SPIN RESONANCE UNDER TOPOLOGICAL DRIVING FIELDS

Dr. Andrés Reynoso

LABORATORY OF PHOTONICS
AND OPTO-ELECTRONICS (LPO)

Centro Atomico Bariloche ARGENTINA

San Carlos de Bariloche, Argentina, (photo taken by S. Cutts)

reynoso@cab.cnea.gov.ar

R&D Grant FIS2014-53385-P

New J. Phys. 19 (2017) 063010

GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

New Journal of Physics

Spin resonance under topological driving fields

A A Reynoso[1,2], J P Baltanás[3], H Saarikoski[4], J E Vázquez-Lozano[3], J Nitta[5] and D Frustaglia[3]

[1] Instituto Balseiro and Centro Atómico Bariloche, Comisión Nacional de Energía Atómica, 8400 Bariloche, Argentina
[2] Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina
[3] Departamento de Física Aplicada II, Universidad de Sevilla, E-41012 Sevilla, Spain
[4] RIKEN Center for Emergent Matter Science (CEMS), Saitama 351-0198, Japan
[5] Department of Materials Science, Tohoku University, Sendai 980-8579, Japan

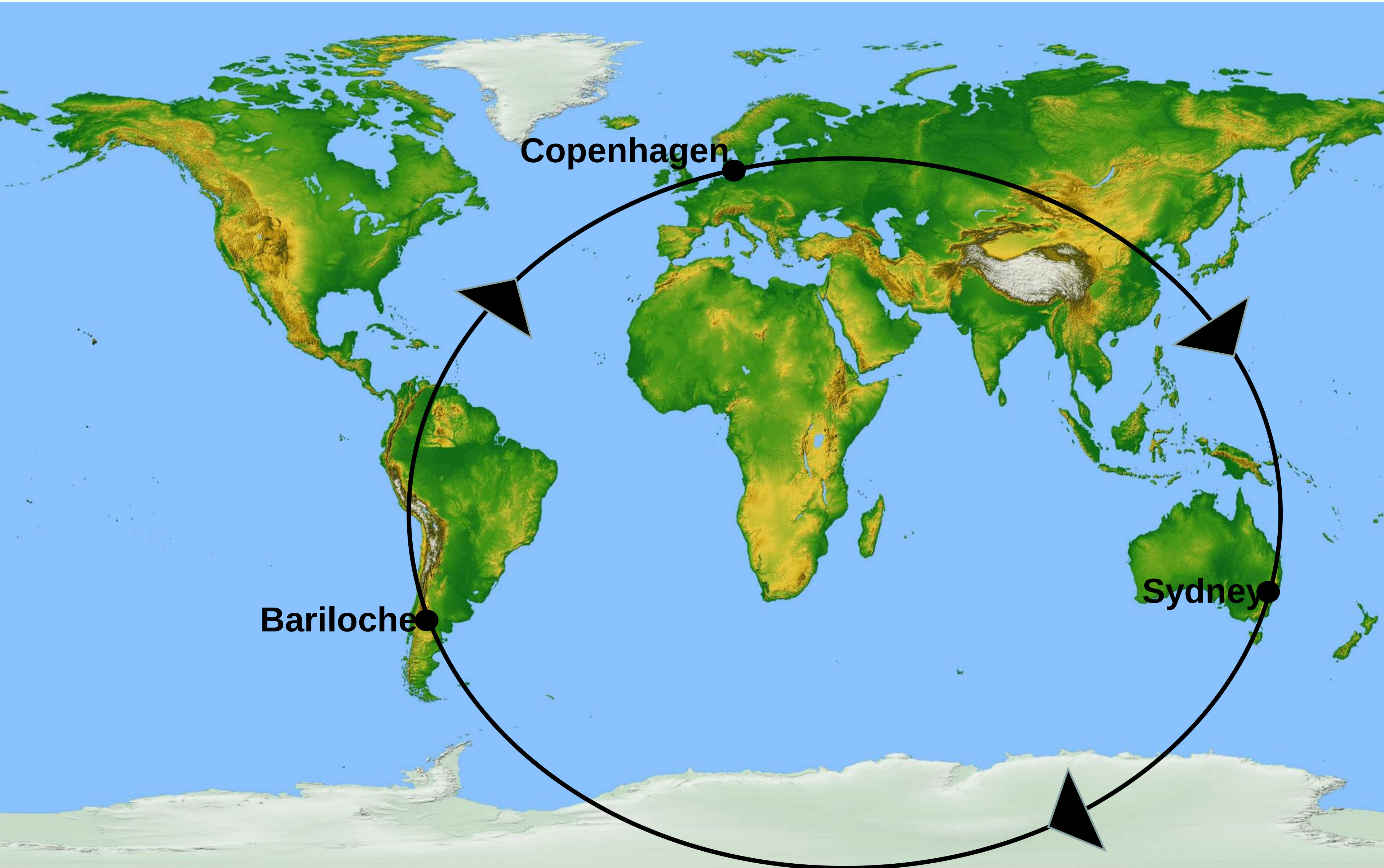
<u>Background and credits</u>

I Motivation: Geometrical phases in Rashba rings

II Proposal: Driven two-level system (TLS)

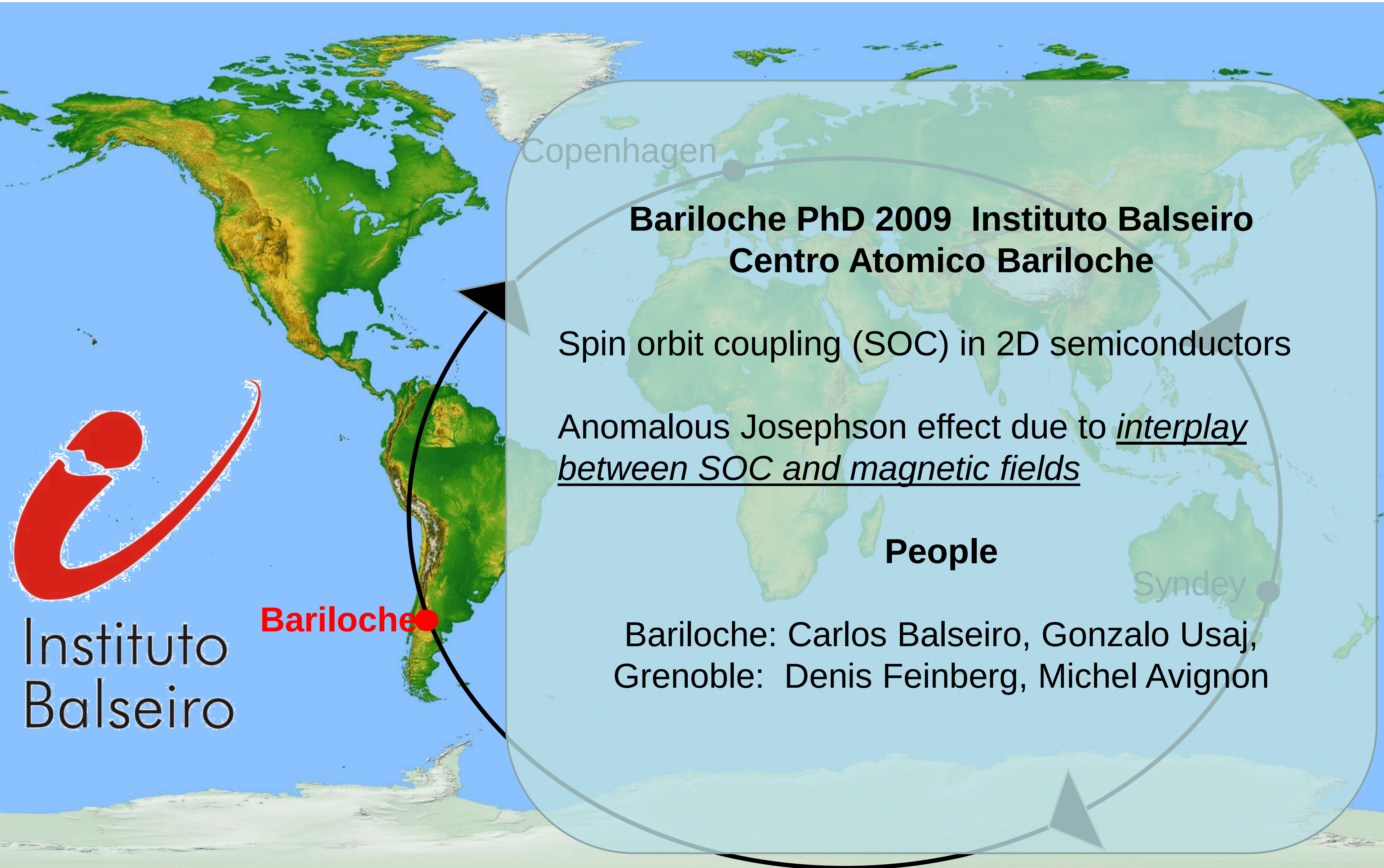
Summary

BACKGROUND AND CREDITS



BACKGROUND AND CREDITS

CONICET



Instituto Balseiro

Bariloche PhD 2009 Instituto Balseiro
Centro Atomico Bariloche

Spin orbit coupling (SOC) in 2D semiconductors

Anomalous Josephson effect due to *interplay between SOC and magnetic fields*

People

Bariloche: Carlos Balseiro, Gonzalo Usaj,
Grenoble: Denis Feinberg, Michel Avignon

