Broadband Ferromagnetic Resonance Spectroscopy: The “Swiss Army Knife” for Understanding Spin–Orbit Phenomena

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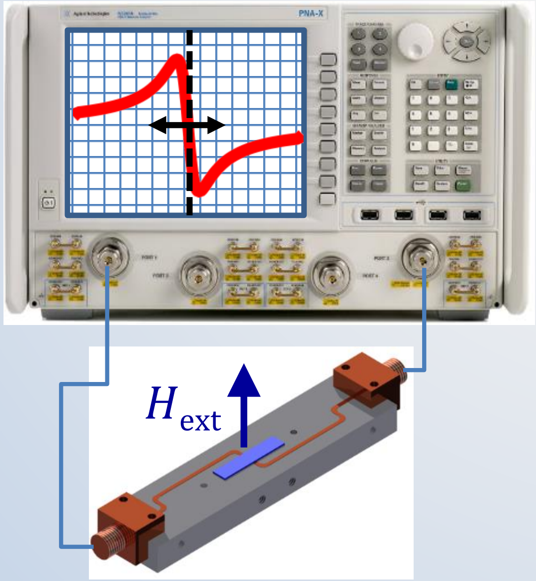

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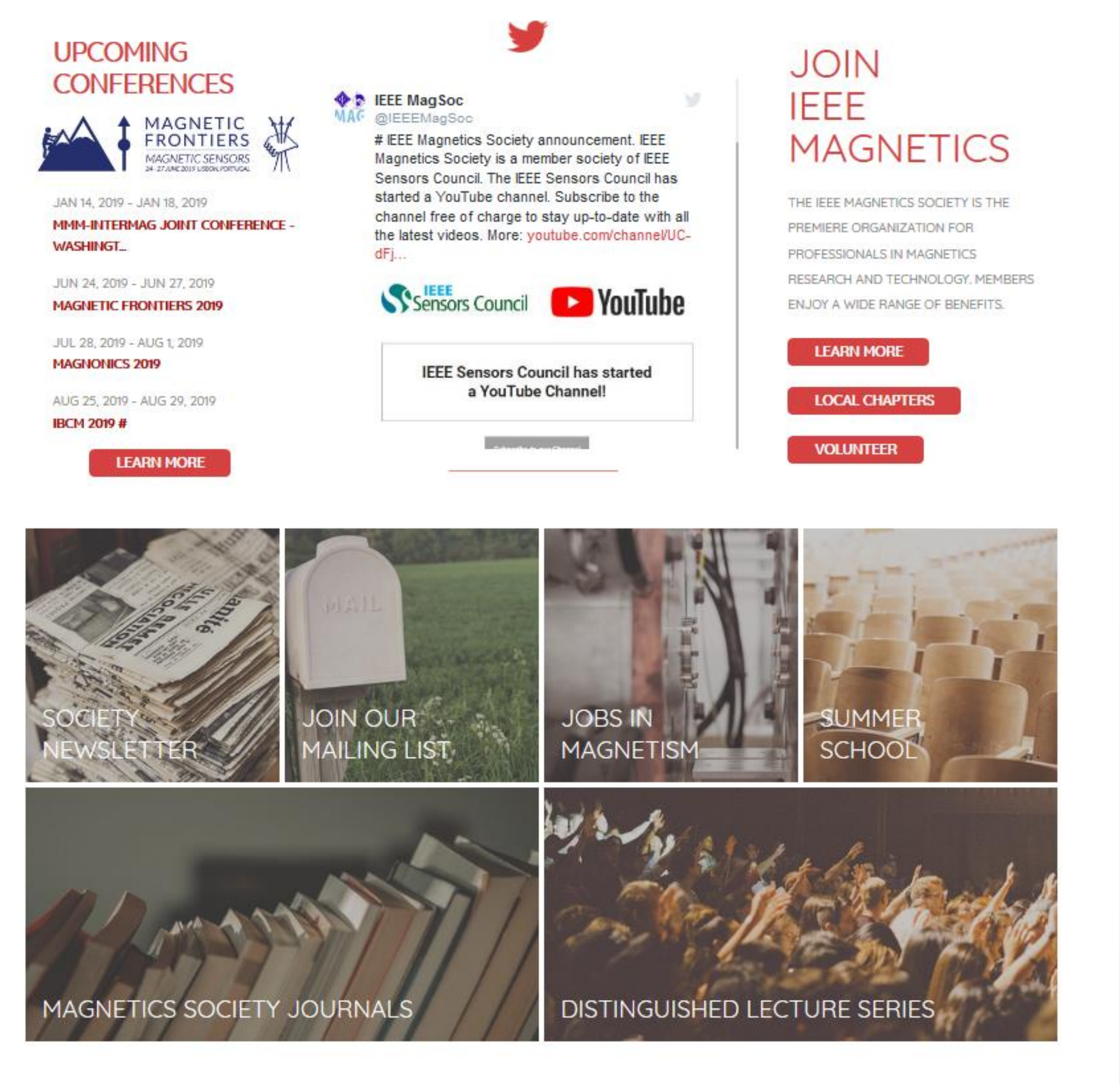

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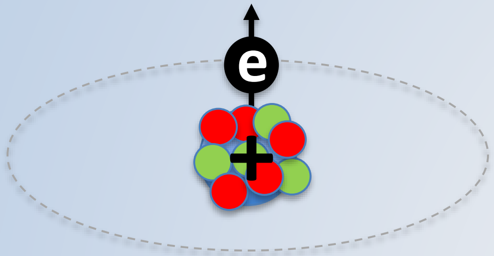
Outline

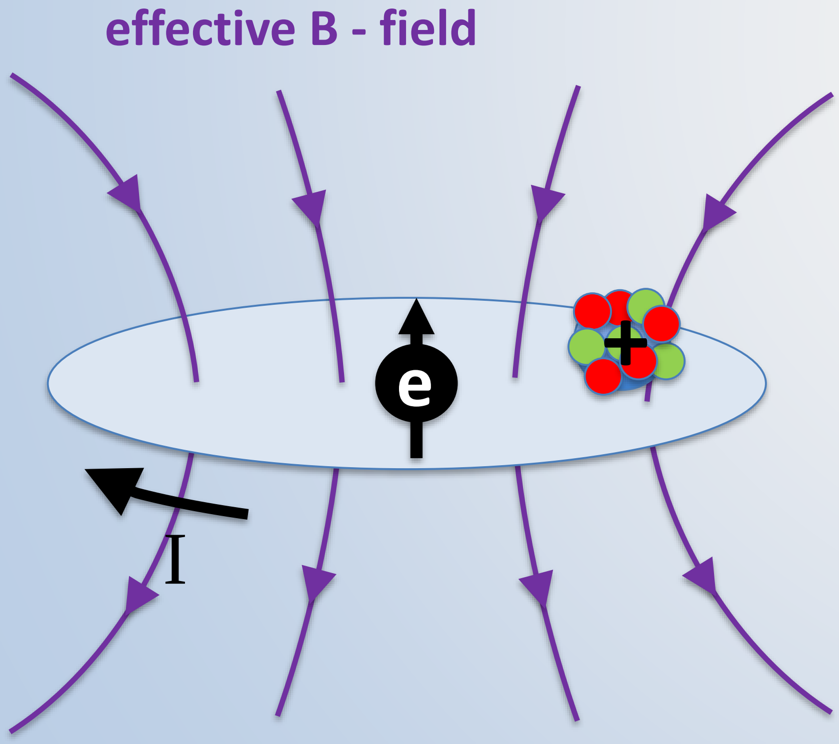
- Spin-Orbit Interaction
- Ferromagnetic Resonance Spectroscopy
- Anisotropy and Orbital Moments
- Damping and Spin-Pumping
- Spin-Orbit Torques

Spin-Orbit Interaction

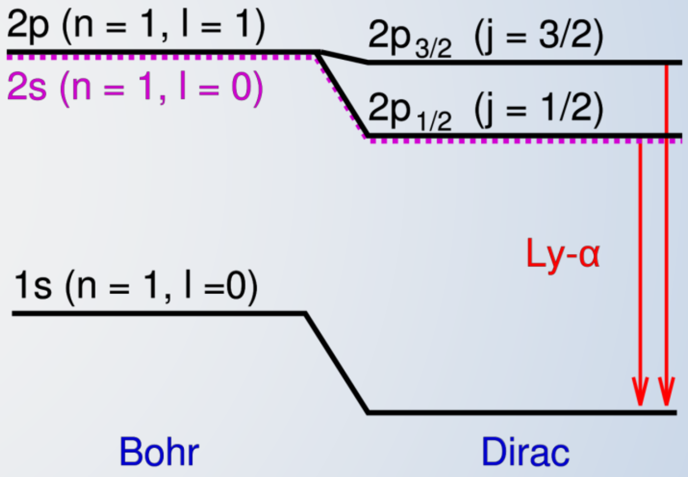
“Classical” electron spin orbiting nucleus



From the rest frame of the electron spin



- In reality, Spin-Orbit is a relativistic effect
- This effective **B** field leads to a splitting of energy levels ➔ Fine Structure

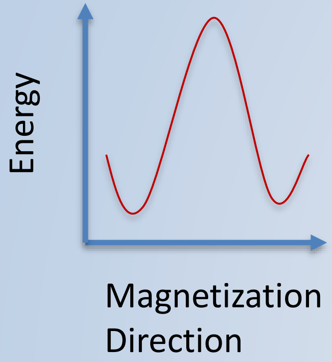


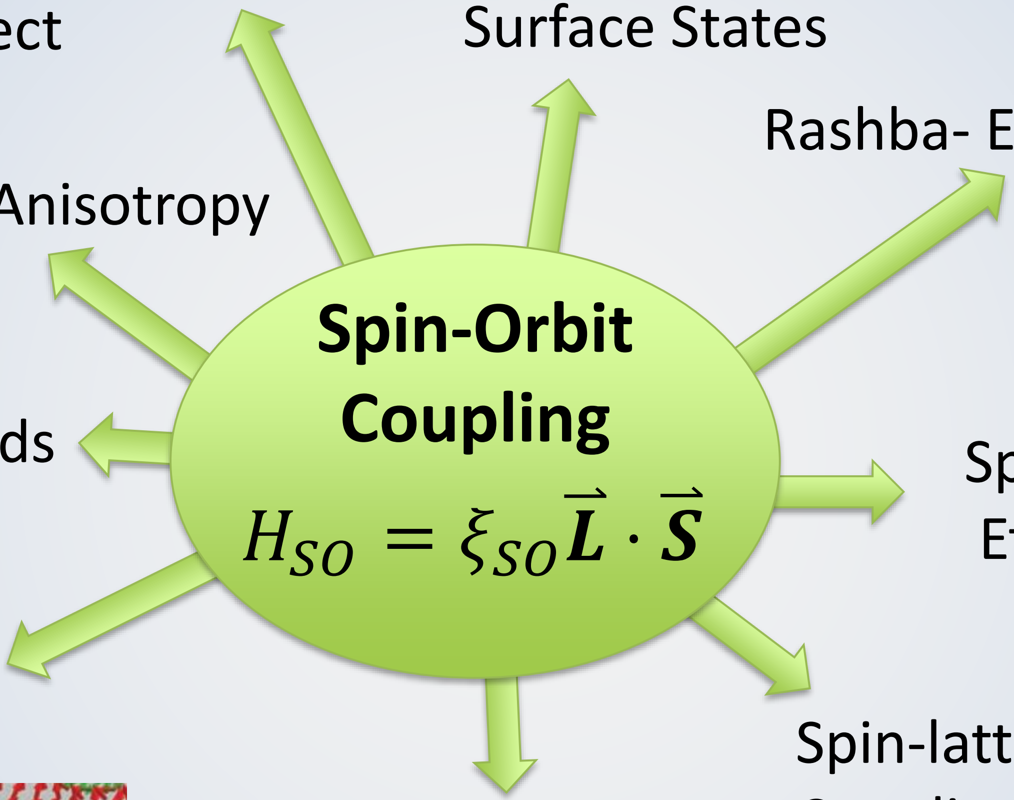
wikipedia

- In solids the spin-orbit interaction is included as an addition to the Hamiltonian

$$H_{SO} = \xi_{SO} \vec{\boldsymbol{L}} \cdot \vec{\boldsymbol{S}}$$

Spin-Orbit Phenomena





Spin-Orbit Coupling

$$H_{SO} = \xi_{SO} \vec{\boldsymbol{L}} \cdot \vec{\boldsymbol{S}}$$

Anomalous Hall Effect

Topological Surface States

Rashba- Edelstein effect

Magnetic Anisotropy

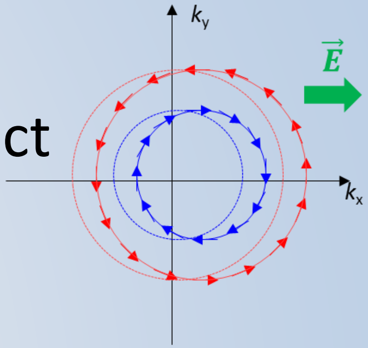
Orbital Moments in Solids

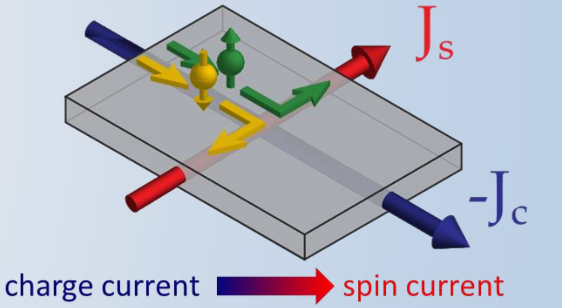
Spin Hall Effect

Dzyaloshinskii-Moriya Interaction (DMI)

Damping

Spin-lattice Coupling





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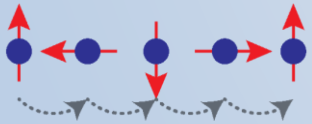
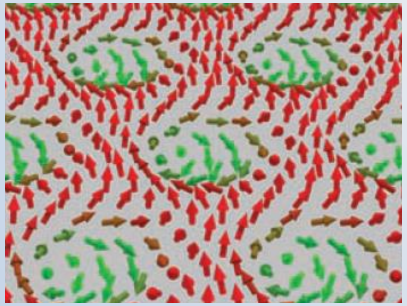
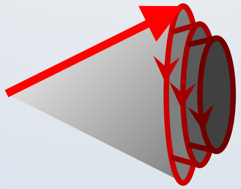
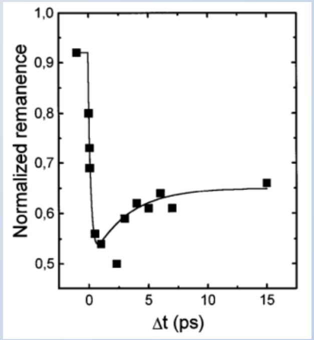




Science, 323, 915 (2009)



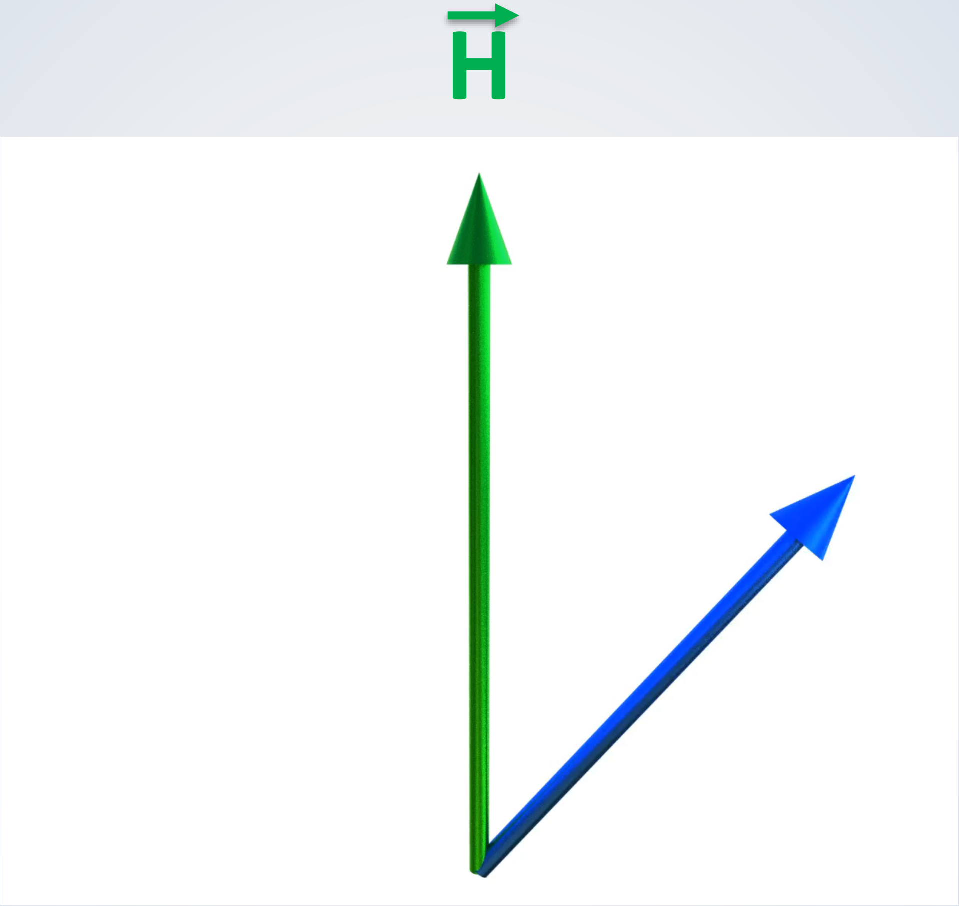


Beaurepaire PRL 76 (1996)

Outline

- Spin-Orbit Interaction
- Ferromagnetic Resonance Spectroscopy
- Anisotropy and Orbital Moments
- Damping and Spin-Pumping
- Spin-Orbit Torques

What happens when we excite a spin?



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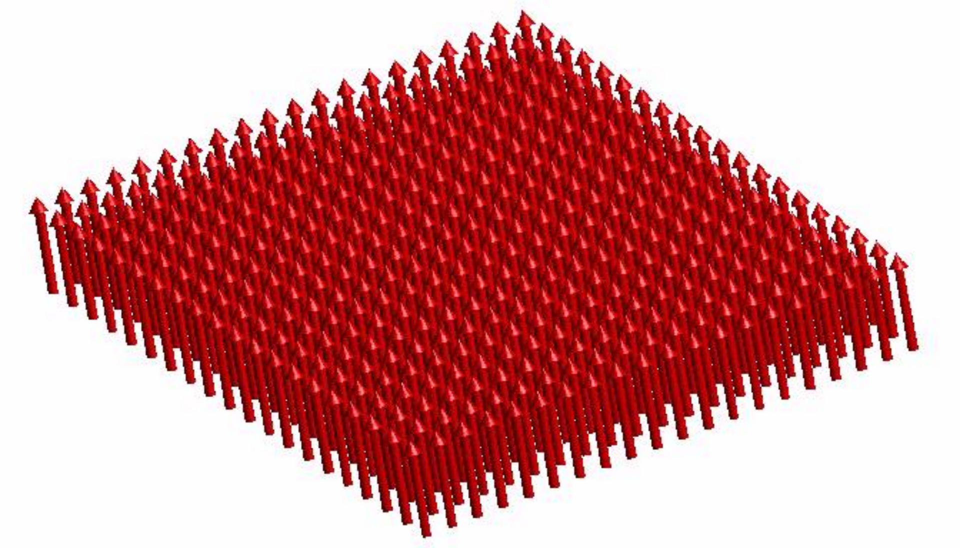
Collective Spin Excitations

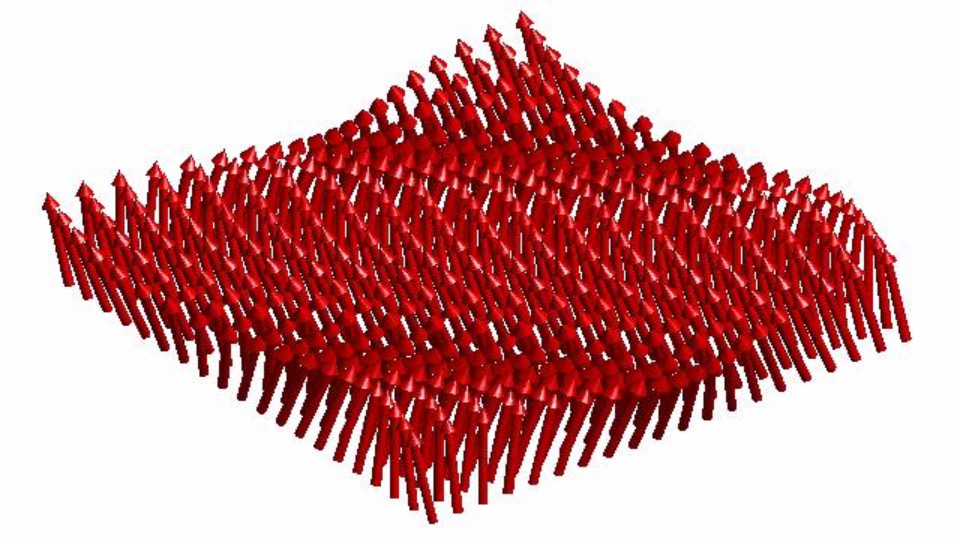
Ferromagnetic Resonance (FMR) Mode

All spin precess in phase



Other Spinwave (Magnon) Modes

Non-zero phase relationship



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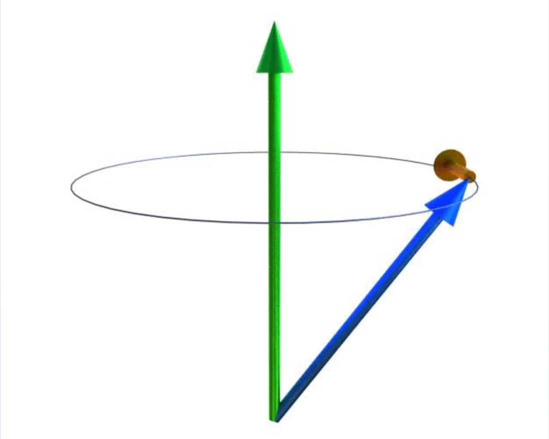
Landau-Lifshitz Equation

Landau-Lifshitz equation

$$\frac{d\vec{M}}{dt} = \underbrace{-|\gamma|\mu_0\left(\vec{M}\times\vec{H}\right)}_{\text{Larmor Term}}$$

H



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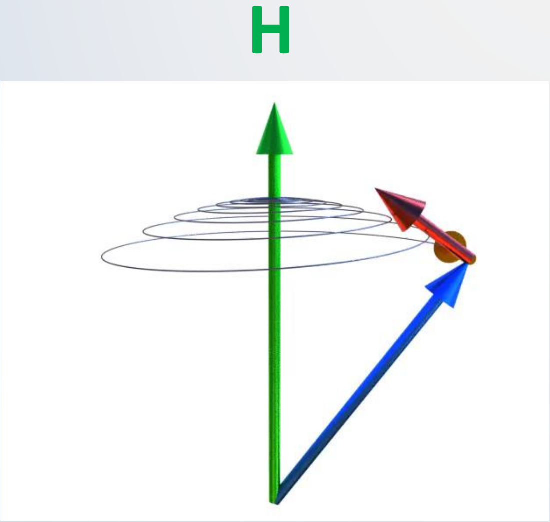
Lev Landau

Evgeny Lifshitz

Landau-Lifshitz Equation

Landau-Lifshitz equation

$$\frac{d\vec{M}}{dt} = \underbrace{-|\gamma|\mu_0\left(\vec{M}\times\vec{H}\right)}_{\text{Larmor Term}} \underbrace{-\frac{\alpha|\gamma|\mu_0}{M_s}\left[\vec{M}\times\left(\vec{M}\times\vec{H}\right)\right]}_{\text{Damping Term}}$$



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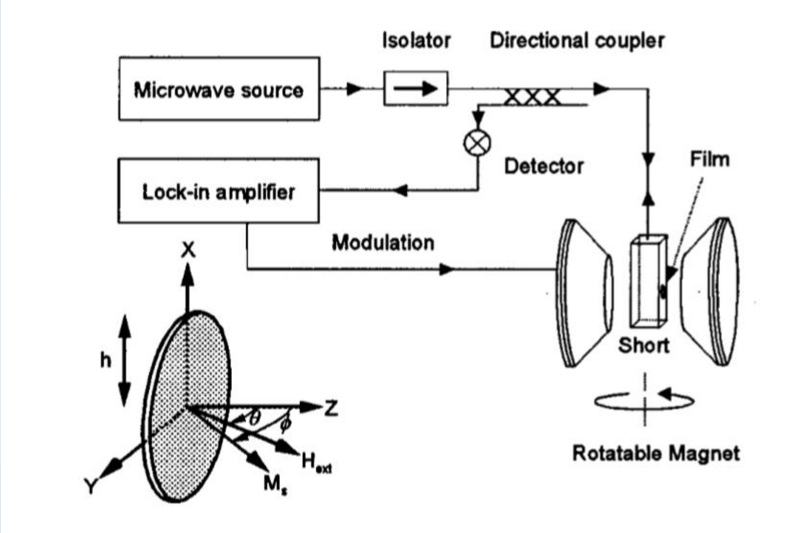
Lev Landau

