Landau theories for collinear altermagnets

Hana Schiff

Friday, October 10th, 2025

Quantum Spin Liquids: Experimental Enigmas & Theoretical Challenges

Not a spin liquid...

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Quantum Spin Liquids: Experimental Enigmas & Theoretical Challenges

Overview

- What are (collinear) altermagnets
- AM Structures
- AM Landau theories at zero SOC
- AM Landau theories at finite SOC: measurable properties *due* to AM

Collaborators

My advisor!

Judit Romhányi
UC Irvine

Paul McClarty
Université Paris-Saclay

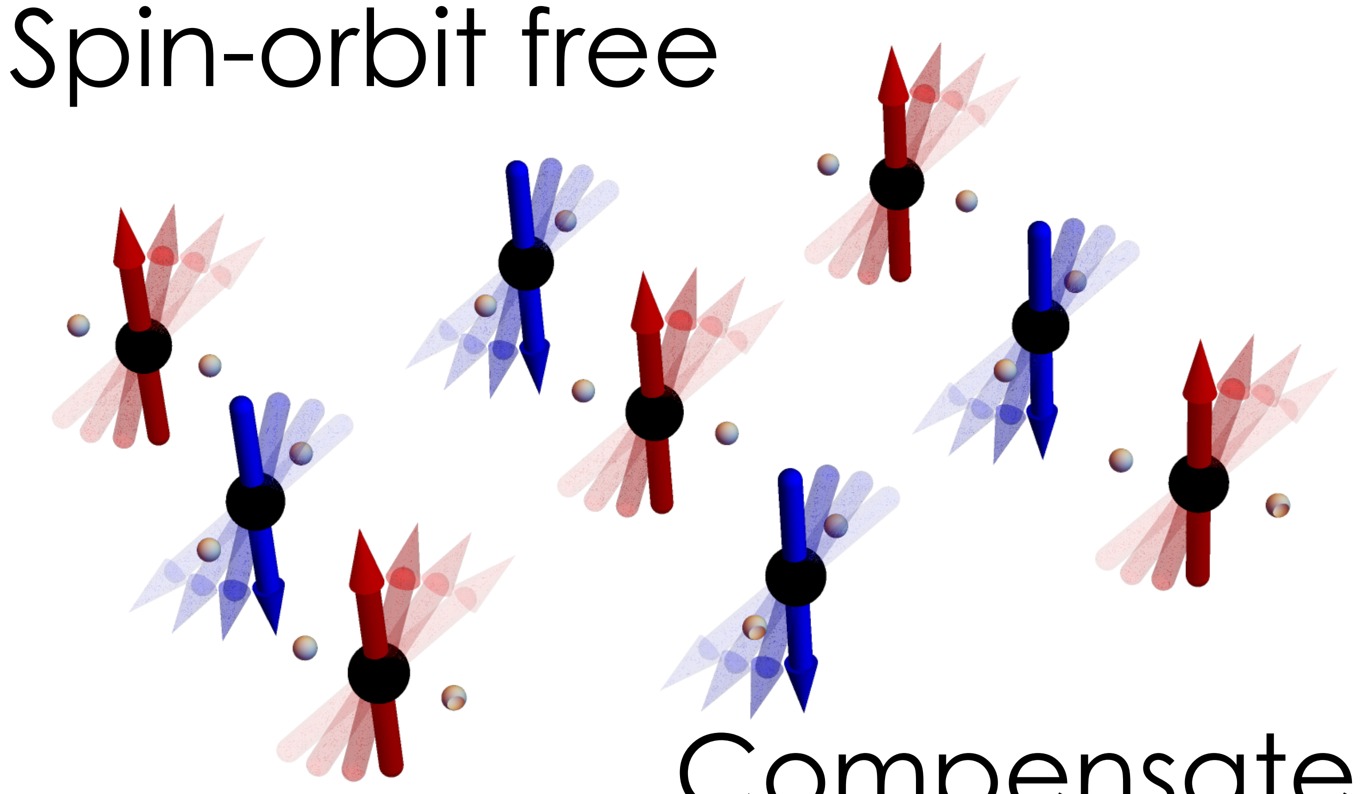
Jeff Rau
University of Windsor

What are altermagnets?

collinear

Ideal Altermagnets

Spin-orbit free



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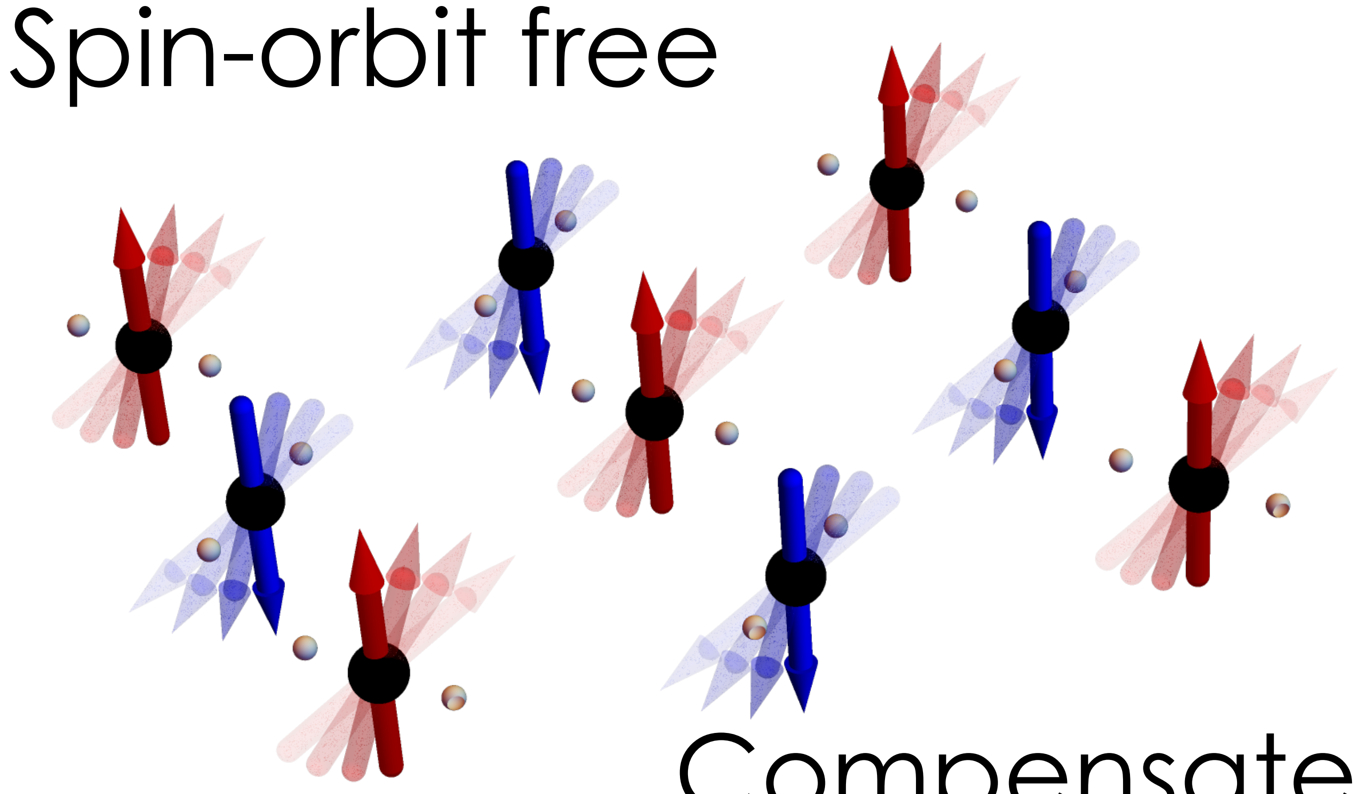

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Litvin, Opechowski, Physica Volume 76, Issue 3 (1974)

Decoupled spin & orbital space

Spins and lattice can transform independently

Spin groups

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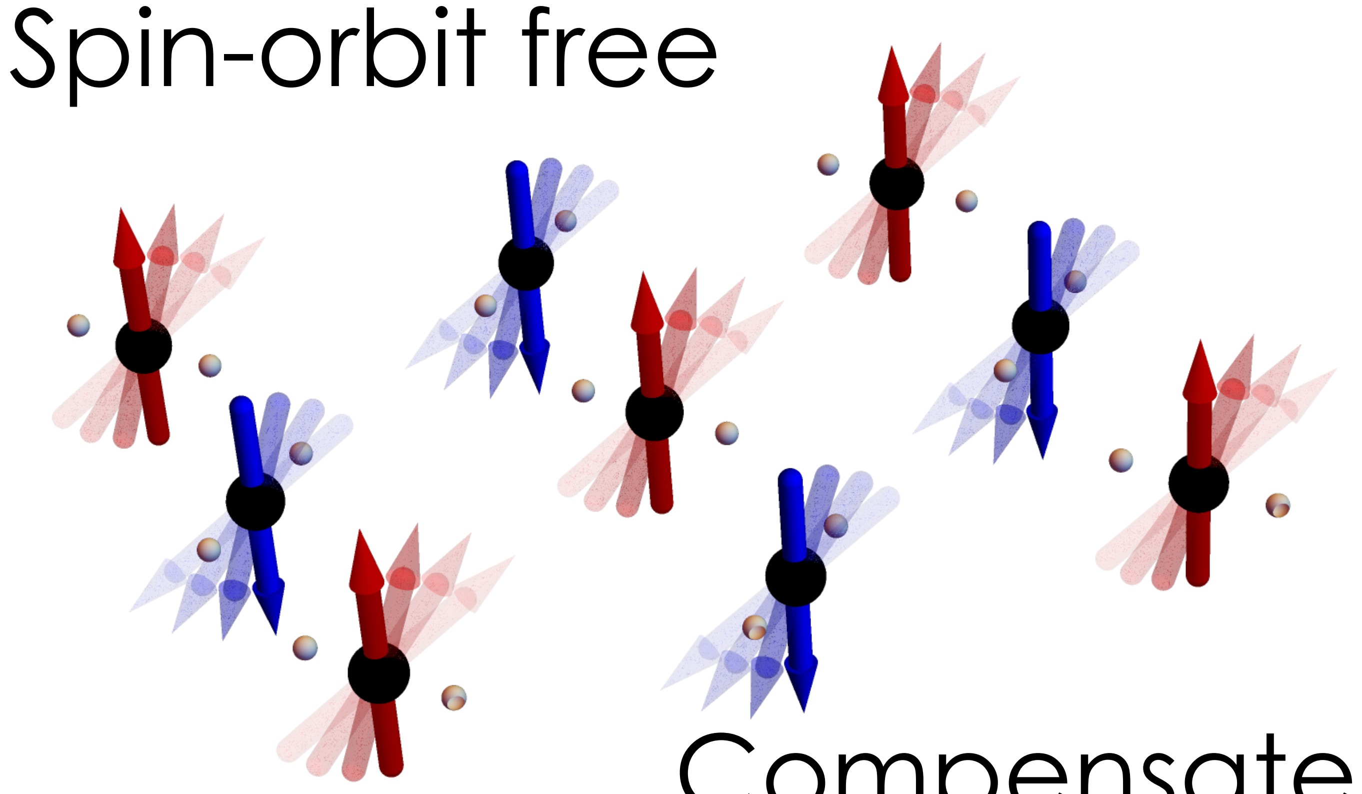

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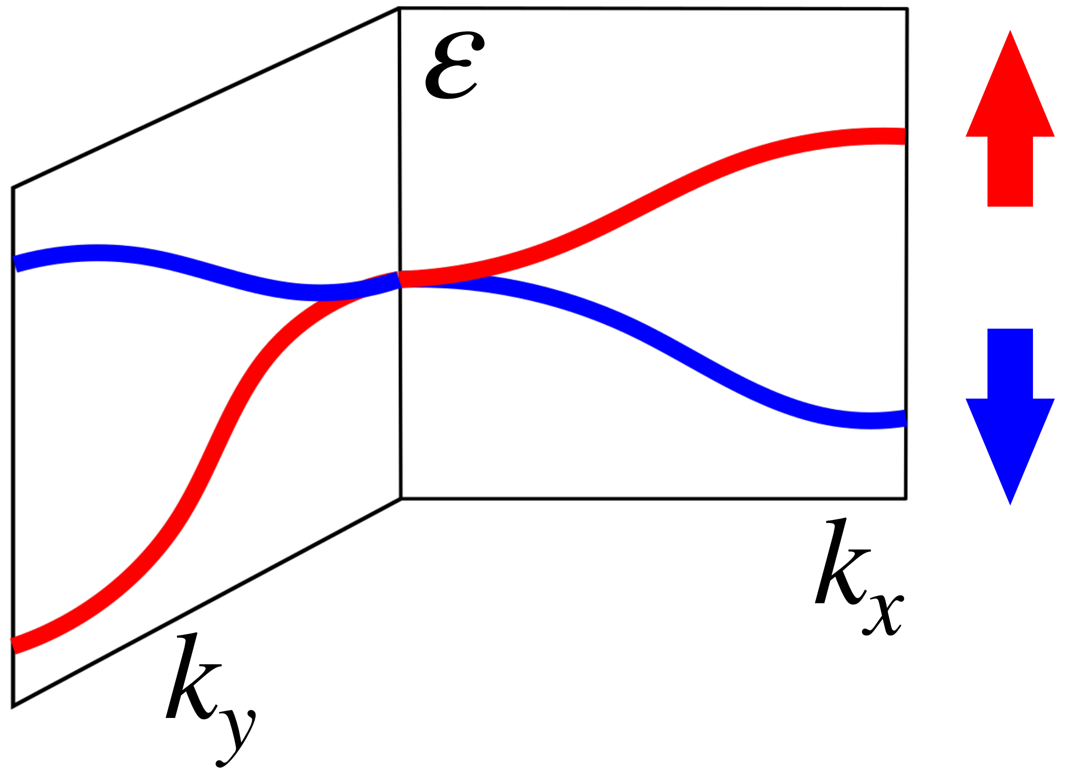

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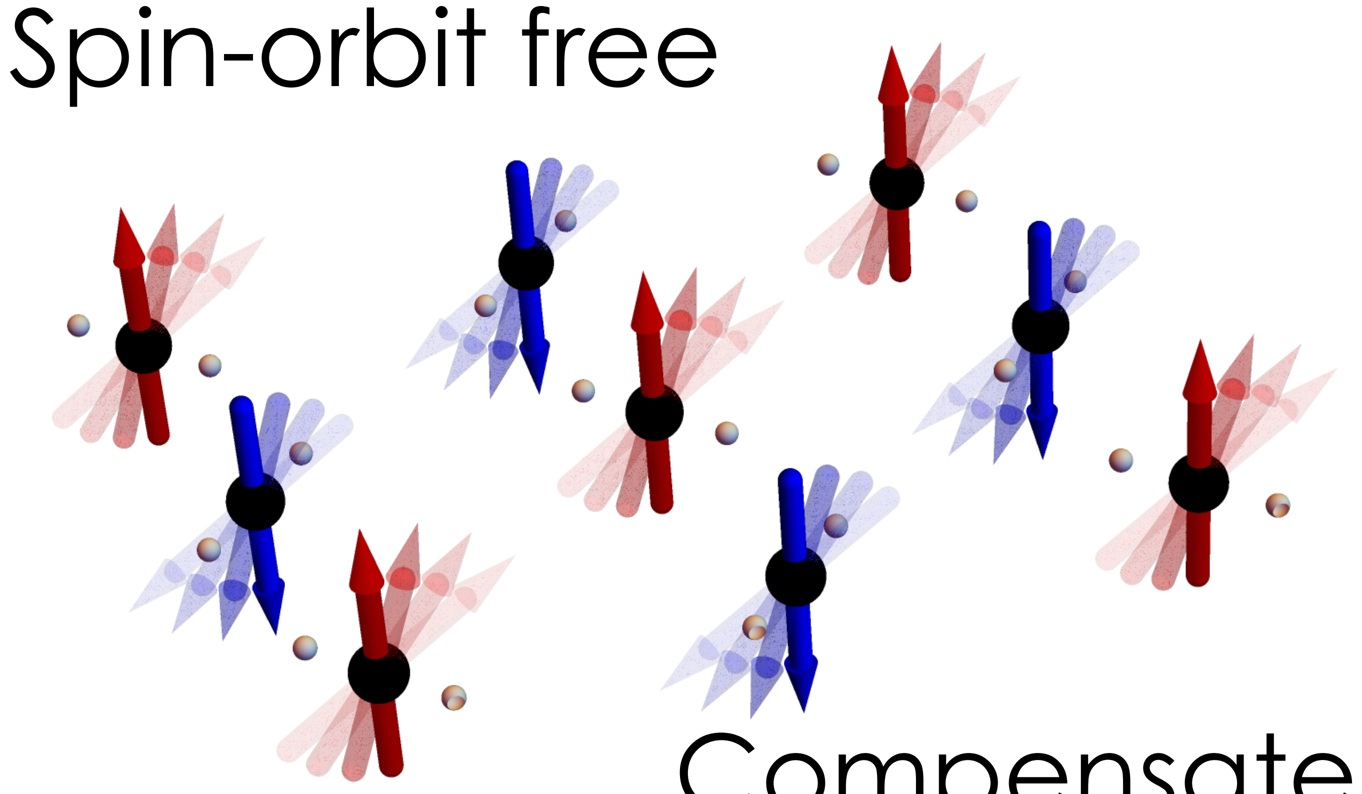

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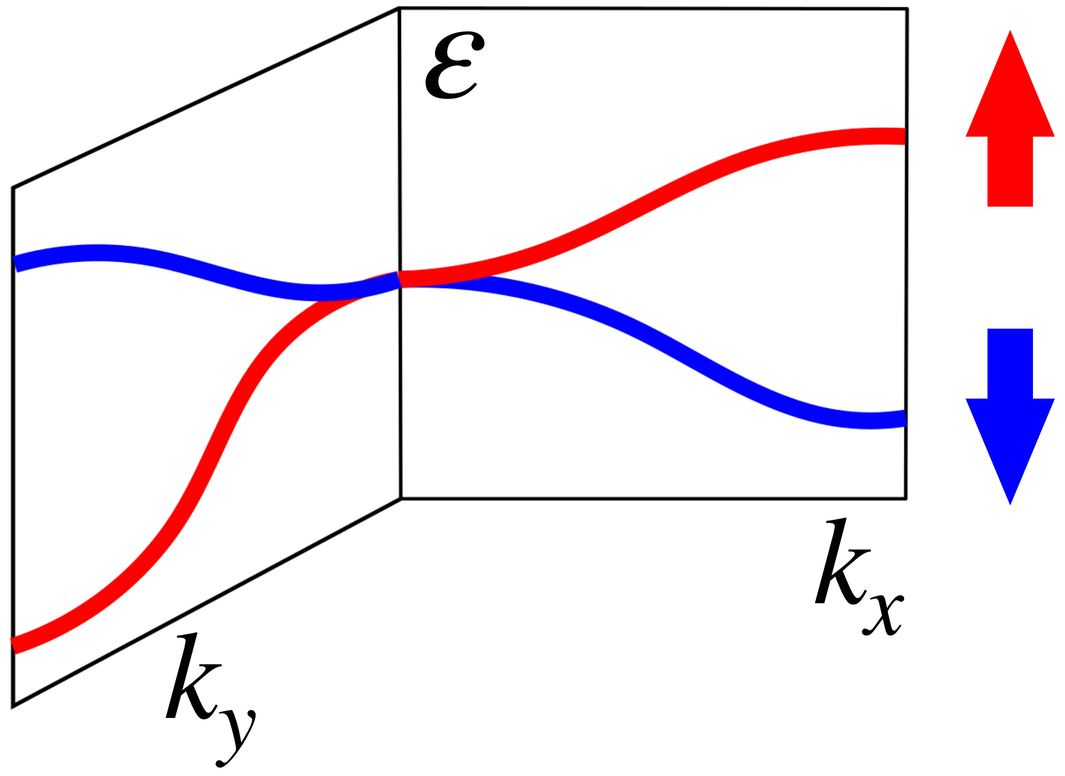

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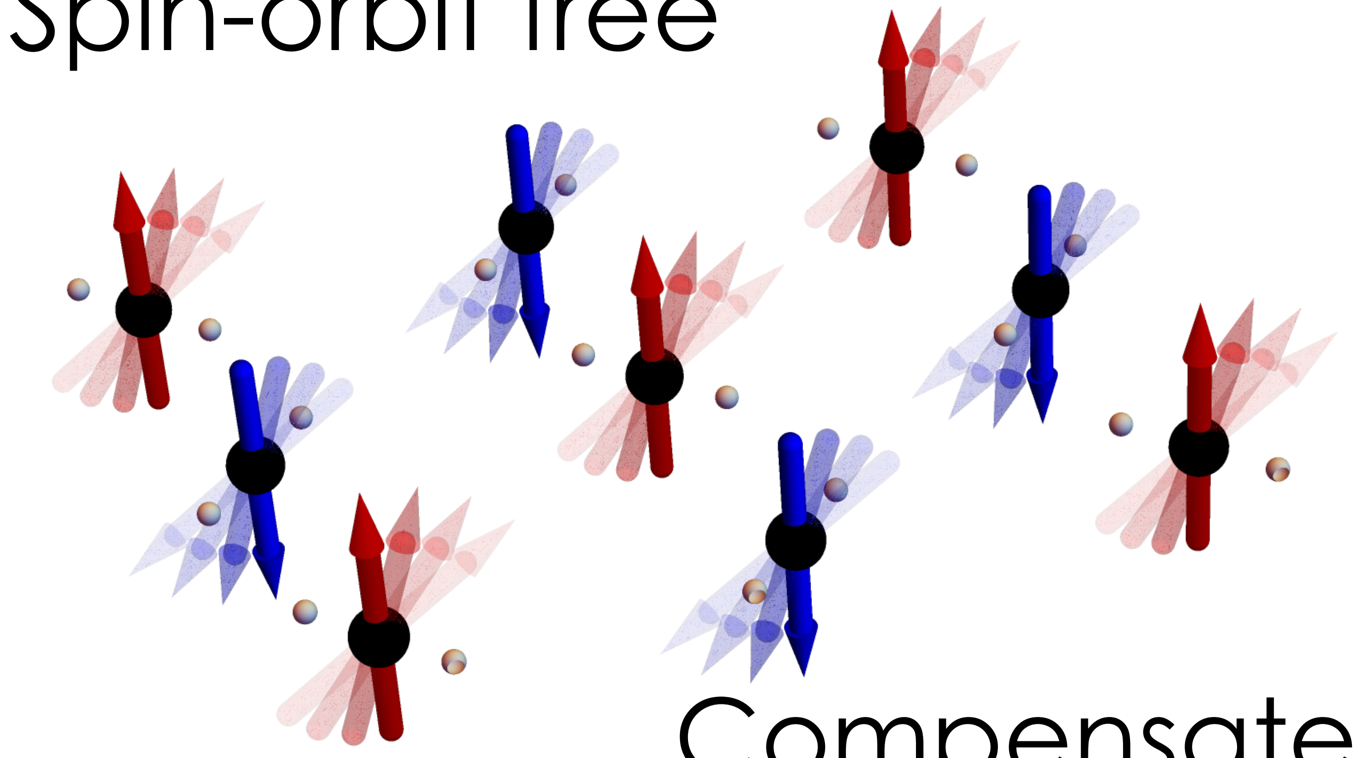

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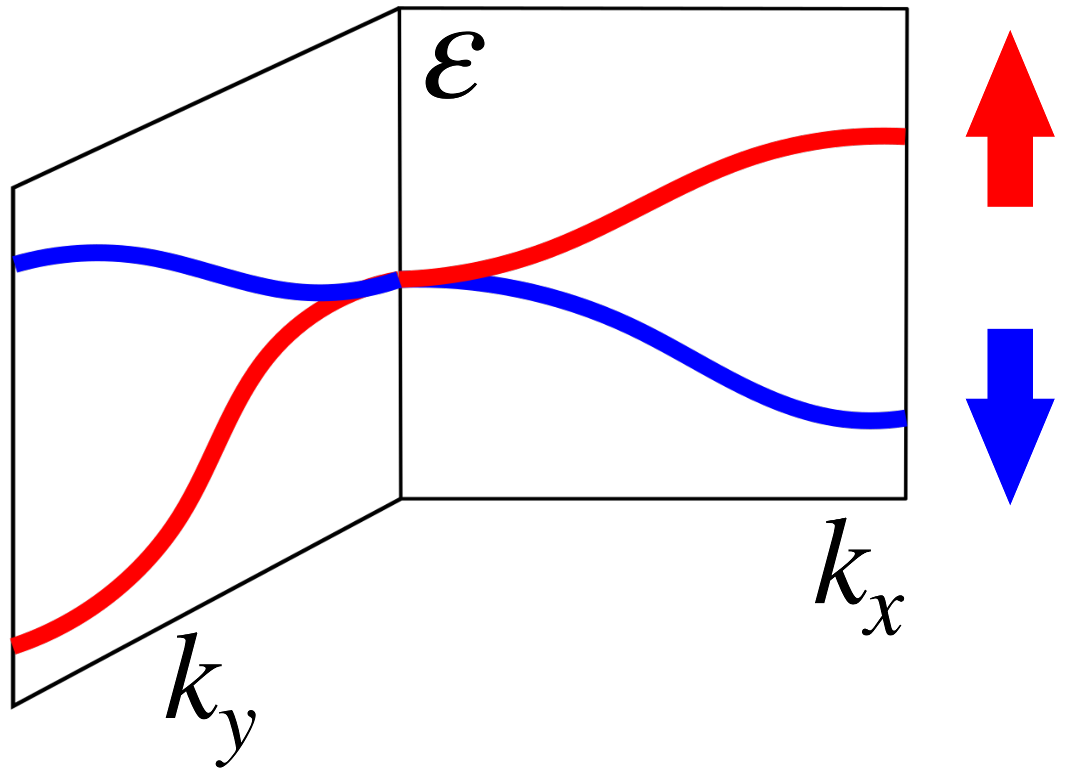

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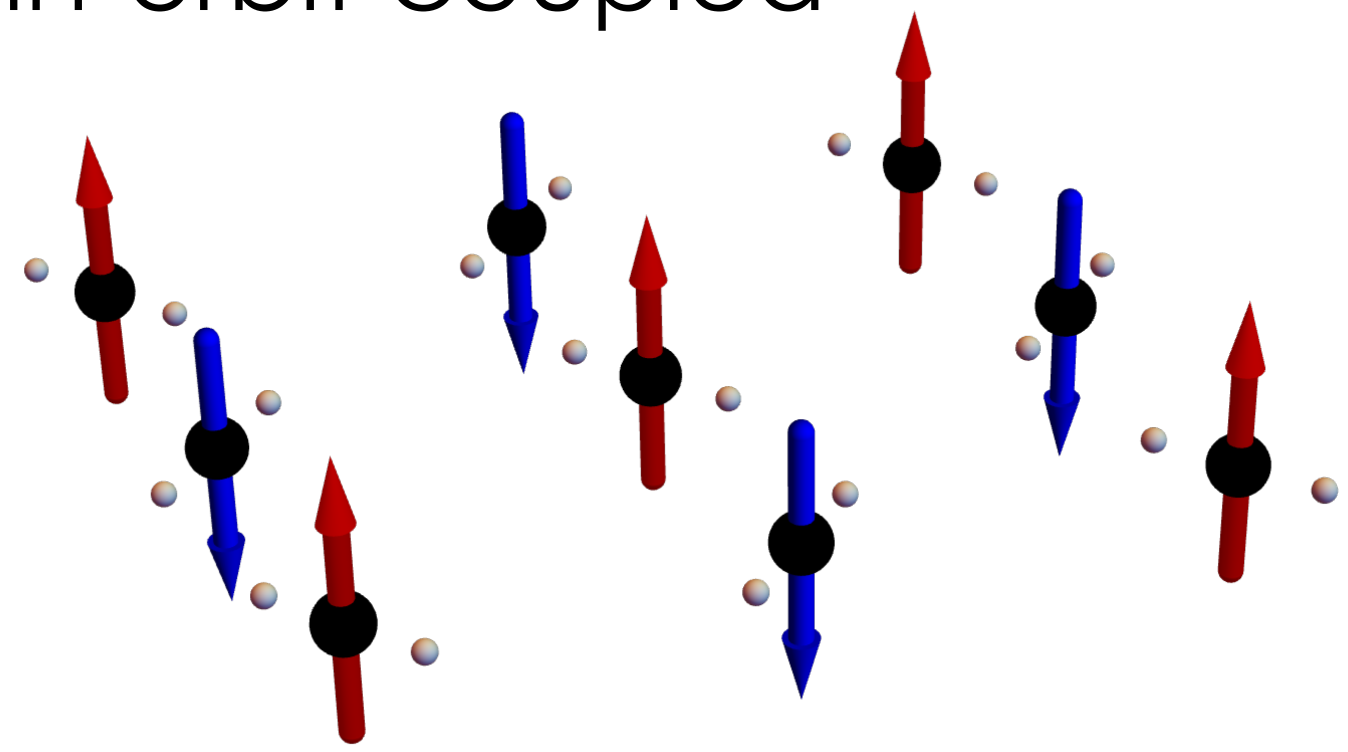
Real Altermagnets

Spin-orbit coupled



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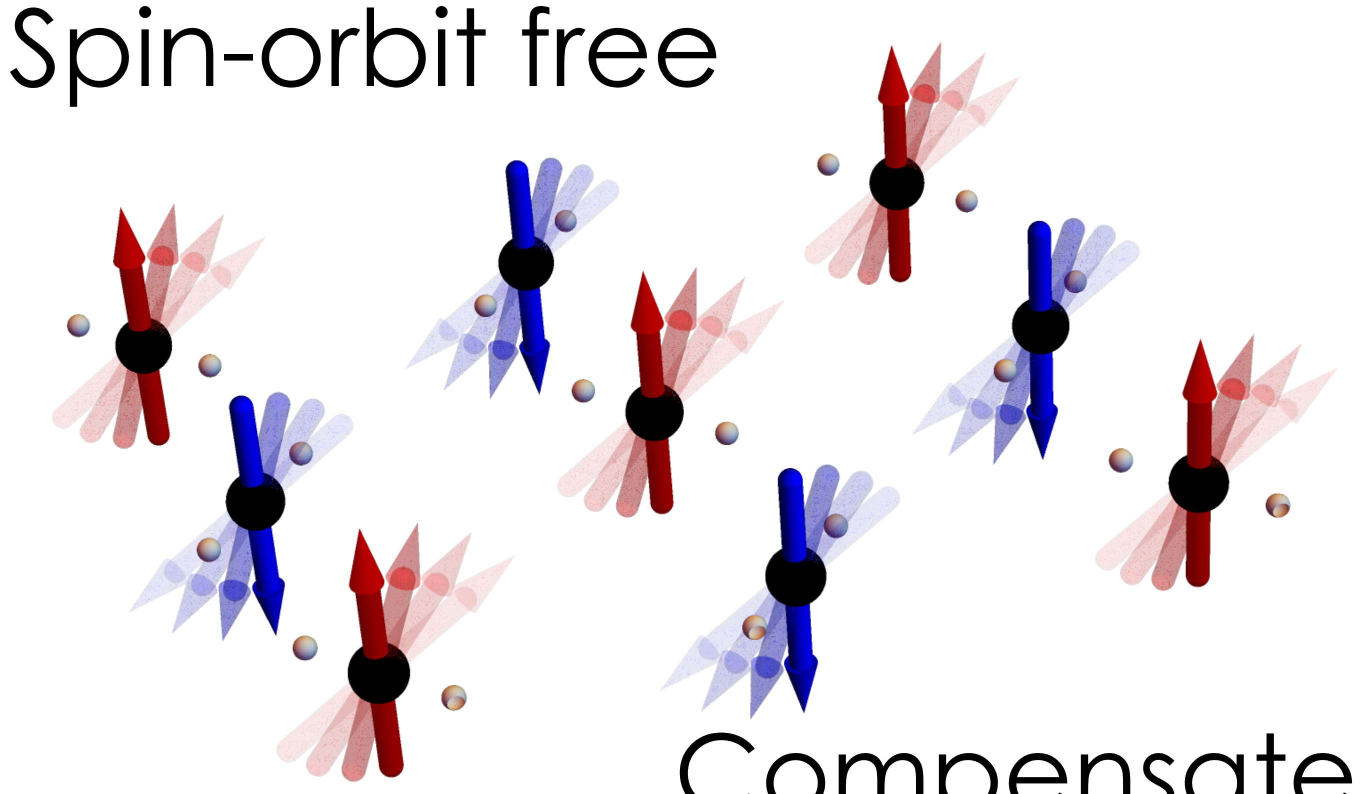

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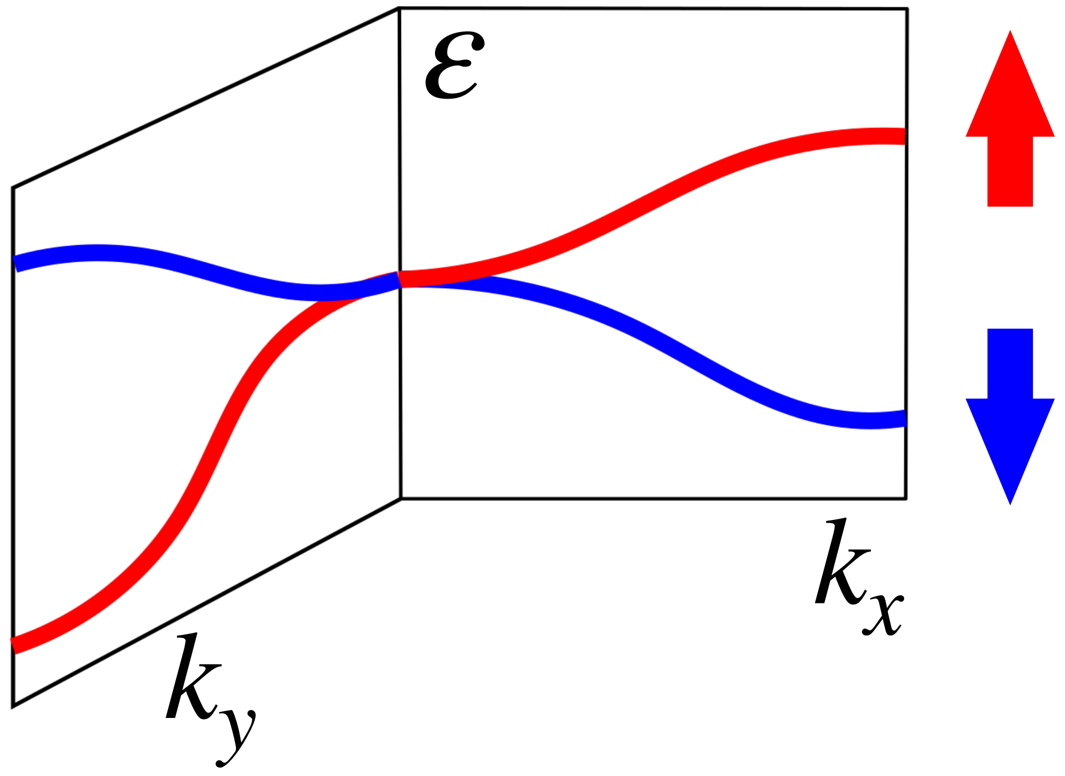

