

KITS - New Horizons Forum

New Horizons in Spintronics

Allan MacDonald

University of Texas at Austin



magnets

A universal force that is powering technology

Magnets at Work

Magnets are at the heart of electric motors that power computers, cars and many renewable energy technologies. However, the raw materials called rare earth elements that make up these magnets can be difficult or expensive to obtain. Preserving our quality of life requires developing magnets made from new kinds of materials as well as stronger magnets that allow these technologies to advance.

Ensuring Our Magnetic Future

Danna Freedman and her students are working to create new kinds of materials that could one day replace rare earth magnets, the strongest type of magnet. They are working with non-toxic elements like bismuth to make magnets that are cheaper, stronger and more environmentally friendly.

On Display at
O'Hare Airport

INHERENT ATTRACTION



Push and Pull

Magnetic materials all have one thing in common: they generate a magnetic field that exerts a force on other magnets. Some materials are only magnetic when a current flows through them. Other materials are always magnetic due to the fundamental properties of their electrons. We use magnetism to store data in computer hard drives, make purchases with credit cards and drive electric cars.

Magnetic World

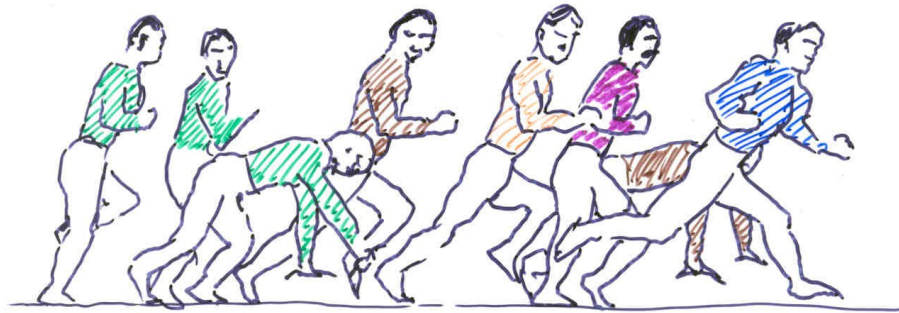
You may not know it, but you are standing on a magnet. The Earth is a giant magnet with a magnetic field generated by the molten iron in its core. Earth's poles interact with magnets, enabling directional tools like compasses.



The entire Earth is a magnet, with a magnetic field that extends thousands of miles into space.

