Kwiat
Quantum
Information
Group

QCrypt 2023

Free-space Photonic Quantum Memory for Networking

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ILLINOIS IQUIST

Office of Naval Research Science & Technology

NSF

Q-NEXT NEXT GENERATION QUANTUM SCIENCE AND ENGINEERING

Outline

- Quantum networks and different memory technologies
- Short single-loop memory applications
- Longer memories
- Performance and comparison
- Summary and outlook

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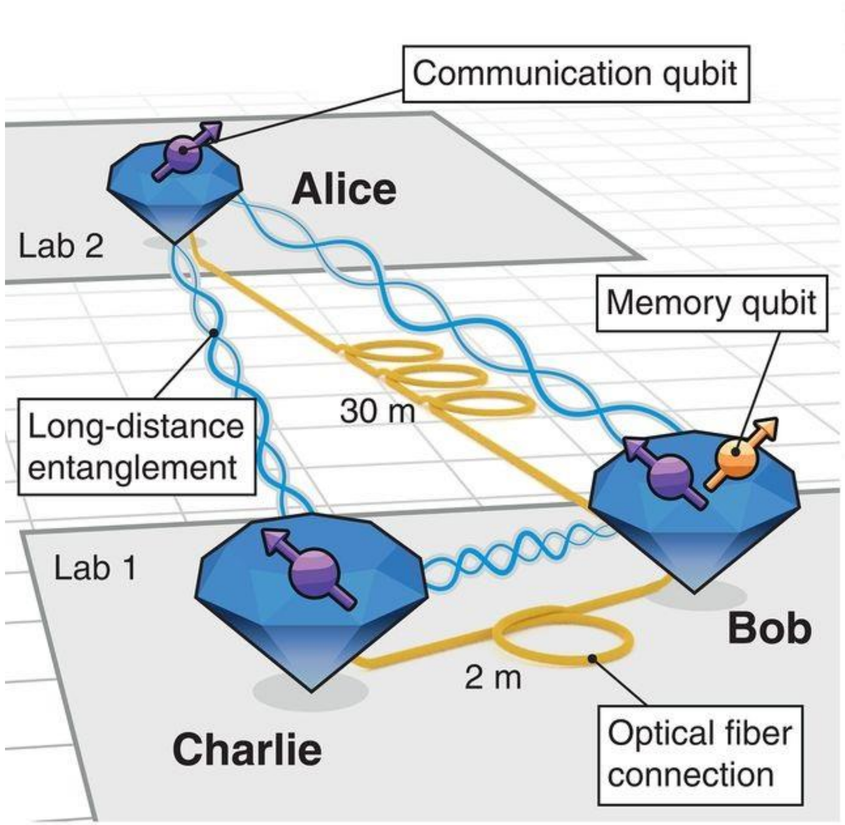
Quantum networks will provide completely secure communication channels

Process of sending qubits is vastly different than that of sending classical bits

Quantum repeaters will be an essential part of future quantum networks

Quantum repeaters rely on short-term photonic memories that can preserve quantum states in order to synchronize signals and swap entanglement

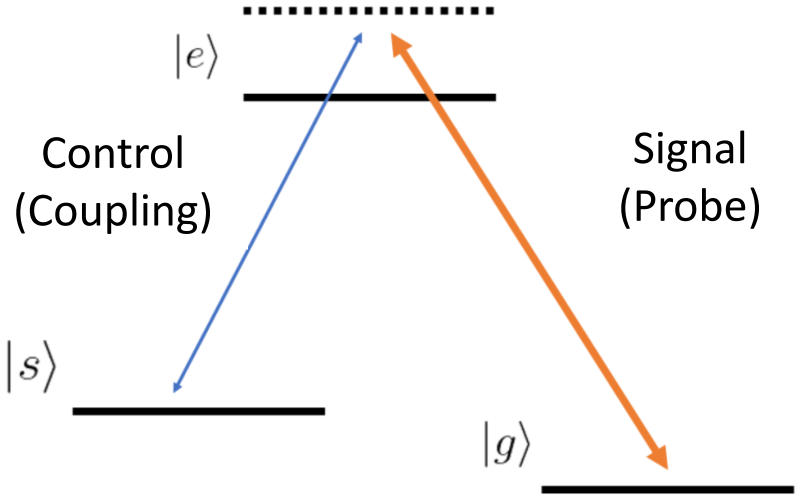


M. Pompili et. al., “Realization of a multinode quantum network of remote solid-state qubits” (2021)

Matter-memory

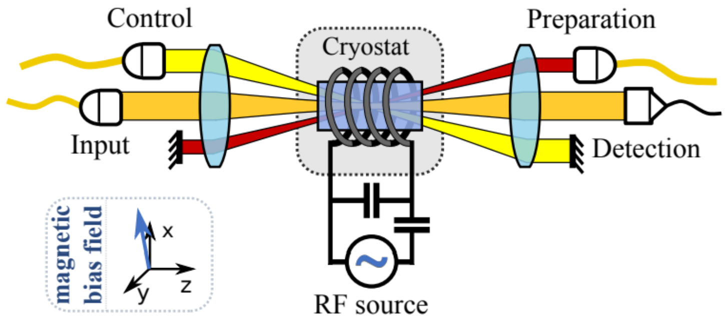
Most current photonic memory schemes utilize a light-matter interaction to store photons.

This approach has drawbacks that are difficult to overcome.



Matter Interaction:

Expensive overhead, narrow bandwidth
(e.g., 3 MHz[1])



Re-emitting Qubit:

High noise and low retrieval efficiency into single-mode fiber (e.g., 0.1%[2])

[1] Y. Wang et. al., “Efficient quantum memory for single-photon polarization qubits” (2019)

[2] A. Holzapfel et. al., “Optical storage for 0.53 seconds in a solid-state atomic frequency comb memory using dynamical decoupling” (2020)

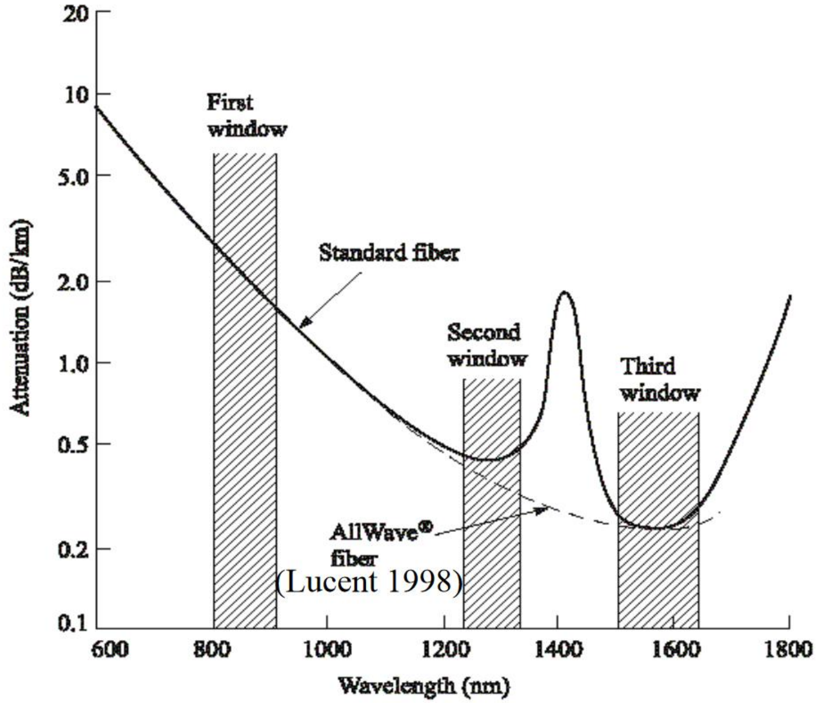
Fiber-memory

Alternate approach is to simply add an extra length of fiber-optic cable to the system in question, “storing” the photon in a delay line

→ Cost-effective alternative but fundamentally limited by dispersion and loss (except at particular λ’s) and offers few degrees of freedom for storage of qudits

→ Single storage time – no (easy) configurability

Typical spectral attenuation in silica



Credit: Lawrence Berkeley Lab

Free-space approach bypasses these drawbacks

There is negligible attenuation of light traveling through free space

How to store light in free space?

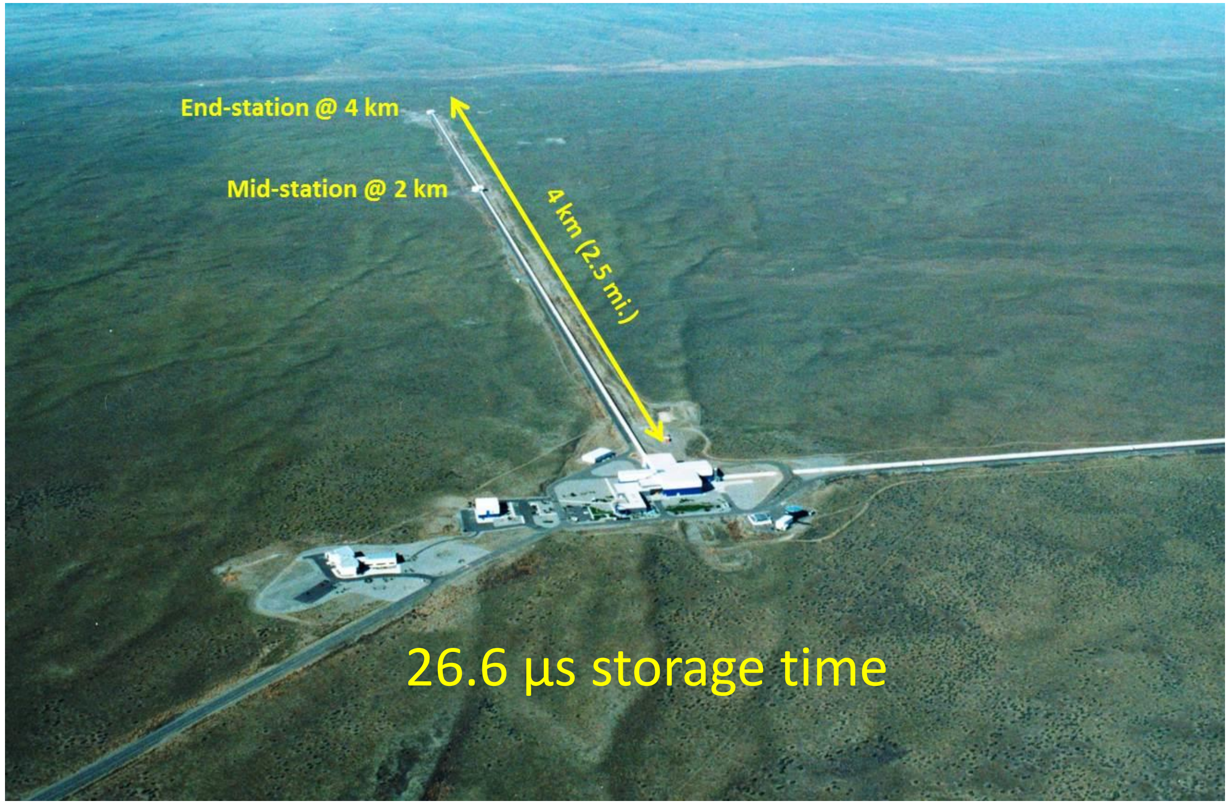
Free-space approach bypasses these drawbacks

There is negligible attenuation of light traveling through free space

How to store light in free space?

→ Just let it fly – think LIGO!

Single reflection off a high-performance mirror retains >99.999% of photons

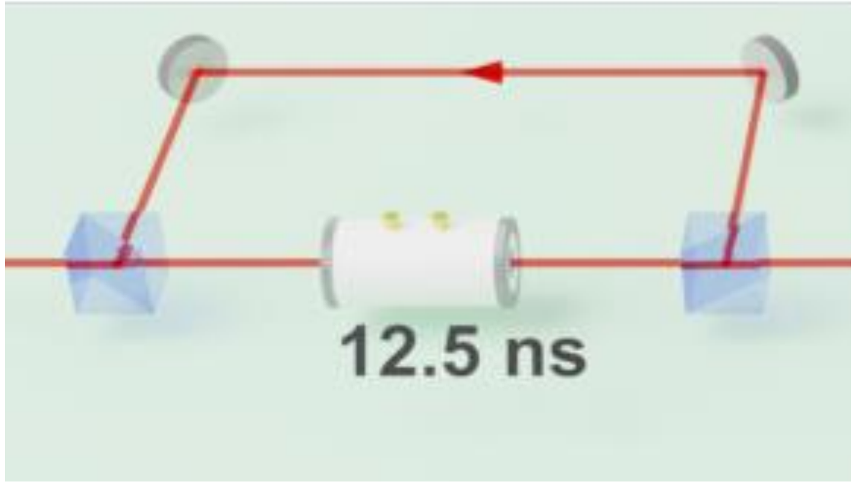


https://www.ligo.caltech.edu/page/ligo-detectors

Making a free-space memory – switchable buffers

LIGO too large → condense space into a loop-based delay-line

- → Provides *configurable* storage time that is an integer multiple of the base storage time



Simplified schematic of our 12.5-ns delay-line memory. Storage is controlled by a Pockels cell with polarizing beam splitters

M. Victora, PhD Thesis, UIUC, Urbana (2020)

Making a free-space memory – switchable buffers

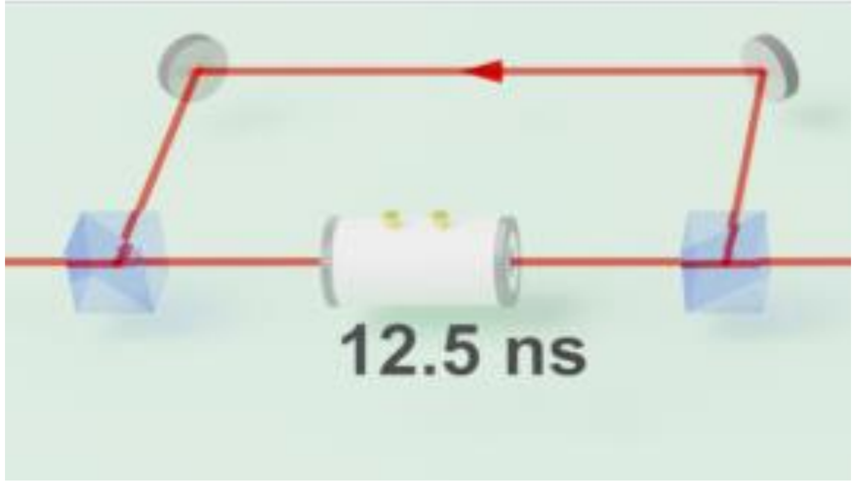
LIGO too large → condense space into a

loop-based delay-line

- → Provides *configurable* storage time that is an integer multiple of the base storage time

