Timing Regimes in Quantum Networks and their Physical Underpinnings

draft-hajdusek-qirg-timing-physics-00

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@IETF125, Shenzhen (CN), March 2026

Objective of this I-D

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Status | Email expansions | History

Versions:
00

Very recent!!

This document is an Internet-Draft (I-D) [illegible]one may submit an I-D to the IETF. This I-D is **not end**
standards process.



Document	**Type**	Active Internet-Draft (individual)
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	Last updated	2026-03-02
	RFC stream	(None)
	Intended RFC status	(None)

Quantum network core function:
distribute entanglement

⬇️

requires coordinating tasks that span 20 orders of magnitude in time!!! ***femtoseconds ~ days***

https://datatracker.ietf.org/doc/draft-hajdusek-qirg-timing-physics/

drive layering decisions & division of responsibilities
for quantum network architecture development

10^{-15} s
fs
10^{-12} s
ps
10^{-9} s
ns
10^{-6} s
µs
10^{-3} s
ms
10^{0} s
s
10^{3} s
ks
10^{5} s
days
IR light cycle / Intra-wave phase
Short photons (wave packets)
High-precision timestamp resolution
Optical clock pulse rate
Ordinary digital logic signal rise times
Data center node-to-node latency
Detector recovery
Classical software interrupt processing
Long photons
TCP/IP message, process to process
MEMS optical switch time
Optical delay line mechanical movement
Application setup request rate (interval)
Hilariously slow wave plate rotation
Full link tomography
System drift
(e.g. 24h thermal fluctuation)

Objective of this I-D

Goals

- Identify and provide introduction to the physical principles related to timing regimes in quantum networks.
- Provide justification behind specific design choices discussed in our *other documents*.
- Serve as a reference for other quantum network specifications.

Non-Goals

- No architectural decision making!!
- Detailed physical derivations.
- Exhaustive coverage of all existing quantum platforms and technologies.
- New research results.

Other documents in development…

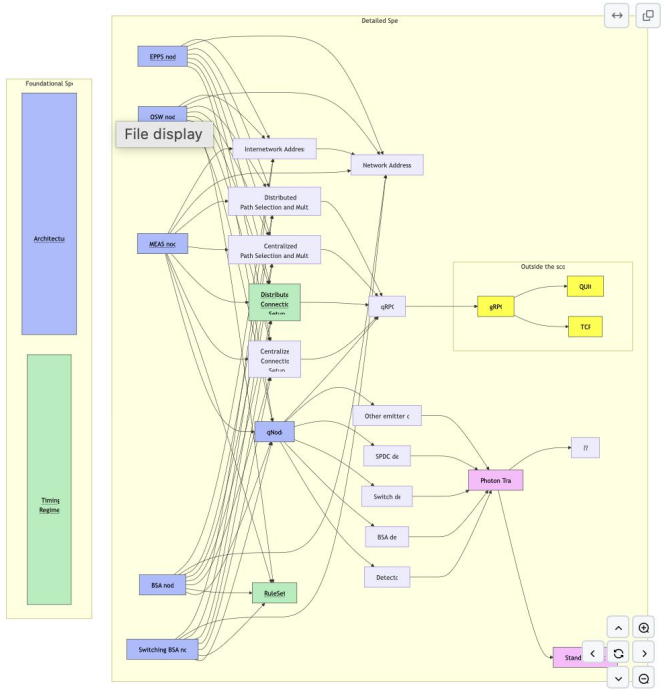
List of specifications:

- Foundational Specifications
  - Network Architecture Specification
  - Timing Regimes
- Node Specifications
  - qNode
  - Overview of EPPS Node
  - Overview of OSW Node
  - Overview of MEAS Node
  - Overview of BSA Node
  - Overview of Switching BSA Node
  - RuleSets
- Shared Protocols
  - qRPC
  - Distributed Connection Setup and Teardown
  - Distributed Path Selection and Multiplexing
  - Centralized Connection Setup and Teardown
  - Centralized Path Selection and Multiplexing
  - Network Addressing
  - Internetwork Addressing
- Devices
  - Detector Device
  - BSA Device
  - Switch Device
  - SPDC Device

