Quantum state geometry in electronic platforms

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FEDER

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

AGENCIA ESTATAL DE INVESTIGACIÓN

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First i-link workshop:
Novel Trends in Topological Systems and Quantum Thermodynamics
Palma de Mallorca, June 5-6 2023.

Collaborators

E.J. Rodríguez (Seville)
Prof. J.P. Baltanás (Seville)
Prof. A. Cabello (Seville)

Prof. J. Nitta (Sendai)

Dr. D. Bercioux (San Sebastian)

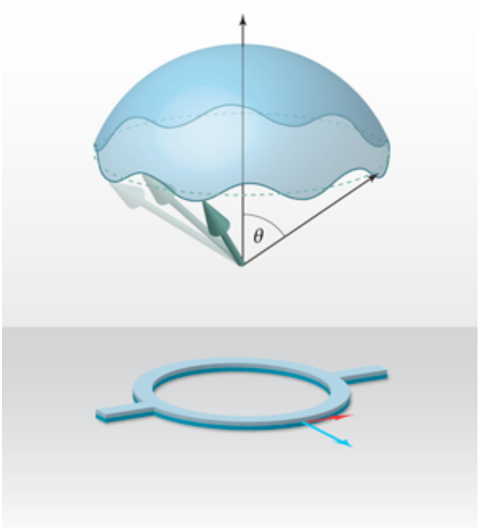
Dr. A. Iñiguez (San Sebastian)

Dr. A. Reynoso (Bariloche)

Three parallel research lines

1.

Geometric resources for spin control



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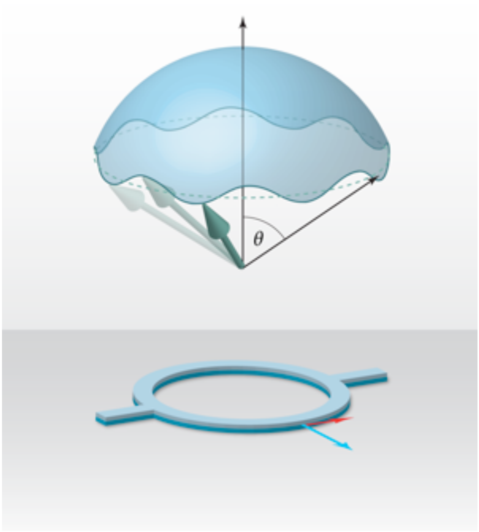
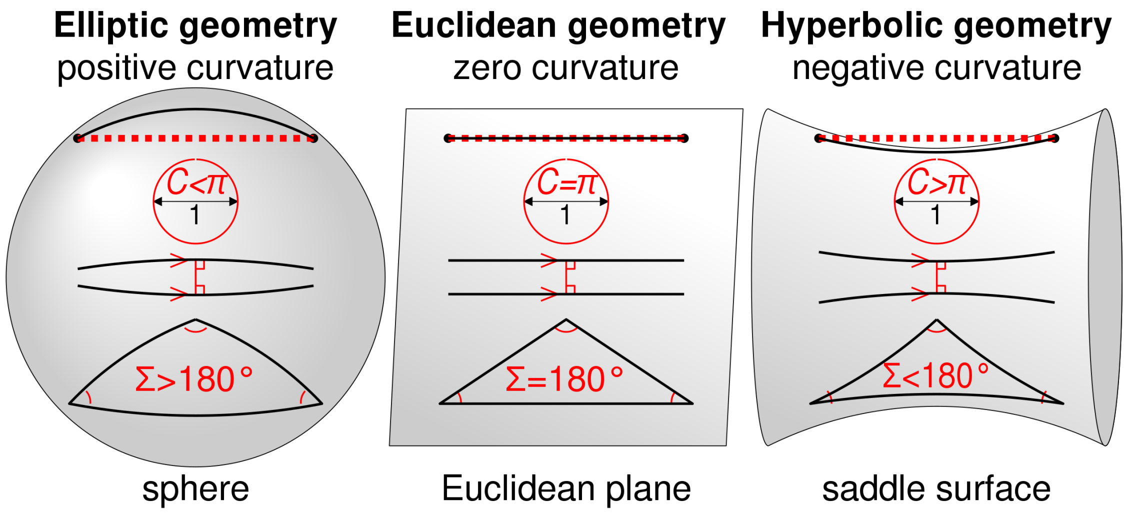


2.
Spin-carrier dynamics in non-Euclidean spaces



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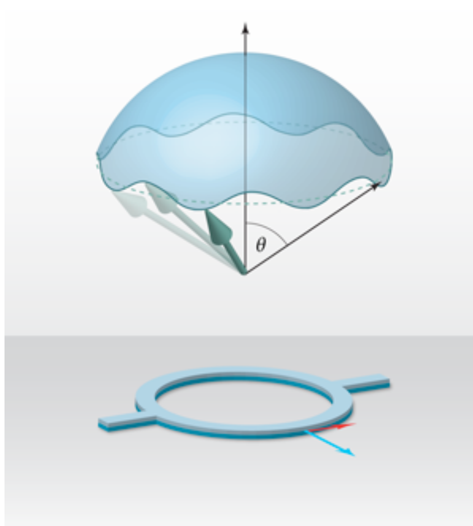

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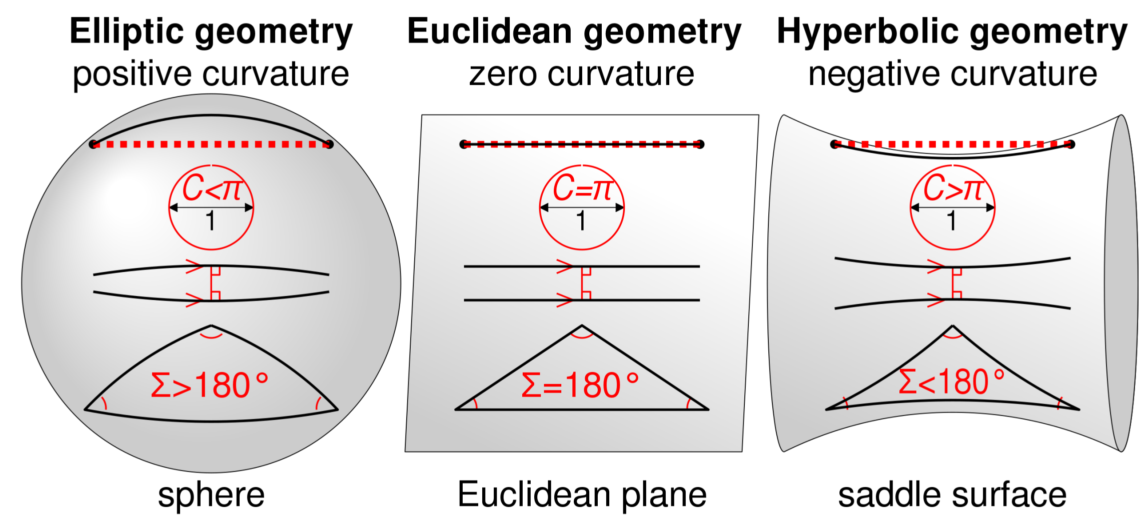
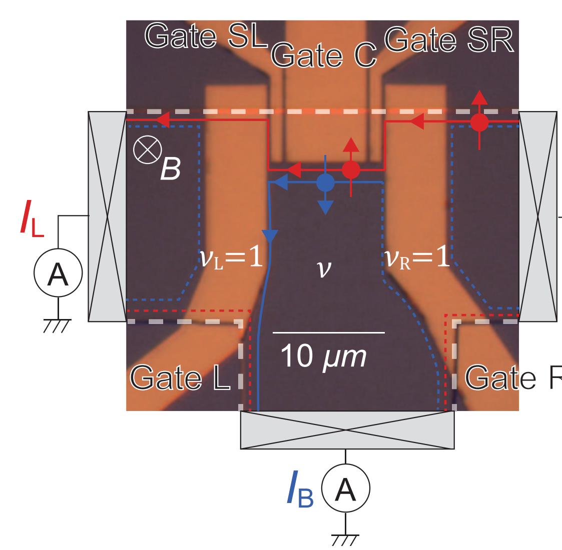
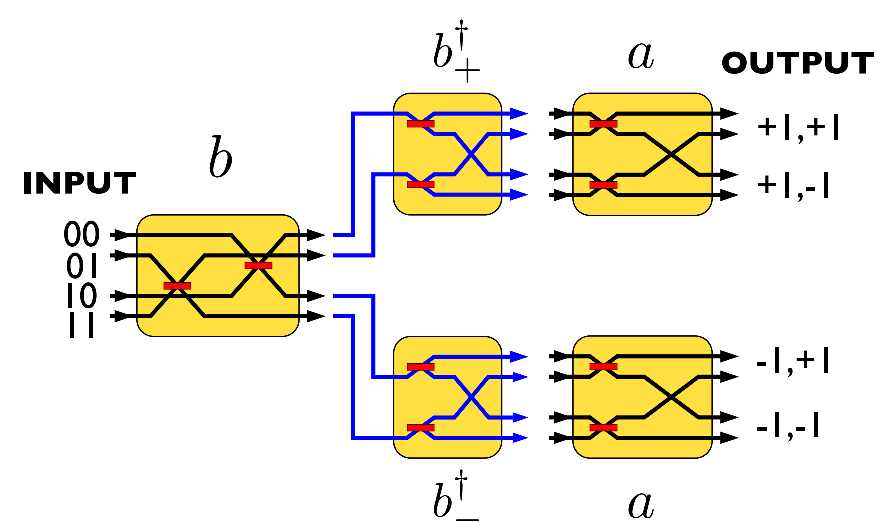


3.
Electron quantum optics for quantum contextuality





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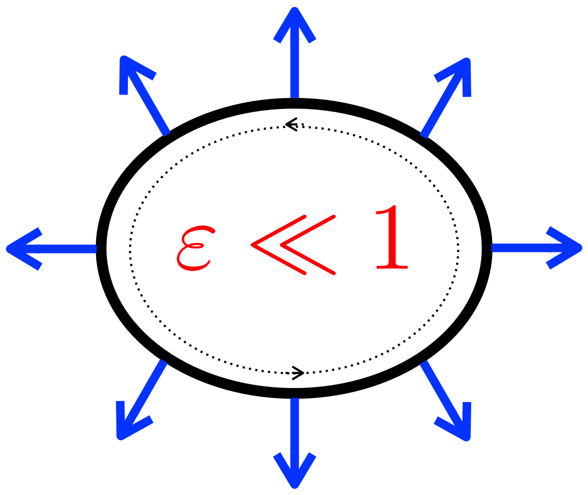

Elliptic circuit with
Rashba SOC

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

**A. Iñiguez,
D. Bercioux,
DF (2023)**

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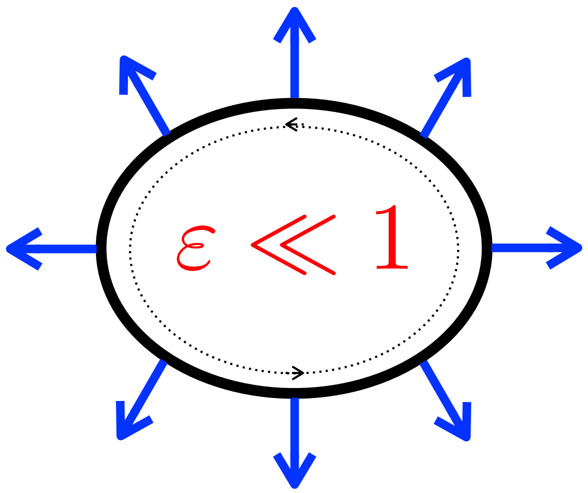

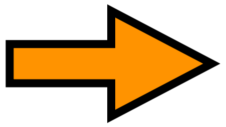

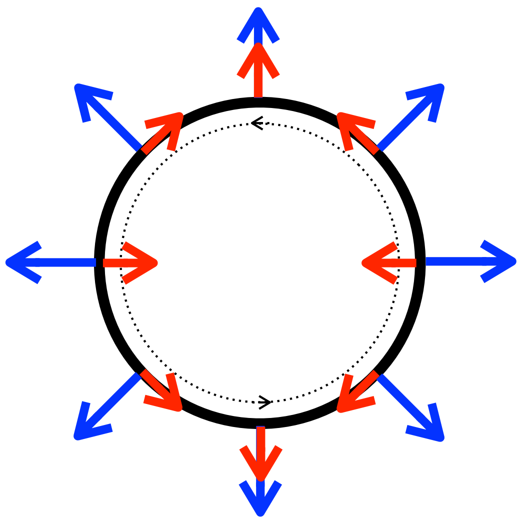

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**A. Iñiguez,
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DF (2023)**