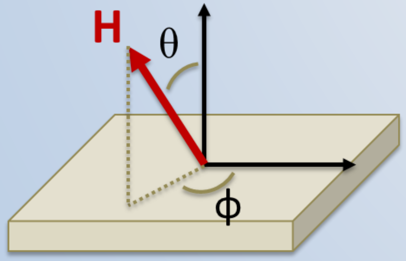
Evgeny Lifshitz

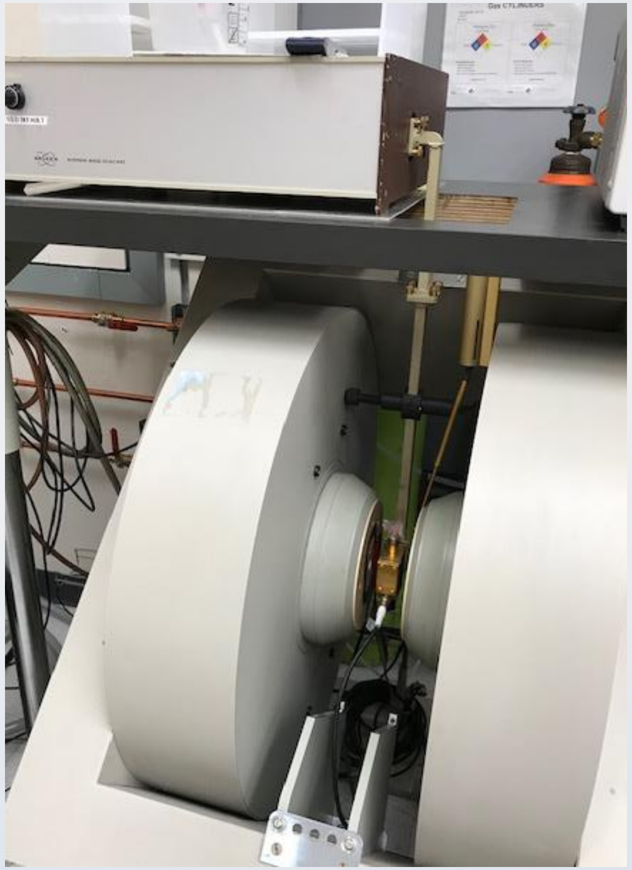
Ferromagnetic Resonance (FMR)

Cavity Based ➔ **single frequency!**

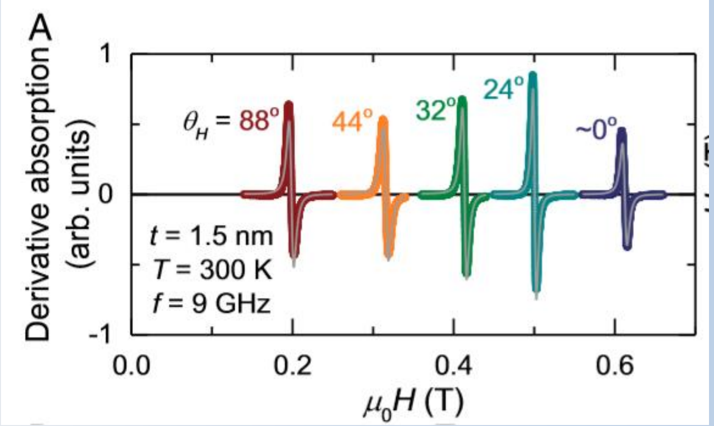


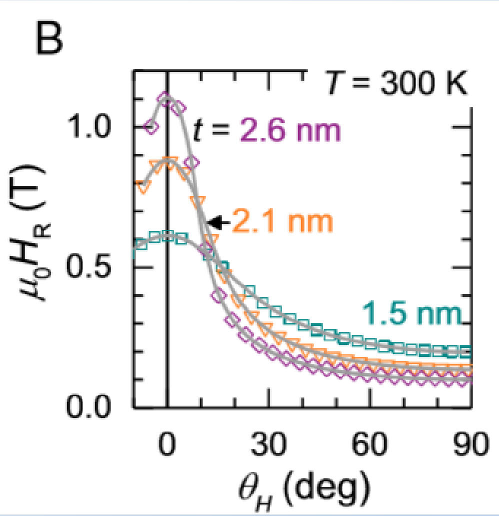
Srivastava, JAP 85 7841 (1999)





Constant Frequency, vary angle

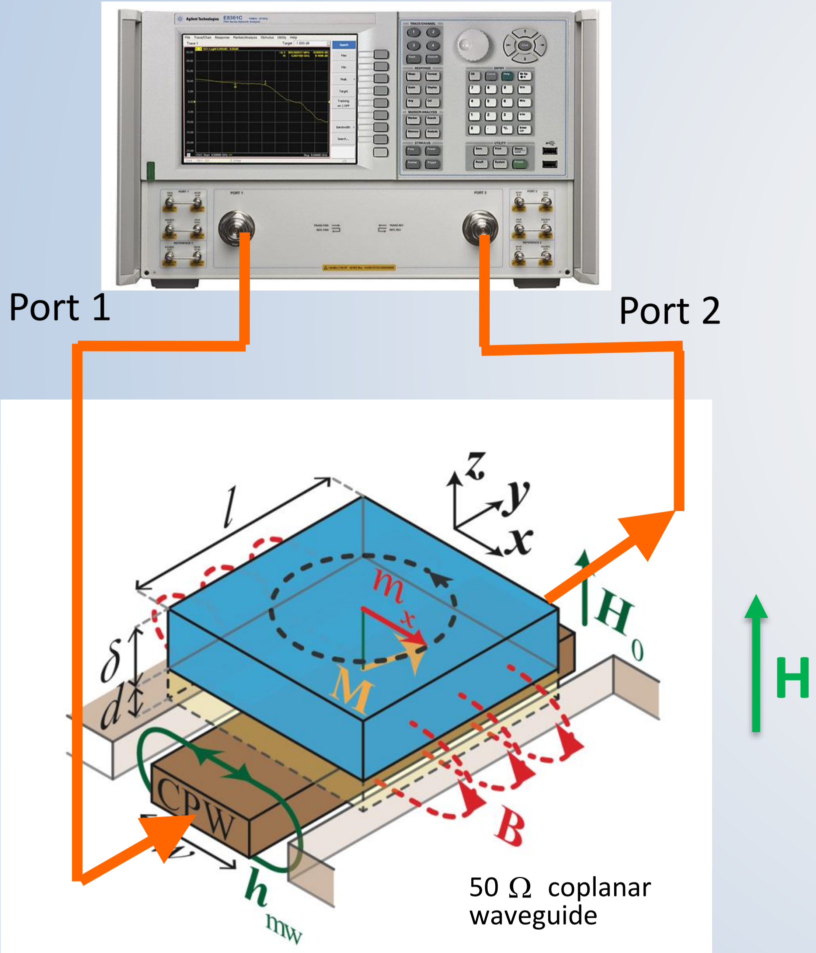




A. Okada, PNAS, 114, 3815 (2017)

Vector Network Analyzer FMR (VNA-FMR)

Vector-network-analyzer



$$\chi(H,f) = \frac{M_{eff}(H - M_{eff})}{(H - M_{eff})^2 - H_{eff}^2 - i\Delta H(H - M_{eff})}$$

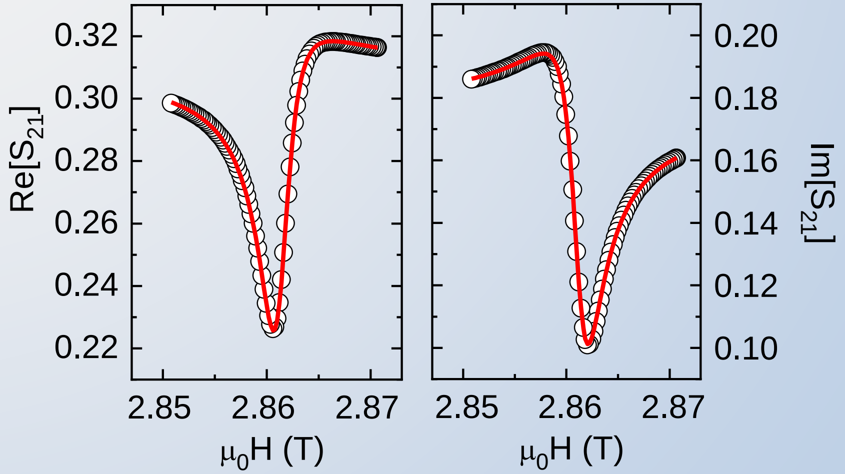
M_{eff}: Effective magnetization = M_s - H_k
H_k: perpendicular anisotropy field
M_S: Saturation magnetization
ΔH: Linewidth

Phase

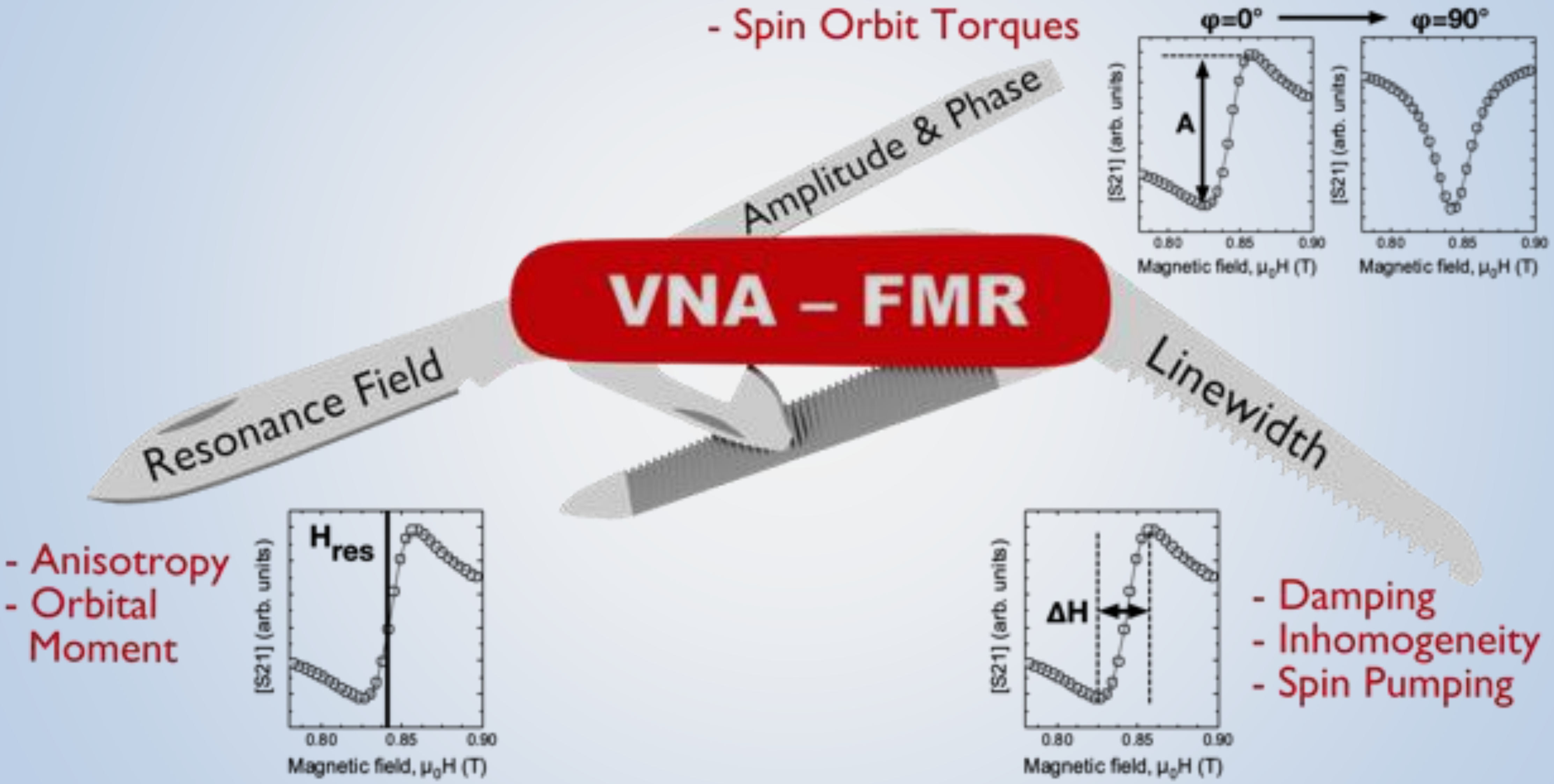
$$S_{21} = A\ e^{i\varphi}\ \chi(H,f) + background$$

Amplitude

Resonance Field, Linewidth



VNA-FMR



- Spin Orbit Torques

- Anisotropy
- Orbital Moment

- Damping
- Inhomogeneity
- Spin Pumping

Outline

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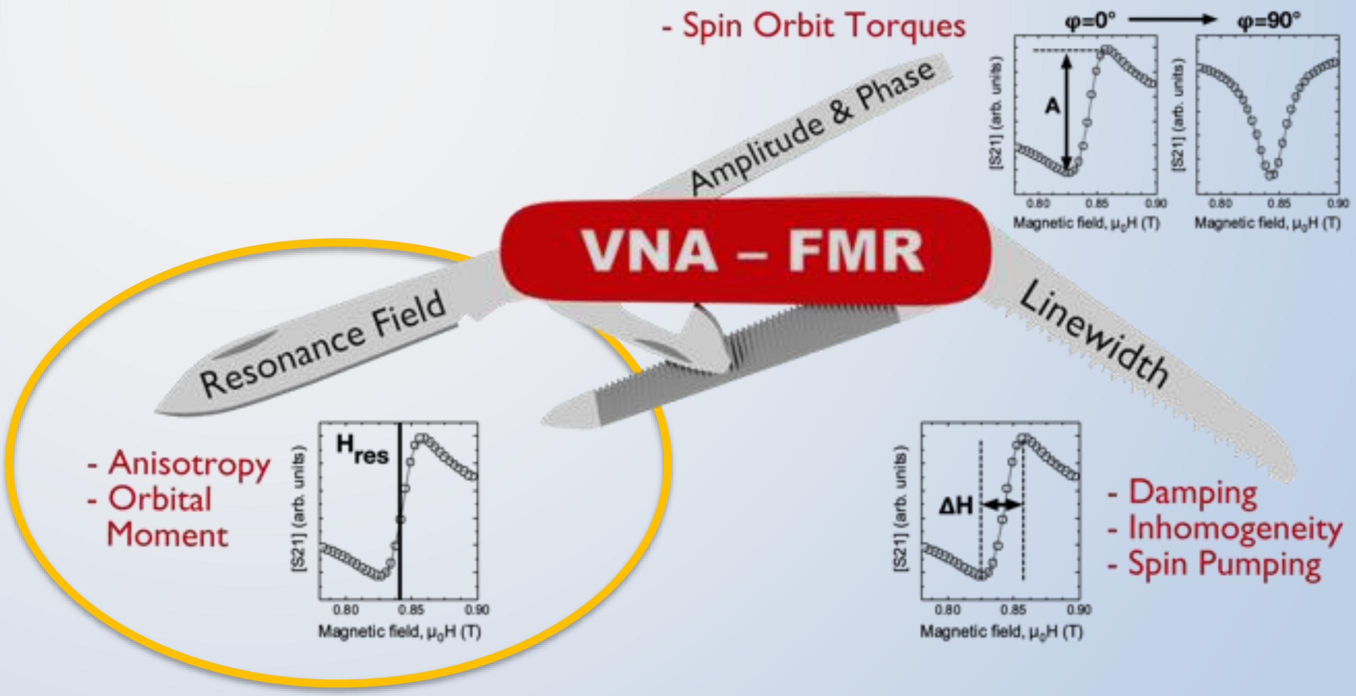
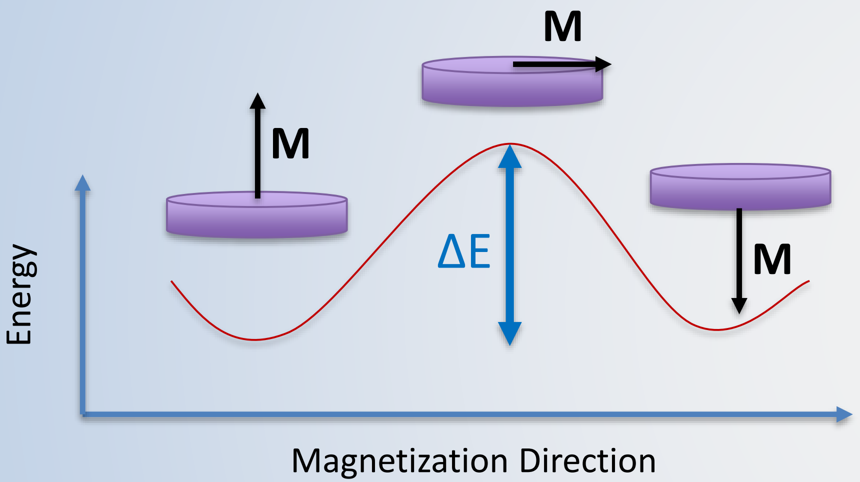
- Ferromagnetic Resonance Spectroscopy
- Anisotropy and Orbital Moments
- Damping and Spin-Pumping
- Spin-Orbit Torques



Magnetic Anisotropy

Magnetic Anisotropy gives a preferred orientation to the spontaneous magnetization



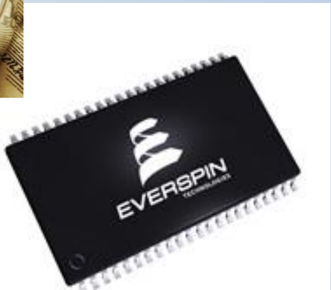
Can originate from:

- Magnetocrystalline
- Interfaces
- Strain (Magnetostriction)
- Shape (Magnetostatic energy)

Why important?

Seagate

Duke U



Simple model of Anisotropy Energy

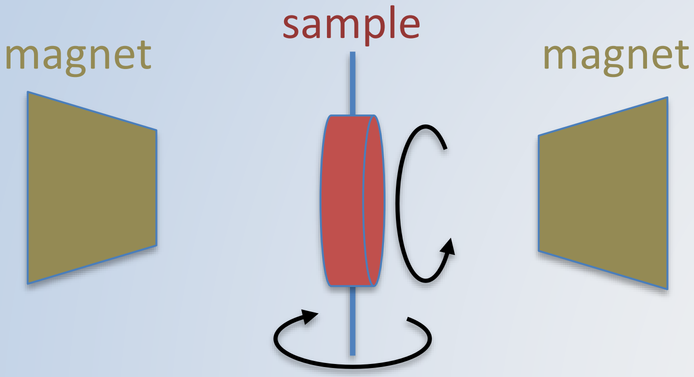
$$\boxed{\Delta E} = A\frac{\xi_{SO}}{4\mu_B}\boxed{(\mu_L^{\perp} - \mu_L^{||})}$$

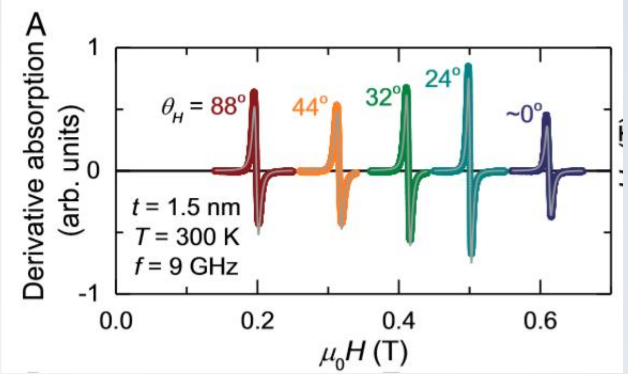
ΔE magnetic anisotropy energy
ξ_{SO} spin-orbit coupling constant
A prefactor (< 0.2) - function of electronic structure
μ_L orbital moment

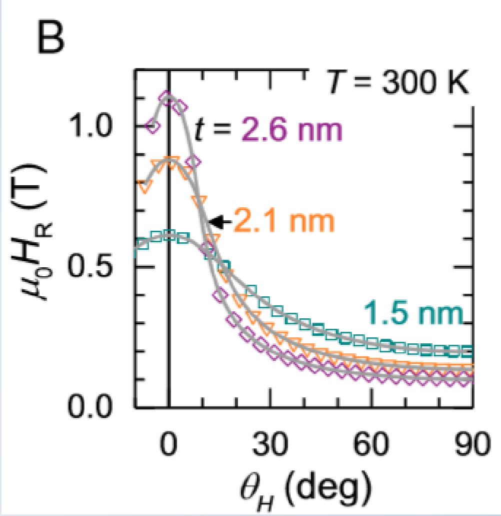
P. Bruno, PRB 39, 865 (1989)

How do we measure anisotropy?

- Angular Dependence of Resonance Field (H_{res})







A. Okada, PNAS, 114, 3815 (2017)

- Frequency (f) Dependence of Resonance Field (H_{res})

Kittel Equation:

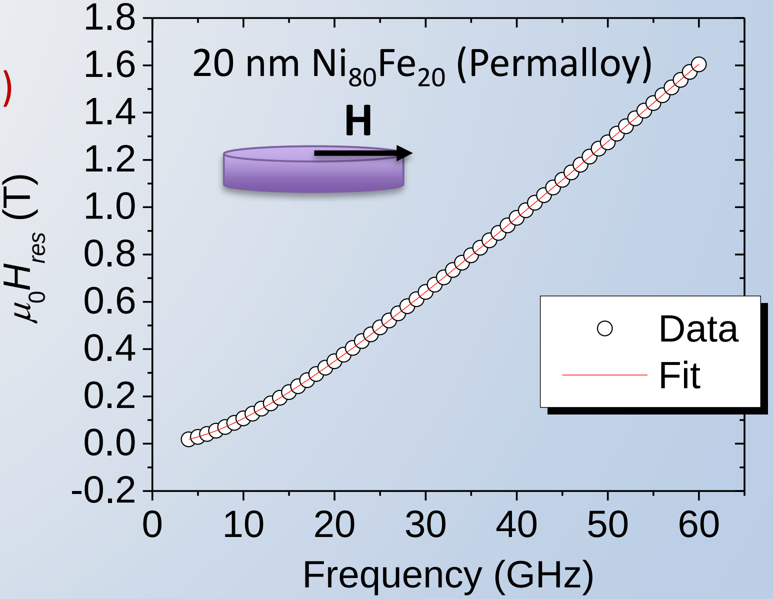
Can include anisotropy terms of any symmetry (see Farle, RPP (1998) for review)

$$f(H_{res}) = \frac{g^{||}\mu_0\mu_B}{2\pi\hbar}\sqrt{(H_{res} + H_K)(H_{res} + M_{eff} + H_K)}$$

In-plane anisotropy field

Perpendicular anisotropy field

Effective Magnetization: $M_{eff} = M_s - H_K^{\perp}$



How do we measure orbital moments?

g-factor relates the spin (μ_S) and orbital (μ_L) moments:

$$g = 2 + \frac{2\mu_L}{\mu_S}$$

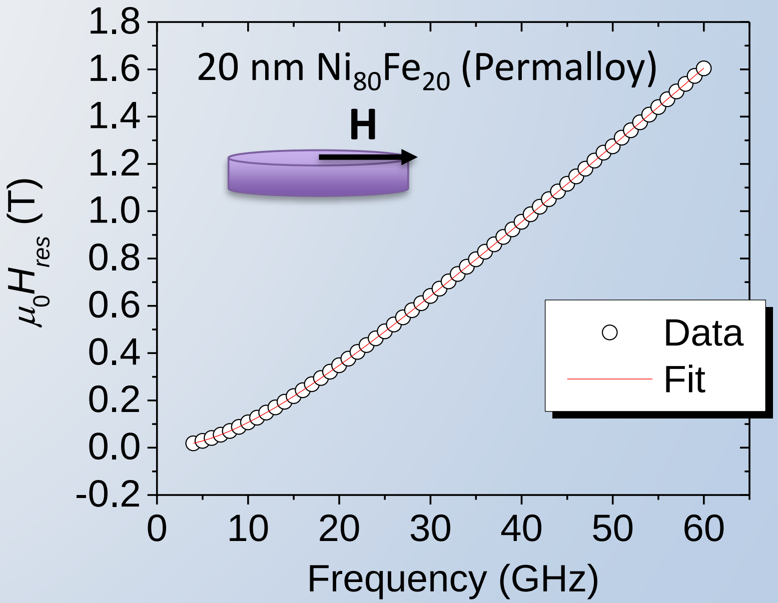
Since $\mu_S >> \mu_L$, *g* is typically slightly larger than 2 in ferromagnets

- Frequency (*f*) Dependence of Resonance Field (H_{res})

Spectroscopic g-factor

$$\boxed{f(H_{res}) = \frac{g^{||}\mu_0\mu_B}{2\pi\hbar}\sqrt{(H_{res}+H_K)\left(H_{res}+M_{eff}+H_K\right)}}$$

Effective Magnetization: $M_{eff} = M_s - H_K^{\perp}$



g-factor and orbital moments

g-factor relates the spin (μ_S) and orbital (μ_L) moments:

$$g = 2 + \frac{2\mu_L}{\mu_S}$$

Since $\mu_S >> \mu_L$, *g* is typically slightly larger than 2 in ferromagnets

PROBLEM: A small error in *g* leads to large error in μ_L

Consider g = 2.05 +/- 0.02 (1% error)
➔ 40% error in μ_L

PROBLEM: Reported values of g-factors can vary considerably

Permalloy Thickness	g–factor	Method	Frequency range	Reference
5 –50 nm (extrapolated to bulk value)	2.109 ± 0.003	VNA-FMR with asymptotic analysis	4—60 GHz	This work
50 nm	2.20 ± 0.12	Einstein-de-Haas	—	[27]
50 nm	2.0—2.1	PIMM	0—2 GHz	[28]
50 nm	2.1	PIMM	0—3 GHz	[29]
10 nm	2.05	PIMM	0—3 GHz	[29]
bulk	2.12 ± 0.02	FMR	19.5 & 26 GHz	[30]
bulk	2.12	Einstein-de-Haas	—	[31]
4—50 nm	2.08 ± 0.01	FMR	not reported	[32]
bulk	2.08 ± 0.03	FMR	10 GHz	[9]
bulk	2.12 ± 0.03	FMR	24 GHz	[9]