※ Still in private repo

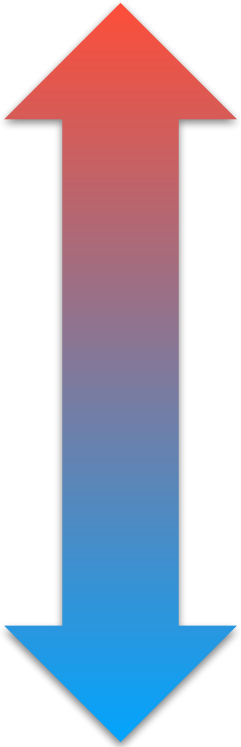
Timing Regimes document will be the core reference to all of the specific node specifications

Overall Scheme of Specifications



Summary of Timing regimes

Most stringent



Least stringent

A. Interferometric stabilization
B. Detector timing windows
C. Measurement basis selection
D. Optical switch control
E. Pre-configured event-driven tasks
F. Urgent but not synchronization-critical tasks
G. Host-side application-level tasks
H. Background tasks

Categorization of Timing regimes

Quantum Optical Path

A. Interferometric stabilization

B. Detector timing windows

Classical Hardware

C. Measurement basis selection

D. Optical switch control

Software

E. Pre-configured event-driven tasks

F. Urgent but not synchronization-critical tasks

G. Host-side application-level tasks

H. Background tasks

10^{-15} s
fs
10^{-12} s
ps
10^{-9} s
ns
10^{-6} s
µs
10^{-3} s
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A. Interferometric stabilization (Quantum optics)

Entanglement distribution in quantum networks is performed by entanglement swapping on photonic qubits.

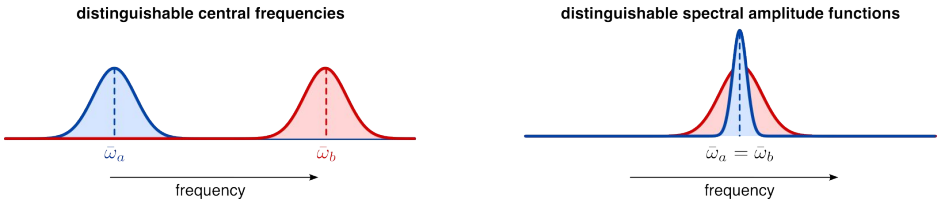
Requirements for Entanglement swapping: ➡️ photon ***indistinguishability*** @ BS

Distinguishable Properties

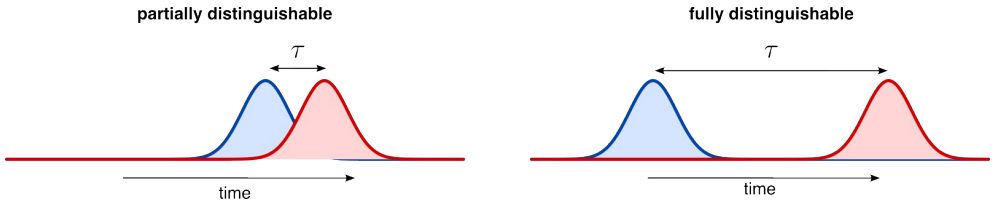
- Polarizations
- Spectral modes
- Temporal modes
- Arrival time
- Transverse spatial time

