Broadcast-based nonlocality activation for noisy states

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Griffith UNIVERSITY Centre for Quantum Dynamics

CENTRE FOR QUANTUM COMPUTATION & COMMUNICATION TECHNOLOGY
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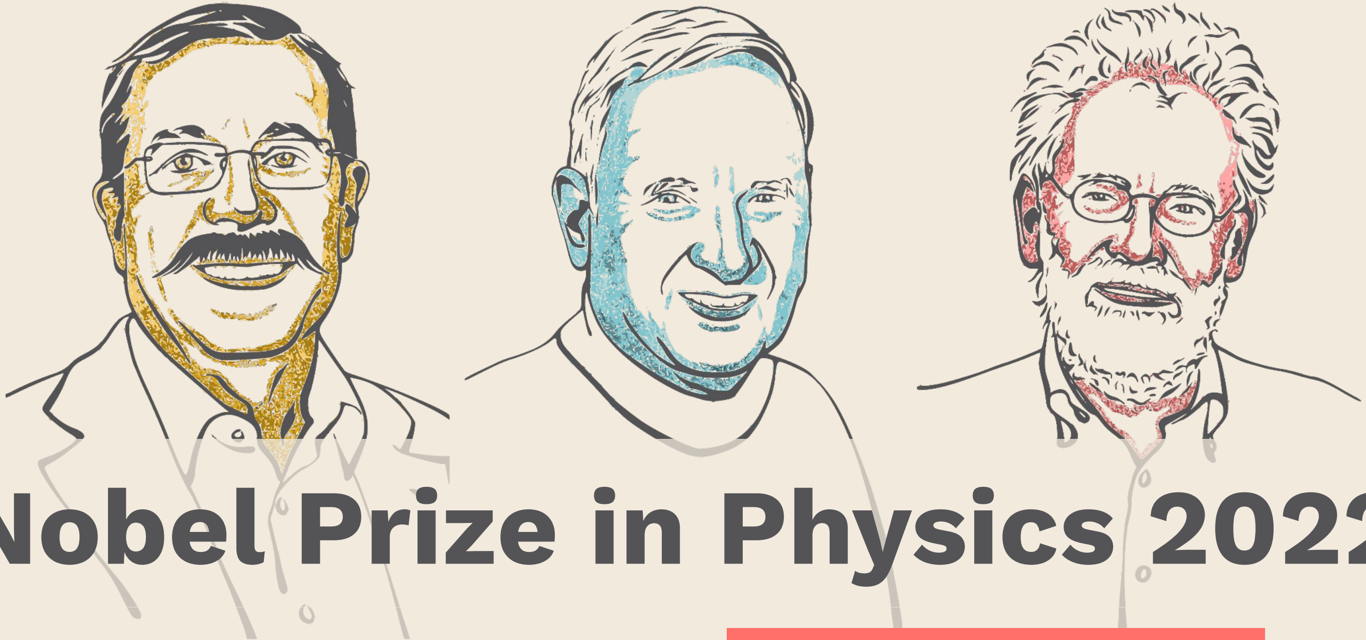


Nobel Prize in Physics 2022

"for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"

Nonlocality

is a key resource for quantum information processing protocols, like

Quantum key distribution [1]

Randomness generation [2]

[1] A. Acín et al. “Device-Independent Security of Quantum Cryptography against Collective Attacks”, Phys. Rev. Lett. 98 (2007)
[2] D. Joch et al. “Certified Random Number Generation from Quantum Steering”, Phys. Rev. A 106 (2022)

One problem:

Noise degrades the nonlocal behaviour of quantum states.

Quantum networks provide a novel context to study nonlocality.

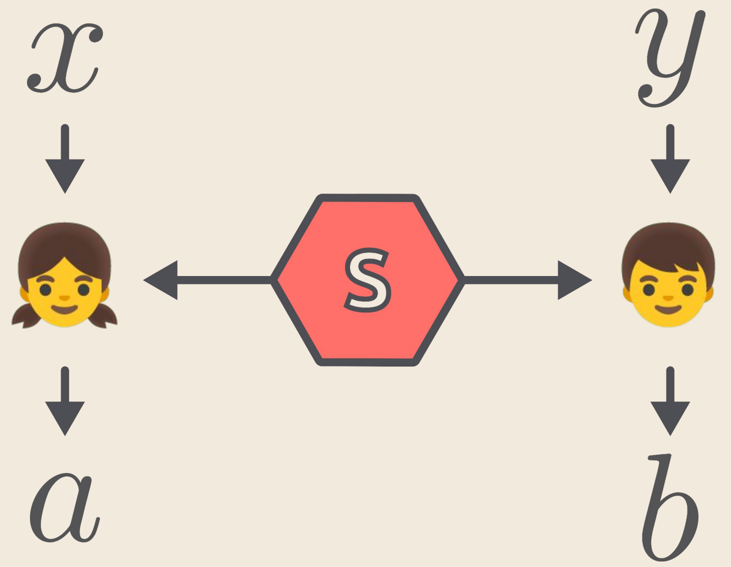
Quantum networks provide a novel context to study nonlocality.

Can we use them to build noise-tolerant nonlocality tests?

Bell tests

The CHSH inequality [3]

$$S = \langle a_0 b_0 \rangle + \langle a_0 b_1 \rangle + \langle a_1 b_0 \rangle - \langle a_1 b_1 \rangle \leq 2$$



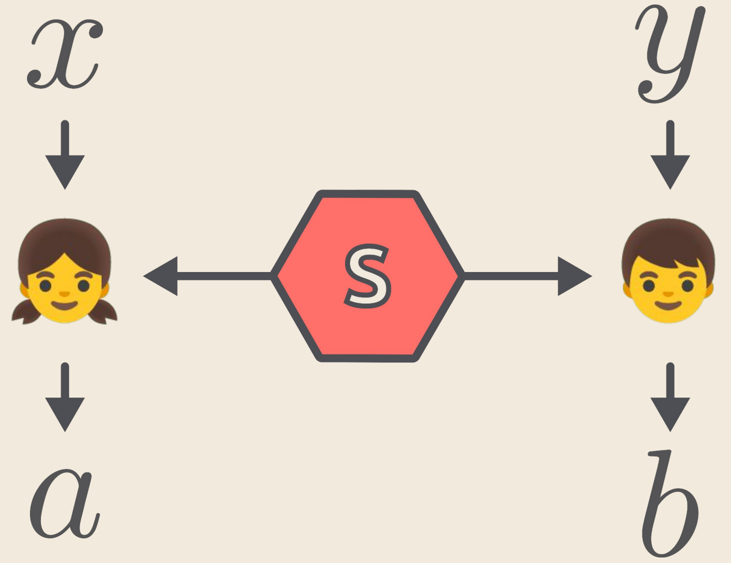
Bell local

[3] John Clauser, Michael Horne, Abner Shimony, and Richard Holt. "Proposed Experiment to Test Local Hidden Variable Theories", Phys. Rev. Lett. 23 (1969)

Bell tests

The CHSH inequality [3]

$$S = 2\sqrt{2} > 2$$



$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

[3] John Clauser, Michael Horne, Abner Shimony, and Richard Holt. “Proposed Experiment to Test Local Hidden Variable Theories”, Phys. Rev. Lett. 23 (1969)

“

What is the relationship between nonlocality and entanglement?

