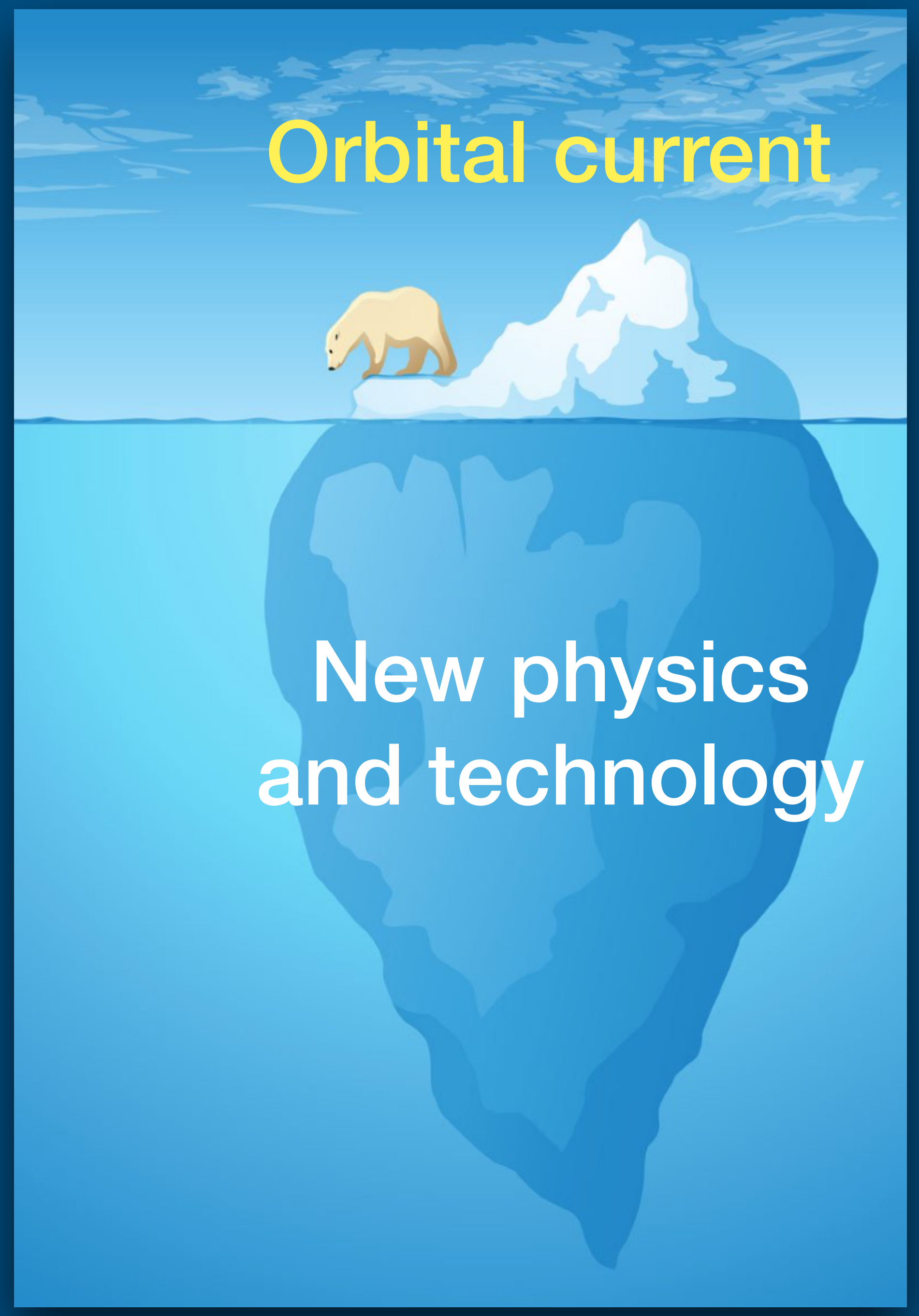
Orbitronics:
Exploiting orbital angular momentum for next-generation electronics



Young Research Leaders Group Workshop: Spins, Orbits, Charges, and Heat in Magnets (7 July 2022)

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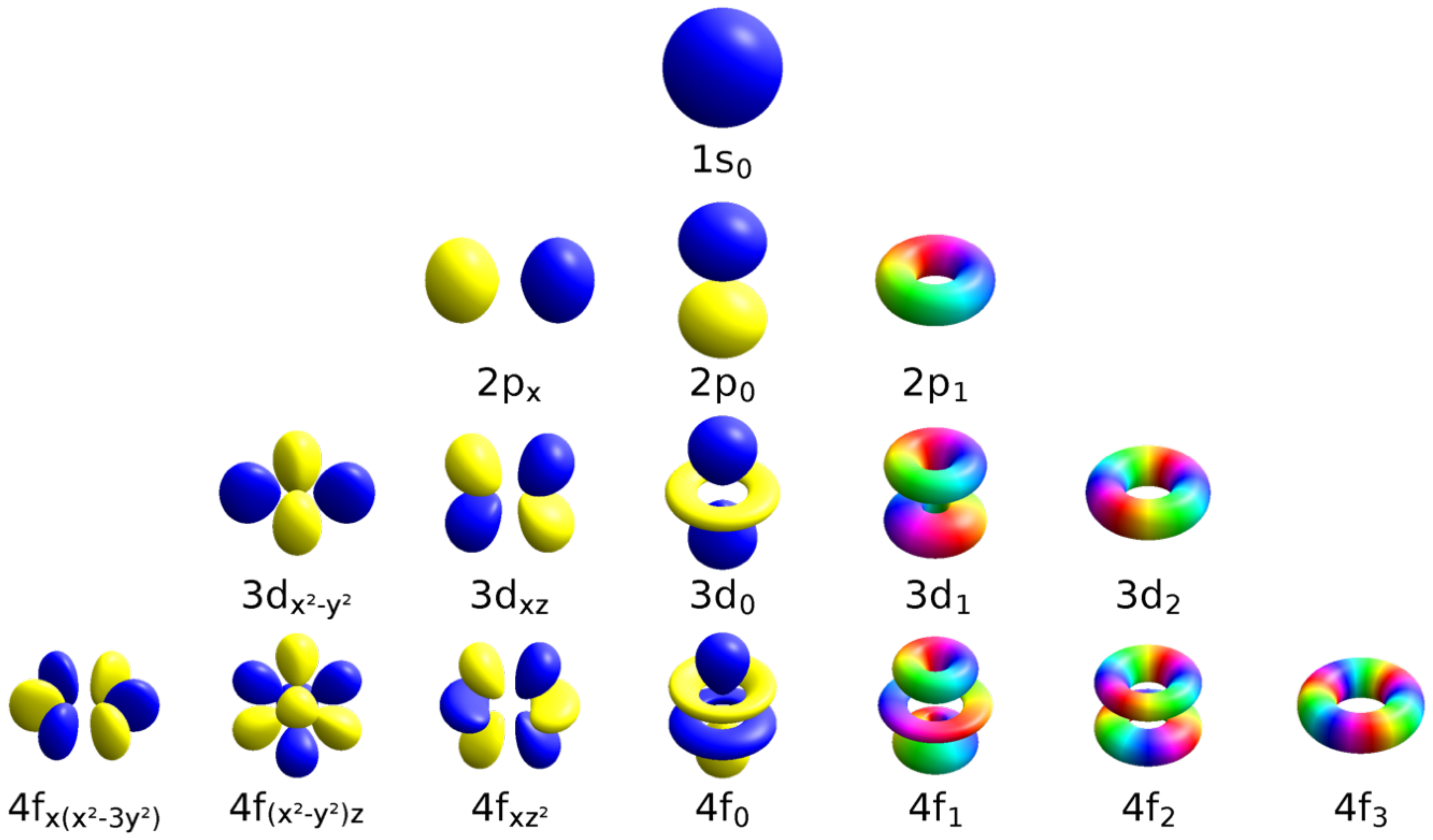
Orbitals: LEGO bricks for molecules and solids



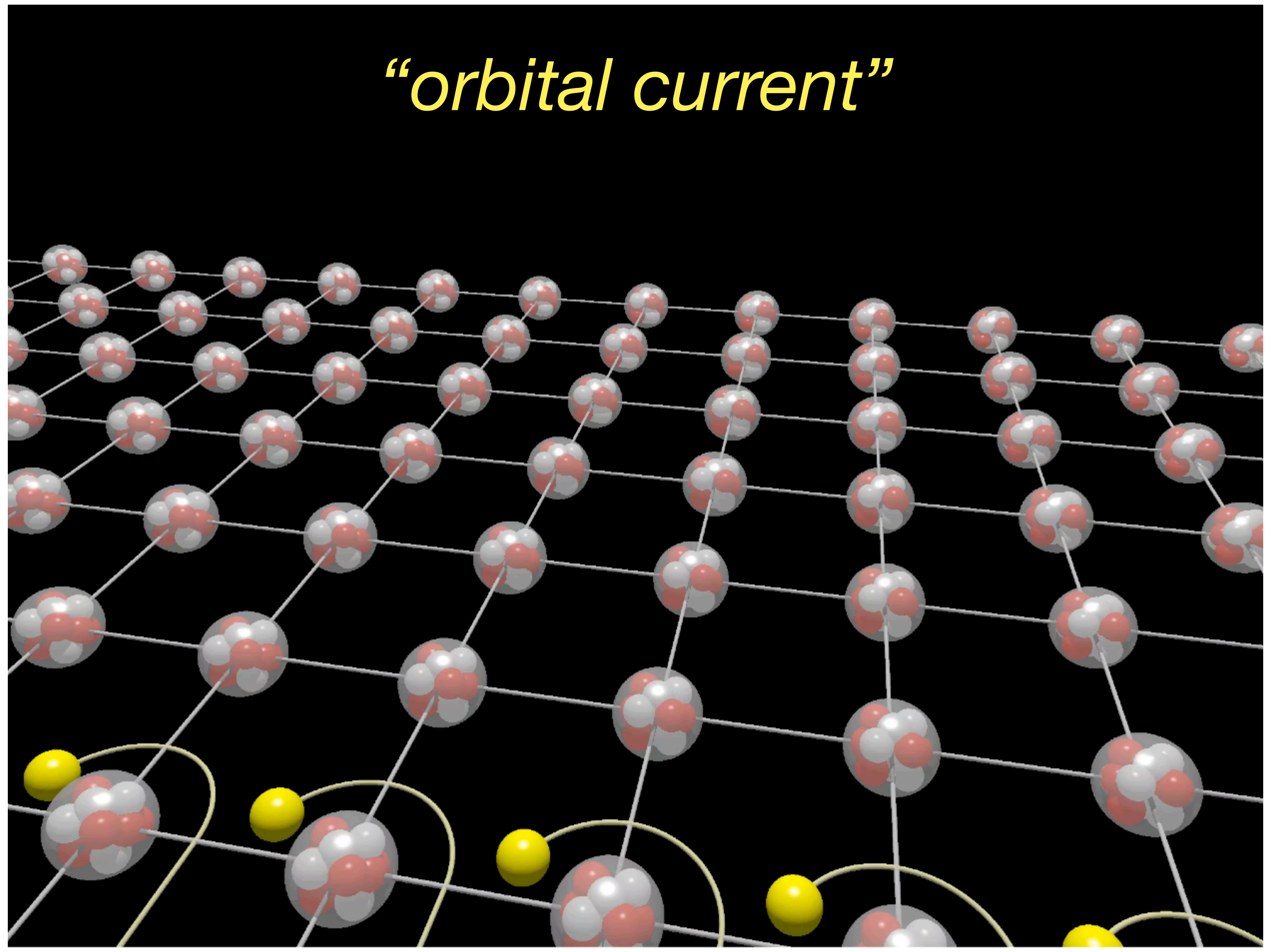
- Considering **how electrons occupy different orbitals** is a good starting point.
- The orbital configuration determines most of the properties of a material.
- **Can we control the orbital wave function in non-equilibrium?**

