QTS

Quantum Teleportation for Space Systems

(ESA Contract No. 4000104180/11/NL/AF)

Outline

- **Motivation**
- **Teleportation protocol**
- **Objectives and requirements**
- **Proof-of-concept demonstrator**
- **Inter-island quantum teleportation**
- **Development roadmap**

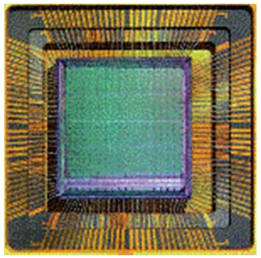
Motivation

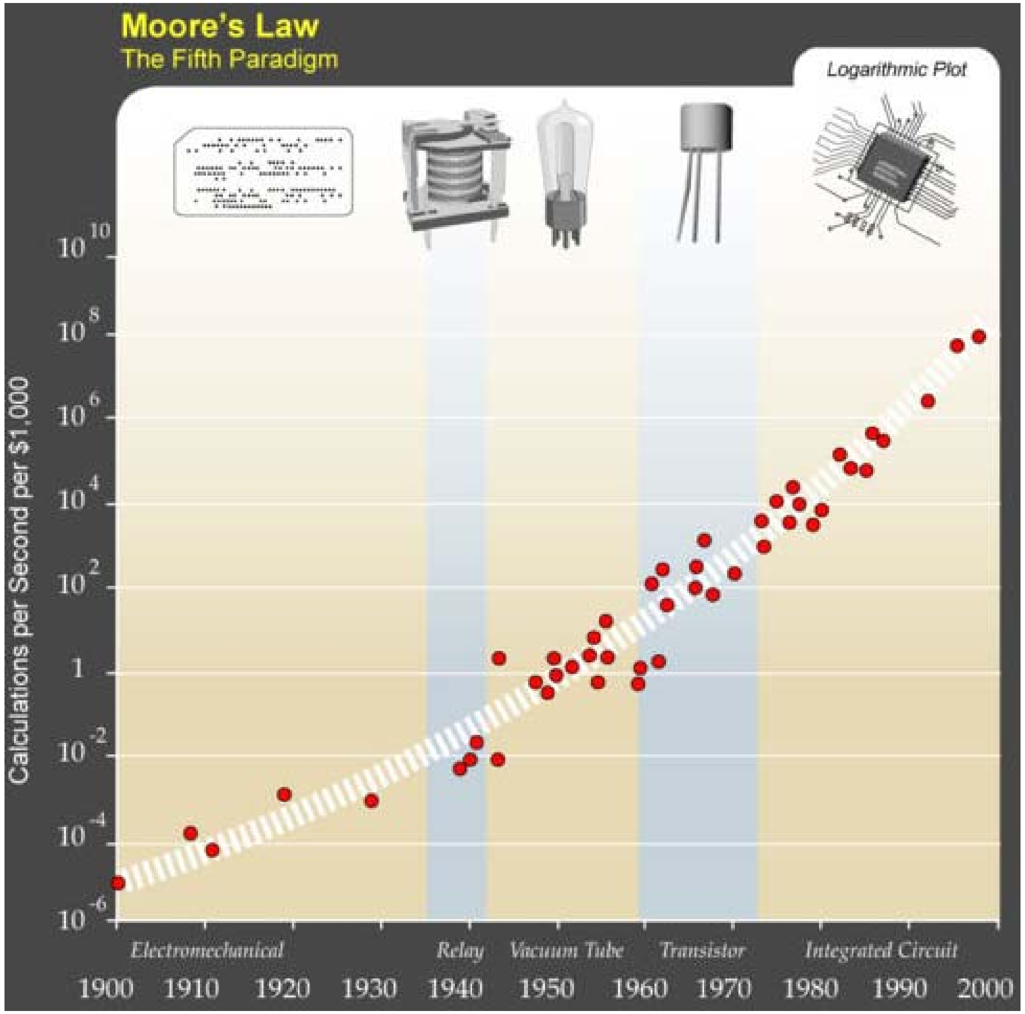
Moore's Law

Gordon Moore (© Intel 1065)

"The number of transistors that can be placed (inexpensively) on an integrated circuit doubles approximately every two years."

Year:	Electron/Bit:
2000	100
2010	10
2020	**1**





We will enter the quantum age soon

Classical and Quantum Information

Bit

Binary Digit

„0“ or „1“

(classical)

A measurement reveal it‘s **true** state

Qubit

Quantum Bit

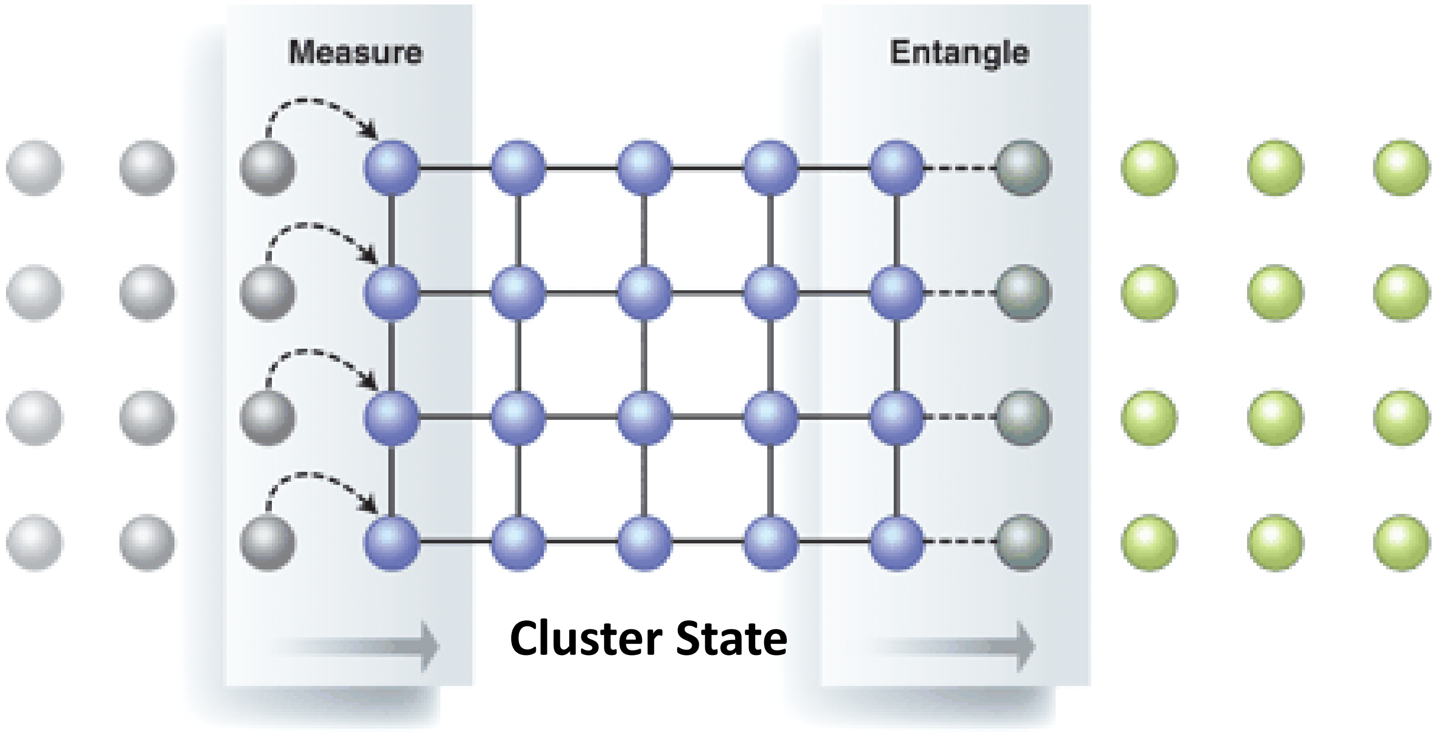
„0“ and „1“

(Superposition)

A measurement reveal **a random** state

Quantum Computing

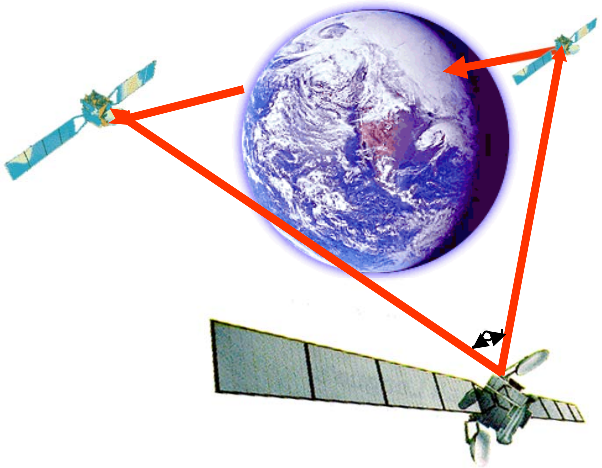
Quantum computing offers substantial computational speedups



Quantum teleportation is the key building block for **generating a cluster state**

Motivation for space-based Quantum Teleportation

Global Quantum Communication Networks



Quantum Internet

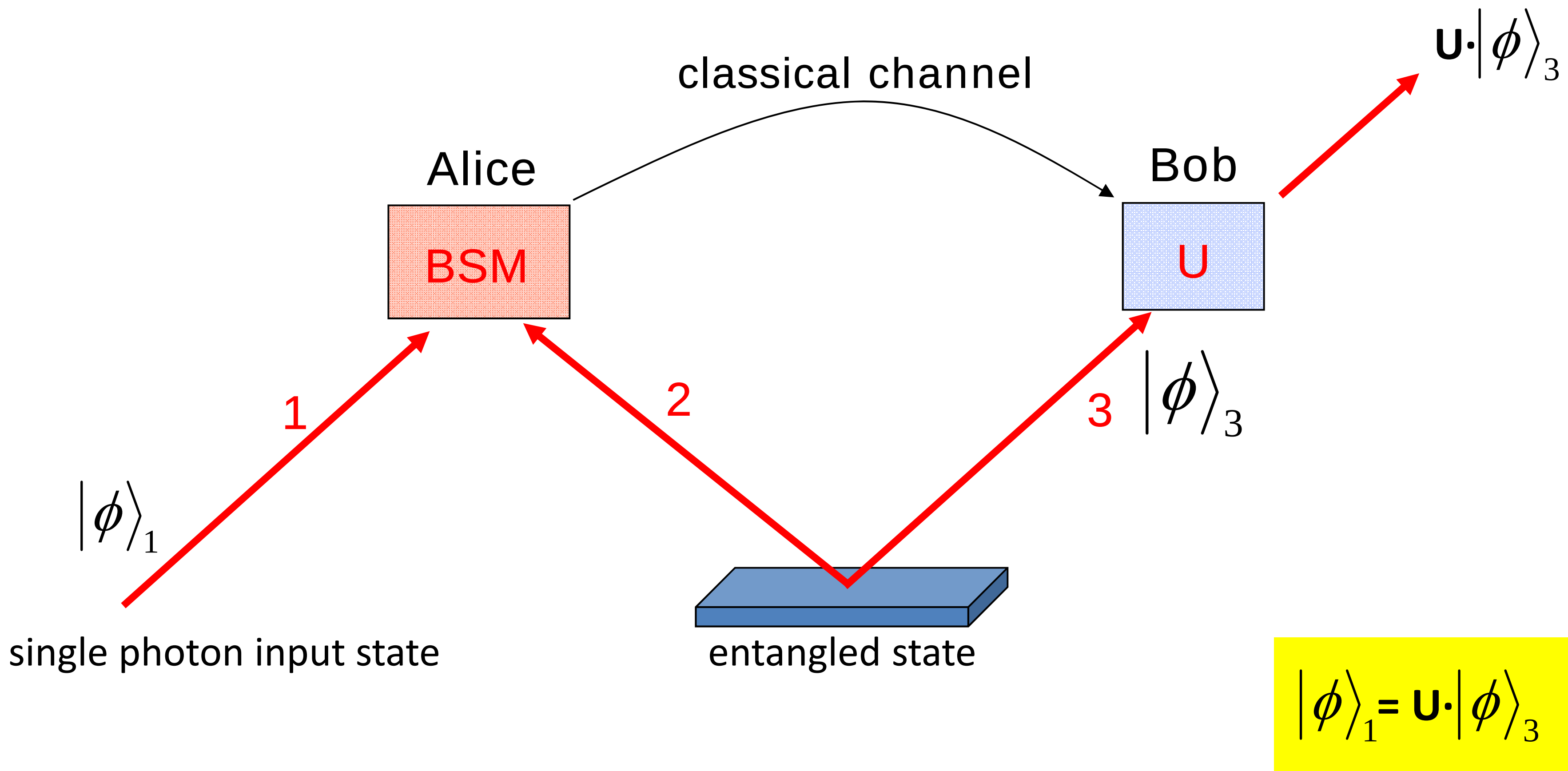
- H. J. Kimble, The Quantum Internet, *Nature* **453**, 1023-1030 (19 June 2008)