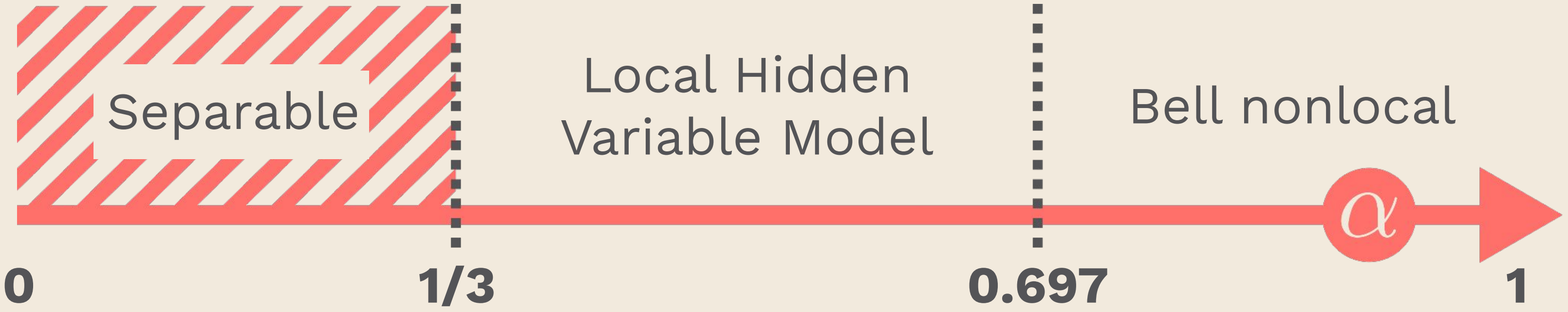
$$\text{Nonlocality} \quad \begin{matrix} \Rightarrow \\ \overset{?}{\Leftarrow} \end{matrix} \quad \text{Entanglement}$$

The Werner State

Maximally **entangled**

$$\rho_\alpha = \alpha|\Phi^+\rangle\langle\Phi^+| + (1-\alpha)\frac{I}{4}$$

White **noise**



[4] Reinhard F. Werner. “Quantum States with Einstein-Podolsky-Rosen Correlations Admitting a Hidden-Variable Model”, Phys. Rev. A 40.8 (1989)

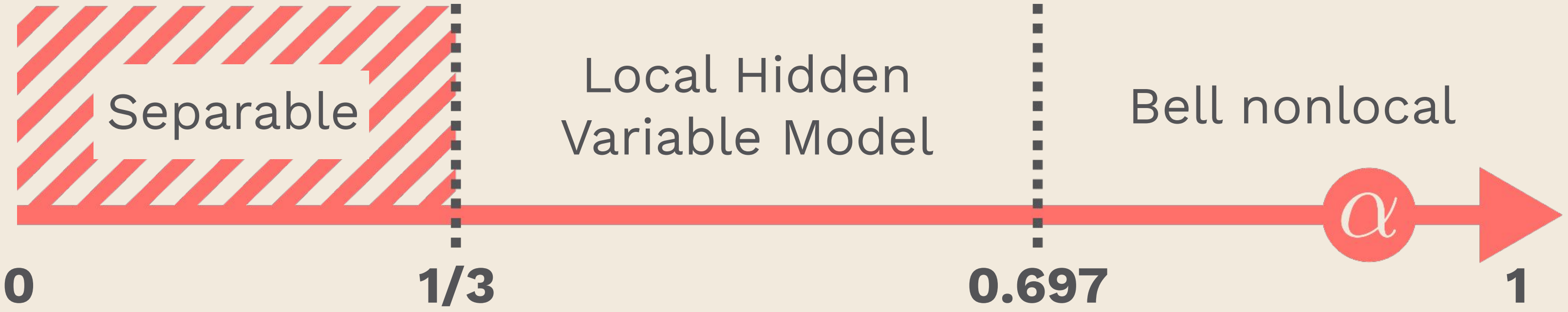
The Werner state

Maximally **entangled**

$+ (1-\alpha)\frac{I}{4}$

e **noise**

Is it possible to <u>lower</u> this bound using **quantum networks**?



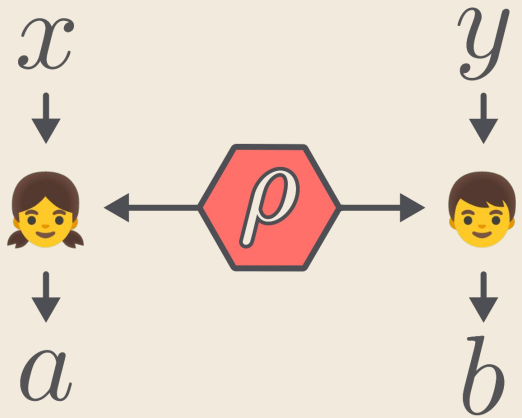
[4] Reinhard F. Werner. “Quantum States with Einstein-Podolsky-Rosen Correlations Admitting a Hidden-Variable Model”, Phys. Rev. A 40.8 (1989)

Nonlocality activation

… where complex measurement scenarios can reveal the nonlocality of some Bell-local states.

Broadcast scenario

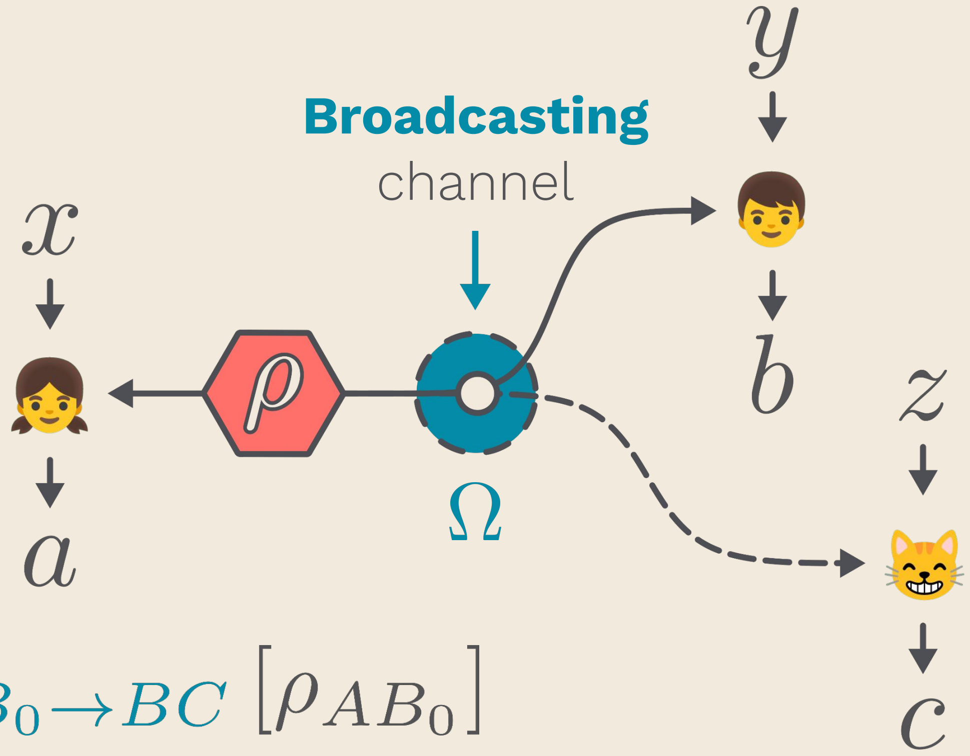
Bowles et. al.



[5] Joseph Bowles, Flavien Hirsch, and Daniel Cavalcanti. "Single-Copy Activation of Bell Nonlocality via Broadcasting of Quantum States", Quantum 5 (2021)

Broadcast scenario

Bowles et. al.

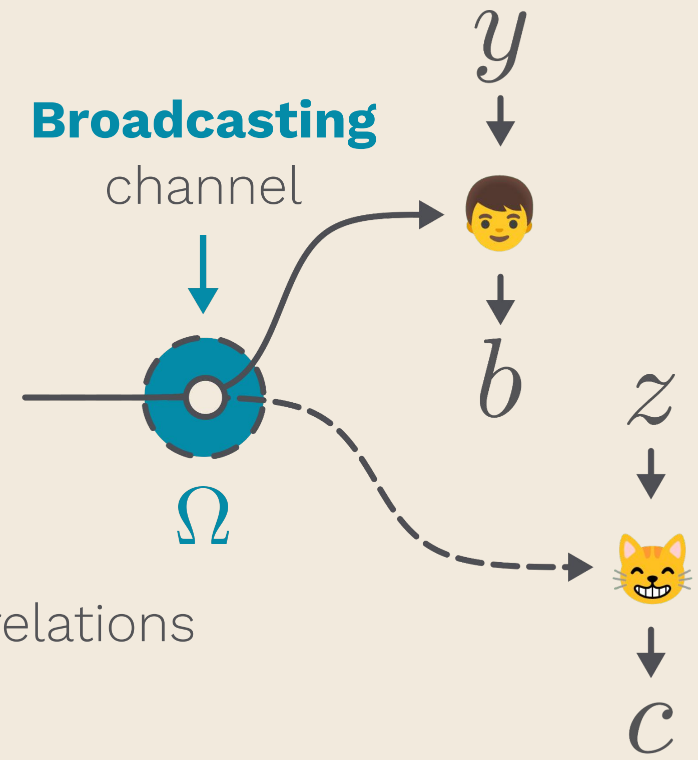


$$\rho_{ABC} = I \otimes \Omega_{B_0 \to BC}\left[\rho_{AB_0}\right]$$

[5] Joseph Bowles, Flavien Hirsch, and Daniel Cavalcanti. “Single-Copy Activation of Bell Nonlocality via Broadcasting of Quantum States”, Quantum 5 (2021)

Broadcast scenario

Bowles et. al.



