ESM 2018
Krakow

# MP3 - Spin-transfer and spin-orbit torques, current topics in magnetisation dynamics

Joo-Von Kim

*Centre for Nanoscience and Nanotechnology, Université Paris-Saclay*
*91120 Palaiseau, France*

*joo-von.kim@c2n.upsaclay.fr*

# MP3: Spin-transfer and spin-orbit torques

- Brief review of concepts in spin-dependent transport
- Spin-transfer torques (CPP, CIP) and spin-orbit torques
  *Slonczewski model, Zhang-Li model, spin Hall effect*
- Effects of current-driven torques on spin waves
  *Self-sustained oscillations, Doppler effect*
- Effect of current-driven torques on soliton dynamics
  *Domain wall propagation, vortex gyration*

# Magnetism affects transport: GMR

- Giant magnetoresistance (GMR): Electrical resistance of a metallic magnetic multilayer that depends on the relative orientation of the constituent layer magnetisations

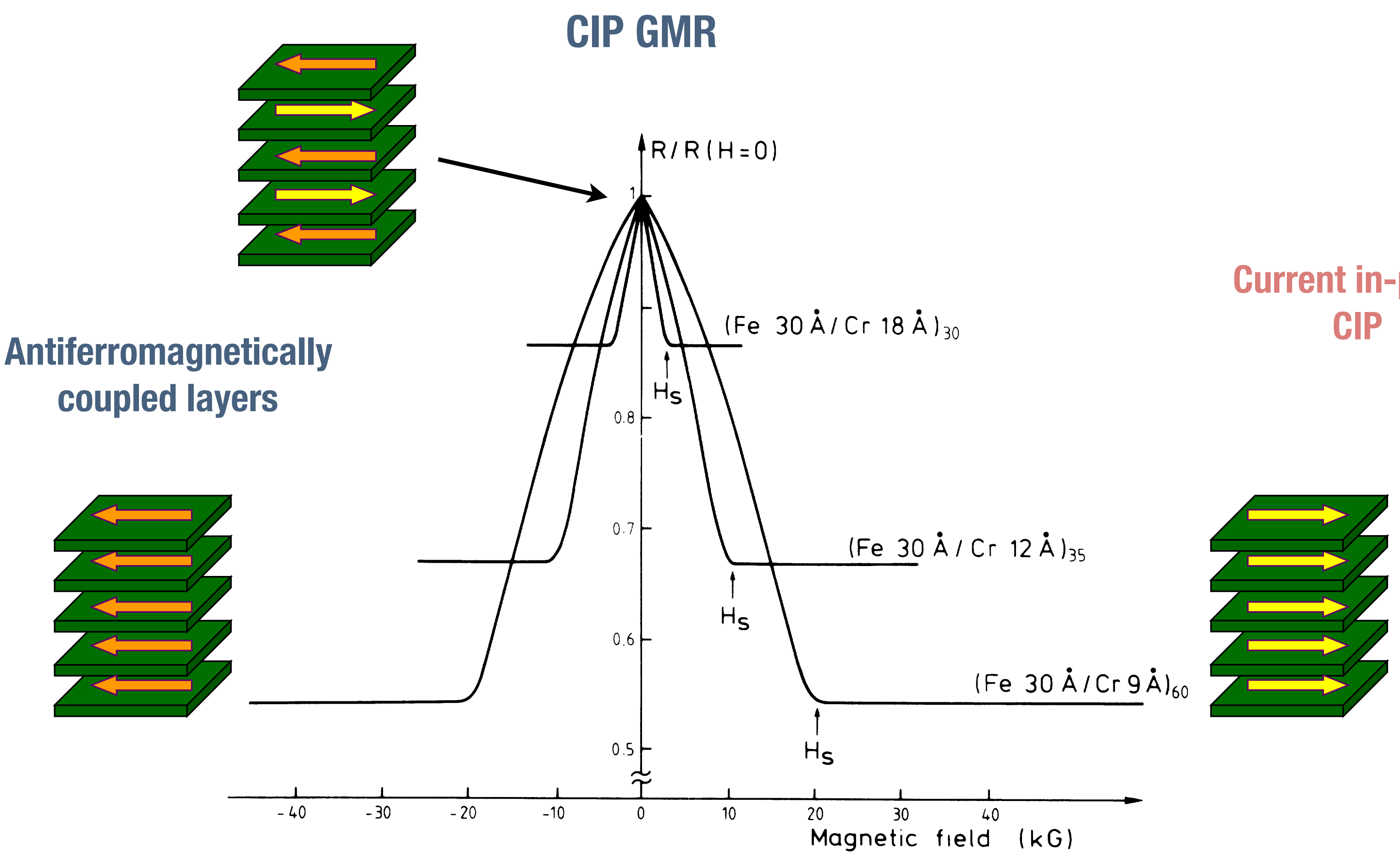
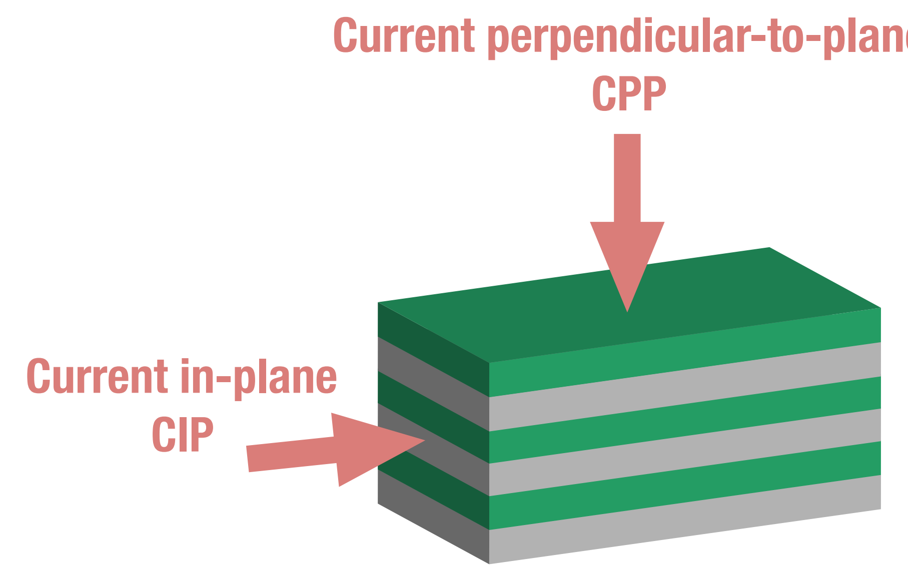



FIG. 3 Magnetoresistance of three Fe/Cr superlattices at 4.2 K. The current and the applied field are along the same [110] axis in the plane of the layers.



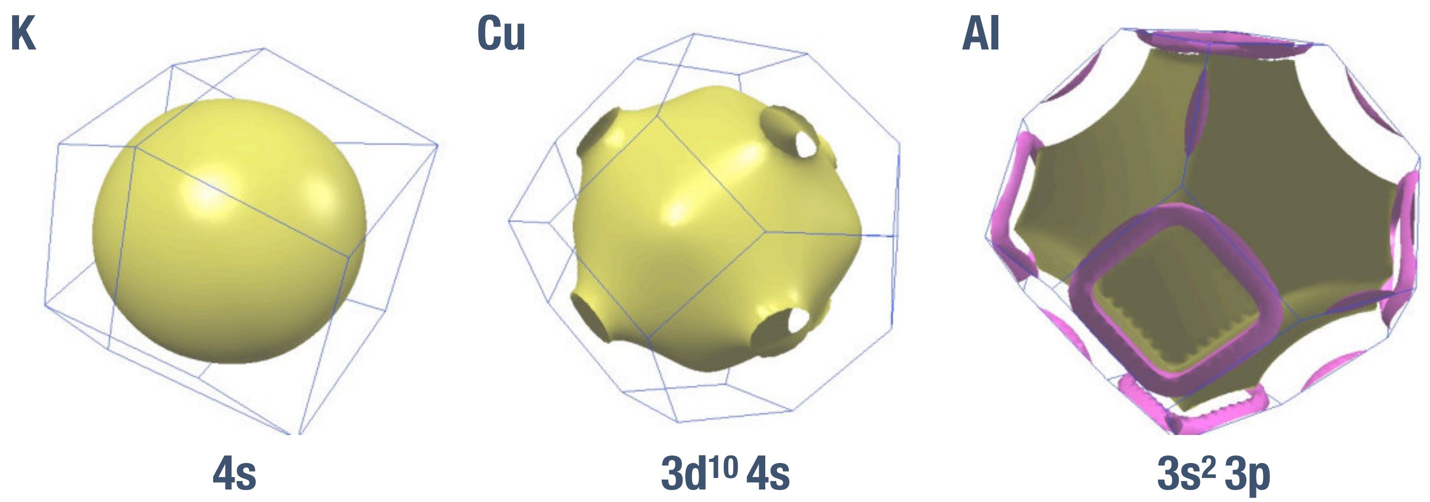

M Baibich et al, *Phys Rev Lett* **61**, 2472 (1988)
G Binasch et al, *Phys Rev B* **39**, 4828 (1989)
2007 Nobel Prize in Physics

# Two-channel model

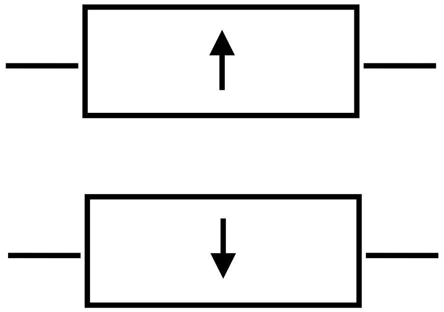
http://www.phys.ufl.edu/fermisurface/

- In metals, conduction processes occur at the Fermi surface
- Assume spin-up and spin-down electrons propagate independently (OK if spin-flip scattering is weak)
- Assign a resistance to each spin channel (Mott)
- In normal metals, spin-up and spin-down channels are equivalent

**Fermi surfaces of some nonmagnetic metals**




$$R_\uparrow = R_\downarrow$$

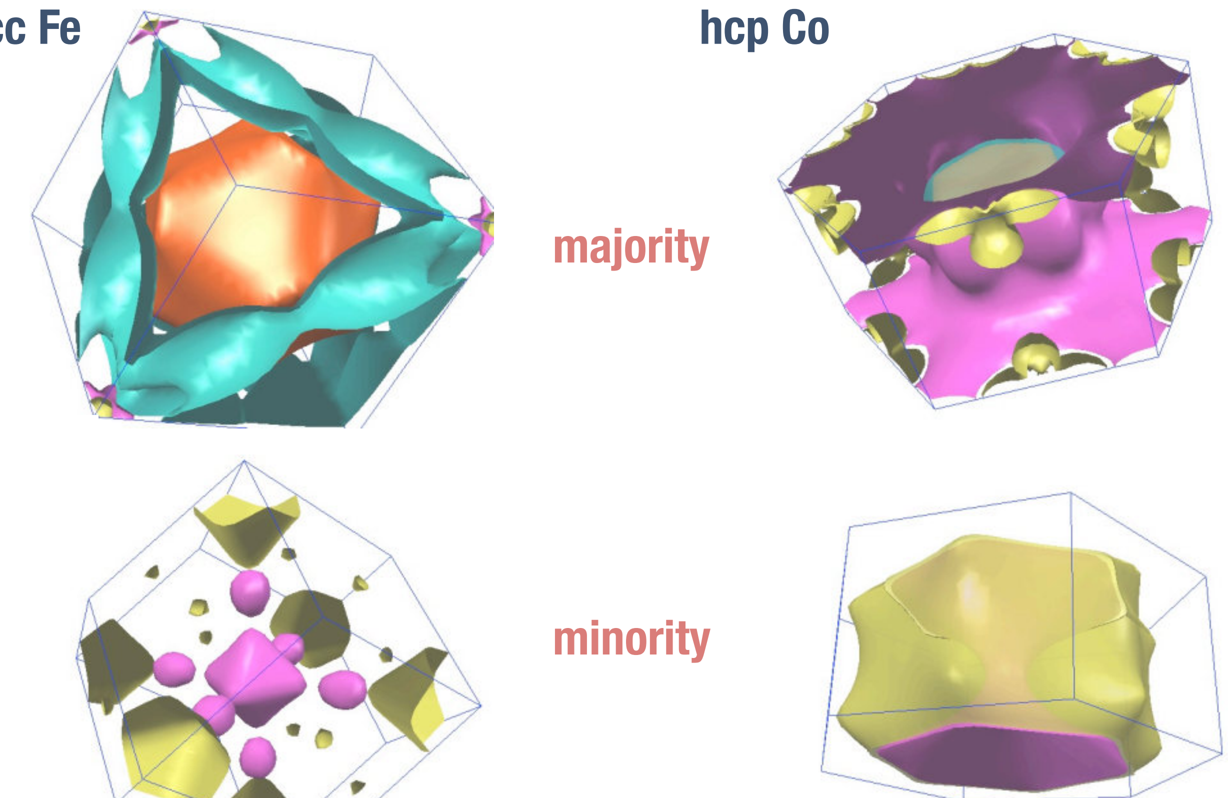


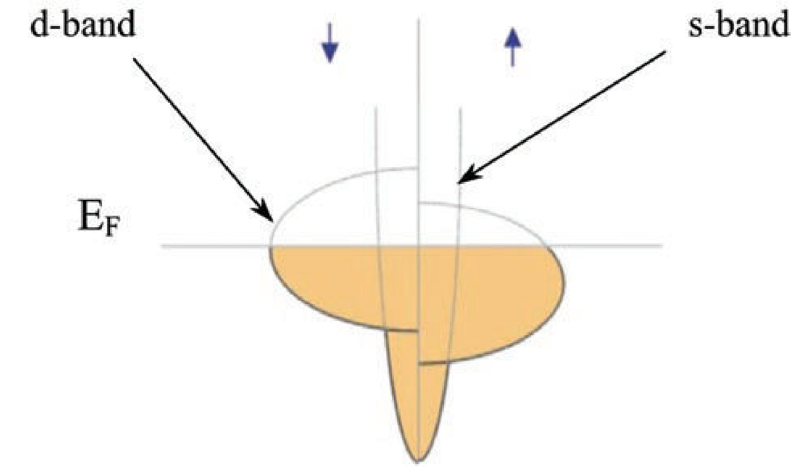
# Two-channel model

http://www.phys.ufl.edu/fermisurface/

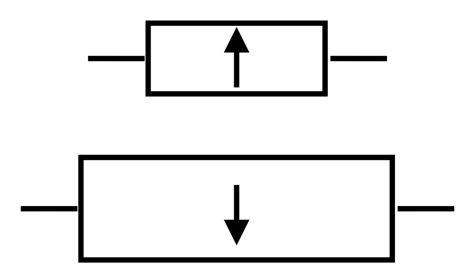
- In ferromagnetic metals, this degeneracy is lifted due to exchange splitting
- Spin-up and spin-down (majority/minority) resistances are different