BACKGROUND AND CREDITS

CONICET

Copenhagen

Bariloche

Syndey

Copenhagen Postdoc 2009-2011
Niels Bohr International Academy

Double quantum dots in carbon nanotubes, interplay hyperfine, external and SOC fields with valley physics

Anomalous Josephson effect due to *interplay between SOC and magnetic fields*

People

Copenhagen: Karsten Flensberg,

BACKGROUND AND CREDITS

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Sydney Postdoc 2011-2014
Quantum group – The Univ. of Sydney

Copenha

Floquet systems, closed & open

Topological Superconductors *interplay between SOC and magnetic fields. Majora Fermions*

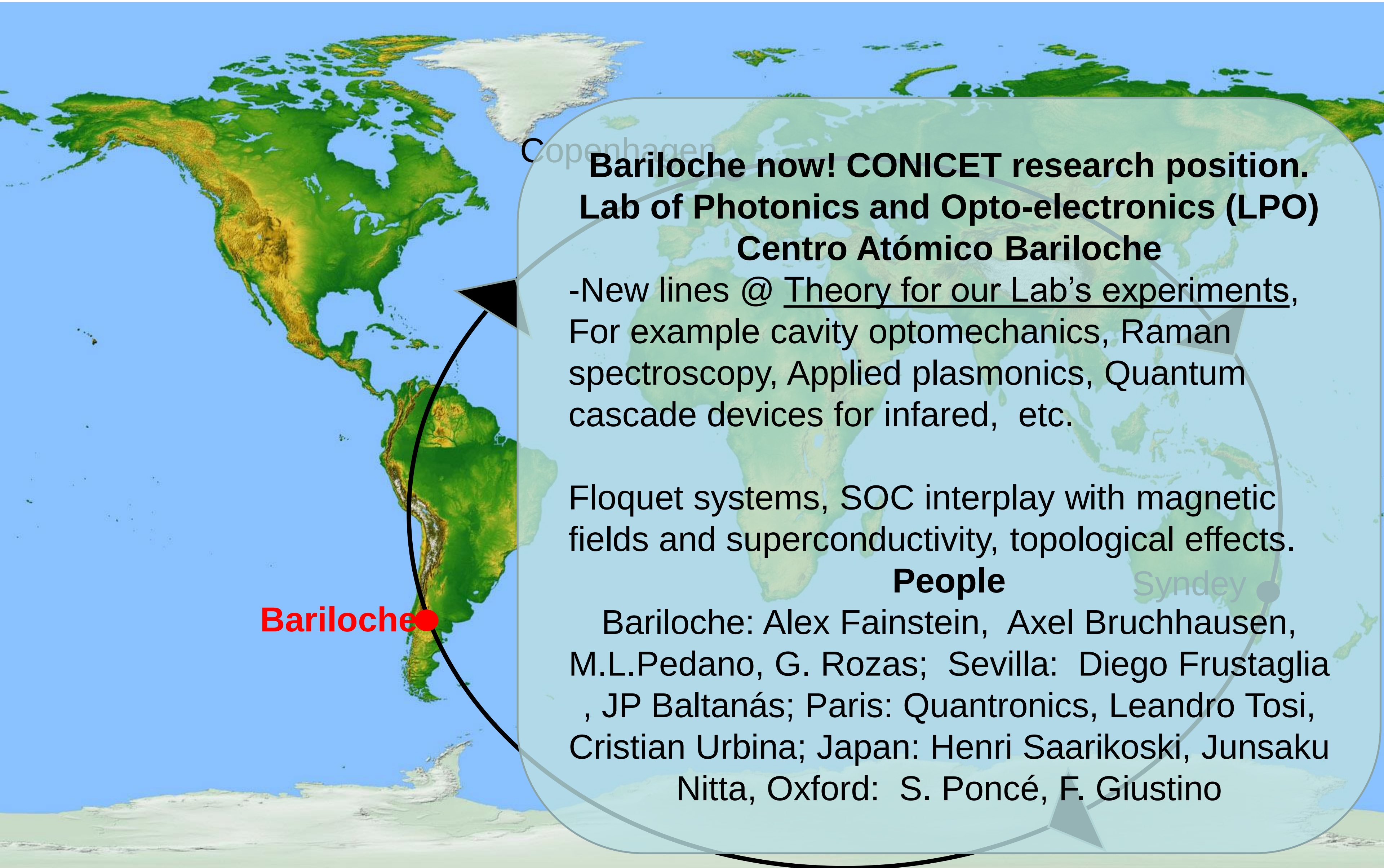
People
Sydney: Andrew Doherty,
Sevilla: Diego Frustaglia

Bariloche

Sydney

eQus
ARC CENTRE OF EXCELLENCE FOR ENGINEERED QUANTUM SYSTEMS

BACKGROUND AND CREDITS



Bariloche now! CONICET research position.
Lab of Photonics and Opto-electronics (LPO)
Centro Atómico Bariloche

-New lines @ Theory for our Lab's experiments, For example cavity optomechanics, Raman spectroscopy, Applied plasmonics, Quantum cascade devices for infared, etc.

Floquet systems, SOC interplay with magnetic fields and superconductivity, topological effects.

People

Bariloche: Alex Fainstein, Axel Bruchhausen, M.L.Pedano, G. Rozas; Sevilla: Diego Frustaglia , JP Baltanás; Paris: Quantronics, Leandro Tosi, Cristian Urbina; Japan: Henri Saarikoski, Junsaku Nitta, Oxford: S. Poncé, F. Giustino

BACKGROUND AND CREDITS

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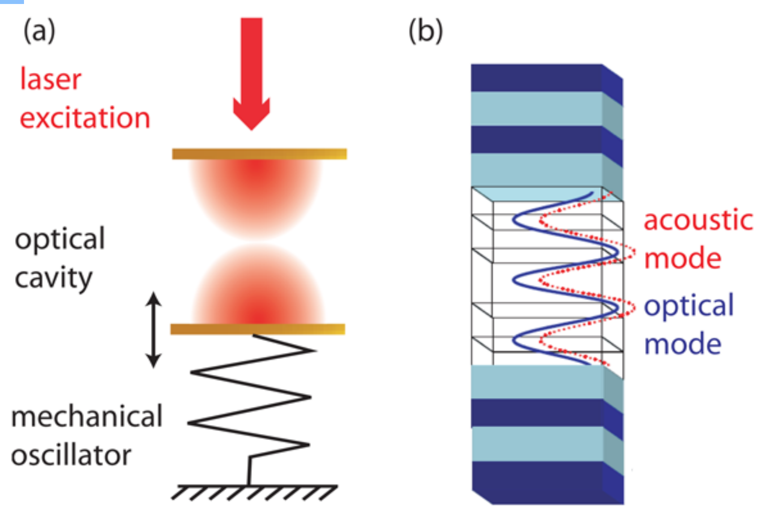
Strong Optical-Mechanical Coupling in a Vertical GaAs/AlAs Microcavity for Subterahertz Phonons and Near-Infrared Light

PRL **110**, 037403 (2013)

