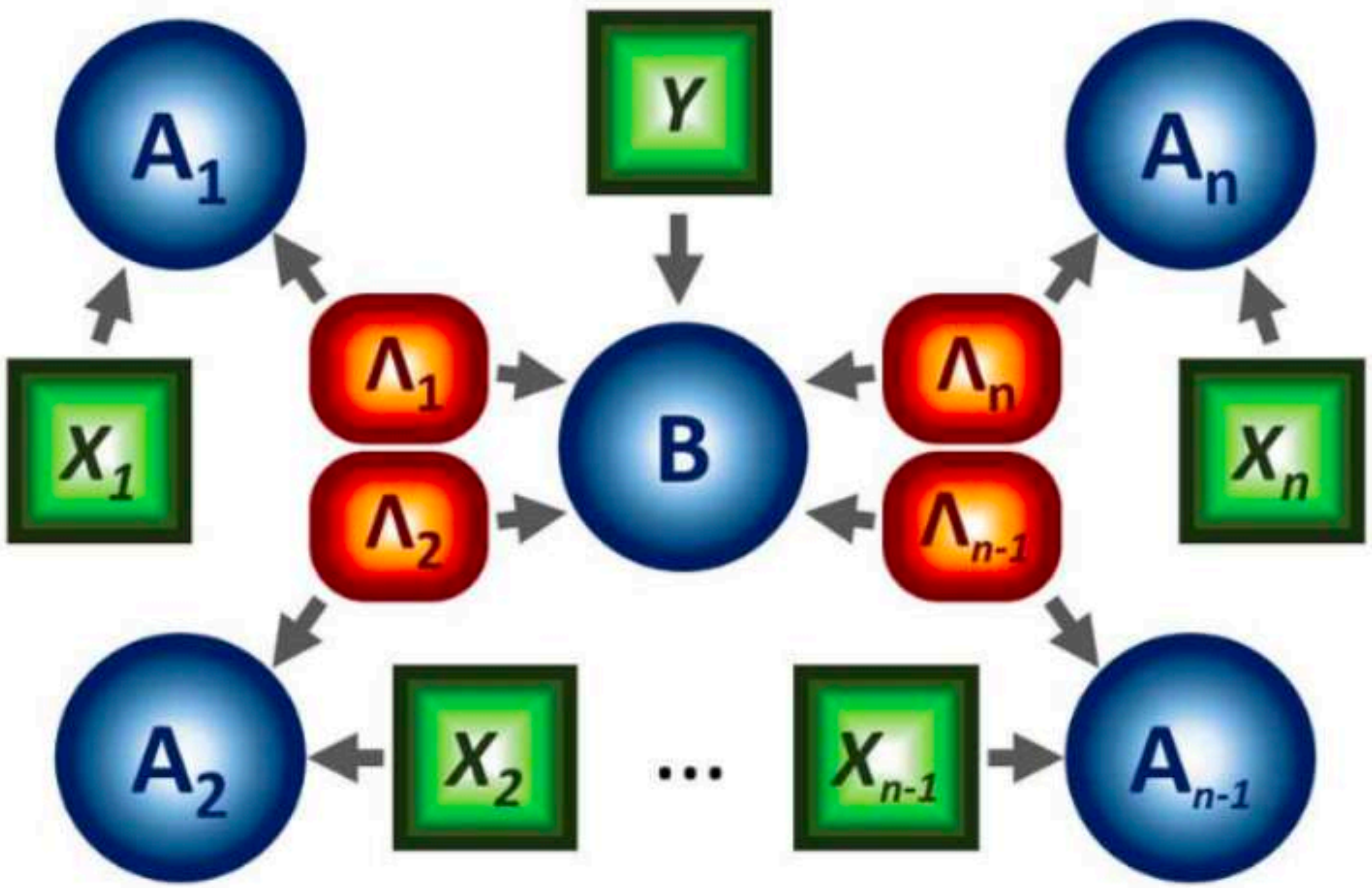
Experimental violation of n-locality in a star quantum network



INTERNATIONAL INSTITUTE OF PHYSICS
Federal University of Rio Grande do Norte

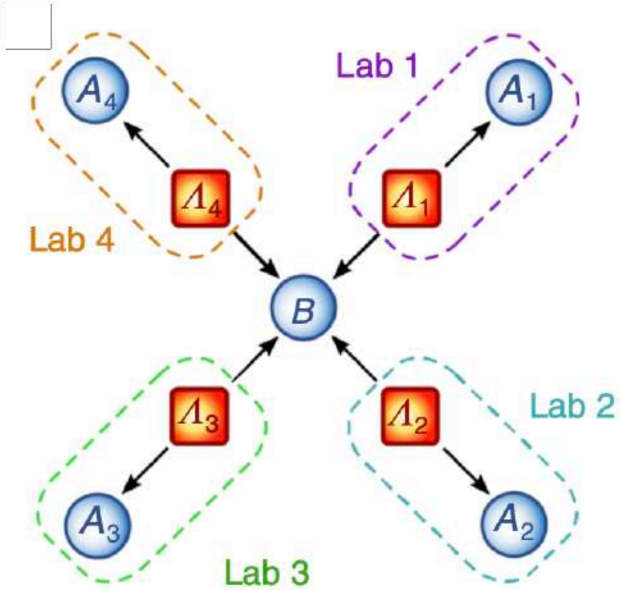
JOHN TEMPLETON FOUNDATION

QUANTUM SCIENCE SEMINAR

SAPIENZA UNIVERSITÀ DI ROMA

Gonzalo Carvacho
Quantum Information Lab
Università di Roma "La Sapienza"

QUANTUM LAB
Quantum Information Lab
Dipartimento di Fisica, Università di Roma La Sapienza



Article | Open Access | Published: 18 May 2020

Experimental violation of *n*-locality in a star quantum network

Davide Poderini, Iris Agresti, Guglielmo Marchese, Emanuele Polino, Taira Giordani, Alessia Suprano, Mauro Valeri, Giorgio Milani, Nicolò Spagnolo, Gonzalo Carvacho, Rafael Chaves & Fabio Sciarrino