➡️

Spectral distinguishability



Temporal distinguishability

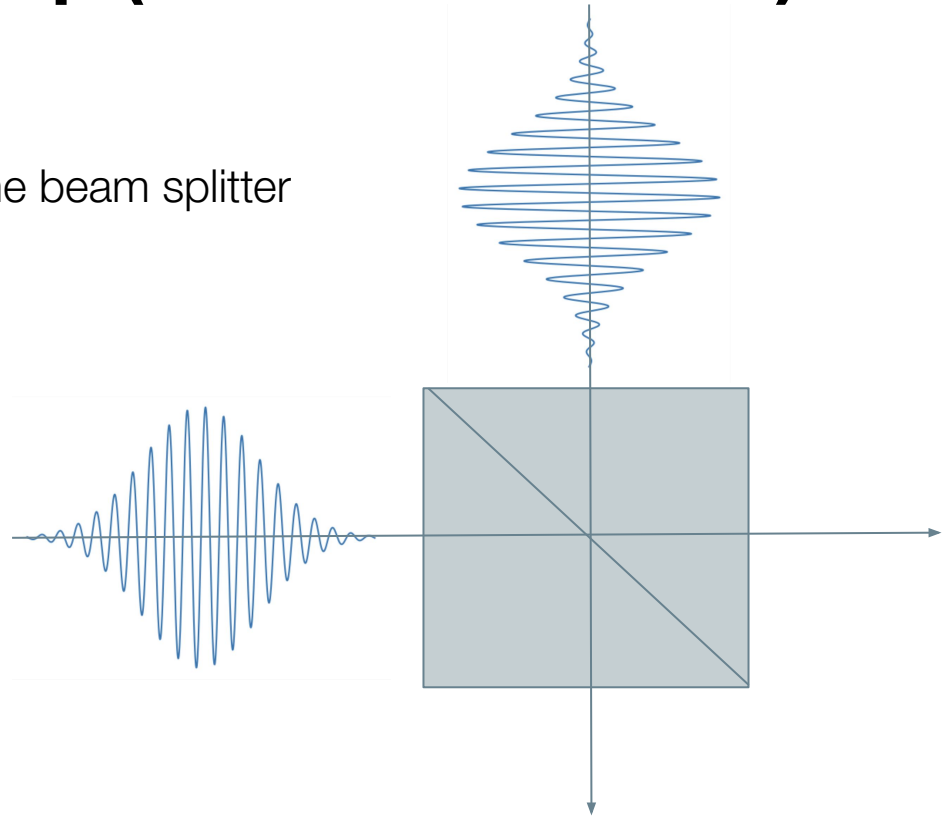


Factors that can lead wave packets to not overlap

- Photon emission time jitter (we can't fix this)
- Physical distance difference between each nodes

Good overlap (same arrival time)

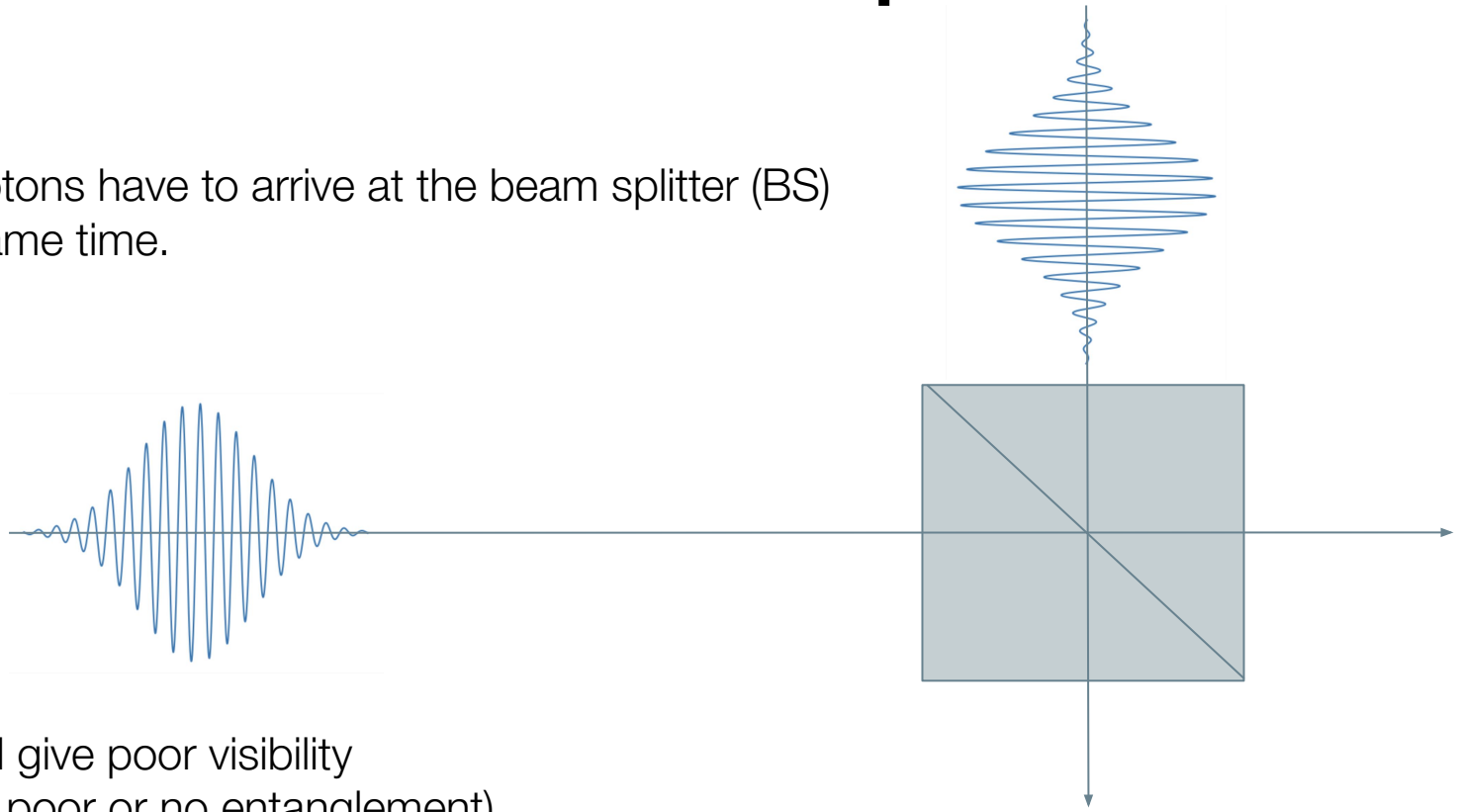
Two photons have to arrive at the beam splitter (BS) at the same time.



