Title: The Quantum Hall Effect and Spintronics

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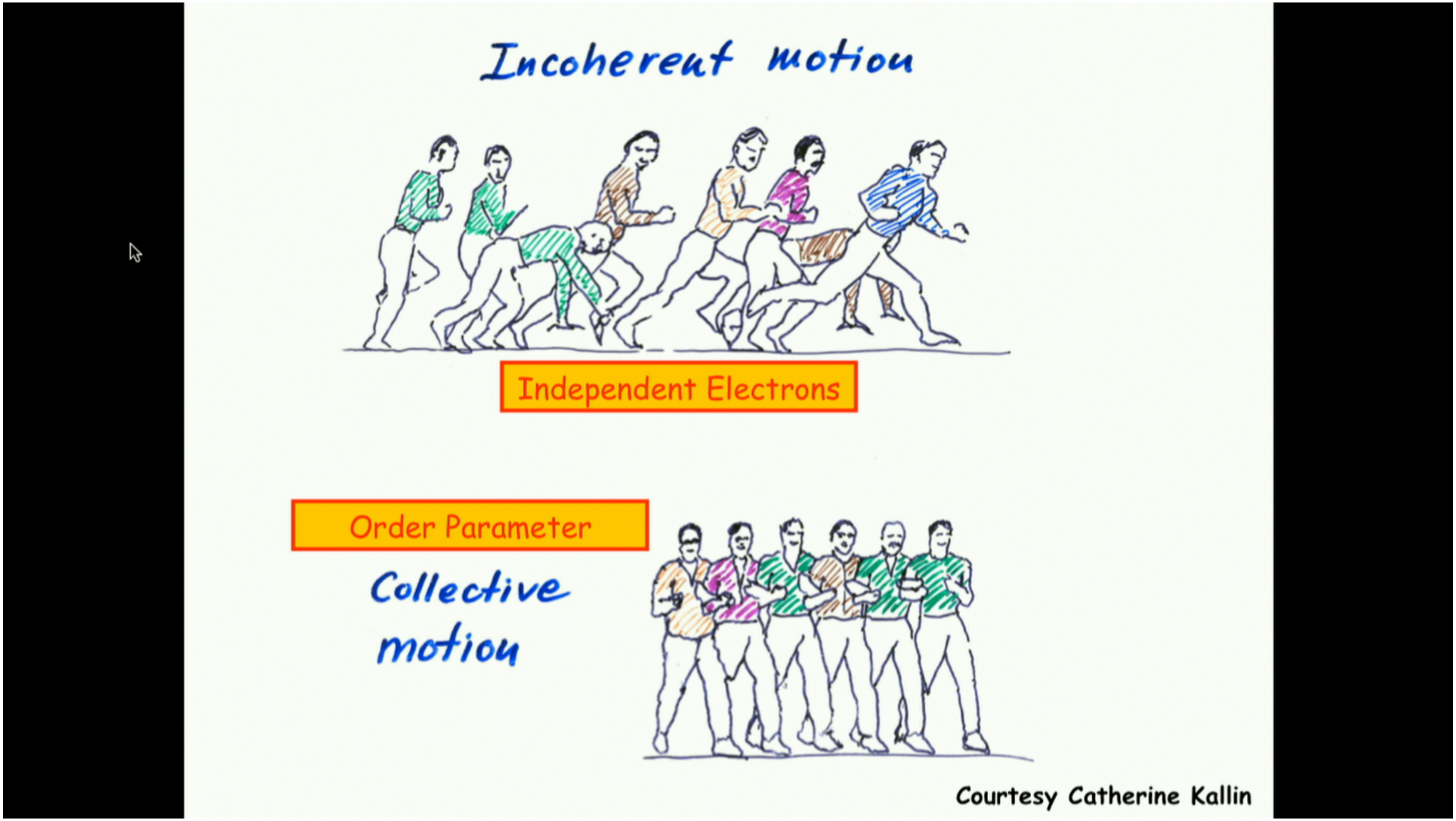
Abstract: A series of fundamental discoveries over the past thirty years has dramatically improved our ability to read, write, and process magnetically stored information. I will briefly review some of these advances before focusing on the recently discovered and particularly promising spin-orbit torques which act on the collective spin of thin film magnetic conductors when they are placed on a substrate with strong spin-orbit interactions. Spin-orbit torques are normally interpreted in terms of the spin Hall effect, spin-current that flows perpendicular to charge current in any conductor. The spin-Hall effect in the best spin-orbit torque materials is thought to have a large contribution from states away from the Fermi energy that is insensitive to disorder and therefore referred to as intrinsic. I will argue that the physics of the intrinsic spin Hall effect is quite closely related to the physics of the quantum Hall effect, and on this basis speculate on strategies to find the material combinations that optimize the spin-orbit torque effect.

