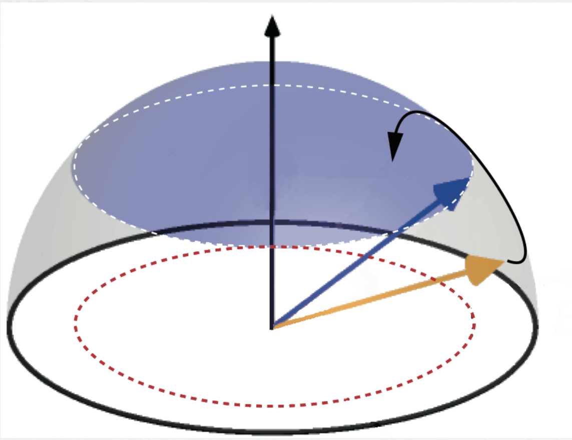
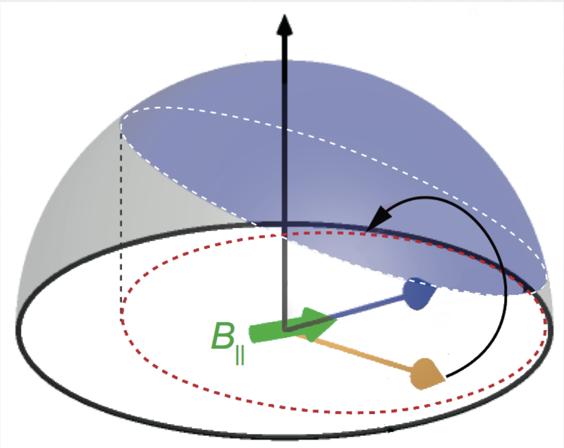
Control of spin geometric phase in a semiconductor quantum ring

Henri Saarikoski, Regensburg University
EP2DS/MSS Conference, Wrocław, 4th of July, 2013

SFB 689



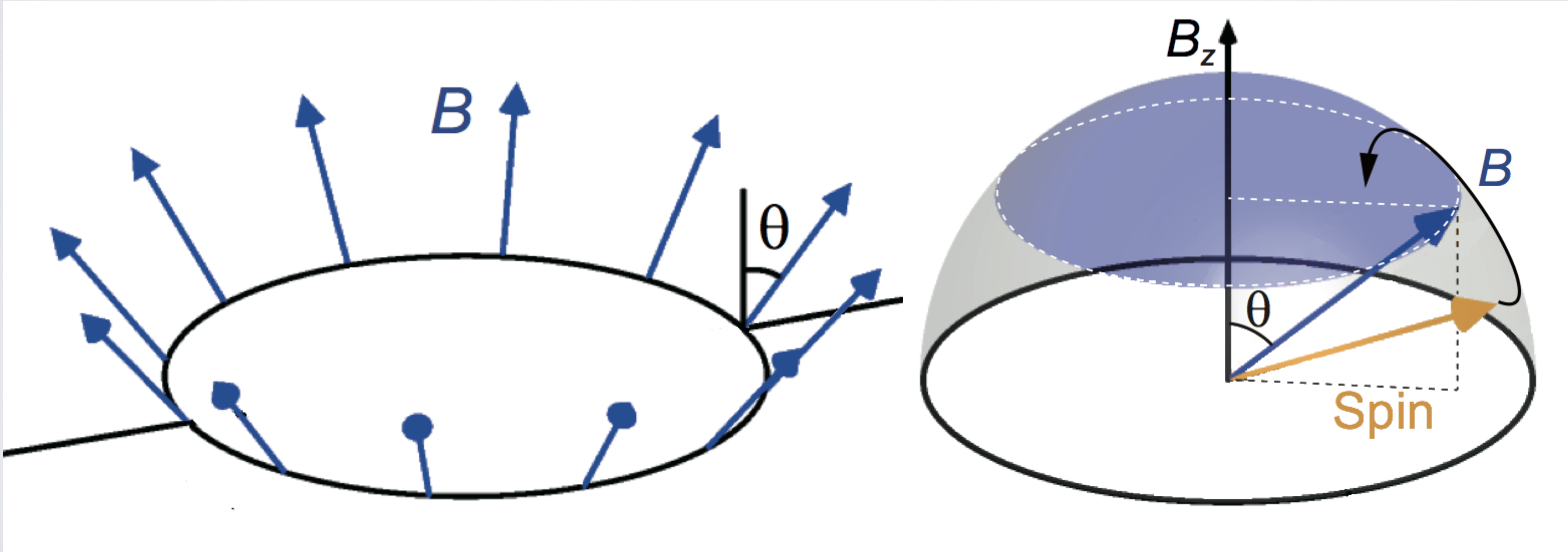


F. Nagasawa, Diego Frustaglia, Henri Saarikoski,
Klaus Richter, Makoto Kohda, and Junsaku Nitta (2013)

Geometric phases

Geometric phases arise in wave systems where the parameters of the wave function are cycled around a circuit. (M. Berry, Proc. R. Soc. Lond. A 392, 45 (1984))

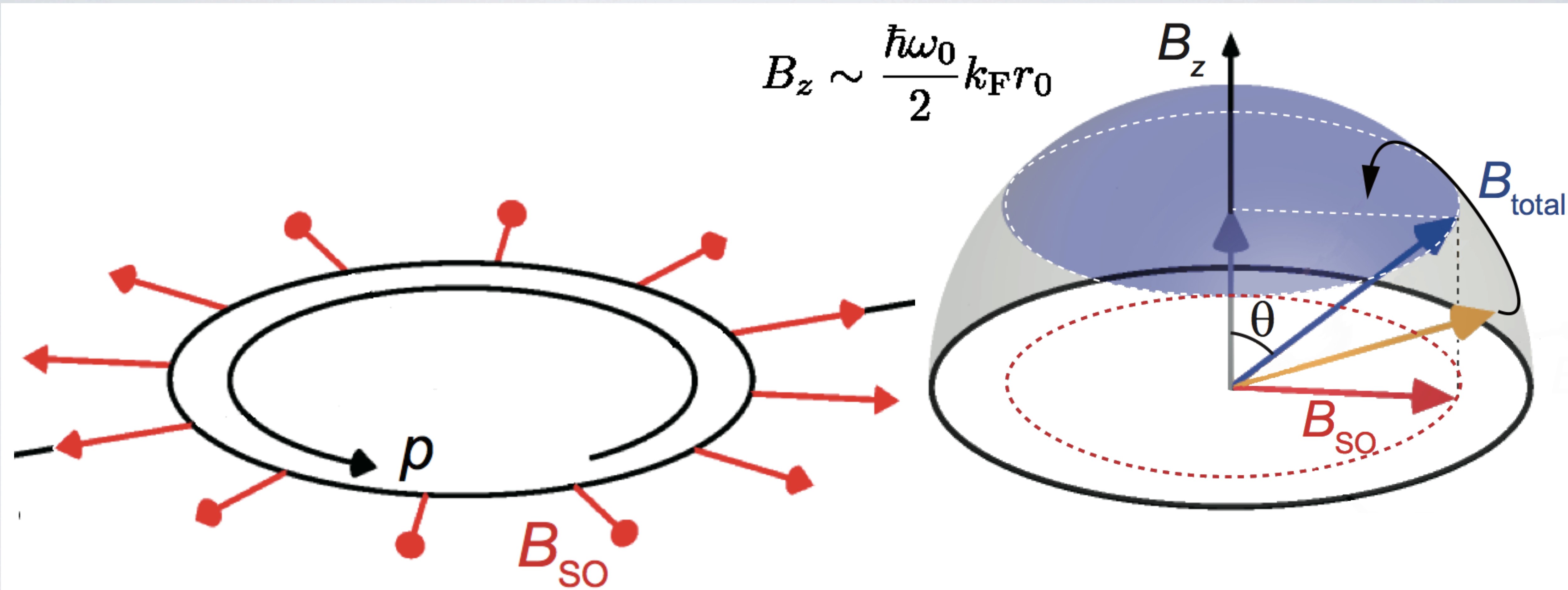
Can be observed via interference of waves traversing different paths.
Depends only on the geometry of the path :
robust against dephasing in contrast with the time-dependent dynamical phase.



