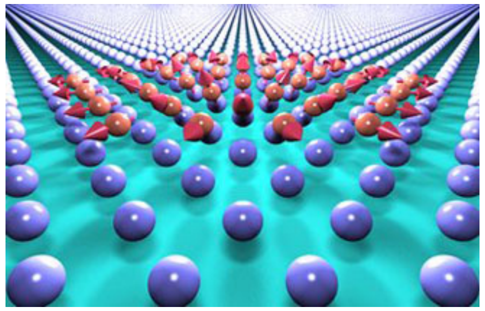


Funsilab

Instituto de Física
Universidade Federal Fluminense

JÜLICH
FORSCHUNGSZENTRUM

Dynamical amplification of magnetoresistances and Hall currents up to the THz regime

Filipe S. M. Guimarães
M. dos Santos Dias, J. Bouaziz, A. T. Costa, R. B Muniz, and S. Lounis

Peter Grünberg Institut & Institute for Advanced Simulation, FZJ
Instituto de Física, Universidade Federal Fluminense, Brazil

July 4, 2017 | Mainz seminar


2:45

1998

- Don’t get into strangers’ cars;
- Don’t meet people from the internet.

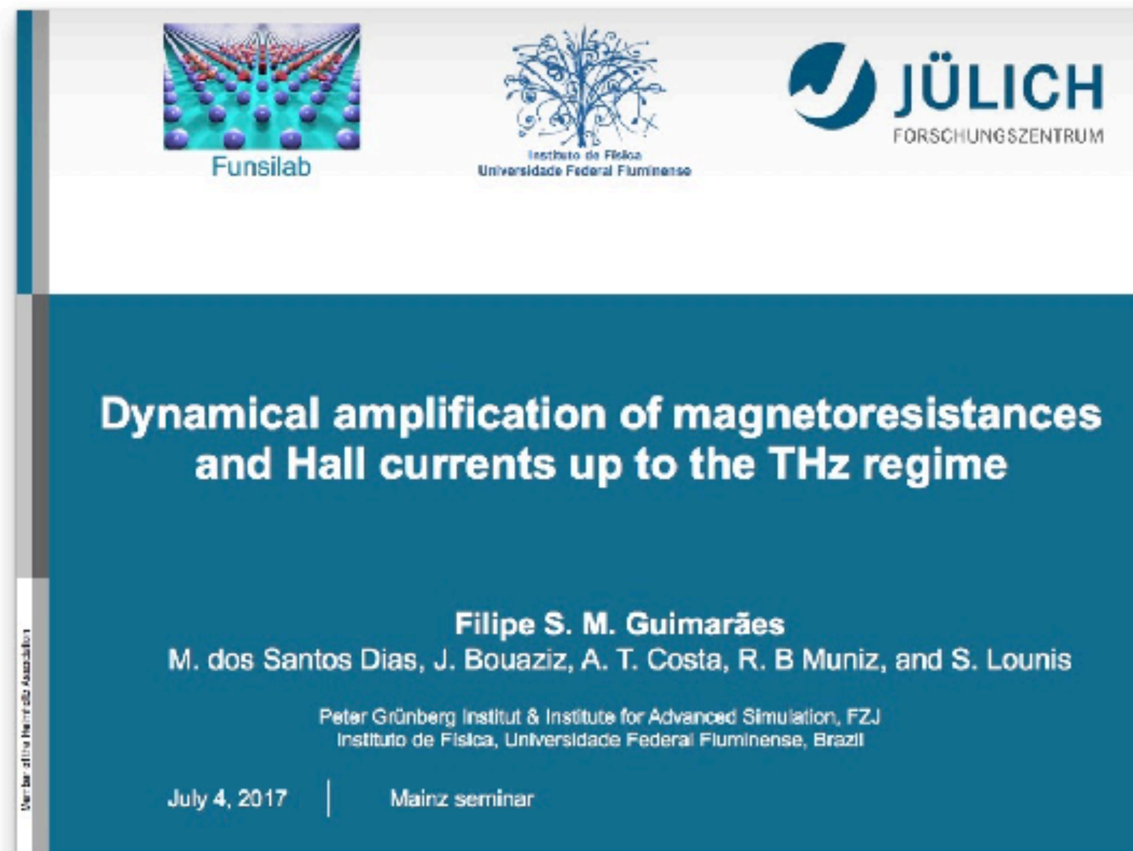
2017

- Literally summon strangers from the internet to get into their car.

UBER

1956

2017



Mainz_04/07/2017.key
77,5 MB

Static-RAM

Dynamic-RAM

volatile

Flash memory

Hard disk

non-volatile

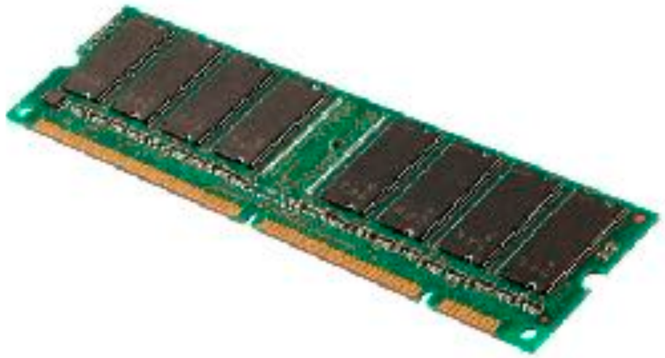
10^6	10^5	10^3	1

← **Speed**

Mb	Gb	100 Gb	Tb

Size →

Static-RAM



Dynamic-RAM

Flash memory

Hard disk

Universal Memory

Speed

Power consumption

Price

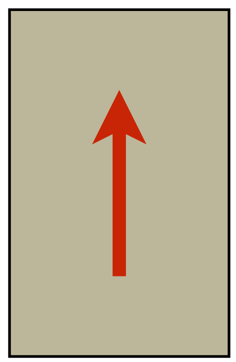
Size

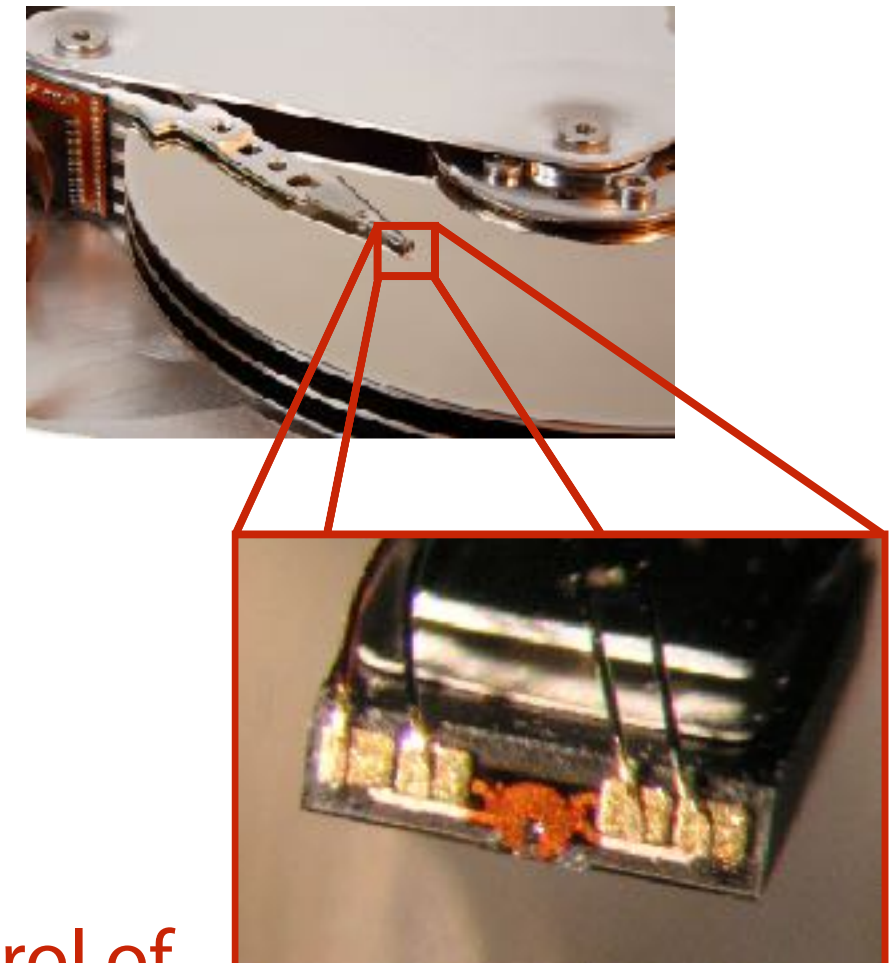
Non-volatility

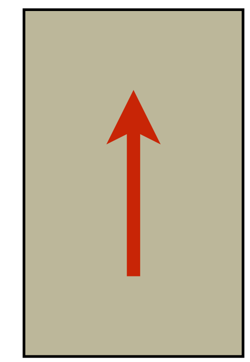
Durability

Spintronics

Spintronics to store, write and read information

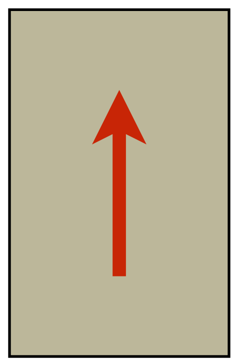


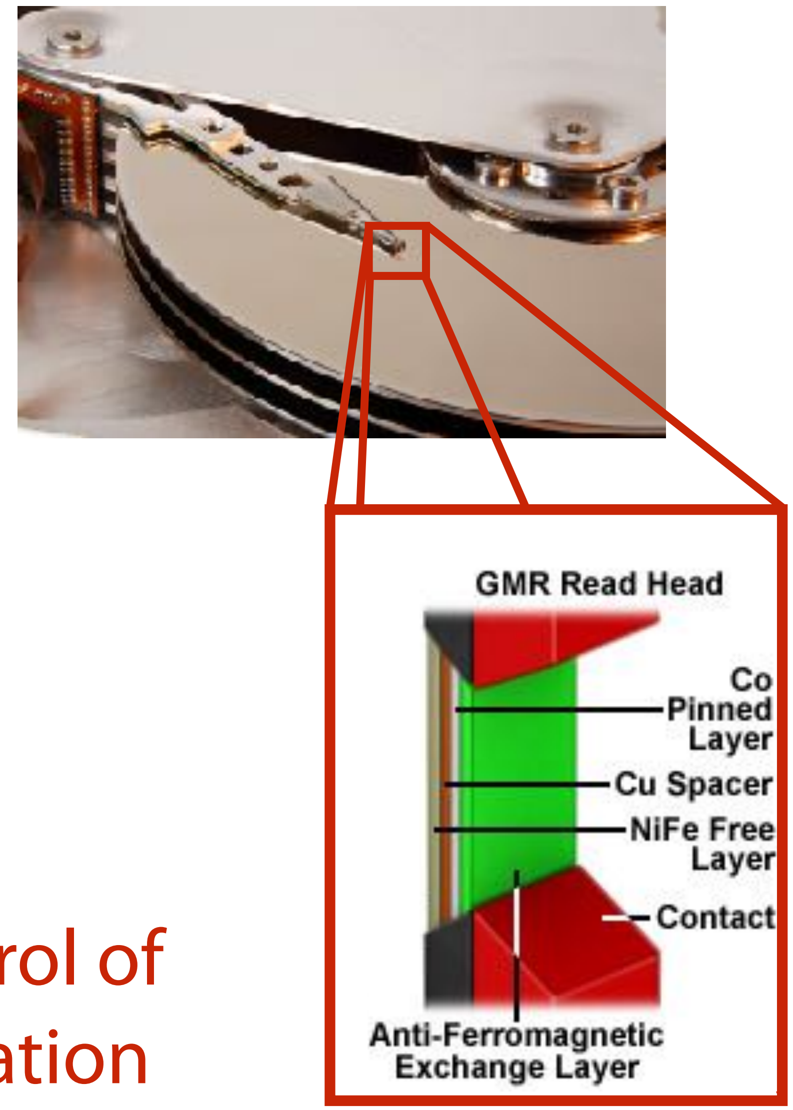


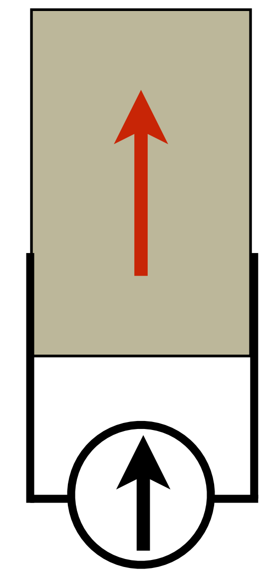


Electrical control of
the magnetization
(writing)

Spintronics to store, write and read information



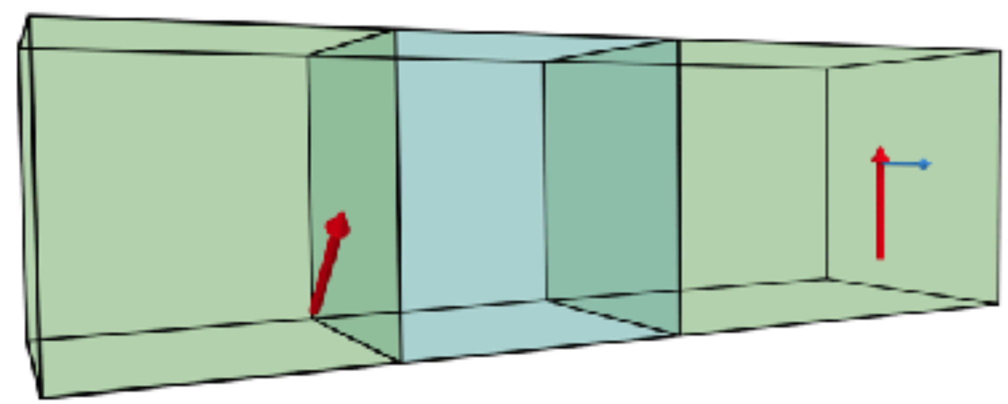




Electrical control of the magnetization (writing)

Electrical detection of the spin dynamics (reading)

Spin-transfer-torque is a possible candidate



proposed by Slonczewski, Berger 1996

http://www.mram-info.com/

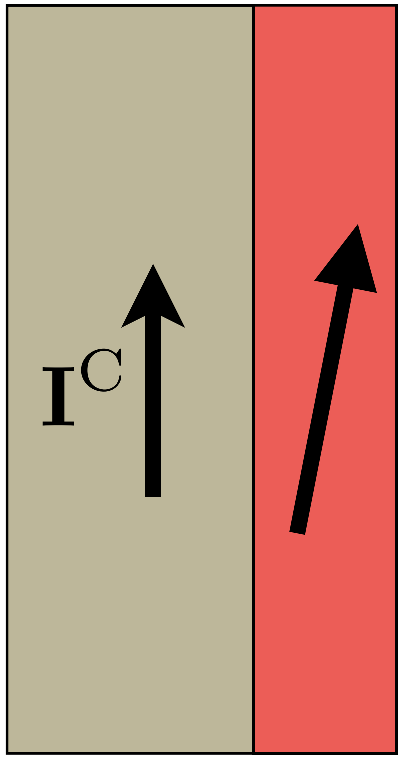
July 7, 2016

Posted in: Cloud Computing, Storage, Thomas J Watson Research Center

Researchers celebrate 20th anniversary of IBM's invention of Spin Torque MRAM by demonstrating scalability for the next decade

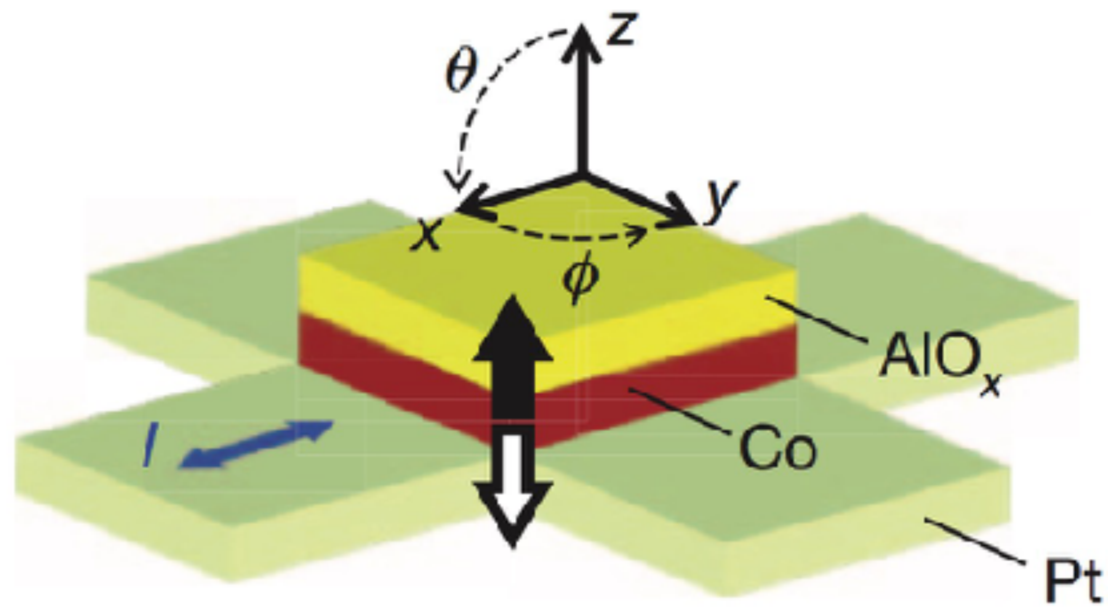
J. J. Nowak *et al.*, IEEE Magnetics Letters **7**, 3102604 (2016)

The next step: using spin-orbit coupling to control the magnetization



SPIN-ORBIT TORQUES

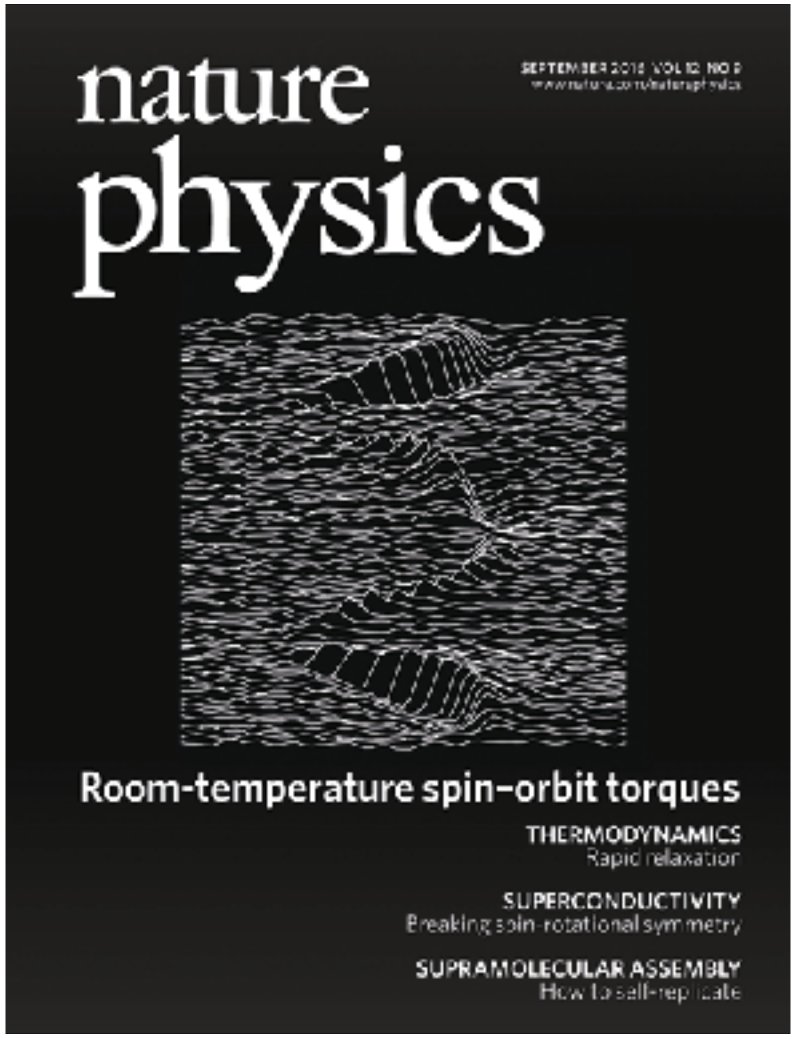
The next step: using spin-orbit coupling to control the magnetization



SPIN-ORBIT TORQUES

I. M. Miron *et al.*, Nature **476**, 189–193 (2011)

The next step: using spin-orbit coupling to control the magnetization



SPIN-ORBIT TORQUES

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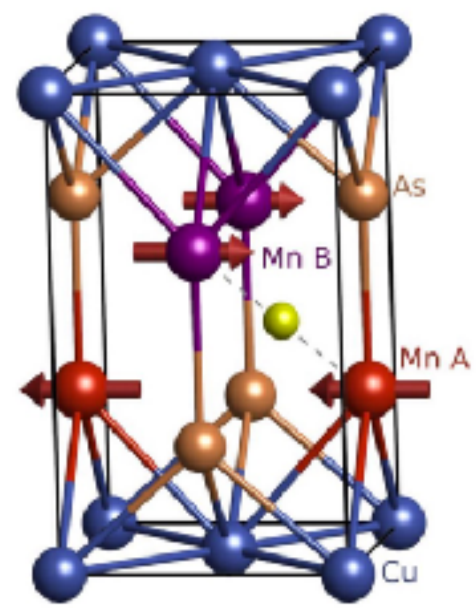
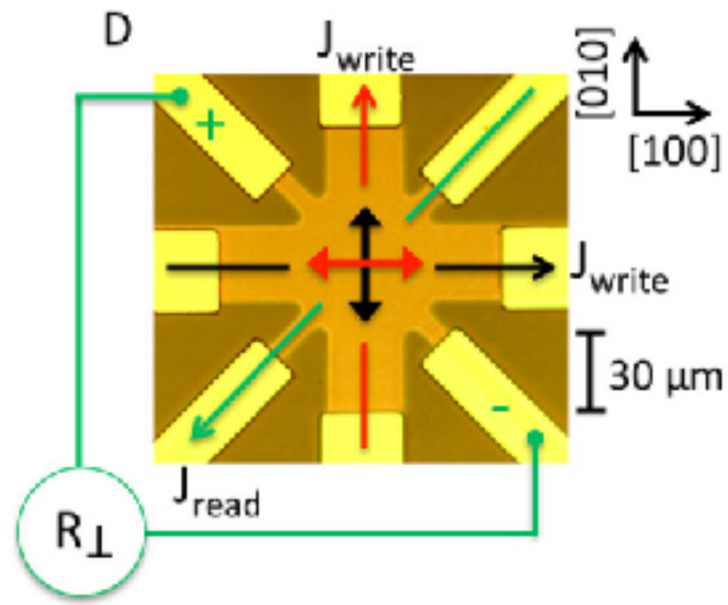
C. Ciccarelli *et al.*, Nature Physics **12**, 855–860 (2016)

