QUANTUM LAB

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Experimental tests on quantum causality

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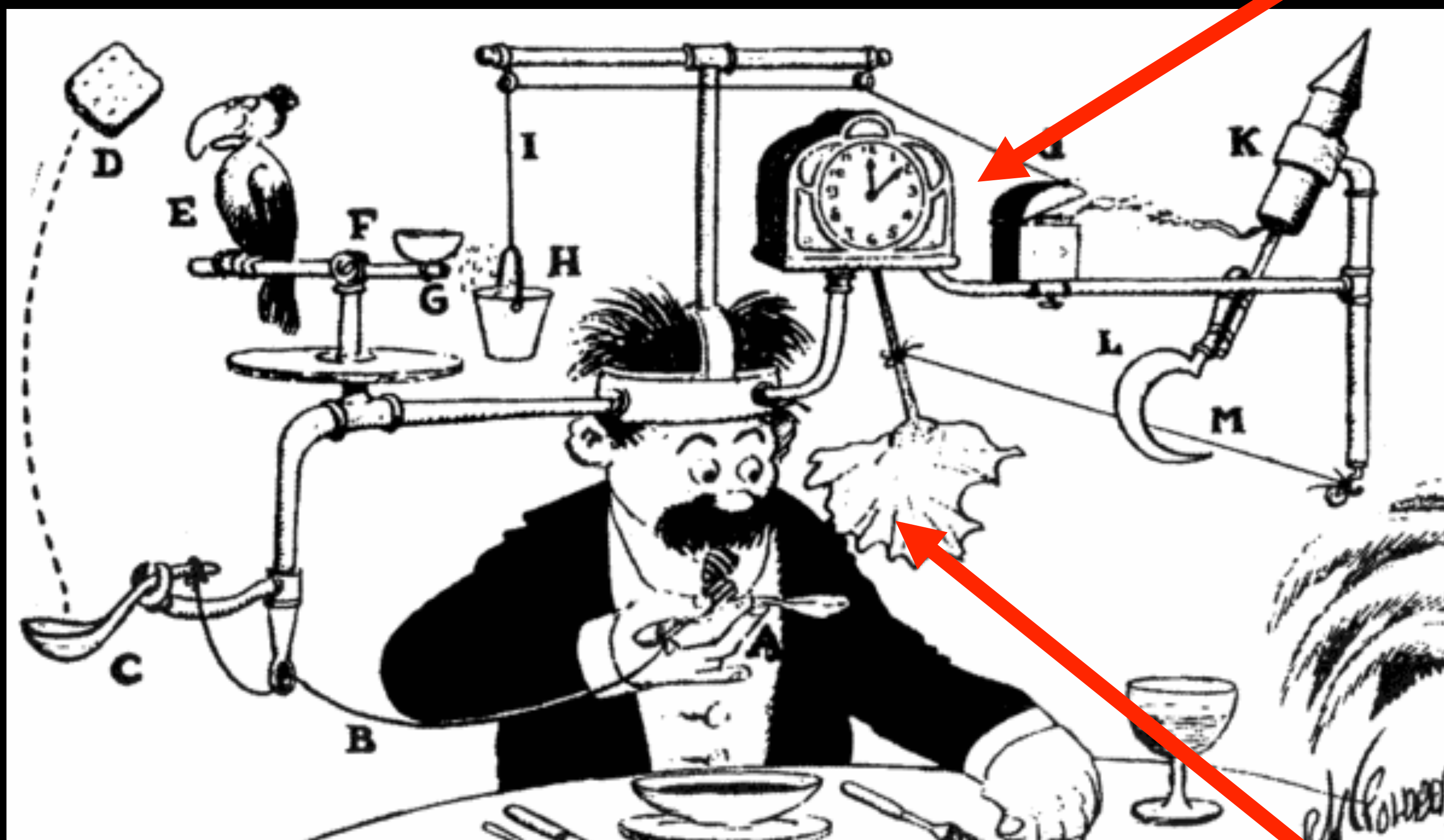
Rafael Chaves
International Institute of Physics, Natal

Leandro Aolita

Causal inference

Causal
explanation

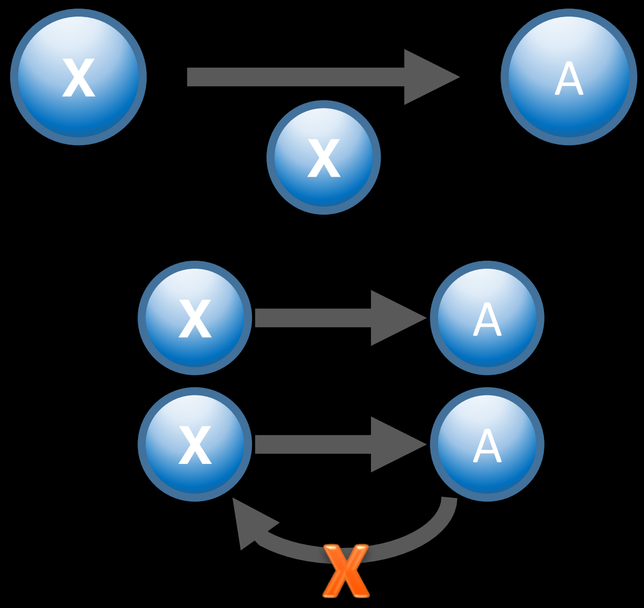


Observed
data

Quantum Nonlocality from a Causal Inference Perspective

Classical Causal Structures

- For n variables $X_1, \ldots, X_n$**,** the causal relationships are encoded in a causal structure, represented by a directed acyclic graph (**DAG**).