Nature Communications **11**, Article number: 2467 (2020) | Cite this article

INTERNATIONAL INSTITUTE OF PHYSICS
Federal University of Rio Grande do Norte

SAPIENZA
UNIVERSITÀ DI ROMA

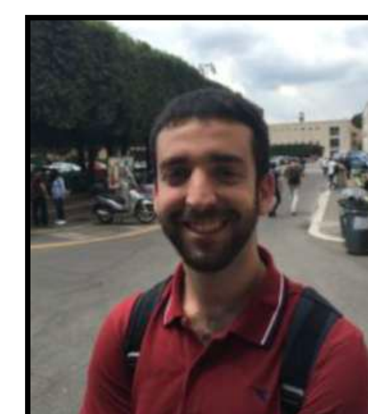
People involved

Prof. Rafael Chaves

Prof. Fabio Sciarrino

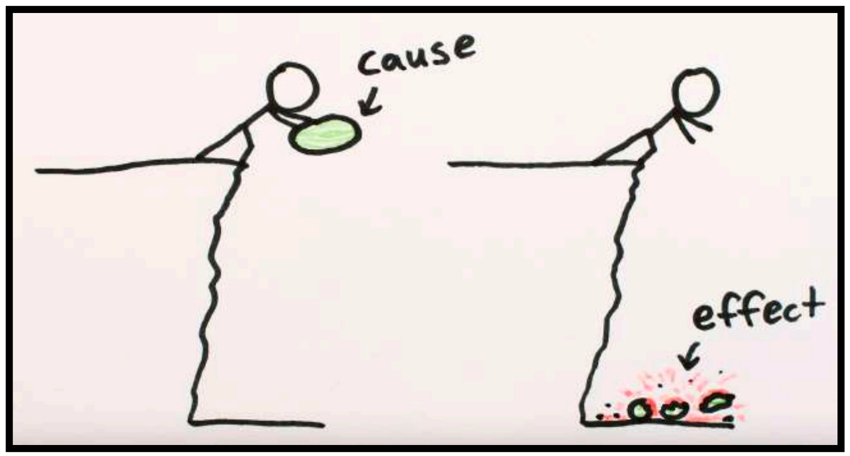
John Templeton Foundation

QUANTUM LAB
Quantum Information Lab
Dipartimento di Fisica, Università di Roma La Sapienza

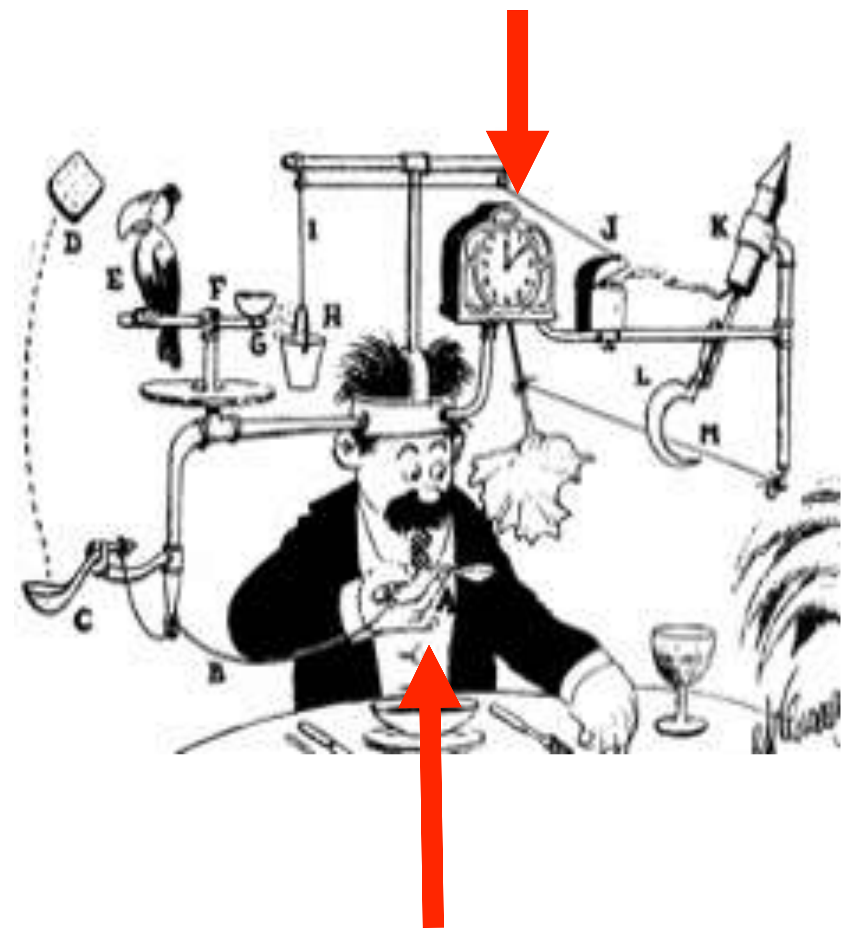


Causal Inference

Causal Inference's aim is to decide which causal models are compatible with observed data.



Causal explanation

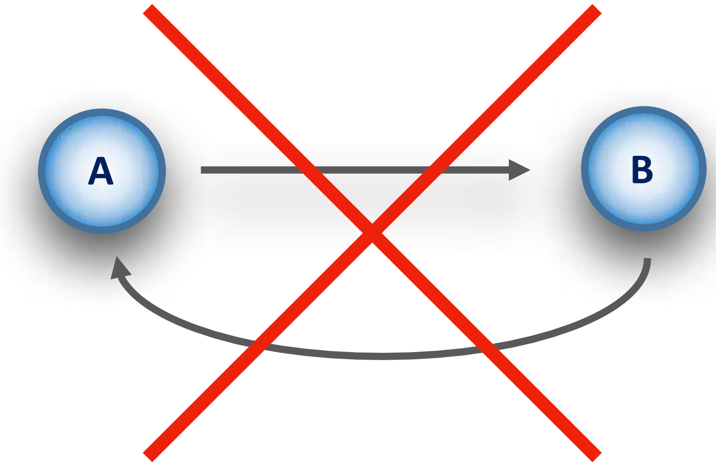


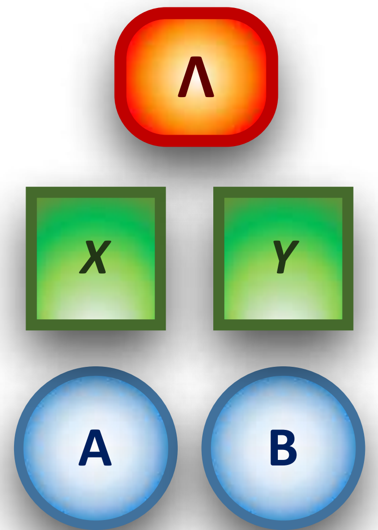
Observed data

If correlation doesn't imply causation, then what does?