The next step: using spin-orbit coupling to control the magnetization





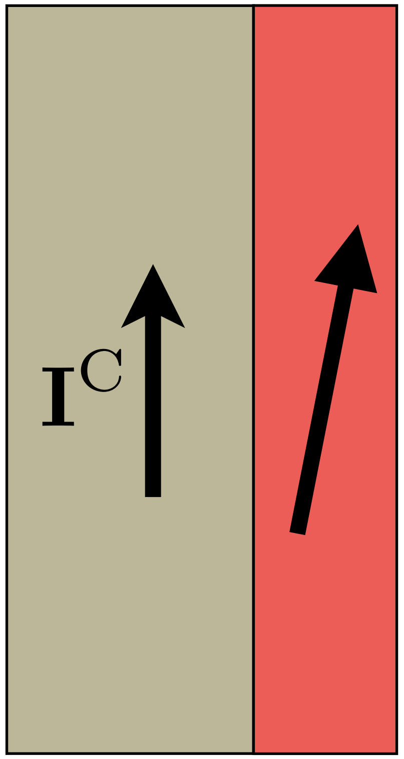
SPIN-ORBIT TORQUES

I. M. Miron *et al.*, Nature **476**, 189–193 (2011)

C. Ciccarelli *et al.*, Nature Physics **12**, 855–860 (2016)

P. Wadley et al., Science 10.1126/science.aab1031 (2016)

The next step: using spin-orbit coupling to control the magnetization



SPIN-ORBIT TORQUES

The next step: using spin-orbit coupling to control the magnetization

SPIN-ORBIT TORQUES

Outlook

Introduction

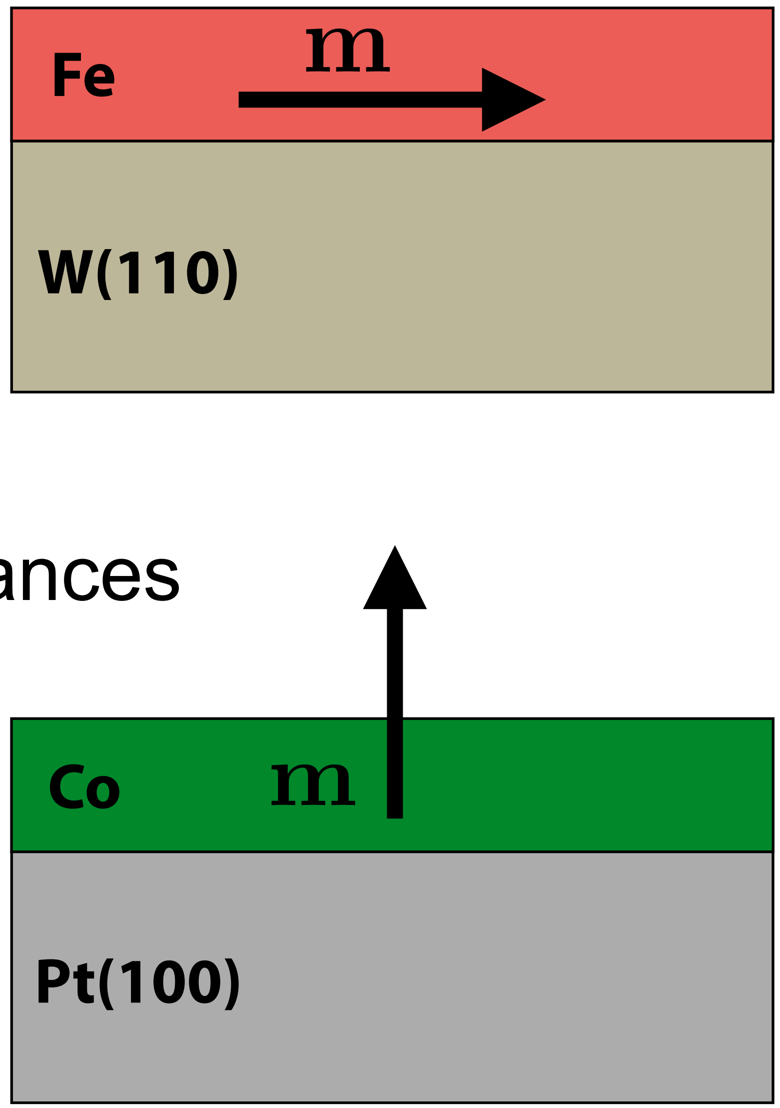
Theoretical framework

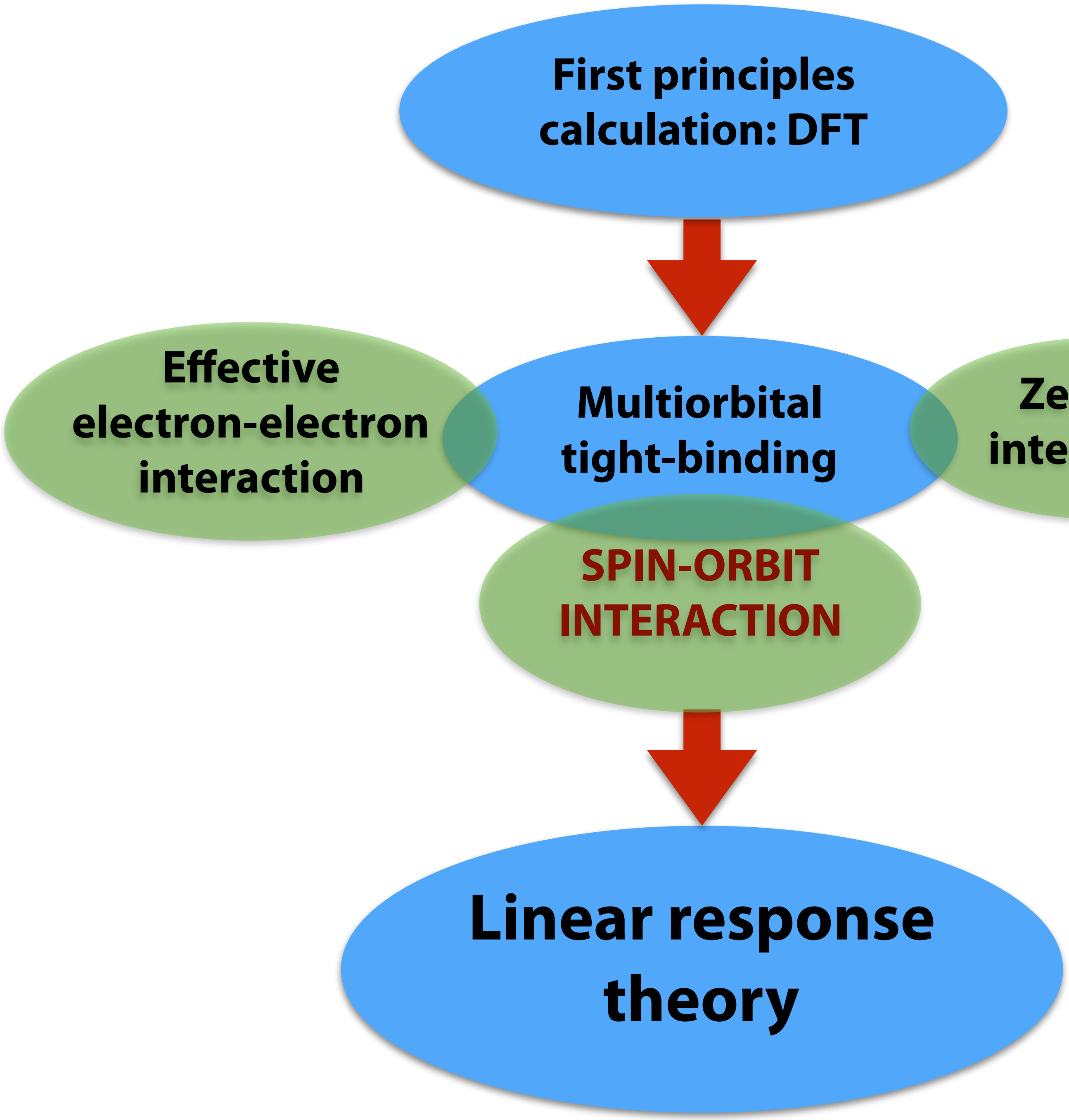
Results

- Spin-spin response functions
- Current-driven resonances
- *Dynamical* Hall effects and magnetoresistances

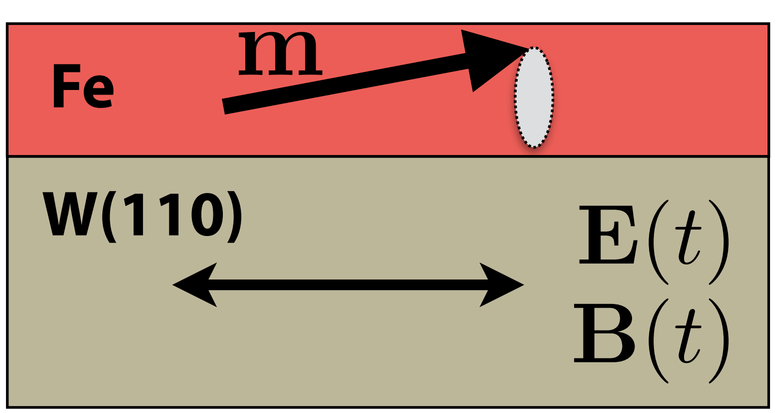
Perspectives

Conclusions




First principles calculation: DFT
Effective electron-electron interaction
Multiorbital tight-binding
Zeeman interaction
SPIN-ORBIT INTERACTION
Linear response theory

TITAN


Fe
m
W(110)
E(t)
B(t)


JUQUEEN

Each combination perturbation/observable describes different phenomenon

perturbation

magnetic field

electric field

FMR

Spin pumping

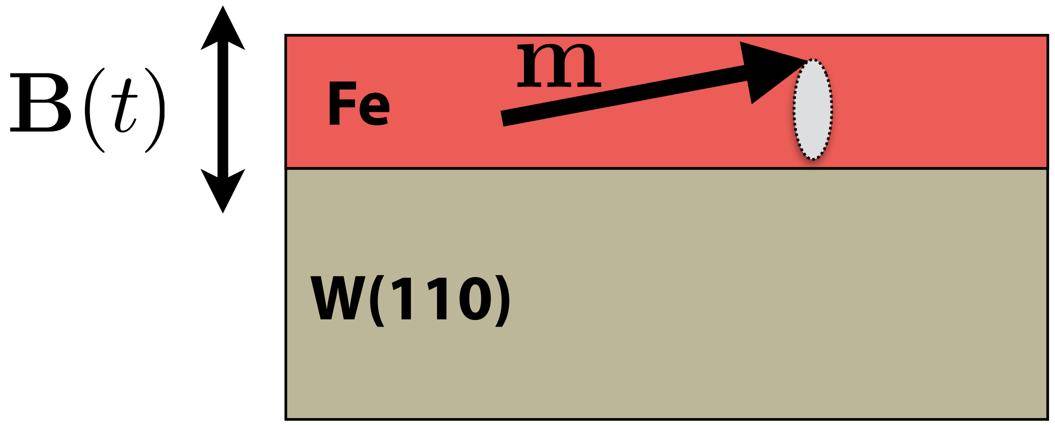
observable

spin density

spin currents

charge currents

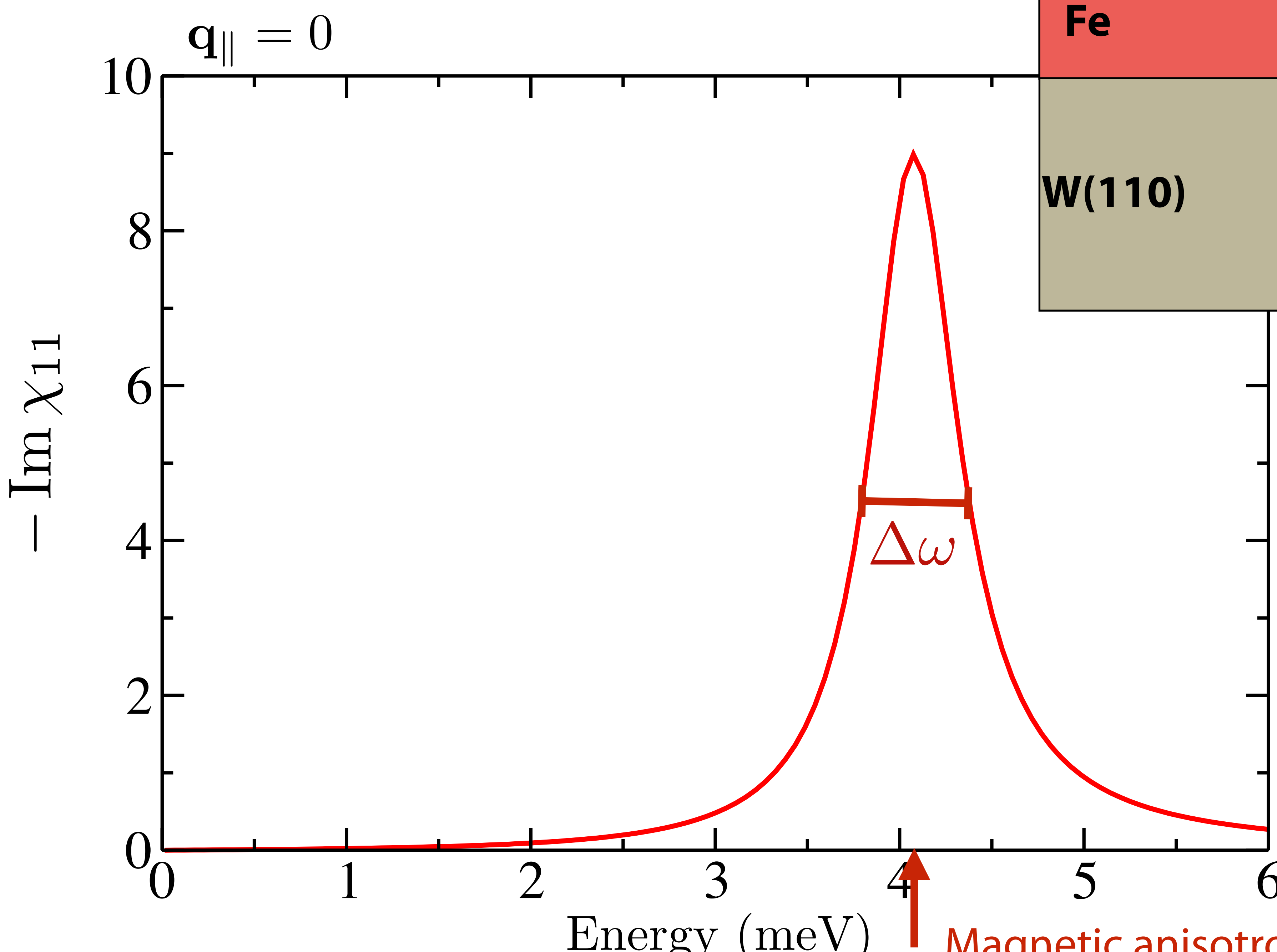
…

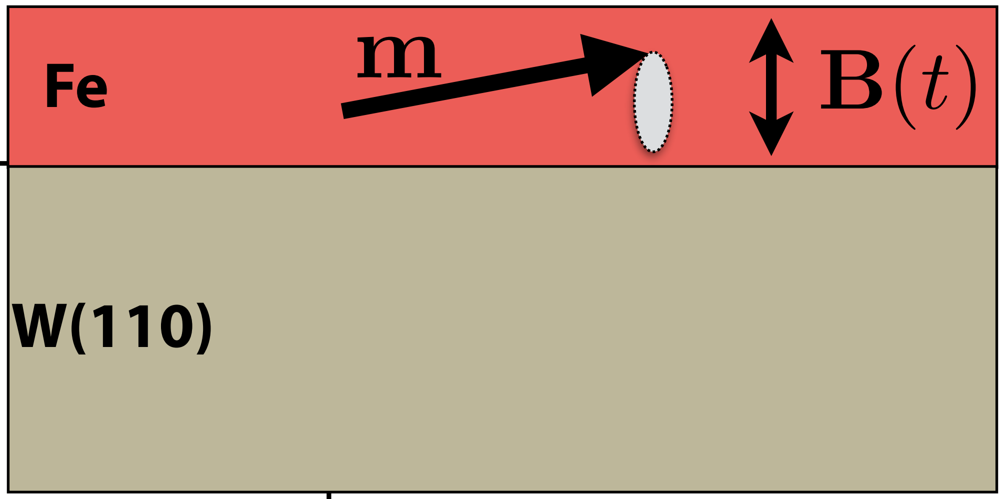


$\delta\langle\mathbf{m}_i\rangle(t)$

$\langle\mathbf{I}_i^{\mathrm{S}}\rangle(t)$

Spin-spin response functions describes the excitation of spin waves





Spin waves

Stoner modes (electron-hole)

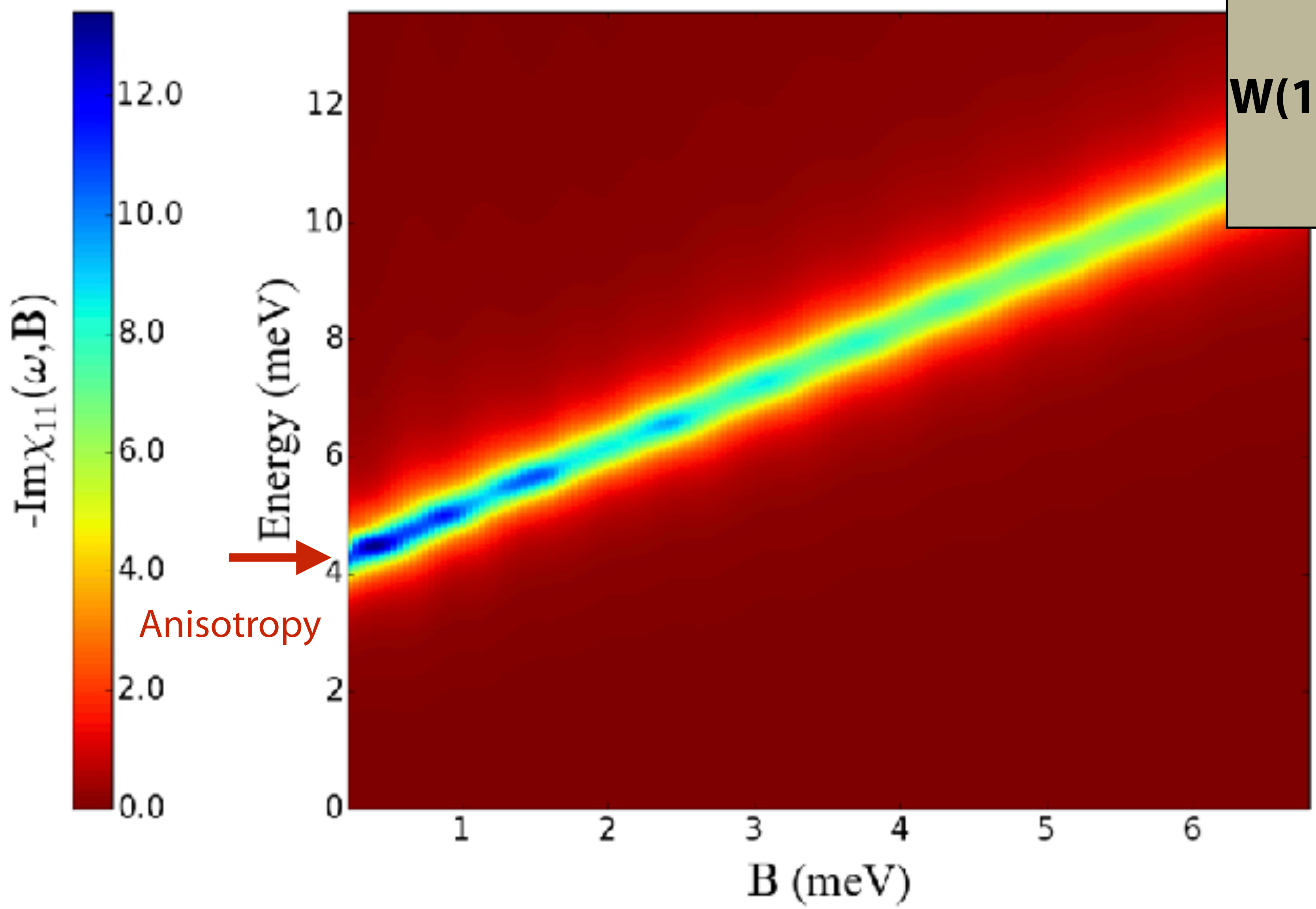
Spin pumping

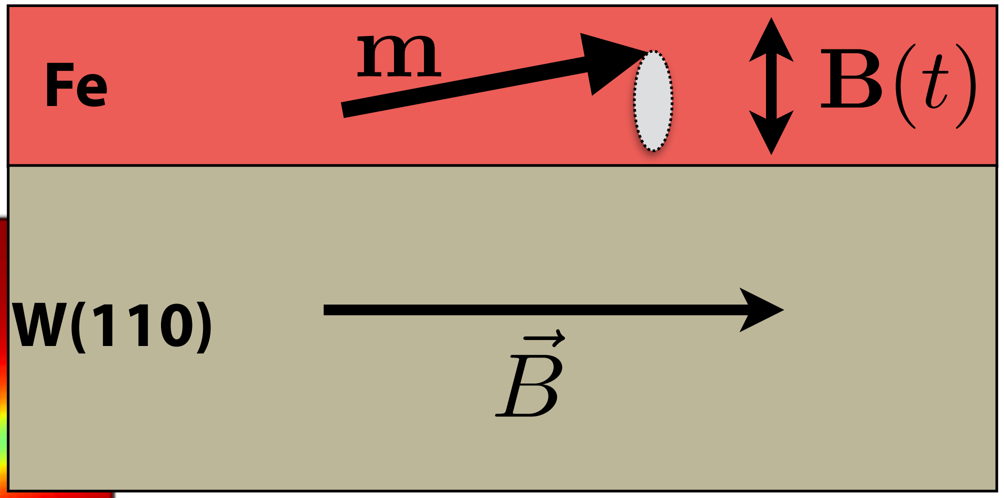
Spin-orbit coupling

Magnetic anisotropy: $\omega_{\mathrm{res}} = \gamma \frac{2K}{M}$

f.guimaraes@fz-juelich.de PRB 92, 220410(R) (2015)

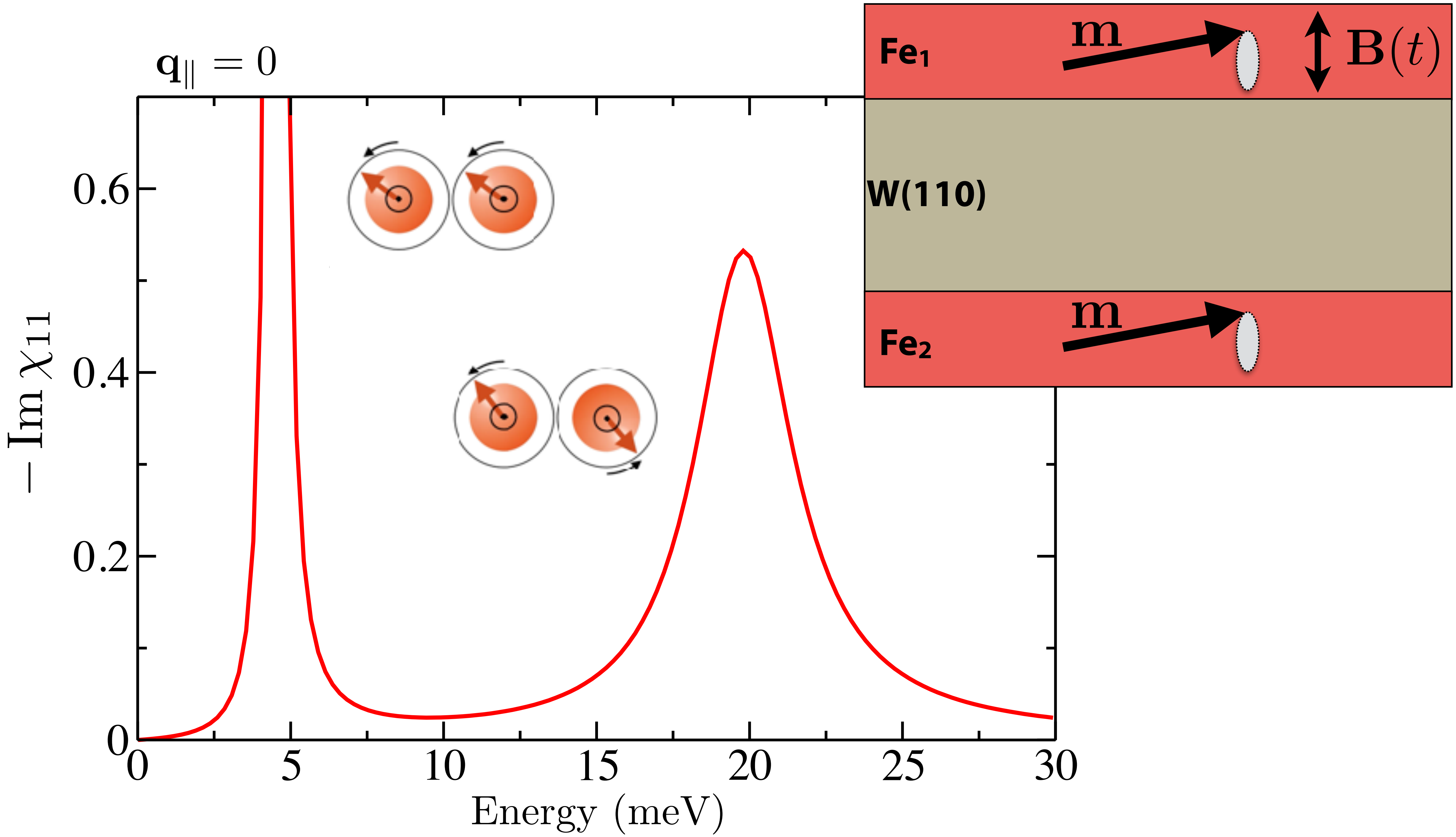
Spin-spin response functions describes the excitation of spin waves



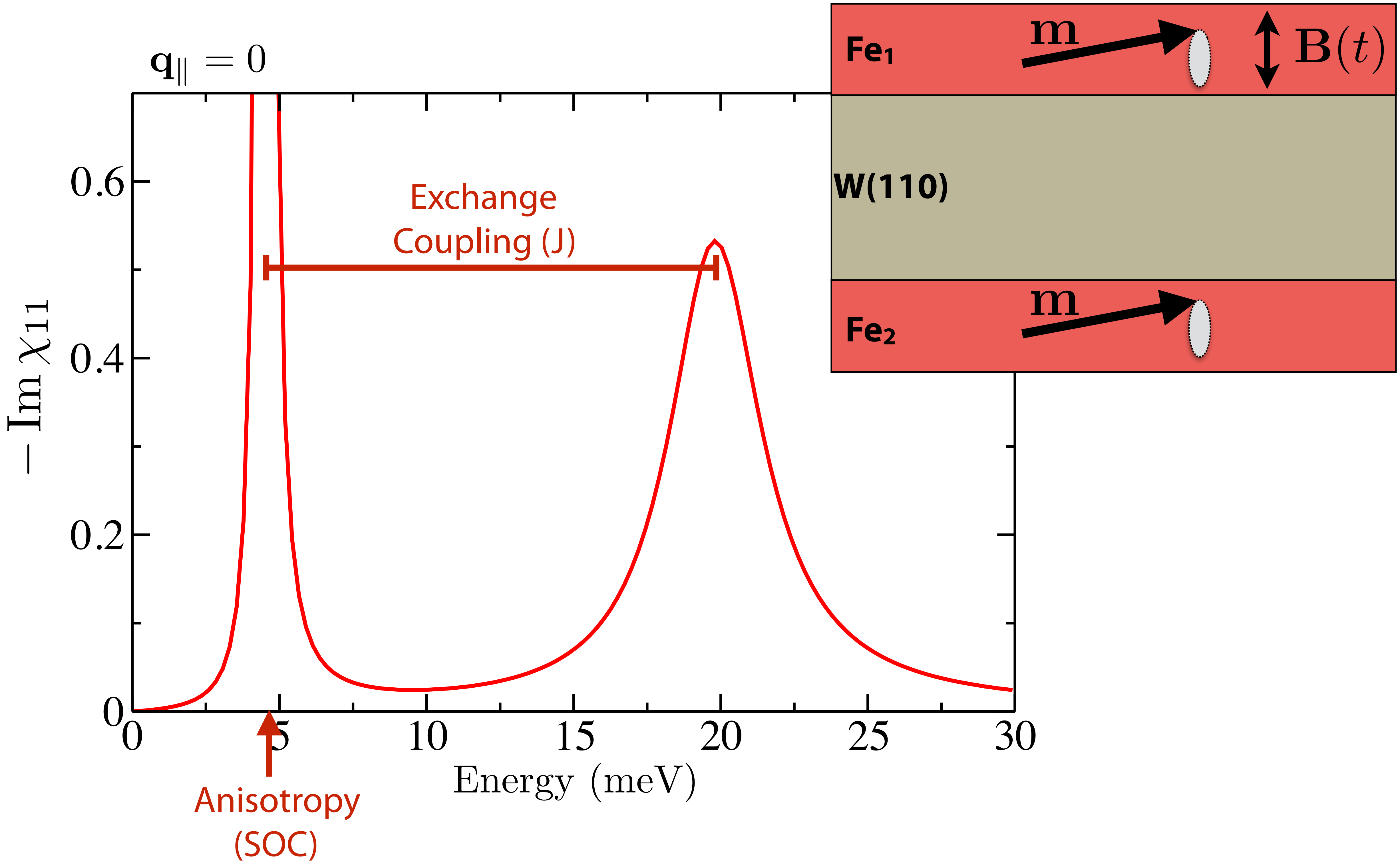


Spin waves

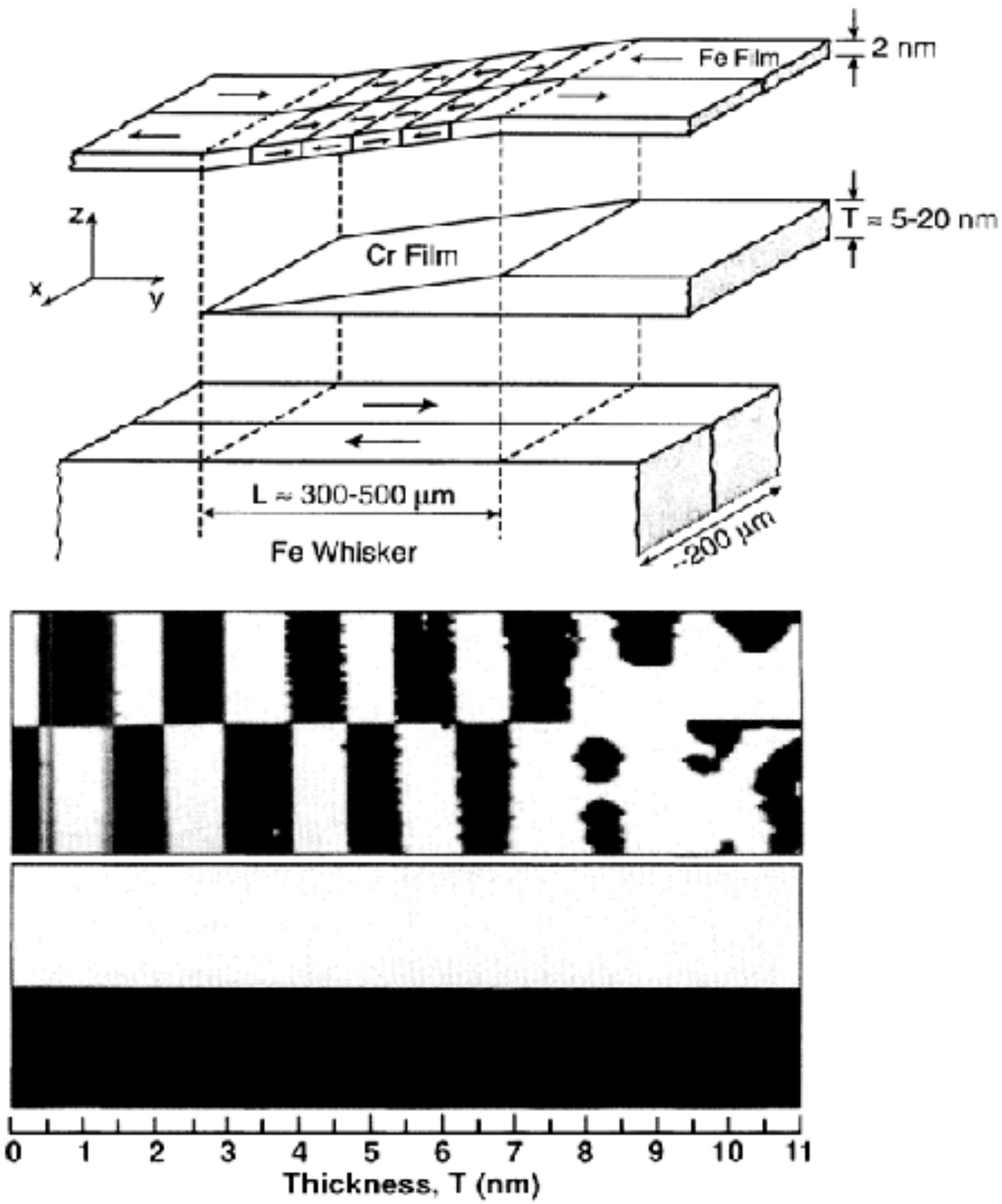
Spin-spin response functions describes the excitation of spin waves