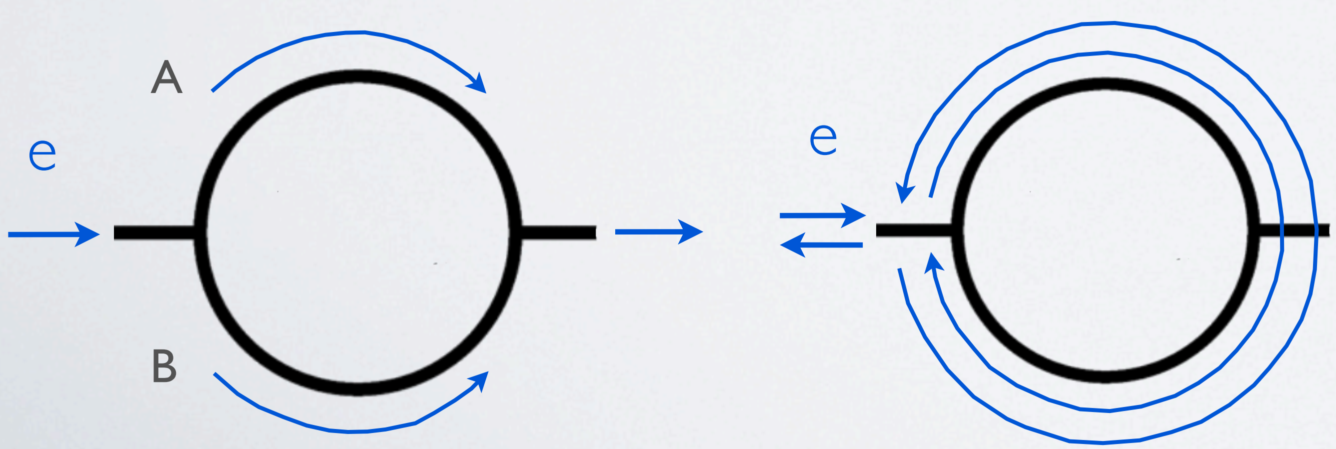
Dynamic phase : spin precession around B
Geometric phase : solid angle subtended by spin eigenstates in B

Geometric phases in SO-coupled quantum rings

Extracted and studied for electron waves in InGaAs rings
F. Nagasawa et al., Phys. Rev. Lett. 108, 086801 (2012)

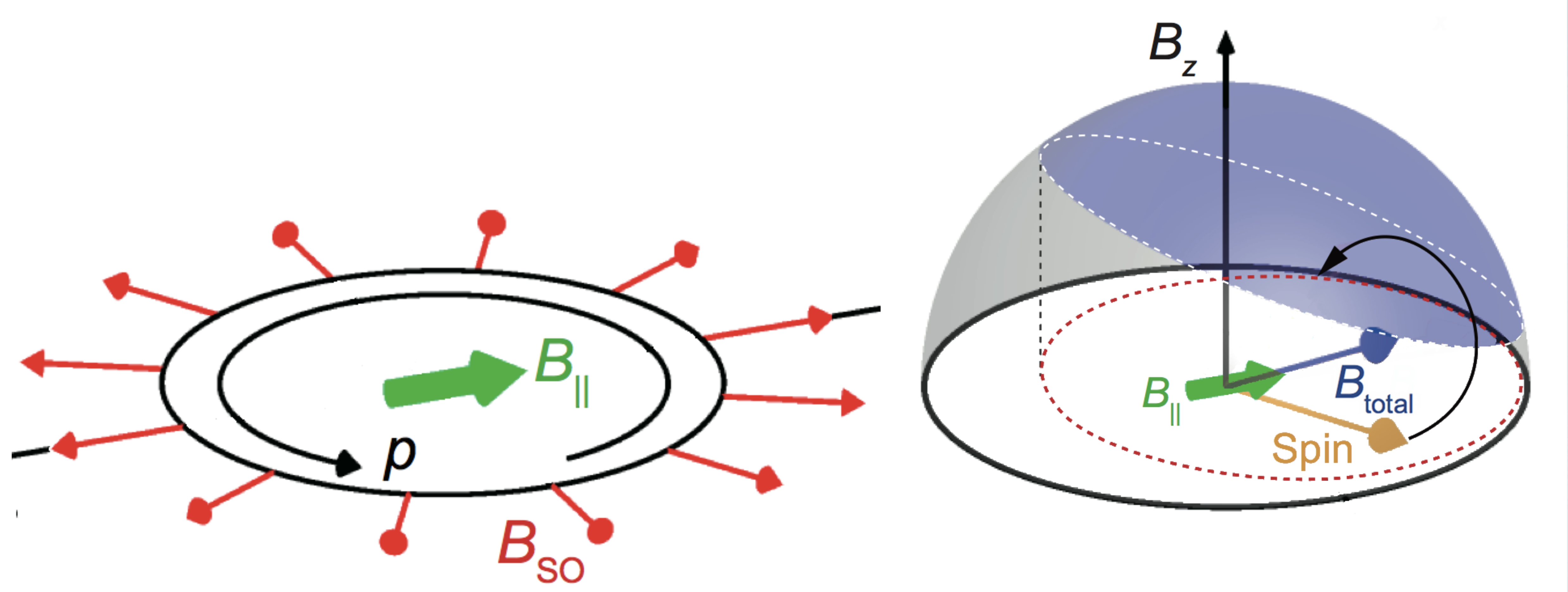


Aharonov-Anandan geometric phase in non-adiabatic evolution.



Interference of dynamic and geometric phases : oscillations in conductance, **Aharonov-Casher effect**

Manipulation of the geometric phase



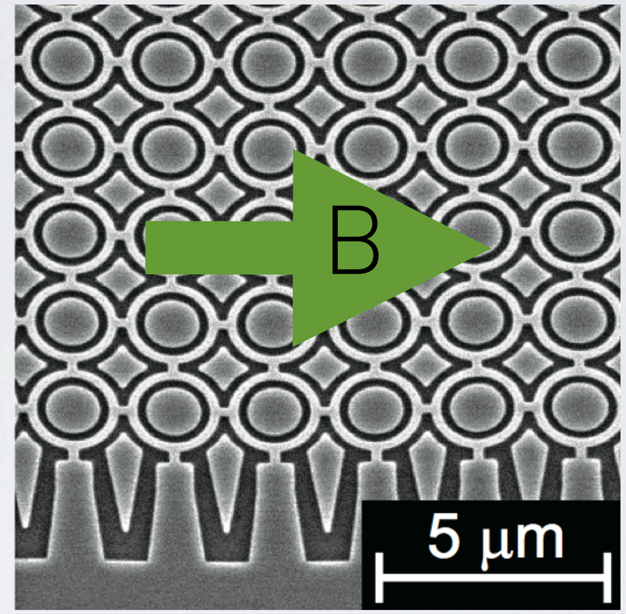
Interference experiments in quantum rings

