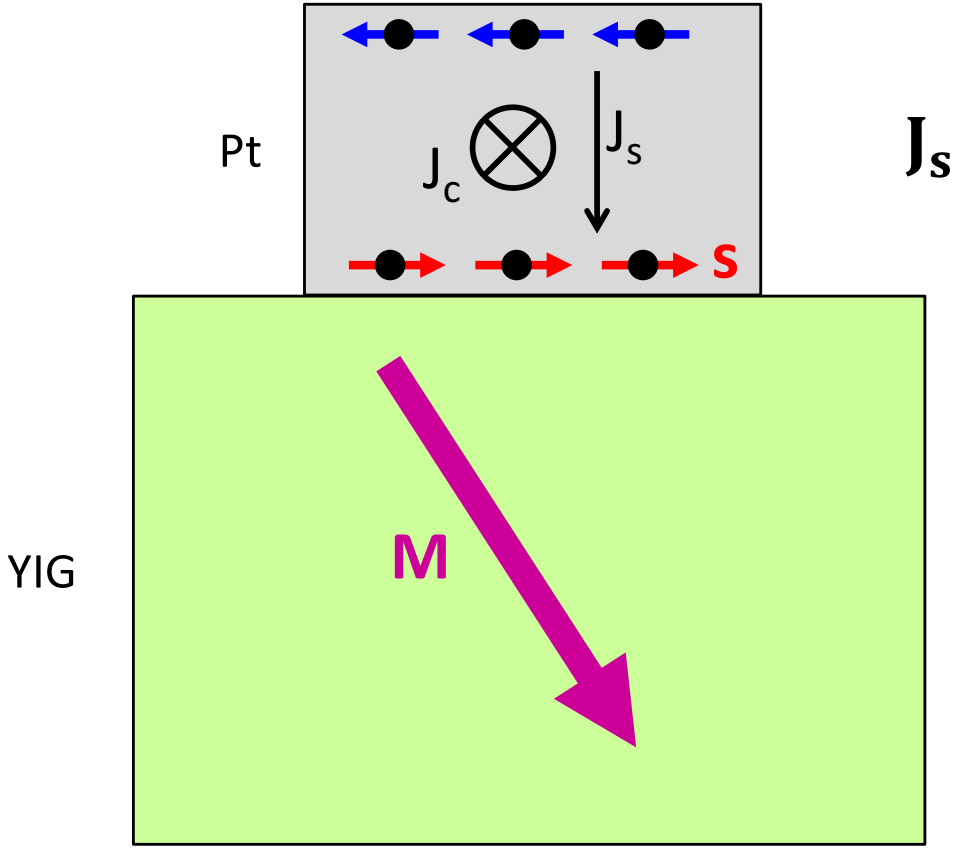


SMR mechanism

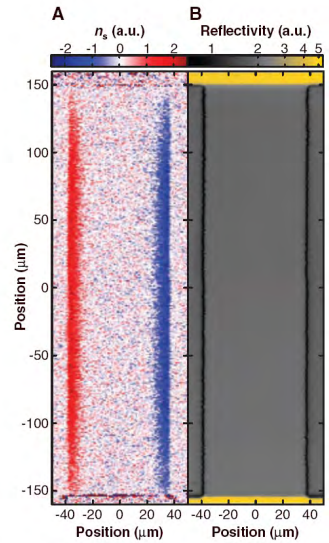


$$\mathbf{J_s} = \alpha^{\mathrm{SHE}} \frac{\hbar}{2e} [\, \mathbf{J_c} \times \mathbf{s} \,]$$

