KITS - New Horizons Forum

New Horizons in Spintronics

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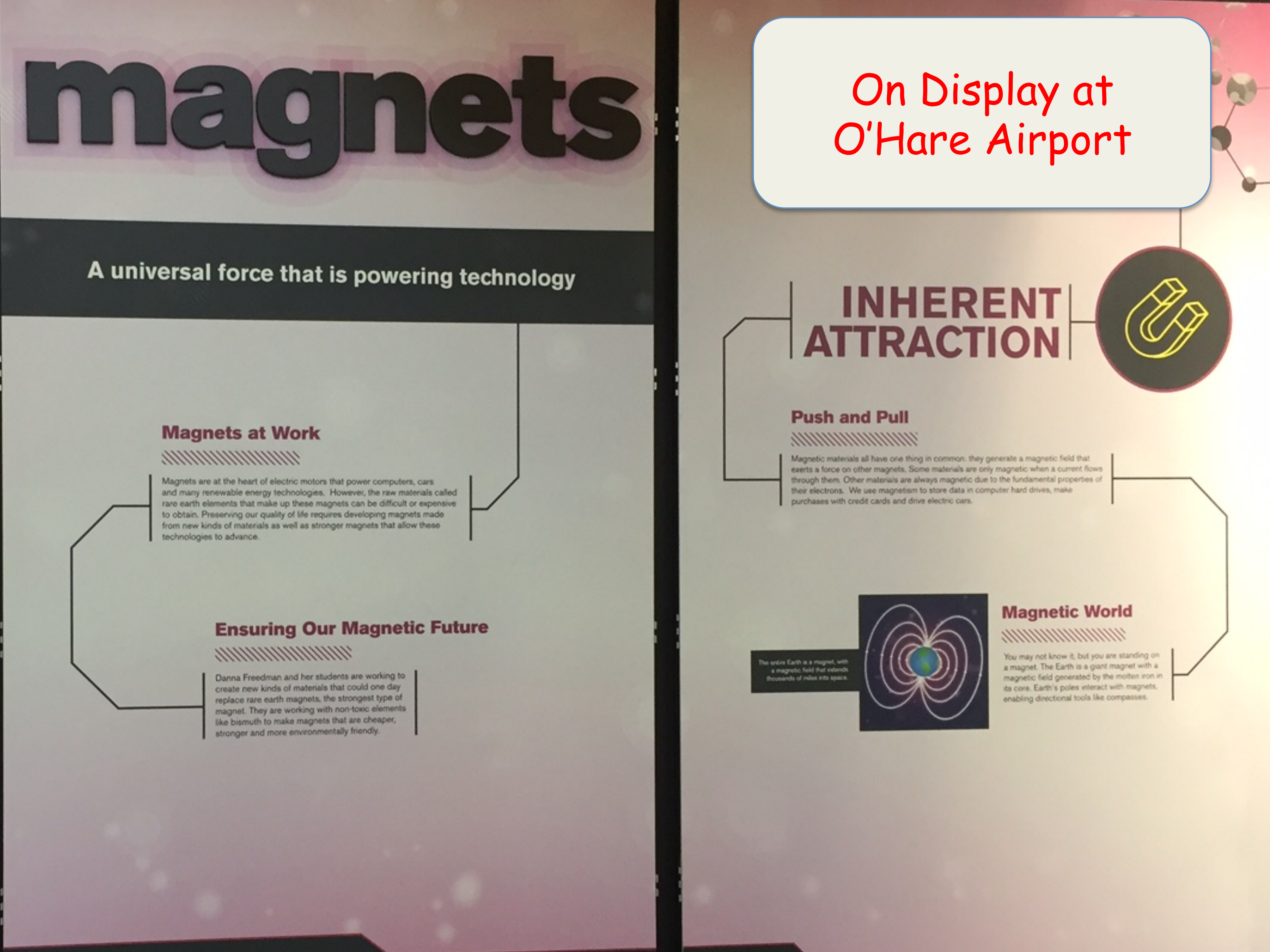
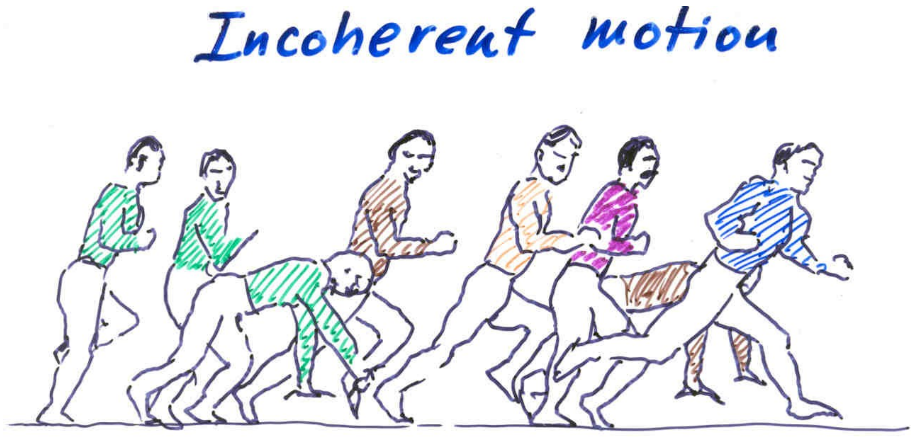
On Display at O'Hare Airport