Orbitronics: Key ideas

An emerging field of electronics that exploits the orbital degree of freedom as an information carrier

Invited review: 📚 D. Go *et al.*, Europhys. Lett. **135**, 37001 (2021)

$$|\psi\rangle = \begin{pmatrix} \psi_s \\ \psi_{p_x} \\ \psi_{p_y} \\ \psi_{p_z} \\ \psi_{d_{xy}} \\ \psi_{d_{yz}} \\ \vdots \end{pmatrix}$$

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Perspective

Orbitronics: Orbital currents in solids

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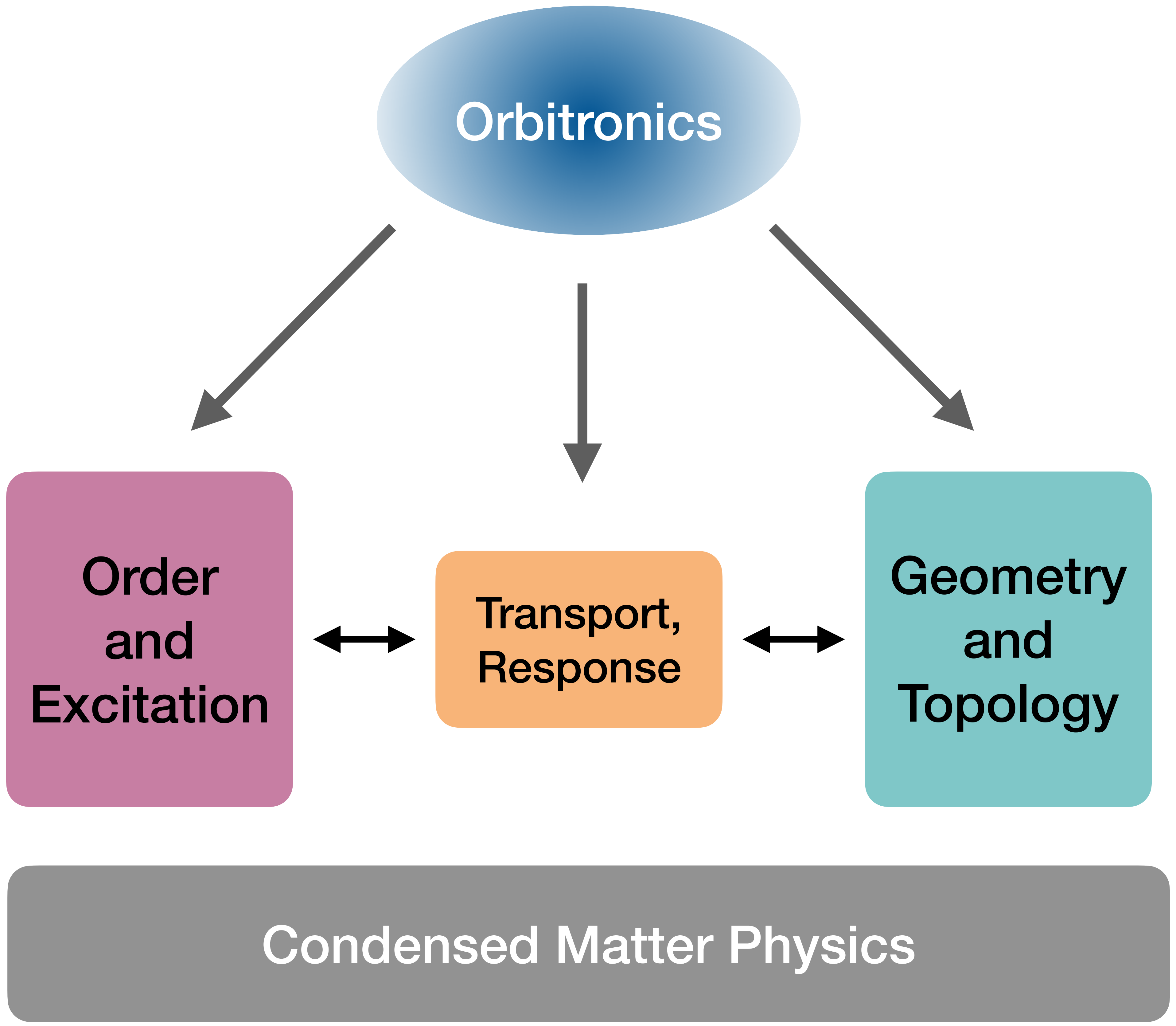
Abstract – In solids, electronic Bloch states are formed by atomic orbitals. While it is natural to expect that orbital composition and information about Bloch states can be manipulated and transported, in analogy to the spin degree of freedom extensively studied in past decades, it has been assumed that orbital quenching by the crystal field prevents significant dynamics of orbital degrees of freedom. However, recent studies reveal that an orbital current, given by the flow of electrons with a finite orbital angular momentum, can be electrically generated and transported in wide classes of materials despite the effect of orbital quenching in the ground state. Orbital currents also play a fundamental role in the mechanisms of other transport phenomena such as spin Hall effect and valley Hall effect. Most importantly, it has been proposed that orbital currents can be used to induce magnetization dynamics, which is one of the most pivotal and explored aspects of magnetism. Here, we give an overview of recent progress and the current status of research on orbital currents. We review proposed physical mechanisms for generating orbital currents and discuss candidate materials where orbital currents are manifest. We review recent experiments on orbital current generation and transport and discuss various experimental methods to quantify this elusive object at the heart of *orbitronics* —an area which exploits the orbital degree of freedom as an information carrier in solid-state devices.

perspective

- How to **generate/detect** the orbital current.
- How to **manipulate** the orbital current.
  (by order parameters/external perturbations).
- How to **measure and control order parameters** by the orbital current

Orbitronics: Why it is important



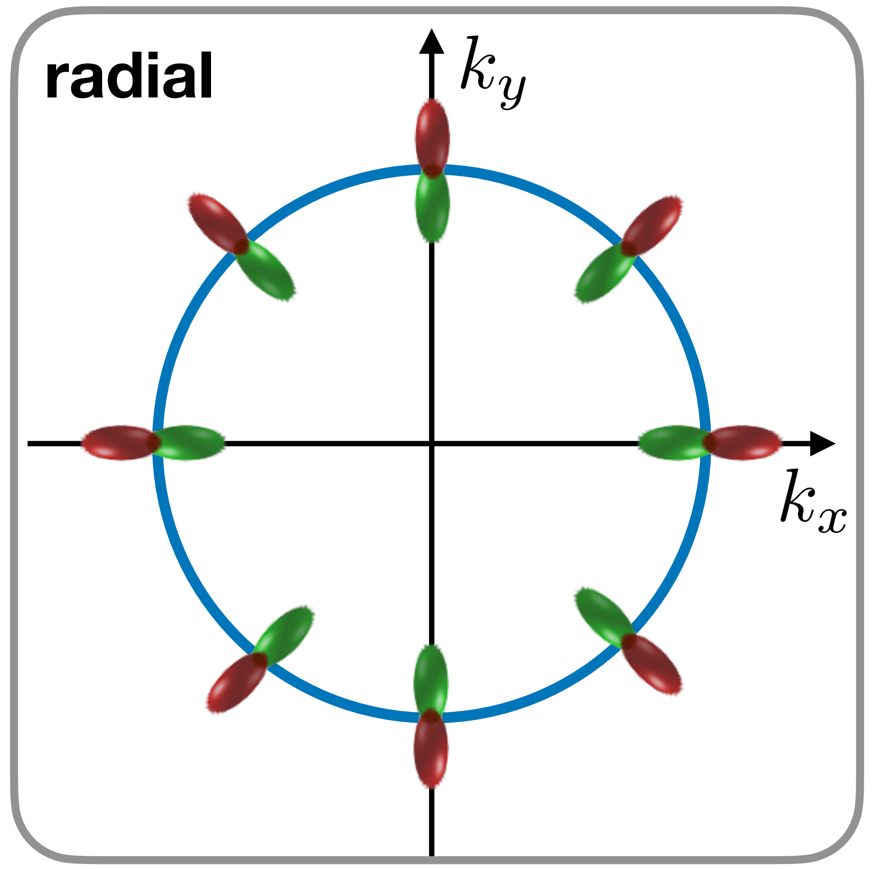
- **Detecting and controlling order parameters and excitations:**
  - Spintronics: Magnetism
    Today's talk
  - Superconductivity: (Cooper) Pair, vortex
    L. Chirolli, M. Cuoco *et al.* PRL **128**, 217703 (2022)
    M. T. Mercaldo, M. Cuoco *et al*. PRB **105**, L140507 (2022)
  - Ferroelectrics: Electric polarization
    In progress.
- **Indicator of the geometry/topology of electronic structure:**
  - "Hidden" Berry curvature measured by OAM
    S. Cho, C. Kim, S. R. Park *et al*. PRL **121**, 186401 (2018)
  - Orbital Hall insulating phase of TMDs
    T. Cysne, T. G. Rappoport *et al*. PRL **126**, 056601 (2021)
  - Orbital Hall effect as an alternative to valley Hall effect
    S. Bhowal and G. Vignale, PRB **103**, 195309 (2021)
  - Orbital magnetism via topological/chiral spin textures
    L. Zhang, **D. Go**, Y. Mokrousov *et al*. Comm. Phys. **3**, 227 (2020)

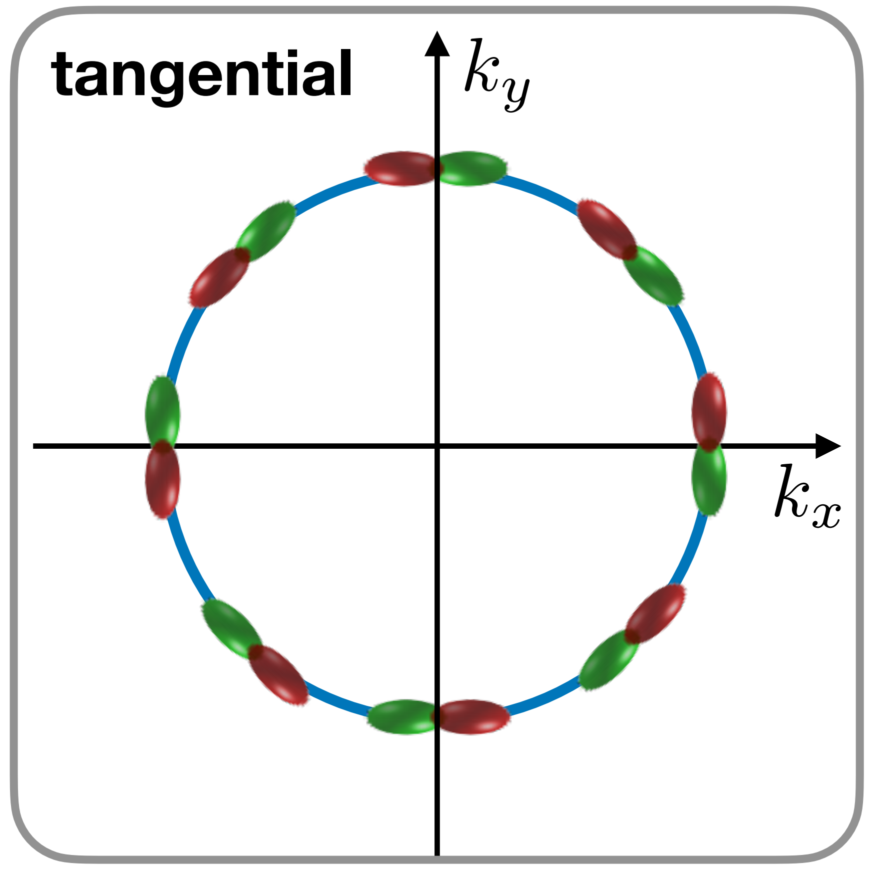
Orbital quenching?

