J. Phys. Mater. **6** 034004 (2023)

Photo-assisted spin transport in double quantum dots with spin–orbit interaction

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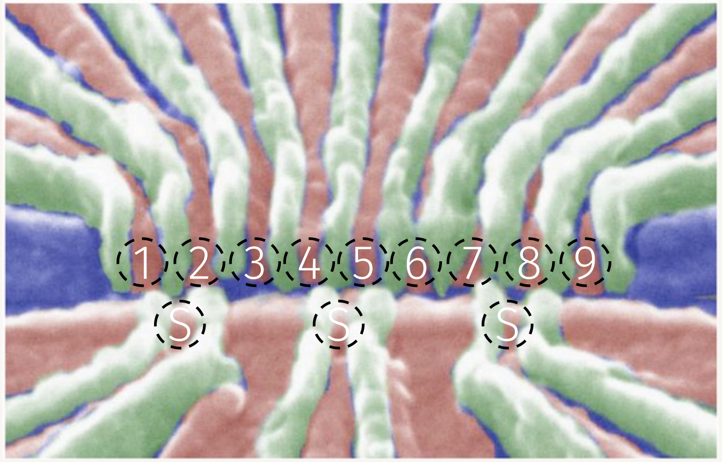
01. Semiconductor spin qubits

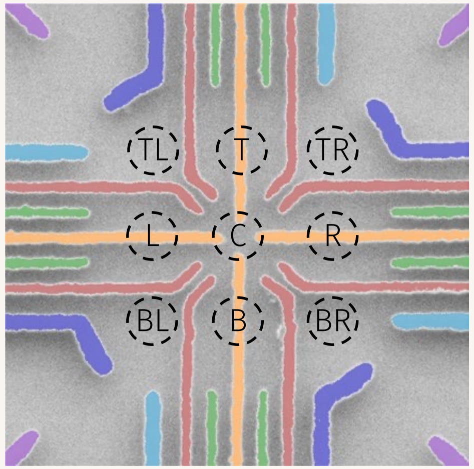
High fidelity **one-** and **two-qubit gates**

Long **dephasing** and **decoherence times**

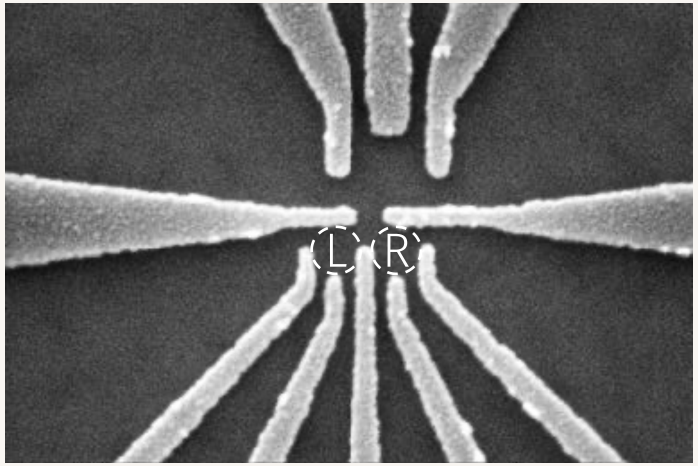
Promise of **scalability** for error correction codes



A. R. Mills, et al., Nat. Commun. **10**, 1063 (2019)



PA. Mortemousque, et al., Nat. Nanotechnol. **16**, 296-301 (2021)



D. Jirovec, et al., PRL. **128**, 126803 (2022)

02. Spin-orbit coupling

\+ Fast **spin control**

\+ Simplify the experimental device
(remove oscillating magnetic fields)

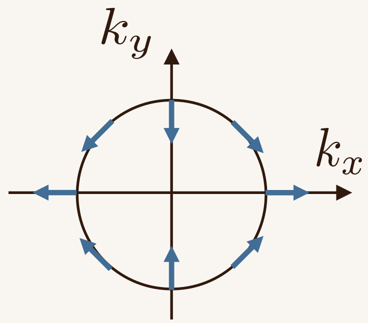
\+ New and interesting phenomena

\- Usually seen as a source of error

\- **Couples spin to electric noise**
(charge noise)

Dresselhaus SOC

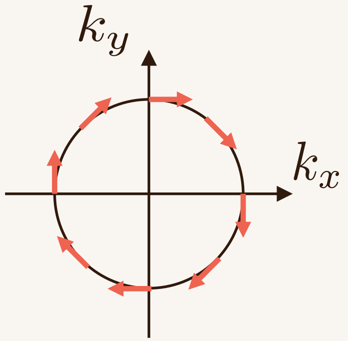
$$H = \beta(\sigma_x k_x - \sigma_y k_y)$$



- Bulk inversion asymmetry
- Fixed at device growing

Rashba SOC

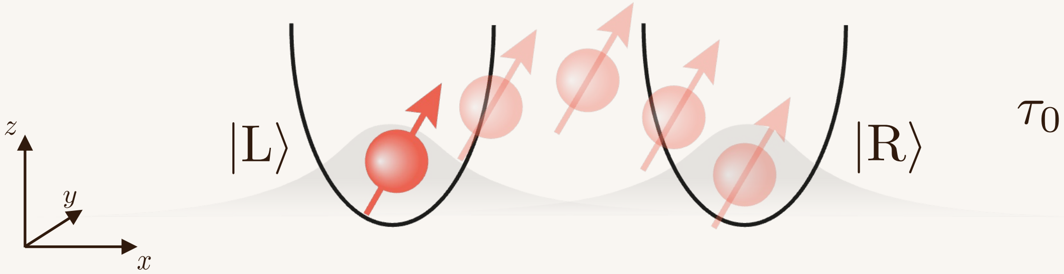
$$H = \alpha(\boldsymbol{\sigma} \times \boldsymbol{k}) \cdot \hat{z}$$



- Structure inversion asymmetry
- **Tunable** with electric fields

02. Spin-orbit coupling + interdot motion

Spin conserving



$$\tau_0 \equiv \langle L\sigma|\,\hat{H}_{\mathrm{DQD}}\,|R\sigma\rangle$$

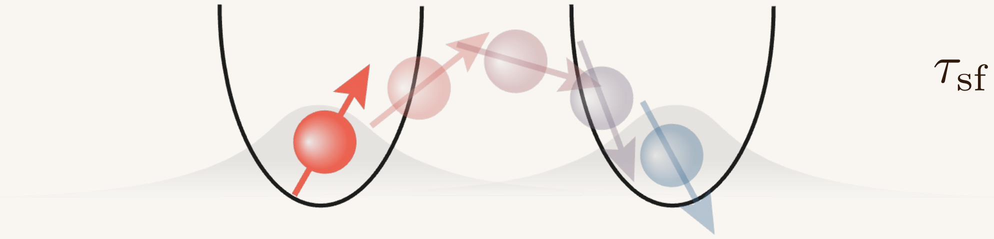
$$\chi \equiv \frac{1}{\tau_0/\tau_{\mathrm{sf}} + 1}$$

$\chi = 0,\ \tau_{\mathrm{sf}} = 0$

$\chi = 1,\ \tau_0 = 0$

$$\tau \equiv \tau_0 + \tau_{\mathrm{sf}}$$

Spin flip (Rashba SOC)



$$\begin{aligned}\tau_{\mathrm{sf}} &\equiv \langle L\sigma|\,\hat{H}_{\mathrm{SOC}}\,|R\sigma'\rangle \\ &= \langle\sigma|\,\boldsymbol{\alpha}\cdot\hat{\boldsymbol{\sigma}}\,|\sigma'\rangle\,\langle L|\,\hat{k}_x\,|R\rangle\end{aligned}$$

Preserves time-reversal symmetry
+
Parallel to SOC vector

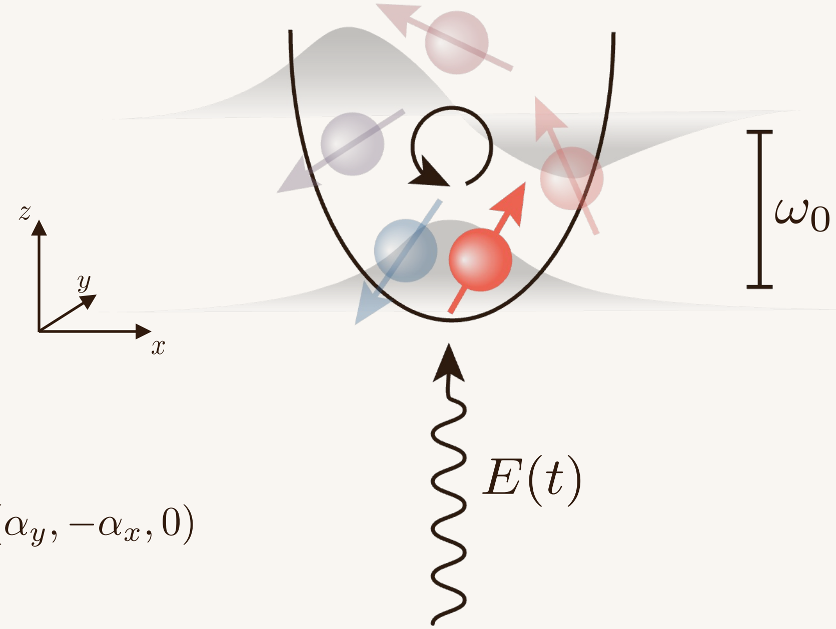
02. Spin-orbit coupling + intradot motion

Single dot Hamiltonian

$$\hat{H}(x,t) = \hat{H}_0 + e\hat{x}E(t) + \boldsymbol{\alpha}\cdot\hat{\boldsymbol{\sigma}}\hat{k}_x + E_z\hat{\sigma}_z/2$$

Quantized Hamiltonian for a **harmonic oscillator**

$$\hat{H}_{\mathrm{osc}} = \omega_0(\hat{a}^\dagger\hat{a}+1) + el_0E(t)(\hat{a}^\dagger+\hat{a}) + \frac{i}{l_0}\boldsymbol{\alpha}\cdot\hat{\boldsymbol{\sigma}}(\hat{a}^\dagger-\hat{a}) + E_z\hat{\sigma}_z/2$$