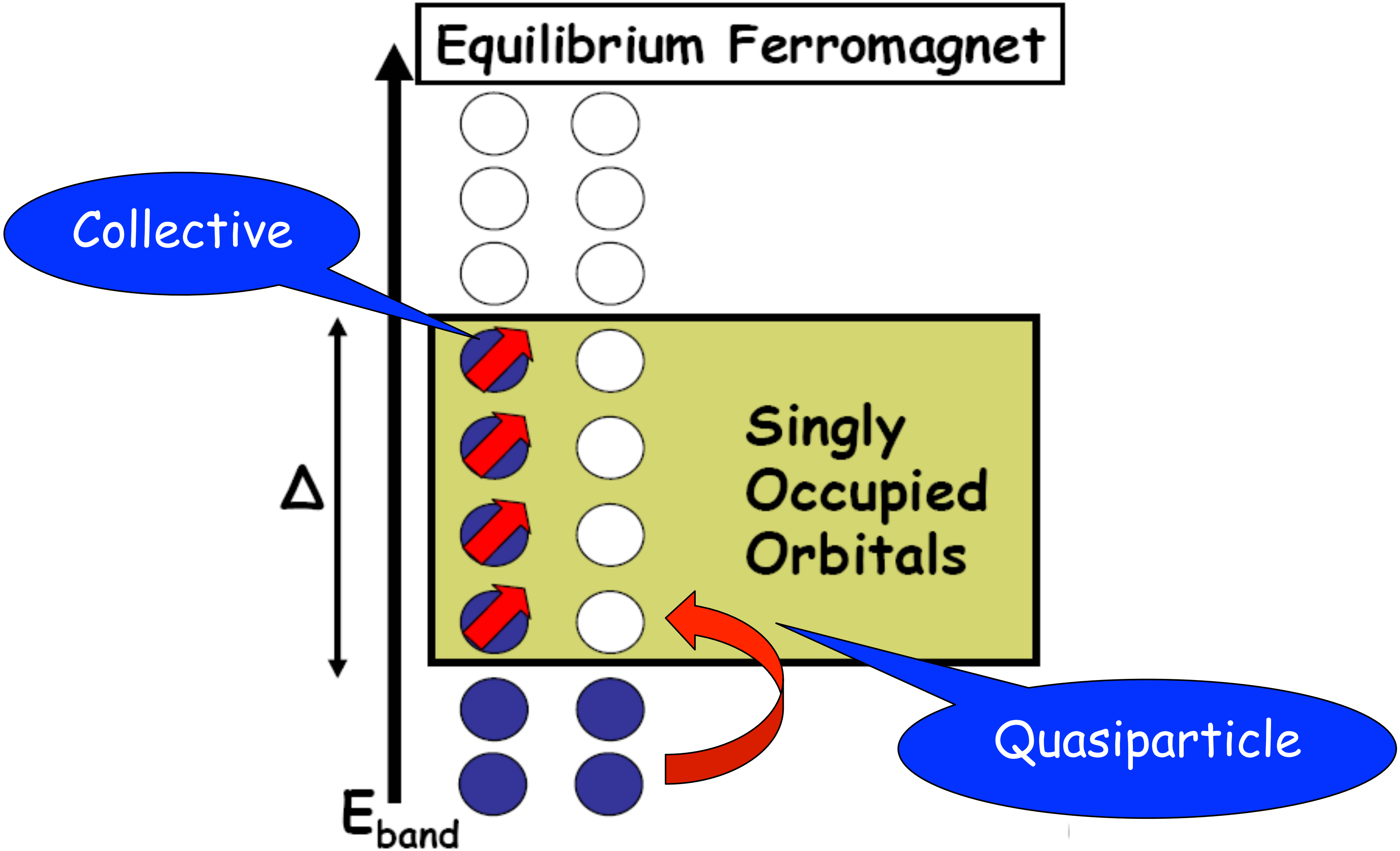


Emergent Collective DOF



Courtesy Catherine Kallin

Collective and Quasiparticle



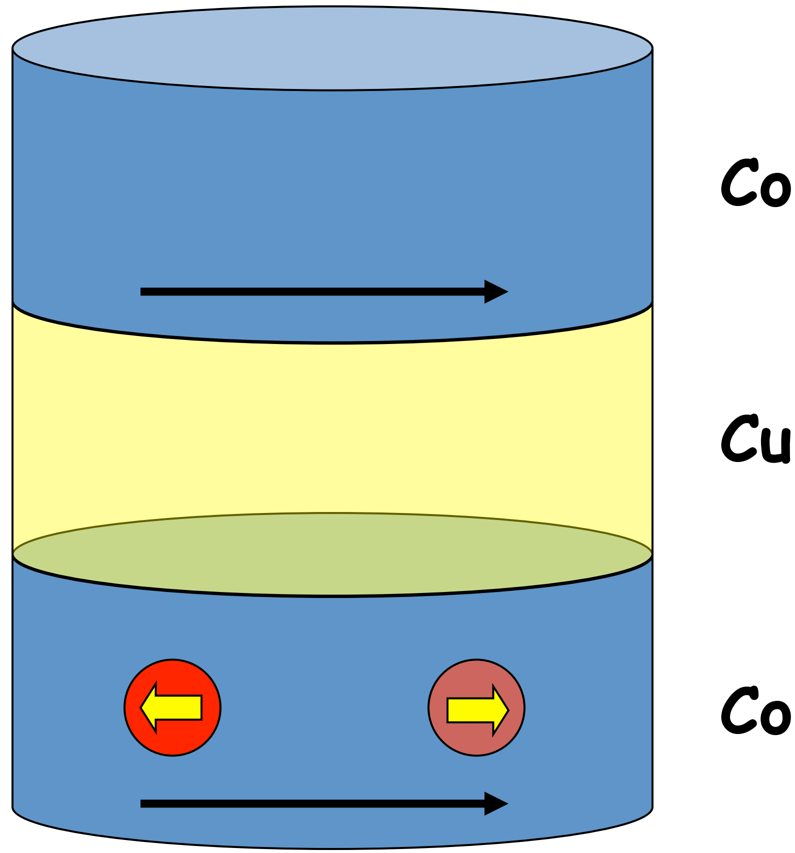
Two-Channel Conduction
&
CPP GMR

CPP = Current Perpendicular to Plane