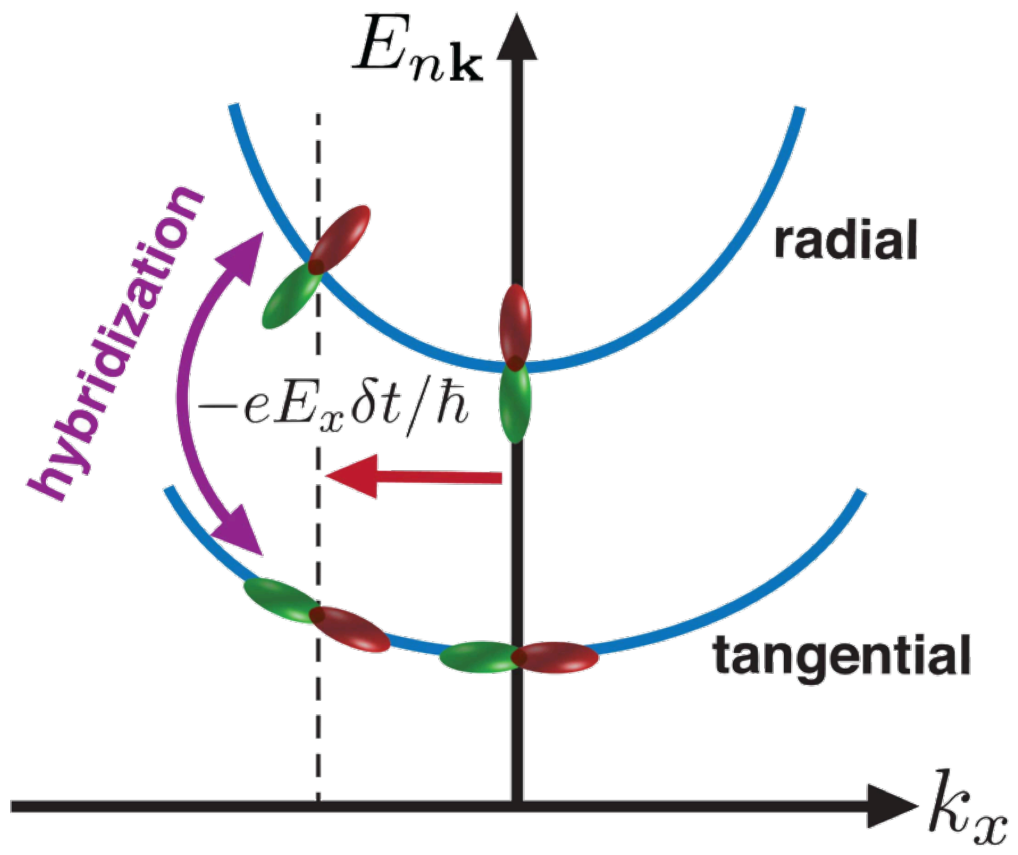
Orbital Hall effect: Mechanism

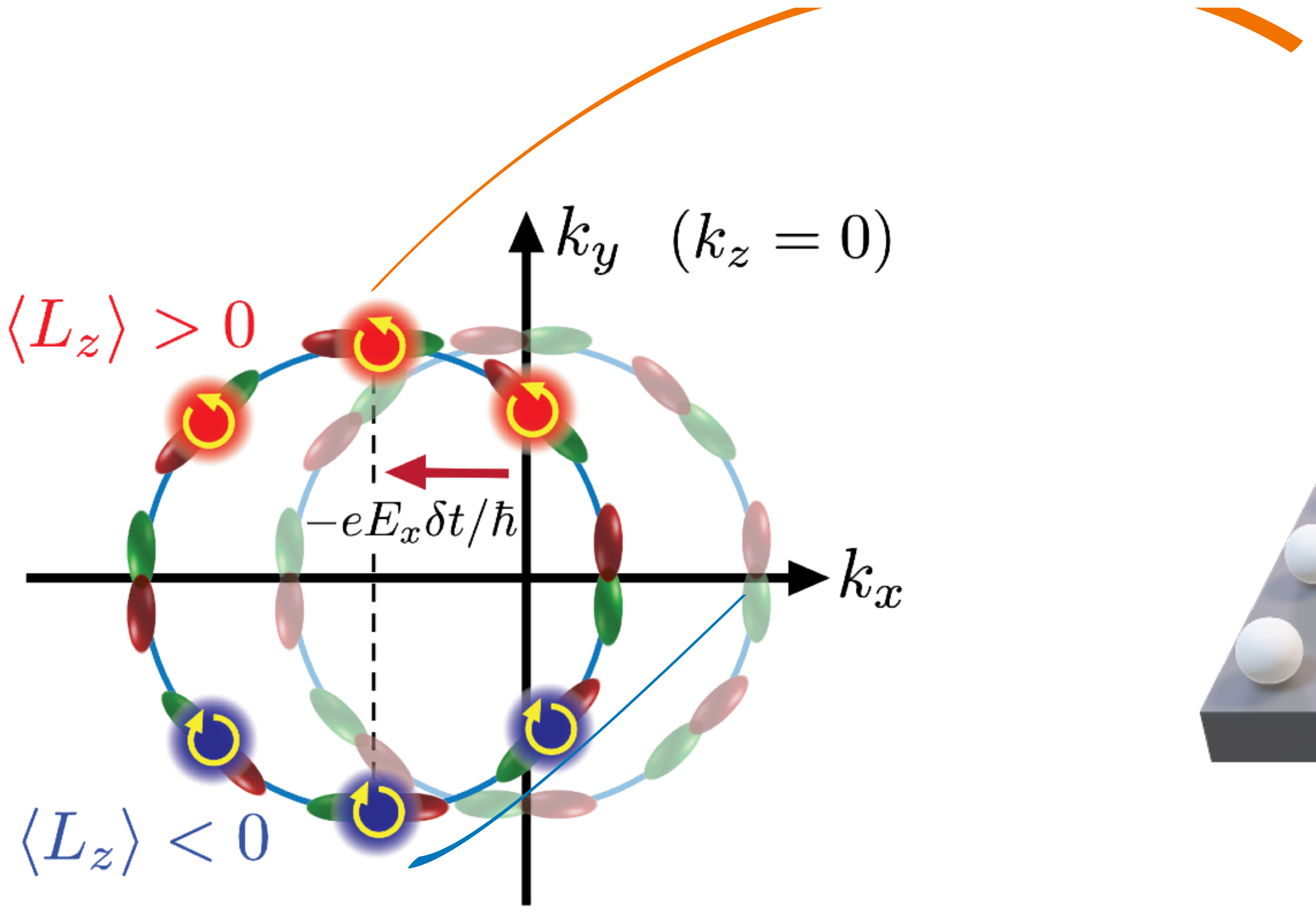
D. Go, D. Jo, C. Kim, H.-W. Lee, PRL **121**, 086602 (2018)

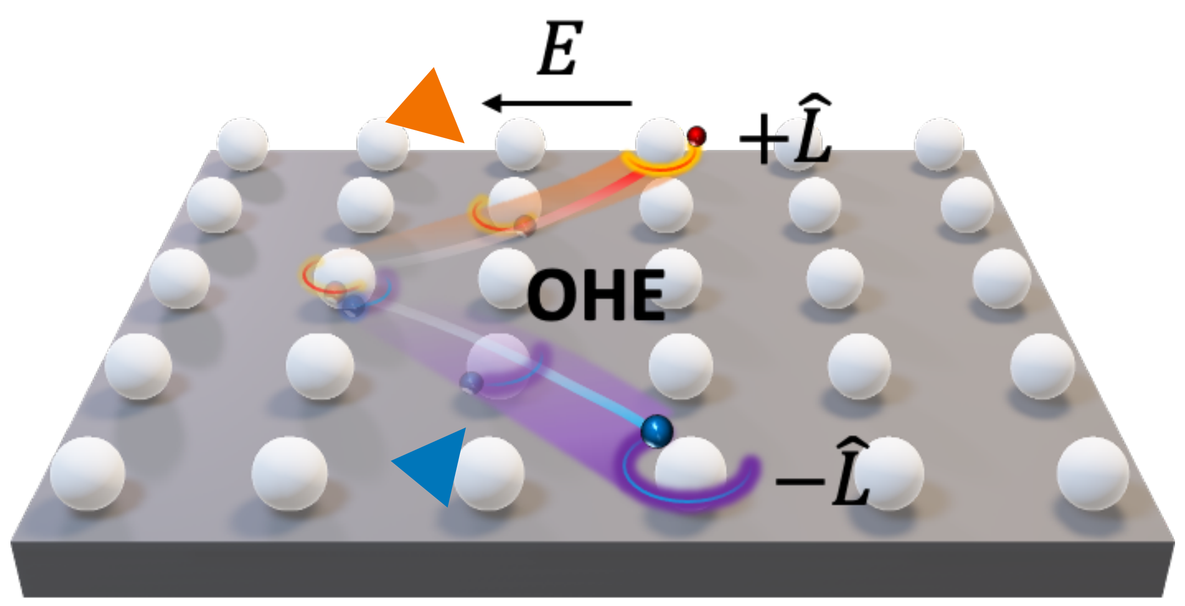
The orbital current can be induced despite the orbital quenching in the ground state.











$$\delta\langle \mathbf{L} \rangle_{n\mathbf{k}} \propto \boldsymbol{\mathcal{E}} \times \mathbf{k}$$