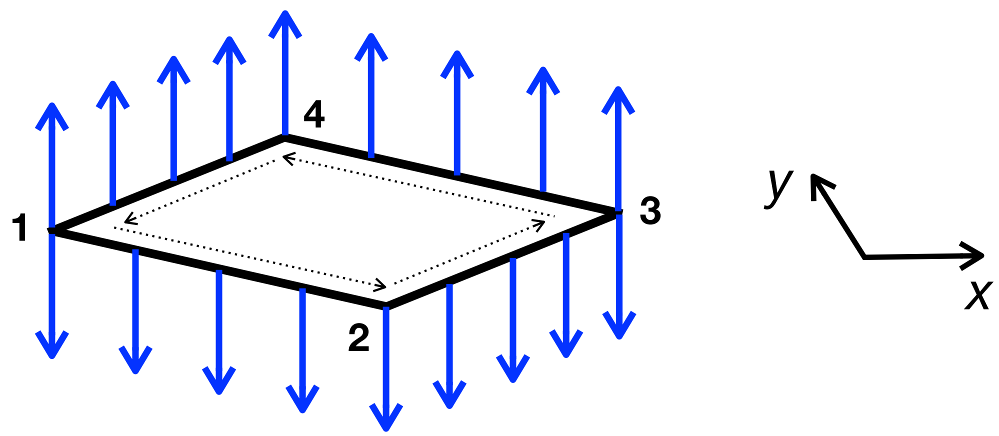
Circular circuit with
Rashba SOC +
Dresselhaus-like SOC

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

$$H_{\mathrm{D}} \approx -\varepsilon\frac{\alpha}{\hbar}(p_x\sigma_y + p_y\sigma_x)$$

**Synthetic
SOC !**

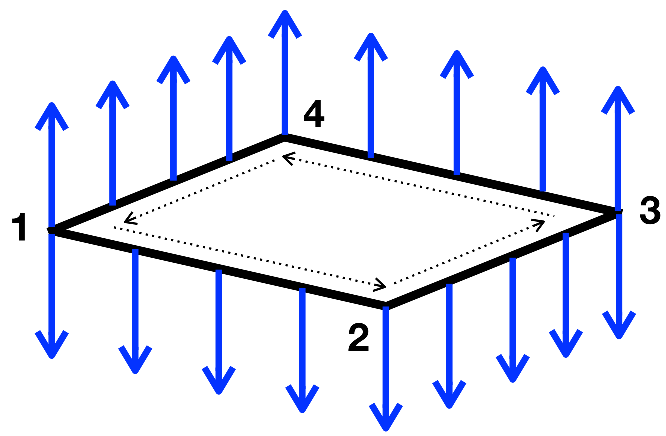
1. Geometric resources for spin control

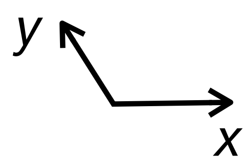


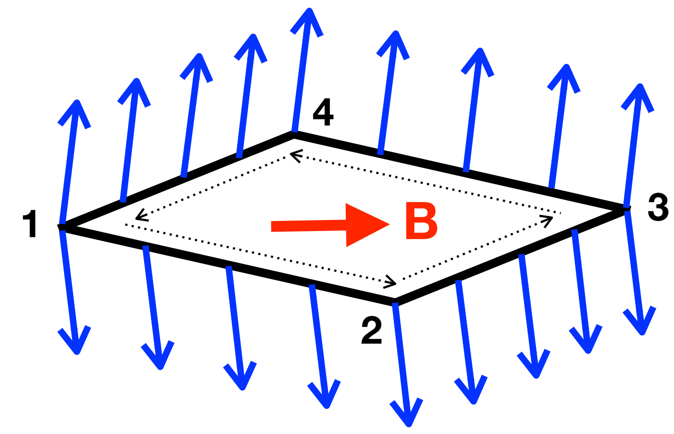
Polygonal circuit with
Dresselhaus 110 SOC

$$H_{\mathrm{D110}} = -\frac{\beta}{\hbar} p_x \sigma_z$$ **: spin helix**

1. Geometric resources for spin control







Activation of spin scattering centers at vertices 1 and 3 !

Polygonal circuit with
Dresselhaus 110 SOC

Polygonal circuit with
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inplane Zeeman

$$H_{\mathrm{D110}} = -\frac{\beta}{\hbar} p_x \sigma_z$$ **: spin helix**

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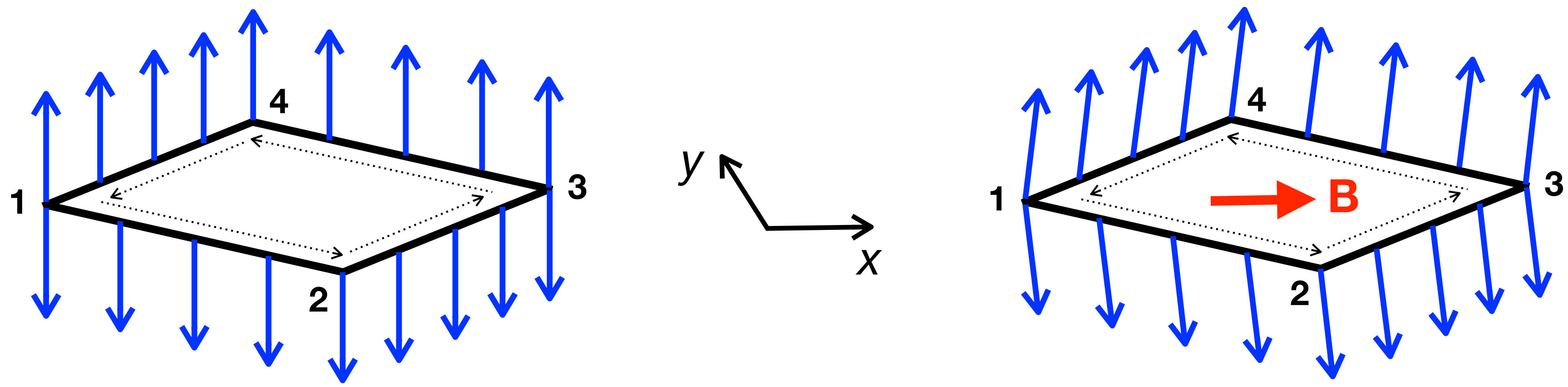

Polygonal circuit with **Dresselhaus 110** SOC

Polygonal circuit with **Dresselhaus 110** SOC + **inplane Zeeman**

Activation of spin scattering centers at vertices 1 and 3 !

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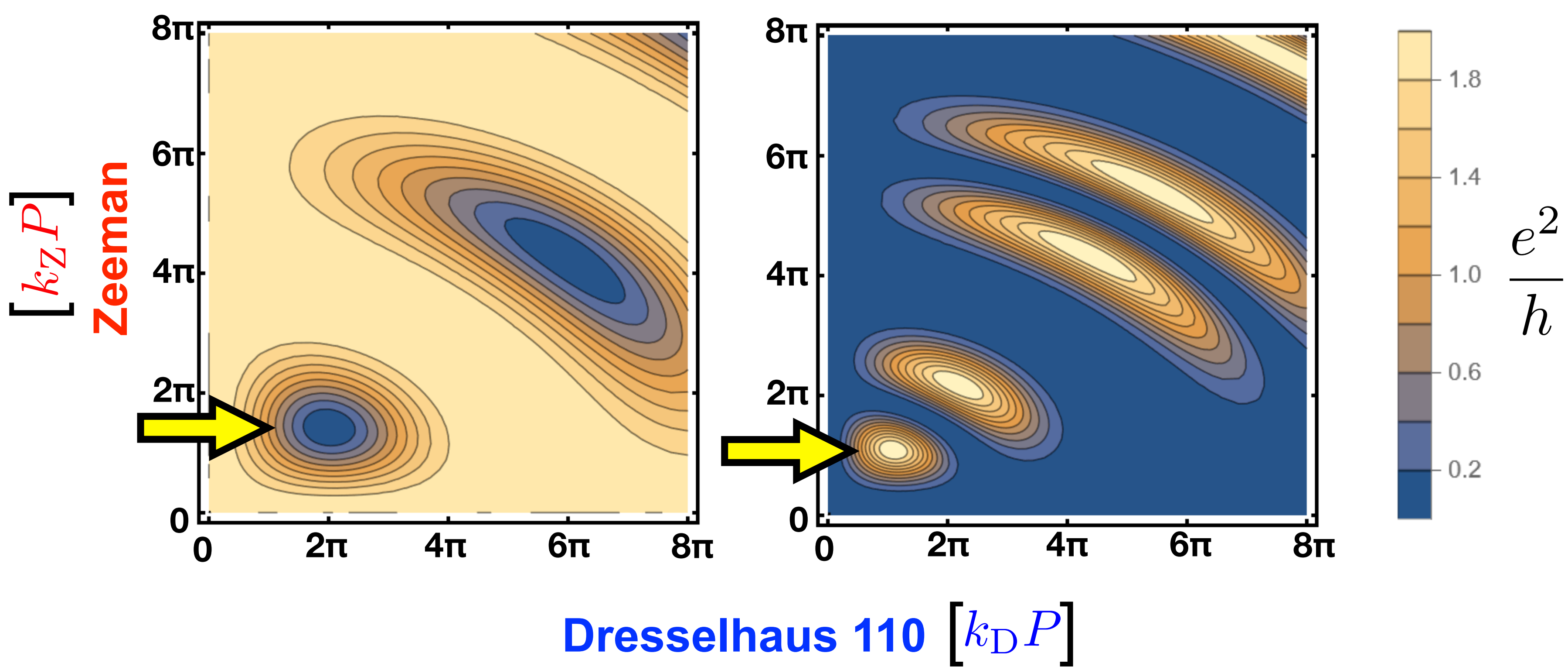
E. Rodríguez, A. Reynoso, J.P. Baltanás, J. Nitta, DF.

arXiv:2302.11271

Ballistic conductance **AAS correction (disorder)**

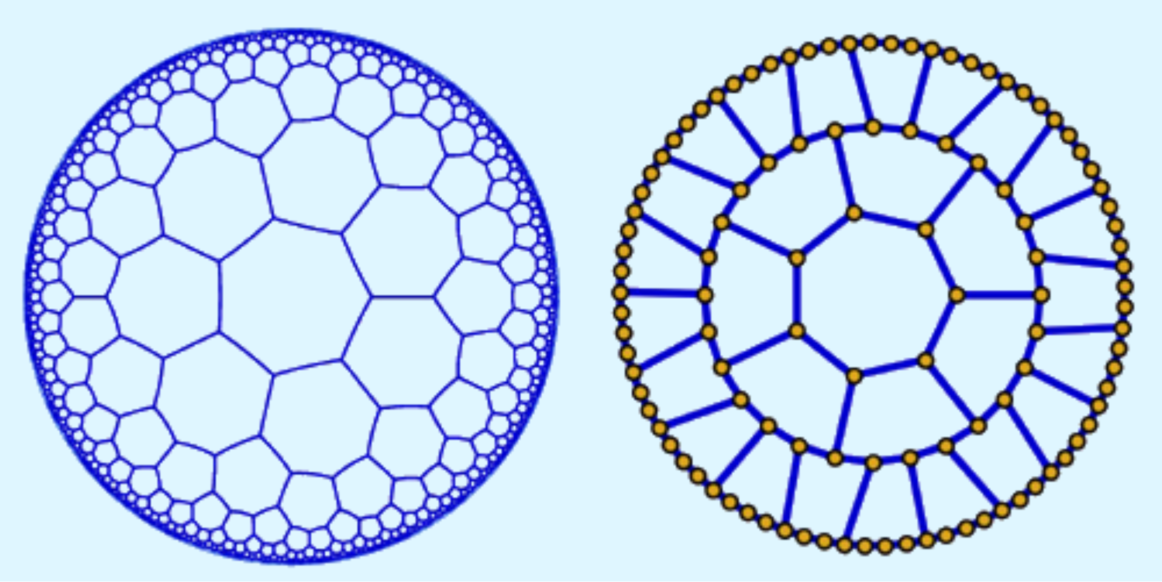


Also a map for the geometric classification of propagating spin states.