### Fermi surfaces of some ferromagnetic metals



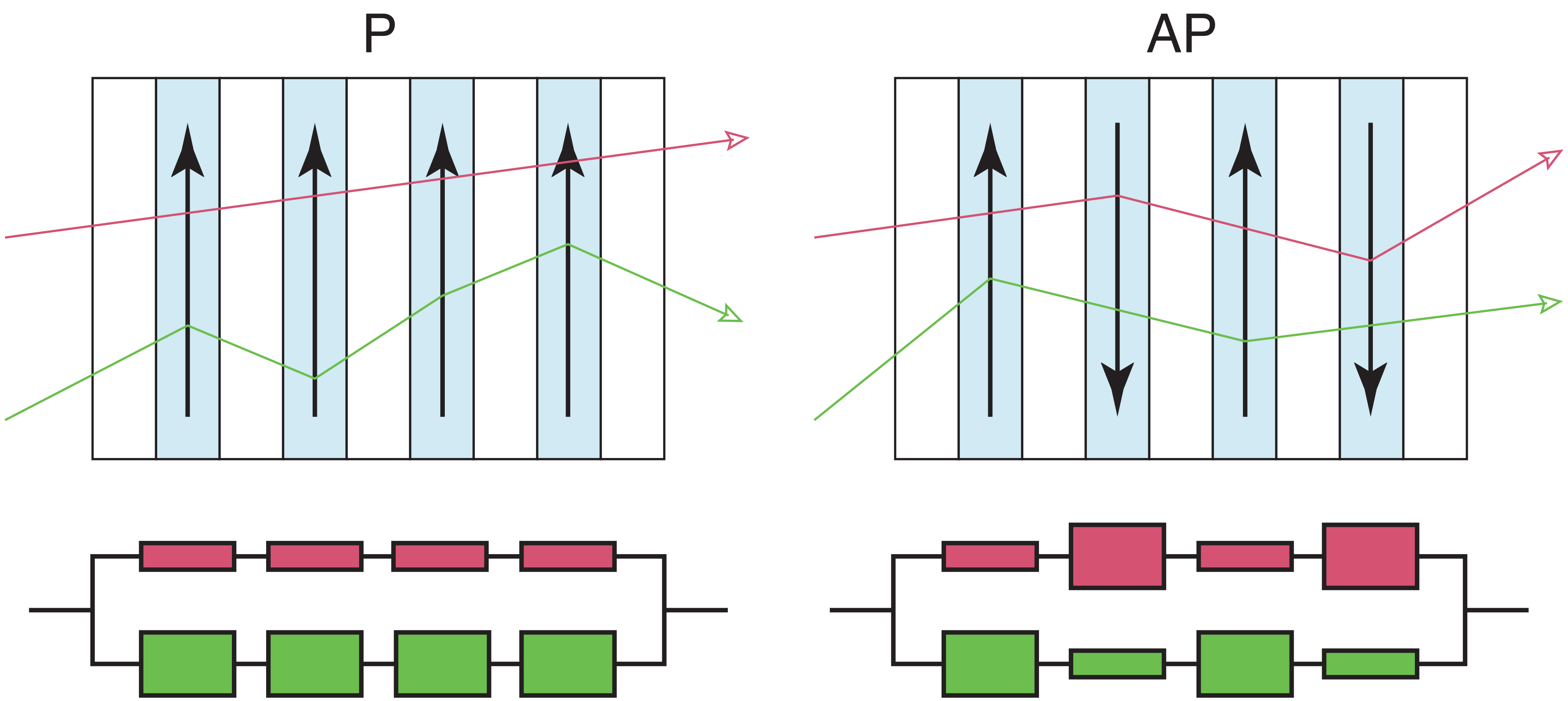




$$R_\uparrow \neq R_\downarrow$$



# GMR with two-channel model

- Simple picture of giant magnetoresistance in terms of two-resistance model

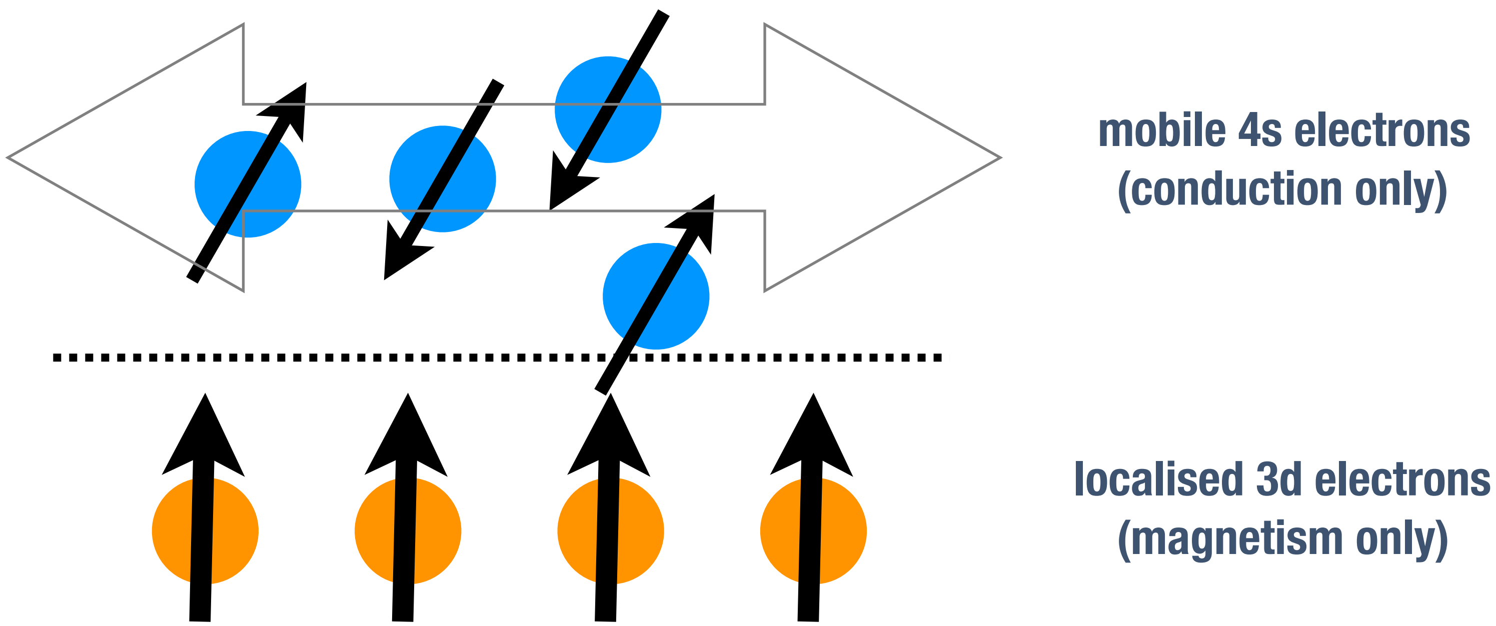


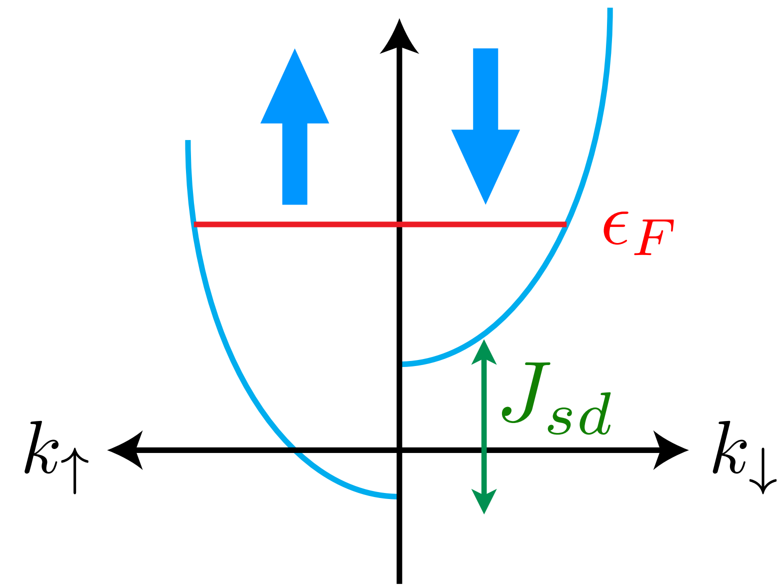

$$R_{\mathrm{P}} \neq R_{\mathrm{AP}}$$

# ... But can transport affect magnetism?

- ***sd* model (Vonsovsky-Zener)**:
  Exchange interaction between local magnetisation (***M***) and conduction electron spin (***s***)

$$\mathcal{E}_{sd} = -J_{sd}\mathbf{M} \cdot \mathbf{s}$$



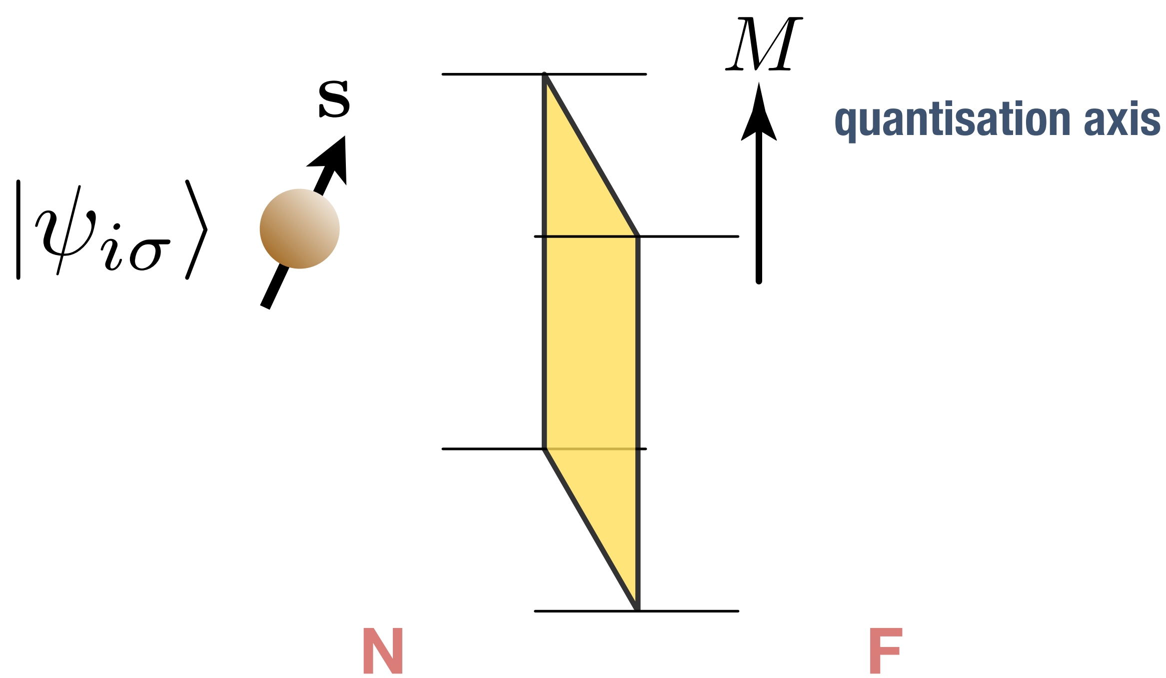



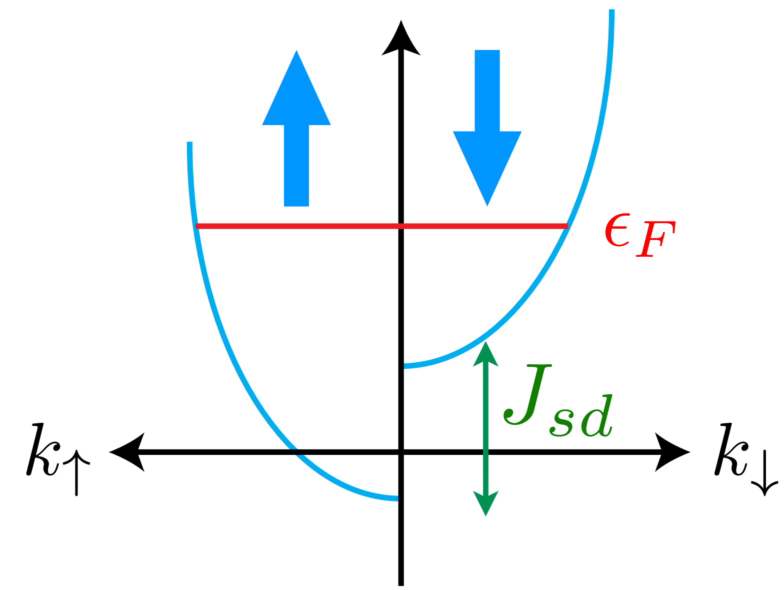

- Torques on the magnetisation can arise from this coupling

# Single electron at N/F interface

M D Stiles & A Zangwill,
*Phys Rev B* **66**, 014407 (2002)

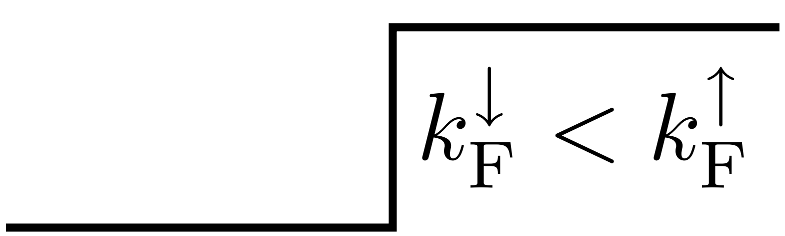
- Exercise: Consider a free electron in the normal metal arriving at the normal metal (N)/ferromagnet (F) interface. Solve 1D Schrödinger equation




$$\epsilon_\mathrm{F} = \frac{\hbar^2 k_\mathrm{F}^2}{2m} \qquad \epsilon_\mathrm{F} = \frac{\hbar^2 (k_\mathrm{F}^{\uparrow,\downarrow})^2}{2m} \mp \frac{J_{sd}}{2}$$

- Because the bands in the ferromagnet are spin-split, there is a spin-dependent step potential at the interface

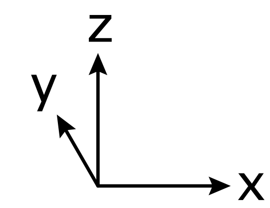


# Spin currents

M D Stiles & A Zangwill, *Phys Rev B* **66**, 014407 (2002)

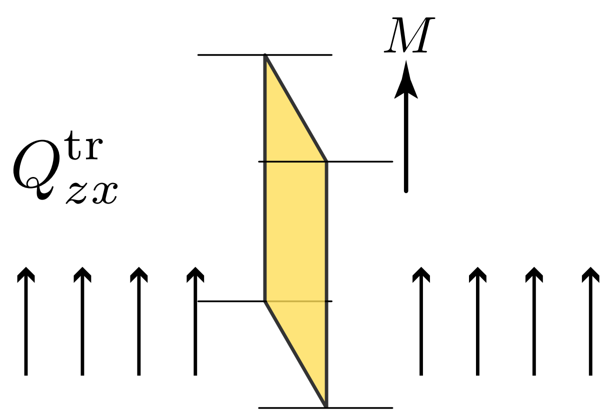
- <u>Exercise</u>: Calculate spin current through this interface. What is conserved?

$$\overleftrightarrow{\mathbf{Q}}(\mathbf{r}) = Re \sum_{i\sigma\sigma'} \psi^*_{i\sigma}(\mathbf{r})\ \hat{\mathbf{s}} \otimes \hat{\mathbf{v}}\ \psi_{i\sigma'}(\mathbf{r})$$




**Conserved**

$$Q^{\rm in}_{zx} + Q^{\rm ref}_{zx} = Q^{\rm tr}_{zx}$$

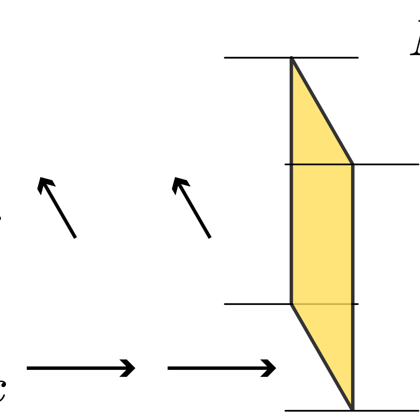



**longitudinal spin current**

**NOT conserved**

$Q_{yx}$

$Q_{xx}$




$$Q^{\rm in}_{\perp x} + Q^{\rm ref}_{\perp x} \neq Q^{\rm tr}_{\perp x}$$

**transverse spin current**

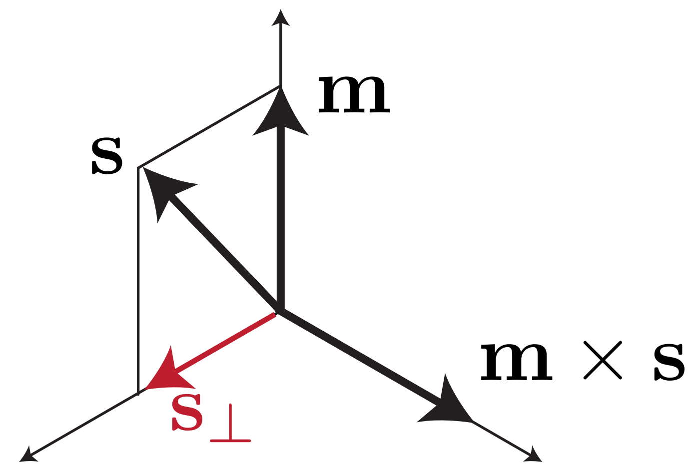
- From conservation of spin angular momentum, argue that **missing transverse spin current is transferred to ferromagnet *M***

$$\left[\frac{\partial \mathbf{m}}{\partial t}\right]_{\rm STT} \propto \mathbf{s}_\perp$$

# Spin-transfer torques

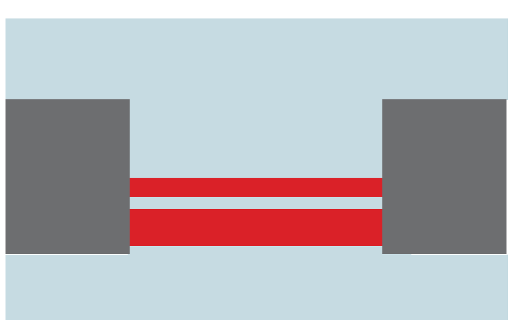
- Express transverse spin component in terms of vector products

$$\mathbf{s}_{\perp} \propto (\mathbf{m} \times \mathbf{s}) \times \mathbf{m}$$

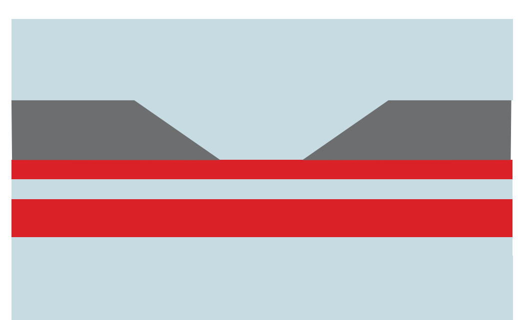



$$\left[\frac{\partial \mathbf{m}}{\partial t}\right]_{\mathrm{STT}} \propto (\mathbf{m} \times \mathbf{s}) \times \mathbf{m}$$

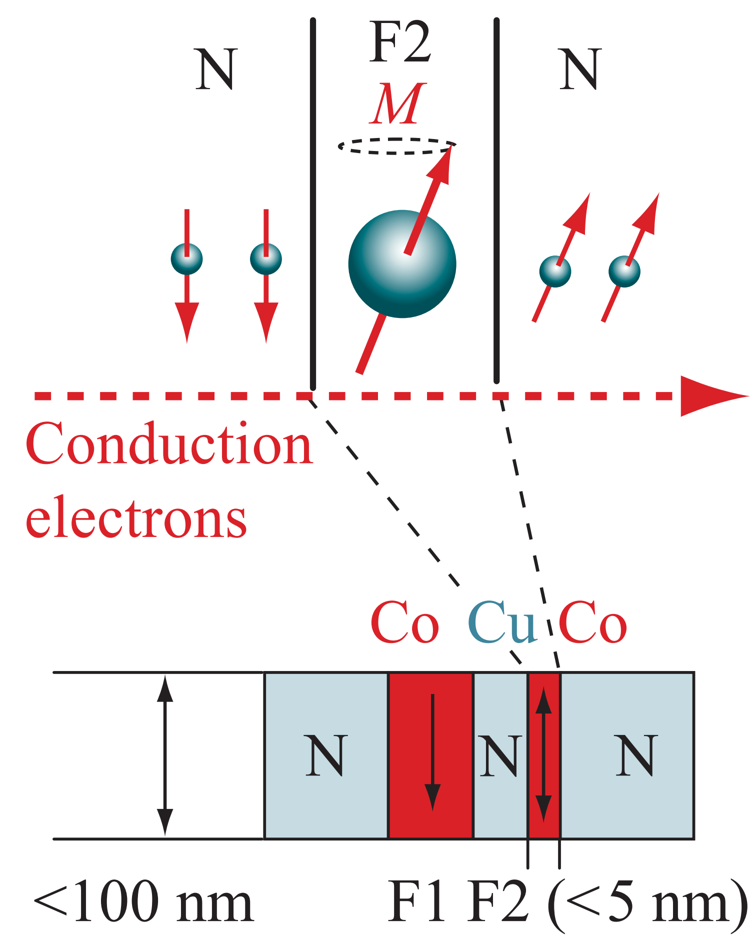
- Typical realisations involve the CPP geometry where ***s*** is related to the magnetisation of a second (reference) layer



**Nanopillars**



**Nanocontacts**

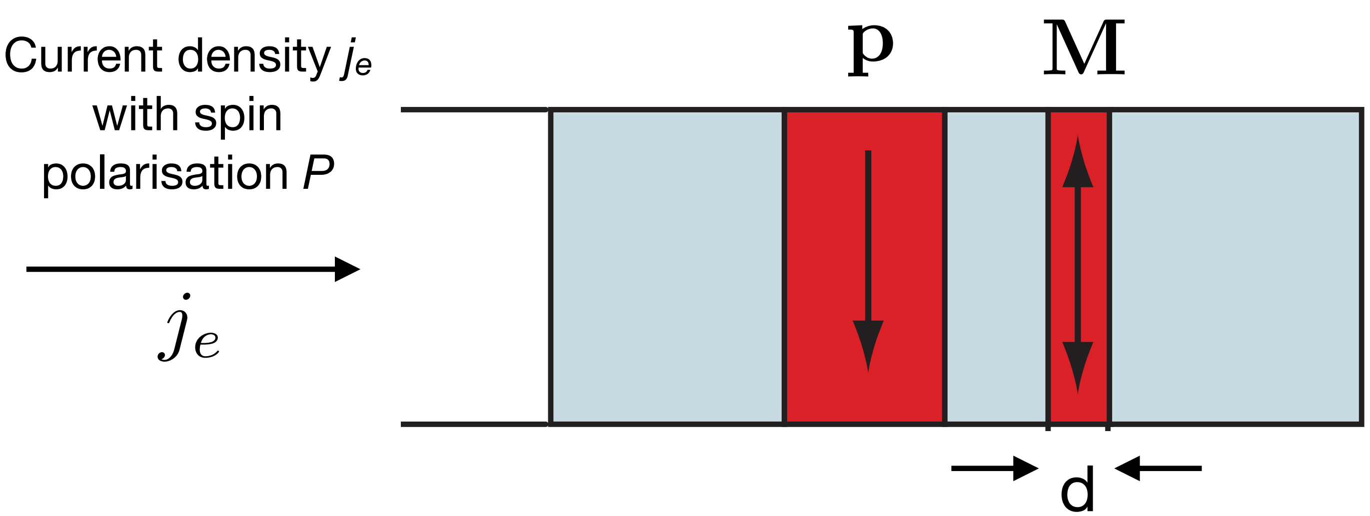


# Slonczewski model of CPP torques

- Accounting for transport properties, obtain Slonczewski term for spin-transfer torques

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma_0 \mathbf{M} \times \mathbf{H}_{\text{eff}} + \frac{\alpha}{M_s} \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t} + \boxed{\sigma j_e \mathbf{M} \times (\mathbf{p} \times \mathbf{M})}$$

Precession — Damping — Spin-transfer torque (Slonczewski)




$$\sigma = \frac{g\mu_B}{2e} \frac{1}{M_s^2 d} P$$

efficiency factor

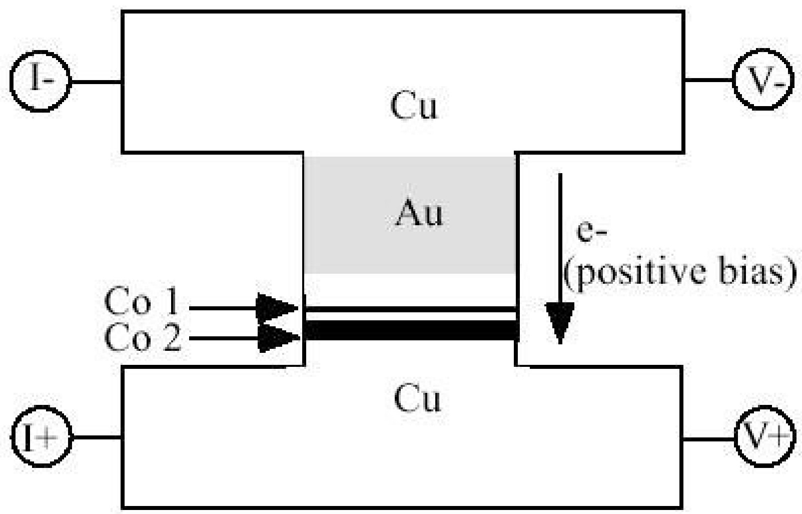
- Current density matters, not currents. We did not observe STT before the advent of *nanofabrication*
- Need typical densities of **$10^{12}$ A/m²** : 1 mA for 1000 nm², 1 000 000 A for 1 mm²