- Isometry $\Omega_{B_0 \to BC}$
- Ω provides **non-signalling** correlations between 👦 and 😸

[5] Joseph Bowles, Flavien Hirsch, and Daniel Cavalcanti. "Single-Copy Activation of Bell Nonlocality via Broadcasting of Quantum States", Quantum 5 (2021)

Broadcast scenario

Bowles et. al.

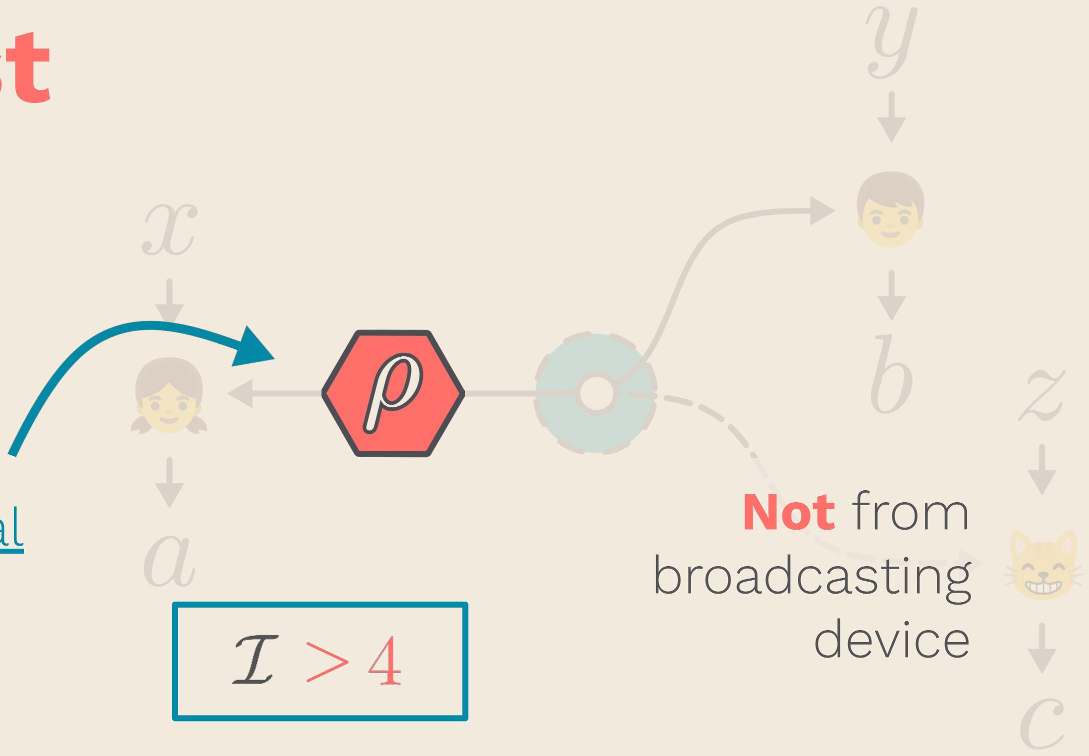
Broadcast local

$$\mathcal{I} = \langle A_0 B_0 C_0 \rangle + \langle A_0 B_1 C_1 \rangle + \langle A_1 B_1 C_1 \rangle - \langle A_1 B_0 C_0 \rangle + \langle A_0 B_0 C_1 \rangle + \langle A_0 B_1 C_0 \rangle + \langle A_0 B_1 C_1 \rangle - \langle A_1 B_1 C_0 \rangle - 2\langle A_2 B_0 \rangle + 2\langle A_2 B_1 \rangle \leq 4$$

[5] Joseph Bowles, Flavien Hirsch, and Daniel Cavalcanti. "Single-Copy Activation of Bell Nonlocality via Broadcasting of Quantum States", Quantum 5 (2021)

Broadcast violation

Nonlocal behaviour originates from initial state ρ_{AB_0}



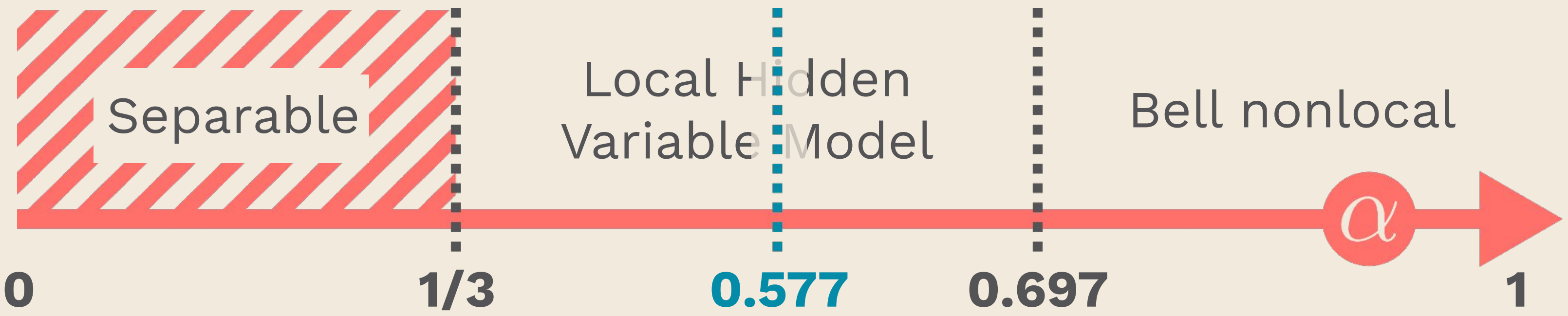
Not from broadcasting device

[5] Joseph Bowles, Flavien Hirsch, and Daniel Cavalcanti. "Single-Copy Activation of Bell Nonlocality via Broadcasting of Quantum States", Quantum 5 (2021)

Broadcast activation

Werner state ρ_α can show nonlocal behaviour for

$$\alpha > 1/\sqrt{3}$$



Experiment:

Single photons as qubits

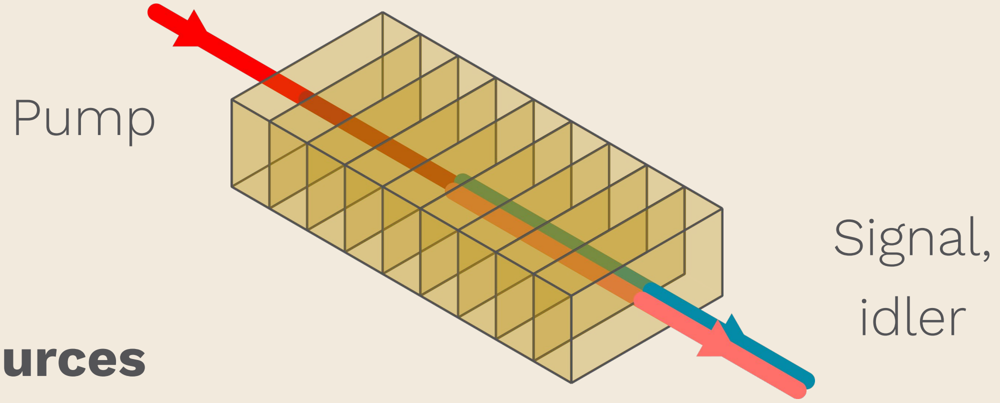
$$|0\rangle = |1\rangle_H \otimes |0\rangle_V \equiv |H\rangle$$