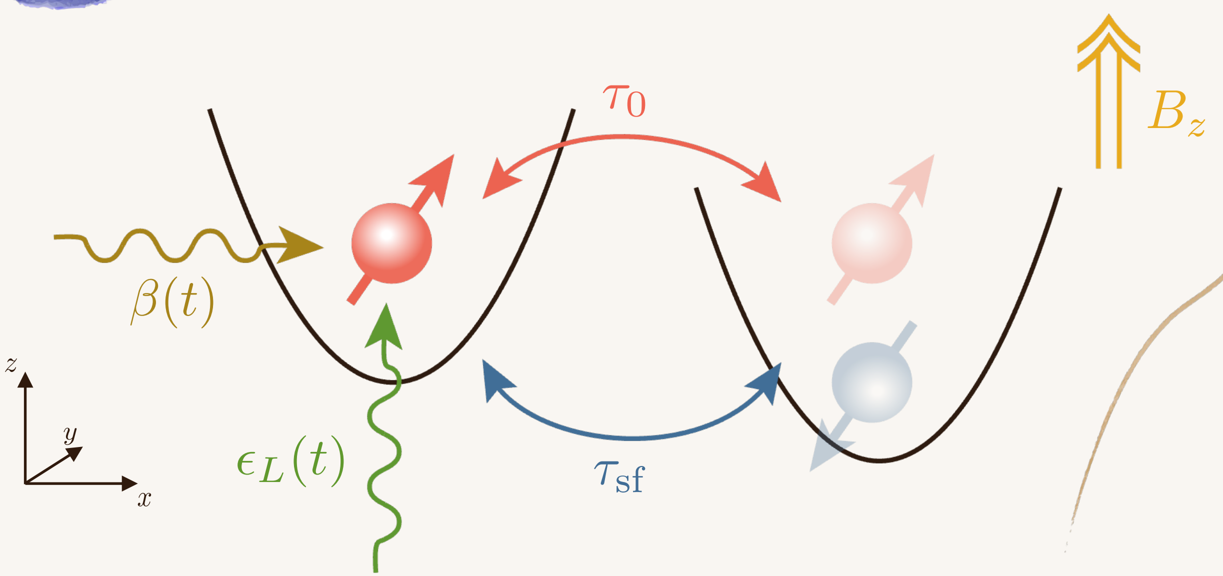
Effective Hamiltonian (Schrieffer-Wolff transformation)

$$\boldsymbol{\alpha}^\perp \equiv (\alpha_y, -\alpha_x, 0)$$

$$\hat{H}_{\mathrm{eff}} = \hat{H}_0 + E_z\left[1 - \frac{|\boldsymbol{\alpha}|^2}{2l_0(\omega_0^2 - E_z^2)}\right]\hat{\sigma}_z + \frac{E_z eE(t)}{\omega_0^2 - E_z^2}\boldsymbol{\alpha}^\perp\cdot\hat{\boldsymbol{\sigma}}$$

Time-reversal symmetry must be broken
+
Perpendicular to SOC vector

03. Model for double quantum dot



$\epsilon_L(t) = \epsilon_{\mathrm{ac}} \cos(\omega t)$
$\epsilon_R(t) = \delta$

$\boldsymbol{\alpha} = (0, \alpha_y, 0)$

$$\hat{H}(t) = \sum_{\eta;\sigma} \boxed{\epsilon_\eta(t)\hat{n}_{\eta,\sigma}} - \boxed{\tau_0 \hat{\eta}_x} + \boxed{\tau_{\mathrm{sf}} \hat{\eta}_y \hat{\sigma}_y} + \sum_\eta \left(\boxed{\frac{E_z}{2}\hat{\sigma}_{z,\eta}} + \boxed{\frac{\beta(t)}{2}\hat{\sigma}_{x,\eta}} \right)$$

$E_z = g\mu_B B_z$

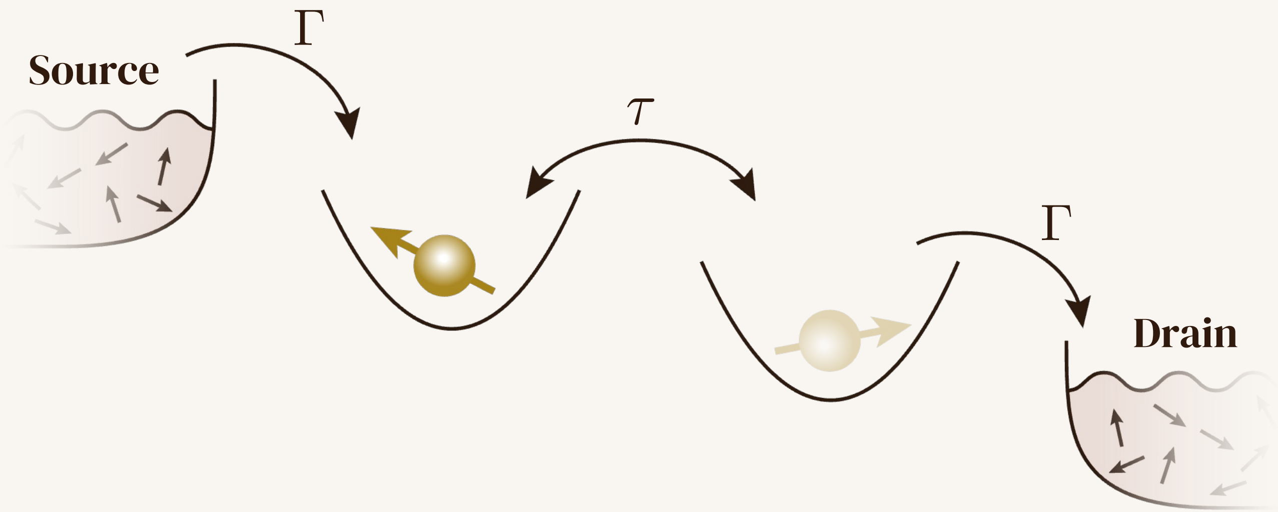
$\beta(t) = \beta_{\mathrm{SO}} \cos(\omega t)$

$$\begin{array}{cccc} |\mathrm{L}\uparrow\rangle & |\mathrm{L}\downarrow\rangle & |\mathrm{R}\uparrow\rangle & |\mathrm{R}\downarrow\rangle \end{array}$$

$$\hat{H}(t) = \begin{pmatrix} \epsilon_L(t) + E_z/2 & \beta(t)/2 & -\tau_0 & -\tau_{\mathrm{sf}} \\ \beta(t)/2 & \epsilon_L(t) - E_z/2 & \tau_{\mathrm{sf}} & -\tau_0 \\ -\tau_0 & \tau_{\mathrm{sf}} & \epsilon_R + E_z/2 & \beta(t)/2 \\ -\tau_{\mathrm{sf}} & -\tau_0 & \beta(t)/2 & \epsilon_R - E_z/2 \end{pmatrix}$$

04. Open system

- **Unpolarized** contacts
- Infinite bias approximation
- Current is **unidirectional**



Master equation in Lindblad form

$$i\dot{\hat{\rho}}(t) = \left[\hat{H}(t), \hat{\rho}(t)\right] + \Gamma \sum_{\sigma} \left(\hat{\mathcal{D}}\left[\hat{d}^{\dagger}_{L,\sigma}\right](\hat{\rho}(t)) + \hat{\mathcal{D}}\left[\hat{d}_{R,\sigma}\right](\hat{\rho}(t)) \right)$$

$$\hat{\mathcal{D}}\left[\hat{o}\right](\hat{\rho}(t)) \equiv \hat{o}\hat{\rho}(t)\hat{o}^{\dagger} - \frac{1}{2}\left\{\hat{o}\hat{o}^{\dagger}, \hat{\rho}(t)\right\}$$

04. Open system

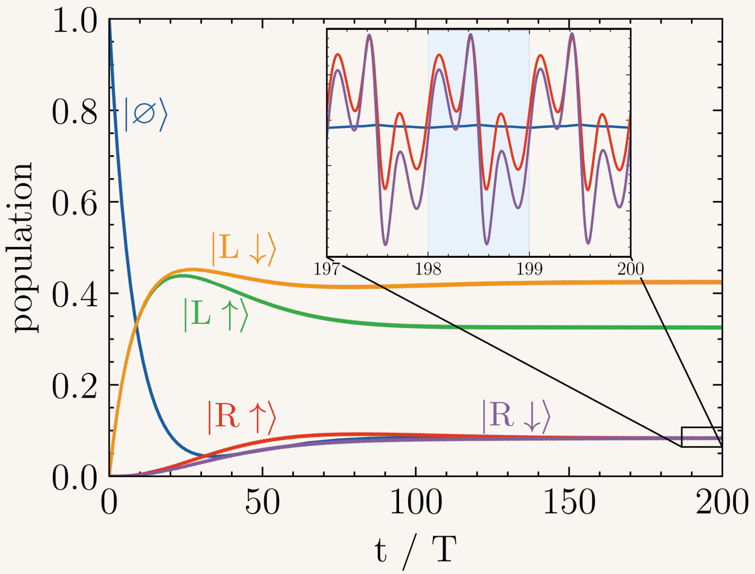
The **Liouvillian** operator define the system dynamic

$$\hat{\mathcal{L}}(t)\hat{\rho}(t) = i\dot{\hat{\rho}}(t)$$

The **steady state** is given by the eigenstate with zero eigenvalue

$$\hat{\mathcal{L}}(T)\hat{\rho}_{\mathrm{ss}}(T) = 0$$

Driving period $T = 2\pi/\omega$



Since the system is periodic in time, we compute the **average populations**

$$\rho^{\infty}_{\eta,\sigma} \equiv \frac{1}{T}\int_0^T dt \,\langle \eta,\sigma|\,\hat{\rho}_{\mathrm{ss}}(t)\,|\eta,\sigma\rangle$$

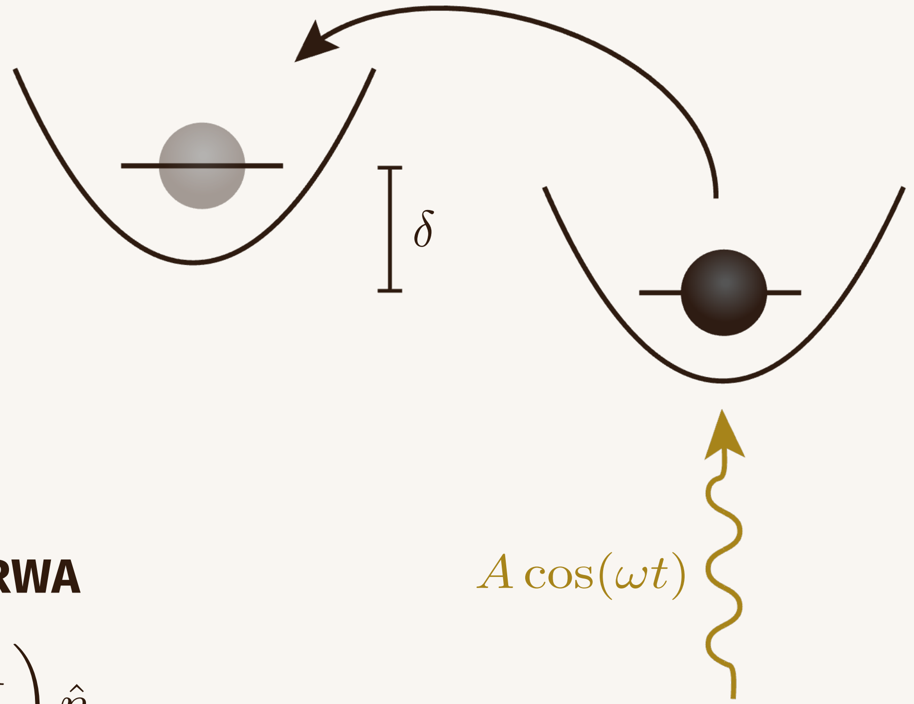
The **current intensity** is defined in terms of the population of the right dot

$$I^{\infty} = e\Gamma\left(\rho^{\infty}_{R,\uparrow} + \rho^{\infty}_{R,\downarrow}\right)$$