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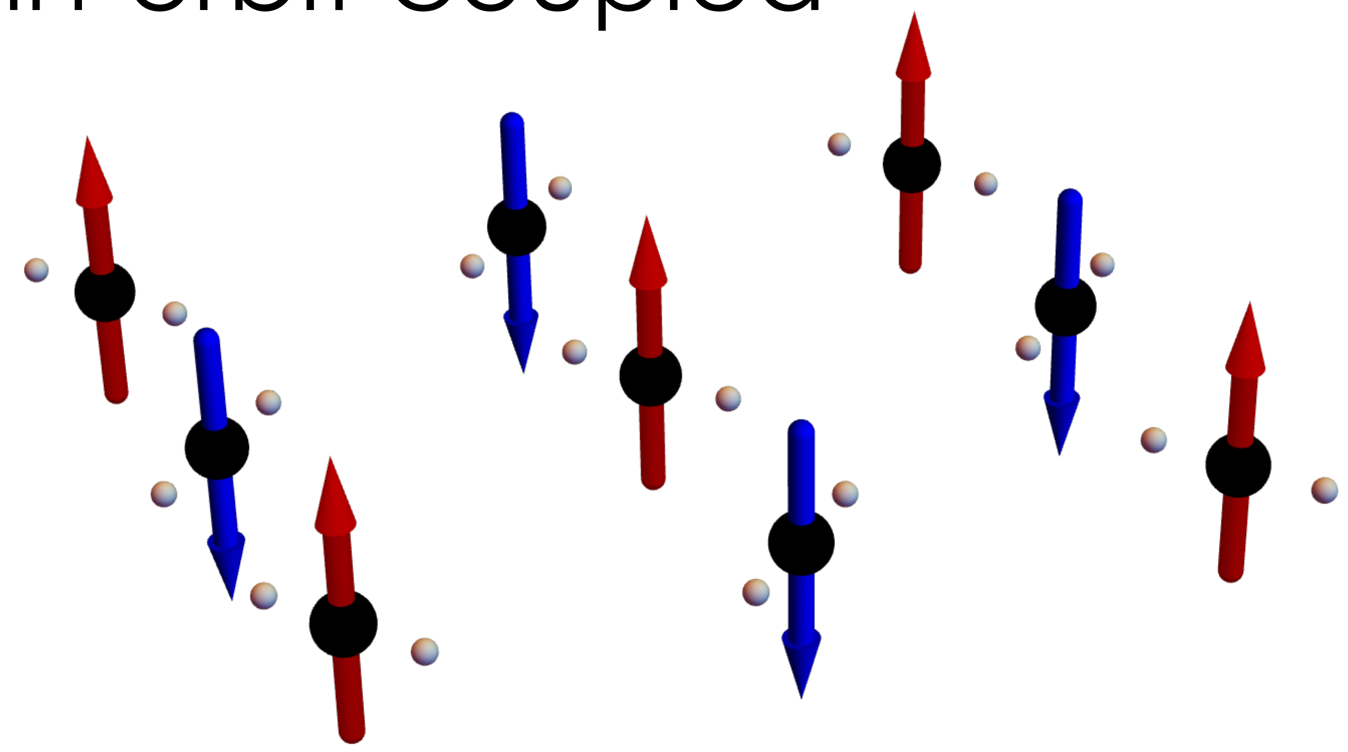

Locked spin & orbital space

Spins transform with lattice

Magnetic groups

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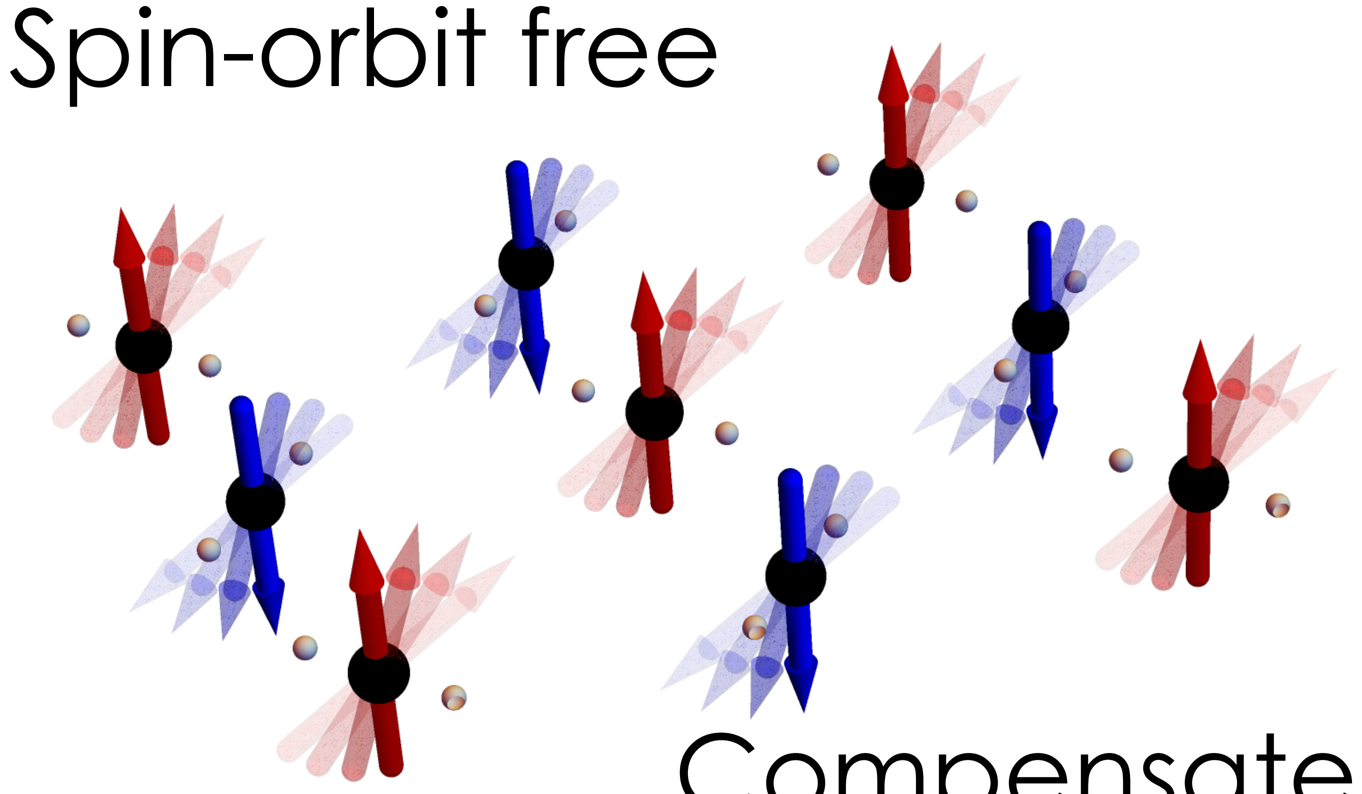

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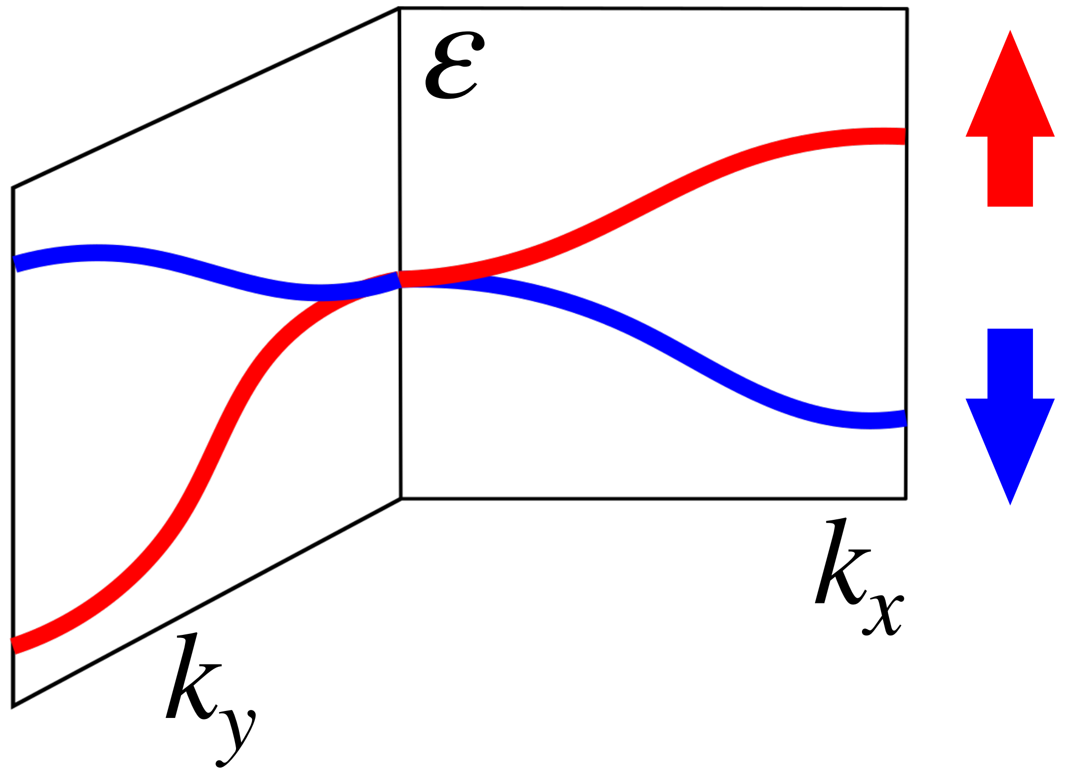

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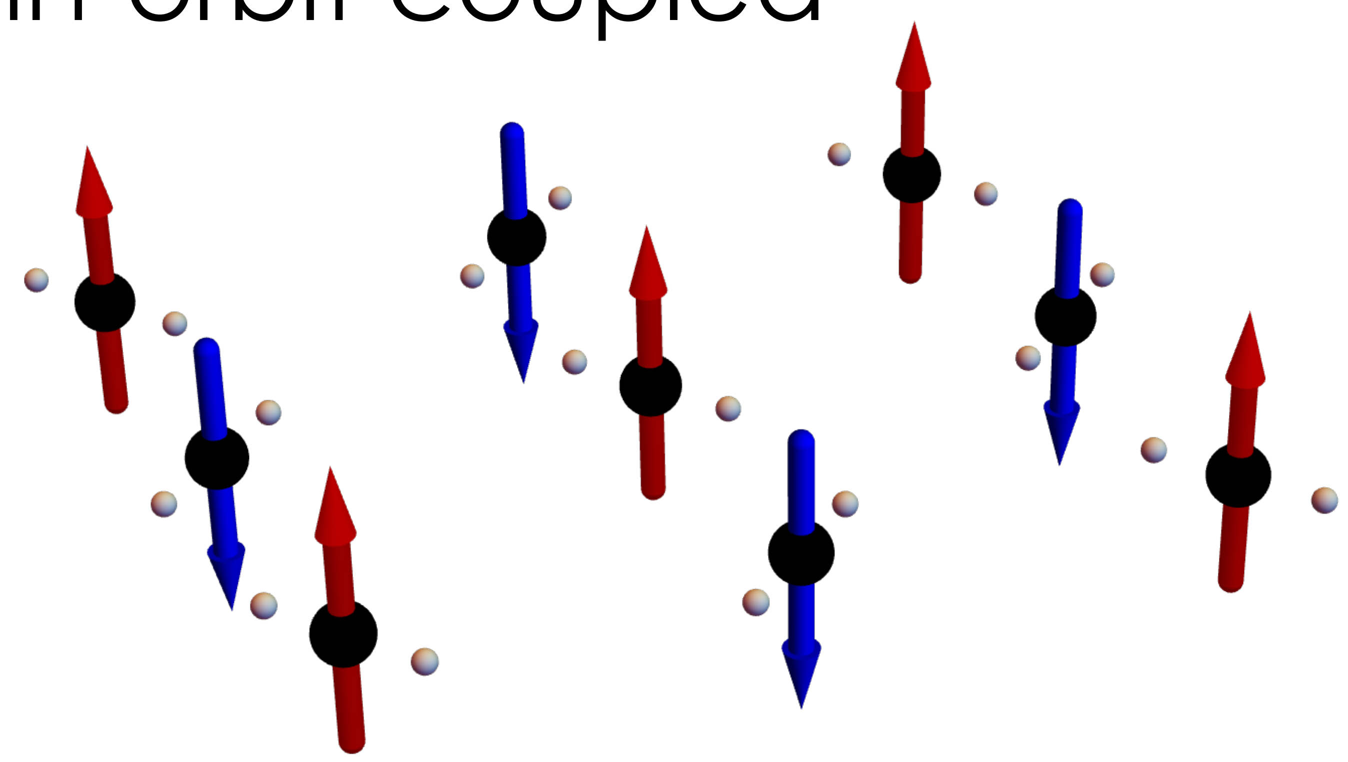

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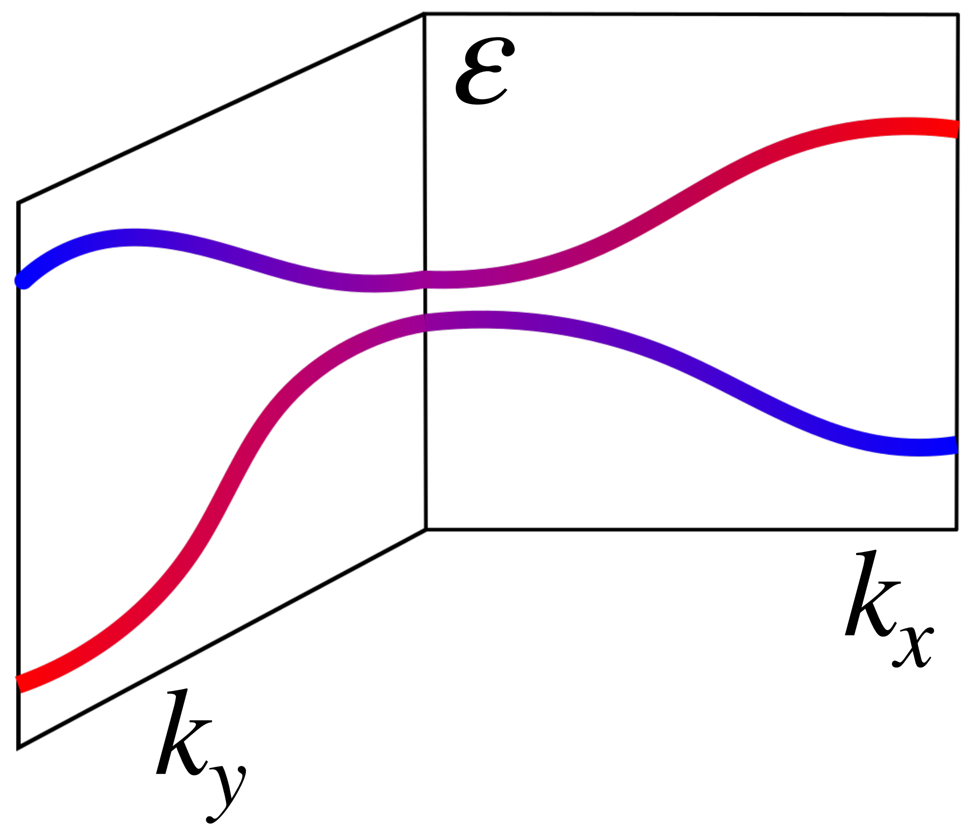

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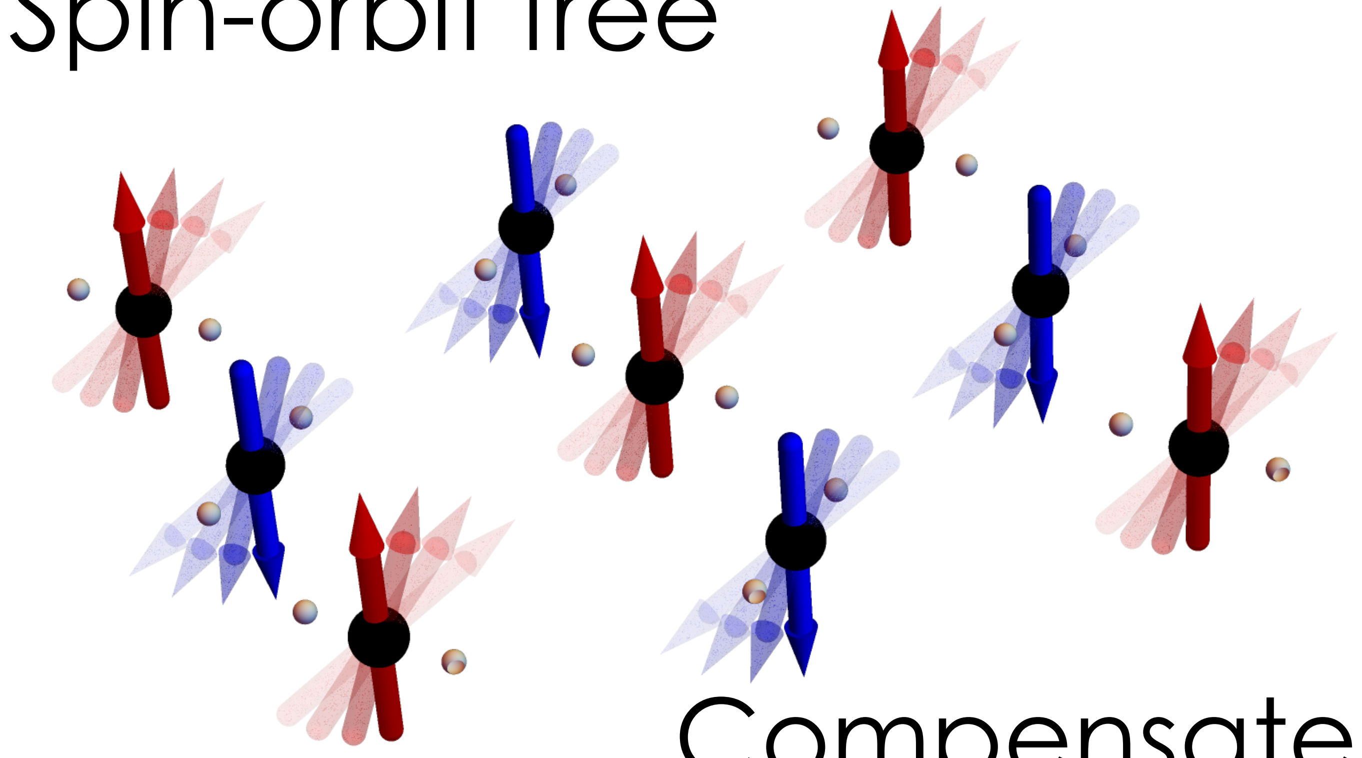

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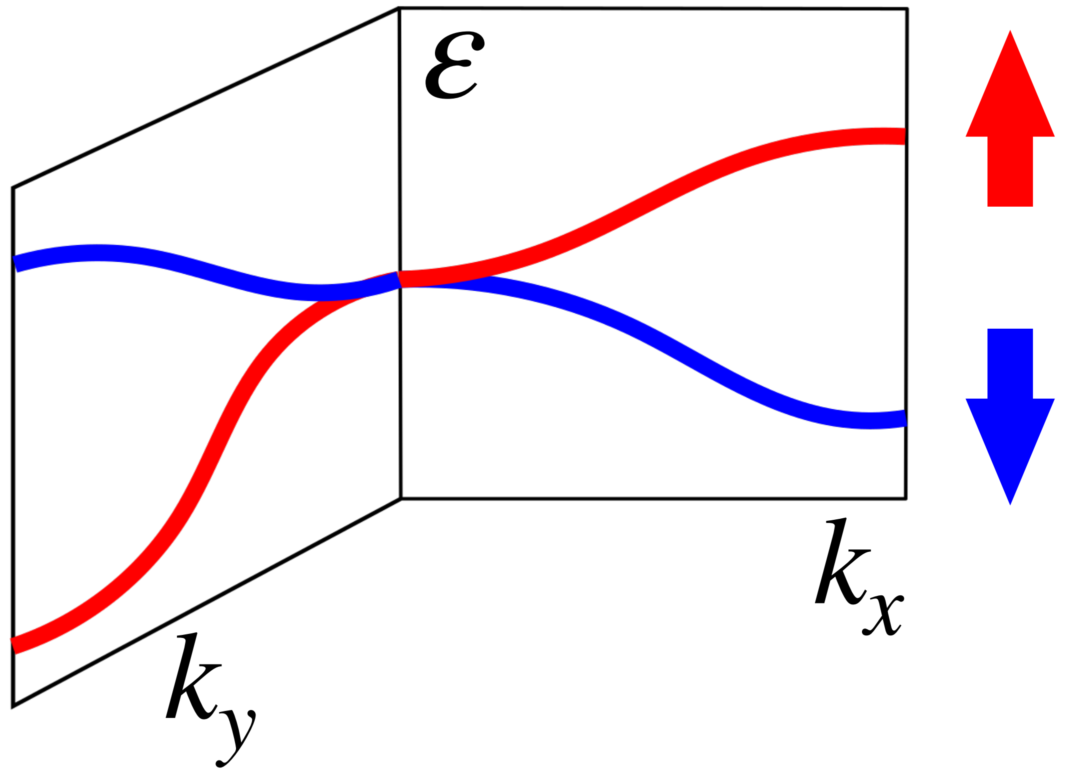

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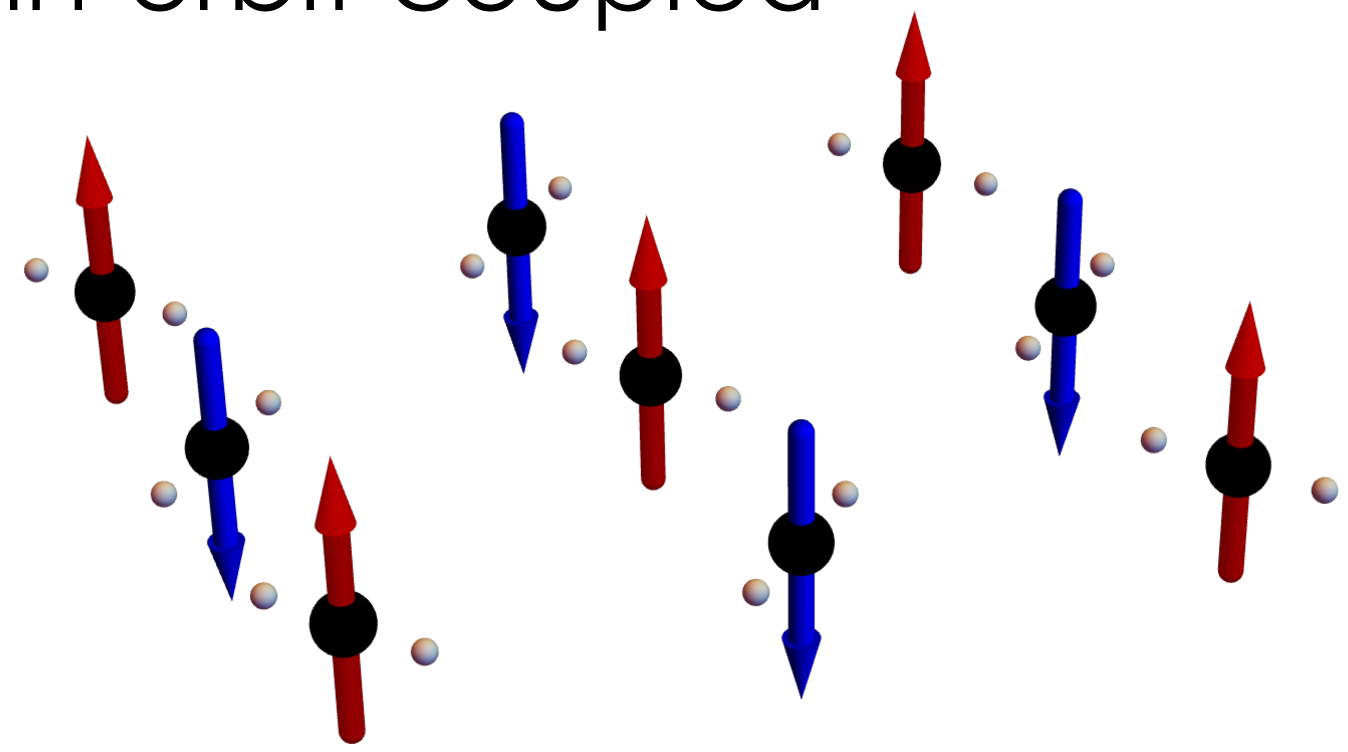

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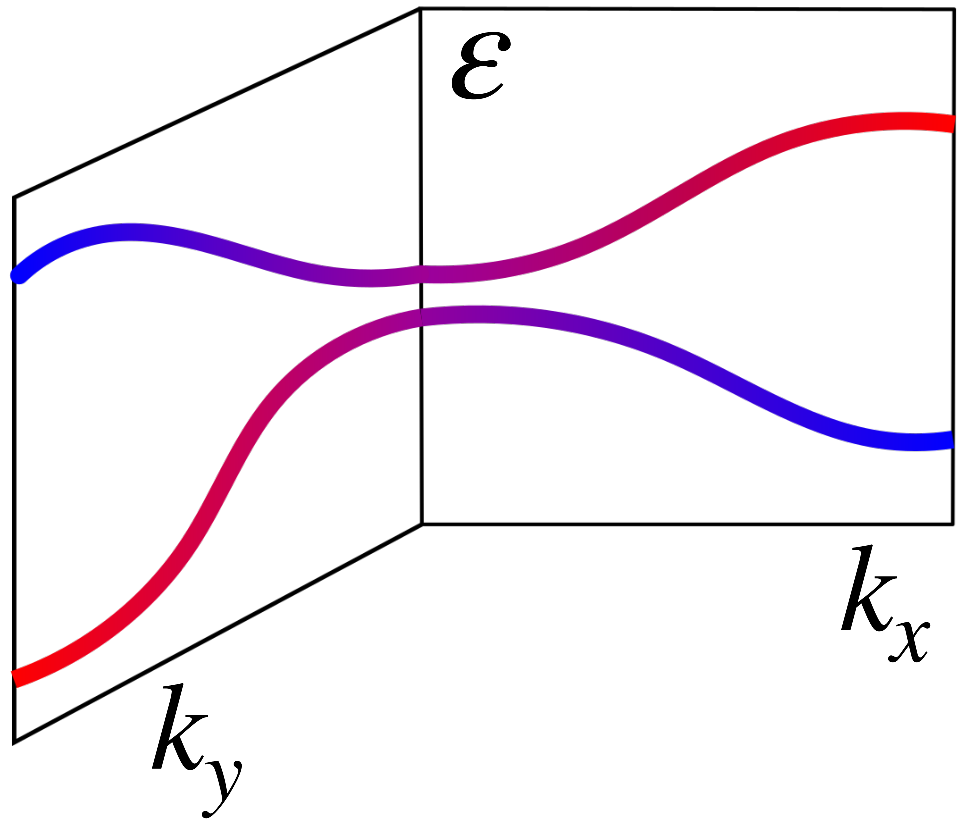

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SOC < Splitting

Dominant features from SO-free limit

Presence of SOC changes symmetry

Šmejkal, Sinova, Jungwirth, Phys. Rev. X 12, 031042 (2022)

collinear
What are altermagnets?

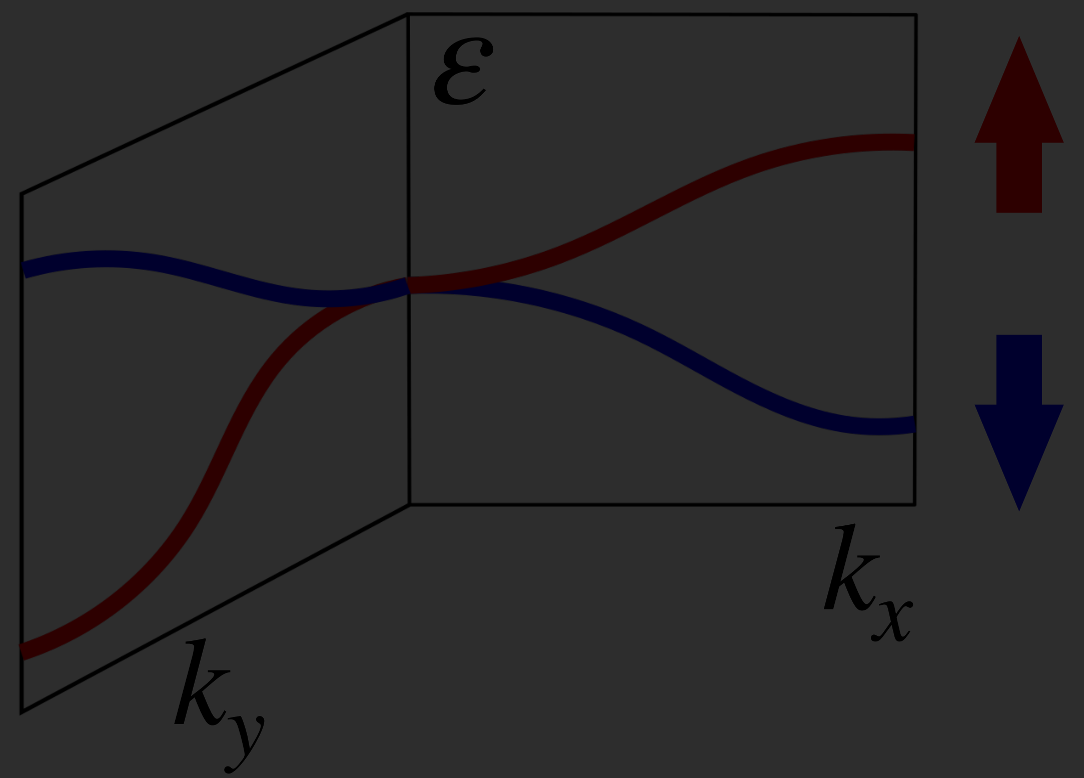
Which **crystal structures** can support altermagnetism?

Can we use Landau theory as a tool to understand **measurable properties** of **realistic** altermagnets based on their **ideal** limits?

Ideal Altermagnets

Compensated

Alternating spin-splitting



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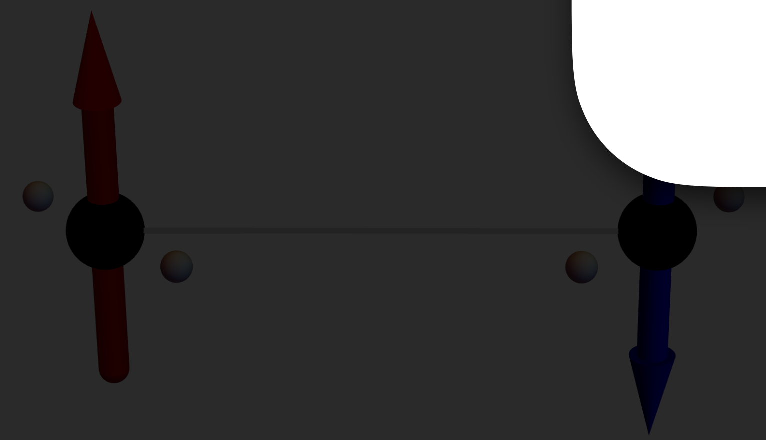
Spin group...

Symmetry cons...



