Spin Coulomb Drag

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Thanks to Irene D'Amico (York)

References

1. I. D'Amico and G. Vignale, PRB **62**, 4853 (2000)
2. I. D'Amico and G. Vignale, PRB **65**, 085109 (2002)
3. I. D'Amico and G. Vignale, Europhys. Lett. **55**, 566 (2001)
4. K. Flensberg, T.S. Jensen, and N.A. Mortensen, PRB **64**, 245308 (2001)
5. I. D'Amico and G. Vignale, PRB **68**, 045307 (2003)
6. I. D'Amico and C.A. Ullrich, PRB **74**, 121303 (2006)

Reviews:

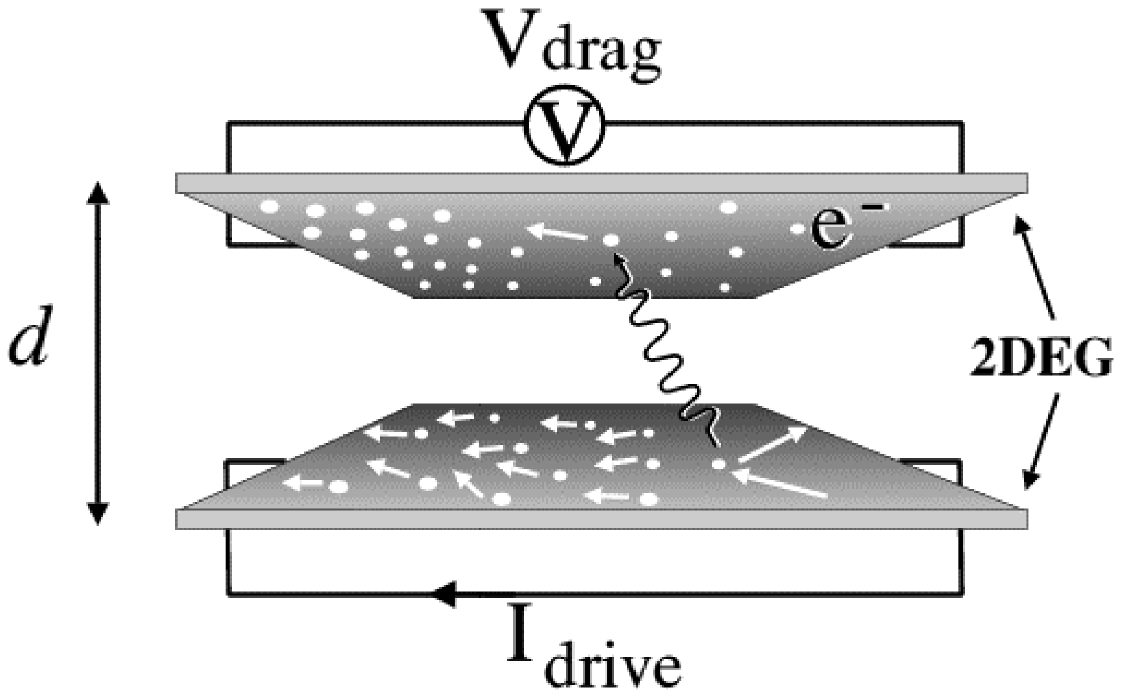
1. G. Vignale, in "Manipulating Quantum Coherence in Solid State Systems", ed. M.E. Flatte and I. Tifrea (Springer, 2007)
2. E. M. Hankiewicz and G. Vignale, J. Phys. Condens. Matter **21**, 253202 (2009)
3. I. D'Amico and C. A. Ullrich, Physica Status Solidi (to appear)

Outline

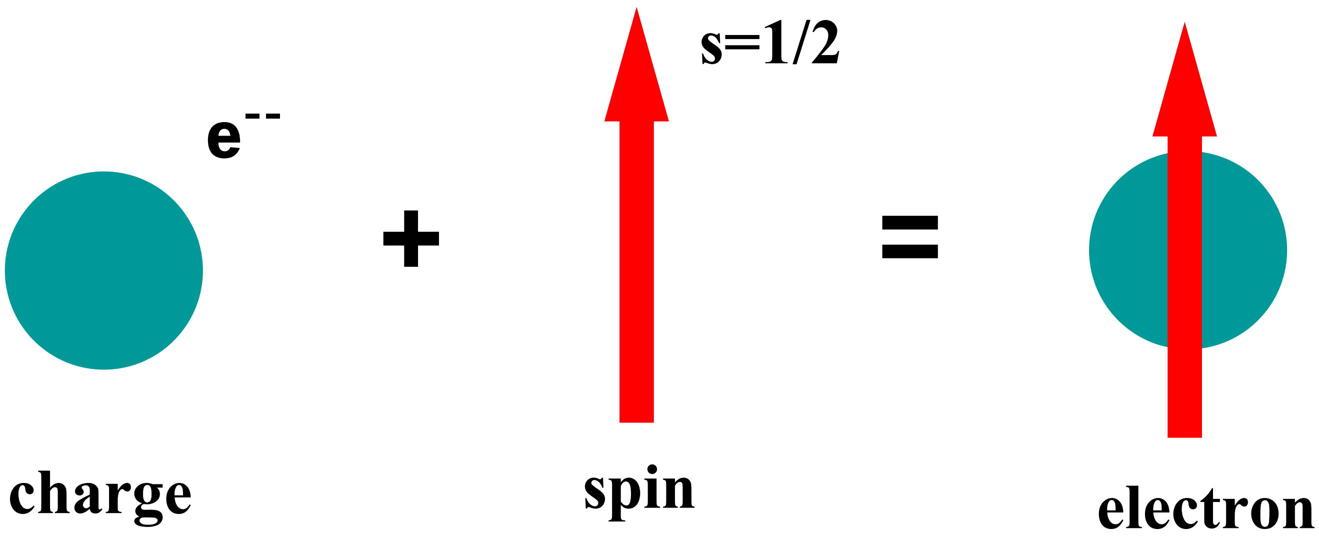
1. Phenomenological introduction of the Spin Coulomb Drag
2. Microscopic models
3. SCD in spin-dependent transport
4. Connection to TDDFT and the linewidth of spin plasmons

Coulomb drag in bilayer systems

Gramila, Eisenstein, MacDonald, Pfeiffer, West, PRL **66**, 1216 (1991)
A. G. Rojo, J. Phys. Condens. Matter **11**, R31 (1999)



Picture from http://www.sp.phy.cam.ac.uk/SPWeb/research/drag/index.html



traditional electronic devices are based on the charge properties only……

SPINTRONICS: Generalization of traditional electronics to devices and circuits based on both the charge and the spin degrees of freedom

Main issues in spintronics

1) Fundamental physics
- ►novel effects in spin-dependent transport (spin Hall effect, many-body effects)
- ►spin-transport across magnetic/semiconductor interfaces (spin injection)
- ►spin-related properties of different materials, e.g. spin coherence length, spin diffusion
- ►spin (collective) excitations

2) New spintronic materials (e.g. DMS) with
- ►high Curie temperatures
- ►large spin polarisation at the Fermi level

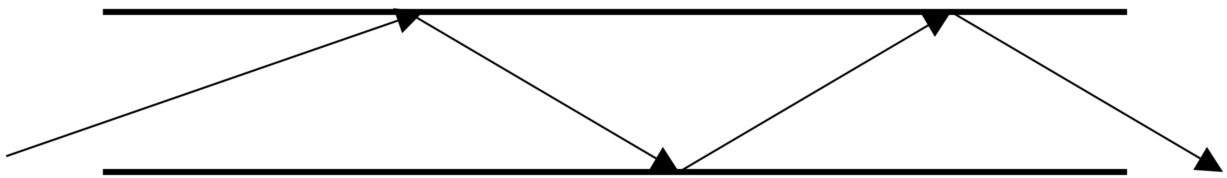
3) Devices: concepts, fabrication, integration (e.g. spin FET)

4) Quantum computing through spin qubits

Spin transport

- ► non-magnetic materials (metals, semiconductors)
- ► low dimensional systems (quantum wells, quantum wires, quantum dots)
- ► magnetic materials (ferromagnets, diluted magnetic semiconductors (DMS))
- ► heterojunctions (FM/NMS/FM, FM/I/FM, FM/S)