GMR = Giant Magnetoresistance

Neville Mott
1905-1996

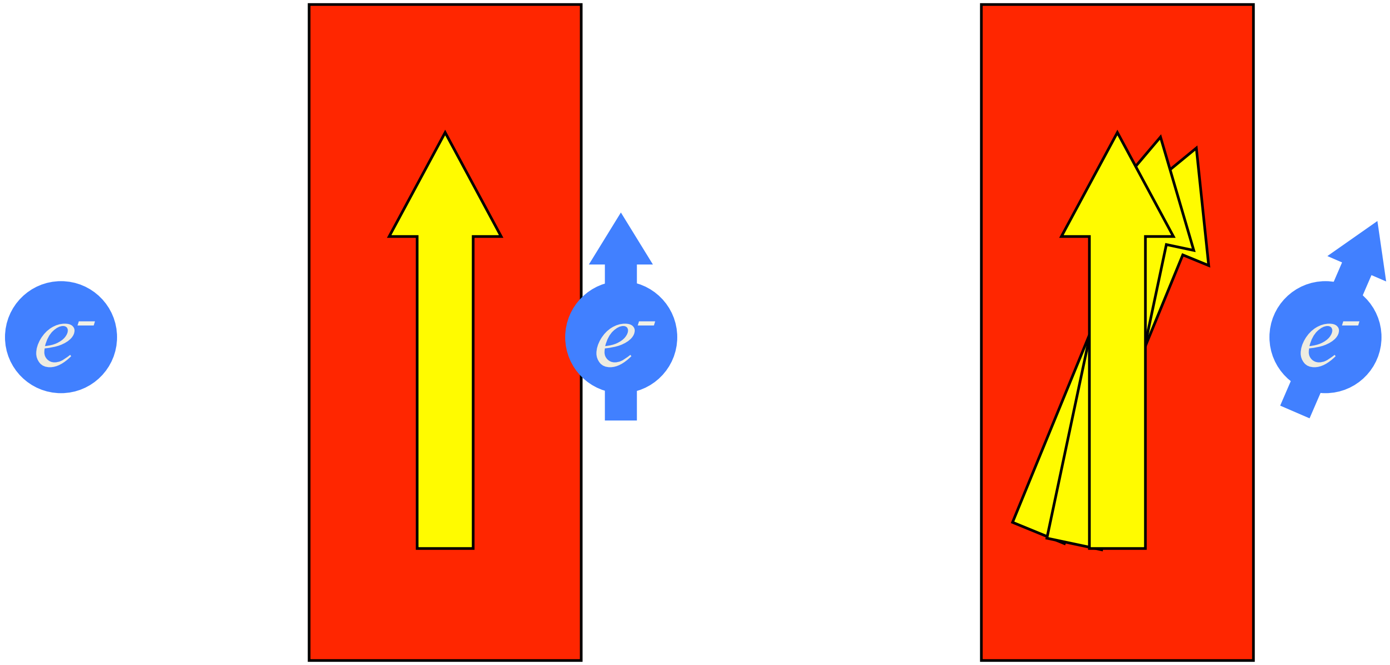
Minority

Majority

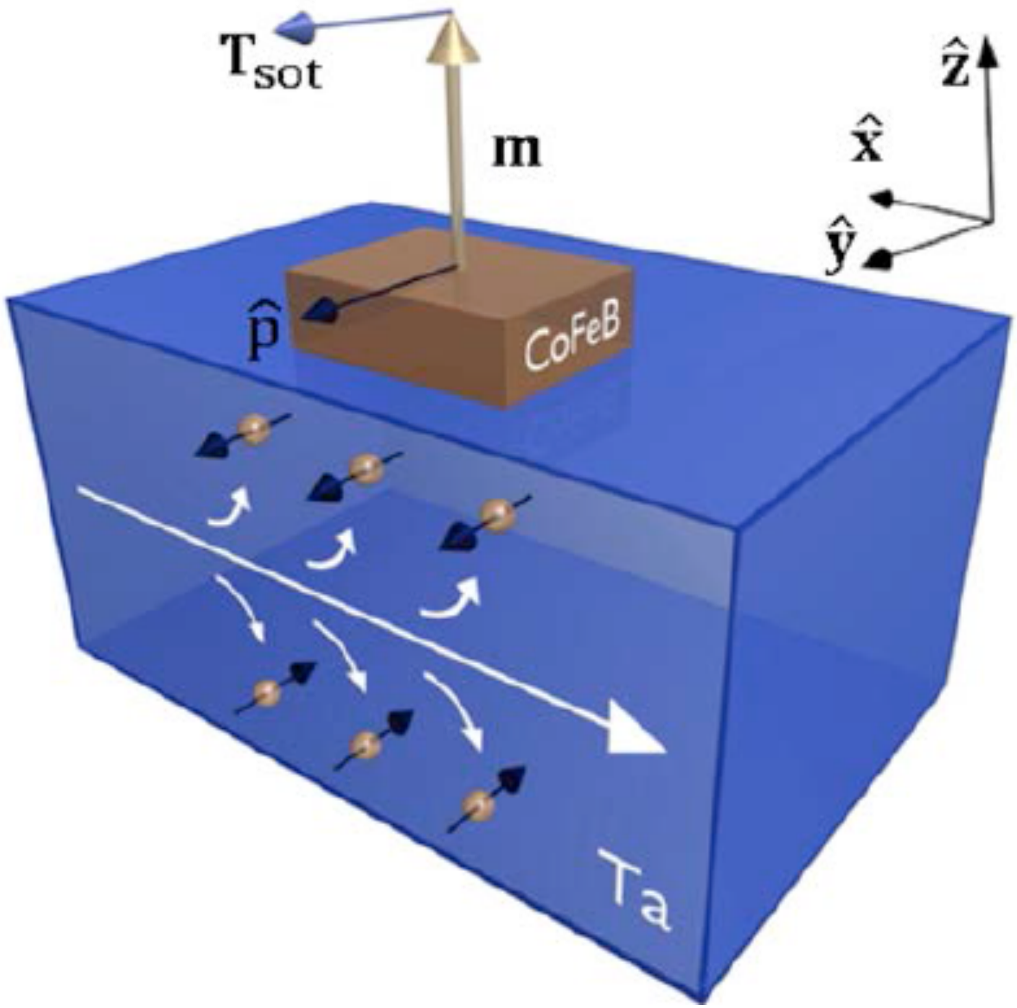


Spin transfer torques

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)

