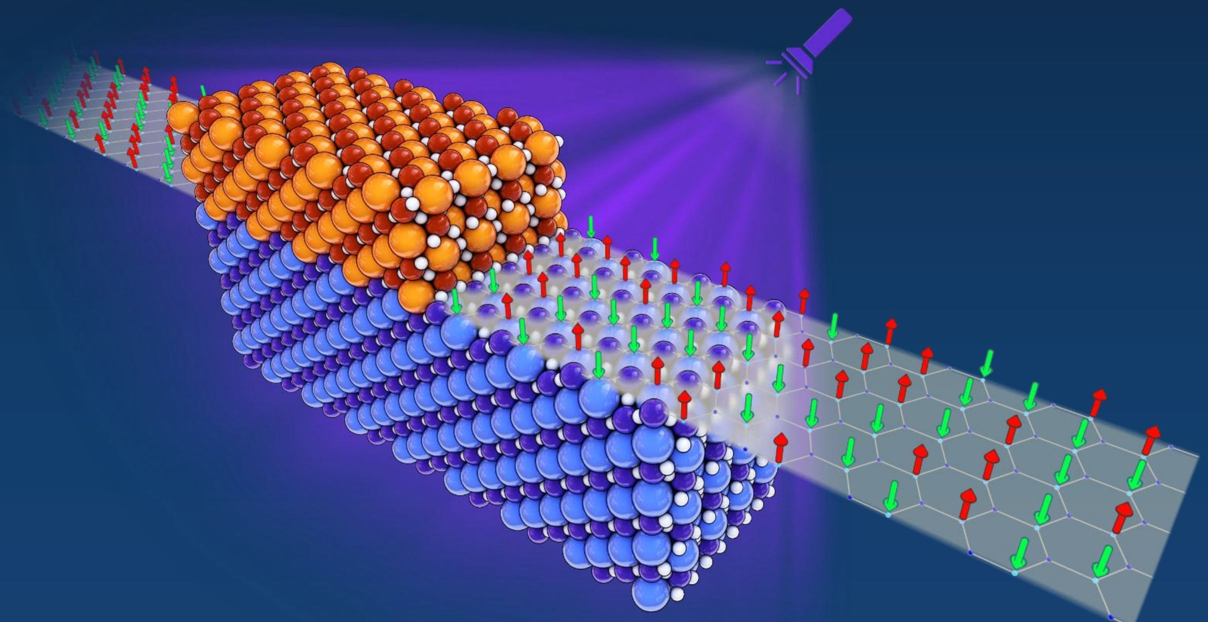
Quantum geometry at oxide interfaces

Caviglia Lab
Department of Quantum Matter Physics
University of Geneva

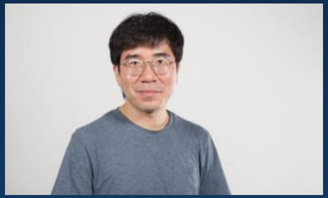


UNIVERSITÉ DE GENÈVE

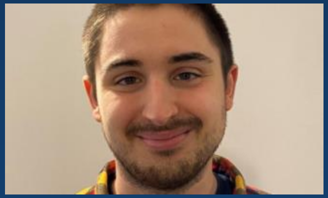
Collaborators and funding

Mattias Matthiesen, Graham Kimbell, **Ian Aupiais**, Giacomo Sala, **Chang Jae Roh**, Greta Segantini, Tancredi Thai Angeloni, Patrick Blah, Ulderico Filippozzi, Marco Lopes, Ioana Novas, **Stefano Gariglio**



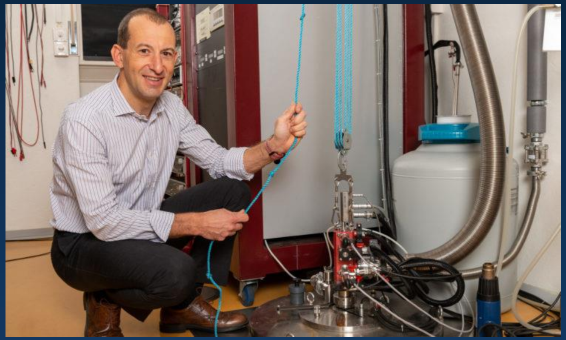






In collaboration with

Eugene Demler, Radu Andrei, Sambuddha Chattopadhyay *ETH Zurich*
Denis Golez Josef Stefan Institute, Ljubljana
Jean-Marc Triscone *Uni Geneva*
Andrea Cavalleri *MPI Hamburg*



