Some Theory Challenges in Spintronics

KITP Spintronics Conference

University of Texas at Austin

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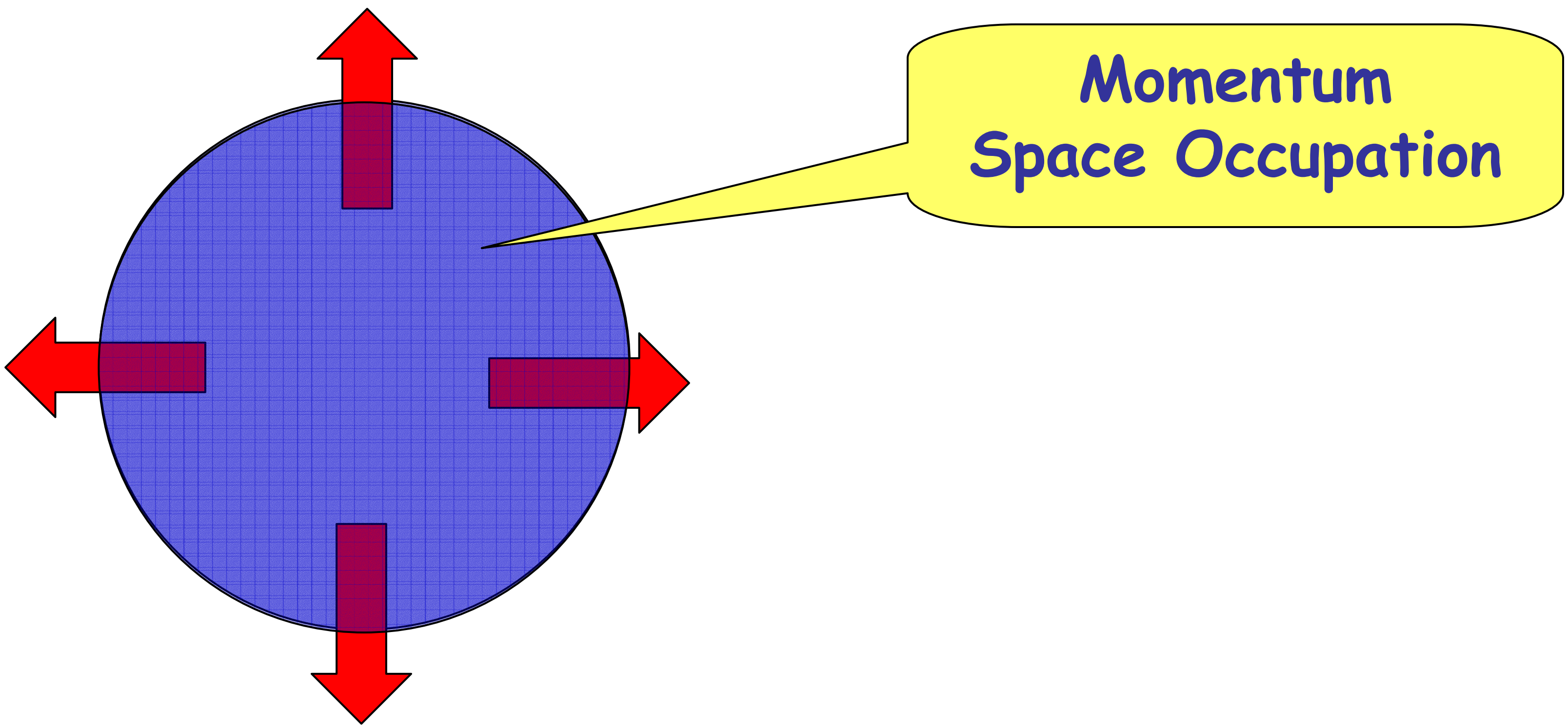
Main Theme
Coherence Response

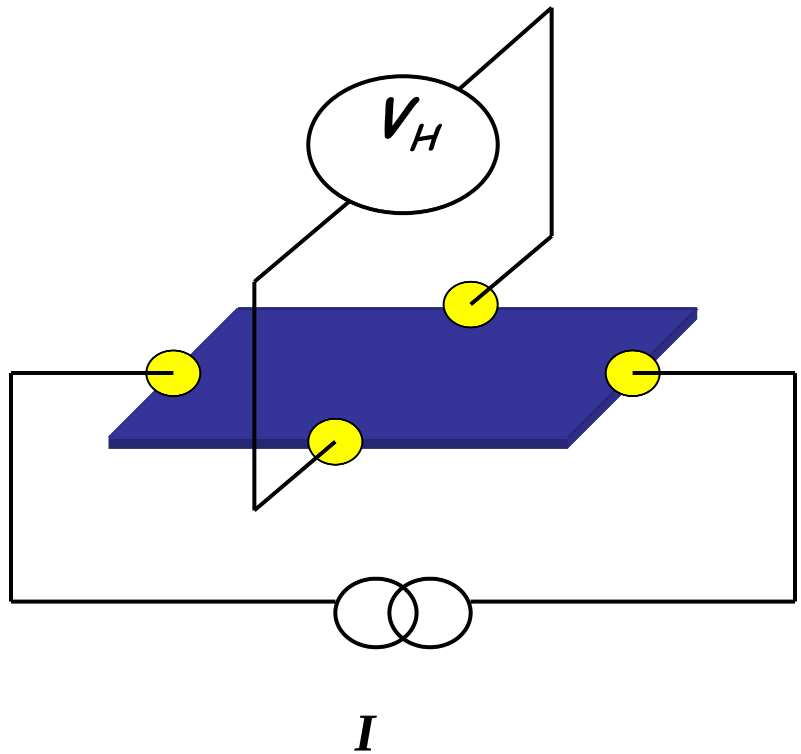


Anomalous Transport

Spin Torques

Ferromagnetic Semiconductors

Anomalous Hall Effect



Ordinary Anomalous

$$\rho_{xy} = R_0 B + \rho_{xy}^{'}$$

Anomalous Hall Effect

$$(\sigma_{xy} - \sigma_{yx})/2 = \sigma_H$$

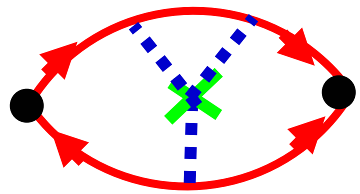
⇨

no time reversal invariance

+

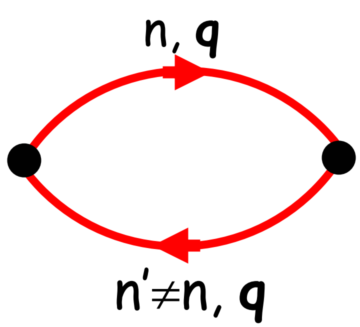
spin-orbit coupling

AHE - Perturbation Theory



Skew

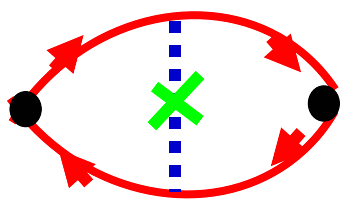
$\sim\sigma_0\, S$



Intrinsic

$\sim\sigma_0 / \varepsilon_F \tau$

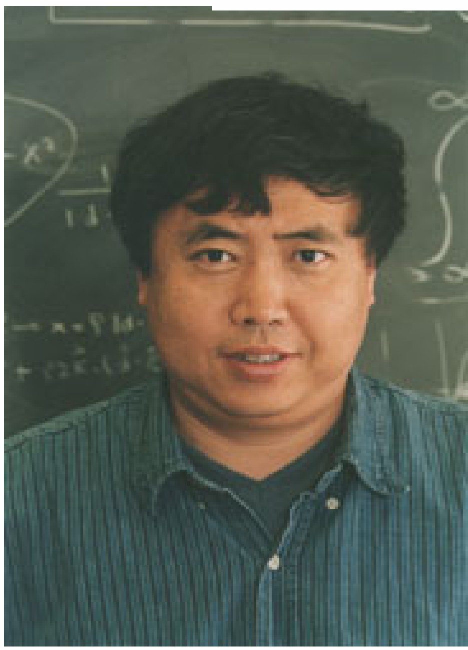
[Ebert: Rep. Prog. Phys. (1996)]

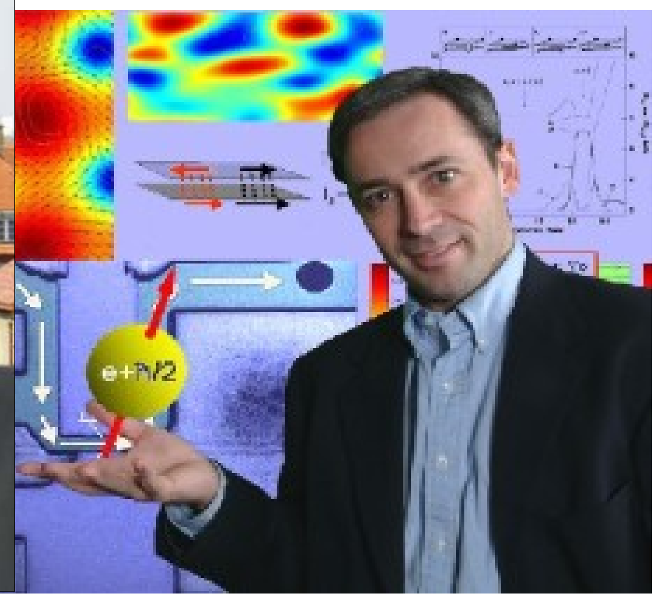


Vertex Corrections

$\sim \boldsymbol{\sigma}_{\mathbf{Intrinsic}}$

[Side Jump ++++]



