



**SMR 1760 - 15**

**COLLEGE ON  
PHYSICS OF NANO-DEVICES**

**10 - 21 July 2006**

***Introduction to Spintronics I:  
Metal spintronics***

Presented by:

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University of Texas at Austin, U.S.A

# Introduction to Spintronics

ICTP July 2006

University of Texas at Austin



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Tomas Jungwirth Brian Gallagher Paul Haney Juergen Koenig Hsiu-Hau Lin **Alvaro Nunez**  
Enrico Rossi Nitin Samarth Peter Schiffer John Schliemann Jairo Sinova Maxim Tsoi



- I Metal Spintronics
- II Magnetic Semiconductors
- III Spin-Orbit Coupling

A Few Remarks About

Magnetism

and

Magnetotransport

in Metals

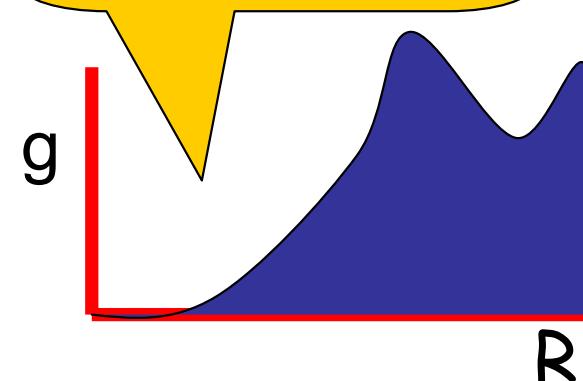
# Electrons are Fermions

$$\Psi(1, 2, \dots, N) = \det \begin{pmatrix} \phi_1(1) & \phi_2(1) & \cdots & \phi_N(1) \\ \phi_1(2) & \phi_2(2) & \cdots & \phi_N(2) \\ \cdots & \cdots & \cdots & \cdots \\ \phi_1(N) & \phi_2(N) & \cdots & \phi_N(N) \end{pmatrix}$$

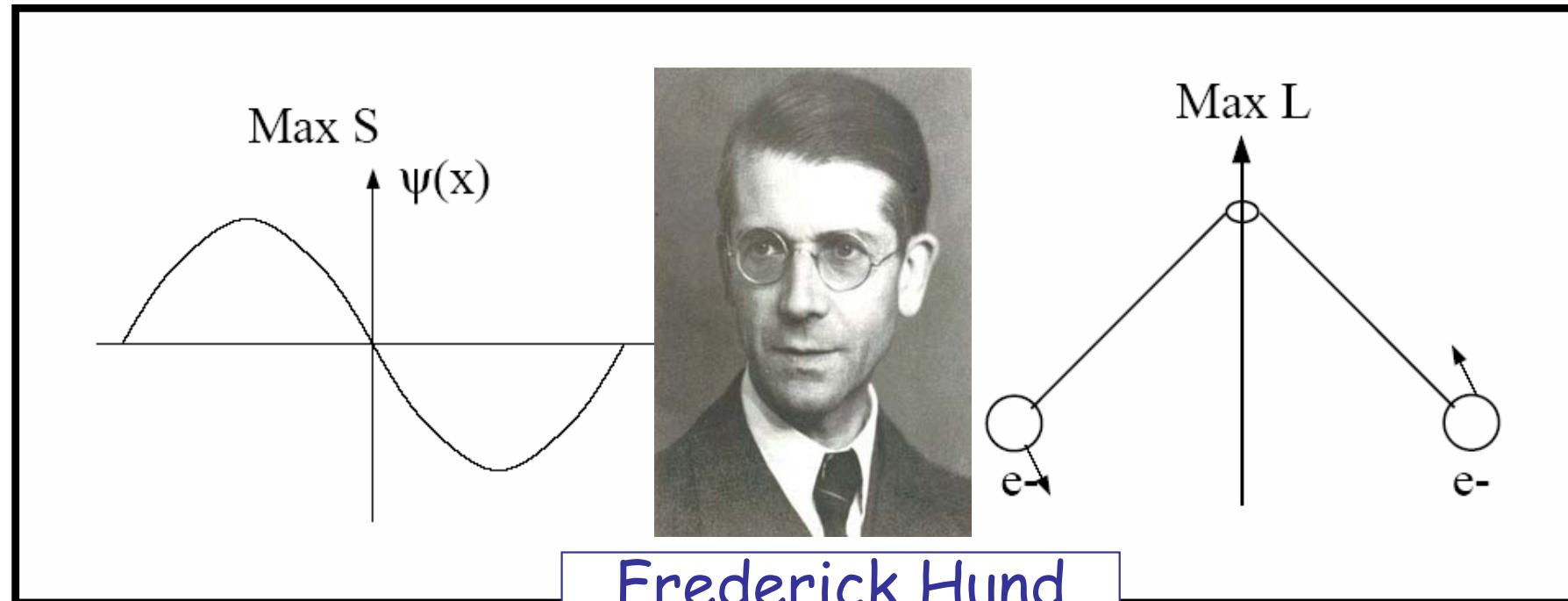
Slater  
Determinant

Exchange  
Hole

$$\rho^{(2)}(\vec{r}, \uparrow; \vec{r}, \uparrow) \equiv 0$$



# Magnetism in Atomic Physics

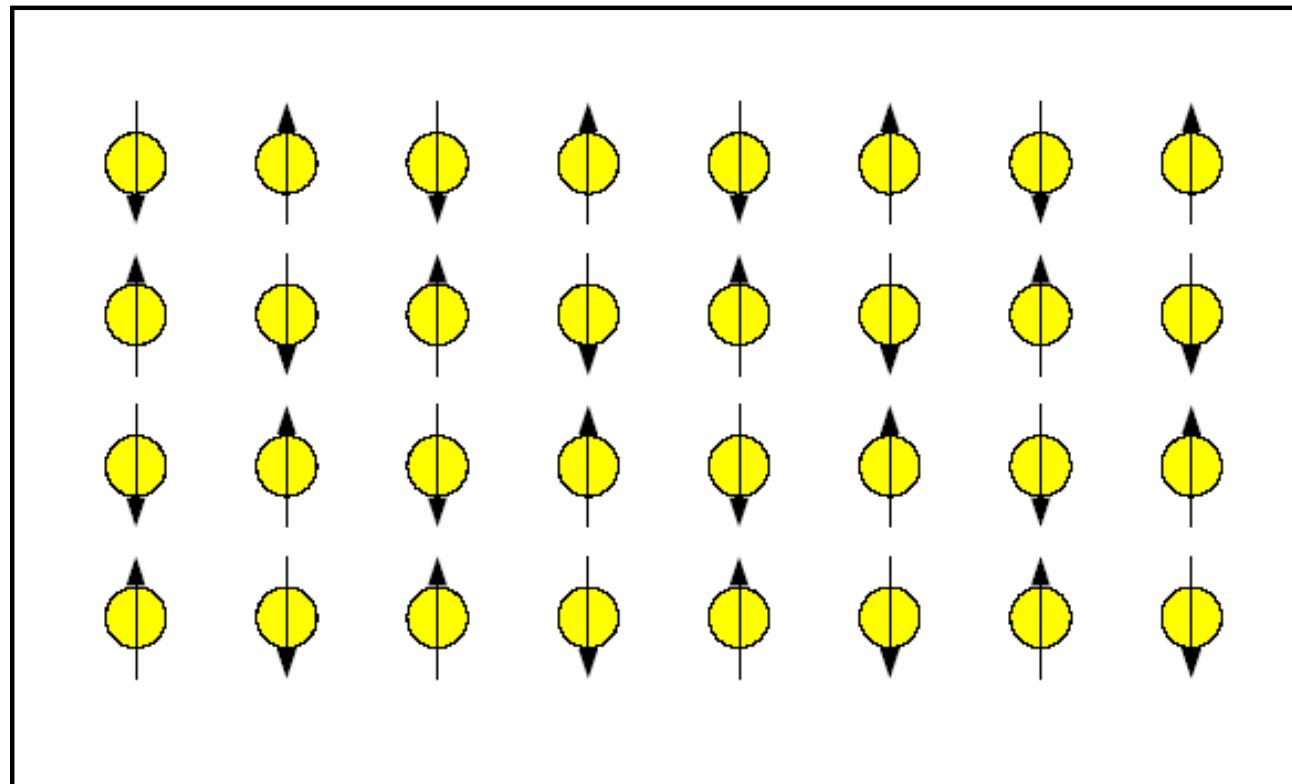


Frederick Hund  
1896-1997

Electrons in Atomic Open Shells are Fermions - Hund's Rules

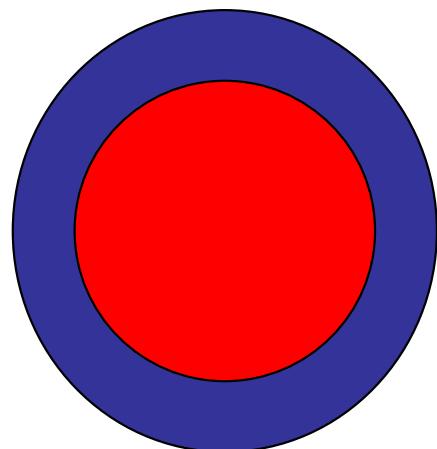
Magnetism due to Fermi Statistics and spin-independent interactions  
Make all orbitals in an open shell as similar to each other as possible

# Magnetism in Insulators

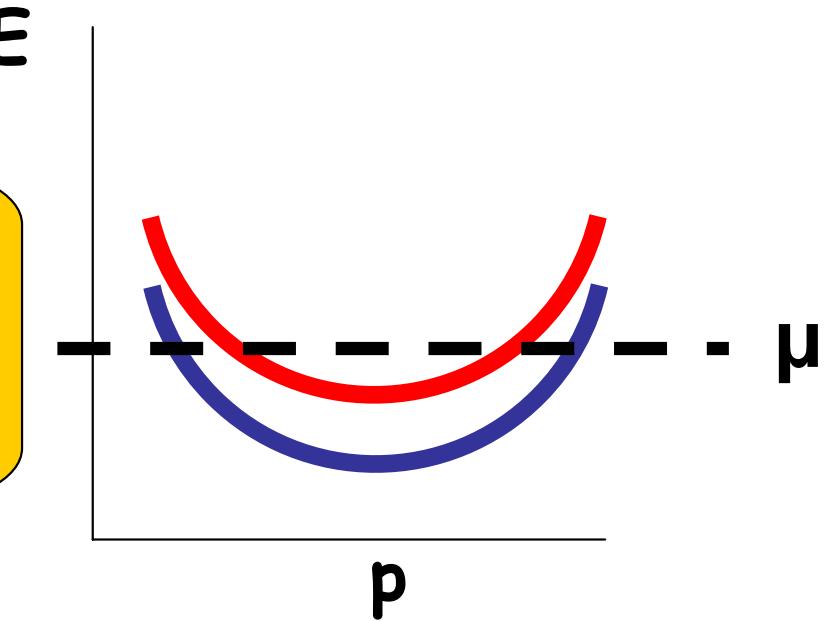


A playground for strongly-correlated electron physics

# Magnetism in an Electron Gas



Majority & Minority Fermi Surfaces



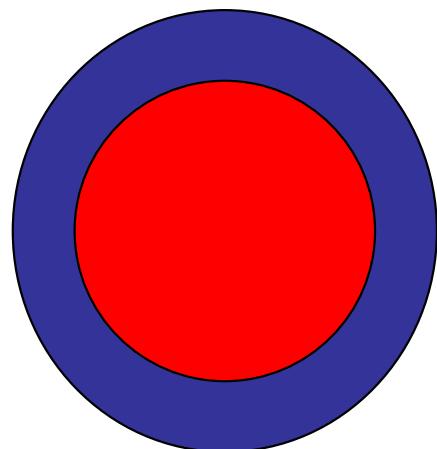
$$E_X = - \sum_{\vec{k}, \sigma} n_{\vec{k}, \sigma} \left[ \frac{1}{2V} \sum_{\vec{k}'} n_{\vec{k}', \sigma} \frac{4\pi e^2}{\epsilon |\vec{k} - \vec{k}'|^2} \right]$$

