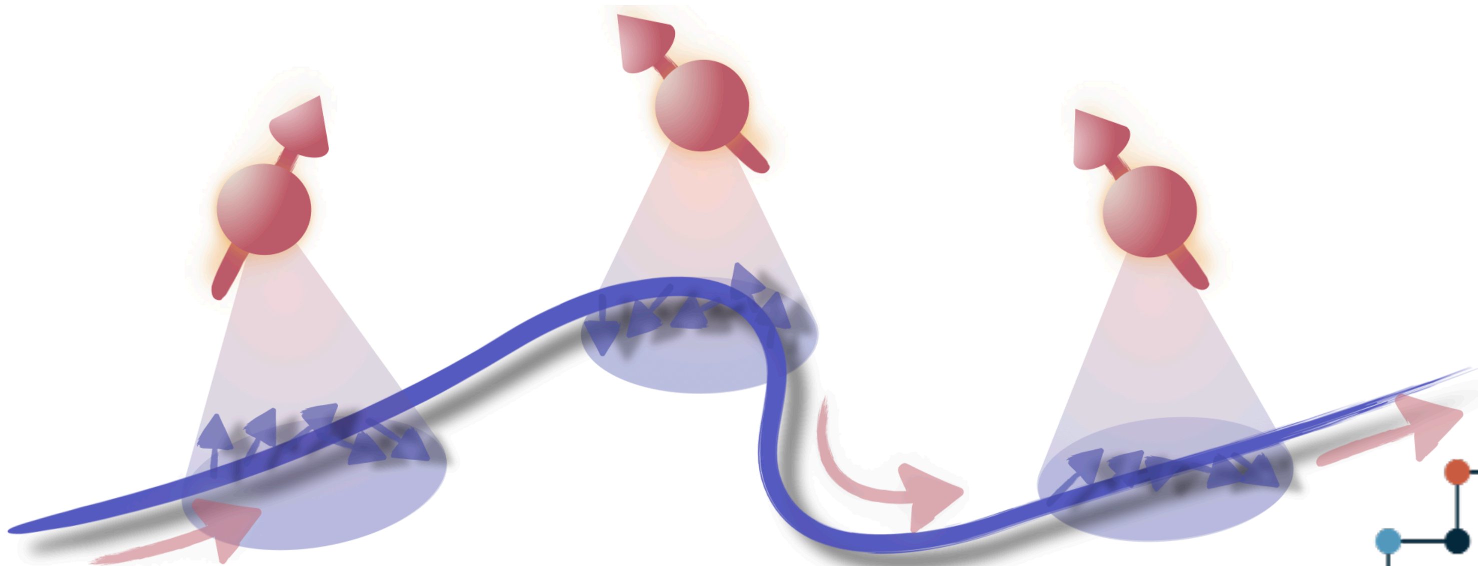
Quantum computing and transmission with mobile *domain wall textures* on racetracks



GEORG H. ENDRESS STIFTUNG

Swiss National Science Foundation

Ji Zou (U of Basel)

J. Zou, et al., Phys. Rev. Research 5, 033166 (2023)

J. Zou, et al., arXiv:2409.14373 (2024)

G. Qu, J. Zou, et al., arXiv:2412.11585 (2024)

University of Basel

NCCR SPIN

Collaborators

Basel:

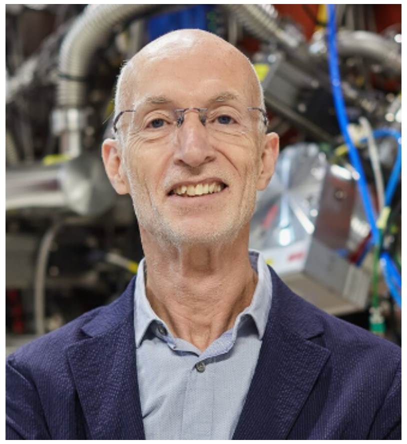
Daniel Loss

Jelena Klinovaja

Stefano Bosco

(Basel->TU Delft)

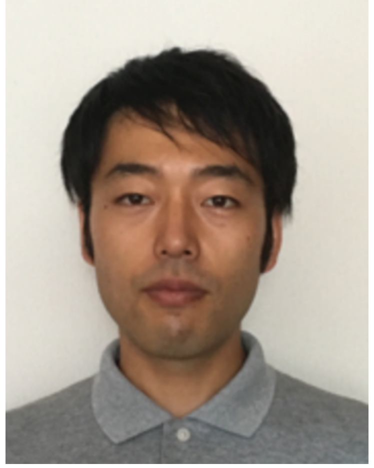
Germany:



Stuart Parkin

Banabir Pal

Japan:



Tomoki Hirosawa

(Aoyama Gakuin University)

Guanxiong Qu

(Riken)

Brief outline

Part I: Quantum Computation with mobile DW qubits

- Background
- Define domain wall (DW) qubit
- DMRG for DW qubit on quantum spin-1/2 chain

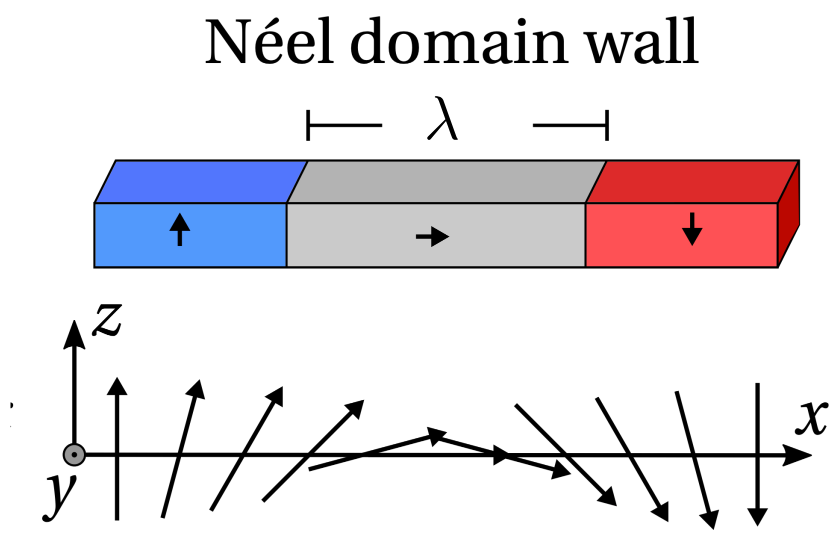
Part II: Quantum information transmission with DW qubits

- Remote entanglement protocol
- Long-distance state transfer and quantum gates
- Summary

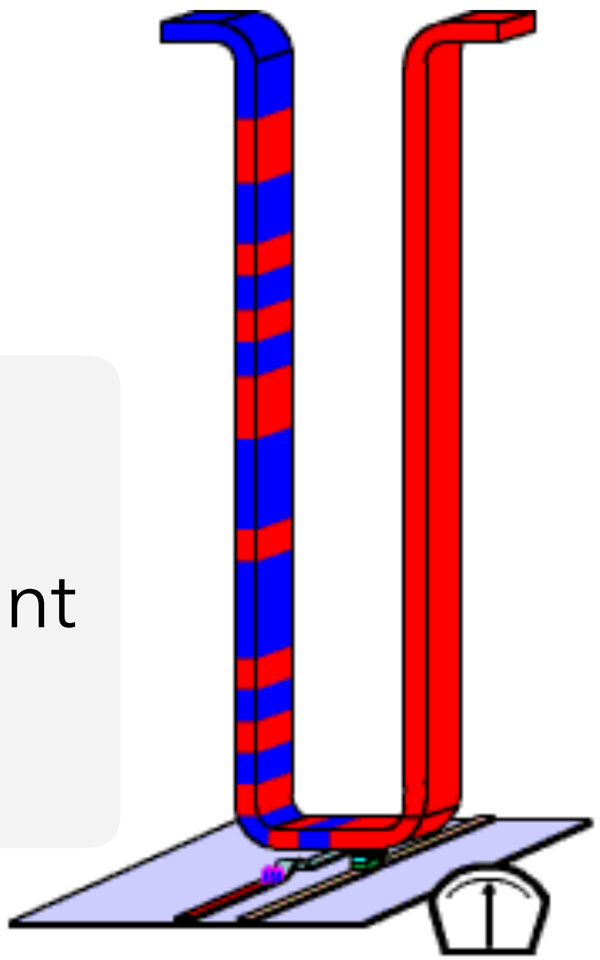
Topological Solitons in Magnetism

Domain wall in magnetic nanowire:

"Topology in Magnetism," edited by J. Zang, V. Cros, A. Hoffmann.



