ALL-ELECTRICAL DEPHASING-PROTECTED SPIN QUBITS IN ALTERMAGNETS

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arXiv:2606.26066

Emergent Topology and Unconventional Order in Quantum Matter · Valladolid, 2026

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Quantum Materials
for Quantum Technologies

FIRST: THANKS TO



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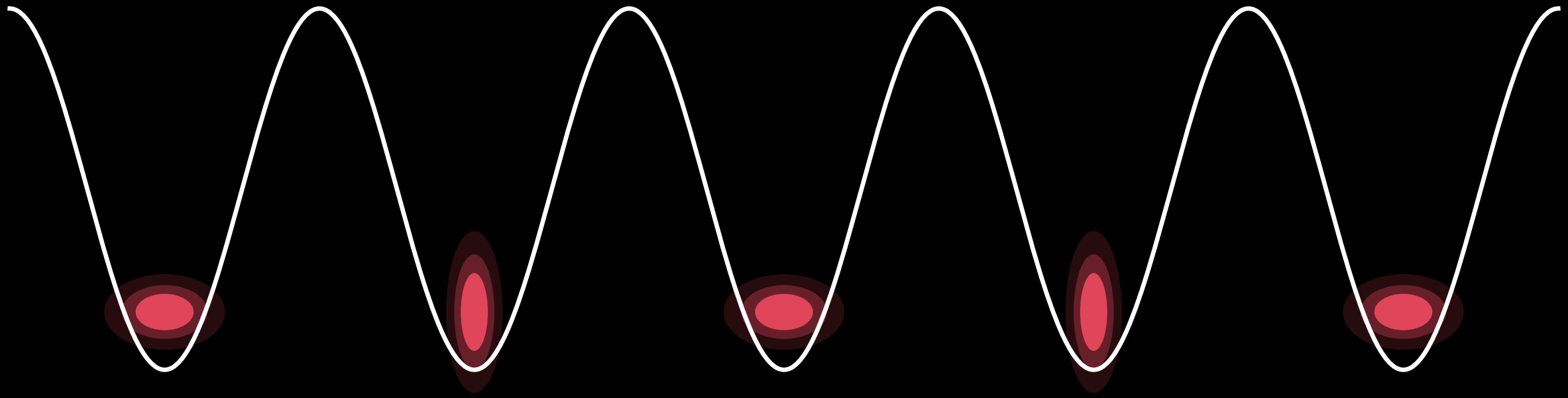
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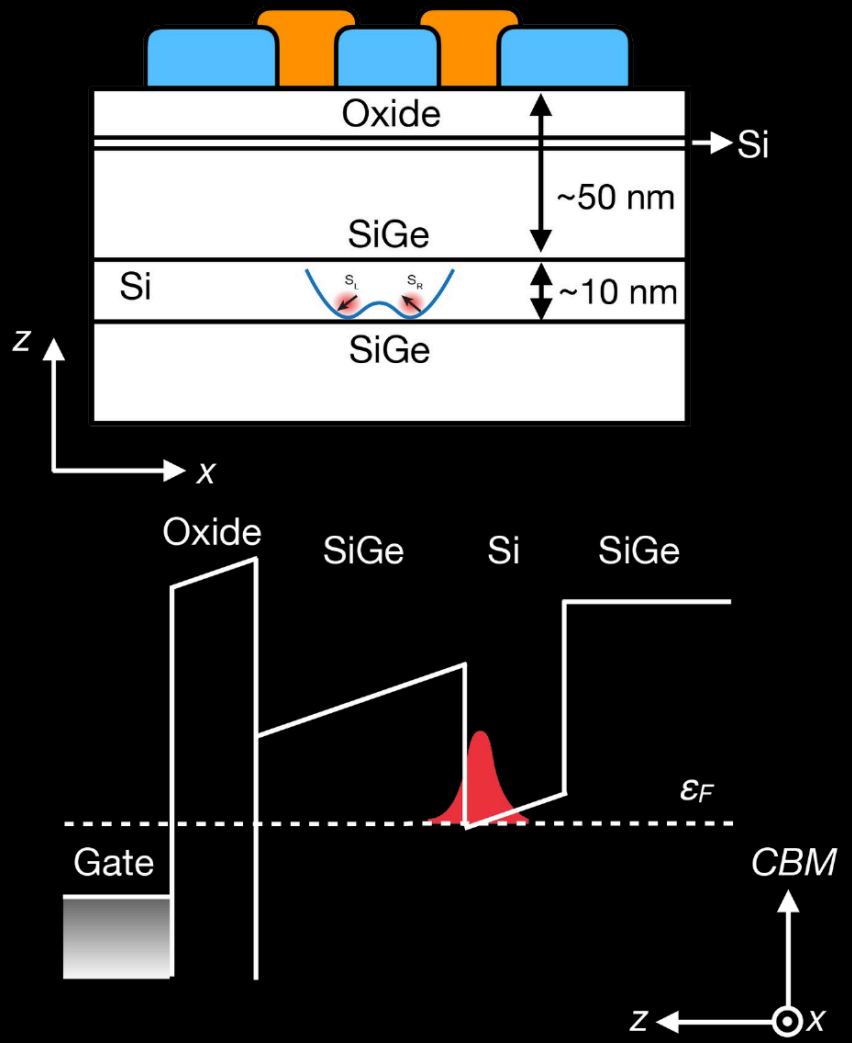
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OUTLINE

1. Spin qubits and the magnetic-field problem
2. A bit on altermagnets
3. The idea: a spin splitting set by the dot shape
4. Gates, noise and readout
5. Materials and outlook



BASIC OPERATION OF QUANTUM-DOT SPIN QUBITS



- An electron (or hole) is confined in a **gate-defined quantum dot**; the qubit is its spin.
- Gates set the confinement, move the electron and **drive** it; readout is spin-to-charge conversion.
- Long coherence, tiny footprint, foundry-compatible fabrication; two-qubit fidelities above 99 % and arrays of ~10 qubits.

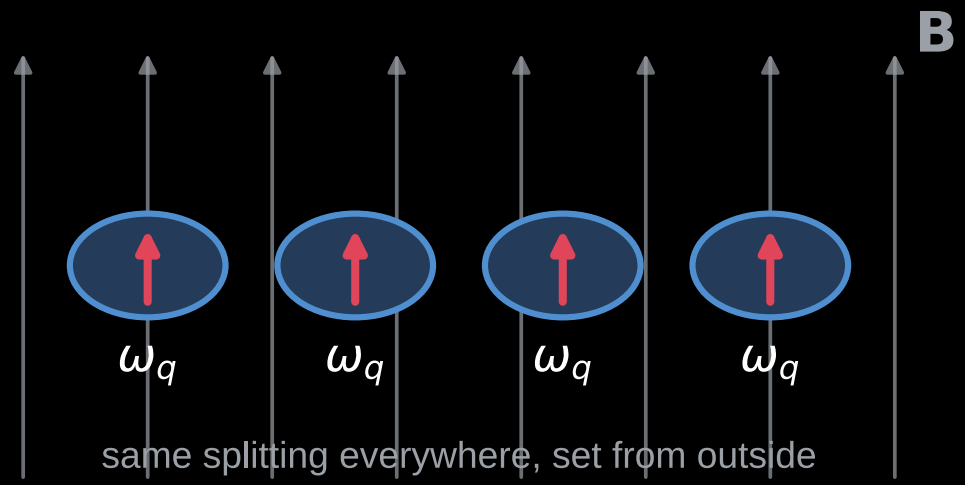
- In (almost) every device the qubit splitting is a **Zeeman energy from an external magnetic field**:

$$H_q = \tfrac{1}{2}\, g\mu_B B\, \sigma_z$$

Loss et al., Phys. Rev. A 57 120–126, (1998); Burkard et al., Rev. Mod. Phys. 95 025003, (2023)

