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FERMILAB-SLIDES-24-0308-ETD

# Quantum Random Walk Simulator Using Ultrafast Optical Switches

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# Before the age of computers…

**Wikipedia:** https://en.wikipedia.org/wiki/Orrery

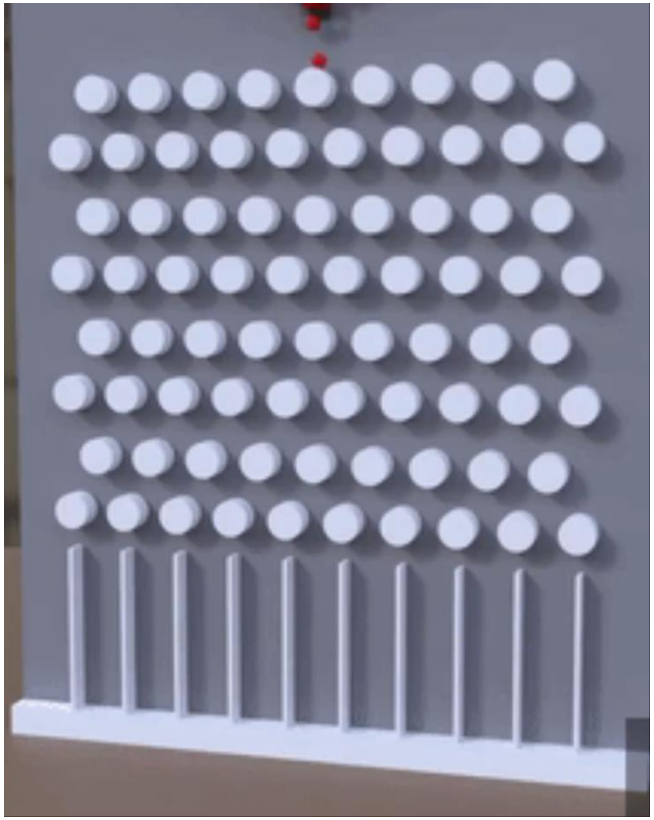
- *"Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy."*

  – Richard Feynman

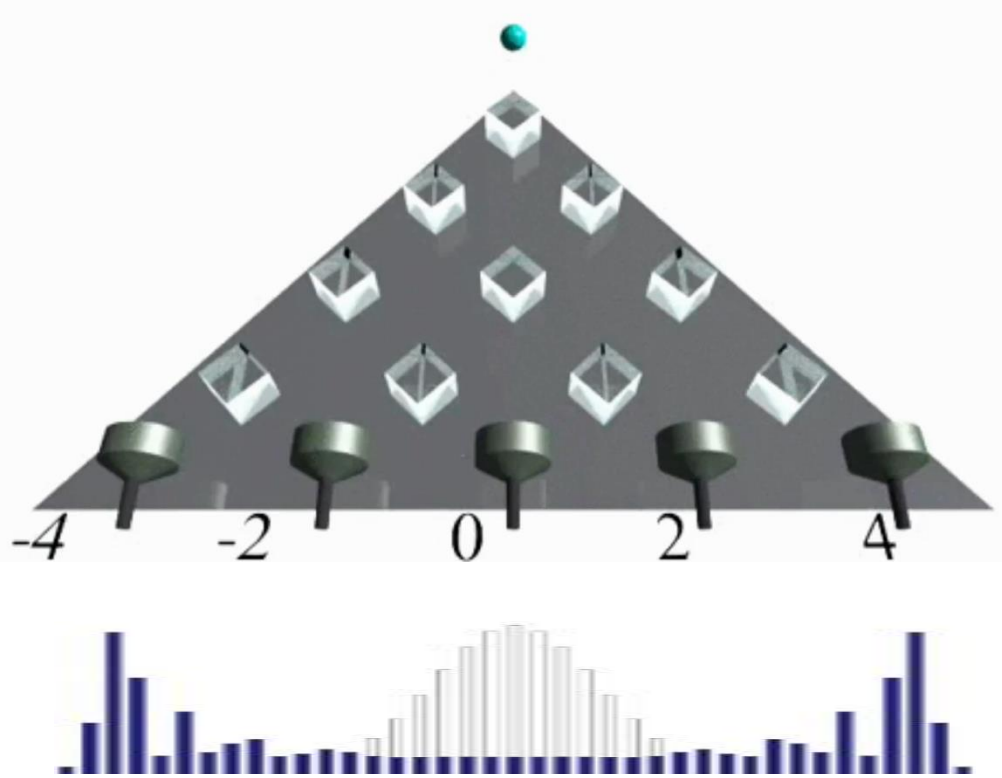
Simulating Physics with Computers", *International Journal of Theoretical Physics* **21**, 467–488 (1982).

# How does a quantum walk work?

## Classical Random Walk



## Quantum Walk

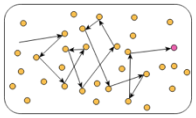



**Random Walk animation:** https://makeagif.com/gif/blender-galton-board-simulation-wblend eQJvR0? origin= user & source=szhao&order=popular&page=&position=1

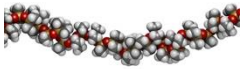
**Quantum Walk animation & plot: Christine Silberhorn group website (**https://physik.uni-paderborn.de/ en/ silberhorn/ forschung/quantum-networking/quantum-walks**).**

# Random Walks are Everywhere!

## Physics Applications

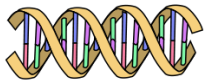


- **Brownian Motion:** Kac, M. (1947). Random Walk and the Theory of Brownian Motion. Am. Math. Mon., ***54*** (7P1), 369–391.



- **Ideal Polymer Chain Simulation:** Rippe, K. (2001). Making contacts on a nucleic acid polymer. *T.I.B.S.,* **26** (12), 733–740.

- **Population Dynamics:** Haydon, D. et al. (2008). Socially informed random walks: incorporating group dynamics into models of population spread and growth. *Proc. R. Soc. B.*, **275** 1101-1109.



- **Genetic Drift Estimation:** Neigel, J., and Avise, J. (1993). Application of a random walk model to geographic distributions of animal mitochondrial DNA variation. *Genetics*, **135** (4), 1209-1220.

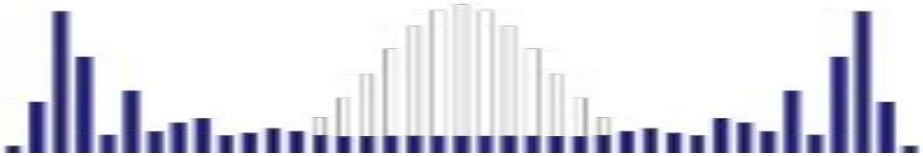
## Broader Applications

- **Sampling Large State Spaces (e.g. the internet):** Bar-Yossef, Z. et al. (2008). Random sampling from a search engine's index. *J.A.C.M.,* **55** (5), 1-74.

- **Twitter Algorithm Follow Suggestions:** Gupta, P. et al. (2013) WTF – The Who-To-Follow service at Twitter. *WWW'13*, 505-514.

