Future Time Synchronization Needs for Quantum Networks

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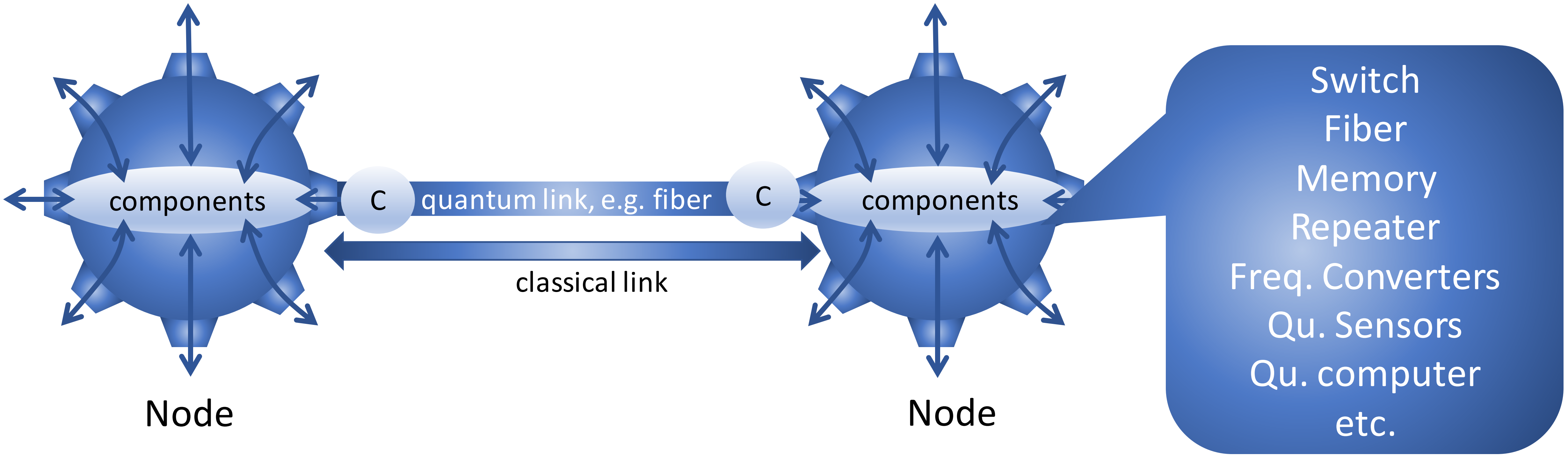
PML

ITL

Use of Quantum Networks

- Distributed Quantum Computing
- Blind Quantum Computing
- Distributed Sensing
- Long-baseline interferometry
- Secure Communication
- Single-Photon Metrology
- etc., and other applications we will think of in the future

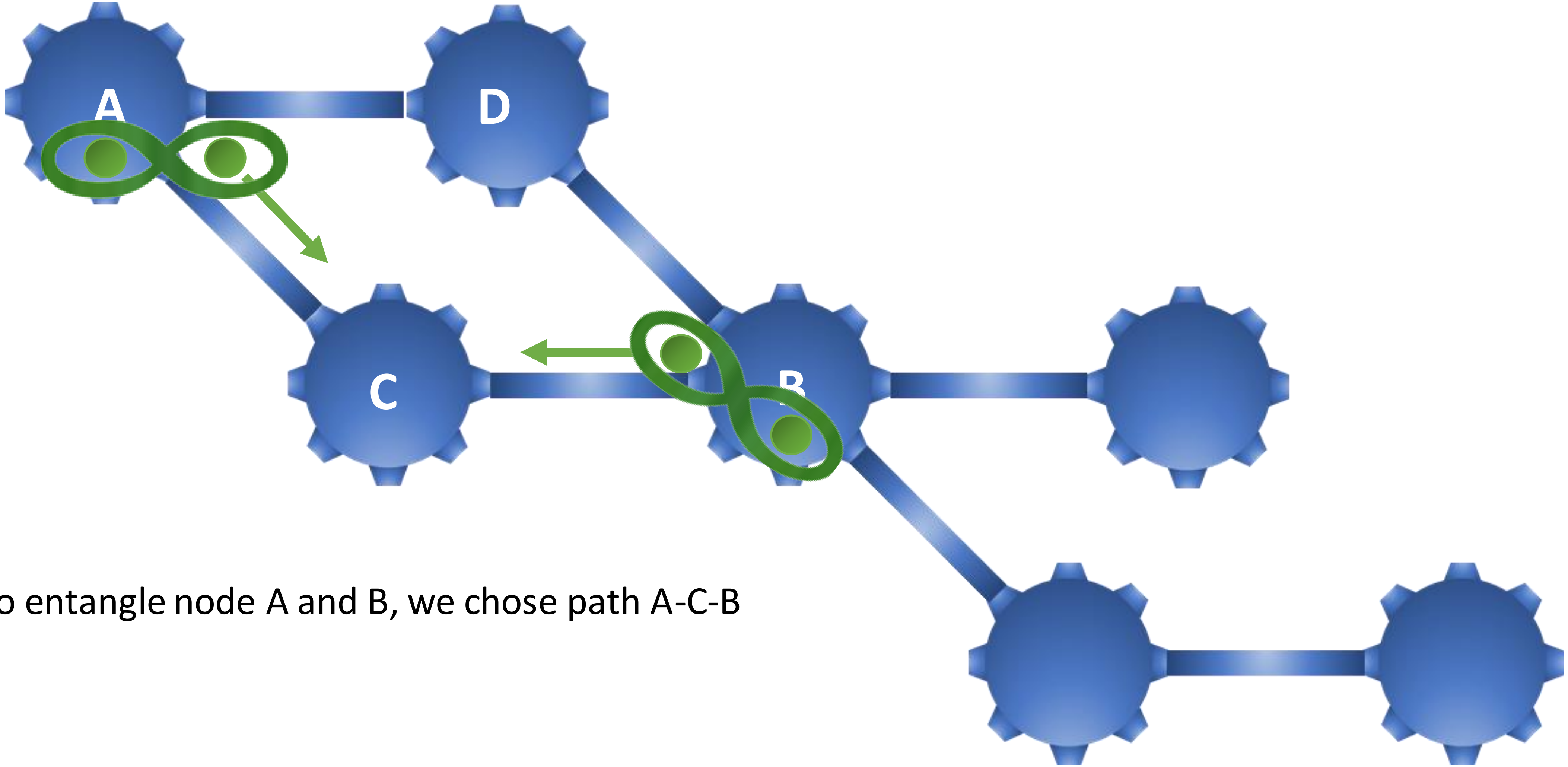
Quantum Network Nodes



A quantum network node will receive, store, send and create a quantum signal based on single photons through an optical quantum channel augmented by a classical channel.

Distribution of Quantum Information

entangle node A and B



1) To entangle node A and B, we chose path A-C-B

Distribution of Quantum Information

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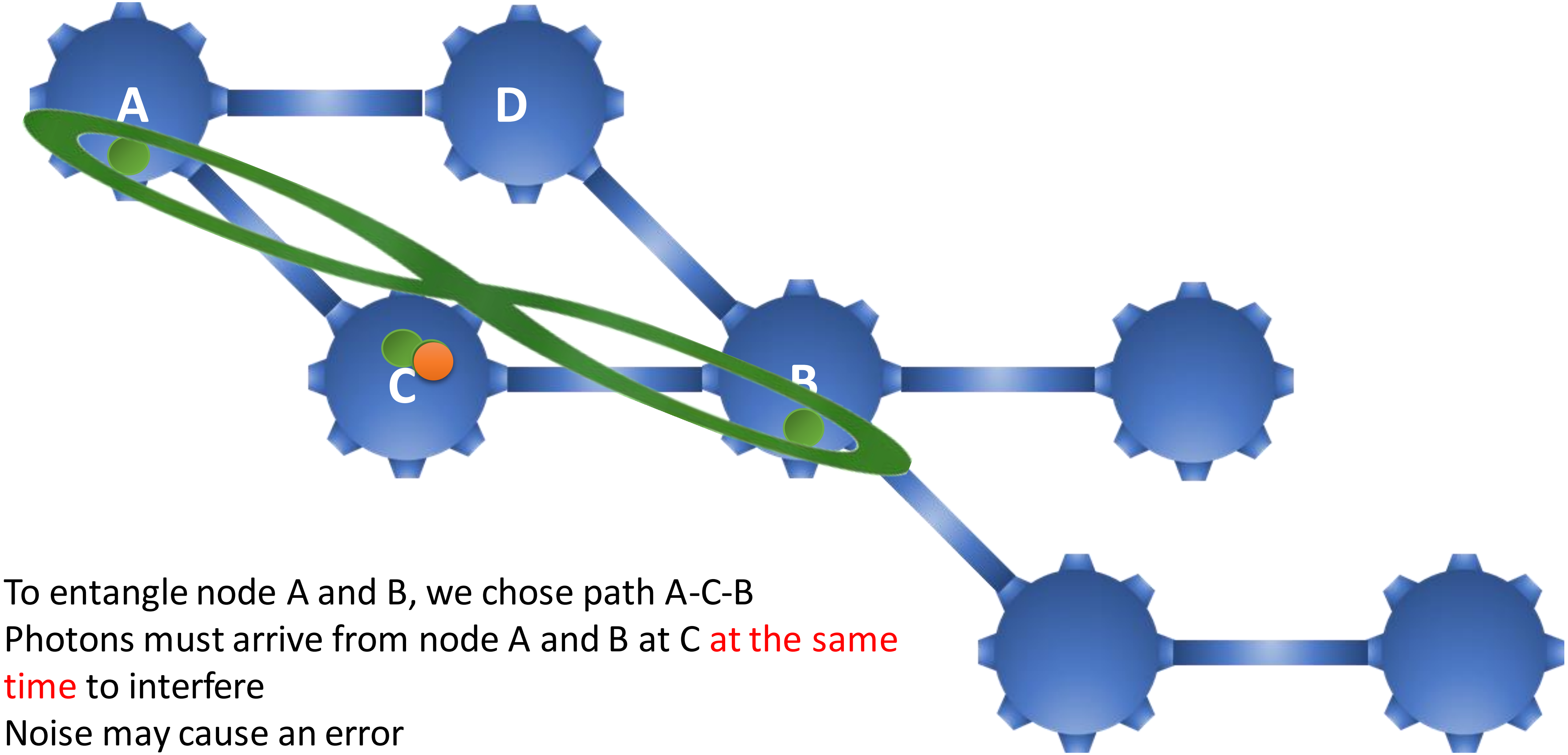
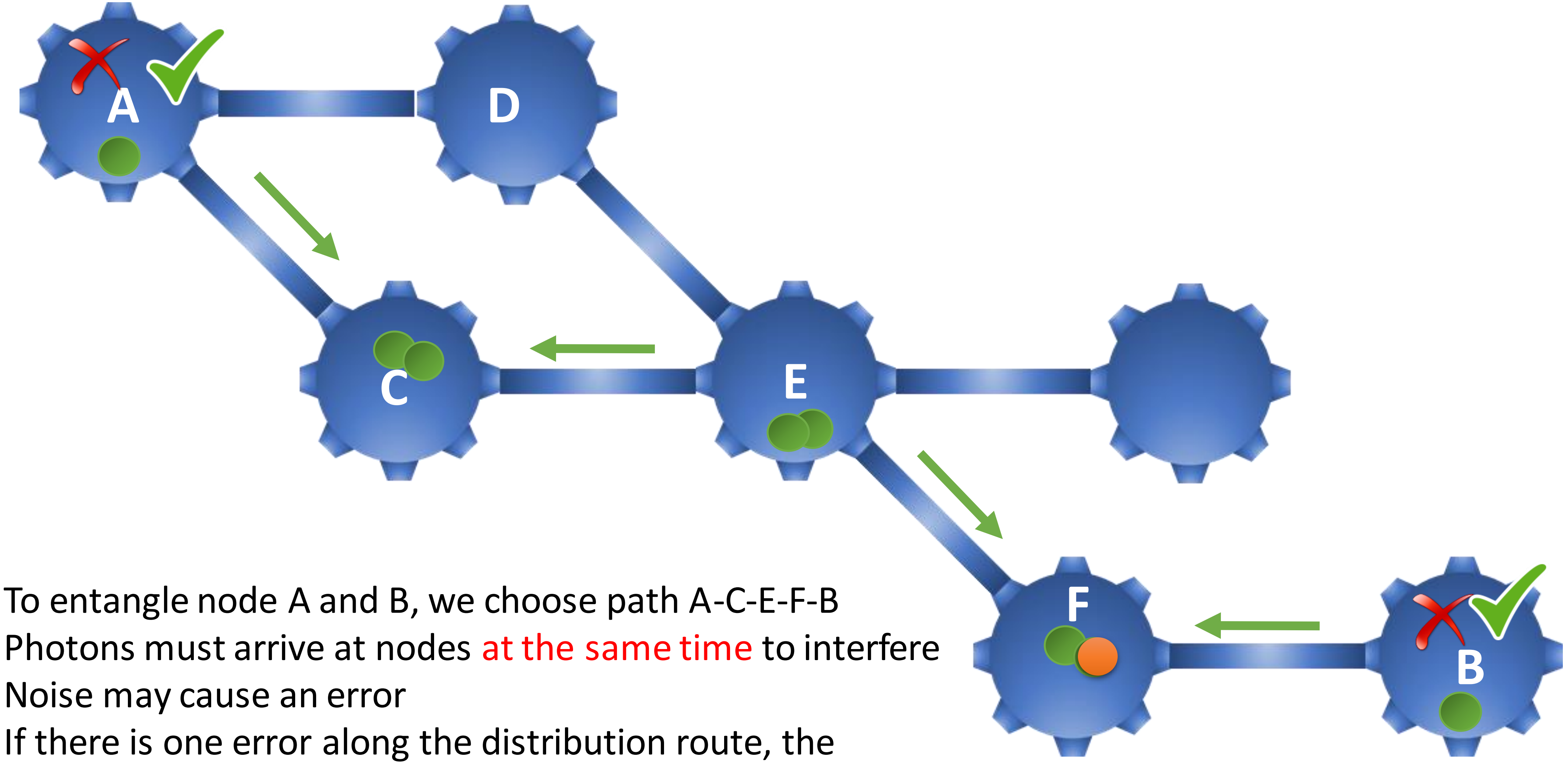