2. Spin-carrier dynamics in non-Euclidean spaces

Regular heptagonal tessellation of the hyperbolic plane

Poincaré disc



Finite representation

2. Spin-carrier dynamics in non-Euclidean spaces

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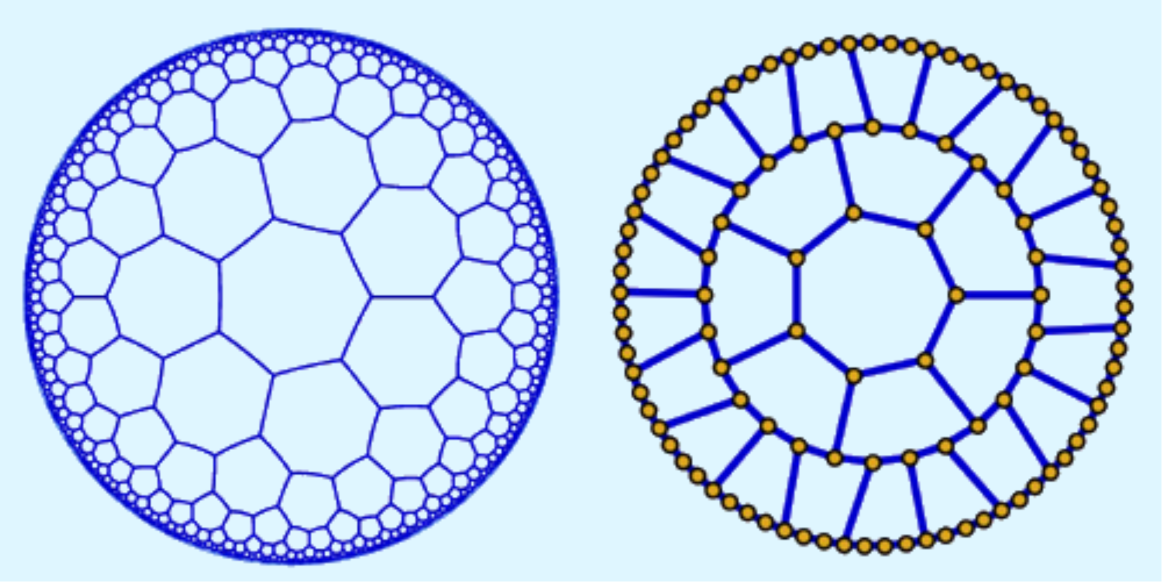
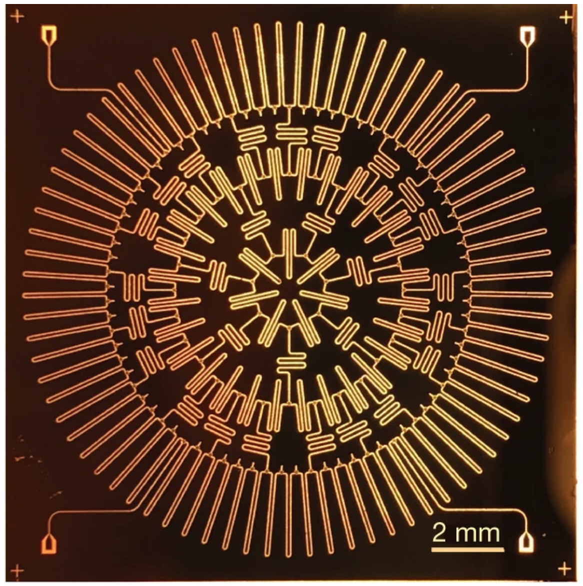


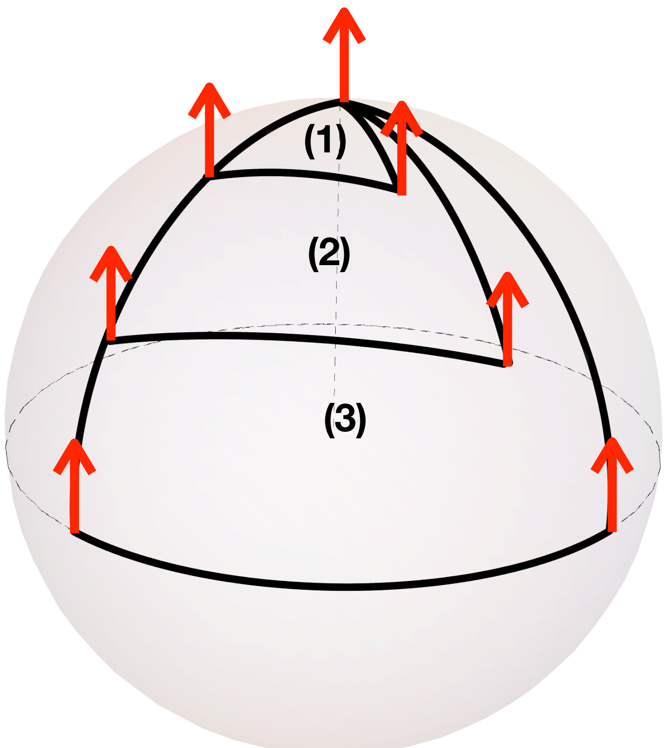
Finite representation

EM realization



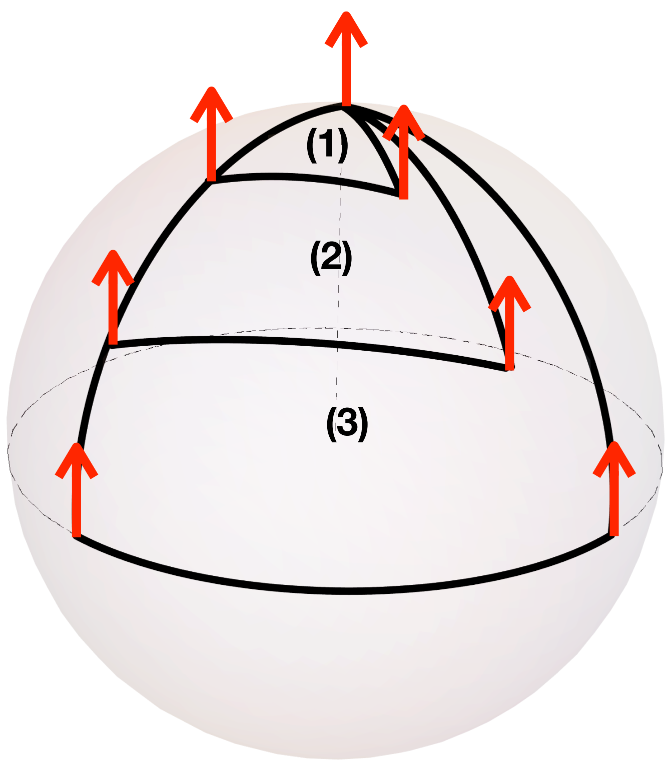
[Kollár et al., Nature (2019)]

2. Spin-carrier dynamics in non-Euclidean spaces



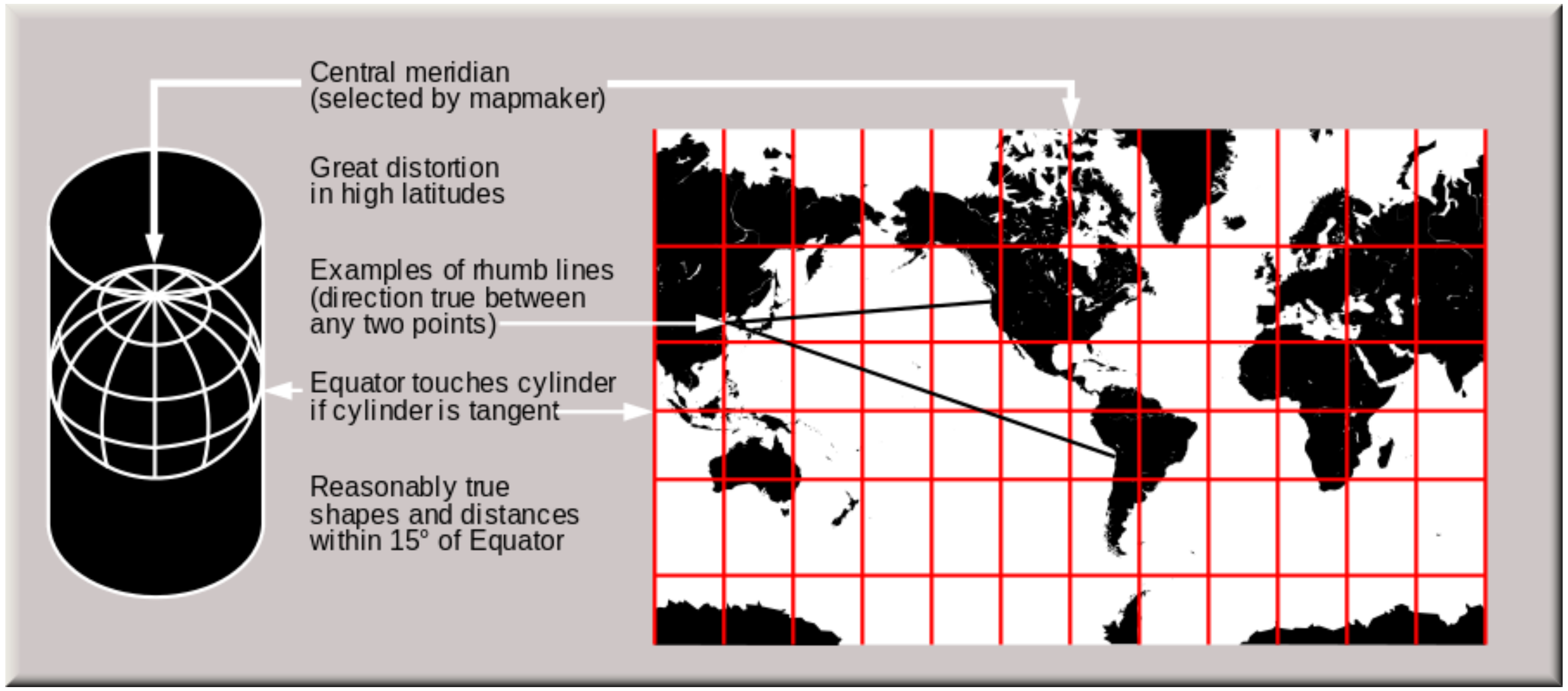
Equilateral triangles (geodesic curves)

2. Spin-carrier dynamics in non-Euclidean spaces



Equilateral triangles (geodesic curves)

Flat 2D circuit realization: Mercator-like projection



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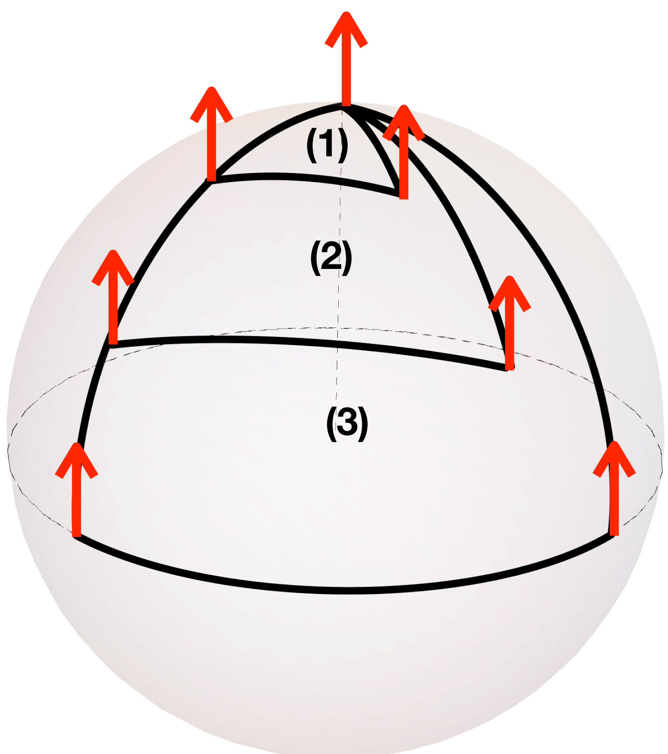

