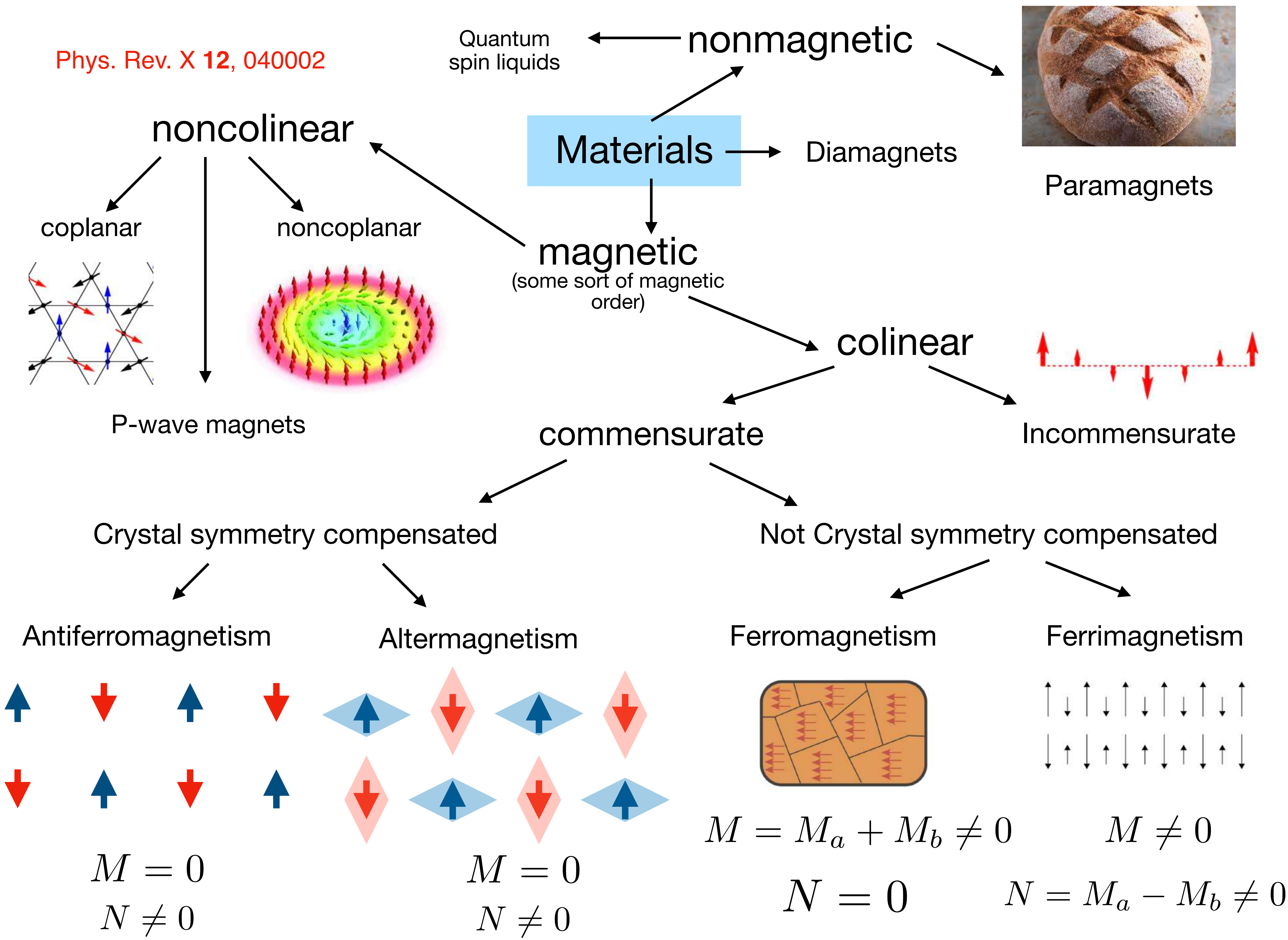
QUANTUM MAGNETISM: ALTERMAGNETS

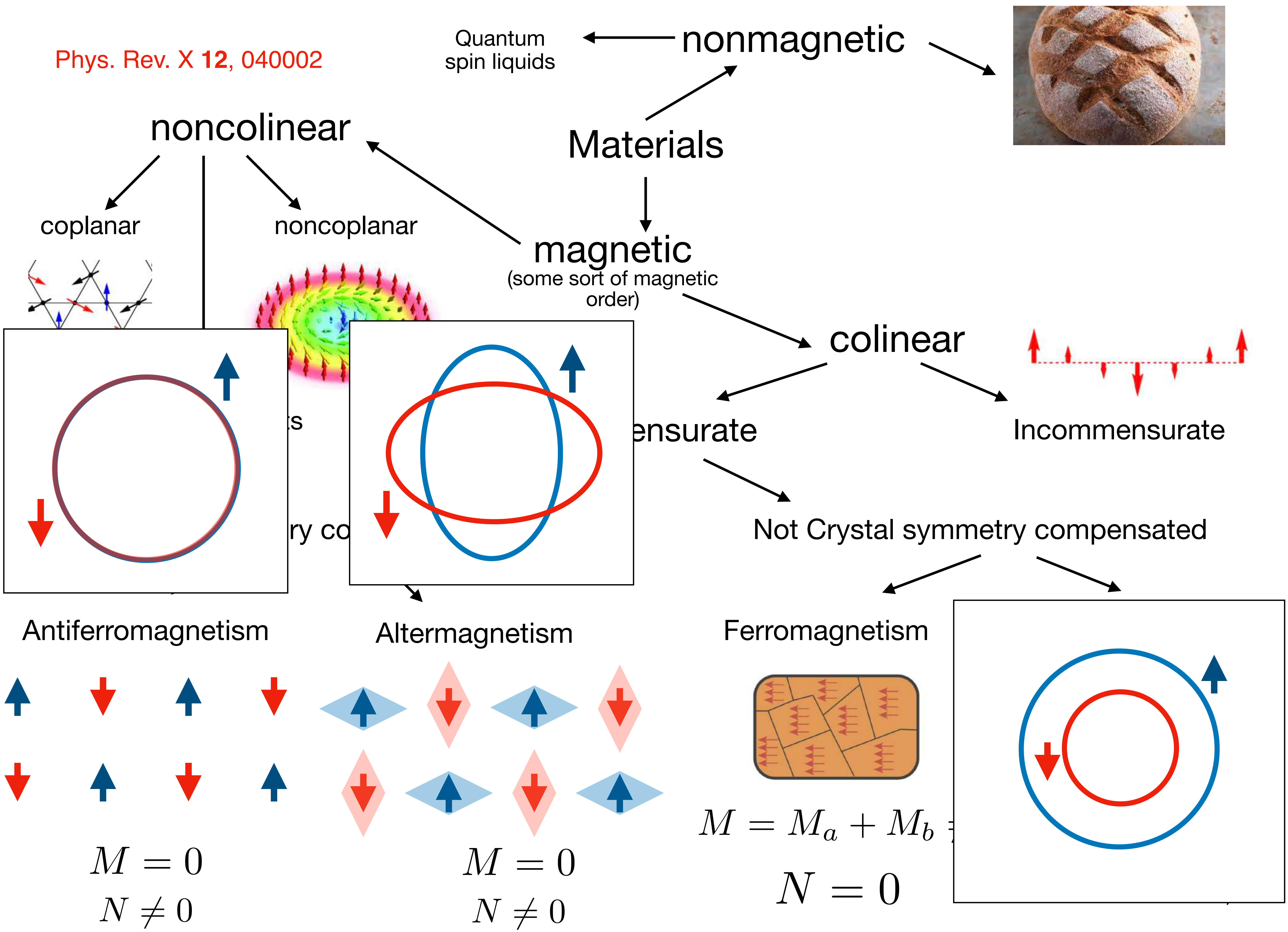
EXCELENCIA SEVERO OCHOA

Alberto Cortijo

icmm



Phys. Rev. X **12**, 040002
Quantum spin liquids
nonmagnetic
Materials
Diamagnets
Paramagnets
noncolinear
coplanar
noncoplanar
P-wave magnets
magnetic
(some sort of magnetic order)
colinear
commensurate
Incommensurate
Crystal symmetry compensated
Not Crystal symmetry compensated
Antiferromagnetism
Altermagnetism
Ferromagnetism
Ferrimagnetism
$M = 0$
$N \neq 0$
$M = 0$
$N \neq 0$
$M = M_a + M_b \neq 0$
$N = 0$
$M \neq 0$
$N = M_a - M_b \neq 0$



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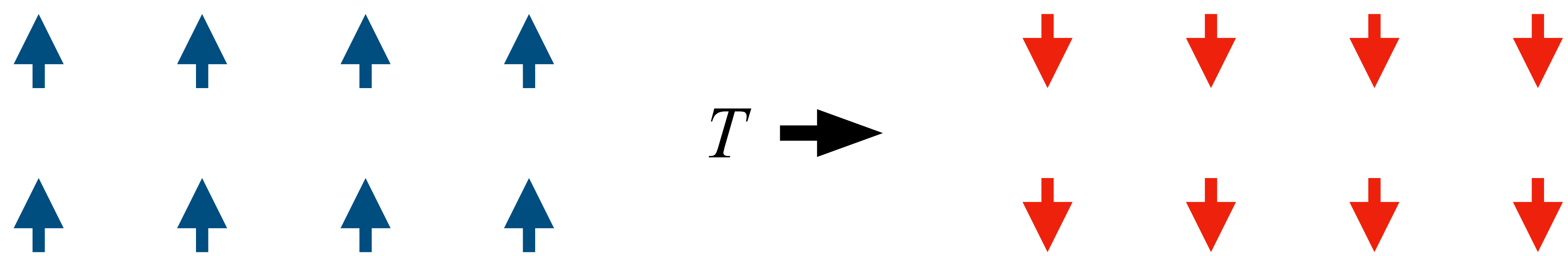
What does symmetry compensated means?

