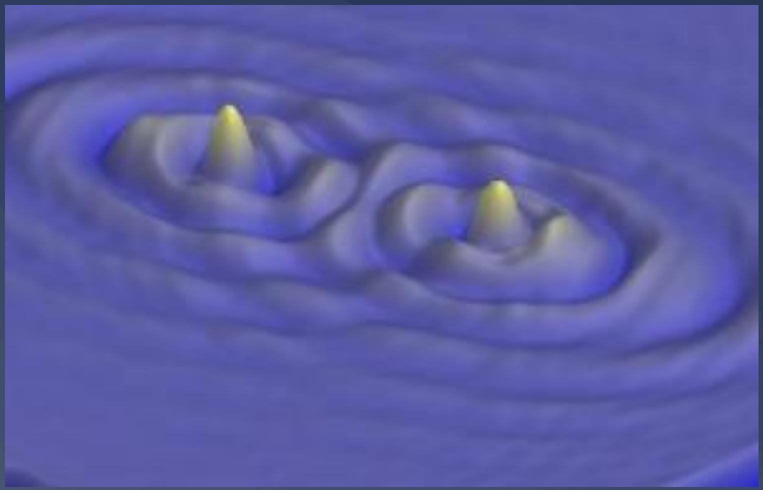
Spin Torque with Point Contacts: Generating Nonlinear Waves with Magnetic Media in a Localized Way

Tom Silva and Mark Keller
NIST
Electromagnetics Division
Boulder, Colorado

Mark Hoefer
North Carolina State University
Mathematics Department
Raleigh, NC



Two Related Mini-Symposia at this meeting:
(1) MS10 "Nonlinear Waves in Magnetic Systems – Part I, Monday 3:00 pm
(2) MS19 "Nonlinear Waves in Magnetic Systems – Part II, Tuesday 10:15 am

NIST National Institute of Standards and Technology

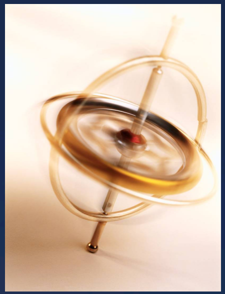
Outline

- ❑ Basics of spin dynamics and spin transport in metals.
- ❑ Spin torque with point contacts: Phenomenology.
- ❑ Spin torque with point contacts: Theoretical advances.
- ❑ Open problems in theory of magnetization dynamics (spin torque and/or general issues).

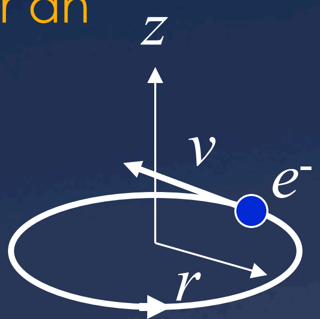
Motivation

- Fundamental advance: Using current to manipulate magnetization, not magnetic field.
- Exploring the details of physics that relate current, spin, and magnetization.
- Applications: Magnetic random access memory (MRAM), Spin-based logic (DARPA), Hard disk drive read sensors, Frequency-agile microwave oscillators.
- Ability to excite **new kinds** of magnetic waves in ways that were never possible before.

Magnets are Gyroscopes



Classical model for an atom:



magnetic moment for atomic orbit:

$$\vec{\mu}_L = I\vec{A}$$

$$= -\left(\frac{ev}{2\pi r}\right)\left(\pi r^2\right)\hat{z}$$

$$= -\frac{evr}{2}\hat{z}$$

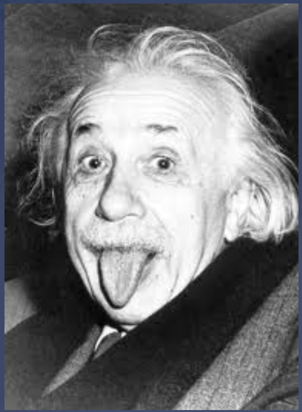
angular momentum for atomic orbit:

$$\vec{L} = \vec{r} \times \vec{p}$$

$$= rmv\hat{z}$$

$$\gamma_L \doteq \frac{\mu_z}{L_z}$$

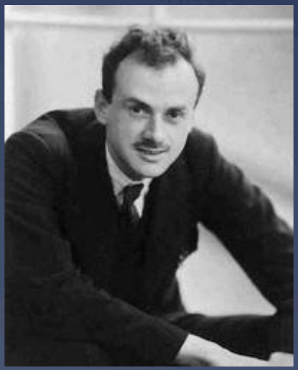
$$= -\frac{evr/2}{rm_e v}$$



Albert Einstein

$$\boxed{\gamma_L = -\frac{e}{2m_e} = -\frac{\mu_B}{\hbar}} \longrightarrow \gamma_s = -\frac{2\mu_B}{\hbar}$$

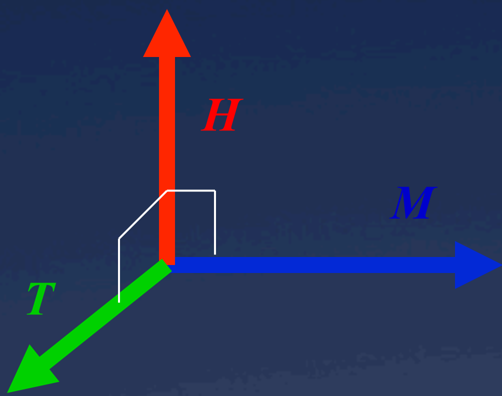
"The gyromagnetic ratio"



Paul Dirac

For spin angular momentum, extra factor of 2 required.

Larmor Equation



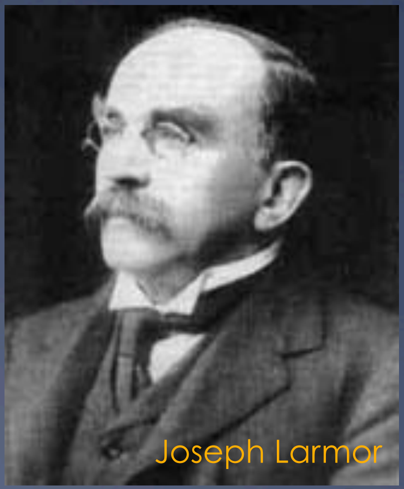
$$\vec{T} = \mu_0 \vec{M} \times \vec{H}$$

Magnetic field exerts torque on magnetization.

(definition of torque) $\frac{d\vec{L}}{dt} = \vec{T}$

$\gamma \equiv \frac{\mu}{L}$ (gyromagnetic ratio)

$$\boxed{\begin{aligned} \frac{d\vec{M}}{dt} &= \gamma \vec{T} \\ &= \gamma \mu_0 \left(\vec{M} \times \vec{H} \right) \end{aligned}}$$


Joseph Larmor

Gyromagnetic precession with energy loss: The Landau-Lifshitz equation

Landau & Lifshitz (1935):

$\vec{T}_p$ = precession torque

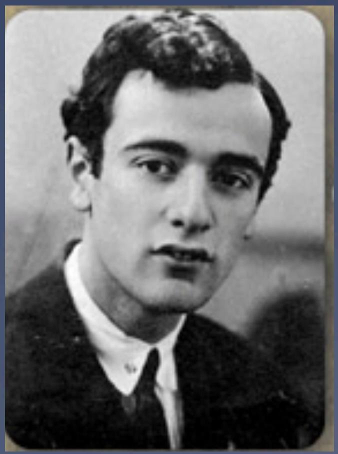
$= \mu_0 \vec{M} \times \vec{H}$

$\vec{T}_d$ = damping torque

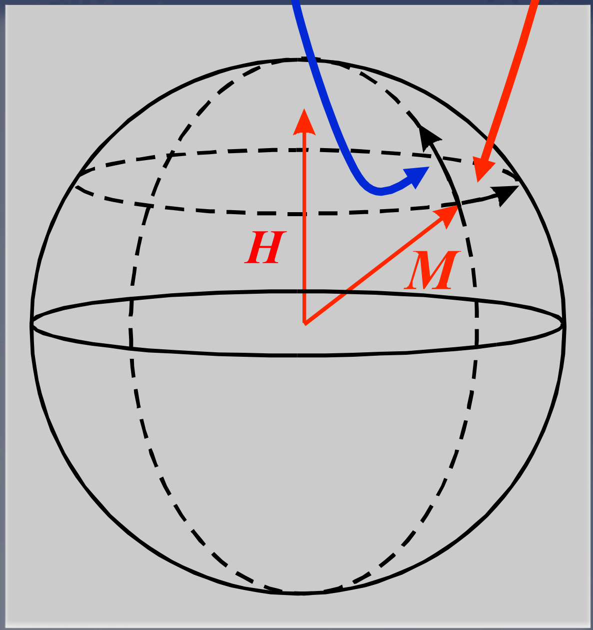
$$= \frac{\alpha \mu_0}{M_s} \vec{M} \times \left(\vec{M} \times \vec{H} \right)$$

α = dimensionless Landau-Lifshitz damping parameter

$$\begin{aligned} \frac{d\vec{M}}{dt} &= -|\gamma| \vec{T} = -|\gamma| \left(\vec{T}_p + \vec{T}_d \right) \\ &= -|\gamma| \mu_0 \vec{M} \times \vec{H} \\ &\quad - \frac{\alpha |\gamma| \mu_0}{M_s} \vec{M} \times \left(\vec{M} \times \vec{H} \right) \end{aligned}$$