Emergent Collective DOF

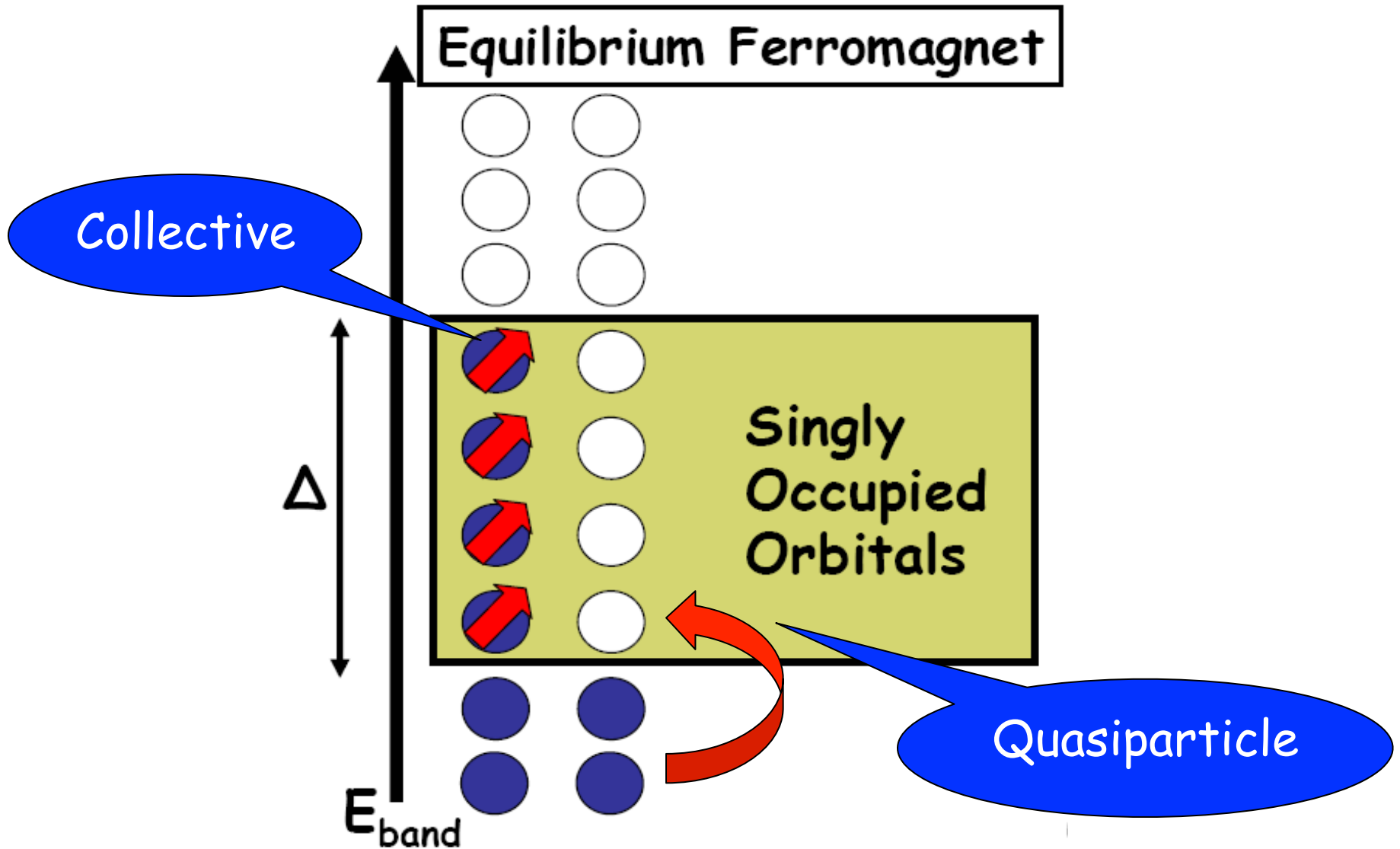
Incoherent motion



Collective motion



Collective and Quasiparticle



Two-Channel Conduction & CPP GMR

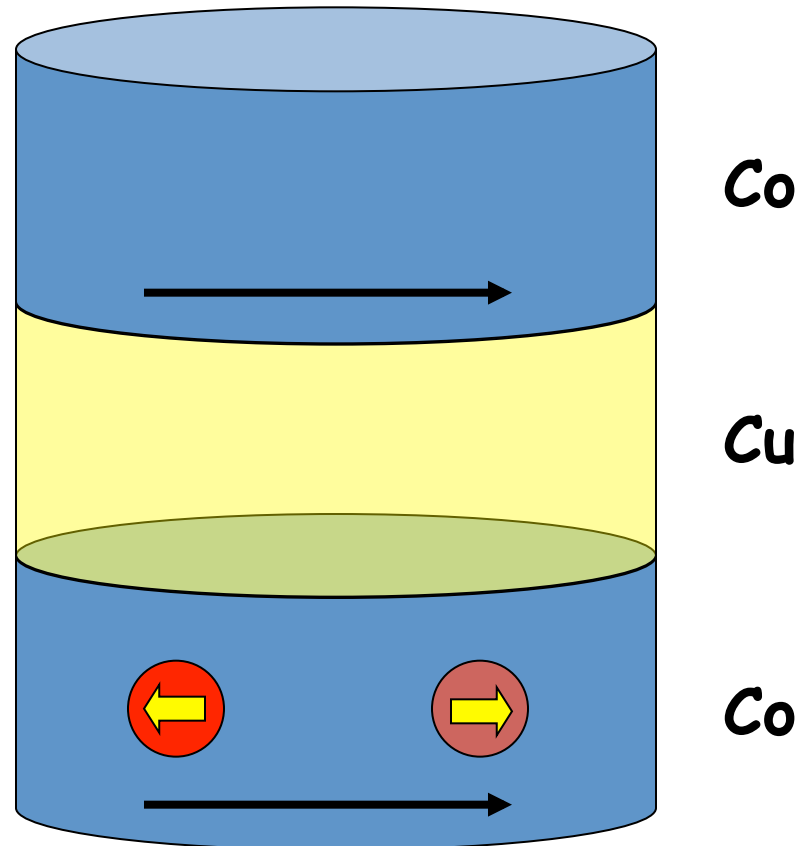
CPP = Current Perpendicular to Plane
GMR = Giant Magnetoresistance