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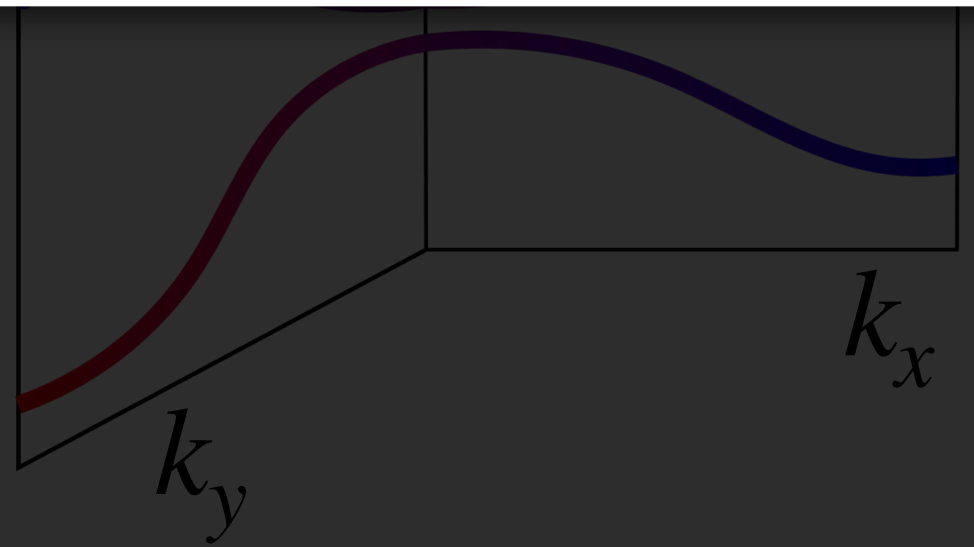
Real Altermagnets

Spin-orbit coupled



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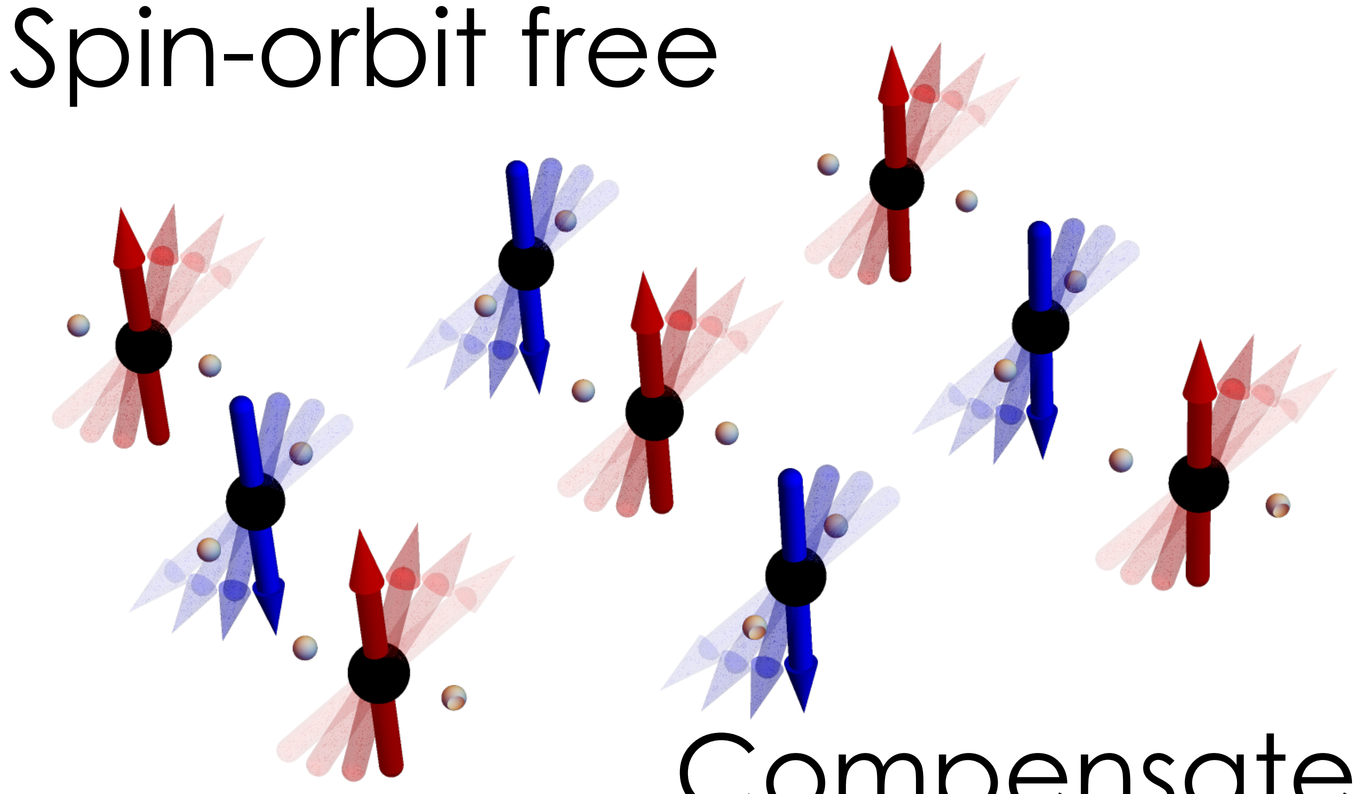
Altermagnetic structures

Preserving the crystal unit cell ($\mathbf{Q} = 0$)

Ideal Altermagnets

Spin-orbit free



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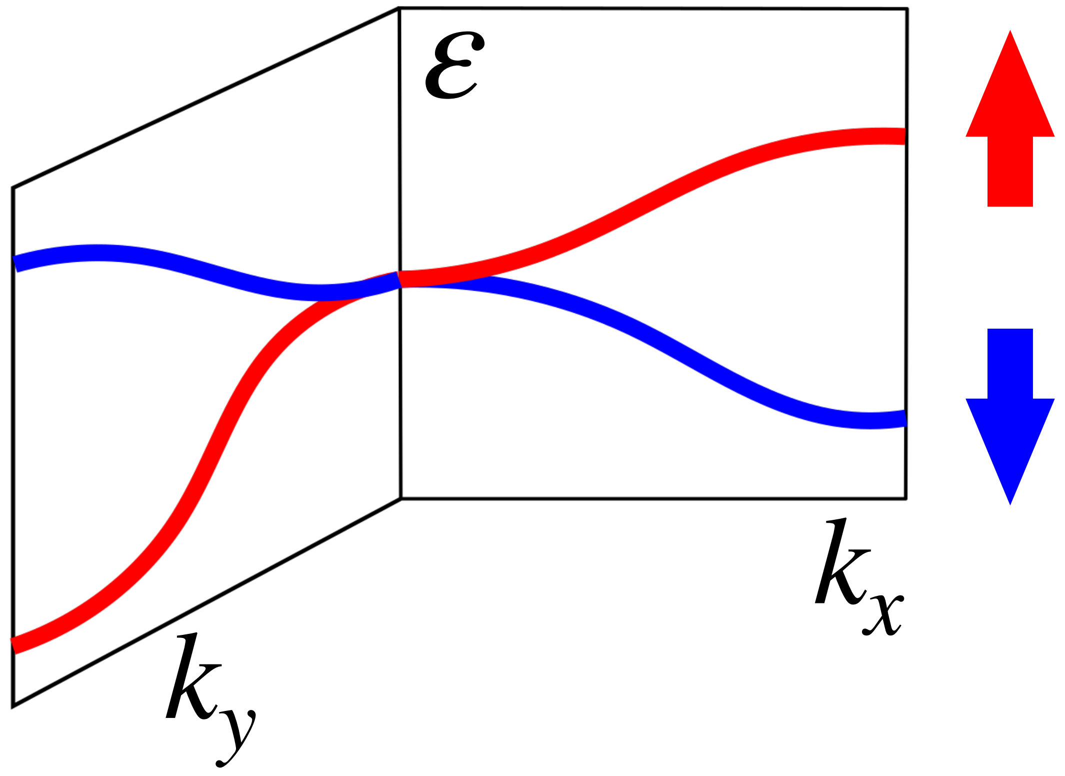

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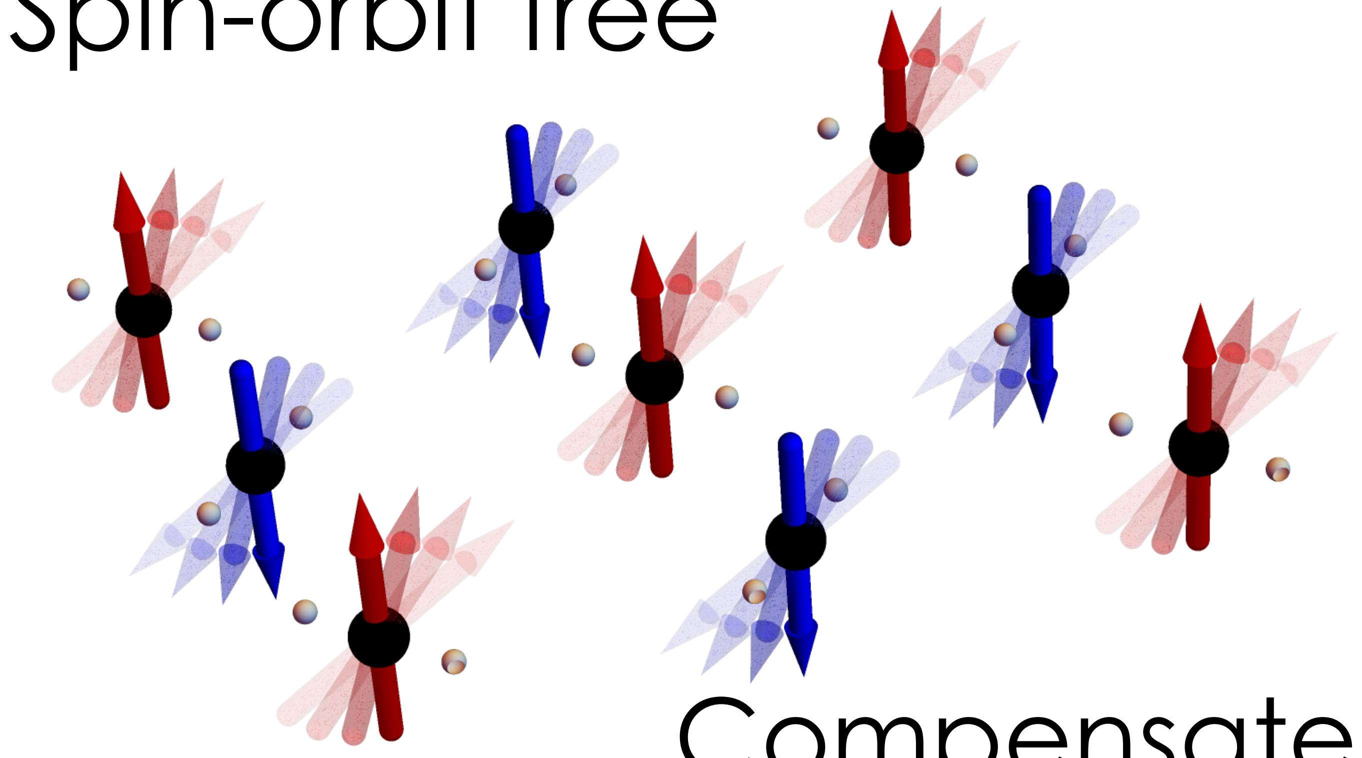

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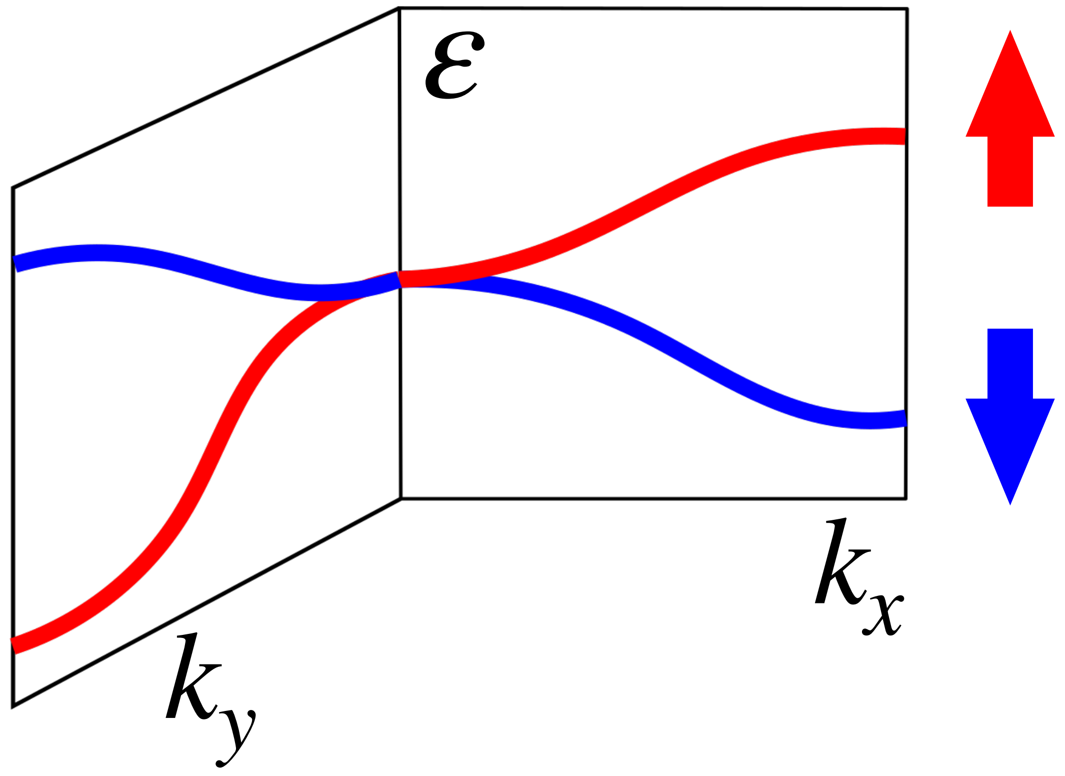

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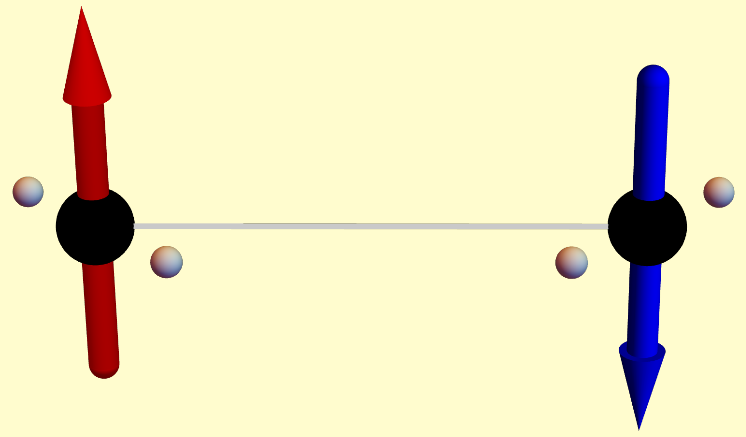

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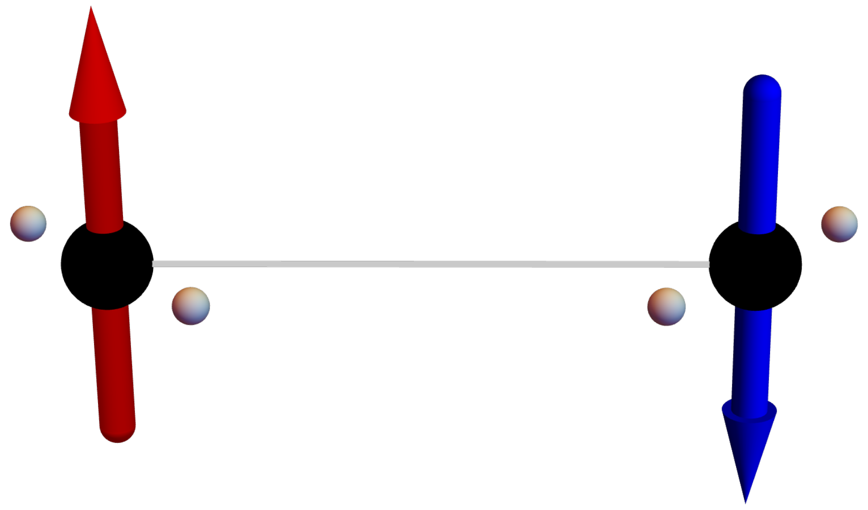

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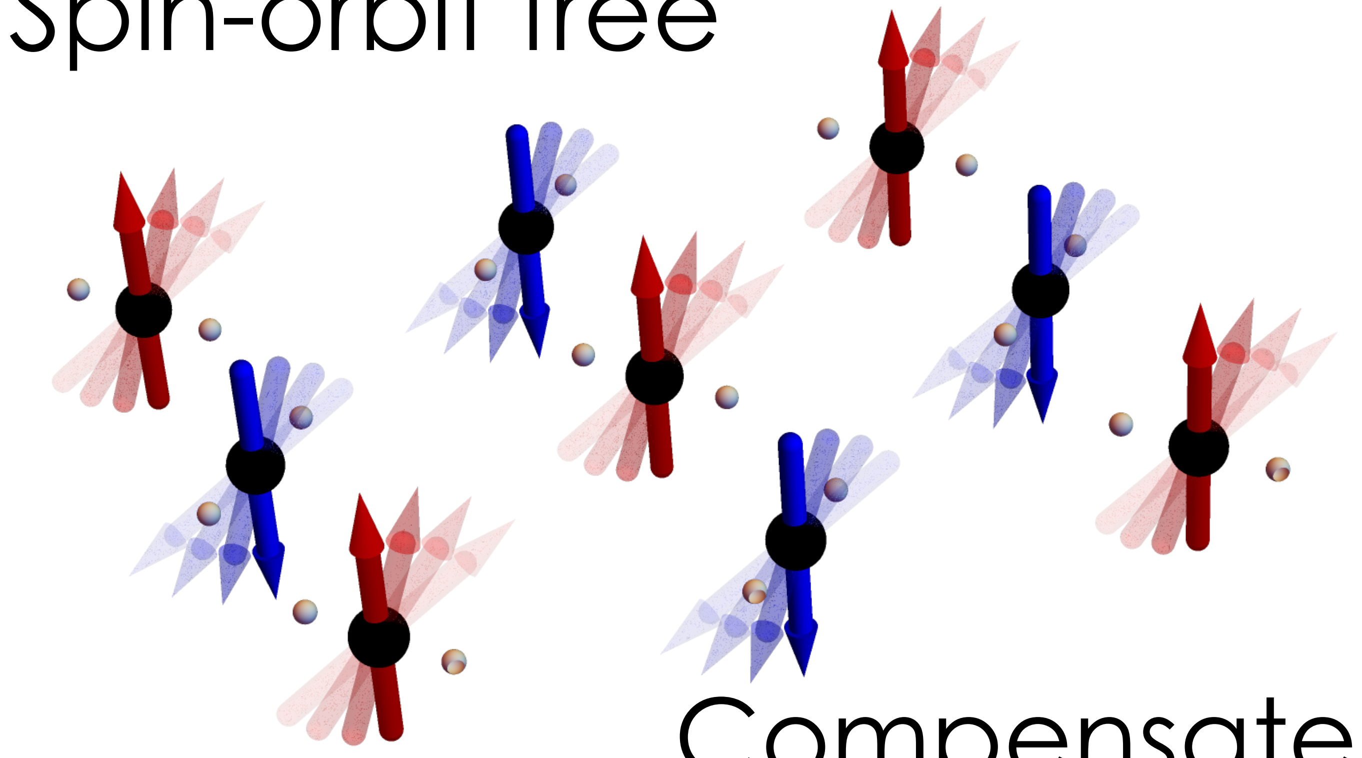
Ideal Altermagnets

Spin-orbit free



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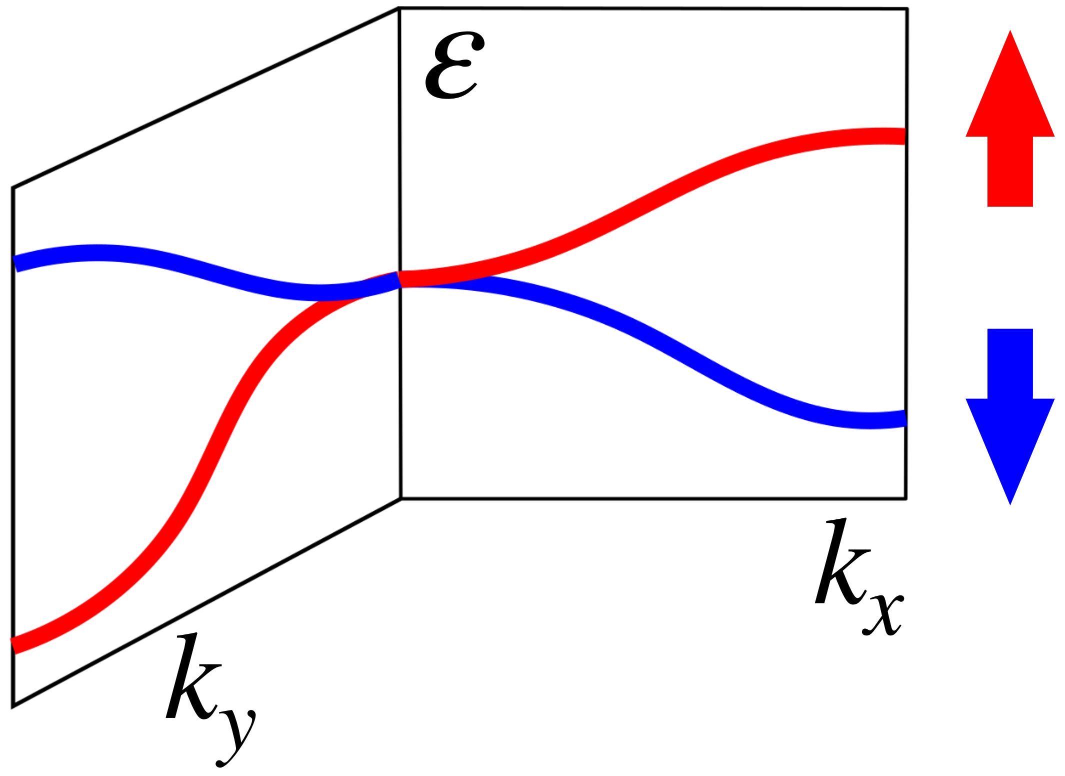

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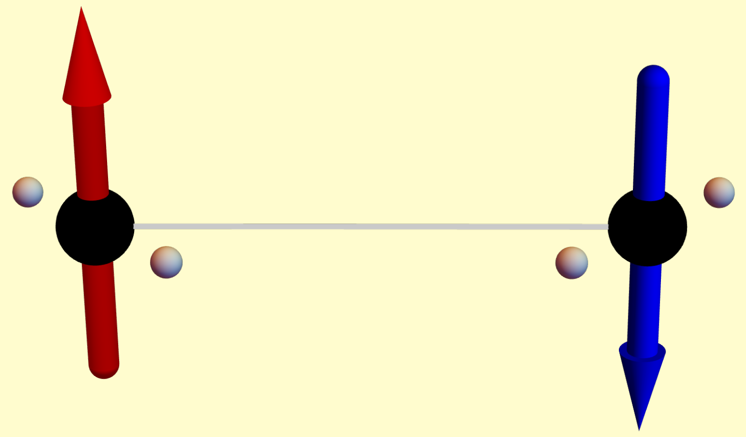

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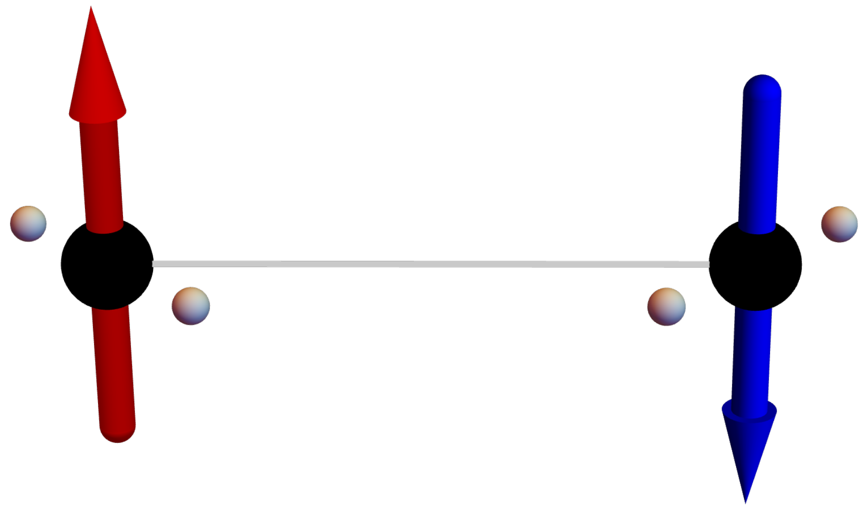

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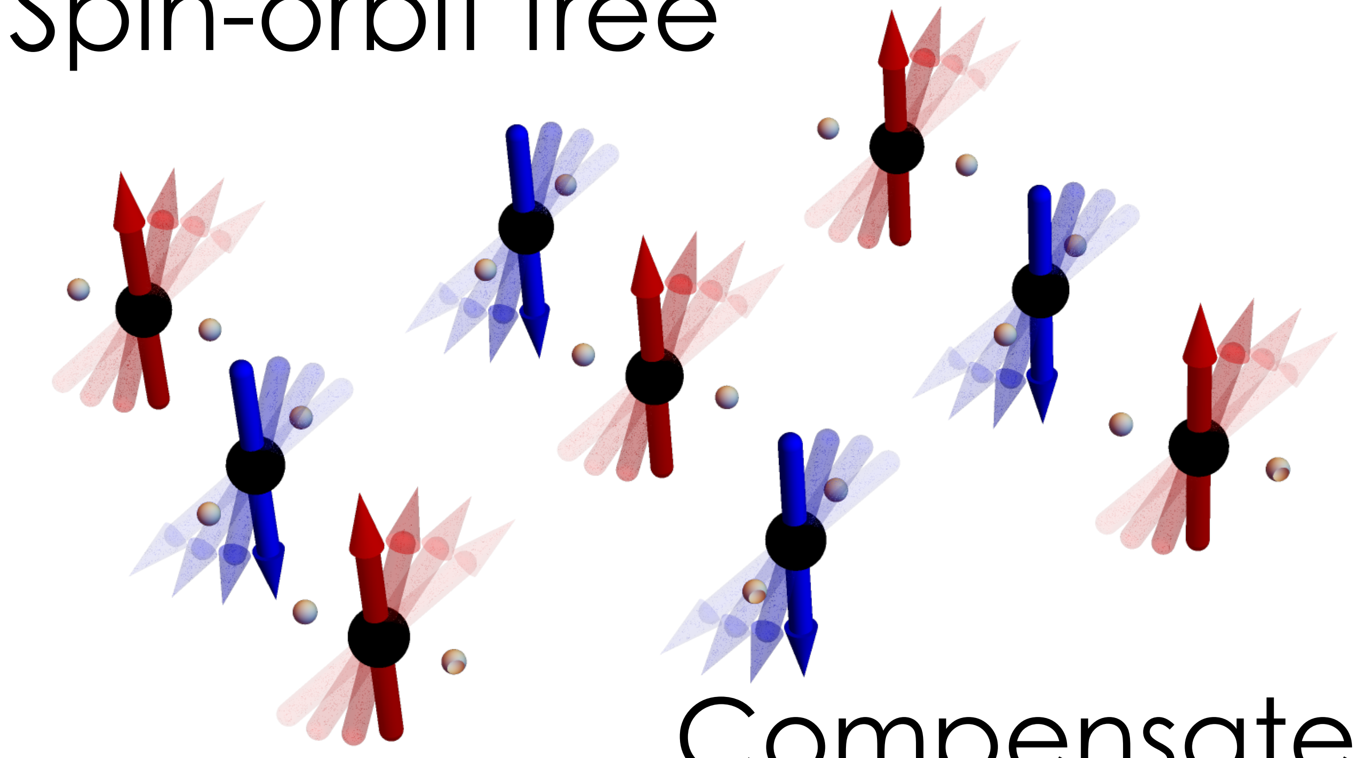

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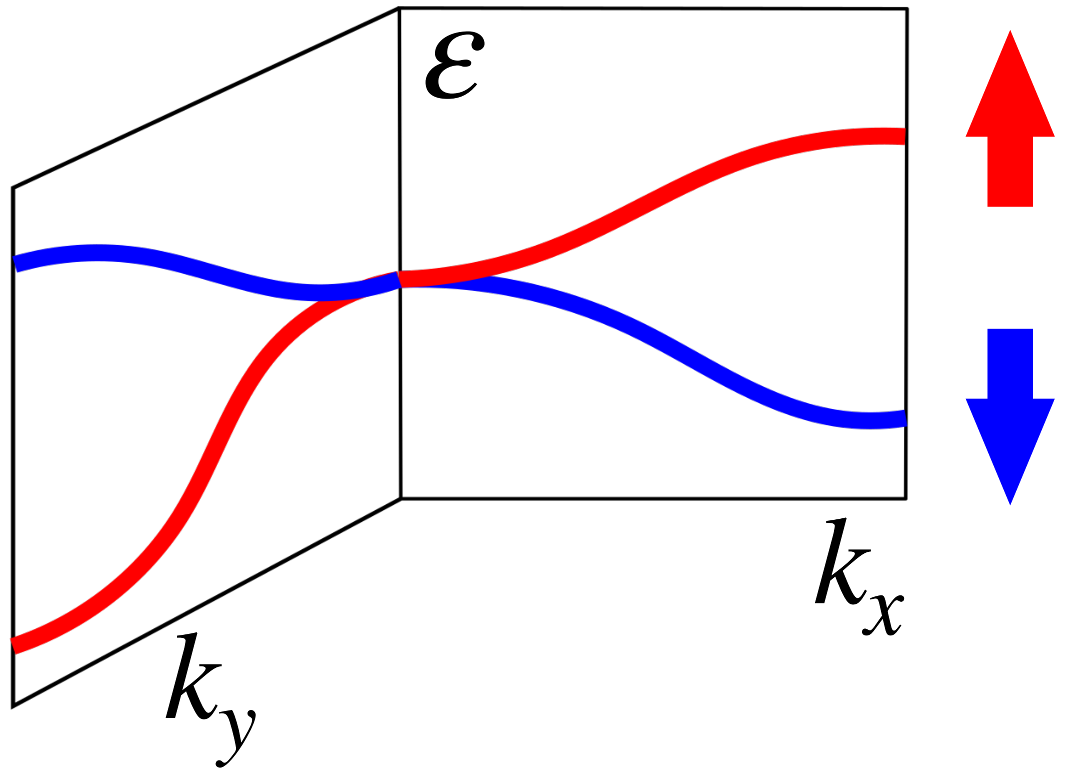

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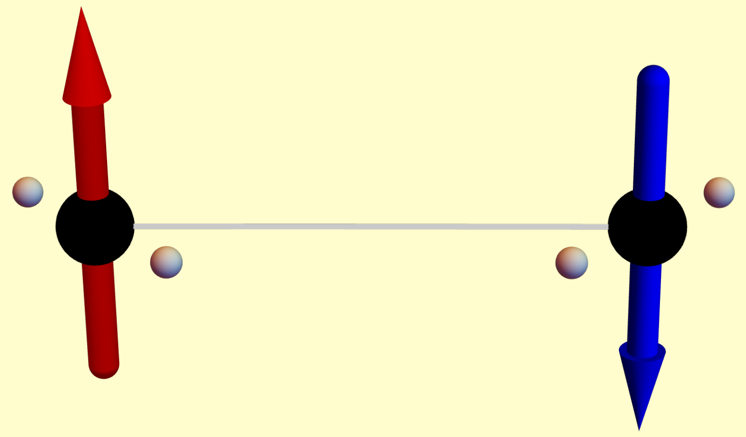

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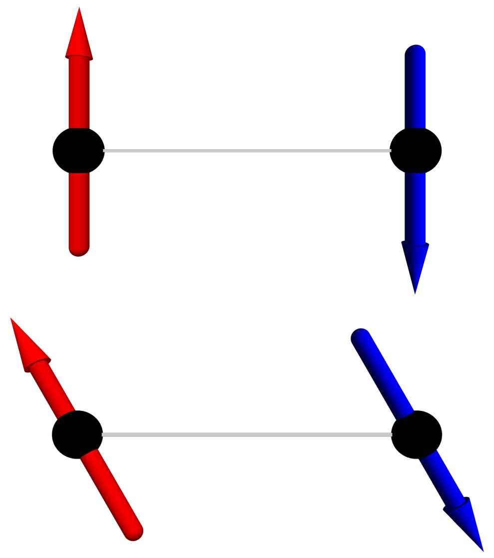
Transformation of the **spin** vectors

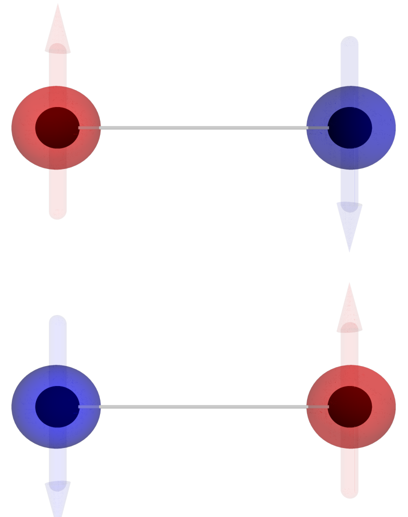
$$\mathbf{N} \to R\mathbf{N}$$



Transformation of **orbital space** (e.g. atoms)

$$\mathbf{N} \to \mathbf{N}$$

$$\mathbf{N} \to -\mathbf{N}$$



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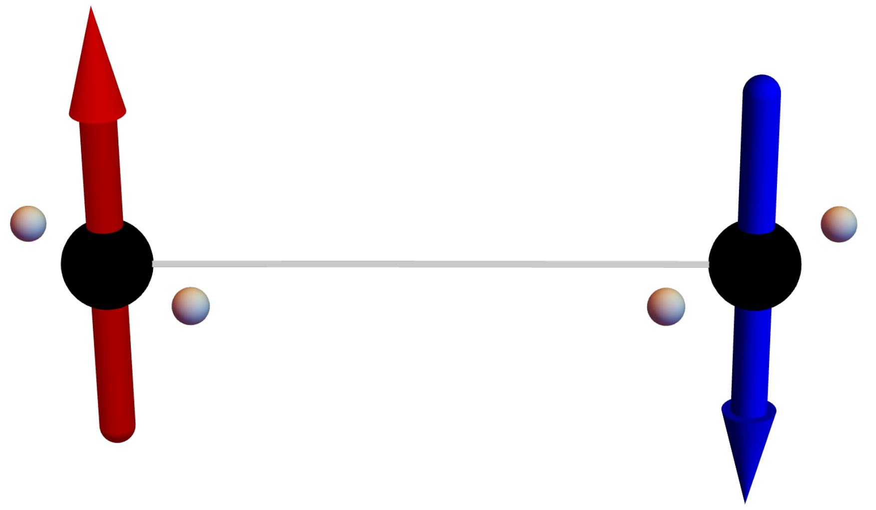

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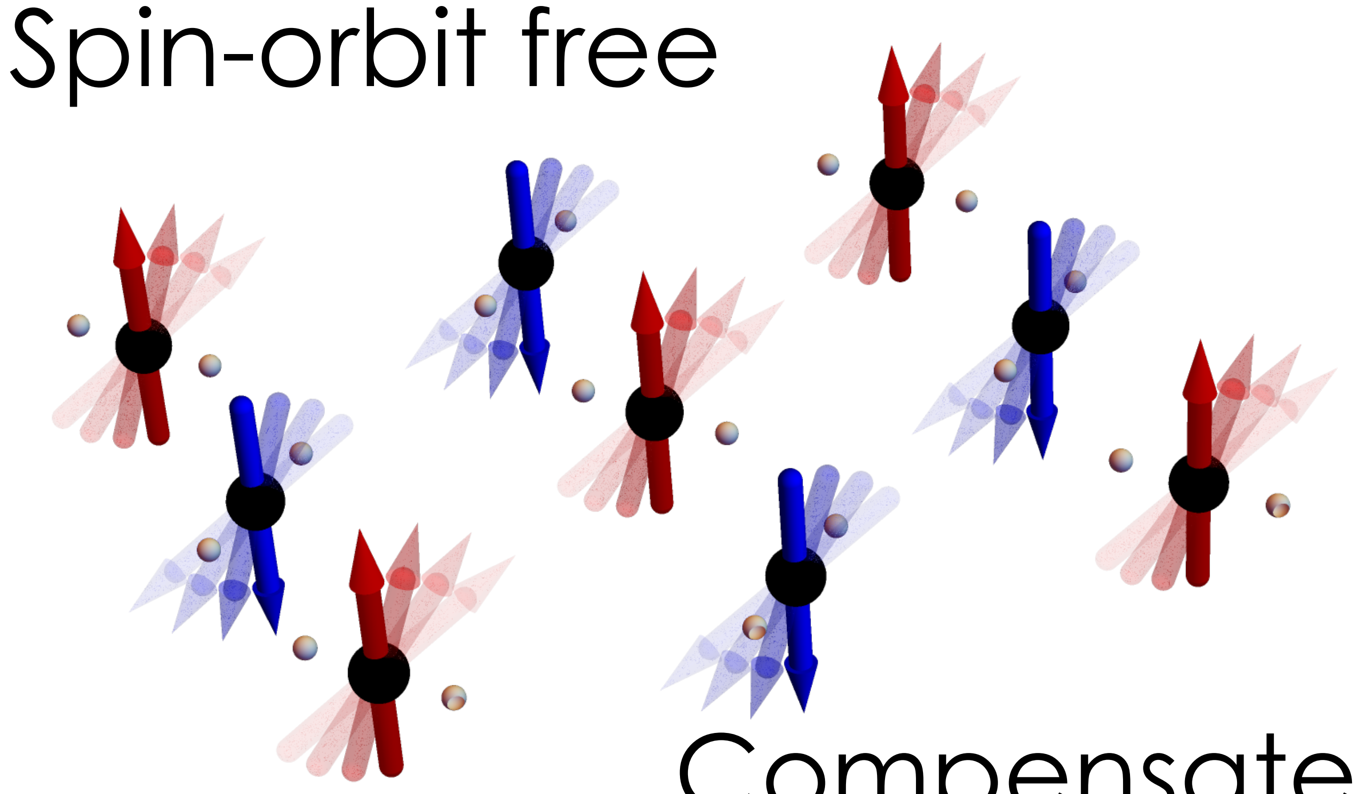

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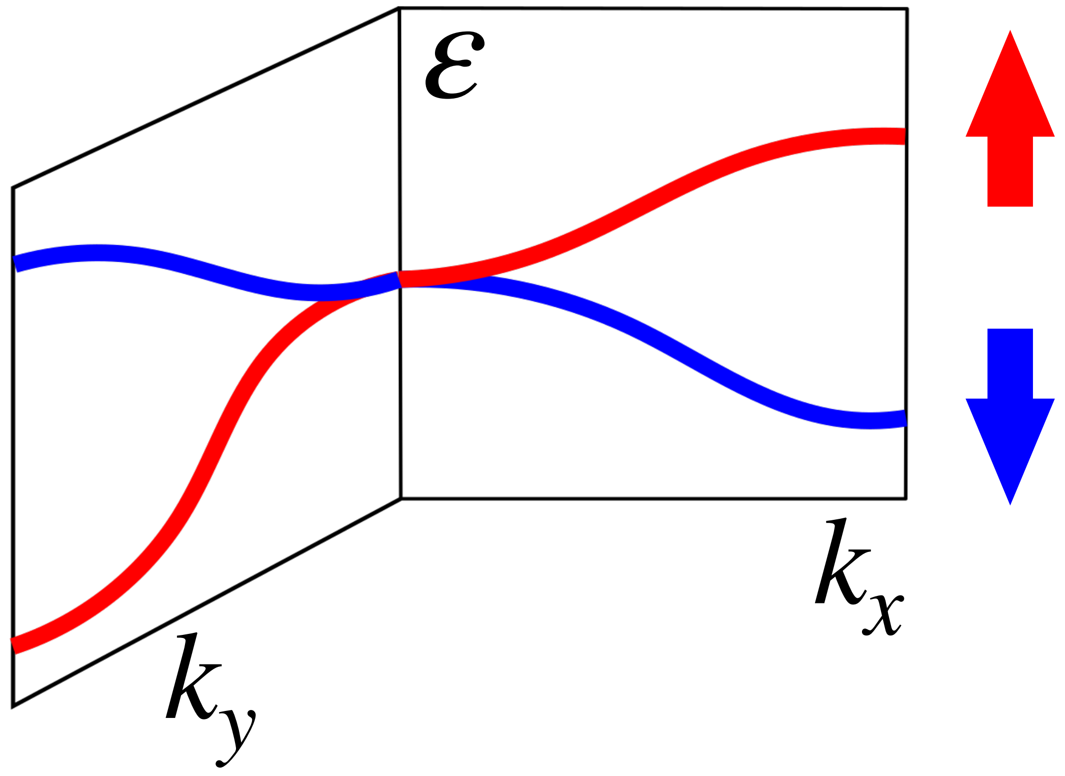