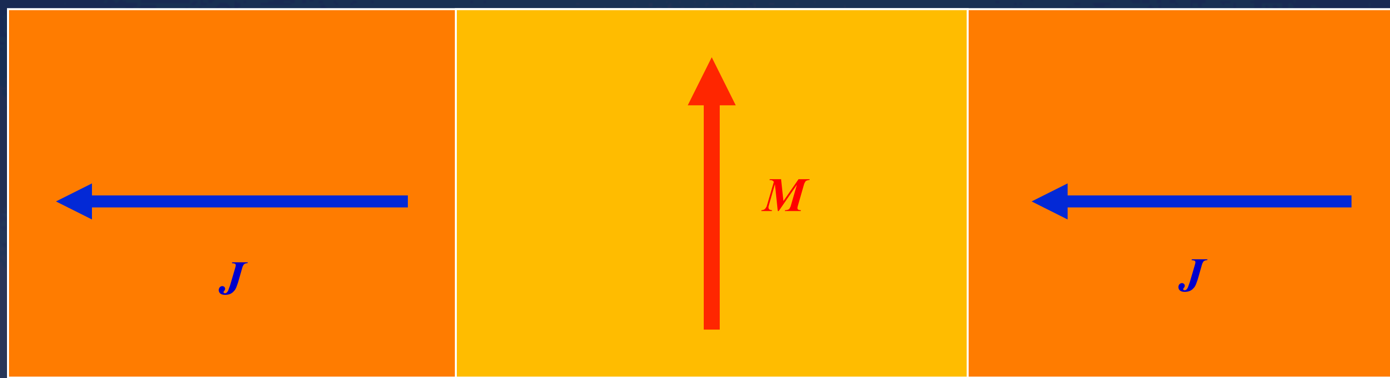


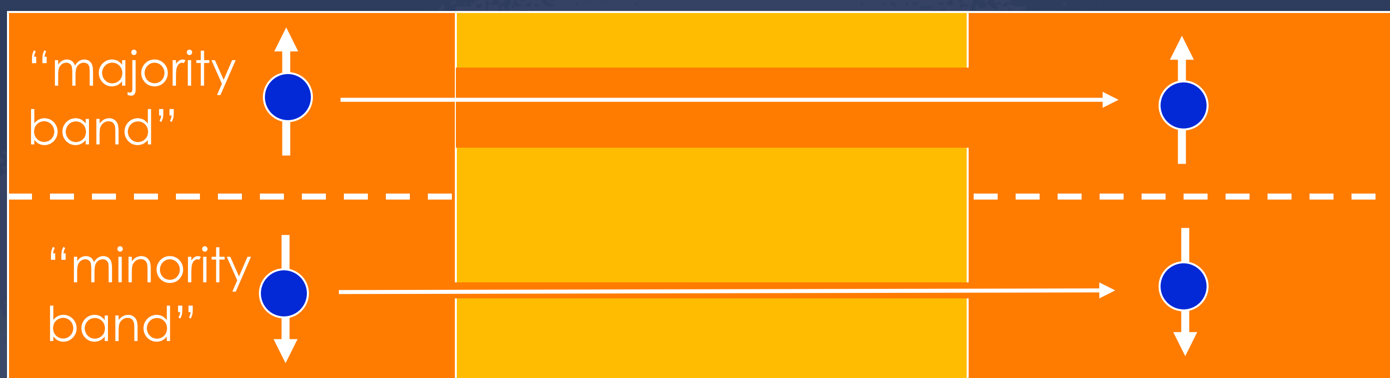
Lev Landau



NIST National Institute of Standards and Technology

Spin-dependent conductivity in ferromagnetic metals

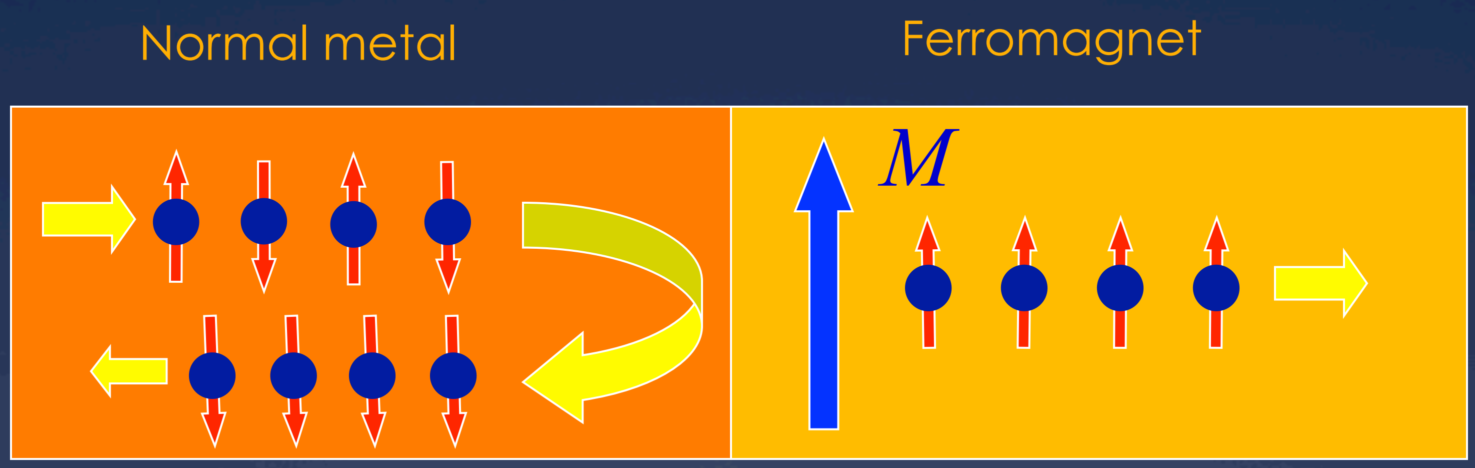




➔Conductivities in ferromagnetic conductors are different for majority and minority spins.

➔In an "ideal" ferromagnetic conductor, the conductivity for minority spins is zero.

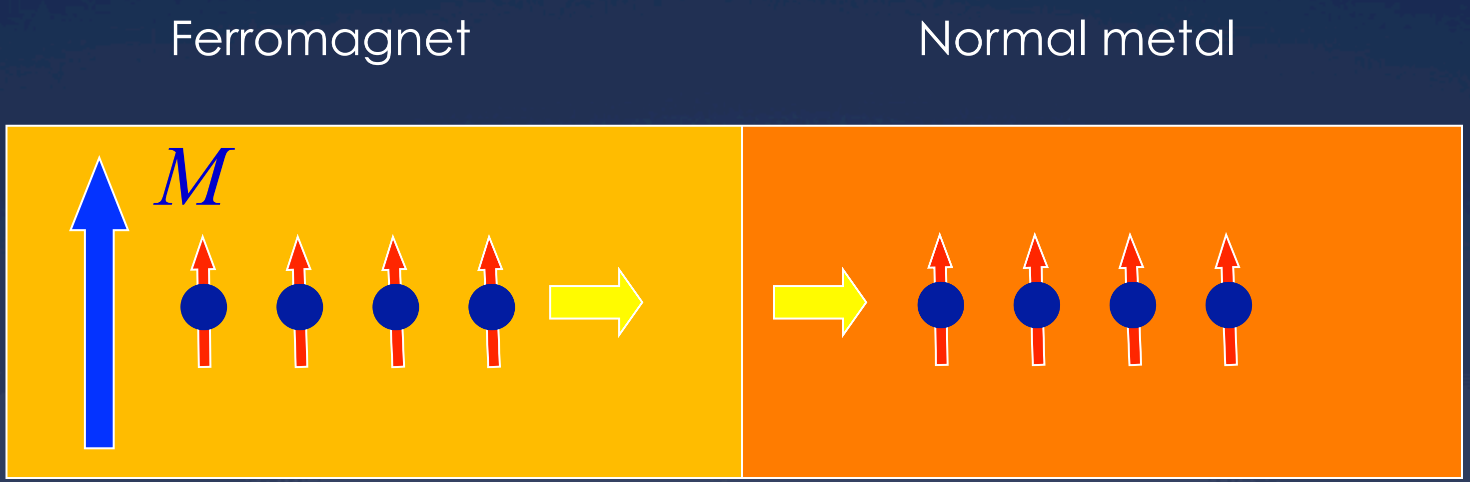
Concept: interfacial spin-dependent scattering



➔"Majority" spins are preferentially transmitted.

➔"Minority" spins are preferentially reflected.

Concept: ferromagnets as spin polarizers

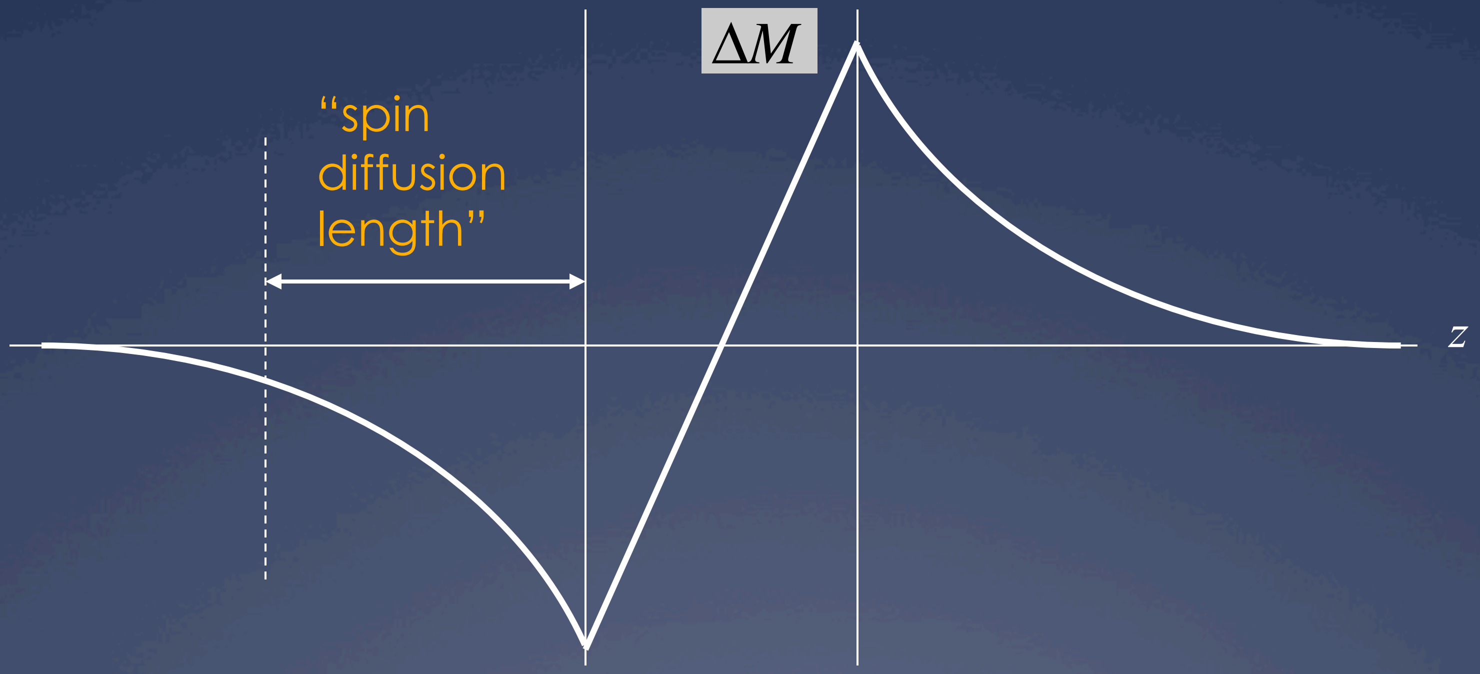


➔ "Majority" spins are preferentially transmitted.

Ferromagnetic conductors are relatively permeable for majority spins. Conversely, they are impermeable for minority spins.

Concept: spin accumulation

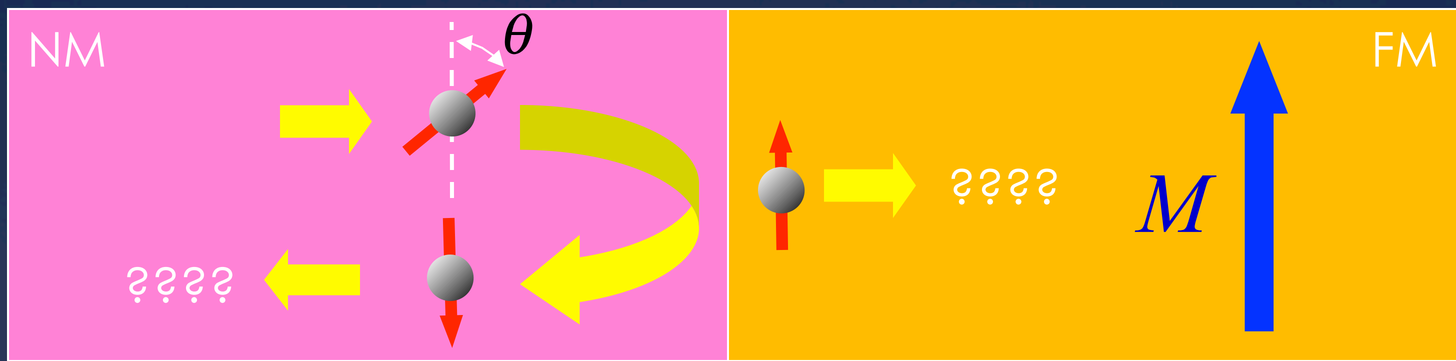
$$M(z) = M_s + \Delta M$$



Non-equilibrium spin polarization "accumulates" near interfaces of ferromagnet and non-magnetic conductors.

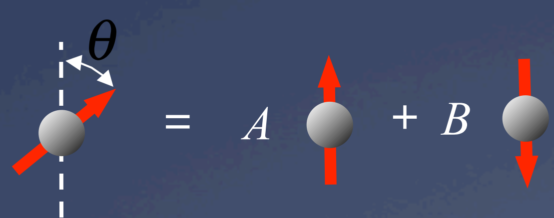
Non-collinear spin transmission

What if the spin is neither in the majority band nor the minority band???



Is the spin reflected or is it transmitted?

Quantum mechanics of spin:



$$\begin{cases} A = \cos\left(\frac{\theta}{2}\right) \\ B = \sin\left(\frac{\theta}{2}\right) \end{cases}$$

An arbitrary spin state is a coherent superposition of "up" and "down" spins.