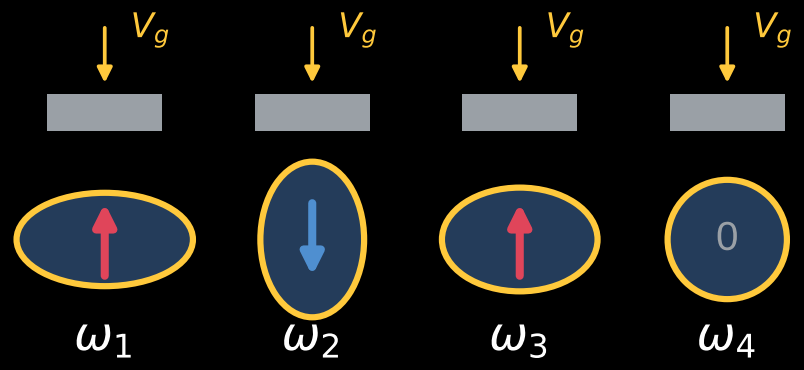
THE MISSING RESOURCE

Today: a global Zeeman field



same splitting everywhere, set from outside

Wanted: a local, field-free knob



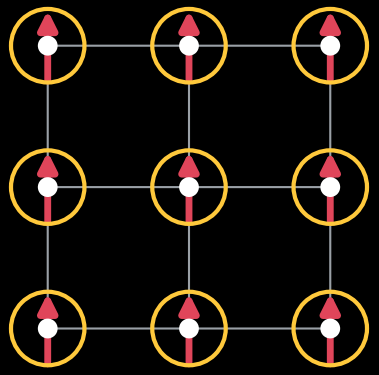
each qubit sets its own splitting, and its sign, with gate voltages

- A global field gives an (almost) **uniform** splitting in low-SOC cases: frequency crowding. In high-SOC: low crowding but high variability.
- Static fields are hard to reconcile with the **superconducting resonators and buses** needed for long-range links.
- Workarounds are incomplete: g-factor tuning stays tied to the global field and needs dedicated sweet spots; **micromagnets** and nuclear polarization add stray fields, fabrication overhead and little *in situ* tunability.

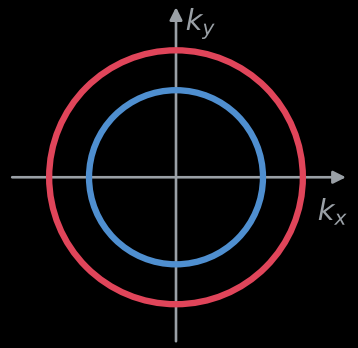
Wanted: a gate-controlled spin splitting that needs neither an applied field nor a fabricated magnet.

THREE KINDS OF COLLINEAR MAGNET

Ferromagnet



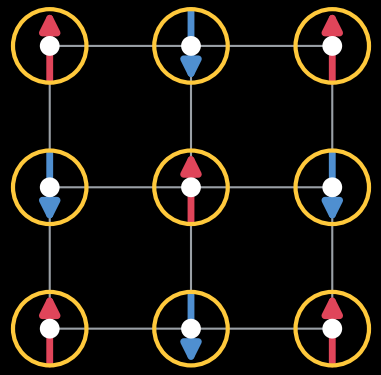
all moments parallel



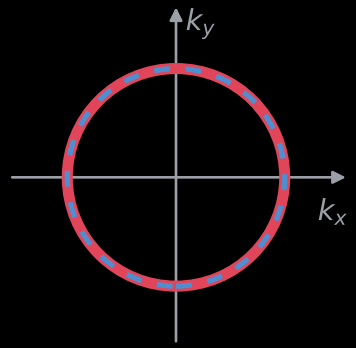
net magnetization $M \neq 0$

spin-split bands (isotropic)

Antiferromagnet



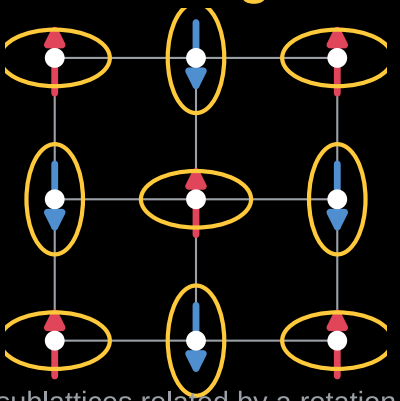
sublattices related by a translation



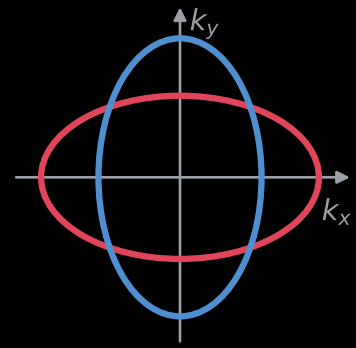
$M = 0$

Kramers-degenerate bands

Altermagnet



sublattices related by a rotation



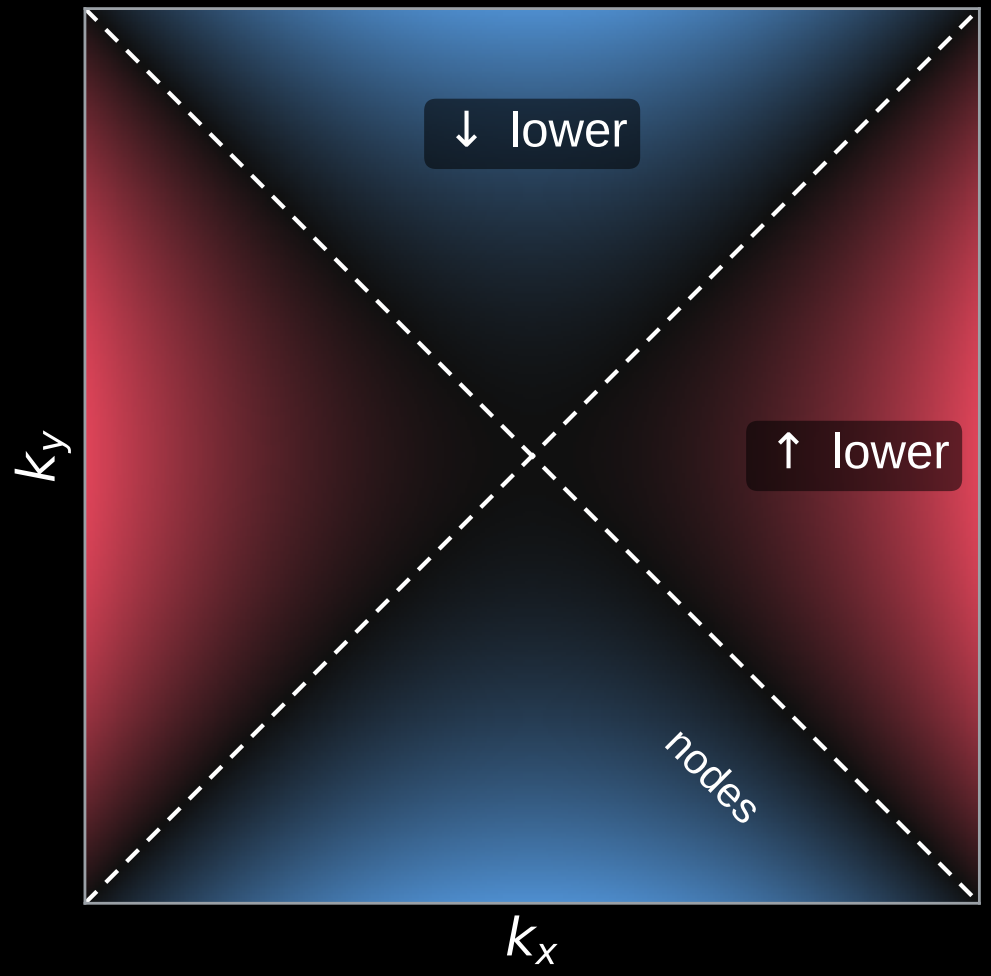
$M = 0$, no stray field

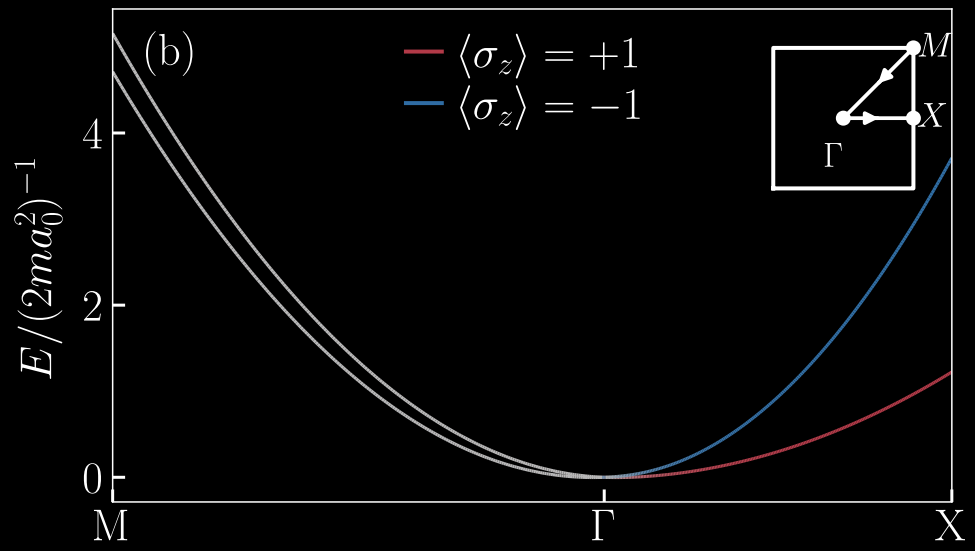
spin-split bands, sign alternates with **k**

