From quantum gates to weak traces & annealers

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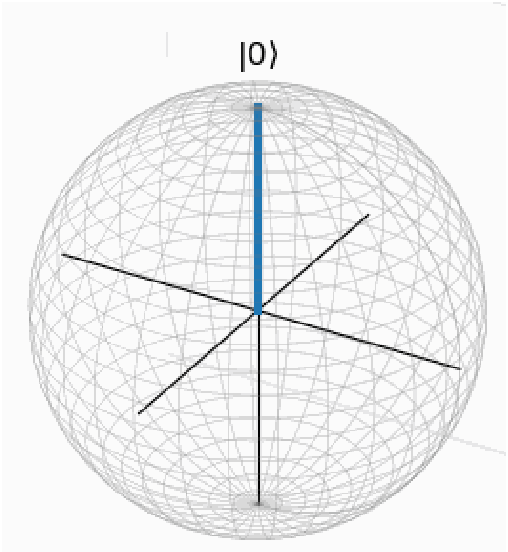
Computational Nonlinear & Quantum Optics Group,
Department of Physics, University of Strathclyde

Introduction to Quantum Computing 2020-21

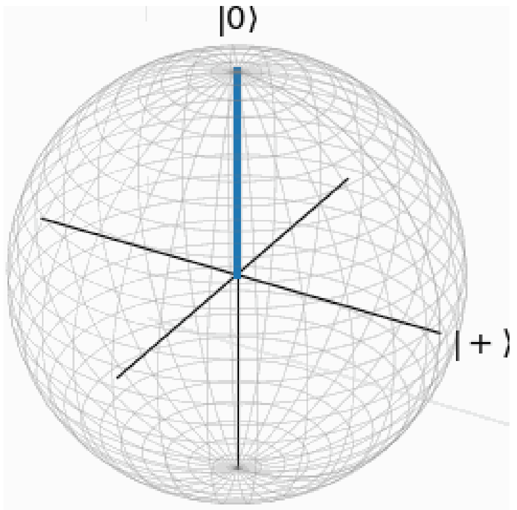
X gate

180° around the X axis



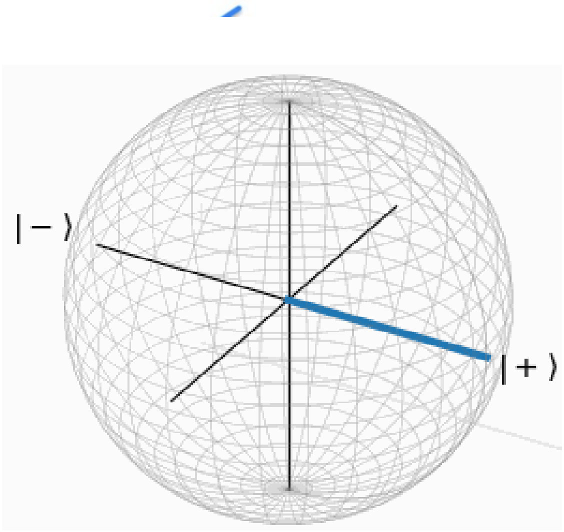
Hadamard gate

Creates equal superposition of |0> and |1>

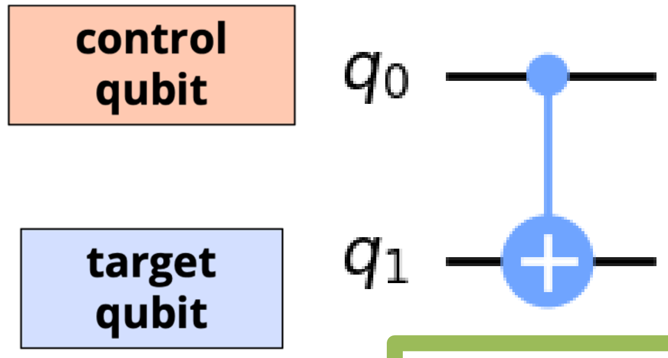


Z gate

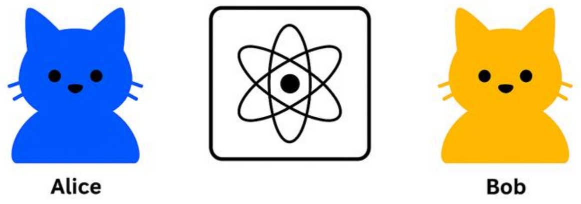
180° around the Z axis



The CX Gate



Quantum Key Distribution

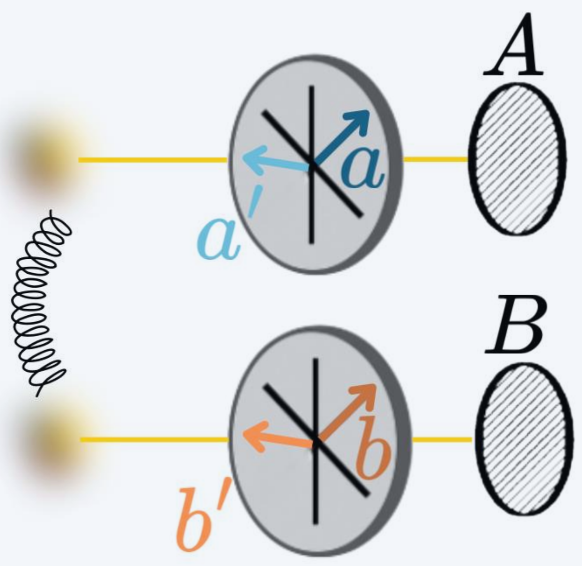


Explained: BB84 & E91 Prtocols

Bell States (EPR Pairs)

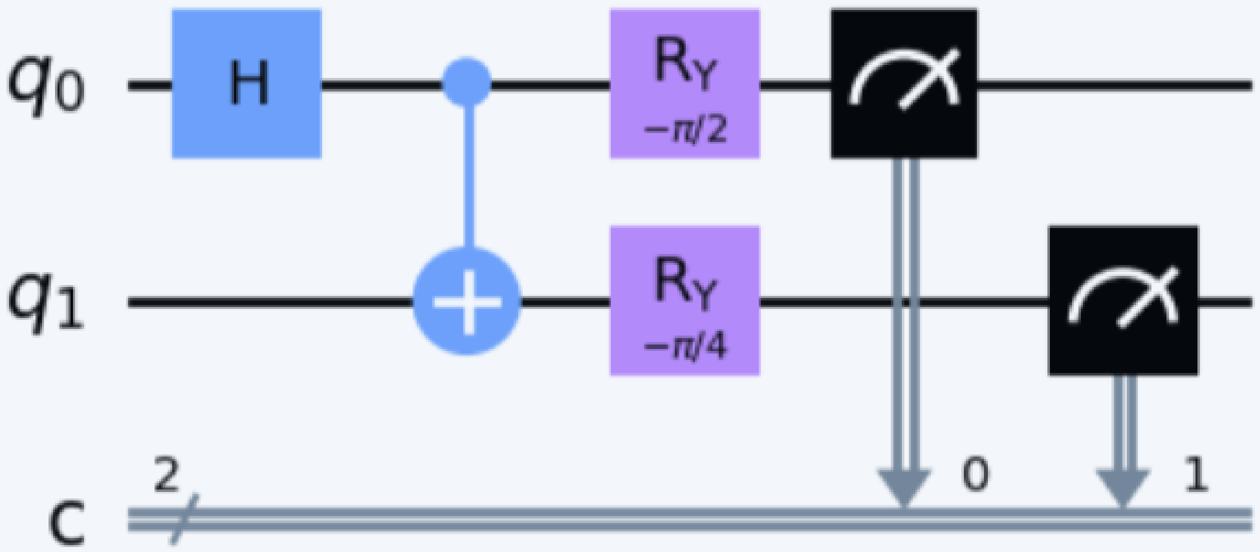
$$\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$
$$\frac{1}{\sqrt{2}}(|00\rangle - |11\rangle)$$
$$\frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$$
$$\frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$$

Experiment



translate

Circuits



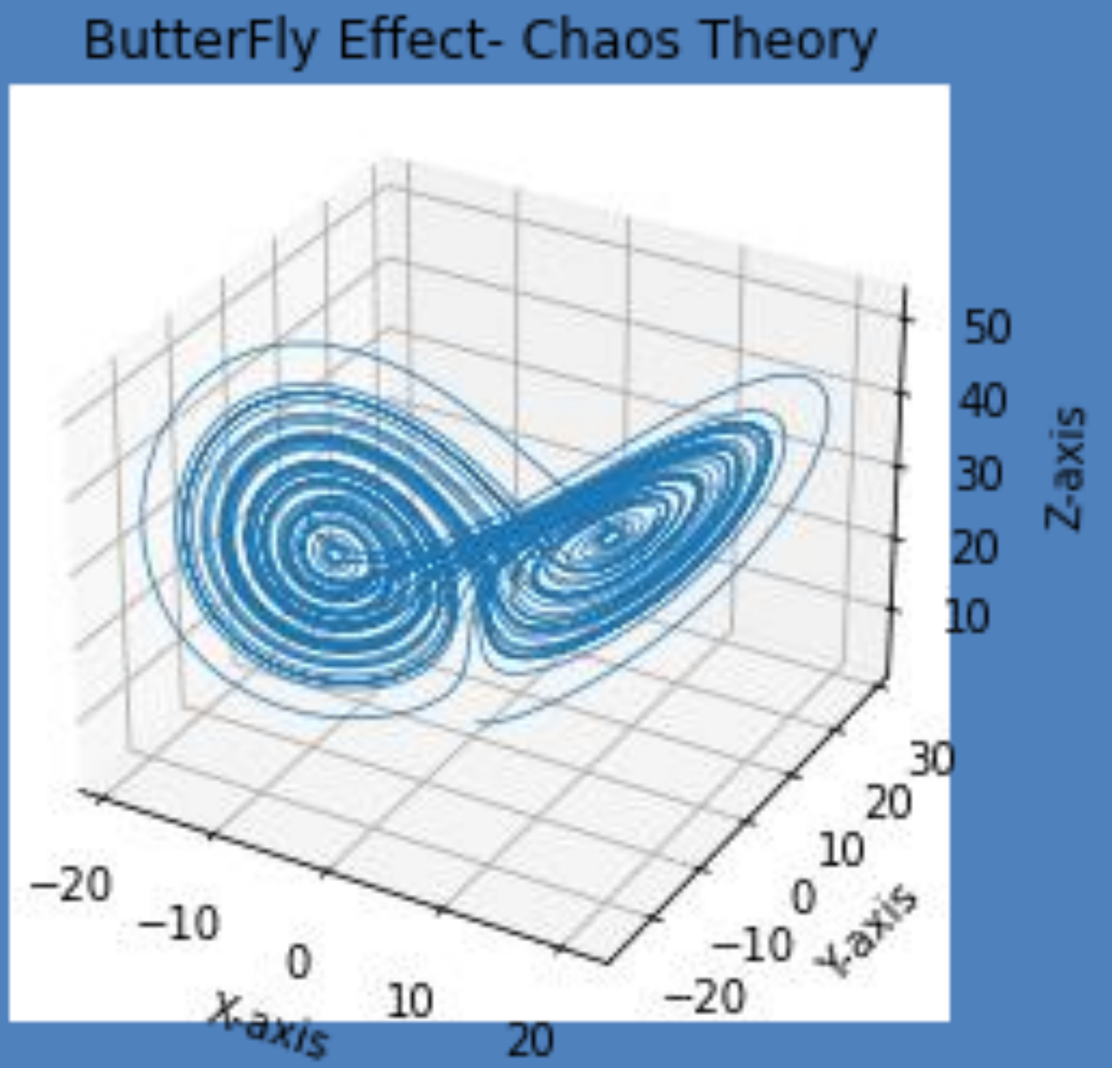
Entanglement Level

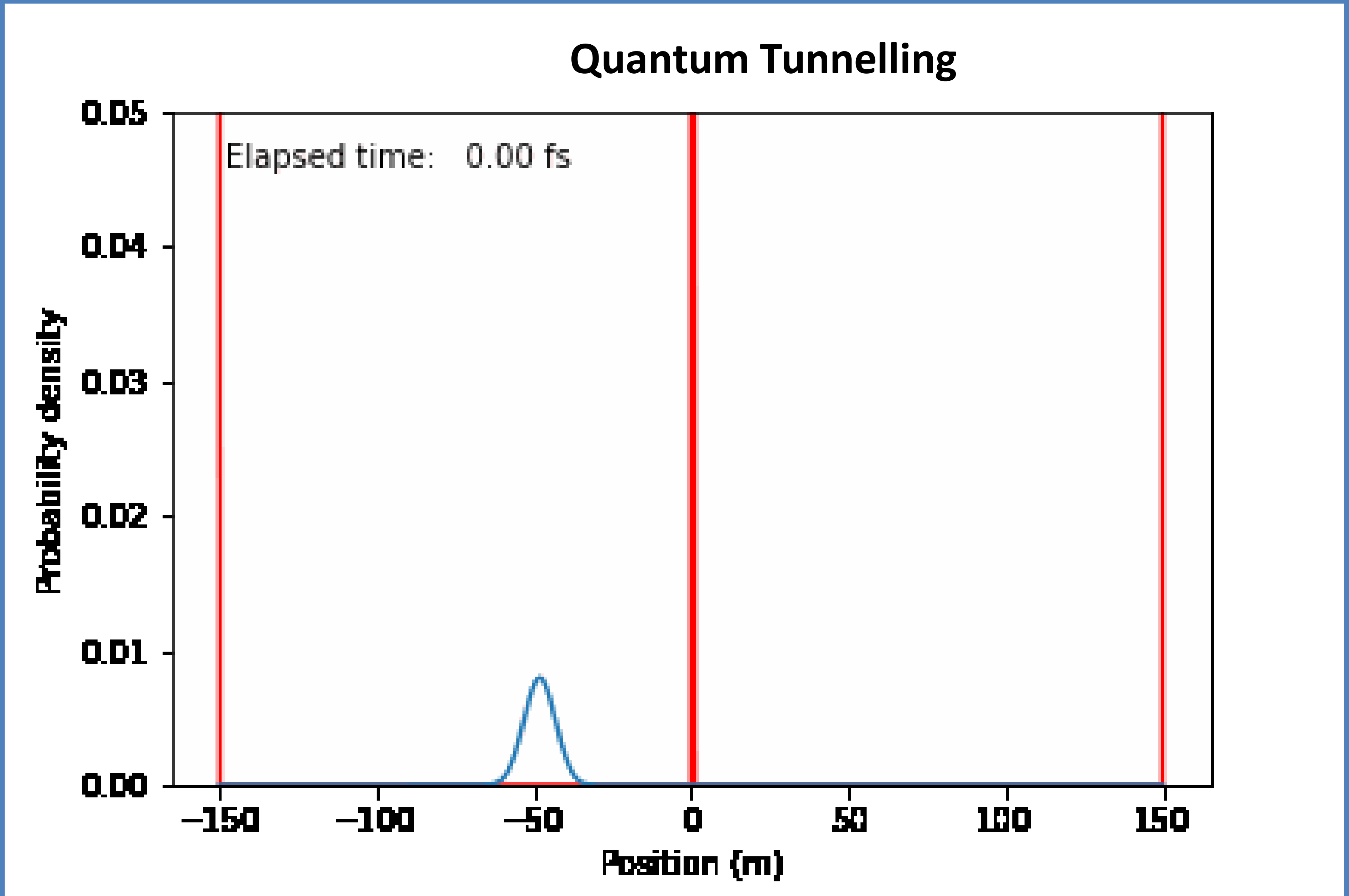
Separable — Bell

$|00\rangle$ | $\sqrt{0.8}\,|00\rangle + \sqrt{0.2}\,|11\rangle$ | $\sqrt{0.6}\,|00\rangle + \sqrt{0.4}\,|11\rangle$ | $\frac{1}{2}(|00\rangle\ |11\rangle)$

Microsoft

Mentor: **Léo Bourdet**





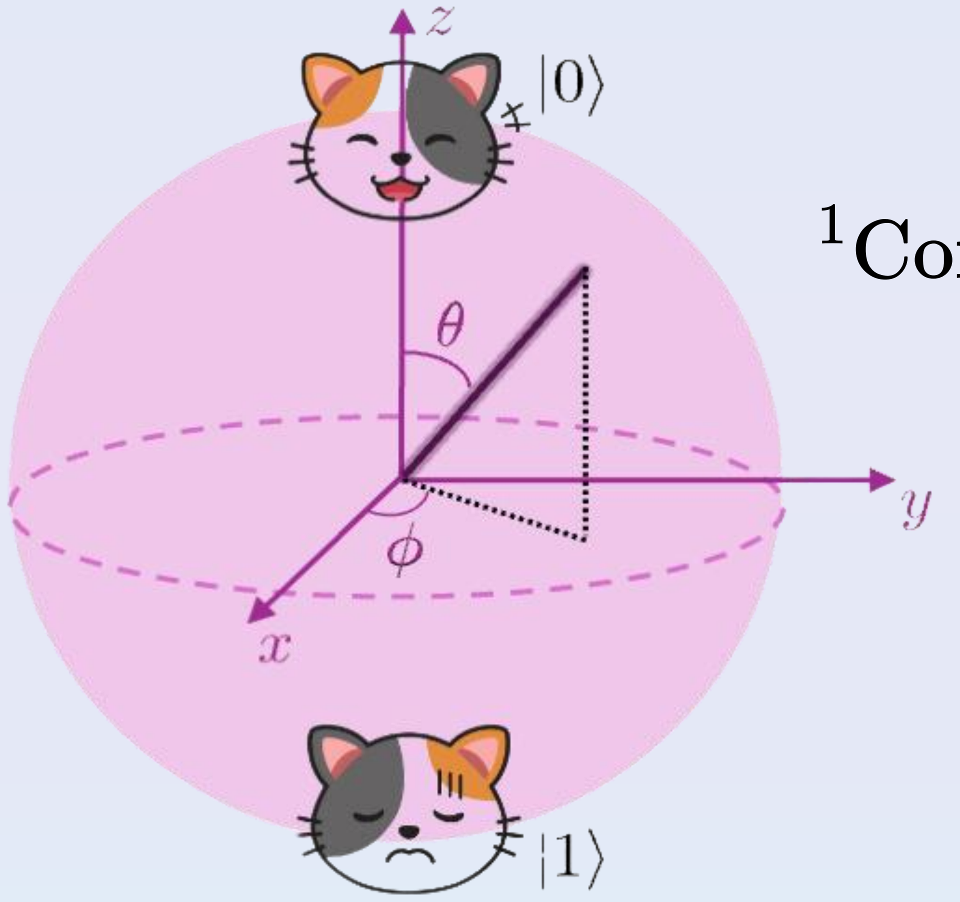
Github:
- spacetime-shushmi/Quantum-tunelling
- spacetime-shushmi/Chaos-Theory

Can higher order weak values resolve particle presence?

Shushmi Chowdhury[1] and Jörg Götte[2]

[1]Computational Nonlinear & Quantum Optics Group, Department of Physics, University of Strathclyde

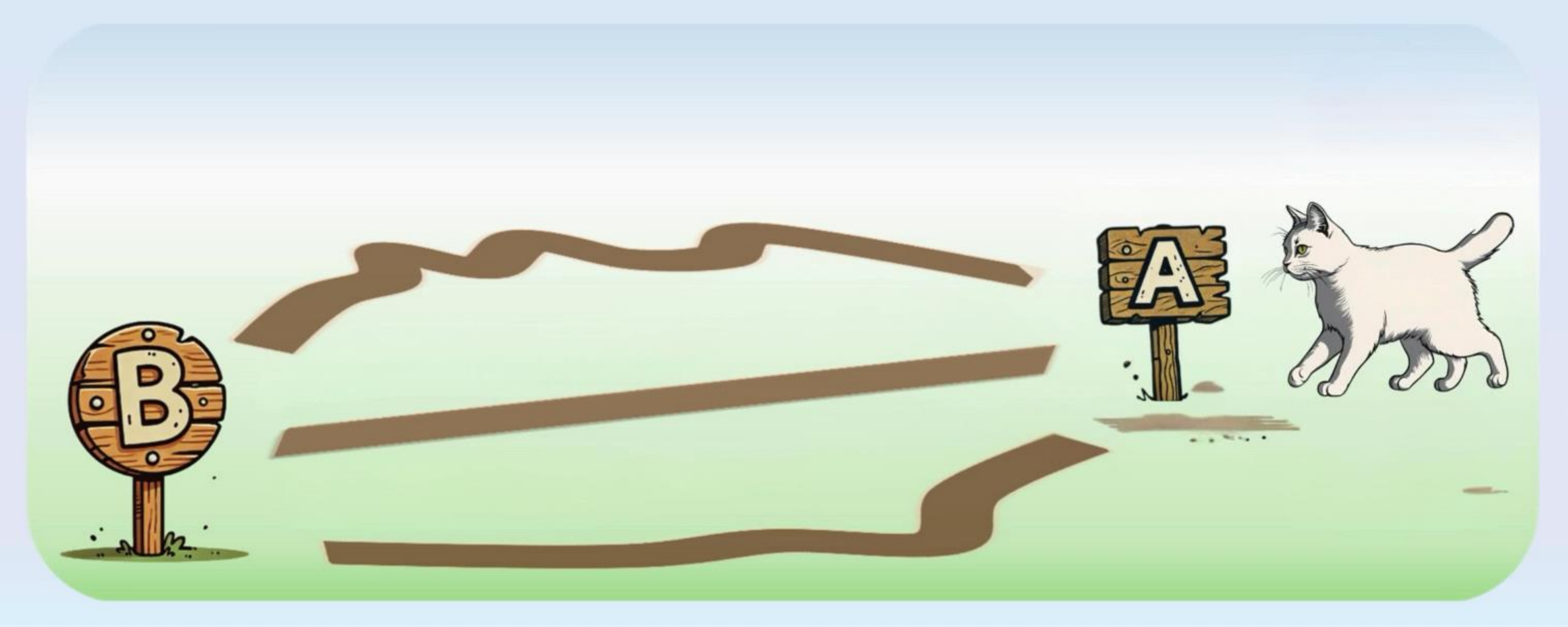
[2]Quantum Theory Group, School of Physics and Astronomy, University of Glasgow



arXiv:2407.06989

Motivation

- Quantum particles exhibit both wave-like and particle-like properties, known as wave-particle duality
- When we attempt to measure a quantum particle, its wave-like behavior collapses, and it appears as a particle in a single state, losing its superposition.



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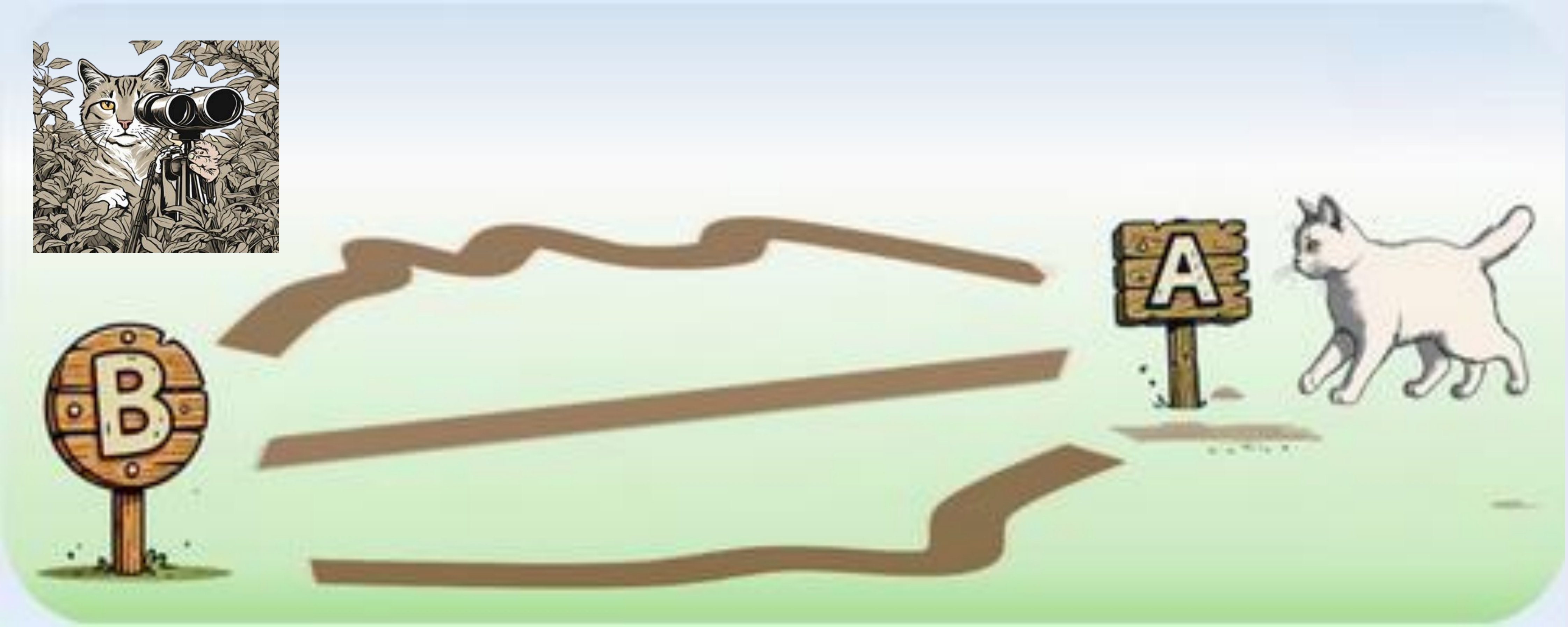


- Under weak measurement, particles can follow discontinuous, unpredictable paths
- By using weak values derived from Feynman's path integrals, we intend to address these unusual paths

Feynman Path Integrals

- System traverses all possible paths simultaneously

- Each path has a some phase factor associated with it:

$$\phi\left[x(t)\right] = G \exp\left\{\frac{i}{\hbar} S\left[x(t)\right]\right\}$$

- Phase $\propto$ S where $S = \int_{t_a}^{t_b} L(\dot{x}, x, t)dt$

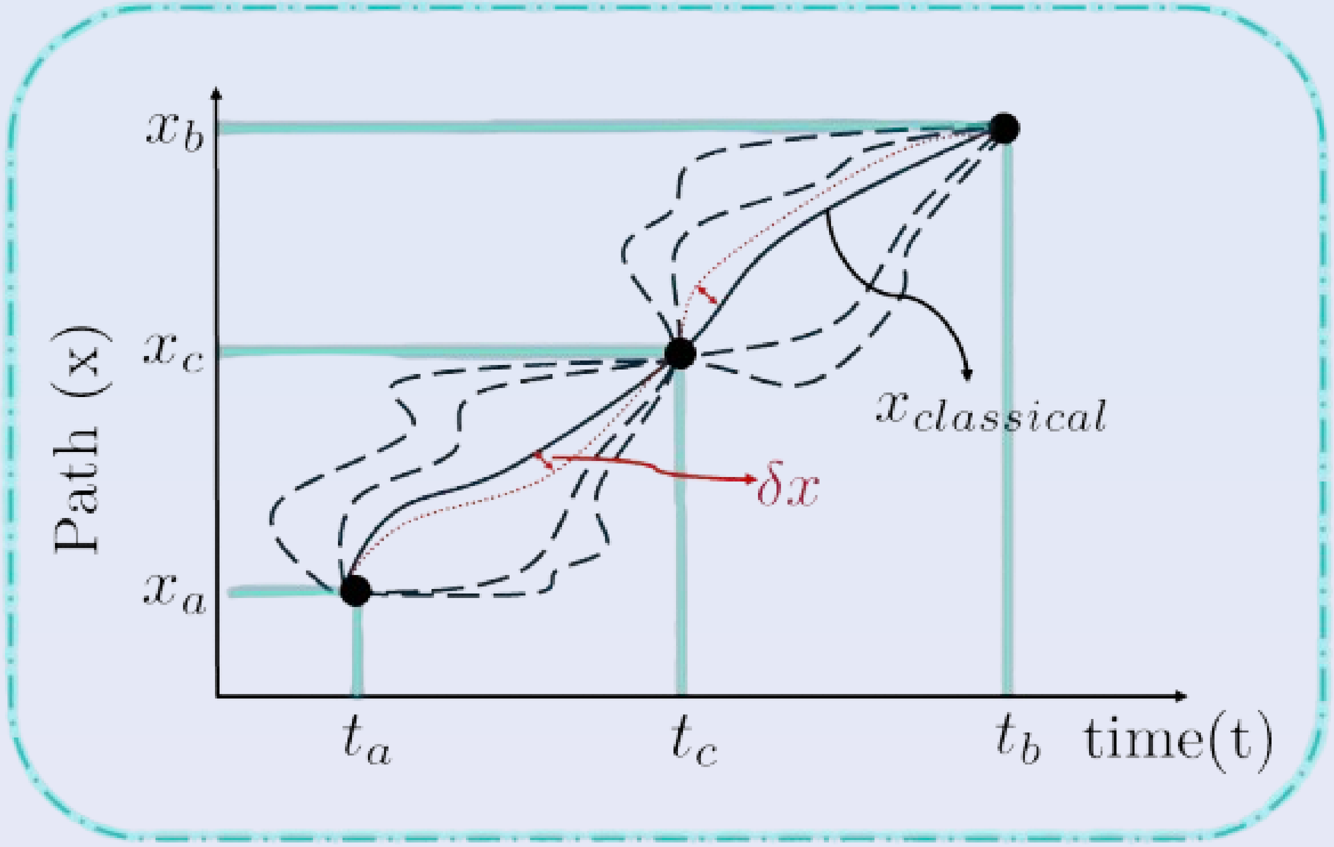
- Lagrangian of particle with mass m in contact with potential V,

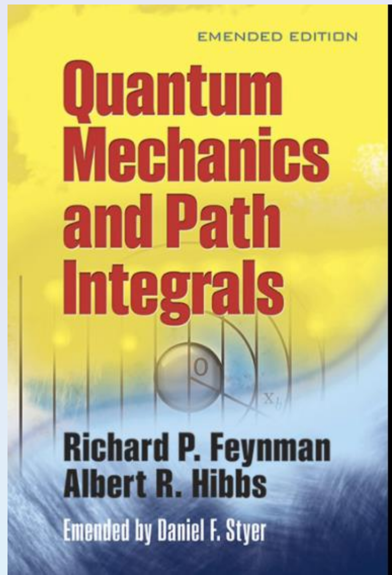
$$L = \frac{m\dot{x}^2}{2} - V(x,t)$$

- Amplitude to go from an initial point, a, to a final point, b:

$$K(B,A) = \sum_{x(t_a)}^{x(t_b)} \phi[x(t)]$$

- Probability to go from $x(t_A)$ to $x(t_B)$ is square of total amplitude: $P(B \leftarrow A) = |K(B,A)|^2$