Blind Quantum Computation

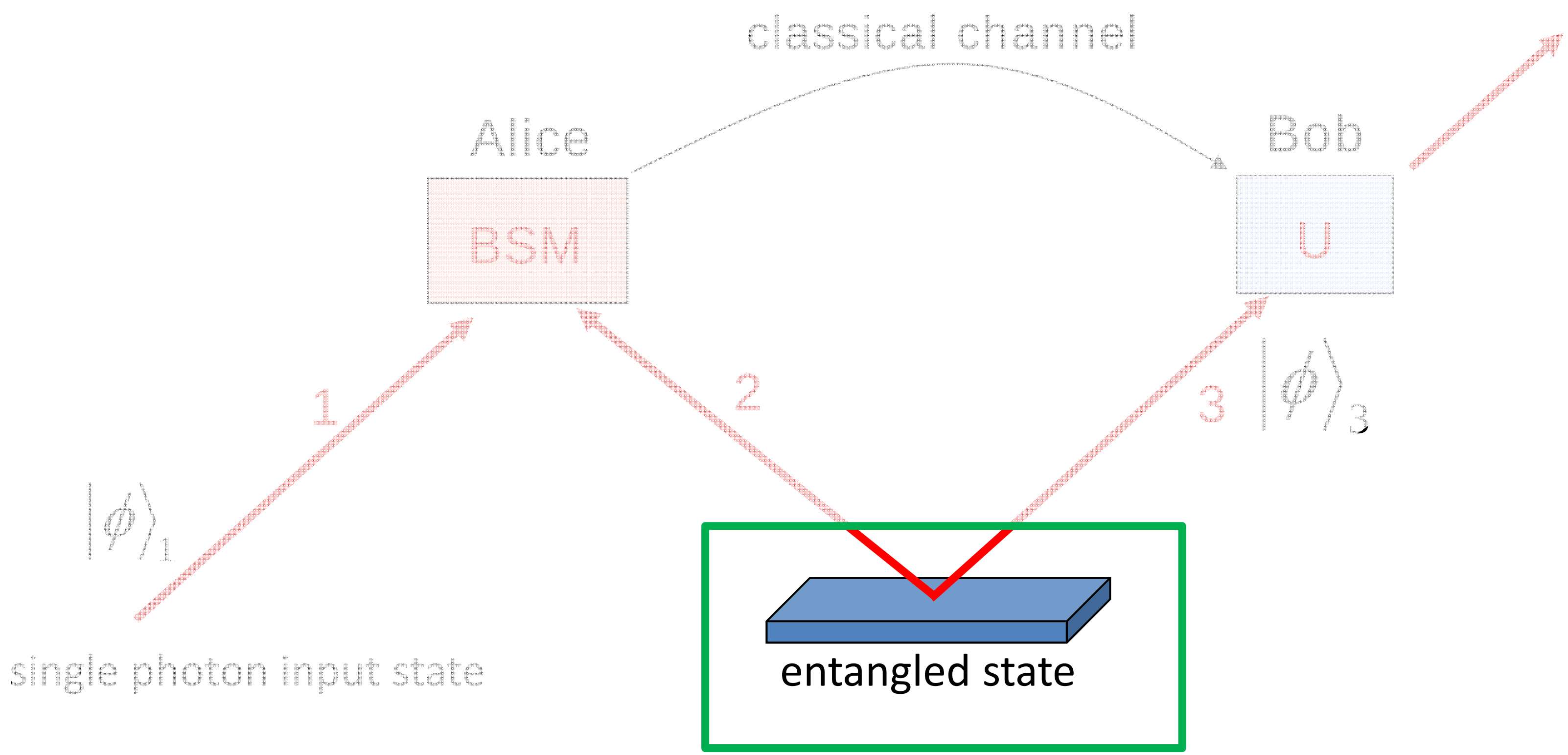
- A. Broadbent, J. Fitzsimons, E. Kashefi, In *Proceedings of the 50th Annual Symposium on Foundations of Computer Science* (IEEE Computer Society, Los Alamitos, CA, 2009), 517–526
- S. Barz et al., Demonstration of Blind Quantum Computing, *Science* **335**(6066), 303–308 (2012)

