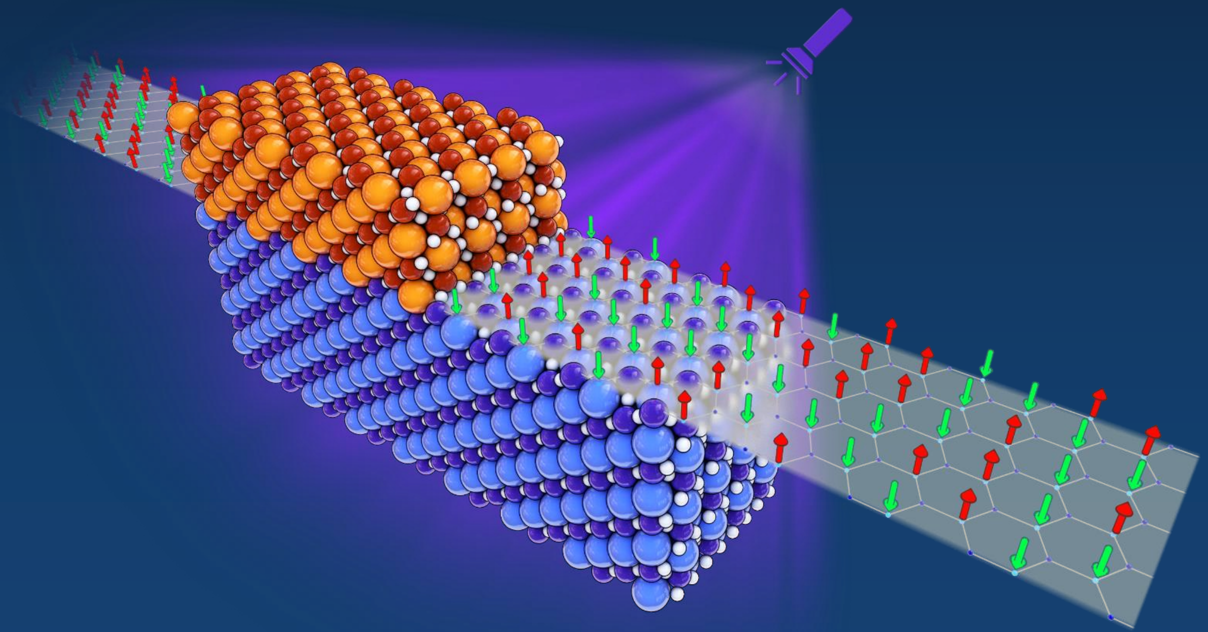
Designing spin and orbital sources of Berry curvature at oxide interfaces

Caviglia Lab

Department of Quantum Matter Physics

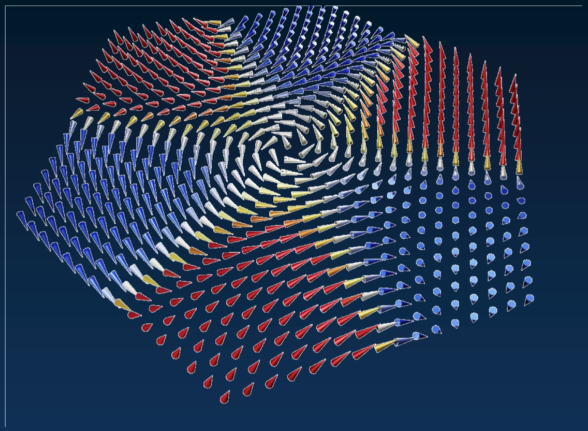
University of Geneva



Spin textures in and out of equilibrium

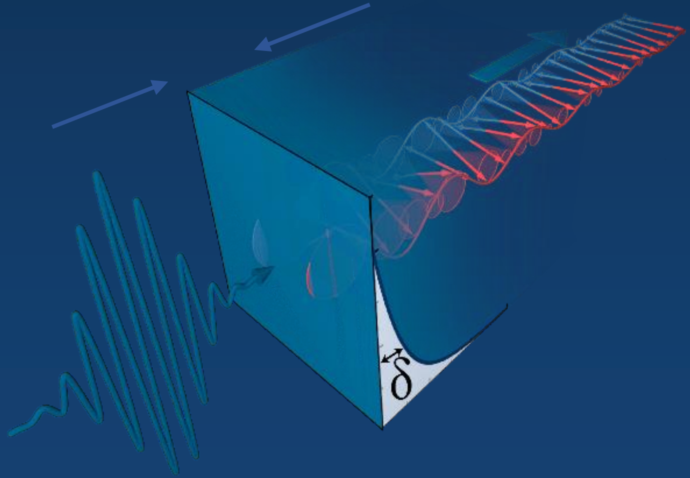
Spin textures by material design

Low-symmetry oxide interfaces
Berry curvature engineering



Light control of spin dynamics

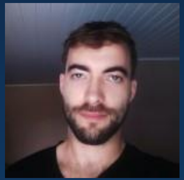
Light-driven antiferromagnets
Propagating coherent magnons



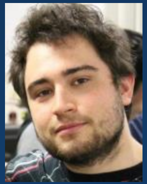
Collaborators and funding

Thierry van Thiel, Yildiz Saglam, Edouard Lesne, Ulderico Filippozzi, Patrick Blah, Graham Kimbell, Mafalda Monteiro, Ian Aupiais, Tancredi Thai Angeloni, Giacomo Sala





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Anomalous velocity and Berry phase

$$\gamma_n = \int_C \boldsymbol{A}_n(\boldsymbol{k}) \cdot d\boldsymbol{k}$$

$$\gamma_n = \oiint_\Omega \boldsymbol{B}_n(\boldsymbol{k}) \cdot d\boldsymbol{\Omega}$$

$$\boldsymbol{A}_n(\boldsymbol{k}) = -i\langle u_n(\boldsymbol{k})|\nabla_{\boldsymbol{k}}|\, u_n(\boldsymbol{k})\rangle$$

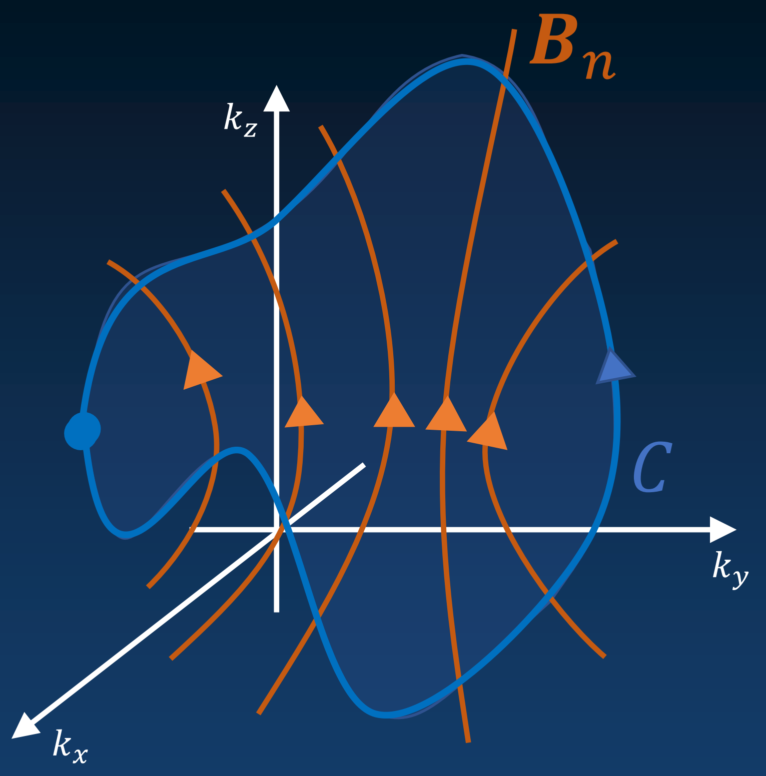
Berry Connection

$$\boldsymbol{B}_n(\boldsymbol{k}) = \nabla_{\mathbf{k}} \times \boldsymbol{A}_n(\boldsymbol{k})$$

Berry Curvature

Effective Vector Potential

Effective Magnetic Field



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

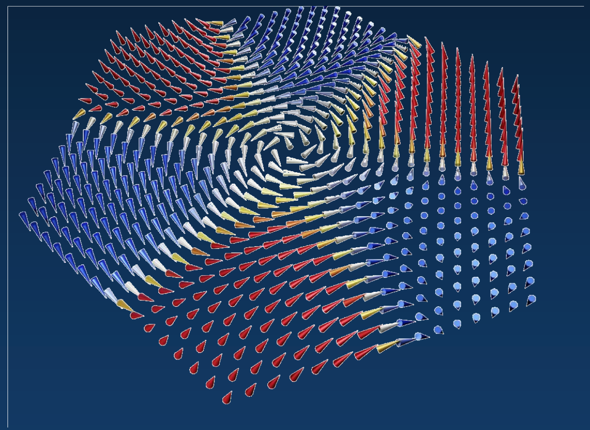
Karplus, Luttinger Phys. Rev. 95, 1154 (1954)
Berry Proc. R. Soc. London A 392, 45 (1984)
Chang, Niu PRL 75, 1348 (1995)

Why Berry curvature?

Controlling dynamics of charges orbitals and spins through purely quantum effects (no Lorentz force).

Engineering strong electromagnetic responses originating from low-energy physics, THz electrodynamics.

Large non-linear responses.



Sources of Berry curvature

1) Zero for real wavefunctions

2) Zero for planar spin textures

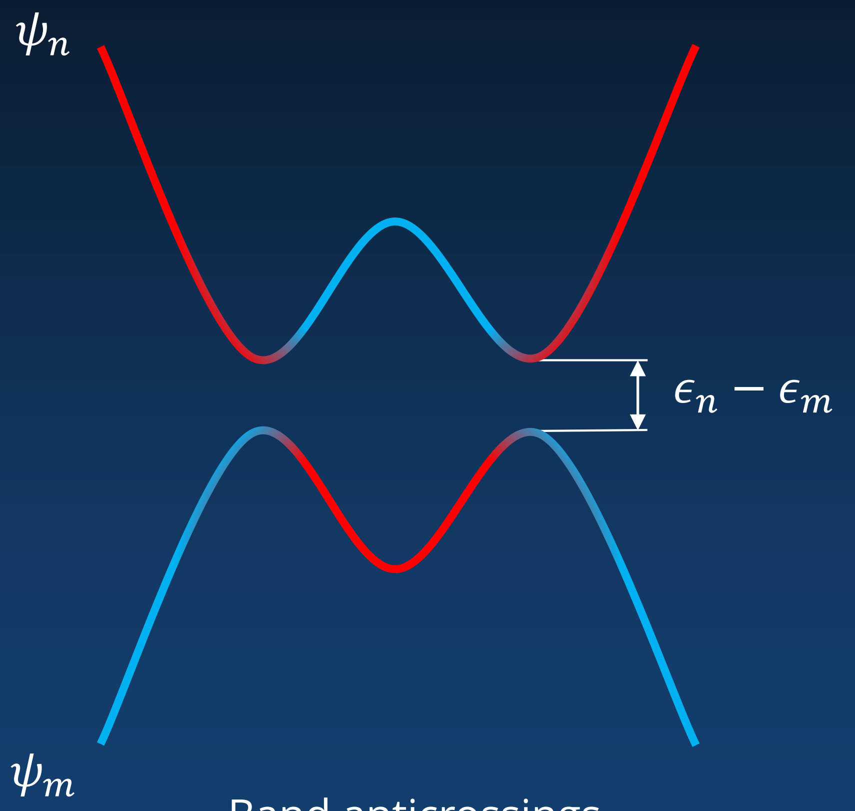
$$\boldsymbol{B}_z^{\pm}(\boldsymbol{k}) = \pm\hat{\boldsymbol{d}} \cdot (\boldsymbol{\partial}_{\boldsymbol{k}_x}\hat{\boldsymbol{d}} \times \boldsymbol{\partial}_{\boldsymbol{k}_y}\hat{\boldsymbol{d}})/\boldsymbol{2}$$

3) Large near avoided band crossings

$$\boldsymbol{B}_z(\boldsymbol{k}) = [\langle\psi_m|\nabla\psi_n\rangle \times \langle\nabla\psi_n|\psi_m\rangle]_z$$

$$= \frac{[\langle\psi_m|\nabla H|\psi_n\rangle \times \langle\psi_n|\nabla H|\psi_m\rangle]_z}{(\epsilon_m - \epsilon_n)^{\,2}}$$

Quantum superposition at finite crystal momentum



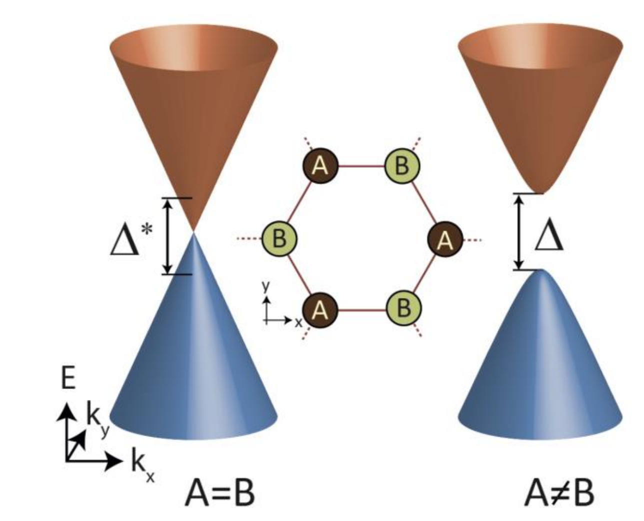
Band anticrossings

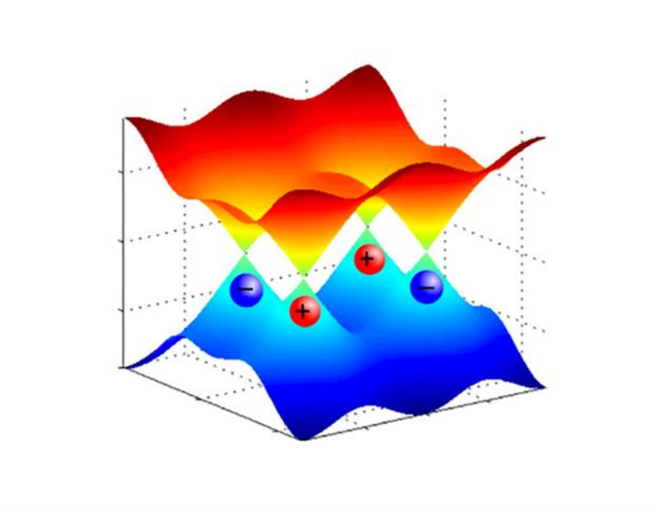
Conventional systems

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

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

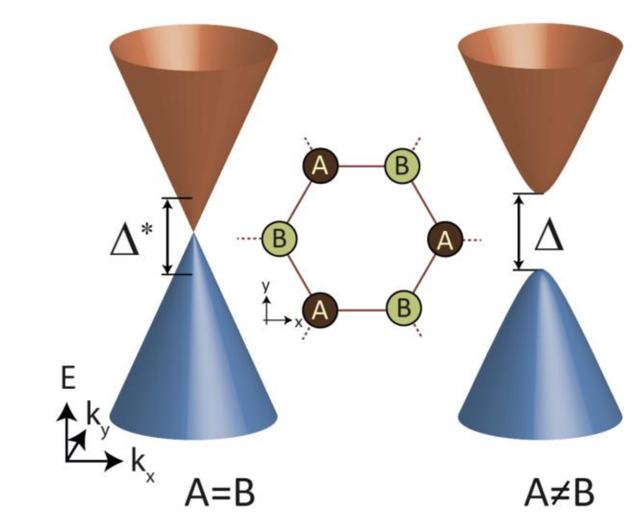
σ spin space

Conventional systems

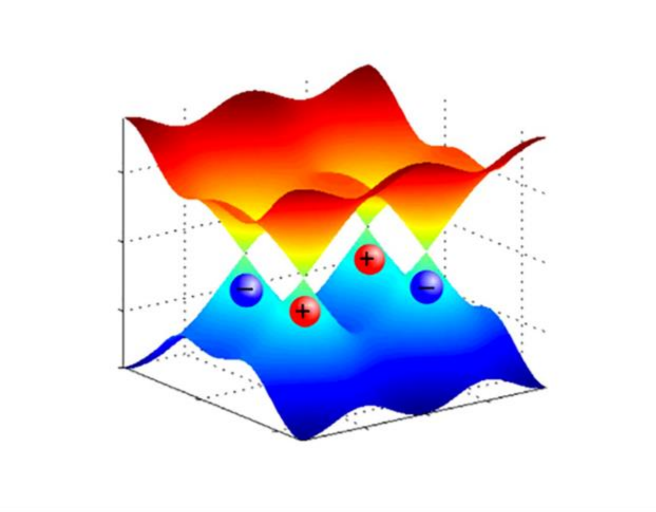
Gapped graphene

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

σ sublattice space



Quantum superposition at finite crystal momentum
of a single quantum number



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

Key questions

Can we design Berry curvature sources
from the quantum superpositions at finite crystal momentum of
multiple quantum numbers?