Simple construction makes this an easy way to achieve a variable storage time

- → **Pros:** fine time resolution, cost-effective
- → **Cons:** storage efficiency significantly limited by switch (Pockels cell transmission ~99%, mirror reflectivity >99.99%)



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Delay-line memory in action – enhanced single-photon source

We need reliable sources of single – or entangled pairs of – photons for many quantum applications

	Deterministic	Retrieval efficiency	Cryogenic requirement	Homogeneity/ scalability	Purity
Single emitters (QD, NV)	✓	✗	✗	✗	✓
Pair source (SPDC, FWM)	✗	✓	✓	✓	✓

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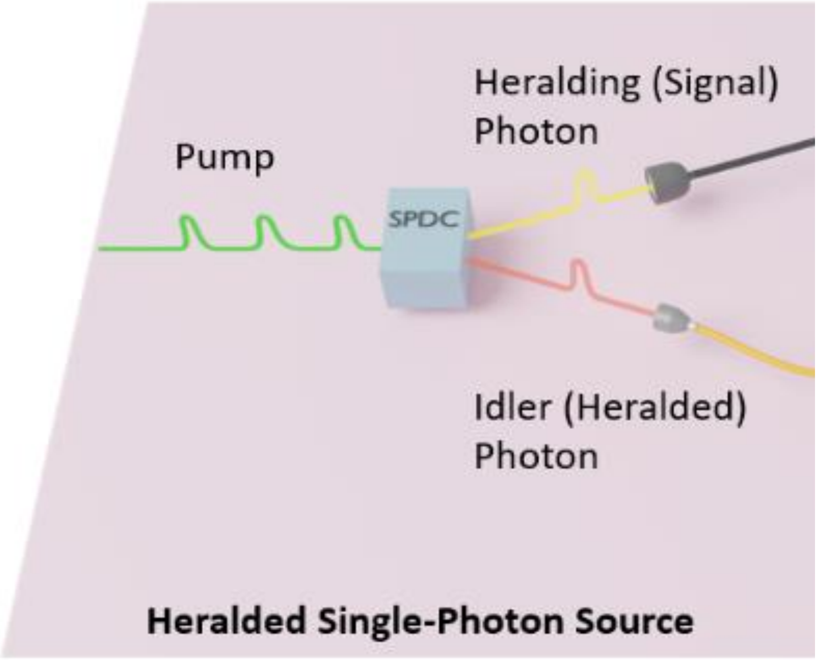
Our focus



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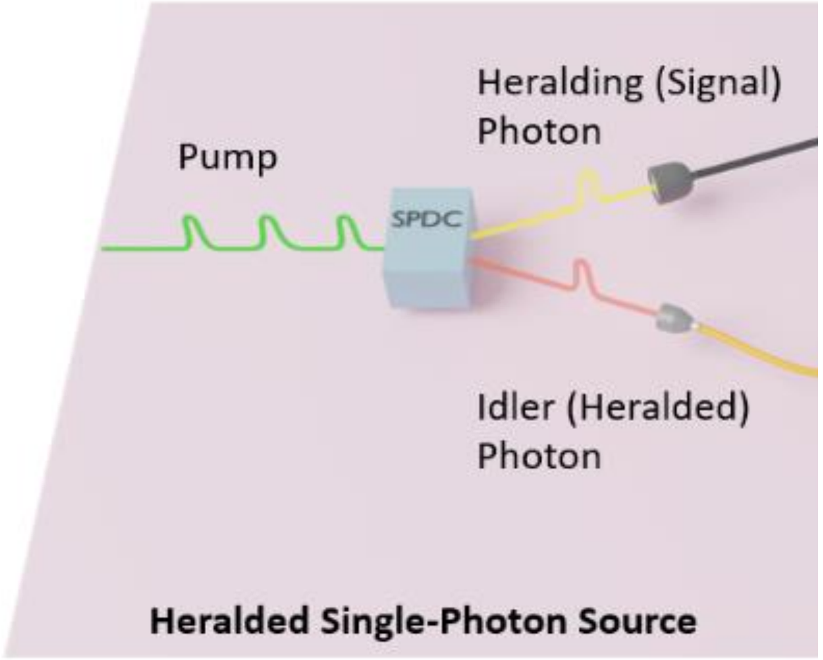

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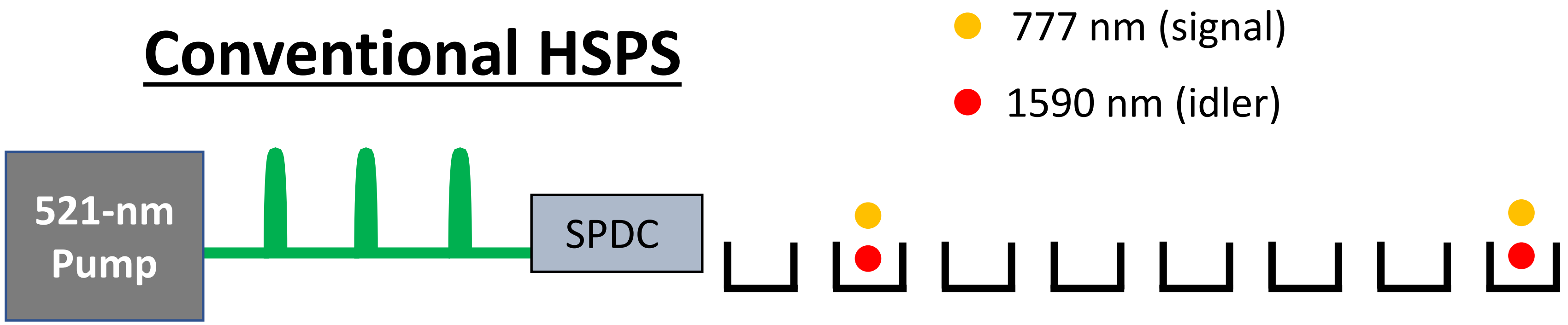
Our focus

$$P(k) = \frac{\mu^k}{(\mu+1)^{k+1}} \xrightarrow{\mu = 1} \frac{1^k}{2^{k+1}} \therefore \boxed{P(1) \leq \mathbf{25\%}}$$

$\mu = mean\ number\ of\ photons\ per\ pump\ pulse$
$\mathrm{k} = number\ of\ pairs\ emitted$

Improving SPDC efficiency via time multiplexing

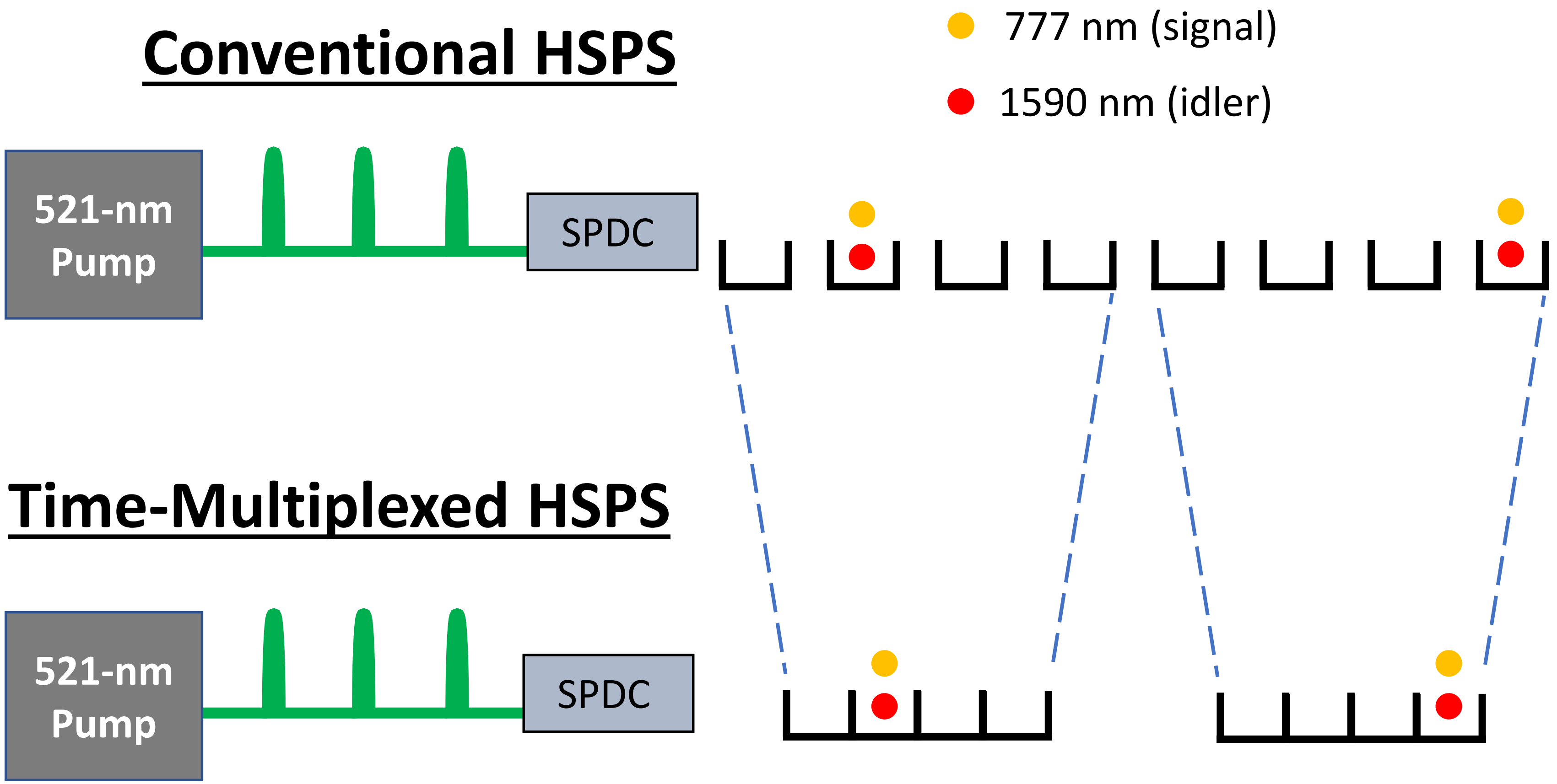
Conventional HSPS



Low Probability
of having a time bin
with a photon pair
(to suppress multiple pairs)

F. Kaneda *et al.*, Science Advances **5**, eaaw8586 (2019)

Improving SPDC efficiency via time multiplexing



Conventional HSPS

● 777 nm (signal)

● 1590 nm (idler)

Time-Multiplexed HSPS

Low Probability
of having a time bin
with a photon pair
(to suppress multiple pairs)

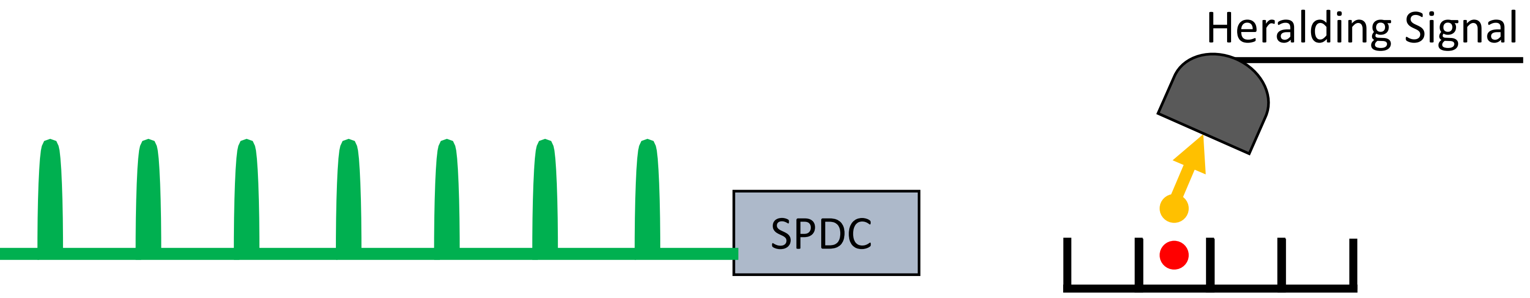
High Probability
of at least one time bin
with a photon pair
in each multiplexing cycle

F. Kaneda *et al.*, Science Advances **5**, eaaw8586 (2019)

Improving SPDC efficiency via time multiplexing

Problem: Photon pairs appear in different time bins for each multiplexing cycle

Solution: Identify photon location using timing information from heralding signal



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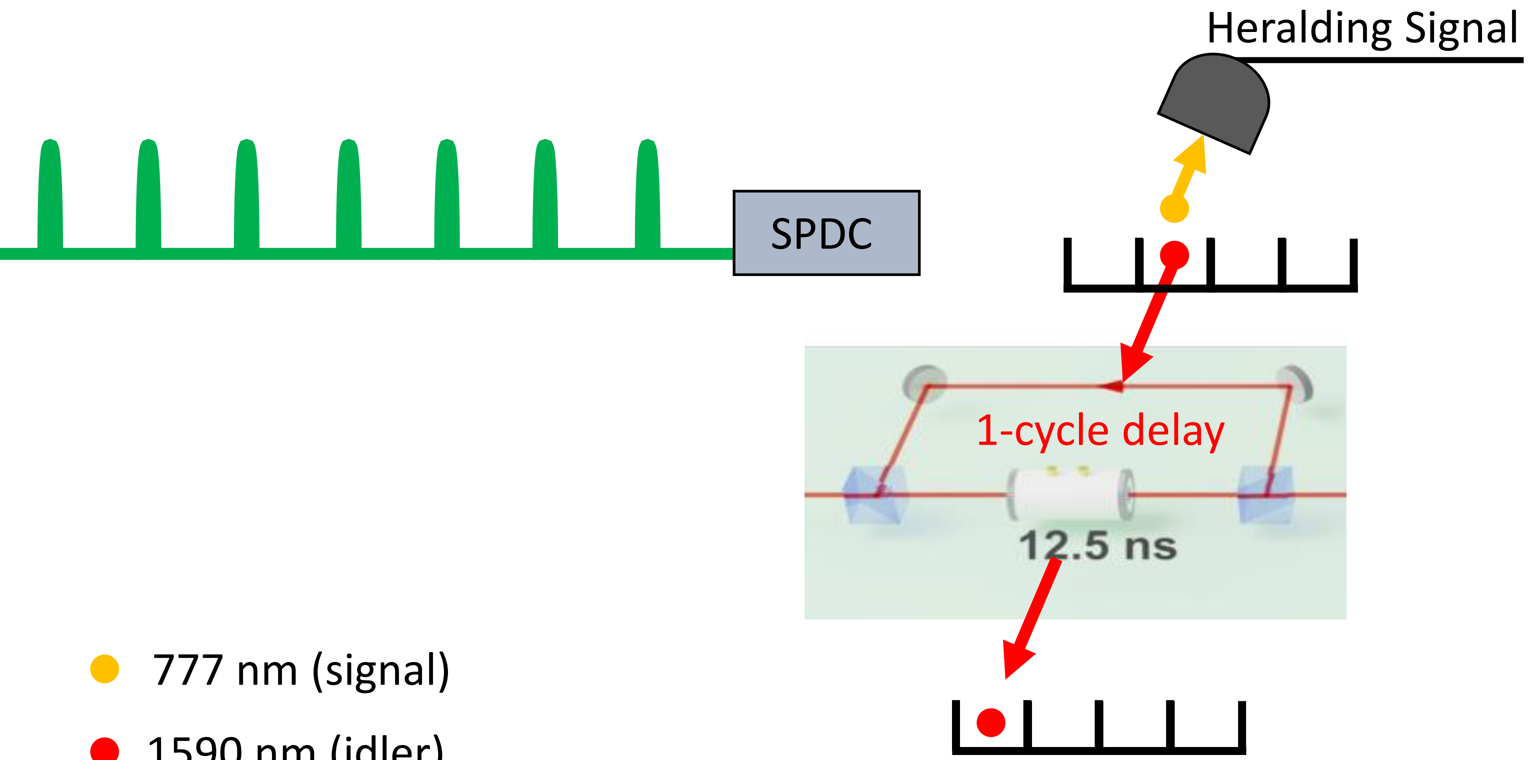