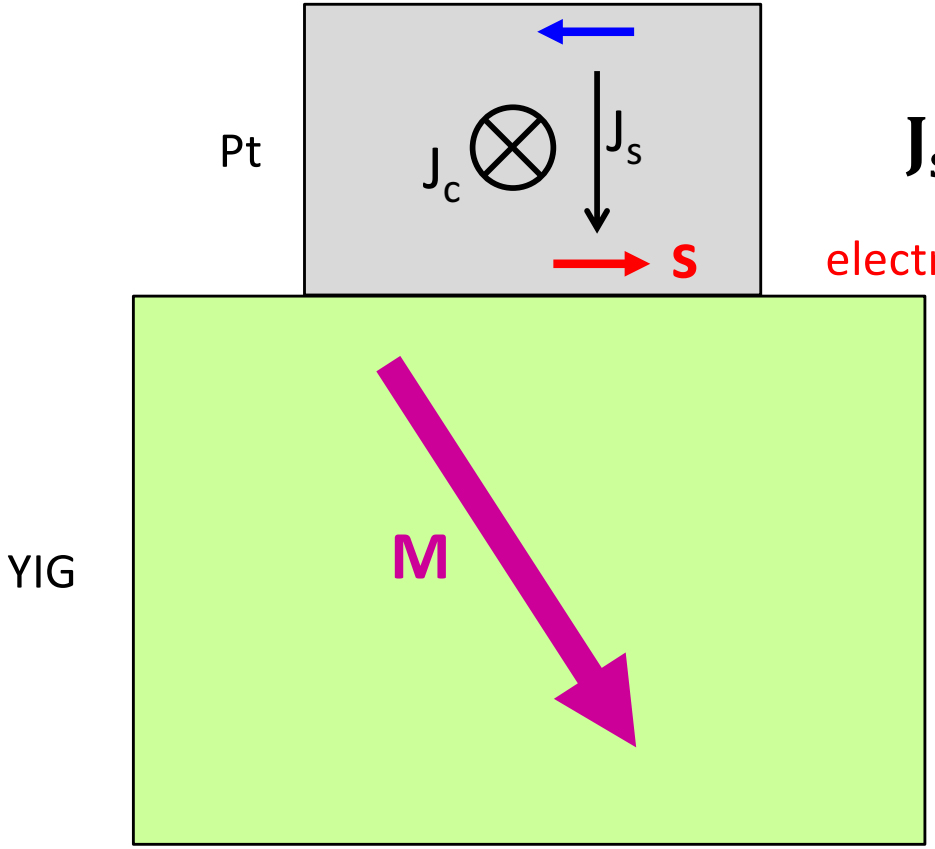
SMR mechanism



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



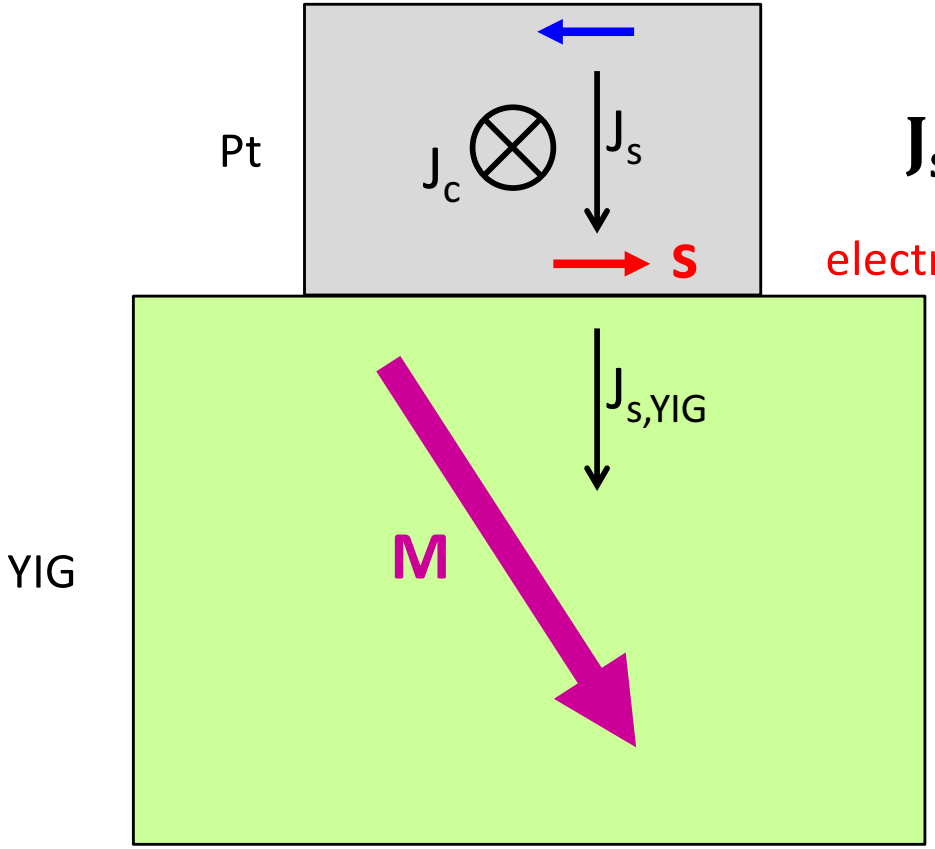
SMR mechanism



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

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**

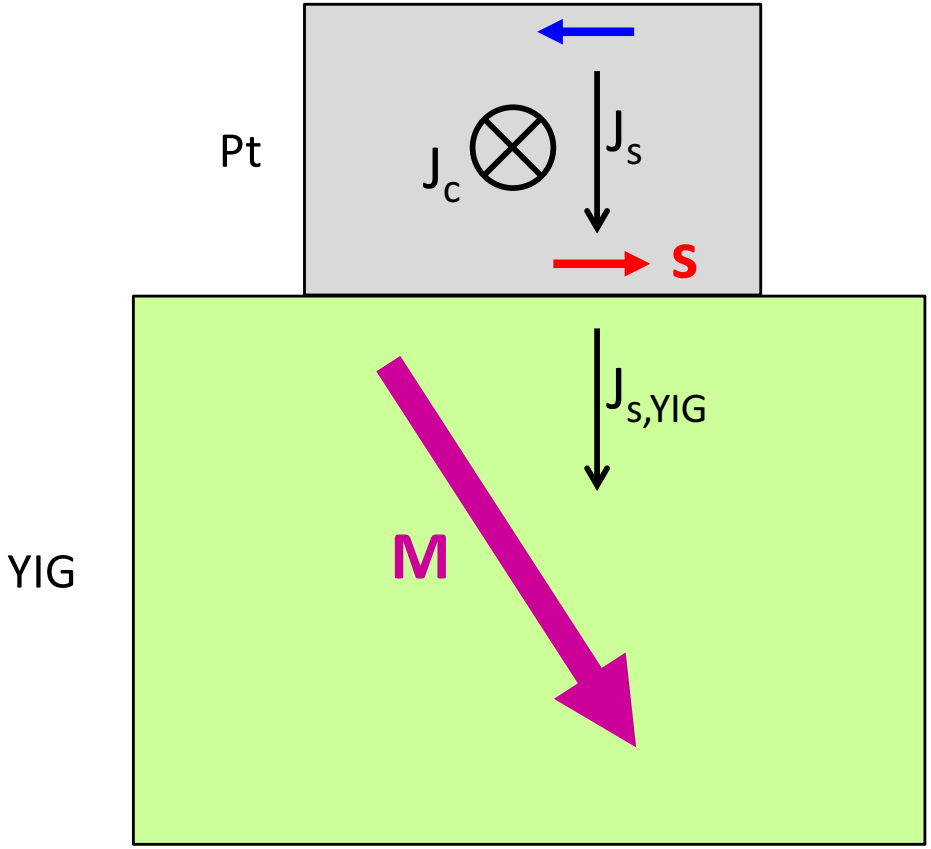
if $\tau_{\mathrm{STT}} \propto \mathbf{M} \times (\mathbf{M} \times \mathbf{s})$ is finite