Nodes of graph

- event: random variable X (A) acquires a precise value

Directed graph

- arrow: causal relation between two variables

Acyclic graph

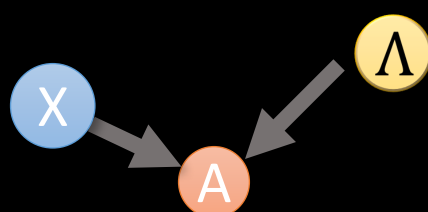
- closed cycle are not allowed (relativistic causality)

Quantum Nonlocality from a Causal Inference Perspective

Classical Causal Structures

- For n variables $X_1, \ldots, X_n$, the causal relationships are encoded in a causal structure, represented by a directed acyclic graph (**DAG**).

- Causal relationships are encoded in the conditional independencies implied by the DAG:

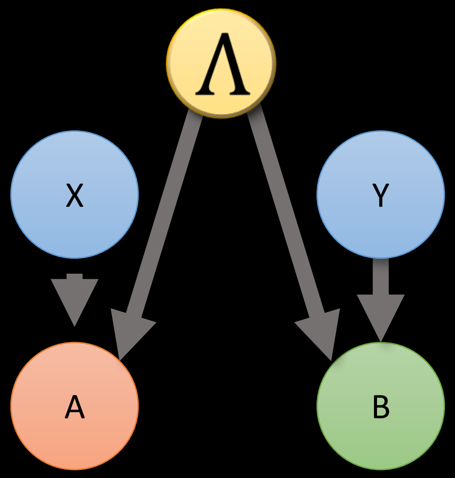


$$p(a|b,x,y,\lambda) = p(a|x,\lambda)$$
$$p(b|a,x,y,\lambda) = p(b|y,\lambda)$$

GOAL: to disregard some classical causal structures from observational (statistical) data.

…more in general: to infer causal relationships

Directed Acyclic Graph associated to Bell inequalities



Nodes: ***relevant random variables in the network***

Arrows: ***causal relations***

Directed Acyclic Graph associated to Bell inequalities

- Alice and Bob measure two possible observables each: A_0, A_1, B_0, B_1

- After sufficiently many repetitions they can estimate statistical quantities. The experiment can be described in terms of . $p(a,b|x,y)$

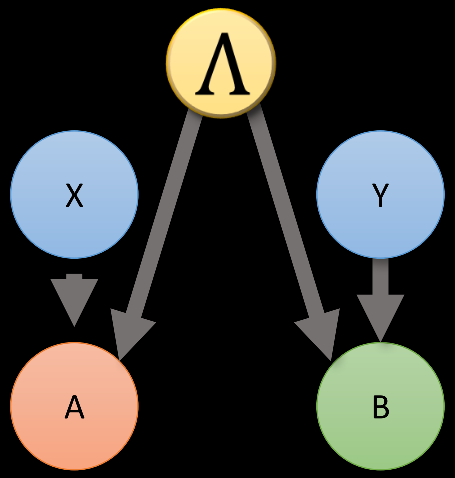
- There are two causal assumptions.

Measurement Independence:

$$p(x,y,\lambda) = p(x)p(y)p(\lambda)$$

Locality:

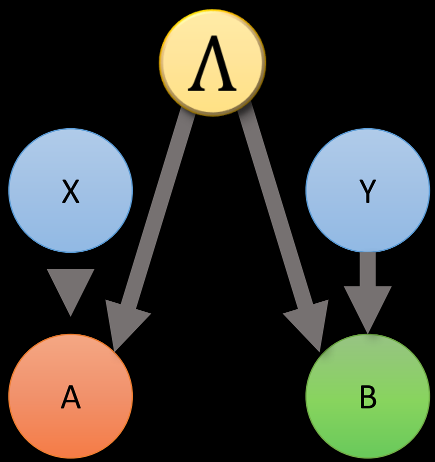
$$p(b|a,x,y,\lambda) = p(b|y,\lambda)$$



Nodes: ***relevant random variables in the network***

Arrows: ***causal relations***

Local Hidden Variable (LHV) Model



$$p(a,b|x,y) \neq p(a|x)p(b|y)$$

$$p(a|b,x,y,\lambda) = p(a|x,\lambda)$$
$$p(b|a,x,y,\lambda) = p(b|y,\lambda)$$

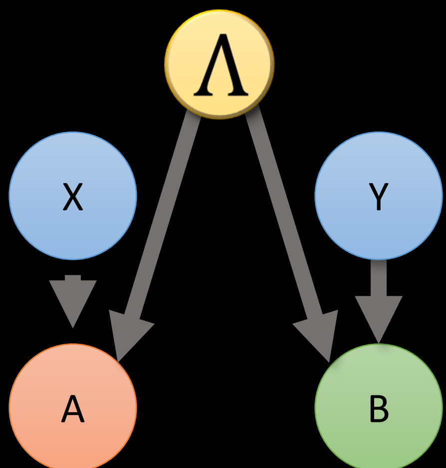
$$p(a,b|x,y) = \int d\lambda \;\; \rho(\lambda)\, p(a|x,\lambda)p(b|y,\lambda)$$

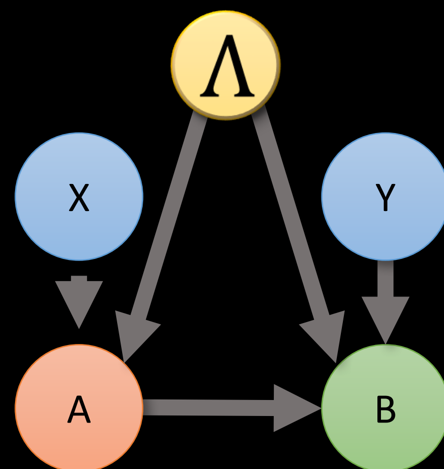
$$\langle O \rangle = \int d\lambda \;\; \rho(\lambda)O(\lambda) \quad \Longrightarrow \quad \langle E(x,y)\rangle = \langle A(\mathrm{x})\mathrm{B}(\mathrm{y})\rangle = \int d\lambda \;\; \rho(\lambda)A(x,\lambda)B(y,\lambda)$$

