Persistent spin helix
in spin-orbit coupled system

Joe Orenstein
UC Berkeley and Lawrence Berkeley National Lab

Persistent spin helix in spin-orbit coupled system

Jake Koralek, Chris Weber, Joe Orenstein
Lawrence Berkeley National Lab

Andrei Bernevig, Shoucheng Zhang
Stanford University

Shawn Mack, Jason Stevens, David Awschalom
Center for Spintronics and Quantum Computation, University of California Santa Barbara

Motivation for studying spin propagation

- Correlated electrons – separation of spin and charge
- "Spintronics"– information carried by spin rather than charge

One of the keys for spintronics is to achieve control over spin via E-fields; logic based on switching *via* B is not feasible.

Spin-orbit coupling provides the potential mechanism, as exemplified in the Datta-Das transistor concept…

…but S-O coupling is a double-edged sword.

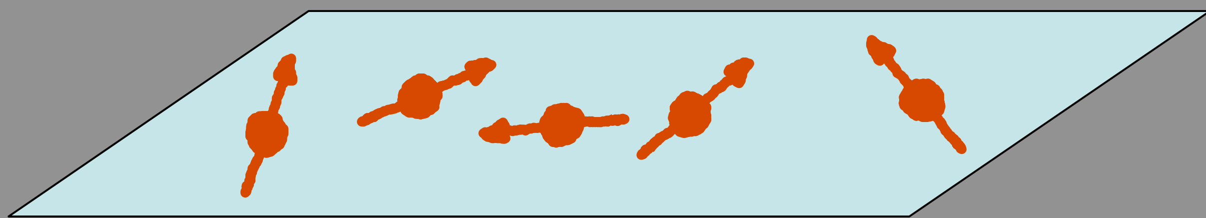
Control over spin state *via E* fields: good

Non-conservation of spin angular momentum: bad

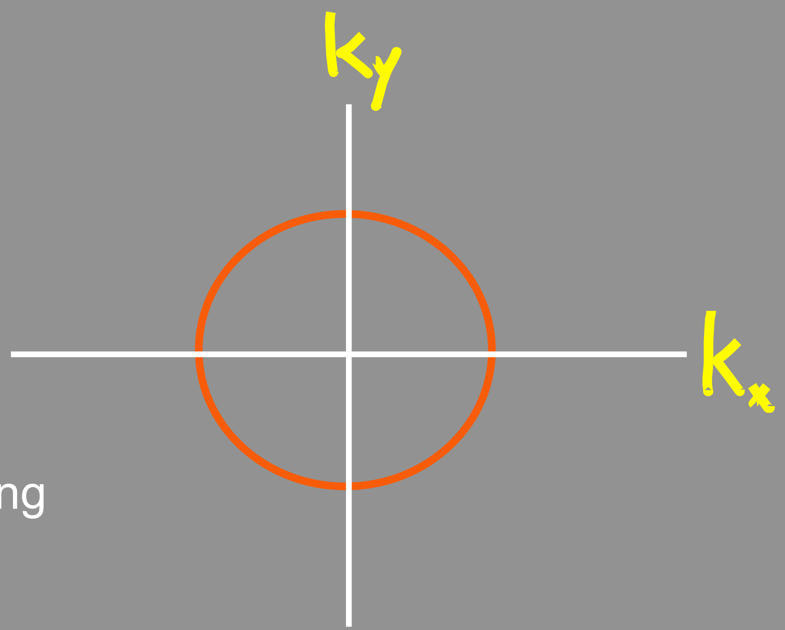
This talk…

- Spin-orbit as both advantage and obstacle.
- Schliemann, Egues, Loss proposal
  - The significance of “Rashba=Dresselhaus”
- Spin propagation in the presence of spin-orbit coupling.
  - Theory and experiment
- The quest for the Persistent Spin Helix.
  - Measurement and control over Rashba, Dresselhaus coupling.
- Spin diffusion coefficient, “violation” of Einstein relation, and spin Coulomb drag.
- The future

Model 2D system:
GaAs/AlGaAs quantum wells



Free-electron-like Fermi surface



2D electron gas parameters

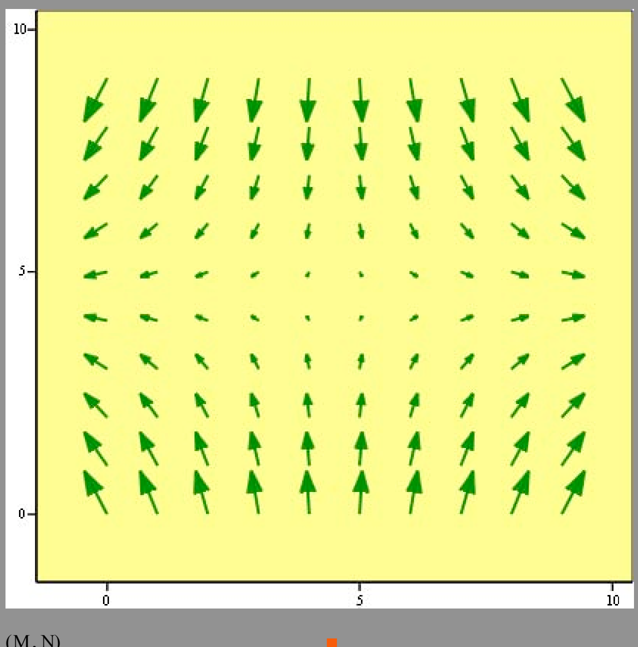
$n \sim 10^{11}$ -10^{12} cm^{-2}
mean-free-time ~ 10 ps
mean-free-path ~ 3 microns

"Trivial" system – except for the spin-orbit coupling

Spin-orbit Hamiltonian: $\mathcal{H} = \mathcal{H}_0 + \sigma \cdot \vec{B}_{so}$

$$|\vec{B}_{so}| \propto |\vec{k}|$$

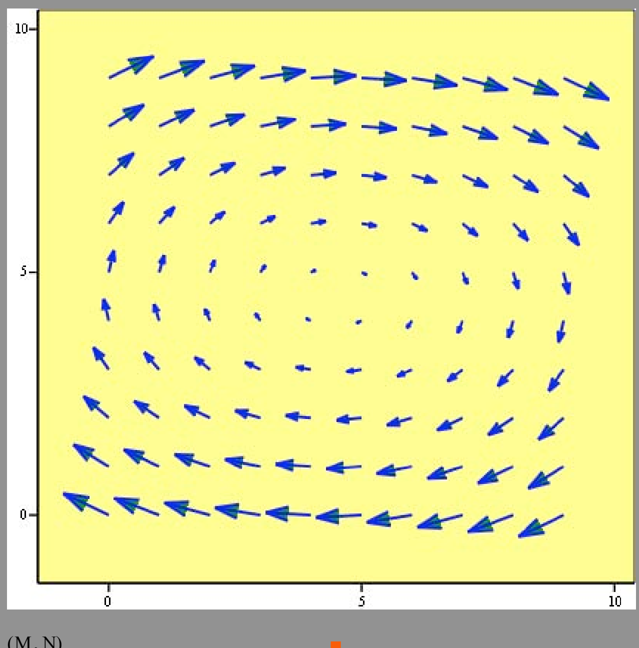
Dresselhaus term (intrinsic)



k_y

k_x

Rashba term ($\propto$ asymmetry of well)



k_y

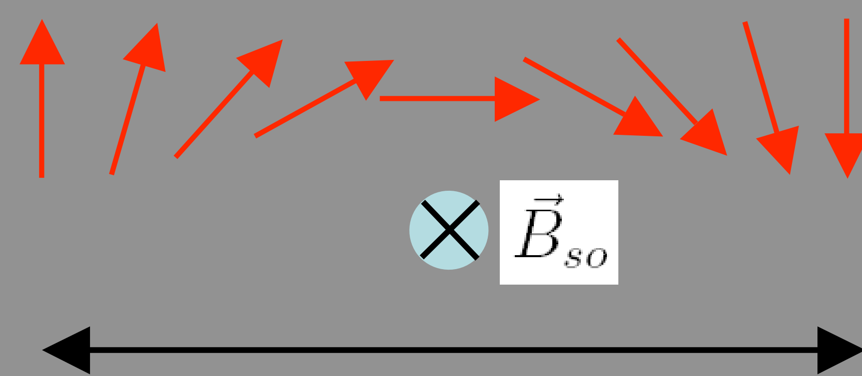
k_x

Length and frequency scale associated with spin-orbit coupling

Spin precesses in Rashba field
With frequency $\Omega = \alpha k_F$

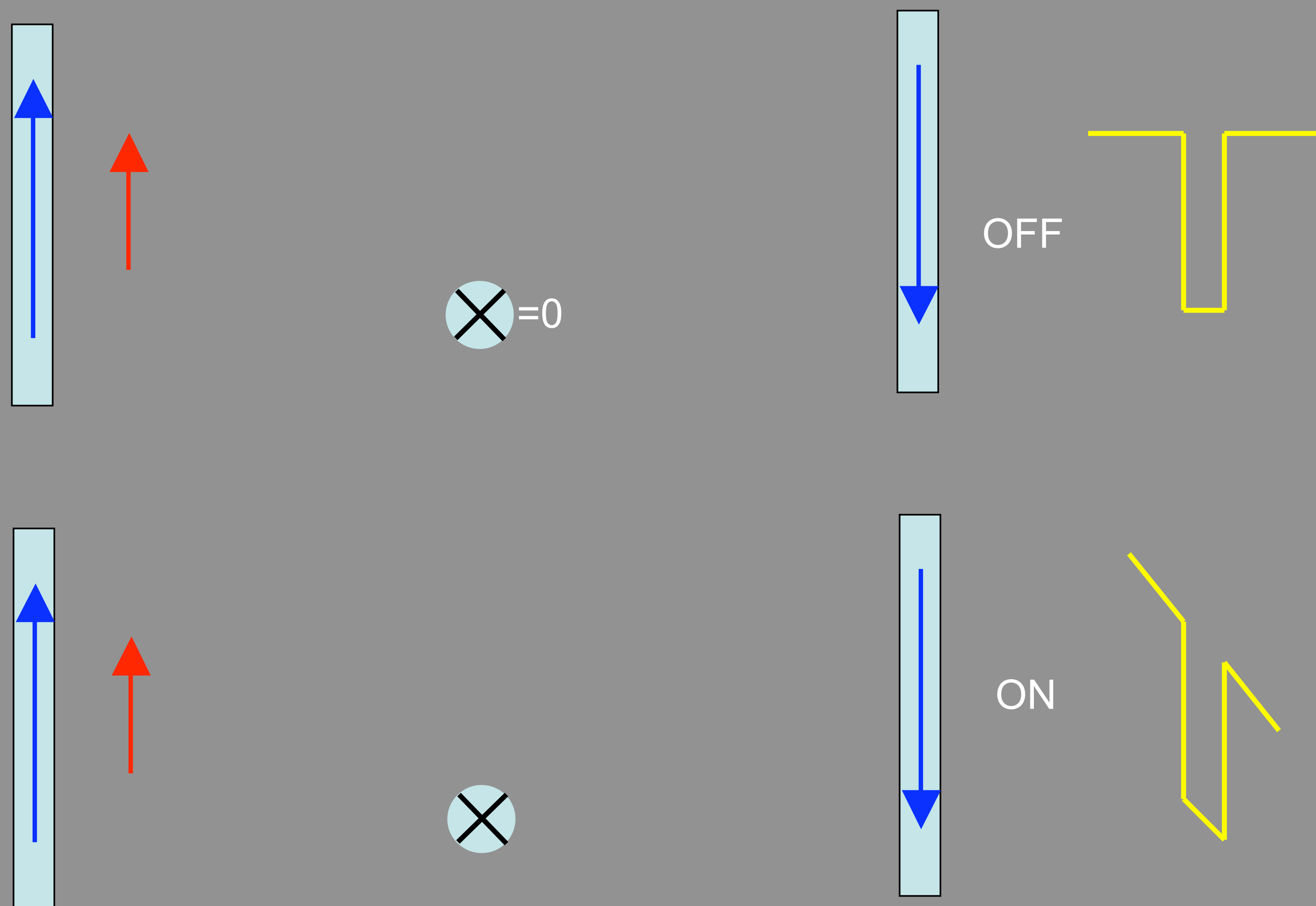
$$\Omega \approx 0.1\text{-}1 \text{ THz}$$

Spin of ballistic electron

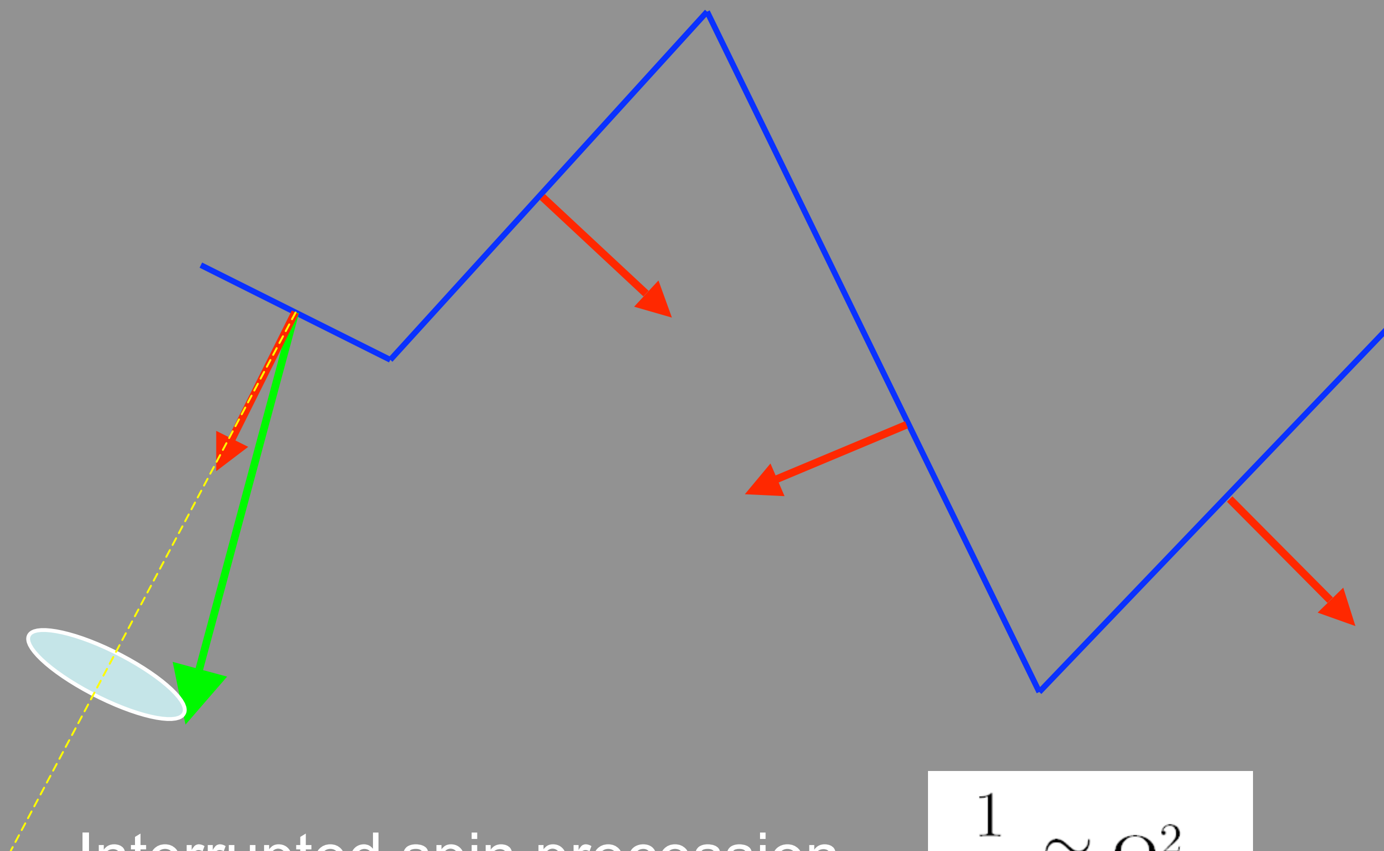


$$L = \frac{2\pi v_F}{\Omega} \approx 1 - 10\mu$$

Datta-Das: spin transistor
based on control of Rashba spin precession.



Datta-Das not robust with respect to disorder, which leads to Dyakanov-Perel spin relaxation.



Interrupted spin precession → $$\frac{1}{\tau_s} \cong \Omega^2 \tau$$

Spin diffusion length < spin precession length

$$L_s = \sqrt{D_s \tau_s}$$

$$\sqrt{D_s \tau_s} = \sqrt{\frac{v_F^2 \cancel{\tau}}{\Omega^2 \cancel{\tau}}} = \frac{L}{2\pi}$$

So this would seem to be the end of the road.

However, Schliemann, Egues, and Loss proposed a way out…

Non-ballistic spin field-effect transistor

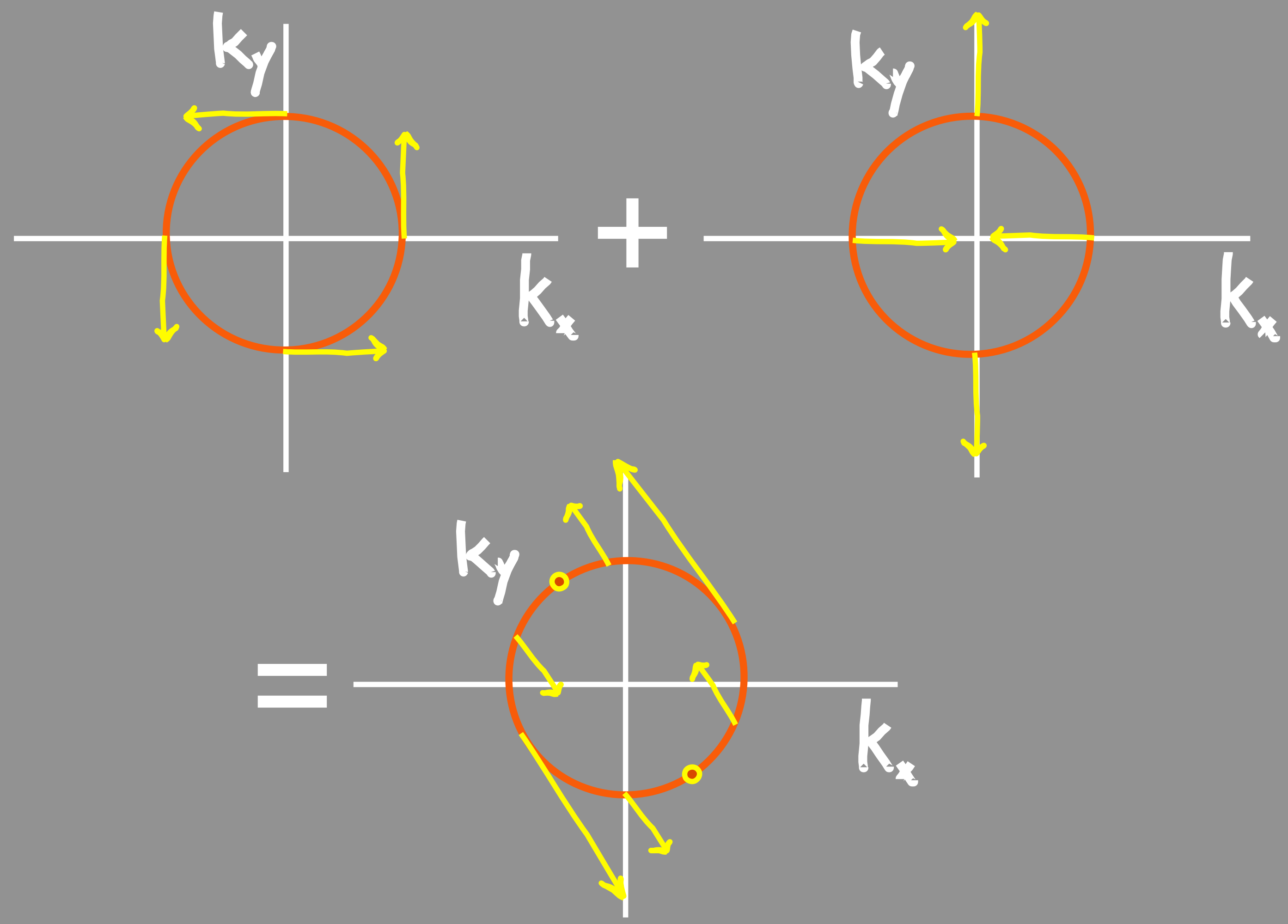
John Schliemann, J. Carlos Egues[1], and Daniel Loss

