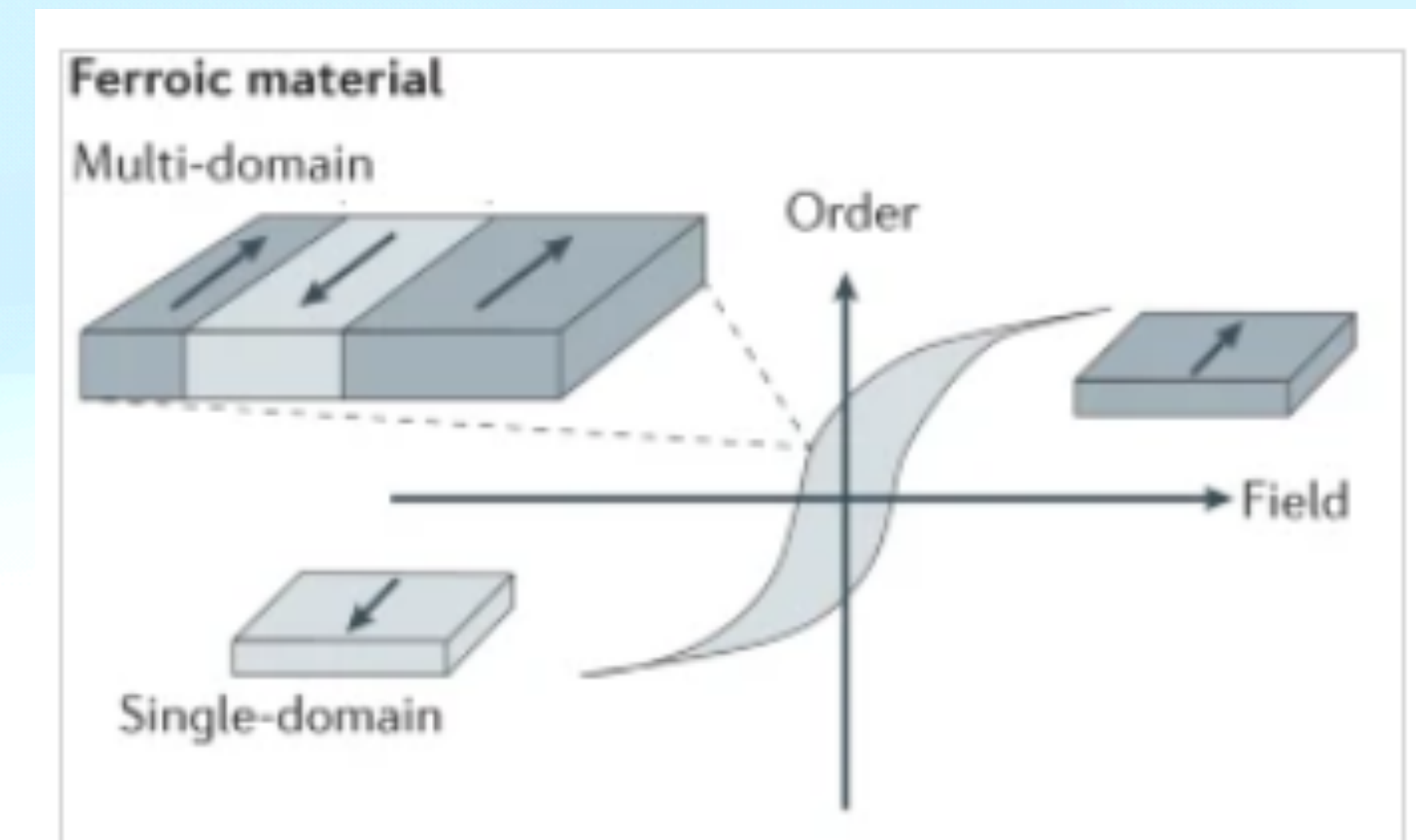


Altermagnetic multiferroics and altermagnetolectric effect

arXiv:2411.19928v1

Ferroics

- **Ferroics**: Ferroic materials display **long-range order** with respect to at least one macroscopic property, and they develop **domains** that can be switched by a conjugate field.