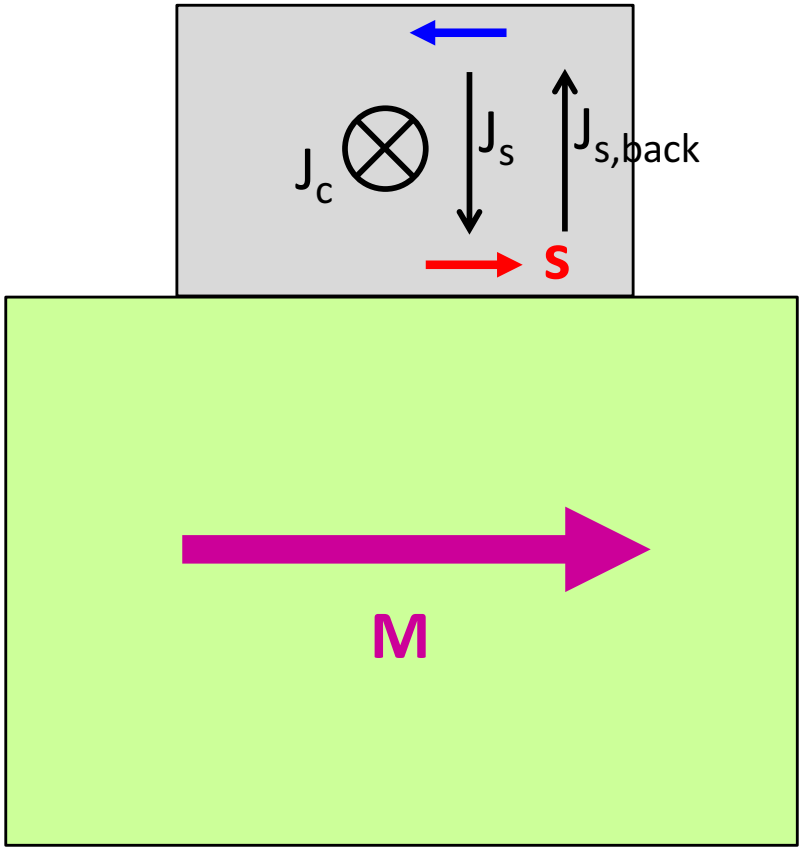
→ outflow of J_s into YIG

enhanced dissipation in Pt

→ larger Pt resistance

SMR mechanism





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

→ outflow of J_s into YIG

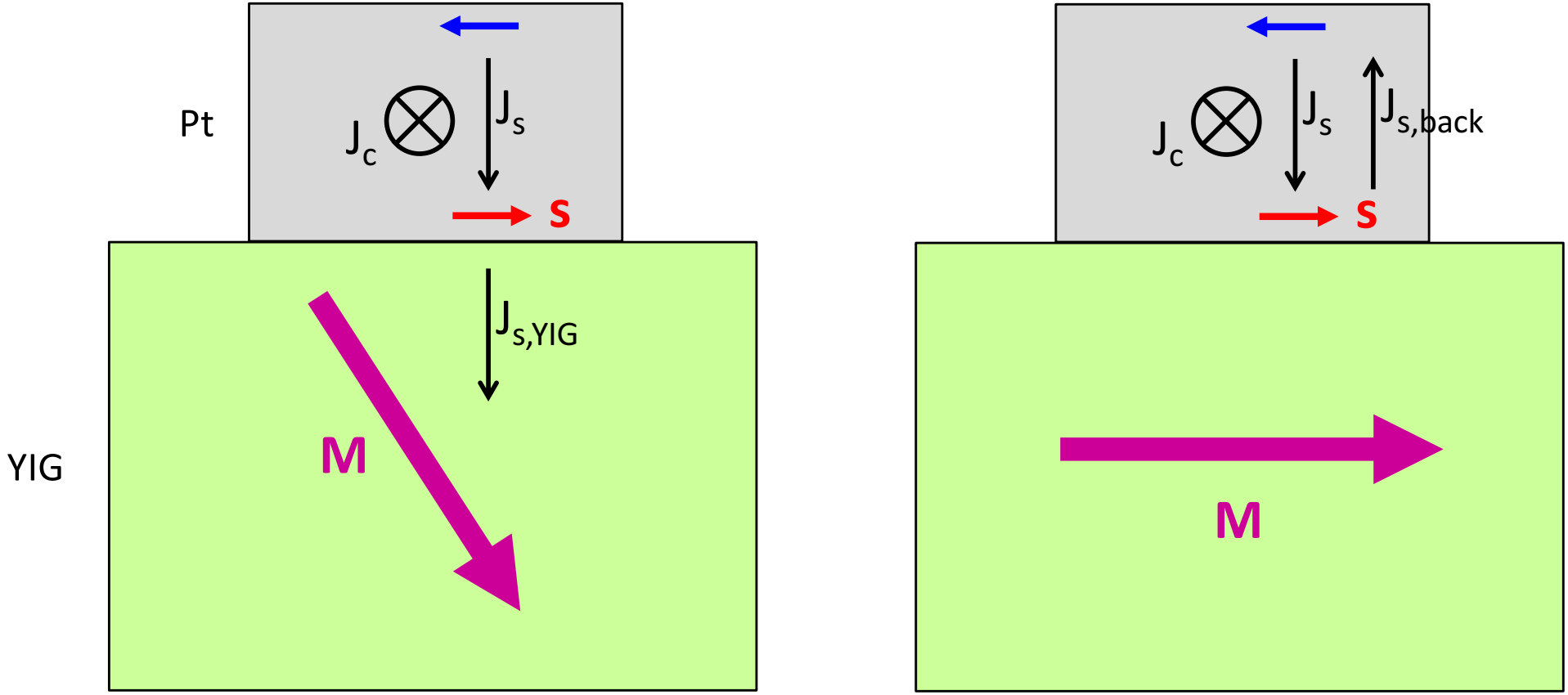
enhanced dissipation in Pt
→ larger Pt resistance