05. Photo-assisted tunneling (PAT)

Two-level system with **driving in the detuning**

$$\hat{H}(t) = \frac{1}{2}\left[\epsilon(t) + \delta\right]\hat{\eta}_z + \tau\hat{\eta}_x$$



Rotating frame

$$\hat{U} = \exp\left[i\int dt\epsilon(t)\hat{\eta}_z\right]$$

$$\hat{\tilde{H}} = \hat{U}\hat{H}\hat{U}^\dagger - i\hat{U}\dot{\hat{U}} = \begin{pmatrix} \delta/2 & \tau\exp\left[i\frac{A}{\omega}\sin(\omega t)\right] \\ \tau\exp\left[-i\frac{A}{\omega}\sin(\omega t)\right] & -\delta/2 \end{pmatrix}$$

Jacobi-Anger expansion + **RWA**

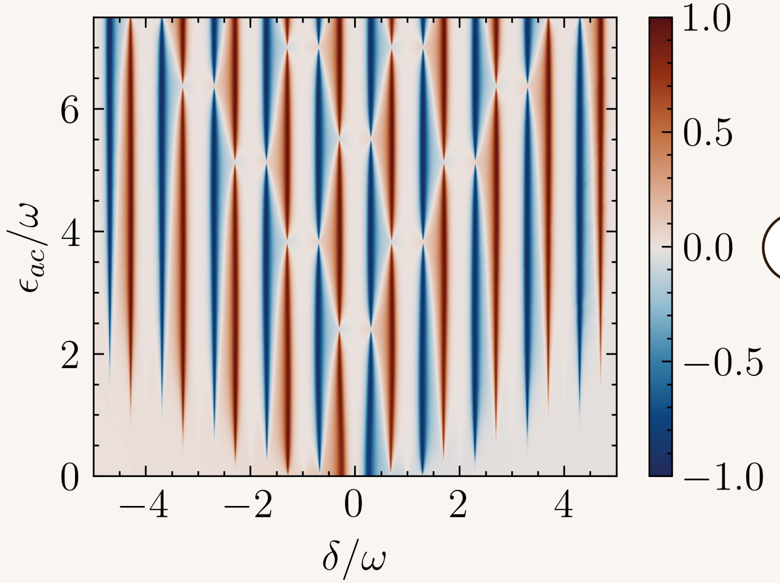
$$\exp\left[iz\sin\theta\right] = \sum_{k=-\infty}^{\infty} J_k(z) e^{ik\theta}$$

Bessel functions

$$\hat{\tilde{H}}_{\mathrm{RWA}}(\delta = n\omega) = \tau J_n\left(\frac{A}{\omega}\right)\hat{\eta}_x$$

06. Landau-Zener-Stückelberg interf.

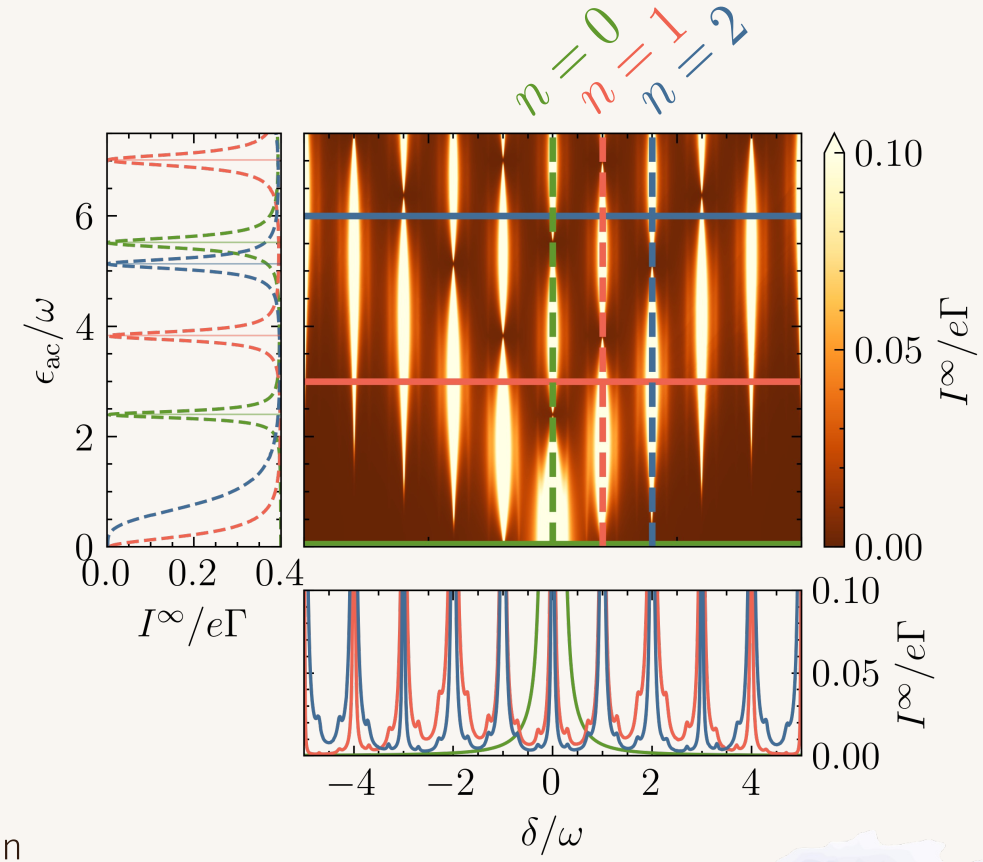
- Coherent destruction of tunneling (**CDT**): $J_n(\epsilon_{\rm ac}/\omega) = 0$
- **Main resonances** for **spin-conserving** processes: $\delta = n\omega$
- **Satellite peaks** for **spin-flip** processes: $\delta \sim n\omega \pm E_z$



P_σ

Spin polarization

$$P_\sigma \equiv \frac{I^\infty_\uparrow - I^\infty_\downarrow}{I^\infty_\uparrow + I^\infty_\downarrow}$$



