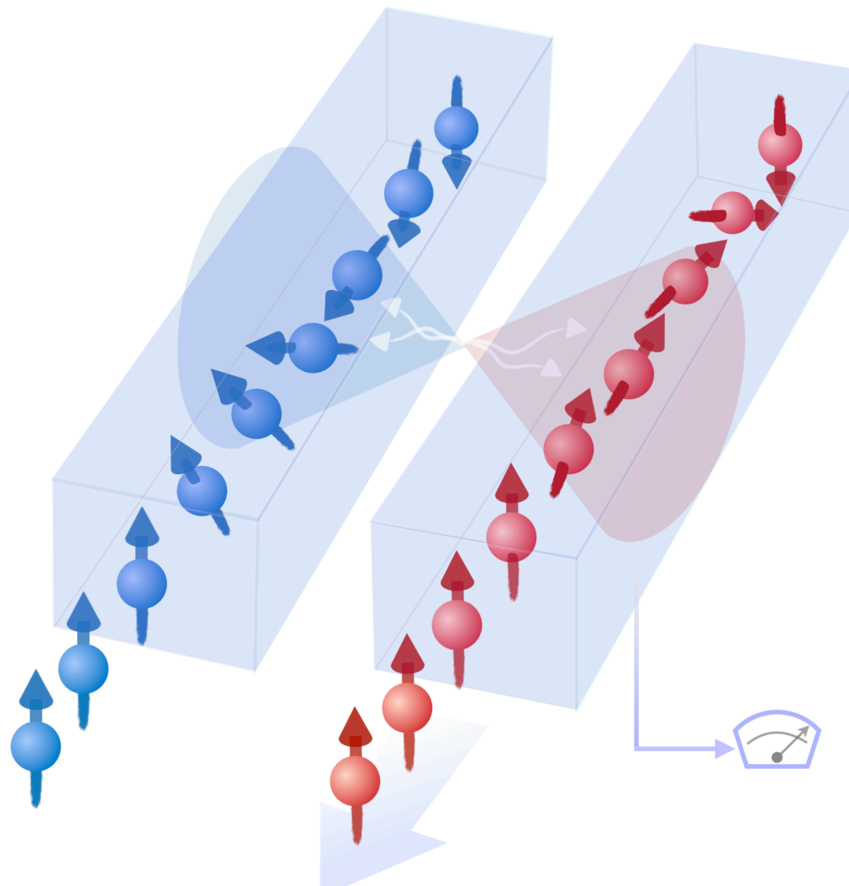
Quantum computing on racetracks with flying domain wall qubits



arXiv:2212.12019

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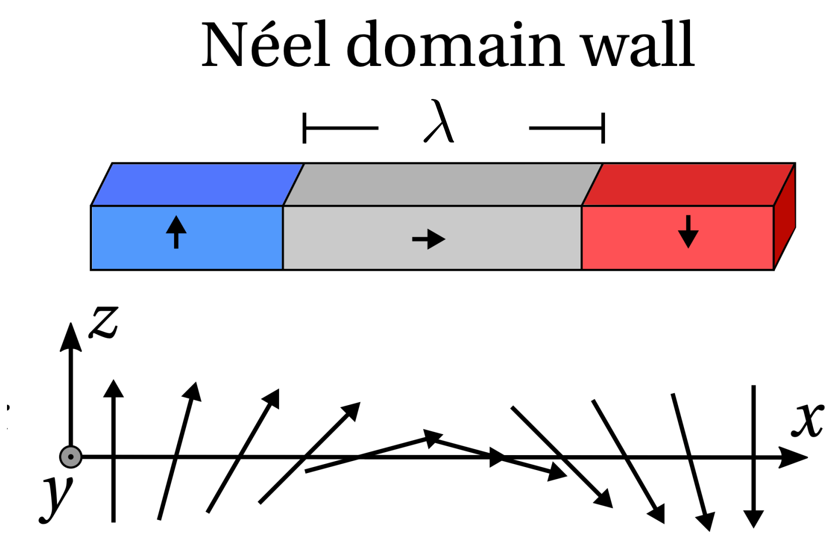
Outline

- Background
- Define the domain wall qubit
- Shuttling the domain wall qubits
- Single- and two-qubit gates
- Qubit readout and lifetime

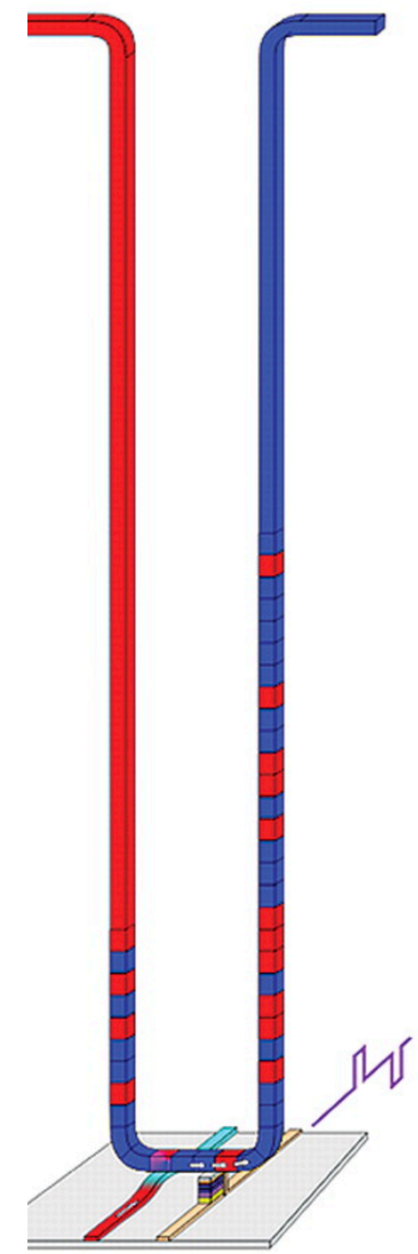
Background

<u>The main role today: domain wall</u>



Parkin et al., Science 320, 190 (2008)

Bits=domains in tracks



racetrack memory

1. one important application (used as classical bits)
2. can be moved by magnetic fields, electric currents
3. Fast speed on antiferro- and ferrimagnetic tracks

$$v > 10^3\,\mathrm{m/s}$$

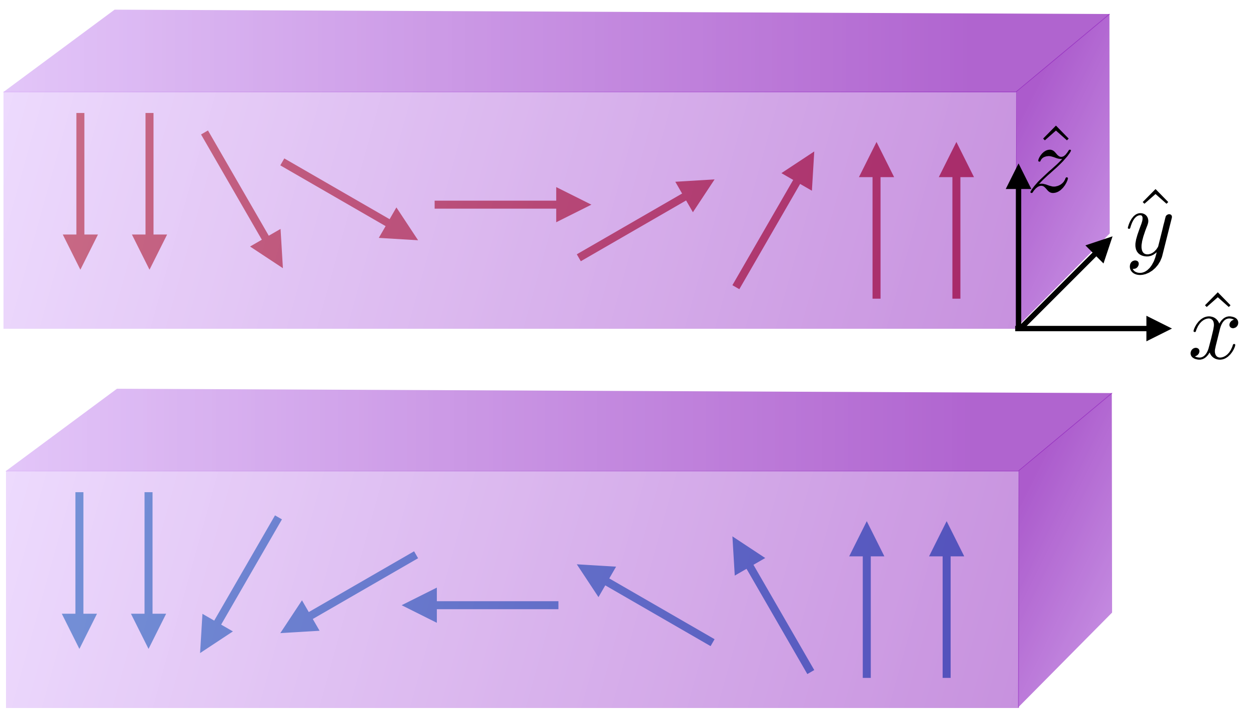
Guan et al., Nature Commun. (2021)

Yang et al., Nature Phys. (2019)

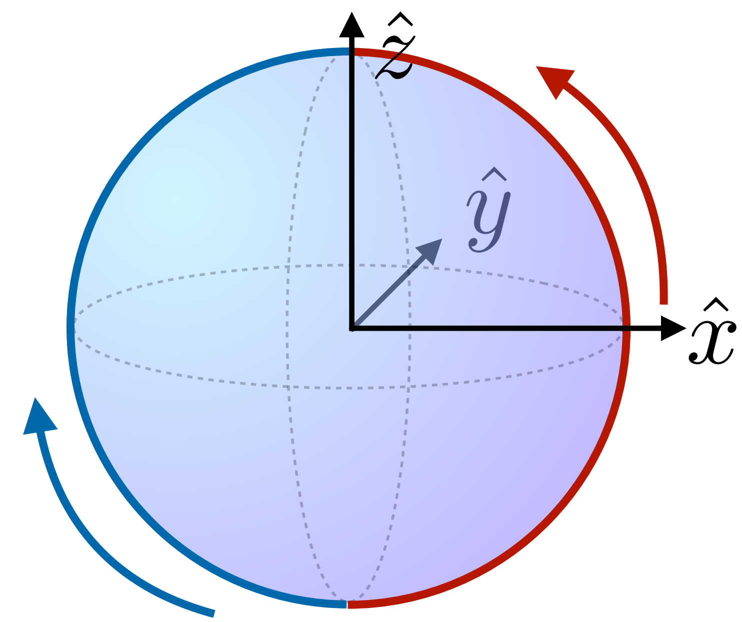
Parkin, Yang, Nature Nano. (2015)

Can we use it as a quantum bit?