Teleportation protocol

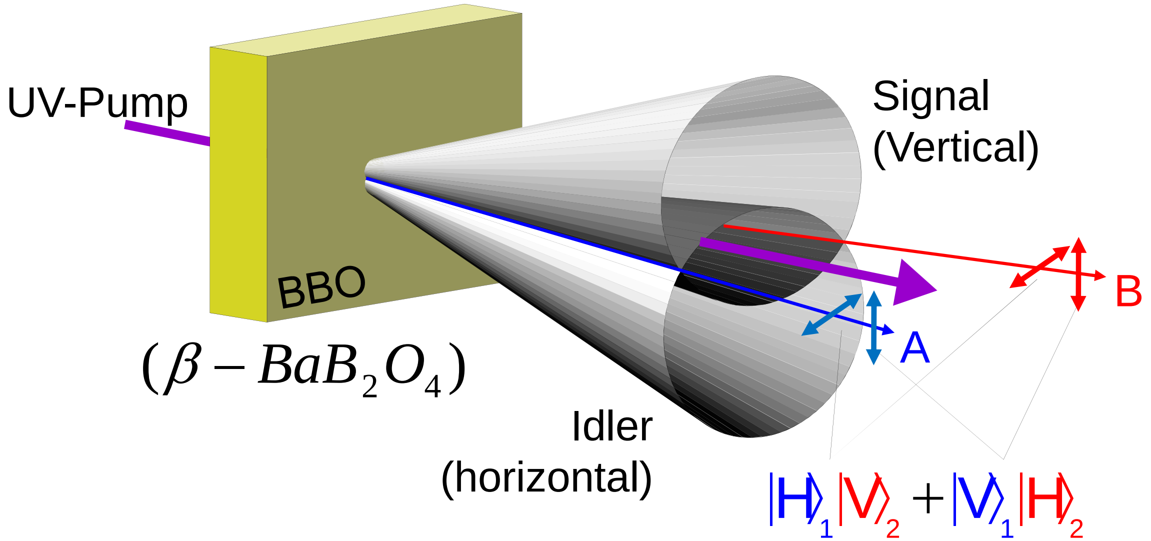
Teleportation scheme

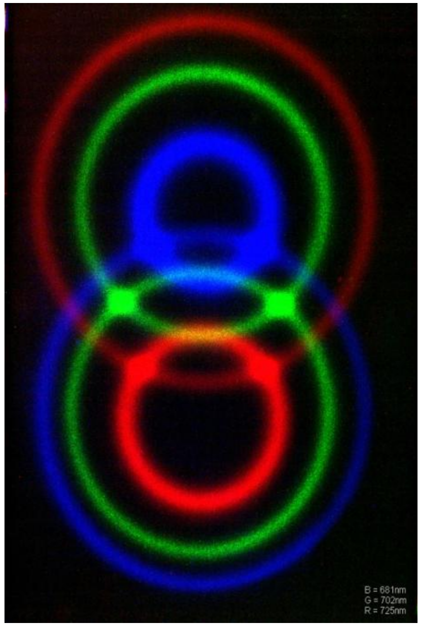


Entangled photon source



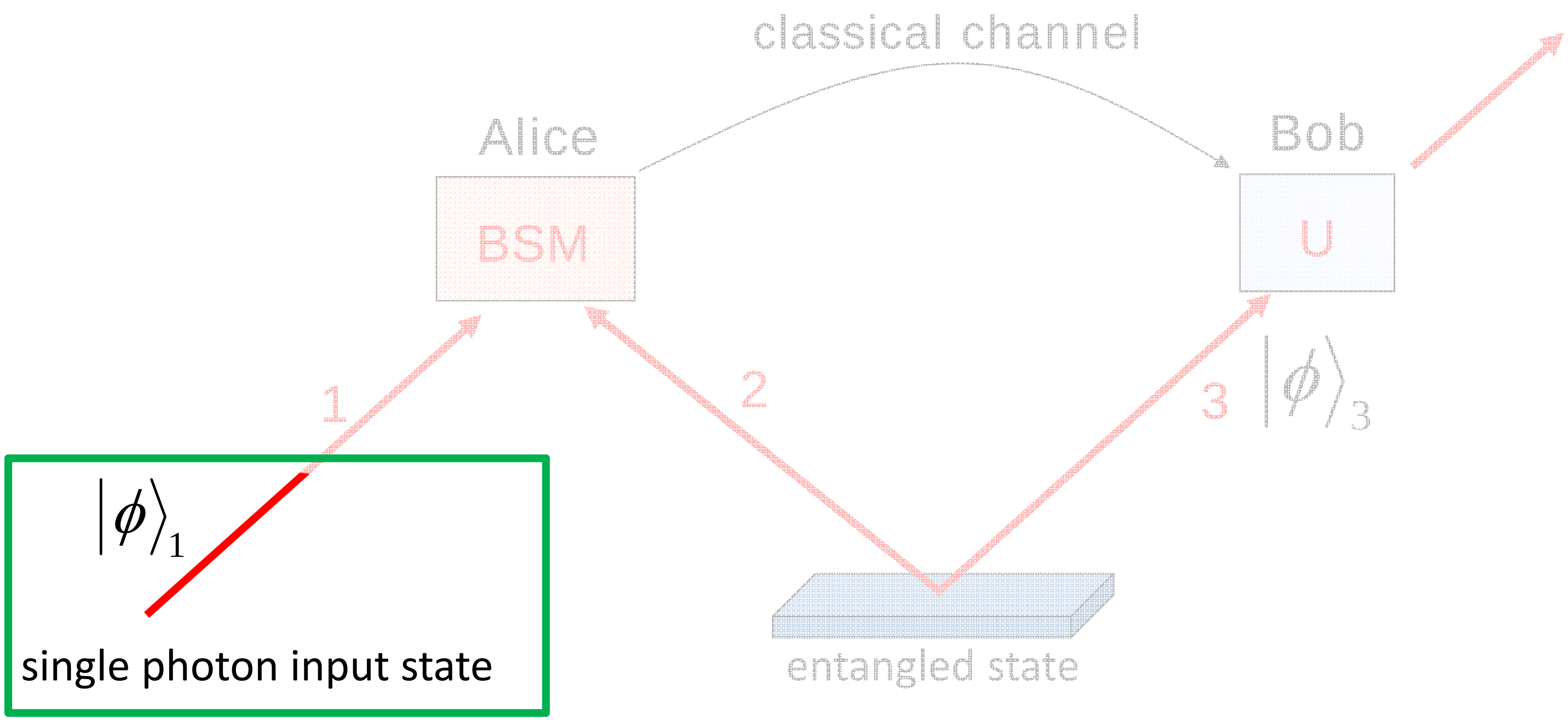
SPDC source



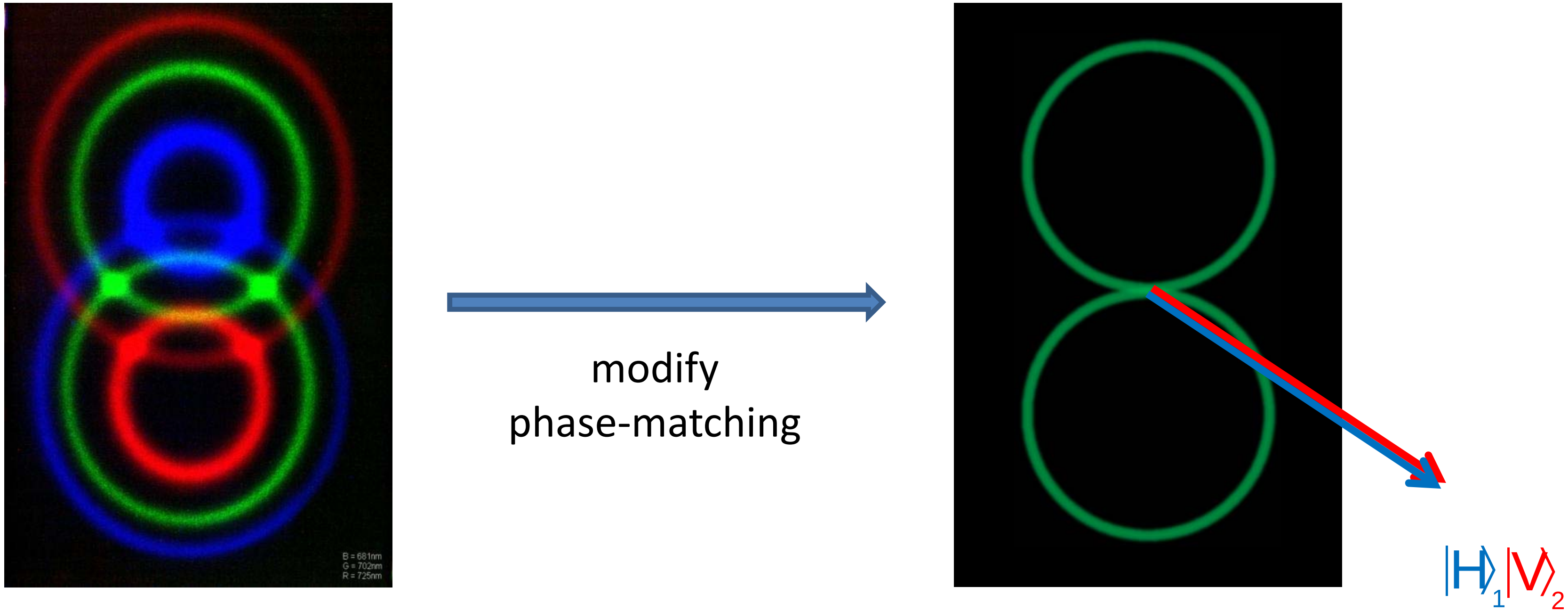


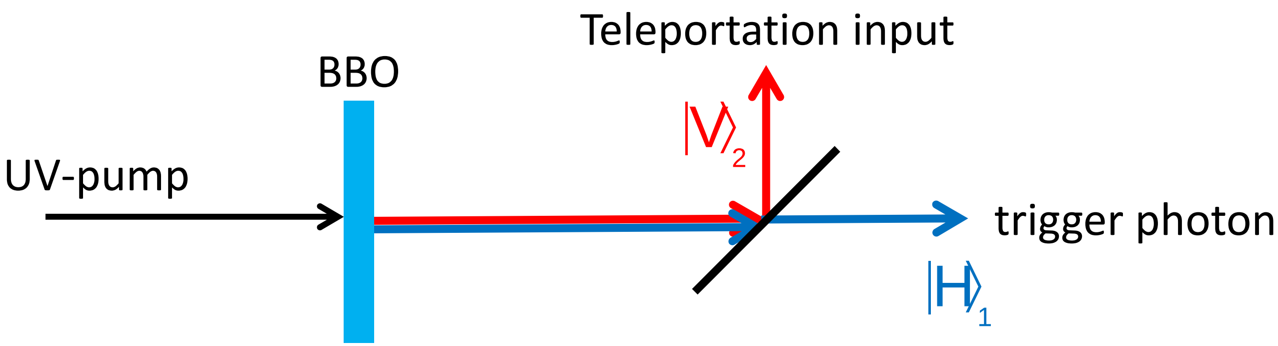
- entanglement is independent from the distance
- quantum mechanics contradicts classical principles
  → **spooky action at a distance (Einstein)**

Heralded single-photon source

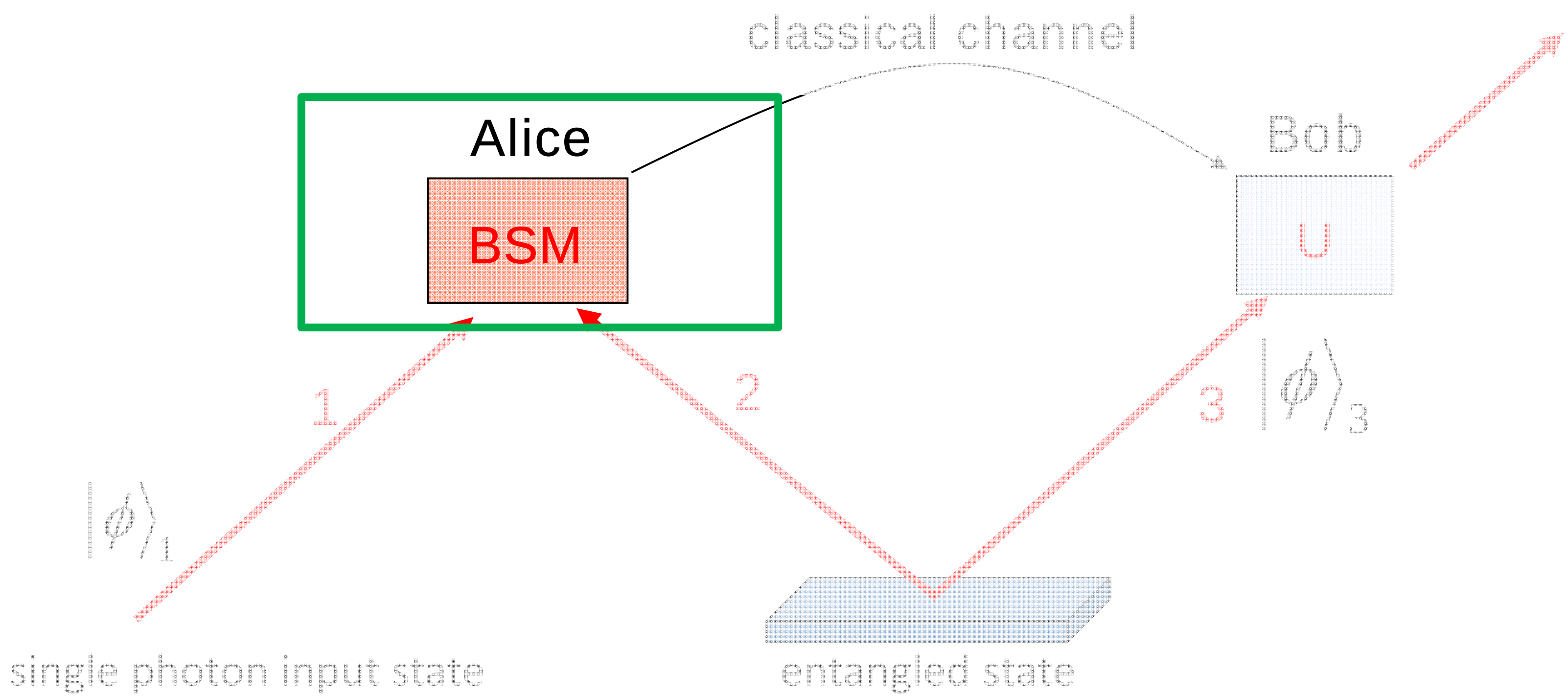


HSP source


modify
phase-matching
$|H\rangle_1|V\rangle_2$


Teleportation input
BBO
$|V\rangle_2$
UV-pump
trigger photon
$|H\rangle_1$

Bell state measurement



Bell state measurement

$$|\phi^{\pm}\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle_1|H\rangle_2 \pm |V\rangle_1|V\rangle_2\right)$$

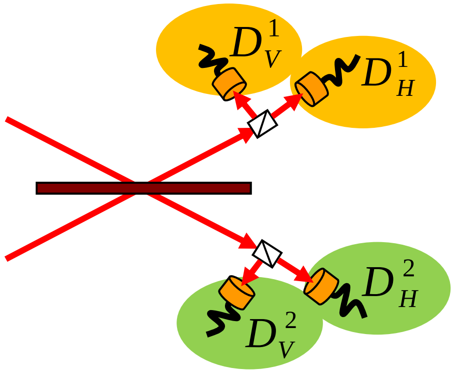
$$|\psi^{\pm}\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle_1|V\rangle_2 \pm |V\rangle_1|H\rangle_2\right)$$