Spin-spin response functions describes the excitation of spin waves

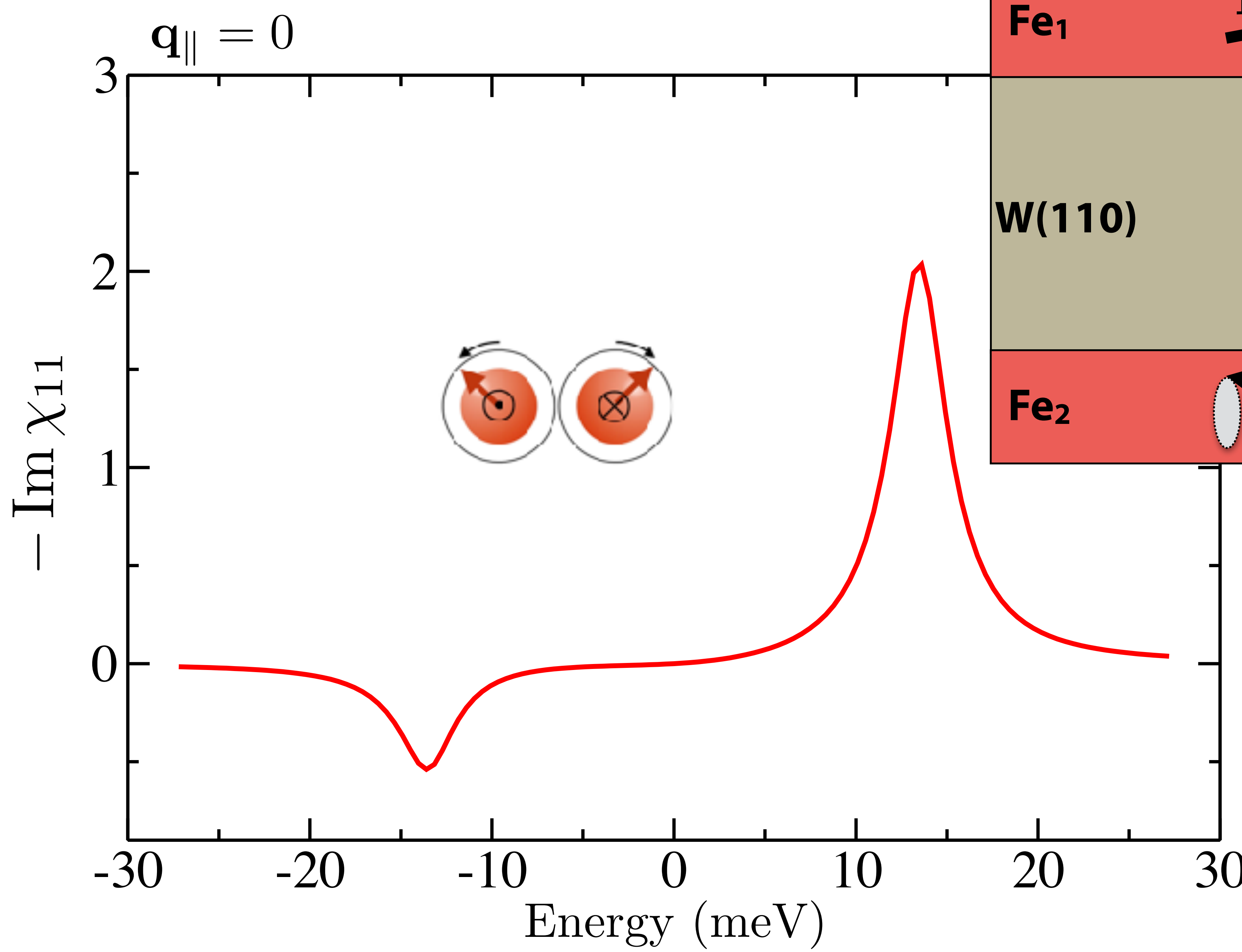


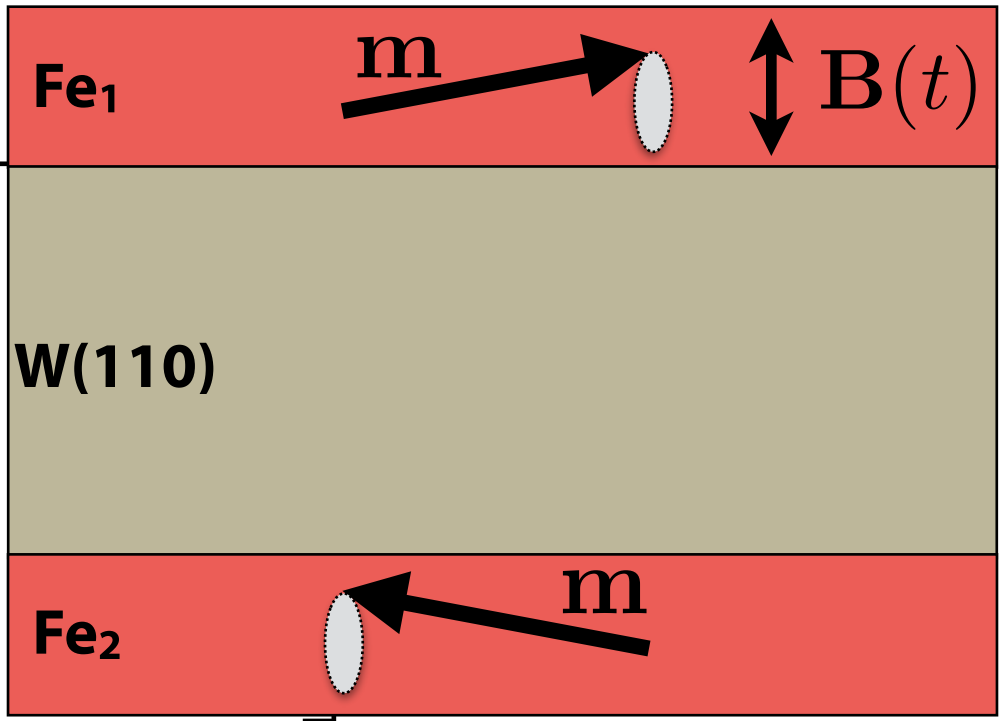
Oscillatory interlayer coupling may be used to design synthetic antiferromagnets



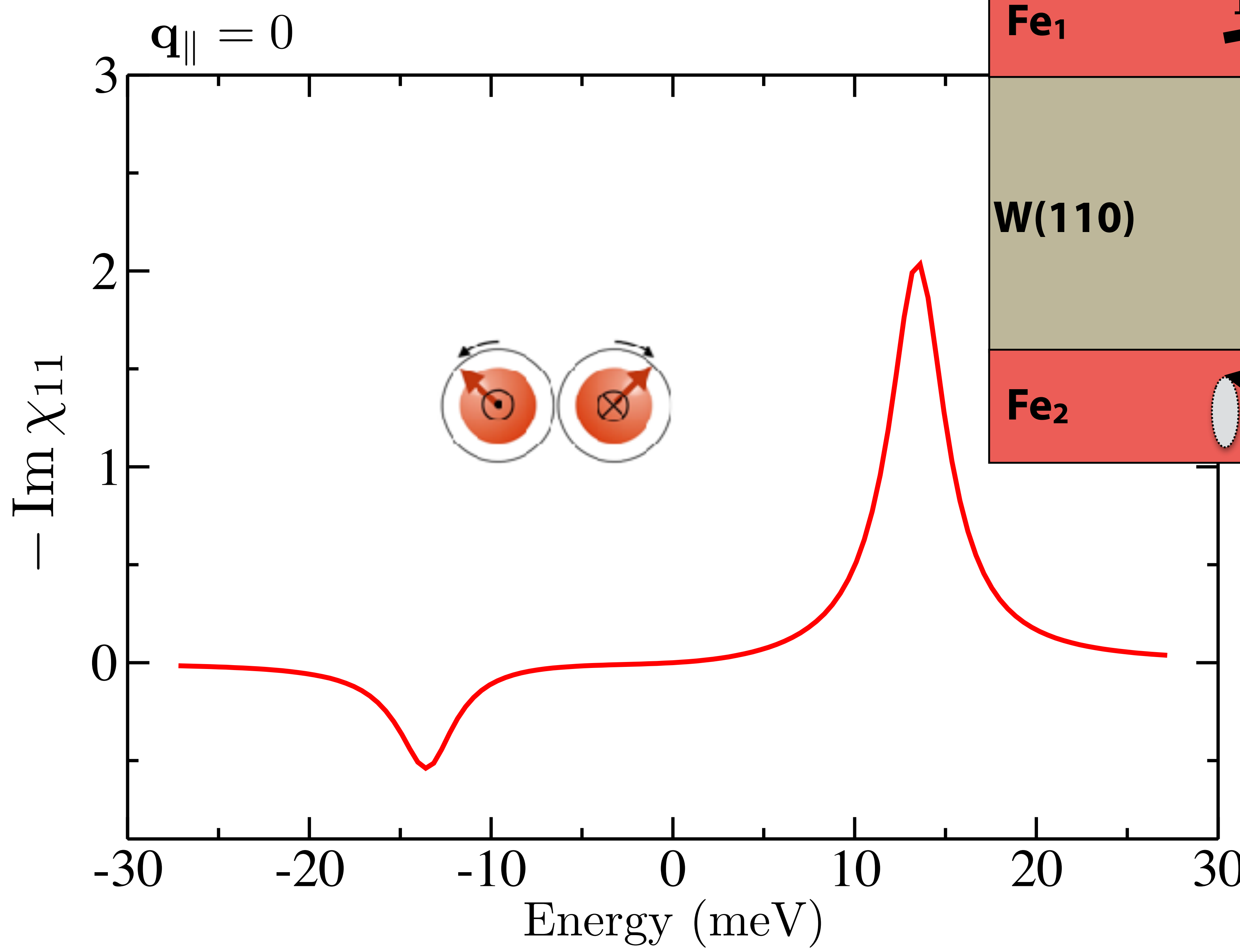
J. Unguris *et al.*, Phys. Rev. Lett. **67**, 140 (1991)

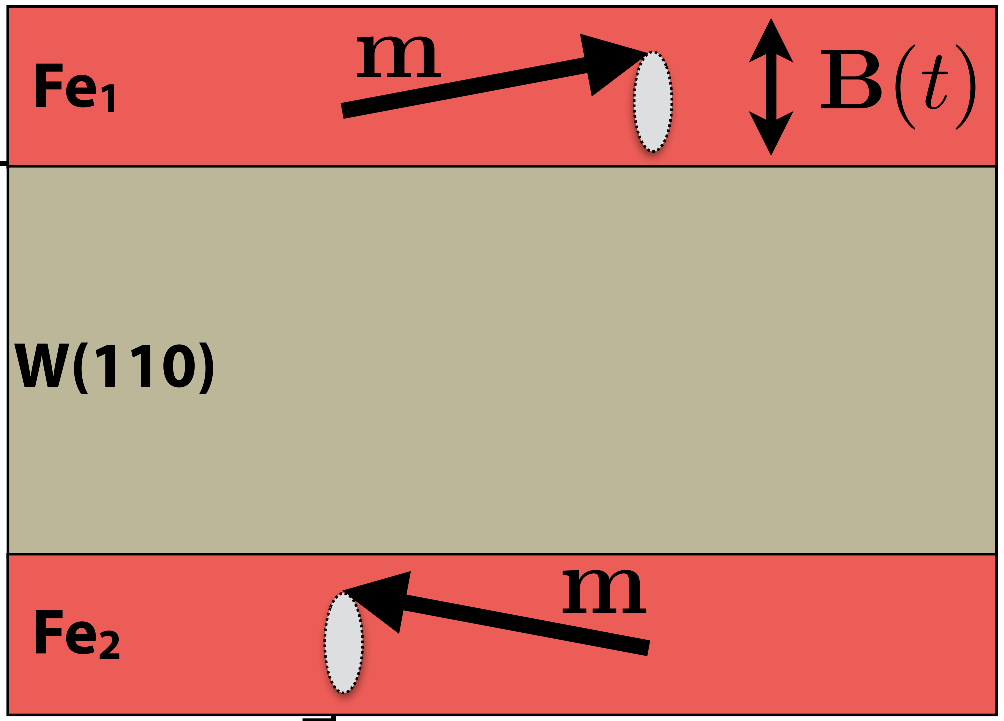
Spin-spin response functions describes the excitation of spin waves





Spin-spin response functions describes the excitation of spin waves





Each combination perturbation/observable describes different phenomenon

perturbation

magnetic field

electric field

Spin Hall Effect

Inverse Spin Galvanic

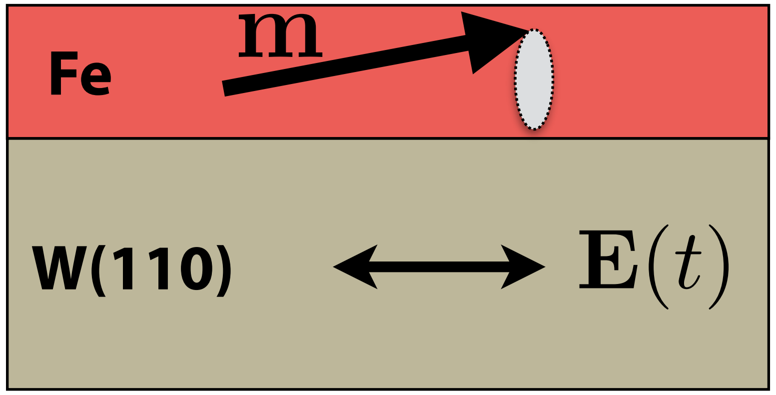
observable

spin density

spin currents

charge currents

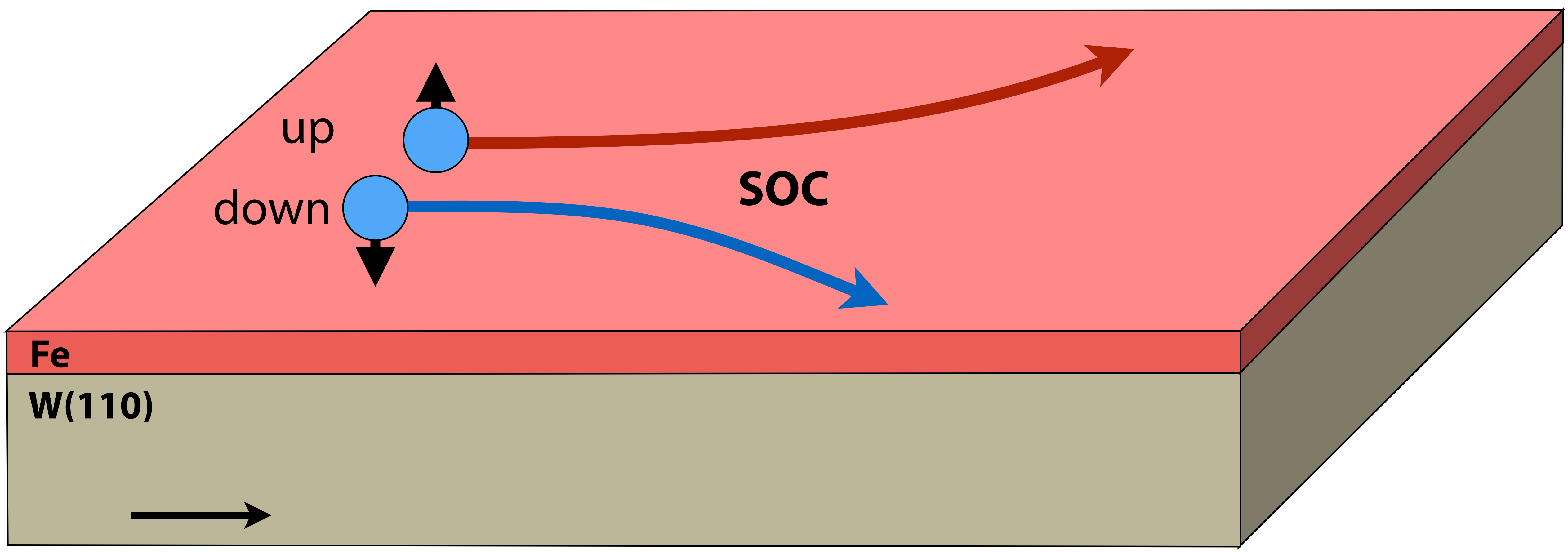
...



$\delta\langle\mathbf{m}_i\rangle(t)$

$\langle\mathbf{I}_i^{\mathrm{S}}\rangle(t)$

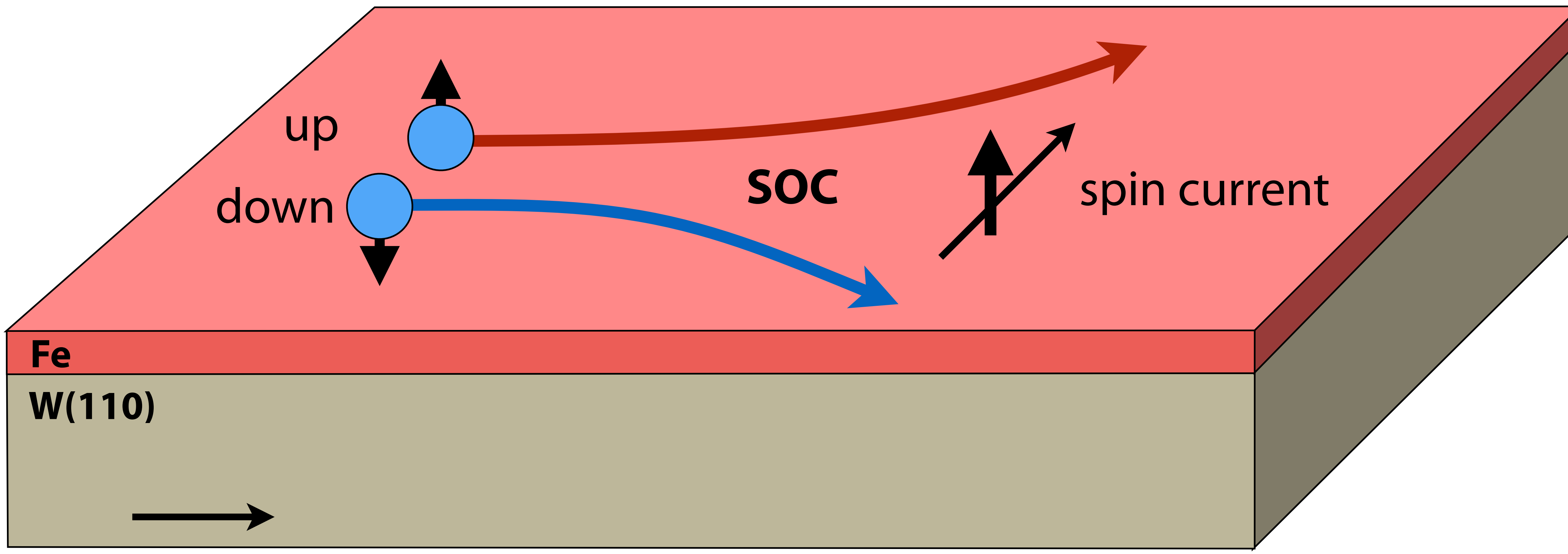
Spin currents are generated by the spin Hall effect



$$\mathbf{E}(\mathbf{r},t) = E_0 \cos(\omega t)\hat{\mathbf{x}}$$

Spin currents are generated by the spin Hall effect

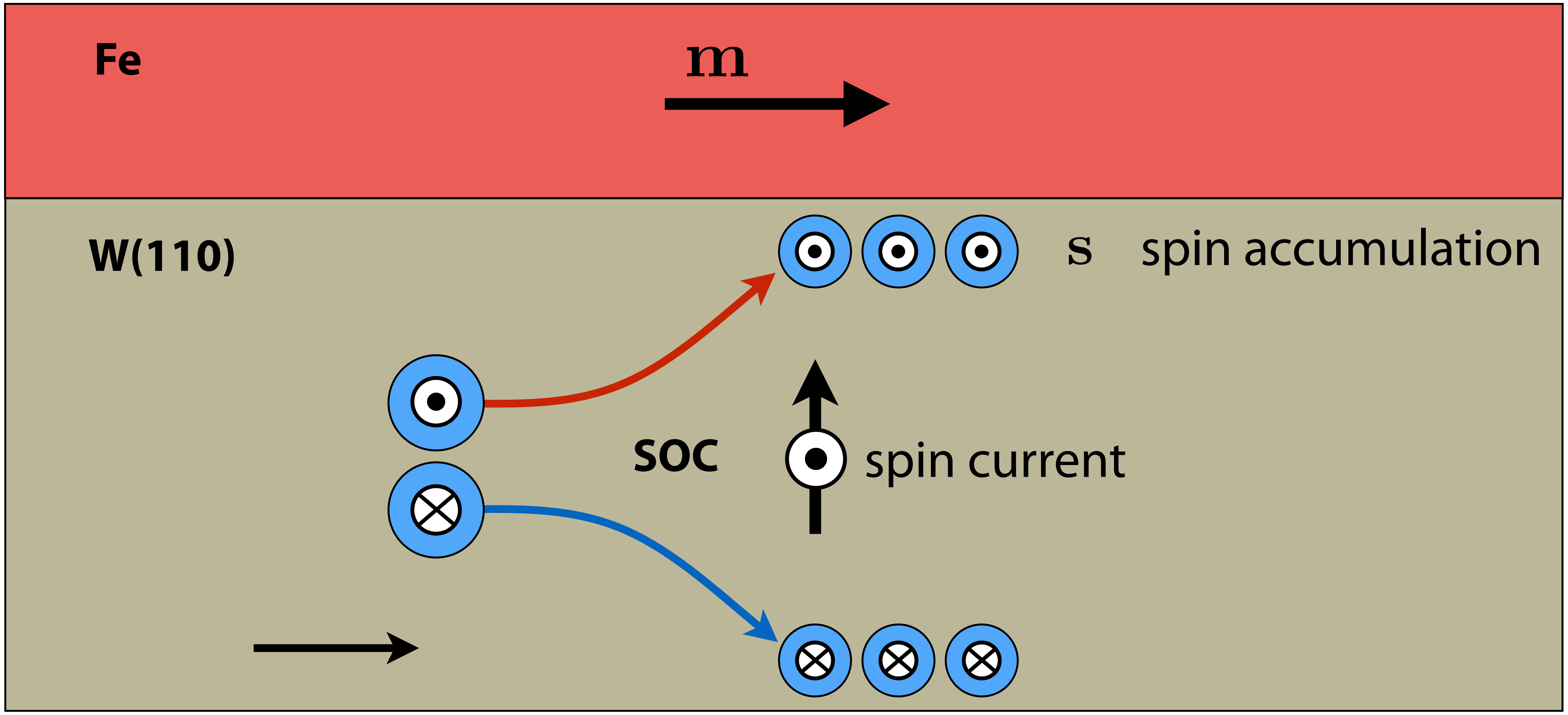
Spin currents are generated by the spin Hall effect



$$\mathbf{E}(\mathbf{r},t) = E_0 \cos(\omega t)\hat{\mathbf{x}}$$

Spin Hall Effect

Spin Hall angle: $\theta_{\mathrm{SH}} \propto \frac{I_{\perp}^{\mathrm{S}}}{I_{\parallel}^{\mathrm{C}}}$