Which degree of freedom we want to use to store quantum information?

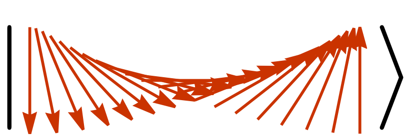


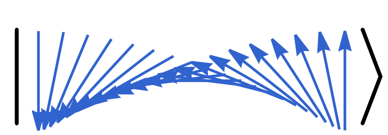
order parameter space



One promising candidate: chirality

pseudo-spin $\quad |\uparrow\rangle = |C = +1\rangle \qquad |\downarrow\rangle = |C = -1\rangle$





DiVincenzo's criteria

From Wikipedia:

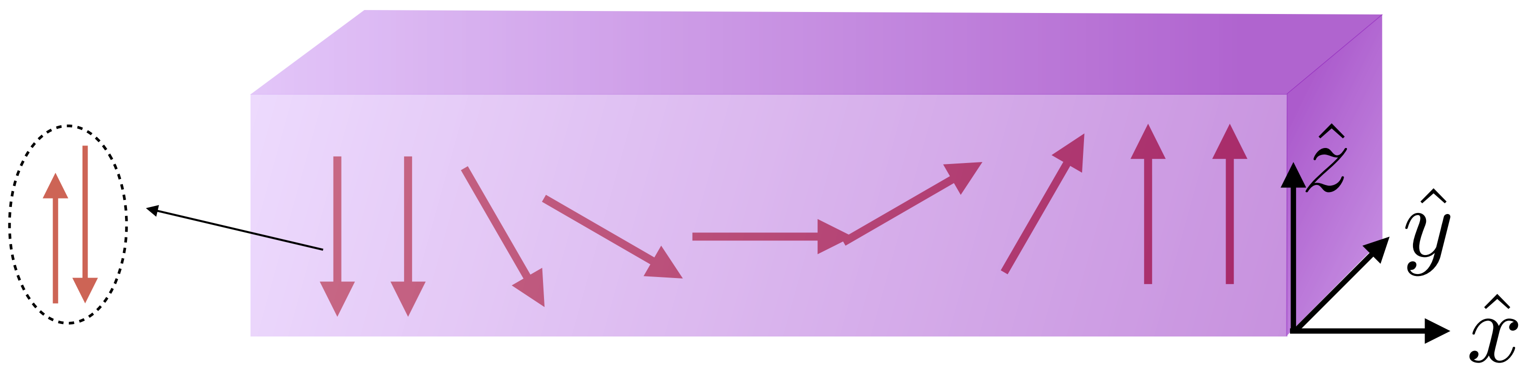
1. A scalable physical system with well-characterized qubit
2. The ability to initialize the state of the qubits to a simple fiducial state
3. Long relevant decoherence times
4. A "universal" set of quantum gates
5. A qubit-specific measurement capability

The remaining two are necessary for quantum communication:

1. The ability to interconvert stationary and flying qubits
2. The ability to faithfully transmit flying qubits between specified locations

Define the computational space

Consider a simple two-sublattice quasi-one-dimensional ferrimagnet:



Dynamics: Antiferromagnetic order + weak ferro order

Néel vector $\mathbf{n}(x,t)$ net spin per site S_e

Low-energy description:

magnetic field

$\nabla_{\mathbf{n}} \times \mathbf{A} = -\mathbf{n}$

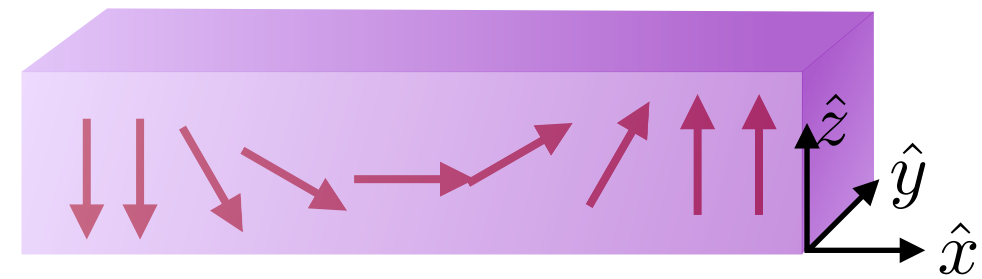
Kinetic energy: $$K[\mathbf{n}(x,t)] = N \int dx \left[\frac{\hbar^2}{8J} (\dot{\mathbf{n}} - \mathbf{h} \times \mathbf{n})^2 + \hbar S_e \dot{\mathbf{n}} \cdot \mathbf{A} \right]$$

antiferro ferro

number of spins within DW

Define the computational space

Low-energy description:



Potential energy: $U[\mathbf{n}(x,t)] = \frac{NK_z}{2}\int dx\,[(\partial_x \mathbf{n})^2 - n_z^2] + N\int dx\,(K_y n_y^2 - \hbar S_e \mathbf{n}\cdot\mathbf{h})$

number of spins within DW

easy-z axis

easy-xz plane

1. rescaled the spatial parameter x: $x \to \lambda x$ $\lambda = Sa\sqrt{J/K_z}$

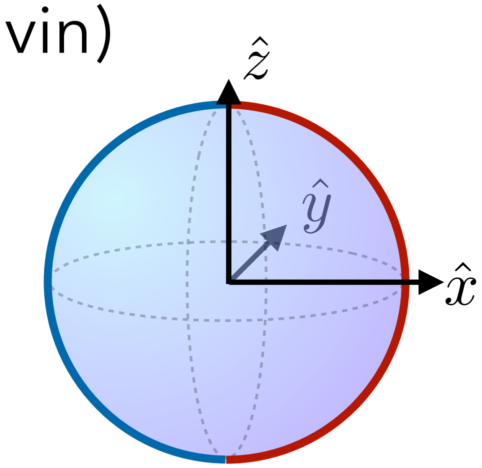
2. hierarchy of energy scales:

$\hbar S_e|\mathbf{h}|, K_y$	K_z	J	energy (Kelvin)
0.1	3	300	

0

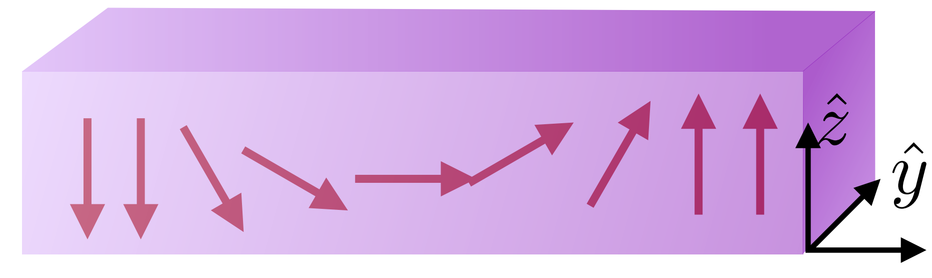
3. domain wall configuration: (two zero modes: X, Φ)

$$n_x + i n_y = e^{i\Phi}\,\mathrm{sech}(x - X), \quad n_z = \tanh(x - X)$$



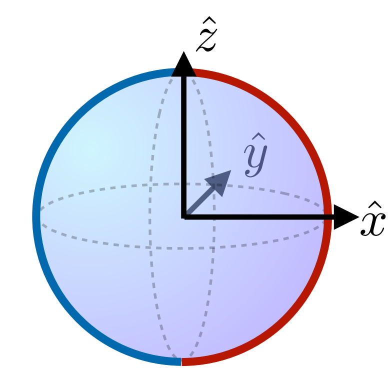
Define the computational space

Low energy dynamics of the domain wall:



$$
\begin{aligned}
L(X,\Phi) =& \frac{M}{2}\dot{\Phi}^2 - N\Big[2K_y \sin^2\Phi + \frac{1}{4J}\big(\hbar h_x \cos\Phi + \hbar h_y \sin\Phi\big)^2 - \pi\hbar S_e (h_x \cos\Phi + h_y \sin\Phi)\Big] && \longrightarrow \text{Lagrangian for } \Phi \\
&+ \frac{M}{2}\dot{X}^2 - \frac{1}{2}M\omega_p^2 X^2 && \longrightarrow \text{Lagrangian for } X \\
&+ \frac{\pi M}{2}(h_x \sin\Phi - h_y \cos\Phi)\dot{X} - 2N\hbar S_e X\dot{\Phi}, && \longrightarrow \text{Couplings between } \Phi \text{ and } X
\end{aligned}
$$