Bits=domains in tracks



racetrack memory

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

1. Important application: classical bits

2. Controllable motion: magnetic field, electric current

3. Fast speed on racetrack: $v > 10^3\ \mathrm{m/s}$

Guan, et al., Nature Commun. (2021)

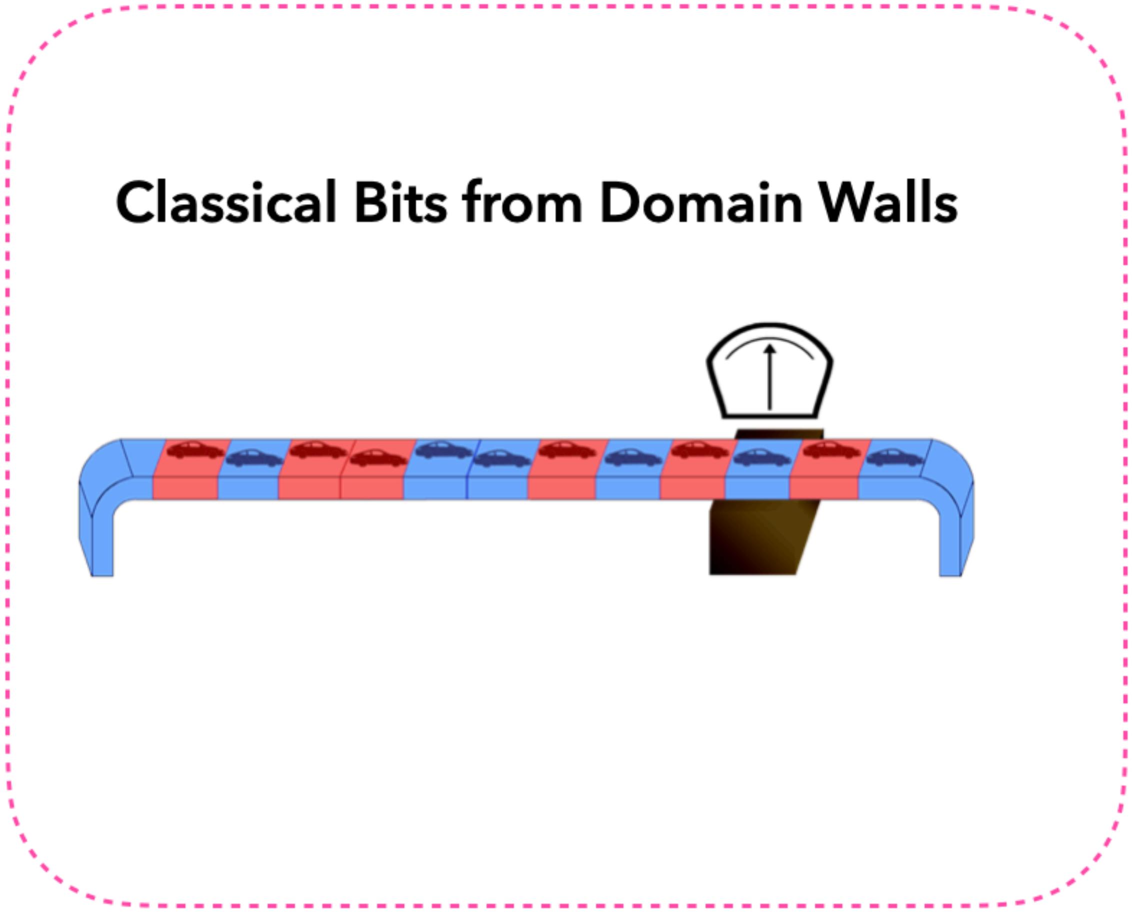
Luo, Hrabec, et al., Nature (2020)

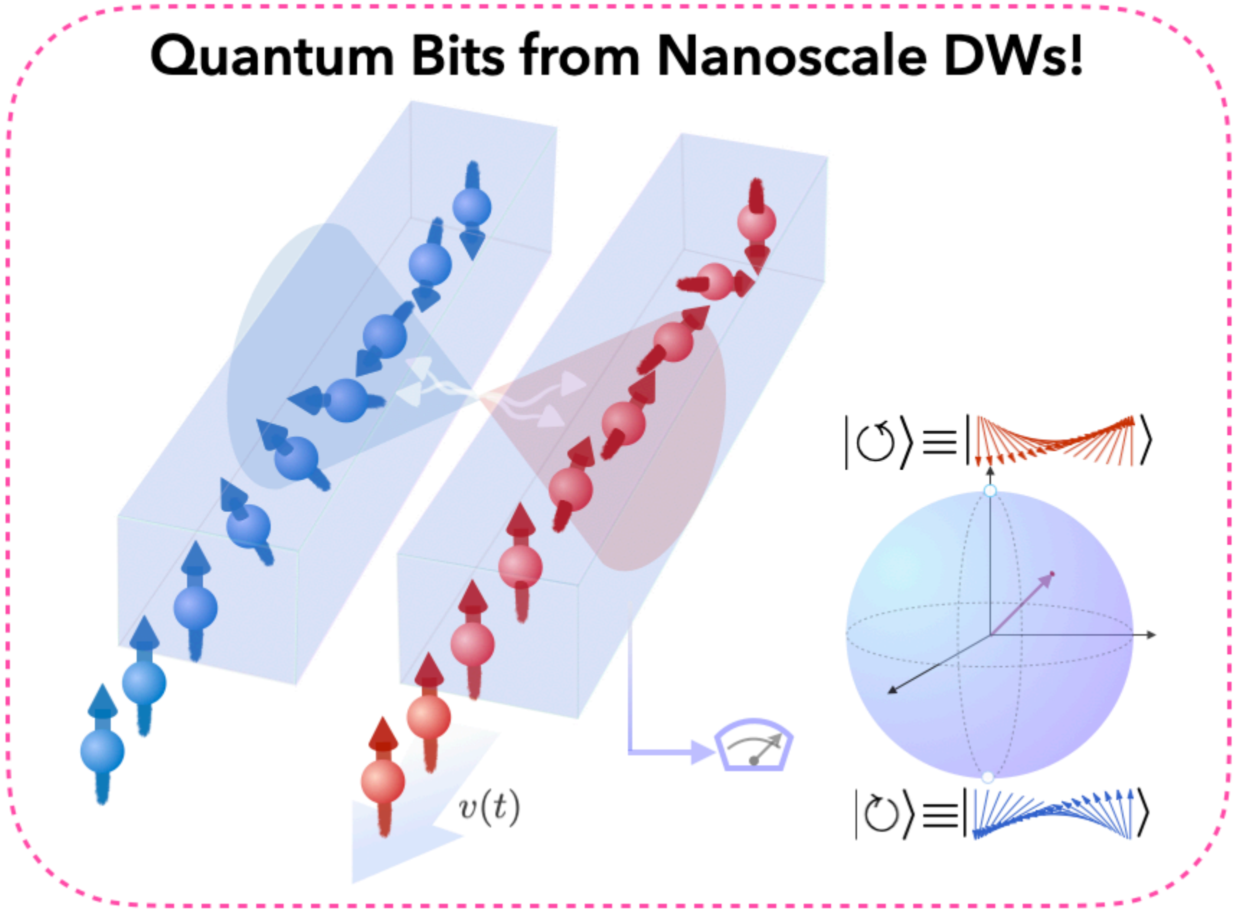
Parkin, Yang, Nature Nano. (2015)

A. Chanthbouala, et al., Nature Physics (2011)

Go beyond the nice picture?

Promote DWs from classical bits to quantum mobile bits!





how to encode information?

how to operate them?

what are the advantages?

...

H. Braun, D. Loss, PRB(1996)

C. Psaroudaki,et al., PRX (2017)

S. Takei, M. Mohseni PRB(2018)

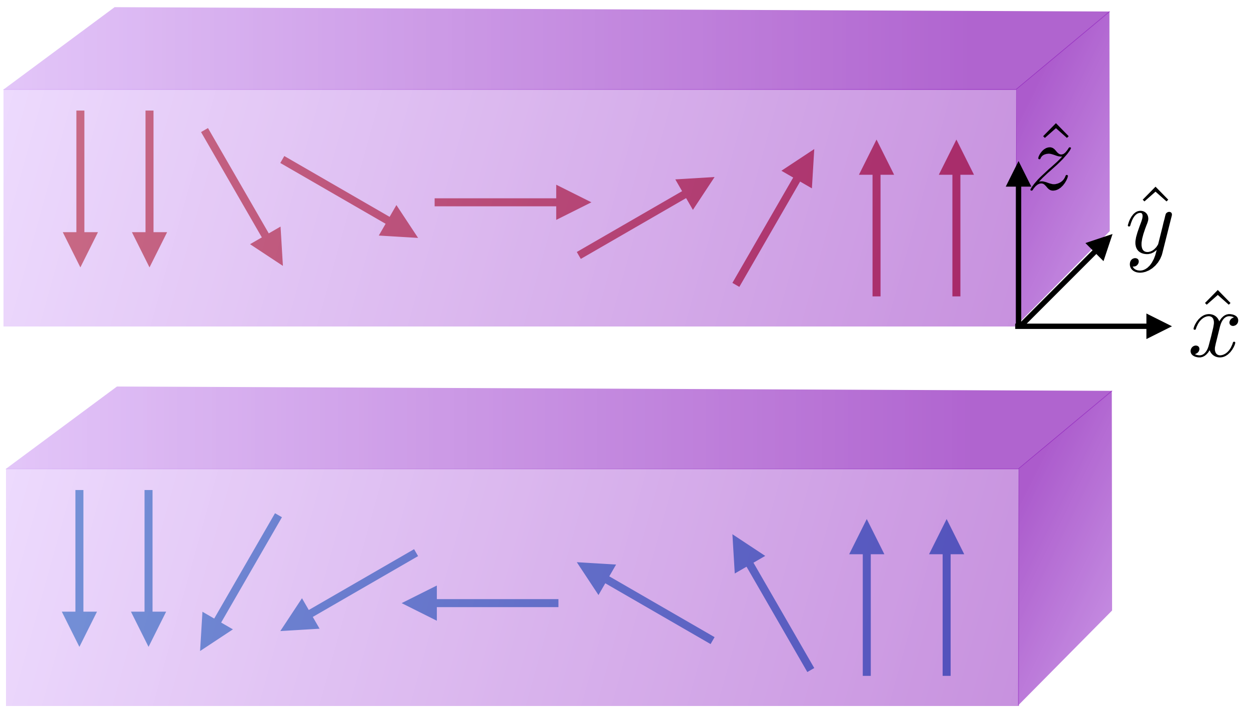
C. Psaroudaki, C. Panagopoulos, PRL(2021)