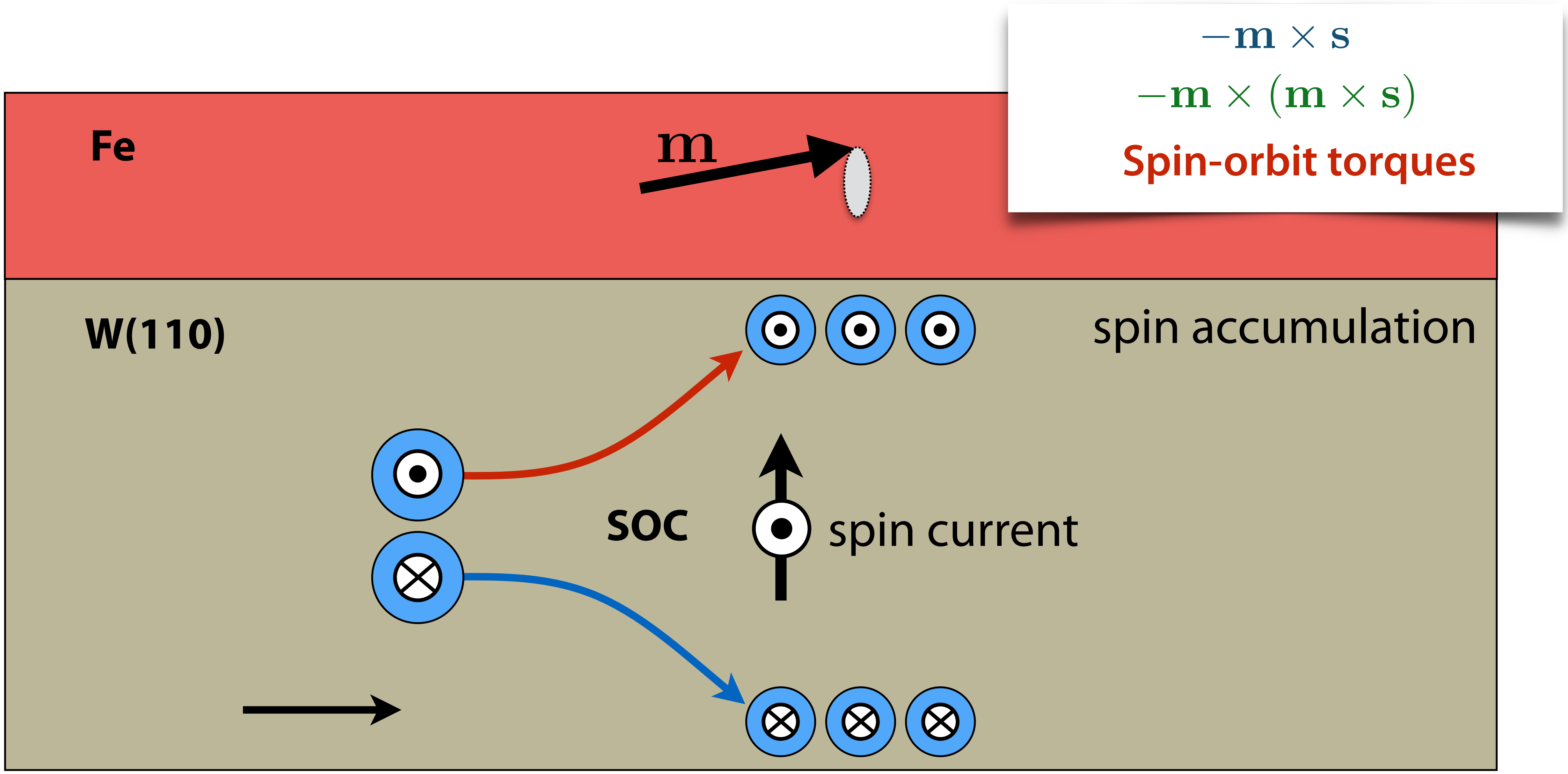


$$\mathbf{E}(\mathbf{r},t) = E_0 \cos(\omega t)\hat{\mathbf{x}}$$

Spin Hall Effect

Inverse Spin Galvanic Effect

Spin dependent scattering



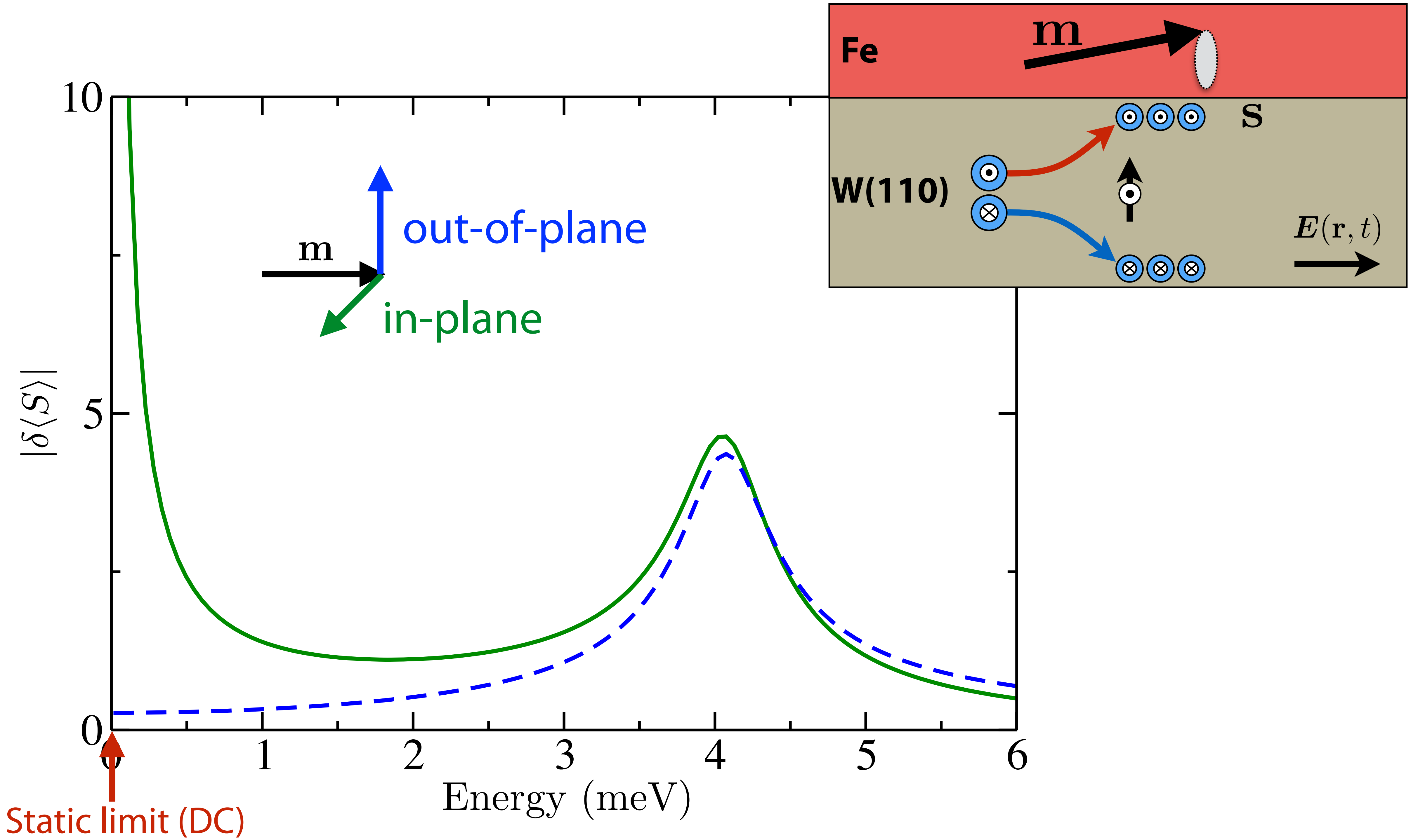
$$\mathbf{E}(\mathbf{r},t) = E_0\cos(\omega t)\hat{\mathbf{x}}$$

Spin Hall Effect

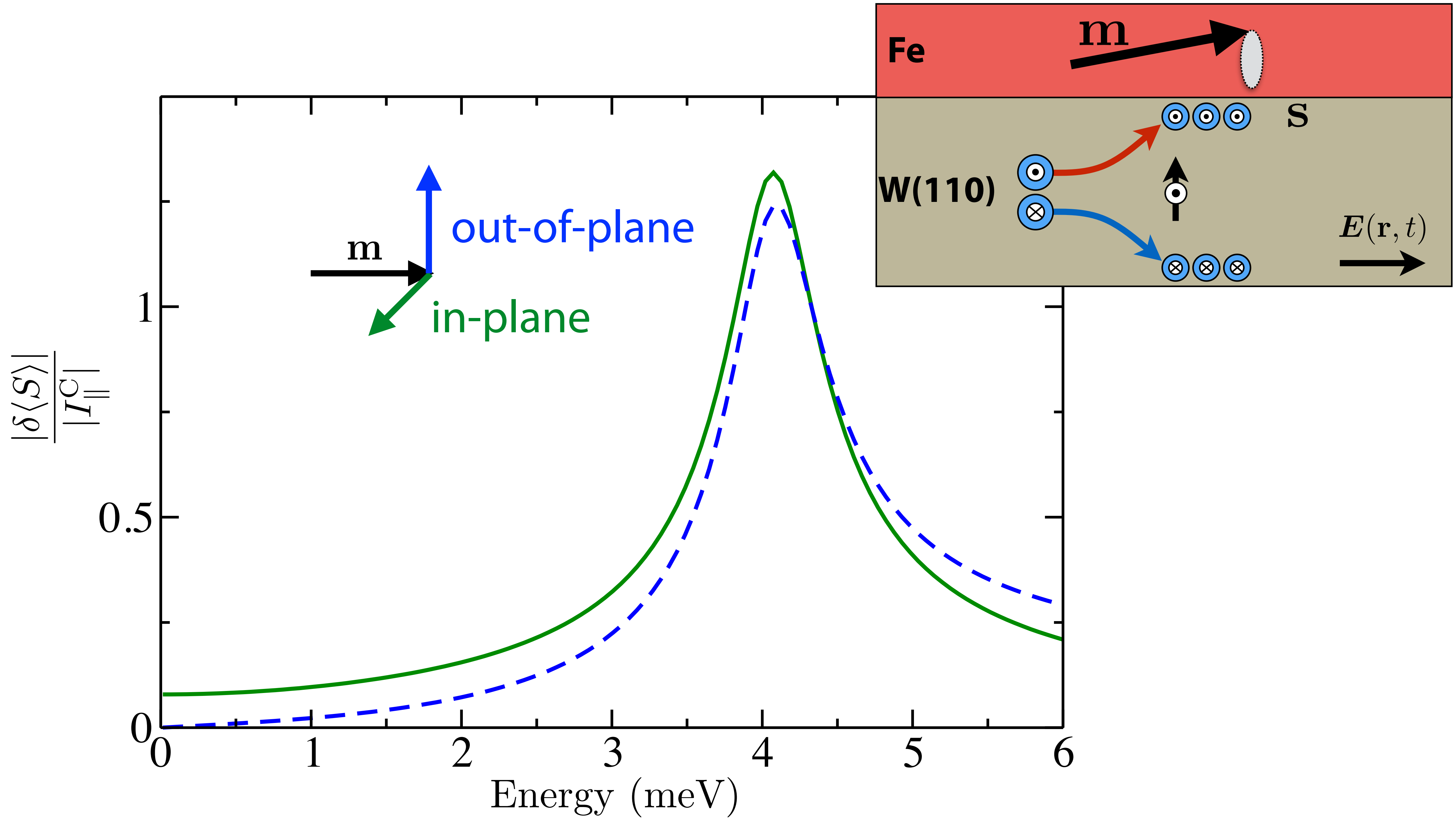
Inverse Spin Galvanic Effect

Spin dependent scattering

Current-driven ferromagnetic resonance



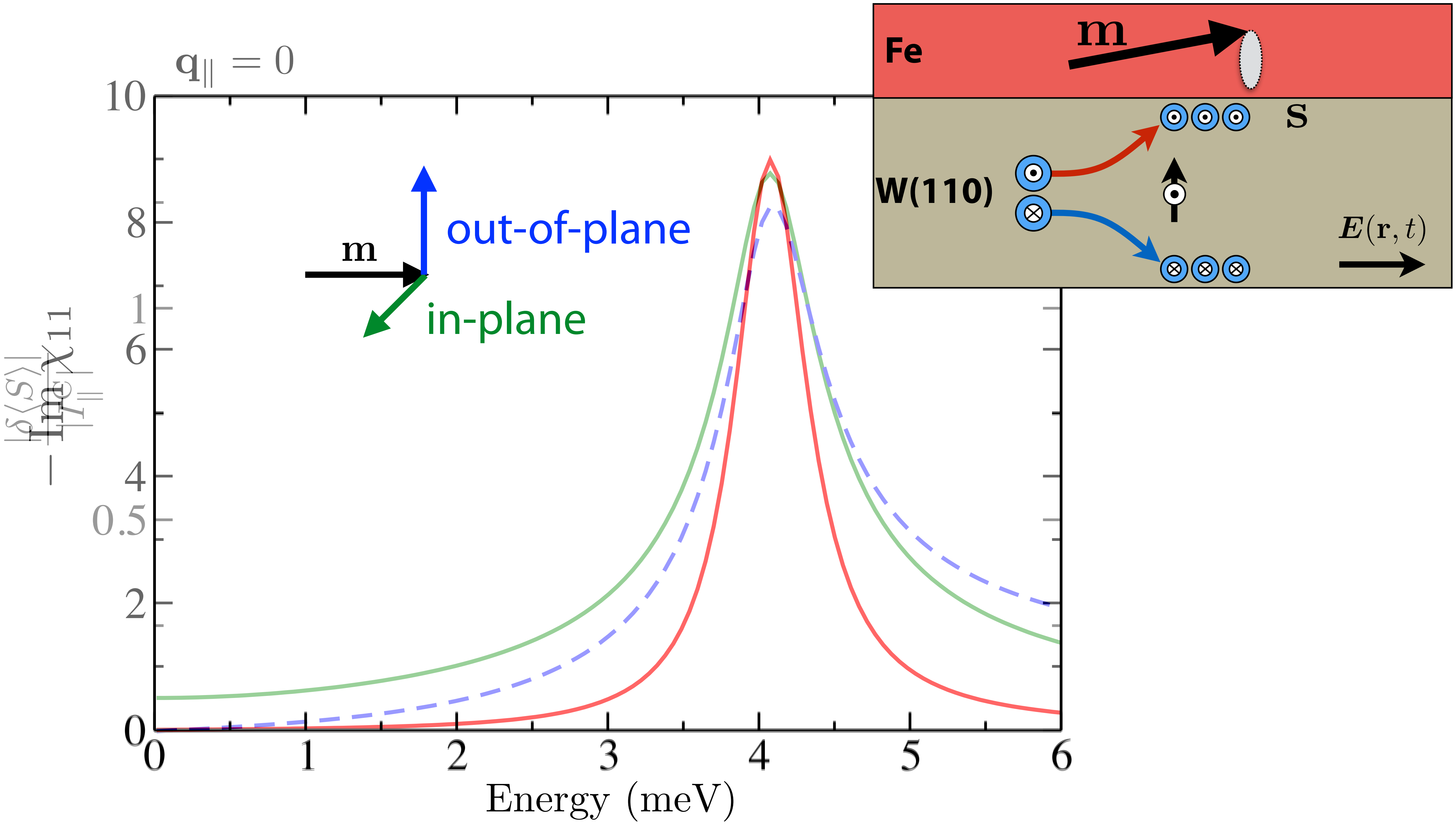
Current-driven ferromagnetic resonance



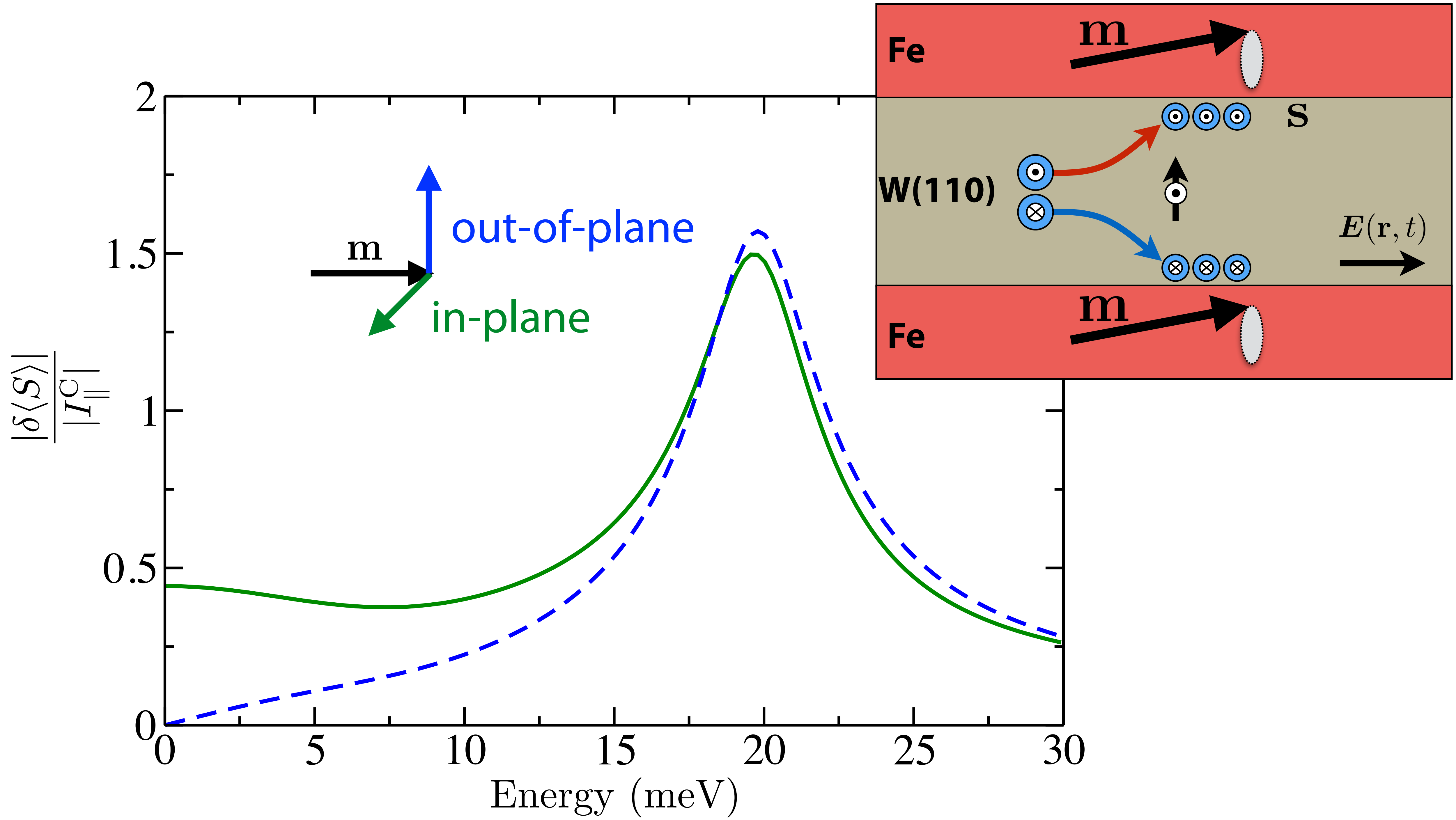
f.guimaraes@fz-juelich.de

PRB 92, 220410(R) (2015)