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

→ open boundary conditions for J_s

reduced dissipation
→ smaller Pt resistance

SMR mechanism

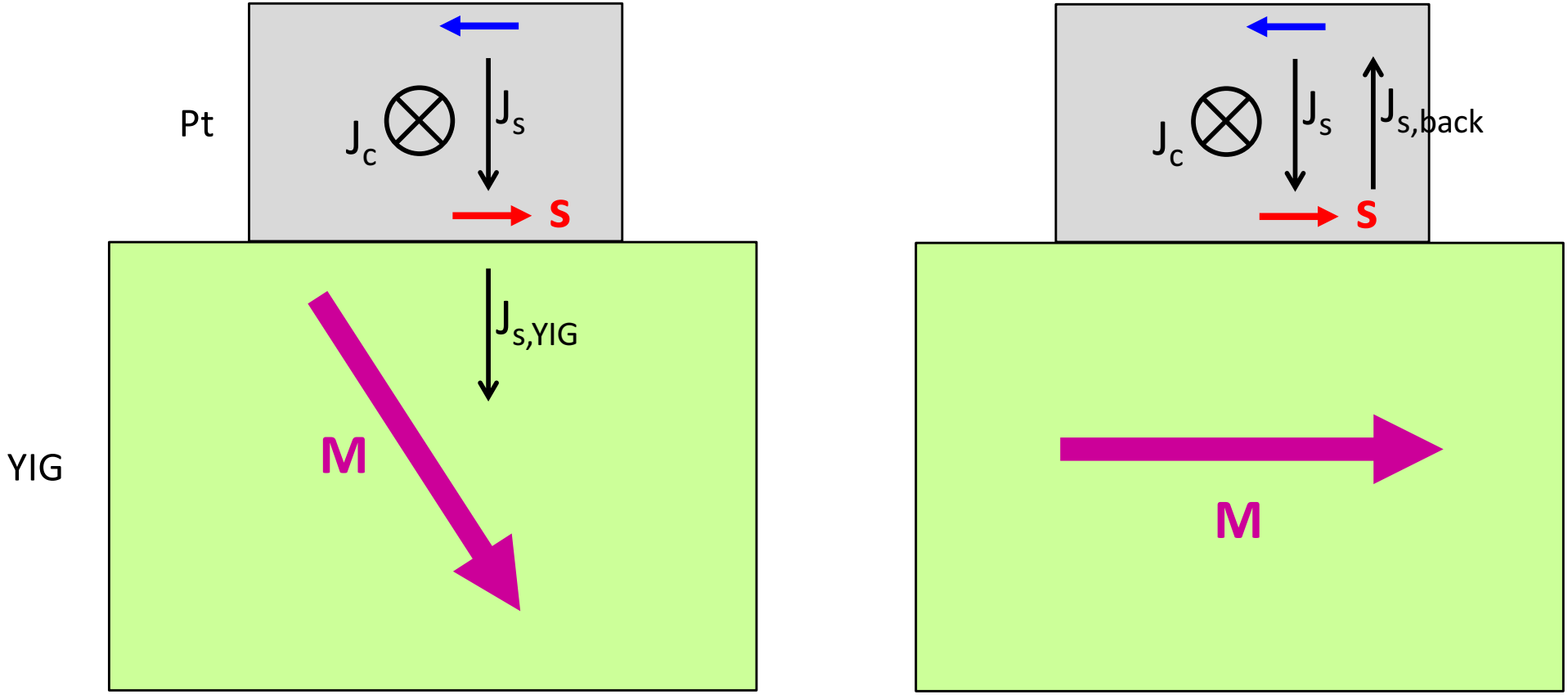


Spin Hall MR (SMR): *R* smallest for **M**||**s** , larger otherwise

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

PRL **110**, 206601 (2013)

