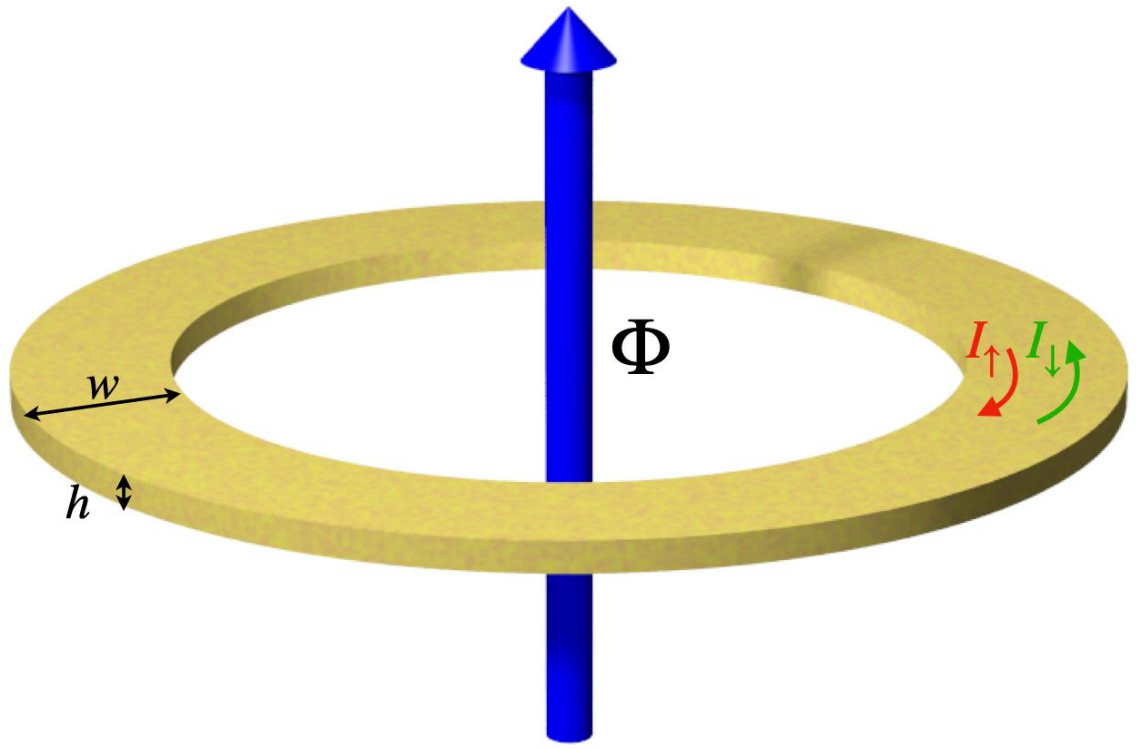
Topology and persistent spin currents

in Superconducting Altermagnets

Marcel Franz, July 2026
The University of British Columbia

with Kyle Monkman, Joan Weng, Alberto Nocera and Niclas Heinsdorf

NSERC CRSNG



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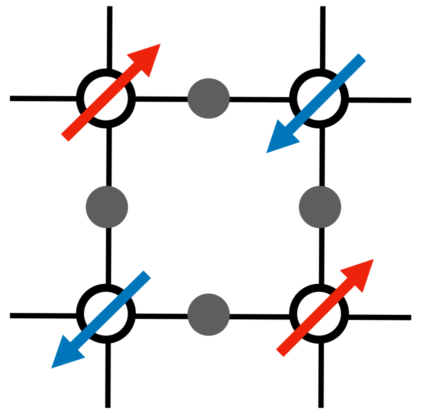
GORDON AND BETTY MOORE FOUNDATION

PRX 16, 011057; PRB 113, L020501 (2026)

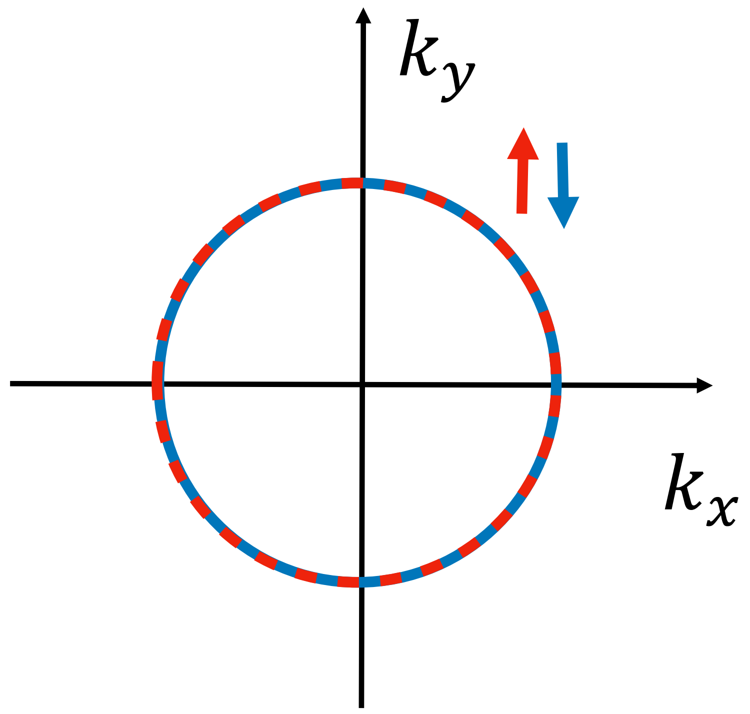
I.A— Background: Altermagnets vs antiferromagnets

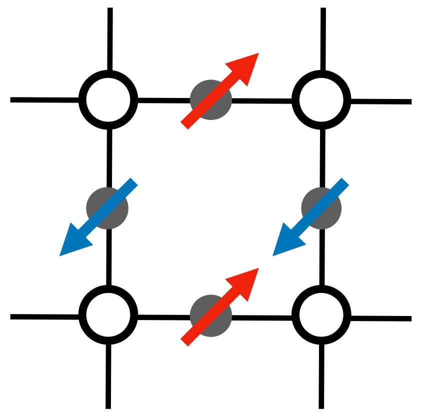
- Altermagnets can be thought of as **unconventional antiferromagnets** characterized by spin-split Fermi surfaces but vanishing total magnetization.



Antiferromagnet:

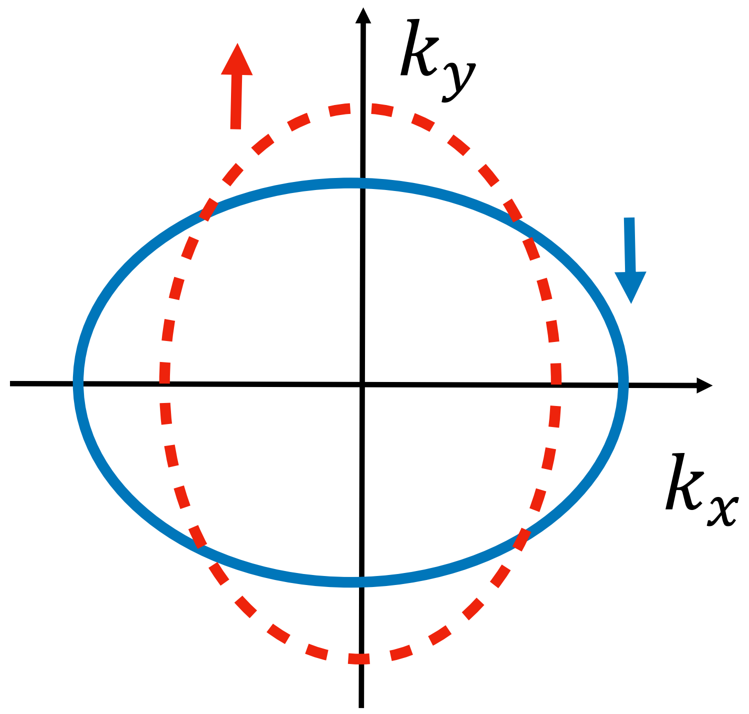
- Two magnetic sublattices are related by translation Θ or inversion *P*
- Obeys symmetry $\mathcal{T}' = \mathcal{T}P$ with $(\mathcal{T}')^2 = -1$ which implies Kramers degeneracy for all momenta $\mathbf{k}$.



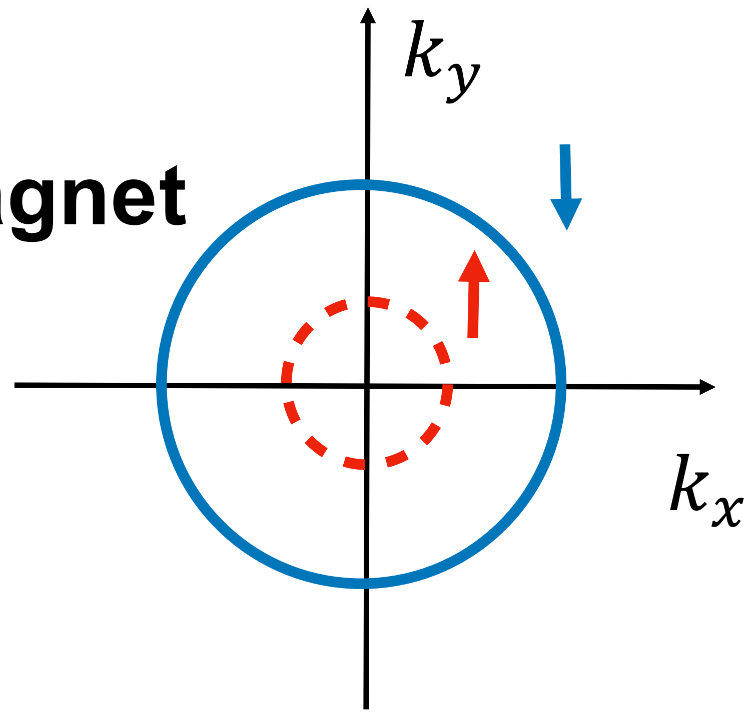


Altermagnet:

- Two magnetic sublattices are related by rotation *R*
- Obeys symmetry $\mathcal{T}' = \mathcal{T}R$ with $(\mathcal{T}')^2 \neq -1$, hence no Kramers degeneracy.



Ferromagnet



- **Altermagnets** thus share properties of **antiferromagnets** (zero total magnetization) and **ferromagnets** (spin-split electron and magnon bands).
- These properties have potential uses in spintronic and other applications.

PRX 12, 040501 (2022)
PRX 12, 031042 (2022)

I.A— Background: Altermagnetic materials

- Several altermagnets have been discovered since 2022:
  - Hexagonal $(C_6\mathcal{T})$: CrSb, MnTe and RuO_2
  - Tetragonal $(C_4\mathcal{T})$: $La_2O_3Mn_2Se_2$, KV_2Se_2O, $Rb_{1-\delta}V_2Te_2O$
- Large number of altermagnets have also been theoretically predicted

Example: $C_4\mathcal{T}$ altermagnet KV_2Se_2O

nature physics

Article https://doi.org/10.1038/s41567-025-02822-y

A metallic room-temperature d-wave altermagnet

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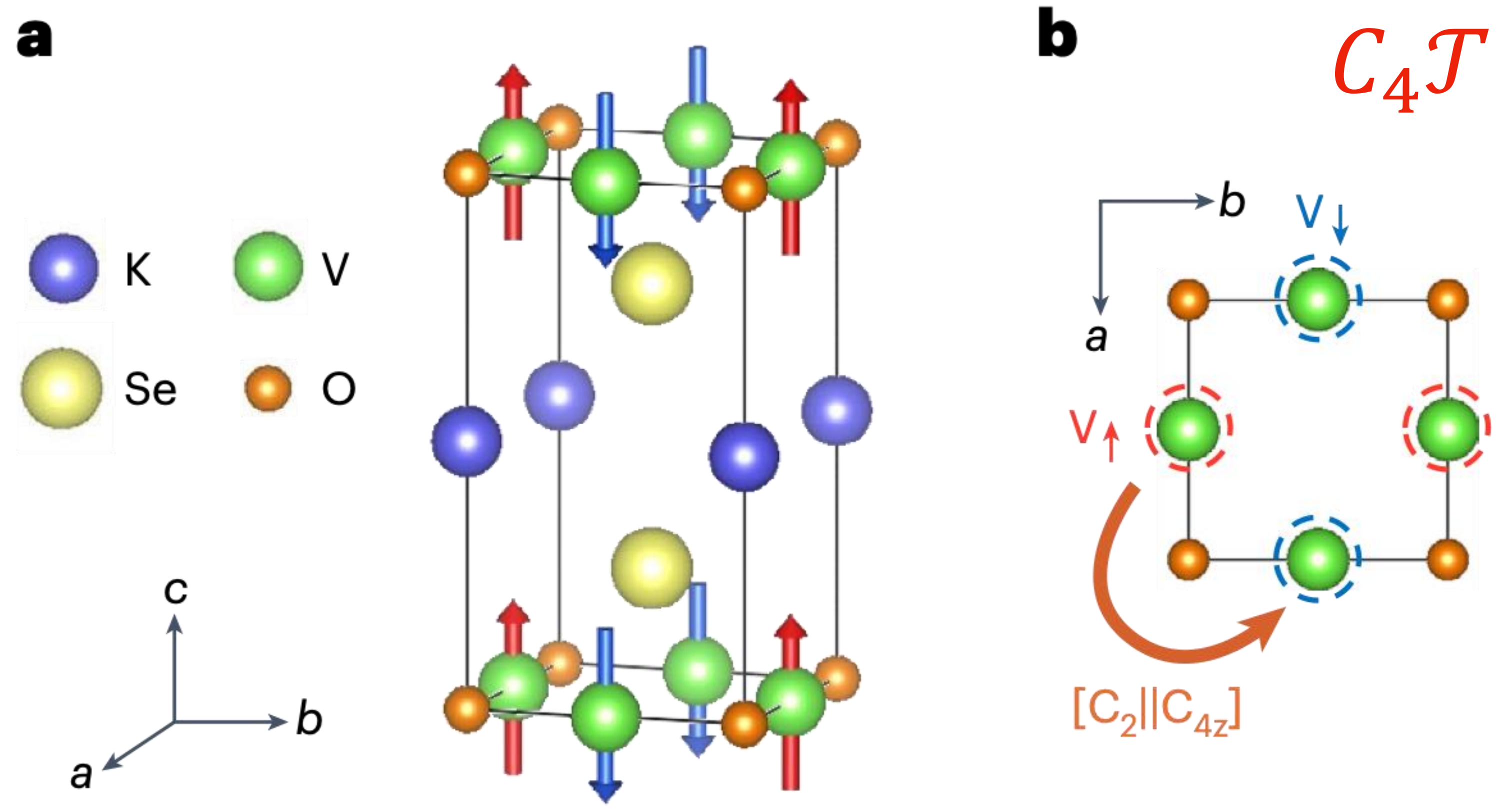
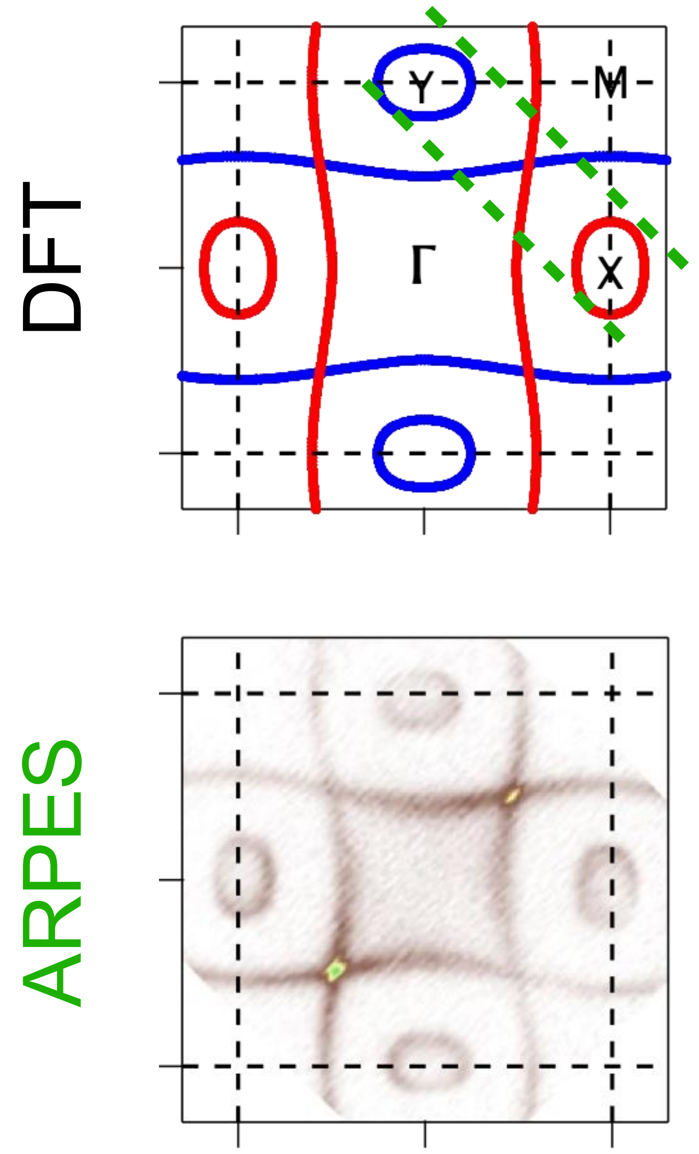
KV_2Se_2O crystal structure