Exchange

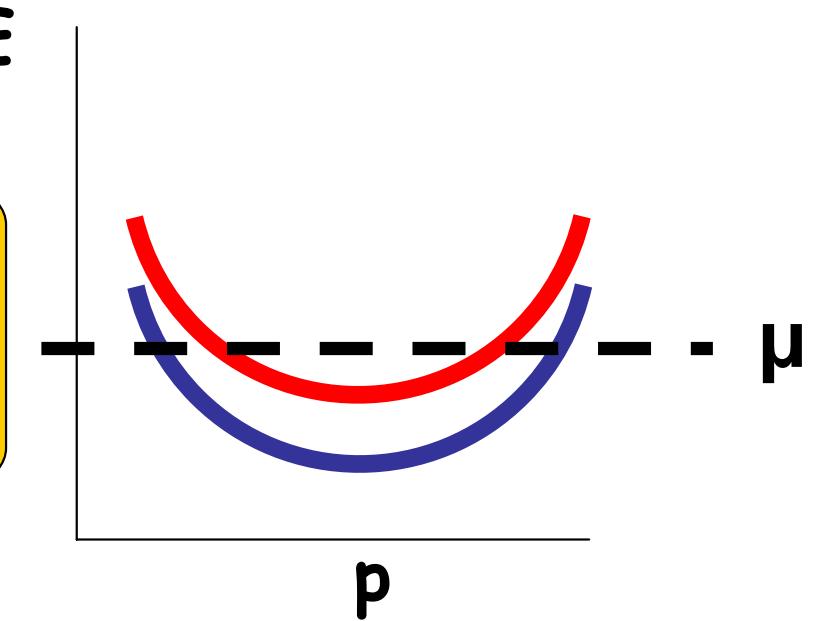
$$E_K = \sum_{\vec{k}, \sigma} n_{\vec{k}, \sigma} \frac{\hbar^2 k^2}{2m^*}$$

Kinetic (Band)

# Magnetism in an Electron Gas



Majority & Minority Fermi Surfaces



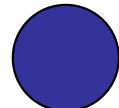
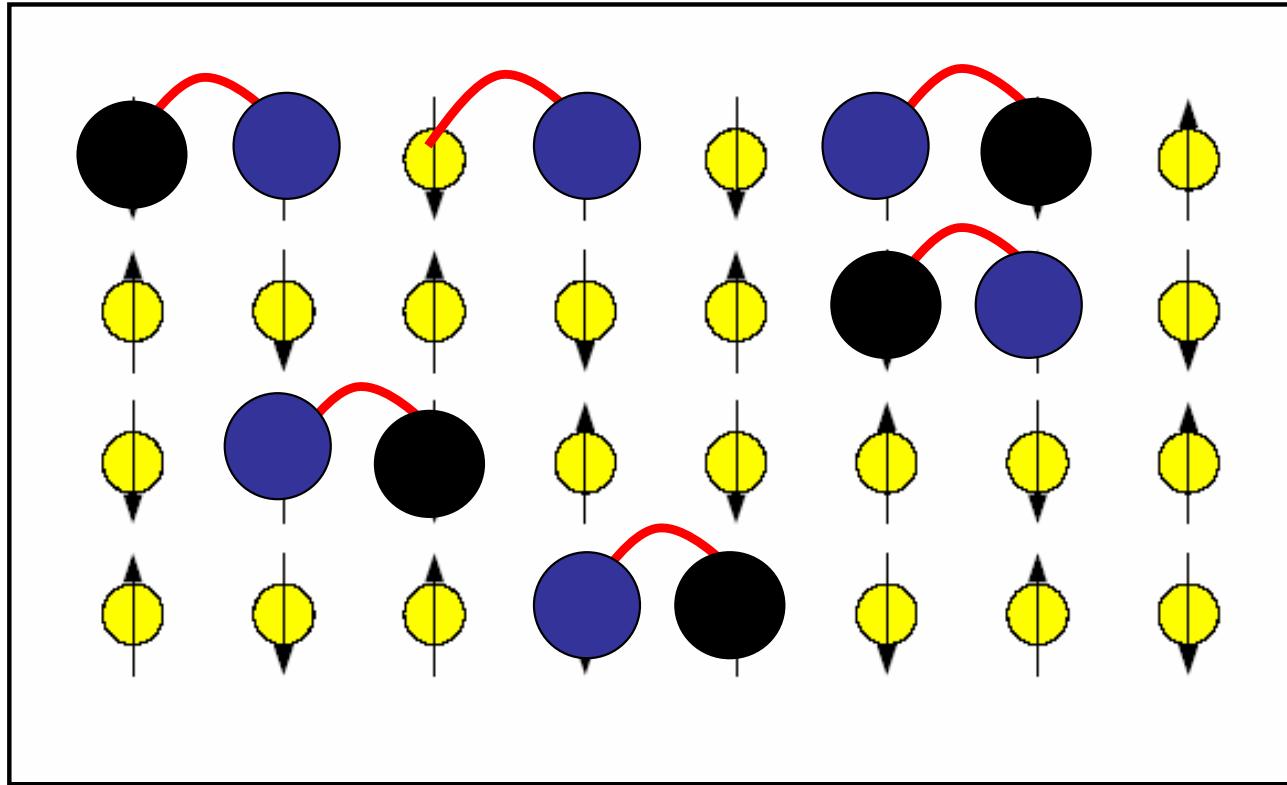
$$\sim \sum_{\sigma} \int^{k_F^{\sigma}} dk k^2 \times \frac{4\pi e^2}{k^2} \times k^3 \sim \sum_{\sigma} \frac{e^2}{\epsilon} k_{F\sigma}^4$$

Exchange

$$\sim \sum_{\sigma} \int^{k_F^{\sigma}} dk k^2 \times k^2 \sim \sum_{\sigma} \frac{\hbar^2}{2m^*} k_{F\sigma}^5$$

Kinetic (Band)

# Magnetism in Metals - Hubbard Picture



Doubles - Interaction Energy Cost  $U$

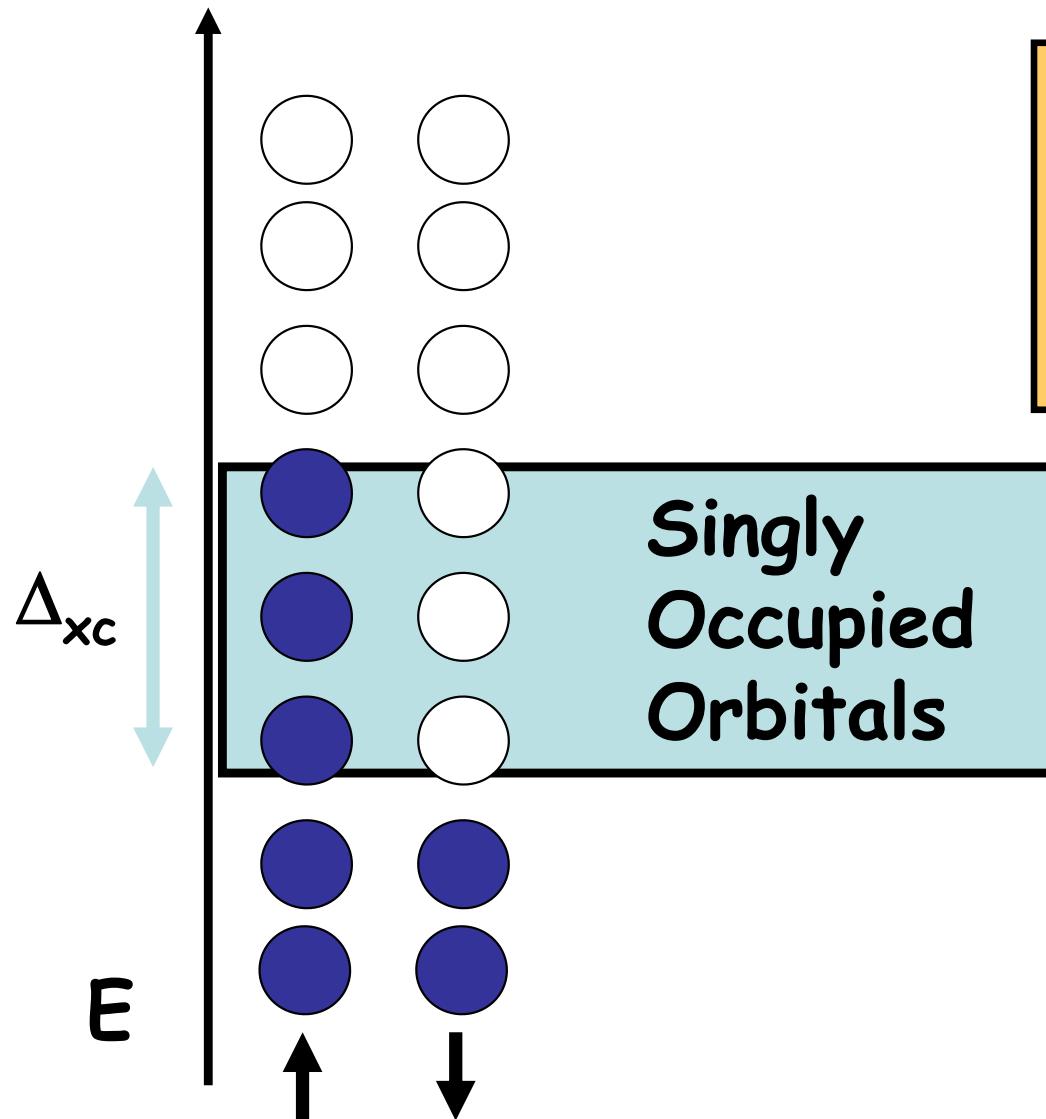


Empties

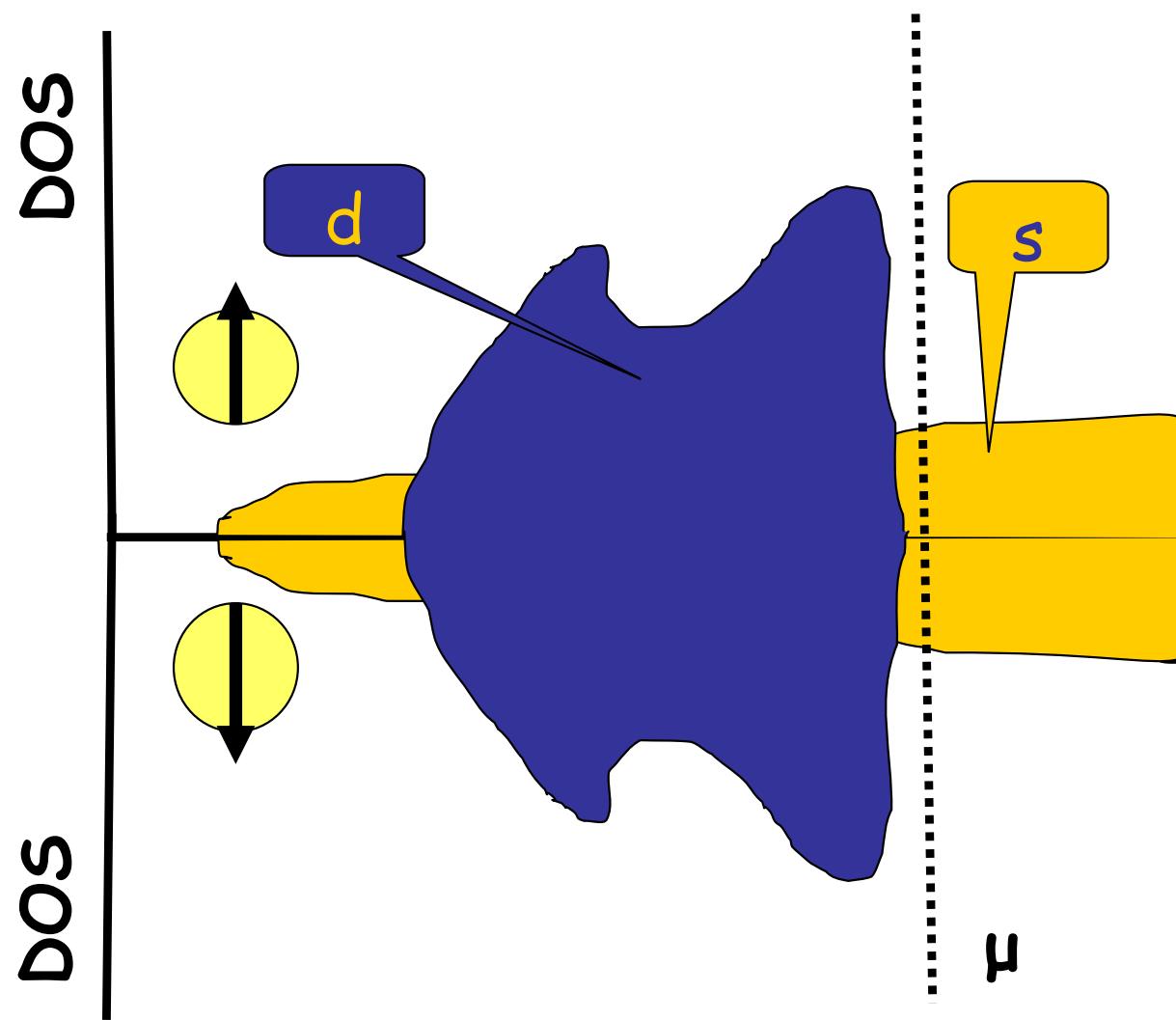
Simple model - Sophisticated QF Theory Possible

# Itinerant Electron Ferromagnetism

## Bloch-Stoner Picture



$$E = E_0 + M^2/D(E_F) - \Delta M^2$$



# Itinerant Electron Ferromagnetism Spin-Density Functional Theory

One very successful picture of transition metal ferromagnetism is Density Functional Theory.