4-Corners Symposium 2015

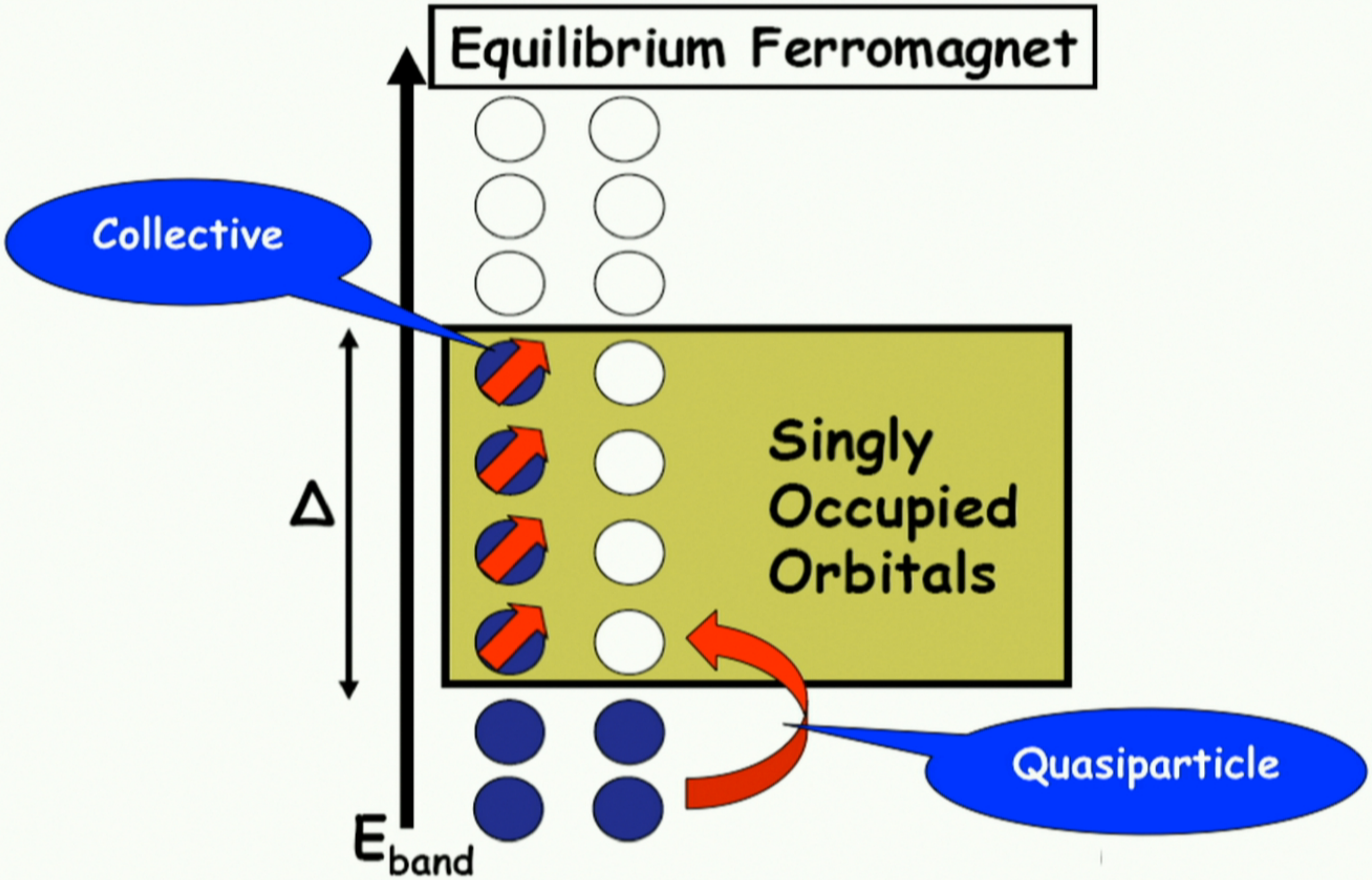
The Quantum Hall Effect & Spintronics

Allan MacDonald – UT Austin

Magnetism and Spintronics

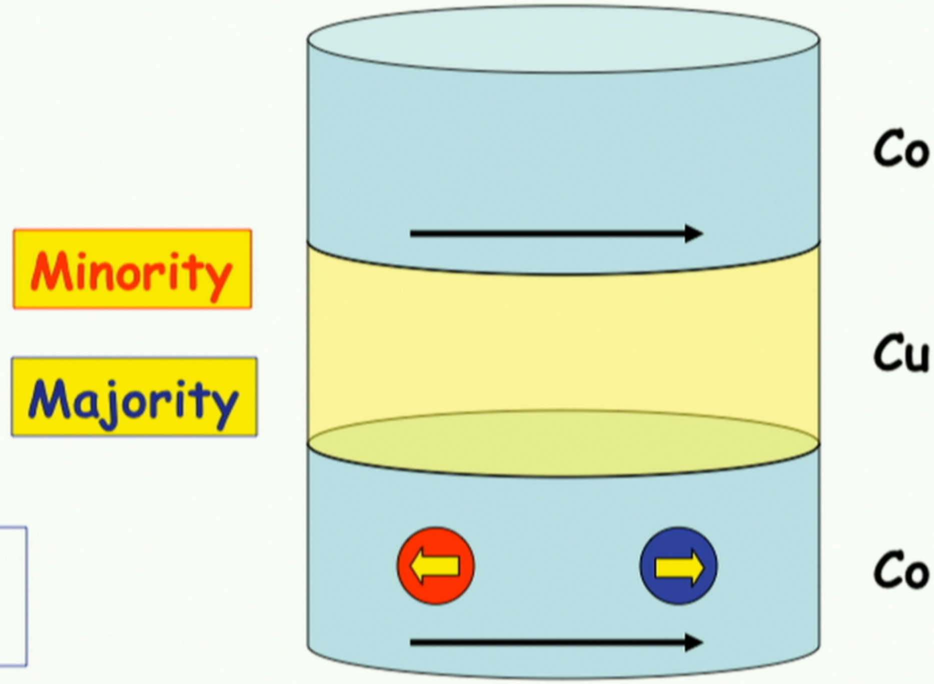

Incoherent motion
Independent Electrons
Order Parameter
Collective motion
Courtesy Catherine Kallin

Collective and Quasiparticle



Two-Channel Conduction
&
CPP GMR

Neville Mott
1905-1996



Landau-Liftshitz-Gilbert

$$\frac{\partial \hat{m}}{\partial t} = \hat{m} \times \left(-\frac{\delta E[\hat{m}]}{\hbar \delta \hat{m}} \right) - \alpha \hat{m} \times \frac{\partial \hat{m}}{\partial t} + \left. \frac{\partial \hat{m}}{\partial t} \right|_{\mathrm{STT}}$$

Damping

Precession

Current-Induced Torques

Landau-Liftshitz-Gilbert

Damping

$$\frac{\partial \hat{m}}{\partial t} = \hat{m} \times \left(-\frac{\delta E[\hat{m}]}{\hbar \delta \hat{m}} \right) - \alpha \hat{m} \times \frac{\partial \hat{m}}{\partial t} + \left. \frac{\partial \hat{m}}{\partial t} \right|_{\mathrm{STT}}$$