# Advantage of a quickly wandering walk

"Grover-like Search Algorithms" – $O(\sqrt{N})$



**Deterministic Search on Star Graphs via Quantum Walks**

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[2]*Department of Physics, Southeast University, Nanjing 211189, China*
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We propose a novel algorithm for quantum spatial search on a star graph using interleaved continuous-time quantum walks and marking oracle queries. Initializing the system in the star's central vertex, we determine the optimal quantum walk times to reach full overlap with the marked state using $\lceil(\pi/4)\sqrt{N}-(1/2)\rceil$ oracle queries, matching the well-known lower bound of Grover's search. We implement the deterministic search in a database of size seven on photonic quantum hardware, and demonstrate the effective scaling of the approach up to size 115. This is the first experimental demonstration of quantum walk-based search on the highly noise-resistant star graph, which provides new evidence for the applications of quantum walk in quantum algorithms and quantum information processing.

DOI: 10.1103/PhysRevLett.128.050501

**Quantum random-walk search algorithm**

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(Received 9 October 2002; published 23 May 2003)

Quantum random walks on graphs have been shown to display many interesting properties, including exponentially fast hitting times when compared with their classical counterparts. However, it is still unclear how to use these novel properties to gain an algorithmic speedup over classical algorithms. In this paper, we present a quantum search algorithm based on the quantum random-walk architecture that provides such a speedup. It will be shown that this algorithm performs an oracle search on a database of $N$ items with $O(\sqrt{N})$ calls to the oracle, yielding a speedup similar to other quantum search algorithms. It appears that the quantum random-walk formulation has considerable flexibility, presenting interesting opportunities for development of other, possibly novel quantum algorithms.

DOI: 10.1103/PhysRevA.67.052307 PACS number(s): 03.67.Lx, 89.70.+c

**Spatial search by quantum walk**

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(Received 16 June 2003; revised manuscript received 27 January 2004; published 23 August 2004)

Grover's quantum search algorithm provides a way to speed up combinatorial search, but is not directly applicable to searching a physical database. Nevertheless, Aaronson and Ambainis showed that a database of $N$ items laid out in $d$ spatial dimensions can be searched in time of order $\sqrt{N}$ for $d>2$, and in time of order $\sqrt{N}\,\mathrm{poly}(\log N)$ for $d=2$. We consider an alternative search algorithm based on a continuous-time quantum walk on a graph. The case of the complete graph gives the continuous-time search algorithm of Farhi and Gutmann, and other previously known results can be used to show that $\sqrt{N}$ speedup can also be achieved on the hypercube. We show that full $\sqrt{N}$ speedup can be achieved on a $d$-dimensional periodic lattice for $d>4$. In $d=4$, the quantum walk search algorithm takes time of order $\sqrt{N}\,\mathrm{poly}(\log N)$, and in $d<4$, the algorithm does not provide substantial speedup.

DOI: 10.1103/PhysRevA.70.022314 PACS number(s): 03.67.Lx

# Application – Parton Showers

PHYSICAL REVIEW D **106,** 056002 (2022)

## Quantum walk approach to simulating parton showers

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[3]*High Energy Physics Group, Blackett Laboratory, Imperial College, Prince Consort Road, London SW7 2AZ, United Kingdom*

(Received 13 October 2021; accepted 16 August 2022; published 2 September 2022)

This paper presents a novel quantum walk approach to simulating parton showers on a quantum computer. We demonstrate that the quantum walk paradigm offers a natural and more efficient approach to simulating parton showers on quantum devices, with the emission probabilities implemented as the coin flip for the walker, and the particle emissions to either gluons or quark pairs corresponding to the movement of the walker in two dimensions. A quantum algorithm is proposed for a simplified, toy model of a 31-step, collinear parton shower, hence significantly increasing the number of steps of the parton shower that can be simulated compared to previous quantum algorithms. Furthermore, it scales efficiently: the number of possible shower steps increases exponentially with the number of qubits, and the circuit depth grows linearly with the number of steps. Reframing the parton shower in the context of a quantum walk therefore brings dramatic improvements, and is a step towards extending the current quantum algorithms to simulate more realistic parton showers.

DOI: 10.1103/PhysRevD.106.056002

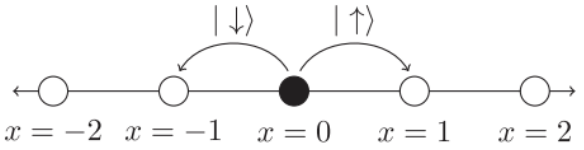


FIG. 1. One-dimensional walker at position $x = 0$ can move either left or right depending on the outcome of the coin flip, $|\downarrow\rangle$ and $|\uparrow\rangle$ respectively.

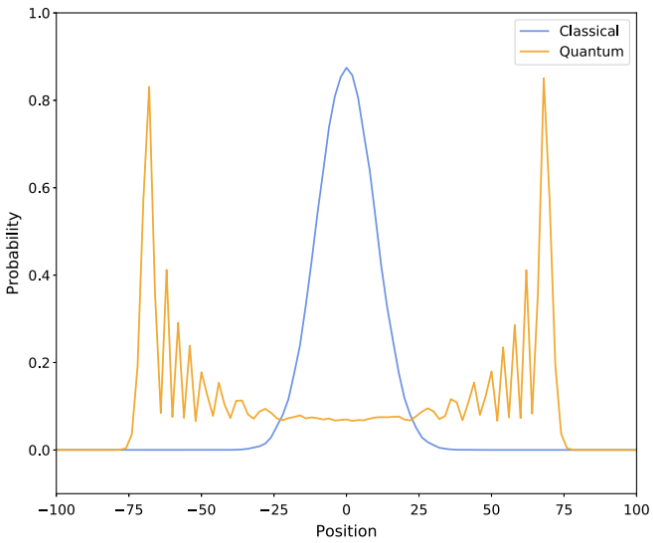


FIG. 2. Simulation of a 100-step random walk using the IBM Q 32-qubit simulator [22] for 100,000 shots for a classical random walk obtained by measuring the coin state after each step, and a quantum random walk using a symmetric initial position and a Hadamard coin. Only nonzero probabilities are shown, as odd-numbered positions will have zero probability for this walk.