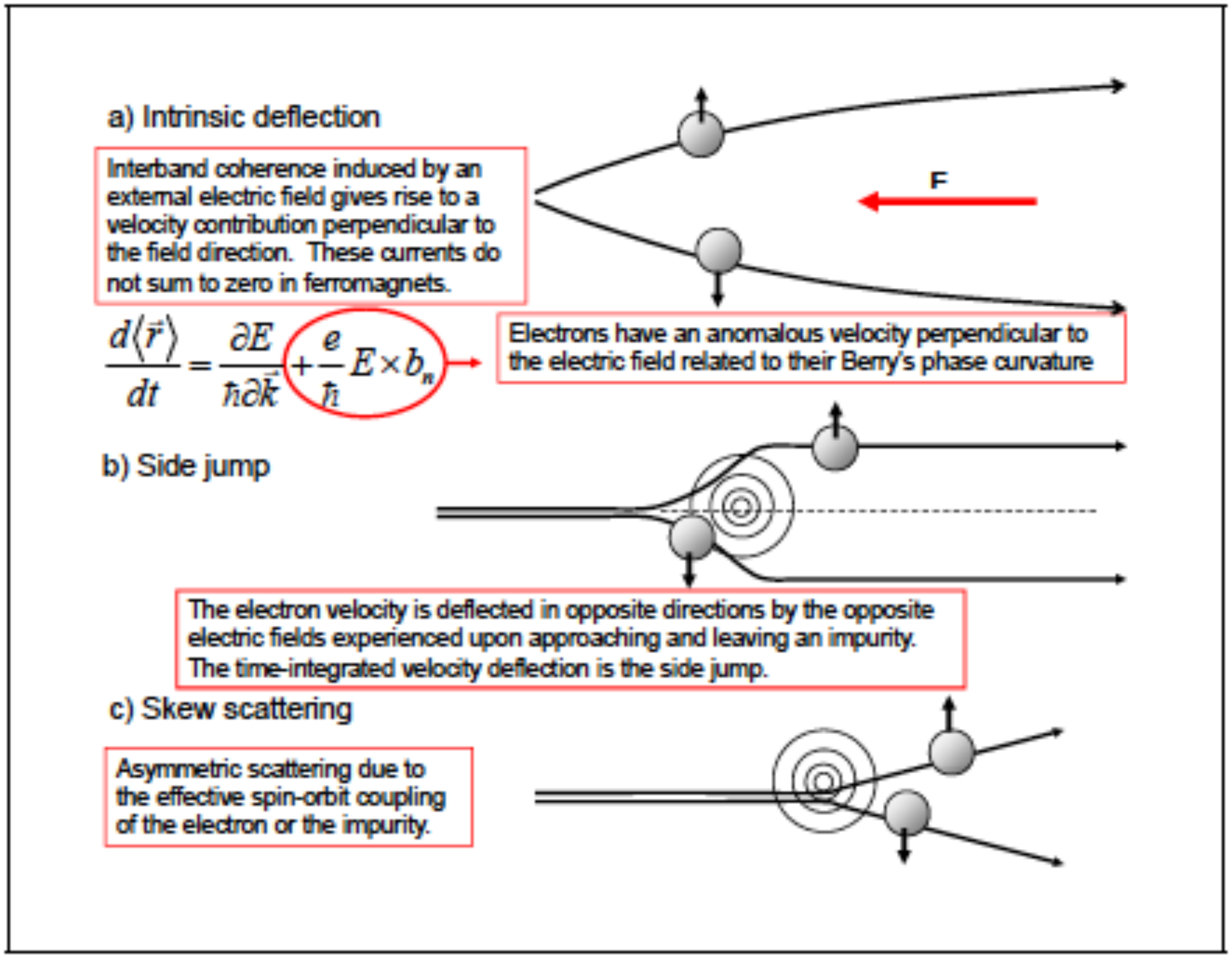
$$\sigma_H = \frac{ie^2}{2\pi h} \sum \int d^2k \int d^2r \left(\frac{\partial u^*}{\partial k_1} \frac{\partial u}{\partial k_2} - \frac{\partial u^*}{\partial k_2} \frac{\partial u}{\partial k_1} \right)$$