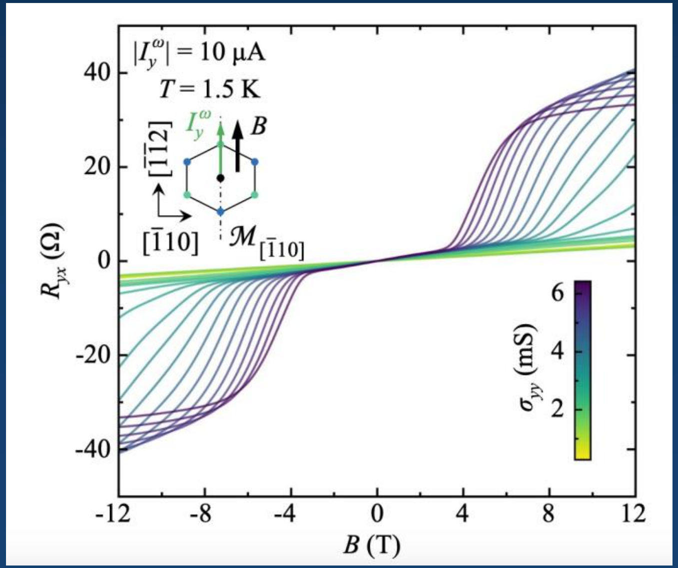
Interplay of correlated and topological physics

(111)LAO/STO: the first material system with coexisting sources of Berry curvature

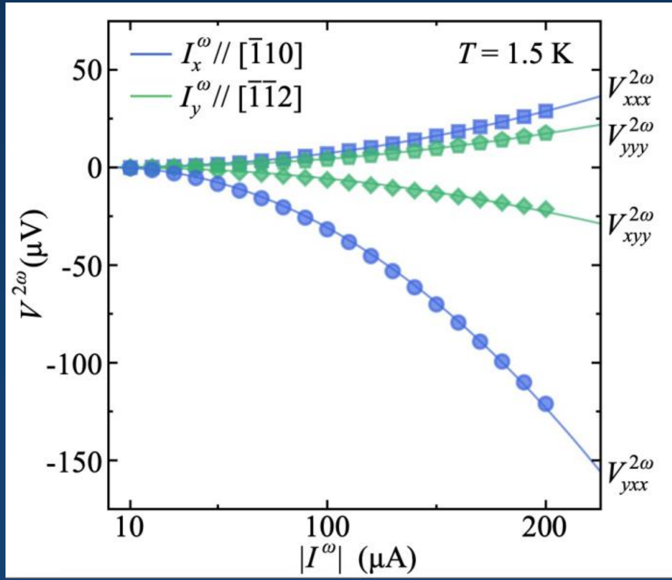
Spin sources

Orbital sources

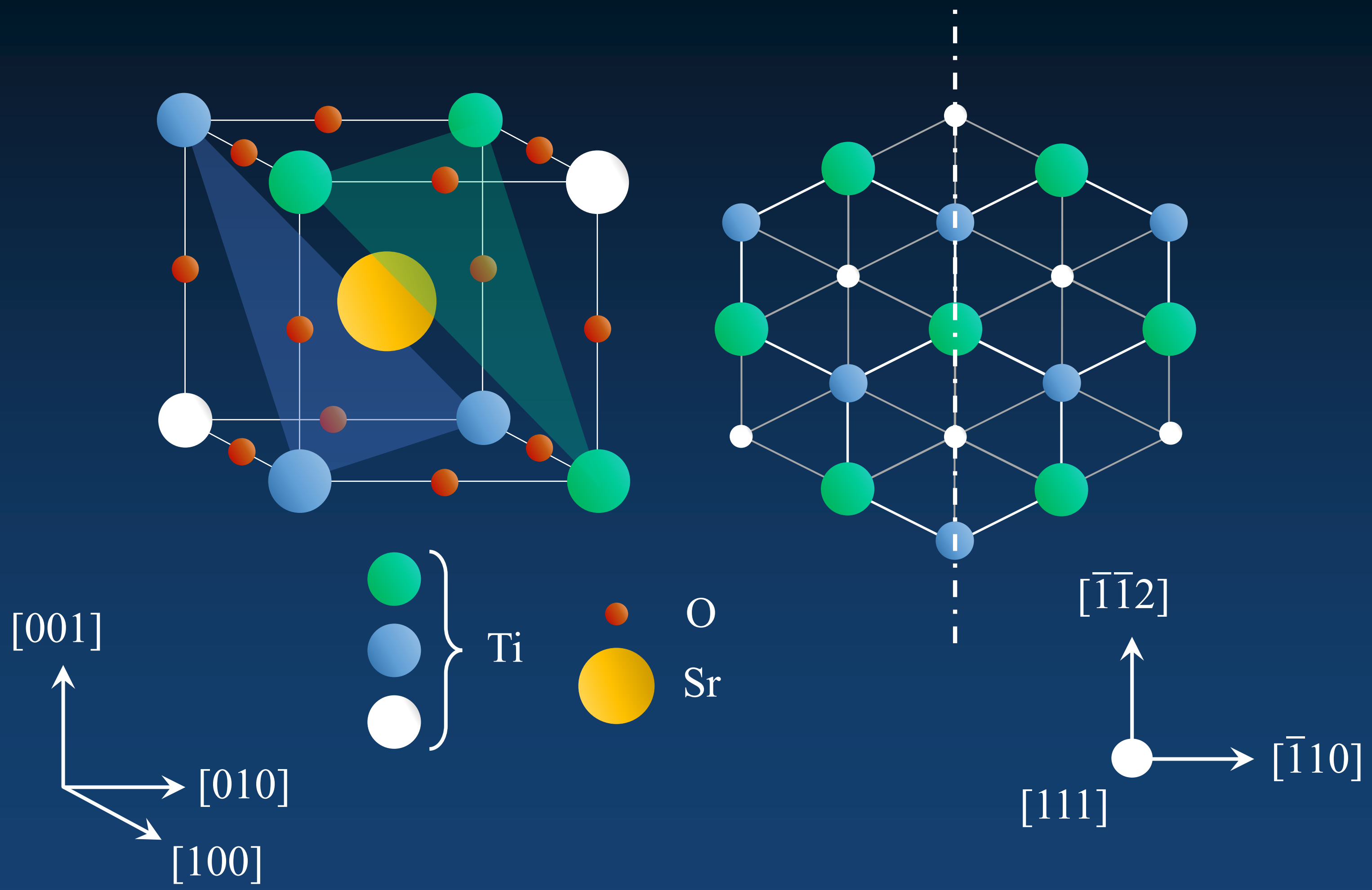
Probed by linear and nonlinear anomalous transport.



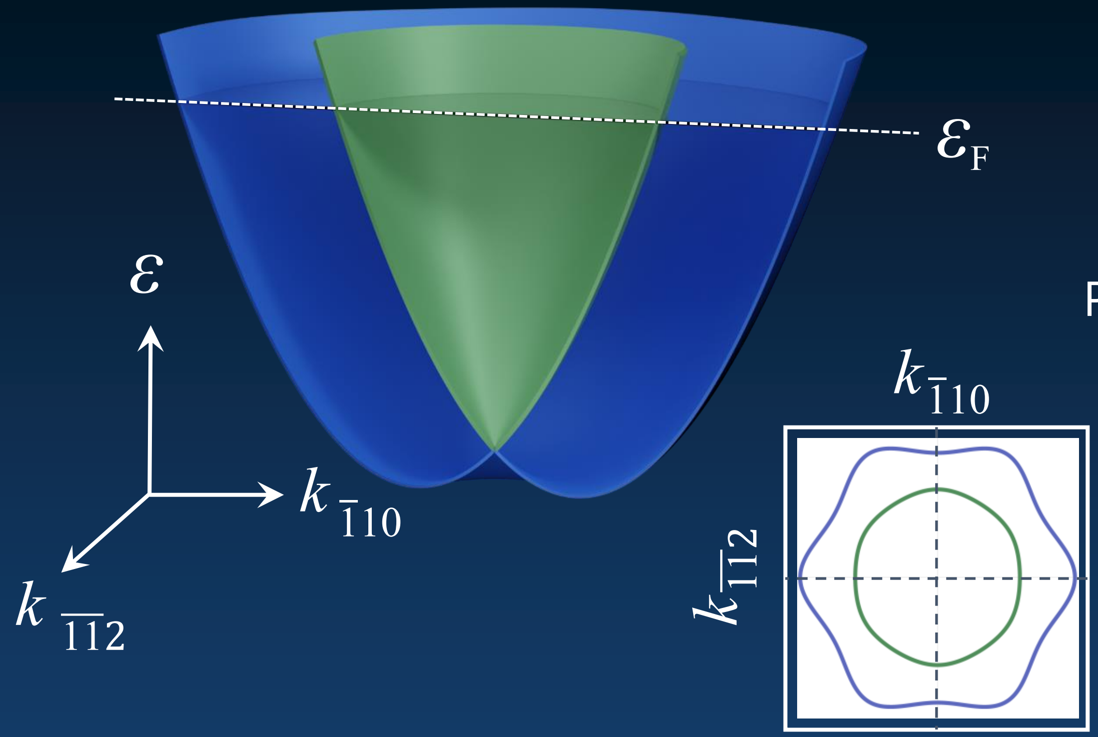
Lesne et al.
Nature Materials 22, 576 (2023)



Exploring hexagonal symmetry



Trigonal warping and spin-orbit coupling

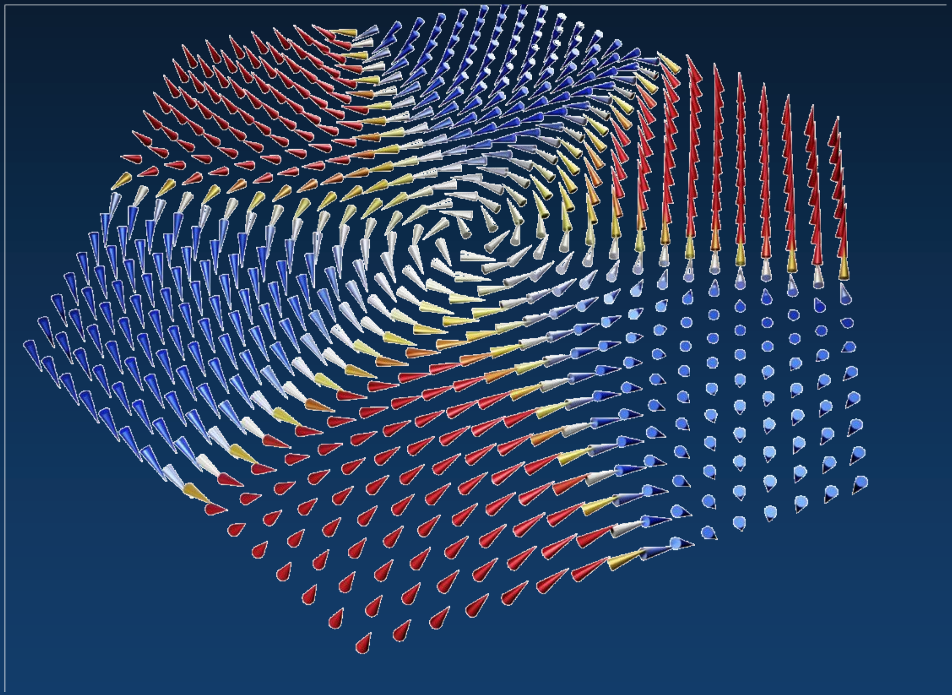


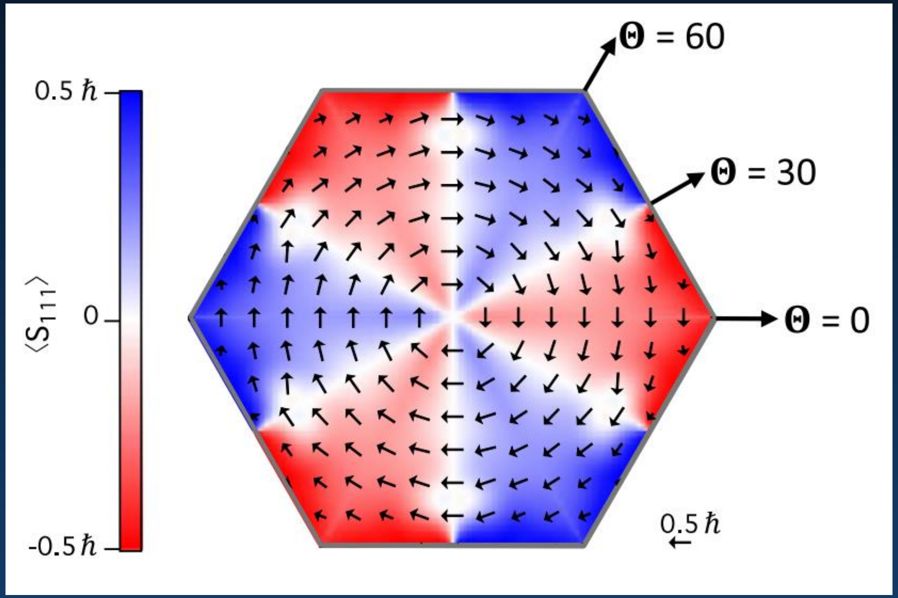
Monteiro et al.
Phys. Rev. B 99, 201102R (2019)

$$\mathcal{H}(\mathbf{k}) = \frac{k^2}{2m}\sigma_0 + (\alpha_R k_x + \mathcal{B}\sin\theta)\sigma_y + (-\alpha_R k_y + \mathcal{B}\cos\theta)\sigma_x + \frac{\lambda}{2}(k_+^3 + k_-^3)\sigma_z$$

$$k_\pm = k_x \pm i k_y$$

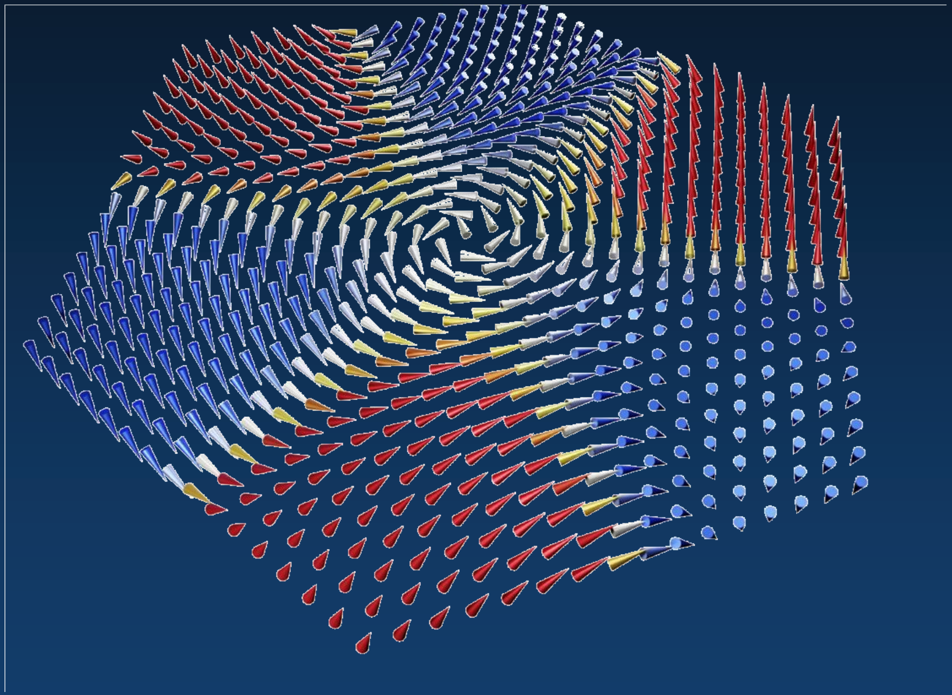
Out-of-plane spin texture

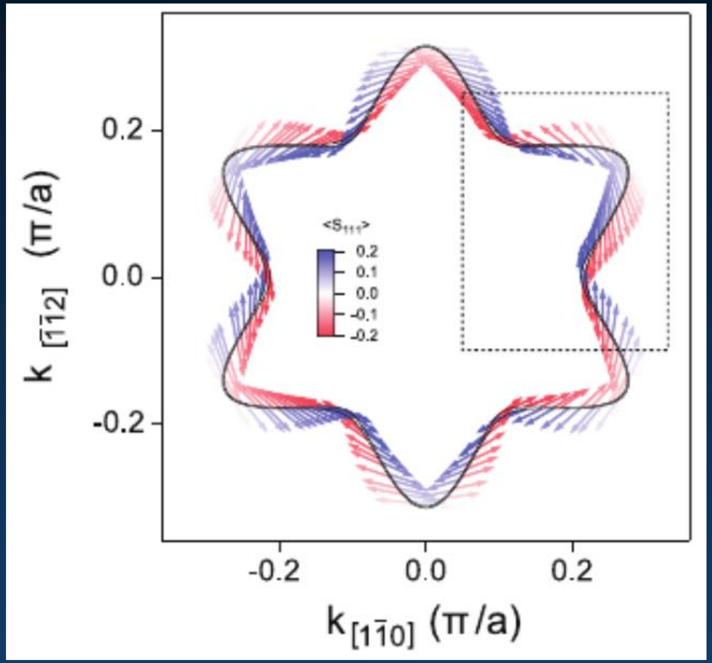




Surface of (111)SrTiO3
He et al. Physical Review Letters 120, 266802 (2018)