Precession

Current-Induced Torques

Spin-Transfer Torques

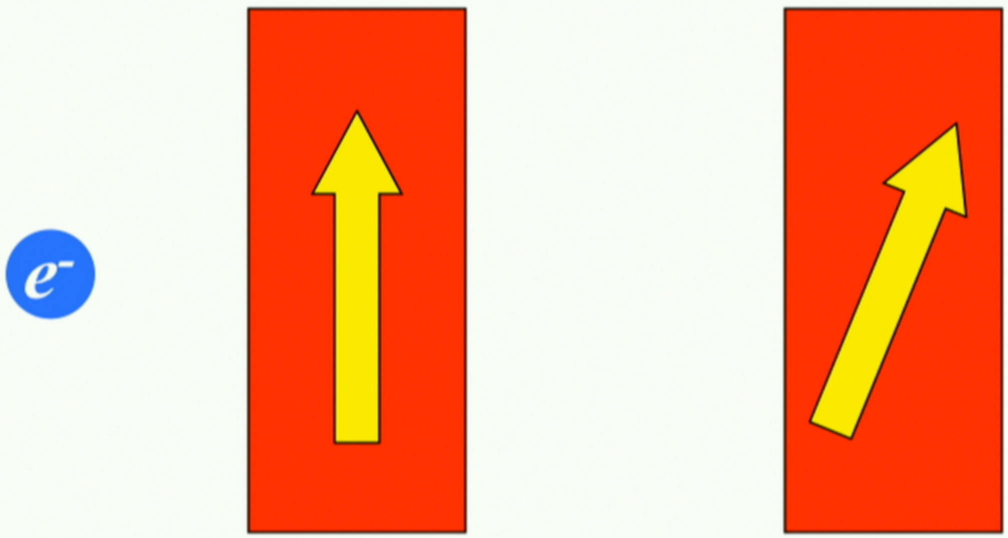
$$\frac{ds_{\alpha,j}(\vec{r})}{dt} = \nabla_i J^i_{\alpha,j}(\vec{r}) + \frac{1}{\hbar}\left[\vec{\Delta} \times \vec{s}_\alpha(\vec{r})\right]_j$$

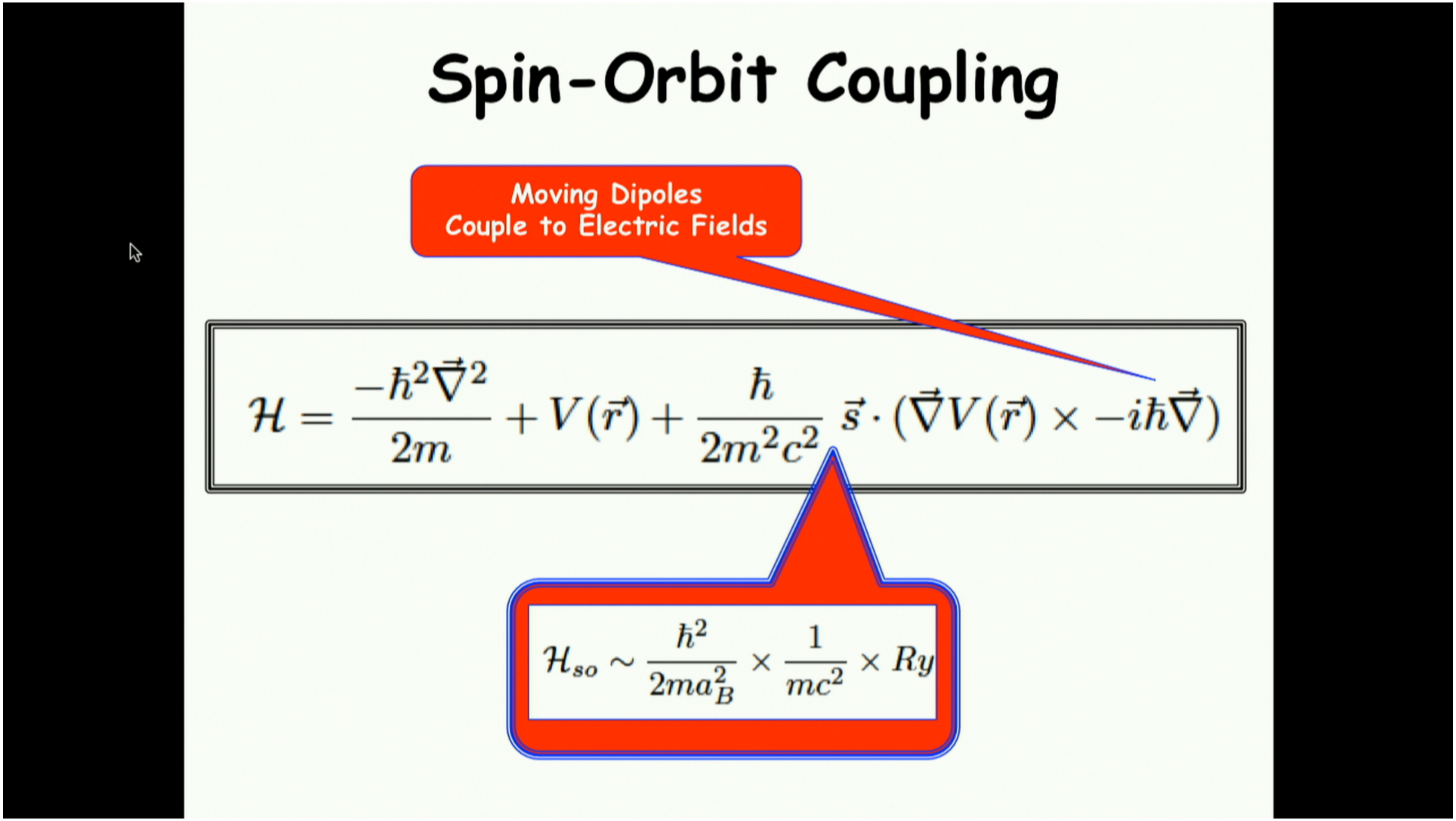
0

$$\frac{dm_j(\vec{r})}{dt} = \sum_\alpha \nabla_i J^i_{\alpha,j}(\vec{r}) + \frac{1}{\hbar}\left[\vec{\Delta} \times \vec{m}(\vec{r})\right]_j$$