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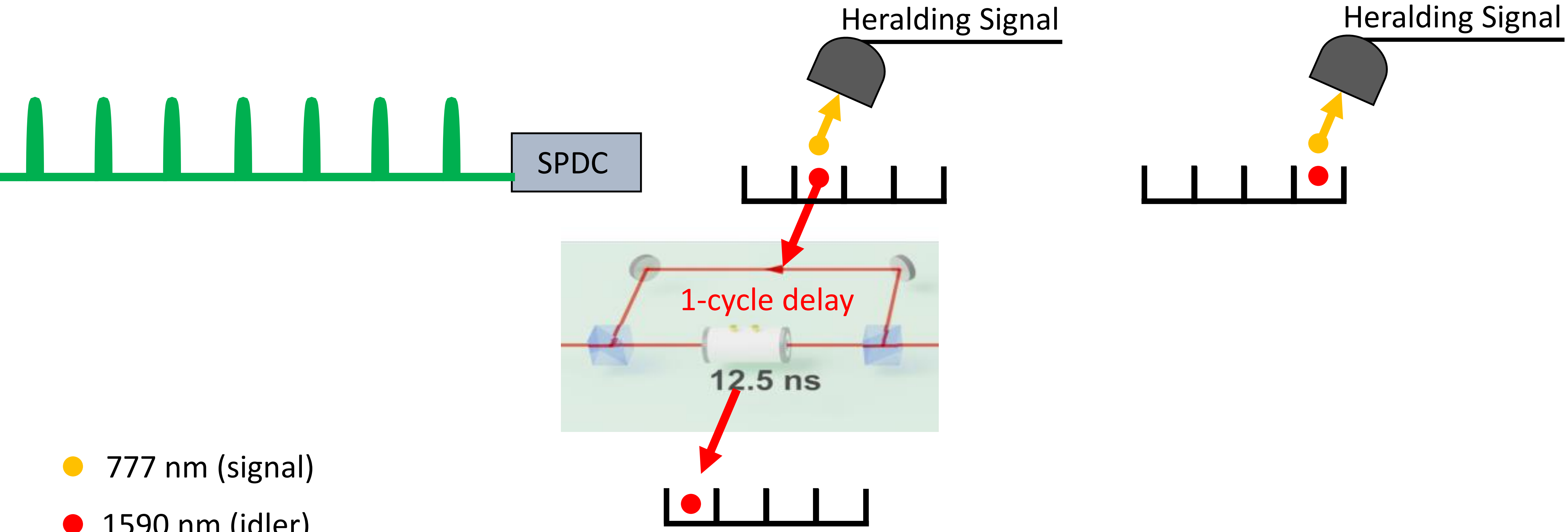

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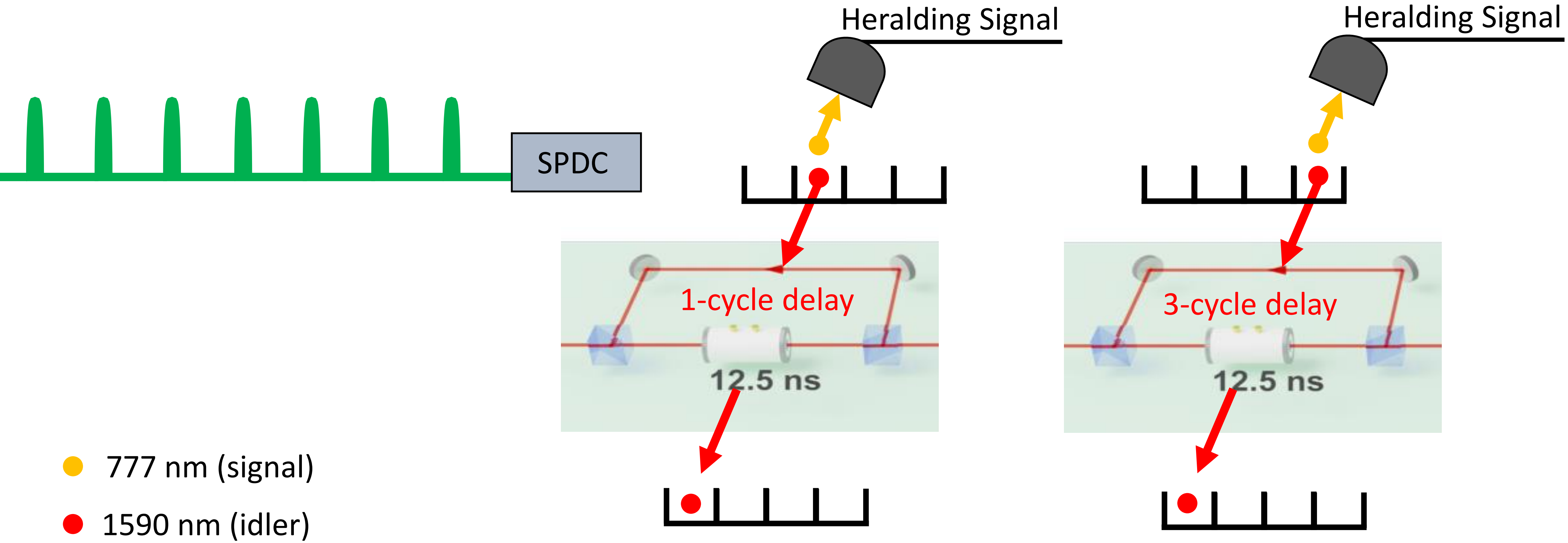

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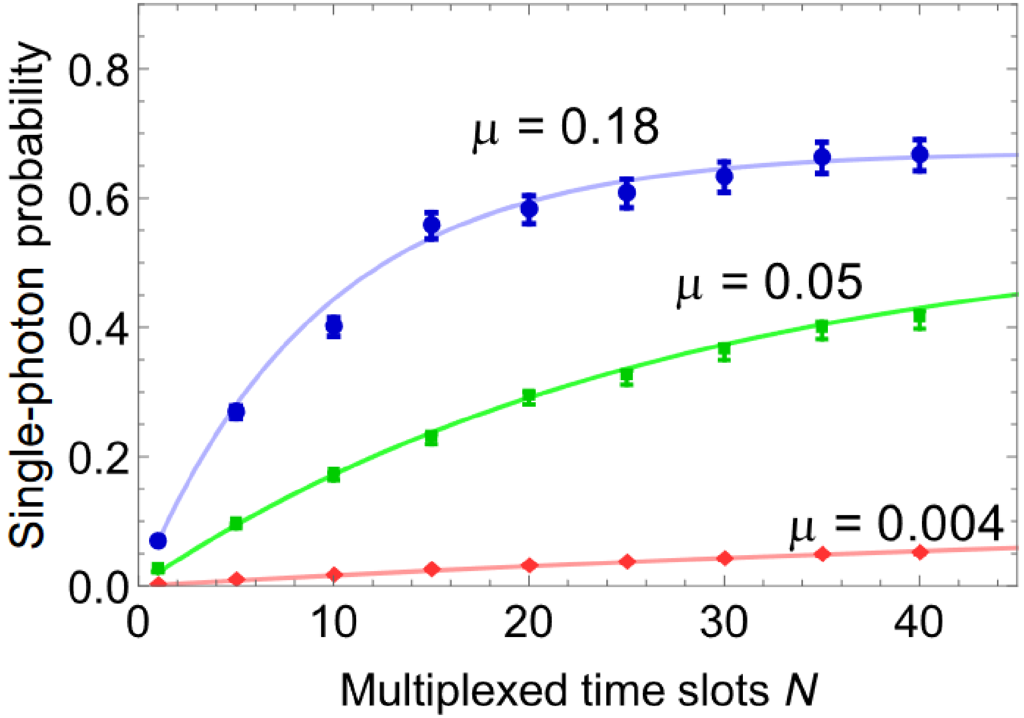
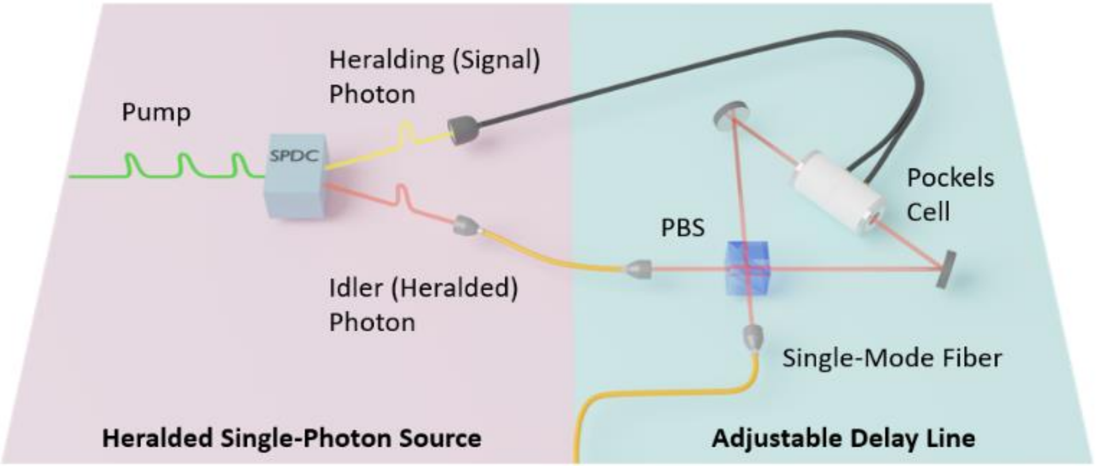
Delay-line memory in action – enhanced single-photon source

Time-multiplexing significantly increases probability of generating single photons, but decreases rate of photon emission



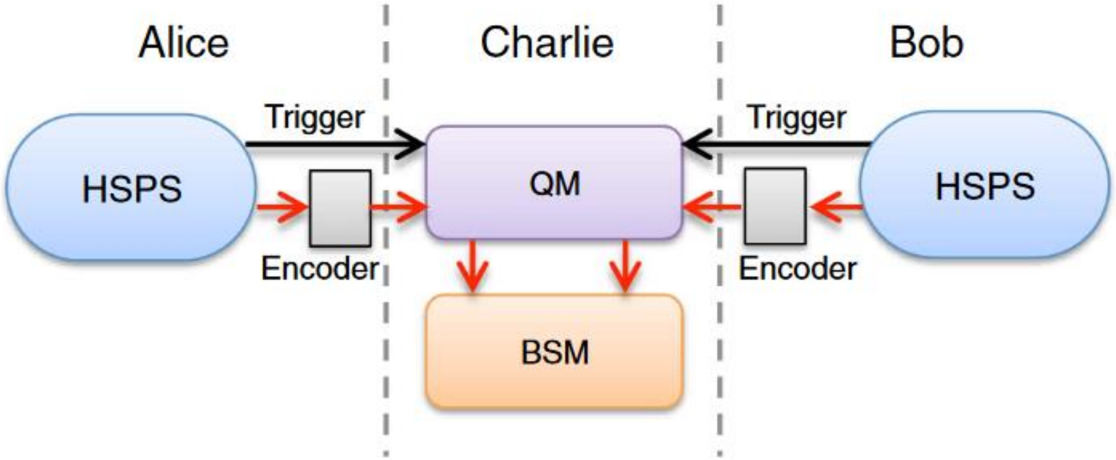


C. K. Hong *et al.*, Phys. Rev. Lett. **56**, 58 (1986)

Delay-line memory in action – memory-enhanced MDI-QKD

We need synchronization of photons at a Bell-state measurement device for MDI-QKD

→ Our proven memory technology is an ideal candidate for synchronizing!



