Probing spin transport with light

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UC Berkeley and Lawrence Berkeley National Lab

Newspin2 December, 2011

Not so easy to measure spin diffusion and mobility

Charge diffusion

$$\sigma = N_F e^2 D_c$$

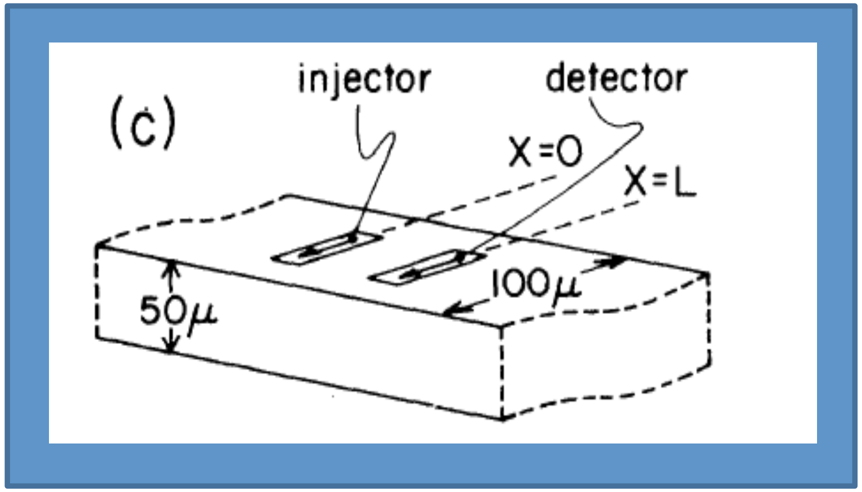
Einstein relation

No multimeter for spin conductivity.

Probe must break time reversal

Two basic approaches: magnetic contacts and optical orientation

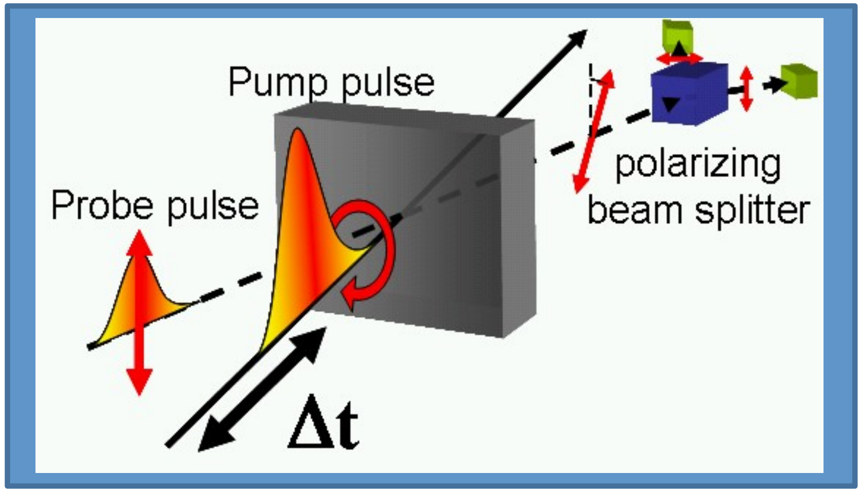
Magnetic contacts



Mark Johnson and R. H. Silsbee

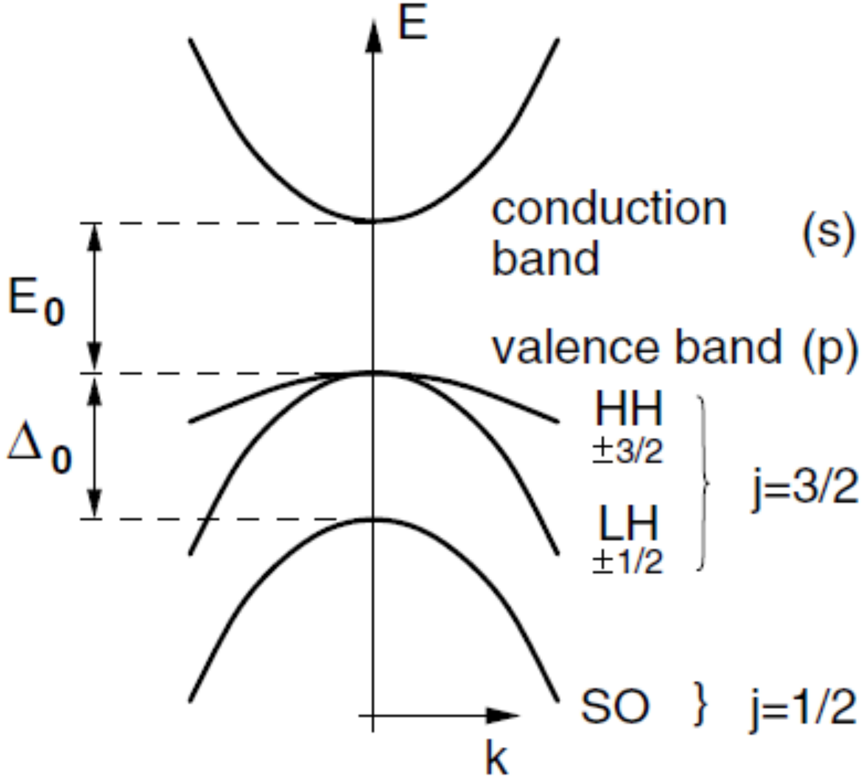
PRL 1985

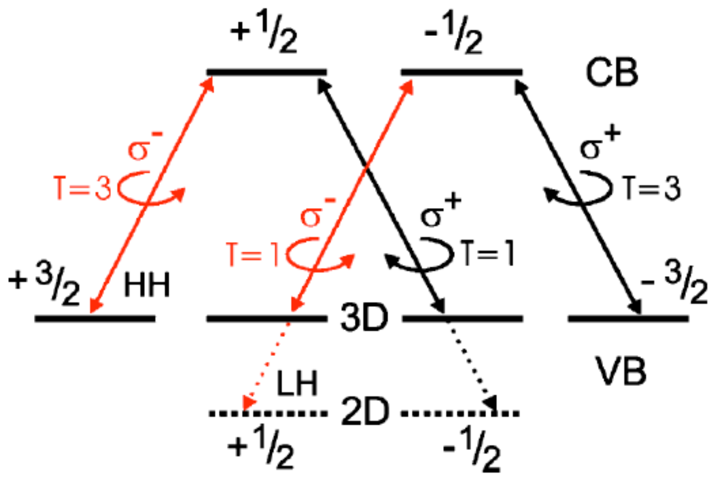
Optical orientation



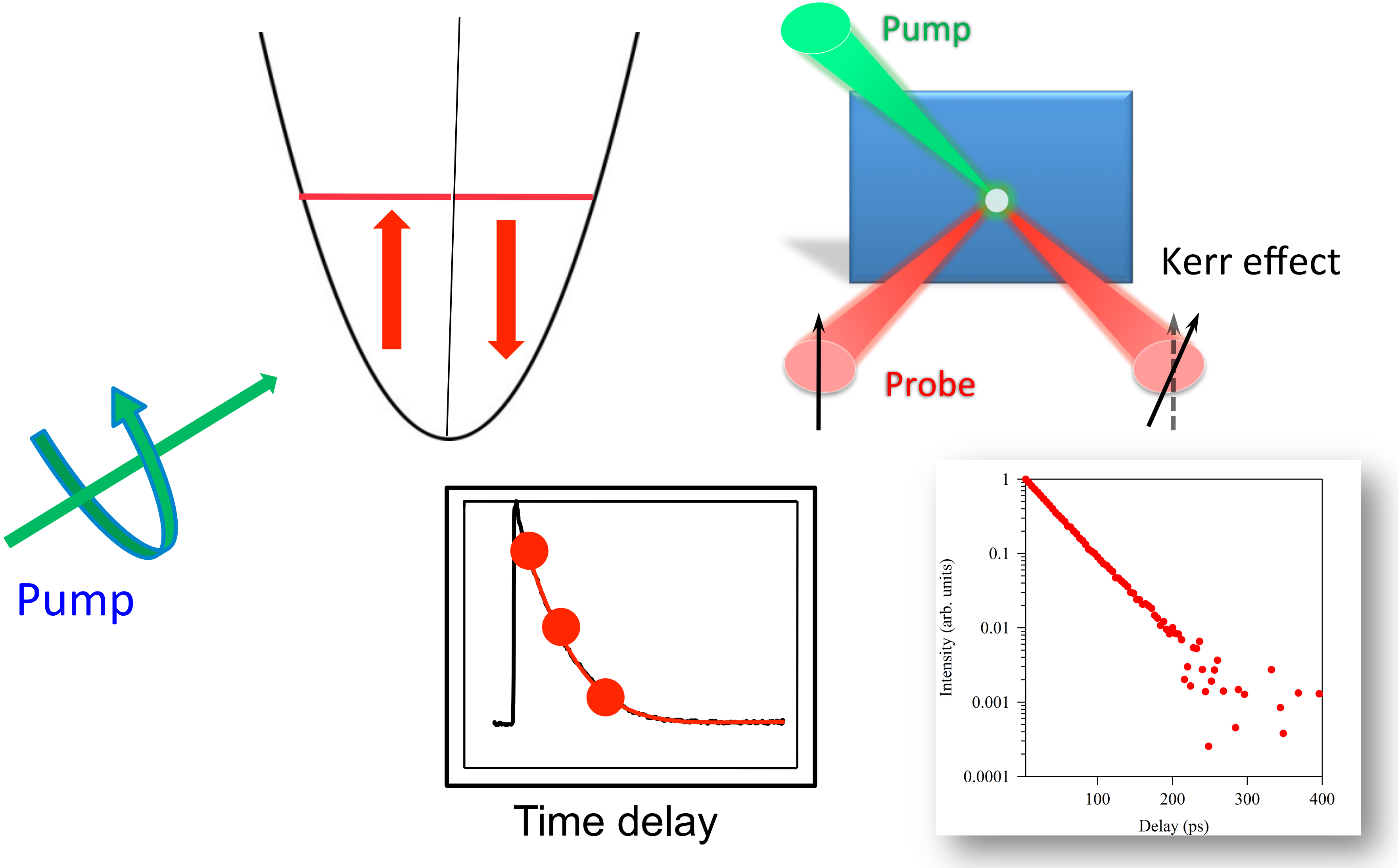
G. Lampel, Phys. *Rev. Lett. 20,491 (1968).*

Optical orientation in III-V semiconductors

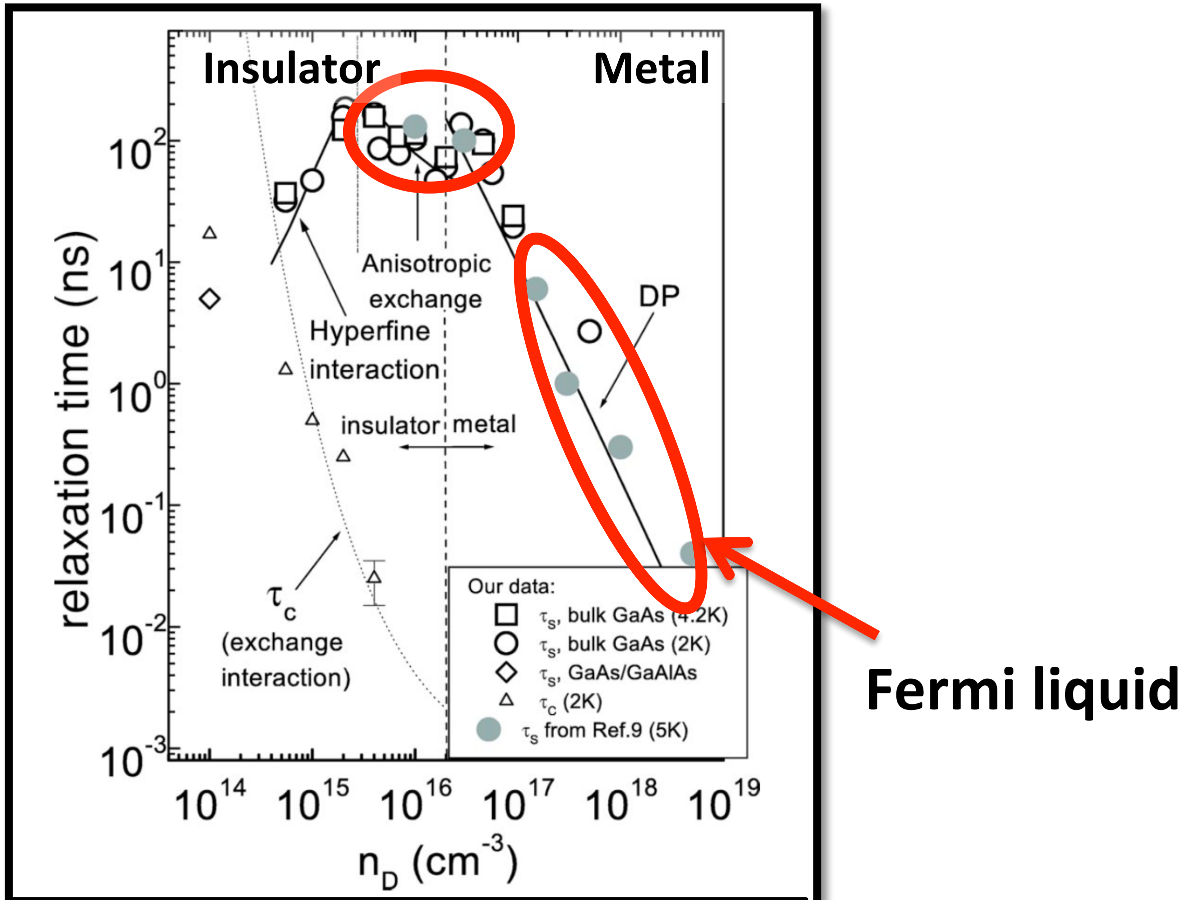




Optical measurement of spin lifetime



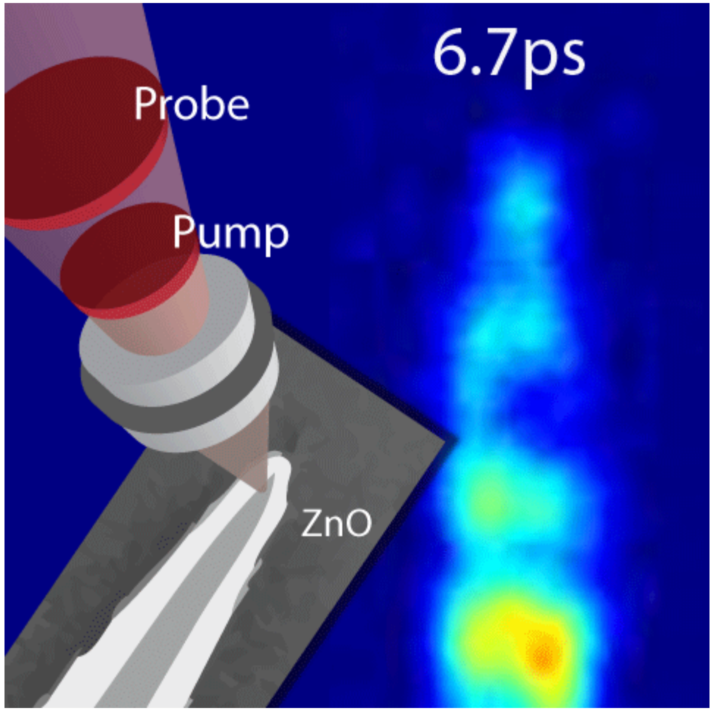
Regimes of spin lifetime in GaAs

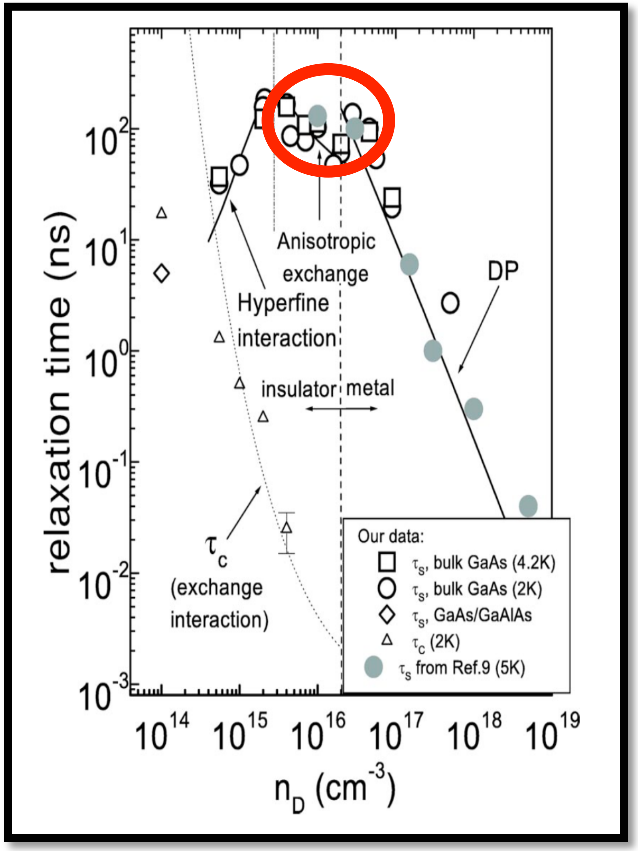


Dzhioev et al. PRB **66** 245204 (2002)
Zutic, Fabian & Das Sarma RMP **76** 2 (2004)

Spin transport measured by time-resolved Kerr microscopy

Pioneering work (Awschalom and co.) focused on very long spin lifetimes found at the insulator-metal transition

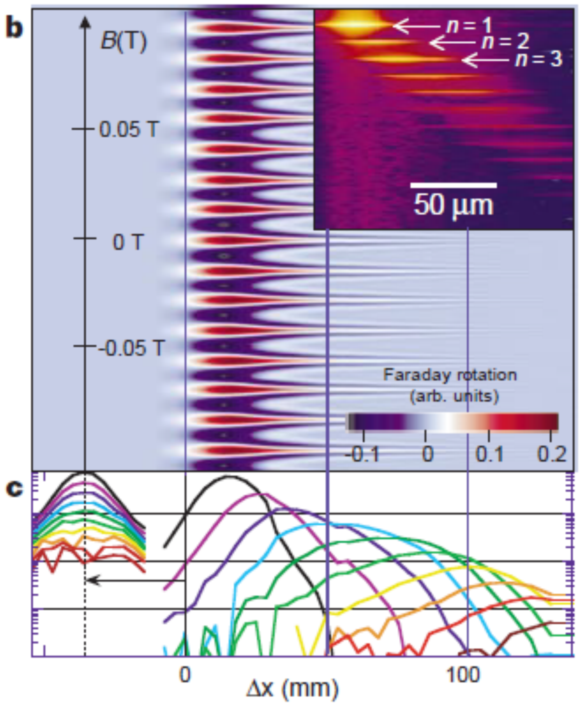




Lateral drag of spin coherence in gallium arsenide

J. M. Kikkawa & D. D. Awschalom

Department of Physics, University of California, Santa Barbara, California 93106, USA