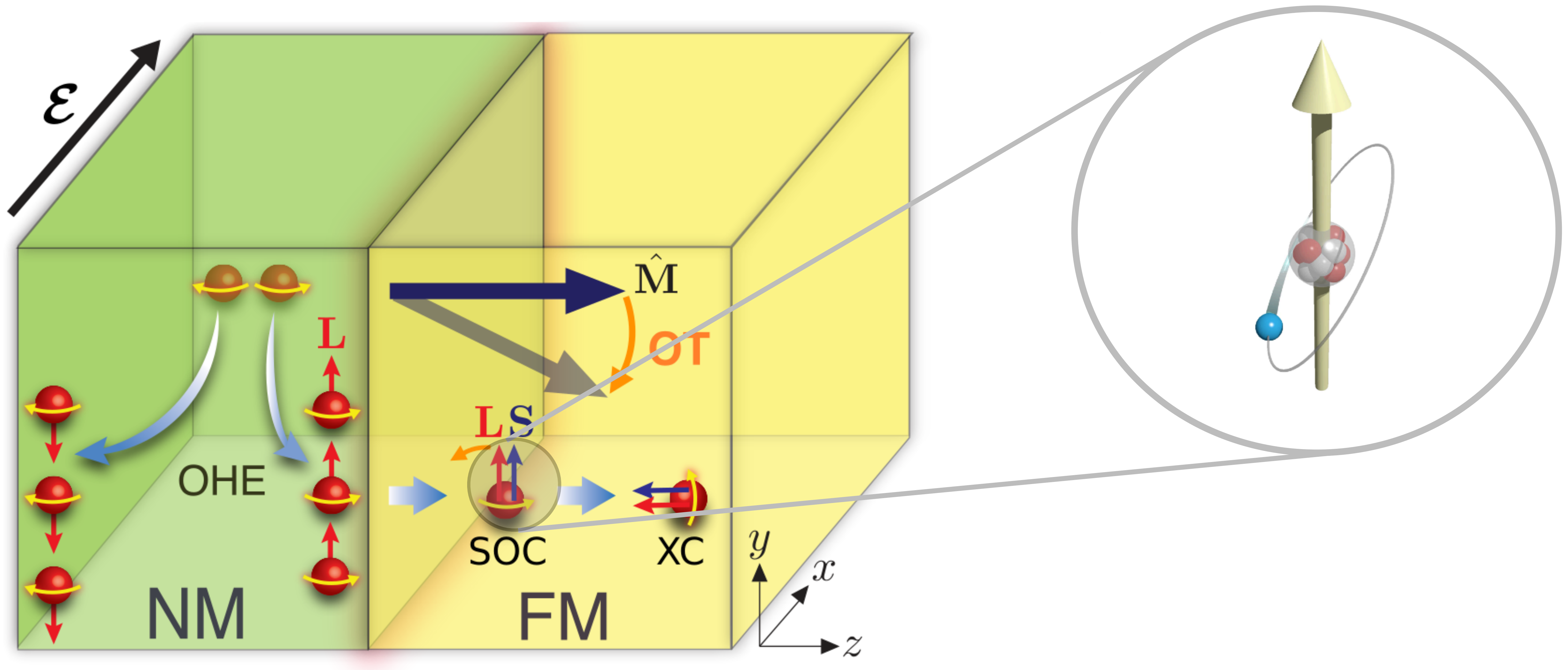
Intrinsic orbital magnetoelectric coupling

The mechanism is independent of the SOC and can be large in light elements

D. Jo, **D. Go,** and H.-W. Lee, PRB **98**, 214405 (2018)

Orbital torque

D. Go and H.-W. Lee, Phys. Rev. Res. **2**, 013177 (2020)



The OAM can be transferred to the magnetization via the spin-orbit coupling of the FM

Advantages

- High efficiency due to large OHE
- Broader choice of materials (among non-heavy elements)

A promising solution for green and sustainable spintronics

Direct orbital torque

- J. Kim. **D. Go**, Y. Otani *et al*. Phys. Rev. B **103**, L020407 (2021)
- D. Lee, **D. Go**, B.-G. Park *et al*. Nat. Comm. **12**, 6710 (2021)

Orbital-to-spin conversion

- S. Ding, **D. Go**, M. Kläui *et al.* Phys. Rev. Lett. **125**, 177201 (2020)
- S. Lee, **D. Go**, K.-J. Kim *et al.* Comm. Phys. **4**, 234 (2021)

Inverse orbital torque

- E. Santos, **D. Go**, A. Azevedo *et al.* arXiv:2204.01825

Orbital magnetoresistance

- S. Ding. **D. Go**, M. Kläui *et al*. Phys. Rev. Lett. **128**, 067201 (2022)

Nonlocal long-range response

- H. Hayashi, **D. Go**, K. Ando *et al*. arXiv:2202.13896

How are the spin and orbital different?
Orbital is NOT an arrow!

Spin

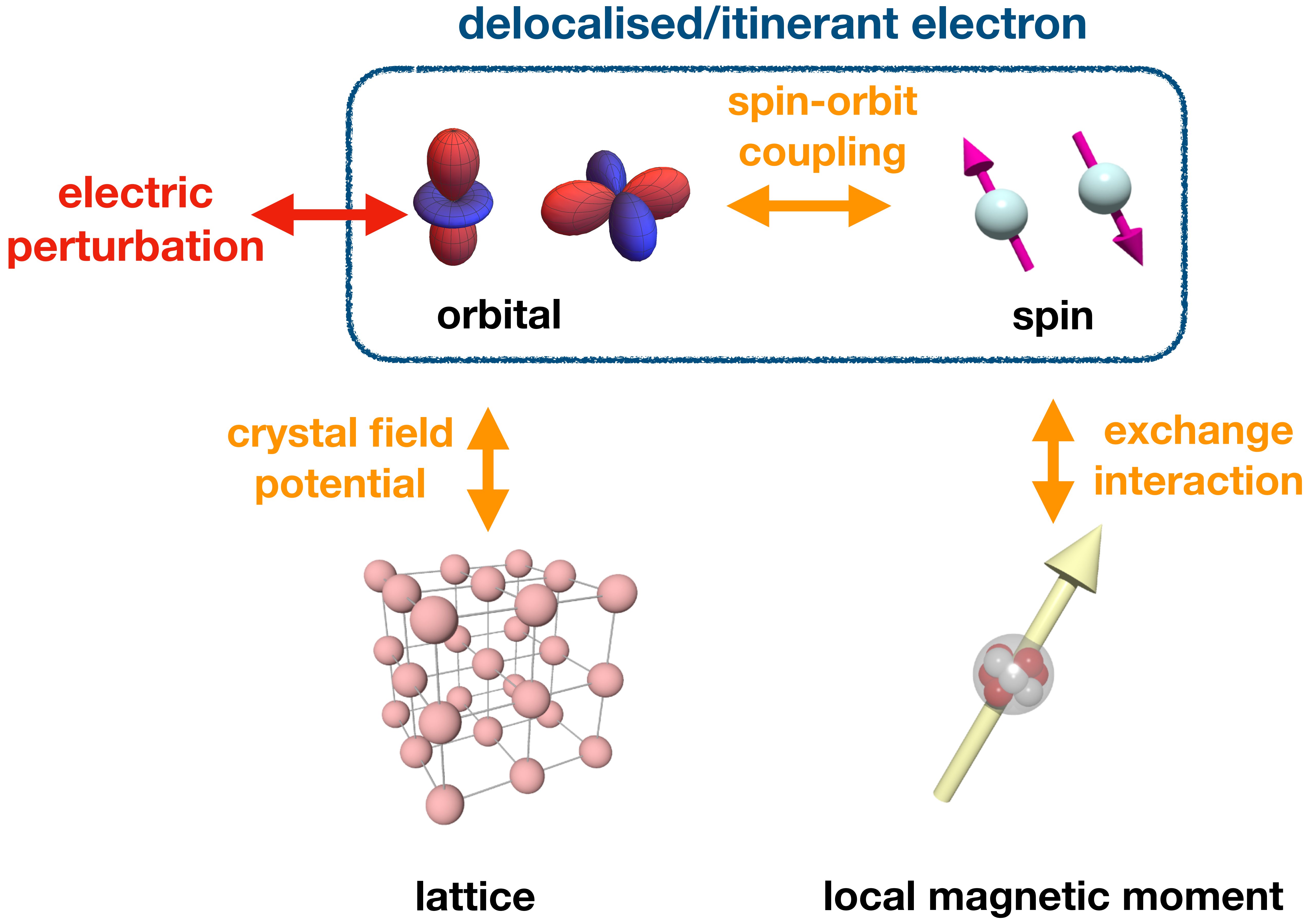
- Can be mapped into an “arrow”
  SU(2)-SO(3) homomorphism
- Nearly conserved
- Directly couple to magnetisation.

Orbital

- Orbital “characters” exist
  as well as “angular momentum”.
- Not conserved.
- Strong interaction with a crystal field.

Tracking angular momentum transfer

📚 **D. Go**, F. Frank, P. M. Haney, H.-W. Lee, Y. Mokrousov *et al.* Phys. Rev. Res. **2**, 033401 (2020)
📚 P. M. Haney and M. D. Stiles, Phys. Rev. Lett. **105**, 126602 (2010)



$$\mathcal{H} = \frac{p^2}{2m} + V_{\mathrm{CF}} + \sum_{\mu \in \mathrm{atom}} \lambda_\mu \mathbf{L}_\mu \cdot \mathbf{S}_\mu + \sum_{\mu \in \mathrm{atom}} J_\mu \hat{\mathbf{m}}_\mu \cdot \mathbf{S}_\mu$$

Mechanical torque +
circular phonon creation/annihilation

$$\frac{\partial}{\partial t}\langle \mathbf{L}_\mu \rangle = \langle \Phi^{\mathbf{L}_\mu} \rangle + \frac{1}{i\hbar}\langle [\mathbf{L}_\mu, V_{\mathrm{CF}}] \rangle + \langle \lambda_\mu \mathbf{S}_\mu \times \mathbf{L}_\mu \rangle$$

$$\frac{\partial}{\partial t}\langle \mathbf{S}_\mu \rangle = \langle \Phi^{\mathbf{S}_\mu} \rangle + \langle J_\mu \hat{\mathbf{m}}_\mu \times \mathbf{S} \rangle - \langle \lambda_\mu \mathbf{S}_\mu \times \mathbf{L}_\mu \rangle$$