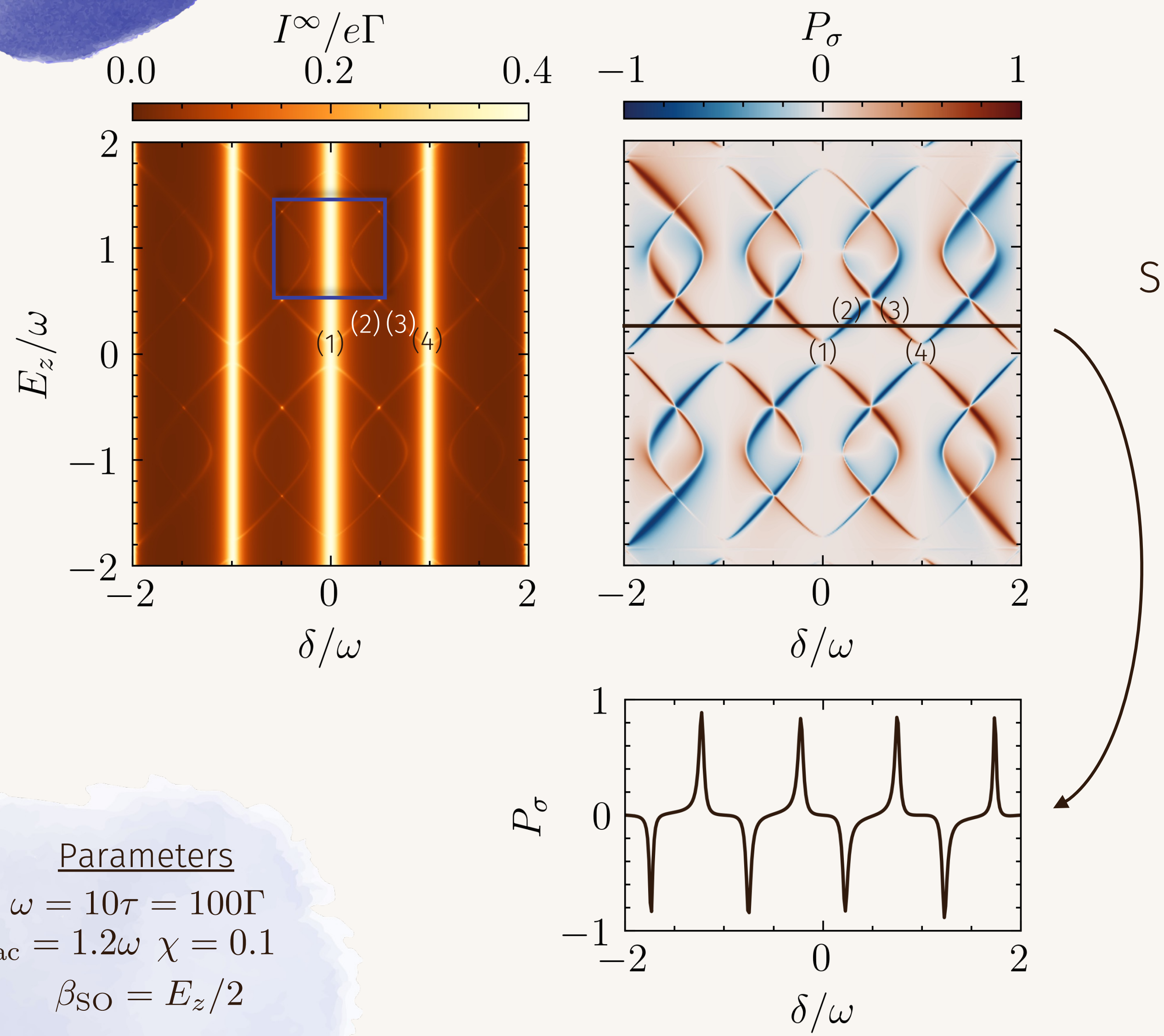
Parameters

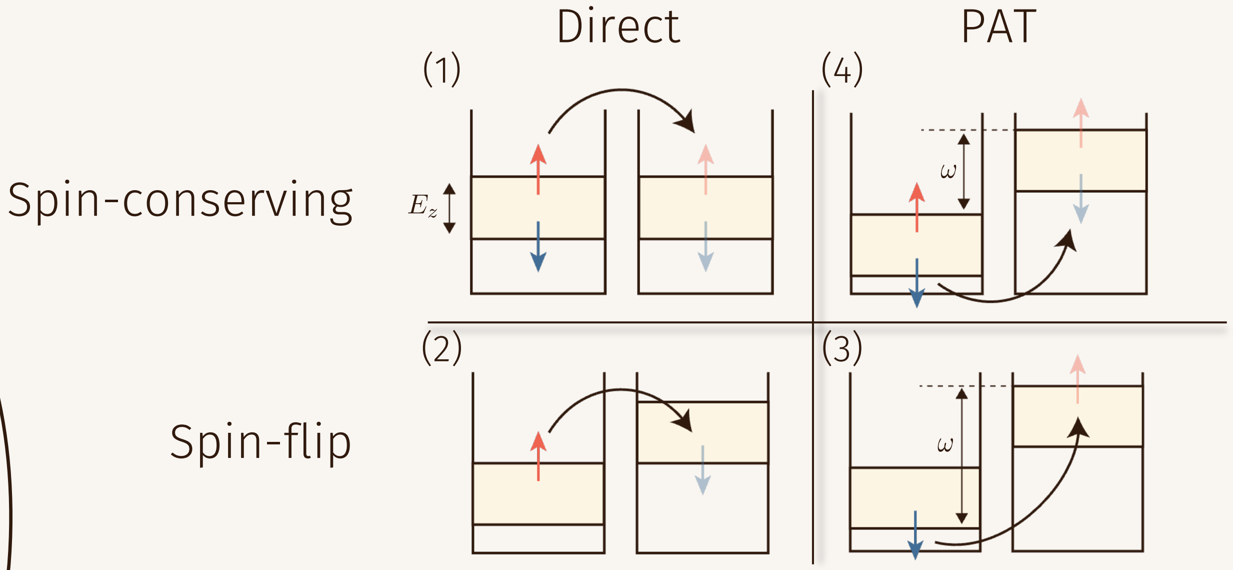
$\omega = 10\tau = 100\Gamma$

$\chi = 0.2$

$E_z = 0.3\omega \quad \beta_{SO} = 0$

07. Current through the DQD





- Four different processes
- **Spin polarized current** for spin-flip processes
- **Highly tunable polarization** with detuning

<u>Parameters</u>

$\omega = 10\tau = 100\Gamma$

$\epsilon_{\mathrm{ac}} = 1.2\omega \;\; \chi = 0.1$

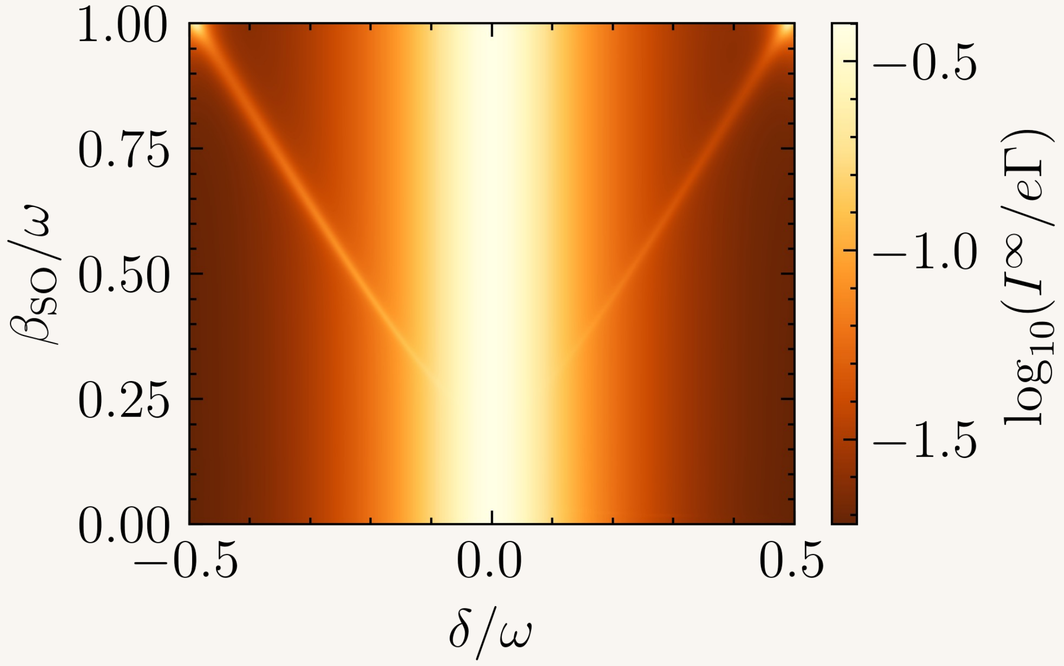
$\beta_{\mathrm{SO}} = E_z/2$

08. Effect of EDSR

When the **magnetic field is in resonance**,
EDSR produces spin rotations

Two satellite peaks appear due to
the **renormalization of the magnetic field**

However, these two peaks are **asymmetric**,
indicating a **spin-imbalance** process



Parameters

$\omega = 10\tau = 100\Gamma$

$\epsilon_{\mathrm{ac}} = 1.2\omega \;\; \chi = 0.2$

$E_z = \omega$

08. Effect of EDSR *(Lots of rotations)*

Resonances

$E_z = \omega$

$\delta \sim 0$

$$\hat{H}(t) = \sum_{\eta;\sigma} \epsilon_\eta(t)\hat{n}_{\eta,\sigma} + \tau_0\hat{\eta}_x + \tau_{\text{sf}}\hat{\eta}_y\hat{\sigma}_y + \frac{E_z}{2}\hat{\sigma}_z + \frac{\beta(t)}{2}\hat{\sigma}_x$$

To understand the origin of the asymmetry, we obtain a simpler **effective system**

RWA

Remove driving in detuning

$$\hat{U}(t) = \boxed{\exp\left(i\theta/2\hat{\sigma}_y\right)}\,\boxed{\exp\left(\frac{-i\omega t\hat{\sigma}_z}{2}\right)}\,\boxed{\exp\left(\frac{-i\epsilon_{\text{ac}}\sin(\omega t)(1+\hat{\eta}_z)}{2\omega}\right)}\,\boxed{\exp\left(\frac{-i\beta_{\text{SO}}\sin(\omega t)\,\hat{\sigma}_x}{2\omega}\right)}$$

Diagonalize spin sector

Remove EDSR

- Spin-flip tunneling
- **Spin-imbalance** tunneling

$$\boxed{\tilde{\hat{H}} = \frac{\tilde{E}_z}{2}\hat{\sigma}_z - \delta\hat{\eta}_z - \tilde{\tau}_{\text{sf}}\hat{\eta}_x\hat{\sigma}_x - \left[\tilde{\tau}_\uparrow(\mathbb{1}_\sigma + \hat{\sigma}_z) + \tilde{\tau}_\downarrow(\mathbb{1}_\sigma - \hat{\sigma}_z)\right]\frac{\hat{\eta}_x}{2}}$$

08. Effect of EDSR *(Lots of rotations)*

Resonances

$E_z = \omega$

$\delta \sim 0$

$$\hat{H}(t) = \sum_{\eta;\sigma} \epsilon_\eta(t)\hat{n}_{\eta,\sigma} + \tau_0\hat{\eta}_x + \tau_{\rm sf}\hat{\eta}_y\hat{\sigma}_y + \frac{E_z}{2}\hat{\sigma}_z + \frac{\beta(t)}{2}\hat{\sigma}_x$$

To understand the origin of the asymmetry, we obtain a simpler **effective system**

$$\hat{U}(t) = \underbrace{\exp\left(i\theta/2\hat{\sigma}_y\right)}_{\text{Diagonalize spin sector}} \overbrace{\exp\left(\frac{-i\omega t\hat{\sigma}_z}{2}\right)}^{\text{RWA}} \overbrace{\exp\left(\frac{-i\epsilon_{\rm ac}\sin(\omega t)(1+\hat{\eta}_z)}{2\omega}\right)}^{\text{Remove driving in detuning}} \underbrace{\exp\left(\frac{-i\beta_{\rm SO}\sin(\omega t)\,\hat{\sigma}_x}{2\omega}\right)}_{\text{Remove EDSR}}$$

- Spin-flip tunneling
- **Spin-imbalance** tunneling
  - **Interference** between EDSR and PAT

$$\tilde{\hat{H}} = \frac{\tilde{E}_z}{2}\hat{\sigma}_z - \delta\hat{\eta}_z - \tilde{\tau}_{\rm sf}\hat{\eta}_x\hat{\sigma}_x - \left[\tilde{\tau}_\uparrow(\mathbb{1}_\sigma + \hat{\sigma}_z) + \tilde{\tau}_\downarrow(\mathbb{1}_\sigma - \hat{\sigma}_z)\right]\frac{\hat{\eta}_x}{2}$$

$$\tau_{\rm sf}^{\rm RWA} = \tau_{\rm sf}\sum_{k=-\infty}^{\infty} J_{2k+1}\left(\frac{\epsilon_{\rm ac}}{\omega}\right)J_{2k}\left(\frac{\beta_{\rm SO}}{\omega}\right)$$

$$\tau_{\rm si}^{\rm RWA} = \tau_{\rm sf}\sum_{k=-\infty}^{\infty} J_{2k+1}\left(\frac{\epsilon_{\rm ac}}{\omega}\right)J_{2k+1}\left(\frac{\beta_{\rm SO}}{\omega}\right)$$