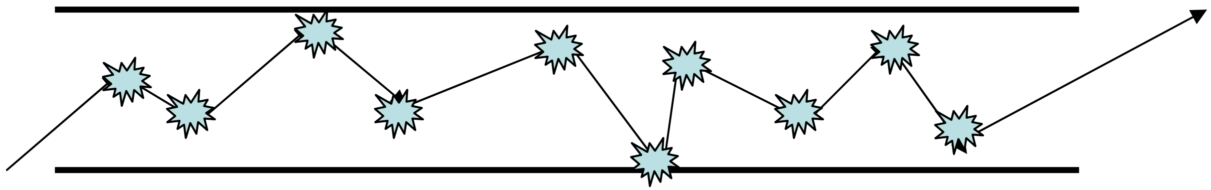
Ballistic vs. diffusive regime



- Ballistic regime:

$$L_{dev}, \tau_{dev} \ll L_{scat}, \tau_{scat}$$

•single-electron devices (spin-based qubits)



- Diffusive regime:

$$L_{dev}, \tau_{dev} \gg L_{scat}, \tau_{scat}$$

•on/off type devices (spin valves)

Diffusive regime in spintronics

- Comparable to traditional electronics
- usually present in integrated circuits
- two possible spin-injection mechanisms:

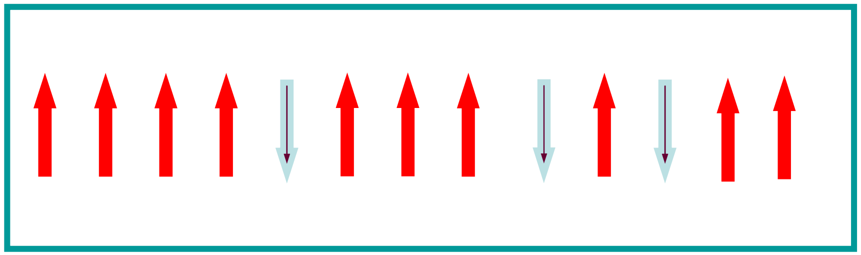
➡ spin packets by polarized laser pulses;

➡ electrical injection from a ferromagnet.

Conduction electrons described as Fermi liquid: $(n_{\uparrow}, n_{\downarrow}, \varepsilon_{F\uparrow}, \varepsilon_{F\downarrow}, k_B T)$

Spin injection

injection of spin-current



useful spin state is usually an excitation of the system

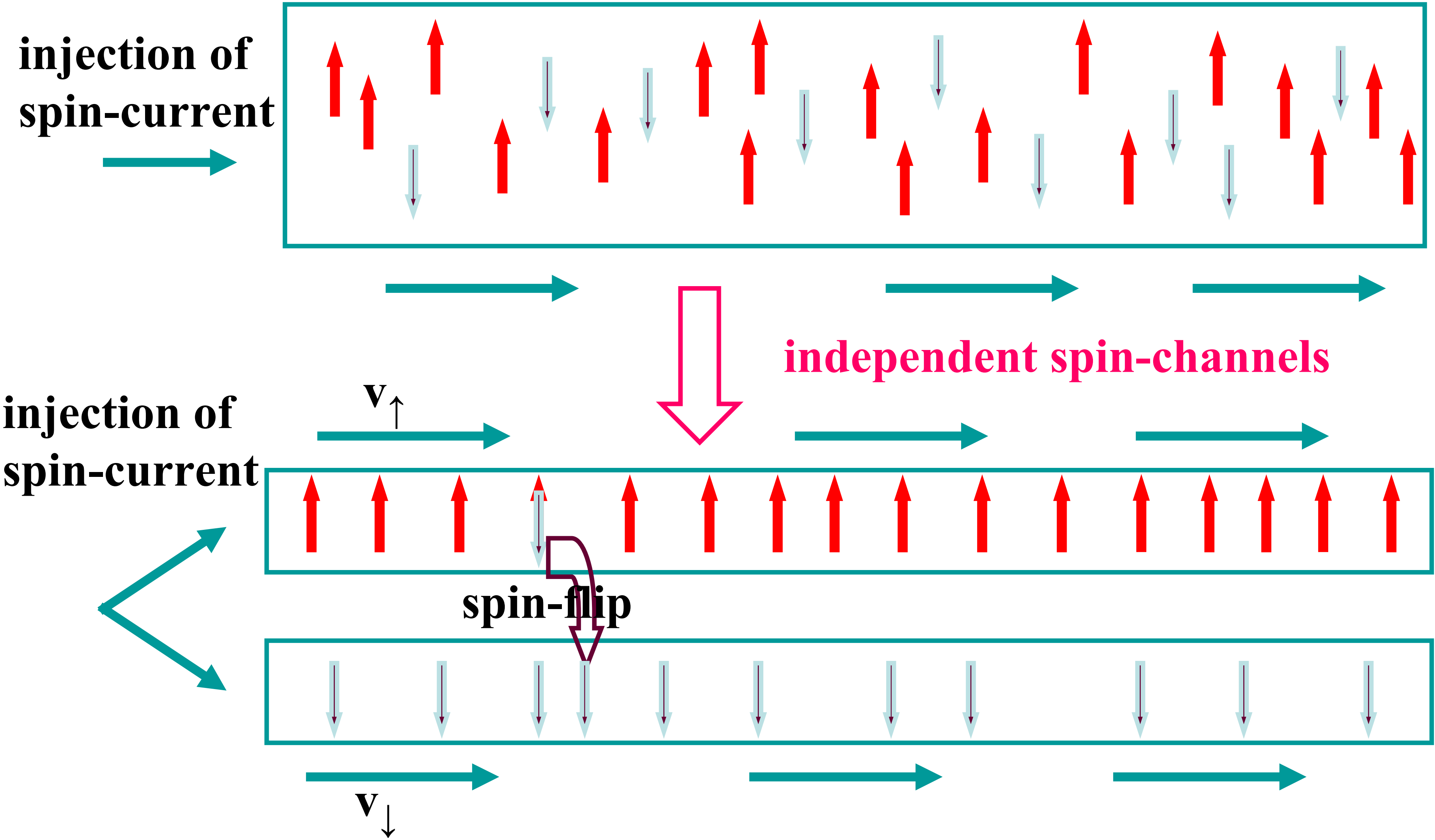
⇨ **it will last for a finite time (decoherence time),**

⇨ **it will propagate for a finite length (decoherence length)**

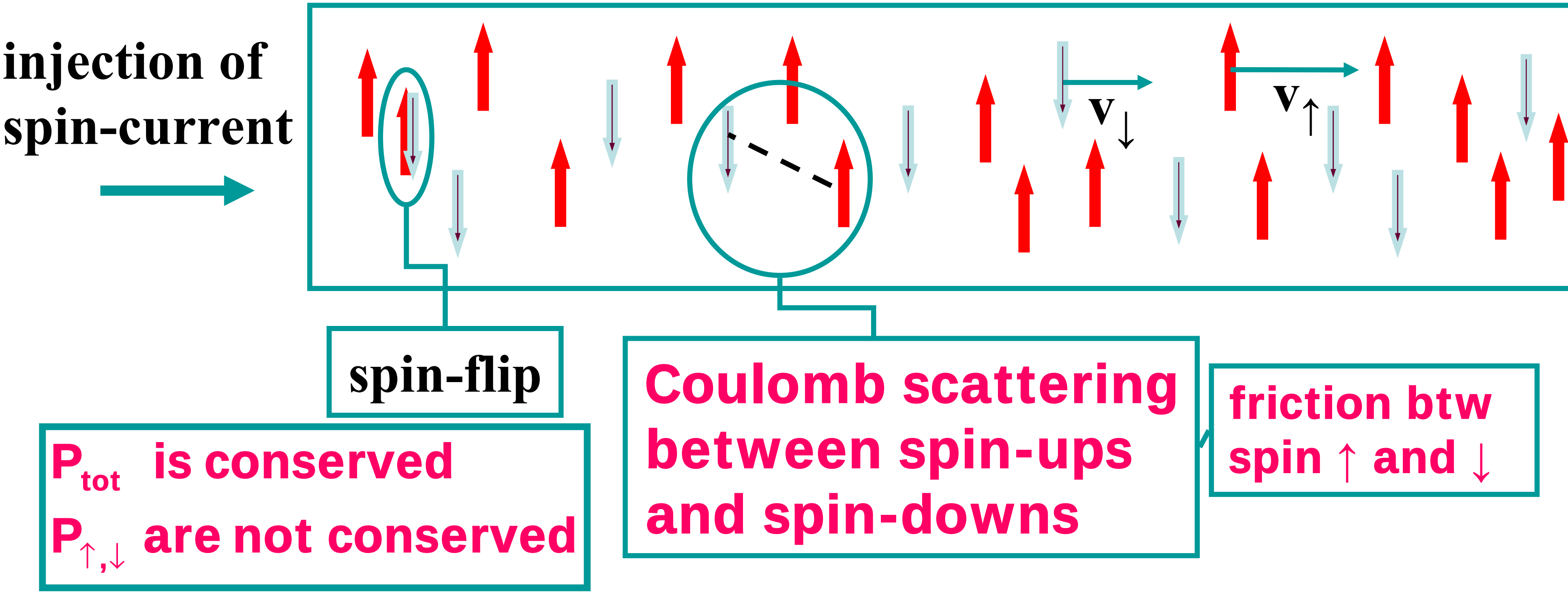
Spintronics needs **long spin coherence times**
(~ characteristic time and length scales of the device)