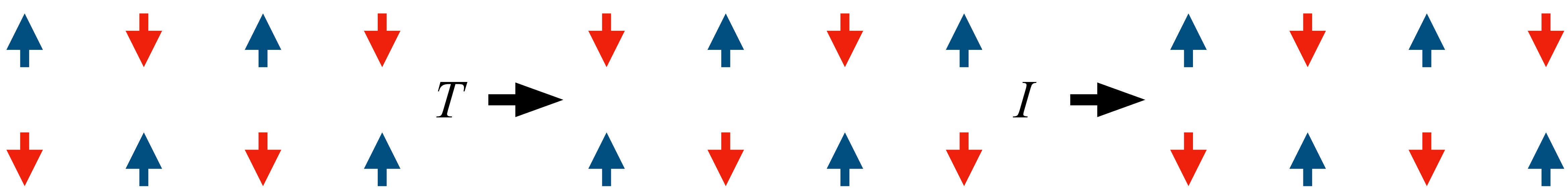
A way to counteract the breakdown of TRS breakdown by lattice symmetries.

FerroMagnets



If the lattice is inversion invariant: $T \cdot I$ is not a symmetry.

AntiFerroMagnets



If the lattice is not inversion invariant: $T \cdot I$ is a symmetry.

Importantly, here the system might or might not be inversion invariant.
It is the combined operation what is a symmetry

What does symmetry compensated means?

If the lattice is inversion invariant: $T \cdot I$ is a symmetry.

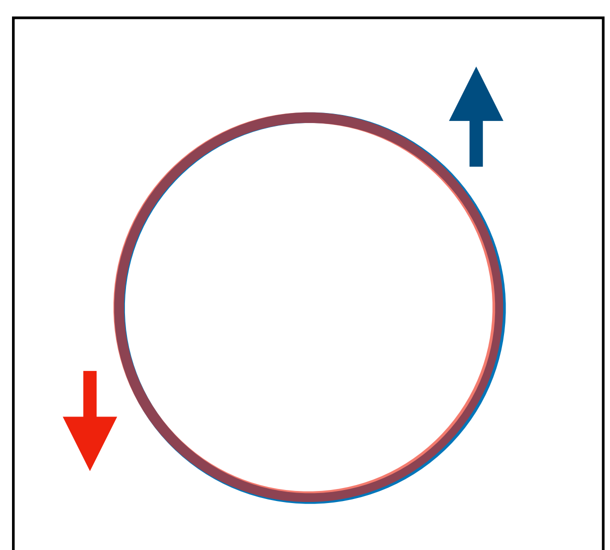
$$\varepsilon_\sigma(\boldsymbol{k}) \xrightarrow{T} \varepsilon_{-\sigma}(-\boldsymbol{k})$$

$$\varepsilon_\sigma(\boldsymbol{k}) \xrightarrow{I} \varepsilon_\sigma(-\boldsymbol{k})$$

$$\xrightarrow{T \cdot I} \varepsilon_{-\sigma}(\boldsymbol{k})$$

$T \cdot I$ is a symmetry: $\varepsilon_{-\sigma}(\boldsymbol{k}) = \varepsilon_\sigma(\boldsymbol{k})$

Spin split bands are degenerate



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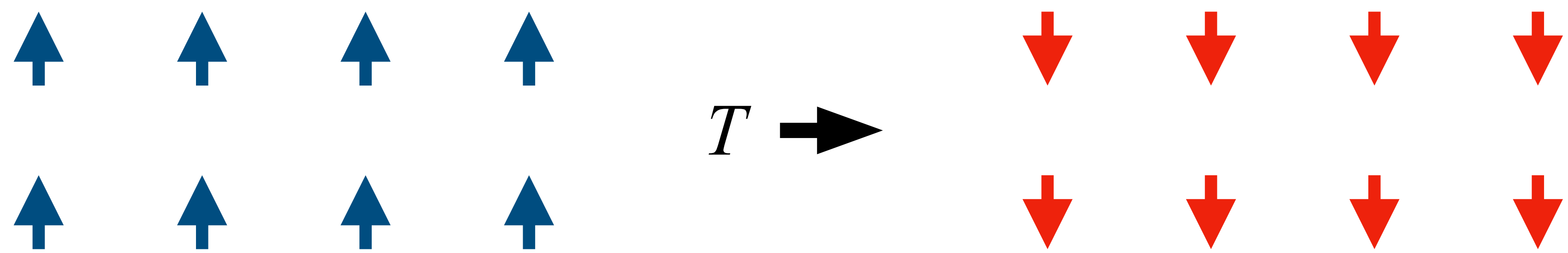

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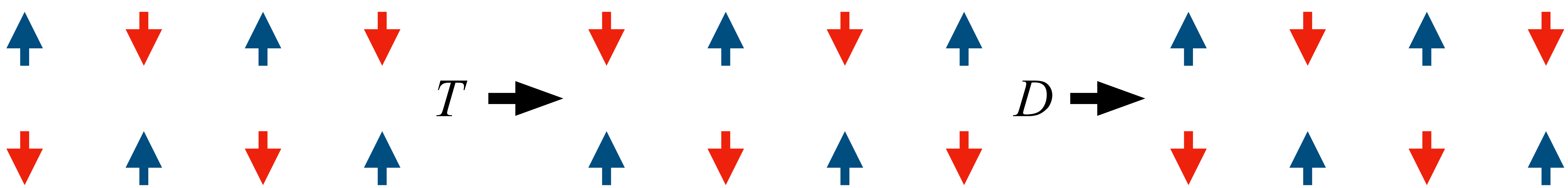
AntiFerroMagnets



If the lattice is inversion invariant: $(T \cdot D) \cdot I$ is a symmetry.

Importantly, here the system might or might not be inversion invariant.
It is the combined operation what is a symmetry

What does symmetry compensated means?

If the lattice is inversion invariant: $T \cdot I$ is a symmetry.

$$\varepsilon_\sigma(\boldsymbol{k}) \xrightarrow{T} \varepsilon_{-\sigma}(-\boldsymbol{k})$$

$$\varepsilon_\sigma(\boldsymbol{k}) \xrightarrow[D]{} \varepsilon_\sigma(\boldsymbol{k}+\boldsymbol{Q})$$

$$\varepsilon_\sigma(\boldsymbol{k}) \xrightarrow{I} \varepsilon_\sigma(-\boldsymbol{k})$$

$$T \cdot D$$

$$\varepsilon_{-\sigma}(-\boldsymbol{k}+\boldsymbol{Q})$$

Spin split bands are degenerate

$(T \cdot D) \cdot I$ is a symmetry: $\varepsilon_{-\sigma}(\boldsymbol{k}+\boldsymbol{Q}) = \varepsilon_\sigma(\boldsymbol{k})$

What does symmetry compensated means?

If the lattice is inversion invariant: $T \cdot I$ is a symmetry.

$$\varepsilon_\sigma(\boldsymbol{k}) \xrightarrow{T} \varepsilon_{-\sigma}(-\boldsymbol{k})$$

$$\varepsilon_\sigma(\boldsymbol{k}) \xrightarrow{D} \varepsilon_\sigma(\boldsymbol{k}+\boldsymbol{Q})$$

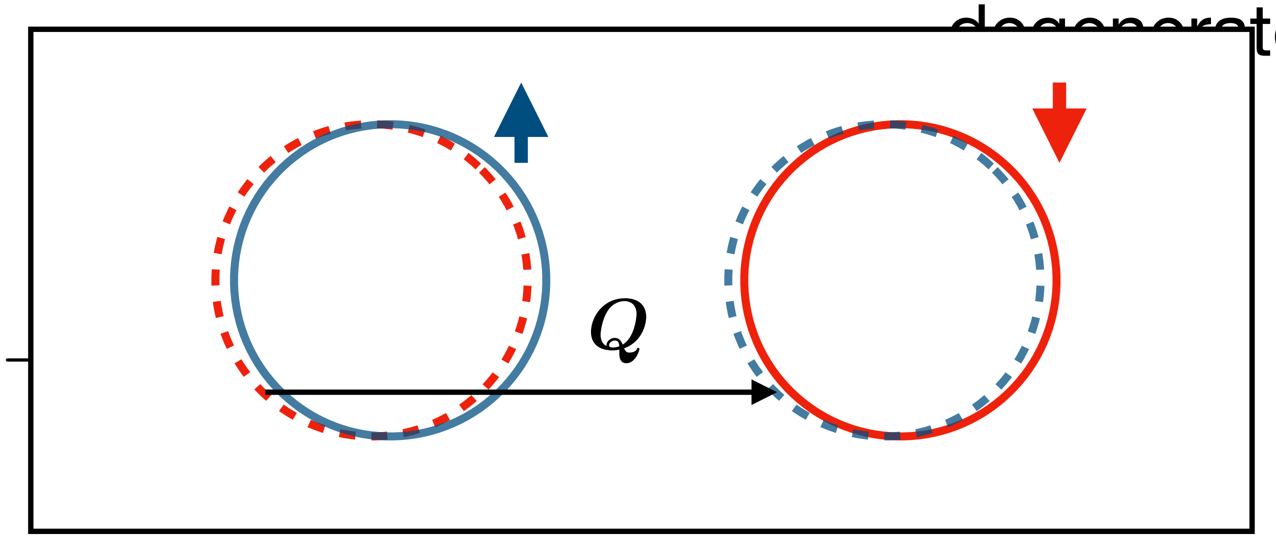
$$\varepsilon_\sigma(\boldsymbol{k}) \xrightarrow{I} \varepsilon_\sigma(-\boldsymbol{k})$$