J C Slonczewski, *J Magn Magn Mater* **159**, L1 (1996)

# Consequences on precessional dynamics

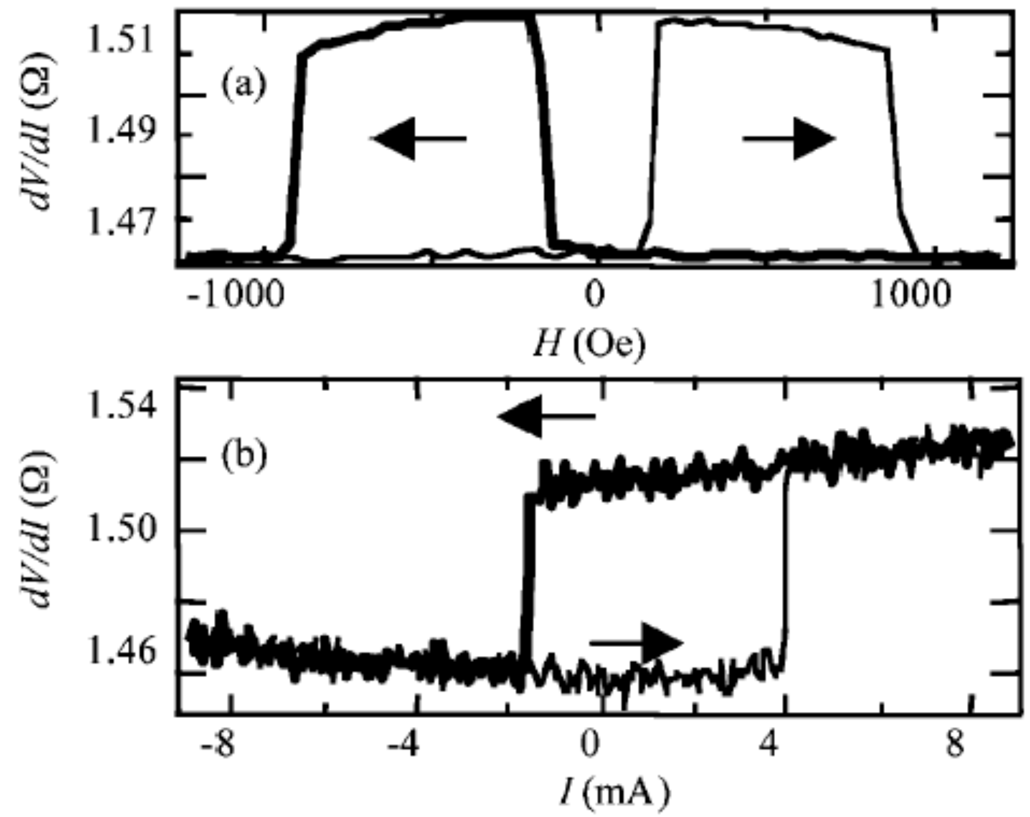
- Spin-transfer torques can reverse magnetisation reversal without magnetic fields

F J Albert et al, *Phys Rev Lett* **89**, 226802 (2002)



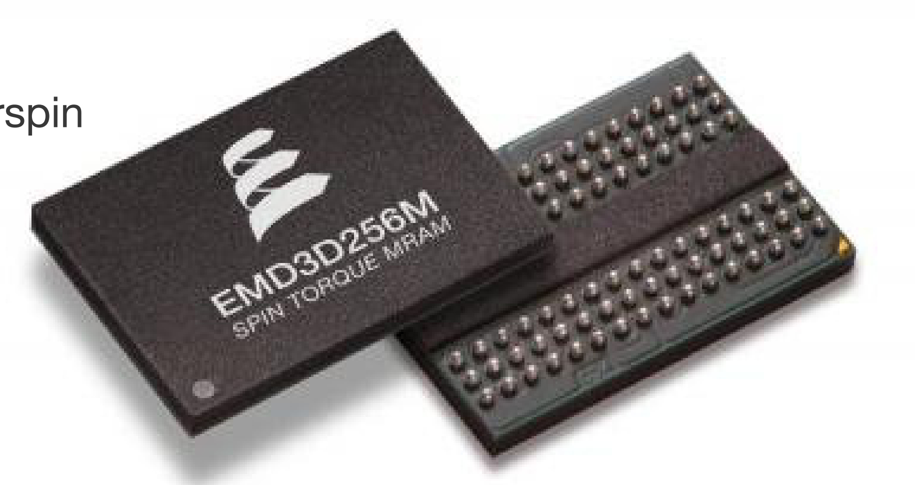

**Nanopillar structure**

Cross-section 60 ×180 nm$^2$




- Basis of spin-torque magnetic random access memories STT-(M)RAM

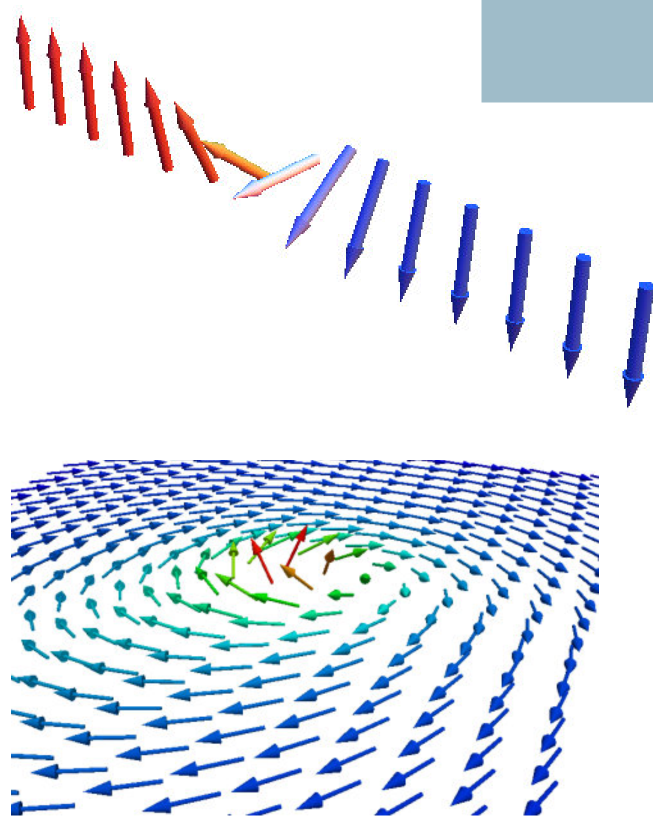
Everspin



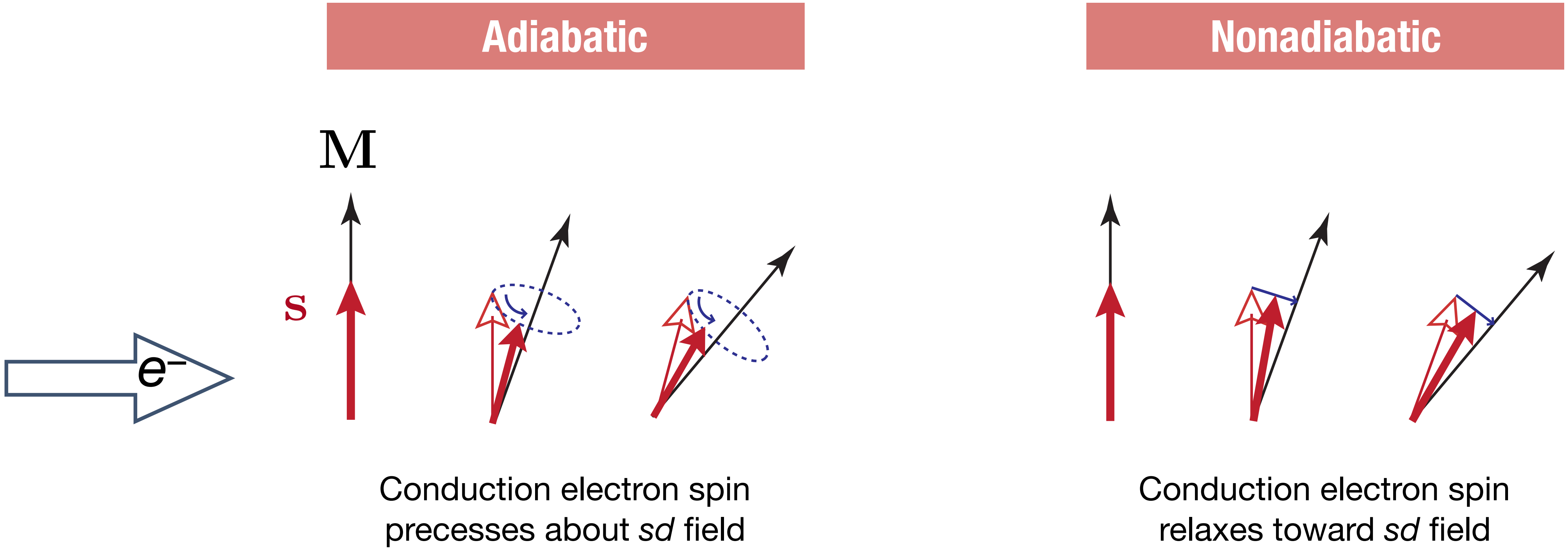


Samsung
28nm pMTJ
STT-RAM

# Current-in-plane (CIP) torques



- Spin-transfer torques also occur in continuous systems in which there are *gradients* in the magnetisation
- Important for micromagnetic states like domain walls, vortices
- Torques are governed by how well the conduction electron spin tracks the local magnetisation
- Like CPP case, spin transfer involves the **absorption of transverse component of spin current**



# Zhang-Li model of CIP torques

S Zhang & Z Li
*Phys Rev Lett* **93**, 127204 (2004)

- In the drift-diffusion limit (not detailed here), Zhang and Li derived

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma_0 \mathbf{M} \times \mathbf{H}_{\mathrm{eff}} + \frac{\alpha}{M_s} \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t} + \mathbf{T}_{\mathrm{CIP}}$$

$$\mathbf{T}_{\mathrm{CIP}} = -\frac{b_J}{\mu_0 M_s^2} \mathbf{M} \times \left[\mathbf{M} \times \left(\mathbf{j}_e \cdot \nabla\right) \mathbf{M}\right] - \frac{c_J}{\mu_0 M_s} \mathbf{M} \times \left(\mathbf{j}_e \cdot \nabla\right) \mathbf{M}$$

**adiabatic** **nonadiabatic**

$$b_J = \frac{P \mu_B}{e M_s (1 + \xi^2)} \qquad c_J = \frac{P \mu_B \xi}{e M_s (1 + \xi^2)}$$

P: spin polarisation

- In this model, nonadiabaticity is a ratio between sd-exchange and spin flip time scales

$$\xi = \frac{\tau_{ex}}{\tau_{sf}} \qquad \tau_{sf} \sim 10^{-12}\ \mathrm{s} \qquad \tau_{ex} \sim 10^{-15}\ \mathrm{s}$$

- Many other theories have been proposed to describe this parameter

# Re-interpreting Zhang-Li

A Thiaville et al, *Europhys Lett* **69**, 990 (2005)

- By recognising that the pre-factors in the CIP torques and the current density $\mathbf{j}_e$ can be expressed in terms of an effective spin-drift velocity **u**

$$\mathbf{u} = P\frac{g\mu_B}{2e}\frac{1}{M_s}\mathbf{j}_e = P\frac{\hbar}{2e}\frac{1}{M_s}\mathbf{j}_e \qquad [\mathbf{u}] = \mathrm{m/s}$$

the equations of motion for the magnetisation **M** can be written as

$$\frac{d\mathbf{M}}{dt} = \underbrace{-\gamma_0 \mathbf{M}\times\mathbf{H}_{\mathrm{eff}}}_{\text{precession}} + \underbrace{\frac{\alpha}{M_s}\mathbf{M}\times\frac{d\mathbf{M}}{dt}}_{\text{damping}} \underbrace{- (\mathbf{u}\cdot\nabla)\,\mathbf{M}}_{\text{adiabatic}} + \underbrace{\frac{\beta}{M_s}\mathbf{M}\times[(\mathbf{u}\cdot\nabla)\,\mathbf{M}]}_{\text{nonadiabatic}}$$

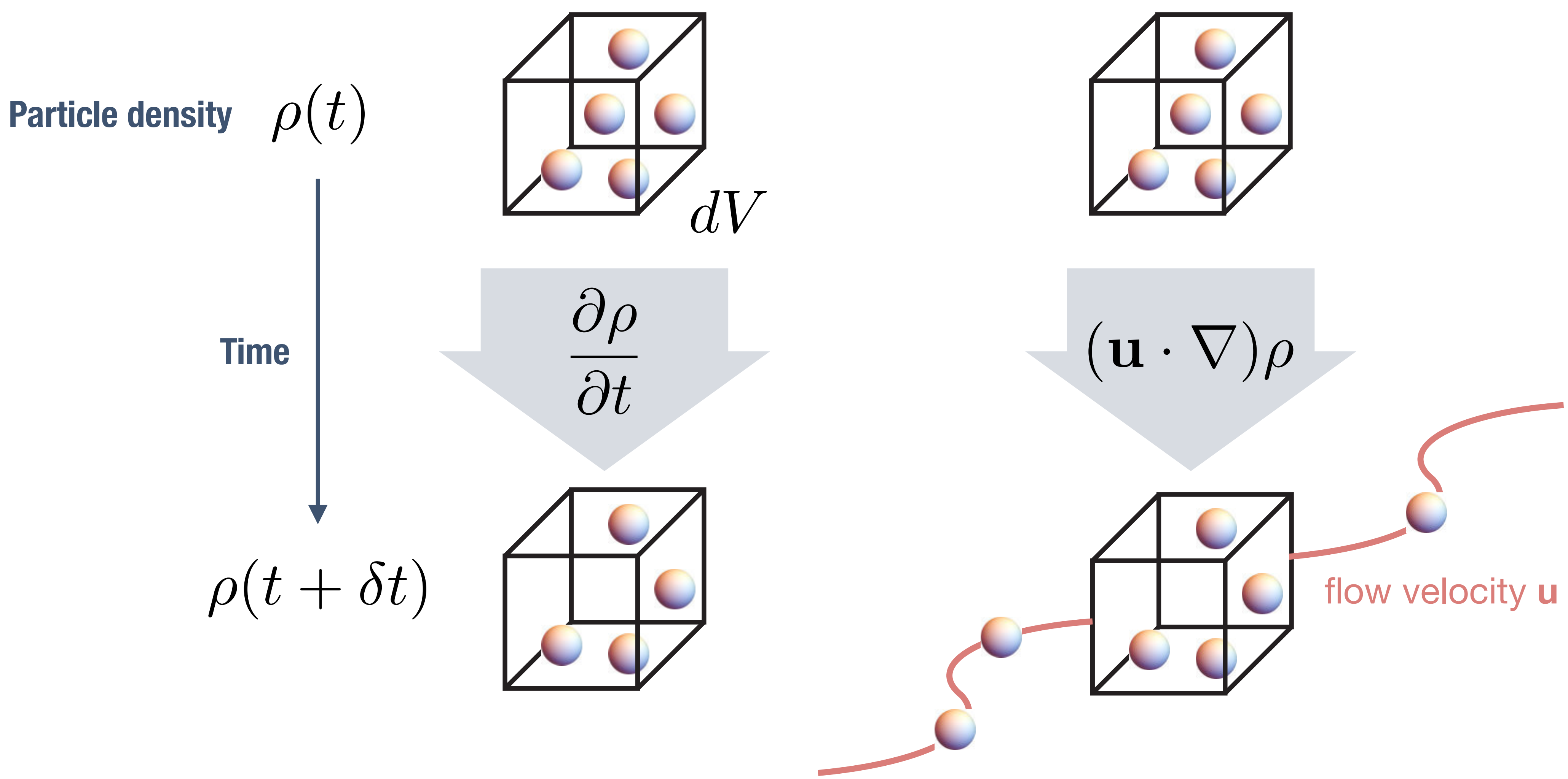
- Rearranging into a more suggestive form:

$$\underbrace{\left(\frac{\partial}{\partial t} + \mathbf{u}\cdot\nabla\right)}_{\text{Convective derivative}}\mathbf{M} = -\gamma_0\mathbf{M}\times\mathbf{H}_{\mathrm{eff}} + \frac{\alpha}{M_s}\mathbf{M}\times\left(\frac{\partial}{\partial t} + \frac{\beta}{\alpha}\mathbf{u}\cdot\nabla\right)\mathbf{M}$$

# Convective derivatives

- Consider time evolution of an element *dV* of a fluid
- Convective derivative *D* accounts for local variations and particle flow

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + (\mathbf{u} \cdot \nabla)$$



# Analogy with fluid dynamics?

$$\left(\frac{\partial}{\partial t} + \mathbf{u}\cdot\nabla\right)\mathbf{M} = -\gamma_0 \mathbf{M}\times\mathbf{H}_{\text{eff}} + \frac{\alpha}{M_s}\mathbf{M}\times\left(\frac{\partial}{\partial t} + \frac{\beta}{\alpha}\mathbf{u}\cdot\nabla\right)\mathbf{M}$$

- This form can *almost* be obtained by replacing the time derivative of the usual Landau-Lifshitz equation

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma_0 \mathbf{M}\times\mathbf{H}_{\text{eff}} + \frac{\alpha}{M_s}\mathbf{M}\times\frac{\partial \mathbf{M}}{\partial t}$$

with the *convective derivative*

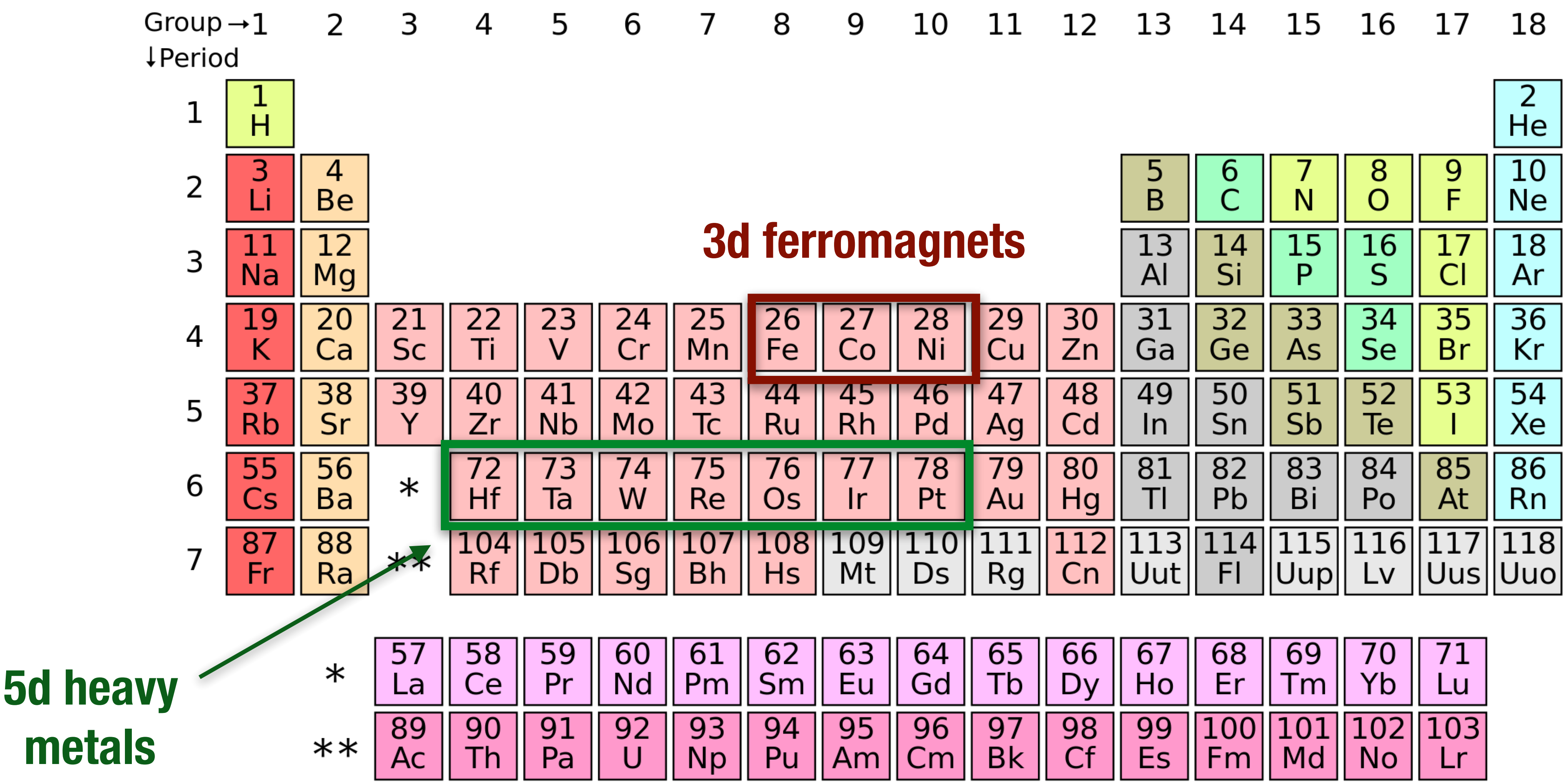
$$\frac{\partial}{\partial t} \to \left(\frac{\partial}{\partial t} + \mathbf{u}\cdot\nabla\right)$$

It almost works *except* for the *β/α* term. **u** therefore represents the average drift velocity of the magnetisation (under applied currents), which for ferromagnetic metals makes some sense.