Funded by

European Research Council
Established by the European Commission

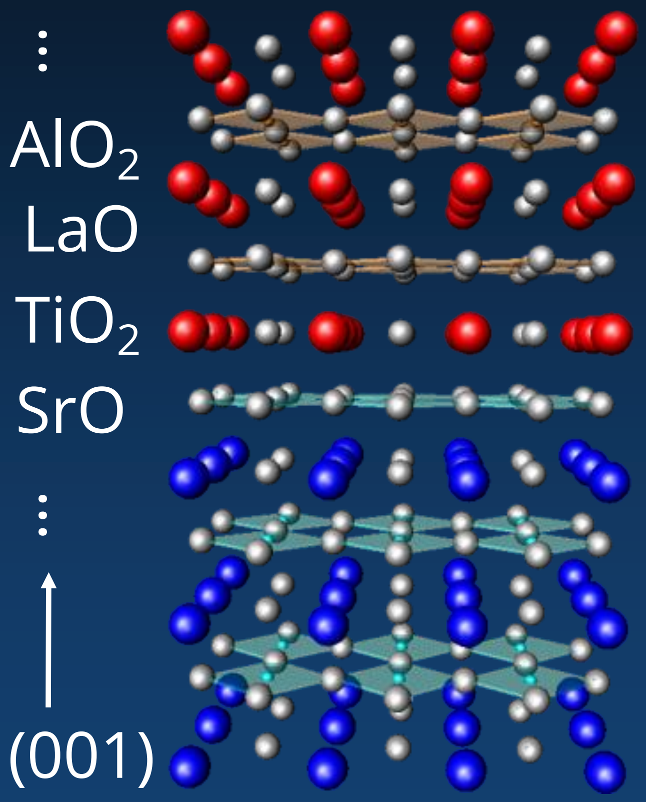
GORDON AND BETTY MOORE FOUNDATION

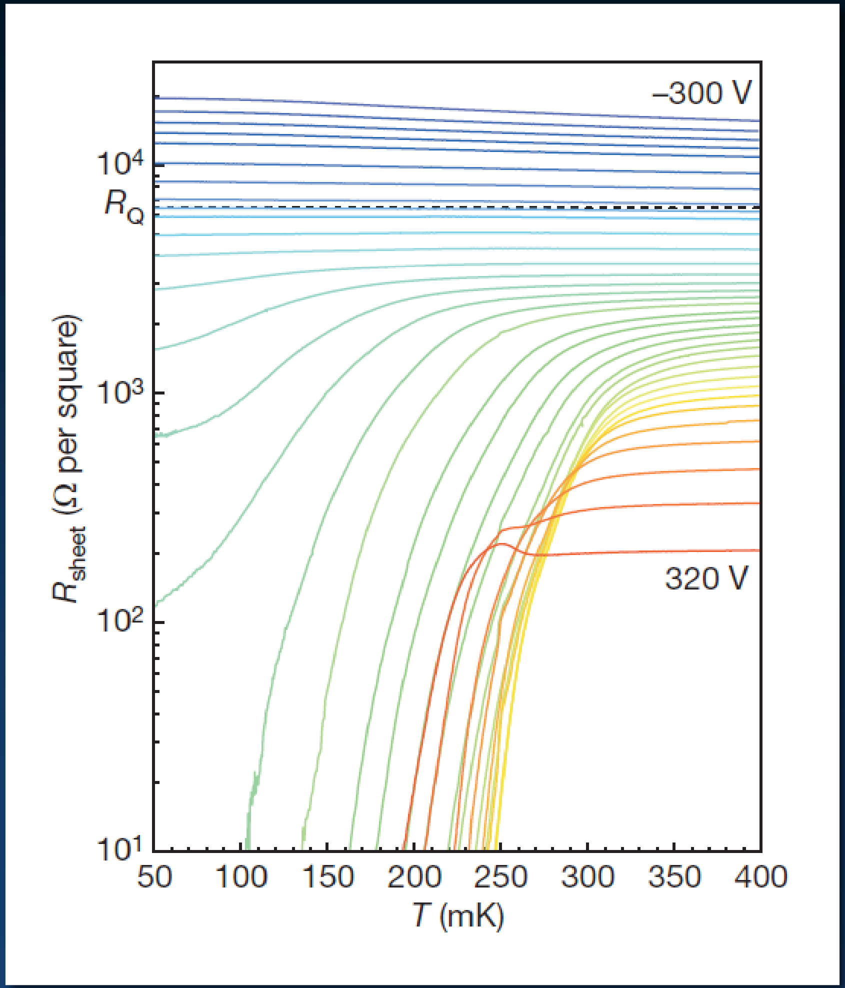
NWO

Fonds national suisse

Conducting oxide interfaces

(001)$LaAlO_3/SrTiO_3$

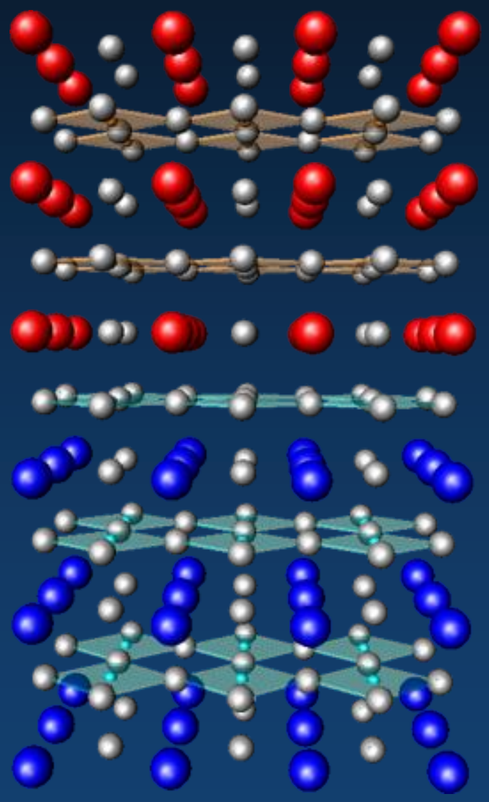




Nature 2008

Two-dimensional electron system with dilute superconductivity
Gate tunable superconductivity
Strong spin-orbit coupling

Open questions



Puzzling experimental observations:

1. Anomalous Planar Hall effect.

2. Non-linear Hall effect in time-reversal invariant conditions.

3. Non-linear magnetoresistance.

Unified description from quantum geometry.

Take-home message

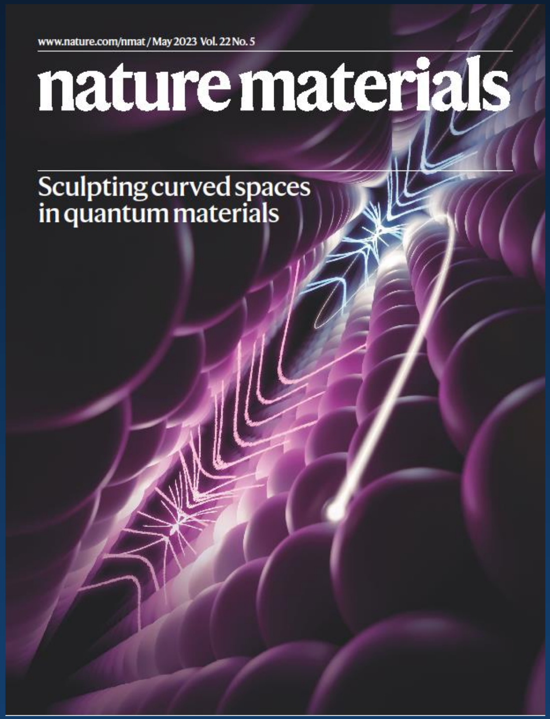


Image:
Xavier Ravinet
UNIGE

Puzzling experimental observations:

1. Anomalous Planar Hall effect.

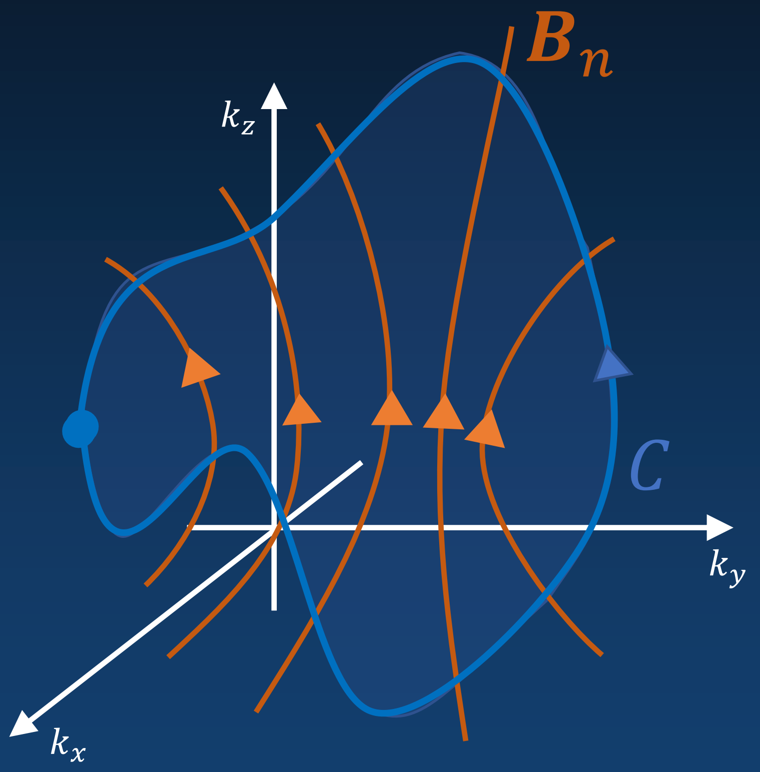
2. Non-linear Hall effect in time-reversal invariant conditions.

3. Non-linear magnetoresistance.

Unified description from quantum geometry.