Department of Physics and Astronomy, University of Basel, CH-4056 Basel, Switzerland

Rashba=Dresselhaus

Rashba spin-orbit coupling

Dresselhaus spin-orbit coupling

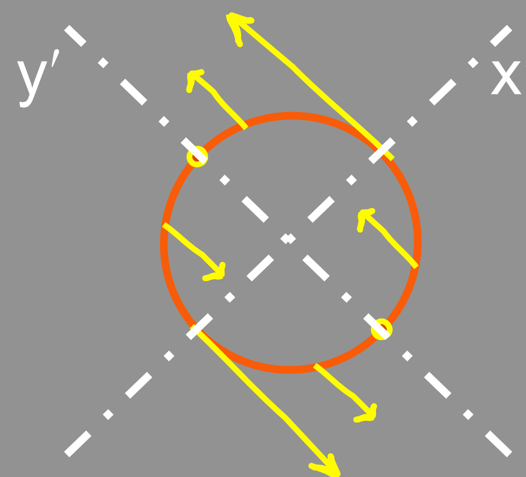


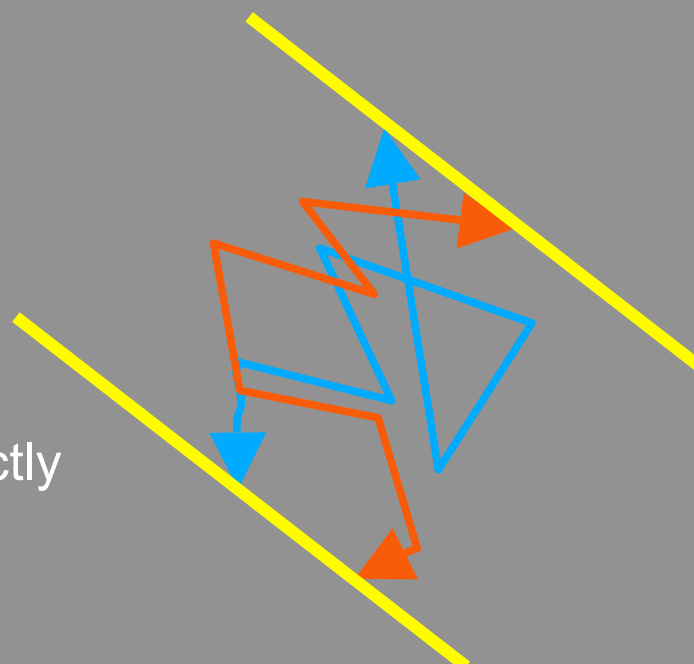
Special properties of “Rashba equals Dresselhaus” spin dynamics

Spin rotation depends on displacement, independent of path

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

$$\Delta\theta = x' \frac{\Omega_0}{v_F}$$





All of these paths experience exactly the same net rotation!

Schliemann, Egues, Loss device

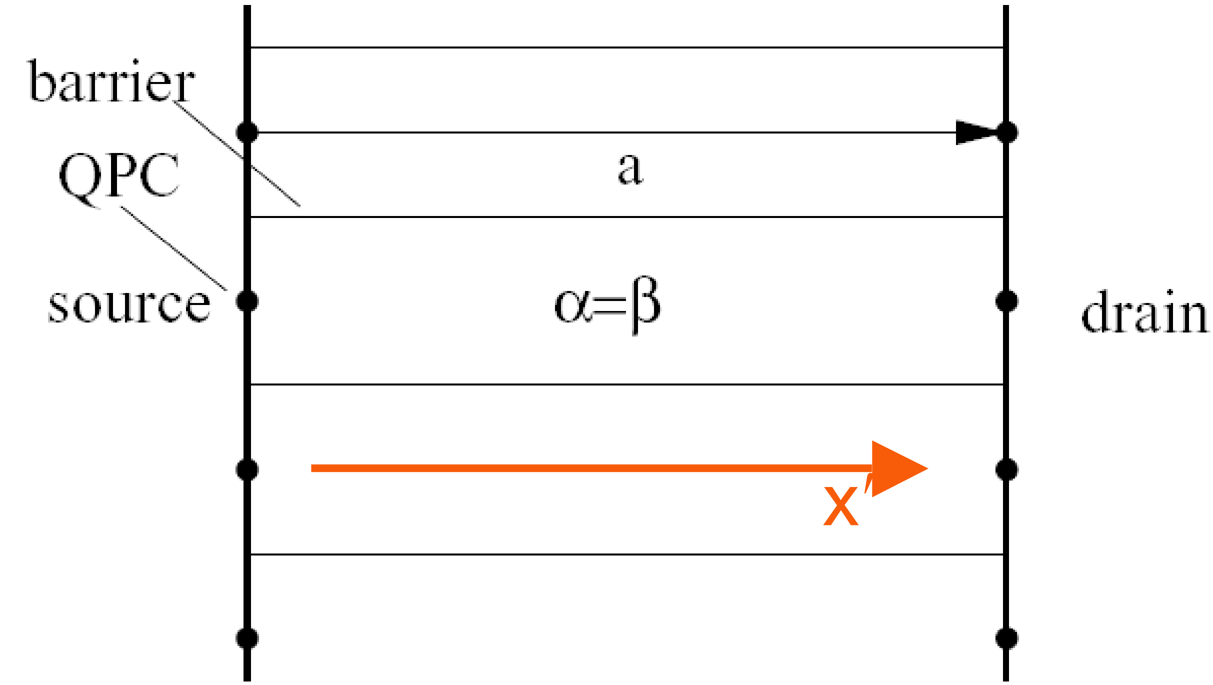


FIG. 1. Schematic of the spin-FET setup using quantum point contacts (QPC) to source and drain. The pairs of QPCs are separated by barriers to avoid crosstalk.

Spin/displacement correlation via spin-orbit coupling leads to anomalous diffusion.

$\Updownarrow$

Measuring spin diffusion can lead us to $\alpha=\beta$

Models of spin propagation typically assume dynamics obey simple diffusion equation, with loss term to describe spin relaxation.

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

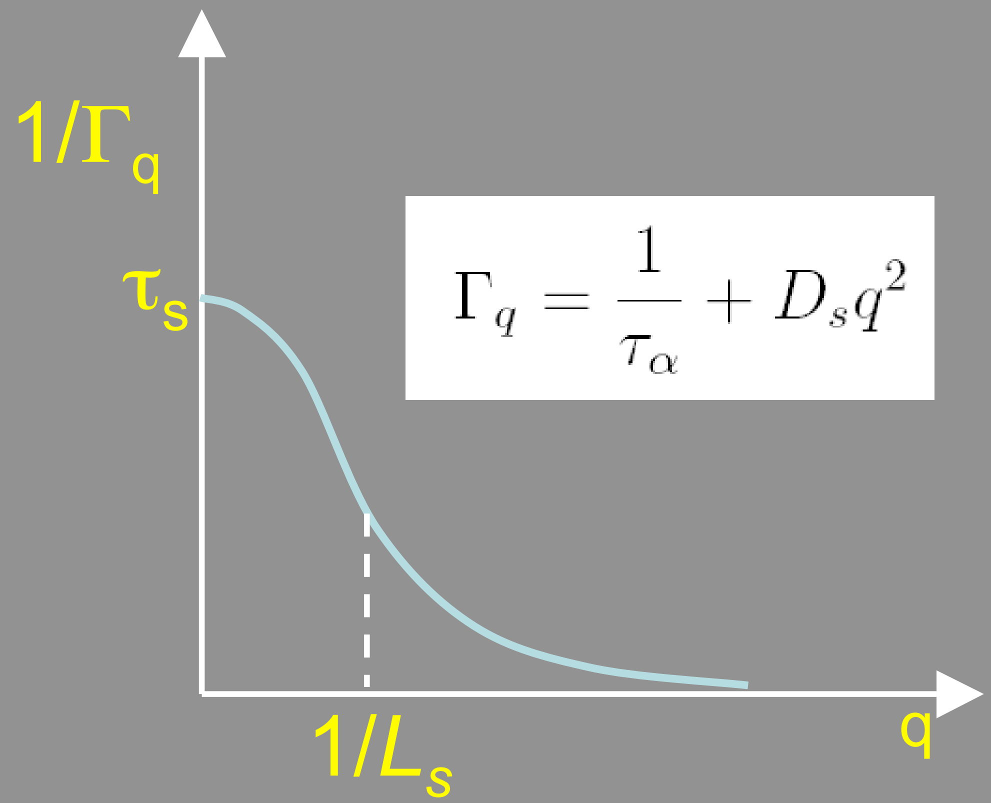
which has solutions of the form:

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

where,

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

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

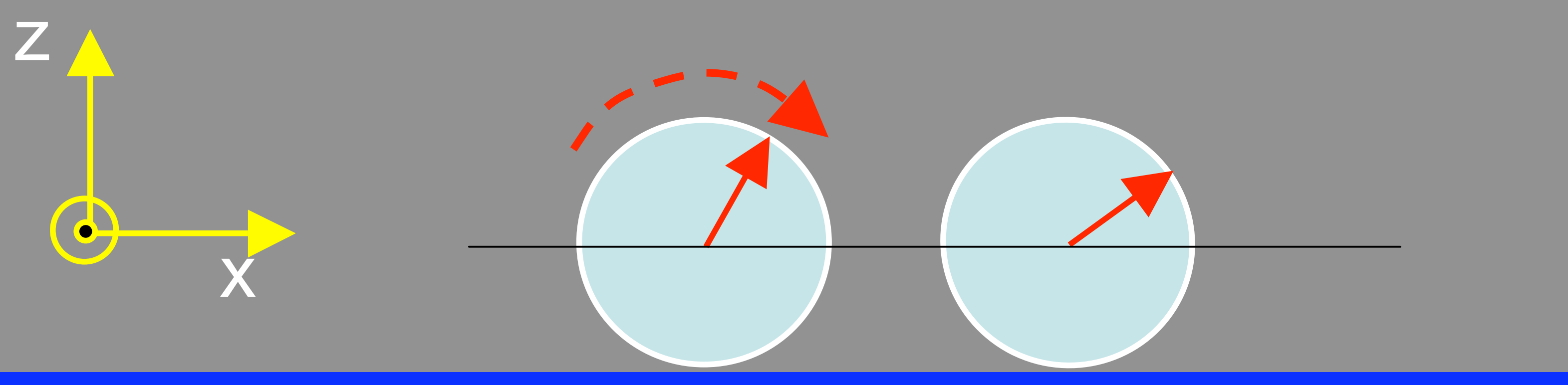


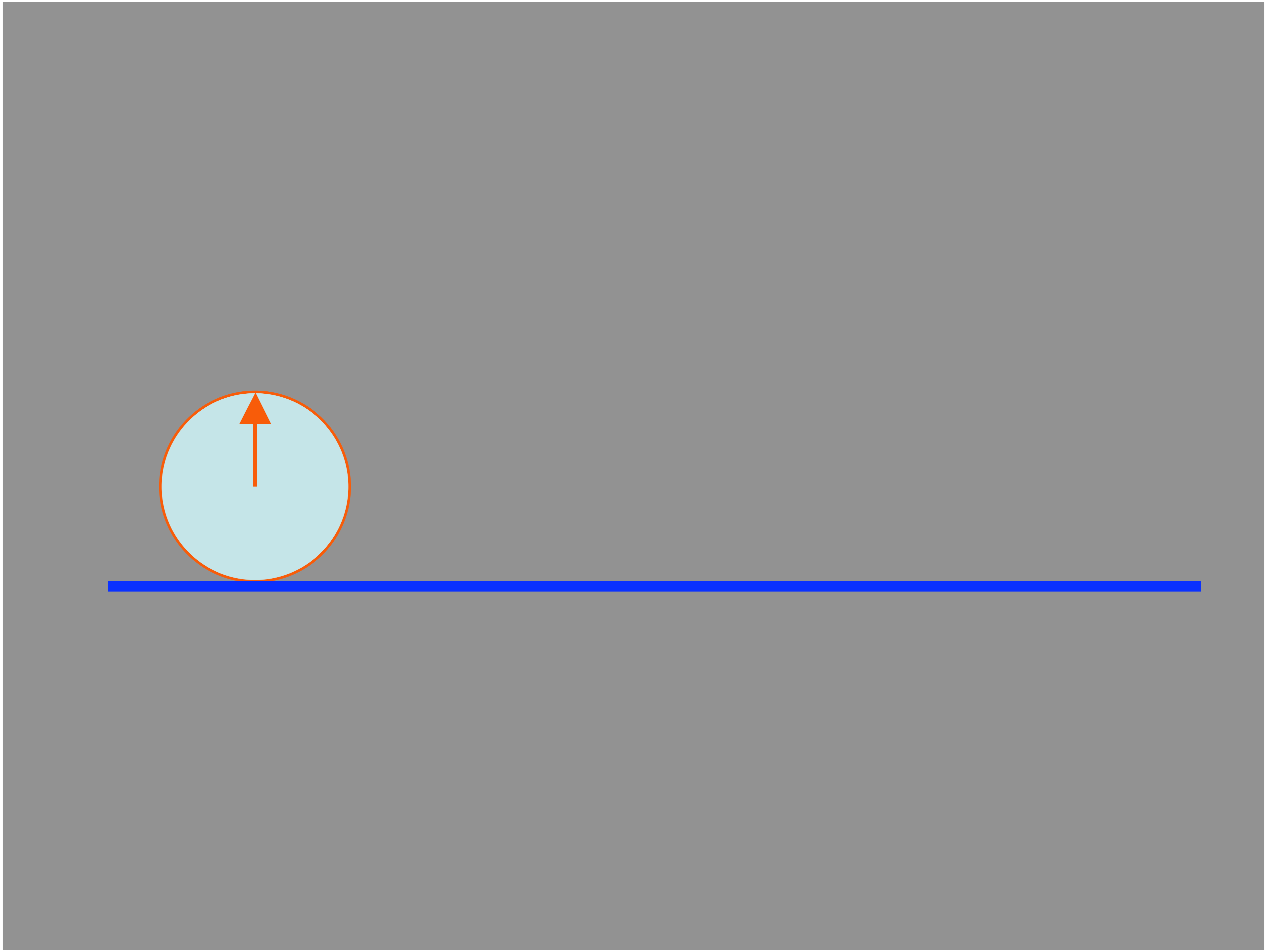
$$\Gamma_q = \frac{1}{\tau_\alpha} + D_s q^2$$

Perfect spin/displacement correlation at $\alpha=\beta$ leads to anomalous spin diffusion.

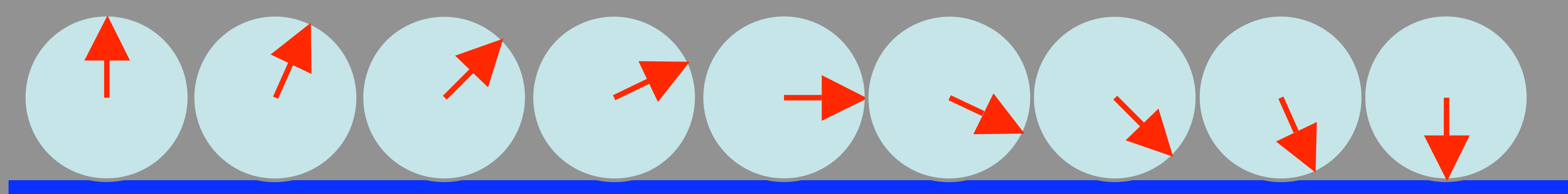
$$\Delta\theta = x' \frac{\Omega_0}{v_F}$$

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



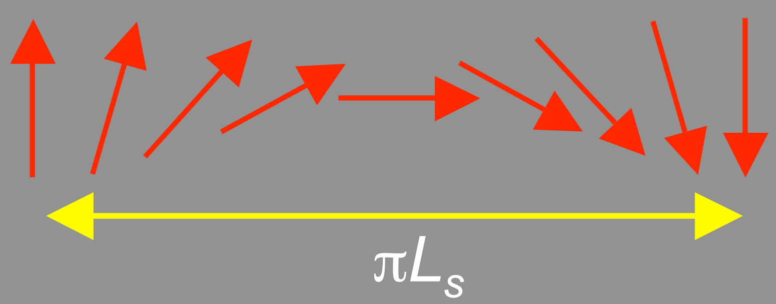


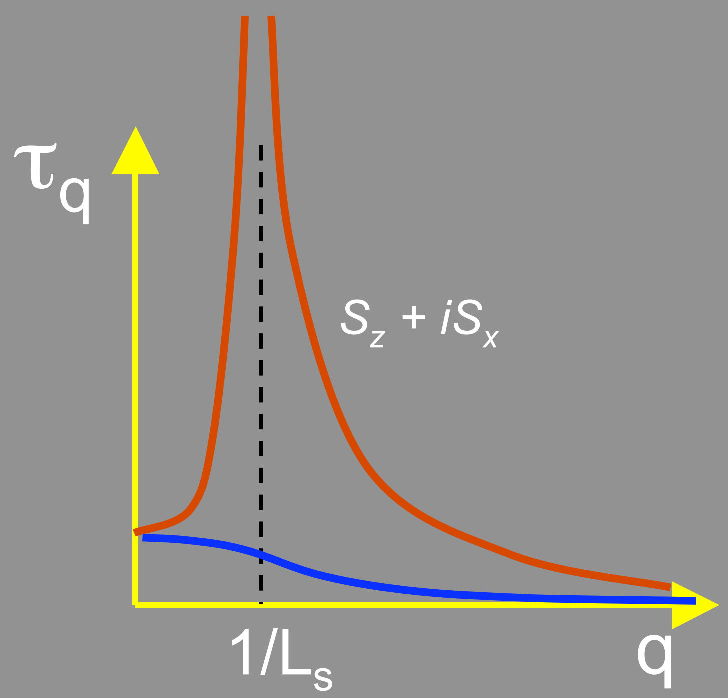
A helical polarization with the “magic” wavevector $q=1/L_s$ will never decay, even though the spin of each individual electron is rapidly randomized.