Neville Mott
1905-1996

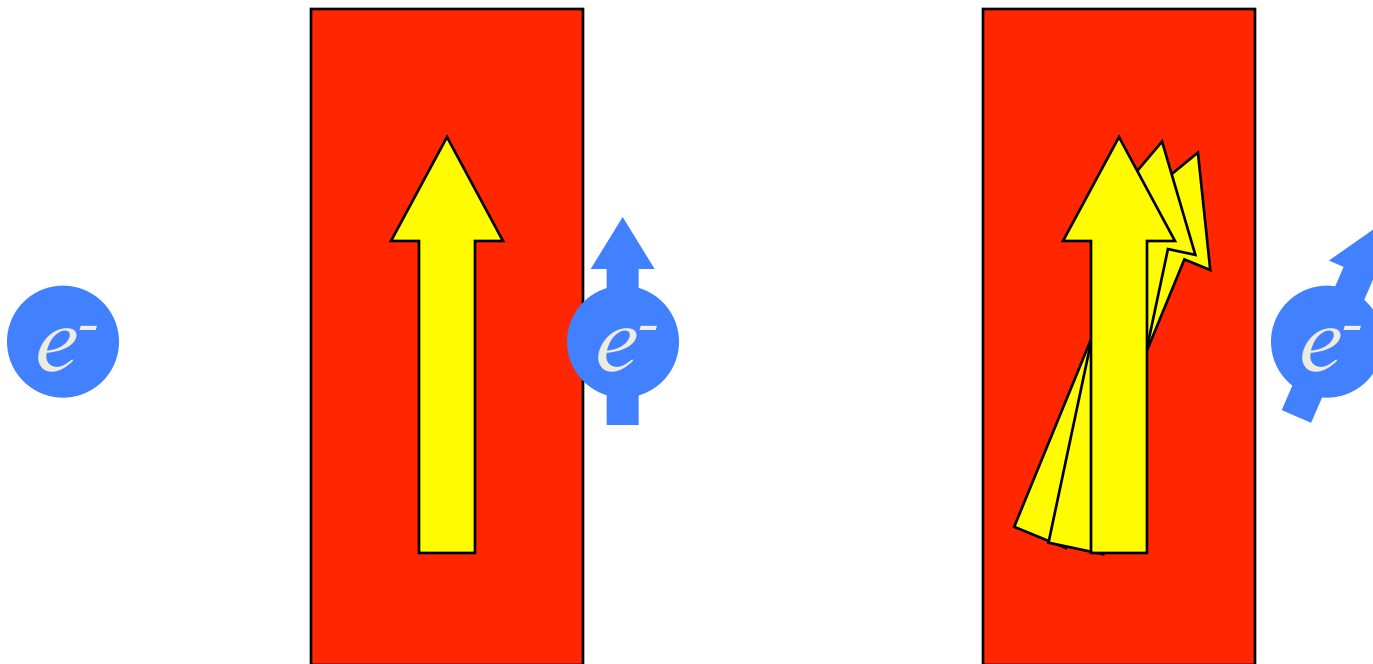
Minority

Majority

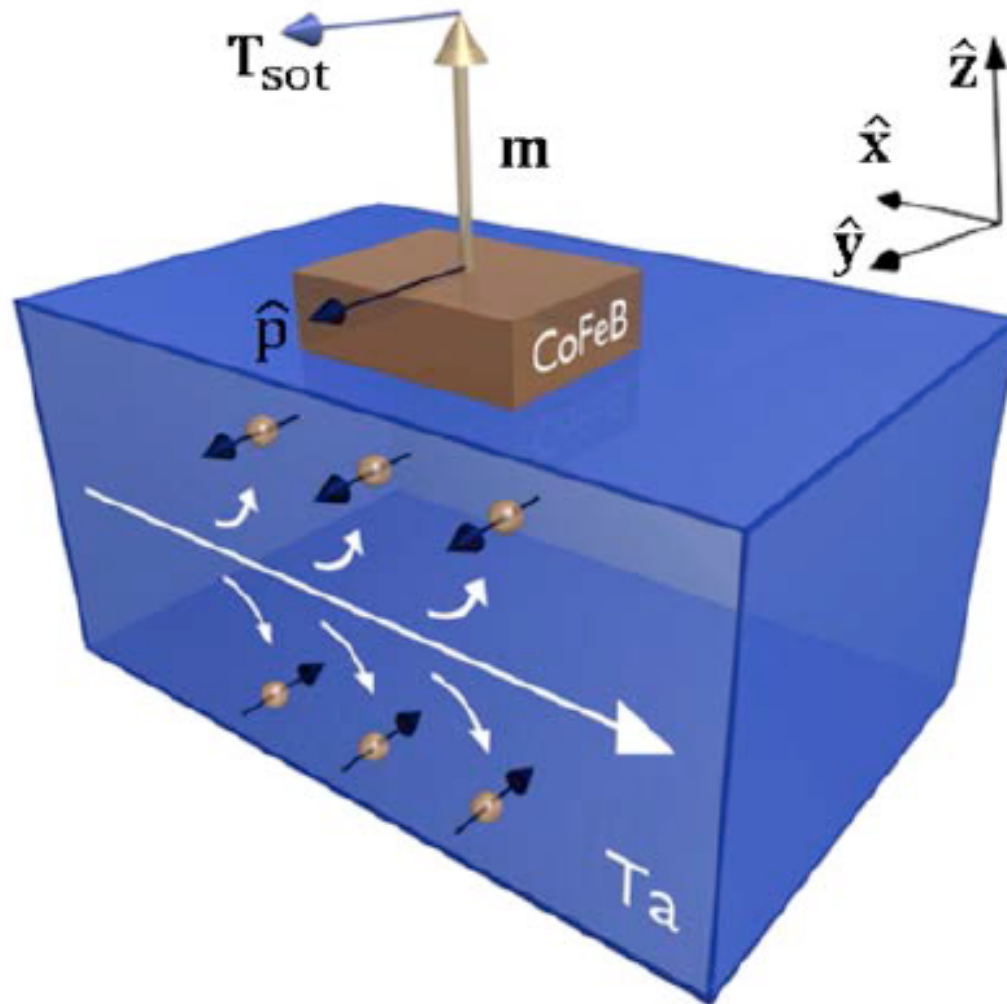


Spin transfer torques

Experiment: M. Tsoi et al., PRL 80, 4281 (1998); Nature 406, 46 (2000)
Theory: J.C. Slonczewski and Luc Berger
Shared 2013 APS Buckley Prize



Spin-Orbit Torques



Miron *et al.* Nature Mat. 9 (2010) Nature 476 (2011)
Liu *et al.* PRL 109 (2012) Science 336 (2012)

Quantized Hall Conductance in a Two-Dimensional Periodic Potential

D. J. Thouless, M. Kohmoto,^(a) M. P. Nightingale, and M. den Nijs
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 30 April 1982)

$$\sigma_H = \frac{ie^2}{2\pi h} \sum \int d^2k \int d^2r \left(\frac{\partial u^*}{\partial k_1} \frac{\partial u}{\partial k_2} - \frac{\partial u^*}{\partial k_2} \frac{\partial u}{\partial k_1} \right)$$

$u(\mathbf{r})$ = electron wave function

Berry
Curvature
Chern Index

(k_1, k_2) = two-dimensional momentum space

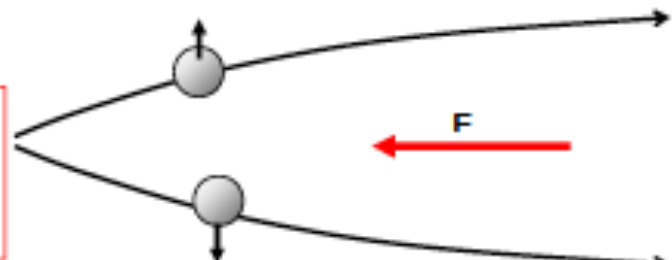
Anomalous Hall Effect

a) Intrinsic deflection

Interband coherence induced by an external electric field gives rise to a velocity contribution perpendicular to the field direction. These currents do not sum to zero in ferromagnets.