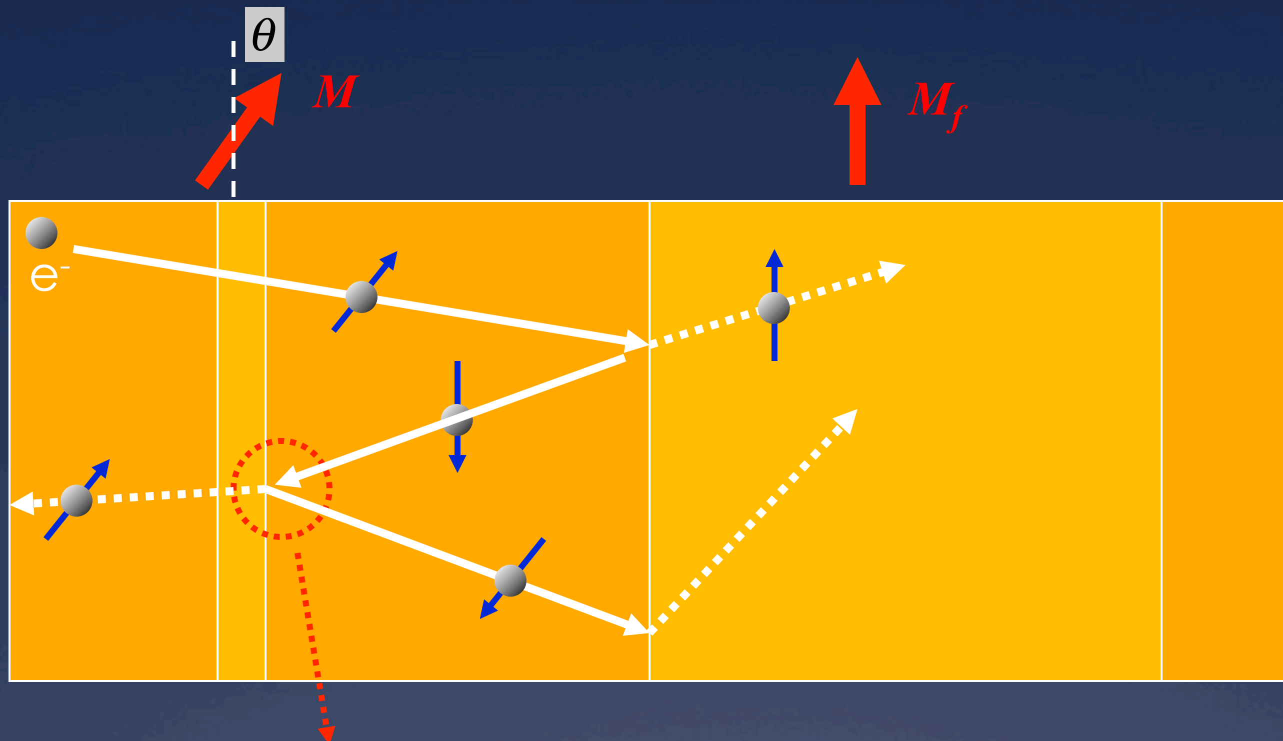
Quantum mechanical probabilities:

$$\Pr[\uparrow] = |A|^2 = \frac{1}{2}(1+\cos(\theta))$$

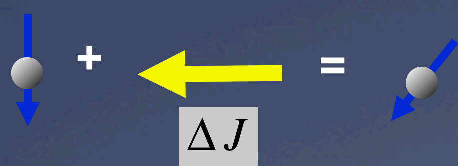
$$\Pr[\downarrow] = |B|^2 = \frac{1}{2}(1-\cos(\theta))$$

NIST National Institute of Standards and Technology

Spin Momentum Transfer: The Basics

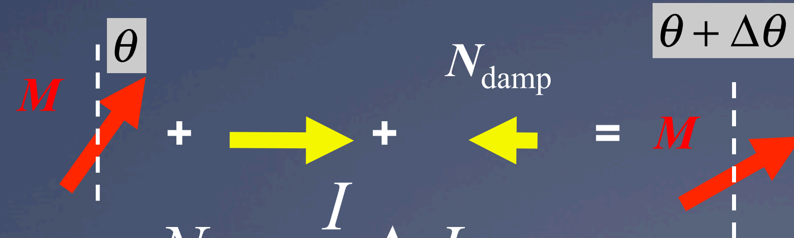


Electrons:



$$\boxed{\Delta J \propto \theta; \theta \ll 1}$$

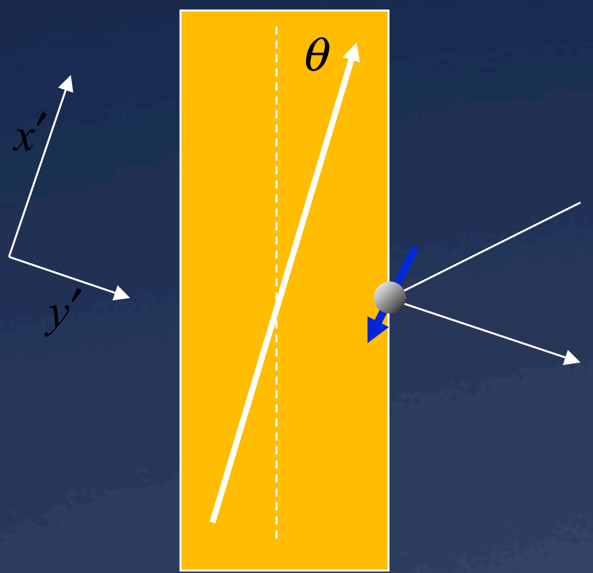
Polarizer:



$$N_{st} = \frac{I}{e} \Delta J$$

For sufficient electron flux, spin torque exceeds damping torque: Magnetization is unstable.

Transverse torque via spin reorientation/ reflection



Consider only reflection events...

AND

Consider only change in angular momentum **transverse** to magnetization axis. (Equivalent to assuming magnitude of $\boldsymbol{M}$ does not change.)

new spin direction

$-\hat{m}$

old spin direction

$\hat{m}_{\text{fixed}}$

$\Delta \vec{J}$

"transferred" angular momentum

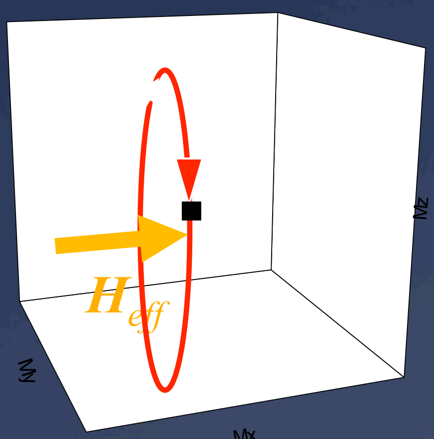
$$\boxed{\begin{aligned}\Delta \vec{J} &= \hbar\left[\hat{m}_{\text{fixed}} - \hat{m}\left(\hat{m}\cdot\hat{m}_{\text{fixed}}\right)\right] \\ &= \hbar\left[\hat{m}\times\left(\hat{m}_{\text{fixed}}\times\hat{m}\right)\right]\end{aligned}}$$

using $\vec{A}\times\left(\vec{B}\times\vec{C}\right)=\vec{B}\left(\vec{A}\cdot\vec{C}\right)-\vec{C}\left(\vec{A}\cdot\vec{B}\right)$

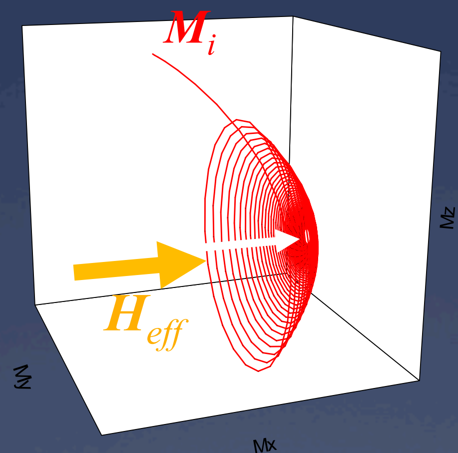
Magnetodynamics: Three Torques

$$\boxed{\frac{d\vec{M}}{dt} = |\gamma|\left(\vec{N}_{Larmor} + \vec{N}_{damp} + \vec{N}_{st}\right)}$$

$$\frac{d\vec{M}}{dt} = \underbrace{-|\gamma|\mu_0 \vec{M}\times\vec{H}_{eff}}\underbrace{-\frac{\alpha|\gamma|\mu_0}{M_s^2}\vec{M}\times\left(\vec{M}\times\vec{H}_{eff}\right)}\underbrace{+\frac{Jg\mu_B\varepsilon}{2e\delta M_s^2}\vec{M}\times\left(\vec{M}\times\hat{m}_f\right)}$$

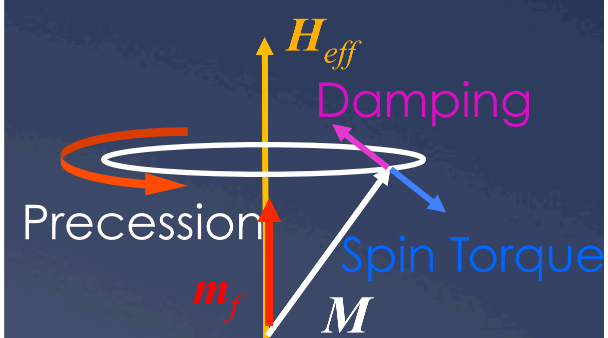


Larmor term:
precession



Damping term:
aligns M with H

Spin Torque Term



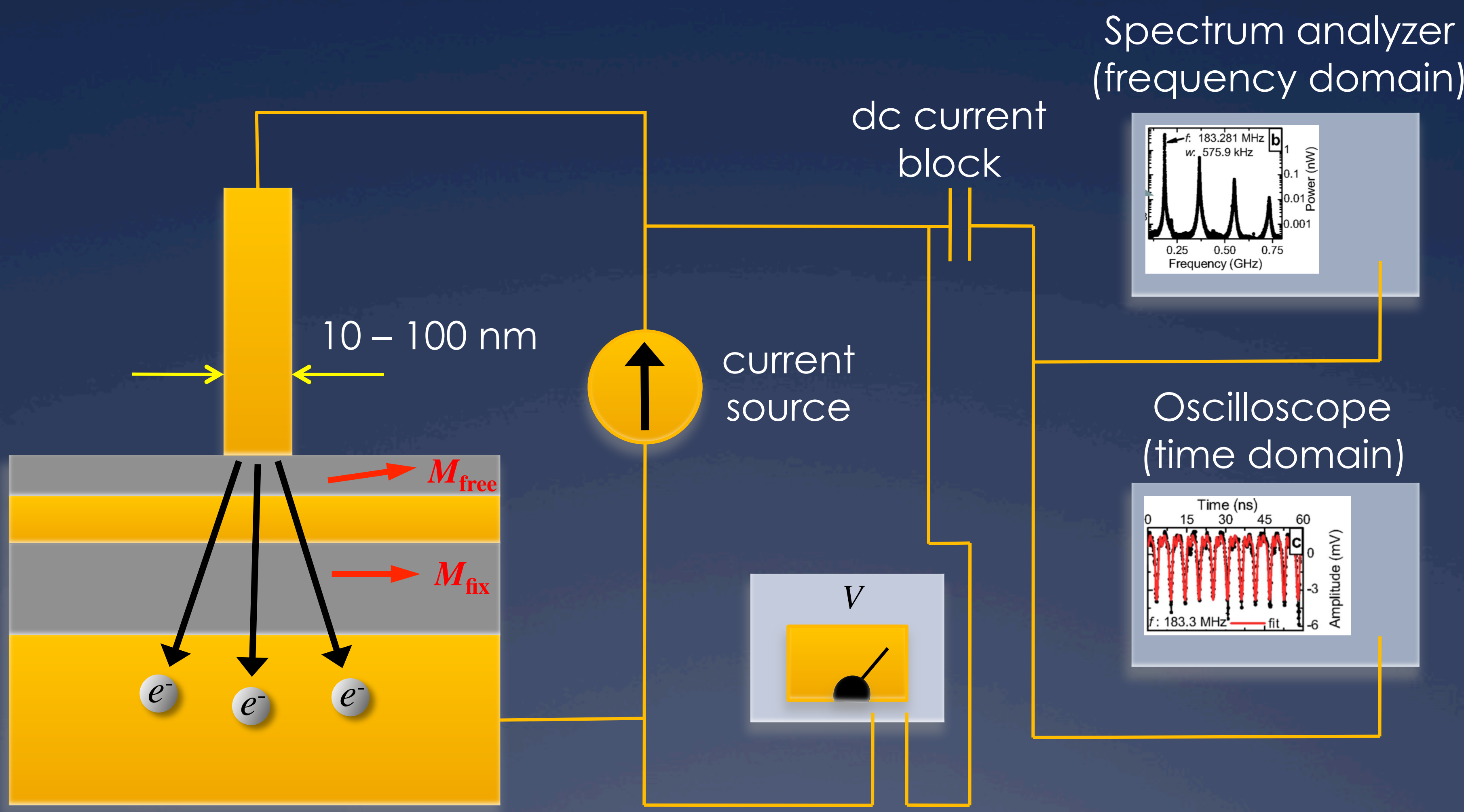
Spin torque can counteract damping

Threshold:

$$N_{\text{damp}} \le N_{\text{st}}$$
$$\Rightarrow J_{crit} \cong 10^8\ \text{A/cm}^2$$