$$T \cdot D$$

$$\varepsilon_{-\sigma}(-\boldsymbol{k}+\boldsymbol{Q})$$

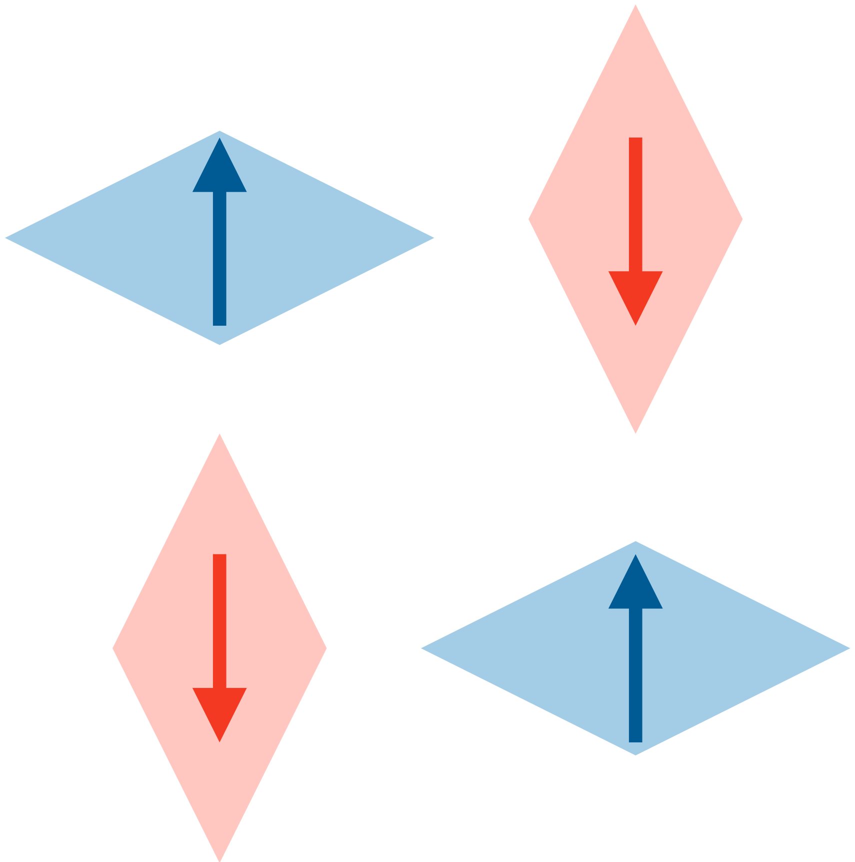
Spin split bands are degenerate

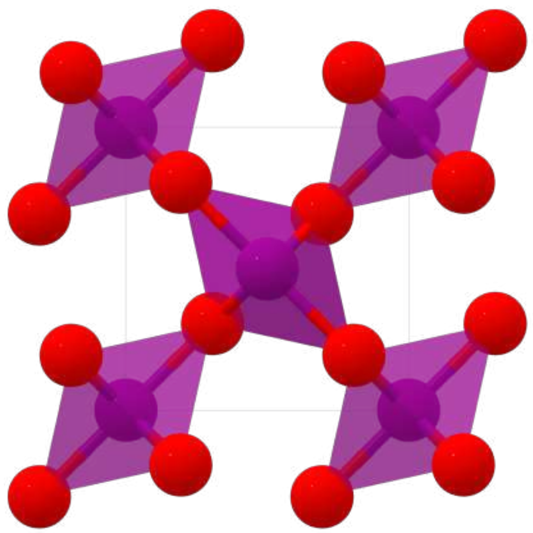
$(T \cdot D) \cdot I$ is a symmetry: ε_-



What does symmetry compensated means?

Now, in altermagnets, the previous symmetries do not apply:





MnO_2

What does symmetry compensated means?

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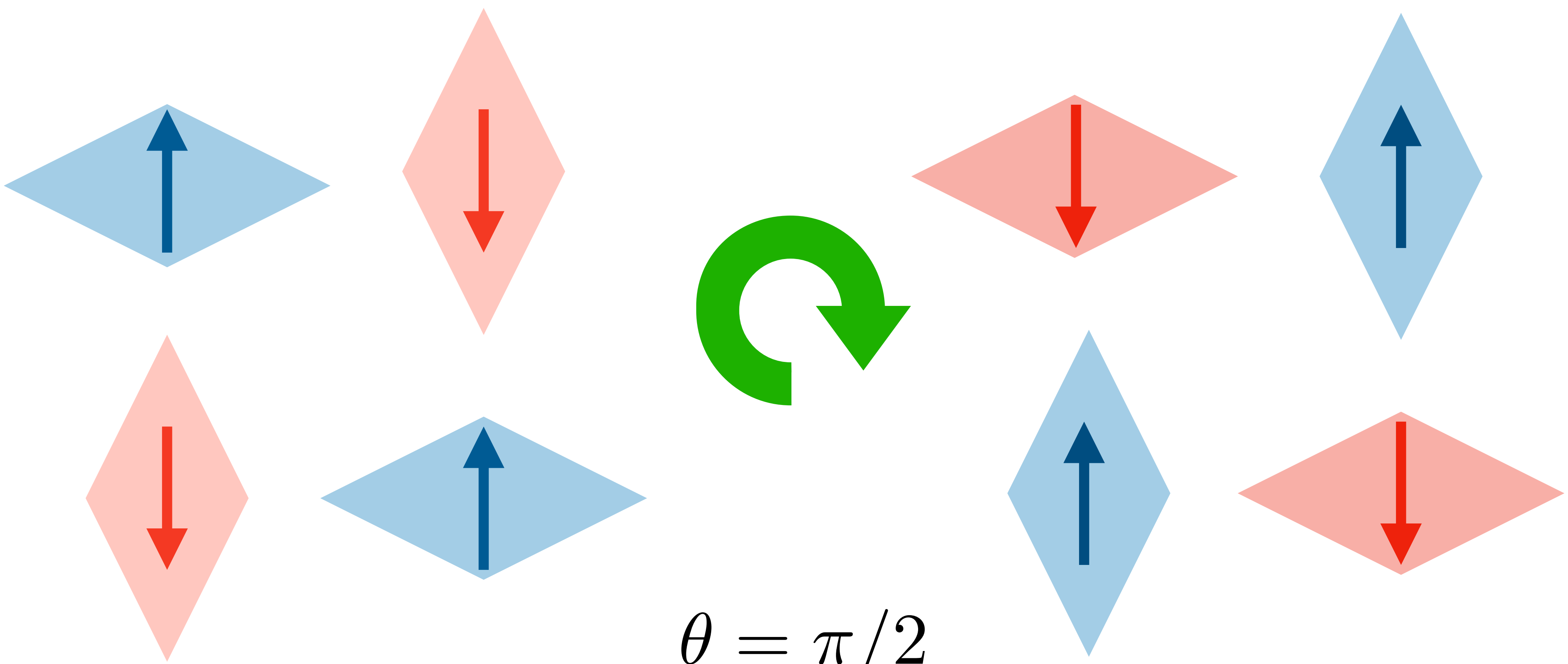

$$\theta = \pi/2$$

What does symmetry compensated means?

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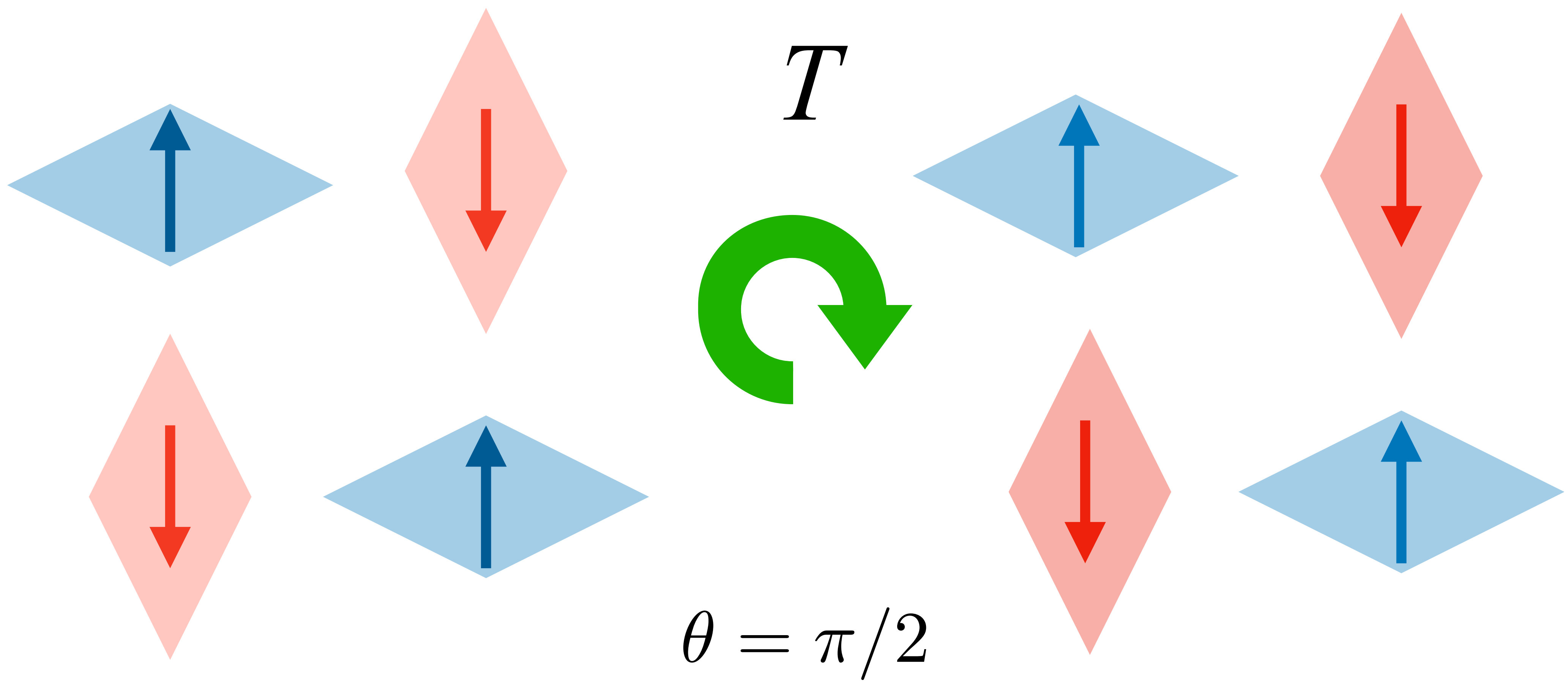

In this example, the system is invariant under T and rotation of $\pi/2$

What does symmetry compensated means?