$$|1\rangle = |0\rangle_H \otimes |1\rangle_V \equiv |V\rangle$$

Spontaneous Parametric Down Conversion

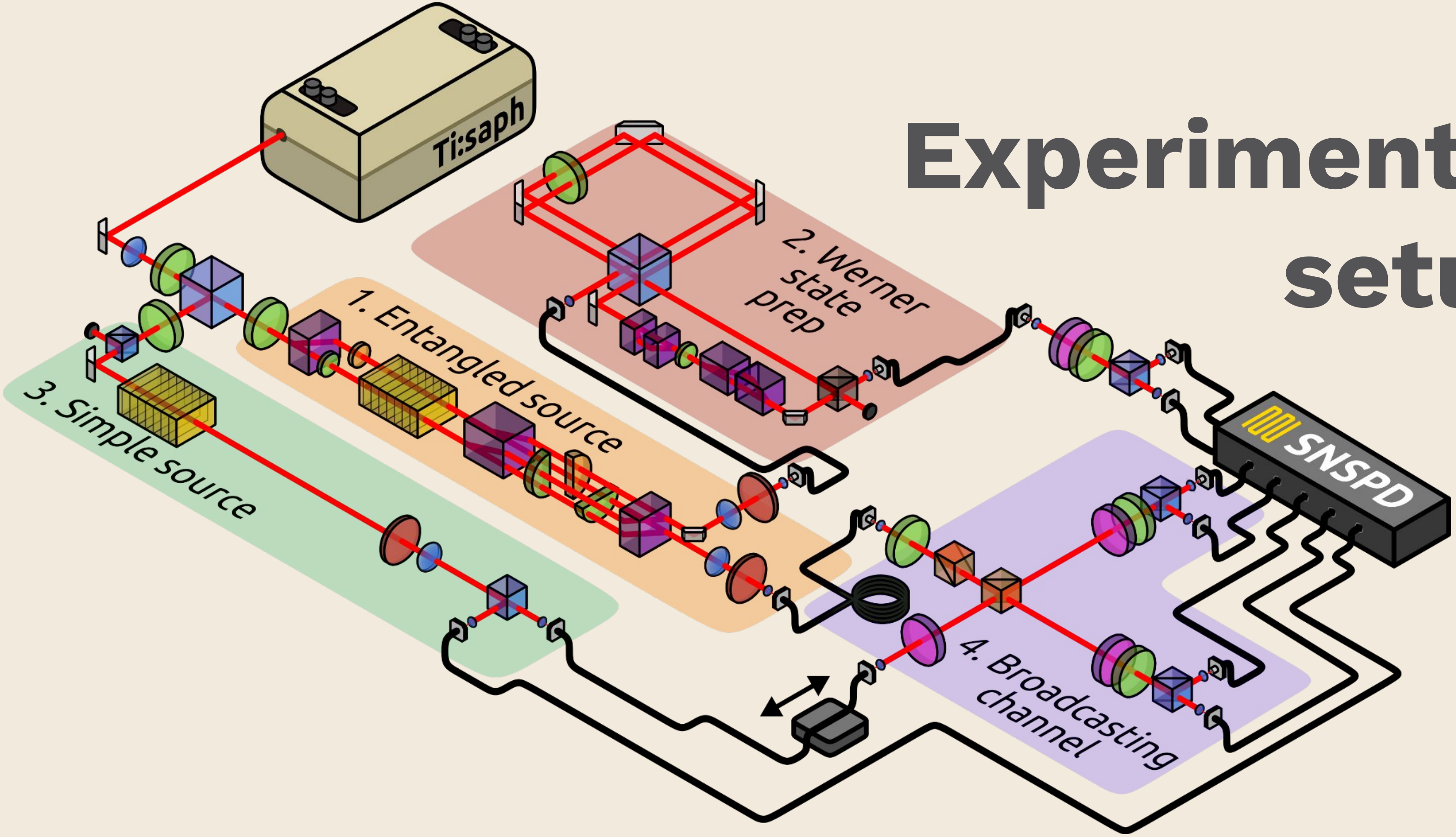
$$\omega_p = \omega_s + \omega_i$$

$$\vec{k}_p = \vec{k}_s + \vec{k}_i$$

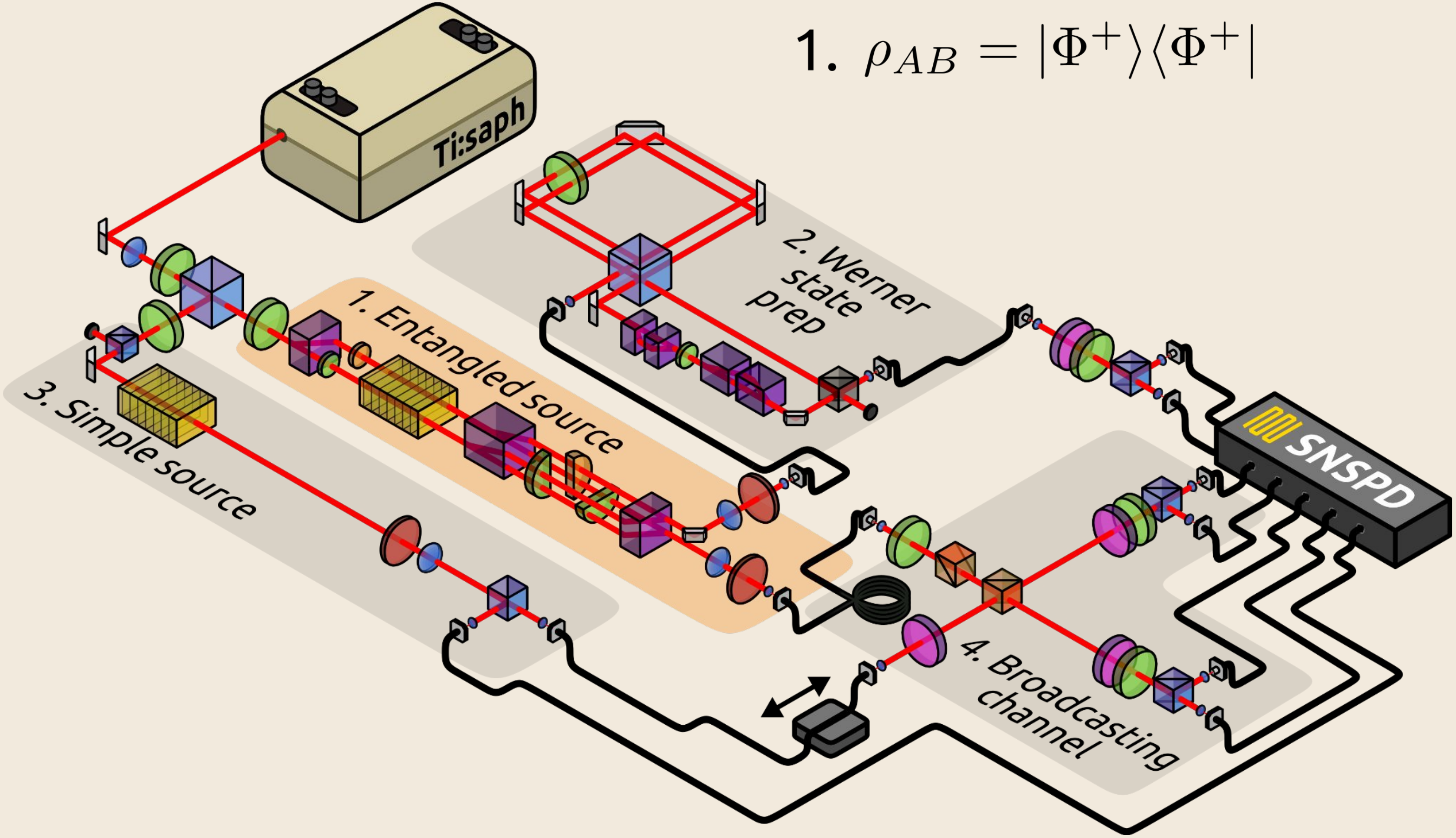


Single-photon pair sources

Experimental setup



$$1.\ \rho_{AB} = |\Phi^+\rangle\langle\Phi^+|$$



[6] Nora Tischler, Farzad Ghafari et. al. “Conclusive Experimental Demonstration of One-Way Einstein-Podolsky-Rosen Steering”, Phys. Rev. Lett 121 (2018)