effective mass: $M = N\hbar^2/2J$



The action is proportional to the domain wall size: N

$$L = L_\Phi + \boxed{L_X + L_{\Phi X}}$$

define the qubit

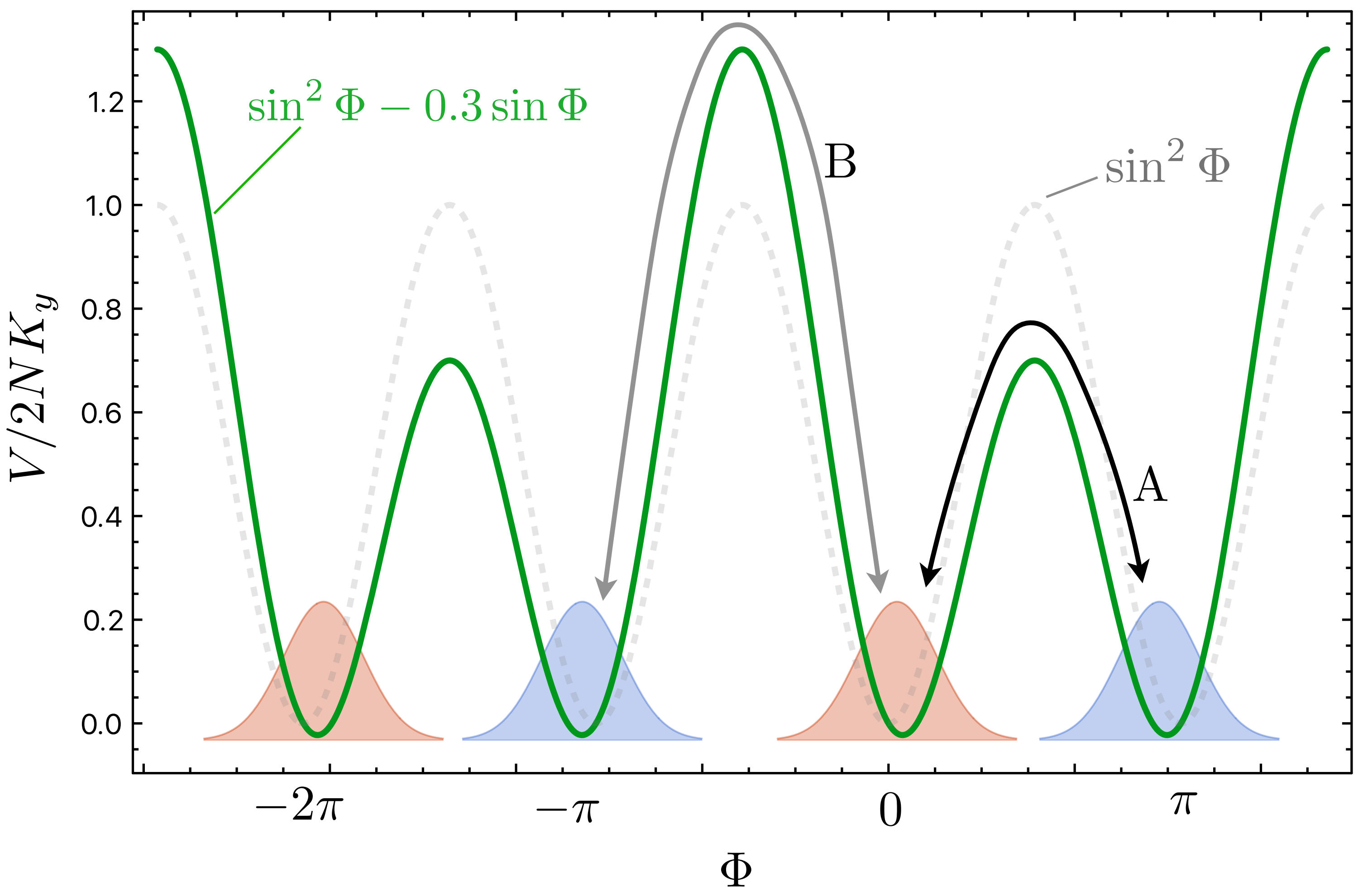
implement single- and two-qubit gates

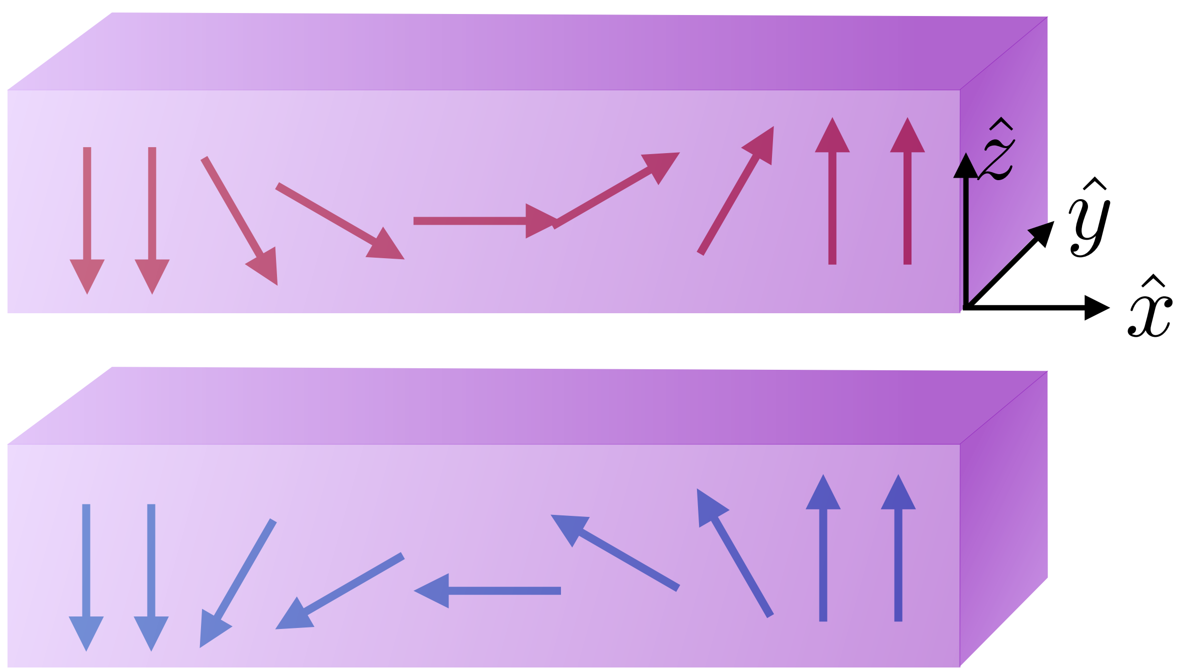
Define the computational space

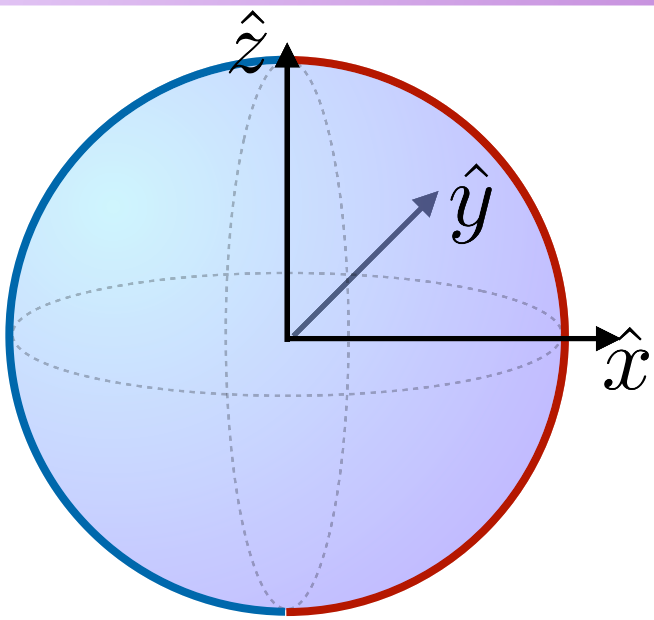
Potential energy: $V(\Phi) = 2NK_y(\sin^2\Phi - 2b_x\cos\Phi - 2b_y\sin\Phi)$