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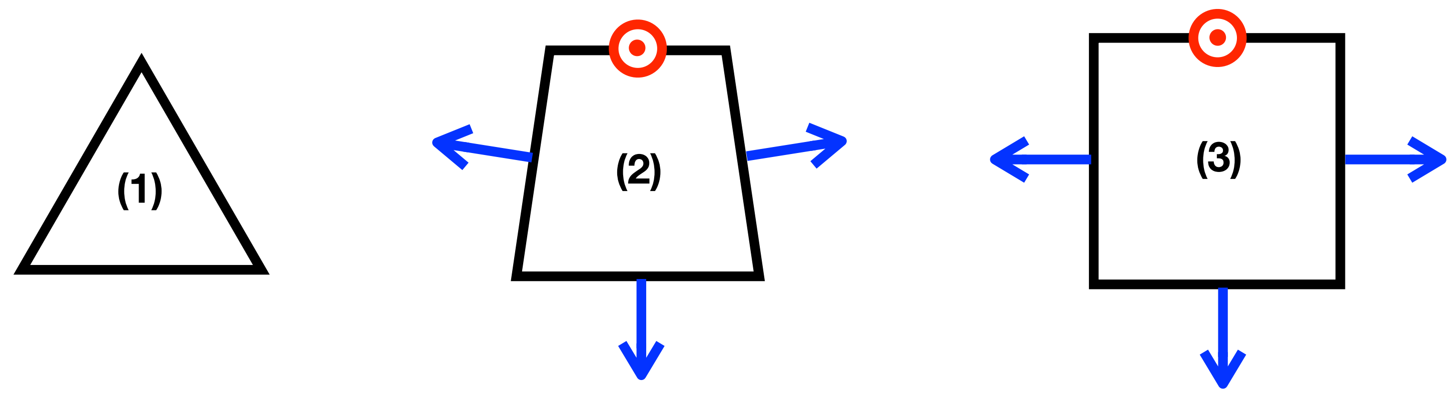

Rashba SOC

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

Dresselhaus 110 SOC

$$H_{\mathrm{D110}} = -\frac{\beta}{\hbar}p_x\sigma_z$$

such that the spin phase in a round trip vanishes

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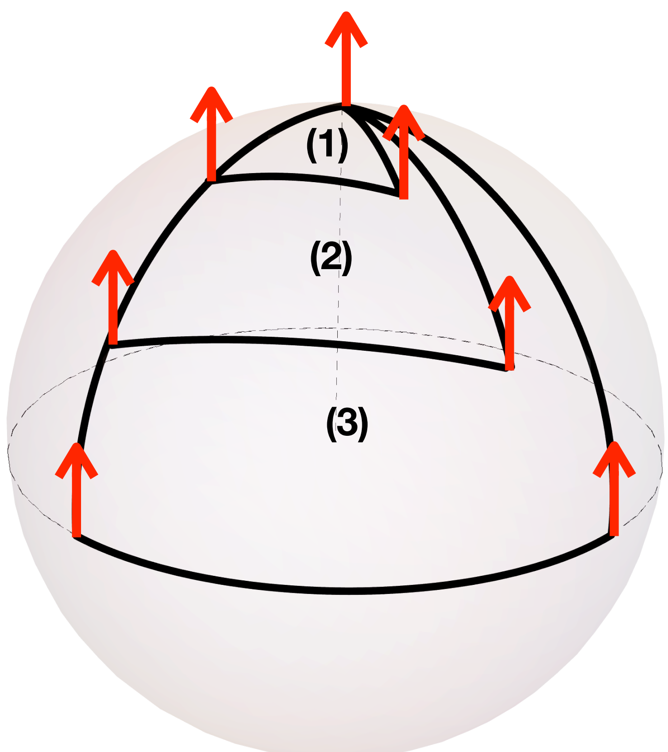

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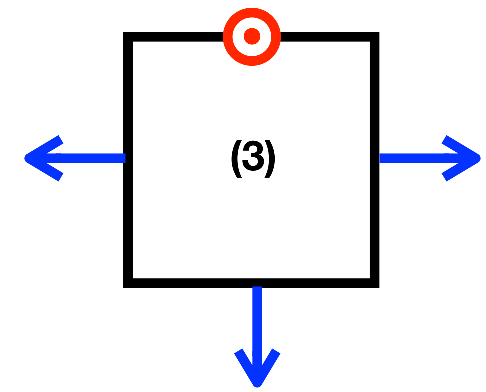

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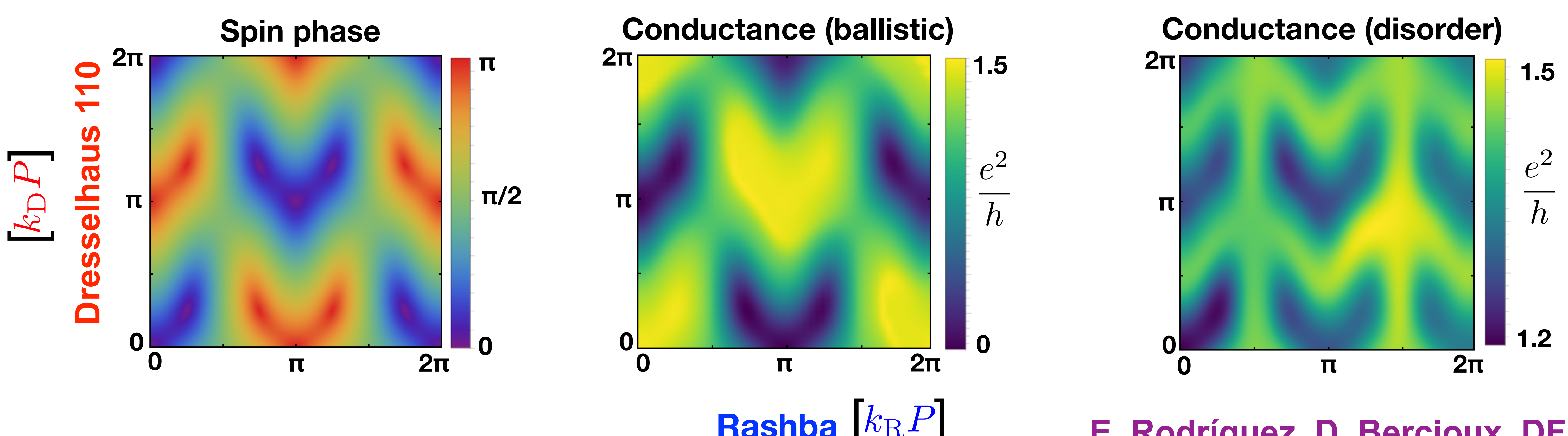
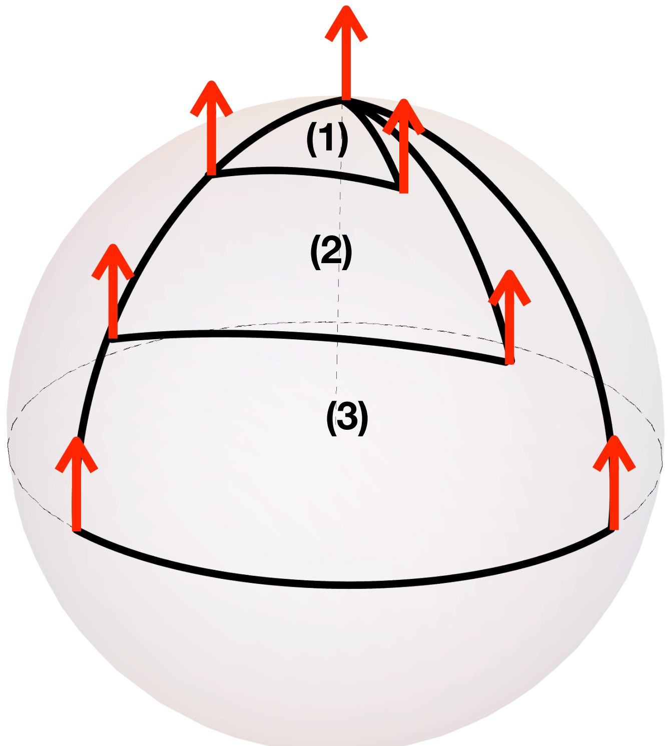


E. Rodríguez, D. Bercioux, DF (2023).

2. Spin-carrier dynamics in non-Euclidean spaces



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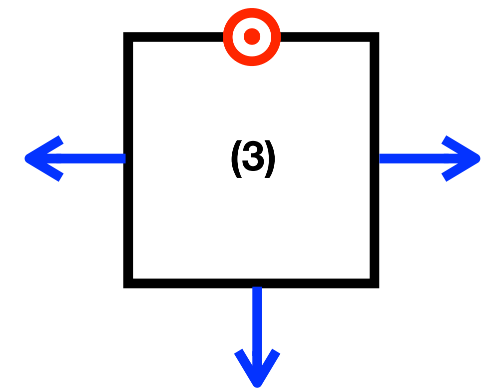
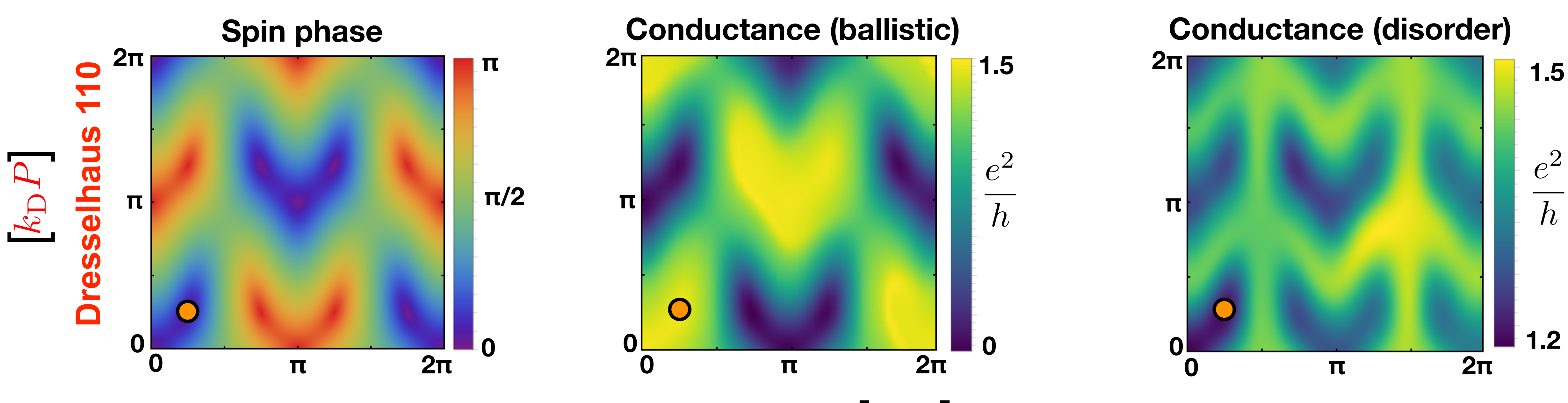


no spin-orbit on the sphere (zero spin phase)



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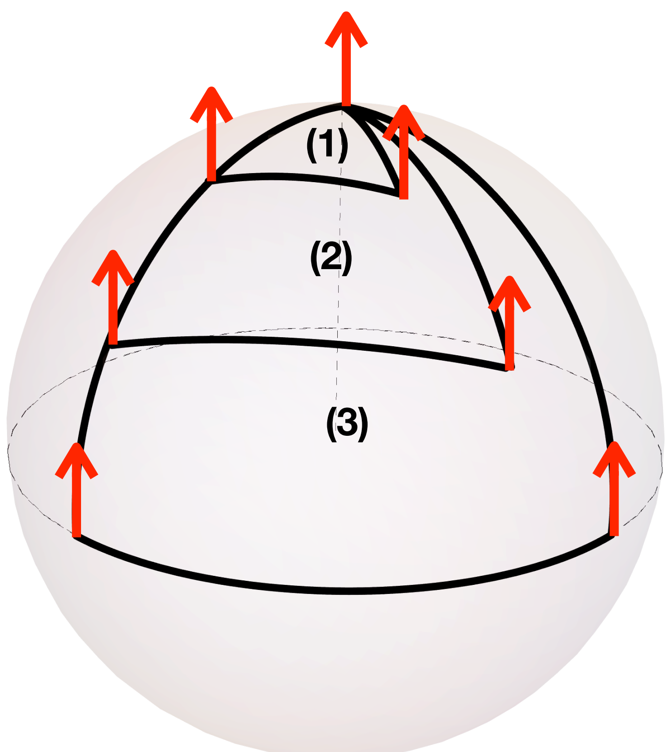