Out-of-plane spin texture

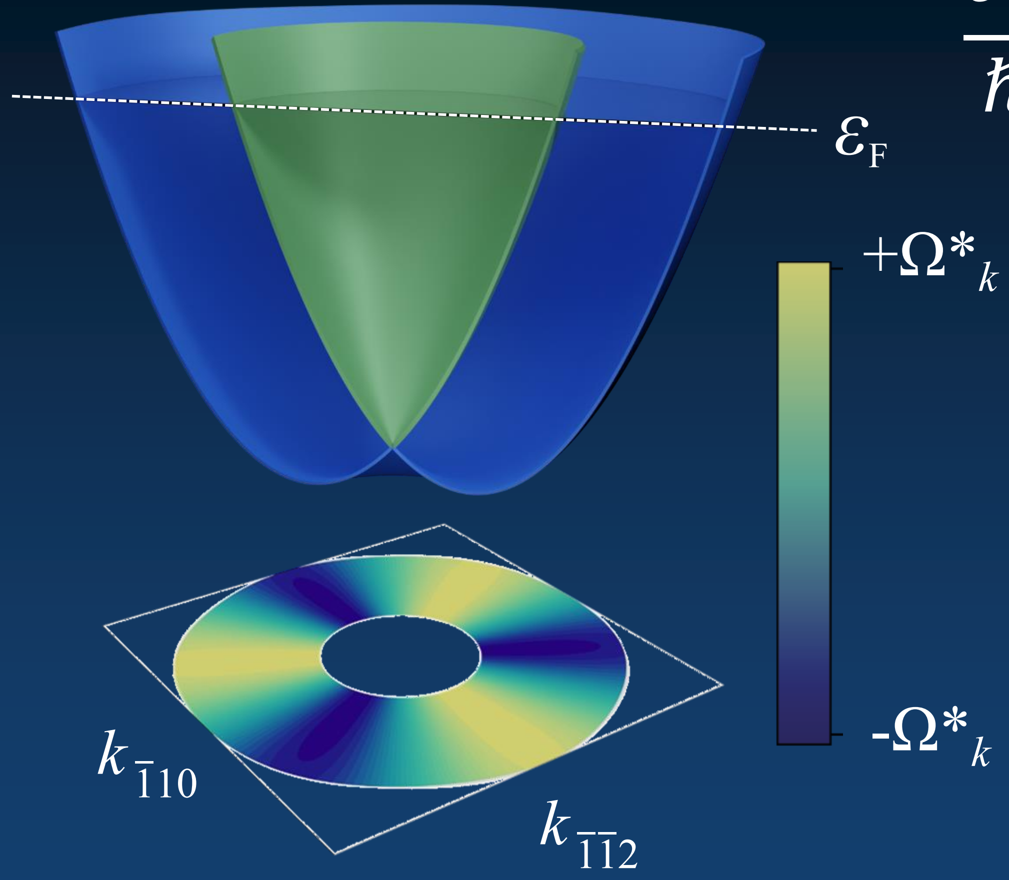




Surface of (111)KTaO3
Bruno et al. Advanced Electronic Materials, 1800860 (2019)

Spin sources of Berry curvature

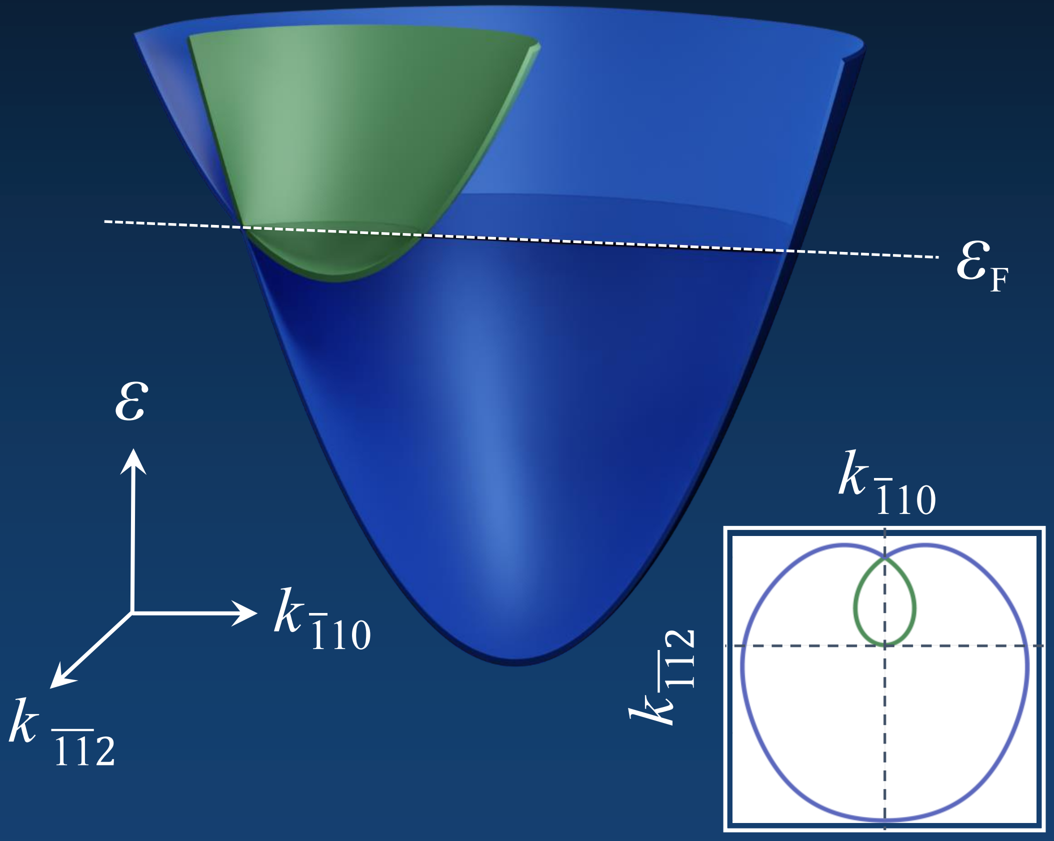
$$\frac{e^2}{\hbar}\int \frac{d^2k}{(2\pi)^2}\boldsymbol{B}(\mathbf{k})f_{\mathbf{k}}^0 = 0$$

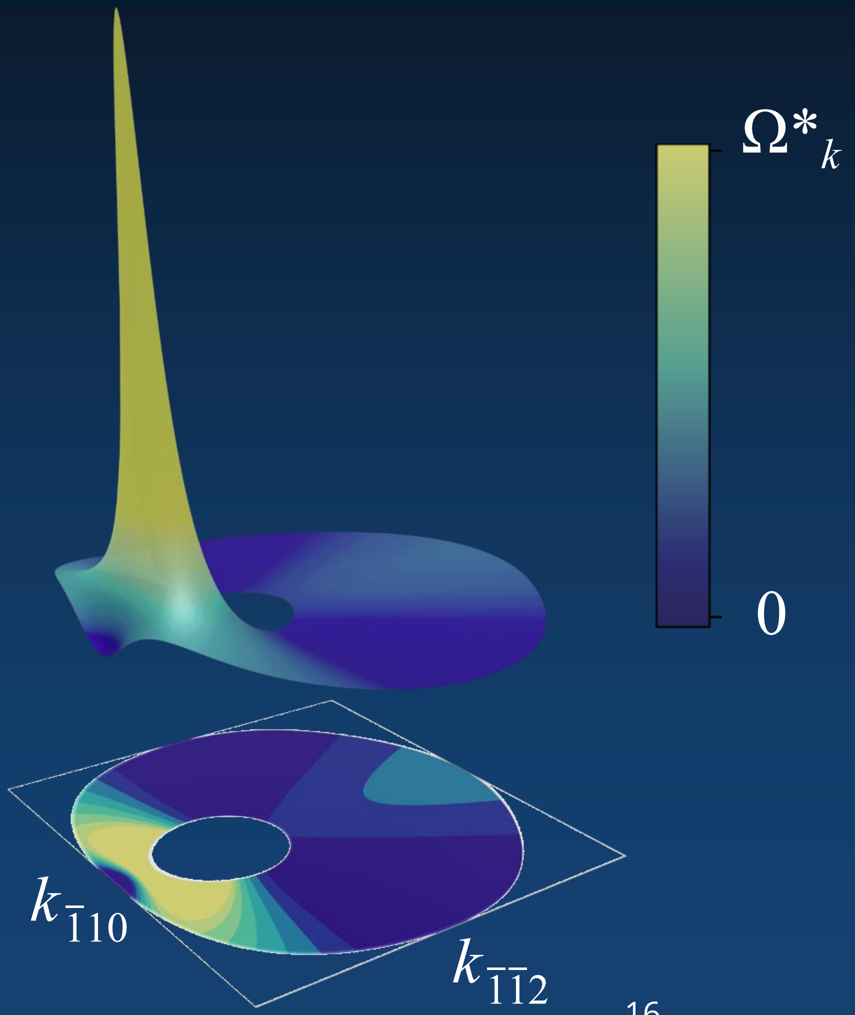


No dipolar distribution

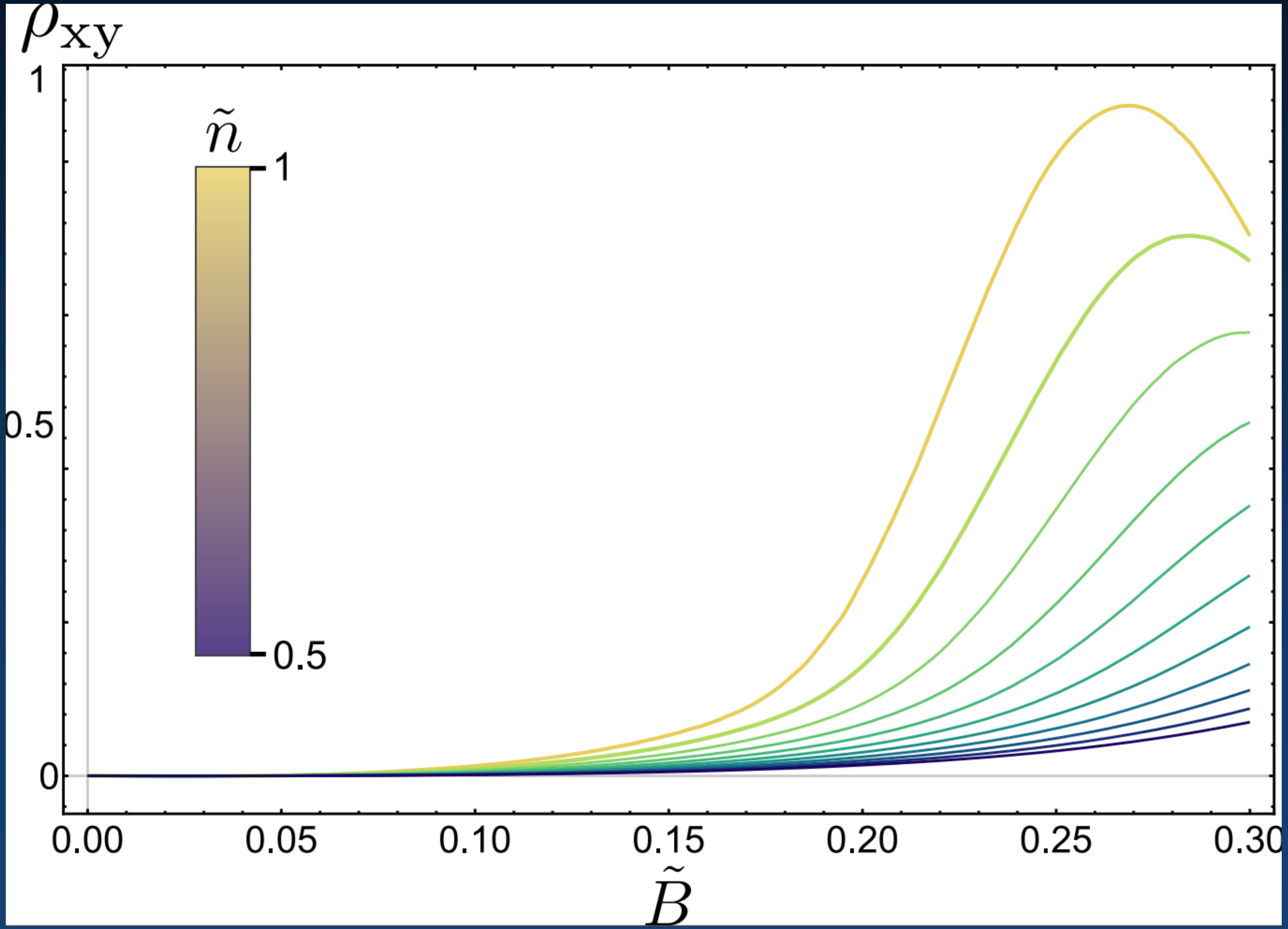
In-plane magnetic field

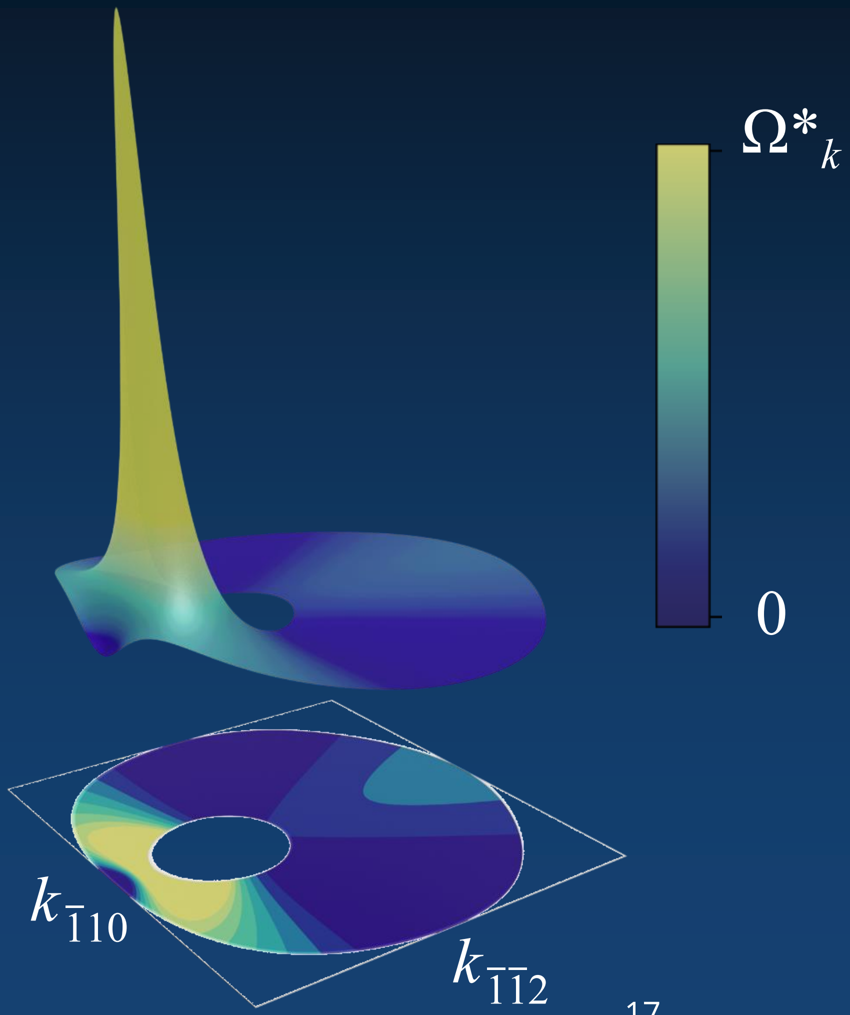
$$\frac{e^2}{\hbar}\int \frac{d^2k}{(2\pi)^2}\boldsymbol{B}(\mathbf{k})f^0_{\mathbf{k}} \neq 0$$