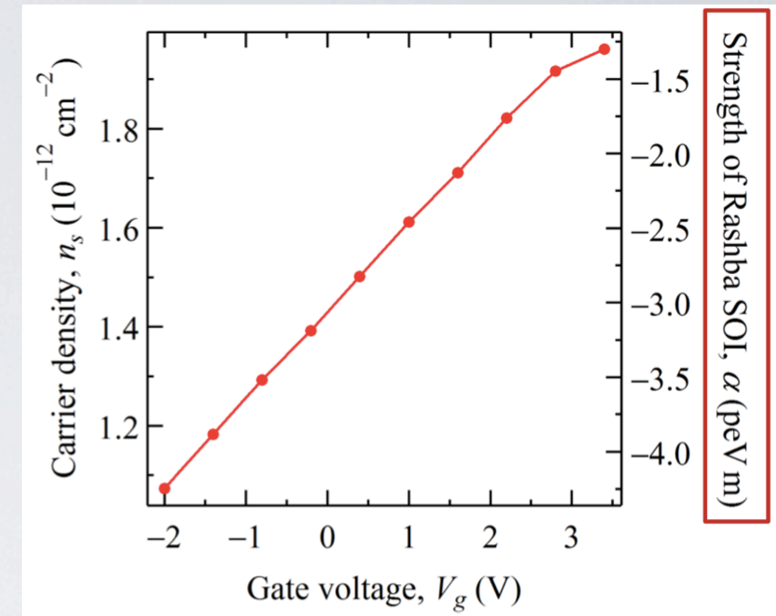
An array of 40 x 40 InGaAs/InAlAs rings
multiple interference paths.

Multi-mode rings (~6 modes)

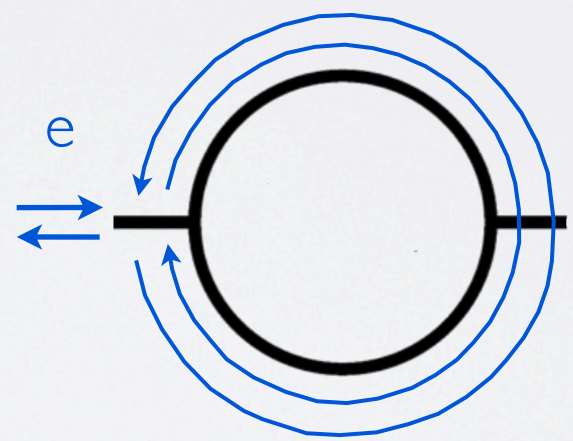
Tuning of the SO interaction with a gate.
SdH analysis of coupling strength

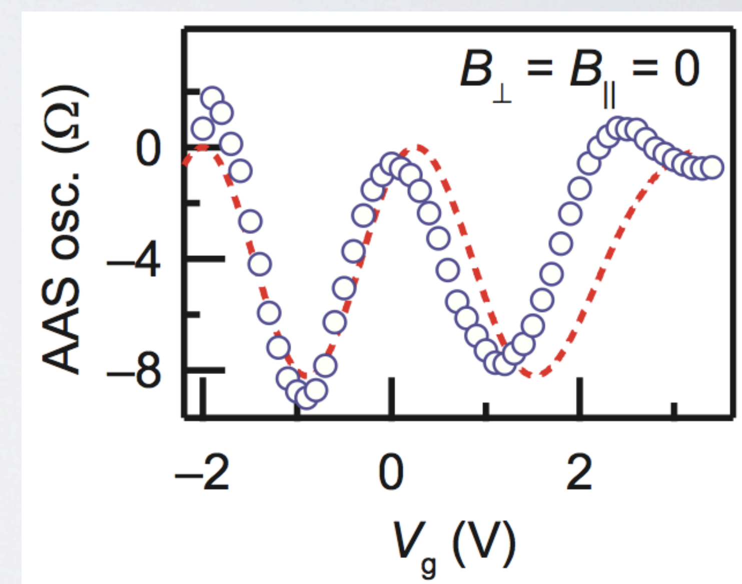
ω_R ~ up to 20 GHz , ω_0 ~ 6 GHz





Quasi-ballistic rings.
Altshuler-Aronov-Spivak (AAS)
conductance oscillations :
interference in a full rotation around the ring in opposite directions





$$\frac{\delta R_{\alpha_R \neq 0}}{\delta R_{\alpha_R = 0}} \propto \cos\left[2\pi\left(\sqrt{1+Q_R^2}-1\right)\right] = \cos\left[2\pi Q_R \sin\theta - 2\pi(1-\cos\theta)\right]$$

dynamic geometric

Geometric phase shift in low Zeeman fields

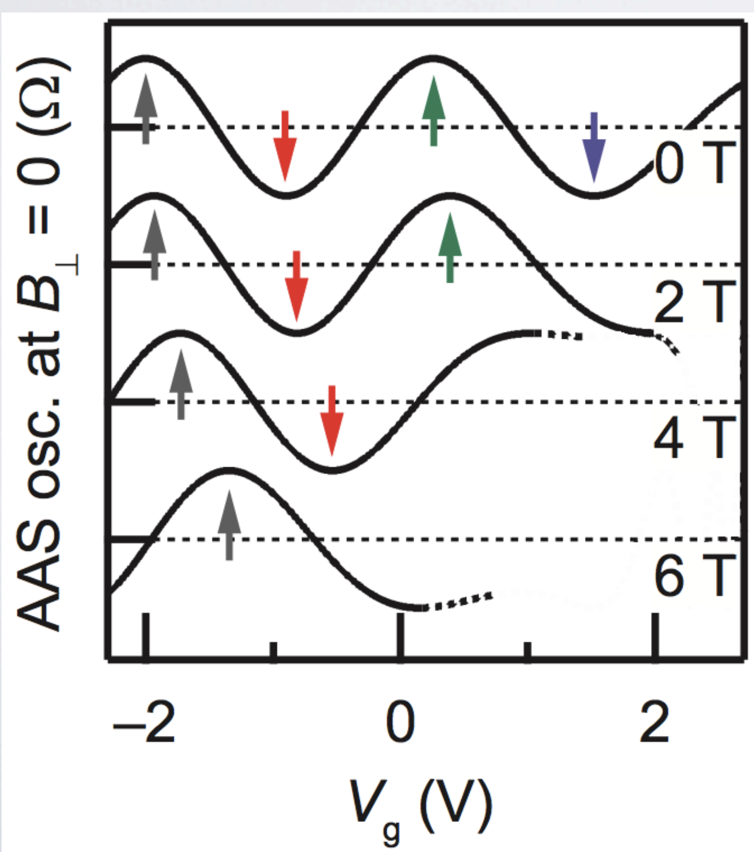
Phase shift, 1st order perturbation theory (D. Frustaglia) :

$$\phi = \left(\frac{\omega_B}{\omega_0 k_F r}\right)^2 \frac{4 + Q_R^2}{4Q_R^2\sqrt{1+Q_R^2}}$$

$$\begin{aligned} 2\pi\phi_{AA} &= 2i\int_0^{2\pi} d\varphi \langle\overline{n,\lambda,s}|\frac{\partial}{\partial\varphi}|\overline{n,\lambda,s}\rangle \\ &= -2\pi[(1-\cos\theta) - \phi - 2j] \end{aligned}$$