Lesne et al. Nature Materials 22, 576 (2023)
Mercaldo et al. npj Quantum Materials (2023)
Sala et al. arxiv (2024)

Origin of quantum geometry



$$\boldsymbol{v}_n(\boldsymbol{k}) = \frac{1}{\hbar}\nabla_{\boldsymbol{k}}\epsilon_n(\boldsymbol{k}) - \frac{e}{\hbar}\boldsymbol{E}\times\boldsymbol{B}_n(\boldsymbol{k})$$

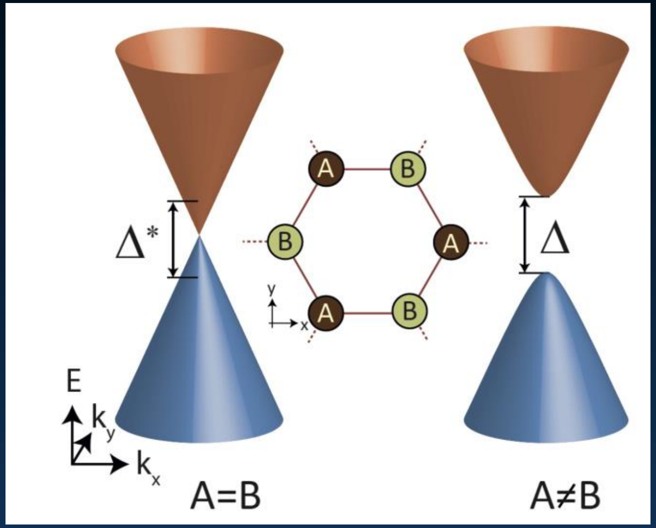
Geometric riformulation of QM
J. Anandan and Y. Aharonov
Geometry of quantum evolution
Phys. Rev. Lett. 65, 1697 (1990)

Quantum Geometric Tensor (QGT)

Re (QGT) : quantum metric.
Mapped to the geodesic distance between two points on the Bloch's sphere, endowed with a Fubini–Study metric

Im (QGT): **Berry curvature**.
Geometric phase of the wavefunction

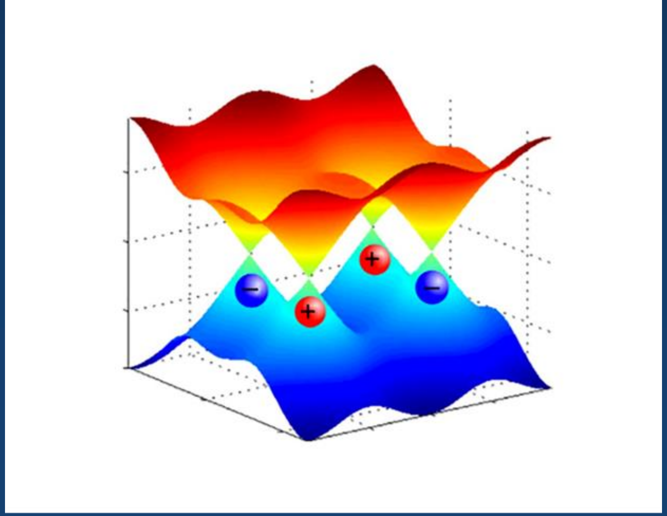
Conventional two-level systems



Gapped graphene

$$\mathcal{H}(\mathbf{k}) = v_F\left[\sigma_x k_x + \sigma_y k_y\right] + m\sigma_z$$

σ sublattice space

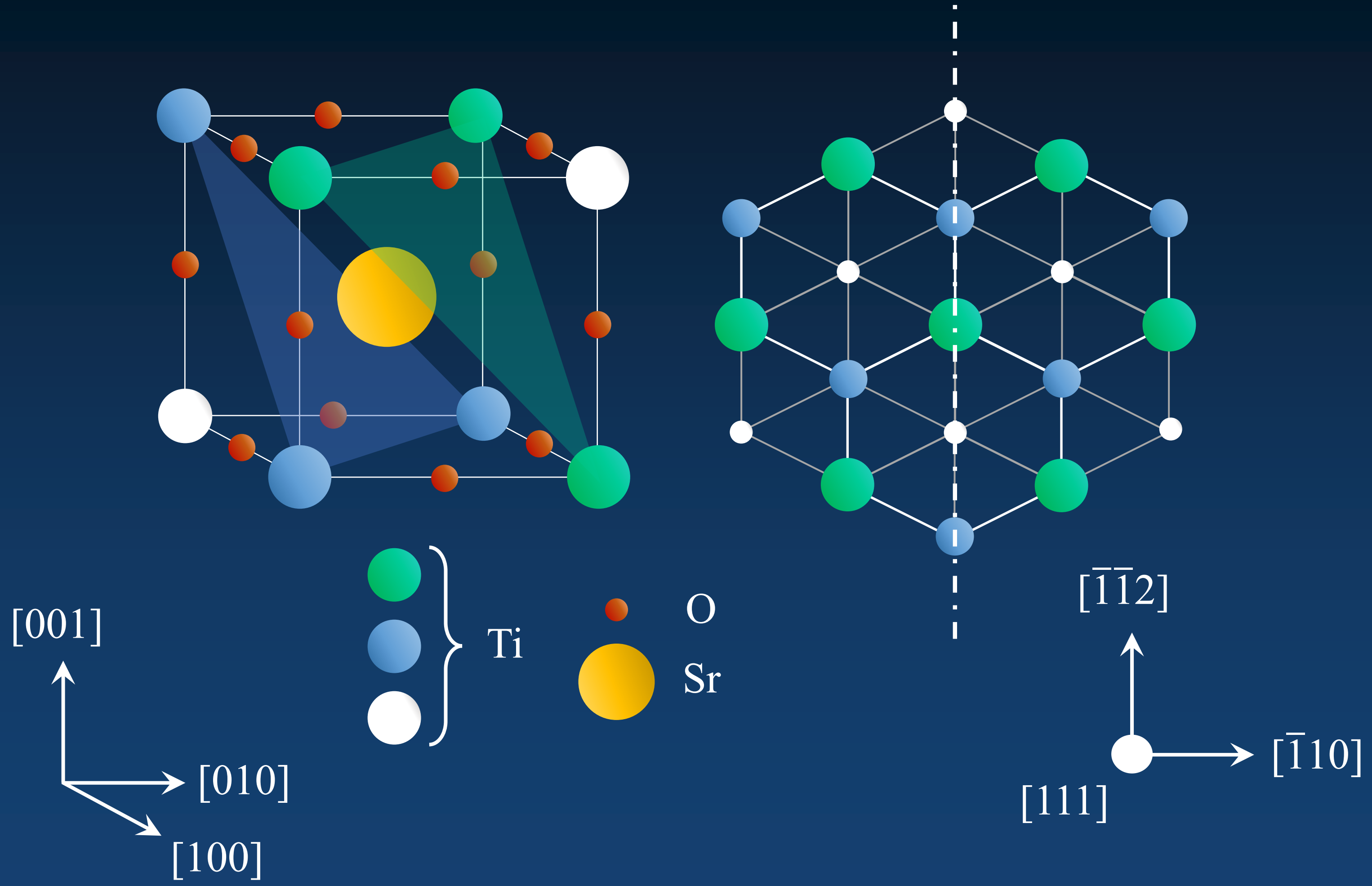


Weyl semimetals

$$\mathcal{H}(\mathbf{k}) = v_F^x \sigma_x k_x + v_F^y \sigma_y k_y + v_F^z \sigma_z k_z$$

σ spin space

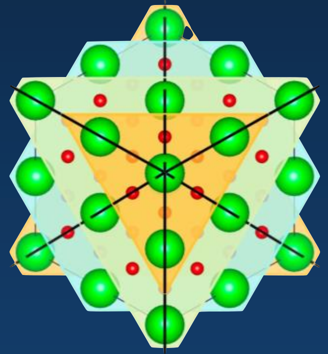
Exploring hexagonal symmetry

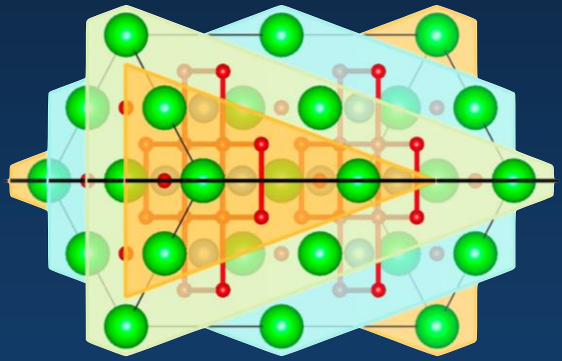


Structural phase transitions in $SrTiO_3$

110 K | 40 K | T

$D_{3d}C_{3v}$	$C_{2h}C_s$	C_s





Polar axis

Δ trigonal crystal field

Δ_m tetragonal distortion acting at gamma
α_m tetragonal distortion acting at finite k