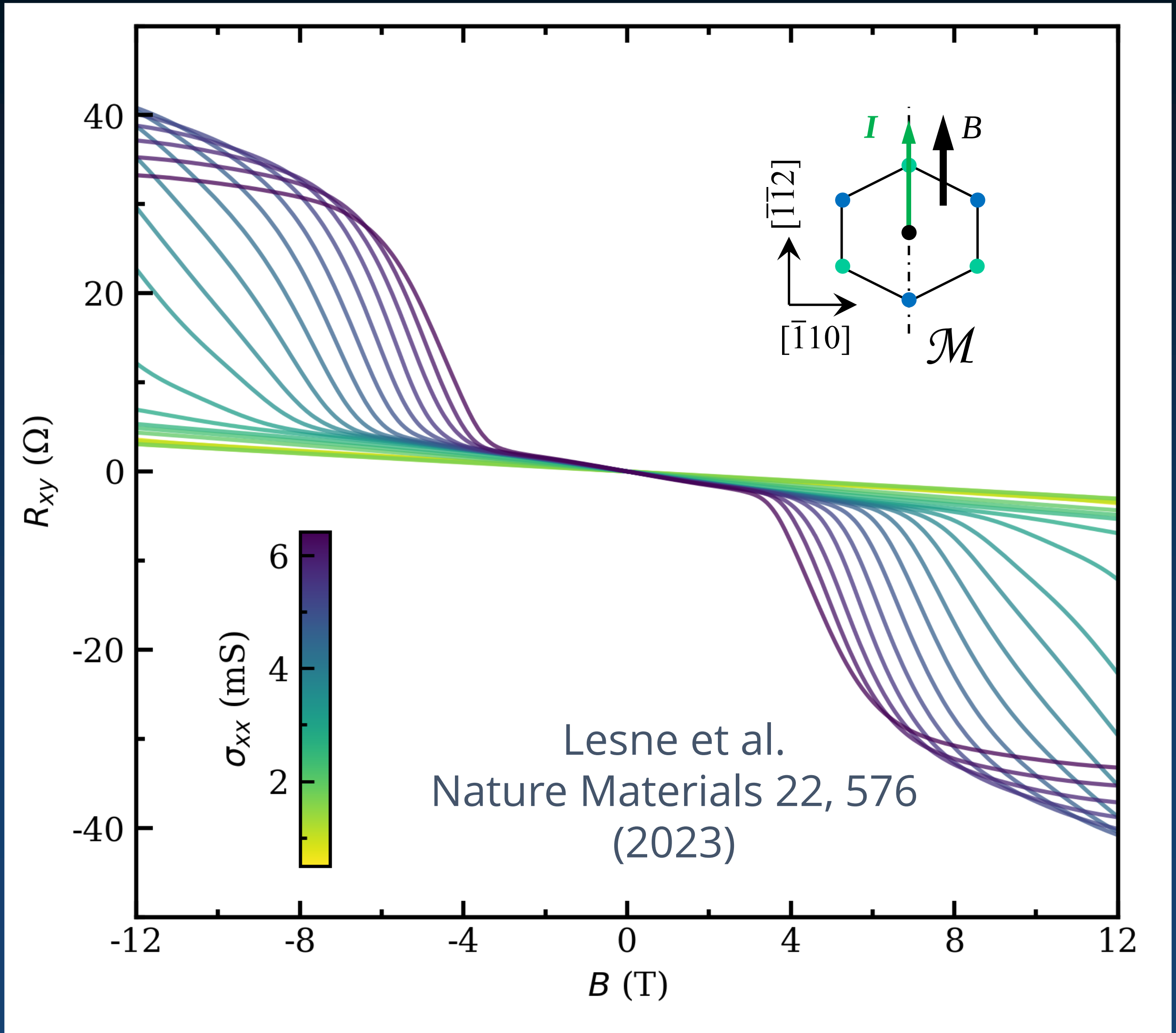


Anomalous planar Hall effect

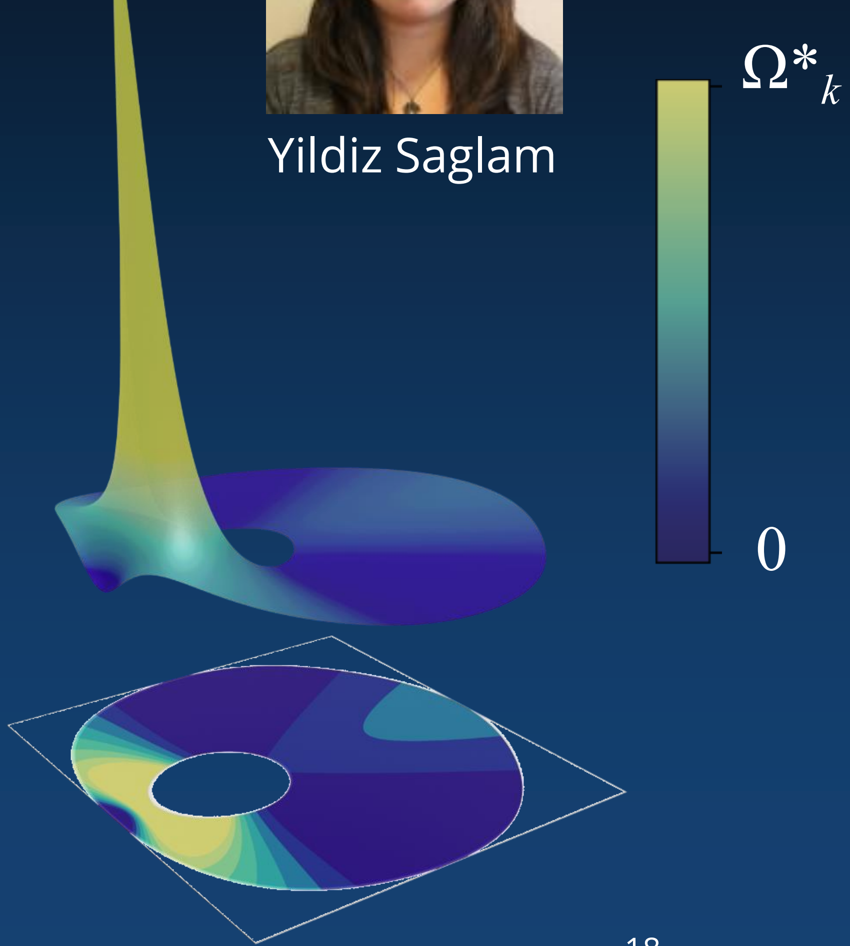




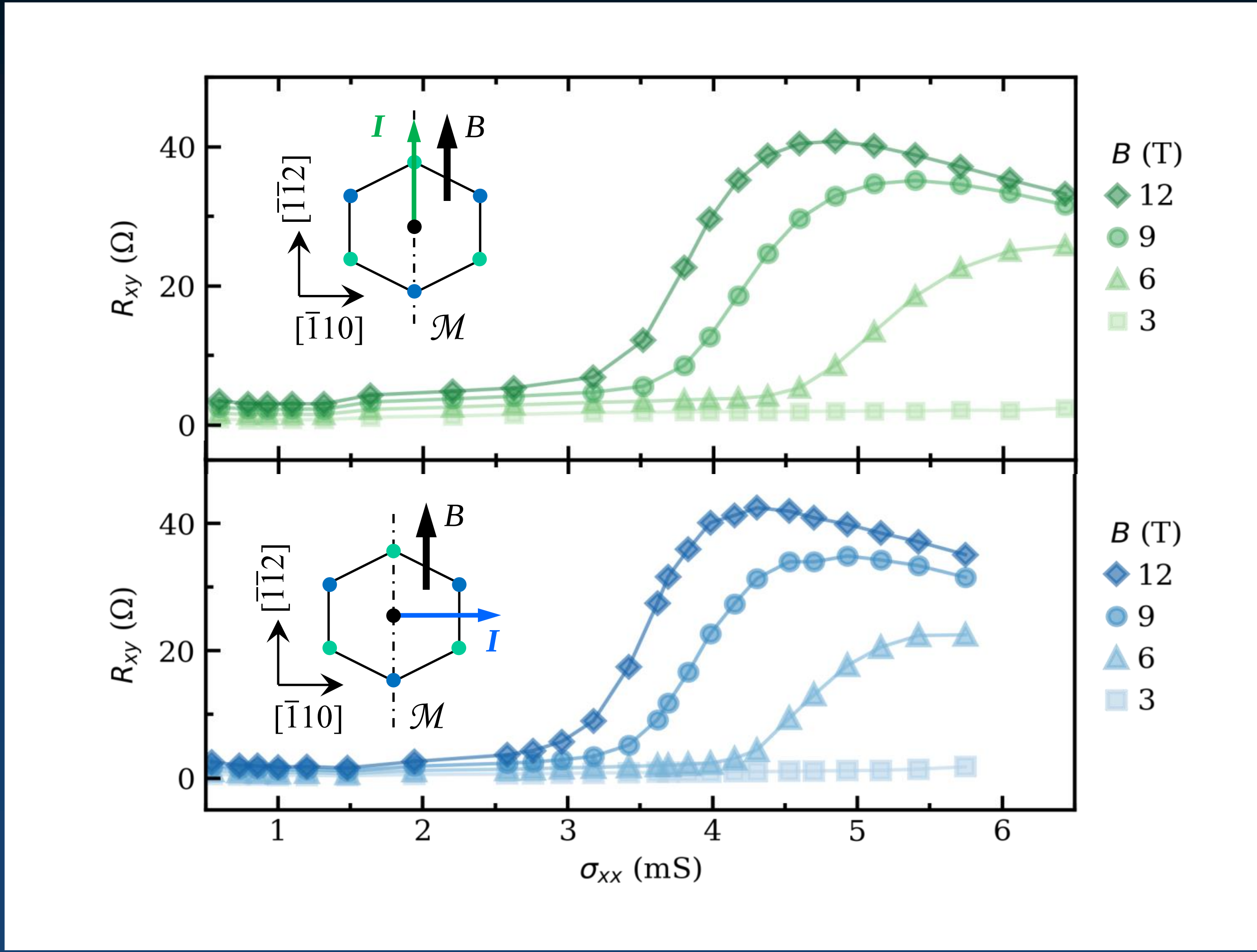
Spin sources of Berry curvature

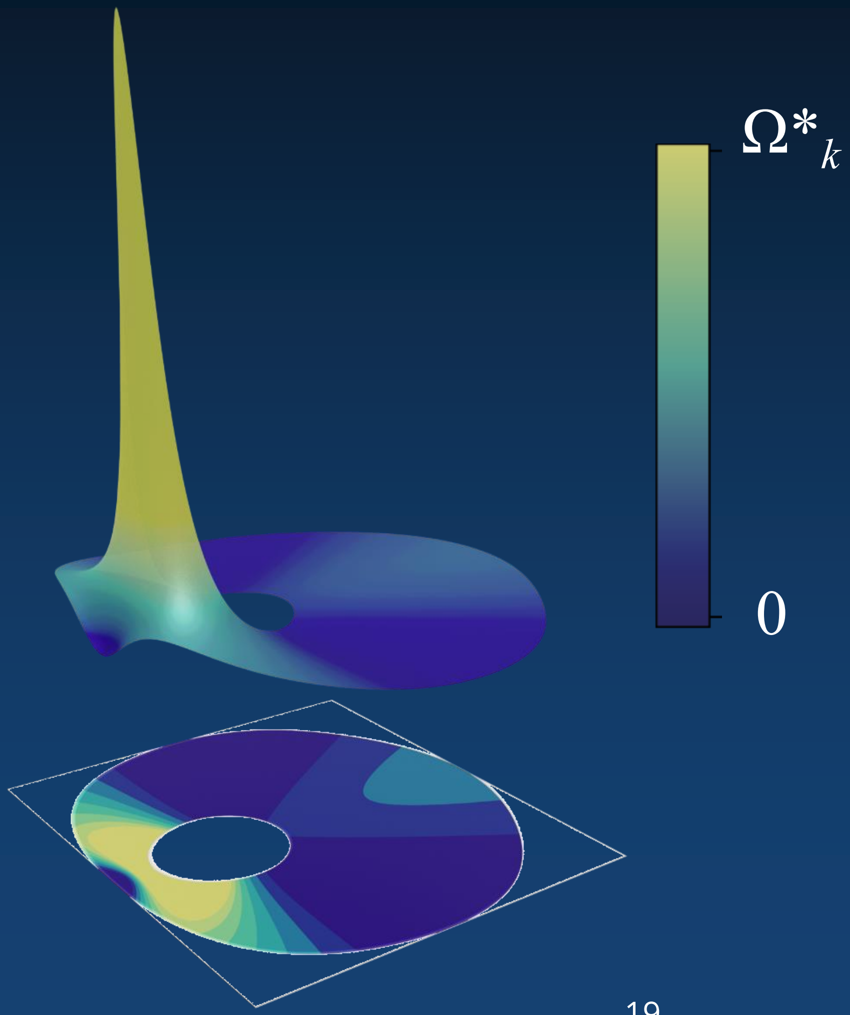


Yildiz Saglam



Spin sources of Berry curvature





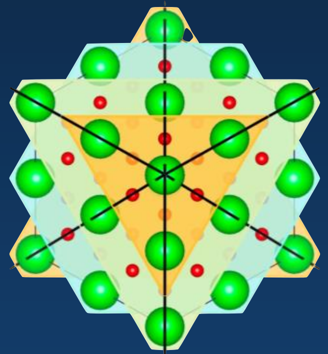
Key questions

Can we design Berry curvature sources
from the quantum superpositions at finite crystal momentum of
multiple quantum numbers?
Can we find transport effects active at B=0?

Structural phase transitions in $SrTiO_3$

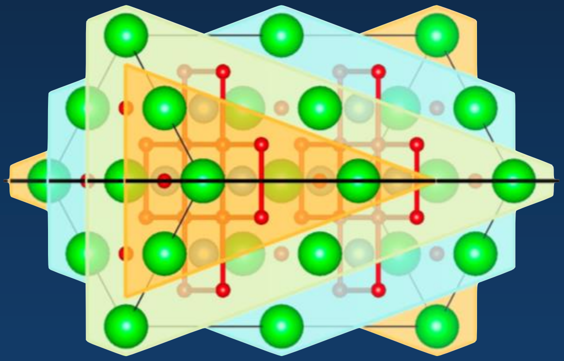
110 K   40 K   T

$D_{3d}C_{3v}$



Δ trigonal crystal field

$C_{2h}C_s$



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

C_s

Polar order

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

(Images courtesy A. Lau)

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

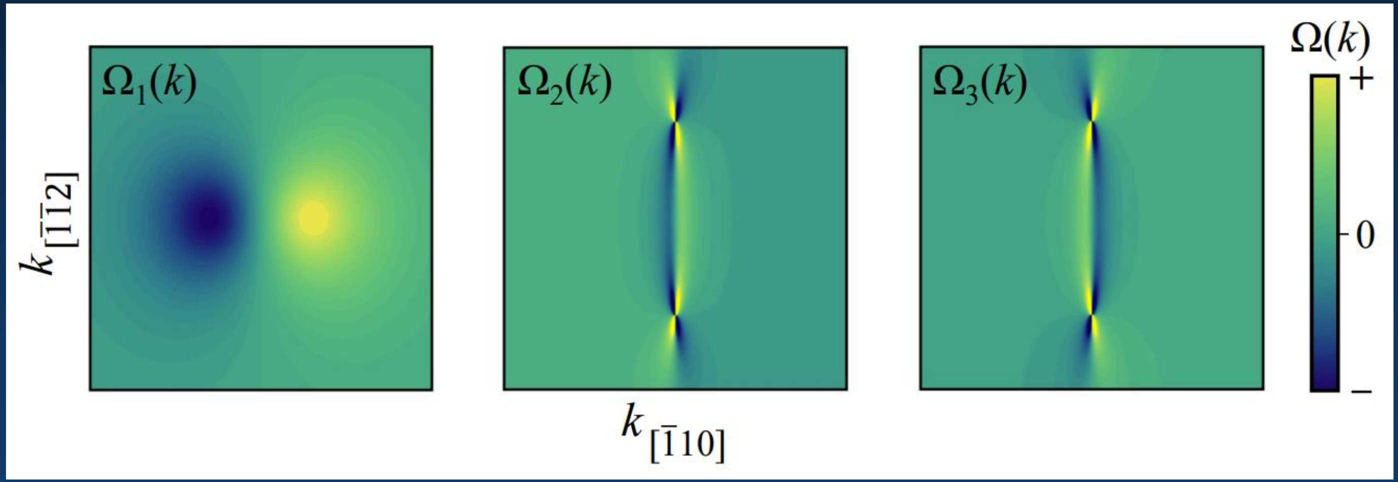
T < 30 K
α_{OR} interfacial breaking of inversion symmetry with polar axis