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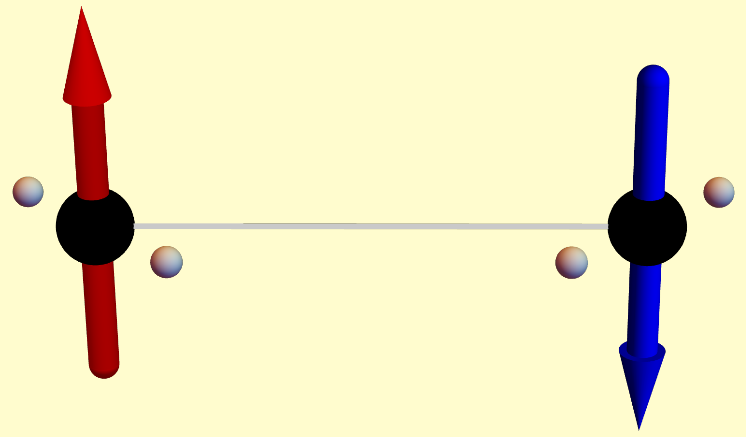

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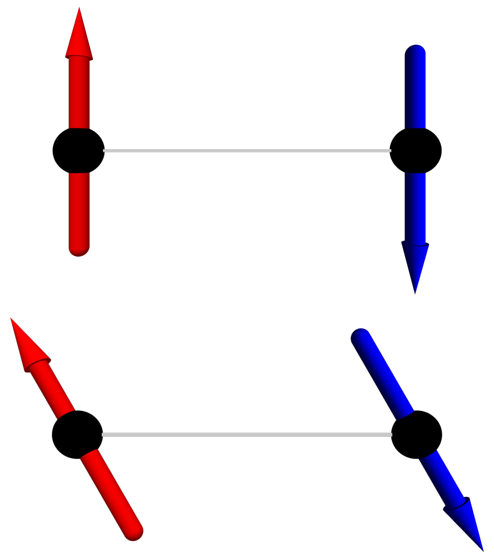

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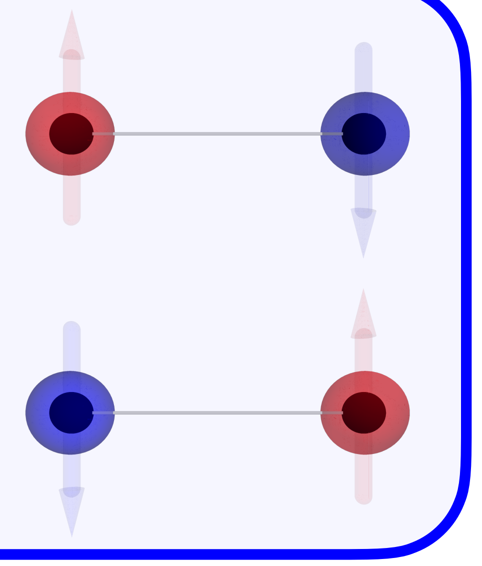

Under spatial transformations, $\mathbf{N}$ transforms as non-trivial 1D, $\mathbb{R}$ (i-even) irrep of the point group: $\Gamma_{\mathbf{N}}$

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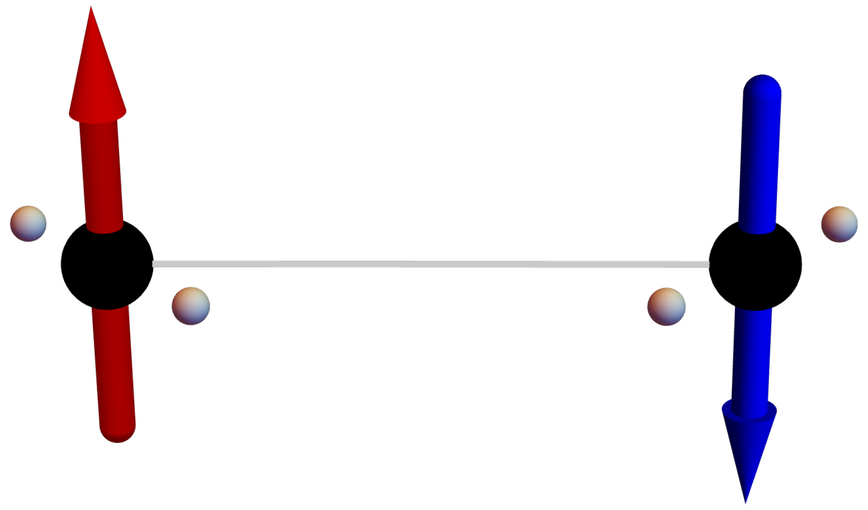

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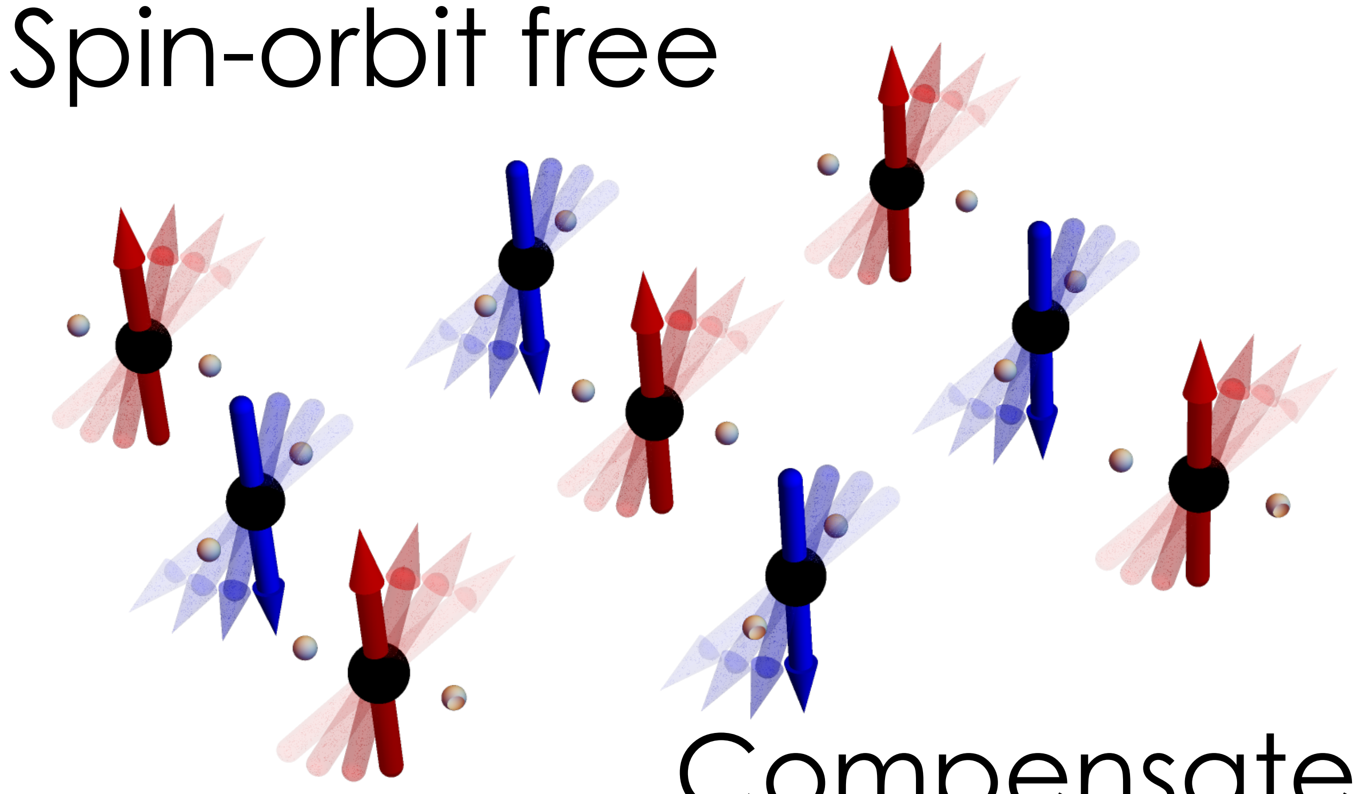

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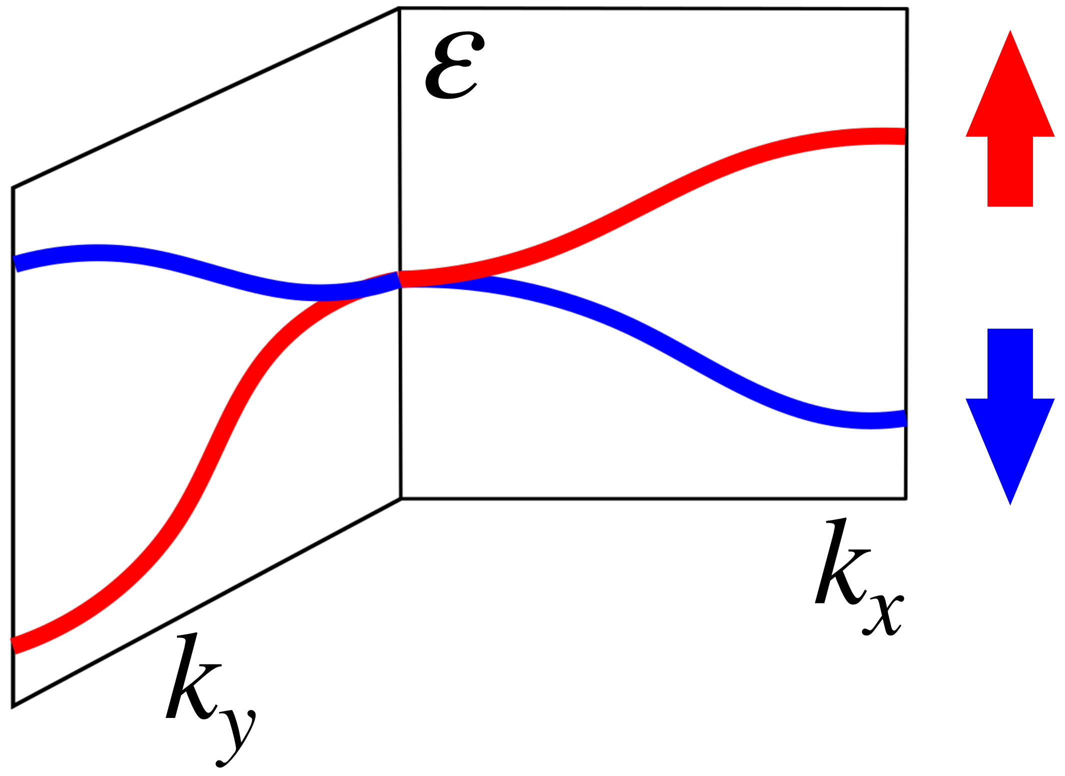

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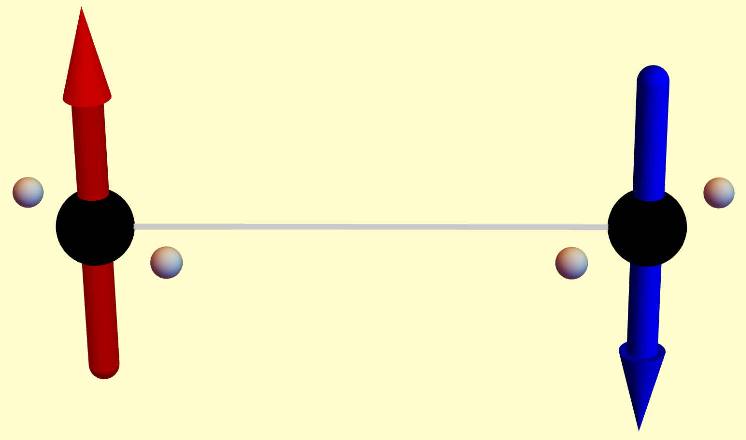

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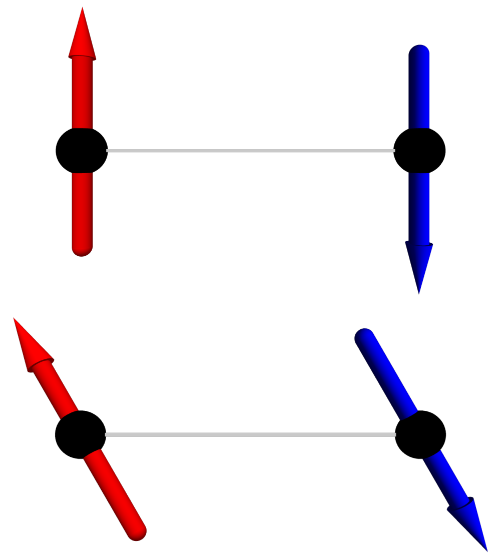

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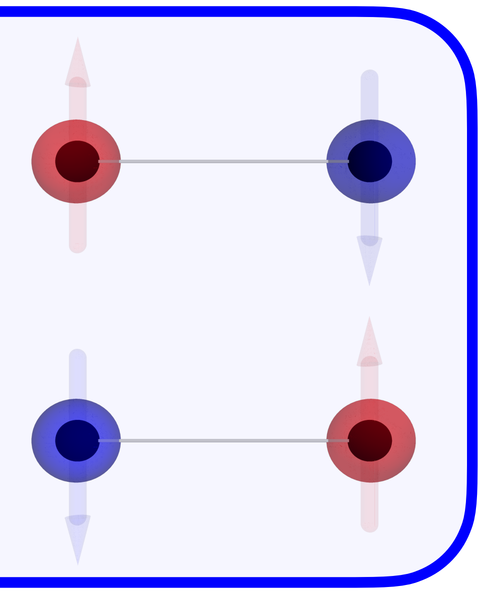

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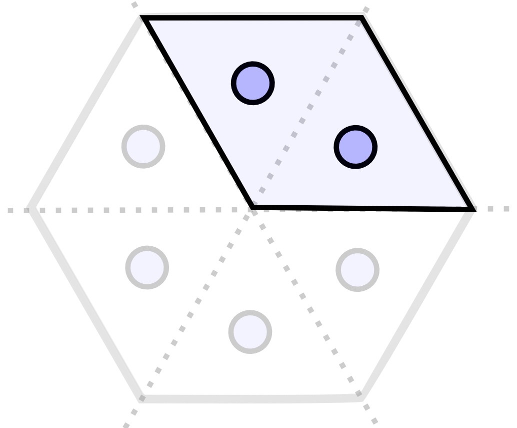
Algorithm For each WP of every space group:



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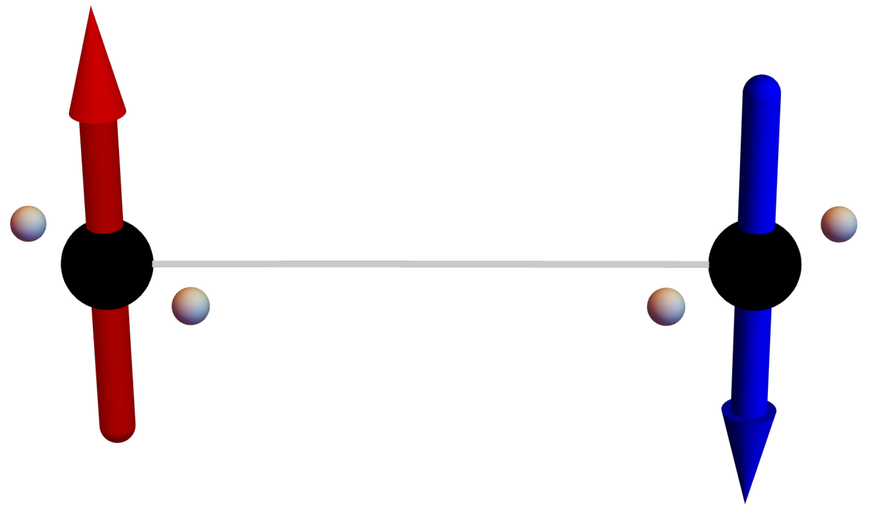

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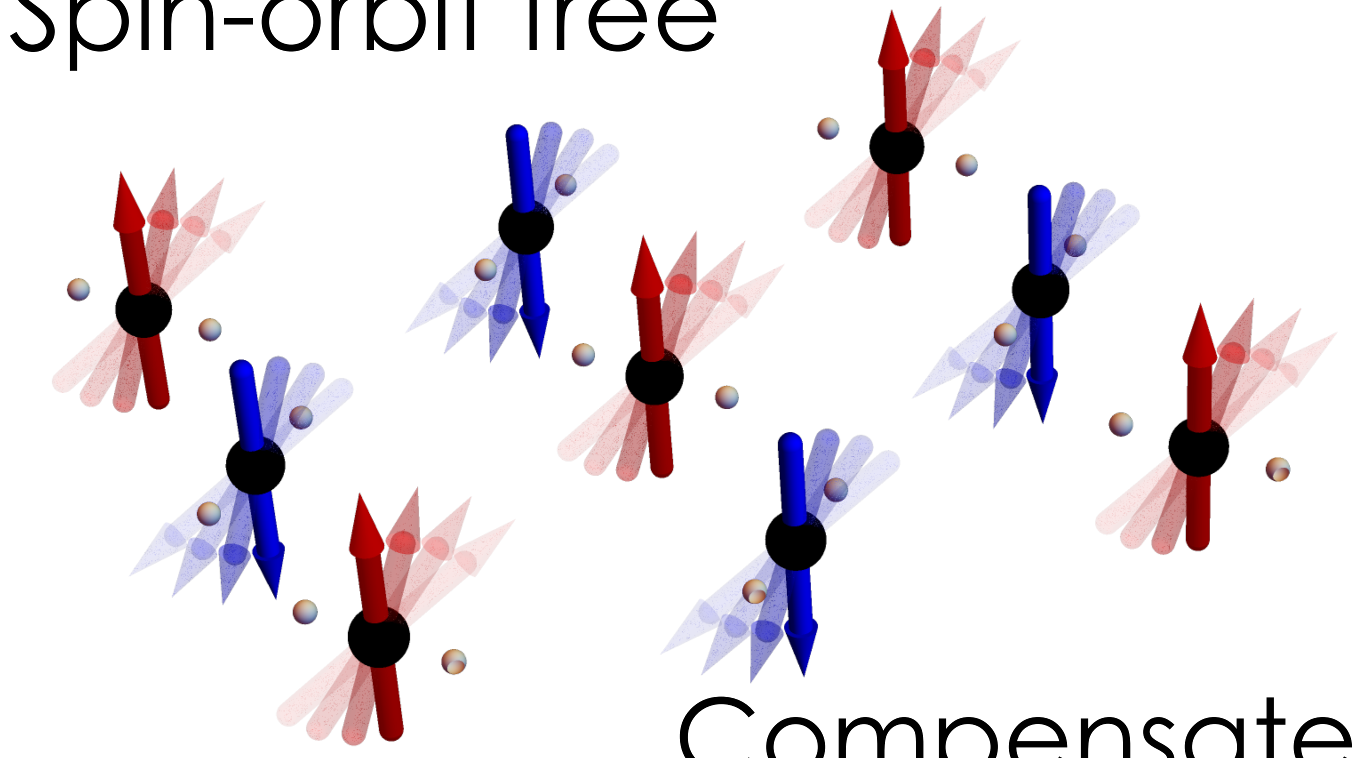
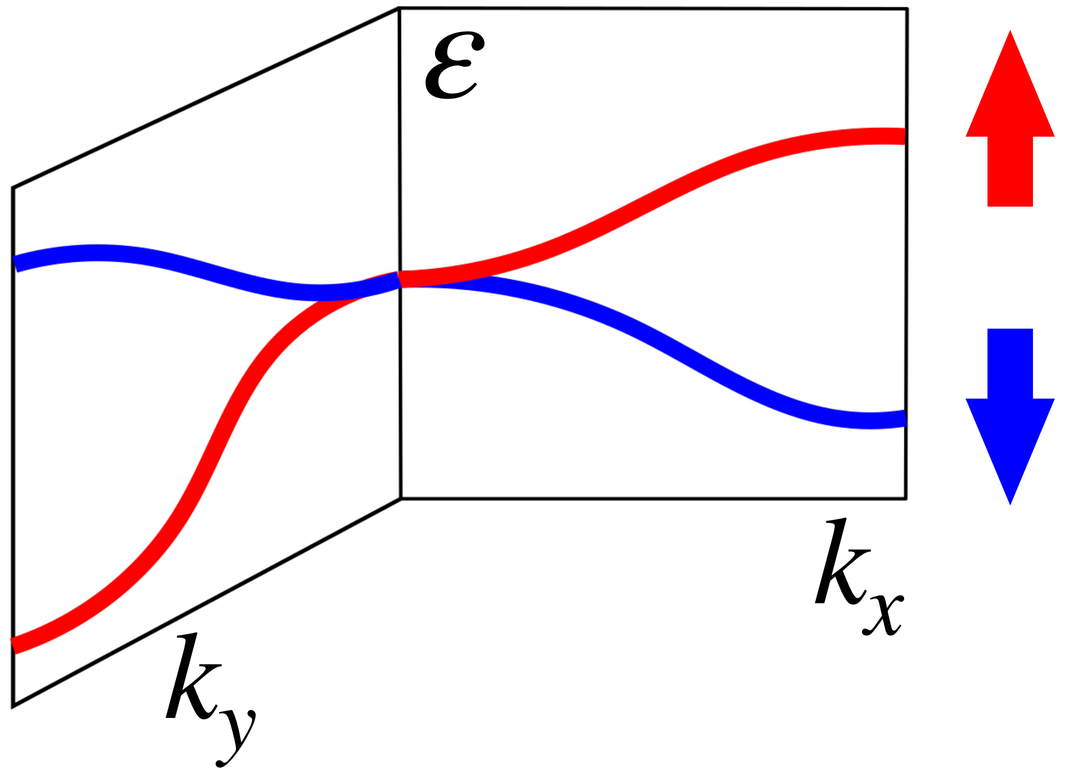
Ideal Altermagnets

Spin-orbit free



Compensated

Alternating spin-splitting



Šmejkal, Sinova, Jungwirth, Phys. Rev. X 12, 031042 (2022)

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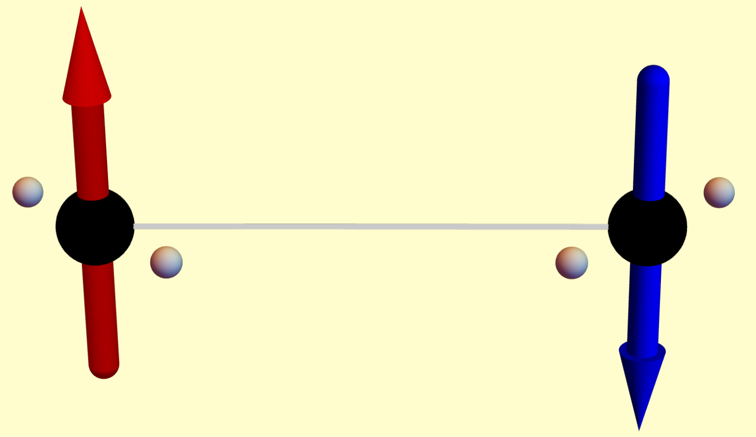
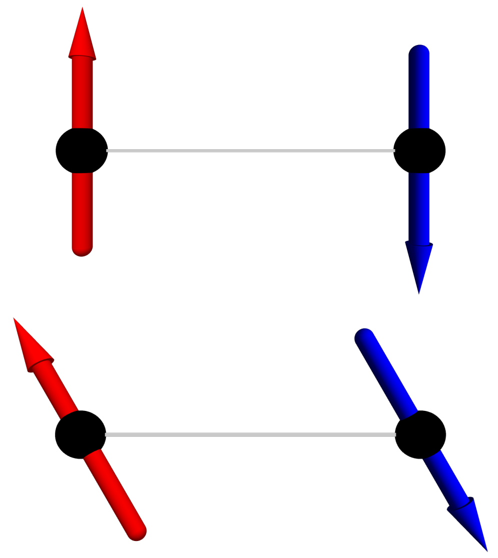


Translation & inversion don't connect ↑ / ↓

Transformation of the **spin** vectors

$\mathbf{N} \to R\mathbf{N}$



Transformation of **orbital space** (e.g. atoms)

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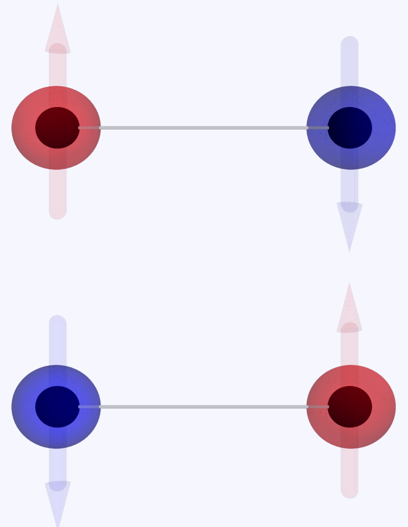
$\mathbf{N} \to -\mathbf{N}$



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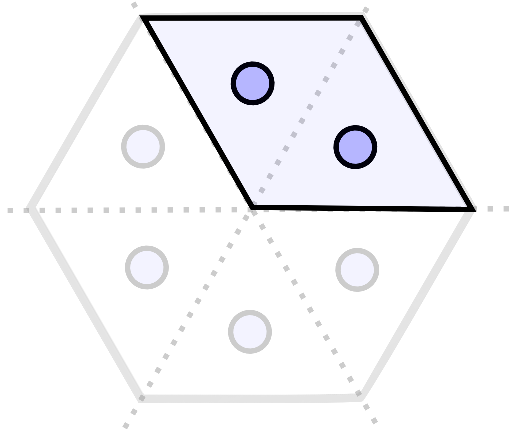

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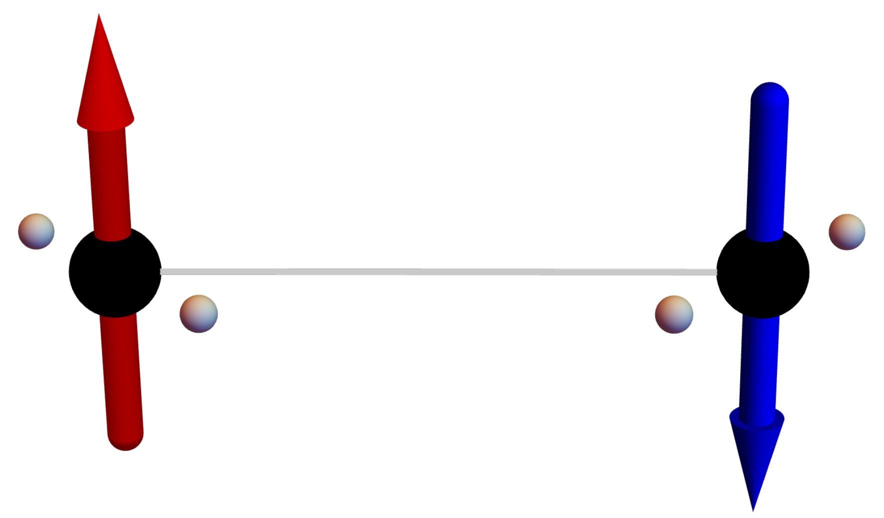

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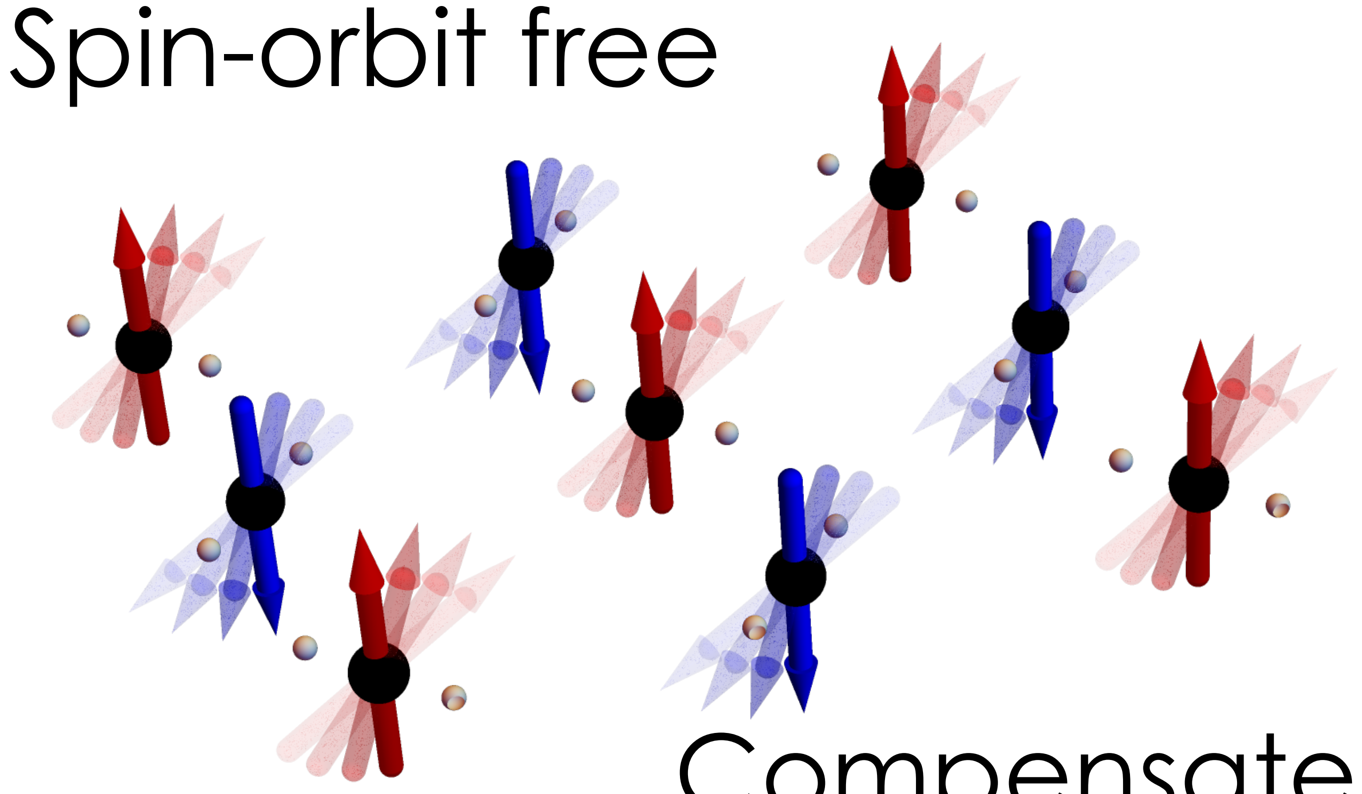

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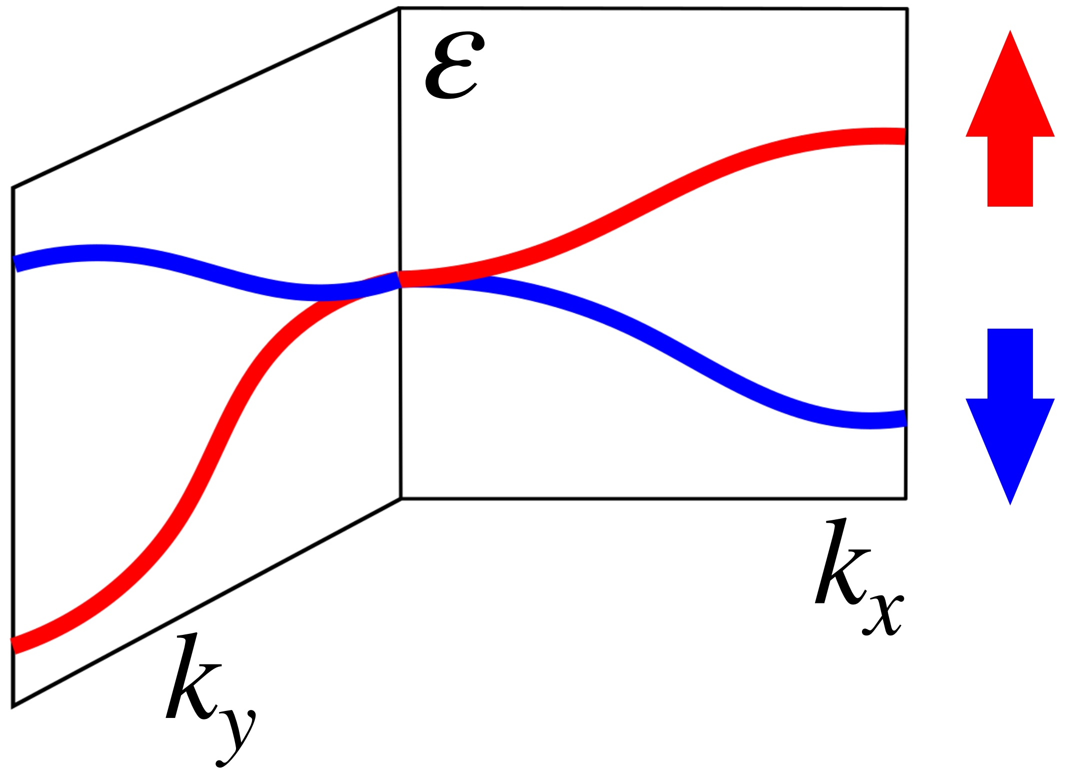

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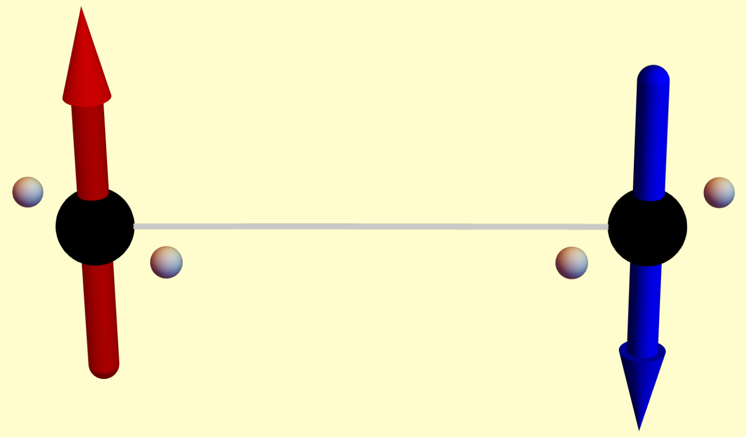