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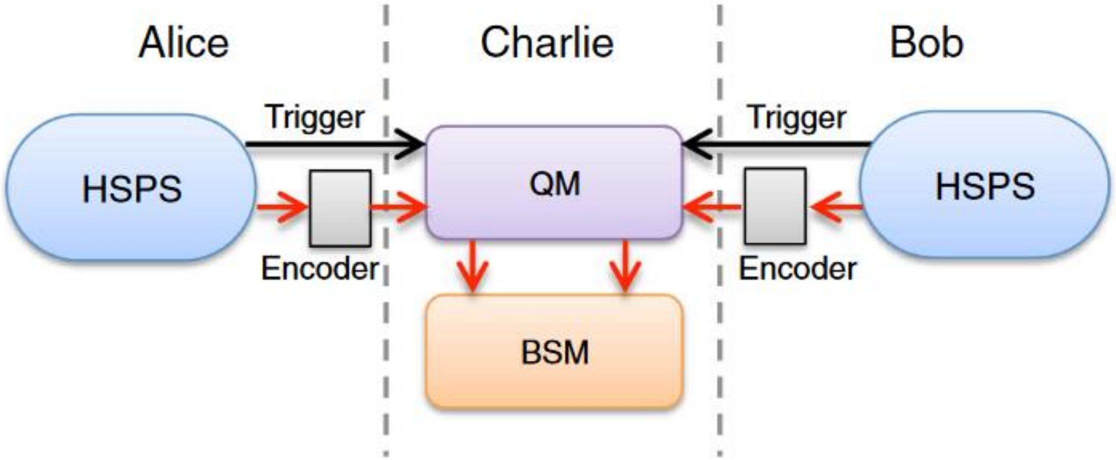

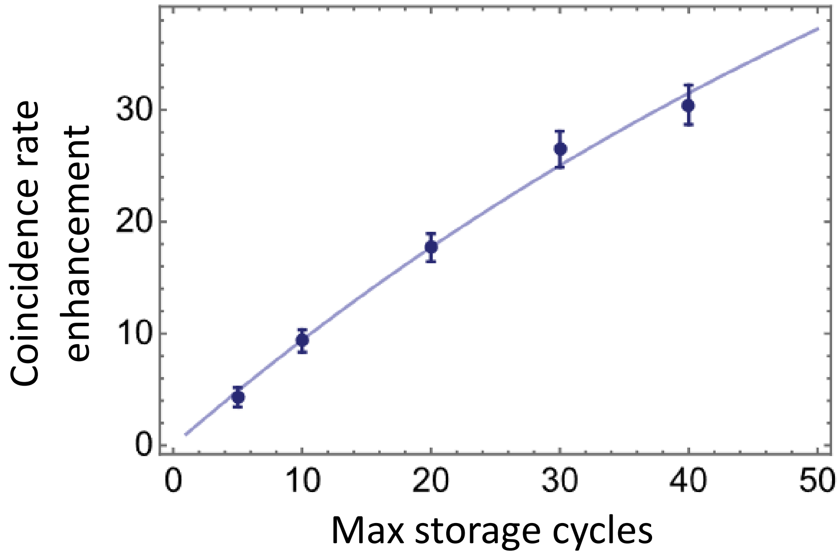

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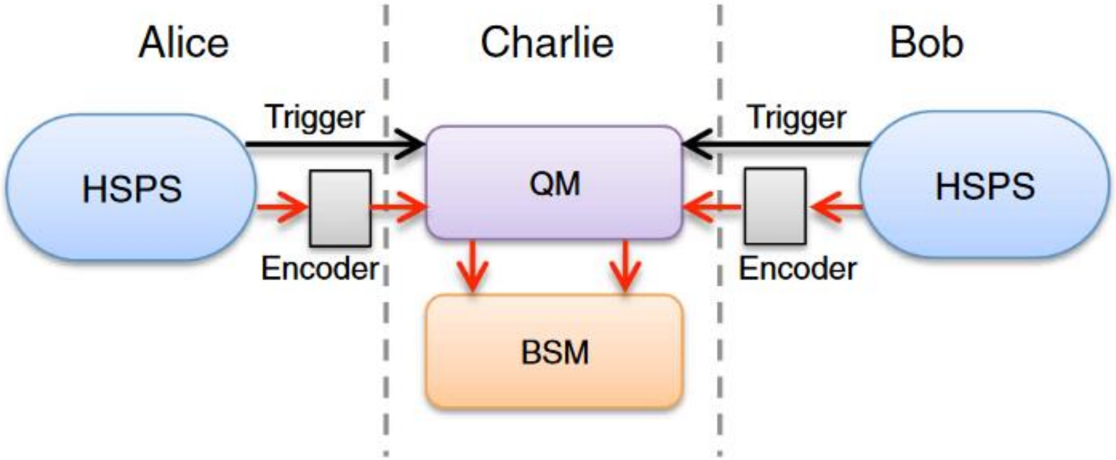

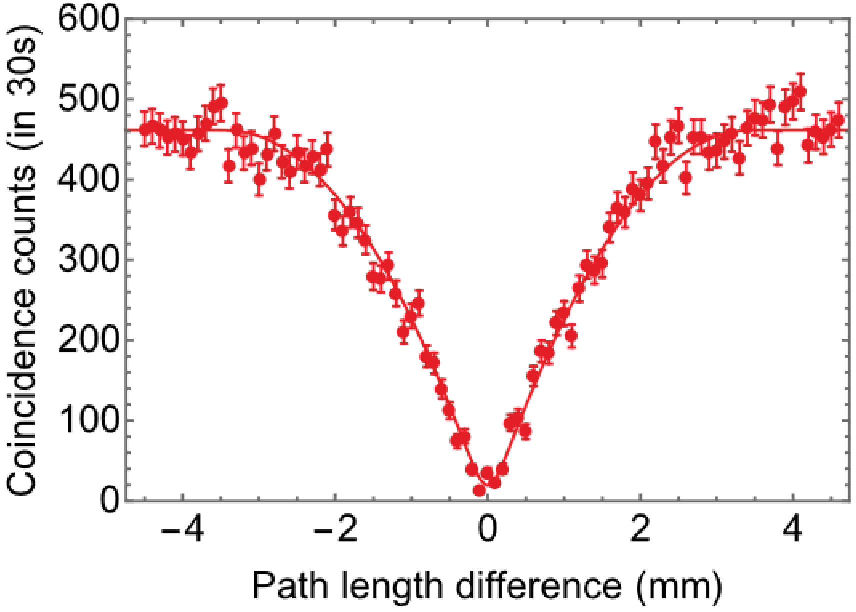

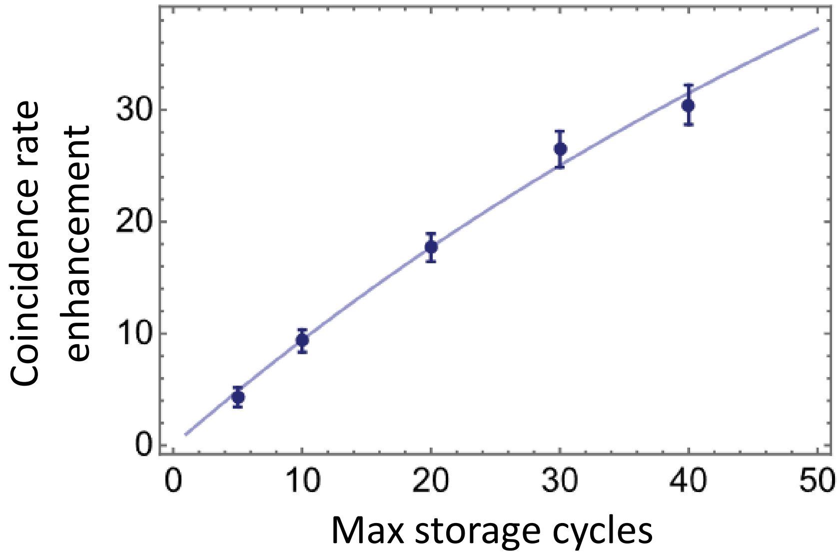

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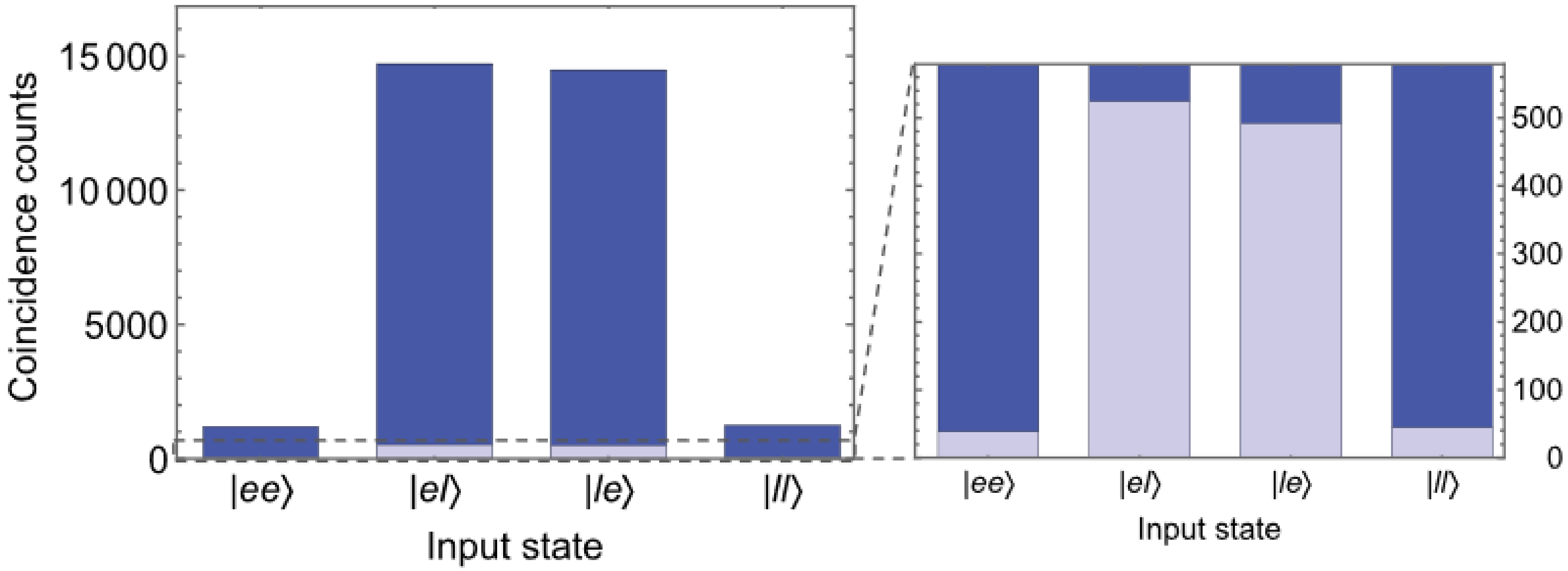
Delay-line memory in action – memory-enhanced MDI-QKD

Synchronization provided ~30x enhancement in coincidence rate, leading to 0.851 bit/s key rate

→ First demonstration of SPDC-based MDI-QKD



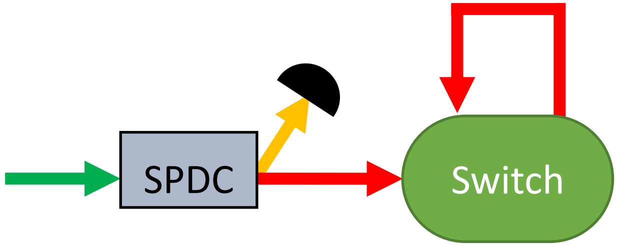
Coincidence counts from BSM of different time-bin encoded photons both with (left) and without (right) synchronization

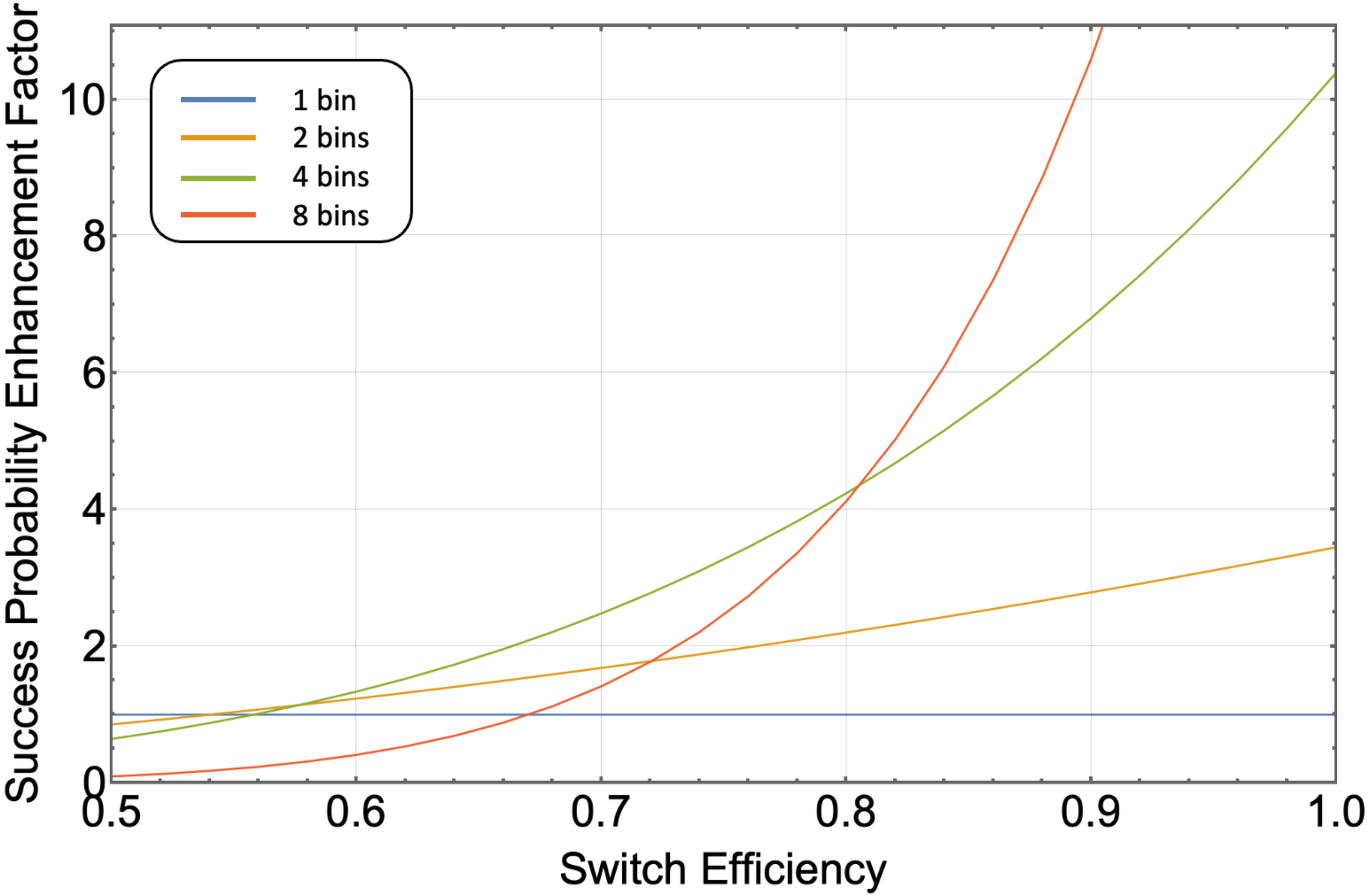
F. Kaneda *et al.*, Optica **4**, 1034-1037 (2017)

Advanced sources: multiplexing

Temporal multiplexing

- Map *N* pulses onto a single output bin
- Requires 1 crystal and a storage loop
- Rep. rate reduced by a factor *N*
- Requires on average $^{N}/_{2}$ switches