$$\tan(\theta) \equiv E_z^{\rm RWA}/\beta_{\rm SO}^{\rm RWA}$$

$$E_z^{\rm RWA} \equiv E_z J_0\left(\beta_{\rm SO}/\omega\right) - \omega$$

$$\beta_{\rm SO}^{\rm RWA} \equiv E_z J_1(\beta_{\rm SO}/\omega)$$

$$\tilde{E}_z \equiv \sqrt{(E_z^{\rm RWA})^2 + (\beta_{\rm SO}^{\rm RWA})^2}$$

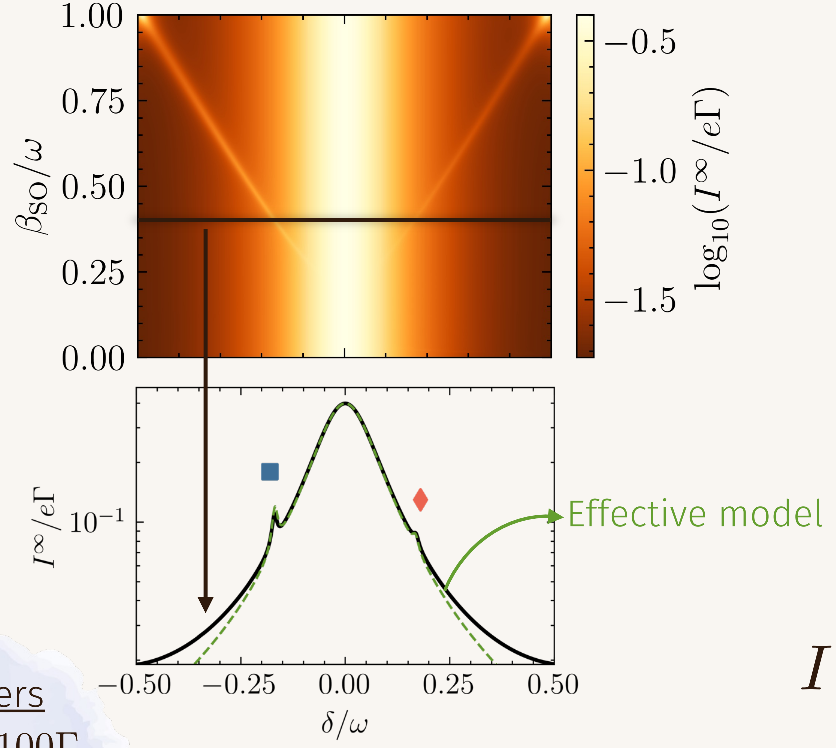
$$\tilde{\tau}_{\uparrow,\downarrow} \equiv \tau_0^{\rm RWA} \mp \left[\sin(\theta)\tau_{\rm sf}^{\rm RWA} - \cos(\theta)\tau_{\rm si}^{\rm RWA}\right]$$

$$\tilde{\tau}_{\rm sf} \equiv \cos(\theta)\tau_{\rm sf}^{\rm RWA} + \sin(\theta)\tau_{\rm si}^{\rm RWA}$$

$$\tau_0^{\rm RWA} \equiv \tau_0 J_0(\epsilon_{\rm ac}/\omega)$$

09. Effective model

$$\hat{\tilde{H}} = \begin{pmatrix} (\tilde{E}_z - \delta)/2 & 0 & -\tilde{\tau}_\uparrow & -\tilde{\tau}_{\rm sf} \\ 0 & (-\tilde{E}_z - \delta)/2 & -\tilde{\tau}_{\rm sf} & -\tilde{\tau}_\downarrow \\ -\tilde{\tau}_\uparrow & -\tilde{\tau}_{\rm sf} & (\tilde{E}_z + \delta)/2 & 0 \\ -\tilde{\tau}_{\rm sf} & -\tilde{\tau}_\downarrow & 0 & (-\tilde{E}_z + \delta)/2 \end{pmatrix}$$

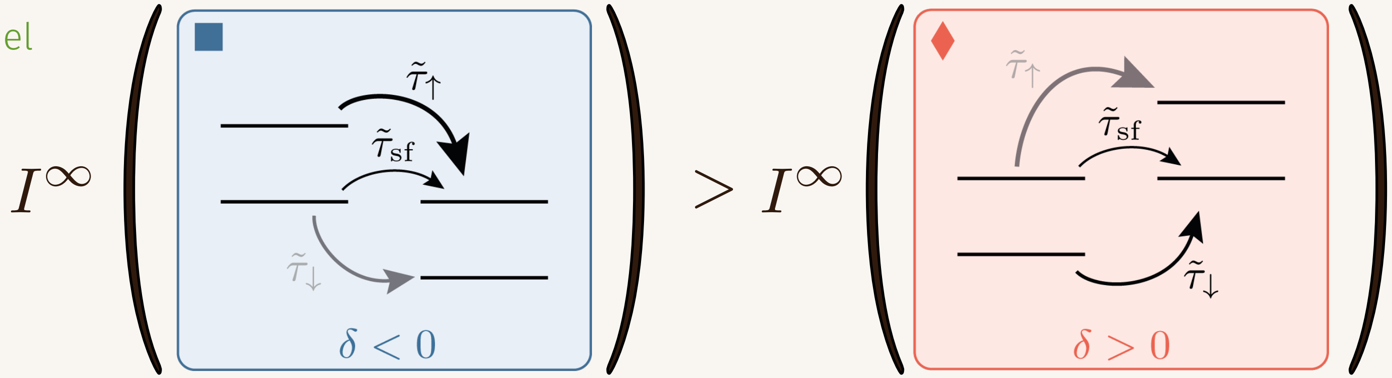


The resonances appear when the **spin levels** are aligned

$$\tilde{E}_z = \beta_{\rm SO}/2 + \mathcal{O}\left((\beta_{\rm SO}/\omega)^5\right) \qquad \delta_{\rm res} \sim \pm\beta_{\rm SO}/2$$

Each spin channel has a **different tunneling rate**, producing the asymmetry in the current intensity

$$\tilde{\tau}_\uparrow \simeq 0.06\omega > \tilde{\tau}_\downarrow \simeq 0.04\omega \qquad \tilde{\tau}_{\rm sf} \simeq 0.002\omega$$



Parameters

$\omega = 10\tau = 100\Gamma$

$\epsilon_{\rm ac} = 1.2\omega \quad \chi = 0.2$

$E_z = \omega$

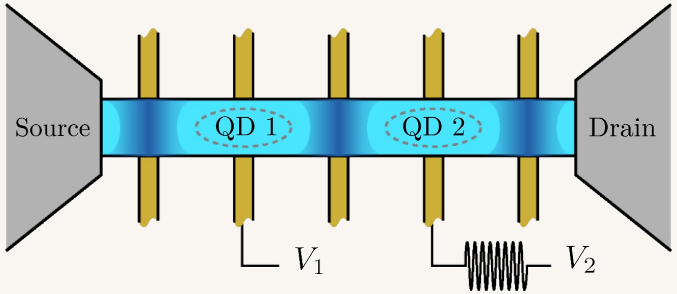
10. Dark states

A dark state is an **eigenstate uncoupled** to the right contact

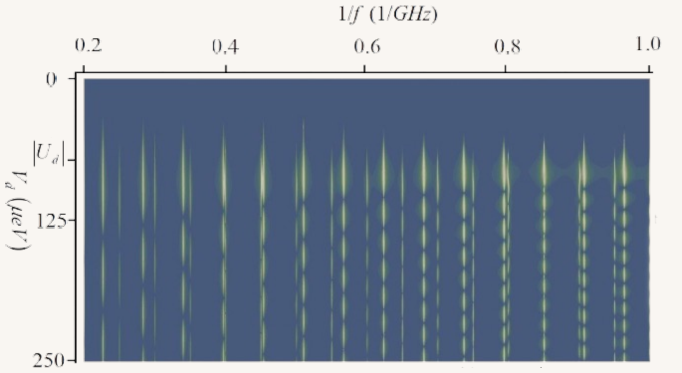
$$|\mathrm{DS}\rangle = \cos(\vartheta/2)\,|\mathrm{L}\uparrow\rangle + \sin(\vartheta/2)e^{i\phi}\,|\mathrm{L}\downarrow\rangle$$

The presence of dark states *(in some cases)* can be attributed to **quantum coherence interferences**

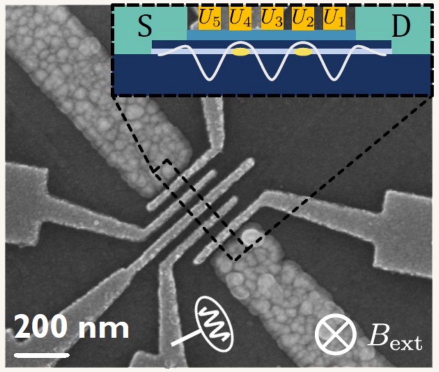
Dark states have been extensively studied in **driven system,** but the presence of high **SOC** is still to be explored



Arnau Sala, et al., PRB. **104**, 085421 (2021)



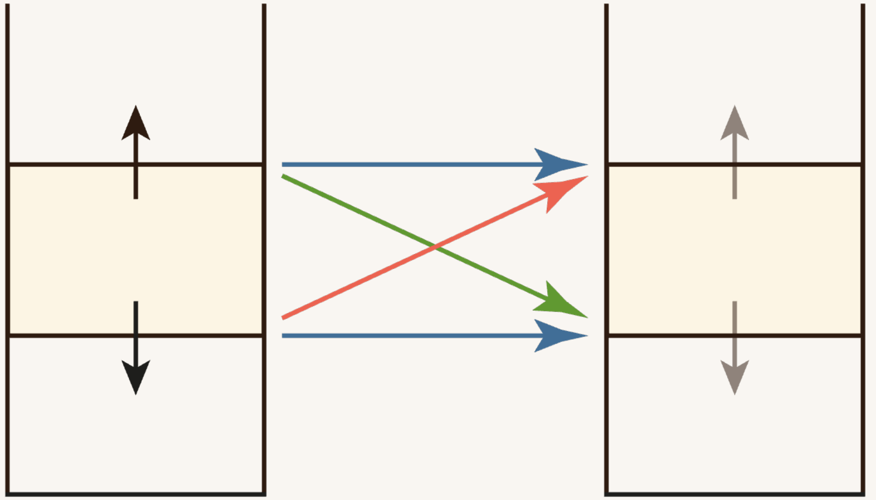
D. V. Khomitsky, et al., PRB. **106**, 195414 (2022)



Yuan Zhou, et al., arXiv 2209.14528v1 (2022)

11. Coherence interferences

$\tau_0 \to \tau_0 J_0(\epsilon_{ac}/\omega)$	Direct transfer
$\tau_{sf} \to \tau_{sf} J_{-n}(\epsilon_{ac}/\omega)$	Emits n photons
$\tau_{sf} \to \tau_{sf} J_n(\epsilon_{ac}/\omega)$	Absorbs n photons



$$\hat{H}^{(n)}_{\mathrm{RWA}} = \begin{pmatrix} 0 & 0 & -\tau_0 J_0(\epsilon_{ac}/\omega) & -\tau_{sf} J_n(\epsilon_{ac}/\omega) \\ 0 & 0 & \tau_{sf} J_{-n}(\epsilon_{ac}/\omega) & -\tau_0 J_0(\epsilon_{ac}/\omega) \\ -\tau_0 J_0(\epsilon_{ac}/\omega) & \tau_{sf} J_{-n}(\epsilon_{ac}/\omega) & 0 & 0 \\ -\tau_{sf} J_n(\epsilon_{ac}/\omega) & -\tau_0 J_0(\epsilon_{ac}/\omega) & 0 & 0 \end{pmatrix}$$

$n = 2k \to \hat{H}^{(n)}_{\mathrm{RWA}} \propto \tau_{sf}\hat{\eta}_y\hat{\sigma}_y \to$ Perpendicular to spin conserving