Many electron system prepared with initial helical polarization

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



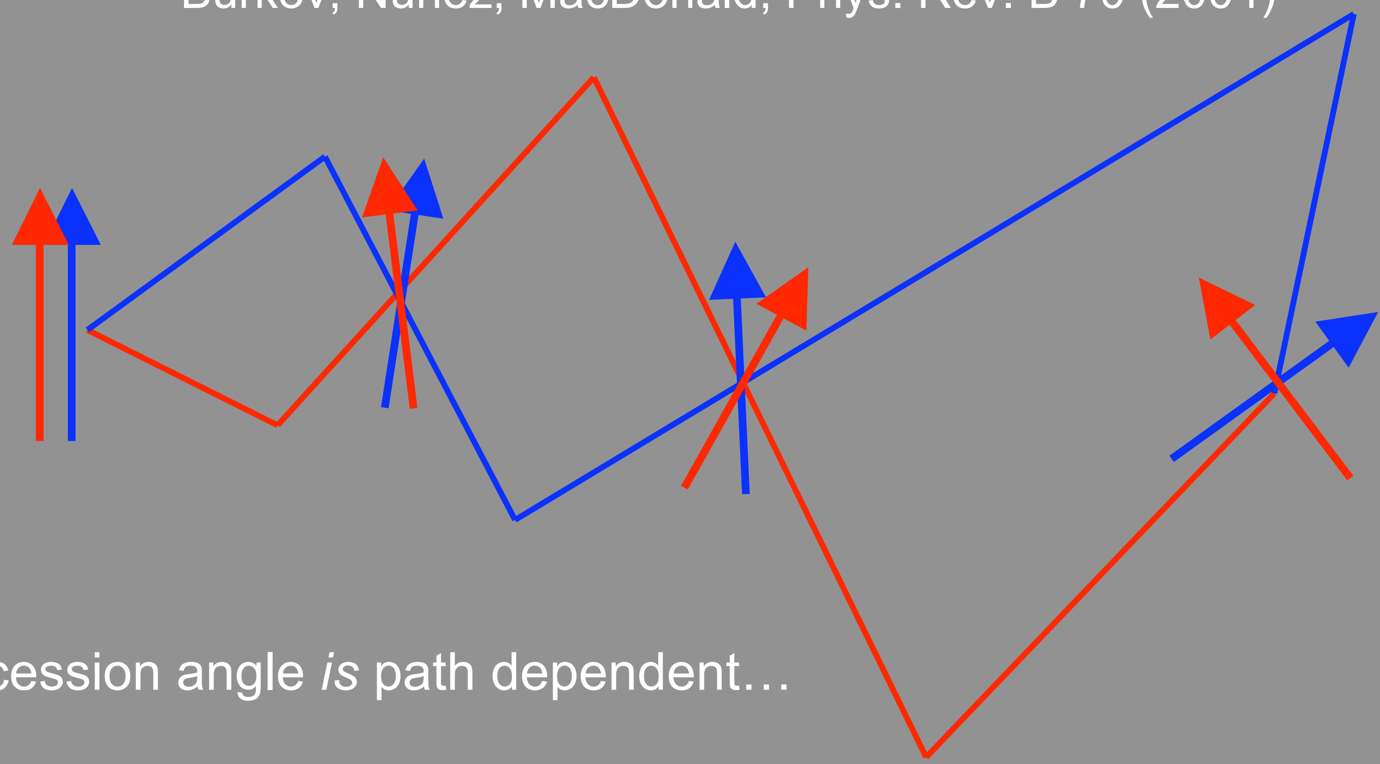


At the resonant *q*, spin precesses by 2π as it propagates one period of the helix

What about $\alpha \neq \beta$?

Spin propagation Rashba only

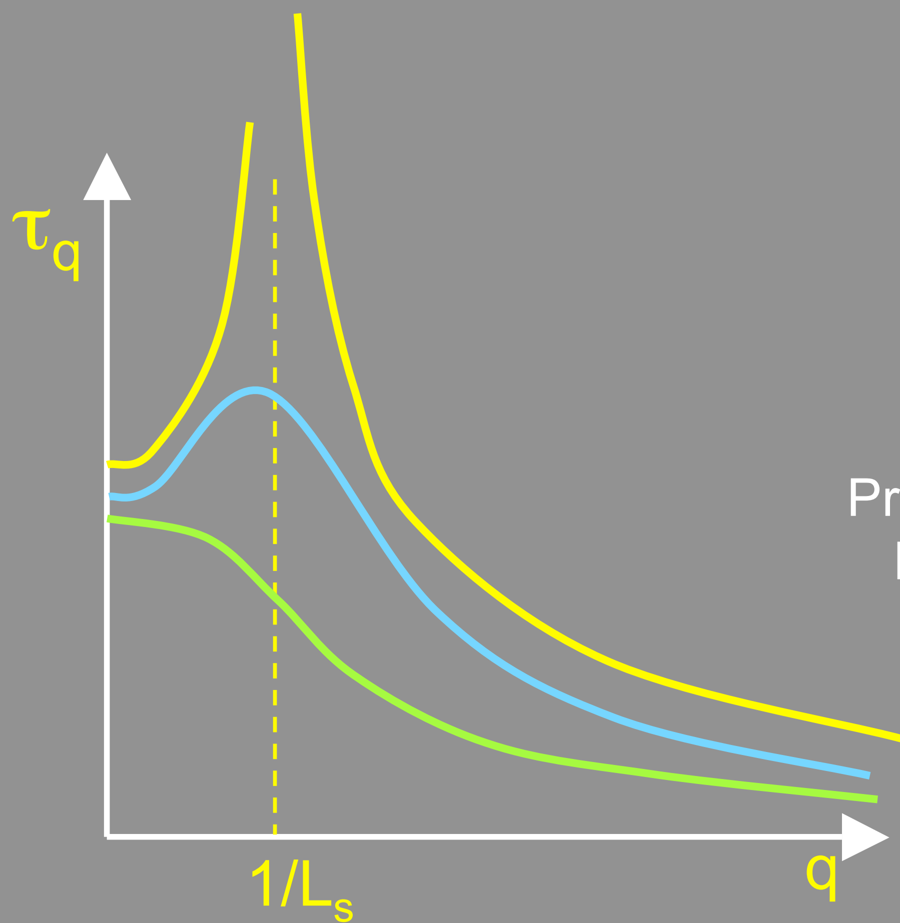
Burkov, Nunez, MacDonald, Phys. Rev. B 70 (2004)



Precession angle *is* path dependent…

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

Summarizing predictions for spin helix lifetime



$\alpha=\beta$

α or $\beta=0$

No spin-orbit

Prediction for 2D (Rashba only)
Burkov, Nunez, MacDonald
Phys. Rev. B 70 (2004)

Surprisingly, there are few direct measurements of spin diffusion in the presence of spin-orbit coupling

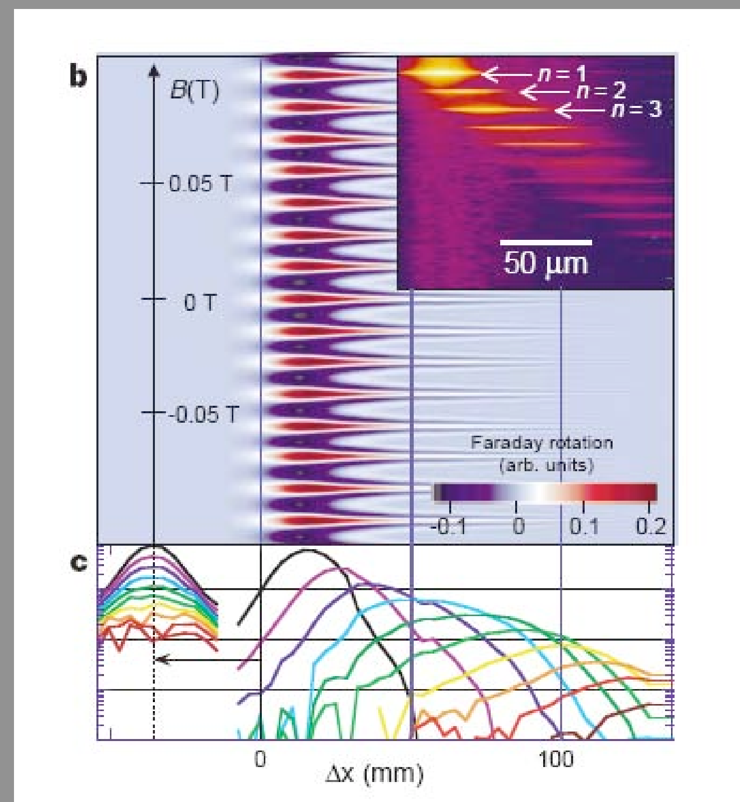
Lateral drag of spin coherence in gallium arsenide

J. M. Kikkawa & D. D. Awschalom

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

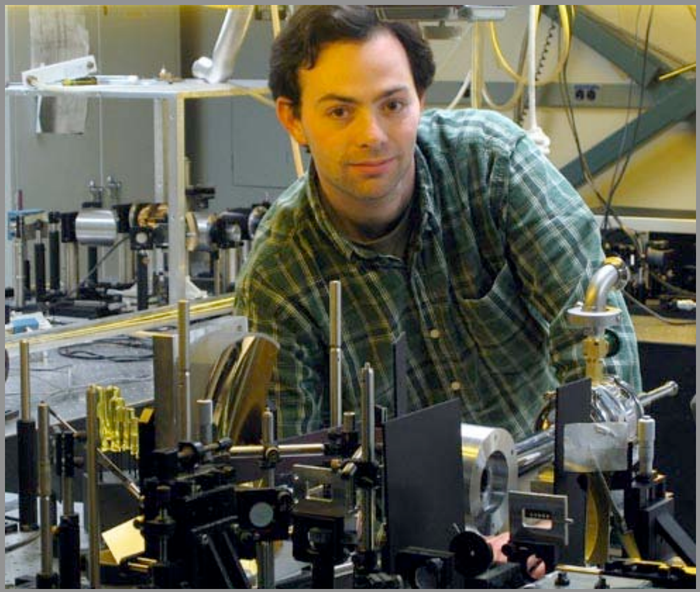
D_s=4 cm^2/s at 1.6 K

n ~ 10^{16} cm^{-3} in bulk GaAs

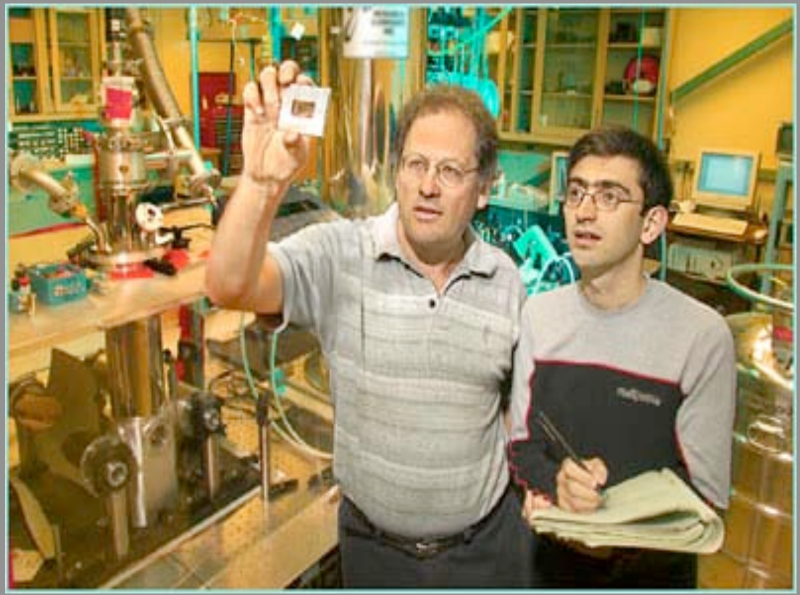


Collaborators at UCB and LBNL

(Quantum well samples grown in Awschalom Lab by Jason Stephens)



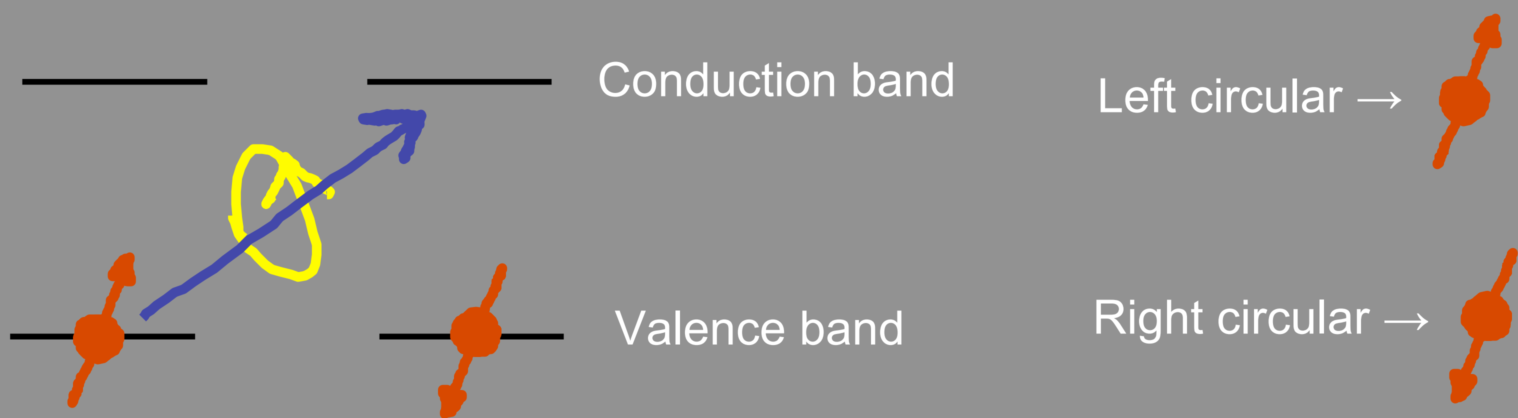
Chris Weber



Joe Orenstein and Nuh Gedik

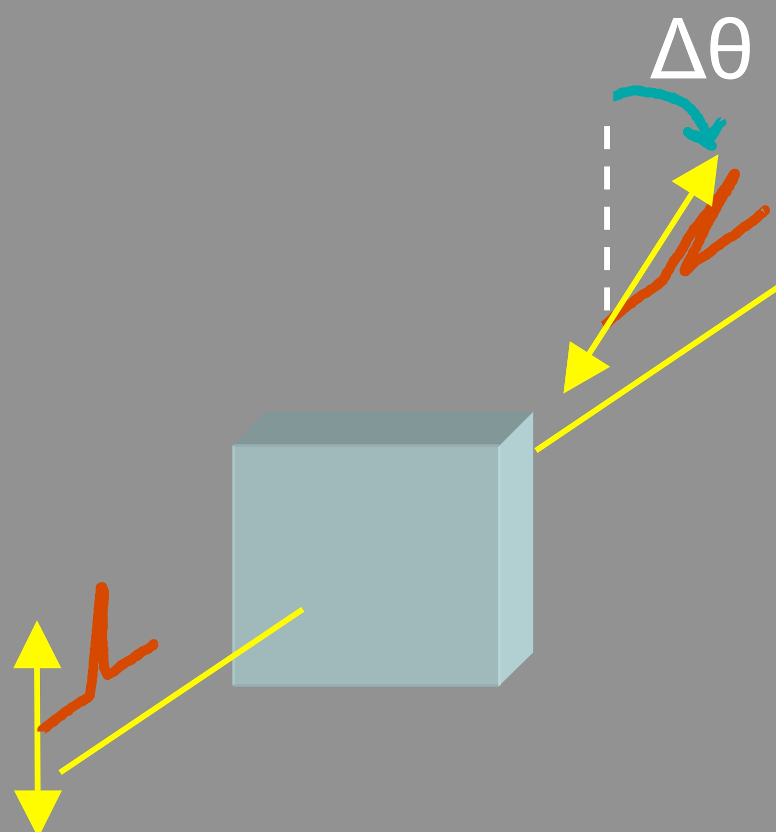
Optical probes of spin dynamics

Injecting spin polarization: optical orientation effect

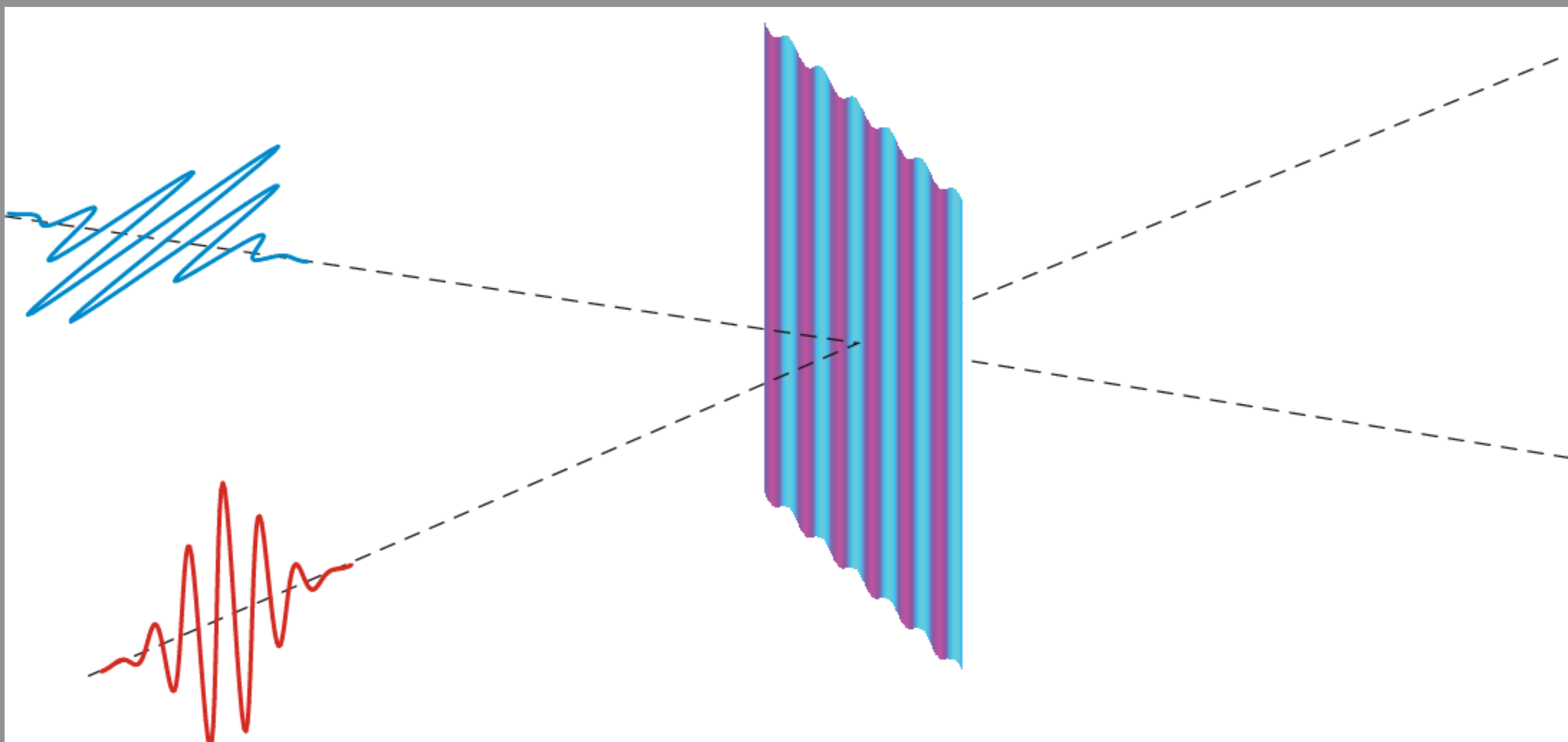


Optical probes of spin dynamics

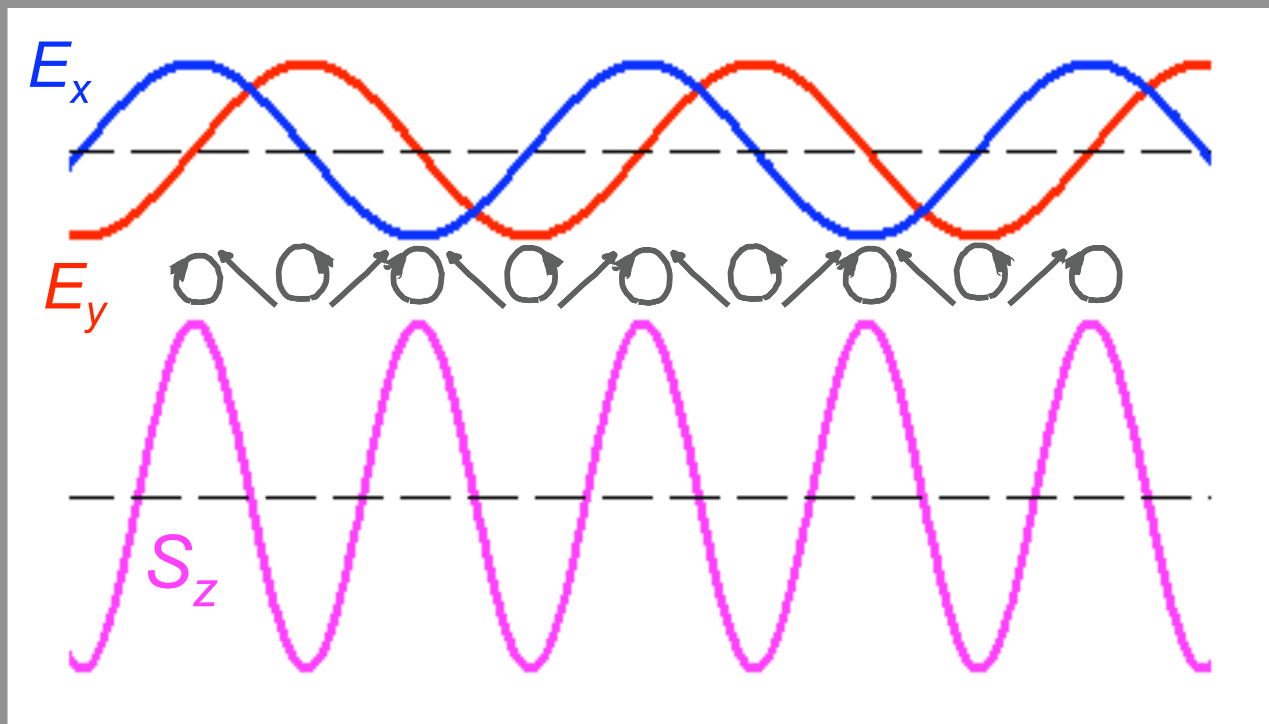
Detecting spin polarization: Faraday rotation