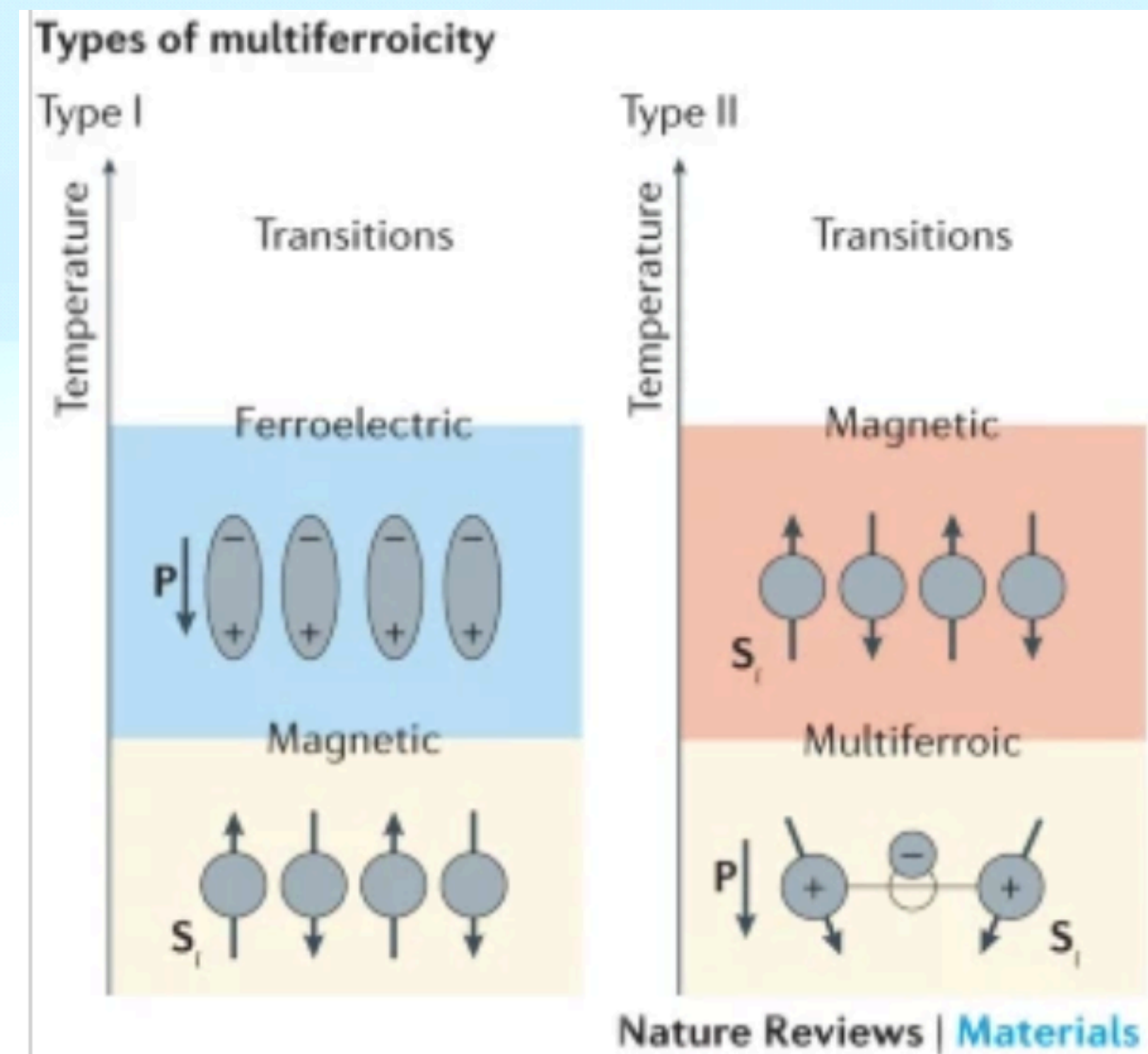


Different Ferroics

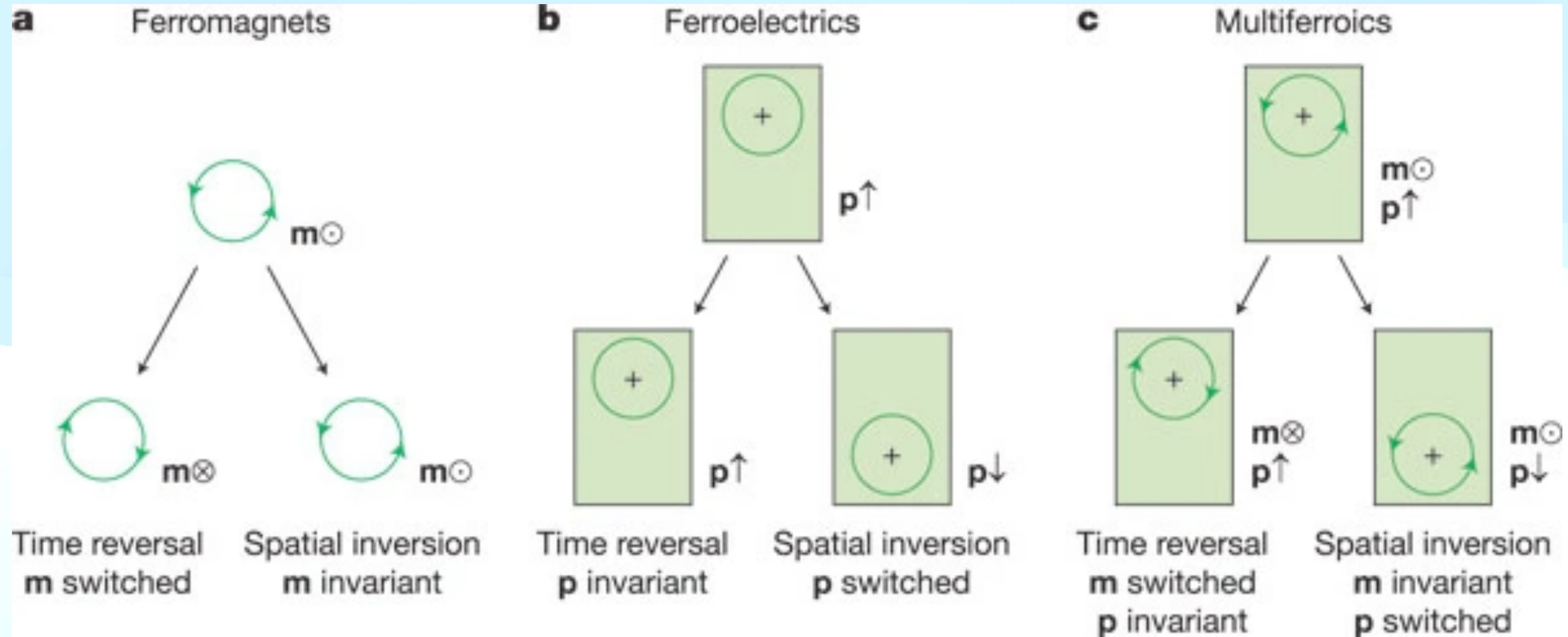
- **Ferroelectric**: possess a spontaneous **polarization** that is **stable** and can be switched **hysteretically** by an applied electric field.
 - **Ferromagnetic**: possess a spontaneous **magnetization** that is **stable** and can be switched **hysteretically** by an applied magnetic field.
 - **Ferroelastic**: display a spontaneous **deformation** that is stable and can be switched **hysteretically** by an applied stress.
-
- Fiebig, Manfred, et al. "The evolution of multiferroics." *Nature Reviews Materials* 1.8 (2016): 1-14.
 - Eerenstein, Wilma, N. D. Mathur, and James F. Scott. "Multiferroic and magnetoelectric materials." *nature* 442.7104 (2006): 759-765.
 - Spaldin, Nicola A., and Rammamoorthy Ramesh. "Advances in magnetoelectric multiferroics." *Nature materials* 18.3 (2019): 203-212.