$n = 2k+1 \to \hat{H}^{(n)}_{\mathrm{RWA}} \propto \tau_{sf}\hat{\eta}_x\hat{\sigma}_x \to$ Parallel to spin conserving

The dark state can be found by **exact diagonalization**

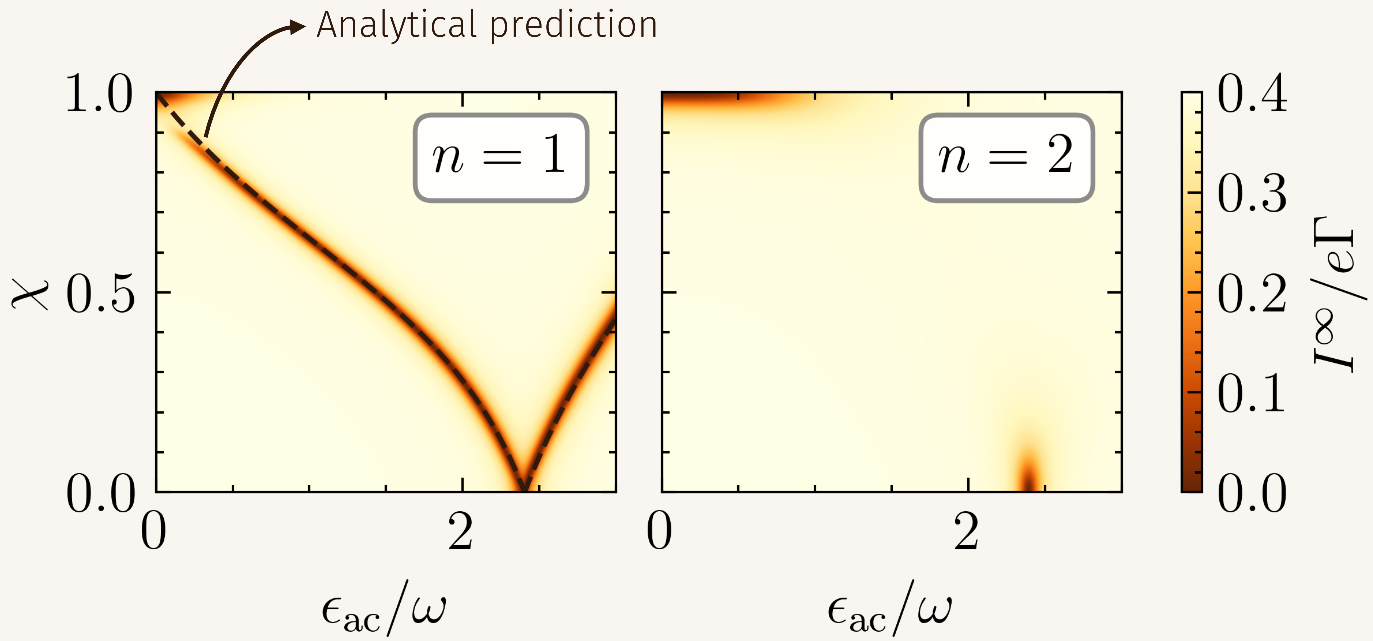
$$\chi^{(n)}_{\mathrm{DS}} = \frac{J_0(\epsilon_{ac}/\omega)}{J_0(\epsilon_{ac}/\omega) \pm i^{n+1} J_n(\epsilon_{ac}/\omega)}$$

$\boxed{J_{-n}(z) = (-1)^n J_n(z)}$

Recall the definition: $\chi \equiv \dfrac{1}{\tau_0/\tau_{sf} + 1} \in \mathbb{R}$

The dark state is only present for an **odd** number of photons

12. Even-odd effect



- Close to $\chi \sim 1$ the dark state is not produced due to coherent interferences
- The dark state is only present when **time-reversal symmetry is broken**
- Analytical prediction in **agreement** with numerical results
- **Sharp drop** in the total current

Locate the dark state versus driving amplitude to **measure the effective SOC** in an experimental device

Parameters

$\omega = 10\tau = 100\Gamma$

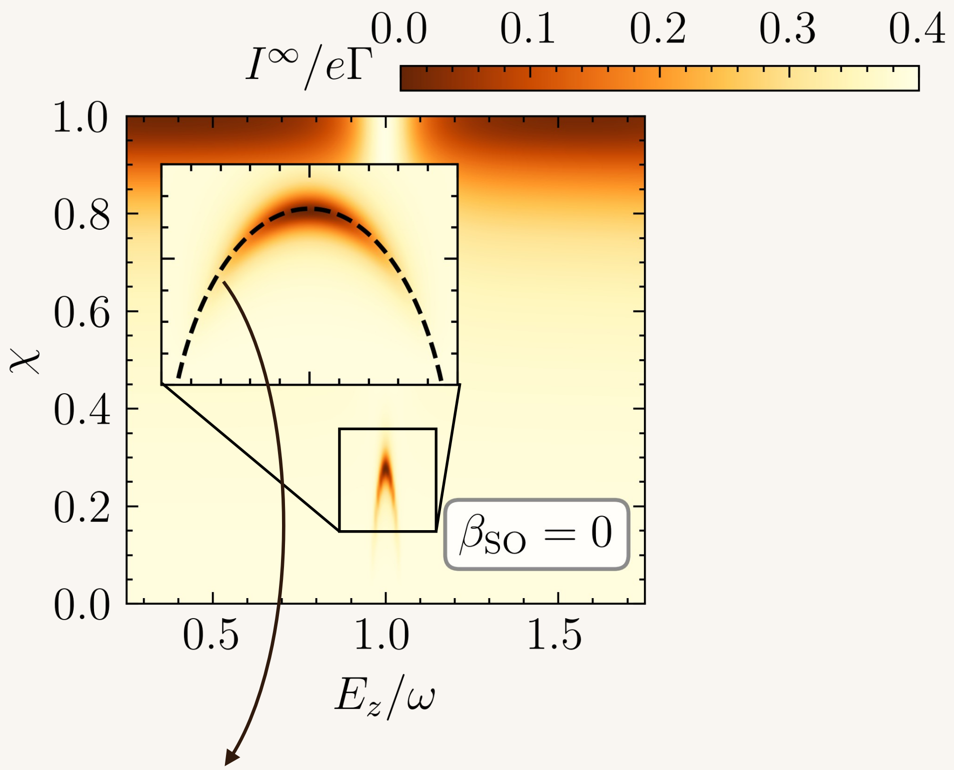
$\delta = 0$

$\beta_{\mathrm{SO}} = 0 \quad E_z = n\omega$

13. Dark state out-of-resonance

$\boxed{\beta_{\mathrm{SO}} = 0}$

- The presence of a dark state is **sensitive to the magnetic field**
- Out of resonance the only dark state corresponds to $\chi \sim 1$



$$\chi_{\mathrm{DS}}^{(1)} = \frac{J_0(\epsilon_{\mathrm{ac}}/\omega)^2 - |J_0(\epsilon_{\mathrm{ac}}/\omega)J_1(\epsilon_{\mathrm{ac}}/\omega)|}{J_0(\epsilon_{\mathrm{ac}}/\omega)^2 - J_1(\epsilon_{\mathrm{ac}}/\omega)^2} - \frac{(E_z-\omega)^2}{\tau^2|J_0(\epsilon_{\mathrm{ac}}/\omega)J_1(\epsilon_{\mathrm{ac}}/\omega)|} + \mathcal{O}\left((E_z-\omega)^4\right)$$

<u>Parameters</u>

$\omega = 10\tau = 100\Gamma$

$\delta = 0$

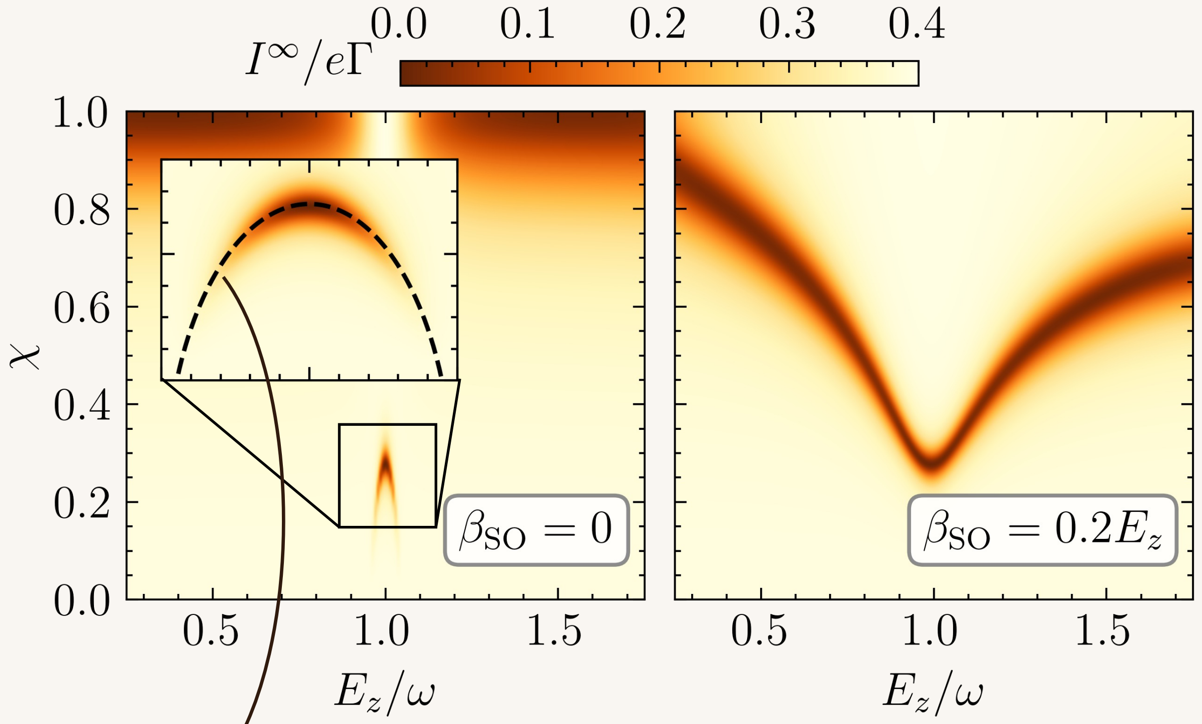
13. Dark state out-of-resonance

$\boxed{\beta_{\mathrm{SO}} = 0}$

- The presence of a dark state is **sensitive to the magnetic field**
- Out of resonance the only dark state corresponds to $\chi \sim 1$

$\boxed{\beta_{\mathrm{SO}} \neq 0}$

- The **dark state survives** for all magnetic field values
- The location of the dark state has not analytical solution