Time Symmetric Formulation of Quantum Mechanics

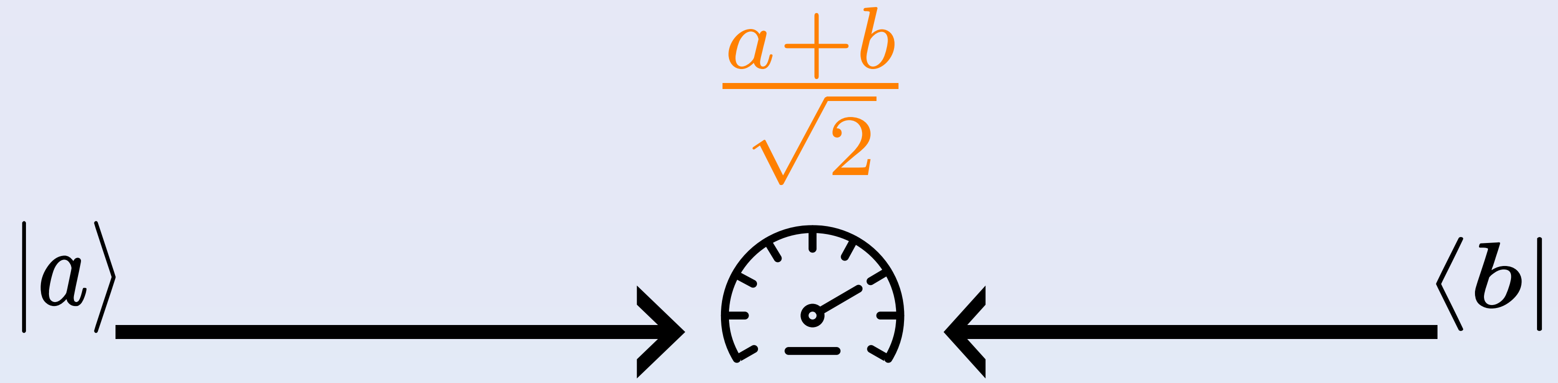
- Time-symmetric framework Phys.Rev.134, B1410 - Consider Initial and Final states

- Coherence-destroying measurements $\{A_1, A_2 \dots A_{N-1} A_N\}$

- If order of events is changed between pre- and post-selection, probability remains unchanged:

$$P\left(a_2, \dots, a_{N-1} | a_1, a_N\right) = P\left(\dots, a_{N-1}, \dots a_2, \dots | a_1, a_N\right)$$

Two State Vector Formalism



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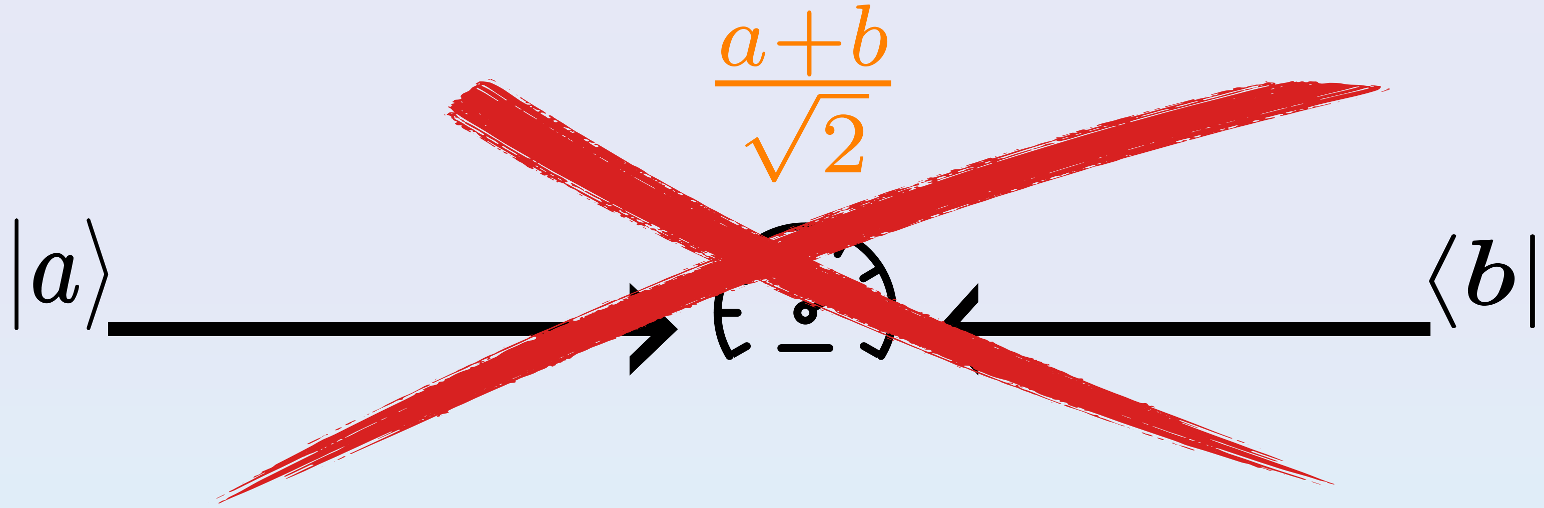
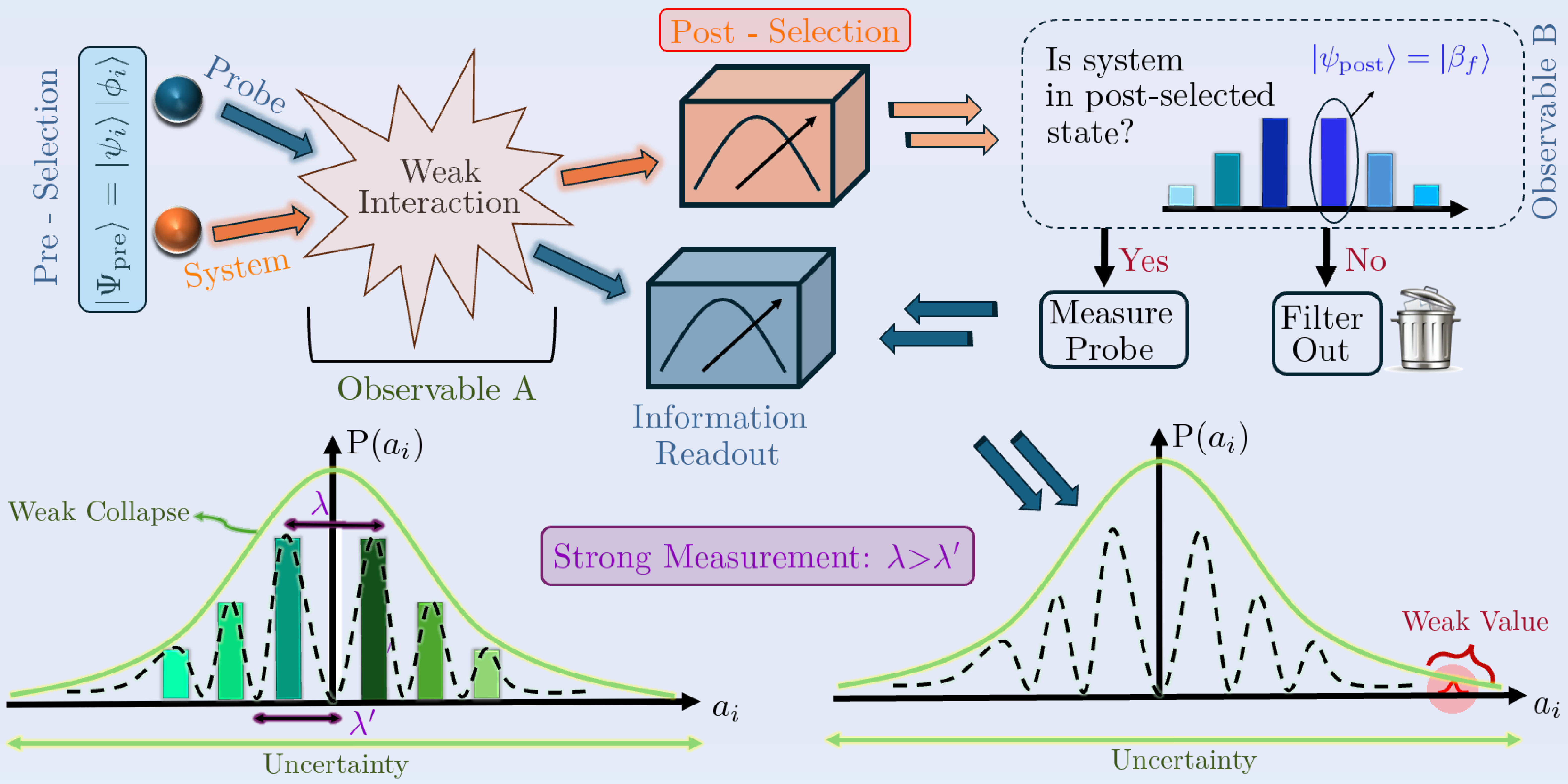


Outline of Weak Measurement Process



Weak Value

Phys. Rev. Lett. **60**, 1351

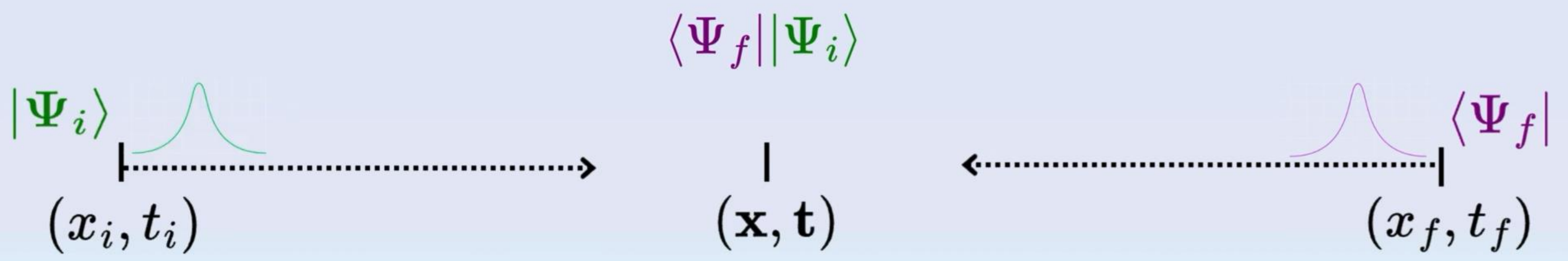
- Average of many slightly perturbed states, with system being in pre- and post-selected states
- Expressed as: $A^w = \frac{\langle\phi|\hat{A}|\psi\rangle}{\langle\phi|\psi\rangle}$
- A^w can lie outside the range of the allowed eigenvalues of a measurement operator
- Can take complex values

Deriving Weak Values from Path Integrals

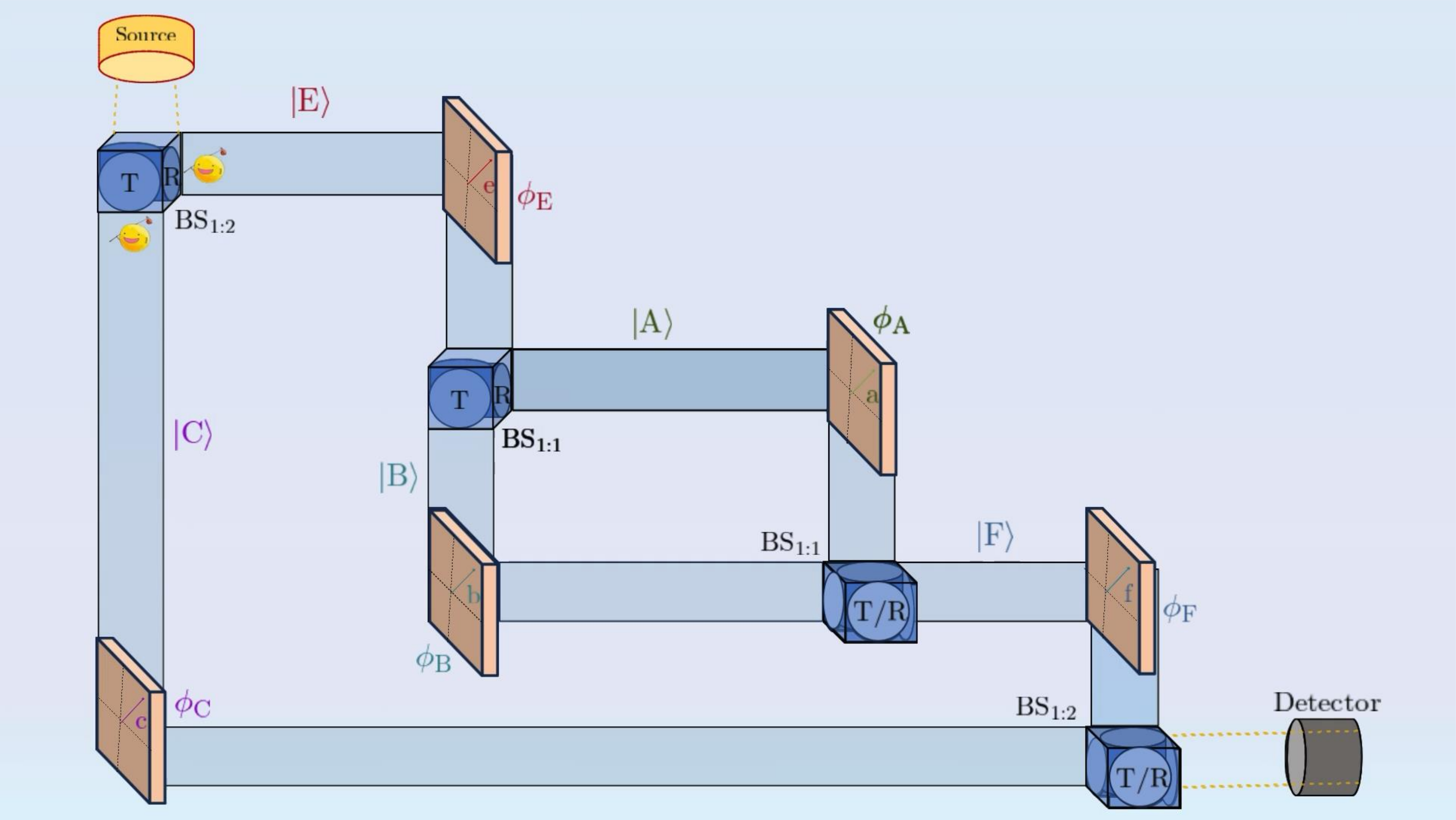
Phys. Rev. Research 2, 032048(R)
Chowdhury S., arXiv:2407.06989 (2024)

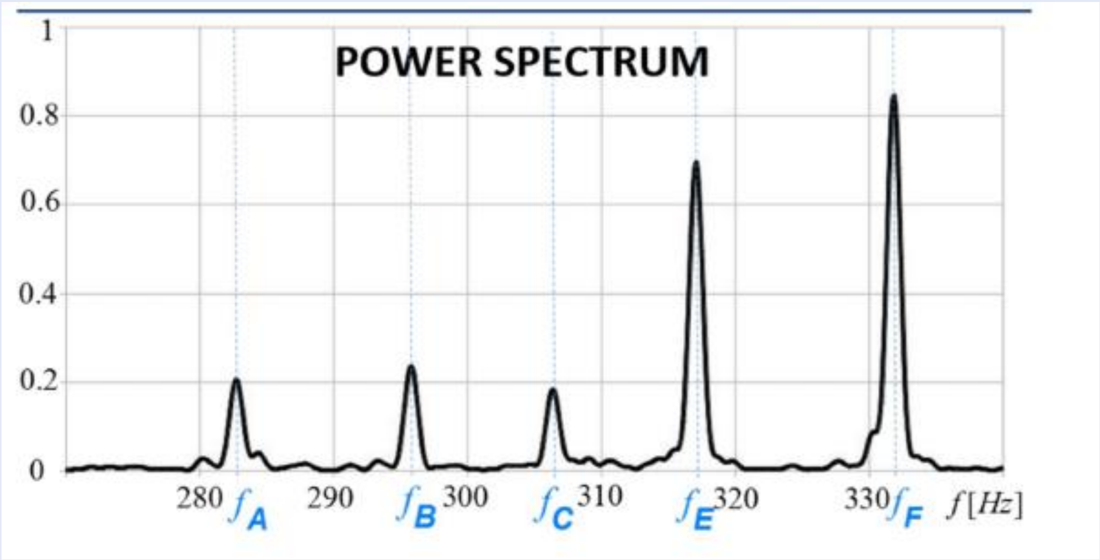
WEAK VALUES + Path Integrals

$$\mathbf{A}^{\mathbf{w}} = \frac{\int dx_i d\mathbf{x} dx_f K_s\Big(x_f, t_f; \mathbf{x}, \mathbf{t}\Big) A(x)\delta(x, \mathbf{X}) K_s\Big(\mathbf{x}, \mathbf{t}; x_i, t_i\Big)\psi(\mathbf{x}, \mathbf{t})\beta^*(\mathbf{x}, \mathbf{t})}{\int d\mathbf{x} dx_f K_s^*\Big(x_f, t_f; x_i, t_i\Big)\psi(\mathbf{x}, \mathbf{t})\beta^*(\mathbf{x}, \mathbf{t})}$$



Particle Paths in a Nested Mach-Zender Interferometer



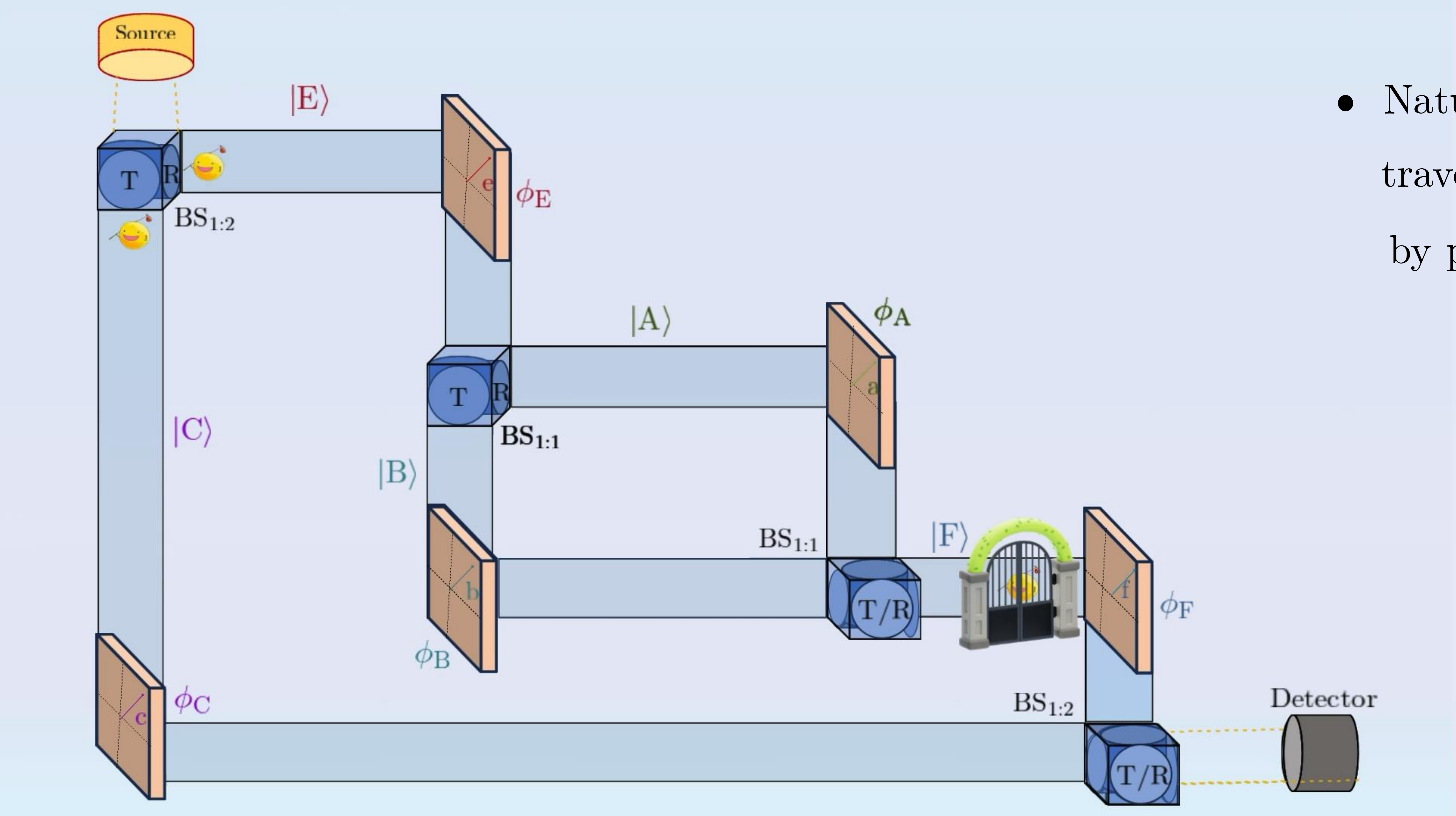


Plots by Danan et al.

Phys. Rev. Lett. 111, 240402

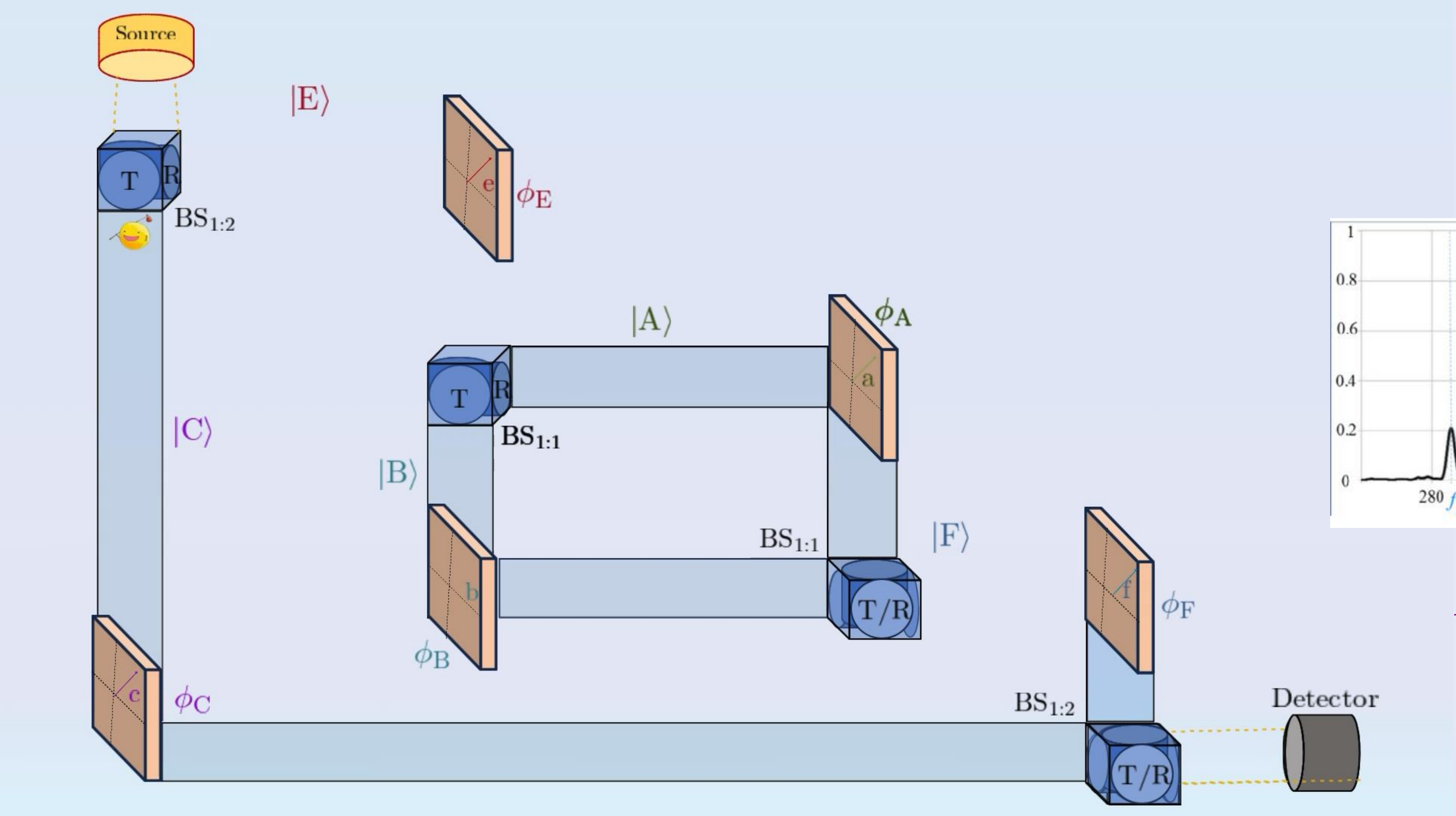
Particle Paths in a Nested Mach-Zender Interferometer

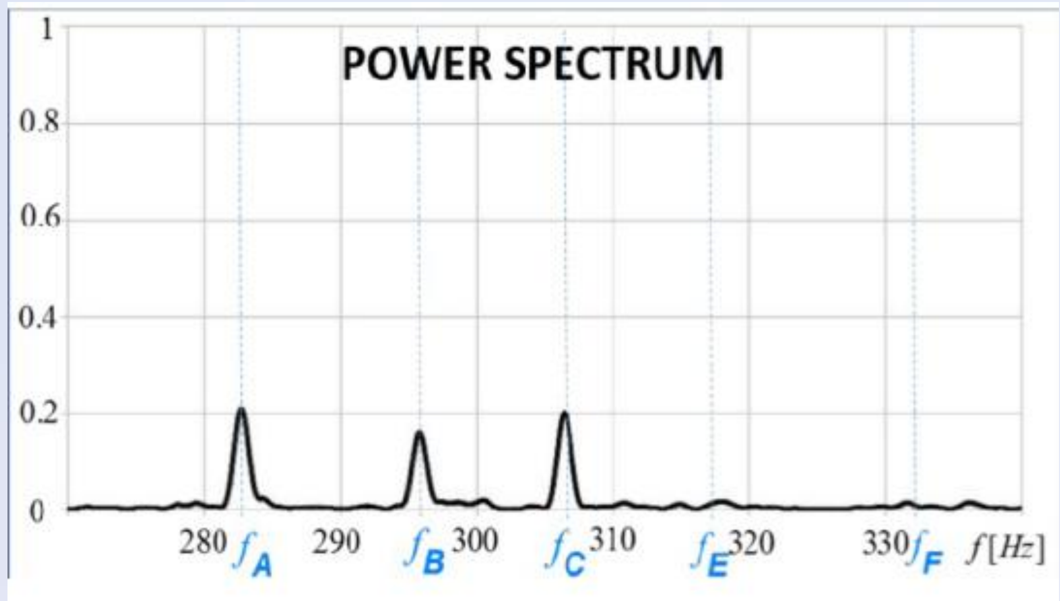
- Tune mirror B to get destructive interference at second beam splitter in inner interferometer preventing beam from reaching Mirror F



- Natural assumption that photon travelled through $|C\rangle$ if detected by post-selected detector