SMR mechanism



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

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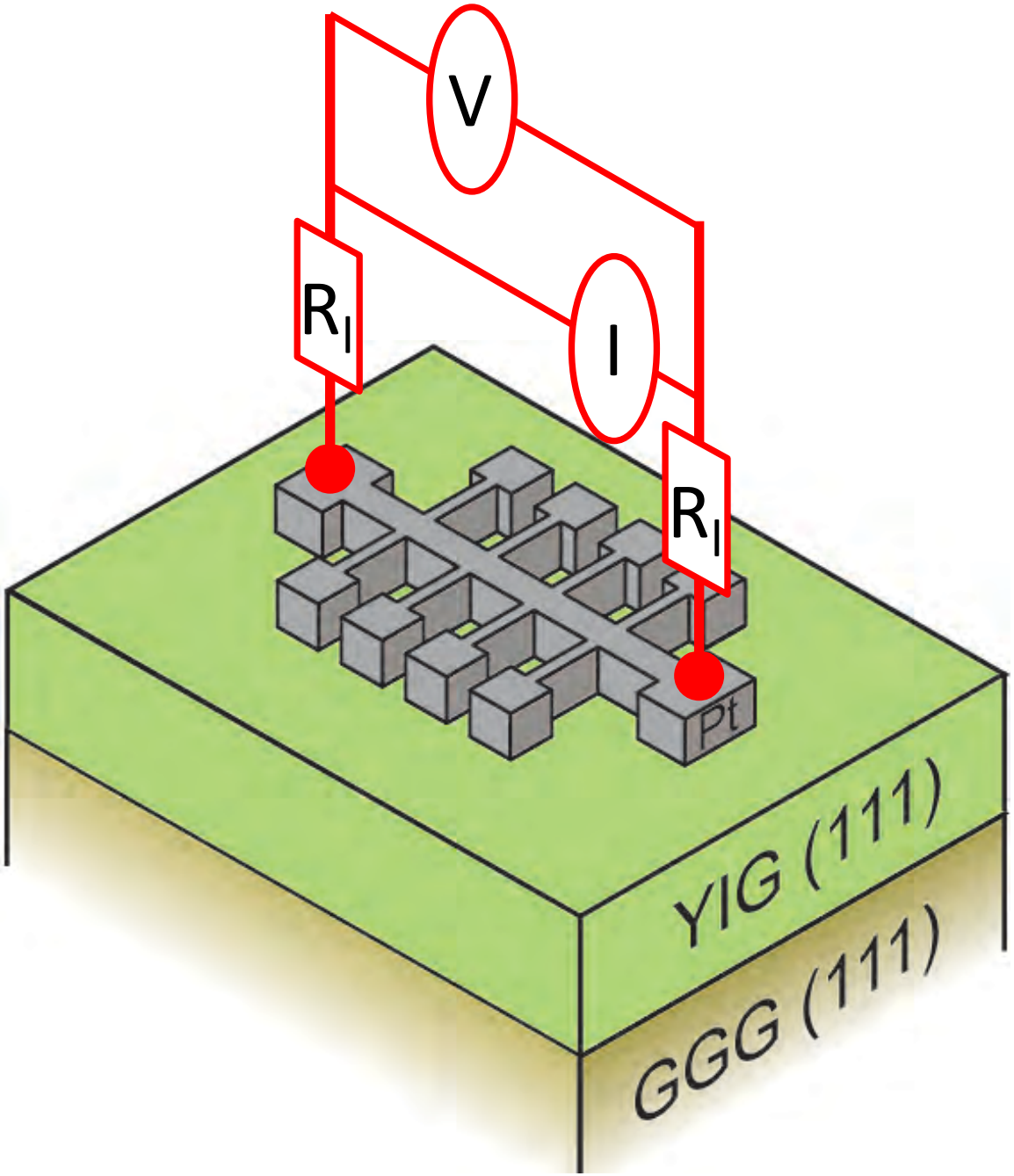
$$= R_0 - R_1 \cos^2(\alpha)$$

PRL **110**, 206601 (2013)