Hohenberg-Kohn Theorem  
Kohn-Sham Trick

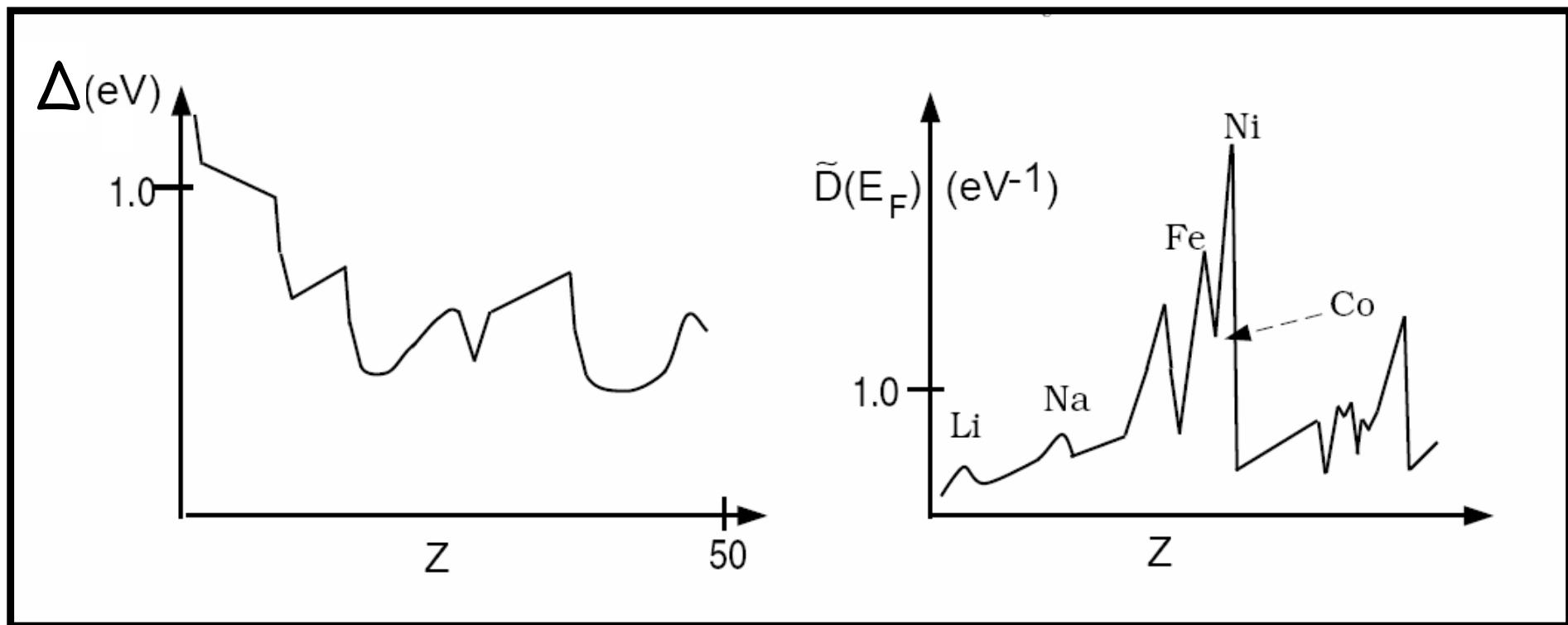
$$E = E[n, m] = E_s[n, m] + E_{xc}[n, m]$$

$$v = v_{es} + v_{xc}$$

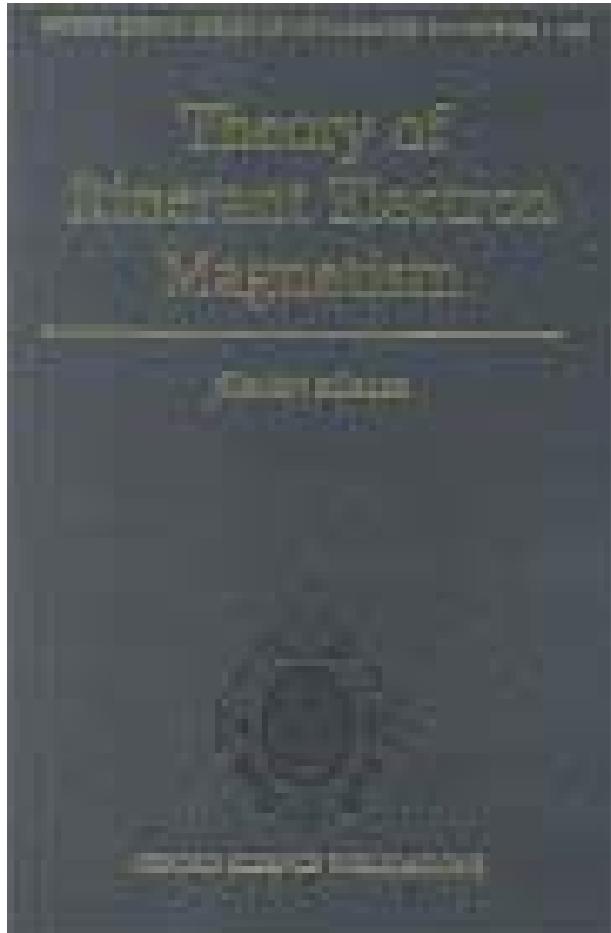
Local Spin-Density Approx.

$$B = \Delta[n, m] m/m$$

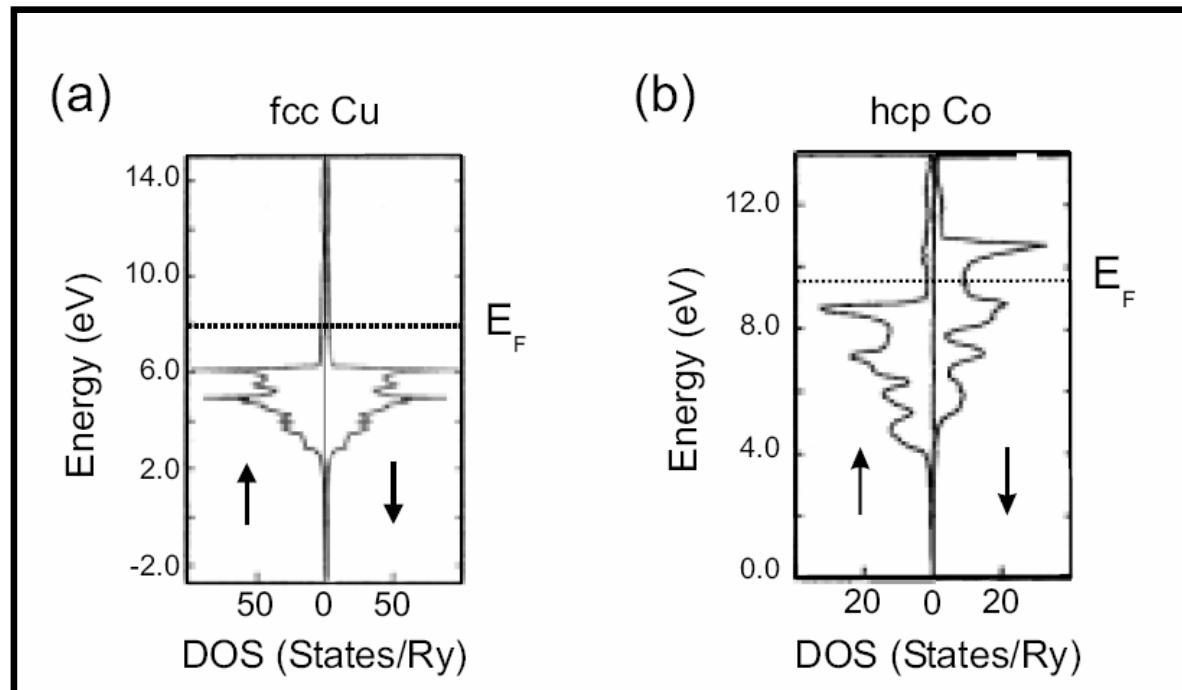
# Stoner Criterion - Elements



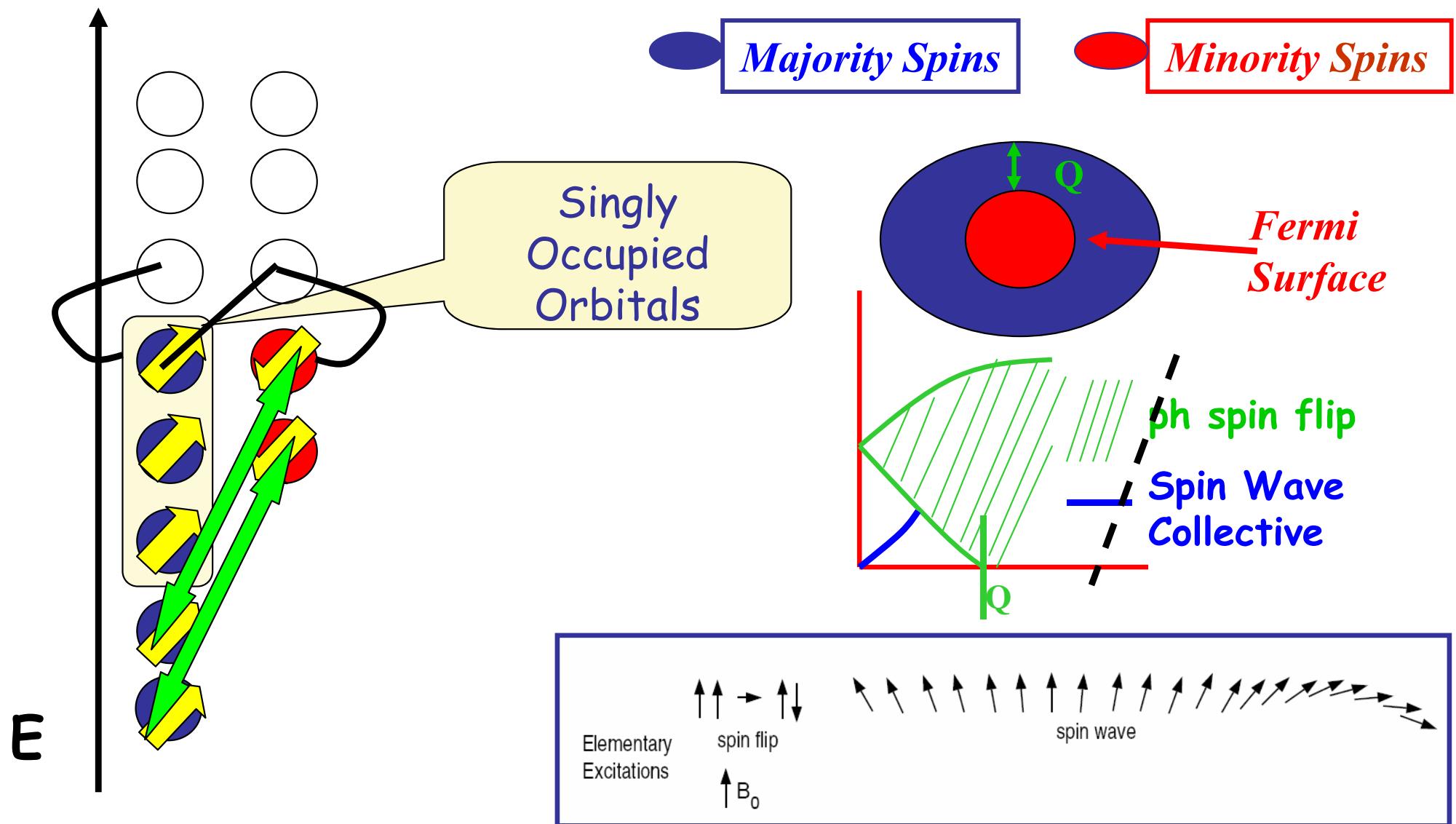
# Itinerant Electron Ferromagnetism Spin-Density Functional Theory