Šmejkal et al., Phys. Rev. X 12 040501, (2022); Mazin, Phys. Rev. X 12 040002, (2022)

WHAT IS SPECIAL: SPIN-SPLIT BANDS WITHOUT A FIELD

$$E_{\uparrow}(\mathbf{k}) - E_{\downarrow}(\mathbf{k}) = -2\eta\,(k_x^2 - k_y^2)$$





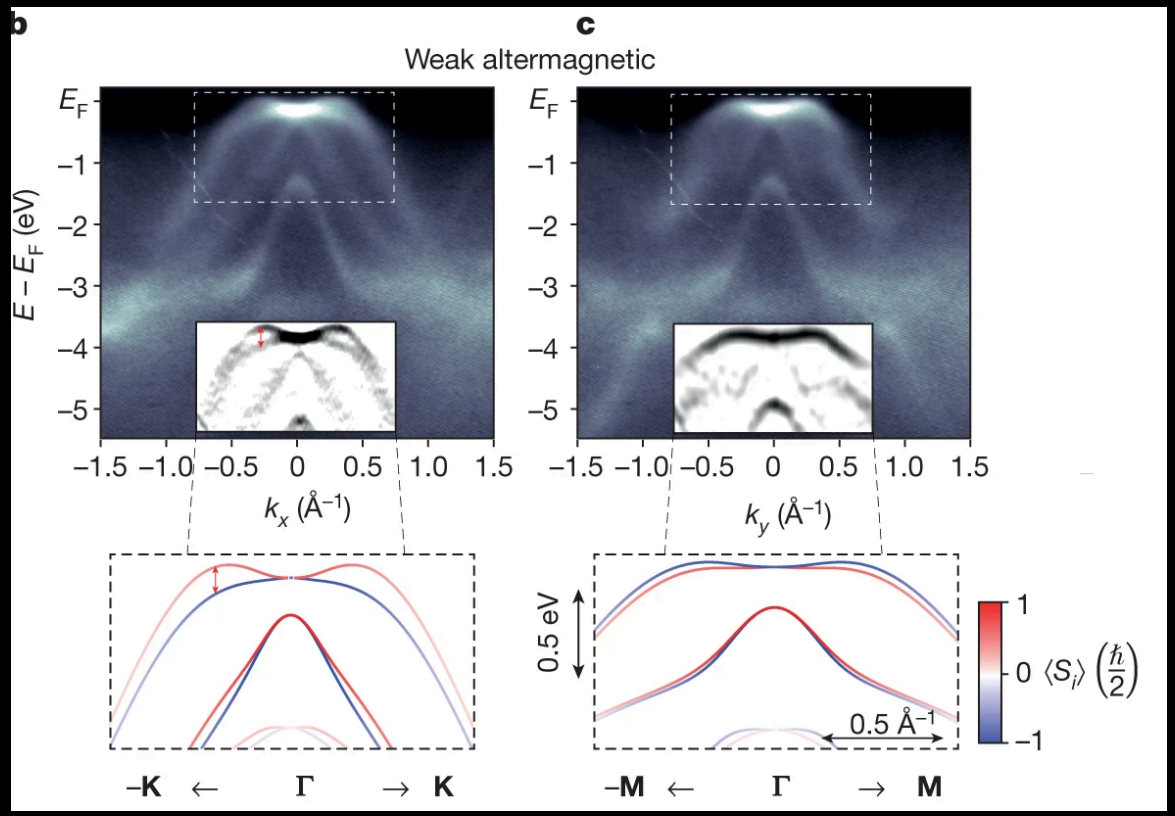
- Splitting is **even in $\boldsymbol{k}$** (d-, g- or i-wave): it changes sign with the direction of $\boldsymbol{k}$ and averages to zero over all directions.
- It comes from **exchange, not spin–orbit coupling** → can reach 0.1–1 eV.
- $M = 0$: **no stray field**.

Šmejkal et al., Phys. Rev. X 12 011028, (2022); Naka et al., Nat. Commun. 10 1, (2019)

ALTERMAGNETS ARE REAL

Material	Type	What is known
α-MnTe	g-wave semiconductor, $T_N \simeq 310$ K	spin-split bands seen by ARPES (2024); nanoscale domain imaging; gapped magnons
CrSb	g-wave metal, $T_N \sim 700$ K	~eV-scale splitting by ARPES
RuO_2	d-wave metal	splitting reported; magnetic order debated
MnF_2, FeF_2, CoF_2	d-wave rutile insulators	Néel vector along c (out of plane)
V_2Se_2O, Cr_2Se_2O	predicted	high T_N, van-der-Waals, isotopically clean

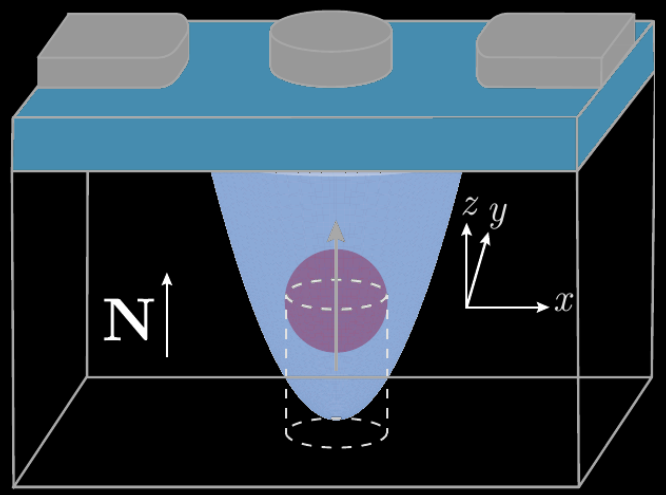
Proximity route: an altermagnet can imprint its momentum-dependent splitting on an adjacent non-magnetic semiconductor.

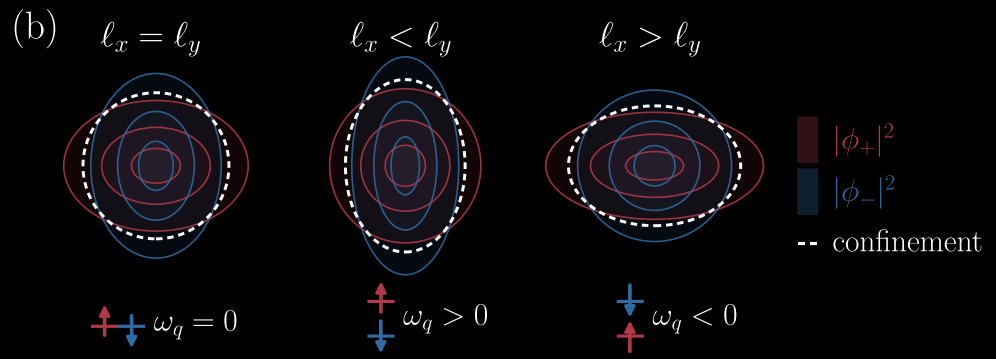


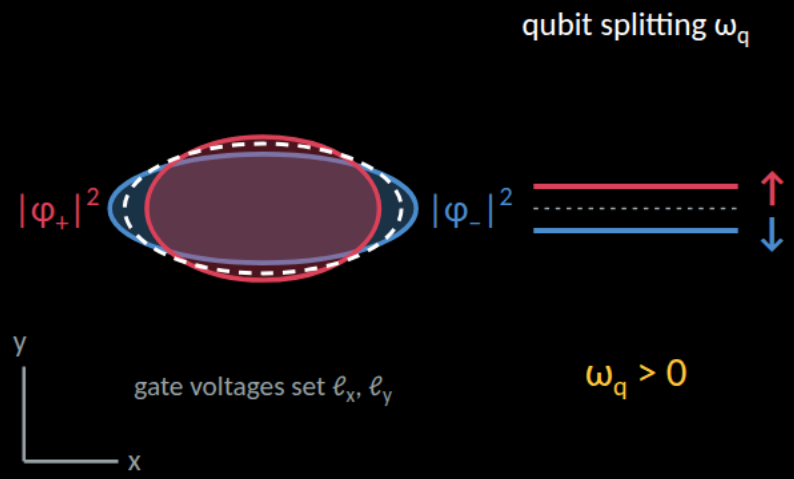
Spin-resolved ARPES on α-MnTe ($k_z = 0$ plane): the Kramers degeneracy is lifted along Γ–K and restored along Γ–M — the splitting depends on the direction of $\boldsymbol{k}$.