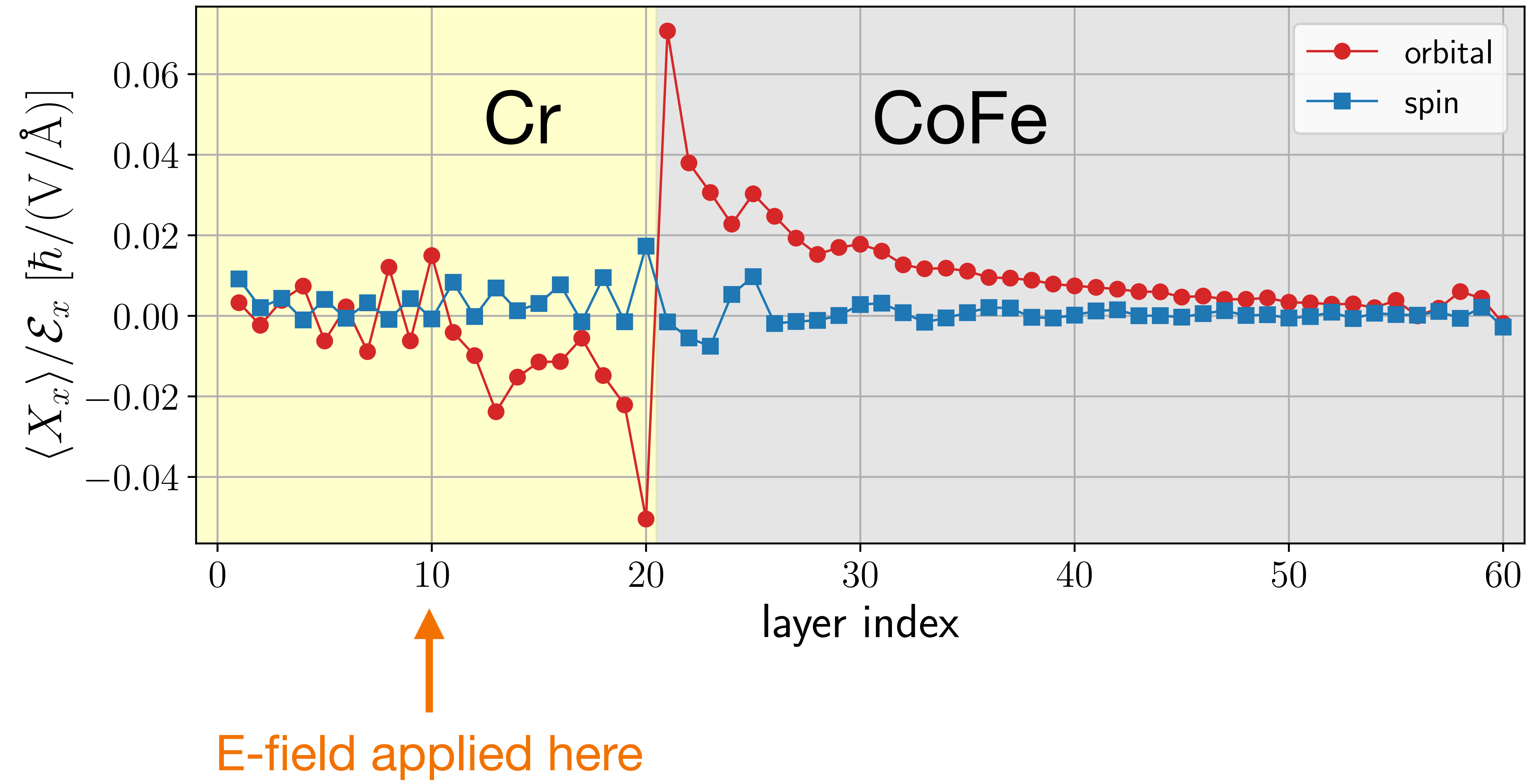
orbital-spin conversion

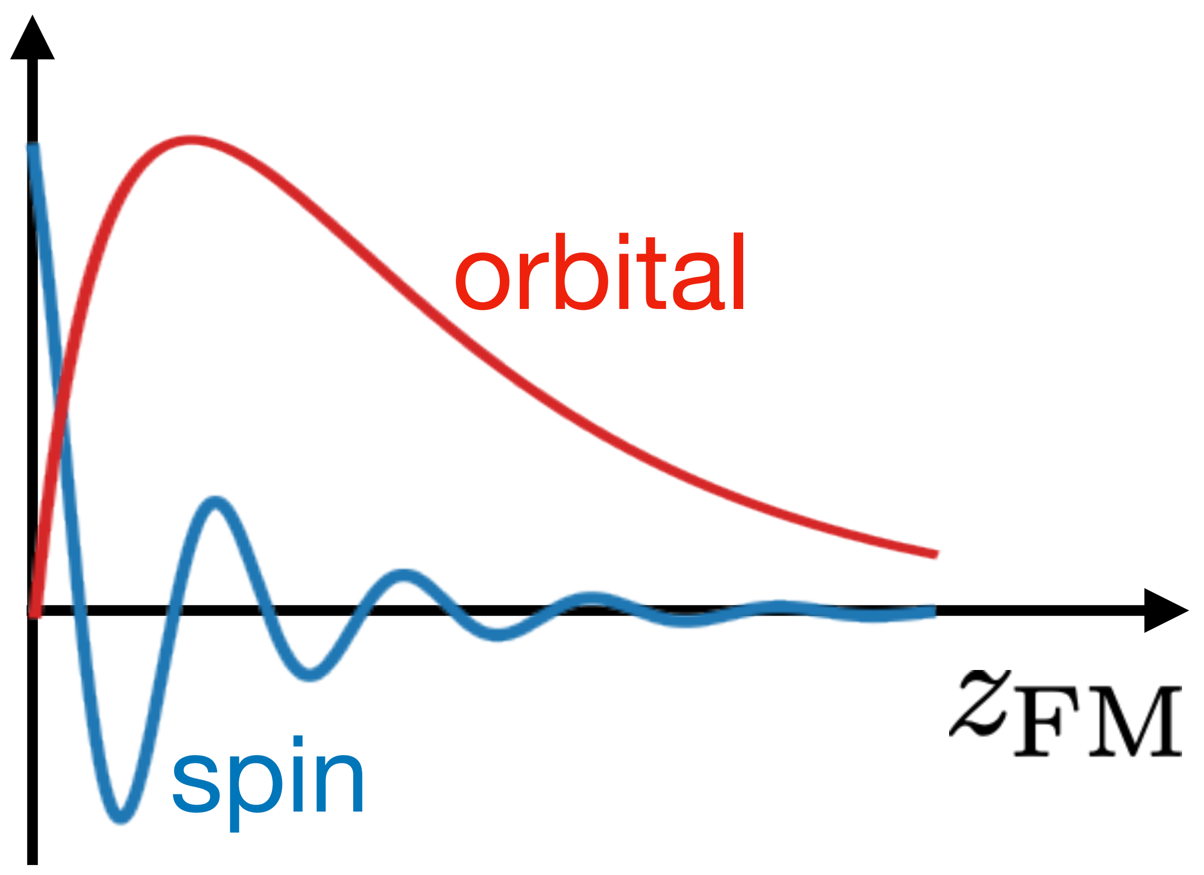
Magnetic torque +
magnon creation/annihilation

Nonlocal orbital magnetoelectric response

D. Go, K.-W. Kim, H.-W. Lee, Y. Mokrousov *et al.* arXiv:2109.14847

Orbital/spin response for the damping-like component ($\hat{\mathbf{m}} \times \hat{\mathbf{y}}$)





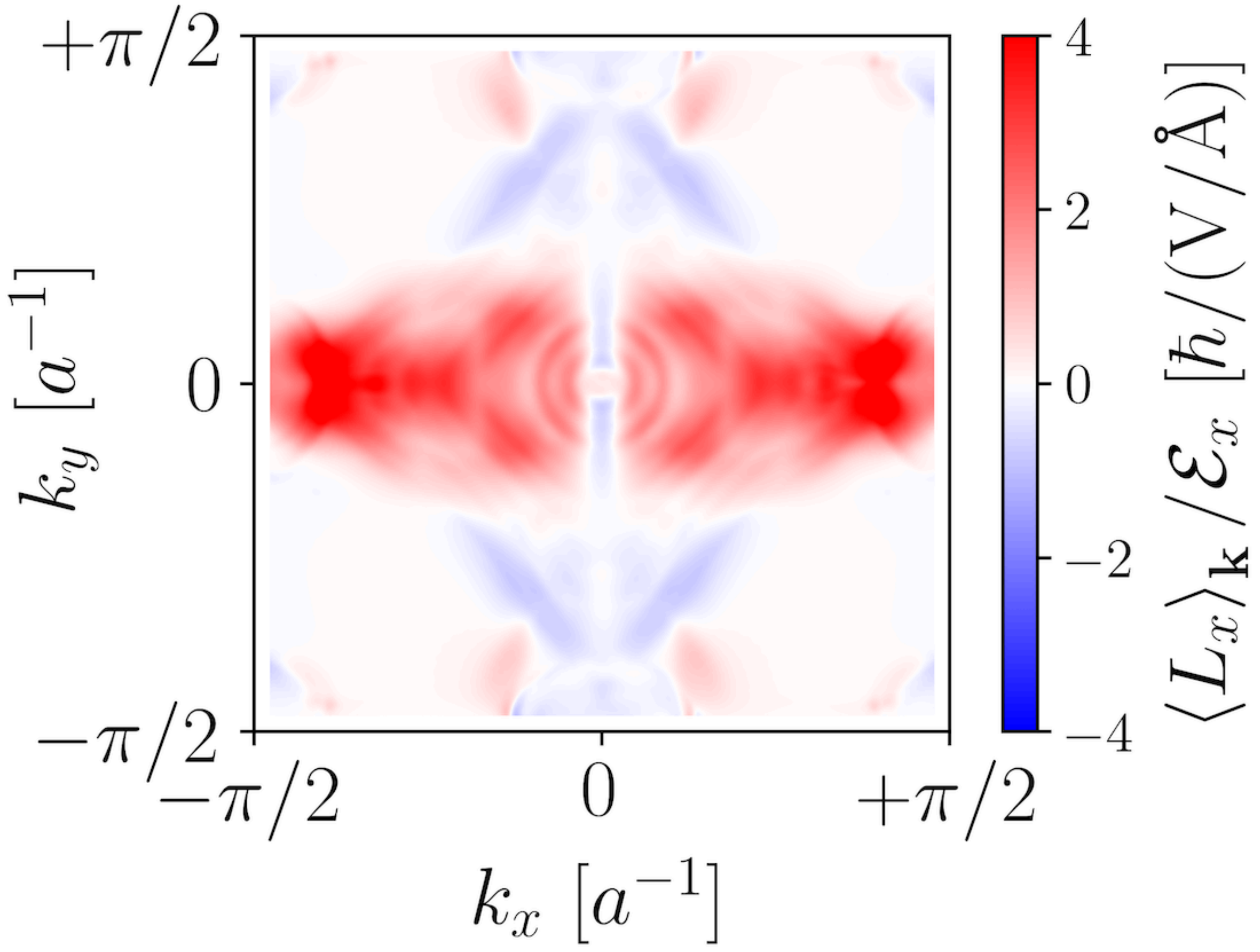
$$\langle L_x \rangle = \frac{1}{2} e\hbar\mathcal{E}_x \sum_{m\neq n} \int d\mathbf{k}(f_{n\mathbf{k}} - f_{m\mathbf{k}}) \times \mathrm{Im}\left[\frac{\langle u_{n\mathbf{k}}| L_x |u_{m\mathbf{k}}\rangle \langle u_{m\mathbf{k}}| (v_x P_{\mathrm{Cr}} + P_{\mathrm{Cr}} v_x) |u_{n\mathbf{k}}\rangle}{(E_{n\mathbf{k}} - E_{m\mathbf{k}} + i\eta)^2}\right]$$

- Spin dephasing occurs in < 10 atomic layers.
  Stiles and Zangwill, PRB **66**, 014407 (2002)
- The correlation between the spin and orbital responses is not noticeable.
- The orbital response is long-ranged and does not oscillate.
- The induced orbital moment can exert a torque on the magnetization via the SOC.