1) To entangle node A and B, we chose path A-C-B
2) Photons must arrive from node A and B at C at the same time to interfere
3) Noise may cause an error

Distribution of Quantum Information

entangle node A and B

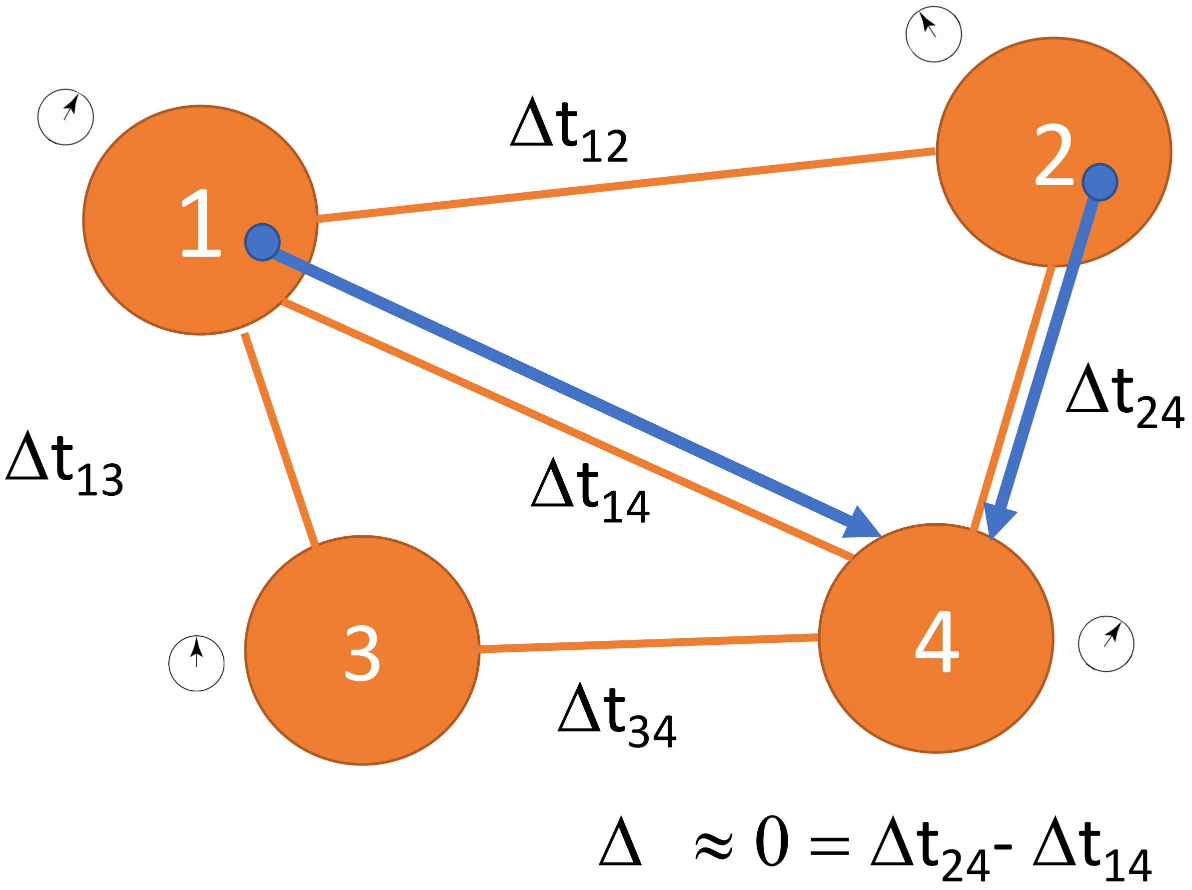


1) To entangle node A and B, we choose path A-C-E-F-B
2) Photons must arrive at nodes at the same time to interfere
3) Noise may cause an error
4) If there is one error along the distribution route, the entanglement fails

Challenges for future quantum networks

- We will not necessarily have dedicated dark fibers, so:
  - ‘Noise’ must be 10 orders of magnitude lower compared to classical requirement, i.e. reduced from -30 dBm to -130 dBm (~1000 photons/sec) – gating can be beneficial!
  - Quantum signals need to coexist with strong classical signals
  - Network needs to be transparent – no OEO conversion
- Polarization Mode Dispersion
- Latency must be small (no quantum memory yet*)
- Need Quantum Repeaters (amplifiers are not an option)
- Nodes must be well synchronized depending on the application (ps to ns)

Node synchronization



Quantum Network Protocols will use ***single*** photons arriving at the detection plane quasi-simultaneously

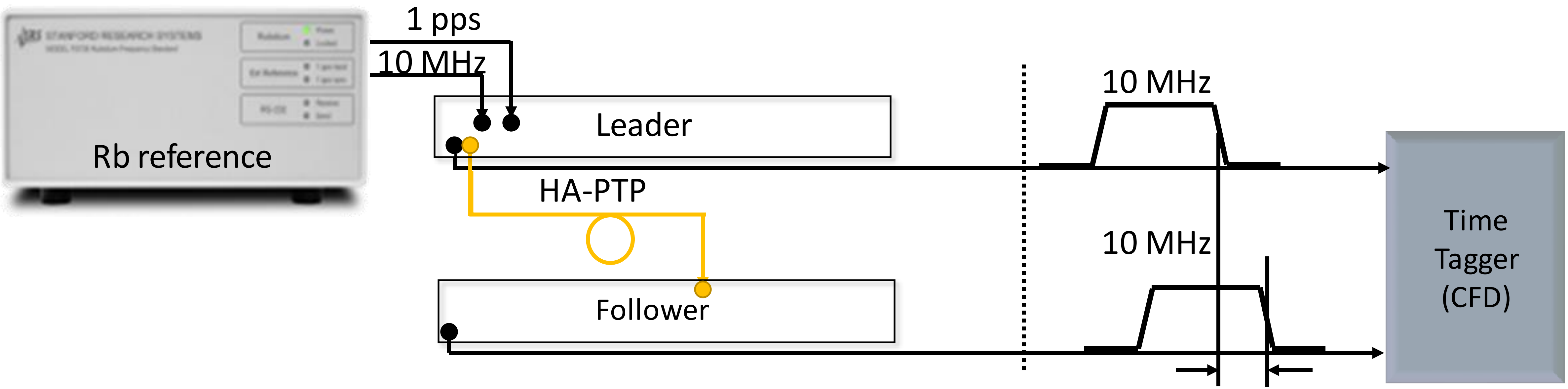
The precision of arrival time depends on the physical implementation of the qubits in the nodes

Precision can range from nanoseconds for atoms and ions to picoseconds or even femtoseconds for spontaneous parametric downconversion.

Some protocols also require phase knowledge between nodes!

Need to know: $\Delta t_{14} - \Delta t_{24}$ and adjust time delays accordingly through local oscillator phase control or physical delay implementations

High-Accuracy PTP (HA-PTP)