Spintronics needs **methods to manipulate the spin**
(electric fields, magnetic fields, polarized laser pulses)

Independent spin channel model



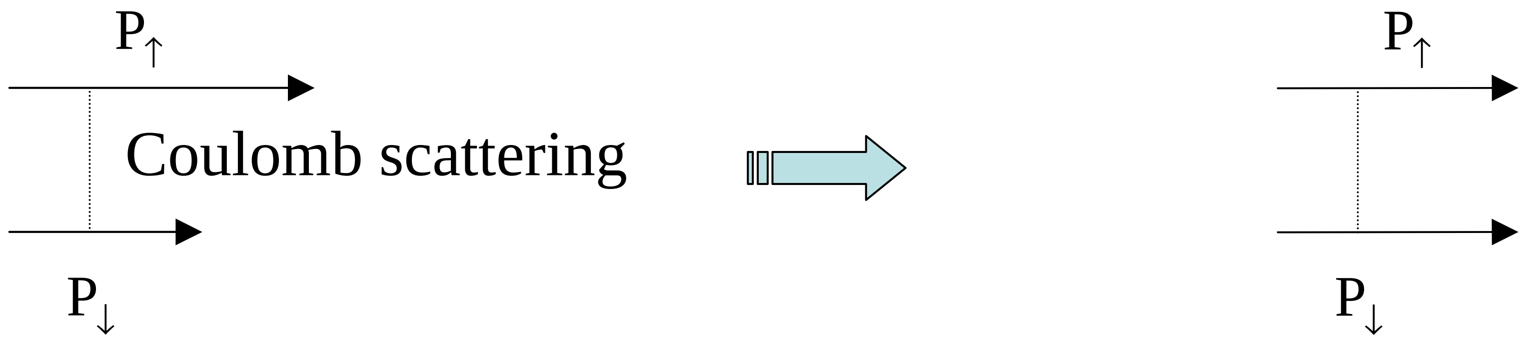
The spin Coulomb drag effect



Even in the purest material and even in the absence of spin-flip mechanisms, a spin current will decay due to Coulomb interactions between different spin populations

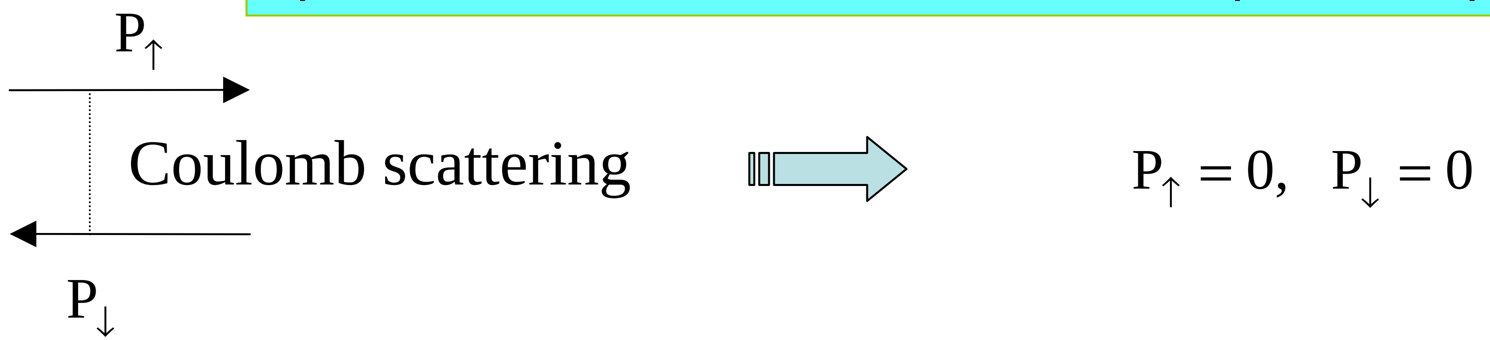
The spin Coulomb drag effect

Spin+ Charge mode — **Charge mode**



SCD ‘pumps’ momentum from faster to slower population

Spin mode — **complete damping**



SCD damps *both* spin populations

P_{tot} conserved, $P_{\uparrow,\downarrow}$ *not* conserved

Equation of motion for momentum of spin-σ

$$\dot{\mathbf{P}}_\sigma = -e n_\sigma \mathbf{E}_\sigma + \mathbf{F}_{\sigma\bar{\sigma}} - \frac{\mathbf{P}_\sigma}{\tau_\sigma} + \frac{\mathbf{P}_{\bar{\sigma}}}{\tau'_\sigma}$$

$\mathbf{E}_\sigma$: effective electric field coupling to σ-spins (external plus local chemical potential gradient)

$\tau_\sigma, \tau'_\sigma$: momentum relaxation times (impurity scattering)

$$\mathbf{F}_{\sigma\bar{\sigma}} = -\gamma m \frac{n_\sigma n_{\bar{\sigma}}}{n} \left(\mathbf{v}_\sigma - \mathbf{v}_{\bar{\sigma}} \right)$$

Net force by $\bar{\sigma}$ spins on σ spins (Newton's 3rd law and Galilean invariance)

γ: (positive) spin-drag coefficient or spin-drag scattering rate

$\mathbf{v}_\sigma - \mathbf{v}_{\bar{\sigma}}$: relative drift velocity

Resistivity matrix

For periodic fields of angular frequency ω one obtains

$$\begin{pmatrix} \mathbf{E}_{\uparrow} \\ \mathbf{E}_{\downarrow} \end{pmatrix} = \begin{pmatrix} \rho_{\uparrow\uparrow} & \rho_{\uparrow\downarrow} \\ \rho_{\downarrow\uparrow} & \rho_{\downarrow\downarrow} \end{pmatrix} \begin{pmatrix} \mathbf{j}_{\uparrow} \\ \mathbf{j}_{\downarrow} \end{pmatrix}$$