Equilateral triangles (geodesic curves)

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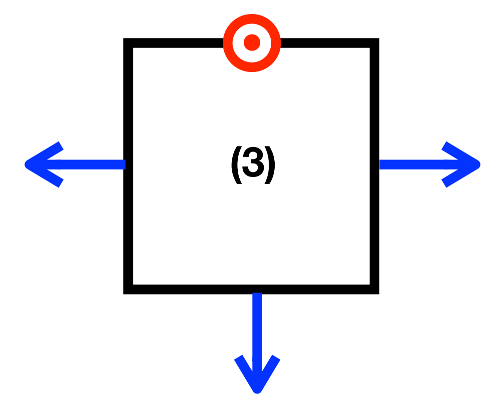
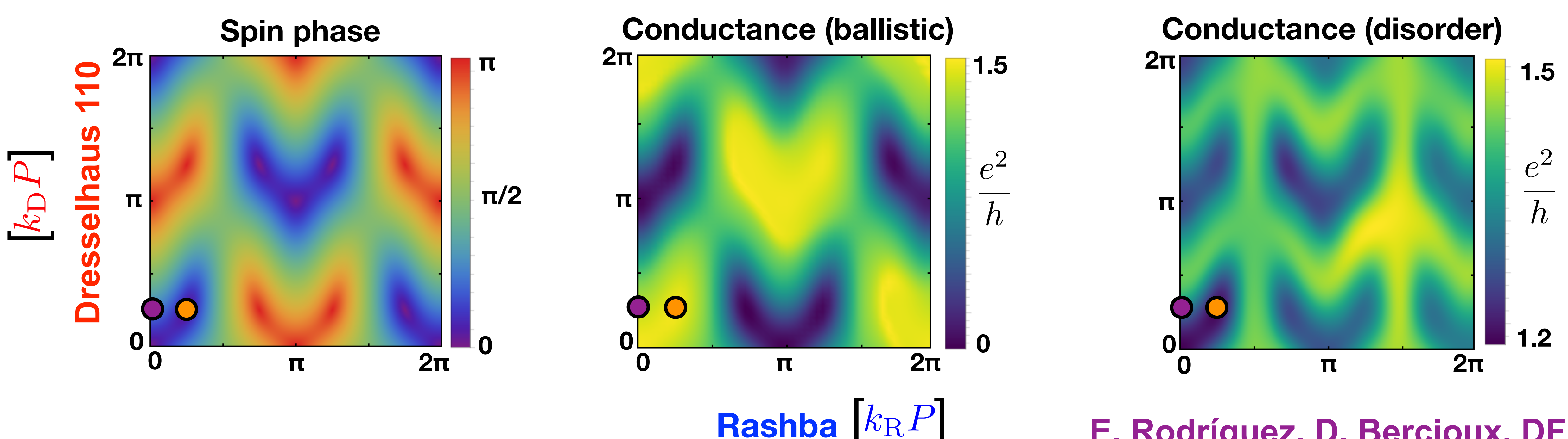


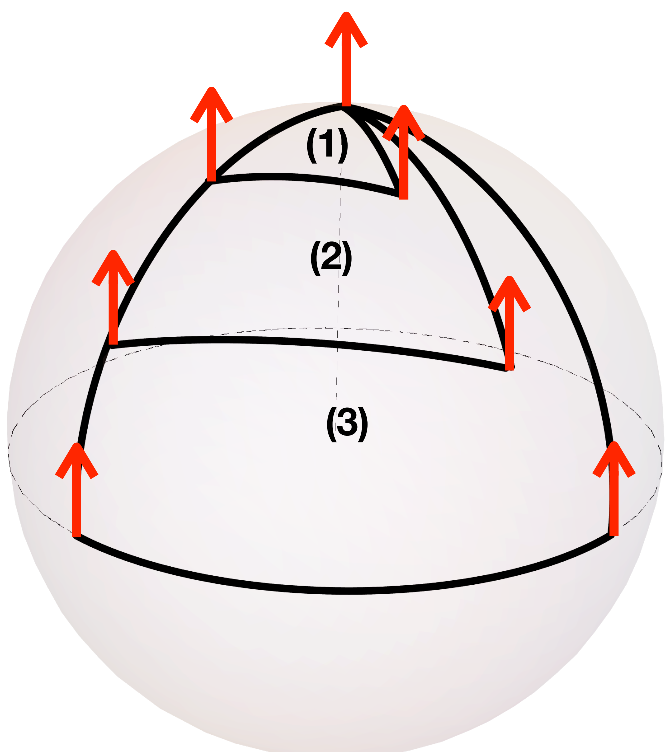
Rashba SOC **Dresselhaus 110 SOC**

- **no spin-orbit on the sphere** (zero spin phase)
- **parallel transport** (some Rashba on the sphere)



E. Rodríguez, D. Bercioux, DF (2023).

2. Spin-carrier dynamics in non-Euclidean spaces



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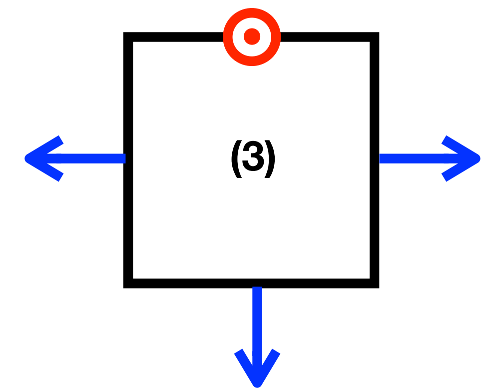
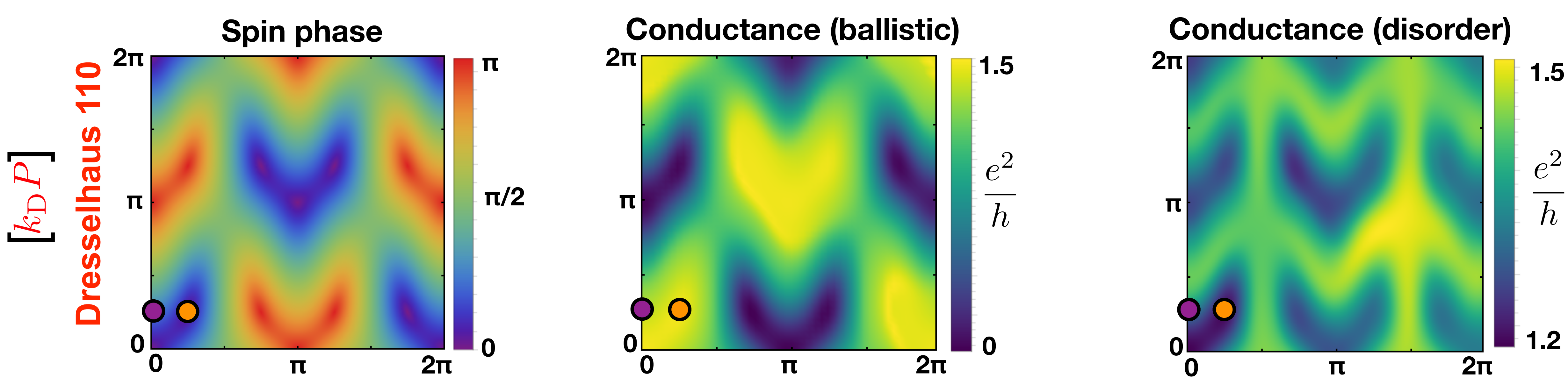


Rashba SOC **Dresselhaus 110 SOC**

no spin-orbit on the sphere (zero spin phase)

parallel transport (some Rashba on the sphere)

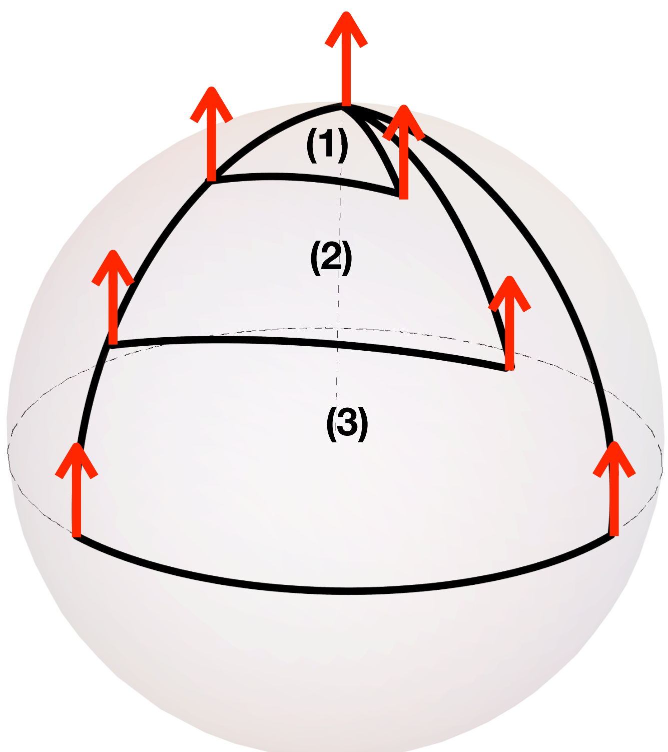
Dresselhaus 110 accounts for the holonomy!



Rashba $[k_{\rm R}P]$

E. Rodríguez, D. Bercioux, DF (2023).

2. Spin-carrier dynamics in non-Euclidean spaces



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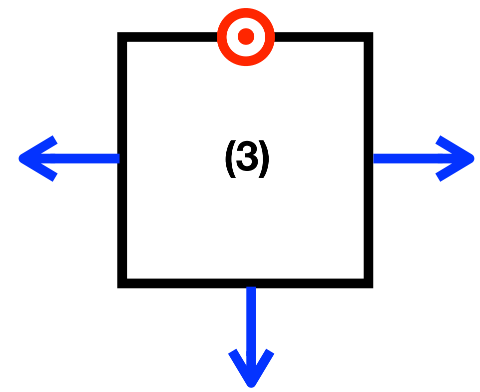

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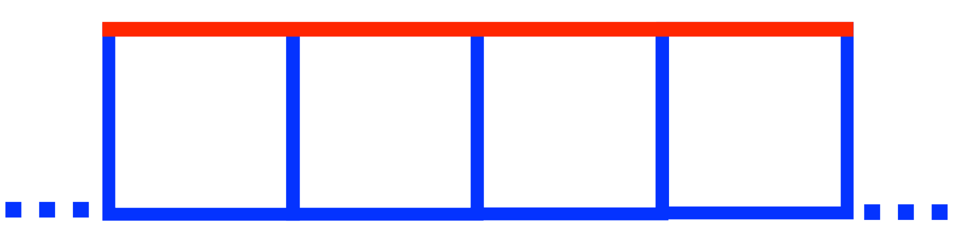
Hemisphere



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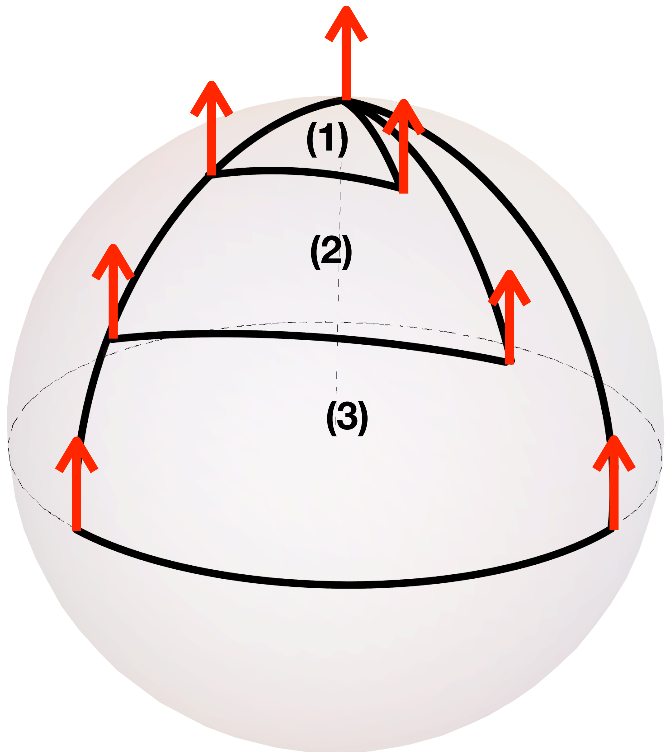