$$|S| = |E(x_0,y_0)\text{-}E(x_0,y_1)+E(x_1,y_0)+E(x_1,y_1)| \leq 2$$

Quantum Non-locality from a Causal Inference Perspective

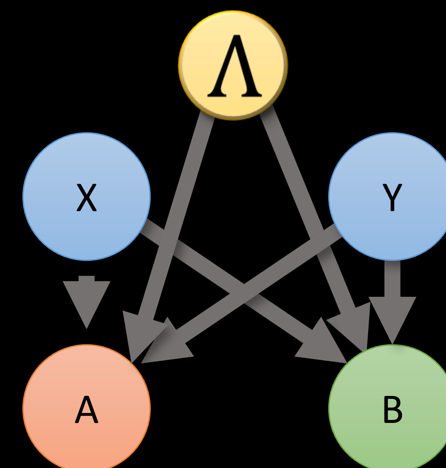
- Alternative causal structures can easily be represented with the graphical notation of directed acyclic graph





$$p(a|b,x,y,\lambda) = p(a|x,\lambda)$$

$$p(b|a,x,y,\lambda) = p(b|a,y,\lambda)$$



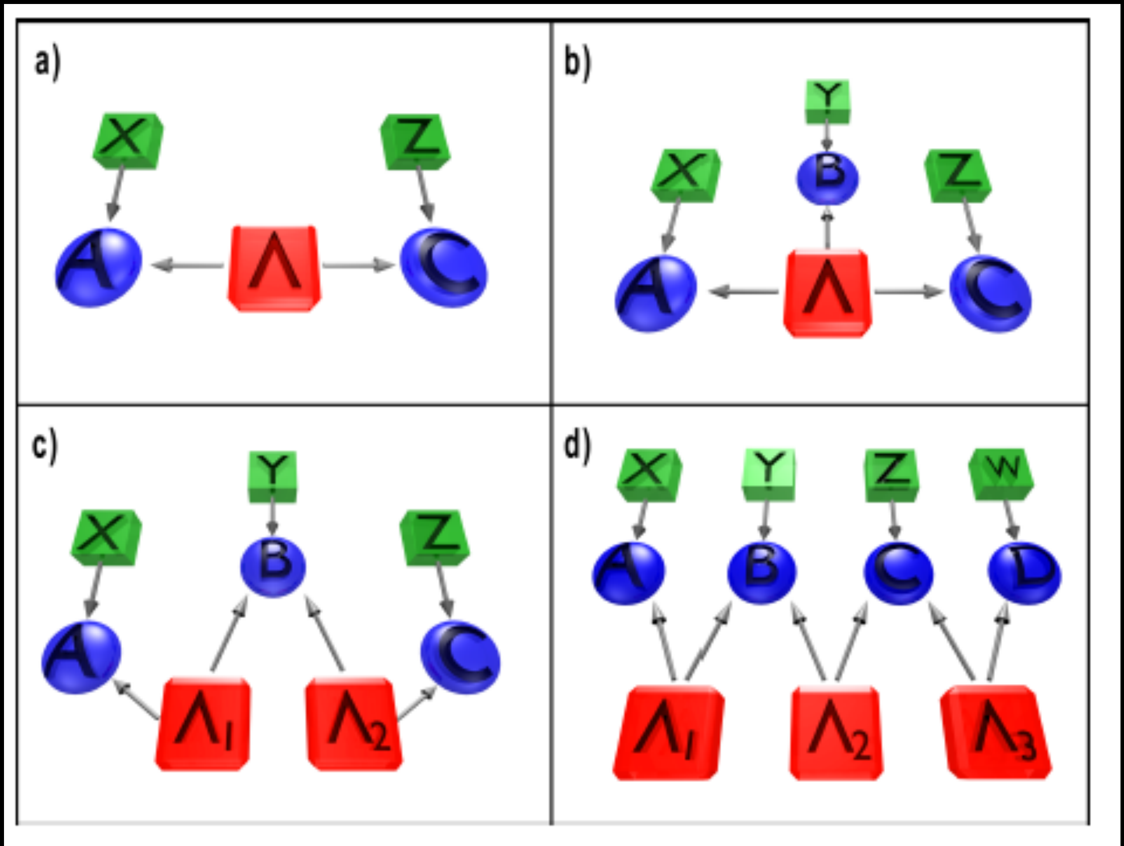
$$p(a|b,x,y,\lambda) = p(a|x,y,\lambda)$$

$$p(b|a,x,y,\lambda) = p(b|x,y,\lambda)$$

Release of locality

M.Ringbauer, C. Giarmatzi, R. Chaves, F. Costa, A-G. White, and A. Fedrizzi, *Science Advances* **2**, e1600162 (2016)

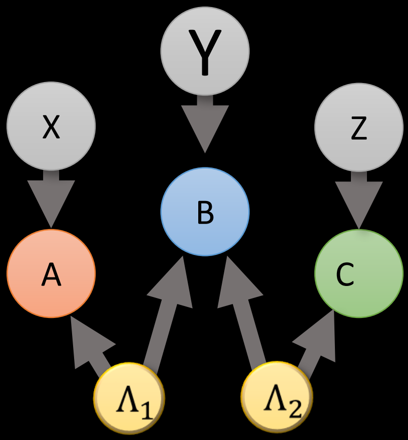
Representation of the causal structures underlying the networks as directed acyclic graphs



To generalize Bell's theorem to more complex networks

C. Branciard, D. Rosset, N. Gisin, and S. Pironio, *Phys. Rev. A*,85:032119 (2012)
Branciard, C., Gisin, N. & Pironio, S. *Phys. Rev. Lett.* 104, 170401 (2010).
Chaves, R., Kueng, R., Brask, J. B. & Gross, D. *Phys. Rev. Lett.* **114**, 140403 (2015).