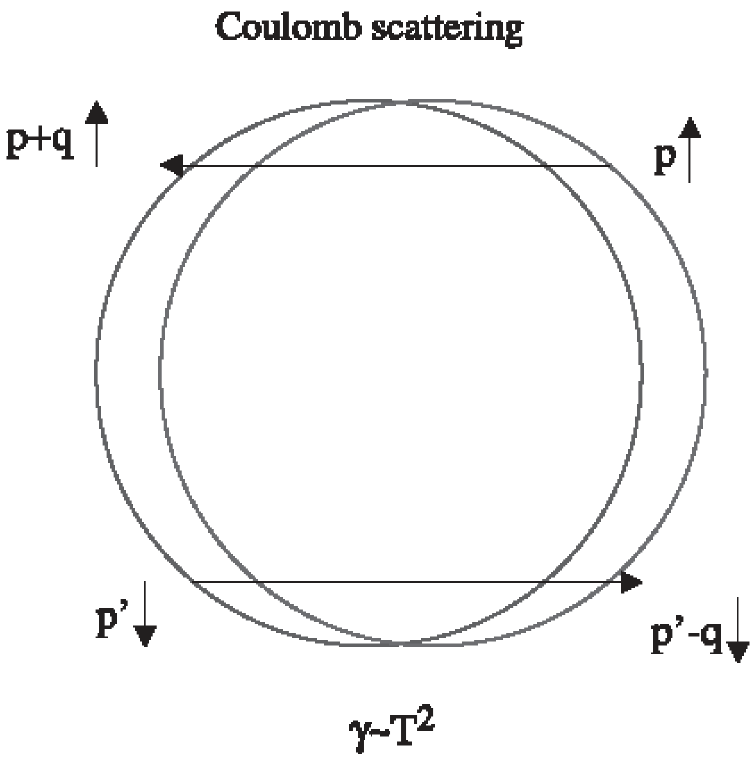
$$\mathbf{j}_{\sigma} = -e n_{\sigma} \mathbf{v}_{\sigma}$$ spin current components

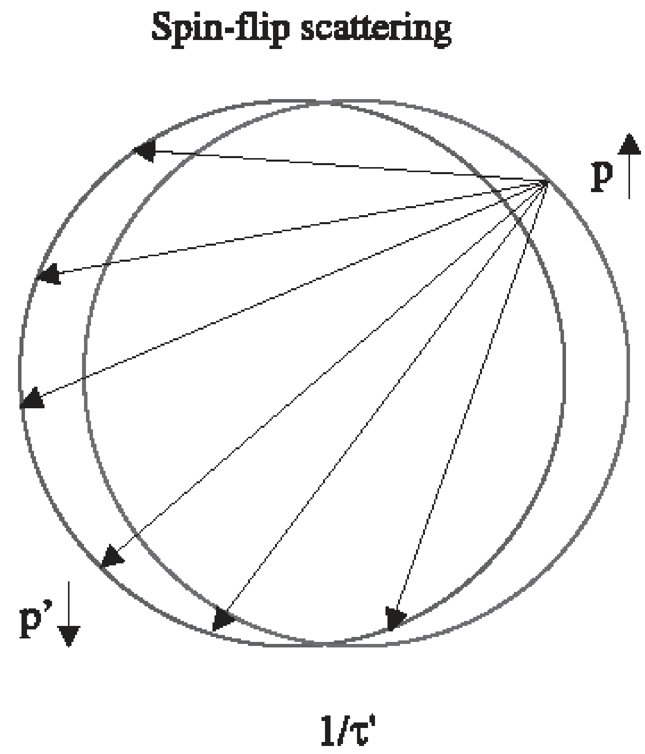
$$\rho_{\uparrow\uparrow} = -\frac{i\omega m}{n_{\uparrow} e^2} + \frac{m}{n_{\uparrow} e^2 \tau_{\uparrow}} + \frac{n_{\downarrow}}{n_{\uparrow}} \frac{m}{n e^2} \gamma$$

$$\rho_{\uparrow\downarrow} = -\frac{m}{n_{\uparrow} e^2 \tau'_{\uparrow}} - \frac{m}{n e^2} \gamma$$

Spin-transresistivity

Coulomb vs spin-flip scattering



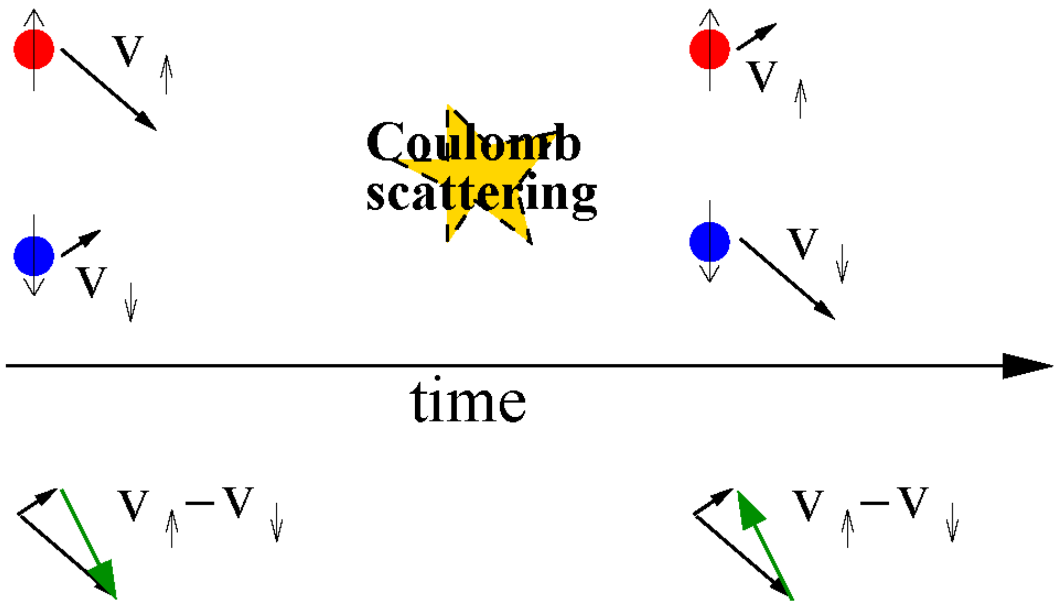


► Low temperatures: Coulomb scattering is suppressed (Pauli principle)

► $1/\tau'$ generally small (SO weak, spin-flip scattering does not transfer momentum effectively between spin channels, tends to randomize)

$$\Rightarrow \quad \rho_{\uparrow\downarrow} \approx -\frac{m}{ne^2}\gamma$$ down to very low T

SCD coefficient in the Boltzmann equation



$$\gamma = \frac{n}{n_\sigma n_{\bar\sigma}} \sum_{\mathbf{kk}',\mathbf{pp}'} W^{Coul}_{\mathbf{k}\sigma,\mathbf{p}\bar\sigma;\mathbf{k}'\sigma,\mathbf{p}'\bar\sigma} \frac{(\mathbf{k}-\mathbf{k}')^2}{4mk_BT}$$

$$\times f_{0\sigma}(\varepsilon_k) f_{0\bar\sigma}(\varepsilon_p) f_{0\sigma}(-\varepsilon_{k'}) f_{0\bar\sigma}(-\varepsilon_{p'})$$

$$\times \delta_{\mathbf{k}+\mathbf{p},\mathbf{k}'+\mathbf{p}'} \delta(\varepsilon_{k\sigma} + \varepsilon_{p\bar\sigma} - \varepsilon_{k'\sigma} + \varepsilon_{p'\bar\sigma})$$

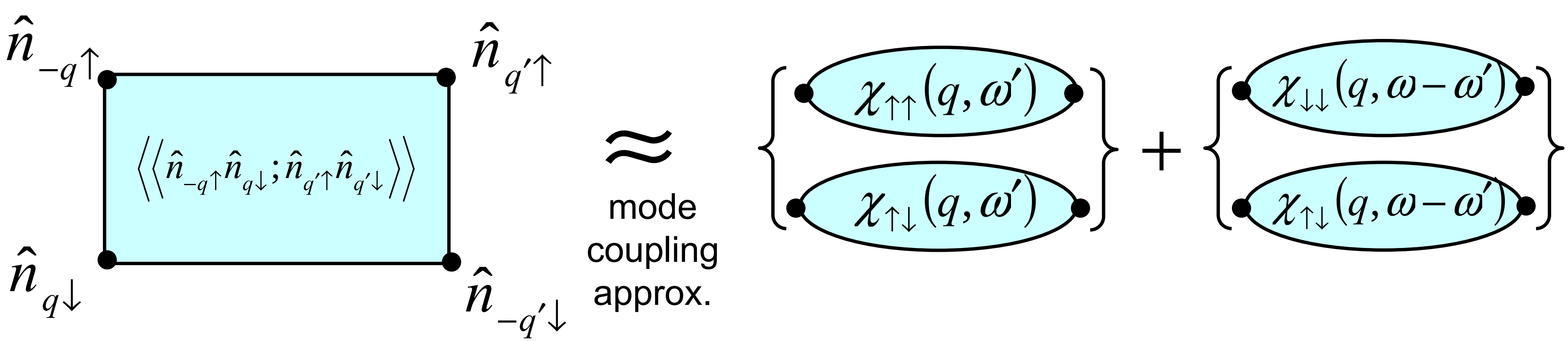
Microscopic theory of the SCD

Kubo formula: $\sigma_{\alpha\beta}(\omega) = -\frac{1}{i\omega}\frac{e^2}{m}\left(n_\alpha \delta_{\alpha\beta} + \frac{1}{m}\langle\langle \mathbf{P}_\alpha ; \mathbf{P}_\beta \rangle\rangle_\omega \right)$