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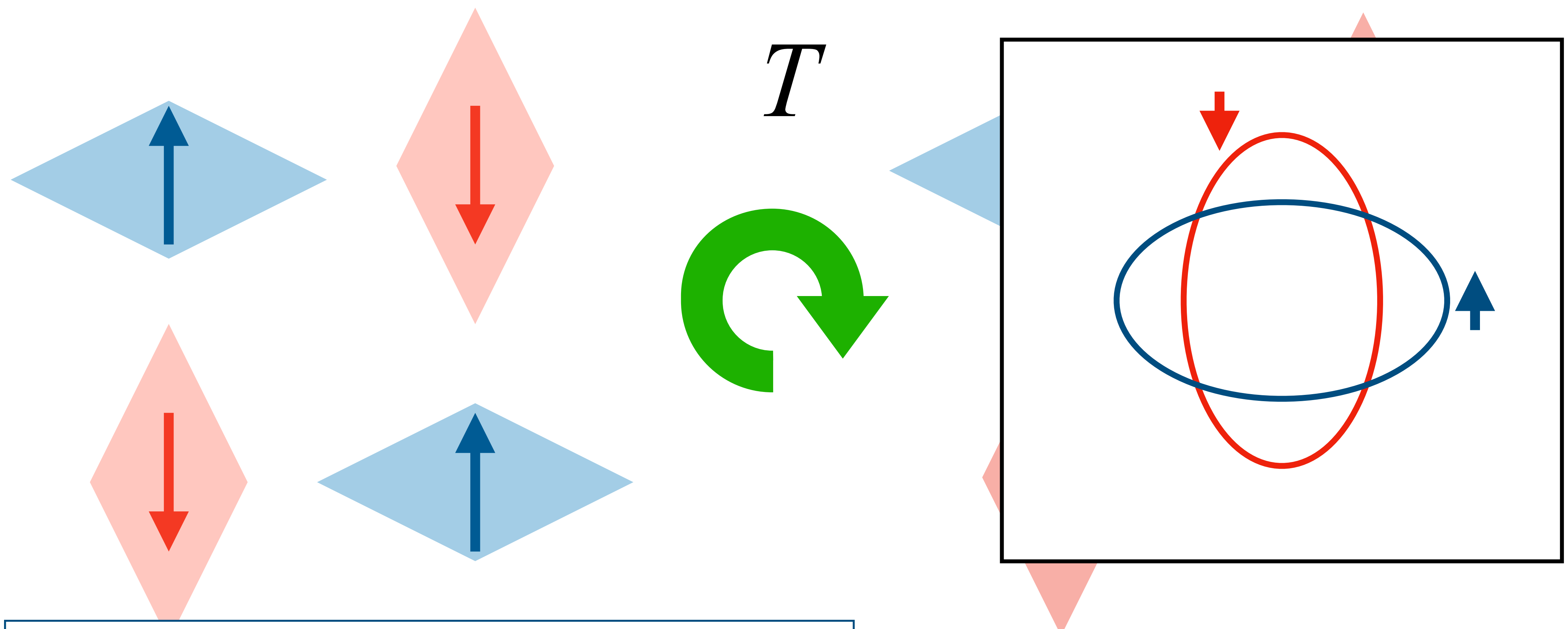

$$\boxed{\varepsilon_\sigma(\boldsymbol{k}) \rightarrow \varepsilon_{-\sigma}(\boldsymbol{k}' = -R\boldsymbol{k})}$$

Kramers degeneracy (Zeeman splitting) is lifted although the magnetization is zero

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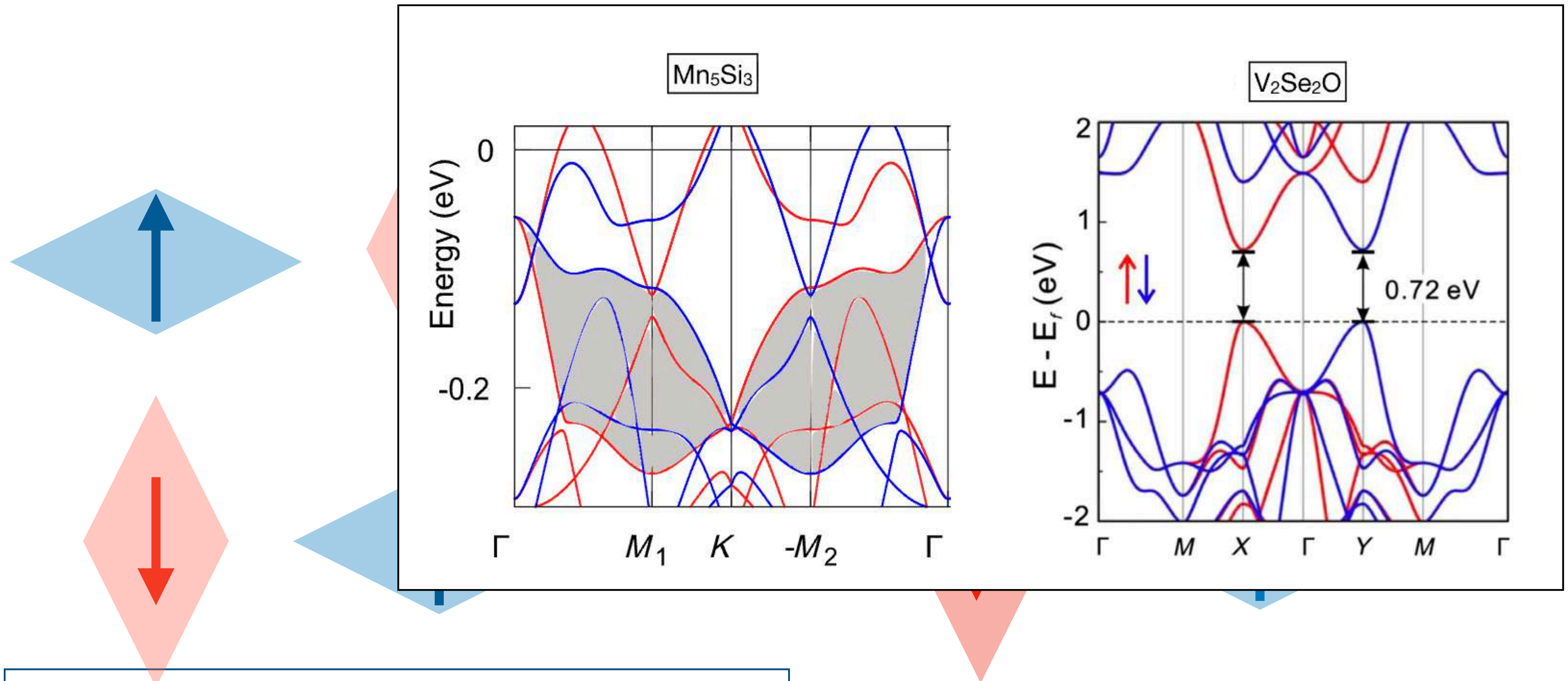

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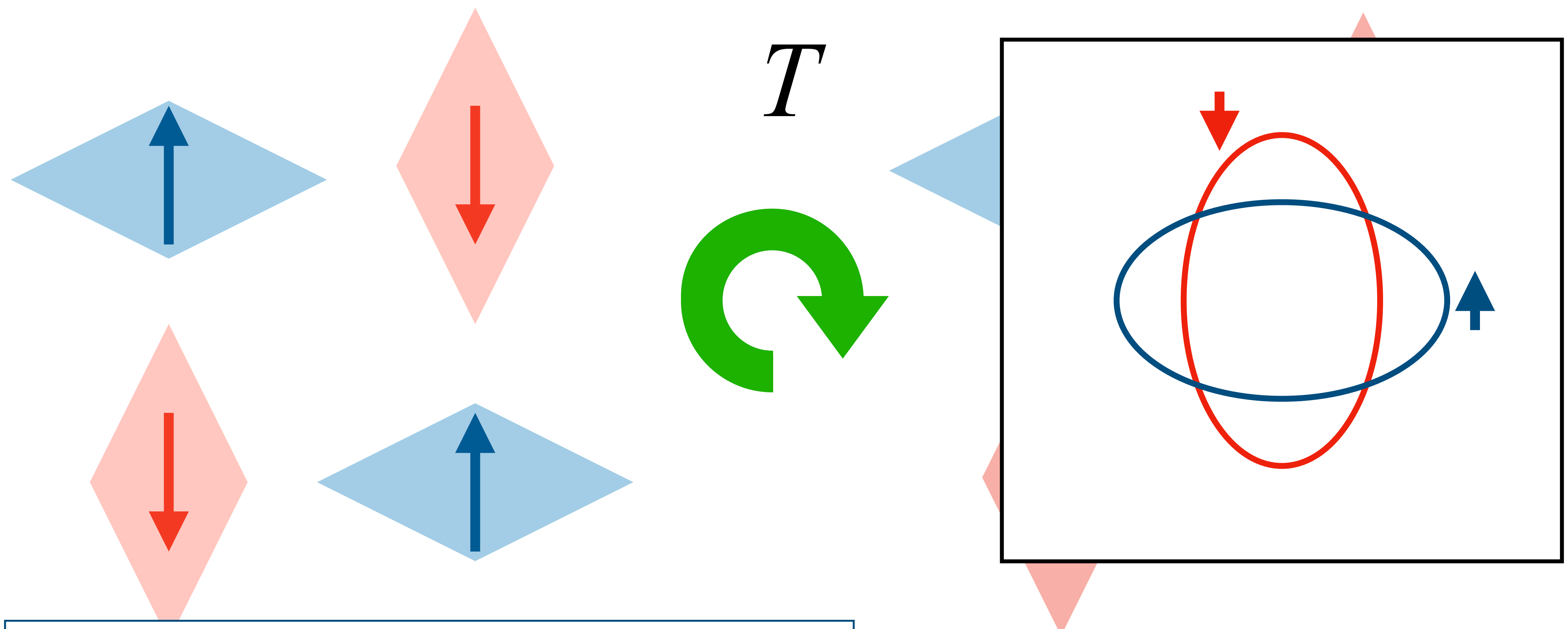


$$\varepsilon_\sigma(\boldsymbol{k}) \rightarrow \varepsilon_{-\sigma}(\boldsymbol{k}' = -R\boldsymbol{k})$$

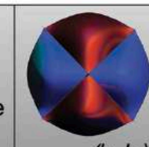
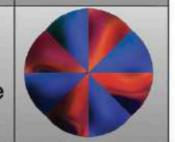
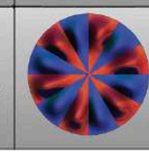
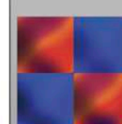
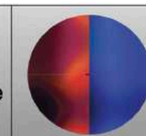
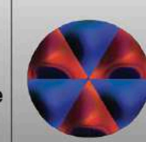
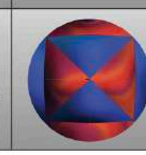
This Zeeman splitting displays the rotation symmetries:

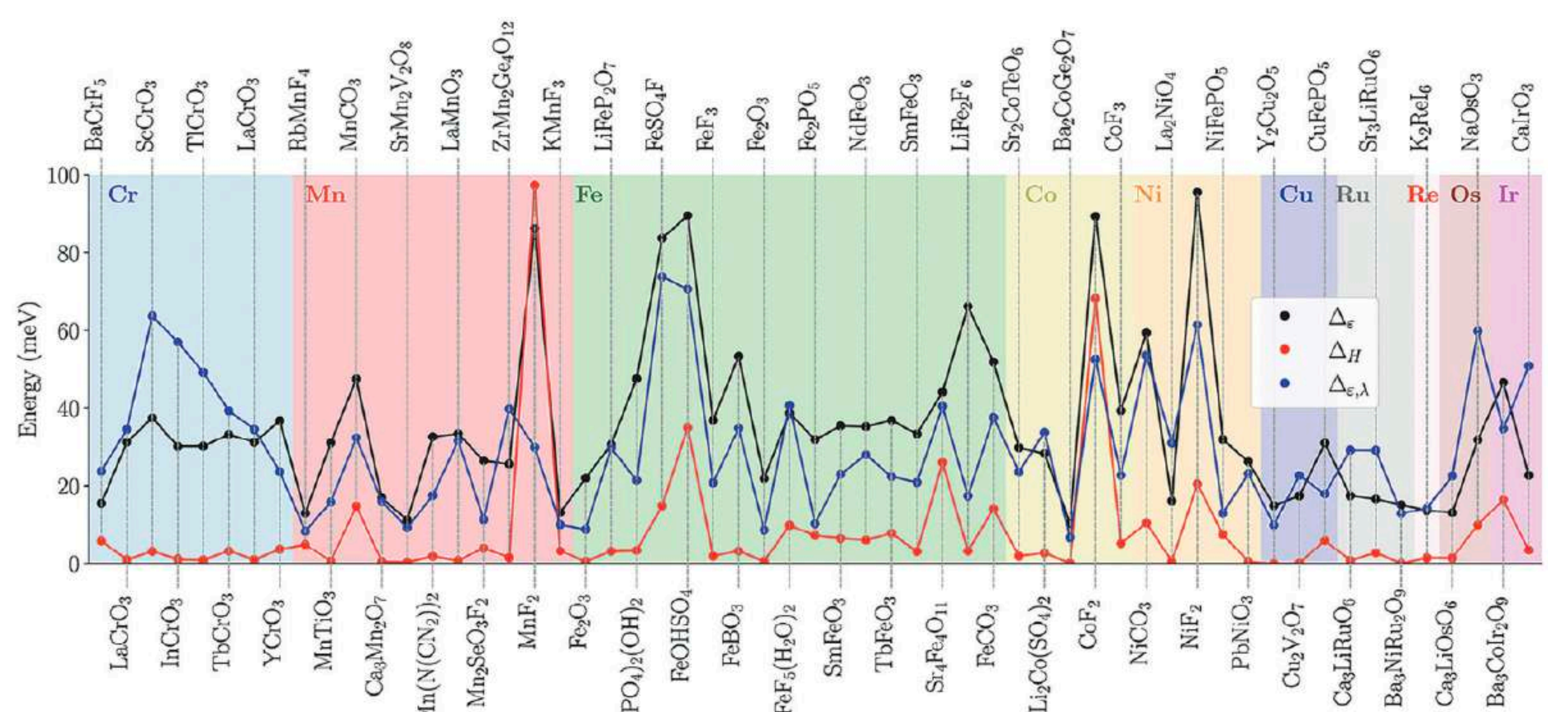
Kramers degeneracy (Zeeman splitting) is lifted although the magnetization is zero

$$\Delta\varepsilon(\boldsymbol{k}) = \varepsilon_\uparrow(\boldsymbol{k}) - \varepsilon_\downarrow(\boldsymbol{k}) \sim \sin k_1 \sin k_2$$

Symmetries in altermagnets

SG (P)	Wyckoff (S)	Γ_N	Spin splitting ($f_{\Gamma_N}(\mathbf{k})$)
11 (C_{2h})	2a-2d (C_i)	B_g	$\alpha k_y k_x + \beta k_y k_z$
12 (C_{2h})	4e, 4f (C_i)	B_g	$\alpha k_y k_x + \beta k_y k_z$
13 (C_{2h})	2a-2d (C_i)	B_g	$\alpha k_y k_x + \beta k_y k_z$
14 (C_{2h})	2a-2d (C_i)	B_g	$\alpha k_y k_x + \beta k_y k_z$
15 (C_{2h})	2a-2d (C_i)	B_g	$\alpha k_y k_x + \beta k_y k_z$
49 (D_{2h})	2a-2d (C_{2h})	B_{1g}	$k_x k_y$
51 (D_{2h})	2a-2d (C_{2h})	B_{2g}	$k_x k_z$
53 (D_{2h})	2a-2d (C_{2h})	B_{3g}	$k_y k_z$
55 (D_{2h})	2a-2d (C_{2h})	B_{1g}	$k_x k_y$
58 (D_{2h})	2a-2d (C_{2h})	B_{1g}	$k_x k_y$
63 (D_{2h})	4a,4b (C_{2h})	B_{3g}	$k_y k_z$
64 (D_{2h})	4a,4b (C_{2h})	B_{3g}	$k_y k_z$
65 (D_{2h})	4e,4f (C_{2h})	B_{1g}	$k_x k_z$
66 (D_{2h})	4c-4f (C_{2h})	B_{1g}	$k_x k_y$
67 (D_{2h})	4c-4f (C_{2h})	B_{3g}	$k_x k_y$
72 (D_{2h})	4c,4d (C_{2h})	B_{1g}	$k_x k_y$
74 (D_{2h})	4a,4b (C_{2h})	B_{3g}	$k_x k_y$
74 (D_{2h})	4c,4d (C_{2h})	B_{2g}	$k_x k_y$

Spin-momentum locking			G	$\mathbf{R}_s^{\mathrm{III}}$	H	A	Candidate
Planar  $(k_{x/y},k_z)$	P-2 d-wave	 (k_x,k_y)	mmm	${}^2m{}^2m{}^1m$ (8)	$2/m$	C_{2x}	La_2CuO_4, $FeSb_2$
			$4/m$	${}^24/{}^1m$ (8)		C_{4z}	KRu_4O_8
			$4/mmm$	${}^24/{}^1m{}^2m{}^1m$ (16)	mmm	C_{4z}	RuO_2, MnO_2, MnF_2
	P-4 g-wave			${}^14/{}^1m{}^2m{}^2m$ (16)	$4/m$	C_{2x}	$KMnF_3$
	P-6 i-wave		$6/mmm$	${}^16/{}^1m{}^2m{}^2m$ (24)	$6/m$	C_{21}	
Bulk 	B-2 d-wave		$2/m$	${}^22/{}^2m$ (4)	$\bar{1}$	C_{2z}	CuF_2
	B-4 g-wave		$\bar{3}m$	${}^1\bar{3}{}^2m$ (12)	$\bar{3}$	C_{21}	CoF_3, FeF_3, Fe_2O_3
			$6/m$	${}^26/{}^2m$ (12)		C_{6z}	
			$6/mmm$	${}^26/{}^2m{}^1m$ (24)	$\bar{3}m$	C_{6z}	CrSb, MnTe, VNb_3S_6
	B-6 i-wave		$m\bar{3}m$	${}^1m{}^1\bar{3}{}^2m$ (48)	$m\bar{3}$	C_{4z}	