Non-localiy in a tripartite scenario with two independent sources



Correlation between distant parties mediated by two independent sources

Bilocal Hidden Variable (BLHV) Model

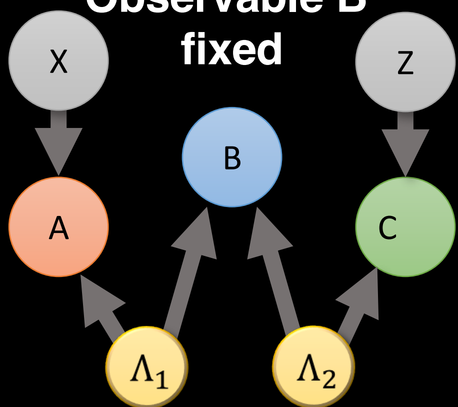
$$p(a,b,c|x,y,z) =$$

$$\int d\lambda_1 d\lambda_2 \ \boxed{\rho_1(\lambda_1)\rho_2(\lambda_2)} p(a|x,\lambda_1)p(b|y,\lambda_1,\lambda_2)p(c|z,\lambda_2)$$

C. Branciard, D. Rosset, N. Gisin, and S. Pironio, *Phys. Rev. A*,85:032119 (2012)
Branciard, C., Gisin, N. & Pironio, S. Phys. Rev. Lett. 104, 170401 (2010).
Tavakoli, A., Skrzypczyk, P., Cavalcanti, D. & Acín, A. Phys. Rev. A 90, 062109 (2014).
Chaves, R., Kueng, R., Brask, J. B. & Gross, D. Phys. Rev. Lett. 114, 140403 (2015).
Chaves, R. Phys. Rev. Lett. 116, 010402 (2016).
Rosset, D. et al. Phys. Rev. Lett. 116, 010403 (2016).

Bilocality inequality

Observable B fixed



$b = b_0 b_1 \qquad b_0, b_1 = 0{,}1$

$x, z = 0{,}1 \quad$ e $\quad a, b = 0{,}1$

$\longrightarrow \boxed{p(a, b_0 b_1, c|x, z)}$

$$\langle A_x B_y C_z \rangle = \sum_{a,b,c} (-1)^{a+b_y+c} p(a, b_0 b_1, c|x, z)$$

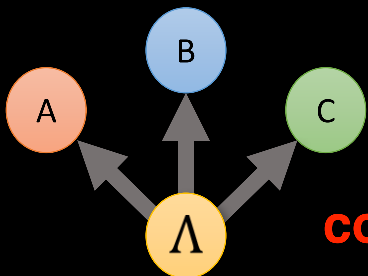
$$I = \frac{1}{4} \sum_{x,z=0,1} \langle A_x B_0 C_z \rangle \qquad J = \frac{1}{4} \sum_{x,z=0,1} (-1)^{x+z} \langle A_x B_1 C_z \rangle$$

Polynomial Bell inequality

$$\mathfrak{B} \equiv \sqrt{|I|} + \sqrt{|J|} \leq 1$$

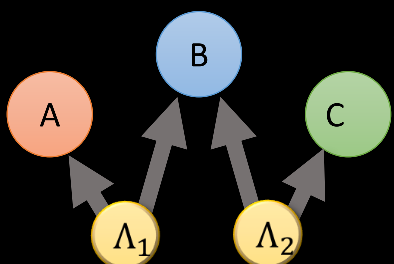
C. Branciard, D. Rosset, N. Gisin, and S. Pironio, *Phys. Rev. A* 85:032119 (2012)