α_{OR} interfacial breaking of inversion symmetry with polar axis

(Images courtesy A. Lau)

Orbital quantum geometry

Orbital
sources

Orbital quantum geometry

Orbital
sources

Orbital quantum superposition at finite crystal momentum

Crystal field

Orbital Rashba coupling

Orbital and spin quantum geometry

Spin
sources

Orbital
sources

Orbital quantum superposition at finite crystal momentum

Crystal field

Orbital Rashba coupling

Orbital and spin quantum geometry

Spin
sources

Orbital
sources

Spin quantum superposition at finite crystal momentum

Spin-orbit

Spin Rashba coupling

Orbital quantum superposition at finite crystal momentum

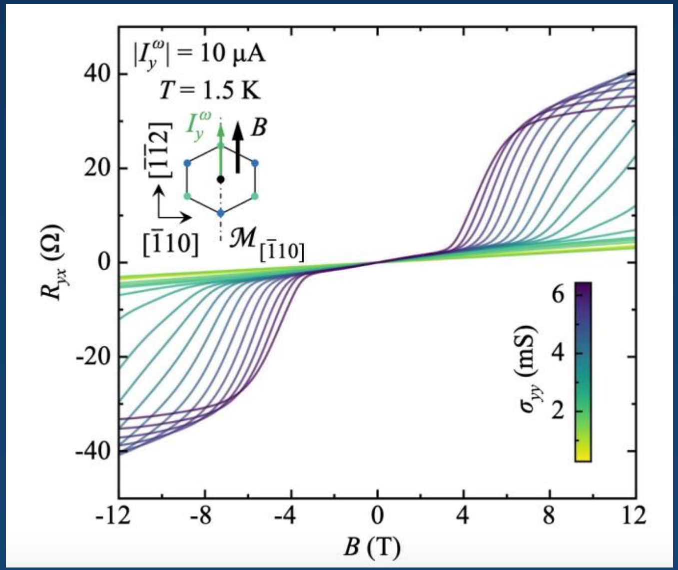
Crystal field

Orbital Rashba coupling

Orbital and spin quantum geometry

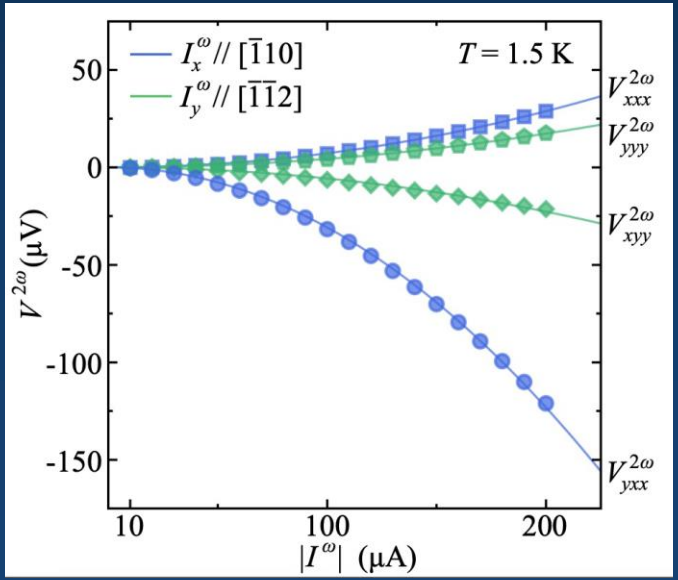
Spin
sources

Orbital
sources



(111)LAO/STO

Lesne et al.
Nature Materials 22, 576
(2023)



Orbital sources of Berry curvature

t_{2g} orbitals with mixing terms (neglecting spin-orbit coupling)

Δ trigonal crystal field

T < 105 K
Δ_m and α_m tetragonal distortion

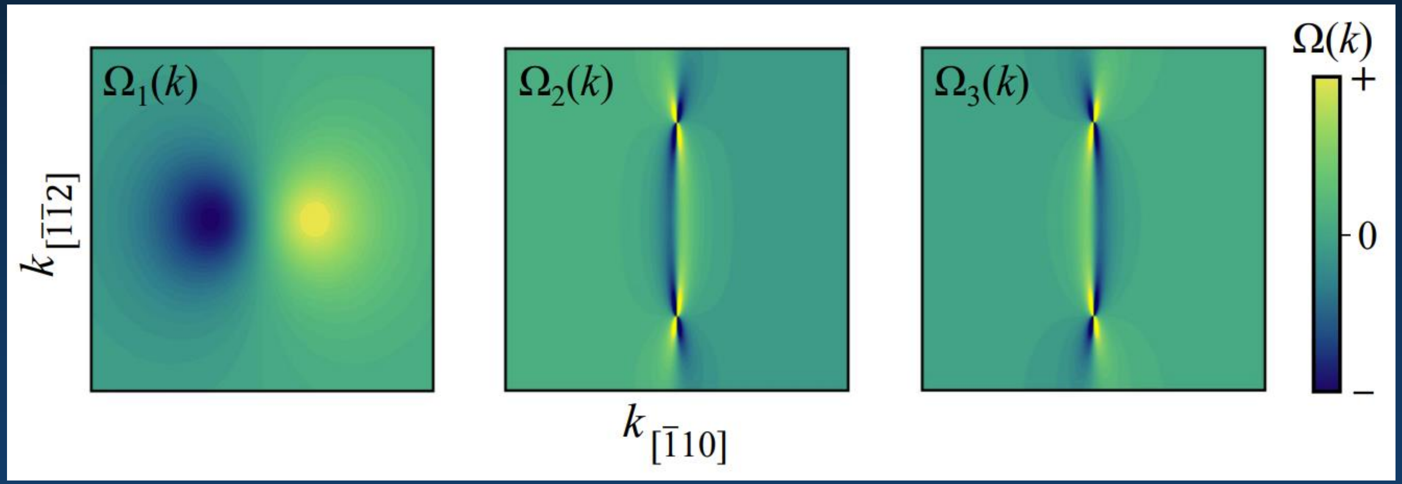
T < 40 K
α_{OR} interfacial breaking of inversion symmetry with polar axis

Mercaldo et al. npj Quantum Materials (2023)
arXiv:2301.04548

$$\mathscr{H}_{\mathrm{OR}}(\mathbf{k}) = \frac{\mathbf{k}^2}{2m}\Lambda_0 + \Delta\left(\Lambda_3 + \frac{1}{\sqrt{3}}\Lambda_8\right) + \Delta_m\left(\frac{1}{2}\Lambda_3 - \frac{\sqrt{3}}{2}\Lambda_8\right) - \alpha_{\mathrm{OR}}\left[k_x\Lambda_5 + k_y\Lambda_2\right] - \alpha_m k_x \Lambda_7$$