Quantum correlations

Quantum steering with vector vortex photon states with the detection loophole closed

Sergei Slussarenko, Dominick J. Joch, Nora Tischler, Farzad Ghafari, Lynden K. Shalm, Varun B. Verma, Sae Woo Nam & Geoff J. Pryde

npj Quantum Information **8**, Article number: 20 (2022) | Cite this article

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Phys. Rev. Lett. **121**, 100401 – Published 7 September 2018

Certified random-number generation from quantum steering

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Quantum technologies

Quantum correlations

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Tuesday 13 Dec

5:15 PM @ Room R6

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Wednesday 14 Dec

3:00 PM @ Room R4

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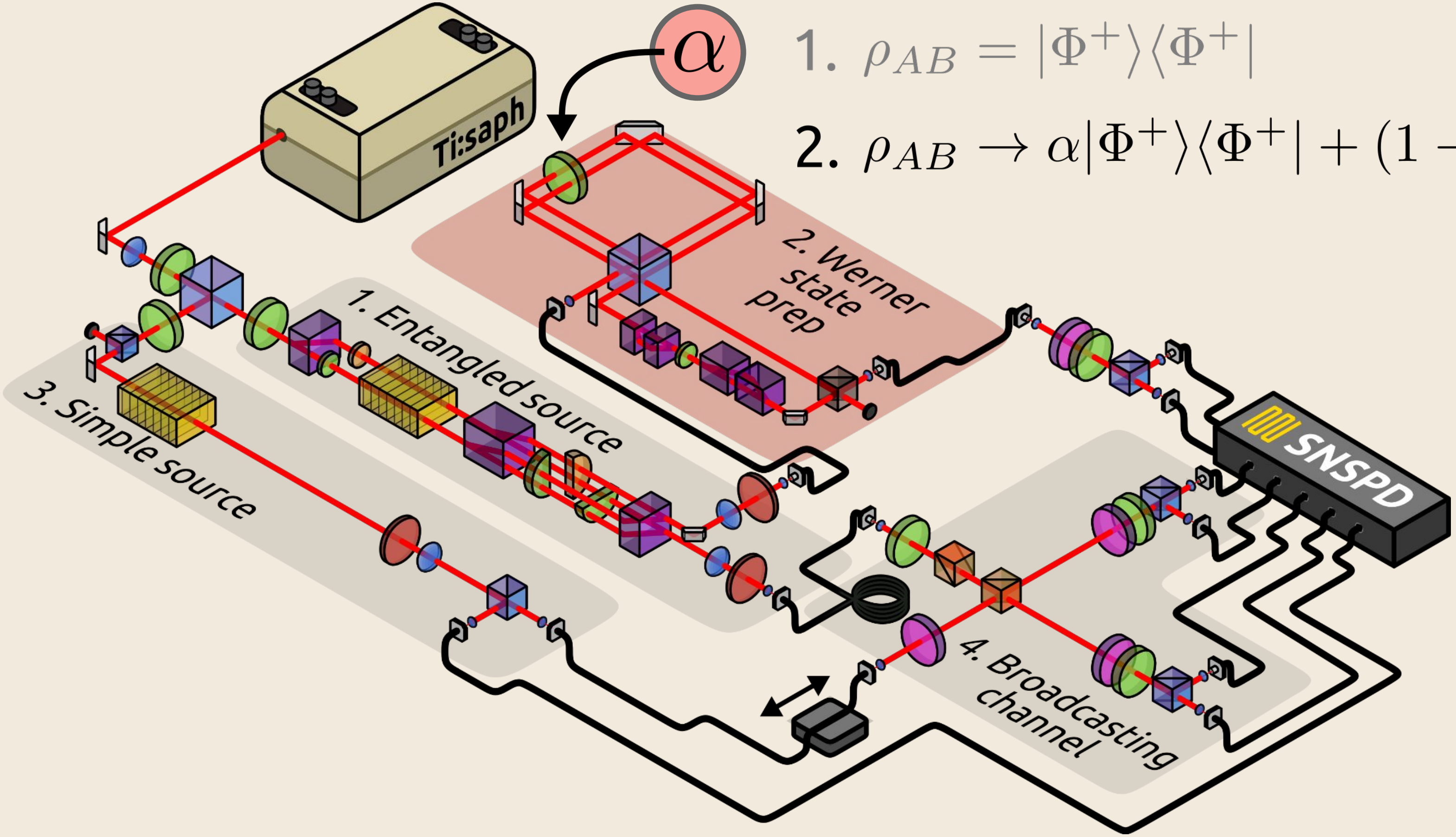
Quantum technologies

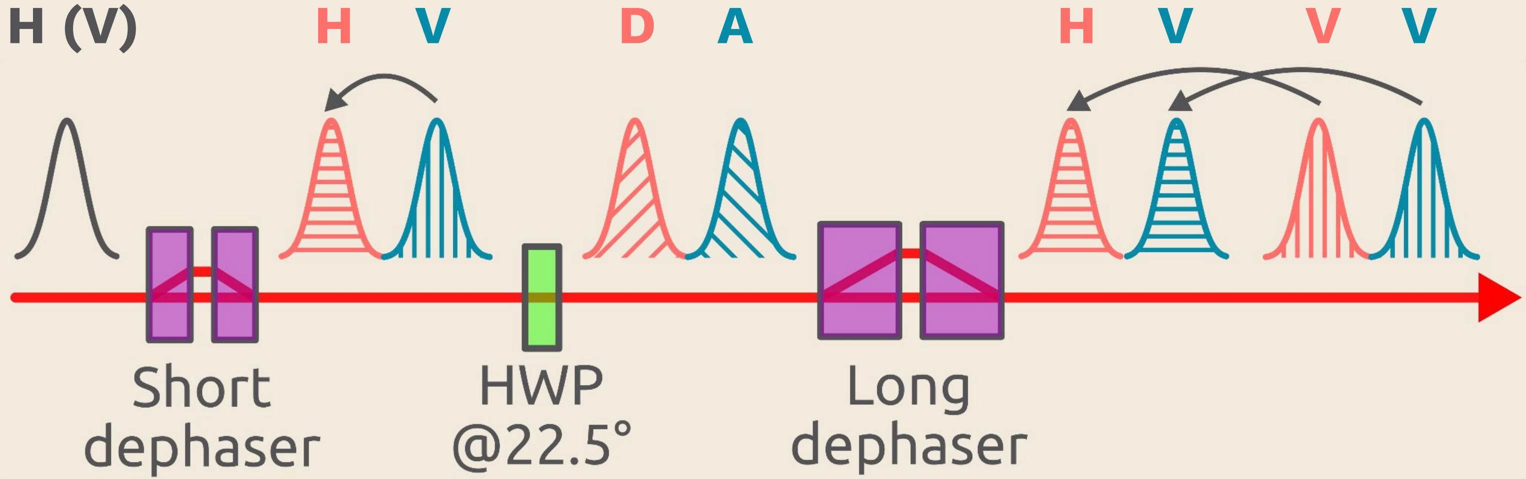
$$1.\ \rho_{AB} = |\Phi^+\rangle\langle\Phi^+|$$

$$2.\ \rho_{AB} \rightarrow \alpha|\Phi^+\rangle\langle\Phi^+| + (1-\alpha)\frac{I}{4}$$