dimensionless magnetic fields: $b_i \equiv \pi\hbar S_e h_i/4K_y$

$b_y = 0.15 \ \ (1\,\mathrm{T}) \qquad b_x = 0$



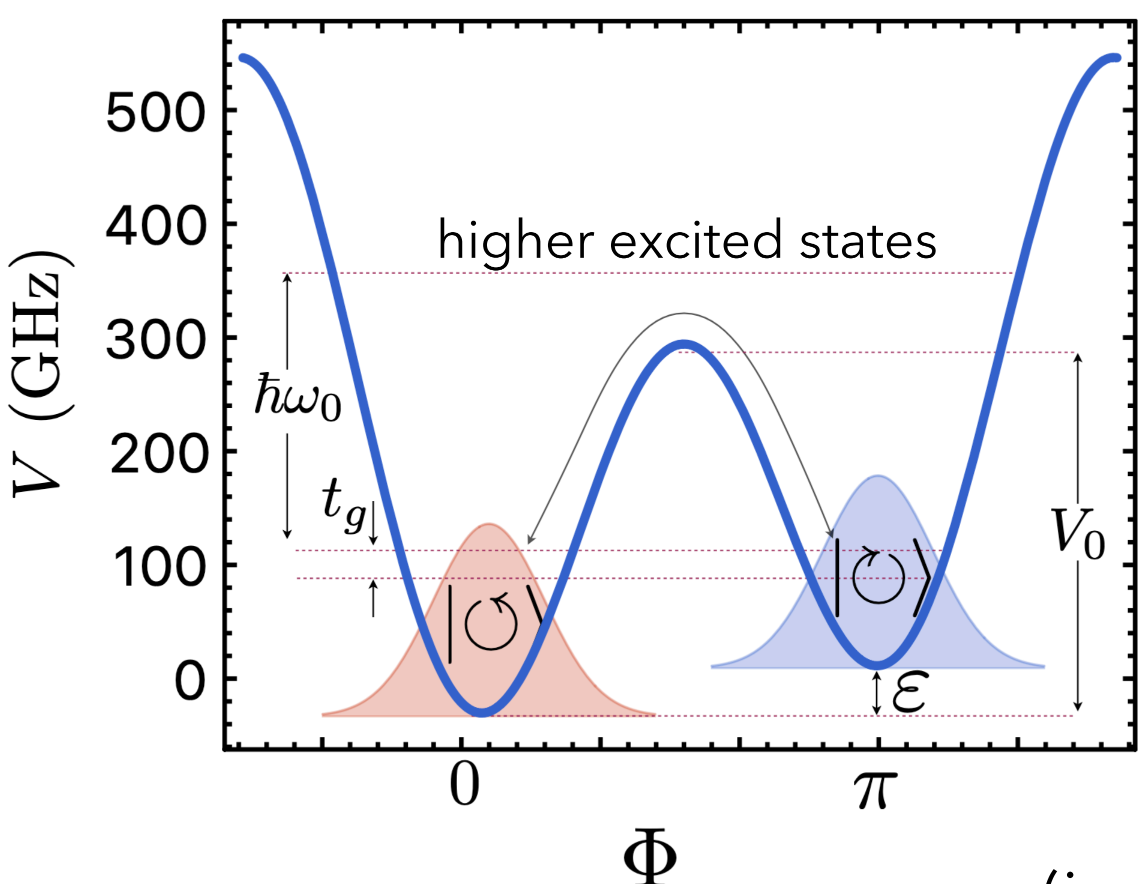


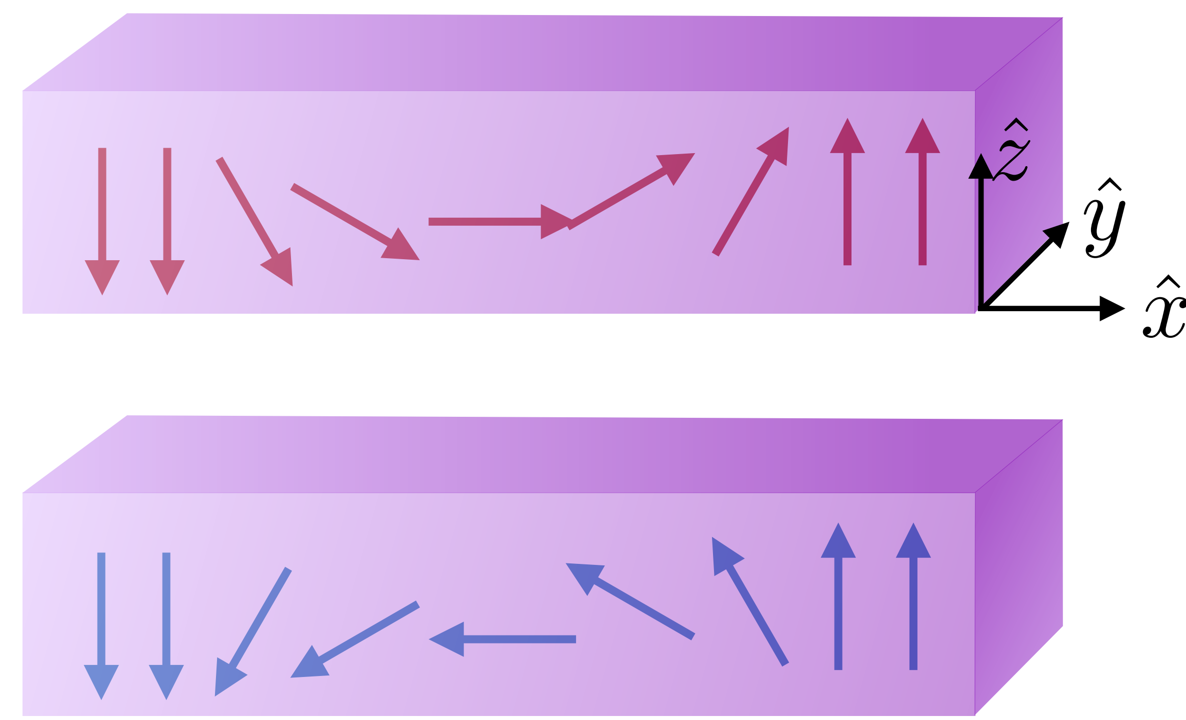


Define the computational space

Potential energy: $V(\Phi) = 2NK_y(\sin^2\Phi - 2b_y \sin\Phi) - 2NK_y \times 2b_x \cos\Phi$

$b_x = 0.02 \ll b_y = 0.15$

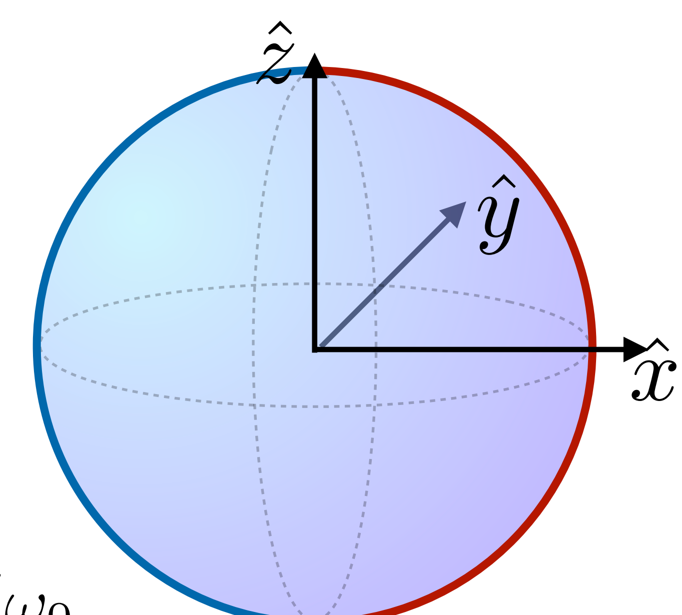




(in chirality basis)

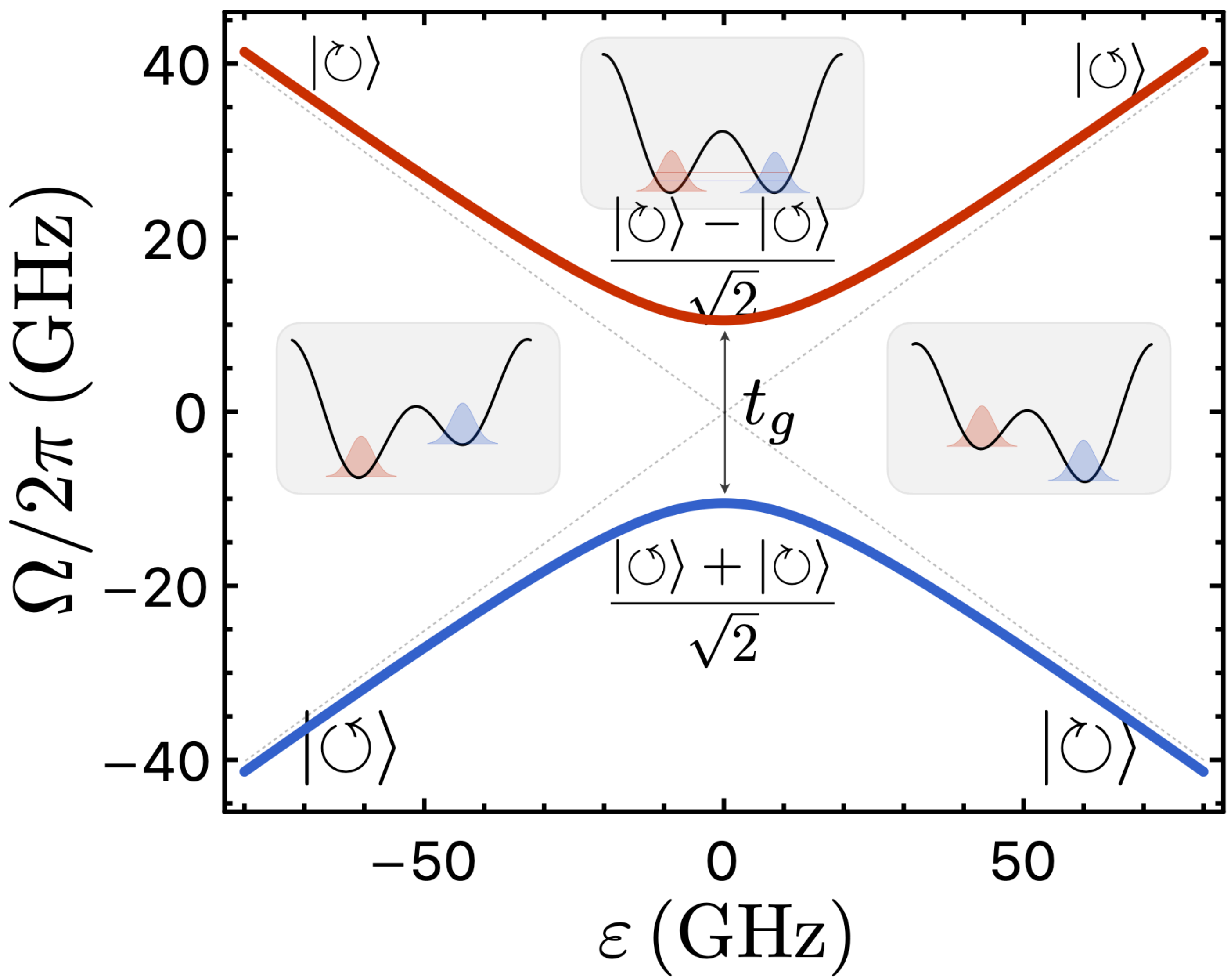
$$H = \frac{\varepsilon}{2}\sigma_z - \frac{t_g}{2}\sigma_x$$

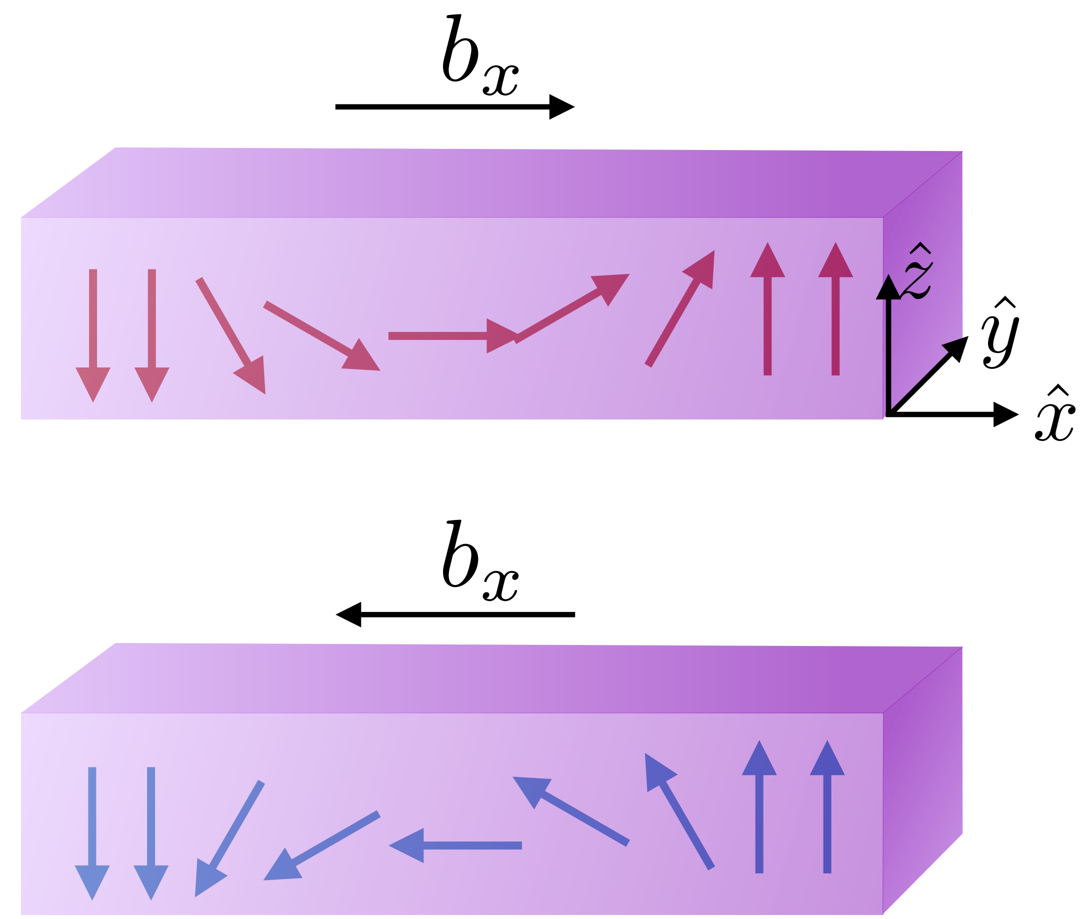
$$\varepsilon = -8NK_y b_x \qquad t_g \approx \hbar\omega_0\sqrt{S_{\mathrm{inst}}/\hbar}\, e^{-S_{\mathrm{inst}}/\hbar}$$