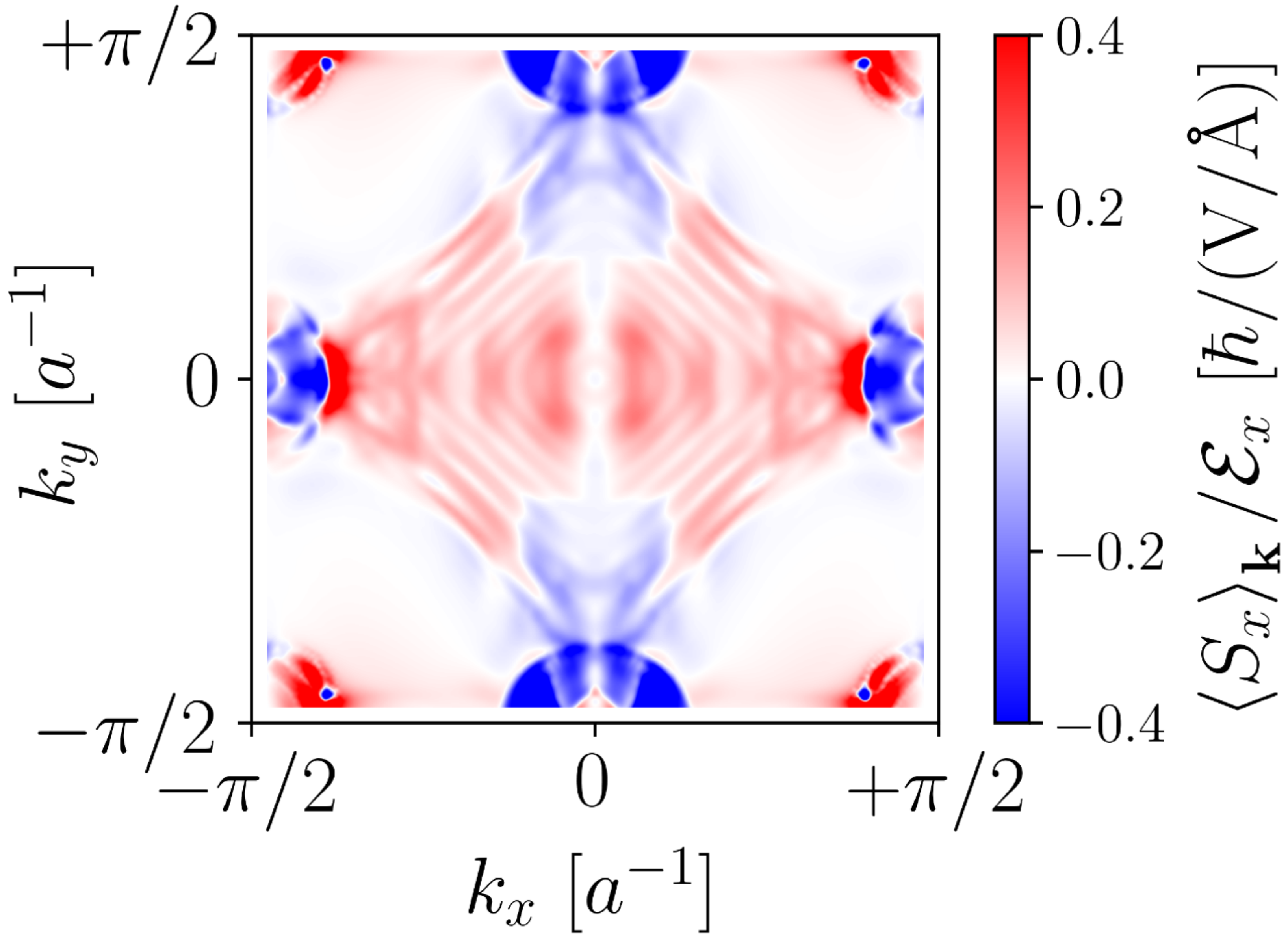
Why the OAM response is different from the spin response

D. Go, K.-W. Kim, H.-W. Lee, Y. Mokrousov *et al.* arXiv:2109.14847

induced OAM



induced spin



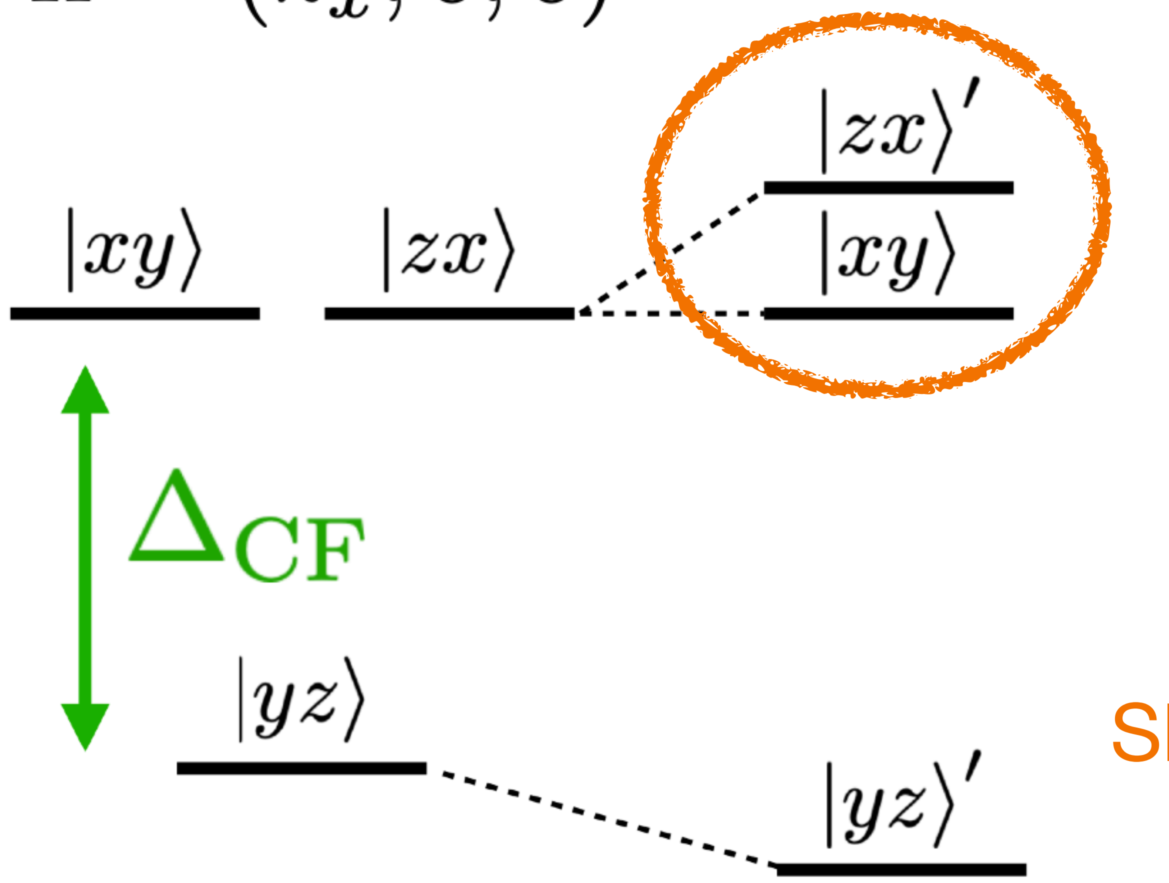
Hotspot along the k_x axis. Why?