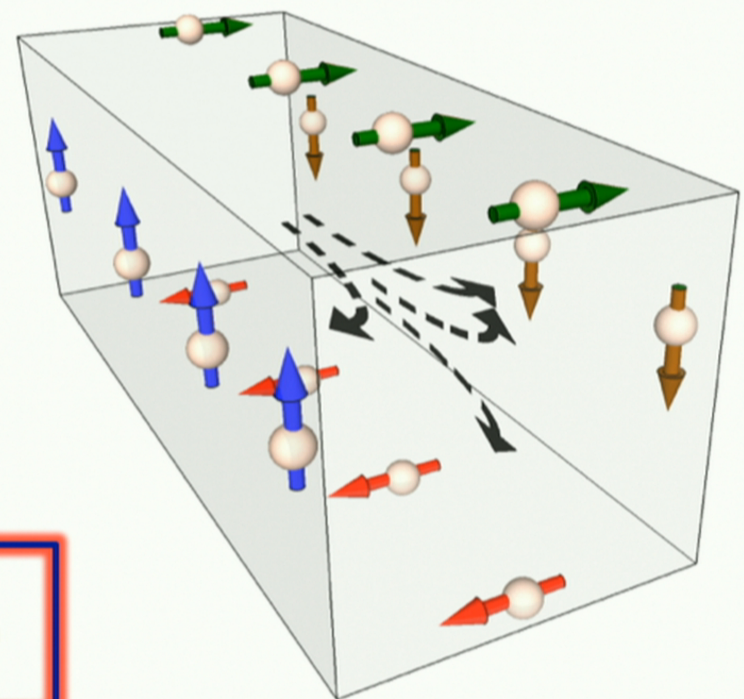
Spin transfer torques

Experiment: M. Tsoi et al., PRL 80, 4281 (1998)
Theory: J.C. Slonczewski, J. Mag. Mat. Mag. 159, L1 (1996).



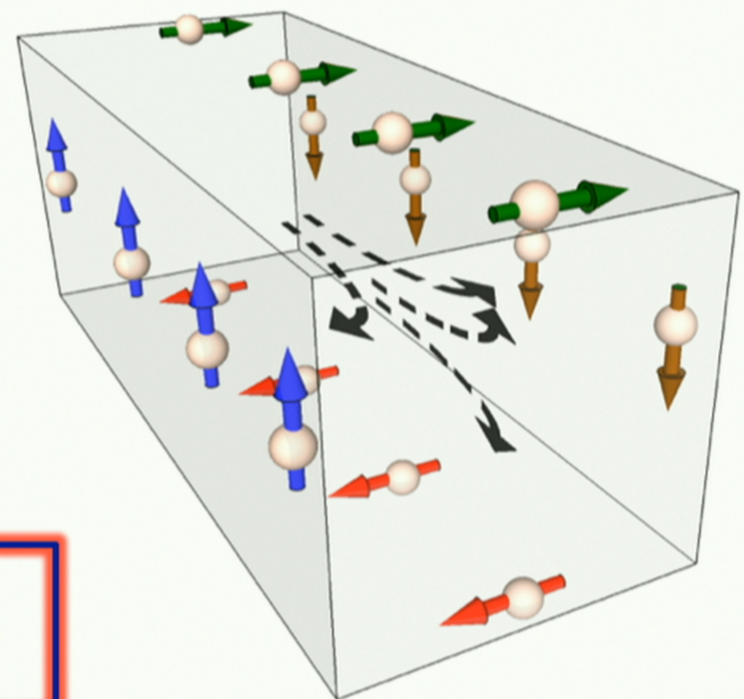

Spin-Orbit Coupling
Moving Dipoles
Couple to Electric Fields
$\mathcal{H} = \frac{-\hbar^2\vec{\nabla}^2}{2m} + V(\vec{r}) + \frac{\hbar}{2m^2c^2}\,\vec{s}\cdot(\vec{\nabla}V(\vec{r}) \times -i\hbar\vec{\nabla})$
$\mathcal{H}_{so} \sim \frac{\hbar^2}{2ma_B^2} \times \frac{1}{mc^2} \times Ry$