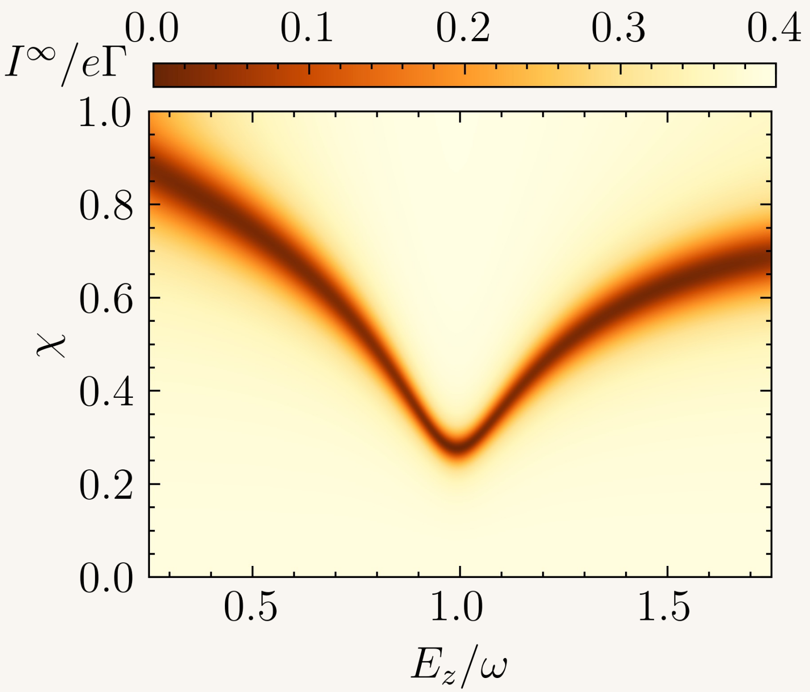
$$\chi_{\mathrm{DS}}^{(1)} = \frac{J_0(\epsilon_{\mathrm{ac}}/\omega)^2 - |J_0(\epsilon_{\mathrm{ac}}/\omega)J_1(\epsilon_{\mathrm{ac}}/\omega)|}{J_0(\epsilon_{\mathrm{ac}}/\omega)^2 - J_1(\epsilon_{\mathrm{ac}}/\omega)^2} - \frac{(E_z-\omega)^2}{\tau^2|J_0(\epsilon_{\mathrm{ac}}/\omega)J_1(\epsilon_{\mathrm{ac}}/\omega)|} + \mathcal{O}\left((E_z-\omega)^4\right)$$

Parameters

$\omega = 10\tau = 100\Gamma$

$\delta = 0$

14. Floquet theory



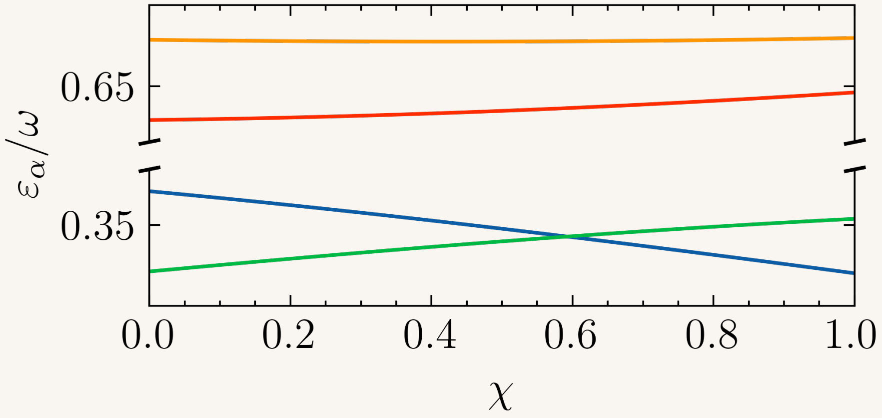
For a **time-periodic Hamiltonian**, define the operator

$$\hat{\mathcal{H}}(t) \equiv \hat{H}(t) - i\partial_t$$

The **Floquet modes** and **quasienegies** are given by

$$\hat{\mathcal{H}}(t)\Phi_\alpha(t) = \varepsilon_\alpha \Phi_\alpha(t)$$

The **crossing of quasienergies** indicates that the driving restores some system's symmetry (Von Neumann-Wigner theorem)

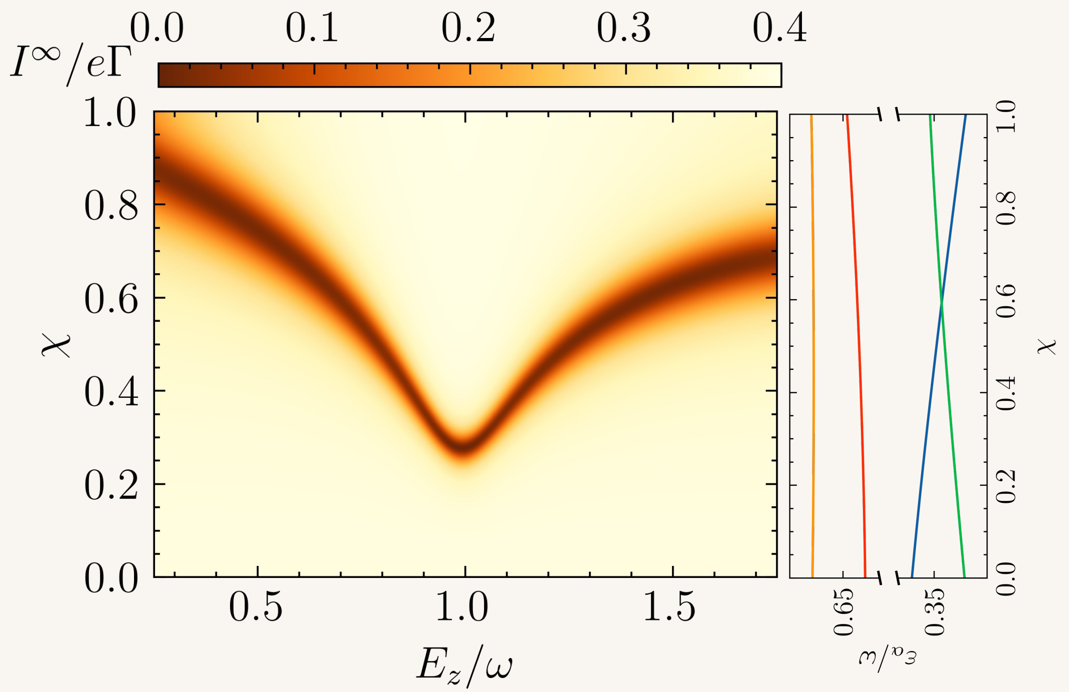


Parameters

$\omega = 10\tau = 100\Gamma$

$\delta = 0 \quad \beta_{\mathrm{SO}} = 0.2E_z$

14. Floquet theory



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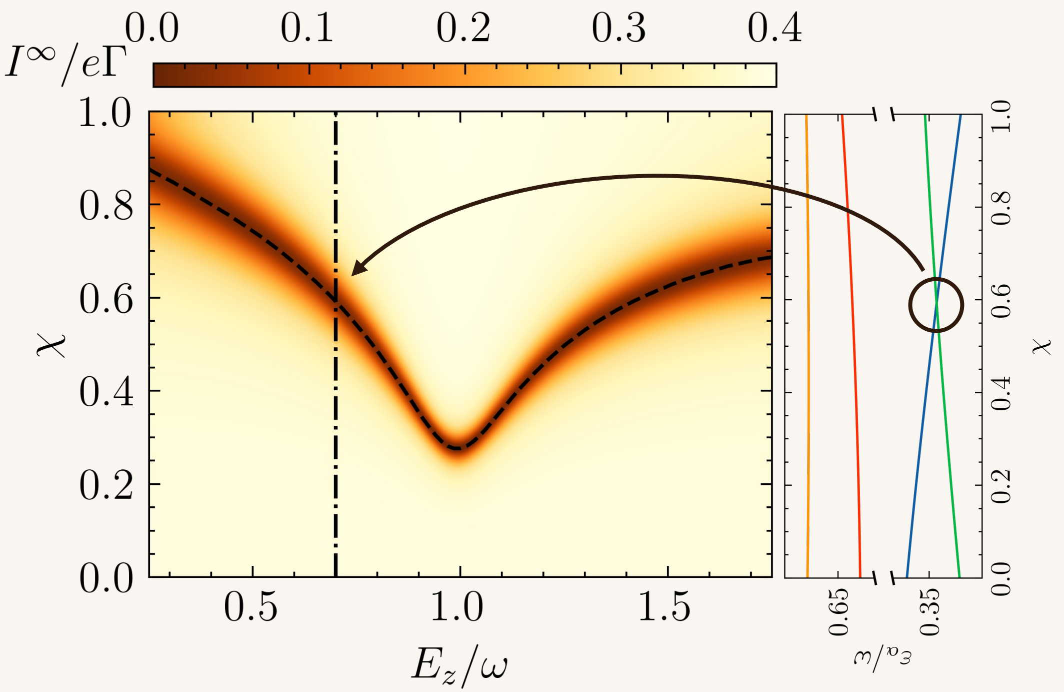

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The **crossing of quasienergies** indicates that the driving restores some system's symmetry (Von Neumann-Wigner theorem)

Agreement between numerical results from dynamics and Floquet theory

Parameters

$\omega = 10\tau = 100\Gamma$

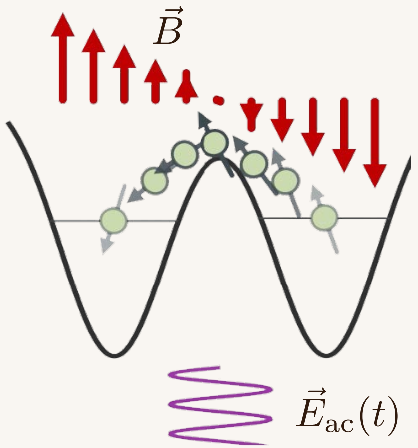
$\delta = 0 \quad \beta_{\mathrm{SO}} = 0.2E_z$

15. Flopping mode qubit

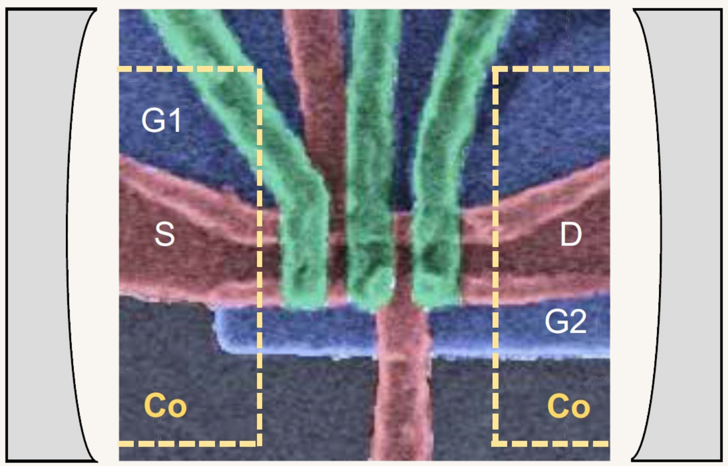
Encode the qubit in the **spin** of the particle