Locality versus bilocality



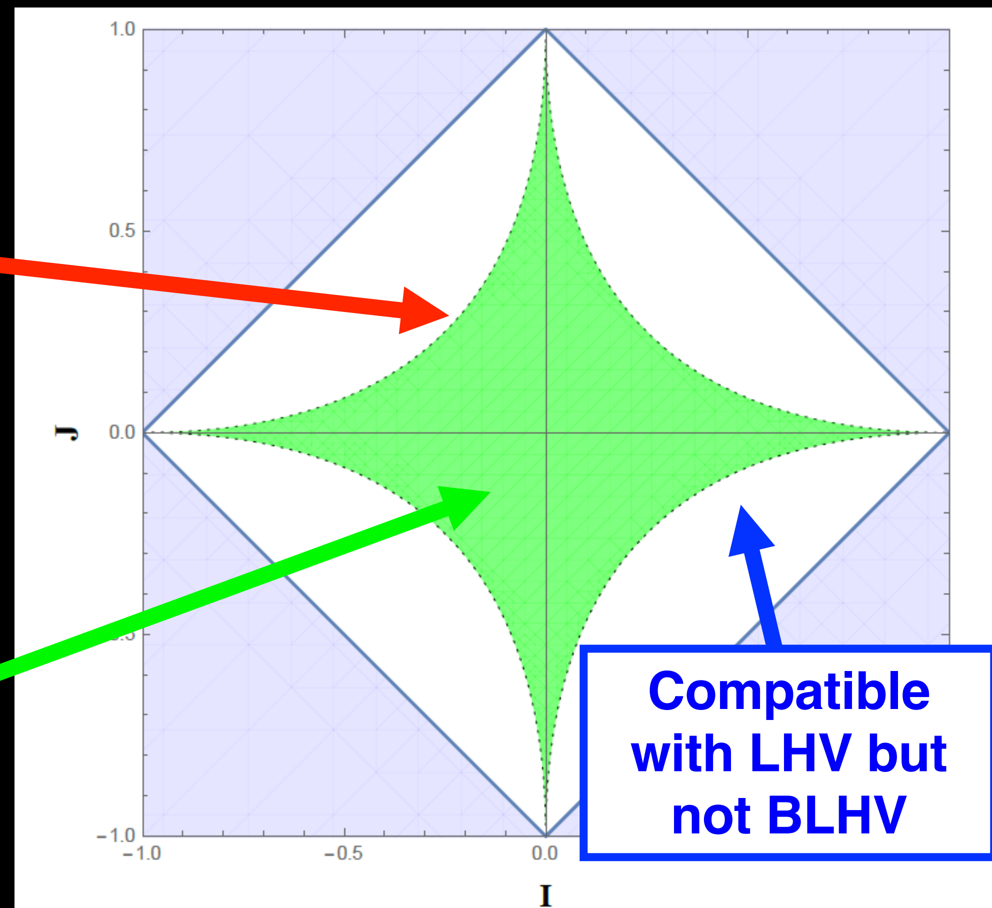
$$|I| + |J| \leq 1$$

convex set of correlations

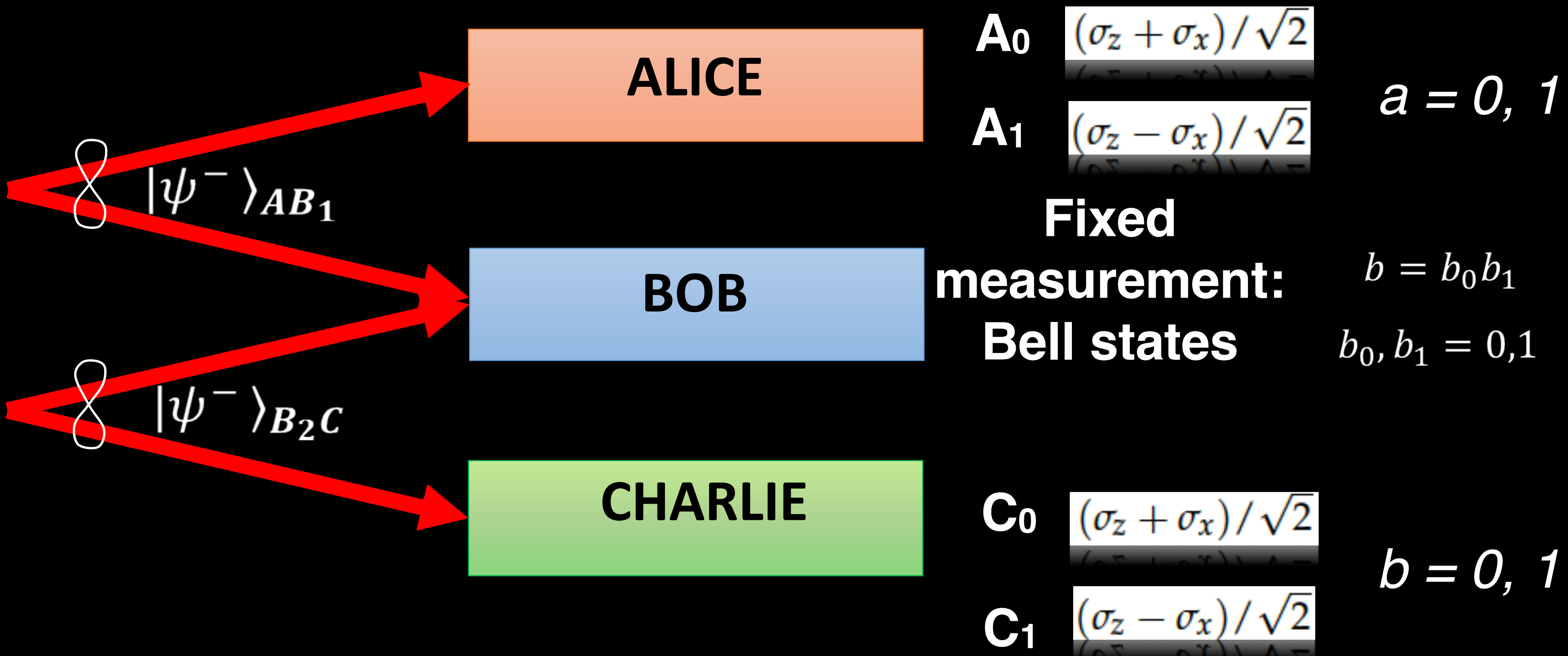


$$\sqrt{|I|} + \sqrt{|J|} \leq 1$$

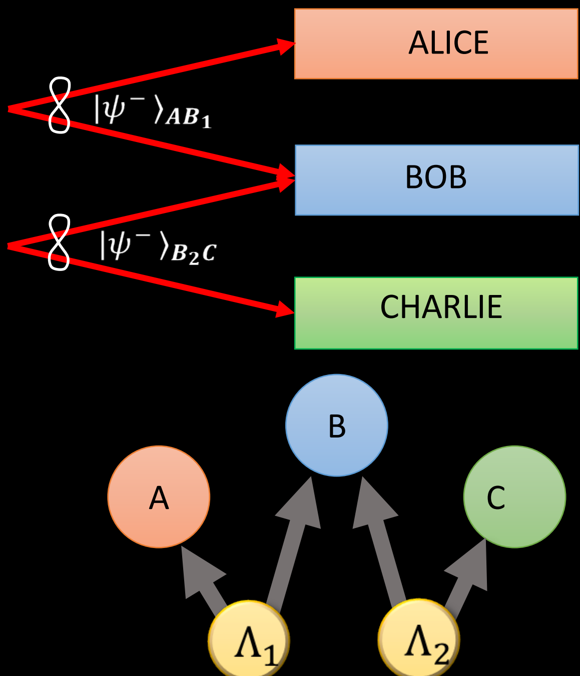