Spin Hall Effect



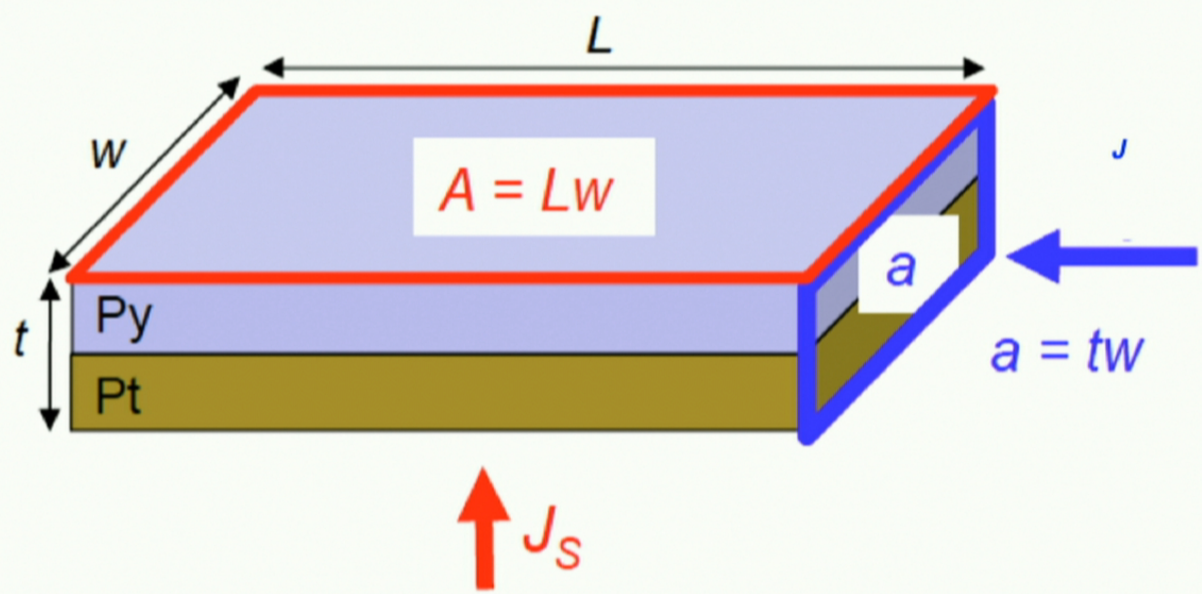
Dyakonof Perel (1971)
Murakami et al. (2003)
Sinova et al. (2004)

Spin Hall Effect



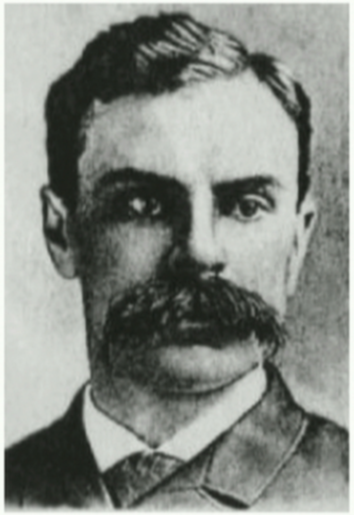
Dyakonof Perel (1971)
Murakami et al. (2003)
Sinova et al. (2004)

The L/t Advantage



Quantum Hall Effect

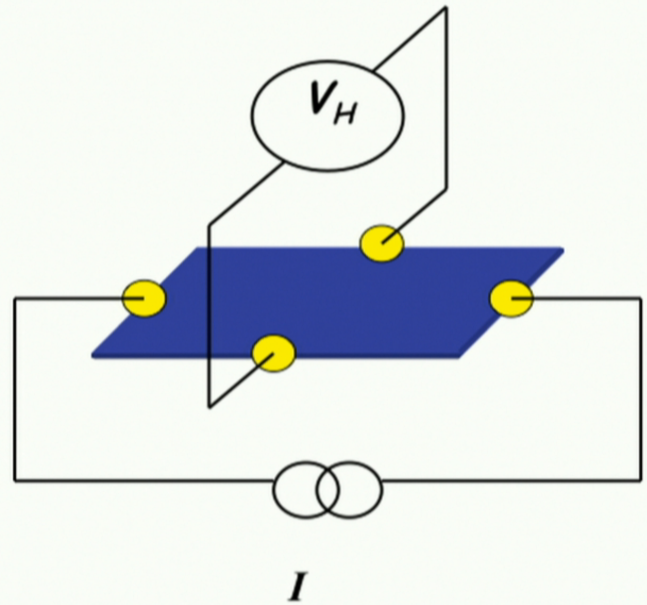
The Hall Effect



Edwin Herbert Hall

On the New Action of Magnetism on a Electric Current, PhD Thesis, The Johns Hopkins University, 1880. Phil Mag. 1880.