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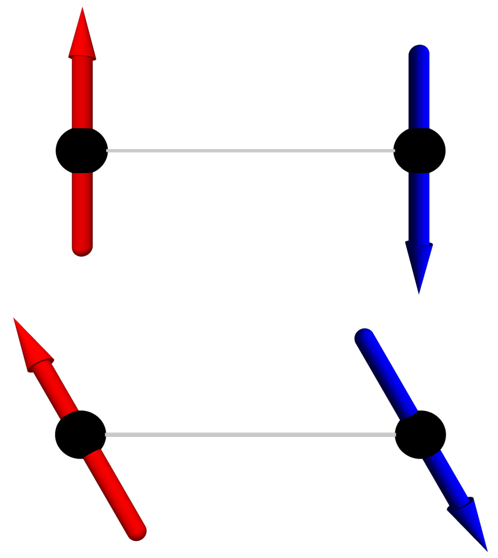

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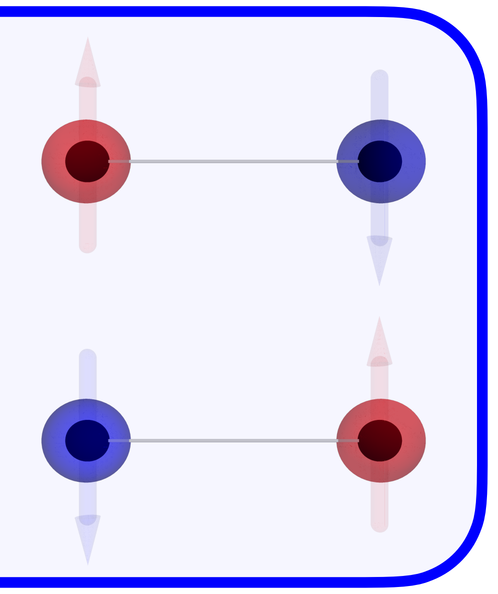

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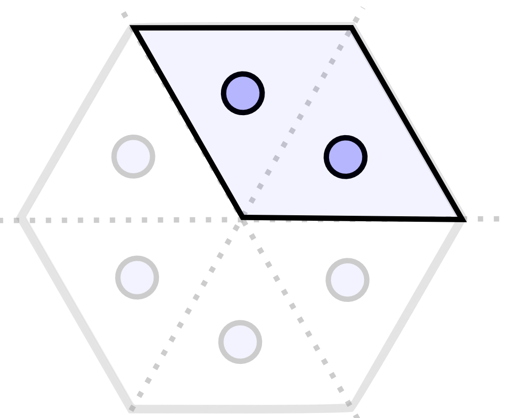

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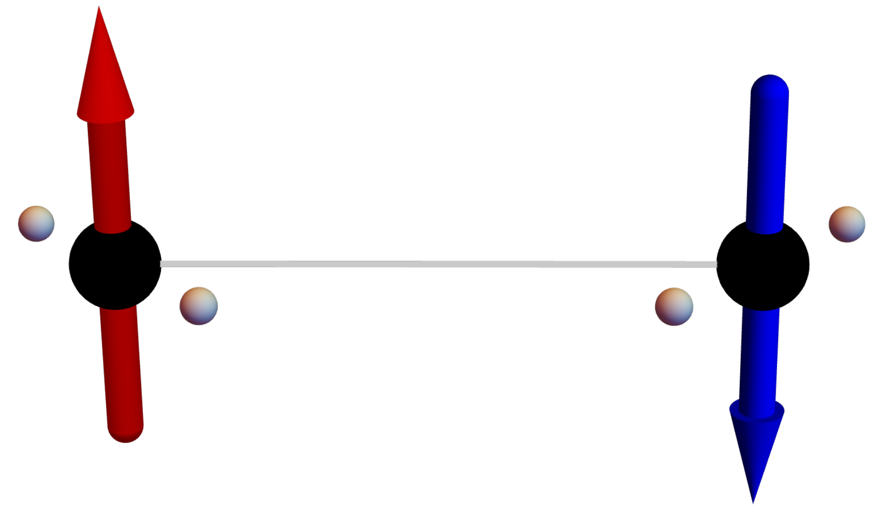

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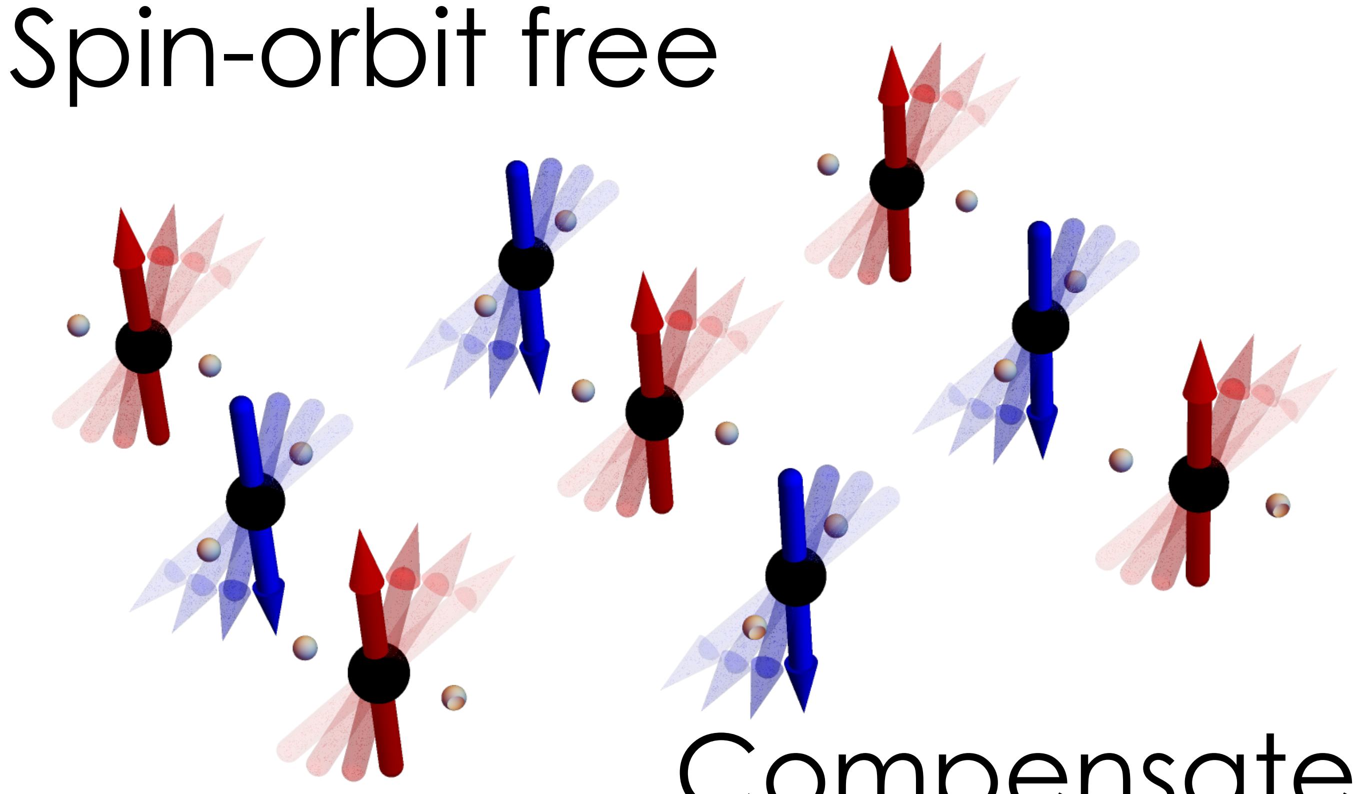

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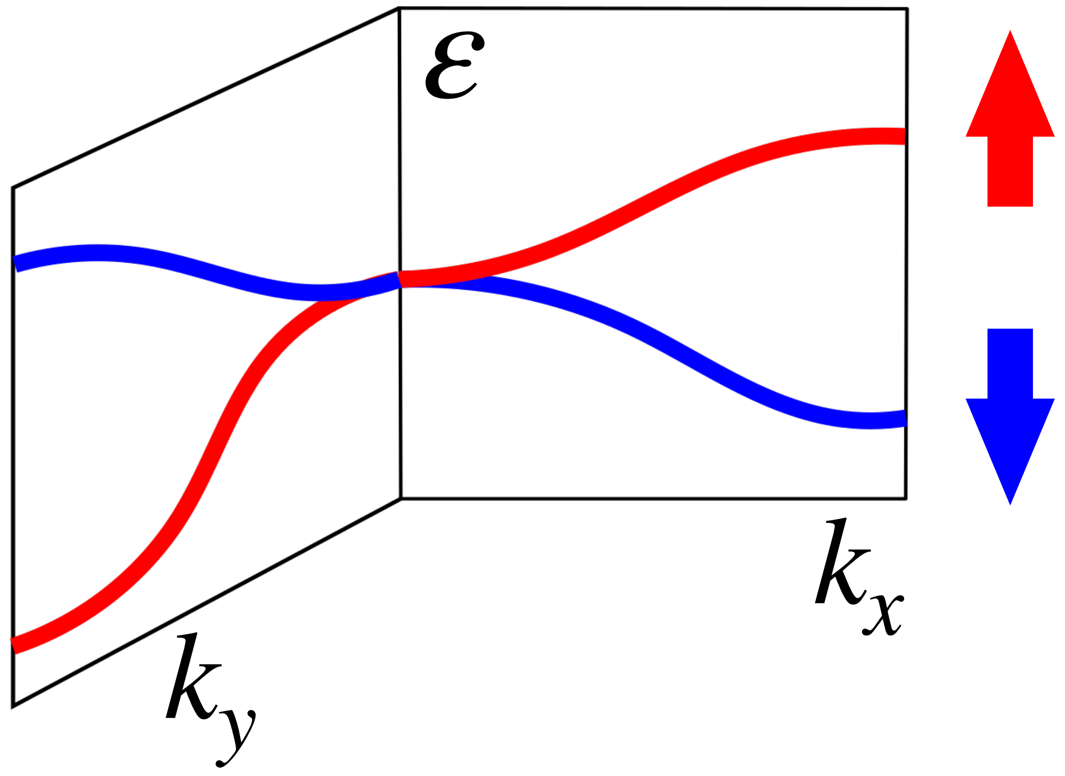

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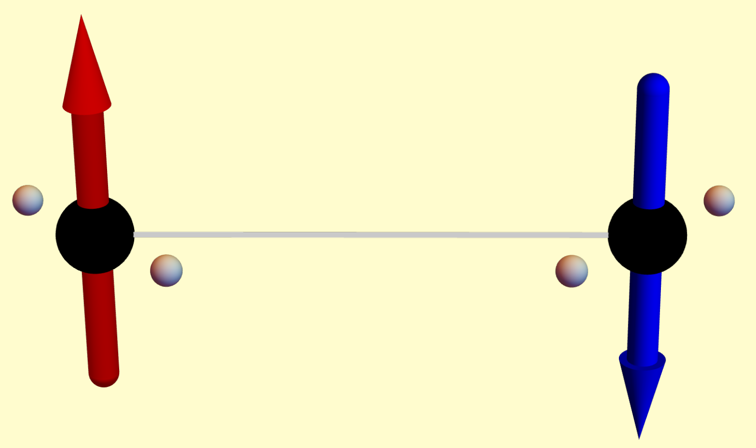

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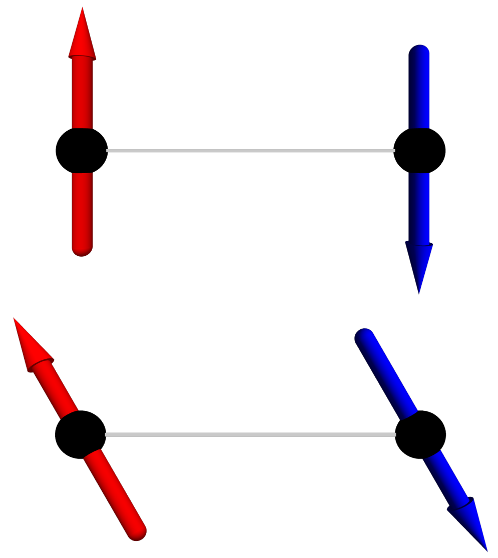

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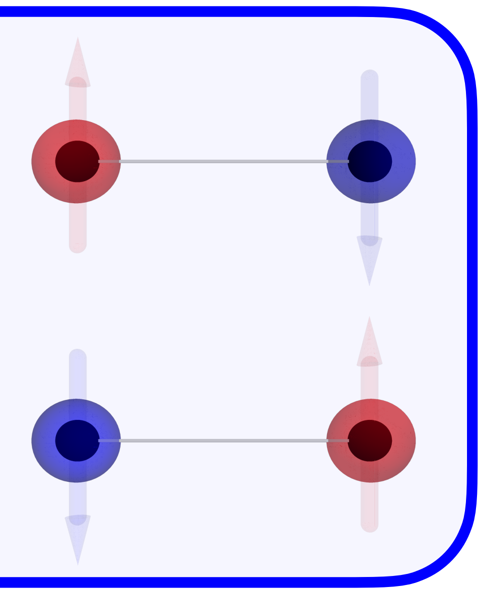

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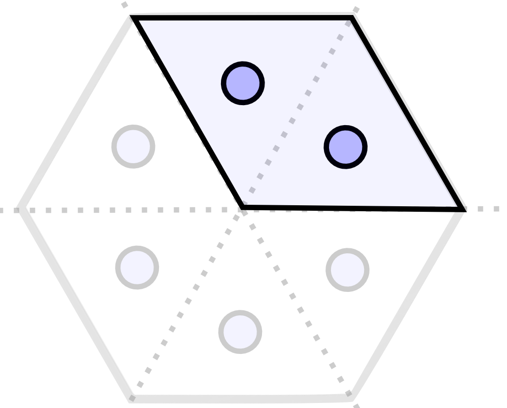

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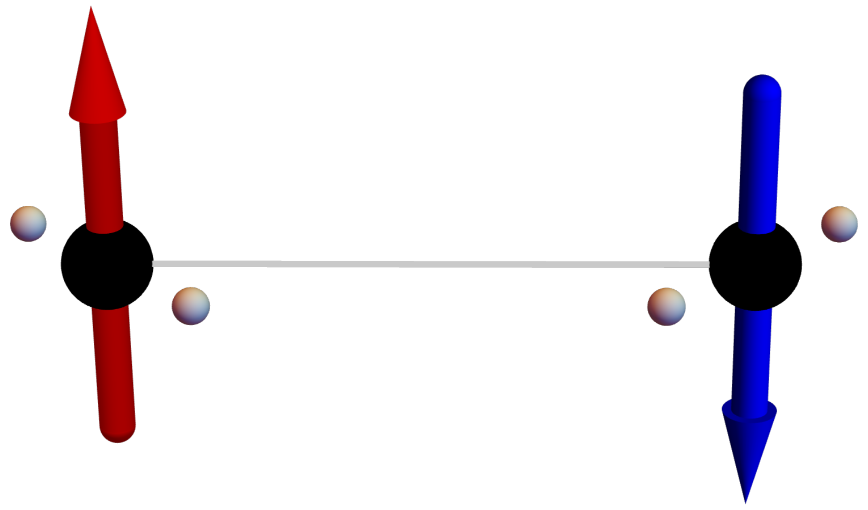

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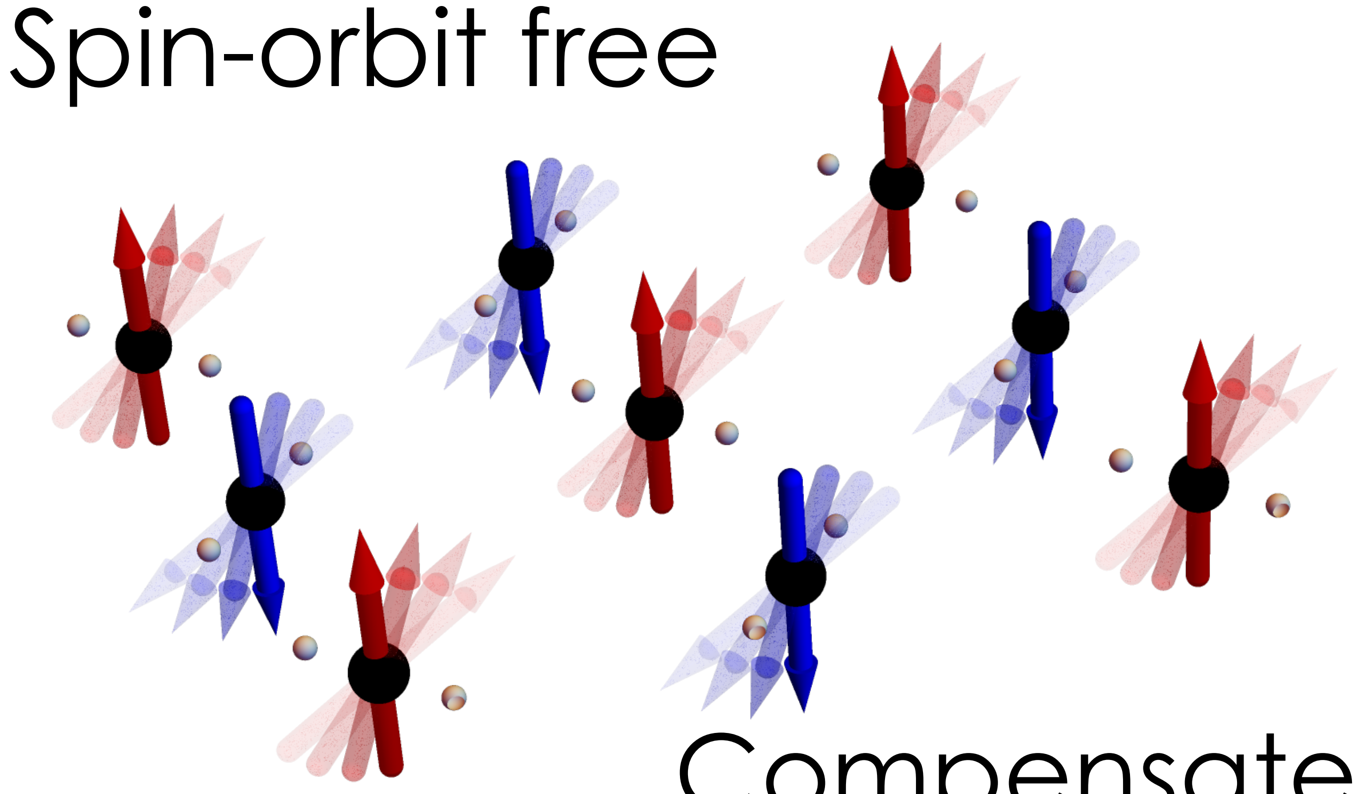

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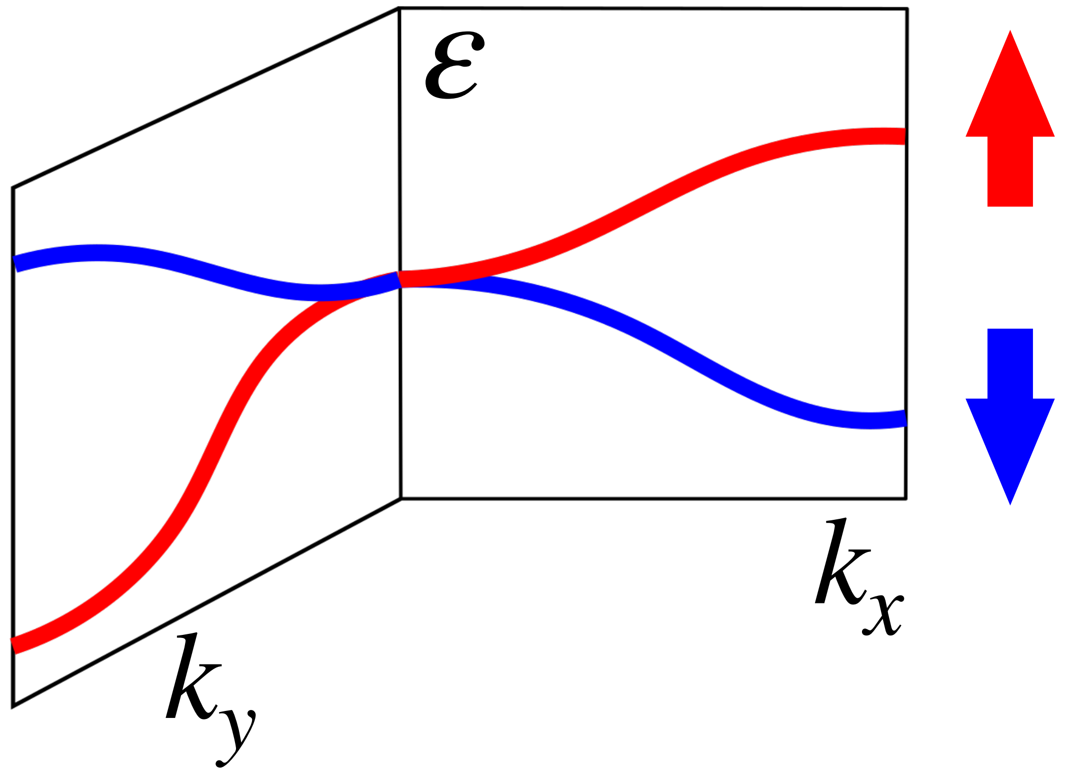

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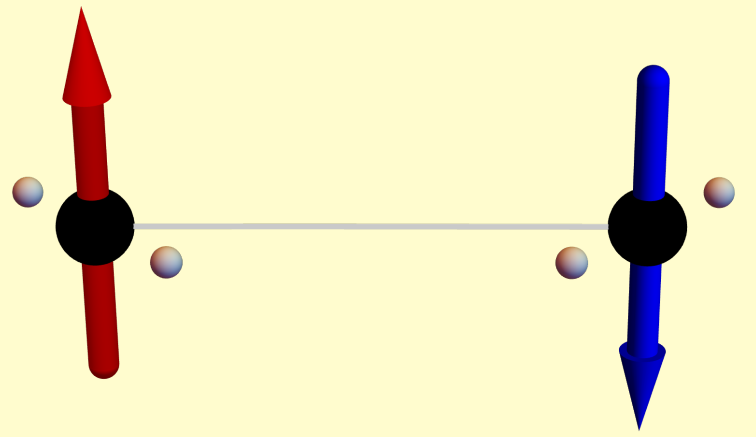

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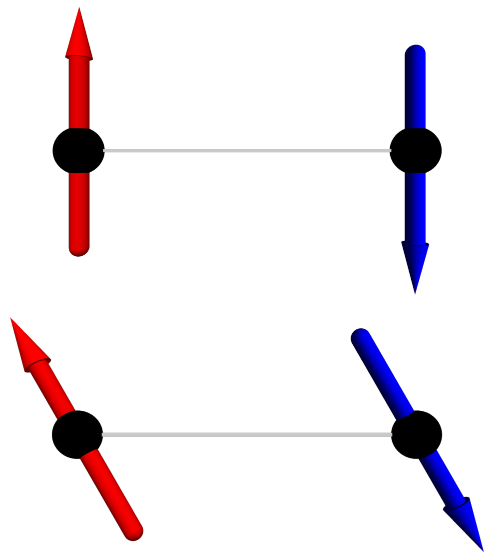

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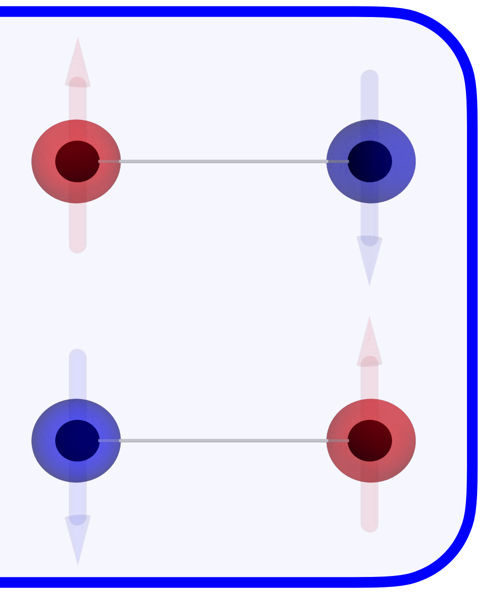

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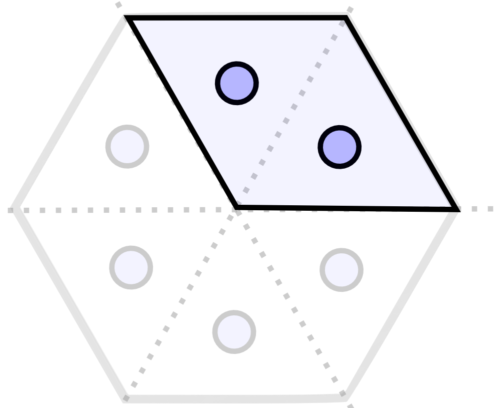
3. Decompose $D^{(\mathrm{P})}(\mathbf{G})$ into irreps of $\mathbf{G}$
4. If decomposition contains any 1D, $\mathbb{R}$, i-even irreps $\Gamma_{\mathbf{N}}$: *can host AM!*



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PHYSICAL REVIEW RESEARCH **7**, 033301 (2025)

Collinear altermagnets and their Landau theories

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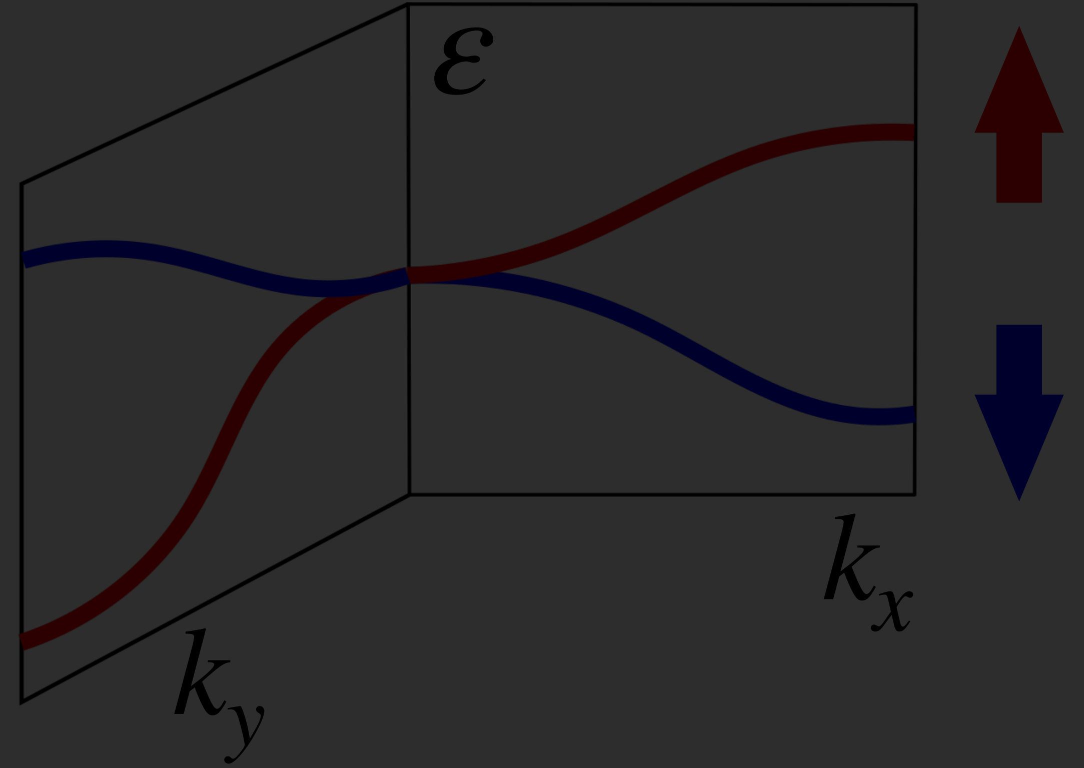
Alternating spin-splitting



PG	SG	WP	$\Gamma_{\mathbf{N}}$
2	3	$\{2e\}$	$\{B\}$
	4	$\{2a\}$	$\{B\}$
	5	$\{4c, 2b, 2a\}$	$\{B\}$
m	6	$\{2c\}$	$\{A''\}$
	7	$\{2a\}$	$\{A''\}$
	8	$\{4b\}$	$\{A''\}$
	9	$\{4a\}$	$\{A''\}$
2/m	10	$\{4o\}$	$\{B_g\}$
	11	$\{4f, 2d, 2c, 2b, 2a\}$	$\{B_g\}$
	12	$\{8j, 4h, 4g, 4f, 4e, 2d, 2b\}$	$\{B_g\}$
	13	$\{4g, 2d, 2c, 2b, 2a\}$	$\{B_g\}$
	14	$\{4e, 2d, 2c, 2b, 2a\}$	$\{B_g\}$
	15	$\{8f, 4e, 4d, 4c, 4b, 4a\}$	$\{B_g\}$
222	16	$\{4u\}$	$\{B_1, B_3, B_2\}$
		$\{2t, 2s, 2r, 2q\}$	$\{B_1\}$
		$\{2p, 2o, 2n, 2m\}$	$\{B_2\}$
		$\{2l, 2k, 2j, 2i\}$	$\{B_3\}$
	17	$\{4e\}$	$\{B_1, B_3, B_2\}$
		$\{2d, 2c\}$	$\{B_2\}$
		$\{2b, 2a\}$	$\{B_3\}$
	18	$\{4c\}$	$\{B_1, B_3, B_2\}$
		$\{2b, 2a\}$	$\{B_1\}$
	19	$\{4a\}$	$\{B_1, B_3, B_2\}$
	20	$\{8c, 4b\}$	$\{B_1, B_3, B_2\}$
		$\{4a\}$	$\{B_3\}$
	21	$\{8l, 4k, 4h, 4g\}$	$\{B_1, B_3, B_2\}$
		$\{4j, 4i, 2b\}$	$\{B_1\}$
		$\{4f, 4e\}$	$\{B_3\}$
	22	$\{16k, 8j, 8i, 8h, 8g, 8f, 8e\}$	$\{B_1, B_3, B_2\}$
		$\{4d, 4b\}$	$\{B_1\}$
	23	$\{8k, 4j, 4i, 4f, 2c\}$	$\{B_1, B_3, B_2\}$
		$\{4h, 4g\}$	$\{B_2\}$
		$\{4e\}$	$\{B_3\}$
	24	$\{8d, 4c, 4a\}$	$\{B_1, B_3, B_2\}$

PG	SG	WP	$\Gamma_{\mathbf{N}}$
4/mmm	130	$\{16g, 8e, 8d\}$	$\{B_{1g}, A_{2g}, B_{2g}\}$
		$\{4c, 4b\}$	$\{A_{2g}\}$
		$\{8f, 4a\}$	$\{B_{2g}\}$
	131	$\{16r, 8q\}$	$\{B_{1g}, A_{2g}, B_{2g}\}$
		$\{8p, 8o, 4m, 4l, 4k, 4j, 4i, 4h, 4g, 2d, 2c, 2b, 2a\}$	$\{B_{1g}\}$
		$\{8n\}$	$\{B_{2g}\}$
	132	$\{16p, 8n, 8k, 4f\}$	$\{B_{1g}, A_{2g}, B_{2g}\}$
		$\{8m, 8l, 4e\}$	$\{B_{1g}\}$
		$\{8o, 4j, 4i, 4h, 4g, 2c, 2a\}$	$\{B_{2g}\}$
	133	$\{16k, 8g, 8f, 8e\}$	$\{B_{1g}, A_{2g}, B_{2g}\}$
		$\{4d\}$	$\{A_{2g}\}$
		$\{8i, 8h, 4b, 4a\}$	$\{B_{1g}\}$
		$\{8j, 4c\}$	$\{B_{2g}\}$
	134	$\{16n, 8h\}$	$\{B_{1g}, A_{2g}, B_{2g}\}$
		$\{8j, 8i, 4c\}$	$\{B_{1g}\}$
		$\{8m, 8l, 8k, 4g, 4f, 4e, 4d\}$	$\{B_{2g}\}$
	135	$\{16i, 8h, 8f, 8e, 4c, 4a\}$	$\{B_{1g}, A_{2g}, B_{2g}\}$
		$\{4b\}$	$\{A_{2g}\}$
		$\{8g, 4d\}$	$\{B_{2g}\}$
	136	$\{16k, 8i, 8h, 4c\}$	$\{B_{1g}, A_{2g}, B_{2g}\}$
		$\{4d\}$	$\{A_{2g}\}$
		$\{8j, 4g, 4f, 4e, 2b, 2a\}$	$\{B_{2g}\}$
	137	$\{16h, 8e\}$	$\{B_{1g}, A_{2g}, B_{2g}\}$
		$\{8g, 4d, 4c\}$	$\{B_{1g}\}$
		$\{8f\}$	$\{B_{2g}\}$
	138	$\{16j, 8f\}$	$\{B_{1g}, A_{2g}, B_{2g}\}$
		$\{4b\}$	$\{A_{2g}\}$
		$\{8i, 8h, 8g, 4e, 4d, 4c, 4a\}$	$\{B_{2g}\}$
	139	$\{32o, 16n, 16l, 16k, 8g, 4d\}$	$\{B_{1g}, A_{2g}, B_{2g}\}$
		$\{8j, 8i, 4c\}$	$\{B_{1g}\}$
		$\{16m, 8h, 8f, 4e, 2b\}$	$\{B_{2g}\}$
	140	$\{32m, 16k, 16j, 16i, 8f, 8e, 4a\}$	$\{B_{1g}, A_{2g}, B_{2g}\}$
		$\{4c\}$	$\{A_{2g}\}$
		$\{16l, 8h, 8g, 4d, 4b\}$	$\{B_{2g}\}$
	141	$\{32i, 16h, 16g, 8e, 4b, 4a\}$	$\{B_{1g}, A_{2g}, B_{2g}\}$
		$\{16f, 8d, 8c\}$	$\{B_{1g}\}$
	142	$\{32g, 16f, 16e, 16d, 16c, 8b, 8a\}$	$\{B_{1g}, A_{2g}, B_{2g}\}$
32	149	$\{6l, 2i, 2h, 2g\}$	$\{A_2\}$
	150	$\{6g, 2d, 2c\}$	$\{A_2\}$
	151	$\{6c\}$	$\{A_2\}$
	152	$\{6c\}$	$\{A_2\}$
	153	$\{6c\}$	$\{A_2\}$
	154	$\{6c\}$	$\{A_2\}$
	155	$\{18f, 9e, 9d, 6c\}$	$\{A_2\}$
3m	156	$\{6e\}$	$\{A_2\}$
	157	$\{6d, 2b\}$	$\{A_2\}$
	158	$\{6d, 2c, 2b, 2a\}$	$\{A_2\}$
	159	$\{6c, 2b, 2a\}$	$\{A_2\}$
	160	$\{18c\}$	$\{A_2\}$
	161	$\{18b, 6a\}$	$\{A_2\}$