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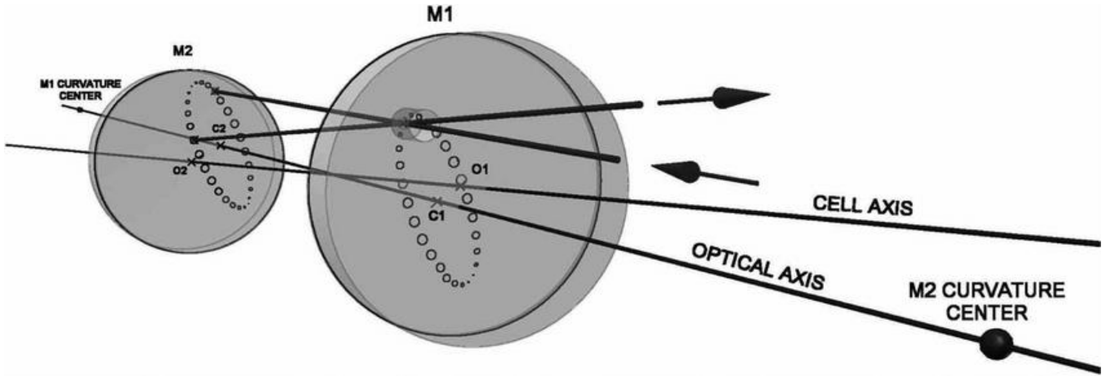
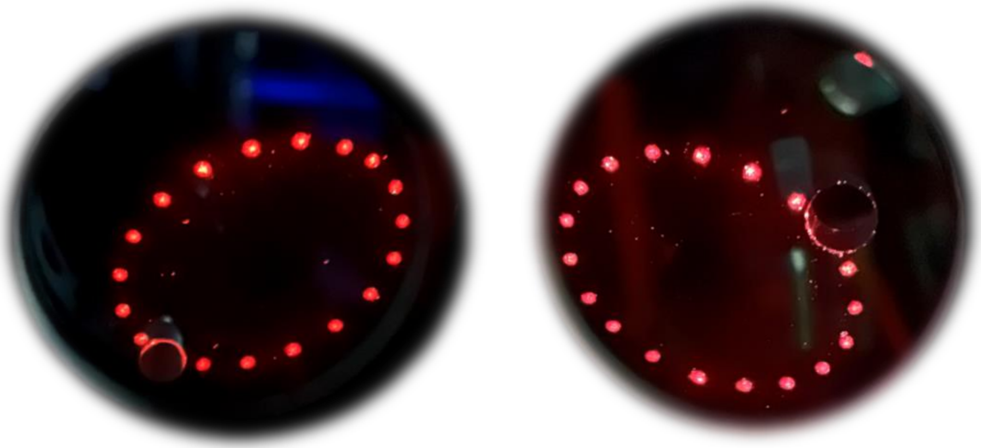
Making a free-space memory viable – Herriott cell

Reflections are low-loss compared to the Pockels cell transmission

→ Make use of a multi-pass reflection cavity to increase storage efficiency



Optical path lengths orders of magnitude longer than the cell itself, limited by circumference of mirrors



D. R. Herriott and H. J. Schulte, “Folded Optical Delay Lines” (1965)

C. Robert, “Simple, stable, and compact multiple-reflection optical cell for very long optical paths” (2007)

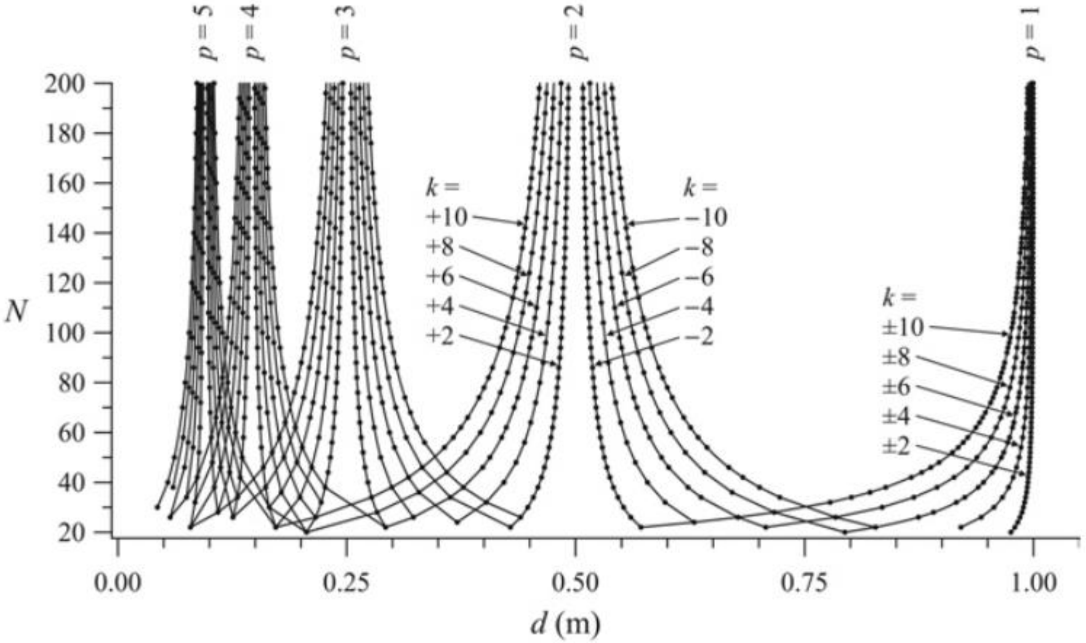
Making a free-space memory viable – Herriott cell

Herriott cells offer a large solution space for a single set of mirrors

→ This makes it possible to realize a variety of storage times with minor changes in alignment

Our cell can provide 169 ns of storage with 0.9999^{50} = 99.5% transmission

→ Poorer time resolution with improved storage efficiency



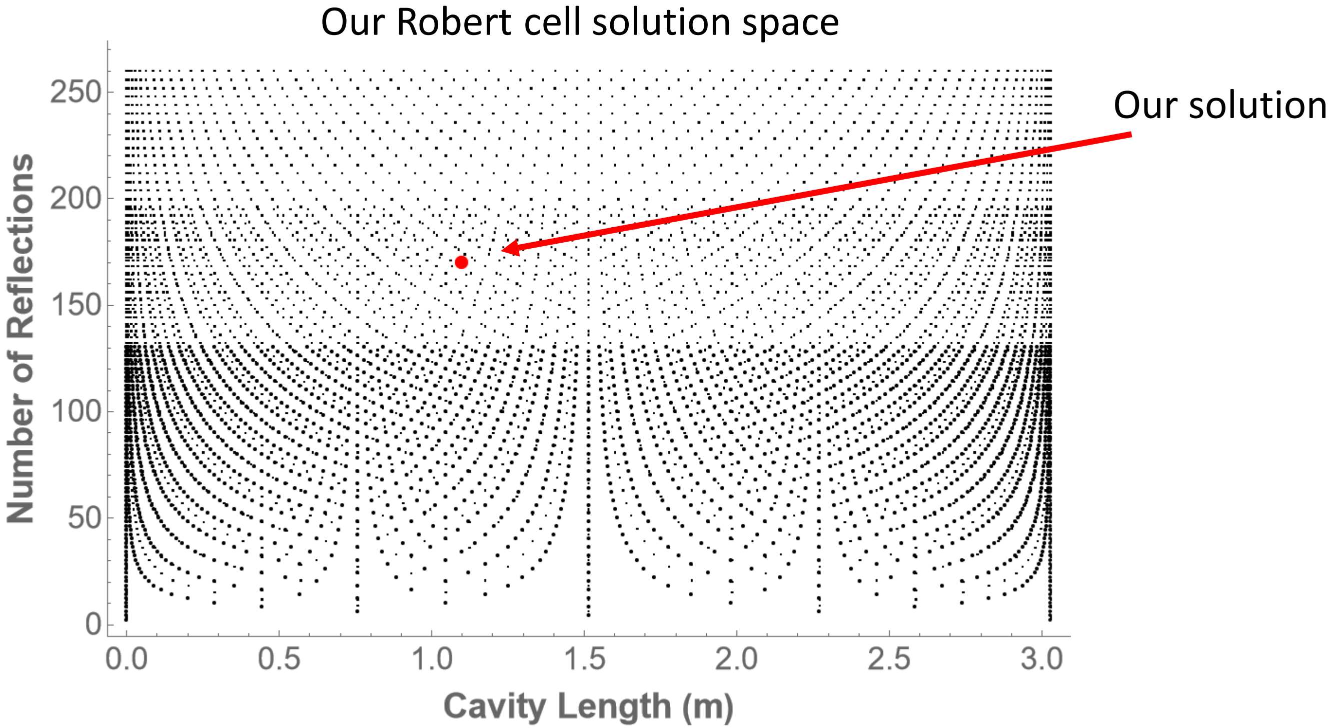
Plot of the number of reflections in a cavity as a function of cavity length (for 0.5m ROC mirrors)

C. G. Tarsitano and C. R. Webster, “Multilaser Herriott cell for planetary tunable laser spectrometers” (2007)

Making a free-space memory viable – Robert cell

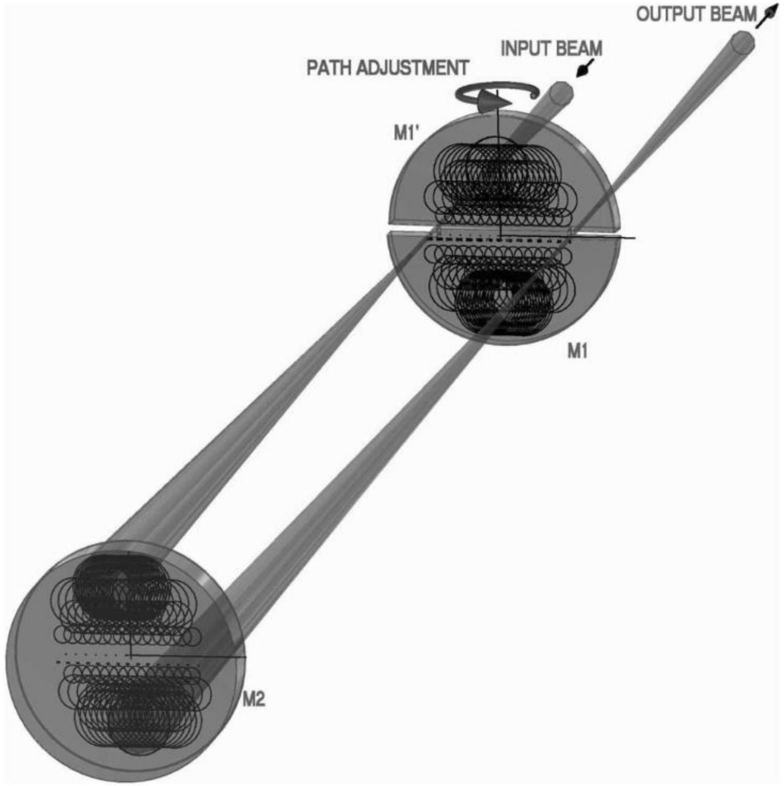
Split one of the spherical mirrors in half and rotate

→ Can achieve path length much greater than a standard Herriott cell with same cavity length



Our Robert cell solution space

Our solution



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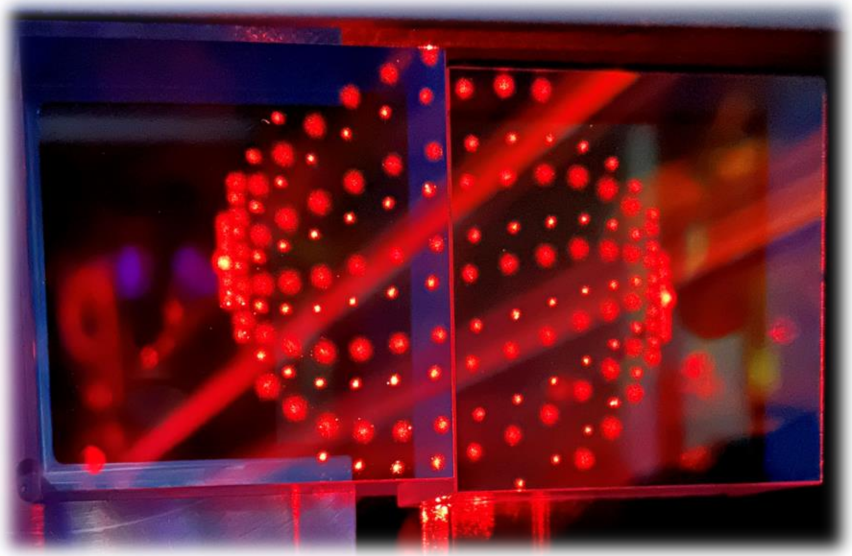
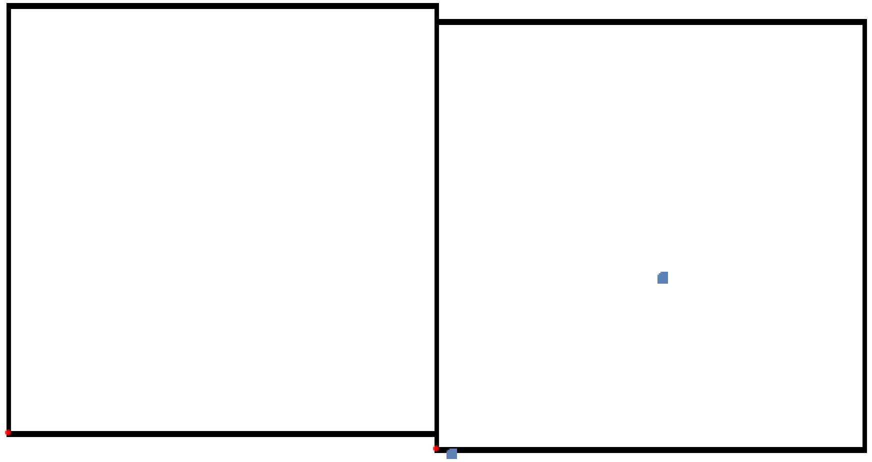


Storage time limited by surface area of mirrors, with light tracing out stacked elliptical patterns

Our cell can provide 1.84 µs of storage with 0.9999^{500} = 95.1% transmission

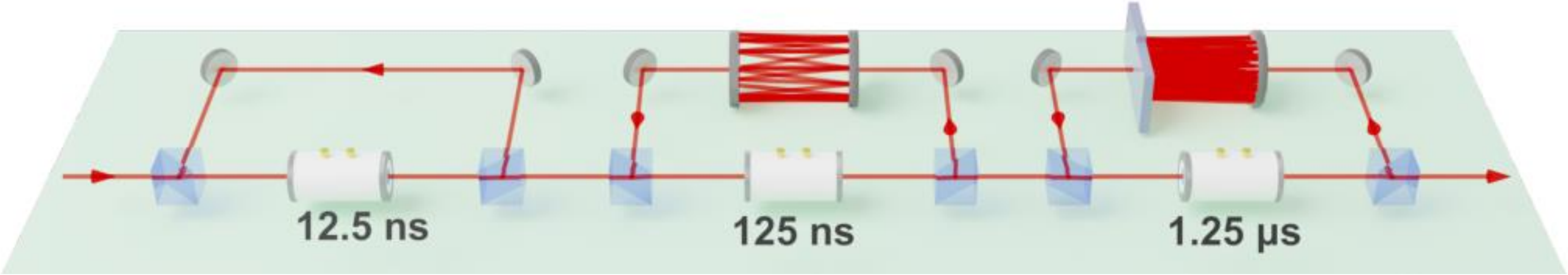
→ Poorer time resolution with greatly improved storage efficiency