$$\Rightarrow \quad \rho_{\uparrow\downarrow}(\omega) = \frac{i\omega}{e^2 n_\uparrow n_\downarrow}\langle\langle \mathbf{P}_\uparrow ; \mathbf{P}_\downarrow \rangle\rangle_\omega$$

can re-write this in terms of a force-force correlation function:

$$\mathrm{Re}\,\rho_{\uparrow\downarrow}(\omega) = -\frac{1}{e^2 n_\uparrow n_\downarrow \omega}\,\mathrm{Im}\langle\langle \mathbf{F}_\uparrow ; \mathbf{F}_\downarrow \rangle\rangle_\omega$$



Microscopic theory of the SCD

$$\mathrm{Re}\,\rho_{\uparrow\downarrow}(\omega,T)=\frac{\hbar^2}{n_\uparrow n_\downarrow V e^2}\sum_q \frac{q^2 v_q^2}{d}\frac{\left(e^{-\hbar\omega/k_BT}-1\right)}{\omega}$$
$$\times\int\frac{d\omega'}{\pi}\frac{\left[\chi''_{\uparrow\uparrow}(q,\omega')\chi''_{\downarrow\downarrow}(q,\omega-\omega')-\chi''_{\uparrow\downarrow}(q,\omega')\chi''_{\downarrow\uparrow}(q,\omega-\omega')\right]}{\left(e^{-\hbar\omega'/k_BT}-1\right)\left(e^{-\hbar(\omega-\omega')/k_BT}-1\right)}$$

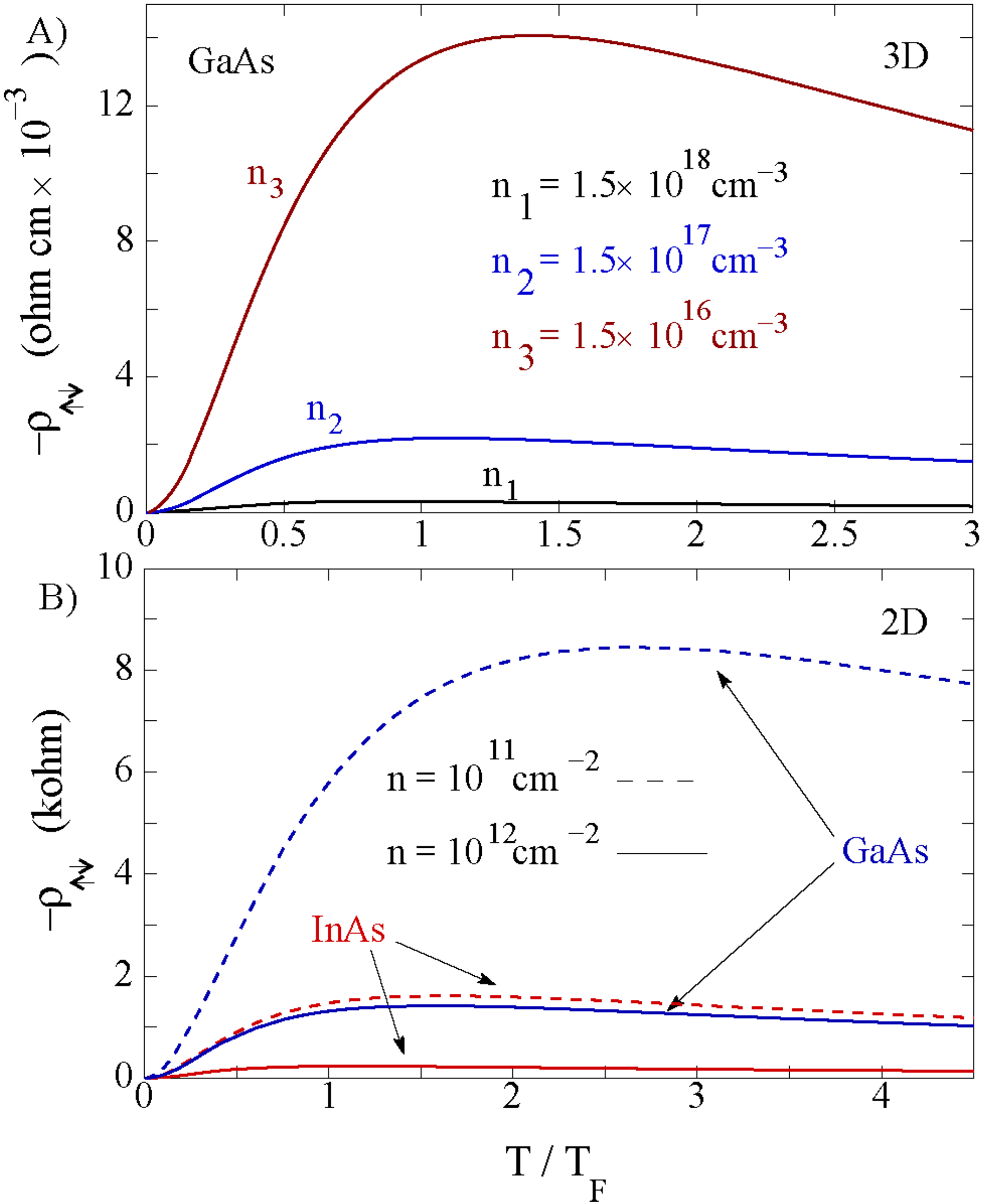
In the DC limit, one obtains

$$\rho_{\uparrow\downarrow}(T)=\frac{\hbar^2}{4n_\uparrow n_\downarrow k_B T V e^2}\sum_q \frac{q^2 v_q^2}{d}\int_0^\infty \frac{d\omega'}{\pi}\frac{\mathrm{Im}\,\chi_{0\uparrow}(q,\omega')\,\mathrm{Im}\,\chi_{0\downarrow}(q,\omega')}{\left|\varepsilon(q,\omega')\right|^2\sinh^2(\hbar\omega'/2k_BT)}$$

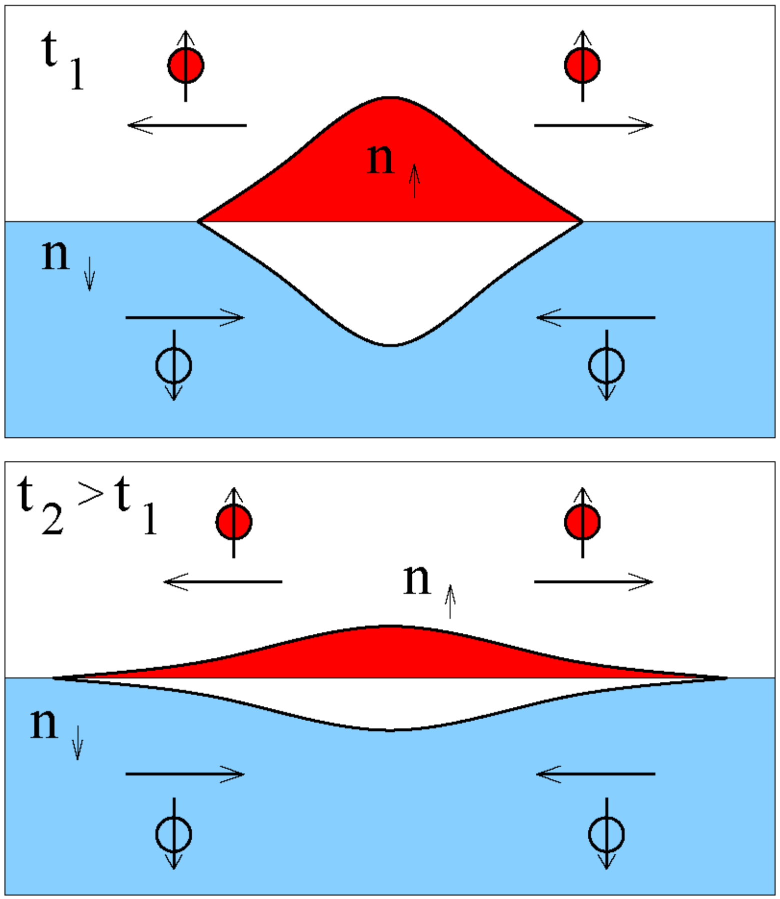
RPA: D’Amico and Vignale, PRB **62**, 4853 (2000)