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63 (D_{2h})	4a,4b (C_{2h})	B_{3g}	$k_y k_z$
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65 ([illegible])	4e,4f ([illegible])	[illegible]	[illegible]
66 [illegible]	[illegible]	[illegible]	[illegible]
67 [illegible]	[illegible]	[illegible]	[illegible]
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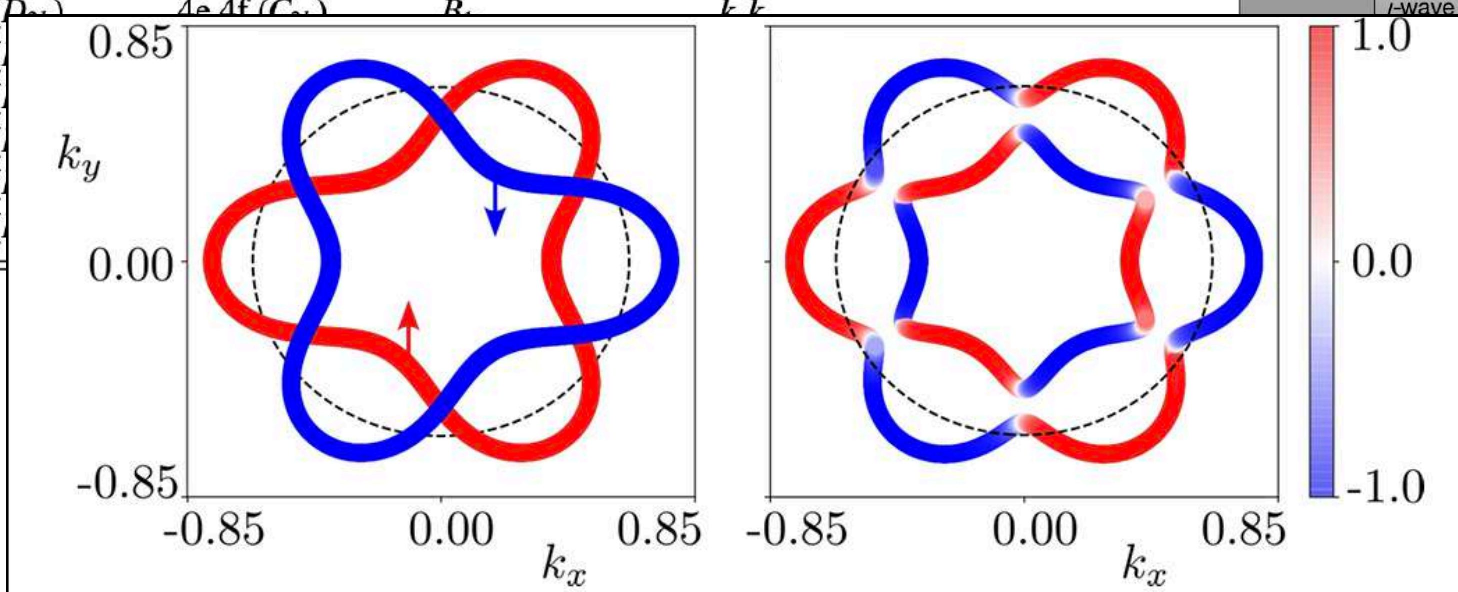
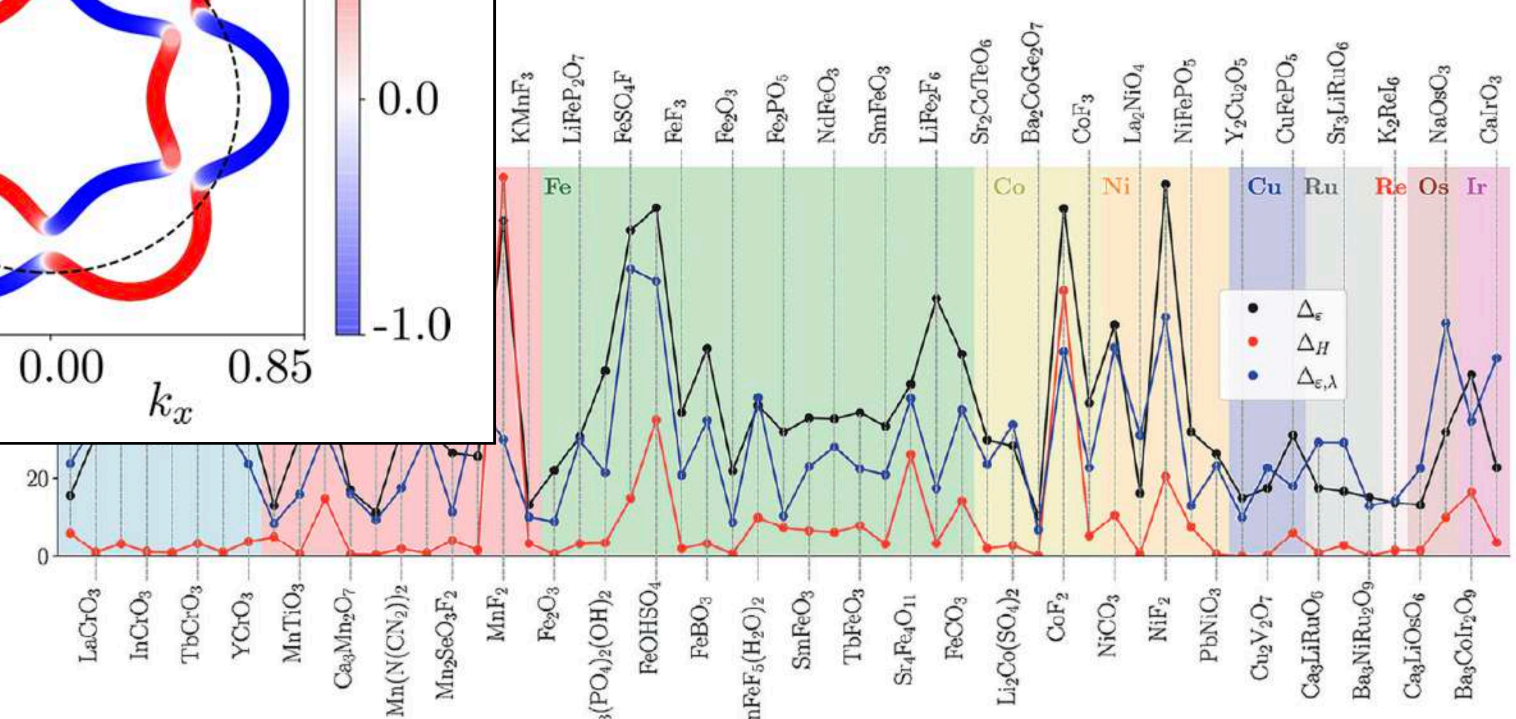
74 [illegible]	[illegible]	[illegible]	[illegible]
74 [illegible]	[illegible]	[illegible]	[illegible]

Spin-momentum locking		G	R_s^{III}	H	$\mathcal{A}$	Candidate
Planar ($k_{x/y}, k_z$)	P-2 *d*-wave (k_x, k_y)	*mmm*	$^2m^2m^1m$ (8)	2/m	C_{2x}	La_2CuO_4, $FeSb_2$
		4/m	$^24/^1m$ (8)		C_{4z}	KRu_4O_8
		4/mmm	$^24/^1m^2m^1m$ (16)	*mmm*	C_{4z}	RuO_2, MnO_2, MnF_2
	P-4 *g*-wave		$^14/^1m^2m^2m$ (16)	*4/m*	C_{2x}	$KMnF_3$
	P-6 *i*-wave	*6/mmm*	$^16/^1m^2m^2m$ (24)	*6/m*	C_{21}	
Bulk	B-2 *d*-wave	*2/m*	$^22/^2m$ (4)	$\bar{1}$	C_{2z}	CuF_2
	B-4 *g*-wave	$\bar{3}m$	$^1\bar{3}^2m$ (12)	$\bar{3}$	C_{21}	CoF_3, FeF_3, Fe_2O_3
		6/m	$^26/^2m$ (12)		C_{6z}	
		6/mmm	$^26/^2m^2m^1m$ (24)	$\bar{3}m$	C_{6z}	CrSb, MnTe, VNb_3S_6
	B-6 *i*-wave	$m\bar{3}m$	$^1m^1\bar{3}^2m$ (48)	$m\bar{3}$	C_{4z}	





Ok, which properties do alter magnets display?

	FM	AM	AF
Nonrelativistic net magnetization	nonzero or zero	zero	zero
Nonrelativistic Kramers spin degeneracy	no	no	yes
Anomalous Hall	yes	yes	no
Magnetooptics	yes	yes	no
Nonrelativistic spin-polarized current	yes	yes	no
Suppression of Andreev reflection: diffuse contact	yes	no	no
Suppression of Andreev reflection: ballistic contact	yes	yes	no
Supports singlet superconductivity	no	no	yes
Supports locally (in k-space) unitary triplet superconductivity	no	no	yes
Supports k-averaged unitary triplet superconductivity	no	yes	yes
Giant or tunneling magnetoresistance and spin-transfer torque	yes	yes	no

Allowed by SOC

In essence, any transport/optical/device properties related to the presence of a Zeeman splitting

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This Zeeman splitting has different physical origin than Spin-Orbit Coupling, and it averages to zero

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	AF
Nonrelativistic net mag	zero
Nonrelativistic Kramers	yes
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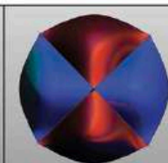
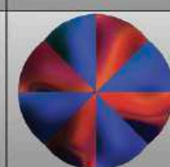
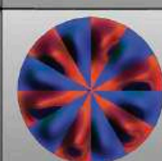
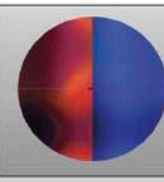
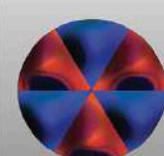
Spin-momentum locking			$\mathbf{G}$	$\mathbf{R}_s^{\mathrm{III}}$	$\mathbf{H}$	$\mathcal{A}$	Candidate
Planar  $(k_{x/y},k_z)$	P-2 *d*-wave	 (k_x,k_y)	mmm	${}^{2}m^{2}m^{1}m$ (8)	$2/m$	C_{2x}	La_2CuO_4, $FeSb_2$
			$4/m$	${}^{2}4/{}^{1}m$ (8)		C_{4z}	KRu_4O_8
			$4/mmm$	${}^{2}4/{}^{1}m^{2}m^{1}m$ (16)	mmm	C_{4z}	RuO_2, MnO_2, MnF_2
	P-4 *g*-wave			${}^{1}4/{}^{1}m^{2}m^{2}m$ (16)	$4/m$	C_{2x}	$KMnF_3$
	P-6 *i*-wave		$6/mmm$	${}^{1}6/{}^{1}m^{2}m^{2}m$ (24)	$6/m$	C_{21}	
Bulk 	B-2 *d*-wave		$2/m$	${}^{2}2/{}^{2}m$ (4)	$\bar{1}$	C_{2z}	CuF_2
	B-4 *g*-wave		$\bar{3}m$	${}^{1}\bar{3}{}^{2}m$ (12)	$\bar{3}$	C_{21}	CoF_3, FeF_3, Fe_2O_3
			$6/m$	${}^{2}6/{}^{2}m$ (12)		C_{6z}	
			$6/mmm$	${}^{2}6/{}^{2}m^{2}m^{1}m$ (24)	$\bar{3}m$	C_{6z}	CrSb, MnTe, VNb_3S_6
	B-6 *i*-wave		$m\bar{3}m$	${}^{1}m^{1}\bar{3}{}^{2}m$ (48)	$m\bar{3}$	C_{4z}	