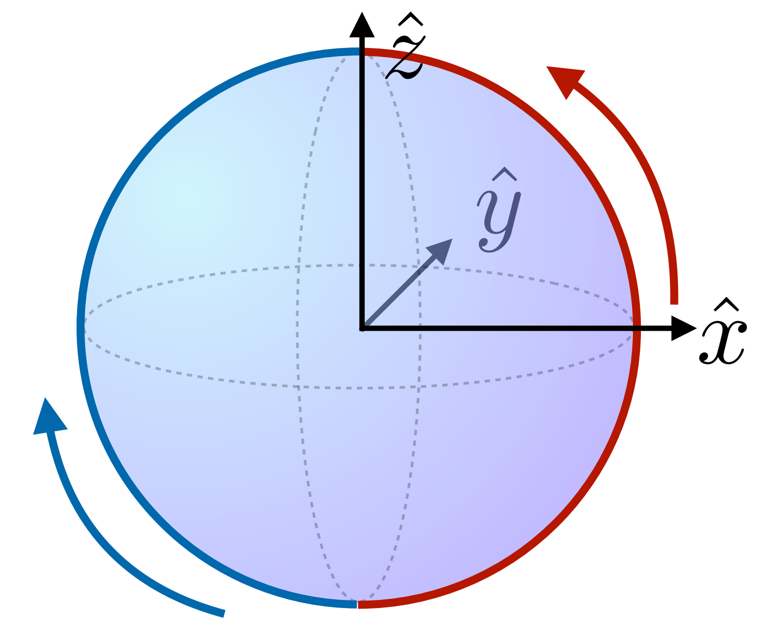
S. Sorn, J. Schmalian, M. Garst, arXiv(2024)

...

Can we use it as a quantum bit?

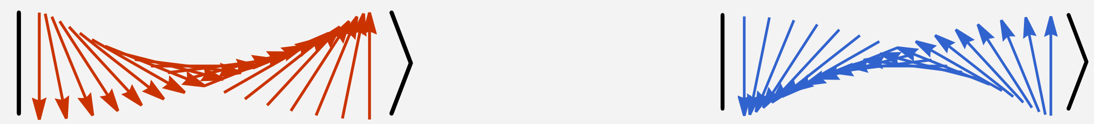
Which d.o.f. we want to use to store quantum information?





One promising candidate: chirality

Pseudo-spin: $|\uparrow\rangle = |C = +1\rangle$ $\quad |\downarrow\rangle = |C = -1\rangle$



DiVincenzo’s criteria

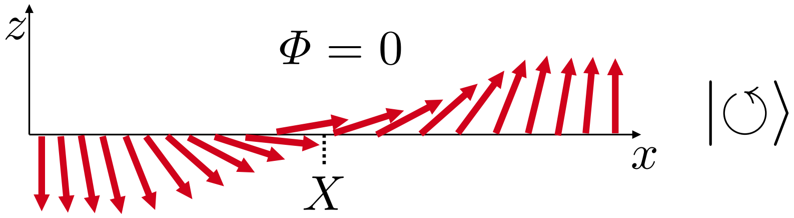
From Wikipedia:

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:

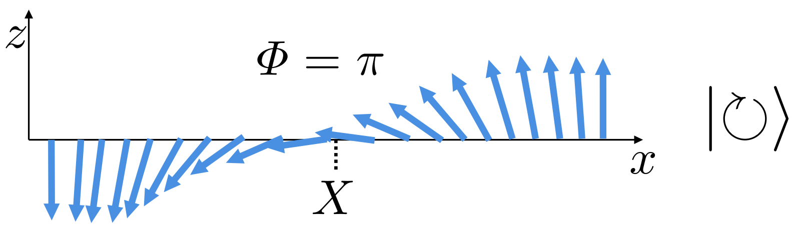
1. The ability to interconvert stationary and flying qubits
2. The ability to faithfully transmit flying qubits between specified locations

Key Ingredients



Consider a magnetic nanowire:

Ingredients we need:



First, we need a stable domain wall!

$$H_{\text{micro}} = -J \sum_{\langle i,j \rangle} \vec{S}_i \cdot \vec{S}_j \; -K_z \sum_i (S_i^z)^2$$

compete with each other → $\lambda = Sa\sqrt{J/K_z}$

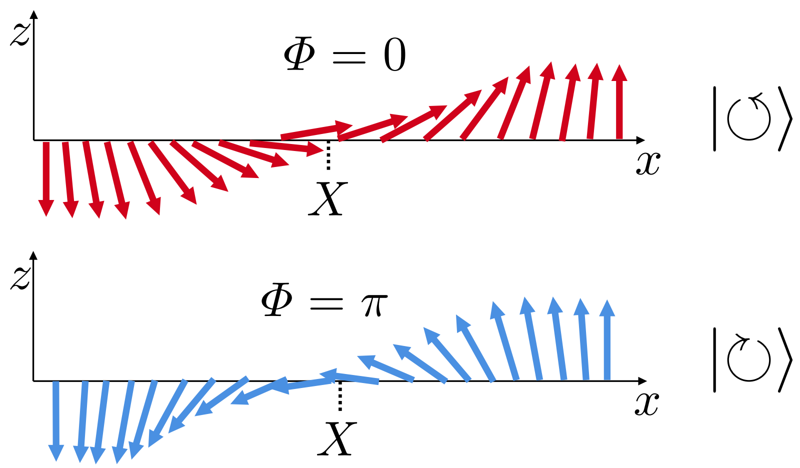
Domain wall solution:

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

Two zero modes: X, Φ

Key Ingredients

Consider a magnetic nanowire:

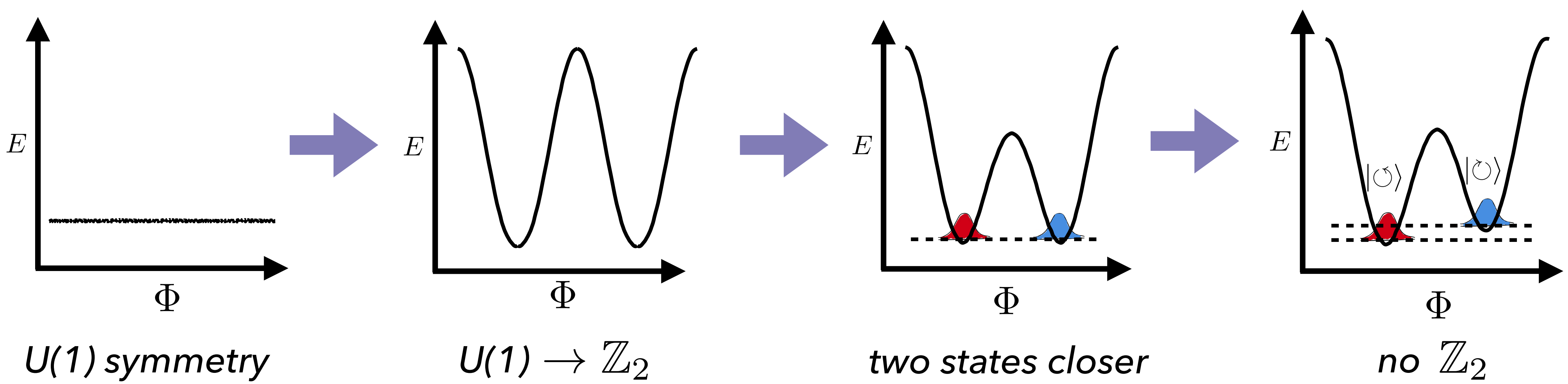


Ingredients we need:

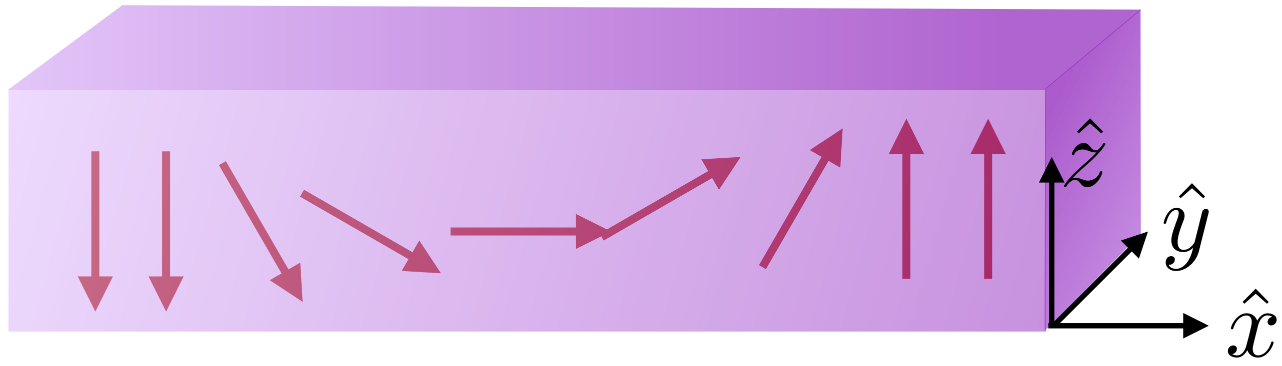
More ingredients:

$$H_{\mathrm{micro}} = -J\sum_{\langle i,j\rangle}\vec{S}_i\cdot\vec{S}_j - K_z\sum_i (S_i^z)^2 + K_y\sum_i (S_i^y)^2 - h_y\sum_i S_i^y - h_x\sum_i S_i^x$$

easy-xz plane



Construct Qubit



<u>Construct DW qubit:</u>

The full dynamics $\mathcal{L}[\mathbf{n}(x)]$

↓

Two low-energy modes $L = L_\Phi + L_X + L_{\Phi X}$

define the qubit — implement qubit gates

↓

Project onto chirality basis

$$H = \frac{(\hat{P} + \beta_z \tau_z)^2}{2M} + \frac{M\omega_p^2}{2}\left[\hat{X} - X_0(t)\right]^2 - \frac{\tilde{t}_g}{2}\tau_x$$