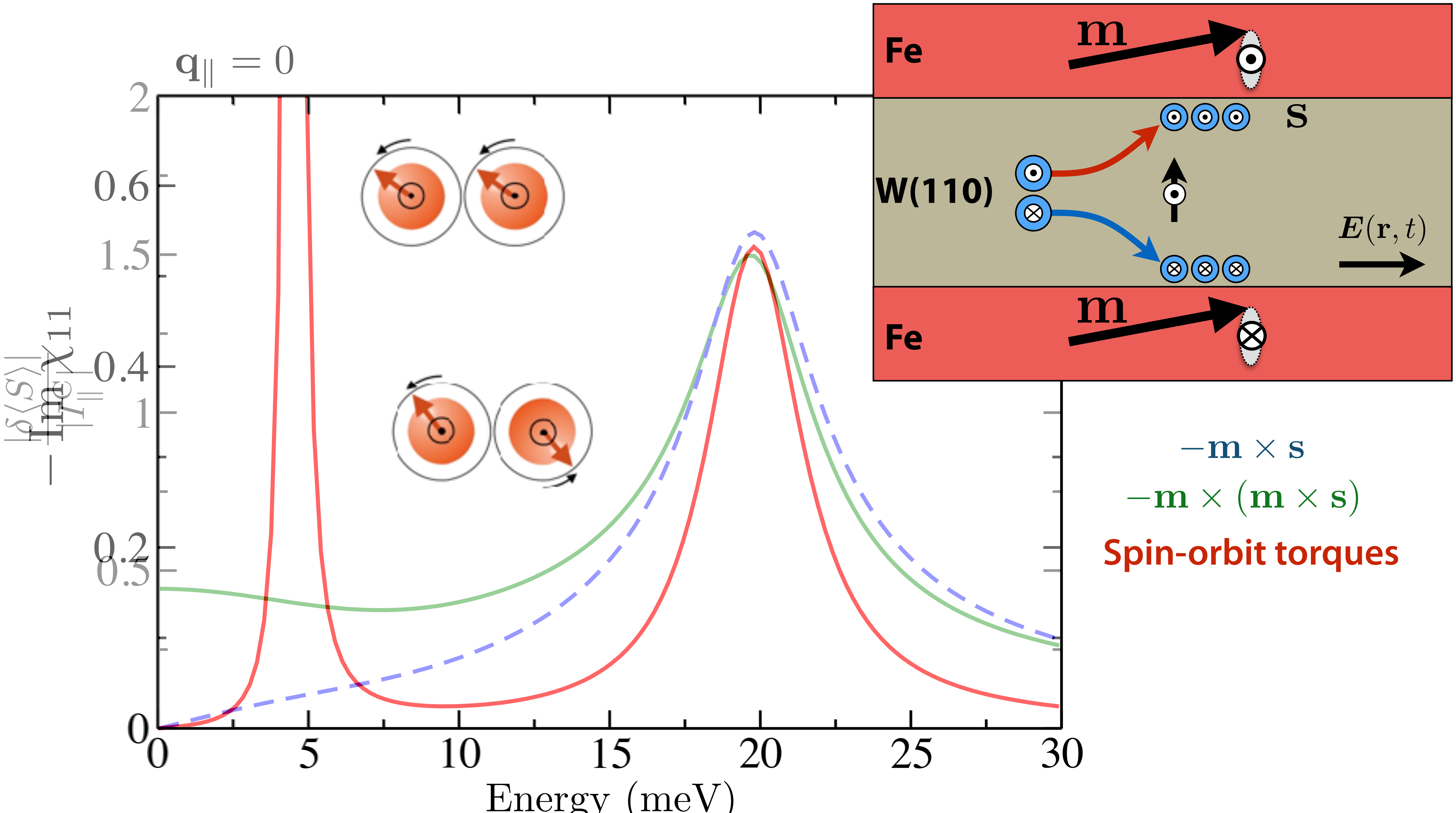
Current-driven ferromagnetic resonance



Current-driven optical resonance



Current-driven optical resonance



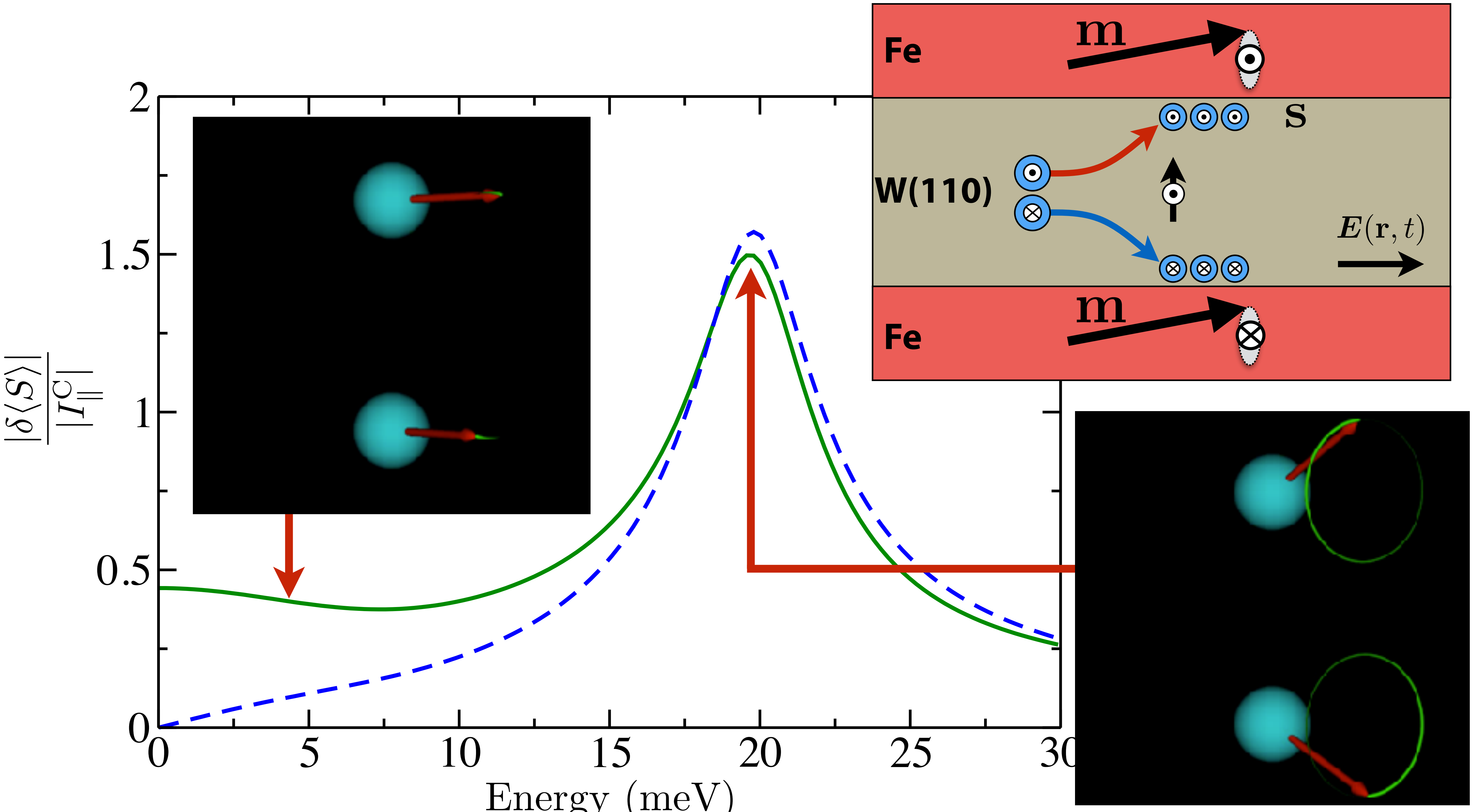
$-\mathbf{m} \times \mathbf{s}$

$-\mathbf{m} \times (\mathbf{m} \times \mathbf{s})$

Spin-orbit torques

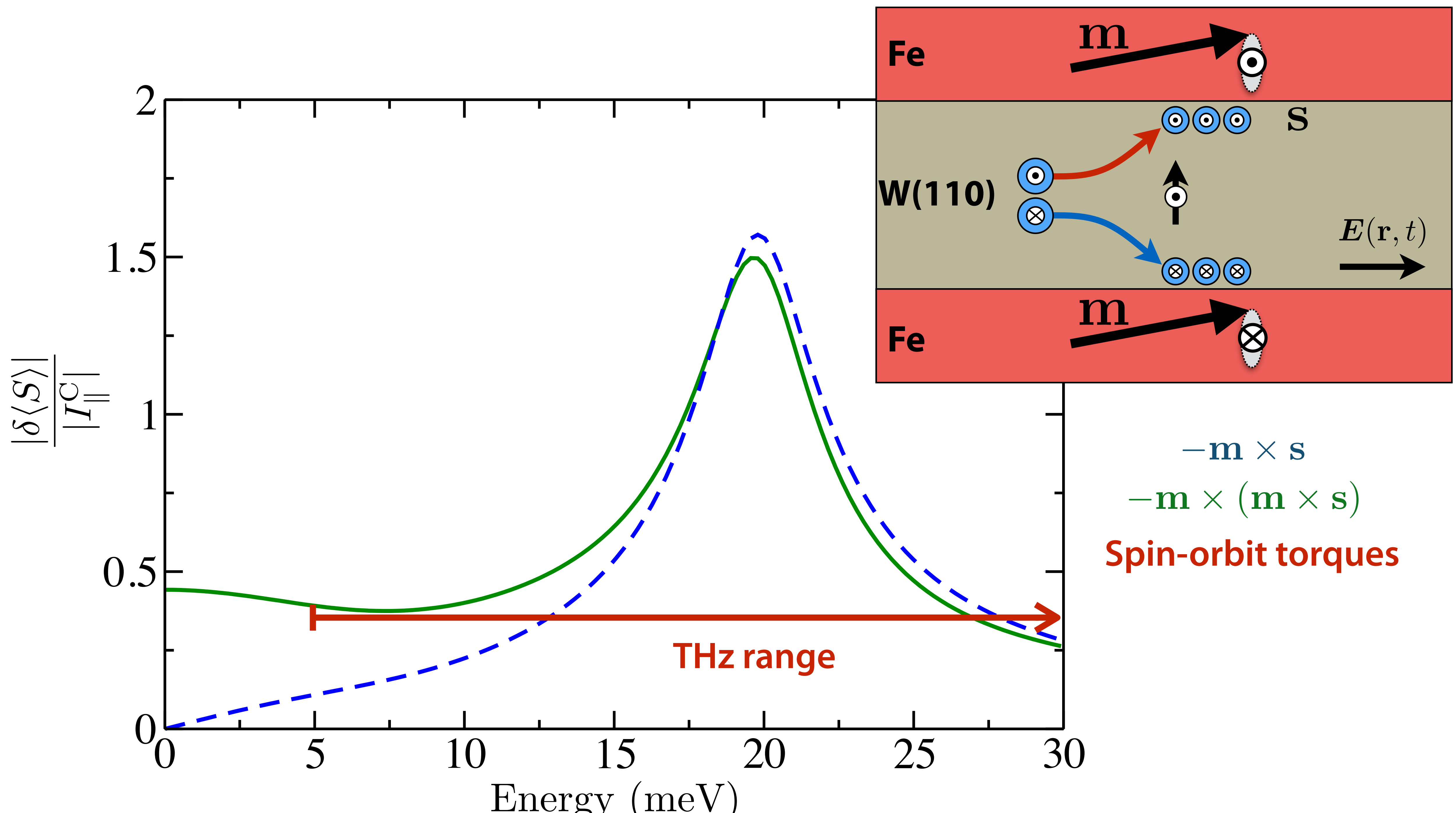
Acoustic mode is silent

Current-driven optical resonance



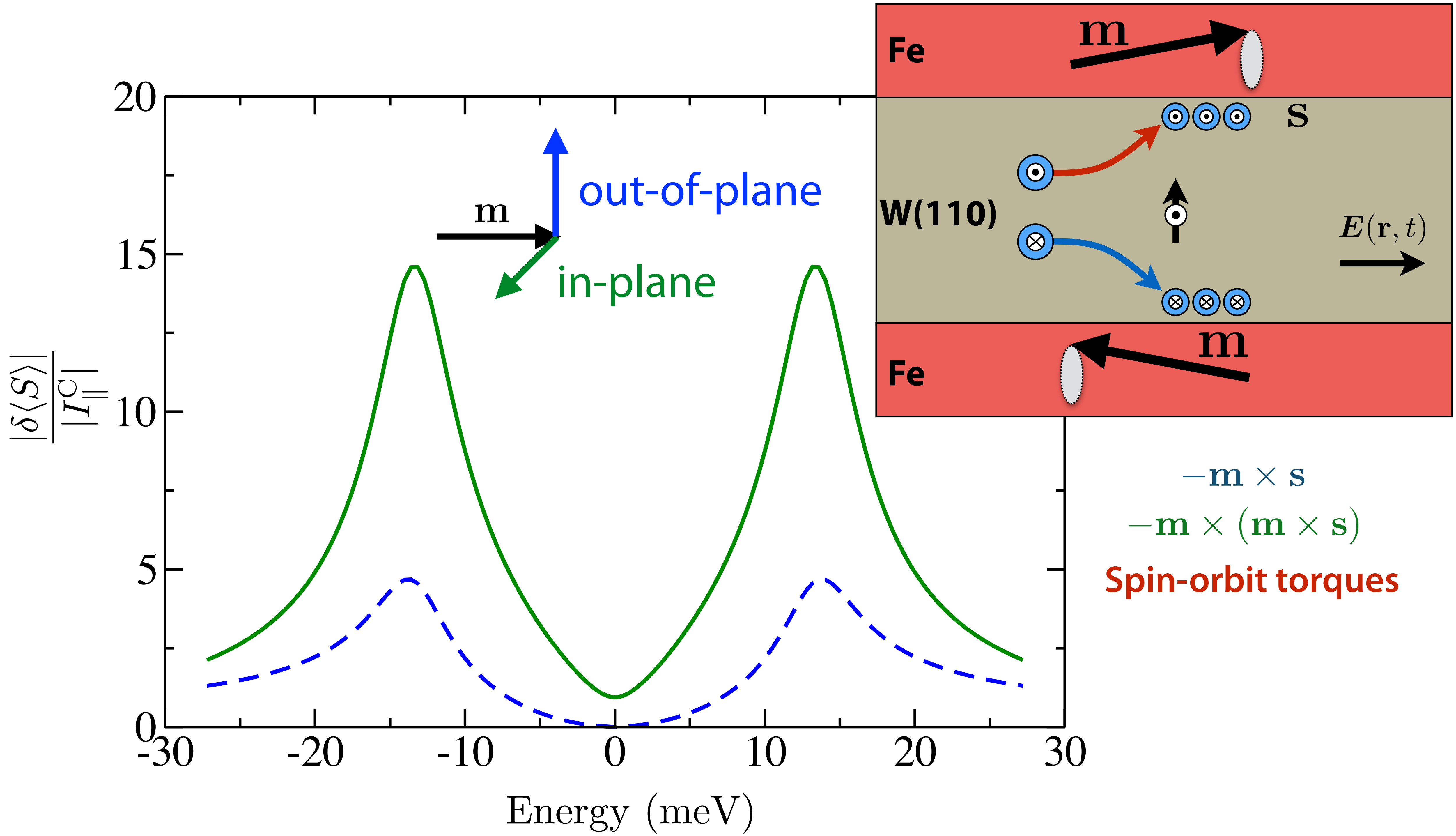
Acoustic mode is silent

Current-driven optical resonance



Acoustic mode is silent

Current-driven antiferromagnetic resonance



$-\mathbf{m}\times\mathbf{s}$

$-\mathbf{m}\times(\mathbf{m}\times\mathbf{s})$

Spin-orbit torques

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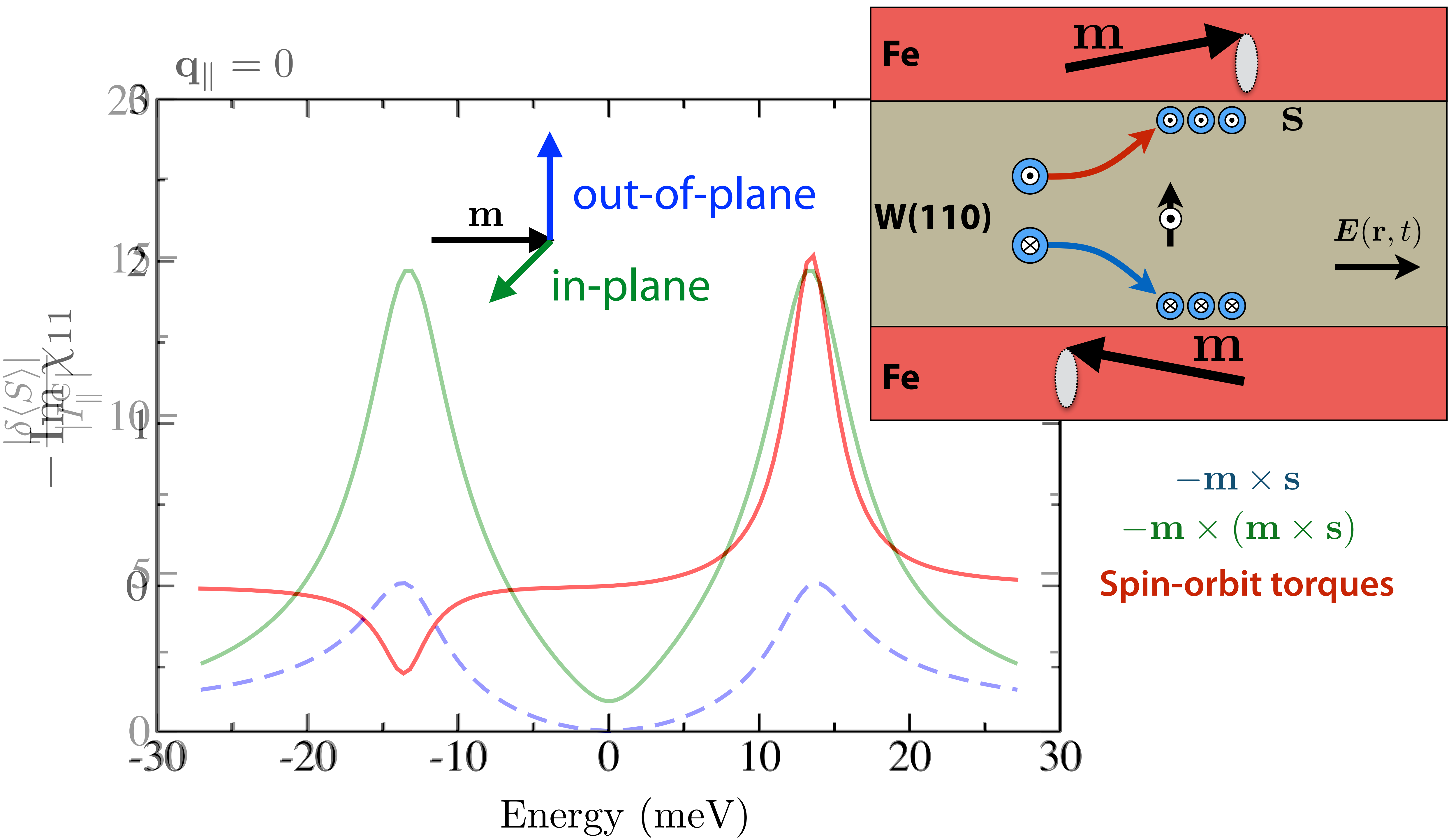

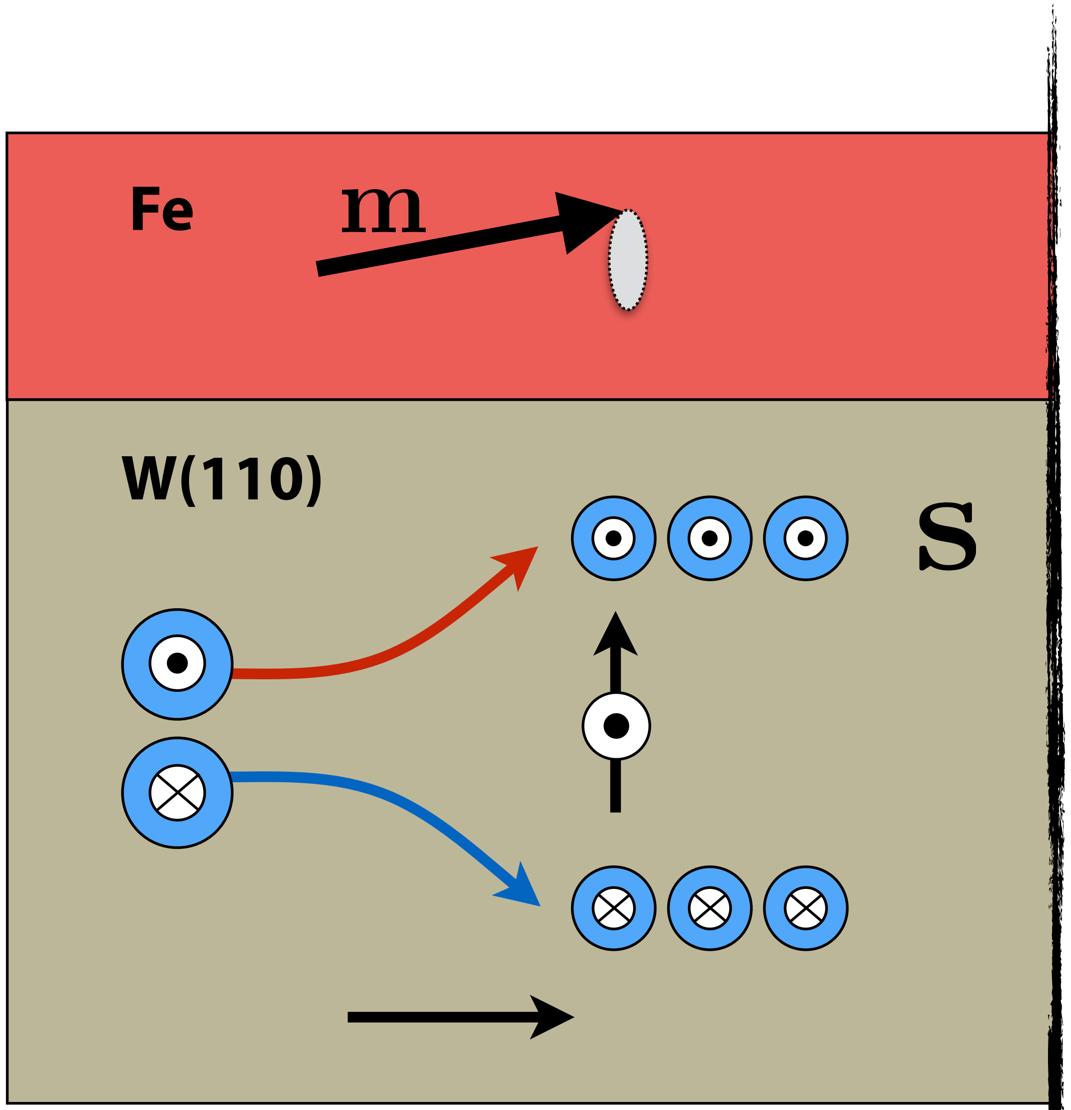

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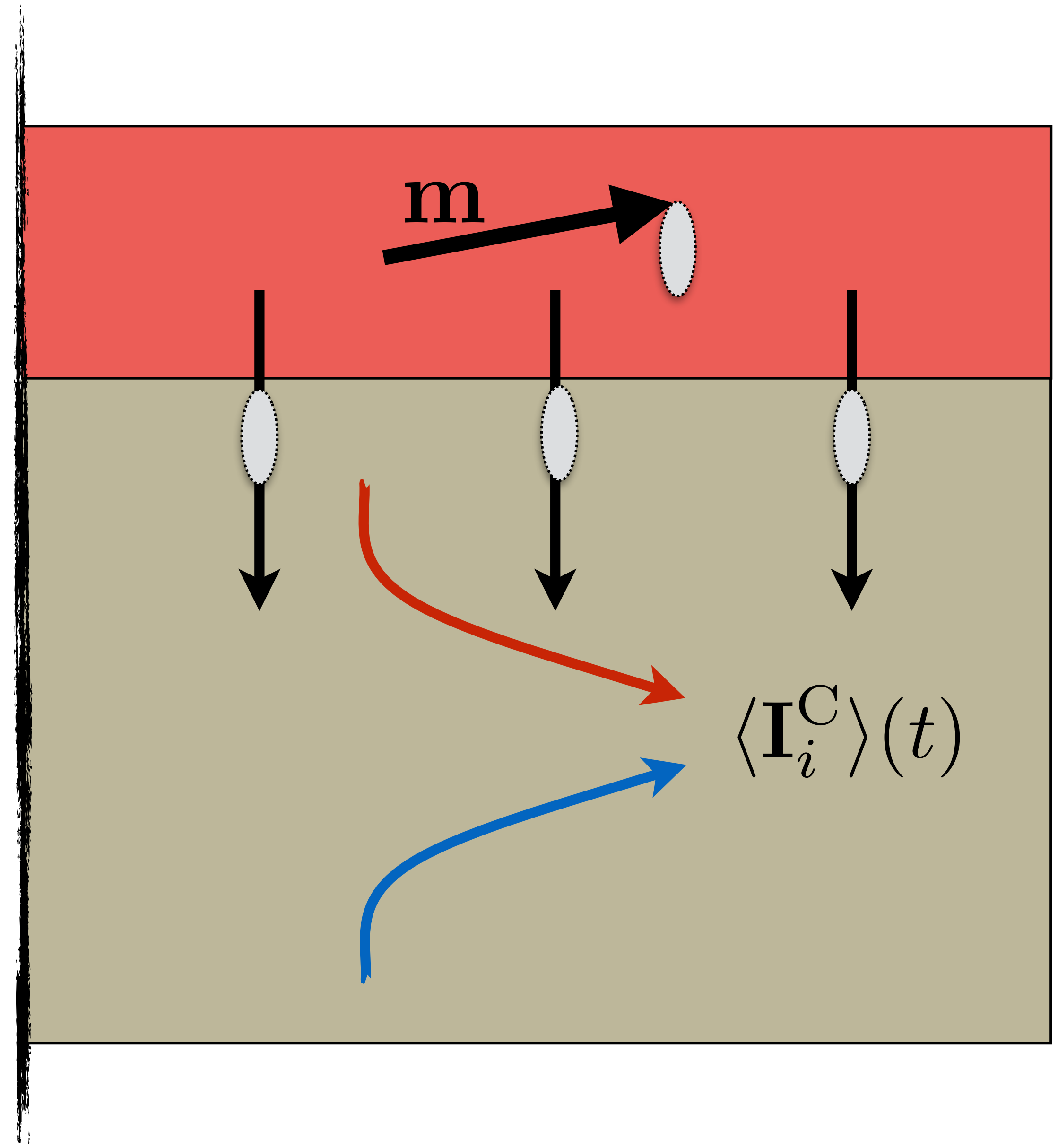
Spin Hall Effect