Orbital sources of Berry curvature

Dipolar distributions: nonlinear transport responses

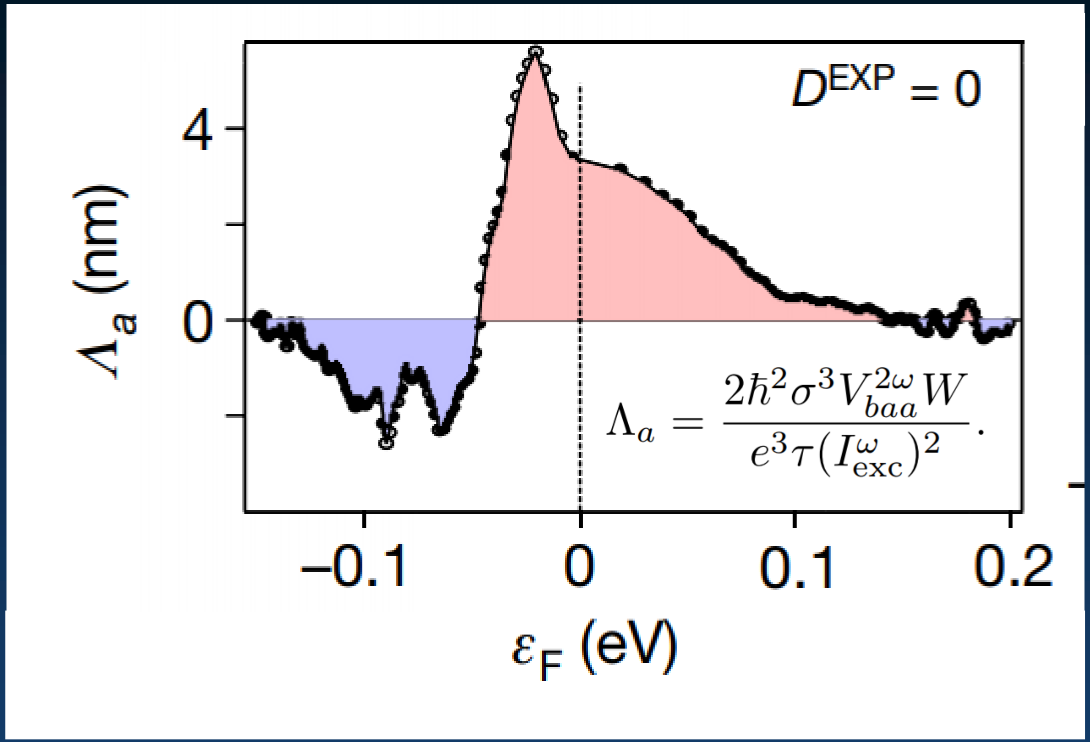


Hot spots

Singular pinch points

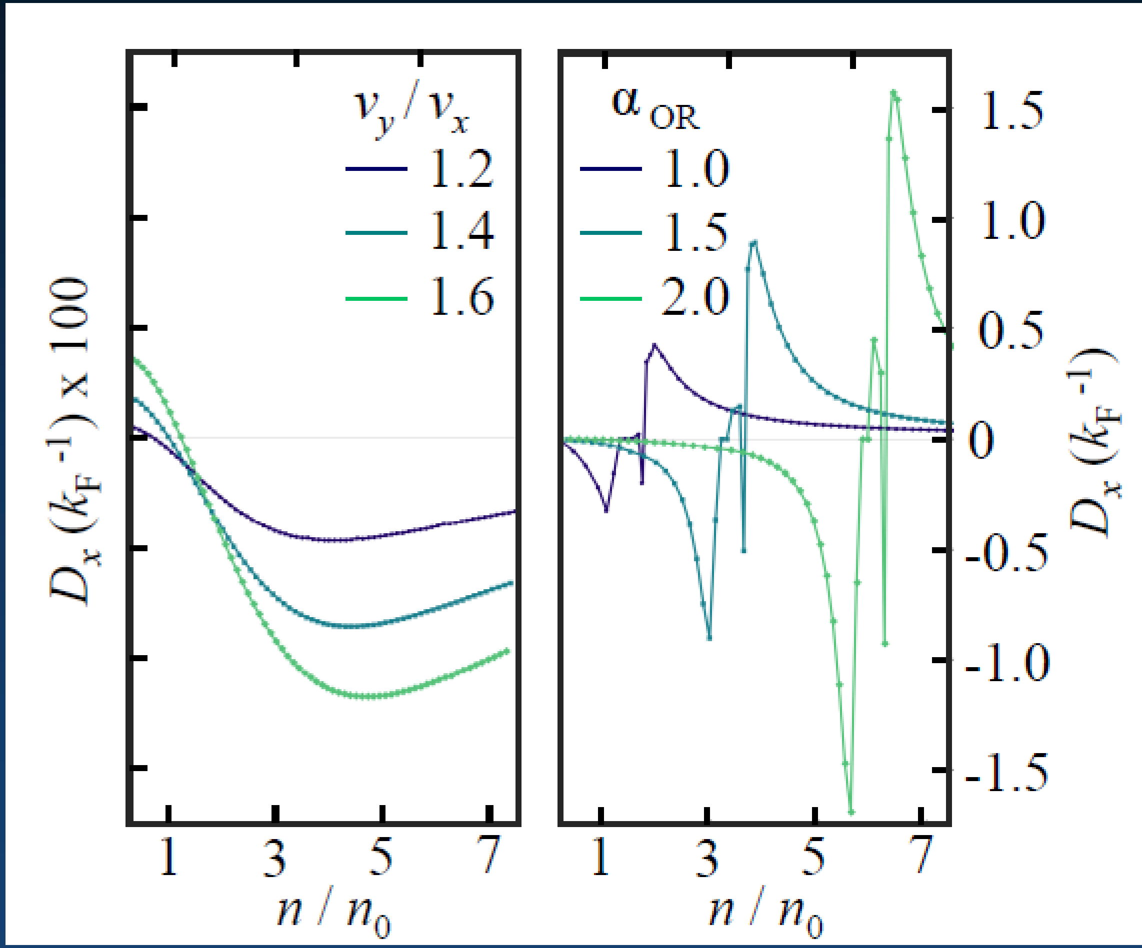
$$\mathscr{H}_{\mathrm{OR}}(\mathbf{k}) = \frac{\mathbf{k}^2}{2m}\Lambda_0 + \Delta\left(\Lambda_3 + \frac{1}{\sqrt{3}}\Lambda_8\right) + \Delta_m\left(\frac{1}{2}\Lambda_3 - \frac{\sqrt{3}}{2}\Lambda_8\right) - \alpha_{\mathrm{OR}}\left[k_x\Lambda_5 + k_y\Lambda_2\right] - \alpha_m k_x \Lambda_7$$