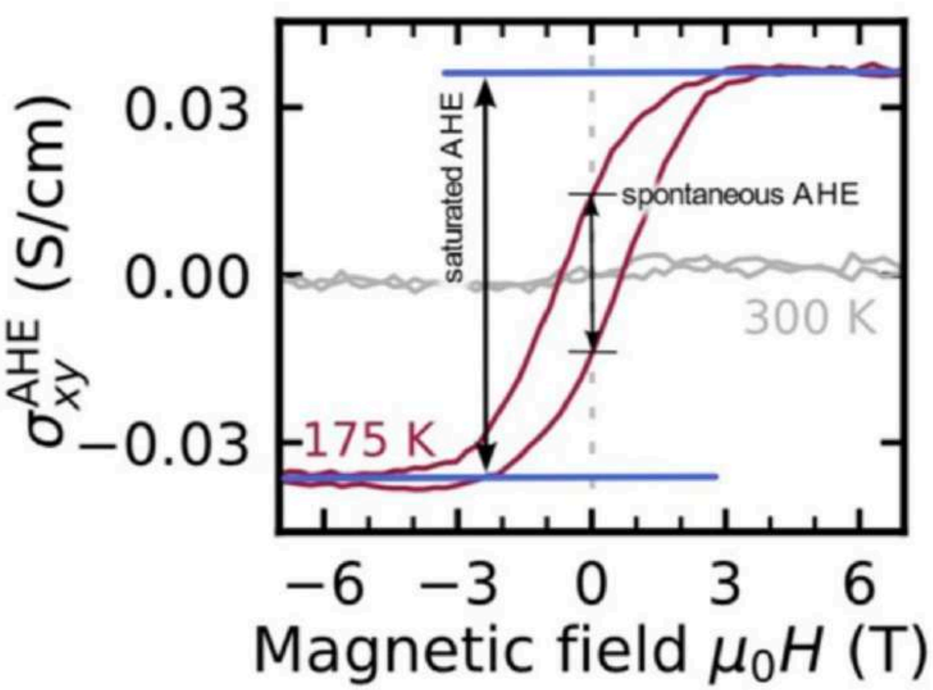
This Zeeman splitting has different physical origin than Spin-Orbit Coupling, and it averages to zero

Anomalous Hall effect in ferromagnets and Altermagnets

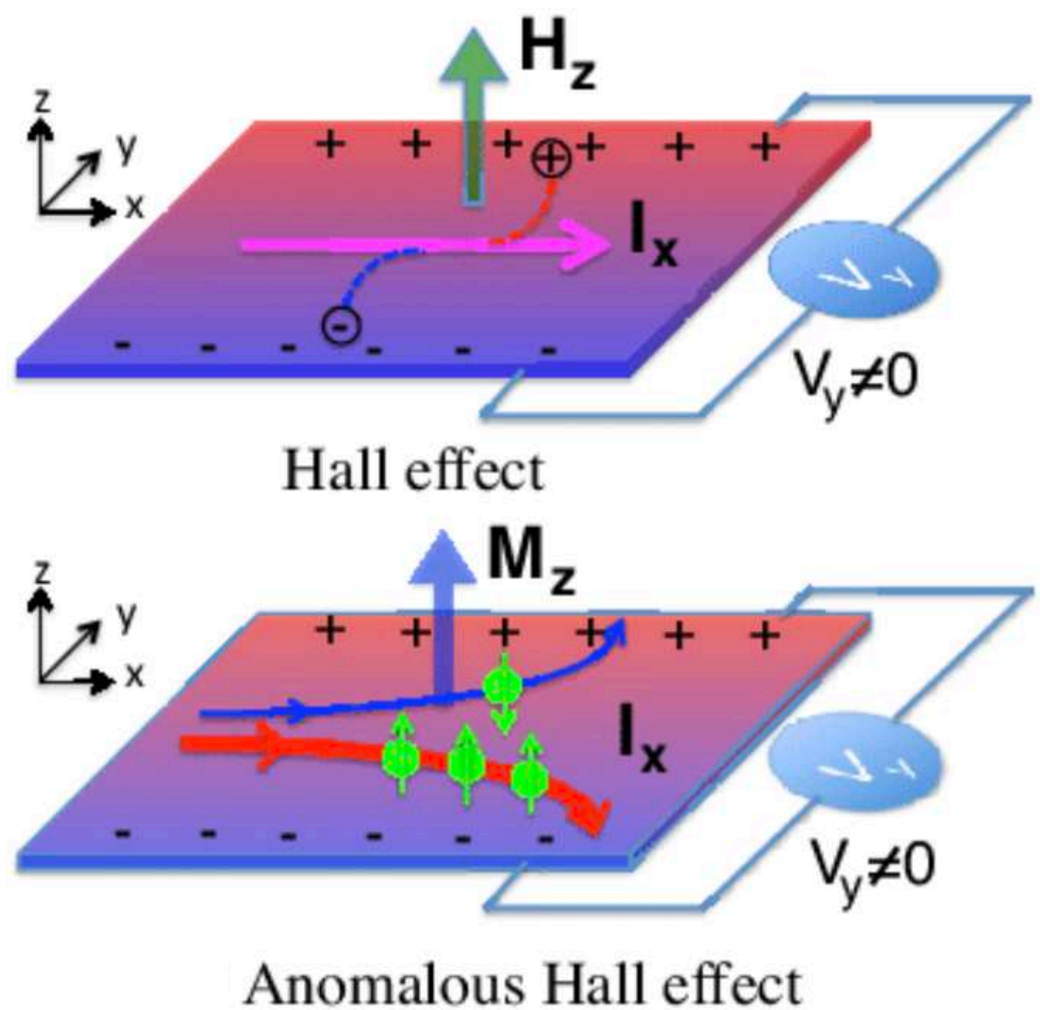
Edwin H Hall (1855-1938)

The anomalous Hall effect is the appearance of a transverse current to an applied electric field, and to the magnetization

$$\sigma_{12} \sim \sigma_H B + \sigma^{AHE} M$$



MnTe



Anomalous Hall effect in ferromagnets and Altermagnets

Something important to keep in mind is that, in order to get a nonzero AHE, we need finite SOC terms, both for FM and altermagnets

$$H_{FM} = -2t(\cos k_1 \cos k_2)\sigma_0 + M\sigma_3$$

$$H_{FM} = -2t(\cos k_1 \cos k_2)\sigma_0 + t_J(\sin k_1 \sin_k 2)\sigma_3$$

$$\Downarrow$$

$$H_{FM} = t(k_1^2 + k_2^2)\sigma_0 + M\sigma_3$$

$$H_{AM} = t(k_1^2 + k_2^2)\sigma_0 + t_J k_1 k_2 \sigma_3$$

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$$H = d_0(\boldsymbol{k})\sigma_0 + d_3(\boldsymbol{k})\sigma_3$$

$$d_1(\boldsymbol{k}) = d_2(\boldsymbol{k}) = 0$$

$$\boldsymbol{\Omega}_3^{\pm} = \pm\frac{1}{2d^3}\varepsilon_{abc} d_a \partial_1 d_b \partial_2 d_c = 0$$

$$\sigma^{AHE} = \sum_{\pm} \frac{e^2}{h} \int \frac{d^2k}{(2\pi)^2} f_F^{p\pm}(\boldsymbol{k}) \boldsymbol{\Omega}_3^{\pm}(\boldsymbol{k}) = 0$$

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SOC is needed

Anomalous Hall effect in ferromagnets and Altermagnets

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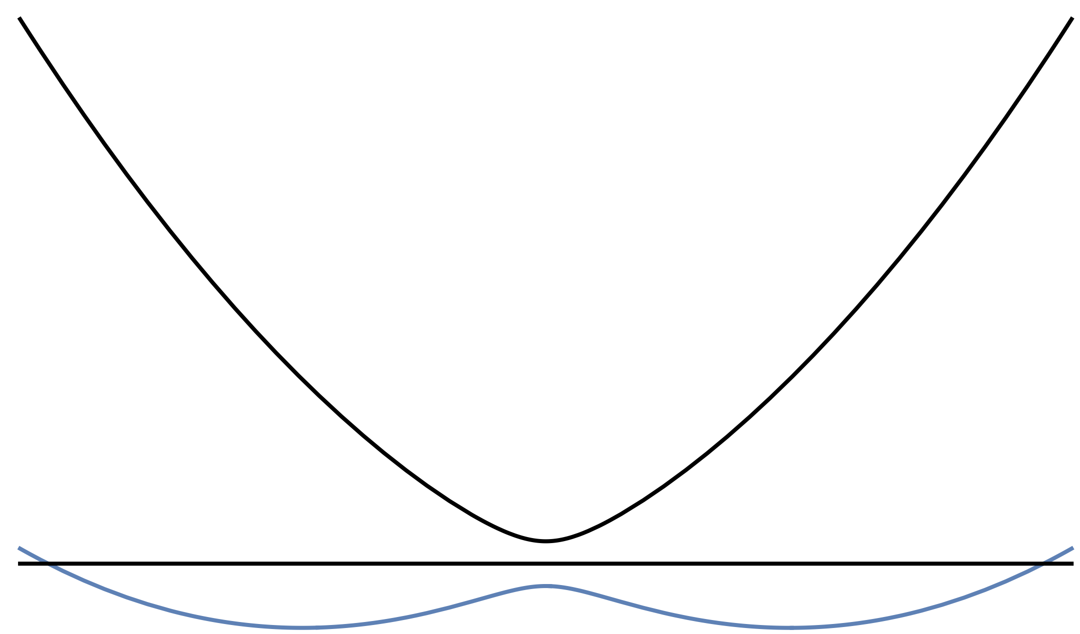
$$\boldsymbol{\Omega}_3^{\pm} = -\frac{1}{2}\frac{M\lambda^2}{(M^2+\lambda^2k^2)^{\frac{3}{2}}}$$



$$\sigma^{AHE} = -\frac{e^2}{h} sign(M) + \frac{e^2}{h}\frac{M\lambda^2}{(k_\mu^2 + M^2)}$$

$$tk^2 - \sqrt{\lambda^2k^2 + M^2} = \mu$$

Anomalous Hall effect in ferromagnets and Altermagnets

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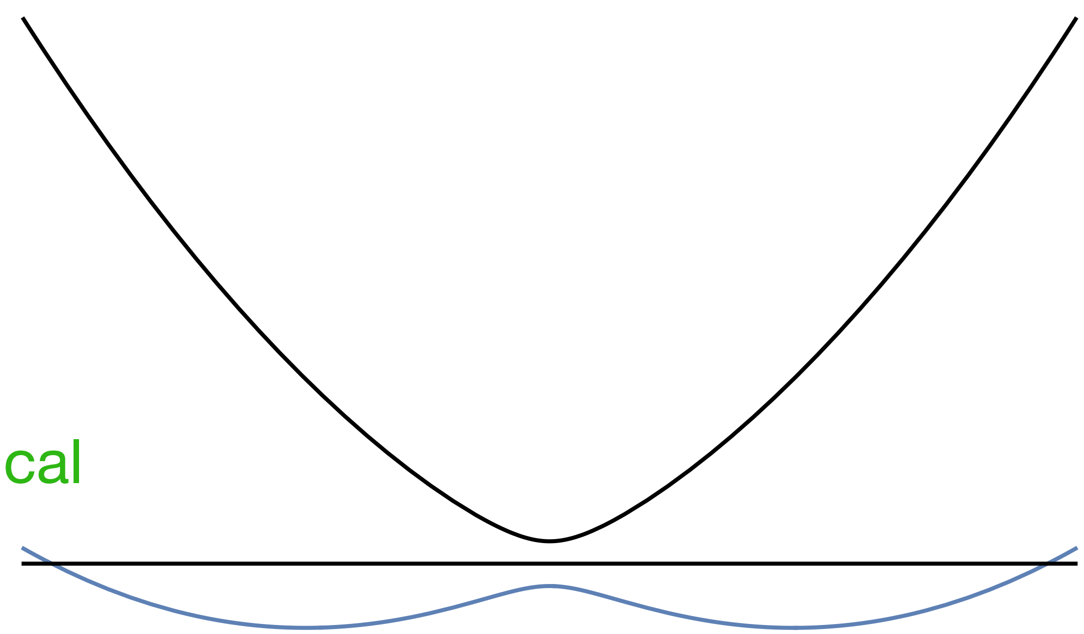
Topological