$S_{\mathrm{inst}} \approx 4V_0/\omega_0$

Define the computational space





$$\varepsilon = -8NK_y b_x$$

$$H = \frac{\varepsilon}{2}\sigma_z - \frac{t_g}{2}\sigma_x \qquad \Omega_\pm = \pm\frac{1}{2}\sqrt{t_g^2 + \varepsilon^2} \qquad \text{with} \qquad t_g \approx 20\,\mathrm{GHz}$$

Shuttling domain wall qubits

Project coupled dynamics onto the qubit space:

$$L = L_\Phi + L_X + L_{\Phi X}$$

$$\Big\downarrow\; b_x = 0$$

$$H = \frac{(\hat{P} + \beta_z \sigma_z)^2}{2M} + \frac{M\omega_p^2}{2}\left[\hat{X} - X_0(t)\right]^2 - \frac{t_g}{2}\sigma_x$$

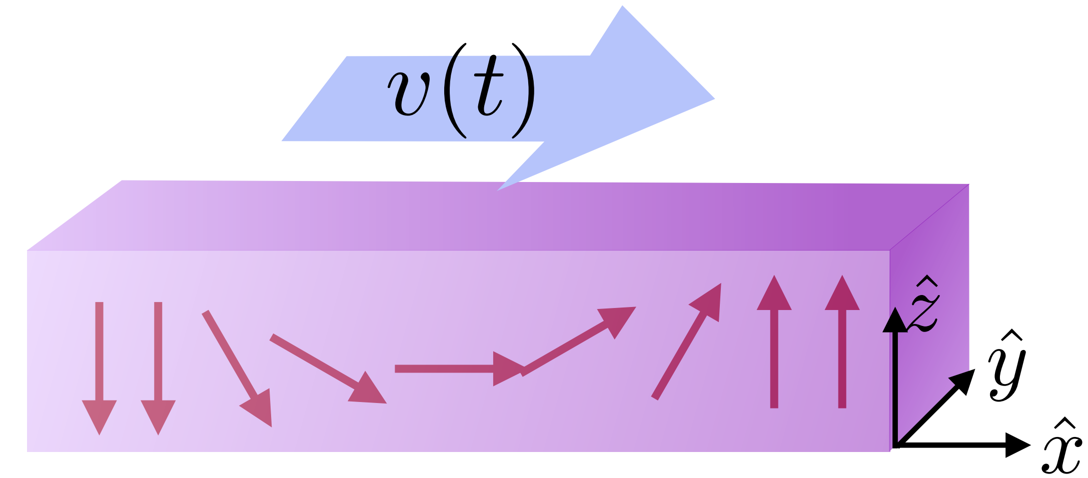
$$\Big\downarrow\; \hat{T} = \exp\left[-i\hat{P}X_0(t)/\hbar\right]$$

$$H_m = \frac{(\hat{P} + \beta_z \sigma_z)^2}{2M} + \frac{M\omega_p^2}{2}\hat{X}^2 - \frac{t_g}{2}\sigma_x - \dot{X}_0(t)\hat{P}$$

$$\Big\downarrow\; \hat{\mathcal{G}} = \exp(-i\hat{X}\sigma_z/l_{\mathrm{so}})$$

$$\mathcal{H}_m = \frac{\tilde{\varepsilon}(t)}{2}\sigma_z - \frac{\tilde{t}_g}{2}\sigma_x$$

Adiabatic condition: $\dot{X}_0(t) < 100\,\mathrm{m/s}$



effective spin-orbital coupling:

$$\beta_z = \pi N \hbar S_e + \pi M h_y/2$$

spin-orbital length:

$$l_{\mathrm{so}} = \hbar/\beta_z \quad \sim 1.5\,\mathrm{nm}$$

harmonic length:

$$l_p = \sqrt{\hbar/M\omega_p} \quad \sim 2.25\,\mathrm{nm}$$

Galilean term: $-i\hbar\hat{T}^\dagger\partial_t\hat{T}$

$$\tilde{\varepsilon}(t) = 2\hbar\dot{X}_0(t)/l_{\mathrm{so}}$$

$$\tilde{t}_g = t_g \exp(-l_p^2/l_{\mathrm{so}}^2) \quad \sim 3\,\mathrm{GHz}$$

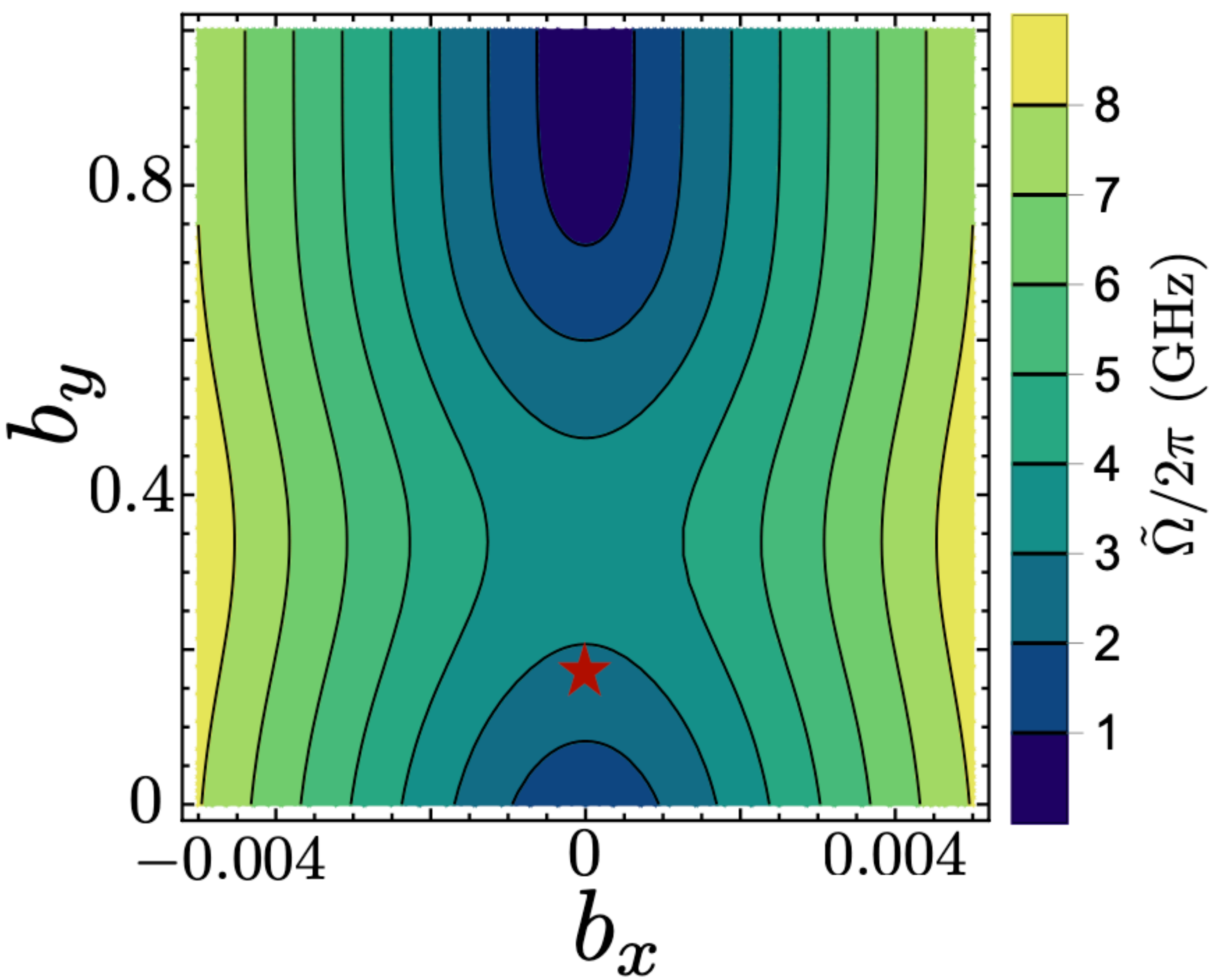
Shuttling domain wall qubits

Physical qubit splitting:

$$\mathcal{H}_m = \frac{\tilde{\varepsilon}(t)}{2}\sigma_z - \frac{\tilde{t}_g}{2}\sigma_x$$

$$\tilde{t}_g = t_g \exp(-l_p^2/l_{\rm so}^2) \qquad \tilde{\varepsilon}(t) = 2\hbar \dot{X}_0(t)/l_{\rm so} - 8NK_y b_x$$

$$\hbar\tilde{\Omega} = \sqrt{\tilde{\varepsilon}^2 + \tilde{t}_g^2}$$



splitting increases first when b_y increases since the barrier is reduced.

splitting decreases when b_y further increases since the the suppression of soc.