Selected for a Viewpoint in *Physics*

PHYSICAL REVIEW LETTERS



An example of the LPO research

Bariloche

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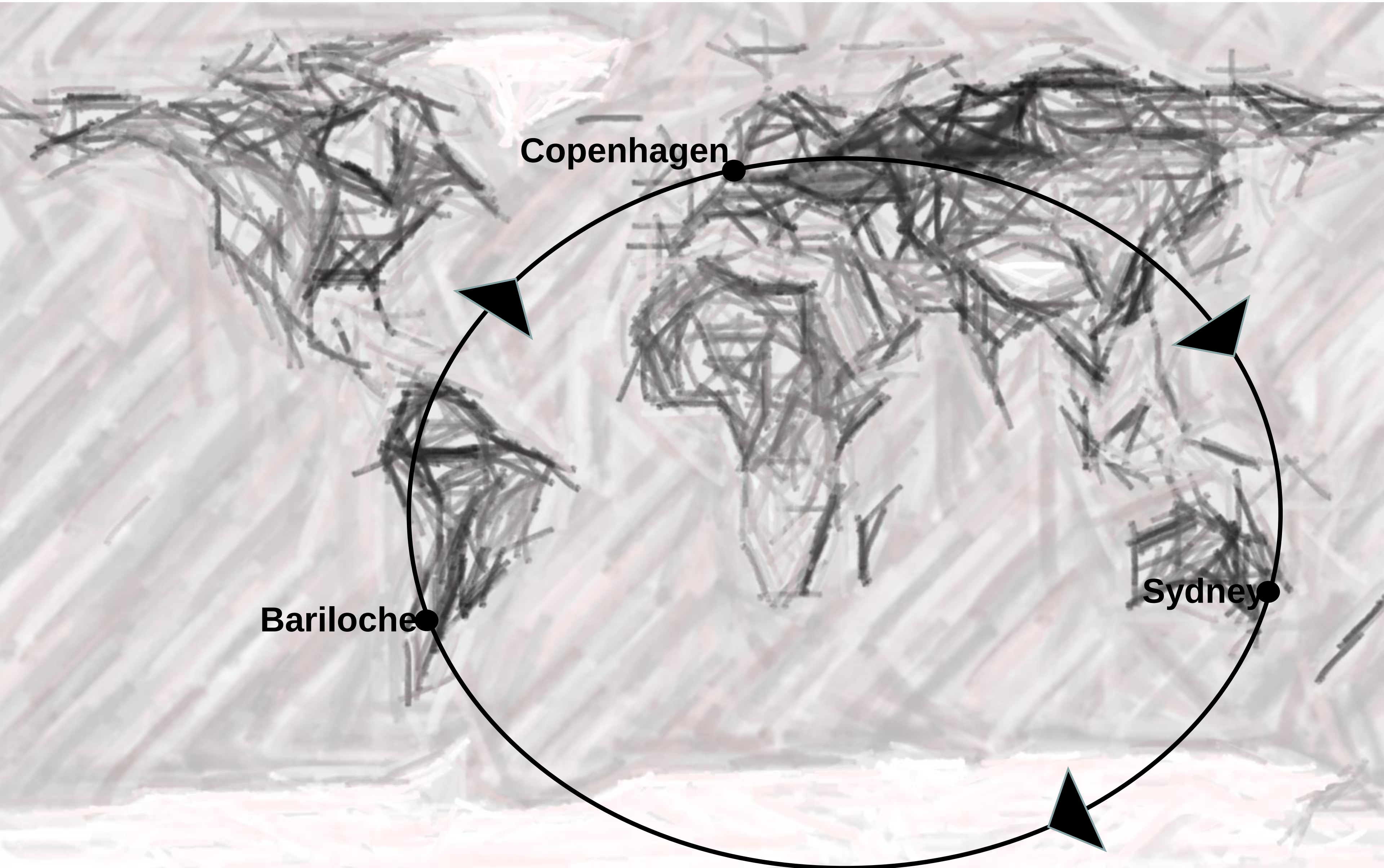

R&D Grant FIS2014-53385-P

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I MOTIVATION: GEOMETRICAL PHASES IN RASHBA RINGS

CONICET

PRL 108, 086801 (2012)

Selected for a Viewpoint in *Physics*

PHYSICAL REVIEW LETTERS

week ending 24 FEBRUARY 2012

Experimental Demonstration of Spin Geometric Phase: Radius Dependence of Time-Reversal Aharonov-Casher Oscillations

Fumiya Nagasawa,[1] Jun Takagi,[1] Yoji Kunihashi,[1] Makoto Kohda,[1,2] and Junsaku Nitta[1,*]

[1]*Graduate School of Engineering, Tohoku University, Sendai 980-8579, Japan*

[2]*PRESTO, Japan Science and Technology Agency, Saitama 331-0012, Japan*

(Received 10 September 2011; published 21 February 2012)

Physics

Physics **5**, 22 (2012)

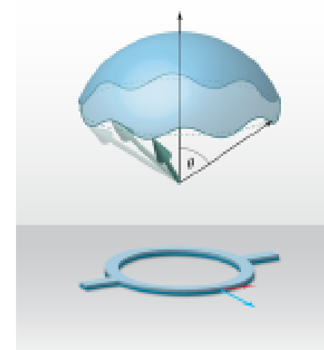
Viewpoint

The ABC of Aharonov Effects

Klaus Richter

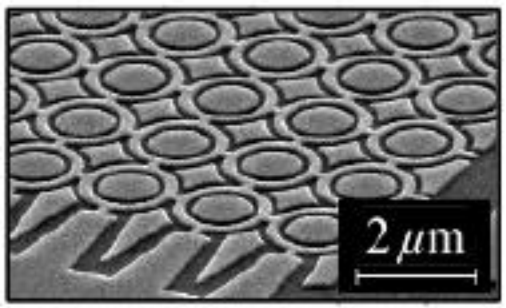
Institut für Theoretische Physik, Universität Regensburg, D-93040 Regensburg, Germany

Published February 21, 2012



I MOTIVATION: GEOMETRICAL PHASES IN RASHBA RINGS

CONICET



40 x 40 ring array

(electrom beam lithography and reactive-ion etching on InAlAs/InGaAs)

Physics

Physics 5, 22 (2012)

Viewpoint

The ABC of Aharonov Effects

Klaus Richter

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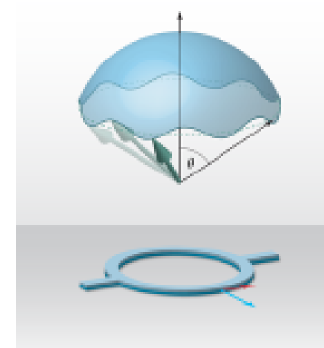