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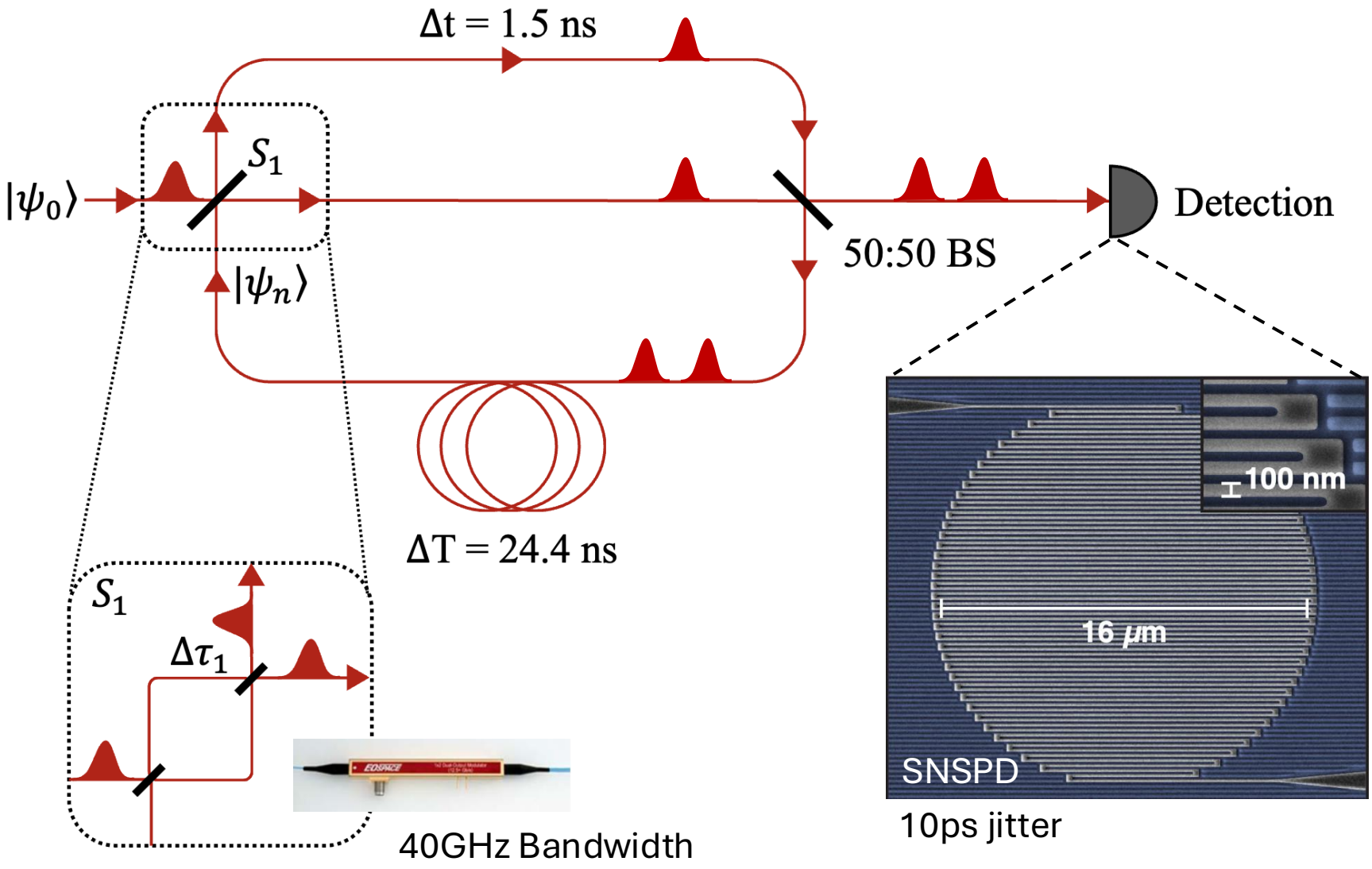