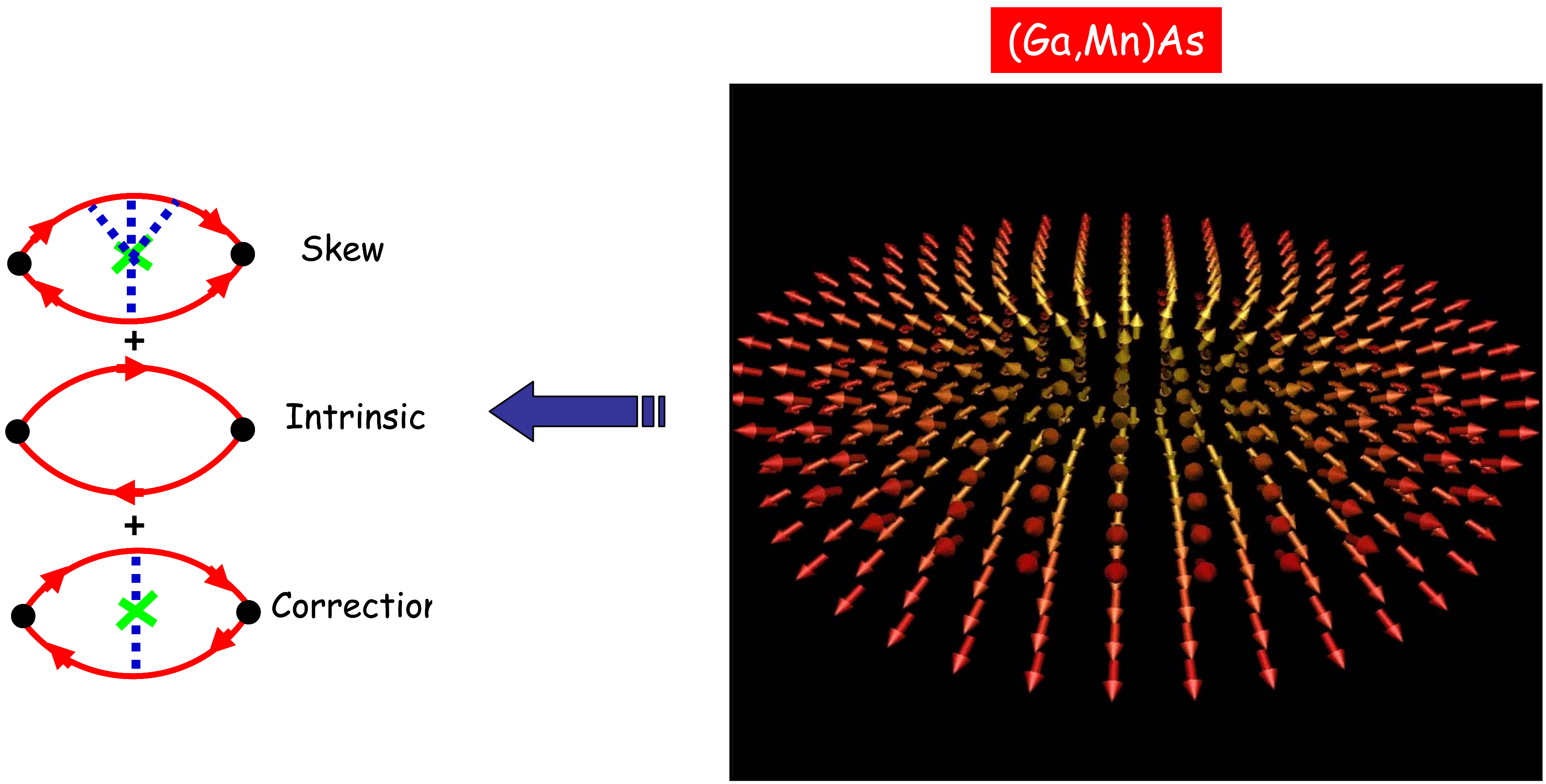


Qian Niu   Tomas Jungwirth - CAS   Jairo Sinova

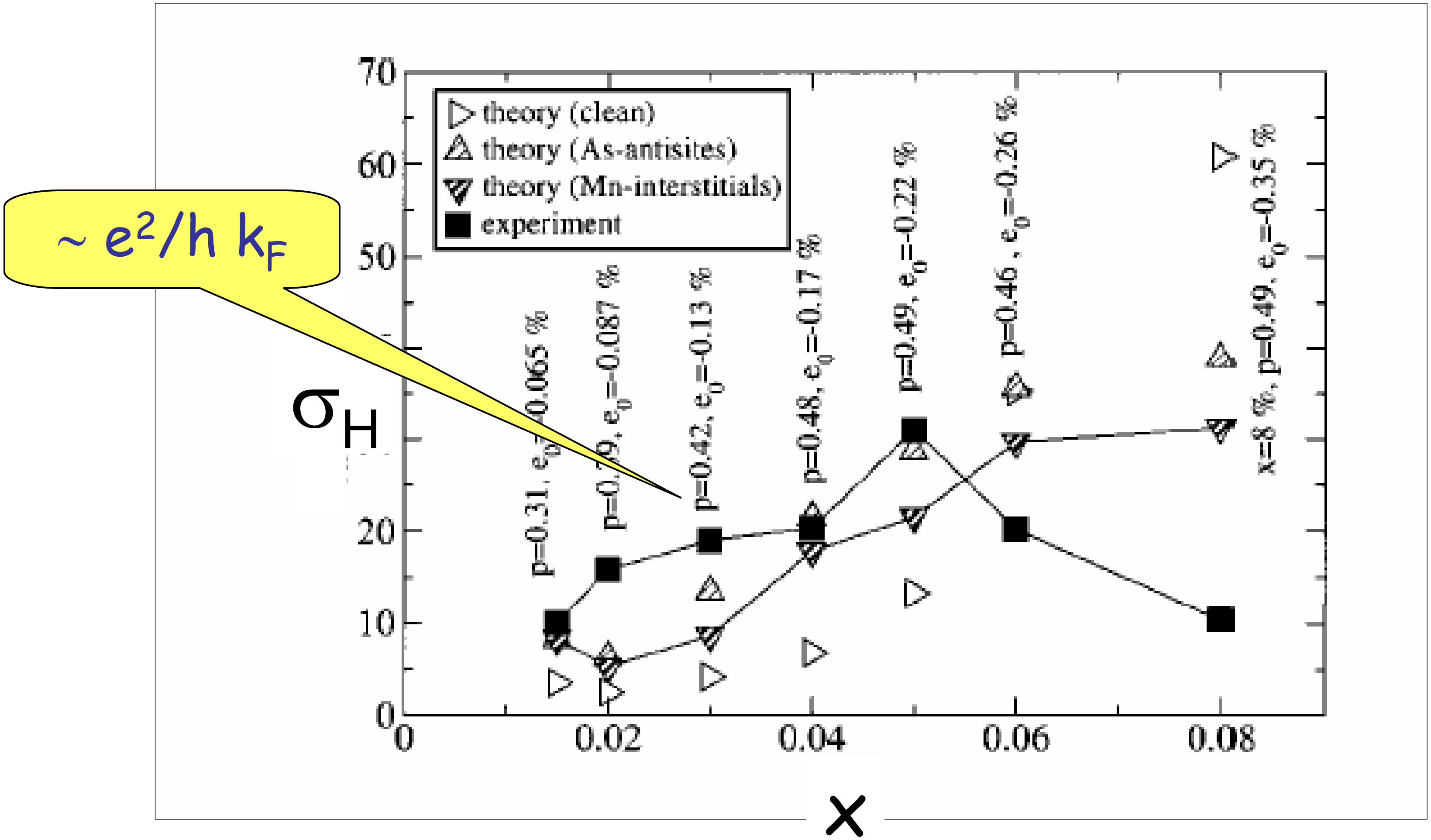
CECAM Workshop (Resta) July 4-6 2005

Bruno Dugaev Kane Nagaosa Haldane Campbell

(Ga,Mn)As k-space Berry phase



AHE in (III,Mn)V Ferromagnets



Jungwirth, Niu, et al. **PHYSICAL REVIEW LETTERS 2002**
Jungwirth, Gallagher et al. **APPLIED PHYSICS LETTERS 2003**

Thursday, March 16, 2006 2:30PM - 4:54PM –
Session W3 DCMP: Topological Aspects of Electron Transport in Solids Baltimore Convention Center

2:30PM W3.00001 Berry Phase and Dissipationless Currents in Solids

NAOTA NAGAOSA

3:06PM W3.00002 Fermi Liquid Berry Phase Theory of the Anomalous Hall Effect[1]

DUNCAN HALDANE

3:42PM W3.00003 The Quantum Spin Hall Effect

CHARLES KANE

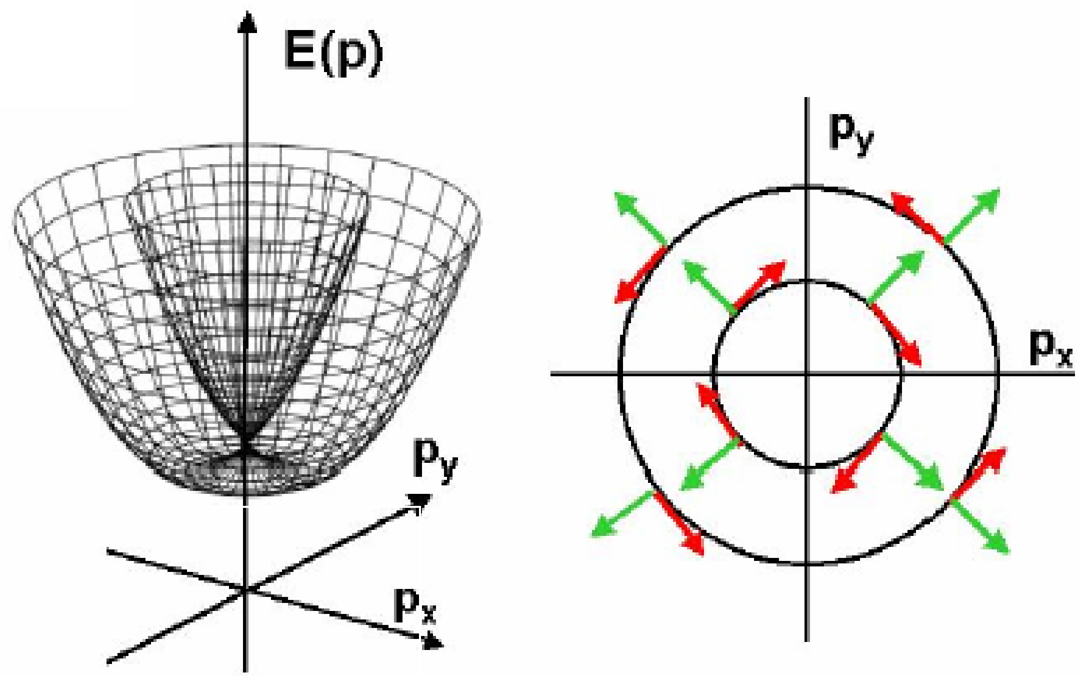
4:18PM W3.00004 Spintronics, propagating mode, (quantum) spin transport

ANDREI BERNEVIG

Spin Drag
(Vignale, D'Amico)

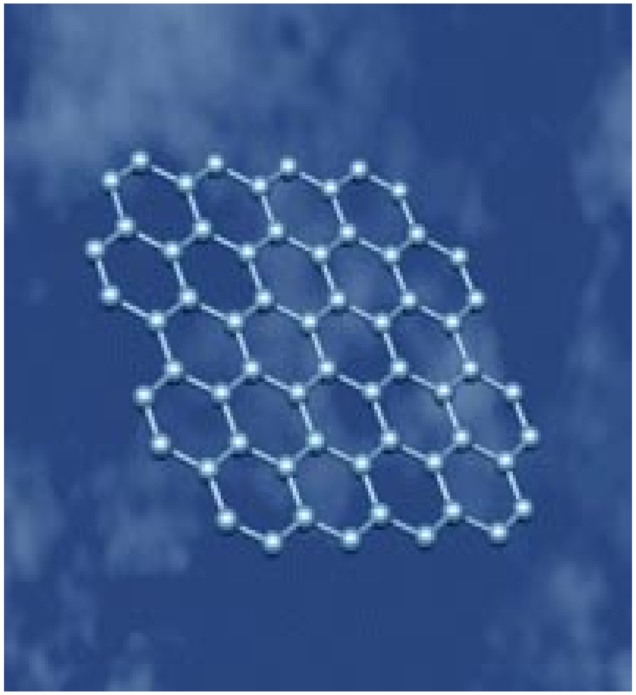
Rashba Model

Culcer et al. PRB (2003)