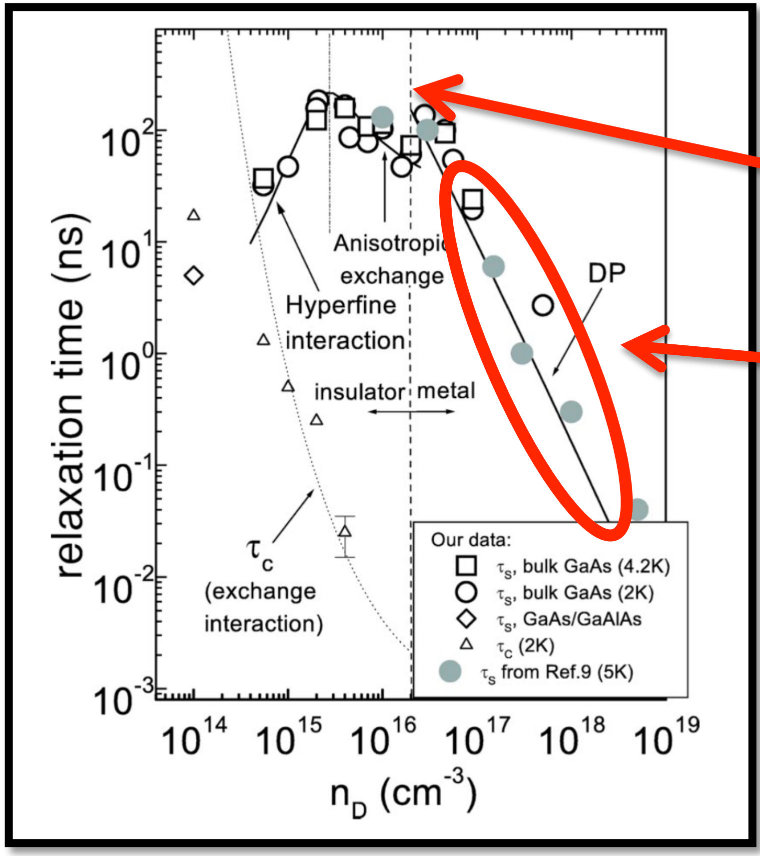
Real space imaging of photoinduced spin polarization

Measurements based on extremely long spin-relaxation times in bulk GaAs with carrier density near the metal insulator transition

Typical parameters near MI transition

$$\tau_s \approx 100ns;\ D_s \approx 10\frac{cm^2}{s};\ L_s \approx 10\ \mu$$

Different method required to study FL regime

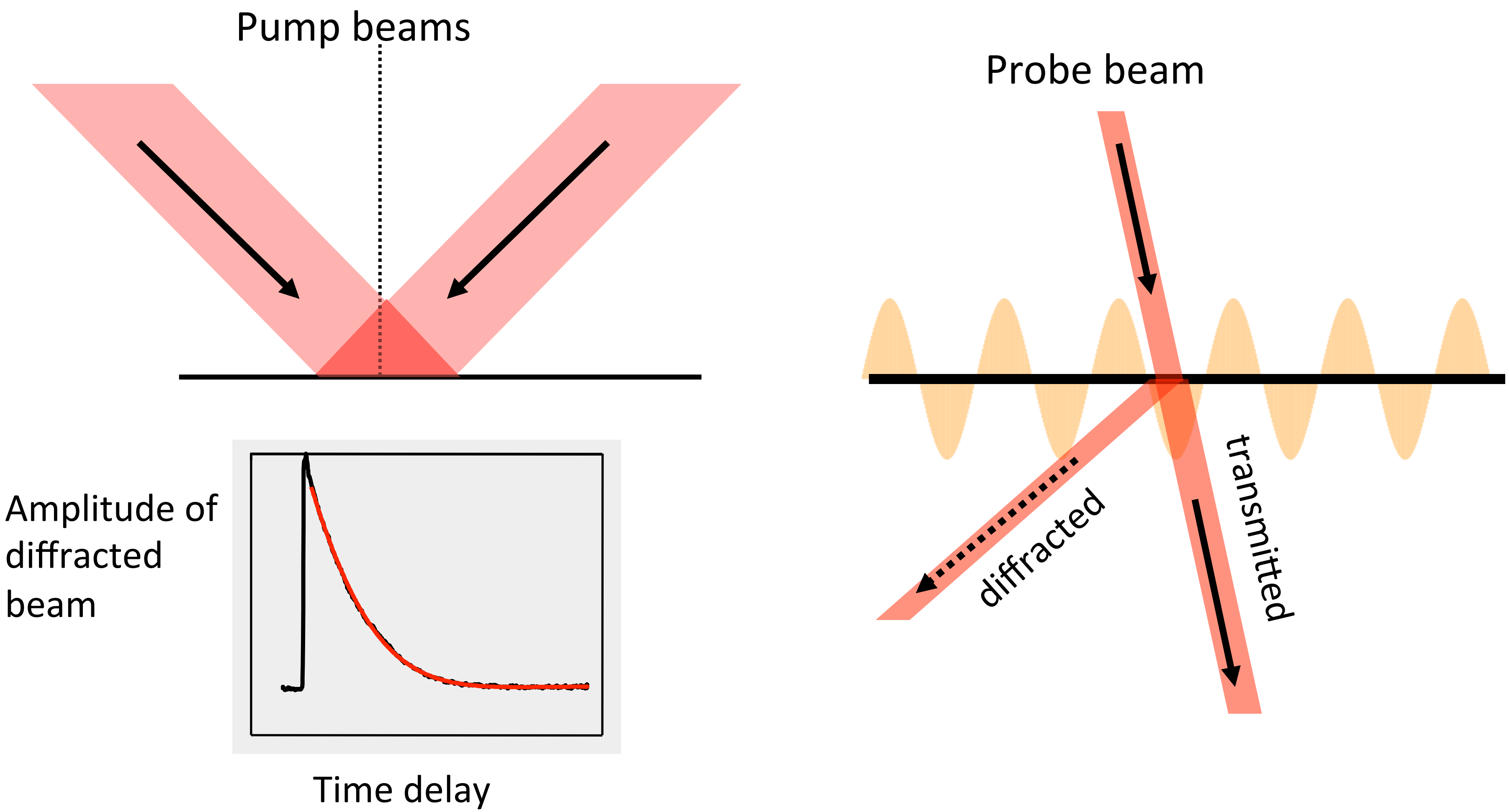


$$\tau_s \approx 100ns;\ D_s \approx 10\frac{cm^2}{s};\ L_s \approx 10\ \mu$$

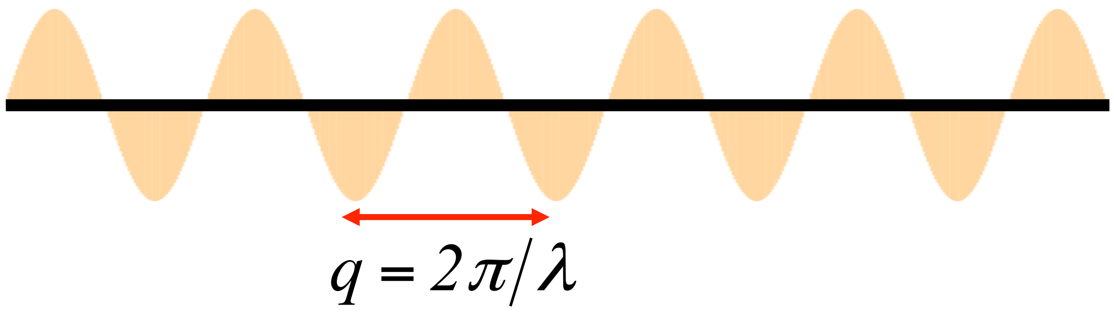
$$\tau_s \approx 10ps;\ D_s \approx 1000\frac{cm^2}{s};\ L_s \approx 1\ \mu$$

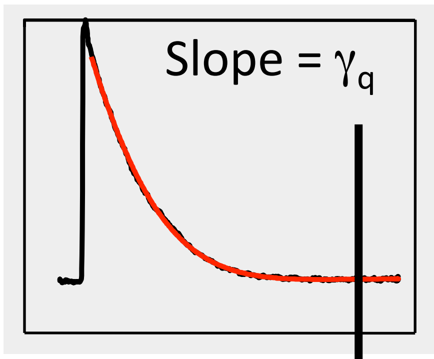
Typical parameters in Fermi liquid regime

Probing exciton diffusion and lifetime: the transient grating technique

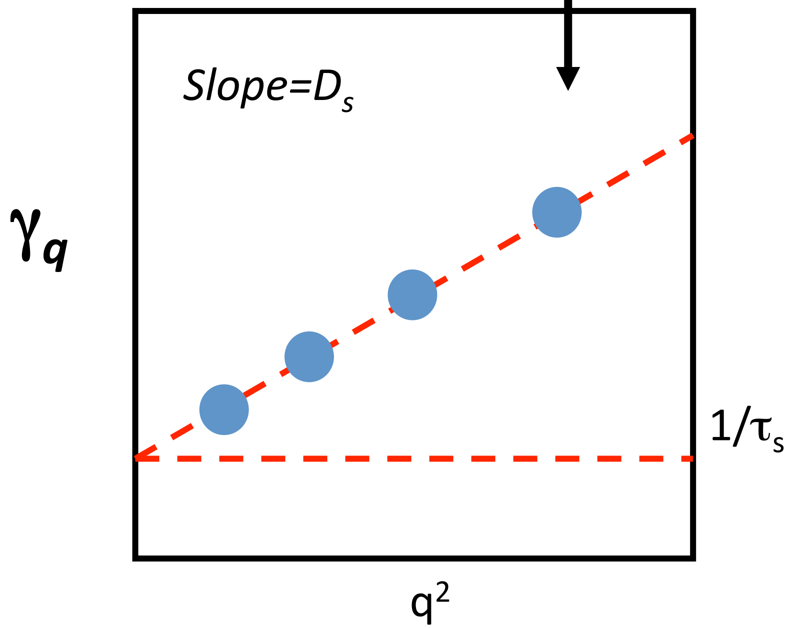


Grating dynamics for simple diffusion





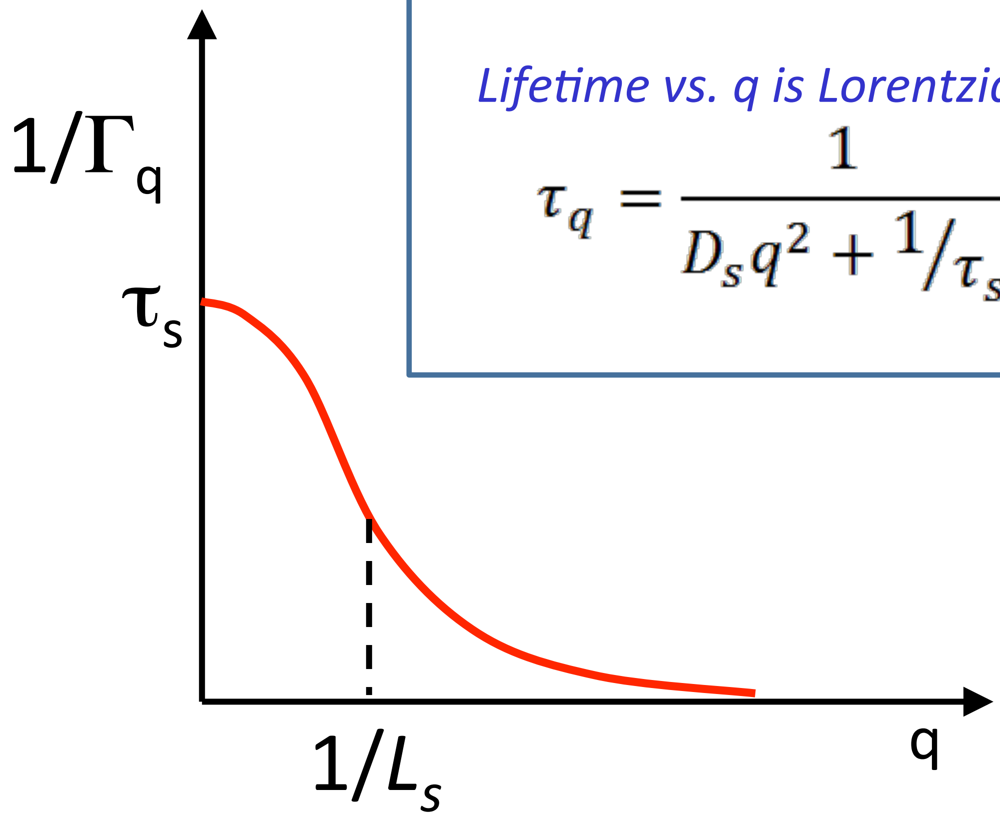
$$\frac{\partial S_\alpha}{\partial t} = \left(D_s \nabla^2 - \frac{1}{\tau_\alpha}\right) S_\alpha$$



$$S_\alpha(q,t) = S_\alpha(q,0)\exp(-\Gamma_q t)$$

$$\Gamma_q = \frac{1}{\tau_\alpha} + D_s q^2$$

Graph of spin polarization lifetime vs. *q* is Lorentzian



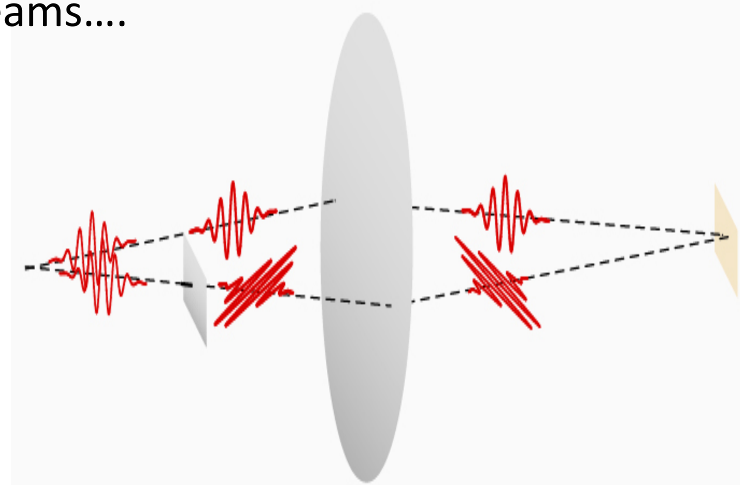
Lifetime vs. q is Lorentzian:

$$\tau_q = \frac{1}{D_s q^2 + {}^1\!/\tau_s}$$

Transient **spin** gratings

Cameron et al., Phys. Rev. Lett. **76**, 4793 (1996)

Interference of two orthogonally polarized beams….

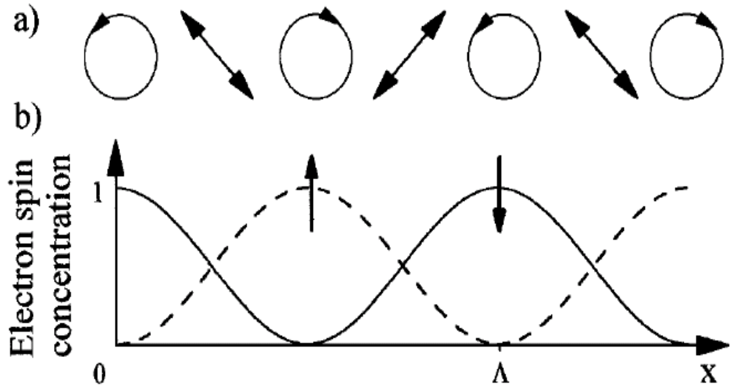


$$\boldsymbol{E}(z) = E_0(\hat{x}e^{ikz} + \hat{y}e^{-ikz})$$

$$\hat{e}_{\pm} = \frac{\hat{x} \pm i\hat{y}}{\sqrt{2}}$$

$$E(z) \propto E_0\left[i\hat{e}_{+}\sin\left(kz - \frac{\pi}{4}\right) + [\hat{e}\_\cos\left(kz - \frac{\pi}{4}\right)\right]$$

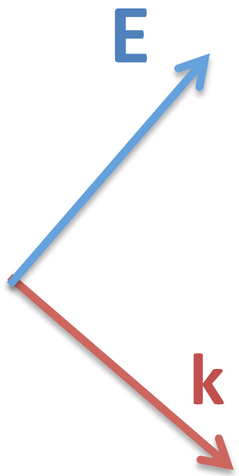
Creates a helicity wave…
which generates a spin density wave.



$$I_{+}(z) \propto E_0^2\left[\sin^2\left(kz - \frac{\pi}{4}\right)\right]$$

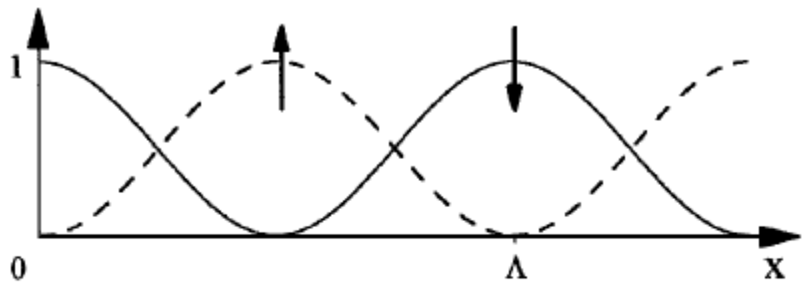
$$I_{+}(z) \propto E_0^2\left[\cos^2\left(kz - \frac{\pi}{4}\right)\right]$$

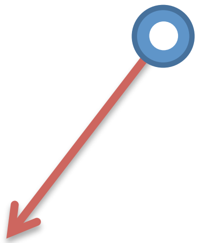
Reading the grating



Incident wave x-polarized

$$\begin{pmatrix}1\\0\end{pmatrix} = \frac{1}{2}\left[\begin{pmatrix}1\\i\end{pmatrix} + \begin{pmatrix}1\\-i\end{pmatrix}\right]$$





Diffracted wave y-polarized

$$\begin{pmatrix}0\\1\end{pmatrix} = \frac{i}{2}\left[\begin{pmatrix}1\\i\end{pmatrix} + e^{i\pi}\begin{pmatrix}1\\-i\end{pmatrix}\right]$$