Inverse Spin Galvanic Effect

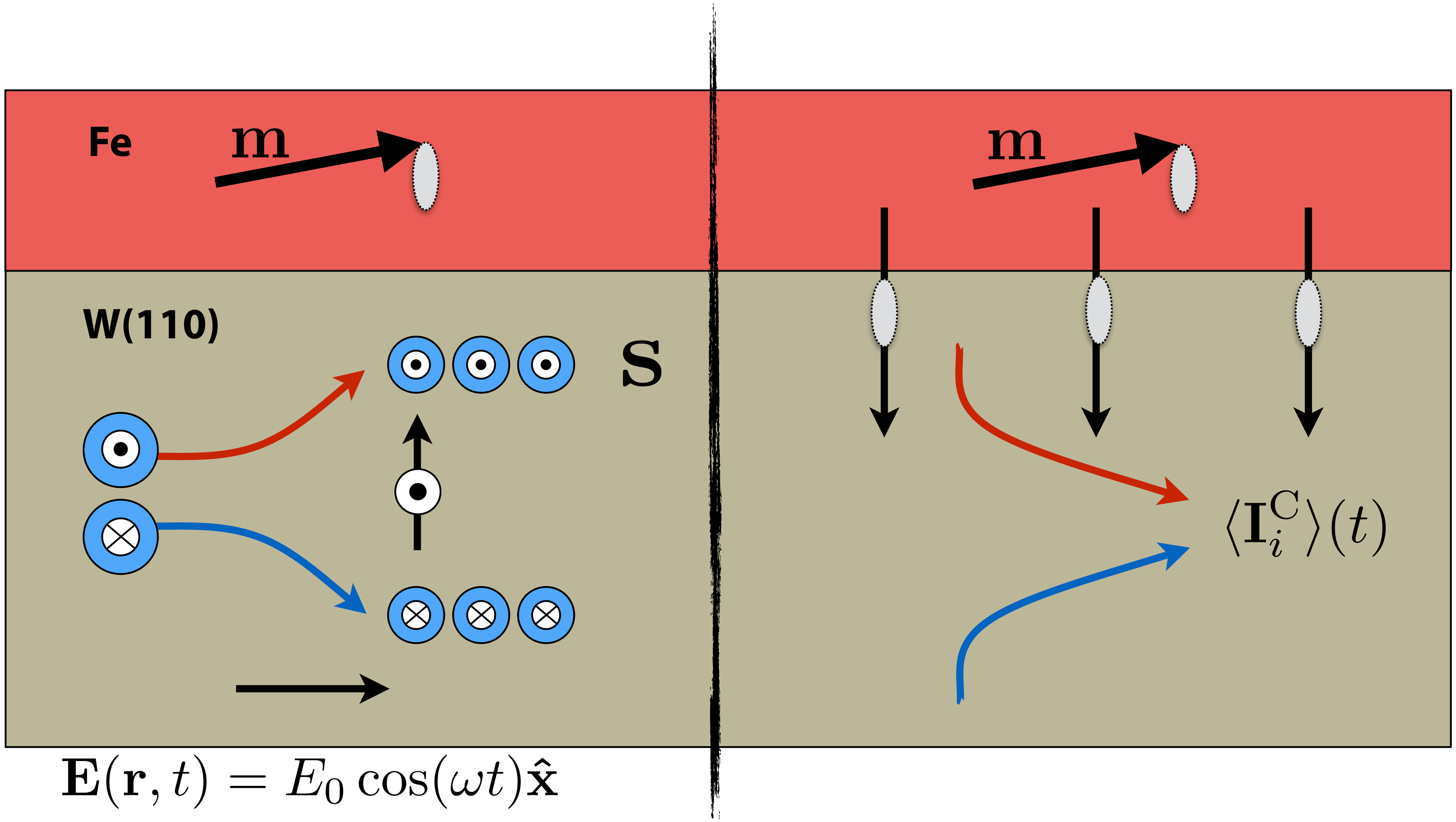
Spin dependent scattering



Spin pumping

Inverse Spin Hall Effect

Spin Galvanic Effect



Spin Hall Effect

Inverse Spin Galvanic Effect

Spin dependent scattering

Spin pumping

Inverse Spin Hall Effect

Spin Galvanic Effect

Each combination perturbation/observable describes different phenomenon

perturbation

magnetic field

electric field

Spin Hall angle
Magnetoresistances
Hall effects

observable

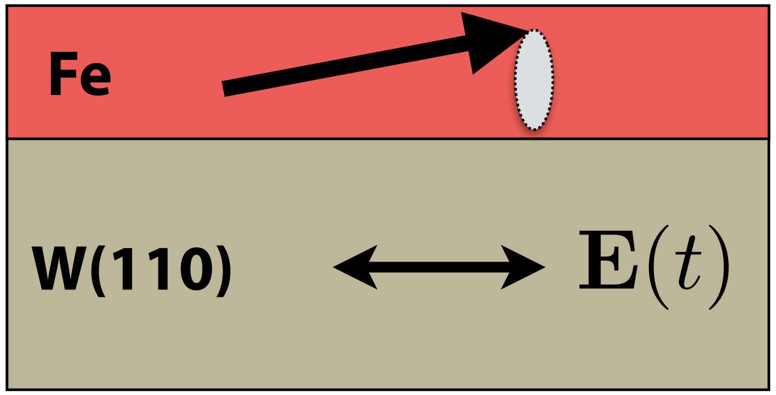
spin density

spin currents

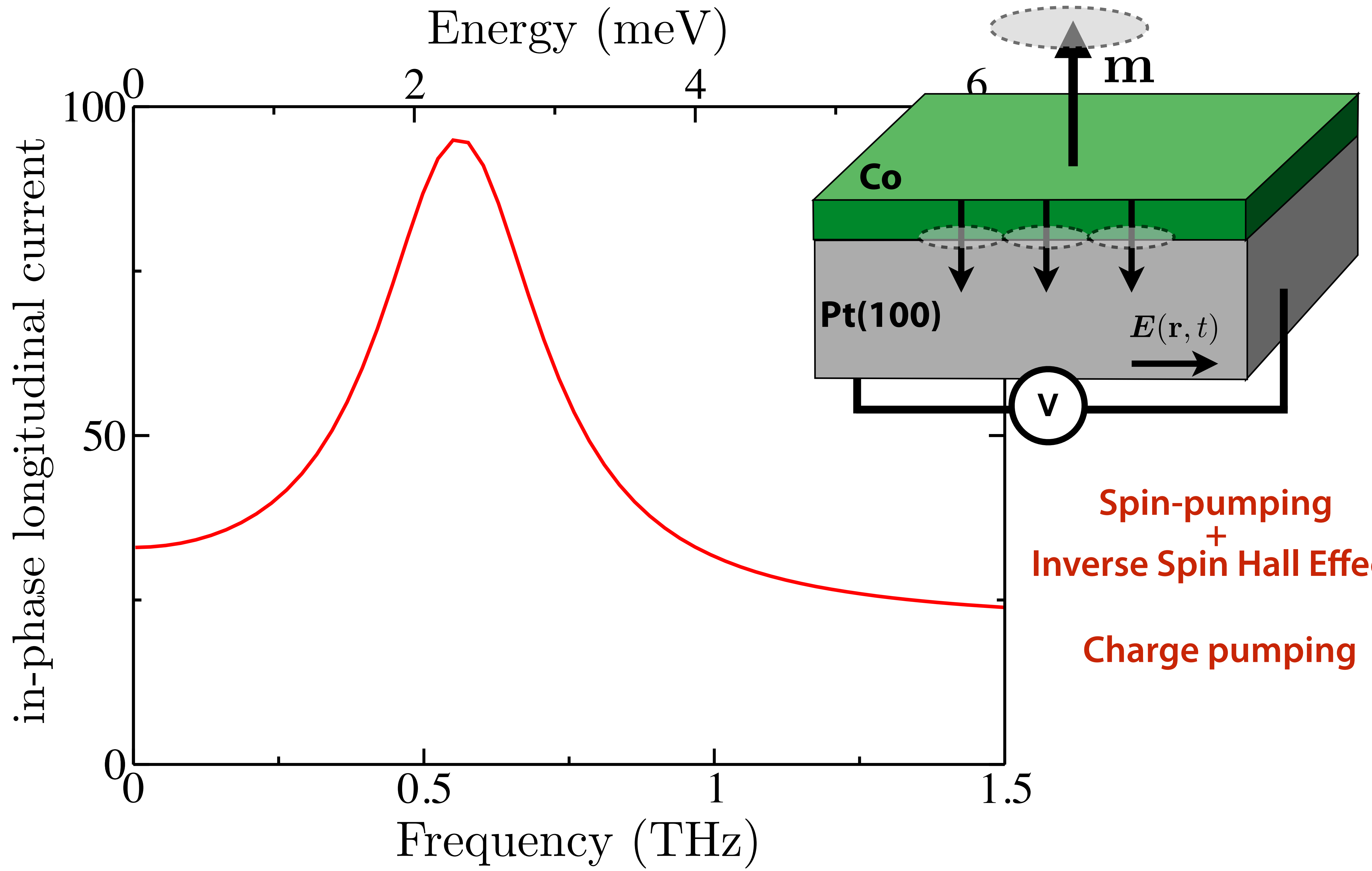
charge currents

…

$\langle \mathbf{I}_i^{\mathrm{C}} \rangle(t)$



Dynamical longitudinal currents

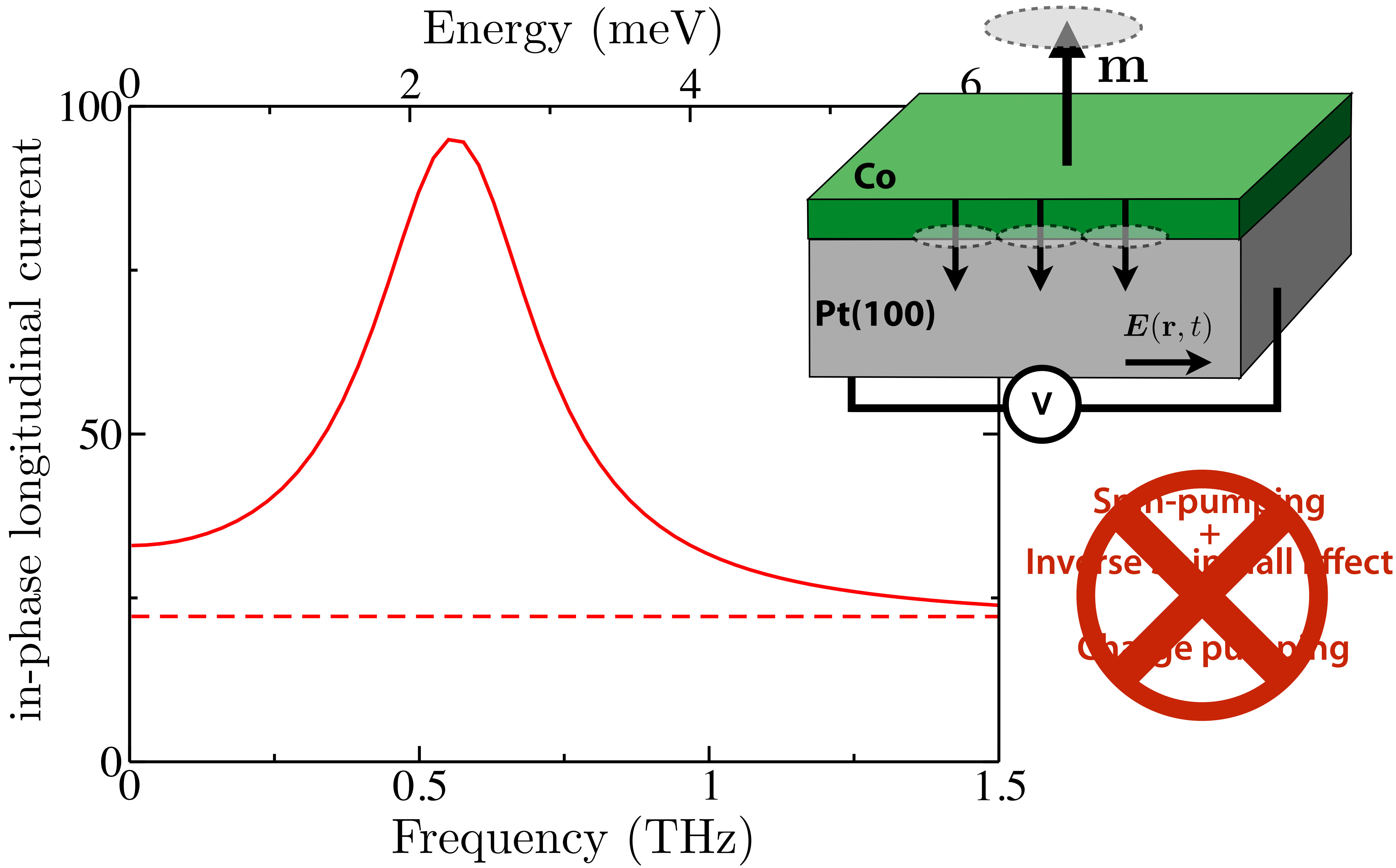


Spin-pumping
+
Inverse Spin Hall Effect

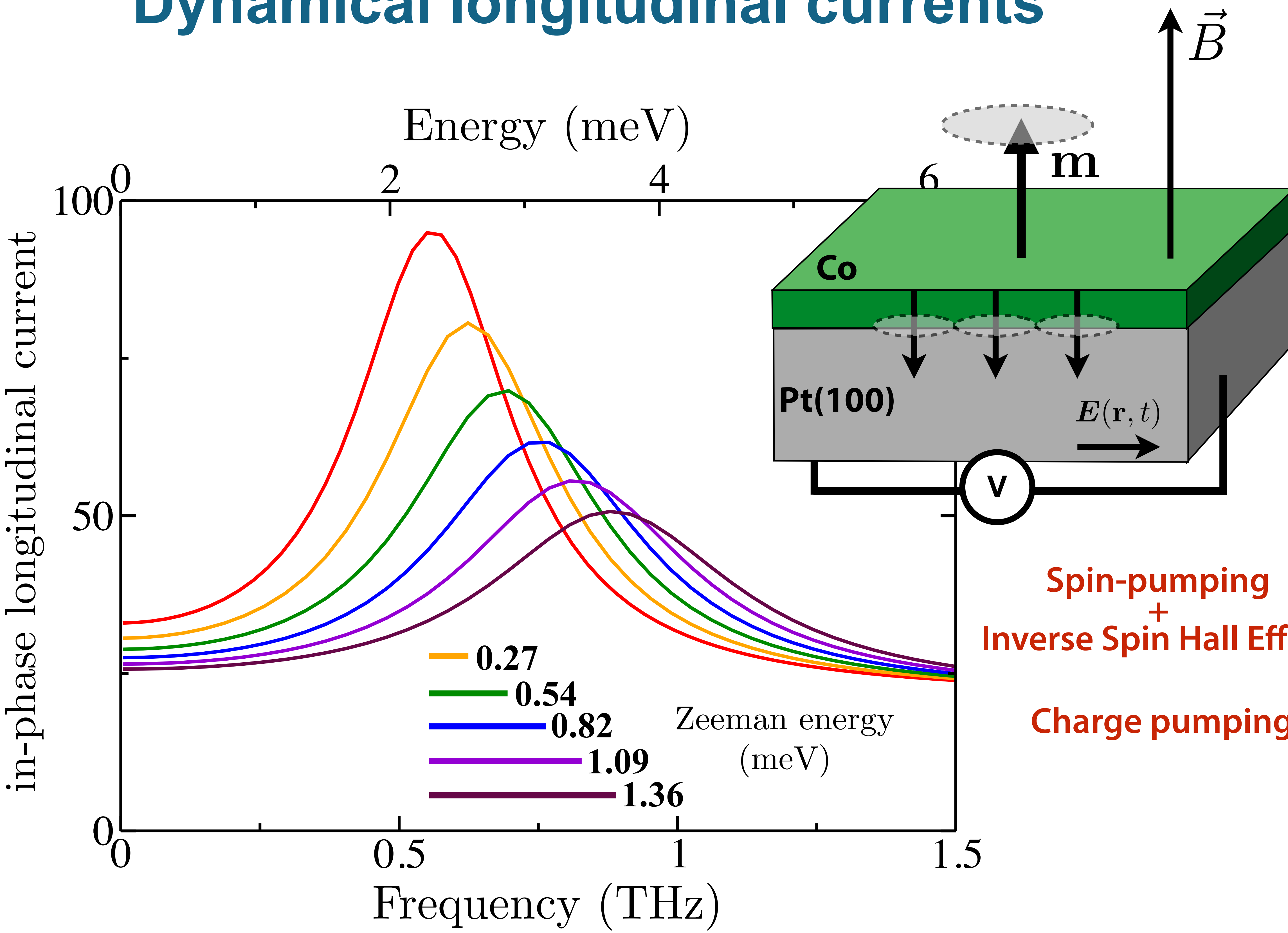
Charge pumping

f.guimaraes@fz-juelich.de

Dynamical longitudinal currents



Dynamical longitudinal currents



Spin-pumping
+
Inverse Spin Hall Effect

Charge pumping

Each combination perturbation/observable describes different phenomenon

perturbation

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electric field

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Magnetoresistances

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spin density

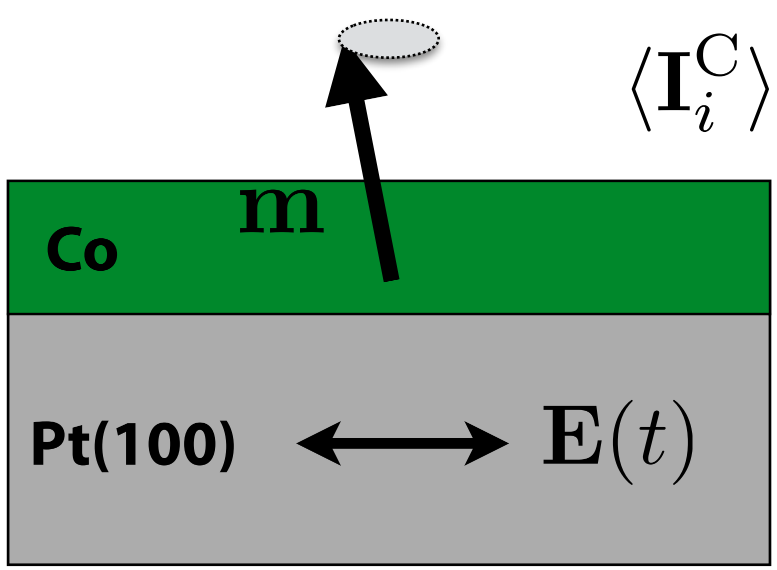
spin currents

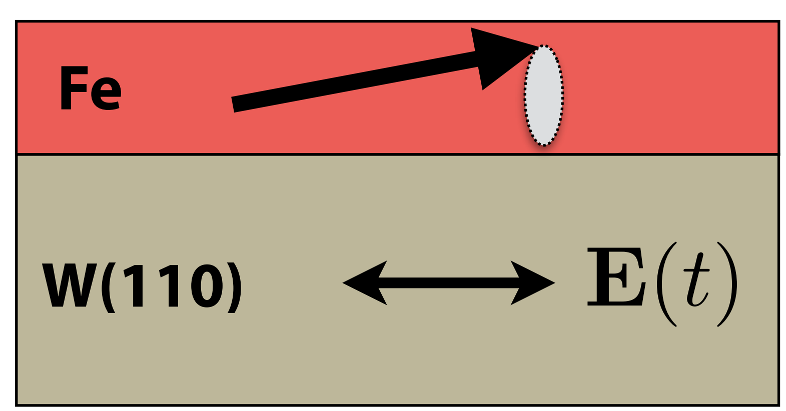
charge currents

...

$$\langle \mathbf{I}_i^{\mathrm{C}} \rangle (t) \propto \theta_{\mathrm{SH}}^2$$

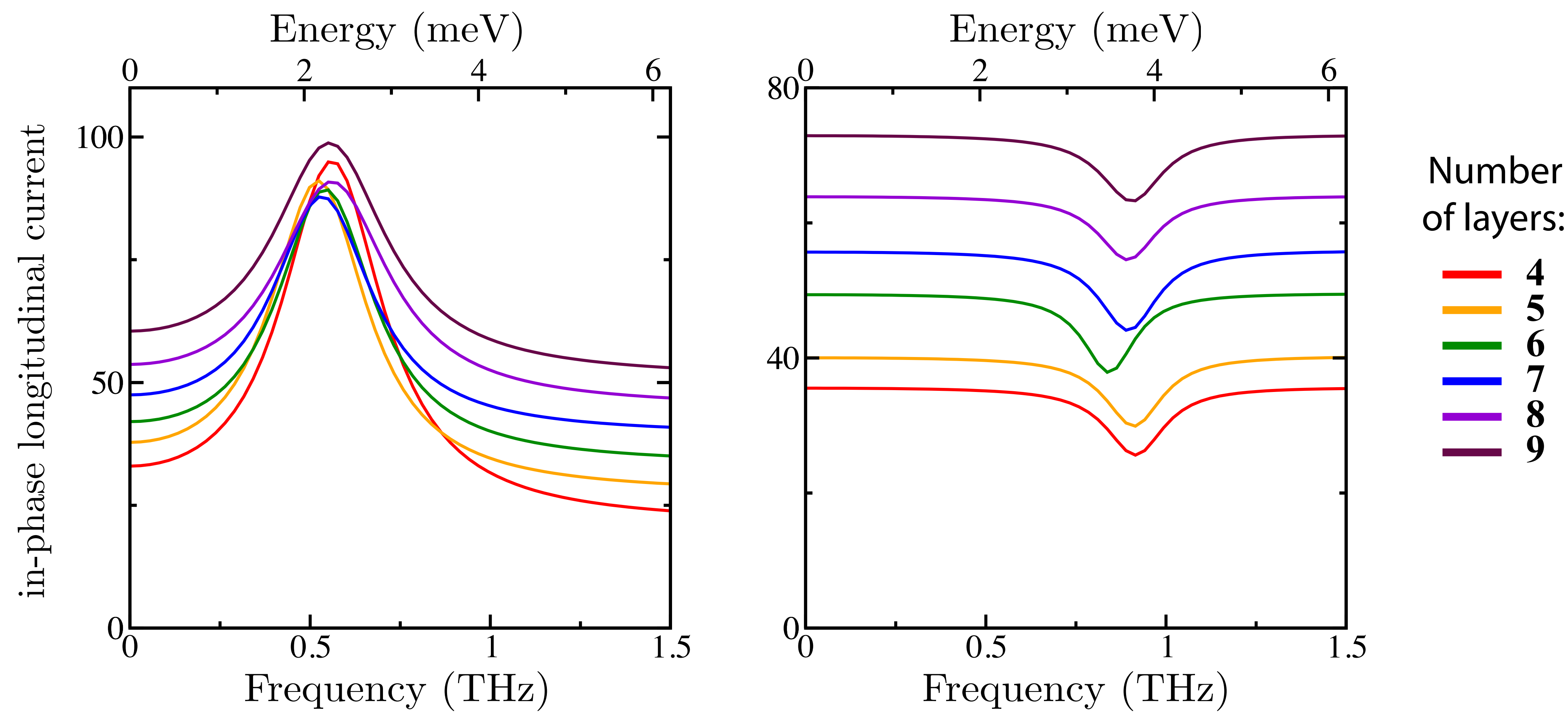
$\theta_{\mathrm{SH}} > 0$



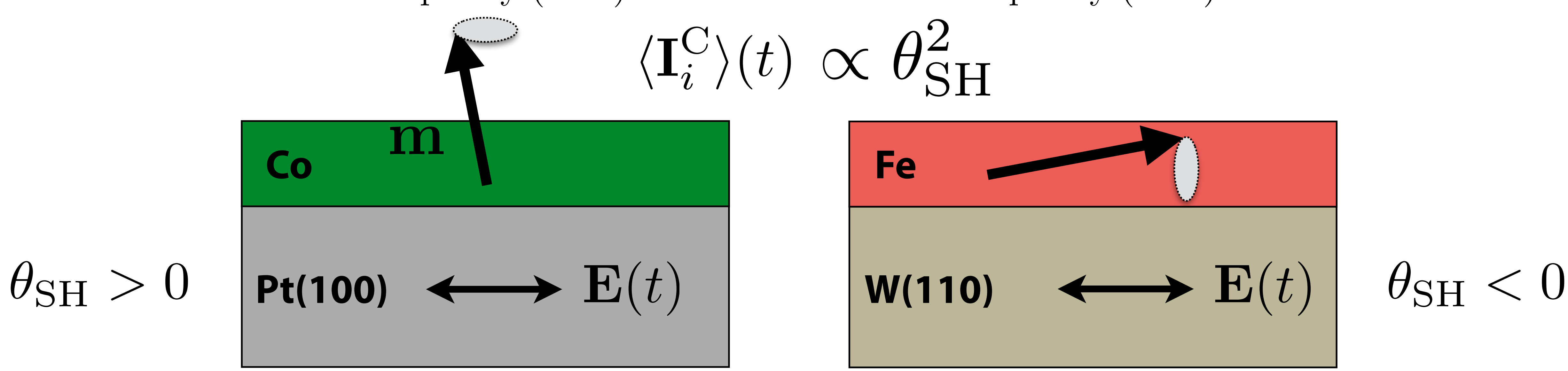


$\theta_{\mathrm{SH}} < 0$

Spin and charge pumping contribute to the currents

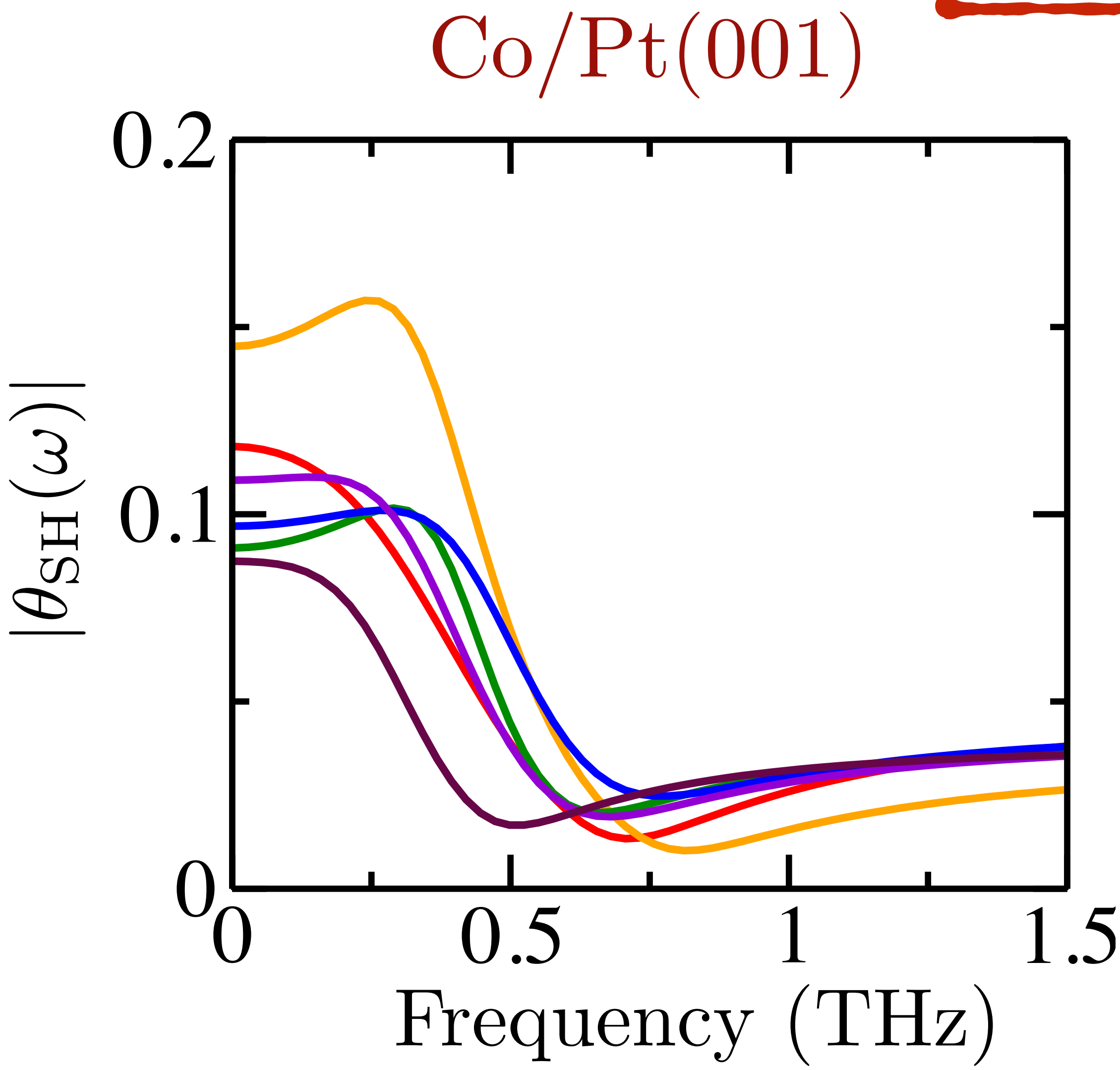


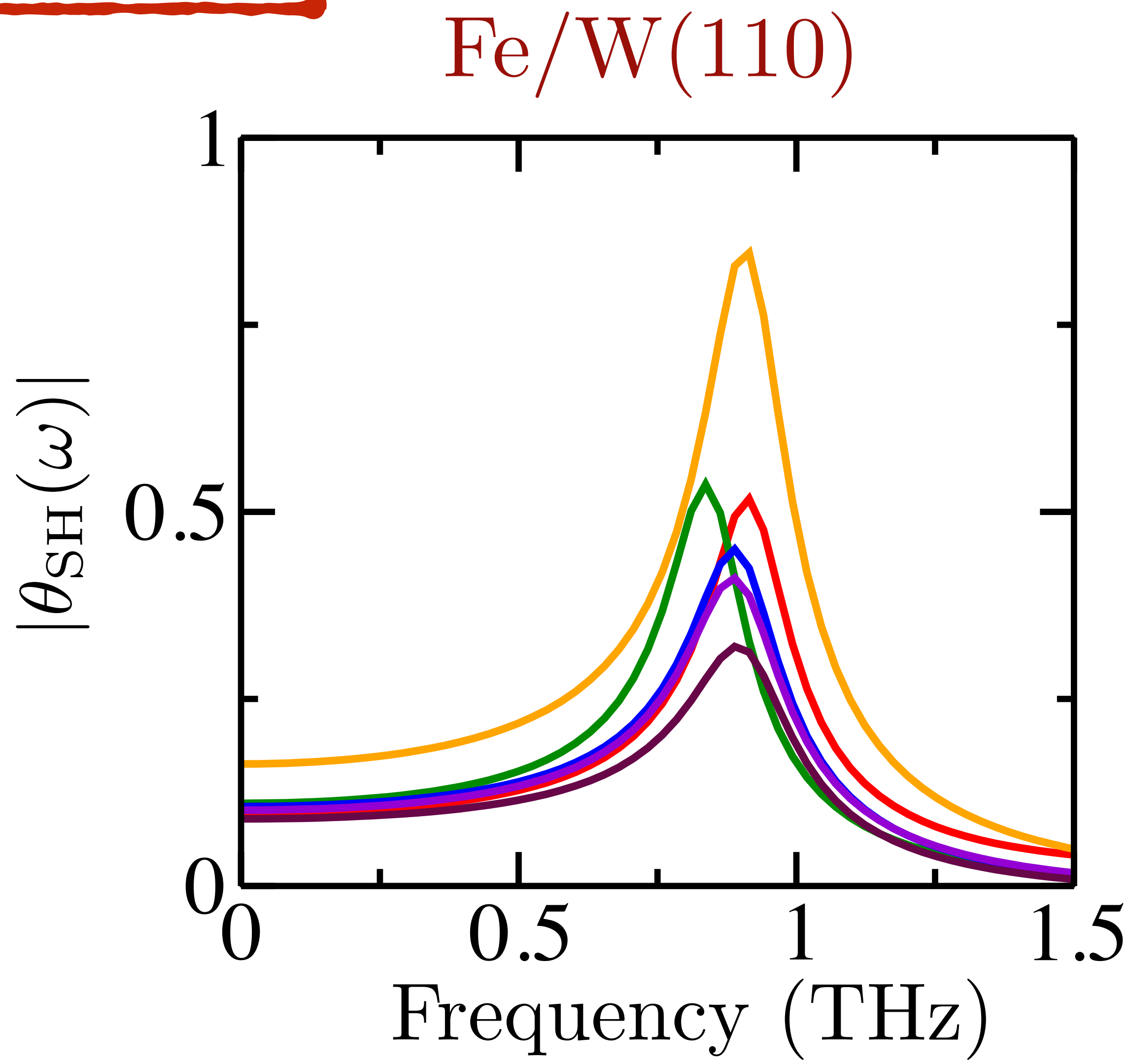
$$\langle \mathbf{I}_i^{\mathrm{C}} \rangle(t) \propto \theta_{\mathrm{SH}}^2$$