4 Bell states

Interference on a BS and coincidence detection

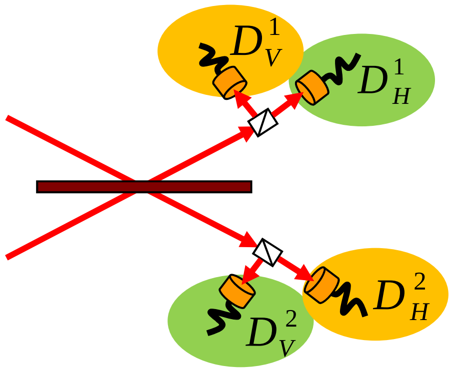
$|\psi^{+}\rangle$

photons take same BS output, but have different polarization



$|\psi^{-}\rangle$

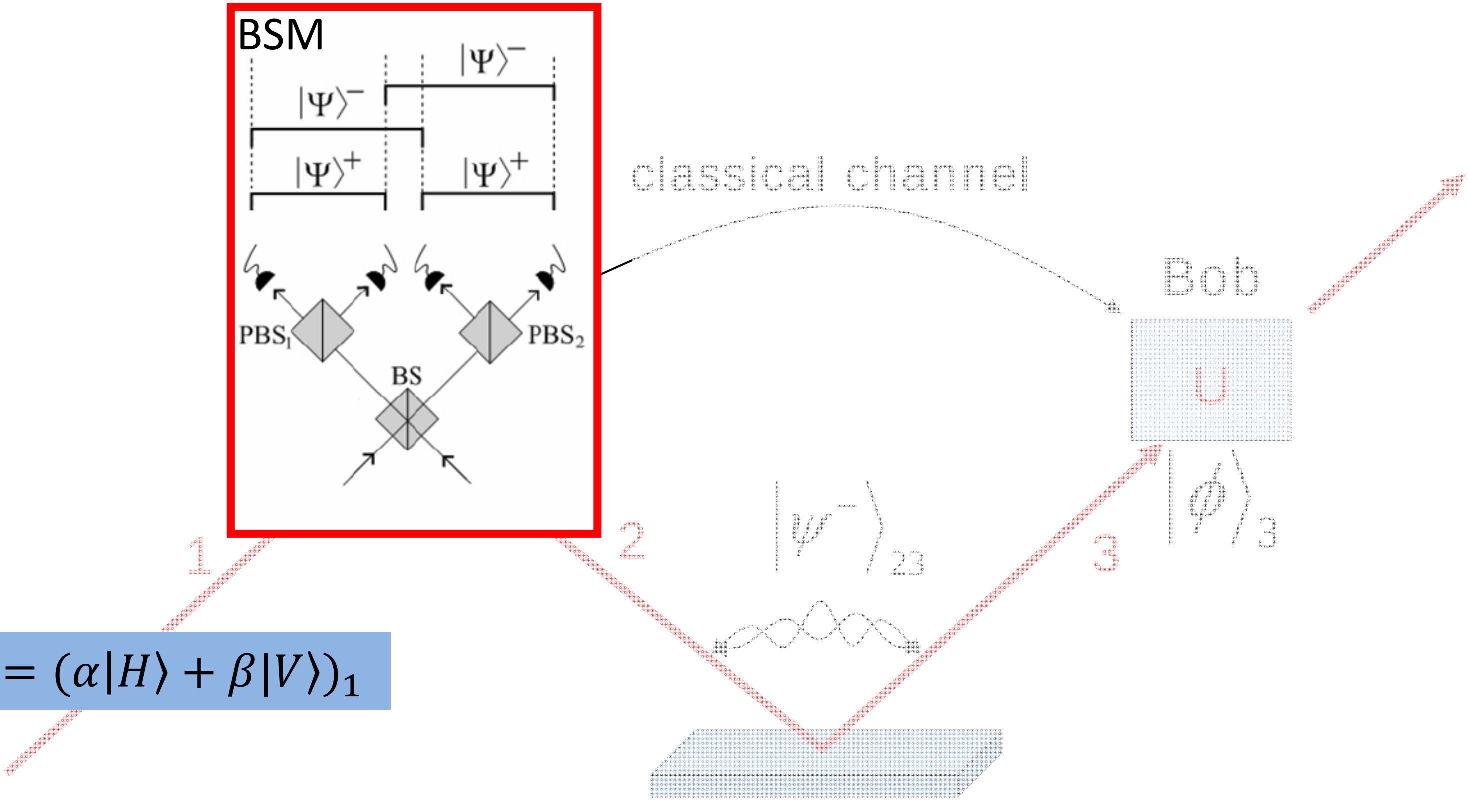
photons take different BS output



$|\phi^{\pm}\rangle$ can not be identified with linear optics, because photons end up in same detector

BSM requires **pulsed photon sources**

Bell state measurement



$|\phi\rangle_1 = (\alpha|H\rangle + \beta|V\rangle)_1$

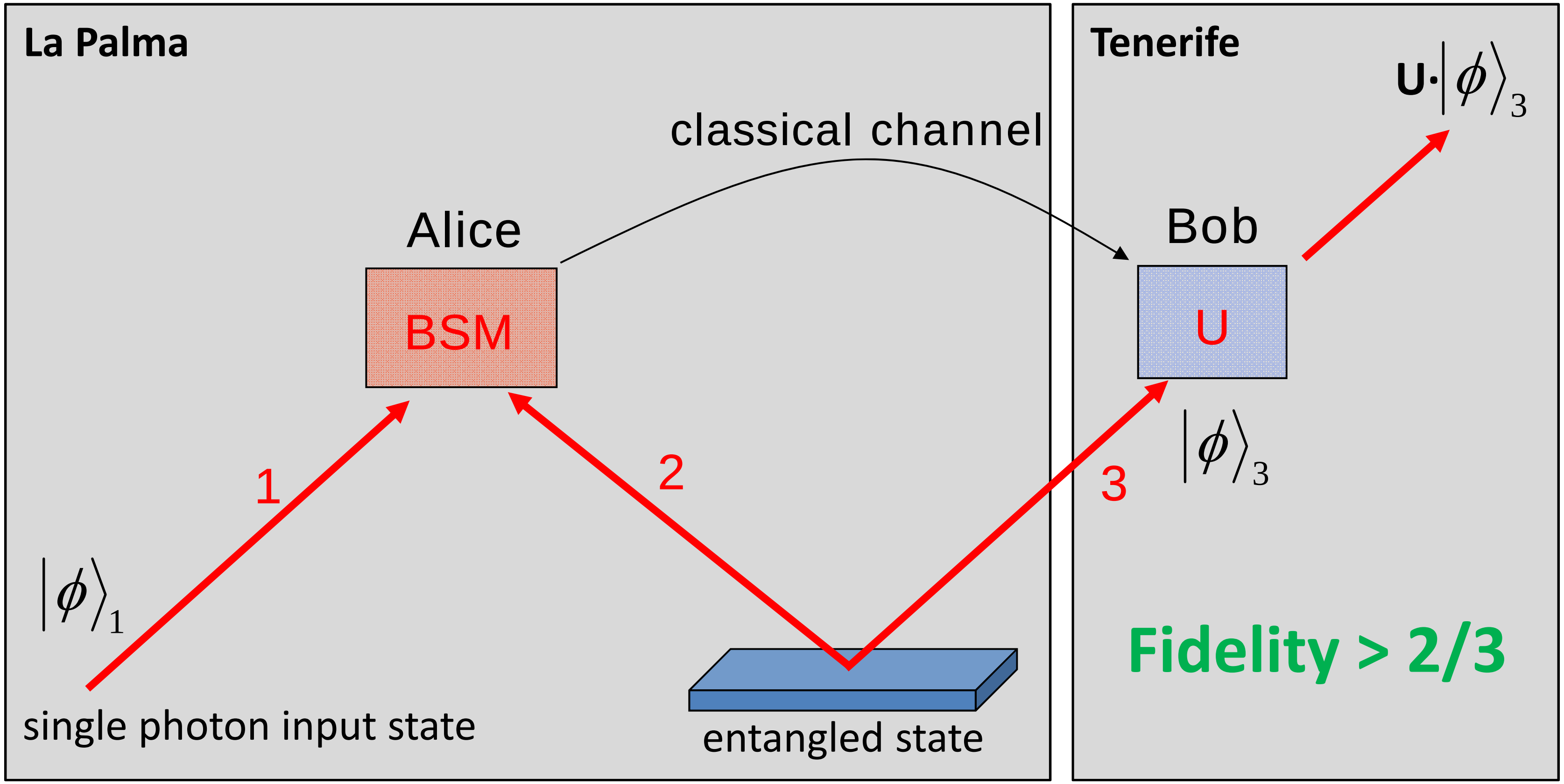
$$|\Psi\rangle_{123} = |\phi\rangle^+{}_{12} \otimes (\alpha|H\rangle + \beta|V\rangle)_3 + |\phi\rangle^-{}_{12} \otimes (\alpha|H\rangle - \beta|V\rangle)_3 +$$

$$+|\psi\rangle^+{}_{12} \otimes (\alpha|H\rangle - \beta|V\rangle)_3 + \quad |\psi\rangle^-{}_{12} \otimes (\alpha|H\rangle + \beta|V\rangle)_3$$

U=„phase-flip“ U=„identity“

QTS project
objectives and requirements

Project objective



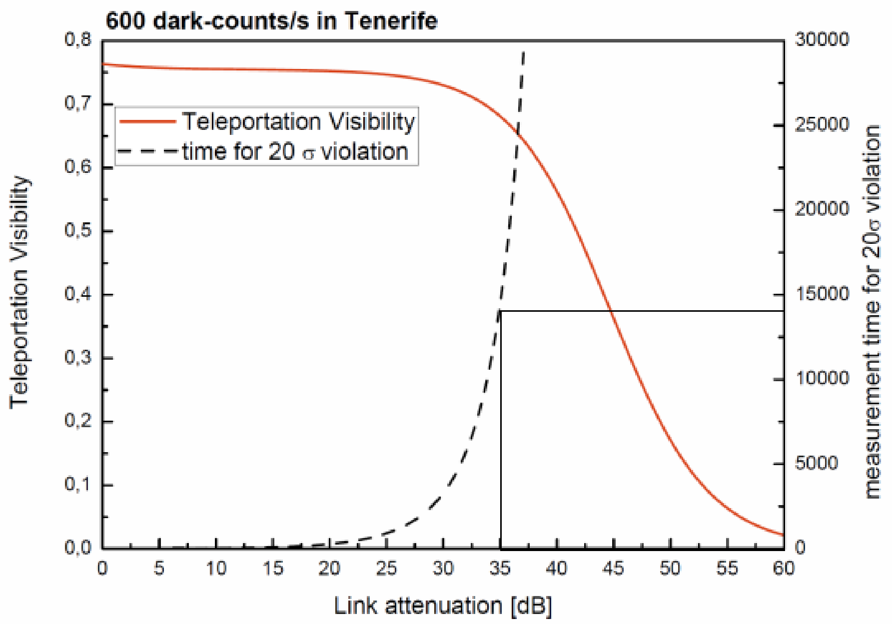
Numerical simulation

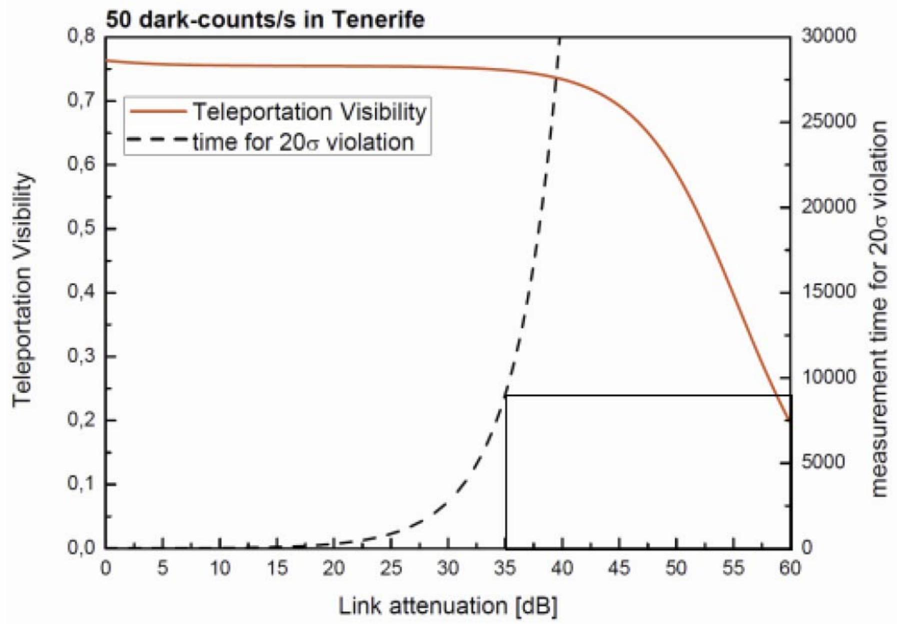
SNR ≈ η/n·τ

η…channel efficiency
n…detector dark counts
τ…coincidence time window

Pre-existing setup in Vienna

Count rate of entangled photon source	Count rate of non-entangled photon source	Expected 4-fold count rate at 30dB attenuation	Entanglement Visibility local	Coinc. time-window
90000 counts/s	110.000 counts/s	0,07 counts/s	91%	1 ns