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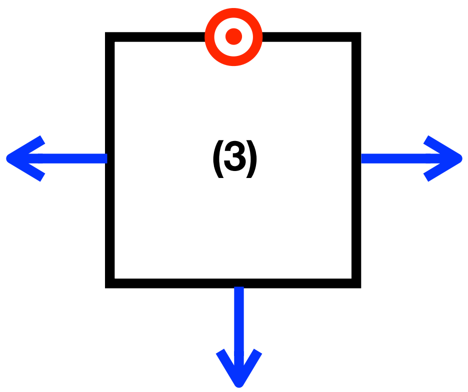

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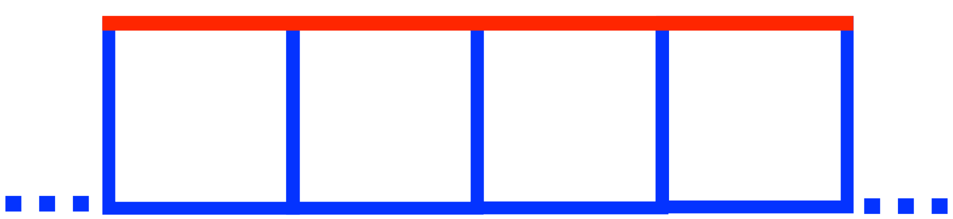
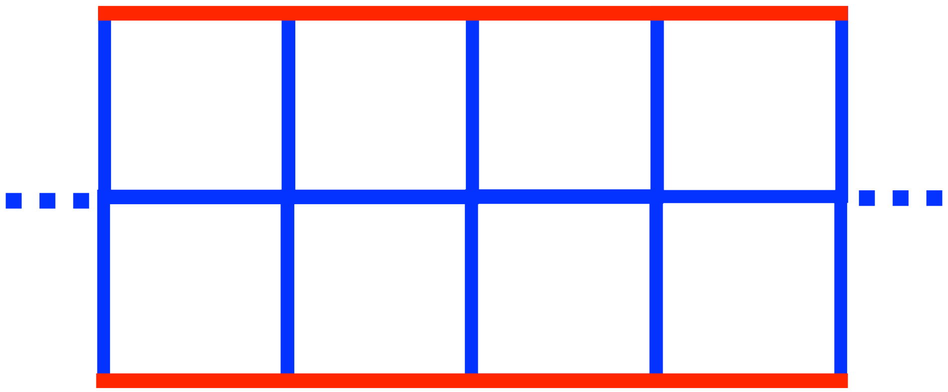


Full sphere



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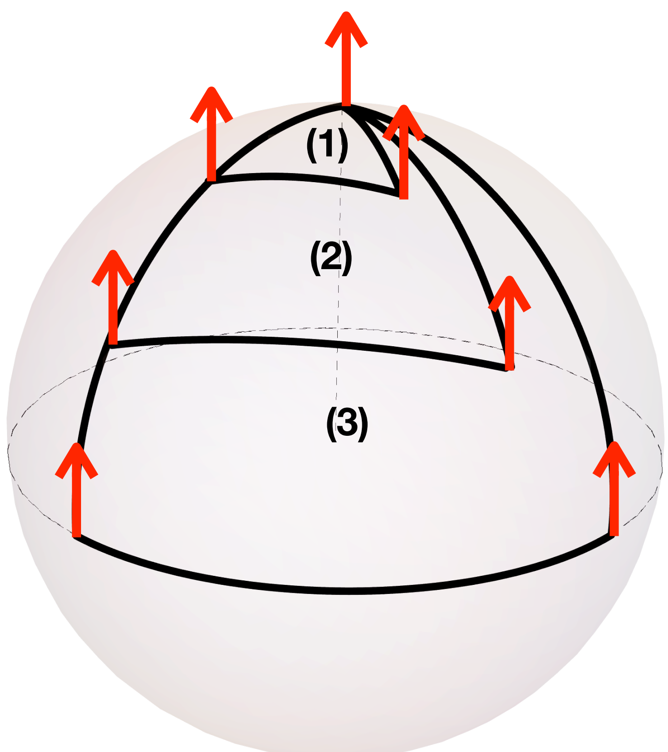

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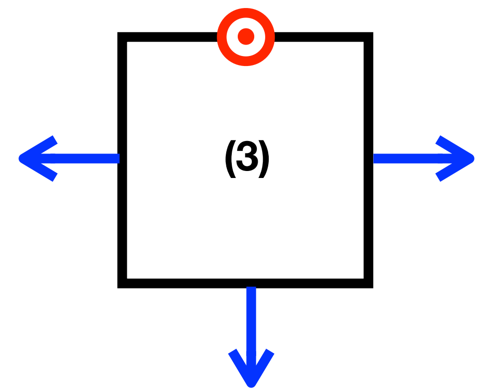

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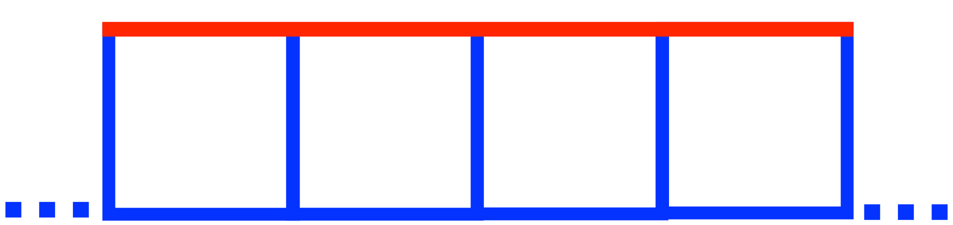

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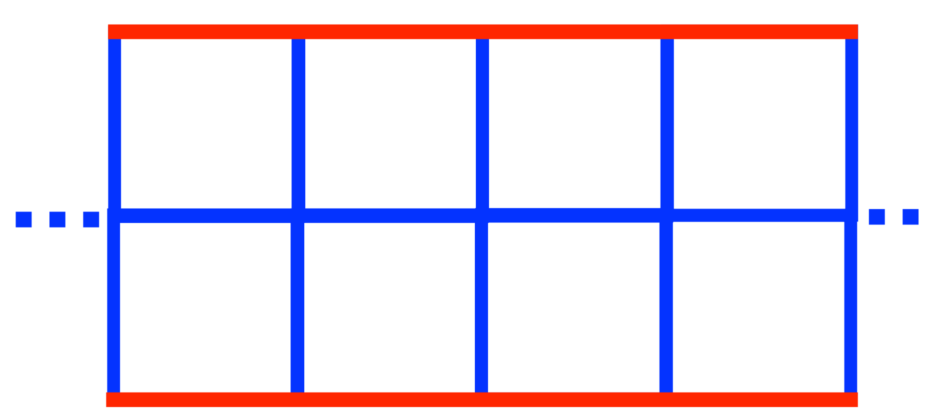
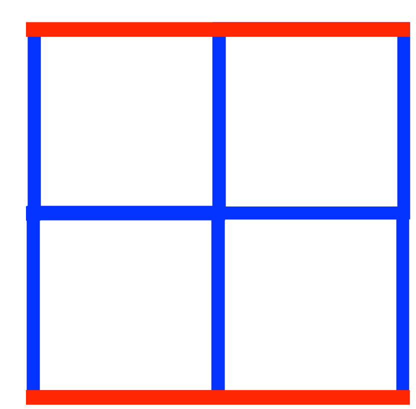


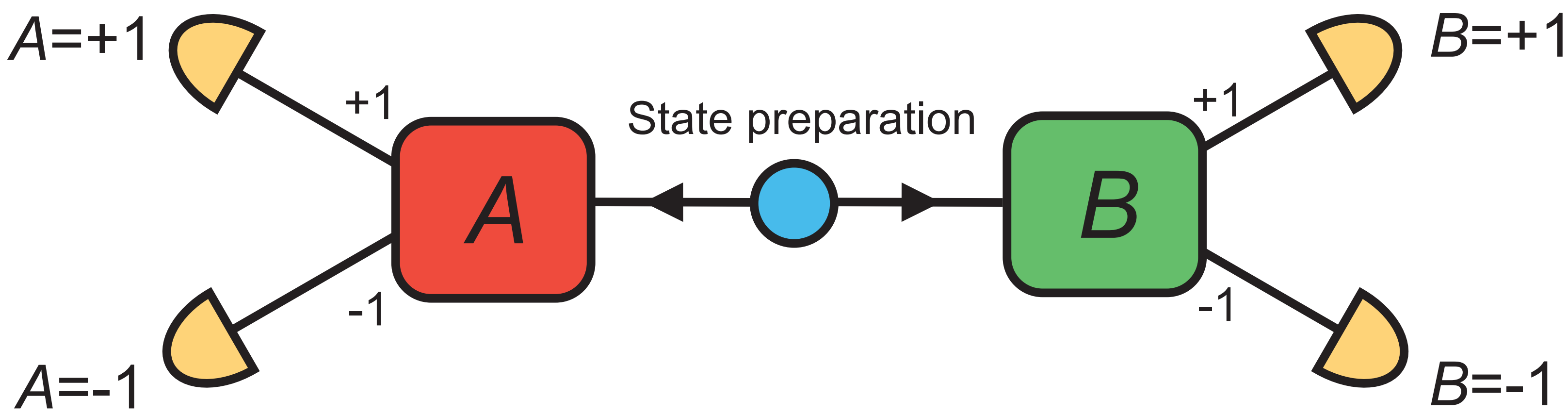
Hemisphere
(non periodic!)



E. Rodríguez, D. Bercioux, DF (2023).

3. Electron quantum optics for quantum contextuality

Bell experiment

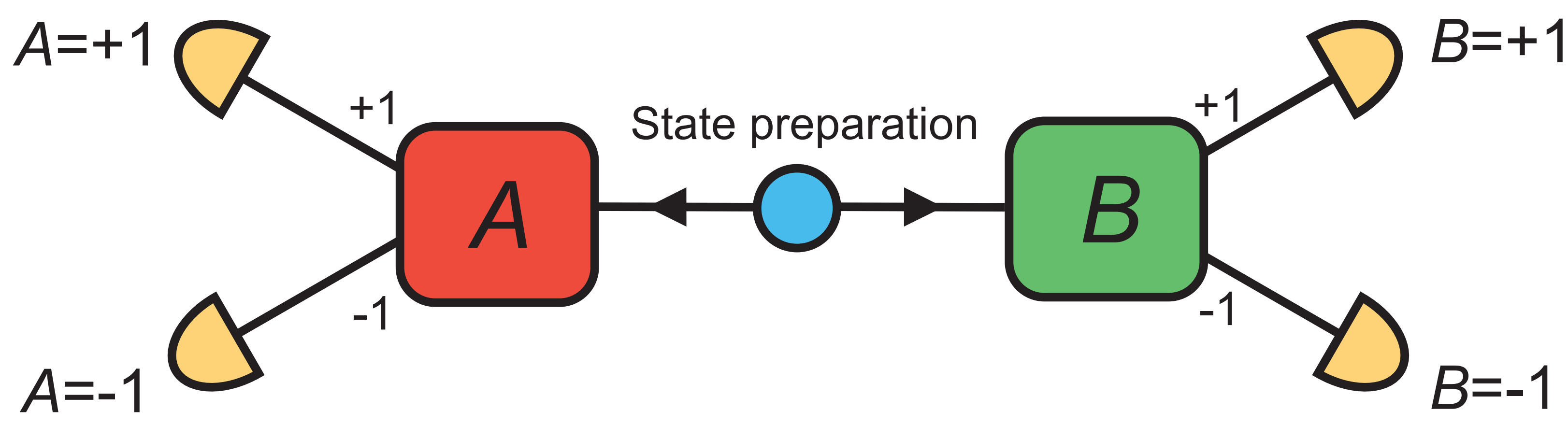


spacelike separation ⇨ **compatible observables *A* & *B***

$$[A, B] = 0$$

3. Electron quantum optics for quantum contextuality

Bell experiment



spacelike separation ⇨ **compatible observables *A* & *B***

$$[A, B] = 0$$

$$E \equiv \langle AB \rangle + \langle A'B \rangle + \langle AB' \rangle - \langle A'B' \rangle$$