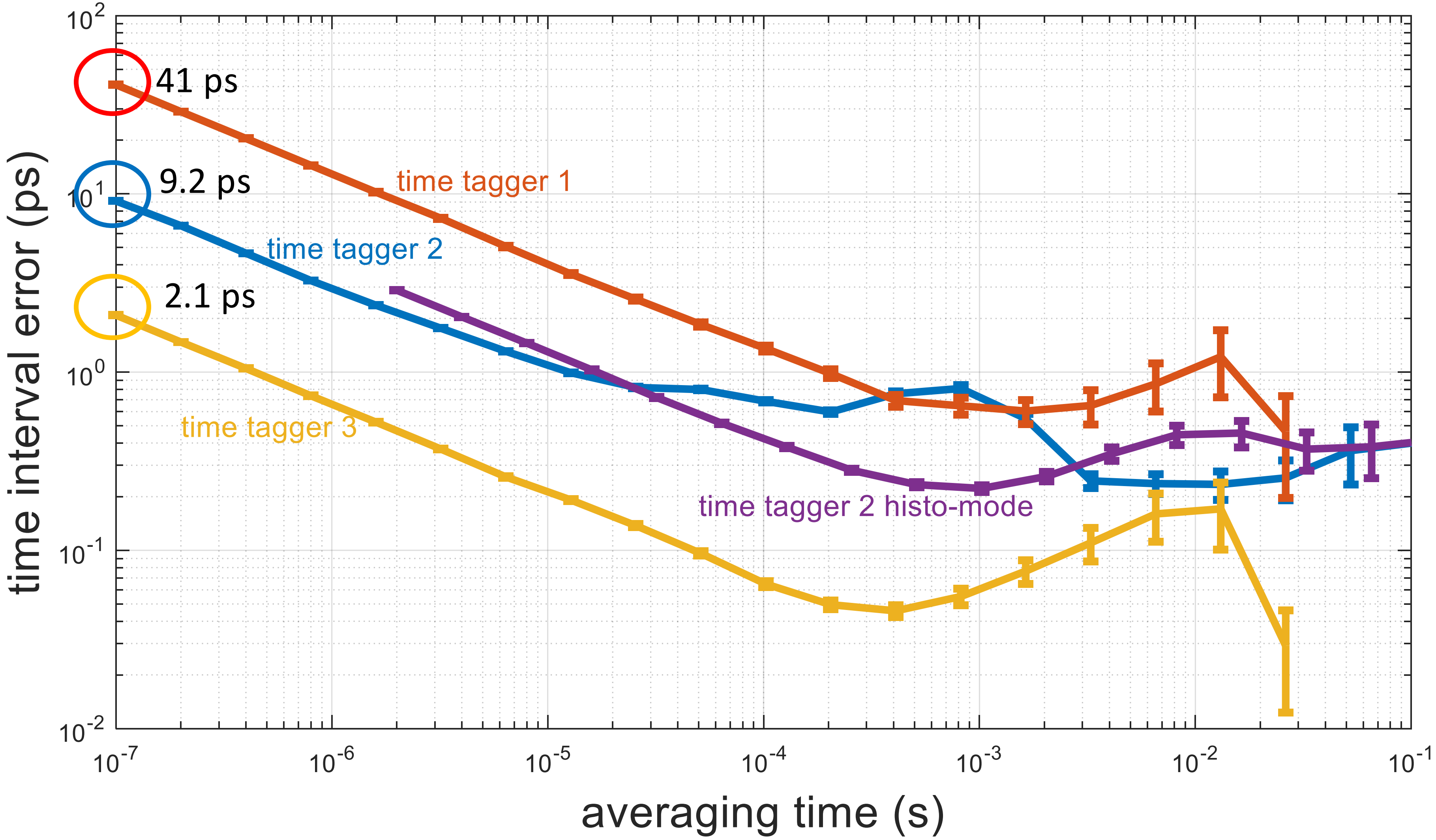


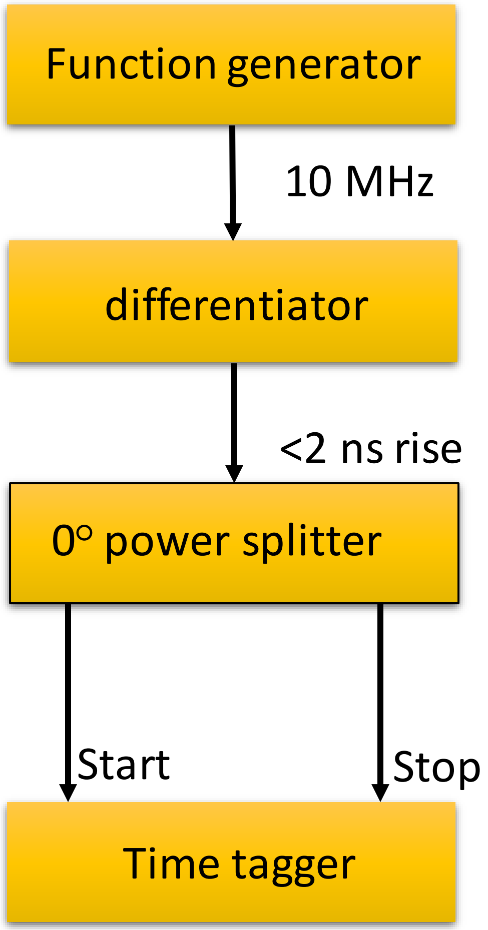
accuracy (sub-1 ns), $\Delta\phi \sim 0$
precision (jitter) < 10 ps

The precision (jitter) is the most important metric, as this will correspond to a shot-to-shot variation of the photon's arrival time
Accuracy (the mean) can be compensated by through LO phase adjustment.

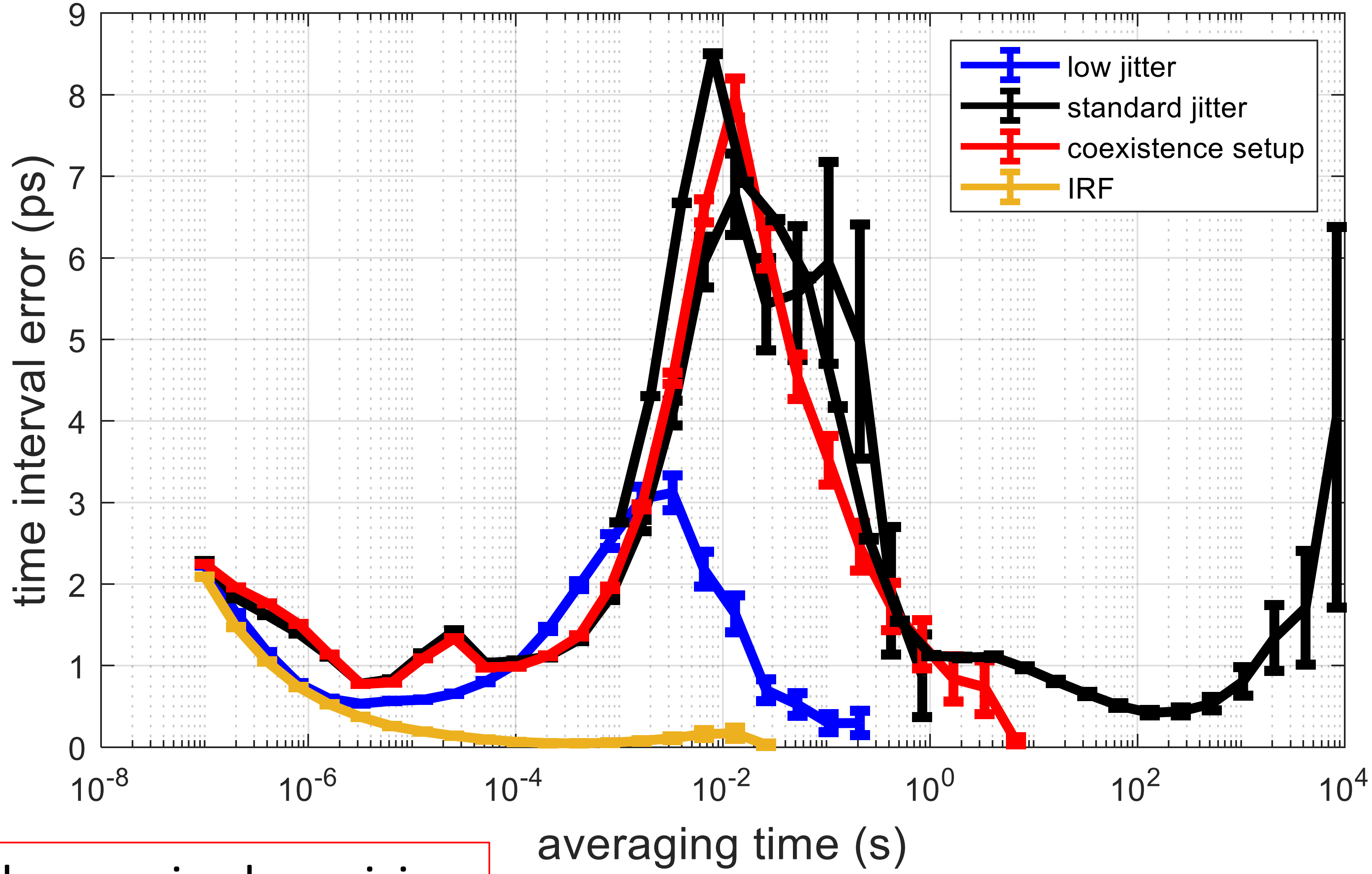
Time Tagger Evaluation

constant fraction discriminator



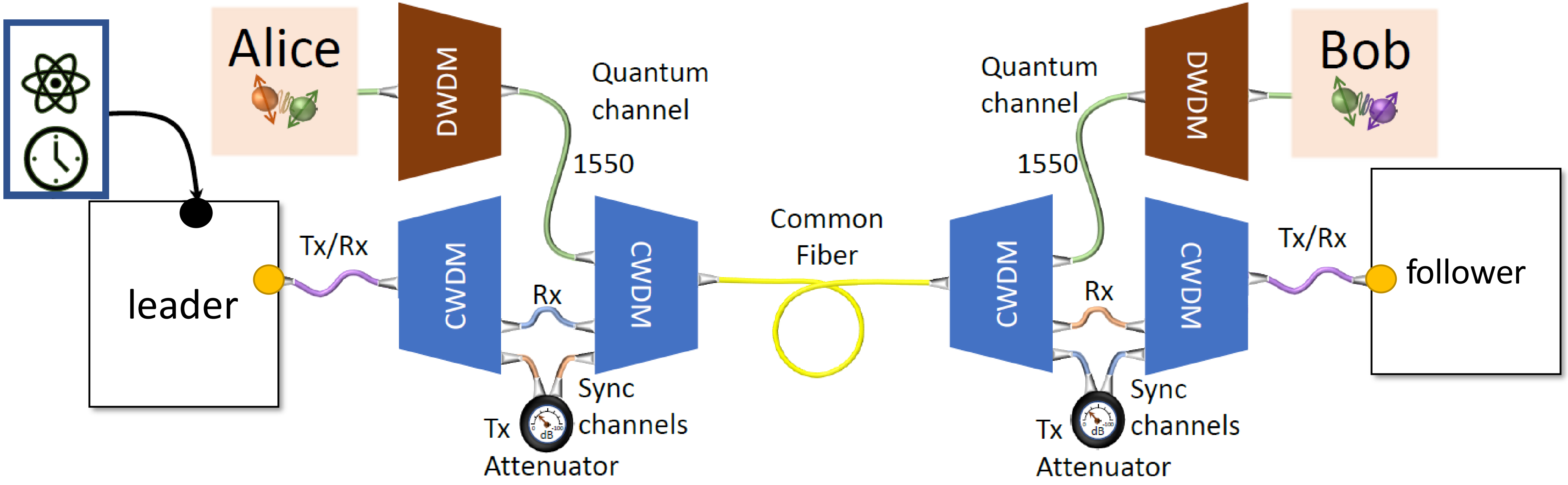


Time Tagging Results

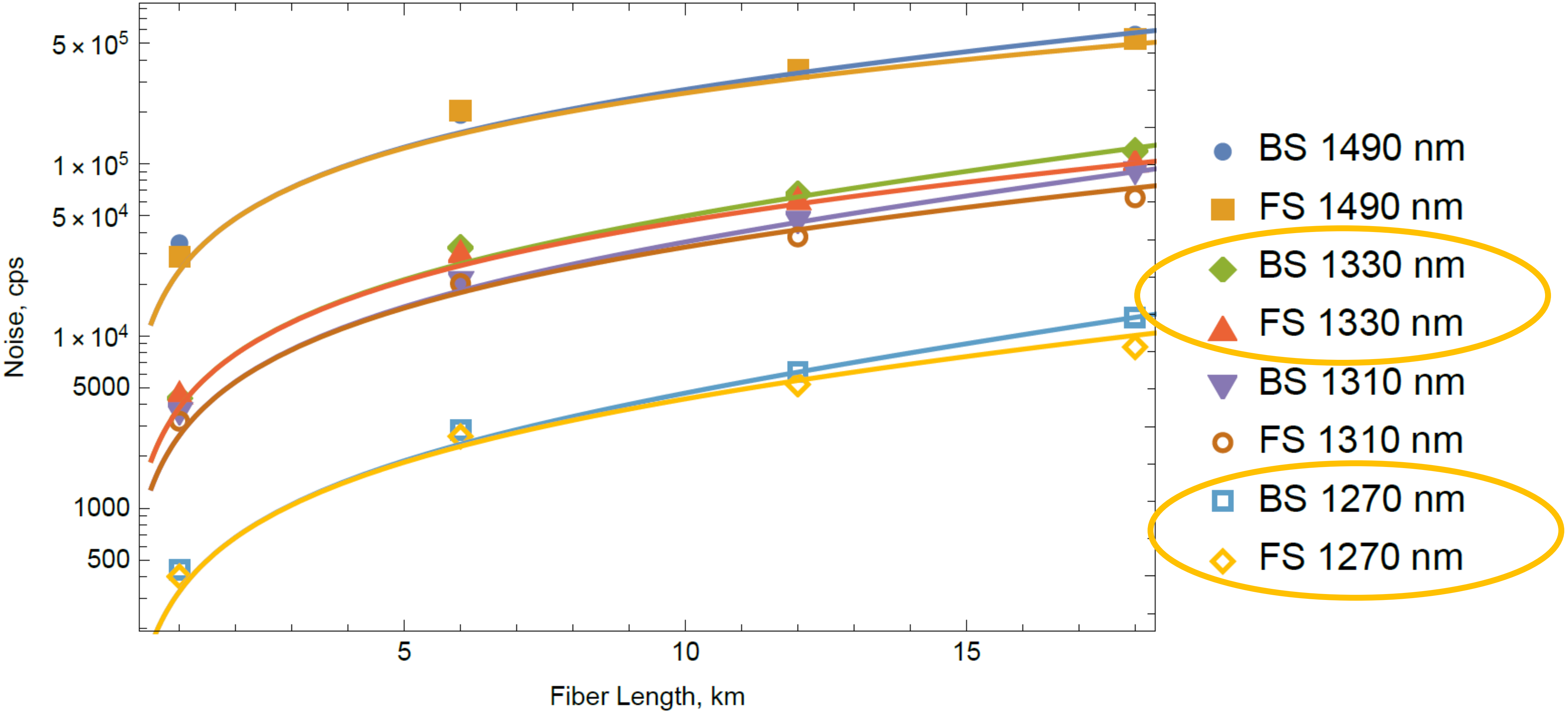


WR can give us the required precision

Coexistence study – noise measurement



Coexistence study – noise measurement



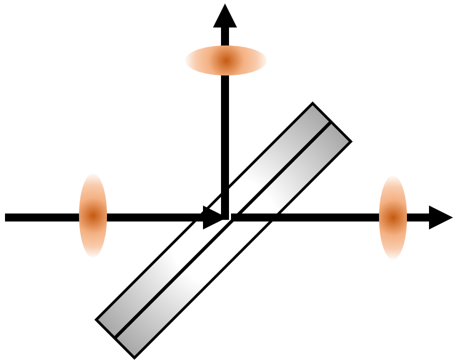
Measured noise in quantum channel can be significant. Forward scattering (FS) and Back scattering (BS) is present at all wavelengths

Conclusions/Outlook

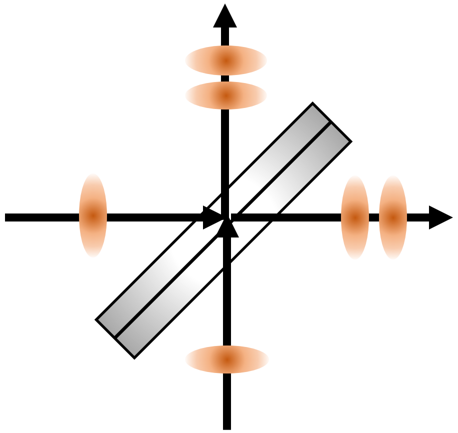
- HA-PTP can be used to synchronize local nodes with picosecond precision, such that entanglement distribution is possible.
- Coexistence of HA-PTP and the quantum signal can work for short distances.