This will give good *visibility* (makes good entanglement)

Bad overlap

Two photons have to arrive at the beam splitter (BS)
at the same time.



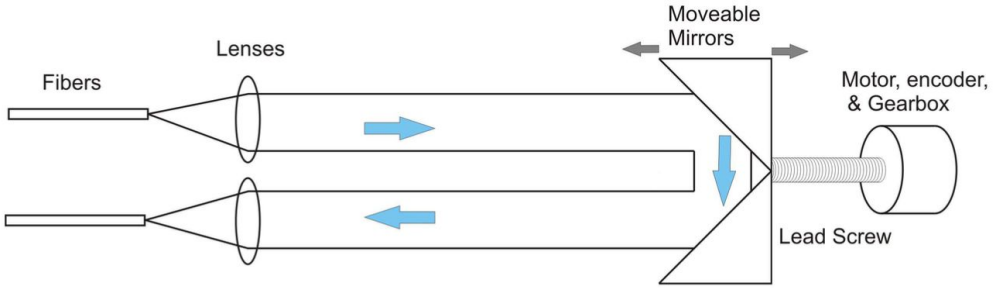
This will give poor visibility
(makes poor or no entanglement)

A. Interferometric stabilization (Quantum optics)

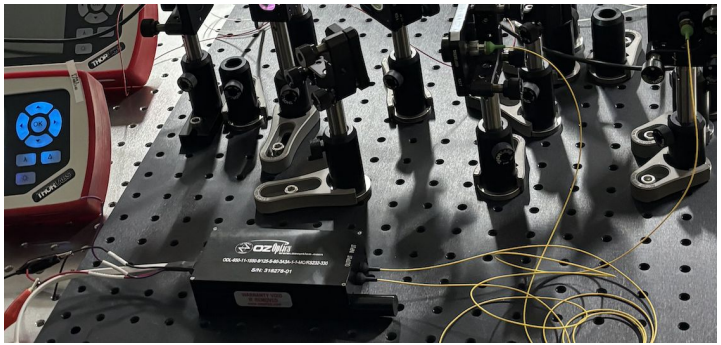
We use **Optical Delay Lines (ODLs)** to *adjust* the timing of the photons

Timings we have to consider

- Time to calculate the “delay” needed for wavepacket overlap
- Time to communicate necessary information to the ODL
- *Time to set/reset the ODL*