Multiferroics

- **Multiferroics** referred to materials with a **coexistence** of **two or more** primary ferroic orders.
- Multiferroics can be of two types:
Type-I: magnetic and ferroelectric order occur **independently**.
Type-II: magnetic and ferroelectric order emerge **jointly**.



Simple explanation of multiferroics

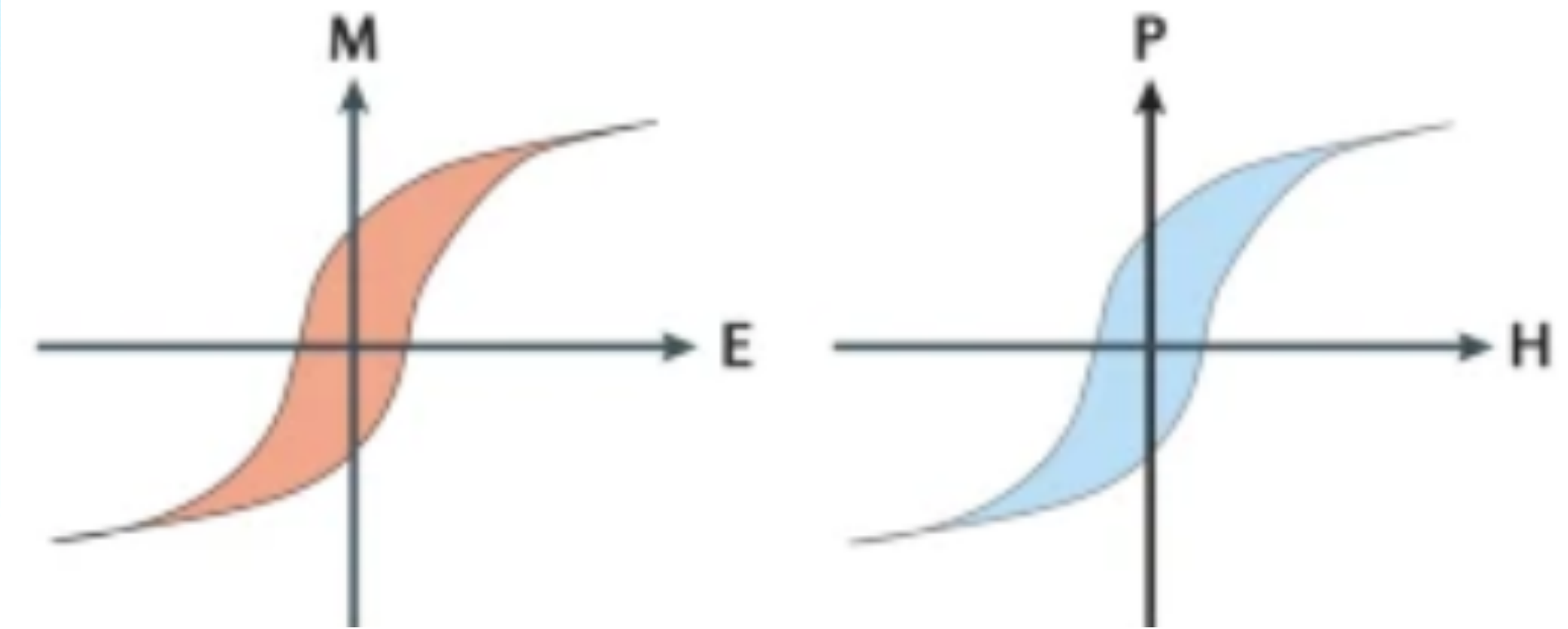


- Eerenstein, Wilma, N. D. Mathur, and James F. Scott. "Multiferroic and magnetoelectric materials." *nature* 442.7104 (2006): 759-765.