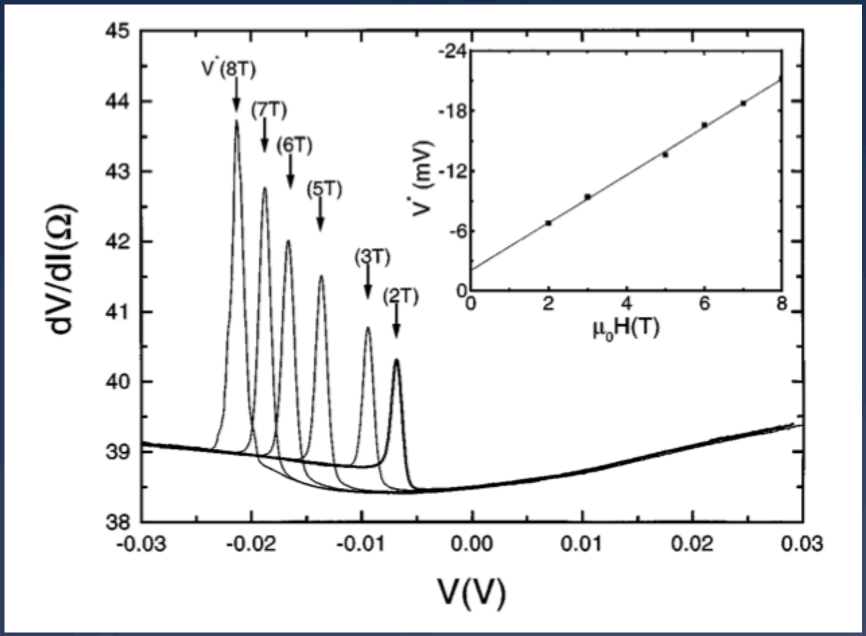
Slonczewski, *J. Magn. Magn. Mater.* **159** (1996)

"Idealized" Point Contact Geometry

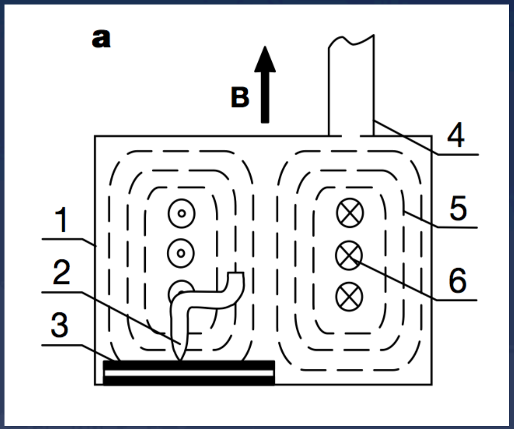


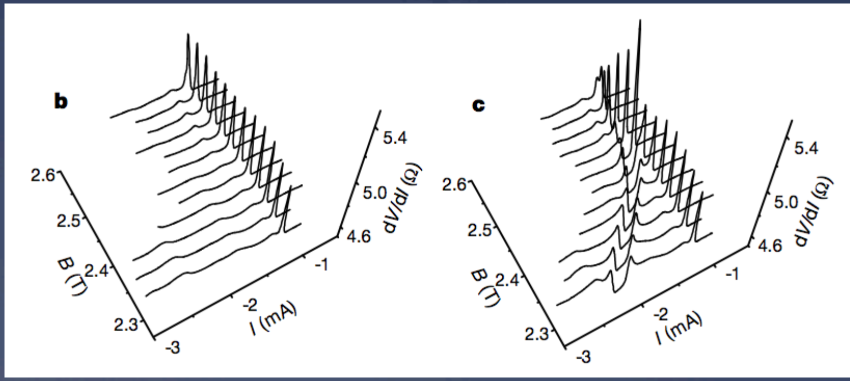
NIST National Institute of Standards and Technology

First Evidence… Mechanical Point Contacts



Tsoi, Jansen, Bass, Chiang, Seck, M. and Tsoi, Wyder, *PRL* **81** (1998)





Tsoi, Jansen, Bass, J. and Chiang, Tsoi, Wyder, *Nature* **406** (2000)

National Institute of Standards and Technology

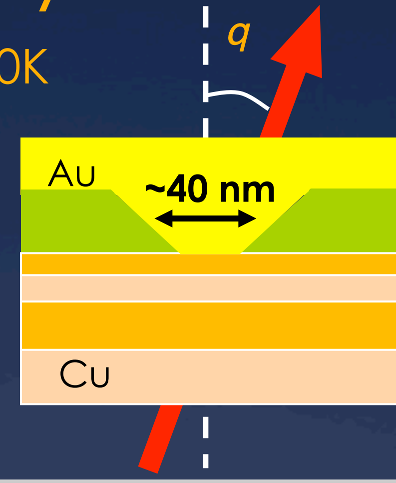
Nanocontact Dynamics

- Lithographically patterned nanocontacts
- Correlate resistance change with observed microwave emissions.

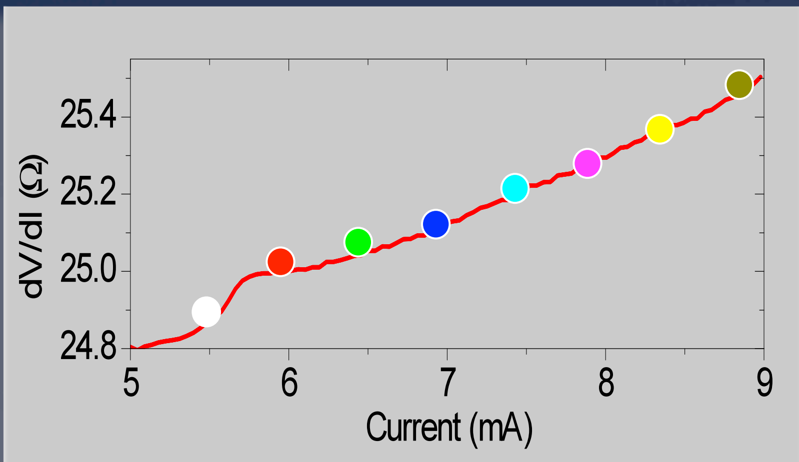
T = 300K

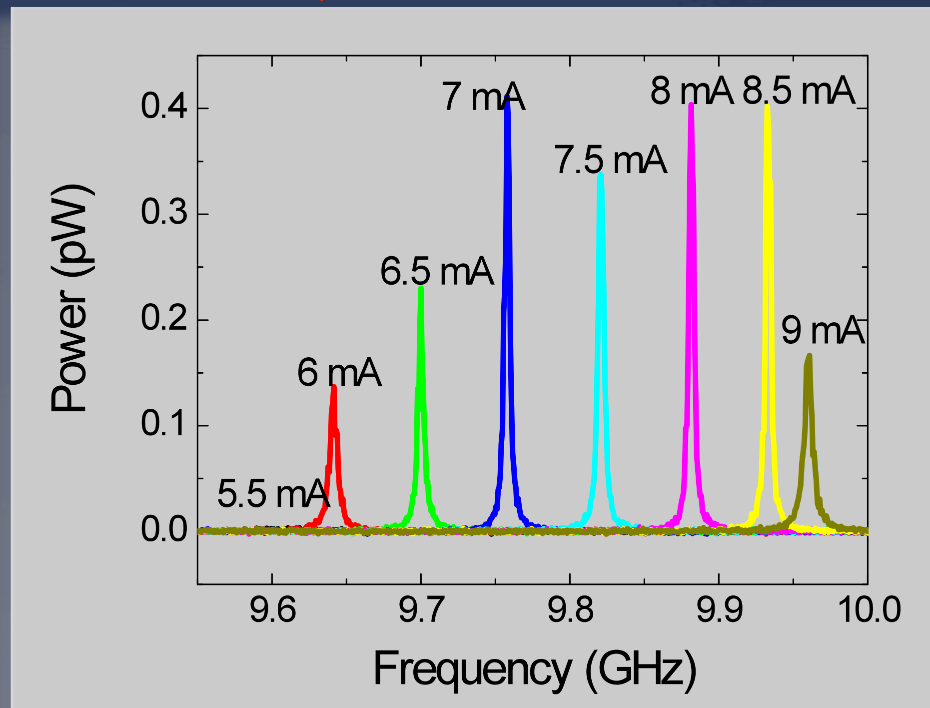
H_0 = 7000 Oe,
q = 10°

"Free" layer
"Fixed" layer



Magnetic layers are of wide lateral extent. ~10-20 micrometers.

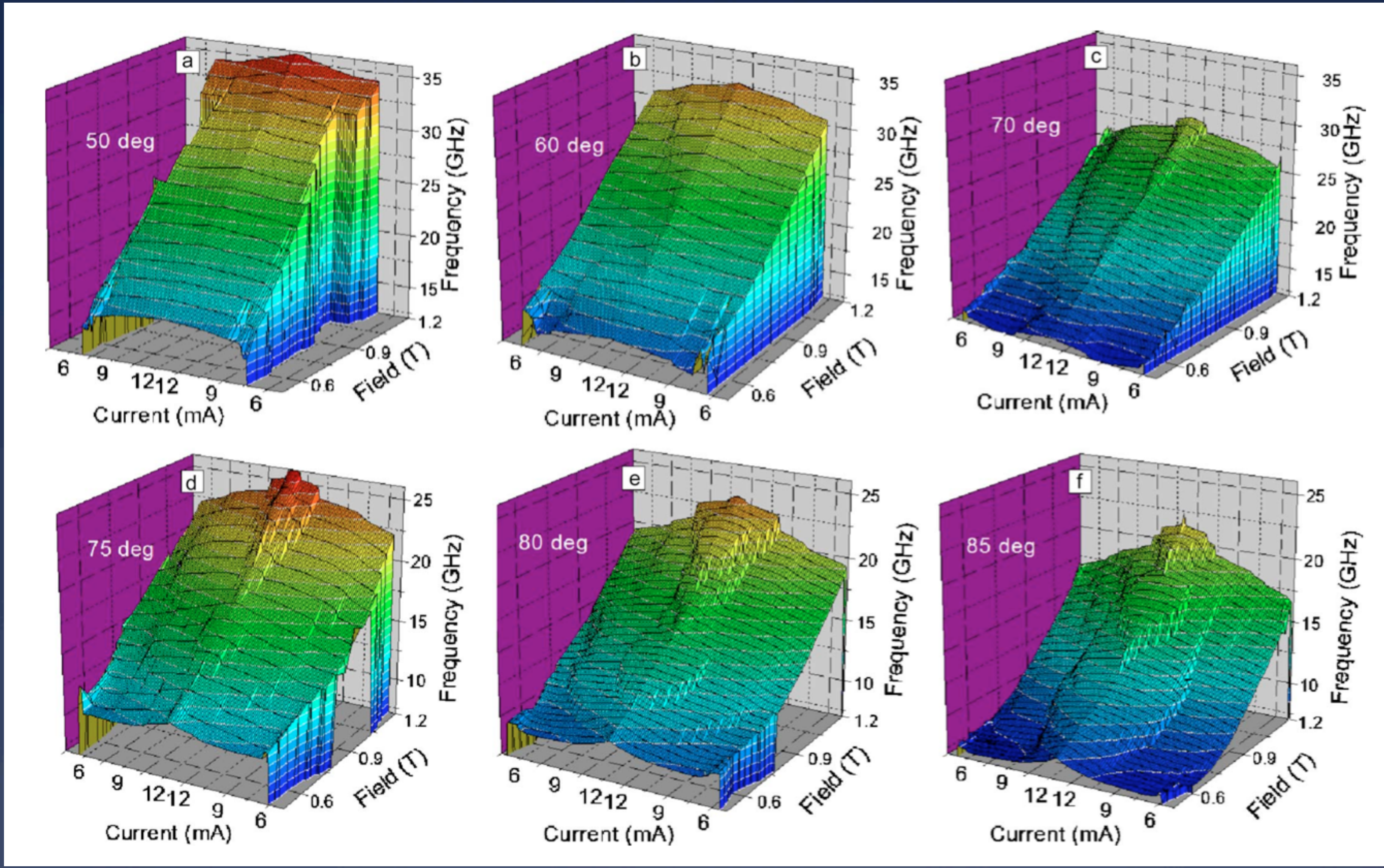




Devices are nanoscale current-controlled microwave oscillators

Rippard, Pufall, Kaka, Russek, and Silva, *PRL* **92** (2004)