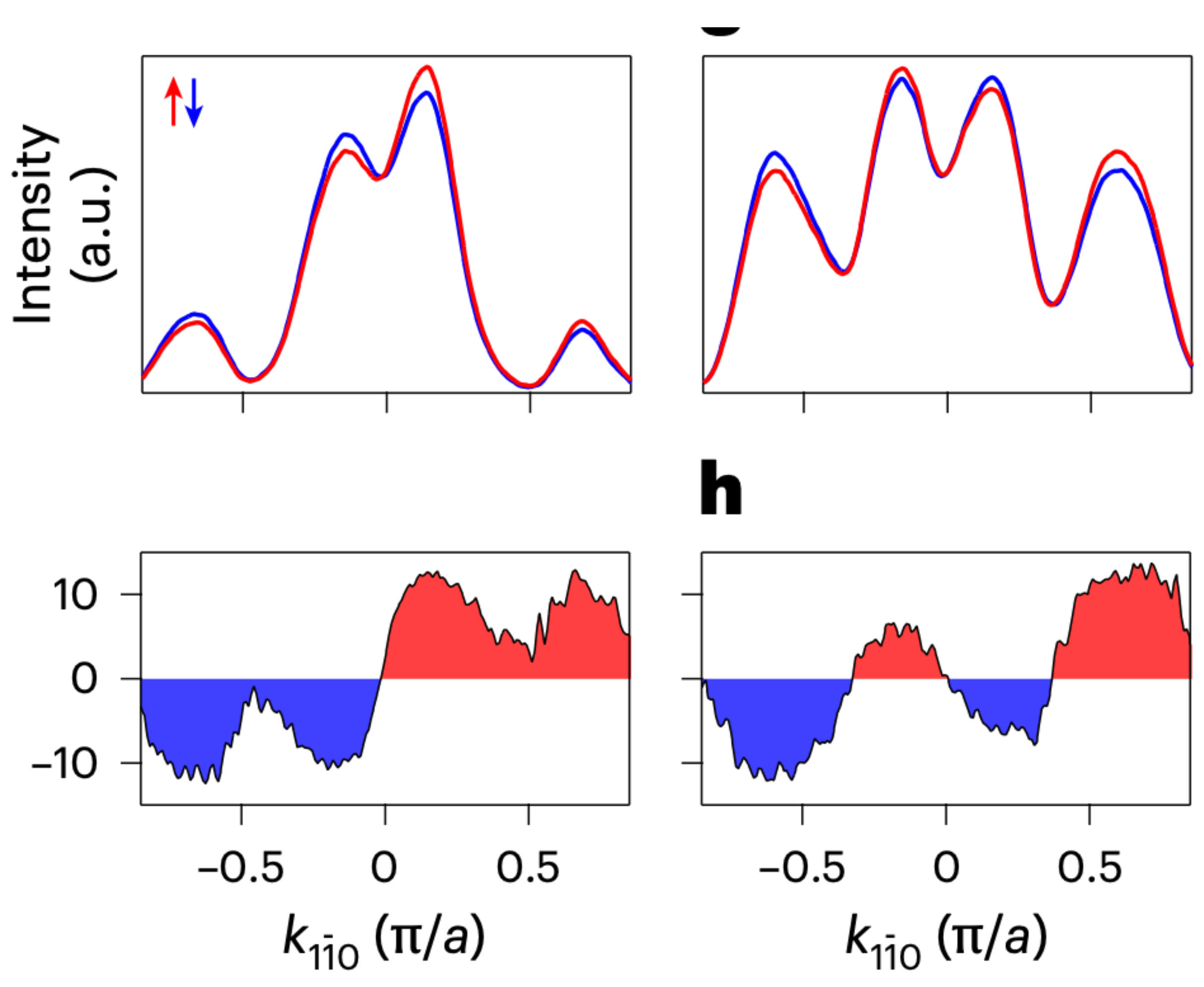
$C_4\mathcal{T}$ symmetry



KV_2Se_2O Fermi surfaces

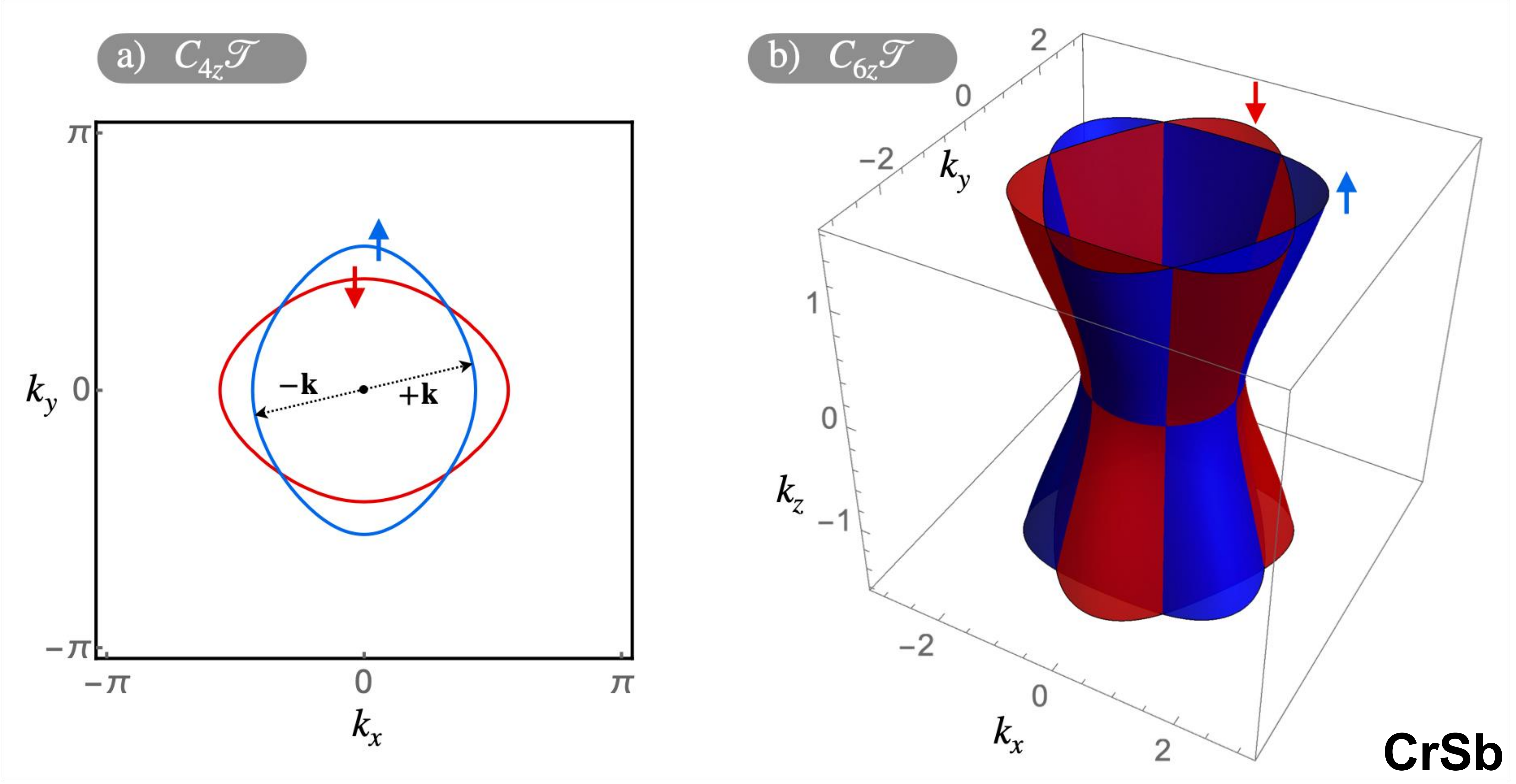


Spin-resolved ARPES



I.B— Motivation: Altermagnetic metals may form unconventional SUPERCONDUCTORS

- Altermagnets are characterized by spin-split Fermi surfaces but vanishing total magnetization.
- An interesting question arises: *"When cooled to a low temperature what are the natural superconducting instabilities of metallic altermagnets?"*
- Answer: One expects unconventional spin-triplet, odd-parity superconducting orders!



Natural zero-momentum Cooper pairs: "equal-spin triplet" channel

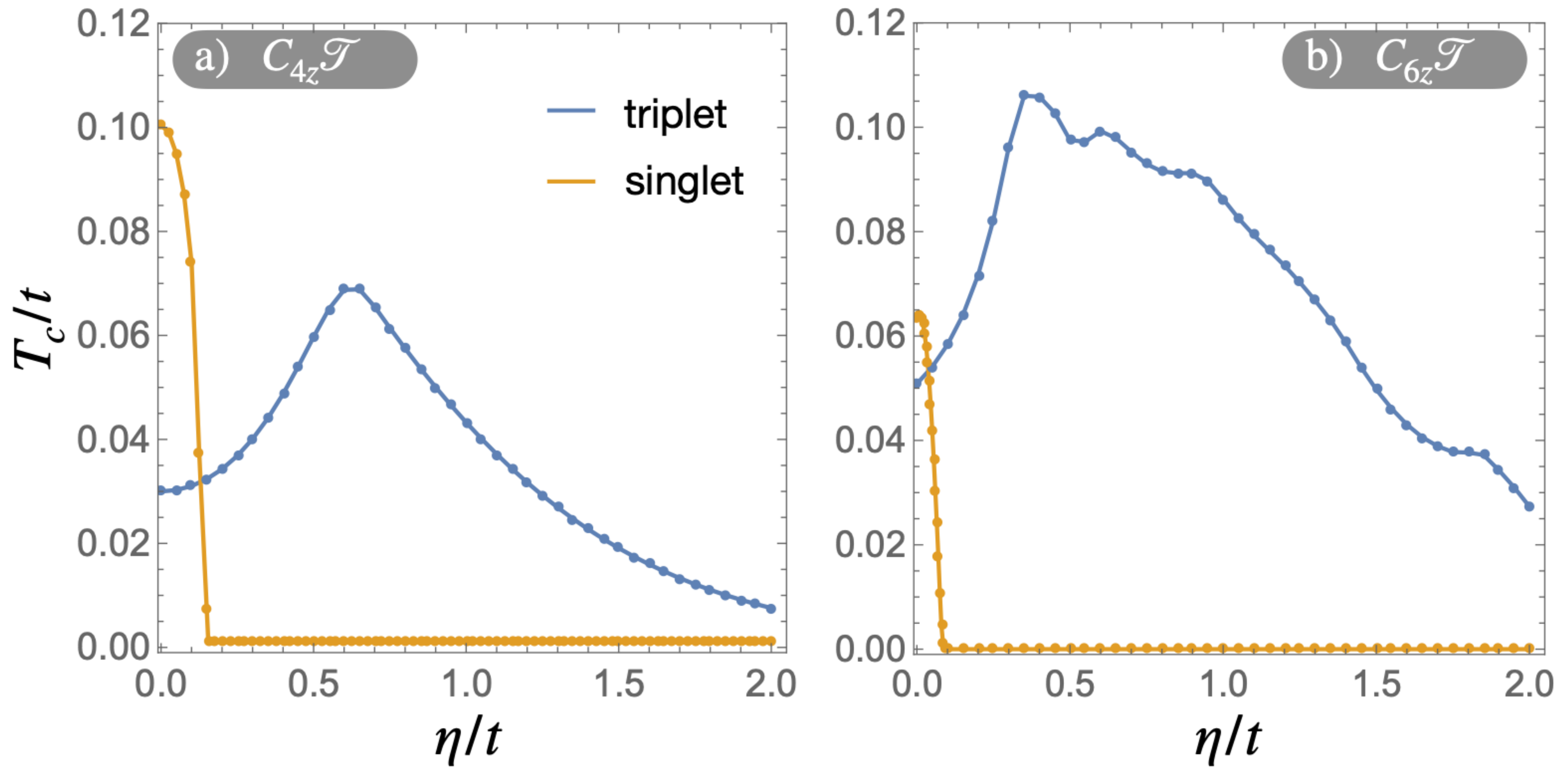
$|\uparrow\uparrow\rangle(p_x \pm ip_y)$ and $|\downarrow\downarrow\rangle(p_x \pm ip_y)$

I.B—Motivation: Altermagnetic metals may form unconventional SUPERCONDUCTORS

- This intuition is indeed confirmed by a model calculation for both $C_{4z}\mathcal{T}$ and $C_{6z}\mathcal{T}$ altermagnets:

$$h_0(\boldsymbol{k}) = -2t(\cos k_x + \cos k_y) - 2\eta\sigma_z(\cos k_x - \cos k_y)$$

+ weak attraction V_1 on n.n. sites

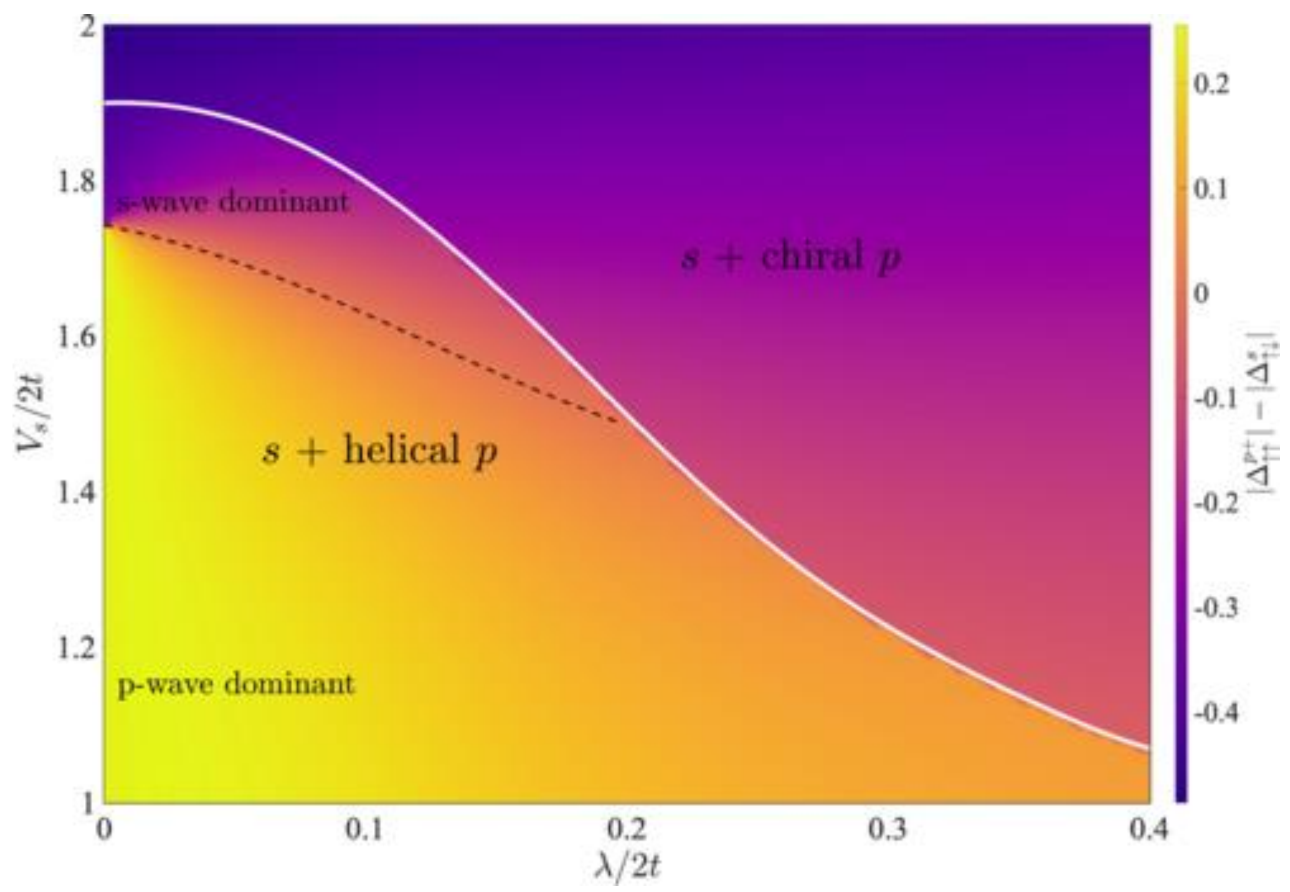


This leads to gap equations for singlet and triplet order parameters:

$$\Delta_0 = \frac{V_1}{2N}\sum_{\boldsymbol{k}} \frac{\Delta_0 C_{\boldsymbol{k}}^2}{\epsilon_{\boldsymbol{k}}} \frac{\sinh \beta\epsilon_{\boldsymbol{k}}}{\cosh \beta\xi_{\boldsymbol{k}-} + \cosh \beta\epsilon_{\boldsymbol{k}}},$$ **singlet** ***s*-wave**

$$\Delta_\sigma = \frac{V_1}{2N}\sum_{\boldsymbol{k}} \frac{\Delta_\sigma |S_{\boldsymbol{k}\sigma}|^2}{E_{\boldsymbol{k}\sigma}} \tanh \frac{1}{2}\beta E_{\boldsymbol{k}\sigma},$$ **triplet** $p_x \pm ip_y$

$$C_{\boldsymbol{k}} = \cos k_x + \cos k_y, \quad S_{\boldsymbol{k}\sigma} = \sin k_x \pm i \sin k_y,$$



D. Zhu, Z.-Y. Zhuang, Z. Wu, and Z. Yan, PRB 108, 184505 (2023).

I.B—Motivation: Altermagnetic metals may form unconventional SUPERCONDUCTORS

Singlet vs triplet competition

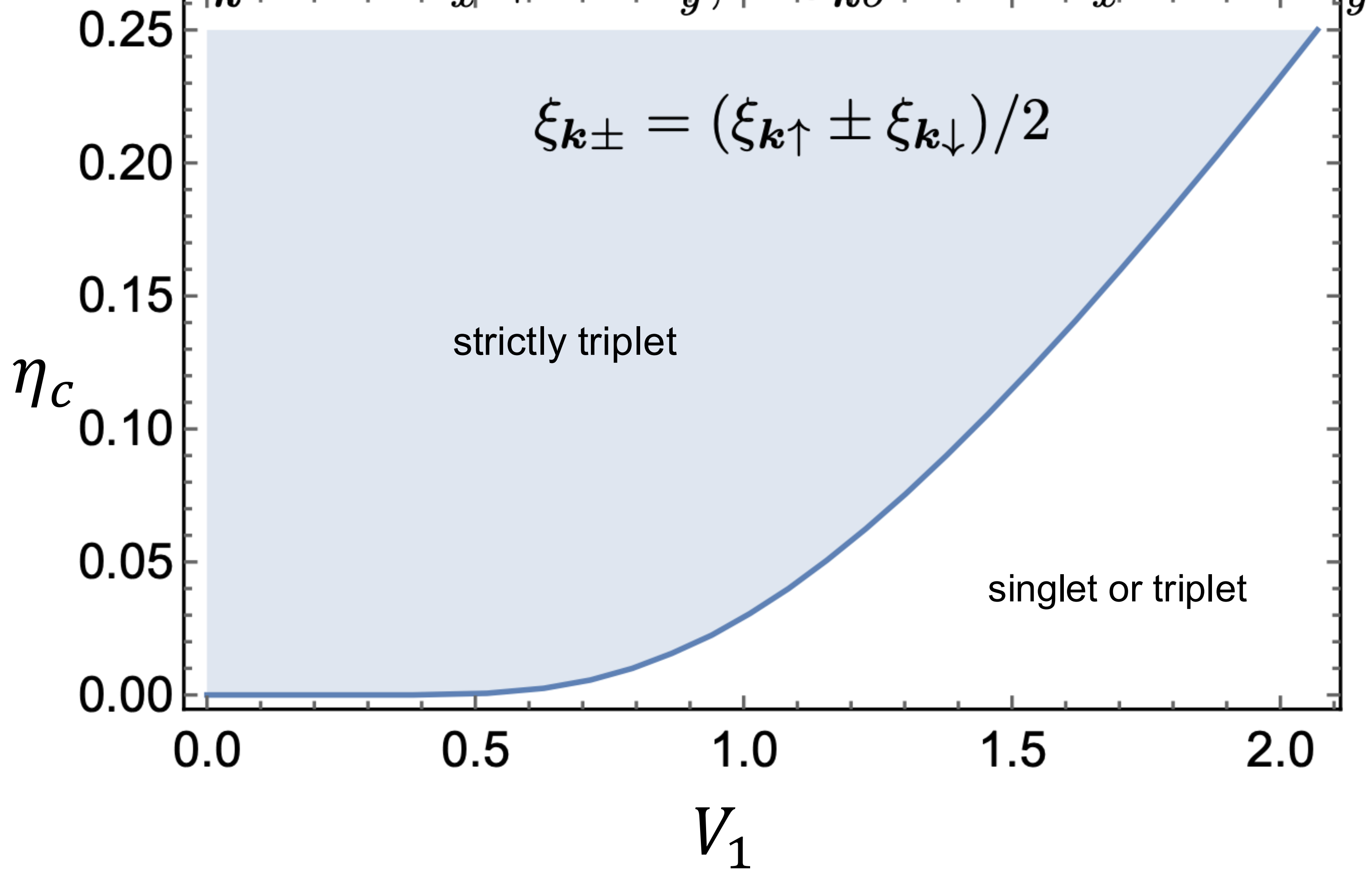
- Rewrite gap equations at $T = T_c$ and define pair susceptibilities:

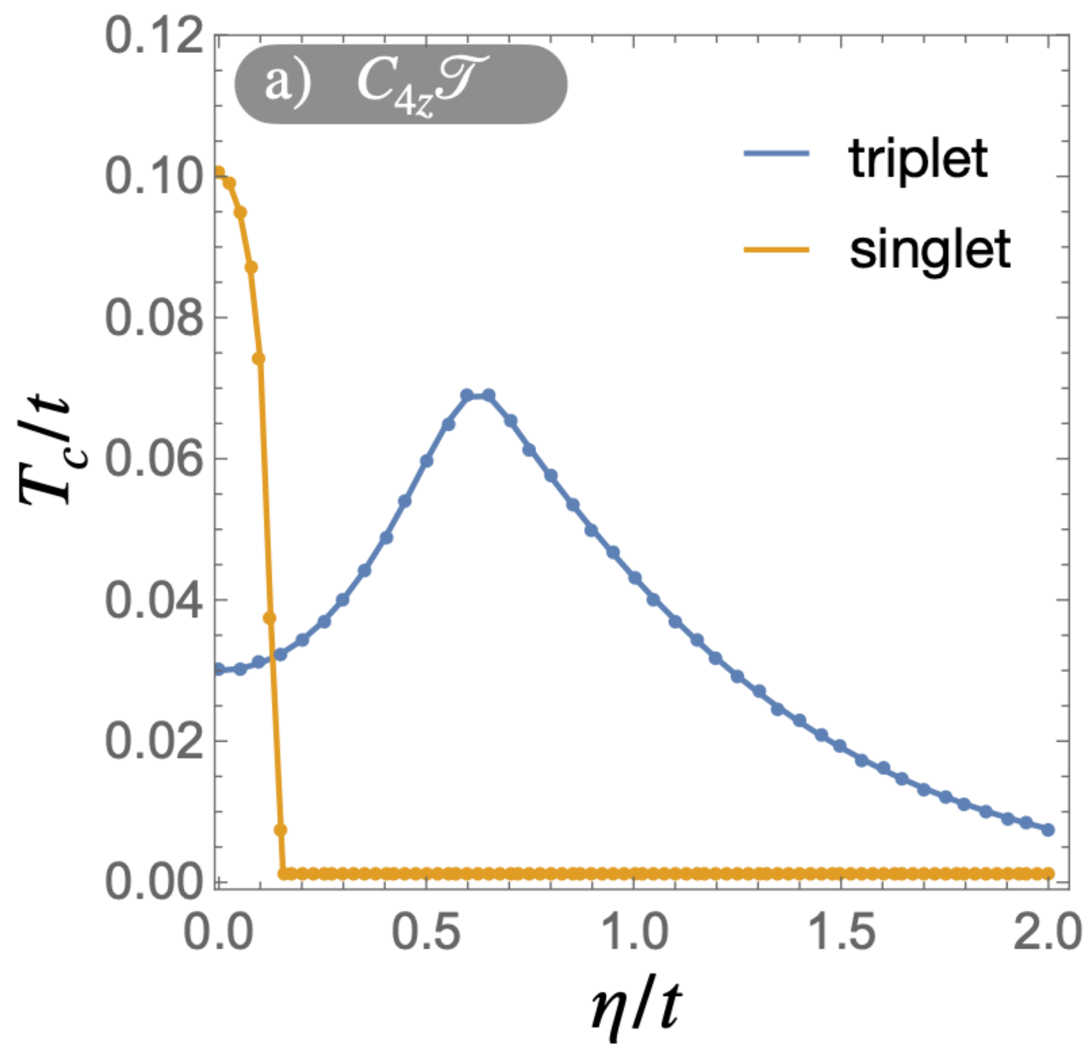
singlet: $$\frac{1}{V_1} = \frac{1}{2N}\sum_{\boldsymbol{k}} \frac{C_{\boldsymbol{k}}^2}{\xi_{\boldsymbol{k}+}} \frac{\sinh \beta\xi_{\boldsymbol{k}+}}{\cosh \beta\xi_{\boldsymbol{k}-} + \cosh \beta\xi_{\boldsymbol{k}+}} = \chi_\Delta^{\uparrow\downarrow}(T)$$

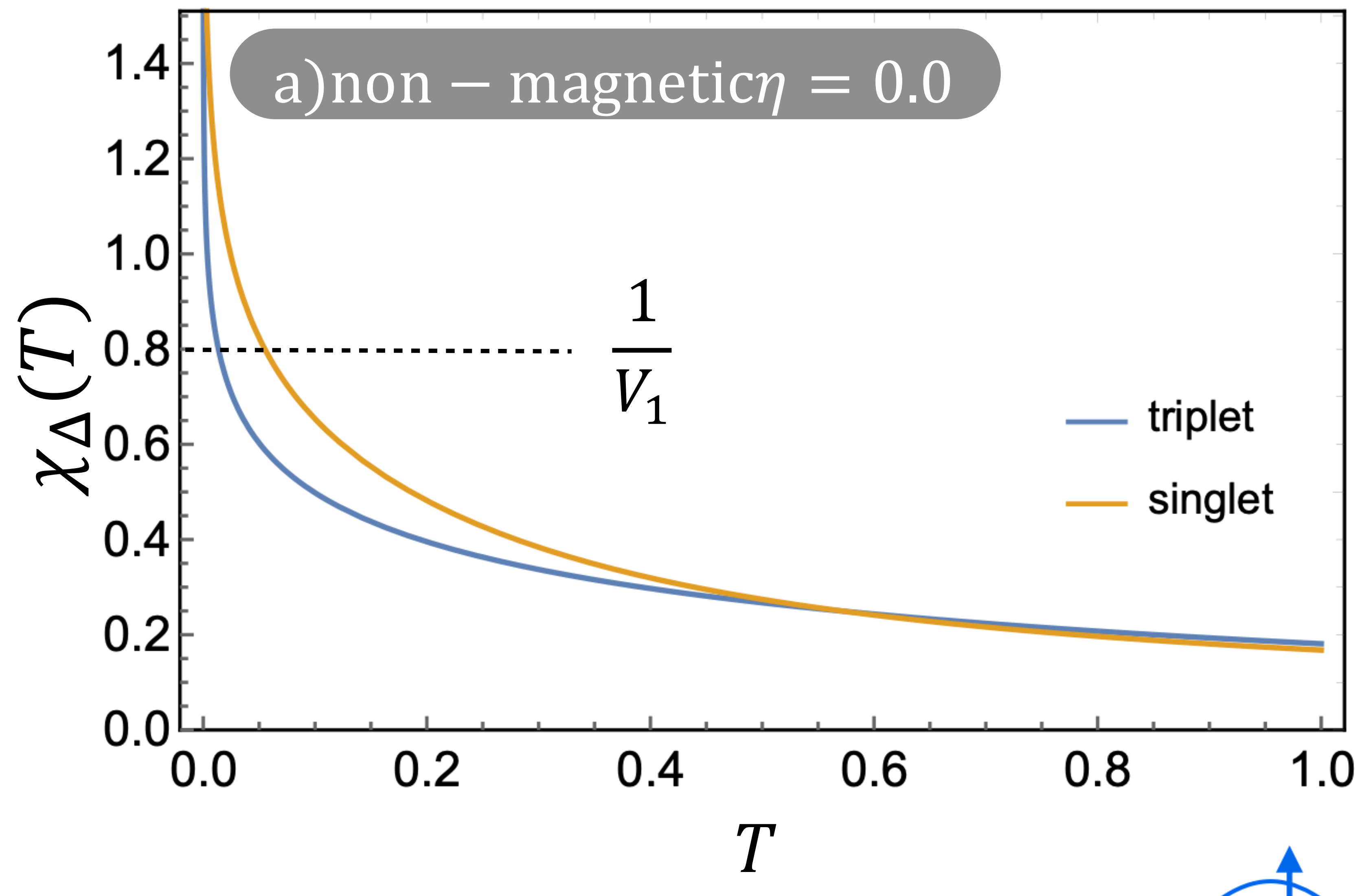
triplet: $$\frac{1}{V_1} = \frac{1}{2N}\sum_{\boldsymbol{k}} \frac{|S_{\boldsymbol{k}\sigma}|^2}{\xi_{\boldsymbol{k}\sigma}} \tanh \frac{1}{2}\beta\xi_{\boldsymbol{k}\sigma} = \chi_\Delta^{\uparrow\uparrow}(T)$$

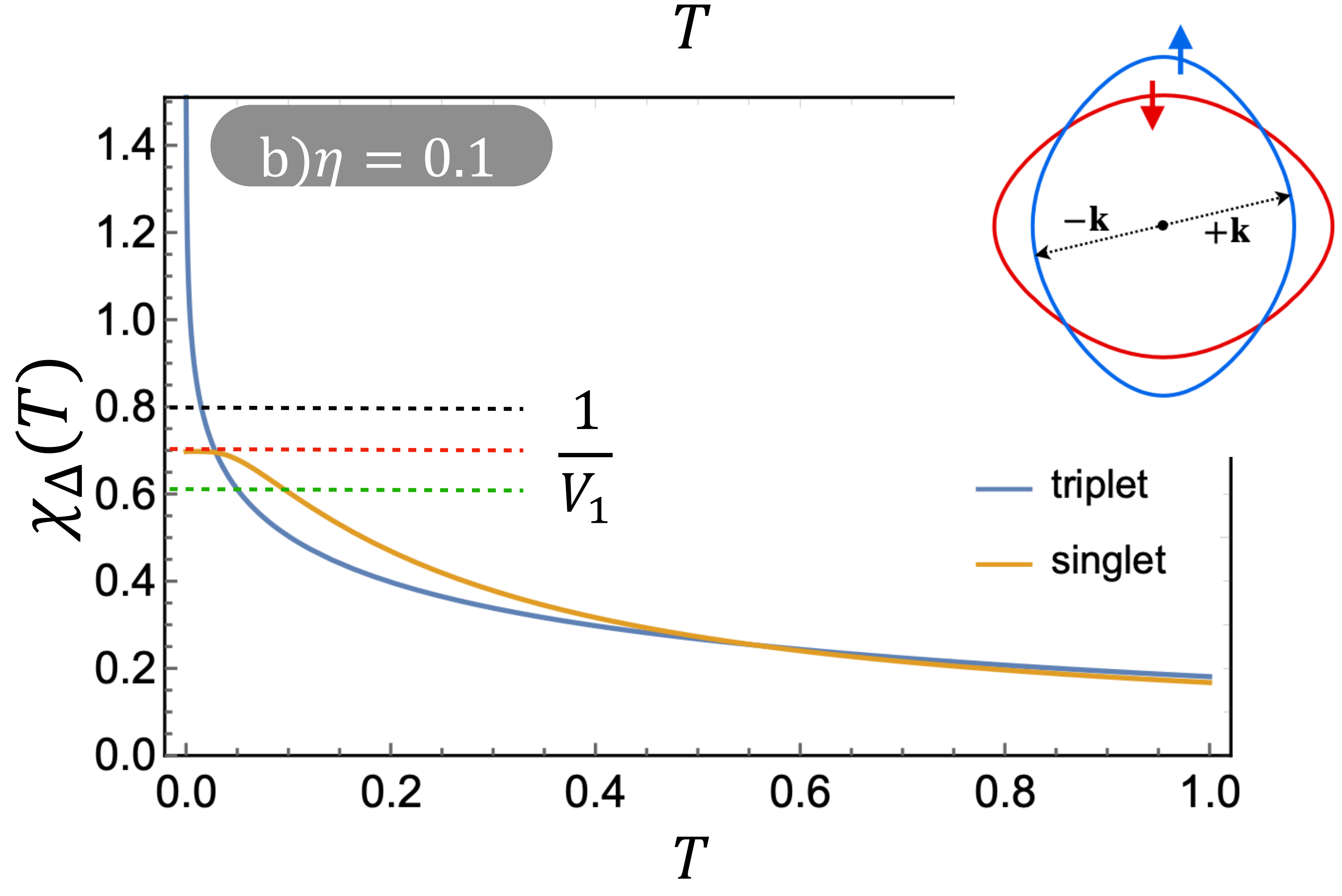
$$C_{\boldsymbol{k}} = \cos k_x + \cos k_y, \quad S_{\boldsymbol{k}\sigma} = \sin k_x \pm i \sin k_y,$$

$$\xi_{\boldsymbol{k}\pm} = (\xi_{\boldsymbol{k}\uparrow} \pm \xi_{\boldsymbol{k}\downarrow})/2$$



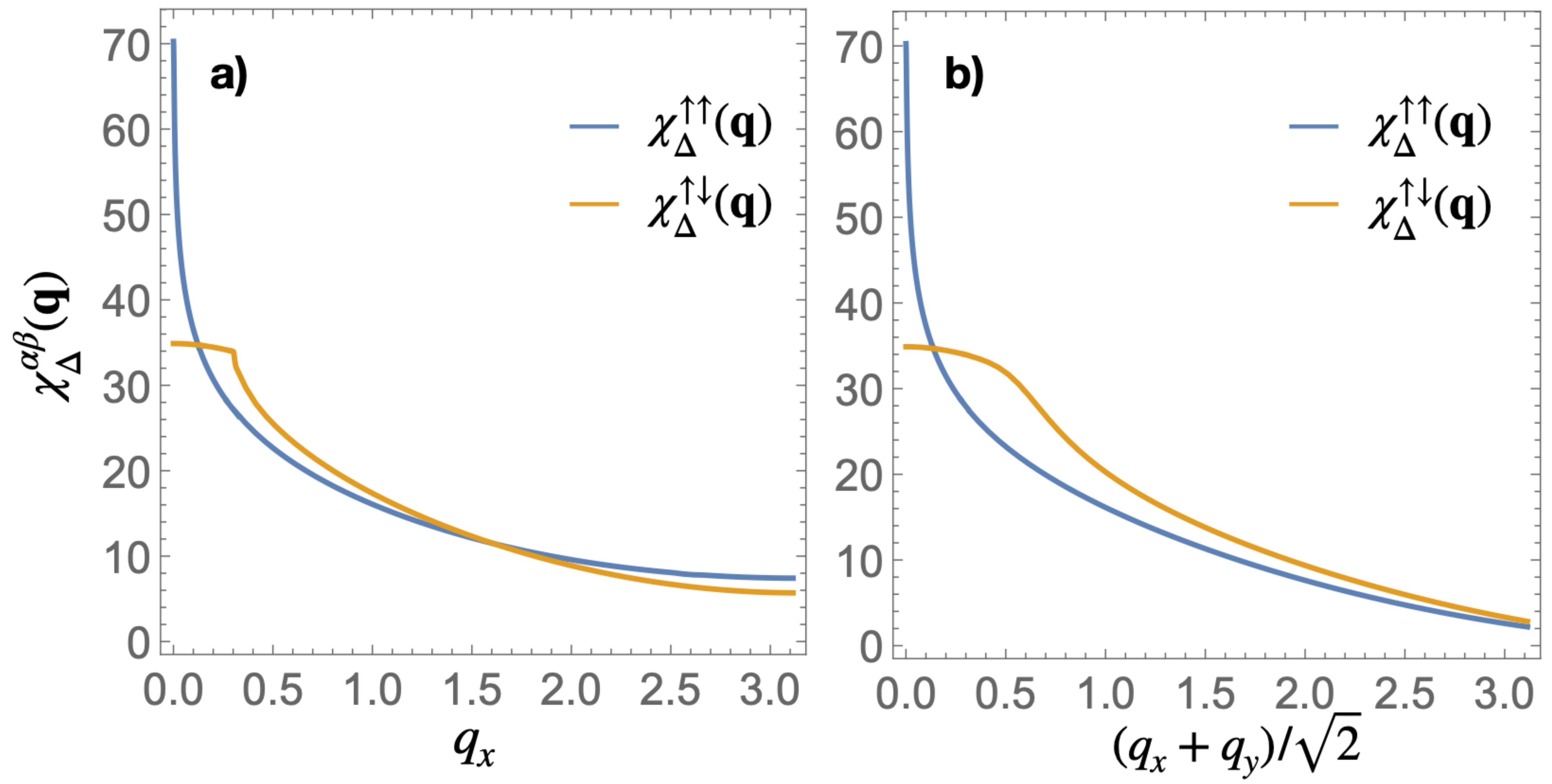






Finite momentum pairing — FFLO states

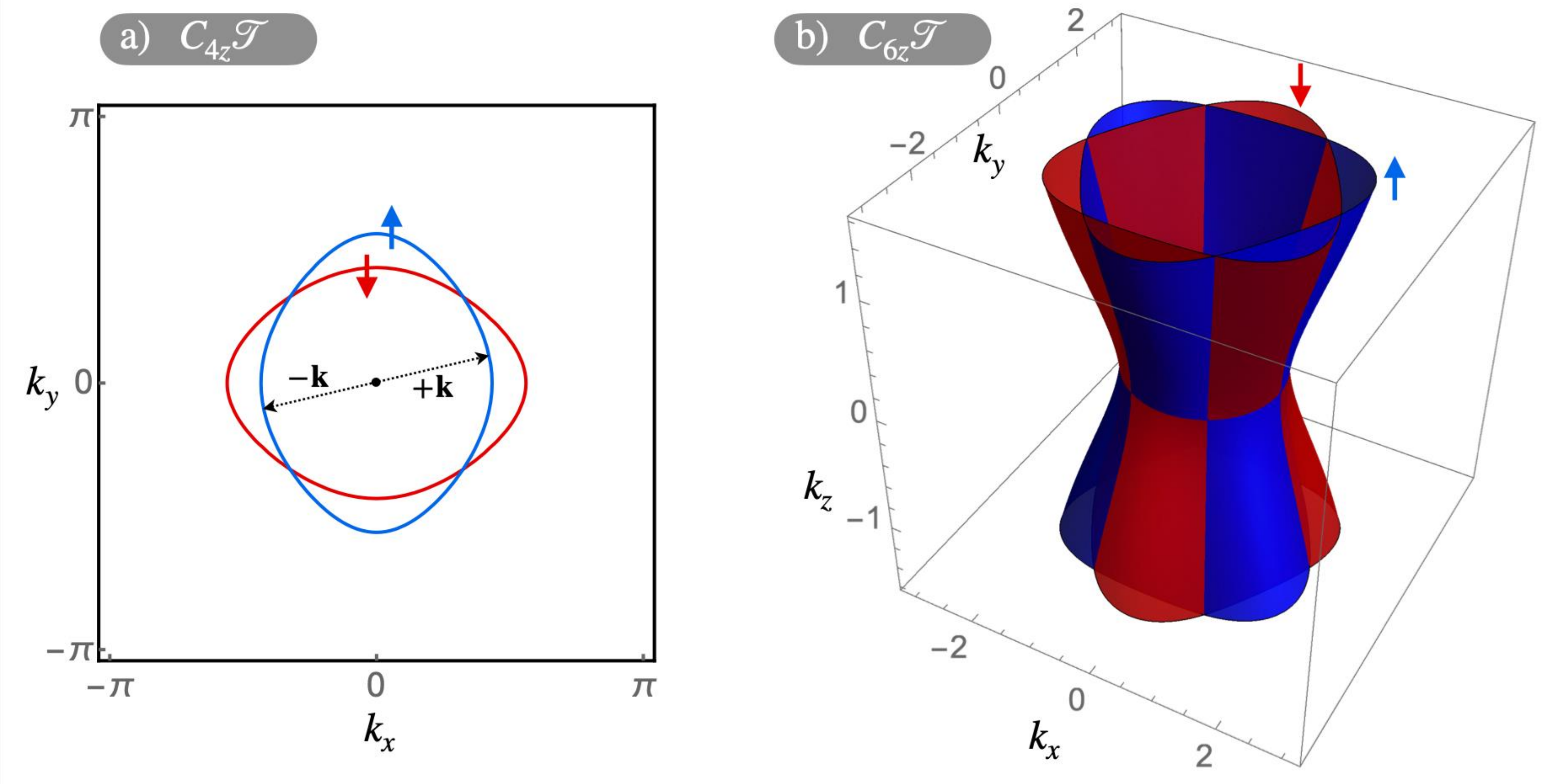
Pair susceptibilities:



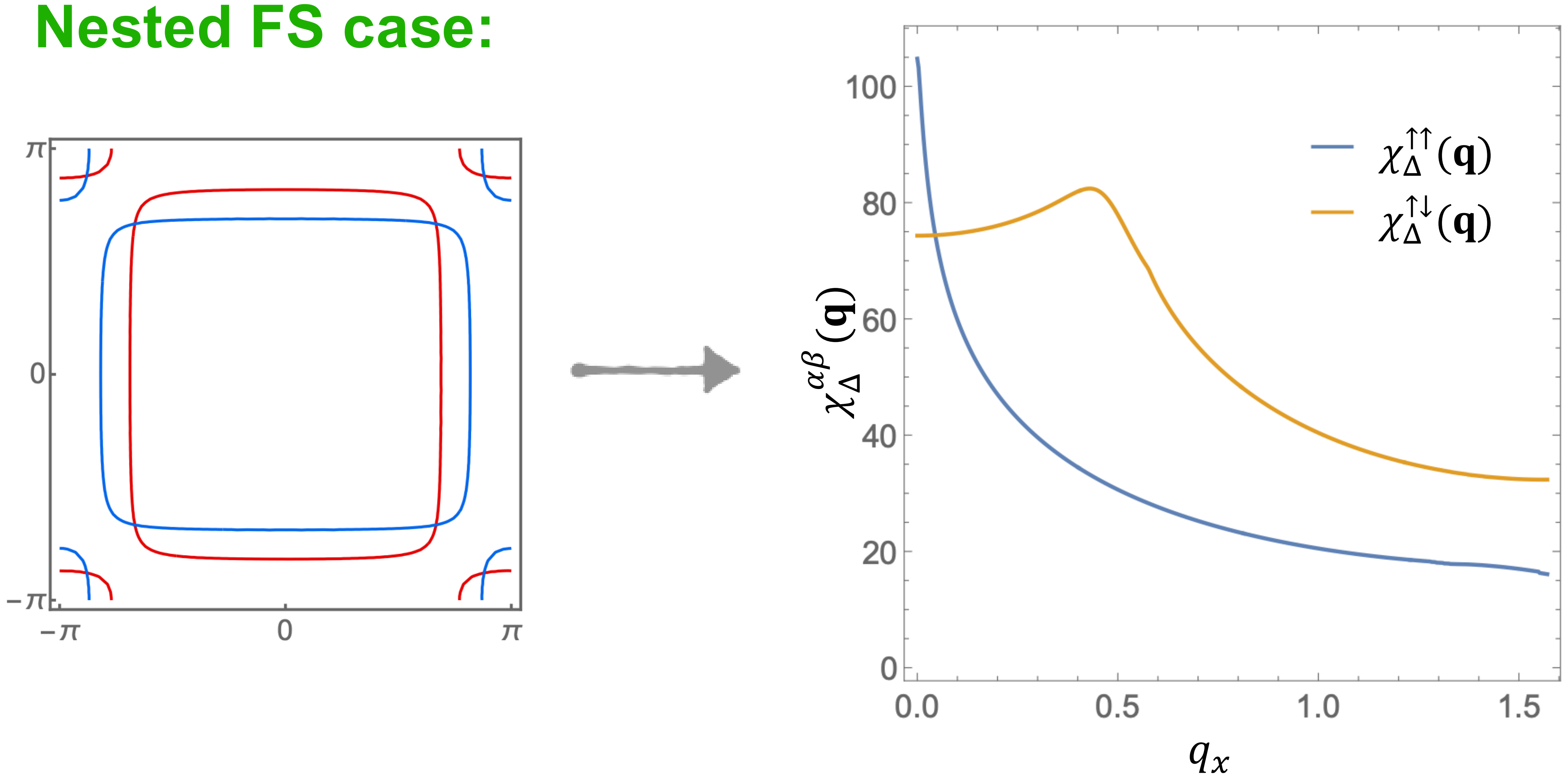
$$\chi_\Delta^{\alpha\beta}(\omega, \boldsymbol{q}) = \int_{-\infty}^{\infty} dt e^{-i\omega t} \langle \hat{\Delta}_{\boldsymbol{q}}^{\alpha\beta}(t)^\dagger \hat{\Delta}_{\boldsymbol{q}}^{\alpha\beta}(0) \rangle$$

$$\hat{\Delta}_{\boldsymbol{q}}^{\alpha\beta} = \sum_{\boldsymbol{k}} g_{\boldsymbol{k}} c_{\boldsymbol{k}+\boldsymbol{q}\alpha}^\dagger c_{-\boldsymbol{k}\beta}^\dagger$$

$$\chi_\Delta^{\alpha\beta}(\boldsymbol{q}) = \sum_{\boldsymbol{k}} |g_{\boldsymbol{k}} + g_{\boldsymbol{k}-\boldsymbol{q}}|^2 \frac{1 - n_F(\xi_{\boldsymbol{k}\alpha}) - n_F(\xi_{\boldsymbol{q}-\boldsymbol{k}\beta})}{\xi_{\boldsymbol{k}\alpha} + \xi_{\boldsymbol{q}-\boldsymbol{k}\beta}}.$$



Nested FS case:

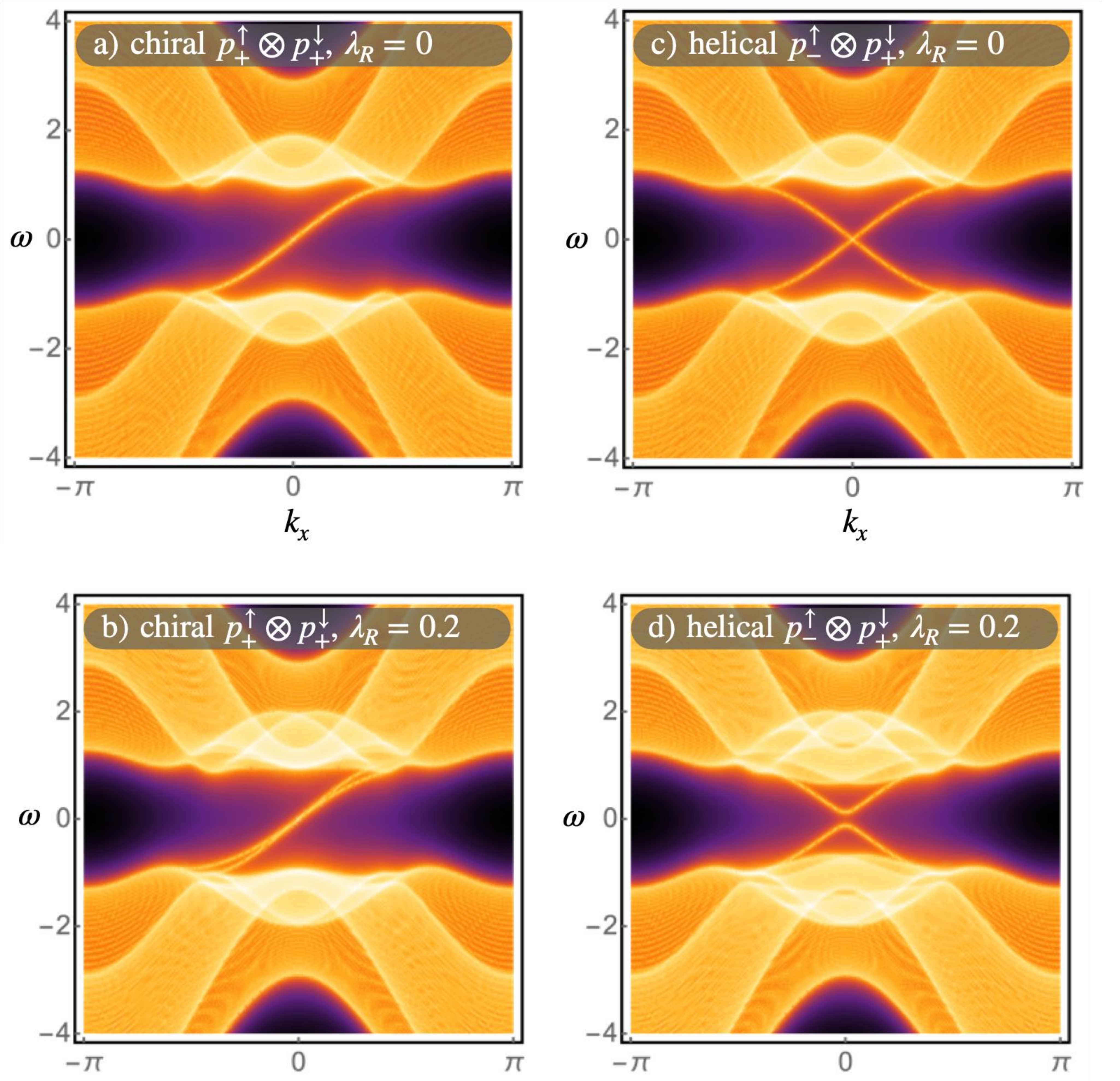


II.A— Non-trivial Topology

Chiral *p*-wave superconductors are TOPOLOGICAL, specifically there are four distinct possibilities:

Ground state	Abbreviation	Chern number	Property
$\lvert\uparrow\uparrow(p_x+ip_y)\rangle\otimes\lvert\downarrow\downarrow(p_x+ip_y)\rangle$	$p_+^\uparrow\otimes p_+^\downarrow$	$+2$	chiral
$\lvert\uparrow\uparrow(p_x-ip_y)\rangle\otimes\lvert\downarrow\downarrow(p_x+ip_y)\rangle$	$p_-^\uparrow\otimes p_+^\downarrow$	0	helical
$\lvert\uparrow\uparrow(p_x+ip_y)\rangle\otimes\lvert\downarrow\downarrow(p_x-ip_y)\rangle$	$p_+^\uparrow\otimes p_-^\downarrow$	0	helical
$\lvert\uparrow\uparrow(p_x-ip_y)\rangle\otimes\lvert\downarrow\downarrow(p_x-ip_y)\rangle$	$p_-^\uparrow\otimes p_-^\downarrow$	-2	chiral

- The two chiral phases are stable, protected by a non-zero Chern number $C=\pm 2$.
- The two helical phases are fragile: helical edge modes are gapped out by perturbations that break the $U(1)^\uparrow\times U(1)^\downarrow$ spin symmetry, e.g. Rashba spin-orbit coupling or in-plane applied magnetic field.



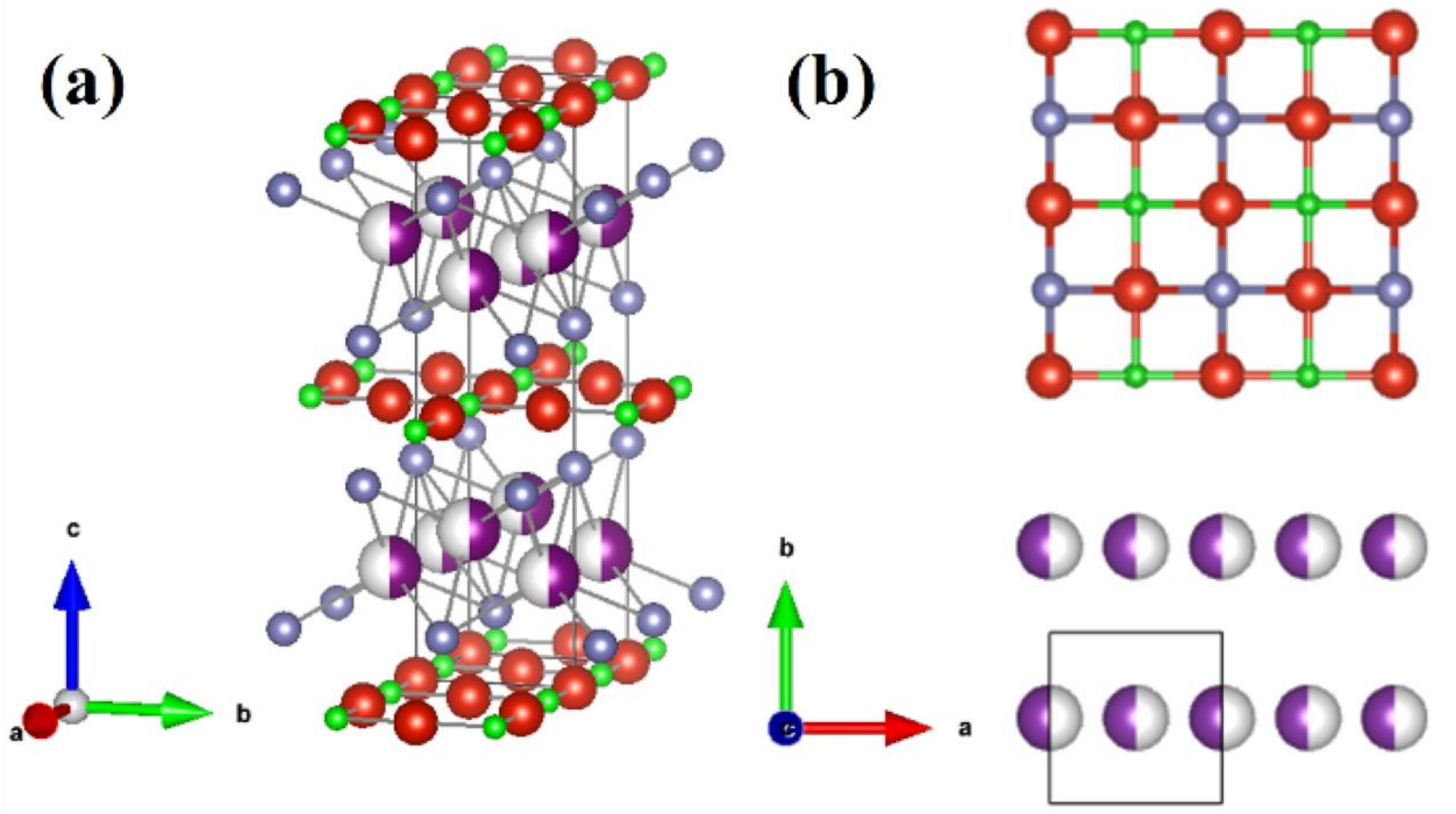
NEW: Possible material candidate $Na_{2-x}V_2Se_2O$

Emergent superconductivity at 16.3 K in an altermagnetic candidate $Na_{2-x}V_2Se_2O$ with broken inversion symmetry

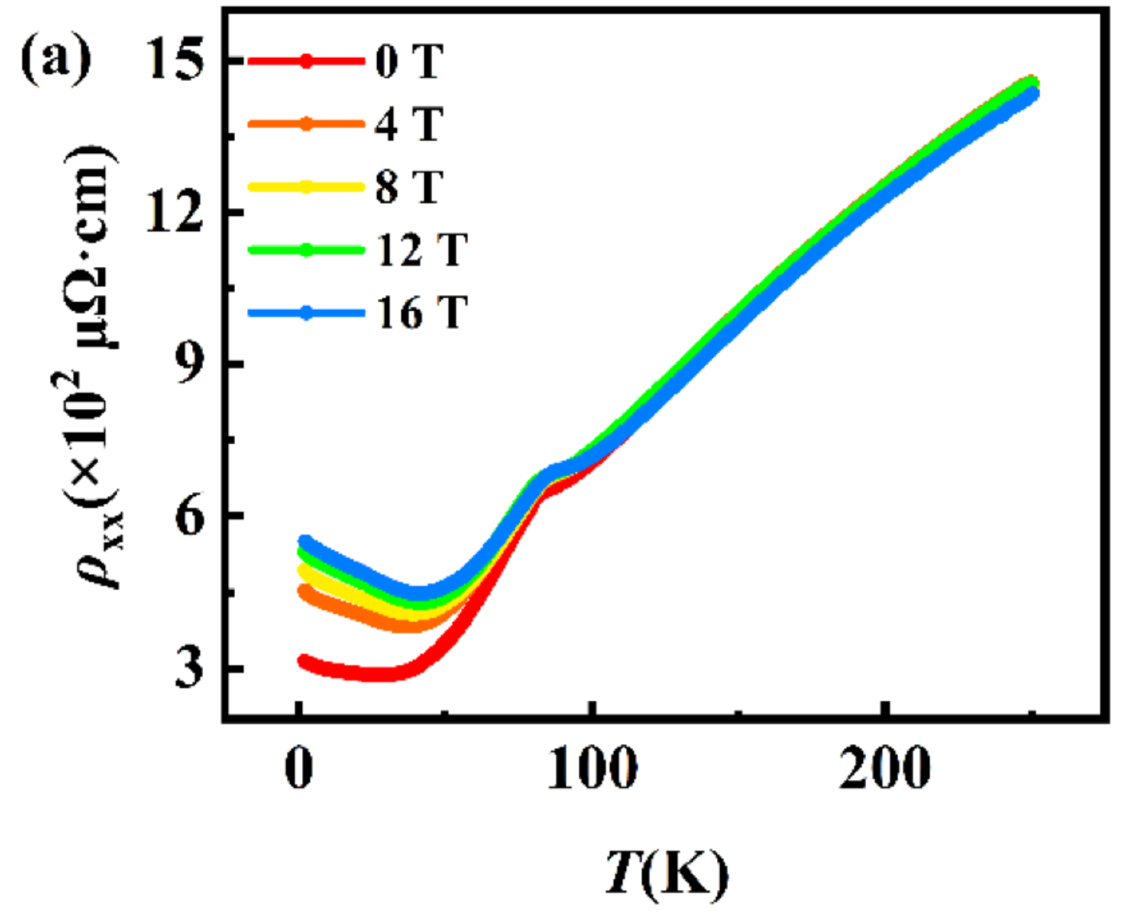
arXiv:2604.00838, April 2026

Yingrui Sun[1,2,§], Zhaocheng Yin[1,2,§], Tengfeng Zhang[1,2,§], Lihan Wang[1,2], Binbin Ruan[3], Yu Huang[1,2], Junbao He[4], Wenliang Zhu[5], Maoyun Ma[1,2], Jianli Bai[1,2], Jingwen Cheng[1,2], Qingxin Dong[1,2], Cundong Li[1,2], Pinyu Liu[1,2], Qiaoyu Liu[1,2], Chengdong Zhang[1,2] and Genfu Chen[1,2,*]

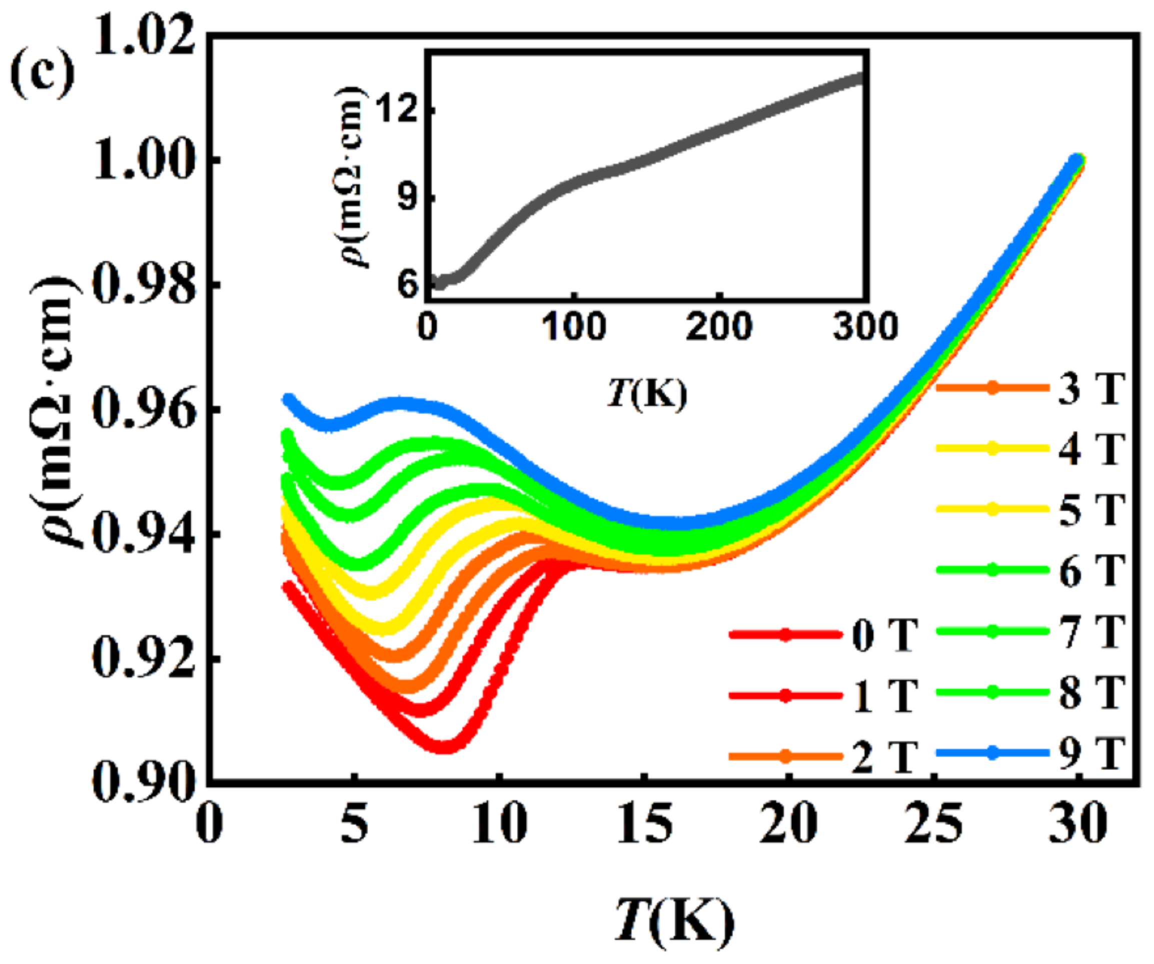
[1]Institute of Physics and Beijing National Laboratory for Condensed Matter Physics, Chinese Academy of Sciences, Beijing, 100190, China