Single-qubit gates

Shuttling with constant speed:

$$\mathcal{H}_m = \frac{\tilde{\varepsilon}(t)}{2}\sigma_z - \frac{\tilde{t}_g}{2}\sigma_x$$

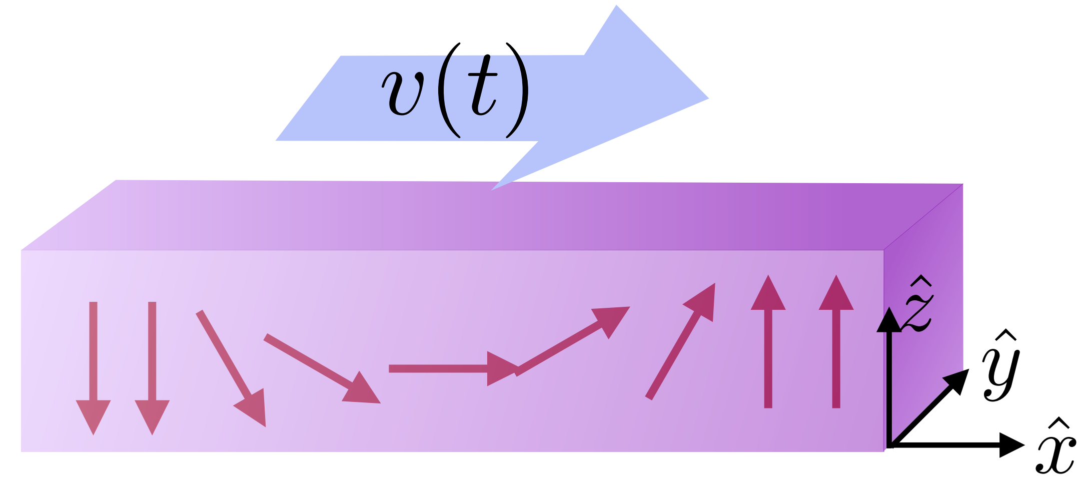
$$\downarrow$$

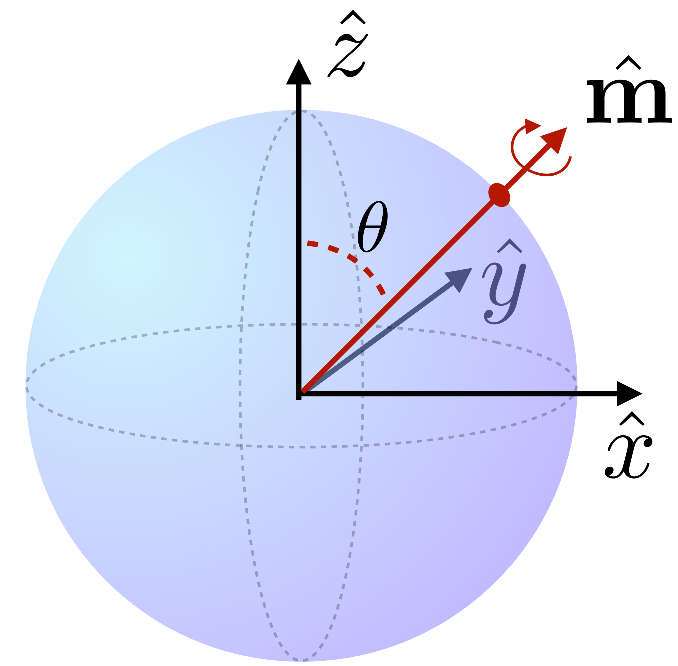
$$U(t) = \exp(-i\tilde{\Omega}t\hat{\mathbf{m}}\cdot\boldsymbol{\sigma}/2)$$

$$\hat{\mathbf{m}} = (\sin\theta, 0, \cos\theta) \quad [\tan\theta = -\tilde{t}_g/\tilde{\varepsilon}]$$

$$\swarrow$$

$$b_y$$





spin rotations around $\hat{\mathbf{m}}$

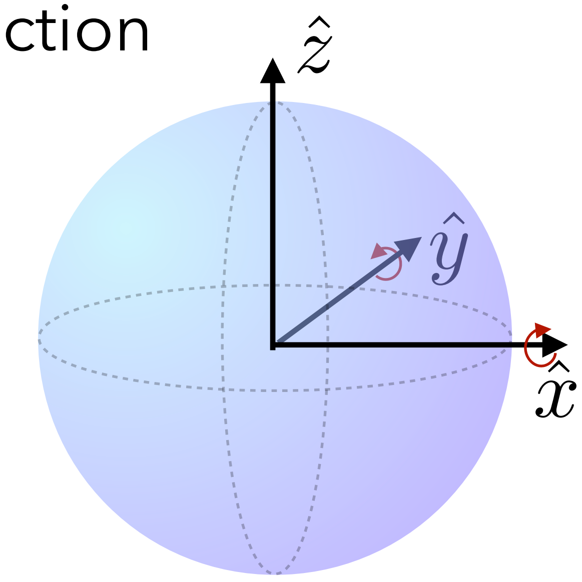
- We can also implement single-qubit gates by shaking the qubit.

Single-qubit gates

Shaking the qubit on the racetrack:

$$\mathcal{H}_m = \frac{\tilde{\varepsilon}(t)}{2}\sigma_z - \frac{\tilde{t}_g}{2}\sigma_x \qquad \tilde{\varepsilon}(t) \propto v(t) = v_0 s(t)\cos(\omega_d t + \phi_0)$$

envelope function



In rotating frame and at resonance: $\omega_d = \tilde{\Omega}$

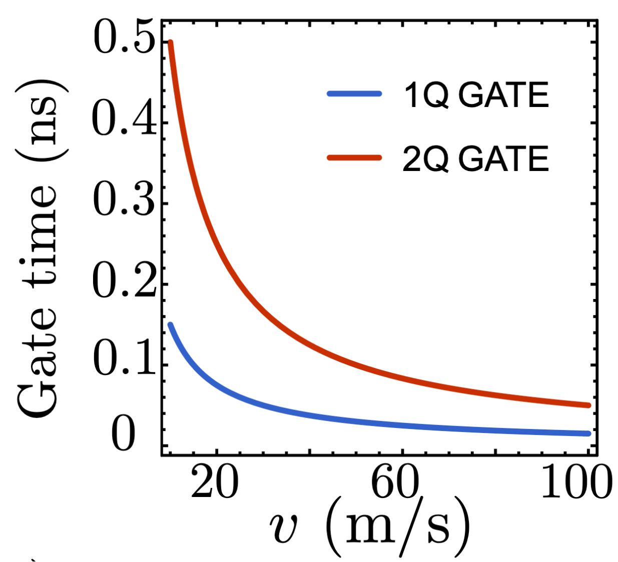
$$\mathcal{H}_r = \frac{\hbar\Omega_R s(t)}{2}(\cos\phi_0\hat{\sigma}_x + \sin\phi_0\hat{\sigma}_y)\,, \quad \Omega_R = v_0/l_{\mathrm{so}}$$

1. In-phase pulse: $\phi_0 = 0$

$$\hat{R}_x^{\phi_0=0} = \exp\left\{-i\Omega_R\int_0^t d\tau\, s(\tau)\frac{\hat{\sigma}_x}{2}\right\}$$

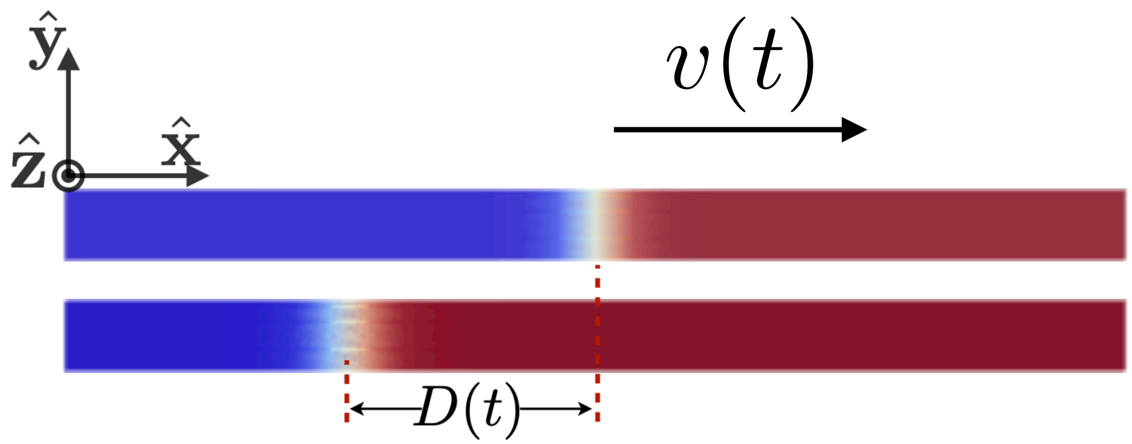
2. out-of-phase pulse: $\phi_0 = \frac{\pi}{2}$

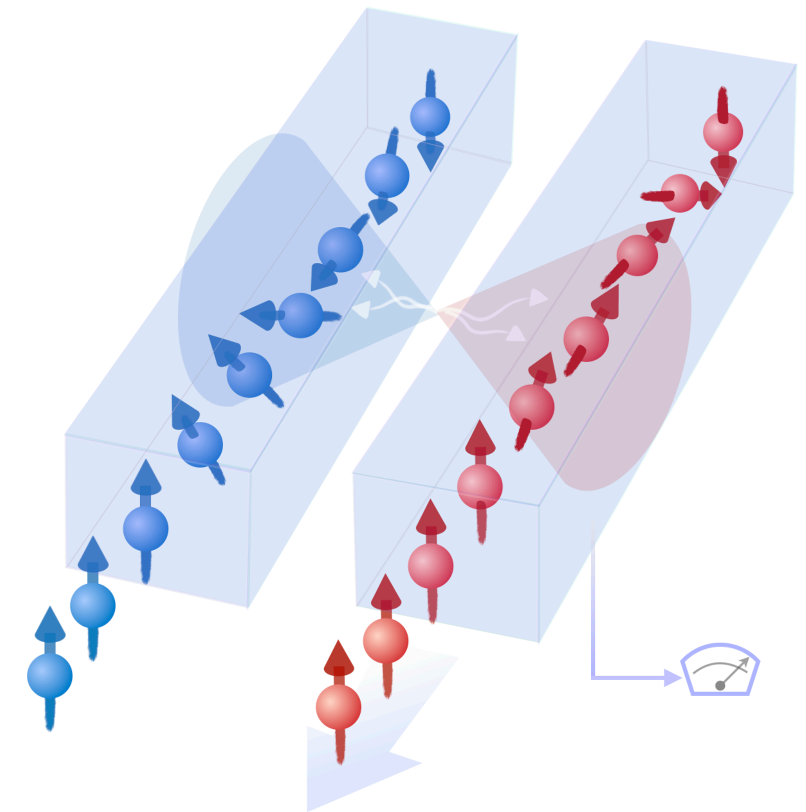
$$\hat{R}_y^{\phi_0=\pi/2} = \exp\left\{-i\Omega_R\int_0^t d\tau\, s(\tau)\frac{\hat{\sigma}_y}{2}\right\}$$