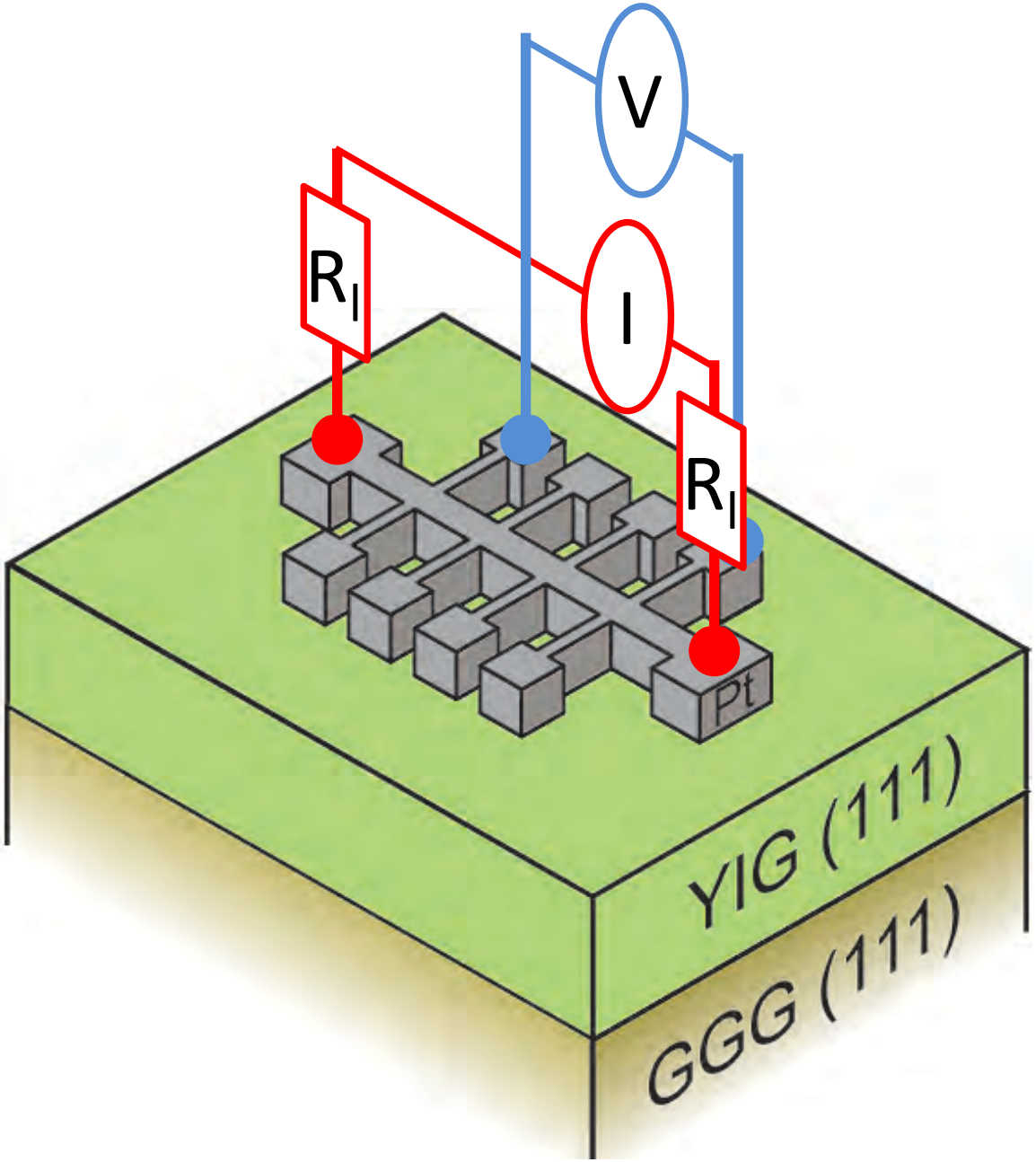
Measuring resistance



$$R = \frac{V}{I}$$

Lead resistance influences results

Measuring resistance

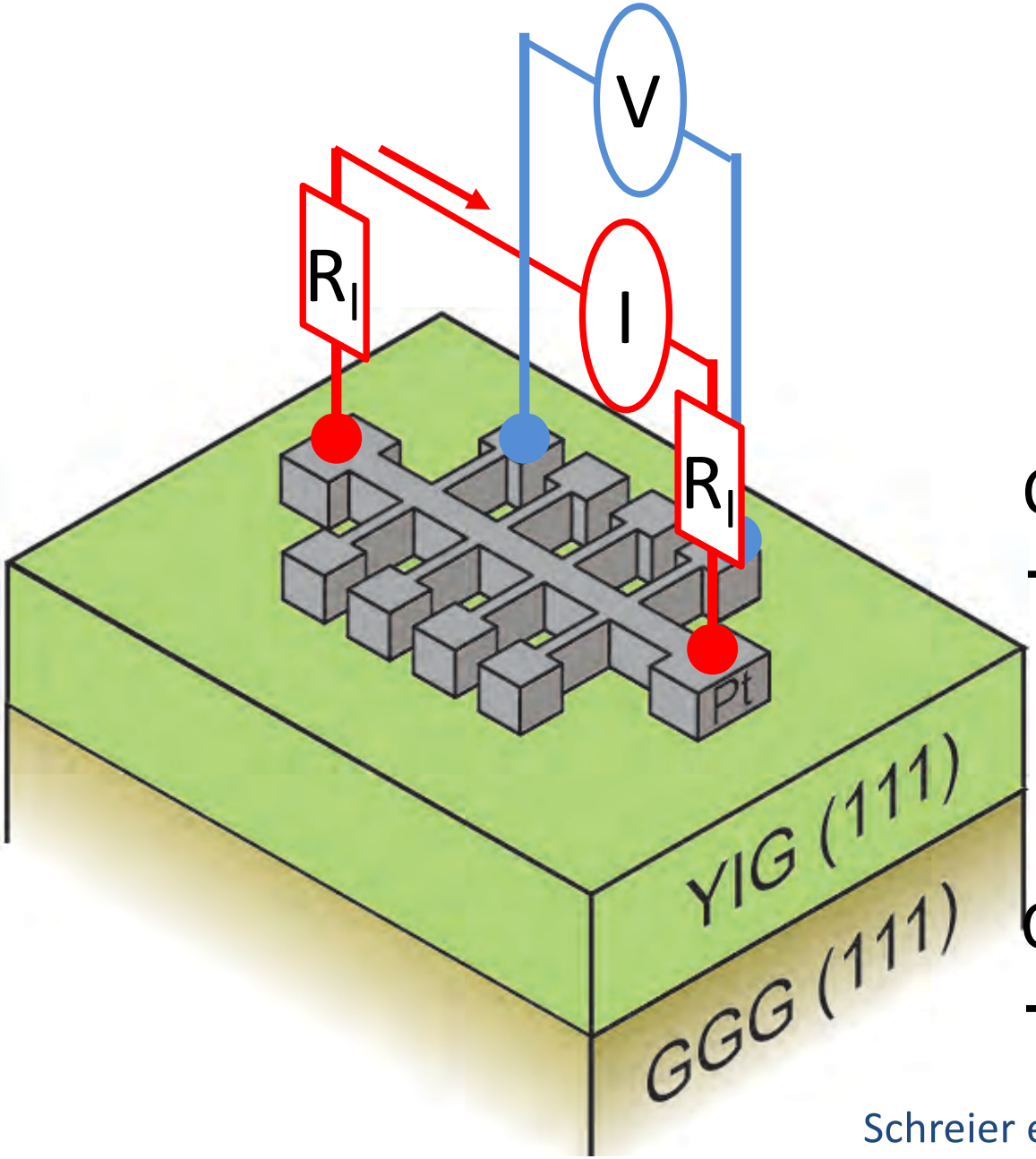


$$R = \frac{V}{I}$$

Lead resistance influences results

4 wire method probes device physics

Measuring resistance — switching techniques



$$R = \frac{V}{I}$$

$$V_{\mathrm{res}}(I) = \frac{1}{2}\left(V(+I) - V(-I)\right)$$

Contains all odd terms in I:
→ resistive effects $\propto I$

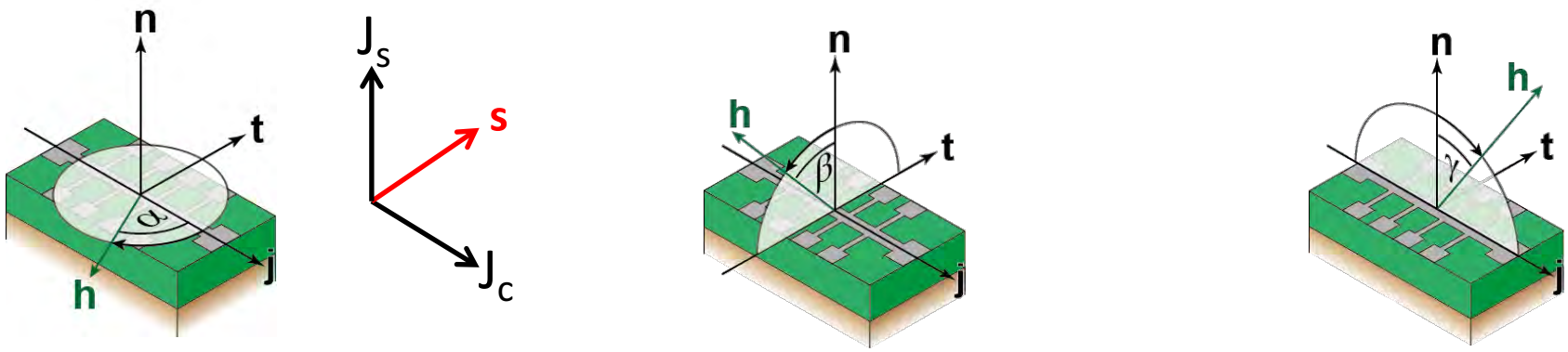
$$V_{\mathrm{therm}}(I) = \frac{1}{2}\left(V(+I) + V(-I)\right)$$