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

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

Orbital sources of Berry curvature

Dipolar distributions: nonlinear transport responses

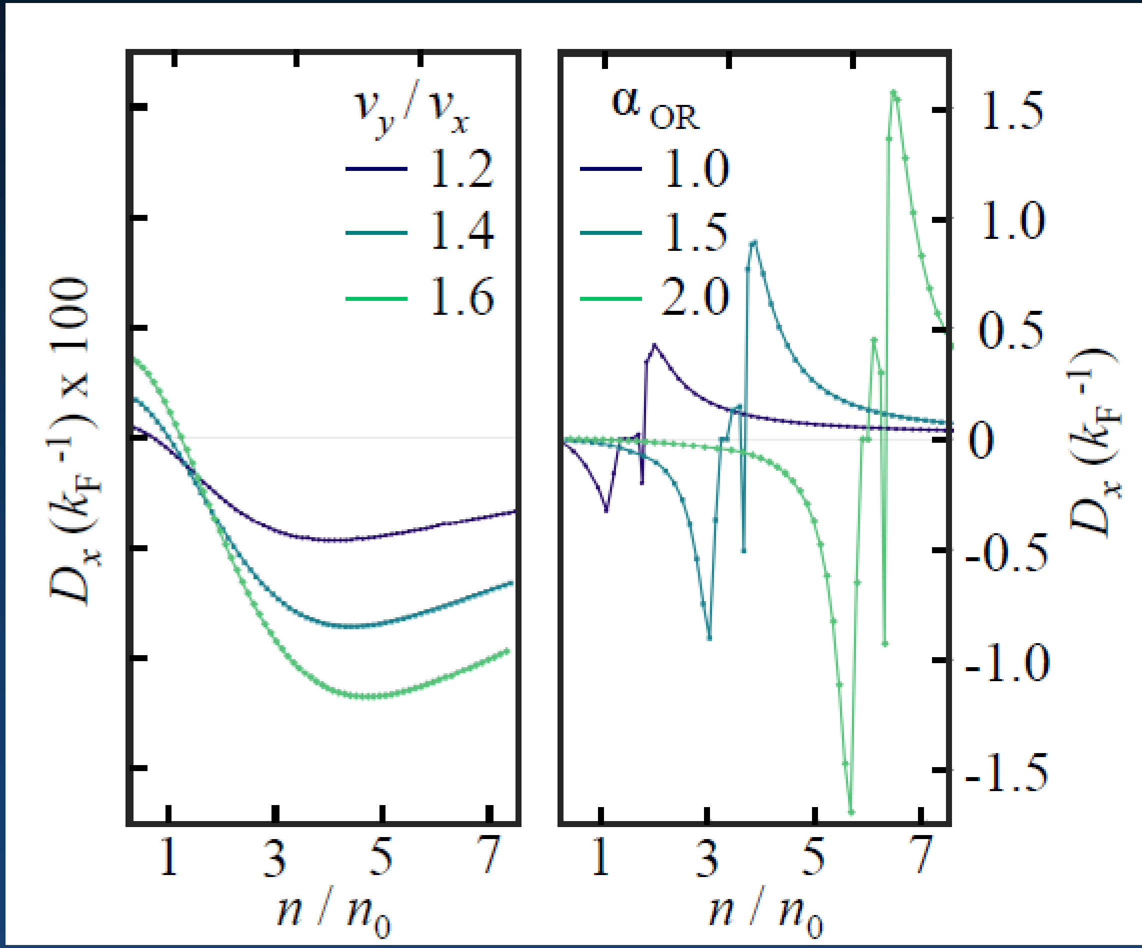


Hot spots

Singular pinch points

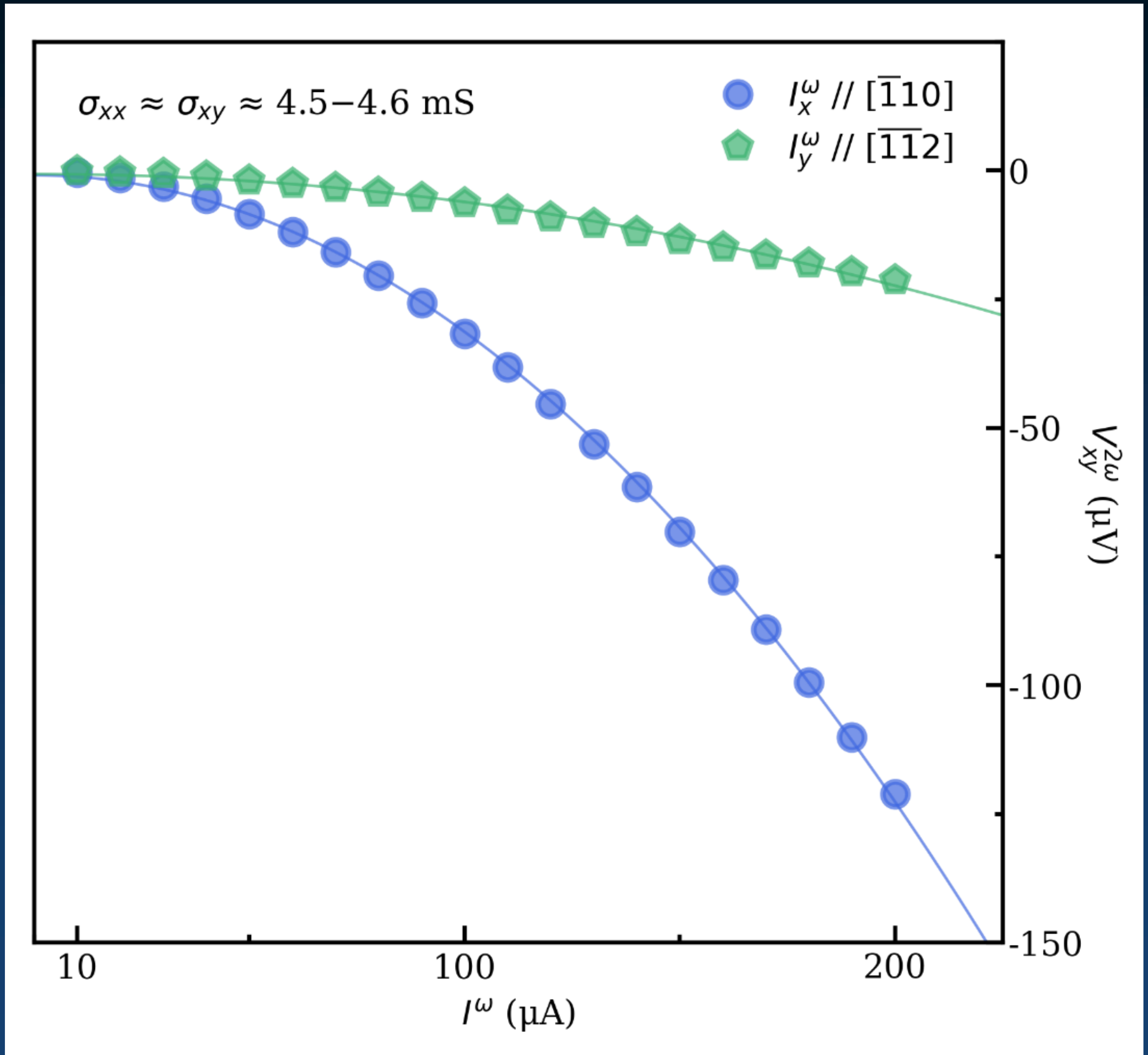
$$\mathscr{H}_{\mathrm{OR}}(\mathbf{k}) = \frac{\mathbf{k}^2}{2m}\Lambda_0 + \Delta\left(\Lambda_3 + \frac{1}{\sqrt{3}}\Lambda_8\right) + \Delta_m\left(\frac{1}{2}\Lambda_3 - \frac{\sqrt{3}}{2}\Lambda_8\right) - \alpha_{\mathrm{OR}}\left[k_x\Lambda_5 + k_y\Lambda_2\right] - \alpha_m k_x \Lambda_7$$

Orbital sources of Berry curvature



Prediction:
BCD in the 10s nm range!

Non linear Hall effect at B=0

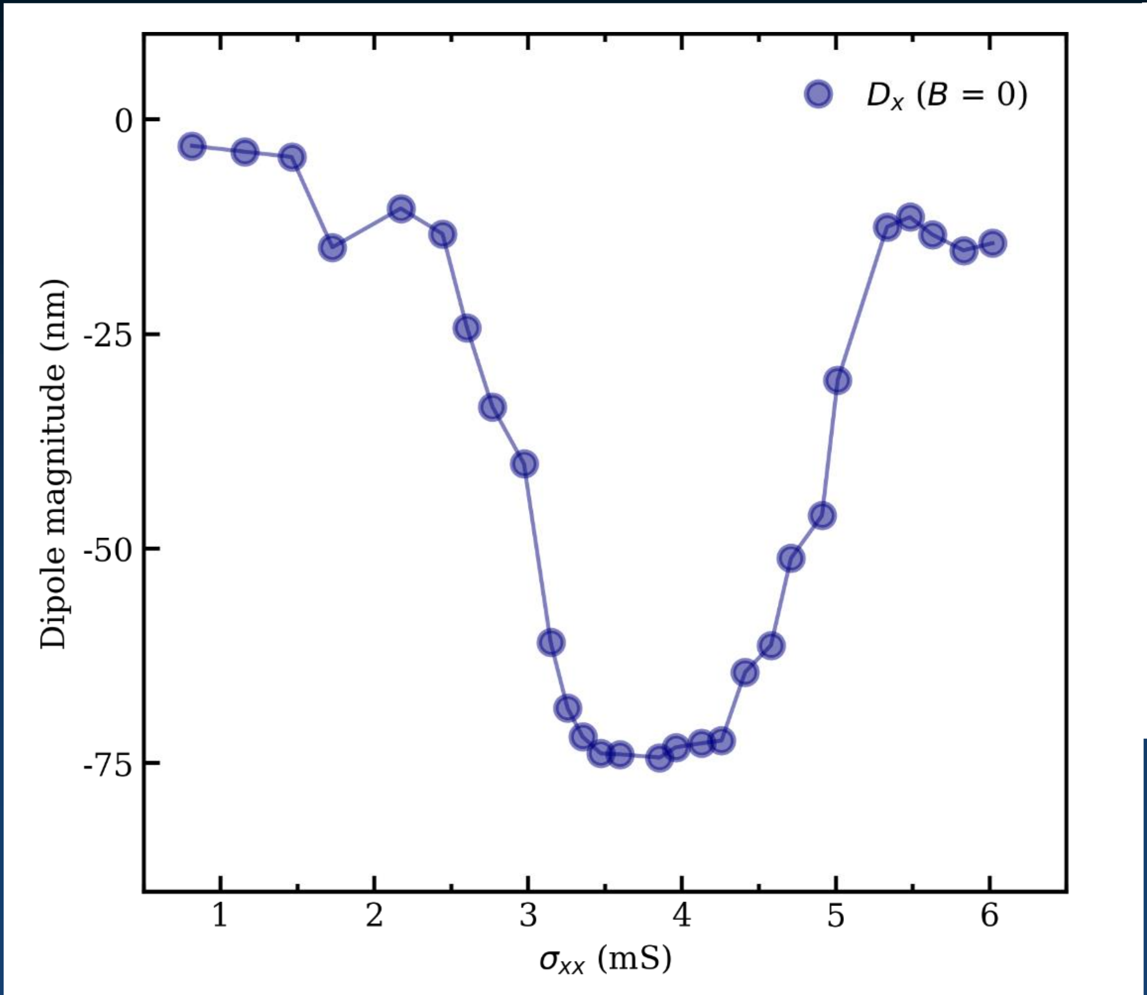


Ulderico Filippozzi

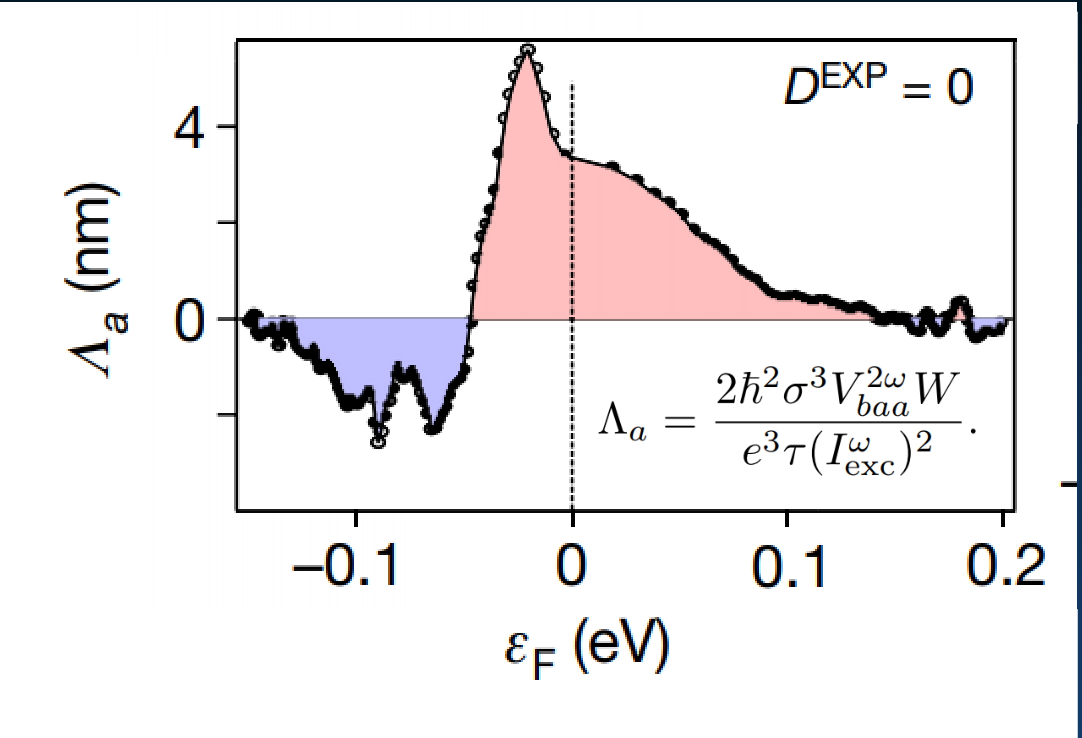
Edouard Lesne

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

Dipole magnitude



(111)$LaAlO_3/SrTiO_3$

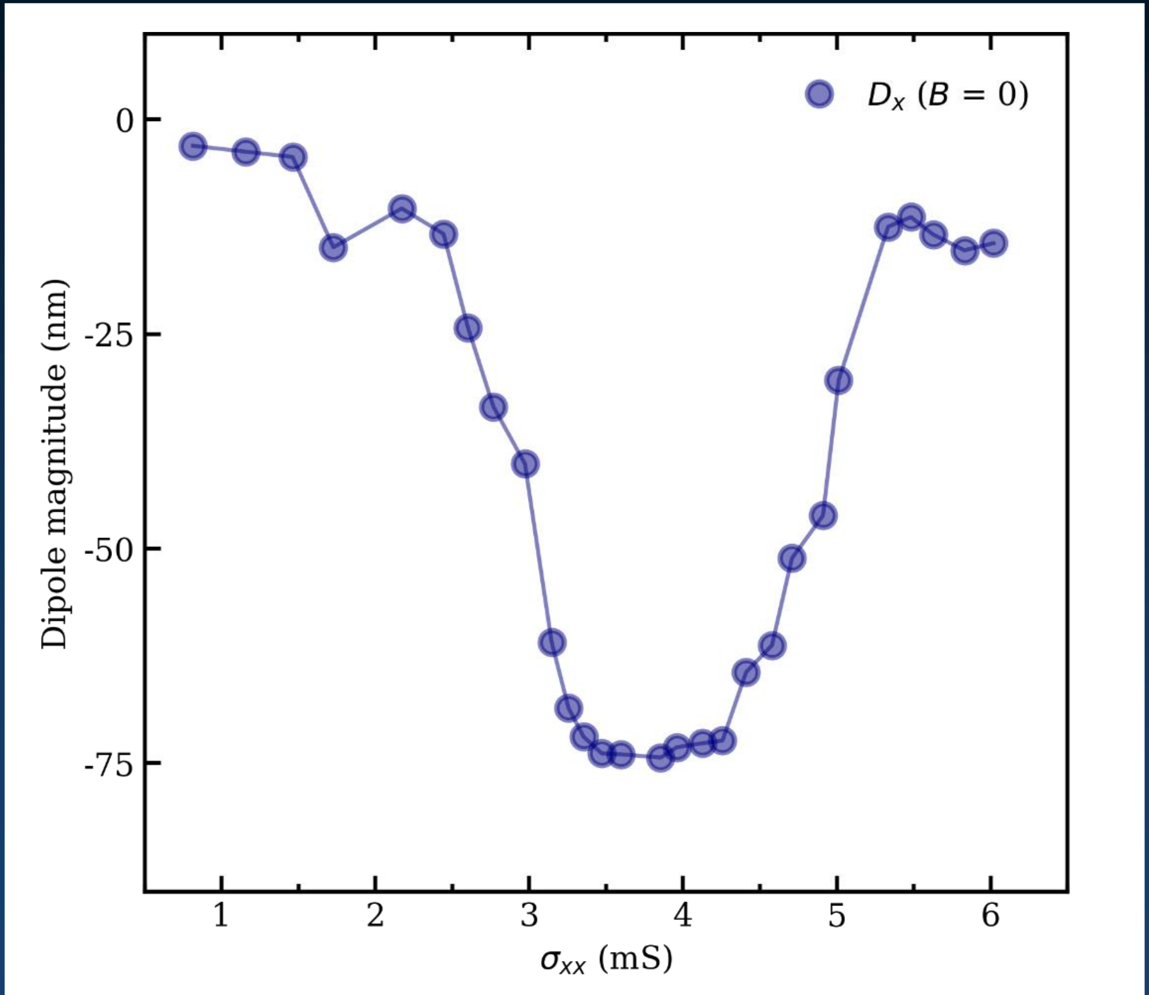


WTe_2

Ma et al. Nature 565, 337 (2019)

Sodemann, I. & Fu, L.. Phys. Rev. Lett. 115, 216806 (2015)

Dipole magnitude



(111)$LaAlO_3/SrTiO_3$

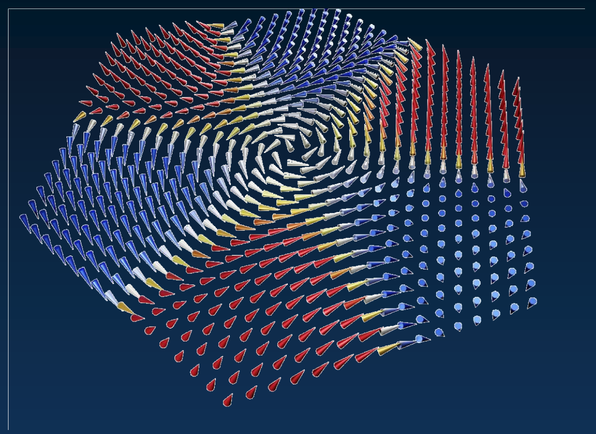
Materials	Dimension	Experimental estimate of Berry curvature dipole (nm)
Bilayer WTe_2	2	5
Few layer WTe_2	2	0.07
Monolayer WTe_2	2	0.06
Corrugated bilayer graphene	2	20
Twisted WSe_2	2	0.5
Strained twisted bilayer graphene	2	20
LAO-STO interface	2	75

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

Spin textures in and out of equilibrium

Spin textures by material design

Low-symmetry oxide interfaces
Berry curvature engineering



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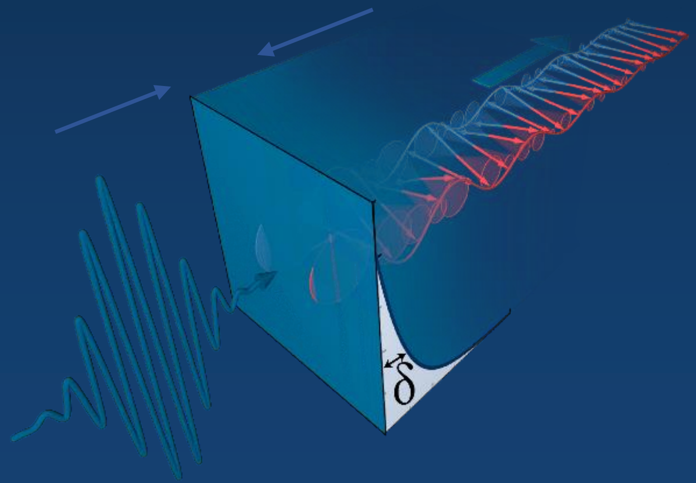
Light-driven antiferromagnets
Propagating coherent magnons



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Dmytro Afanasiev, Jorrit Hortensius, **Mattias Matthiesen**

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Eric Bousquet, Alireza Sazani
Uni Liege

Roberta Citro
University of Salerno

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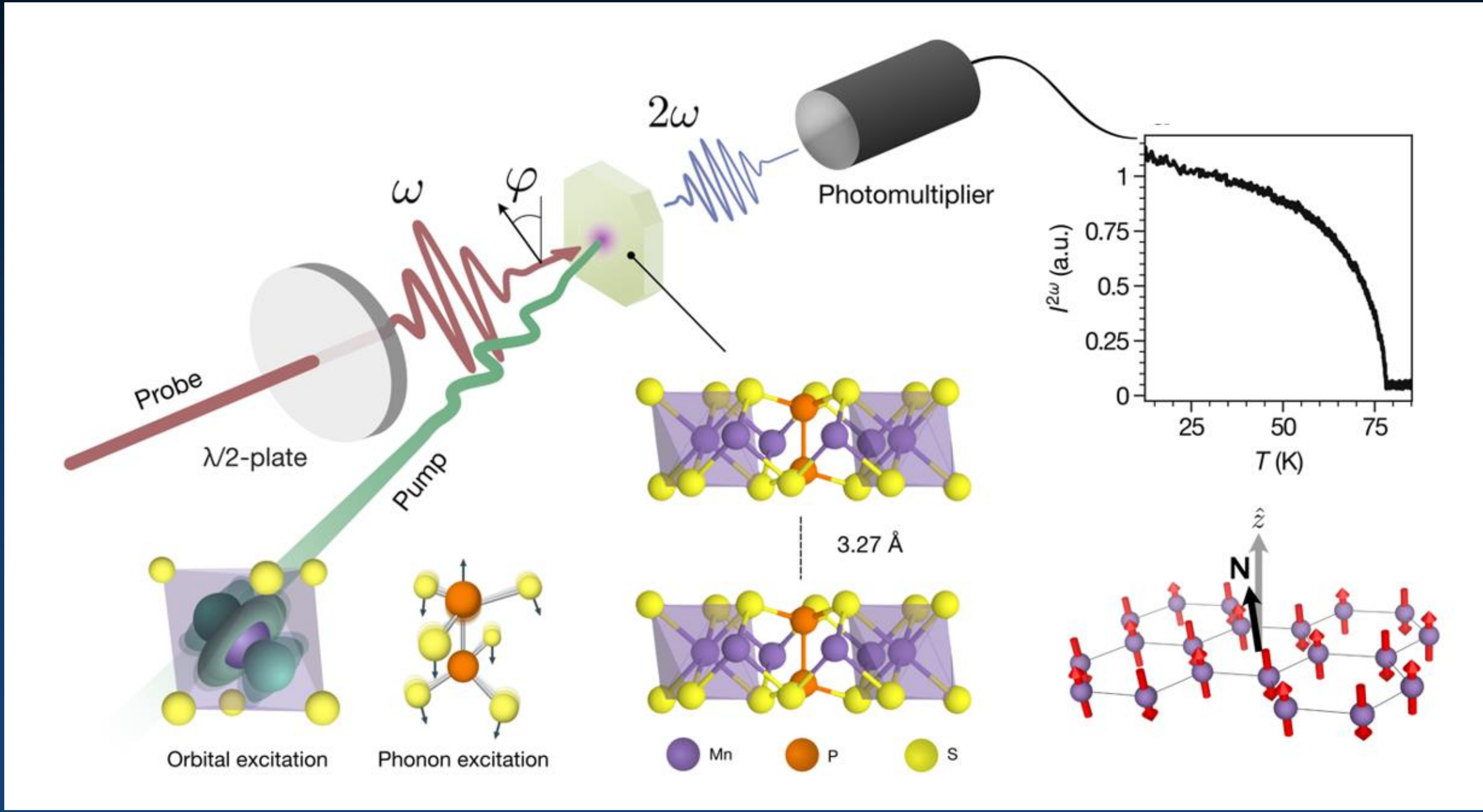
Key questions

Can we use selective optical excitation of lattice and orbital degrees of freedom to excite spin waves?