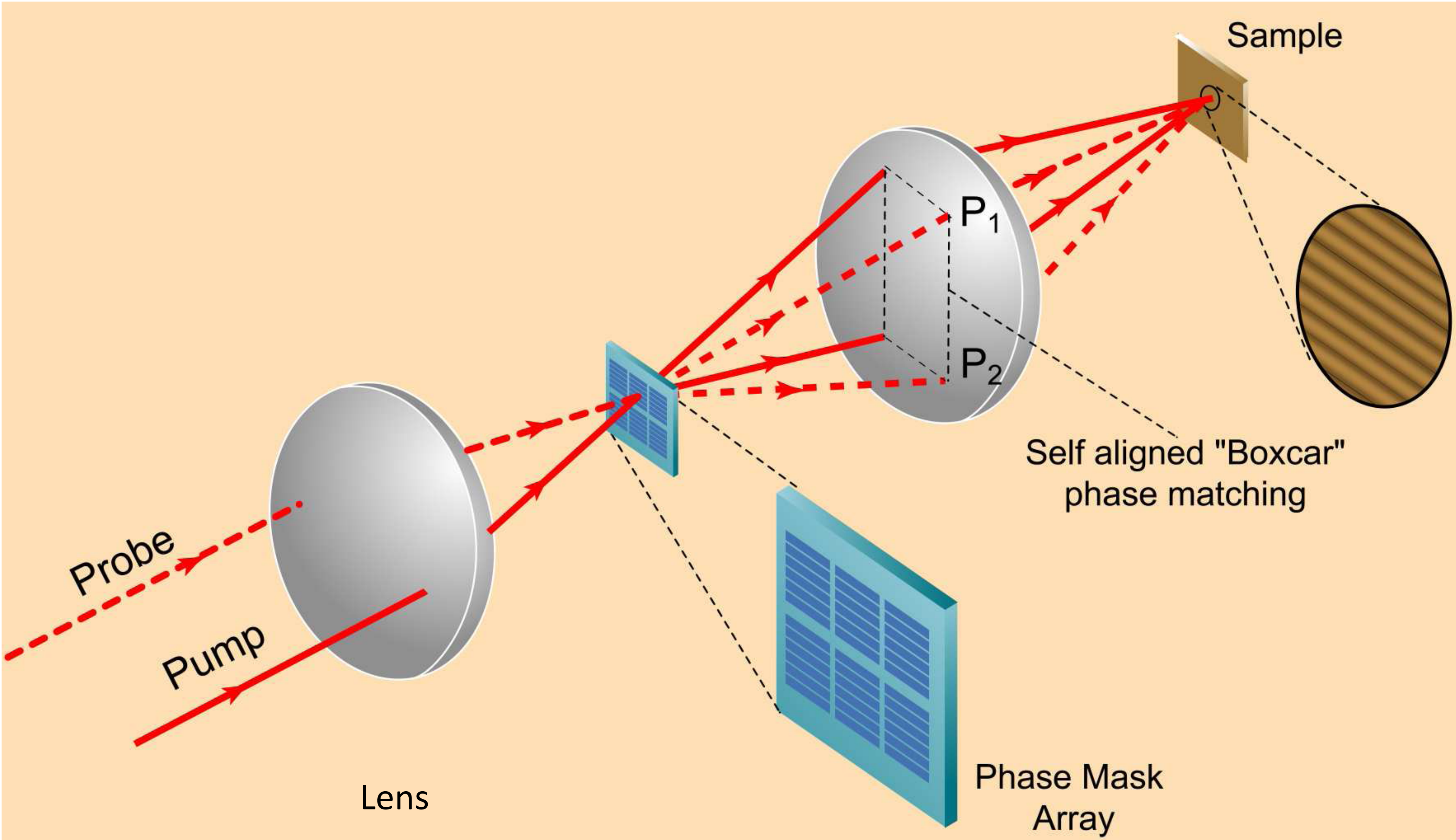
Time reversal symmetry

$$\Delta n_{LC}(S_z) = \Delta n_{RC}(-S_z)$$

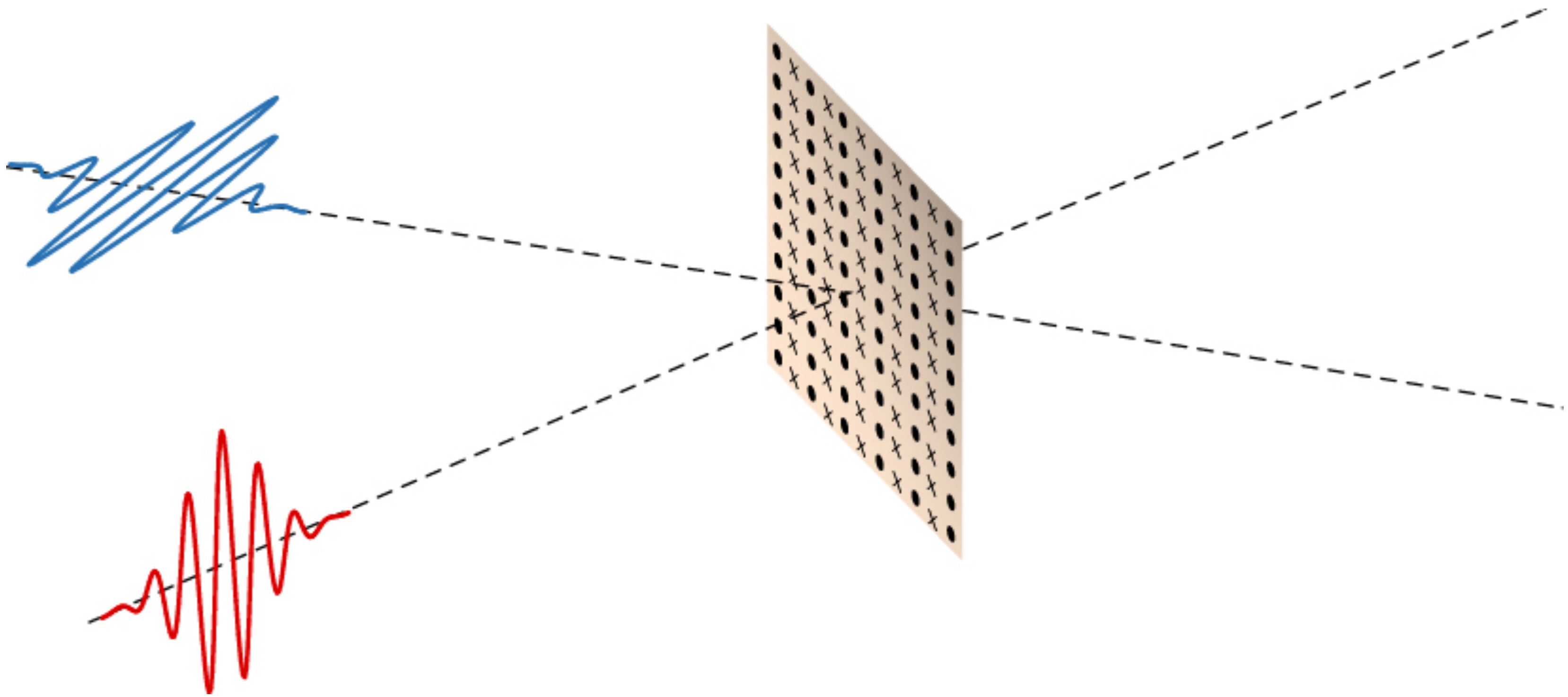
$$\Downarrow$$

$$\Delta n_{LC}(z) = \Delta n_{RC}(z + \lambda/2)$$

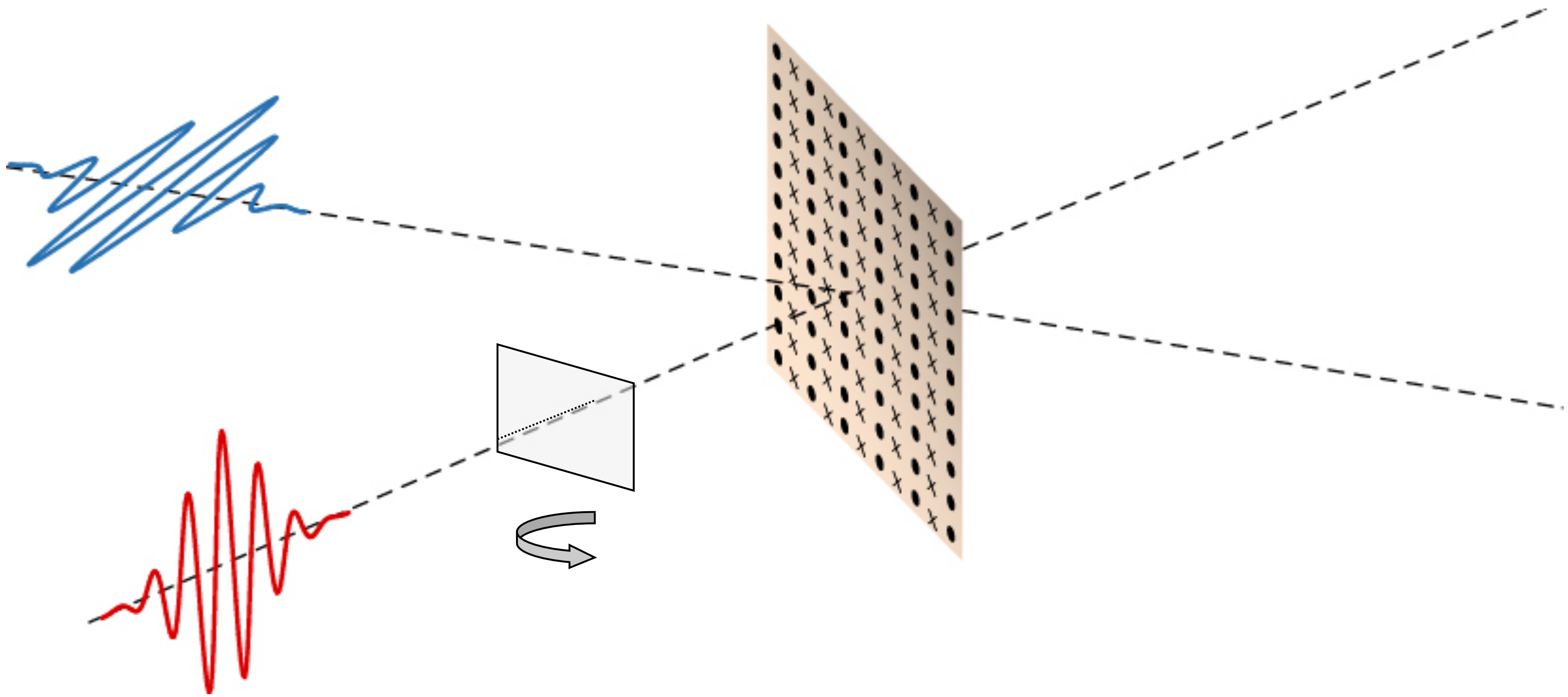
Transient grating setup



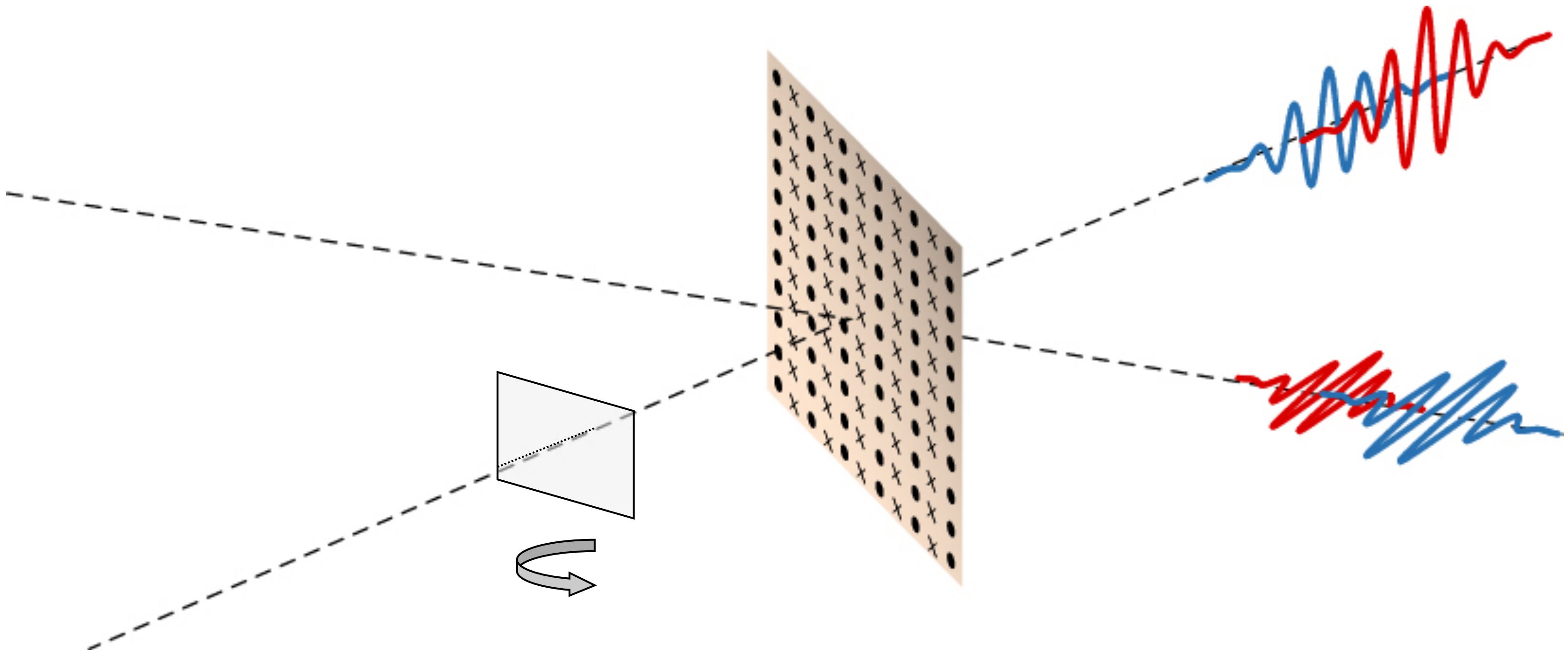
Writing the grating



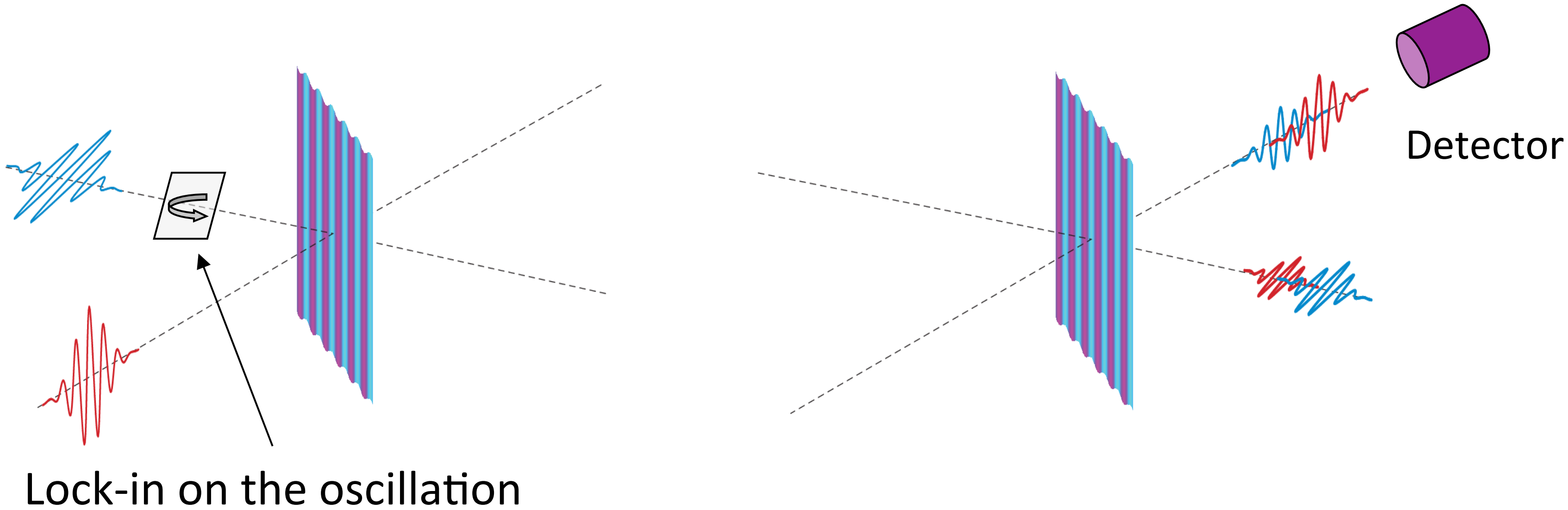
Reading the grating

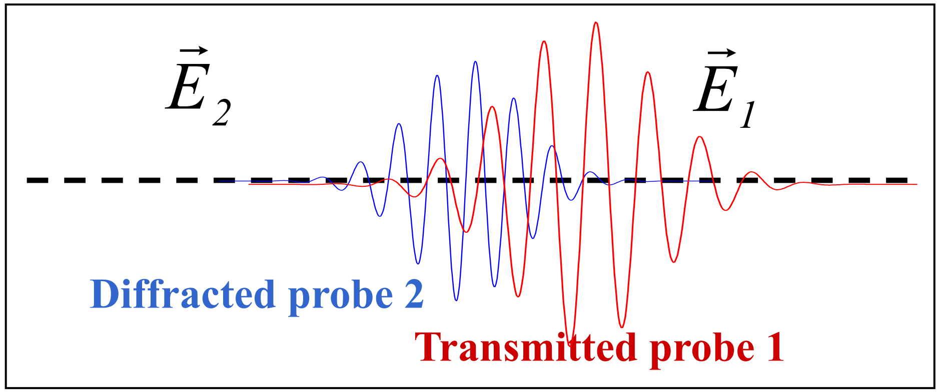


Reading the grating



Detection of spin polarization wave





$$V_{out} \propto E_t E_d \cos\varphi$$

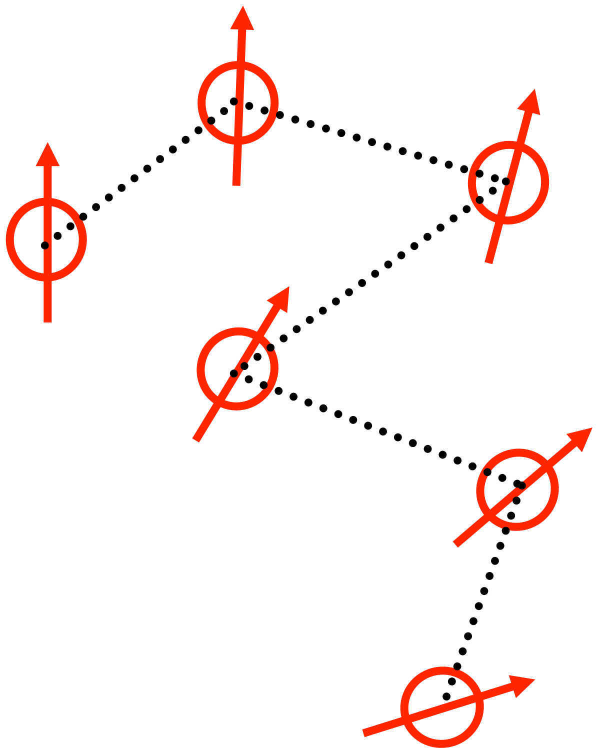
φ has contributions from:

Phase of index change
Path length difference
Lateral position of grating

Spin diffusion and relaxation: the "naïve view"

Spin diffusion can be defined when:

$\tau_{spin} \gg \tau_{coll}$

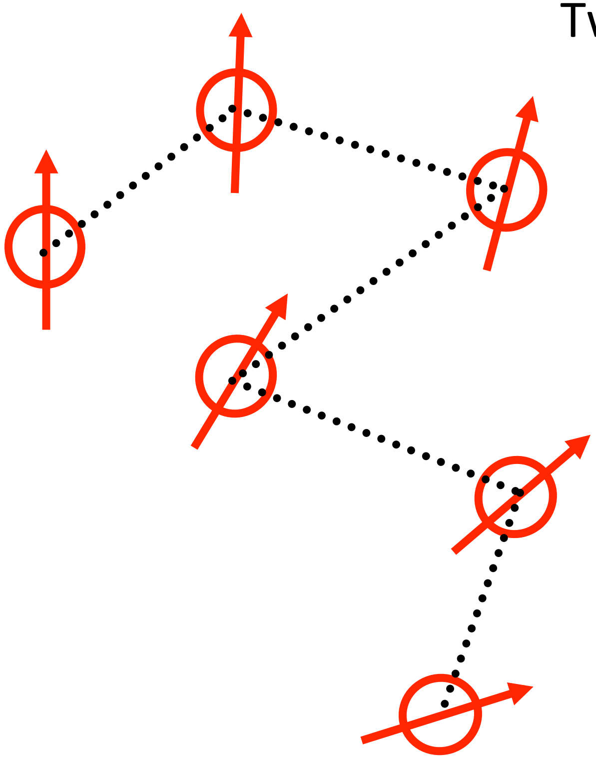


Describe by same equation that applies to exciton density.