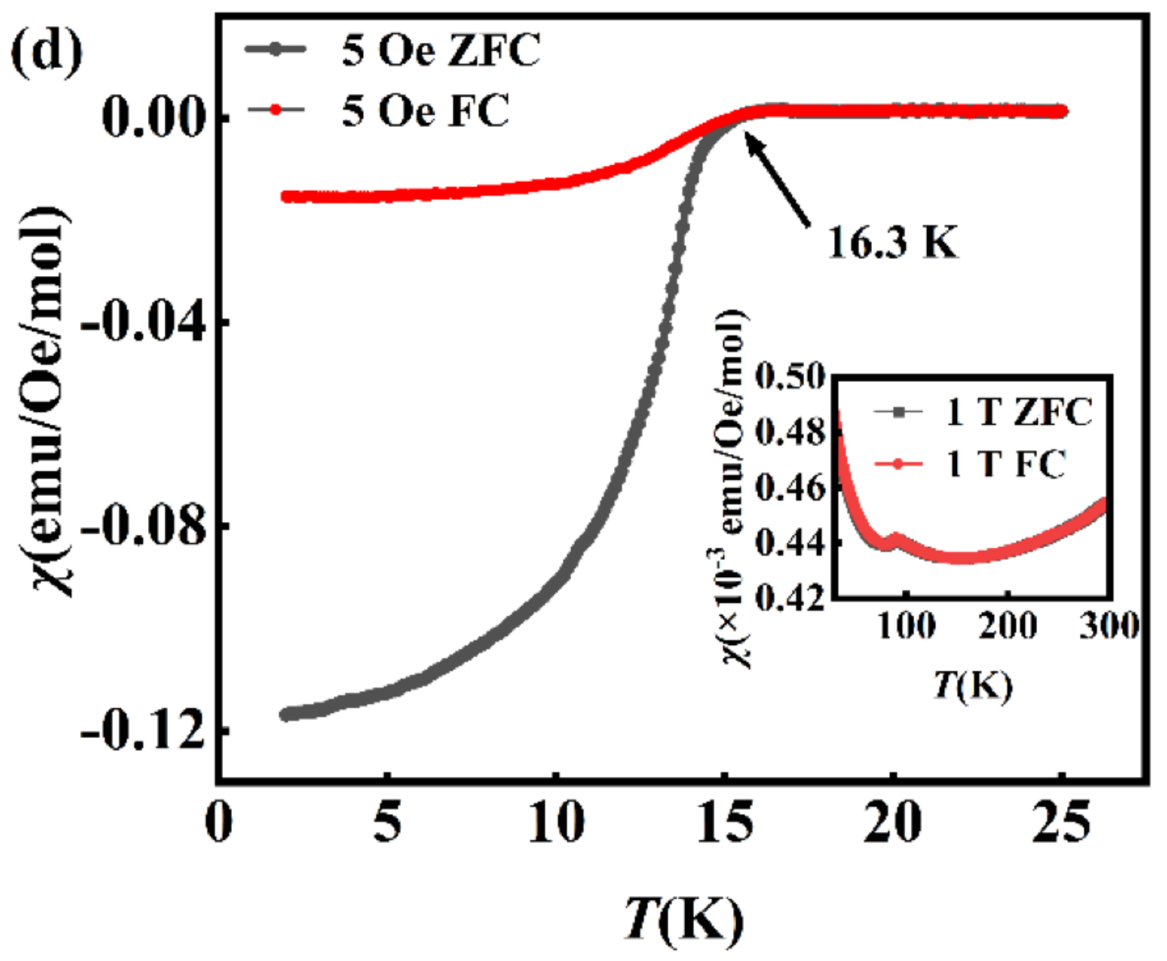


Evidence for a magnetic transition near 90K:
Could be an altermagnet?



Superconductivity at 16.3K





II.B — Persistent spin currents and pure spin supercurrents

We argued that a natural SC ground state of the metallic altermagnet is equal spin chiral *p*-wave

$|\uparrow\uparrow(p_x \pm ip_y)\rangle$ and $|\downarrow\downarrow(p_x \pm ip_y)\rangle$

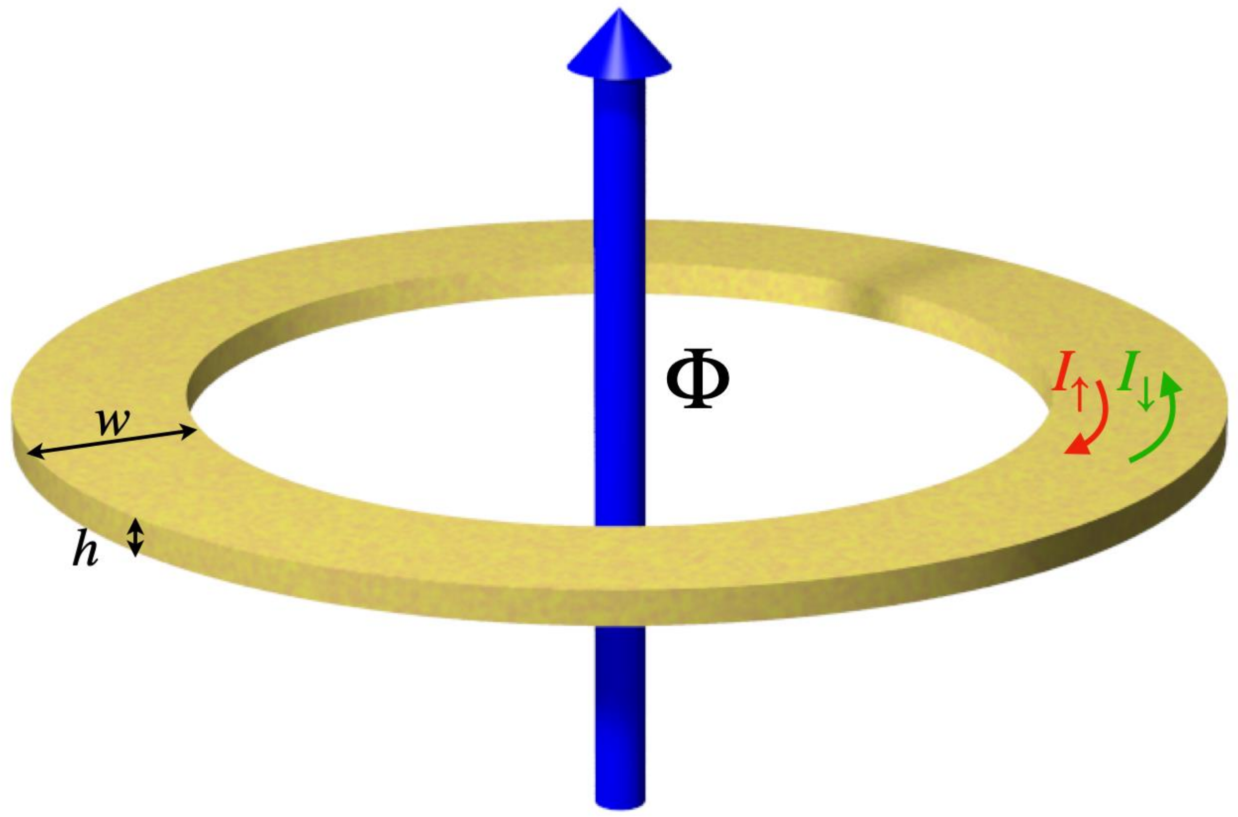
In the strict non-relativistic limit the spin-up and spin-down condensates are decoupled:

$$H = \begin{pmatrix} h^{\uparrow}_{\mathrm{BdG}} & 0 \\ 0 & h^{\downarrow}_{\mathrm{BdG}} \end{pmatrix}$$

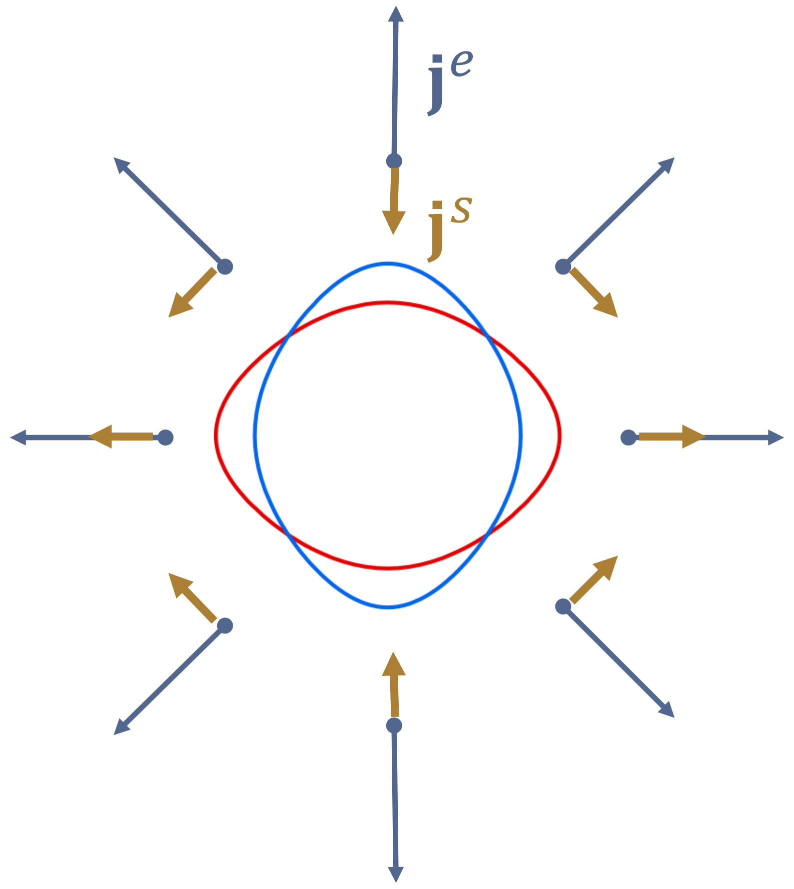
One thus expects an interesting possibility of spin-polarized persistent currents in these materials!

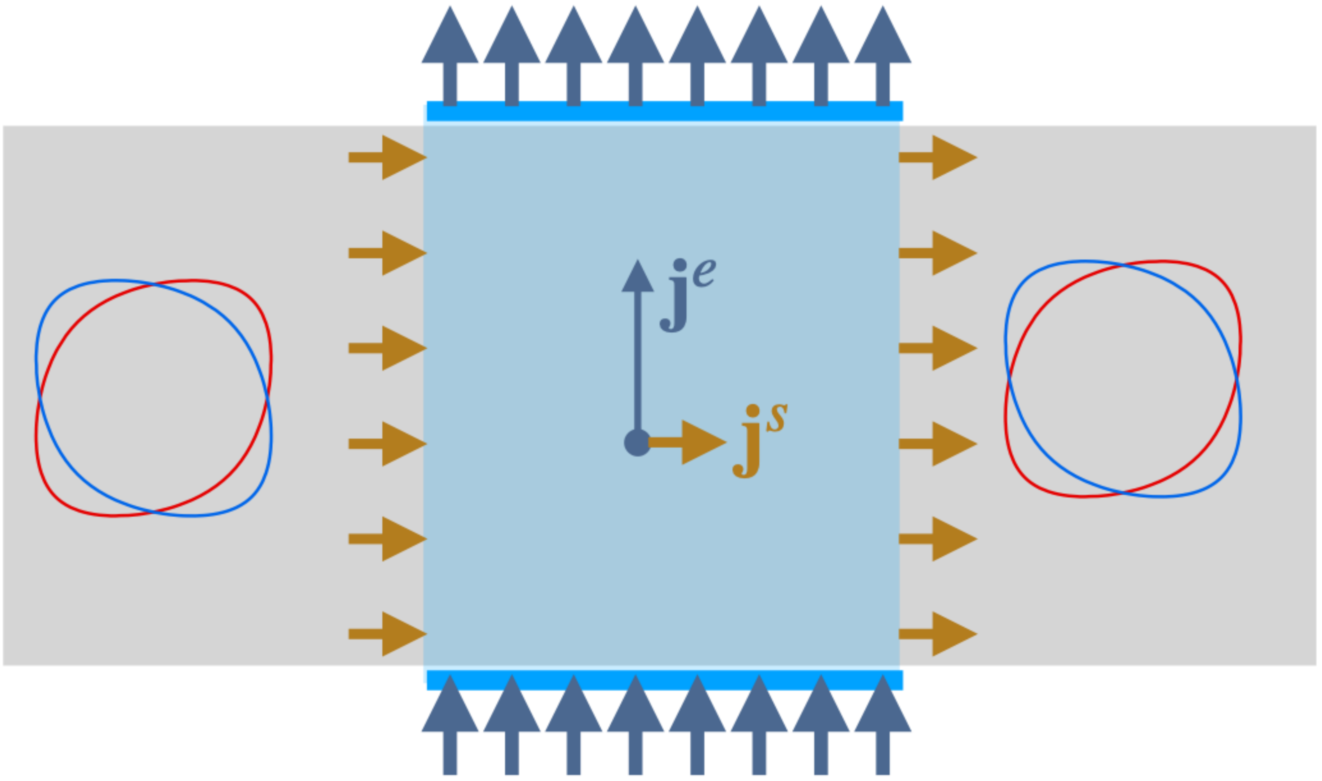
This leads to the following novel effects:

A. Pure spin supercurrent in a ring



B. "Spin-current dynamo effect" — generation of spin-polarized supercurrent in a *d*-wave altermagnet



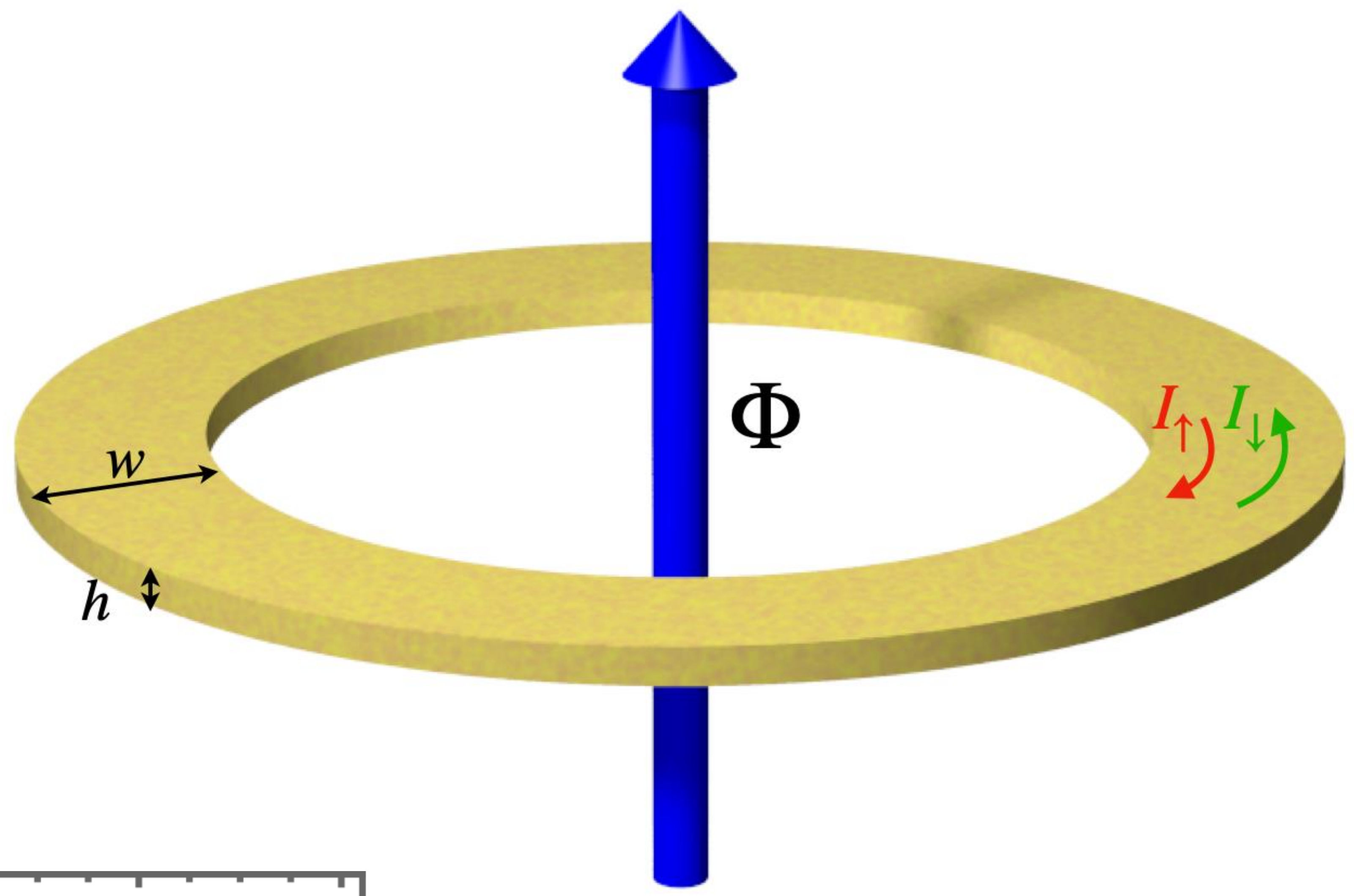


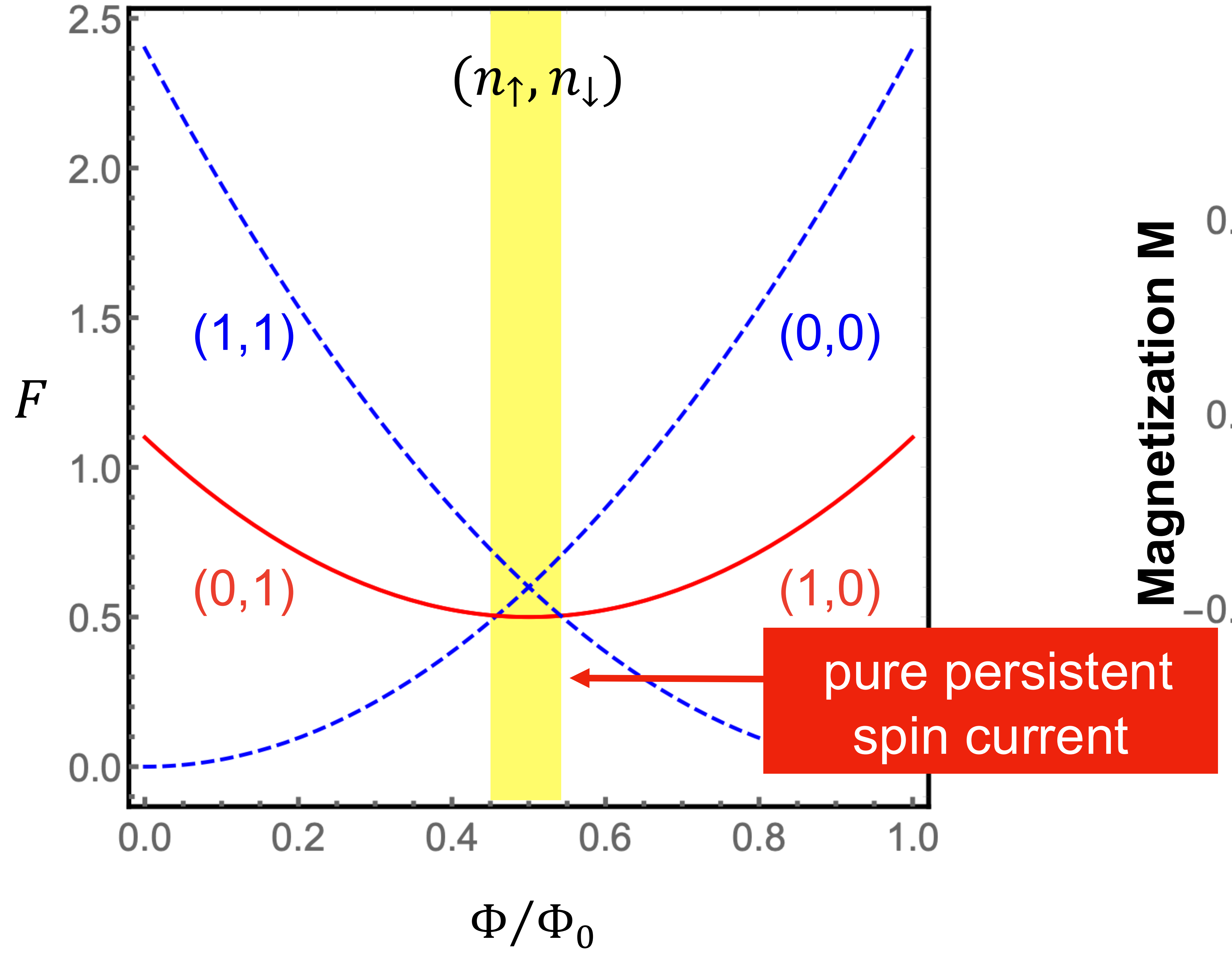
PRX 16, 011057 (2026)