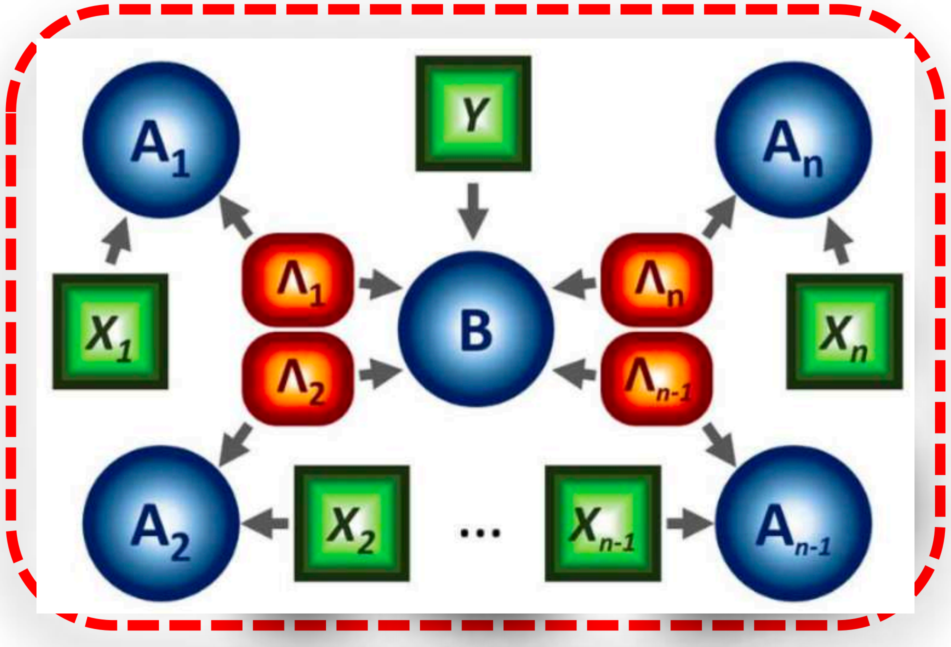
Some definitions

Directed Acyclic Graph (DAG)





- Hidden variable
- Measurement settings
- Measurement outcomes



$$S \equiv \left|\mathbf{E}(\hat{a},\hat{b}) \pm \mathbf{E}(\hat{a},\hat{b}')\right| + \left|\mathbf{E}(\hat{a}',\hat{b}) \mp \mathbf{E}(\hat{a}',\hat{b}')\right| \leq 2$$

Applications of Bell Inequalities

Quantum Information & Quantum Foundations	Quantum Computing	Quantum Communication	Quantum Networks	Quantum RNG
				

PHYSICAL REVIEW LETTERS

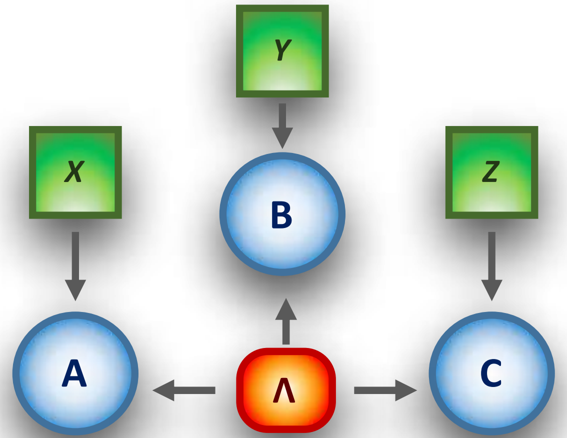
Characterizing the Nonlocal Correlations Created via Entanglement Swapping

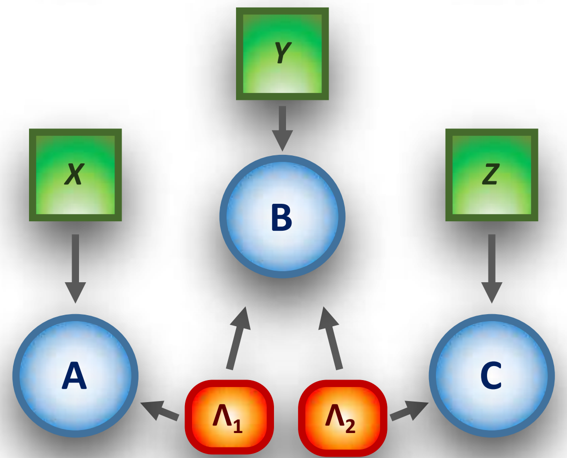
C. Branciard, N. Gisin, and S. Pironio
Phys. Rev. Lett. **104**, 170401 – Published 26 April 2010

PHYSICAL REVIEW A

Bilocal versus nonbilocal correlations in entanglement-swapping experiments

Cyril Branciard, Denis Rosset, Nicolas Gisin, and Stefano Pironio
Phys. Rev. A **85**, 032119 – Published 19 March 2012





Bilocal Hidden Variables (BLHV) Model

$$p(a,b,c\,|\,x,y,z) = \sum_{\lambda_1\lambda_2} p(\lambda_1)p(\lambda_2)p(a|x,\lambda_1)p(b|\,y,\lambda_1\lambda_2)\,p(c|\,z,\lambda_2)$$

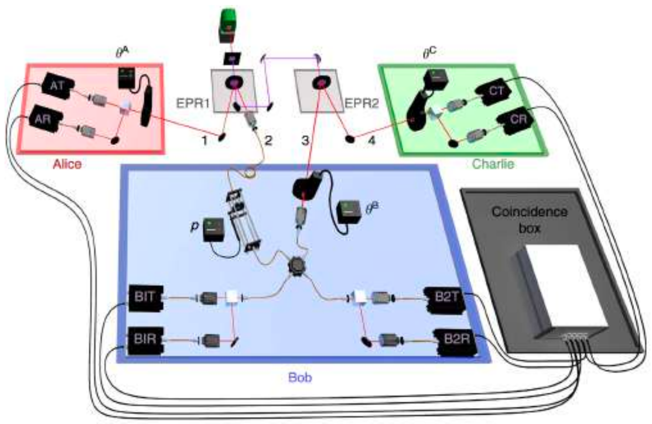
$$S = \sqrt{|I_1|} + \sqrt{|I_2|} \leq 1$$

nature COMMUNICATIONS

Experimental violation of local causality in a quantum network

Gonzalo Carvacho, Francesco Andreoli, Luca Santodonato, Marco Bentivegna, Rafael Chaves & Fabio Sciarrino