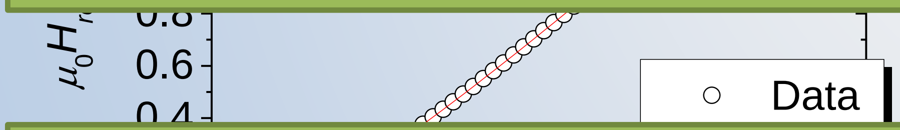
g-factor: Asymptotic Analysis

$$f(H_{res}) = \frac{g^{||}\mu_0\mu_B}{2\pi\hbar}\sqrt{H_{res}(H_{res}+M_{eff})}$$

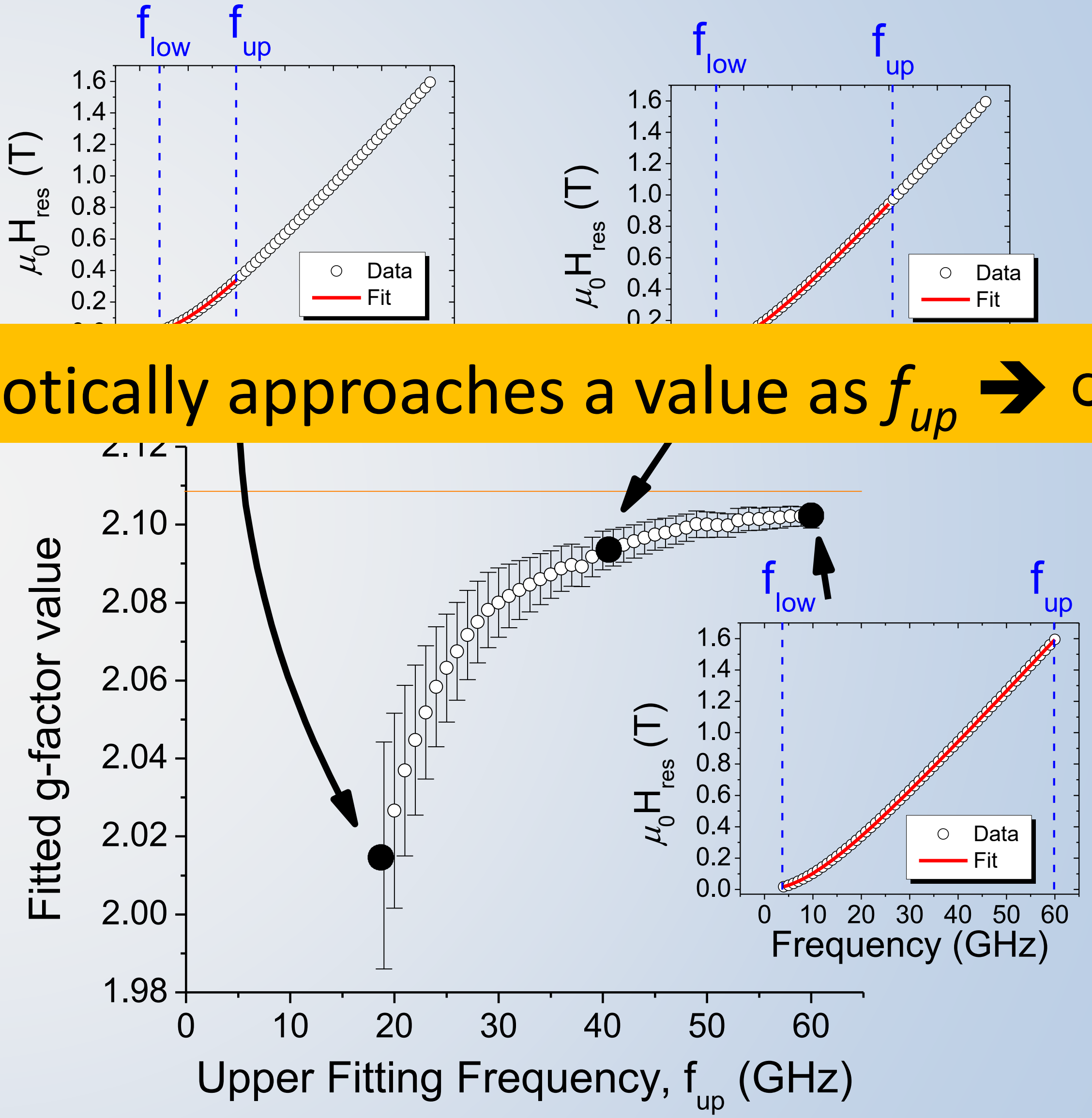
$$M_{eff} = M_s - \frac{2K}{\mu_0 M_s}$$

g_{fit} asymptotically approaches a value as f_{up} ➔ ∞

We make the assumption that the *y*-intercept (limit of f_{up} ➔ ∞) is the <u>intrinsic</u> value of *g* and M_{eff}.



Can achieve a precision better than 0.2 % in permalloy

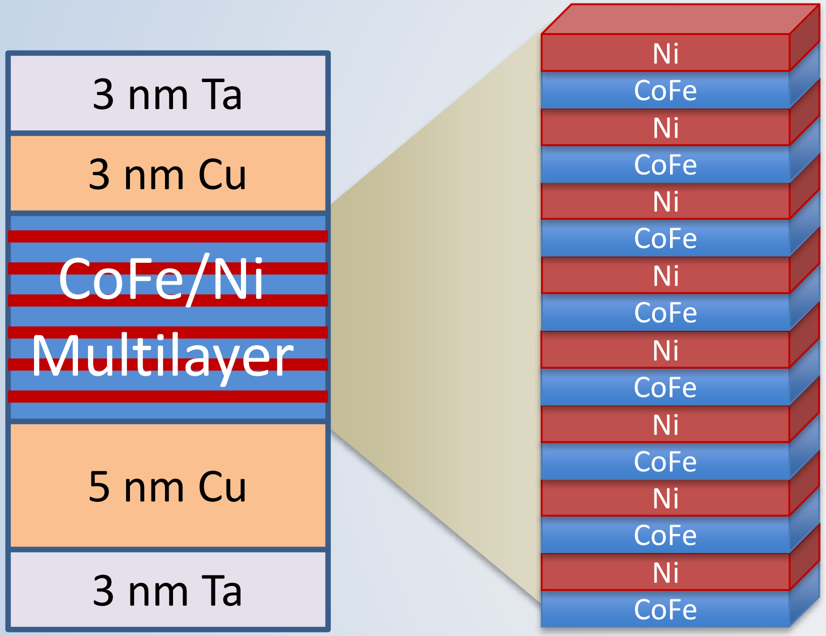


Shaw, JAP 114 243906 (2013)

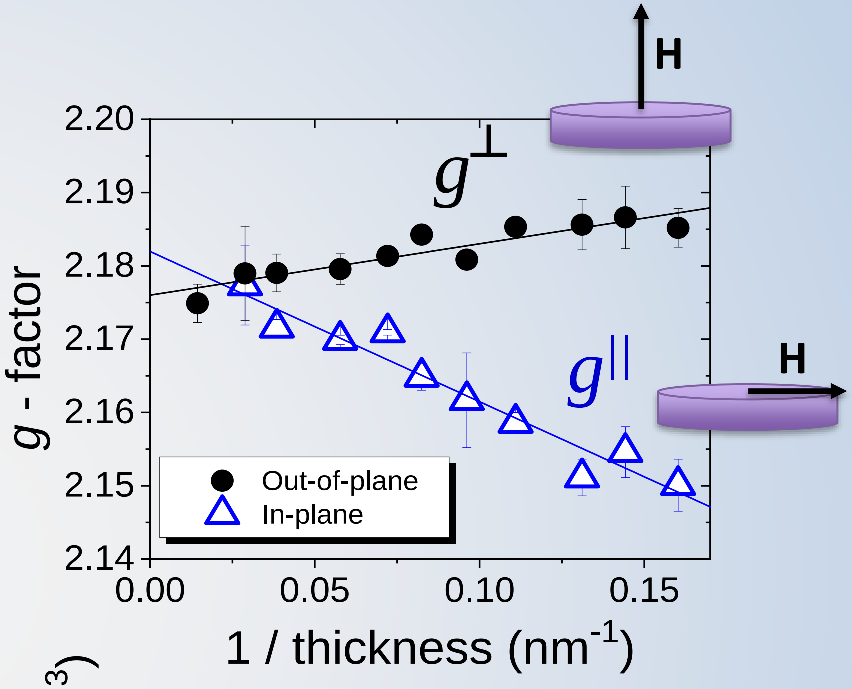
What can cause errors in g-factors

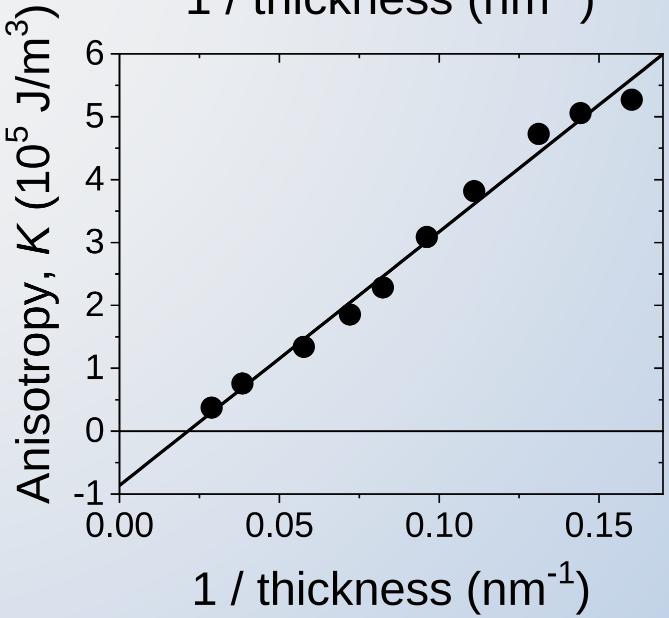
- Field misalignment
- Higher order anisotropy terms
- Rotatable (history dependent) anisotropy
- Pinning of local spins
    - Defects
    - Interfaces
- Excessive fitting parameters
- Any missing or field dependent term in Kittel eqn.

Application: $Co_{90}Fe_{10}$/Ni Superlattices



- Anisotropy is tuned by varying the thickness.





J.M. Shaw, *et al.*, Phys. Rev. B, 87, 054416 (2013)

Application of g-factor analysis: CoFe/Ni

A test of Bruno’s theory:

$$\boxed{K} = -\left(A\frac{\xi_{SO}N}{4V}\right)\boxed{\frac{(\mu_L^{\perp}-\mu_L^{||})}{\mu_B}}$$

P. Bruno, PRB 39, 865 (1989)

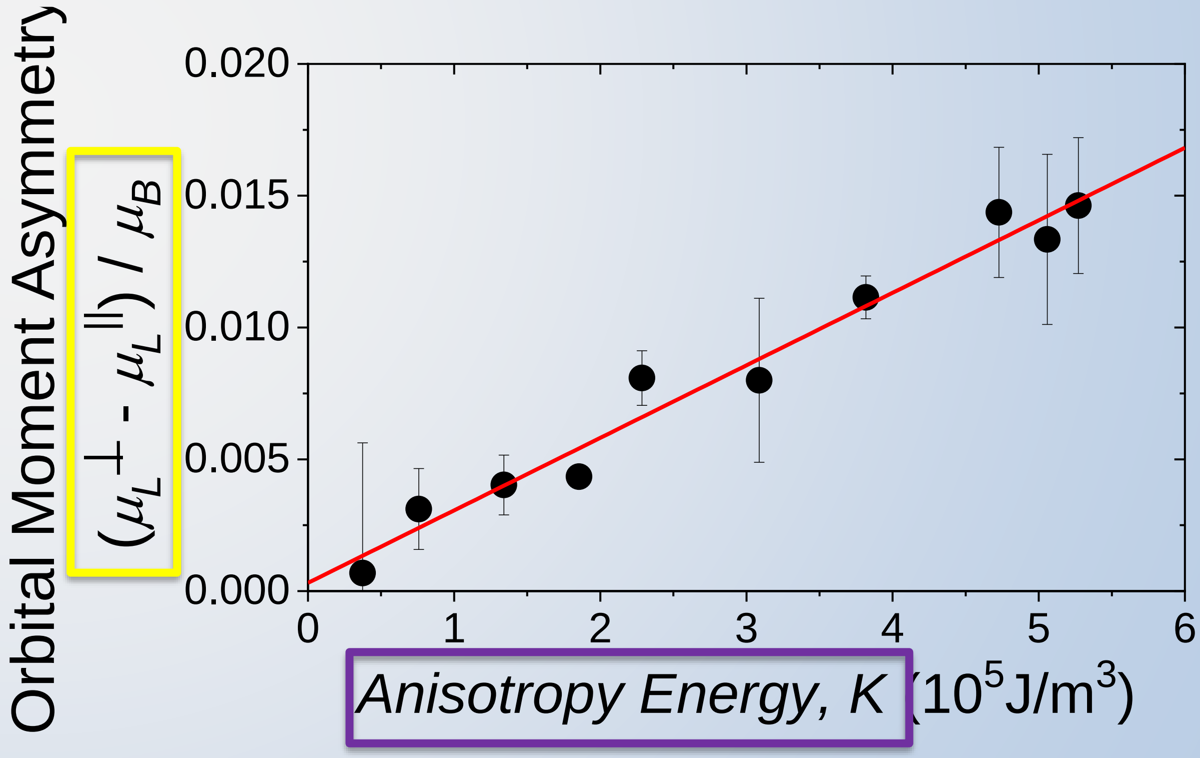
K anisotropy energy density
ξ spin-orbit coupling constant
A prefactor due to electronic structure
N number atoms per unit cell
V volume of unit cell

Fit to the data:

***A* = 0.097 ± 0.007**

Compare to previous reports:

- ***A* = 0.2** at RT, Au/Co/Au
  D. Weller, et al. PRL 75, 3752 (1995)
- ***A* = 0.1** at near 0 K, Ni/Pt MLs
  F. Wilhelm, et al. PRL 75, 3752 (1995)
- ***A* = 0.05** at near 0 K, Fe/V MLs
  A.Anisimov, et al. PRL 82, 2390 (1999)



J.M. Shaw, *et al.*, Phys. Rev. B, 87, 054416 (2013)

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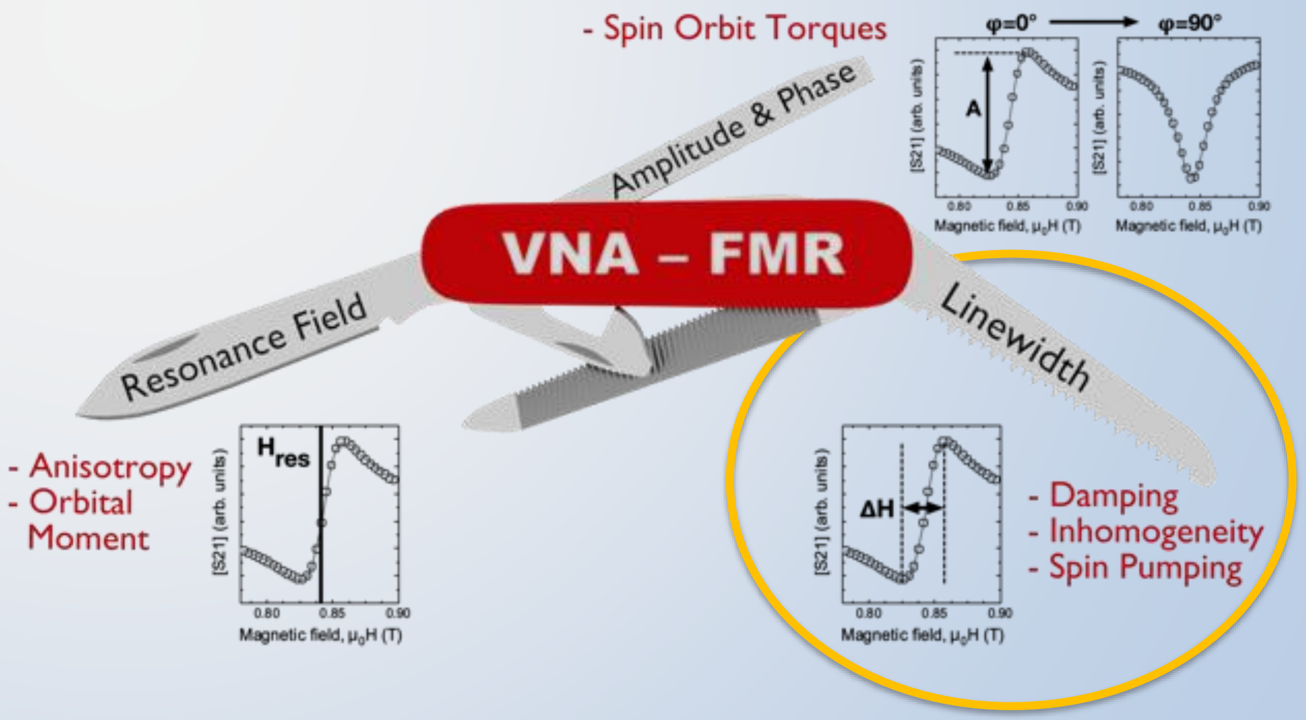
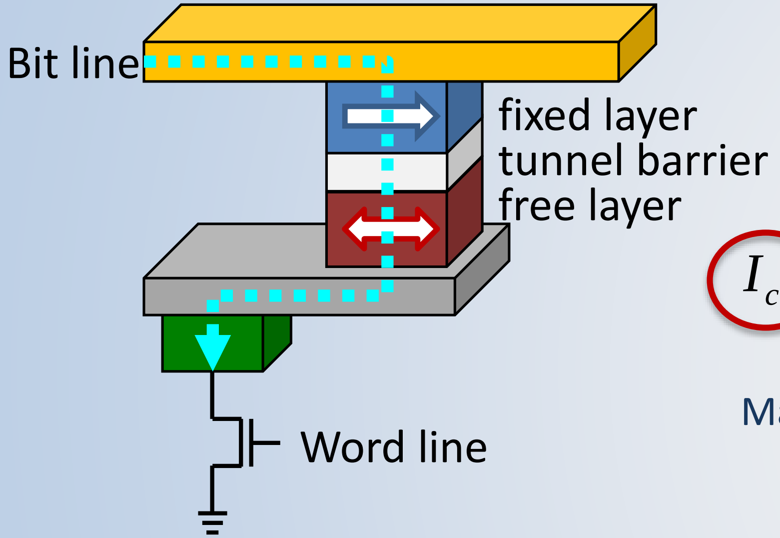


Why is damping important?

Data Storage & Magnetic Memory (STT-RAM)

2-terminal Spin-Transfer Torque (STT)


Bit line

fixed layer

tunnel barrier

free layer

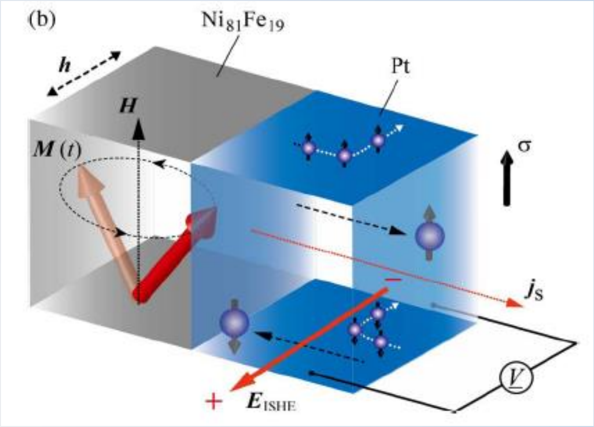
Word line

Critical current needed to switch an MRAM cell

$$I_{c0} = \left(\frac{2e}{\hbar}\right)\frac{\alpha M_s V}{g(\theta)p}H_{eff}$$

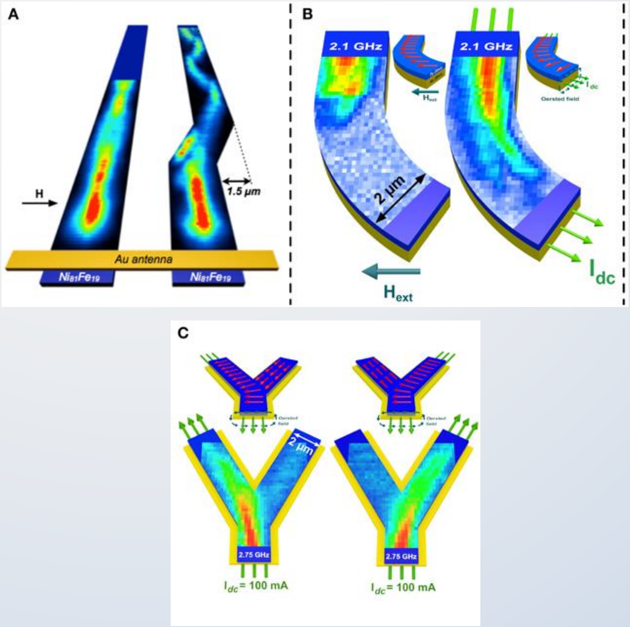
Mangin APL (2009)

Spin current source

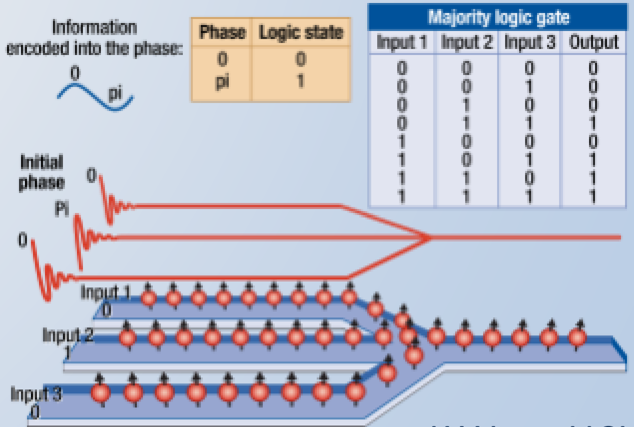


Nakayama, IEEE Trans Mag. (2010)

Magnonics and Spin Logic



H.Schultheiss, HZDR

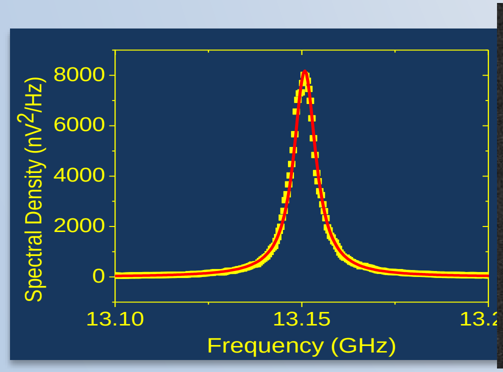


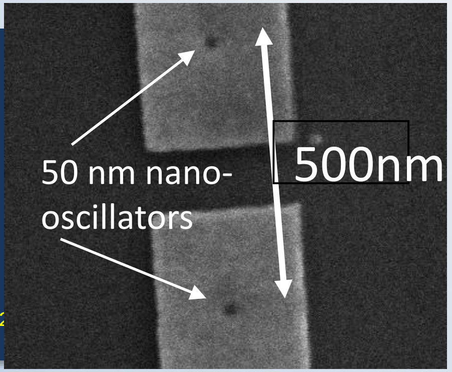
Phase	Logic state
0	0
pi	1

Majority logic gate			
Input 1	Input 2	Input 3	Output
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

K.Wang UCLA

Spin-torque nano-oscillators





Intrinsic Damping Theories

$$\frac{d\vec{M}}{dt} = -|\gamma|\mu_0\left(\vec{M}\times\vec{H}\right) - \boxed{\boldsymbol{\alpha}}\,\frac{|\gamma|\mu_0}{M_s}\left[\vec{M}\times\left(\vec{M}\times\vec{H}\right)\right]$$

- Breathing Fermi surface model:

  Kamberský, V. *Czechoslovak Journal of Physics B* **34**, 1111–1124 (1984)
  Kamberský, V. *Czechoslovak Journal of Physics B* **26**, 1366–1383 (1976)
  Kambersky, V. & Patton, C. E. *Phys. Rev. B* **11**, 2668–2672 (1975)

- Generalized torque correlation model:

  Gilmore, K., Idzerda, Y. U. & Stiles, M. D. *Phys. Rev. Lett.* **99**, 027204 (2007)
  Thonig, D. & Henk, J. *New J. Phys.* **16**, 013032 (2014)

- Scattering theory:

  Brataas, A., Tserkovnyak, Y. & Bauer, G. E. W. *Phys. Rev. Lett.* **101**, 037207 (2008)
  Liu, Y., Starikov, A. A., Yuan, Z. & Kelly, P. J. *Phys. Rev. B* **84**, 014412 (2011)

- Numerical realization of torque correlation via linear response:

  Mankovsky, S., Ködderitzsch, D., Woltersdorf, G. & Ebert, H. *Phys. Rev. B* **87**, 014430 (2013)