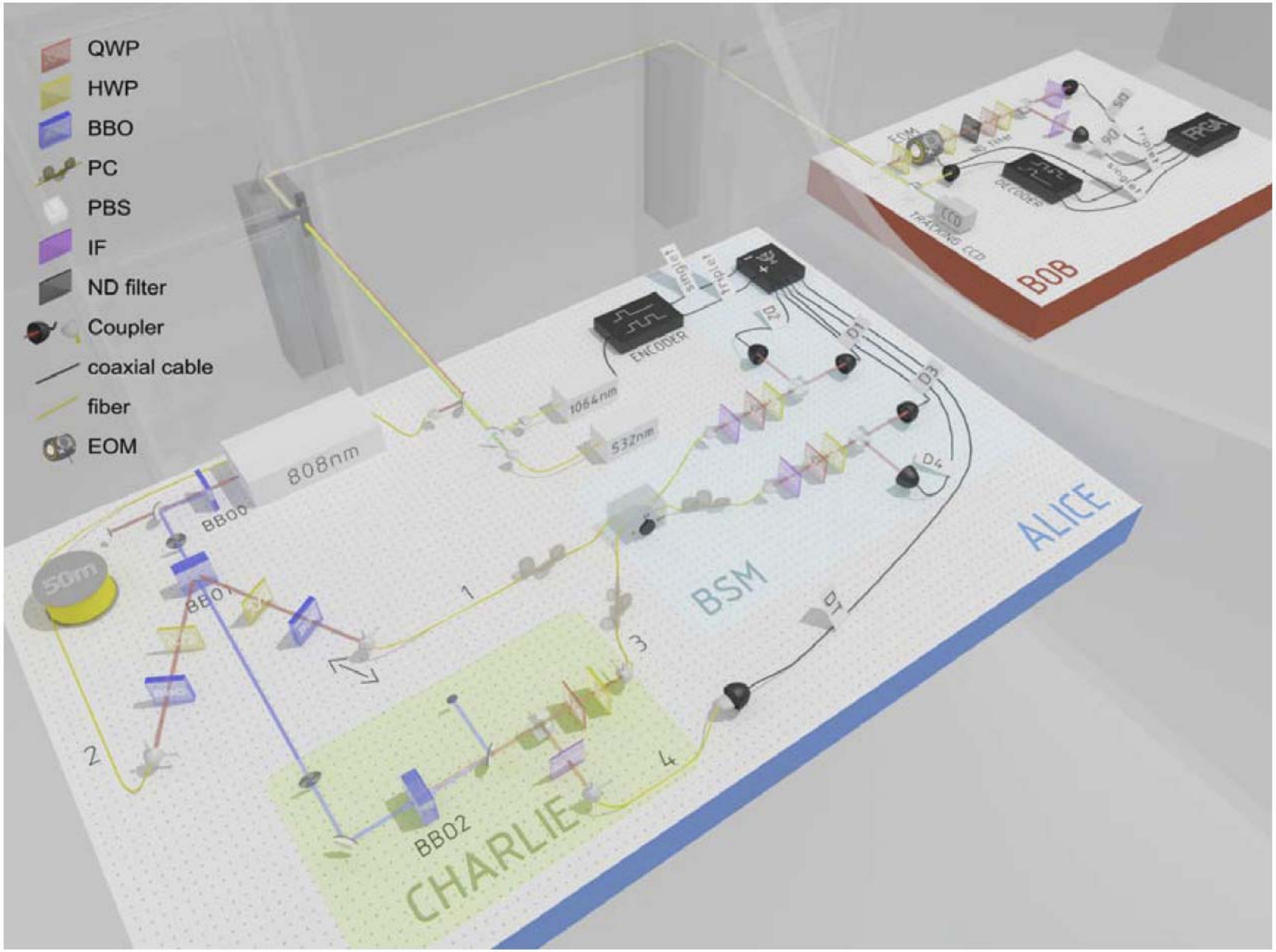


Requirement specification

	Parameter	Requirements
goals	Local 4-fold rate	≥ 70 counts/s
	Setup stability	≥ 6 hrs
	Detector dark counts	≤ 100 counts/s
	Coincidence window	≤ 5 ns
	AO system	≥ 3dB improvement
strict requirement	Teleportation fidelity @ 35dB	≥ 66.6%

Proof-of-concept demonstrator (POCD)

POCD – Setup Illustration

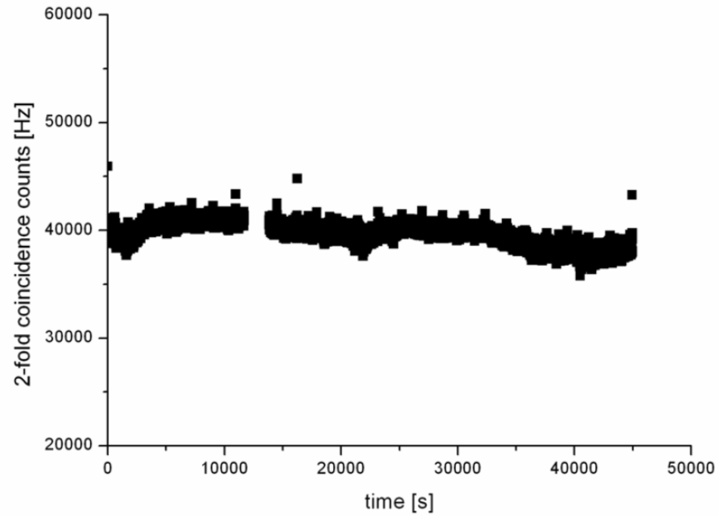


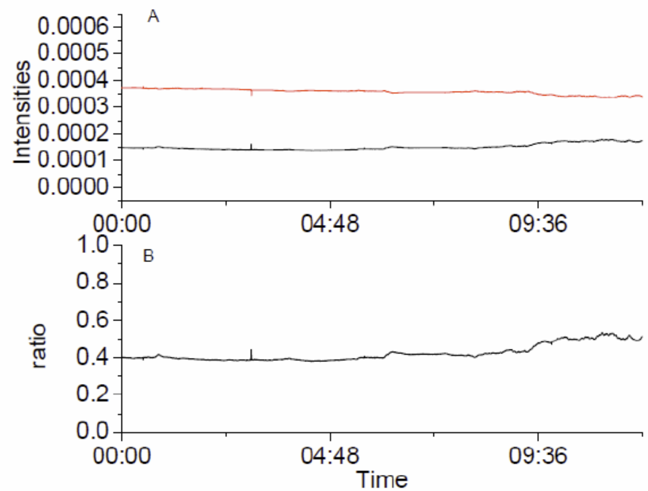
POCD – Teleportation setup

Compact and stable quantum teleportation source

Coherent Chameleon Ultra:

- Ti:Saphire
- 808nm
- 4W average power
- 80 MHz rep. rate
- 140 fs pulse length



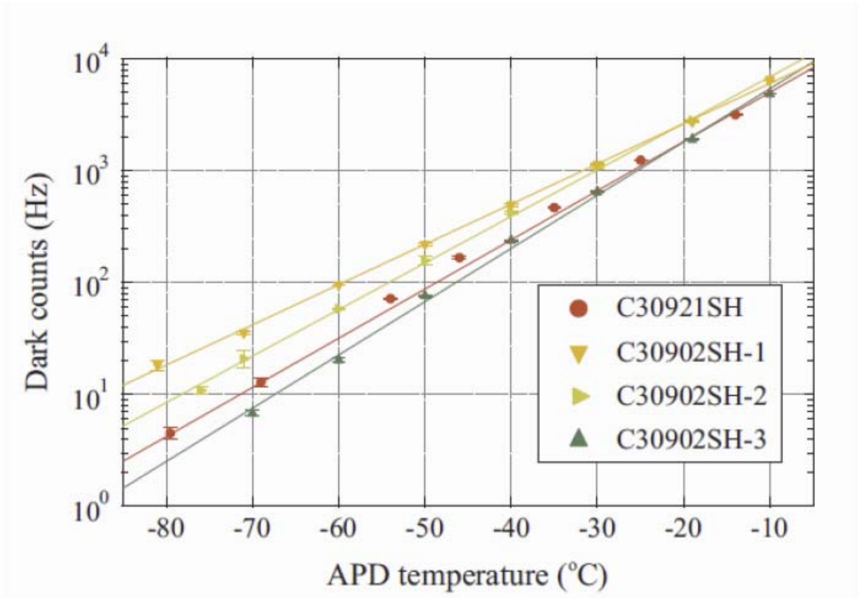


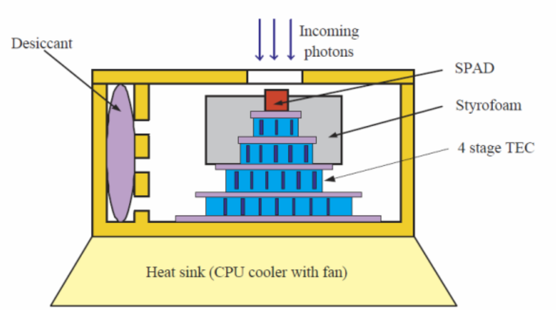
POCD – Detectors

Large sensitive area, ultra-low noise Si-APD

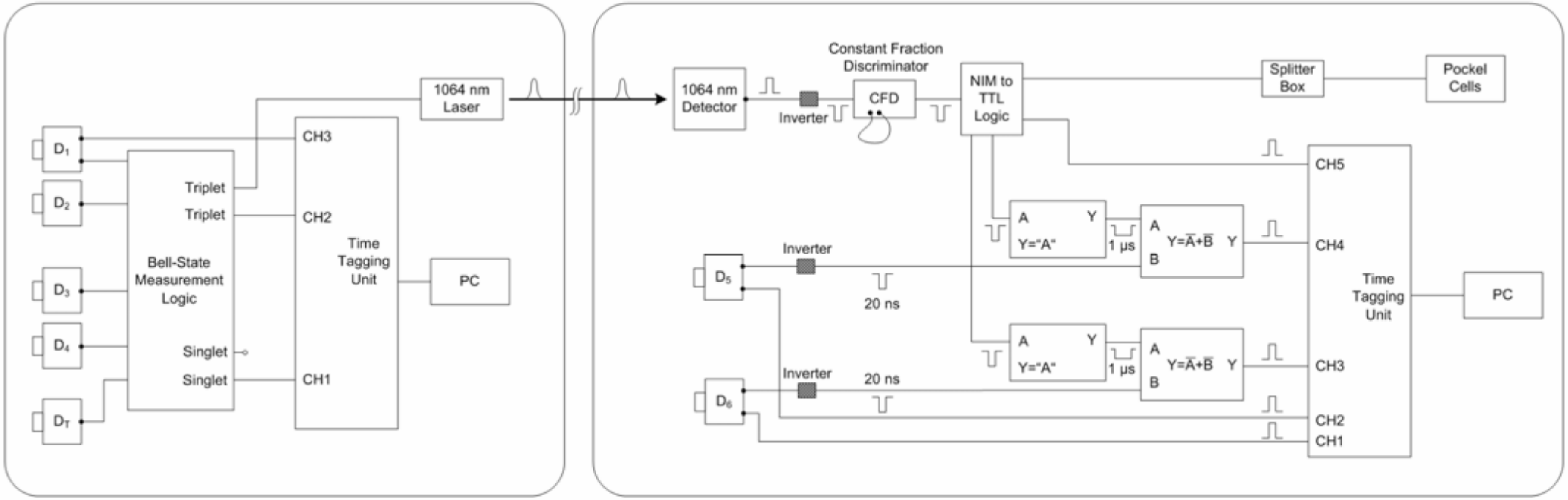
Detection efficiency	Dark count rate	Active area	After-pulsing probability	Saturation count rate
50%	< 20Hz	500µm	0.15%	0.4MHz