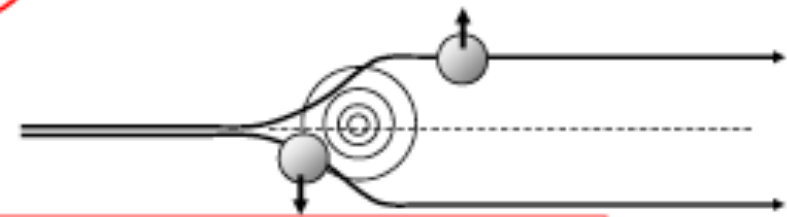
$$\frac{d\langle \vec{r} \rangle}{dt} = \frac{\partial E}{\hbar \partial \vec{k}} + \frac{e}{\hbar} \mathbf{E} \times \mathbf{b}_n$$

Electrons have an anomalous velocity perpendicular to the electric field related to their Berry's phase curvature



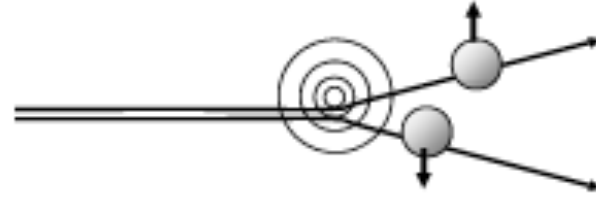
b) Side jump

The electron velocity is deflected in opposite directions by the opposite electric fields experienced upon approaching and leaving an impurity. The time-integrated velocity deflection is the side jump.

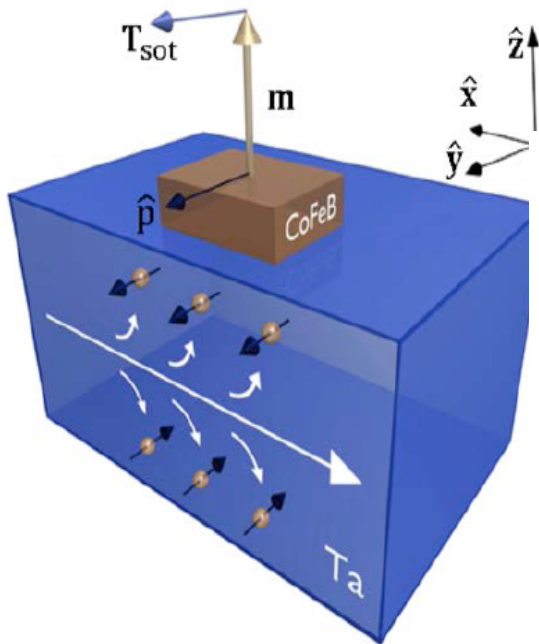


c) Skew scattering

Asymmetric scattering due to the effective spin-orbit coupling of the electron or the impurity.



Spin-Orbit Torques



$$H_{qp} = \frac{\vec{p}^2}{2m} + V(\vec{r}) + \lambda \vec{p} \cdot (\vec{\nabla} V(\vec{r}) \times \vec{s}) - J(\vec{r}) \vec{s} \cdot \hat{\Omega}$$

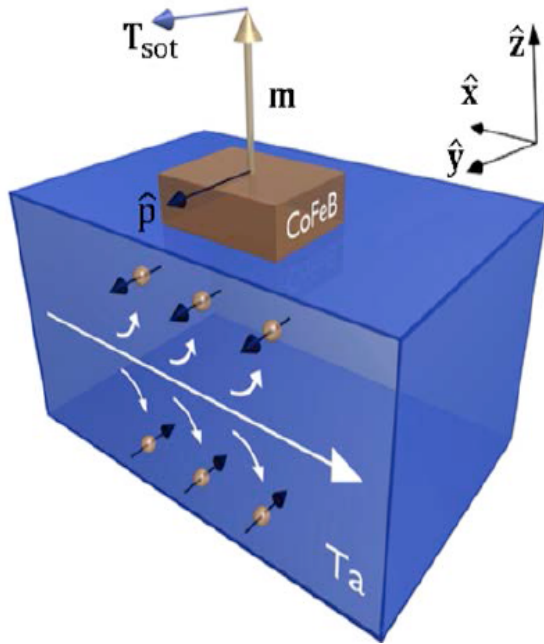
Schrodinger

SO

Coupling to
Magnetic
Condensate

Miron *et al.* Nature Mat. 9 (2010) Nature 476 (2011)
Liu *et al.* PRL 109 (2012) Science 336 (2012)

Spin-Orbit Torques



$$\begin{aligned}\langle \vec{\tau}_{qp} \rangle &= \frac{i}{\hbar} [\vec{s}, H_{qp}] \\ &= \langle \vec{\tau}_{so} \rangle + \int d\vec{r} J(\vec{r}) \langle \vec{s}(\vec{r}) \rangle \times \hat{\Omega} \\ &= 0\end{aligned}$$

Miron *et al.* Nature Mat. 9 (2010) Nature 476 (2011)
Liu *et al.* PRL 109 (2012) Science 336 (2012)