Role of crystal field splitting

D. Go, K.-W. Kim, H.-W. Lee, Y. Mokrousov *et al.* arXiv:2109.14847

$\mathbf{k} = (k_x, 0, 0)$

C_4 symmetry w.r.t. x-axis

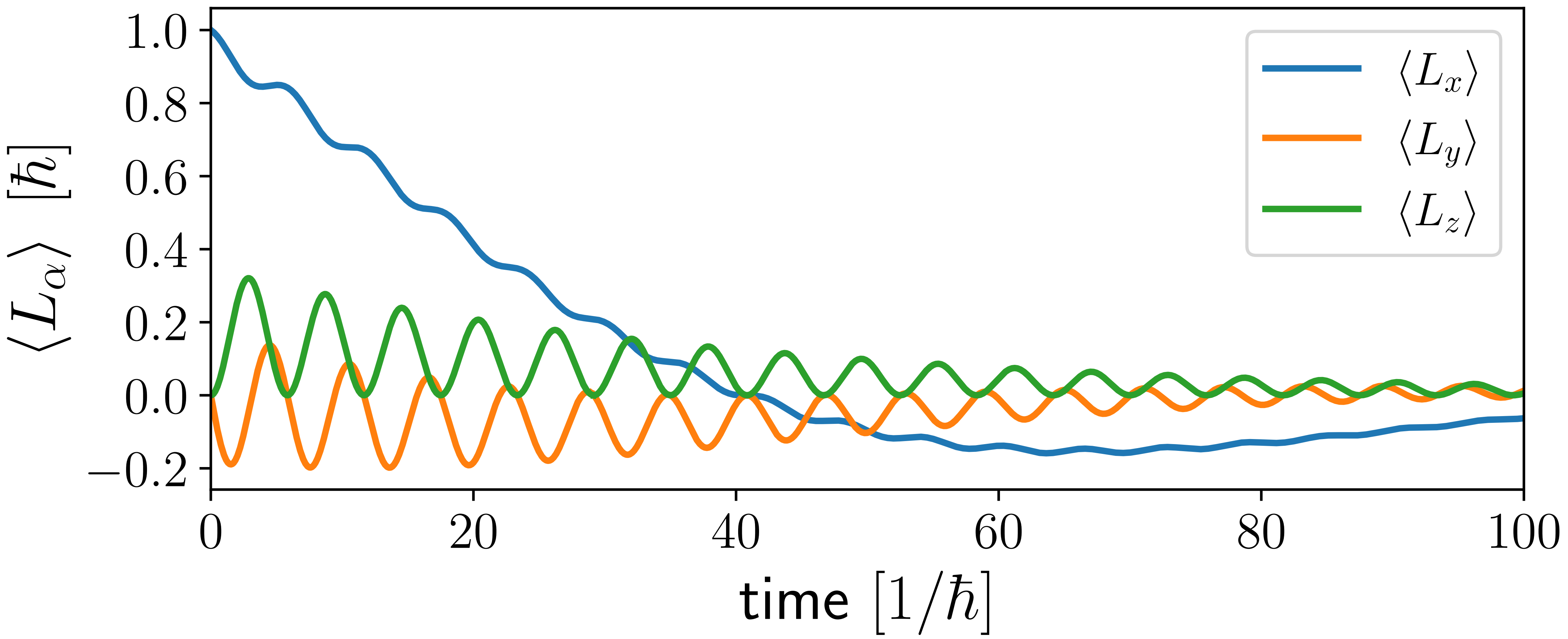


Hotspot for the DL-component (L_x) of the OAM

↓

Slow orbital precession

A solution of the time-dependent Schrödinger equation for a 3-orbital model



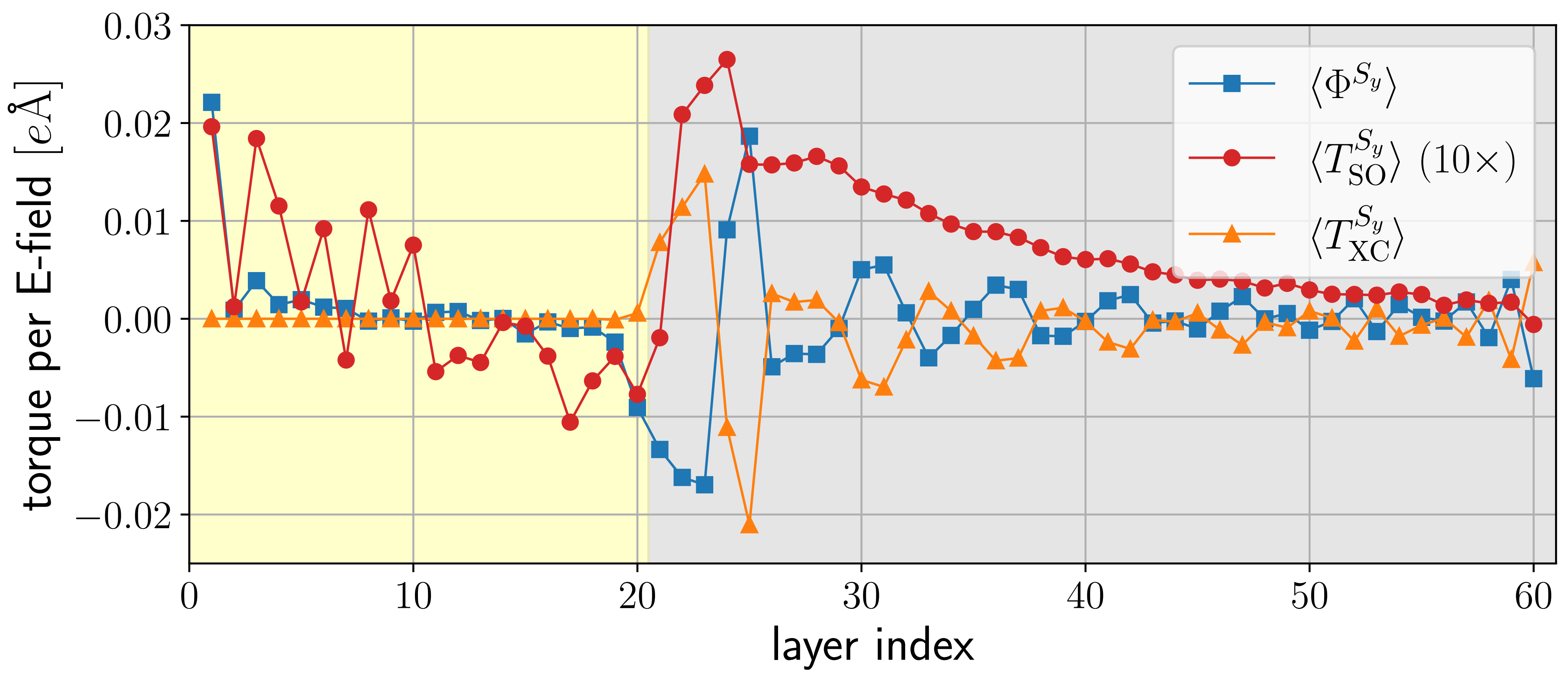
Dynamics of the induced $\langle L_x \rangle$ on the hotspot is strongly suppressed.

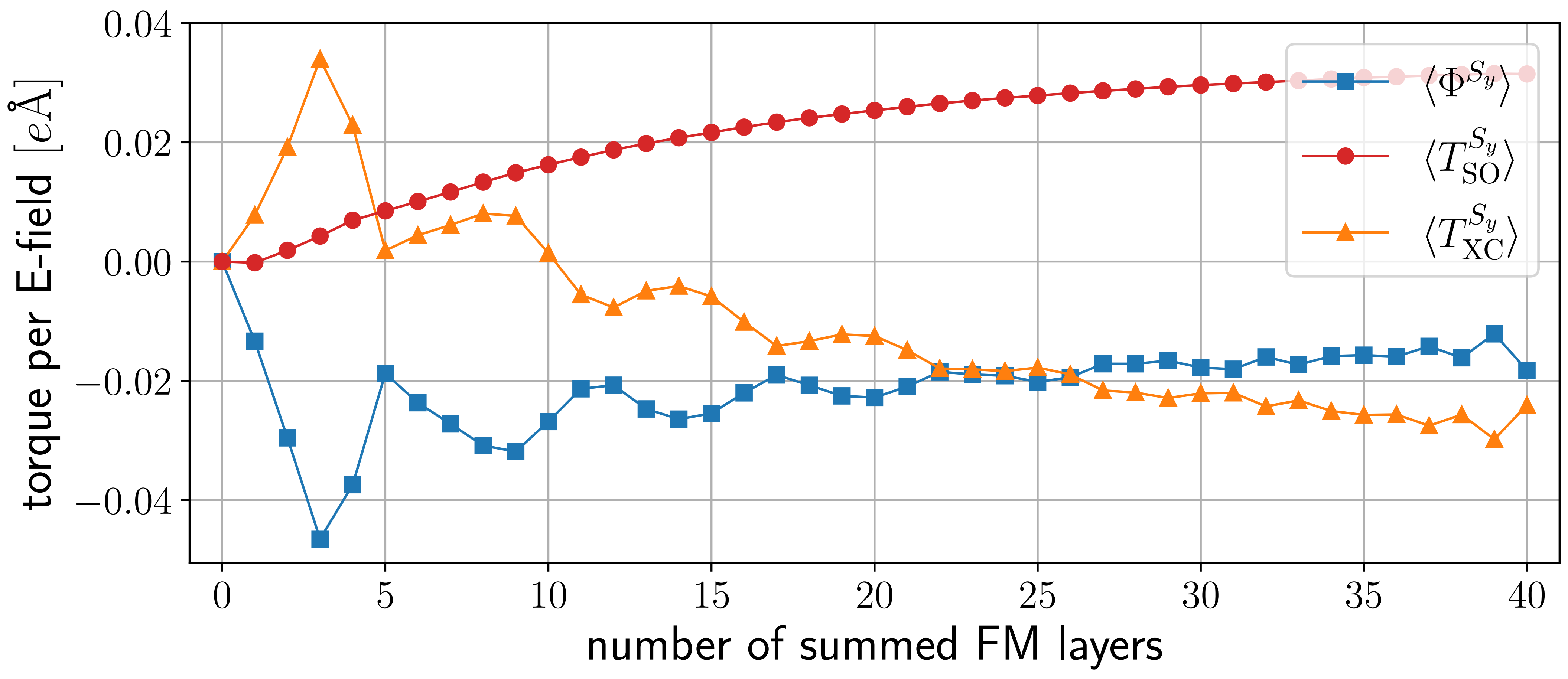
"orbital trap"

c.f. **Spin trap** against the Dyakonov-Perel spin dephasing: Long, Mokrousov, Blügel *et al.* PRB **94**, 180406(R) (2016)

Consequences on the torques

D. Go, K.-W. Kim, H.-W. Lee, Y. Mokrousov *et al.* arXiv:2109.14847





$$\frac{\partial}{\partial t}\langle \mathbf{S}_\mu \rangle = \langle \Phi^{\mathbf{S}_\mu} \rangle + \langle J_\mu \hat{\mathbf{m}}_\mu \times \mathbf{S} \rangle - \langle \lambda_\mu \mathbf{S}_\mu \times \mathbf{L}_\mu \rangle = 0$$

$T_{\mathrm{XC}}^{\mathbf{S}}$ $T_{\mathrm{SO}}^{\mathbf{S}}$

$$\langle T_{\mathrm{XC}}^{S_y} \rangle \approx -\langle \Phi^{S_y} \rangle - \langle T_{\mathrm{SO}}^{S_y} \rangle$$