Berry
Curvature
Chern Index

u(r) = electron wave function

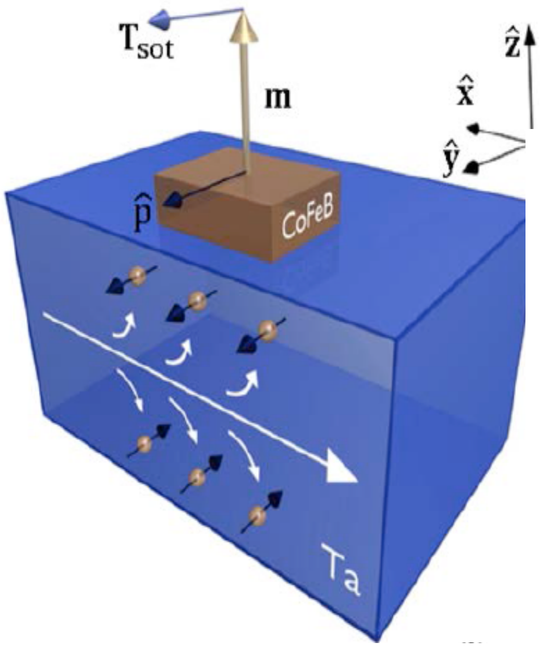
(k_1, k_2) = two-dimensional momentum space

Anomalous Hall Effect



Nagaosa et al., RMP (2004)

Spin-Orbit Torques



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

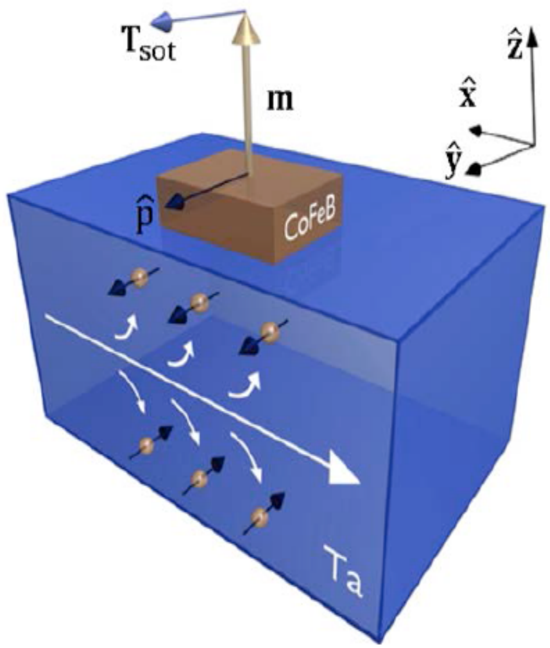
Schrodinger

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

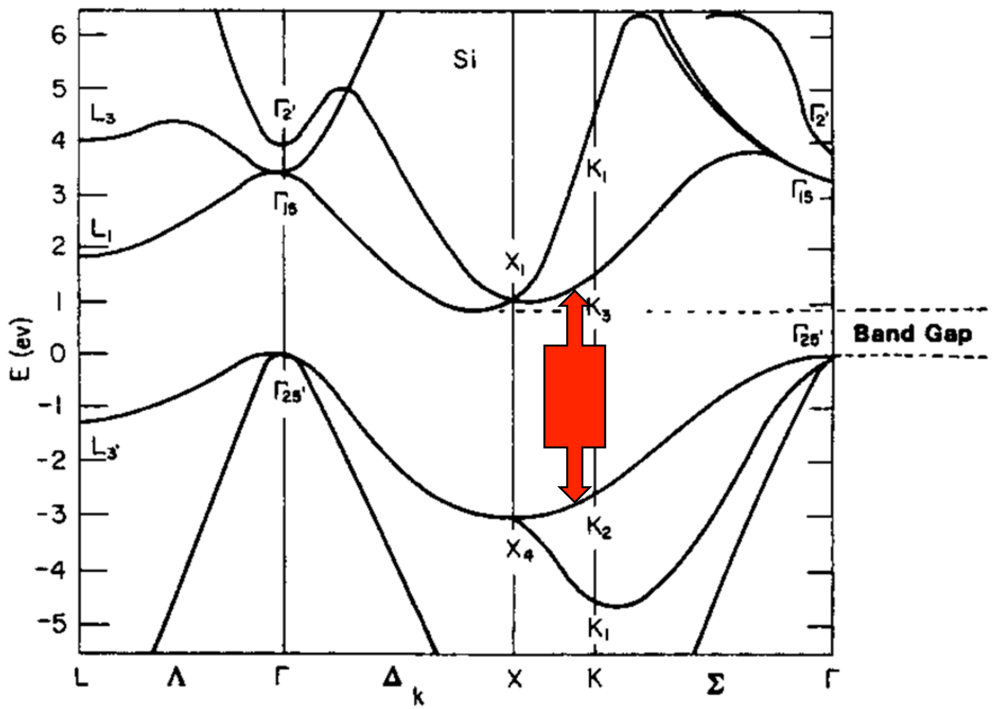
$$\frac{\partial \rho}{\partial t} = -\frac{i}{\hbar}[H, \rho] + \frac{1}{\hbar}\frac{\partial \rho}{\partial \mathbf{k}} \cdot e\mathbf{E} - \frac{\rho - \rho_0}{\tau}$$