Pure geometric phase modulation. Independent of dynamical phases

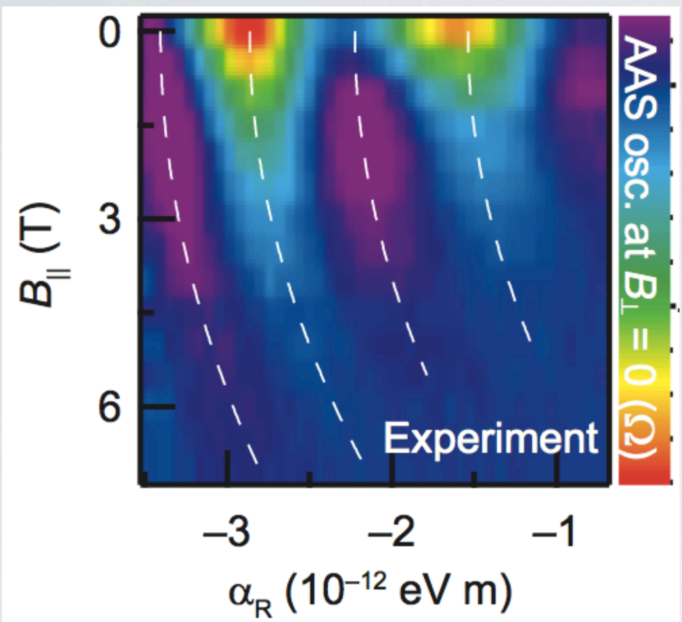
$$G \approx \frac{e^2}{h}\left\{1 + \cos\left[\pi\left(\sqrt{1+Q_R^2} - 1 + \left(\frac{\omega_B}{\omega_0 k_F r_0}\right)^2 \frac{4+Q_R^2}{4Q_R^2\sqrt{1+Q_R^2}}\right)\right]\right\}$$

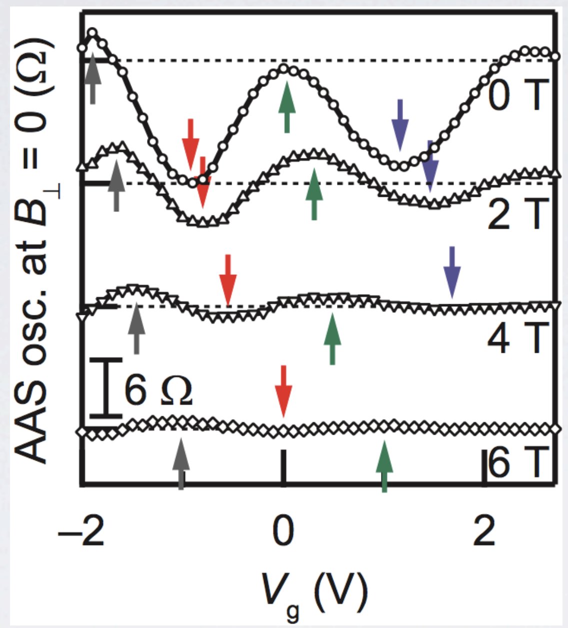


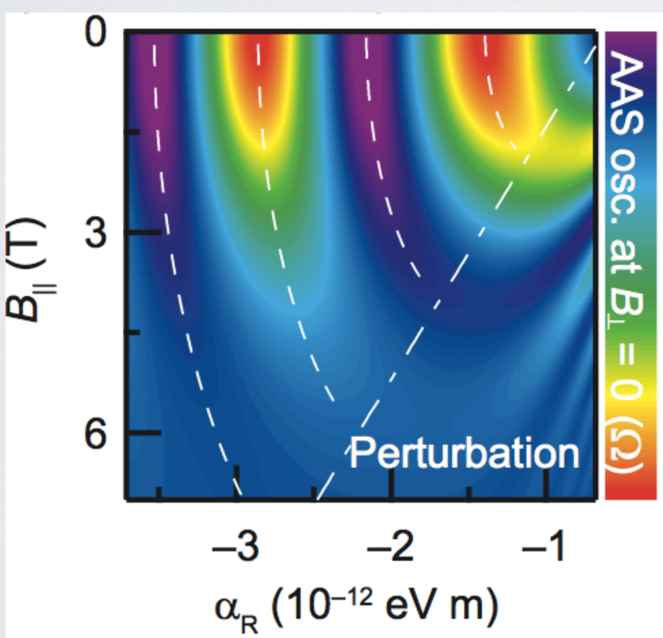
Calculated also for weakly coupled rings F. K. Joibari, Y. M. Blanter & G. E. W. Bauer, Aharonov-Casher effect in quantum ring ensembles. arXiv:1304.6195 [cond-mat.mes-hall] (2013).

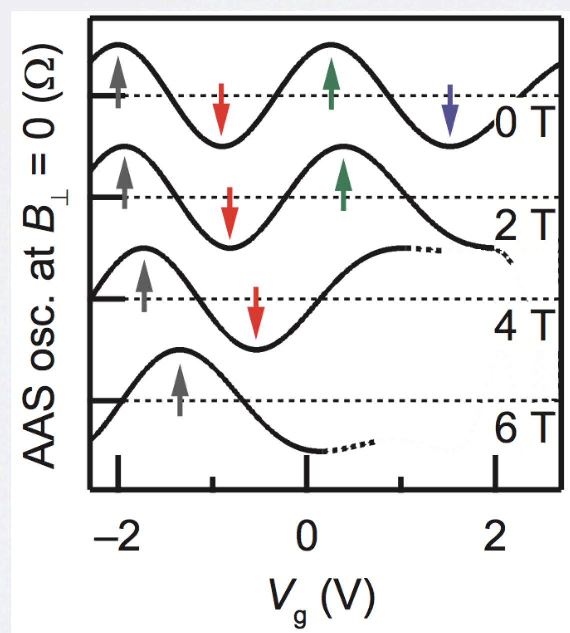
Dip and peak shifts of AAS oscillations

Quadratic phase shift, decoherence with B

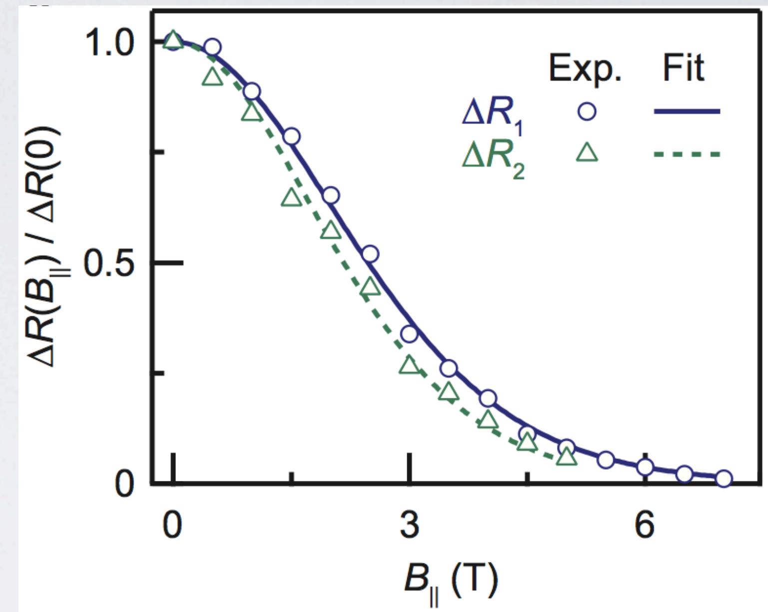








TR symmetry breaking:
suppression of spin interference



$$\frac{\Delta R(B_{\parallel})}{\Delta R(0)} = \exp\left[-4\pi r\left(\frac{1}{l_{\varphi}(B_{\parallel})} - \frac{1}{l_{\varphi}(0)}\right)\right]$$