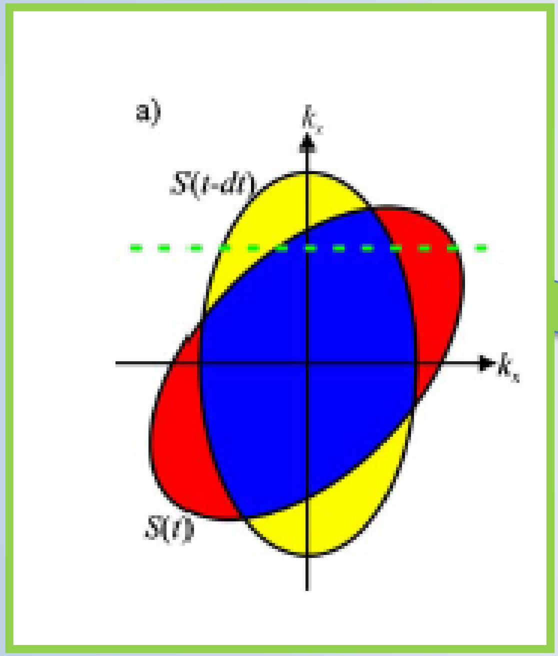
- First priciples calculations:

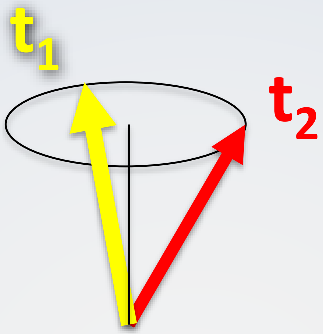
  M. C. Hickey & J. S. Moodera, *Phys. Rev. Lett.* 102,137601 (2009)
  Ritwik Mondal,* Marco Berritta, and Peter M. Oppeneer, *Phys. Rev. B* **94,** 144419 (2016)

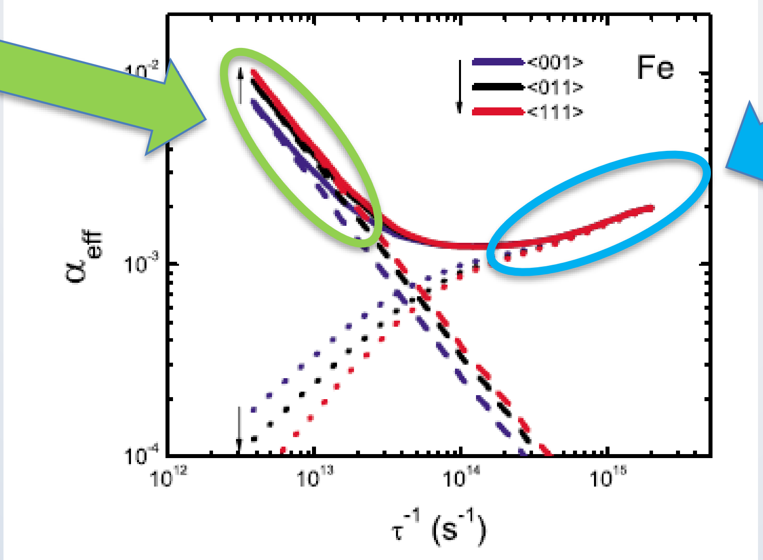
Intraband versus Interband

Intraband

"Breathing Fermi Surface"
"Conductivity-like damping"



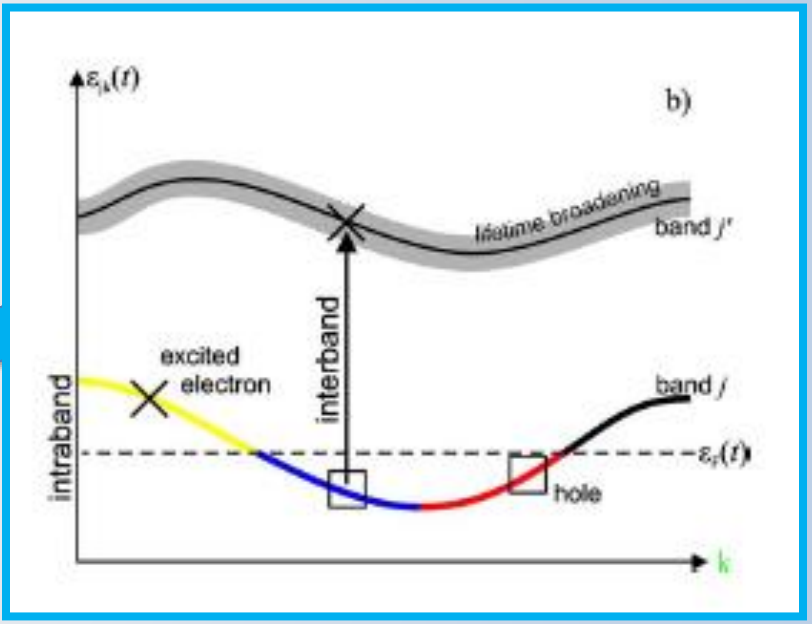




Inverse scattering time (1/τ)
Temperature ➔
Defect density ➔

Interband

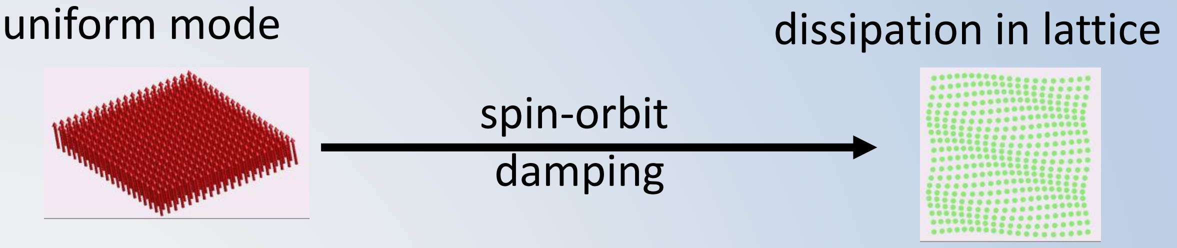
"Bubbling Fermi Surface"
"Resistivity-like damping"



Gilmore and Stiles, *PRB* **81,** 174414 (2010)

Intrinsic Damping: Critical Parameters

Kamberský's Torque Correlation model:



Courtesy of Claudia Mewes

Sum over all electronic states, bands

$$\alpha \propto \left\langle \sum_{m,n} \left| \Gamma^{-}_{mk,nk} \right|^2 W_{mk,nk} \right\rangle_k$$

Torque between spin and orbital moments $\propto \xi_{SO}$

spectral overlap function of Bloch state lifetime

Critical Parameters affecting intrinsic damping:

$N(E_F)$: Density of states at the Fermi energy, E_F

ξ_{SO} : Spin-Orbit Interaction

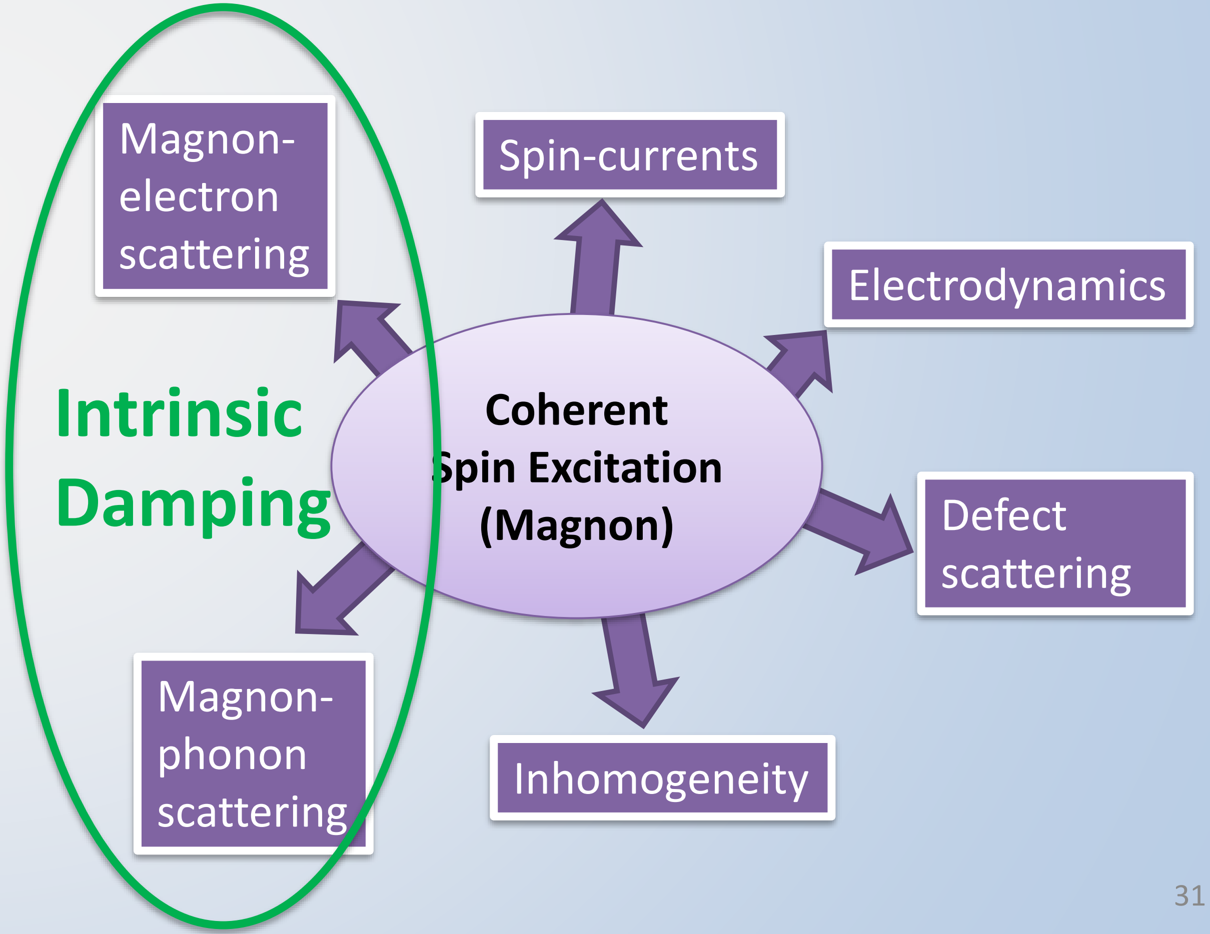
τ: Spin scattering times

Origin of damping

$$\frac{d\vec{M}}{dt} = -|\gamma|\mu_0\left(\vec{M}\times\vec{H}\right) - \boxed{\boldsymbol{\alpha}}\,\frac{|\gamma|\mu_0}{M_s}\left[\vec{M}\times\left(\vec{M}\times\vec{H}\right)\right]$$

- Originally just a phenomenological parameter
- Theory has worked to calculate damping parameter α from first principles

In reality, α includes **many** intrinsic and extrinsic sources and is not necessarily a constant



Intrinsic Damping

Magnon-electron scattering

Magnon-phonon scattering

Coherent Spin Excitation (Magnon)

Spin-currents

Electrodynamics

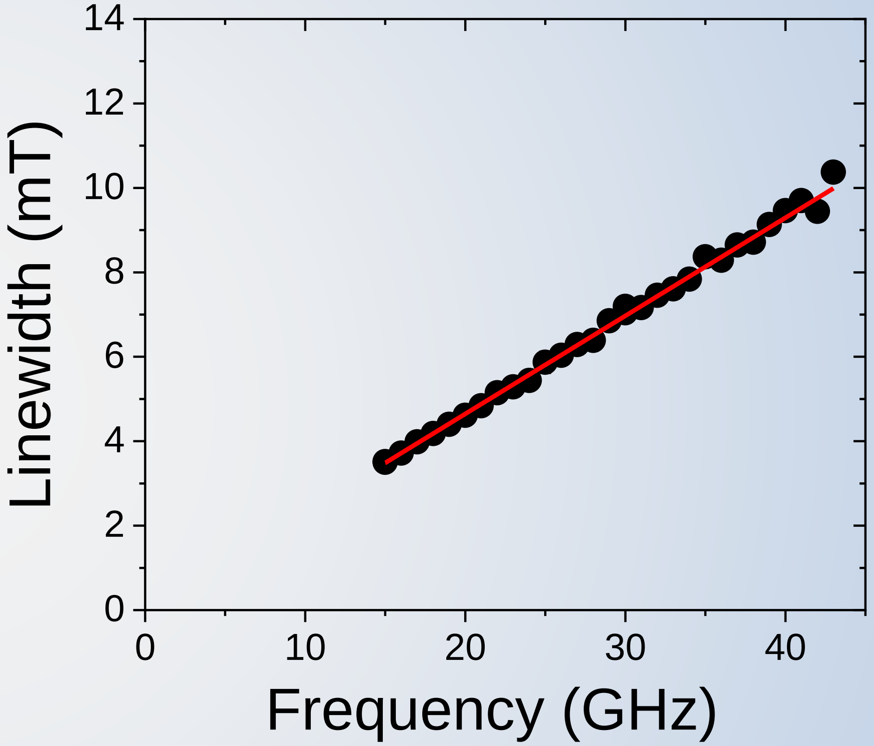
Defect scattering

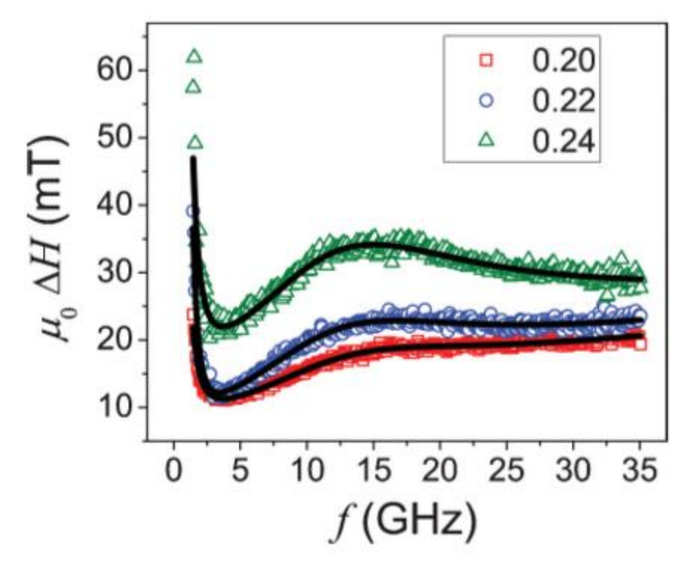
Inhomogeneity

How Do We Measure Damping?

LL equation predicts linewidth is proportional to frequency

$$\Delta H = \frac{2h\boldsymbol{\alpha}}{g\mu_0\mu_B} f$$





However, that is not always observed

Linewidth Analysis

☐ Inhomogeneous Broadening
☐ Low-field losses
☐ 2-magnon scattering
☐ Spin-pumping
☐ Radiative Damping
☐ k^2 Damping
☐ Other Contributions
    ☐ Eddy Currents
    ☐ Slow relaxer
    ☐ Motional Narrowing
    ☐ Chiral Damping
☐ Intrinsic Damping

- **Many** relaxation mechanisms and contributions to linewidth exist
- Careful separation and quantification of all mechanisms is needed to compare with theory

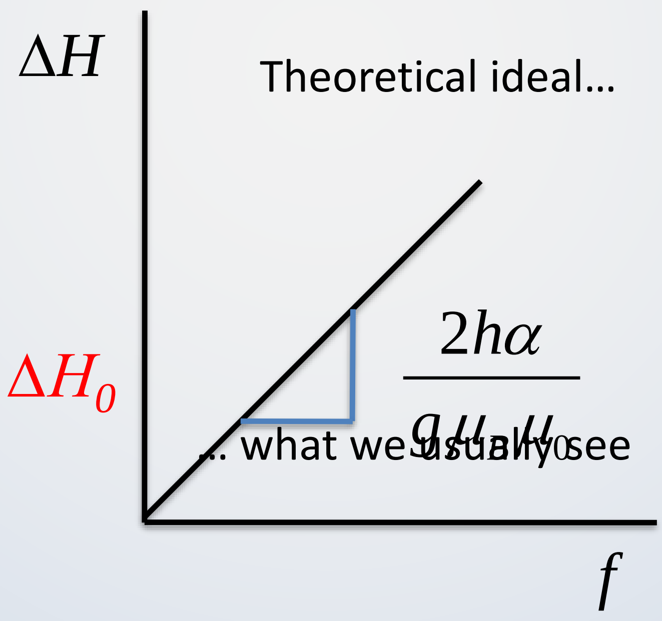
Point of emphasis:
Broadband measurements are critical.

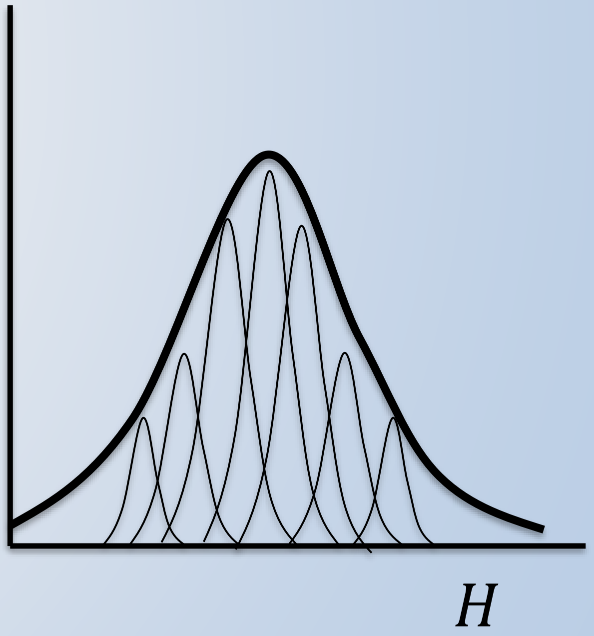
Inhomogeneous Linewidth

- ☐ **Inhomogeneous Broadening**
- ☐ Low-field losses
- ☐ 2-magnon scattering
- ☐ Spin-pumping
- ☐ Radiative Damping
- ☐ k^2 Damping
- ☐ Other Contributions
  - ☐ Eddy Currents
  - ☐ Slow relaxer
  - ☐ Motional Narrowing
  - ☐ Chiral Damping
- ☐ Intrinsic Damping

$$\boxed{\Delta H = \frac{2h\alpha}{g\mu_0\mu_B} f + \boldsymbol{\Delta H_0}}$$

Inhomogeneous Linewidth





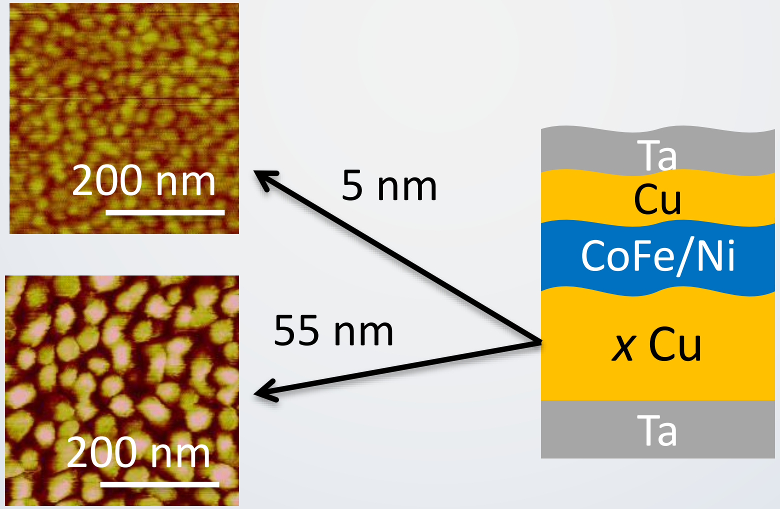
Heinrich, JAP, 57, 3690 (1985)
Farle, Rep. Prog. Phys. 61, 755 (1998)
McMichael, PRL 90, 227601 (2003)

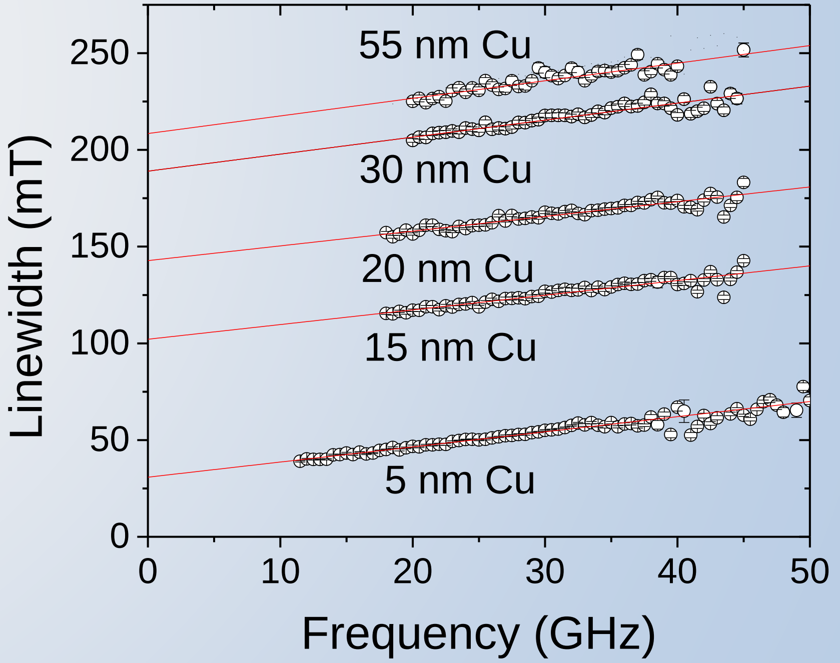
Inhomogeneous Linewidth

- ☐ **Inhomogeneous Broadening**
- ☐ Low-field losses
- ☐ 2-magnon scattering
- ☐ Spin-pumping
- ☐ Radiative Damping
- ☐ k^2 Damping
- ☐ Other Contributions
  - ☐ Eddy Currents
  - ☐ Slow relaxer
  - ☐ Motional Narrowing
  - ☐ Chiral Damping
- ☐ Intrinsic Damping

$$\boxed{\Delta H = \frac{2h\alpha}{g\mu_0\mu_B} f + \Delta H_0}$$

Inhomogeneous Linewidth





Heinrich, JAP, 57, 3690 (1985)
Farle, Rep. Prog. Phys. 61, 755 (1998)
McMichael, PRL 90, 227601 (2003)

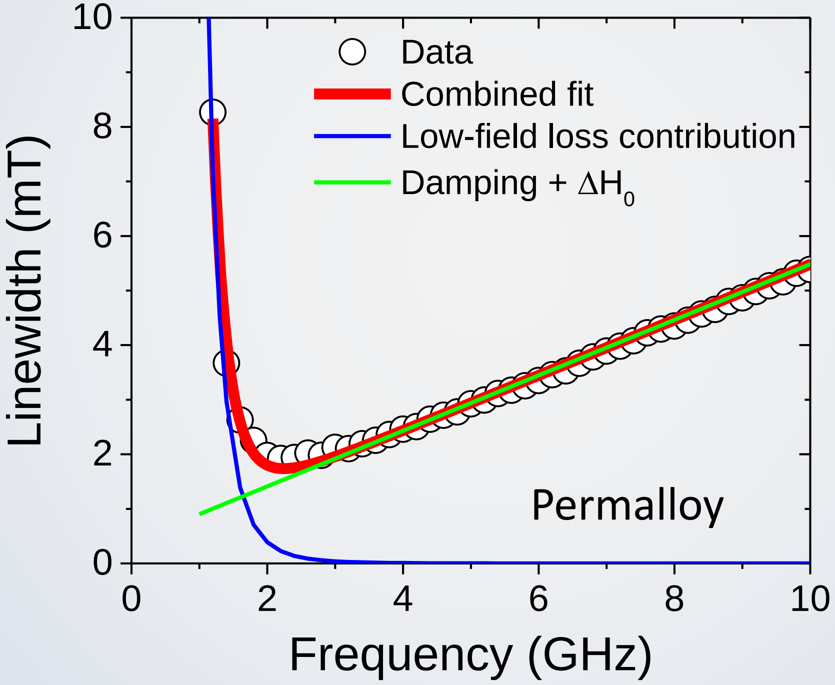
Low Field Loss

- ☐ Inhomogeneous Broadening
- ☐ **Low-field losses**
- ☐ 2-magnon scattering
- ☐ Spin-pumping
- ☐ Radiative Damping
- ☐ k^2 Damping
- ☐ Other Contributions
  - ☐ Eddy Currents
  - ☐ Slow relaxer
  - ☐ Motional Narrowing
  - ☐ Chiral Damping
- ☐ Intrinsic Damping

- At low fields (frequency), sample may not be saturated.