Digital free-space quantum memory

A single loop <u>cannot</u> be optimal for both storage time and resolution

→ Time-multiplex each delay line to achieve optimal balance



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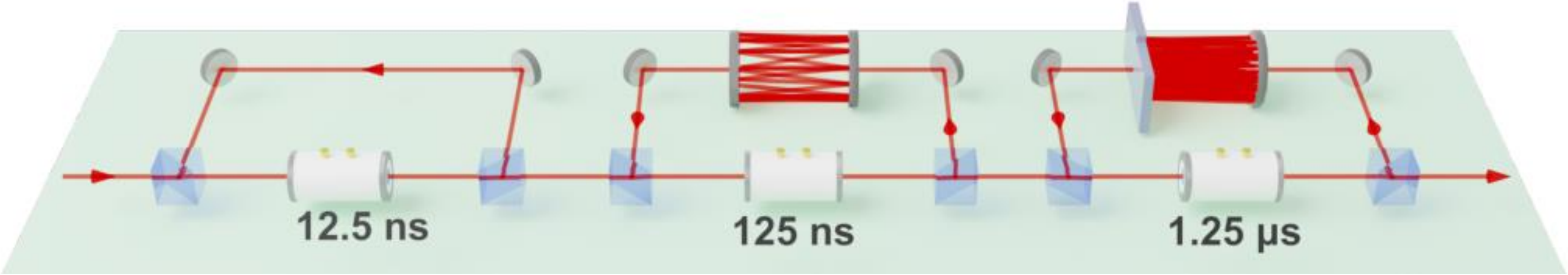

Scenario: user wants to store for 537 x 12.5 ns

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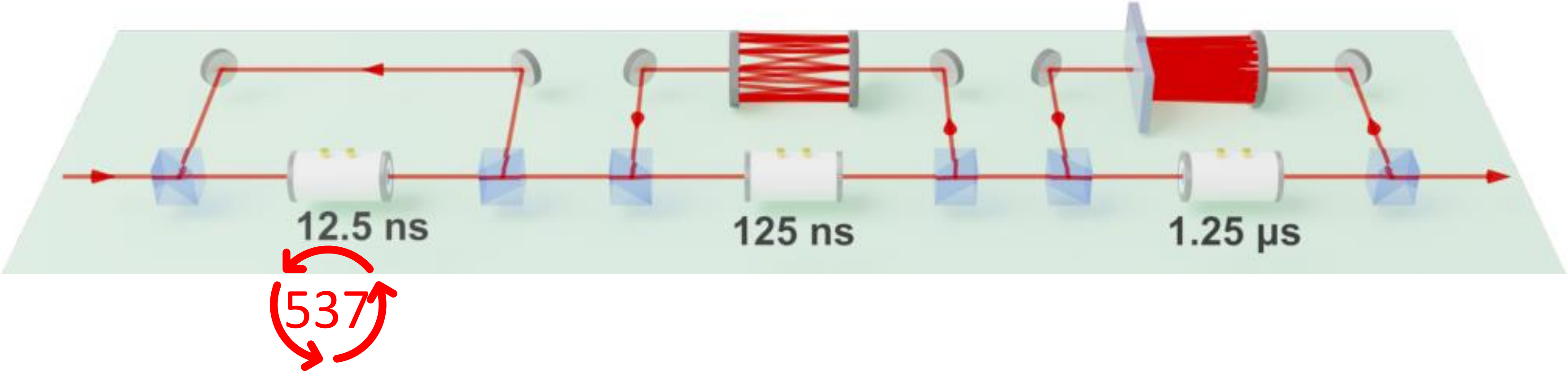

<u>Scenario: user wants to store for 537 x 12.5 ns</u>

Without multiplexing

Transmission $\cong (0.99 * 0.9999^5)^{537} = 0.3\%$

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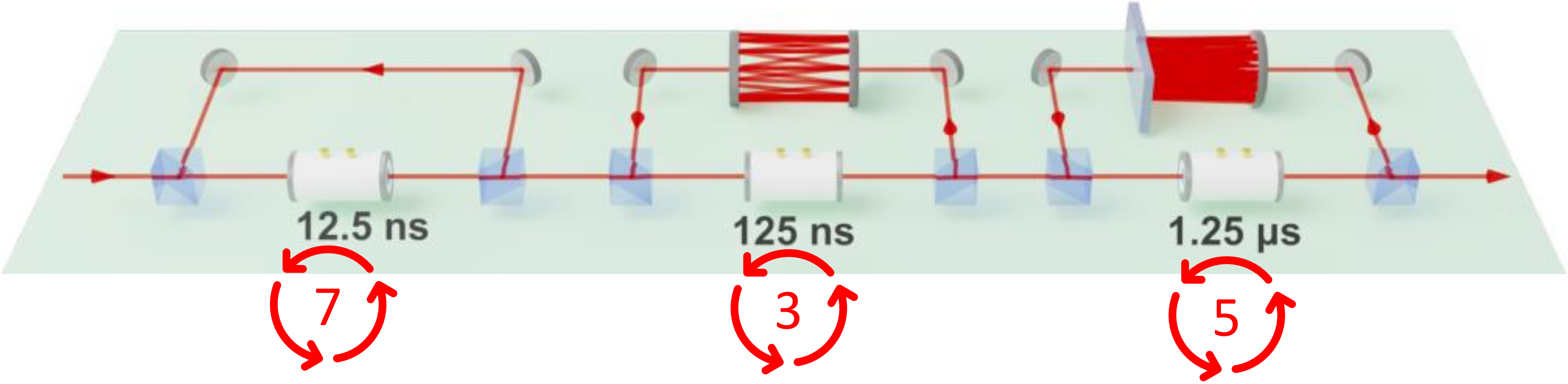

Scenario: user wants to store for 537 x 12.5 ns

Without multiplexing

Transmission $\cong (0.99 * 0.9999^{5})^{537} = 0.3\%$

With multiplexing

Transmission $\cong (0.99 * 0.9999^{5})^{7} * (0.99 * 0.9999^{50})^{3} * (0.99 * 0.9999^{500})^{5} = \mathbf{65}\%$

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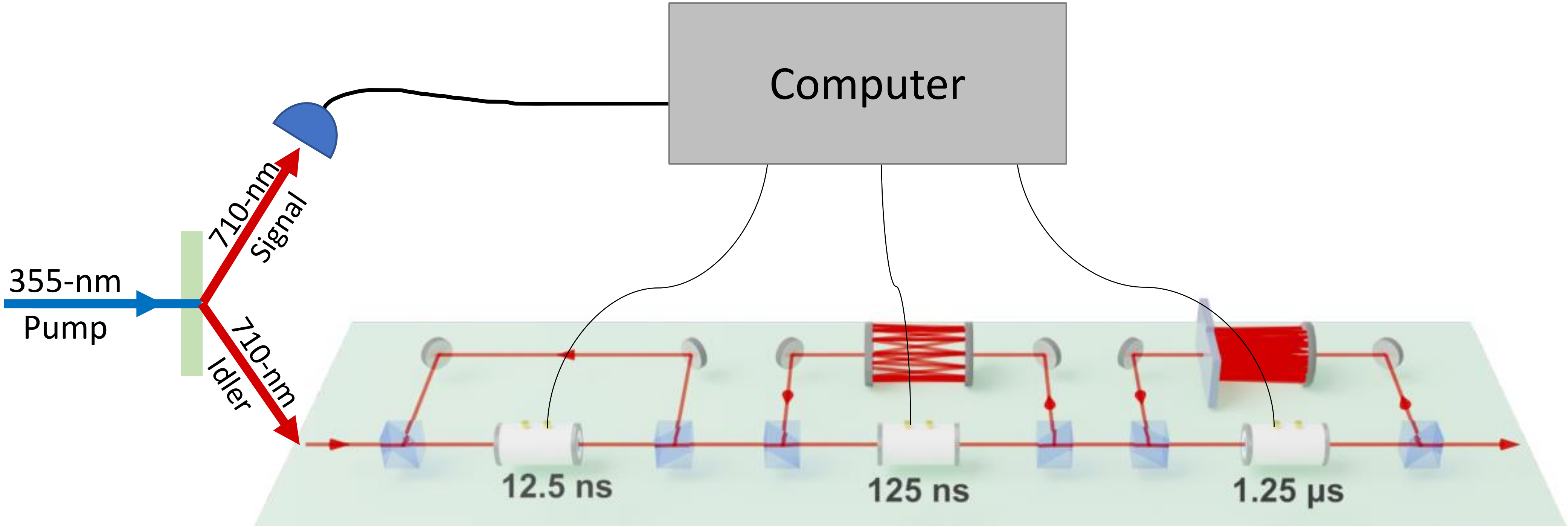
Memory has low noise and can store single photons from an entangled single-photon source

Down-converted photons @710 nm are stored in our memory by triggering from idler photon



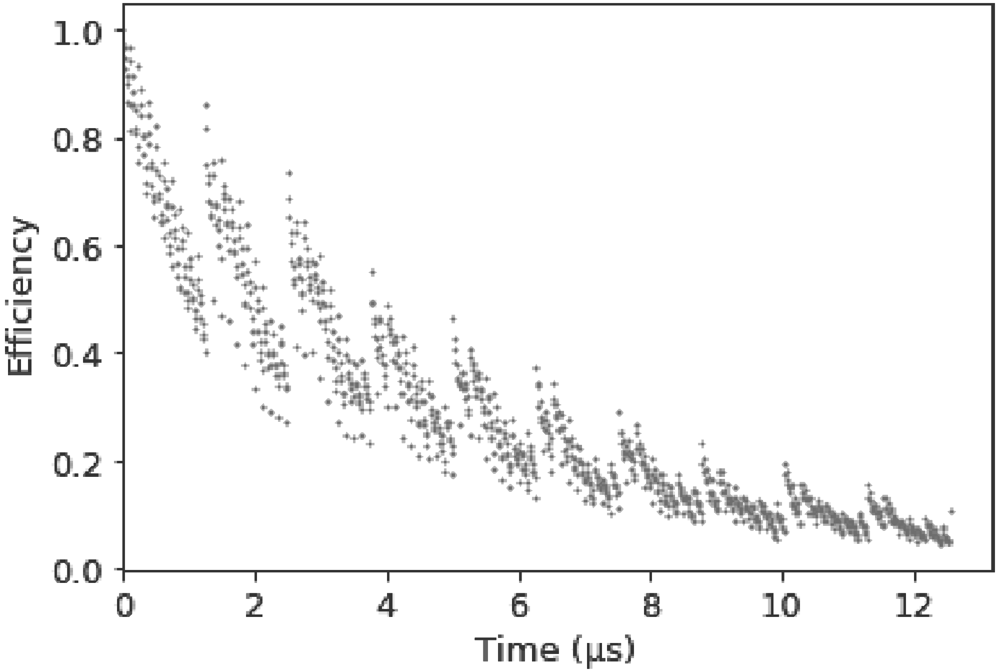
Memory characterization – efficiency

Mirrors with R>99.99%, paired with low-loss switch (99% efficiency), enable competitive storage times

Requirement of a *configurable* delay makes fiber memories intractable

→ Bulk optics typically have low loss compared to integrated counterparts (e.g., commercial fiber switches have >13% loss[1])

Memory efficiency – free-space measurement



[1] https://agiltron.com/product/nanospeed-premium-1x1-1x2-2x2-high-speed-optical-switch/

Memory characterization – efficiency

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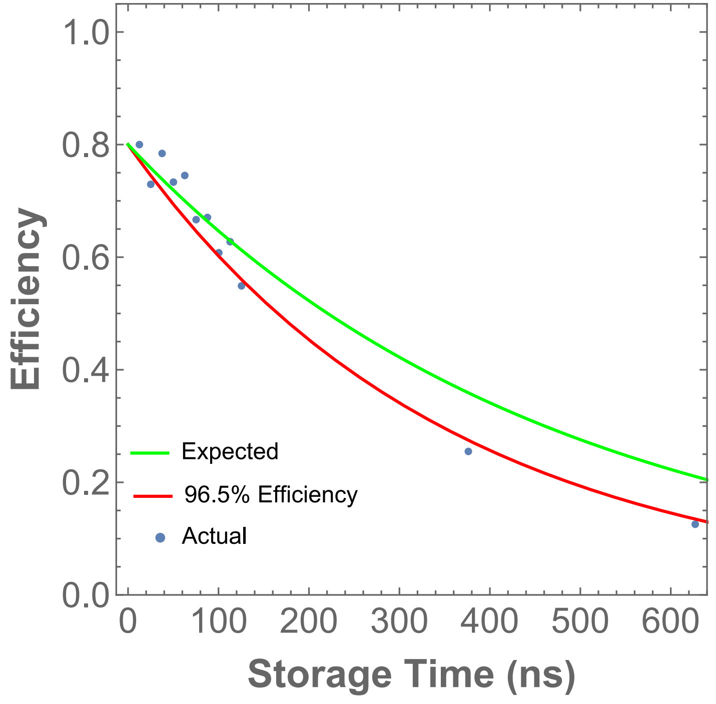
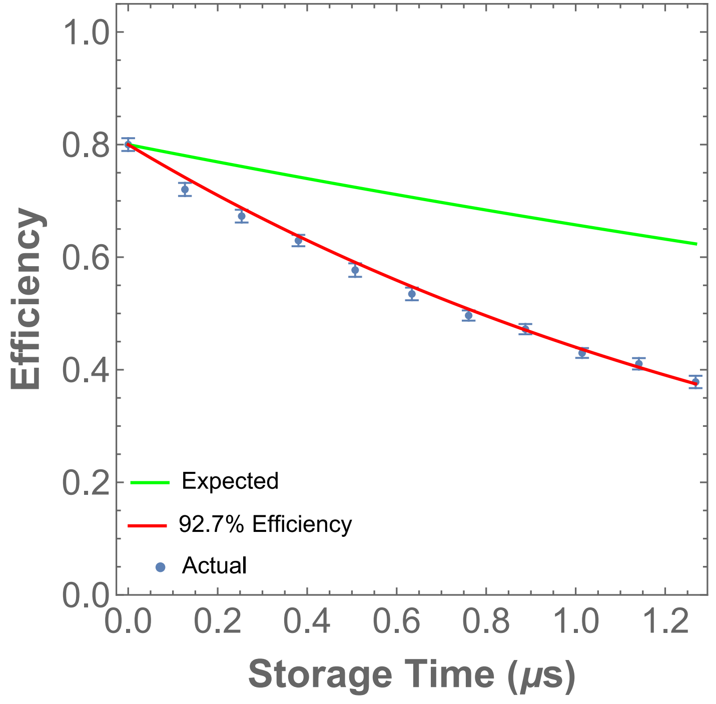
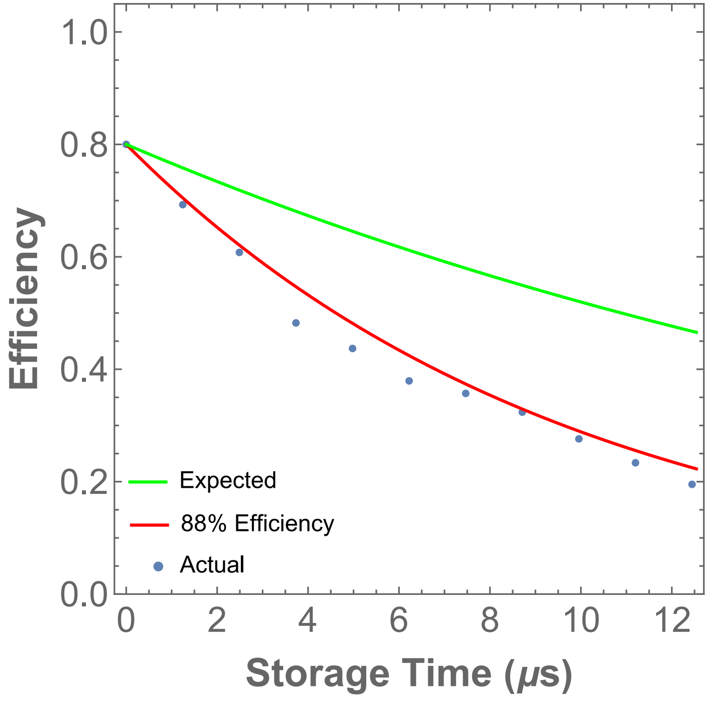
12.5-ns loop
end-to-end efficiency