Theory of Itinerant Electron Magnetism  
JÜRGEN KÜBLER, Institute of Solid State Physics  
Darmstadt University of Technology



# Itinerant Electron Ferromagnetism Quasiparticle and Collective Aspects



# Micromagnetics

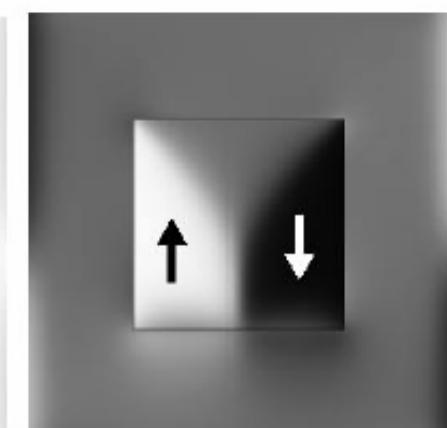
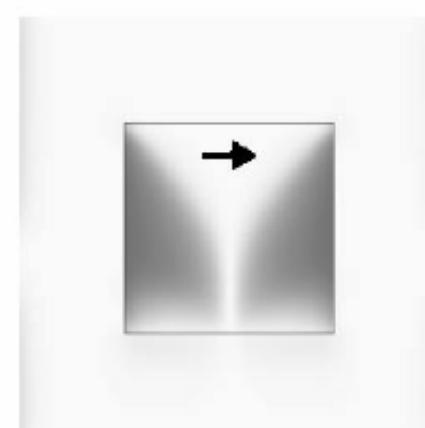
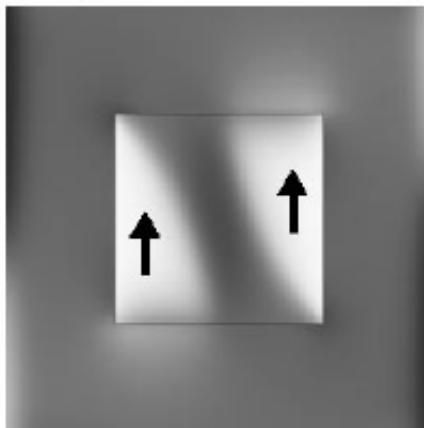
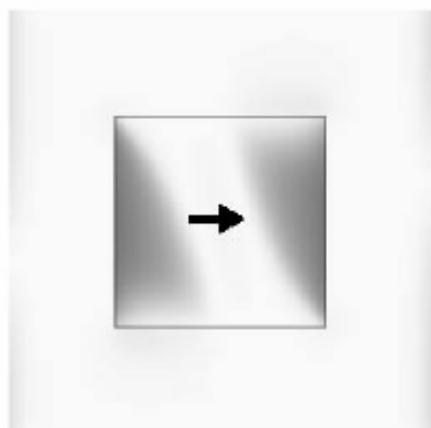
$$E_t = \int \left\{ -\frac{1}{2} \mathbf{H}_d \cdot \mathbf{J} + A \sum_{i=1}^3 (\nabla \beta_i)^2 - K_u (\mathbf{u} \cdot \boldsymbol{\beta})^2 - \mathbf{H}_{app} \cdot \mathbf{J} \right\} dV$$

Dipole-Dipole  
Interactions

Direction of  
Magnetization

S-state,  $H_{ext} = 0$

C-state,  $H_{ext} = 0$



# Micromagnetics

**Table 10.1.** Intrinsic and structural properties of some magnetic materials (FM = ferromagnet, FIM = ferrimagnet).

	$m$ $\mu_B/\text{f.u.}$	$\mu_0 M_S$ T	$T_C$ K	$K_1$ MJ/m <sup>3</sup>	Comment
Fe	2.23	2.15	1044	0.05	Cubic FM
Co	1.73	1.81	1390	0.53	Hexagonal FM
Ni	0.62	0.62	628	-0.005	Cubic FM
SmCo <sub>5</sub>	8.0	1.07	1020	17.2	Hexagonal FM
Nd <sub>2</sub> Fe <sub>14</sub> B	37.6	1.61	585	4.9	Tetragonal FM
BaFe <sub>12</sub> O <sub>19</sub>	19.9	0.47	742	0.33	Hexagonal FIM
Fe <sub>3</sub> O <sub>4</sub>	4.0	0.63	860	-0.012	Cubic FIM