non-convex set of correlations



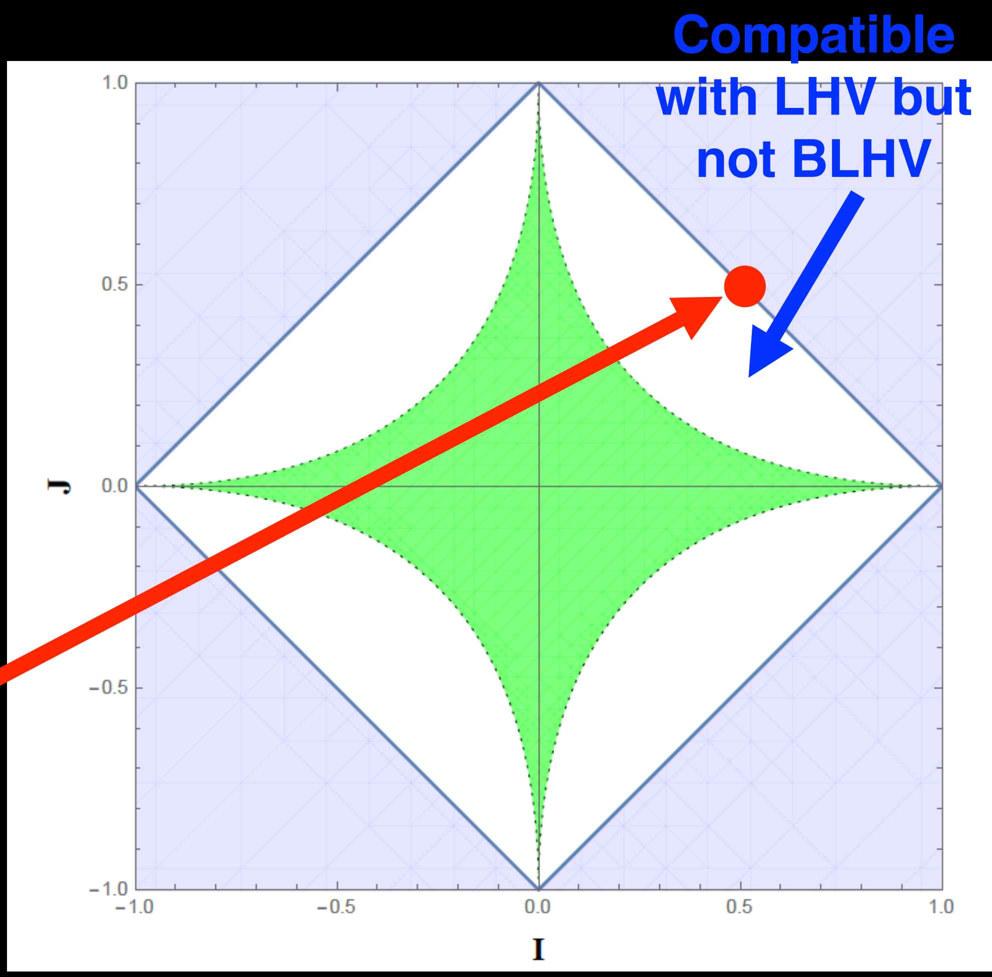
How to violate bilocality?
Entanglement swapping scenario



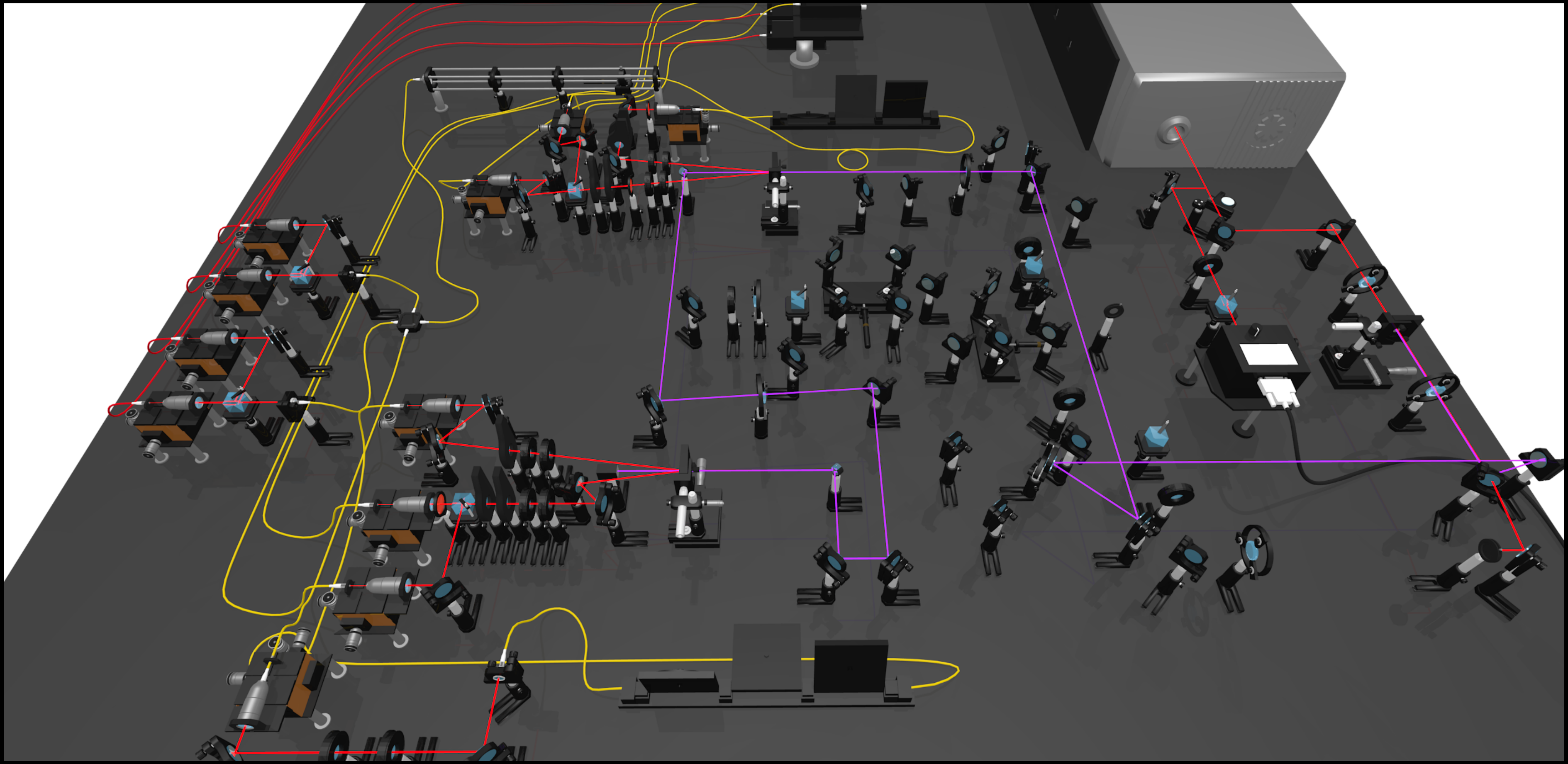
Violation of bilocality via entanglement swapping