Quantum Kinetic Equation

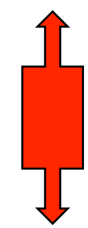
Driving Term

Relaxation Time Approximation

Response of Insulator to static Electric Field

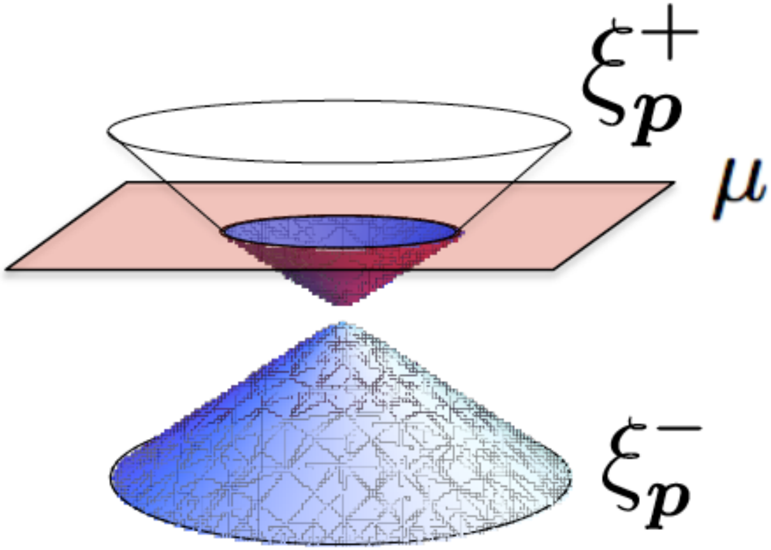


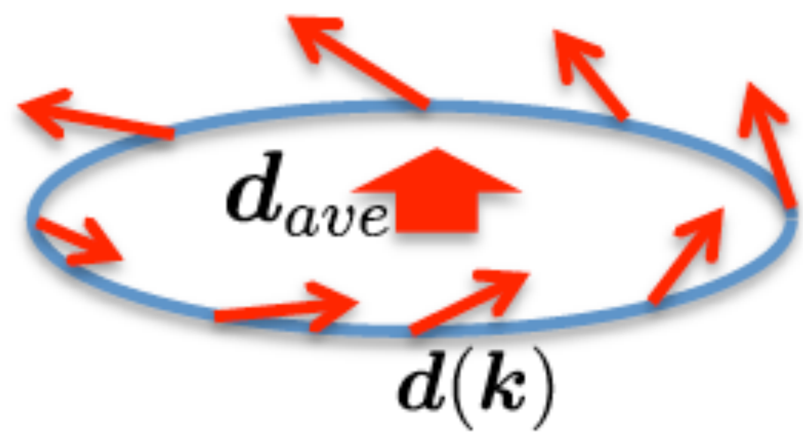
Interband Transitions



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

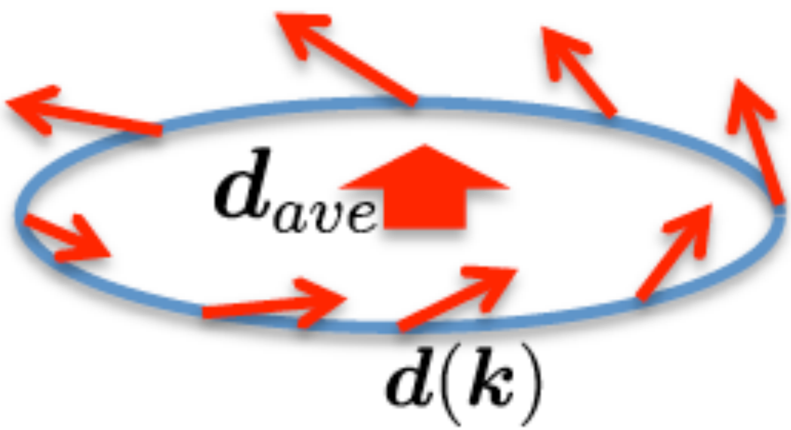
Topological Insulators
A Model Spin-Orbit-Torque System

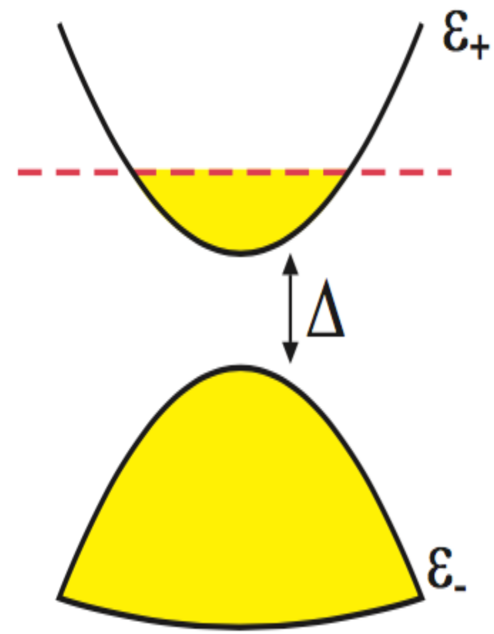




$$\hat{\mathcal{H}} = v(-p_x\hat{\sigma}_2 + p_y\hat{\sigma}_1) + \Delta\hat{\sigma}_3$$

Massive Dirac Model for Current-Induced Spin Density





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

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

Electric Field Induced Spin Densities

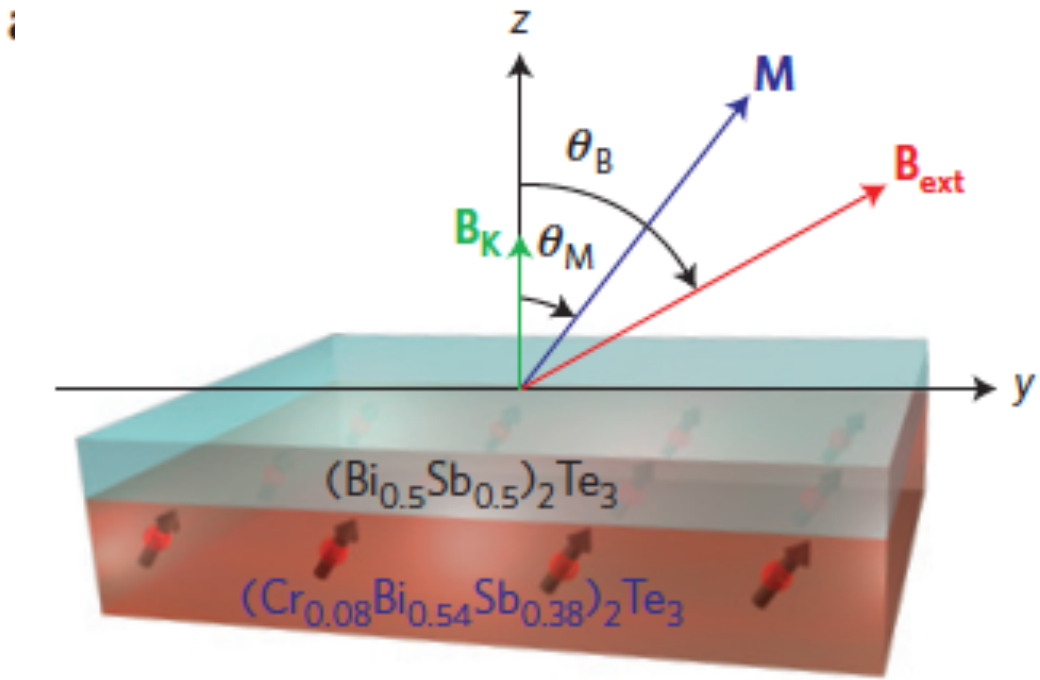
$$S_y/n \approx (e\,E\,a)/(\hbar/\tau) \times (1/k_F a)$$