Model by diffusion eq. with loss term:

$$-D_s \nabla^2 s_z + \frac{\partial s_z}{\partial t} = -\frac{s_z}{\tau_s}$$

What we have learned: the “naïve view” is naïve.



Two types of interaction change this picture completely

(1) Electron-electron interactions

D’Amico, I. & Vignale, G. *PRB* **62,** 4853-4857 (2000).
Flensberg, K., Jensen, T. S. & Mortensen, N. A. *PRB* **64,** 245308 (2001).
D’Amico, I. & Vignale, G. *PRB* **68,** 45307 (2003).

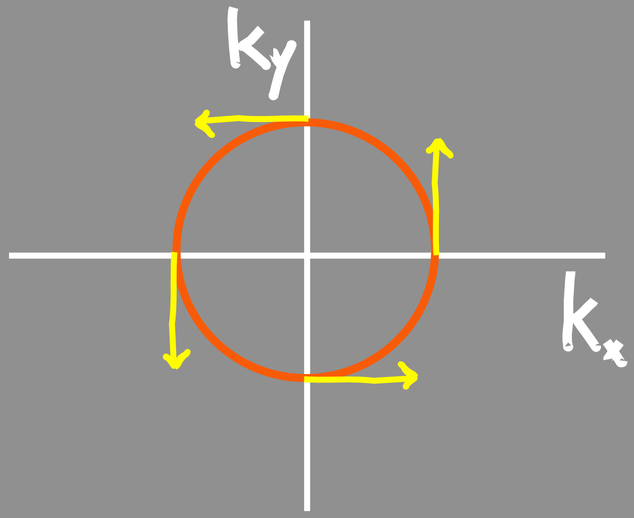
(2) Rashba/Dresselhaus SO interactions

Schliemann, J., Egues, J. C. & Loss, D. *PRL*. **90**, 146801 (2003).
Burkov, A. A., Nunez, A. S. & MacDonald, A. H. *PRB* **70,** 155308 (2004).
Bernevig, B. A., Orenstein, J. & Zhang, *PRL* **97**, 236601 (2006).
Stanescu, T. D. & Galitski, *PRB* **75,** 125307 (2007).

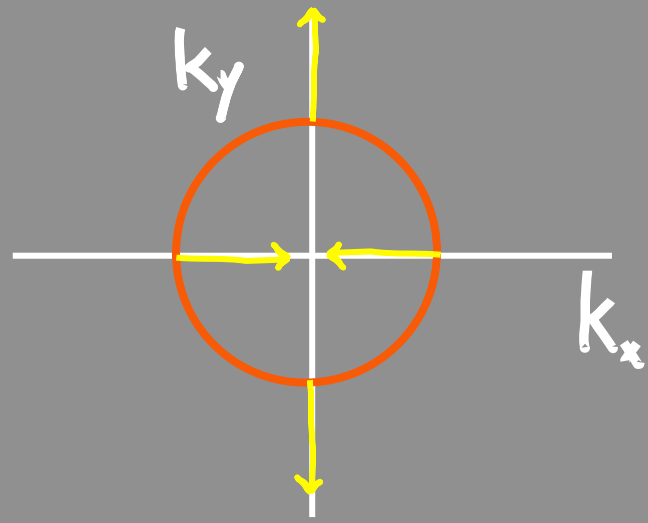
Rashba and Dresselhaus interactions

$$\boldsymbol{\Omega} = 2k_F \left[\hat{\boldsymbol{x}} \left(\alpha - \beta_1 - \frac{2\beta_3 (v_x^2 - v_y^2)}{v_F^2} \right) v_y - \hat{\boldsymbol{y}} \left(\alpha + \beta_1 - \frac{2\beta_3 (v_x^2 - v_y^2)}{v_F^2} \right) v_x \right]$$

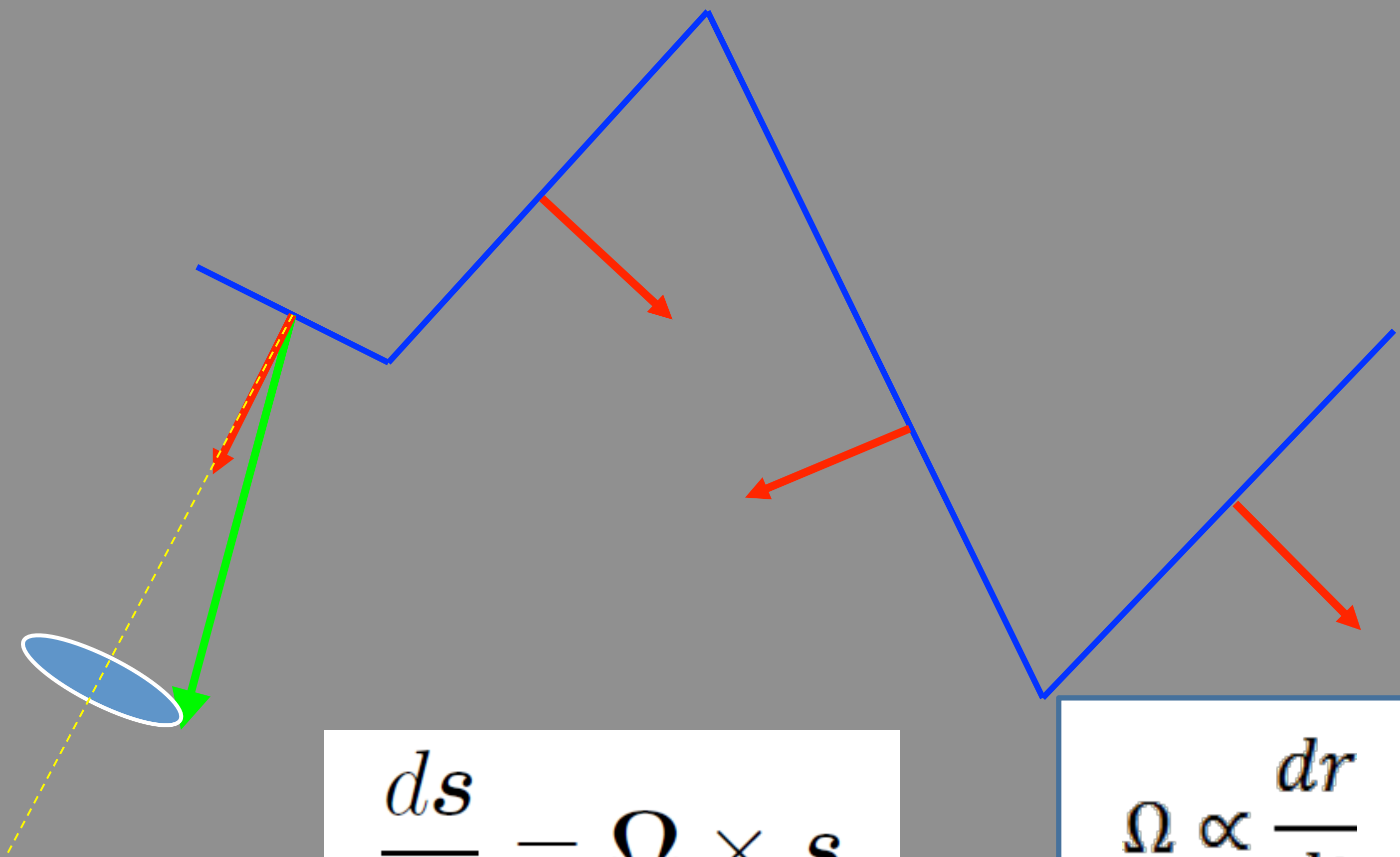
Rashba spin-orbit coupling



Dresselhaus spin-orbit coupling



As electron propagates there is a correlation between random walks in position and spin direction



$$\frac{d\boldsymbol{s}}{dt} = \boldsymbol{\Omega} \times \boldsymbol{s}.$$

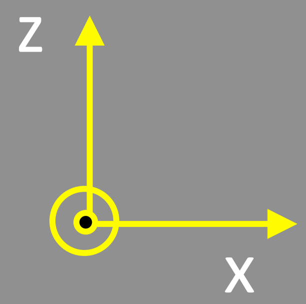
$$\Omega \propto \frac{dr}{dt}$$

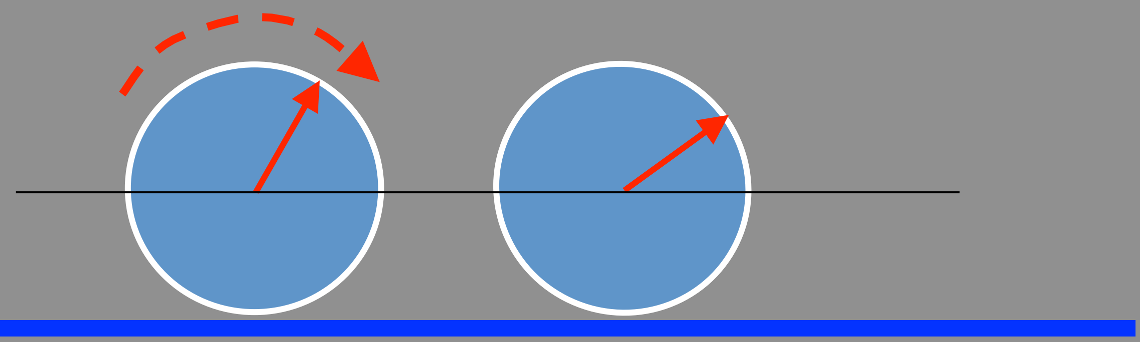
In 1-D there is perfect spin/displacement correlation leading to infinite spin lifetime at a nonzero wavevector

$$\frac{d\Theta}{dt} = \Omega_y = \alpha v_x = \alpha \frac{dx}{dt}$$

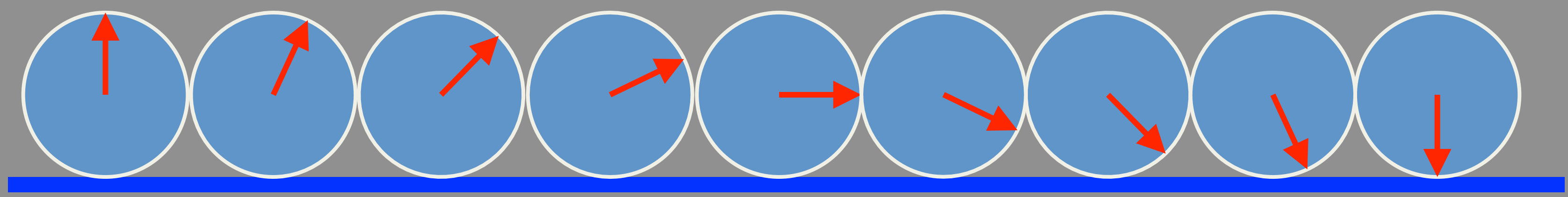
$$\Delta\Theta = \alpha \Delta x$$

Spin precesses in x-z plane like an arrow on a disk that rolls w/o slipping





A helical polarization with the "magic" wavevector $q=1/L_s$ will never decay, even though the spin of each individual electron is rapidly randomized.



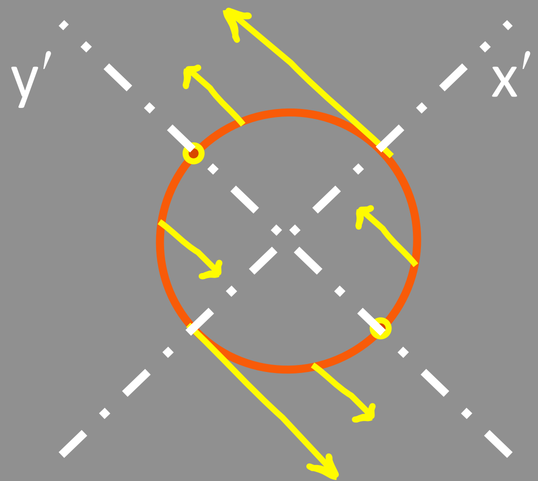
Many electron system prepared with initial helical polarization

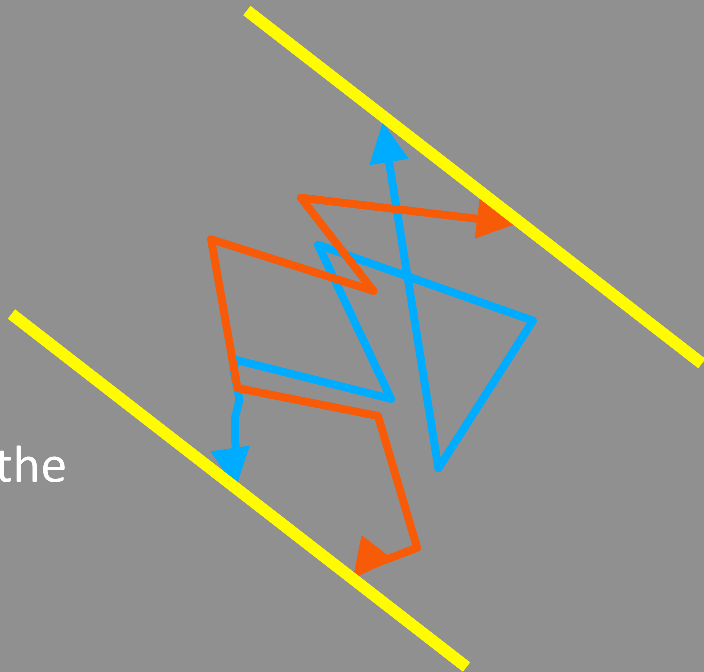
Special properties of “Rashba equals Dresselhaus” spin dynamics

Spin rotation depends on displacement, independent of path

$$\vec{\Omega} = -\Omega_0 \frac{k_{x'}}{k} \hat{y}'$$

$$\Delta\Theta = \alpha \Delta x'$$

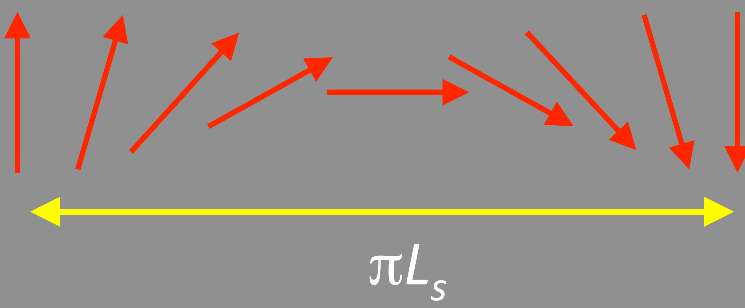


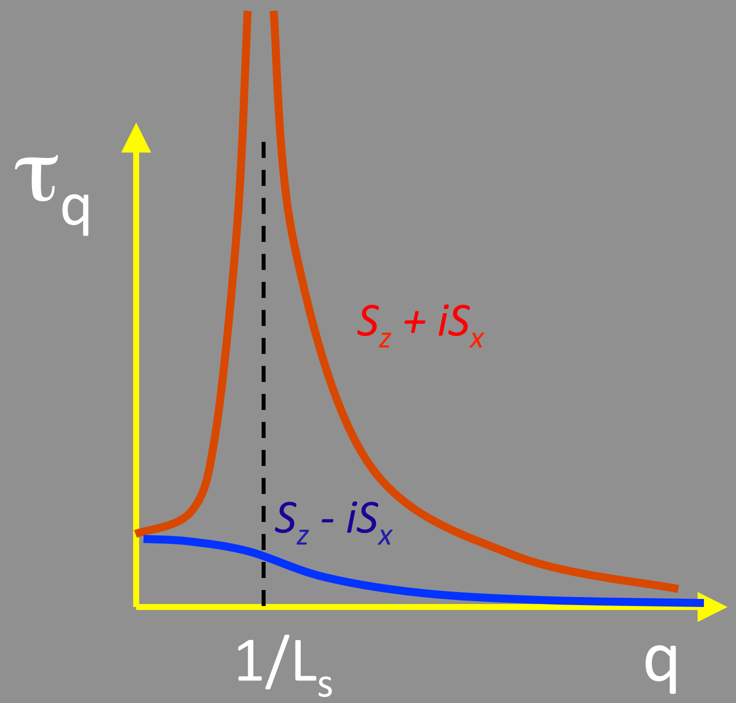


All of these paths experience exactly the same net rotation!

When $\alpha=\beta$ spin helix has infinite lifetime!