PG	SG	WP	$\Gamma_{\mathbf{N}}$
$\bar{6}$**2m**	189	$\{12l, 4h\}$	$\{A_1'', A_2'', A_2'\}$
		$\{6k, 6j, 2d, 2c\}$	$\{A_2'\}$
		$\{6i, 2e\}$	$\{A_2''\}$
	190	$\{12i, 4f, 4e\}$	$\{A_1'', A_2'', A_2'\}$
		$\{6g, 2a\}$	$\{A_1''\}$
		$\{6h, 2d, 2c, 2b\}$	$\{A_2'\}$
6/mmm	191	$\{24r\}$	$\{A_{2g}, B_{2g}, B_{1g}\}$
		$\{12q, 12p\}$	$\{A_{2g}\}$
		$\{12n\}$	$\{B_{1g}\}$
		$\{12o, 4h\}$	$\{B_{2g}\}$
	192	$\{24m, 8h\}$	$\{A_{2g}, B_{2g}, B_{1g}\}$
		$\{12l, 12i, 6g, 4e, 4d, 2b\}$	$\{A_{2g}\}$
		$\{12k, 4c\}$	$\{B_{1g}\}$
		$\{12j\}$	$\{B_{2g}\}$
	193	$\{24l, 8h\}$	$\{A_{2g}, B_{2g}, B_{1g}\}$
		$\{12j, 4c\}$	$\{A_{2g}\}$
		$\{12k, 12i, 6f, 4e, 4d, 2b\}$	$\{B_{1g}\}$
	194	$\{24l\}$	$\{A_{2g}, B_{2g}, B_{1g}\}$
		$\{12j\}$	$\{A_{2g}\}$
		$\{12k, 12i, 6g, 4f, 4e, 2a\}$	$\{B_{2g}\}$
m$\bar{3}$**m**	221	$\{48n, 24l, 24k, 12h\}$	$\{A_{2g}\}$
	222	$\{48i, 24g, 16f, 8c\}$	$\{A_{2g}\}$
	223	$\{48l, 24k, 16i, 12h, 12g, 12f, 6b, 2a\}$	$\{A_{2g}\}$
	224	$\{48l, 24h\}$	$\{A_{2g}\}$
	225	$\{192l, 96j\}$	$\{A_{2g}\}$
	226	$\{192j, 96i, 96h, 64g, 48e, 24c, 8b\}$	$\{A_{2g}\}$
	227	$\{192i\}$	$\{A_{2g}\}$
	228	$\{192h, 96g, 96f, 64e, 48d, 32c, 16a\}$	$\{A_{2g}\}$
	229	$\{96l, 48i\}$	$\{A_{2g}\}$
	230	$\{96h, 48g, 48f, 32e, 24d, 24c, 16b, 16a\}$	$\{A_{2g}\}$
432	207	$\{24k, 12h, 8g\}$	$\{A_2\}$
	208	$\{24m, 12j, 12i, 12h, 8g, 6d, 2a\}$	$\{A_2\}$
	209	$\{96j, 48i, 48h, 48g, 32f, 24d, 8c\}$	$\{A_2\}$
	210	$\{96h, 48f, 32e, 8b, 8a\}$	$\{A_2\}$
	211	$\{48j, 24i, 24h, 24g, 16f, 8c\}$	$\{A_2\}$
	212	$\{24e, 8c\}$	$\{A_2\}$
	213	$\{24e, 8c\}$	$\{A_2\}$
	214	$\{48i, 24h, 24g, 24f, 16e, 12d, 12c, 8b, 8a\}$	$\{A_2\}$
$\bar{4}$**3m**	215	$\{24j, 12h\}$	$\{A_2\}$
	216	$\{96i\}$	$\{A_2\}$
	217	$\{48h, 24f\}$	$\{A_2\}$
	218	$\{24i, 12h, 12g, 12f, 8e, 6b, 2a\}$	$\{A_2\}$
	219	$\{96h, 48g, 48f, 32e, 24d, 24c, 8b, 8a\}$	$\{A_2\}$
	220	$\{48e, 24d, 16c, 12b, 12a\}$	$\{A_2\}$

$\mathbb{R}$, i-even irreps $\Gamma_{\mathbf{N}}$: *can host AM!*

Šmejkal, Sinova, Jungwirth, Phys. Rev. X 12, 031042 (2022)

Spin-orbit free Landau Theory

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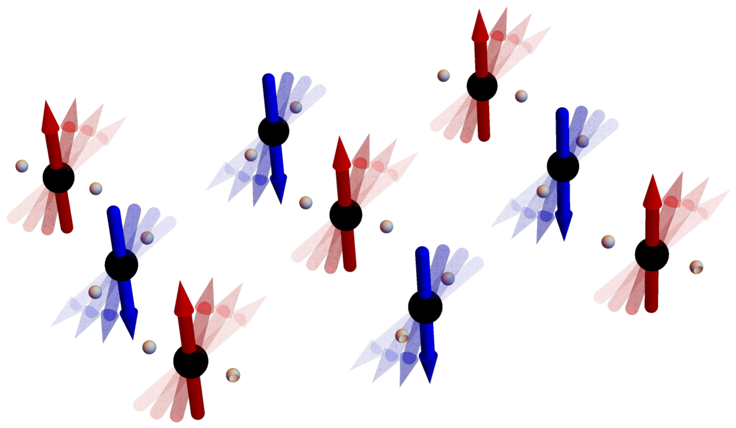

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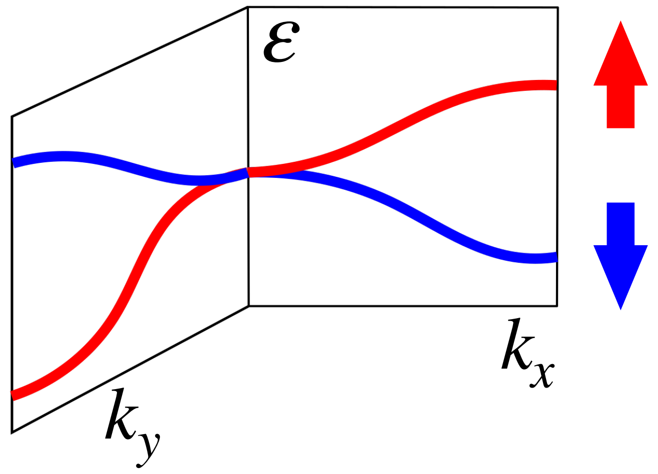

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Hayami, Yanagi, Kusunose J. Phys. Soc. Jpn. 88, 123702 (2019)

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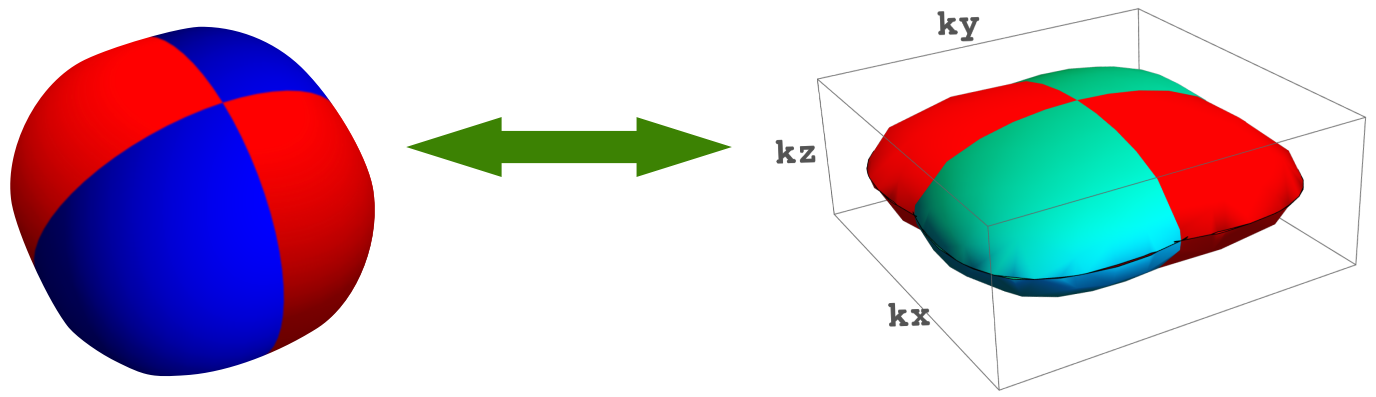
Multipole $\int d^3r\, xy\, \mathbf{m}(\mathbf{r})$

k-space spin splitting $k_x k_y\, \mathbf{s}$



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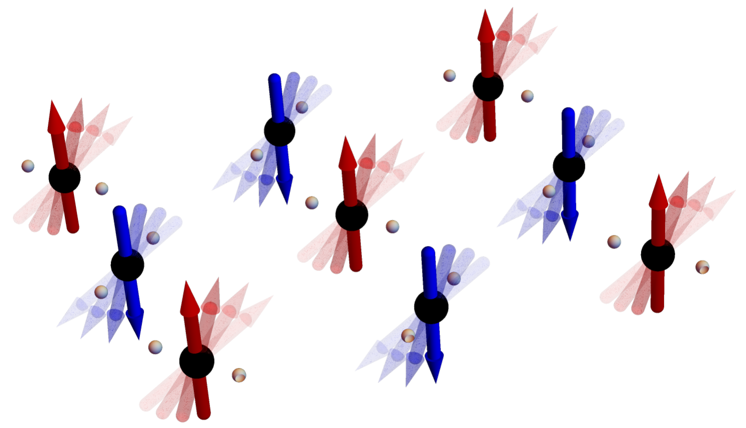

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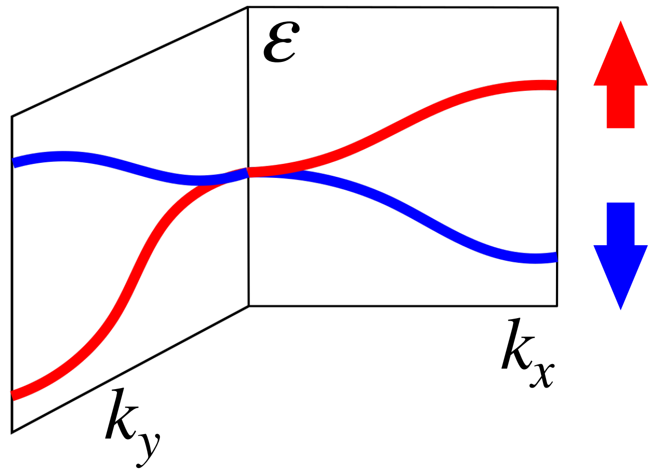

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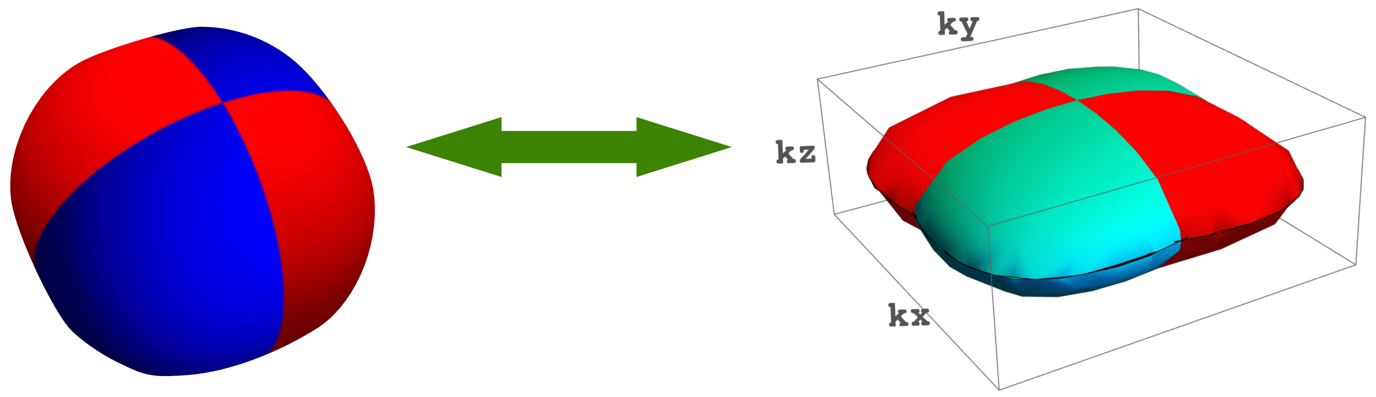

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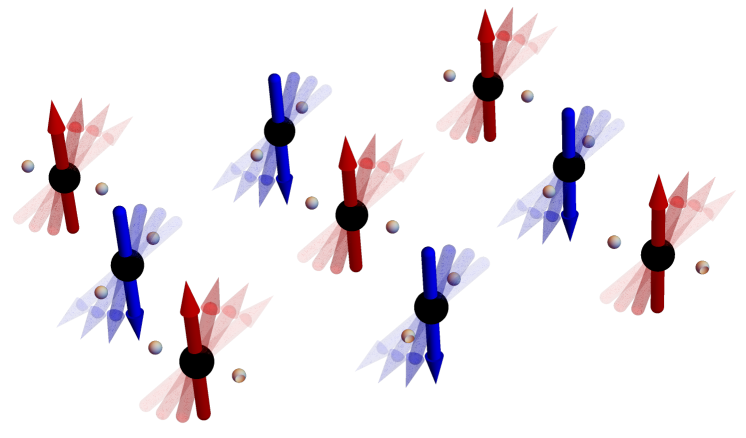

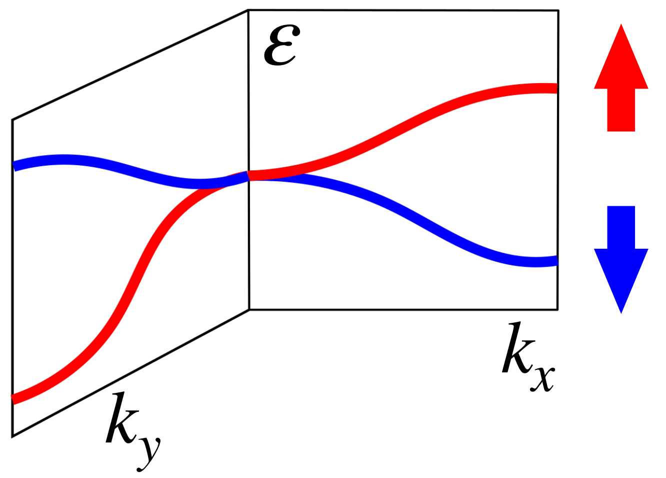

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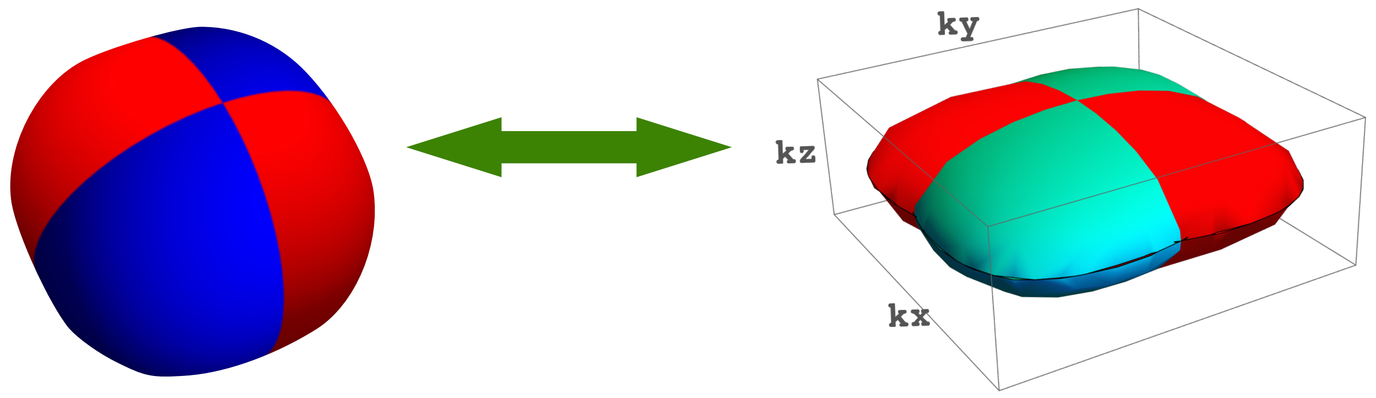

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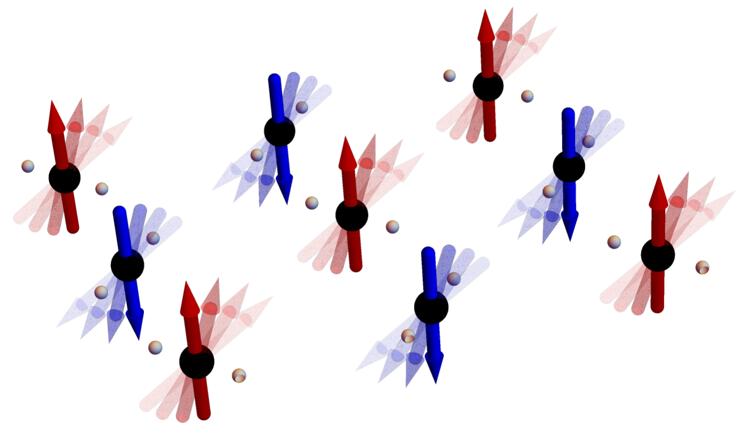

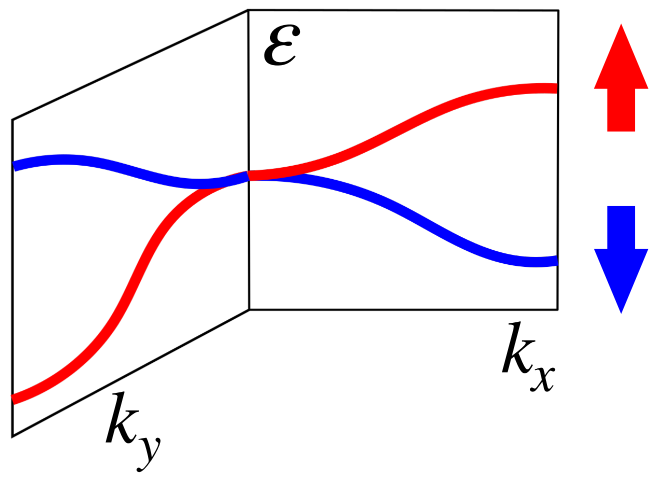

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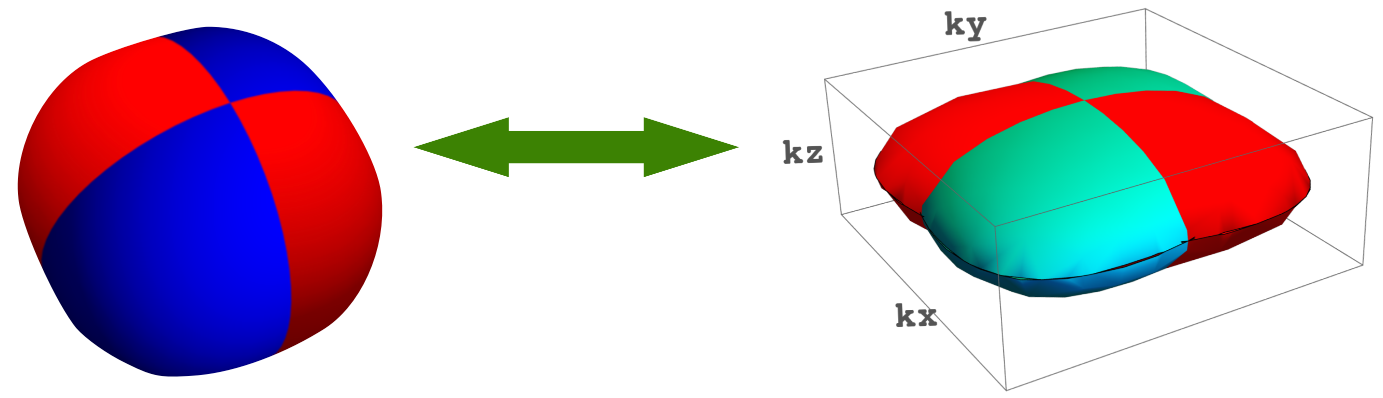

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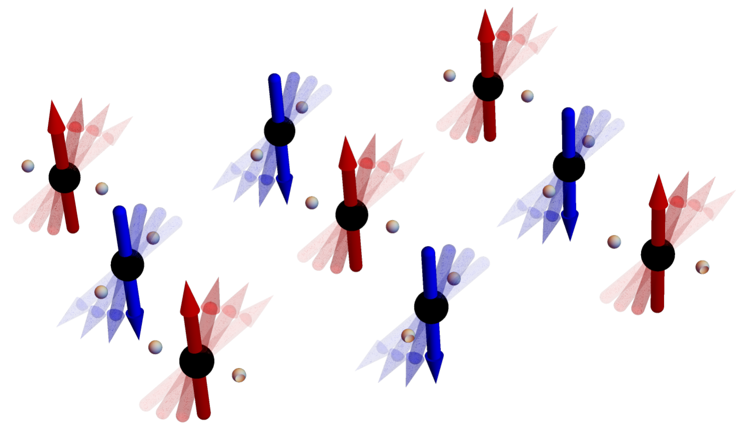

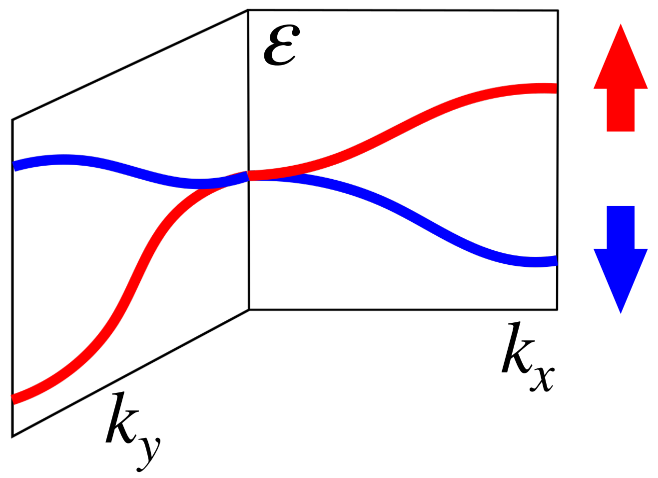

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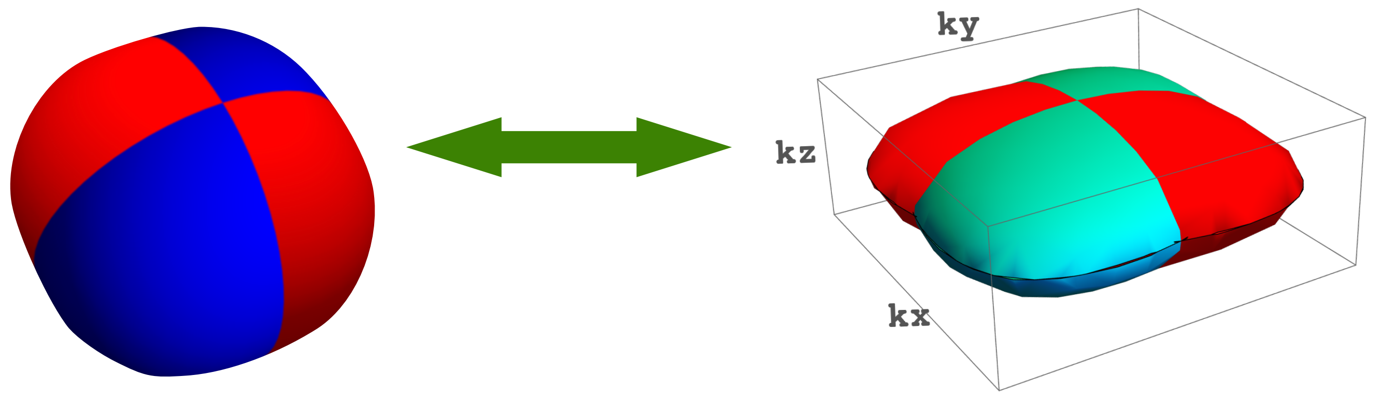

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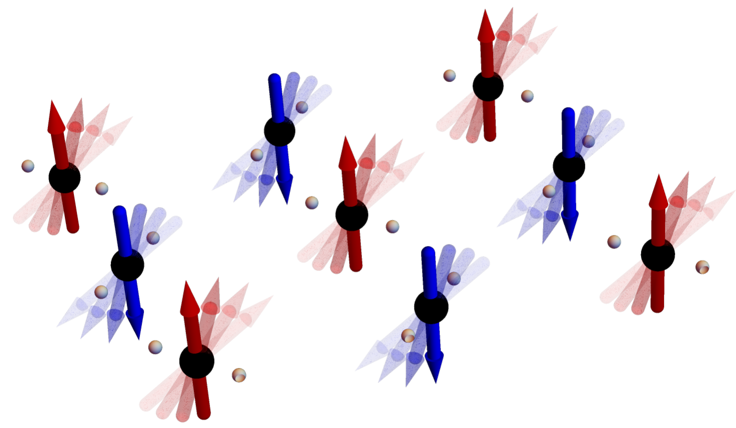

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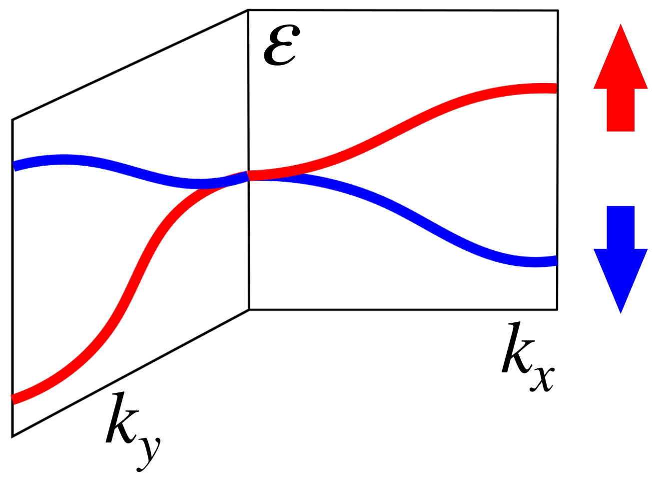

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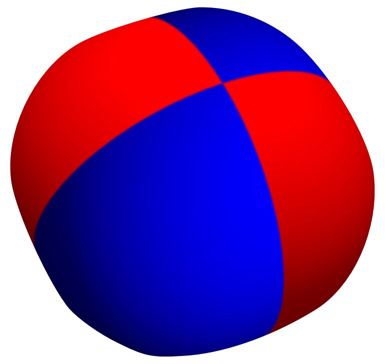

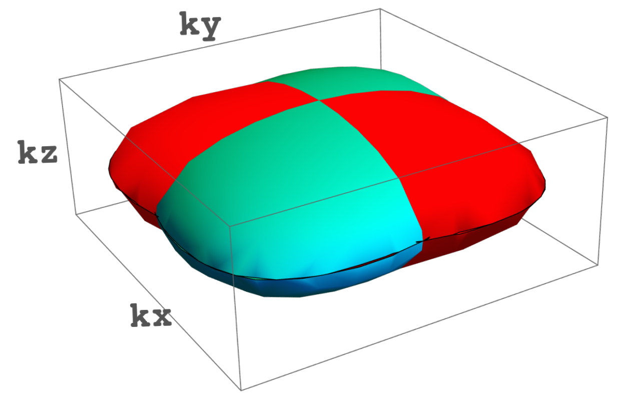

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Just **54** possible SO-free Landau theories for collinear altermagnets
(whose chemical and magnetic unit cells coincide)

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Real Altermagnets

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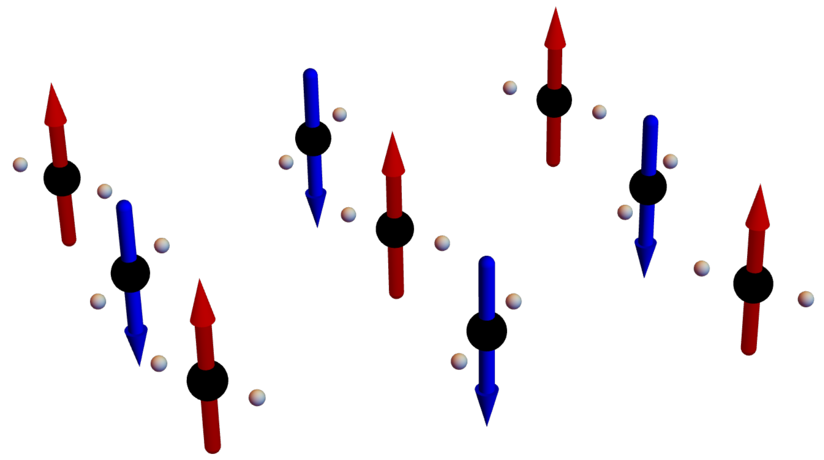

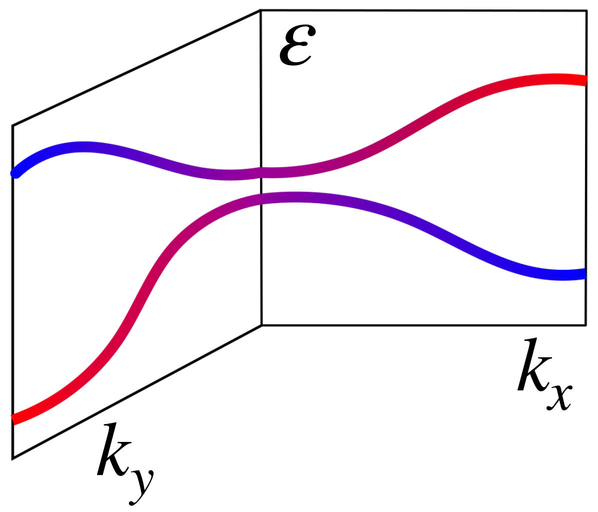

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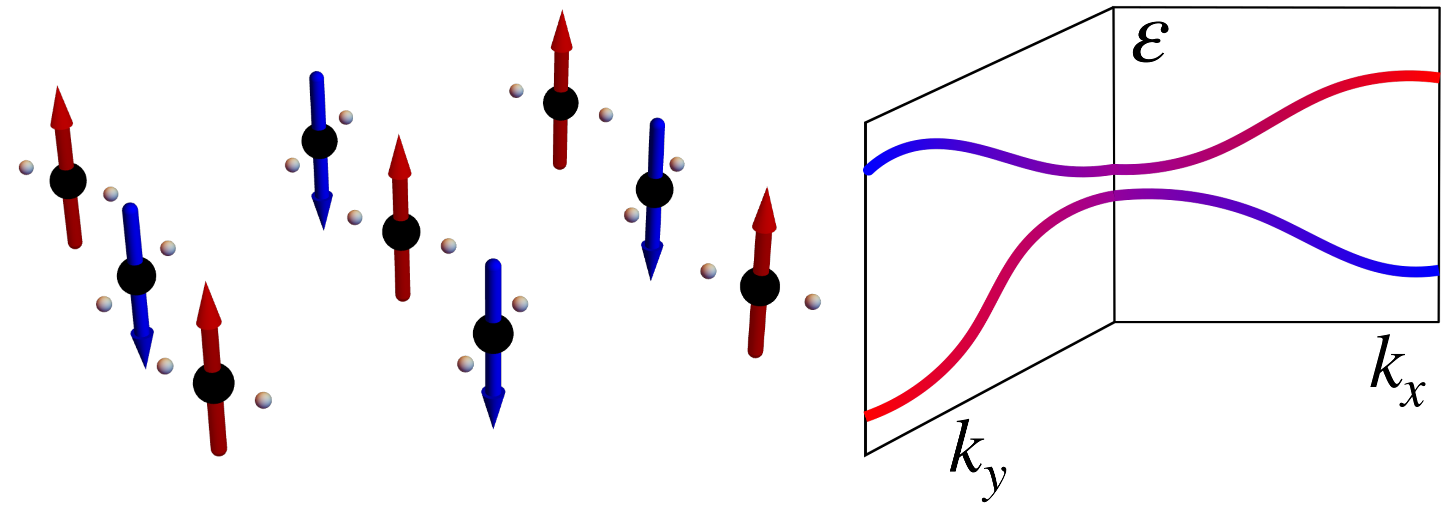

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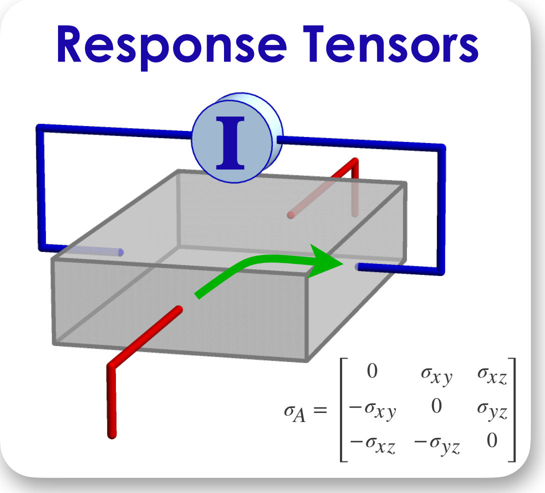

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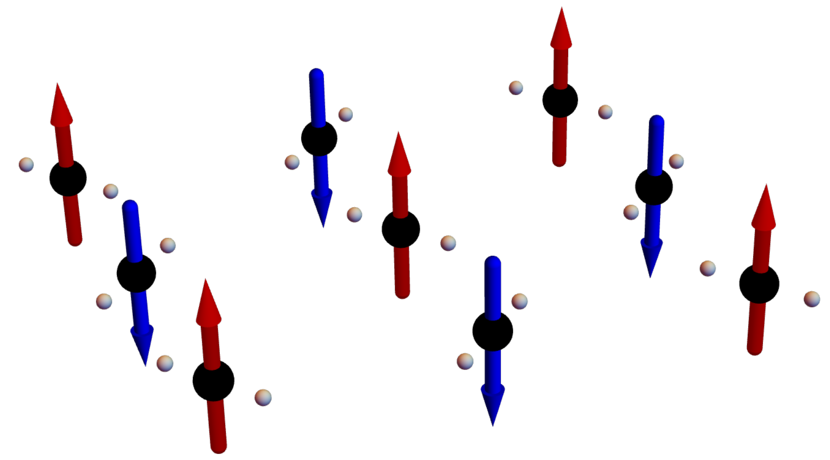

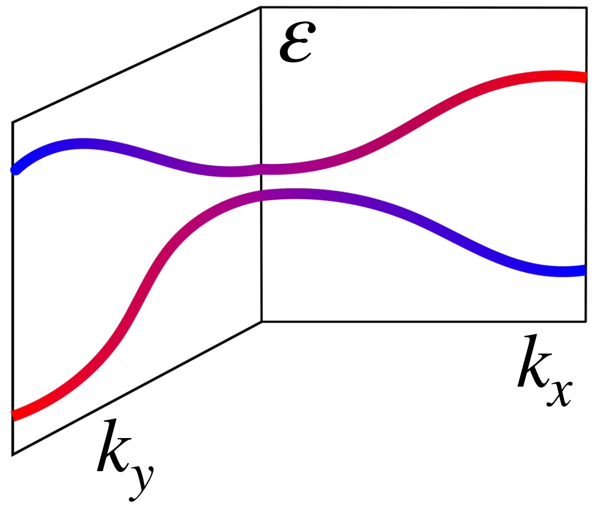

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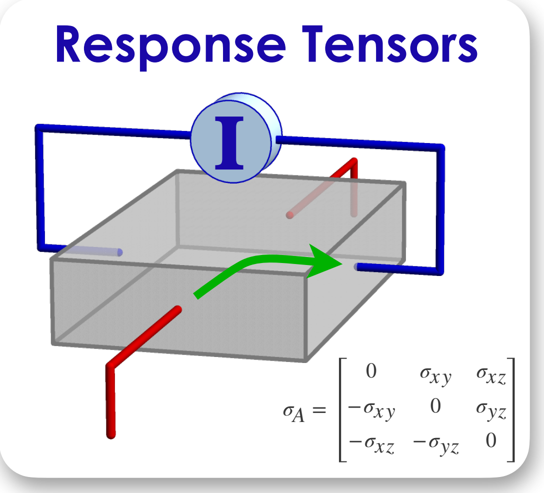