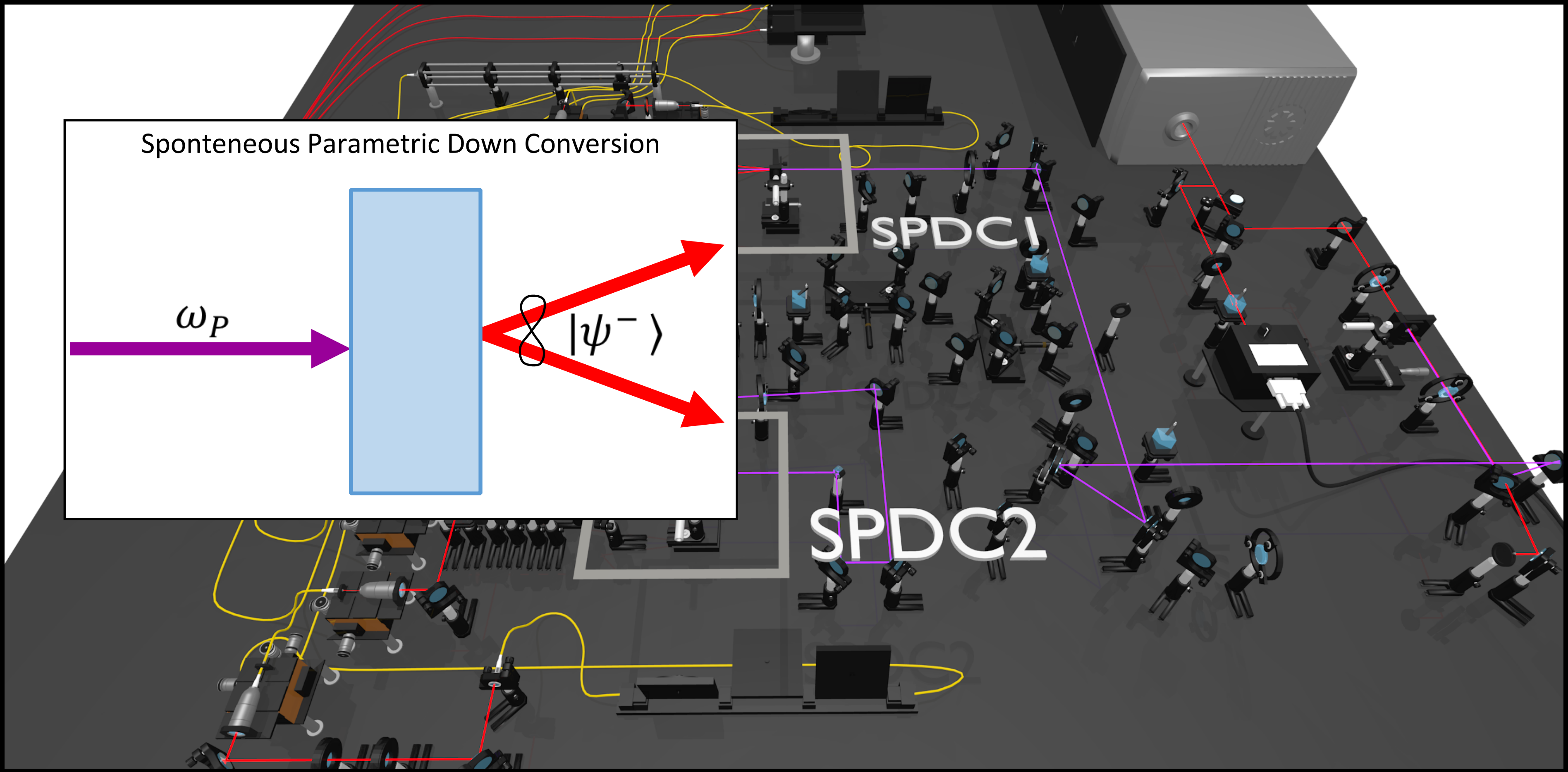


$$\mathfrak{B}_{QM} = 1.41 > 1$$

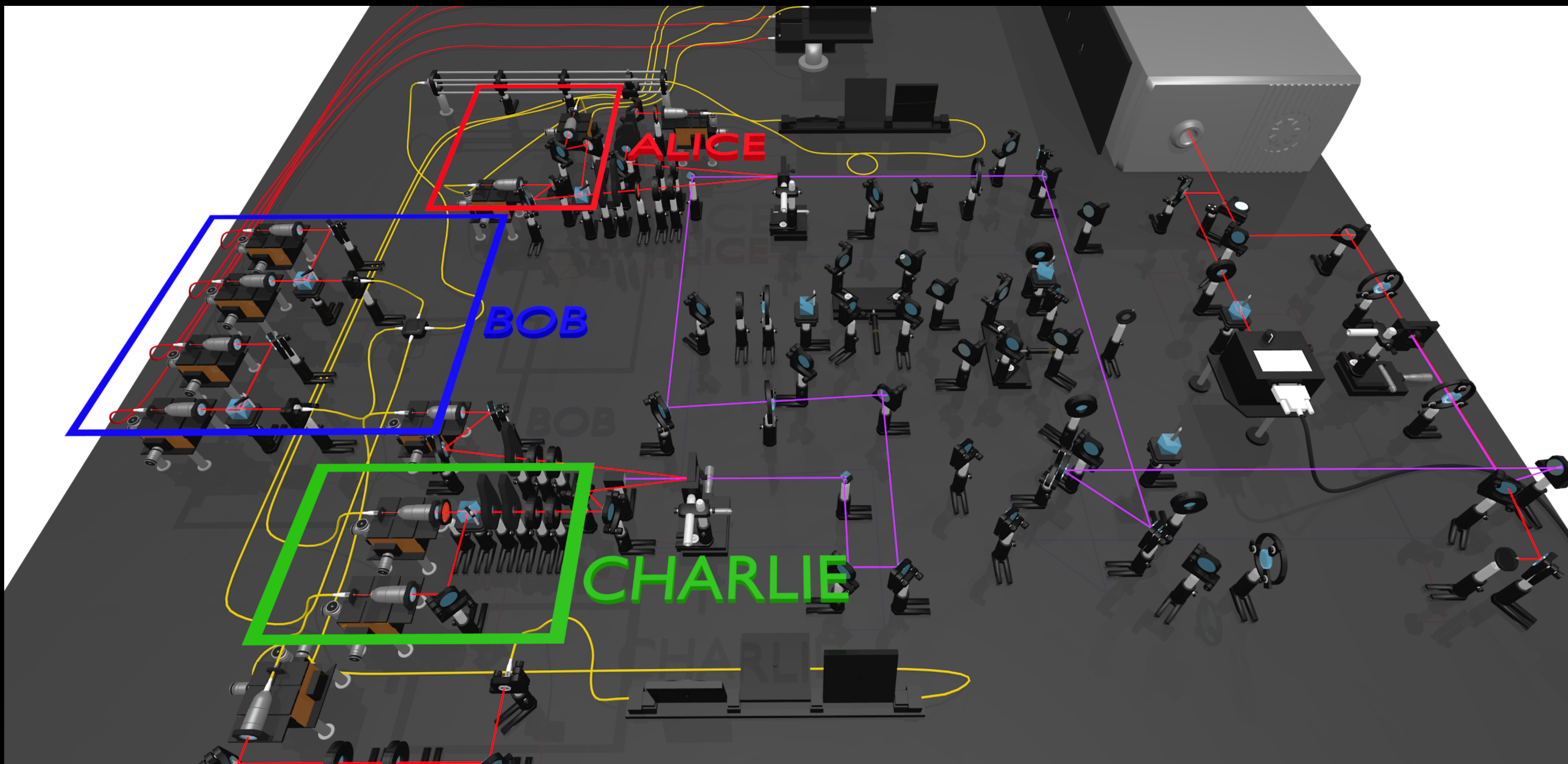


Our goal: to experimentally observe non-locality