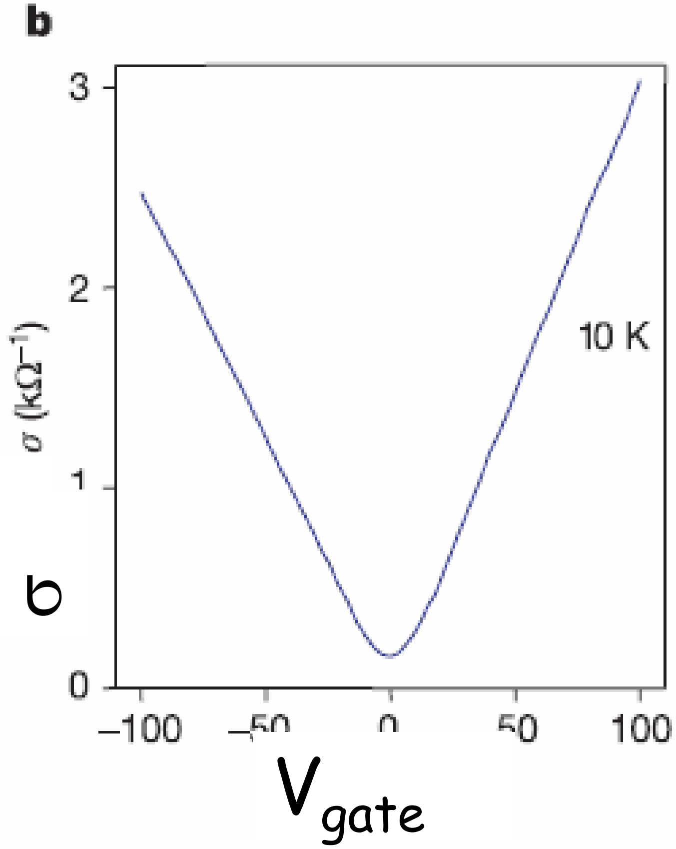
$$H_R = \frac{1}{2m}[\mathbf{p} + \frac{e}{c}\mathbf{A}]^2 + \frac{\lambda}{\hbar}\hat{\mathbf{z}} \cdot \boldsymbol{\sigma} \times [\mathbf{p} + \frac{e}{c}\mathbf{A}]$$

Graphene – a new 2DES



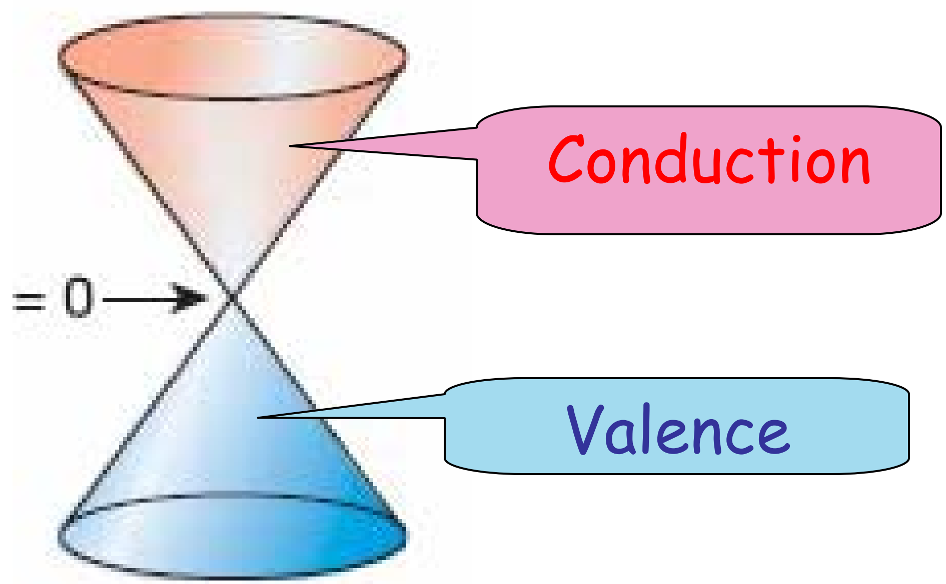
Manchester
Columbia

Geim Nature (2005)



Topological Bands

$$\hat{H}_0 = v(k_x \tau_z \sigma_x + k_y \sigma_y) + \Delta \sigma_z \tau_z s_z$$

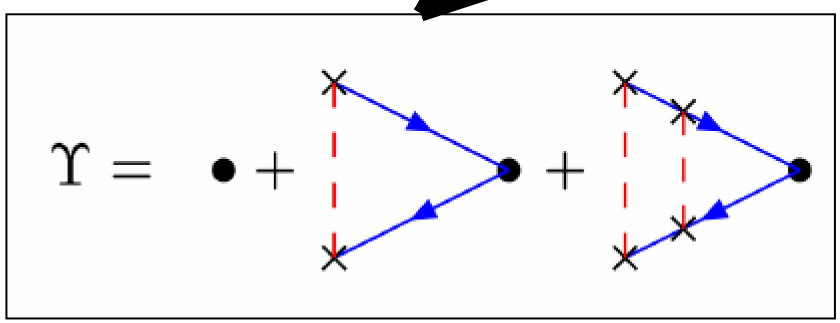


Kane Mele
Semenoff Haldane

Spin Hall Effect in Metallic Graphene

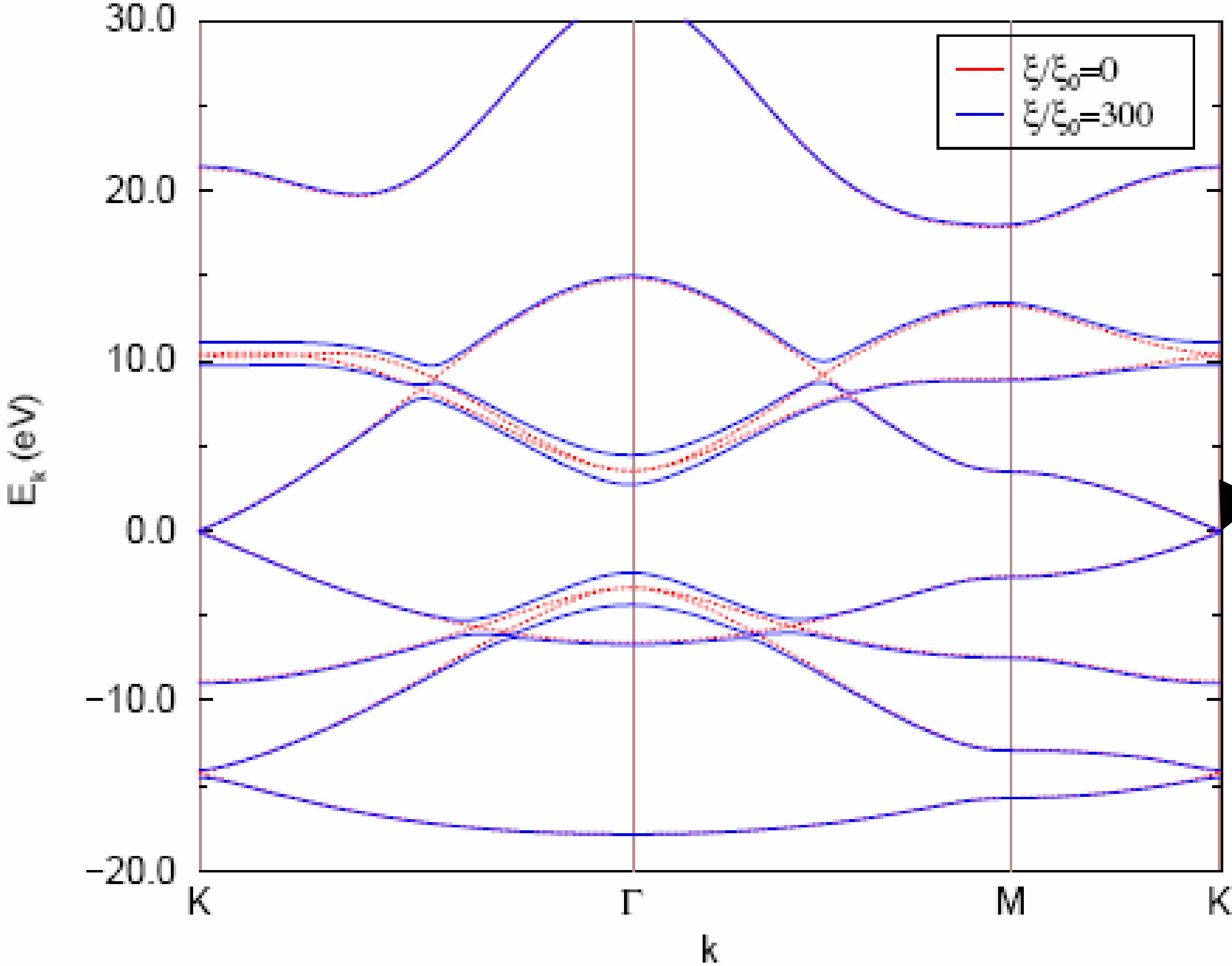
Sinitsyn, Sinova et al. cond-mat/0602

$$\sigma_{xy} = \frac{-e^2\Delta}{4\pi\sqrt{(vk_F)^2+\Delta^2}}\left[1 + \frac{4(vk_F)^2}{4\Delta^2+(vk_F)^2} + \frac{3(vk_F)^4}{(4\Delta^2+(vk_F)^2)^2}\right]$$



SO-coupling in Graphene

Hongki Min & AHM



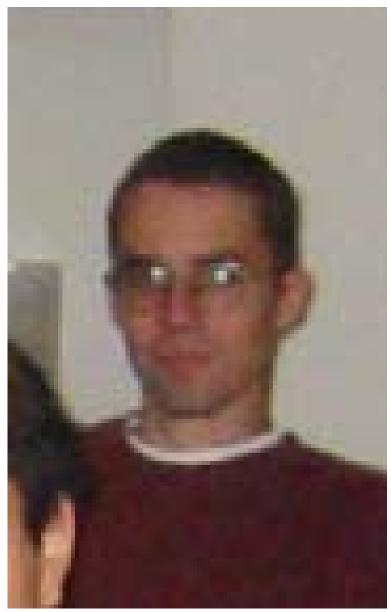
$$2\Delta_{SO} \equiv \frac{|s-p|}{9(sp\sigma)^2}\xi^2$$