I MOTIVATION: GEOMETRICAL PHASES IN RASHBA RINGS

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nature COMMUNICATIONS

ARTICLE

Received 26 May 2013 | Accepted 30 Aug 2013 | Published 26 Sep 2013

DOI: 10.1038/ncomms3526

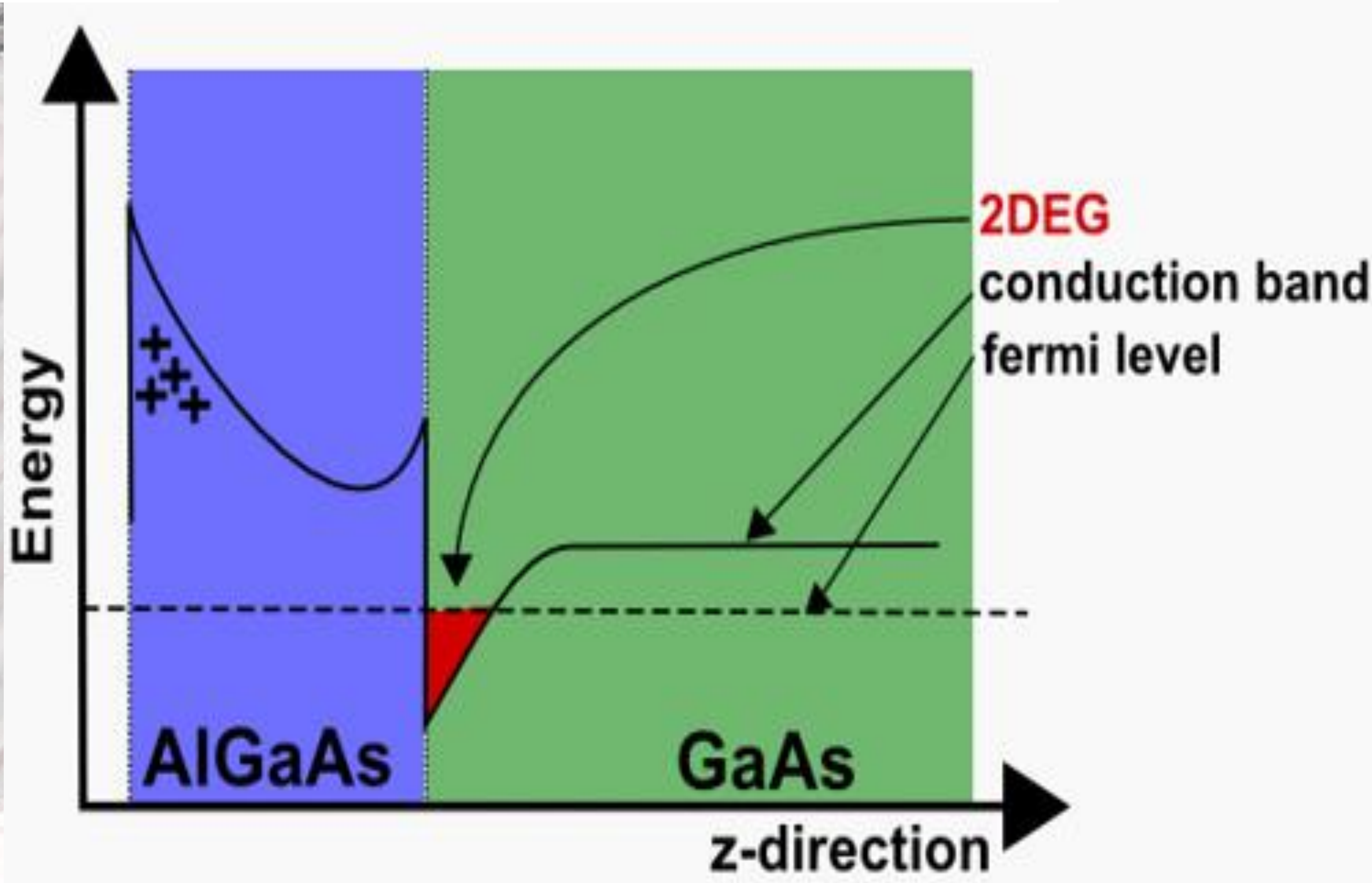
OPEN

Control of the spin geometric phase in semiconductor quantum rings

Fumiya Nagasawa[1], Diego Frustaglia[2], Henri Saarikoski[3], Klaus Richter[3] & Junsaku Nitta[1]

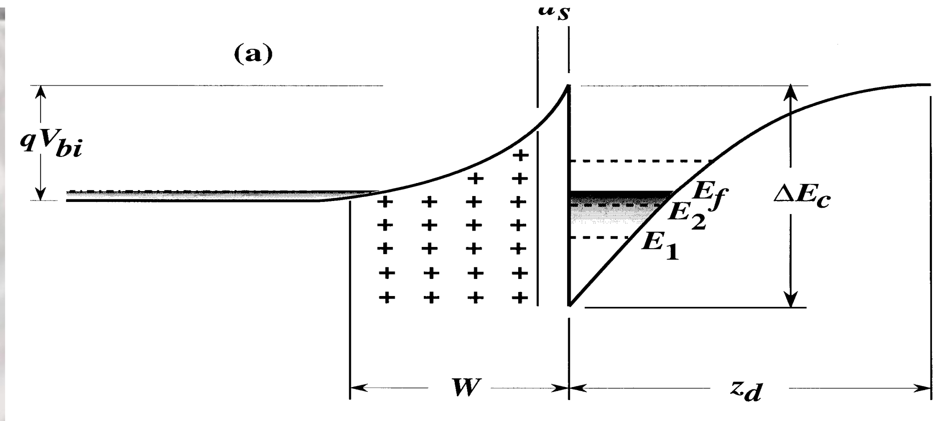
I MOTIVATION: GEOMETRICAL PHASES IN RASHBA RINGS

2 Dimensional Electron Gases (2DEGs)



I MOTIVATION: GEOMETRICAL PHASES IN RASHBA RINGS

Rashba spin-orbit coupling (RSOC)



Rashba E. I., Sov. Phys. Solid State, 2 1109 (1960).

$$H_{SO} = \frac{\hbar}{2m^2c^2}\sigma.[\nabla V(r)\times p]$$

Relativistic effect

$$H_{SO} = \frac{\alpha}{\hbar}(p_y\sigma_x - p_x\sigma_y)$$

It can be modified with gate voltages

Nitta *et al*. PRL **78** (1997)

Miller *et al* PRL **90** 076807 (2003)

	α
GaAs/AlGaAs	0.5–1 meV nm
InSb/InAlSb	5–10 meV nm

I MOTIVATION: GEOMETRICAL PHASES IN RASHBA RINGS

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Free space solution for the RSOC Hamiltonian

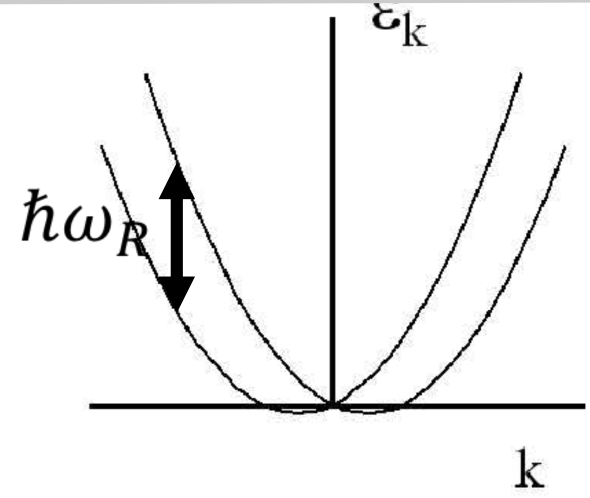
$$H = \frac{p_x^2 + p_y^2}{2m^*} + \frac{\alpha}{\hbar}\left(p_y\sigma_x - p_x\sigma_y\right)$$

$$\Psi_\pm(\boldsymbol{r}) = \frac{1}{\sqrt{2A}} e^{\mathrm{i}\,\boldsymbol{k}\cdot\boldsymbol{r}} \begin{pmatrix} \pm e^{-\mathrm{i}\phi/2} \\ e^{\mathrm{i}\phi/2} \end{pmatrix}$$

$$e^{\mathrm{i}\phi} = (k_y - \mathrm{i}k_x)/k$$

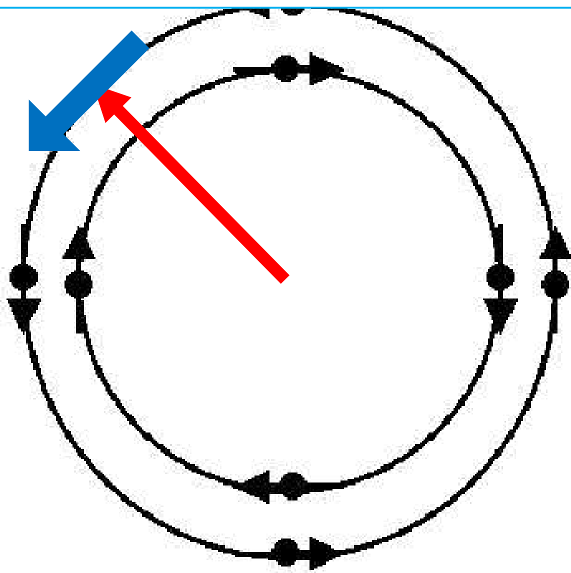
$$\varepsilon_\pm(\mathbf{k}) = \frac{\hbar^2}{2m^*}\left(k_x^2 + k_y^2\right) \pm \alpha\sqrt{k_x^2 + k_y^2}$$