At the resonant *q*, spin precesses by 2π as it propagates one period of the helix



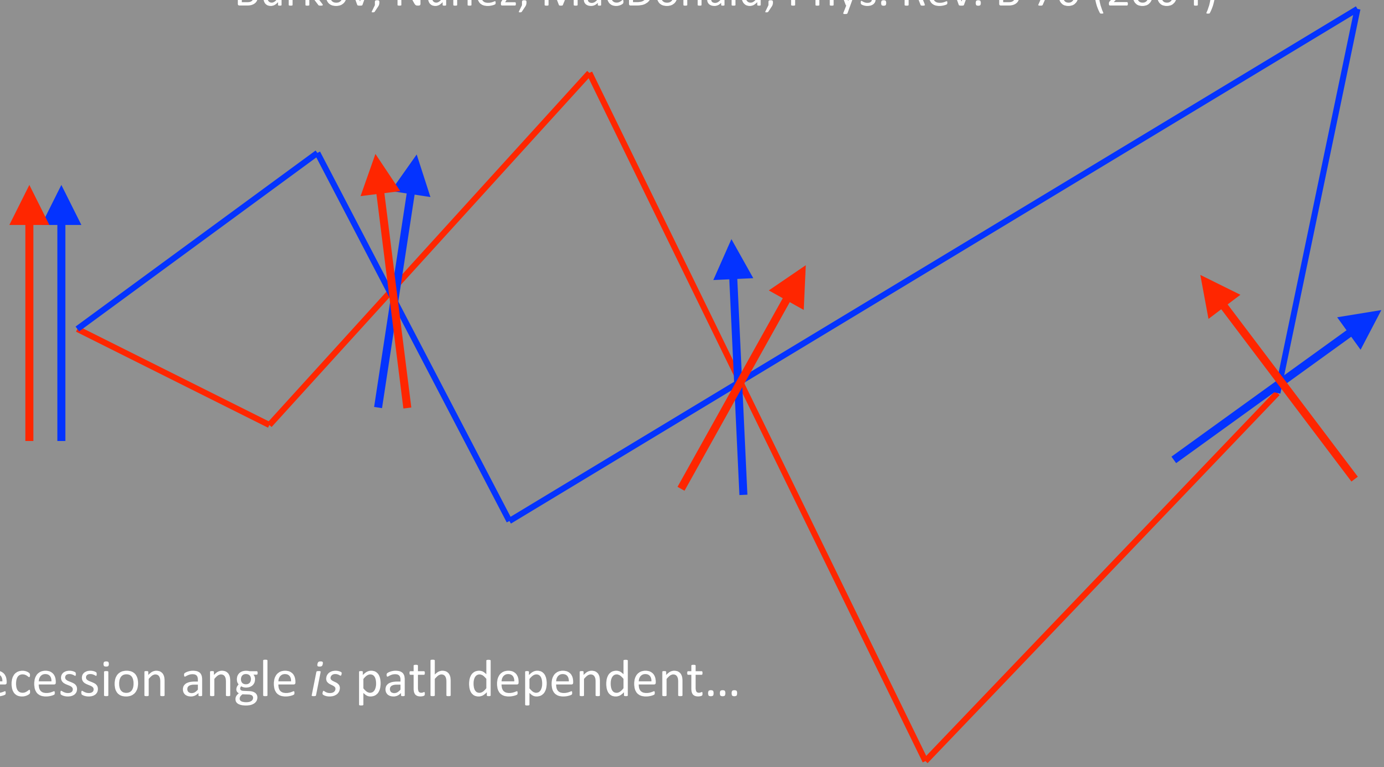


Predict two lifetimes at each wavevector corresponding to the two senses of spin rotation

What about $\alpha \neq \beta$?

Spin propagation Rashba only

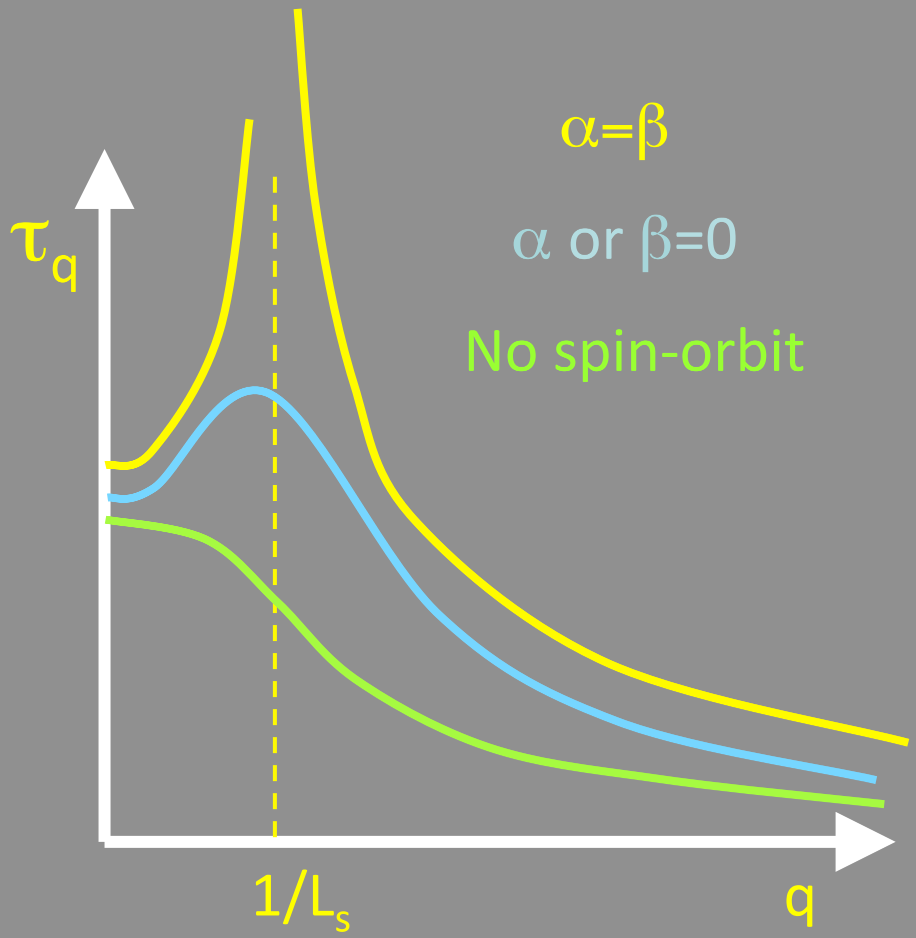
Burkov, Nunez, MacDonald, Phys. Rev. B 70 (2004)



Precession angle *is* path dependent…

…leading to weaker, *but nonzero*, spin/space correlations.

Summarizing predictions for spin helix lifetime



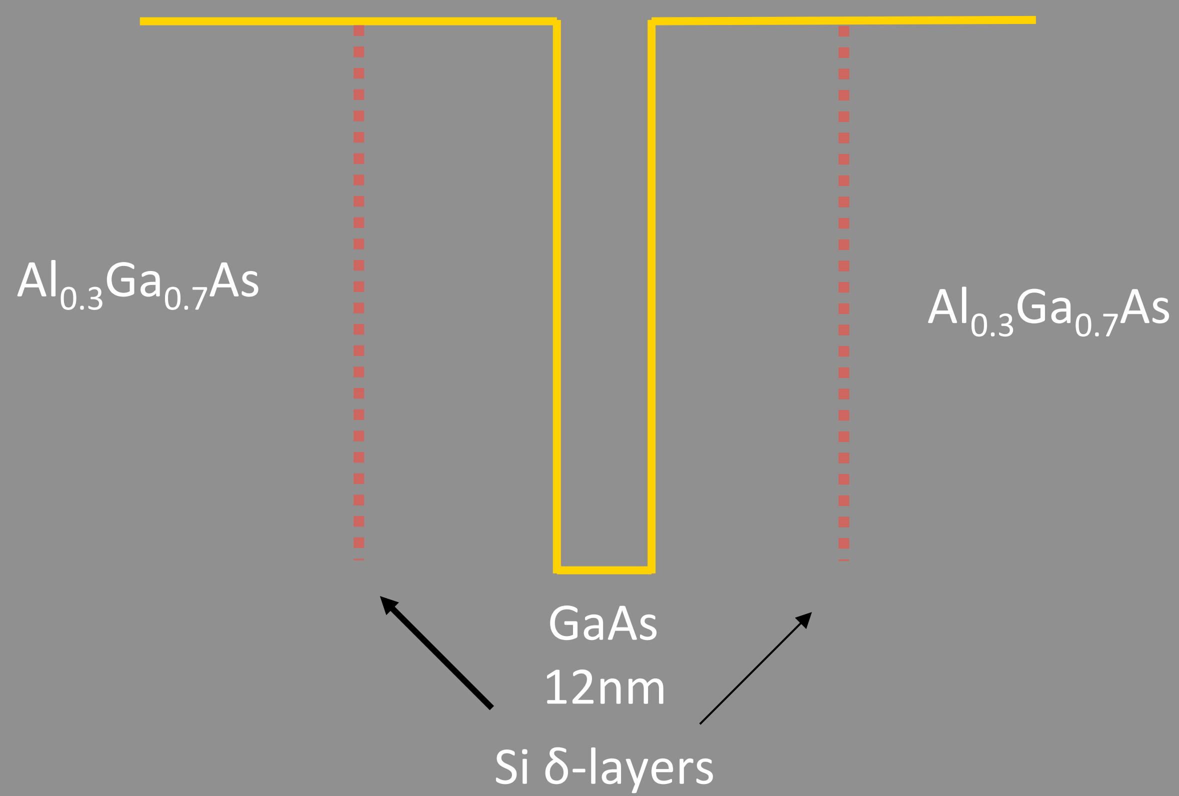
Transient gratings: overview of experiments

Weber, C.P. *et al.* Observation of spin-Coulomb drag in a two-dimensional electron gas. *Nature* **437,** 1330-1333 (2005).

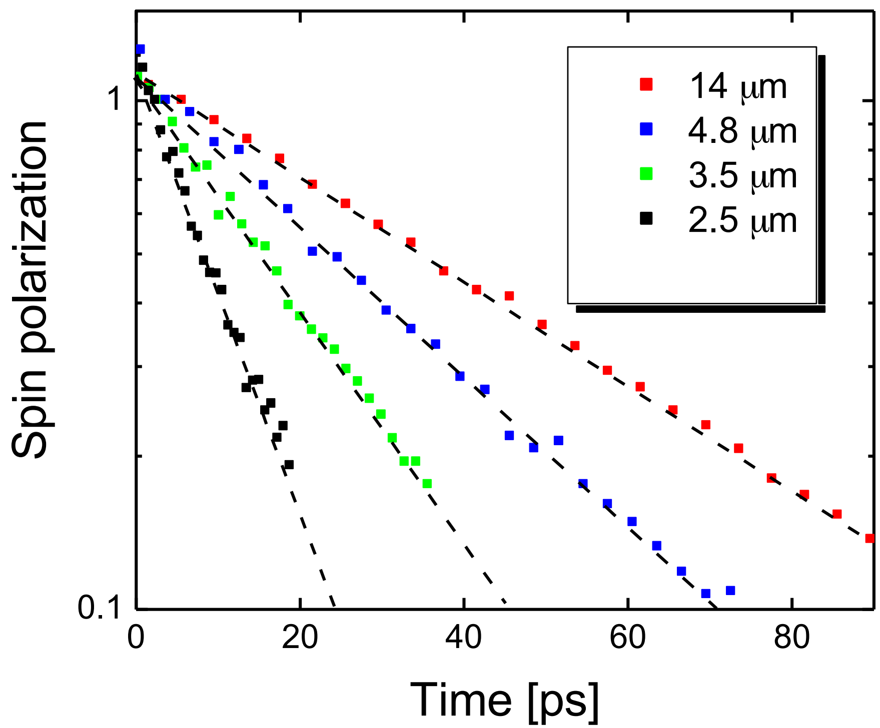
Weber, C. P. *et al*. Nondiffusive spin dynamics in a two-dimensional electron gas. *Phys. Rev. Lett.* **98,** 076604 (2007).

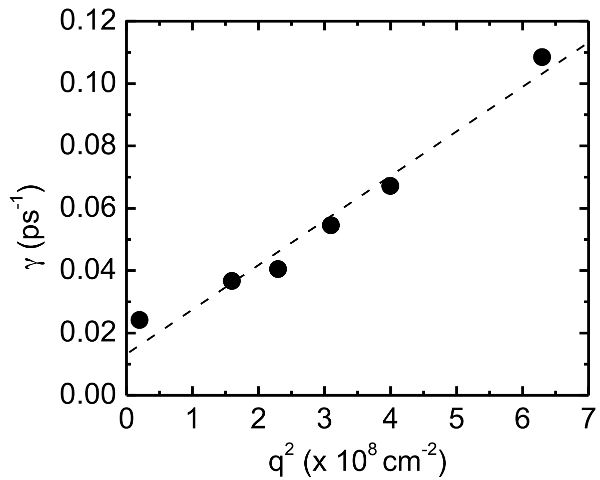
Koralek, J. D. *et al*. Emergence of the persistent spin helix in semiconductor quantum wells. *Nature* **458,** 610-613 (2009).

High mobility modulation doped quantum wells
Designed to be symmetric: Rashba should equal zero



Puzzling initial observation:
Naïve picture seems to work

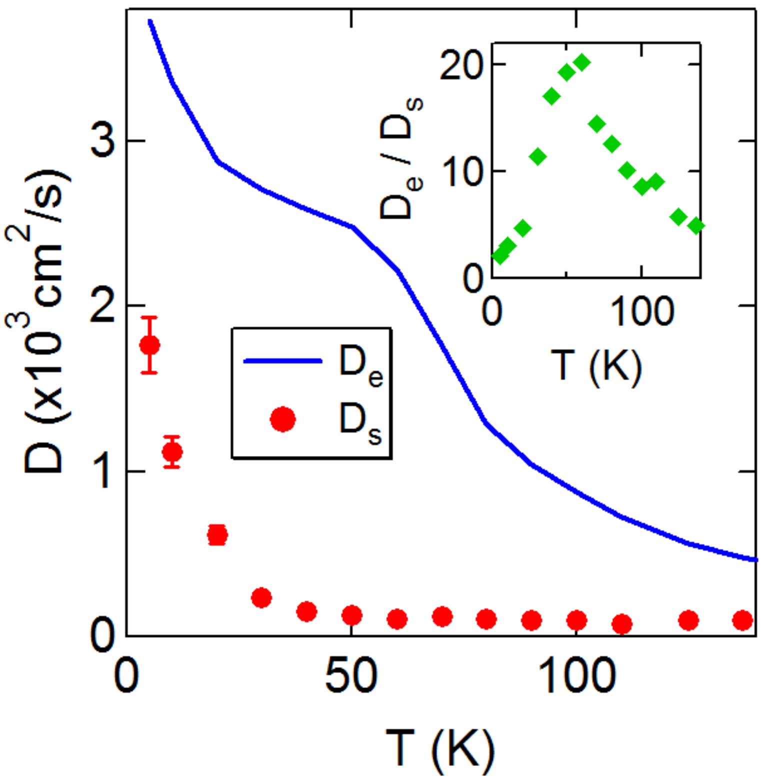




$$\gamma_q = D_s q^2 + 1/\tau_s$$

Single decay rate at each wavevector that obeys diffusion equation

Surprise: comparison of spin and charge diffusion coefficients

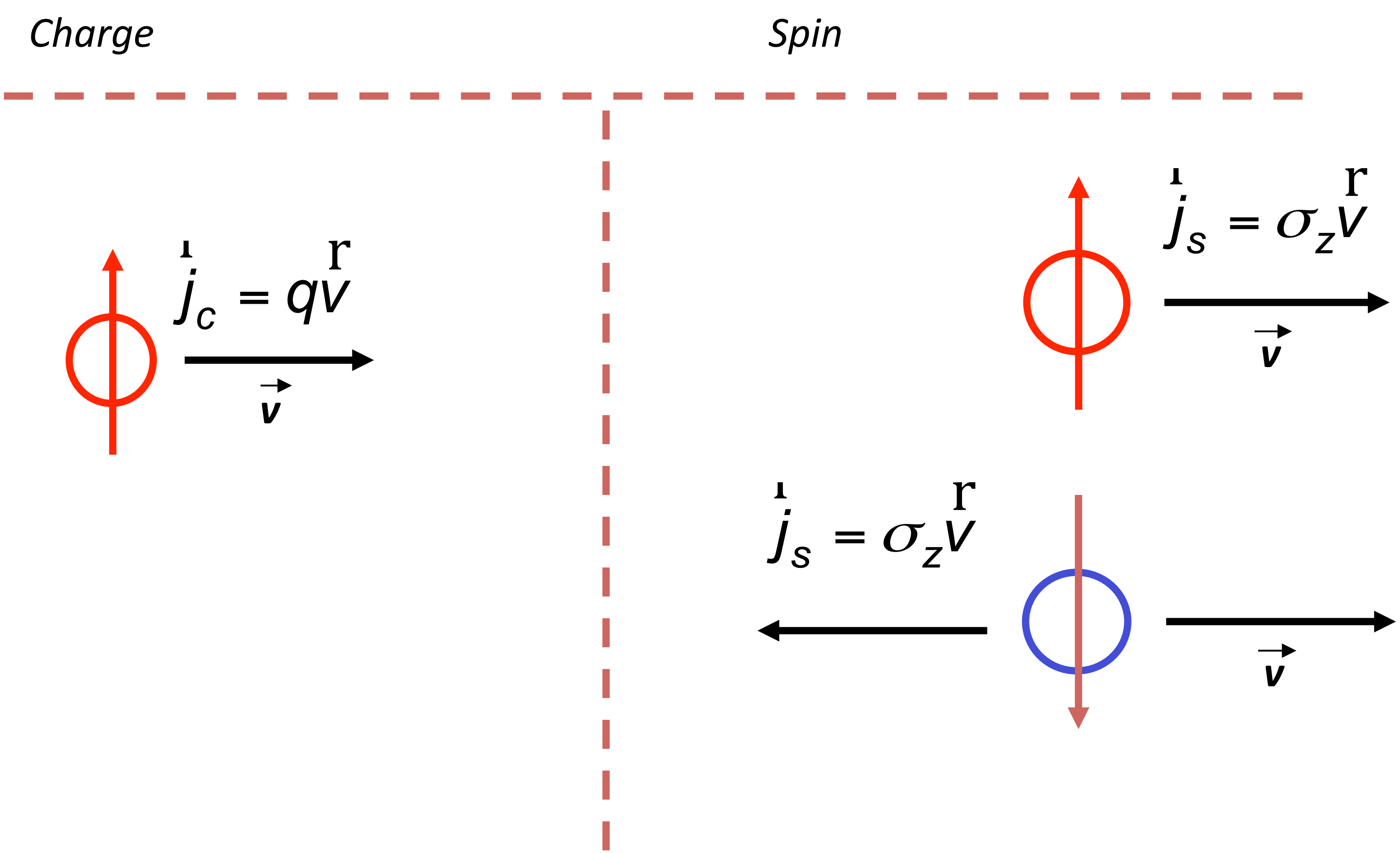


$$D_e = \frac{kT}{e}\mu \text{ for } T \gg T_F$$

$$D_e = \frac{E_F}{e}\mu \text{ for } T \ll T_F$$

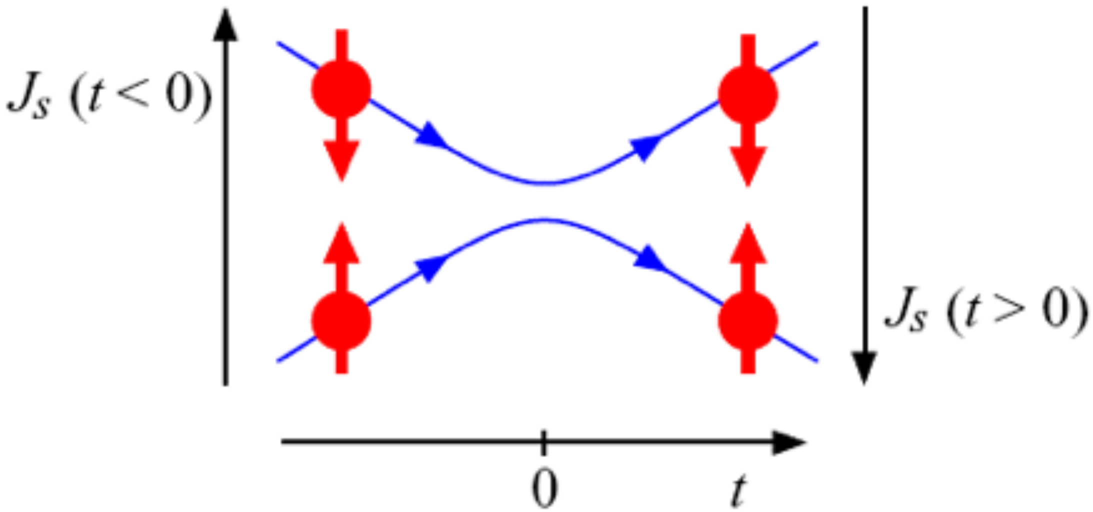
Weber, *et al*, *Nature*, **437**, 27 (2005).