Non topological



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Anomalous Hall effect in ferromagnets and Altermagnets

$$\sigma^{AHE} = \sum_{\pm} \frac{e^2}{h} \int \frac{d^2k}{(2\pi)^2} f_F^{\pm}(\boldsymbol{k}) \boldsymbol{\Omega}_3^{\pm}(\boldsymbol{k})$$

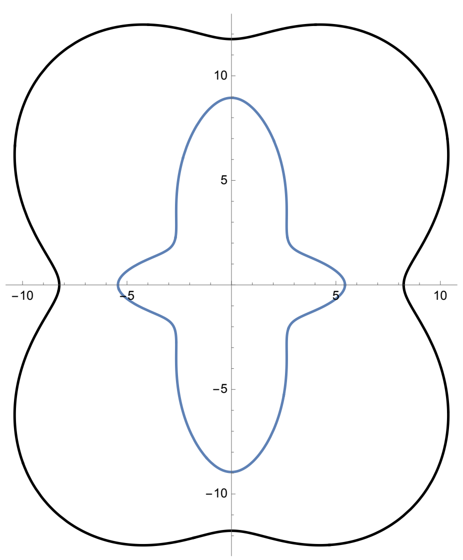
$$H = tk^2\sigma_0 + t_J(k_1k_2 + \varepsilon_{12})\sigma_3 + \underbrace{\lambda(k_1\sigma_2 - k_2\sigma_1)}_{\lambda(\boldsymbol{k}\times\boldsymbol{\sigma})}$$

$$\boldsymbol{\Omega}_3^{\pm} = -\frac{1}{2}\frac{\lambda^2 t_J k^2 \sin 2\theta}{(t_J^2 k^4 \sin^2 2\theta + \lambda^2 k^2)^{\frac{3}{2}}}$$

$$\mu = tk^2 - \sqrt{\lambda^2 k^2 + t_J^2 (k^2 \sin 2\theta + \varepsilon_{12})^2}$$

$$\sigma^{AHE} \sim \frac{e^2}{h}\varepsilon_{12} t_J f(\lambda, \mu, t)$$

$\boxed{\text{Strain is needed!!}}$



$\varepsilon_{12} \to -\varepsilon_{12}$ under C4

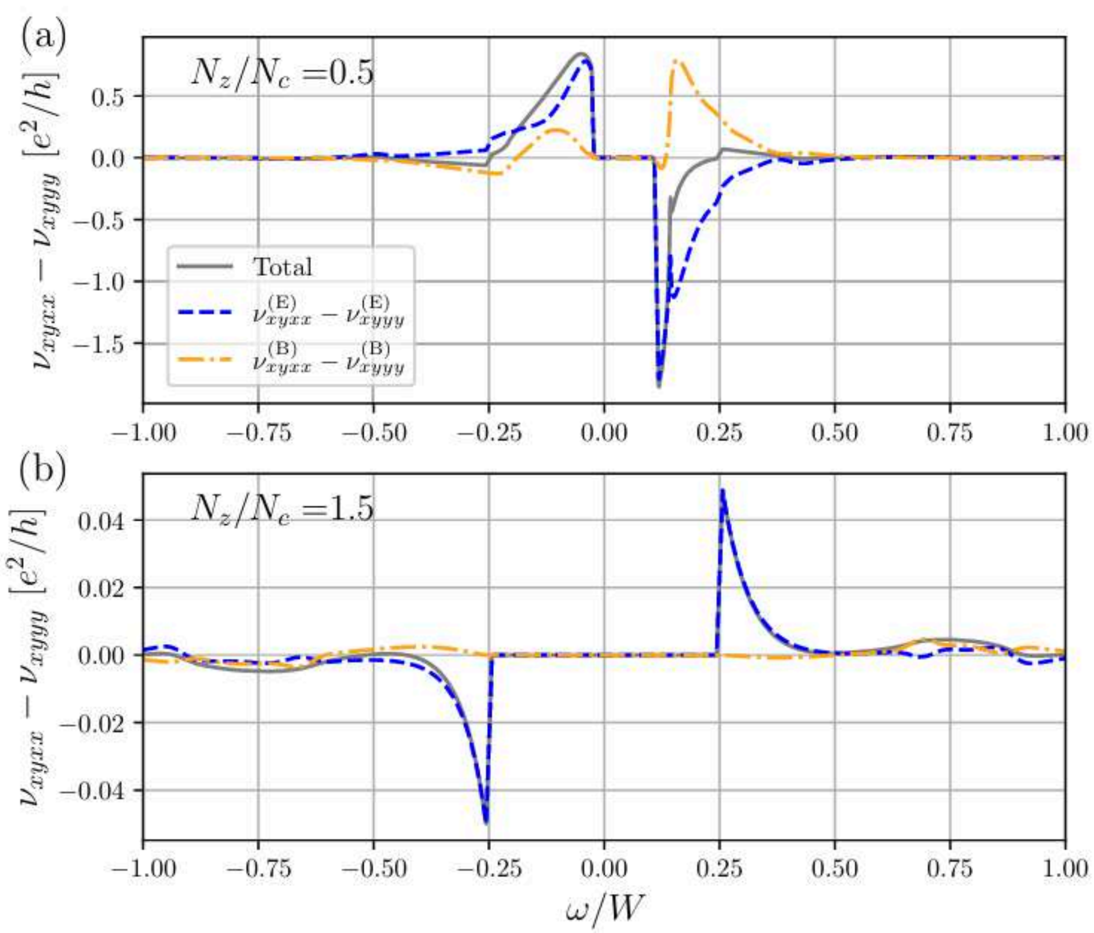
$t_J\sigma_3 \to -t_J\sigma_3$ under T

$\varepsilon_{12} t_J \sigma_3 \to \varepsilon_{12} t_J \sigma_3$

under $C_4 \cdot T$

Piezomagnetic effect

Anomalous Hall effect in ferromagnets and Altermagnets



Elasto-Hall conductivity and the anomalous Hall effect in altermagnets

Keigo Takahashi[1], Charles R. W. Steward[2], Masao Ogata[1,3], Rafael M. Fernandes[4,5], and Jörg Schmalian[2,6]

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arXiv > cond-mat > arXiv:2506.06257

Condensed Matter > Materials Science

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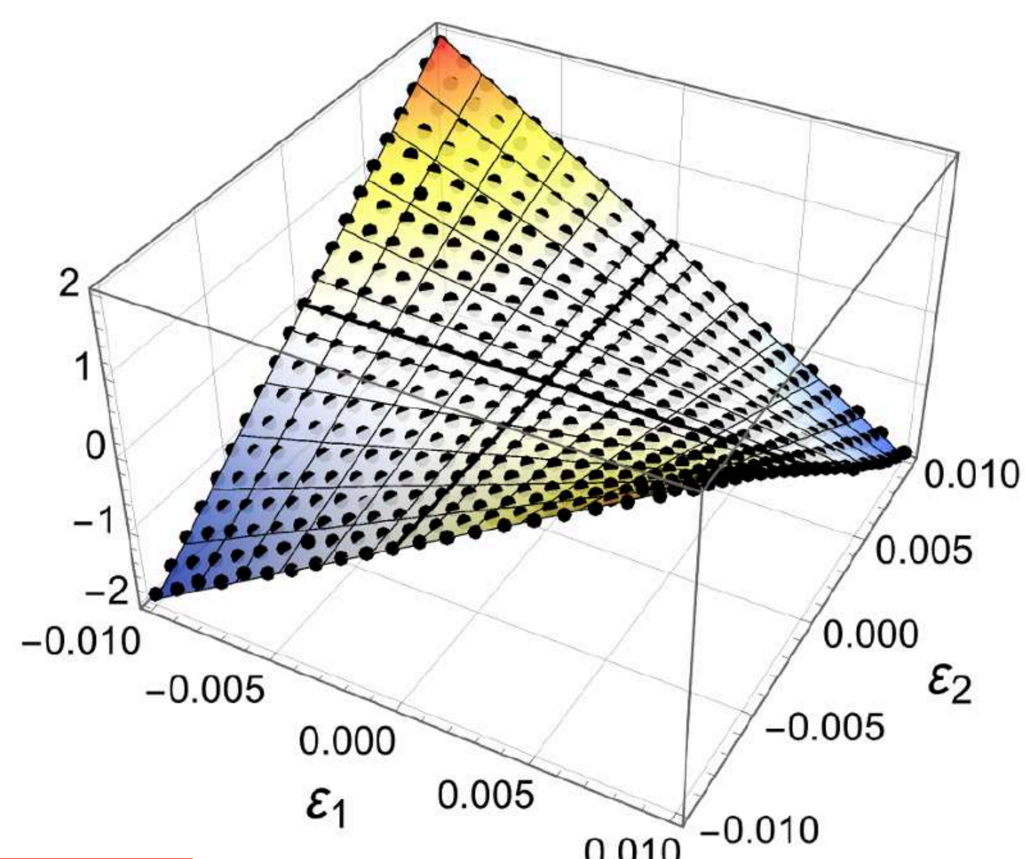
Tuning of altermagnetism by strain

M. Khodas, Sai Mu, I. I. Mazin, K. D. Belashchenko



Piezomagnetic effect

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