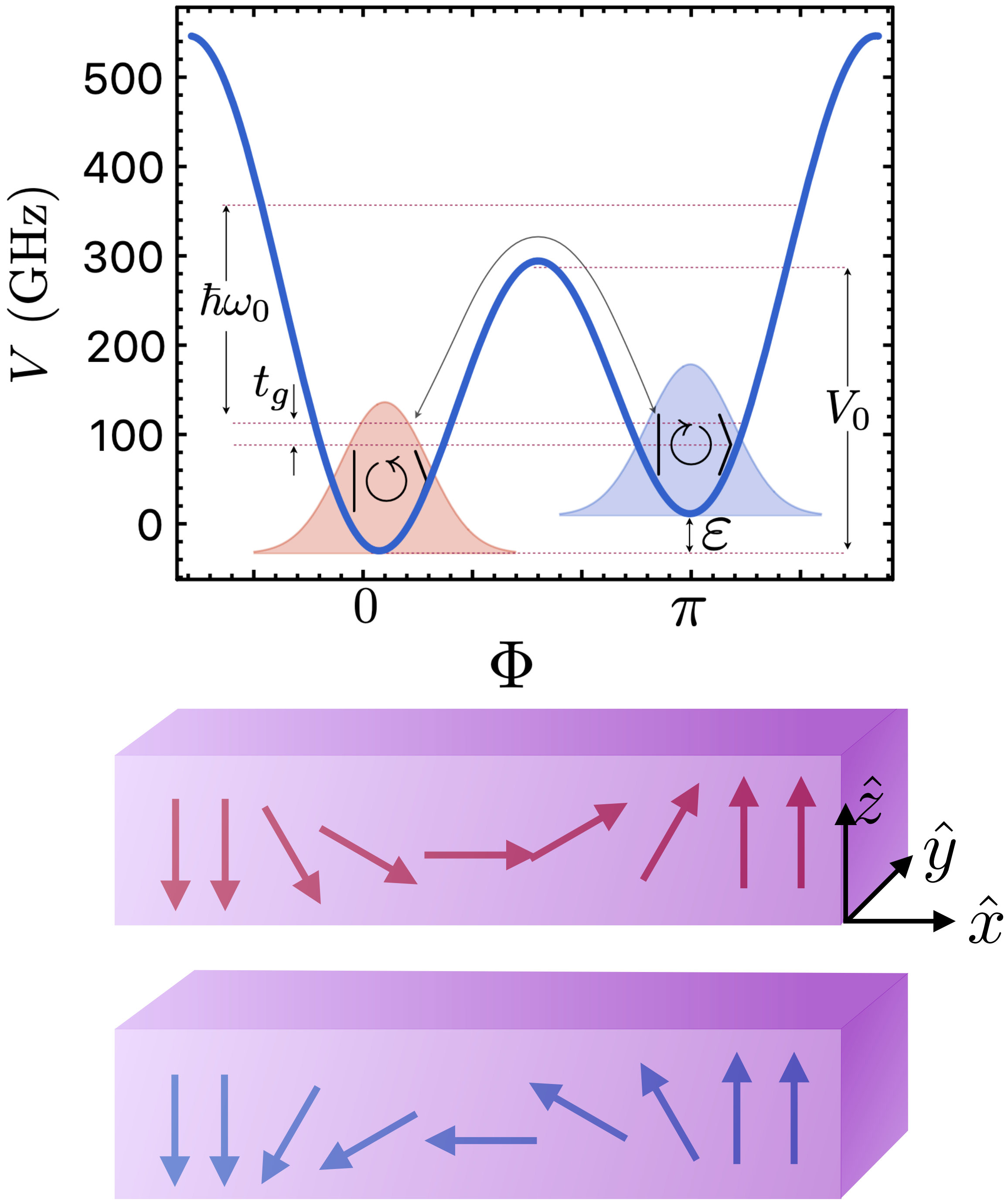
↓

Final qubit Hamiltonian

$$\mathcal{H}_m = \frac{\varepsilon(t)}{2}\tau_z - \frac{t_g}{2}\tau_x$$

Effective DW qubit Hamiltonian

Project dynamics onto chirality space:



In chirality basis: $\mathcal{H}_m = \frac{\varepsilon(t)}{2}\tau_z - \frac{t_g}{2}\tau_x$

→ $t_g \approx \hbar\omega_0\sqrt{S_{\text{inst}}/\hbar}\,e^{-S_{\text{inst}}/\hbar}e^{-l_p^2/l_{\text{so}}^2}$

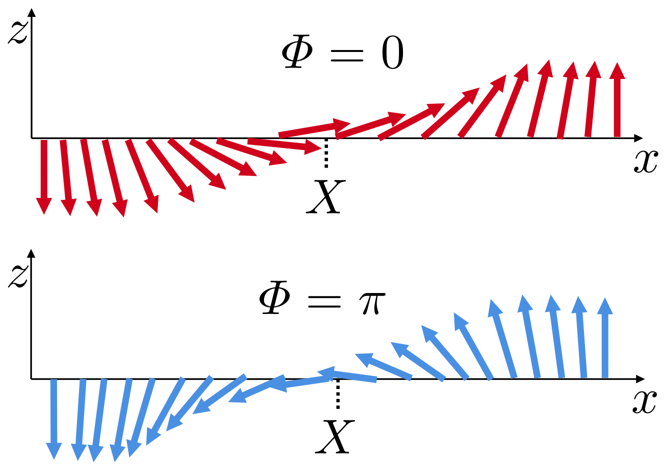
→ $\varepsilon(t) = 2\hbar\dot{X}_0(t)/l_{\text{so}} - 8NK_y b_x$

→ $\hbar\Omega = \sqrt{\varepsilon^2 + t_g^2}$ (~3 GHz)

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

DMRG for DW Qubit

<u>***Consider quantum spin-1/2 chain:***</u>



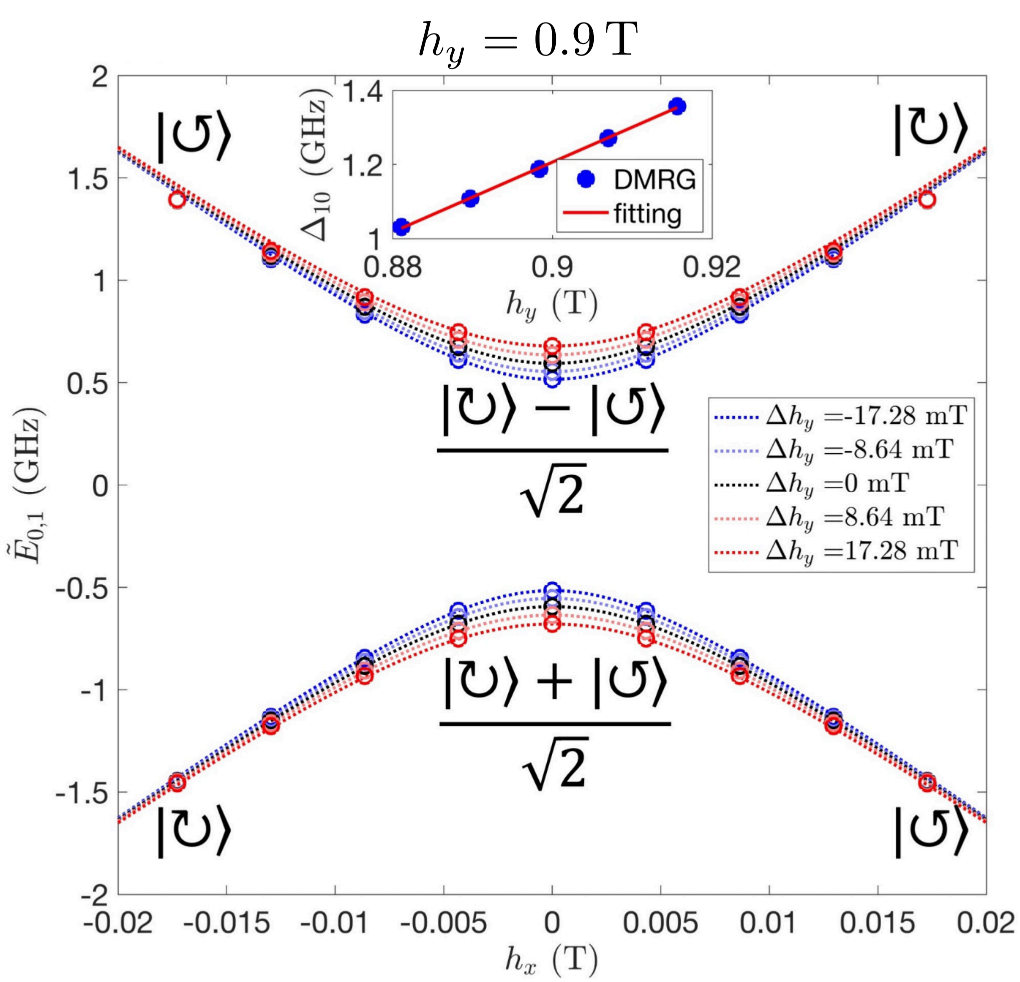
Simulate a static DW qubit: *arXiv:2412.11585 (2024)*

$$H_{\text{chain}} = \sum_{i=1}^{N-1} \left(-J\boldsymbol{S}_i \cdot \boldsymbol{S}_{i+1} - K_z S_i^z S_{i+1}^z + K_y S_i^y S_{i+1}^y\right)$$

$$+ \sum_{i=1}^{N} (\mu_B h_x S_i^x + \mu_B h_y S_i^y) + \mu_B h_z (S_1^z - S_N^z)$$

impose the boundary condition

Calculating the eigen-energies:



- Chirality states are well-isolated:

$$E_{21} \sim 10\,\mathrm{GHz}$$

- Well captured by an effective Hamiltonian:

$$H = -\frac{\Delta_{10}}{2}\tau_x - g_y \Delta h_y \tau_x + g_x h_x \tau_z$$

Δ_{10}	g_x	g_y
1.2 GHz	76.2 GHz/T	9.4 GHz/T

Qubit gates

Single qubit gates

$$\mathcal{H}_m = \frac{\varepsilon(t)}{2}\tau_z - \frac{t_g}{2}\tau_x$$

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

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

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

$t_g \to b_y$

$$\mathcal{H}_m = \frac{\varepsilon(t)}{2}\tau_z - \frac{t_g}{2}\tau_x$$

$\downarrow$ $\varepsilon(t) \propto v(t) = v_0 s(t)\cos(\omega_d t + \phi_0)$

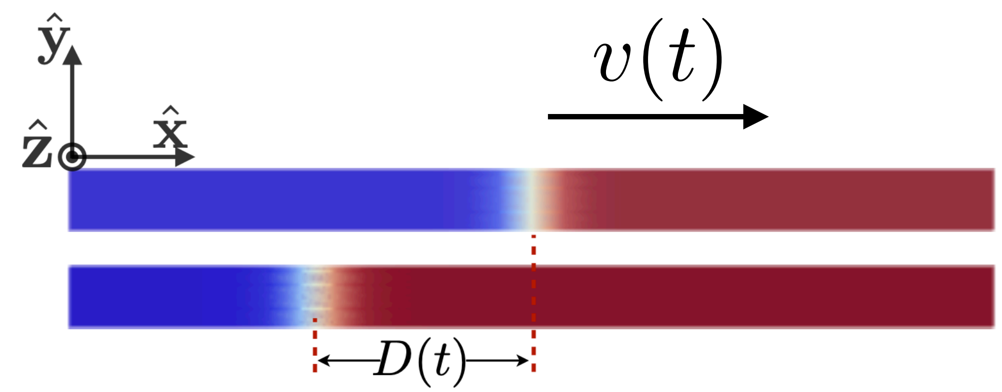
1. In-phase pulse: $\phi_0 = 0$

   rotation around x axis

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

   rotation around y axis

Two qubit gates



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

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

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

$\pi/4$ CNOT gate

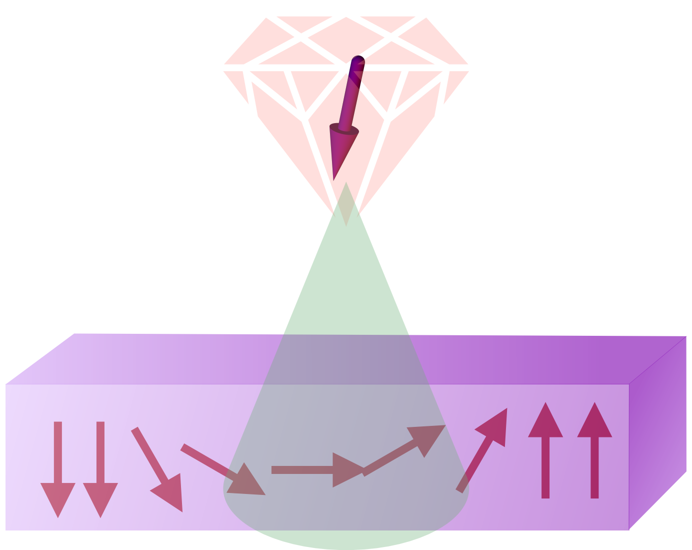
$$N^2\mathcal{J}_{xx} \sim 50\,\mathrm{MHz}$$

$$v = 20\,\mathrm{m/s}$$

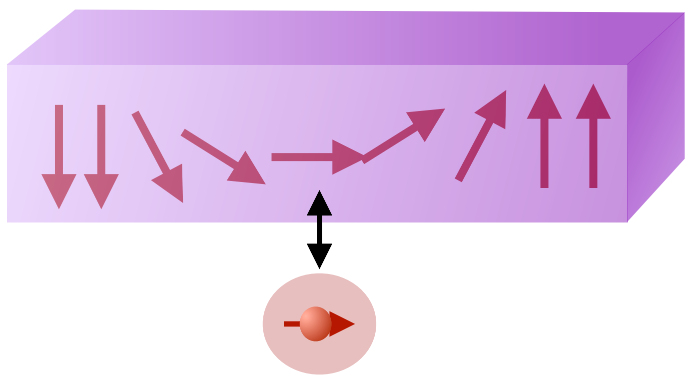
$$T_G \approx 0.2\,\mathrm{ns}$$

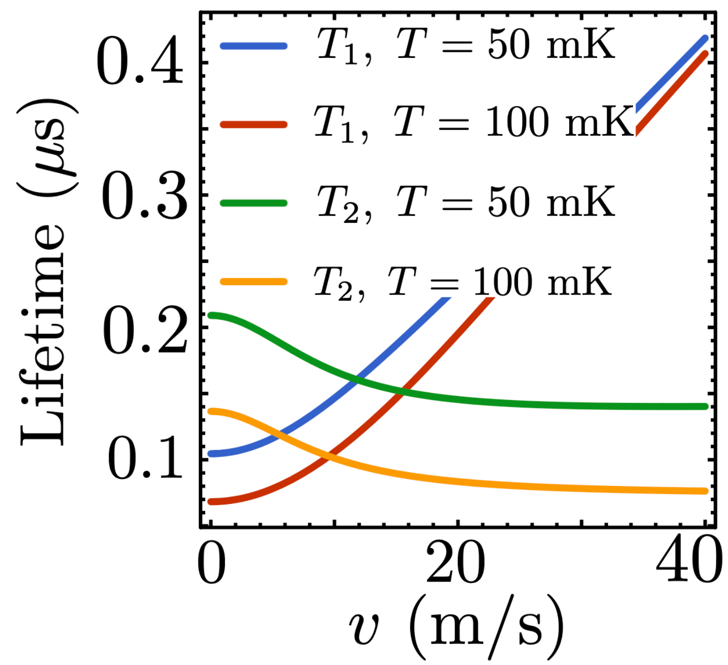
Qubit readout and lifetime

use NV center to image the texture



couple to other qubits





$v = 20\,\mathrm{m/s} \quad T = 50\,\mathrm{mK} \quad \alpha = 10^{-5}$:

$T_1 = 0.23\,\mu\mathrm{s} \quad T_2 = 0.15\,\mu\mathrm{s}$

Quality factor: $\Omega_R T_2 \sim 10^3$

Coherent shuttling distance: $3\,\mu\mathrm{m}$

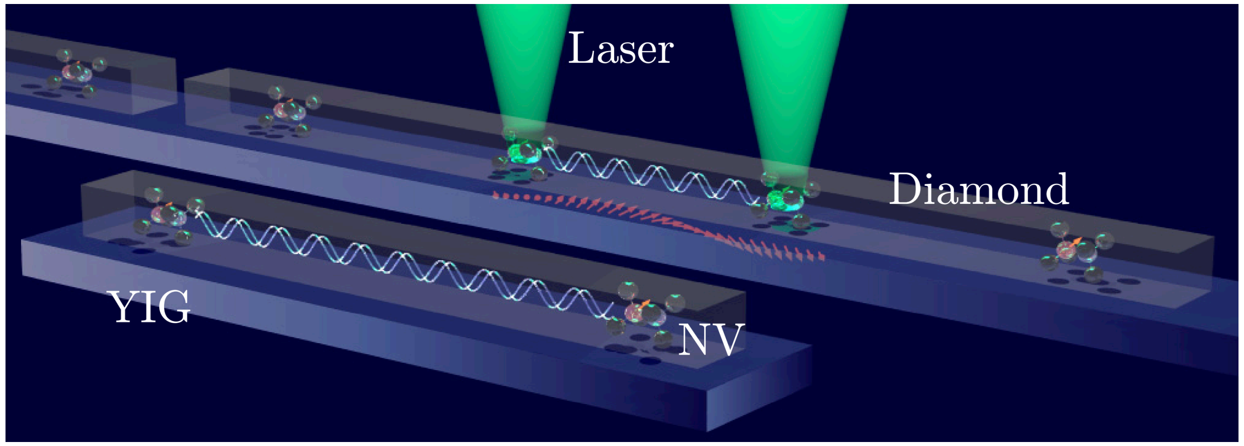
Song, et al., Science 374, 1140 (2021)
Finco, et al., Nature Com. 12, 767 (2021)
Y. Nakamura, et al., Science (2015, 2020)

Part II:
Quantum Information Transmission

Long distance communication

Magnon-based scheme:

use magnon-mediated coherence coupling



See Denis's talk!