Vadim Makarov





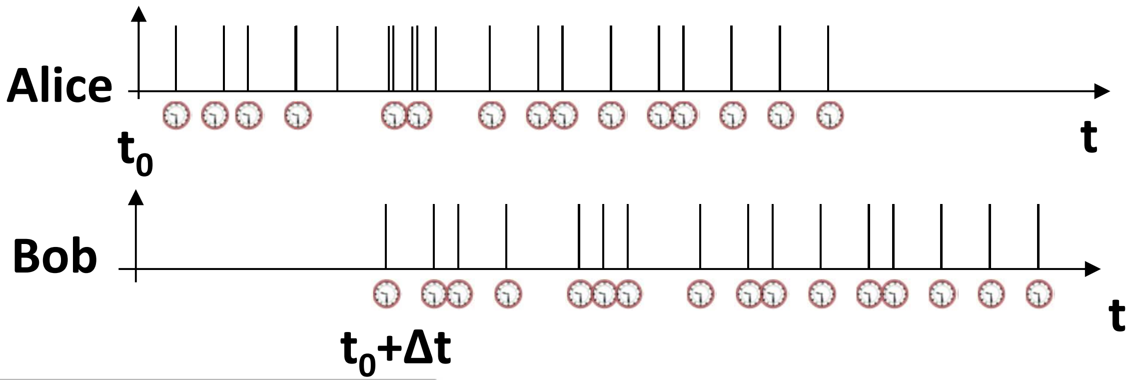
POCD – Electronics Design

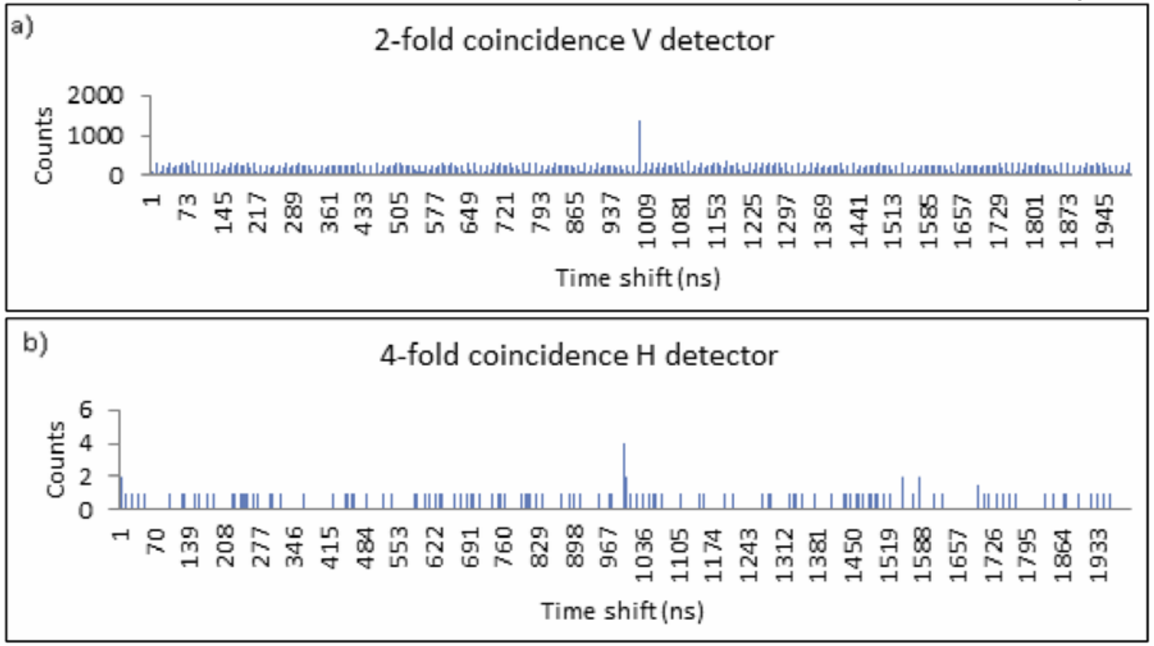


POCD – Clock synchronization

GPS
10MHz disciplined on 1pps

Time tagging unit





Cross-correlation function

Time tagging unit
- 156 ps resolution

GPS synchronization
- 40 ns resolution

Detector
- ≈1 ns jitter

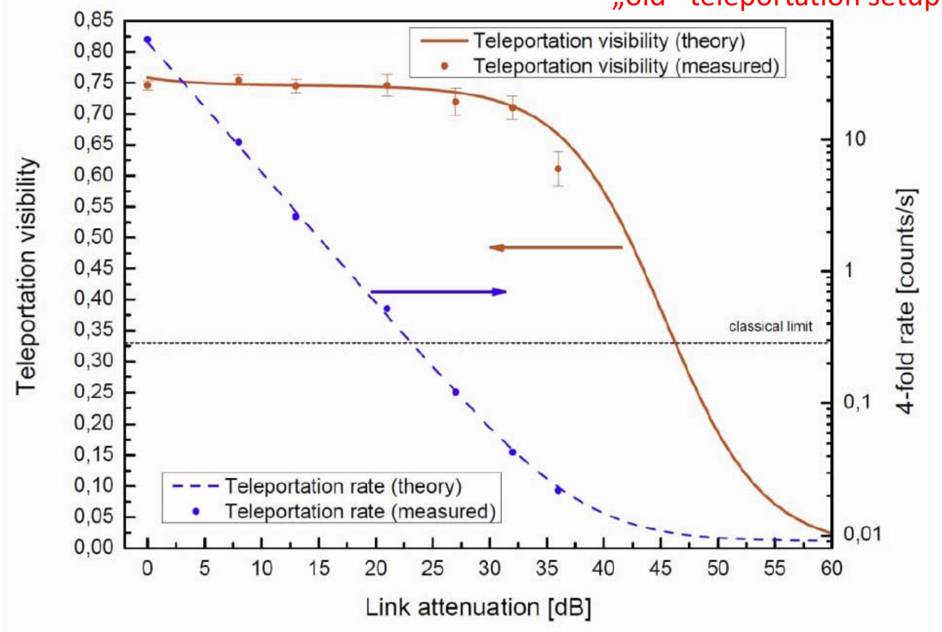
Entanglement assisted clock synchronization
- 2-3 ns coincidence window

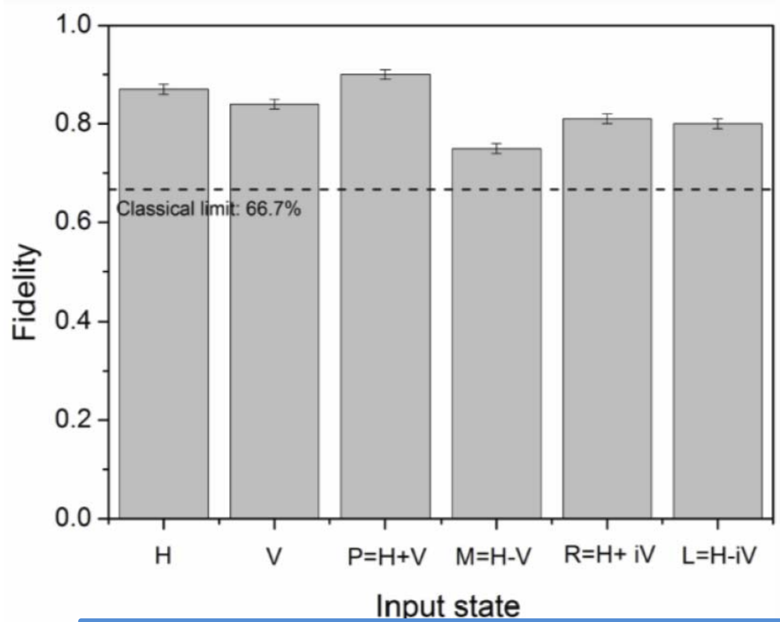
POCD – Results

EPR rate	Fock source rate	4-fold count rate local	4-fold count rate expected at 30dB	Entanglement Visibility local	Teleportation Visibility local
150.000 counts/s	140.000 counts/s	150 counts/s	0,15 counts/s	88%	75%

factor 2 higher than „old"-teleportation setup

@ 31 dB



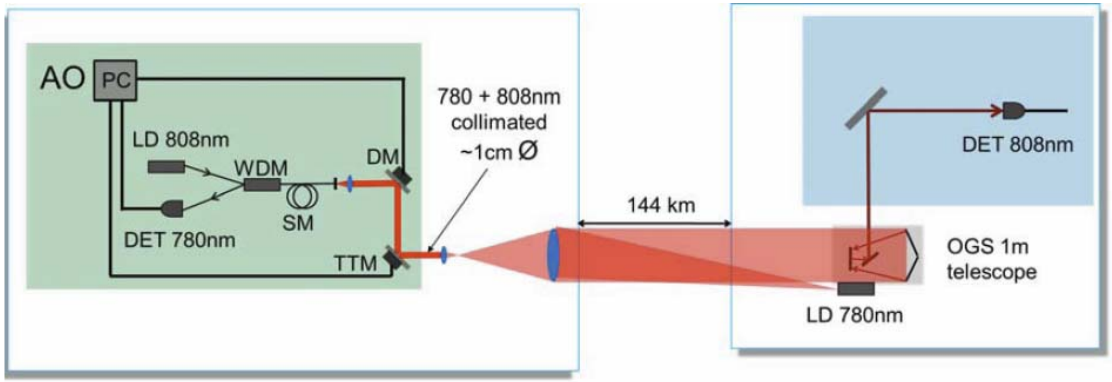


Low dark count detectors not available at this time (600 cps dark counts)

9891 teleportation events in 40 hrs

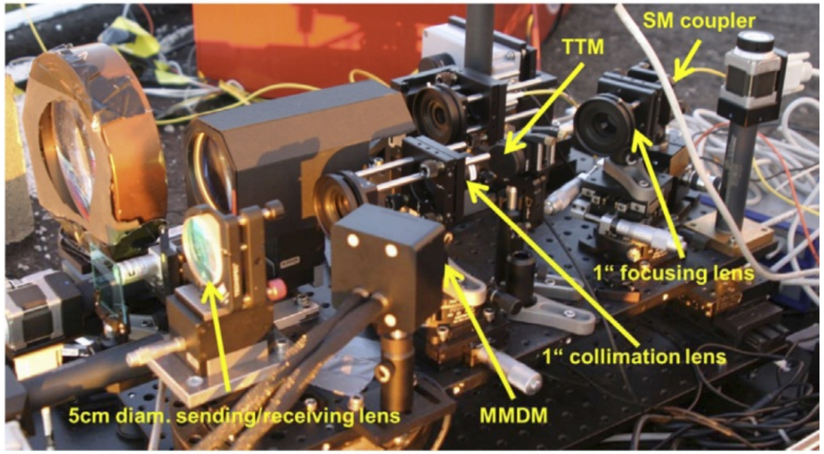
X. S. Ma, *Optics Express* **20**(21), 23126-23137 (2012)