Use the **spatial extension** of the wave function to **manipulate** the qubit

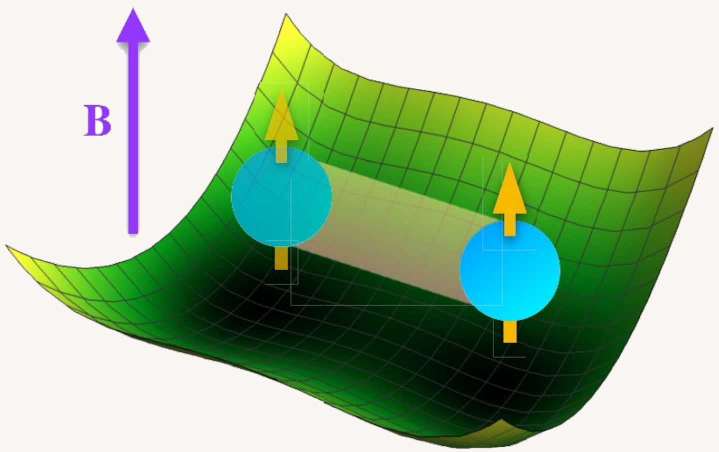
Due to **the large dipole moment**, the coupling with a **cavity** can be higher than the decoherence rate



M. Benito, et al., PRB. **100**, 125430 (2019)



X. Croot, et al., Phys. Rev. Research **2**, 012006(R) (2020)



P. M. Mutter, et al., Phys. Rev. Research **3**, 013194 (2021)

16. Effective driven system

- The Zeeman splitting is in **resonance** with the driving ($E_z = n\omega$)
- **Time-dependent** Schrieffer–Wolff transformation
- Effective model for **large driving amplitude**

✓ **Two-axis control** by tuning the driving phase, and the detuning

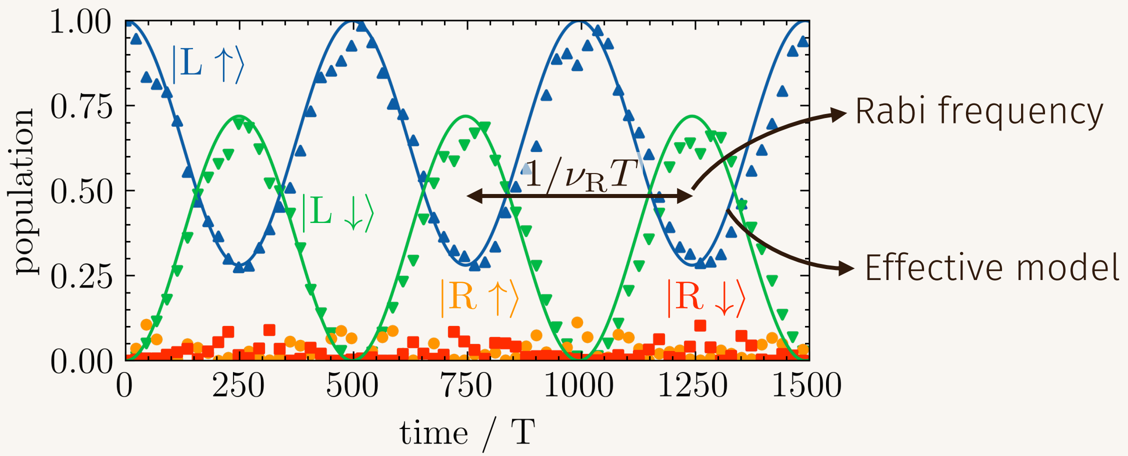
$$\epsilon_{\mathrm{L}}(t) = \epsilon_{\mathrm{ac}} \cos(\omega t + \varphi)$$

$$\epsilon_{\mathrm{R}} = \delta$$

$$\begin{aligned}\hat{H}_n^{(2)}(t) = \frac{\hat{\tau}_z}{2} \Big\{ & -\tilde{\delta}^{(2)} + (E_z + \tilde{b}_z^{(2)} - n\omega)\hat{\sigma}_z \\ & + \tilde{b}_{n,\perp}^{(2)} [\cos(n\varphi)\hat{\sigma}_x + \sin(n\varphi)\hat{\sigma}_y] \Big\}\end{aligned}$$

$$\boxed{\begin{aligned}\tilde{b}_{n,\perp}^{(2)} \equiv & \sum_\nu J_\nu\left(\frac{\epsilon_{\mathrm{ac}}}{\omega}\right) J_{\nu+n}\left(\frac{\epsilon_{\mathrm{ac}}}{\omega}\right)\left(\frac{\tau_0\tau_{\mathrm{sf}}}{\delta - \nu\omega} - \frac{\tau_0\tau_{\mathrm{sf}}}{\delta - E_z - \nu\omega}\right) \\ & - \sum_\nu J_\nu\left(\frac{\epsilon_{\mathrm{ac}}}{\omega}\right) J_{\nu-n}\left(\frac{\epsilon_{\mathrm{ac}}}{\omega}\right)\left(\frac{\tau_0\tau_{\mathrm{sf}}}{\delta - \nu\omega} - \frac{\tau_0\tau_{\mathrm{sf}}}{\delta + E_z - \nu\omega}\right)\end{aligned}}$$

Virtual second-order PAT



Parameters

$\chi = 0.2 \quad E_z = \omega$
$\beta_{\mathrm{SO}} = 0$

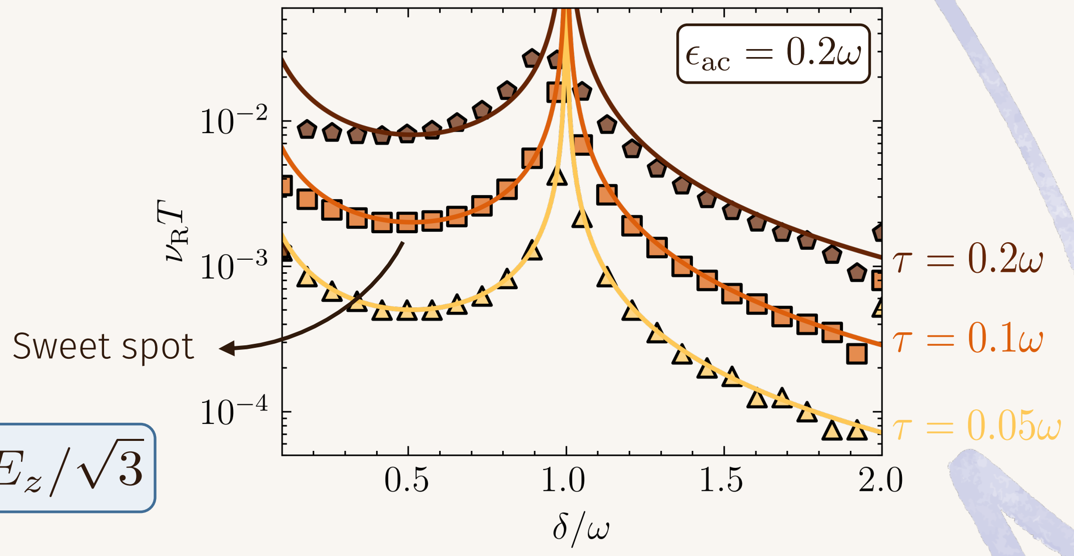
17. Rabi frequency

The Rabi frequency is given by

$$\nu_{\mathrm{R}} = \frac{1}{2\pi}\sqrt{\left(\tilde{b}_z^{(2)}\right)^2 + \left(\tilde{b}_{n,\perp}^{(2)}\right)^2}$$

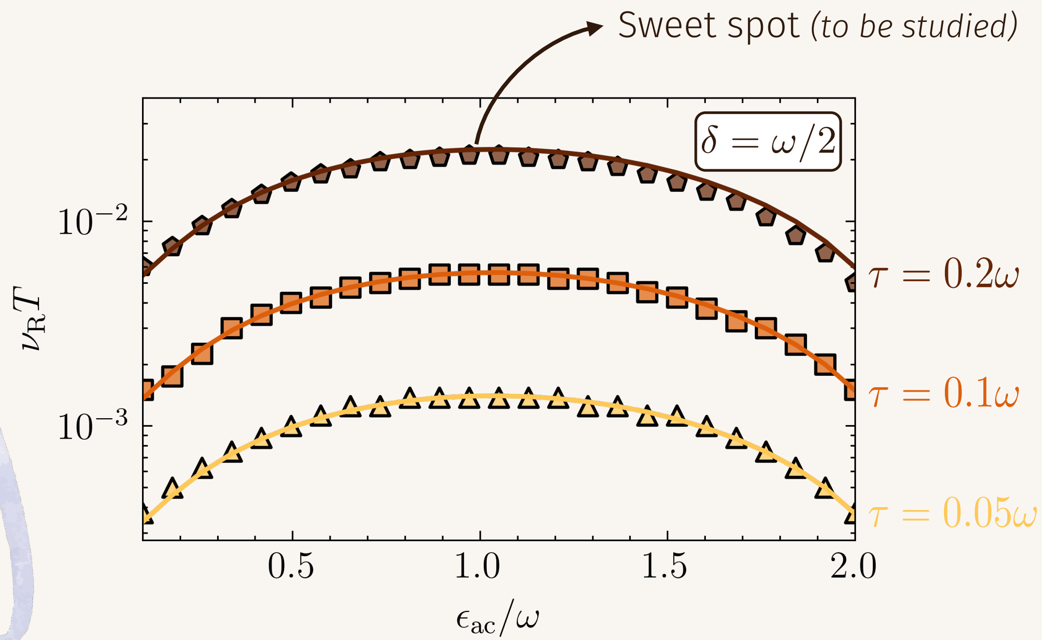
Low amplitude limit

$$\tilde{b}_z^{(2)} = \tau_{\mathrm{sf}}^2 \left(\frac{1}{\delta + E_z} - \frac{1}{\delta - E_z}\right) \qquad \tilde{b}_{1,\perp}^{(2)} = \frac{2\epsilon_{\mathrm{ac}}\tau_0\tau_{\mathrm{sf}}E_z}{\delta\left(\delta^2 - E_z^2\right)}$$



$\boxed{\delta_{\mathrm{sweet}} = \pm E_z/\sqrt{3}}$

High amplitude limit



18. Conclusions

J. Phys. Mater. **6** 034004 (2023)

- Study of a **periodically driven** system with **high SOC**
- **Highly polarizable** spin current

- Creation of **dark states** due to quantum **coherent interferences**
- System as a **flopping-mode** qubit with **sweep-spots**