- Outlook:
  - Polarization entanglement distribution along with HA-PTP in the same fiber
  - Implementing PLL and stable oscillator to get better TIE @10 ms
  - Interference between two single photons synchronized with HA-PTP
  - Compare HA-PTP with weak photon pulses and photon counting

Hong-Ou-Mandel Interference

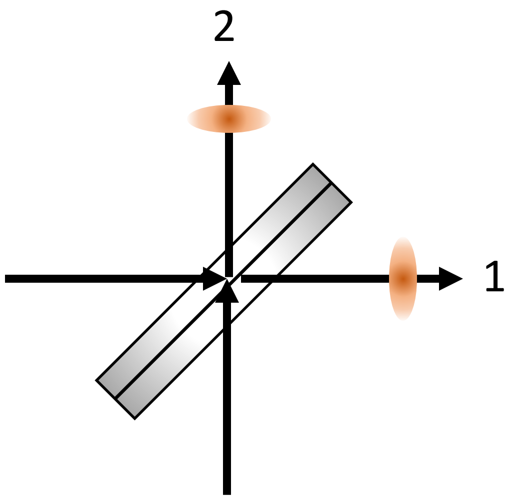


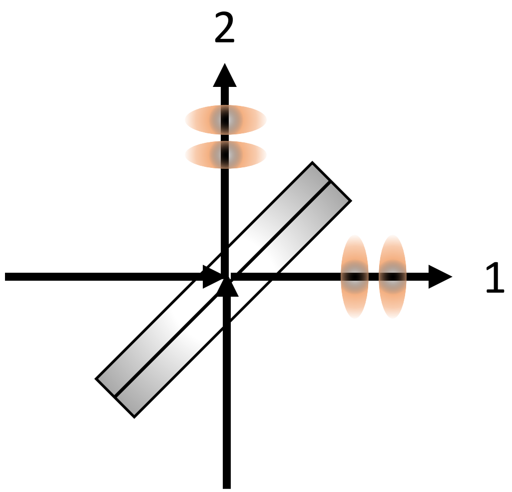
Hong-Ou-Mandel Interference



classical

Hong-Ou-Mandel Interference

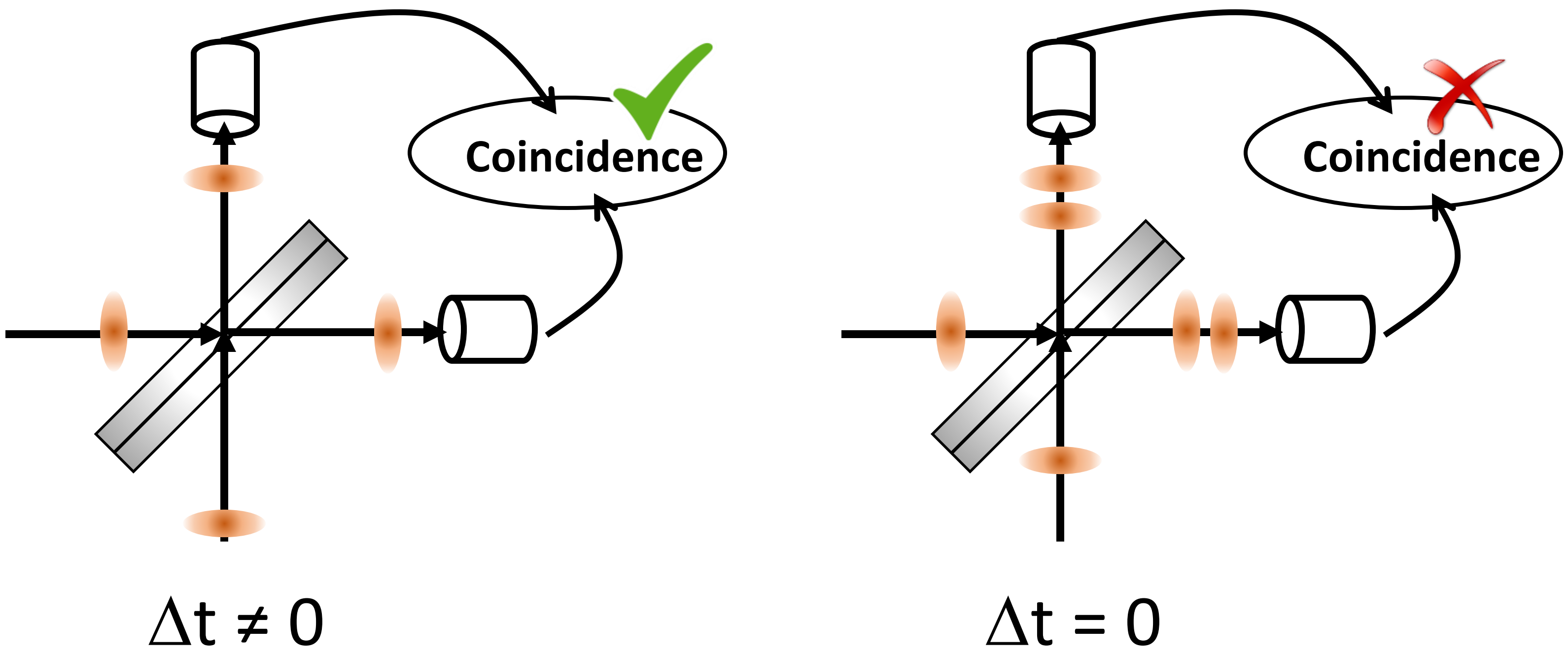




$$|\Psi\rangle_{out} = (\hat{a}_1^\dagger \hat{a}_1^\dagger - \hat{a}_2^\dagger \hat{a}_1^\dagger + \hat{a}_1^\dagger \hat{a}_2^\dagger + \hat{a}_2^\dagger \hat{a}_2^\dagger)|0\rangle_1|0\rangle_2$$

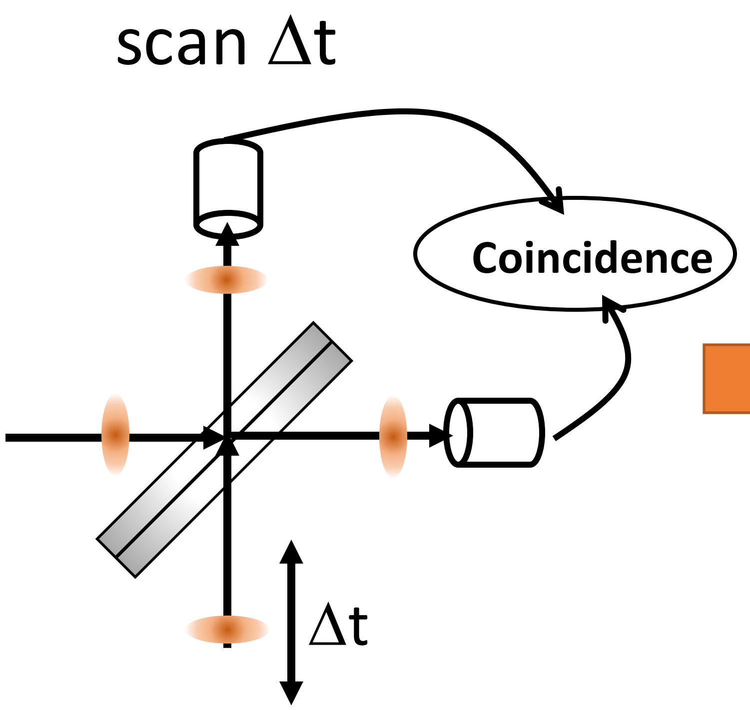
$$|\Psi\rangle_{out} = (|2\rangle_1|0\rangle_2 + |0\rangle_1|2\rangle_2)$$