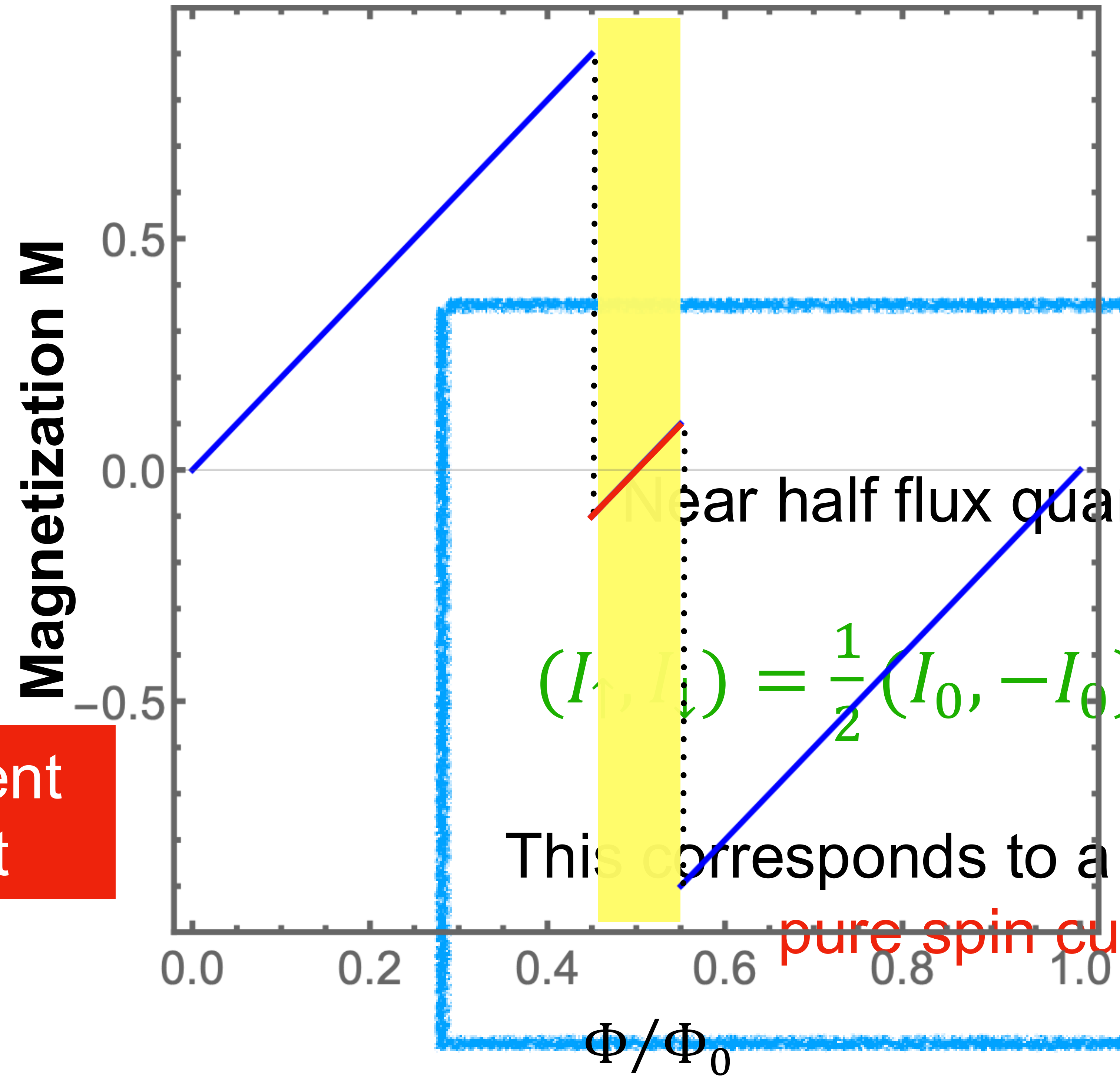
II.A — Pure persistent spin current in a ring

$$F = \frac{1}{2} L_K (I_\uparrow^2 + I_\downarrow^2) + \frac{1}{2} L_G (I_\uparrow + I_\downarrow)^2 .$$

$$I_\sigma = I_0 (n_\sigma - \Phi/\Phi_0), n_\sigma = 0, \pm 1, \pm 2, \ldots$$







Near half flux quantum F is minimized when

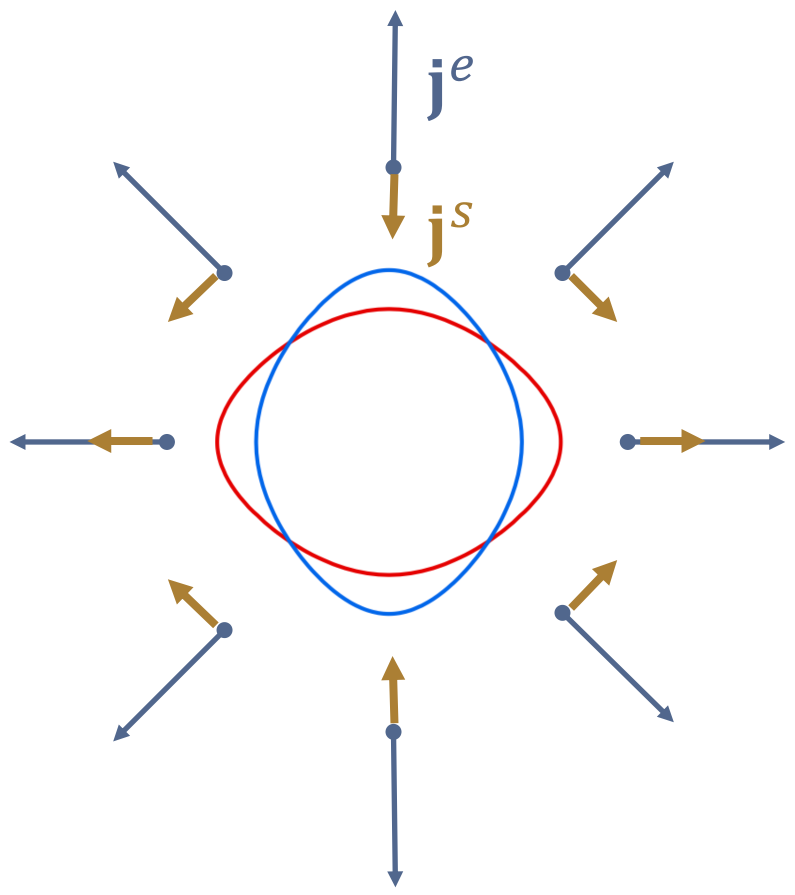
$(I_\uparrow, I_\downarrow) = \frac{1}{2}(I_0, -I_0)$ or $(I_\uparrow, I_\downarrow) = \frac{1}{2}(-I_0, I_0)$

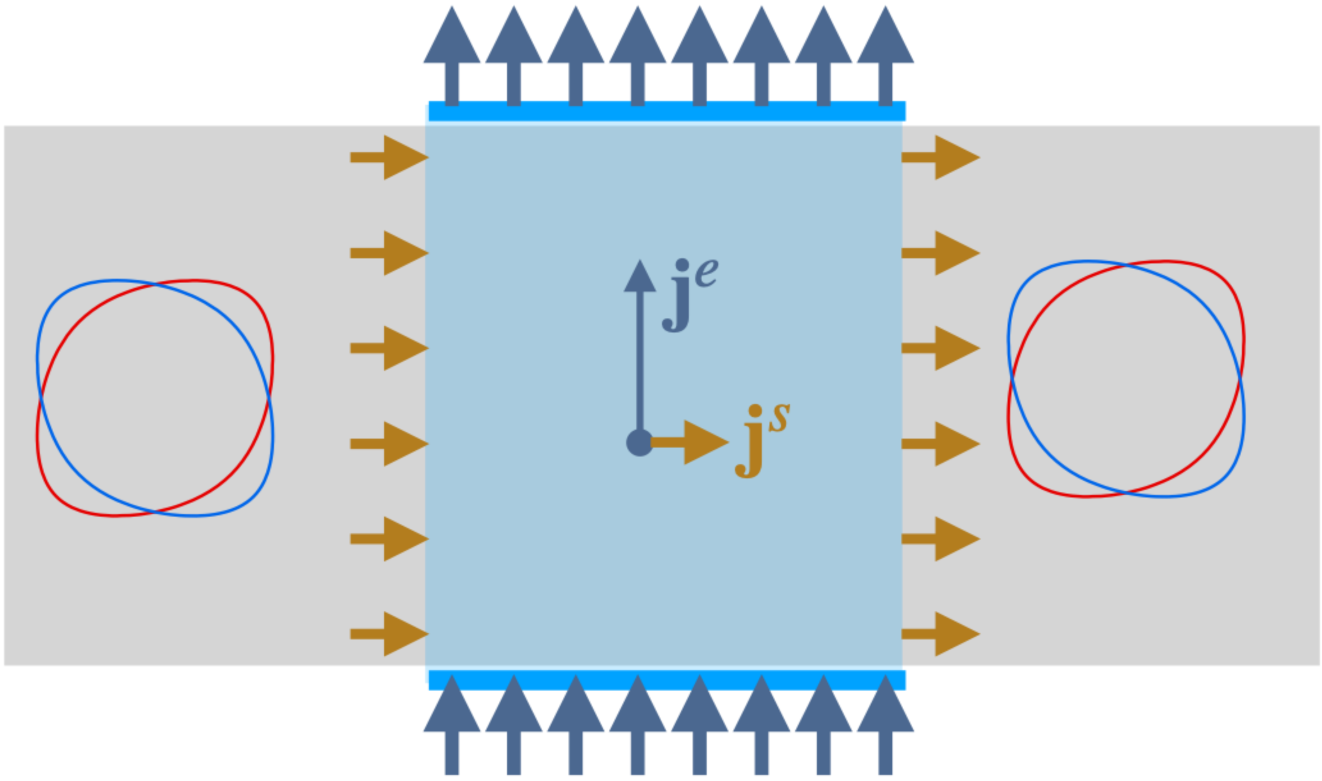
This corresponds to a “charge counterflow” regime —> pure spin current flows in the ring.

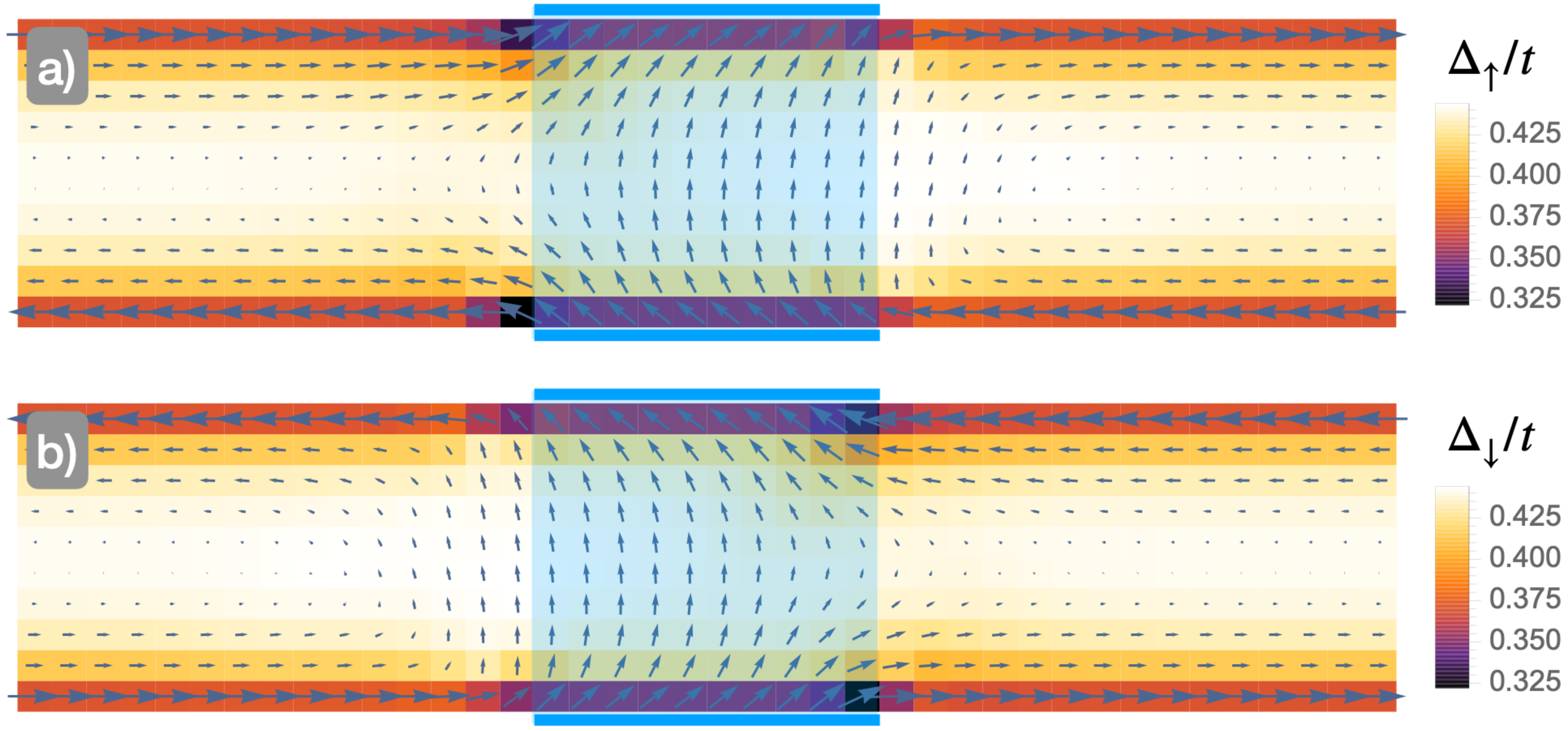
Can be detected via **magnetization measurement** — no spin-current probe is necessary!

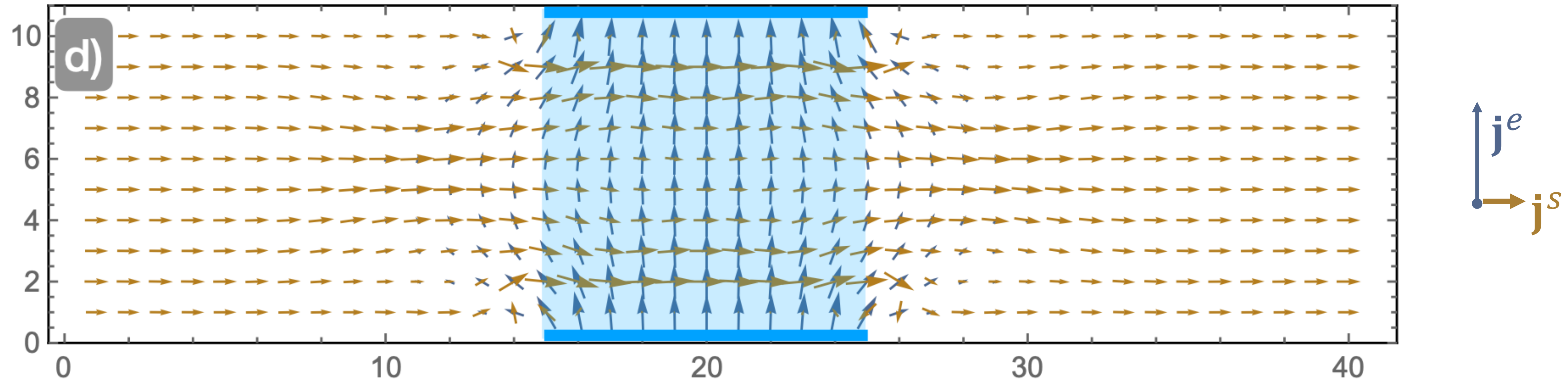
II.C — Spin-current dynamo effect

- A d-wave SC altermagnet can be used to generate spin current from applied charge current
- We call this "spin-current dynamo effect"
- We illustrate this effect below based on self-consistent solutions of the Bogoliubov-de Gennes theory for equal spin triplet chiral p-wave SC