Anomalous Transport

Spin Torques

Ferromagnetic Semiconductors

Alvaro Nunez

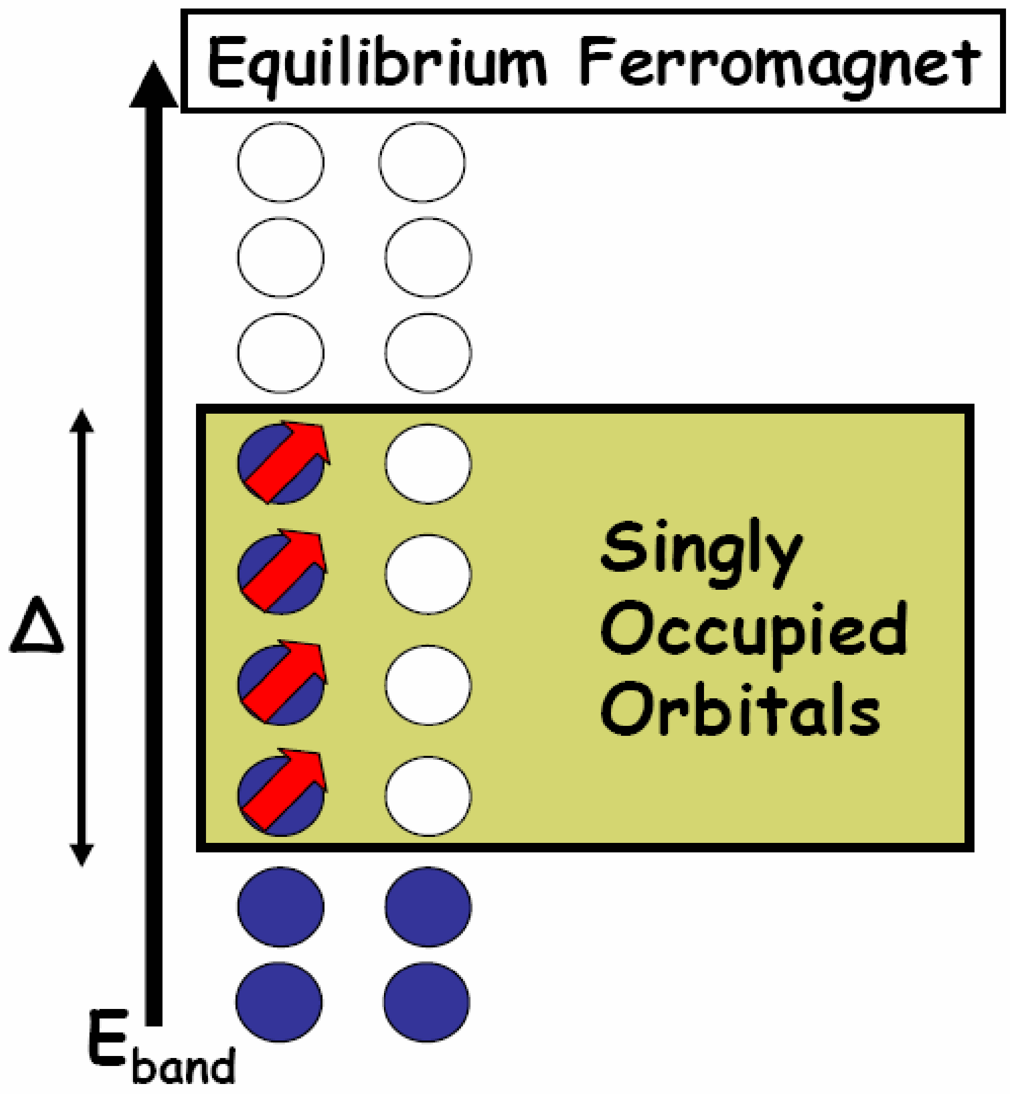


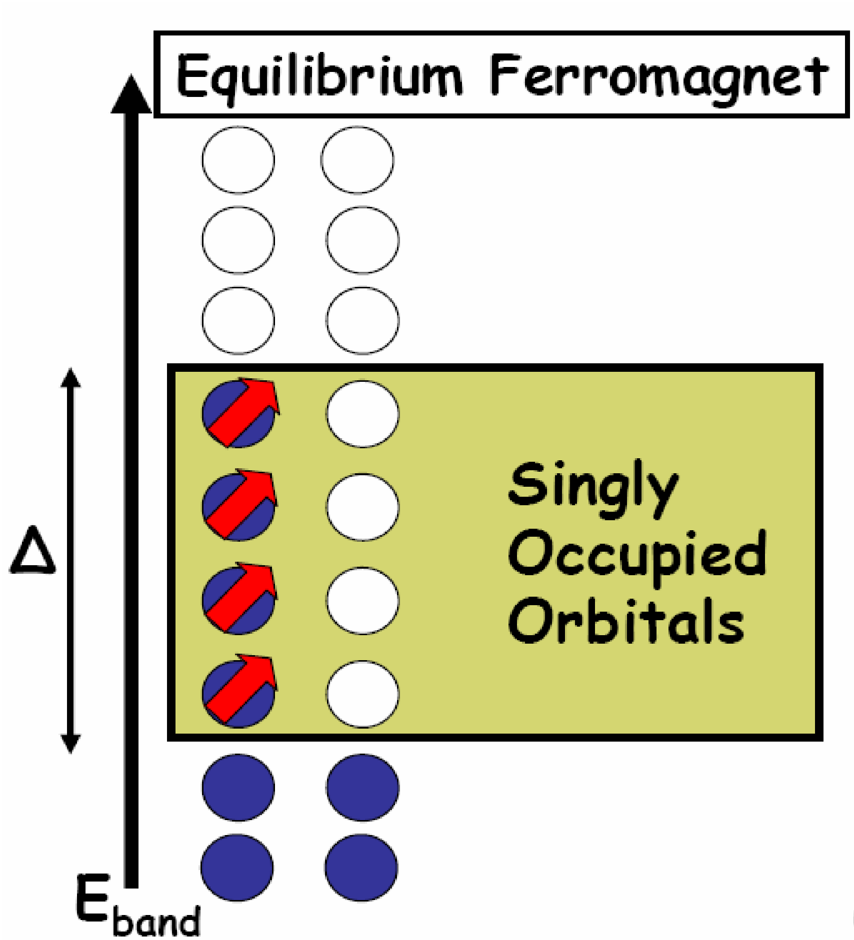
Paul Haney

Rembert Duine

Adiabatic Theory of Spin Transfer Torque (Conceptual)

(how to calculate ST Torque in principle – Nunez cond-mat/0403710)


Equilibrium Ferromagnet
Δ
Singly
Occupied
Orbitals
E_{band}

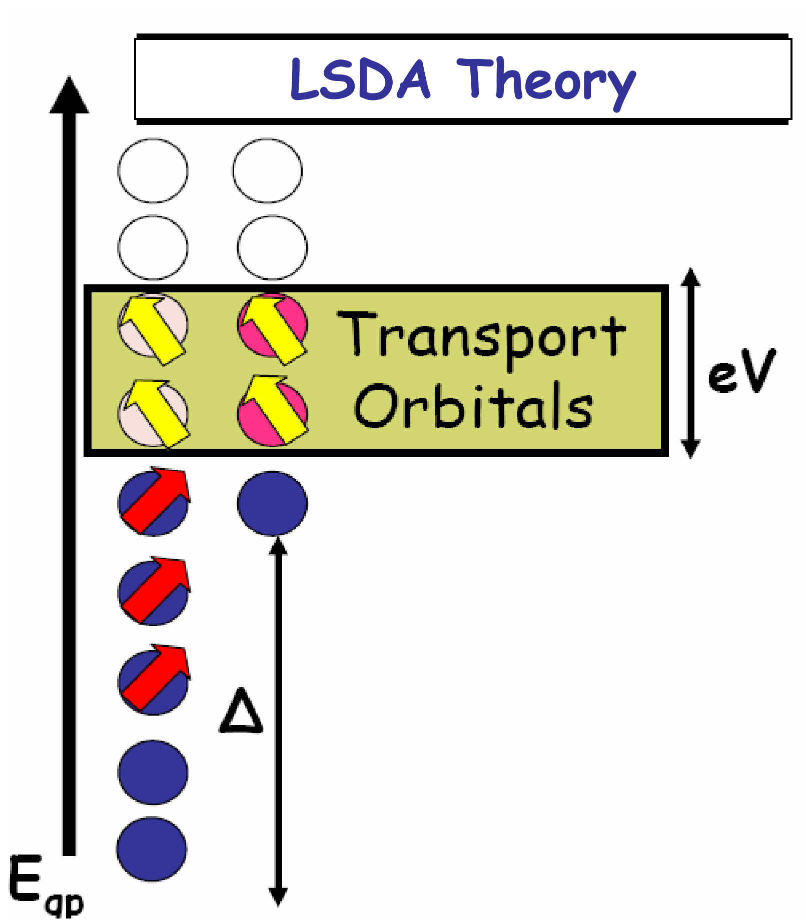


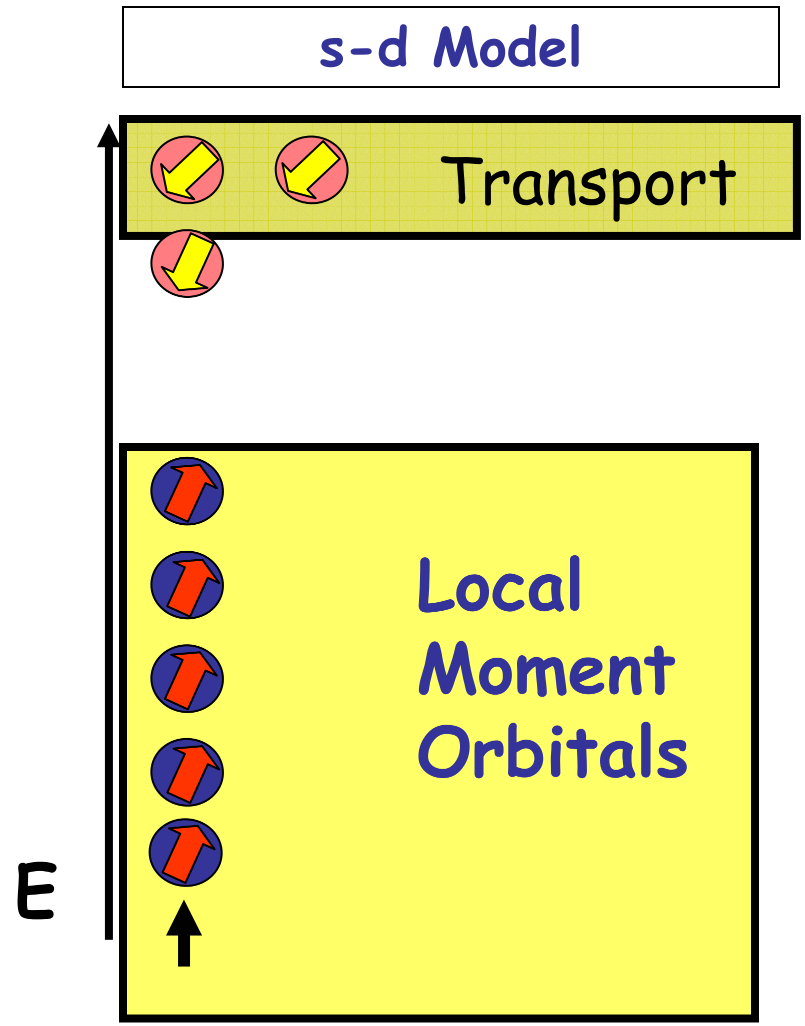
Spin-Transfer Theory

Nunez+AHM, cond-mat/0403710

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

Spin Transfer Torques





Spin Transfer Torques

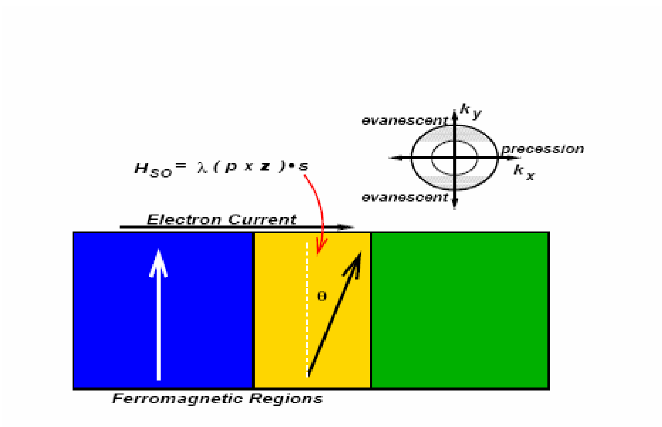
(Summary)