Quantum Nonlinear Hall Effect



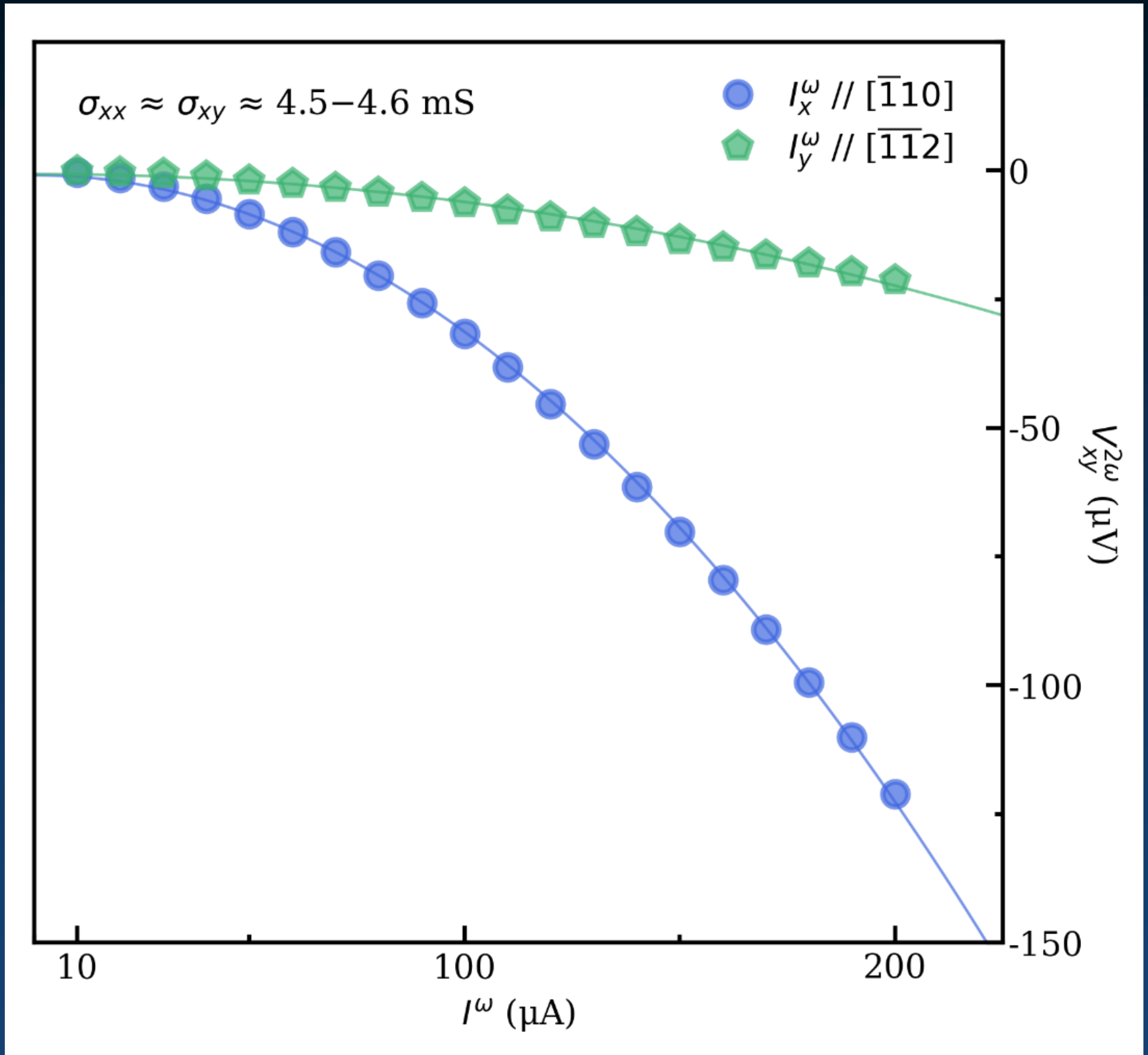
WTe_2
Ma et al. Nature 565, 337 (2019)
Sodemann, I. & Fu, L.. Phys. Rev. Lett. 115, 216806 (2015)

Orbital sources of Berry curvature



Prediction:
BCD in the 10s nm range!