Point Contact Complexity



- Frequency jumps
- Non-monotonic

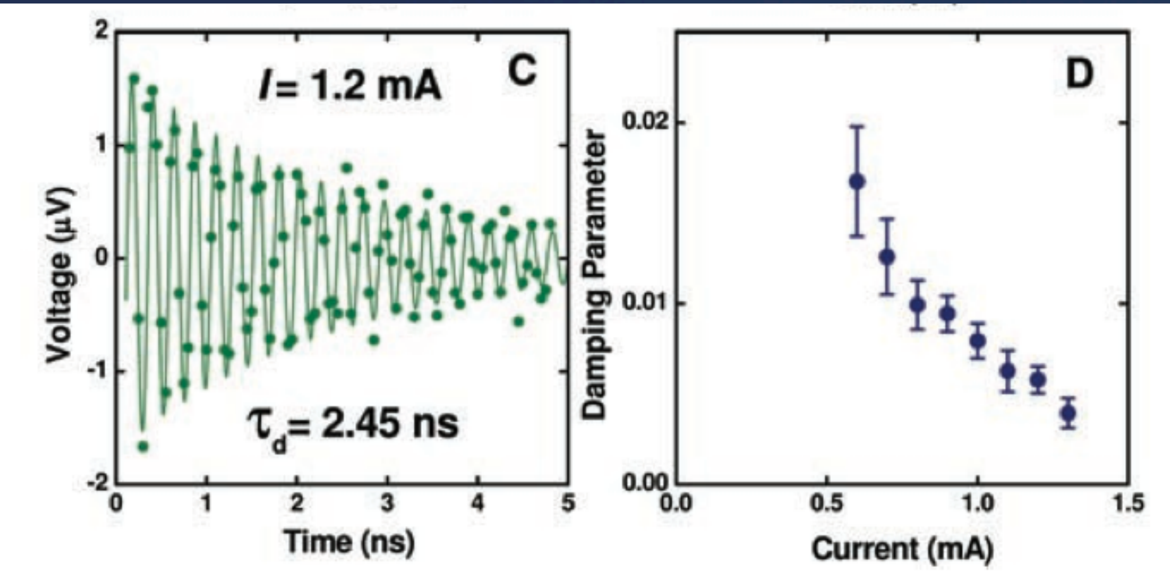
Individual device behavior tends to be complicated function of field and current.

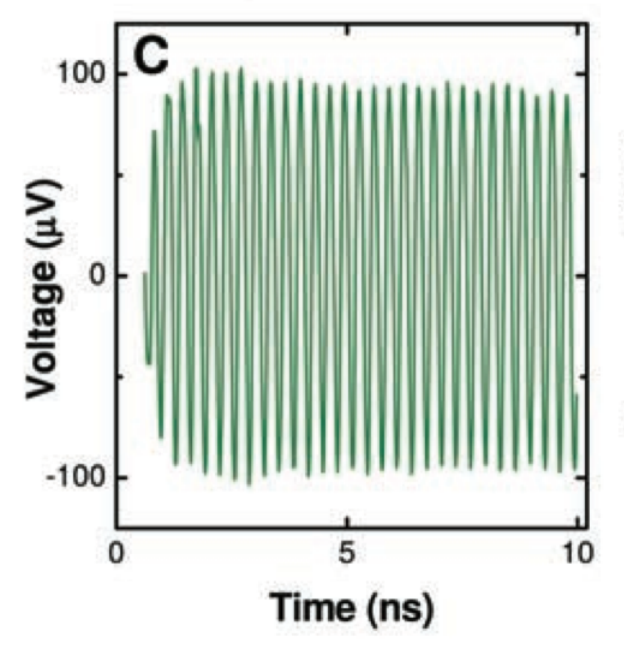
Rippard, Pufall, and Russek, *PRB* **74** (2006).

Time Domain Data (Nanopillars)

Below threshold... Current reduced effective damping.

Above threshold... steady-state oscillations

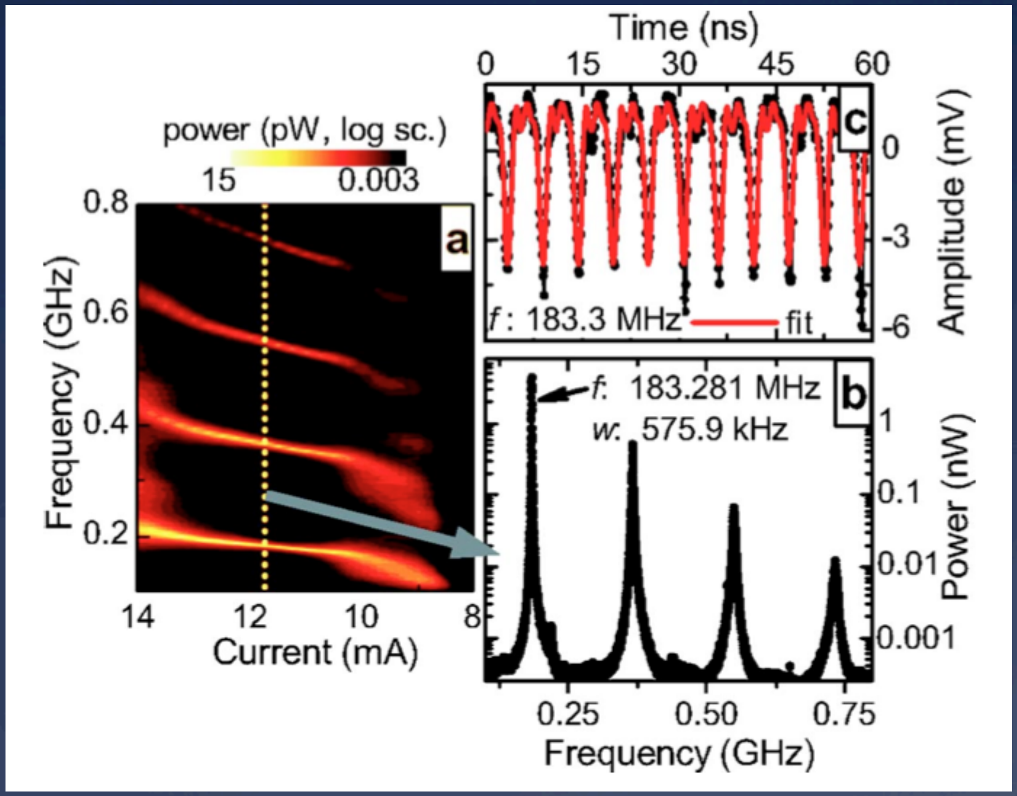




Krivorotov, Emley, Sankey, Kiselev, Ralph, Buhrman, *Science* **307** (2005)

NIST
National Institute of Standards and Technology

Low field experiments



New kind of mode observed when weak magnetic fields applied perpendicular to plane.

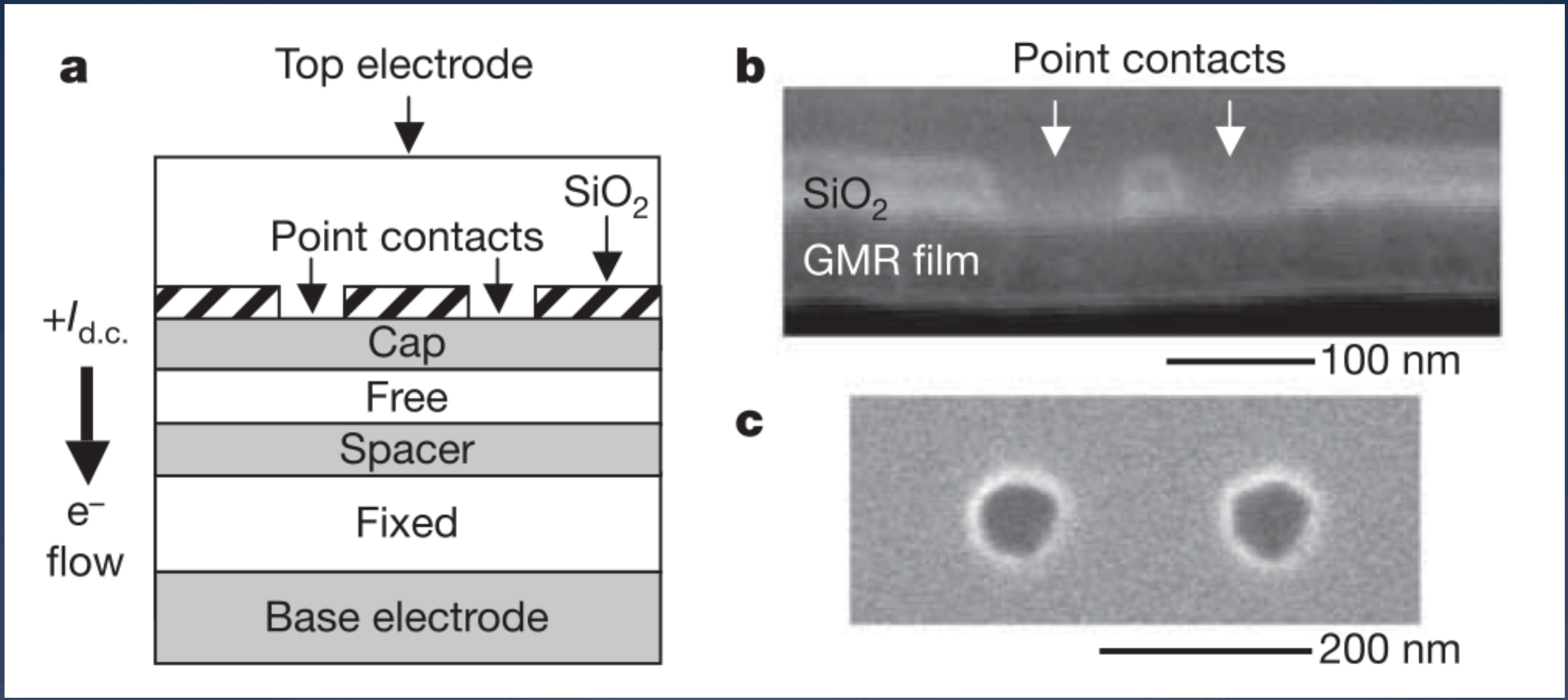
- Large amplitude
- Non-sinusoidal (many harmonics)
- Low frequencies in the 100's of MHz ("radio frequency", or "rf")

Pufall, Rippard, Schneider, and Russek, PRB, **75** (2007).

also...

Mistral, Kampen, Hrkac, Kim, Devolder, Crozat, Chappert, Lagae, and Schrefl, PRL, 100 (2008).