Bulk Transport Theory

Relaxation Time Approx

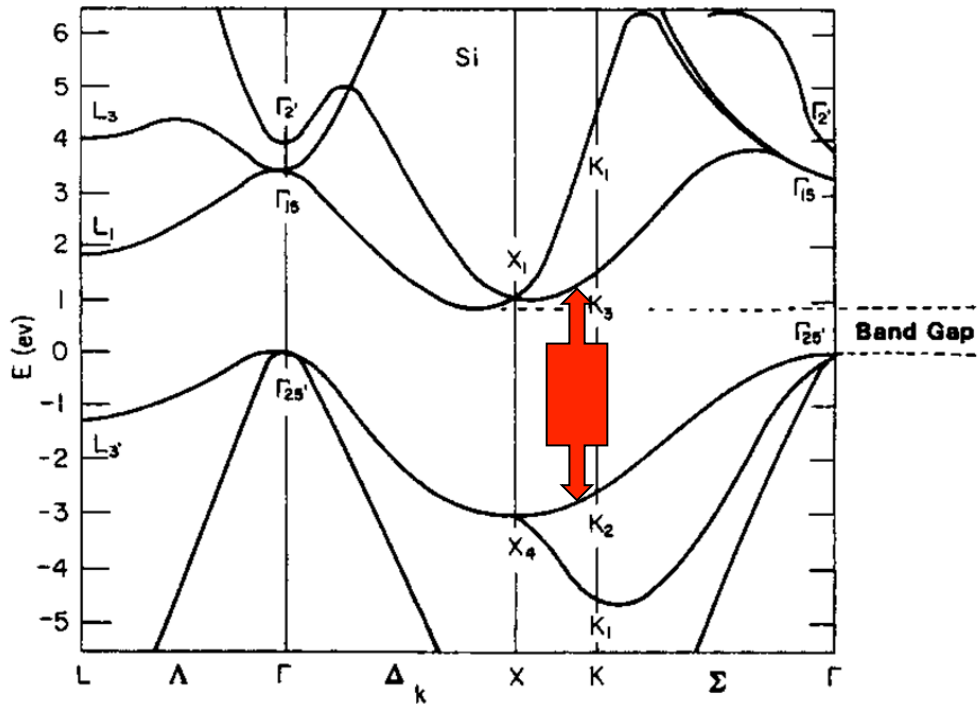
$$\frac{\partial \rho}{\partial t} = -\frac{i}{\hbar} [H, \rho] + \frac{1}{\hbar} \frac{\partial \rho}{\partial \mathbf{k}} \cdot e\mathbf{E} - \frac{\rho - \rho_0}{\tau}$$

Quantum
Kinetic Equation

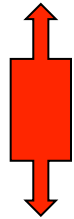
Driving
Term

Relaxation
Time
Approximation

Response of Insulator to static Electric Field



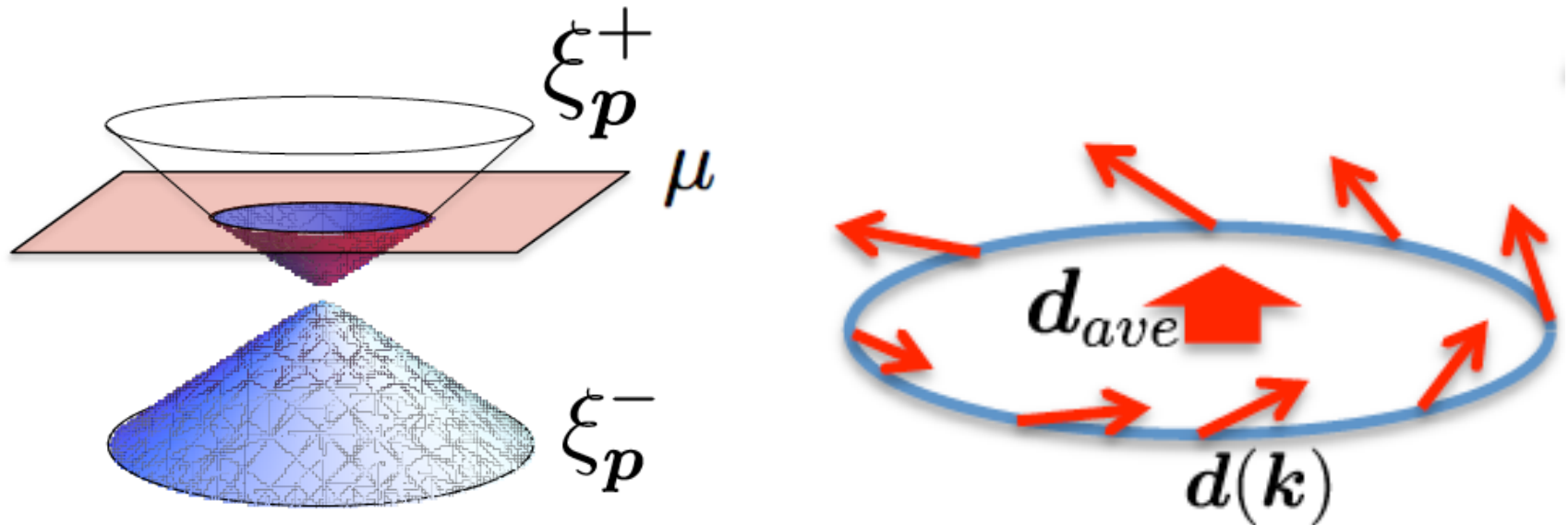
Interband
Transitions



$$\rho_{n'n}^{(1)}(\vec{k}) = ieE \frac{f_{n',\vec{k}} - f_{n,\vec{k}}}{(E_{n',\vec{k}} - E_{n,\vec{k}})^2} \langle \Psi_{n',\vec{k}} | \frac{\partial H}{\partial k_x} | \Psi_{n,\vec{k}} \rangle$$