M. Fukami, D. R. Candido, et al. PRX Quantum (2021)

M. Dols, S. Sharman, et al., PRB (2024)

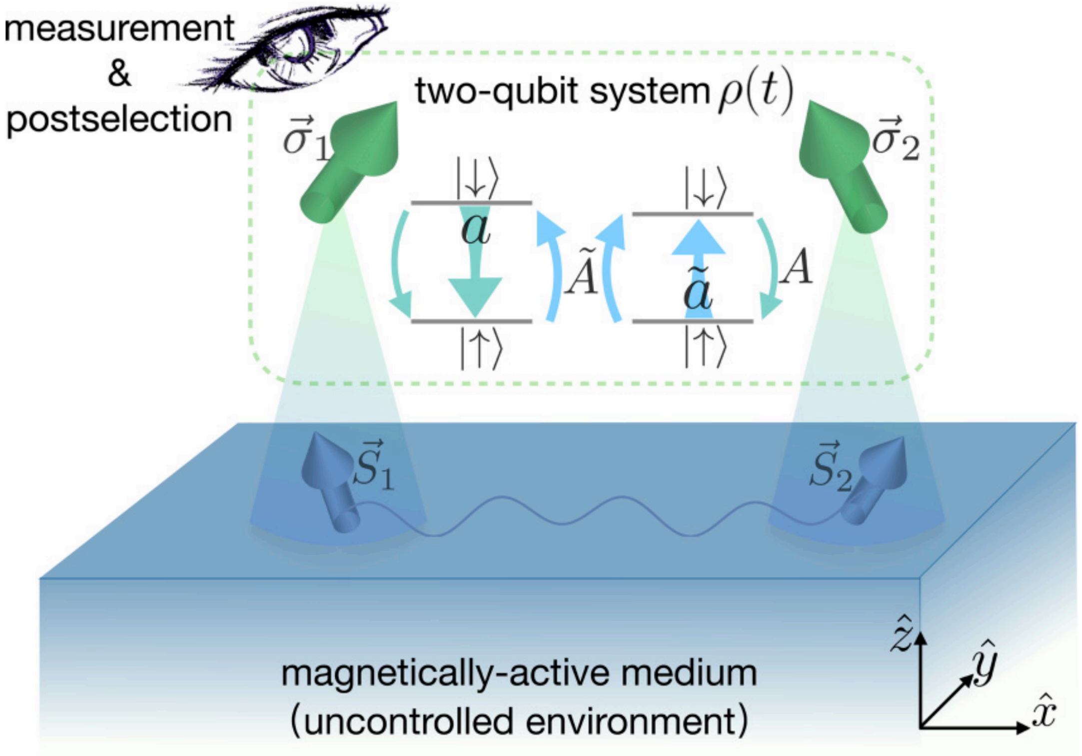
M. Fukami, J. C. Marcks, et al. PNAS (2024)

L. Trifunovic, F. Pedrocchi, D. Loss, PRX(2013)

B. Flebus and Y. Tserkovnyak, PRB(2019)

...

use magnon-mediated dissipative coupling



J. Zou, S. Zhang, Y. Tserkovnyak, PRB (2022)

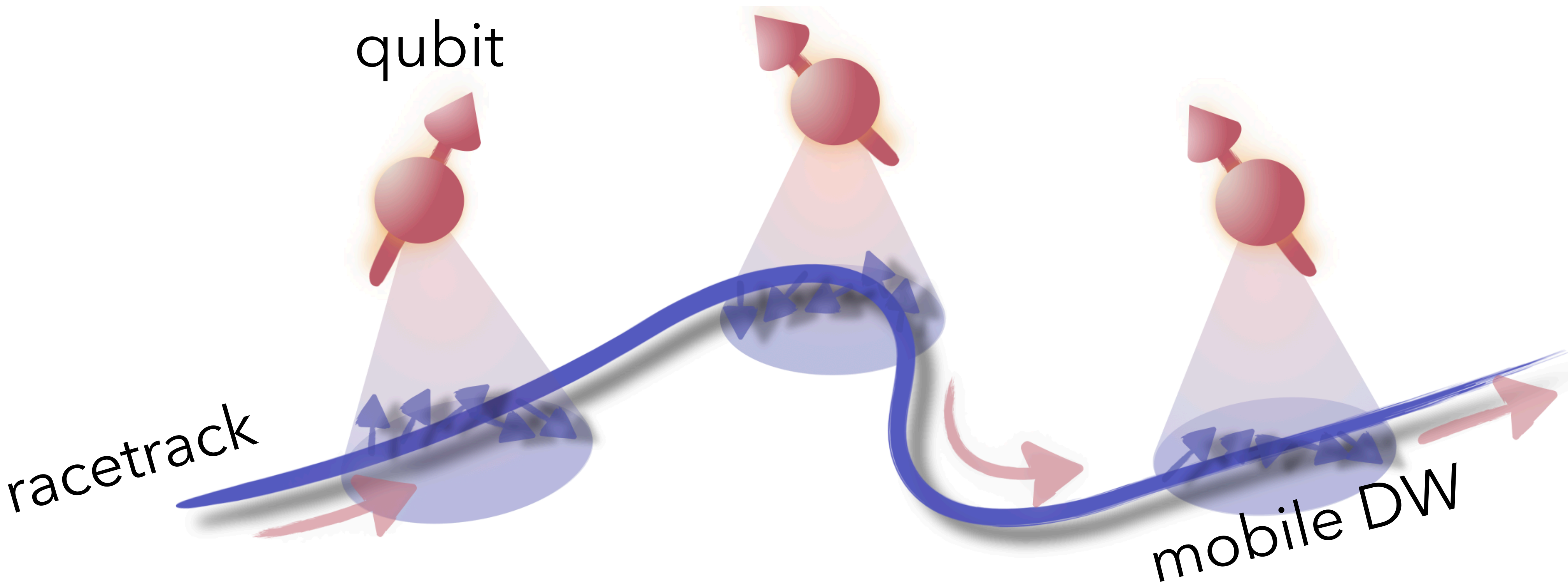
J. Zou, S. Bosco, D. Loss, npj Quantum Inf. (2024)

T. Yu, **J. Zou**, et al., Physics Report (2024)

E. Kleinherbers, S. Kelly, Y. Tserkovnyak, PRL(2025)

Quantum information transmission

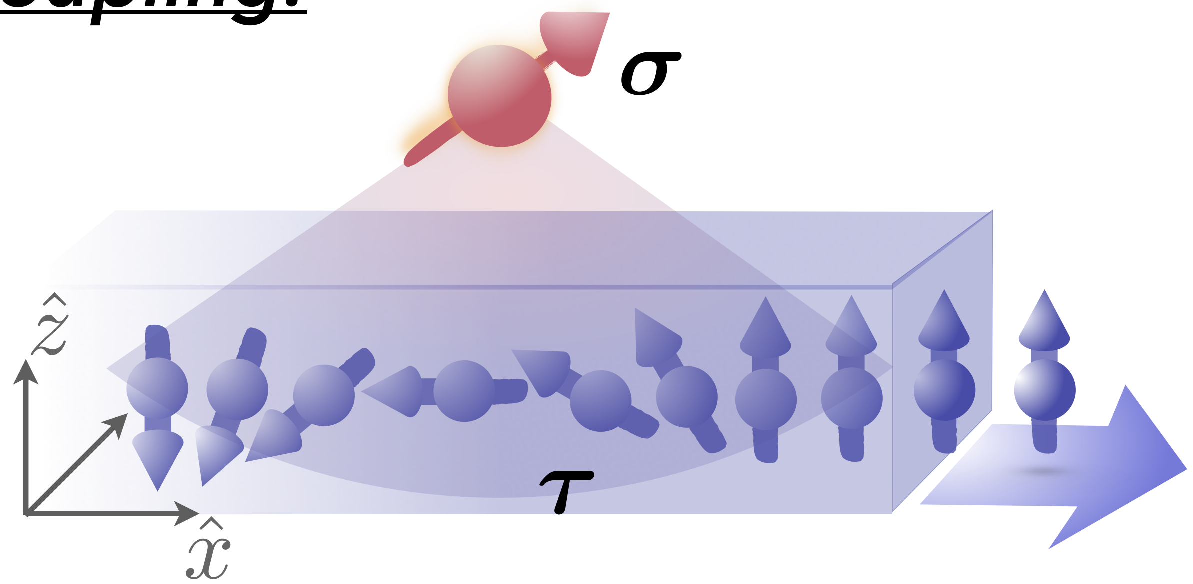
Use topological excitations!



Use mobile DWs to communicate distant qubits and generate entanglement

Hybrid racetrack-spin qubit

Racetrack-spin qubit coupling:

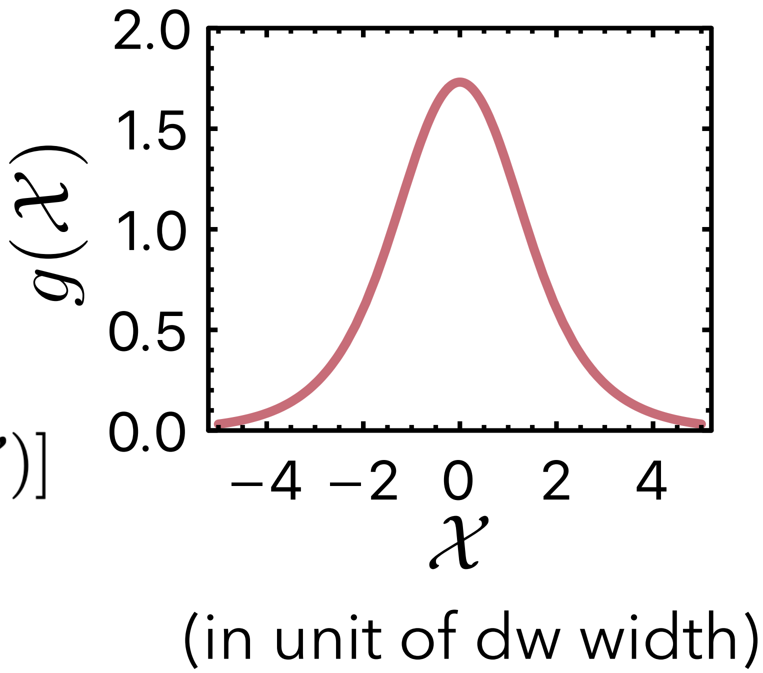


$$\mathcal{V}(t) = -\mathcal{J}\, g[\mathcal{X}(t)]\, \tau_z \otimes \sigma_x$$

Coupling strength:

$$\mathcal{J} \sim 100\,\mathrm{MHz}$$

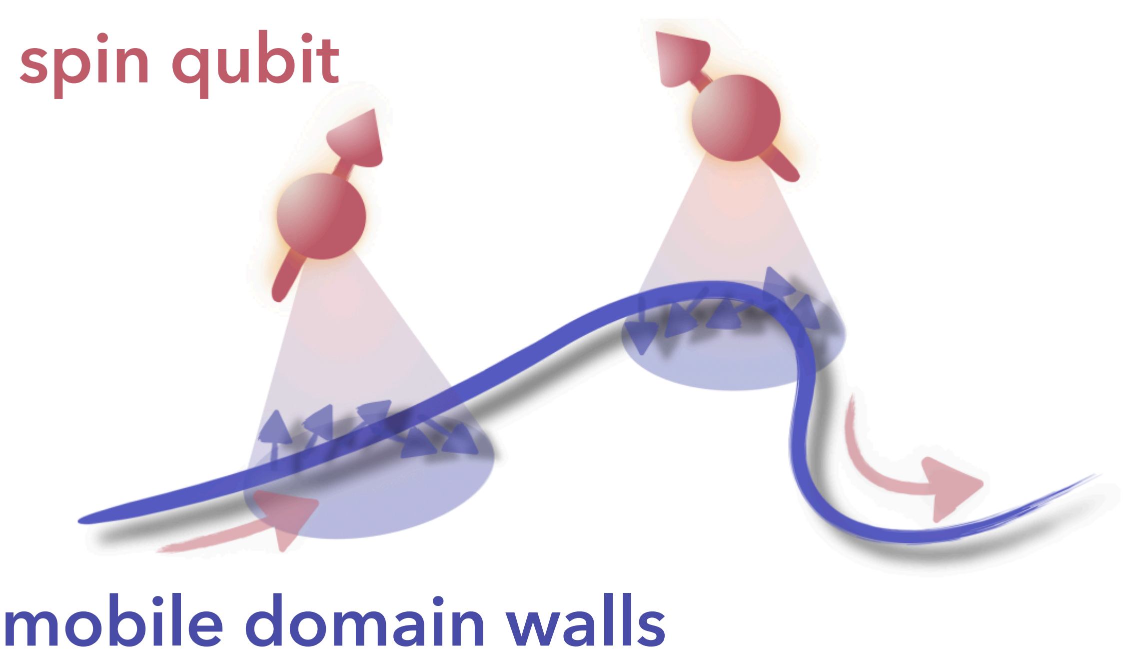
$$g(\mathcal{X}) = \sum_{k=\pm 1} \arctan[\sinh(l + k\mathcal{X})]$$

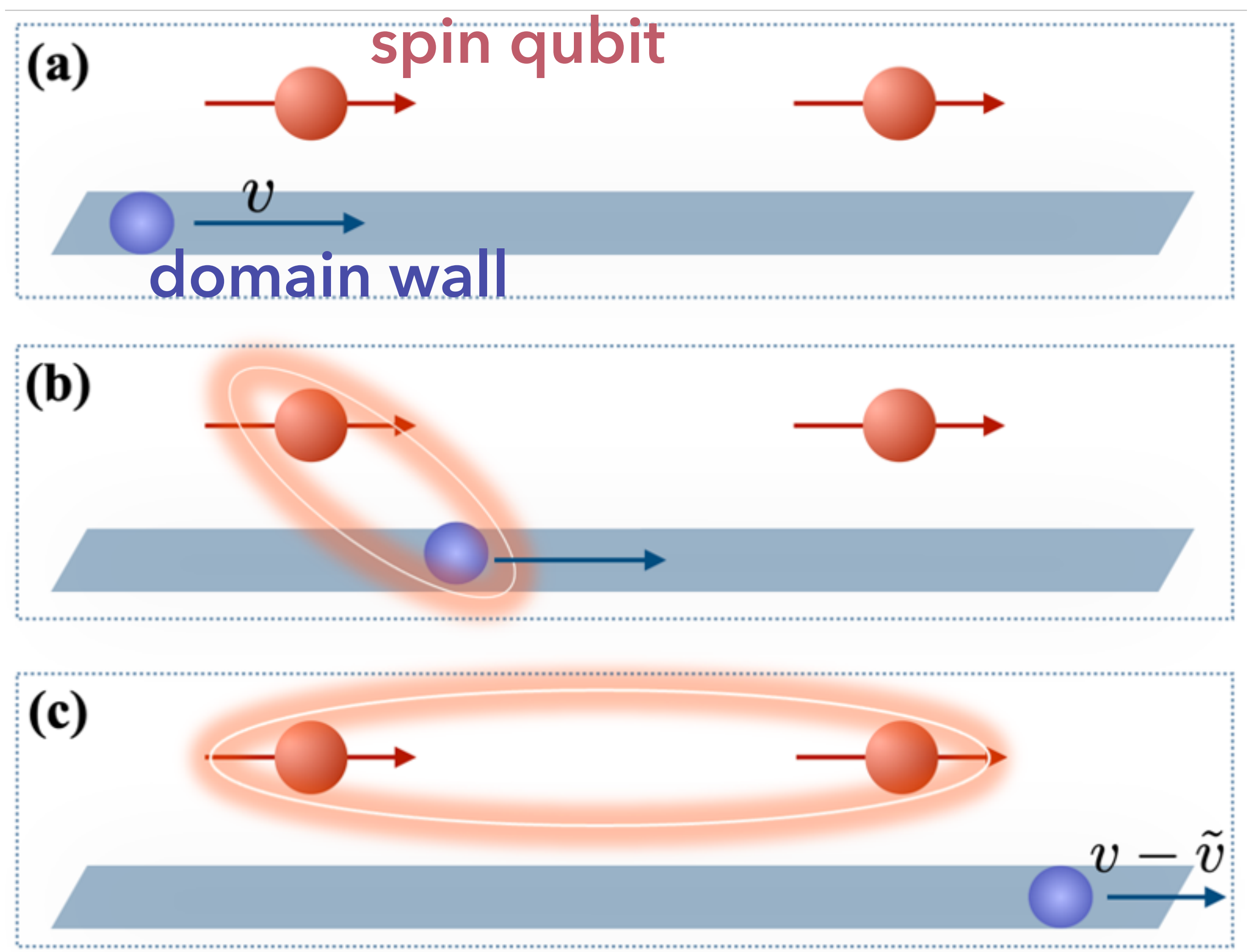


Remote entanglement protocol

System effective Hamiltonian:

$$\mathcal{H}(t) = -\sum_{i=1,2} \frac{\hbar\omega_s^{(i)}}{2}\sigma_y^{(i)} - \frac{t_g}{2}\tau_x + \frac{\varepsilon}{2}\tau_z - \mathcal{J}\sum_{i=1,2} g[\mathcal{X}_i(t)]\sigma_x^{(i)}\tau_z$$





Remote entanglement protocol

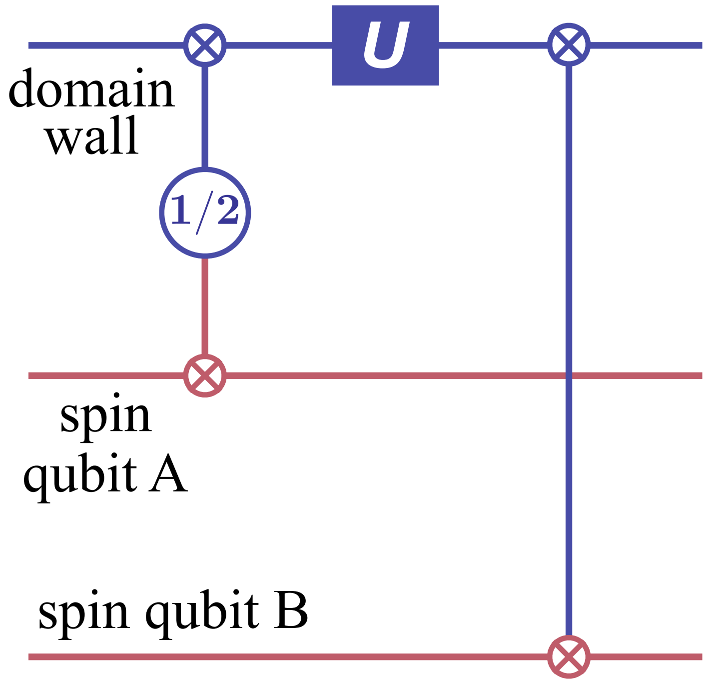
Quantum gates by moving the domain wall qubit:

$$\mathcal{U}(v) \approx \cos^2\frac{\Phi}{2} + \sin^2\frac{\Phi}{2}\hat{\sigma}_z\hat{\tau}_z - \frac{i}{2}\sin\Phi[\hat{\sigma}_x\hat{\tau}_x + \hat{\sigma}_y\hat{\tau}_y] \qquad \Phi = \frac{6\mathcal{J}}{\hbar v}$$