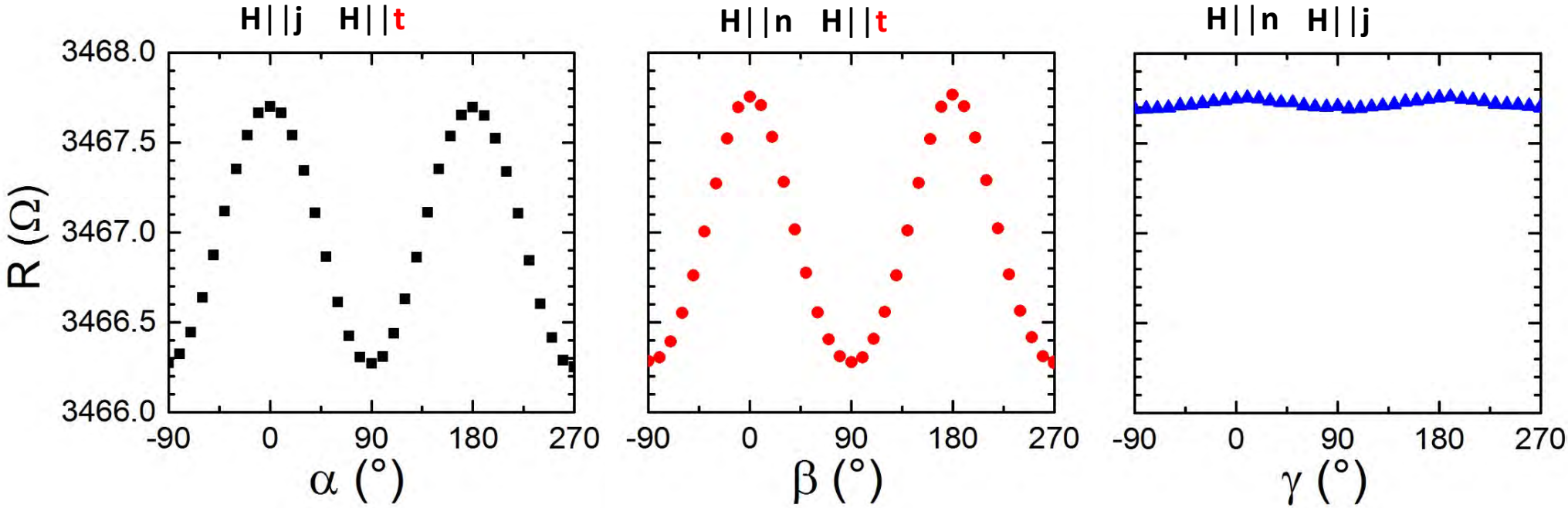
Contains all even terms in I:
→ thermal effects $\propto I^2$

Schreier et al., Appl. Phys. Lett. **103**, 242404 (2013)