We define $\hbar\omega_R = 2\alpha k$



Spin is ⊥ to the k-vector

Fermi surface



I MOTIVATION: GEOMETRICAL PHASES IN RASHBA RINGS

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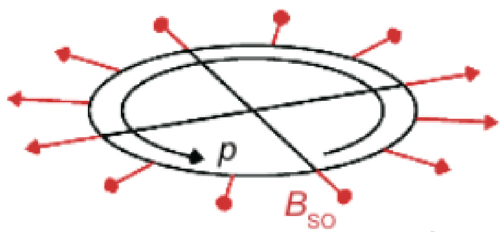
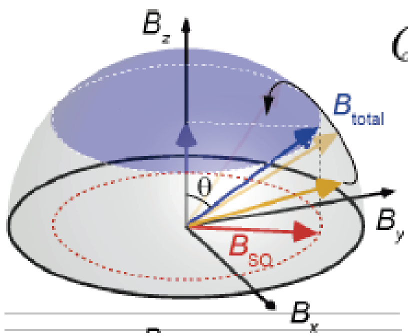
The RSOC Ring



$$\omega_R = 2\alpha k$$

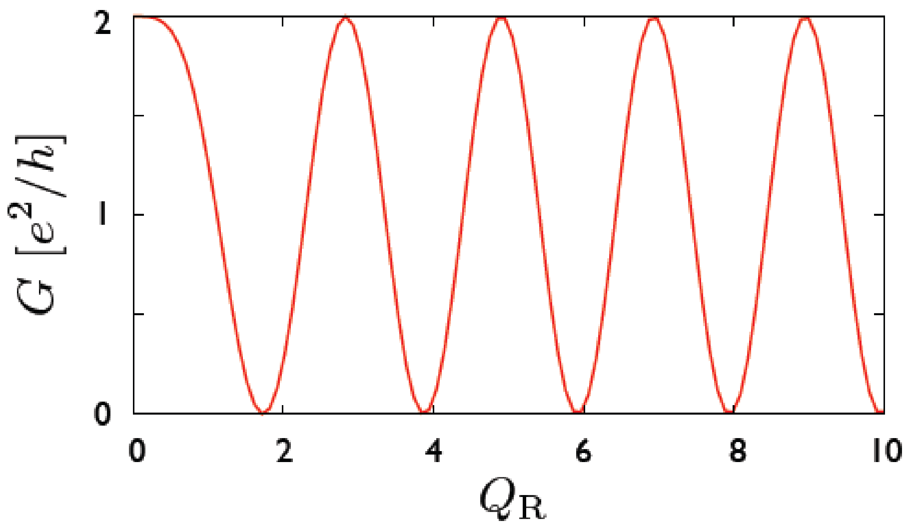
$$\omega_0 = \frac{velocity}{R} = \frac{\hbar^2 k}{m^* R}$$

$$\tan\theta = \frac{\omega_R}{\omega_0} = Q_R$$ **adiabaticity parameter**



$$Q_R = \frac{2\alpha m^* R}{\hbar^2}$$

[Frustaglia & Richter, PRB (2004)]



$$G = \frac{e^2}{h}\left\{1 + \cos\left[\pi\left(\sqrt{1 + {Q_R}^2} - 1\right)\right]\right\}$$

$$\pi\left(\sqrt{1 + {Q_R}^2} - 1\right) = \pi Q_R \sin\theta - \pi(1 - \cos\theta)$$

geometric phase $\equiv$ **solid angle**

total phase **dynamic phase** **geometric phase**

I MOTIVATION: GEOMETRICAL PHASES IN RASHBA RINGS

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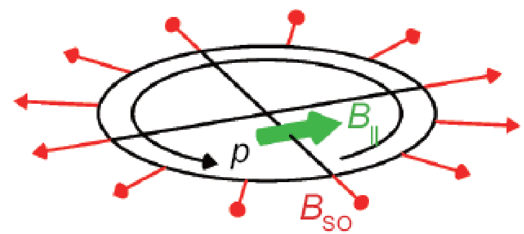
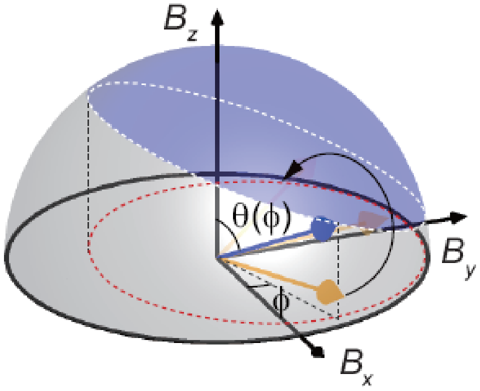
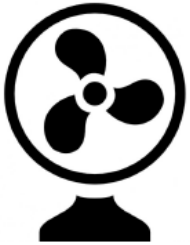
The RSOC Ring + a competing inplane field.

GOAL: Study the effect of changing the topology of the driving







rotating fan
(weak in-plane ***B***)

beating hand fan
(strong in-plane ***B***)

Fully adiabatic case

[Lyanda-Geller, PRL (1993)]

Spin texture & geometric phase undergo a topological transition

I MOTIVATION: GEOMETRICAL PHASES IN RASHBA RINGS

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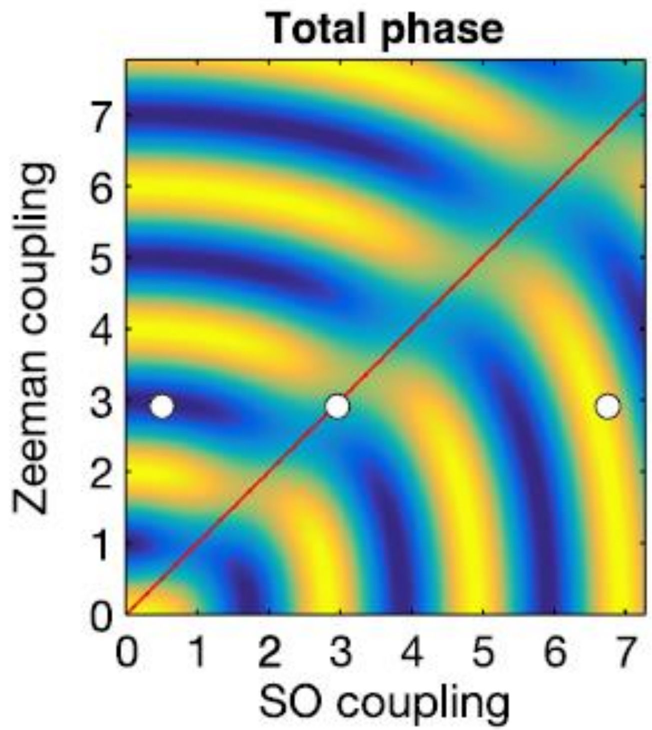
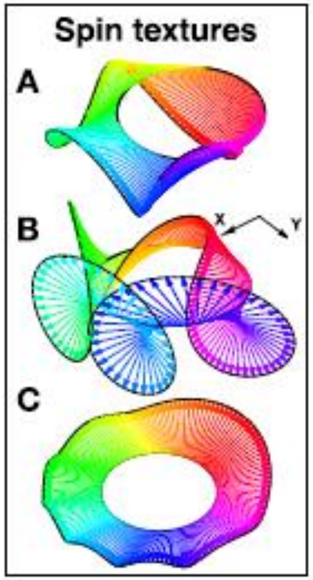
The RSOC Ring + a competing inplane field.

Adiabatic-like
phase dislocation
(field's topology)

Effective Berry phase





Non-adiabatic spin dynamics

Saarikoski, Vázquez-Lozano, Baltanás, Nagasawa, Nitta & Frustaglia, PRB(R) 2015.

Difficulties with spin carriers: disorder, multichannel transport and dephasing in hybrid spin-orbit/magnetic textures.