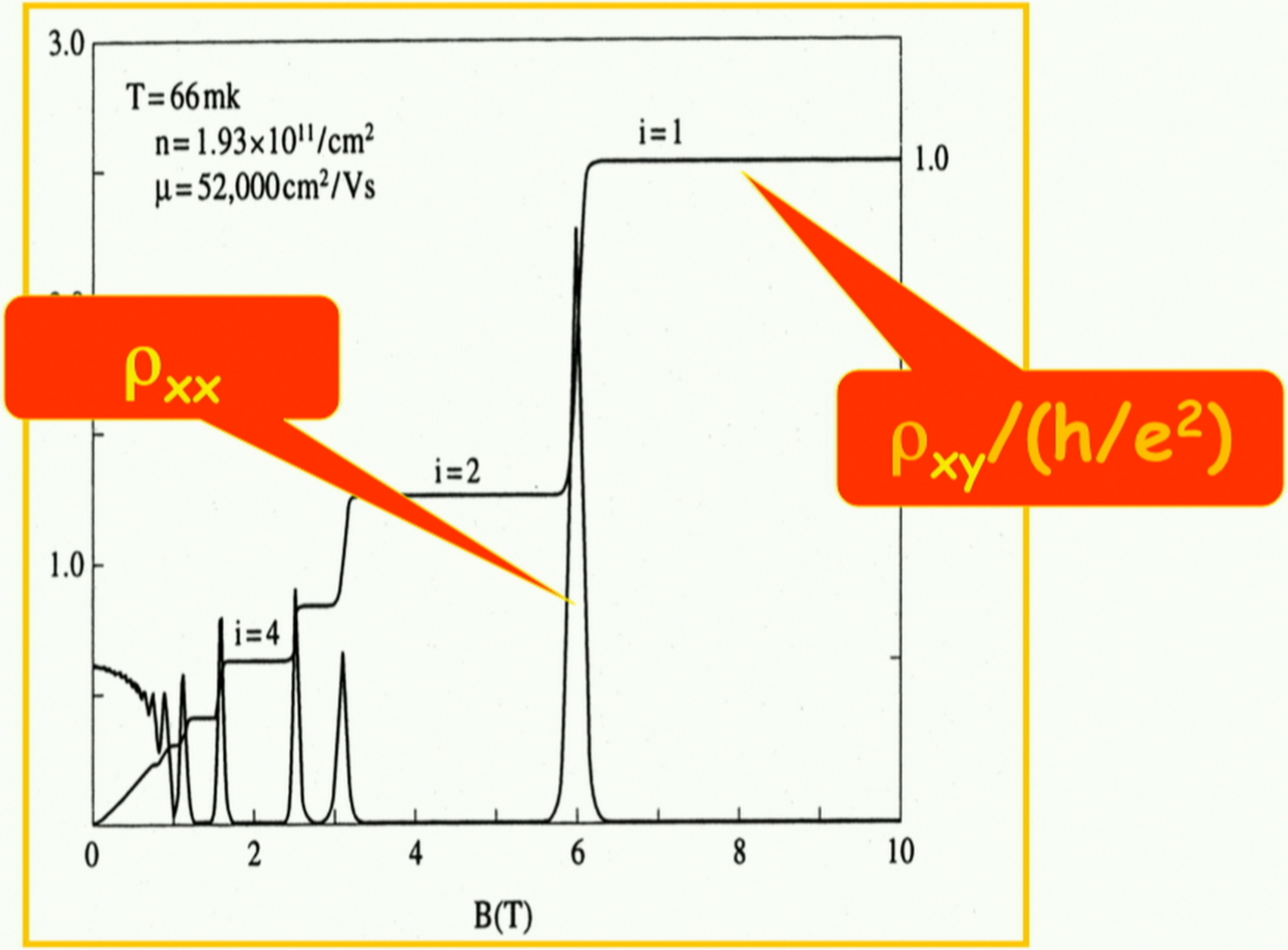
Anomalous Hall Effect



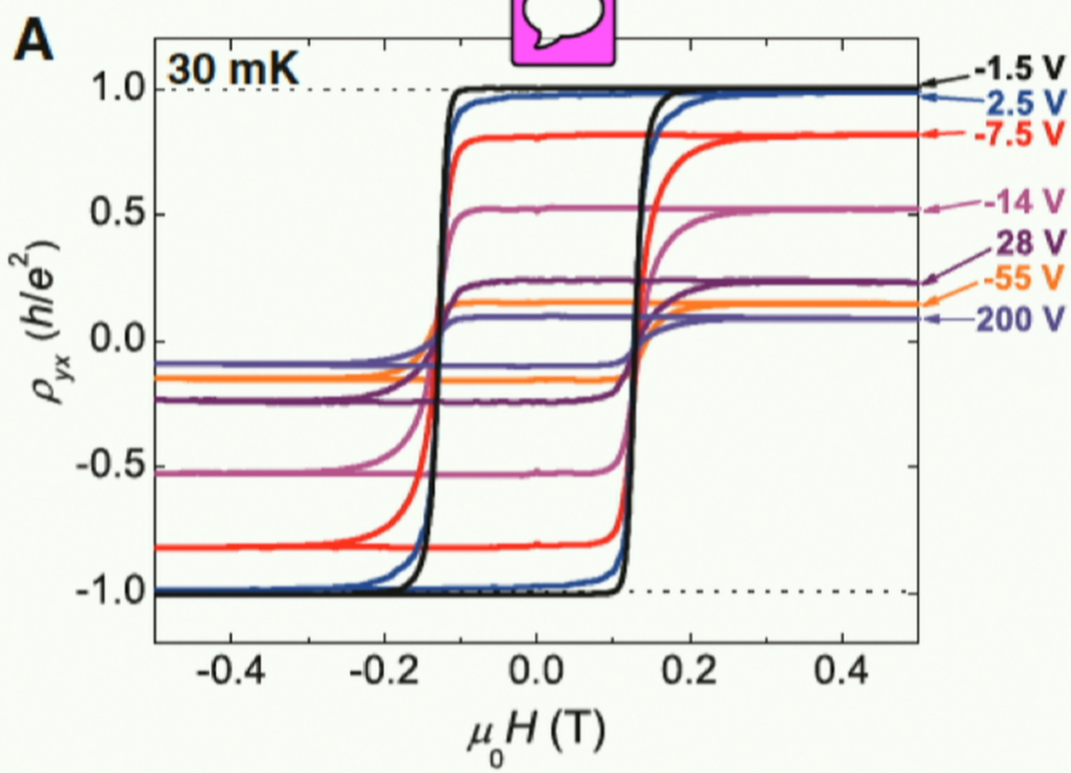
Ordinary Anomalous

$$\rho_{xy} = R_0 B + \rho'_{xy}$$

Quantum Hall Effect



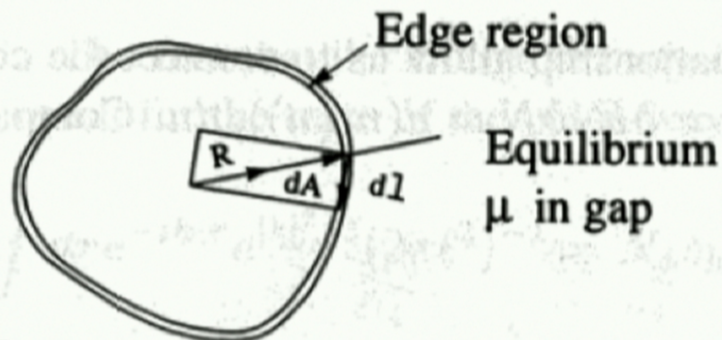
Quantized Anomalous Hall