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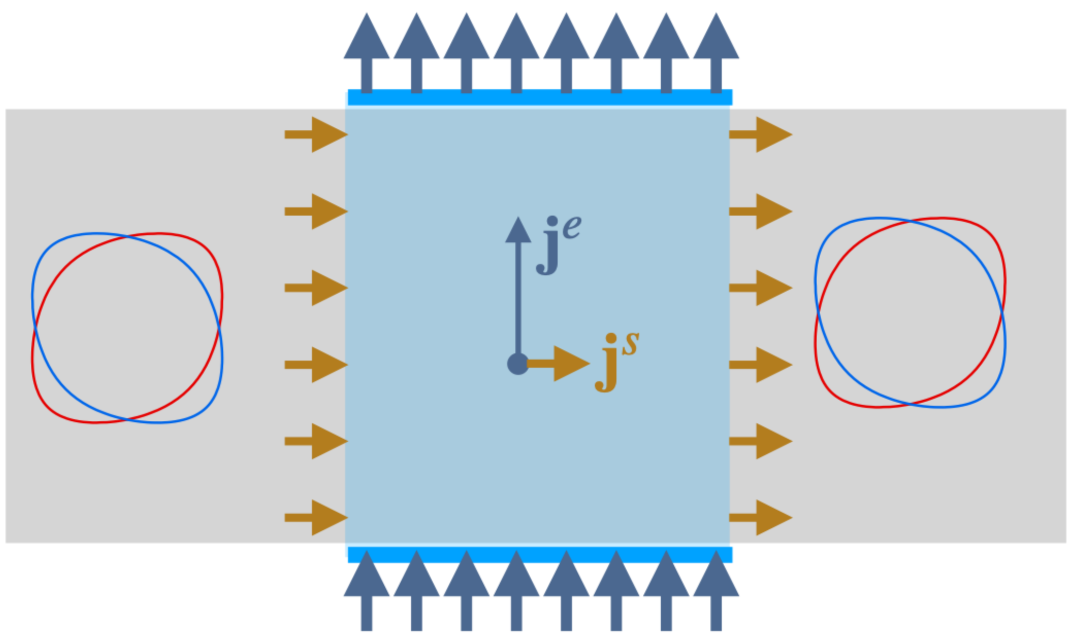
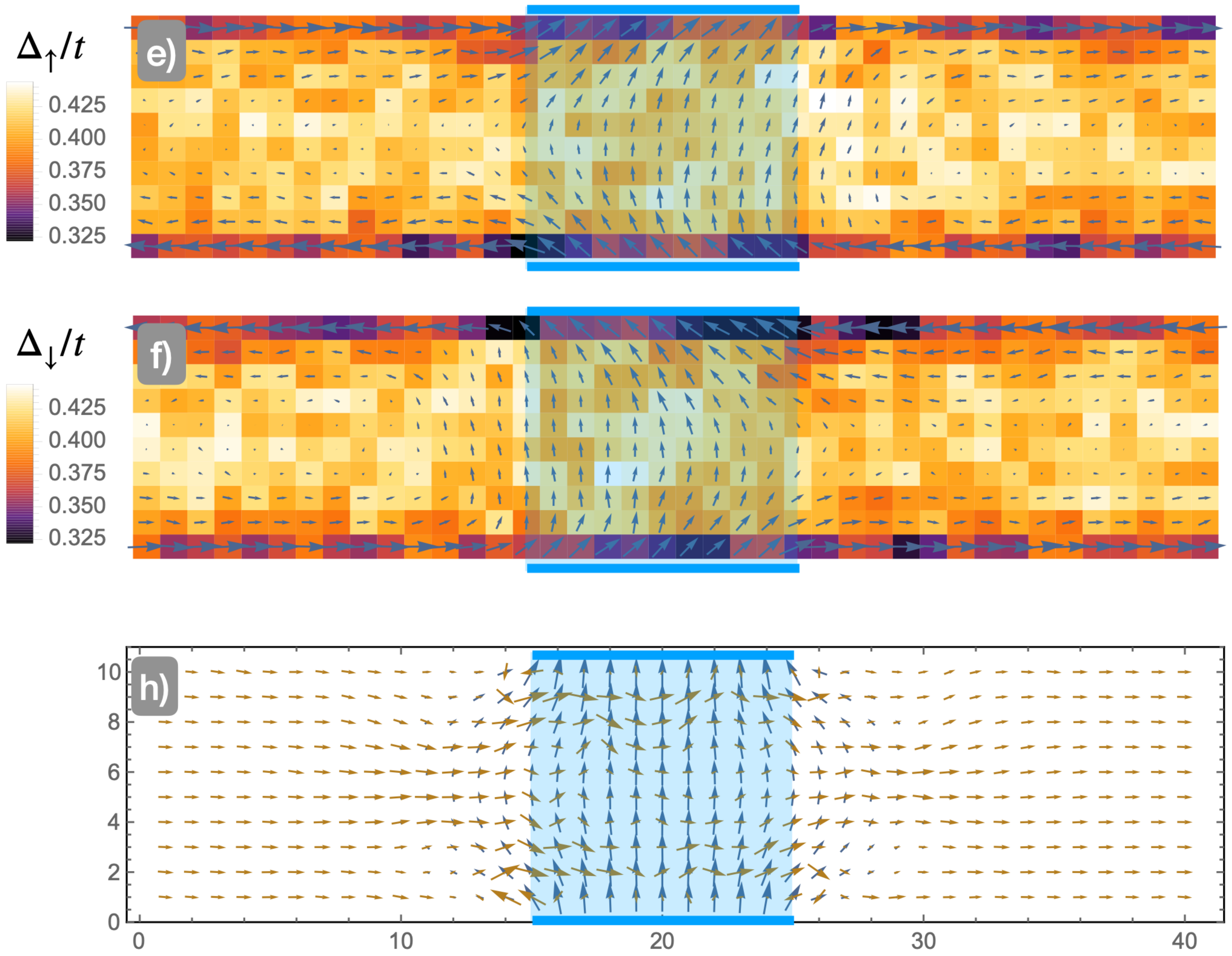
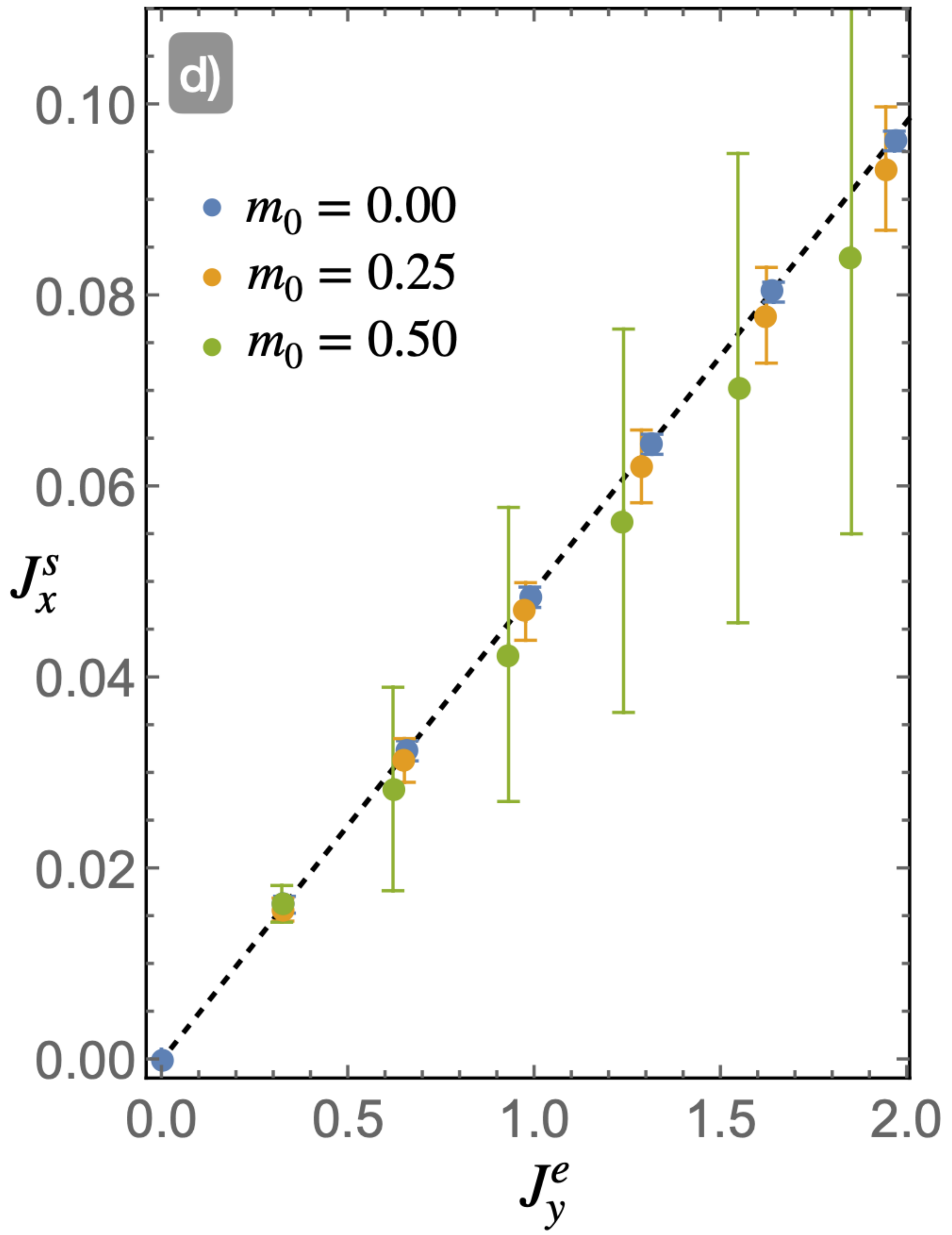
II.C — Spin-current dynamo effect



- **Q:** Is the dynamo effect robust against magnetic disorder?



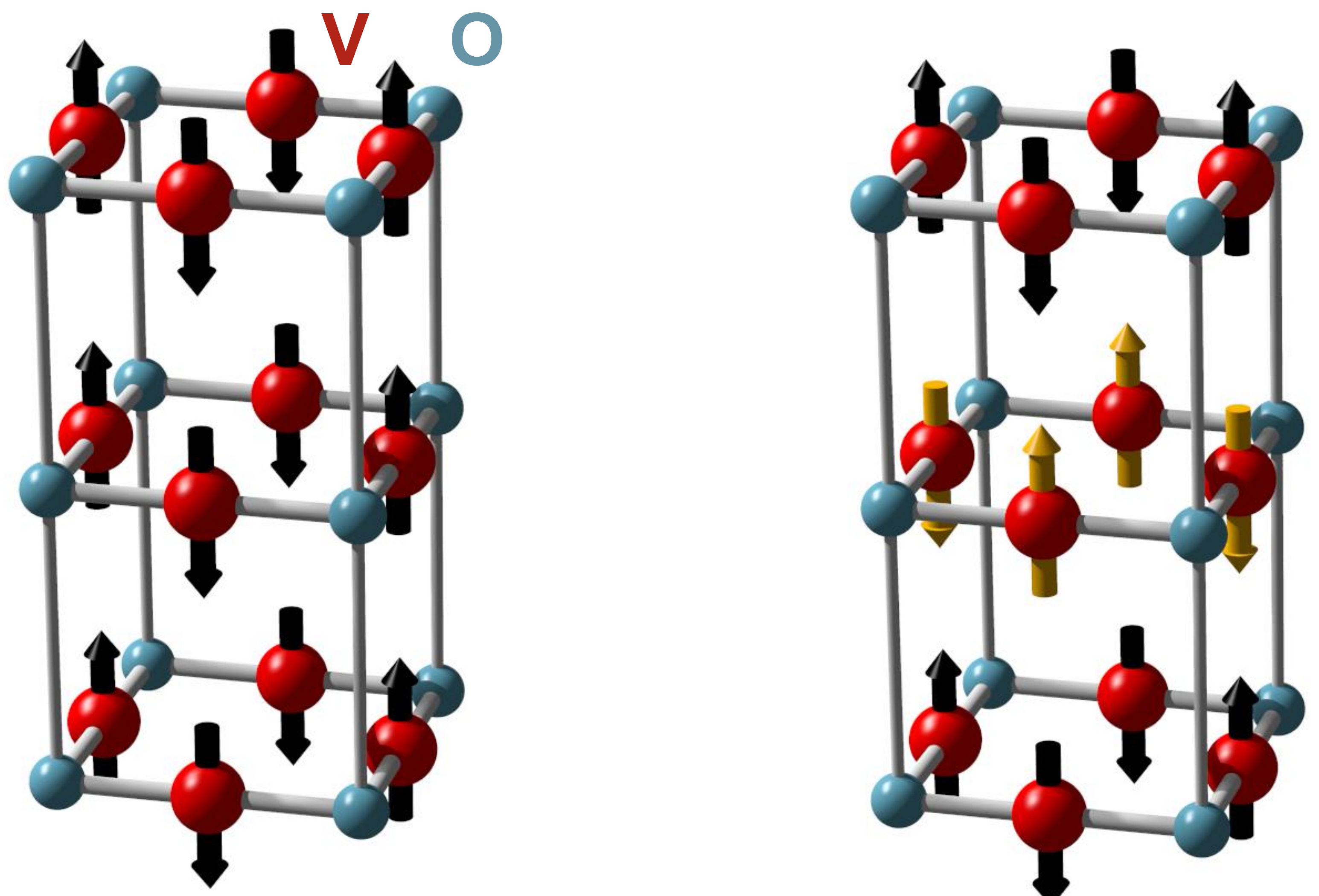
- **A:** Yes, the dynamo effect is robust against magnetic disorder.



III.A — Superconductivity in surface altermagnets

NEW! arXiv:2602.10108

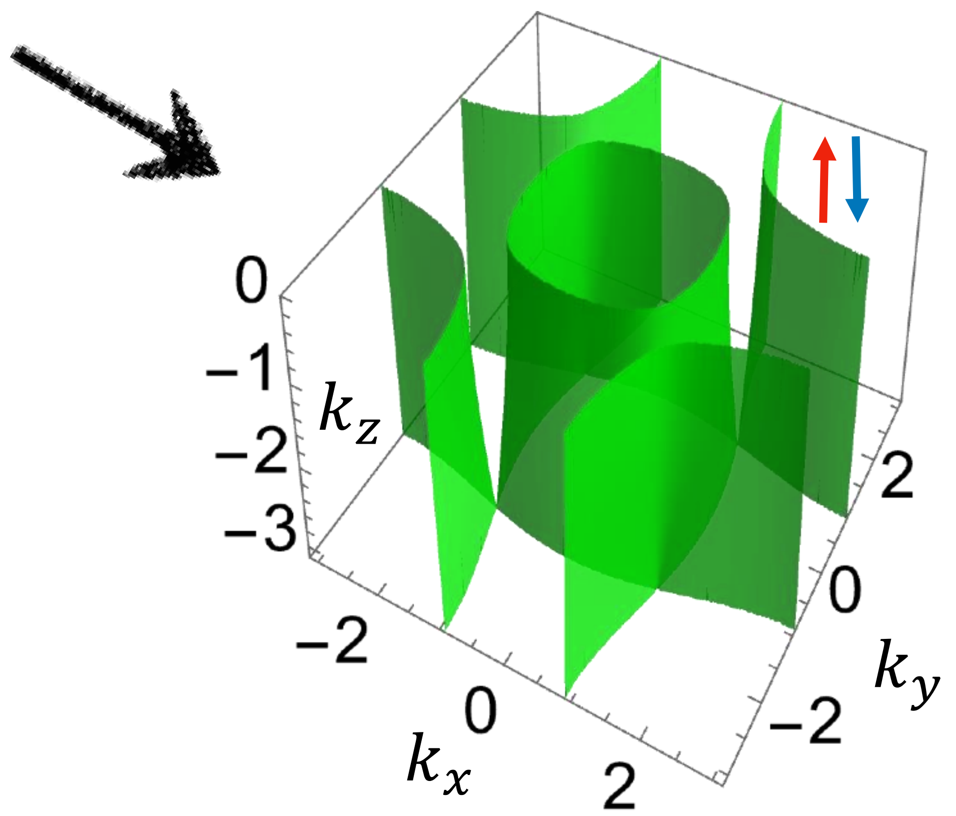
- Materials in the AV_2X_2O (A = Na, K, Rb, Cs; X = Se, Te) oxychalcogenide family are likely SURFACE altermagnets
- This means AF bulk with spin-degenerate electron bands BUT spin-split surface bands.



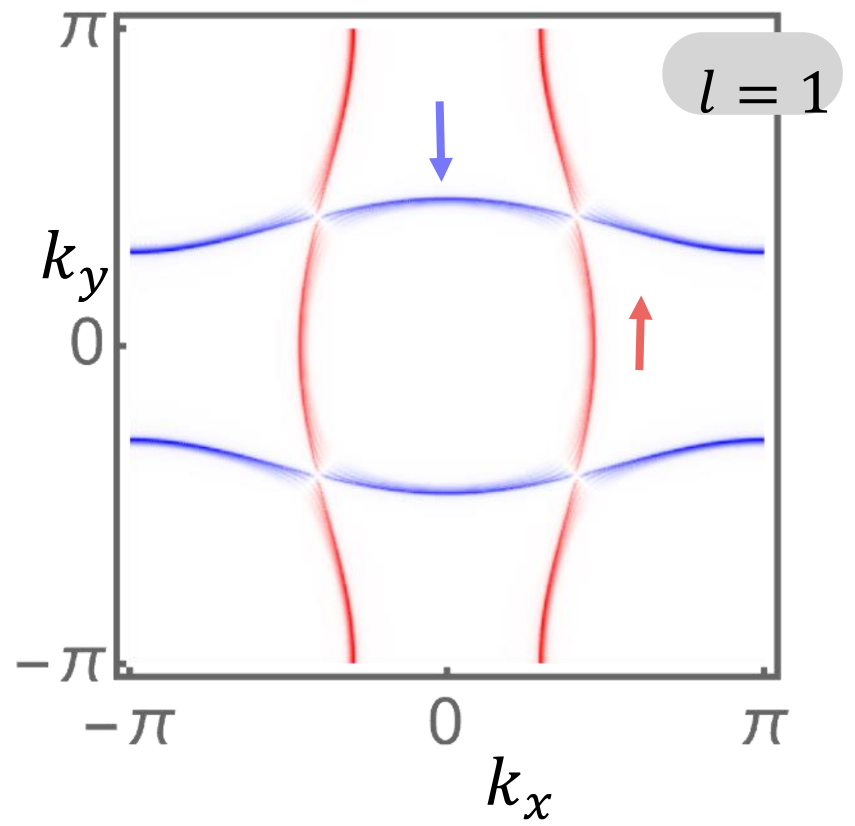
Genuine altermagnet

Surface altermagnet

- Two magnetic sublattices are related by inversion P
- Obeys symmetry $\mathcal{T}' = \mathcal{T}P$ with $(\mathcal{T}')^2 = -1$ which implies Kramers degeneracy for all momenta $\mathbf{k}$.



- However, near the surface inversion is locally broken —> spin-split bands can appear!

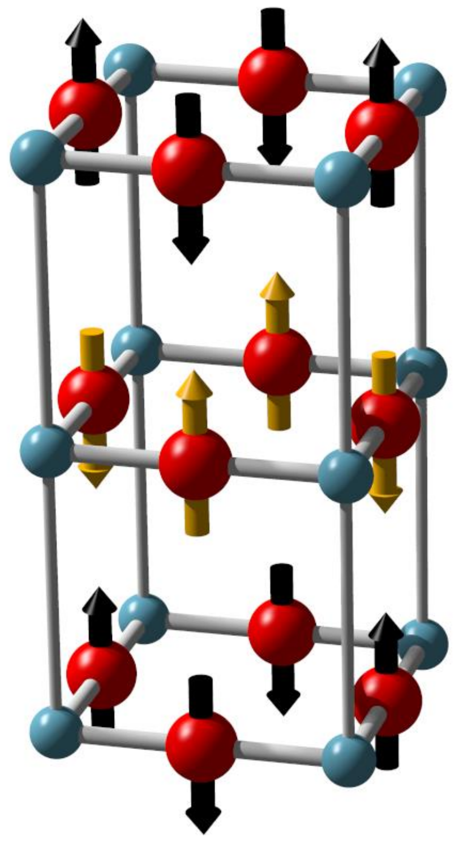


Spectral function $A_{l\sigma}(\omega, \mathbf{k}_\perp)$ of the surface layer in a stack of $M_z = 24$ V_2O layers.