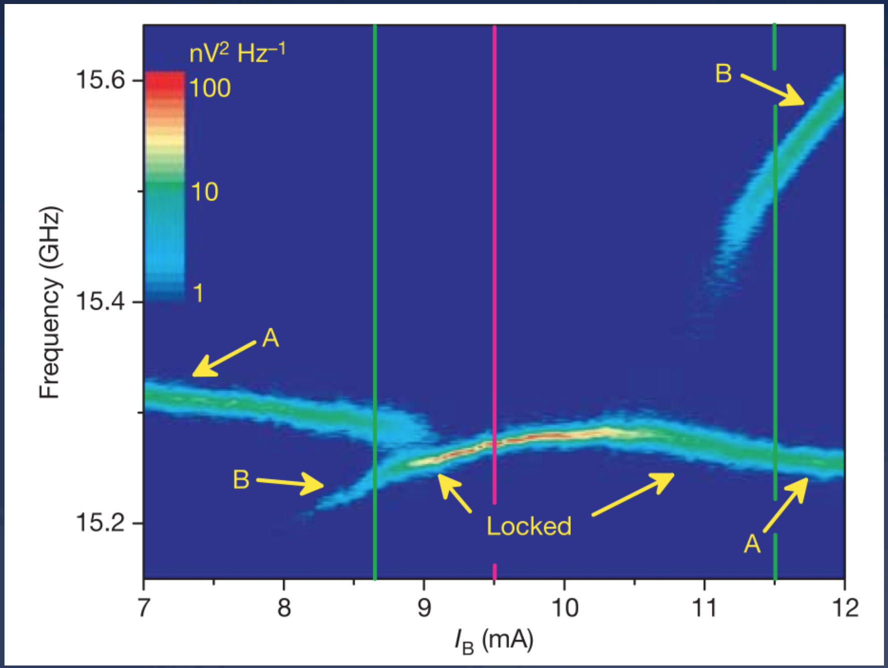
Dual Lithographic Point Contacts

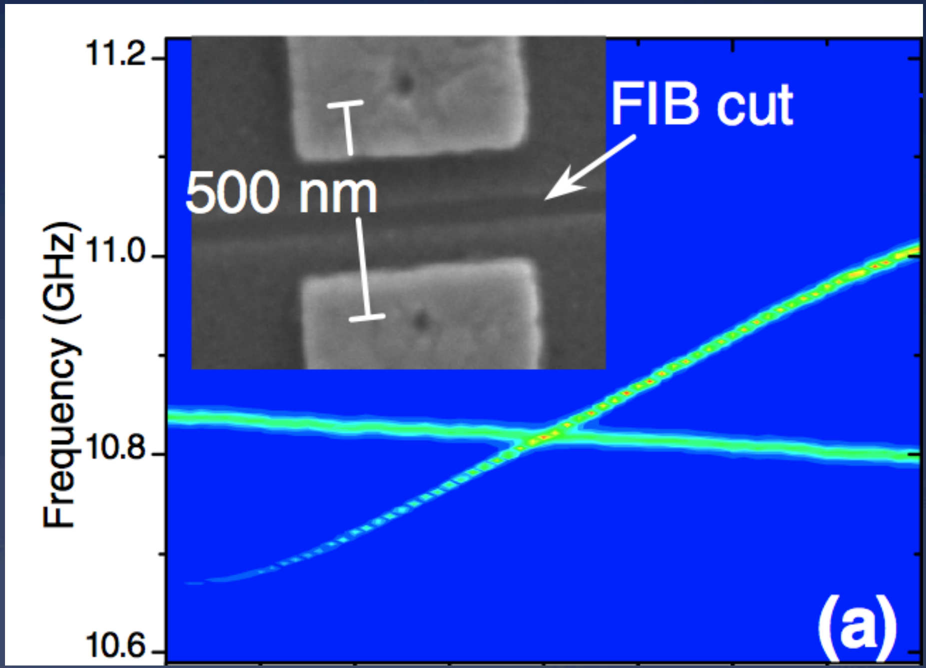


Mancoff, Rizzo, Engel, Tehrani, *Nature*, **437** (2005)

National Institute of Standards and Technology

Dual Contact Data





Kaka, Pufall, Rippard, Silva, Russek, and Katine, *Nature* **437** (2005)

Pufall, Rippard, Russek, Kaka, Katine, *PRL* **97** (2006)

Neighboring contacts “talk” to each other via waves radiating between them in a common magnetic film that joins the contacts.

Slonczewski Linear Solution

Linear approximation to LL + Slonczewski spin torque in point contact:

$$i\frac{\partial \tilde{m}}{\partial t} = \left(\nabla^2 - (h-1) + i\left[\, j\Phi(x,y) - \alpha[h-1]\right]\right)\tilde{m}$$

normalized field

spin current distribution at contact

normalized current **density**

Calculated threshold for Hopf bifurcation:

$$j_{crit} = \left(\frac{1.86}{\rho_*^2} + \alpha\left[h - 1 + \frac{1.43}{\rho_*^2}\right]\right)$$

Slonczewski, *J. Magn. Magn. Mater.*, **195** (1999)

normalized contact radius

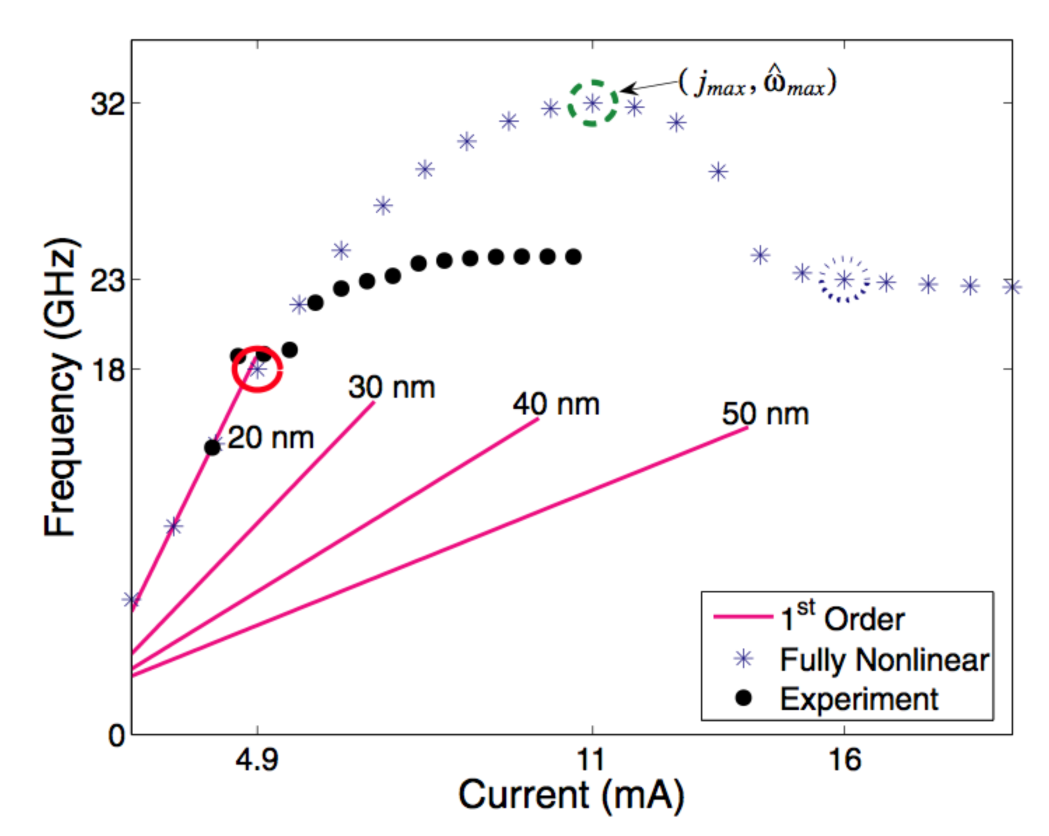
Effective damping due to spin wave radiation ***away*** *from contact into surrounding magnetic film.*

Nonlinear Slonczewski Solution

$$i\frac{\partial\tilde{m}}{\partial t}=\left(\nabla^2-(h-1)+i\left[j\Phi(x,y)-\alpha[h-1]\right]\right)\tilde{m}+\frac{a^2}{2}\left\{-|\tilde{m}|^2\tilde{m}+i\left[j\Phi(x,y)-\alpha[h-2]\right]|\tilde{m}|^2\tilde{m}\right\}$$
$$+\left[\tilde{m}\nabla^2\tilde{m}^*+2(1+i\alpha)|\nabla^2\tilde{m}|^2\right]\tilde{m}$$

nonlinear exchange

local dipole nonlinearity

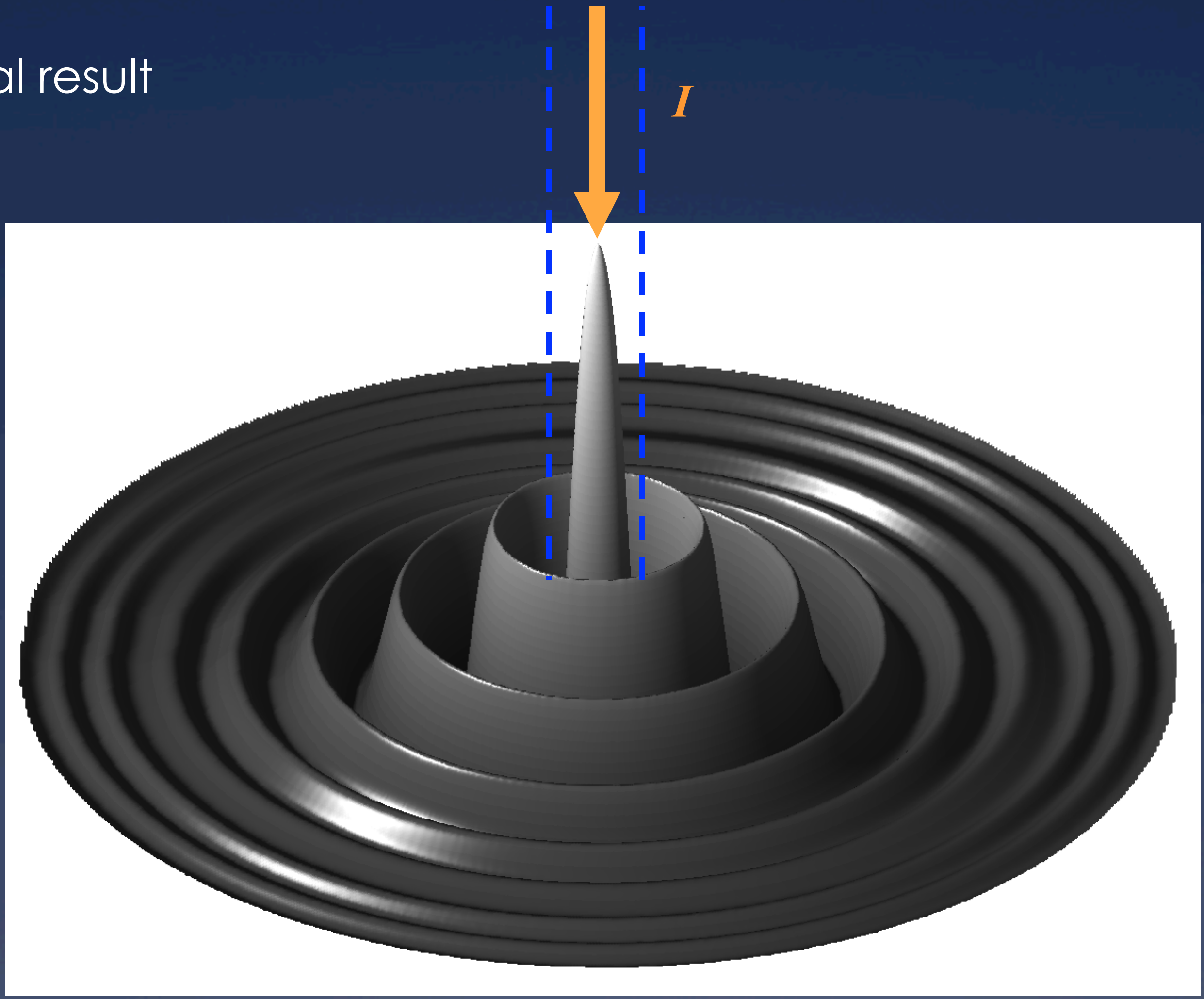


Hoefer, Ablowitz, Ilan, Pufall, Silva, *PRL*, **95** (2005)