Krempaský et al., Nature 626 517–522, (2024); Lee et al., Phys. Rev. Lett. 132 036702, (2024); Amin et al., Nature 636 348–353, (2024); Fedchenko et al., Sci. Adv. 10 5, (2024); Zhu et al., Phys. Rev. Lett. 136 186702, (2026)

THE IDEA: LET THE DOT SHAPE PICK THE SPLITTING







- A gate-defined dot in an altermagnetic semiconductor, Néel vector $\boldsymbol{n} \parallel \hat{z}$ fixed by the crystal.
- A **circular dot** samples all directions equally → the d-wave splitting **averages to zero**.
- An **elliptical dot** samples the two crystal axes differently → a net splitting ω_q along $\boldsymbol{n}$, whose **sign flips** when the long axis rotates by 90°.

Gate voltages set the dot shape → gate voltages set the magnitude and the sign of a Zeeman-like splitting. No field.

MINIMAL MODEL AND THE RESULT

Continuum model: parabolic band + d-wave altermagnetism + Rashba SOC + gate potential

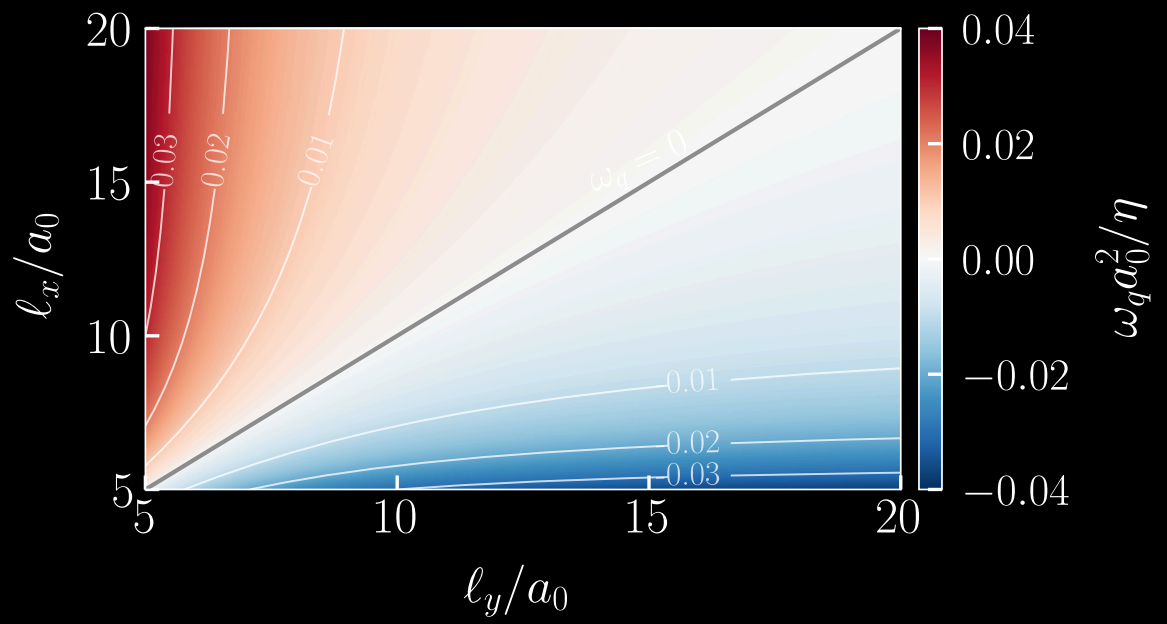
$$H_{\text{eff}} = \frac{\boldsymbol{k}^2}{2m} - \eta\,(k_x^2 - k_y^2)\,\sigma_z + \alpha_R(\sigma_y k_x - \sigma_x k_y) + V$$

The altermagnetic term is a **spin-dependent mass**: each spin sees a differently squeezed harmonic dot,

$$\ell_{x,\pm} = \ell_x(1 \mp 2m\eta)^{1/4}, \qquad \ell_{y,\pm} = \ell_y(1 \pm 2m\eta)^{1/4}$$

Zero-point energies differ → qubit splitting

$$\omega_q \simeq \eta\left(\frac{1}{\ell_y^2} - \frac{1}{\ell_x^2}\right)$$



1 meV of confinement anisotropy (routine in Si/SiGe dots) gives $|\omega_q|/2\pi \simeq 242\ \text{GHz} \times |m\eta|$ → **2–60 GHz** for $|m\eta| = 0.01$–0.25; strained α-MnTe estimates: ~10–60 GHz.

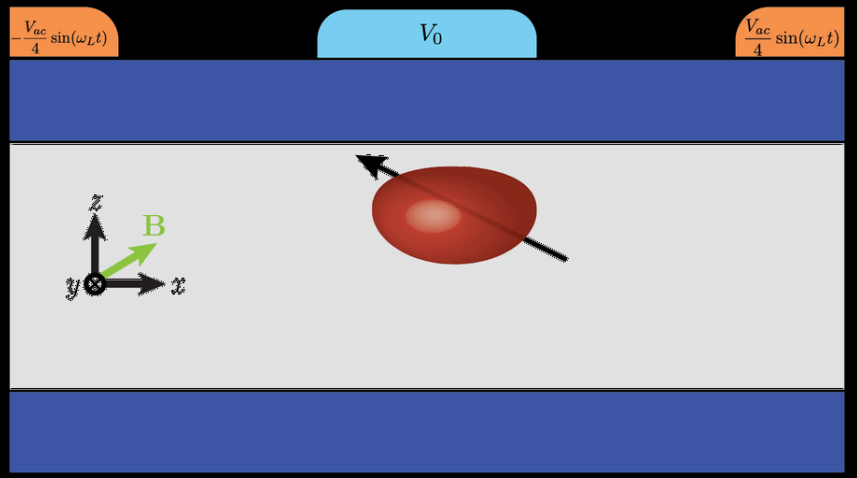
Künne et al., Nat. Commun. 15 1, (2024); Belashchenko, Phys. Rev. Lett. 134 086701, (2025)

COMPLETE SINGLE-QUBIT CONTROL, ALL ELECTRICAL

Transverse axis — Rashba-assisted EDSR

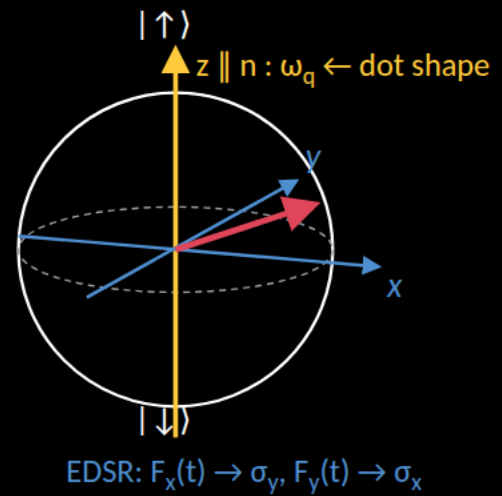
- An ac gate field $F_x(t)$ shakes the dot; Rashba SOC turns the motion into a spin drive:

$$H_{\mathrm{EDSR}} = -e\,\frac{m\ell_x^4}{\ell_{\mathrm{so}}}\,\partial_t F_x(t)\,\sigma_y, \qquad \Omega_R = \frac{e\,m\,\ell_x^4\,\omega_q F_0}{\ell_{\mathrm{so}}}$$