From OZ optics manual



B. Detector timing windows (Quantum optics)

An *ideal* Single Photon Detector (SPD) will…

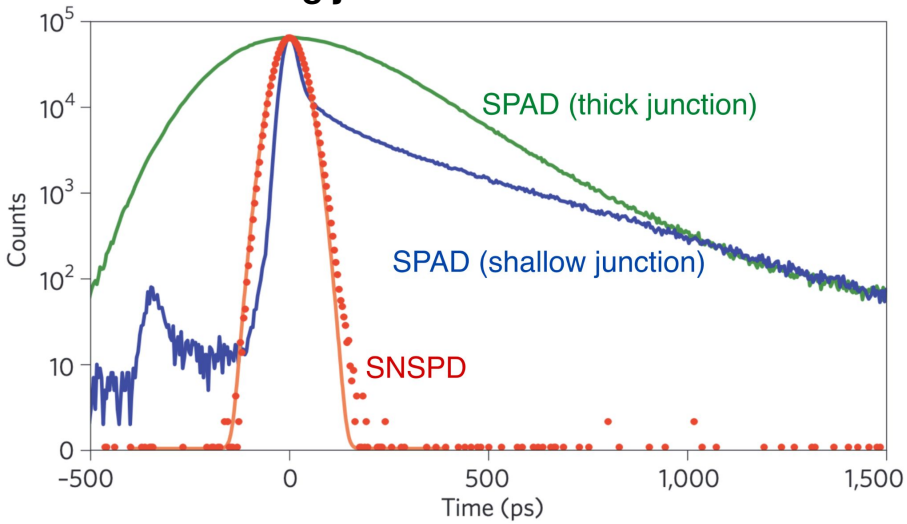
generate an electric signal after absorbing a photon and only after absorbing a photon!!

In the real world, we have to consider

- Spectral range
- Detection efficiency
- Recovery time
- Dark count rate
- Timing jitter

Need to consider this jitter for synchronization tasks!

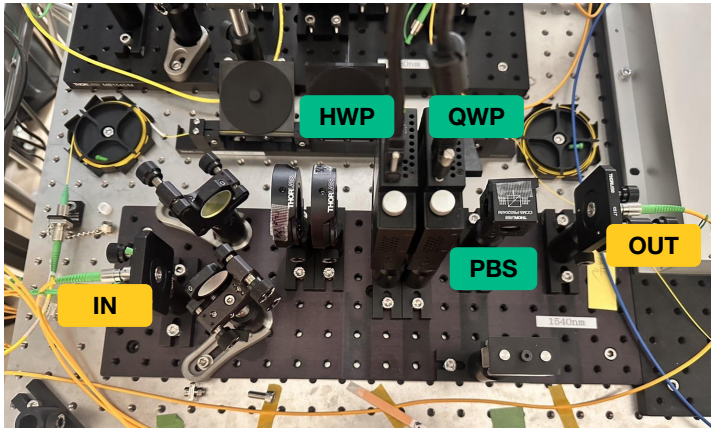
Timing jitter in different SPDs



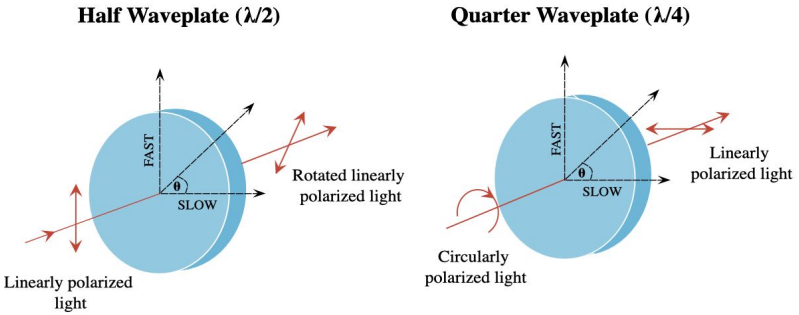
R. H. Hadfield, Single-photon detectors for optical quantum information applications, *Nature Photonics* 3, 696 (2009)

C. Measurement basis selection (Classical hardware)

We **monitor the quality of entanglement** in our quantum network w/ state tomography!