125-ns loop
end-to-end efficiency



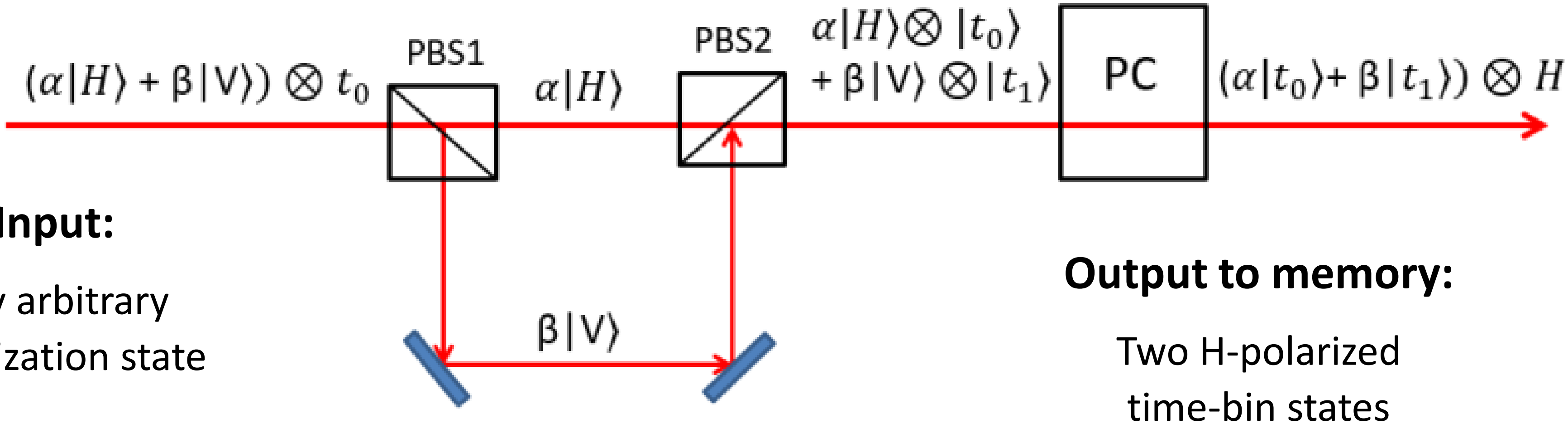
1.25-μs loop
end-to-end efficiency



Polarization qubits transduced into time-bin qubits

Our memory uses polarization-dependent optics to switch photons in/out of each storage loop

To store arbitrary polarization states, the signal first goes through a transducer that converts polarization qubits into time-bin qubits

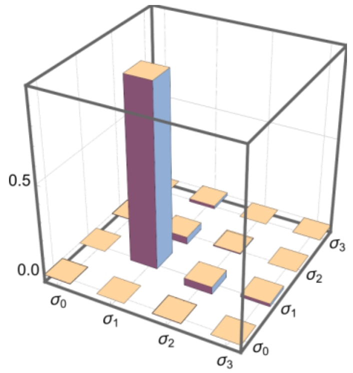


Input:

Any arbitrary polarization state

Output to memory:

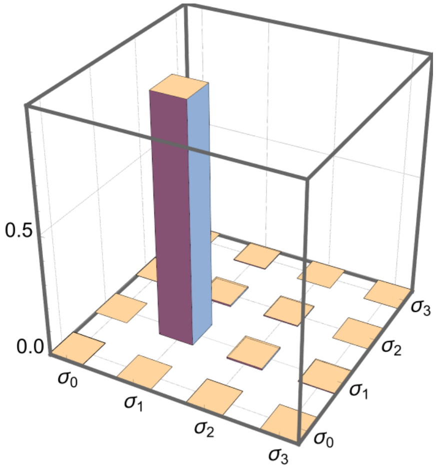
Two H-polarized time-bin states



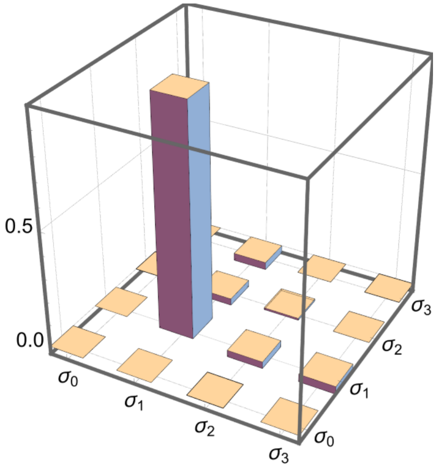
Fidelity: entry & exit of transducer → 99.12(4)% χ-fidelity

Memory characterization – fidelity

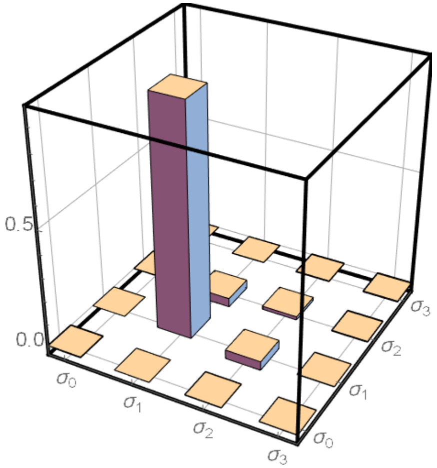
Bulk optics typically can achieve high fidelity with low noise, whereas atomic-based schemes lose fidelity and add more noise the longer they store



Fidelity: 12.5-ns loop
→ 99.35(25)% χ-fidelity



Fidelity: 125-ns loop
→ 99.0(1)% χ-fidelity

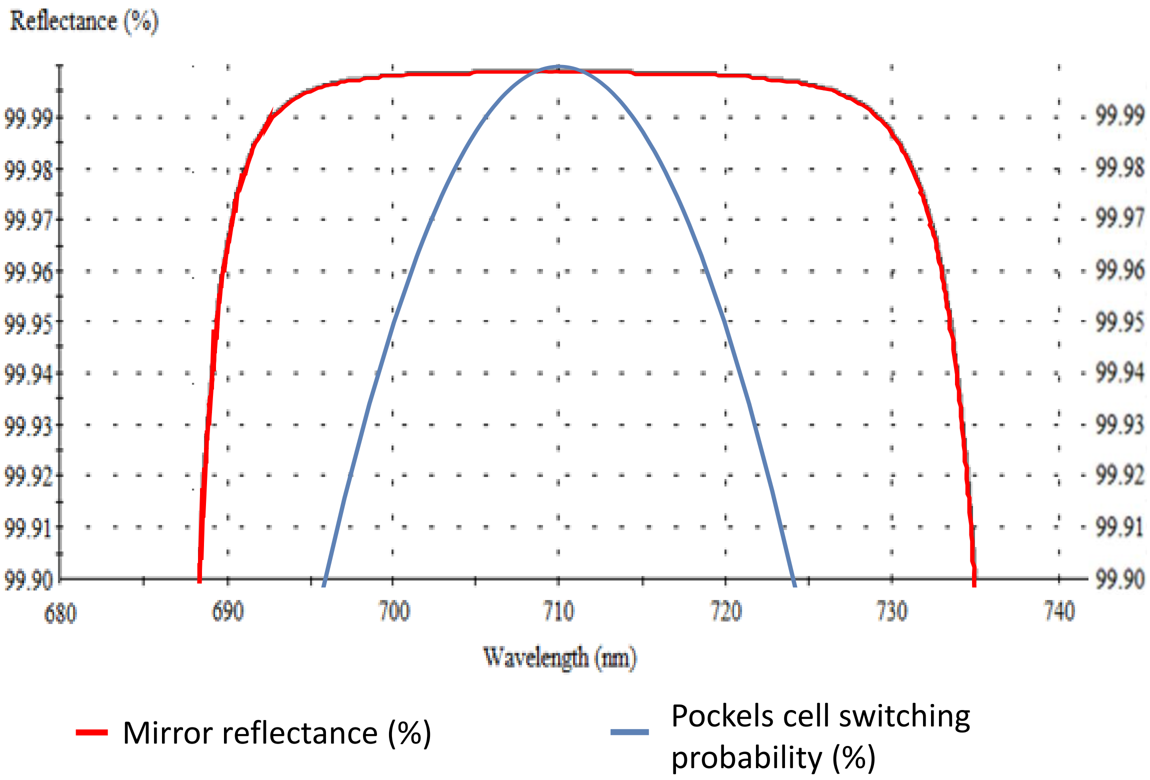


Fidelity: 1.25-µs loop
→ 97.8(2)% χ-fidelity

Memory characterization - bandwidth

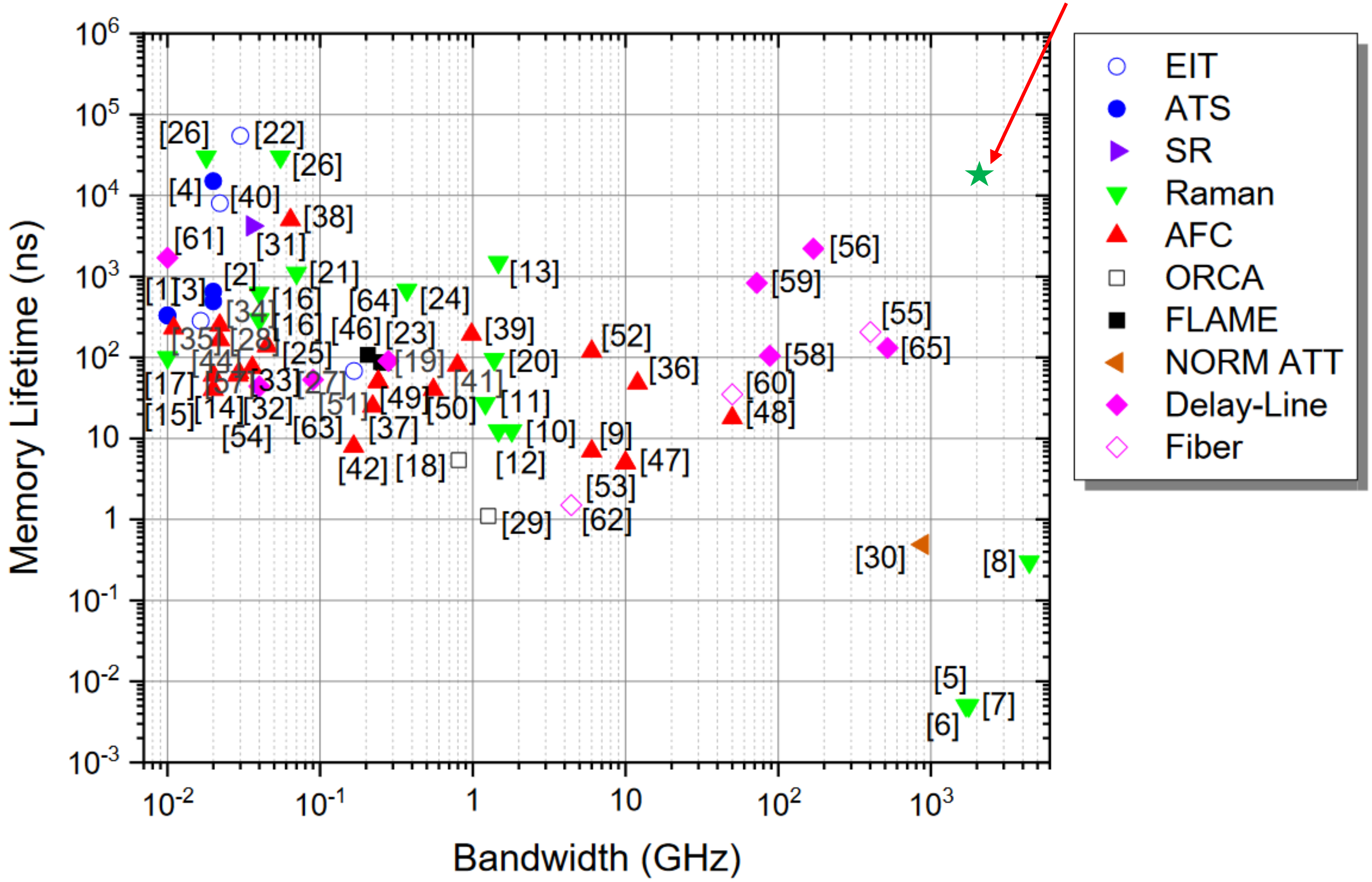
Current state-of-the-art mirrors (including ours) work well for a large range of wavelengths

→ Bulk optics in general typically work well over a broad bandwidth



	Bandwidth (FWHM)	Time-Bandwidth
Single reflection	22 THz	N/A
Single rotation	420 THz	N/A
12.5-µs storage	23 THz	$\sim 3 * 10^8$