CHSH-Bell parameter

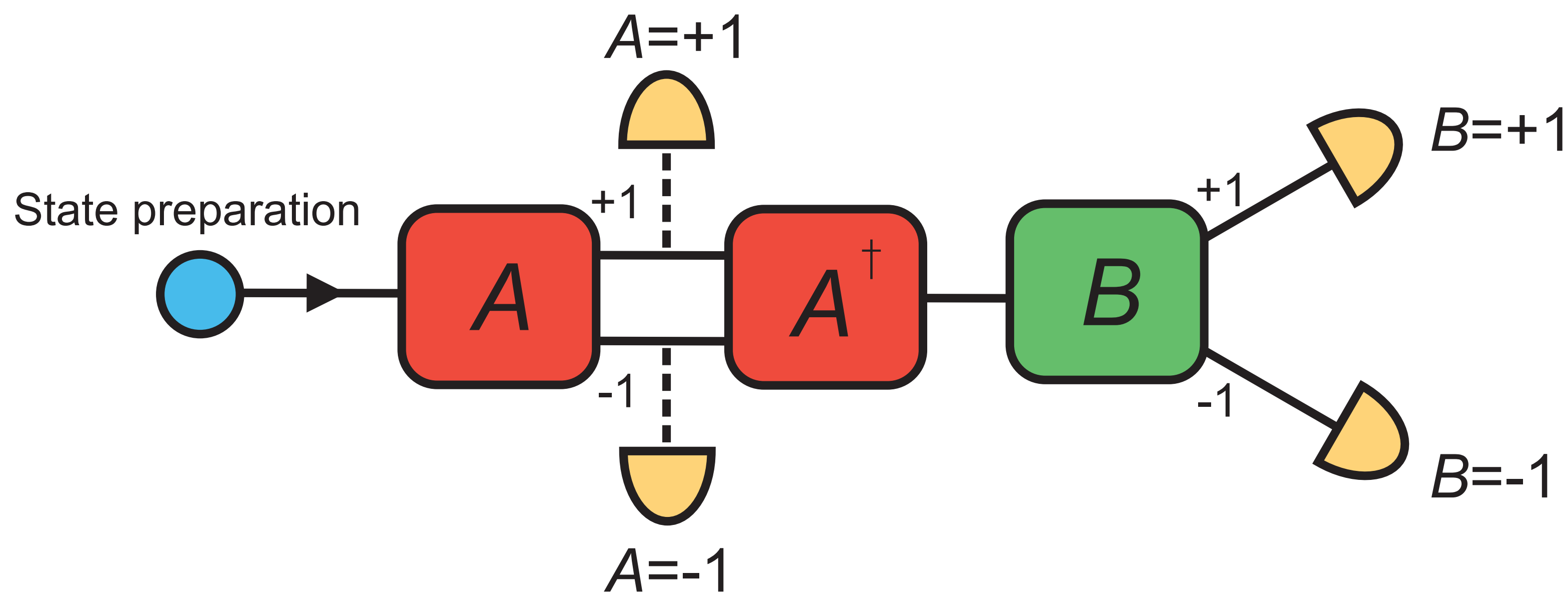
$$E \quad \leq \quad 2 \quad \leq \quad {\color{red}2\sqrt{2}} \quad \leq \quad 4$$

local realism | **quantum mechanics** | **non signalling**

3. Electron quantum optics for quantum contextuality

Sequential experiment

with compatible observables *A* & *B*.



Results of partial ND measurements recorded in an external device.

(state recomposition/Lüders rule).

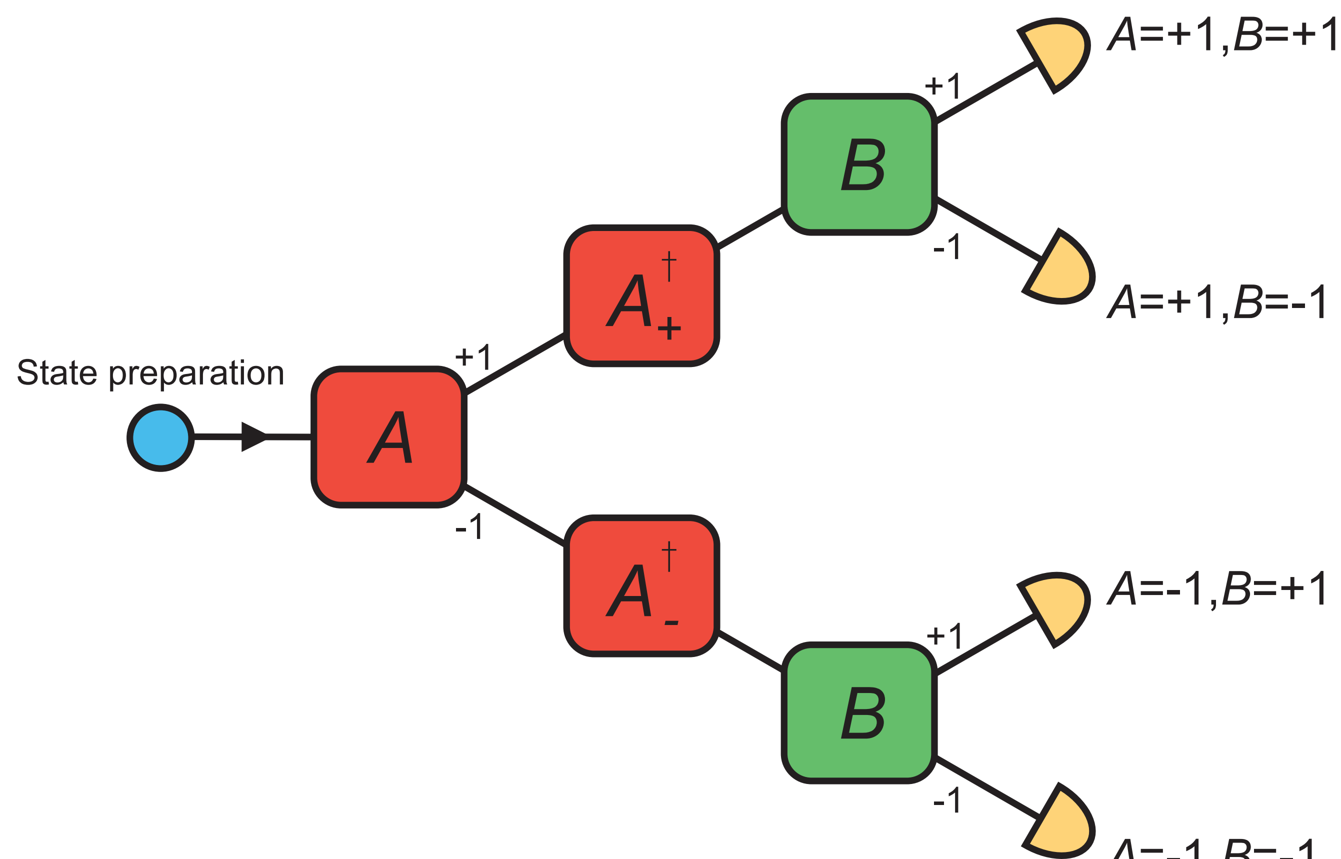
$$E \quad \leq \quad 2 \quad \leq \quad 2\sqrt{2}$$

non-contextual realism **quantum mechanics**

3. Electron quantum optics for quantum contextuality

Arborescent network

Compatible observables *A* & *B*.



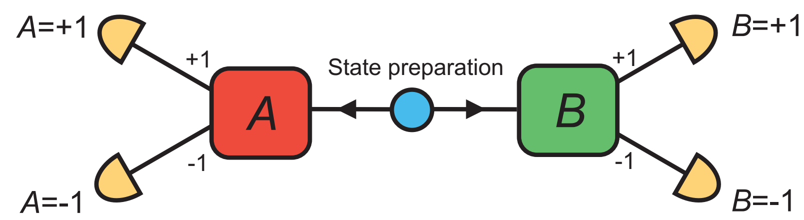
Results of partial measurements encoded in extra paths.

$$E \leq 2 \leq 2\sqrt{2}$$

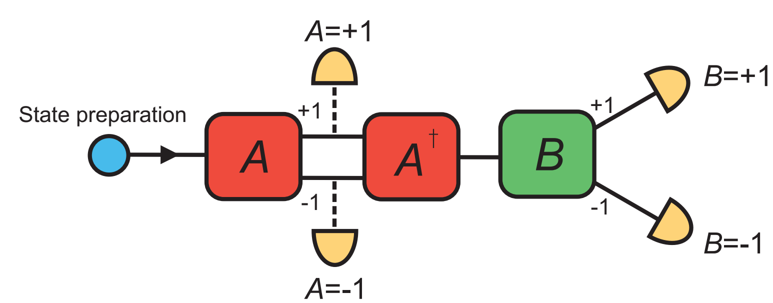
non-contextual realism | **quantum mechanics**

3. Electron quantum optics for quantum contextuality

spacelike separated



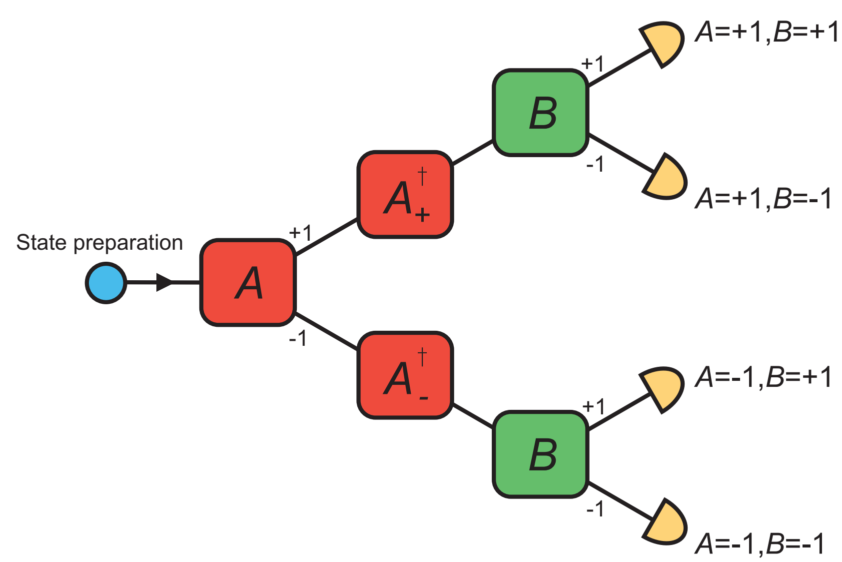
sequential ND



ALWAYS
POSSIBLE

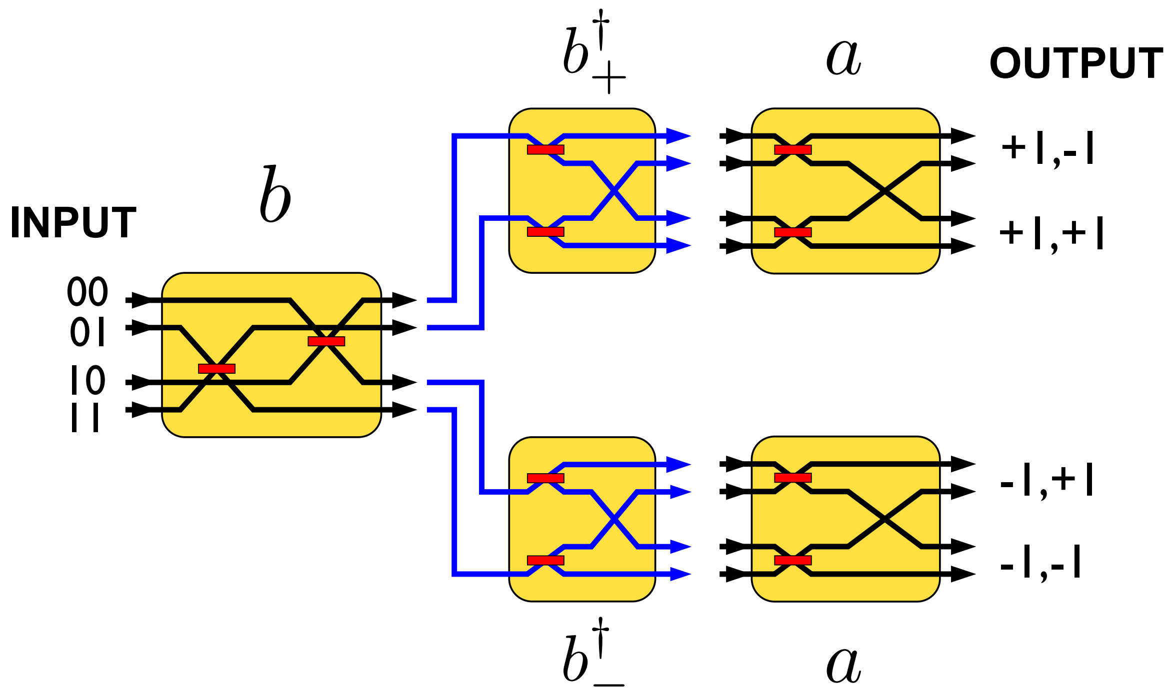
NOT ALWAYS
POSSIBLE

arborescent



3. Electron quantum optics for quantum contextuality

Sequential CHSH-Bell: correlator $\langle ba \rangle$



$a = \mathbb{1} \otimes \sigma_x \qquad b = \sigma_x \otimes \mathbb{1}$

Any finite dimensional unitary operation realized by a BS array [Reck et al., PRL (1994)].