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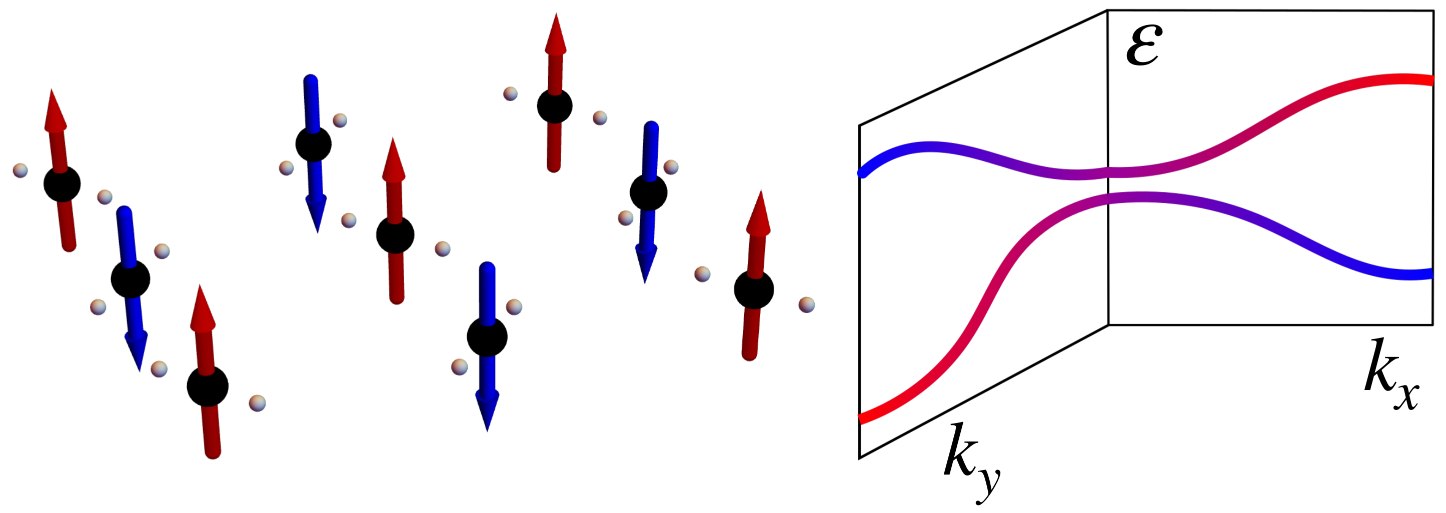

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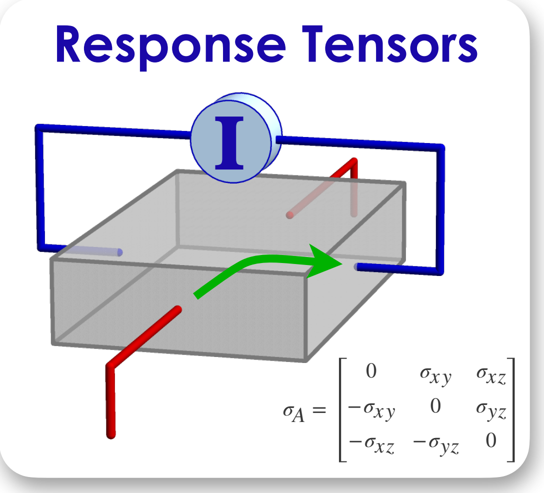

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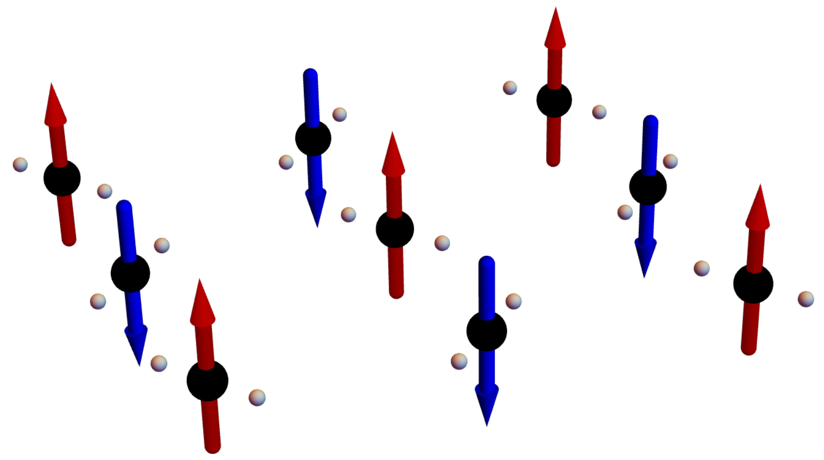

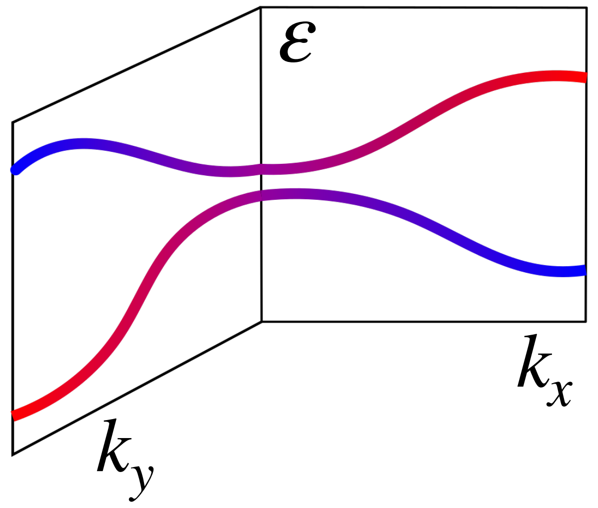

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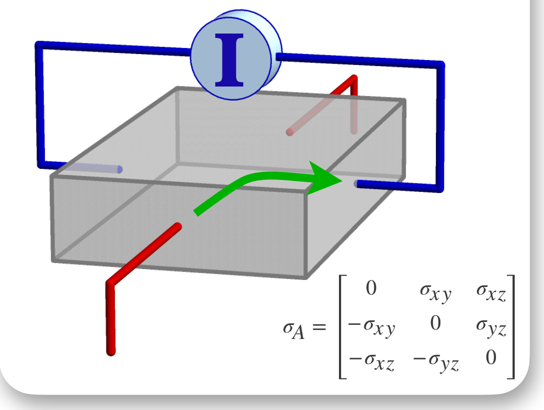

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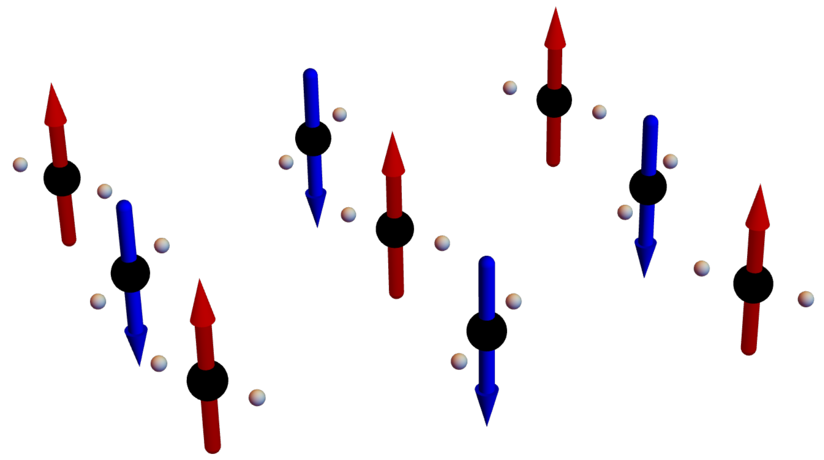

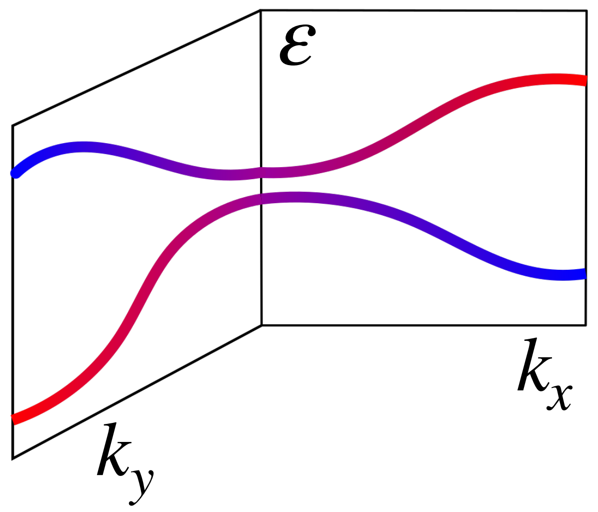

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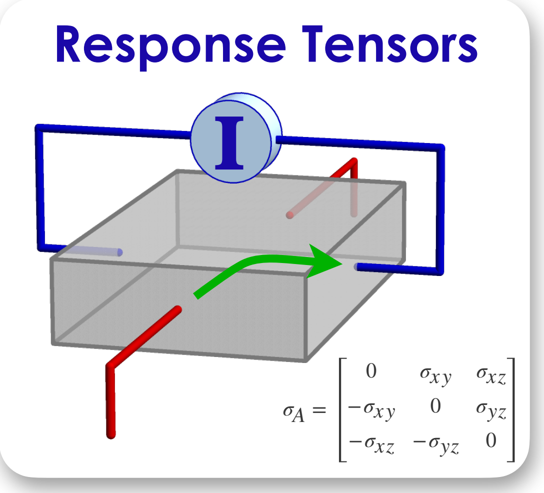

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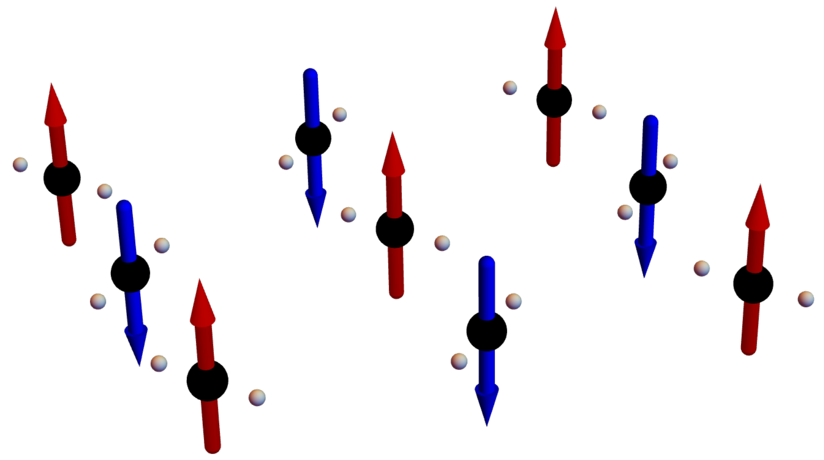

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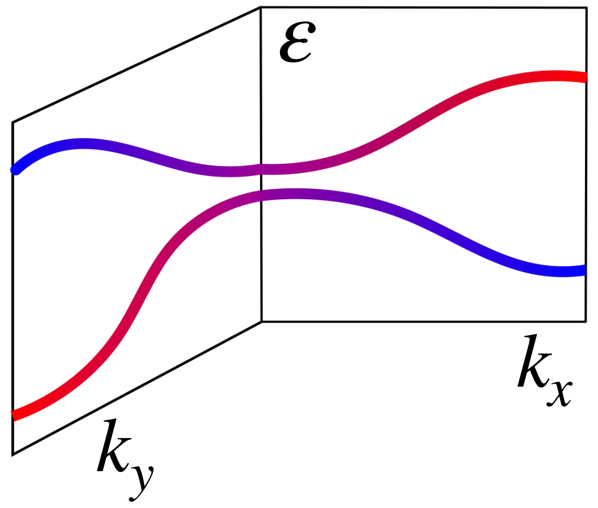

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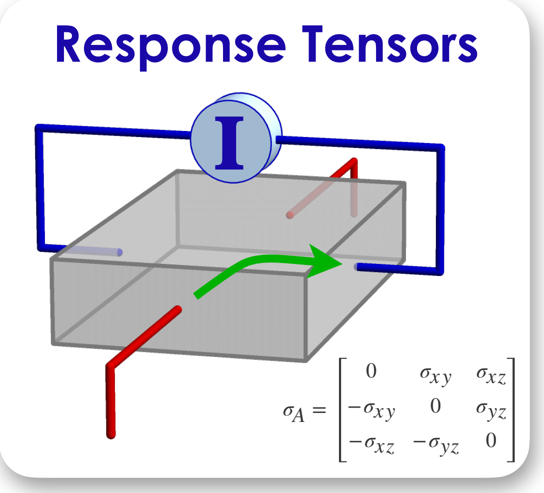

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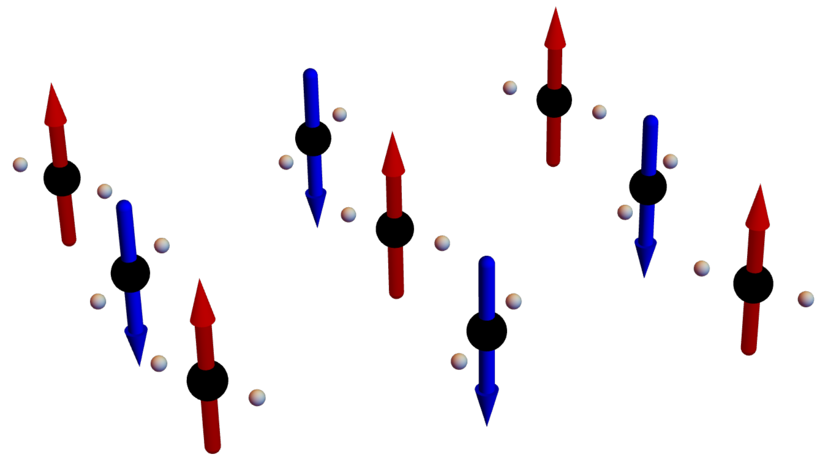
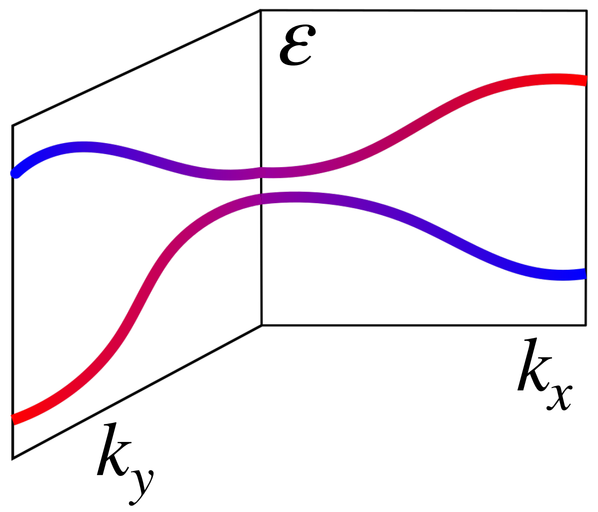




Order parameter: $\mathbf{N} = \mathbf{S}_A - \mathbf{S}_B$

(transforms as $\Gamma_{\mathbf{N}} \otimes aeV$)

Multipolar pseudo-primary order parameter

$$\int d^3r\,[r_{\mu_1}\ldots r_{\mu_n}]\,\mathbf{m}(\mathbf{r})$$

Transforms as $[V^n] \otimes aeV$

Locked spin & orbital space

Spins transform with lattice

Magnetic groups

SOC < Splitting

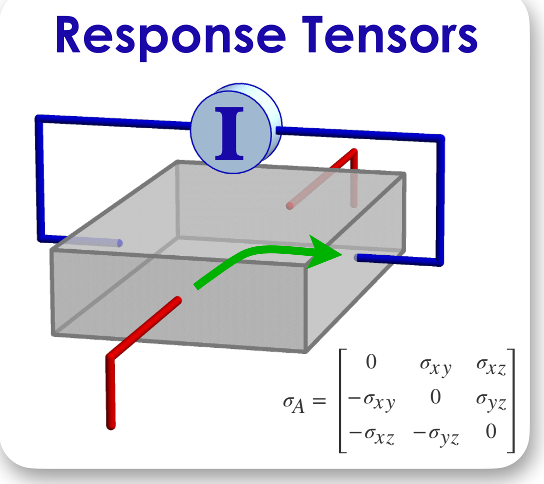
Dominant features from SO-free limit

Presence of SOC changes symmetry

Physical property tensors

ξ: tensor for physical property of interest
(e.g. Hall conductivity, magnetoresistance...)

Γ_ξ SOC paramagnetic group rep.
(point group + time-reversal)



Coupling to $\mathbf{N}$

Requires that

$$\Gamma_{\mathbf{N}} \in \Gamma_\xi \otimes aeV$$

When is this **guaranteed?**

Since we already know that

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HS, McClarty, Rau, Romhányi, Phys. Rev. Research 7, 033301 (2025)

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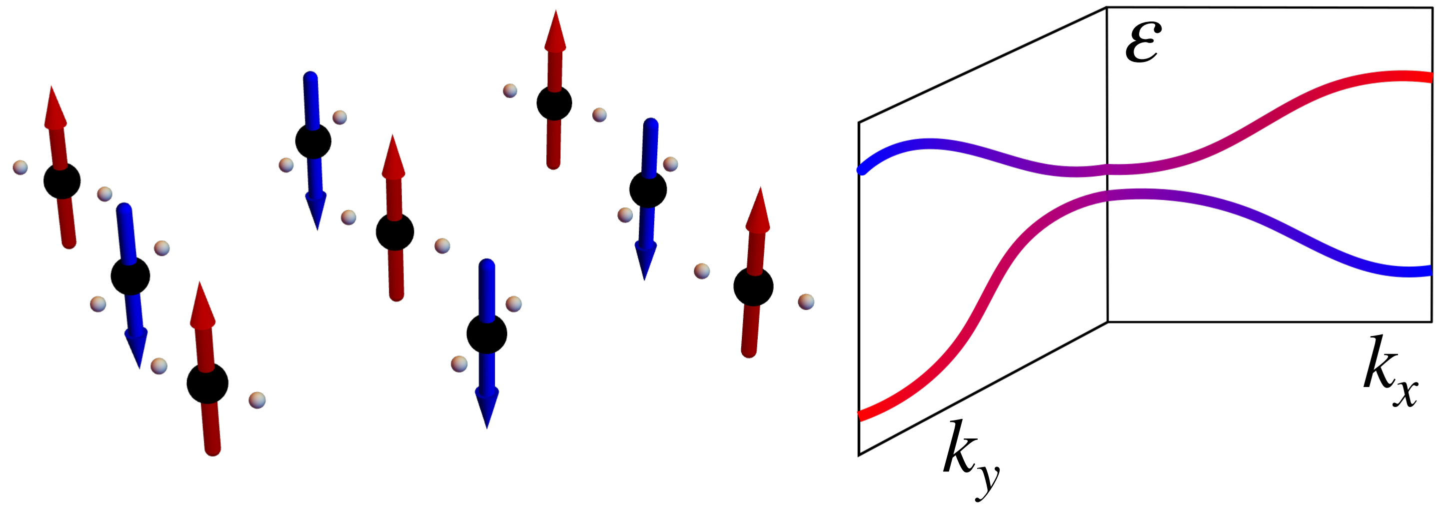

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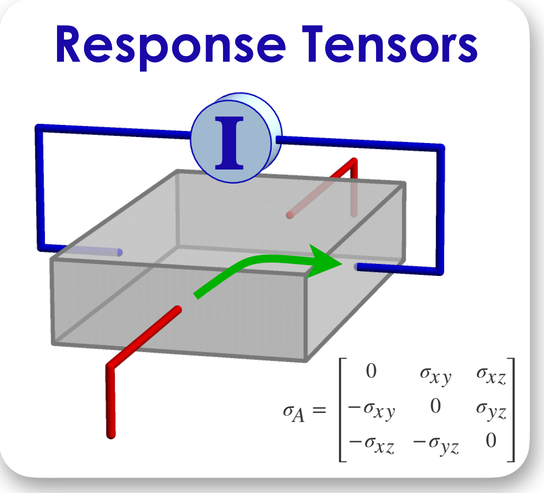

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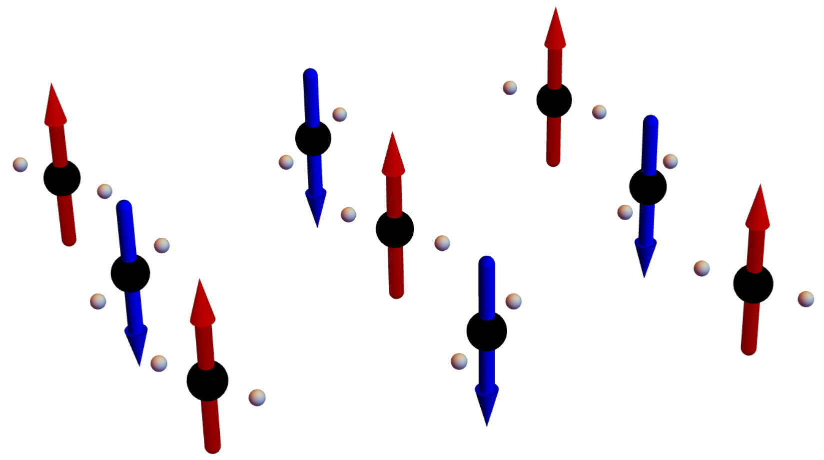

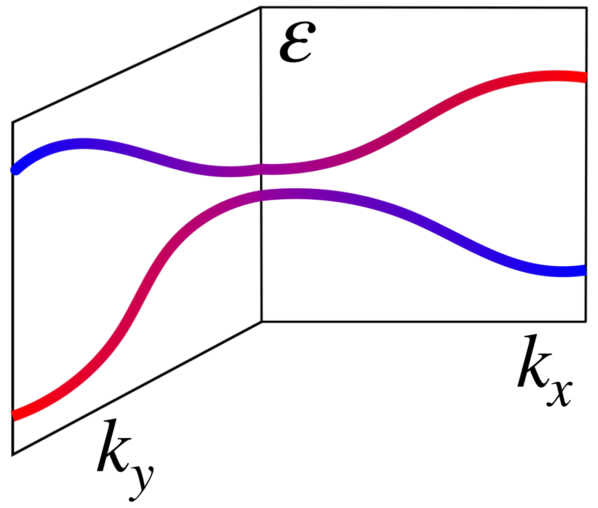

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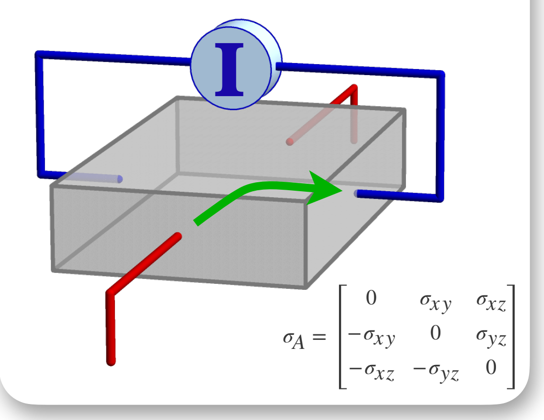

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Just **4 classes** of observable properties ξ according to n

Multipole rank (n)	Representation Γ_ξ
1	$aV,\ aeV^2$
2	aeV
3	aeV^2
4, 6	$aeV[V^2]$

Inherently altermagnetic!

(Can distinguish AFM from AM)

HS, McClarty, Rau, Romhányi, Phys. Rev. Research 7, 033301 (2025)

Spin-orbit coupled Landau Theory

Γ_ξ	n	Quantity (ξ)	Defining equation	Tensor part
aV	1	Polar Toroidal Moment T_i	-	Full
		Pyrotoroidic tensor r_i	$T_i = r_i \Delta T$	Full
aeV	2	Magnetization M_i	-	Full
		Electric conductivity σ_{ij}	$J_i = \sigma_{ij} E_j$	$\sigma^A_\alpha = \frac{1}{2}\varepsilon_{\alpha ij}\sigma^A_{ij}$
		Soret thermodiffusion tensor s_{ij}	$J_i = s_{ij}(\nabla T)_j$	$s^A_\alpha = \frac{1}{2}\varepsilon_{\alpha ij} s^A_{ij}$
		Thermal conductivity κ_{ij}	$q_i = \kappa_{ij}(\nabla T)_j$	$\kappa^A_\alpha = \frac{1}{2}\varepsilon_{\alpha ij}\kappa^A_{ij}$
		Peltier tensor π_{ij}	$q_i = \pi_{ij} J_j$	$\tilde{S}_\alpha = \frac{1}{2}\varepsilon_{\alpha ij}(\pi^A_{ij} + \beta^A_{ij})$
		Seebeck tensor β_{ij}	$E_i = \beta_{ij}(\nabla T)_j$	
		Spontaneous Faraday effect F_{ij}	-	$F_\alpha = \frac{1}{2}\varepsilon_{\alpha ij} F_{ij}$
aeV^2	1 & 3	Magnetoelectric tensor α_{ij}	$M_i = \alpha_{ij} E_j$	Full
$aeV[V^2]$	4 & 6	Piezomagnetic tensor Λ_{ijk}	$M_i = \Lambda_{ijk}\Sigma_{jk}$	Full
		Second order magnetoelectric tensor α_{ijk}	$M_i = \alpha_{ijk} E_j E_k$	Full
		Magneto-optic Kerr effect z^S_{ijk}	$\varepsilon_{ij} = i z^S_{ijl} H_l$	Full
		Quadratic magneto-optic Kerr effect iC^A_{ijkl}	$\varepsilon_{ij} = C^A_{ijkl} H_k H_l$	$C_{\alpha kl} = \frac{1}{2}\varepsilon_{\alpha ij} C^A_{ijkl}$
		Magnetoresistance R_{ijk}	$E_i = R_{ijk} J_j H_k$	$R^S_{ijk} = \frac{1}{2}(R_{ijk} + R_{jik})$
		Righi-Leduc magnetorhermal tensor Q_{ijk}	$q_i = Q_{ijk}(\nabla T)_j H_k$	$Q^S_{ijk} = \frac{1}{2}(Q_{ijk} + Q_{jik})$
		Ettinghausen tensor M_{ijk}	$q_i = M_{ijk} J_j H_k$	$S_{ijk} = \frac{1}{2}(M^S_{ijk} + N^S_{ijk})$
		Nernst tensor N_{ijk}	$E_i = N_{ijk}(\nabla T)_j H_k$	
		Magnetic resistance tensor T_{ijkl}	$E_i = T_{ijkl} J_j H_k H_l$	$T^A_{\alpha kl} = \frac{1}{2}\varepsilon_{\alpha ij} T^A_{ijkl}$
		Magneto-heat-conductivity tensor $\mathcal{S}_{ijkl}$	$q_i = \mathcal{S}_{ijkl}(\nabla T)_j H_k H_l$	$\mathcal{S}^A_{\alpha kl} = \frac{1}{2}\varepsilon_{\alpha ij}\mathcal{S}^A_{ijkl}$
		Piezoresistivity tensor Π_{ijkl}	$\Delta\rho_{ij} = \Pi_{ijkl}\Sigma_{kl}$	$\Pi^A_{\alpha kl} = \frac{1}{2}\varepsilon_{\alpha ij}\Pi^A_{ijkl}$
		Magneto–Seebek tensor α_{ijkl}	$E_i = \alpha_{ijkl}(\nabla T)_j H_k H_l$	$\tilde{A} = \frac{1}{4}\varepsilon_{\alpha ij}(\alpha^A_{ijkl} - P^A_{ijkl})$
		Magneto-Peltier tensor P_{ijkl}	$q_i = P_{ijkl} H_k H_l H_j$	

…operty tensors

…perty of interest
…gnetoresistance…)

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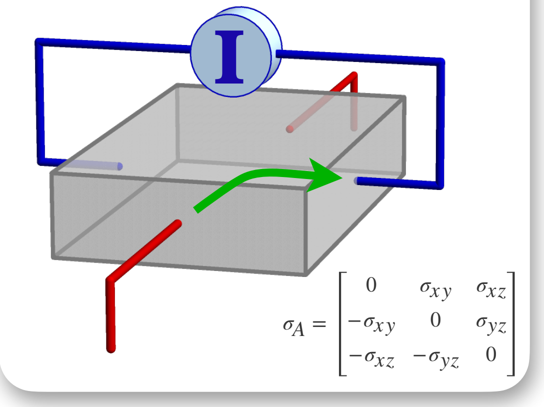

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Example: MnTe

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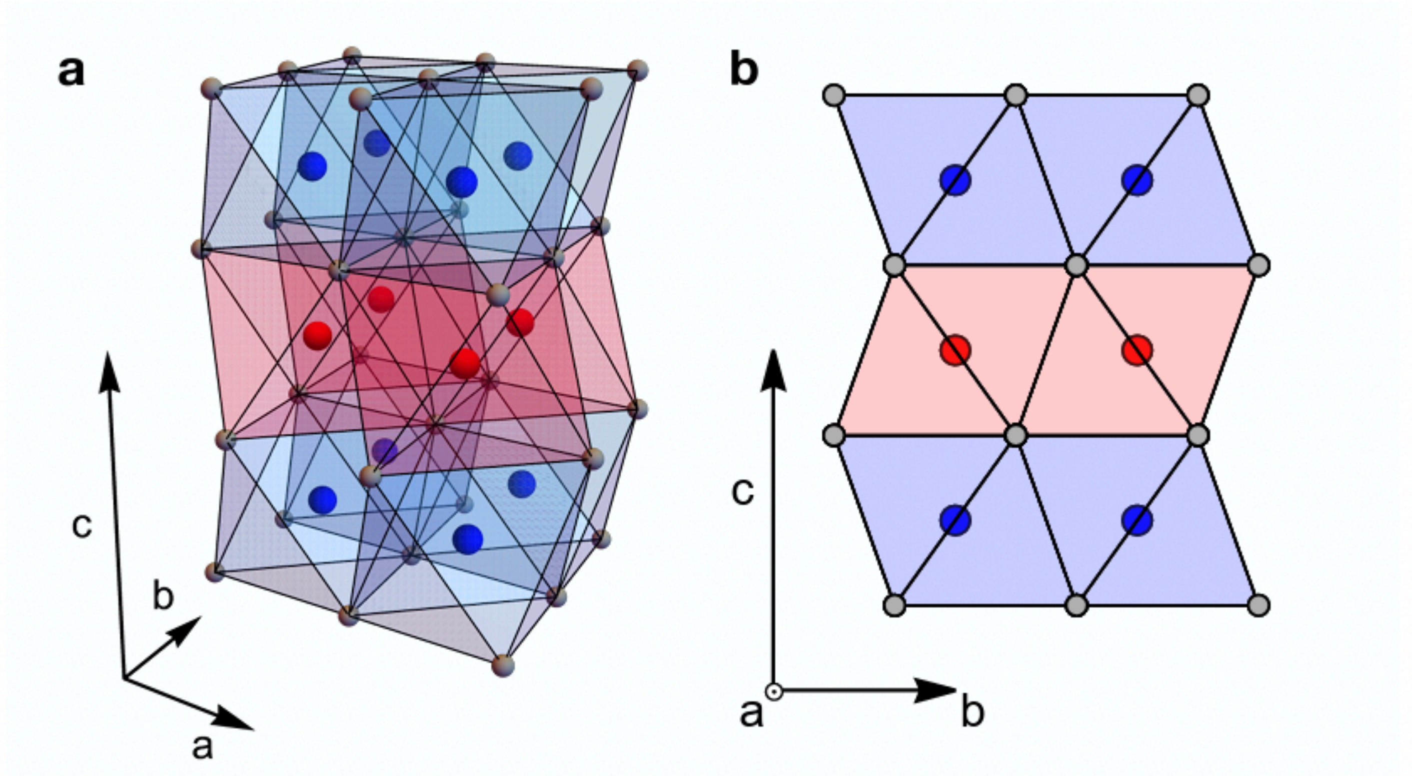

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Point group: $6/mmm$

Irrep: $\Gamma_{\mathbf{N}} = B_{2g}$

Krempasky et al. Nature volume 626, pages 517–522 (2024)

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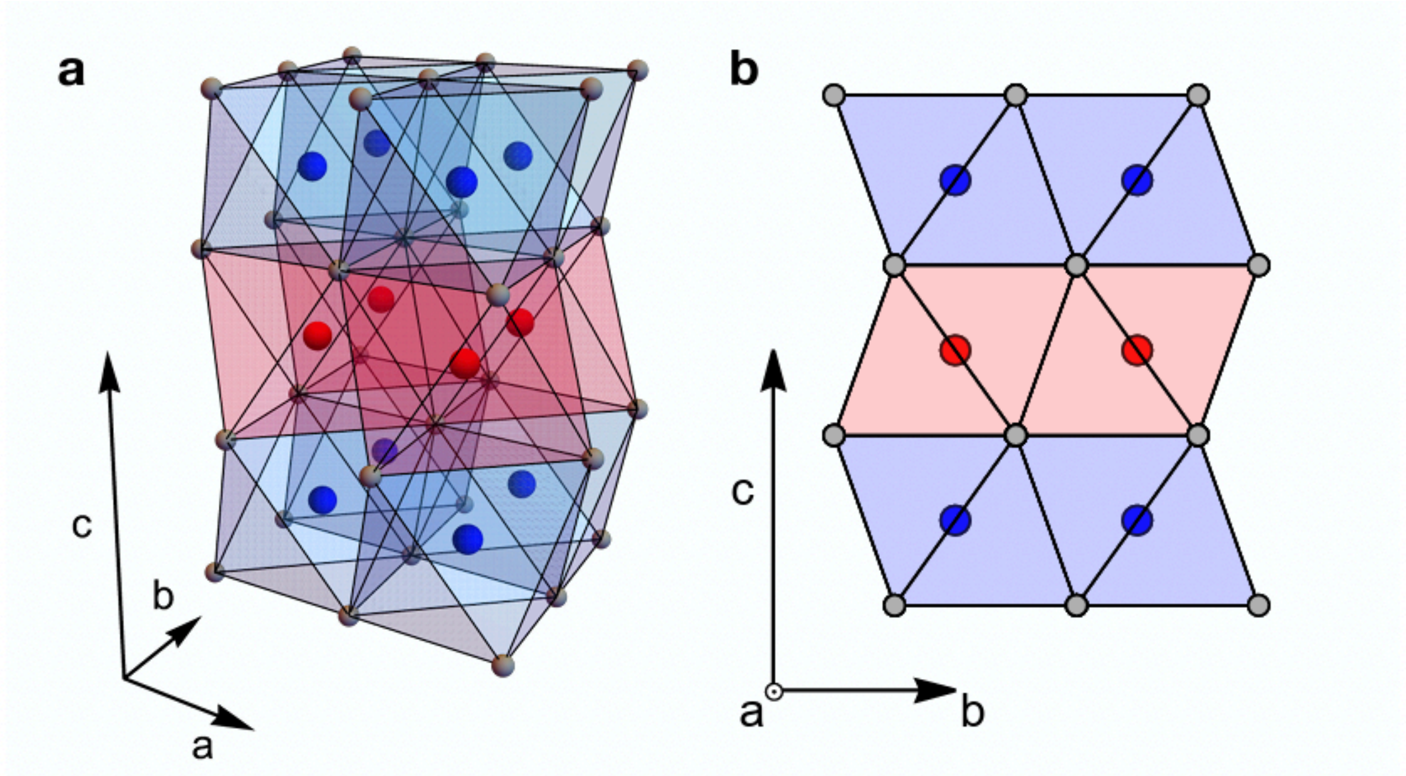