Particle Paths in a Nested Mach-Zender Interferometer





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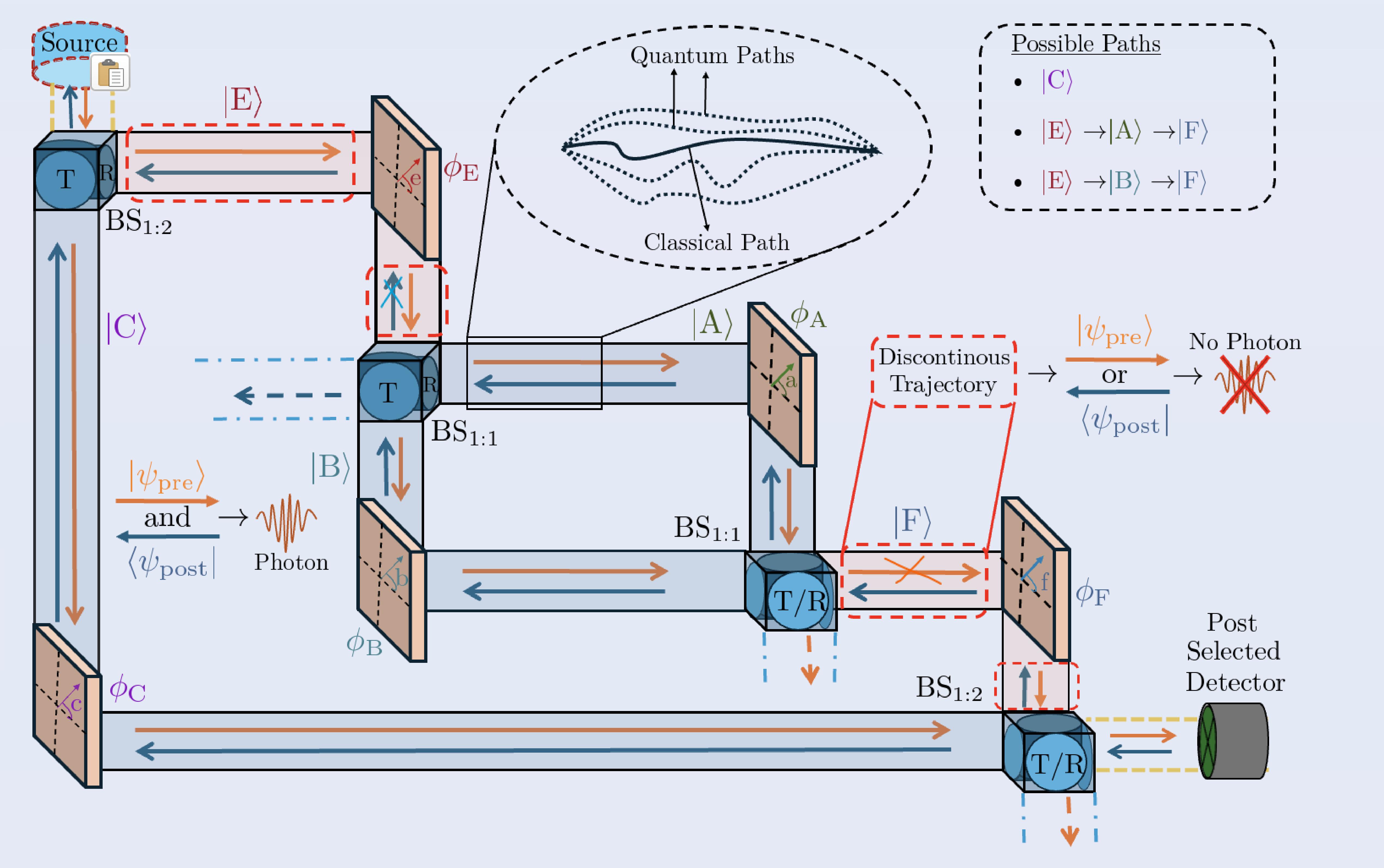
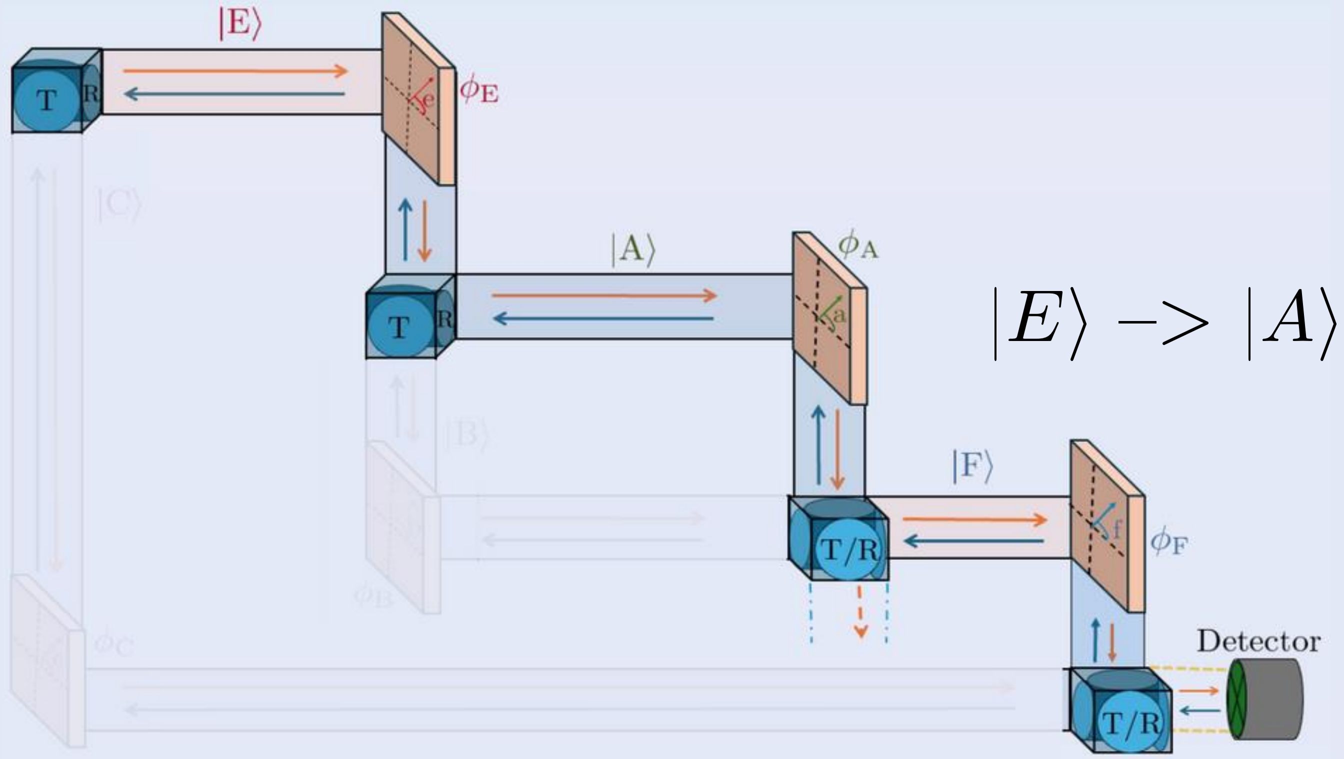


- Two State Vector Formalism

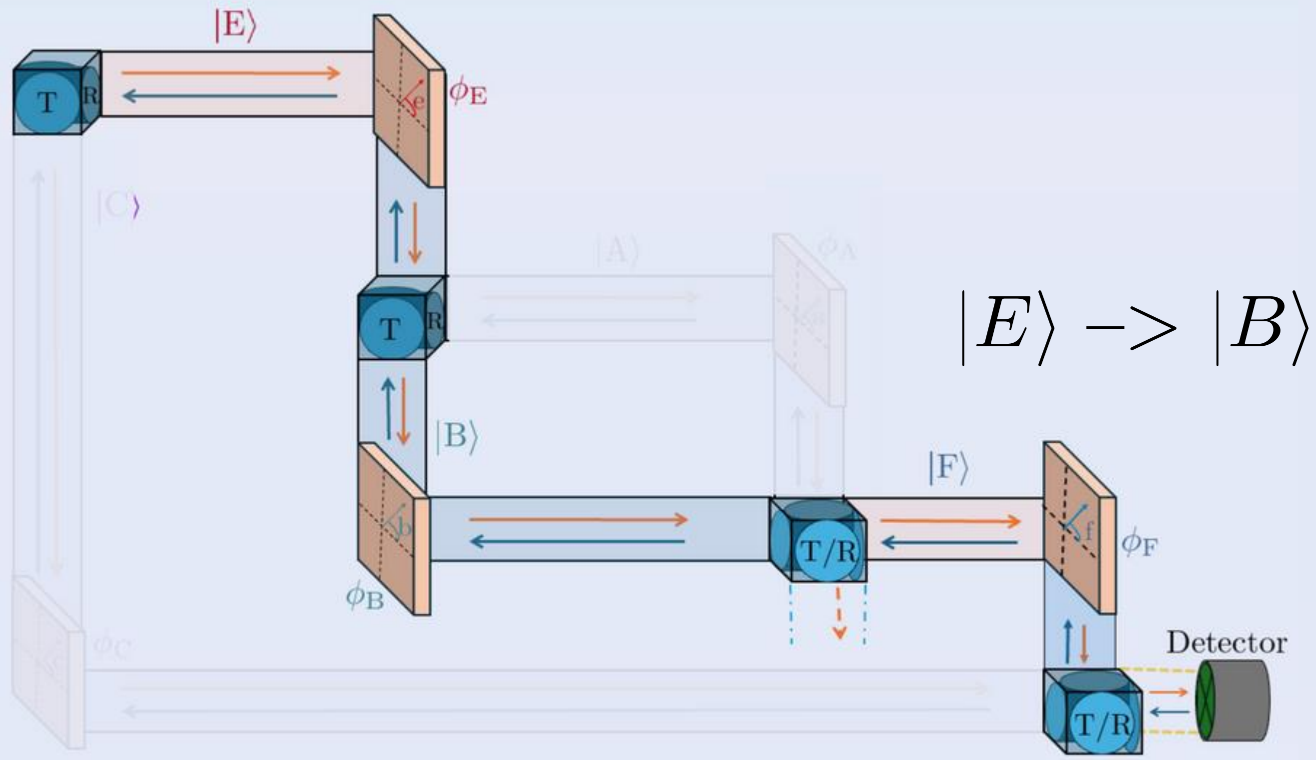
Particle Paths in a Nested Mach-Zender Interferometer

Add all paths (Interference)



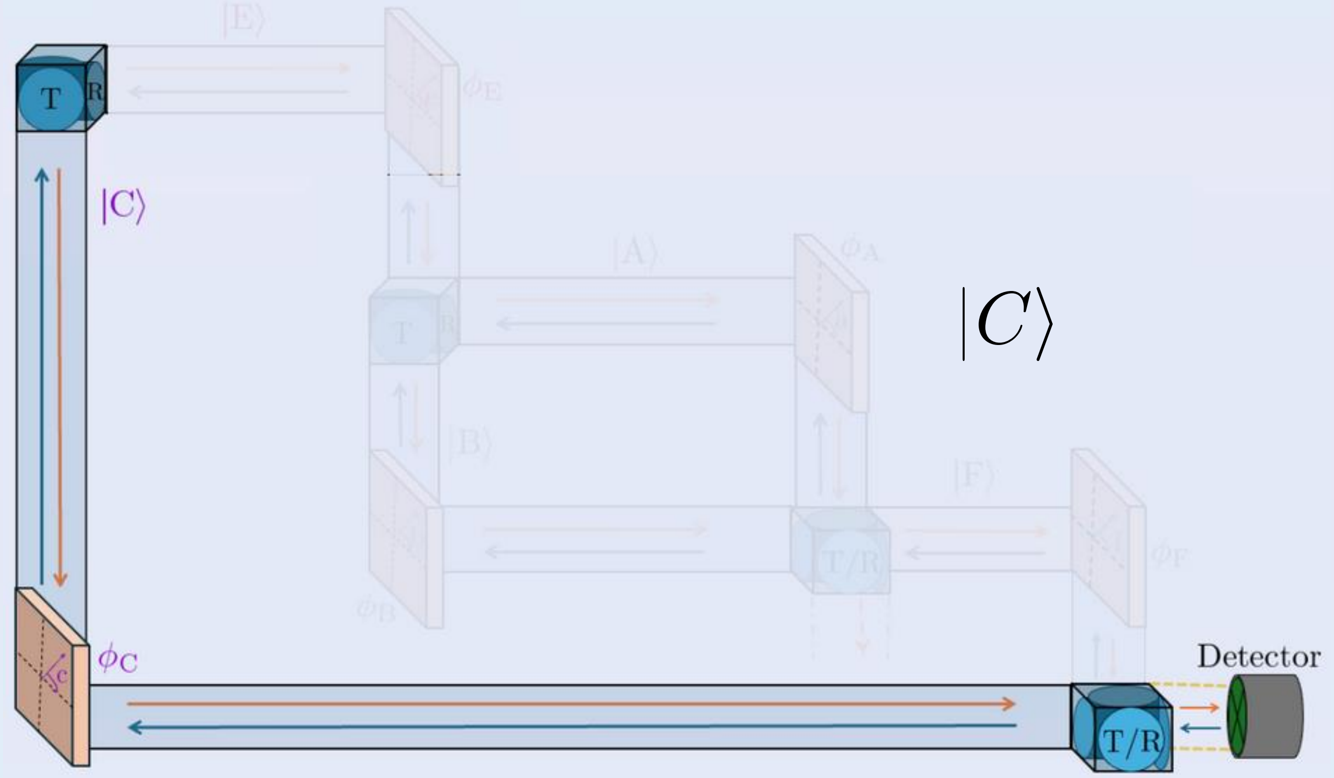
$|E\rangle$ –> $|A\rangle$ –> $|F\rangle$

+



$|E\rangle$ –> $|B\rangle$ –> $|F\rangle$

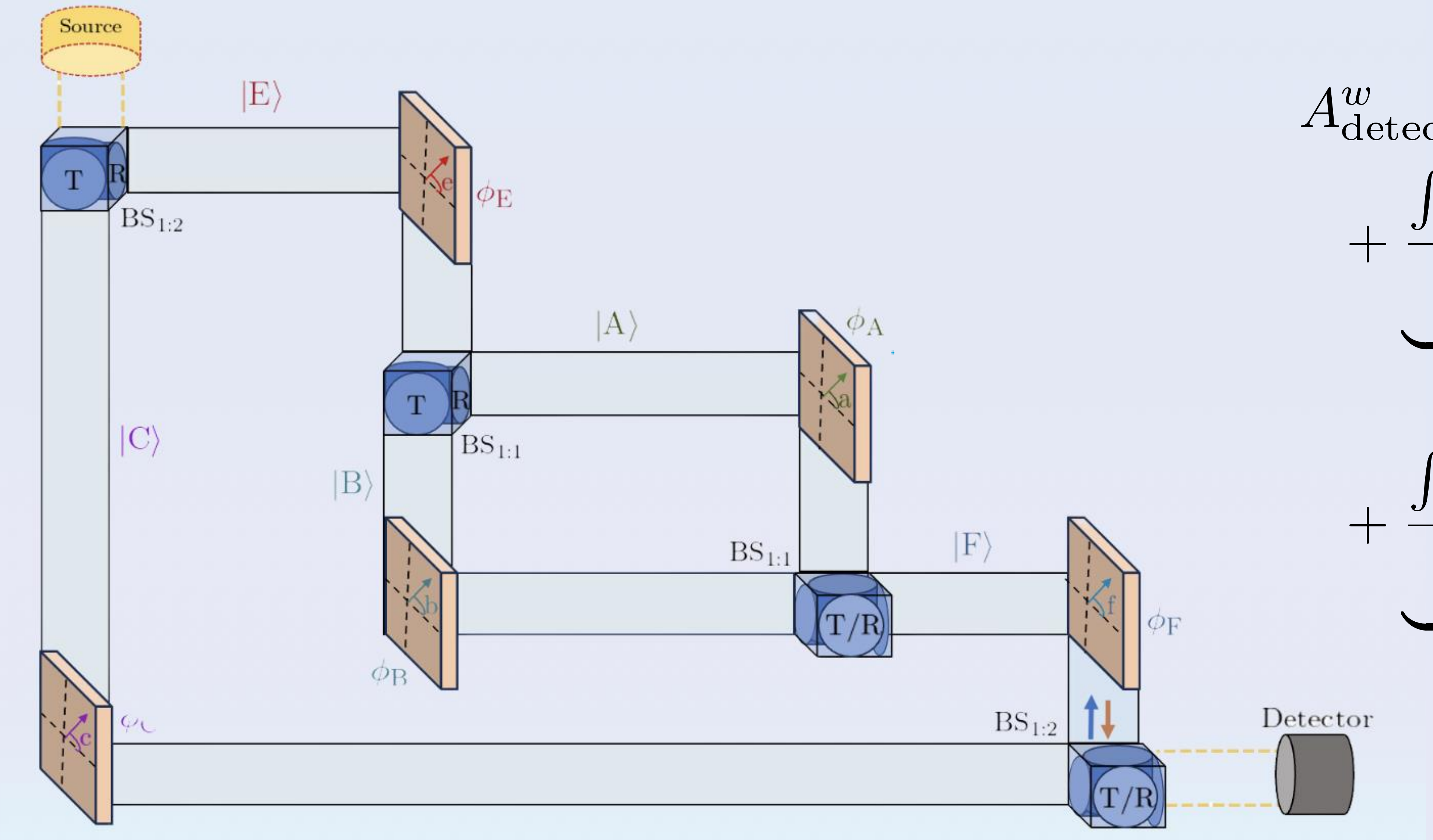
+



$|C\rangle$

Particle Paths in a Nested Mach-Zender Interferometer

Combined Weak Value for Path 1+ Path 2 + Path 3 :

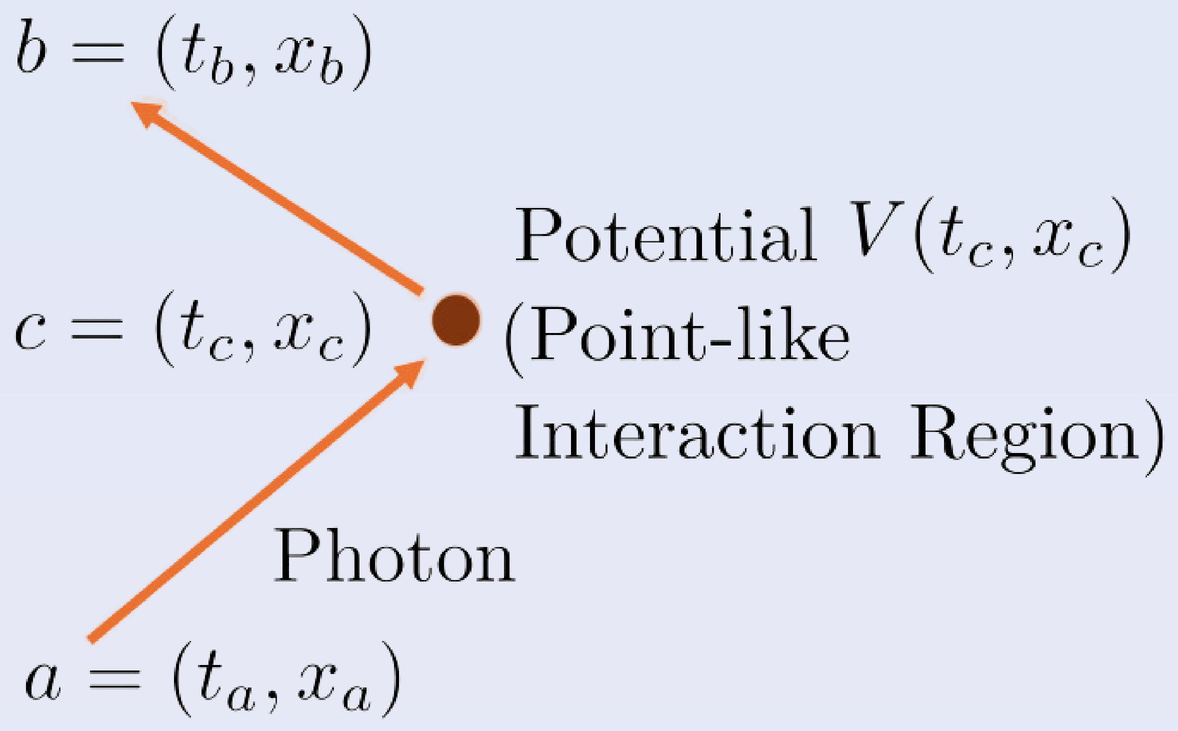


$$A^w_{\text{detector}} = A^w_{\phi_A} + A^w_{\phi_B} + A^w_{\phi_C} + \underbrace{\frac{\int K_s(x_f,t_f;x_i,t_i)_E b^*_f(x_f,t_f)\left[(\boldsymbol{\epsilon}+\boldsymbol{\epsilon})_E\right]\psi(x_i,t_i)}{M_E\dot{X}_E g\int K_s(x_f,t_f;x_i,t_i) b^*_f(x_f,t_f)\psi(x_i,t_i)}}_{A^w_{\phi_E}} + \underbrace{\frac{\int K_s(x_f,t_f;x_i,t_i)_F b^*_f(x_f,t_f)\left[(\boldsymbol{\epsilon}+\boldsymbol{\epsilon})_F\right]\psi(x_i,t_i)}{M_F\dot{X}_F g\int K_s(x_f,t_f;x_i,t_i) b^*_f(x_f,t_f)\psi(x_i,t_i)}}_{A^w_{\phi_F}}$$

If $\epsilon + (-\epsilon)$ for probes E and F, the weak values disappear

Higher Order Terms with a Simpler approach

- Interaction treated as particle scattering on encountering a potential
- Paths can be constructed for successive events with amplitudes, $k(B, A)$, multiplying



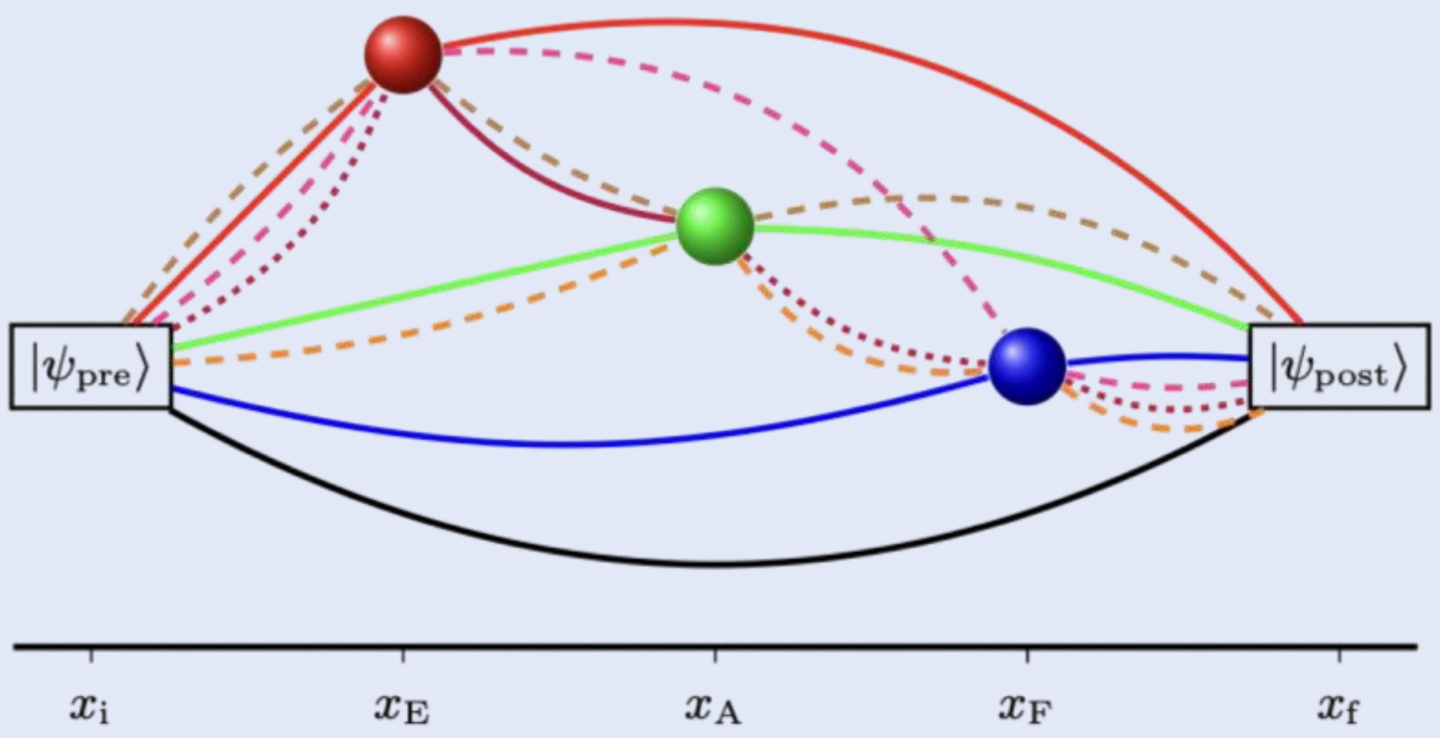
Higher Order Terms with a Simpler approach

Path 1' + Path 2' + Path 3' =

$$3 - \underbrace{(\cancel{\epsilon_A} + \cancel{\epsilon_B} + \epsilon_C) - (2\cancel{\epsilon_E} + 2\cancel{\epsilon_F})}_{\text{1st order}}$$

$$+ \underbrace{[(-\epsilon_A - \epsilon_B)(-\epsilon_E - \epsilon_F) + 2(\epsilon_E \epsilon_F)]}_{\text{2nd order}}$$

$$+ \underbrace{(-\epsilon_A - \epsilon_B)\,\epsilon_E \epsilon_F}_{\text{3 d order}}\,.$$



- excluding second-order terms isn't necessarily justified, so we still have contributions from ϵ_E and ϵ_F in the second order.

- Non-trivial to associate discontinuous paths with 0 weak values without taking into account the second and higher-order terms

Higher Order Terms with a Simpler approach

- Second-order terms could be ascribed as secondary presence arXiv:1312.7566 [quant-ph]

Quantum Cheshire Cats

Yakir Aharonov,[1,2] Sandu Popescu,[3] Daniel Rohrlich,[4] and Paul Skrzypczyk[5]

[1]Tel Aviv University, School of Physics and Astronomy, Tel Aviv 69978, Israel
[2]Schmid College of Science, Chapman University, 1 University Drive, Orange, CA 92866, USA
[3]H. H. Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol, BS8 1TL, United Kingdom
[4]Physics Department, Ben Gurion University of the Negev, Beersheba, Israel
[5]Department of Applied Mathematics and Theoretical Physics, University of Cambridge,
Centre for Mathematical Sciences, Wilberforce Road, Cambridge CB3 0WA, United Kingdom

In this paper we present a quantum Cheshire Cat. In a pre- and post-selected experiment we find the Cat in one place, and its grin in another. The Cat is a photon, while the grin is its circular polarization.

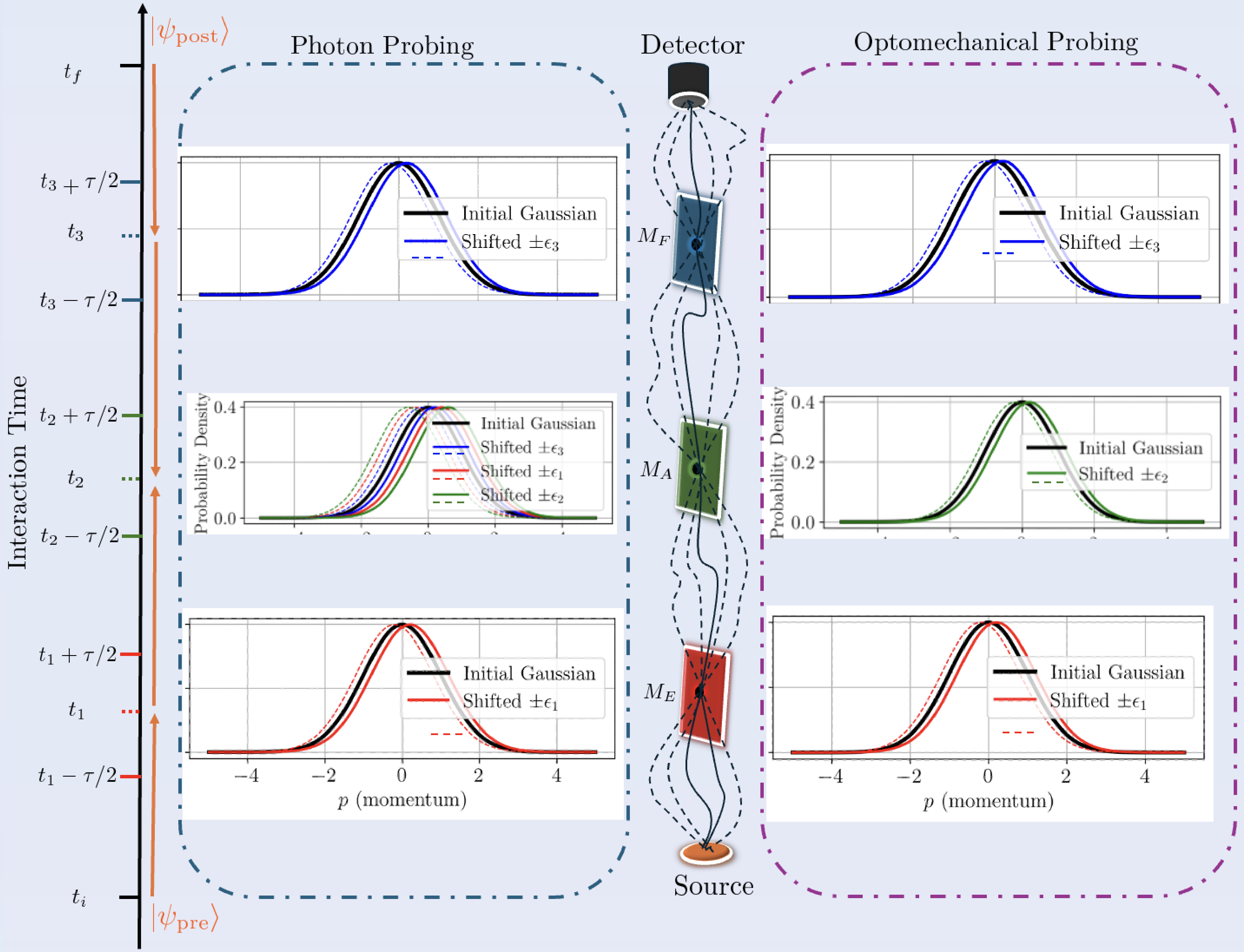
I. INTRODUCTION

'All right,' said the Cat; and this time it vanished quite slowly, beginning with the end of the tail, and ending with the grin, which remained some time after the rest of it had gone.

'Well! I've often seen a cat without a grin,' thought Alice, 'but a grin without a cat! It's the most curious thing I ever saw in my life!'

No wonder Alice is surprised. In real life, assuming that cats do indeed grin, the grin is a *property* of the cat – it makes no sense to think of a grin without a cat. And this goes for almost all physical properties. Polarization is a property of photons; it makes no sense to have polarization without a photon. Yet, as we will show here, in the curious way of quantum mechanics, photon polarization may exist where there is no photon at all. At least this is the story that quantum mechanics tells via measurements on a pre- and post-selected ensemble.

Experimental Proposal - Optomechanical Treatment



- May reduce discrepancies between theory and experiment
- Mirrors mounted on harmonic mechanical oscillators, initially on ground state
- Oscillator move from its ground state given enough photons interact
- Feedback post-selection

Conclusion

Higher order weak values for paths in nested Mach-Zender interferometers

Shushmi Chowdhury, Jörg B. Götte

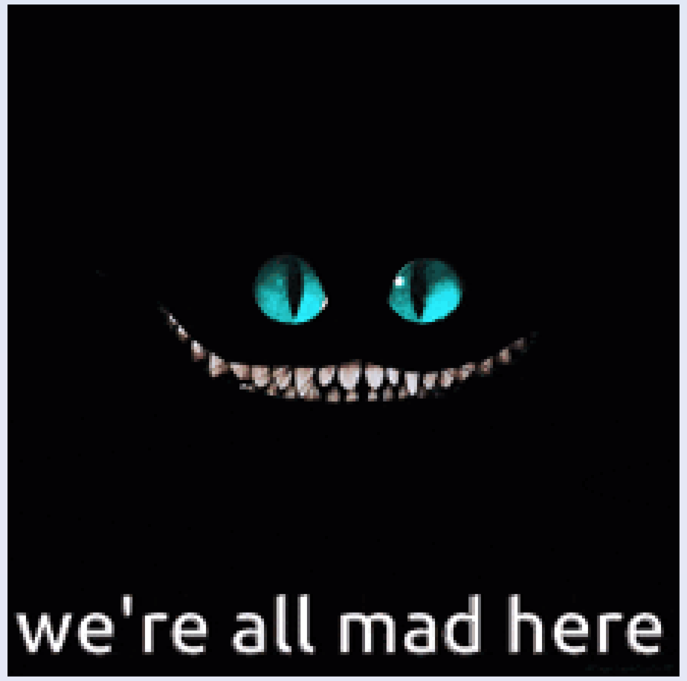
We consider weak values in the Feynman propagator framework, to gain a broader understanding of their interpretation in terms of path integrals. In particular, we examine the phenomenon of seemingly discontinuous paths that particles take in nested Mach-Zender interferometer experiments. We extend on existing path integral approaches for weak values by deriving expressions to model a sequence of weak measurements, and study the probe shifts across the different branches of a weak value interferometer. We apply this to scrutinise two scenarios of interest, one which treats photons as measurement apparatus via their spatial projection operators, and the second treating mirrors as probes.