F. E. Meijer, A. F. Morpurgo, T. M. Klapwijk, and J. Nitta, PRL 94, 186805 (2005)

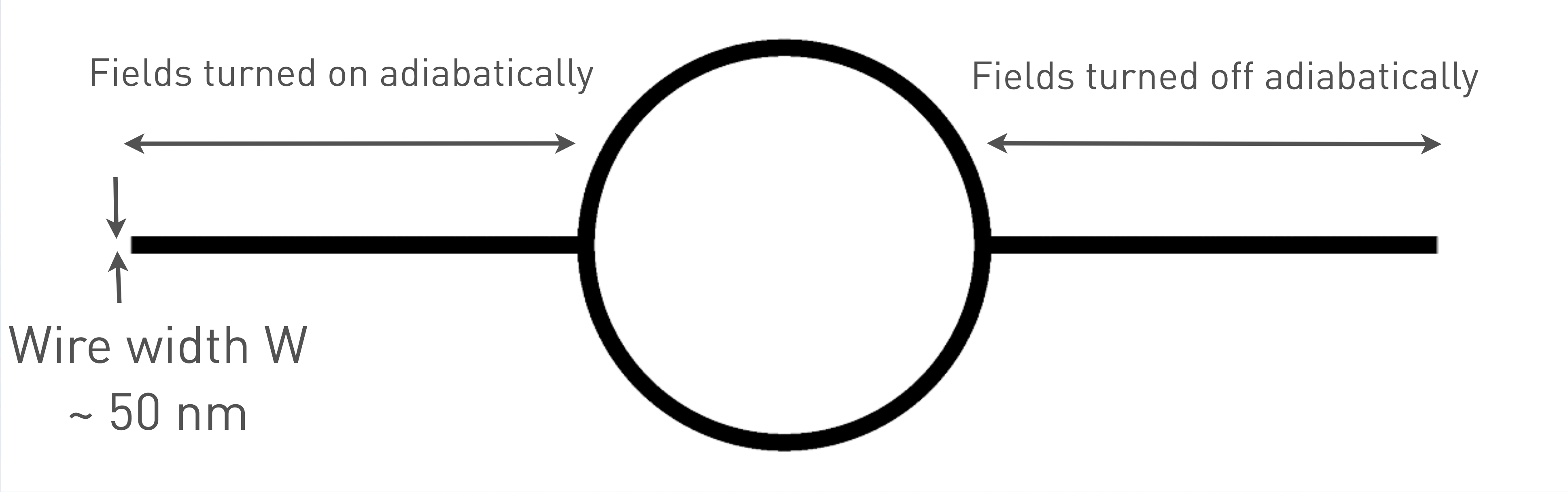
Computational approach

Multiple transport modes, disorder and high Zeeman fields

$$\hat{\mathrm{H}} = \frac{1}{2m^*}\ \hat{\mathbf{P}}^2 + \alpha(k_y\sigma_x - k_x\sigma_y) + \frac{1}{2}g_{\mathrm{eff}}\mu_{\mathrm{B}}B\sigma_x + V_{\mathrm{dis}}(\mathbf{x})$$

Bychov-Rashba SOI — Zeeman field — Anderson-like disorder potential

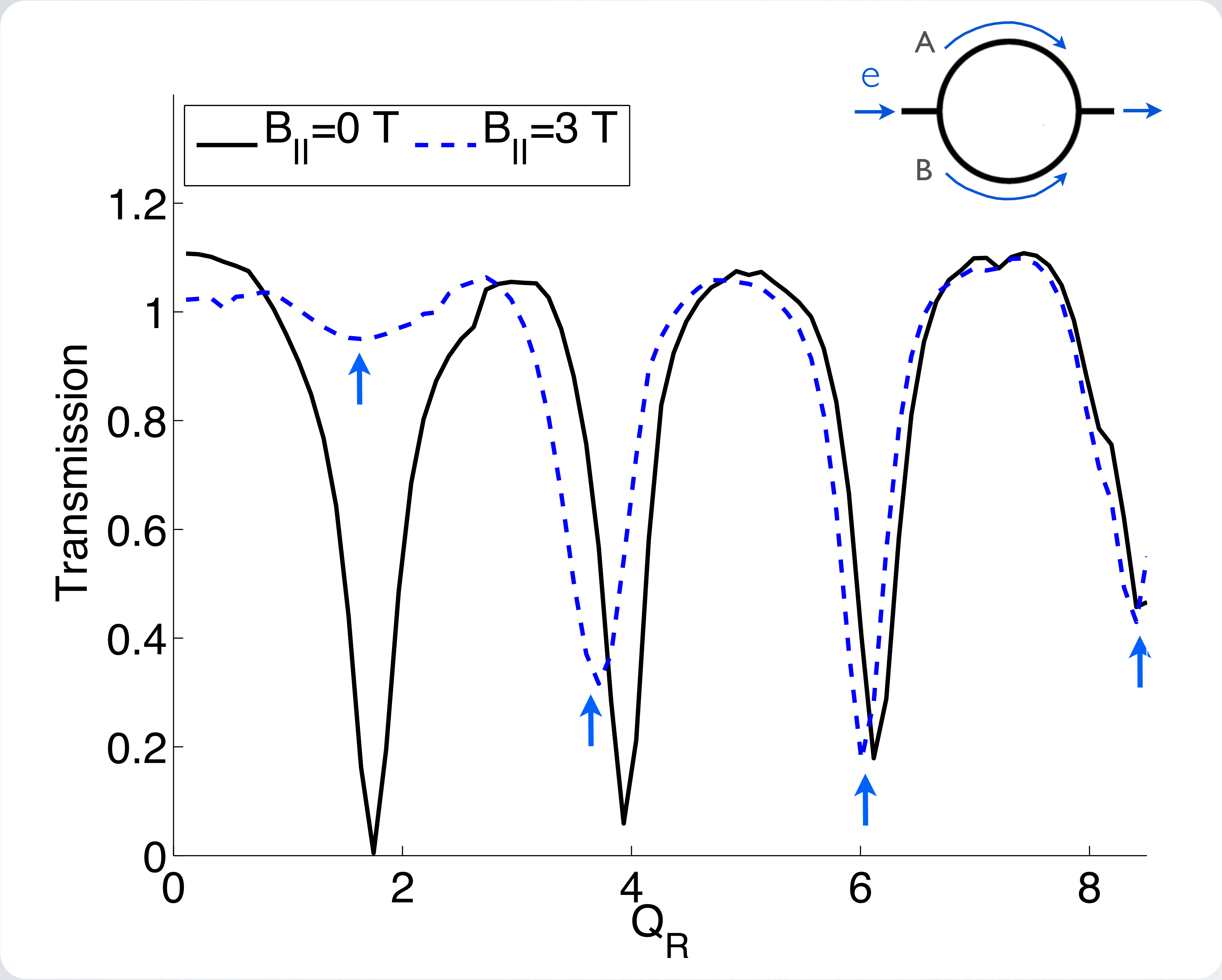
Transport equation solution with the Recursive Green's Function method (RGFM)