Spin vs. charge currents



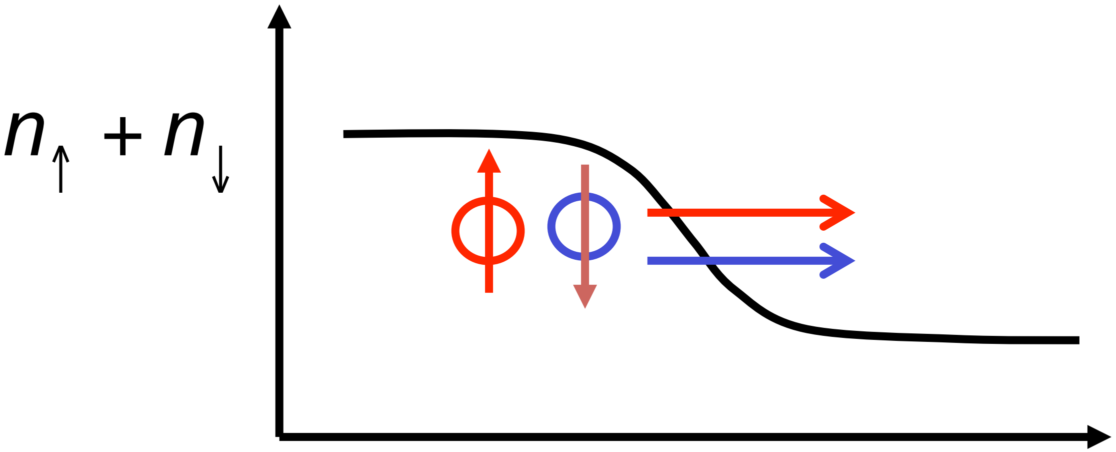
Spin coulomb drag (D'amico &Vignale)

e-e collisions affect spin current, not charge current

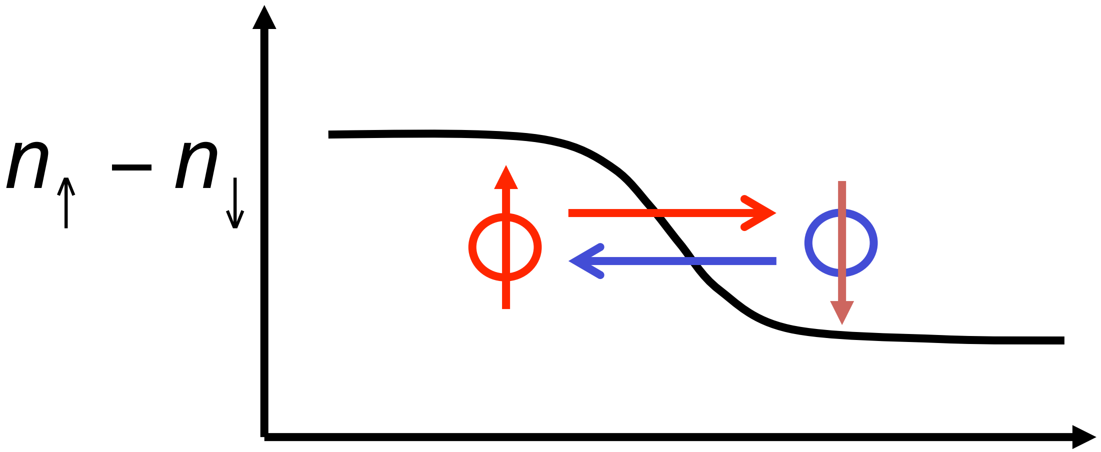


e-e collisions conserve total momentum, but cause exchange of momentum between spin up and spin down populations.

‘Drag’ leads to different D’s for spin and charge



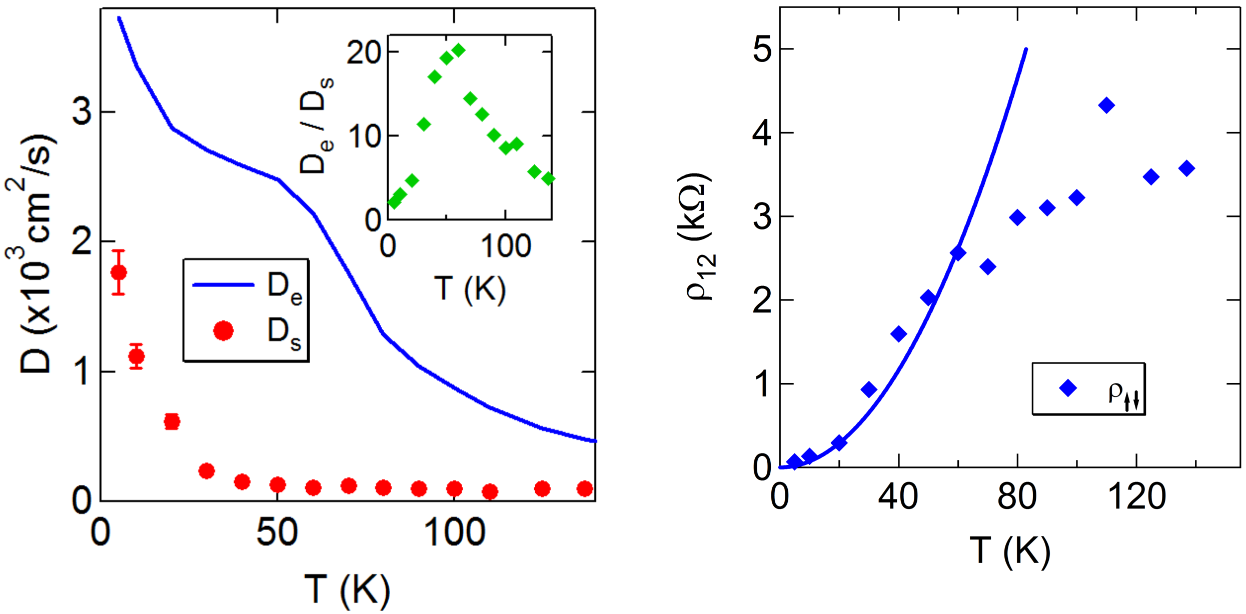
$$D_c = \sigma / \chi$$



$$D_s = \frac{D_c}{1 + \rho_{\uparrow\downarrow} / \rho}$$

spin Drag resistance

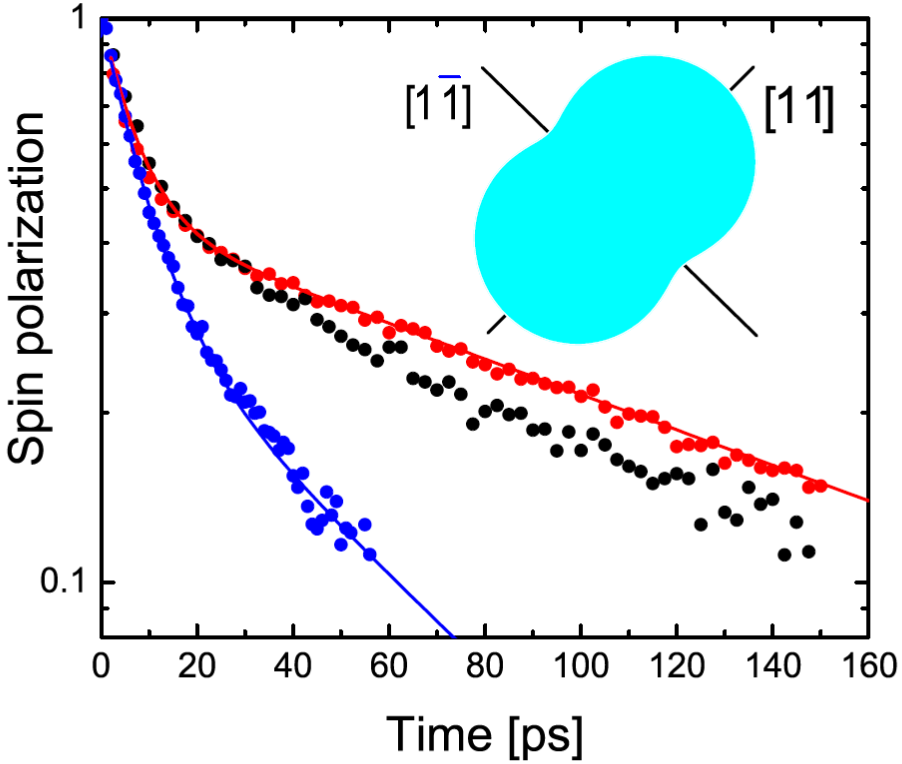
Comparison with spin Coulomb drag theory



Weber, *et al*, *Nature*, **437**, 27 (2005).

So far: e-e interaction but no SO coupling?

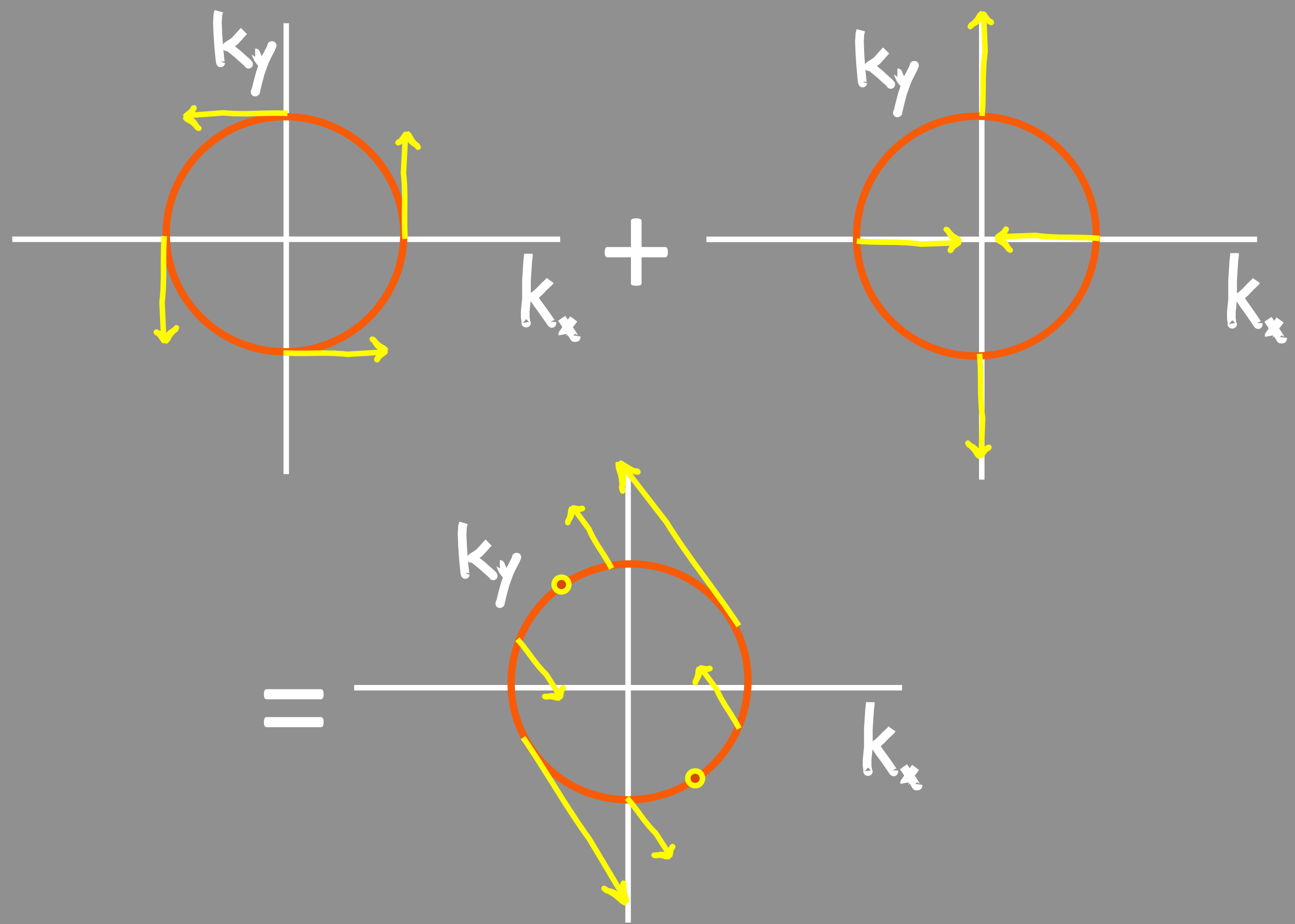
Wavevector in the wrong direction!



Isotropic for Rashba or Dresselhaus only
Even small admixture leads to strong anisotropy