Two-qubit gates

<u>*two domain wall qubits on two racetracks*</u>





$$H^{(2)} = N^2 \mathcal{J}_{\alpha\beta} \int dx\, n_1^{\alpha}(x) n_2^{\beta}(x)$$

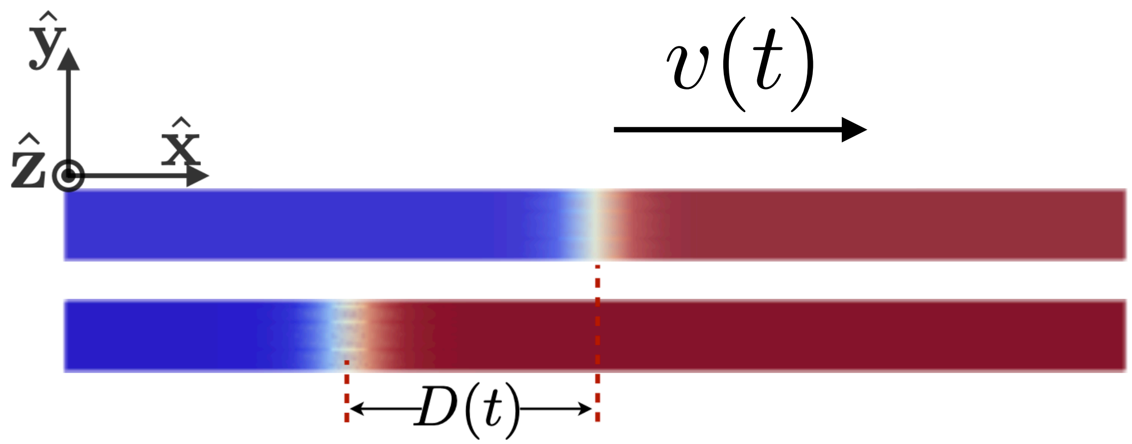
$$\mathbf{n}_1 = \mathbf{n}_0(\Phi_1, X_1) \qquad \mathbf{n}_2 = \mathbf{n}_0(\Phi_2, X_2 = X_1 + D)$$

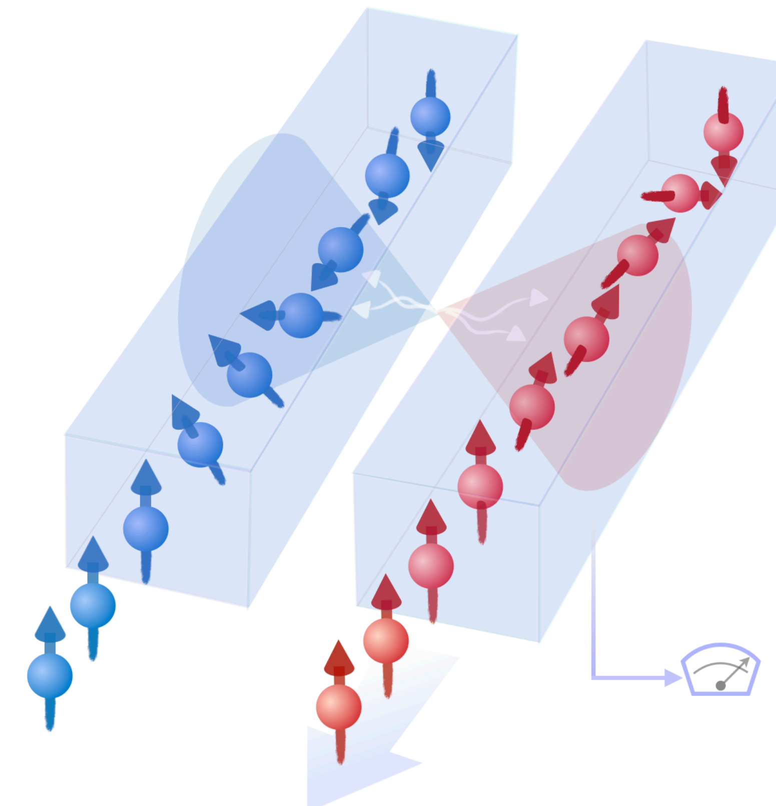
$$\mathcal{H}^{(2)} = \frac{2N^2 \mathcal{J}_{xx} D}{\sinh D} \hat{\sigma}_1^x \hat{\sigma}_2^x$$

interactions decreases exponentially when two DWs are far away

Two-qubit gates

two domain wall qubits on two racetracks





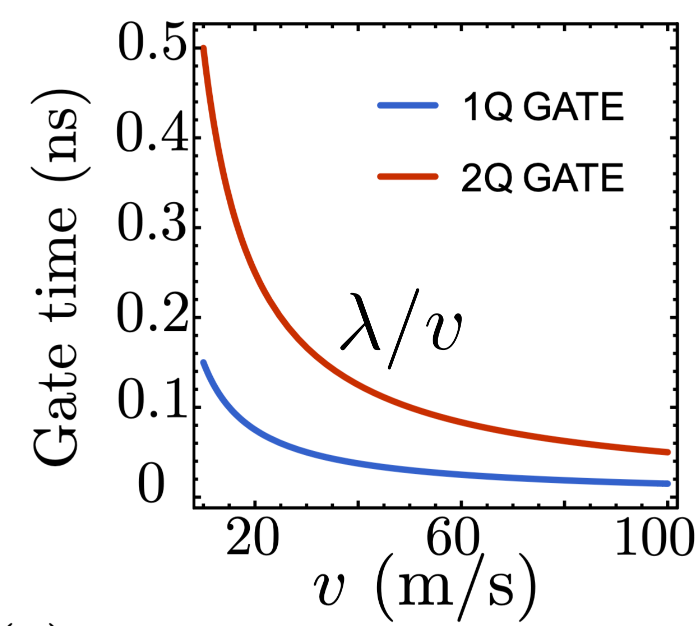
$$\mathcal{H}^{(2)} = \frac{2N^2 \mathcal{J}_{xx} D}{\sinh D} \hat{\sigma}_1^x \hat{\sigma}_2^x$$

$$\Big\downarrow \; v(t) = v$$

$\pi/4$ CNOT gate

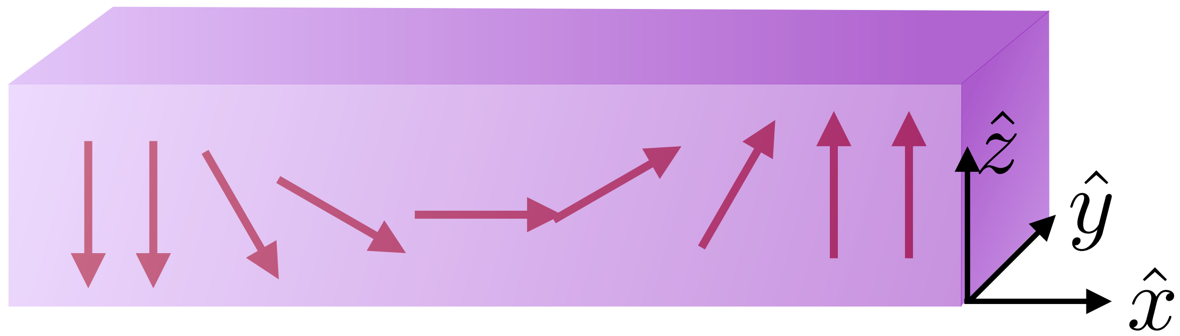
$$\hat{\mathcal{U}}^{(2)} = \exp\left\{ - \frac{i\pi^2 N^2 \mathcal{J}_{xx}}{\hbar v} \hat{\sigma}_1^x \otimes \hat{\sigma}_2^x \right\}$$

$N^2 \mathcal{J}_{xx} \sim 50\,\mathrm{MHz}$ $\quad v = 20\,\mathrm{m/s}$ $\quad T_G \approx 0.2\,\mathrm{ns}$



Qubit lifetime

1. Both Φ and X would fluctuate due to random kicks from the environment



2. Fluctuations in the potential:

$$U(\Phi, X) \to U(\Phi, X) + \xi(t)\Phi + \xi(t)X$$

$$\langle \xi(t) \rangle = 0, \langle \xi(t)\xi(t') \rangle = S(t-t')$$

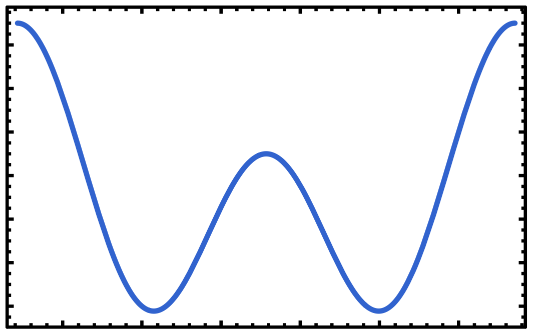
$$S_\xi(\omega) = \tilde{\alpha}\hbar\omega \coth \frac{\hbar\omega}{2k_B T}$$

$$\tilde{\alpha} = \alpha N \hbar S$$

Gilbert damping

3. Fluctuating terms in the qubit Hamiltonian:

$$\delta\mathcal{H}_m = \frac{\xi(t)}{2}\sigma_z + \partial_{V_0}\tilde{t}_g \frac{\xi(t)}{2}\sigma_x + \frac{l_p^2 \dot{\xi}(t)}{\omega_p l_{\text{so}}}\sigma_z$$