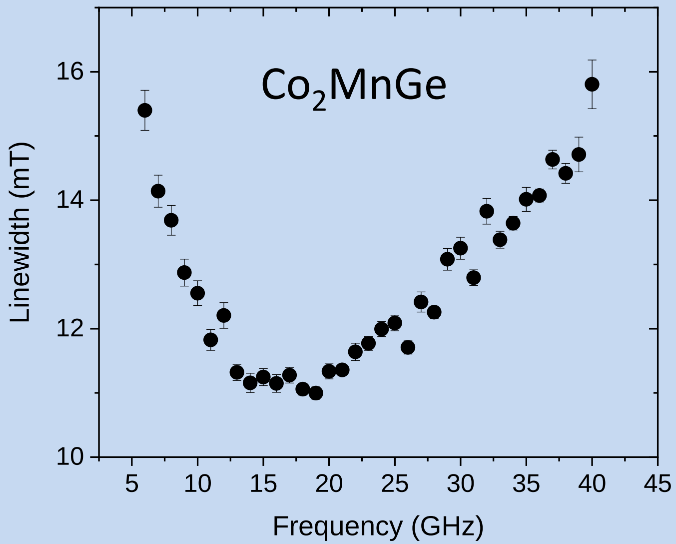
  ➔ Linewidth Broadening

$$\boxed{\Delta H_{low-field} = \frac{\beta}{f^{n}}}$$



- Described by a power law fit

- Effect can extend to higher frequencies for some materials



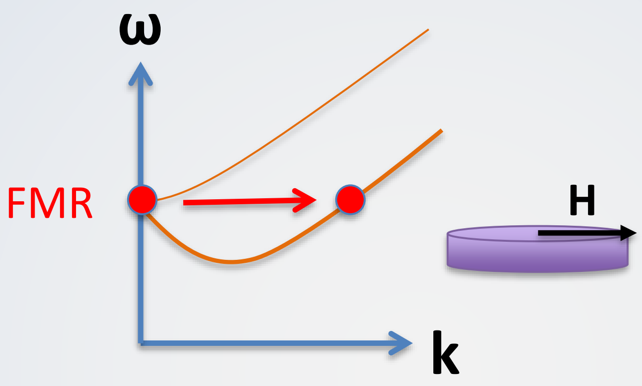
E. Schloemann: JAP 41, 204 (1970)

2-Magnon Scattering

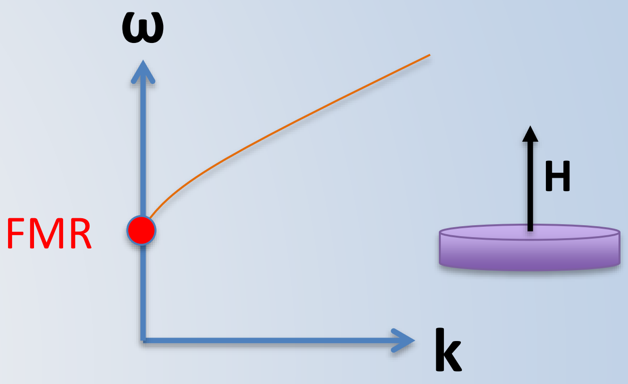
- ☐ Inhomogeneous Broadening
- ☐ Low-field losses
- ☐ **2-magnon scattering**
- ☐ Spin-pumping
- ☐ Radiative Damping
- ☐ k^2 Damping
- ☐ Other Contributions
  - ☐ Eddy Currents
  - ☐ Slow relaxer
  - ☐ Motional Narrowing
  - ☐ Chiral Damping
- ☐ Intrinsic Damping

- Mediated by Defect Scattering

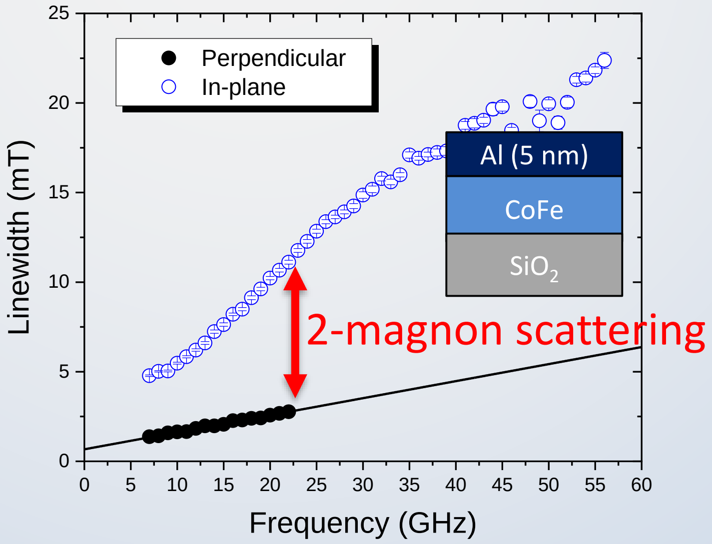
In-plane geometry

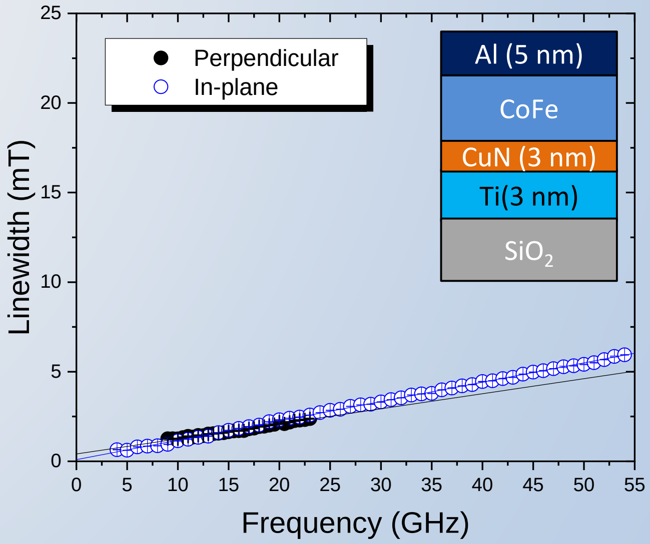


Out-of-plane geometry



- Can reduce/eliminate with out-of-plane geometry





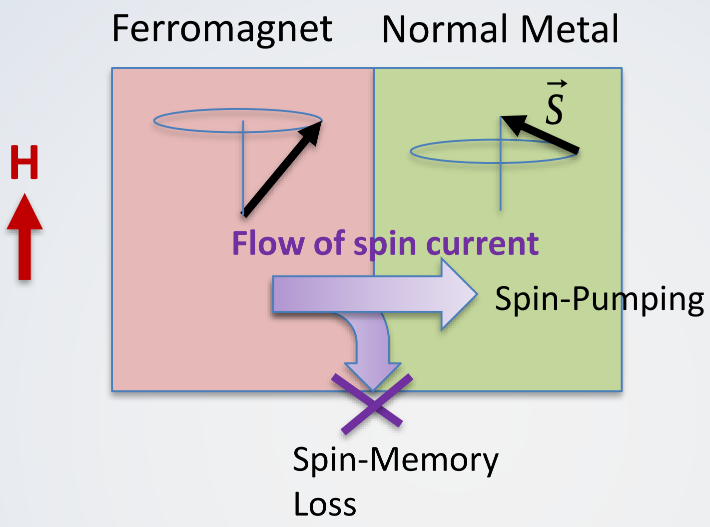
Sparks, Phys Rev. 122, 791 (1961)
Hurben, JAP 83, 4344 (1989)
McMichael, JAP 91, 8647 (2002)
Lindner, PRB 68, 060102 (2003)
Barsukov, PRB 84, 140410 (2011)

arXiv:1804.08786

Spin-Pumping & Spin-Memory Loss

- ☐ **Inhomogeneous Broadening**
- ☐ **Low-field losses**
- ☐ **2-magnon scattering**
- ☐ **Spin-pumping**
- ☐ **Radiative Damping**
- ☐ **k^2 Damping**
- ☐ **Other Contributions**
  - ☐ **Eddy Currents**
  - ☐ **Slow relaxer**
  - ☐ **Motional Narrowing**
  - ☐ **Chiral Damping**
- ☐ **Intrinsic Damping**

Loss of angular momentum at or across an interface

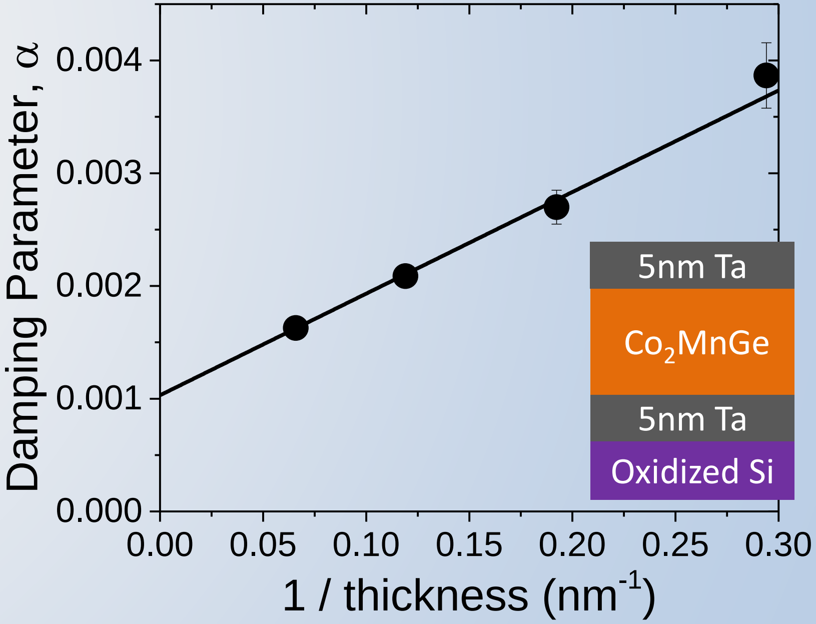


Can be phenomenologically treated as an interfacial damping term

$$\alpha(t) = \alpha_{int} + g\mu_B \frac{g_{eff}^{\uparrow\downarrow}}{4\pi M_s}\frac{1}{t}$$

t = thickness
g = g-factor
$g^{\uparrow\downarrow}$ = *effective* real part spin-mixing conductance

y-intercept is the damping without spin-pumping contribution

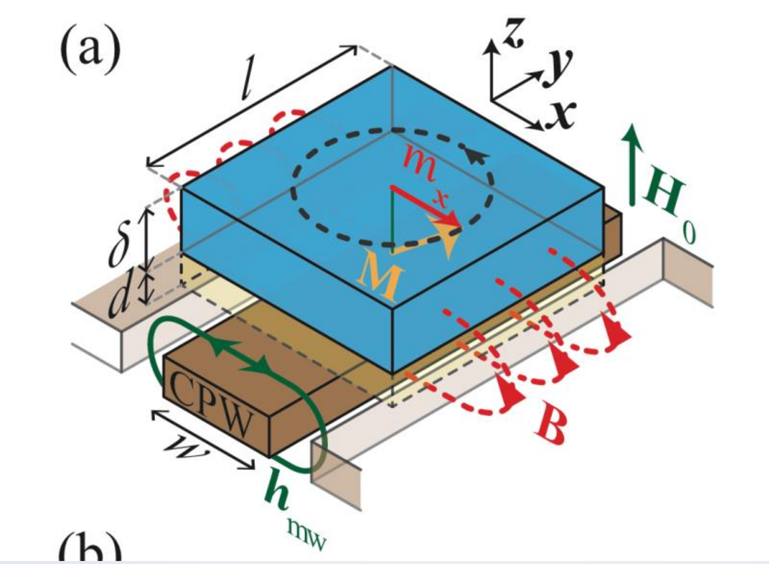


Y. Tserkovnyak, PRL 88, 117601 (2002)
O.Mosendz, PRB 82, 214403 (2010)

Radiative Damping

- ☐ **Inhomogeneous Broadening**
- ☐ **Low-field losses**
- ☐ **2-magnon scattering**
- ☐ **Spin-pumping**
- ☐ **Radiative Damping**
- ☐ **k^2 Damping**
- ☐ **Other Contributions**
  - ☐ **Eddy Currents**
  - ☐ **Slow relaxer**
  - ☐ **Motional Narrowing**
  - ☐ **Chiral Damping**
- ☐ **Intrinsic Damping**

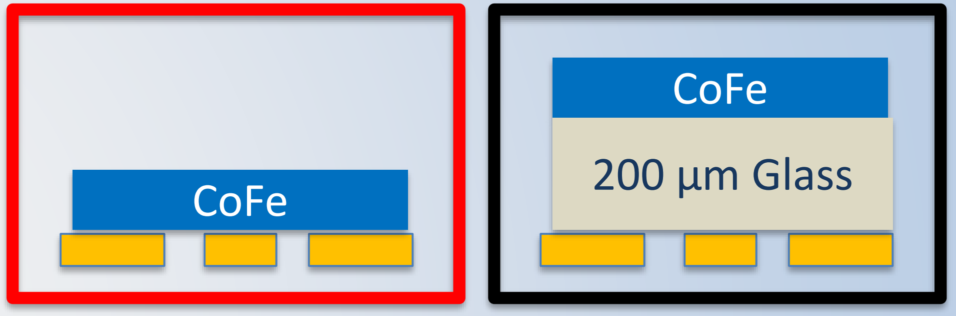
Damping contribution due to inductive coupling of the sample to the waveguide

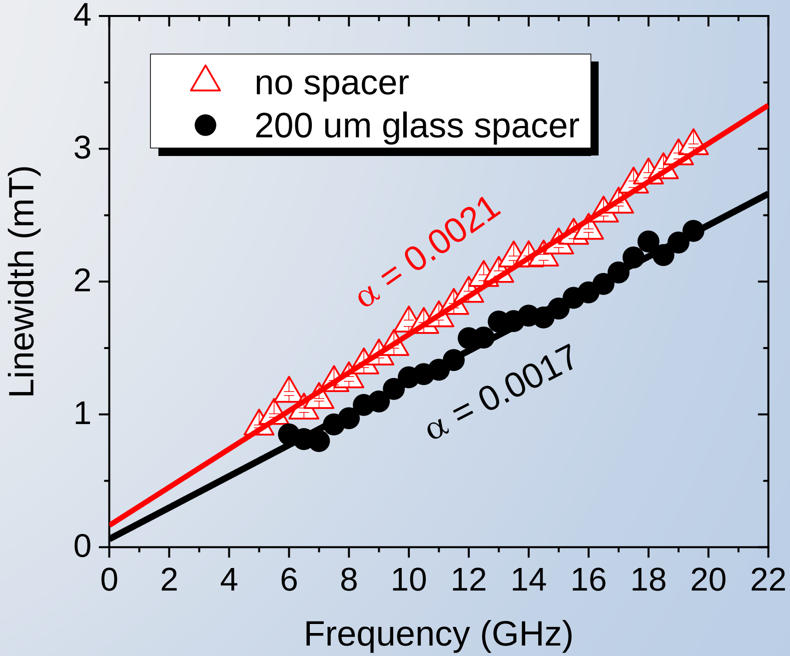


δ = thickness

Z_0 = waveguide impedance

30 nm $Co_{25}Fe_{75}$ Sample





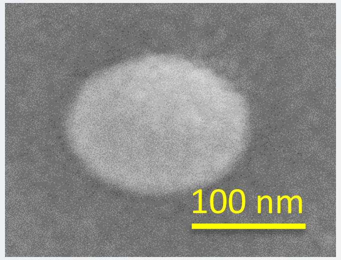
M.Schoen, PRB, 92, 184417 (2015)

Wavevector Dependent Damping

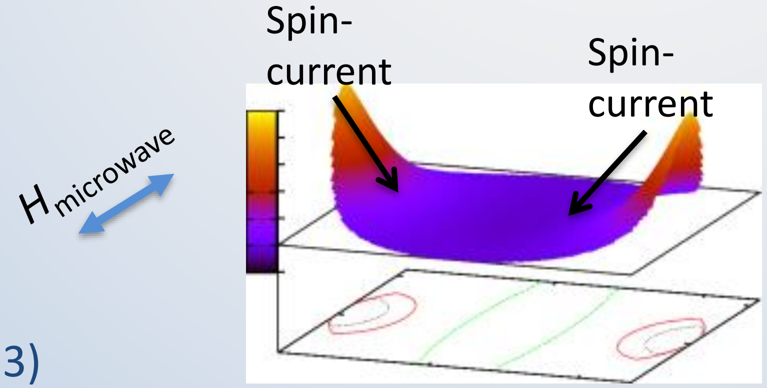
- ☐ Inhomogeneous Broadening
- ☐ Low-field losses
- ☐ 2-magnon scattering
- ☐ Spin-pumping
- ☐ Radiative Damping
- ☐ **k^2 Damping**
- ☐ Other Contributions
  - ☐ Eddy Currents
  - ☐ Slow relaxer
  - ☐ Motional Narrowing
  - ☐ Chiral Damping
- ☐ Intrinsic Damping

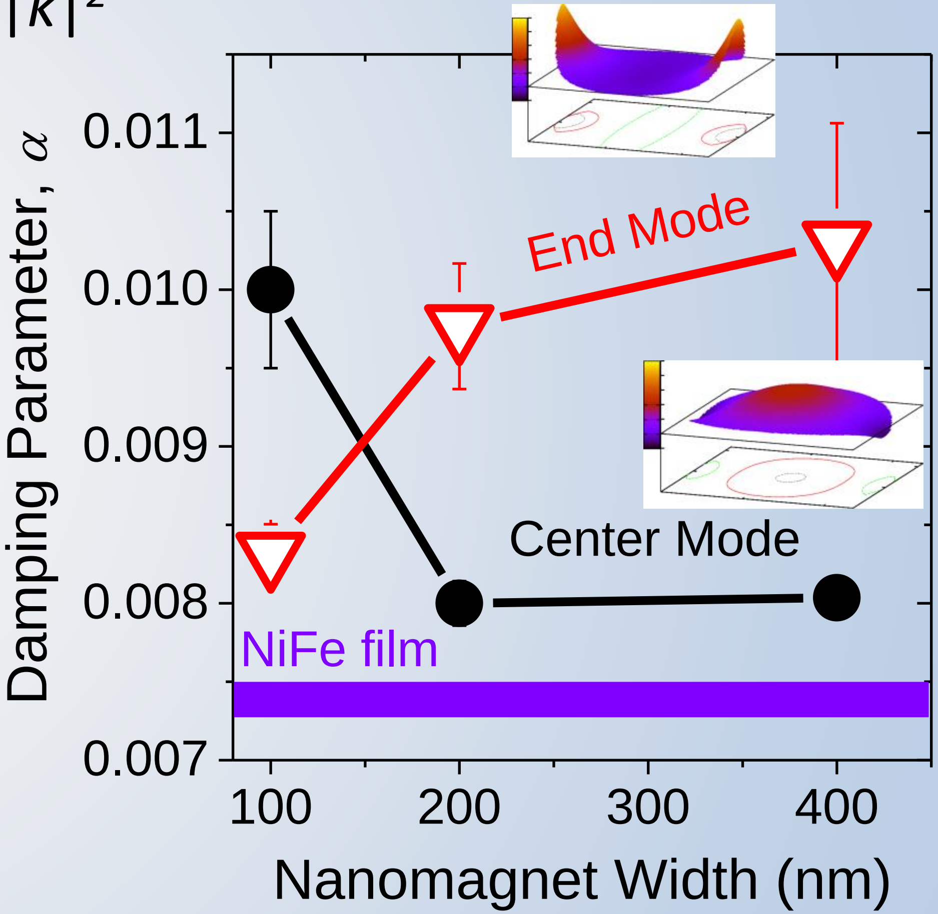
Theory predicts a wavevector (***k***) dependence of damping $\propto |k|^2$

Y. Tserkovnyak Phys. Rev. B 79, 094415 (2009)
S. Zhang Phys. Rev. Lett., 102, 086601 (2009)



➔Generation of intralayer spin currents



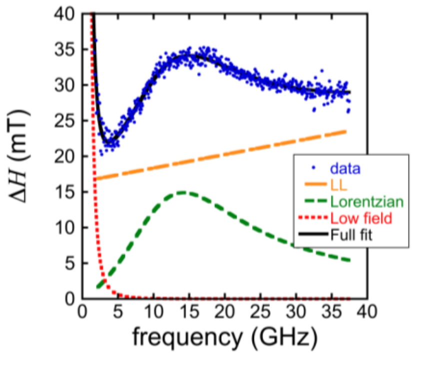


Nembach PRL 110, 117201 (2013)

Other Sources of Linewidth and Damping

- ☐ Inhomogeneous Broadening
- ☐ Low-field losses
- ☐ 2-magnon scattering
- ☐ Spin-pumping
- ☐ Radiative Damping
- ☐ k^2 Damping
- ☐ **Other Contributions**
  - ☐ **Eddy Currents**
  - ☐ **Slow relaxer**
  - ☐ **Motional Narrowing**
  - ☐ **Chiral Damping**
- ☐ Intrinsic Damping

Slow Relaxer (Resonant Damping)



Van Vleck, PRL 11, 65 (1963).
Woltersdorf, PRL 102, 257602 (2009)
Nembach, PRB, 84, 054424 (2011)

Eddy Currents

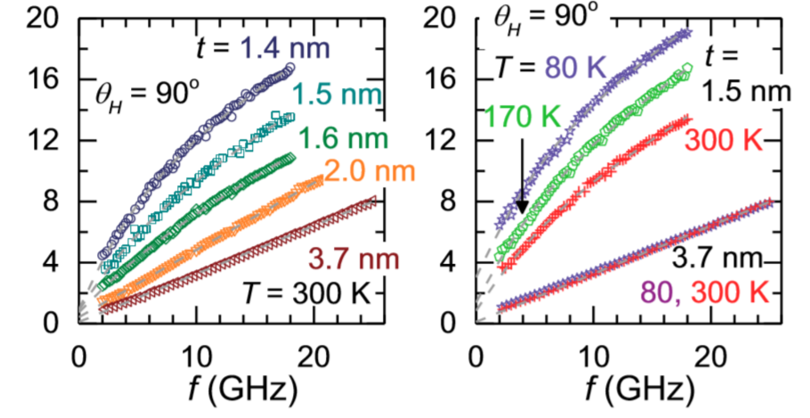
$$\alpha^{\text{eddy}} = \frac{C}{8}\frac{\gamma\mu_0^2 M_s \delta^2}{\rho},$$

δ = thickness
ρ = resistivity
C = correction factor

Generally not significant for metallic thin films < 20 nm

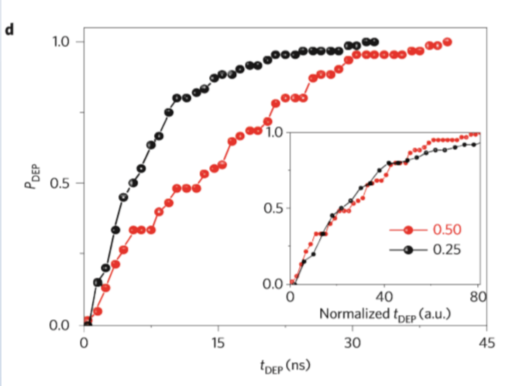
J. M. Lock, British JAP 17, 1645 (1966)
C. Scheck, APL 88, 252510 (2006)

Motional Narrowing



A. Okada, PNAS, 114, 3815 (2017)

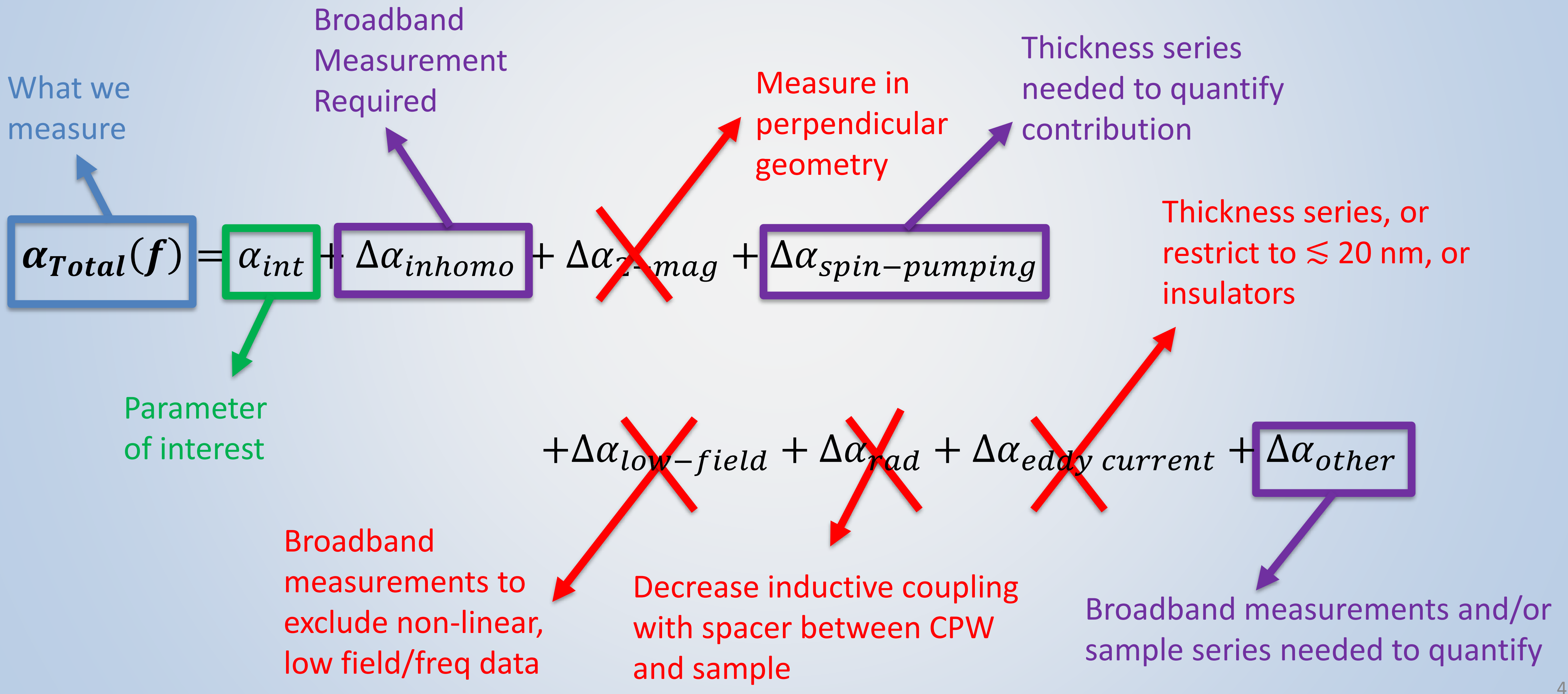
Chiral Damping



E. Jue, Nature Materials 15, 272 (2015)

Intrinsic and Total Damping

- To compare with theory, we must account for or eliminate additional damping terms.