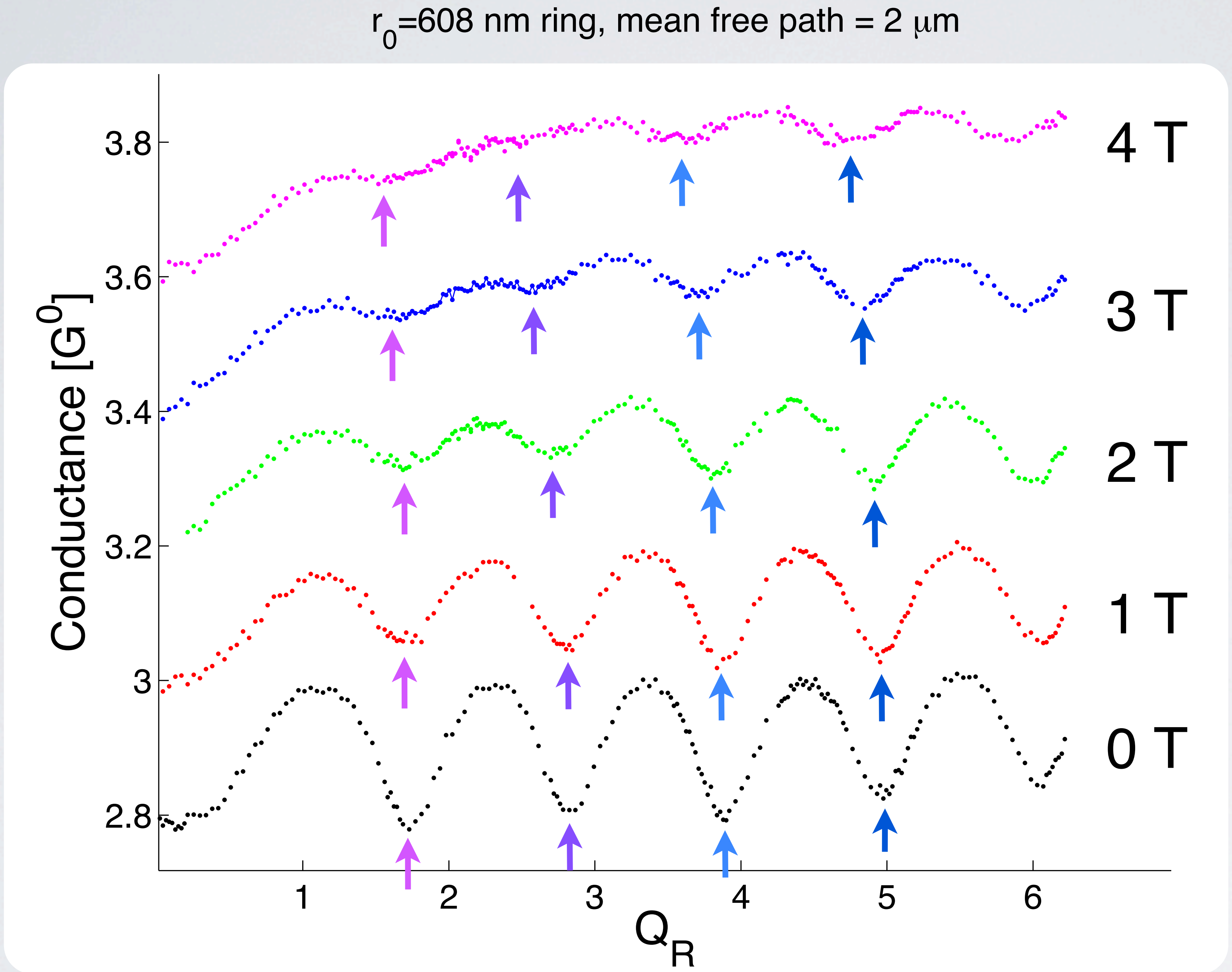
Mean free path in the numerical calculations = 2-6 microns, T = 1.7 K, g-factor = 3, ring displacement 10-20 nm, no Dresselhaus term

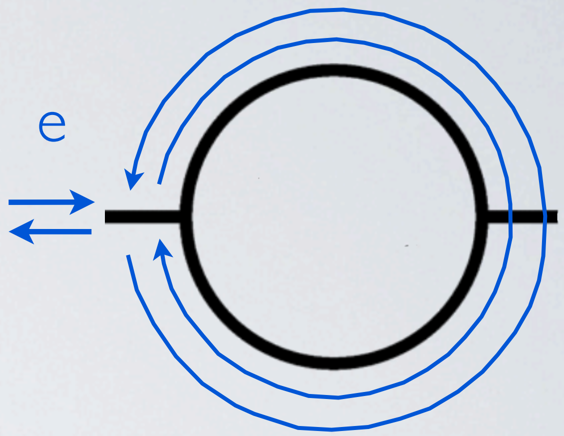
RQMG method in ballistic rings

Geometric phase shift for direct interference paths through a ballistic ring.