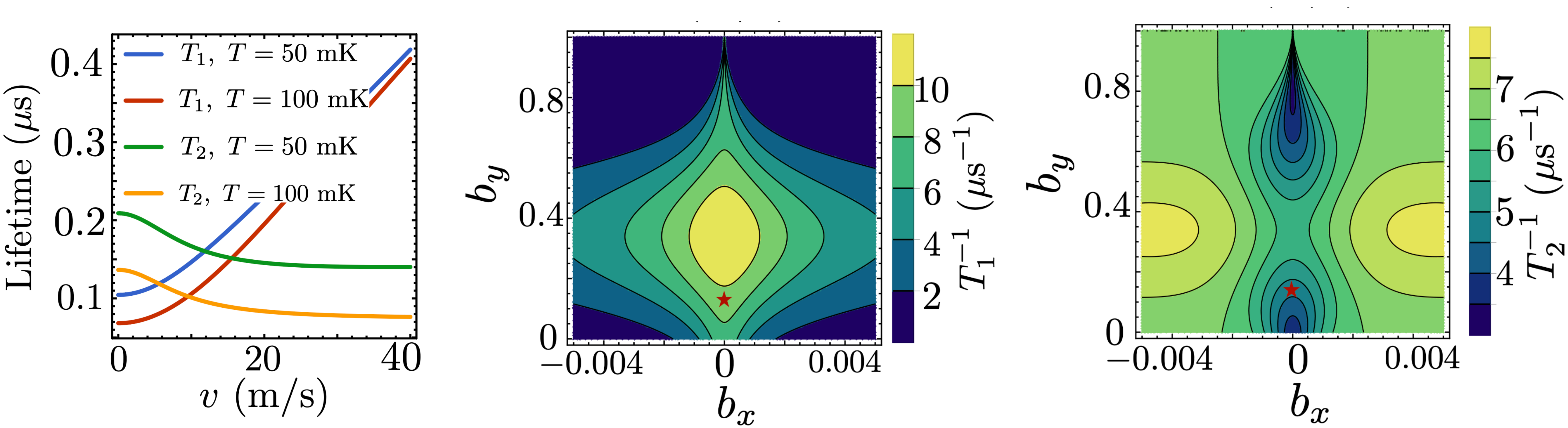


Qubit lifetime

Relaxation rate: $\Gamma_1 = T_1^{-1} = \frac{\sin^2\theta S_\xi(\tilde{\Omega})}{2\hbar^2}\left(1 + \frac{4 l_p^4 \tilde{\Omega}^2}{\omega_p^2 l_{\rm so}^2}\right)$ $\qquad \cos\theta = \frac{\tilde{\varepsilon}}{\sqrt{\tilde{\varepsilon}^2 + \tilde{t}_g^2}}$

Dephasing rate: $\Gamma_2 = T_2^{-1} = \frac{\Gamma_1}{2} + \Gamma_\varphi$ with $\Gamma_\varphi = \frac{\cos^2\theta S_\xi(0)}{2\hbar^2}$ $\qquad b_x = \hbar v/(l_{\rm so} N K_y)$

sweet spot

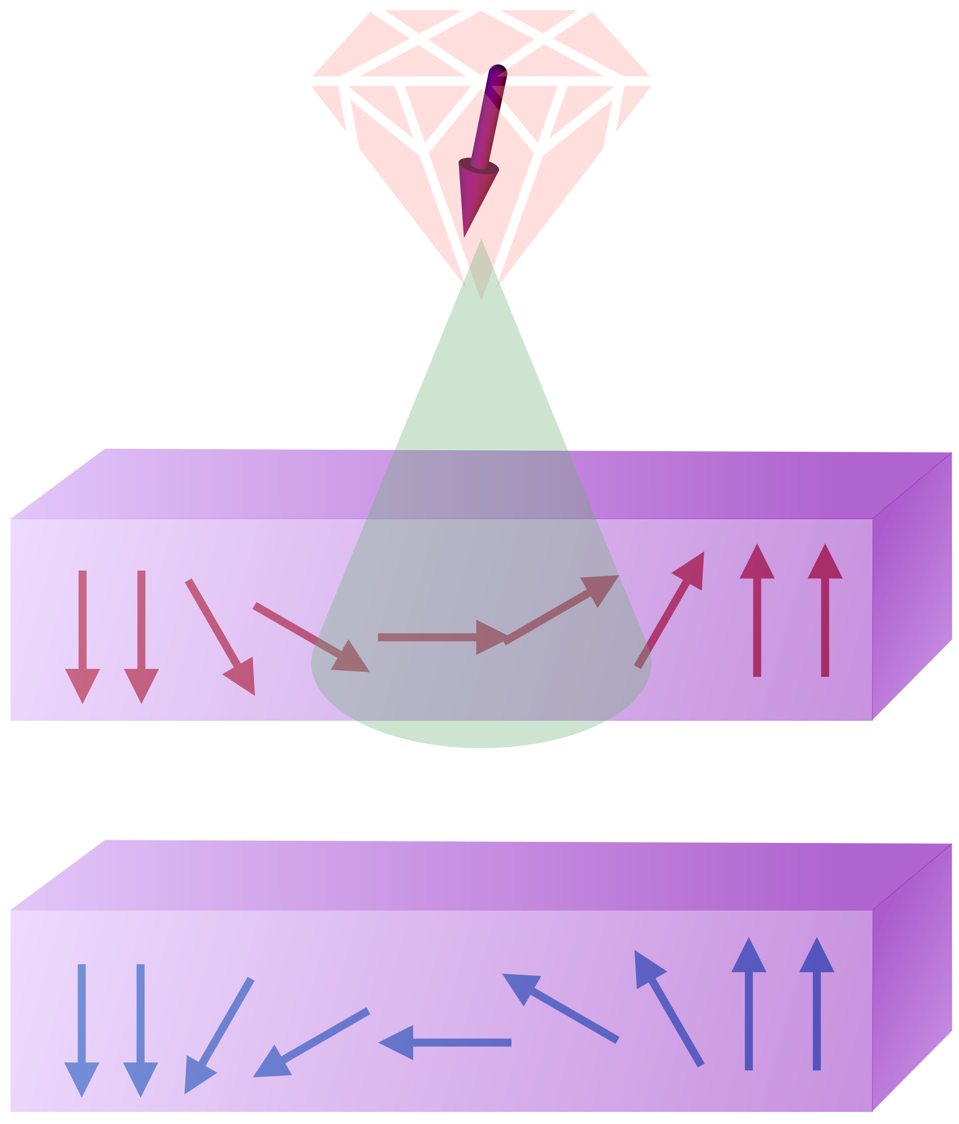


$v = 20\,\mathrm{m/s}$ $\quad T = 50\,\mathrm{mK}$: $\qquad T_1 = 0.23\,\mu\mathrm{s} \qquad T_2 = 0.15\,\mu\mathrm{s}$

Coherent shuttling distance: $3\,\mu\mathrm{m}$ $\qquad$ Quality factor: $\Omega_R T_2 \sim 10^3$

Qubit readout

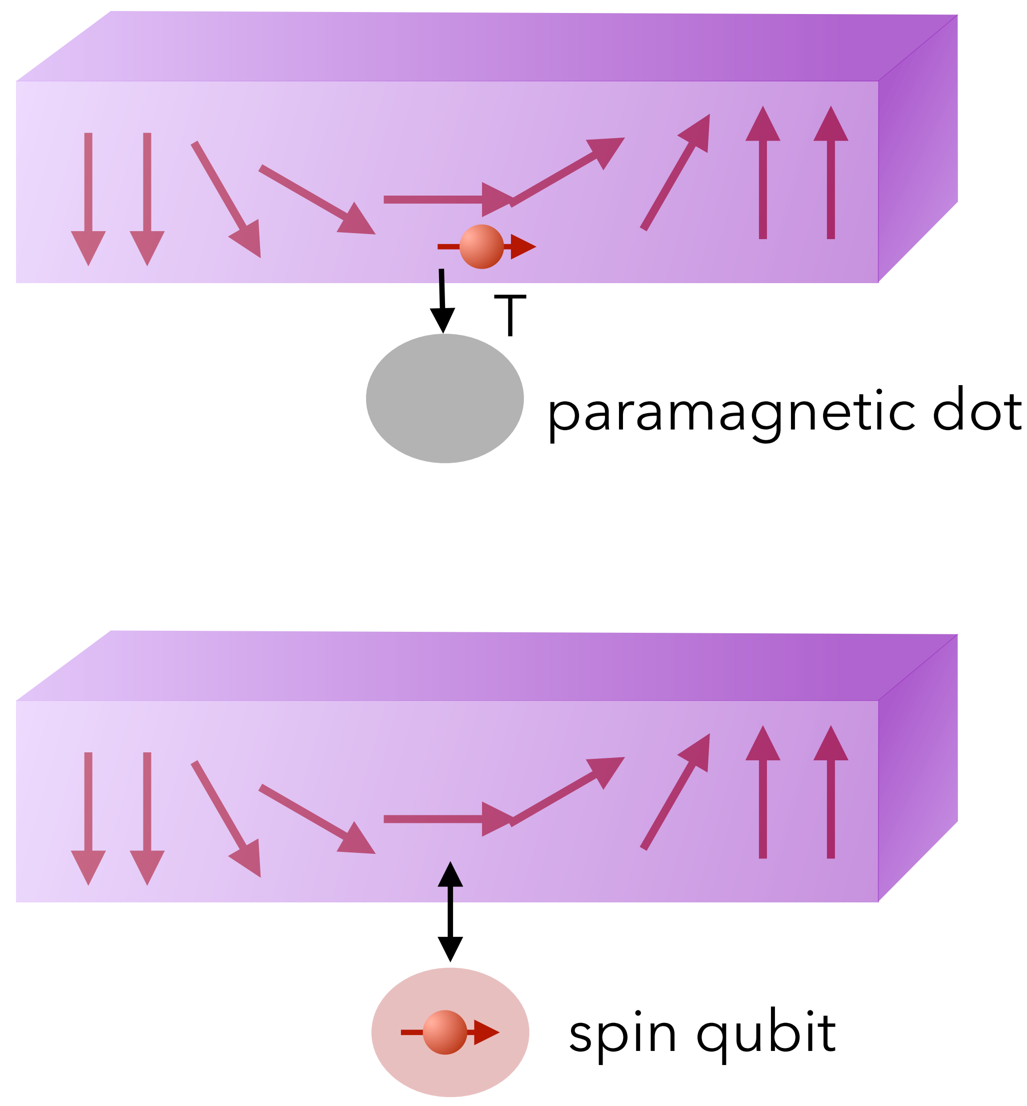
use NV center to image the texture



Song, et al., Science 374, 1140 (2021)

Finco, et al., Nature Com. 12, 767 (2021)

use readout for spin qubits



Elzerman, et al., Nature 430, 431 (2004)

Pla, et al., Nature 496, 334 (2013)

What we have achieved

Our setup is perfect for both quantum computation and communication

1. A scalable physical system with well-characterized qubit
2. The ability to initialize the state of the qubits to a simple fiducial state
3. Long relevant decoherence times
4. A "universal" set of quantum gates
5. A qubit-specific measurement capability

The remaining two are necessary for quantum communication:

1. The ability to interconvert stationary and flying qubits
2. The ability to faithfully transmit flying qubits between specified locations

Thank you !

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