Experiments in optical and MW circuits. [DF et al., PRL (2016)].

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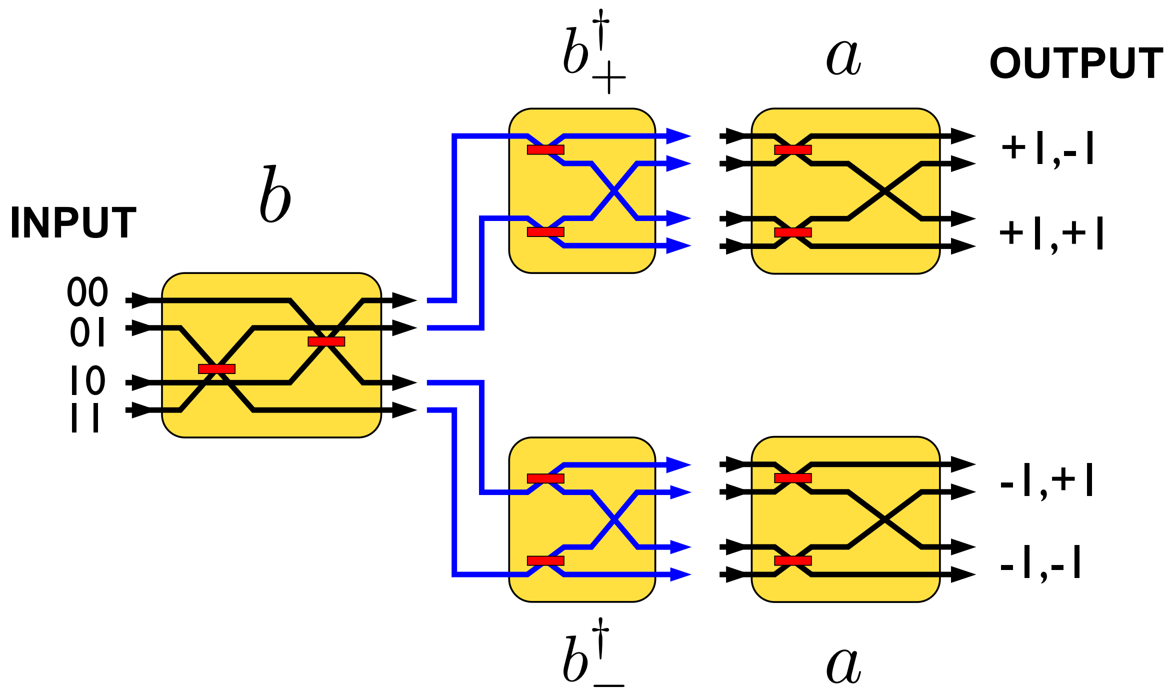

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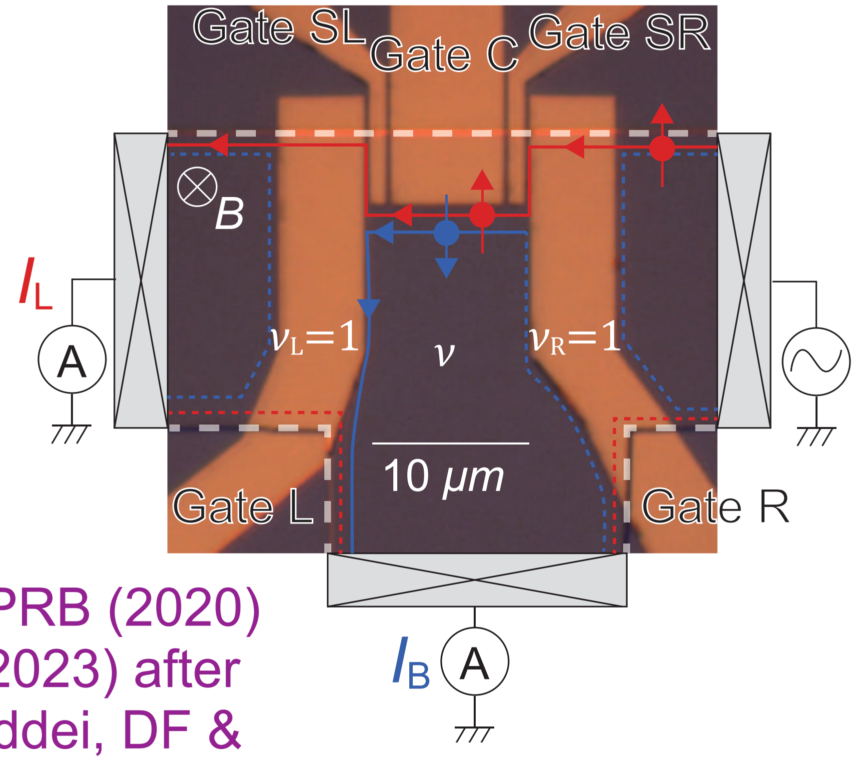


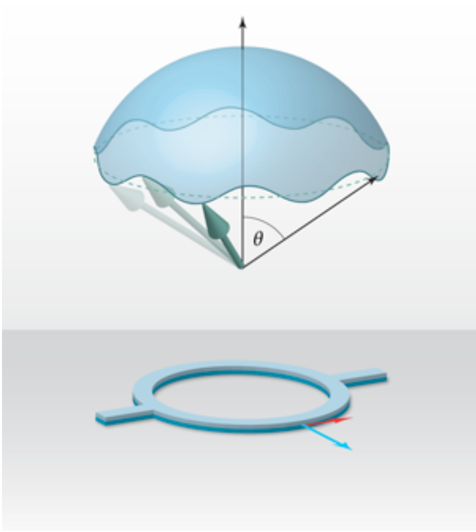
[Shimizu et al., PRB (2020) and PR Appl. (2023) after Giovannetti, Taddei, DF & Fazio, PRB (2008)].

Aim: realization in multichannel quantum Hall circuits.

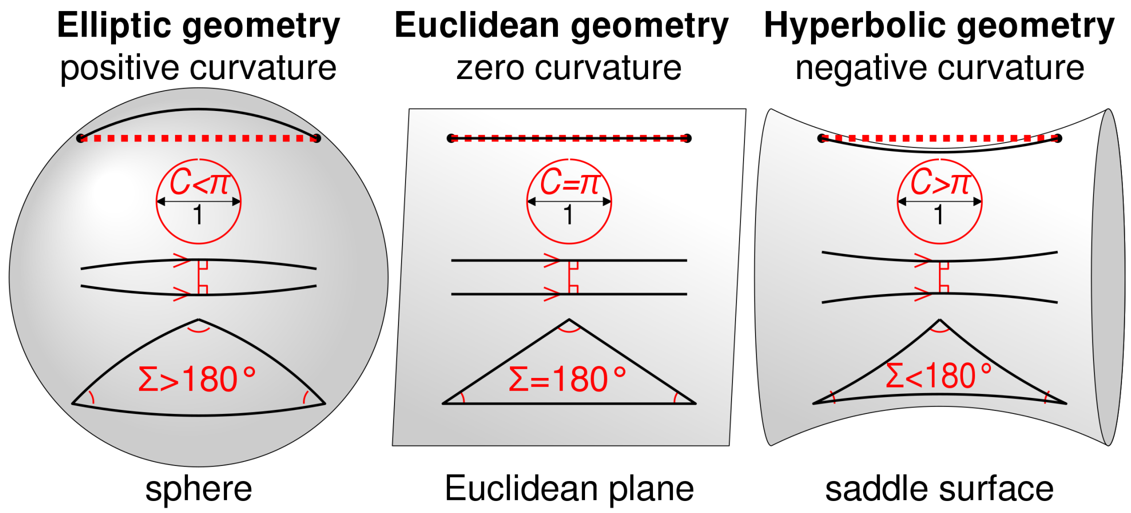
J.P. Baltanás, A. Cabello, DF (2023).

Summary

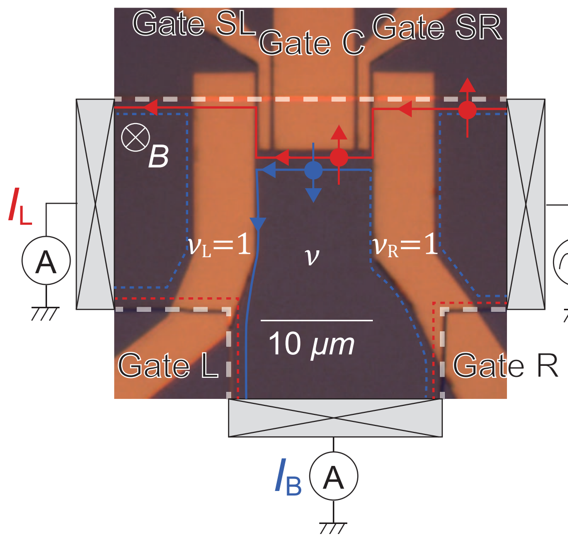
1. Geometric resources for spin control

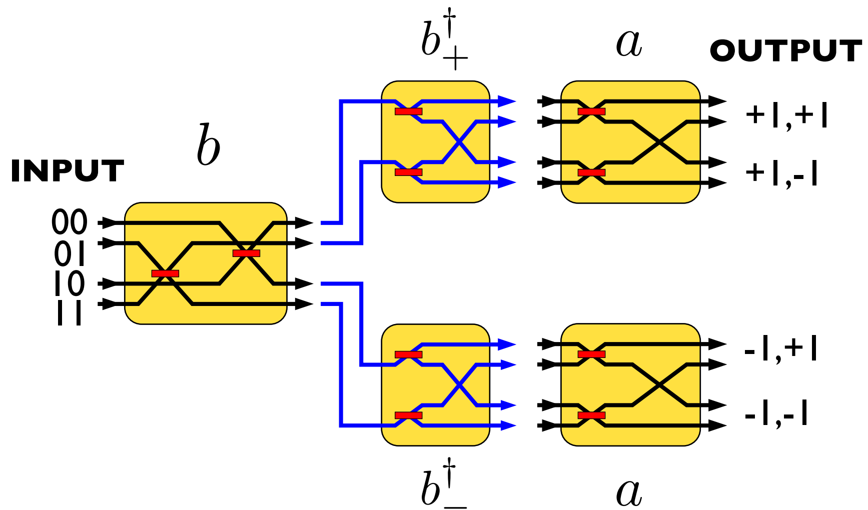


2. Spin-carrier dynamics in non-Euclidean spaces



3. Electron quantum optics for quantum contextuality





THANK YOU !