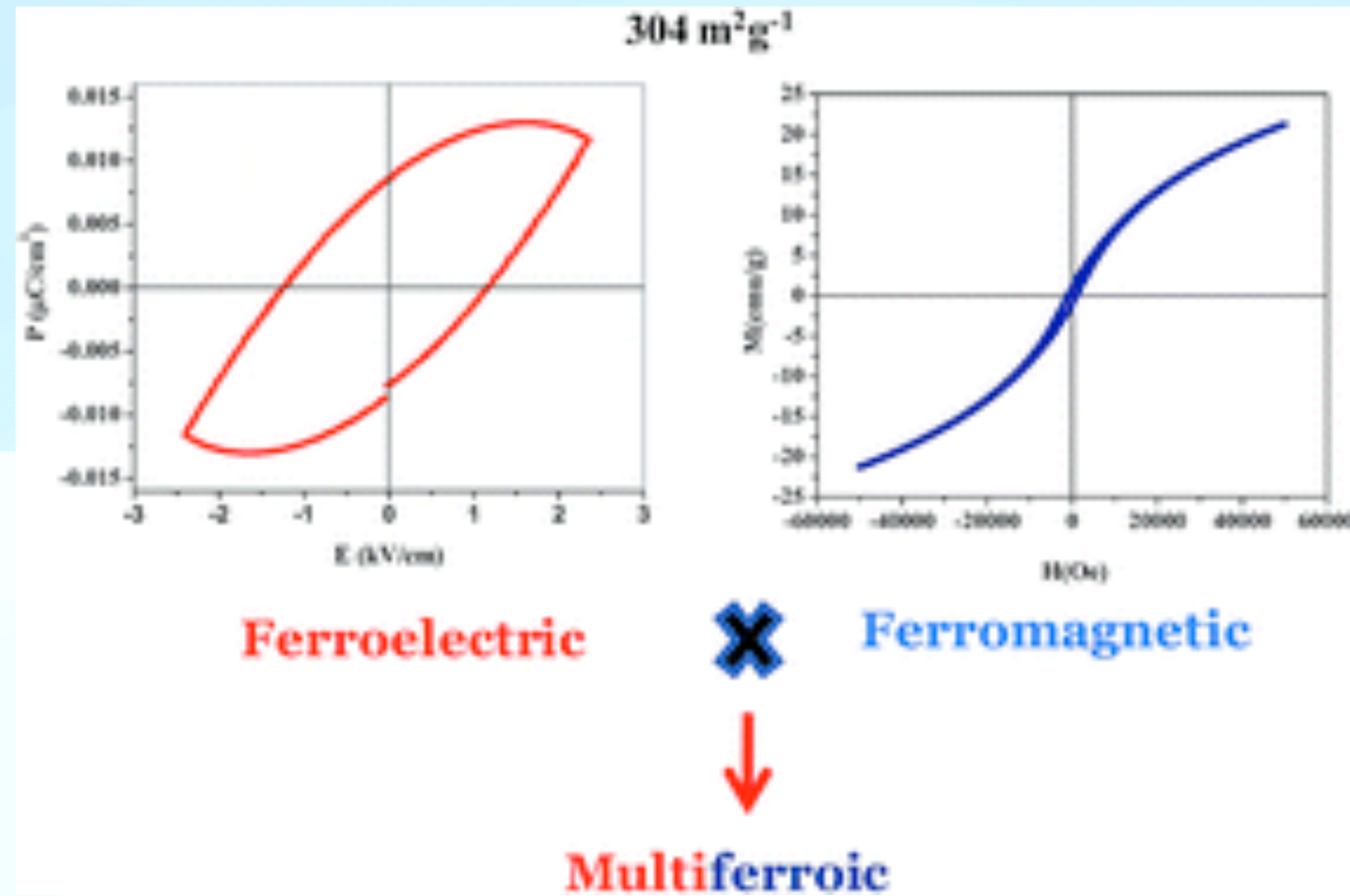
Magnetolectric

- **Magnetolectric**: Materials in which a **magnetic (electric)** field induces a proportional **polarization (magnetization)** were referred to as linear Magnetolectrics.