Nature Communications **8**, Article number: 14775 (2017)



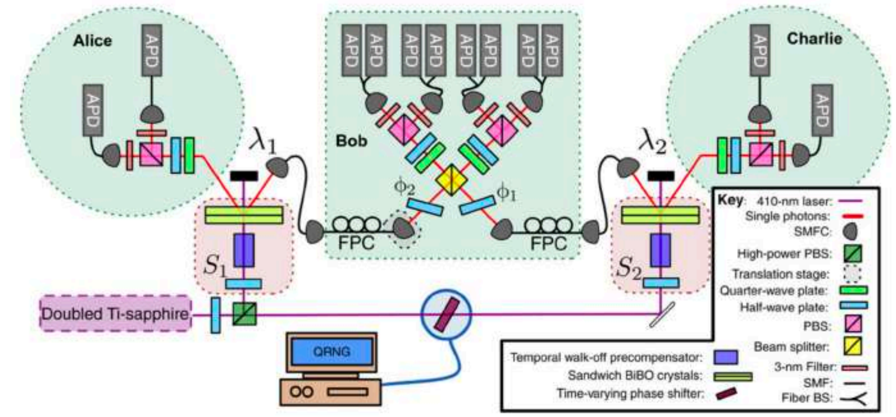
2017

Science Advances

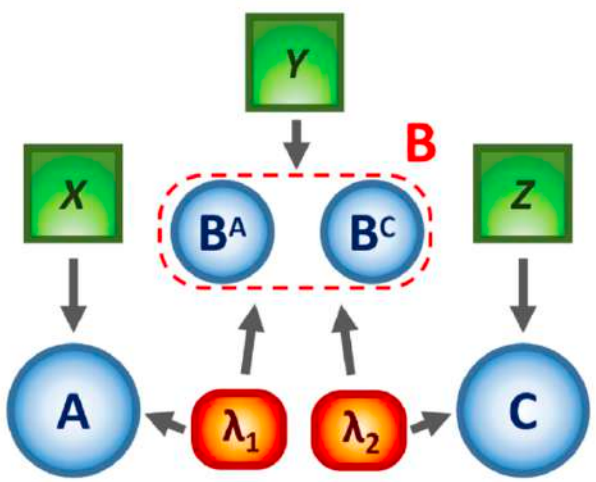
Experimental demonstration of nonbilocal quantum correlations

Dylan J. Saunders[1,2,*], Adam J. Bennet[1], Cyril Branciard[3] and Geoff J. Pryde[1]
+ See all authors and affiliations

Science Advances 28 Apr 2017:
Vol. 3, no. 4, e1602743
DOI: 10.1126/sciadv.1602743



2017



PHYSICAL REVIEW LETTERS

Nonlinear Bell Inequalities Tailored for Quantum Networks

Denis Rosset, Cyril Branciard, Tomer Jack Barnea, Gilles Pütz, Nicolas Brunner, and Nicolas Gisin
Phys. Rev. Lett. **116**, 010403 – Published 7 January 2016

PHYSICAL REVIEW A
covering atomic, molecular, and optical physics and quantum information

Experimental bilocality violation without shared reference frames

Francesco Andreoli, Gonzalo Carvacho, Luca Santodonato, Marco Bentivegna, Rafael Chaves, and Fabio Sciarrino
Phys. Rev. A **95**, 062315 – Published 9 June 2017

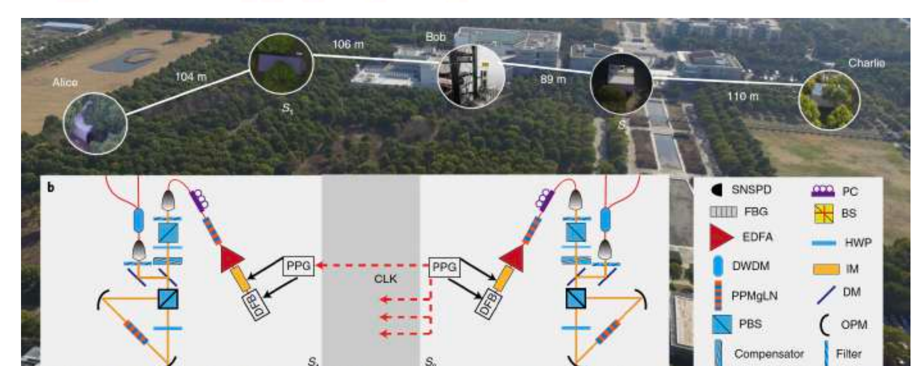
2019

nature photonics

Letter | Published: 26 August 2019

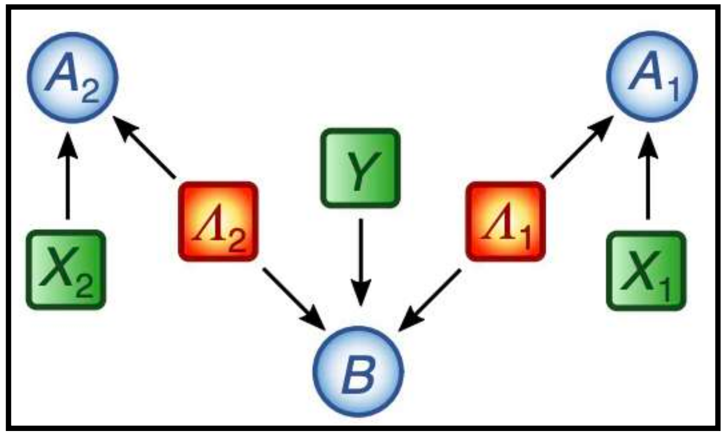
Experimental demonstration of non-bilocality with truly independent sources and strict locality constraints

Qi-Chao Sun, Yang-Fan Jiang, Bing Bai, Weijun Zhang, Hao Li, Xiao Jiang, Jun Zhang, Lixing You, Xianfeng Chen, Zhen Wang, Qiang Zhang, Jingyun Fan & Jian-Wei Pan



n-locality in a star-network

Bilocal case:

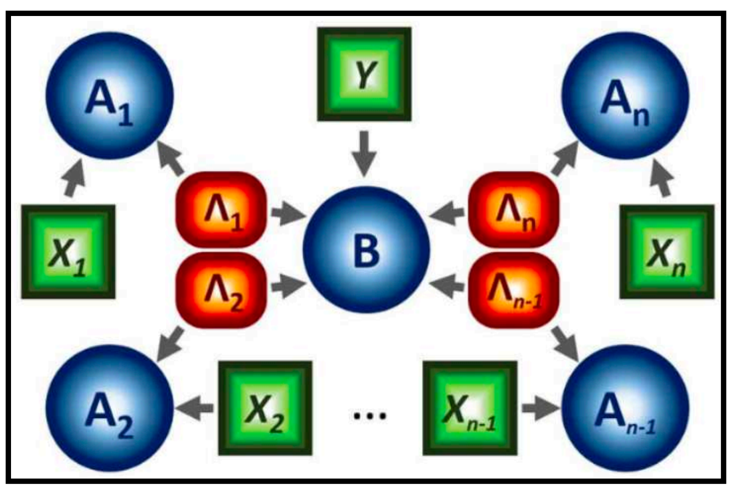


$$S = \sqrt{|I_1|} + \sqrt{|I_2|} \le 1$$

$$I_1 = \frac{1}{4} \sum_{x_1, x_2 = 0,1} \langle A_1^{x_1} A_2^{x_2} B^0 \rangle \quad I_2 = \frac{1}{4} \sum_{x_1, x_2 = 0,1} (-1)^{x_1 + x_2} \langle A_1^{x_1} A_2^{x_2} B^1 \rangle$$

$$\langle A_1^{x_1} A_2^{x_2} B^y \rangle = \sum_{a_1, a_2, b = 0,1} (-1)^{a_1 + a_2 + b} p(a_1, a_2, b | x_1, x_2, y)$$

n-local case:



The inequalities make the explicit assumption that the sources are independent

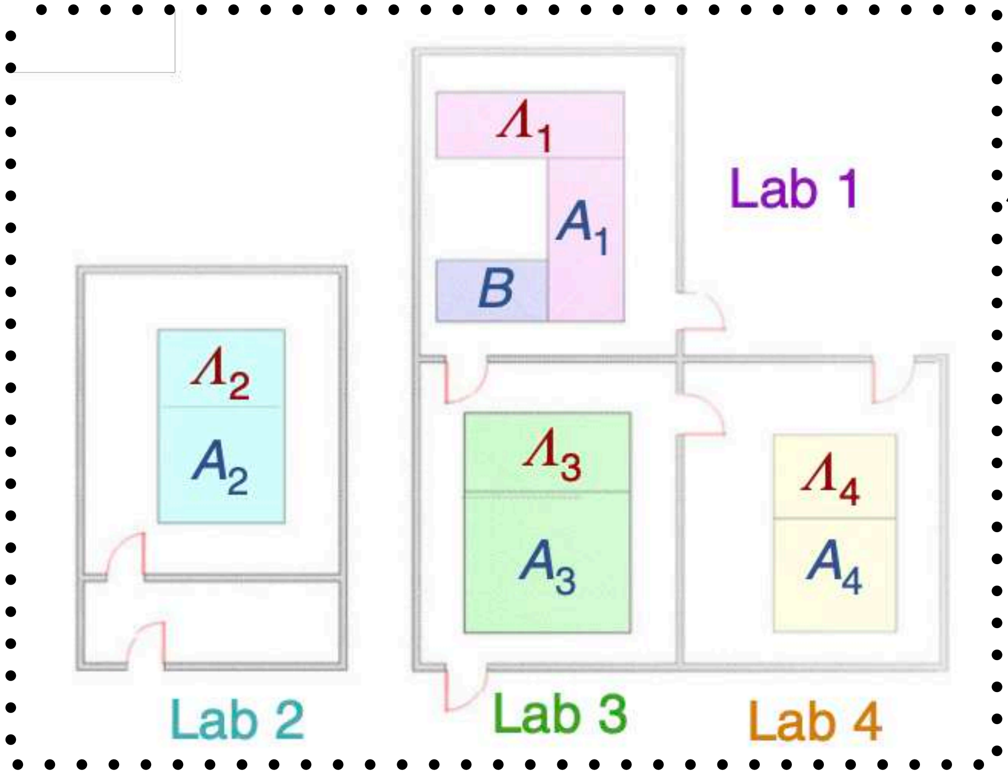
$$p(a_1 \dots a_n b | x_1 \dots x_n y)$$

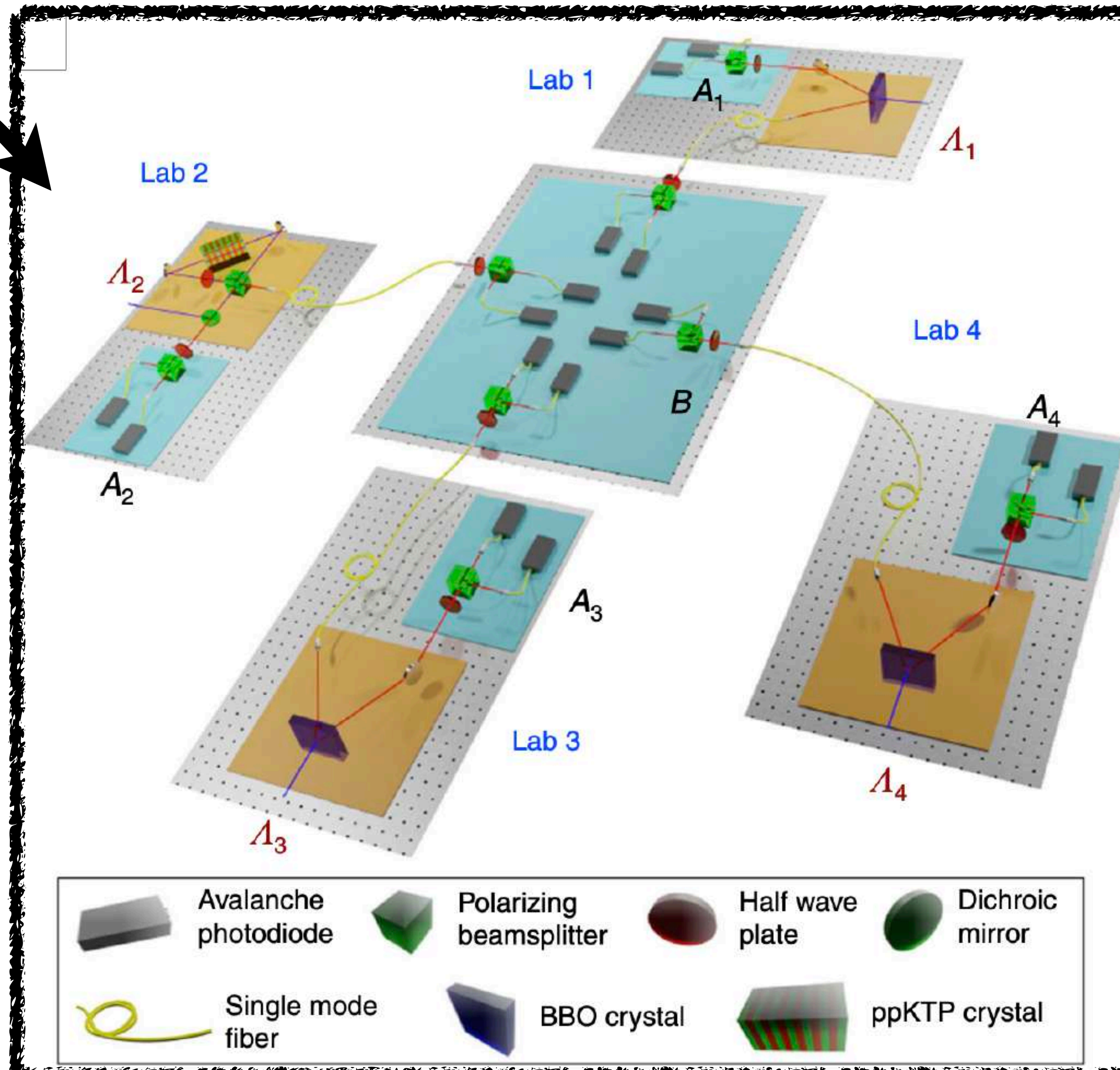
$$= \sum_{\lambda_1, \dots \lambda_n} p(a_1 | x_1 \lambda_1) \dots p(a_n | x_n \lambda_n) p(b | y \lambda_1 \dots \lambda_n) p(\lambda_1) \dots p(\lambda_n)$$