What we measure

Broadband Measurement Required

Measure in perpendicular geometry

Thickness series needed to quantify contribution

$$\boxed{\boldsymbol{\alpha}_{\boldsymbol{Total}}(\boldsymbol{f})} = \boxed{\alpha_{int}} + \boxed{\Delta\alpha_{inhomo}} + \cancel{\Delta\alpha_{2-mag}} + \boxed{\Delta\alpha_{spin-pumping}}$$

Thickness series, or restrict to $\lesssim$ 20 nm, or insulators

Parameter of interest

$$+\cancel{\Delta\alpha_{low-field}} + \cancel{\Delta\alpha_{rad}} + \cancel{\Delta\alpha_{eddy\ current}} + \boxed{\Delta\alpha_{other}}$$

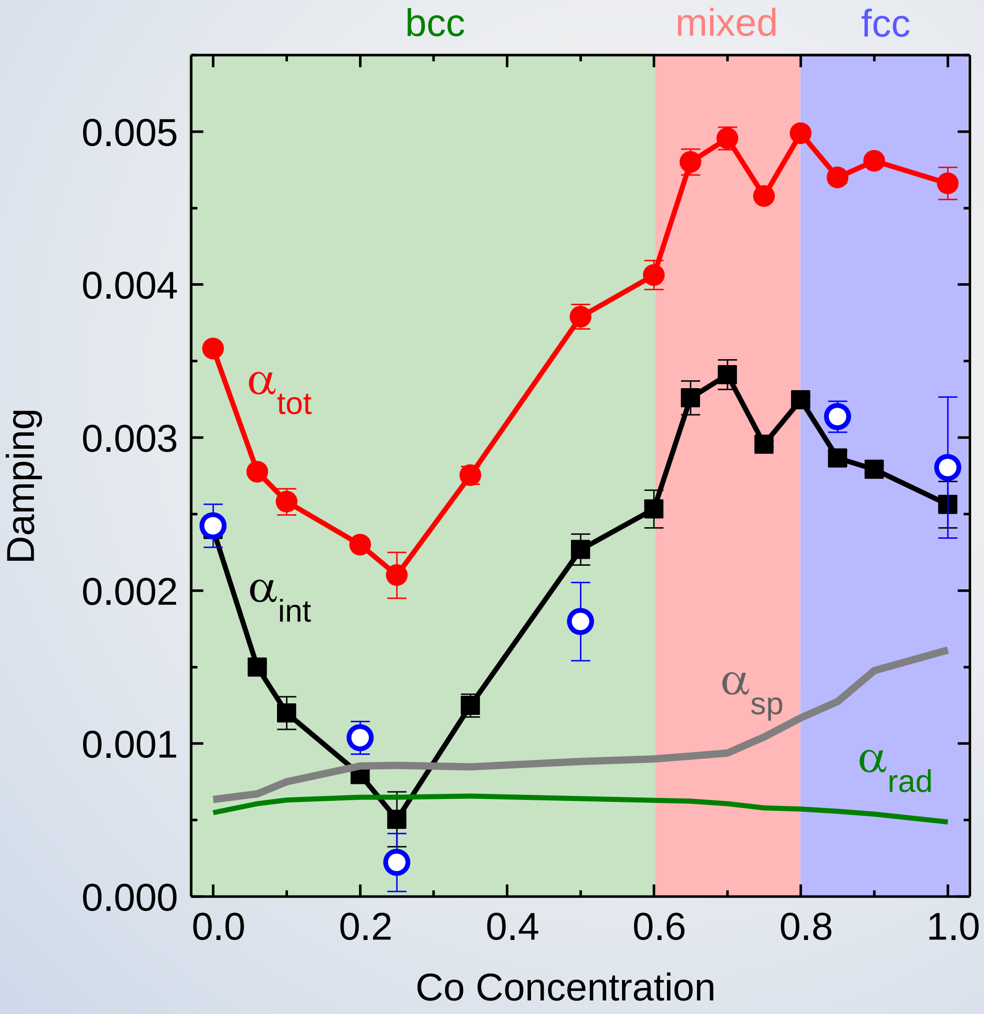
Broadband measurements to exclude non-linear, low field/freq data

Decrease inductive coupling with spacer between CPW and sample

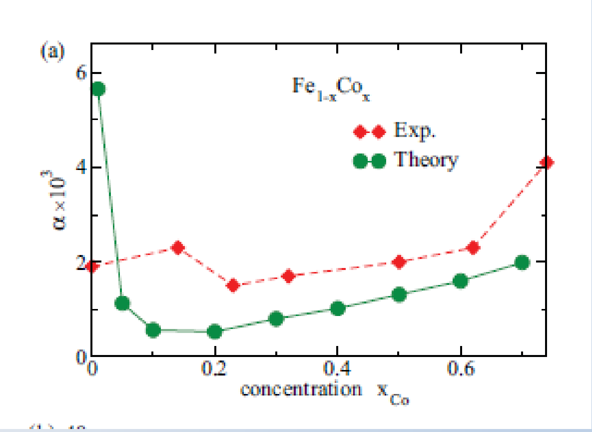
Broadband measurements and/or sample series needed to quantify

Why is LW analysis so important?

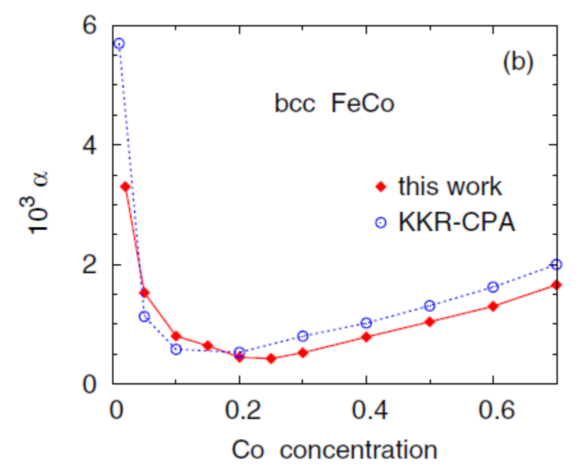
Prediction of ultra-low damping ($\alpha \approx 0.0005$) in CoFe



Schoen, Nature Physics 12, 839 (2016)



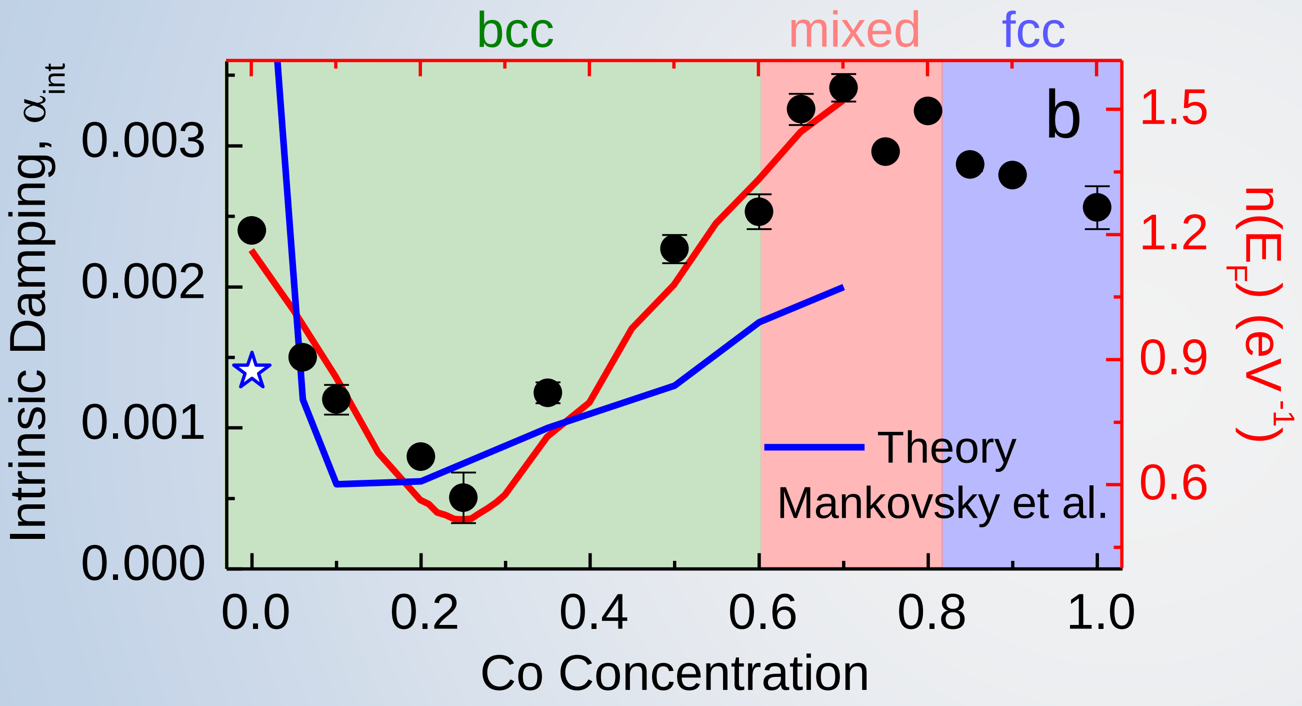
Mankovsky, PR*B* **87**, 014430 (2013)

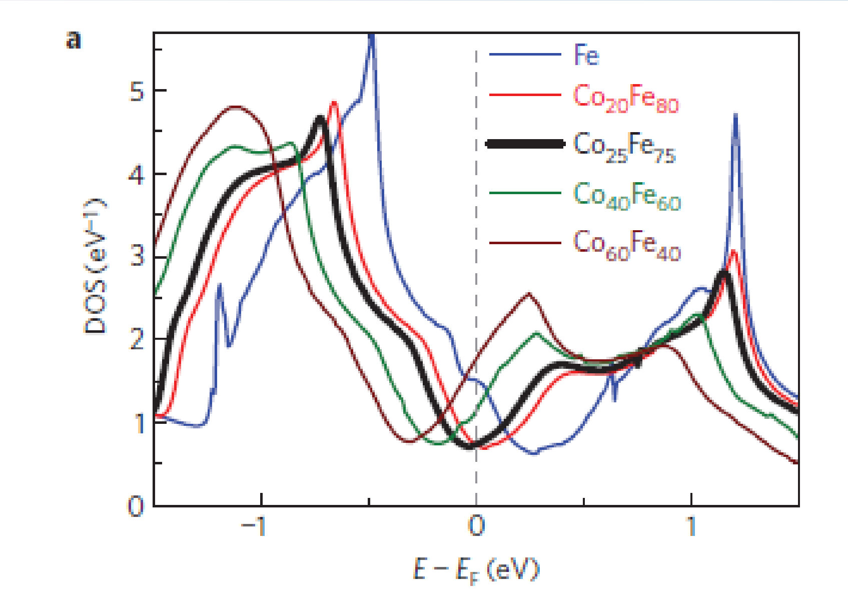


Turek, PR*B* **92,** 214407 (2015)

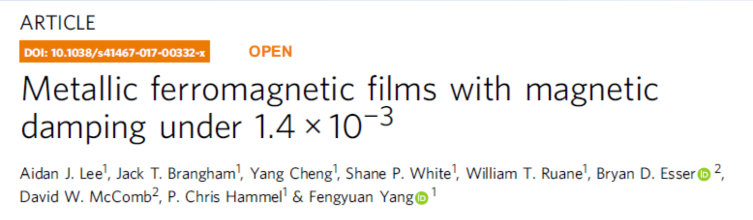
Why is LW analysis so important?

Damping is strongly controlled by the DOS at E_F





Schoen, Nature Physics 12, 839 (2016)

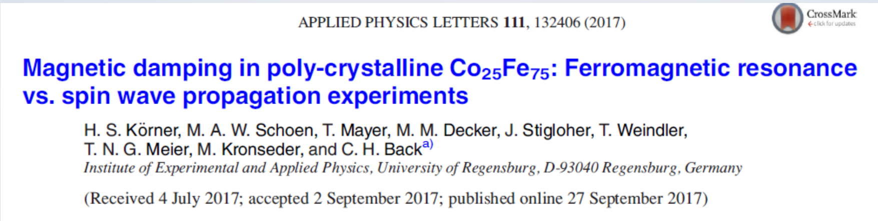


ARTICLE

DOI: 10.1038/s41467-017-00332-x OPEN

Metallic ferromagnetic films with magnetic damping under 1.4×10^{-3}

Aidan J. Lee[1], Jack T. Brangham[1], Yang Cheng[1], Shane P. White[1], William T. Ruane[1], Bryan D. Esser[2], David W. McComb[2], P. Chris Hammel[1] & Fengyuan Yang[1]



APPLIED PHYSICS LETTERS **111**, 132406 (2017)

CrossMark

Magnetic damping in poly-crystalline $Co_{25}Fe_{75}$: Ferromagnetic resonance vs. spin wave propagation experiments

H. S. Körner, M. A. W. Schoen, T. Mayer, M. M. Decker, J. Stigloher, T. Weindler, T. N. G. Meier, M. Kronseder, and C. H. Back[a]

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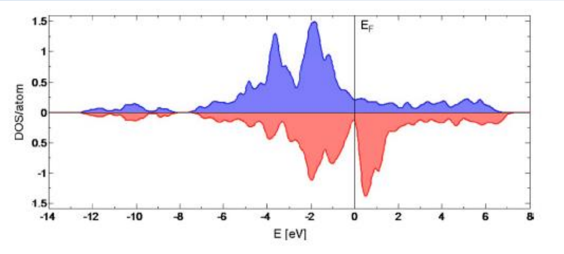
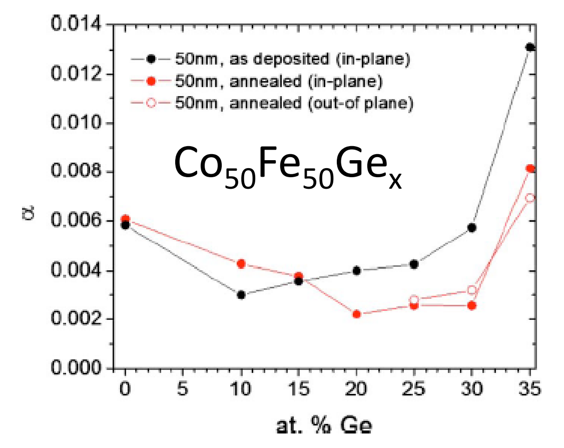
(Received 4 July 2017; accepted 2 September 2017; published online 27 September 2017)

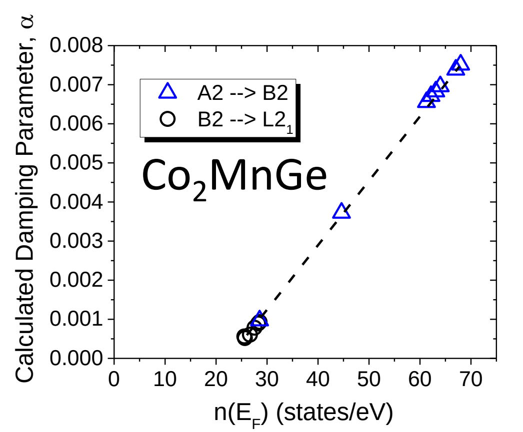
DOS and damping

Alloying in Ge in $Co_{50}Fe_{50}$ enhances the “pseudo-gap” a moves it to the Fermi level

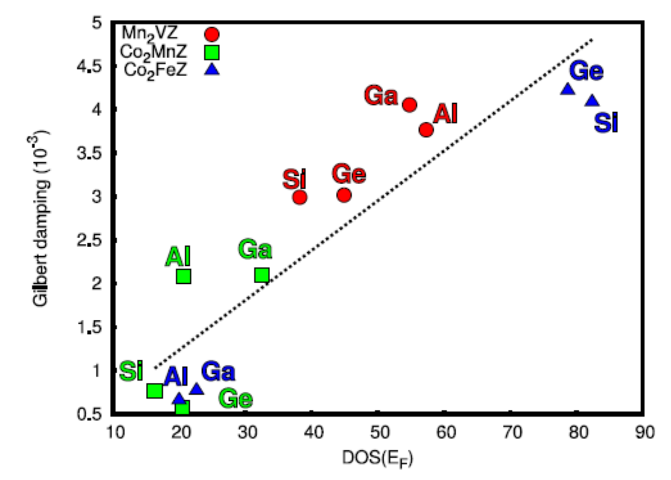




H.Lee, APL 95, 082502 (2009)



J.Shaw, PRB, 97, 094420 (2018)



J.Chico, PRB, 93, 214439 (2016)

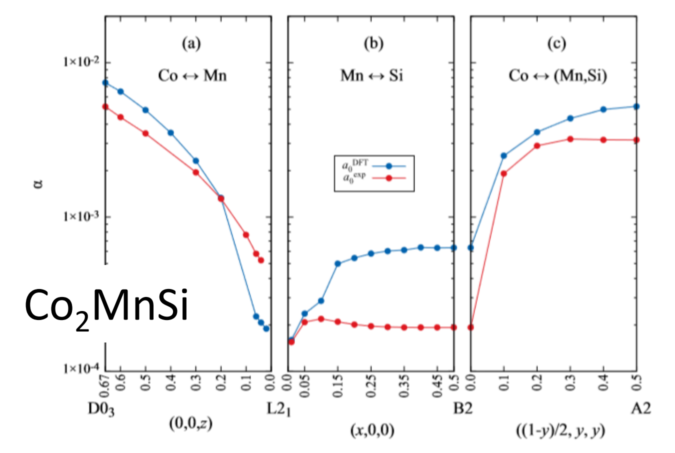
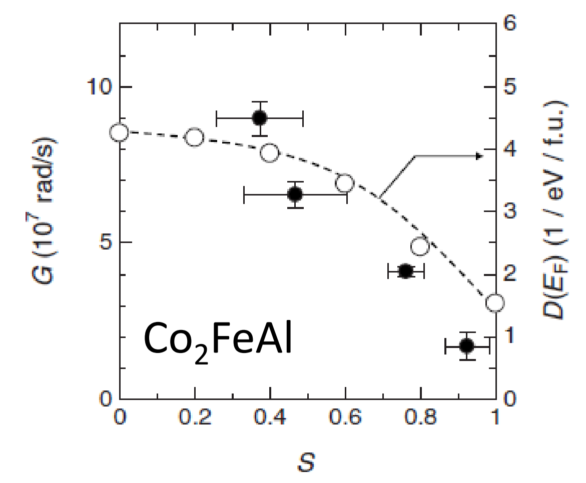


FIG. 7. Gilbert damping parameter α as a function of the disorder rates (x, y, z) and calculated with the two values of the lattice parameter.

Pradines, PRB, 95, 094425 (2017)



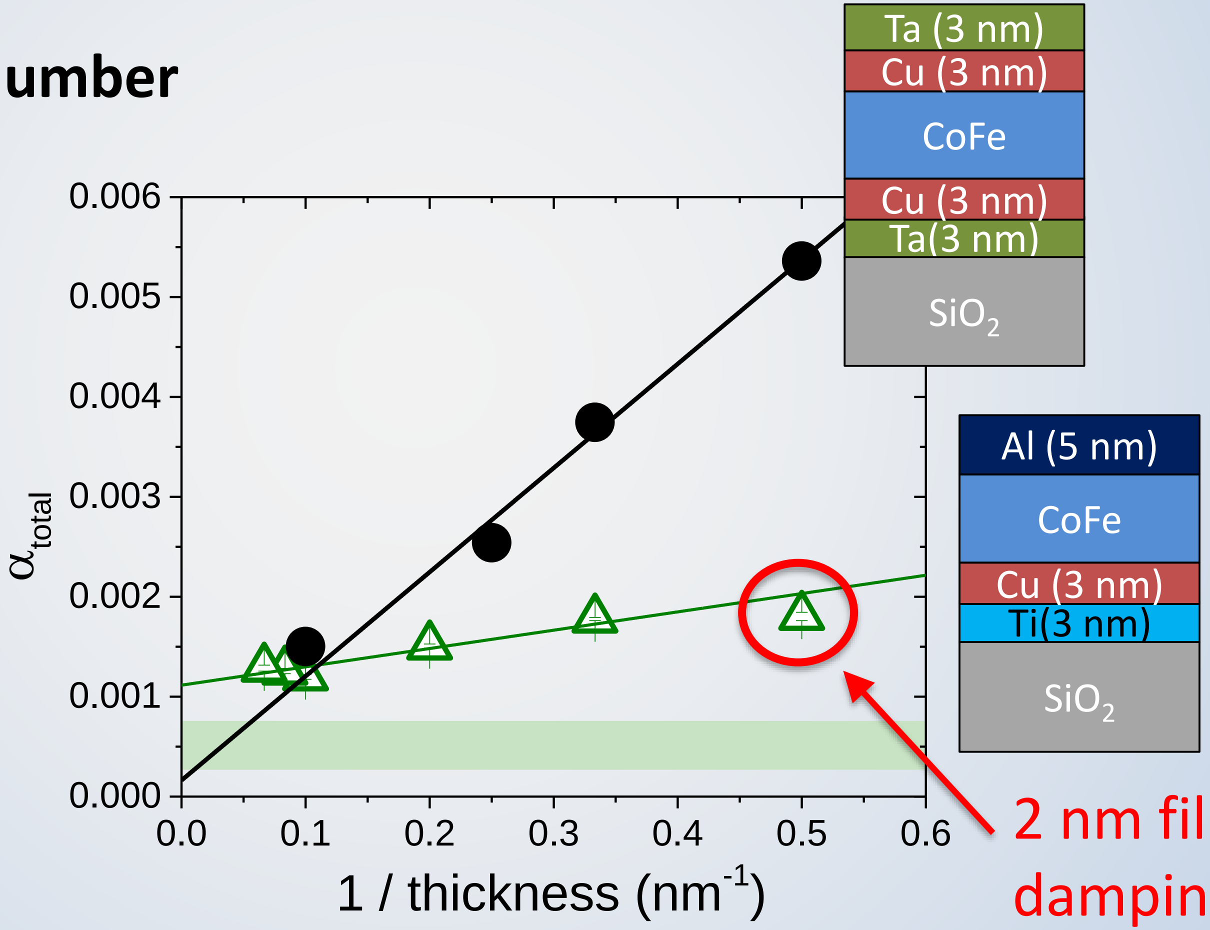
Mizukami, JAP, 105, 07D306 (2009)

How can we control Damping?

How do we reduce spin pumping?

Replace Ta with low atomic number elements or insulators

11, 054036 (2019)



2 nm film with a **total** damping of 0.0018 !!!

E. Edwards, *Phys. Rev. Applied* 11, 054036 (2019)

Why is LW analysis so important?

Consider Relationship between Perpendicular Anisotropy (PMA) and Damping

APPLIED PHYSICS LETTERS 98, 082501 (2011)

Tunable magnonic frequency and damping in [Co/Pd]$_8$ multilayers with variable Co layer thickness

S. Pal,[1] B. Rana,[1] O. Hellwig,[2] T. Thomson,[2] and A. Barman[1,a)]
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[2]*San Jose Research Center, Hitachi Global Storage Technologies, 3403 Yerba Buena Rd., San Jose, California 95135, USA*

Applied Physics Express **4** (2011) 013005
DOI: 10.1143/APEX.4.013005

Gilbert Damping in Ni/Co Multilayer Films Exhibiting Large Perpendicular Anisotropy

Shigemi Mizukami*, Xianmin Zhang, Takahide Kubota, Hiroshi Naganuma[1],
Mikihiko Oogane[1], Yasuo Ando[1], and Terunobu Miyazaki

WPI Advanced Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan
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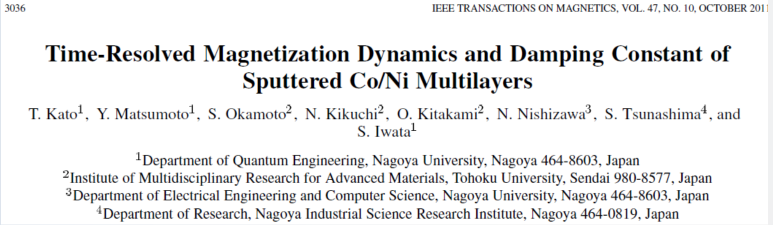
Received November 17, 2010; accepted December 14, 2010; published online January 7, 2011

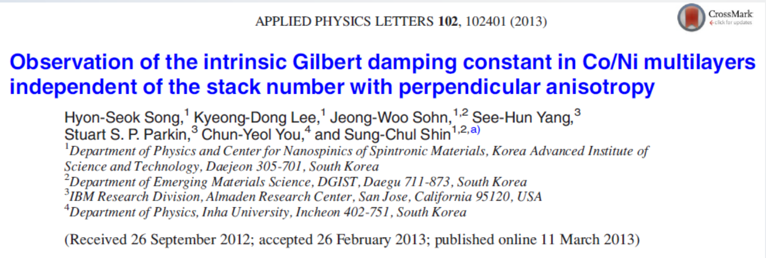


3036 IEEE TRANSACTIONS ON MAGNETICS, VOL. 47, NO. 10, OCTOBER 2011

Time-Resolved Magnetization Dynamics and Damping Constant of Sputtered Co/Ni Multilayers

T. Kato[1], Y. Matsumoto[1], S. Okamoto[2], N. Kikuchi[2], O. Kitakami[2], N. Nishizawa[3], S. Tsunashima[4], and S. Iwata[1]

[1]Department of Quantum Engineering, Nagoya University, Nagoya 464-8603, Japan
[2]Institute of Multidisciplinary Research for Advanced Materials, Tohoku University, Sendai 980-8577, Japan
[3]Department of Electrical Engineering and Computer Science, Nagoya University, Nagoya 464-8603, Japan
[4]Department of Research, Nagoya Industrial Science Research Institute, Nagoya 464-0819, Japan



APPLIED PHYSICS LETTERS **102**, 102401 (2013)

CrossMark

Observation of the intrinsic Gilbert damping constant in Co/Ni multilayers independent of the stack number with perpendicular anisotropy

Hyon-Seok Song,[1] Kyeong-Dong Lee,[1] Jeong-Woo Sohn,[1,2] See-Hun Yang,[3]
Stuart S. P. Parkin,[3] Chun-Yeol You,[4] and Sung-Chul Shin[1,2,a)]
[1]*Department of Physics and Center for Nanospinics of Spintronic Materials, Korea Advanced Institute of Science and Technology, Daejeon 305-701, South Korea*
[2]*Department of Emerging Materials Science, DGIST, Daegu 711-873, South Korea*
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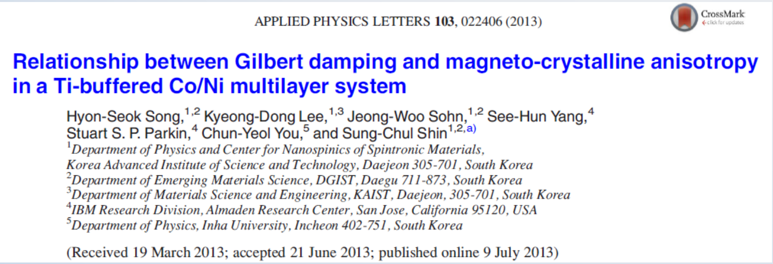
[4]*Department of Physics, Inha University, Incheon 402-751, South Korea*

(Received 26 September 2012; accepted 26 February 2013; published online 11 March 2013)



APPLIED PHYSICS LETTERS **103**, 022406 (2013)

CrossMark

Relationship between Gilbert damping and magneto-crystalline anisotropy in a Ti-buffered Co/Ni multilayer system

Hyon-Seok Song,[1,2] Kyeong-Dong Lee,[1,3] Jeong-Woo Sohn,[1,2] See-Hun Yang,[4]
Stuart S. P. Parkin,[4] Chun-Yeol You,[5] and Sung-Chul Shin[1,2,a)]
[1]*Department of Physics and Center for Nanospinics of Spintronic Materials, Korea Advanced Institute of Science and Technology, Daejeon 305-701, South Korea*
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[5]*Department of Physics, Inha University, Incheon 402-751, South Korea*

(Received 19 March 2013; accepted 21 June 2013; published online 9 July 2013)

"...**a linear relation** between the perpendicular magnetic anisotropy and α is established"

"No correlation of g with the increase in α... is enhanced locally at the interface between the multilayer and buffer (capping) layer... may be **attributed to the spin-pumping** effect"

"The estimated α was found to be **independent** both on total thickness and anisotropy field of the multilayer..."