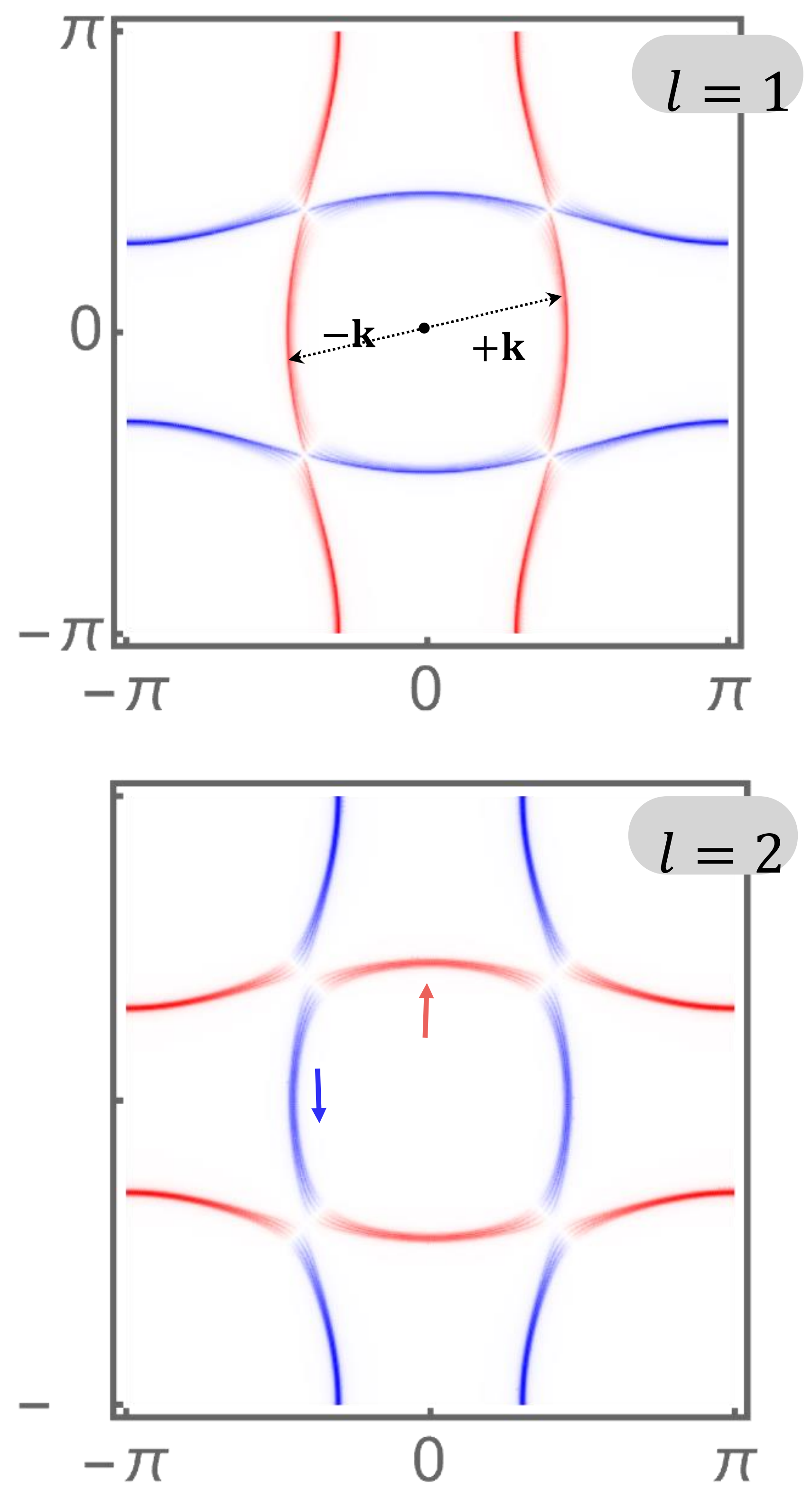
C. Lange et al., arXiv:2602.08773
V. Leeb et al., arXiv:2602.10108

III.B — Superconductivity in surface altermagnets

- **Q:** What kind of superconducting instabilities will dominate in surface altermagnets in the presence of a weak attractive interaction?
- **A:** We expect **unconventional triplet SC** if the attraction is primarily in the V_2O plane.



G-type



Model — on-site & n.n. attraction:

$$\mathcal{H}_I = -V_0 \sum_{\boldsymbol{r}} n_{\boldsymbol{r}\uparrow} n_{\boldsymbol{r}\downarrow} - \sum_{\boldsymbol{r},\boldsymbol{\delta}} V_1^{\delta} n_{\boldsymbol{r}} n_{\boldsymbol{r}+\boldsymbol{\delta}},$$

Mean-field decoupling in all singlet and triplet channels gives the Bogoliubov-de Gennes Hamiltonian

$$H(\boldsymbol{k}) = \begin{pmatrix} h(\boldsymbol{k}) - \mu & \hat{\Delta}_{\boldsymbol{k}} \\ \hat{\Delta}_{\boldsymbol{k}}^{\dagger} & -\sigma_y h(-\boldsymbol{k})^* \sigma_y + \mu \end{pmatrix},$$

with the pairing matrix

$$\hat{\Delta}_{\boldsymbol{k}} = \begin{pmatrix} \boldsymbol{d}_{\boldsymbol{k}} \cdot \boldsymbol{\sigma} & d_{\boldsymbol{k}}^0 \\ d_{\boldsymbol{k}}^0 & \boldsymbol{d}_{\boldsymbol{k}} \cdot \boldsymbol{\sigma} \end{pmatrix}$$

III.C — Superconductivity in surface altermagnets

$$\hat{\Delta}_{\boldsymbol{k}} = \begin{pmatrix} \boldsymbol{d_k} \cdot \boldsymbol{\sigma} & d^0_{\boldsymbol{k}} \\ d^0_{\boldsymbol{k}} & \boldsymbol{d_k} \cdot \boldsymbol{\sigma} \end{pmatrix}$$

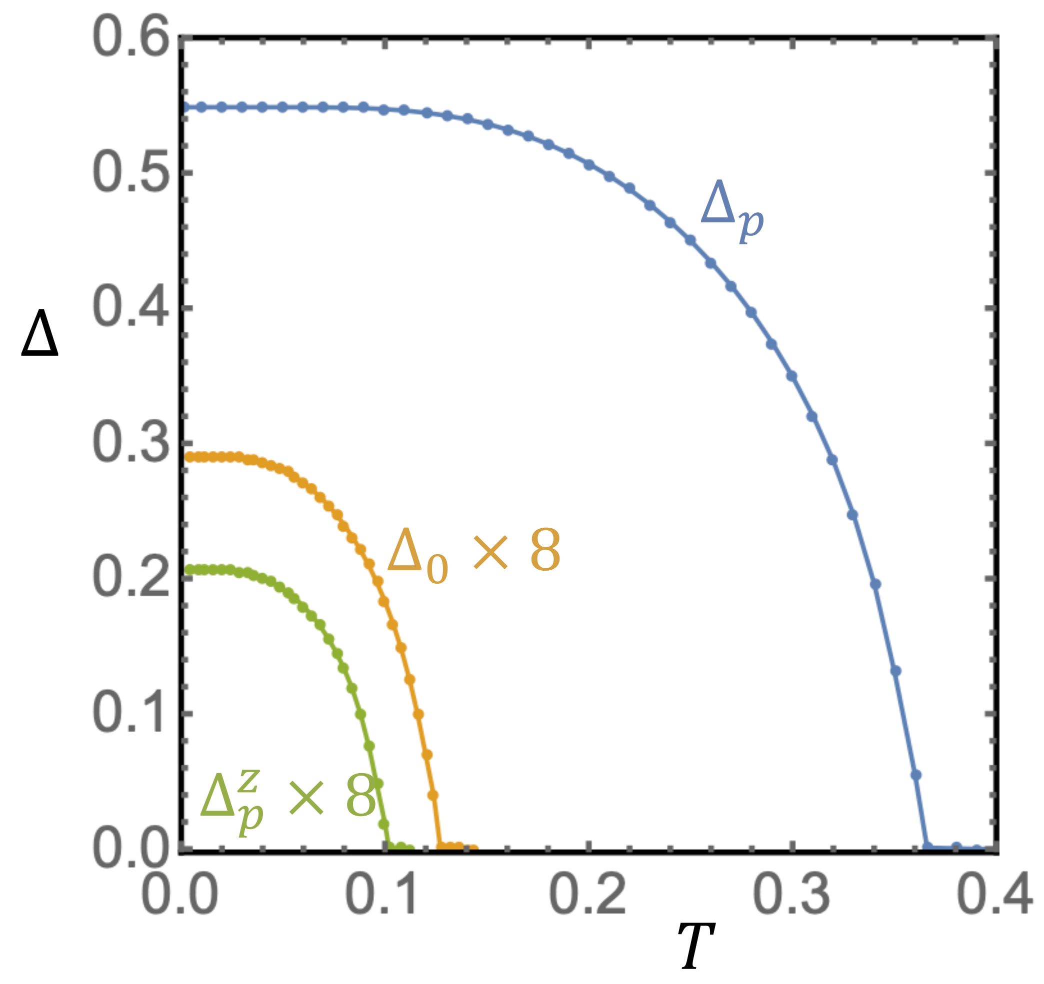
Order parameter	$d^0_{\boldsymbol{k}}$ or $\boldsymbol{d_k}$	BdG matrix	coupling	max gap $[t]$	$T_c[t]$
on-site singlet	Δ_0	τ_x	V_0	0.03625	0.0159
in-plane singlet	$\Delta_s(\cos k_x + \cos k_y)$	τ_x	V_1	0.00687	0.0033
interplane singlet	$\Delta^z_s \cos(k_z/2)$	$\tau_x \lambda_x$	V^z_1	0.02590	0.0127
in-plane triplet	$\Delta_p(\sin k_x, \pm \sin k_y, 0)$	$\tau_x \sigma_x,\ \tau_x \sigma_y$	V_1	0.54858	0.3661
interplane triplet	$\Delta^z_p(0, 0, \sin(k_z/2))$	$\tau_x \lambda_x \sigma_z$	V^z_1	0.02772	0.0135

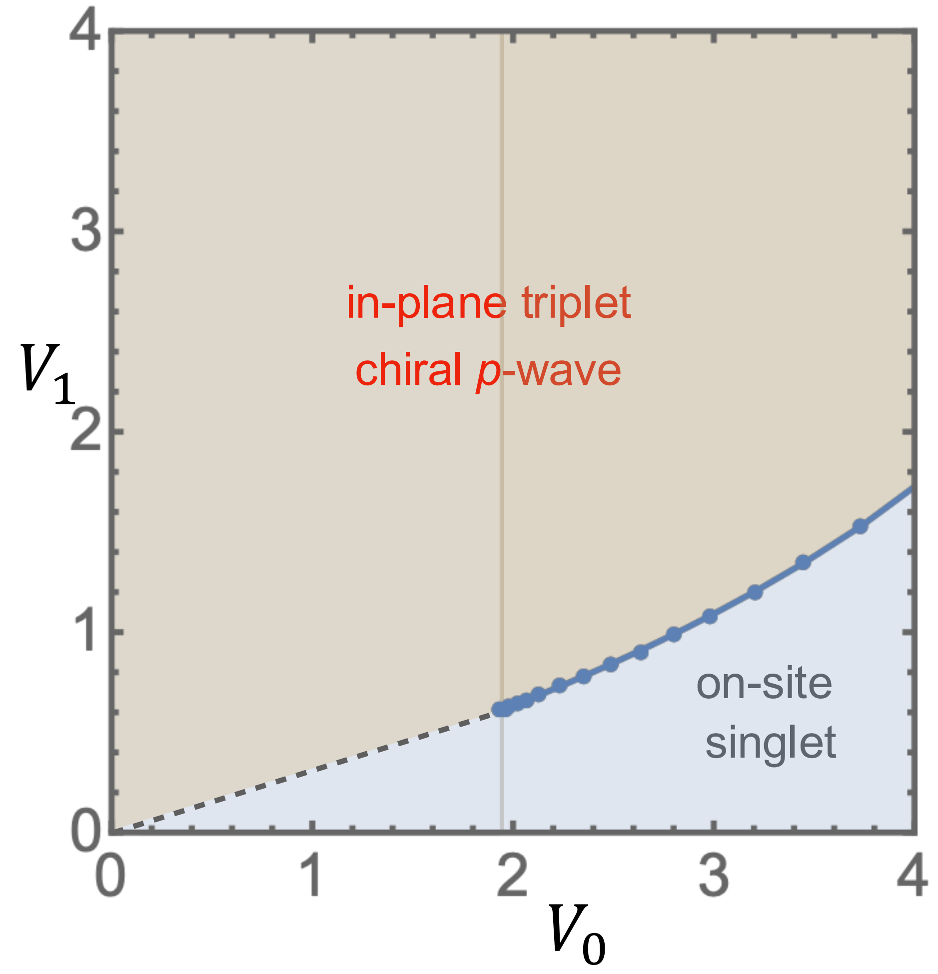
Derive and solve the BCS **gap equation** for all the order parameters:

$$\Delta^z_s = \frac{V^z_1}{4N} \sum_{\boldsymbol{k},\alpha} \frac{\Delta^z_s \cos^2(k_z/2)}{E_{\boldsymbol{k}\alpha}} \tanh \frac{\beta E_{\boldsymbol{k}\alpha}}{2},$$

$$E_{\boldsymbol{k}\alpha} = \sqrt{(\epsilon_{\boldsymbol{k}\alpha} - \mu)^2 + |\Delta_{\boldsymbol{k}}|^2},$$

extract T_c and maximum gap.



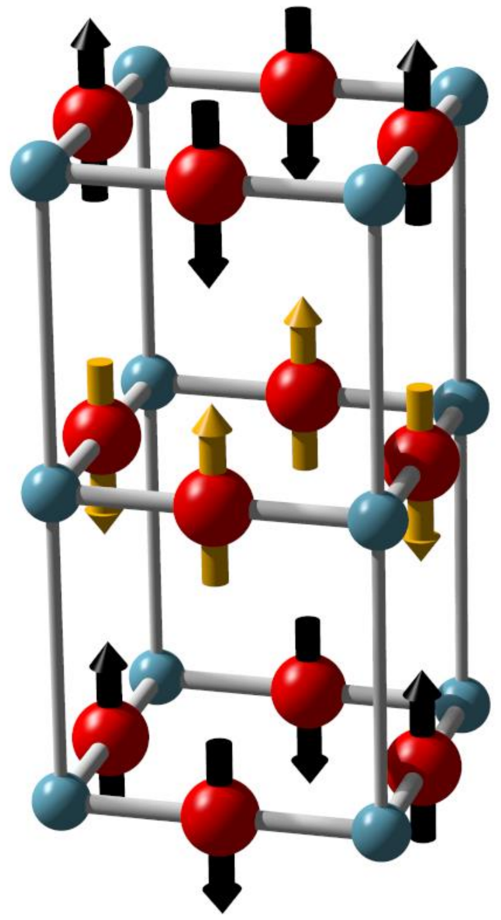


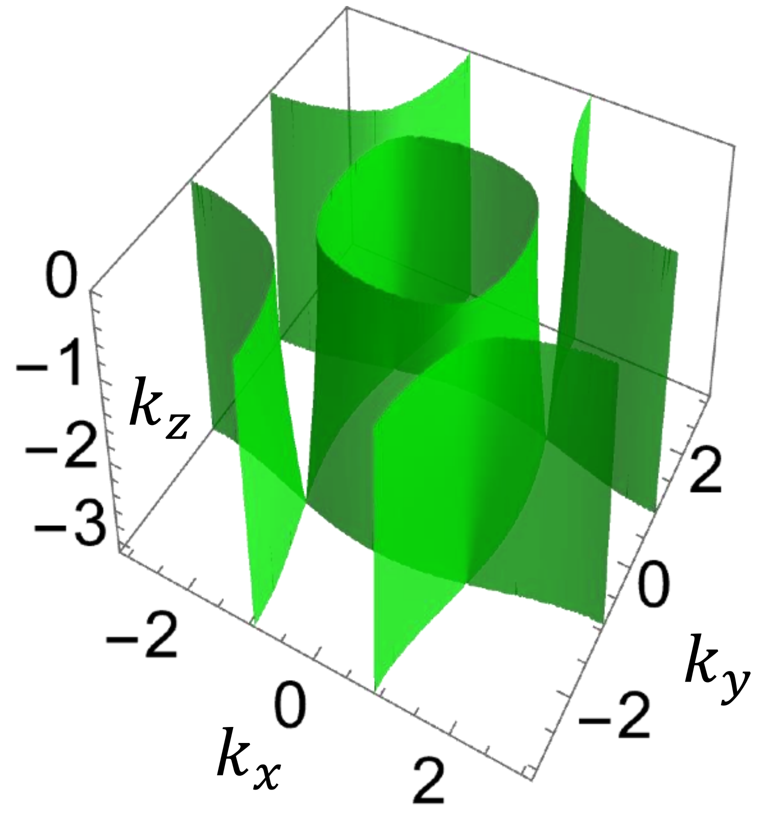
Conclusion: Equal-spin triplet chiral p-wave is the dominant SC order in the surface altermagnet — as long as it is composed of weakly coupled altermagnetic planes.

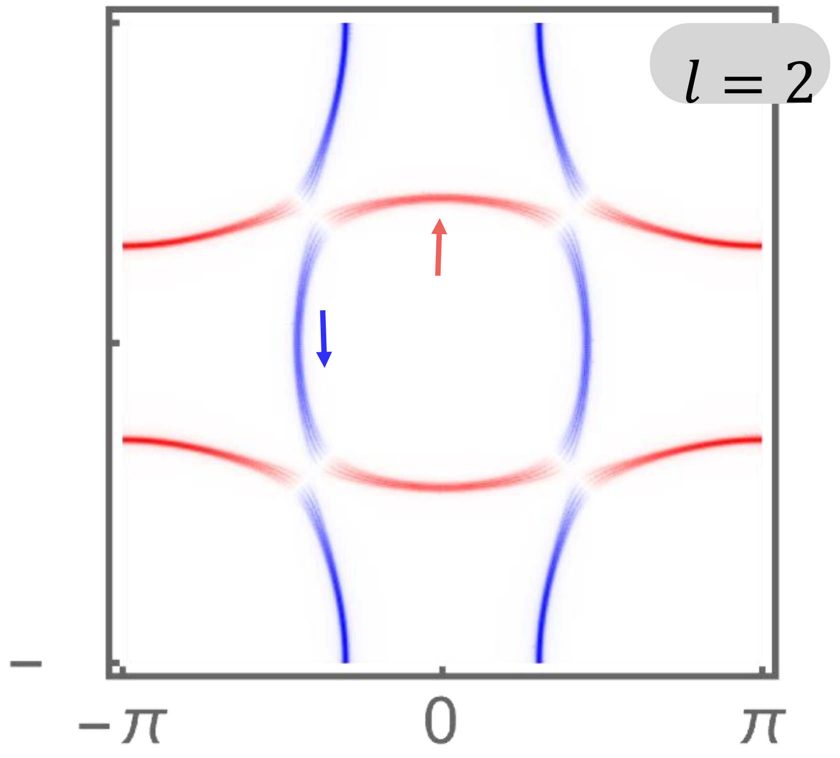
IV. — Conclusions

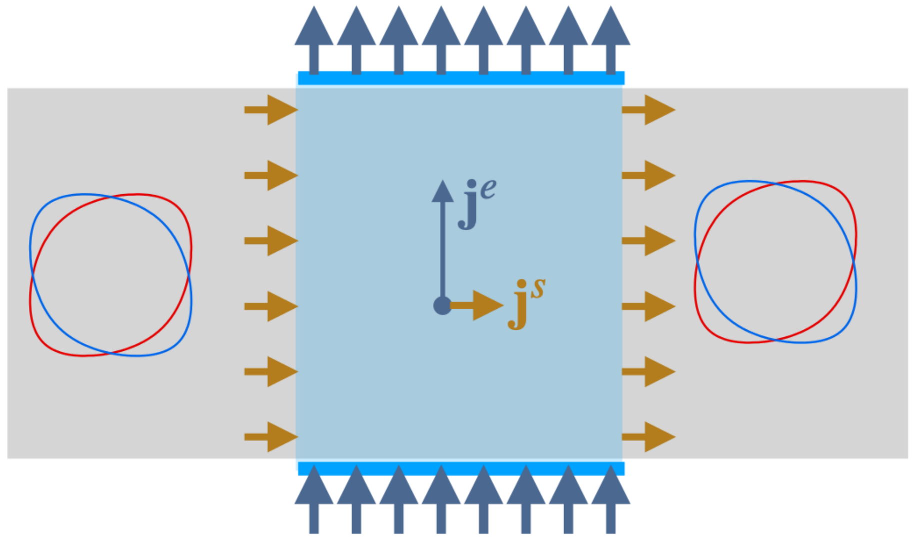
1. Metallic altermagnets are likely to produce unconventional equal-spin triplet superconductors with chiral *p*-wave order parameter
2. In such superconductors persistent spin currents can be observed in various geometries:
   A. Persistent spin current in a ring with half-integer flux
   B. Robust to SOC
   C. Spin-current dynamo effect robust to strong magnetic disorder
3. Unconventional SC order is also expected in surface altermagnets

PRX 16, 011057 (2026); PRB 113, L020501 (2026)









Thank you for your attention!