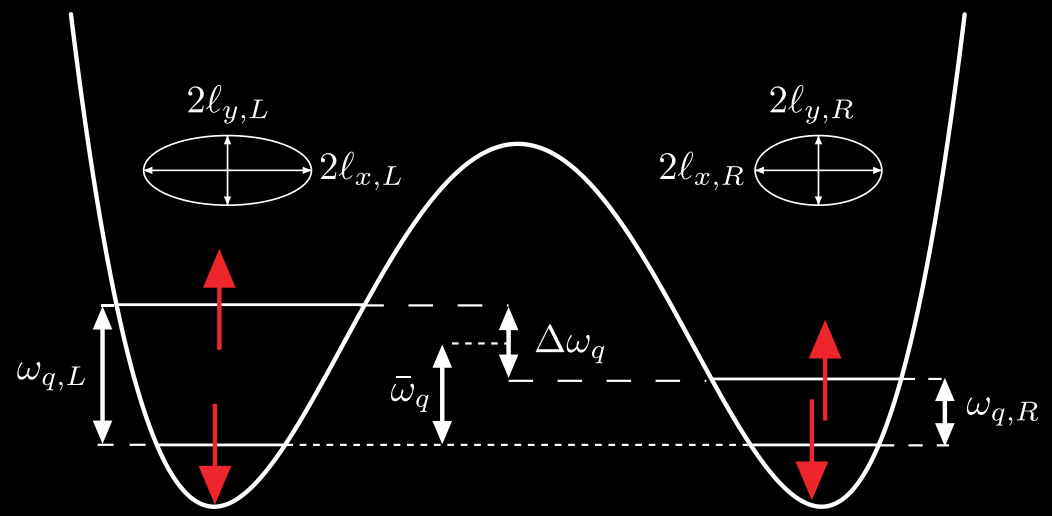
EDSR animation from the hole-spin talk: side gates shake the dot, SOC rotates the spin — here read **B** as the Néel vector $\boldsymbol{n}$

- Driving along y gives σ_x: both transverse axes are available.



Rashba et al., Phys. Rev. Lett. 91 126405, (2003); Nowack et al., Science 318 1430–1433, (2007)

TWO-QUBIT GATES FROM THREE ELECTRICAL KNOBS



Two dots of **different ellipticity** in the (1,1) charge state:

$$H_{\mathrm{DQD}} = \frac{J}{4}\left(\boldsymbol{\sigma}_L\cdot\boldsymbol{\sigma}_R - 1\right) + \frac{\omega_{q,L}}{2}\sigma_z^L + \frac{\omega_{q,R}}{2}\sigma_z^R$$

- $\bar{\omega}_q$ (common-mode shape): gap to $|\uparrow\uparrow\rangle, |\downarrow\downarrow\rangle$
- $\Delta\omega_q$ (shape **difference**): relative precession of $|\uparrow\downarrow\rangle, |\downarrow\uparrow\rangle$
- J (barrier gate): exchange

Modulate the barrier at the gradient frequency, $J(t) = J_0 + 2j(t)\cos(|\Delta\omega_q|t)$ → **fSim**(θ, ϕ) family, with

$$\theta = \tfrac{1}{2}\int_0^T j\,dt, \qquad \phi = -\int_0^T J\,dt$$

$\Delta\omega_q = 0$ + J pulse → $\sqrt{\mathrm{iSWAP}}$; zero swap area, $\phi = \pi$ → **CZ**.

$$\mathrm{fSim}(\theta,\phi) = \begin{array}{c} \begin{matrix} |\uparrow\uparrow\rangle & |\uparrow\downarrow\rangle & |\downarrow\uparrow\rangle & |\downarrow\downarrow\rangle \end{matrix} \\ \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta & -i\sin\theta & 0 \\ 0 & -i\sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 & e^{-i\phi} \end{pmatrix} \end{array}$$

basis $|\sigma_L\,\sigma_R\rangle$ = |left spin, right spin⟩; swap angle θ, conditional phase ϕ

Yu et al., Phys. Rev. Applied 25 024076, (2026); Kivlichan et al., Phys. Rev. Lett. 120 110501, (2018)

AN ALL-ELECTRICAL SINGLET–TRIPLET QUBIT

Encode in the unpolarized two-electron states of the same double dot:

$$|S\rangle = \frac{|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle}{\sqrt{2}}, \qquad |T_0\rangle = \frac{|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle}{\sqrt{2}}$$

$$H_{\mathrm{ST}} = -\frac{J}{2}\,\tilde{\sigma}_z + \frac{\Delta\omega_q}{2}\,\tilde{\sigma}_x$$

- J: longitudinal axis, barrier gate (symmetric operating point available)
- $\Delta\omega_q$: transverse axis, **shape difference** between the dots
- $|\bar{\omega}_q|$: leakage gap to $|T_\pm\rangle$, raised by common-mode ellipticity

Transverse axis of an ST qubit	Source
Conventional	micromagnet gradient, nuclear polarization, or engineered g-factor difference
Here	**a gate voltage**, pulsed on gate timescales, sign included

Useful when Rashba SOC is weak, or when zero-spin-projection operation is preferred. Rashba terms do not act inside $\{S, T_0\}$: they only renormalize parameters and couple off-resonantly to $T_\pm$.

Pioro-Ladrière et al., Nat. Phys. 4 776–779, (2008); Foletti et al., Nat. Phys. 5 903–908, (2009); Jirovec et al., Nat. Mater. 20 1106–1112, (2021)

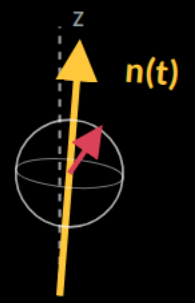
DOES MAGNETIC ORDER ADD DEPHASING? MOSTLY NOT

Magnetic channel — smooth rotations of the Néel vector

In the frame that follows $\boldsymbol{n}$, the qubit couples to the *angular velocity*, transversely:

$$\delta H_q = \frac{\Lambda}{2}\left[\dot{n}_y \sigma_x - \dot{n}_x \sigma_y\right] + \mathcal{O}(\ell^2/L_m^2, \delta n^2)$$

- no σ_z term → **no pure dephasing at leading order**
- noise weighted by $\omega^2 S_n(\omega)$ → slow drift suppressed
- what survives is T_1 at $|\omega_q|$; gapped magnons (as in α-MnTe) push it away



quantization axis follows **n**(t)
→ no longitudinal term

only the angular velocity **ṅ** couples, transversely

(smooth, fixed-length rotations)

Hyperfine noise may still be an issue.

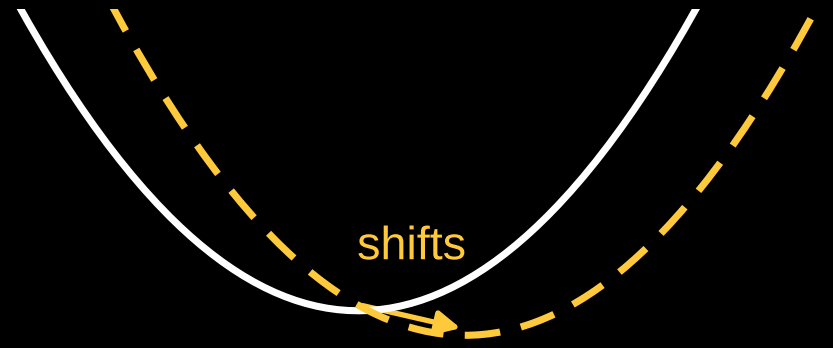
Liu et al., Phys. Rev. Lett. 133 156702, (2024); Dzian et al., Phys. Rev. B 112 2, (2025)