- No consensus (theoretically and experimentally) over the ratio *β/α*, which can vary between 0.1 and 10

# Spin-orbit coupling

- In magnetic multilayered structures, metallic ferromagnets in contact with 5d transition metals (“heavy metals”) exhibit strong effects due to **spin-orbit coupling**

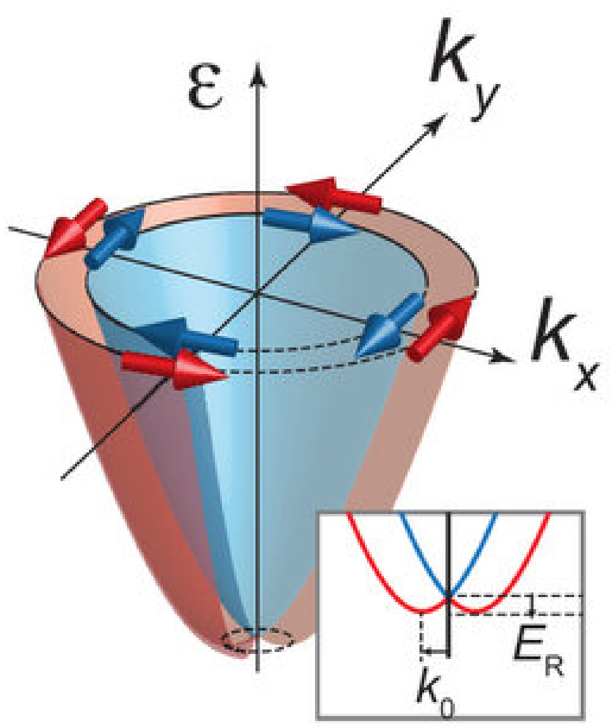



$$E_{\mathrm{SO}} \sim \mathbf{L} \cdot \mathbf{S}$$

# Spin-orbit coupling

- Examples:
  - Pt/**Co (0.4 - 1 nm)** /AlOx
  - Ta/**CoFeB (1 nm)**/MgO
  - Pt/[**Co (0.4 nm)/Ni (0.6 nm)**]$_n$
- Such multilayers are interesting for applications because they possess a strong anisotropy perpendicular to the film plane
- Such multilayers also lack *inversion symmetry*, which gives rise to a class of spin-orbit interactions seen in two-dimensional systems, e.g. *Rashba interaction*

**Wave vector dependent effective Rashba field**



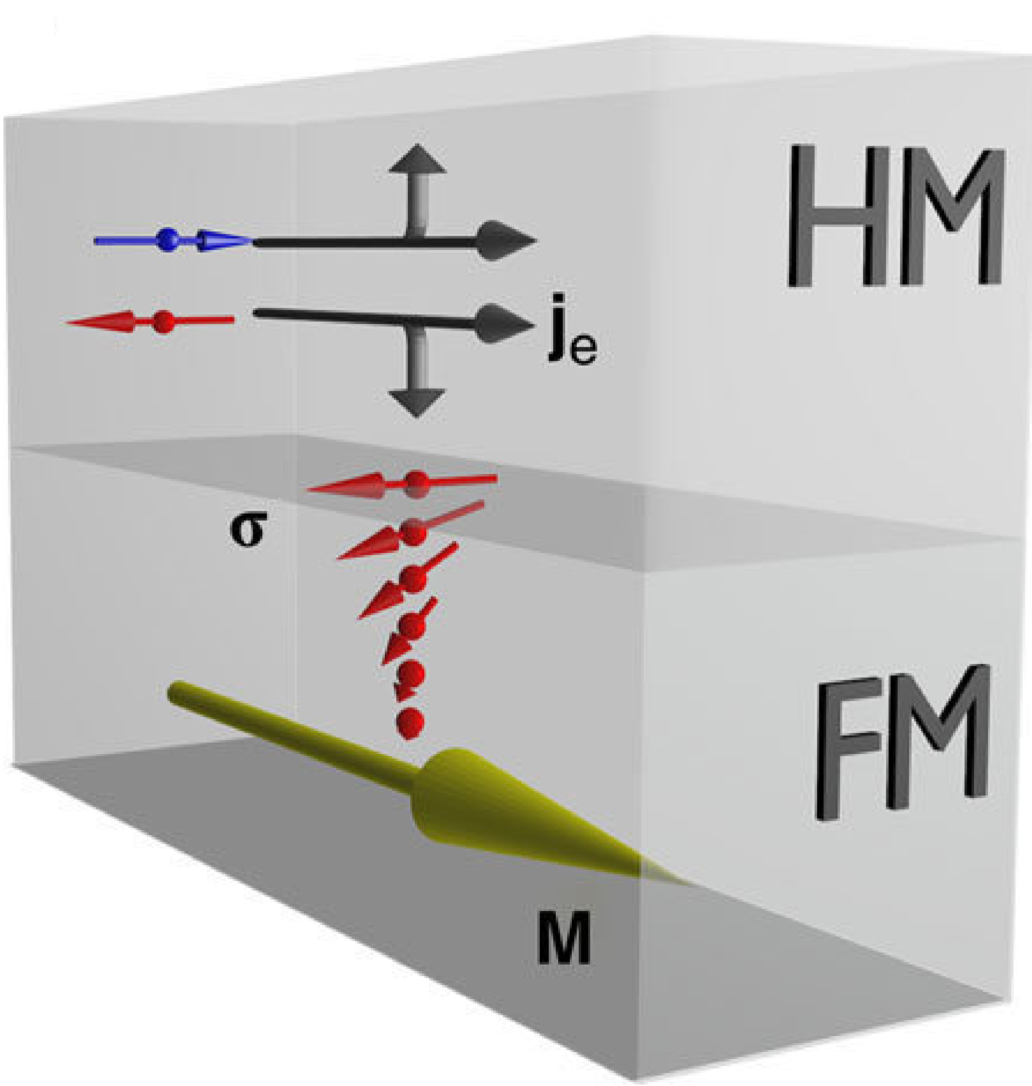

$$H_R = \alpha_R \left(\sigma \times \mathbf{p}\right) \cdot \hat{z}$$

**Rashba Hamiltonian**

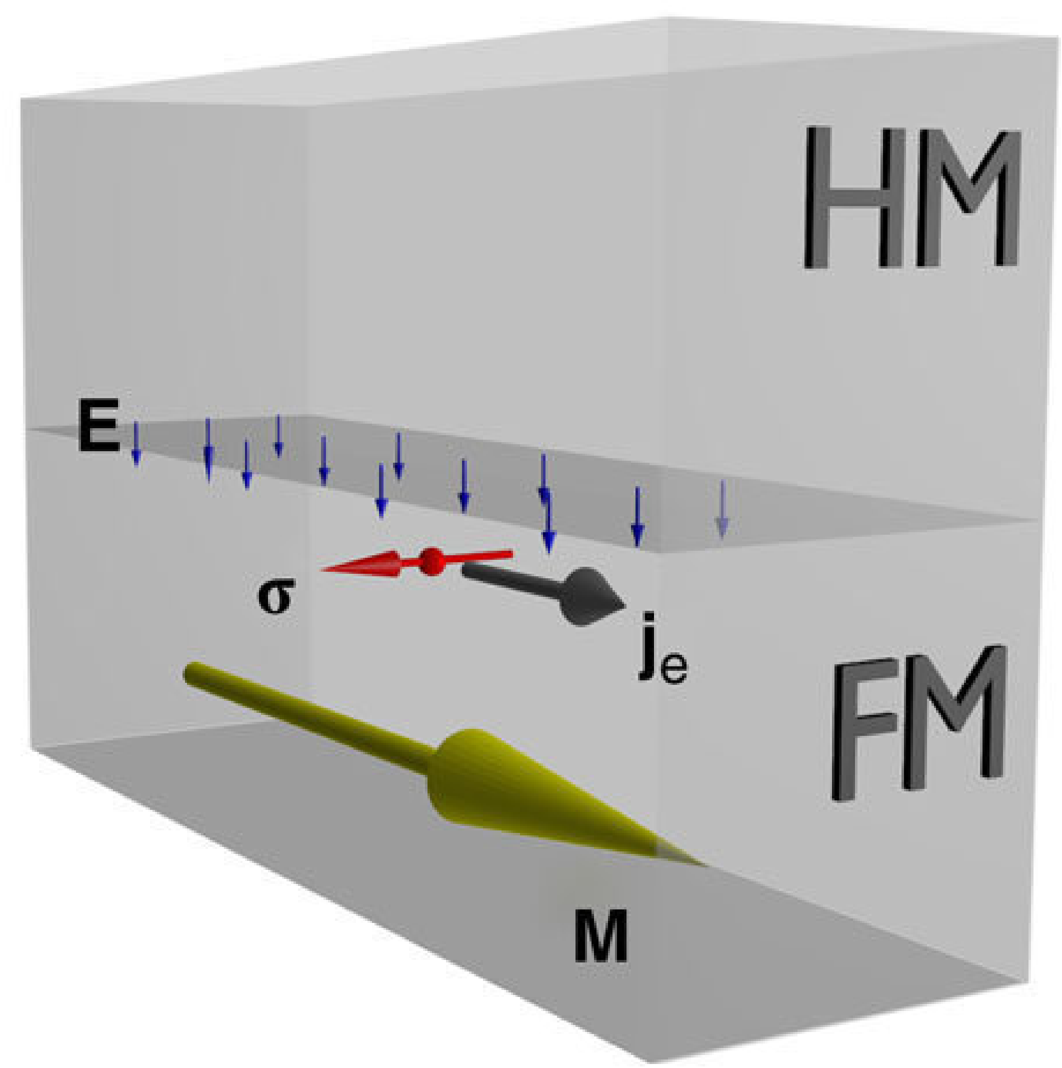
# Spin-orbit torques

- Such spin-orbit effects due to the heavy metal (HM) give rise to ***spin-orbit torques*** on the ferromagnet (FM)

**Spin Hall effect**

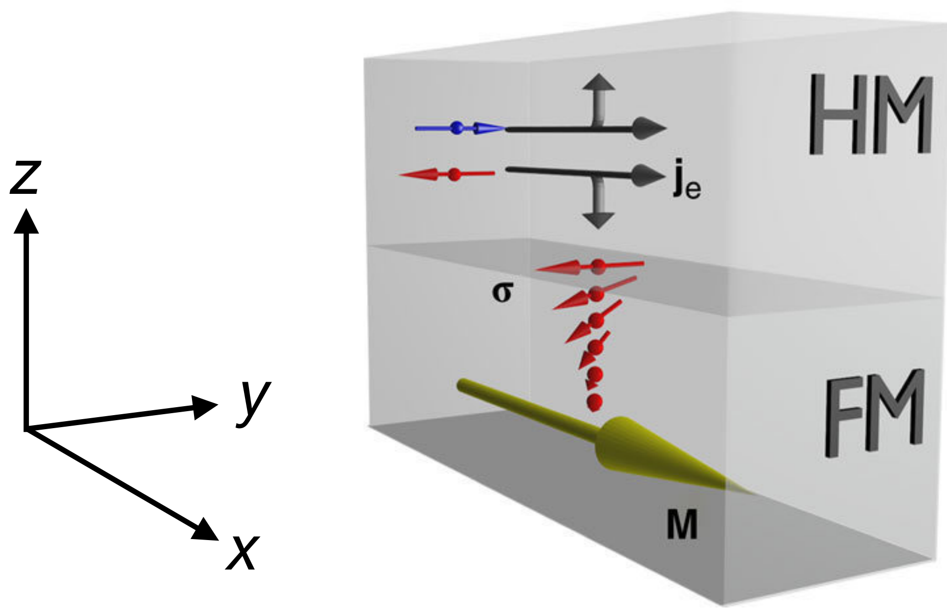



**Rashba torques**



# Spin-orbit torques

- Torques due to the spin Hall effect can be described using the Slonczewski form

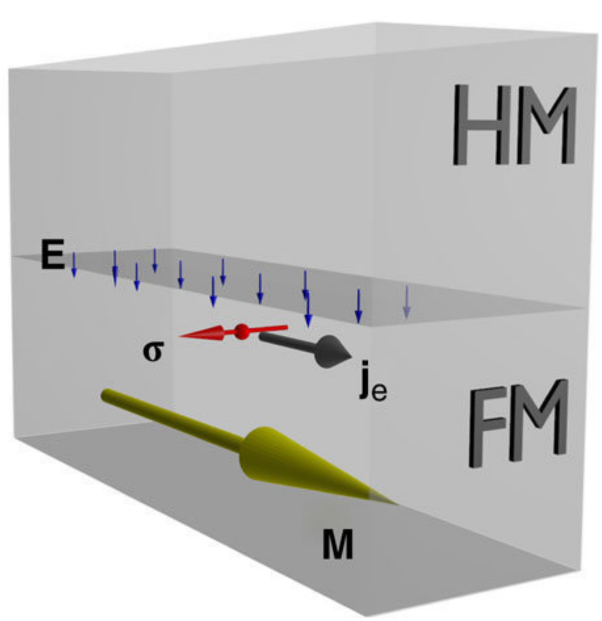



$$\mathbf{T}_{\mathrm{SH}} = \sigma_{\mathrm{SH}} j_e \, \mathbf{M} \times (\hat{\mathbf{y}} \times \mathbf{M})$$

$$\sigma_{\mathrm{SH}} = \frac{g\mu_B}{2e} \frac{1}{M_s^2 d} \theta_{\mathrm{SH}}$$

**efficiency** **spin Hall angle**

- Torques due to the Rashba effect can be assimilated to an effective field




$$\mathbf{T}_{\mathrm{R}} = -\gamma_0 \mathbf{M} \times (H_R \, \hat{\mathbf{y}})$$

# Spin-orbit torques with topological insulators?

- Another class of materials exhibiting strong spin-orbit coupling are topological insulators
- Unique materials in which bulk is insulating but surfaces have momentum-locked spin currents

LETTER

doi:10.1038/nature13534

## Spin-transfer torque generated by a topological insulator

A. R. Mellnik[1], J. S. Lee[2], A. Richardella[2], J. L. Grab[1], P. J. Mintun[1], M. H. Fischer[1,3], A. Vaezi[1], A. Manchon[4], E.-A. Kim[1], N. Samarth[2] & D. C. Ralph[1,5]

**Many open questions!**

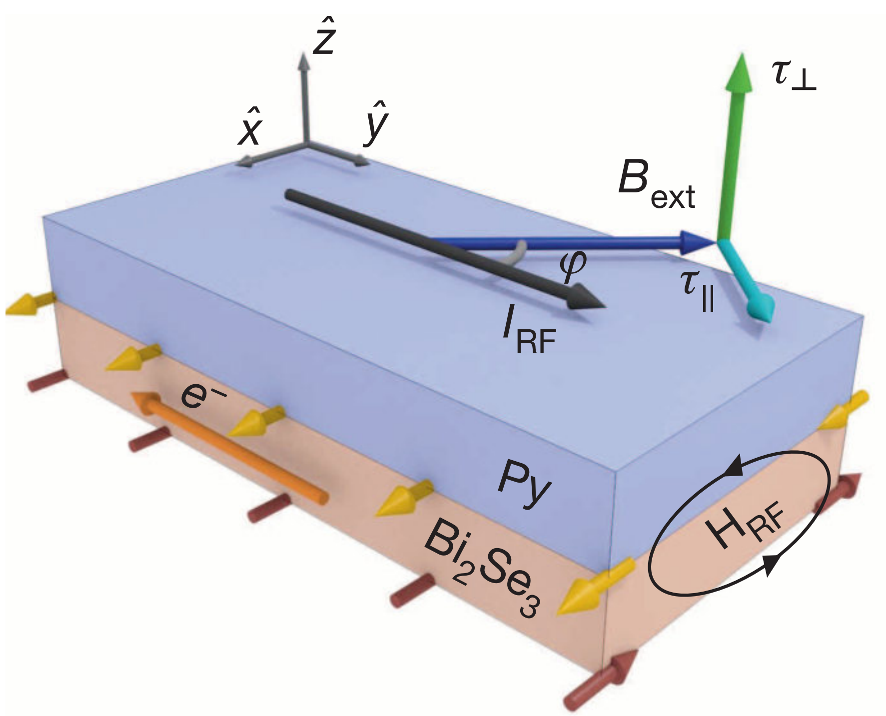



**Table 1 | Comparison of room-temperature $\sigma_{s,\parallel}$ and $\theta_{s,\parallel}$ for $Bi_2Se_3$ with other materials**

| Parameter | $Bi_2Se_3$ (this work) | Pt (ref. 4) | β-Ta (ref. 6) | Cu(Bi) (ref. 23) | β-W (ref. 24) |
|---|---|---|---|---|---|
| $\theta_\parallel$ | 2.0–3.5 | 0.08 | 0.15 | 0.24 | 0.3 |
| $\sigma_{S,\parallel}$ | 1.1–2.0 | 3.4 | 0.8 | — | 1.8 |

$\theta_\parallel$ is dimensionless and the units for $\sigma_{S,\parallel}$ are $10^5\hbar/2e\ \Omega^{-1}\ \mathrm{m}^{-1}$.