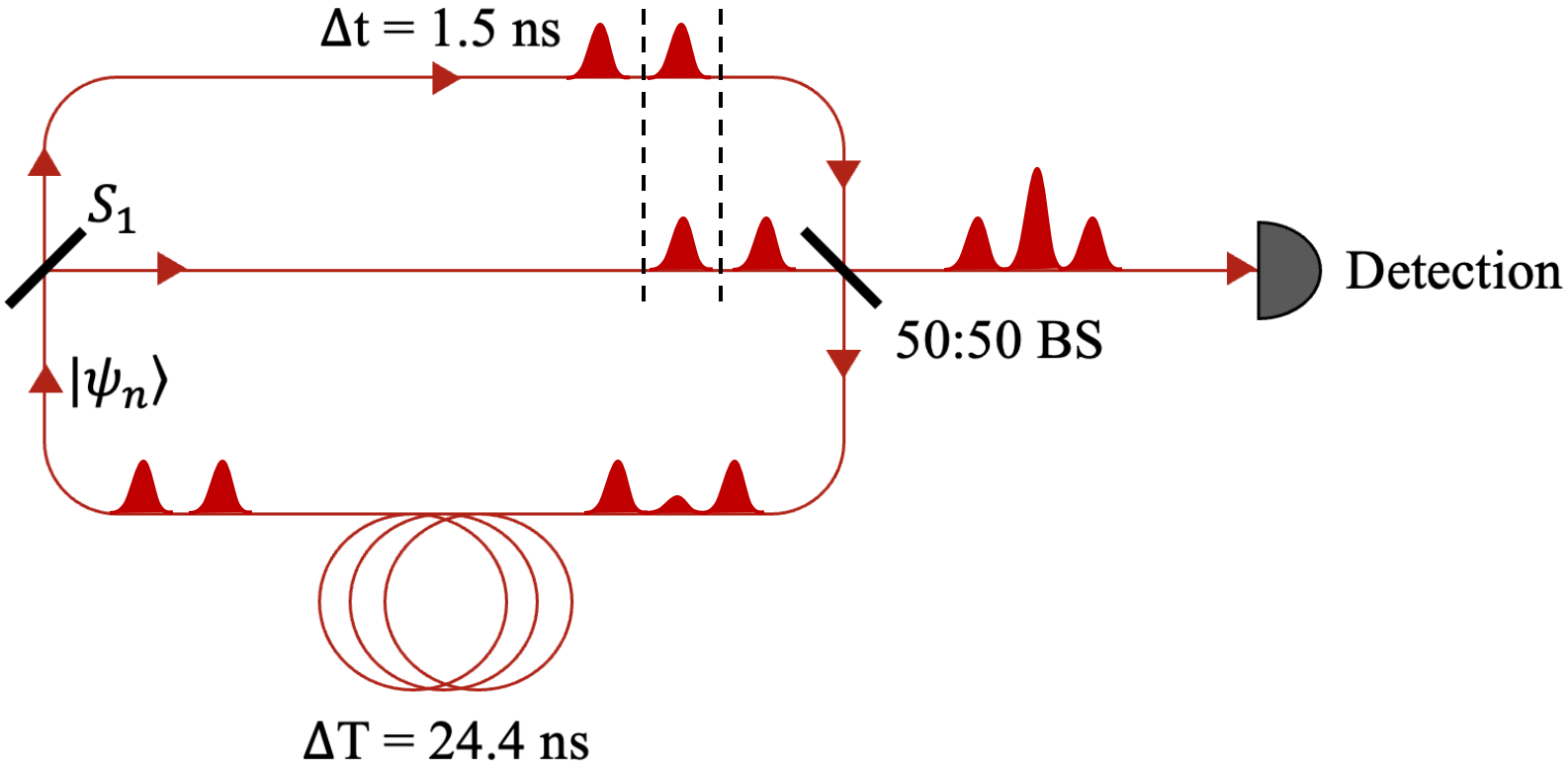
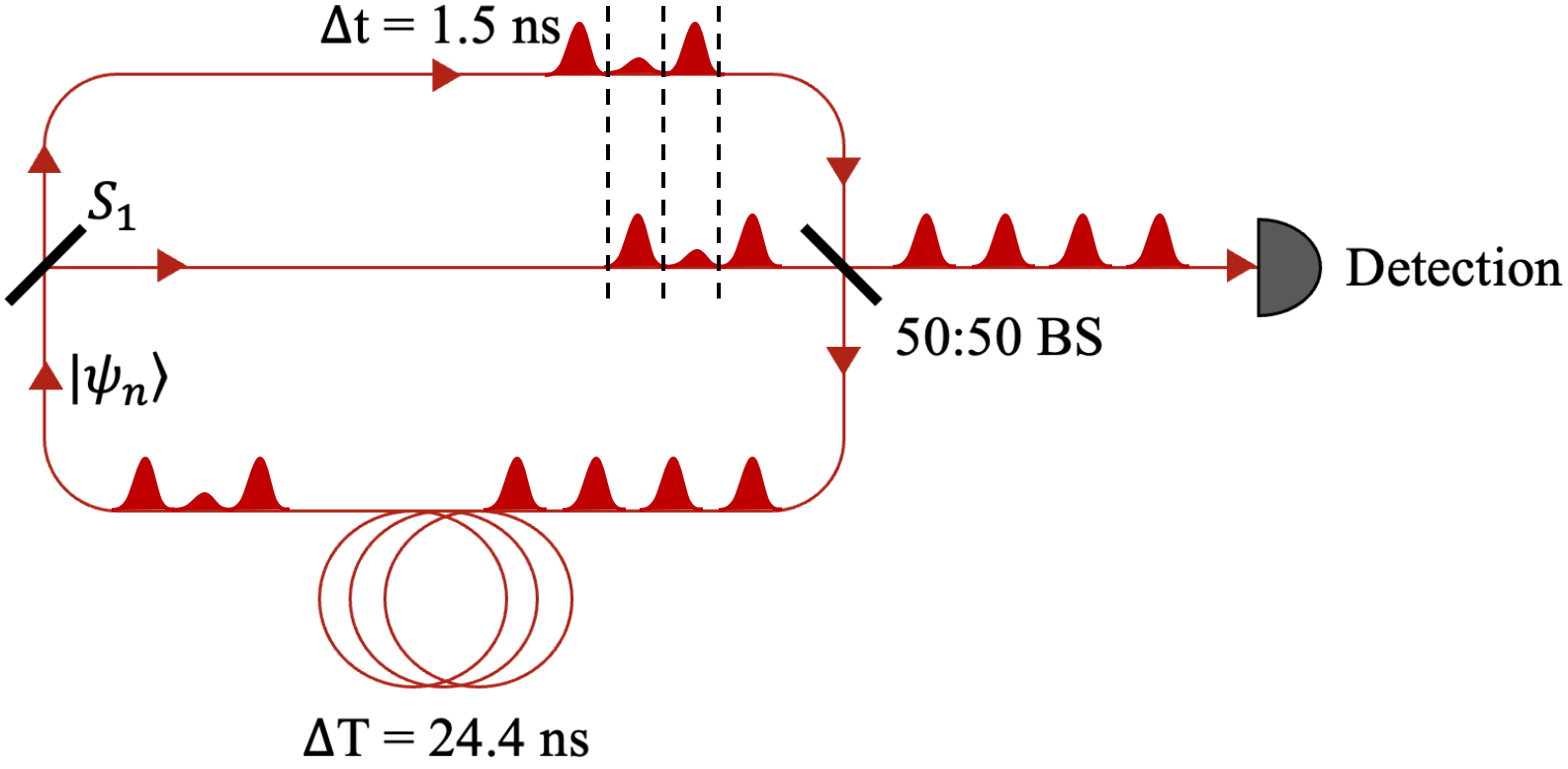
# Quantum Walk in the Lab - Fiber Loops