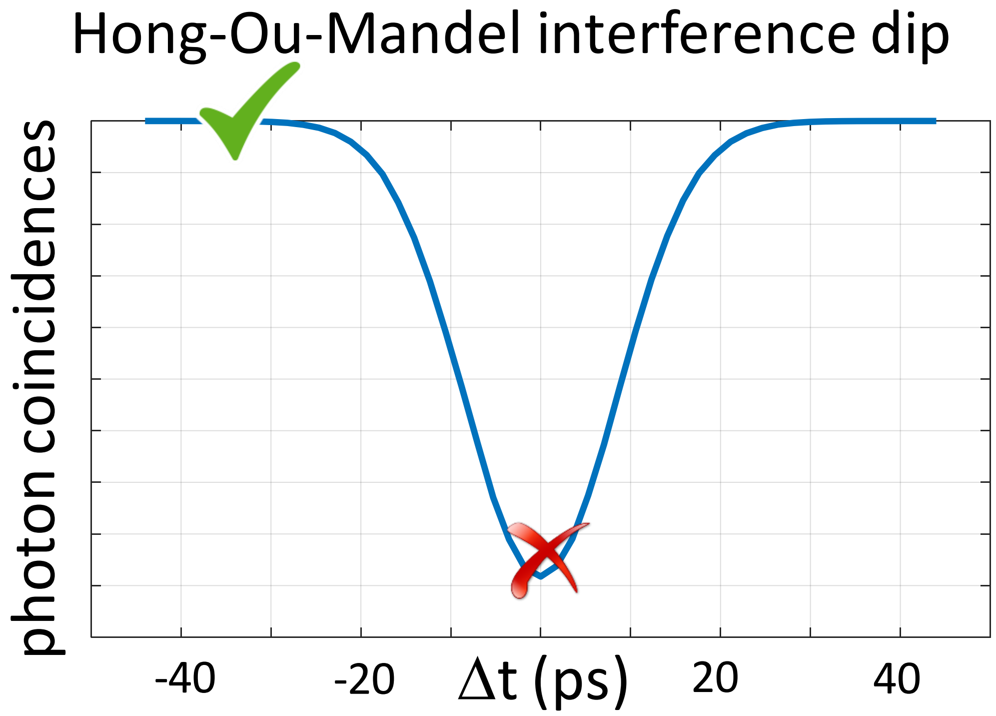
Hong-Ou-Mandel Interference



Photons must be indistinguishable in frequency, polarization and time

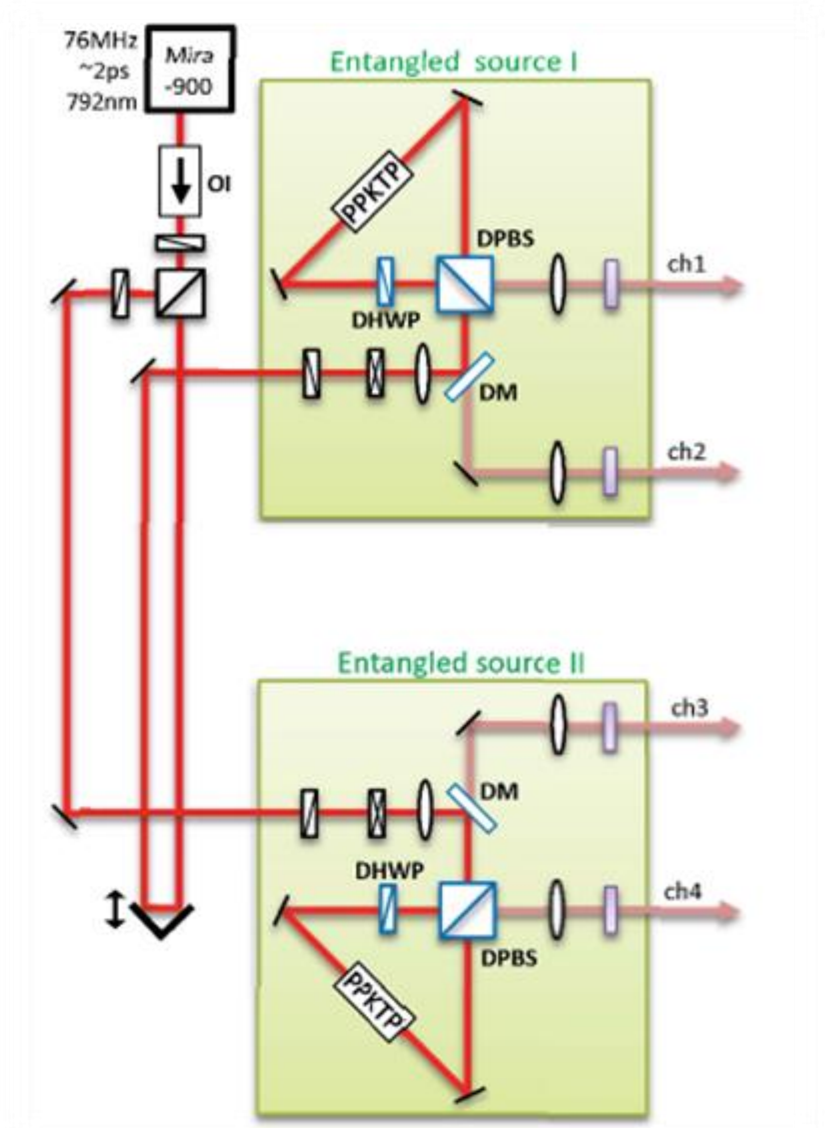
Hong-Ou-Mandel (HOM) Interference



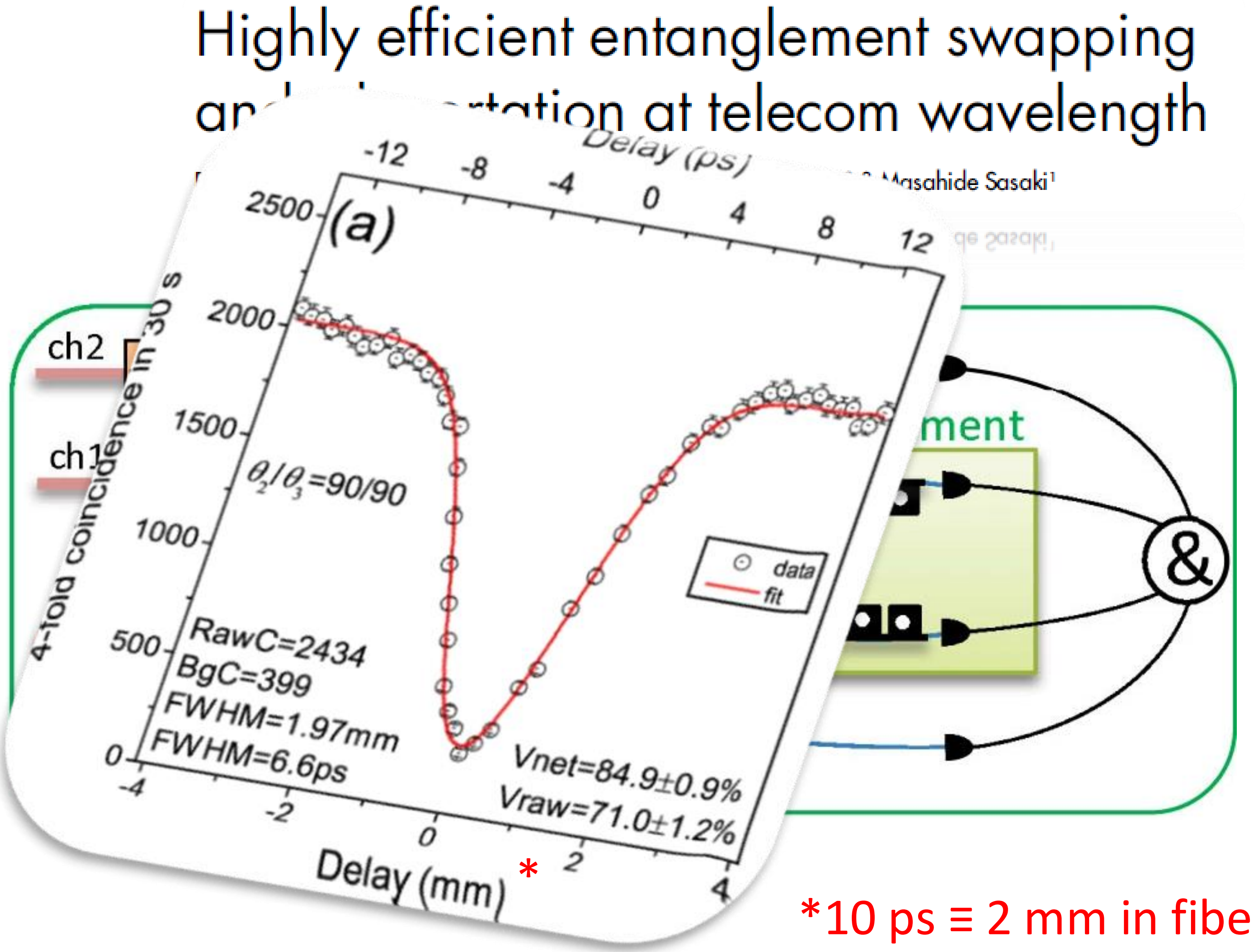


HOM interference lies at the heart of quantum information applications

Quantum State Teleportation

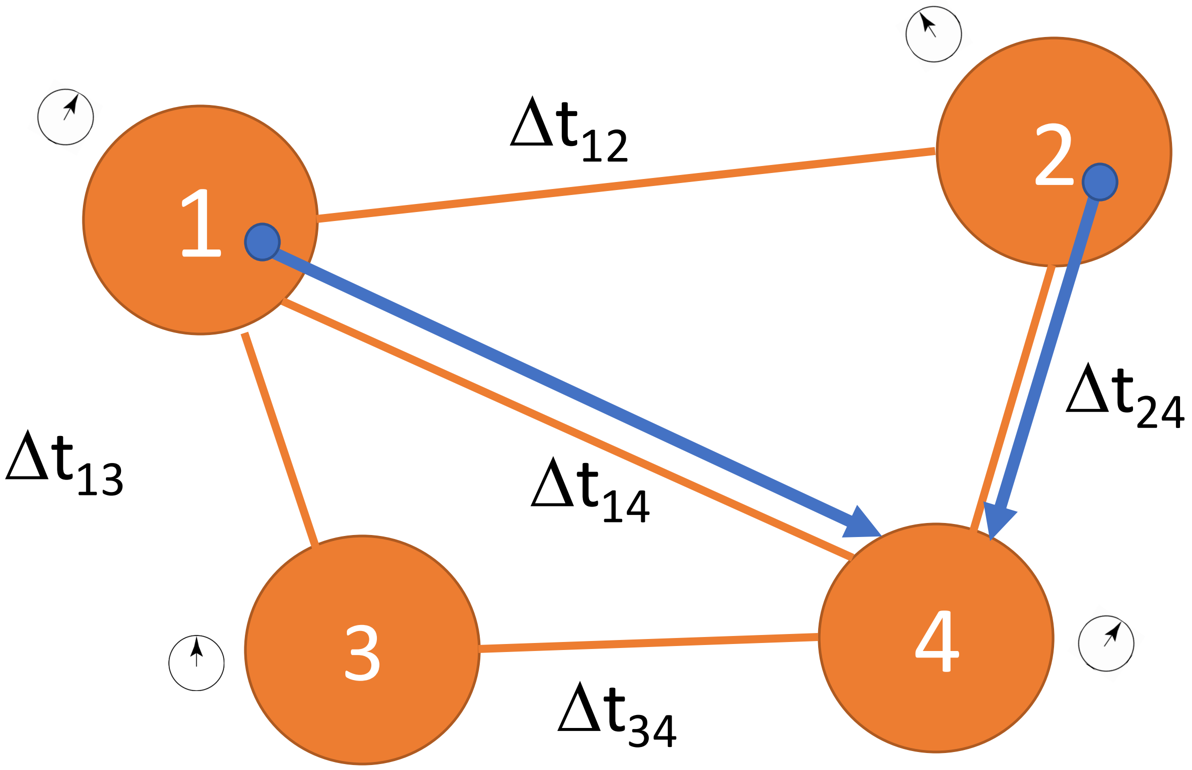


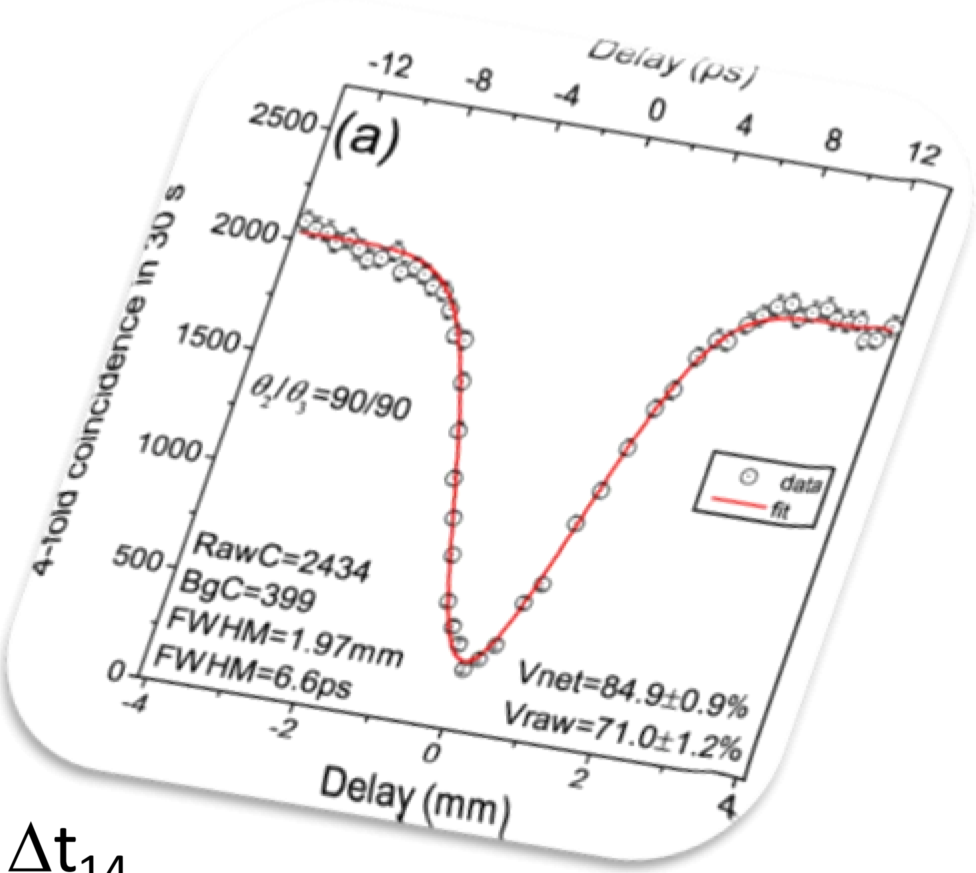
Jin et al, Sci Rep **5**, 9333 (2015)