$$S_n^k = \sum_{i=1}^{k} |I_i|^{1/n} \le k - 1 \qquad I_i = \frac{1}{2^n} \sum_{x_1, \dots, x_n = i-1}^{i} \langle A_1^{x_1} \cdots A_n^{x_n} B^{i-1} \rangle$$

Optimal violation can be obtained through separable measurements!!!

Experimental implementation





- ☑ 4 independent entangled sources.
- ☑ 4 independent lasers to pump the nonlinear crystals.
- ☑ 5 Time-taggers.
- ☑ Up to 1024 separable measurement were performed.
- ☑ Violations were obtained within a coincidence window of 80μs as well as 0.49μs.

Upper bound

$$S_n^k = k\cos(\pi/2k)$$

Experimental Results

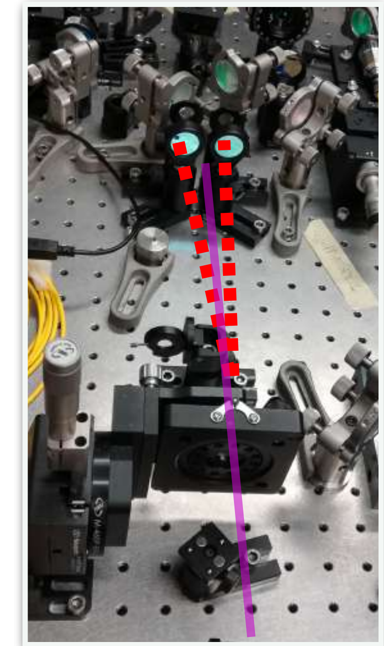
Measurements

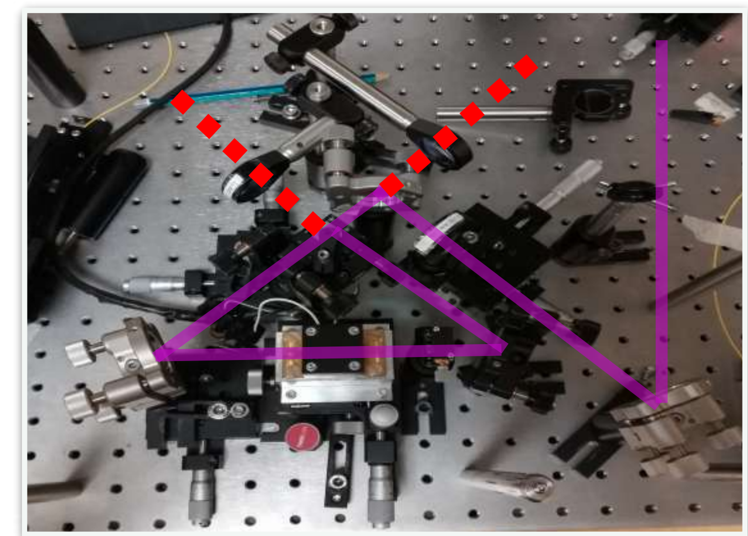
$$|\Psi_x^0\rangle = \cos(x\pi/2k)\,|0\rangle + \sin(x\pi/2k)\,|1\rangle$$
$$|\Psi_x^1\rangle = -\sin(x\pi/2k)\,|0\rangle + \cos(x\pi/2k)\,|1\rangle$$