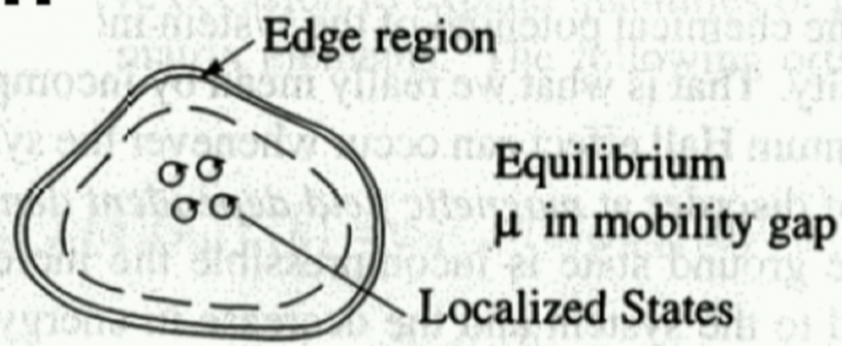


Xue Group - Tsinghua U

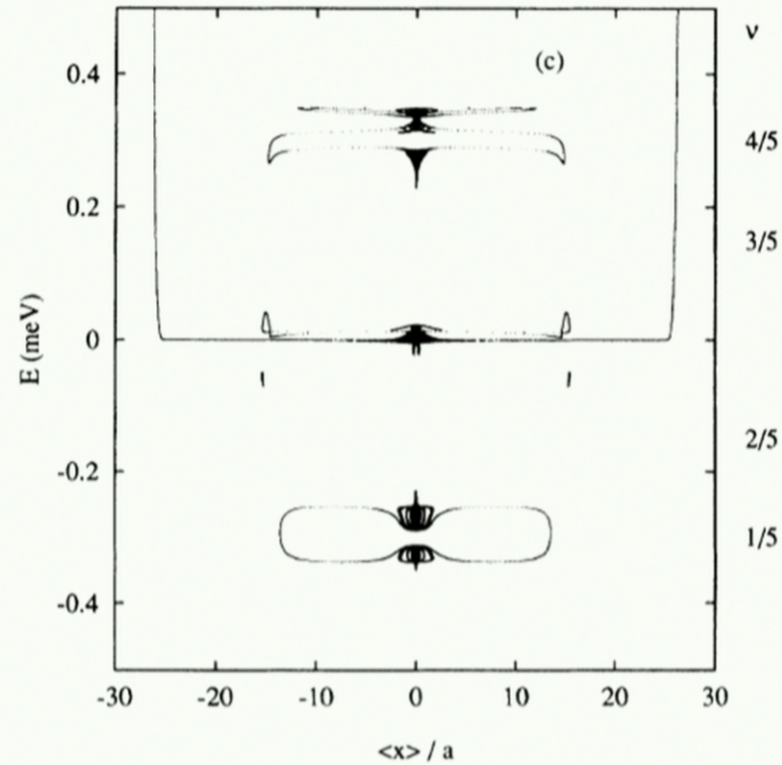
QHE and Edge States

$\delta I/\delta\mu = e\sigma/h$



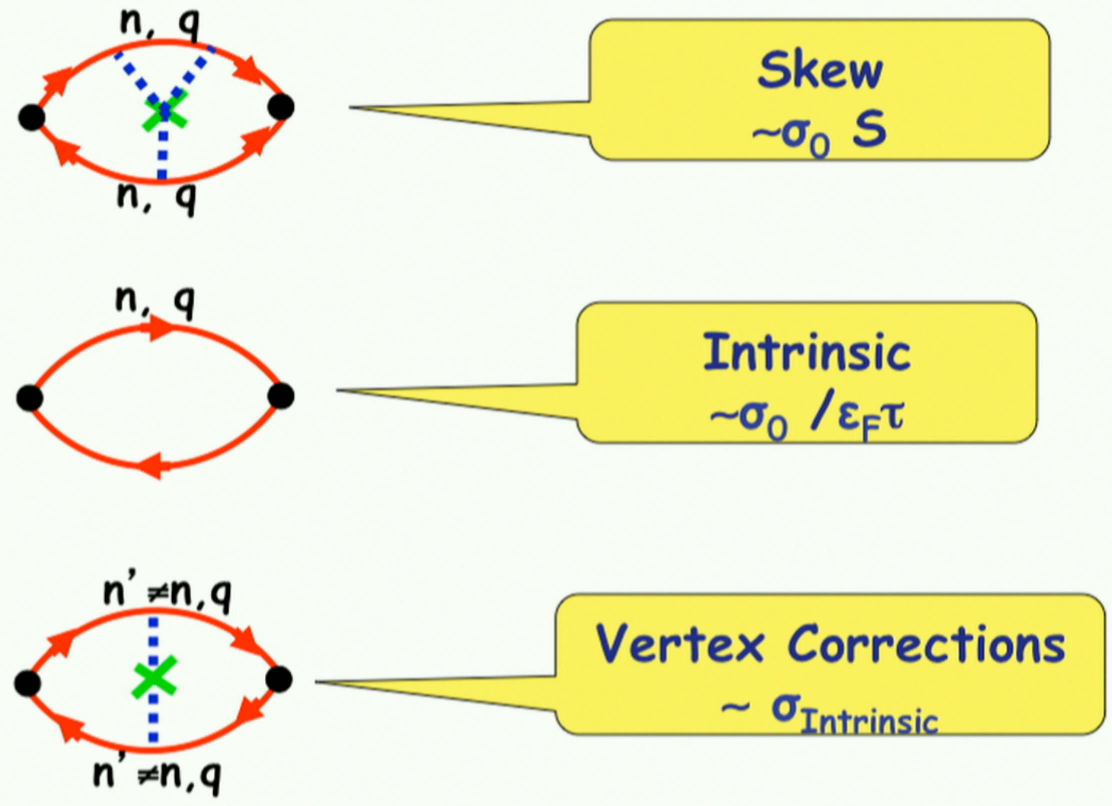


QHE + edge states



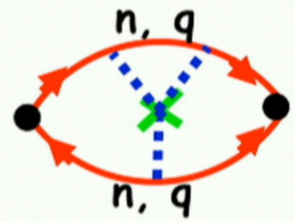
Streda et al. PRB (1994)