*10 ps ≡ 2 mm in fiber

Node synchronization

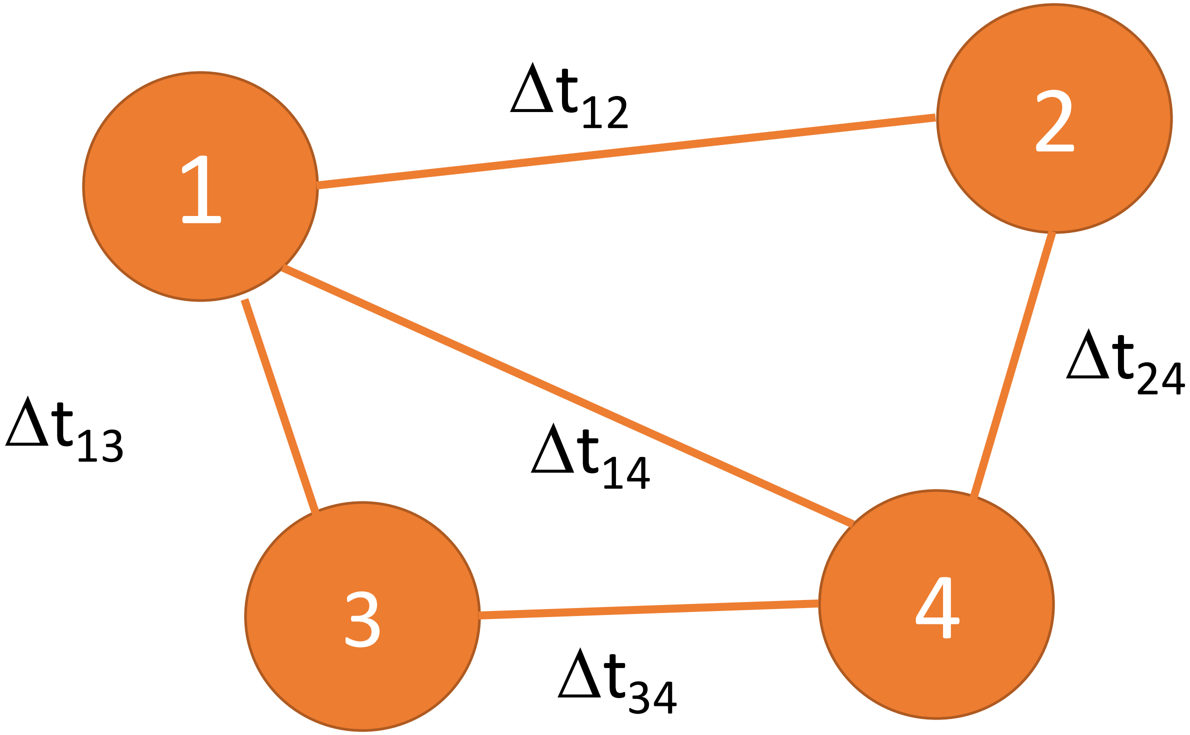




$\Delta \approx 0 = \Delta t_{24} - \Delta t_{14}$

Need to know: $\Delta t_{14} - \Delta t_{24}$ and adjust time delays accordingly through local oscillator phase control or physical delay implementations

Synchronization requirements



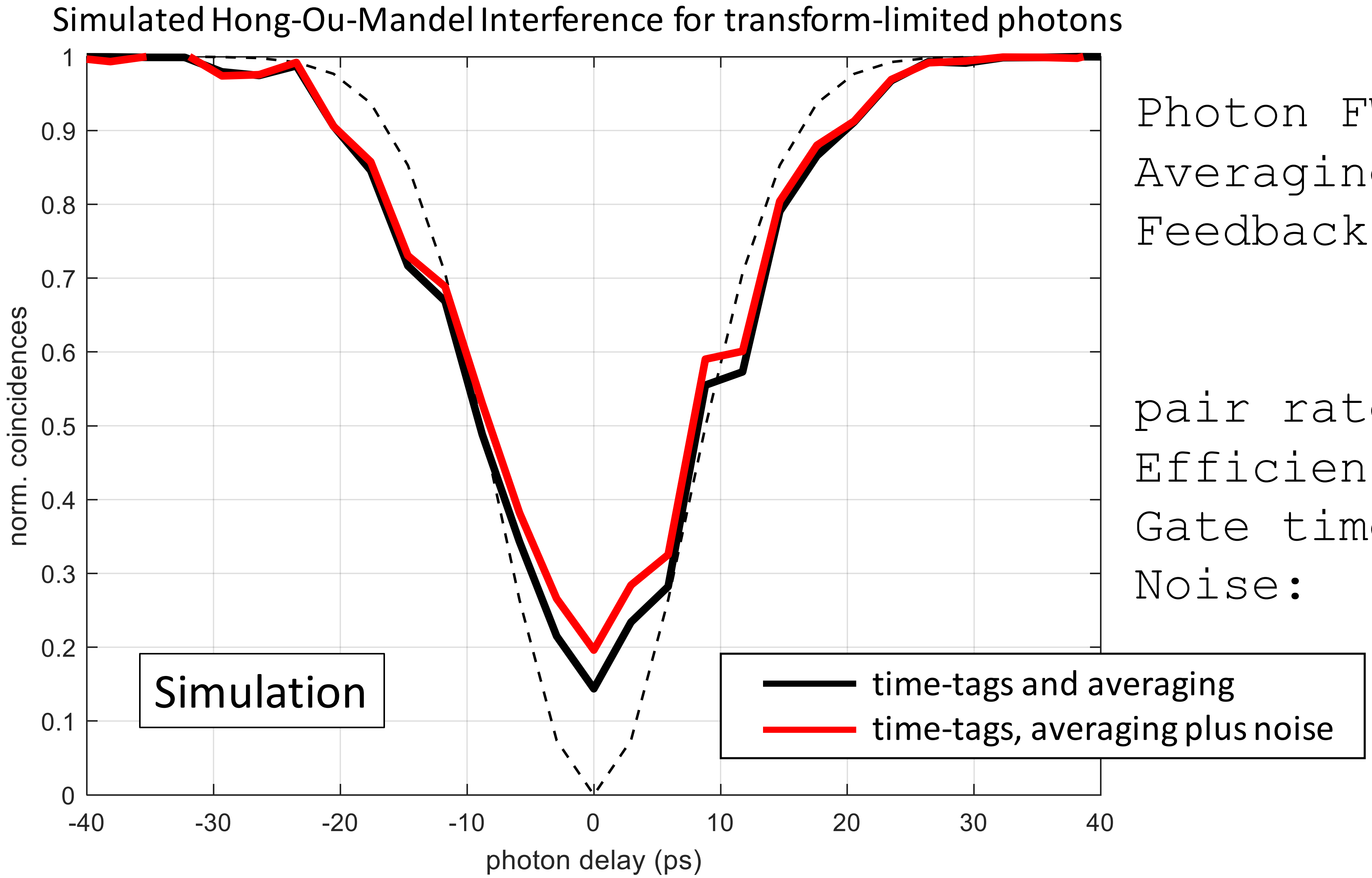
Quantum Network Protocols will make use of Hong-Ou-Mandel-type interference, *i.e.* two photons must arrive at the detection plane within a certain time interval

The precision of arrival time depends on the physical implementation of the qubits

Precision can range from nanoseconds for atoms and ions to picoseconds or even femtoseconds for SPDC

Some protocols also require phase knowledge between nodes!