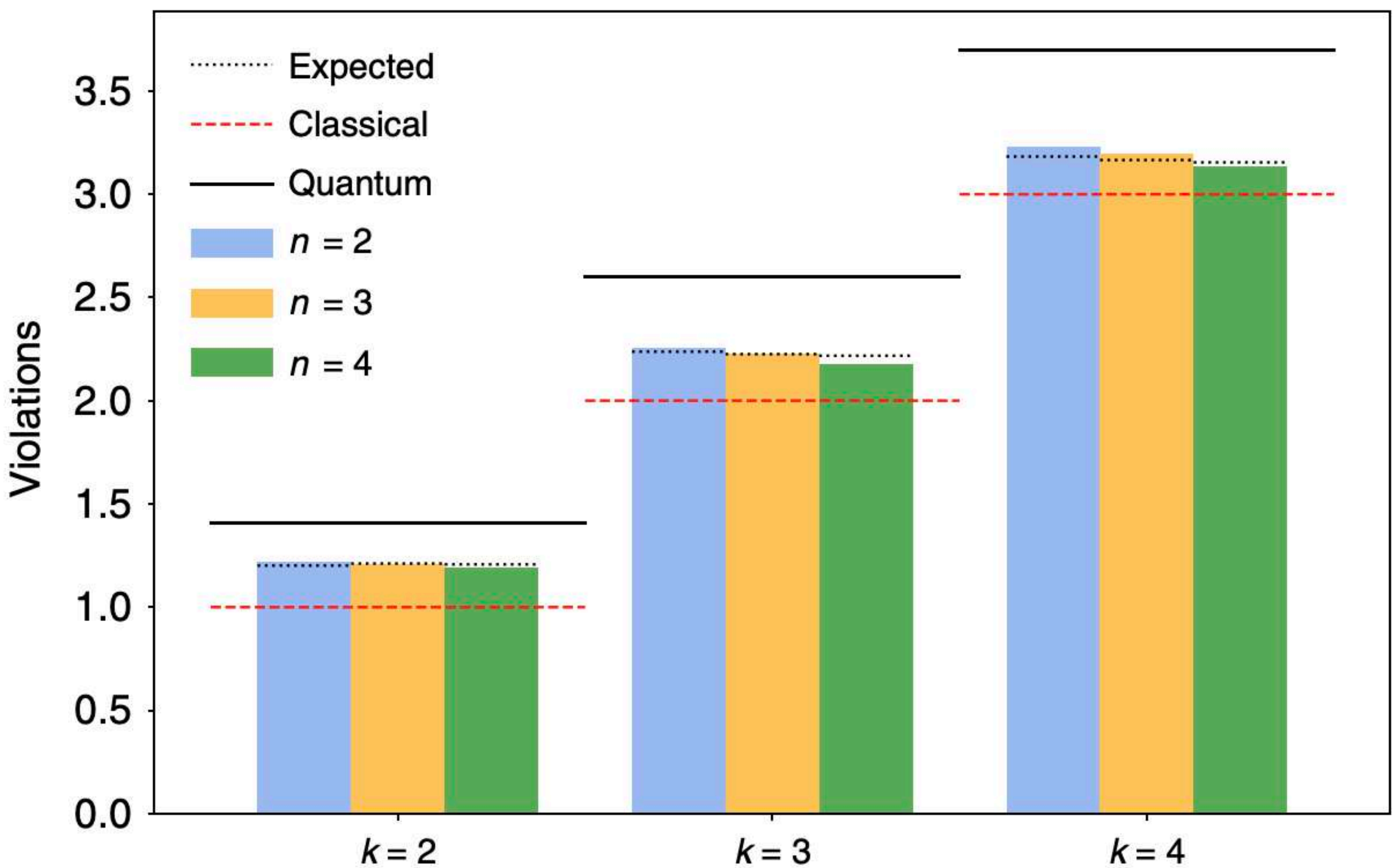
A_1 A_2 A_3 A_4

$$|\Phi_y^0\rangle = \cos((2y+1)\pi/4k)\,|0\rangle + \sin((2y+1)\pi/4k)\,|1\rangle$$
$$|\Phi_y^1\rangle = -\sin((2y+1)\pi/4k)\,|0\rangle + \cos((2y+1)\pi/4k)\,|1\rangle$$

B







Non-classicality demonstrated for different number of measurement settings (k) and involved sources (n).

Ruled-out models

Non-classicality demonstration of the implemented networks with different number of nodes.

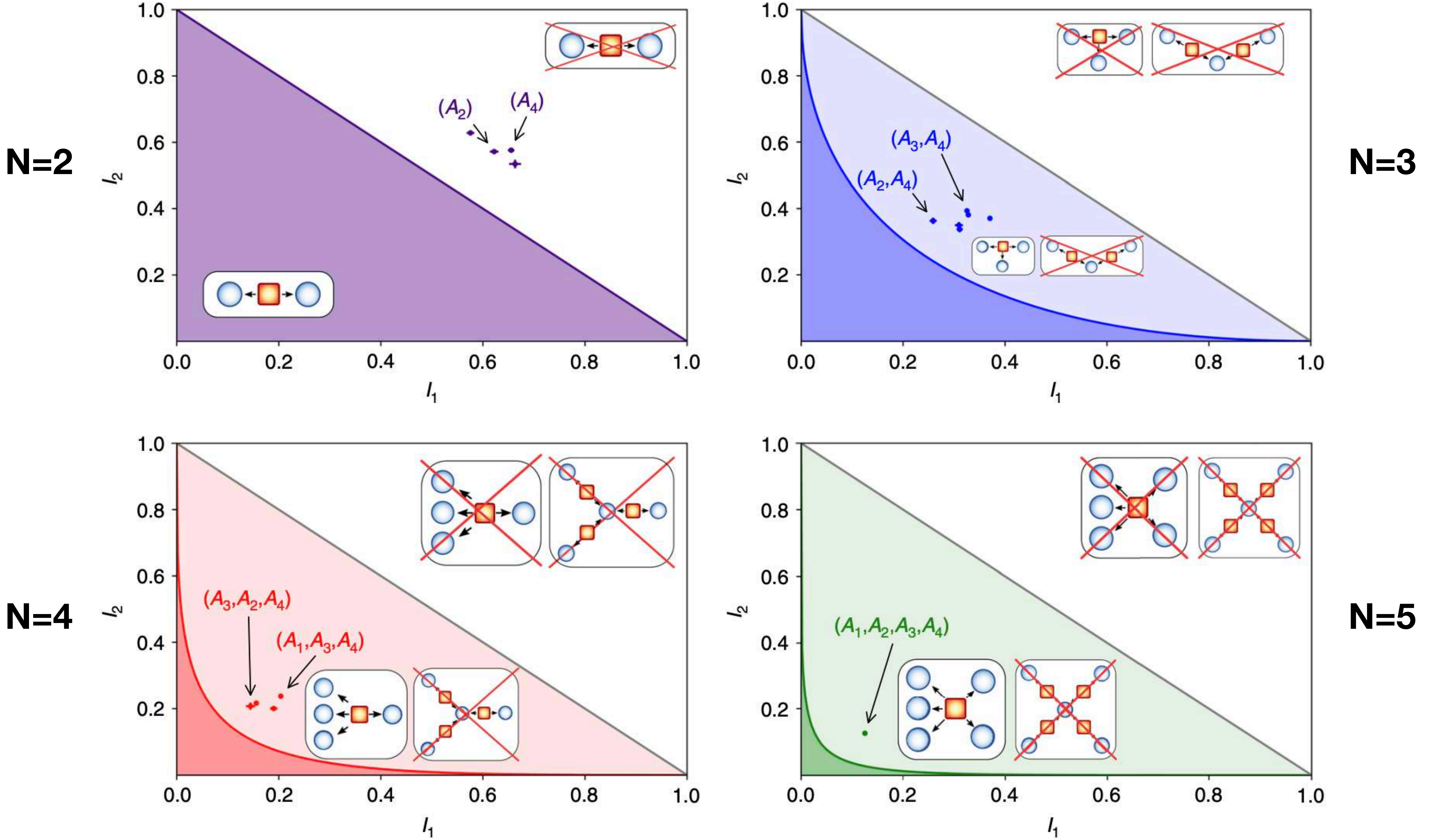


Table 1 Experimental results for different number of sources *n* and *k* = 2 measurement settings.