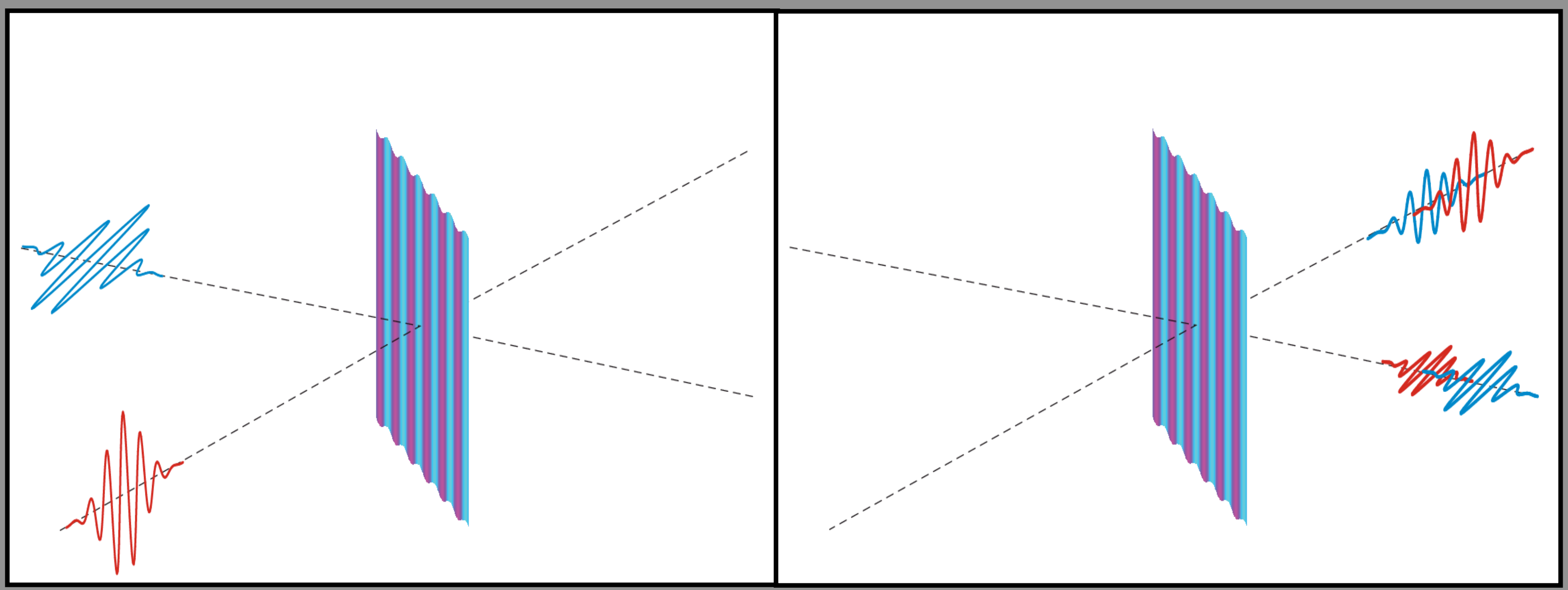
Creating a spin polarization wave



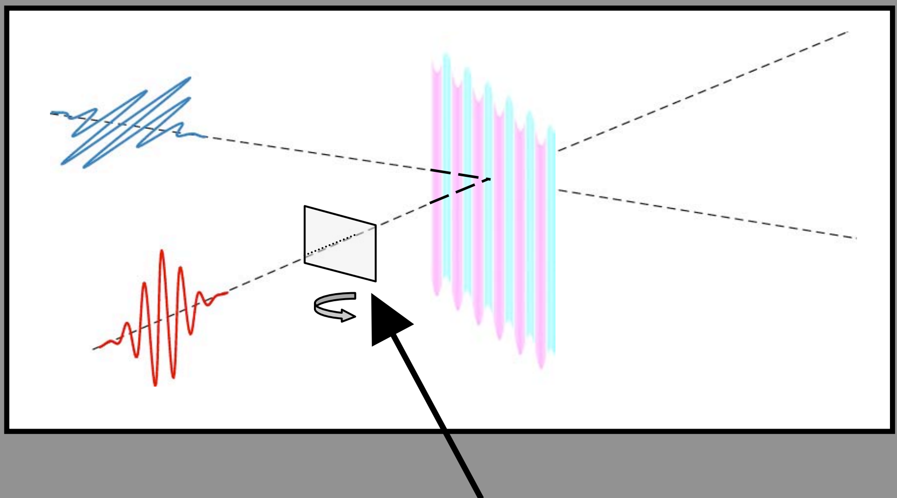
Photon helicity wave creates a spin-density-wave in S_z