# A Few Remarks About Metal Spintronics Technology

**SPIN (Elec)TRONICS**

=

**GMR + Spin-Torques**

+

**Spin-Orbit (AHE+SHE+Spin-Galvanic)**

+

**Magnetic Semiconductors**

# Two-Channel Conduction & CPP GMR

CPP = Current Perpendicular to Plane

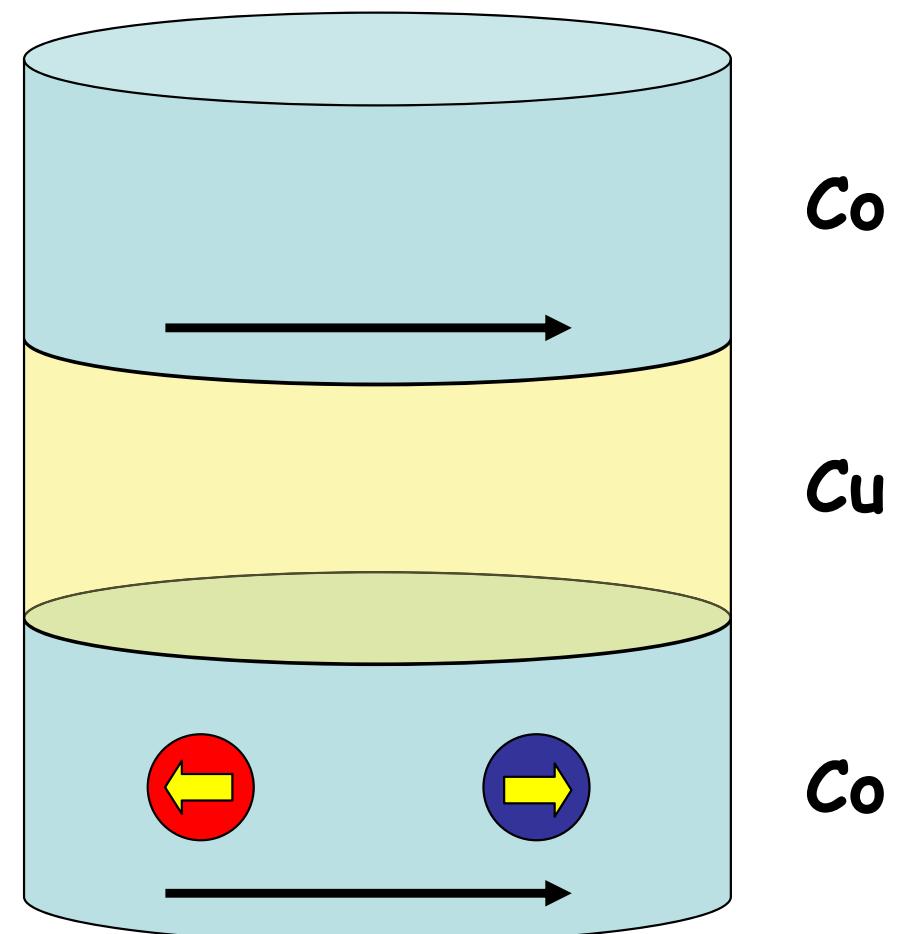
GMR = Giant Magnetoresistance



Neville Mott  
1905-1996

Minority

Majority



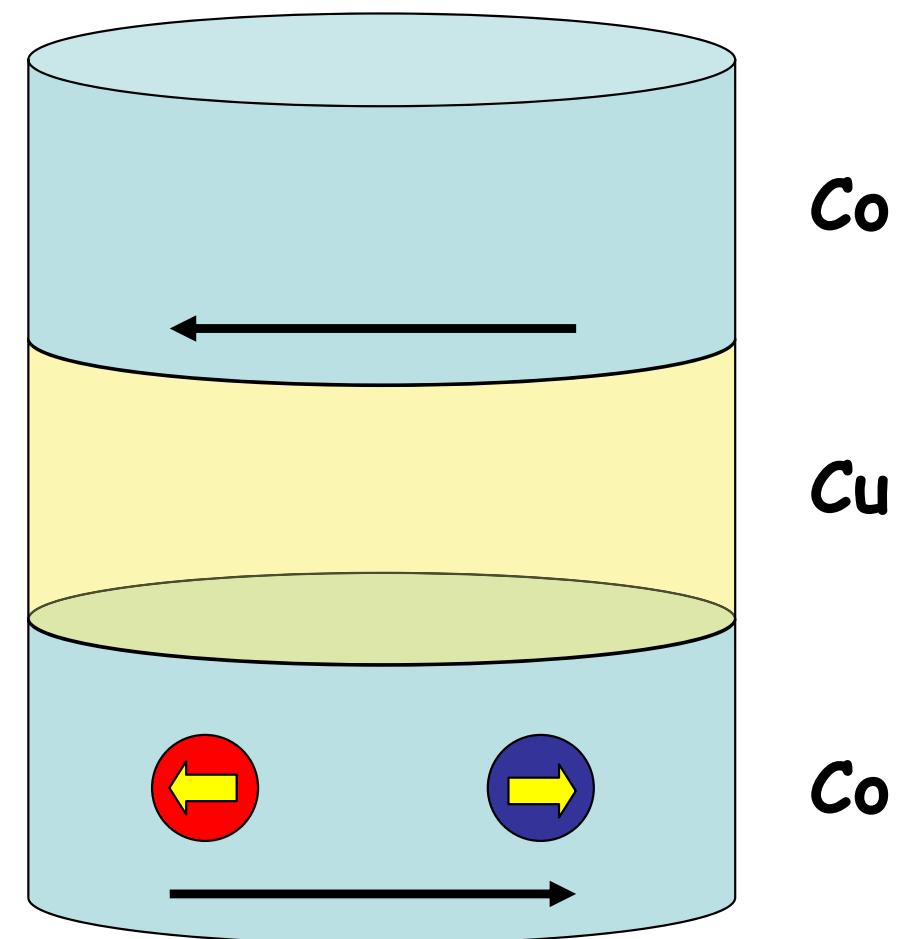
# CPP GMR - High Resistance State

Majority



Minority

Neville Mott  
1905-1996



# Spin Accumulation - Weak SO

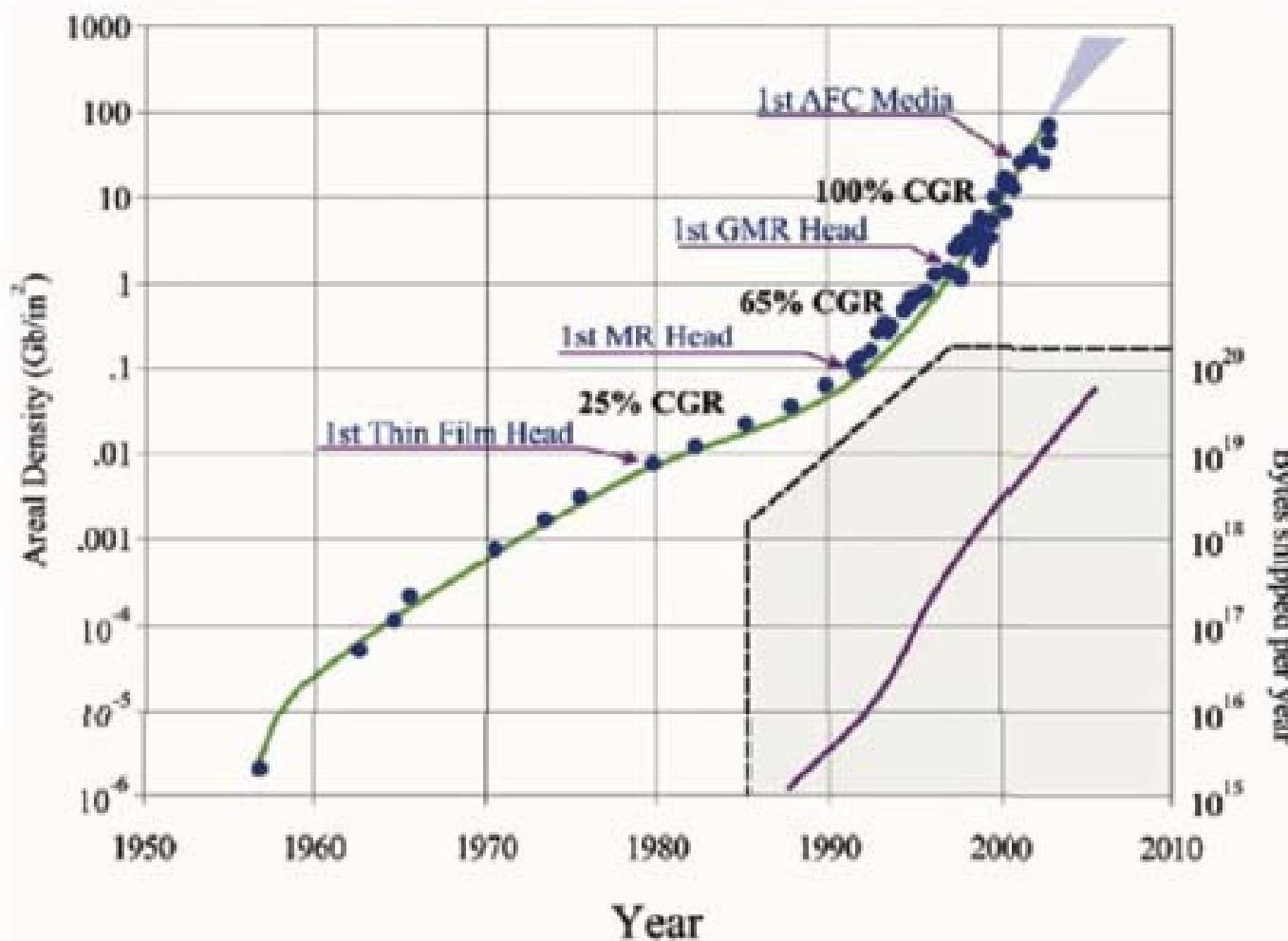
Spin  
Not Conserved

$$\partial_t(n_\uparrow - n_\downarrow) = \frac{\sigma}{e^2} \partial_x^2 \left( \frac{n_\uparrow - n_\downarrow}{\nu_0} \right) - \frac{n_\uparrow - n_\downarrow}{\tau_s}$$

Spin Memory  
Length

$$L_s^2 = D\tau_s \sim v_F^2 \tau \tau_s \gg \ell^2$$

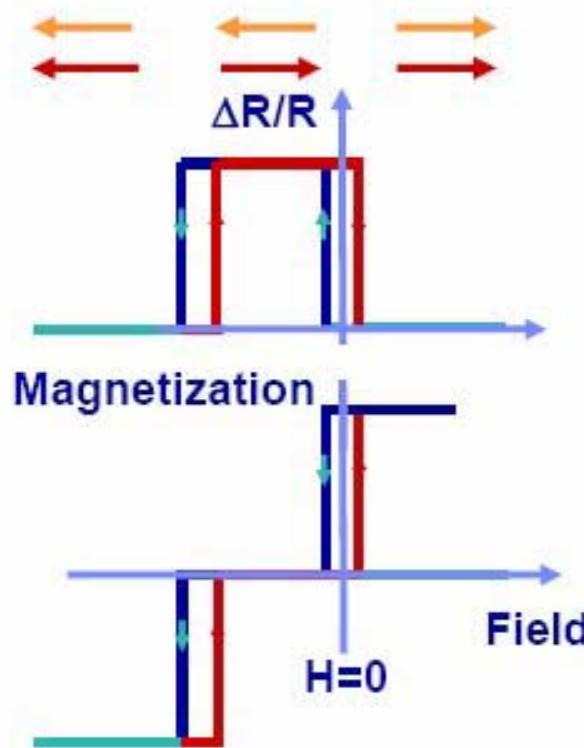
# Hard-disk Technology



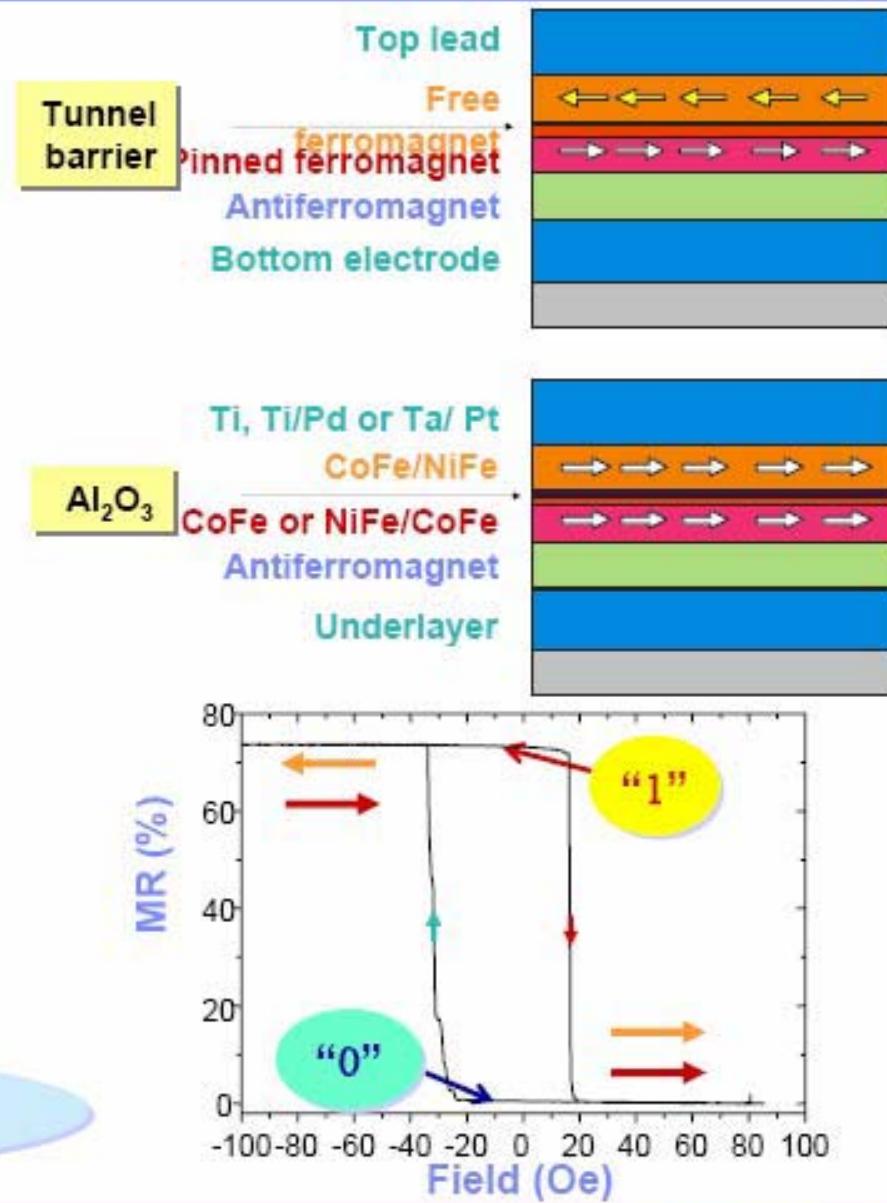
10 GByte/(person·year)



## Exchange-Biased Magnetic Tunnel Junction (MTJ)



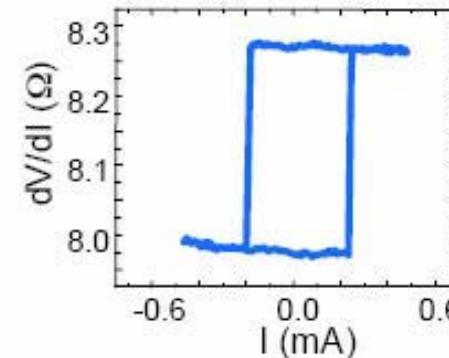
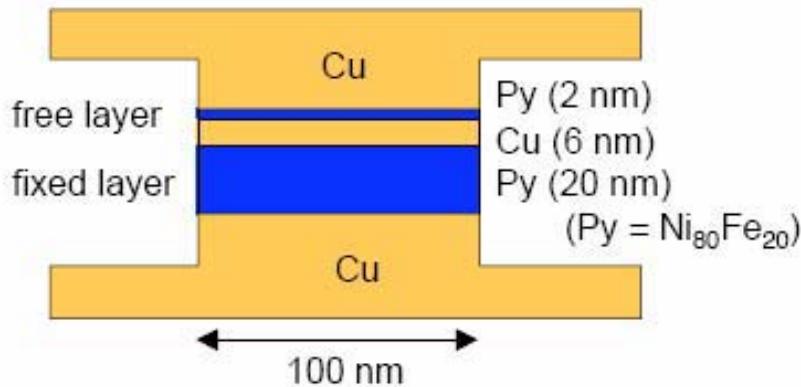
*Non-Volatile Memory!*



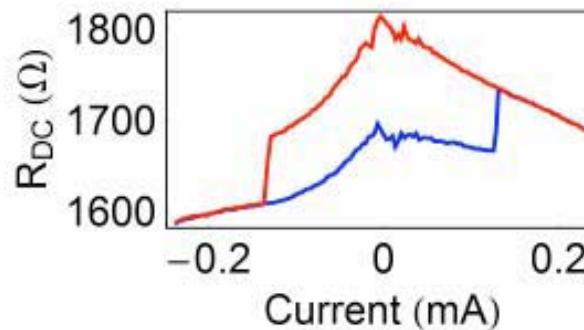
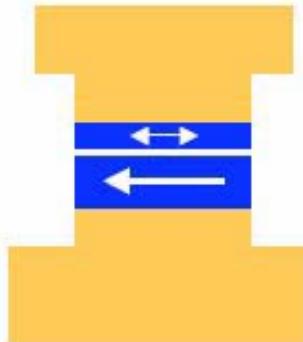
# Spin Transfer Torques

## Spin-Transfer-Driven Magnetic Switching

### Metal Multilayer Devices



### Magnetic Tunnel Junctions

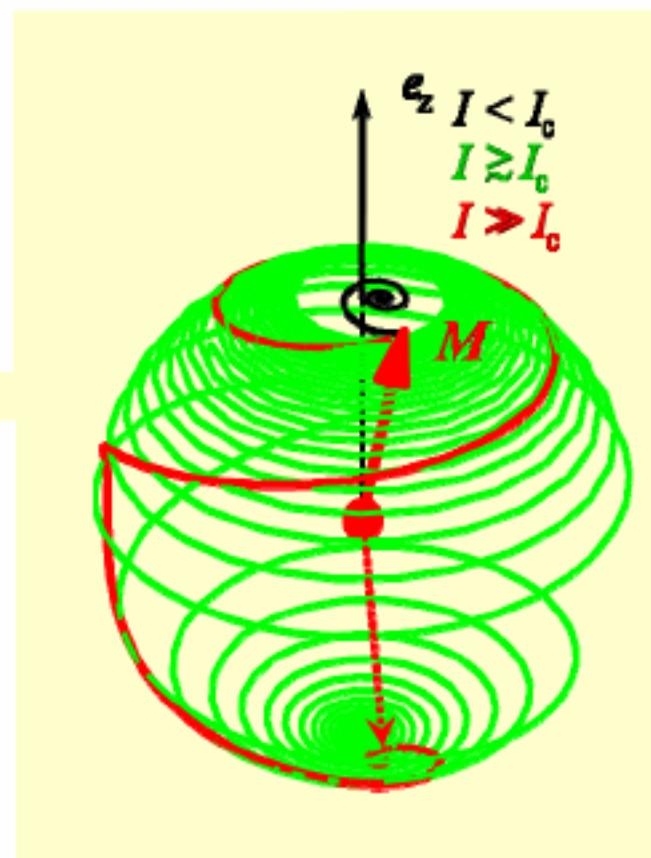
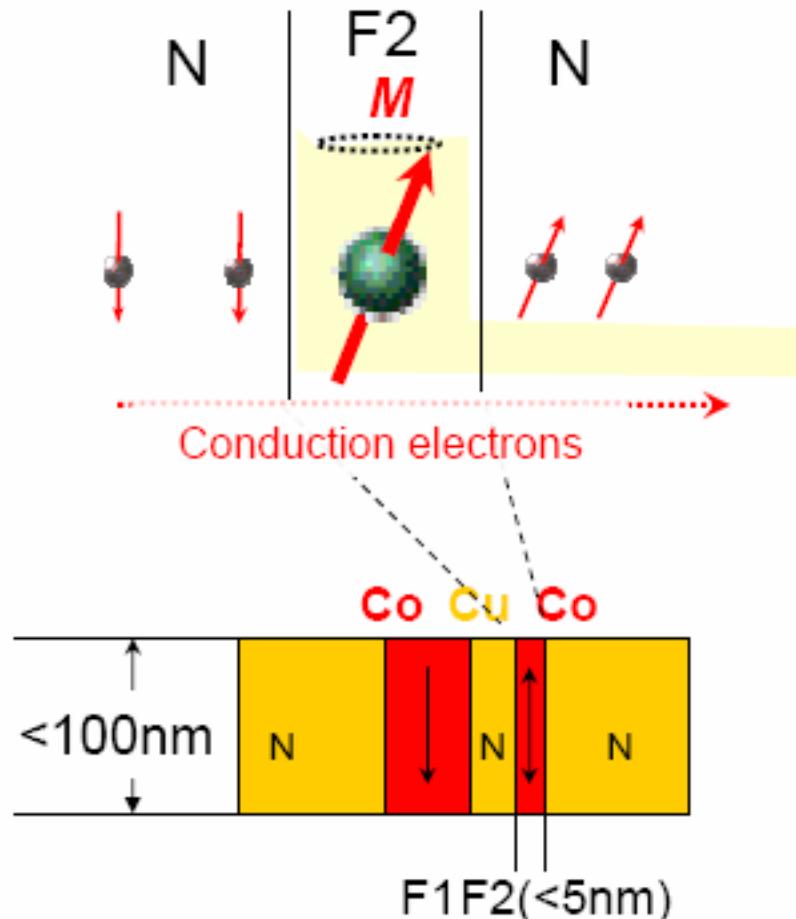