# Quantum Walk in the Lab - Fiber Loops (Step 2)

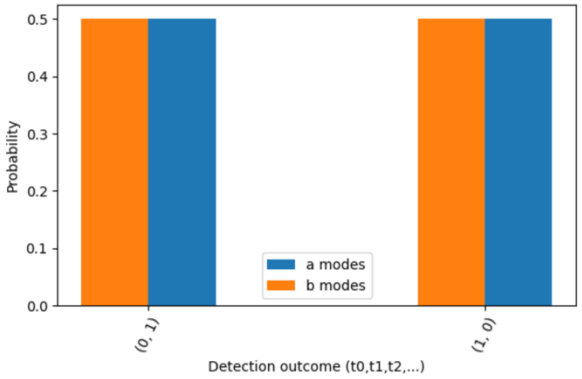


# Quantum Walk in the Lab - Fiber Loops (Step 3)

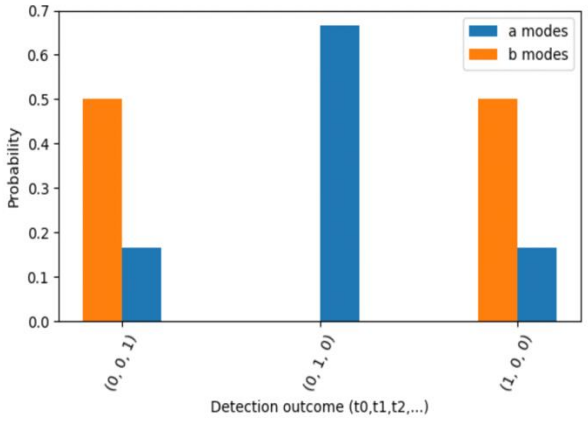


# Simulation Results (Setting input switch to 50:50)

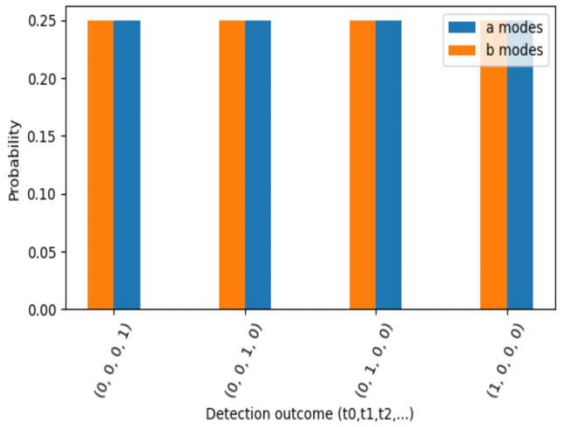
Step 1



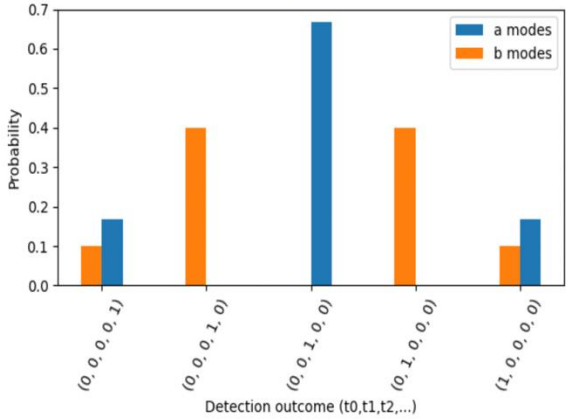

Step 2



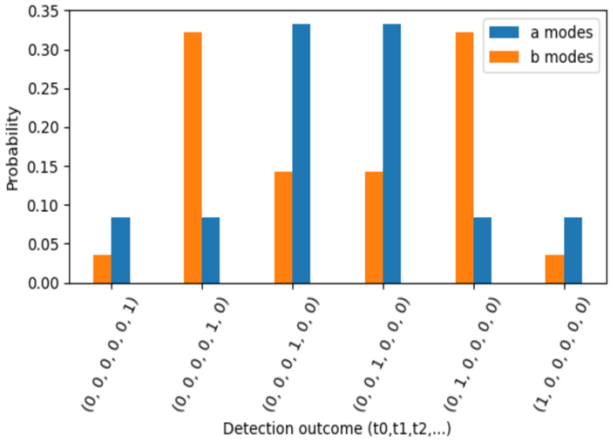

Step 3



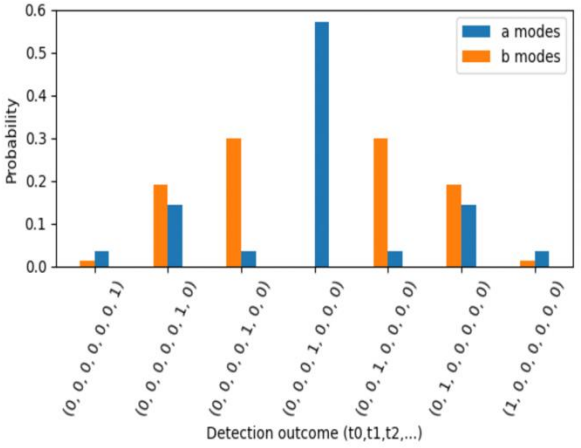

Step 4




Step 5




Step 6



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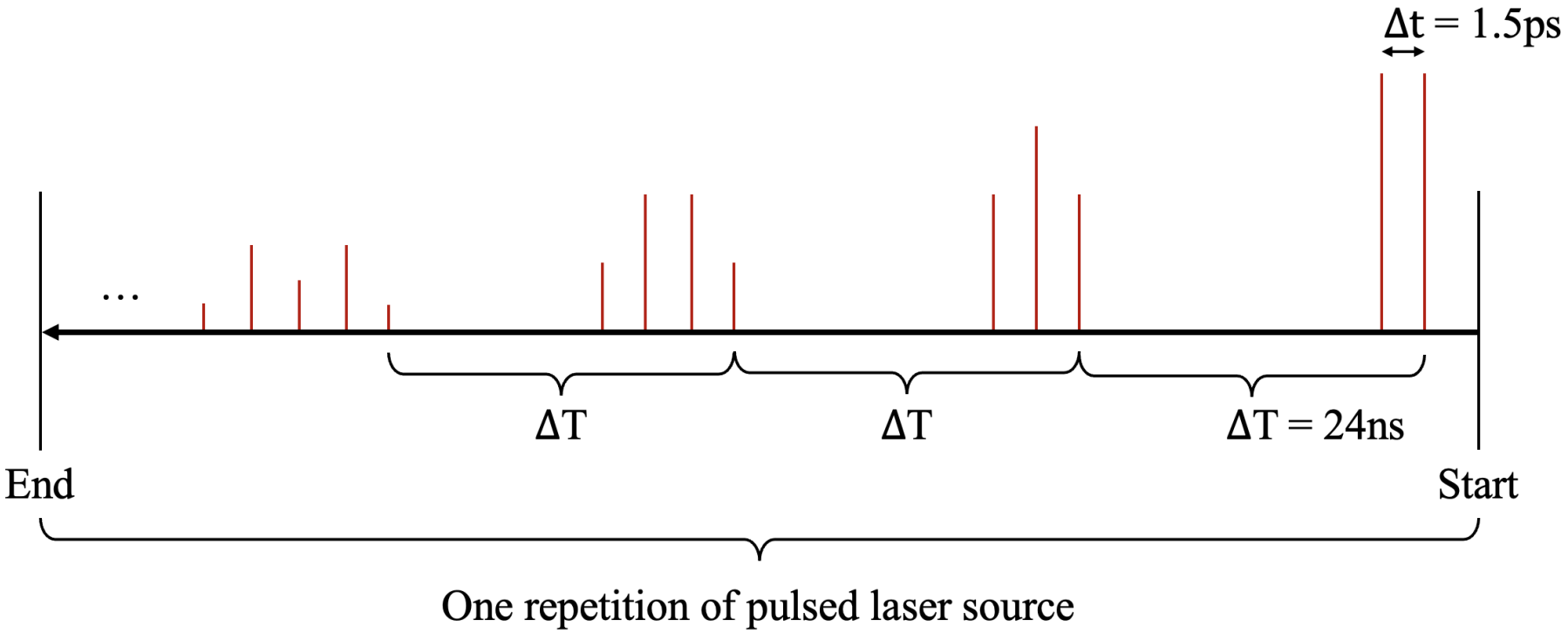
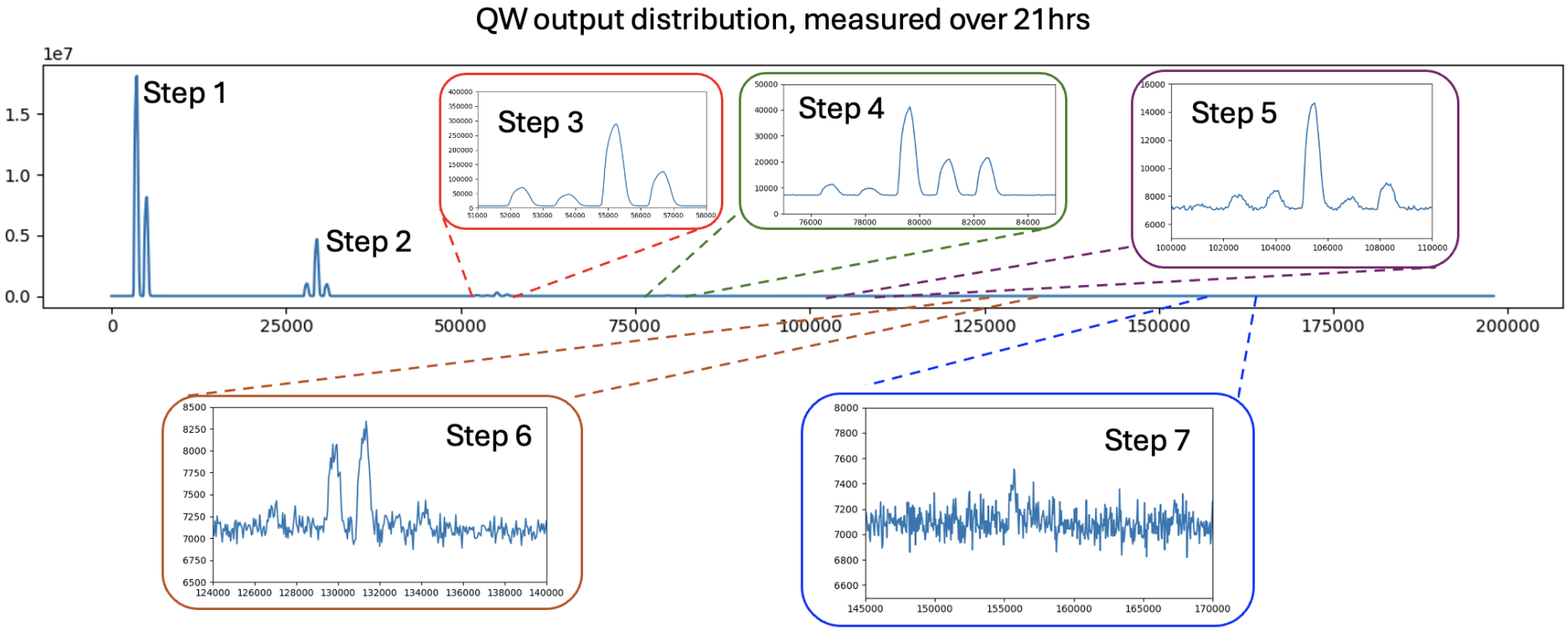
# Quantum Walk in the Lab – Stream of Data