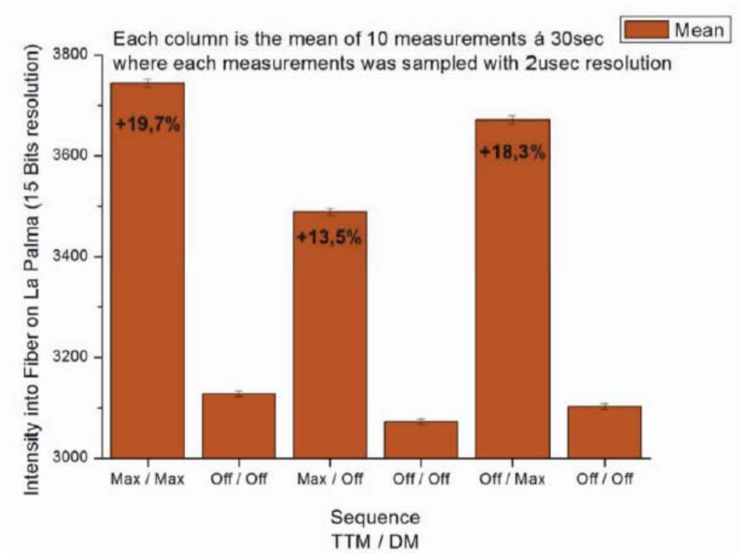
POCD – Adaptive Optics System



Beacon wavelength	Beacon output power
780nm	100mW

update rate deformable mirror	Transmitting aperture
≈ 1-2kHz	5cm

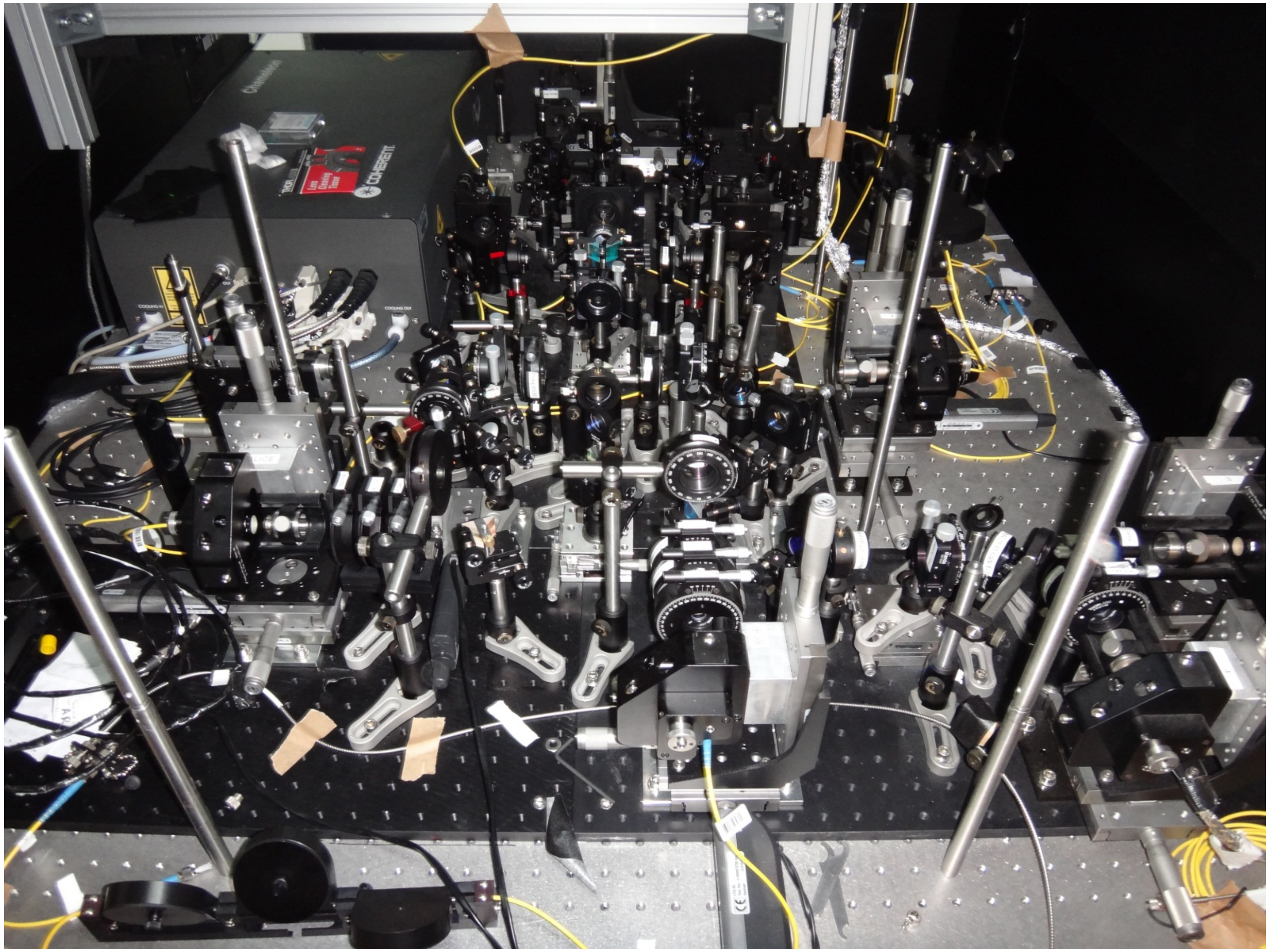




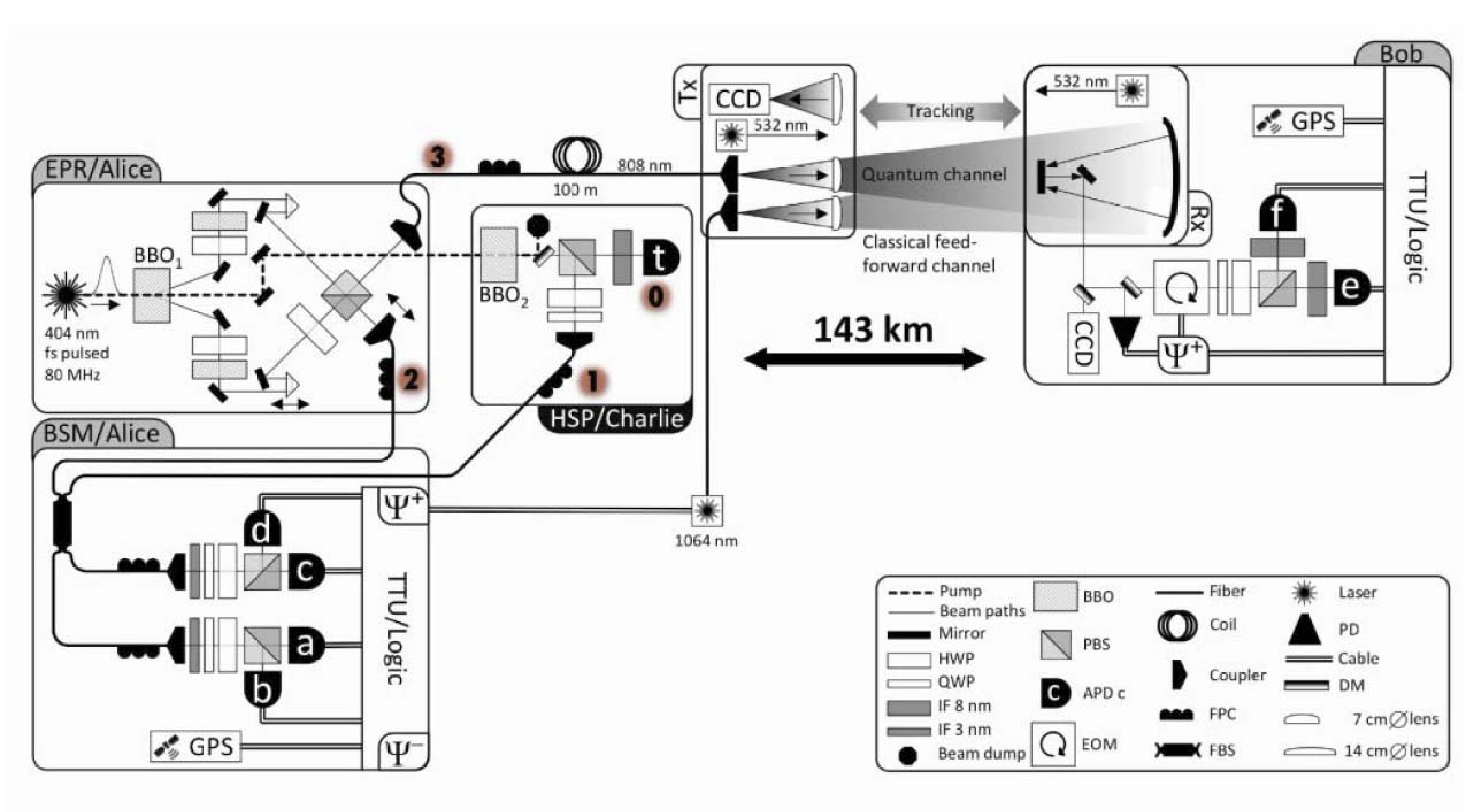
Greenwood frequency:	200 Hz
# of guesses for best setting:	10
→ **Bandwidth required:**	**2 kHz**
→ Bandwidth actual:	0.5 kHz

Inter-island quantum teleportation

Inter-Island QT setup (La Palma)

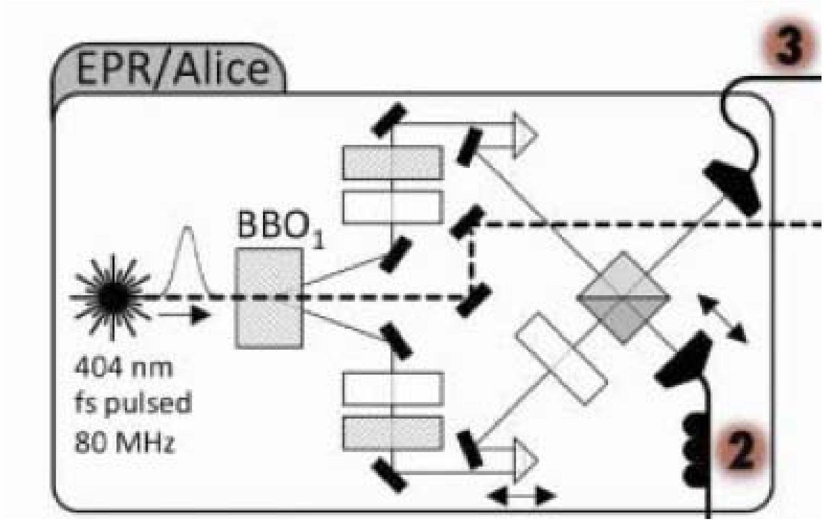


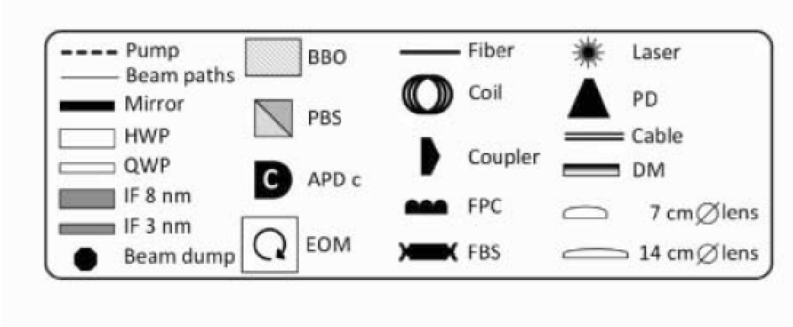
Inter-Island QT setup (La Palma)



Inter-Island QT setup (La Palma)

Spectral compensation scheme



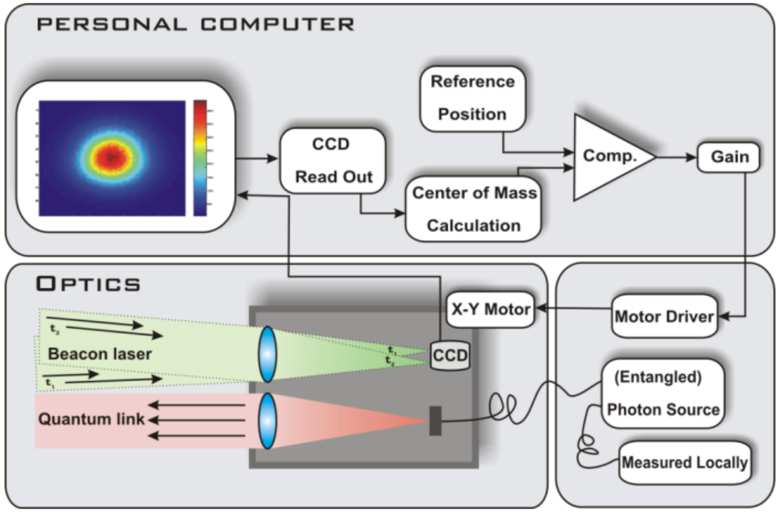


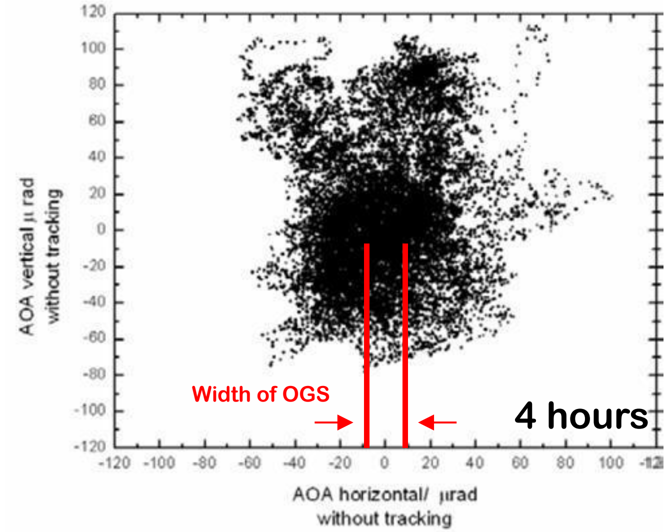
→ **only e-photons interfere at BSM**

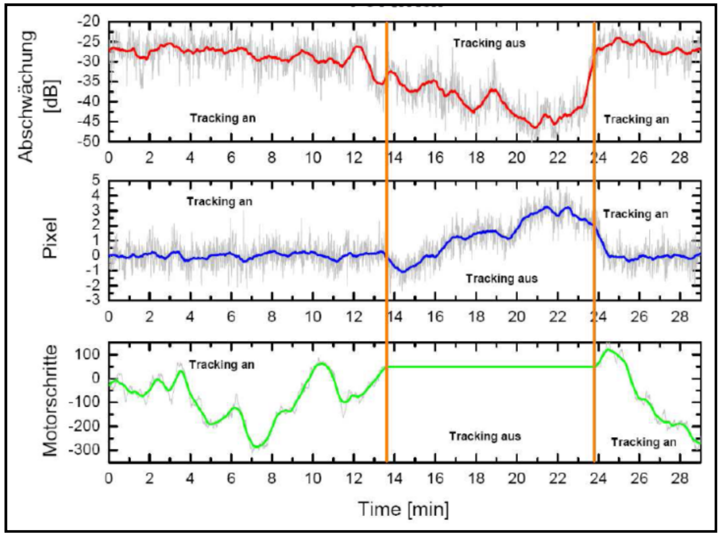
- increased coupling
- higher 4-fold count rate