Adding noise to the system

Map orthogonal polarisation modes to orthogonal time modes



State fidelity

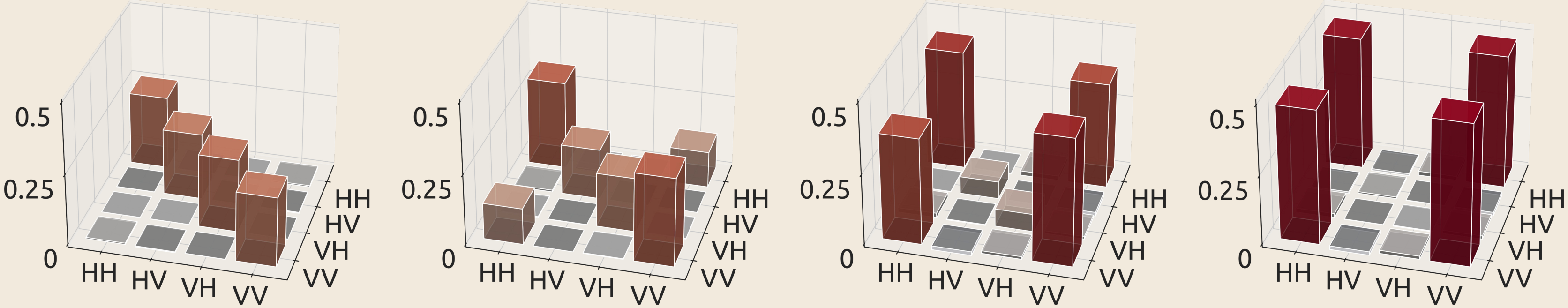
$$F = \left[\mathrm{Tr}\left(\sqrt{\sqrt{\rho_{\exp}}\,\rho_\alpha\sqrt{\rho_{\exp}}}\right)\right]^2$$

$F = 0.9994 \pm 0.0001$, $\alpha = 0.010 \pm 0.004$

$F = 0.9978 \pm 0.0002$, $\alpha = 0.257 \pm 0.004$

$F = 0.9943 \pm 0.0007$, $\alpha = 0.758 \pm 0.003$

$F = 0.9904 \pm 0.0006$, $\alpha = 0.984 \pm 0.001$



α

0

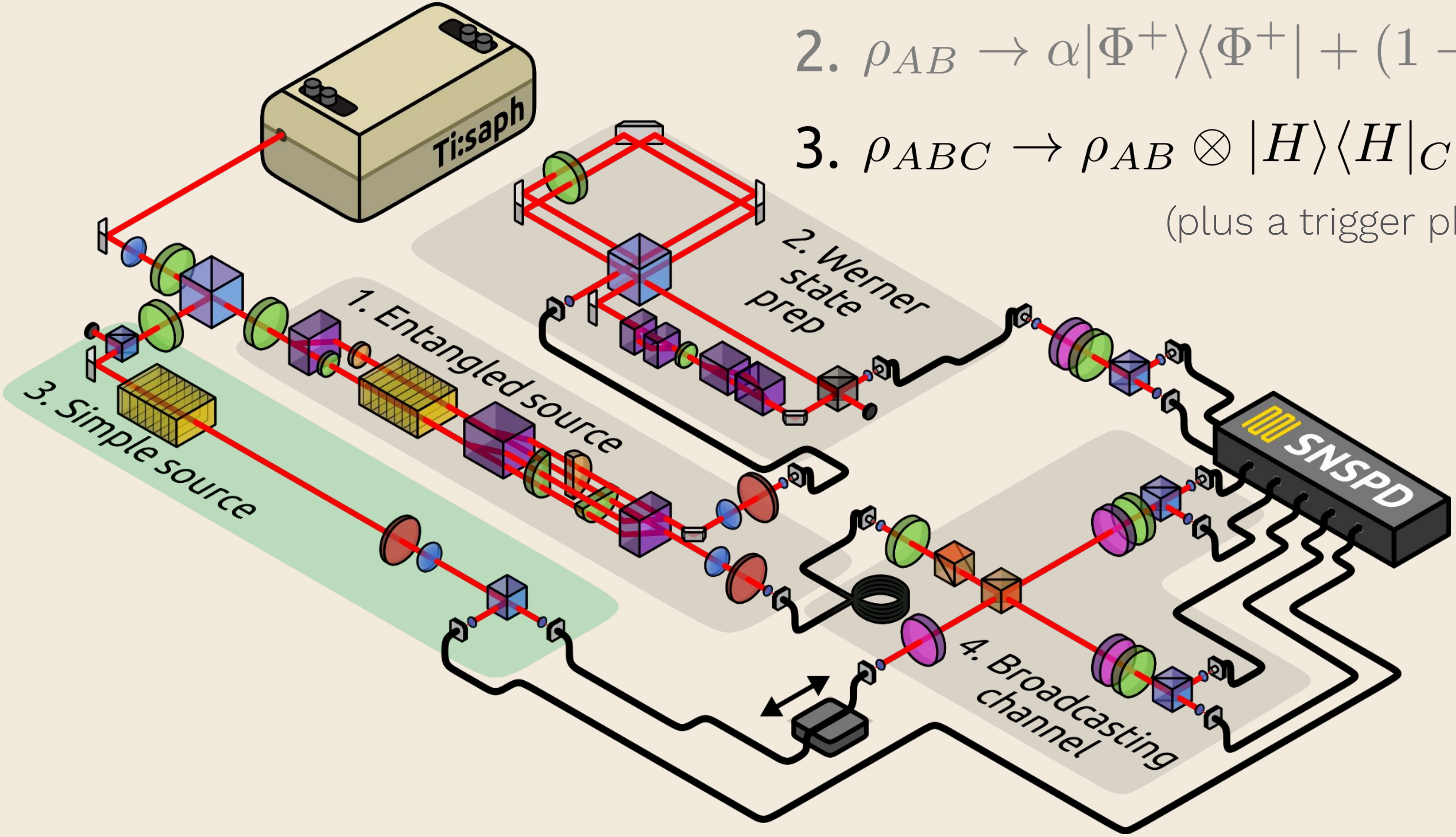
1

$$\rho_\alpha = \alpha|\Phi^+\rangle\langle\Phi^+| + (1-\alpha)\frac{I}{4}$$

$$2.\ \rho_{AB} \to \alpha|\Phi^+\rangle\langle\Phi^+| + (1-\alpha)\frac{I}{4}$$

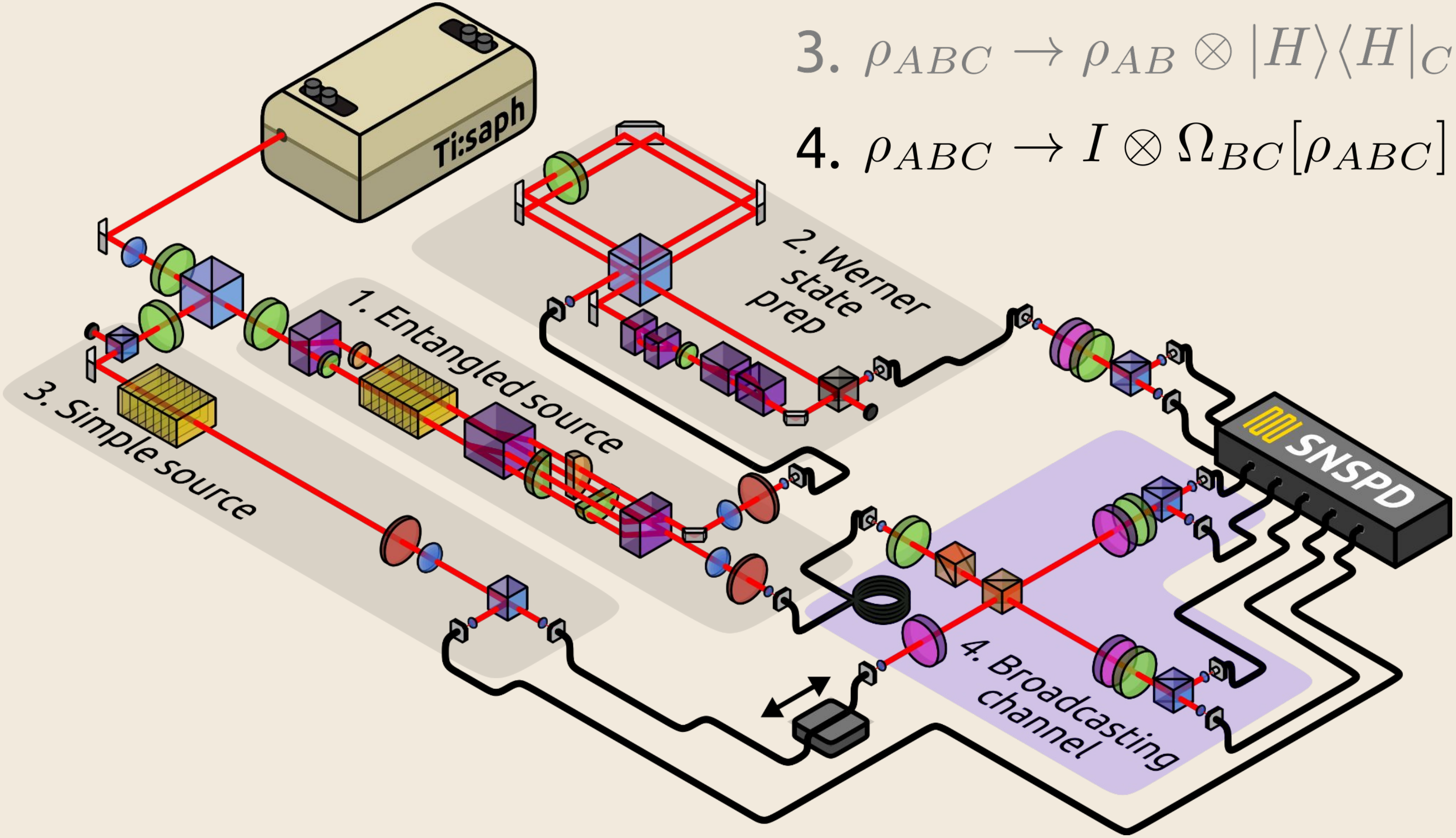
$$3.\ \rho_{ABC} \to \rho_{AB} \otimes |H\rangle\langle H|_C$$