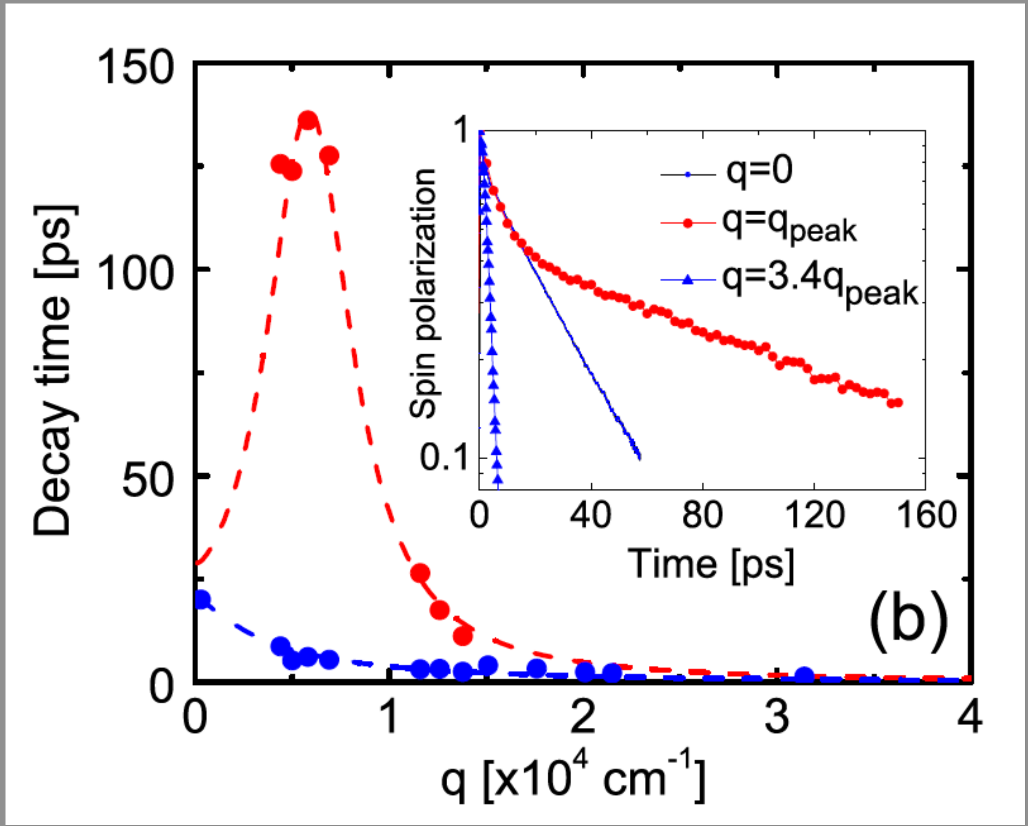
Rashba spin-orbit coupling

Dresselhaus spin-orbit coupling



Wavevector dependence of lifetime

Enhancement relative to q=0 larger than predicted
for 2D Rashba model

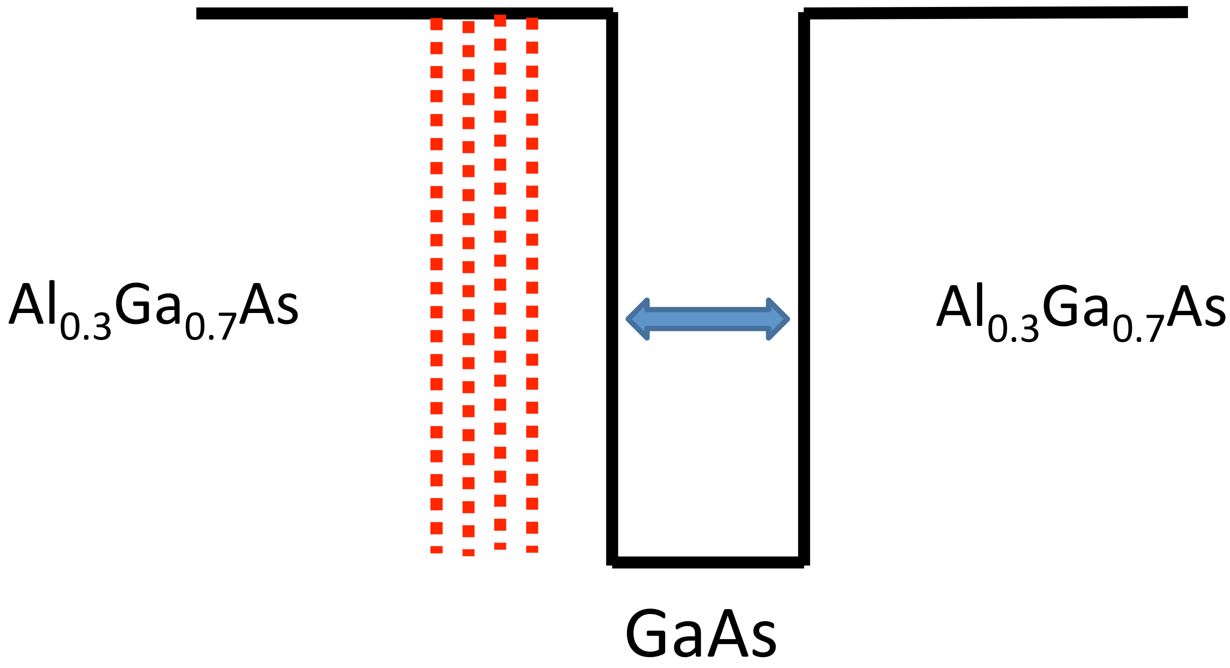


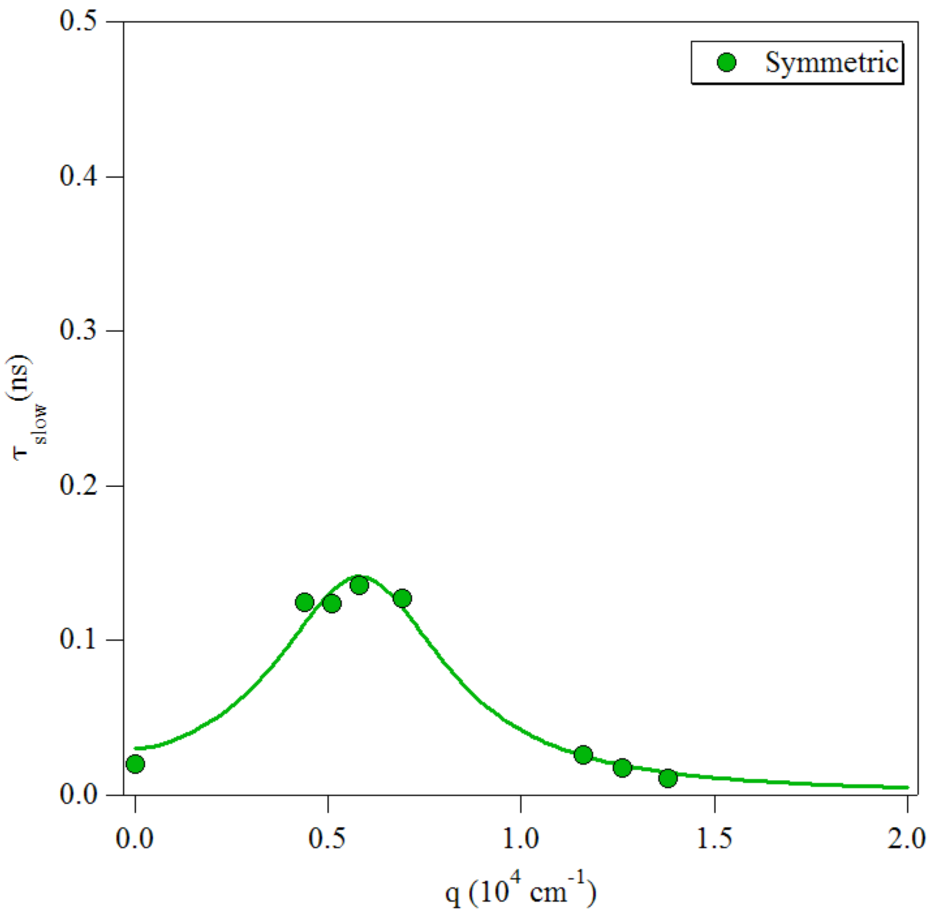
Tuning for Rashba = Linear Dresselhaus

Electric field is generated by asymmetric doping

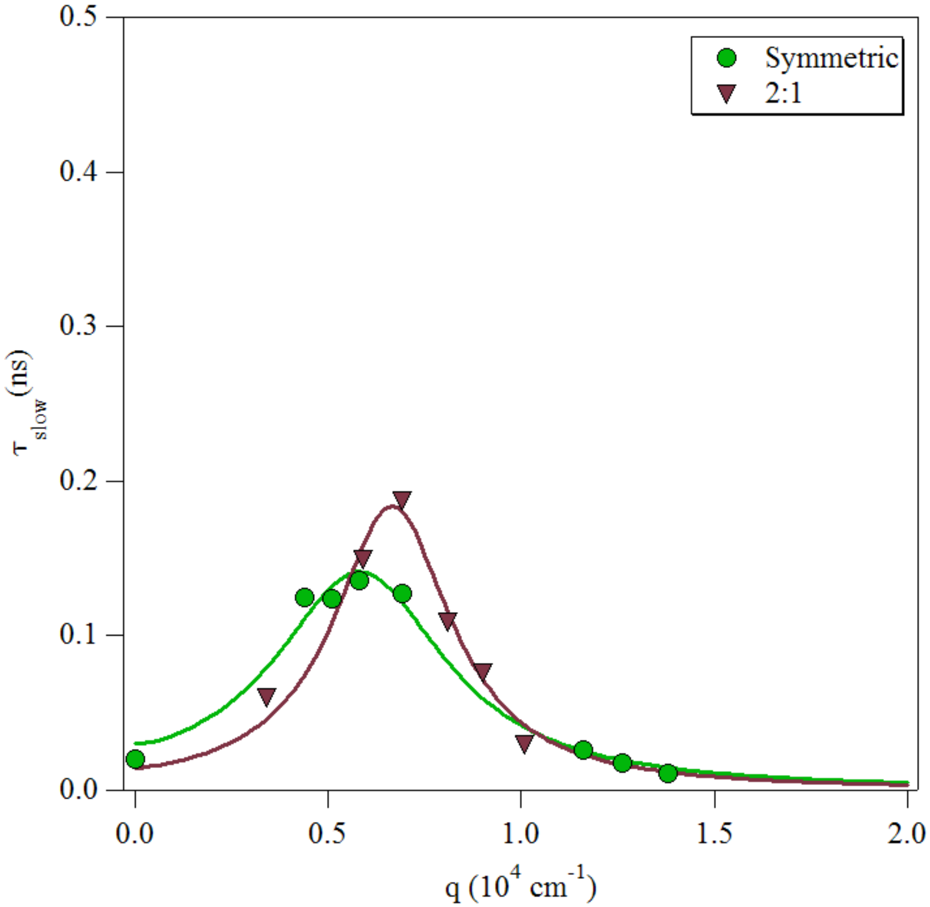
Tune Dresselhaus term by changing well width

$$\beta = \gamma k \left\langle k_z^2 \right\rangle \propto \frac{1}{d^2}$$

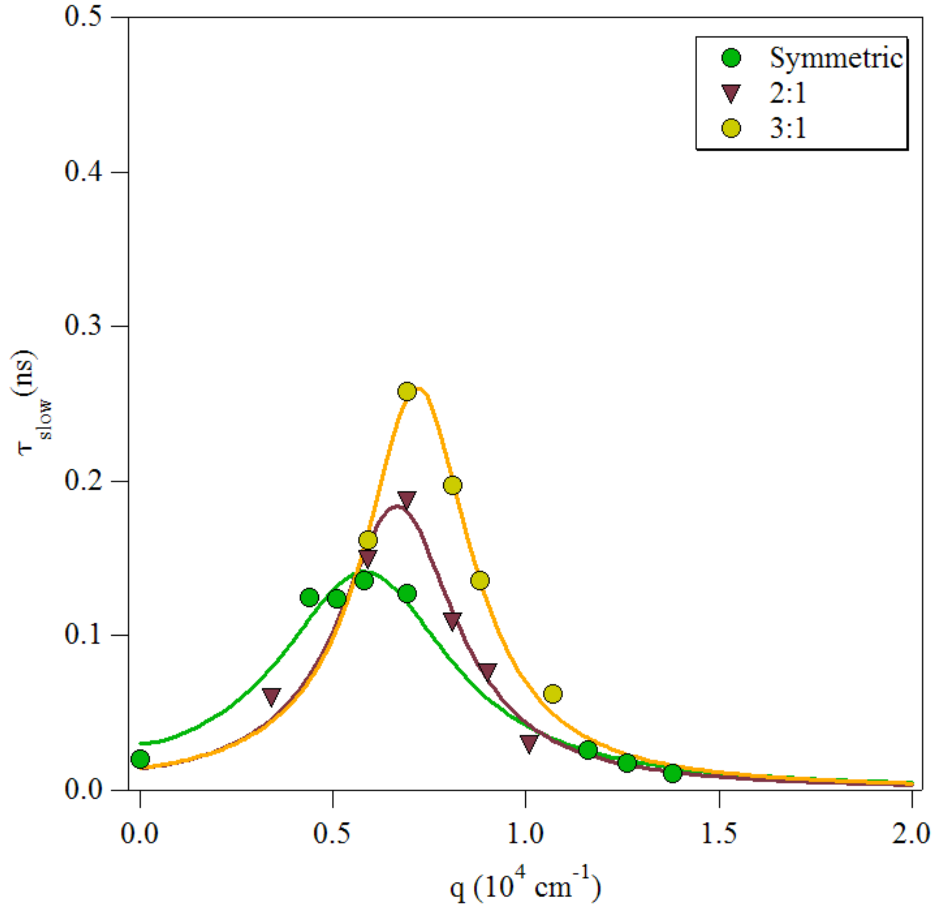




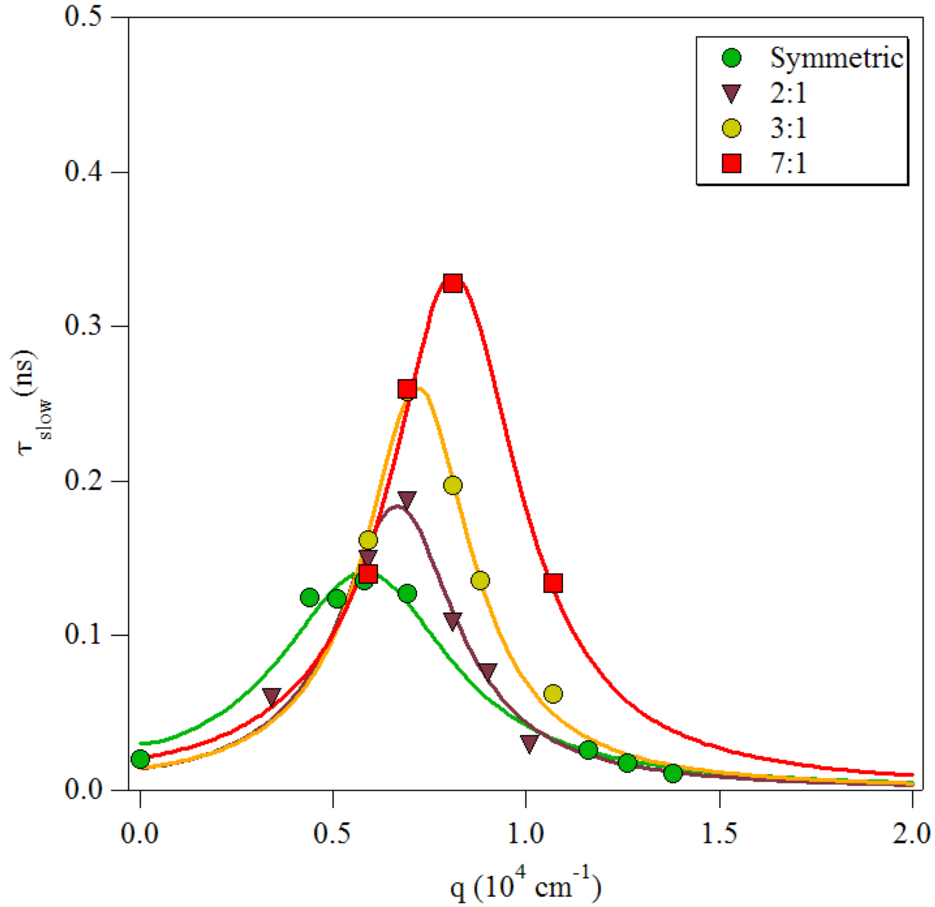
0.5
0.4
0.3
0.2
0.1
0.0
τ slow (ns)
Symmetric
0.0
0.5
1.0
1.5
2.0
q (10^4 cm^-1)



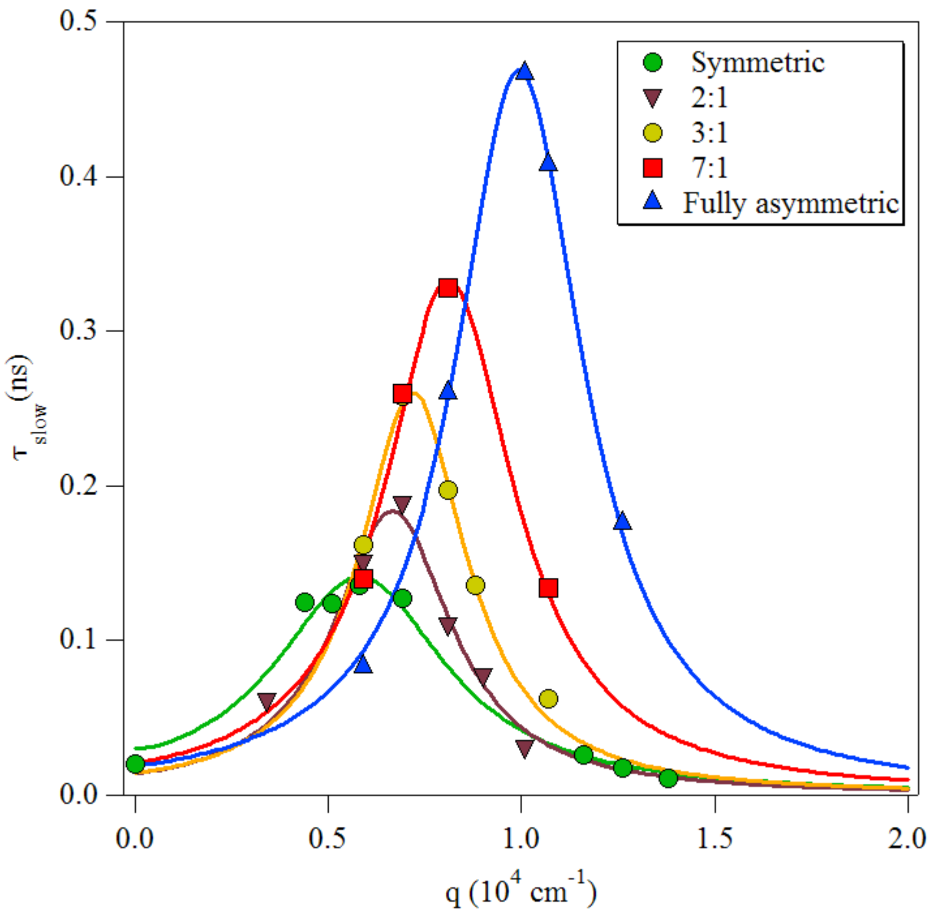
Symmetric
2:1
0.0
0.1
0.2
0.3
0.4
0.5
0.0
0.5
1.0
1.5
2.0
τ_{slow} (ns)
q (10^4 cm^{-1})



0.5
0.4
0.3
0.2
0.1
0.0
τ_{slow} (ns)
0.0
0.5
1.0
1.5
2.0
q (10^4 cm^{-1})
Symmetric
2:1
3:1

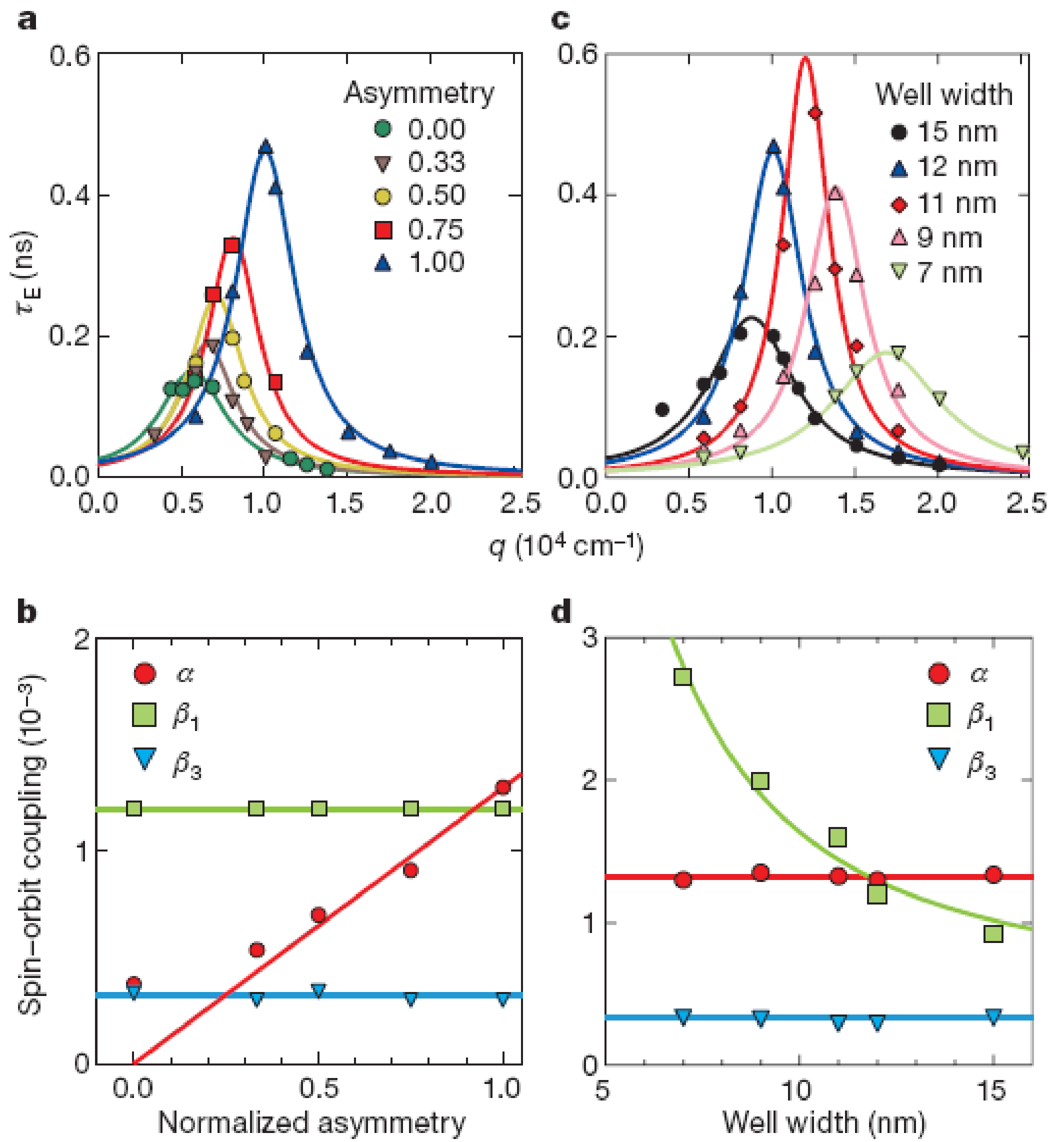


Symmetric
2:1
3:1
7:1
τ slow (ns)
q (10^4 cm^-1)
0.0
0.1
0.2
0.3
0.4
0.5
0.0
0.5
1.0
1.5
2.0



0.5
0.4
0.3
0.2
0.1
0.0
τ_{slow} (ns)
0.0
0.5
1.0
1.5
2.0
q (10^4 cm^{-1})
Symmetric
2:1
3:1
7:1
Fully asymmetric