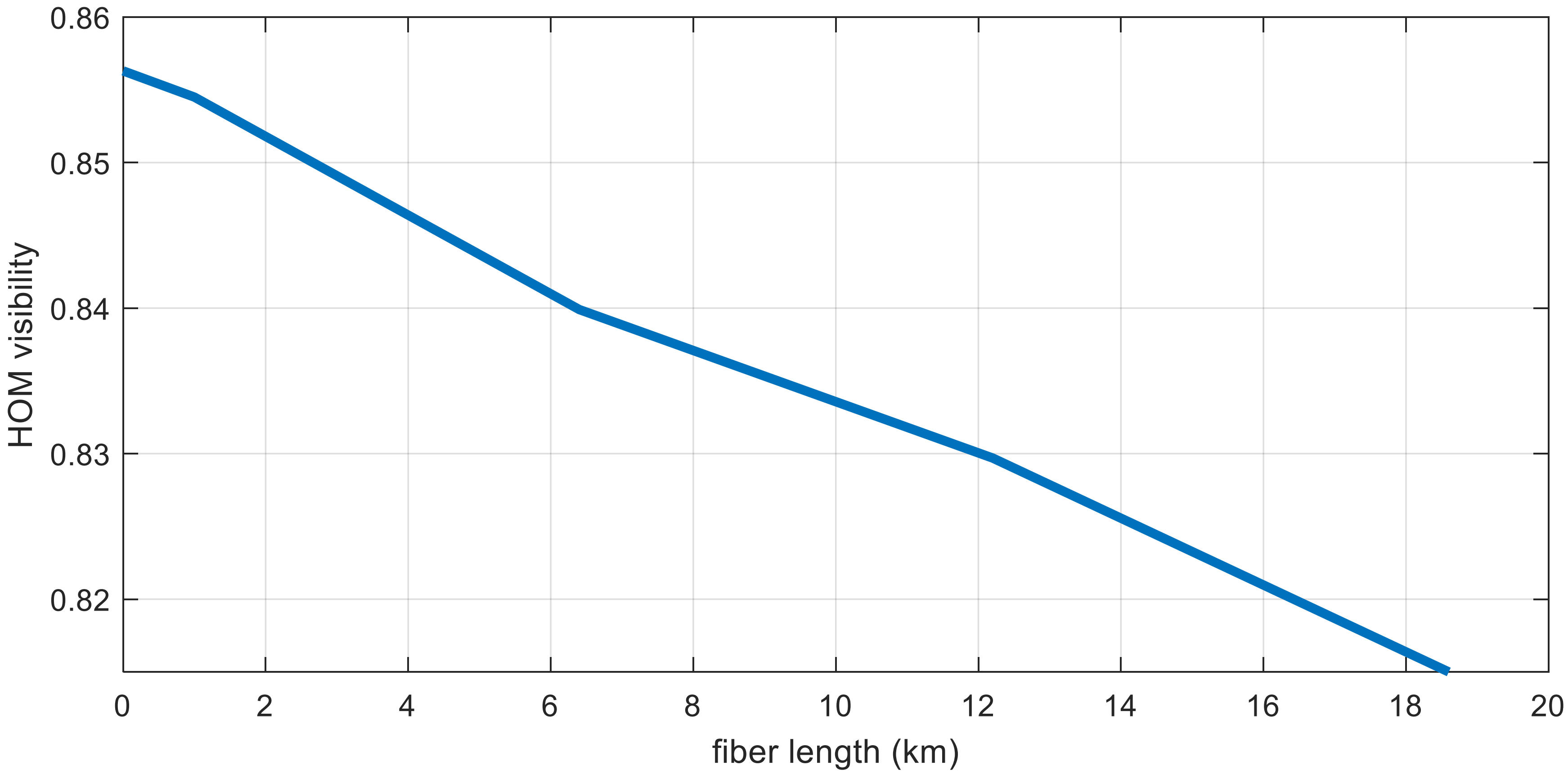
Hong-Ou-Mandel interference



Photon FWHM: 8.8 ps
Averaging: 1 ms
Feedback: 1 kHz

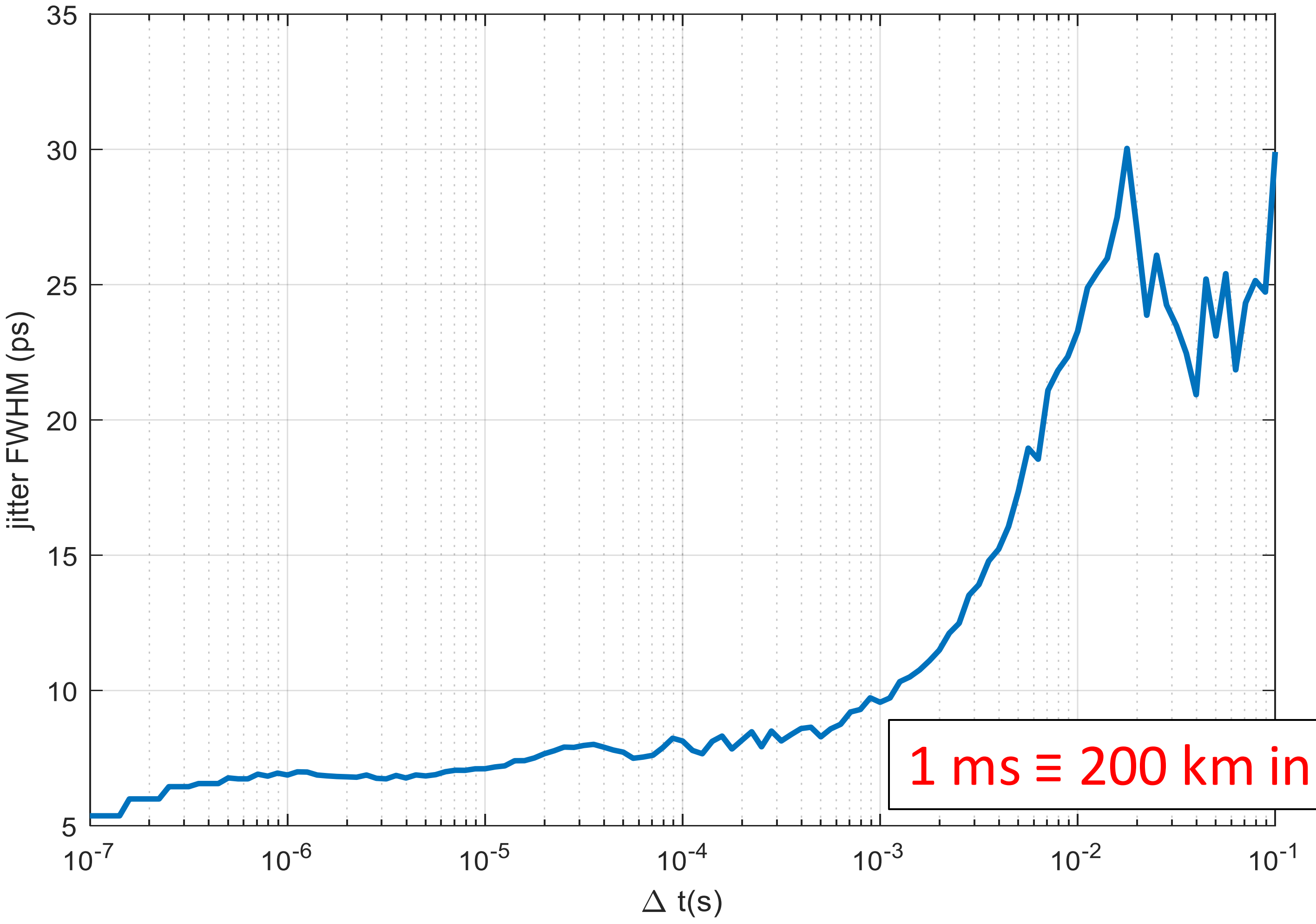
pair rate: 200,000 sec^{-1}
Efficiency: 30 %
Gate time: 1 ns
Noise: 150,000 sec^{-1}

Simulated HOM visibility vs. fiber length



Noise will reduce the HOM interference visibility. However, the main decrease in visibility is caused by timing uncertainty.

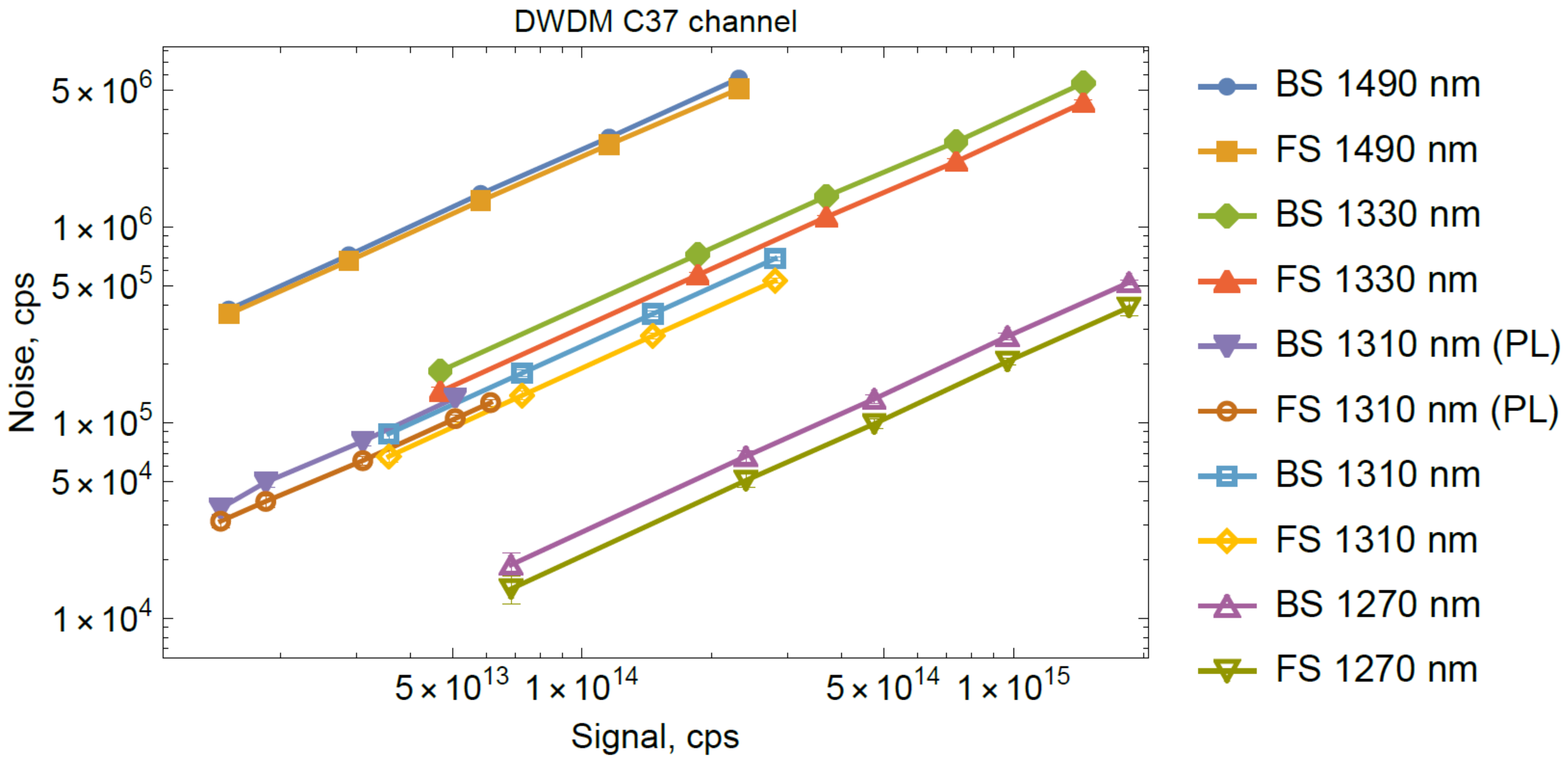
Pulse n-to-m jitter



1 ms ≡ 200 km in fiber

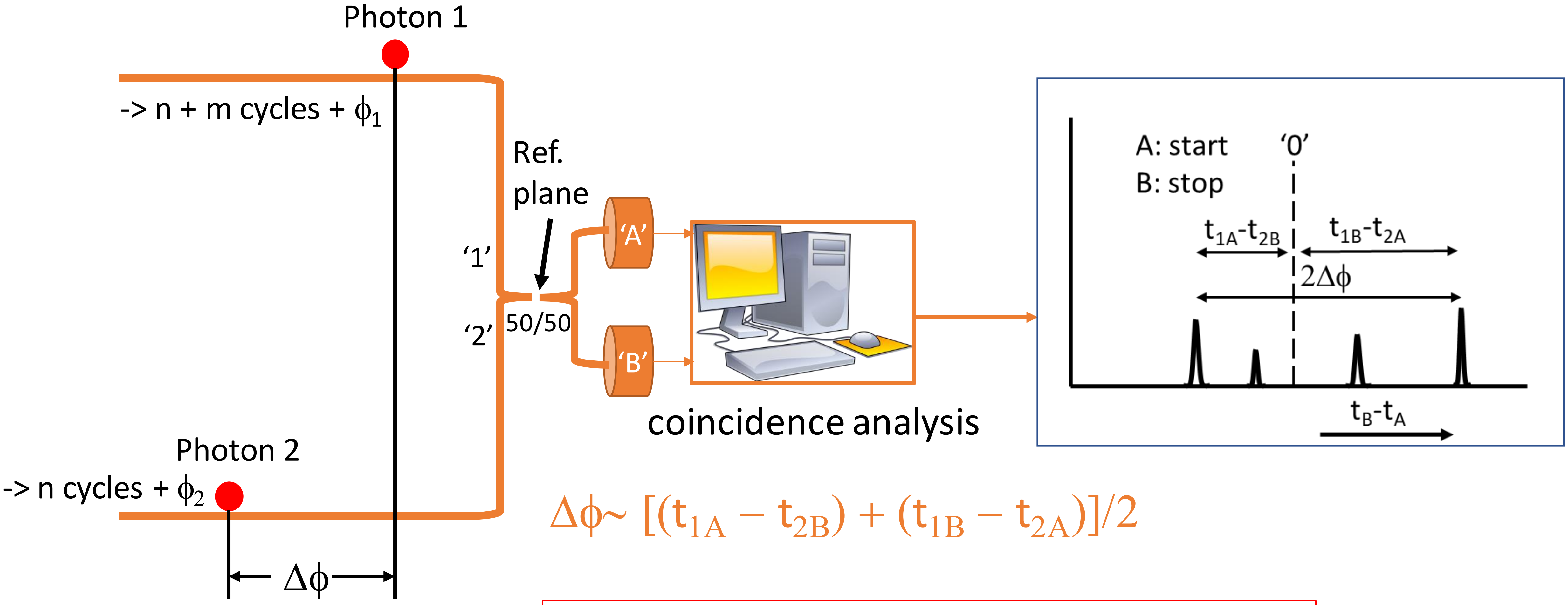
Coexistence study – noise measurement

NIST



Measured noise in quantum channel can be significant. Forward scattering (FS) and Back scattering (BS) is present at all WR wavelengths