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

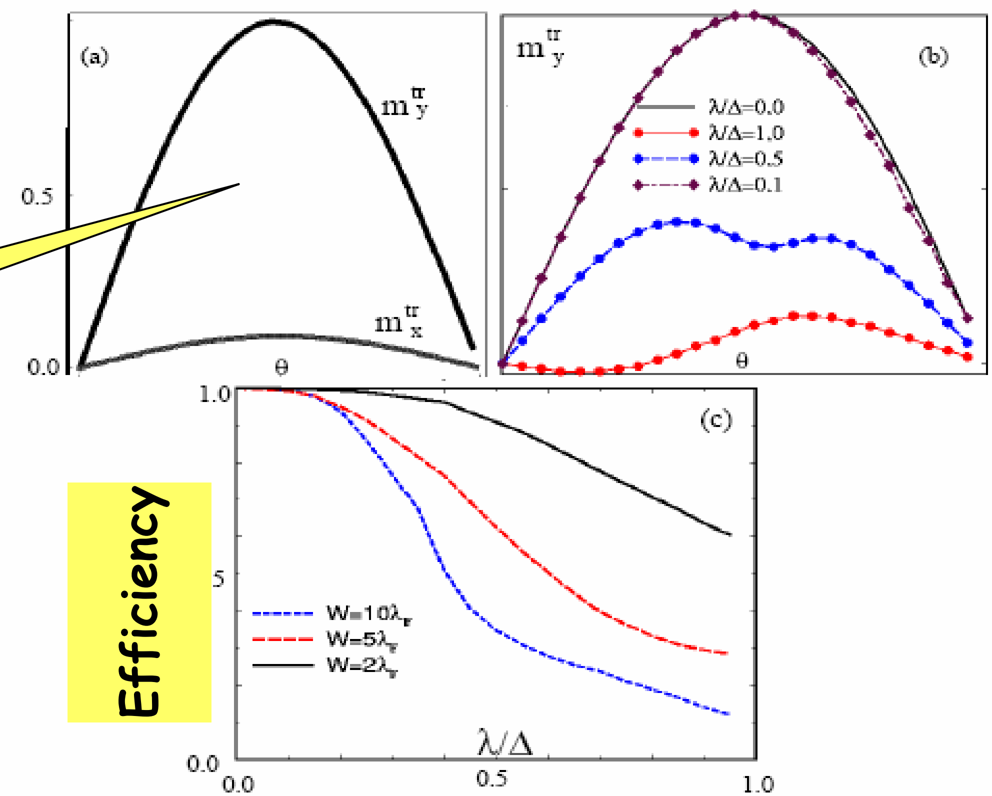
$$\vec{\Delta}^{\mathrm{tr}}(\vec{r}) = \frac{\nabla_i \vec{J}^{\mathrm{tr},i}(\vec{r}) \times \hat{m}}{m}$$

Toy-Model SO Effect

$$\frac{d\, s_i(\vec{r}_0)}{dt} = \partial_l J^S_{li} + 2m\lambda\left(\delta_{i3} J^S_{mm} - J^S_{i3}\right)$$



Rashba Model



SO Coupling Strength

Bulk Transport Theory SO Effect

TBB cond-mat/0512715
XZS cond-mat/0601172

$$\partial_t \delta\mathbf{s} - (\Delta_{\rm xc}/\hbar)\hat{\mathbf{z}} \times \delta\mathbf{s} - (\Delta_{\rm xc}/\hbar)\hat{\mathbf{z}} \times \mathbf{u}s_0 = (\hbar/4)\sum_s \int dk(\mathbf{v_k}\cdot\partial_{\mathbf{r}})\mathbf{g}_{\mathbf{k}s} - (\delta\mathbf{s} + \mathbf{u}s_0)/\tau_{\rm sd}$$

$$\partial_t \mathbf{m}|_{\rm LLG} = -\gamma\mathbf{m}\times\mathbf{H}_{\rm eff} + \alpha_{\rm LDA}\,\mathbf{m}\times\partial_t\mathbf{m}$$

$$\partial_t \mathbf{m}|_j = \mathcal{P}\left[1 - \mathbf{m}\times\left(\beta + \frac{\hbar\partial_t}{\Delta_{\rm xc}}\right)\right](\mathbf{j}\cdot\partial_{\mathbf{r}})\,\mathbf{m}$$

Magnetic Action of Current-Carrying Ferromagnet

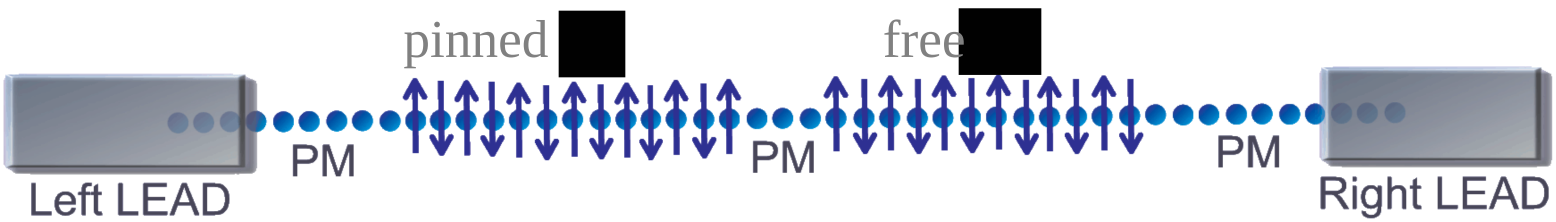
Fernandez-Rossier, Braun, Nunez, AHM PRB (2004)
Bazaliy, Jones, Zhang PRB (2003)

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

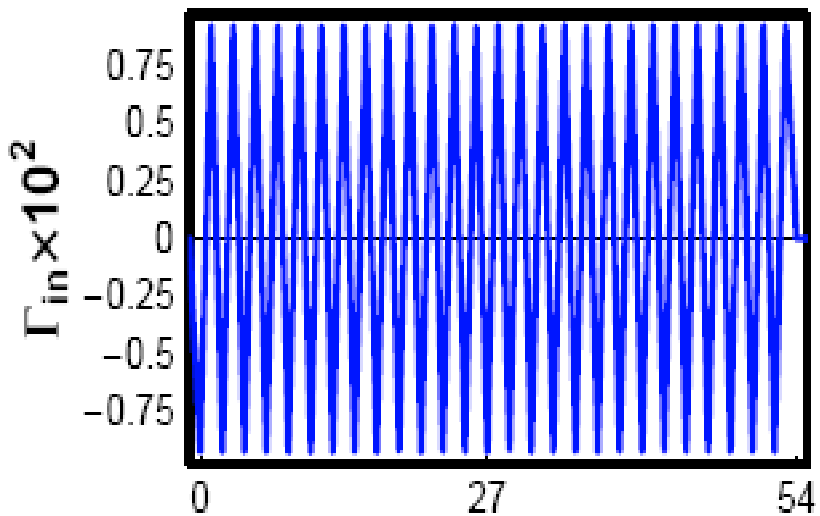
$$D_{\pm}^{\mathrm{ret}}(\vec{q},\omega) = \frac{4U}{3} \frac{1}{1 + \frac{2}{3}U\Gamma(\pm\vec{q},\pm\omega)}$$

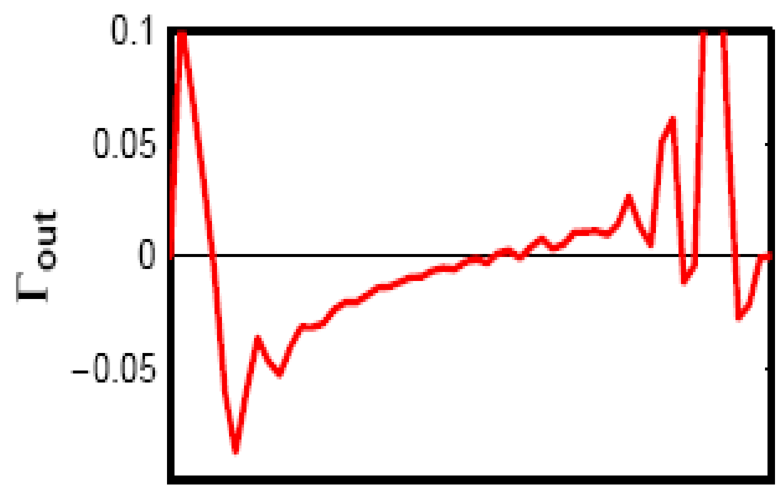
$$\Gamma(\vec{q},\omega) = \frac{1}{\mathcal{N}} \sum_{\vec{k}} \frac{n_{\vec{k}}^{\uparrow} - n_{\vec{k}+\vec{q}}^{\downarrow}}{\epsilon_{\vec{k}}^{\uparrow} - \epsilon_{\vec{k}+\vec{q}}^{\downarrow} + \omega + i0^{+}},$$

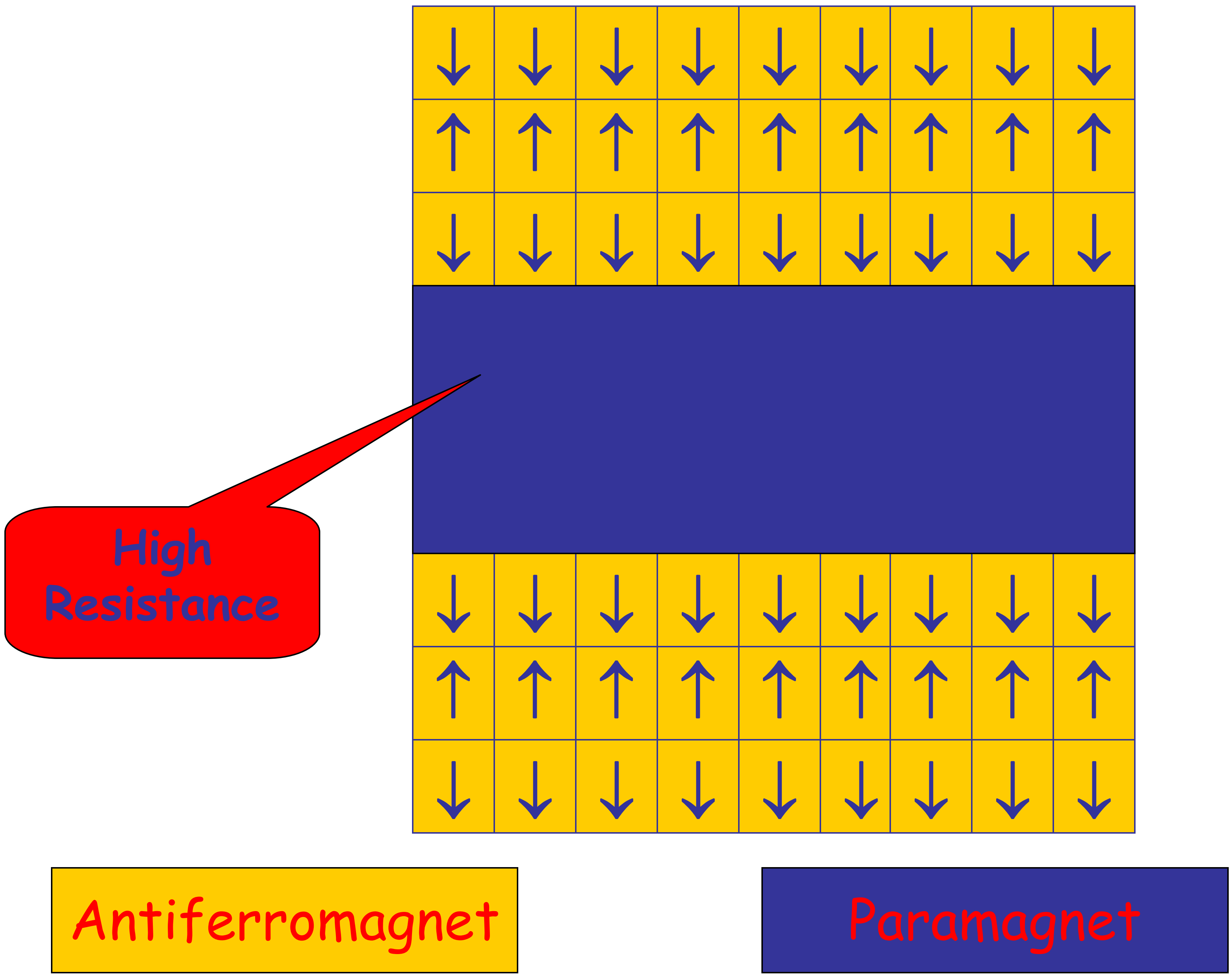
What About Antiferromagnets?