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



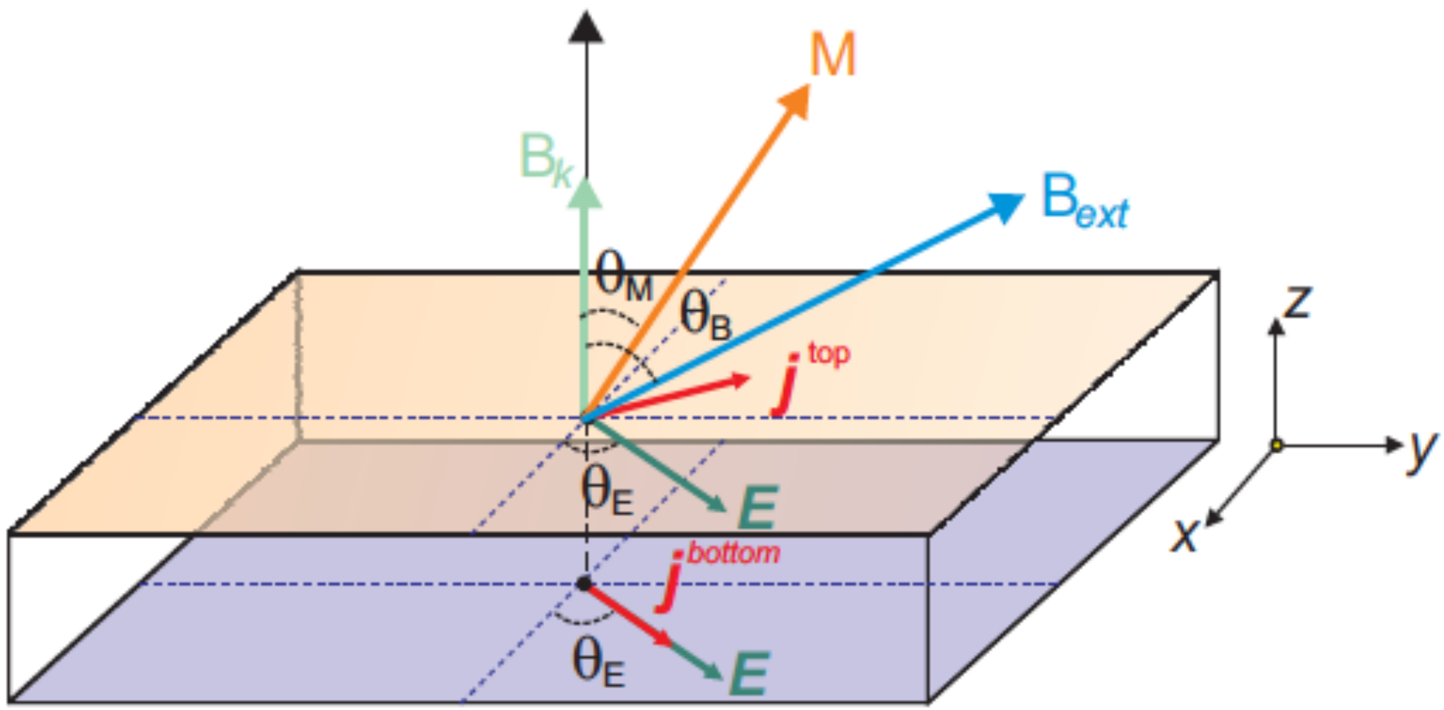
Experiment:

$\Delta\,(s^z_{tr}/S) \approx 10^{-6}$ eV

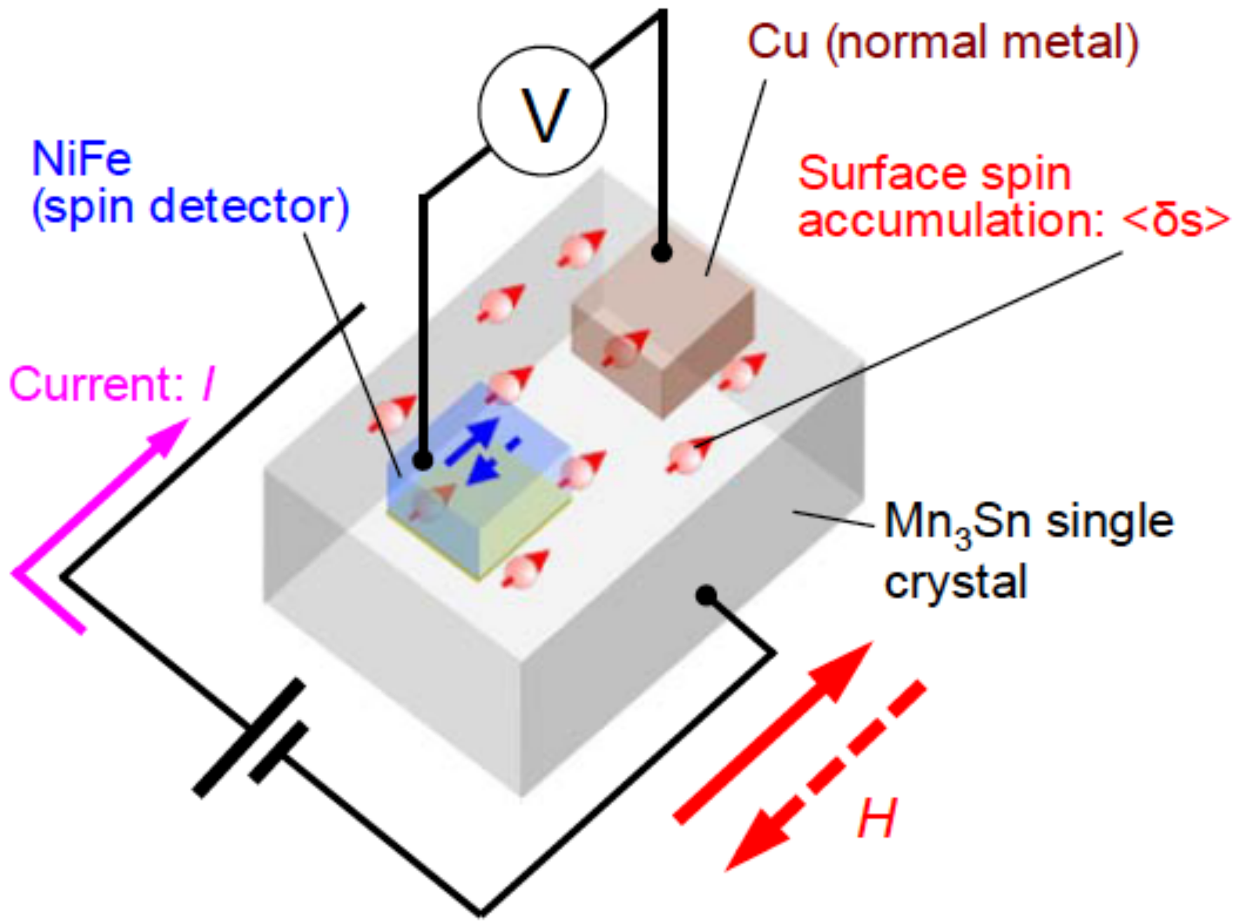
$\gg \Delta\,(s^y_{tr}/S)$

Fan et al., Nature Mat. (2014)

Spin-Orbit Torques in TI Ferromagnets

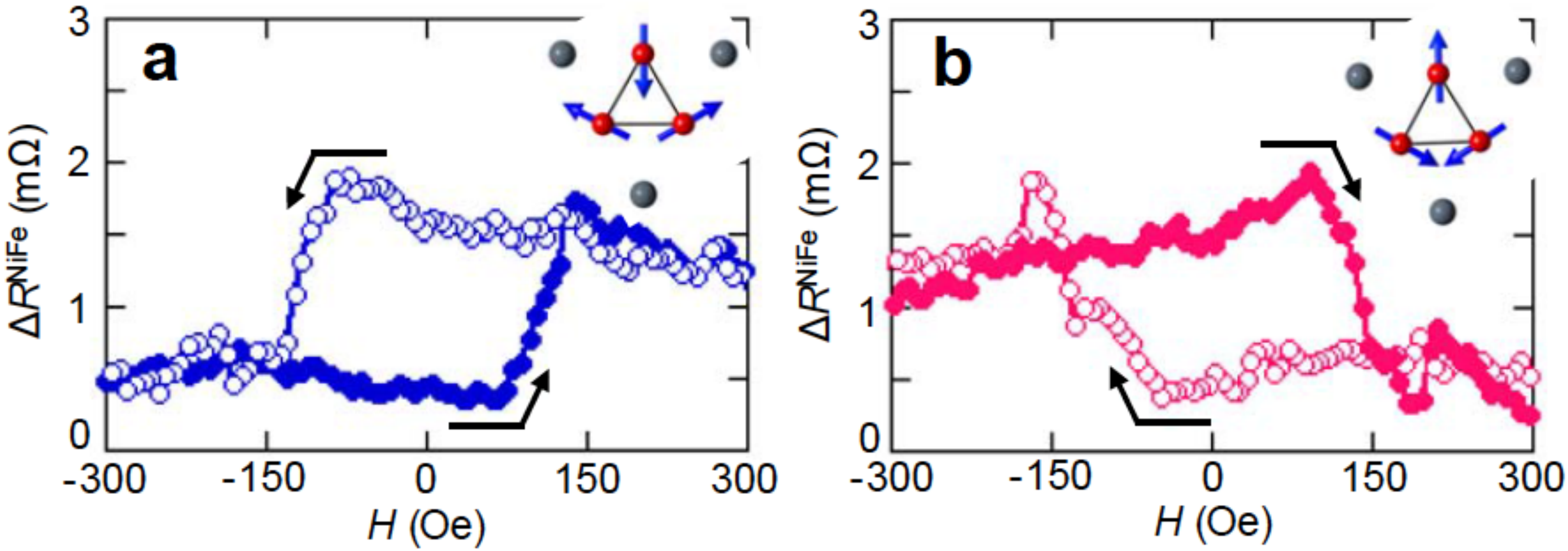


Mn_3Sn Spintronics



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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