Dan Ralph - KITP Spintronics Program Talk  
[www.kitp.ucsb.edu](http://www.kitp.ucsb.edu)

# Spin-angular momentum flow: a basic picture

- Angular momentum exchange between a spin-current and a ferromagnet (FM).
- Precession and reversal of FM moment.

J. C. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996); ibid, **195**, L261 (1999).

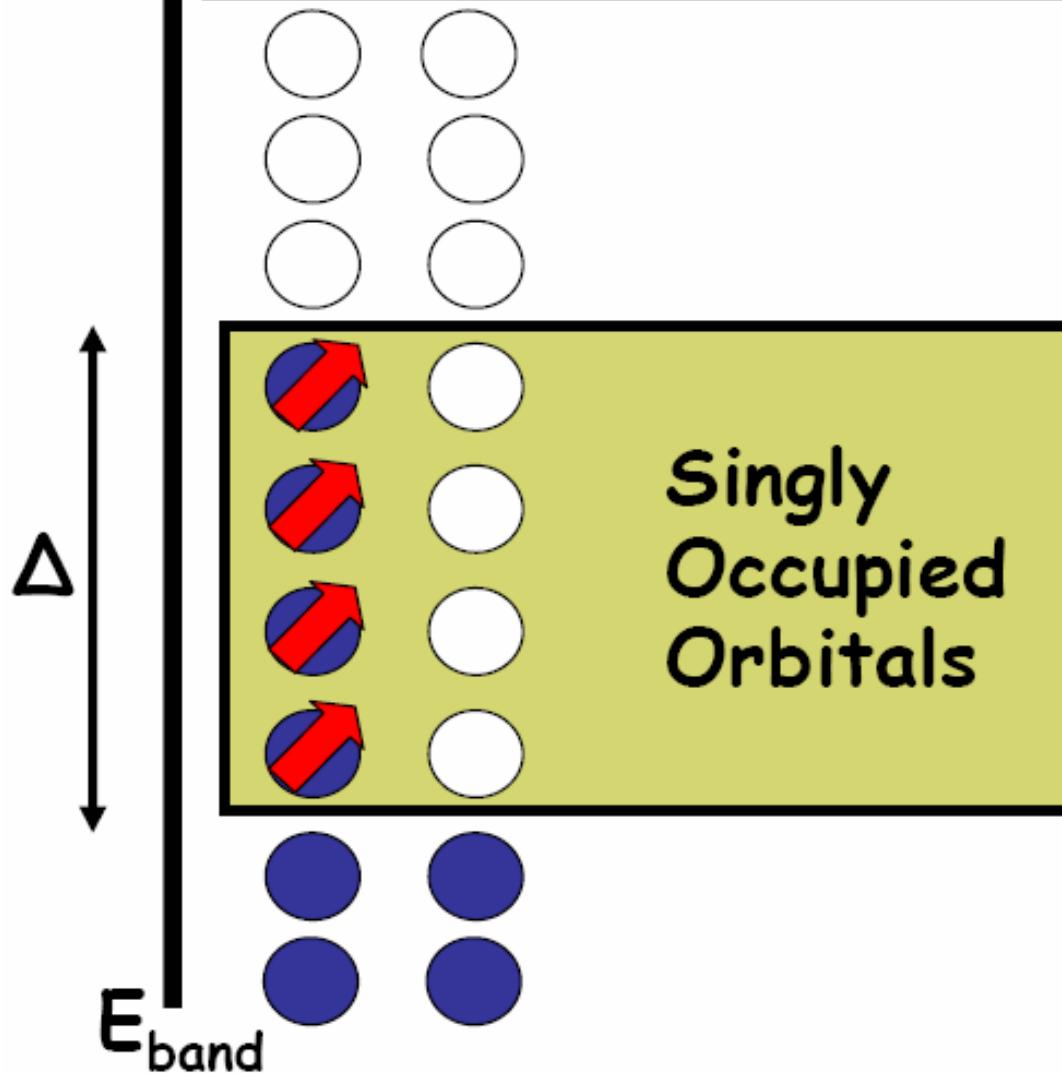


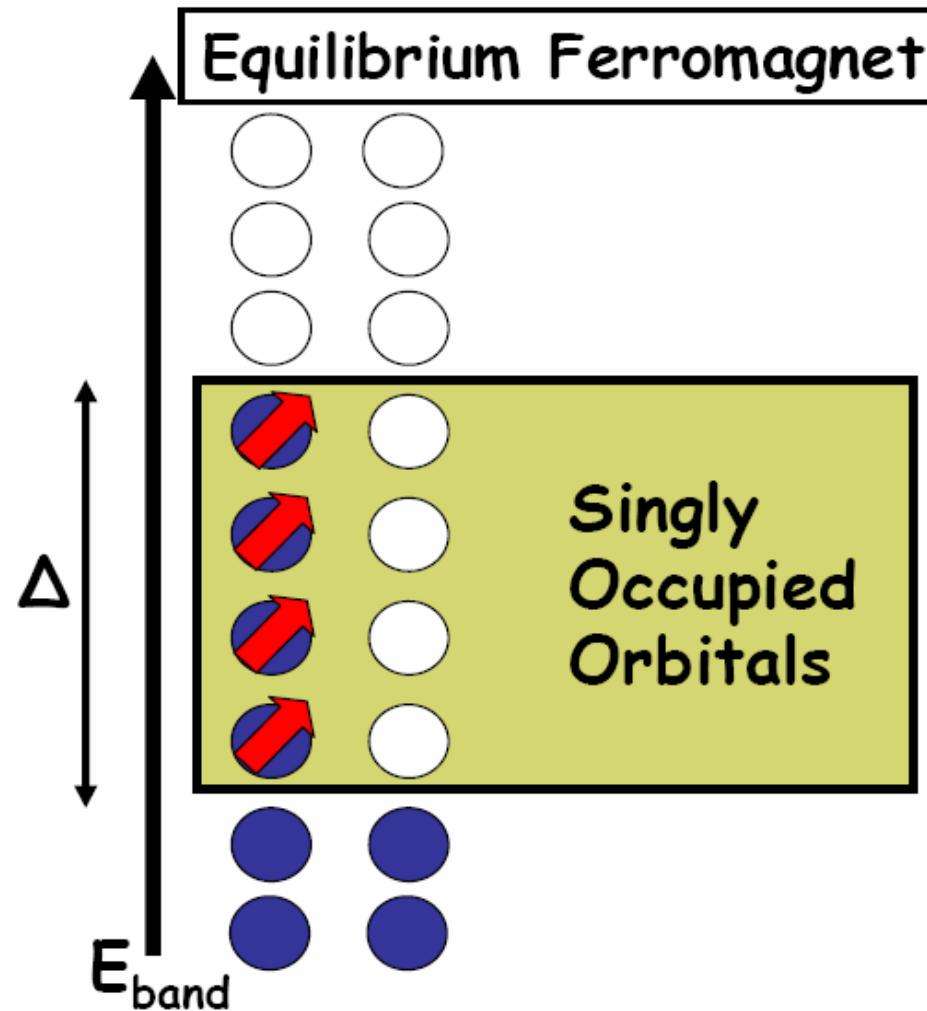
J. Z. Sun, J. Magn. Magn. Mater. **202**, 157 (1999); Nature **425**, 359 (2003).

# Microscopic Picture of Spin Transfer

Application to  
Antiferromagnetic Metal Spintronics  
&  
Current-Driven Domain Wall Motion

## Equilibrium Ferromagnet



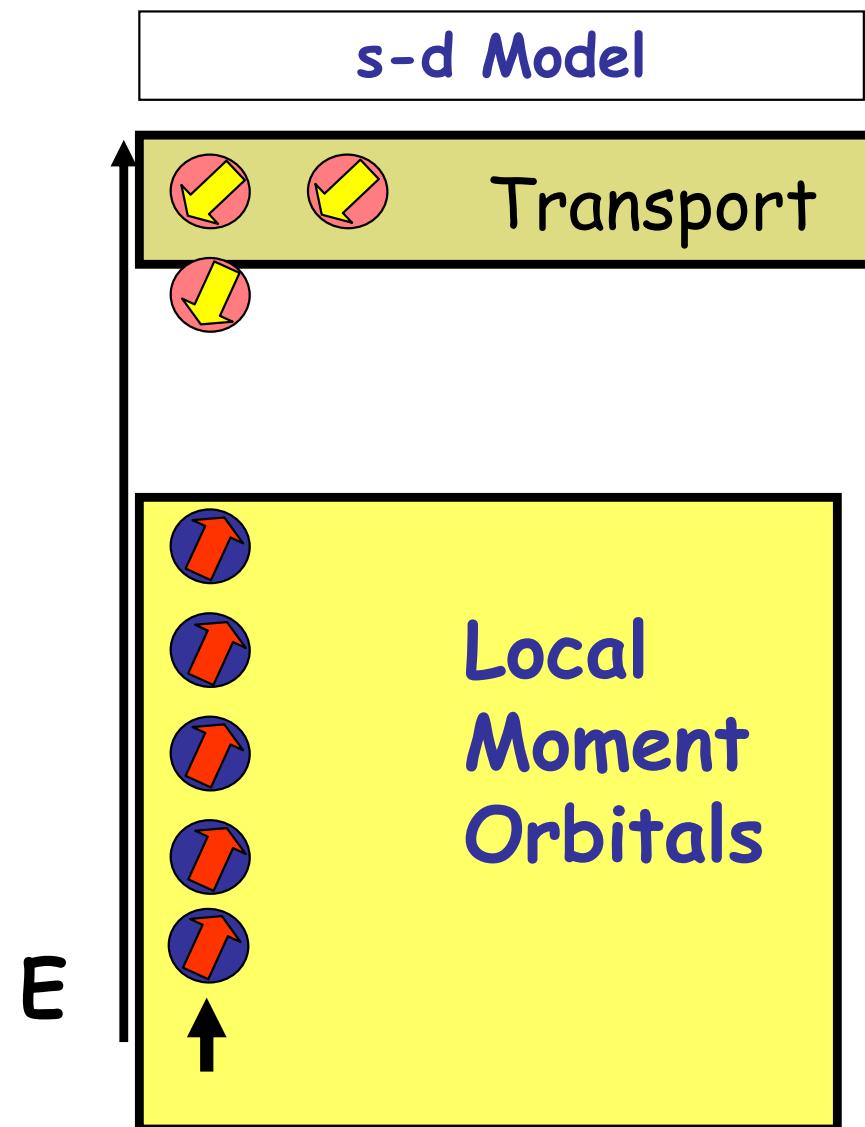
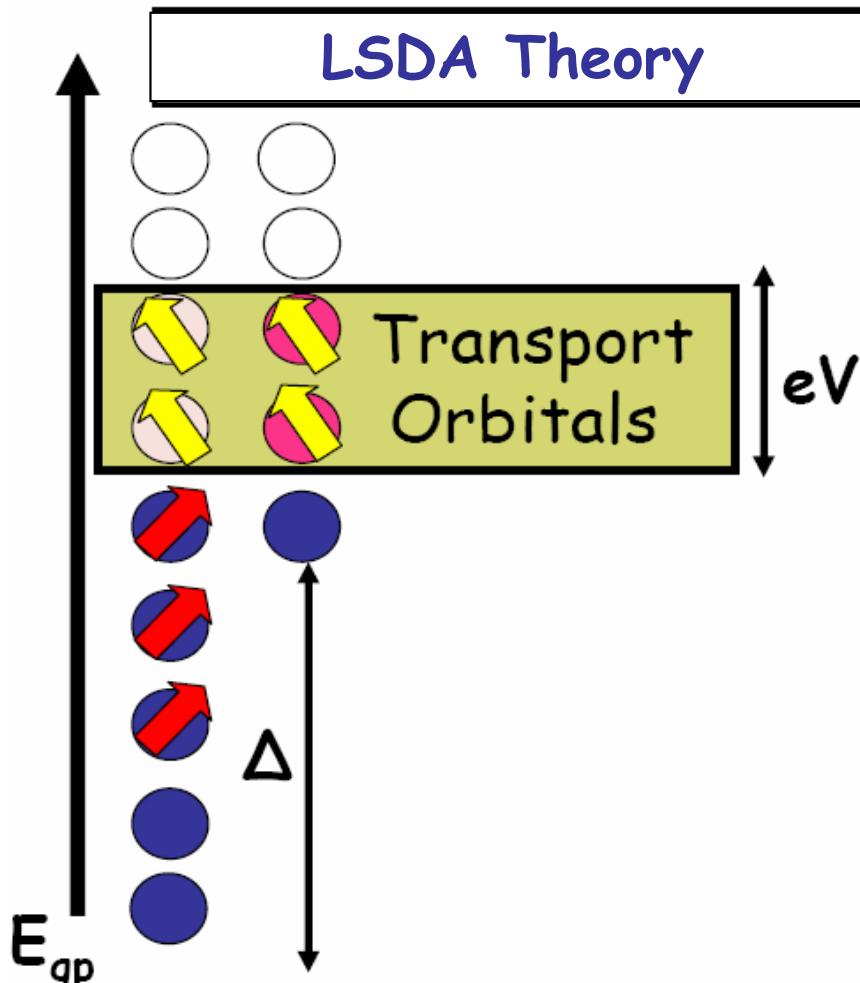