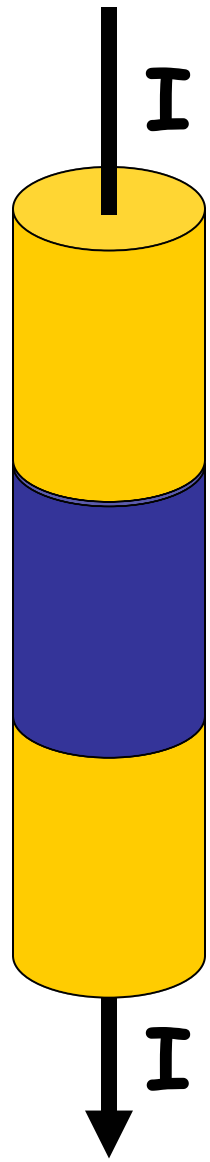
GMR and Robust Spin Torques






High Resistance
Antiferromagnet
Paramagnet

+


I
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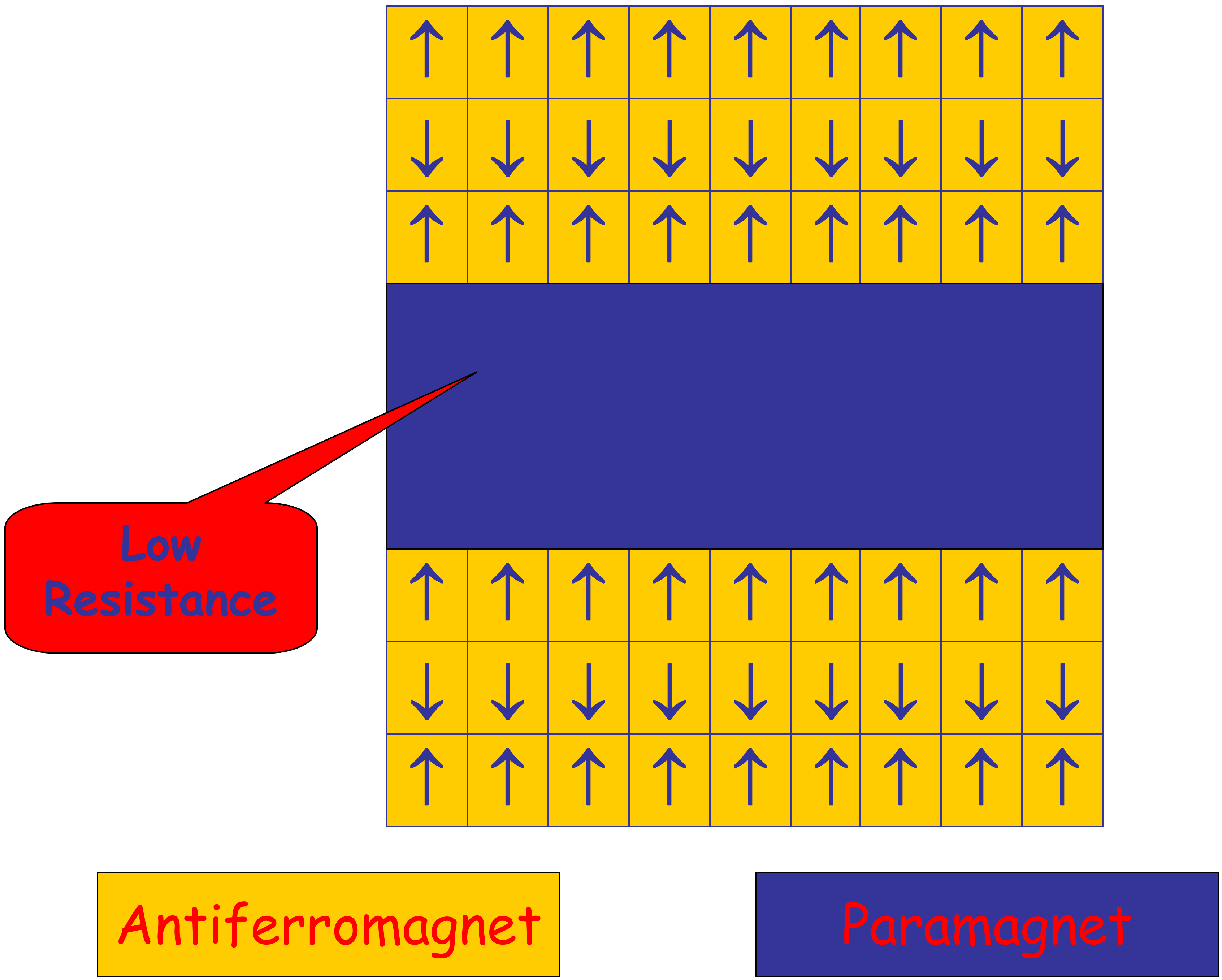
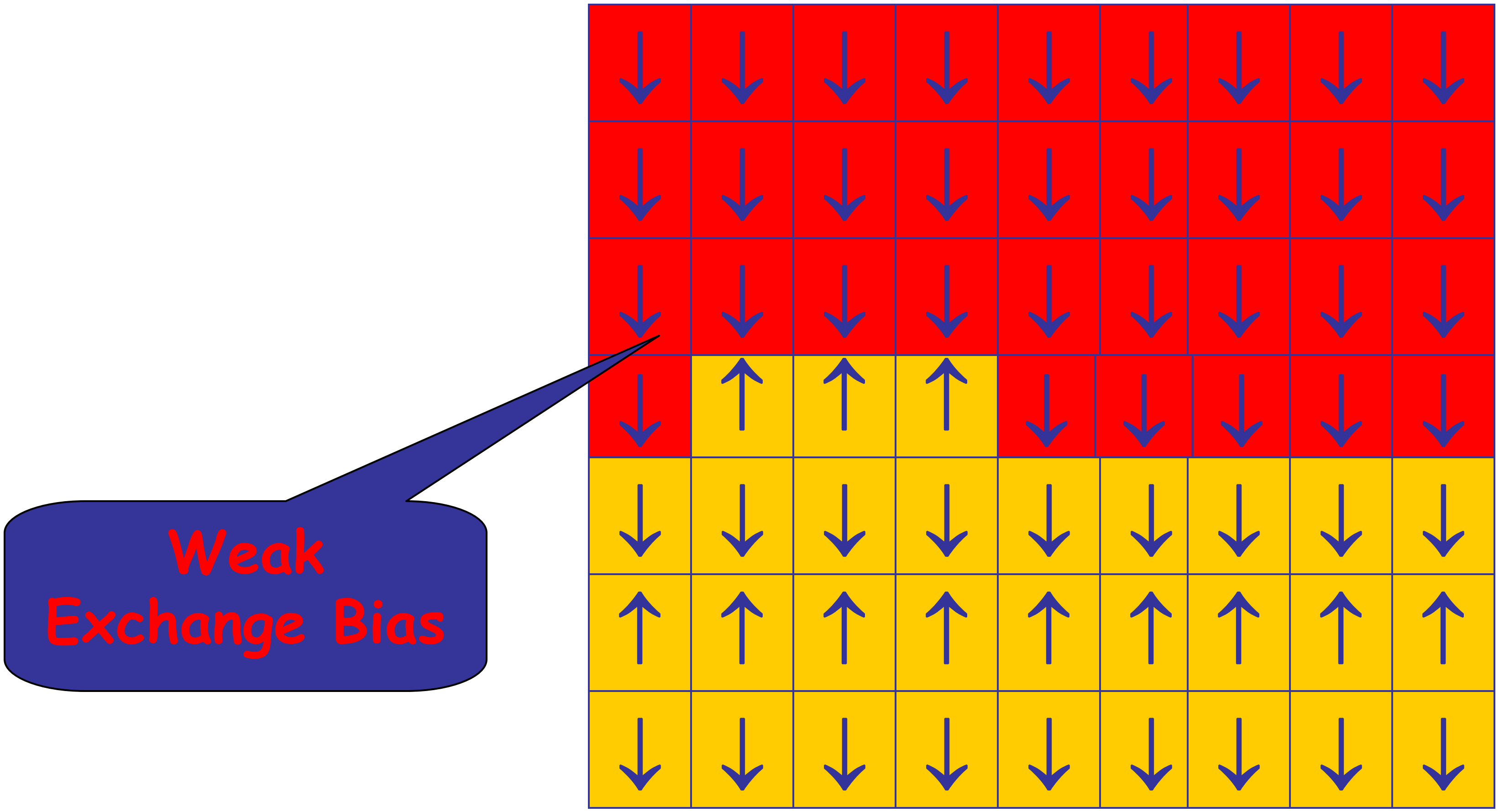
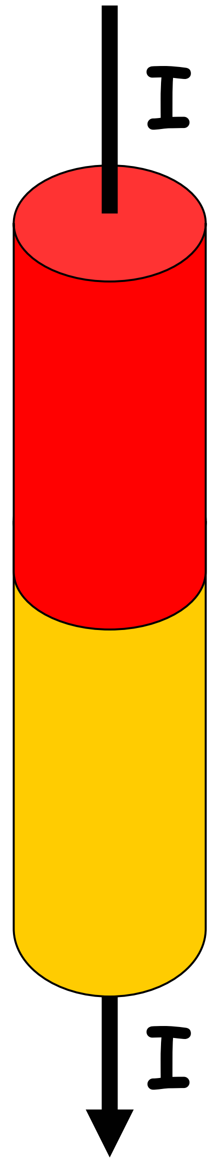