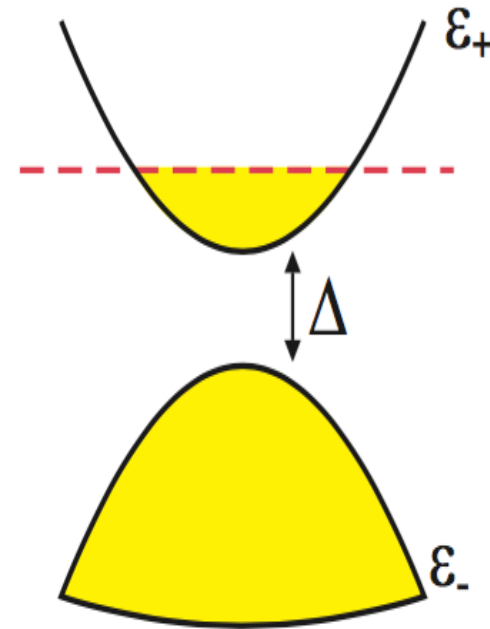
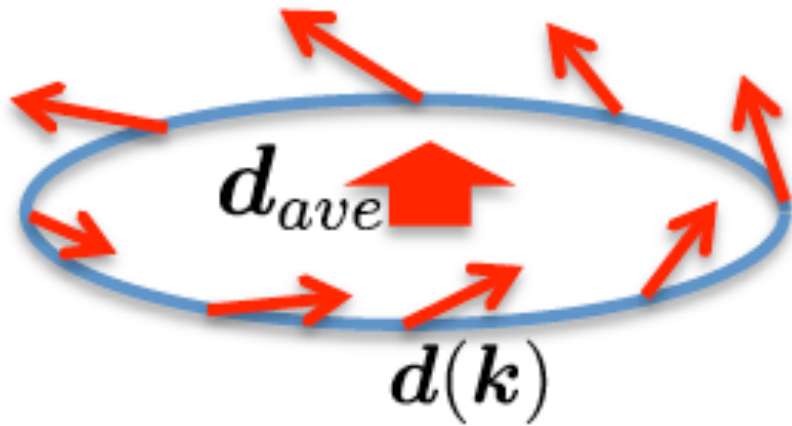
Topological Insulators

A Model Spin-Orbit-Torque System



$$\hat{\mathcal{H}} = v(-p_x \hat{\sigma}_2 + p_y \hat{\sigma}_1) + \Delta \hat{\sigma}_3$$

Massive Dirac Model for Current-Induced Spin Density



$$2v_D \delta \mathbf{s}_{\mathbf{k}} \times \mathbf{b}_{\mathbf{k}} + \frac{\delta \mathbf{s}_{\mathbf{k}}}{\tau} = -\mathbf{F}_{\mathbf{k}}$$

$$\mathbf{F}_{\mathbf{k}} = \left(\sum_n \langle n, \mathbf{k} | \mathbf{s} | n, \mathbf{k} \rangle \frac{\partial f_{n, \mathbf{k}}}{\partial \mathbf{k}} + \sum_n \sum_{m \neq n} \langle n, \mathbf{k} | \mathbf{s} | m, \mathbf{k} \rangle \left(\frac{f_{n, \mathbf{k}} - f_{m, \mathbf{k}}}{\epsilon_{n, \mathbf{k}} - \epsilon_{m, \mathbf{k}}} \right) \langle m, \mathbf{k} | \frac{\partial H}{\partial \mathbf{k}} | n, \mathbf{k} \rangle \right) \cdot \frac{e\mathbf{E}}{\hbar}$$

Electric Field Induced Spin Densities

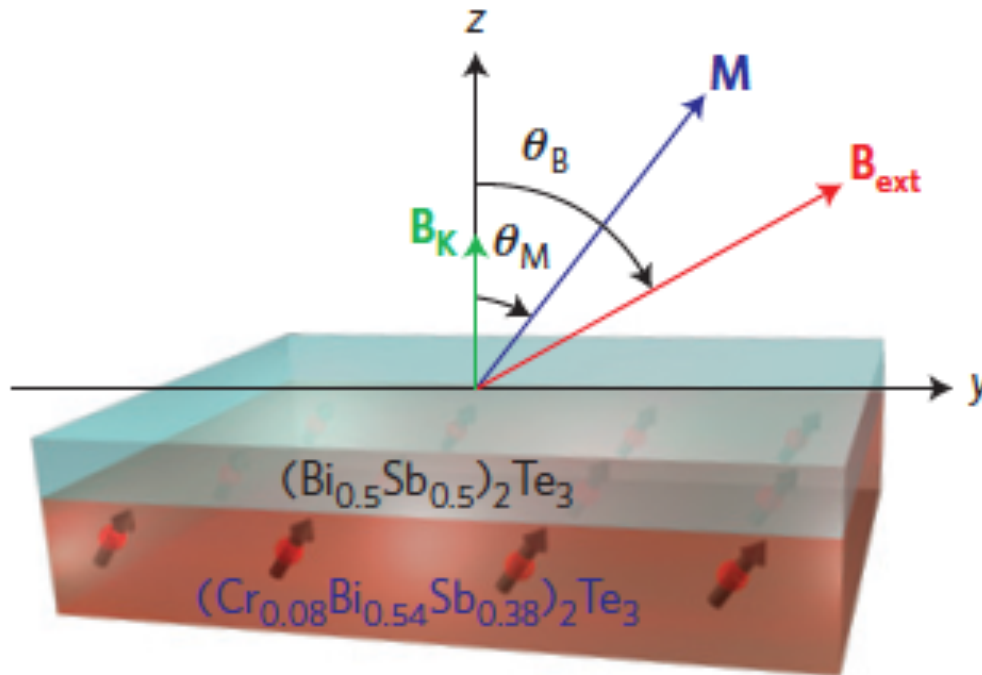
$$S_y/n \approx (e E a)/(\hbar/\tau) \times (1/k_F a)$$