# Spin-Transfer Theory

Nunez+AHM, cond-mat/0403710  
Solid State Commun. (2006)

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

# Spin Transfer Torques



# Spin Transfer Torques

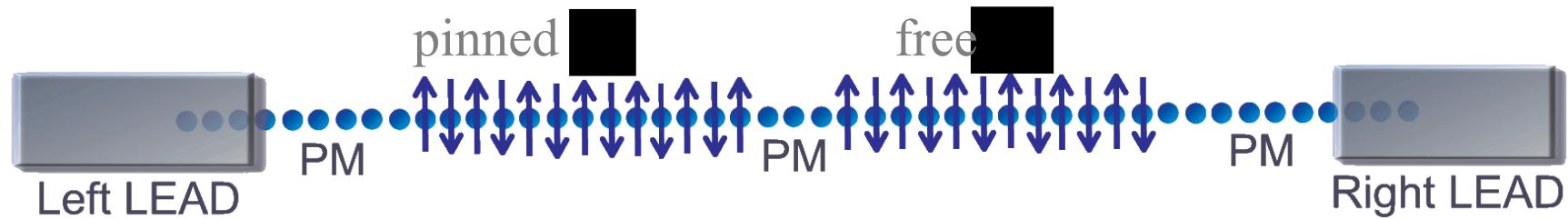
## (Summary)

$$\left[ \vec{\Delta}(\vec{r}) \times \vec{m}^{\text{tr}}(\vec{r}) \right]_j = -\hbar \nabla_i J_j^{\text{tr},i}(\vec{r})$$

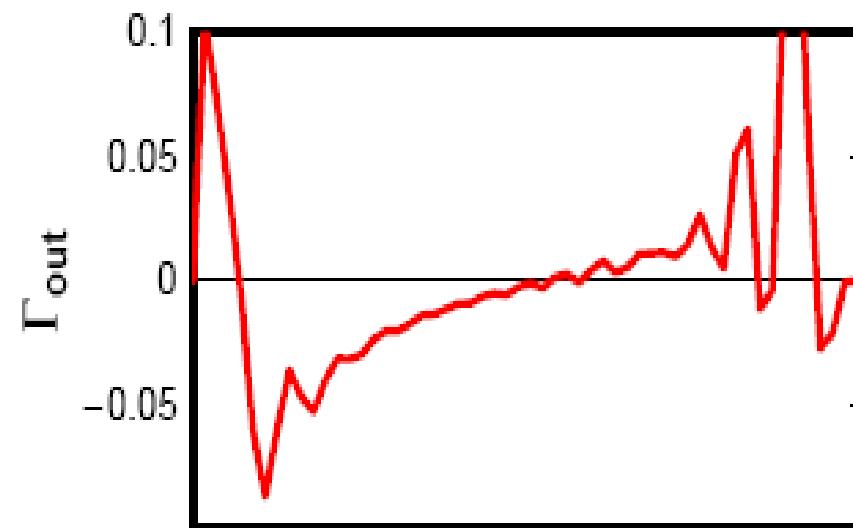
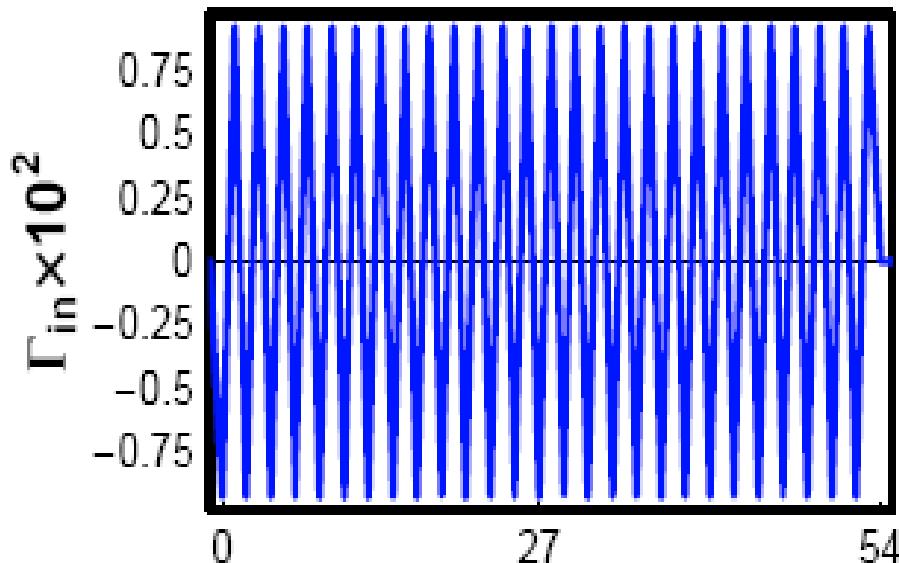
$$\vec{\Delta}^{\text{tr}}(\vec{r}) = \frac{\nabla_i \vec{J}^{\text{tr},i}(\vec{r}) \times \hat{\vec{m}}}{m}$$

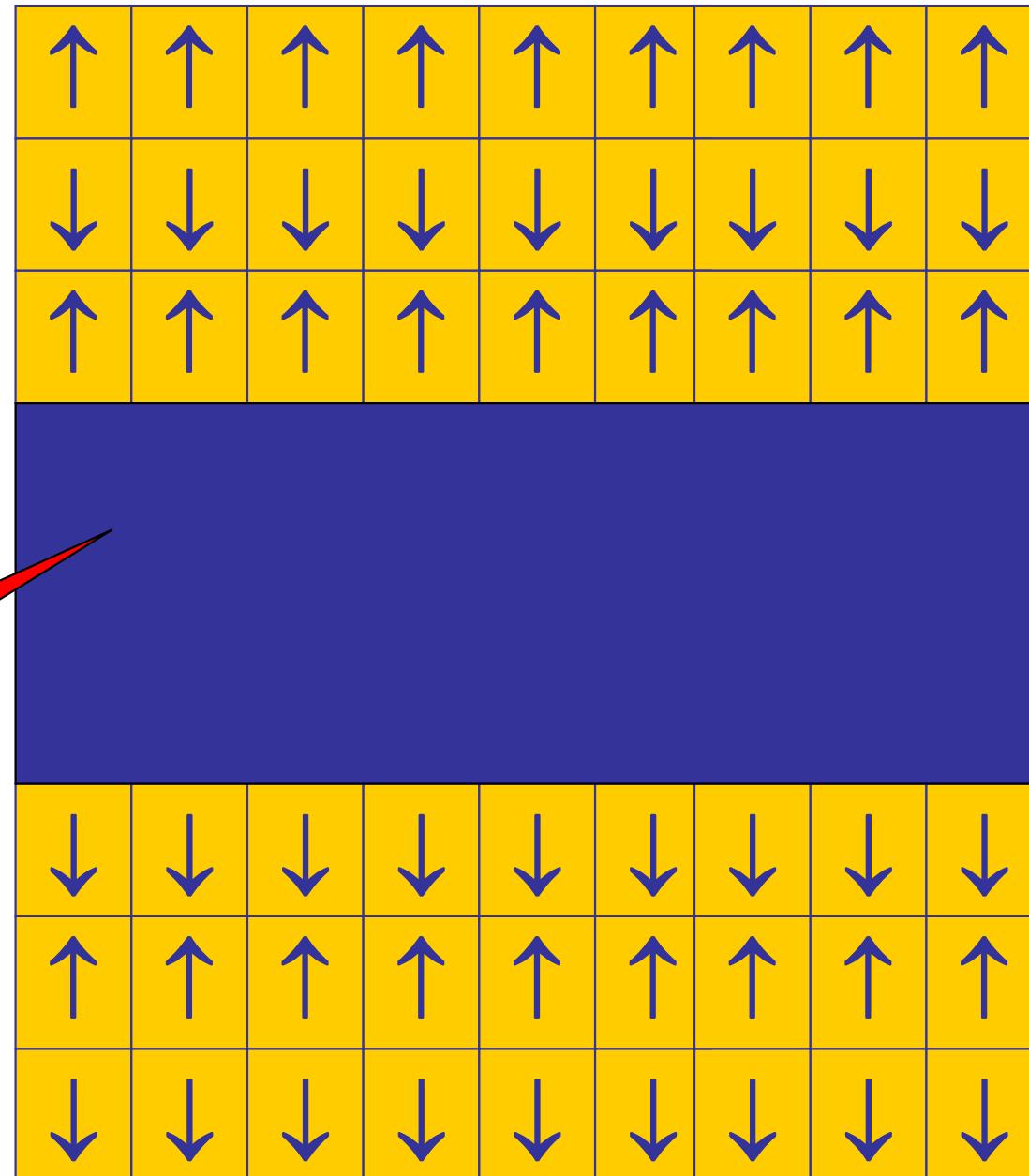
# What About Antiferromagnets?