# Spin waves: Effects of CPP torques

- Q: How do spin torques influence spin waves?
  A: Depends very much on the spin polarisation vector *p*

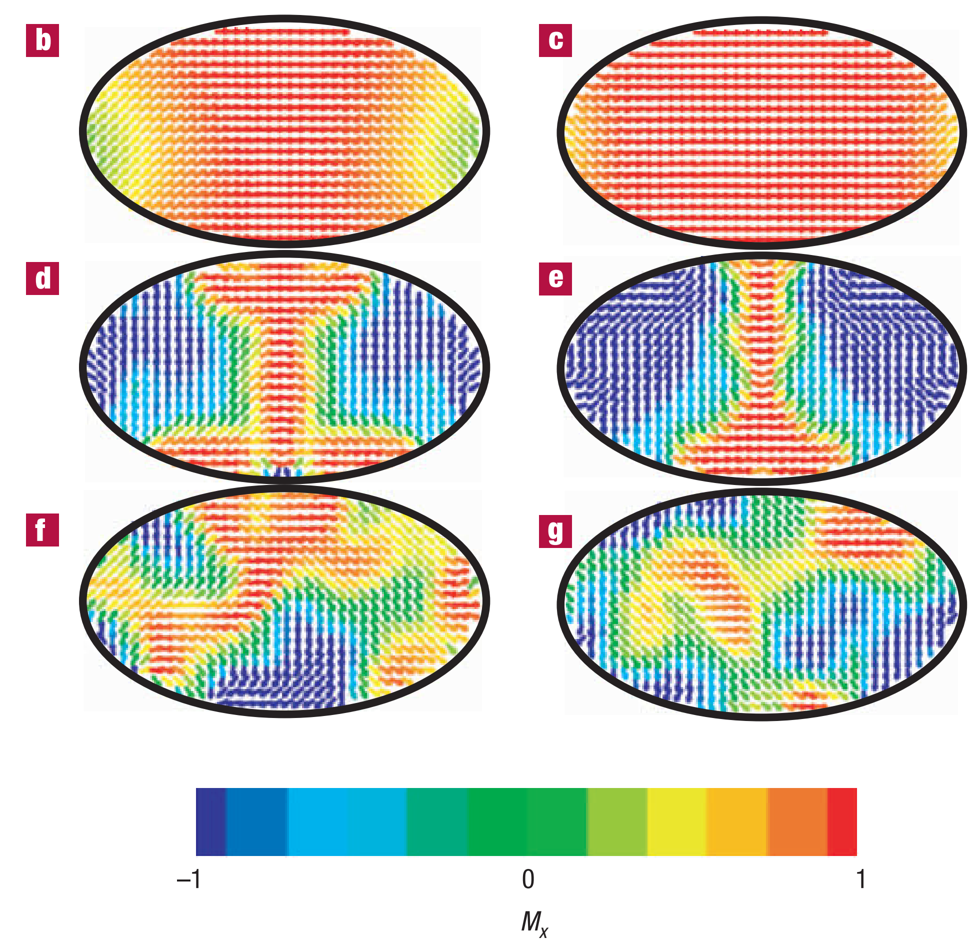
$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma_0 \mathbf{M} \times \mathbf{H}_{\mathrm{eff}} + \frac{\alpha}{M_s} \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t} + \sigma j_e \, \mathbf{M} \times (\mathbf{p} \times \mathbf{M})$$

- One possibility is the excitation of incoherent spin waves

LETTERS

## Excitations of incoherent spin-waves due to spin-transfer torque

KYUNG-JIN LEE[1,2*†], ALINA DEAC[1,2], OLIVIER REDON[1,2], JEAN-PIERRE NOZIÈRES[1] AND BERNARD DIENY[1]
[1]SPINTEC — Unité de Recherche Associée CEA/DSM & CNRS/SPM-STIC, CEA Grenoble, 38054 Grenoble, France
[2]CEA/DRT/LETI–CEA/GRE, 17 Rue des Martyrs, 38054 Grenoble, Cedex 9, France
*Permanent address: Storage Laboratory, Samsung Advanced Institute of Technology, Suwon, Korea
†e-mail: lee@drfmc.ceng.cea.fr




*Nat Mater* **3**, 877 (2004)

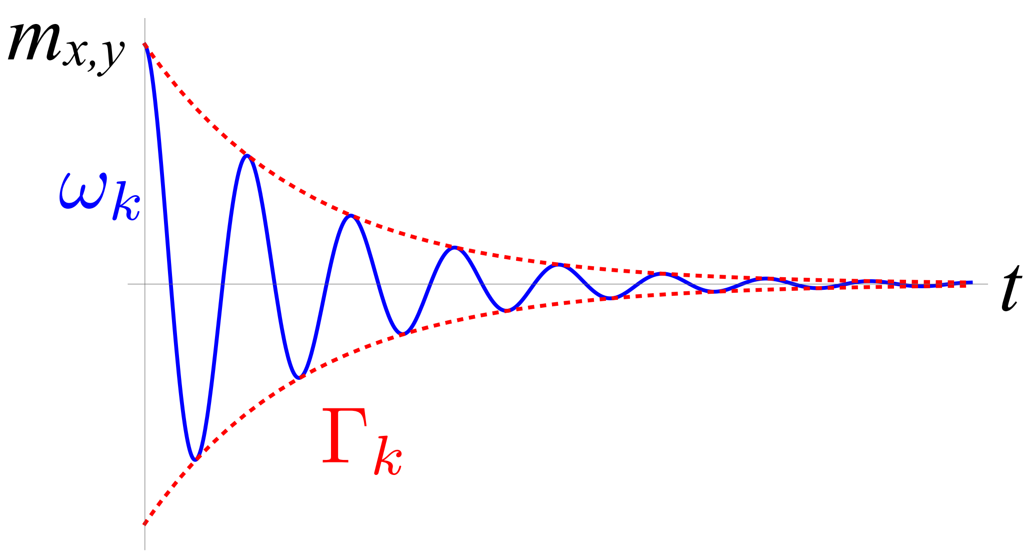
# Compensating relaxation processes

- Certain spin polarisation orientations can lead to self-sustained oscillations
- Consider alternate form of Landau-Lifshitz equation with spin torques:

$$\frac{d\mathbf{M}}{dt} = -\gamma_0 \mathbf{M} \times \mathbf{H}_{\mathrm{eff}} - \frac{\alpha\gamma_0}{M_s}\mathbf{M} \times (\mathbf{M} \times \mathbf{H}_{\mathrm{eff}}) + \sigma j_e \mathbf{M} \times (\mathbf{M} \times \mathbf{p})$$

**Precession** **Damping** **Spin torques**

- If ***p*** is collinear (on average) with $\boldsymbol{H}_{\mathrm{eff}}$, spin torques can either increase or decrease the damping depending on the sign of $j_e$



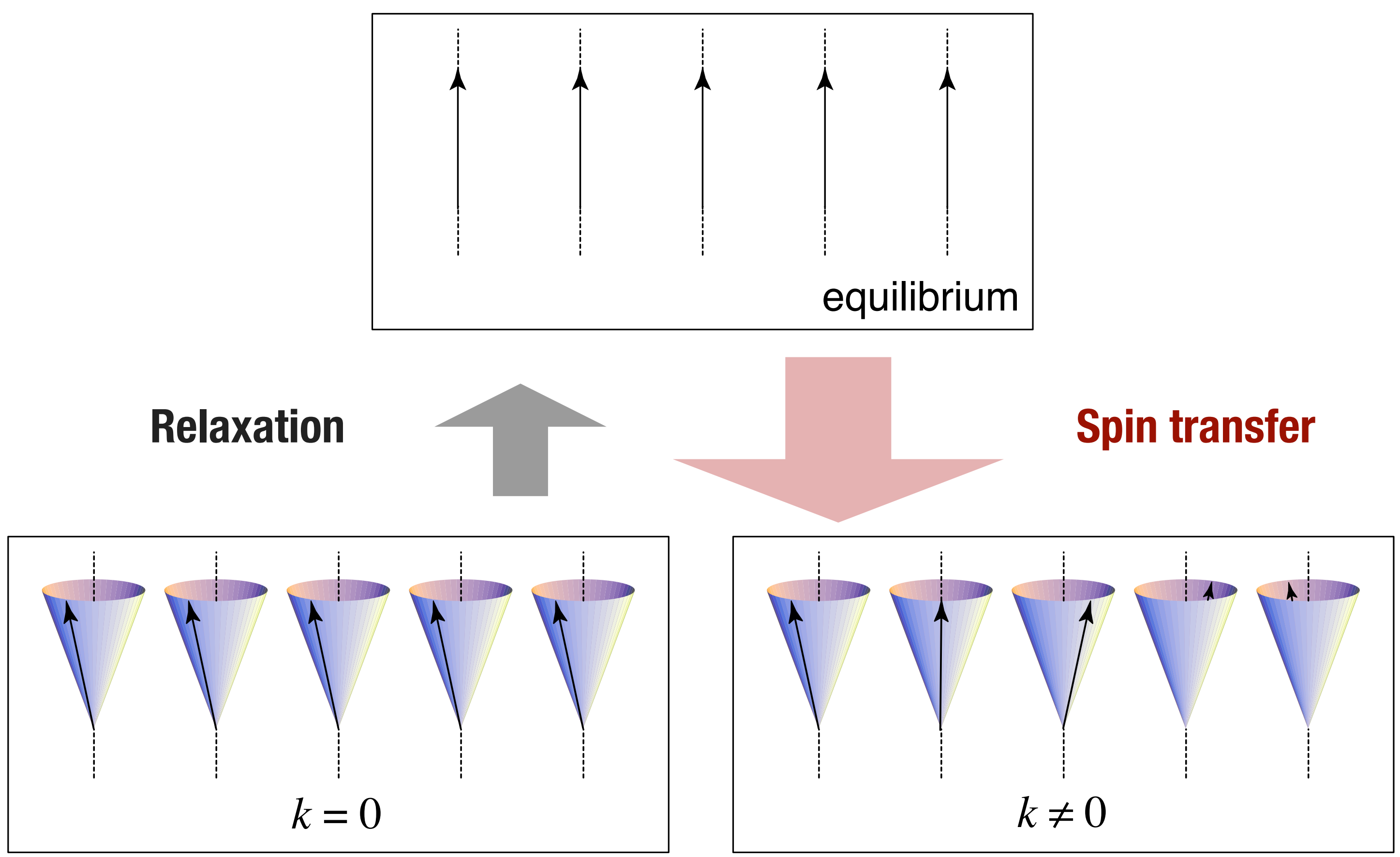

$$e^{-i(\omega_k - i\Gamma_k + i\sigma j_e)t}$$

# Compensating relaxation processes

- Certain spin polarisation orientations can lead to self-sustained oscillations
- Consider alternate form of Landau-Lifshitz equation with spin torques:

$$\frac{d\mathbf{M}}{dt} = \underbrace{-\gamma_0 \mathbf{M} \times \mathbf{H}_{\text{eff}}}_{\text{Precession}} \underbrace{- \frac{\alpha\gamma_0}{M_s} \mathbf{M} \times (\mathbf{M} \times \mathbf{H}_{\text{eff}})}_{\text{Damping}} \underbrace{+ \sigma j_e \mathbf{M} \times (\mathbf{M} \times \mathbf{p})}_{\text{Spin torques}}$$

- For sufficiently large currents, the spin torques can overcome the damping entirely

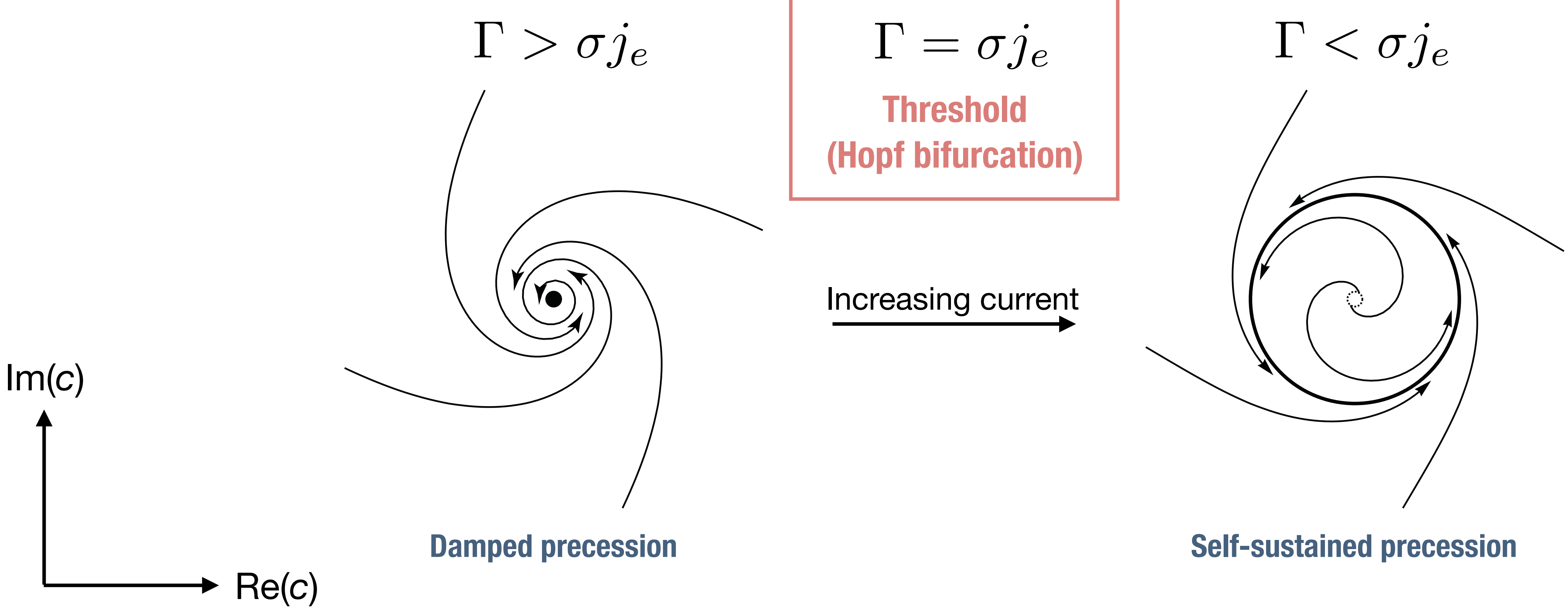


# Self-sustained oscillations

A N Slavin & P Kabos
*IEEE Trans Magn* **41**, 1264 (2005)

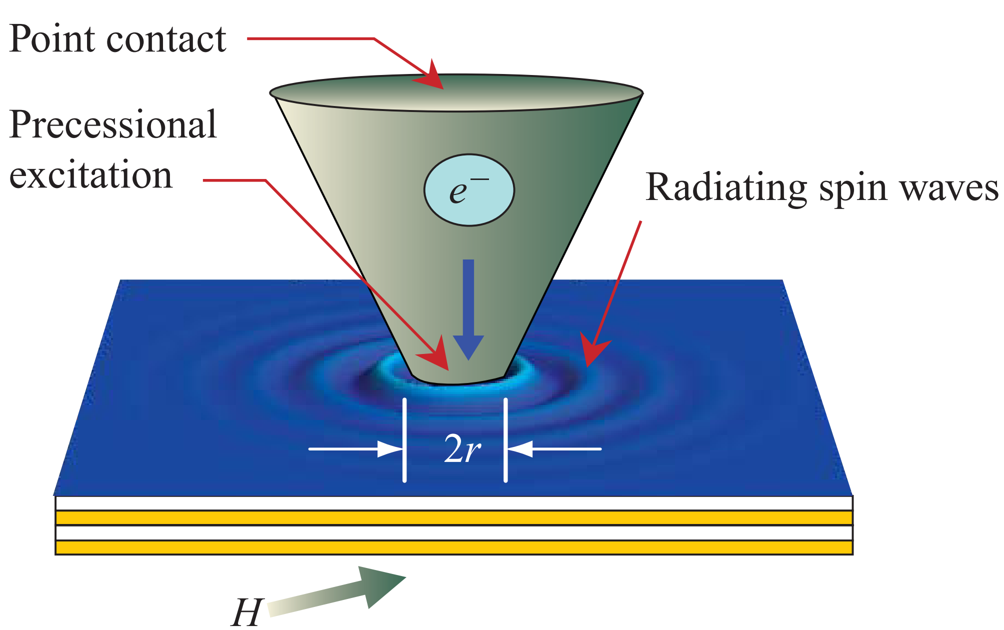
- From spin wave theory, we can derive an oscillator model with spin torque dynamics
- Let $c(t)$ represent a complex spin wave (oscillator) amplitude

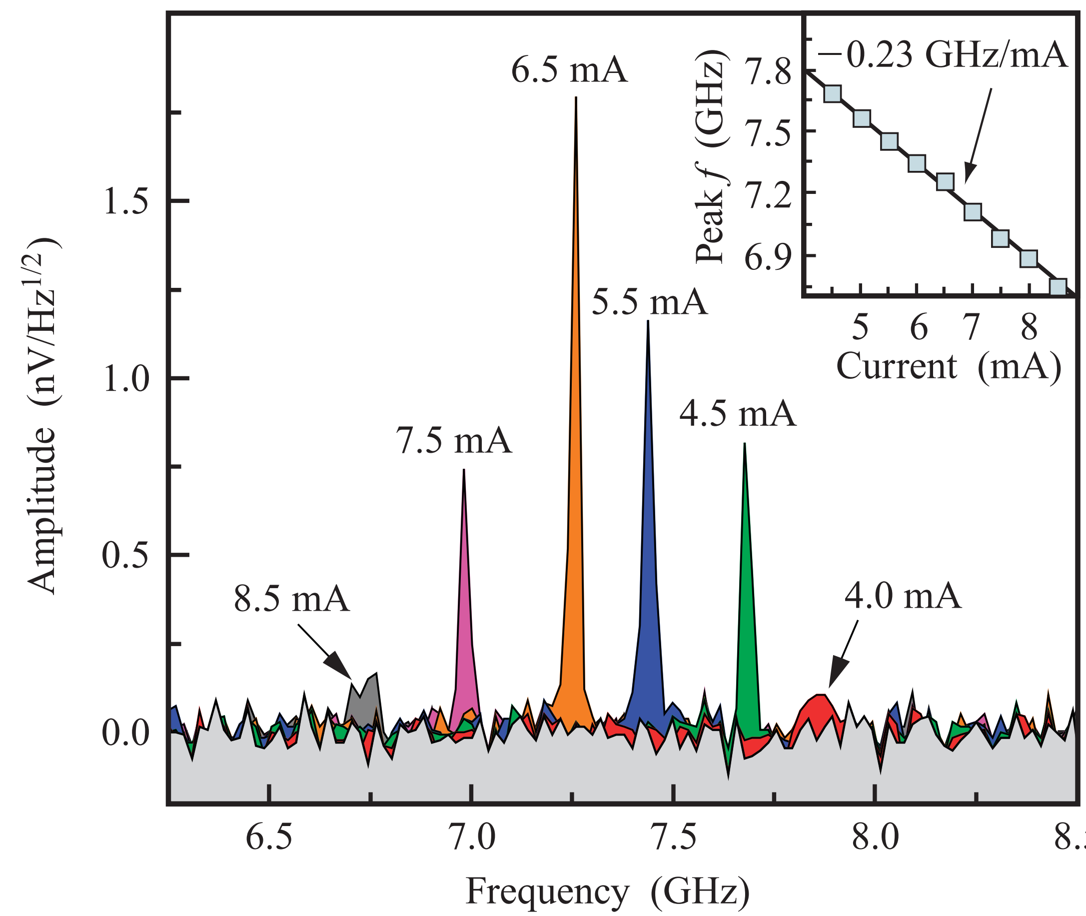
$$\frac{dc}{dt} = \underbrace{-i\omega c}_{\text{Precession}} \underbrace{- \Gamma c}_{\text{Damping}} + \underbrace{\sigma j_e (1 - |c|^2) c}_{\text{Spin torques}} \qquad c \simeq m_x + i m_y$$



# Spin-torque oscillators

- Self-sustained magnetisation oscillations observed in nanopillar and nanocontact geometries
- Oscillation frequencies are tunable with field and current




W H Rippard et al, *Phys Rev Lett* **92**, 027201 (2004)

# Spin waves: Effects of CIP torques

- In-plane currents can also lead to interesting effects involving spin waves
- Recall that spin torques due to CIP currents can be described by

$$\left(\frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla\right) \mathbf{M} = -\gamma_0 \mathbf{M} \times \mathbf{H}_{\text{eff}} + \frac{\alpha}{M_s} \mathbf{M} \times \left(\frac{\partial}{\partial t} + \frac{\beta}{\alpha} \mathbf{u} \cdot \nabla\right) \mathbf{M}$$