National Institute of Standards and Technology

Spin torque nanocontact as spin wave source

Theoretical result

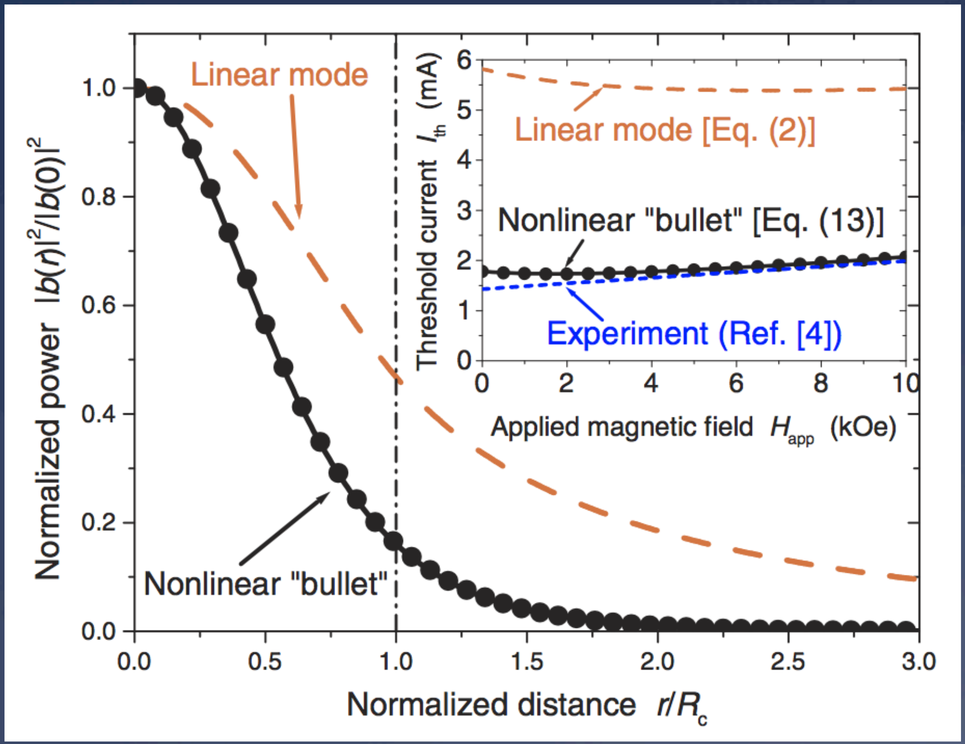


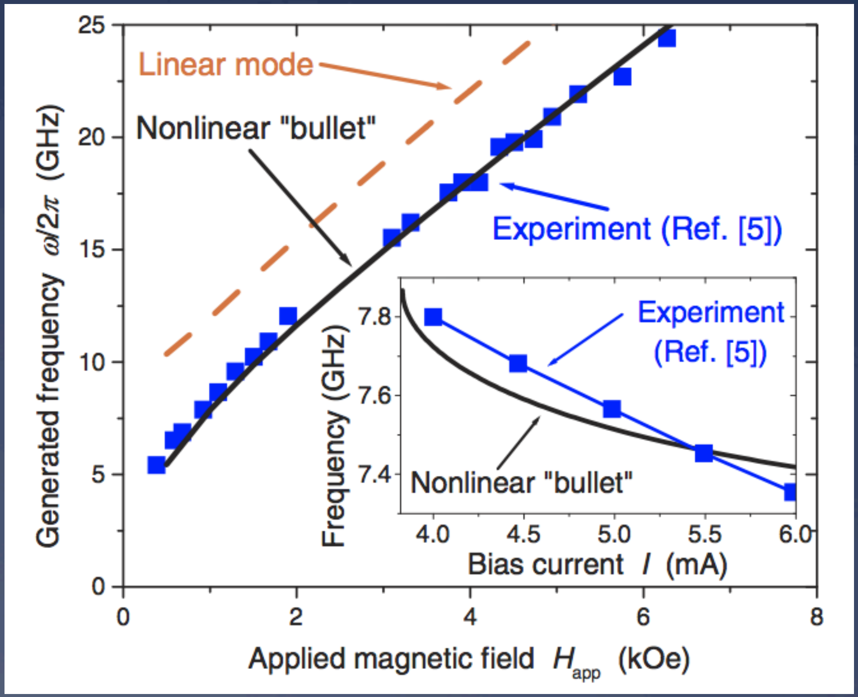
M. A. Hoefer, *et al*., Phys. Rev. Lett. **95**, 267206 (2005)

Weakly Nonlinear Bullet for In-plane Fields

$$i\frac{\partial \tilde{m}}{\partial t} = \left(\nabla^2 - \omega_0 + i\left[j\Phi(x,y) - \Gamma\right]\right)\tilde{m} + \frac{a^2}{2}\left\{-N|\tilde{m}|^2\tilde{m} + ij\Phi(x,y)|\tilde{m}|^2\tilde{m}\right\}$$

Treated like NLSE, but with dissipative perturbation.
Examine stability of mode energy



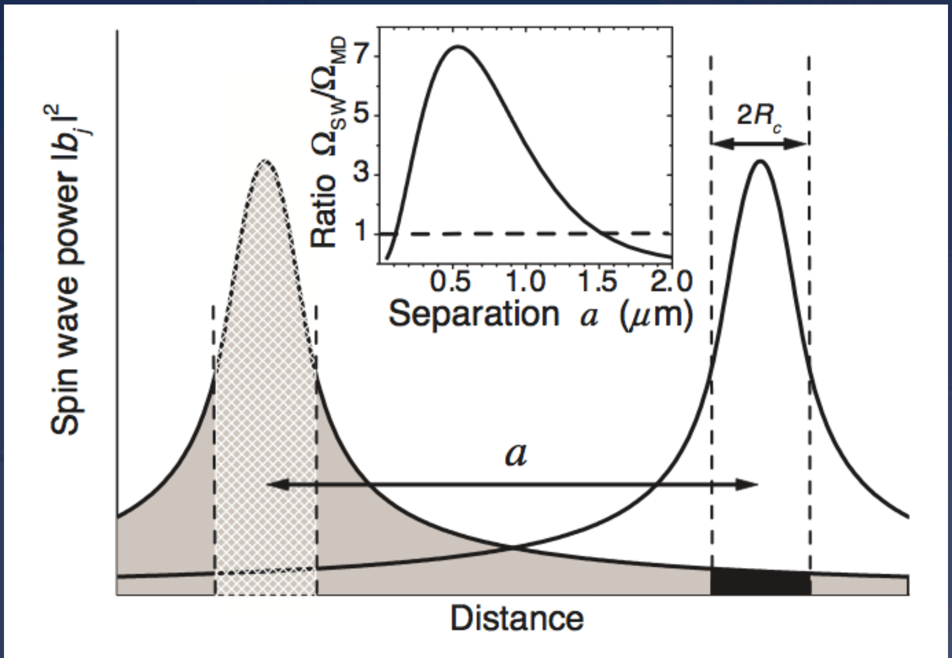


Slavin and Tiberkevich, *PRL* **95** (2005)

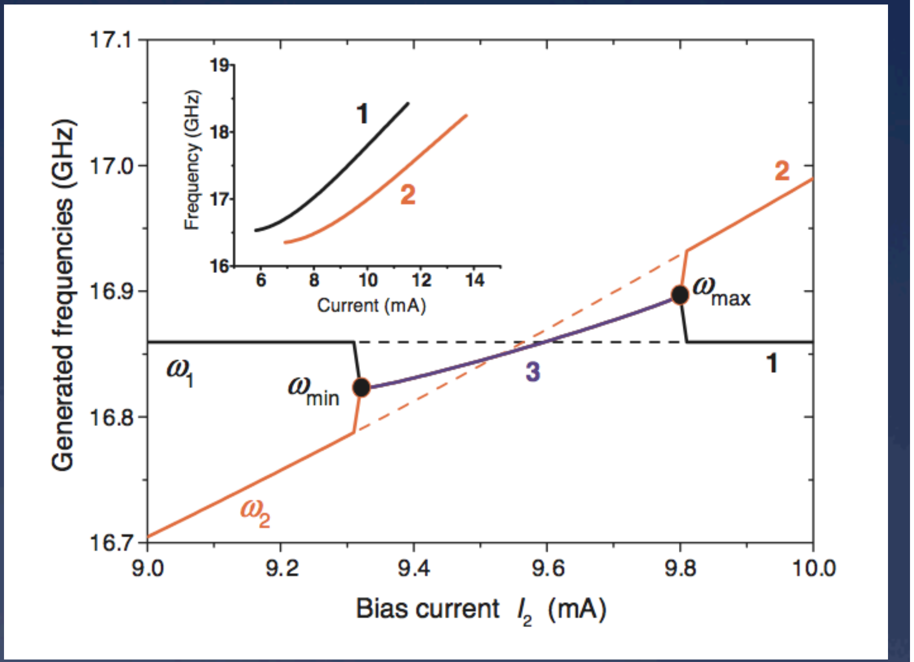
National Institute of Standards and Technology

Theory for spin-wave-mediated locking

Spin wave mode overlap:



Finite locking range:



$$i\frac{\partial \tilde{m}_1}{\partial t} = \left(-\omega_1 - Dk_1^2 + i\left[j\Phi(x,y) - \Gamma_1\right]\right)\tilde{m}_1 + \left\{-N + i\left[j\Phi(x,y) - \alpha q\right]\right\}\left|\tilde{m}_1\right|^2 \tilde{m}_1 + \Omega_{12}\tilde{m}_2$$

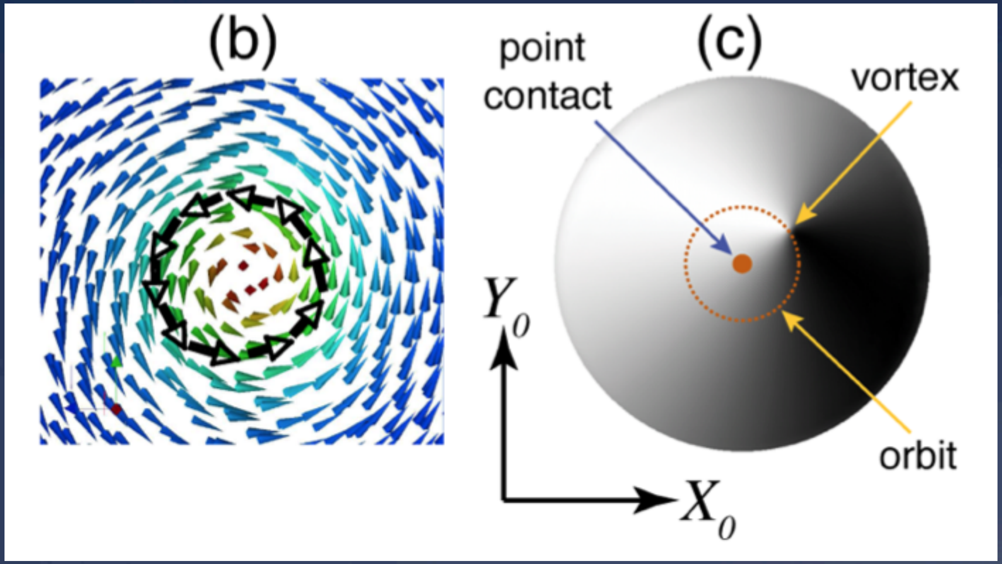
$$i\frac{\partial \tilde{m}_2}{\partial t} = \left(-\omega_2 - Dk_2^2 + i\left[j\Phi(x,y) - \Gamma_2\right]\right)\tilde{m}_2 + \left\{-N + i\left[j\Phi(x,y) - \alpha q\right]\right\}\left|\tilde{m}_2\right|^2 \tilde{m}_2 + \Omega_{21}\tilde{m}_1$$

See Andrei Slavin 4:00 talk in Session MS10 today: “Devil’s Staircase...”