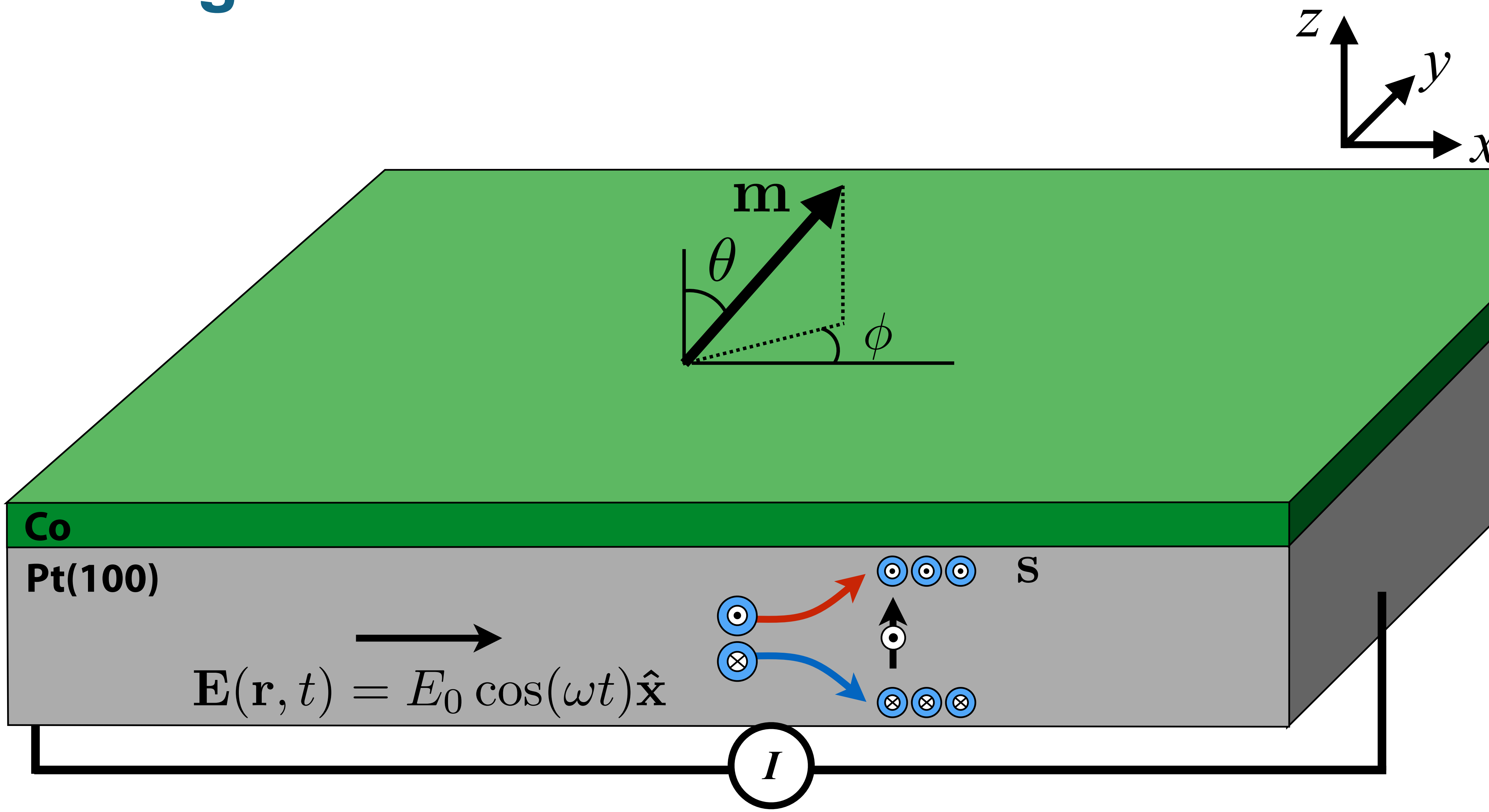
Spin Hall angle is a complex quantity

$$\theta_{\mathrm{SH}}(\omega) \propto \frac{I_{\perp}^{\mathrm{S}}(\omega)}{I_{\parallel}^{\mathrm{C}}(\omega)}$$





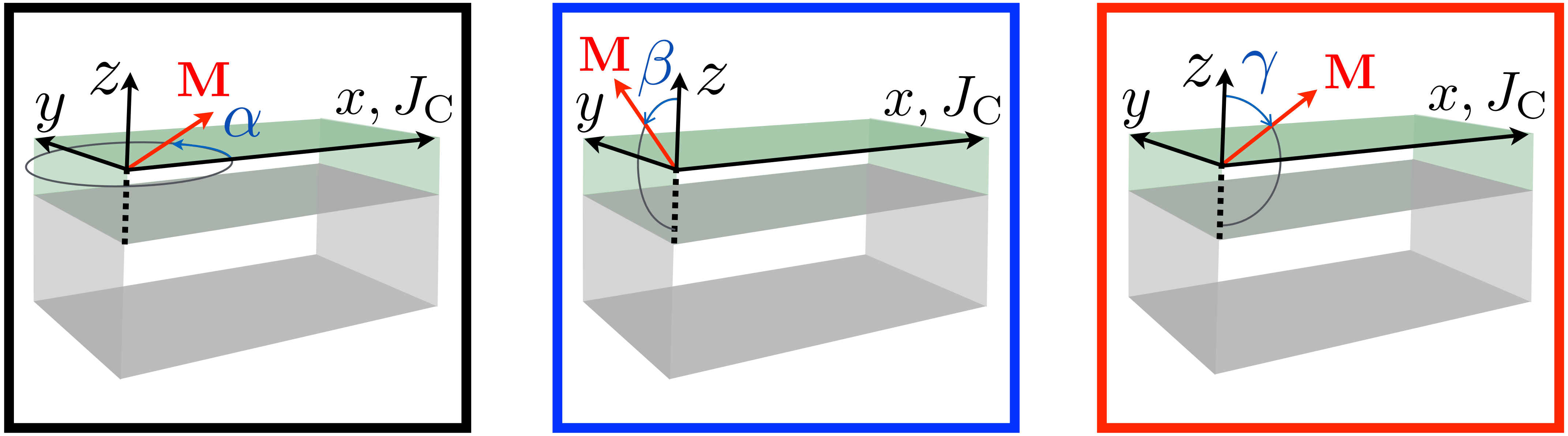
Magnetization direction affects the currents

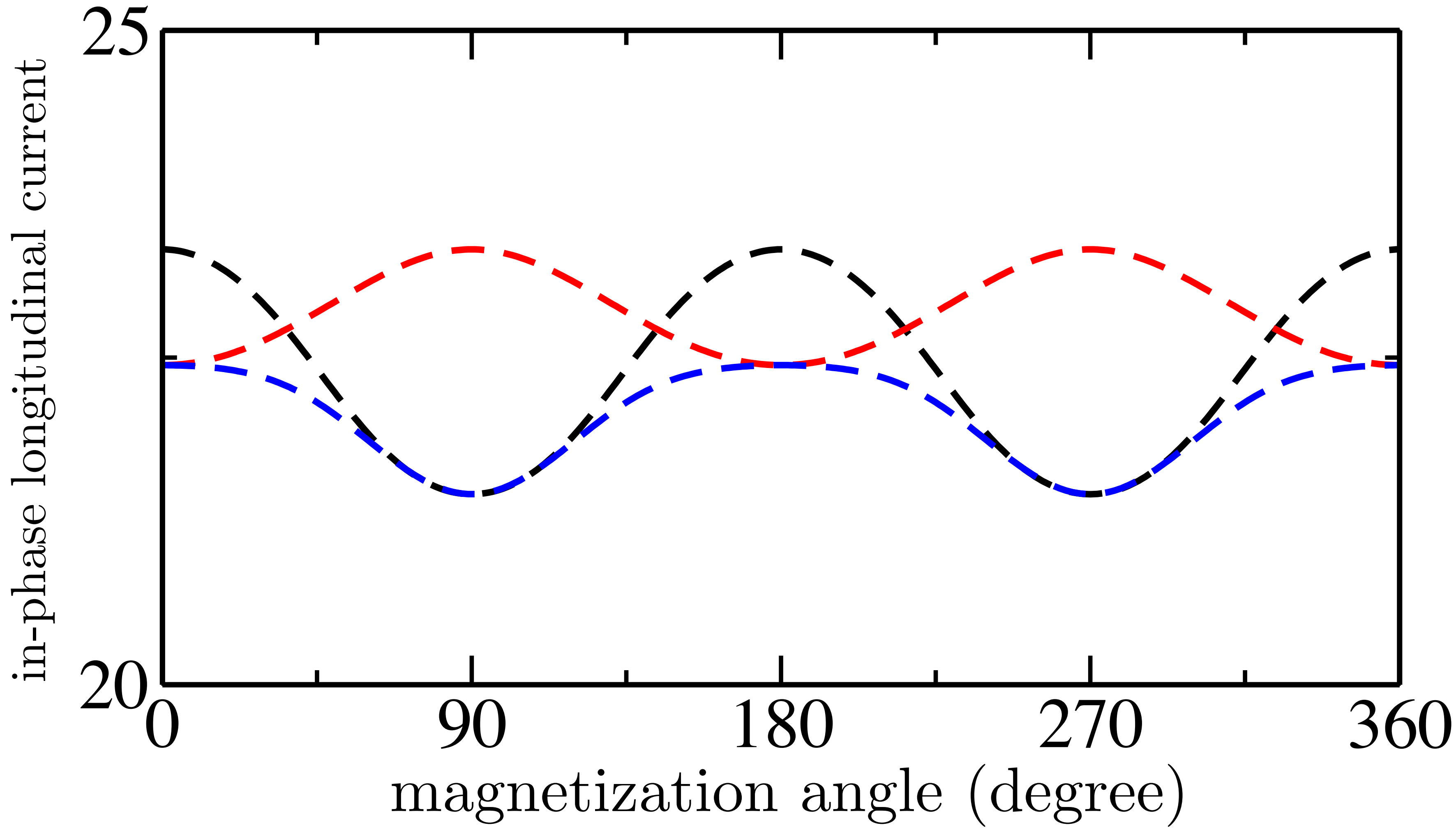


Anisotropic + Spin Hall Magnetoresistance

$$I = (G_0 + \Delta G_{\mathrm{AMR}} \underbrace{\sin^2\theta\cos^2\phi}_{m_x^2} + \Delta G_{\mathrm{SMR}} \underbrace{\sin^2\theta\sin^2\phi}_{m_y^2})V$$

Co/Pt(001)

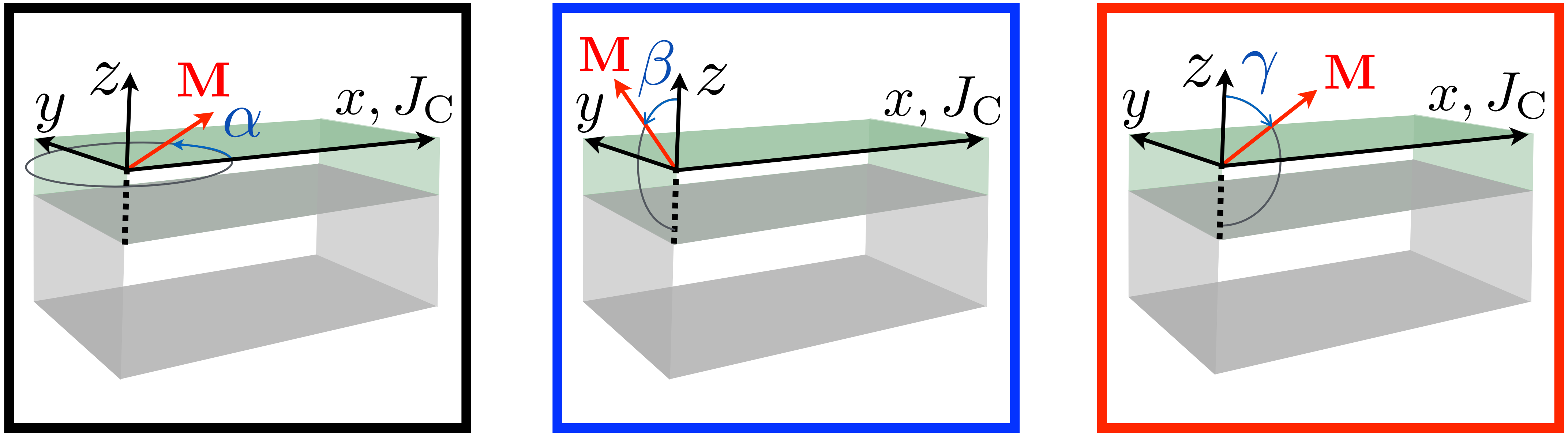


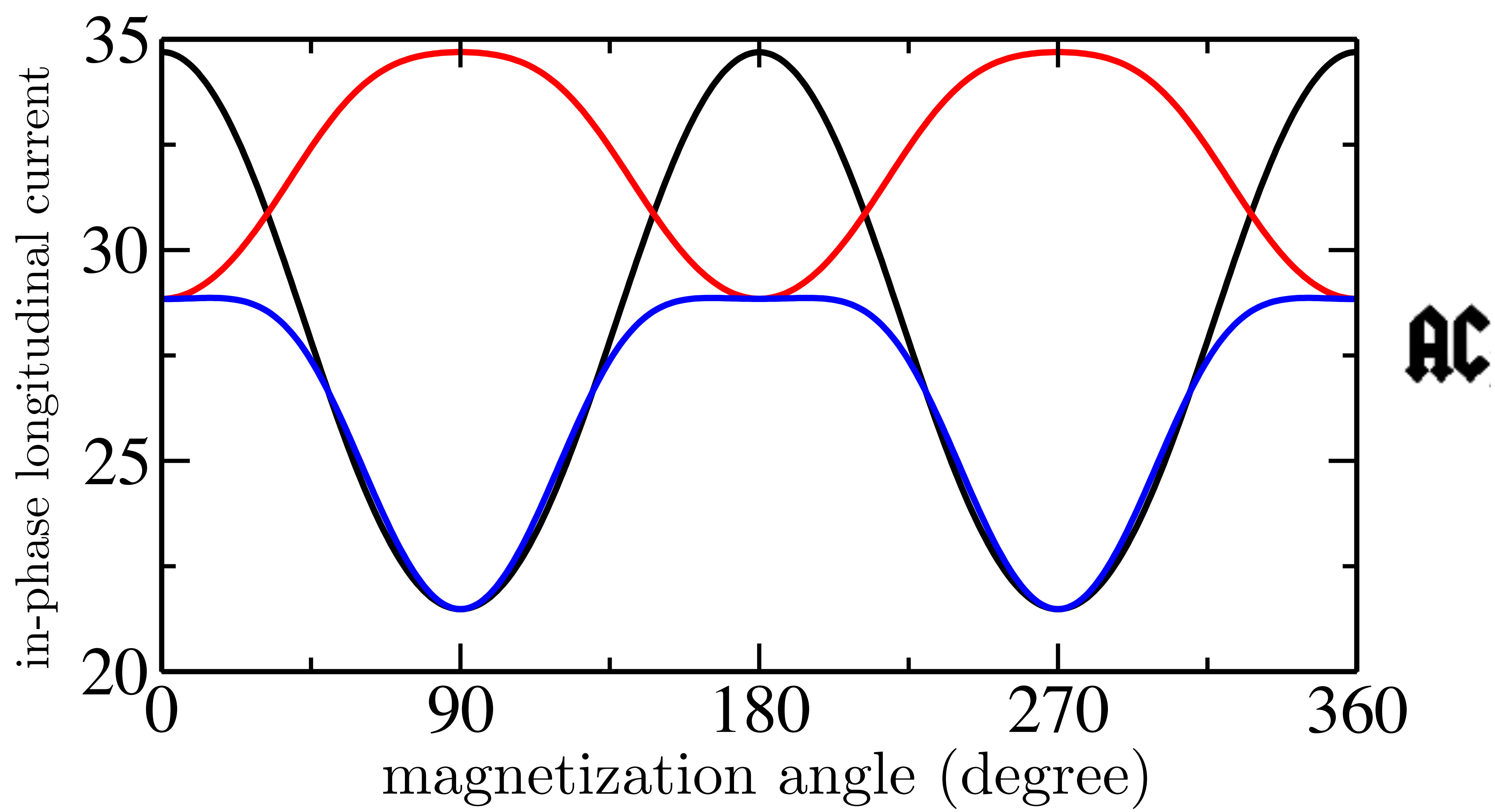


DC
($\omega = 0$)

$$I = (G_0 + \Delta G_{\mathrm{AMR}} \sin^2\theta \cos^2\phi + \Delta G_{\mathrm{SMR}} \sin^2\theta \sin^2\phi)V$$

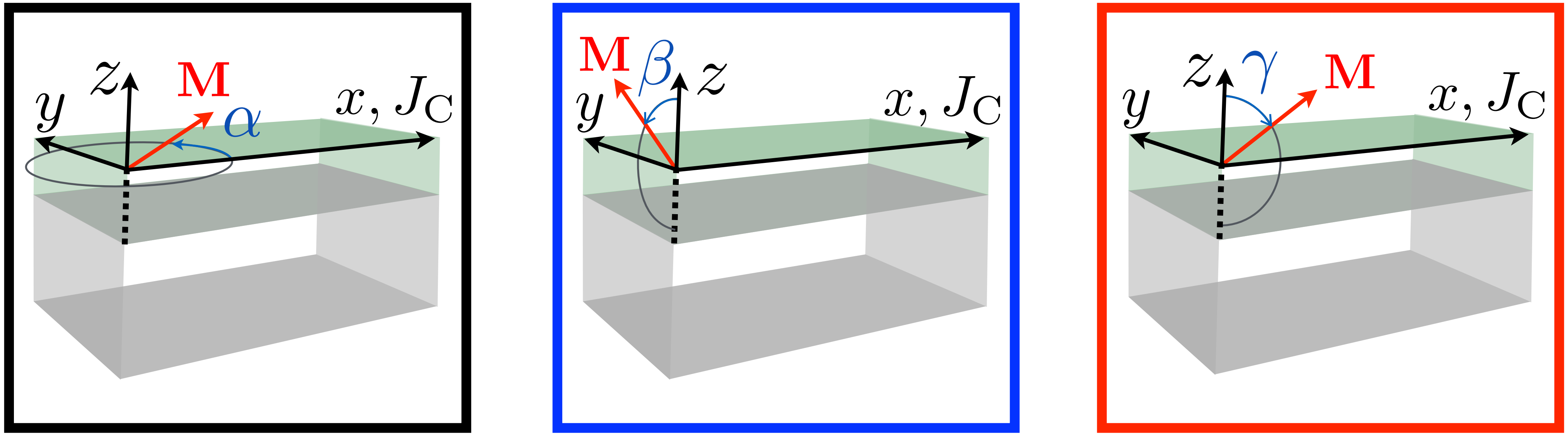
Co/Pt(001)

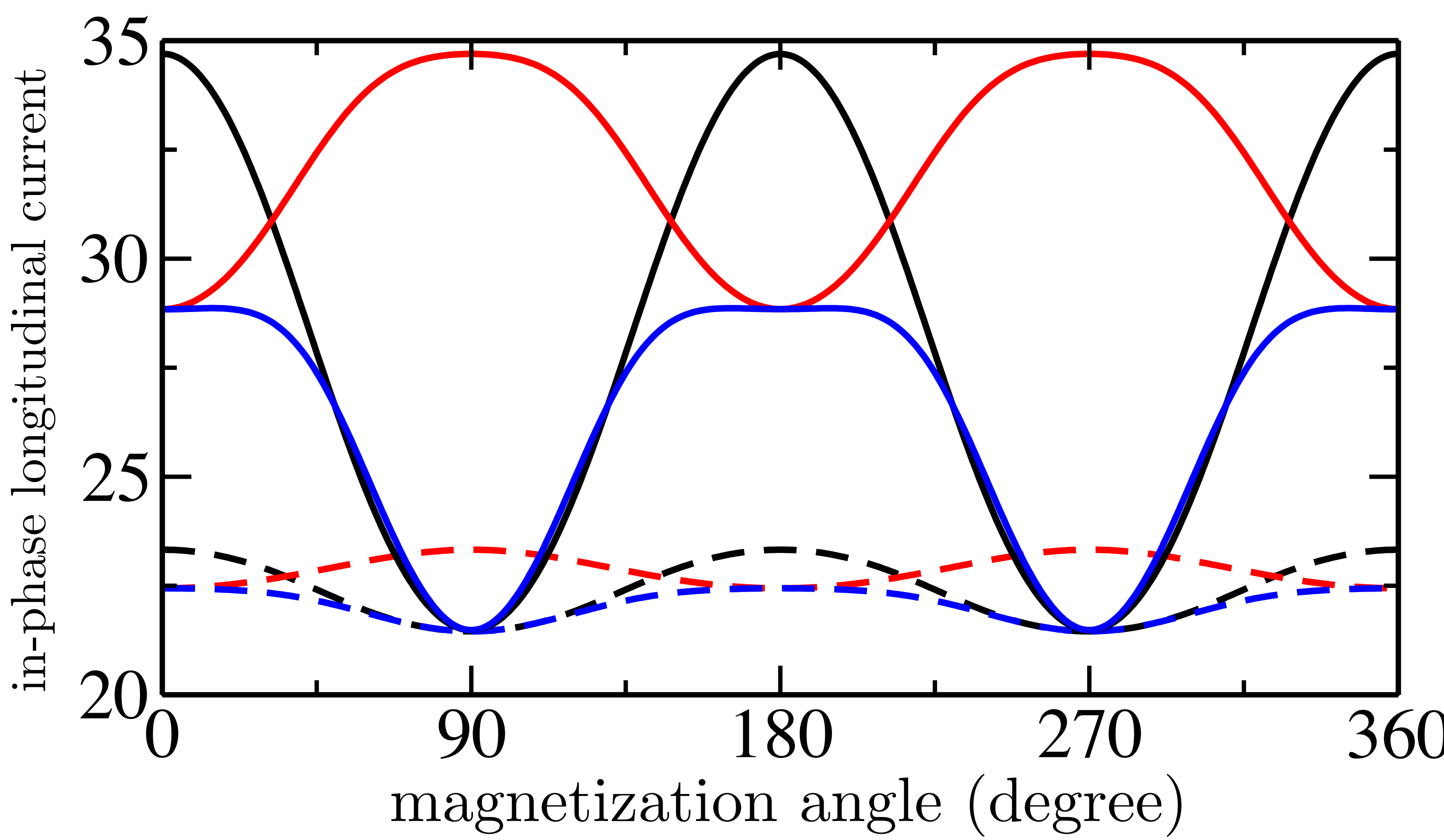




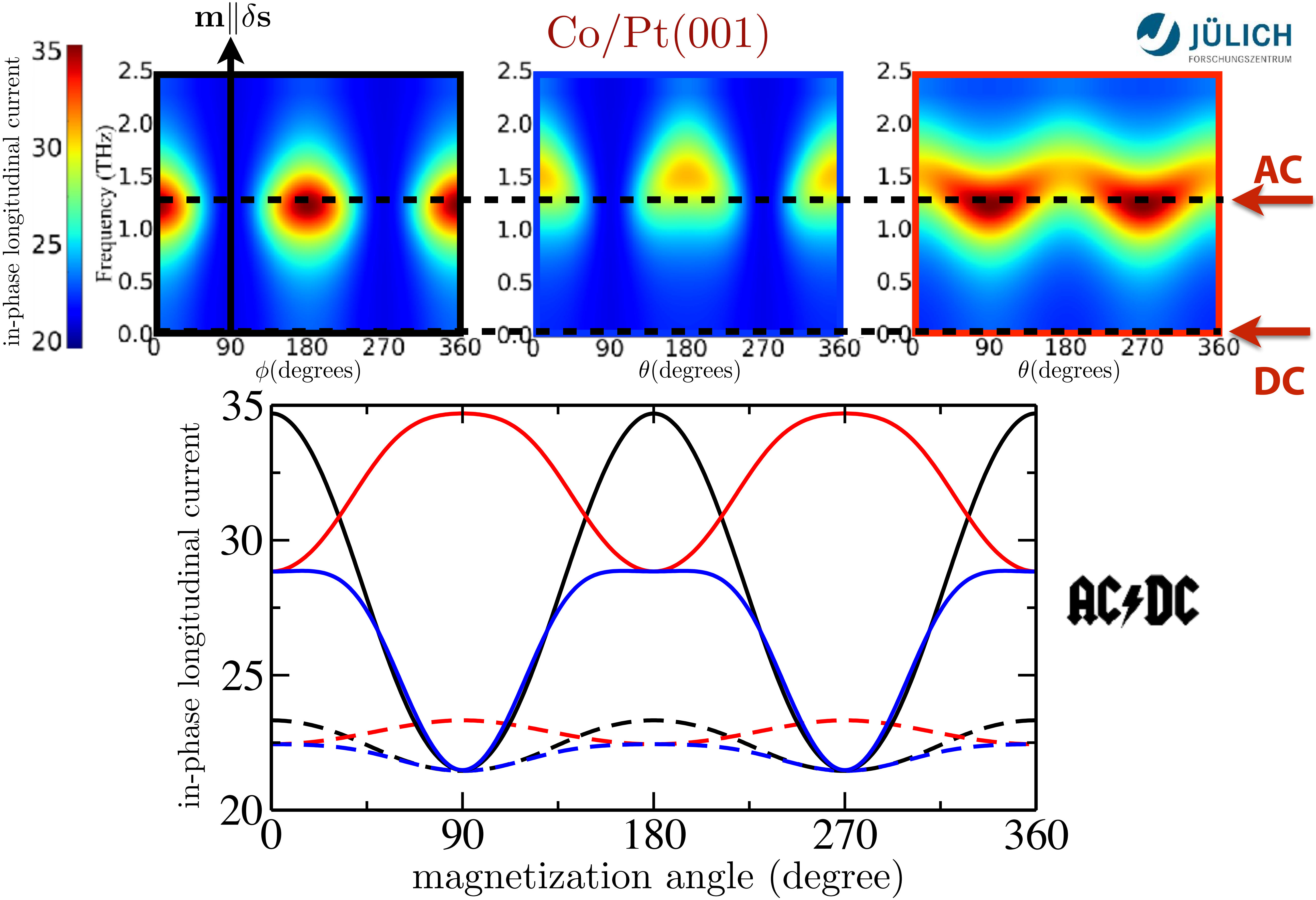
$$I = (G_0 + \Delta G_{\mathrm{AMR}} \sin^2\theta \cos^2\phi + \Delta G_{\mathrm{SMR}} \sin^2\theta \sin^2\phi)V$$