R&D Grant FIS2014-53385-P

New J. Phys. **19** (2017) 063010

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5 Department of Materials Science, Tohoku University, Sendai 980-8579, Japan

Background and credits ✓

I Motivation: Geometrical phases in Rashba rings ✓

II <u>Proposal: Driven two-level system (TLS)</u>

Summary

II PROPOSAL: DRIVEN TWO-LEVEL SYSTEM (TLS)

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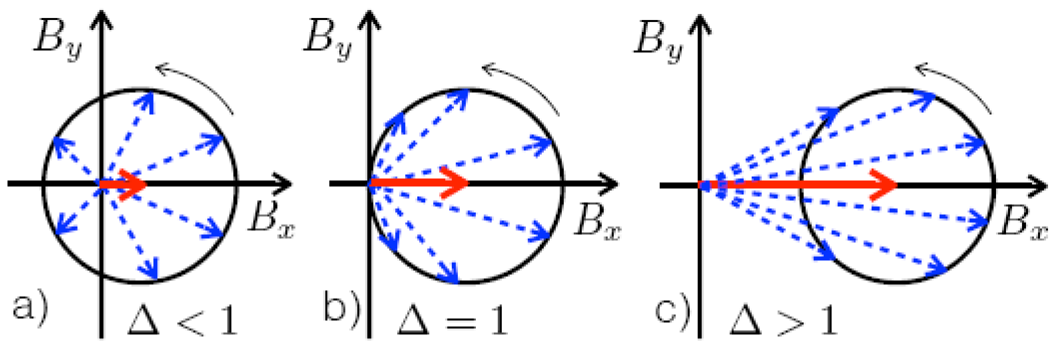
Alternative (as a proof of concept)**: spin-dynamics (resonance) under time-dependent topological driving fields.**

Topological driving: Floquet treatment

$$\mathbf{B}_1(t) = B_1(\cos\omega_0 t\ \hat{\mathrm{x}} + \sin\omega_0 t\ \hat{\mathrm{y}}) \qquad \mathbf{B}_2 = B_2\ \hat{\mathrm{x}}$$

$$\Delta = \frac{\omega_2}{\omega_1}$$



$$H(t) = \frac{\hbar\omega_1}{2}(\cos\omega_0 t\ \sigma_x + \sin\omega_0 t\ \sigma_y) + \frac{\hbar\omega_2}{2}\sigma_x$$

II PROPOSAL:
DRIVEN TWO-LEVEL SYSTEM (TLS)

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1- Schroedinger equation

$$\left(\hat{H}(t) - \mathrm{i}\hbar\frac{d}{dt}\right)|\phi(t)\rangle = 0$$

$$\left|\phi_a(t)\right\rangle = \mathrm{e}^{-\frac{\mathrm{i}}{\hbar}\varepsilon_a t}\left|\phi_a^T(t)\right\rangle$$

2- ***Floquet*** quasi-energy state (FQE)

3- Equation for the FQE

$$\left(\hat{H}(t) - \mathrm{i}\hbar\frac{d}{dt}\right)\left|\phi_a^T(t)\right\rangle = \varepsilon_a\left|\phi_a^T(t)\right\rangle$$

Fourier expansion for H and the FQEs in order to solve (3)

$$\hat{H}(t) = \sum_{n=-\infty}^{\infty}\mathrm{e}^{-\mathrm{i}\Omega nt}\hat{H}^{(n)}, \quad \left|\phi_a^T(t)\right\rangle = \sum_{n=-\infty}^{\infty}\mathrm{e}^{-\mathrm{i}\Omega nt}\left|\phi_a^{(n)}\right\rangle$$

$$\begin{pmatrix} \ddots & \vdots & \vdots & \vdots & \iddots \\ \cdots & \left(\hat{H}^{(0)} + \hbar\Omega\right) & \hat{H}^{(-1)} & \hat{H}^{(-2)} & \cdots \\ \cdots & \hat{H}^{(1)} & \hat{H}^{(0)} & \hat{H}^{(-1)} & \cdots \\ \cdots & \hat{H}^{(2)} & \hat{H}_{(1)} & \left(\hat{H}^{(0)} - \hbar\Omega\right) & \cdots \\ \iddots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}\begin{pmatrix} \vdots \\ \left|\phi_a^{(-1)}\right\rangle \\ \left|\phi_a^{(0)}\right\rangle \\ \left|\phi_a^{(1)}\right\rangle \\ \vdots \end{pmatrix} = \varepsilon_a\begin{pmatrix} \vdots \\ \left|\phi_a^{(-1)}\right\rangle \\ \left|\phi_a^{(0)}\right\rangle \\ \left|\phi_a^{(1)}\right\rangle \\ \vdots \end{pmatrix}$$

Shirley J H 1965 *Phys. Rev.* 138 B979

II PROPOSAL:
DRIVEN TWO-LEVEL SYSTEM (TLS)

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We know

TOTAL PHASE @ period *T* = **DYNAMIC PHASE** @ period *T* + **GEOMETRICAL PHASE** @ period *T*

Exact evolution of a FQE

$$\hat{\mathcal{U}}\left(t_0+T,t_0\right)\left|\phi_a^T(t_0)\right\rangle = \mathrm{e}^{-\frac{\mathrm{i}}{\hbar}\varepsilon_a T}\left|\phi_a^T(t_0)\right\rangle$$

Quasi-energy phase times T → From this we directly get **TOTAL PHASE** @ period *T*

Mean energy @ period T of a FQS

$$\overline{E}_a = \frac{1}{T}\int_0^T dt\left\langle\phi_a^T(t)|\hat{H}(t)|\phi_a^T(t)\right\rangle$$

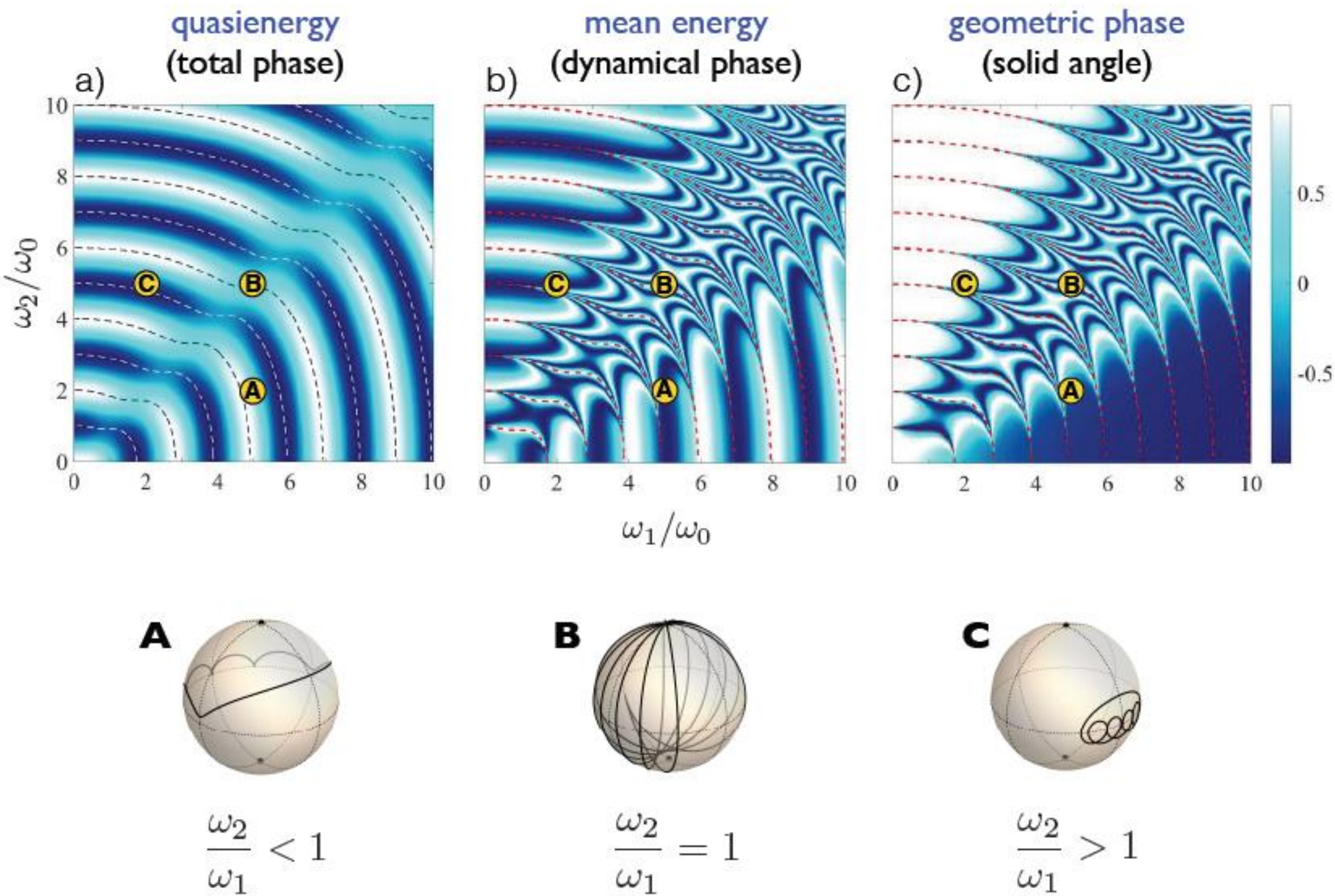
→ From this we directly get **DYNAMIC PHASE** @ period *T*

$$= \frac{1}{T}\int_0^T dt\left\langle\phi_a^T(t)\left|\hat{H}(t)-\mathrm{i}\hbar\frac{d}{dt}+\mathrm{i}\hbar\frac{d}{dt}\right|\phi_a^T(t)\right\rangle$$

$$= \varepsilon_a - \Omega\frac{\partial\varepsilon_a}{\partial\Omega}, \qquad = \epsilon_a - \hbar\omega_0\left\langle k\right\rangle_a ,$$

$$\left\langle k\right\rangle_a \equiv \sum_k k w_a(k)\ , \quad w_a(k) \equiv \left\langle\phi_a^{(k)}\middle|\phi_a^{(k)}\right\rangle$$