SMR fingerprint

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

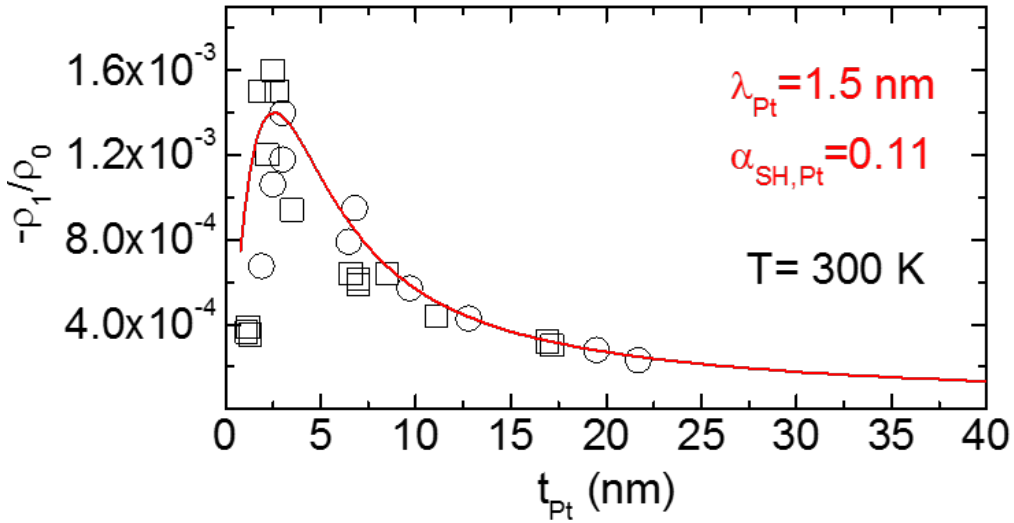




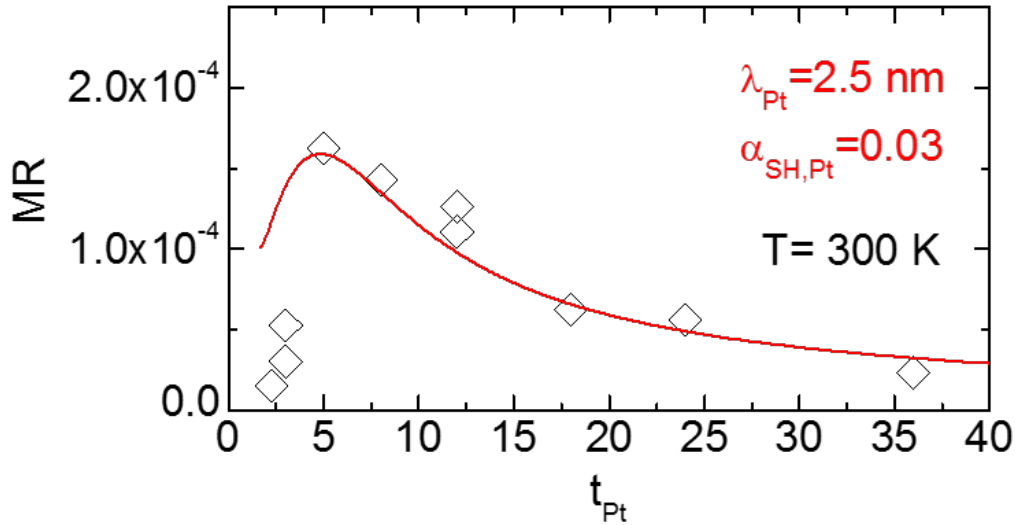
SMR amplitude: $\Delta R/R \cong 4\times10^{-4}$

Extraction of spin Hall angle from SMR

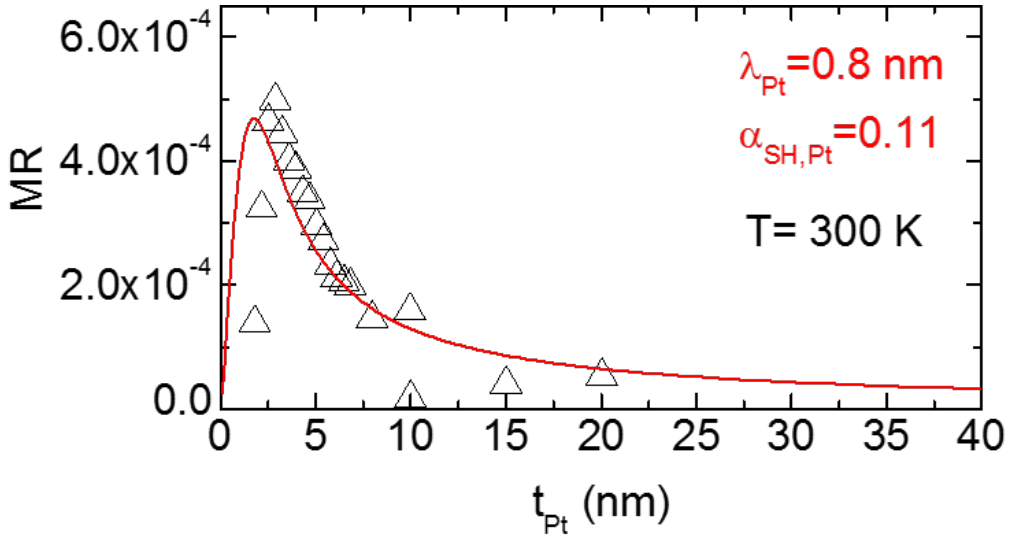
YIG/Pt @ WMI



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

Acknowledgements

"Magnetiker"

Sebastian T. B. Goennenwein
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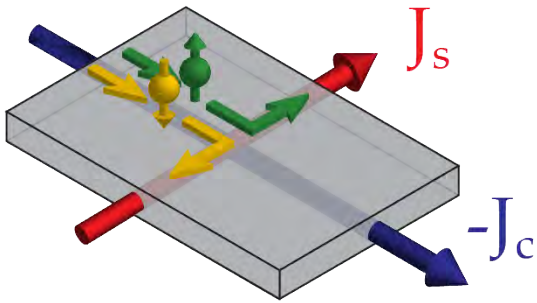
Kathrin Ganzhorn
Stefan Klingler
Matthias Pernpeintner
Richard Schlitz
Tobias Wimmer
Sybille Meyer
Hannes Maier-Flaig
Franz Czeschka
Andreas Brandlmayer

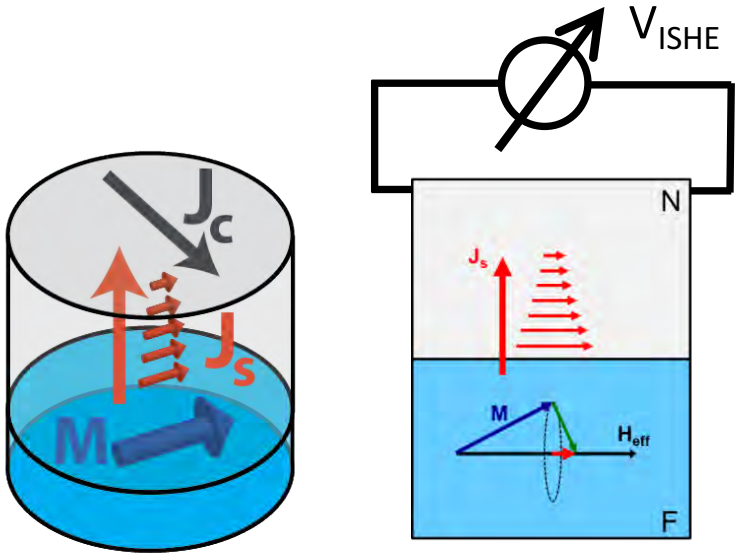
Gerrit Bauer
Akash Kamra
Yunshan Cao
Joe Barker
Y.-T. Chen

Summary

pure spin currents
spin Hall effect



„simple“ spin current circuits
spin pumping



spin Hall magnetoresistance