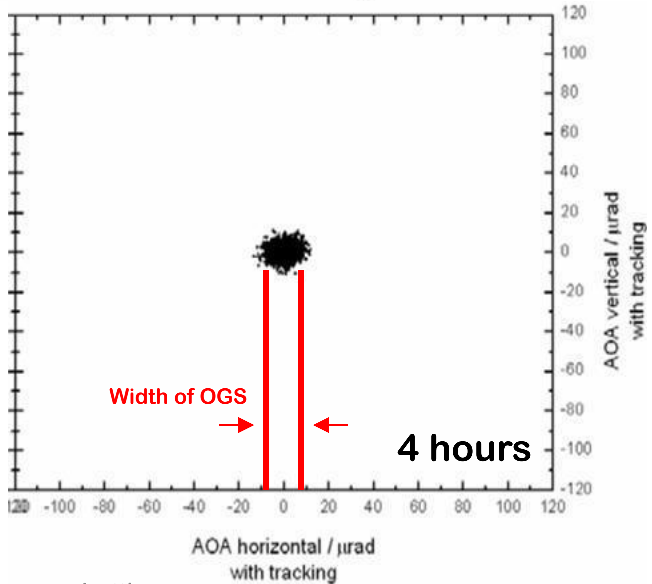
	EPR rate	Fock source rate	4-fold count rate local	4-fold count rate expected at 30dB	Entanglement Visibility local	Teleportation Fidelity local
"old" scheme	150.000 counts/s	140.000 counts/s	150 counts/s	0,15 counts/s	88%	87%
new scheme	**180.000 counts/s**	**140.000 counts/s**	**180 counts/s**	**0,18 counts/s**	**88%**	**89%**

Transmitter telescope (La Palma)

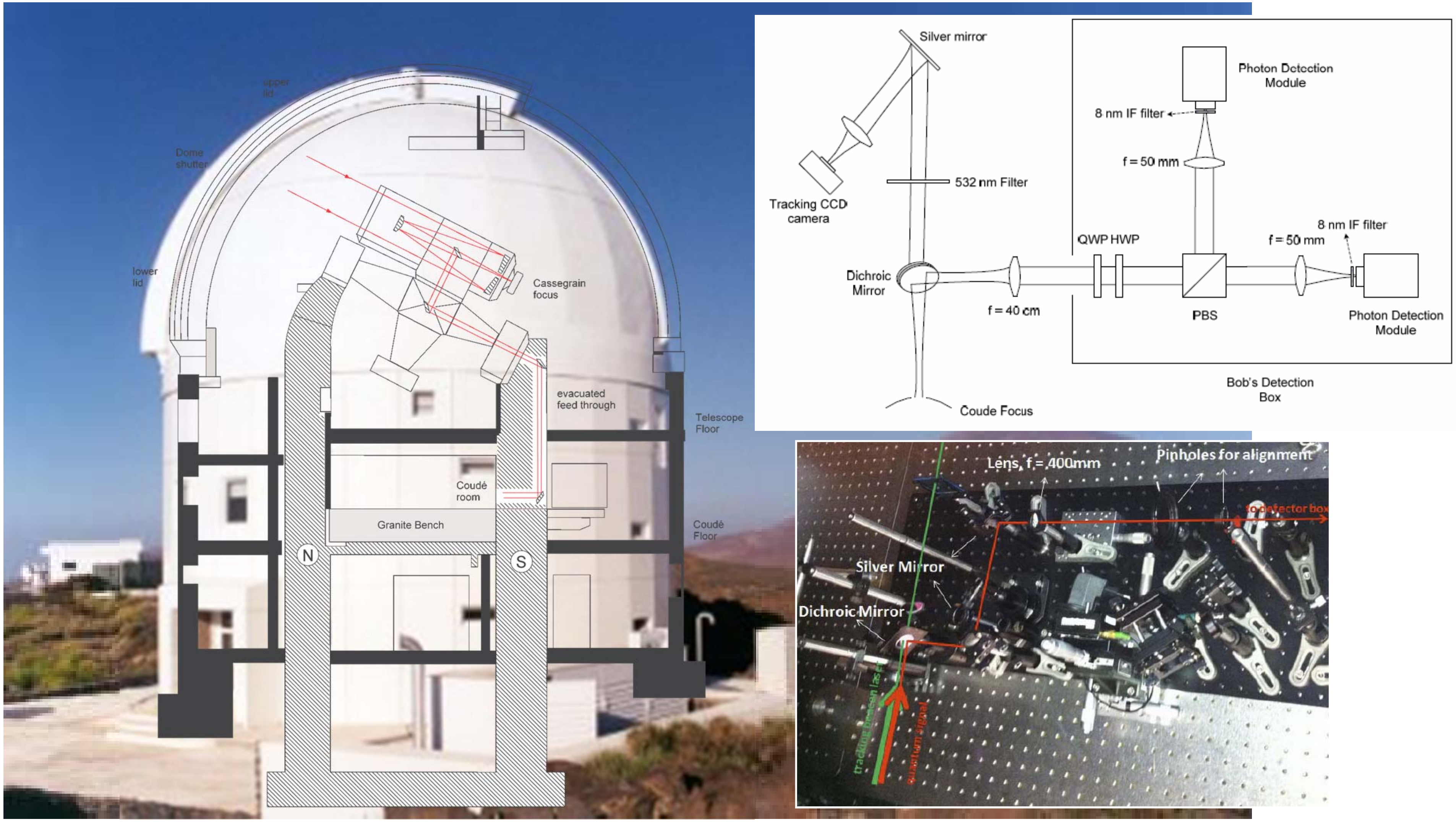






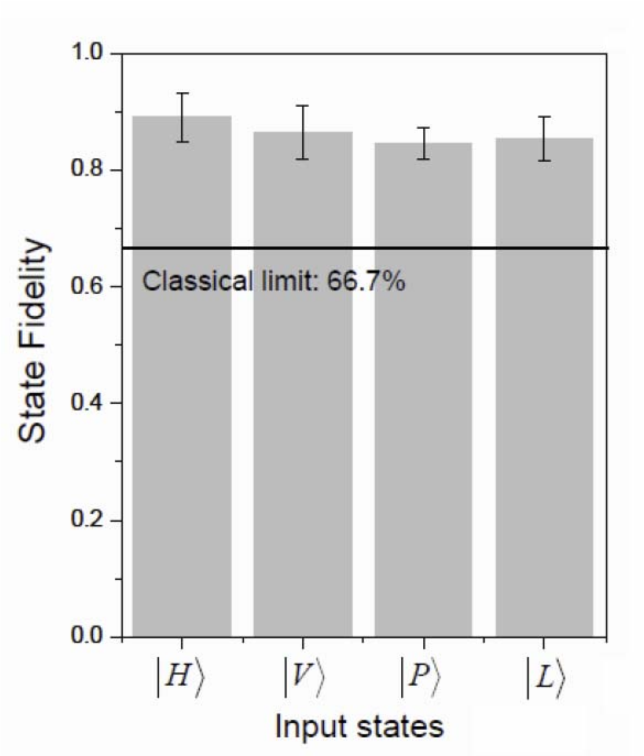


Receiver telescope and pol. analyzer (Tenerife)



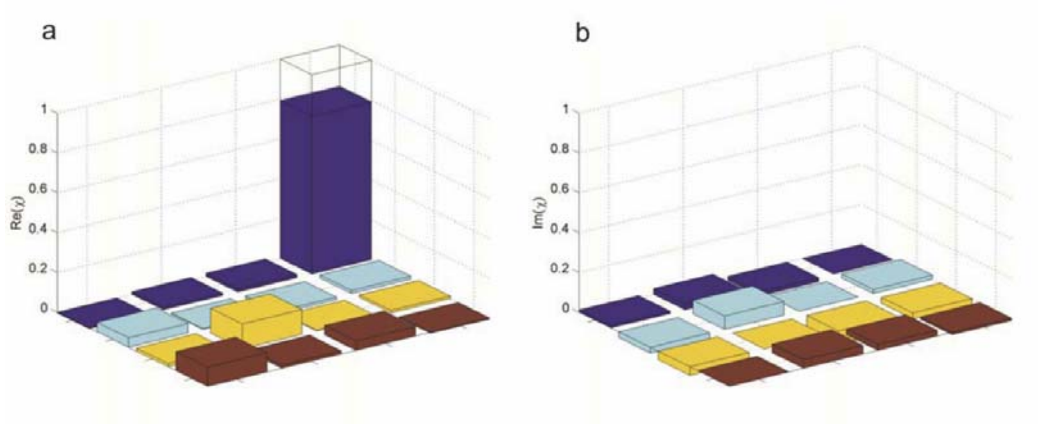
Results

State Fidelities



f_{av}=0.863±0.038
(classical limit < 2/3)

Process tomography



$f_{process}$=0.710±0.042
(classical limit < 1/2)

Average linkattenuation: 36 dB
→ 605 teleportation events in 6.5 hrs

X. Ma et al, *Nature* **489**, 269-273 (2012)

Compliance matrix

	Parameter	Requirements	Results	Compliance
goals	**Local 4-fold rate**	≥ 70 counts/s	180 counts/s	+
	Setup stability	≥ 6 hrs	≥ 6 hrs	+
	Detector dark counts	≤ 100 counts/s	≈ 100 counts/s	+
	Coincidence window	≤ 5 ns	3 ns	+
	AO system	≥ 3dB improvement	0.8 dB	-
strict require-ment	**Teleportation fidelity @ 35dB**	≥ 66.6%	86.3±3.8%	+

Development roadmap

Roadmap for space implementation

Description	pulsed laser source
Development objectives	• increase repetition rate • reduce space-, mass- and power consumption • synchronization of two laser systems separated over long distances • Test radiation hardness
Estimated time required	> 5 years
ROM cost estimates	5Mio to achieve TRL4

Roadmap for space implementation

Description	SPDC sources
Development objectives	• Mounting, vacuum compatibility, radiation testing of SPDC crystals. • Assessment of periodically poled crystals for quantum teleportation applications • Assessment of new schemes for generating pulsed entangled photon pairs
Estimated time required	> 2 years
ROM cost estimates	3 Mio to achieve TRL4

Roadmap for space implementation

Description	Geiger mode avalanche photodiodes (APDs)
Development objectives	• increase detection efficiency • reduce intrinsic dark count probability, timing jitter (≈100 ps desirable) • Radiation hardness, lifetime and reliability testing • Long-term: Assessment of superconducting TES (transition-edge-sensor) detectors for being used in a space environment
Estimated time required	2 years
ROM cost estimates	3 Mio to achieve TRL4

Thank you for your attention

Inter-Island QT setup (La Palma)