AAS oscillations in quasi-ballistic multi-mode rings

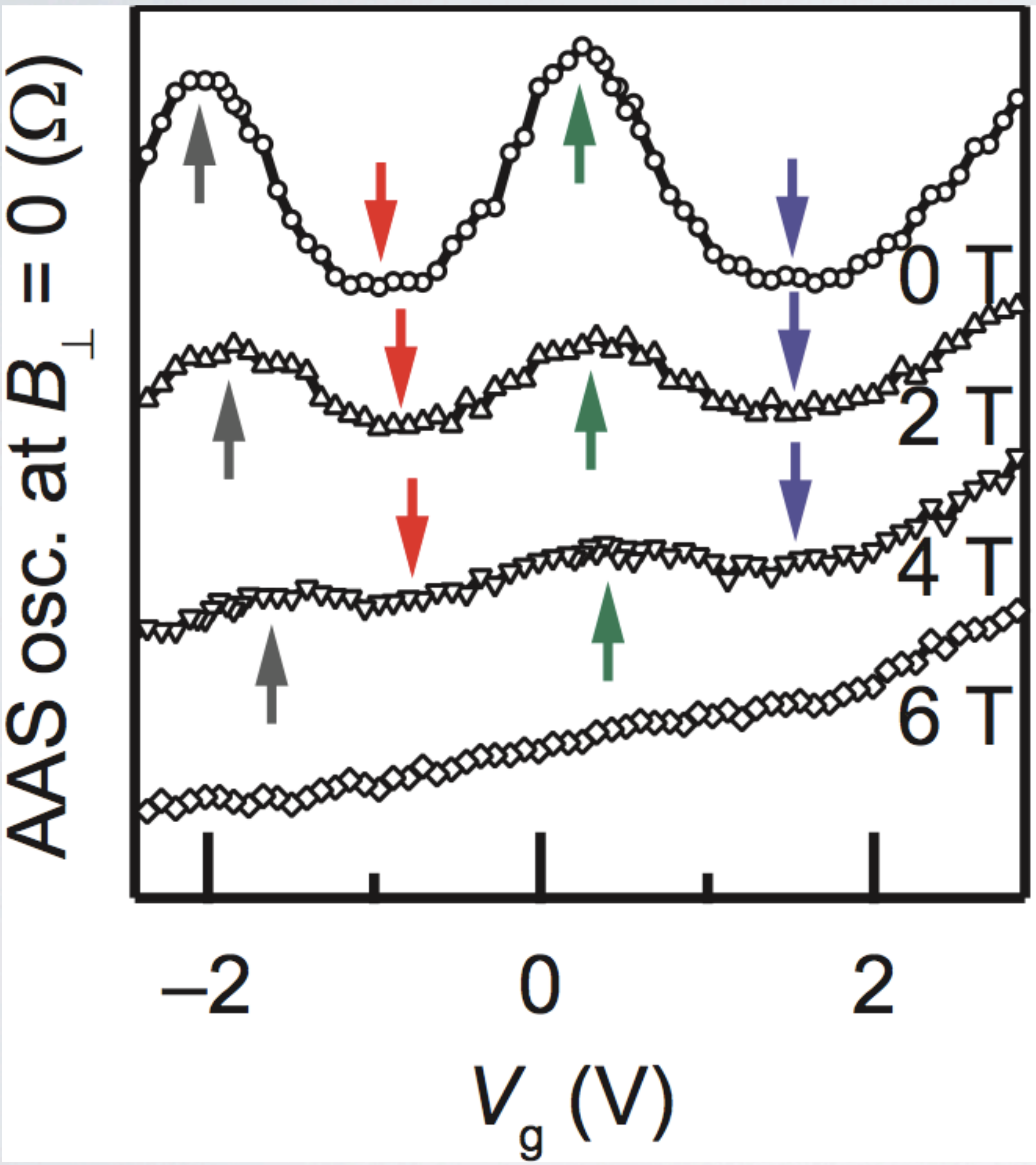




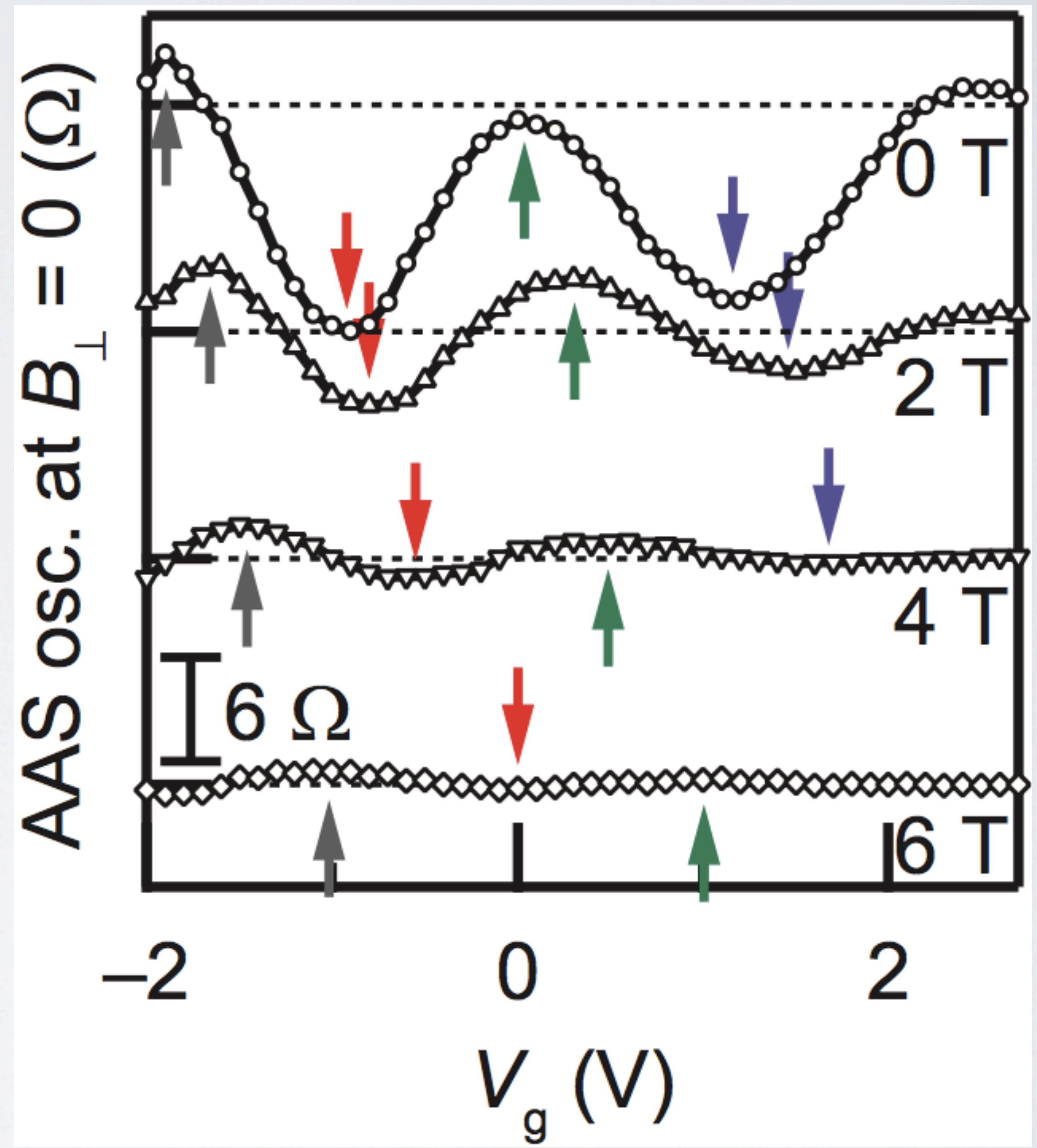
Dips shifts to lower SO fields; an additional phase shift due to the magnetic field.