- From our plane wave solution for spin waves,

$$m_{x,y}(\vec{r}, t) = m_{x0,y0} \, e^{i\left(\vec{k}\cdot\vec{r} - \omega t\right)}$$

we can immediately deduce the effect of CIP spin torques on the spin wave frequency,

$$\omega + \mathbf{u} \cdot \mathbf{k} = \omega_k \qquad\qquad \omega = \omega_k - \mathbf{u} \cdot \mathbf{k}$$

- The CIP torques appear as a *Doppler shift* in the spin wave frequency

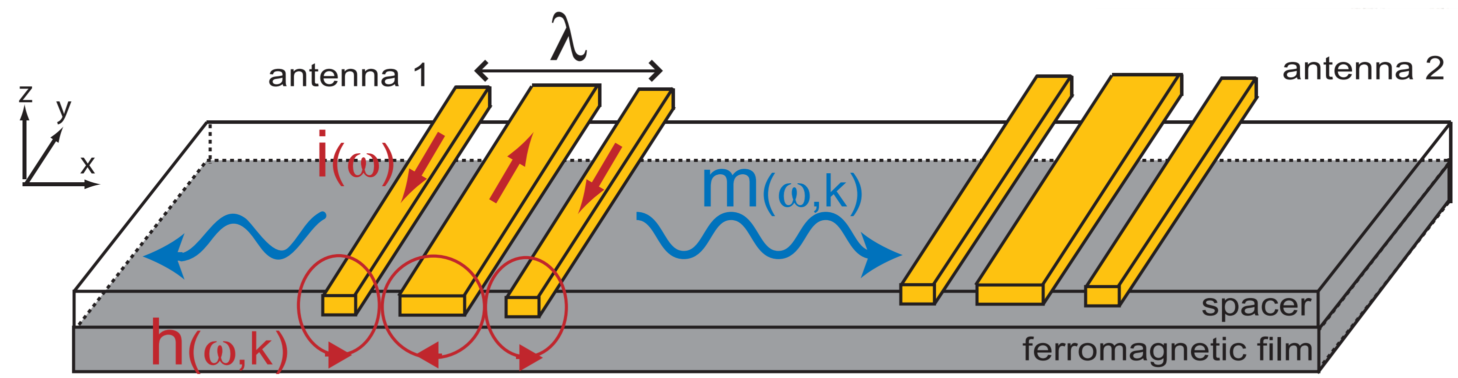
REPORTS

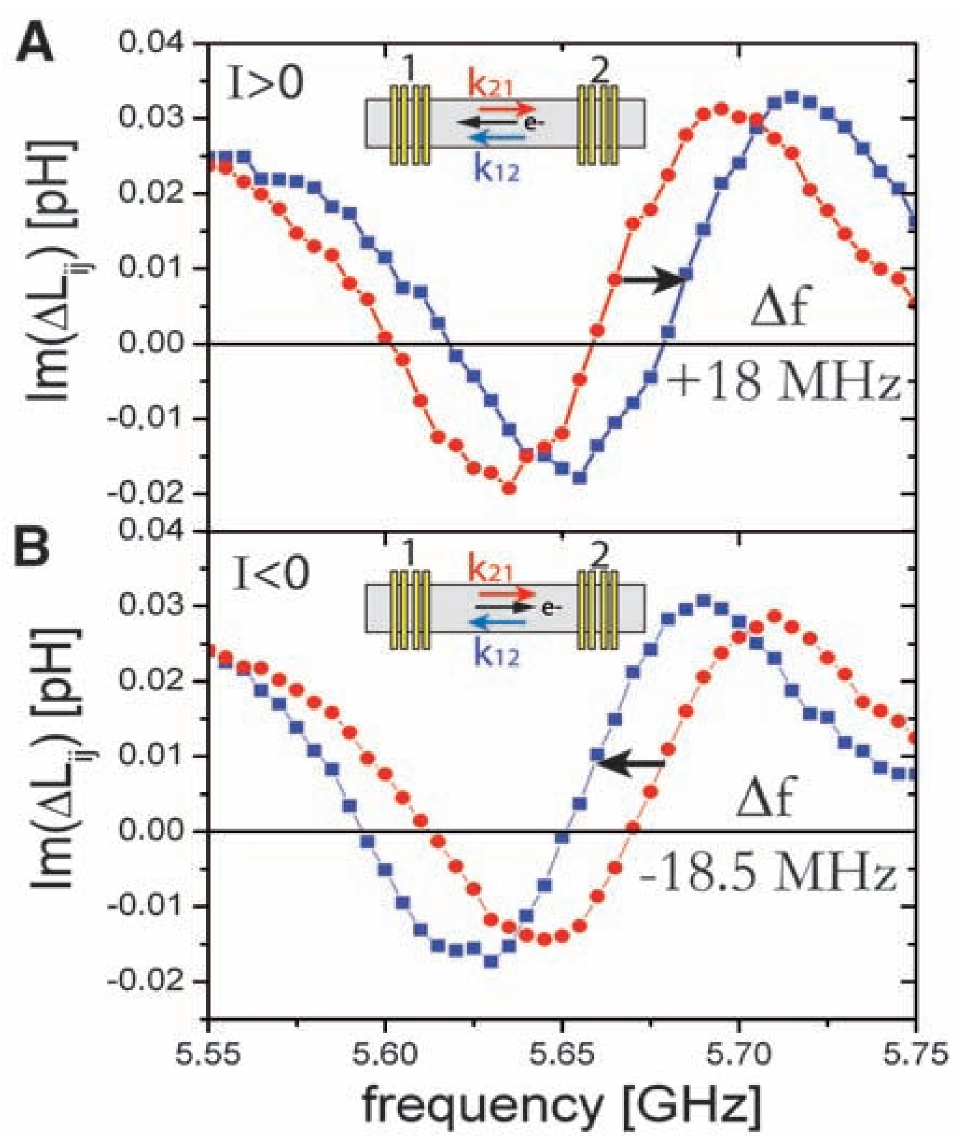
*Science* **332**, 410 (2008)

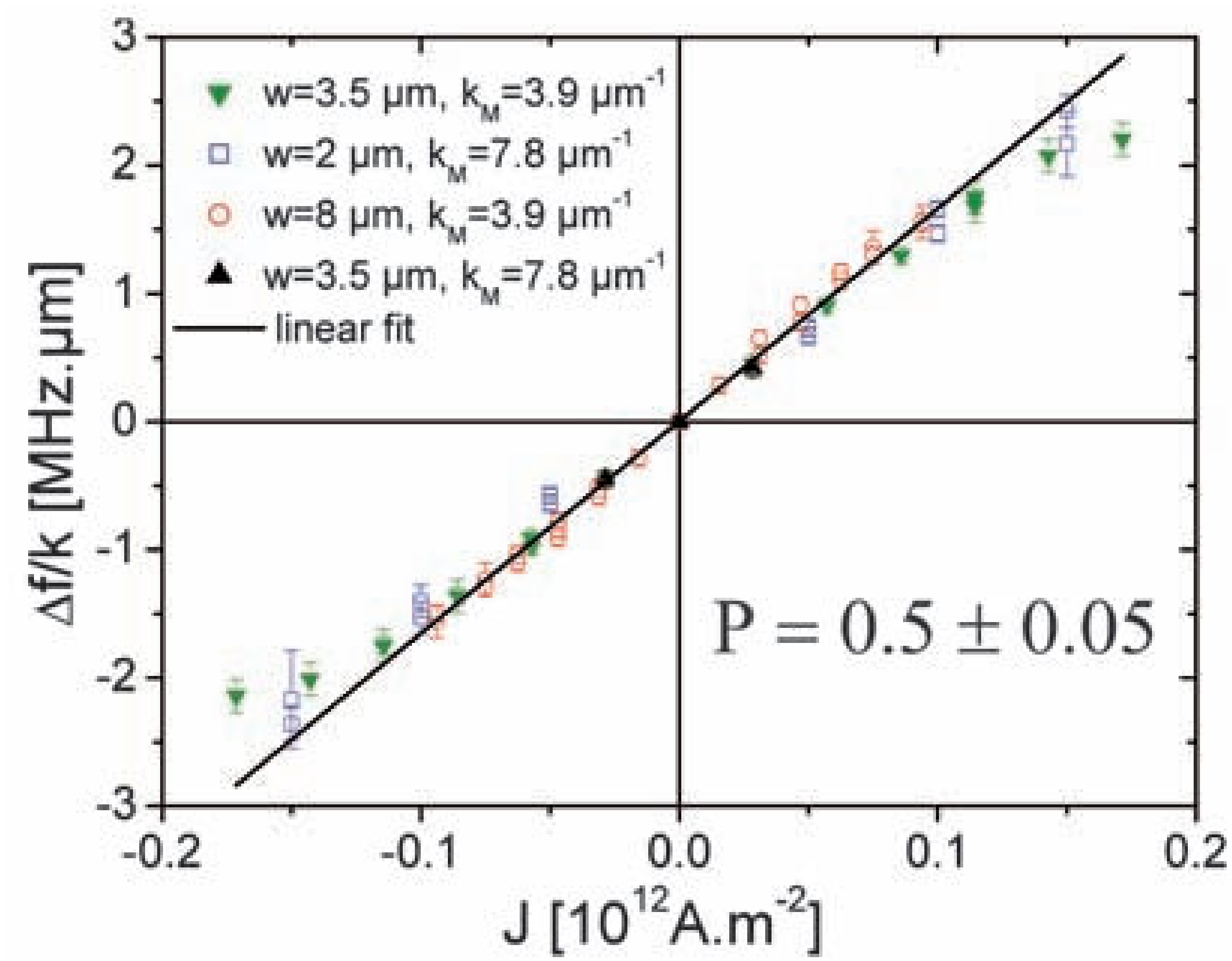
# Current-Induced Spin-Wave Doppler Shift

Vincent Vlaminck and Matthieu Bailleul

$$\omega = \omega_k - \mathbf{u} \cdot \mathbf{k}$$



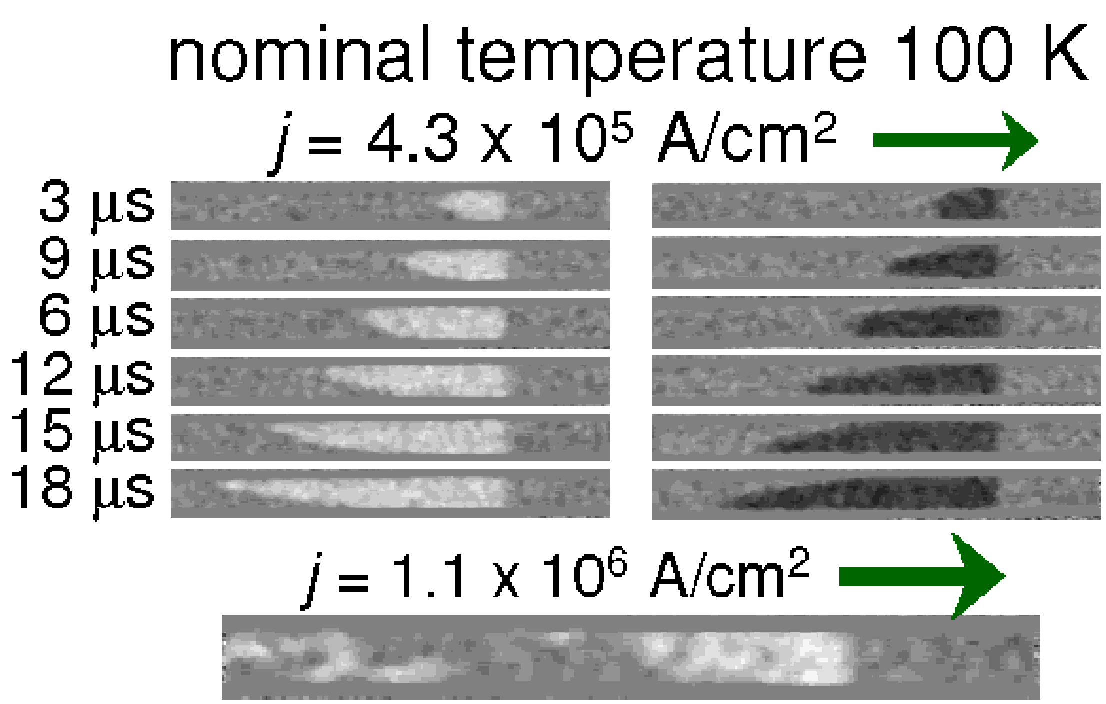



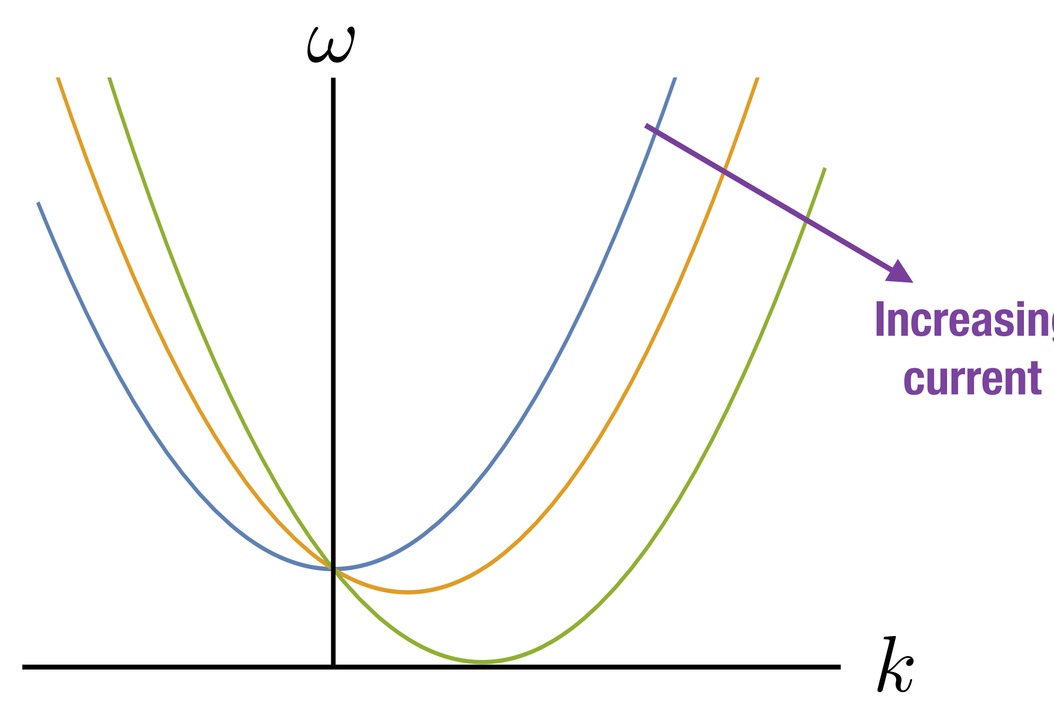
# Current-induced spin wave instabilities

- The current-induced Doppler effect leads to a frequency shift that is linear in the wave vector

$$\omega = \omega_k - \mathbf{u} \cdot \mathbf{k} \qquad\qquad \mathbf{u} = P\frac{g\mu_B}{2e}\frac{1}{M_s}\mathbf{j}_e = P\frac{\hbar}{2e}\frac{1}{M_s}\mathbf{j}_e$$

- For sufficiently large currents, the mode frequency can decrease to zero. At this point, the ferromagnetic state becomes **unstable** (*why?*)




M Yamanouchi et al, *Phys Rev Lett* **96**, 096601 (2006)

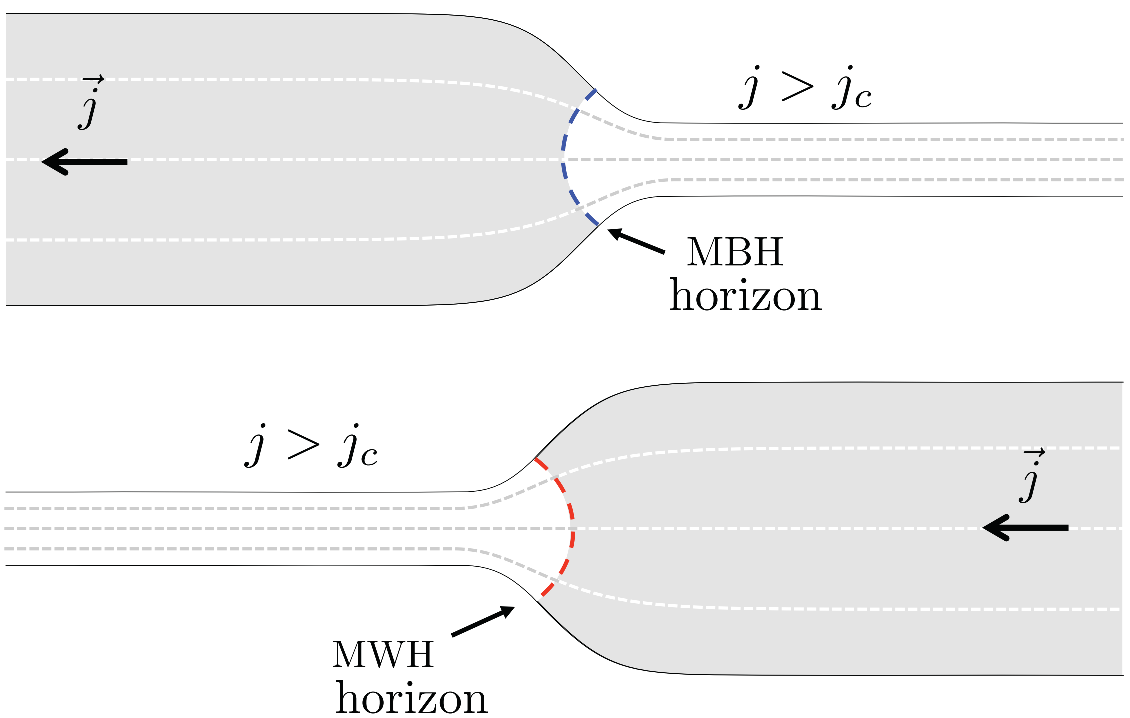
PRL **118,** 061301 (2017) PHYSICAL REVIEW LETTERS week ending 10 FEBRUARY 2017

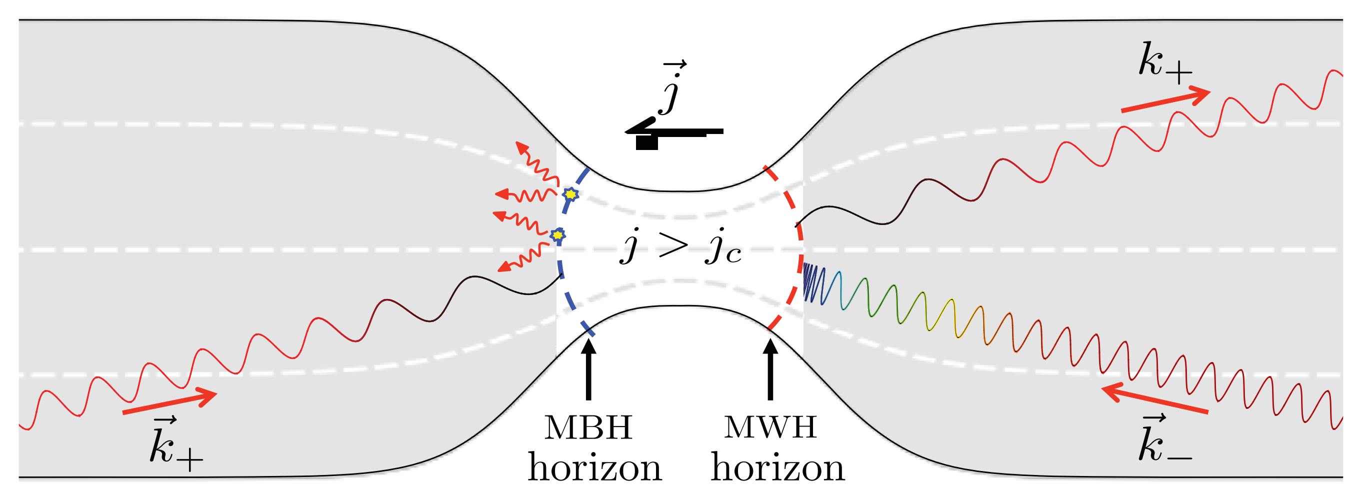
# Magnonic Black Holes

$$\omega = \omega_k - \mathbf{u} \cdot \mathbf{k}$$

A. Roldán-Molina,[1,2] Alvaro S. Nunez,[2] and R. A. Duine[3,4]
[1]*Centro para el Desarrollo de la Nanociencia y la Nanotecnología, CEDENNA, Avenida Ecuador 3493, Santiago 9170124, Chile*
[2]*Departamento de Física, Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile, Casilla 487-3, Santiago, Chile*
[3]*Institute for Theoretical Physics, Utrecht University, Leuvenlaan 4, 3584 CE Utrecht, Netherlands*
[4]*Department of Applied Physics, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, Netherlands*
(Received 19 October 2016; published 8 February 2017)

We show that the interaction between the spin-polarized current and the magnetization dynamics can be used to implement black-hole and white-hole horizons for magnons—the quanta of oscillations in the magnetization direction in magnets. We consider three different systems: easy-plane ferromagnetic metals, isotropic antiferromagnetic metals, and easy-plane magnetic insulators. Based on available experimental data, we estimate that the Hawking temperature can be as large as 1 K. We comment on the implications of magnonic horizons for spin-wave scattering and transport experiments, and for magnon entanglement.