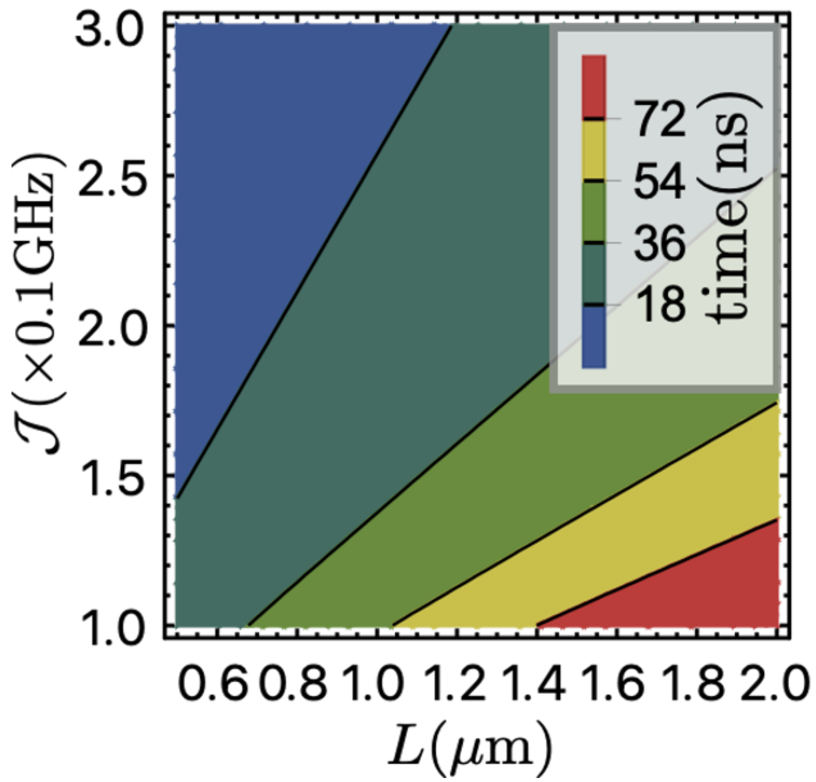
$\Phi = \frac{\pi}{4}$ local $\sqrt{\text{iSWAP}}$ gate

$\Phi = \frac{\pi}{2}$ local iSWAP gate

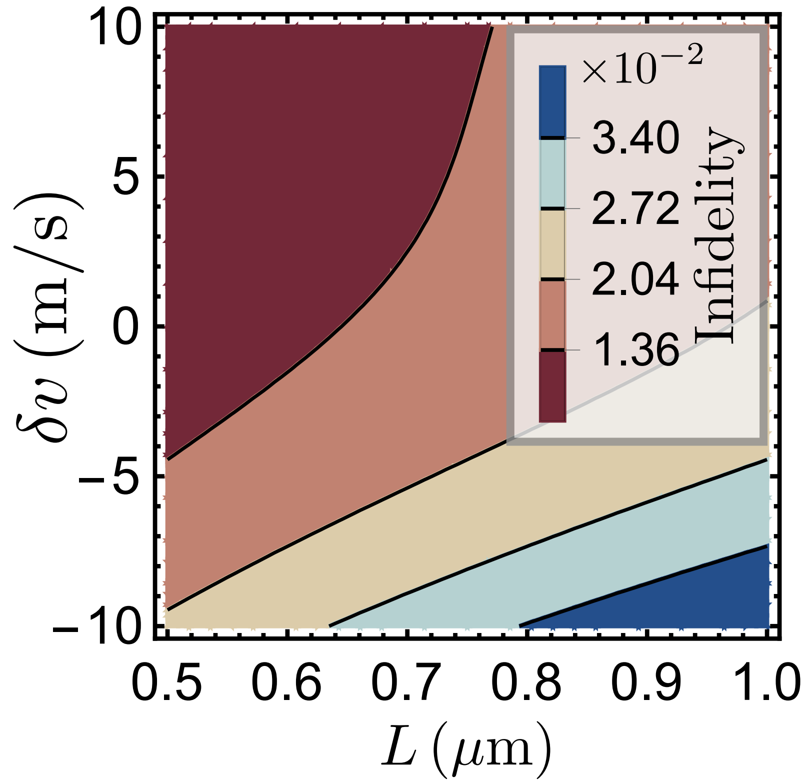
Quantum circuit



Operational time

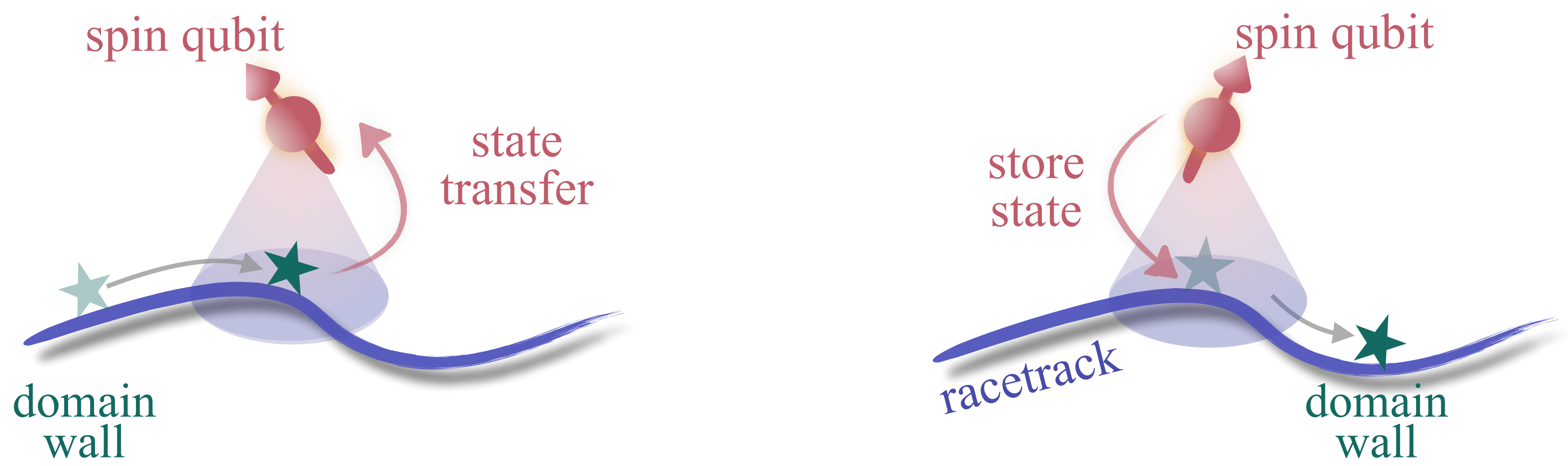


Infidelity

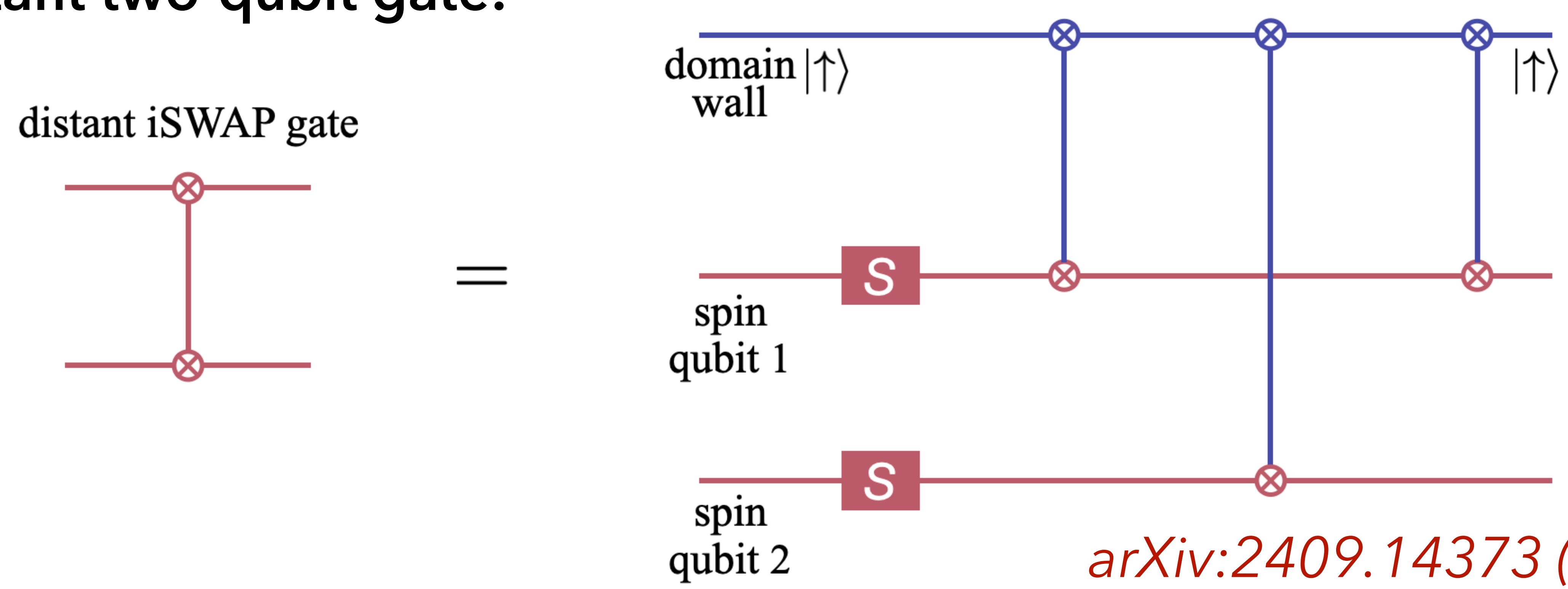


Quantum state transfer and distant gate

Quantum state transfer:



Distant two-qubit gate:



arXiv:2409.14373 (2024)

What we have achieved

Topological textures are 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

Take-home messages

★ Nanoscale *topological textures* can be used as a qubit.

★ Implementing qubit gates by *moving the texture.*

★ Their *mobility* makes them ideal for *communicating distant qubits*.

Related works:

J. Zou, et al., Phys. Rev. Research 5, 033166 (2023)

J. Zou, et al., arXiv:2409.14373 (2024)

G. Qu, J. Zou, et al., arXiv:2412.11585 (2024)

ghe GEORG H. ENDRESS STIFTUNG

University of Basel

NCCR SPIN

MAX PLANCK INSTITUTE of Microstructure Physics