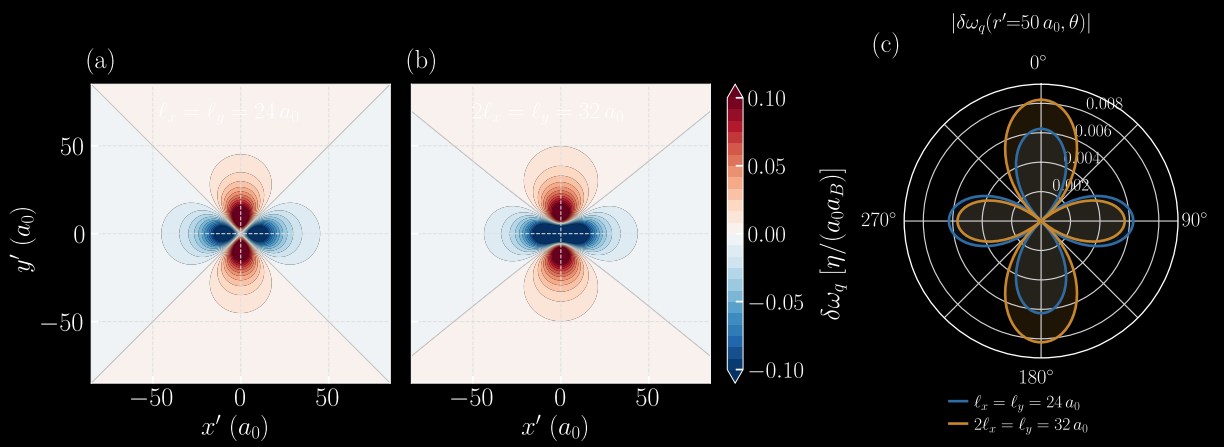
CHARGE NOISE: UNIFORM FIELDS ONLY MOVE THE DOT

Electric channel — a sweet spot by construction

- ω_q depends on $\ell_{x,y}$, not on the dot position → **first-order sweet spot by construction**
- a uniform field $\delta \boldsymbol{F}$ only *shifts* the confinement (right): same curvature, same $\ell_{x,y}$, same ω_q
- residual: field *curvature* of nearby charges reshapes the dot (right, bottom)

Contrast: in a Zeeman-split qubit, strain and g-factor fluctuations modulate the *amplitude* of the splitting and dephase at first order; here neither uniform fields nor smooth Néel rotations do.

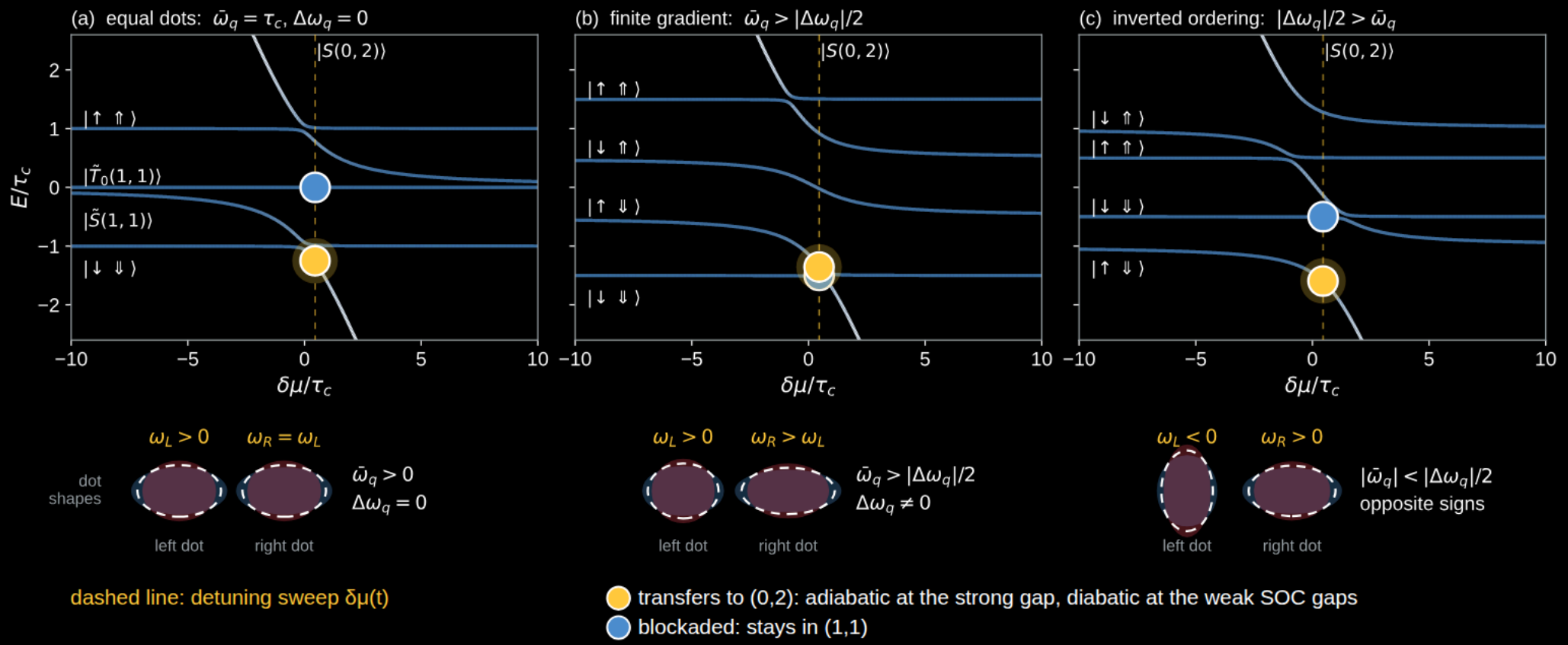




Frequency shift $\delta\omega_q$ from a single charge at (x', y') for a circular (a) and an elliptical (b) dot, and its angular dependence (c): four lobes, nodes on the diagonals.

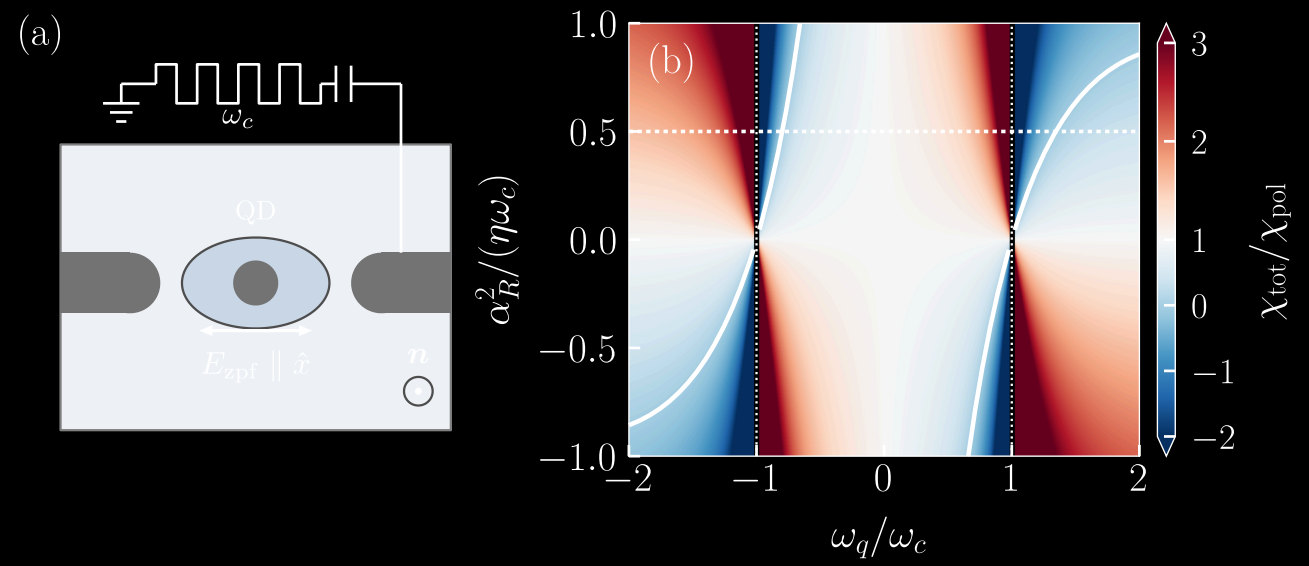
Connors et al., Nat. Commun. 13 1, (2022)

SPIN-TO-CHARGE READOUT, SHAPE-TUNABLE



- **Pauli blockade** near (1,1)–(0,2): blue = (1,1) character, white = $|S(0,2)\rangle$ weight; the dot shapes below each panel set $\bar{\omega}_q$ and $\Delta\omega_q$.
- **(a)** equal dots: singlet-vs-triplet contrast reads the ST qubit; raising $|\bar{\omega}_q|$ moves the $T_\pm$ leakage away. **(b)** unequal dots: **single-spin readout**, but the transferred state still crosses the weak T_- gap → finite window.
- **(c)** orthogonal elongations, opposite signs: inverted ordering, the weak gaps come first and the window constraint disappears (Elzerman readout: backup).