II PROPOSAL:
DRIVEN TWO-LEVEL SYSTEM (TLS)



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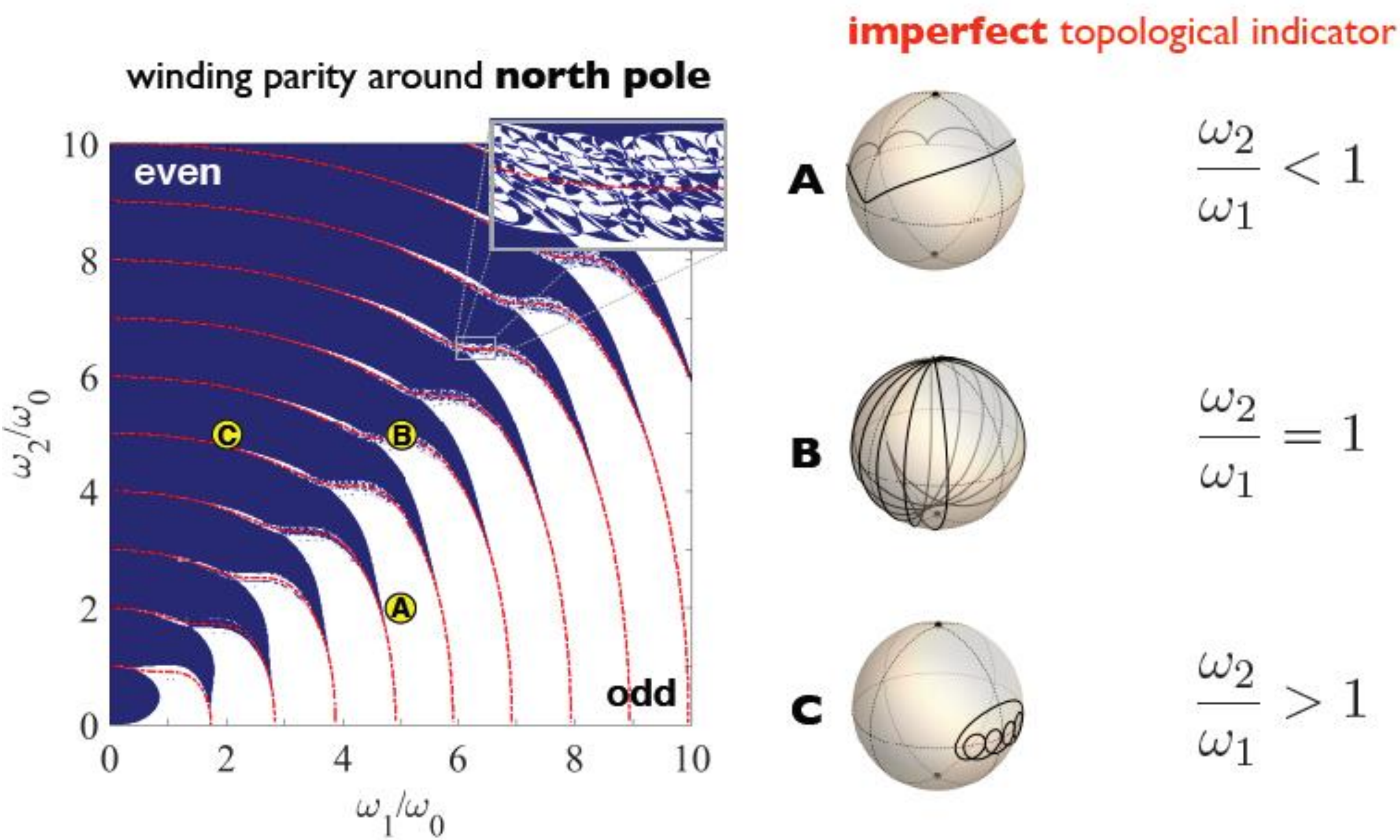

$$H(t) = \frac{\hbar\omega_1}{2}(\cos\omega_0 t\ \sigma_x + \sin\omega_0 t\ \sigma_y) + \frac{\hbar\omega_2}{2}\sigma_x$$

II PROPOSAL:
DRIVEN TWO-LEVEL SYSTEM (TLS)

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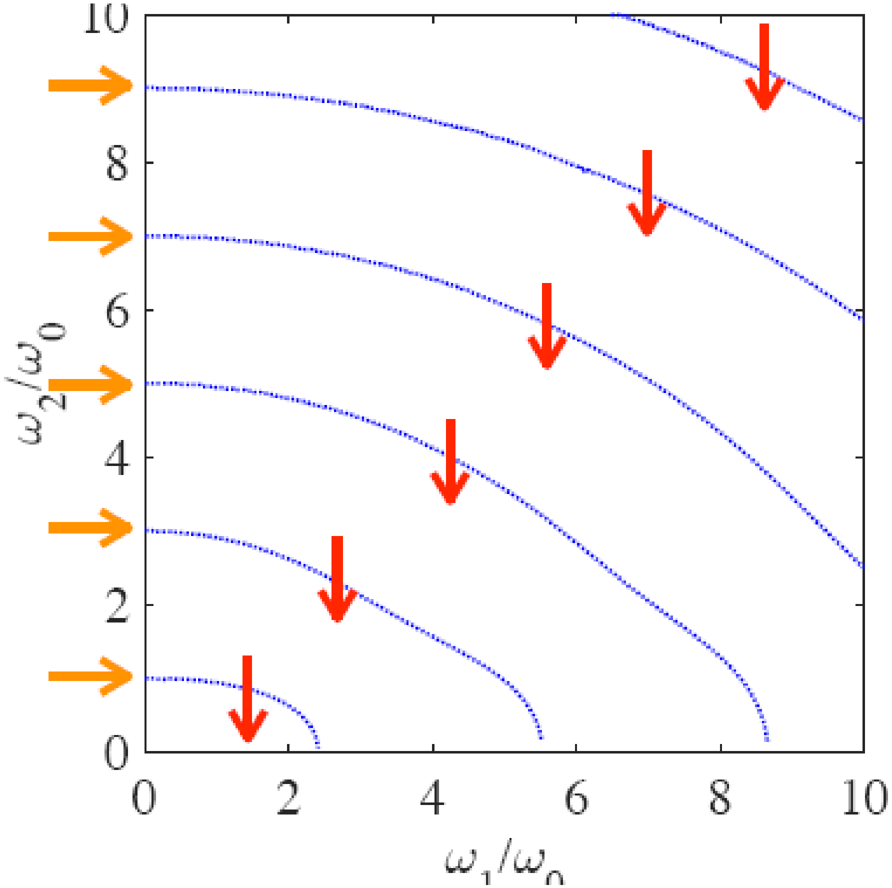
Linear driving: resonances and Bloch-Siegert shift

Rabi's resonances (odd # photons)