Non linear Hall effect at B=0

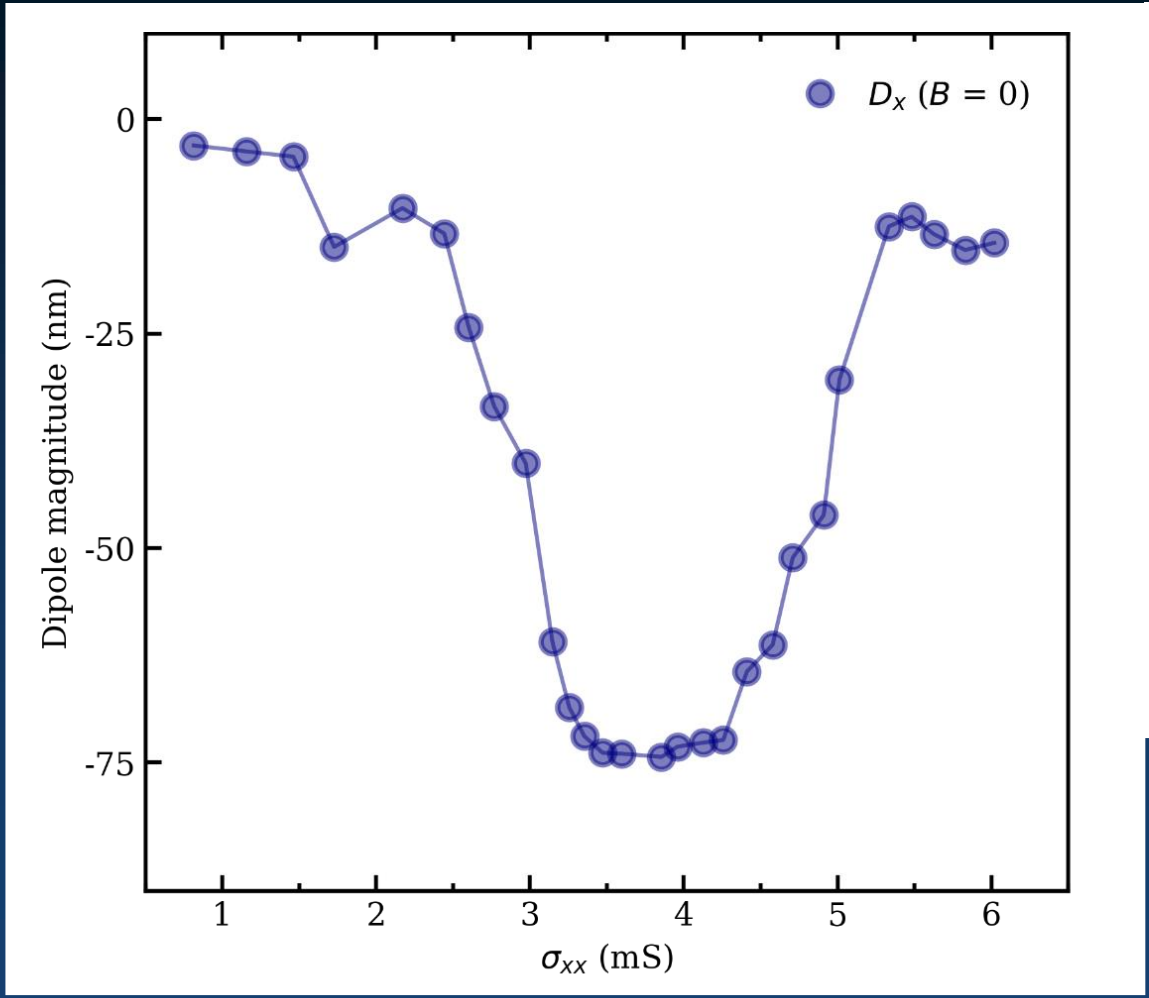


Ulderico Filippozzi

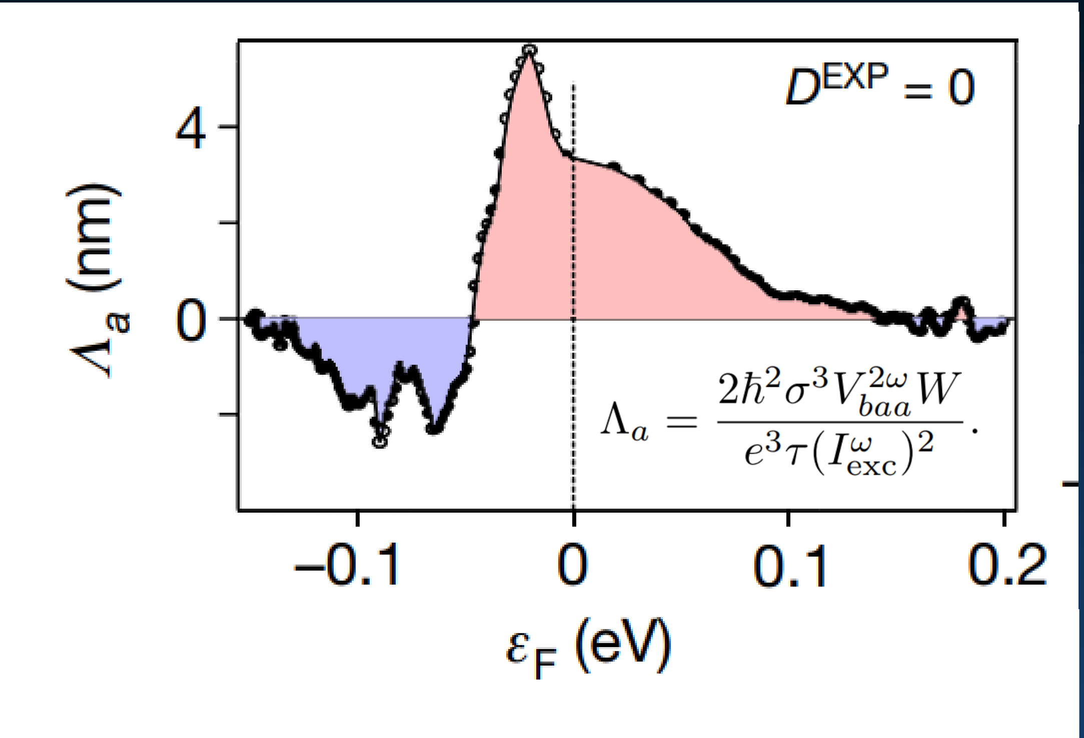
Edouard Lesne

Lesne et al.
Nature Materials 22, 576
(2023)

Dipole magnitude

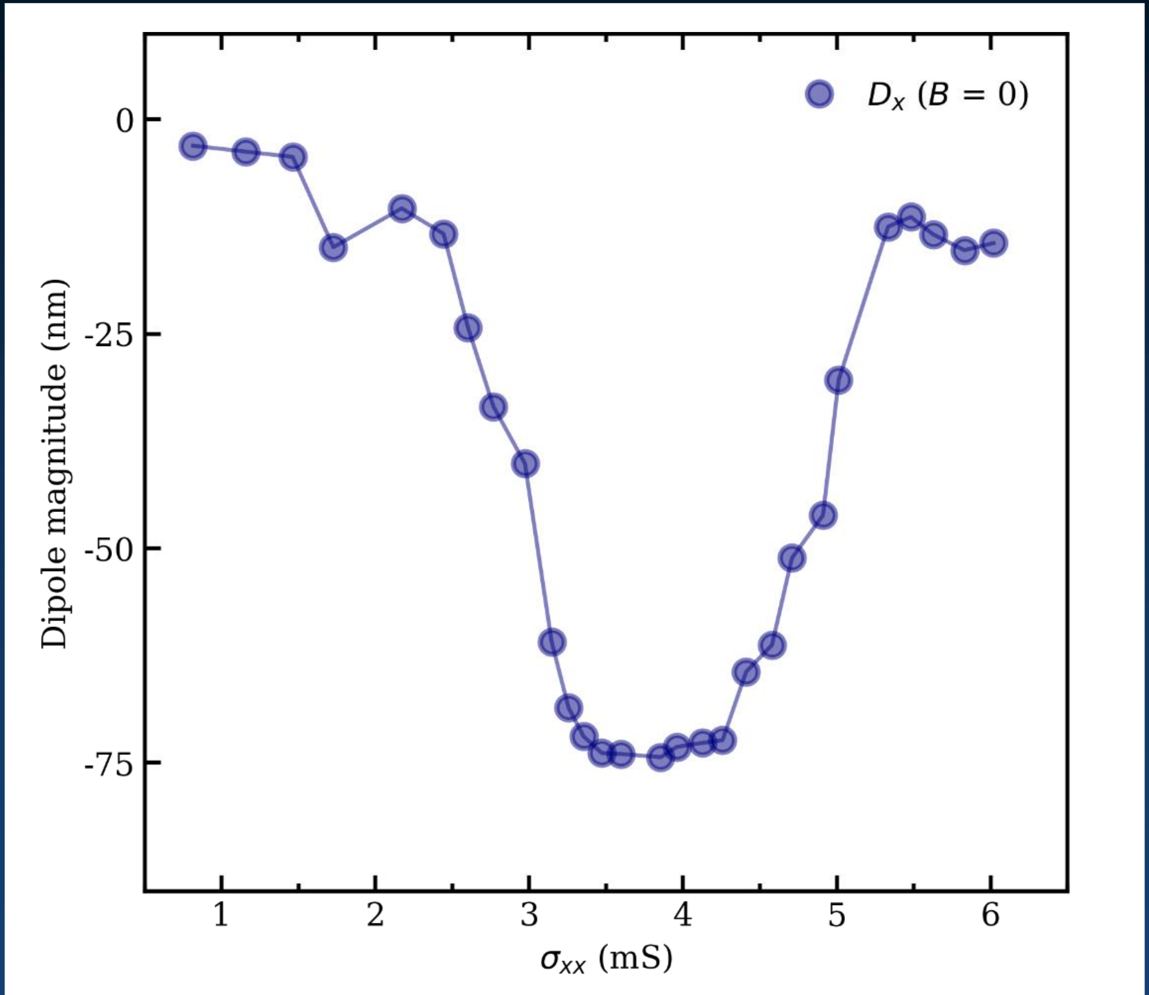


(111)$LaAlO_3/SrTiO_3$



WTe_2
Ma et al. Nature 565, 337 (2019)
Sodemann, I. & Fu, L.. Phys. Rev. Lett. 115, 216806 (2015)

Dipole magnitude

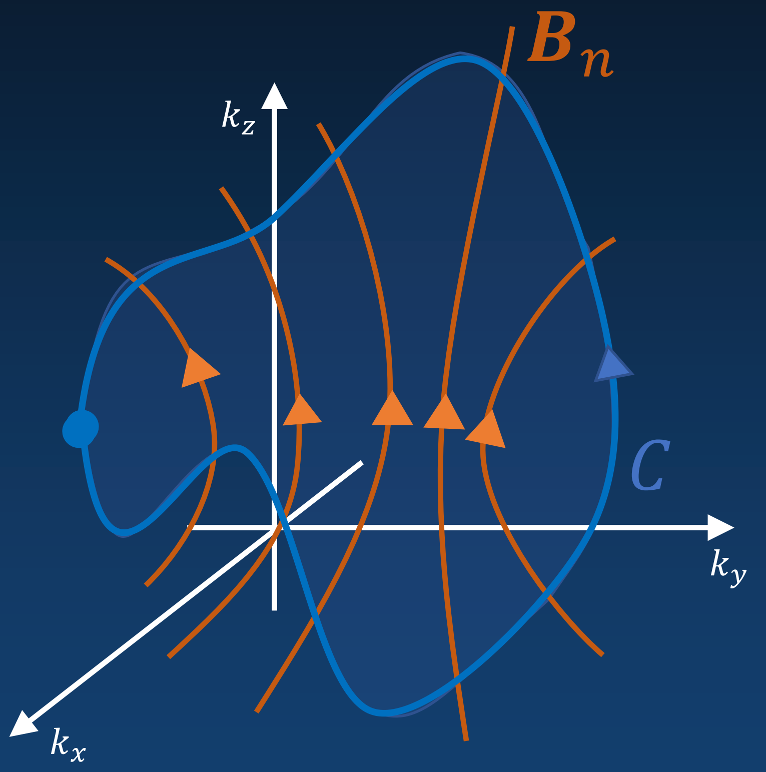


(111)$LaAlO_3/SrTiO_3$

Materials	Dimension	Experimental estimate of Berry curvature dipole (nm)
Bilayer WTe_2	2	5
Few layer WTe_2	2	0.07
Monolayer WTe_2	2	0.06
Corrugated bilayer graphene	2	20
Twisted WSe_2	2	0.5
Strained twisted bilayer graphene	2	20
LAO-STO interface	2	75