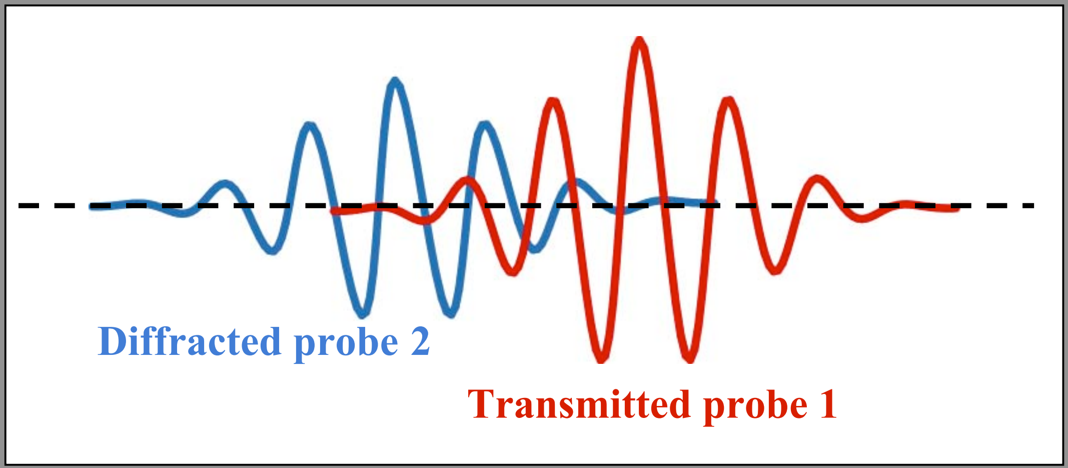
Detecting a spin polarization wave



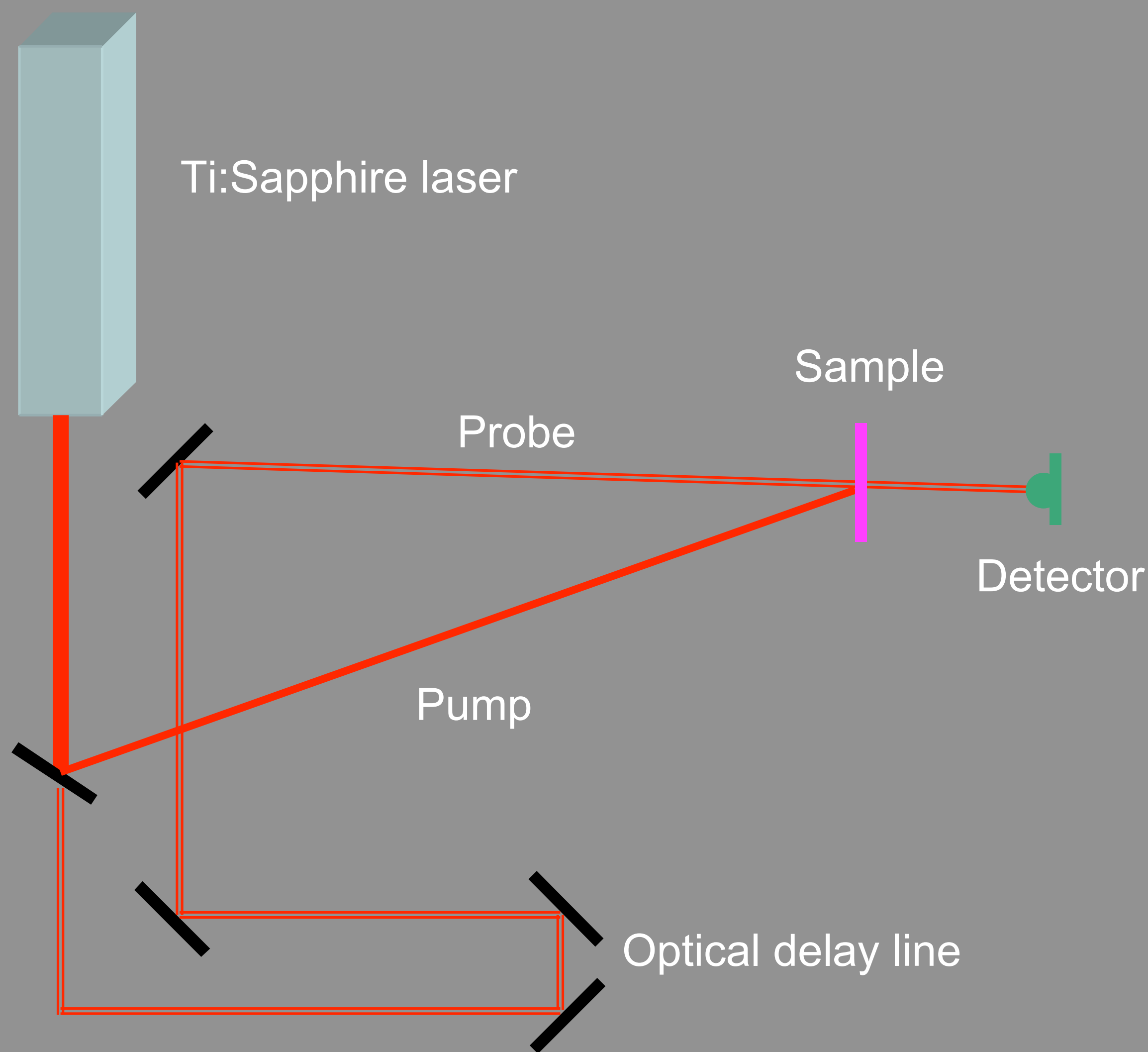
Heterodyne detection



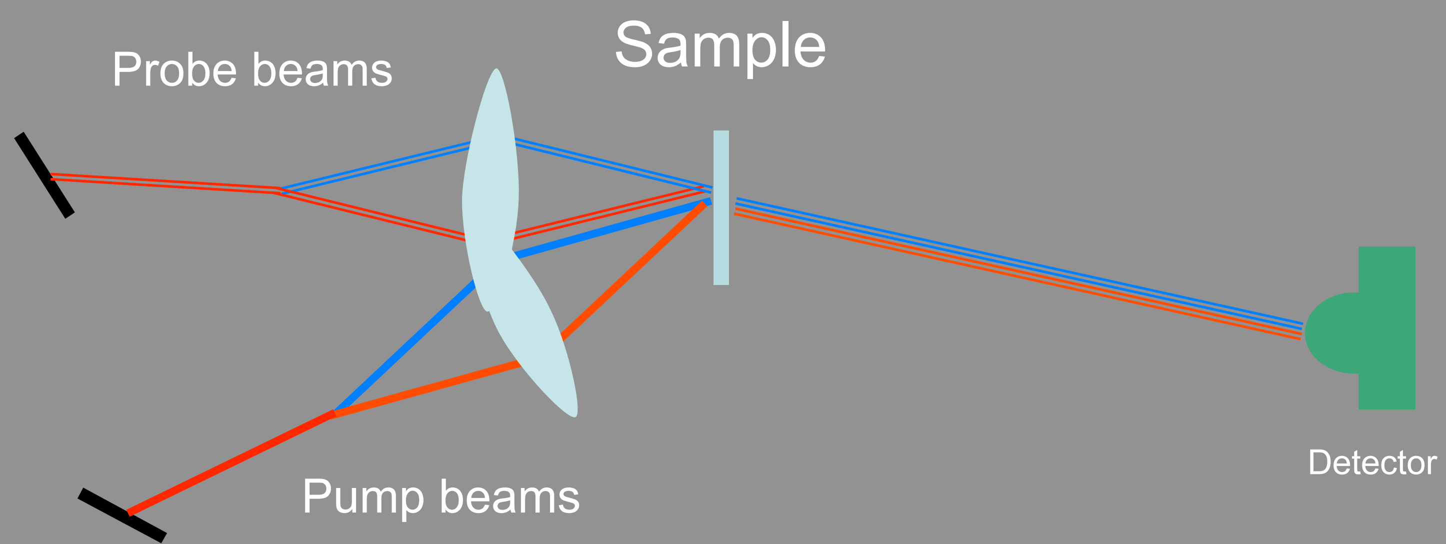
Modulate relative phase at 210 Hz



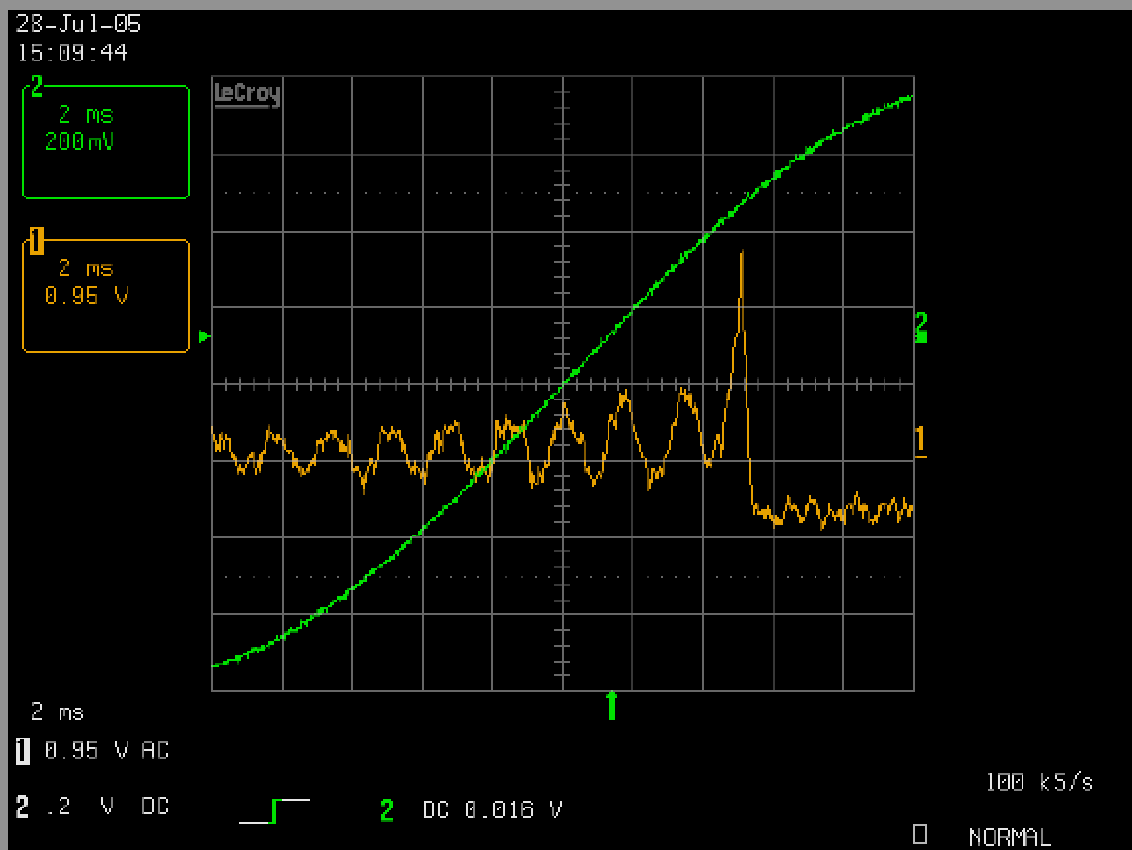
Basic pump-probe set-up



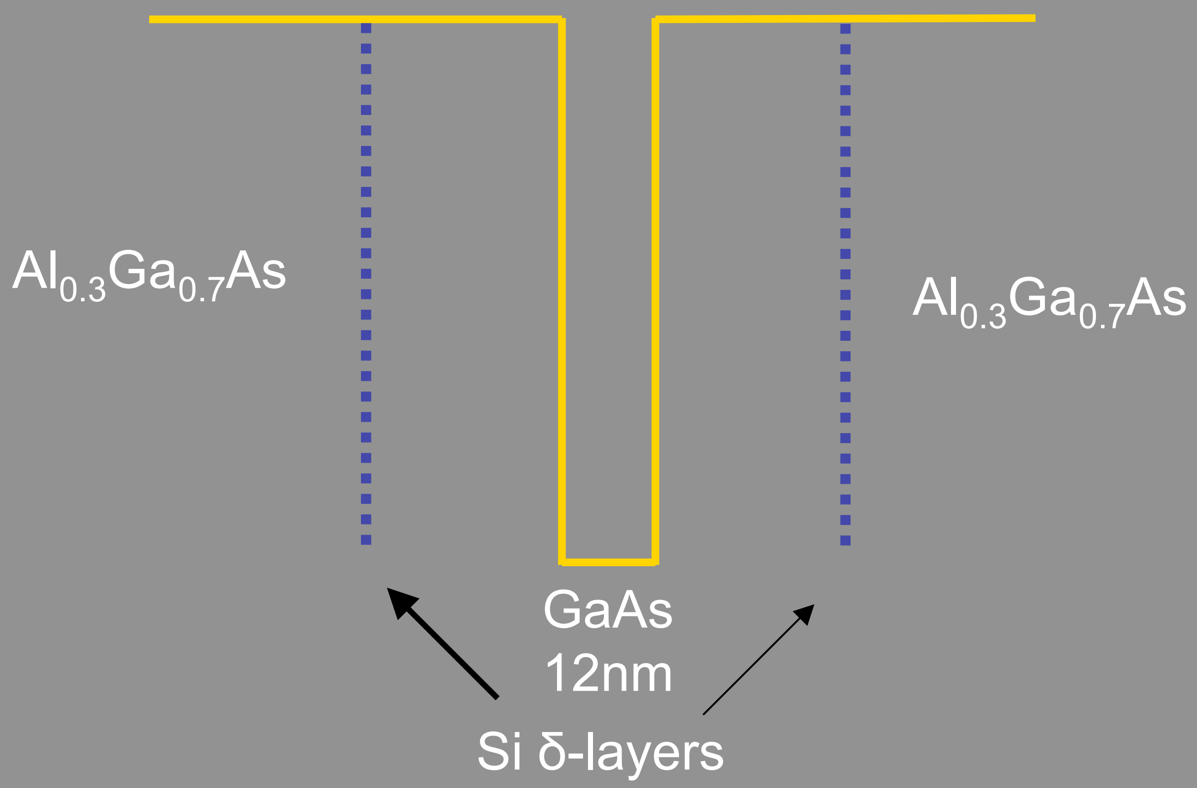
Coherent transient grating set-up

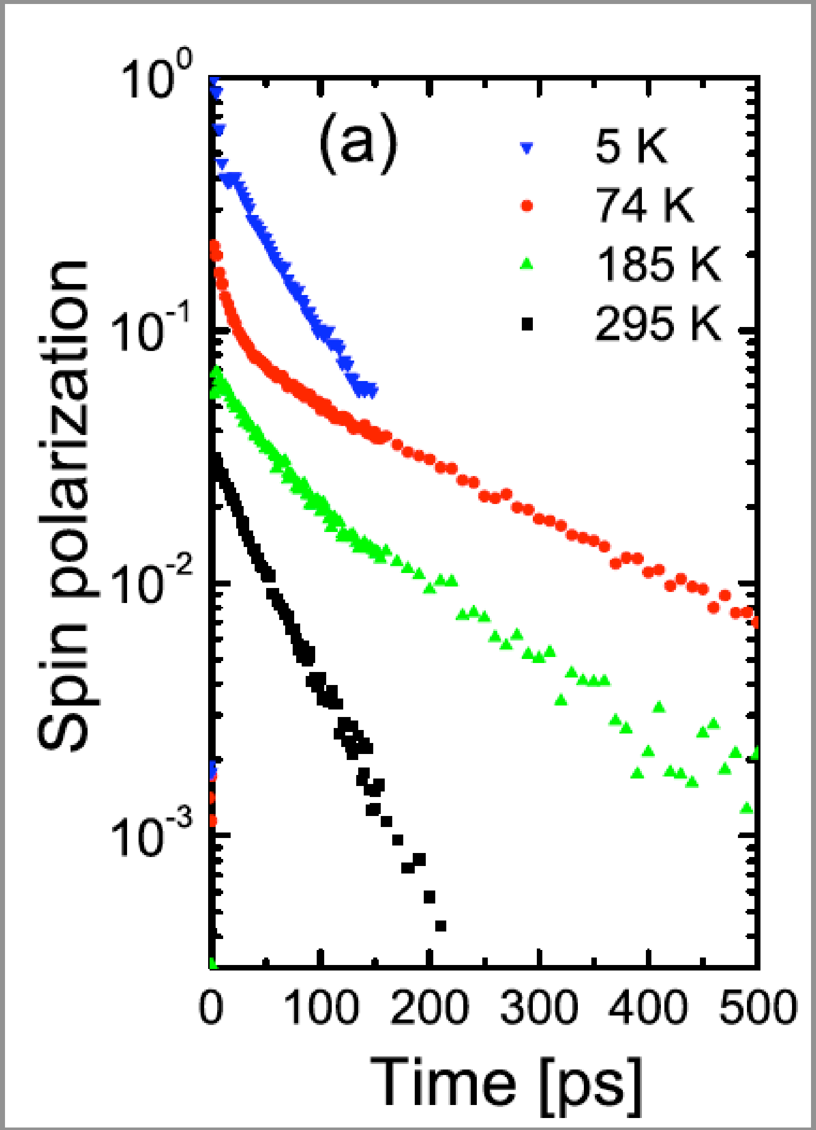


Oscillating cover-slip modulates reference phase



Quantum well samples

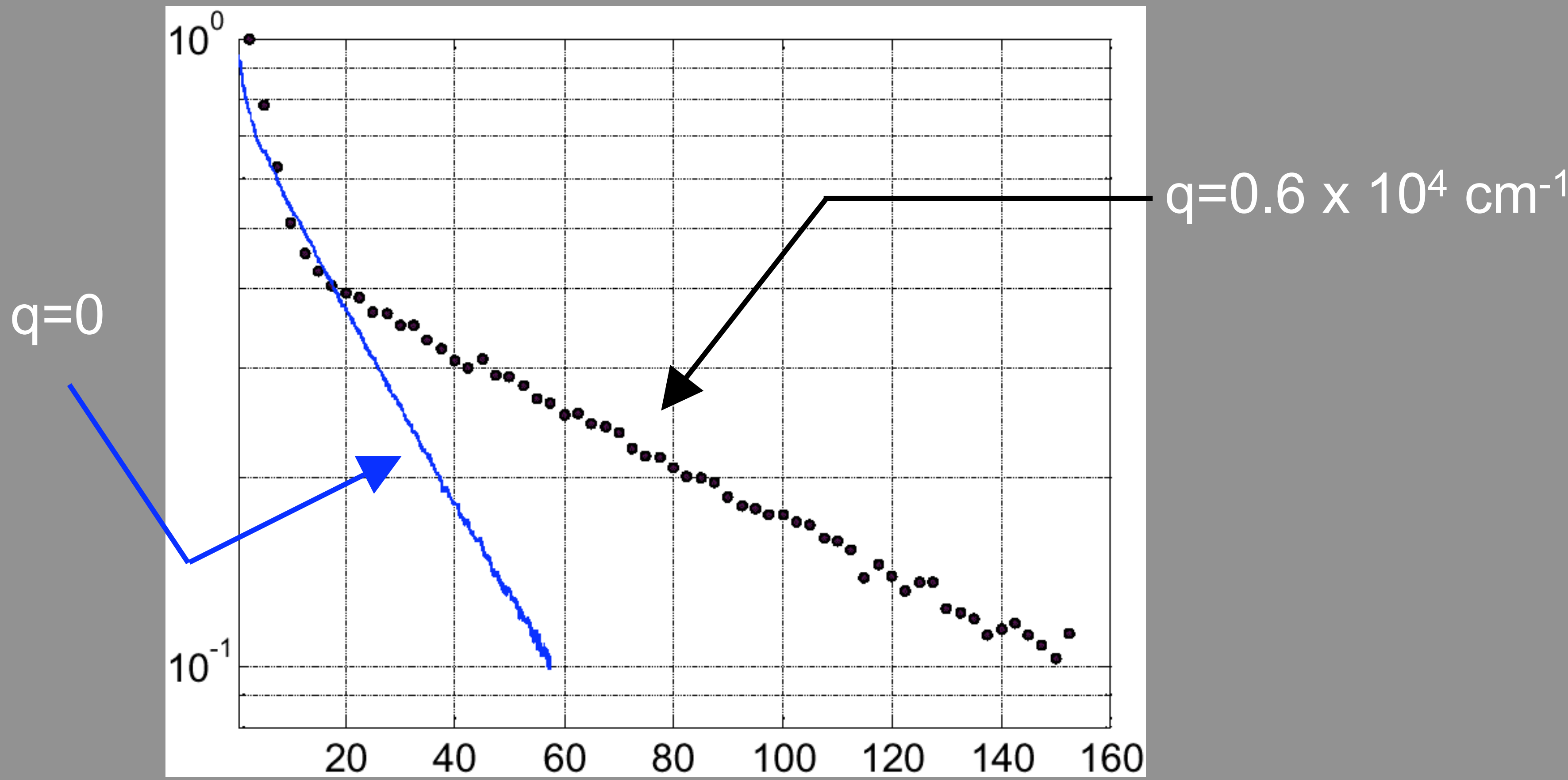




Temperature dependence of spin polarization decay at fixed wavevector

Double exponential decay appears below about 200 K

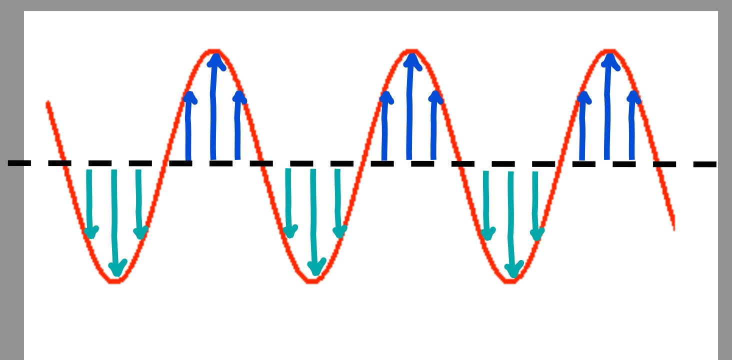
Direct demonstration of anomalous diffusion: Decay faster for q≠0 than for q=0



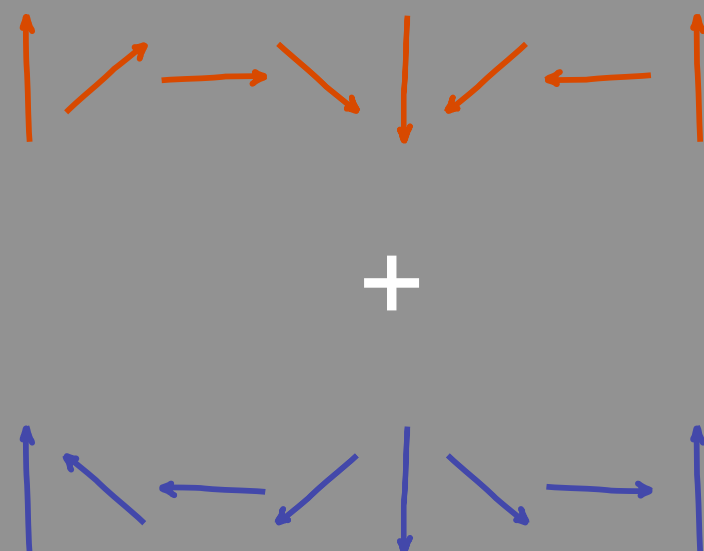
Two exponentials of equal weight…

Normal modes

Initial condition

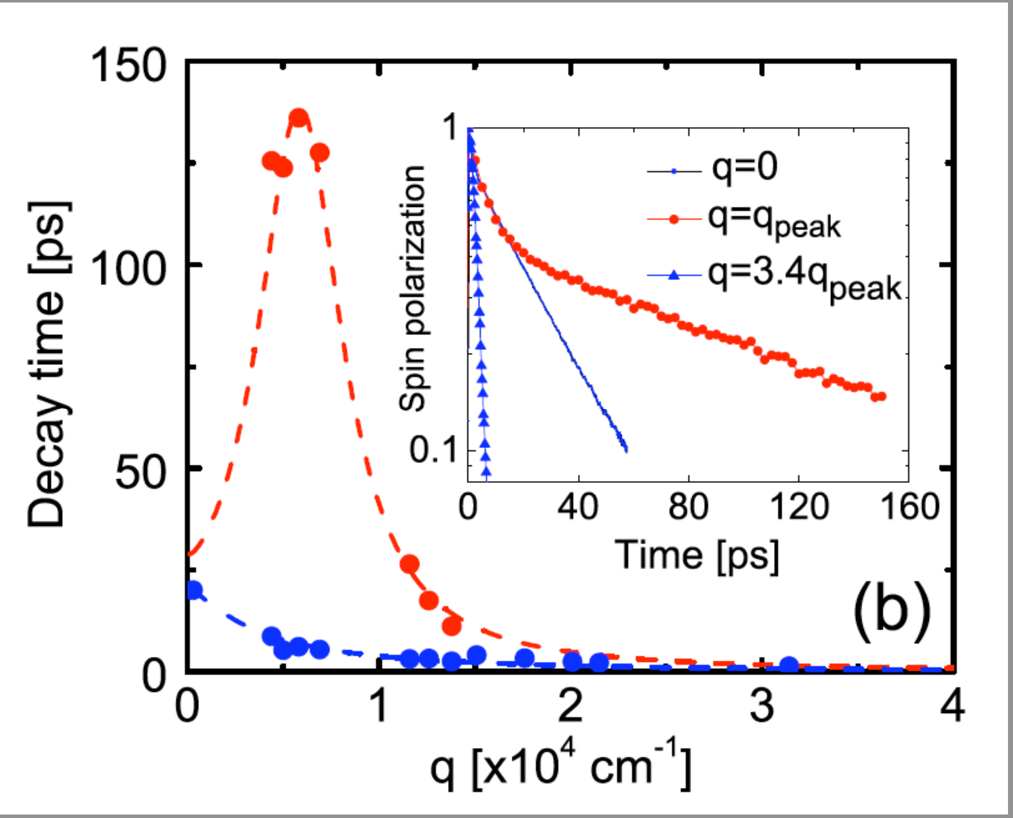


=

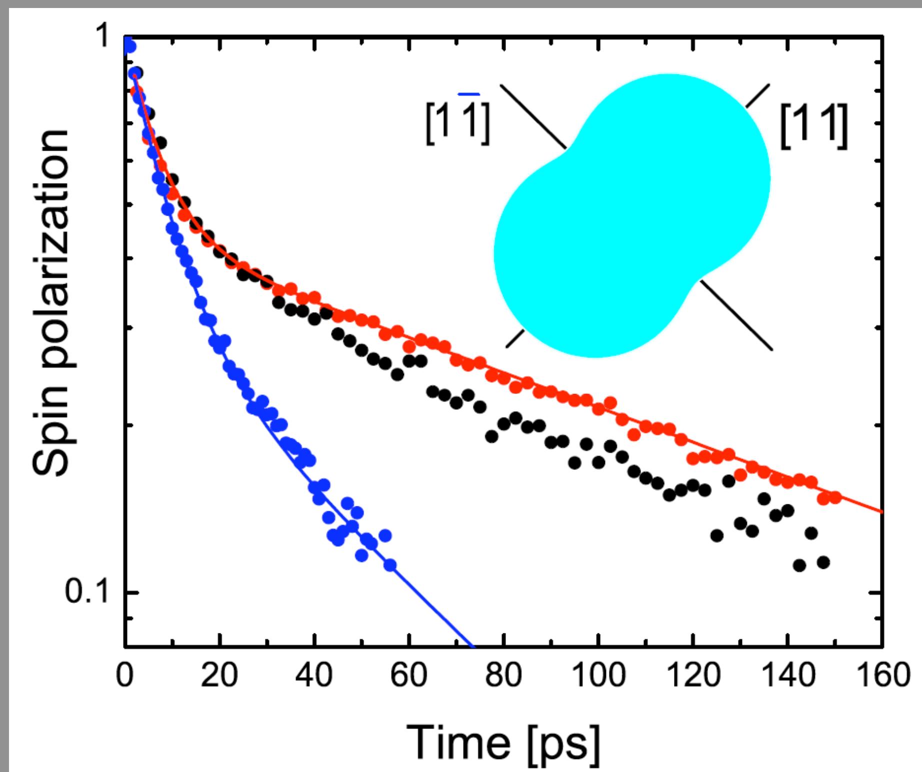


Wavevector dependence of lifetime

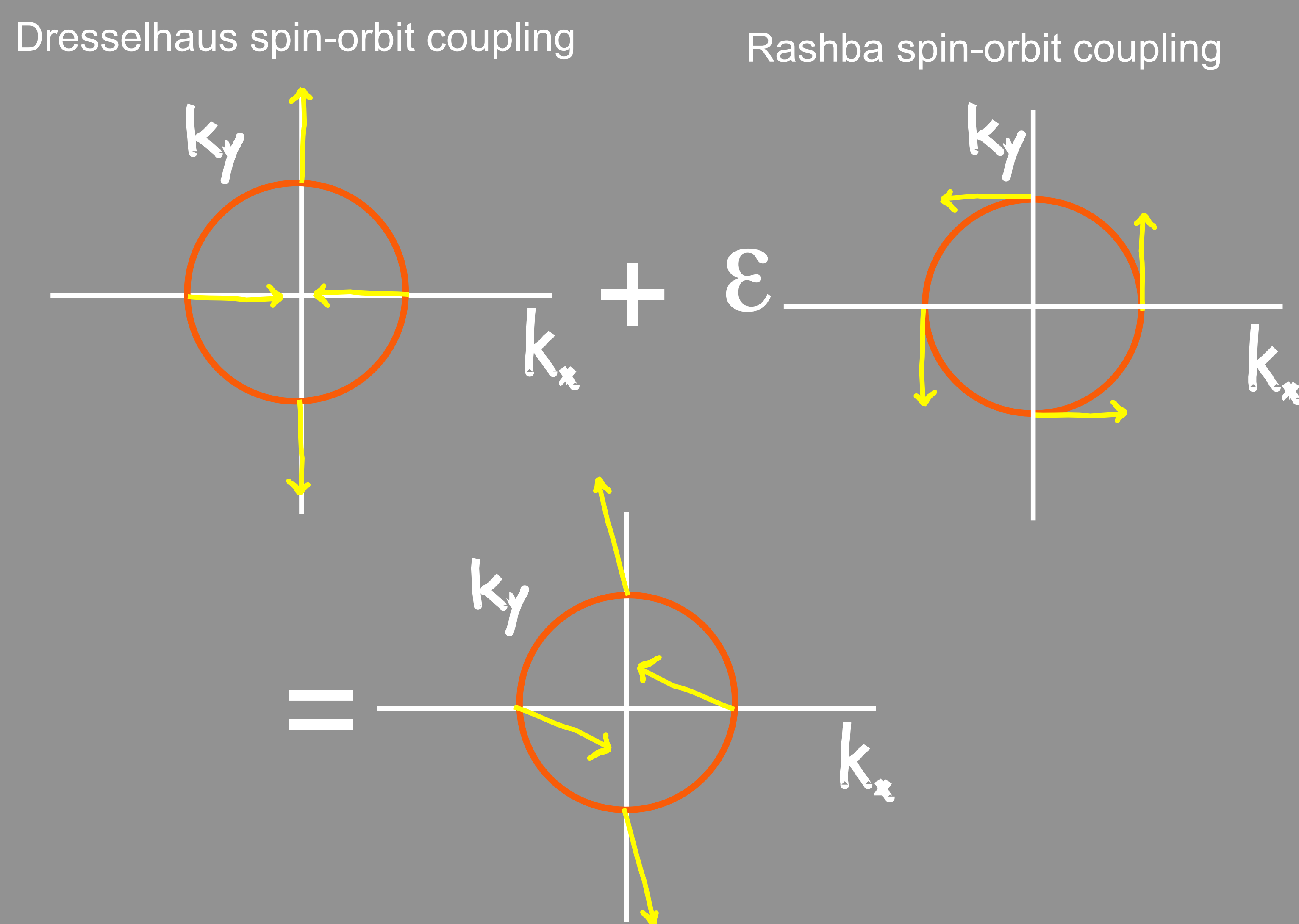
Enhancement relative to q=0 larger than predicted for 2D Rashba model



Decay rate depends strongly on direction of wavevector in the plane



Dresselhaus+$\varepsilon\cdot$Rashba



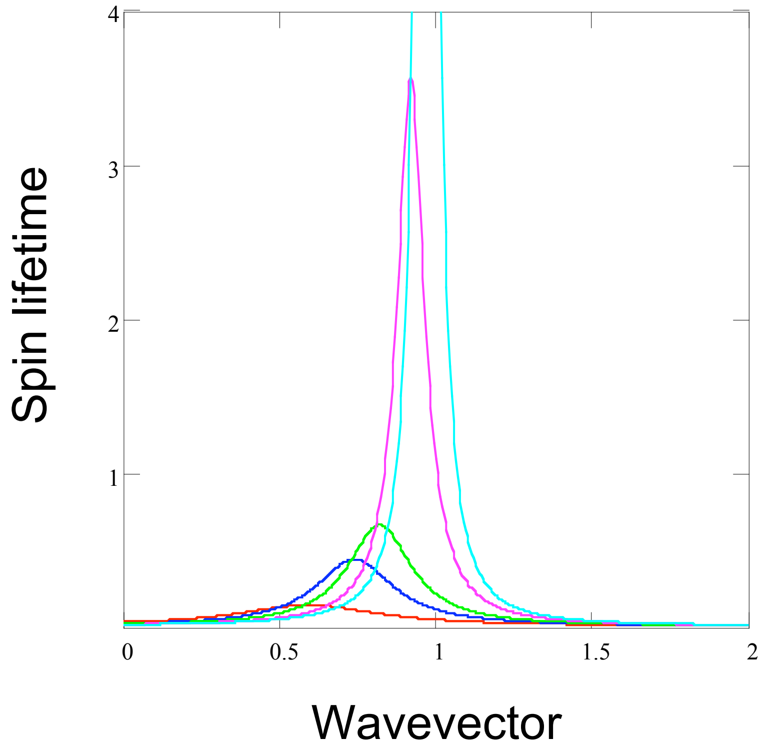
Bernevig-Zhang model: $\alpha, \beta \neq 0$