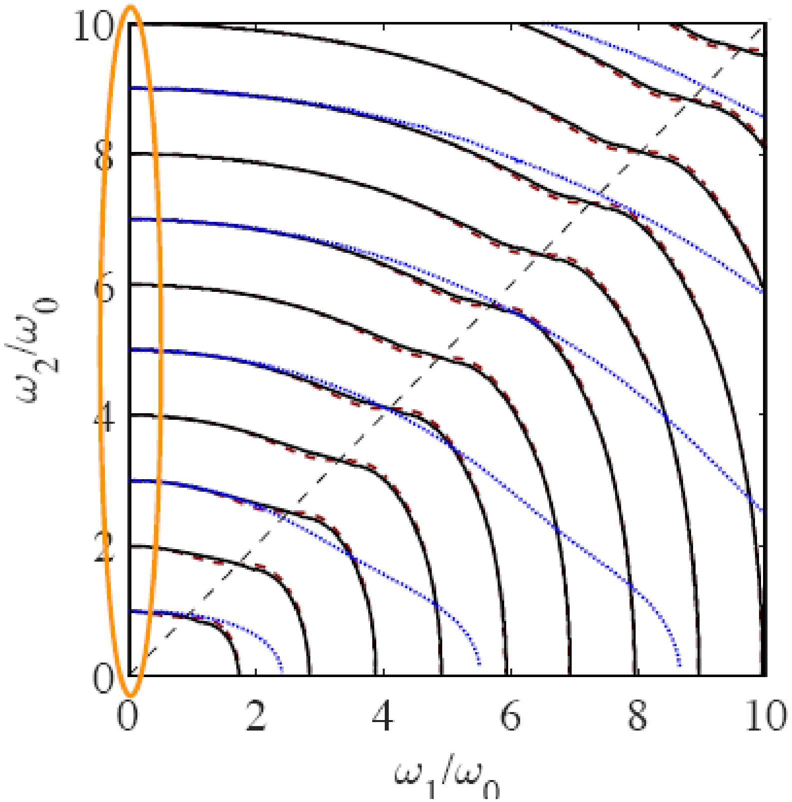
Bloch-Siegert shift

$$H(t) = \frac{\hbar\omega_1}{2}\sin\omega_0 t\ \sigma_y + \frac{\hbar\omega_2}{2}\sigma_x$$

II PROPOSAL:
DRIVEN TWO-LEVEL SYSTEM (TLS)

Topological driving: characteristic resonance profile

Rabi's resonances
(integer # photons)



$$H(t) = \frac{\hbar\omega_1}{2}\left(\cos\omega_0 t\ \sigma_x + \sin\omega_0 t\ \sigma_y\right) + \frac{\hbar\omega_2}{2}\sigma_x$$

II PROPOSAL:
DRIVEN TWO-LEVEL SYSTEM (TLS)

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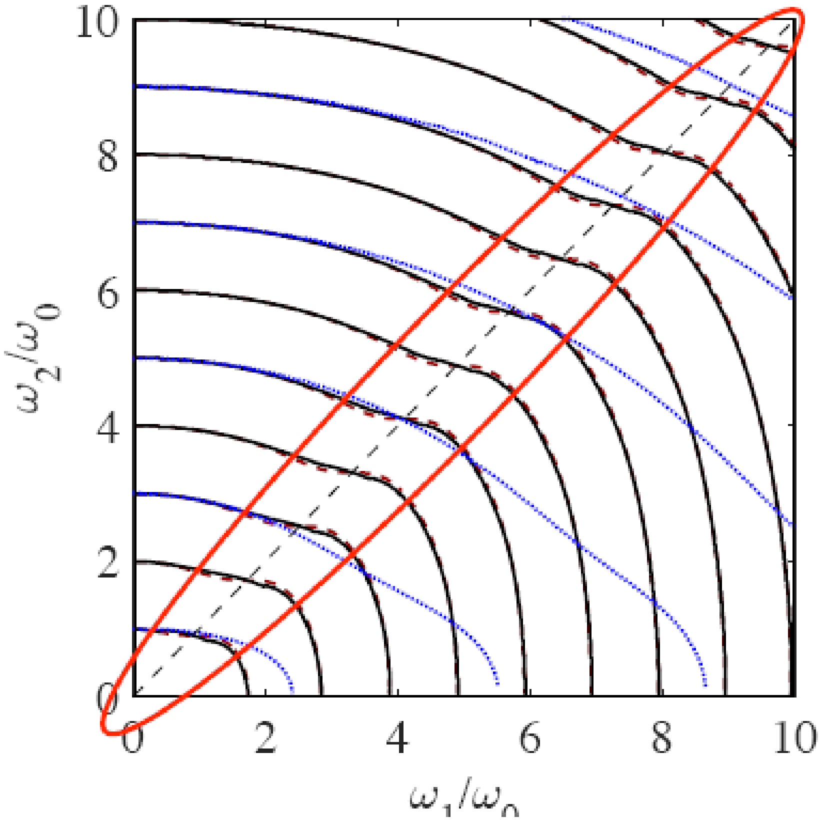
Topological driving: characteristic resonance profile



definite
INFLECTIONS
along critical line

$$\frac{\omega_2}{\omega_1} = 1$$

$$H(t) = \frac{\hbar\omega_1}{2}\left(\cos\omega_0 t\ \sigma_x + \sin\omega_0 t\ \sigma_y\right) + \frac{\hbar\omega_2}{2}\sigma_x$$

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SUMMARY

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Spin-1/2 driven by topological field textures
(either in **transport** or **resonant** settings)

> Topological field characteristics **imprinted** in non-adiabatic spin states.

> **Implementations** in resonant two-level systems:

- **NMR:** Radio-frequency pulse engineering (available).

- **Strongly-driven superconducting qubits:** adapted Landau-Zener-Stückelberg interferometry.

Mach-Zehnder Interferometry in a Strongly Driven Superconducting Qubit

$$\nu = \omega/2\pi.$$

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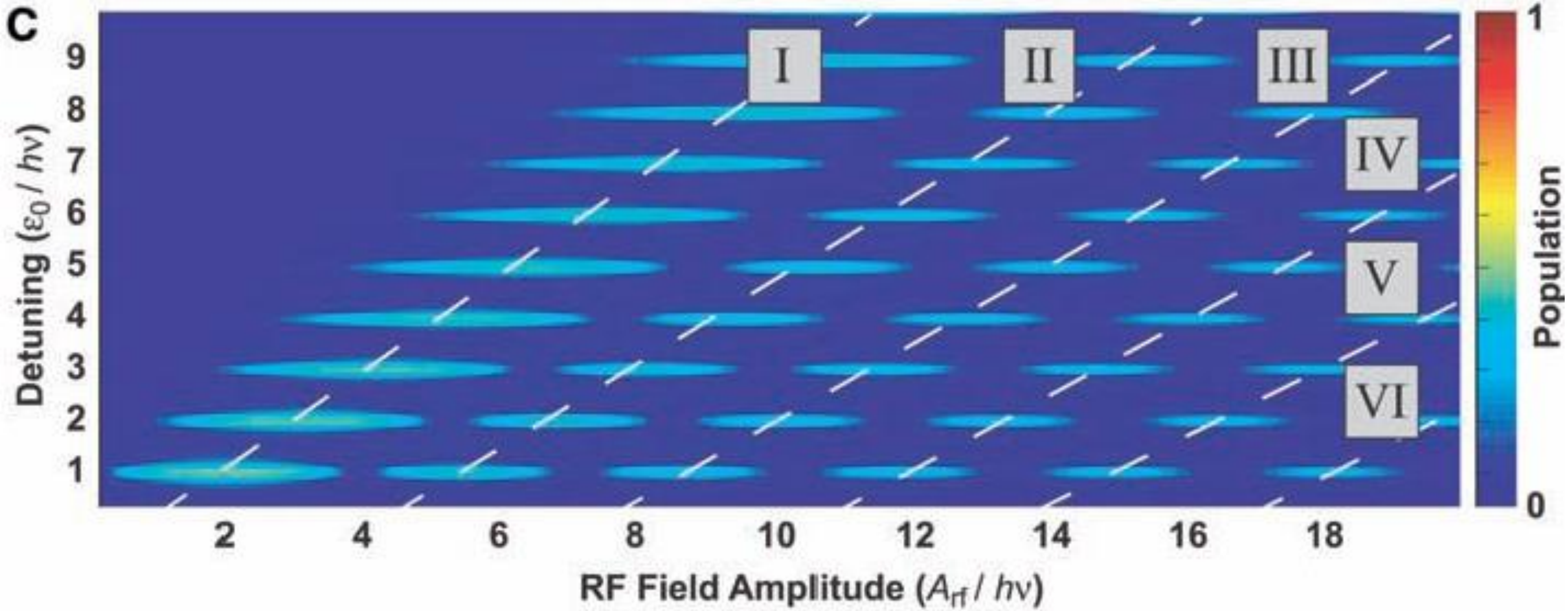
$$\mathcal{H} = -\frac{1}{2}(\Delta\sigma^x + \varepsilon(t)\sigma^z),$$

$$\varepsilon(t) = \varepsilon_0 + A_{\mathrm{rf}} \cos\omega t$$



SUMMARY

CONICET

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