Spatial gradients in current densities result in different Doppler shifts

# CIP torques for domain walls, vortices …

- In MP2, we saw that soliton dynamics can be described with method of collective coordinates
- CIP torques can be included in Lagrangian and dissipation function using convective derivative analogy

$$\mathcal{L}_B = \frac{M_s}{\gamma}\frac{\partial \phi}{\partial t}(1-\cos\theta) \rightarrow \frac{M_s}{\gamma}\left(\frac{\partial \phi}{\partial t} + \mathbf{u}\cdot\nabla\right)(1-\cos\theta)$$

Berry phase term

adiabatic torques

$$\mathcal{F} = \frac{\alpha M_s}{2\gamma}\left[\left(\frac{\partial \theta}{\partial t}\right)^2 + \sin^2\theta\left(\frac{\partial \phi}{\partial t}\right)^2\right]$$

Dissipation function

$$\left(\frac{\partial \theta}{\partial t}\right)^2 \rightarrow \left[\left(\frac{\partial}{\partial t} + \frac{\beta}{\alpha}\mathbf{u}\cdot\nabla\right)\theta\right]^2$$

etc

nonadiabatic torques

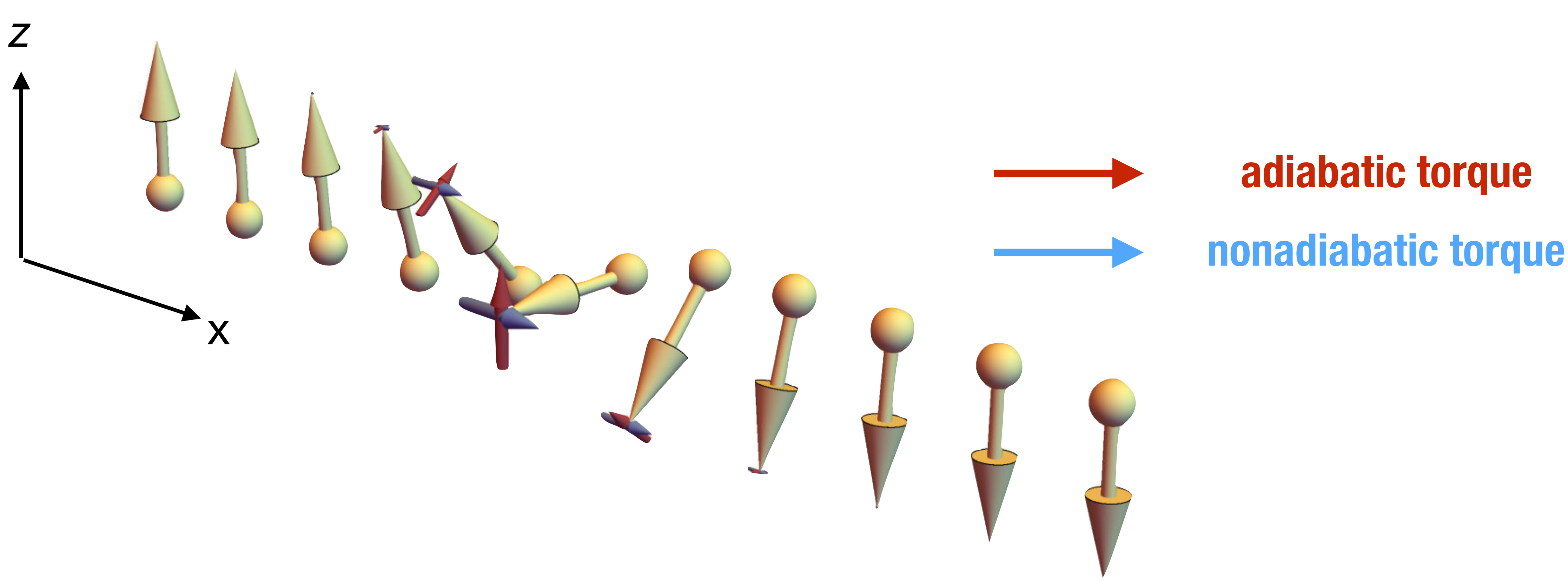
# Domain walls: CIP torques

- Similar equations of motion for domain walls in the presence of CIP spin torques:

$$\dot{\phi}_0(t) + \frac{\alpha \dot{X}_0(t)}{\Delta} - \boxed{\frac{\beta u}{\Delta}} = -\frac{\gamma}{2M_s}\frac{\partial E}{\partial X_0}$$

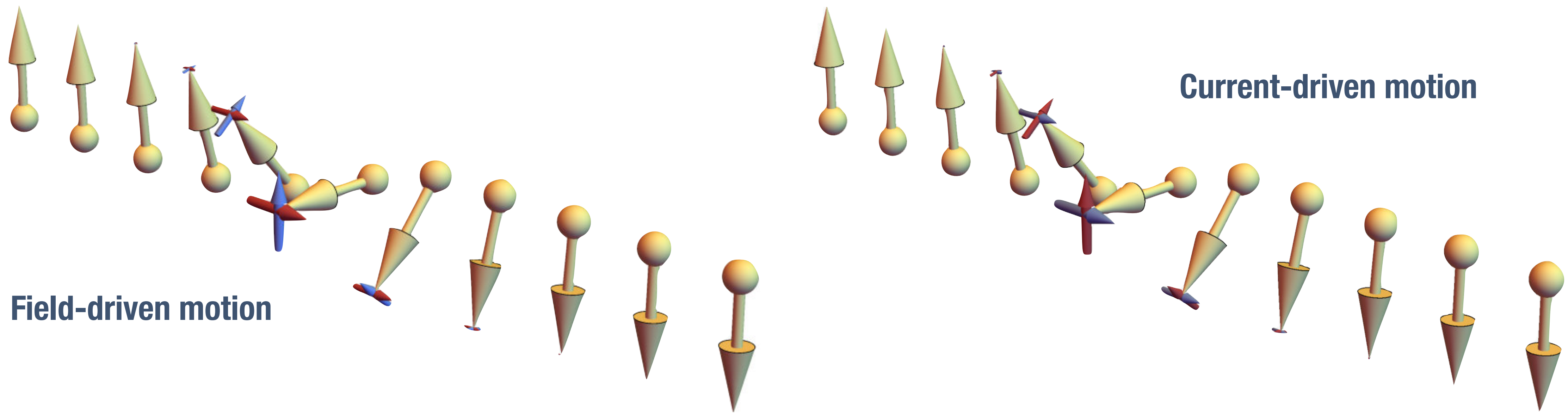
$$-\frac{\dot{X}_0(t)}{\Delta} + \alpha\dot{\phi}_0(t) + \boxed{\frac{u}{\Delta}} = -\frac{\gamma}{2M_s\Delta}\frac{\partial E}{\partial \phi_0}$$

$$\mathbf{u} = P\frac{g\mu_B}{2e}\frac{1}{M_s}\mathbf{j}_e = P\frac{\hbar}{2e}\frac{1}{M_s}\mathbf{j}_e$$

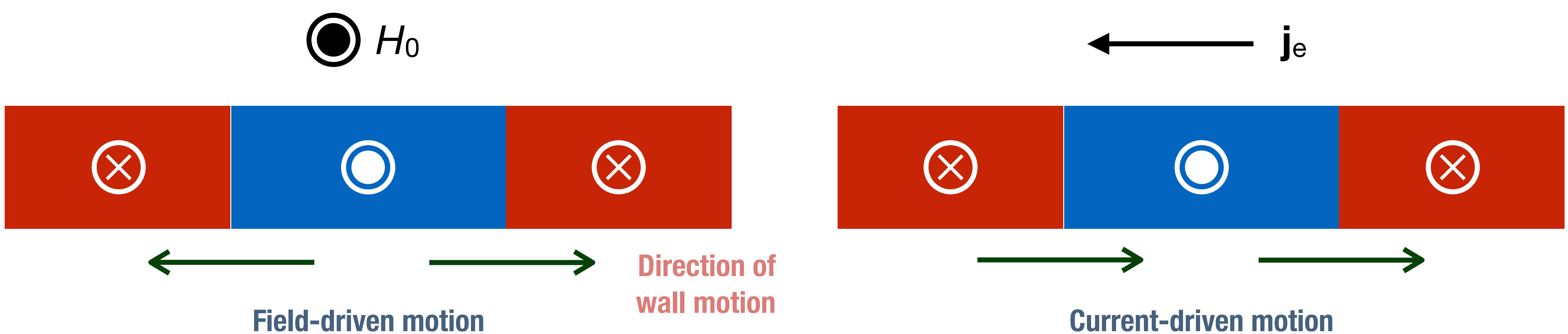


# Current-driven domain wall motion

- Field and current driven motion result in very similar torque profiles on a single domain wall



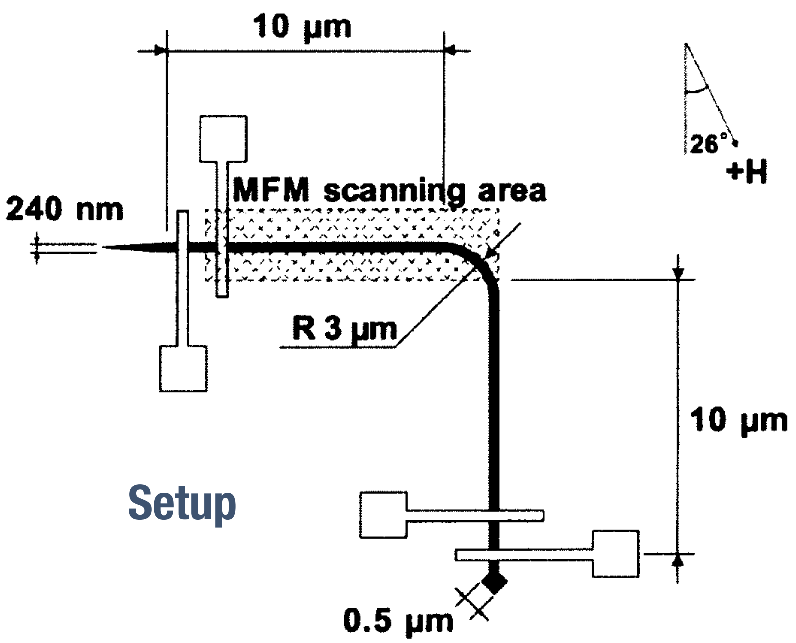

- However, for a sequence of domain walls, the overall effect is very different



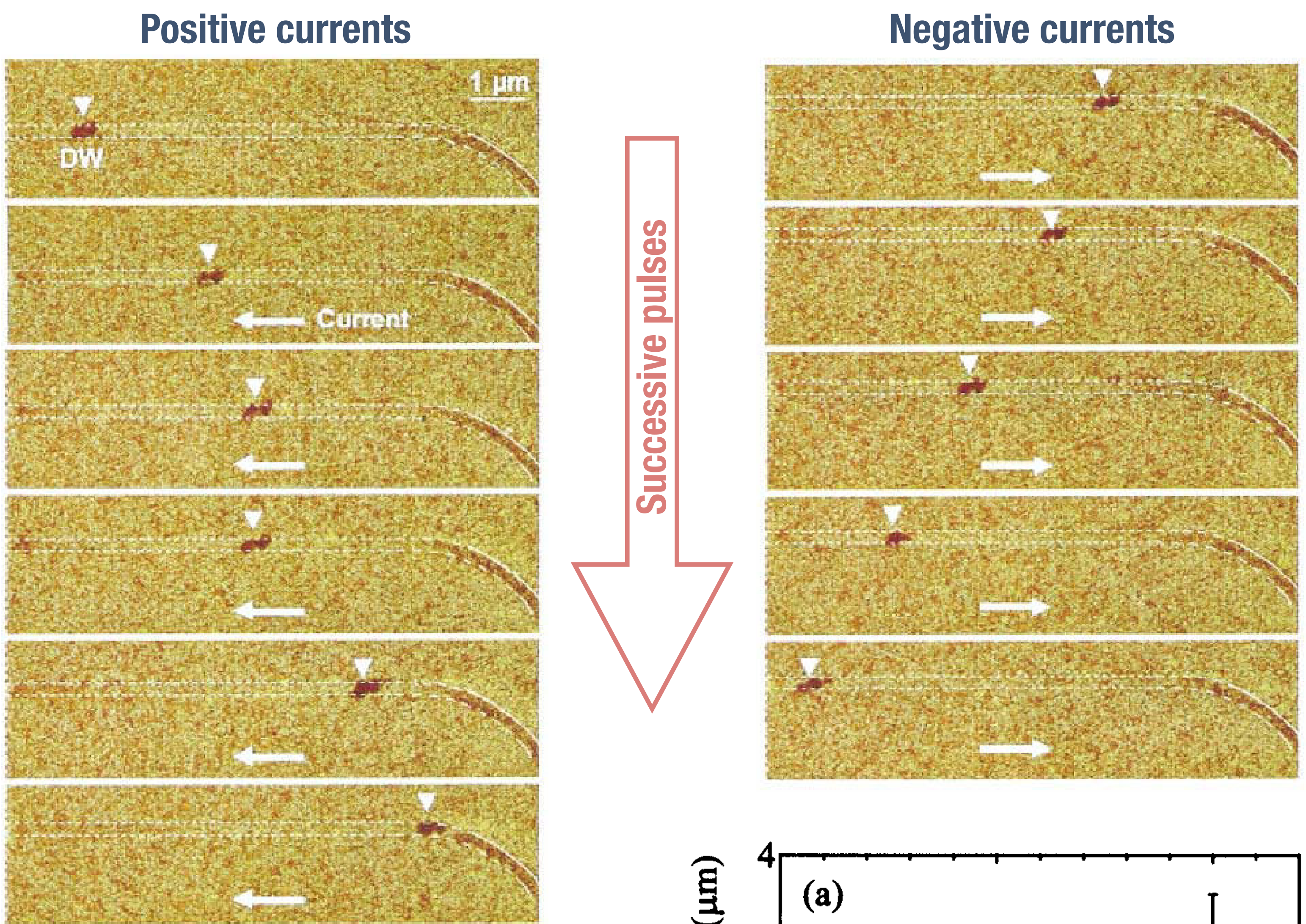
# Current-driven domain wall motion

A Yamaguchi et al,
*Phys Rev Lett* **92**, 077205 (2004)

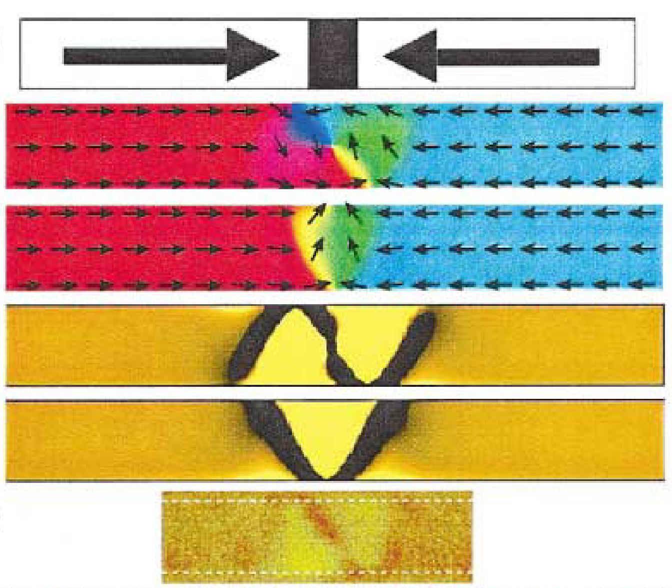
- Back and forth motion of domain wall driven by bipolar current pulses

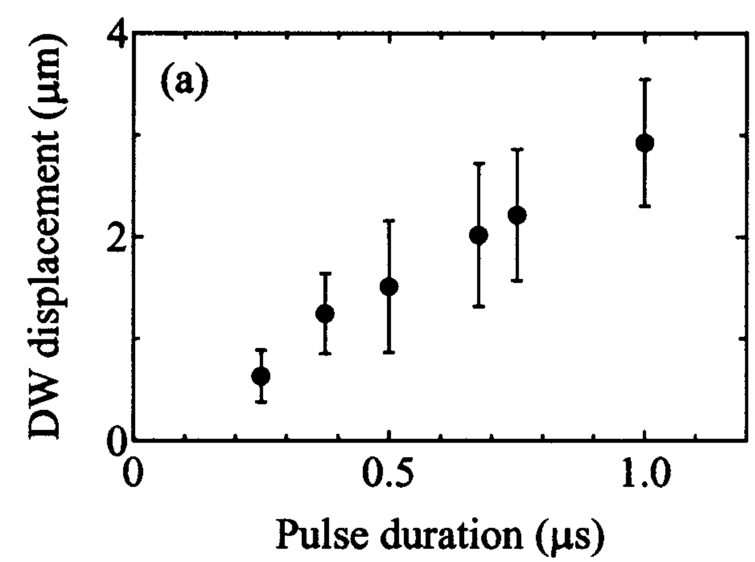



Setup




Interpretation of domain wall state from MFM





# Magnetic Domain-Wall Racetrack Memory

11 APRIL 2008 VOL 320 SCIENCE

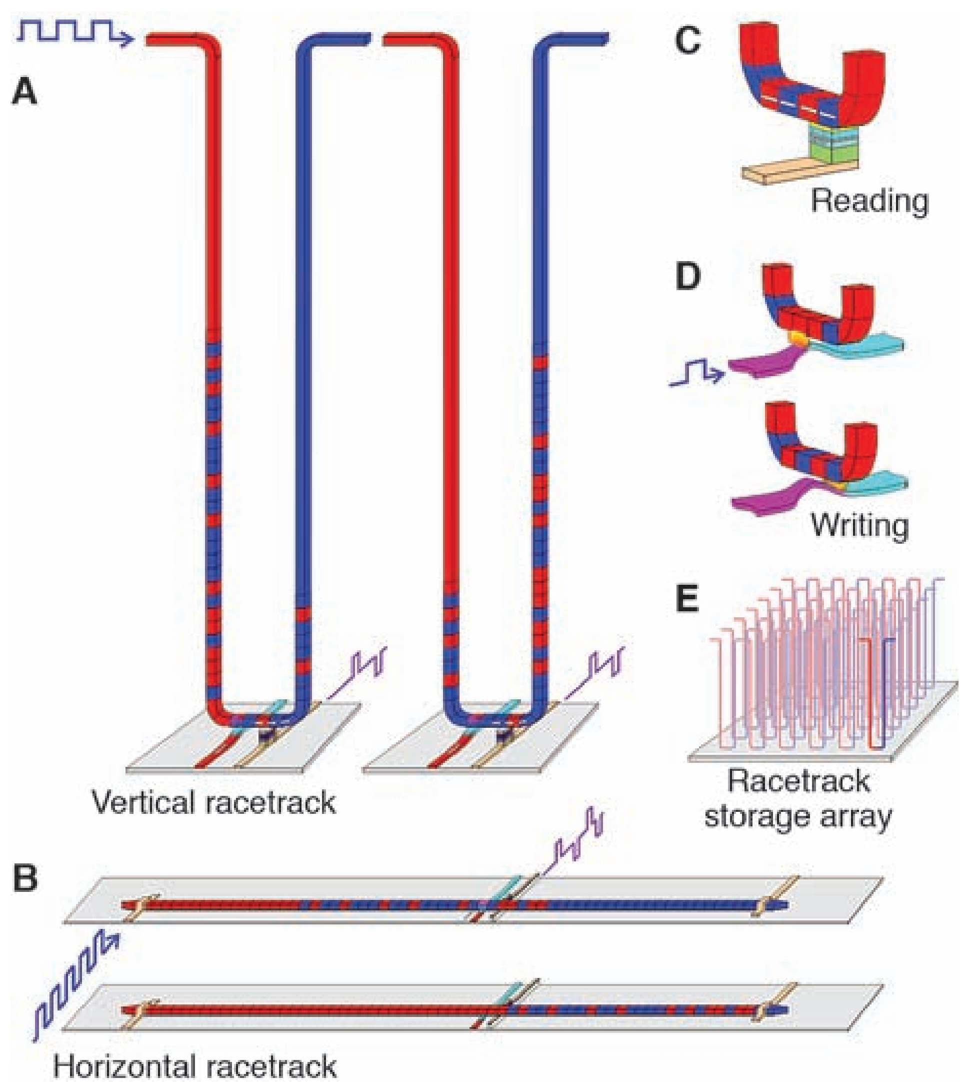
**Stuart S. P. Parkin,* Masamitsu Hayashi, Luc Thomas**