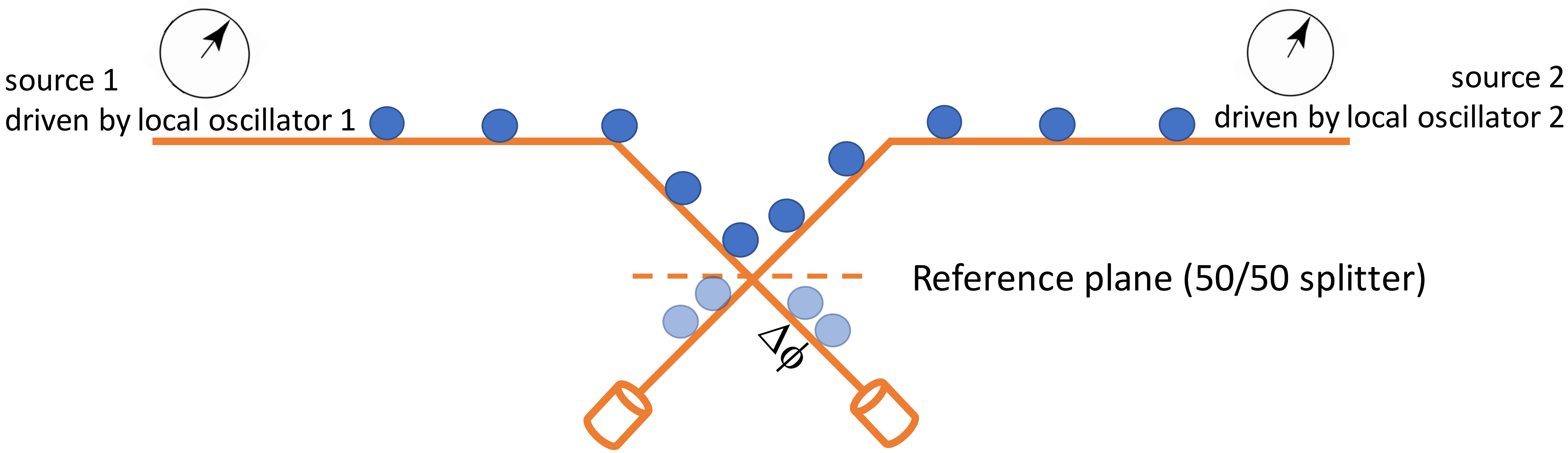
Phase offset measurement



$$\Delta\phi \sim [(t_{1A} - t_{2B}) + (t_{1B} - t_{2A})]/2$$

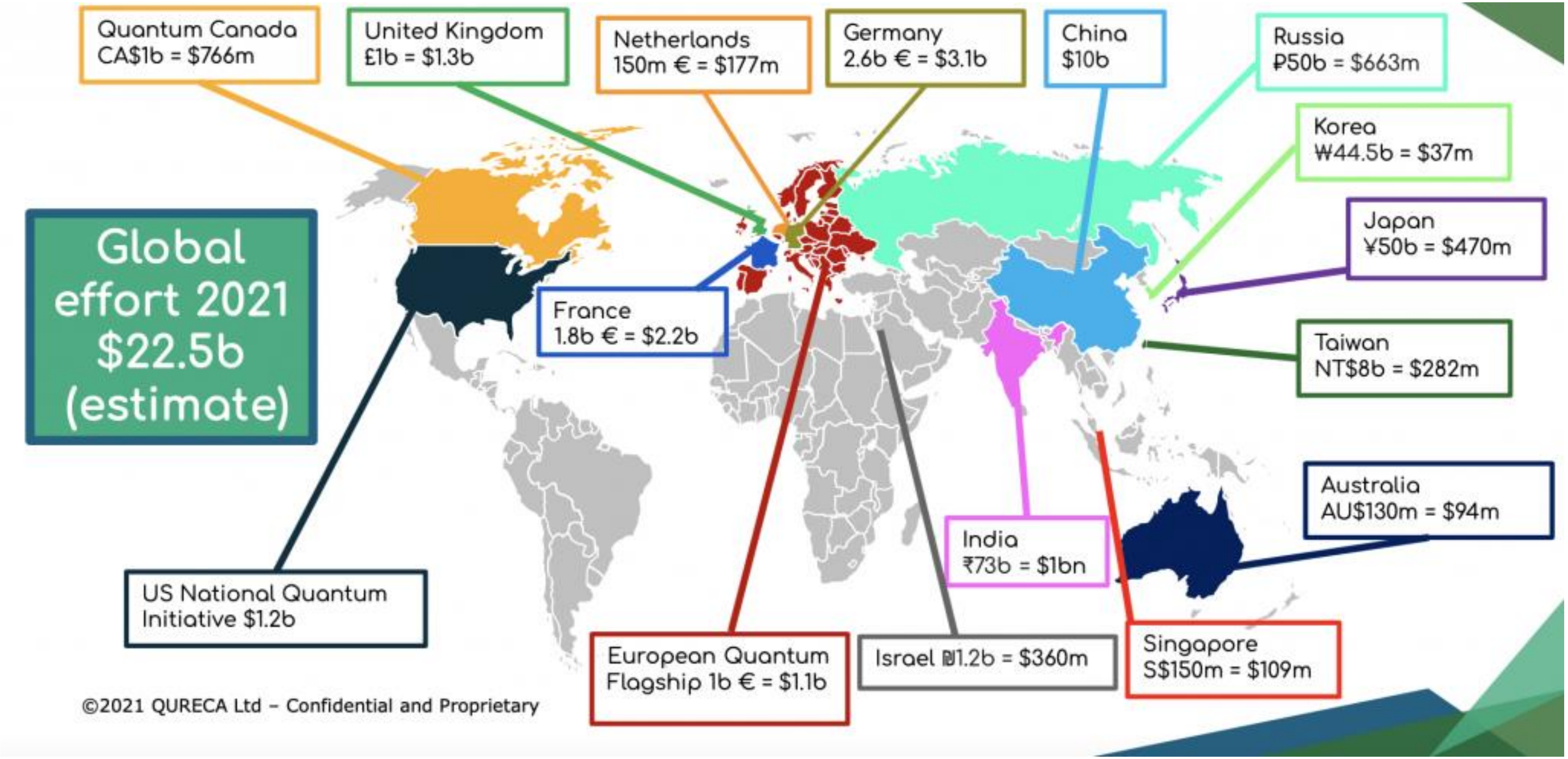
Phase offset adjustment requires low latency

Source synchronization



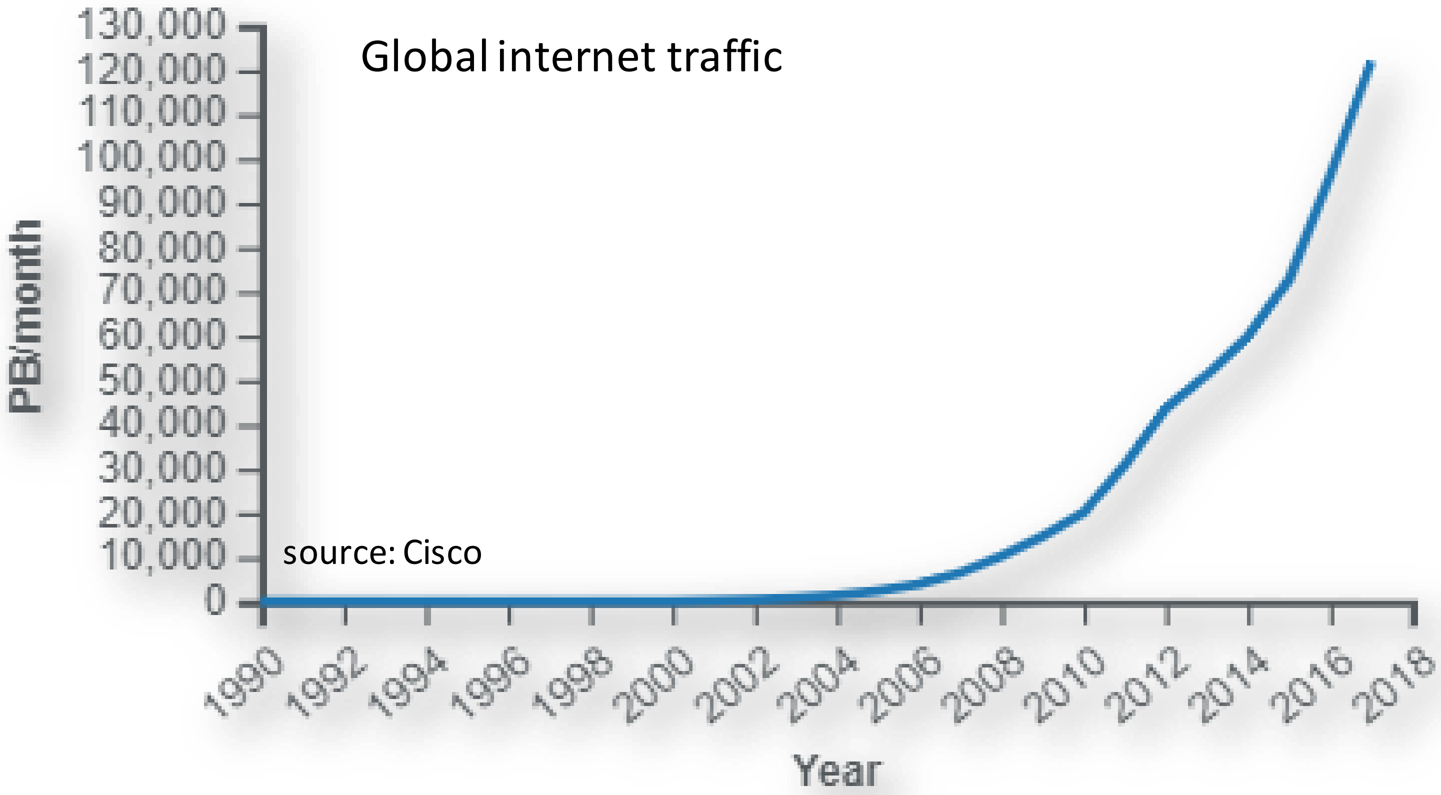
With synchronized LOs, the relative LO phase offset will manifest itself in a time-of-arrival (TOA) difference between the photons from each source. Measurement of that TOA difference can be used to adjust LO phase.

Worldwide Quantum Efforts

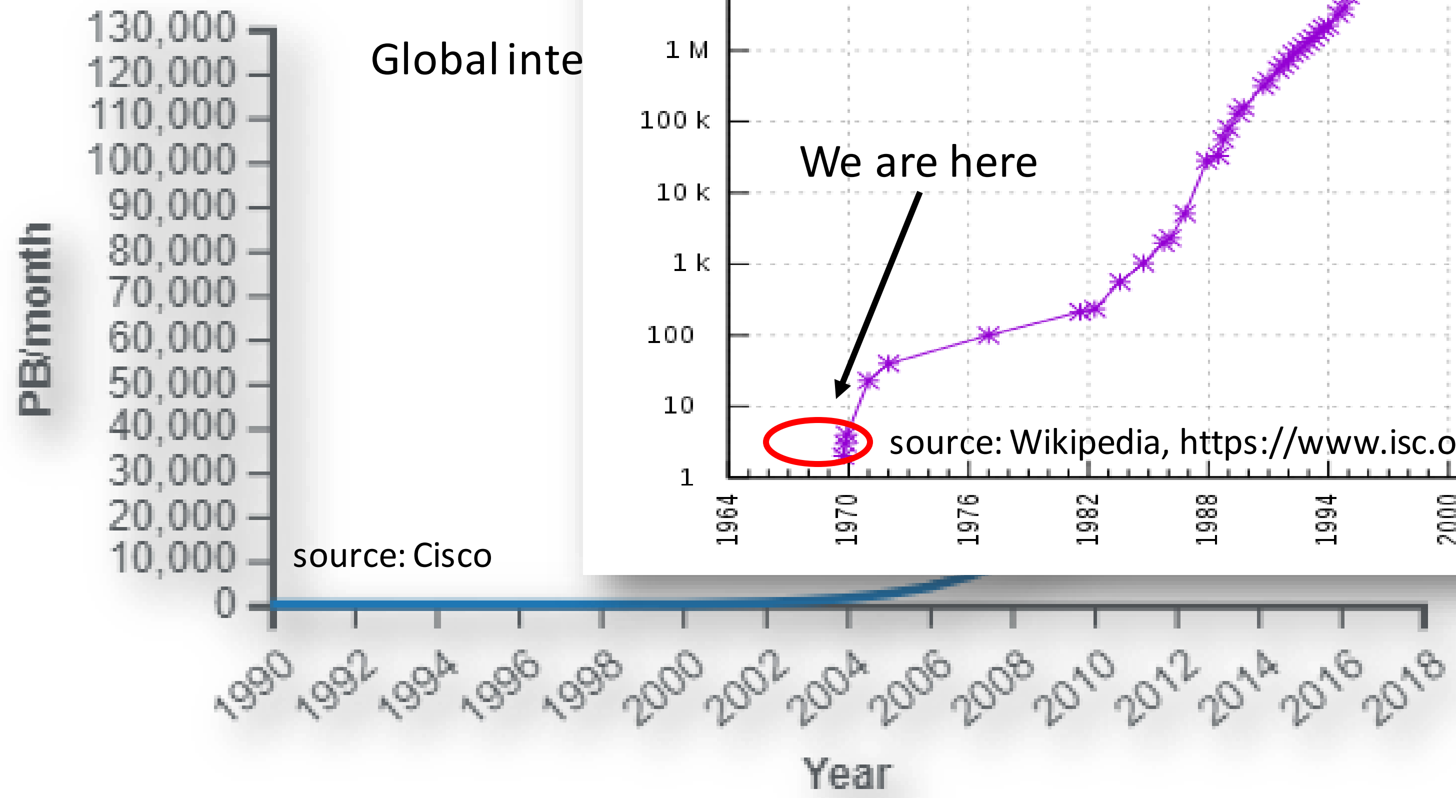


Source: https://www.qureca.com/overview-on-quantum-initiatives-worldwide/

Internet Growth



Internet Growth



Total internet hosts survey