The ideal magnetolectric multiferroic



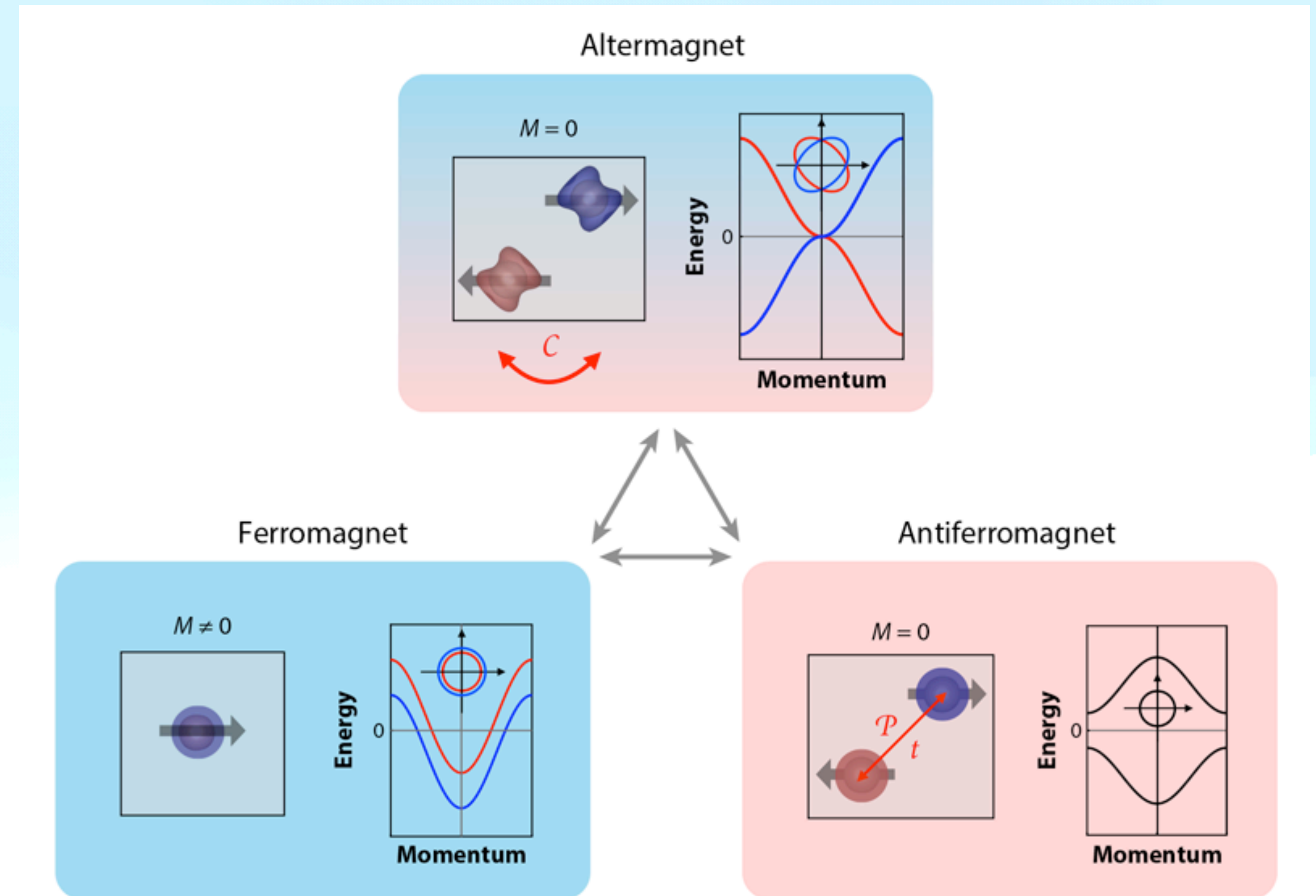
Magnetoelectric effect in multiferroic YMnO₃ nanoparticles



Ahmad, Tokeer, Irfan H. Lone, and Mohd Ubaidullah. "Structural characterization and multiferroic properties of hexagonal nano-sized YMnO₃ developed by a low temperature precursor route." *RSC Advances* 5.71 (2015): 58065-58071.