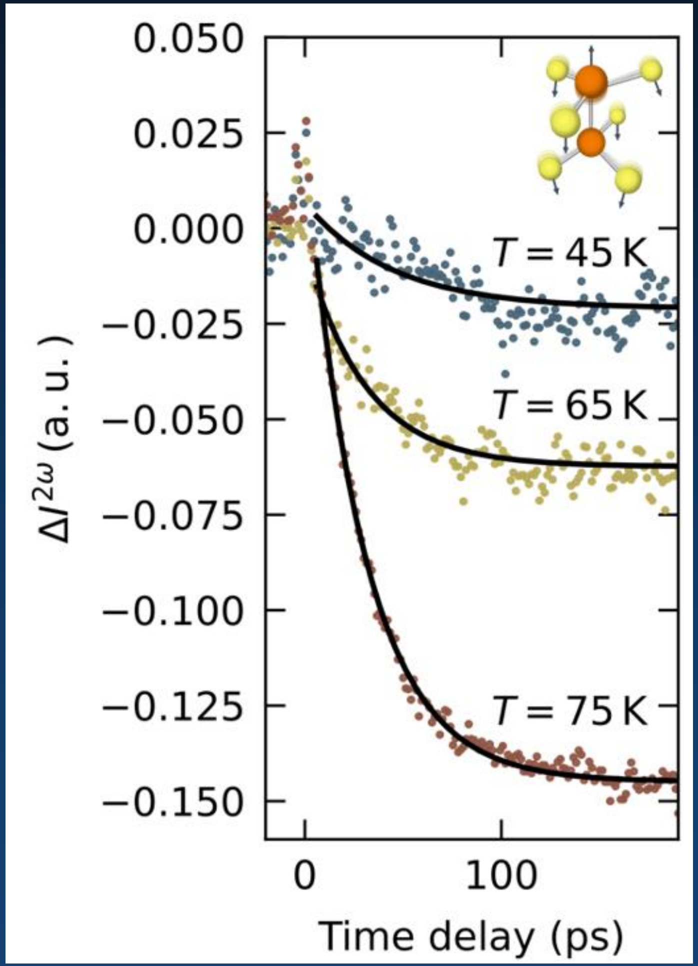
How do we stimulate propagating spin waves by optical means?

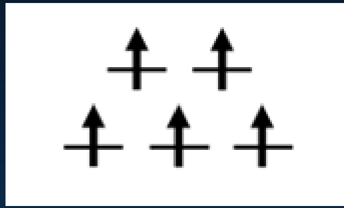
MnPS3



2ω
ω
φ
Photomultiplier
Probe
λ/2-plate
Pump
1
0.75
0.5
0.25
0
$I^{2\omega}$ (a.u.)
25
50
75
T (K)
3.27 Å
ẑ
N
Orbital excitation
Phonon excitation
Mn
P
S

Phonon excitation





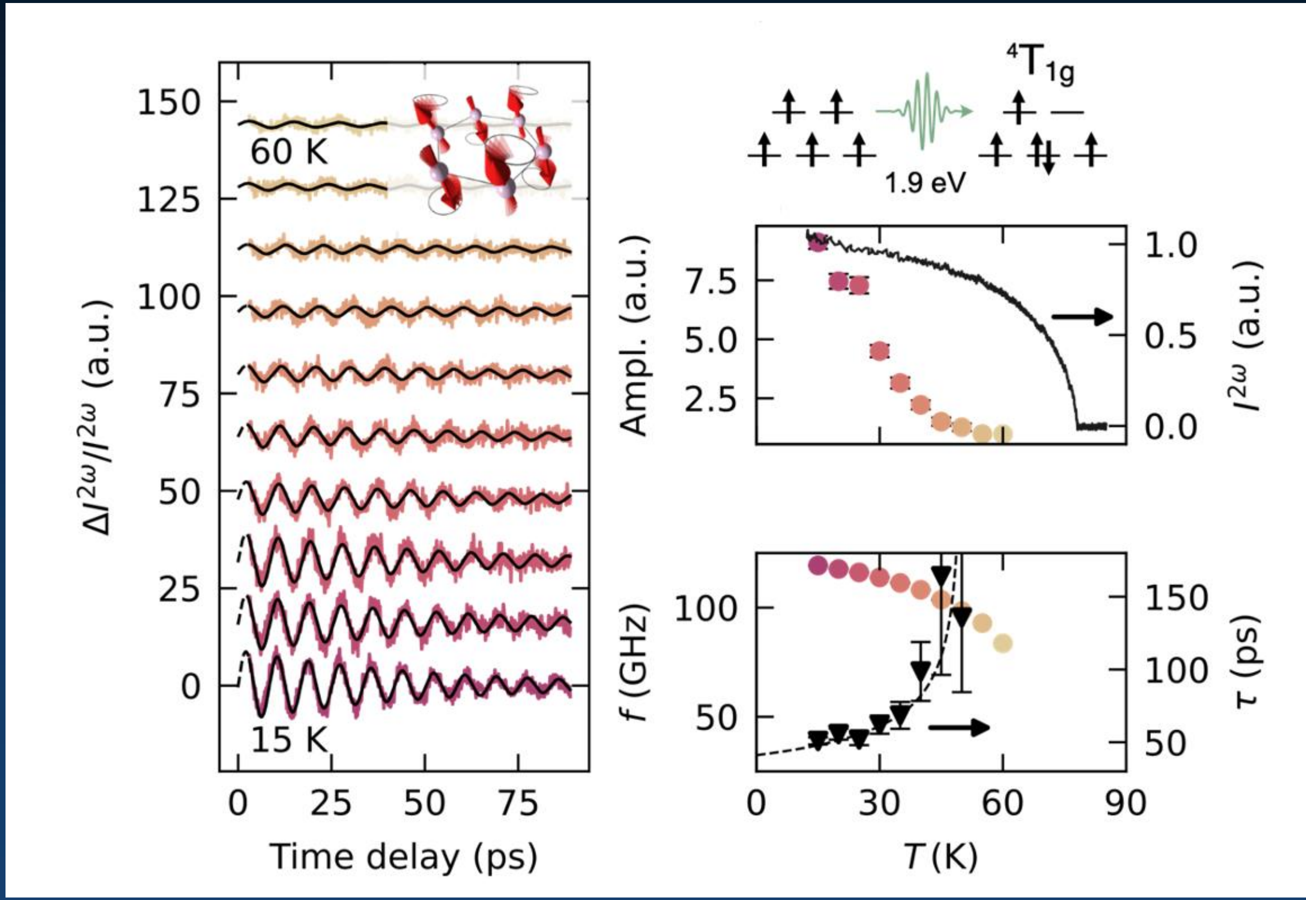
Mattias Matthiesen

Mn^{2+} ground state:
$^6A_{1g}$ ($t_{2g}{}^3e_g{}^2$)
orbital singlet (L = 0)
five unpaired spins (S = 5/2).

Resonant phonon excitation leads to thermal spin disorder.

M. Matthiesen et al.
Physical Review Letters 130, 076702 (2023)

Orbital excitation



Mattias' poster

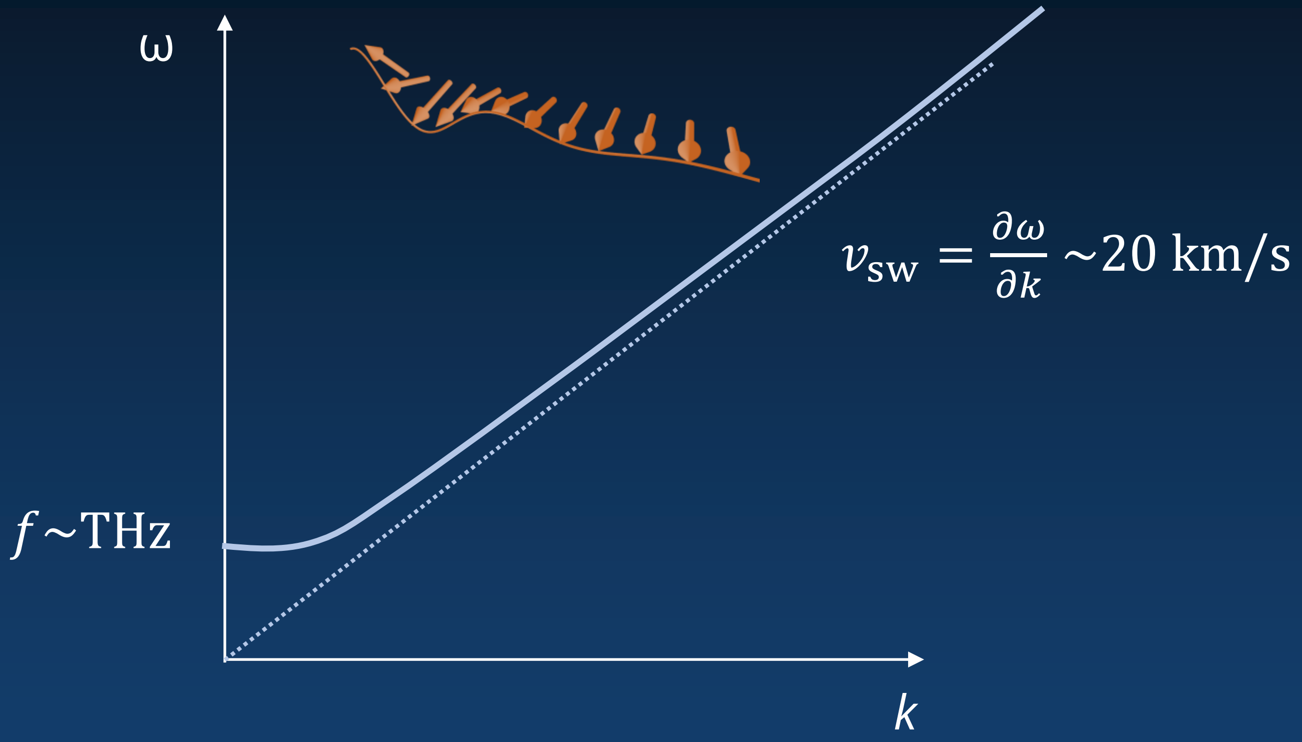
Sudden coupling of spin and orbital angular momentum reorients the magnetic anisotropy direction throughout the 4T1g lifetime.

Impulsive torque.

M. Matthiesen et al. Physical Review Letters 130, 076702 (2023)

Why antiferromagnetic spin transport?

- THz operation
- High-speed wave propagation
- Phase coherence
- Macroscopic ballistic propagation

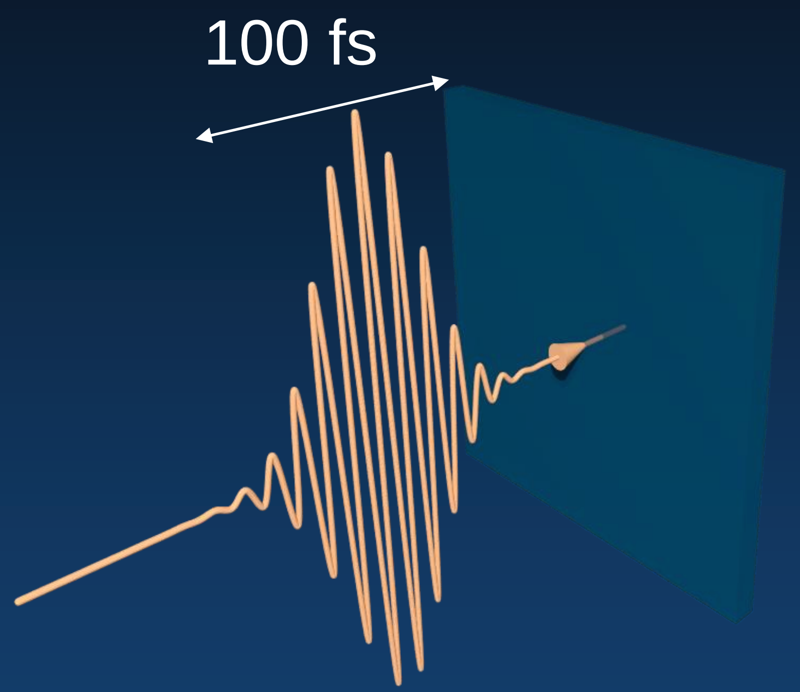


Current approaches:
spin-currents
via thermally-driven spin accumulation.

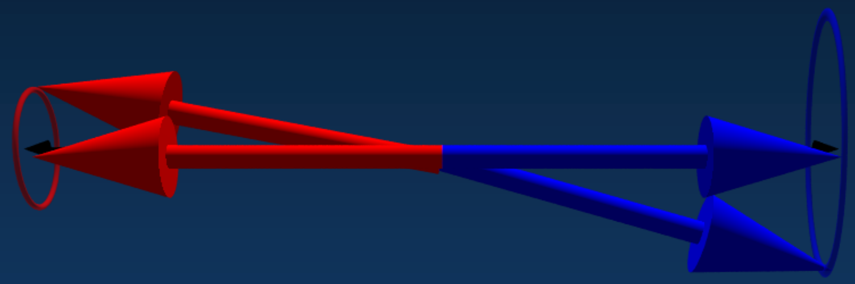
Incoherent diffusive spin transport.