Rashba

$$S_z/n \approx (e E a)/(E_g) \times (1/k_F a) \times (\Delta/E_F)$$

' Spin Hall '

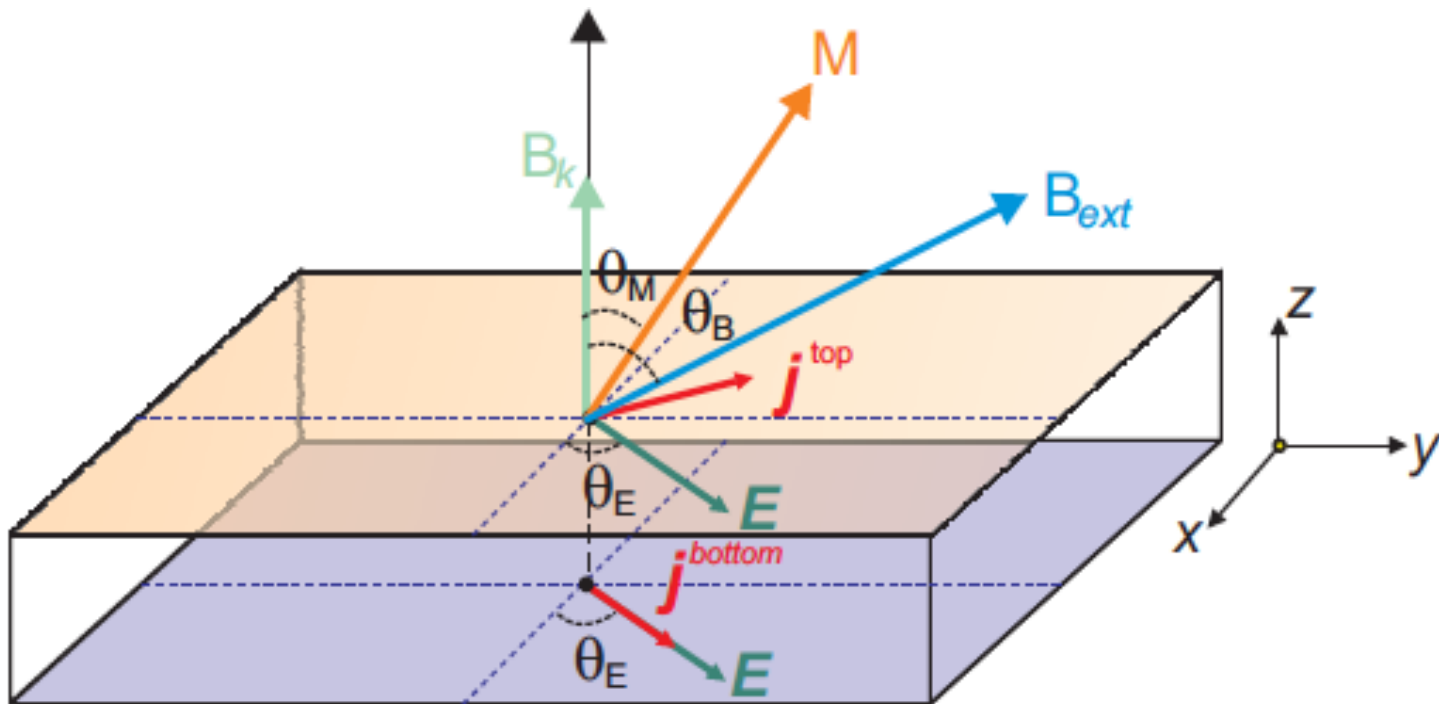
Spin-Orbit Torques in TI DMSs



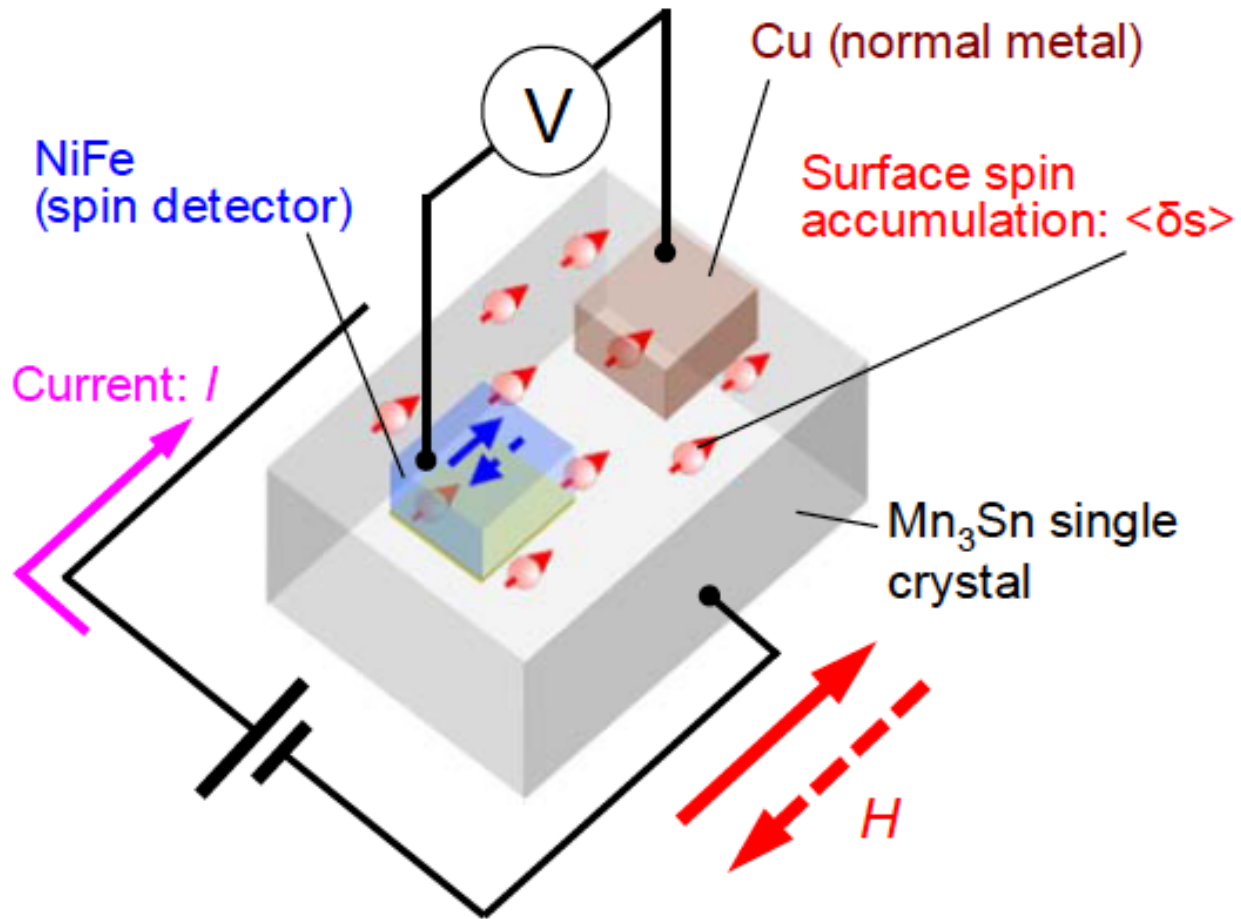
Experiment:
 $\Delta (s^z_{\text{tr}}/S) \approx 10^{-6} \text{ eV}$
 $\gg \Delta (s^y_{\text{tr}}/S)$

Fan et al., Nature Mat. (2014)