Lesne et al.
Nature Materials 22, 576 (2023)

Origin of quantum geometry



$$\boldsymbol{v}_n(\boldsymbol{k}) = \frac{1}{\hbar}\nabla_{\boldsymbol{k}}\epsilon_n(\boldsymbol{k}) - \frac{e}{\hbar}\boldsymbol{E} \times \boldsymbol{B}_n(\boldsymbol{k})$$

Geometric riformulation of QM
J. Anandan and Y. Aharonov
Geometry of quantum evolution
Phys. Rev. Lett. 65, 1697 (1990)

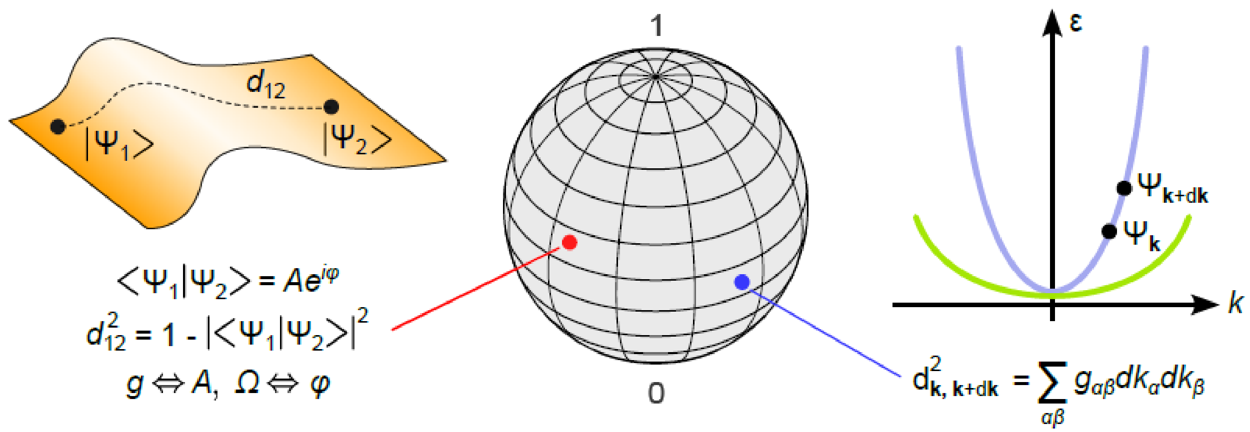
Quantum Geometric Tensor (QGT)

Re (QGT) : quantum metric.
Mapped to the geodesic distance between two points on the Bloch's sphere, endowed with a Fubini–Study metric

Im (QGT): **Berry curvature**.
Geometric phase of the wavefunction

Origin of quantum geometry

Sala et al. arxiv 2407.06659 (2024)



$$\dot{x}_a = \frac{1}{\hbar}\partial_{k^a}\mathcal{E}(\mathbf{k}) + (\dot{\mathbf{k}} \times \mathbf{\Omega})_a + \frac{\zeta}{\hbar}\Gamma_{bca}\dot{k}^b\dot{k}^c,$$

$$\Gamma_{bca} \sim \partial_c g_{ab}$$

$$\dot{k}^b\dot{k}^c \sim E^b E^c$$

Geometric riformulation of QM
J. Anandan and Y. Aharonov
Geometry of quantum evolution
Phys. Rev. Lett. 65, 1697 (1990)

Quantum Geometric Tensor (QGT)

Re (QGT) : **quantum metric**.
Mapped to the geodesic distance between two points on the Bloch's sphere, endowed with a Fubini–Study metric

Im (QGT): Berry curvature.
Geometric phase of the wavefunction

Conclusions

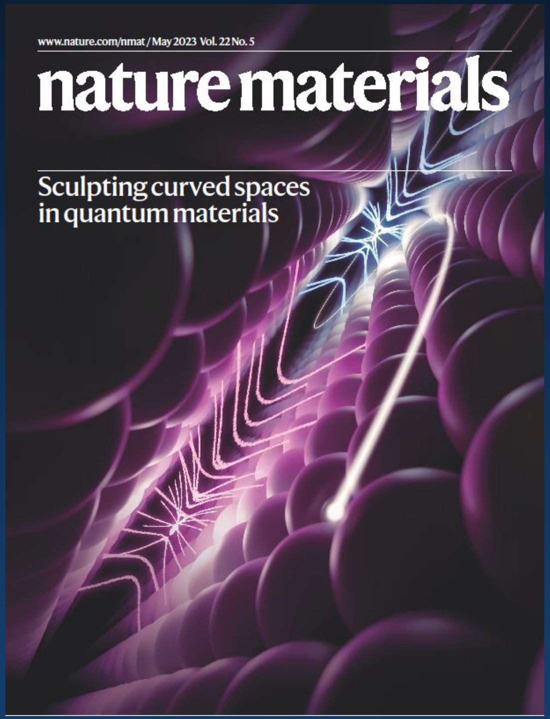


Image:
Xavier Ravinet
UNIGE

Puzzling experimental observations:

1. Anomalous Planar Hall effect.

2. Non-linear Hall effect in time-reversal invariant conditions.

3. Non-linear magnetoresistance.

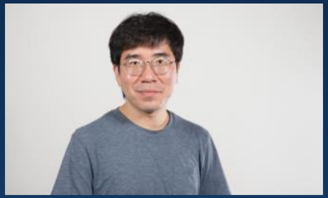
Lesne et al. Nature Materials 22, 576 (2023)
Mercaldo et al. npj Quantum Materials (2023)
Sala et al. arxiv 2407.06659 (2024)

Spin quantum metric in principle applicable to a broad class of surface and interface states of materials with strong spin-orbit coupling. Geometric contribution to superconductivity?

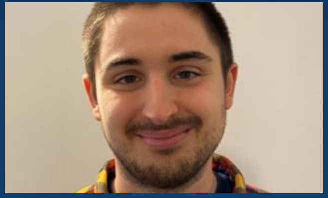
Collaborators and funding

Edouard Lesne, Mattias Matthiesen, Graham Kimbell, Ian Aupiais, **Giacomo Sala**, Chang Jae Roh, Greta Segantini, Tancredi Thai Angeloni, Patrick Blah, **Ulderico Filippozzi**, Marco Lopes, Ioana Novas, **Stefano Gariglio**



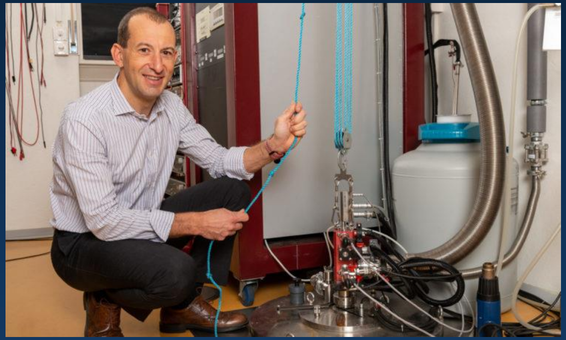






In collaboration with

Mario Cuoco
CNR Spin
Raffaele Battilomo,
Maria Teresa Mercaldo,
Canio Noce,
Carmine Ortix
Uni Salerno



Funded by

European Research Council
Established by the European Commission

GORDON AND BETTY MOORE FOUNDATION

NWO

Fonds national suisse