Graphs show dispersion of spin lifetime for different α/β

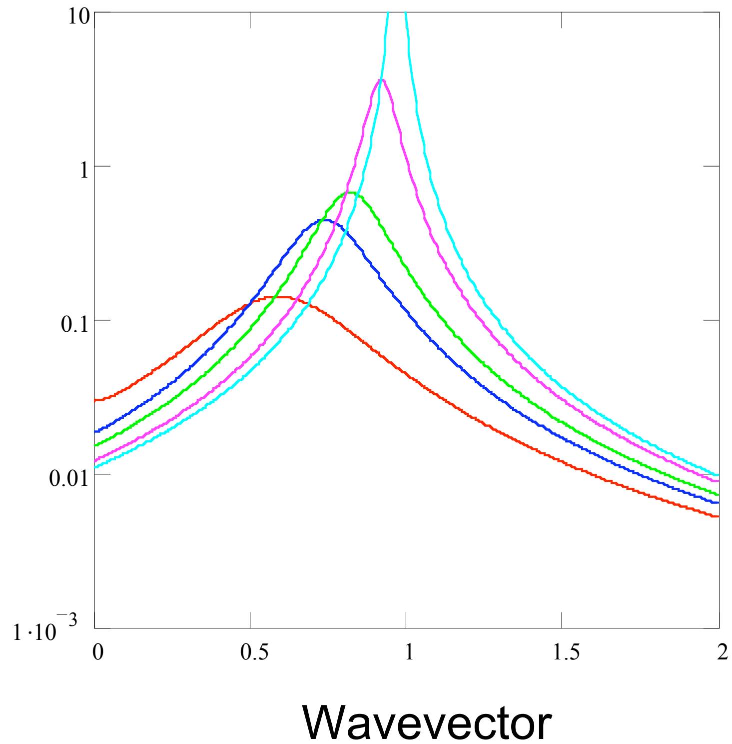
Lifetime diverges as $\alpha \rightarrow \beta$

Fit parameters are α/β, $\alpha^2+\beta^2$, and D_s

Linear plot



Log plot



PRL 97, 236601 (2006) PHYSICAL REVIEW LETTERS week ending 8 DECEMBER 2006

Exact SU(2) Symmetry and Persistent Spin Helix in a Spin-Orbit Coupled System

B. Andrei Bernevig,[1,2] J. Orenstein,[3,4] and Shou-Cheng Zhang[1]

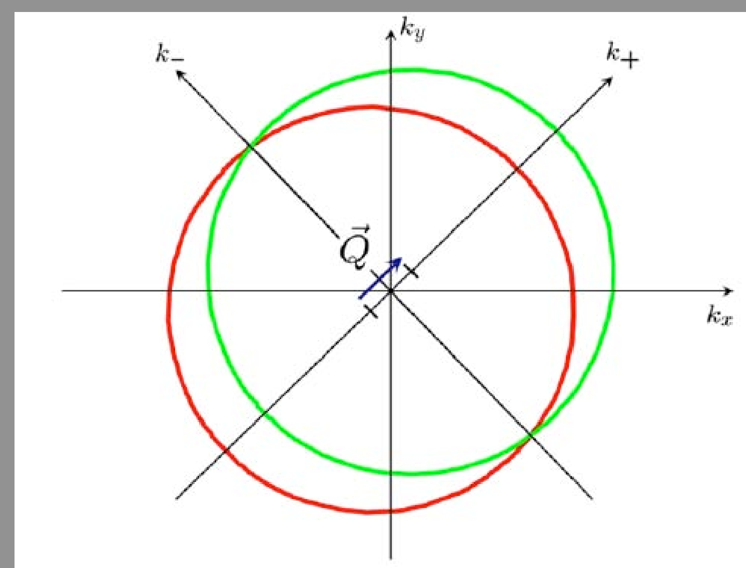
$$S_Q^- = \sum_{\vec{k}} c^\dagger_{\vec{k}\downarrow} c_{\vec{k}+\vec{Q}\uparrow}, \qquad S_Q^+ = \sum_{\vec{k}} c^\dagger_{\vec{k}+\vec{Q},\uparrow} c_{\vec{k}\downarrow},$$

$$S_0^z = \sum_{\vec{k}} c^\dagger_{\vec{k}\uparrow} c_{\vec{k}\uparrow} - c^\dagger_{\vec{k}\downarrow} c_{\vec{k}\downarrow},$$

$$[S_0^z, S_Q^\pm] = \pm 2 S_Q^\pm; \qquad [S_Q^+, S_Q^-] = S_0^z.$$

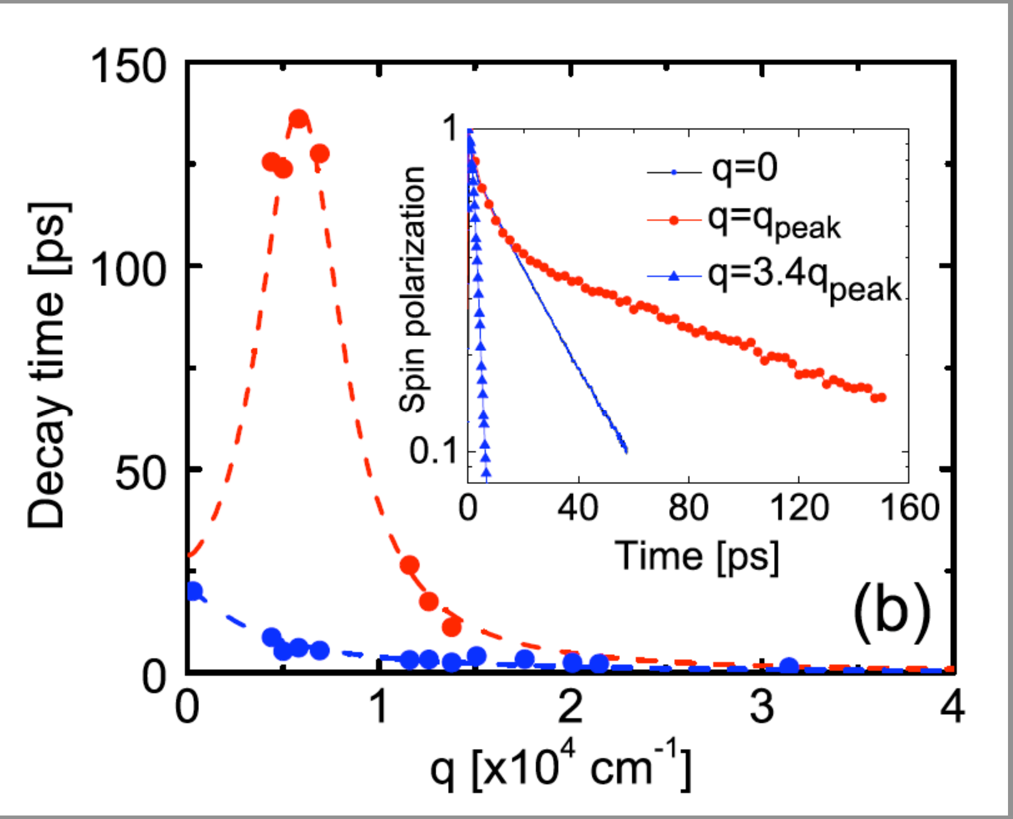
Creation operator for spin density wave commutes with the Hamiltonian

Fermi surface for $\alpha = \beta$



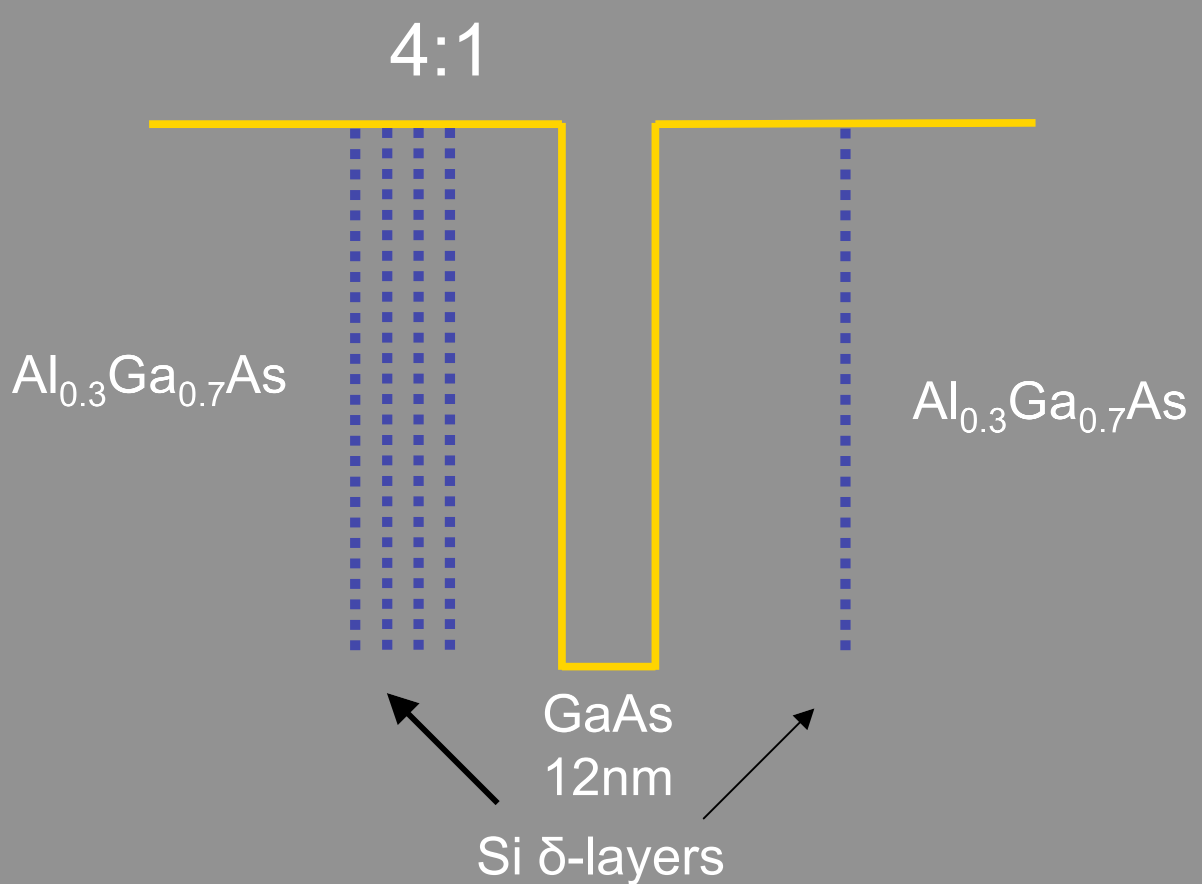
Wavevector dependence of lifetime

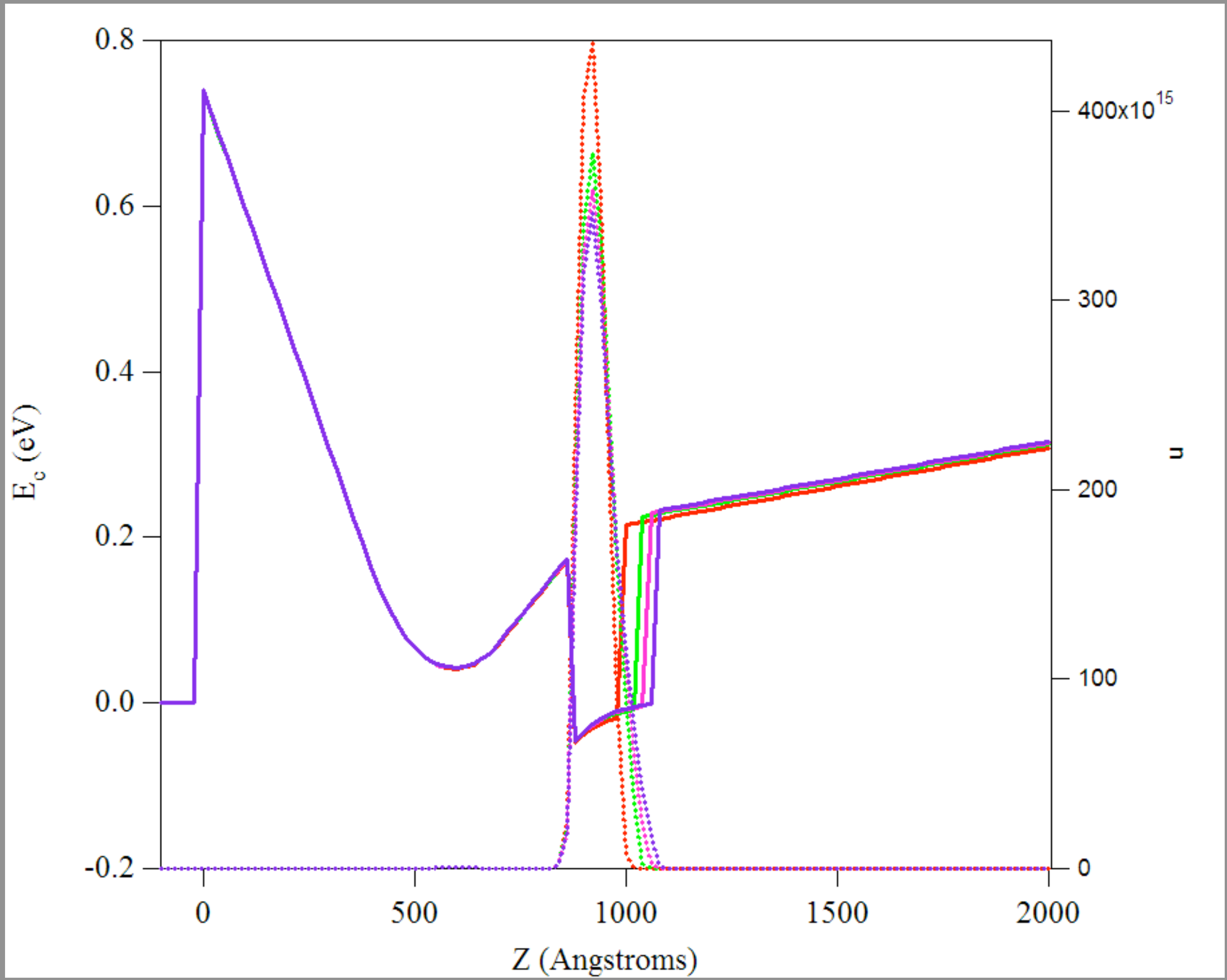
Fit to $\alpha = 0.2\beta$

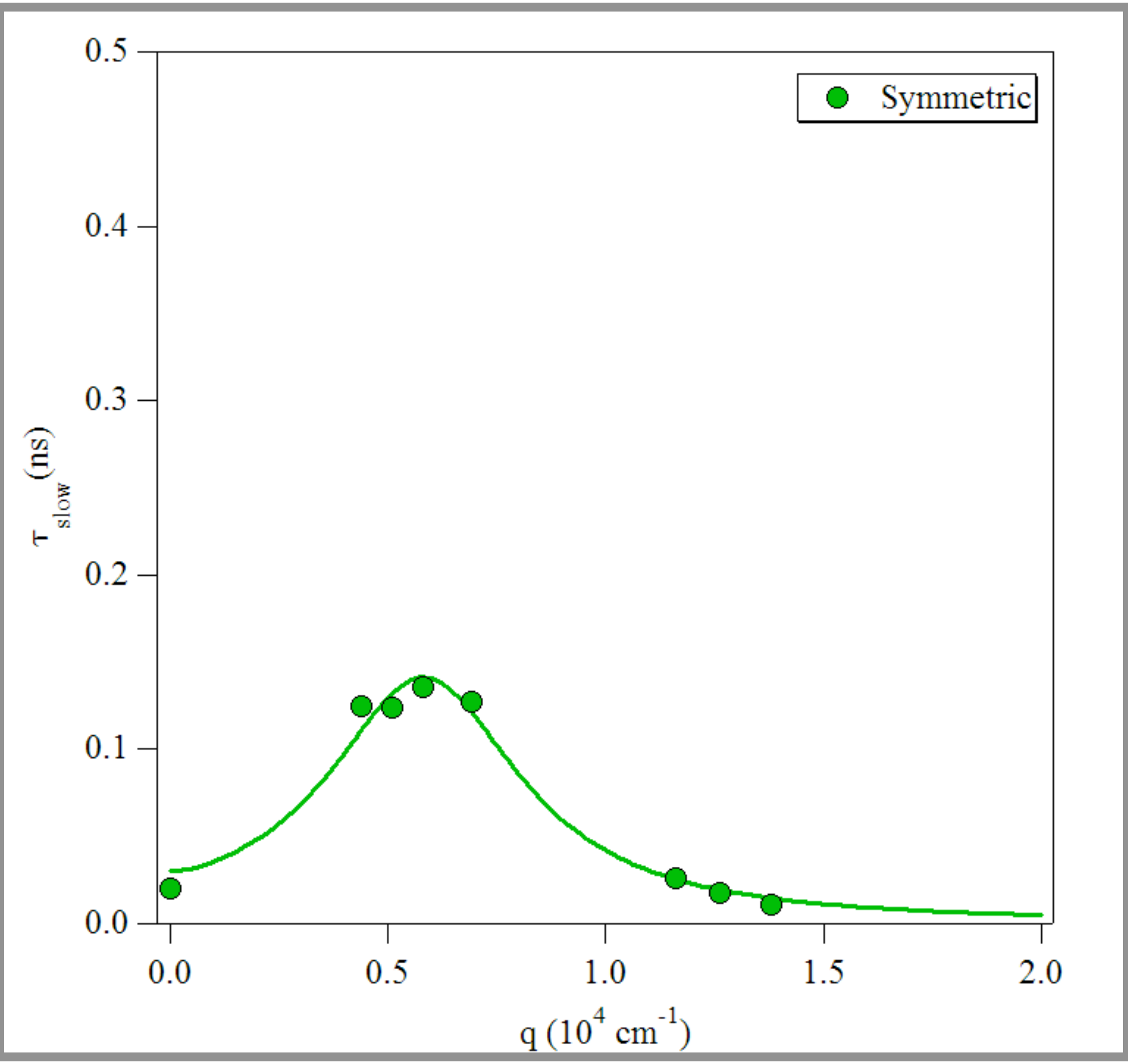


The Holy Grail: $\alpha=\beta$

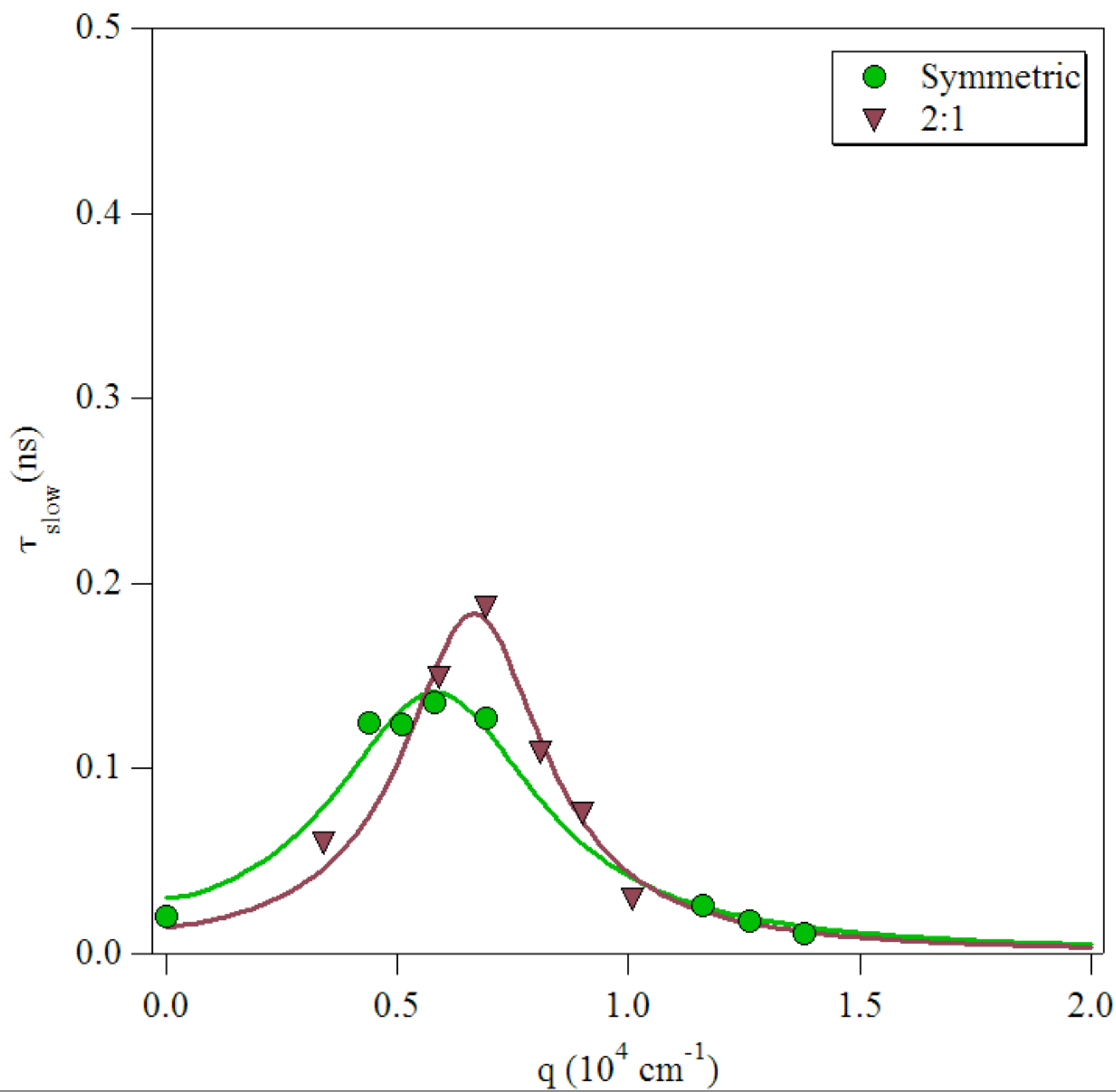
Tune Rashba coupling by varying doping asymmetry