Beyond RPA: Badalyan, Kim, and Vignale, PRL **100**, 016603 (2008)

Spin-transresistivity: Temperature-dependence



Diffusion of unipolar spin packets



SCD counteracts spin diffusion in opposite directions. The spin diffusion constant is reduced:

$$D_s = \frac{k_B T}{e^2 n} \frac{S}{S_c} \frac{1}{(\rho_D - \rho_{\uparrow\downarrow})}$$

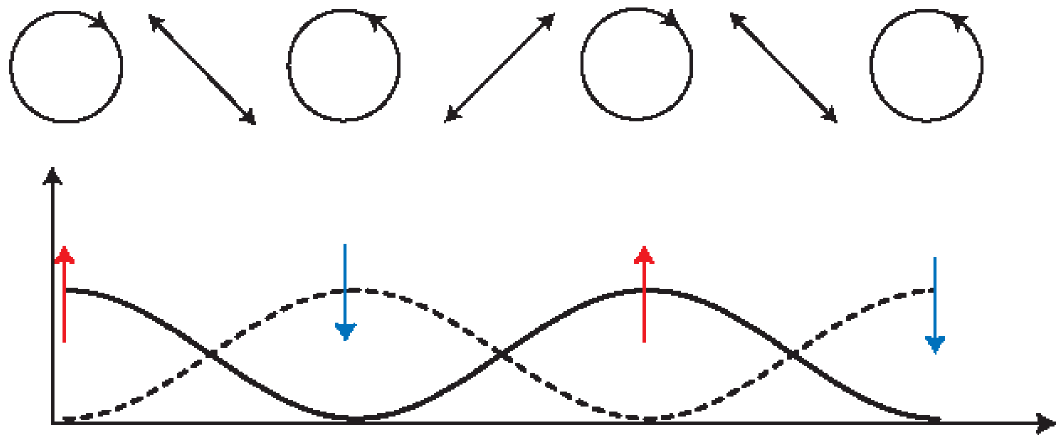
$$S_c = \frac{k_B T n}{4 n_\uparrow n_\downarrow}$$ Curie spin stiffness

$$S = \frac{1}{4}\left(S_{\uparrow\uparrow} - S_{\uparrow\downarrow} + S_{\downarrow\downarrow} - S_{\downarrow\uparrow}\right)$$

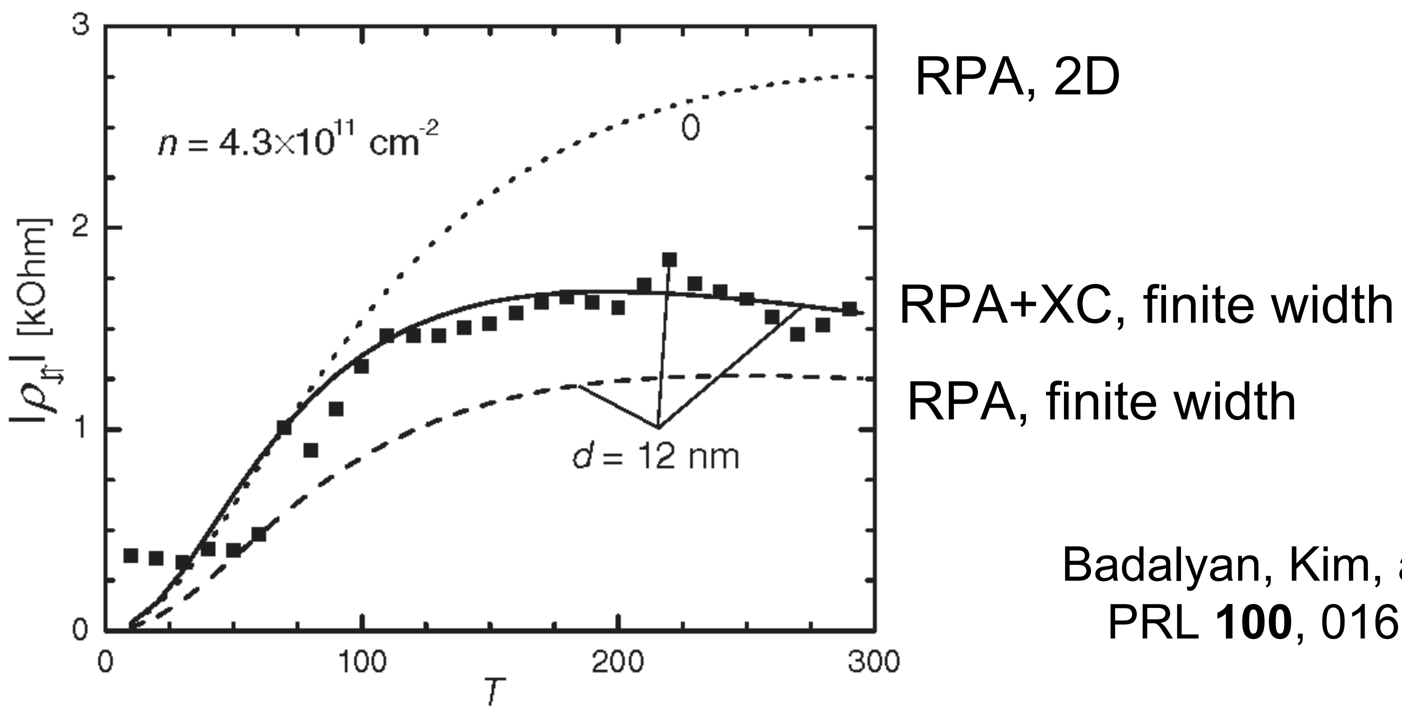
longitudinal spin stiffness

Experimental evidence of SCD

Weber, Gedik, Moore, Orenstein, Stephens, and Awschalom, Nature **437**, 1330 (2005)



Transient spin grating plus time-resolved Kerr effect spectroscopy to measure spin diffusion constant



Badalyan, Kim, and Vignale, PRL **100**, 016603 (2008)

SCD in spin-dependent transport

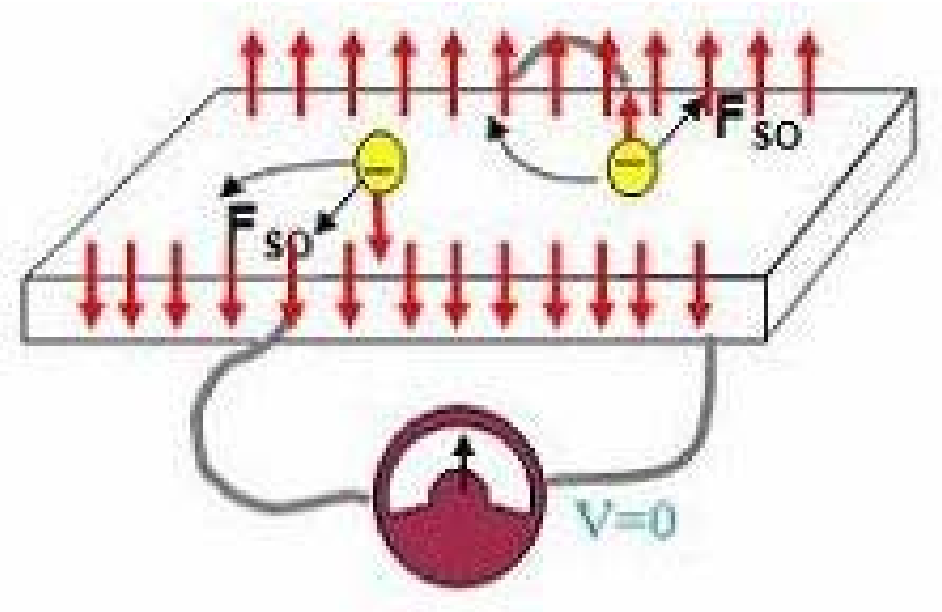
► Counteracts spin diffusion

► Opposes spin injection (e.g. from FM metal into semiconductor)