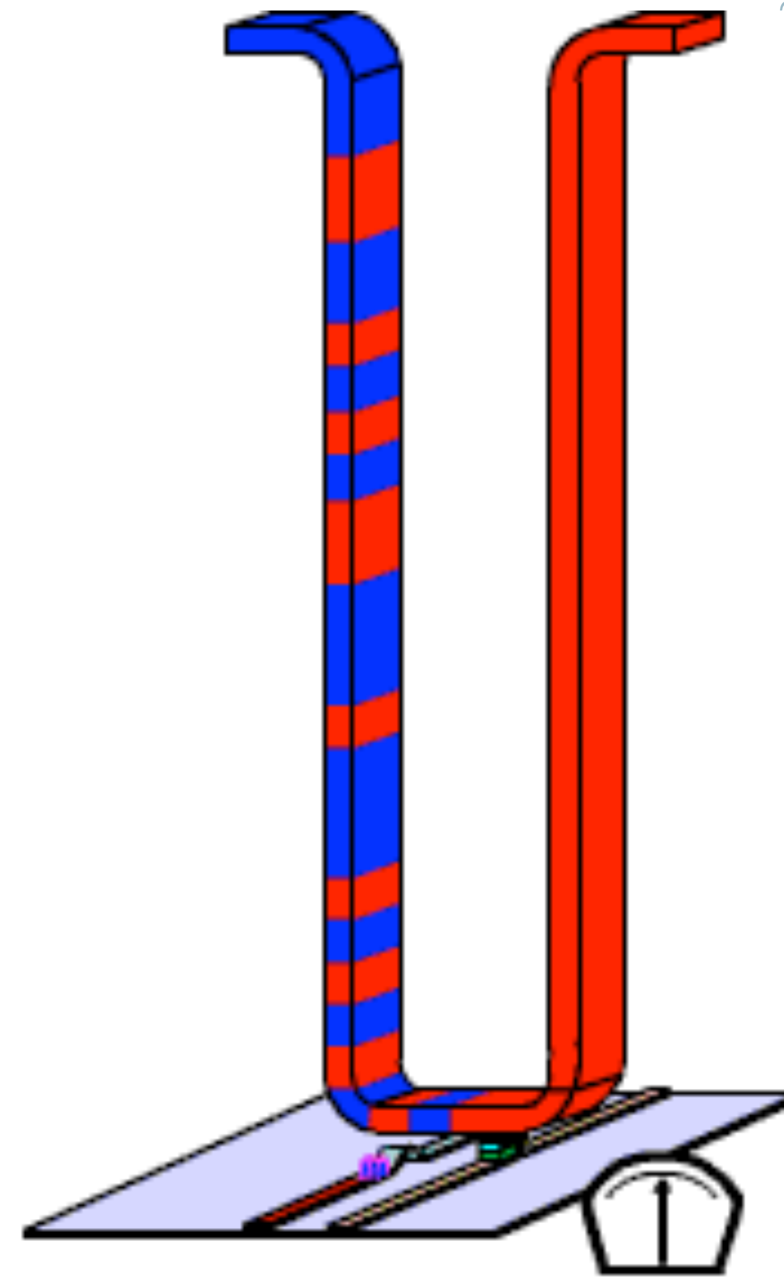
Recent developments in the controlled movement of domain walls in magnetic nanowires by short pulses of spin-polarized current give promise of a nonvolatile memory device with the high performance and reliability of conventional solid-state memory but at the low cost of conventional magnetic disk drive storage. The racetrack memory described in this review comprises an array of magnetic nanowires arranged horizontally or vertically on a silicon chip. Individual spintronic reading and writing nanodevices are used to modify or read a train of ~10 to 100 domain walls, which store a series of data bits in each nanowire. This racetrack memory is an example of the move toward innately three-dimensional microelectronic devices.

There are two main means of storing digital information for computing applications: solid-state random access memories (RAMs) and magnetic hard disk drives (HDDs). Even though both classes of devices are evolving at a very rapid pace, the cost of storing a single data bit in an HDD remains approximately 100 times cheaper than in a solid-state RAM. Although the low cost of HDDs is very attractive, these devices are intrinsically slow, with typical access times of several milliseconds because of the large mass of the rotating disk. RAM, on the other hand can be very fast and highly reliable, as in static RAM and dynamic RAM technologies. The architecture of computing systems would be greatly simplified if there were a single memory storage device with the low cost of the HDD but the high performance and reliability of solid-state memory.

## Racetrack Memory

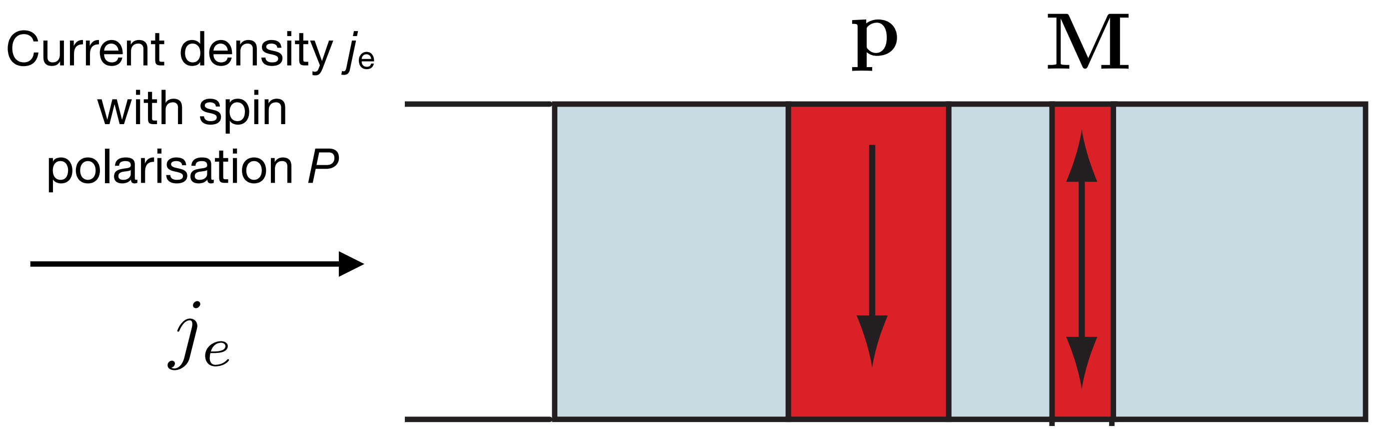
Because both silicon-based microelectronic devices and HDDs are essentially two-dimensional (2D) arrays of transistors and magnetic bits, respectively, the conventional means of develop-



# CPP torques for vortices, etc.

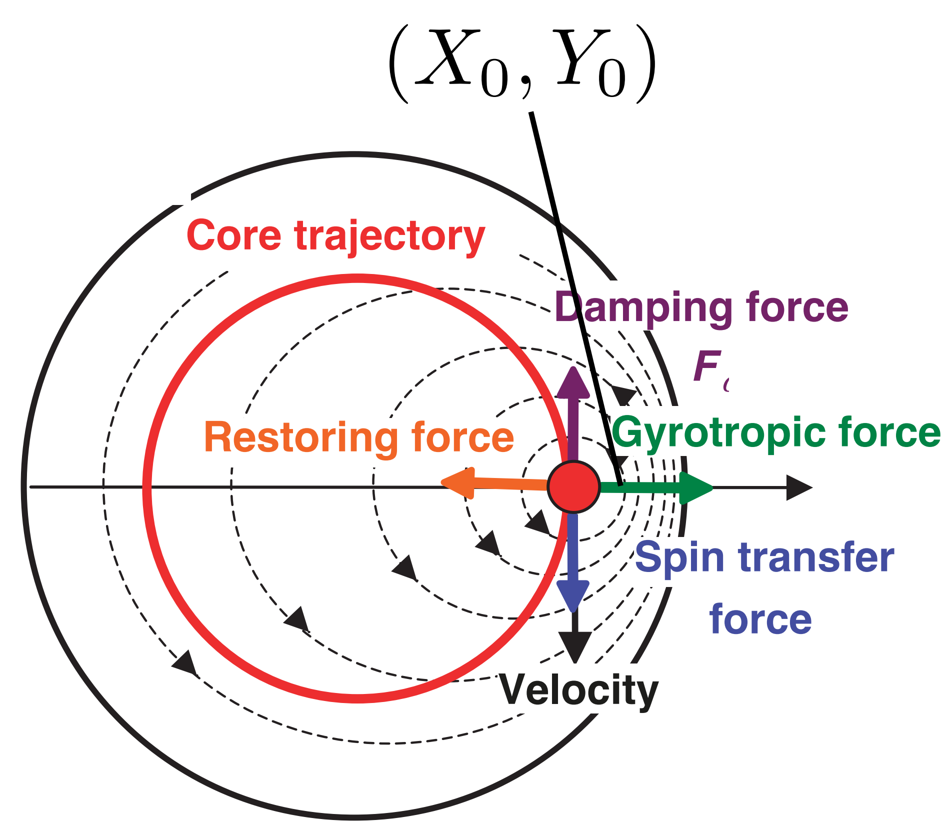
- CPP (Slonczewski) torques can be described with a dissipation function




$$\mathcal{F}_{\mathrm{CPP}} = -\frac{\sigma j_e}{\gamma}\,\mathbf{p}\cdot\left(\mathbf{M}\times\frac{\partial \mathbf{M}}{\partial t}\right)$$

- For vortices in dots, CPP torques can compensate damping

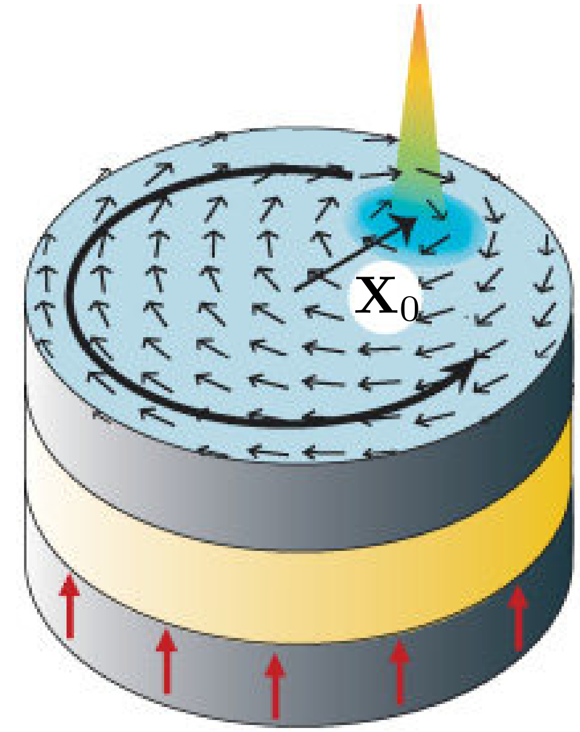
$$\underbrace{\mathbf{G}\times\dot{\mathbf{X}}_0}_{\text{Gyrotropic}} + \underbrace{\alpha D\dot{\mathbf{X}}_0}_{\text{Damping}} + \underbrace{\frac{\partial F_{\mathrm{CPP}}}{\partial \dot{\mathbf{X}}_0}}_{\text{STT}} = \underbrace{-\frac{\partial U}{\partial \mathbf{X}_0}}_{\text{Restoring}}$$



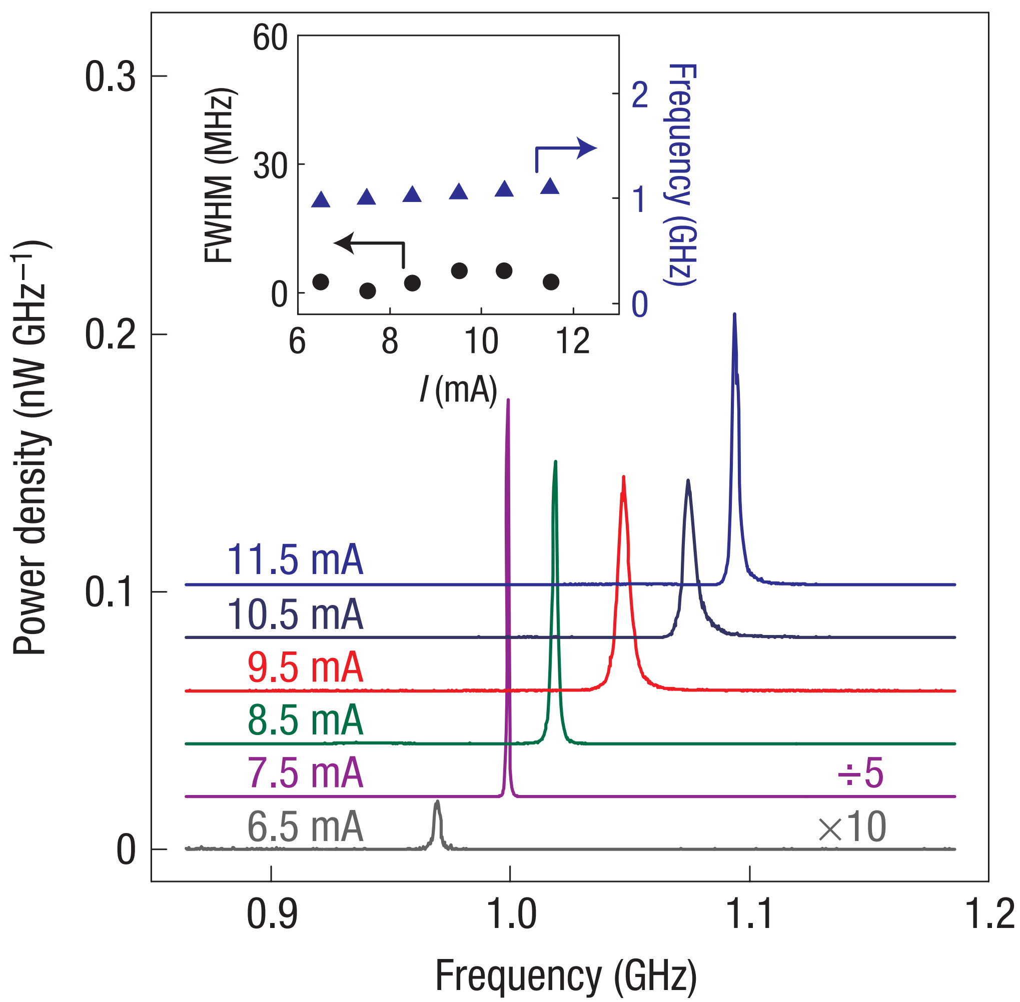

$$\frac{\partial F_{\mathrm{CPP}}}{\partial \dot{\mathbf{X}}_0} \propto \sigma I p_z\left(\hat{\mathbf{z}}\times\mathbf{X}_0\right)$$

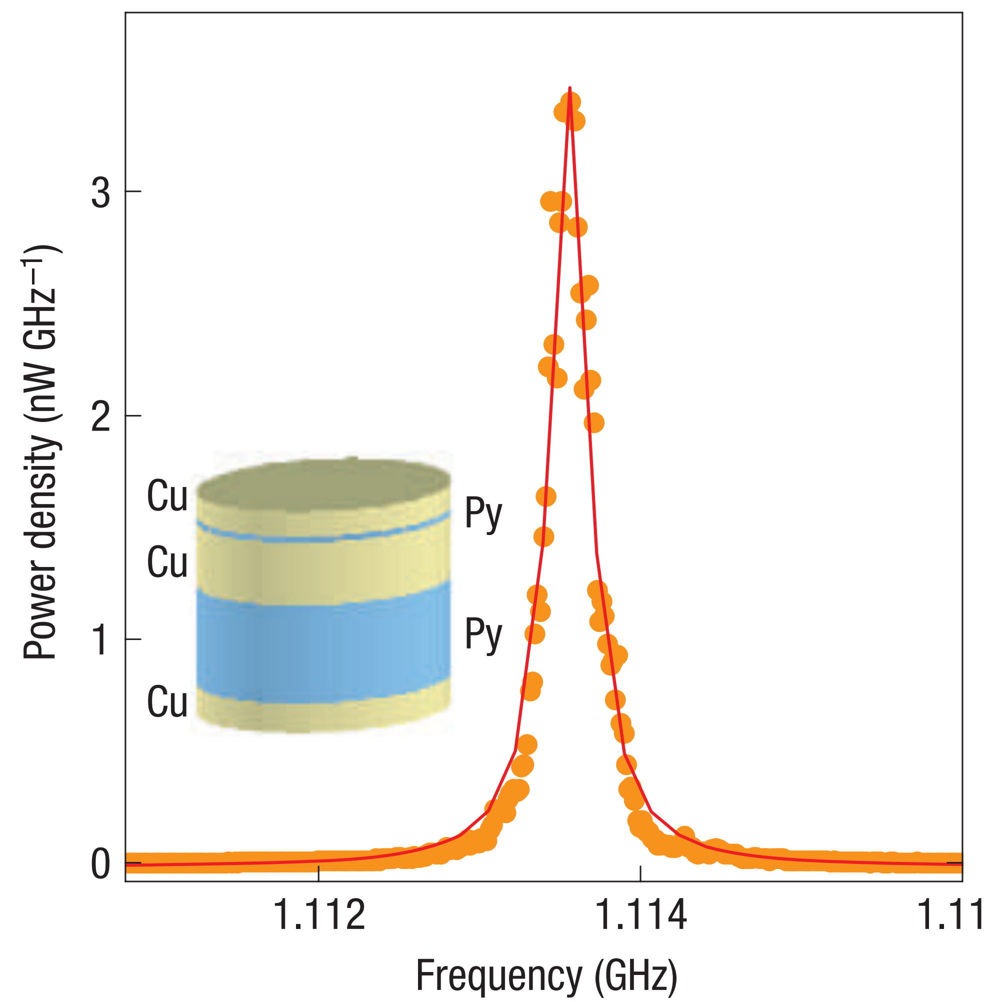
# Vortex oscillators

- Self-sustained gyration of vortices with CPP torques in spin valves (GMR) and magnetic tunnel junctions (TMR)
- Gyration frequencies determined by confinement potential, GHz range




V S Pribiag et al, *Nat Phys* **3**, 498 (2007)



# Summary

- Magnetism affects transport and vice versa
- Spin torques involve the absorption of transverse spin currents
  *sd model, current-driven magnetisation reversal*
- Spin torques can compensate spin wave damping in certain geometries, modify frequencies in others
  *Self-sustained oscillations, Doppler effect*
- Spin torques can displace magnetic solitons such as domain walls and vortices
  *Back and forth wall propagation in wires, vortex oscillators*