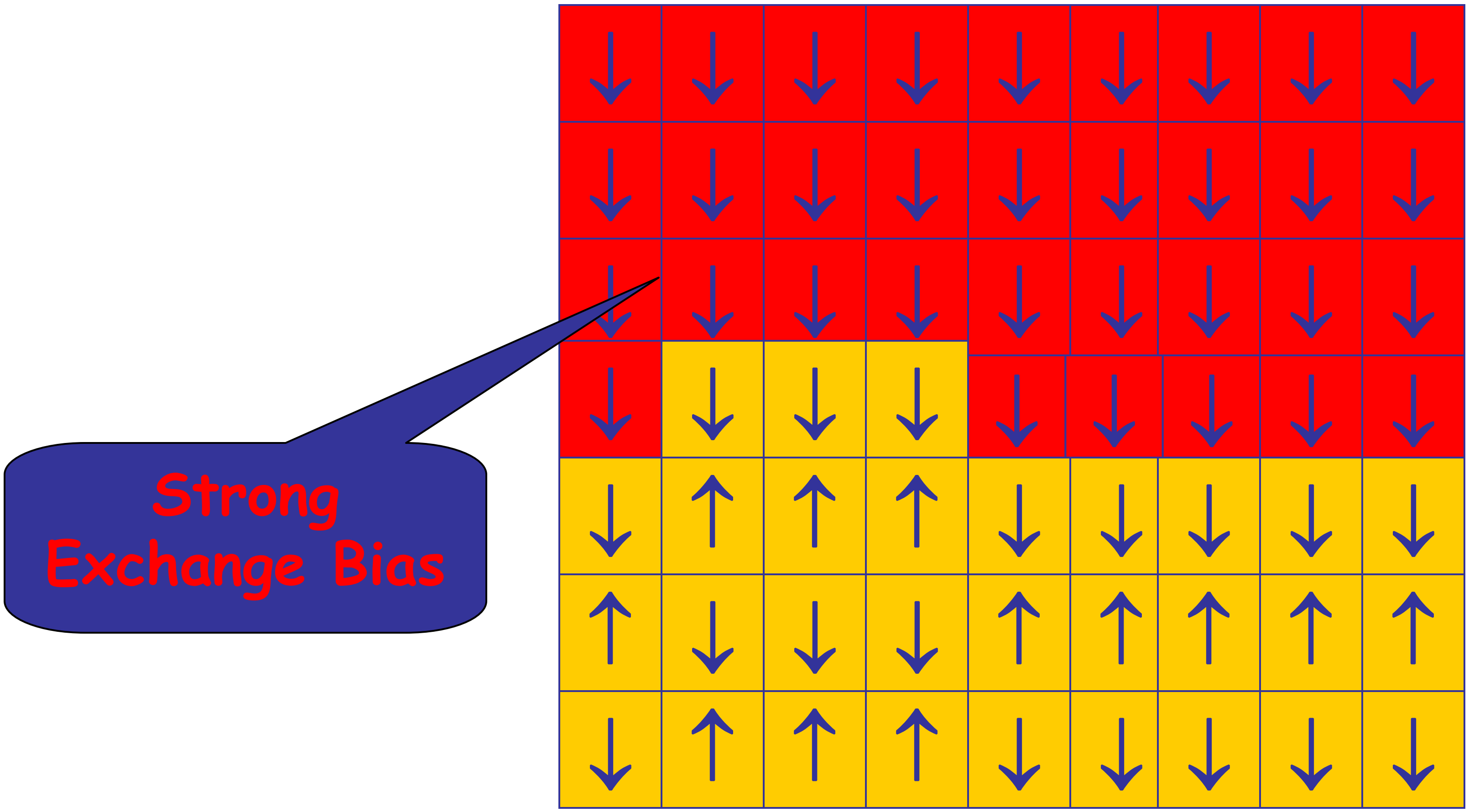
Low Resistance
Antiferromagnet
Paramagnet


Weak
Exchange Bias

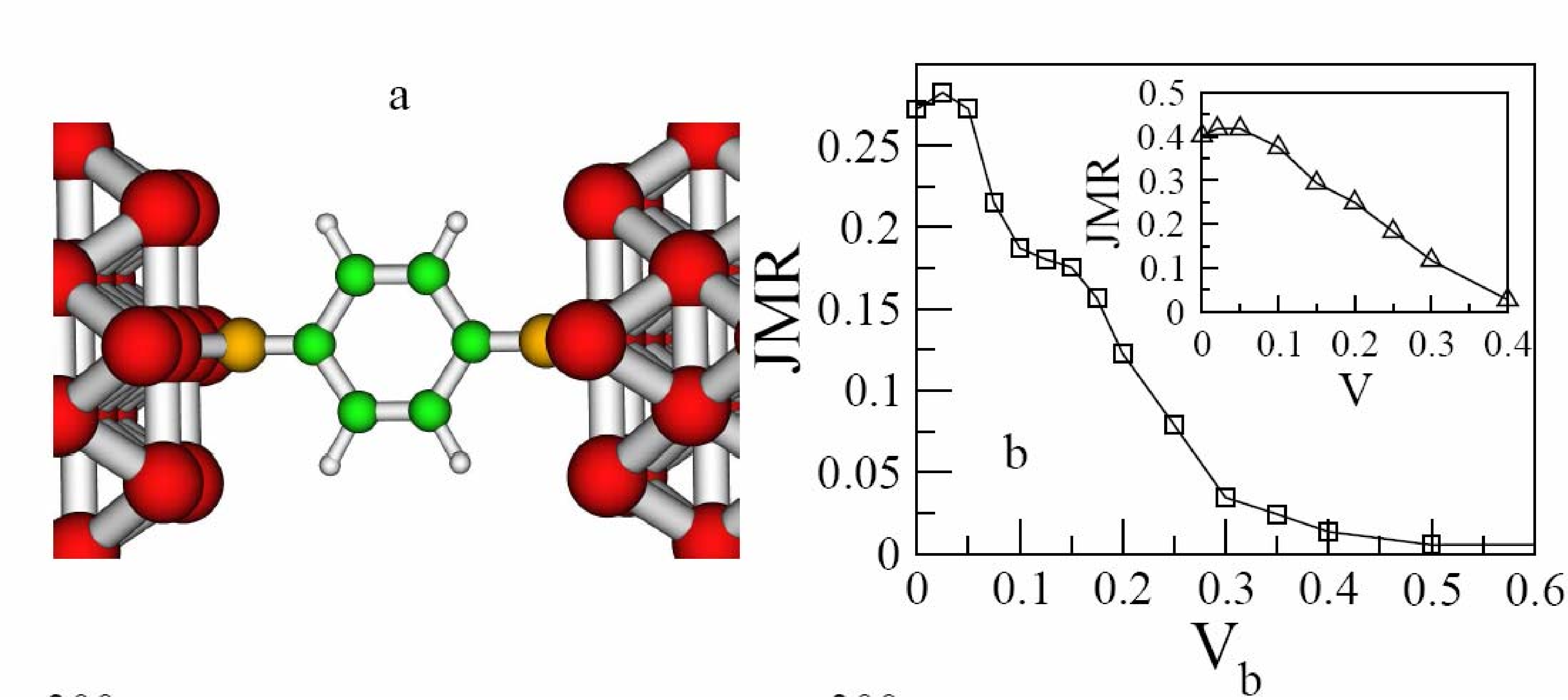
+


I
I

=


Strong
Exchange Bias

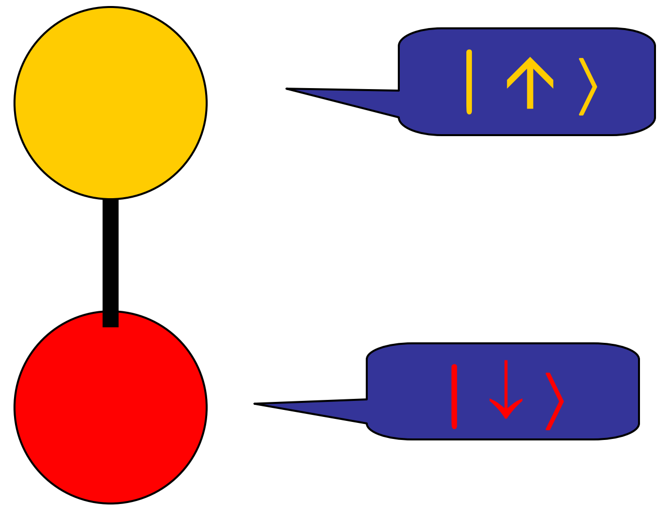
Molecular Spintronics



Waldron *et al.* - preprint (2006)

Molecular Electronics

$$\mathcal{H}_0 = -t(c_1^\dagger c_2 + c_2^\dagger c_1)$$



$$\mathcal{H} = \mathcal{H}_0 + V\hat{n}_1\hat{n}_2$$

Spinless Hubbard Molecule

Mean-Field Hamiltonian

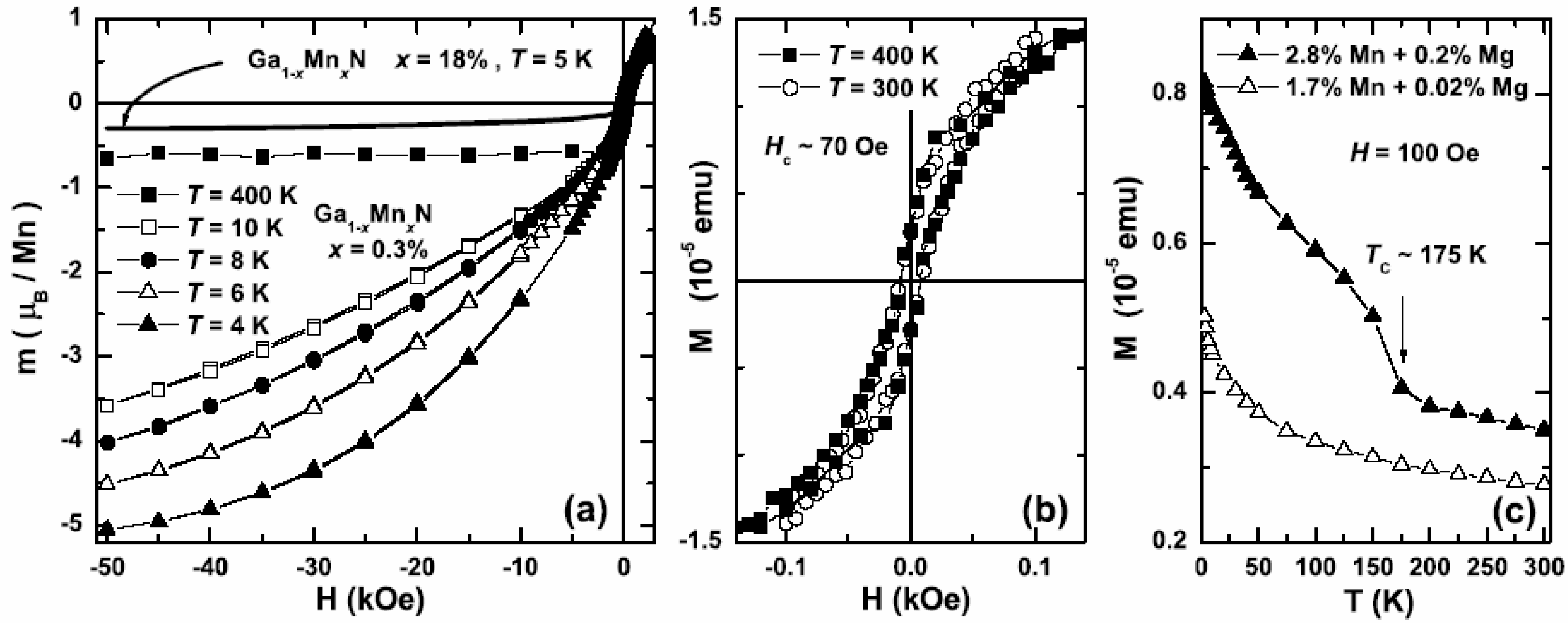
$$\mathcal{H}_{MF} = -c_1^\dagger c_2(t + V\langle c_2^\dagger c_1\rangle) - c_2^\dagger c_1(t + V\langle c_1^\dagger c_2\rangle)$$

Anomalous Transport

Spin Torques

Ferromagnetic Semiconductors
(Review to appear in RMP)
cond-mat/0603380

(Ga,Mn)N - high T_c?