Comparison of memory bandwidths



Our current performance

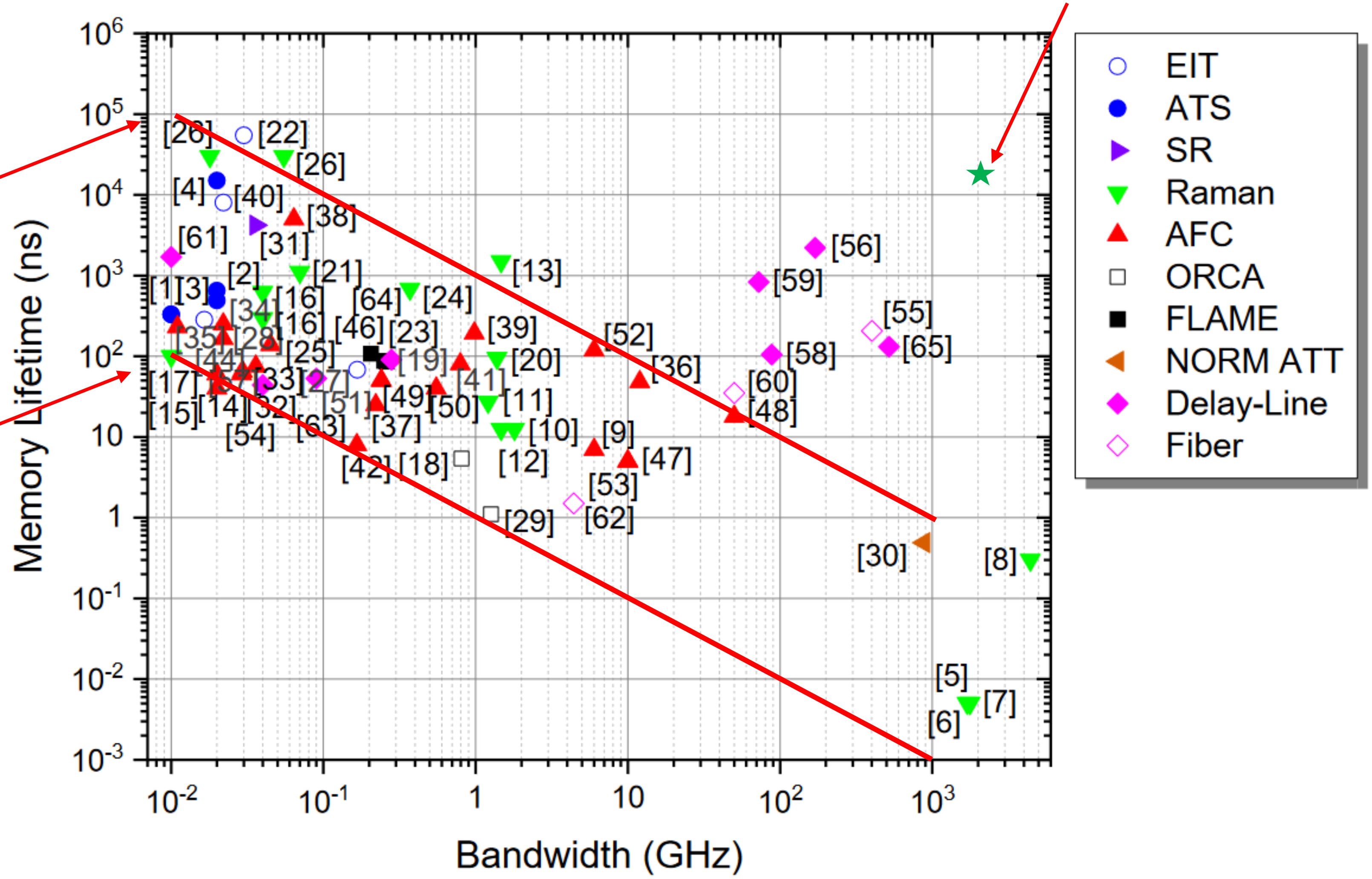
arXiv:**2301.08772**

Comparison of memory bandwidths

Our current performance

TxBW = 1000

TxBW = 1



arXiv:**2301.08772**

Memory comparisons

Most current photonic memory schemes utilize a light-matter interaction to store photons.

This approach has drawbacks that are difficult to overcome.

	Storage time		Bandwidth	Time-Bandwidth	Wavelength	Noise	Configurability	Temperature
Atomic	1 ns – 10^4 s		MHz - GHz	1-1000	NIR	High	Trivial	Extreme
Fiber	Single <200 μs	Configurable <20 μs	>THz	10^6 - 10^8	Telecom	Low	Too lossy	Room temp
Free-space	<100 μs		>THz	~10^8	Arbitrary	Low	Possible	Room temp

Outline

- Quantum networks and different memory technologies
- Short single-loop memory applications
- Longer memories
- Performance and comparison
- Summary and outlook

Summary

- Quantum networks and different memory technologies
  - Several quantum applications benefit heavily from quantum memories
- Short single-loop memory applications
  - A single short-storage memory is enough to realize incredible performance enhancements!
- Longer memories
  - Digital memory with longer storage times can achieve optimal efficiency-resolution tradeoff
- Performance and comparison
  - Free-space memories are incredibly competitive with other technologies, especially in bandwidth

Outlook

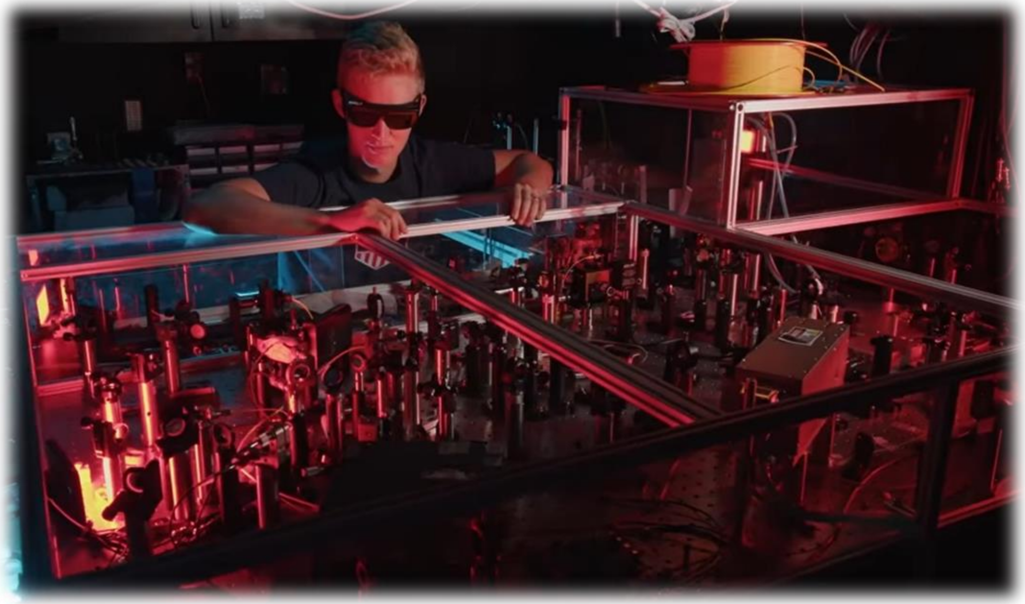
There is more room to grow with our technology

→ Our mirrors are 99.99% reflective, but 99.99**9**%-reflectivity mirrors exist!

→ Optimization of spatial mode can greatly improve efficiency coupling into SMF

System is large, but there is a path forward for scalability

→ Cavity design and optical engineering can allow for ultra-compact system that provides long storage times



Credit: Chicago Quantum Exchange

Join us!

Are you a bowtie scientist?

Interested students & postdocs, contact
Paul Kwiat: kwiat@illinois.edu

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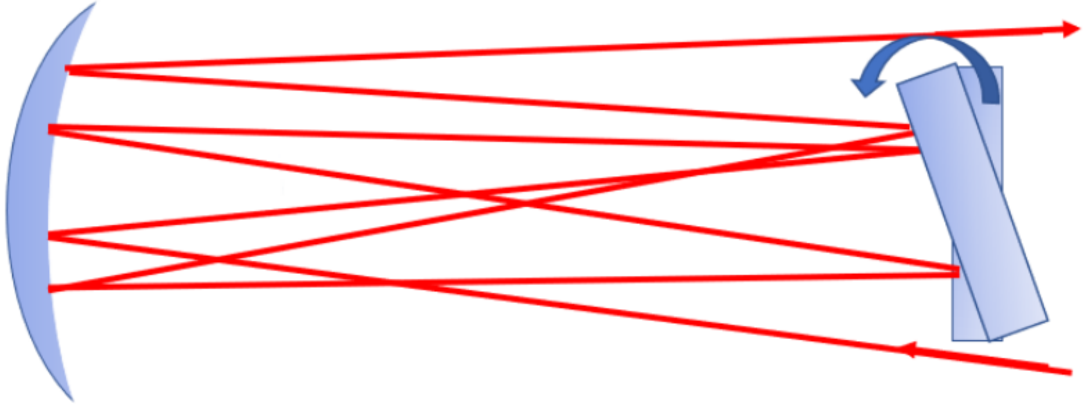
Memory characterization – thermal stability

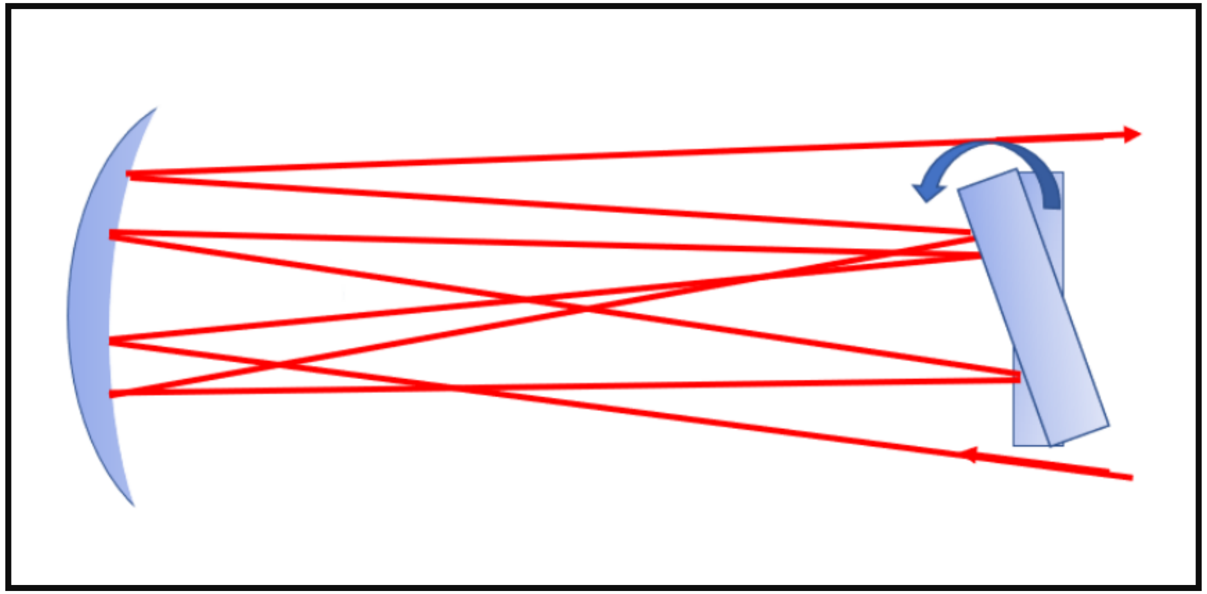
Our memory has achieved storage times for several tens of microseconds, which is >10km of **free-space** optical path length



Room temperature means we are susceptible to thermal fluctuations

→ **Solution**: passive and active stabilization

Memory characterization – thermal stability



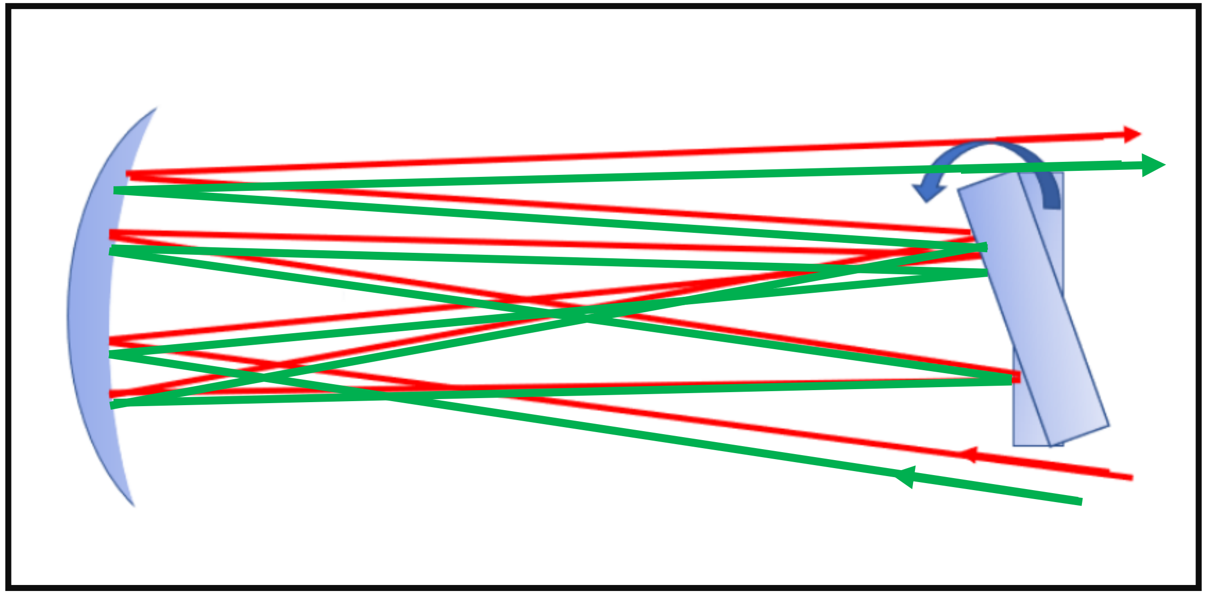
Our memory has achieved storage times for several tens of microseconds, which is >10km of **free-space** optical path length

Room temperature means we are susceptible to thermal fluctuations

→ **<u>Solution</u>**: passive and active stabilization

Passive: enclosure

Memory characterization – thermal stability



Our memory has achieved storage times for several tens of microseconds, which is >10km of **free-space** optical path length

Room temperature means we are susceptible to thermal fluctuations

→ **<u>Solution</u>**: passive and active stabilization

Passive: enclosure

Active: ancilla laser for stabilization system with piezo feedback