Comments: 14 pages, 7 figures plus one in appendix
Subjects: **Quantum Physics (quant-ph)**
Cite as: arXiv:2407.06989 **[quant-ph]**
(or arXiv:2407.06989v1 **[quant-ph]** for this version)
https://doi.org/10.48550/arXiv.2407.06989

Submission history
From: Jörg Götte [view email]
[v1] Tue, 9 Jul 2024 16:04:05 UTC (4,036 KB)

Just the cool ideas, not pages of derivation.

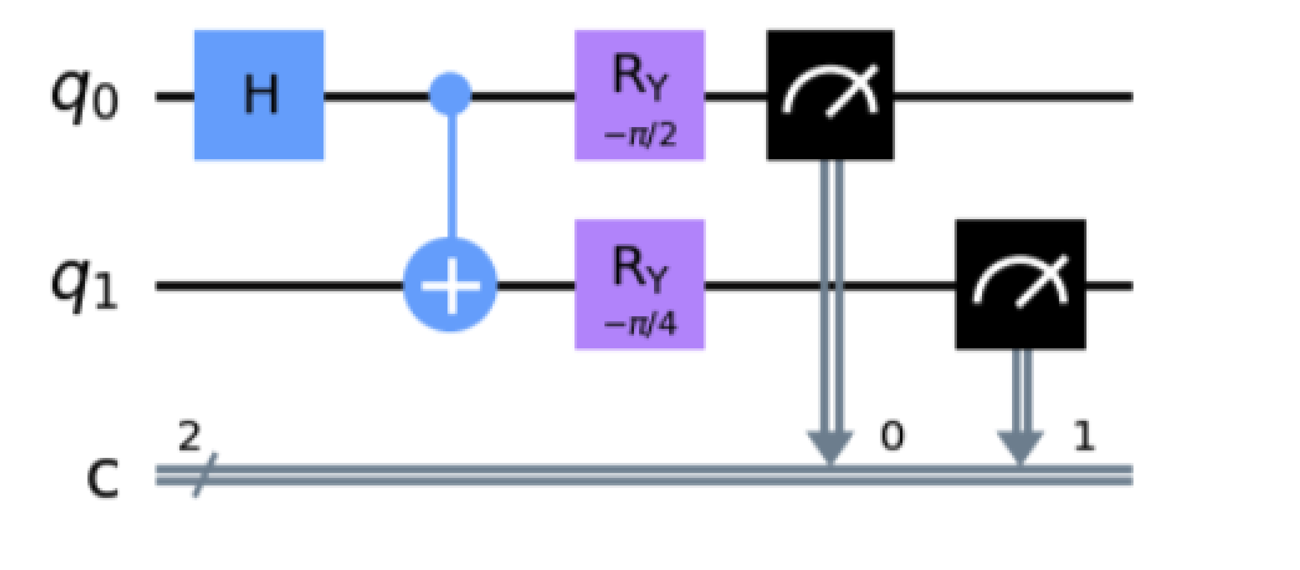
Because why not -



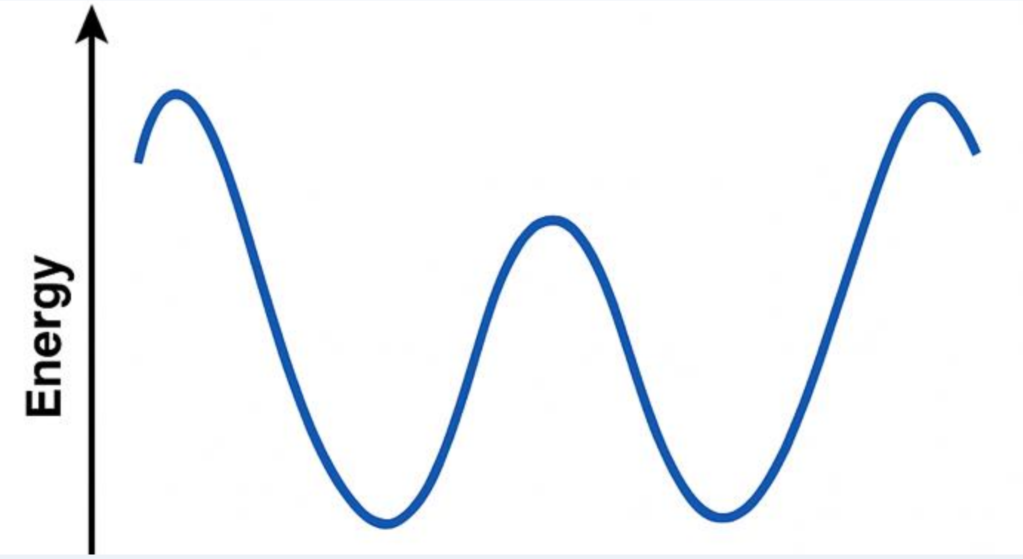
Time for some Quantum Computing…

We have heard a lot about digital Quantum Computers but what about Analog?

- Like programming a classical computer, but with **qubits.**



- System naturally evolves toward the **lowest-energy state**.



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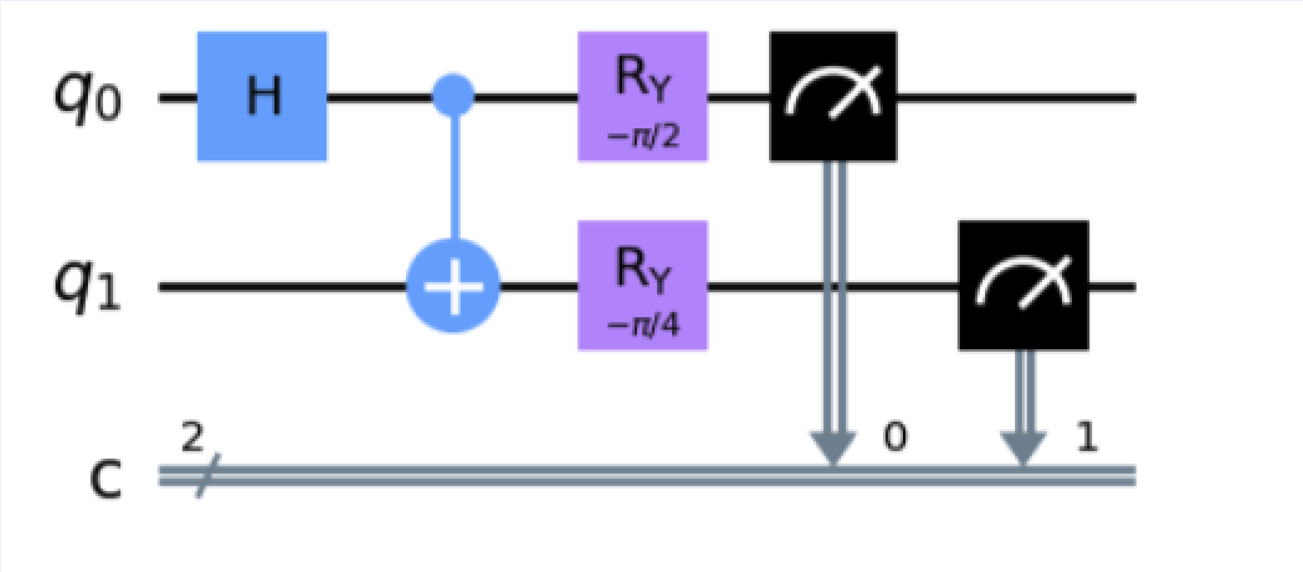


IONQ

- System naturally evolves toward the **lowest-energy state**.

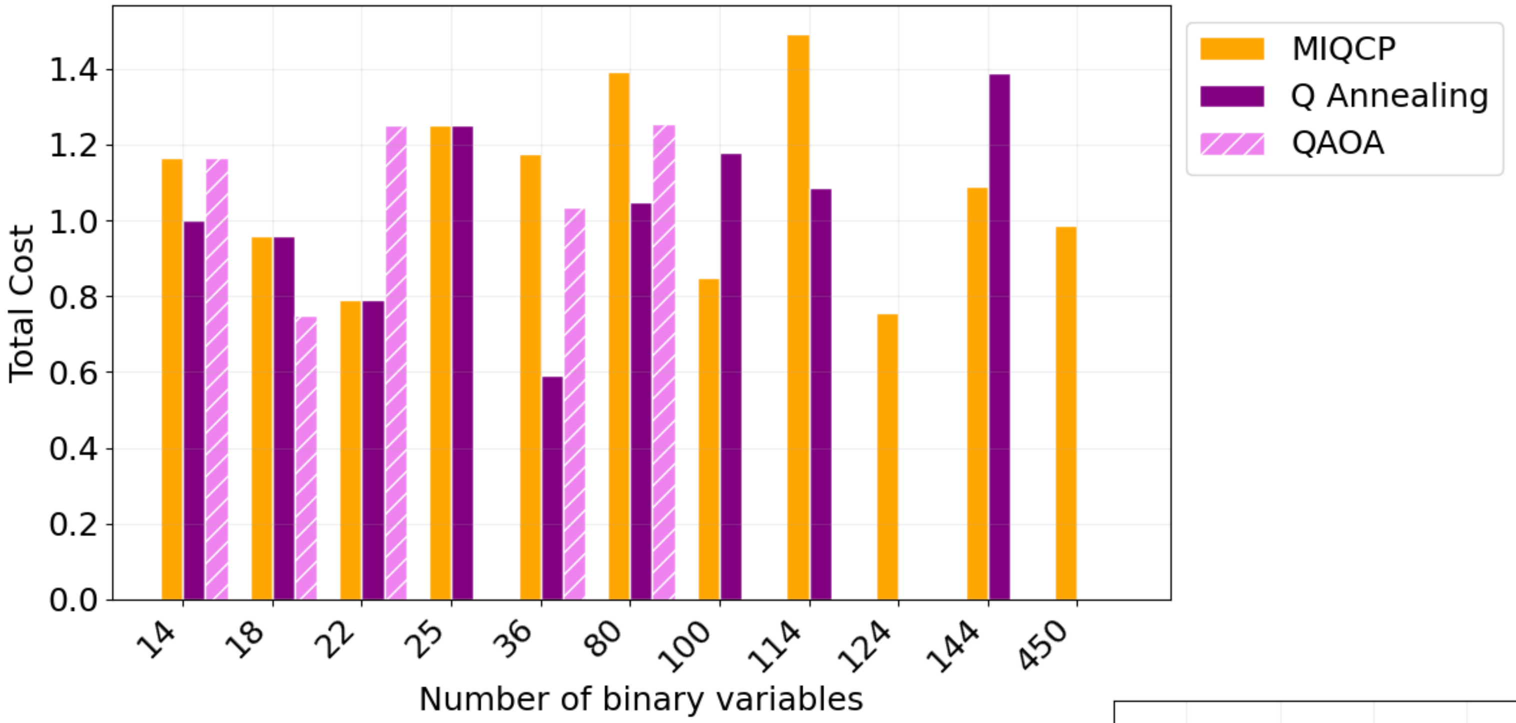
- **Not universal**
- **Only specific problems can be encoded**
- **Can run quantum algorithms like Shors, Grovers, QAOA**

Computing Inc.

QUANTINUUM

UK Quantum Hackathon

- More vehicles -> more road wear
- Tight budgets -> need smarter planning
- Scheduling road maintenance is a complex
- combinatorial problem, hard to find optimal
- solutions at increasing scales
- How can quantum hardware help with this issue?



GUROBI OPTIMIZATION

D-Wave

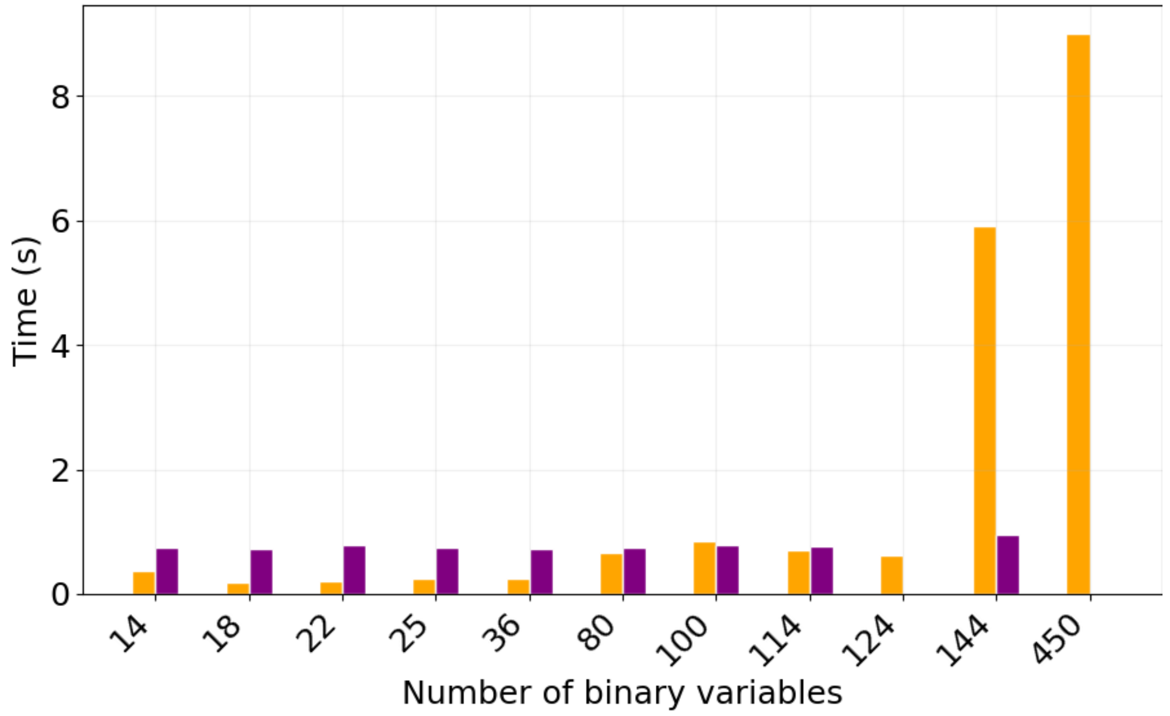
Qiskit

Iteratively solving QUBO using D-Wave

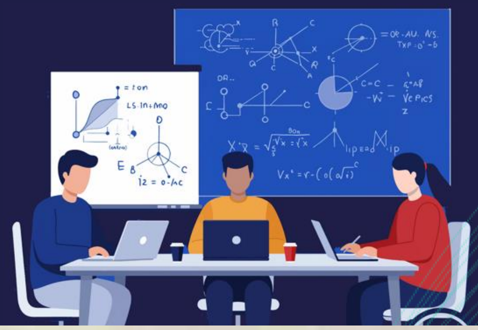
5000 runs, 30 micro-seconds

Quantum Hardware	Qiskit IBM	D-Wave (Zephyr)
Qubits	156	4596

UKRI National Quantum Computing Centre



UK Quantum Hackathon



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GUROBI OPTIMIZATION

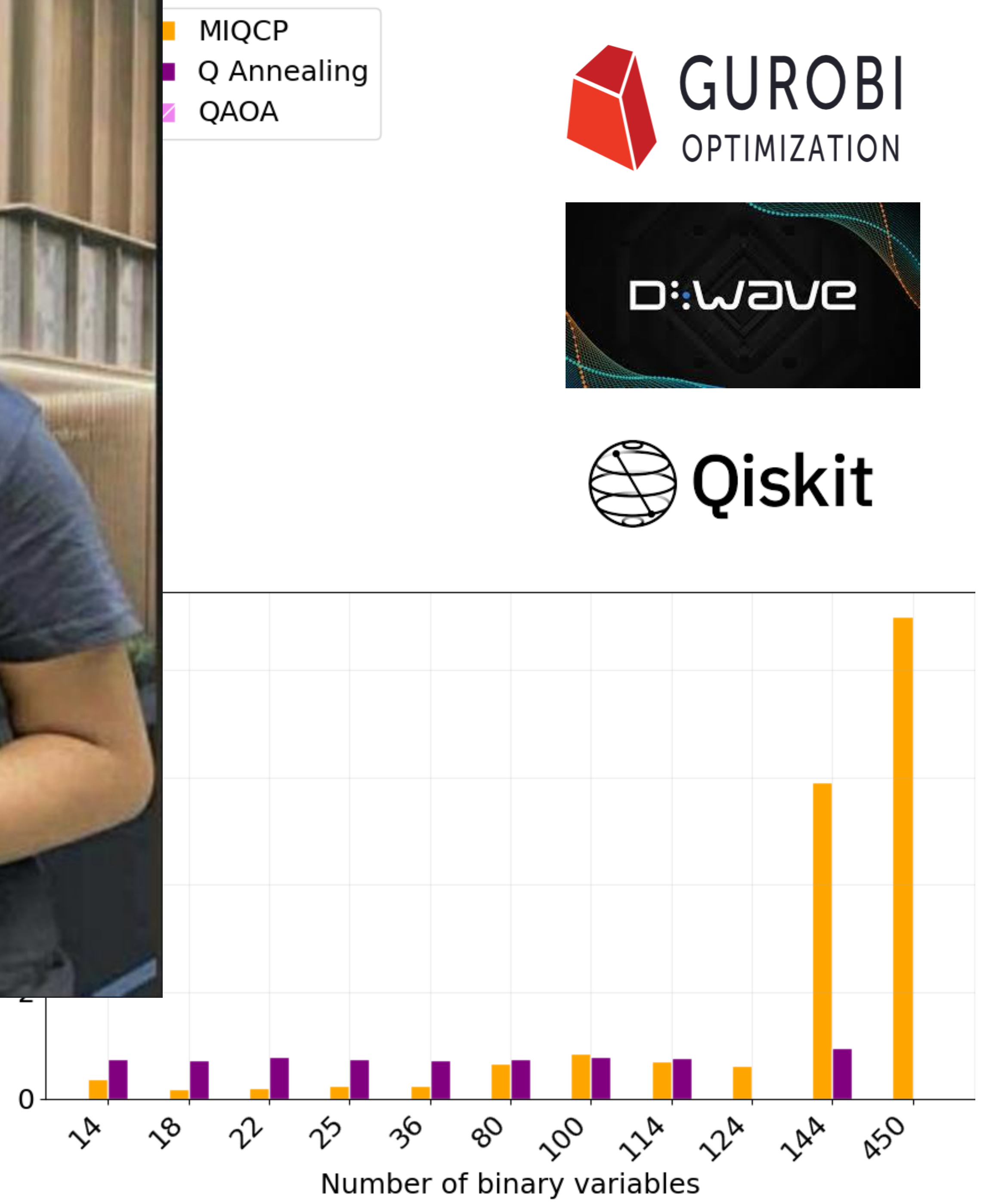
D:WAVE

Qiskit

QUBO

Quantum Hardware	Qiskit IBM	D-Wave (Zephyr)
Qubits	156	4596

National Quantum Computing Centre



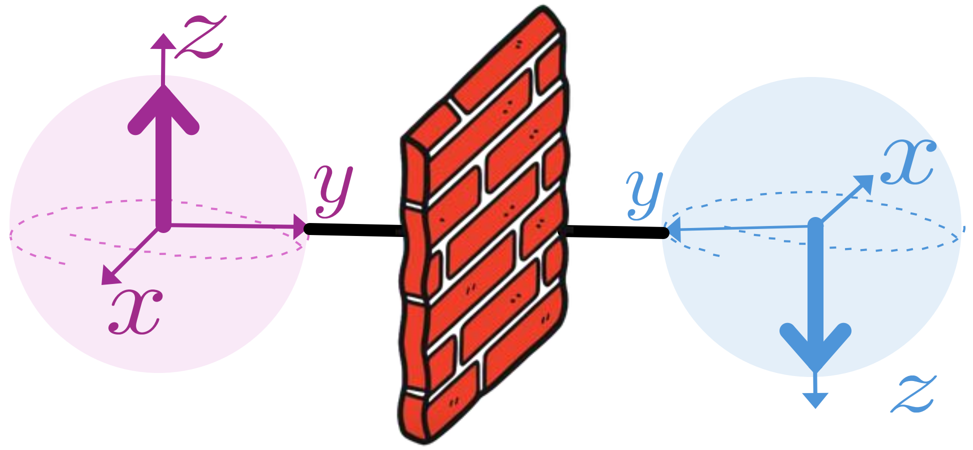
University of Strathclyde Glasgow

Benchmarking coherence and noise through domain-wall distributions in quantum annealers

Shushmi Chowdhury[1], Asa Hopkins[1], Nicholas Chancellor[2] and Viv Kendon [1]

[1]CNQO, Department of Physics, University of Strathclyde

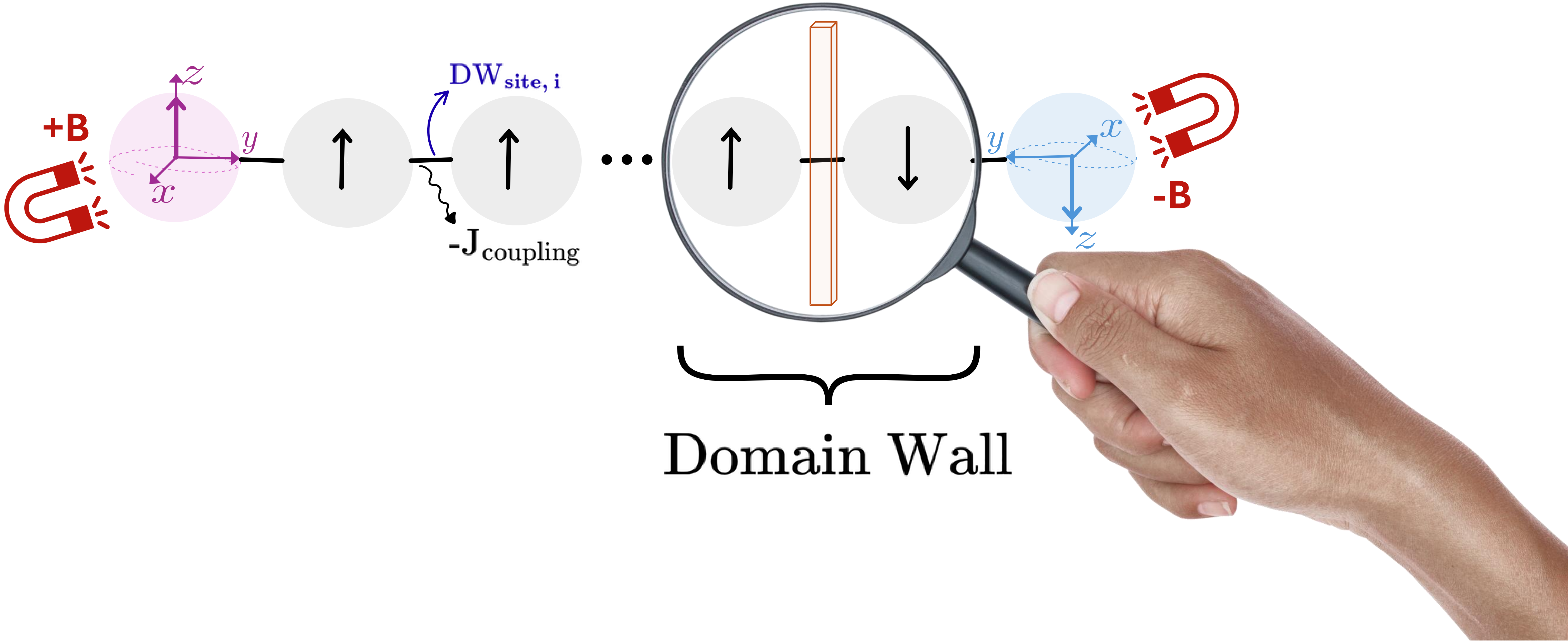
[2]School of Computing, Newcastle University



IGSQT International Graduate School for Quantum Technologies

Motivation

A finite ferromagnetic spin chain in which the spins at the two ends of the chain are constrained to have opposite polarisations, thereby introducing an inherent frustration into the system.



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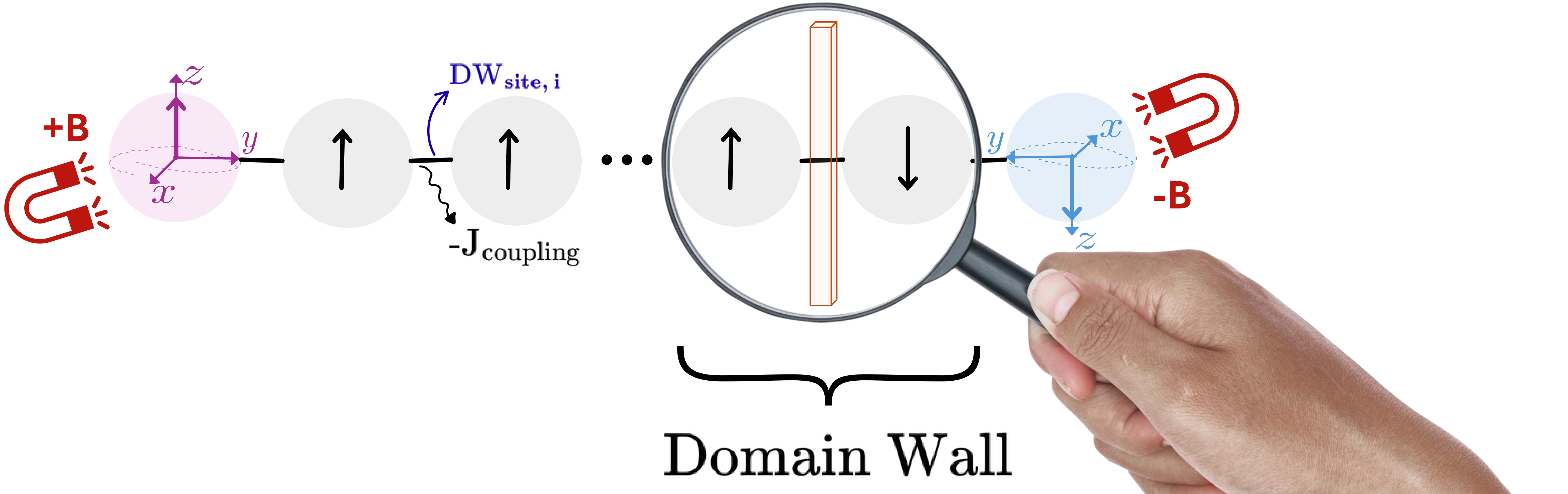

Problem formulated using: $H_{Ising} = J\sum_{i=1}^{N} -\sigma_i^z\sigma_{i+1} + h(\sigma_i^z - \sigma_{N+1}^z)$

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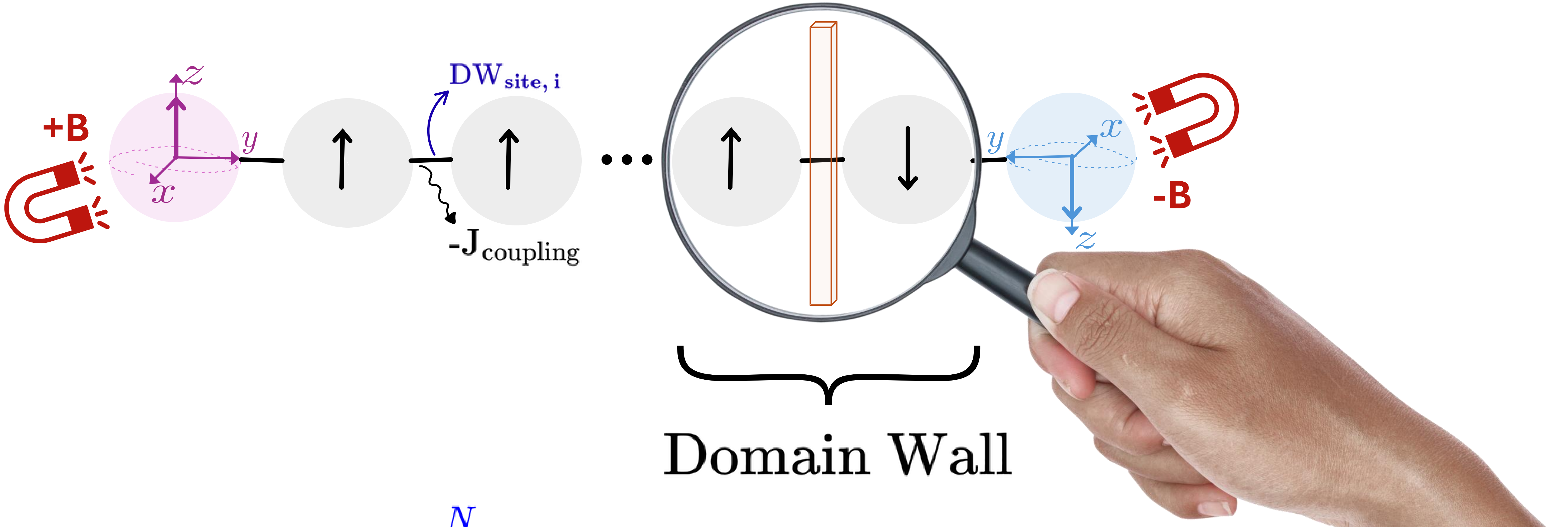

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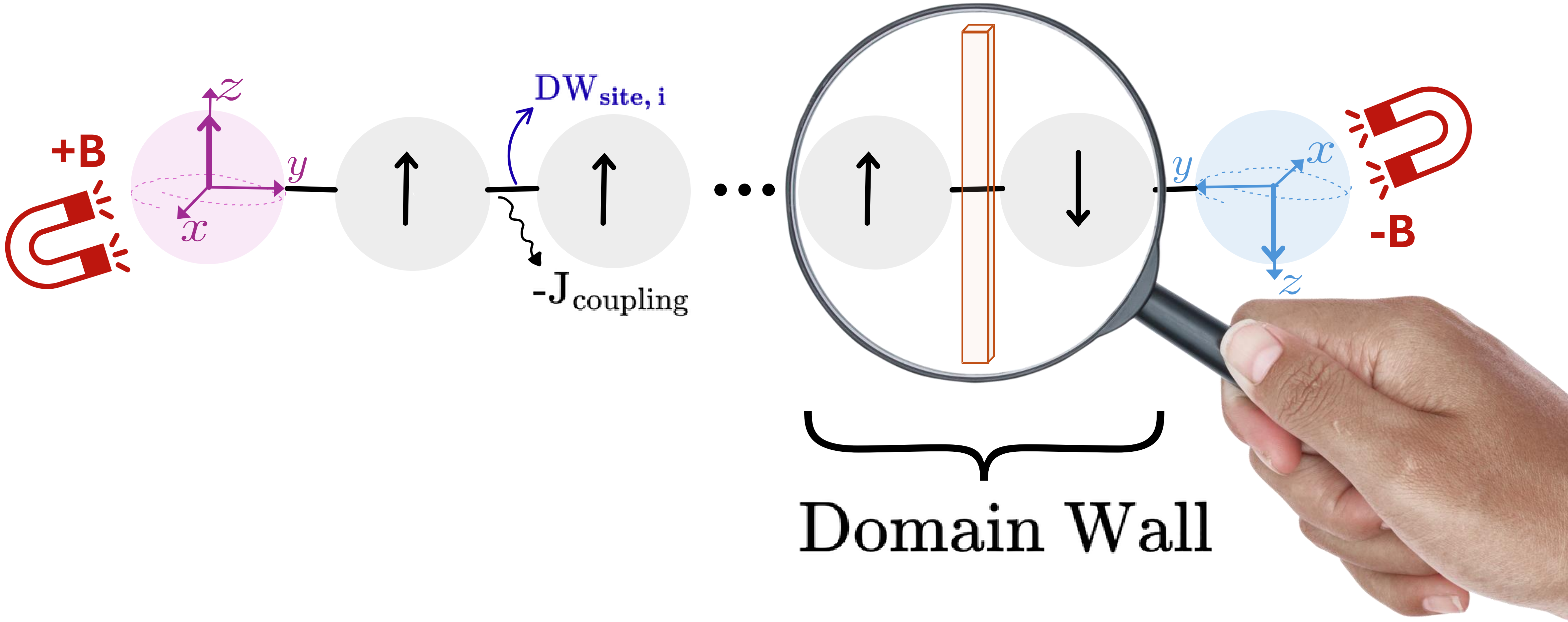
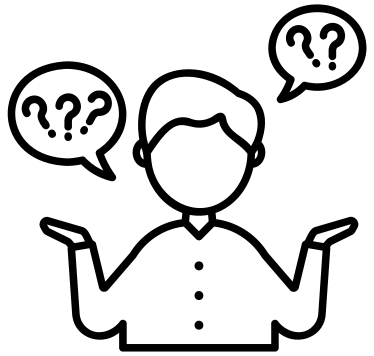
$$\left.\begin{aligned} &\text{Ferromagnetic}: \ H = -J\sum_i \sigma_i\sigma_{i+1} = -J(1)(1). \\ &\text{Anti-Ferromagnetic}: \ H = -J\sum_i \sigma_i\sigma_{i+1} = -J(-1)(1) \end{aligned}\right\} \text{Energy Penalty}: |E_{ferro} - E_{anti}| = 2J$$

Motivation

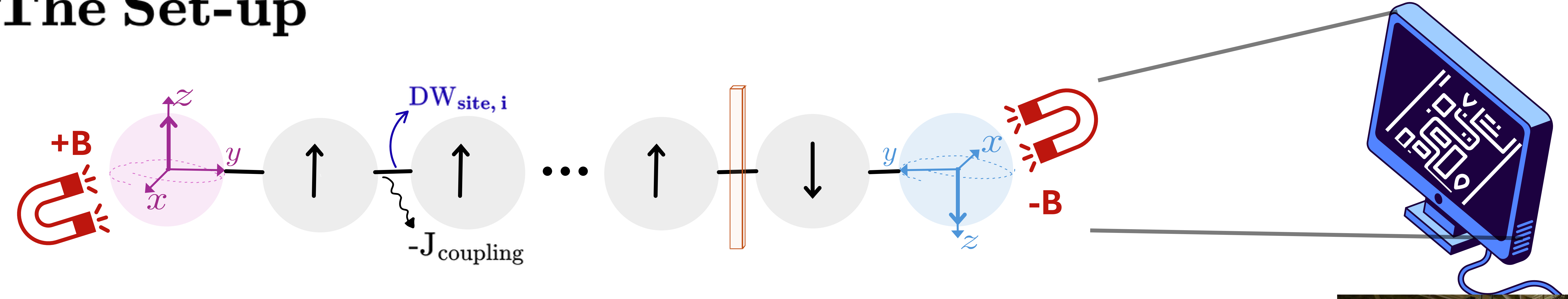




Why we care: The domain wall location reflects how the system resolves frustration

What it tells us:
- Domain-wall distributions provide a simple probe of *coherence* and *noise*.
- Short Ising chains offer a minimal model for benchmarking device quality.
- Shape of the domain-wall distribution indicates regime of the device, classical to coherent.