Giraud *et al.* Eur. Phys. Lett. 65 (2004)

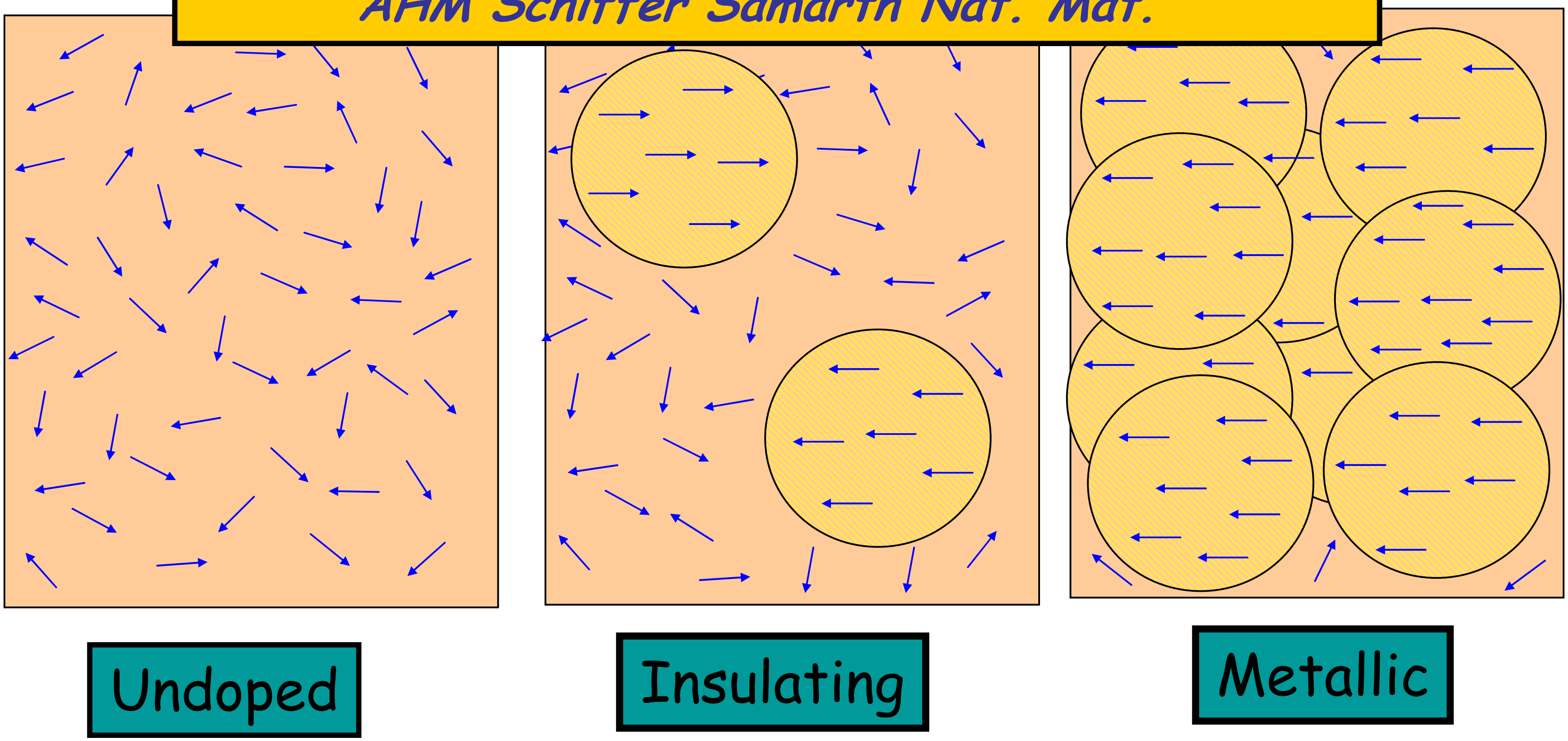
Semiconductor Ferromagnetism

Mechanism

Carrier-mediated Long-range Order

Ohno, Munekata *et al. PRL '89 PRL '92 APL '96*

AHM Schiffer Samarth Nat. Mat.

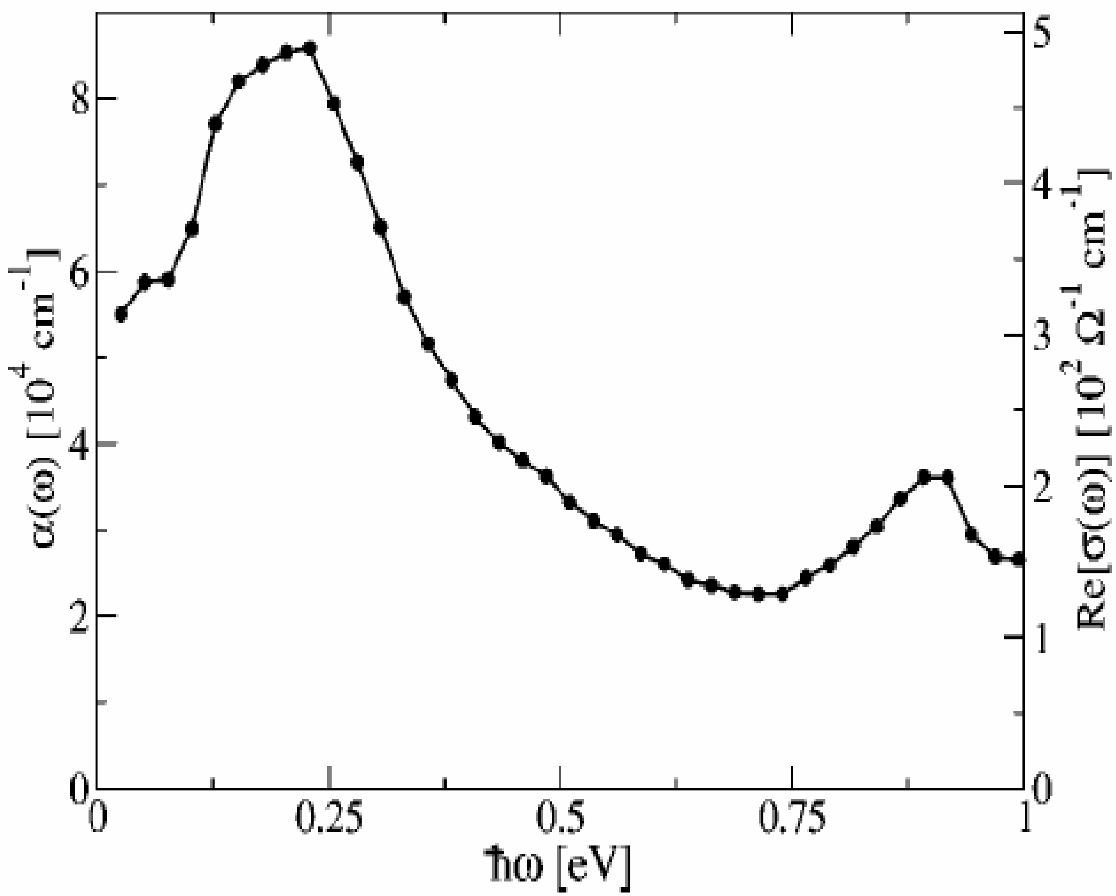


Is k.p description OK ?

$$\mathcal{H} = \mathcal{H}_{holes} + J_{pd} \sum_{i,I} \mathbf{S}_I \cdot \mathbf{s}_i \delta(\mathbf{r}_i - \mathbf{R}_I)$$

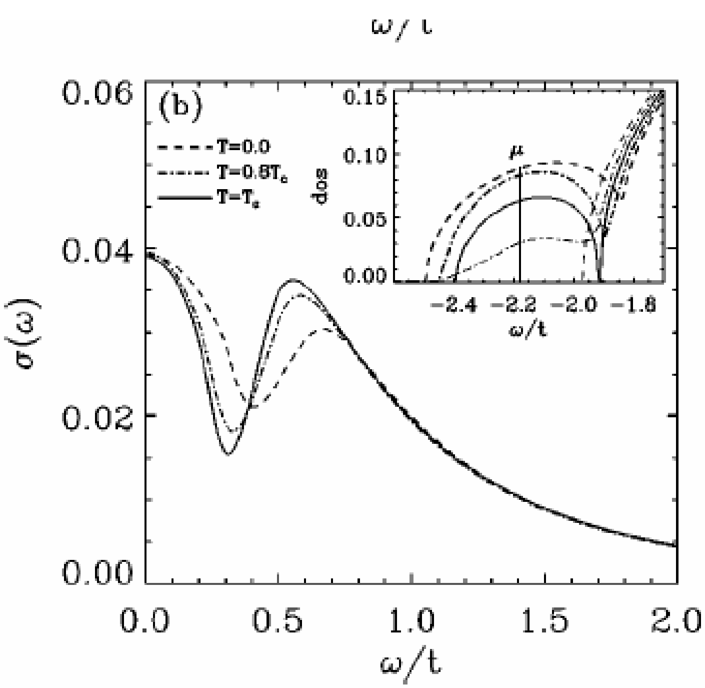
+ Coulomb

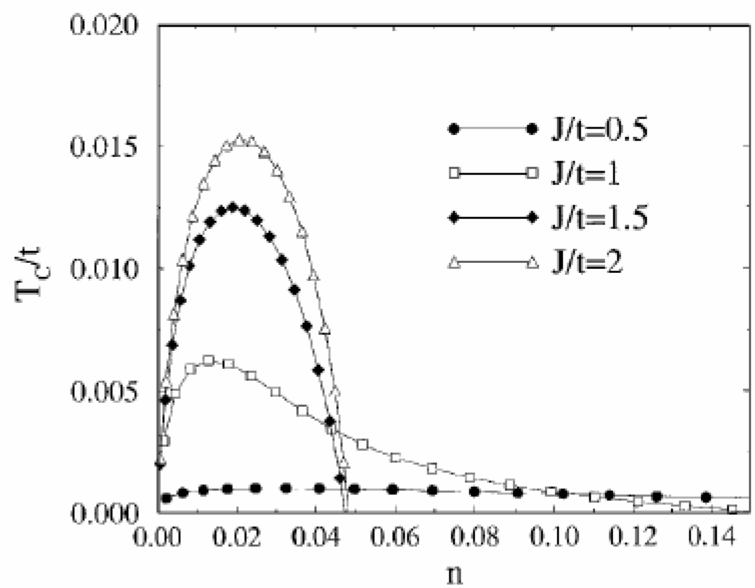
k.P theory IR conductivity



Yang Sinova et al. PRB (2003)

Impurity Band Picture?





Chattopadhyah et al. PRL (2001) PRB (2002)

Anomalous Transport

Spin Torques

Ferromagnetic Semiconductors