HWP = Half waveplate
QWP = Quarter waveplate
PBS = Polarization beam splitter



Change measurement combination with waveplate configurations

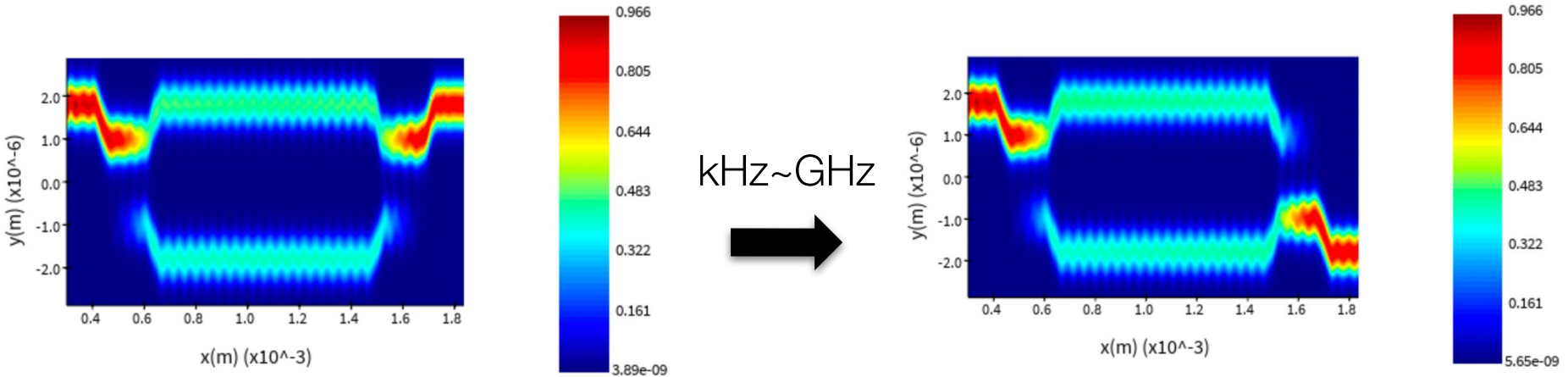
➡️ HWP + QWP

Rotating the waveplates takes time!!

https://www.meetoptics.com/academy/waveplates?srsltid=AfmBOopeLe5f9fZaf5U8F-fzbq5-xXSH76v4EBqbezewG_hTCF11ZoH3#what-are-waveplates

D. Optical switch control (Classical hardware)

- **Switching time:** time required to configure the switch
- **Propagation time:** time required for the photon to travel across the switch



E-G. Software Tasks!!

All of the background and control software holding together the functions of a quantum network!!
(The *"normal"* software processing tasks we are use to)

Timing regime	Example
Pre-config event driven	QEC encoding on photon emission, pre configured in FPGA / ASIC
Urgent, not sync-critical	Some event driven processes too complex for FPGA /ASIC
Application level	Connection setup, near-real time processing, post processing, connection teardown
Background	Link monitoring, routing table updates

Future prospects for this document

- Adding figures some how...
- Change equation formatting to make it more reader friendly
- Adding different types of wavepackets to the timing regimes
- Expand discussion on visibility..
    - Given an infidelity budget, what is the maximum misalignment in wavepacket overlap that can be tolerated?
- *Accessibility for the IETF community*
    - Show how the physics connects to code

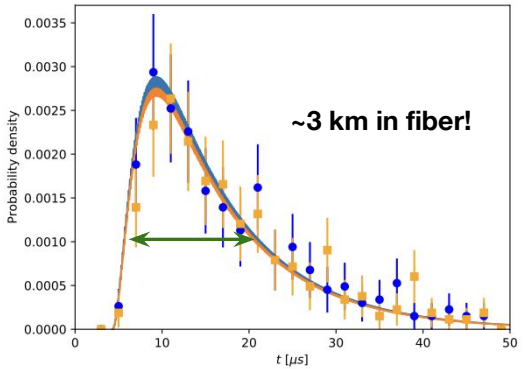


FIG. 2. Single-photon temporal wavepacket emitted from Node B and detected on the PBSM setup. Orange squares and blue circles correspond to vertical and horizontal polarizations. Squares and circles represent experimental data; error bars are calculated from Poissonian statistics. Lines are the envelopes found theoretically, which have been multiplied by $\eta = 1/10.5 \approx 0.095$.

V. Krutyanskiy *et al.*, *Phys. Rev. Lett.*, vol. 130, no. 5, p. 050803, Feb. 2023

Any kind of feedback/contribution is appreciated!!