► Spin transresistivity increases in the presence of Rashba SO coupling [Tse and Das Sarma, PRB **75**, 045333 (2007)]

► SCD reduces skew-scattering component of spin-Hall conductivity [Hankiewicz and Vignale, PRB **73**, 115339 (2006)]

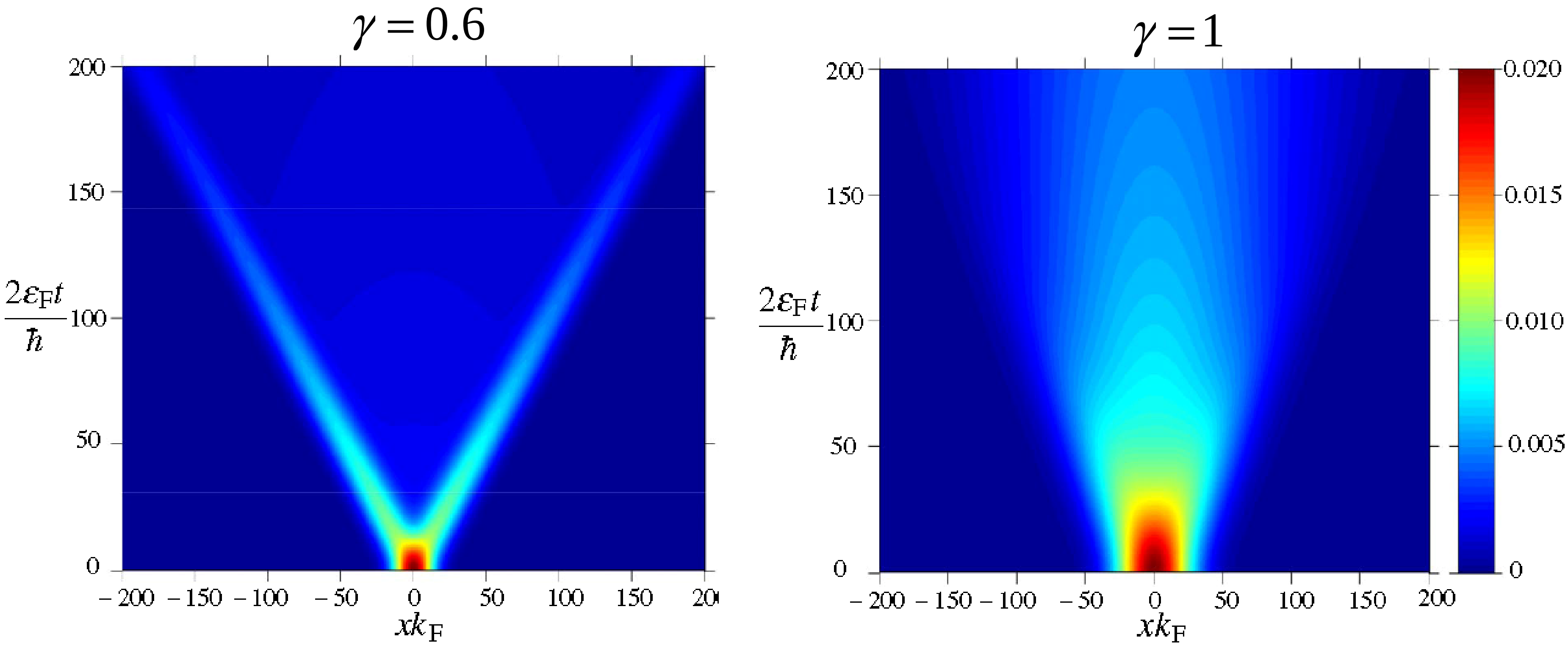
► SCD shows up in Gilbert damping constant [Hankiewicz, Vignale, and Tserkovnyak, PRB **75**, 174434 (2007)]



Picture from http://www.phy.cam.ac.uk/research/oe/nanospintronics.php

Spin-charge separation in 1D Fermi gases

Polini et al., PRL **98**, 266403 (2007), PRB **77**, 035113 (2008), PRL **101**, 206402 (2008)



Charge packets are essentially ballistic, whereas spin packets are diffusive and intrinsically damped by SCD.

Spin-dependent optical excitations in TDDFT

$$\mathbf{j}_\sigma(\mathbf{r},\omega) = \int d^3r' \, \overleftrightarrow{\chi}_\sigma(\mathbf{r},\mathbf{r}',\omega)\left\{ \mathbf{A}_{ext,\sigma}(\mathbf{r},\omega) + \mathbf{A}_{H,\sigma}(\mathbf{r},\omega) + \mathbf{A}_{xc,\sigma}(\mathbf{r},\omega)\right\}$$

exact current response

noninteracting current response tensor

effective perturbation: external + Hartree + exchange-correlation

$\mathbf{A}_{xc,\sigma}(\mathbf{r},\omega)$: dynamical xc vector potential, containing

► adiabatic LDA contribution

► nonadiabatic contributions (viscoelastic + SCD)

Z.Qian, A.Costantinescu, and G.Vignale, PRL **90**, 66402 (2003)

XC vector potential: nonadiabatic contributions

Qian, Constantinescu, Vignale,
PRL **90**, 066402 (2003)

- spin-dependent generalization of the xc viscoelastic stress tensor
- depends on velocity gradients

$$\mathbf{A}_{xc,\sigma}(\mathbf{r},\omega) = \mathbf{A}^{ALDA}_{xc,\sigma}(\mathbf{r},\omega) - \frac{1}{i\omega n_\sigma(\mathbf{r})}\sum_{\sigma'}\vec{\nabla}\cdot\overleftrightarrow{\sigma}_{xc,\sigma\sigma'}(\mathbf{r},\omega)$$

$$-\frac{n_\downarrow(\mathbf{r})n_\downarrow(\mathbf{r})\rho_{\uparrow\downarrow}(\mathbf{r},\omega)}{i\omega}\sum_{\sigma'}\frac{\sigma\sigma'}{n_\sigma(\mathbf{r})n_{\sigma'}(\mathbf{r})}\mathbf{j}_{\sigma'}(\mathbf{r},\omega)$$

- depends on the velocities themselves
- real part: spin mass
- imaginary part: spin Coulomb drag

Spin-resolved excitation spectrum in TDDFT

(complex) excitation frequency

$$\Omega^2_{\pm\sigma} \approx \omega^2_{pq\sigma} + 2\omega_{pq\sigma} S_{\pm\sigma}$$

linewidth

$$\Gamma_{\pm} \approx \mathrm{Im}\, S_{\pm\sigma}$$

$\omega_{pq\sigma}$ = bare single-particle excitation frequency between levels p and q

$$S_{\pm\sigma} = \left(S^{H+ALDA}_{\sigma\bar{\sigma}} \pm S^{H+ALDA}_{\sigma\bar{\sigma}}\right) + \left(S^{VE}_{\sigma\bar{\sigma}} \pm S^{VE}_{\sigma\bar{\sigma}}\right) + \left(S^{SCD}_{\sigma\bar{\sigma}} \pm S^{SCD}_{\sigma\bar{\sigma}}\right)$$

Hartree + ALDA: real
(no dissipation)

Viscoelastic + SCD: complex
(dissipative)

Total linewidth: $\Gamma_{\pm} = \Gamma^{disorder}_{\pm} + \Gamma^{VE}_{\pm} + \Gamma^{SCD}_{\pm}$