(plus a trigger photon)



$$3.\ \rho_{ABC} \to \rho_{AB} \otimes |H\rangle\langle H|_C$$

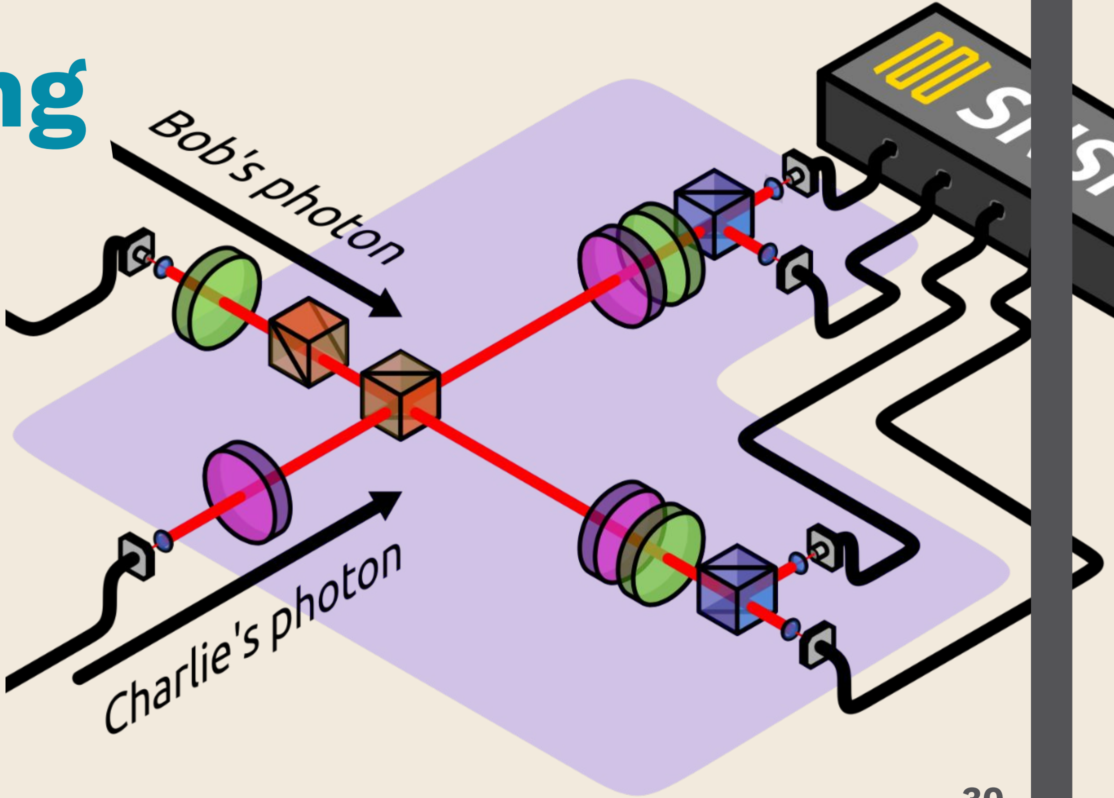
$$4.\ \rho_{ABC} \to I \otimes \Omega_{BC}[\rho_{ABC}]$$



Broadcasting operation

Through a controlled NOT gate [7]

Before		After	
Control	Target	Control	Target
H	H	H	H
H	V	H	V
V	H	V	V
V	V	V	H



[7] Nathan Langford, Till Weinhold et. al. "Demonstration of a Simple Entangling Optical Gate and Its Use in Bell-State Analysis", Phys. Rev. Lett 95 (2005)

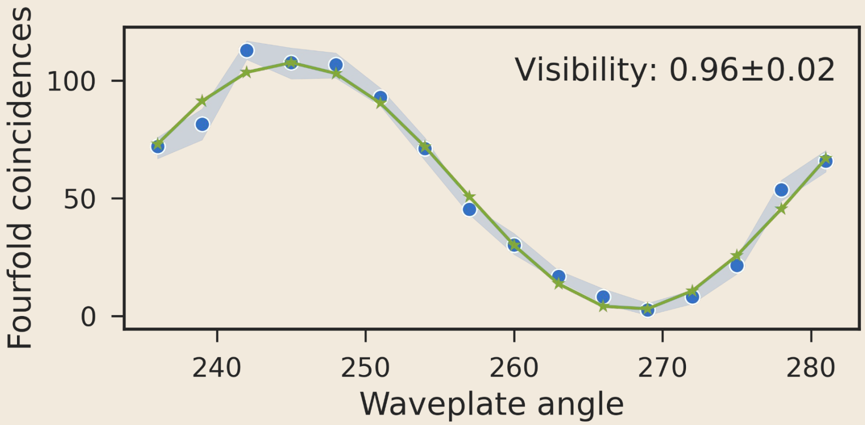
An optical CNOT gate

Hong-Ou-Mandel interference [8]

[8] Chung Ki Hong, Zheyu Ou, and Leonard Mandel. "Measurement of subpicosecond time intervals between two photons by interference", Phys. Rev. Lett 59 (1987)