Simulations of AAS conductance oscillations

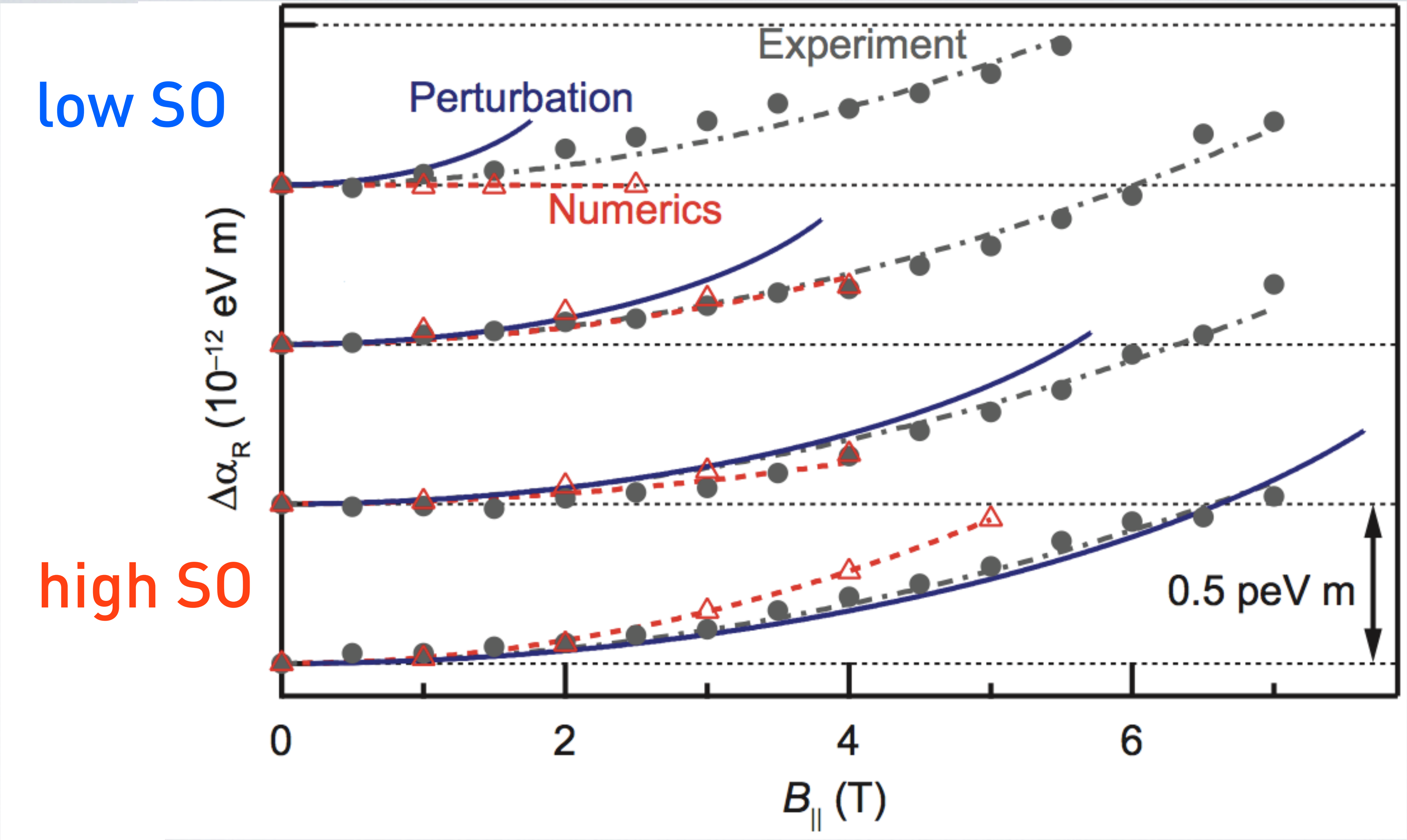
Numerical RGFM



Experiments



Phase shifts : experiments vs. theory



Quadratic shift calculated and observed in experiments

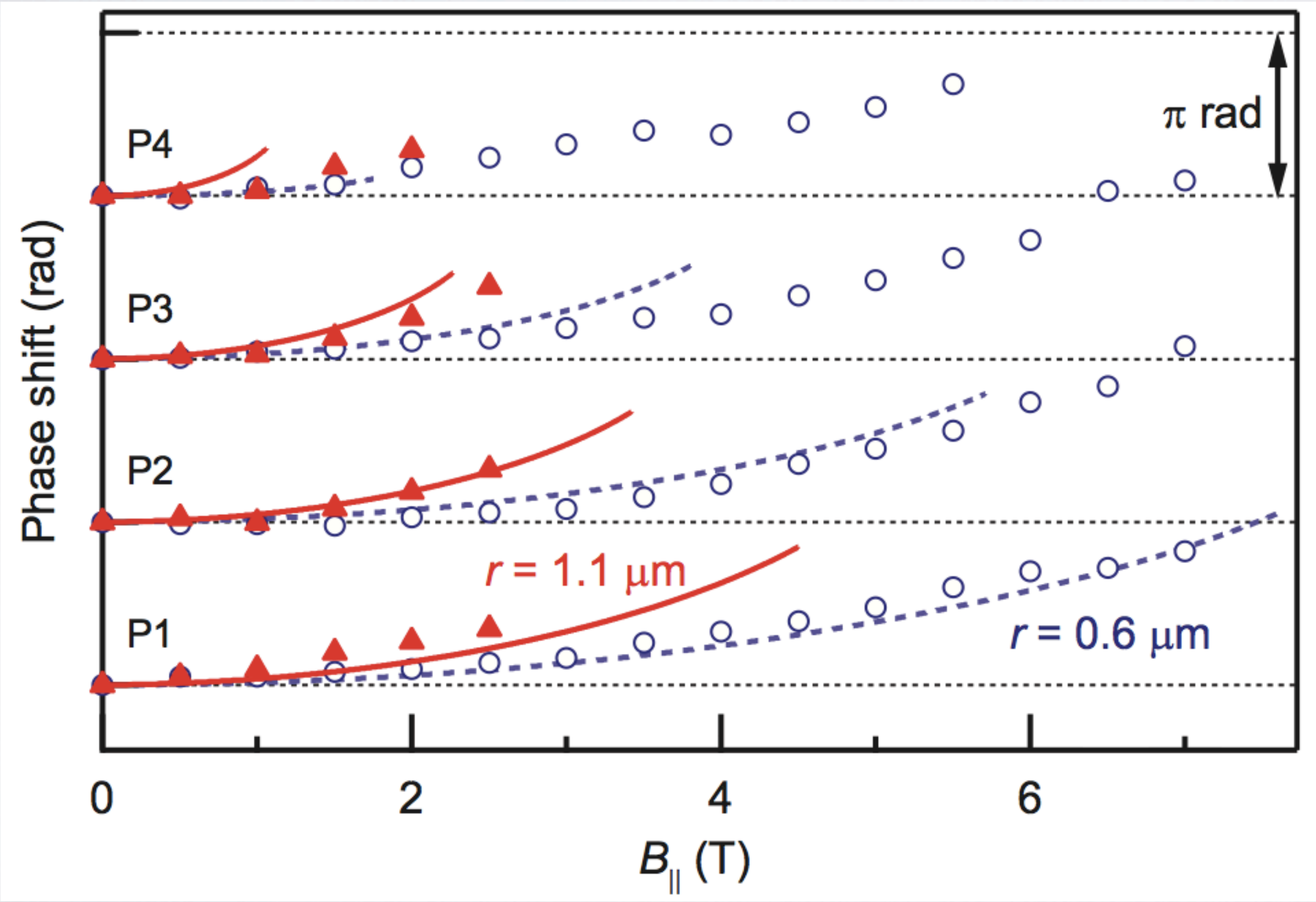
Perturbation theory works fine in high SO fields :
phase shift is dominated by a few modes or just the lowest one due to dephasing.

Radius dependence

$$\phi = \left(\frac{\omega_B}{\omega_0 k_F r}\right)^2 \frac{4+Q_R^2}{4Q_R^2\sqrt{1+Q_R^2}}$$

$$\omega_0 = \hbar/(m^\star r^2)$$

$\phi \sim r^2$



Qualitative agreement with the perturbation theory

Summary

Geometric phase shift with the in-plane magnetic field:
quadratic in the in-plane magnetic field strength

Phase manipulation independent of the dynamic phase and
without resorting to other geometric phases such as the Aharonov-Bohm phase

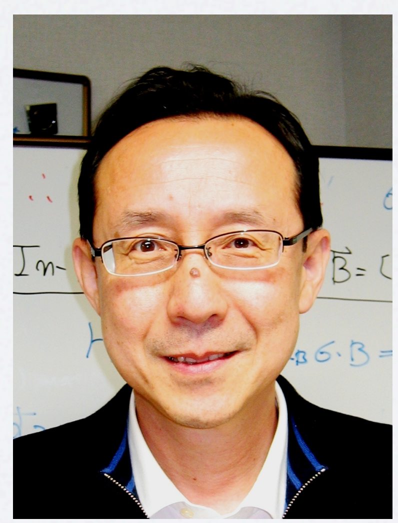
Phase shift dominated by a few modes or just the lowest one due to dephasing

Collaboration

Tohoku group (experiments)

Fumiya Nagasawa

Makoto Kohda



Junsaku Nitta

Sevilla

Diego Frustaglia

Regensburg

Klaus Richter