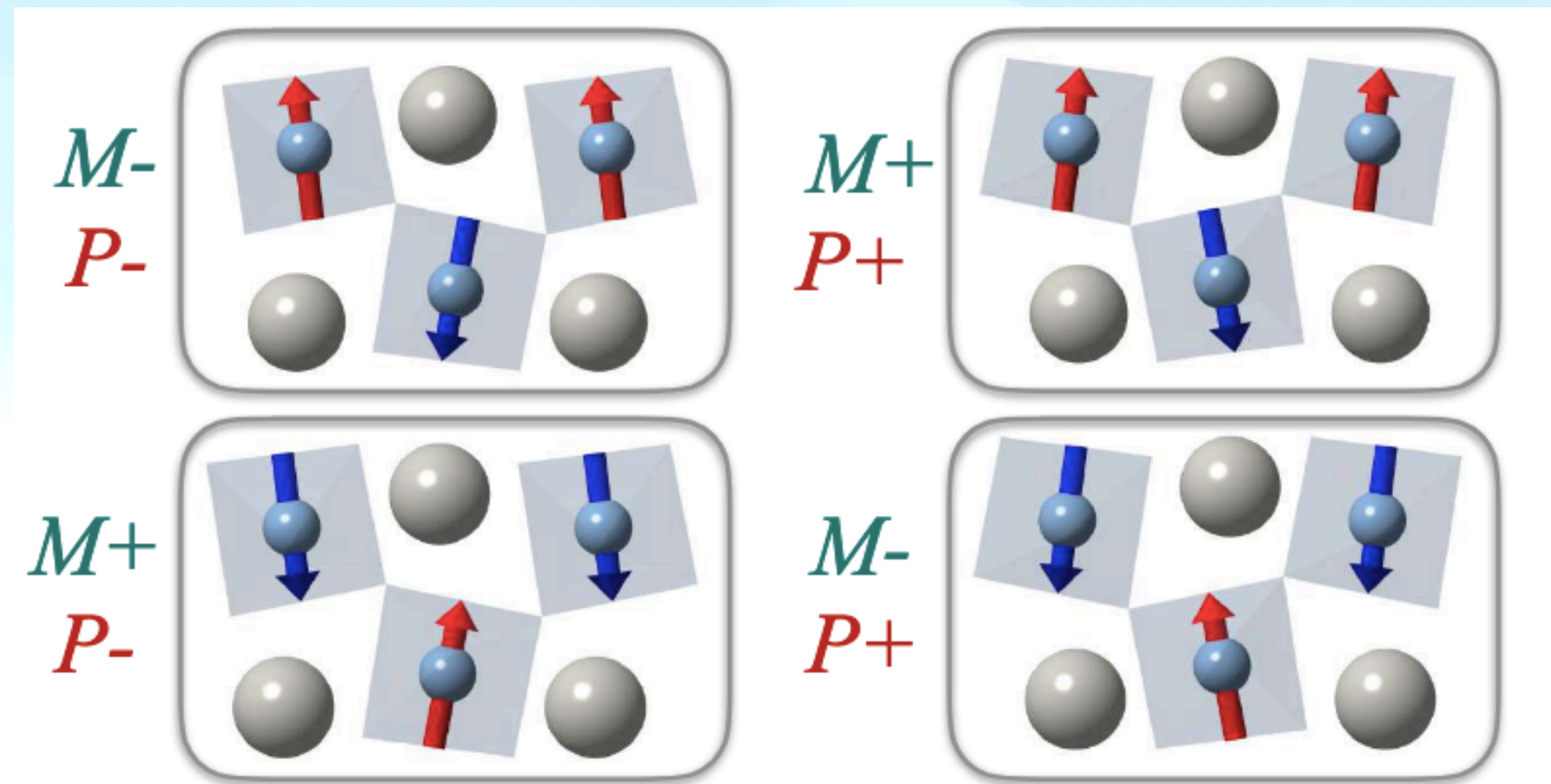
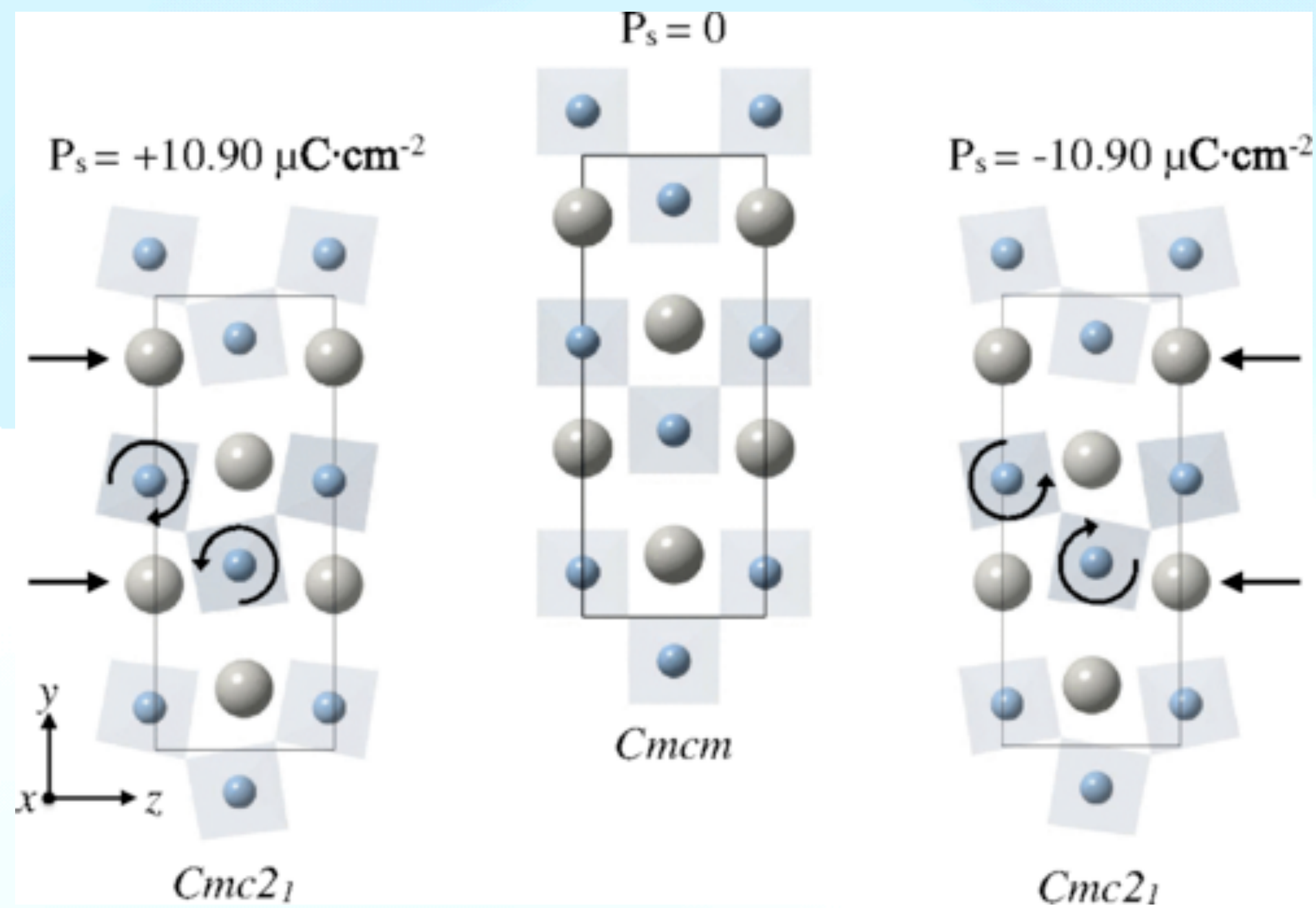
Altermagnetism