Measurement of all spin-Hamiltonian parameters

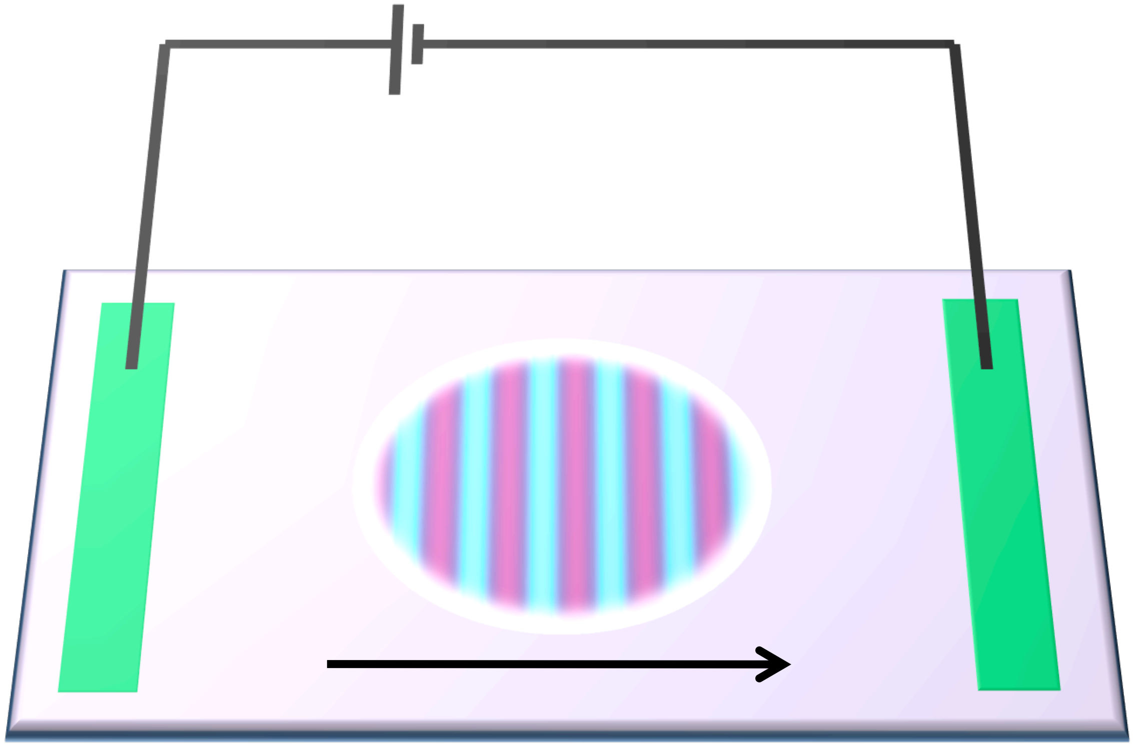


Newer measurements

(1) Doppler spin velocimetry

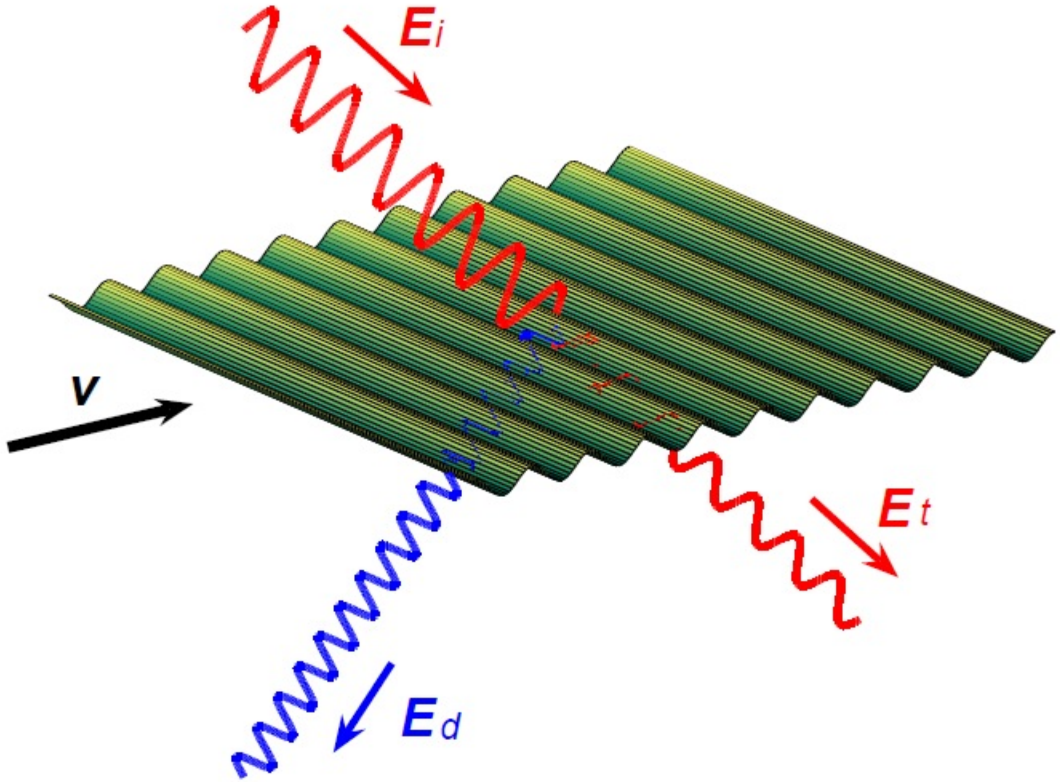
(2) Mixed spin/charge gratings and anomalous Hall effects

Measurement of PSH drift

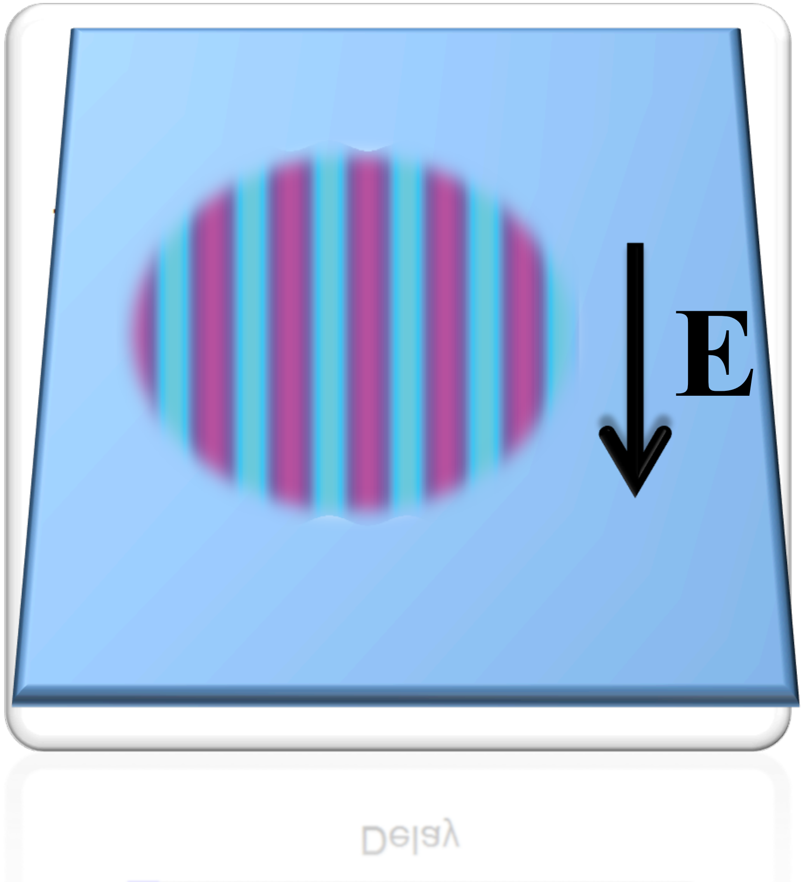


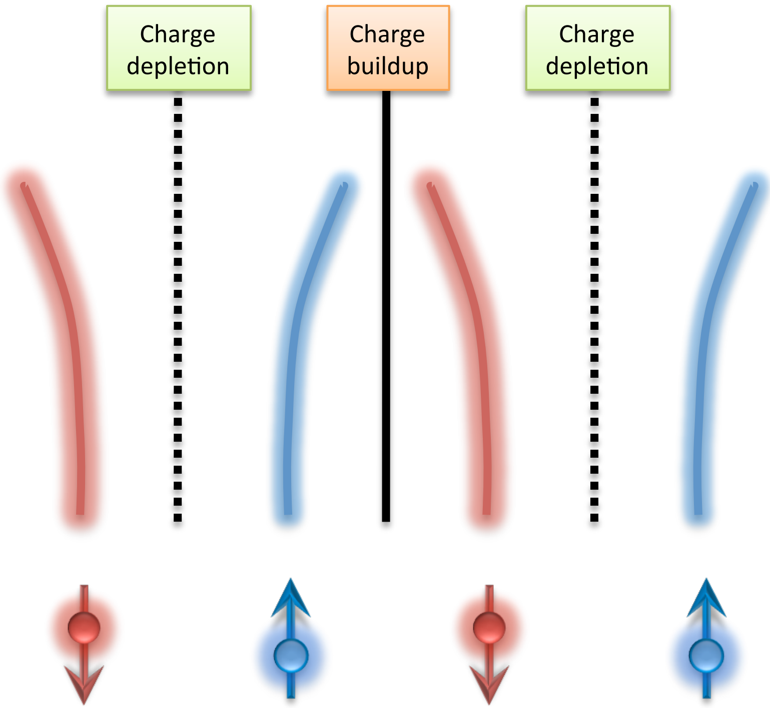
Doppler spin velocimetry

Velocity of grating leads to linear advance with time of phase of diffracted wave – equivalent to frequency shift



Measure the anomalous Hall effect or the spin Hall effect





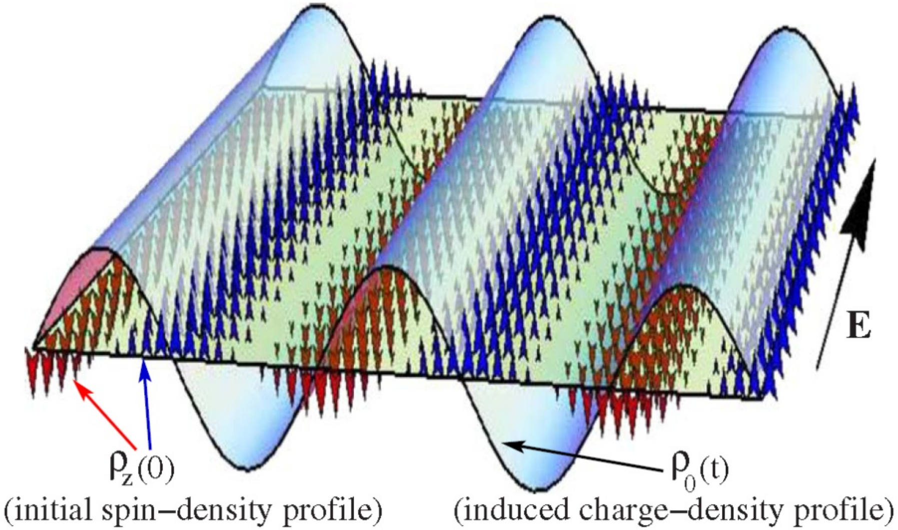
The End
Thank you

Joe Orenstein
UC Berkeley and Lawrence Berkeley National Lab

Newspin2 December, 2011

How big is the signal?

Tune Rashba SO coupling to test whether is ***intrinsic*** or not.



Anderson, Stanescu and Galitski, *PRB* **81**, 121304(R) (2010).

Spin Hall angle

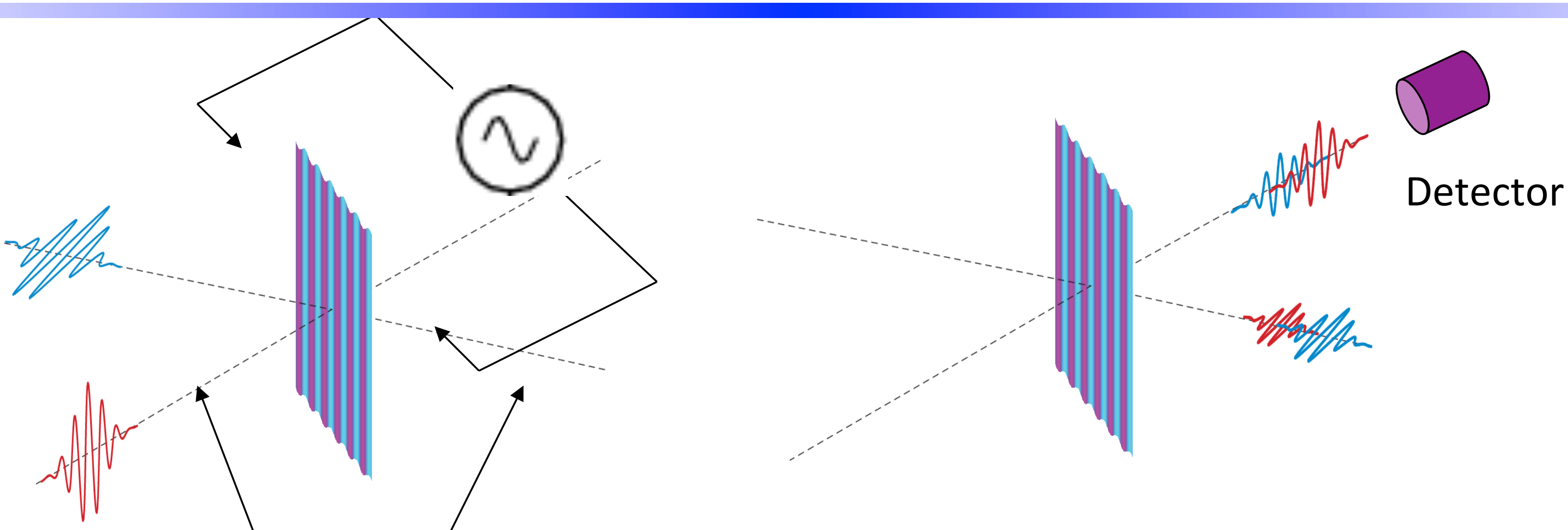
$$\theta_H = \sigma_{xy}/\sigma_{xx} = 1/k_F l \sim 1/100$$

If $v_d = v_F = 10^7$ cm/s , then

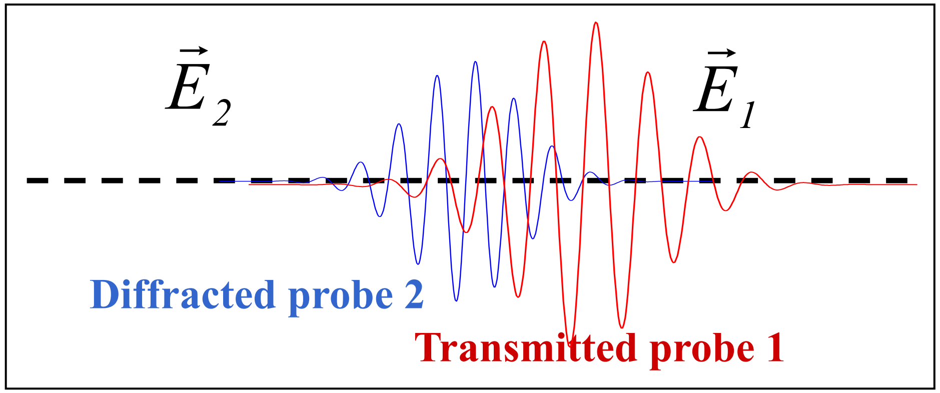
$$v_H = v_d\, \theta_H = 10^5 \text{ cm/s}$$

Resolution ~10^4 cm/s

Detection of spin polarization wave



Lock-in on the oscillation



$$S_z(q,t) = [\text{Amp.}] \times [\text{Phase}]$$

$[\text{Amp.}] \downarrow D_s$

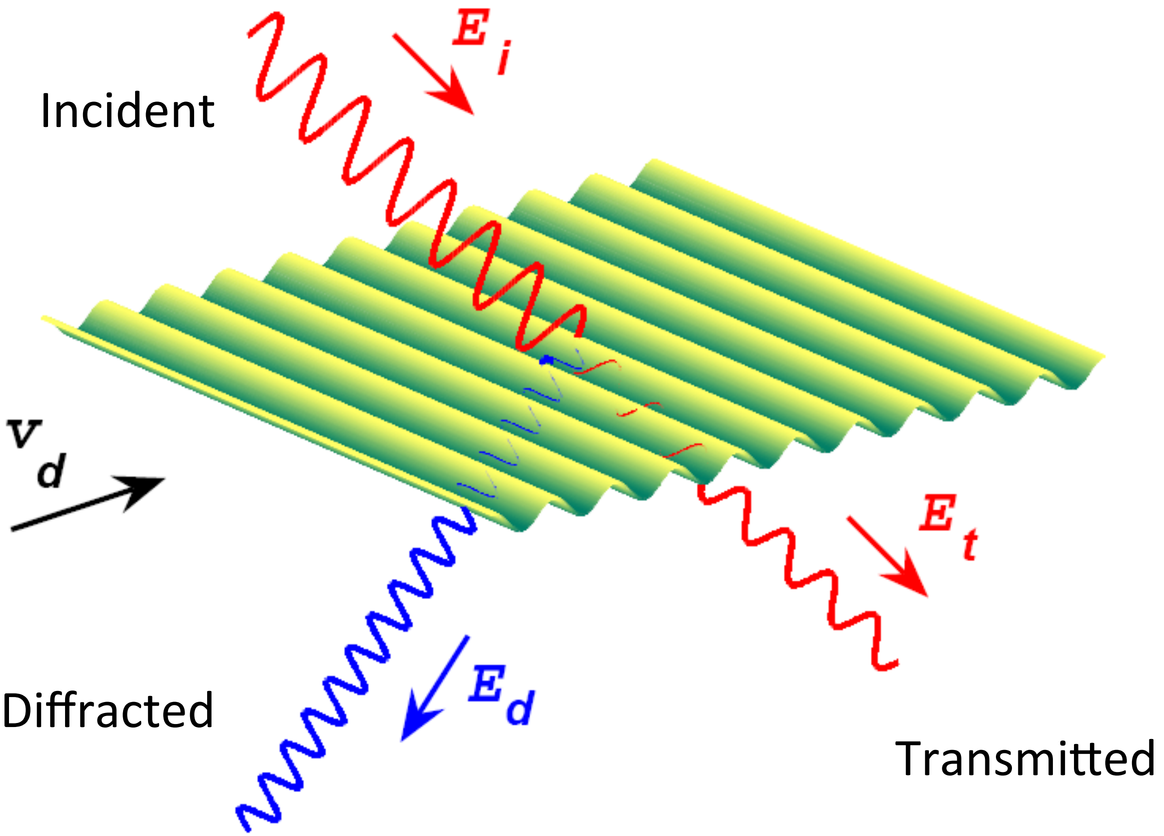
$[\text{Phase}] \downarrow \mu_s$

Doppler spin velocimetry

$$\boldsymbol{S}(x,t)=\boldsymbol{S}_0 \exp[-t/\tau(q)]\cos[qx-qx_0(t)]$$

phase

$$x_0(t)=v_d t$$



n-GaAs quantum well