FIELD-FREE CIRCUIT-QED READOUT



- No stray field → on-chip superconducting resonators without compromise.
- Dipole coupling $-eE_{\rm zpf}\, x\,(a + a^\dagger)$ projected on the qubit gives a dispersive shift with **two contributions**:

$$\chi_{\rm tot} = \chi_{\rm pol} + \chi_{\rm lin}, \qquad \frac{\chi_{\rm tot}}{\chi_{\rm pol}} = 1 - \frac{\alpha_R^2}{4\eta\omega_c}\,\frac{(\omega_q/\omega_c)\left[(\omega_q/\omega_c)^2 + 3\right]}{(\omega_q/\omega_c)^2 - 1}$$

- $\chi_{\rm pol} \propto \eta$: **spin-dependent polarizability**, a longitudinal coupling absent in any spin-degenerate dot.
- $\chi_{\rm lin} \propto \alpha_R^2$: the usual transverse (Rashba) term, odd in ω_q.
- Because ω_q is electrical, **tune into the cooperative region** (red), away from the cancellation line and the poles.

Blais et al., Rev. Mod. Phys. 93 025005, (2021); Dijkema et al., Nat. Phys. 21 168–174, (2024)

WHAT WE NEED FROM A MATERIAL

Electronic

- a bulk gap, so single-electron dots can be formed (α-MnTe: gap + spin-split bands)
- a simple, isolated band edge with both spins in one valley
- a sizeable **near-edge curvature** $m\eta$ (a large splitting far from the edge is not enough)
- Rashba SOC for fast EDSR (otherwise: the ST encoding)

Magnetic

- collinear, stiff, preferably **gapped** magnons above the qubit window
- Néel vector well defined or pinned by strain / interfaces
- a **single domain** larger than the dot (10–50 nm): strain pinning, field cooling, sub-critical sizes

Environment: isotopically clean hosts (e.g. Cr_2Se_2O), clean gateable interfaces

Or split the job in two

Altermagnetic proximity effect: form the dot in a clean, gate-compatible, isotopically favourable semiconductor and let a neighbouring altermagnet supply the field-free splitting.

Predicted, e.g., for a PbO monolayer on V_2Se_2O, with the induced splitting set by the interlayer distance.

Open experimental challenge: demonstrate reversible gate control of the *magnitude and sign* of a confined-state splitting, in an intrinsic or proximity-induced altermagnet.

Krempaský et al., Nature 626 517–522, (2024); Singh et al., Mater. Sci. Eng.: R: Rep. 166 101017, (2025); Zhu et al., Phys. Rev. Lett. 136 186702, (2026); Vakili, arXiv:2606.24150, (2026)

TAKE-HOME

- An electron in an **elliptical dot in an altermagnet** acquires a Zeeman-like splitting **without any magnetic field**; gates set its size *and* sign.

- Shape + Rashba EDSR give **full single-qubit control**; shape difference + exchange give **fSim gates** and an **all-electrical singlet–triplet qubit**.

- The splitting is tied to a fixed Néel axis: smooth magnetic rotations couple **transversely**, uniform electric fields **do not shift it** → dephasing protection by construction.

- Spin-to-charge **and** dispersive circuit-QED readout survive, with a new altermagnetic (polarizability) cavity pull.

- The ball is now in the materials court: intrinsic or **proximity-induced** altermagnetic semiconductors with a clean band edge.

arXiv:2606.26066 — Abadillo-Uriel, Maiani, Cortijo, Aguado, Seoane Souto

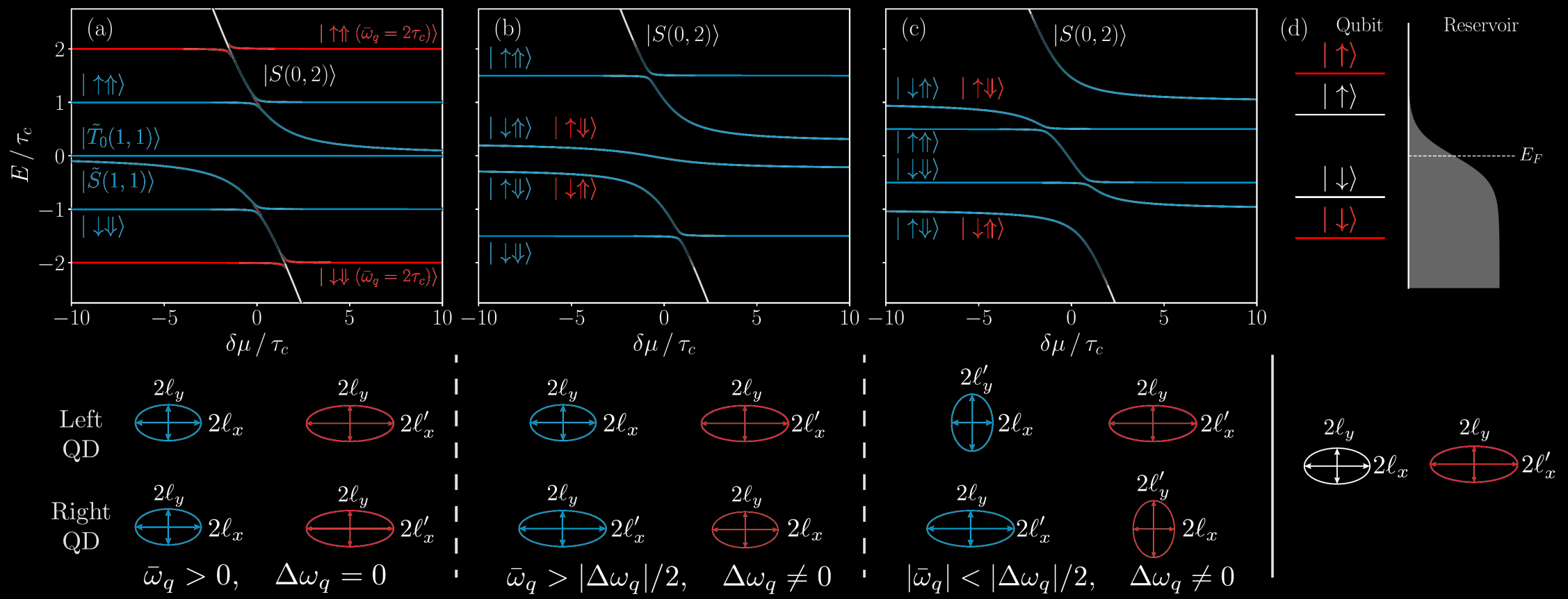
THANK YOU

Questions?

jc.abadillo.uriel@csic.es · arXiv:2606.26066

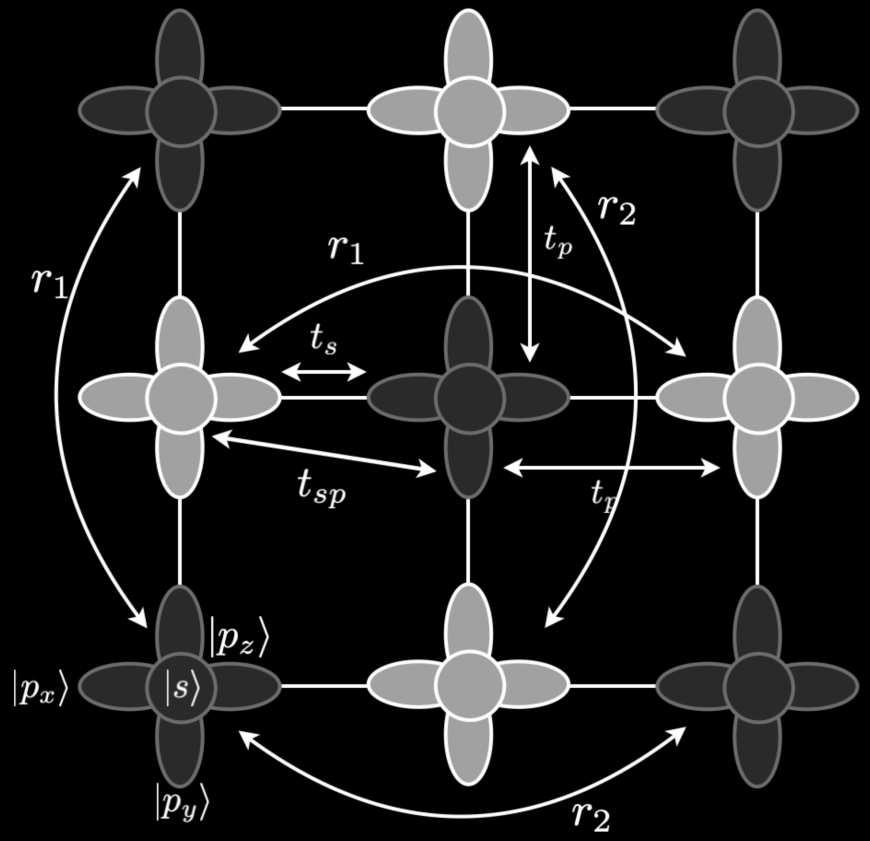
Quantum Materials
for Quantum Technologies