- Ferromagnet: Time reversal symmetry is **broken**. Have two spin split bands. Kramers degeneracy is lifted.
- Antiferromagnet: Time reversal is preserved. Don't have spin split bands. The two spin sub-lattices are connected by translational or inversion symmetry.
- Altermagnets: Net magnetization is zero as in antiferromagnets but two sublattices are joined by rotation symmetry.



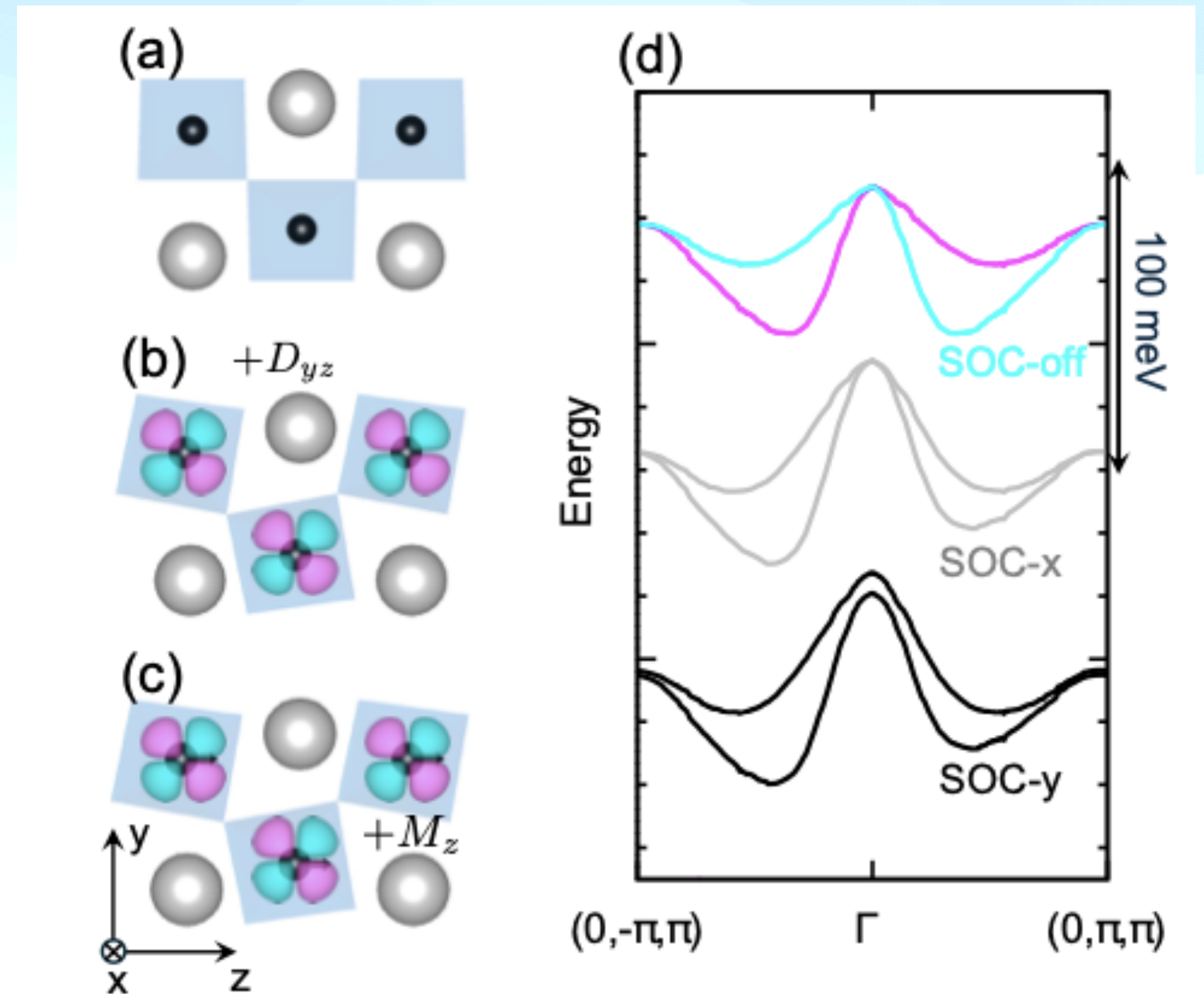
- Šmejkal L., Sinova J., Jungwirth T. Emerging research landscape of altermagnetism //Physical Review X. – 2022. – T. 12. – N^o. 4. – C. 040501.
- Cheong S. W., Huang F. T. Altermagnetism with non-collinear spins //npj Quantum Materials. – 2024. – T. 9. – N^o. 1. – C. 13.