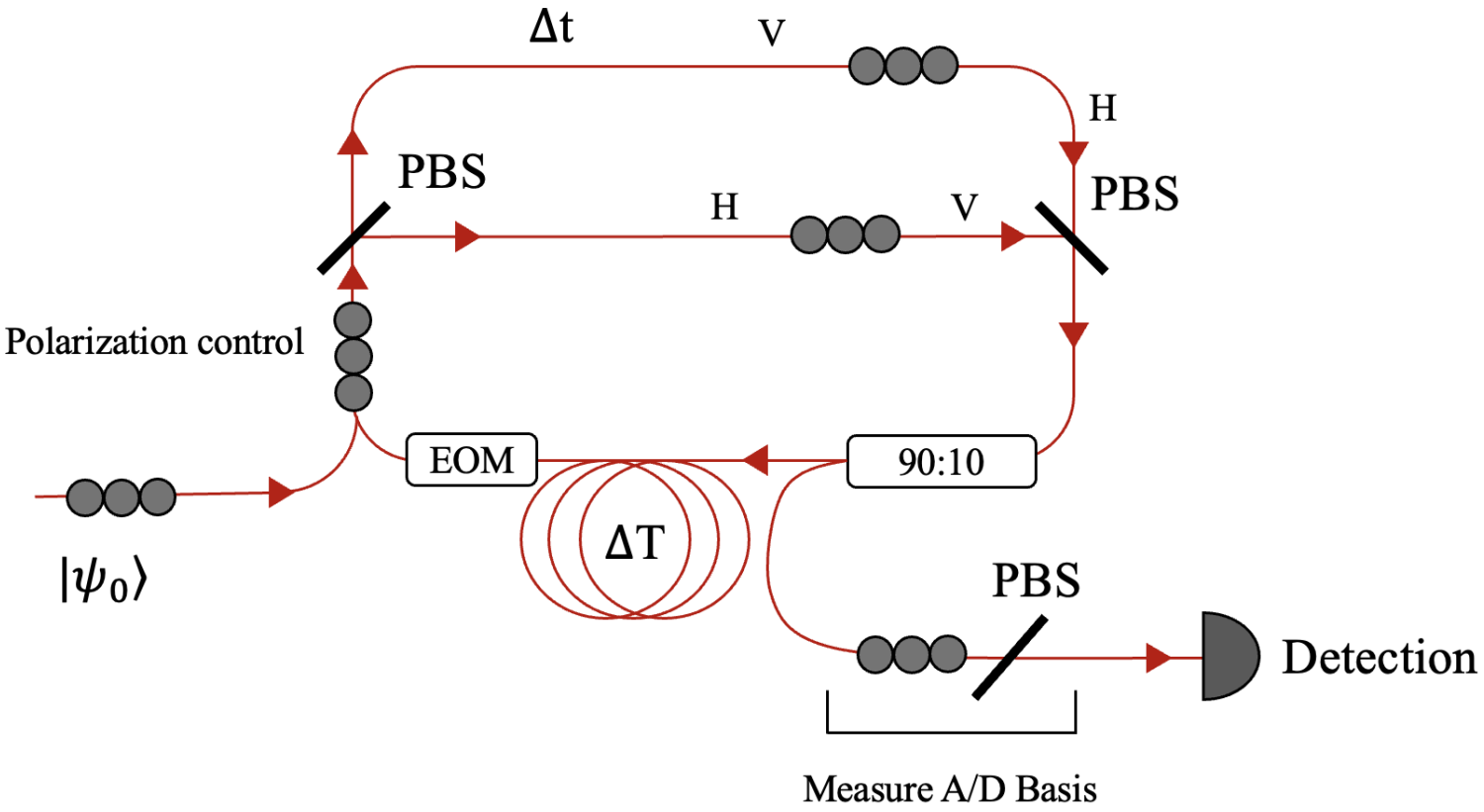


# Preliminary Results




- With lossy switch and 50:50 output beamsplitter, loss scales exponentially with 5dB loss/step
- Are there experimental designs which lower loss/step?

# Experiment Next Steps – Polarizing Beam Splitters



# Acknowledgements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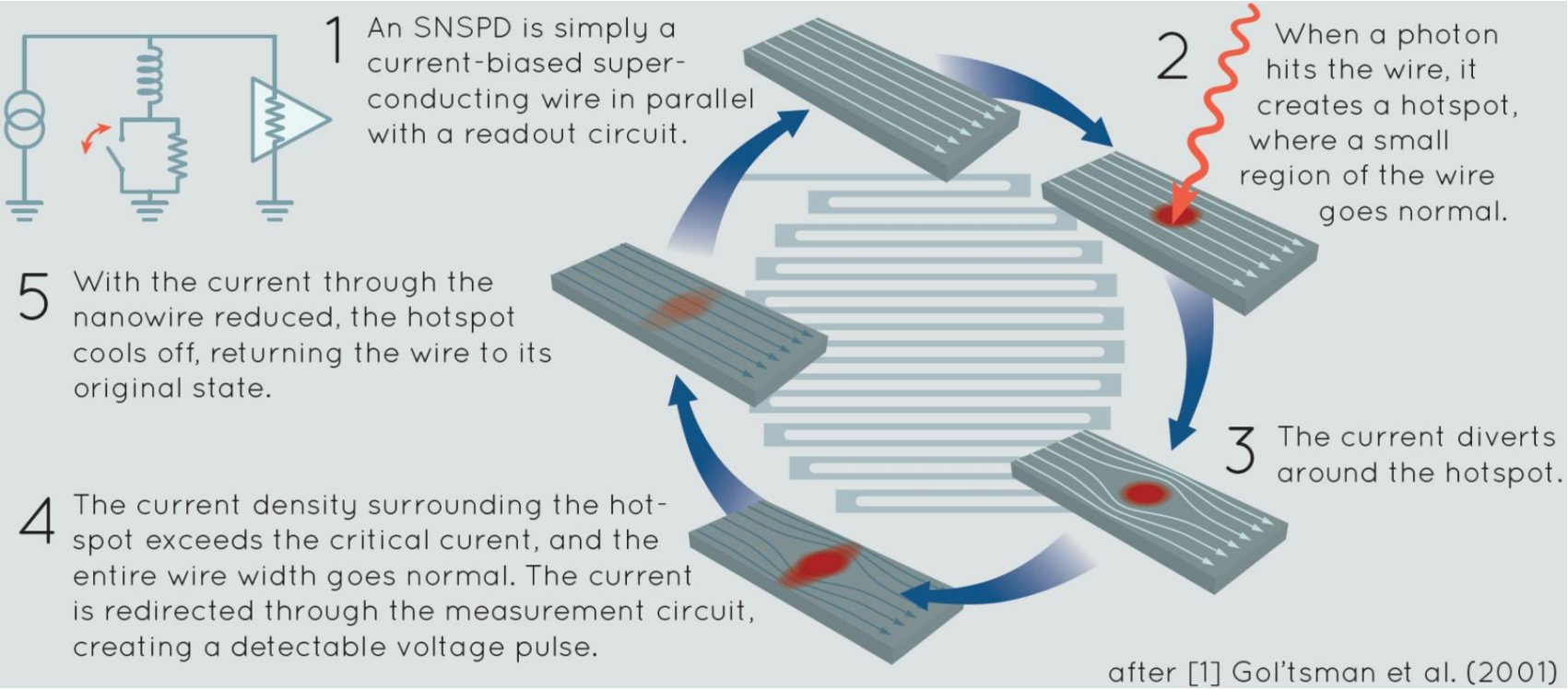
Maria Spiropulu