The Set-up



D-Wave implements transverse field Ising Model (TFIM):

$$H(t) = -A(t)\sum_{i=1}\sigma_i^x + B(t)\underbrace{H_{Ising}}_{= J\sum_{i=1}^{N} -\sigma_i^z\sigma_{i+1} + h(\sigma_i^z\sigma_{N+1}^z)}$$

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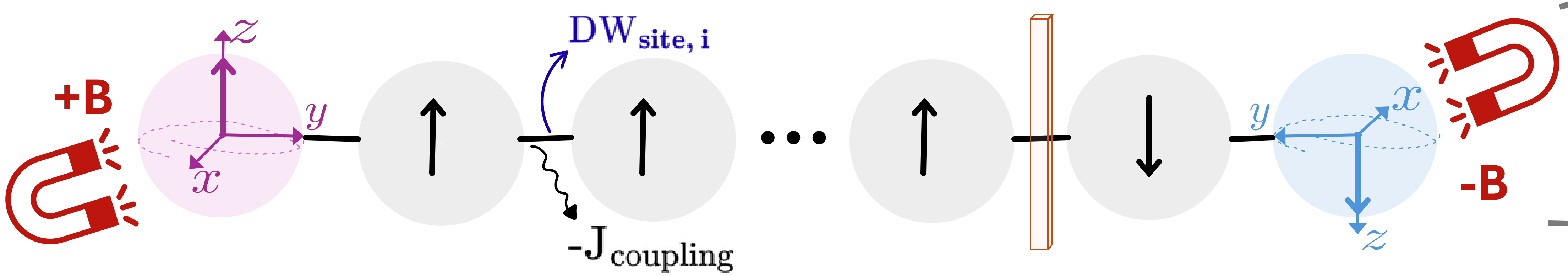

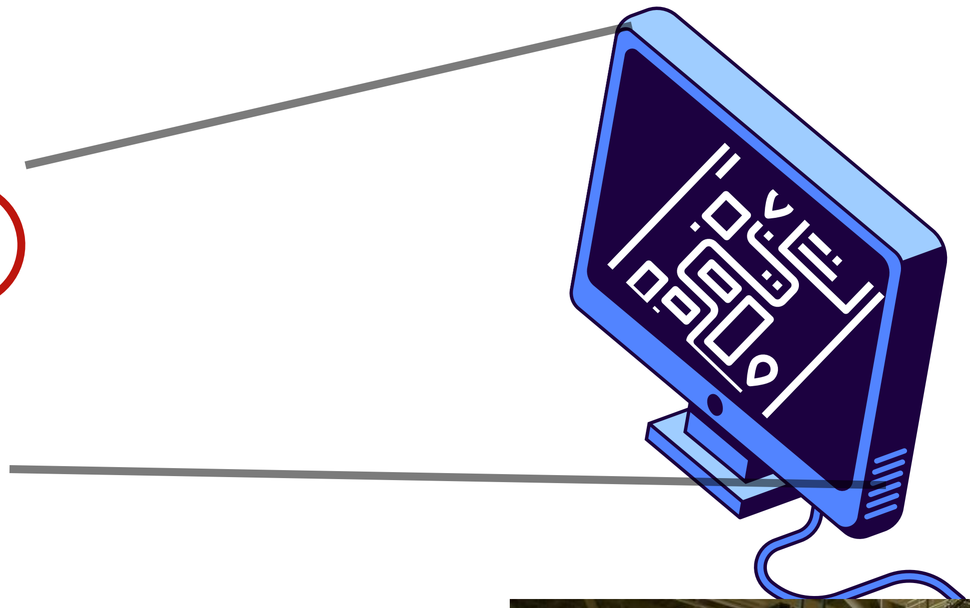

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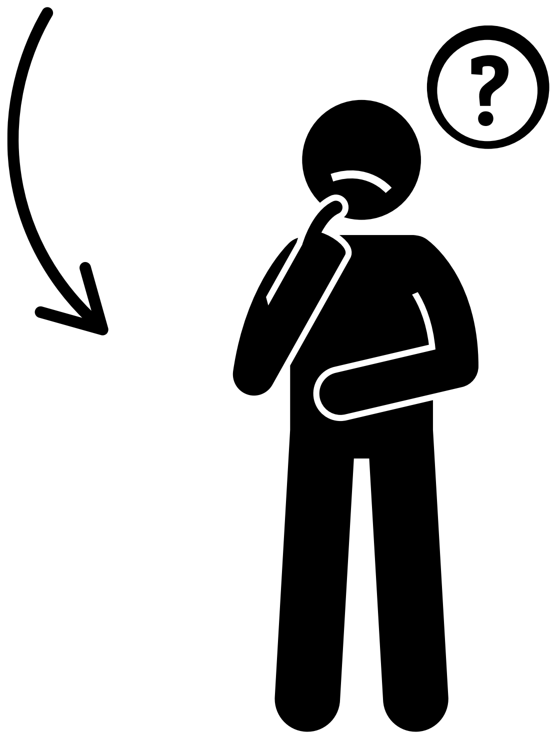
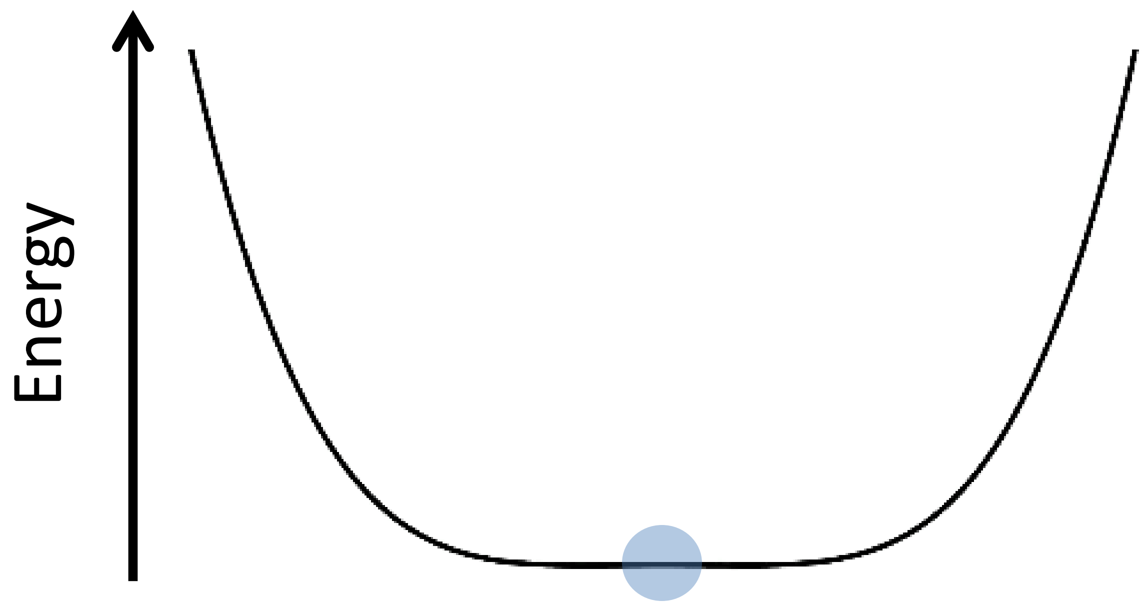


Quantum Annealing



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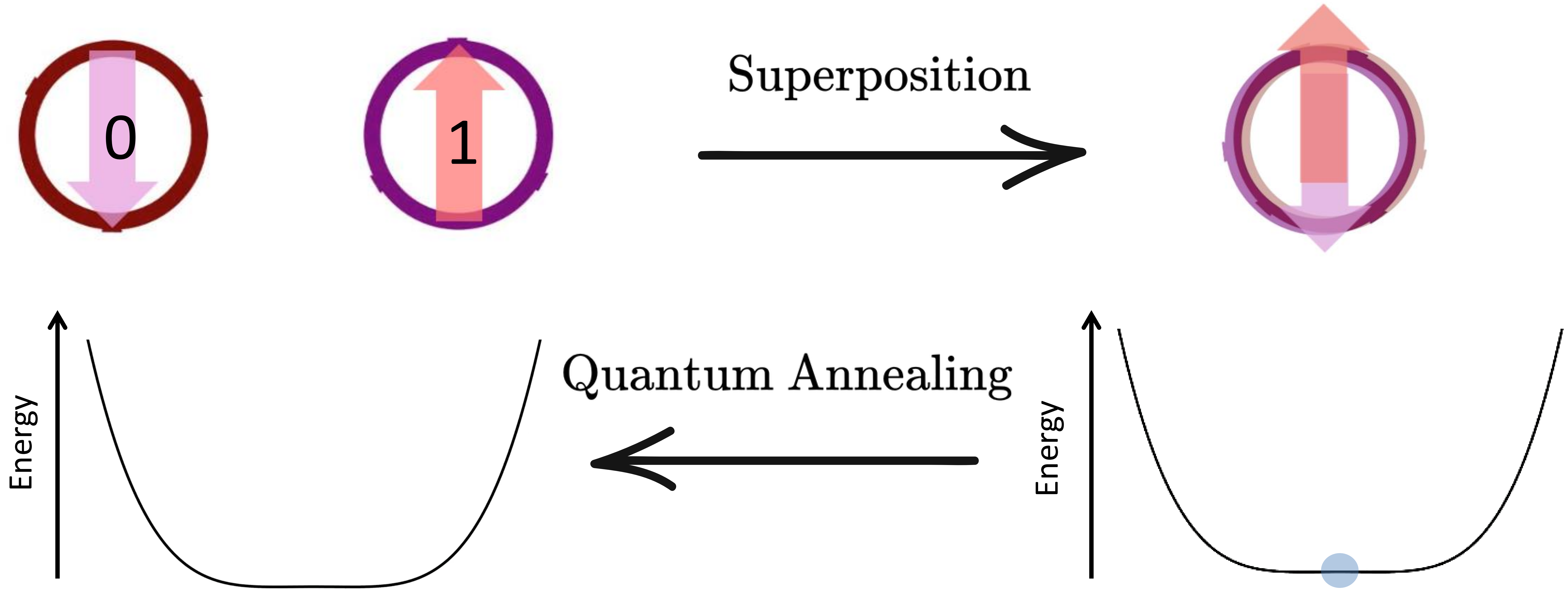

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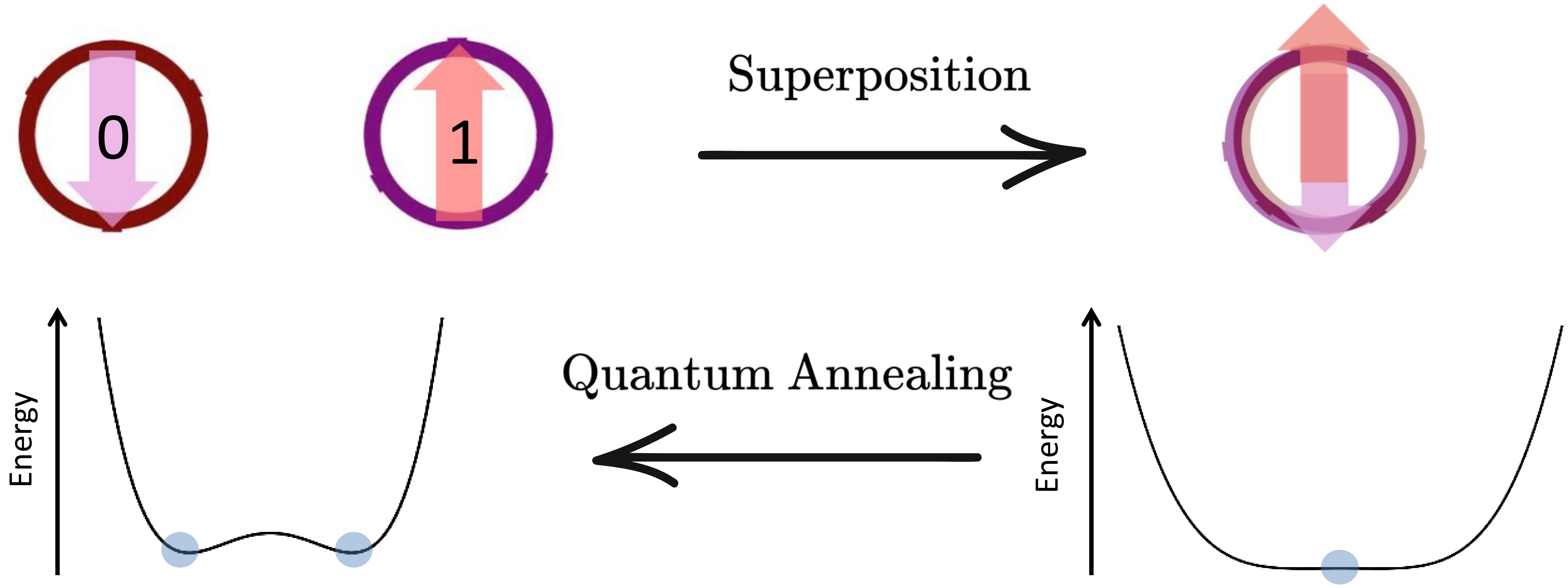

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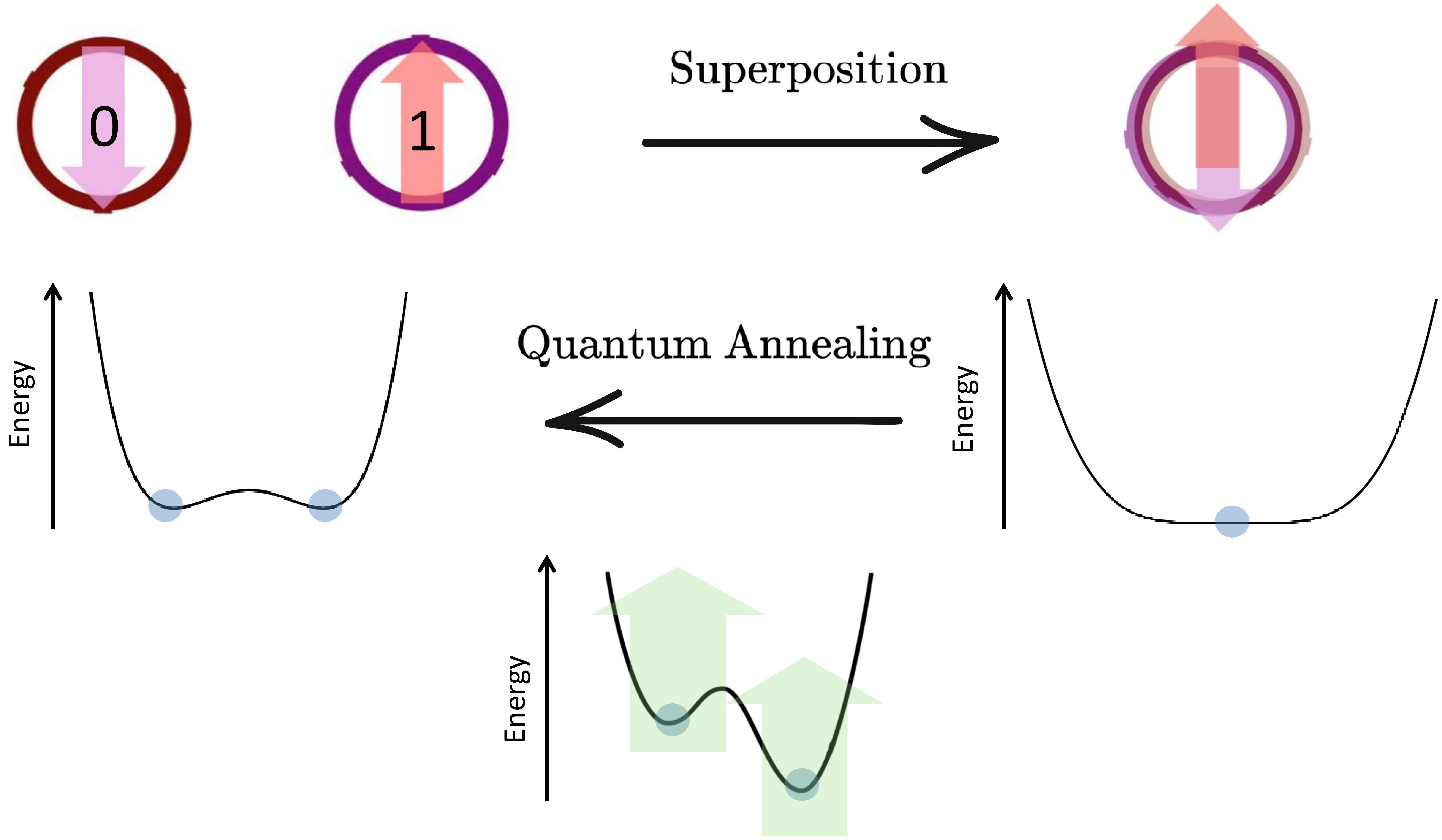

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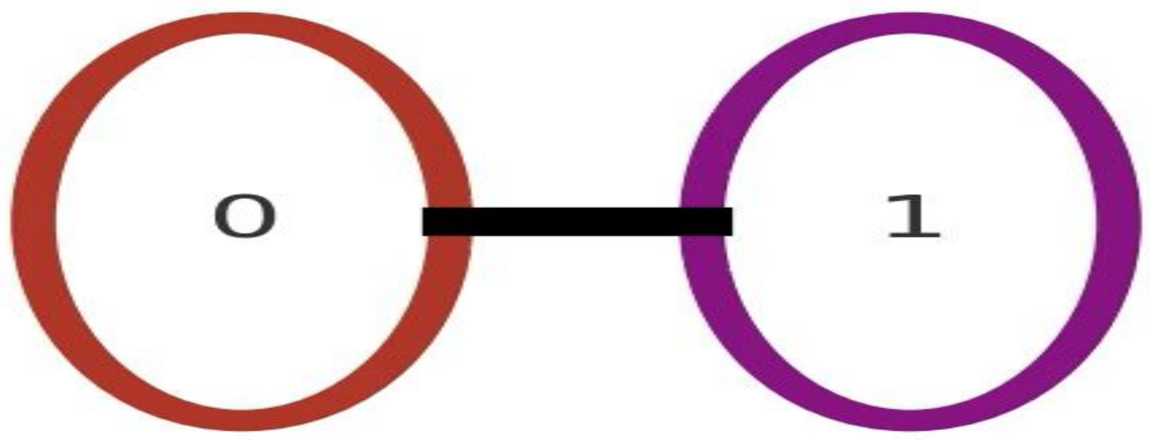

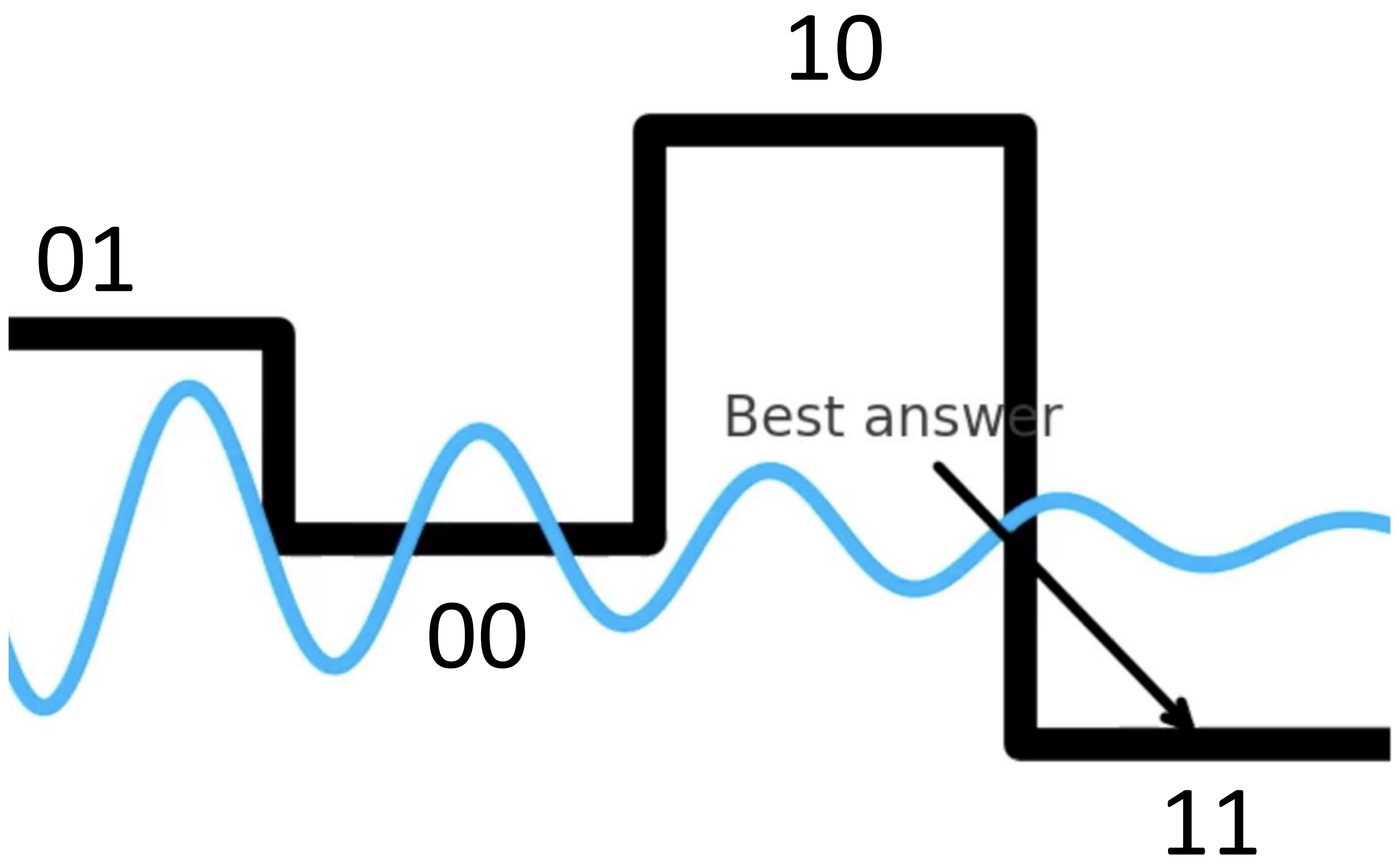

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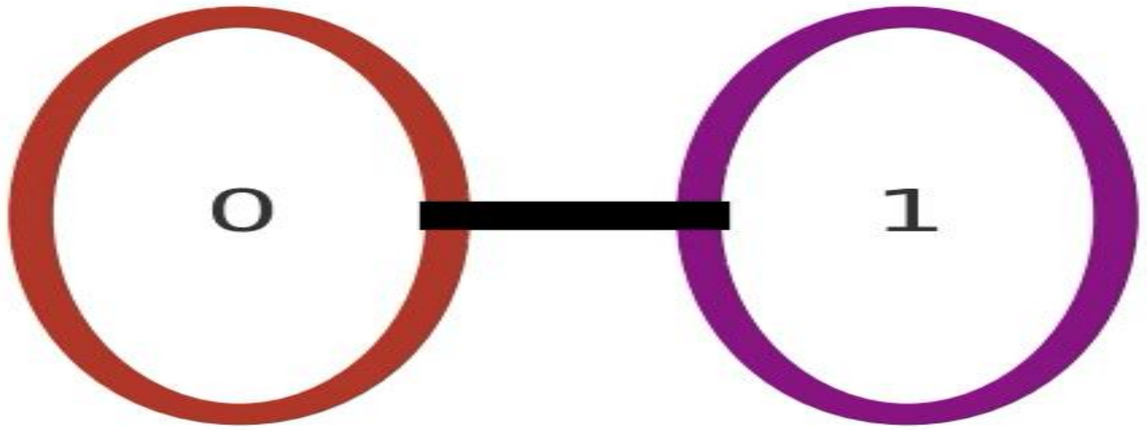
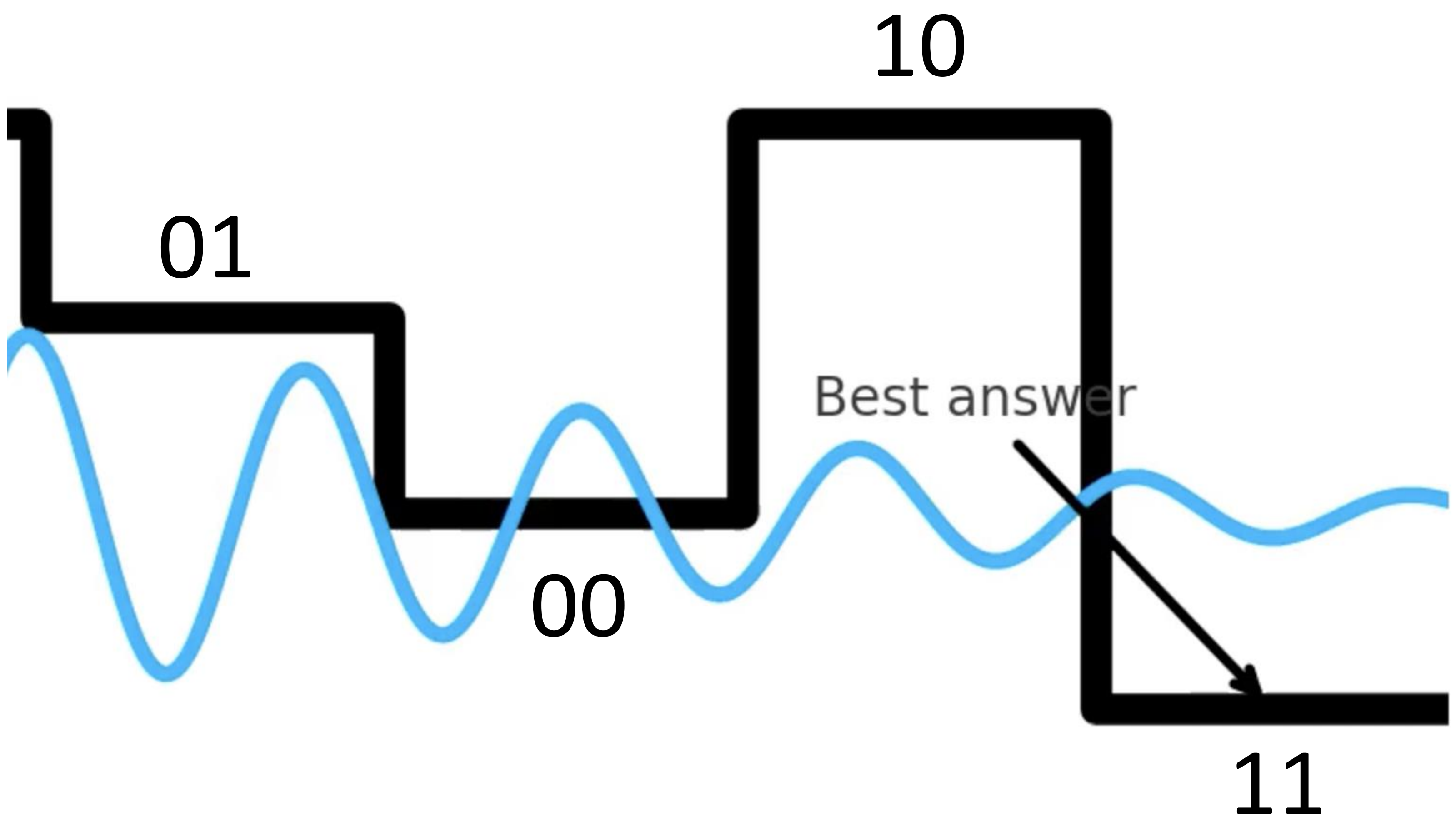
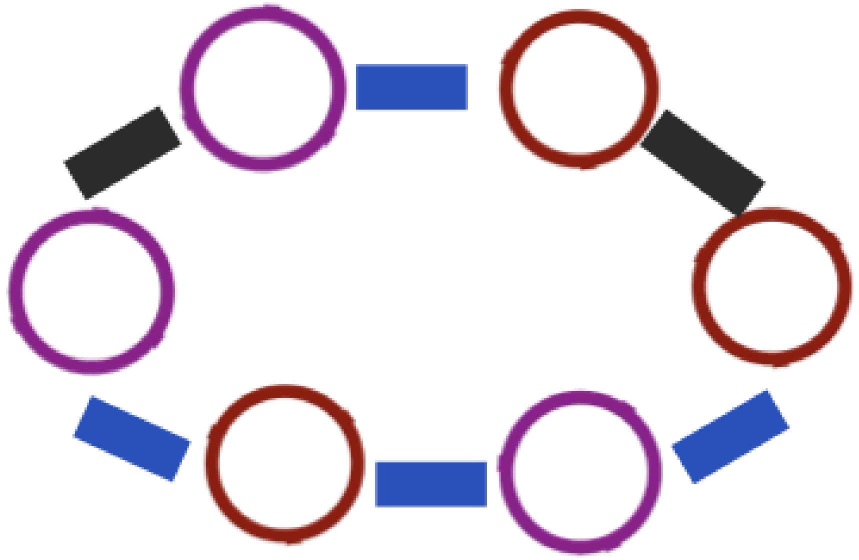
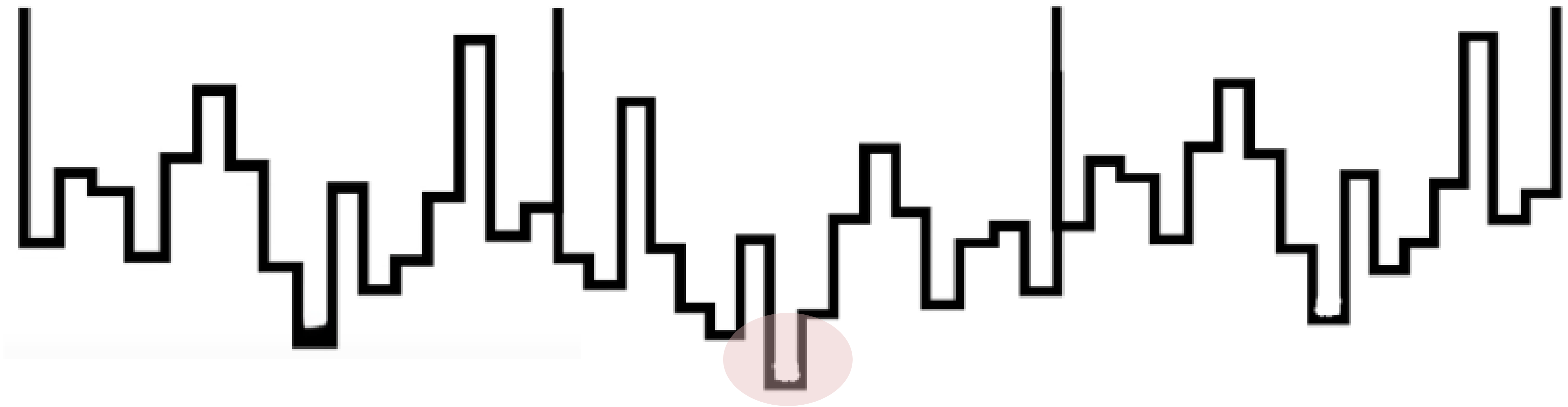