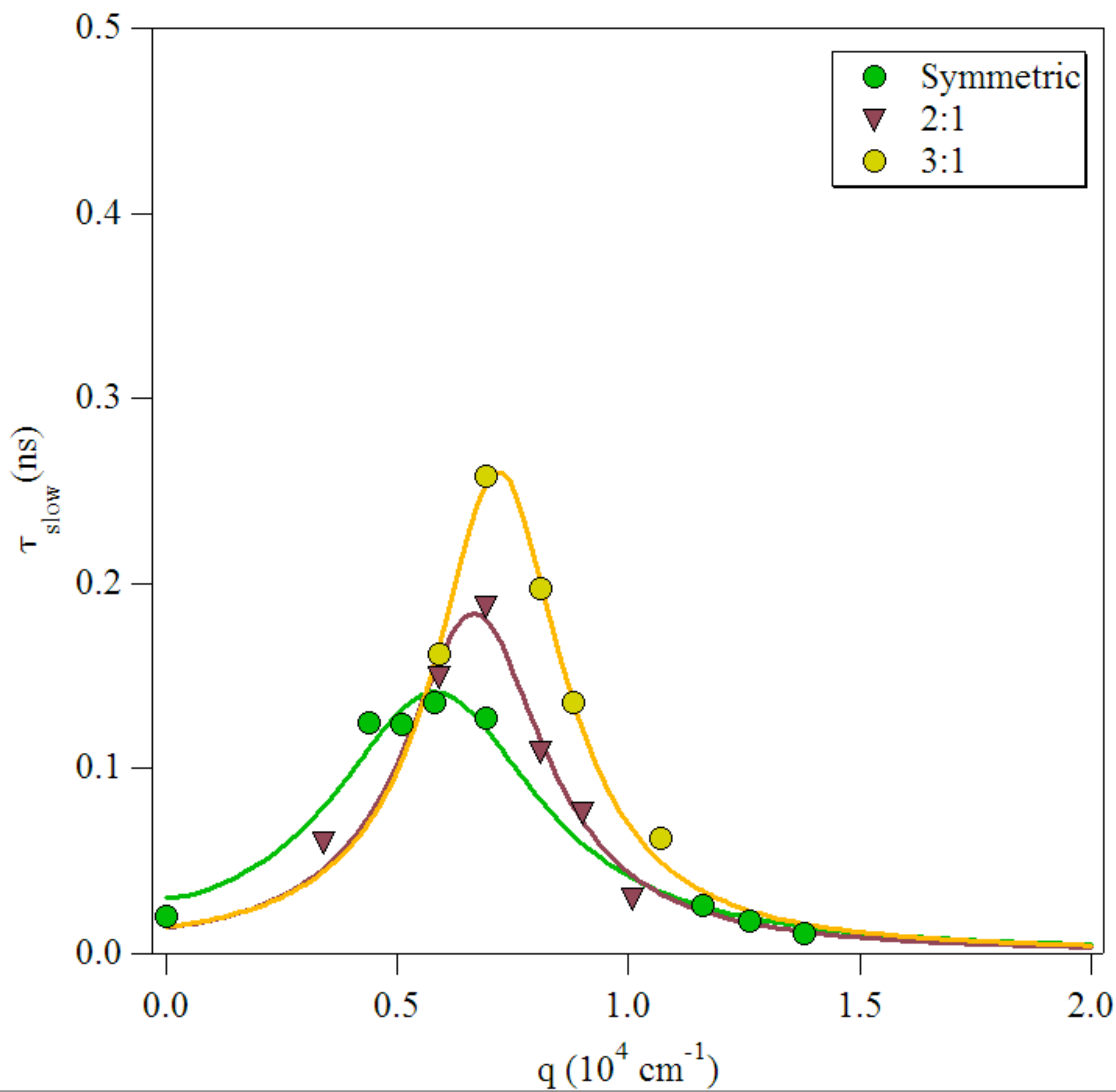

0.8
0.6
0.4
0.2
0.0
-0.2
E_c (eV)
400x10^15
300
200
100
0
n
0
500
1000
1500
2000
Z (Angstroms)

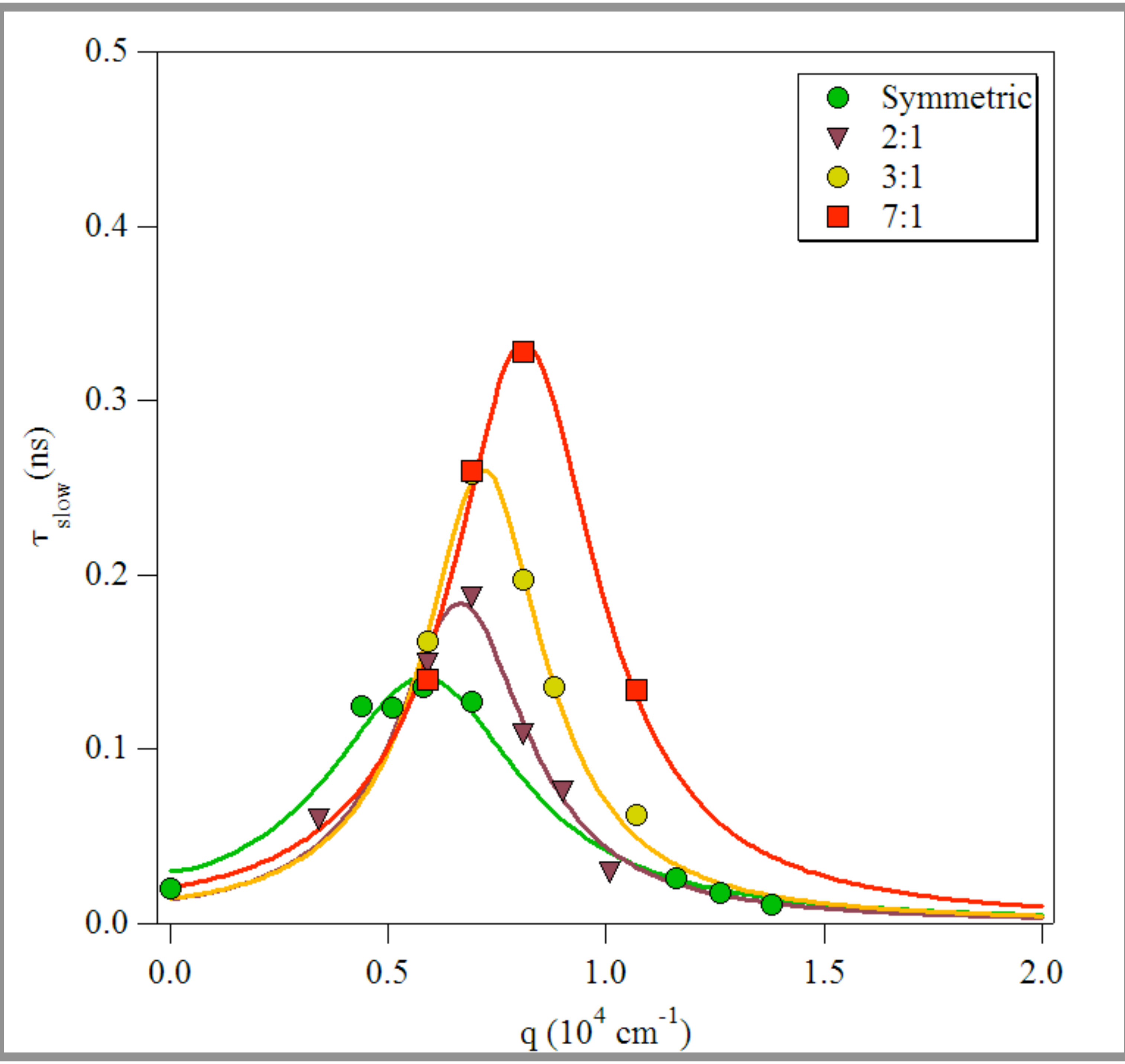


0.5
0.4
0.3
0.2
0.1
0.0
τ slow (ns)
Symmetric
0.0
0.5
1.0
1.5
2.0
q (10^4 cm^-1)

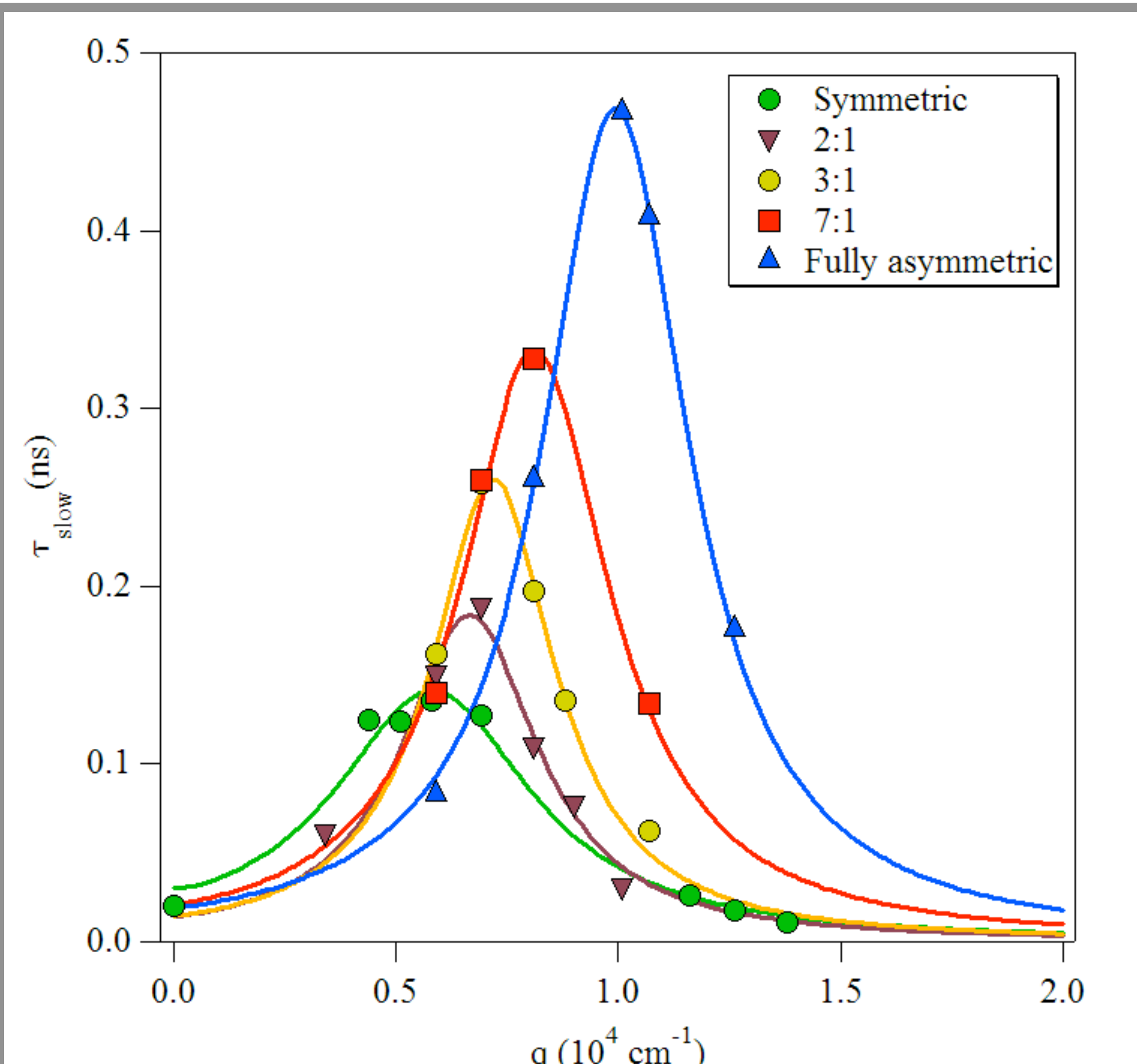


Symmetric
2:1
τ_{slow} (ns)
q (10^4 cm^{-1})
0.0
0.1
0.2
0.3
0.4
0.5
0.0
0.5
1.0
1.5
2.0


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

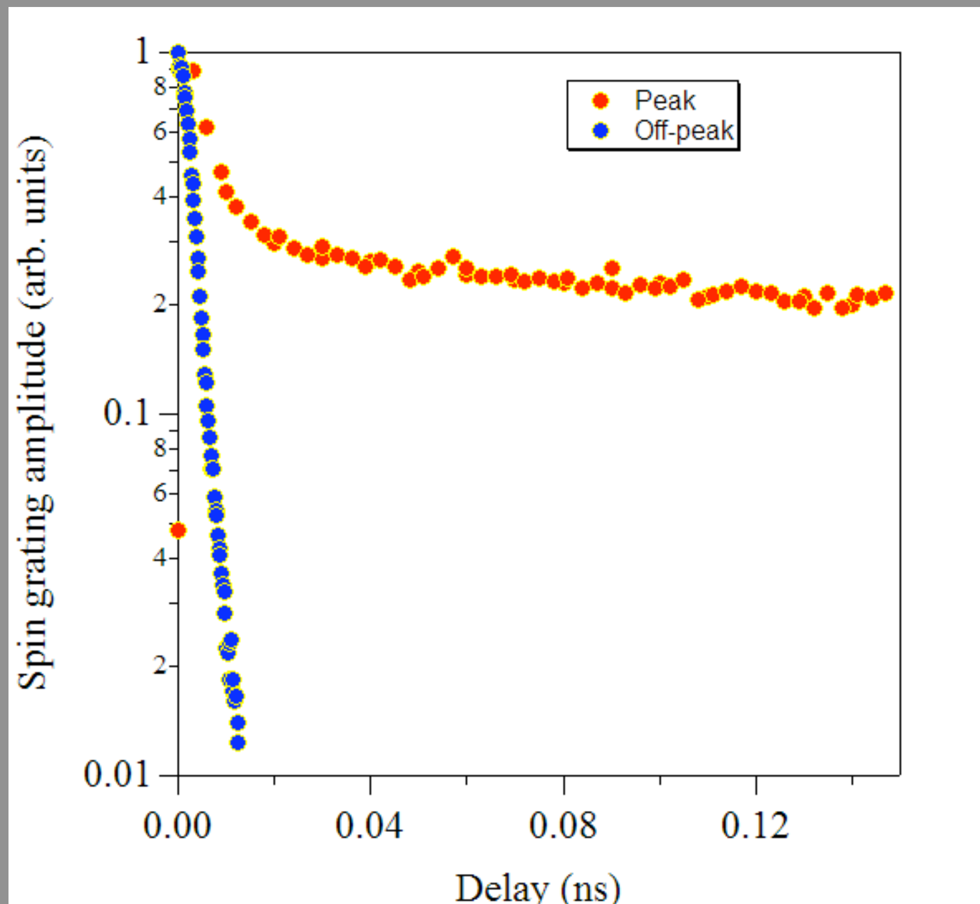


Symmetric
2:1
3:1
7:1
0.5
0.4
0.3
0.2
0.1
0.0
τ slow (ns)
0.0
0.5
1.0
1.5
2.0
q (10^4 cm^-1)



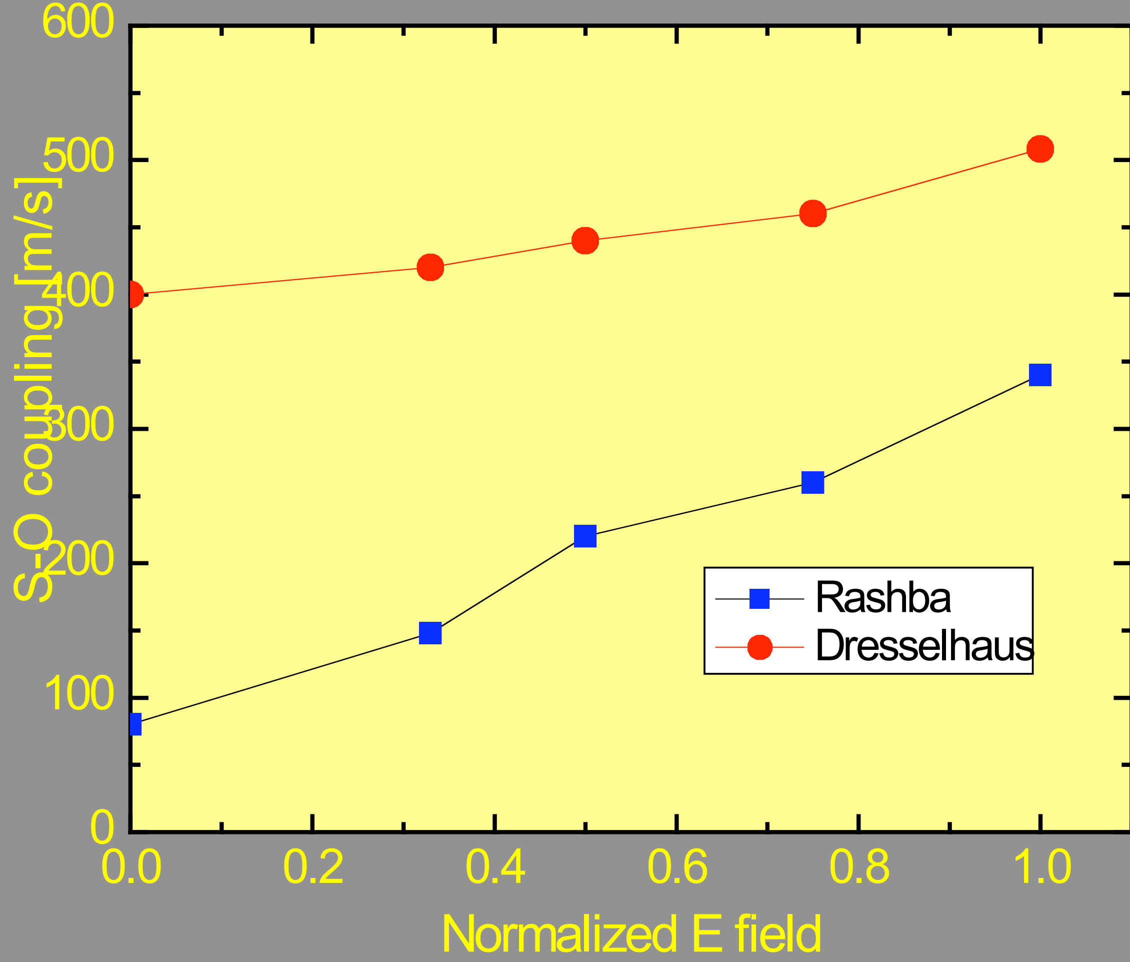
Symmetric
2:1
3:1
7:1
Fully asymmetric
0.0
0.1
0.2
0.3
0.4
0.5
τ_{slow} (ns)
0.0
0.5
1.0
1.5
2.0
q (10^4 cm^{-1})

This plot emphasizes the contrast between grating decays on and off the peak of the PSH effect.