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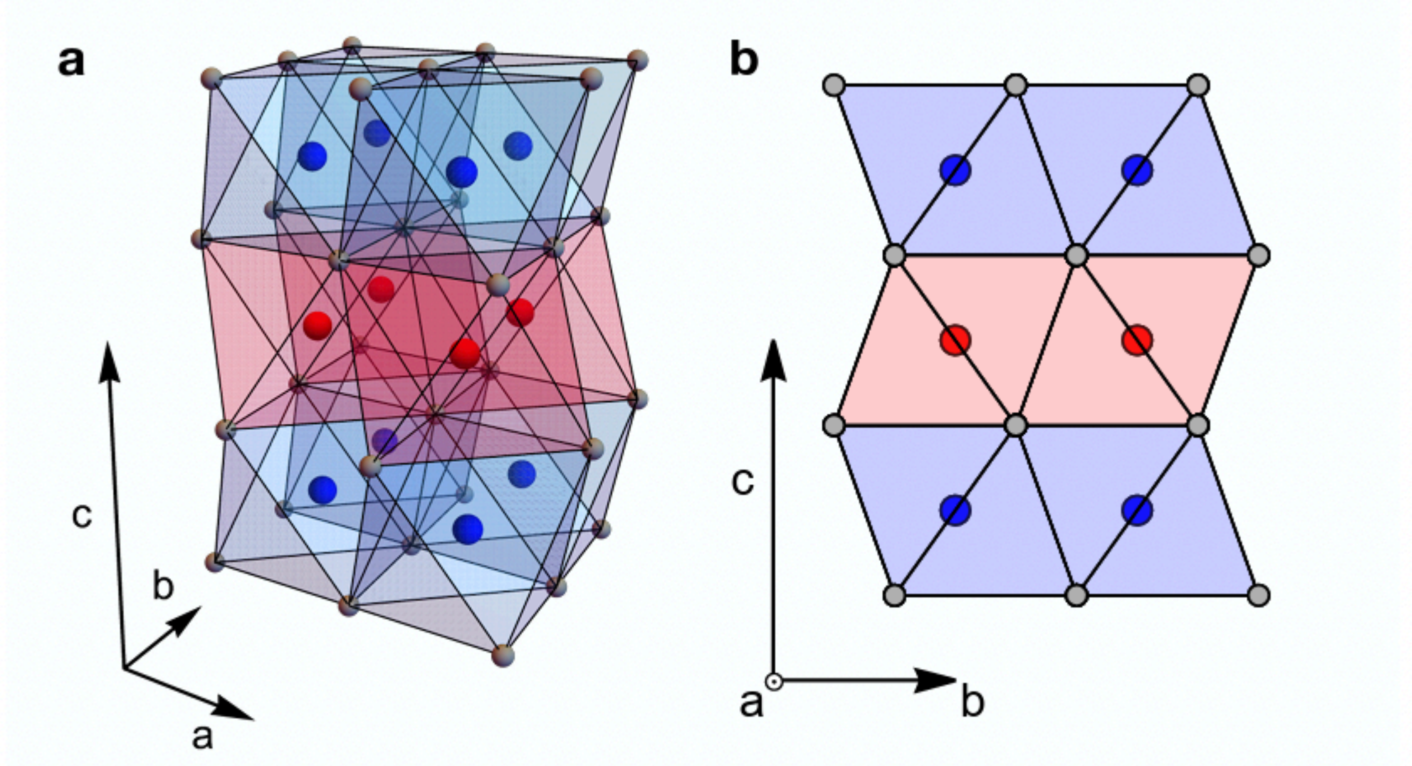

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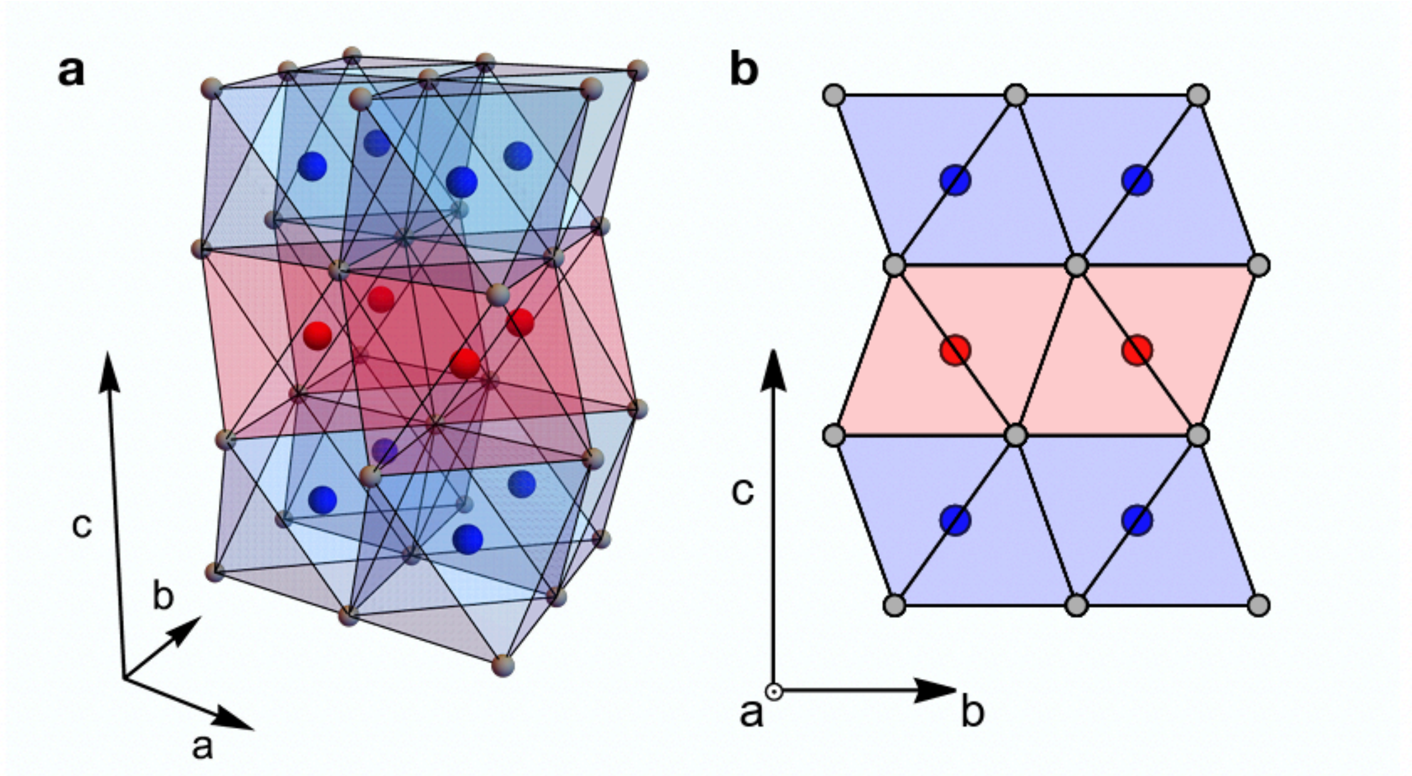

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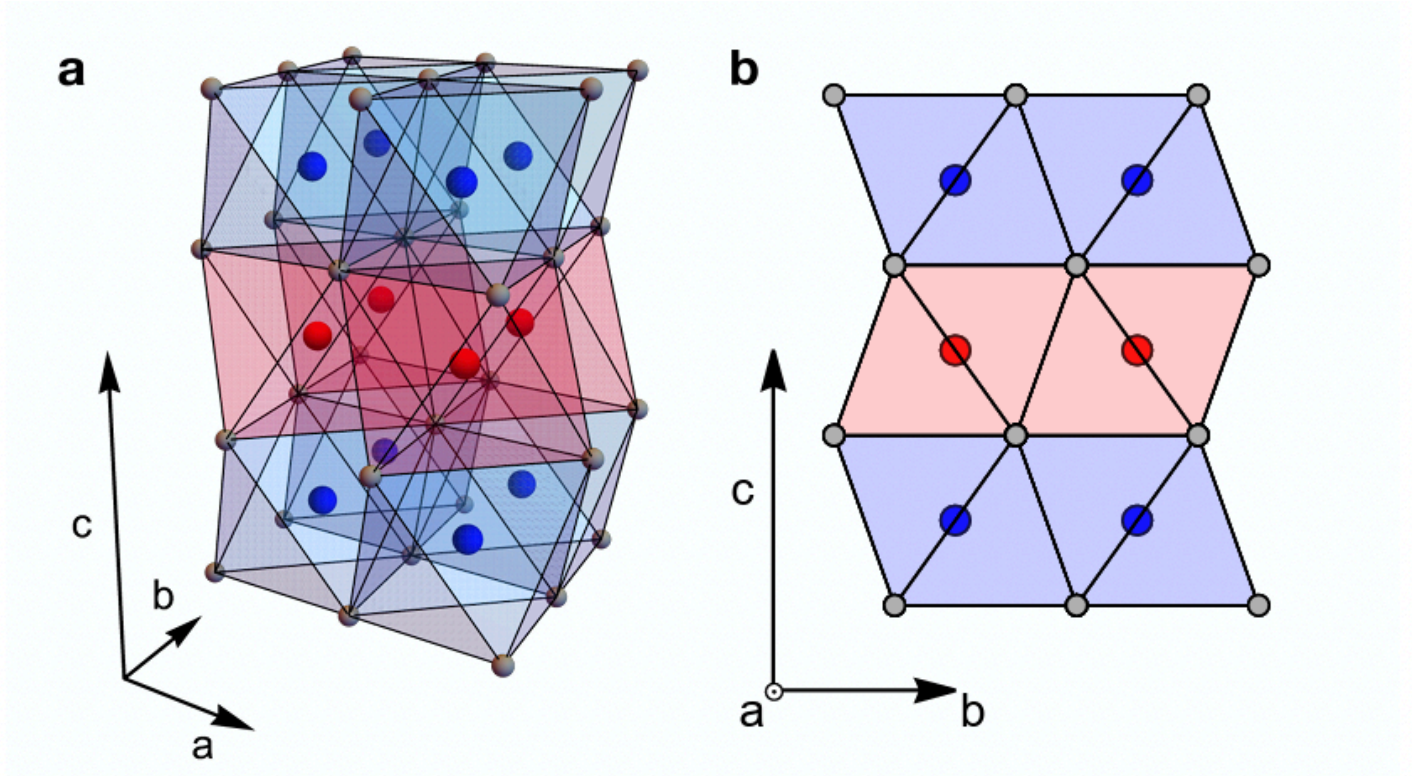

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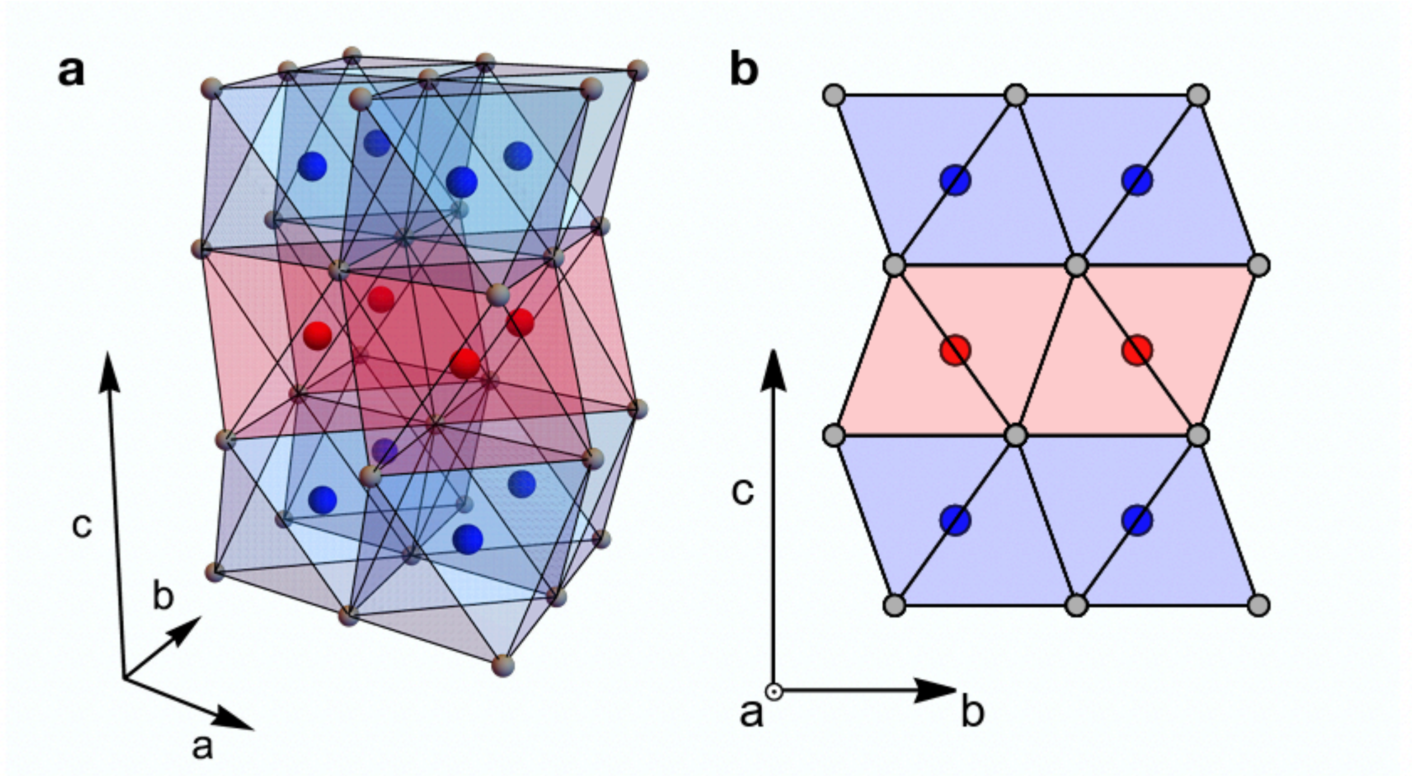

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$$n = 4$$

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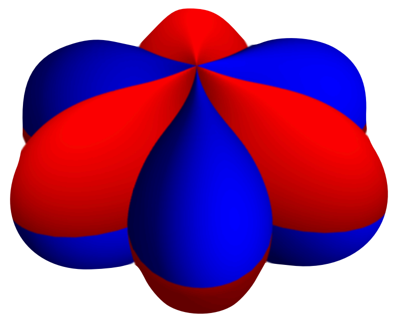

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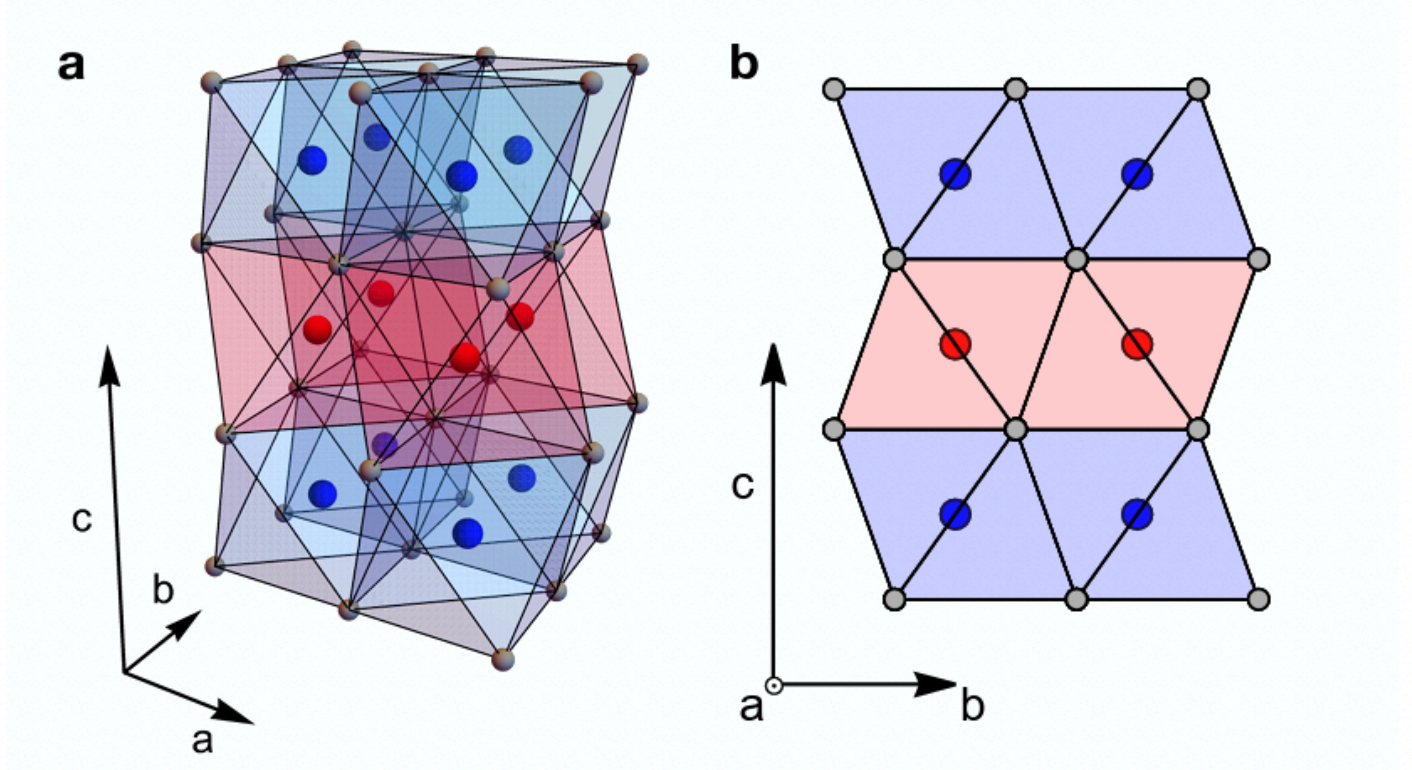

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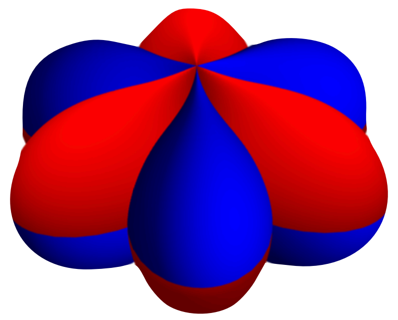

SOC Landau Theory

Guaranteed quantities $\xi \quad aeV[V^2]$

Magnetoresistance, piezomagnetism, Nernst, Ettinghausen, magneto-optic Kerr, etc…

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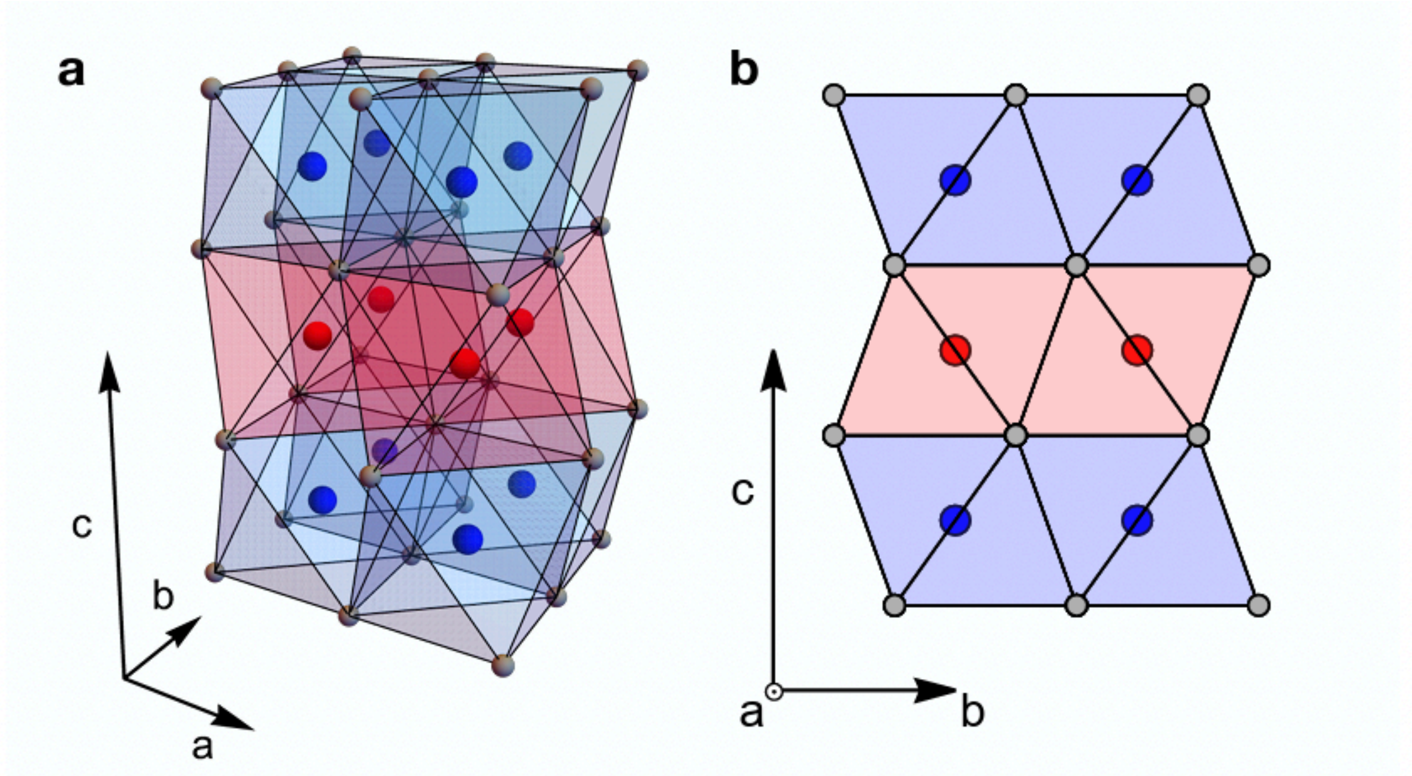

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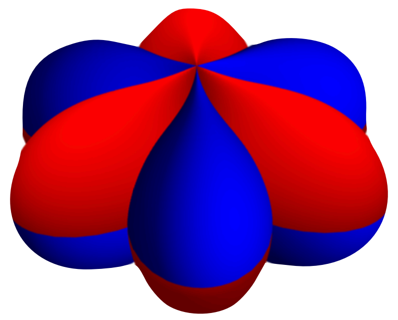

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TABLE IV. Transformation properties of the order parameter $\mathbf{N}$ in MnTe and the part of the magnetoresistance that is symmetric in the first two indices.

Irrep.	Order parameter	Magnetoresistance component
B_{1g}	N_z	$2R^S_{xyx} + R^S_{xxy} - R^S_{yyy}$
E_{2g}	$\begin{pmatrix} N_x \\ N_y \end{pmatrix}$	$\begin{pmatrix} 2R^S_{xyz} \\ R^S_{xxz} - R^S_{yyz} \end{pmatrix}$ $\begin{pmatrix} R^S_{yzx} + R^S_{xzy} \\ R^S_{xzx} - R^S_{yzy} \end{pmatrix}$

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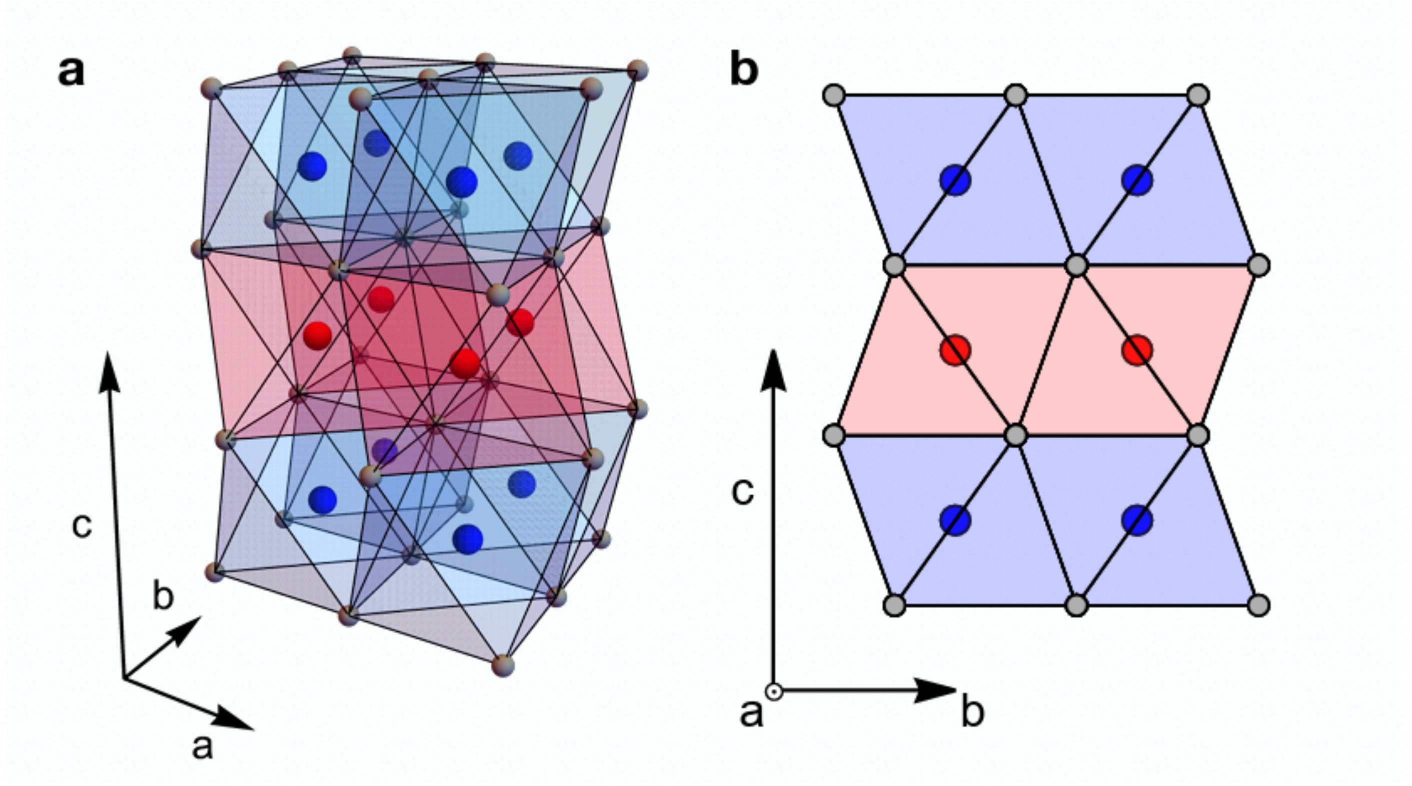

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SO-free Landau Theory

Lowest order multipole:

$$\int d^3r\,[r_{\mu_1}\ldots r_{\mu_n}]\,\mathbf{m}(\mathbf{r})$$

$$V = A_{1u} \oplus E_{2u}$$ ✗

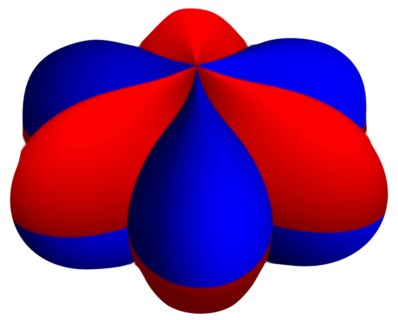
$$[V^2] = 2A_{1g} \oplus A_{2g} \oplus E_{2g} \oplus 2E_{1g}$$ ✗

$$[V^3] = 3A_{1u} \oplus 4A_{2u} \oplus B_{2u} \oplus B_{1u} \oplus 3E_{2u} \oplus 6E_{1u}$$ ✗

$$[V^4] = 10A_{1g} \oplus 9A_{2g} \oplus 4B_{2g} \oplus 4B_{1g} \oplus 11E_{2g} \oplus 16E_{1g}$$ ✓

$$n = 4$$

$$\int d^3r\, yz\,(y^2 - 3x^2)\,\mathbf{m}(\mathbf{r})$$



SOC Landau Theory

Guaranteed quantities $\xi \quad aeV[V^2]$

Magnetoresistance, piezomagnetism, Nernst, Ettinghausen, magneto-optic Kerr, etc...

TABLE IV. Transformation properties of the order parameter $\mathbf{N}$ in MnTe and the part of the magnetoresistance that is symmetric in the first two indices.

Irrep.	Order parameter	Magnetoresistance component
B_{1g}	N_z	$2R^S_{xyx} + R^S_{xxy} - R^S_{yyy}$
E_{2g}	$\begin{pmatrix} N_x \\ N_y \end{pmatrix}$	$\begin{pmatrix} 2R^S_{xyz} \\ R^S_{xxz} - R^S_{yyz} \end{pmatrix}$ $\begin{pmatrix} R^S_{yzx} + R^S_{xzy} \\ R^S_{xzx} - R^S_{yzy} \end{pmatrix}$

Néel components transform as

$$\left\{N_x, N_y\right\} \sim E_{2g} \qquad N_z \sim B_{1g}$$

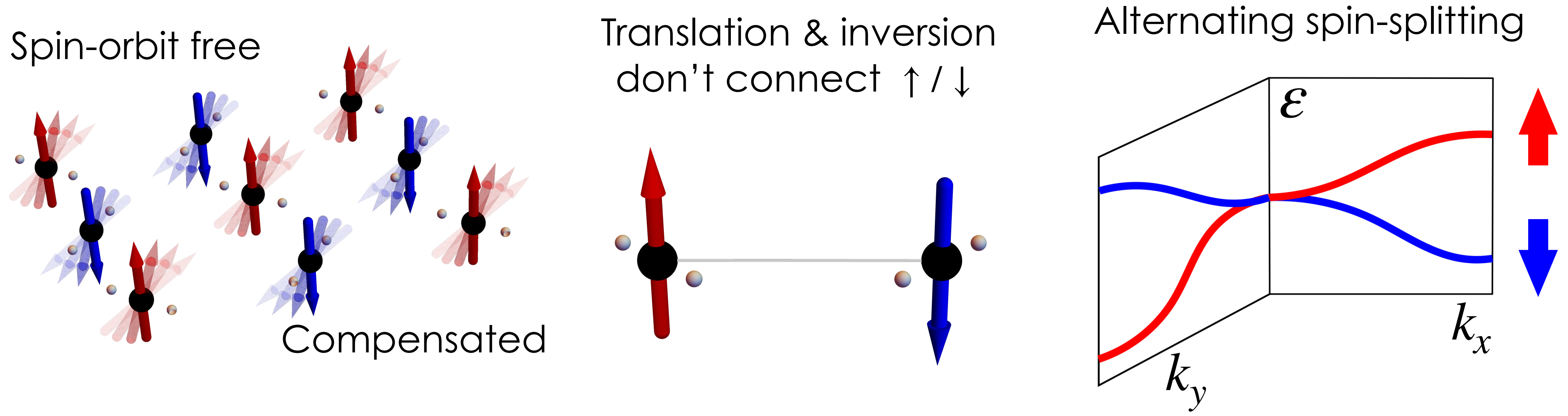
Observed experimentally!

Krempasky et al. Nature volume 626, pages 517–522 (2024)

HS, McClarty, Rau, Romhányi, Phys. Rev. Research 7, 033301 (2025)

Collinear AM Landau theory summary

Collinear AM Landau theory summary

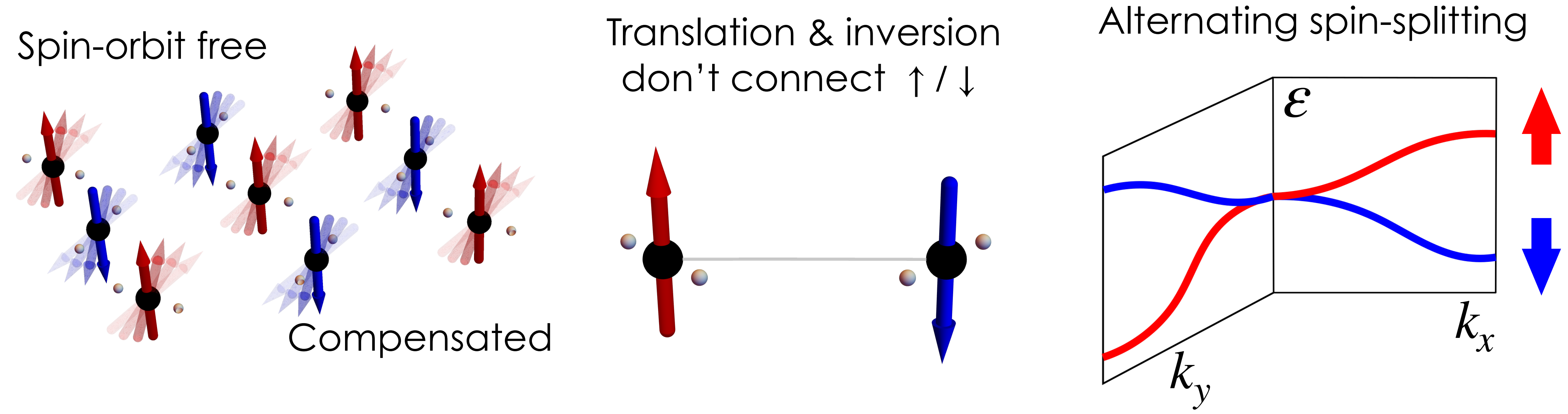


Altermagnetism **defined** by features inherited from ideal SO-free limit

Derive *all* SO-free Landau theories

- ✦ All structures (space groups WP) compatible with AM
- ✦ All irreps characterizing AM $\mathbf{N}$
- ✦ All minimal multipoles coupling to AM $\mathbf{N}$

Collinear AM Landau theory summary



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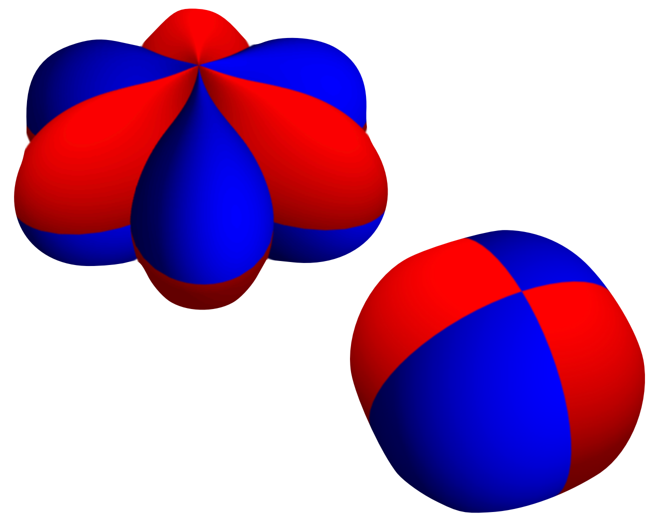
TABLES!

Bridge SO-free & SOC limits

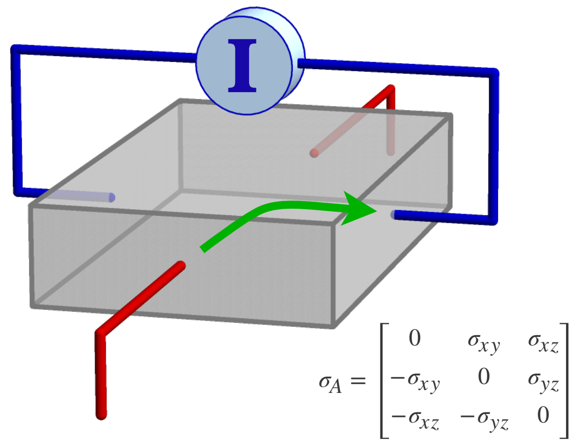
- ✦ SO-free multipole gives insight into symmetry with SOC
- ✦ Classify response tensors by symmetry type & multipole order

TABLES!



Multipole rank (n)	Representation Γ_ξ
1	$aV,\ aeV^2$
2	aeV
3	aeV^2
4, 6	$aeV[V^2]$

Response Tensors



Symmetry-allowed effects with SOC **determined** by SO-free multipoles

Thanks!

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