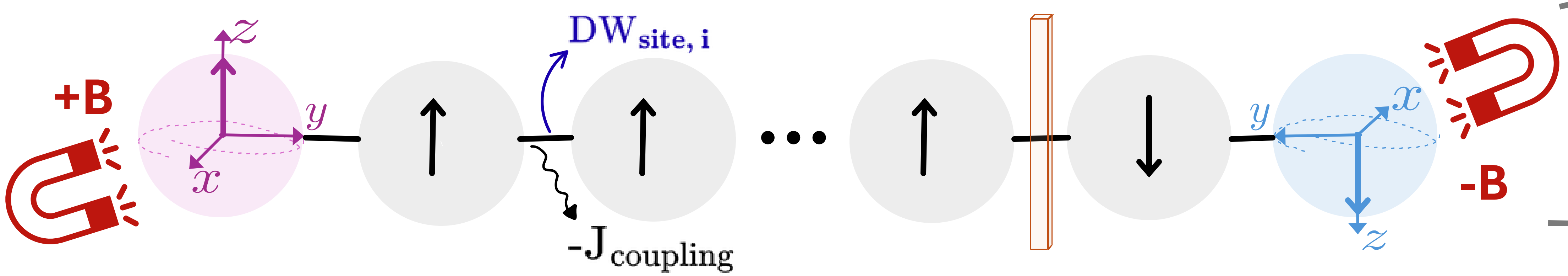
Many Qubit Coupling

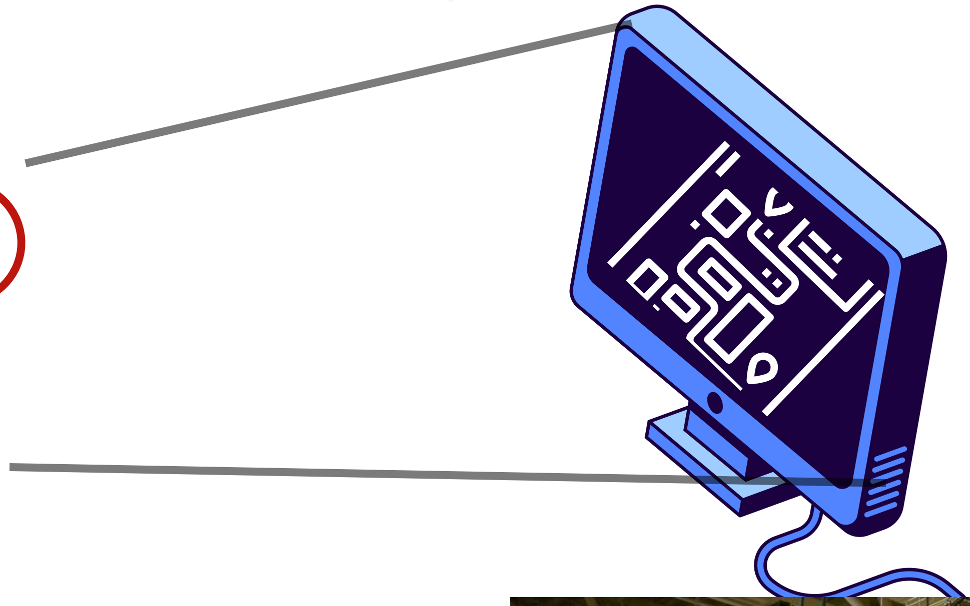




Previous work

Chancellor et. al. npj Quantum Information, 8, 73





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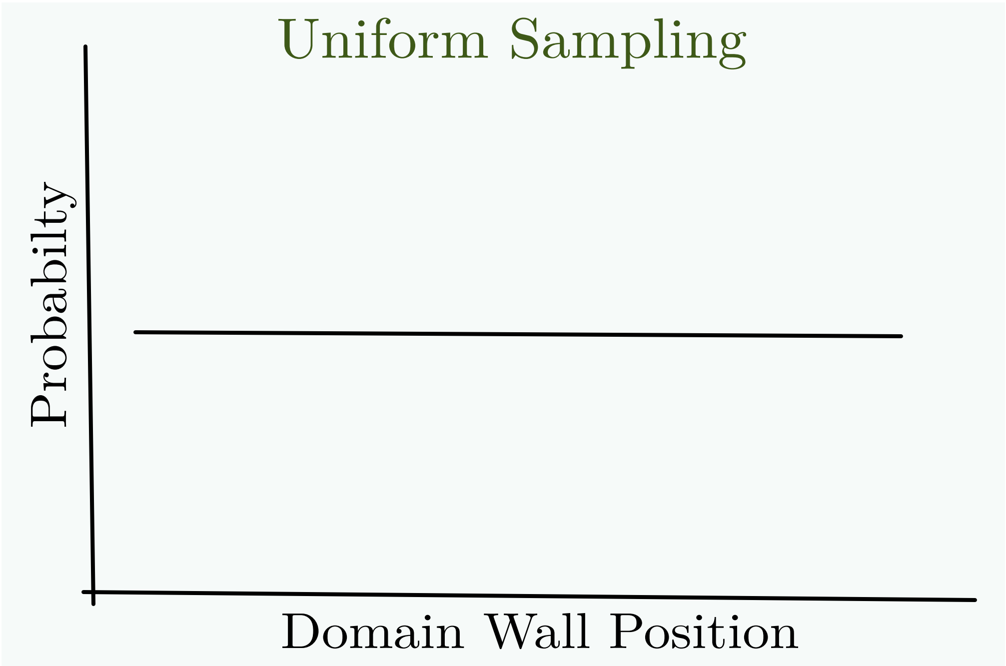
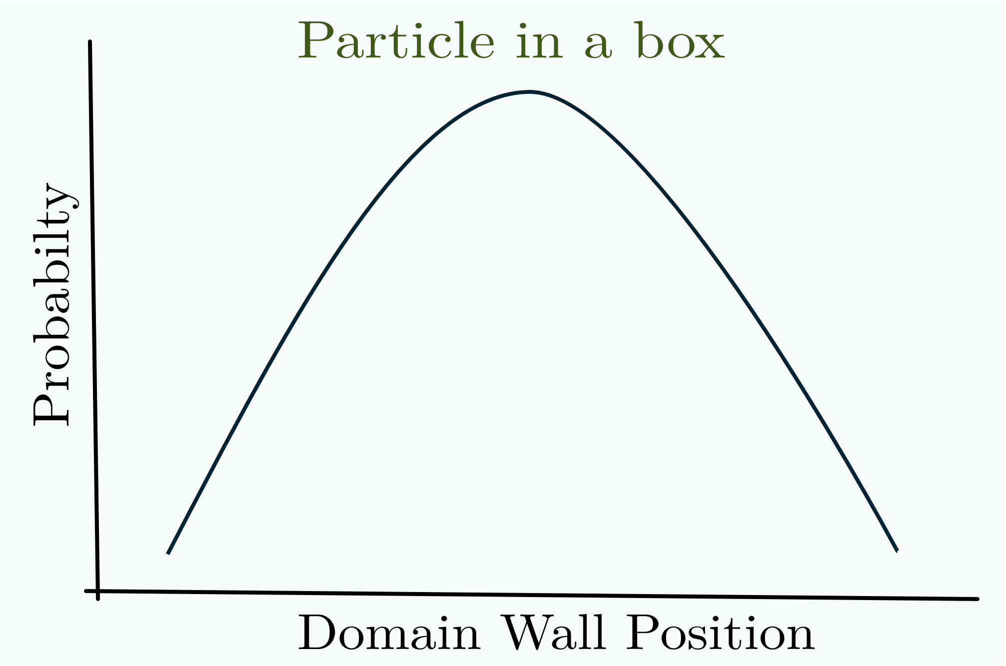
(i)

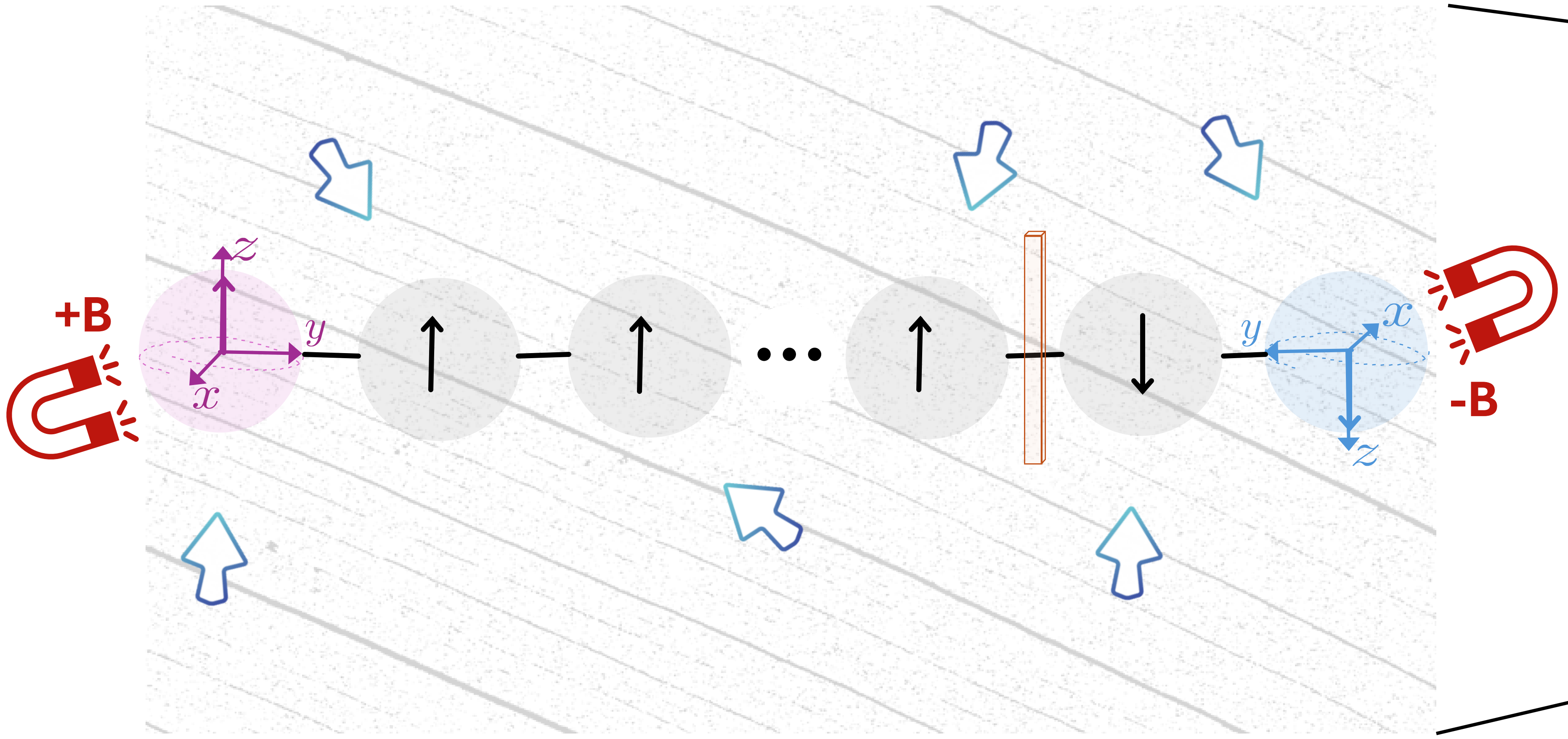


Expected Result
in absence of noise

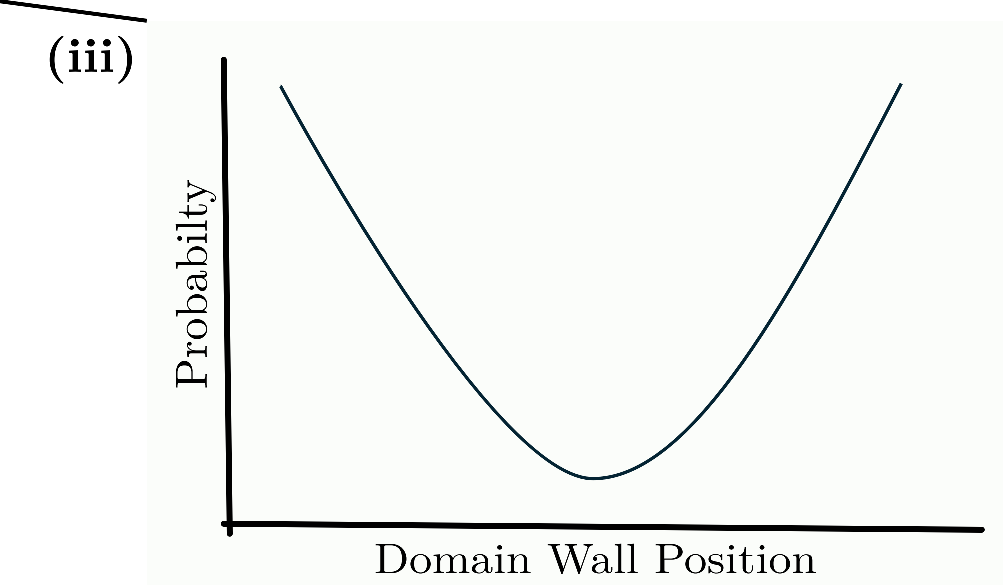
(ii)



Single Qubit Control Errors



Errors appear as random local magnetic fields



- Control errors in the single qubit regime arise due to a device implementing a Hamiltonian different from the intended one.

Chancellor et. al. npj Quantum Information, 8, 73

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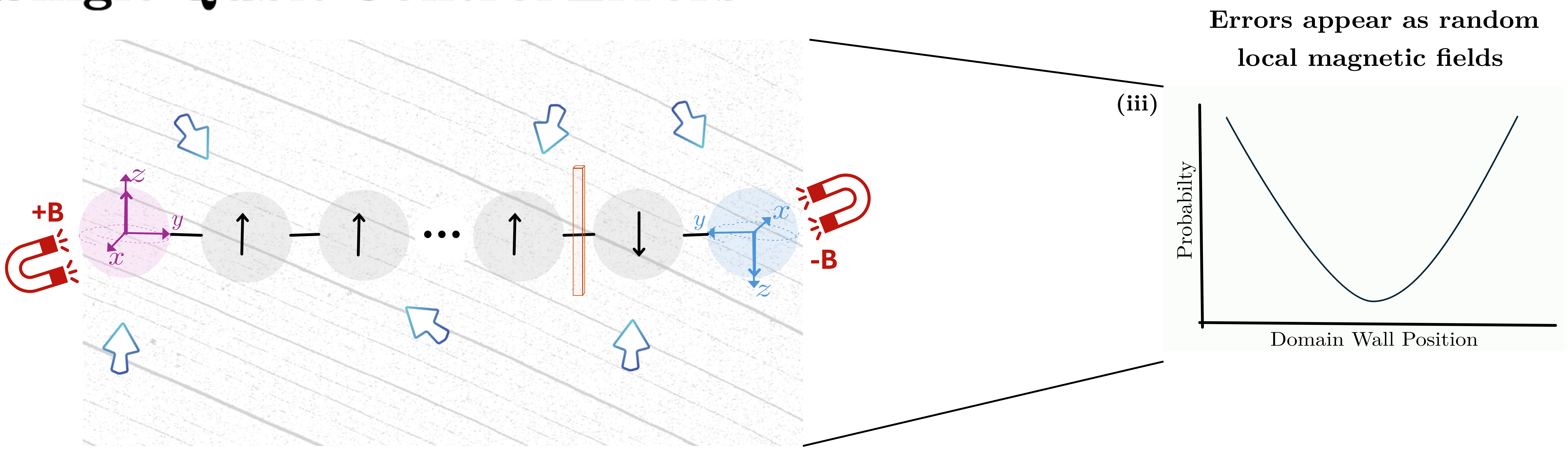


- Control errors in the single qubit regime arise due to a device implementing a Hamiltonian different from the intended one.

- Add to the Hamiltonian, the following control errors: $H_{fields} = \sum_i \epsilon_i \sigma_i^z$

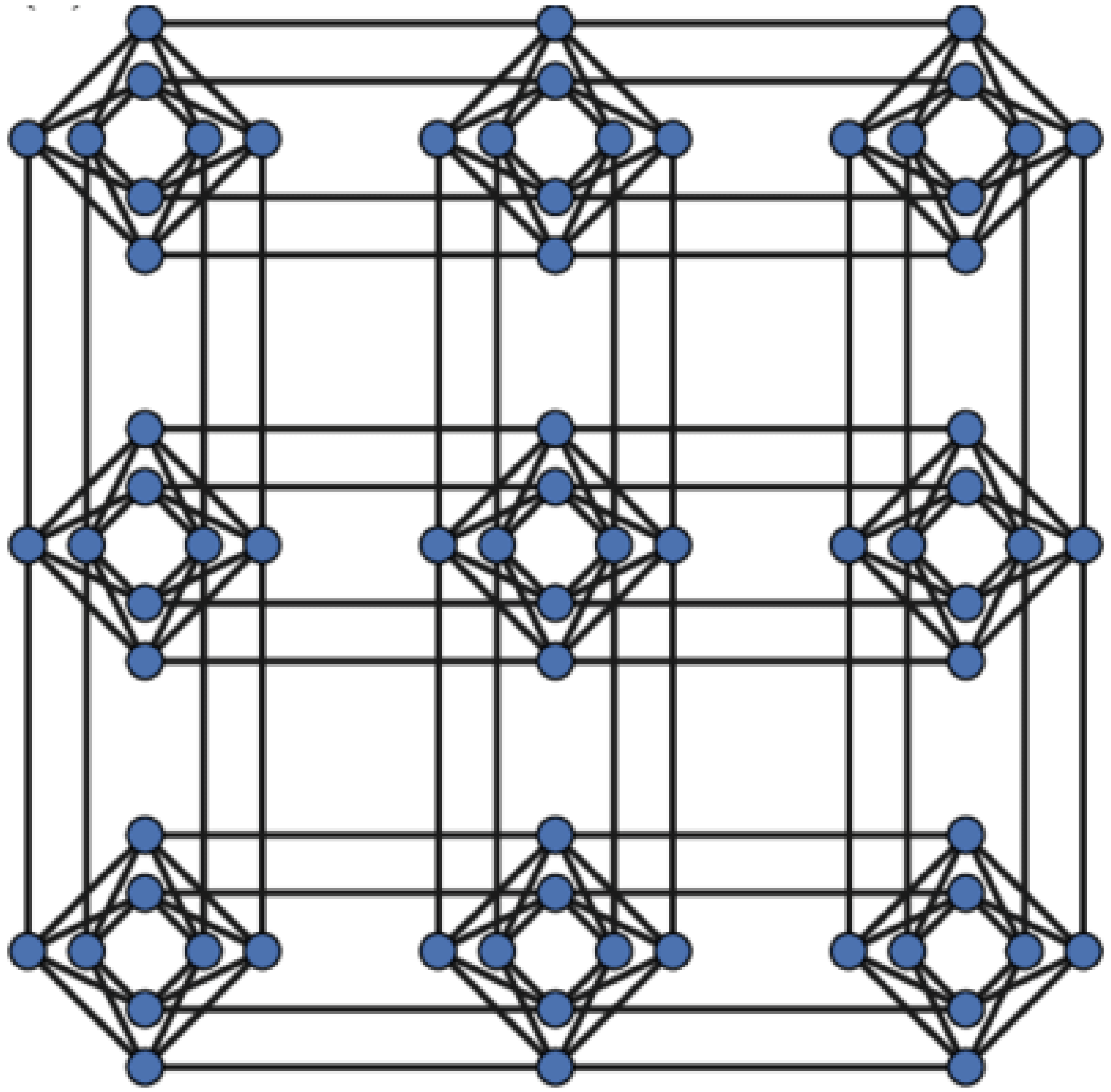
- The Boltzmann distribution is taken over the random-field–induced energy shifts within the degenerate ground-state manifold : $P_n = \frac{e^{-\beta \sum_{i=1}^{n} \epsilon_i}}{Z}$

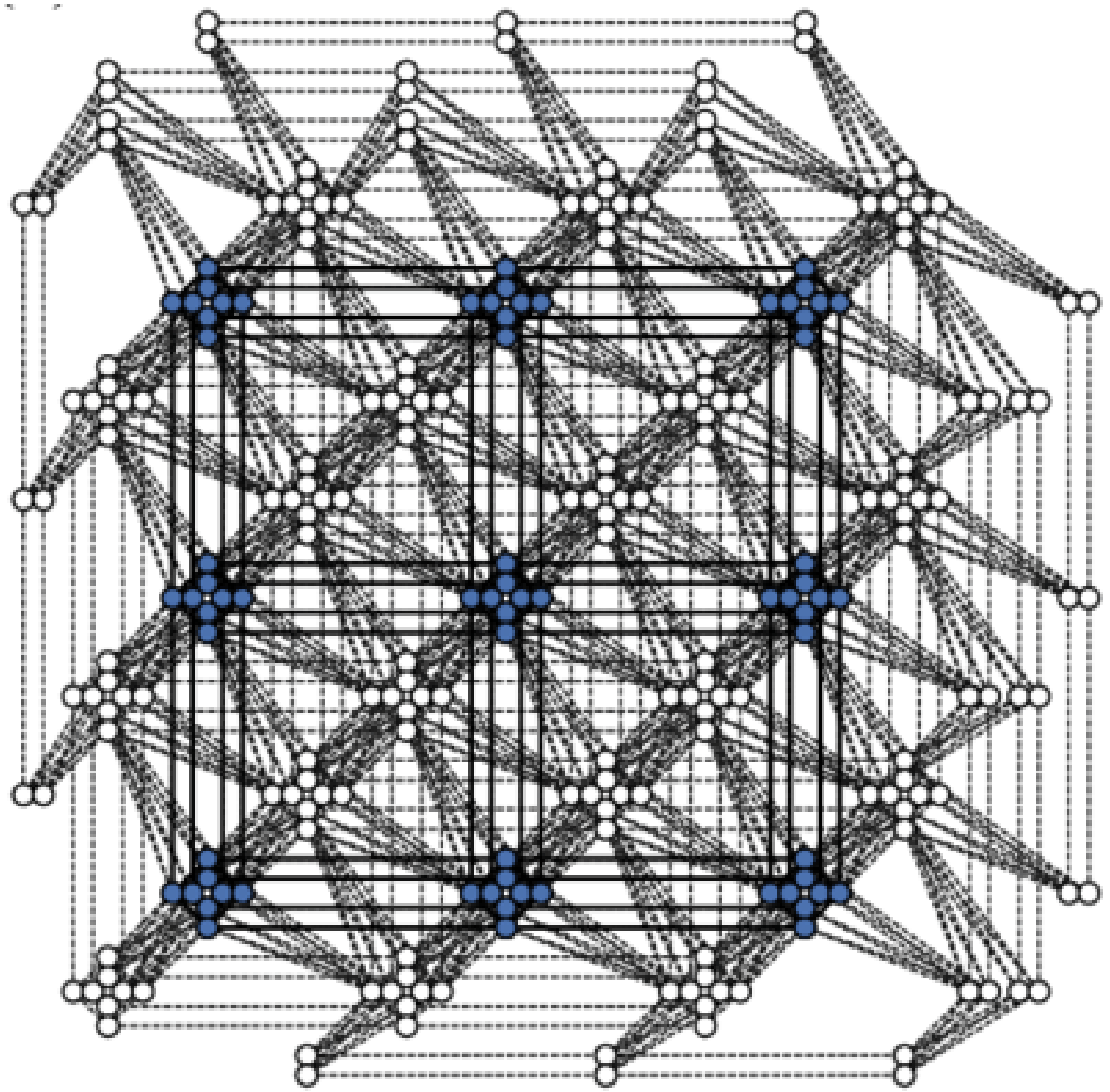
where $\beta = 1/K_B T$

What we set out to do...

We study the U-shaped domain wall distribution from an Ising chain with anti-parallel boundaries on the D-Wave Two (Chimera) -**npj Quantum Inf. 8, 73 (2022)**- and extend the analysis to the newer Advantage 4.1 (Pegasus) QPU.

- $\sim$ 500 qubits
- Fastest Anneal $\sim 20\mu s$





- $\sim$ 5000 qubits
- Fastest Anneal $\sim 0.005\mu s$

Quantum Information Processing. 20. 10.1007/s11128-021-03226-6 (2021).