Co/Pt(001)



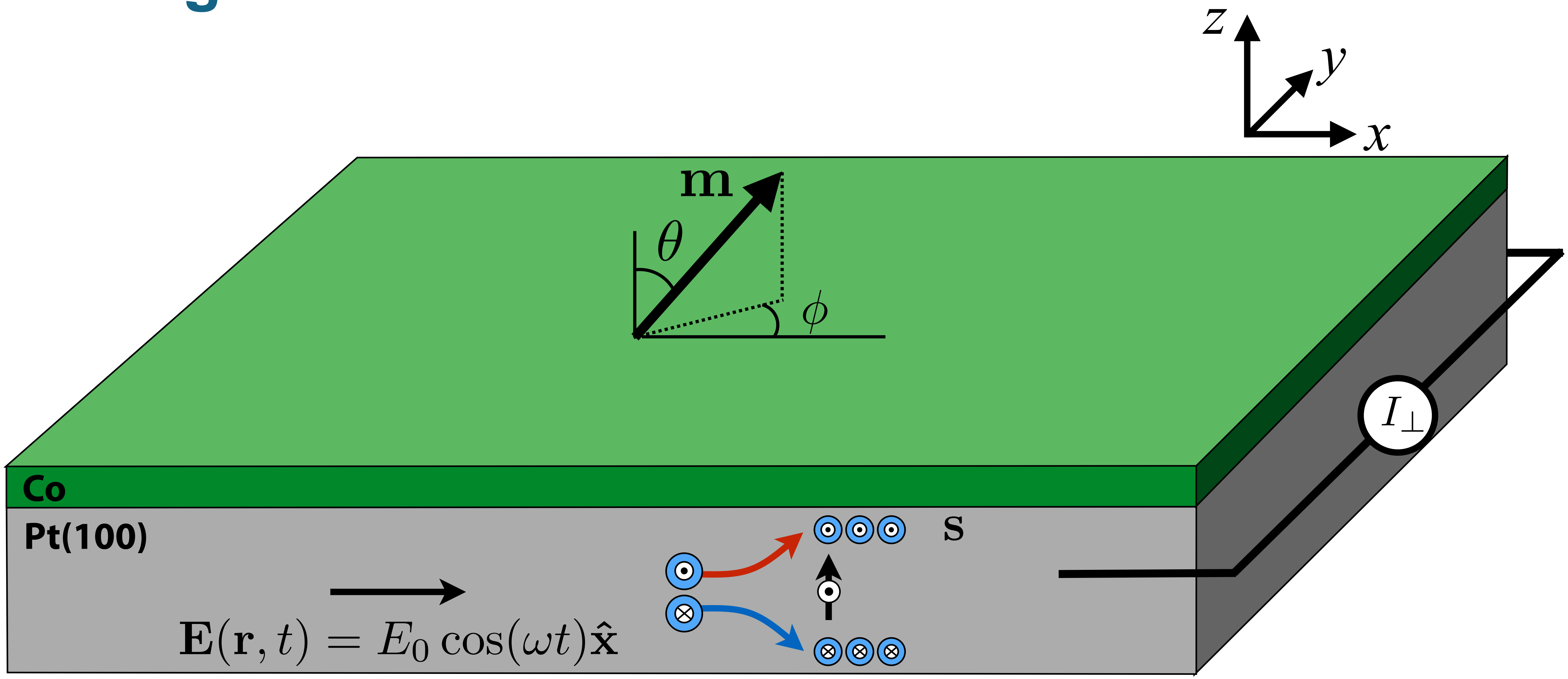


$$I = (G_0 + \Delta G_{\mathrm{AMR}} \sin^2\theta \cos^2\phi + \Delta G_{\mathrm{SMR}} \sin^2\theta \sin^2\phi) V$$



$$I = (G_0 + \Delta G_{\mathrm{AMR}} \sin^2\theta \cos^2\phi + \Delta G_{\mathrm{SMR}} \sin^2\theta \sin^2\phi) V$$

Magnetization direction affects the currents



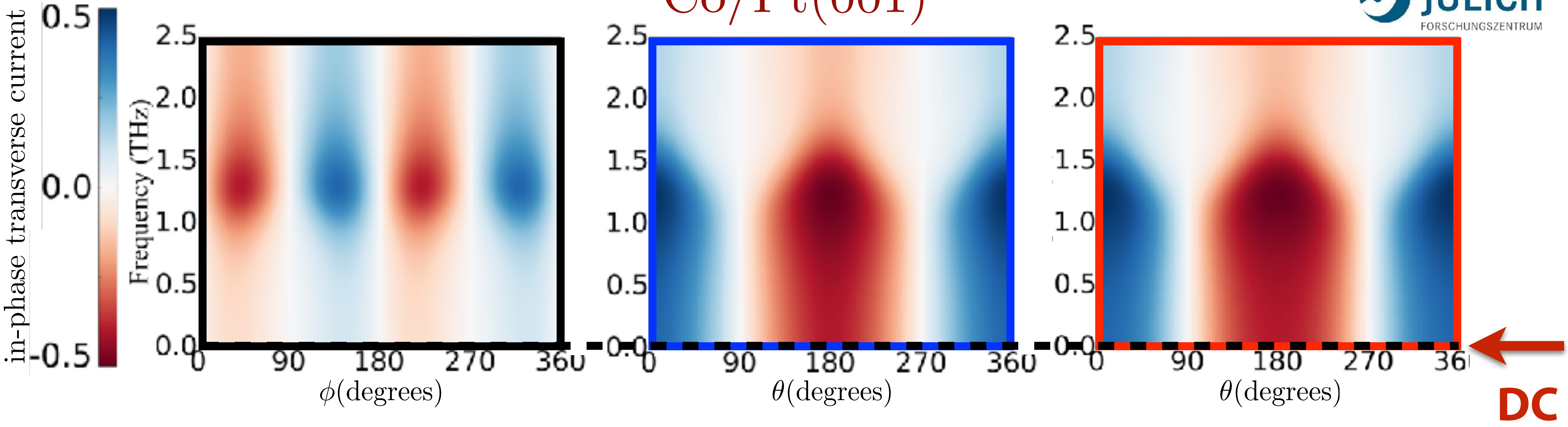
Anomalous + Planar Hall Effects

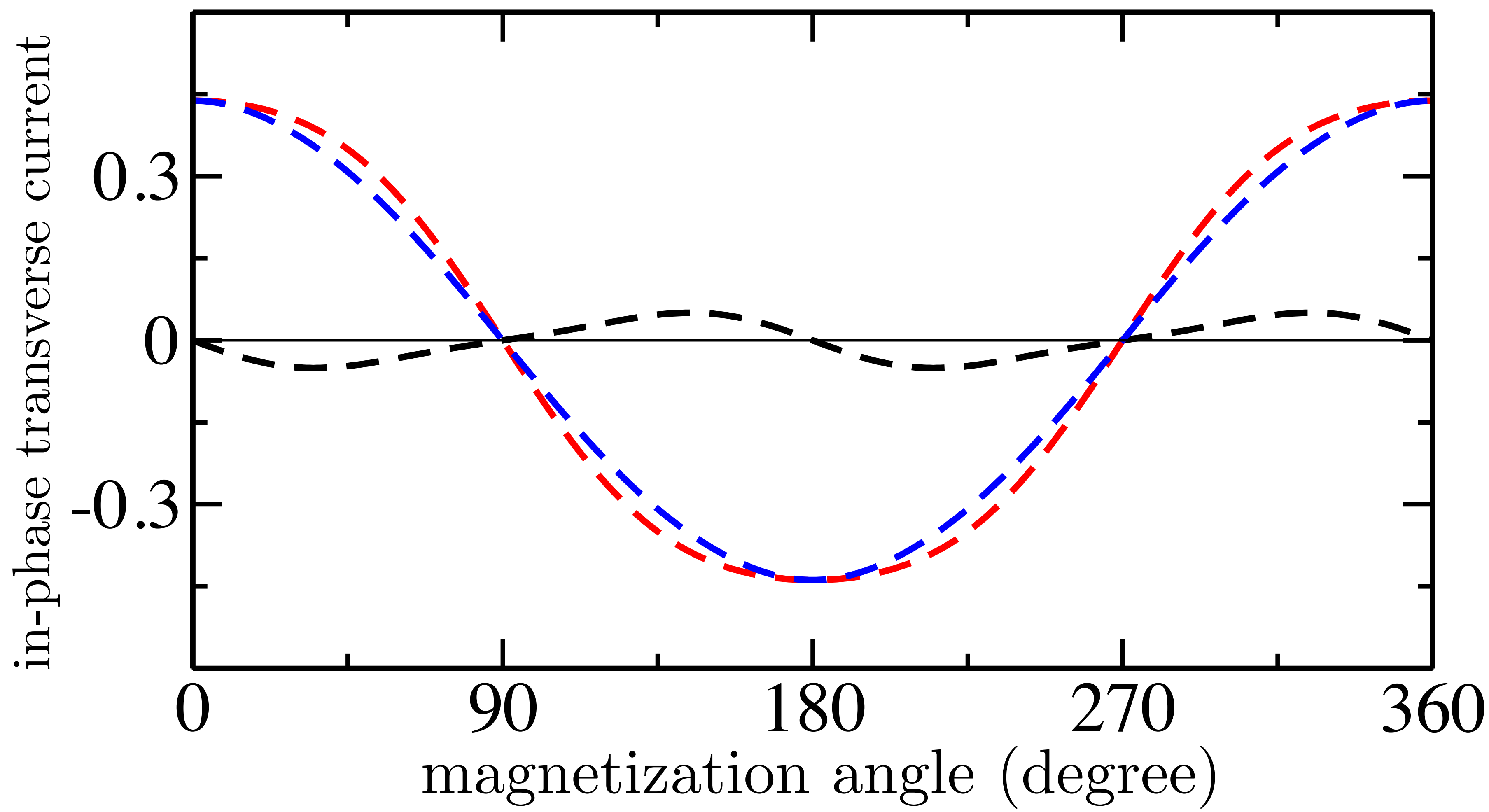
$$I_\perp = \left(G_{\mathrm{AHE}} \underbrace{\cos\theta}_{m_z} + G_{\mathrm{PHE}} \underbrace{\sin^2\theta \sin 2\phi}_{m_x m_y}\right) V$$

f.guimaraes@fz-juelich.de

Sci. Rep. 7, 3686 (2017)

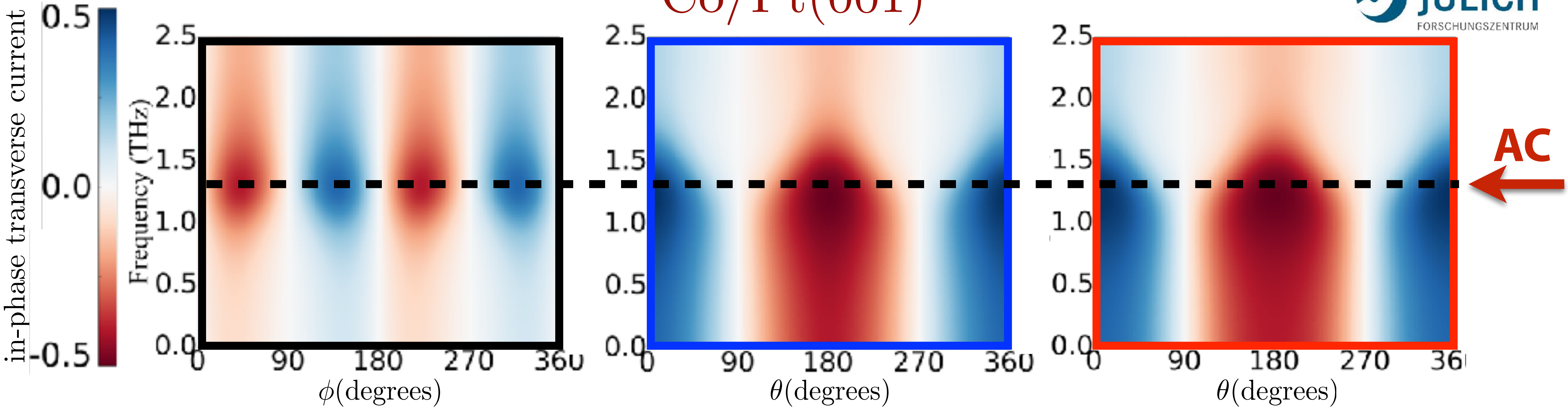
Co/Pt(001)

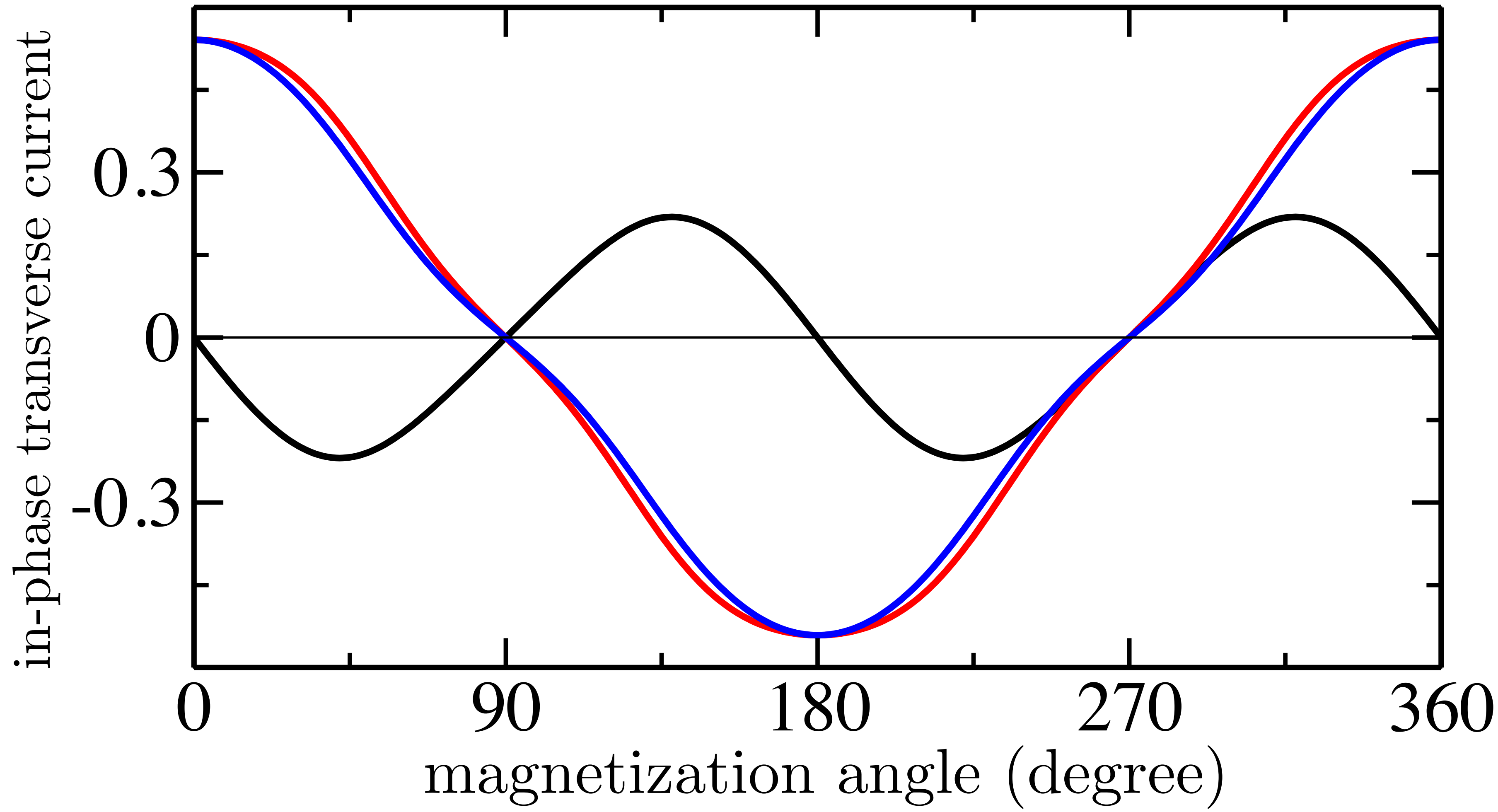




$$I_{\perp} = \left(G_{\text{AHE}} \cos\theta + G_{\text{PHE}} \sin^2\theta \sin 2\phi\right) V$$

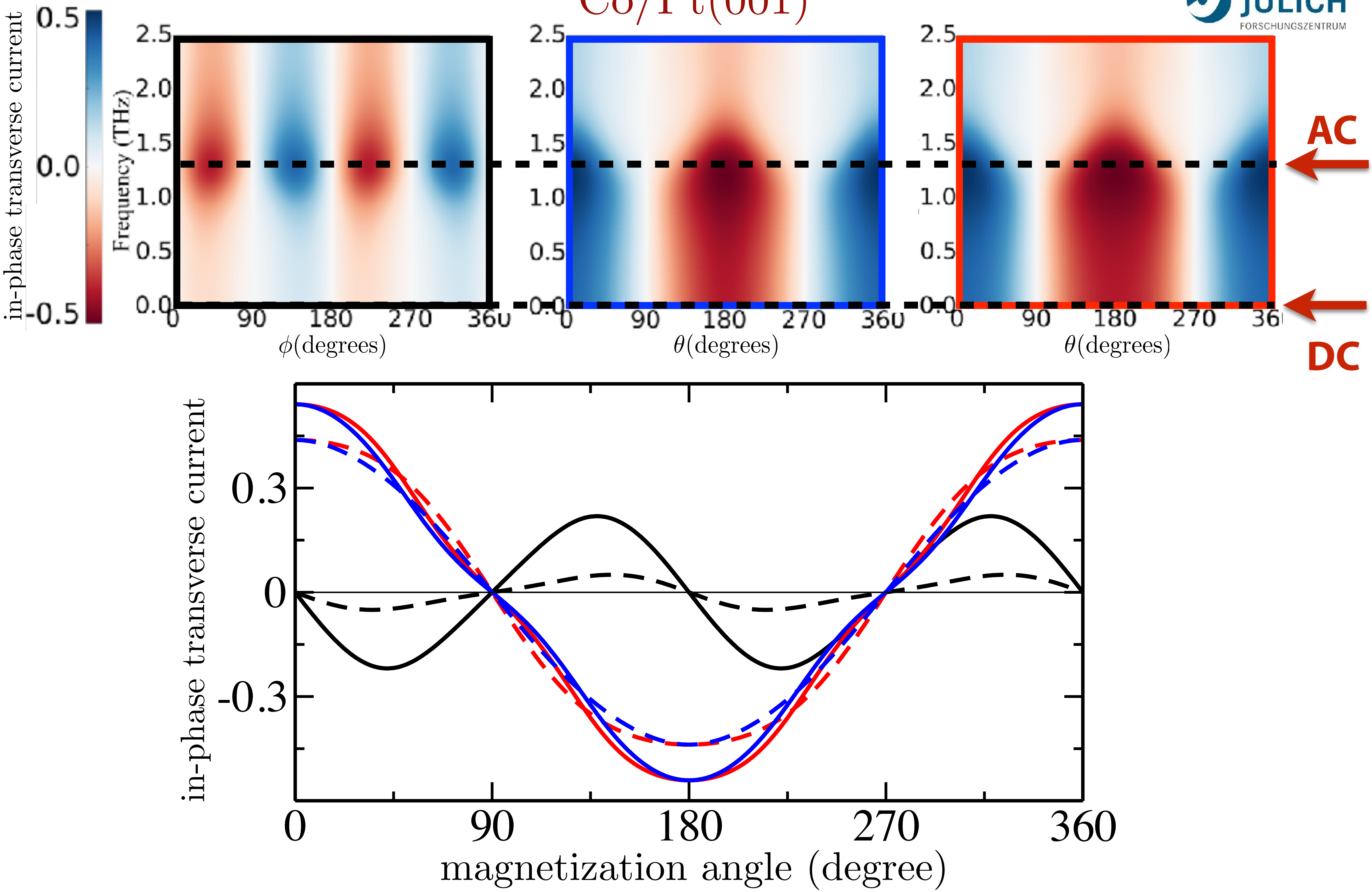
Co/Pt(001)





$$I_\perp = \left(G_{\text{AHE}} \cos\theta + G_{\text{PHE}} \sin^2\theta \sin 2\phi \right) V$$

Co/Pt(001)



$$I_\perp = \left(G_{\mathrm{AHE}} \cos\theta + G_{\mathrm{PHE}} \sin^2\theta \sin 2\phi\right) V$$

Perspectives

TITAN

magnetic field

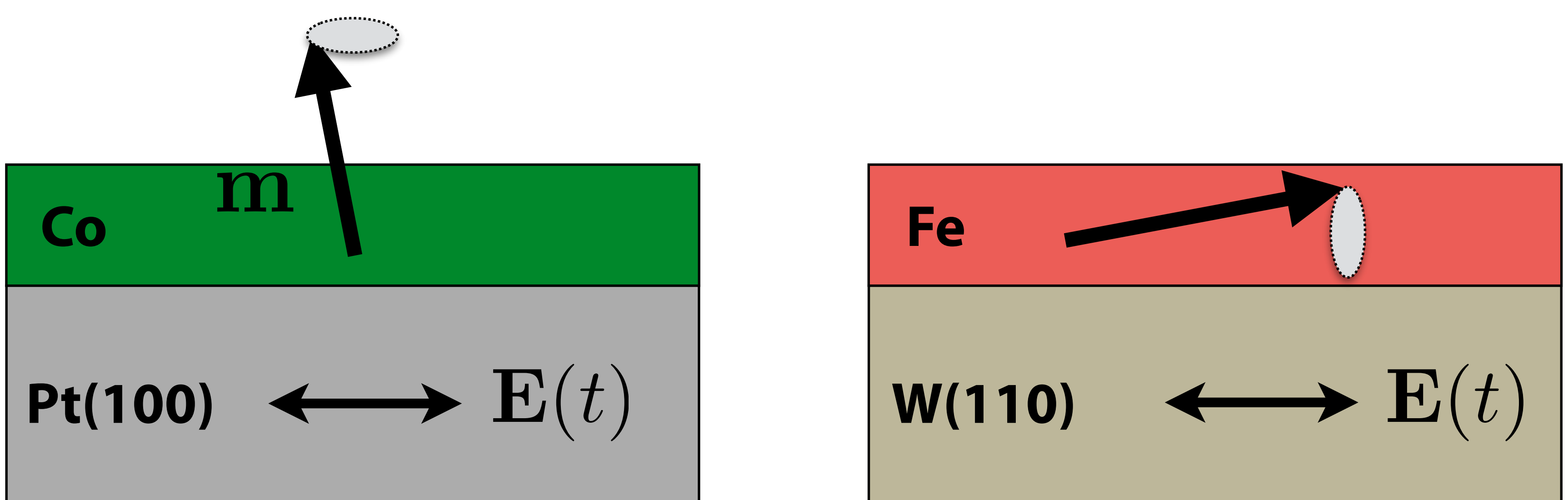
electric field

spin density

spin current

charge currents

orbital angular momentum



Perspectives

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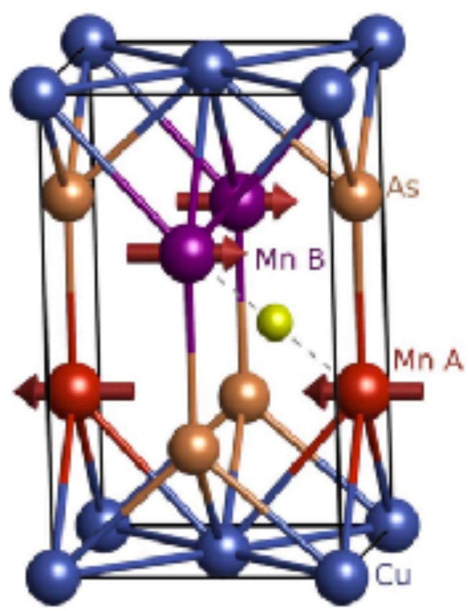
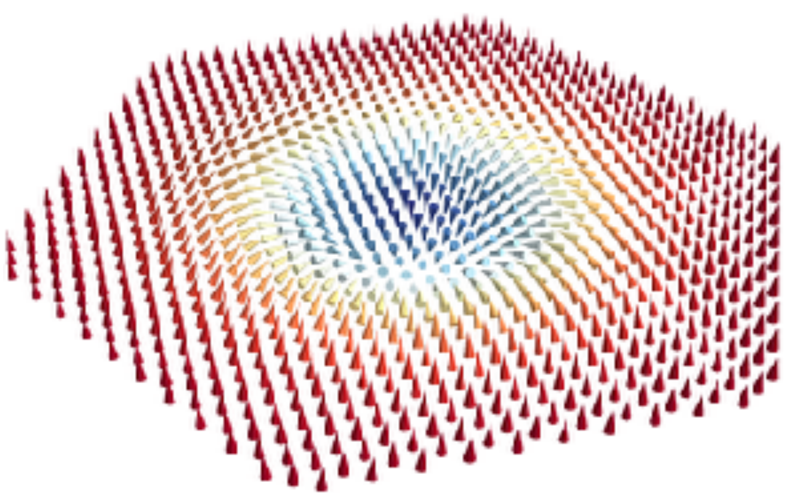


P. Wadley et al.,
Science 10.1126/science.aab1031 (2016)



M. dos Santos Dias et al.,
Nat. Commun. 7, 13613 (2016)

- **Dynamical effects provide very rich phenomena**
- ac currents can excite spin wave resonances in a controllable fashion
- Spin and charge pumping contribute to the currents flowing on the system
- Spin Hall angle is a complex quantity
- Magnetoresistances and Hall currents in heterostructures have a dramatic variation due to the excitation of magnetic resonances
- AC currents can be manipulated by varying the frequency of electric field or using static magnetic fields

PRB 92, 220410(R) (2015)

Sci. Rep. 7, 3686 (2017)

Thank you!

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DYNASORE: dynamical magnetic excitations with spin-orbit interaction in realistic nanostructures