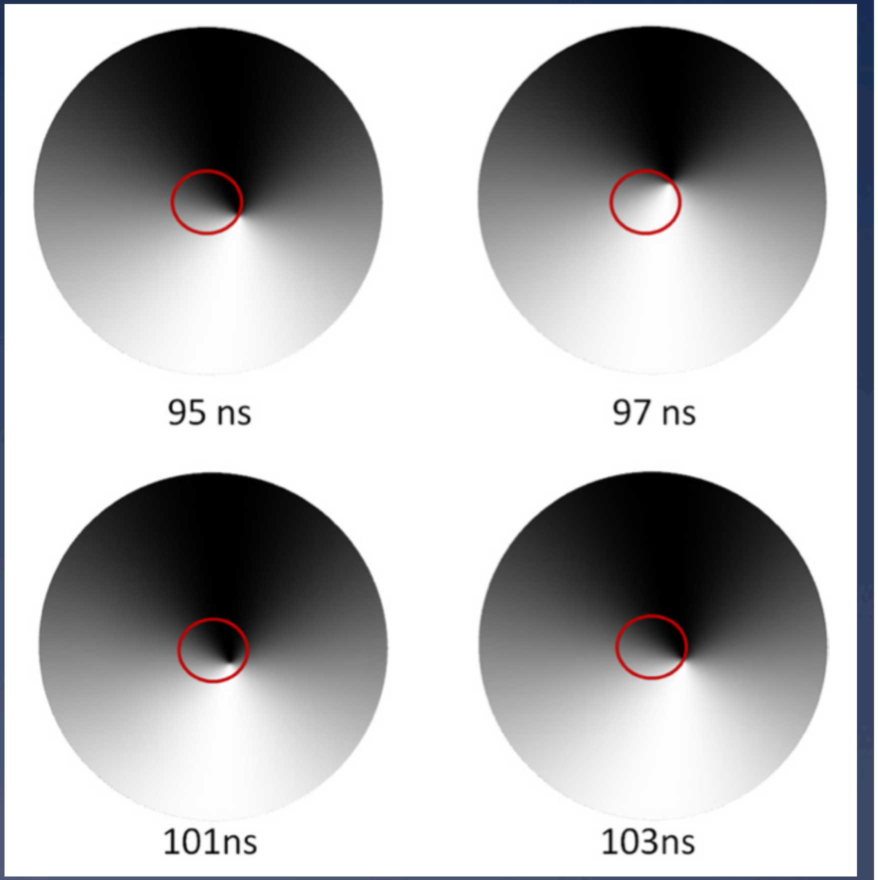
Slavin, Tiberkevich, *PRB* **74** (2006)

Topological Soliton ("Vortex") Mode

An explanation for low field, low frequency modes in point contacts



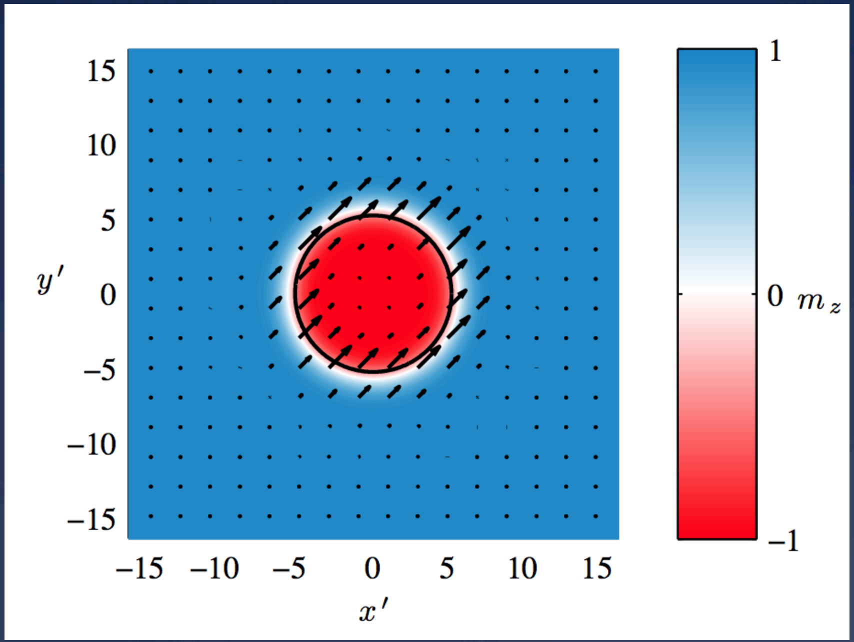
Mistral, van Kampen, Hrkac, Kim, Devolder, Crozat, Chappert, Lagae, and Schrefl, *PRL* **100** (2008)



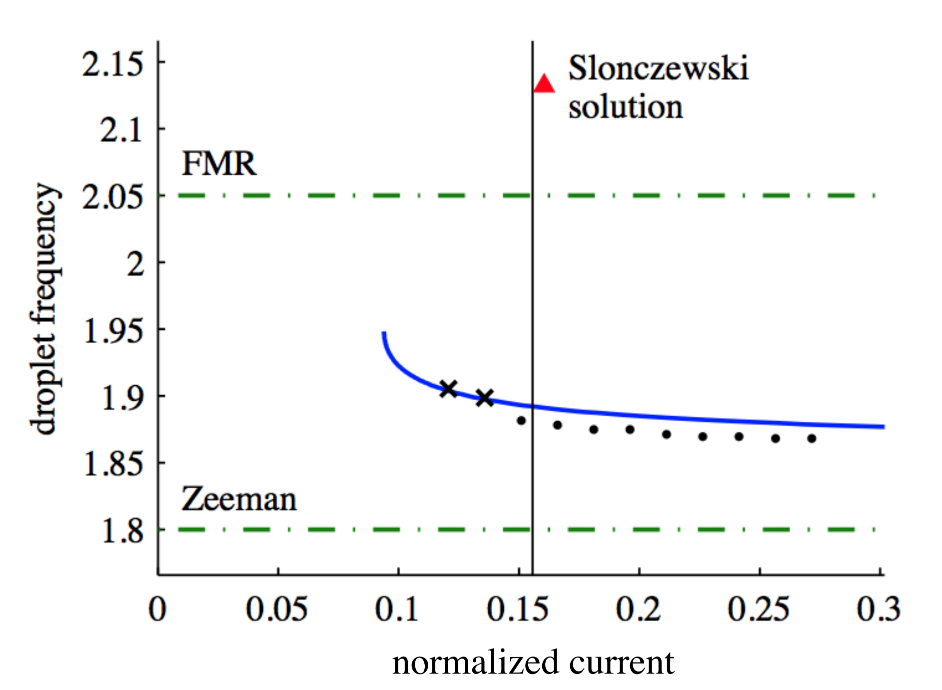
Kampen, Hrkac, Schrefl, Kim, Devolder, and Chappert, *J Phys. D* **42** (2009)

See Gino Hrkac 3:30 talk in Session MS10 today: "Influence of Free and SAF Layer Modes on the RF Emission Line Width..."

Dissipative Droplet Soliton in point contacts



• Requisite condition: Perpendicular anisotropy in "free" layer *sufficient to overcome shape anisotropy*, which pushes magnetization into the film plane



•A new kind of mode: Stable solution to **full** Landau-Lifshitz equation.

•Localized. Weak dependence of frequency on current.

See Mark Hoefer 3:00 talk in Session MS10 today: Dissipative Droplet Solitons

Hoefer, Silva, and Keller, PRB, In press. (cond-mat http://arxiv.org/abs/1008.1898)

NIST National Institute of Standards and Technology

Open Theory Problems (1)

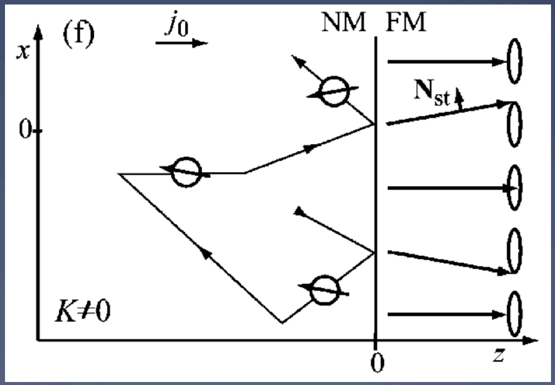
(1) The time killer: Nonlocal dipole field calculations

Thin film approximation with only local terms? When applicable?

Nonlocal correction terms? (Arias and Mills, *PRB* **75** (2007))

(2) How to efficiently solve the "self-consistent" problem? (Spin currents affect magnetization dynamics affect spin currents affect magnetization dynamics affect spin current…)

Stiles, M. D. and Xiao, J. and Zangwill, A., Phys. Rev. B, 2004, 69



Open Theory Problems (2)

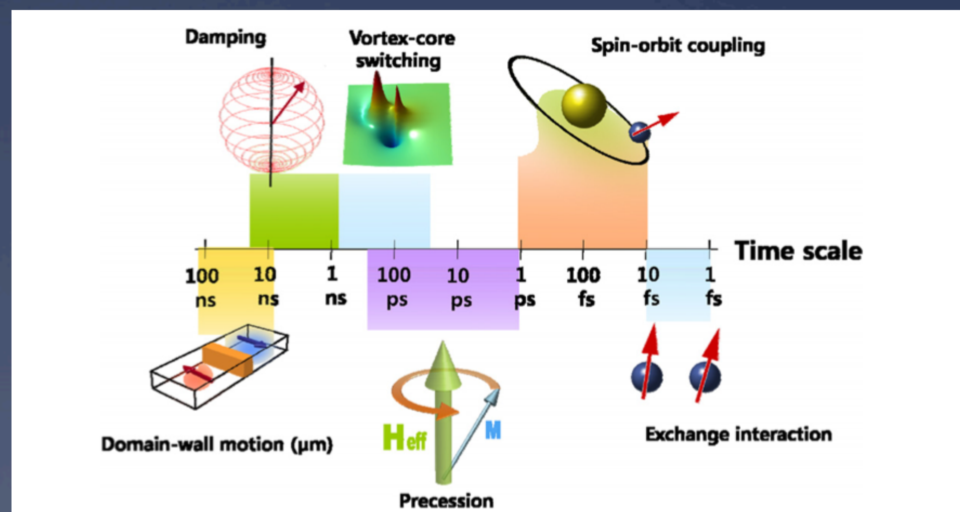
J. Phys. D: Appl. Phys. **43** (2010) 264004 S-K Kim

Table 1. Comparison of several numerical simulation codes.

	Code	Calculation method	Program features
Free Software Package	OOMMF (M. Donahue and D. Porter in NIST)	FDM	Open source Runge–Kutta integration Uniform cell size http://math.nist.gov/oommf/
	MAGPAR (Werner Scholtz)	FEM	Unstructured graded meshes Restriction on current effects http://magnet.atp.tuwien.ac.at/scholz/magpar
	NMAG (H. Fangohr and T. Fischbacher)	FEM	Unstructured graded meshes Periodic boundary condition Arbitrary crystal anisotropy http://nmag.soton.ac.uk
Commercial Software Package	LLG Simulator (M. R. Scheinfein)	FDM	Gauss–Seidel integration Finite temperature (Langevin) Periodic boundary condition Uniform cell size http://llgmicro.home.mindspring.com/
	MicroMagus (D.V. Berkov and N. L. Gorn)	FDM	Periodic boundary condition Finite temperature (Langevin) Uniform cell size http://www.micromagus.de/

Many "packages" exist.
Which one is right for the job?

No absolute accuracy with respect to dynamics problems, including spin torque. Need analytical results for comparison.



Thermal fluctuations: How to include? Huge range of time scales… Convergence issues… Correlations on short time scales and short length scales are not a solved analytical problem …

Martínez, López-Díaz,Torres, García-Cervera, *J. Phys. D* **40** (2007)

NIST National Institute of Standards and Technology

Conclusions

- Spin torque: A revolutionary new way to control magnetism

- Potential applications: non-volatile "universal" CMOS-compatible memory (On-going DARPA program), low-power "spin" logic (Initial stages of DARPA program), low-cost Si-compatible oscillators for telecom (Proposal stage at DARPA).

- Experimental issues: device-to-device reproducibility.

- Theory issues: Very difficult nonlinear PDEs, especially when keeping all terms. Modeling is costly... ways to improve speed? Self-consistent? How to correctly convert from PDEs to stochastic PDEs?

- Promise of tractable problems. Example: Dissipative Droplet Soliton.