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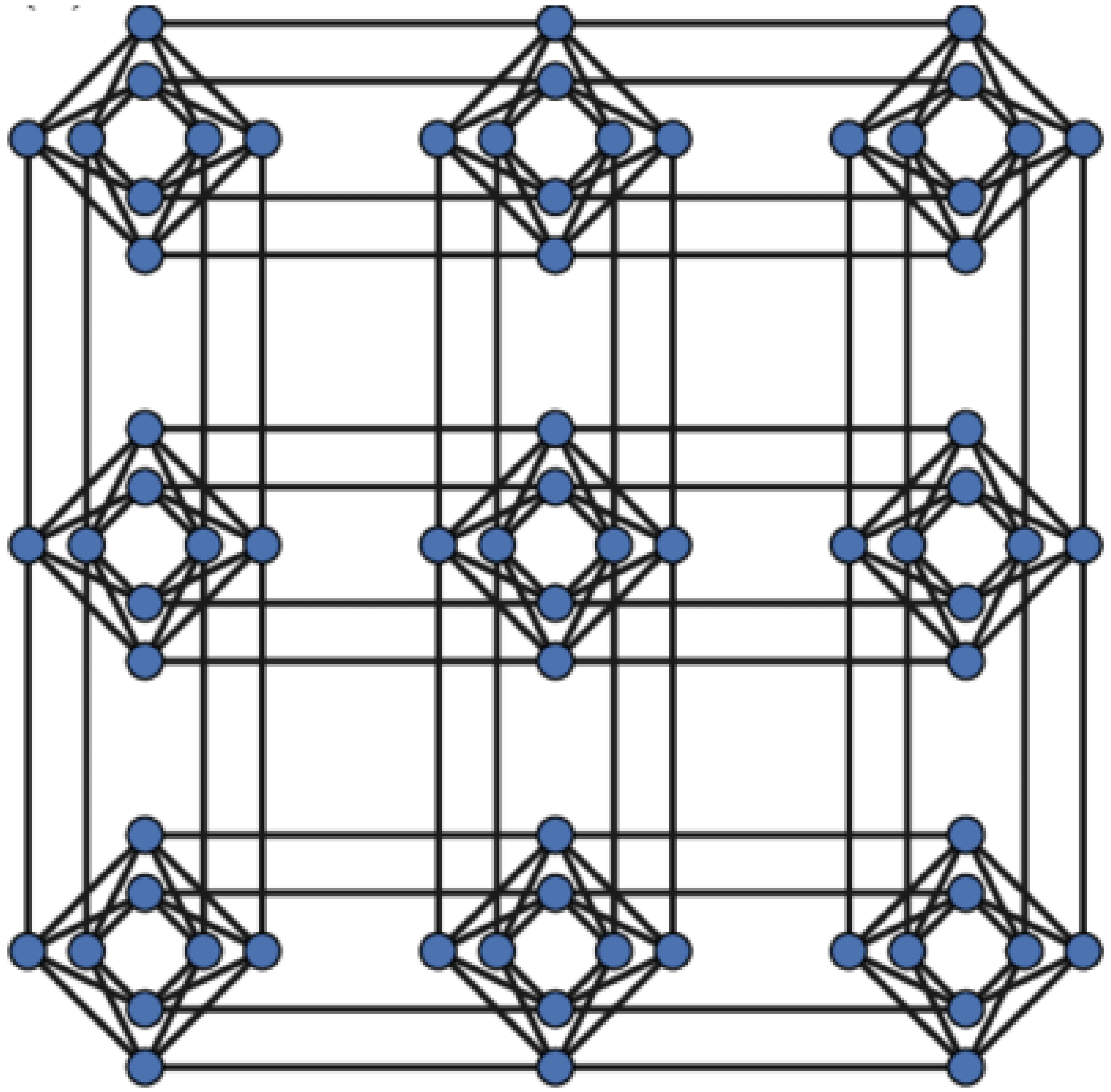

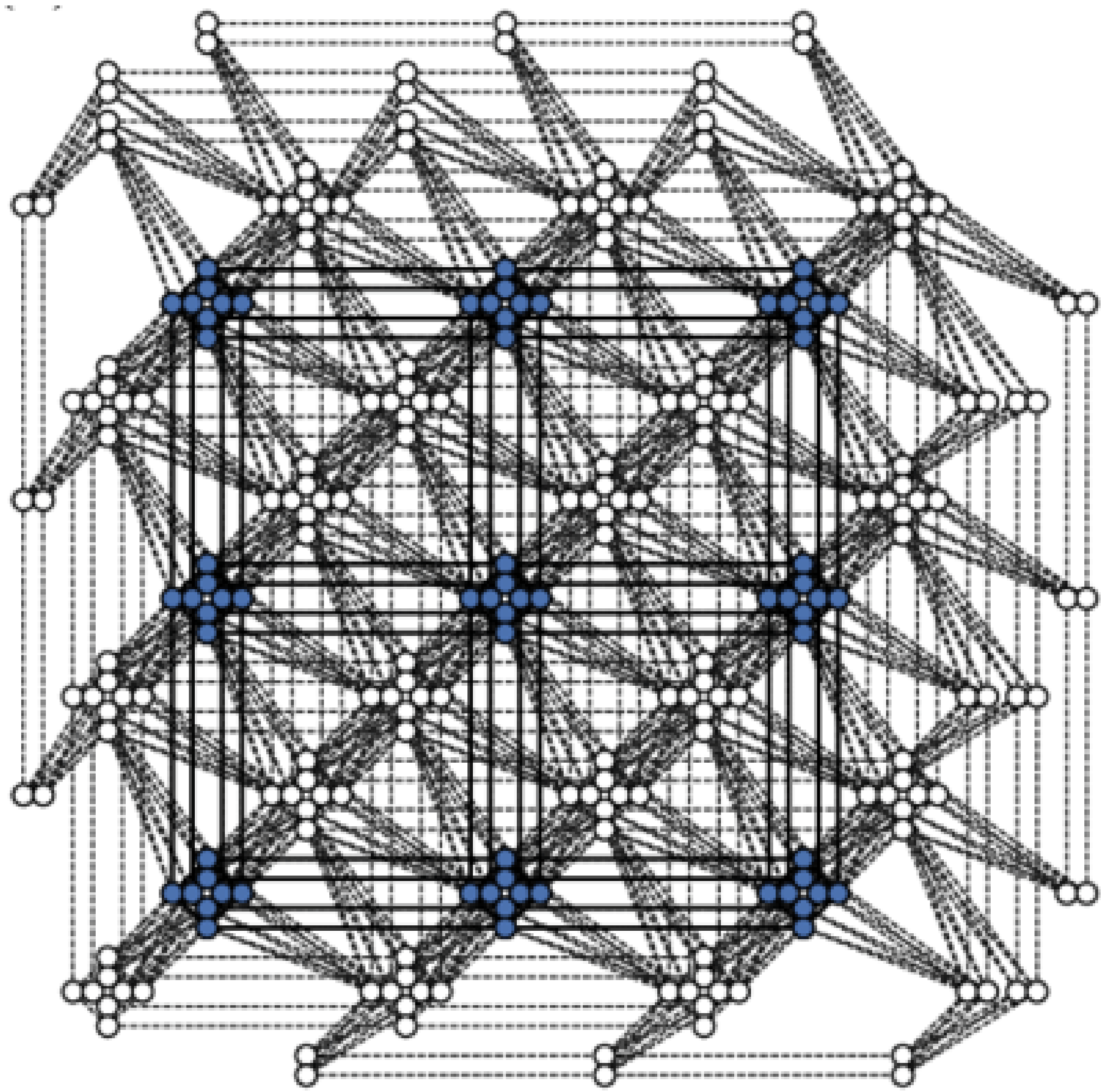

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Results...

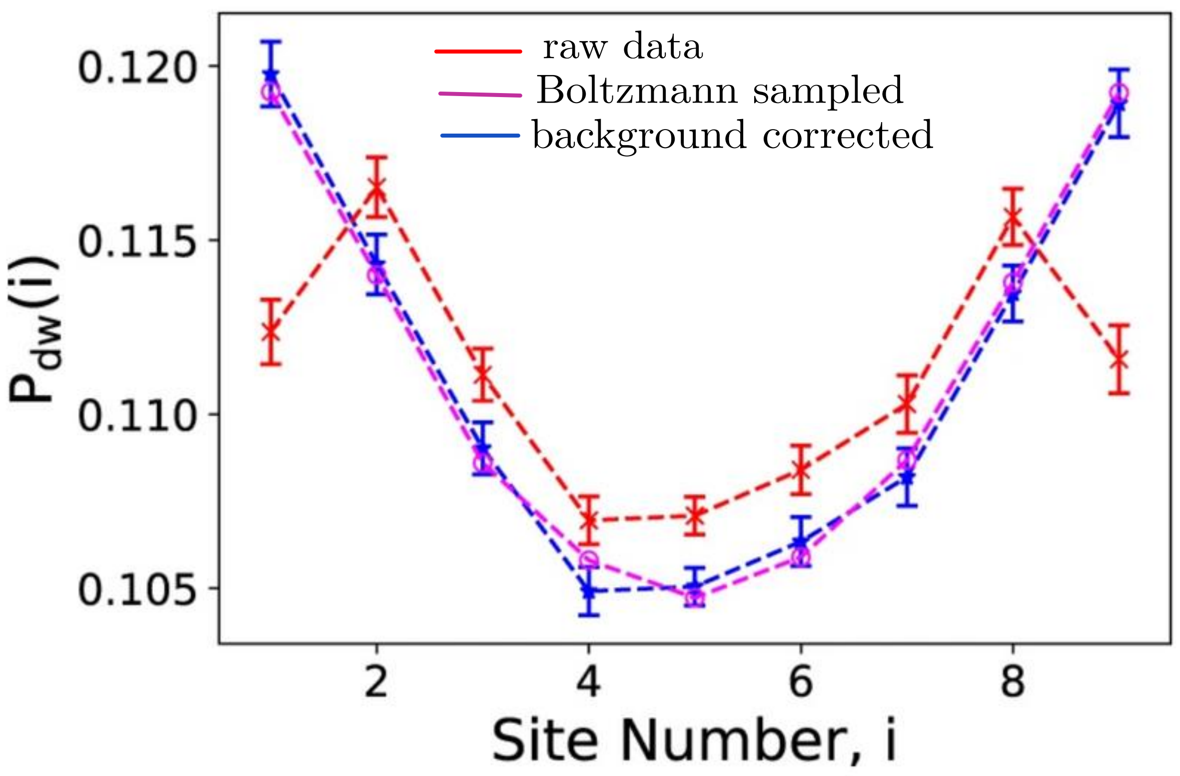
D-Wave Two

<u>Default anneal regime</u>

U-shape distribution due to random effective longitudinal fields.

End point susceptibility correction :

$$P_{dw}(i) \;\rightarrow\; P_{dw}(i)\left(1 + \frac{B(t_{\text{freeze}})}{k_B T}\,\chi J(h-J)\right).$$



Domain wall distribution for a 10 qubit frustration chain on a Chimera graph, in **npj Quantum Inf 8, 73(2022)**

Standard Anneal time $20\mu s$

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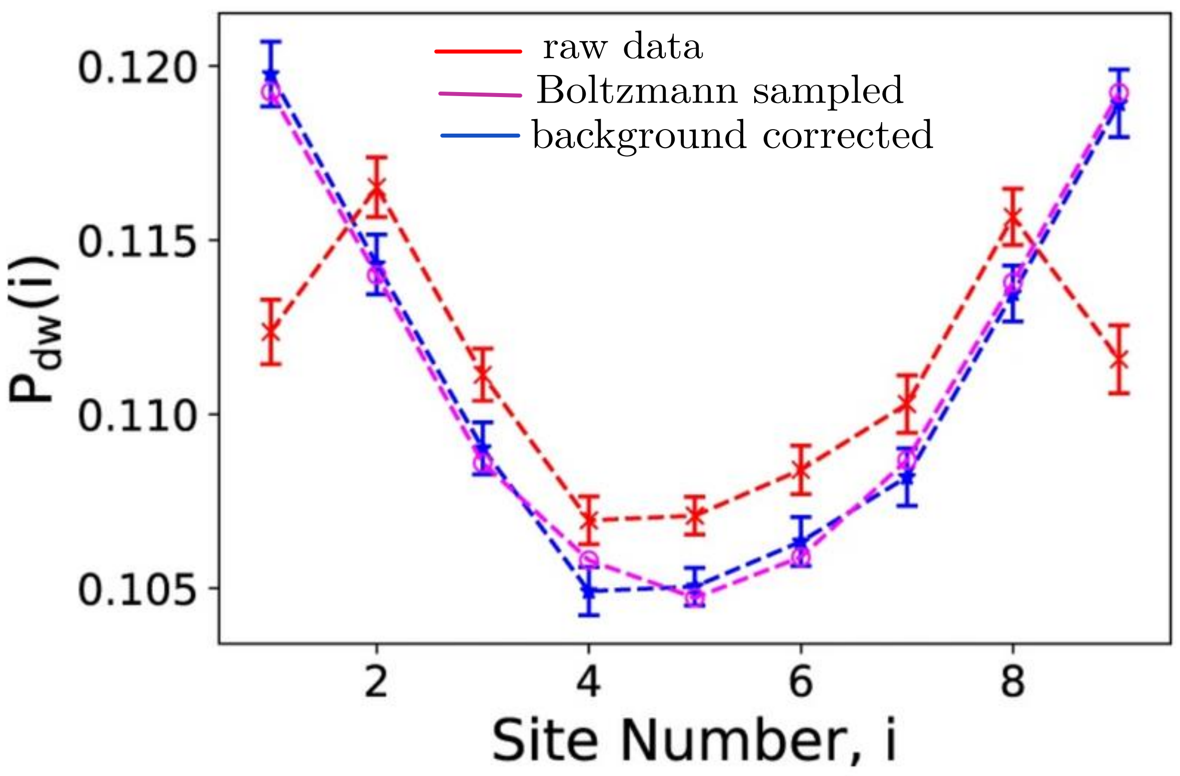

Domain wall distribution for a 10 qubit frustration chain on a Chimera graph, in **npj Quantum Inf 8, 73(2022)**

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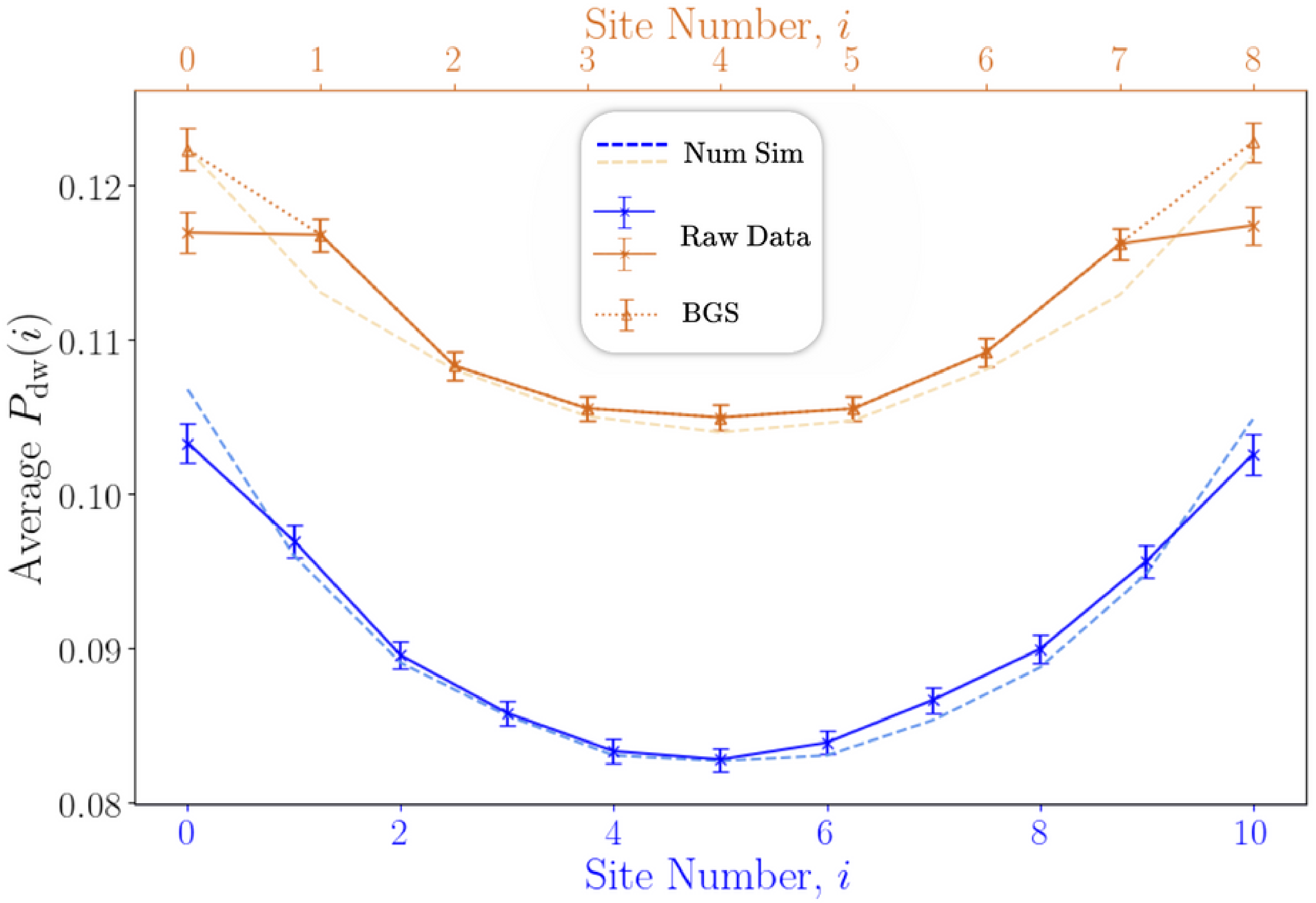
Advantage 4.1

Default anneal regime :

The distribution closely matches the original reporting.

Fast anneal regime :

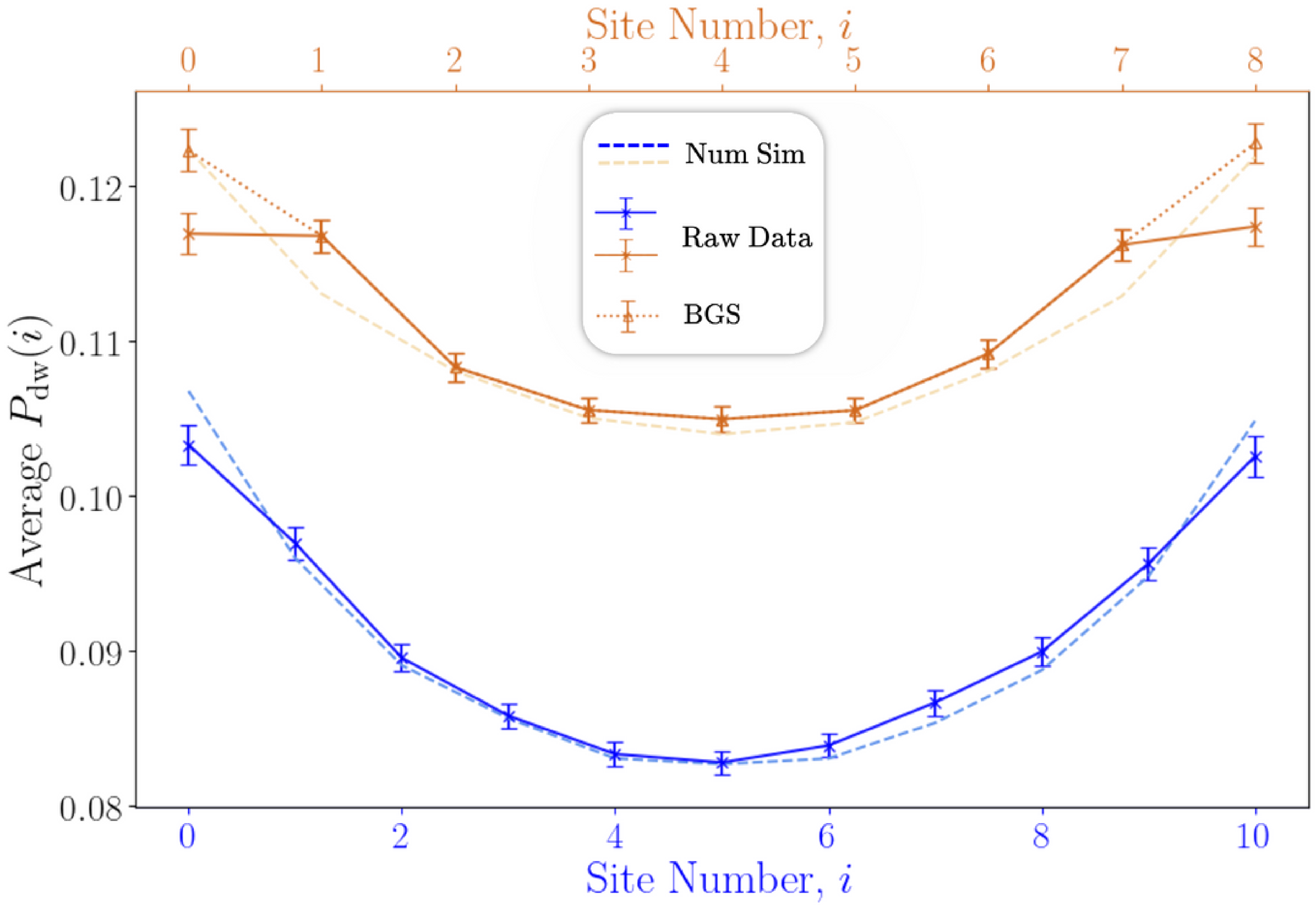
Lower probabilities and smoother edges.



Domain wall distribution for a 12 qubit frustration chain on a Pegasus graph, **manuscript in prep**

Coming back to single Qubit Control Errors

Deep Lall et al. 10.48550/arXiv.2502.06717



Best Fit :

- $P_{sim} = \dfrac{e^{-\beta \sum_{i=1}^{n} \epsilon_i}}{Z}$

where $\beta = \sigma_\epsilon / K_B T$

- P_{Exp}

		L	Time (μs)	β	σ_ζ
Random	Default	10	20	0.472	0.152
		50	20	0.400	0.1284
	Fast	12	20	0.507	0.163
		12	0.03	0.491	0.158

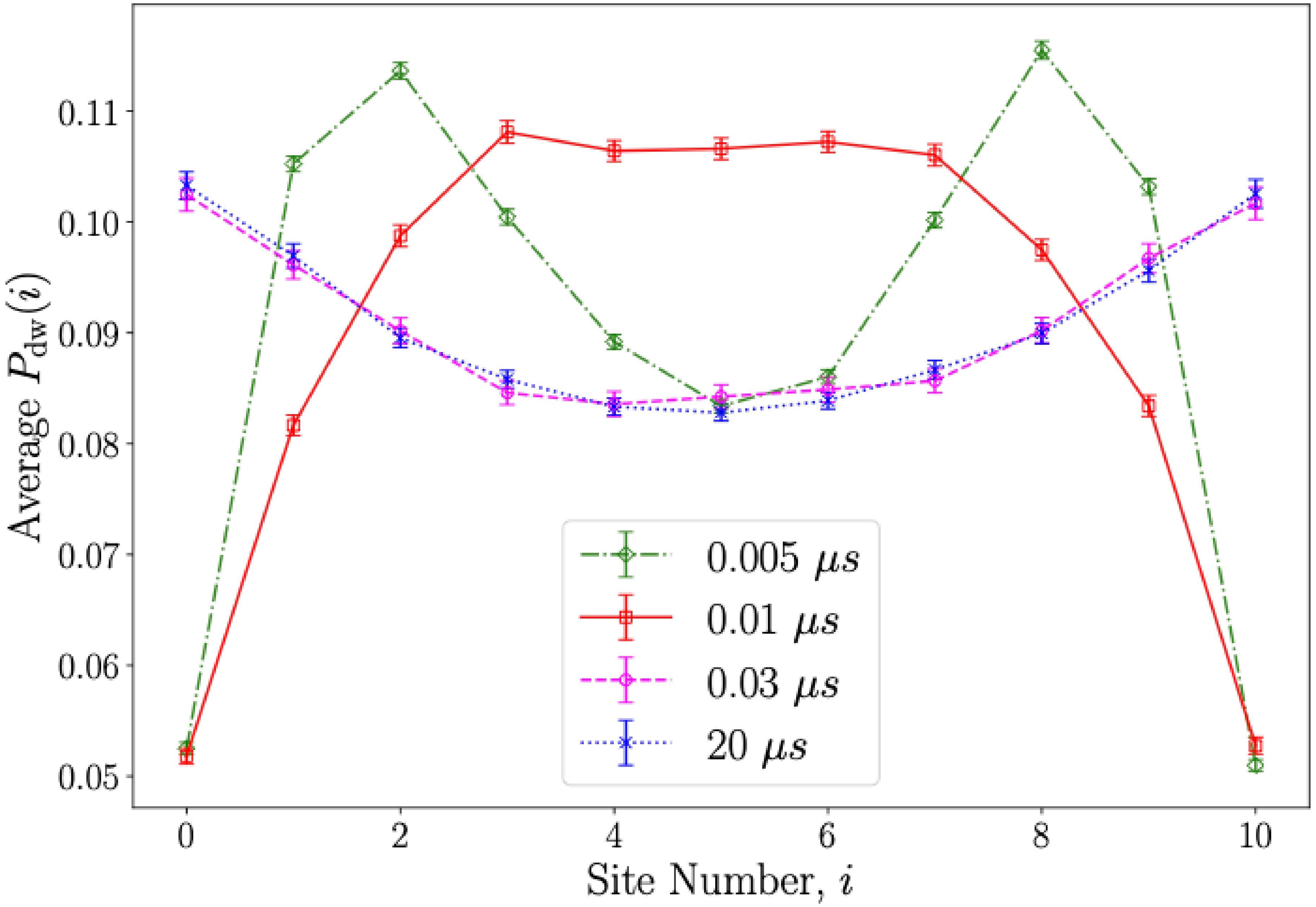
Results…

- Probability distribution in the fast anneal regime for a chain length of 12 with

j chain length of 12 with 10,000 for different anneal times.

- For 0.01 μs : particle in a box distribution f

- For later times the system thermalises , giving the U-shape



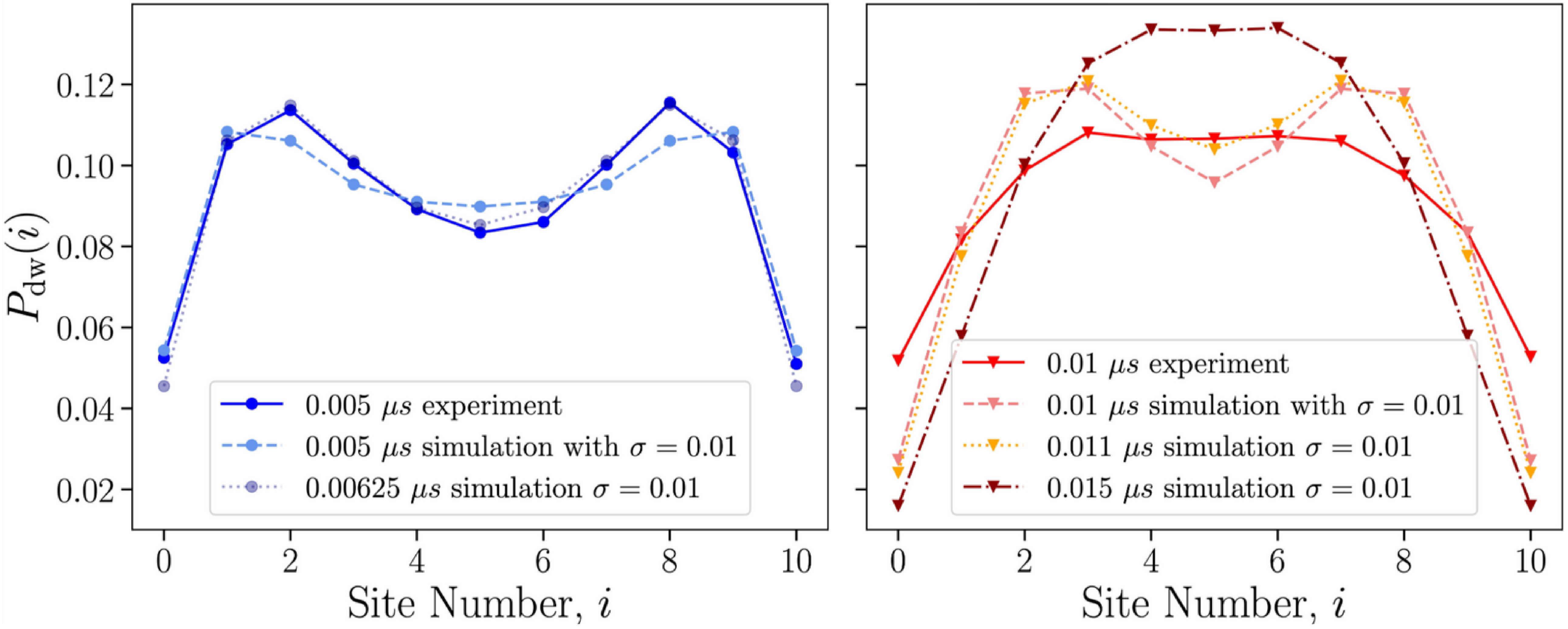
Simulation I

Simulate coherent unitary dynamics in the presence of static disorder.

$$H_{prob} = J\sum_{i=1}^{N} -\sigma_i^z\sigma_{i+1}^z + h(\sigma_i^z - \sigma_{N+1}^z) + \sum_i \zeta_i\sigma_i^z$$

Static noise simulation:

$\zeta_i \sim \mathcal{N}(0,\, 0.01),$ averaged over **10k realizations** to mimic the hardware's thermal averaging in experiments.