n Sources	Combination	I_1	I_2	S^{obs}
2	A_2, A_4	0.259 ± 0.007	0.363 ± 0.010	1.111 ± 0.011
	A_3, A_4	0.325 ± 0.004	0.393 ± 0.004	1.198 ± 0.005
	A_3, A_2	0.310 ± 0.008	0.350 ± 0.010	1.147 ± 0.011
	A_1, A_4	0.3279 ± 0.0017	0.381 ± 0.003	1.190 ± 0.003
	A_1, A_2	0.311 ± 0.006	0.337 ± 0.009	1.138 ± 0.010
	A_1, A_3	0.370 ± 0.003	0.371 ± 0.003	1.217 ± 0.003
3	A_3, A_2, A_4	0.145 ± 0.009	0.207 ± 0.010	1.116 ± 0.015
	A_1, A_2, A_4	0.156 ± 0.005	0.217 ± 0.007	1.139 ± 0.009
	A_1, A_3, A_4	0.204 ± 0.005	0.238 ± 0.005	1.208 ± 0.006
	A_1, A_3, A_2	0.190 ± 0.007	0.200 ± 0.008	1.160 ± 0.010
4	A_1, A_2, A_3, A_4	0.125 ± 0.005	0.125 ± 0.005	1.190 ± 0.008

The table shows the experimental values of I_1, I_2, and S^{obs} for each possible combination of parties $\{A_1, ..., A_4\}$.

Table 2 Experimental results for different number of sources *n* and measurement settings *k*.

n Sources	*k* Settings	S^{obs}	Classical	Violation σ	S^{sim}	S^Q
2	2	1.217 ± 0.003	1	72	1.201 ± 0.007	1.41
	3	2.253 ± 0.002	2	127	2.237 ± 0.010	2.60
	4	3.2261 ± 0.0014	3	162	3.182 ± 0.014	3.70
3	2	1.208 ± 0.006	1	35	1.211 ± 0.005	1.41
	3	2.227 ± 0.003	2	76	2.225 ± 0.009	2.60
	4	3.195 ± 0.002	3	97	3.165 ± 0.013	3.70
4	2	1.190 ± 0.008	1	24	1.207 ± 0.005	1.41
	3	2.177 ± 0.005	2	35	2.218 ± 0.008	2.60
	4	3.135 ± 0.004	3	34	3.154 ± 0.012	3.70

The values of S^{obs}, S^{sim}, and S^Q are the observed, the expected, and the maximum quantum violation, respectively. S^{sim} has been computed using the state visibility estimated by Bell violations performed in each single source.

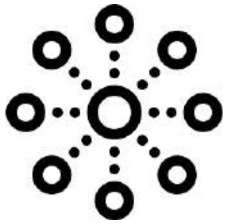
Summary and perspectives

- We experimentally performed a scalable quantum network with:

☑ Increasing number of sources.

☑ Increasing number of measurement settings.

☑ Certification of nonlocal correlations among the parties.

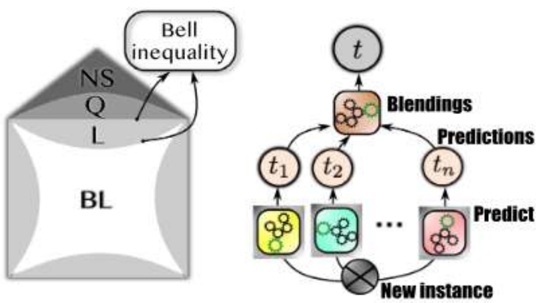


➢ Machine Learning for characterizing non-local correlations

PHYSICAL REVIEW LETTERS **122**, 200401 (2019)

Machine Learning Nonlocal Correlations

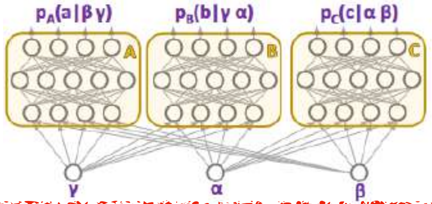
Askery Canabarro,[1,2] Samuraí Brito,[1] and Rafael Chaves[1,3]



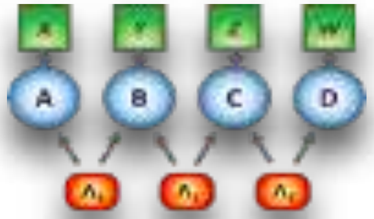
npj | Quantum Information

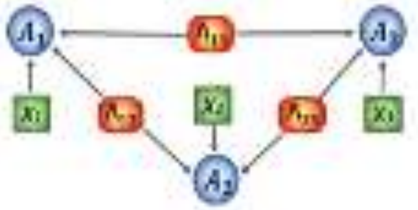
A neural network oracle for quantum nonlocality problems in networks

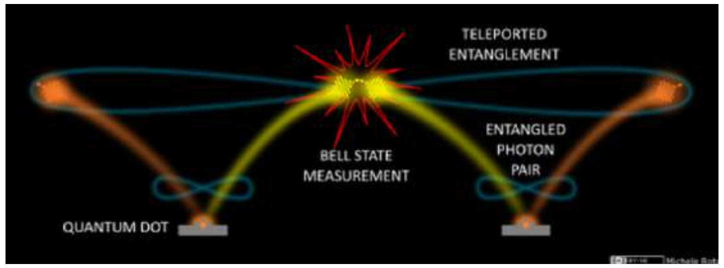
Tamás Kriváchy[1], Yu Cai[1], Daniel Cavalcanti[2], Arash Tavakoli[3], Nicolas Gisin[1] and Nicolas Brunner[1]



➢ Experimental realization of more complex networks







Phys. Rev. Lett. **123**, 160501 – Published 14 October 2019