At the “magic” wavector the spin polarization wave survives about x100 longer than it would in the absence of SO coupling

Where we are now in the search for $\alpha=\beta$



Measurements of spin diffusion coefficient in 2DEG's

Observation of "spin Coulomb drag"

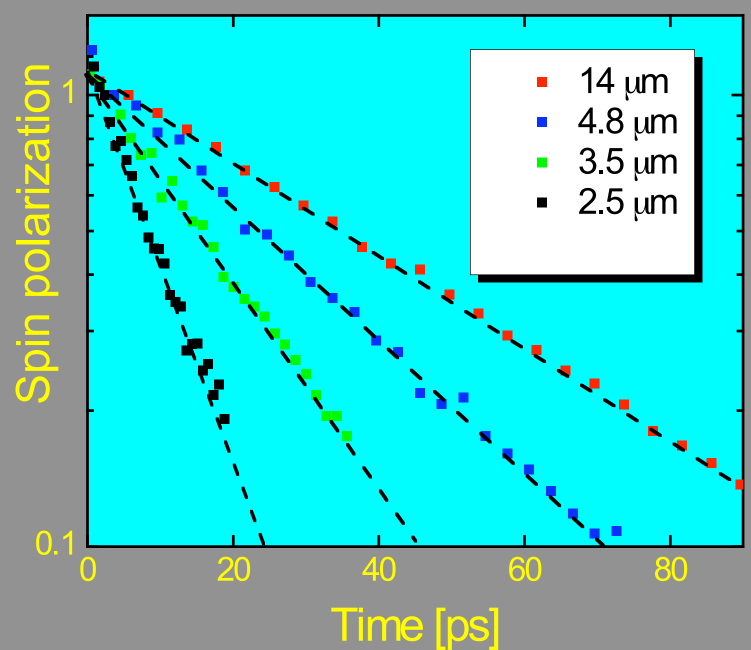
Weber et al. *Nature* **437**, 1330-1333 (2005)

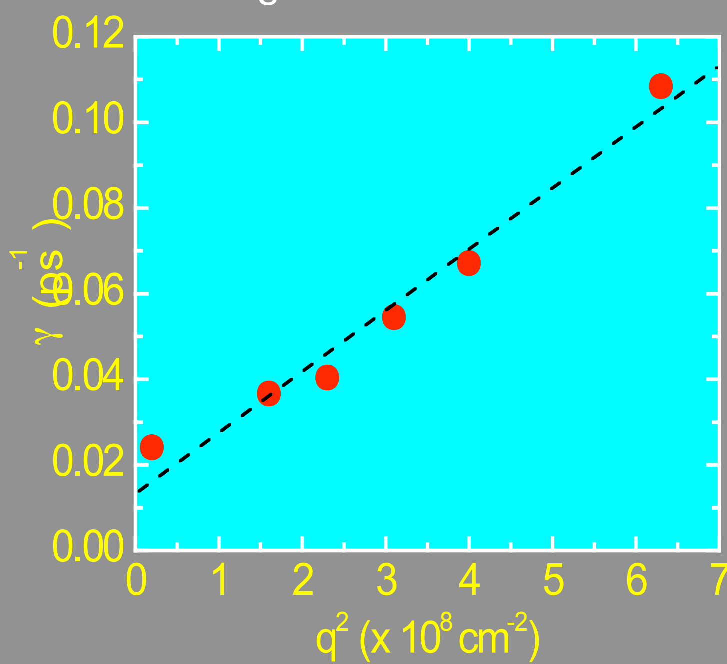
Direct measurement of spin diffusion coefficient, D_s, in 2DEG

Decay rate of a fluctuation with wavevector q

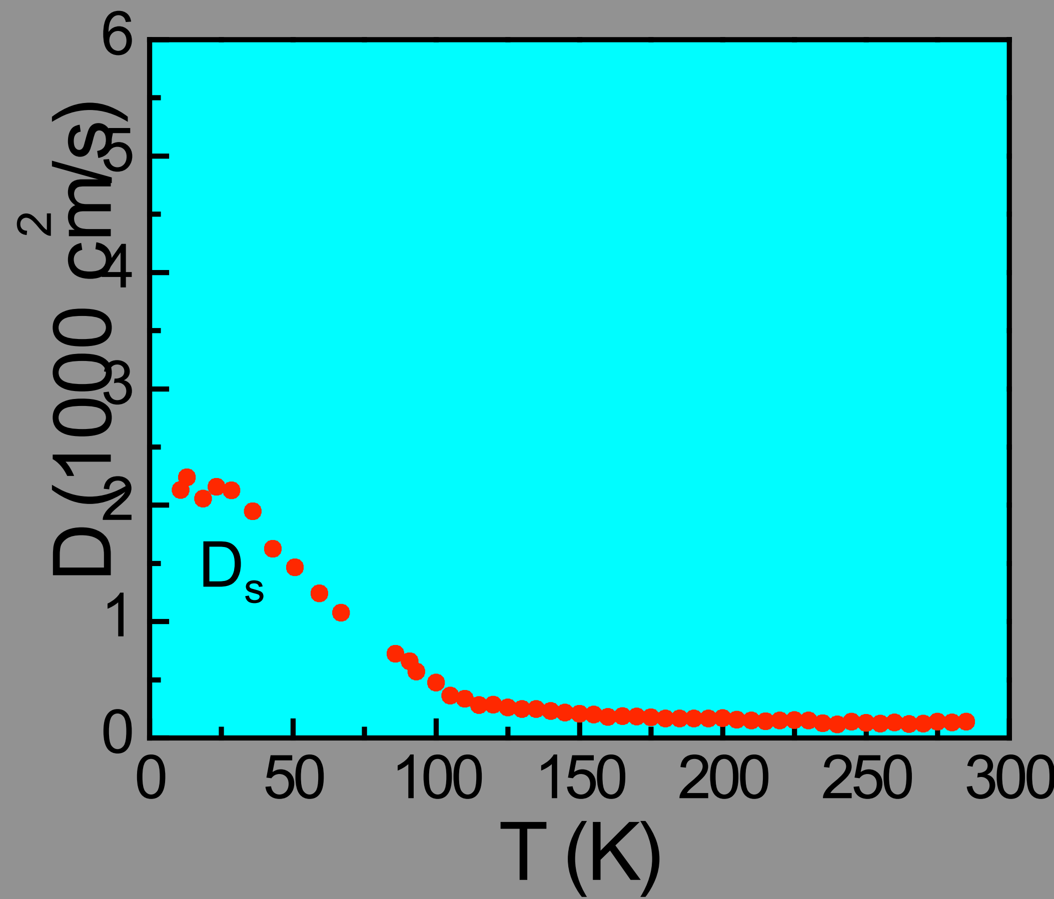
$$\Gamma_q = \frac{1}{\tau_\alpha} + D_s q^2$$

D_s=120 cm^2/s

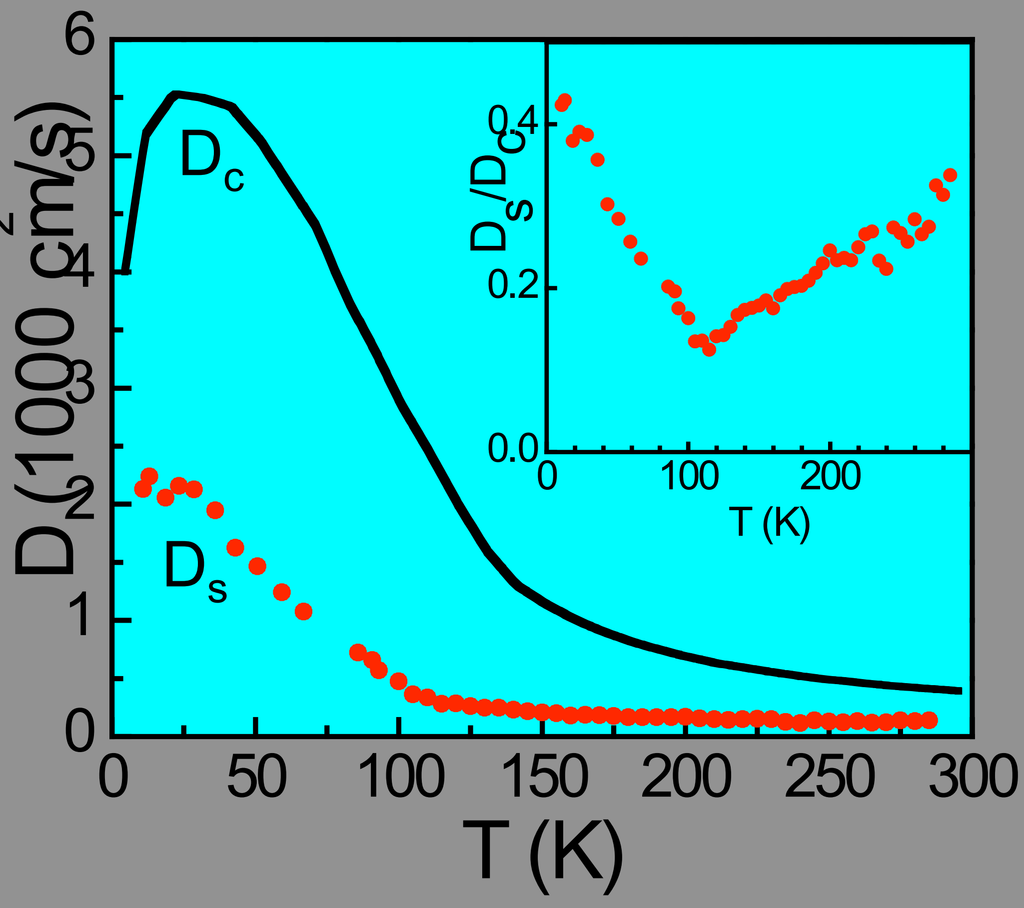




Comparison of spin and charge diffusion coefficients

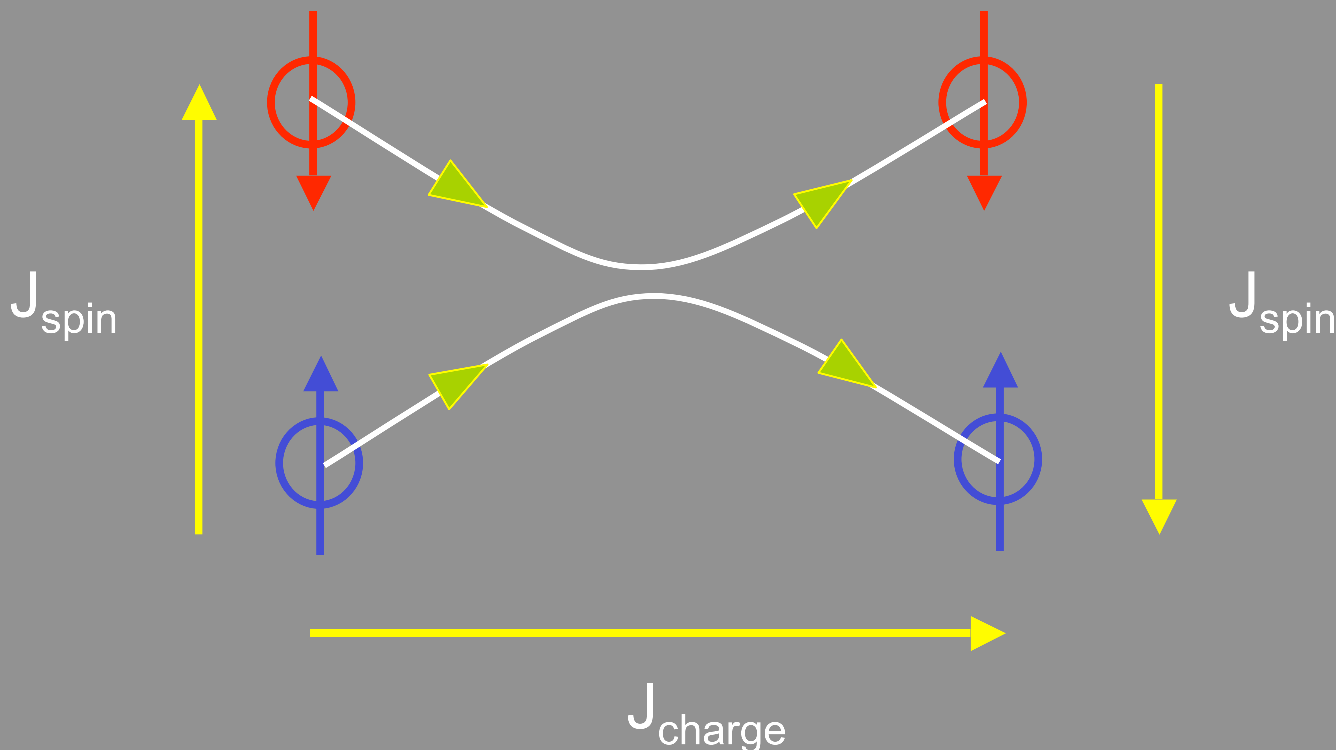


Comparison of spin and charge diffusion coefficients



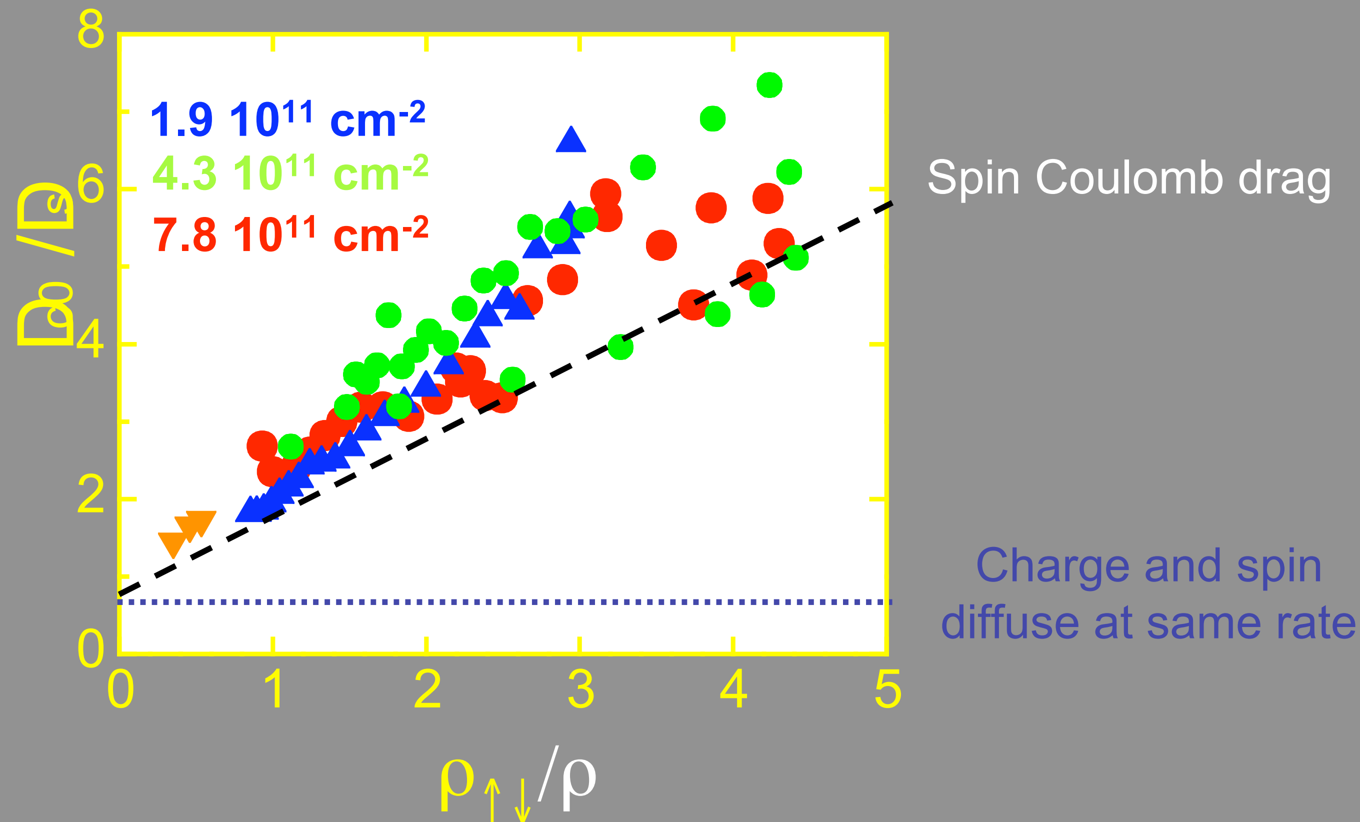
Presented at the PITP/SpinAps Asilomar Conference in June 2007

Spin Coulomb drag (D'Amico &Vignale)



e-*e* collisions conserve total momentum, but exchange momentum between spin up and spin down populations creating spin drag resistance $\rho_{\uparrow\downarrow}$

Direct comparison with theory



Future

- Continue the quest – to infinity and beyond.
- Use the spin grating to study exotic effects such as spin Hall effect.
- Can we change spin polarization lifetime by orders of magnitude through a gate applied electric field?
- Is the Datta-Das device feasible under these conditions?

Datta-Das does not require point contacts

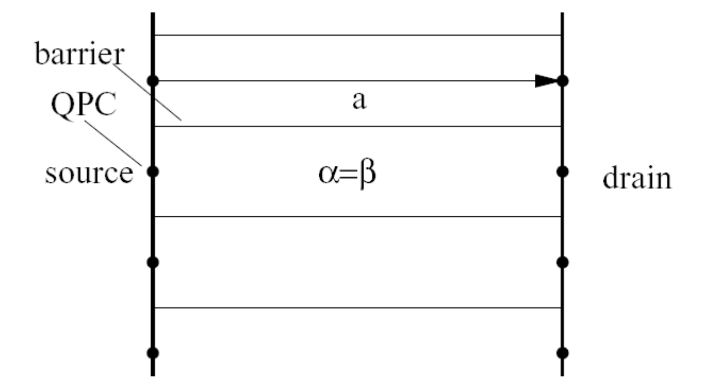


FIG. 1. Schematic of the spin-FET setup using quantum point contacts (QPC) to source and drain. The pairs of QPCs are separated by barriers to avoid crosstalk.