AHE - Theory

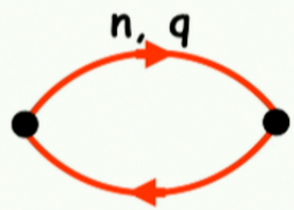


n, q
n, q
Skew
$\sim\sigma_0\ S$
n, q
Intrinsic
$\sim\sigma_0\ /\varepsilon_F\tau$
n' ≠n,q
n' ≠n,q
Vertex Corrections
$\sim\ \sigma_{Intrinsic}$

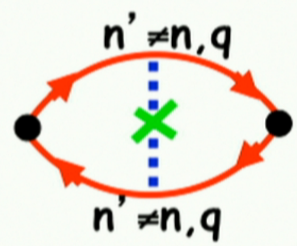
AHE - Theory



Skew
$\sim\sigma_0 \, S$

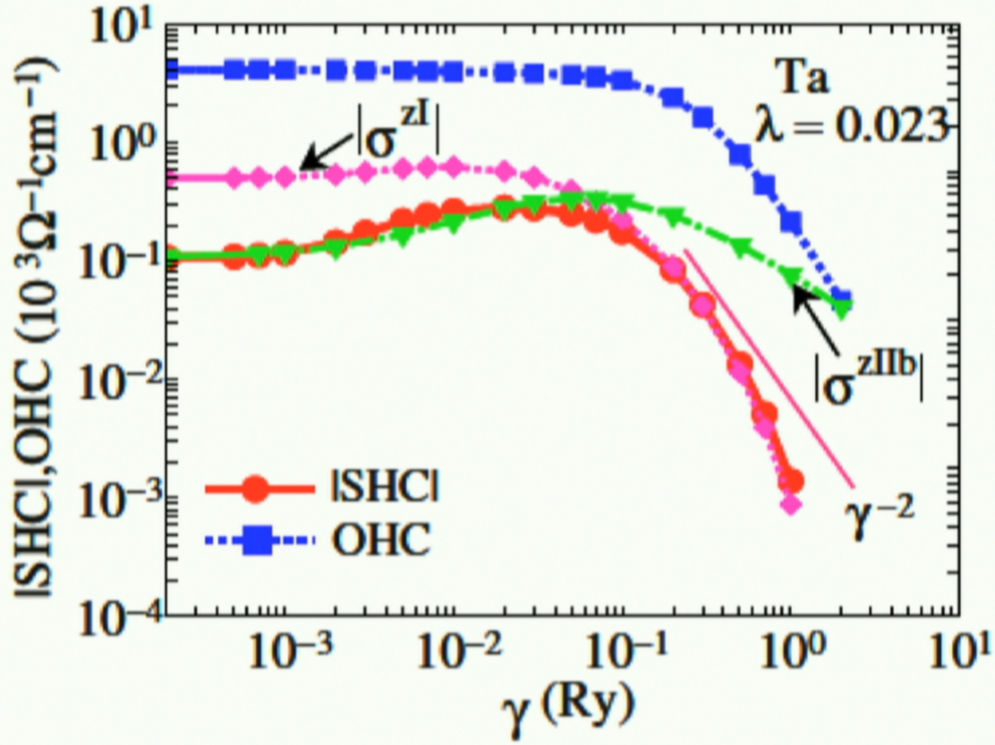


Intrinsic
$\sim\sigma_0 \, / \varepsilon_F \tau$



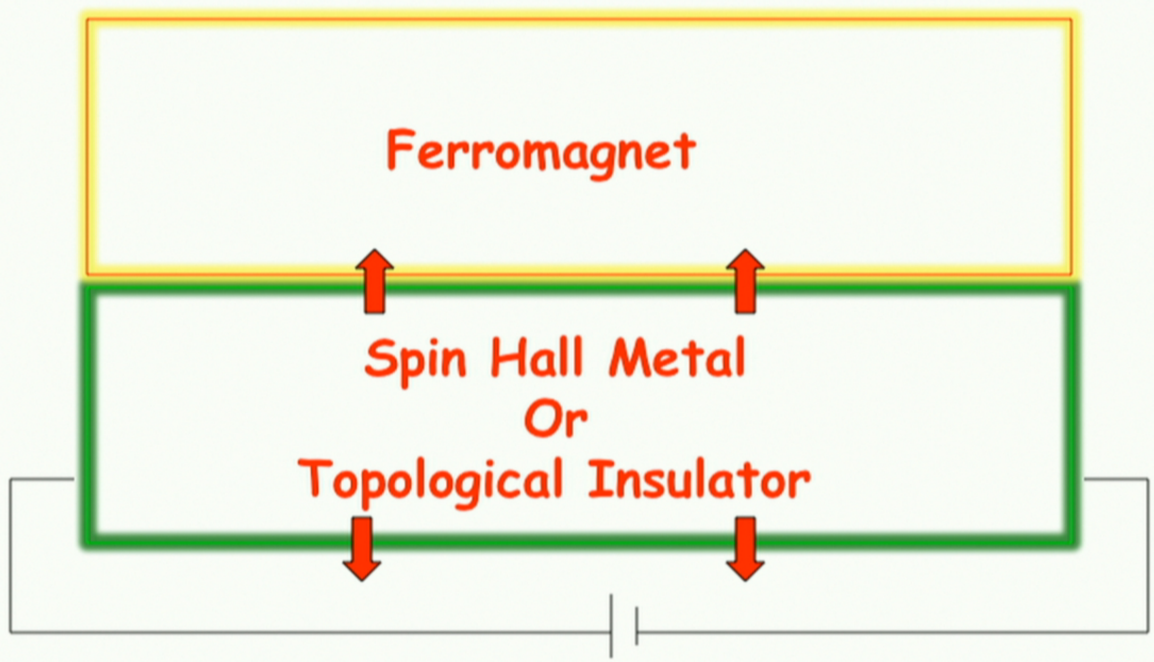
Vertex Corrections
$\sim \sigma_{Intrinsic}$

5d Intrinsic SHE



Tanaka et al. PRB (2008)

Spin-Orbit Torques and Edge States



Spin-Orbit Torque Transistor

Spin Hall Transistor- III