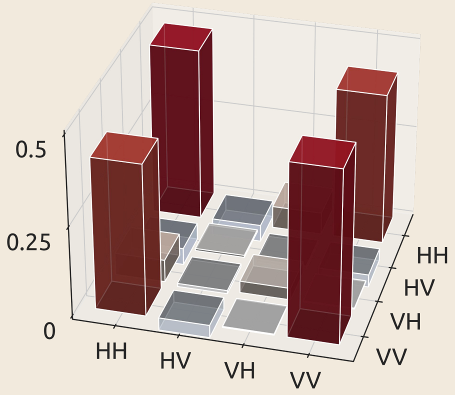
An optical CNOT gate

Current status



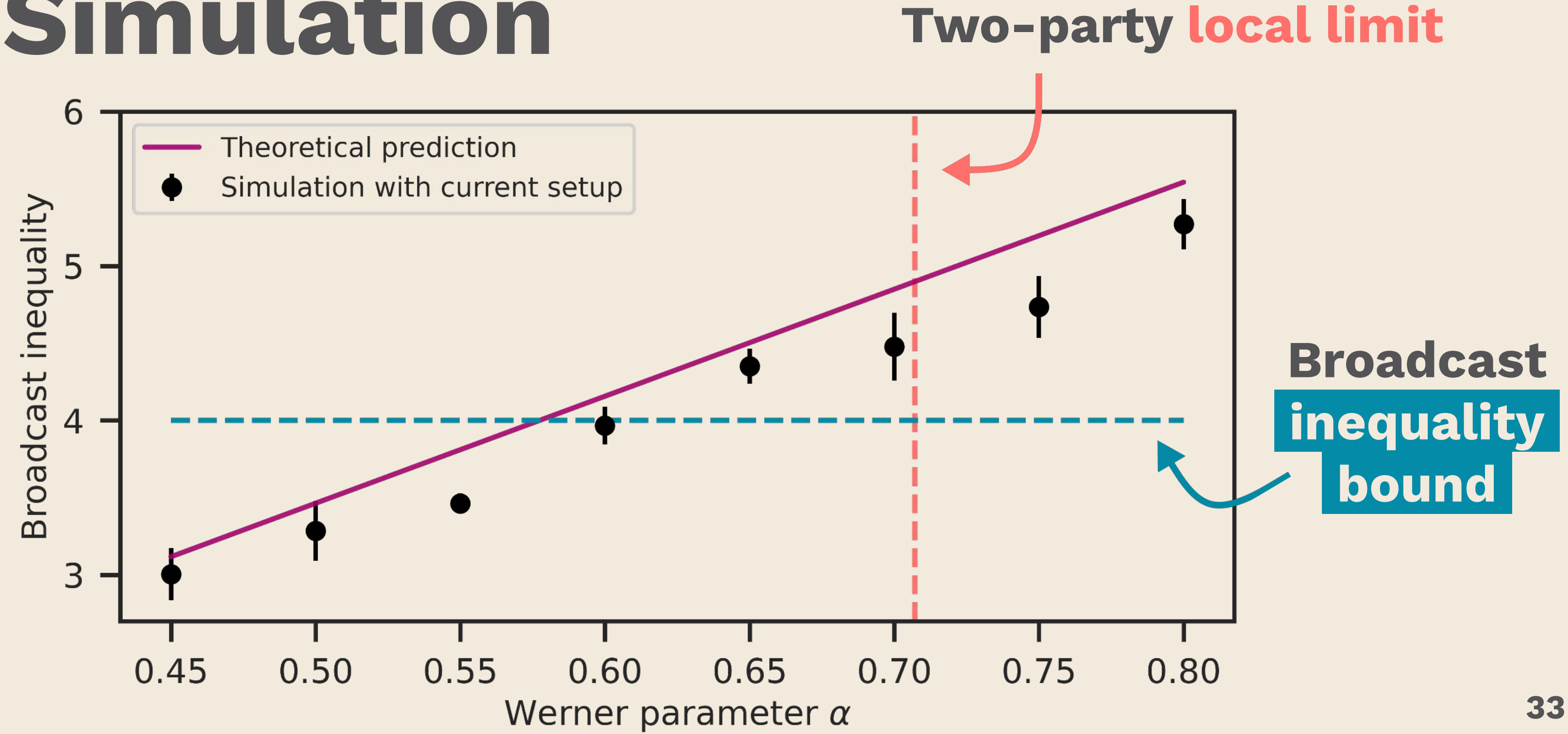
$$|DH\rangle = \frac{1}{\sqrt{2}}\left(|HH\rangle + |VH\rangle\right)$$

$$\rightarrow \frac{1}{\sqrt{2}}\left(|HH\rangle + |VV\rangle\right)$$



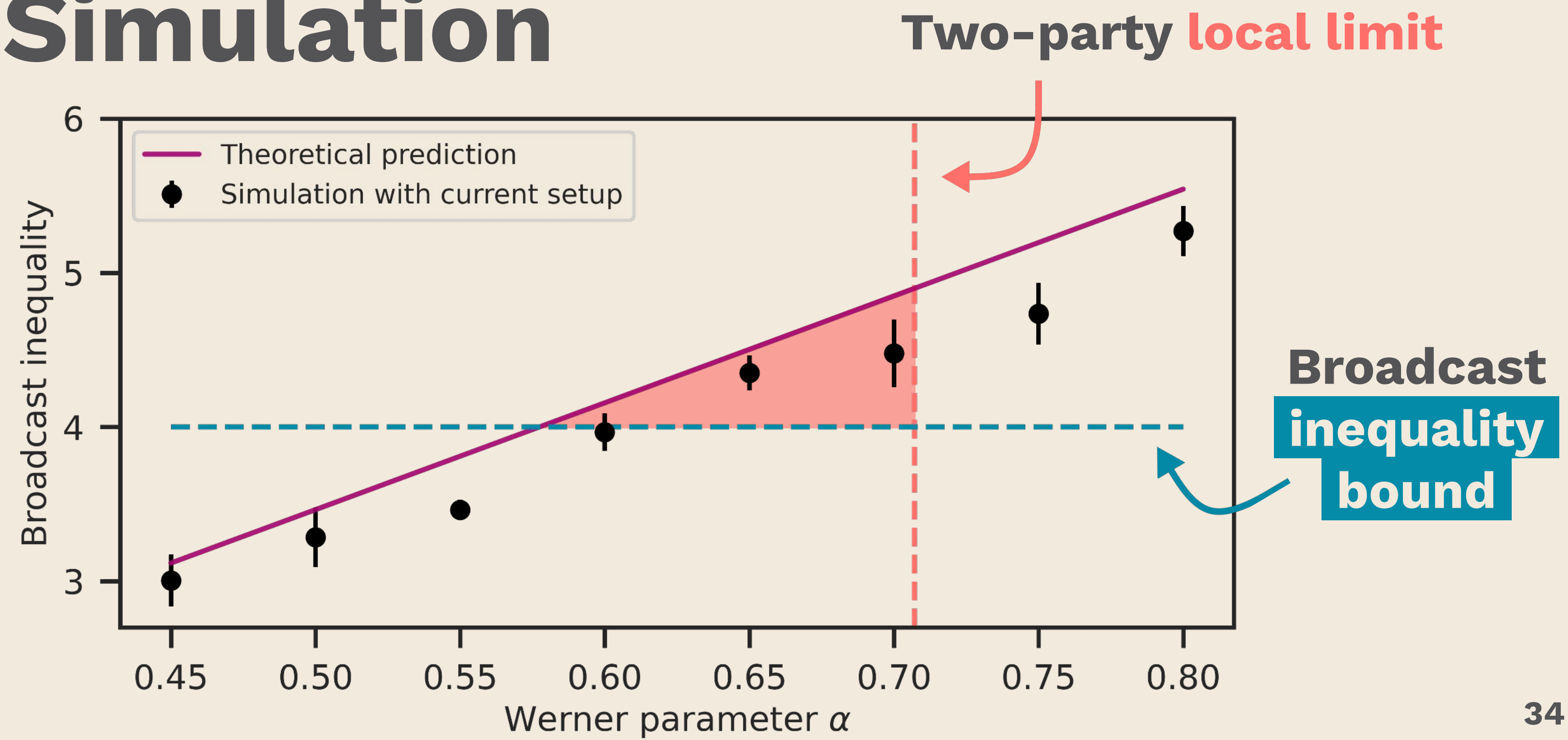
F ~90%

Simulation



Two-party local limit
Theoretical prediction
Simulation with current setup
Broadcast inequality
Werner parameter α
6
5
4
3
0.45
0.50
0.55
0.60
0.65
0.70
0.75
0.80
Broadcast
inequality
bound

Simulation



Two-party local limit
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Werner parameter α
6
5
4
3
0.45
0.50
0.55
0.60
0.65
0.70
0.75
0.80
Broadcast inequality bound

In a nutshell

- Nonlocality is key for quantum protocols
- Noise degrades these nonlocal correlations
- We can **bring them back** with the help of quantum networks

In a nutshell: experiment

- Source of very high-quality, high-fidelity photonic quantum states
- Fully controllable mixture in the system
- Optimising two-photon interference for data collection

Thanks!