BACKUP · READOUT MECHANISMS, FIG. 4 OF THE PAPER



- **(a)–(c)** as in the animated slide, with the dot-shape sketches for each regime. **(d)** Energy-selective (Elzerman) readout: with $E_\downarrow < E_F < E_\uparrow$ only $|\uparrow\rangle$ tunnels out; the selectivity window $|\omega_q|/k_BT$ is enlarged by pulsing the ellipticity during the measurement.

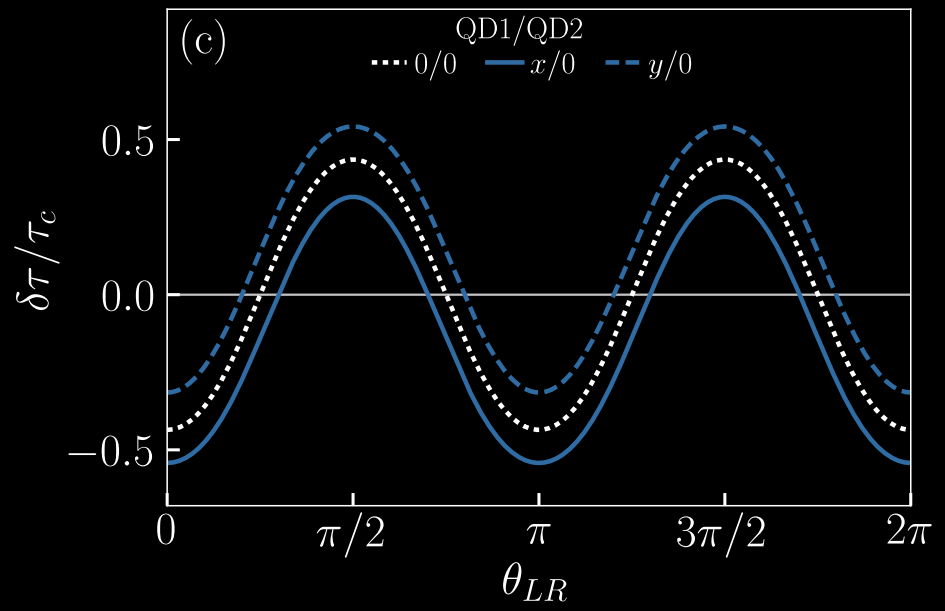
BACKUP · MICROSCOPIC LATTICE MODEL

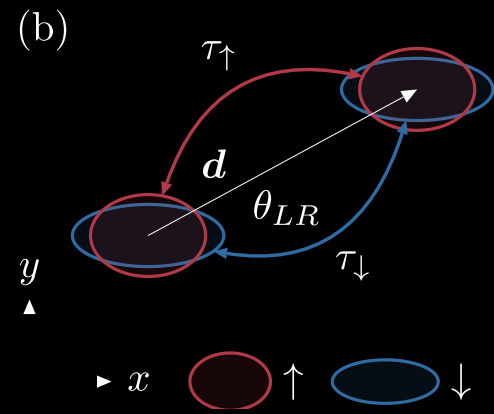


- BHZ-type square lattice, $(s, p_\pm, p_z) \otimes (\uparrow, \downarrow)$ per site, staggered collinear magnetization and **anisotropic next-nearest-neighbour hopping**.
- Two Schrieffer–Wolff steps: project out p_z (SIA + local SOC seed the Rashba term), then $p_\pm \to$ single conduction band at Γ.
- The d-wave term $\eta(k_x^2 - k_y^2)\sigma_z$ is symmetry-allowed **only when both** the Néel order and the hopping anisotropy are present.
- Dimensionless inputs: $m\eta$ and $m\alpha_R a_0$; energy unit $(2ma_0^2)^{-1}$.
- Rotated dot: $\omega_q \longrightarrow \omega_q \cos 2\theta_d$. g- and i-wave hosts couple to 4th and 6th shape moments.

BACKUP · EXCHANGE IS WEAKLY ANISOTROPIC

- Spin-dependent squeezing makes the tunnel amplitudes spin dependent, $\tau_\uparrow \neq \tau_\downarrow$; the asymmetry inherits the d-wave symmetry of the host and changes sign when the dots lie along the diagonals.
- $J_z - J_\perp = 8\,\delta\tau^2/E_C \propto \tau_c^2 (m\eta)^2/E_C$: quadratic in $m\eta$, perturbative in the charging-dominated regime.
- Rashba tunnelling rotates the exchange tensor by $2\theta_{\mathrm{so}} = 2d/\ell_{\mathrm{so}}$; the rotated terms couple only states detuned by $|\bar{\omega}_q|$.
- Net effect: the scalar exchange of the main text is a good approximation; corrections are calibrated away.





BACKUP · RELAXATION AND CURVATURE FORMULAS

Golden-rule relaxation from Néel-vector fluctuations ($\Lambda = \langle \phi_+ | \phi_- \rangle$):

$$T_1^{-1} = \frac{\Lambda^2 \omega_q^2}{4} \left[\mathcal{S}_{n_x n_x}(|\omega_q|) + \mathcal{S}_{n_y n_y}(|\omega_q|) \right]$$

Transverse susceptibility modelled by damped antiferromagnetic-resonance modes with gaps Δ_a; modes gapped above $|\omega_q|$ leave only a sub-gap damping tail.

Coulomb fluctuator at (x', y', z'), expanded to second order in the electron coordinates:

$$\delta\omega_q \simeq -\frac{\eta}{2 a_0 a_B} \mathcal{F}, \qquad \mathcal{F} = \frac{a_0}{r'^5} \left[\ell_x^2 (3x'^2 - r'^2) - \ell_y^2 (3y'^2 - r'^2) \right]$$

Only the quadratic terms renormalize the spring constants; the dipolar (uniform) part translates the dot and leaves ω_q unchanged.

BACKUP · DISPERSIVE COEFFICIENTS

Effective spin–photon Hamiltonian after projecting the dot–cavity system on the qubit doublet ($X = a + a^\dagger$, $P = i(a^\dagger - a)$):

$$H = \frac{\omega_q}{2}\sigma_z + \tilde{\omega}_c a^\dagger a + g_X X\sigma_x + g_P P\sigma_y + \frac{\chi_{\mathrm{pol}}}{2} X^2\sigma_z$$

$$\chi_{\mathrm{pol}} \simeq -2(eE_{\mathrm{zpf}})^2\eta\,\frac{\omega_c^2}{(\omega_x^2-\omega_c^2)^2}, \qquad \chi_{\mathrm{lin}} \simeq \frac{\alpha_R^2(eE_{\mathrm{zpf}})^2}{2\omega_x^4}\,\frac{\omega_q(\omega_q^2+3\omega_c^2)}{\omega_q^2-\omega_c^2}$$

- $g_X\,, g_P \propto \alpha_R\, eE_{\mathrm{zpf}}$, with $g_X \propto \omega_q$ switching off at the circular geometry.
- Validity: dispersive regime $|\omega_q \pm \omega_c| \gg g_X\,, g_P$; poles masked in the map.
- Readout condition $2|\chi_{\mathrm{tot}}| \gtrsim \kappa$; QND at the level of the leading dispersive Hamiltonian.