...the intrinsic Gilbert damping constant was found to be **independent of the perpendicular magnetic anisotropy**..."

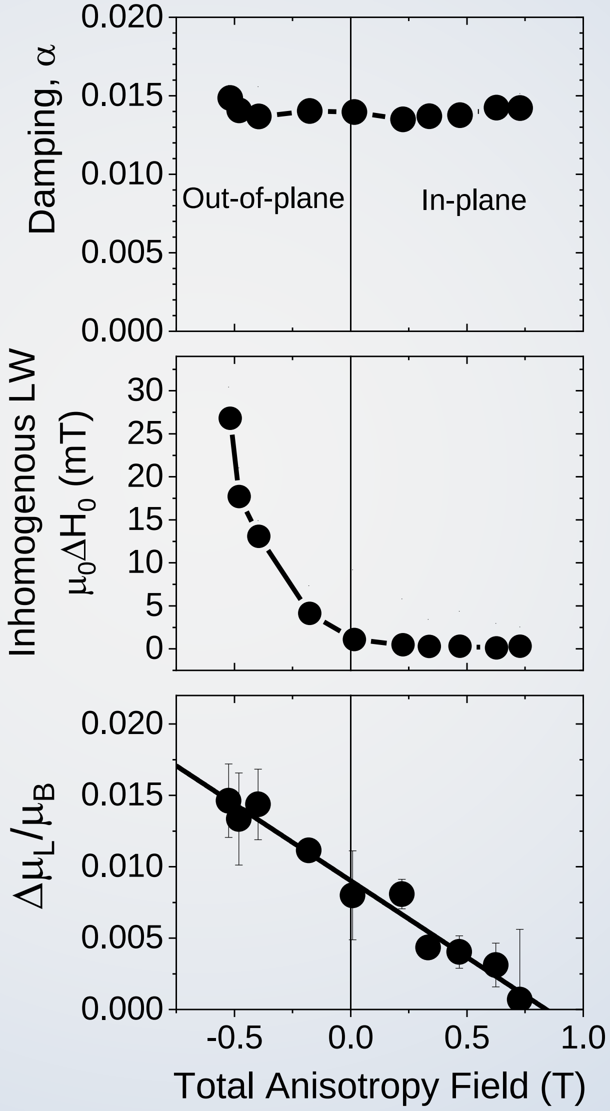
"We find that the magneto-crystalline anisotropy and the Gilbert damping constant **show a linear relationship**."

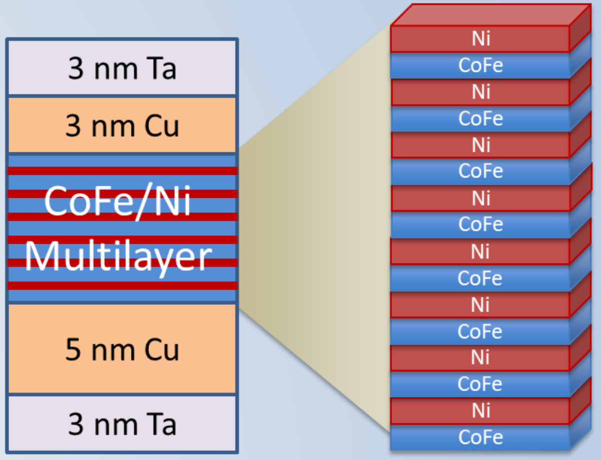
Relationship between PMA and α?

- No relationship between anisotropy and PMA
  ➔spin-orbit parameter does not vary

- Anisotropy results from orbital moment asymmetry NOT increased spin-orbit
  ➔ Independent of damping.

$$K = -\left(A\frac{\xi_{SO}N}{4V}\right)\frac{\Delta\mu_L}{\mu_B}$$



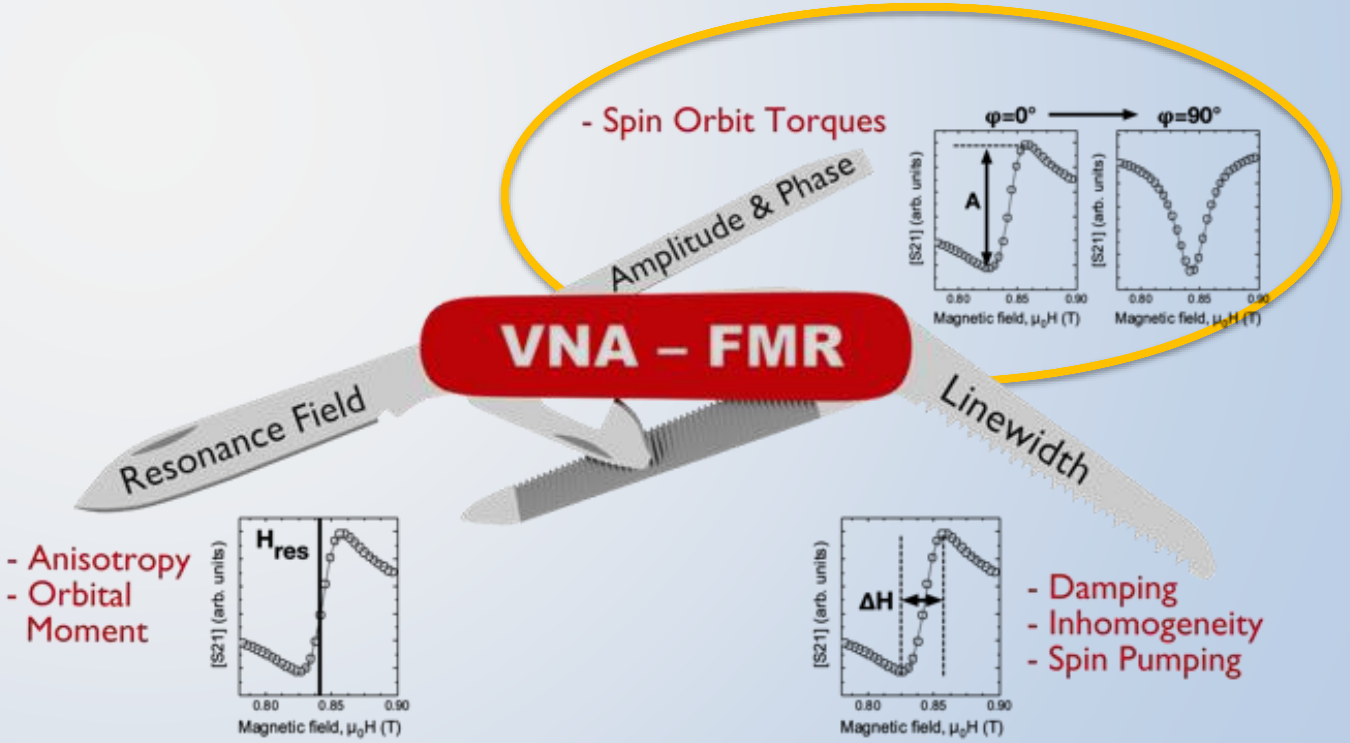


$Co_{90}Fe_{10}$/Ni Multilayers
Anisotropy is tuned by varying the total thickness.

J.M. Shaw, APL 105, 062406 (2014)

Outline

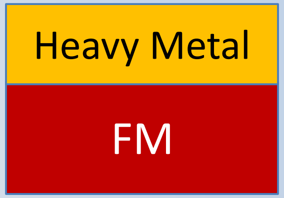
- Spin-Orbit Interaction
- Ferromagnetic Resonance Spectroscopy
- Anisotropy and Orbital Moments
- Damping and Spin-Pumping
- **Spin-Orbit Torques**

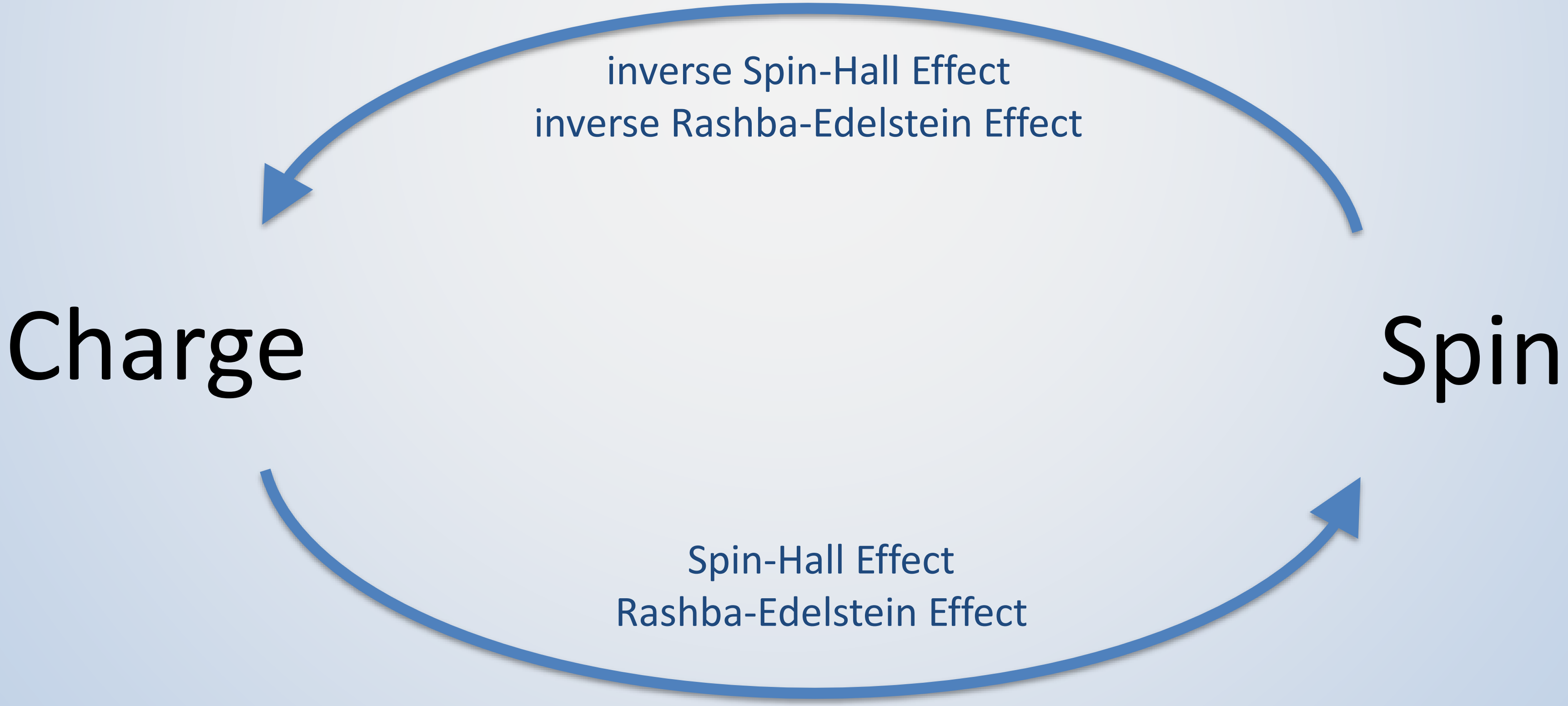


Spin-Orbit Torques (SOT)

Spin-Orbit Torques ➔ transfer of angular momentum from lattice to carriers to magnetization

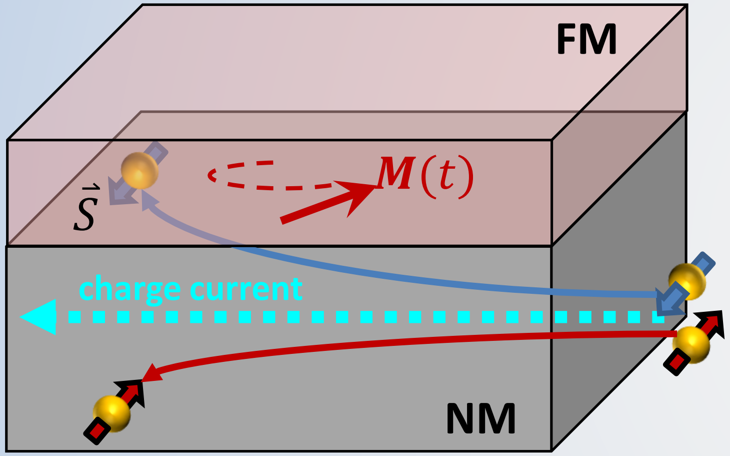
- Consider Ferromagnet (FM)/Heavy Metal interface
- Heavy metals have large spin-orbit coupling
- A charge current through the heavy metal can generate a transverse pure spin current





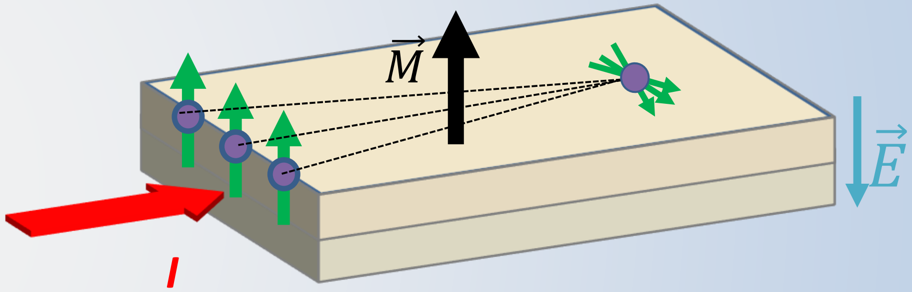
Spin-Orbit Torques (SOT)

Spin-Hall Effect
“Damping-like Torque”



$$SOT \propto \vec{M} \times (\vec{M} \times \vec{S})$$

Rashba-Edelstein Effect (intefacial)
“Field Like Torque”



$$SOT \propto \vec{M} \times \vec{S}$$

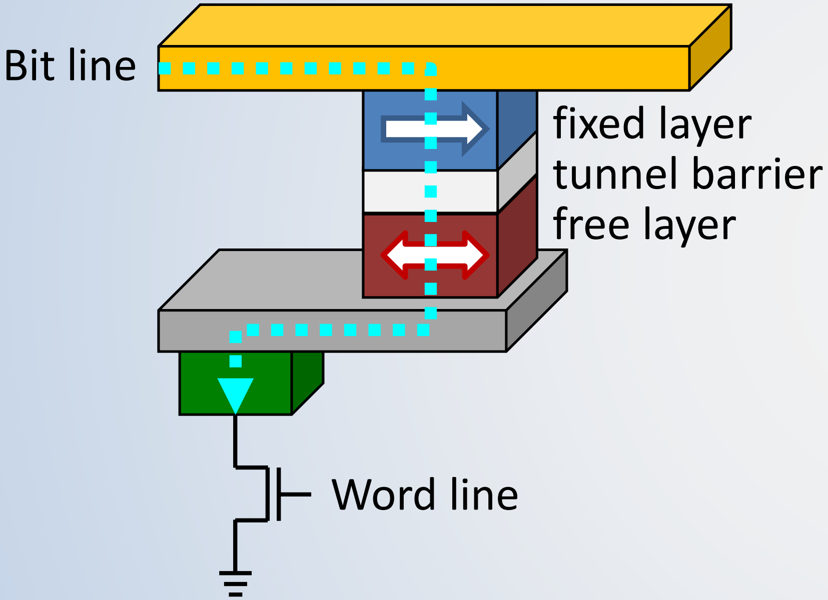
In reality, neither SHE or REE are purely “damping-like” or “field-like,” but can be mixed.

V. Amin and M.Stiles PRB 94, 104420 (2016)
V. Amin and M.Stiles PRB 94, 104419 (2016)

Why are SOT important?

Efficient switching of magnetic memory

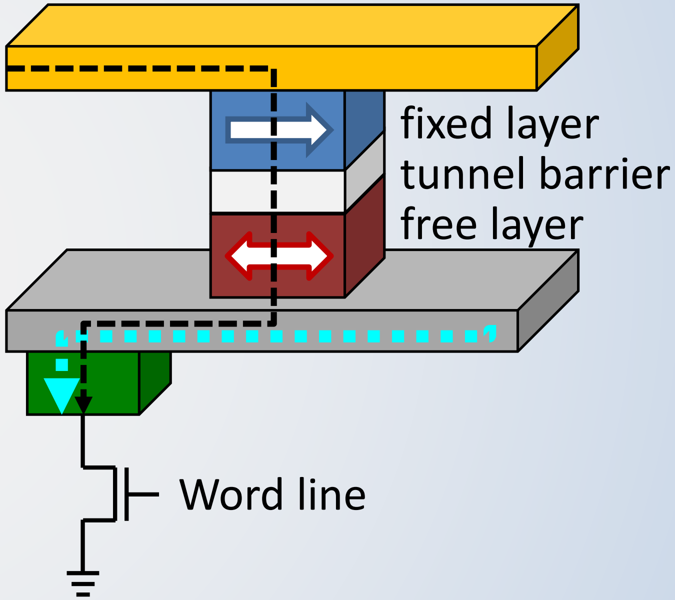
2-terminal Spin-Transfer Torque (STT)



Shared read/write path:

- ✗ Large current density for write operations can damage tunnel barrier
- ✗ Read operations have finite probability of flipping the bit

3-terminal Spin-Orbit Torque (SOT)

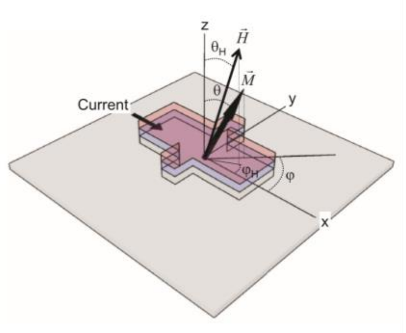


Separate read and write paths

- ✓ Can apply large current density through write line without damaging MTJ

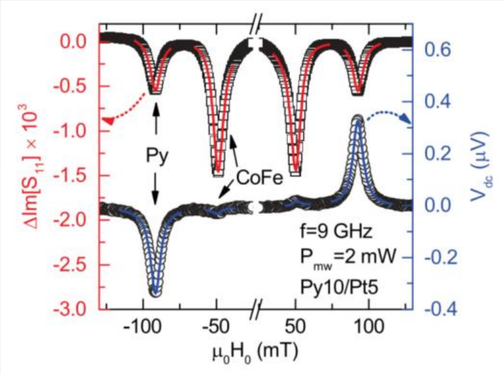
SOT Measurements Methods

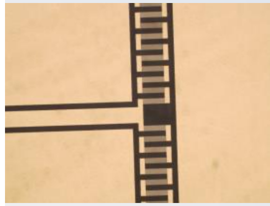
Harmonic Method with Hall Cross



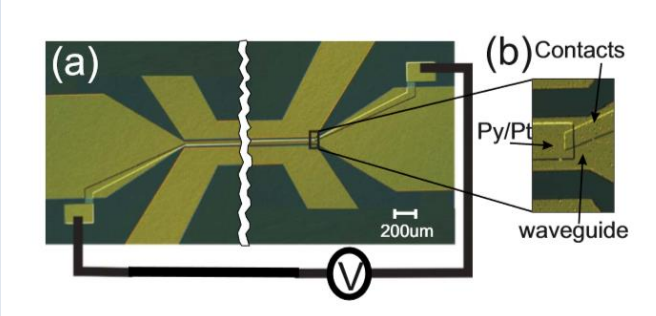
Hayashi et al. PRB 89, 144425 (2014)

Inverse SHE DC devices



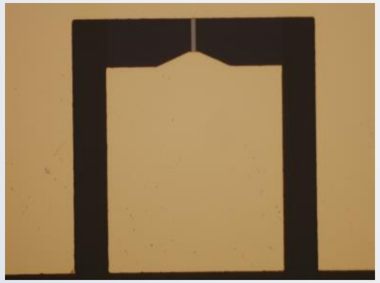


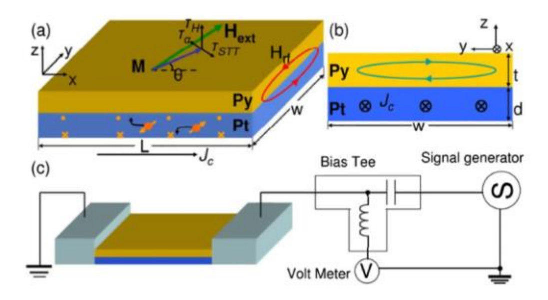
Weiler, IEEE Magn. Lett. 5, 3700104 (2014)

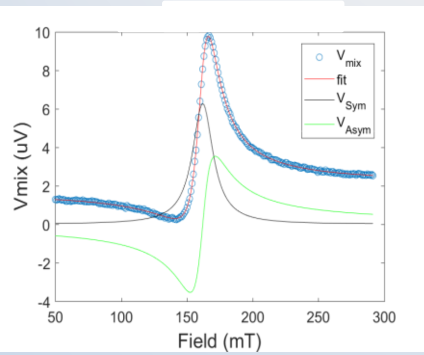


Mosendz *et al.*, PRB, 82, 214403 (2010)

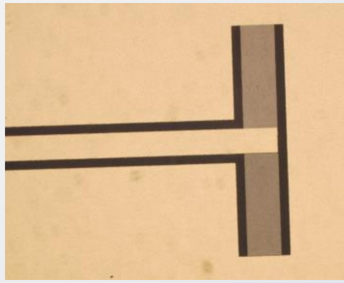
Spin-Torque Ferromagnetic Resonance



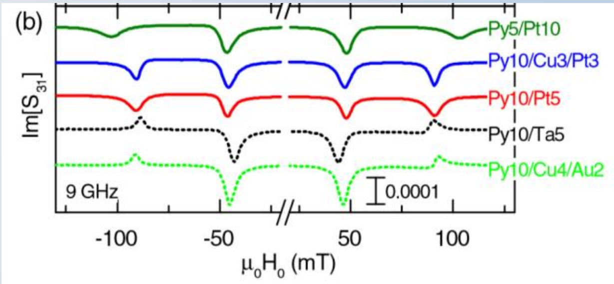


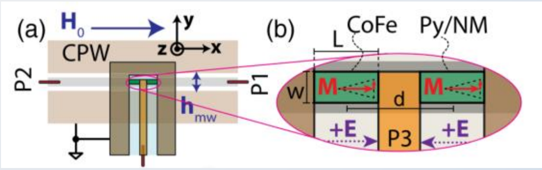


Liu *et al.*, PRL, 106 (2011)