Nunez et al. cond-mat/0510797 PRB (2006)



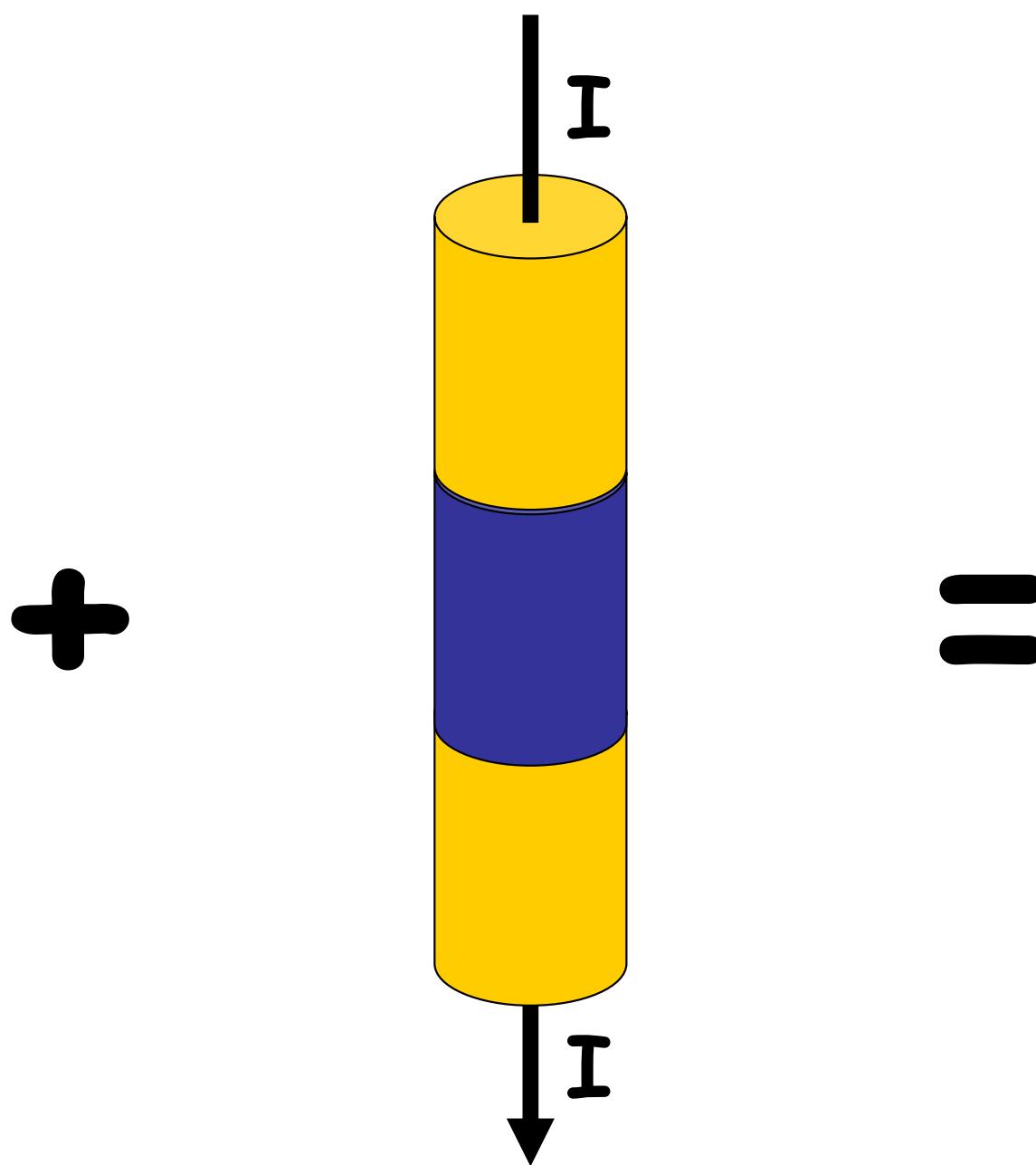
GMR and Robust Spin Torques

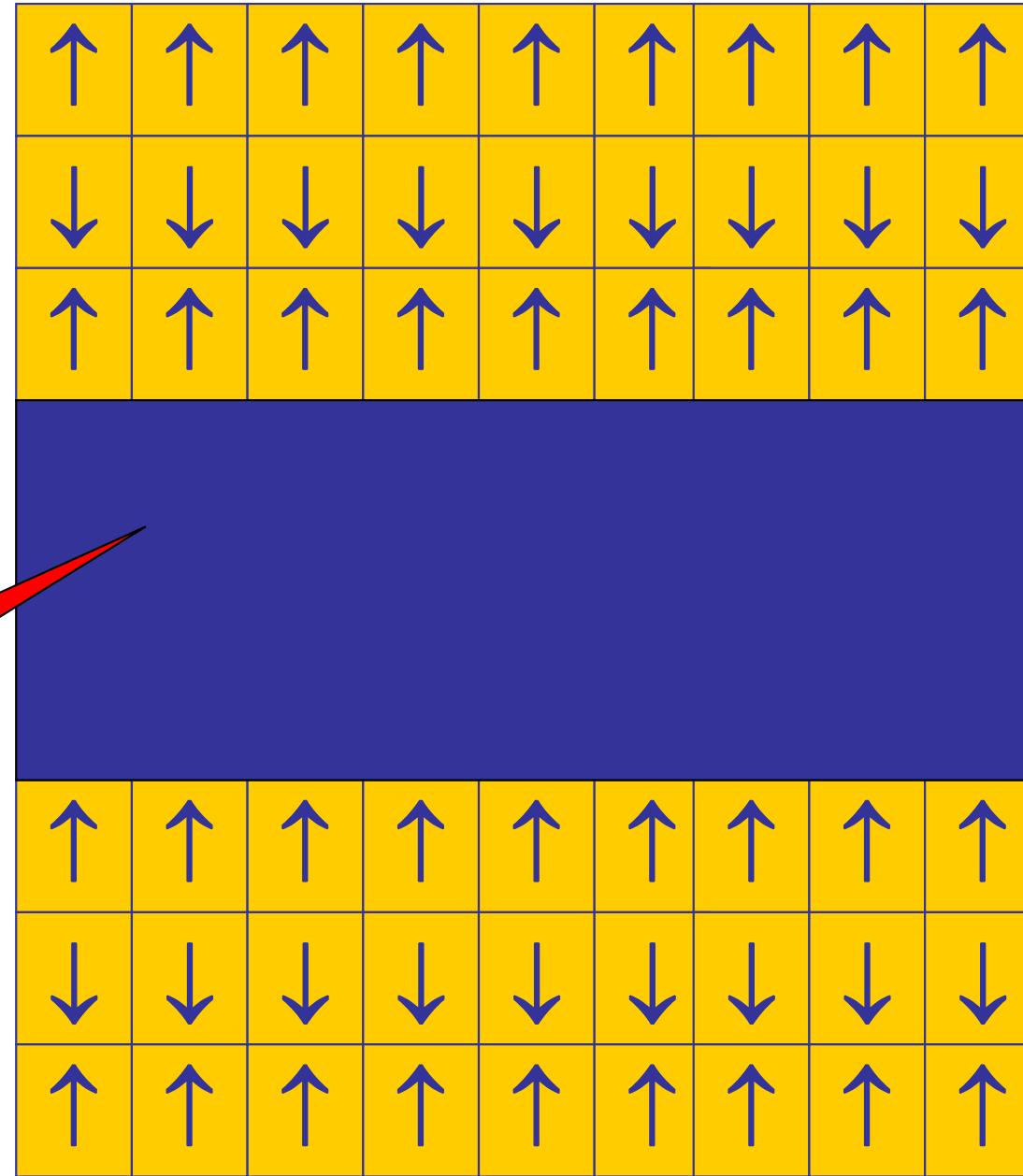




Antiferromagnet

Paramagnet

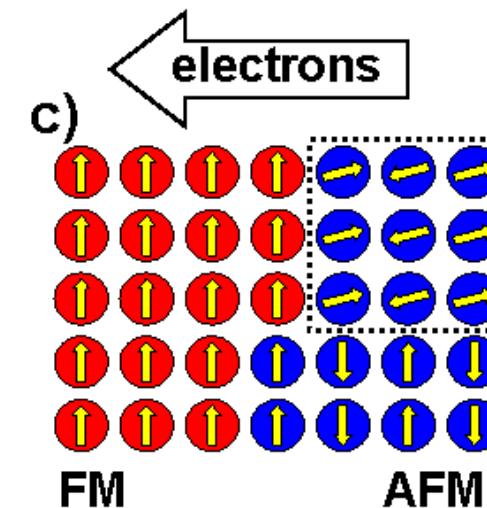
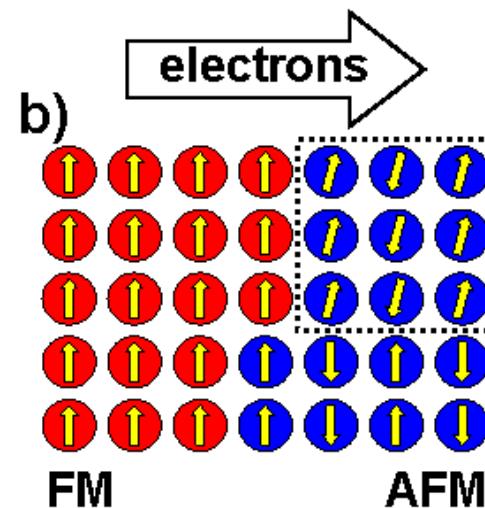
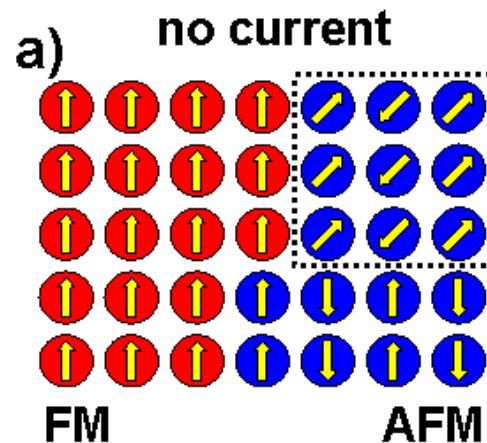




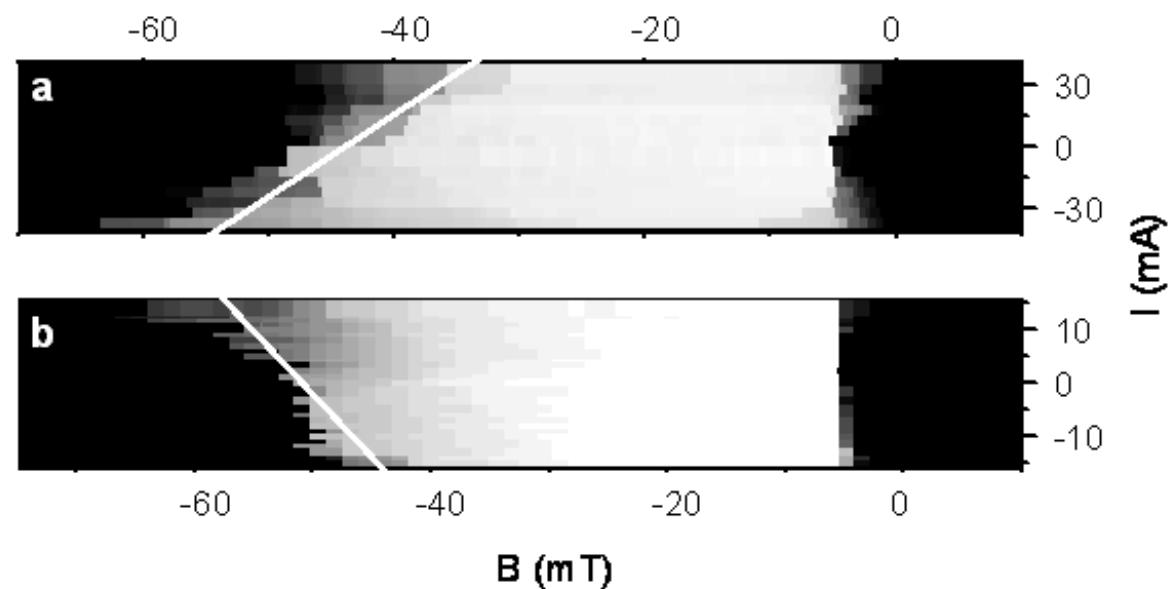
Antiferromagnet

Paramagnet

# Current-Modulated Exchange Bias



Tsoi et al.  
cond-mat/0606462



# Magnetic Action of Current-Carrying Ferromagnet

Fernandez-Rossier, Braun, Nunez, AHM PRB (2004)  
Bazaliy, Jones, Zhang PRB (2003)

$$S_{SW} = \frac{1}{2\beta N} \sum_{Q,a,b} \delta\Delta_a(Q) \mathcal{K}_{ab}(Q) \delta\Delta_b(-Q).$$

$$D_{\pm}^{\text{ret}}(\vec{q}, \omega) = \frac{4U}{3} \frac{1}{1 + \frac{2}{3} U \Gamma(\pm \vec{q}, \pm \omega)}$$

$$\Gamma(\vec{q}, \omega) = \frac{1}{N} \sum_{\vec{k}} \frac{n_{\vec{k}}^{\uparrow} - n_{\vec{k}+\vec{q}}^{\downarrow}}{\epsilon_{\vec{k}}^{\uparrow} - \epsilon_{\vec{k}+\vec{q}}^{\downarrow} + \omega + i0^+}$$



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- III Spin-Orbit Coupling