R. Lebrun et al., *Nature* **561,** 222 (2018)
J. Li et al., *Nature* **578,** 70 (2020)
P. Vaidya et al., *Science* **368,** 160 (2020)

Coherent AFM spin dynamics



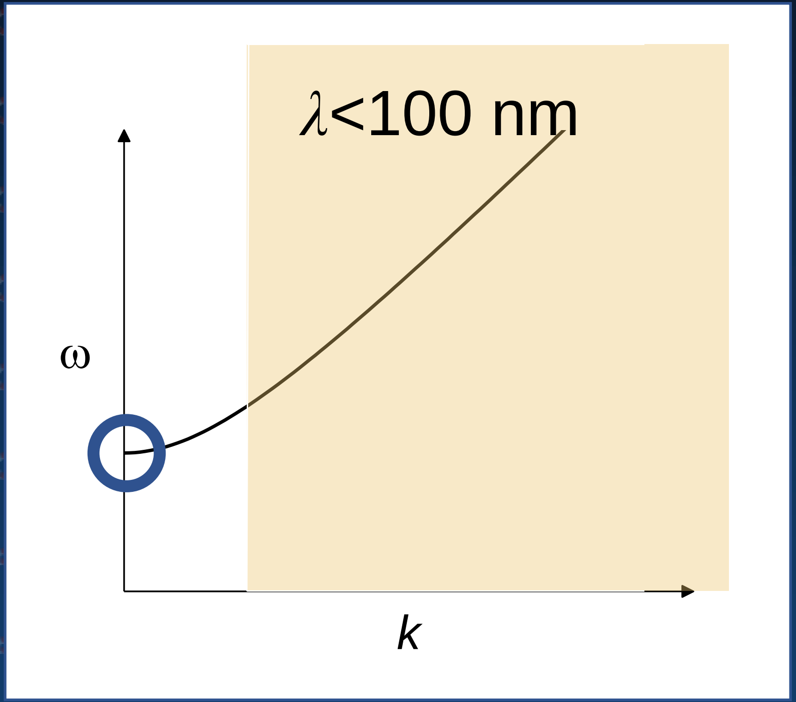
Impulsive excitation in transparent AFM

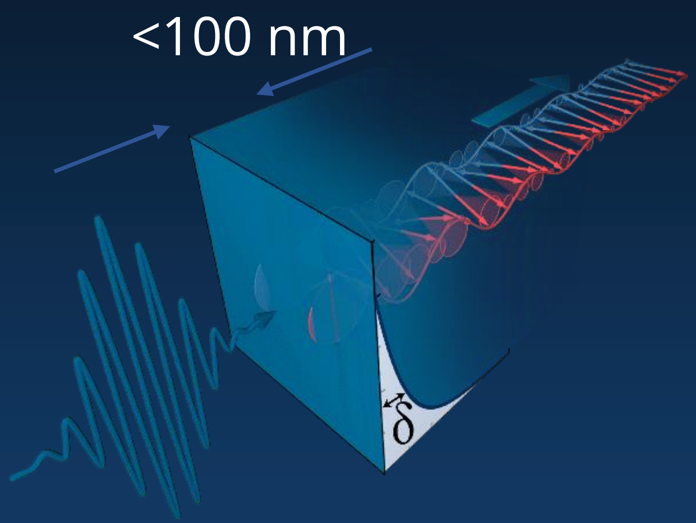


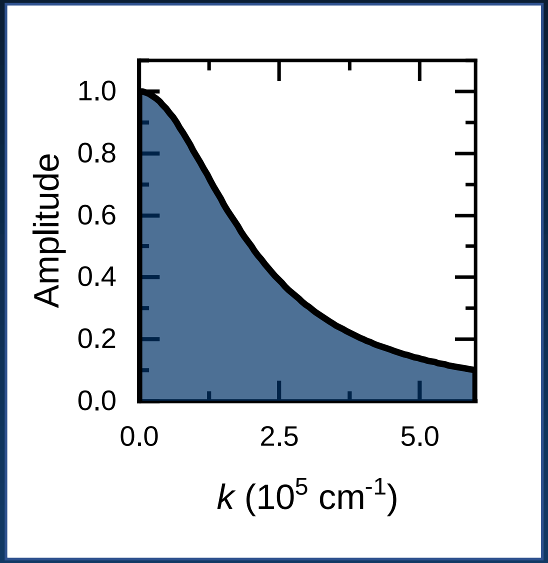
Uniform AFM spin precession does not propagate

P. Němec, M. Fiebig, R. Kampfrath, A.V. Kimel. *Nat. Phys.* **14,** 229 (2018)

Propagating spin waves in AFMs





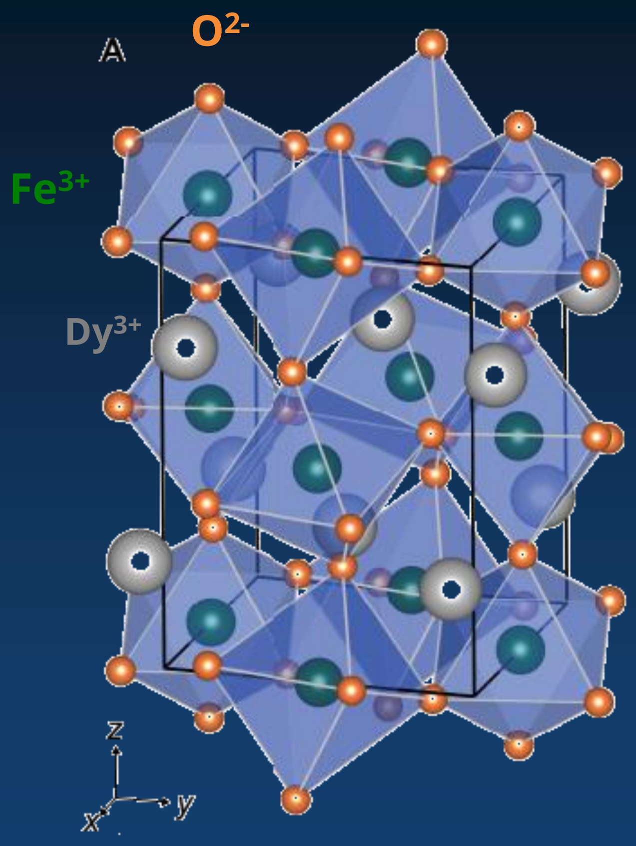


confined optical excitation

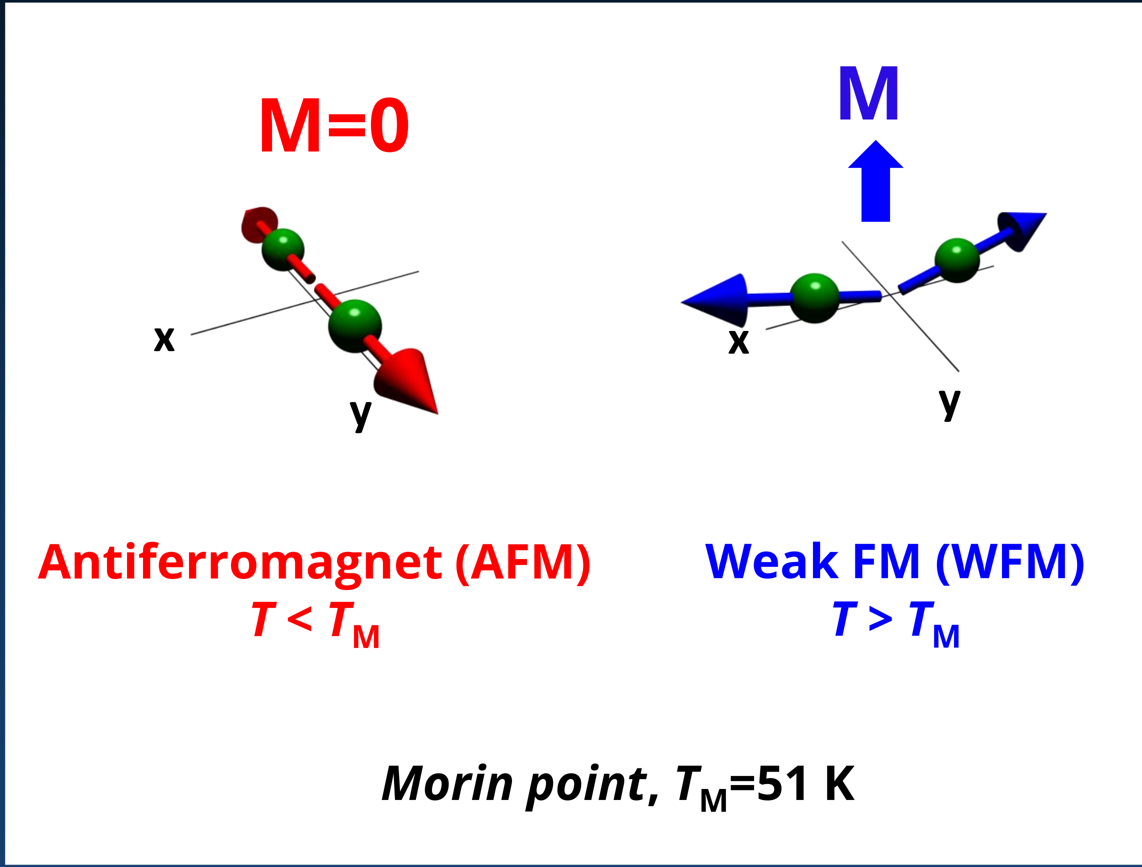
magnon wavepacket

Hortensius et al. Nature Physics 17, 1001 (2021)

Rare earth orthoferrite $DyFeO_3$

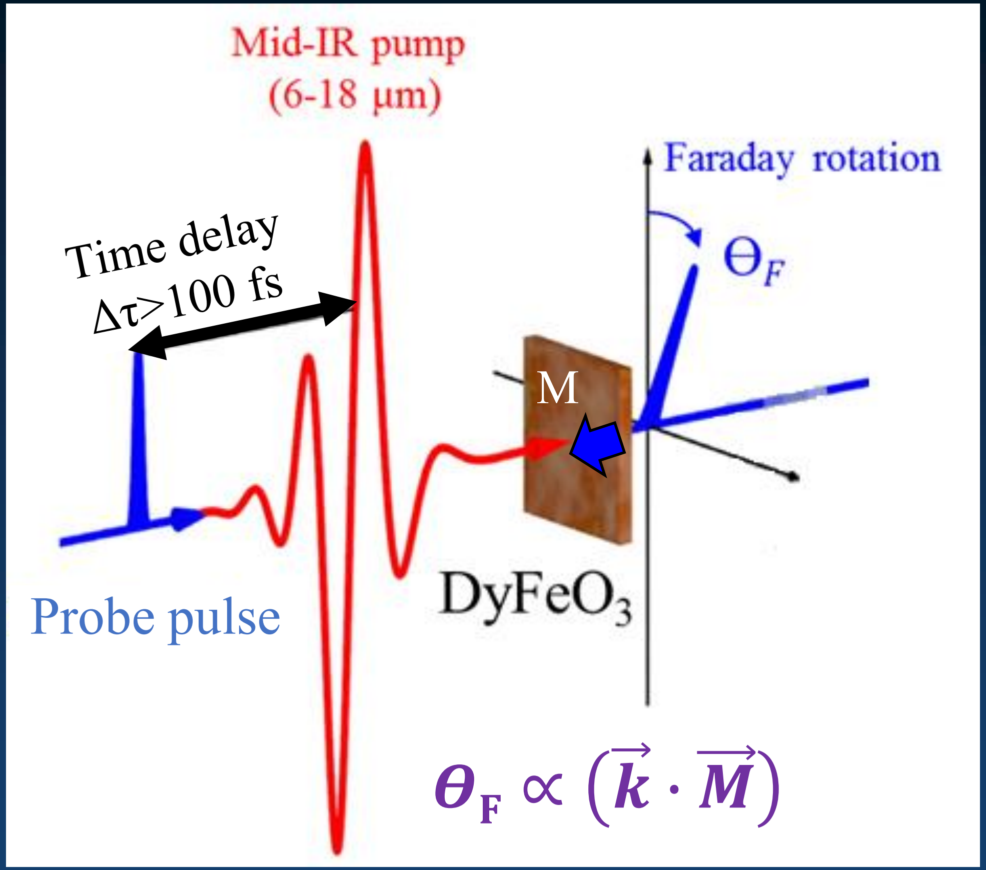


Orthorhombic perovskite (*Pnma)*
Fe^{3+} are AFM ordered (T_N=650 K)