Lautaro Narvaez

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

# Extra Slides

# Superconducting Nanowire Single Photon Detectors




**Highest performance single-photon detector, from UV to mid-infrared (5ps jitter possible)**

**Operating temperature : 1-4 Kelvin**



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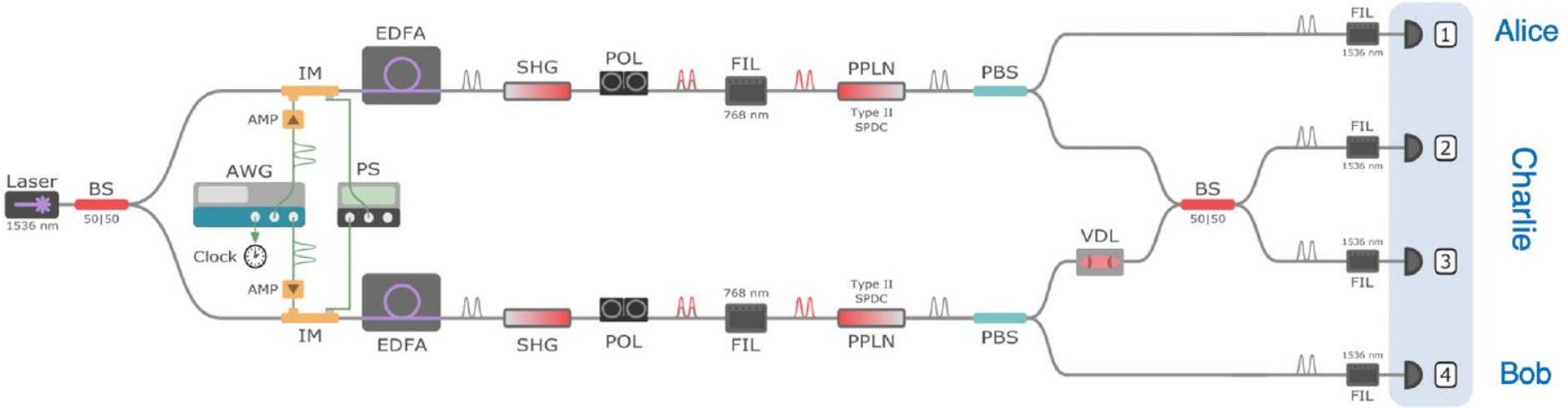
# Single Photon Source