SC-TDDFT energy shift for excitation energies

$$S_{\sigma\sigma'}^{H+ALDA} = \int d^3r \int d^3r' \left[\frac{1}{|\vec{r}-\vec{r}'|} + f_{xc,\sigma\sigma'}^{ALDA}(\vec{r},\vec{r}') \right] \varphi_{p\sigma}(\vec{r})\varphi_{q\sigma}(\vec{r})\varphi_{p\sigma'}(\vec{r}')\varphi_{q\sigma'}(\vec{r}')$$

$$S_{\sigma\sigma'}^{VE} = \frac{i\omega}{\omega_{pq\sigma}^2} \int d^3r \, \overleftrightarrow{\sigma}_{\sigma\sigma'}^{xc,pq}(\vec{r},\omega) \vec{\nabla} \left[\frac{\vec{j}_{pq\sigma}(\vec{r})}{n_\sigma(\vec{r})} \right]$$

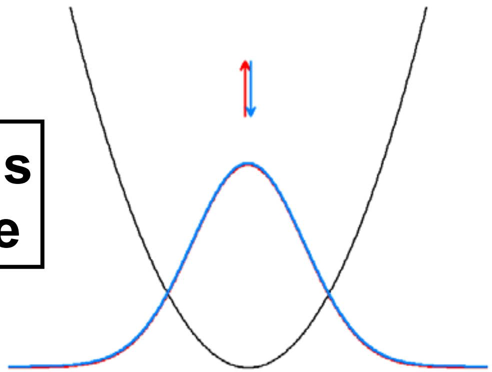
$$\left(S_{\sigma\bar{\sigma}}^{SCD} \pm S_{\sigma\bar{\sigma}}^{SCD} \right) = \frac{ie^2\omega}{\omega_{pq\sigma}^2} \int d^3r \left[\frac{n_{\bar{\sigma}}}{n_\sigma} \left| \vec{j}_{pq\sigma} \right|^2 \mp \vec{j}_{pq\bar{\sigma}} \cdot \vec{j}_{pq\sigma} \right] \rho_{\uparrow\downarrow}(\omega; n_\uparrow, n_\downarrow)$$

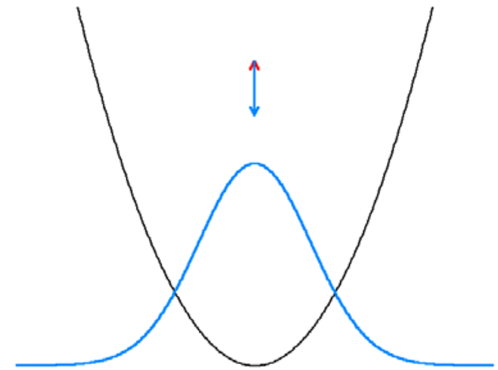
structure of a (complex) power loss
term in an AC spintronics circuit

Is there a system in which the SCD power loss channel dominates?

Intersubband plasmons in parabolic quantum wells

Kohn's mode





Charge-density excitation (CDE)

$$\Gamma_{CDE}^{VE} = 0, \quad \Gamma_{CDE}^{SCD} = 0$$

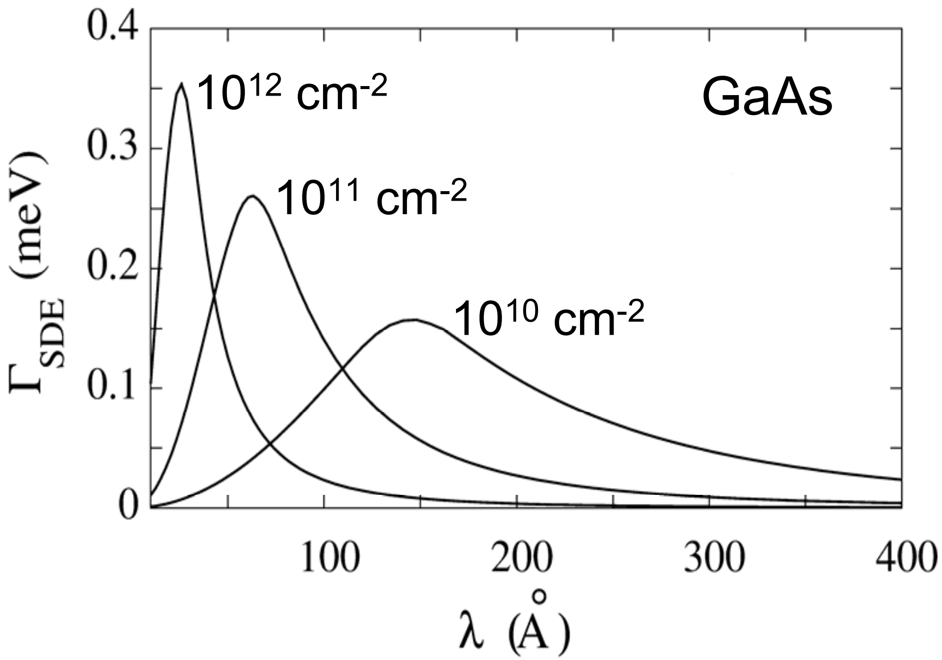
Spin-density excitation (SDE)

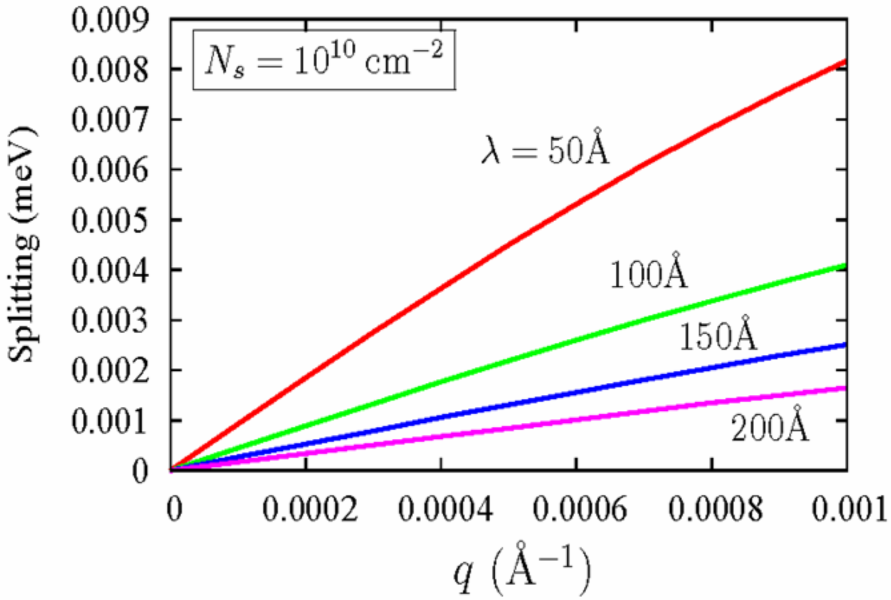
Γ_{SDE}^{VE} small, Γ_{SDE}^{SCD} not small

$$\Gamma_{SDE} - \Gamma_{CDE} \approx \left(\Gamma_{SDE}^{disorder} + \Gamma_{SDE}^{SCD}\right) - \Gamma_{CDE}^{disorder} \approx \Gamma_{SDE}^{SCD}$$

impurity scattering affects CDE & SDE similarly

Spin plasmon linewidth vs. parabolic well curvature





proposed experiment:

1) measure linewidth of CDE and SDE collective modes in the same parabolic well (inelastic light scattering)
2) Difference of linewidths due (mostly) to SCD effect
3) Spin-orbit splitting of the plasmons is insignificant here

I. D'Amico and C.A. Ullrich, PRB **74**, 121303(R) (2006)

Summary

- ►Spin Coulomb drag is an intrinsic source of dissipation for spin currents
- ►Plays a role in various phenomena in semiconductor spintronics (not in metals)
- ►SCD is also important in low-dimensional systems (1D cold Fermi gases)
- ►Also occurs in spinor Bose gas [PRL **103**, 170401 (2009)]
- ►SCD can be treated in TDDFT as a dynamical XC effect
- ►Linewidth of spin-dependent optical excitations