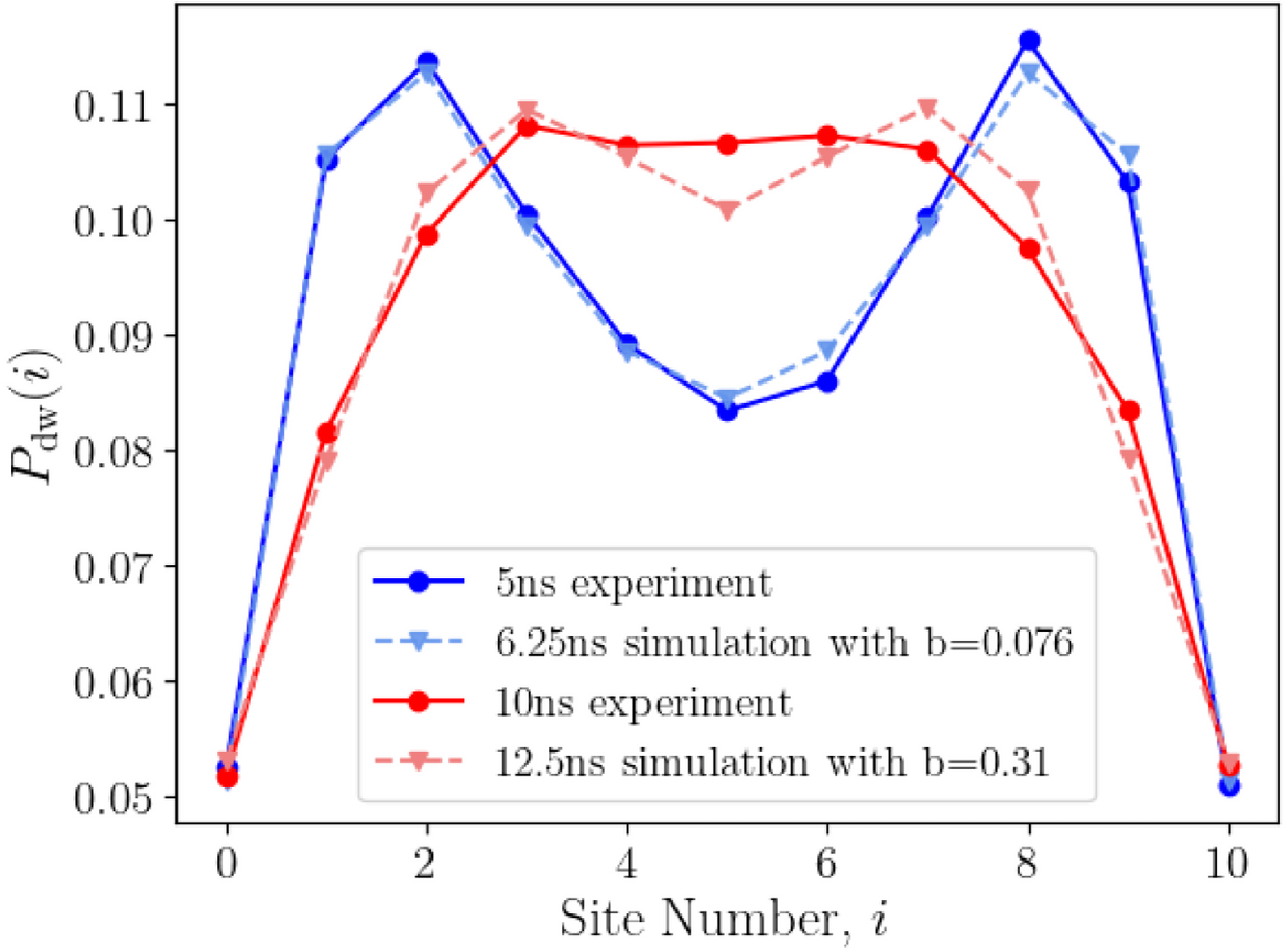


Simulation II

- Model experimental data as a linear combination of quantum and thermal contributions

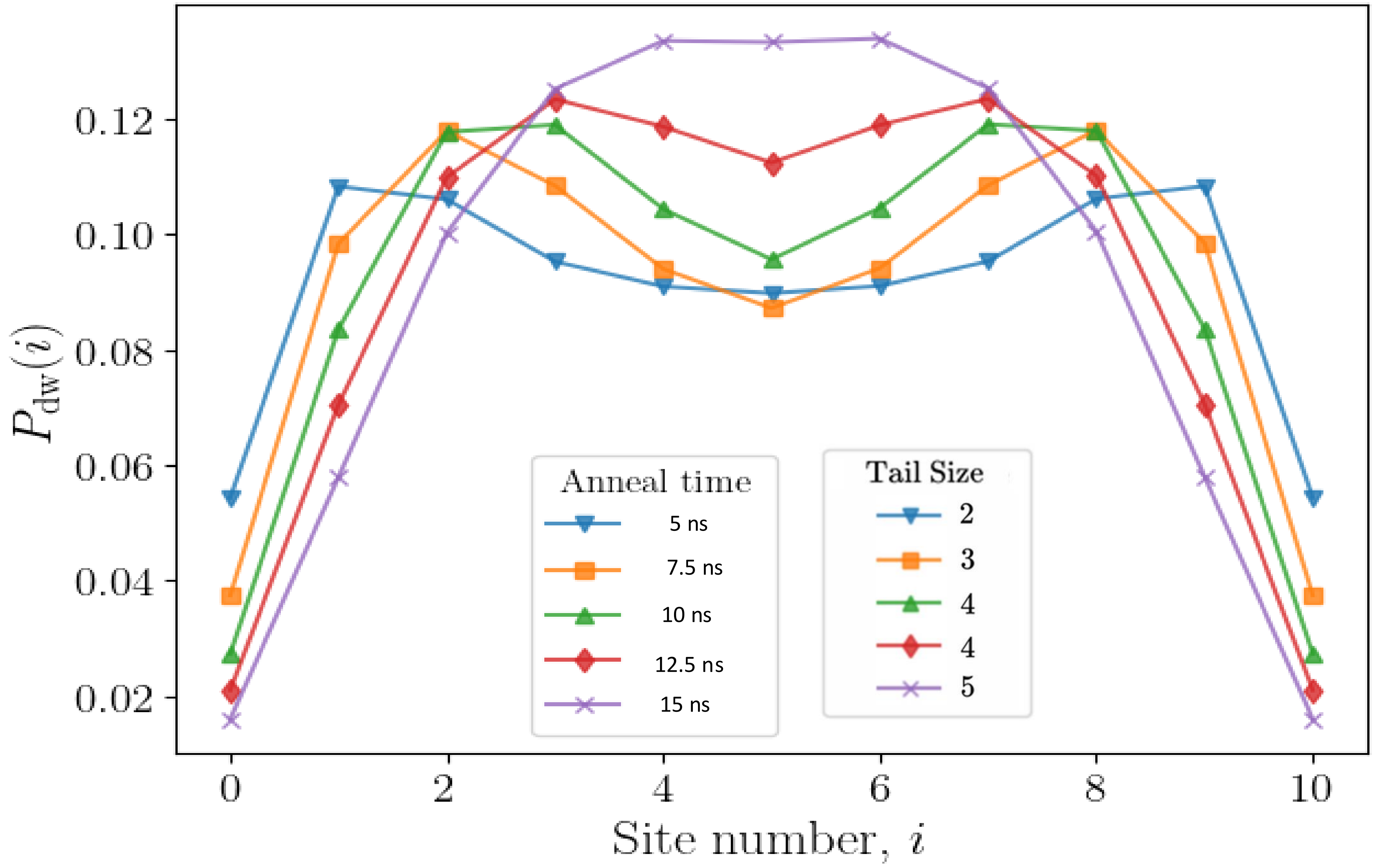
$$P_{Exp} = aP_{Quantum} + bP_{Thermal}$$

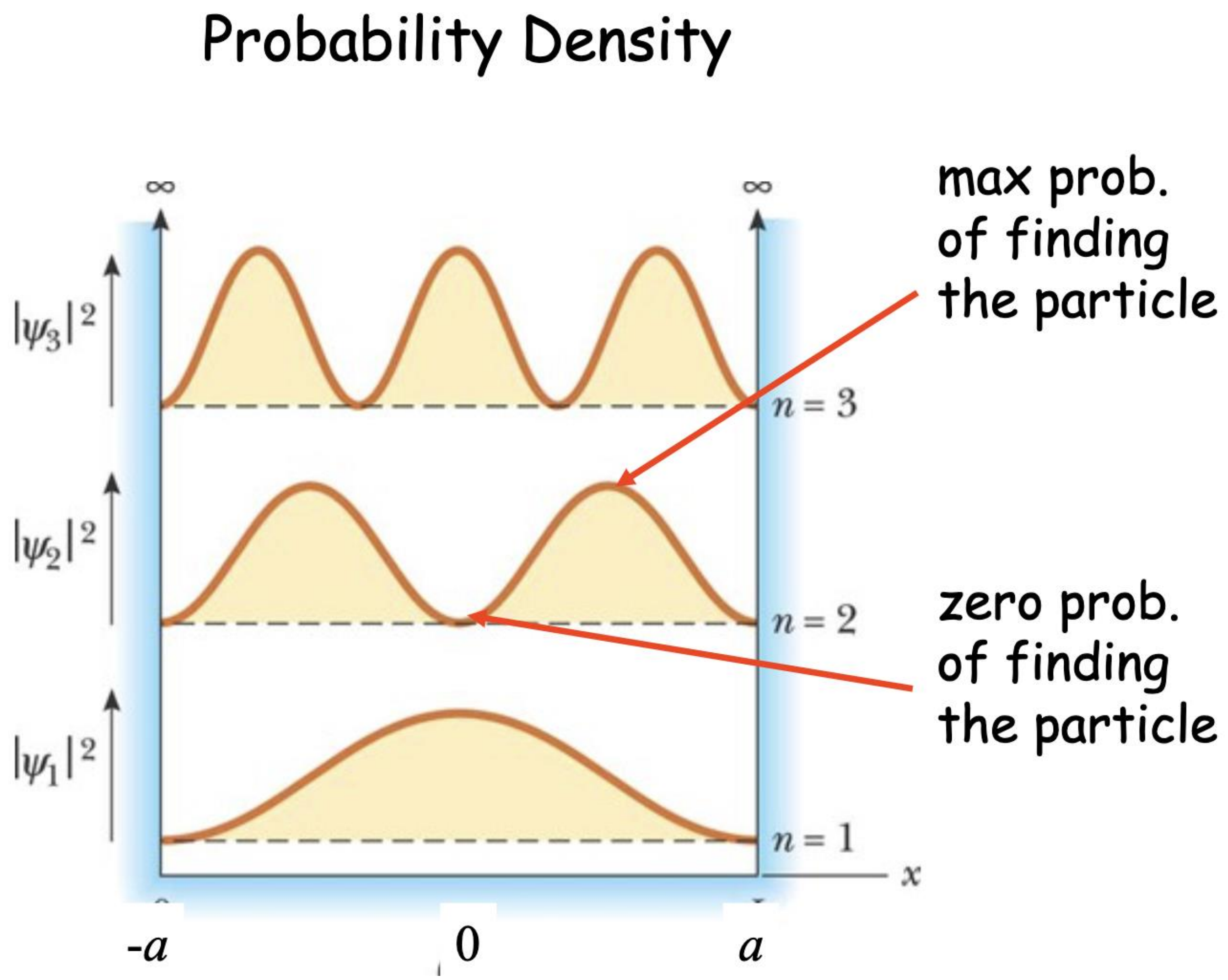
$$a + b = 1$$



What we set out to do...

Propose a general benchmarking framework in which the extent of the domain-wall tails serves as a robust metric of device performance, capturing both coherence and noise levels.





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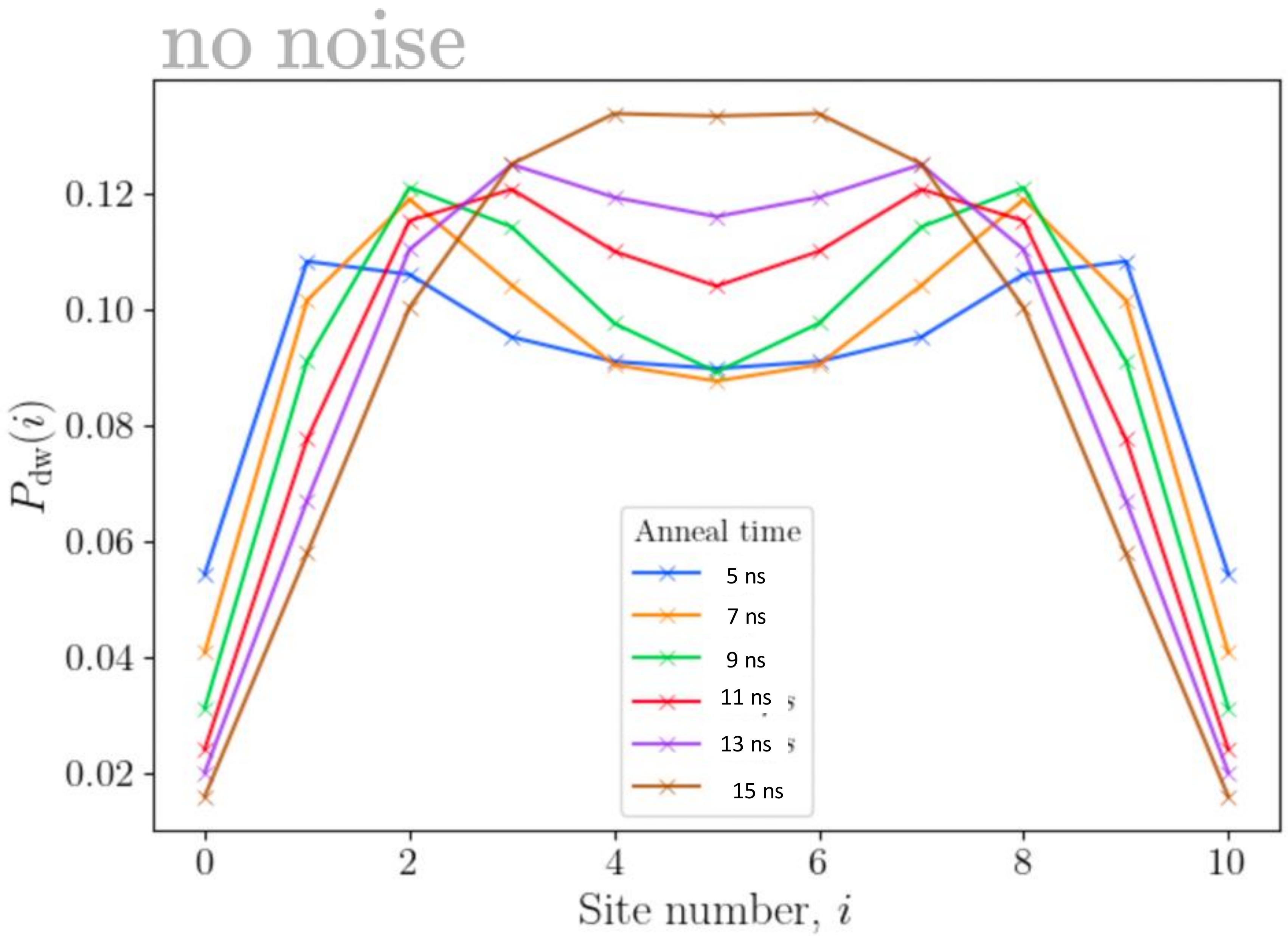

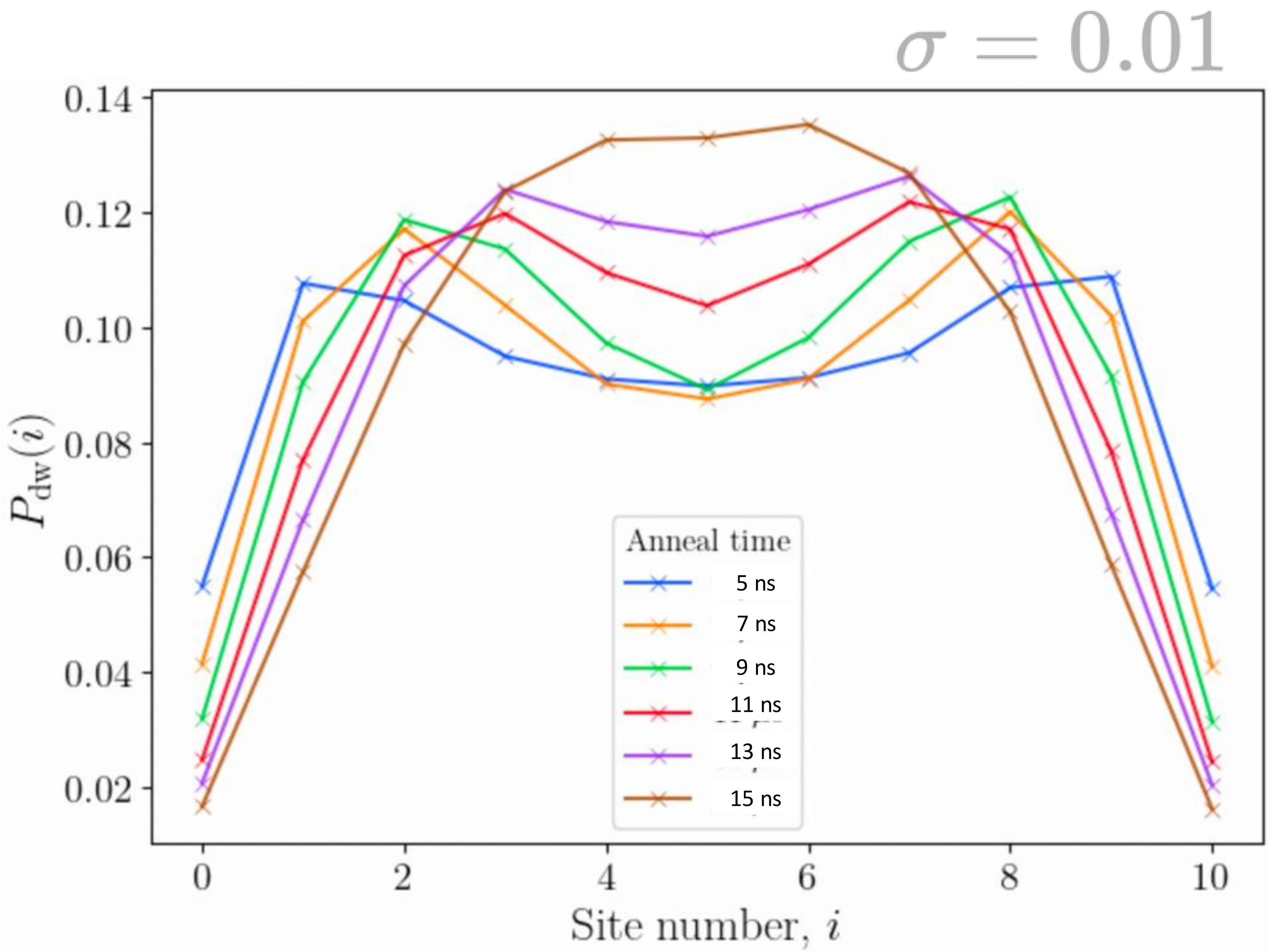

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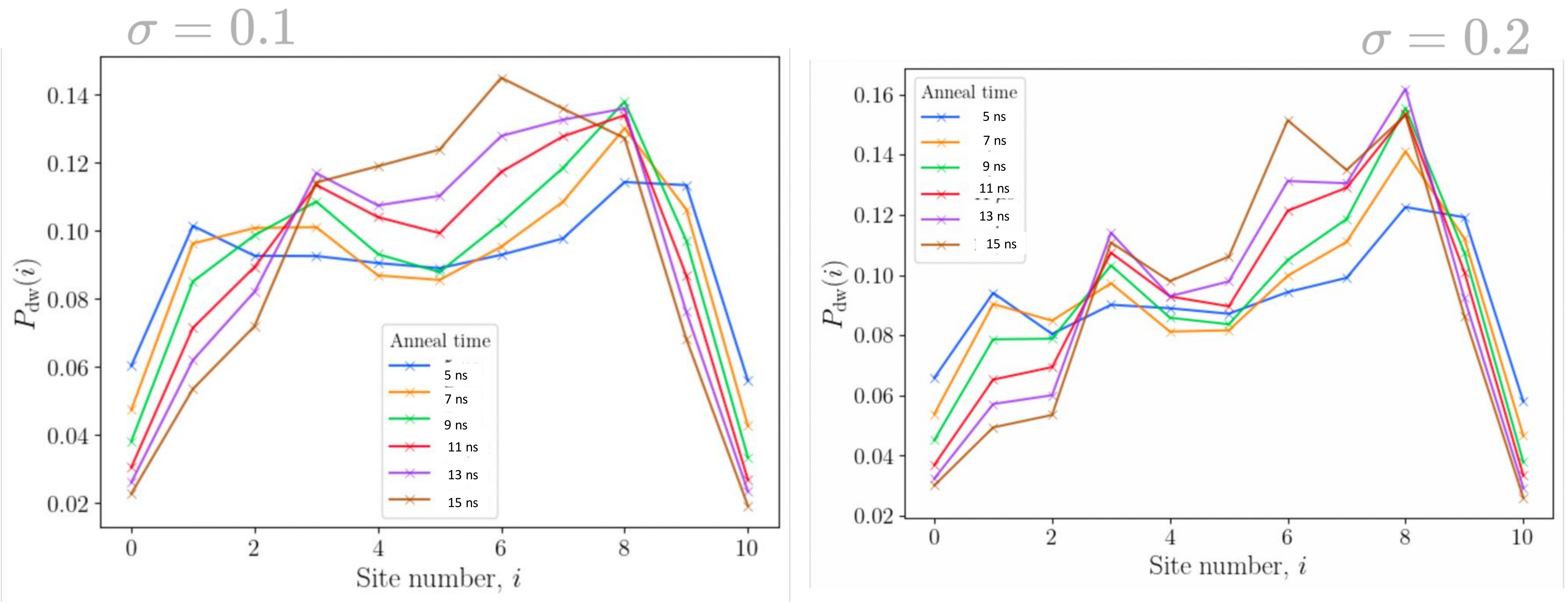

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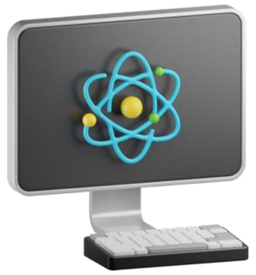
To conclude...

Quantum behaviour observed! Fast annealing($0.01\ \mu s$)on Advantage 4.1 produced the expected particle-in-a-box domain-wall distribution.



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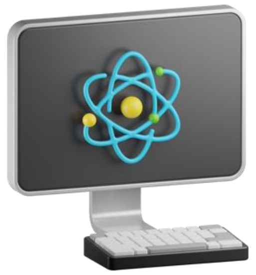

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Proposed a benchmarking framework where the **extent of the domain-wall tails** serves as a metric of device performance.

Tail captures both **coherence** and **noise levels**, providing a unified measure of analog device quality, and is **generalizable** to other platforms such as *Rydberg-atom simulators*.

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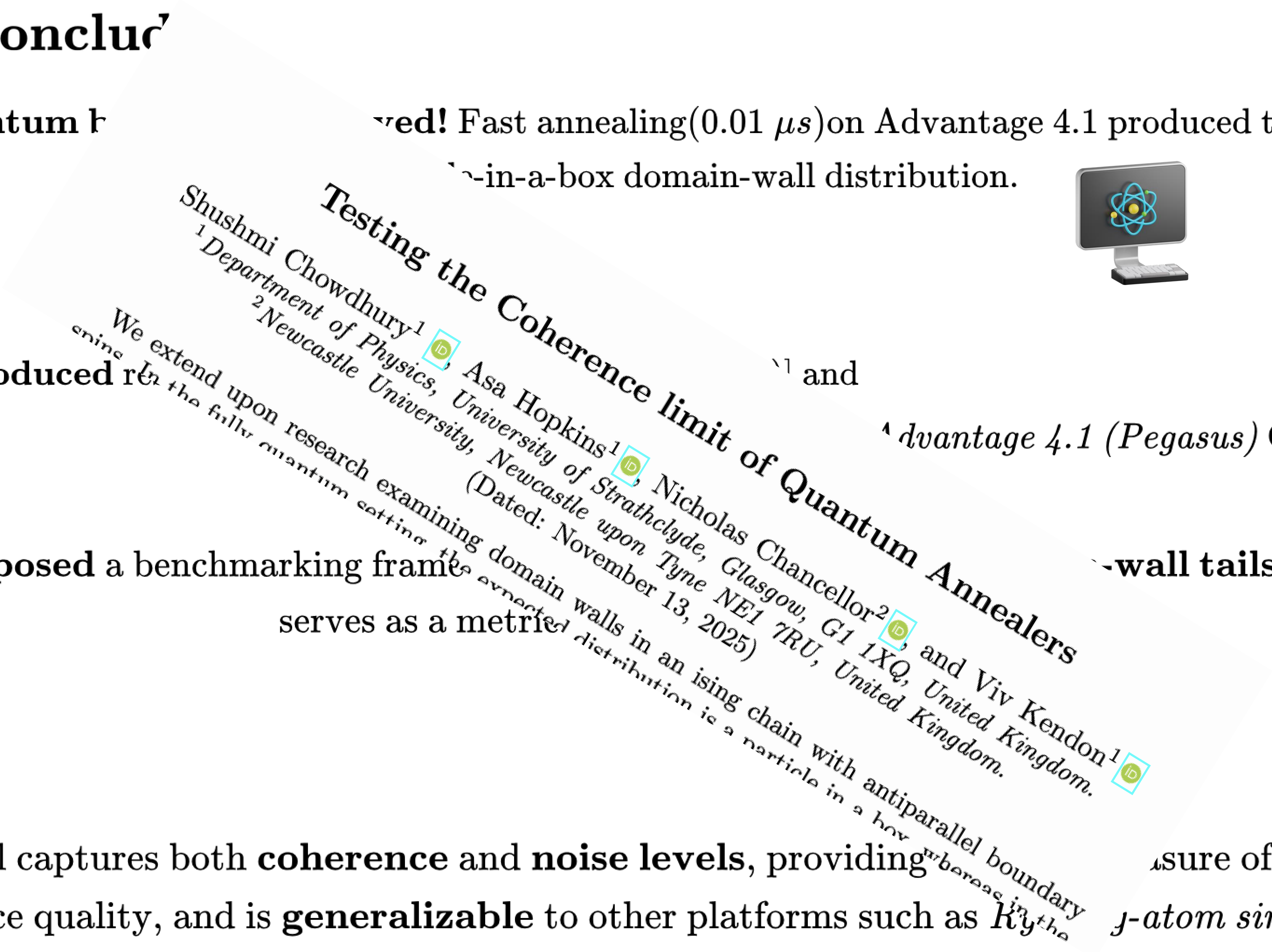

Testing the Coherence limit of Quantum Annealers

Shushmi Chowdhury[1], Asa Hopkins[1], Nicholas Chancellor[2], and Viv Kendon[1]
[1]*Department of Physics, University of Strathclyde, Glasgow, G1 1XQ, United Kingdom.*
[2]*Newcastle University, Newcastle upon Tyne NE1 7RU, United Kingdom.*
(Dated: November 13, 2025)

We extend upon research examining domain walls in an ising chain with antiparallel boundary spins. In the fully quantum setting the expected distribution is a particle in a box whereas in the

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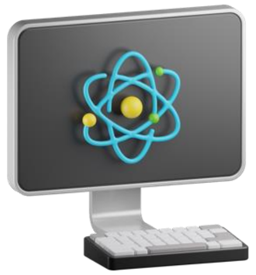

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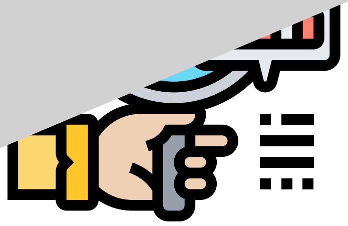

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Scalable Qubit Arrays for Quantum Computing and Optimisation (SQuAre)

SQuARE

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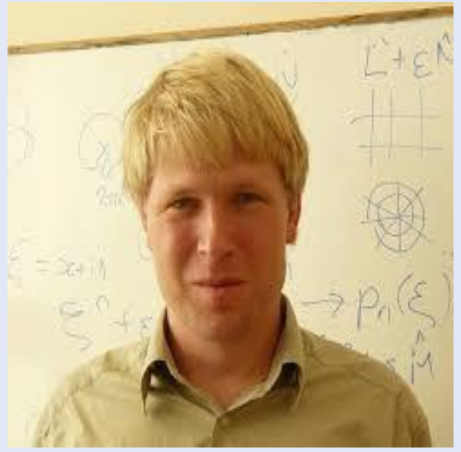
Acknowledgements

Dr.Léo Bourdet,
Simulation Engineer,
Microsoft



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PROFESSOR Viv Kendon
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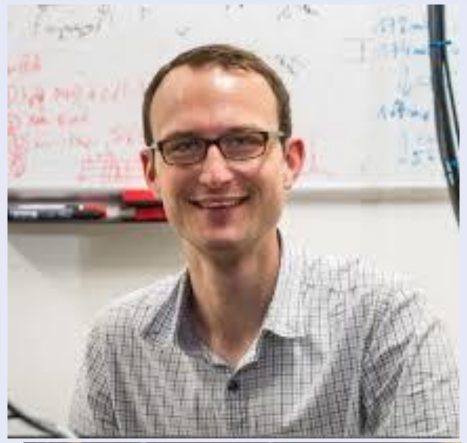

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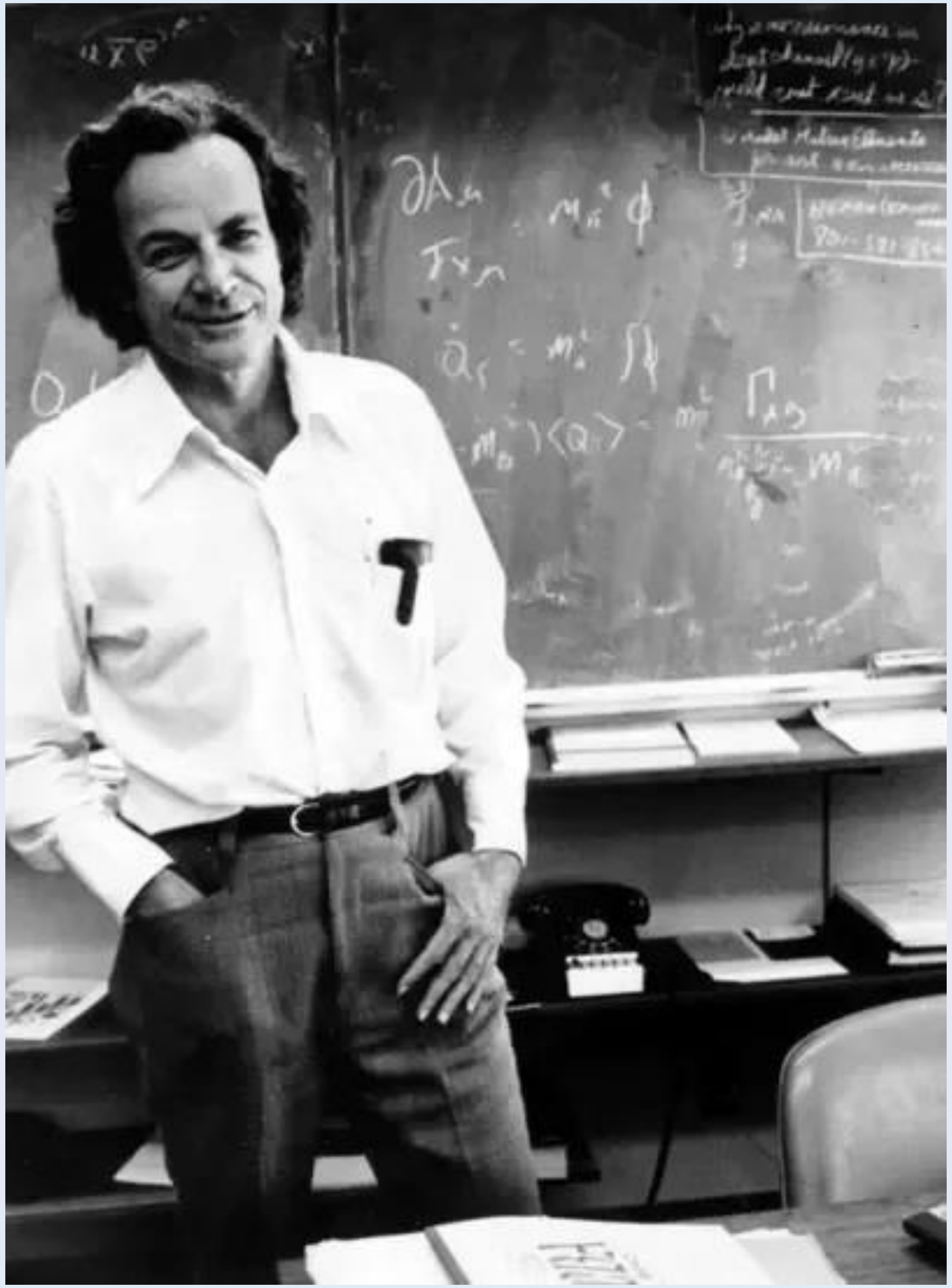

“The imagination of nature is far, far greater than the imagination of man.”

— Richard P. Feynman