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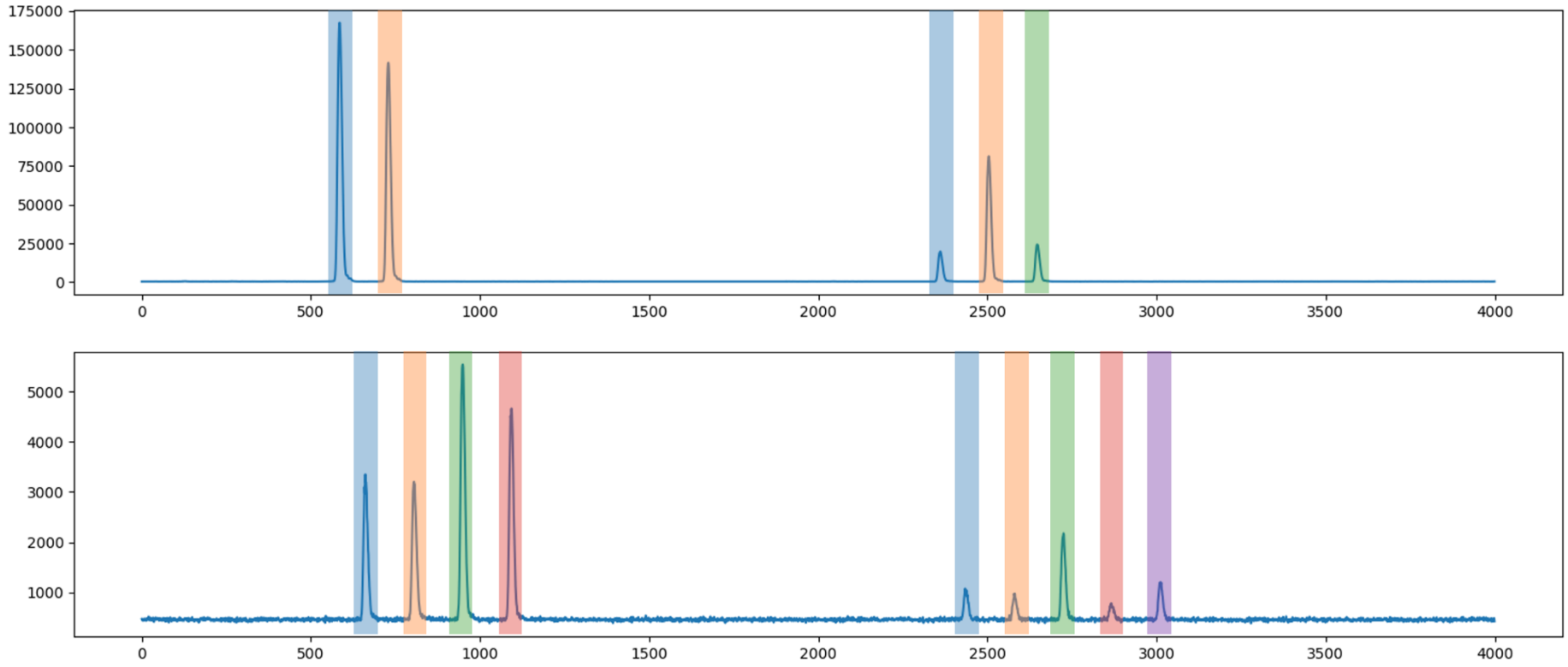
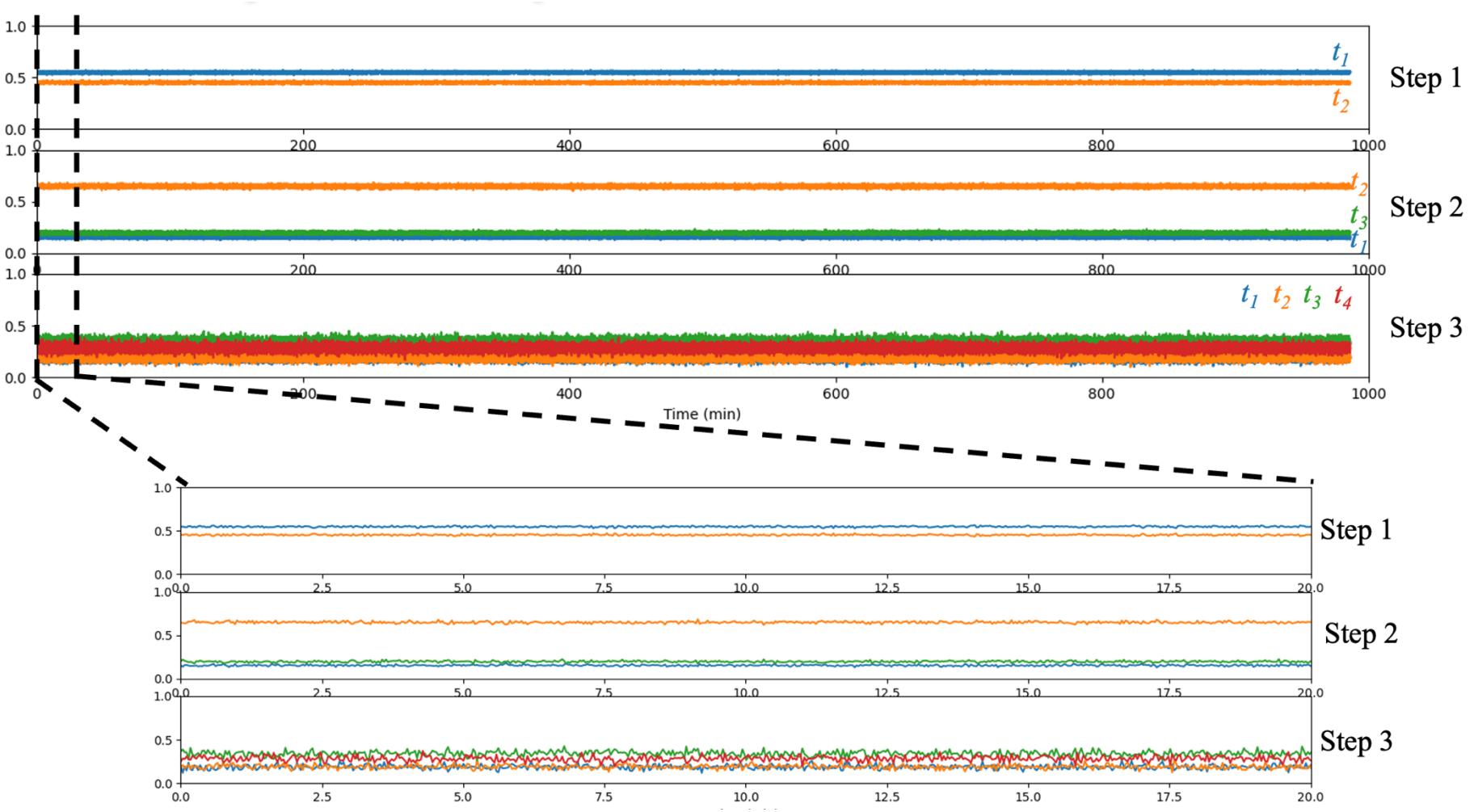
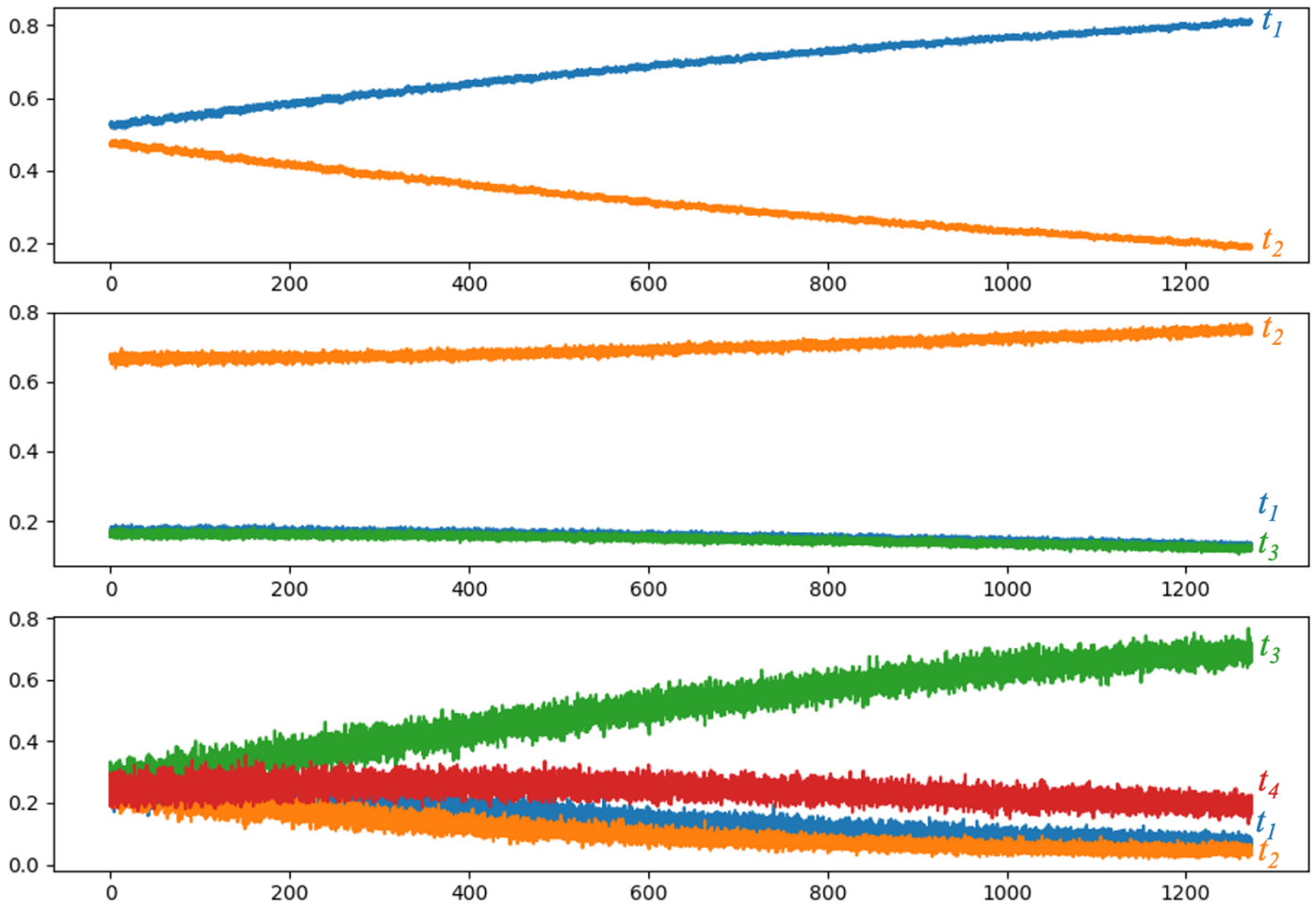
# Interferometer Stability



# Interferometer Stability – two 50/50 beamsplitters



# Interferometer stability – with switch added



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