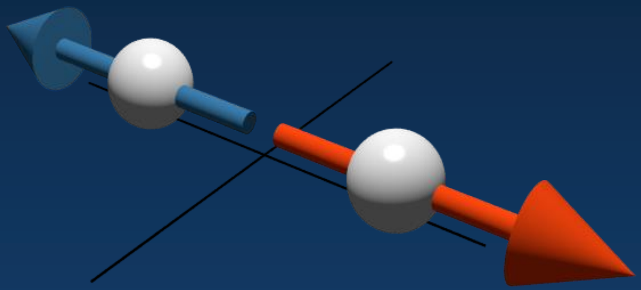
Measurement scheme

Dmytro Afanasiev

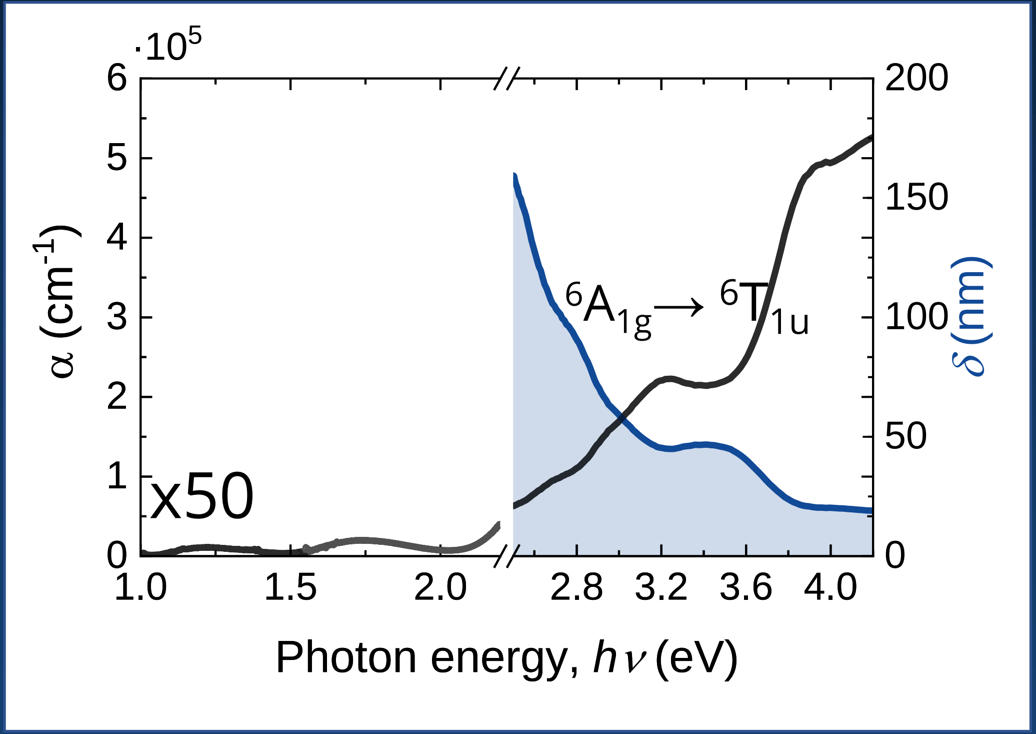


M is the magnetization of Fe^{3+}

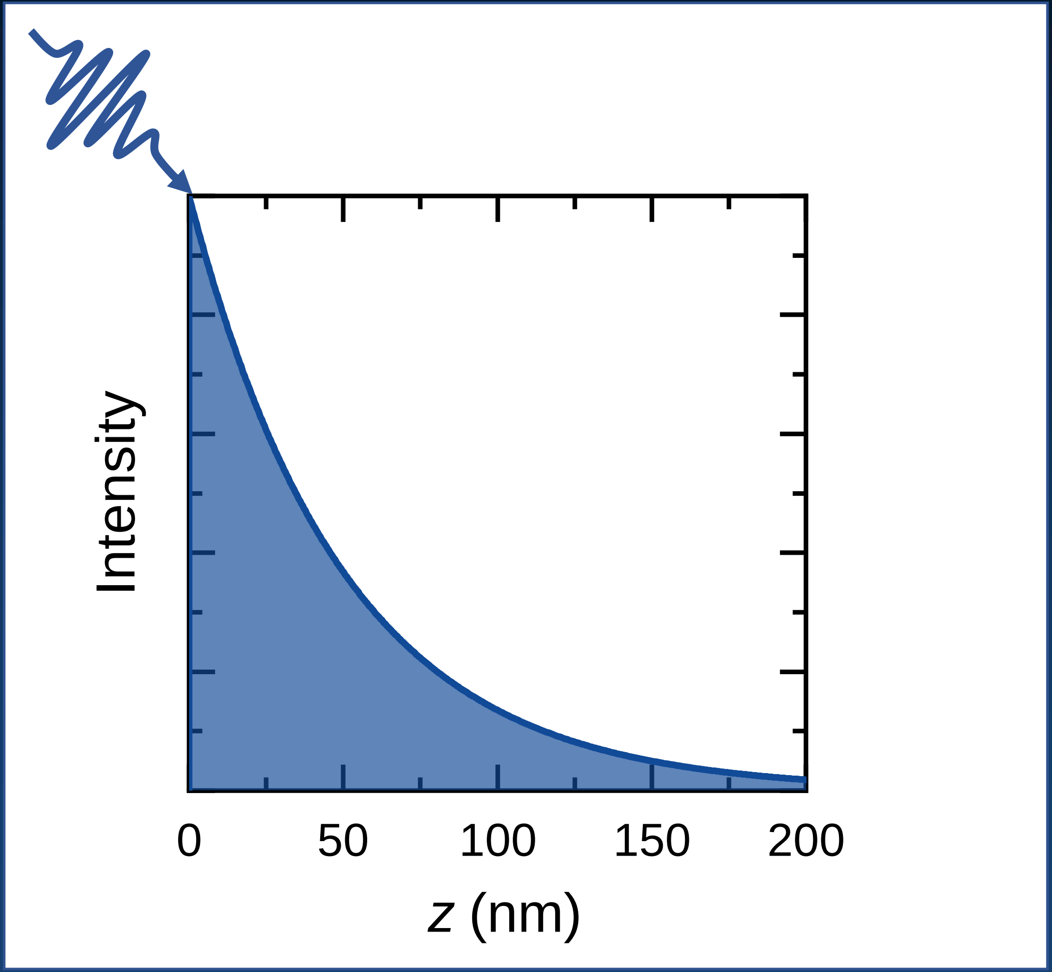
$DyFeO_3$

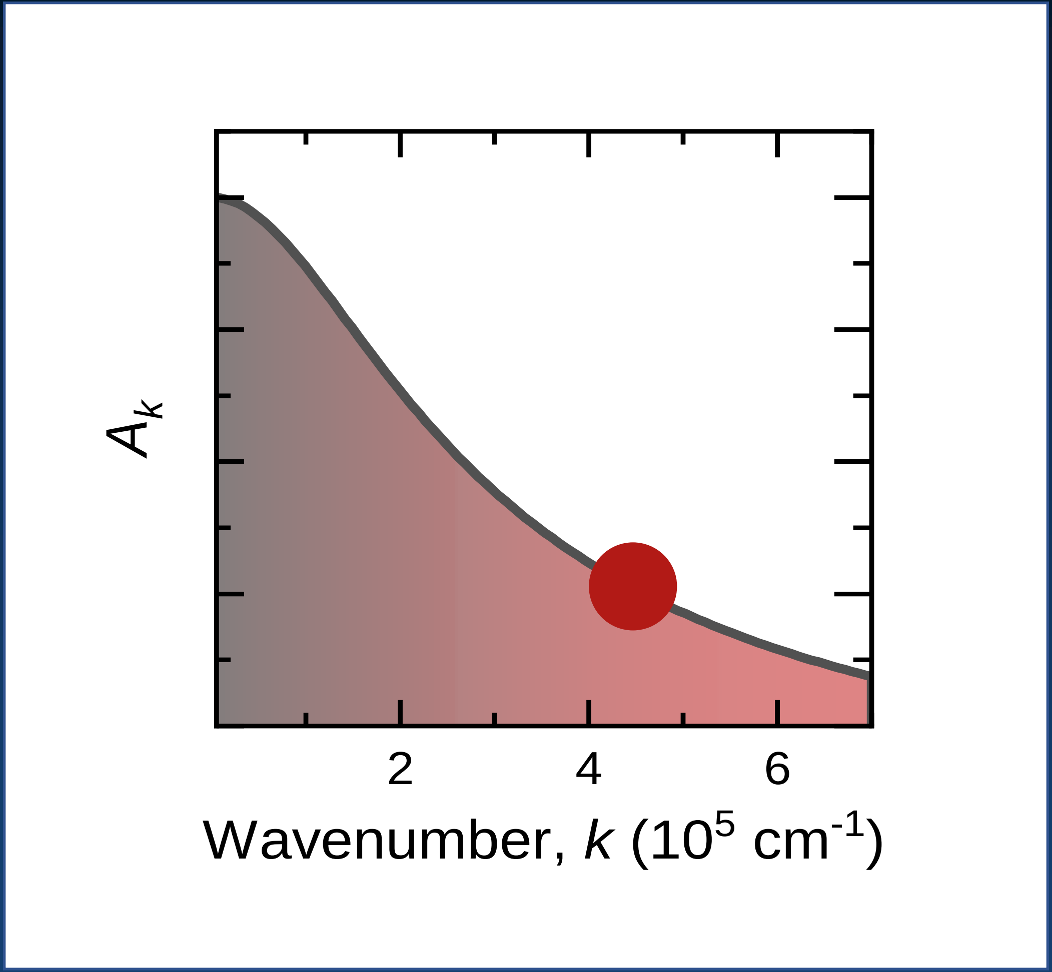


Optical absorption



Propagating spin wavepacket

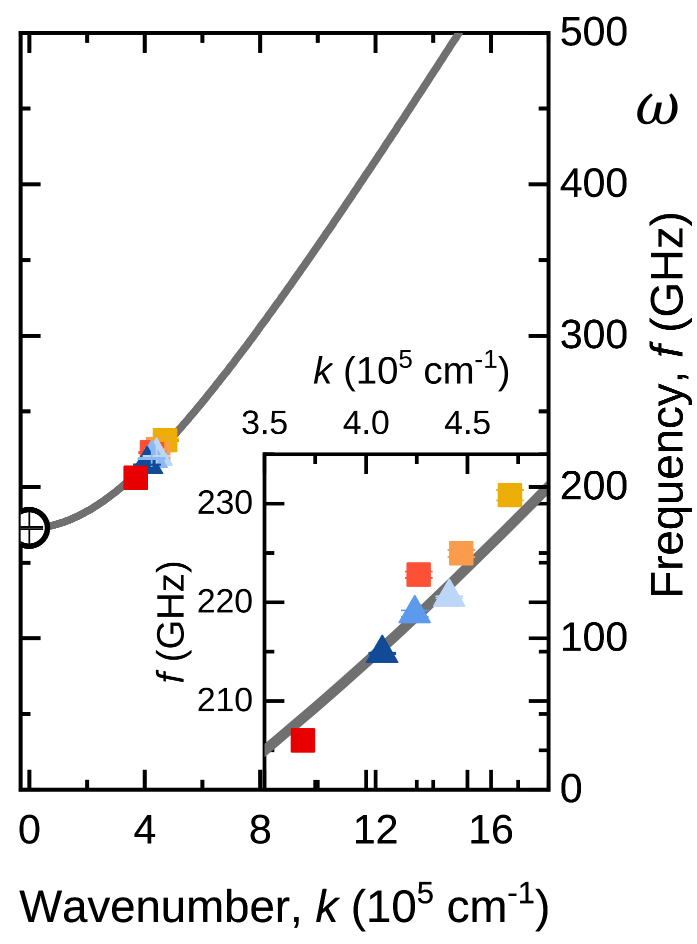




Spectral components of the magnon wavepacket

$$k_{\text{sw}} = 2k_0 n \cos\gamma'$$

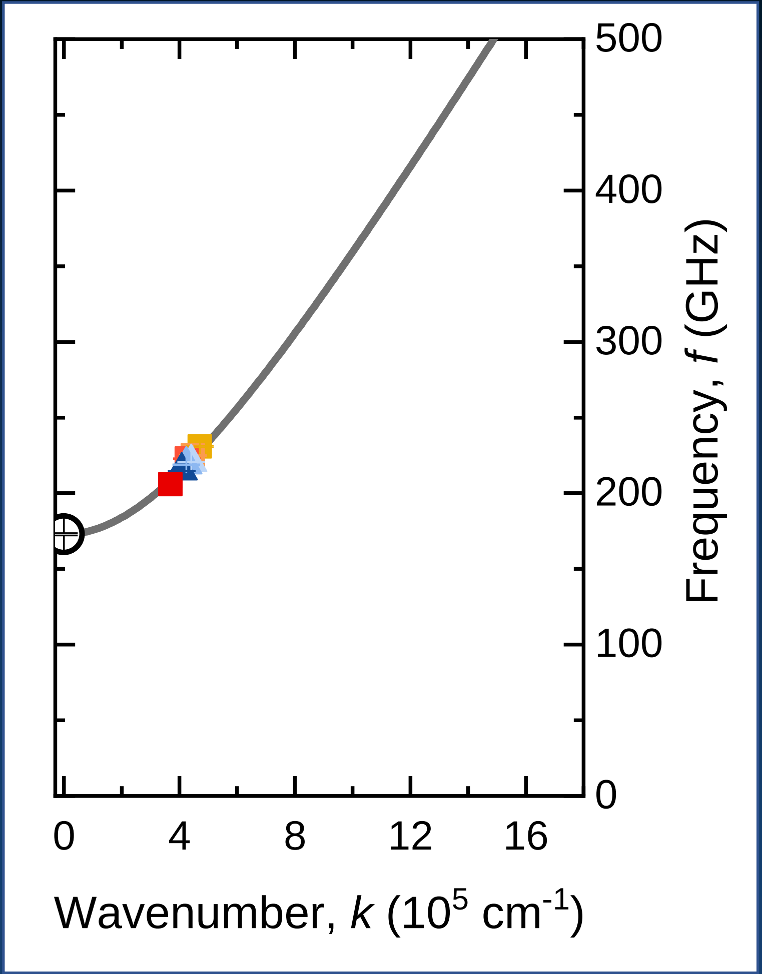
k-selective detection



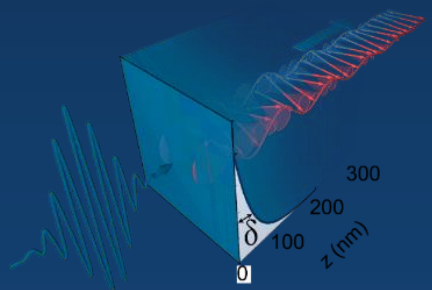
$$\omega = \sqrt{\omega_0^2 + (ck)^2}$$

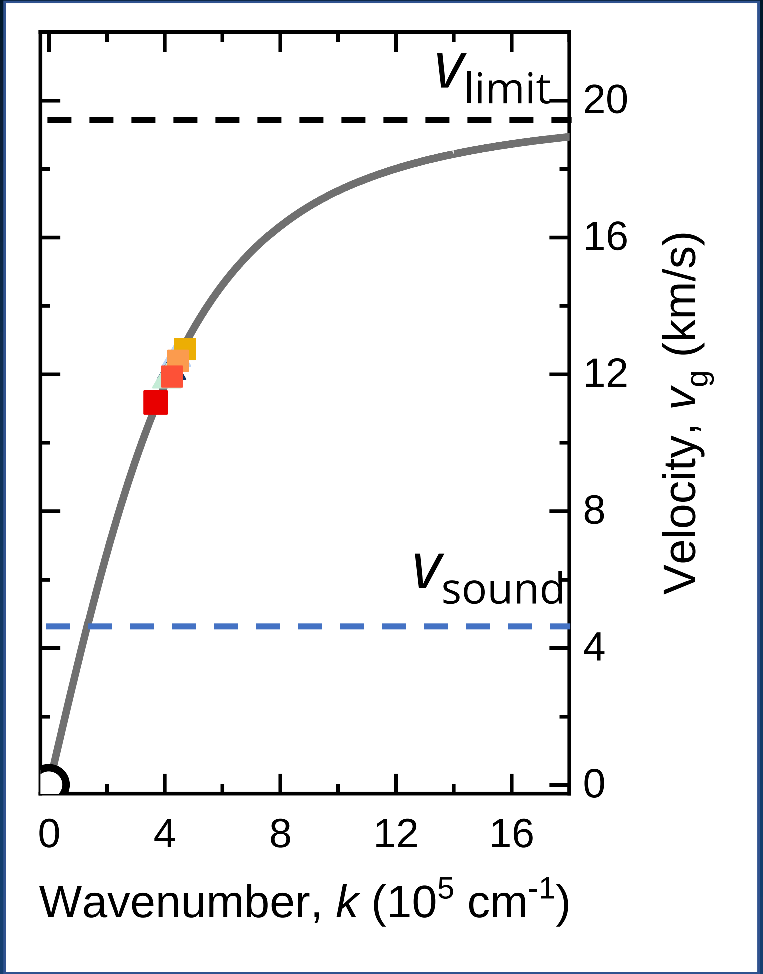
Spin wave velocity

Jorrit Hortensius

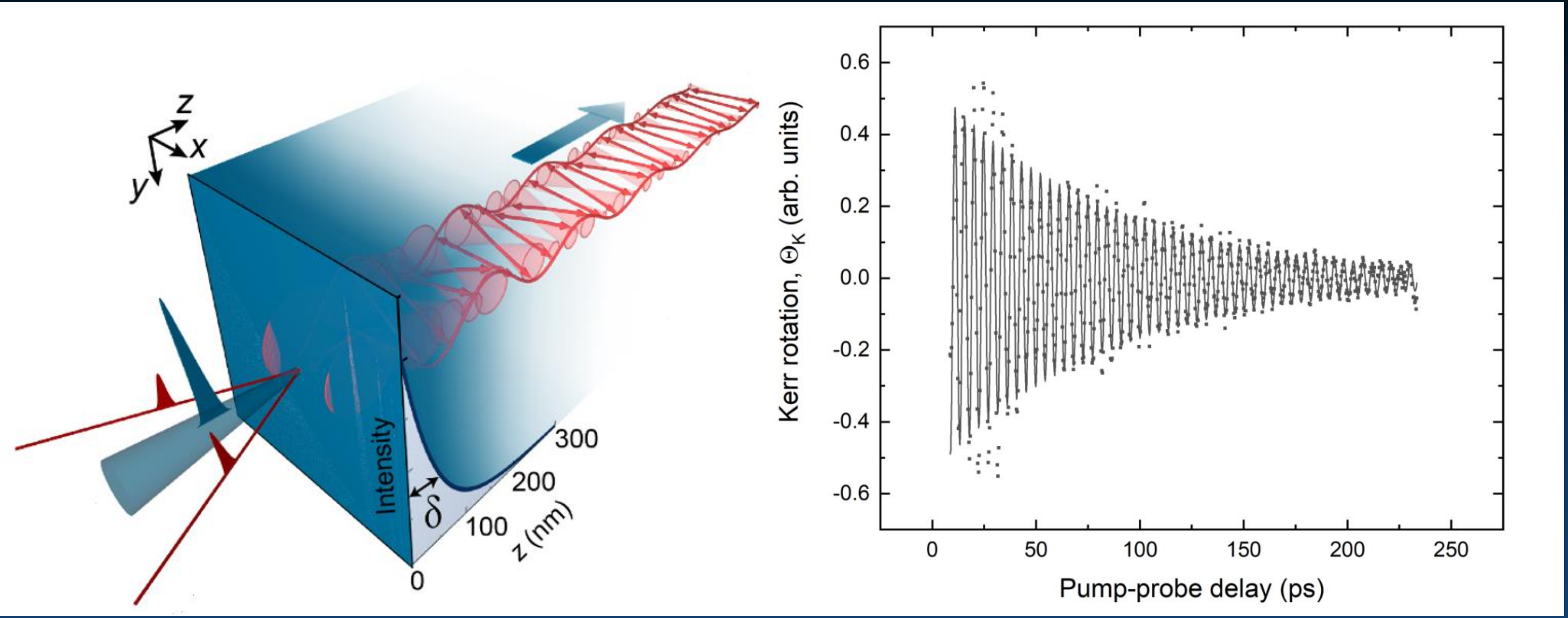


Coherence length
1 μm





Antiferromagnetic spintronics

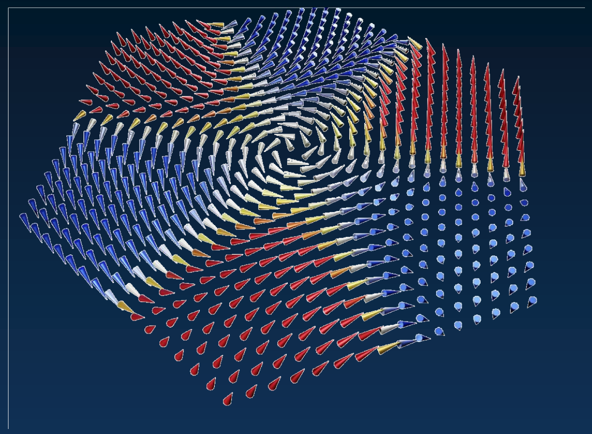


First ballistic antiferromagnetic spin-wave propagating at supersonic velocity (~12 km/s) and macroscopic distance (~ μm)
Hortensius et al. Nature Physics 17, 1001 (2021)

Spin textures in and out of equilibrium

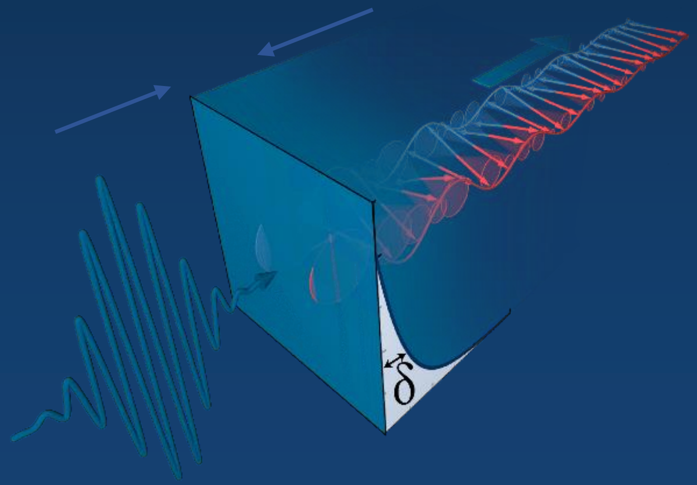
Spin textures by material design

Low-symmetry oxide interfaces
Berry curvature engineering



Light control of spin dynamics

Light-driven antiferromagnets
Propagating coherent magnons



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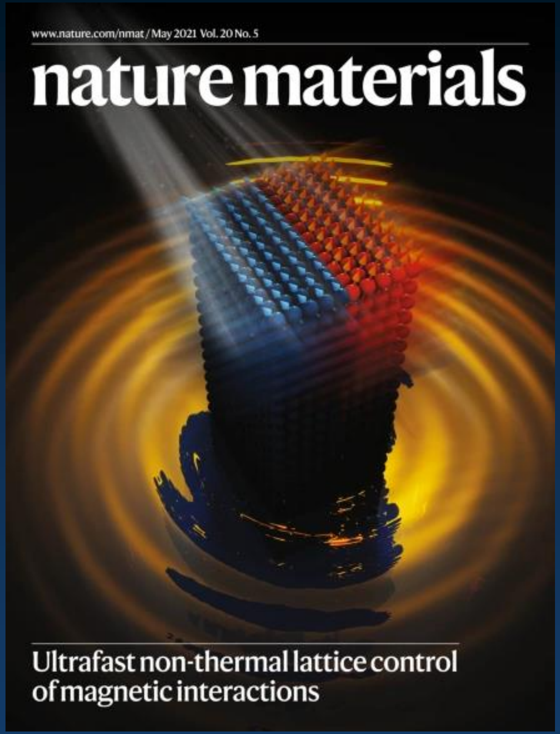

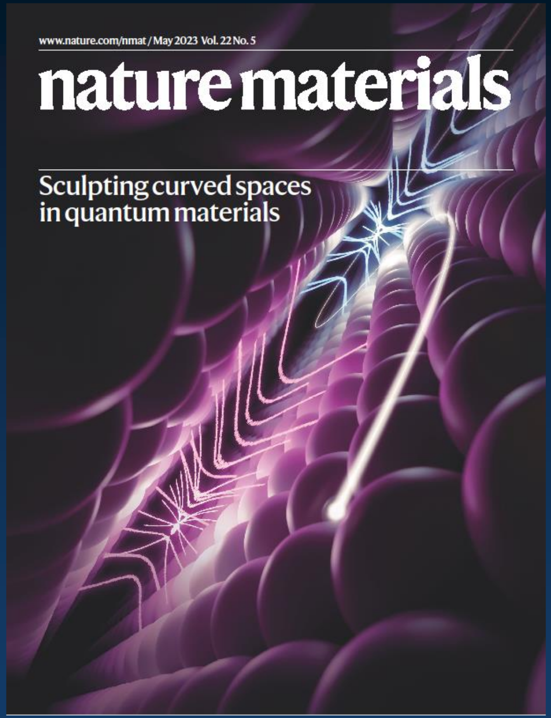

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Afanasiev et al. Science Advances 7 eabf3096 (2021)
Hortensius et al. npj Quantum Materials (2020)

Image:
Xavier Ravinet
UNIGE

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