The crystal structure of BaCuF4



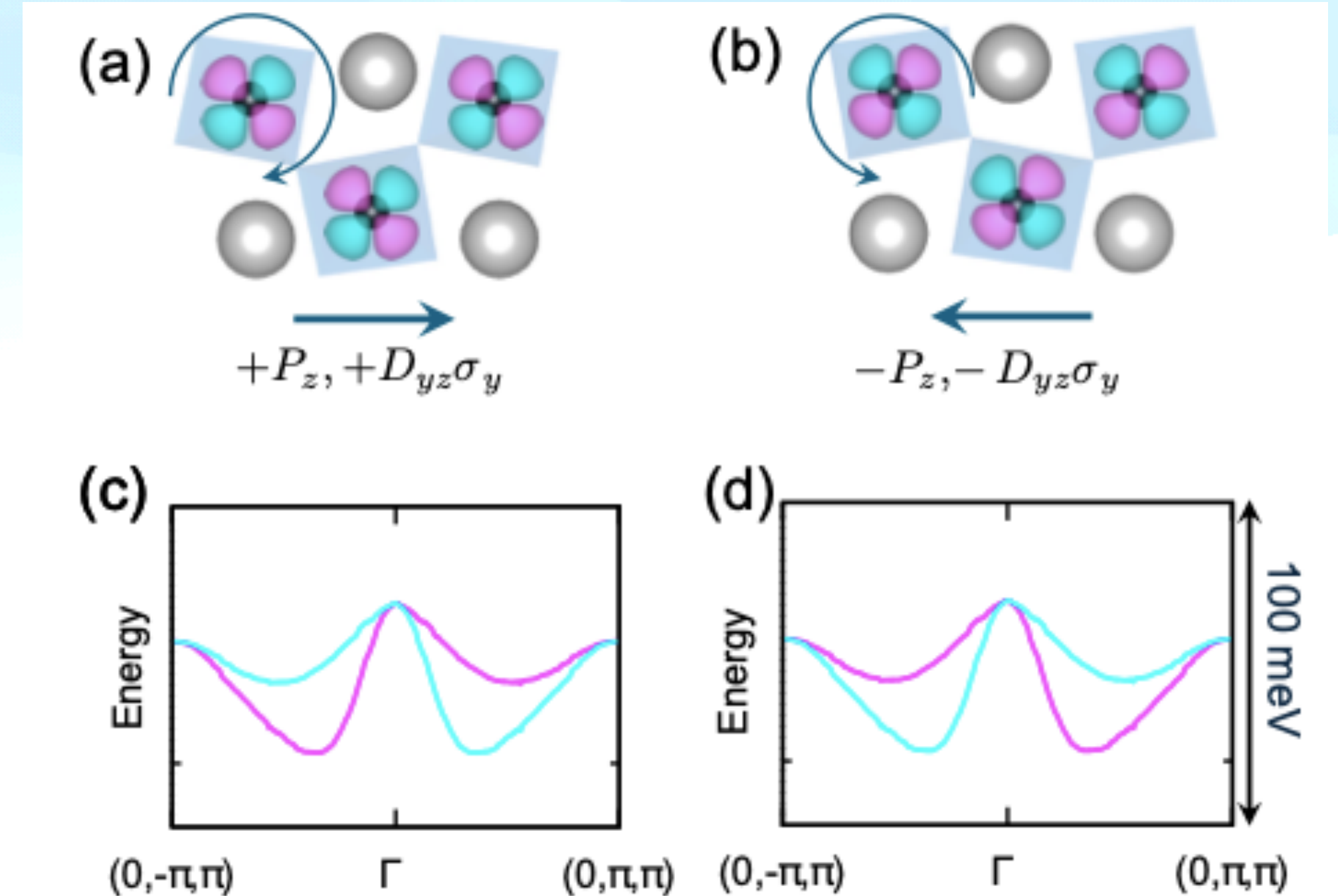
Ferroic altermagnetic order on BaCuF4

FIG. 1. **Ferroic altermagnetic order on polar crystal structure.** (a) Section of nonmagnetic high symmetric centrosymmetric crystal BaCuF₄ (Cu atoms marked in black, Ba grey, and F atoms occupy the corners of blue shaded octahedra). (b) Nonrelativistic ferroic altermagnetic $D_{yz}\sigma_y$ -wave order generated by a geometric rotation of light-blue octahedra and antiferroic magnetic ordering on the Cu sublattices (see Fig. 3 for details). (c) Altermagnetism with additional relativistic spin-orbit coupling induced magnetization M_z . (d) Electronic band structure calculated without spin-orbit coupling, with spin-orbit coupling and moments along (001)-axis, and with spin-orbit coupling along (010)-axis.



Altermagnetolectric effect

FIG. 2. **Altermagnetolectric effect.** (a) Clockwise rotation of the blue-shaded octahedra generates a positive ferroelectric polarization and ferroic altermagnetic order on the Cu sublattices. (b) Density functional theory (DFT) calculated nonrelativistic altermagnetic spin splitting for the state described in (a). (c) Counterclockwise rotation of the blue-shaded octahedra reverses both the ferroelectric polarization and the ferroic altermagnetic order. (d) The reversal of the altermagnetic order is confirmed by the sign change of the corresponding spin splitting in the electronic structure calculated for the state in (c).



Thank you