Spin-Orbit Torques in TI Ferromagnets

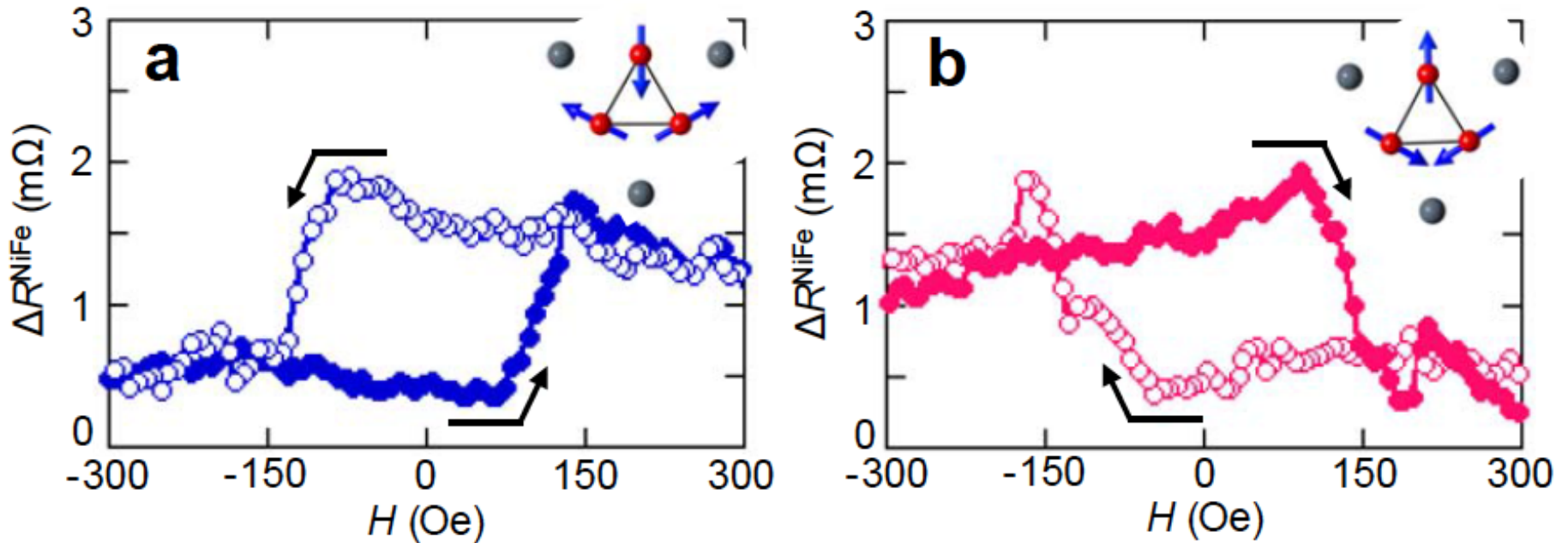


Mn₃Sn Spintronics



Nakatsuji et al. Nature (2015) and unpublished

Spin-Accumulation Depends on Mn_3Sn Spin-Configuration



Nakatsuji et al. Nature (2015) and unpublished

KITS - March 2017

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