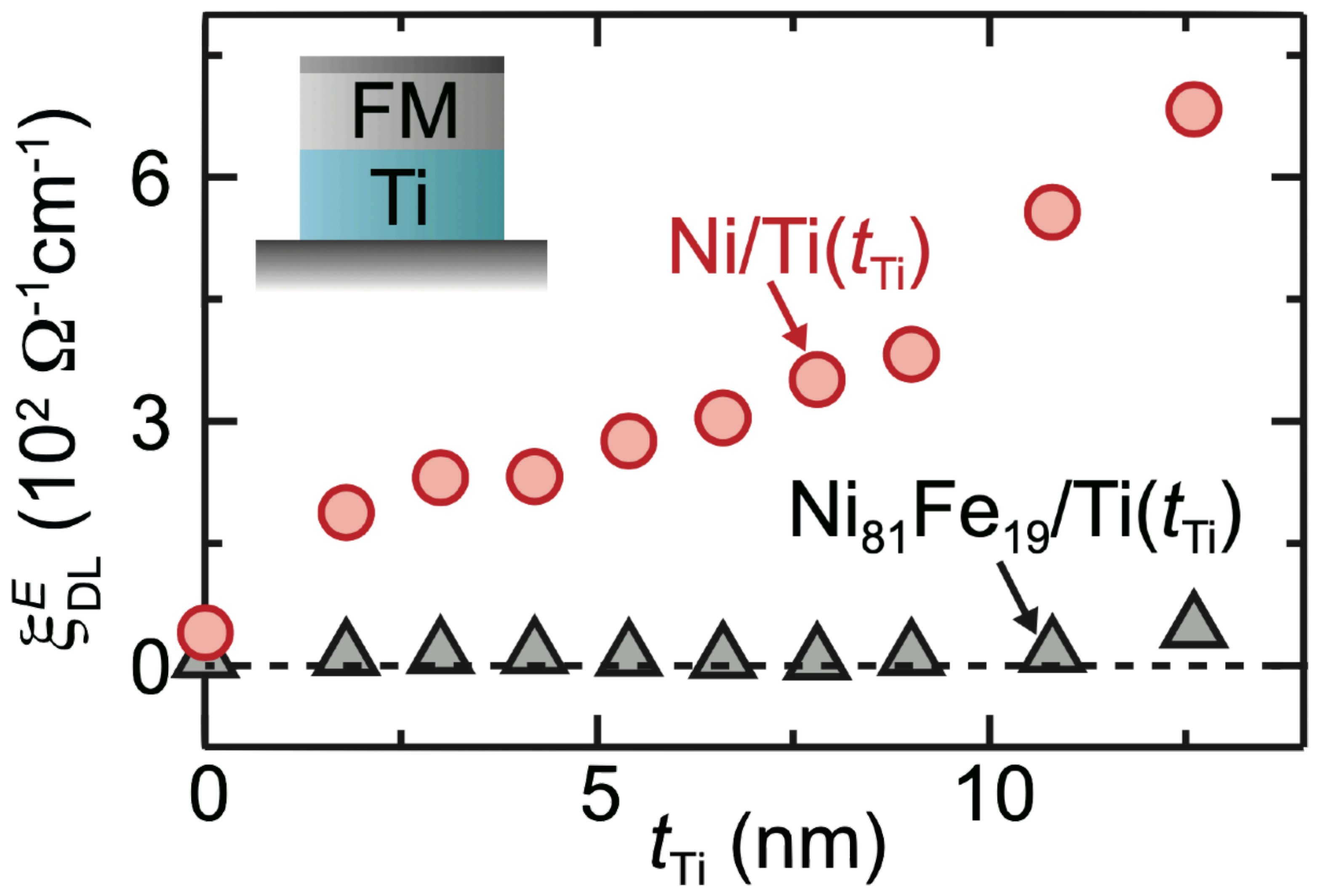
spin-transfer

orbital magneto-electric

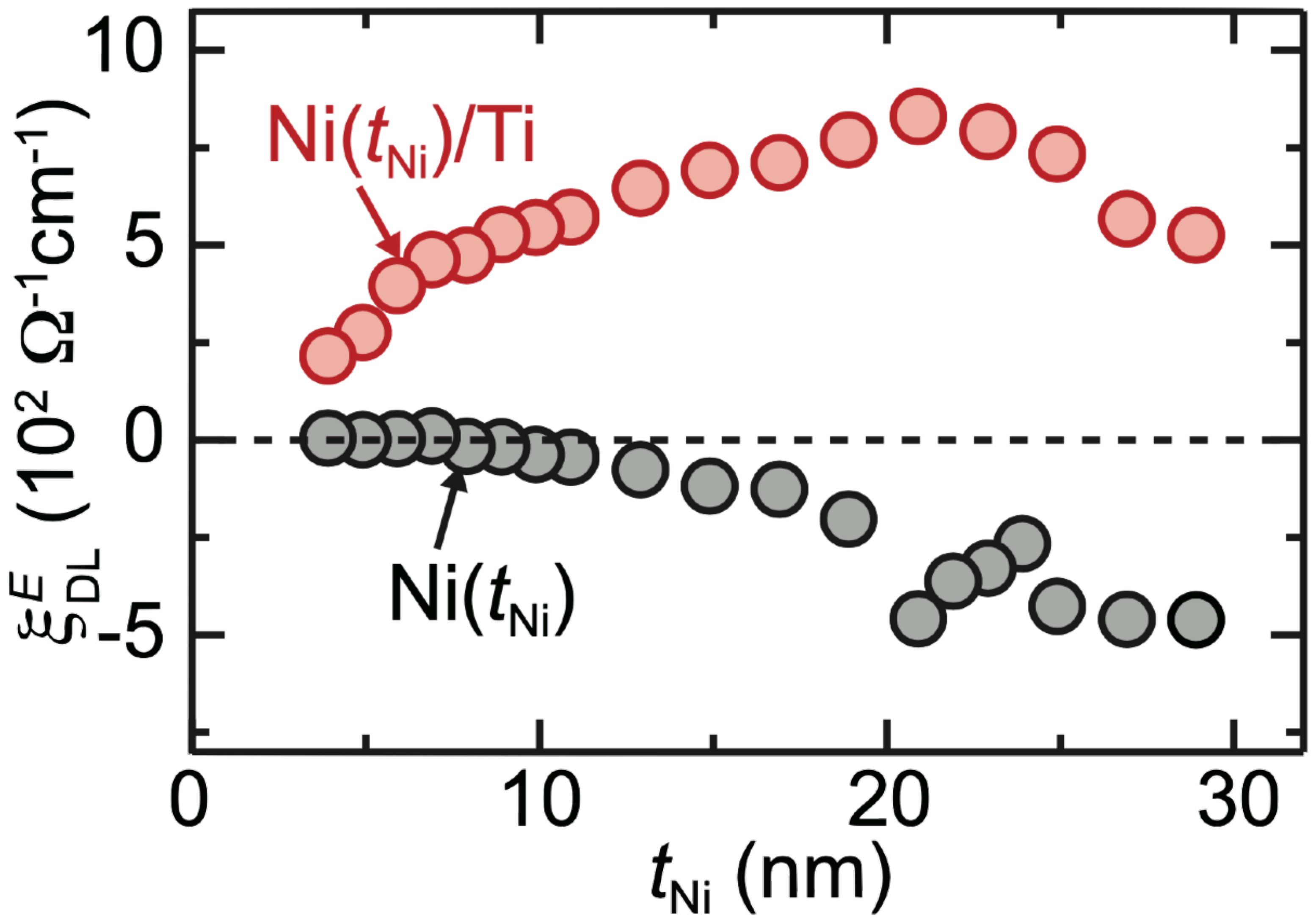
*The **"orbital magnetoelectric torque"** is expected to increase as the thickness of the FM increases*

Experimental demonstration

H. Hayashi, D. Jo, **D. Go**, Y. Mokrousov, H.-W. Lee, K. Ando, arXiv: 2202.13896



The torque efficiency is much larger in Ni/Ti than in Py/Ti



The torque efficiency keeps increasing in Ni/Ti upon increasing the Ni thickness, up to ~ 20 nm.

Similar behaviour was also observed by:

- L. Liao, Y. Otani *et al*. Phys. Rev. B **105**, 104434 (2022)
- S. Ding. **D. Go**. M. Kläui *et al*. Phys. Rev. Lett. **128**, 067201 (2022)
- A. Bose, **D. Go**, M. Kläui *et al.* in preparation.

Conclusion

- **Orbital torque** opens a promising route for spintronics.
  📚 **D. Go** and H.-W. Lee, PRRes **2**, 013177 (2020)

- The main challenge is to describe the **interplay between the spin and orbital** degrees of freedom of **itinerant/delocalised electrons**.

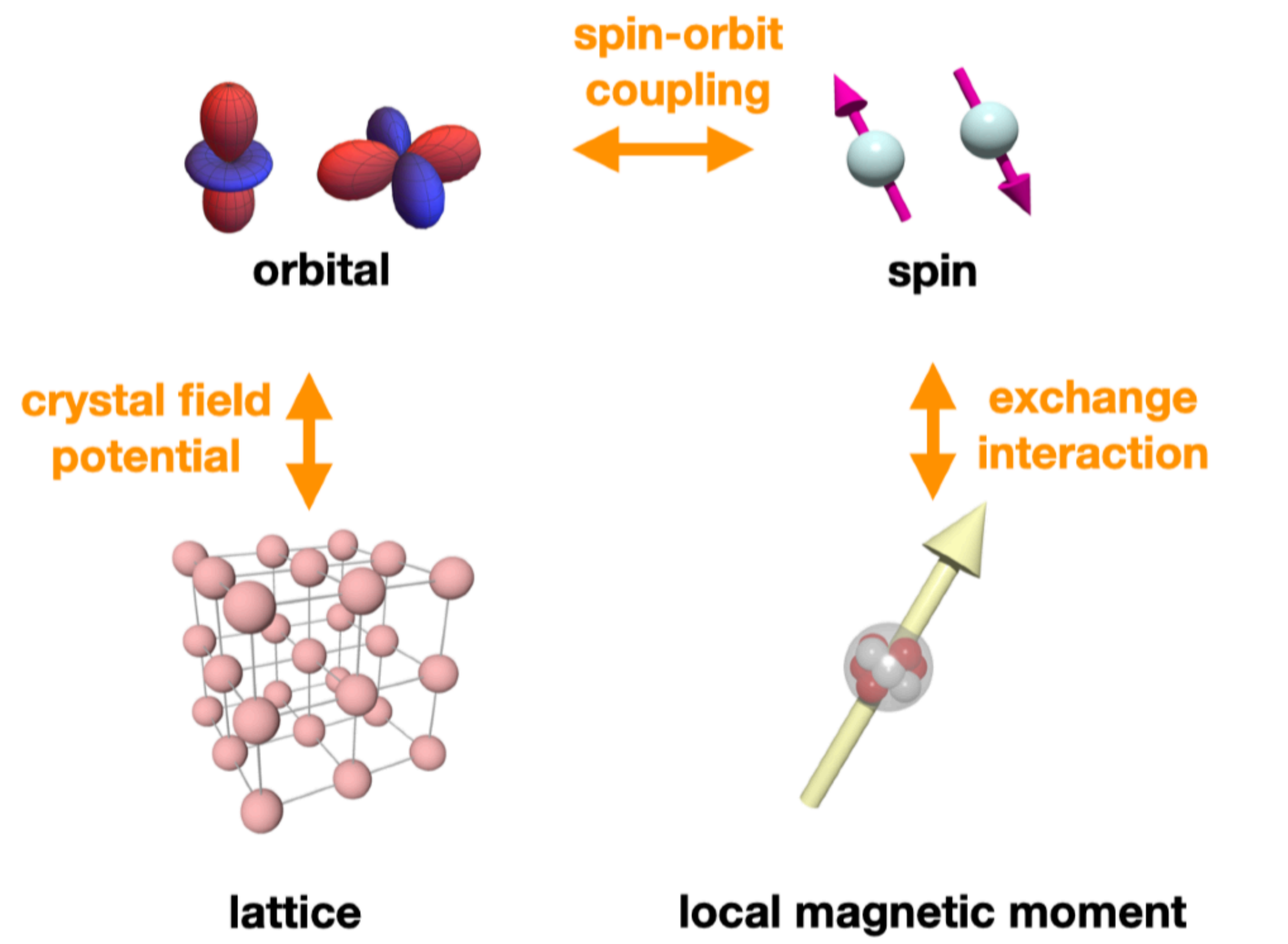
- This can be systematically analysed by tracking angular momentum transfer via the **spin/orbital continuity equations**.
  📚 **D. Go**, Y. Mokrousov *et al.* PRRes **2**, 033401 (2020)

- The analysis reveals the **nonlocal** and **long-range** nature of the orbital torque.
  📚 **D. Go**, Y. Mokrousov *et al.* arXiv:2109.14847

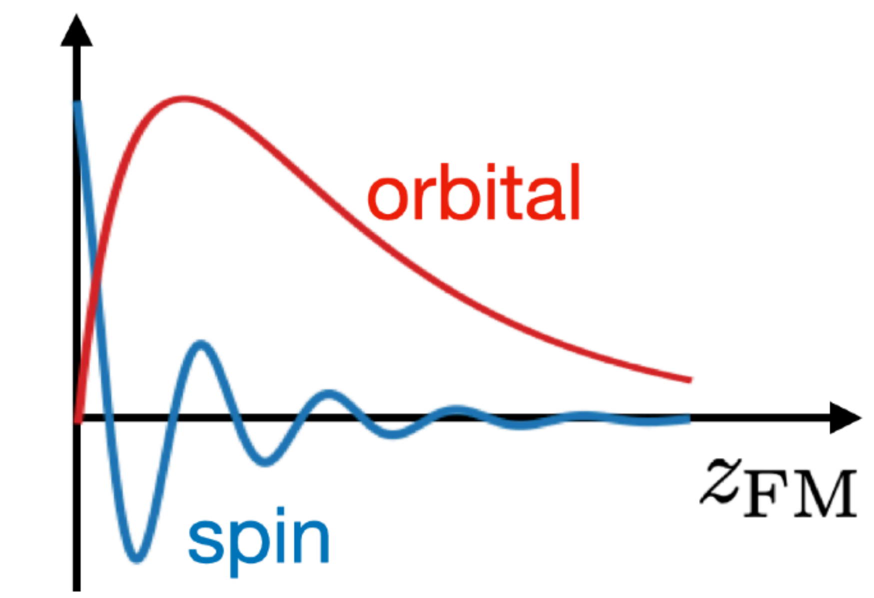
- This originates from the itinerant electrons in the ***"orbital trap"***, where the orbital dynamics is strongly suppressed.

- The key prediction is a monotonic increase of the torque efficiency upon increasing the thickness of the ferromagnet.

- Experimental data supports the theoretical prediction.
  📚 H. Hayashi, D. Jo, **D. Go**, Y. Mokrousov, H.-W. Lee, K. Ando, arXiv: 2202.13896



📚 **D. Go**, Y. Mokrousov *et al.* PRRes **2**, 033401 (2020)



📚 **D. Go**, Y. Mokrousov *et al.* arXiv:2109.14847

Thank You

Theory

- **Yuriy Mokrousov**, **Frank Freimuth**, Stefan Blügel (FZ Jülich, Germany)
- Daegeun Jo, Hyun-Woo Lee (POSTECH, Korea)
- Changyoung Kim (SNU, Korea)
- Kyoung-Whan Kim (KIST, Korea)
- Kyung-Jin Lee (KAIST, Korea)
- Paul Haney (NIST, USA)

Experiment

- Shilei Ding, Zhongyu Liang, Jinbo Yang (Peking Univ, China)
- Tom Saunderson, Arnab Bose, Gerhard Jakob, Mathias Kläui (JGU Mainz)
- Soogil Lee, Min-Gu Park, Byong-Guk Park (KAIST, Korea)
- Dongjoon Lee, OukJae Lee (KIST, Korea)
- Young-Gwan Choi, Gyung-Min Choi (Sungkyunkwan Univ, Korea)
- Junyeon Kim, YoshiChika Otani (RIKEN, Japan)
- Hiroki Hayashi, Tenghua Gao, Kazuya Ando (Keio Univ)

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