Inverse SHE AC devices





M. Weiler, PRL 113, 157204 (2014)

…and now VNA-FMR…at the film level

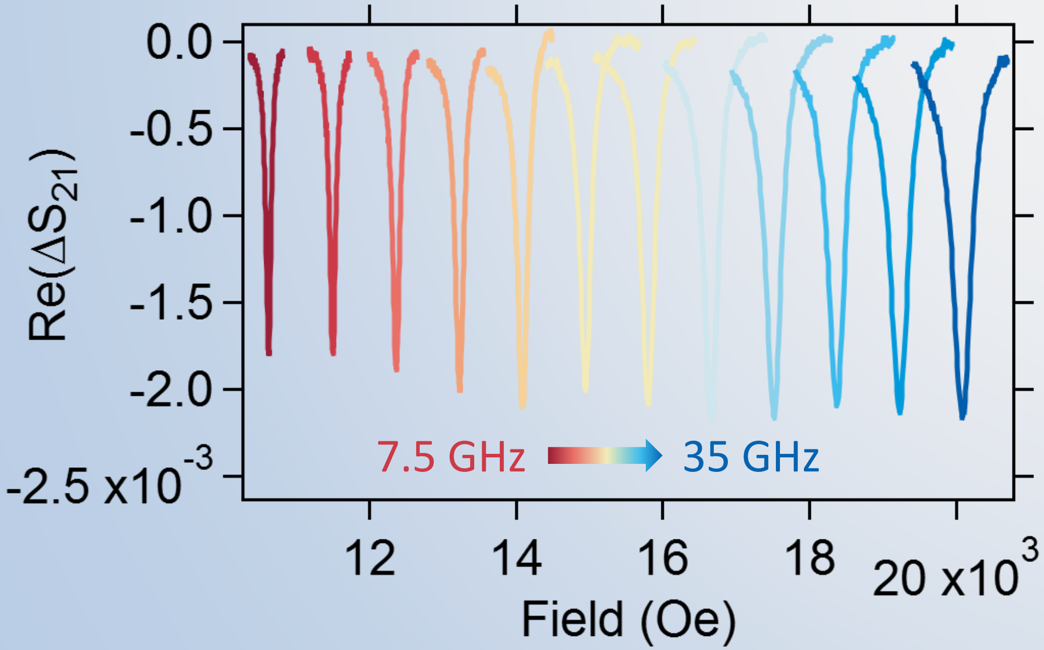
Measured Inductances in VNA-FMR

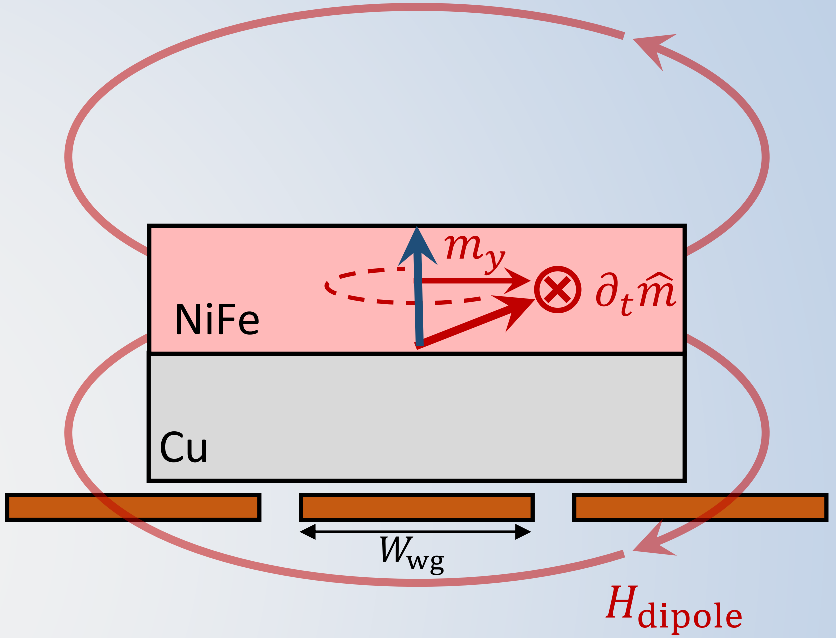
Measured signal

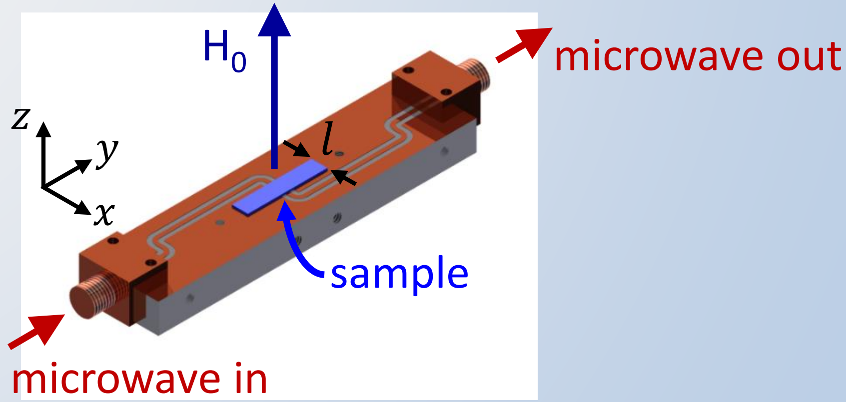
$$\Delta S_{21} \approx -\frac{i\omega}{Z_0}\left(L_{NiFe} + \cancelto{\sim 0}{L_{Cu}}\right)$$

$$L_{\mathrm{FM}} = \frac{\mu_0 l d_{\mathrm{FM}}}{4W_{\mathrm{wg}}}\chi_{yy}$$

~ Constant signal as a function of frequency

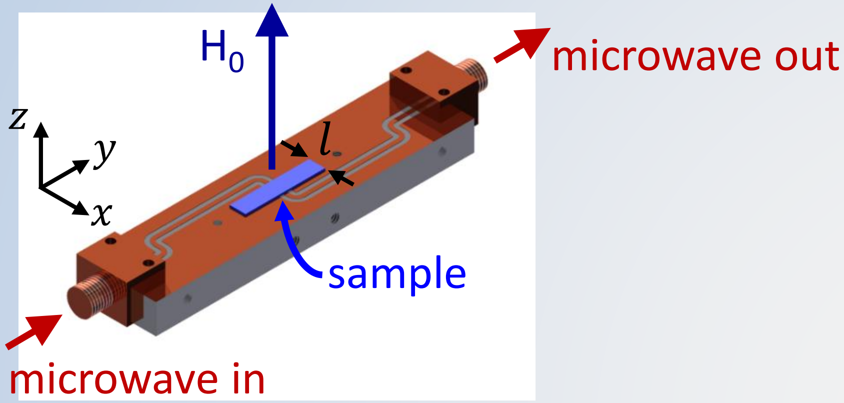






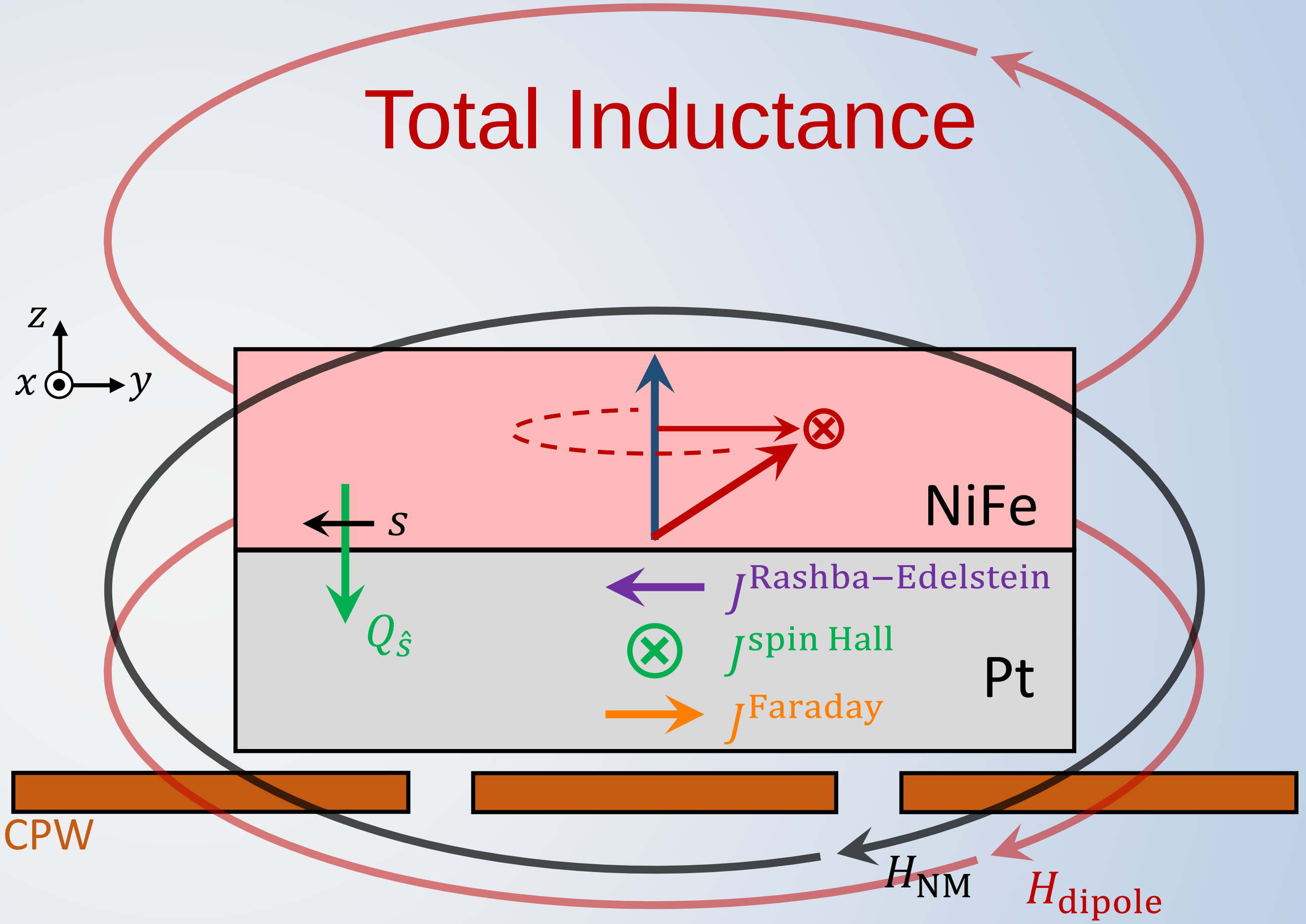
Berger, et al. PRB **97** 094407 (2018)

Measured Inductances in NiFe/Pt



The inductance (L) of the sample arises from anything that produces a flux around the CPW

$$L=\frac{\Phi}{I_{\text{CPW}}}=L_{\text{NiFe}}+L_{Pt}(\omega)$$



1. Dipolar inductive coupling, ~ frequency-independent
2. Second-order inductive coupling ~ $i\omega$ (Faraday-induced currents in the NM)
3. Damping-like ~ ω (e.g. spin Hall effect)
4. Field-like ~ $i\omega$ (e.g. Rashba-Edelstein effect)

$\}$ L_{NiFe}

Spin-charge transduction,
a.k.a Spin-Orbit Torque (SOT)

$\}$ $L_{Pt}(\omega)$

Berger, PRB **97** 094407 (2018)

Measurement of SOT in NiFe/Pt

Frequency Dependent

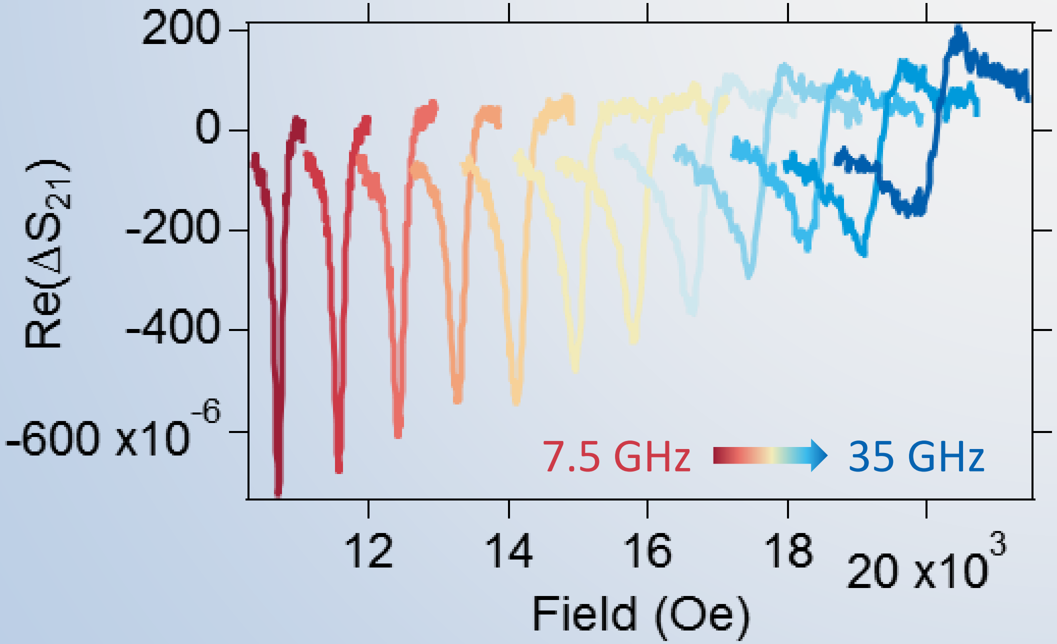
$$\Delta S_{21} \approx -\frac{i\omega}{Z_0}\left(L_{NiFe} + \boxed{L_{Pt}(\omega)}\right)$$

Field-like terms

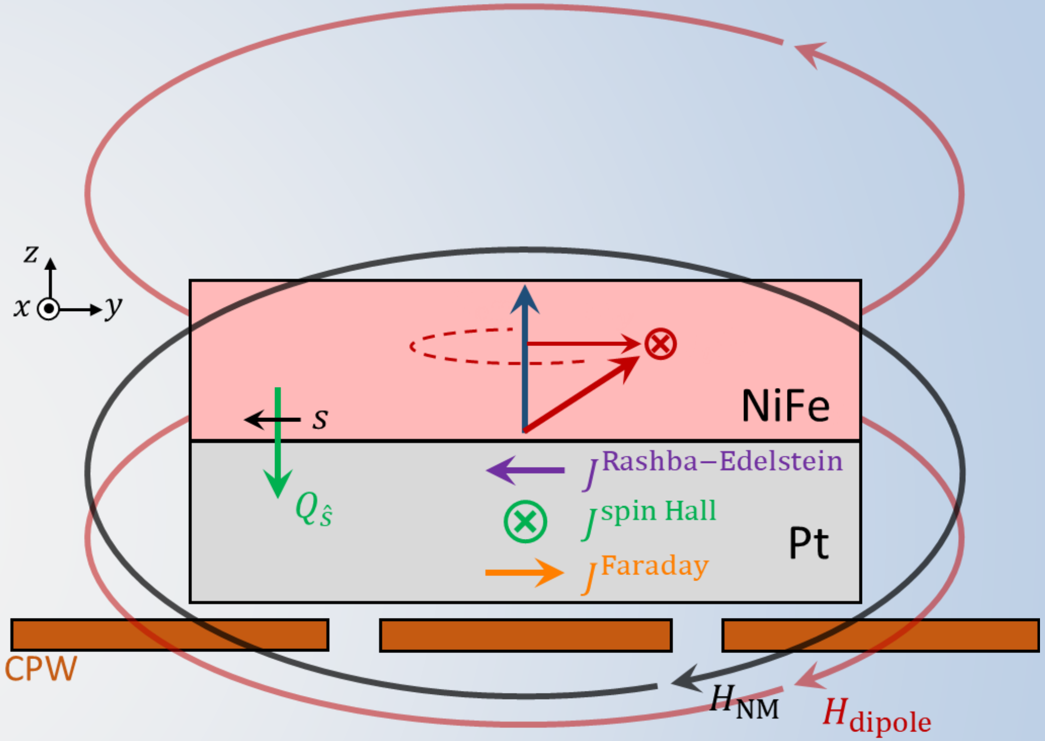
$$\mathrm{Re}(L) \propto \mu_0 l d_{FM} + L_{12}\frac{\hbar\omega}{e}\left(\sigma_{fl}^{\mathrm{SOT}} - \sigma_{fl}^{\mathrm{F}}\right)$$

Damping-like terms

$$\mathrm{Im}(L) \propto -L_{12}\frac{\hbar\omega}{e}\sigma_{dl}^{\mathrm{SOT}}$$

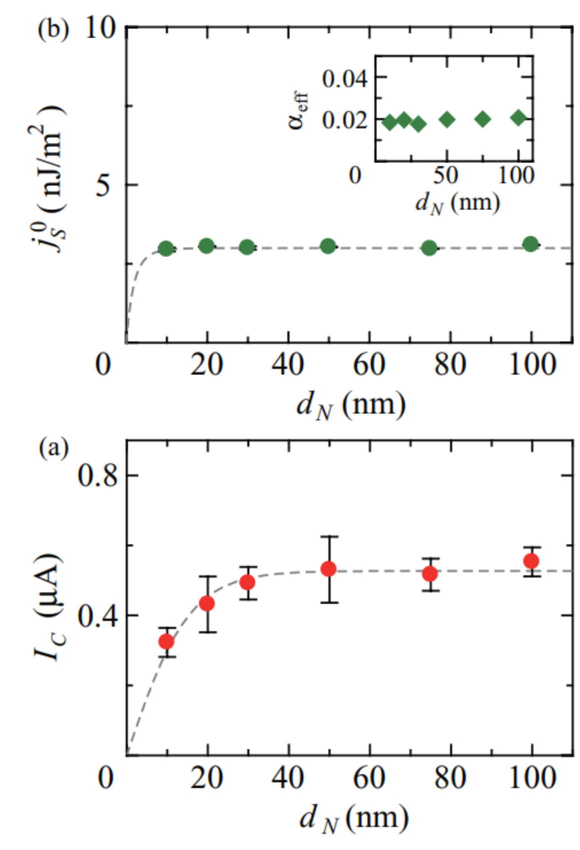


Change in both Amplitude and Phase

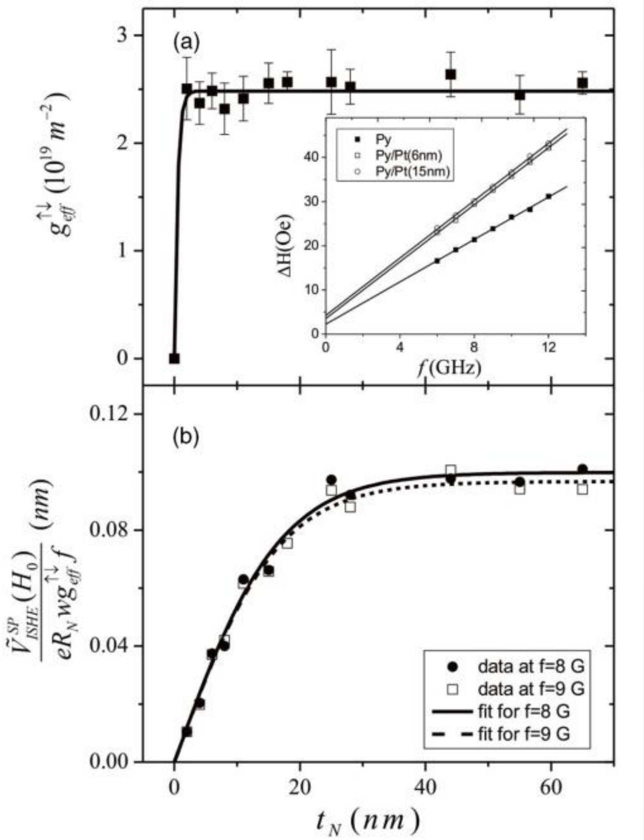


Berger, et al. PRB **97** 094407 (2018)

Inconsistency in spin diffusion length



Nakayama,
PRB **85**, 144408 (2012)



Feng,
PRB **85**, 214423 (2012)

From damping measurements

From spin Hall measurements

If the pumped spin current is generating the charge current via the SHE, *how can this be*?

Application: Spin-Diffusion Length

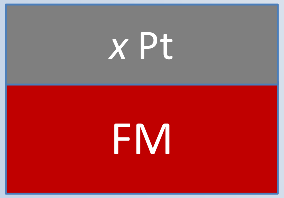
PROBLEM: Inconsistency in Spin diffusion length in Pt

Spin-pumping ➔ < 2 nm

iSHE measurements ➔ 4-8 nm

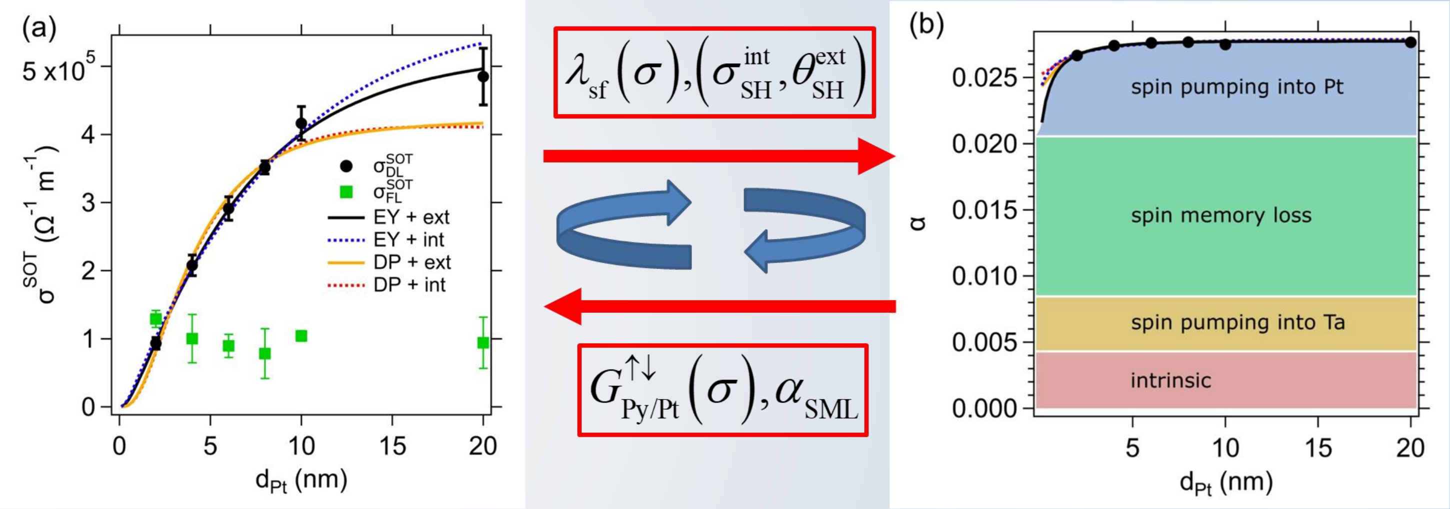
Nakayama, PRB **85**, 144408 (2012)

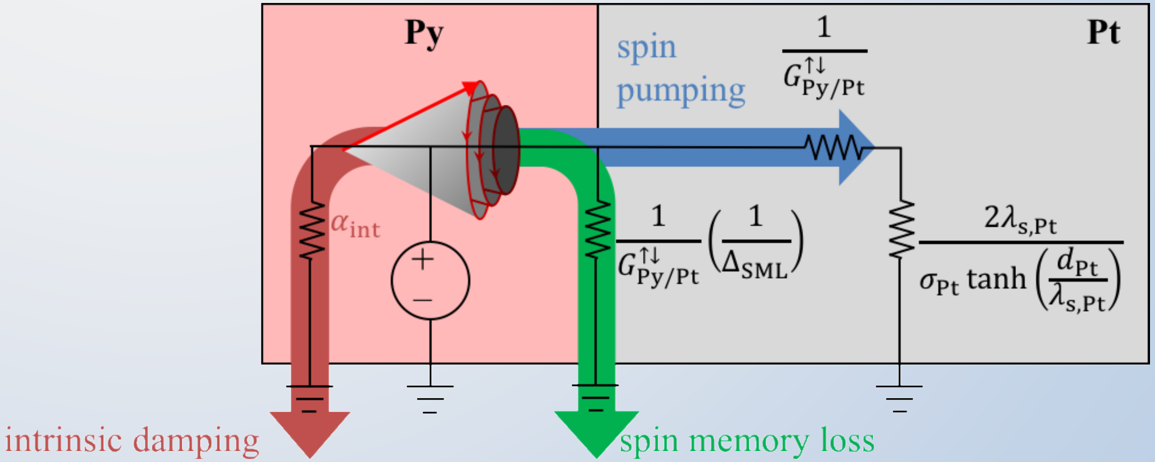
Feng, PRB **85**, 214423 (2012)



Berger, et al. PRB **97** 094407 (2018)

VNA-FMR ➔ self-consistent, simultaneous measurement of spin-pumping and iSHE





Advantages of VNA-FMR Method

- No rectification artifacts
- No need for sample patterning
- Phase sensitive separation of damping-like and field-like contributions
- Simultaneous extraction of spin pumping contribution to damping
- Identical method for both perpendicular and in-plane anisotropy FM materials

Acknowledgements

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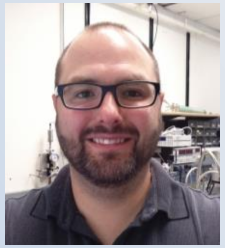
Eric Edwards (IBM)
Carl Boone
Mike Schneider
Matt Pufall
Emilie Jue
Andy Berger (SRS)







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Olof “Charlie” Karis





T.U. Munich

Christian Back

Eindhoven University

Juriaan Lucassen
Bert Koopmans


Summary

- Spin-orbit (SO) coupling generates a wealth of phenomena in magnetic systems

- Recent advances in VNA-FMR techniques enables access to measure many of these SO phenomena.

- Improved precision of VNA-FMR measurements advanced our understanding of many phenomena:
  - Precise measurement of orbital moment to compare with theory
  - Determination of intrinsic damping and quantification of other sources
  - Better understanding of factors that control damping
  - Quantification of SOT without device fabrication
  - Self-consistent separation of spin-pumping and spin-memory losses