in a quantum network





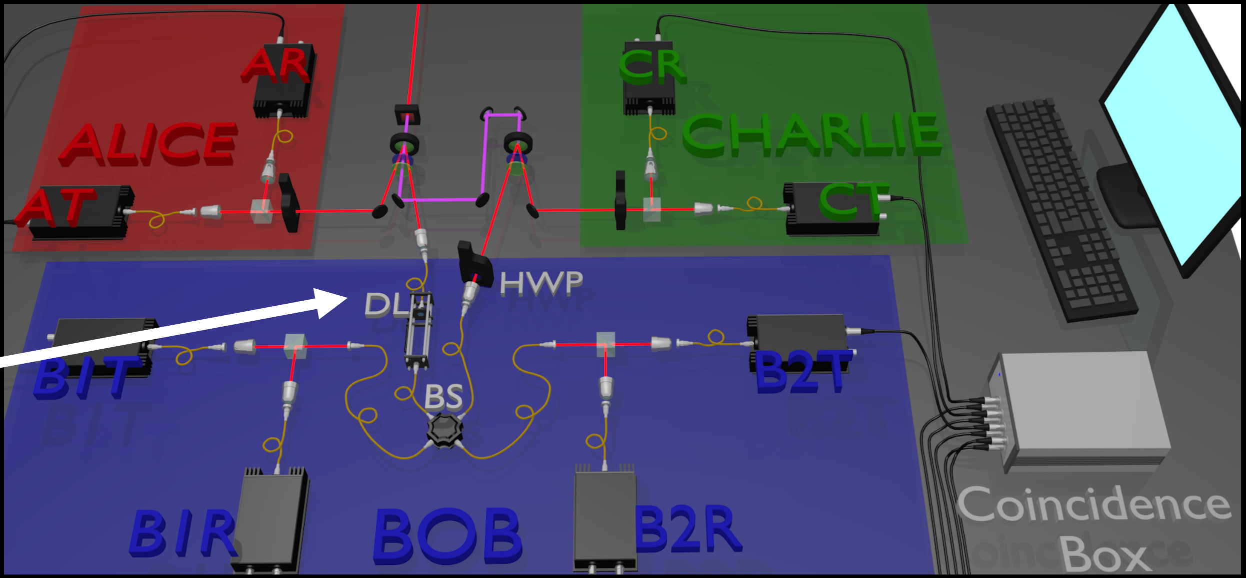
Sponteneous Parametric Down Conversion
ω_P
$\otimes\ |\psi^-\rangle$
SPDC1
SPDC2



ALICE
BOB
CHARLIE

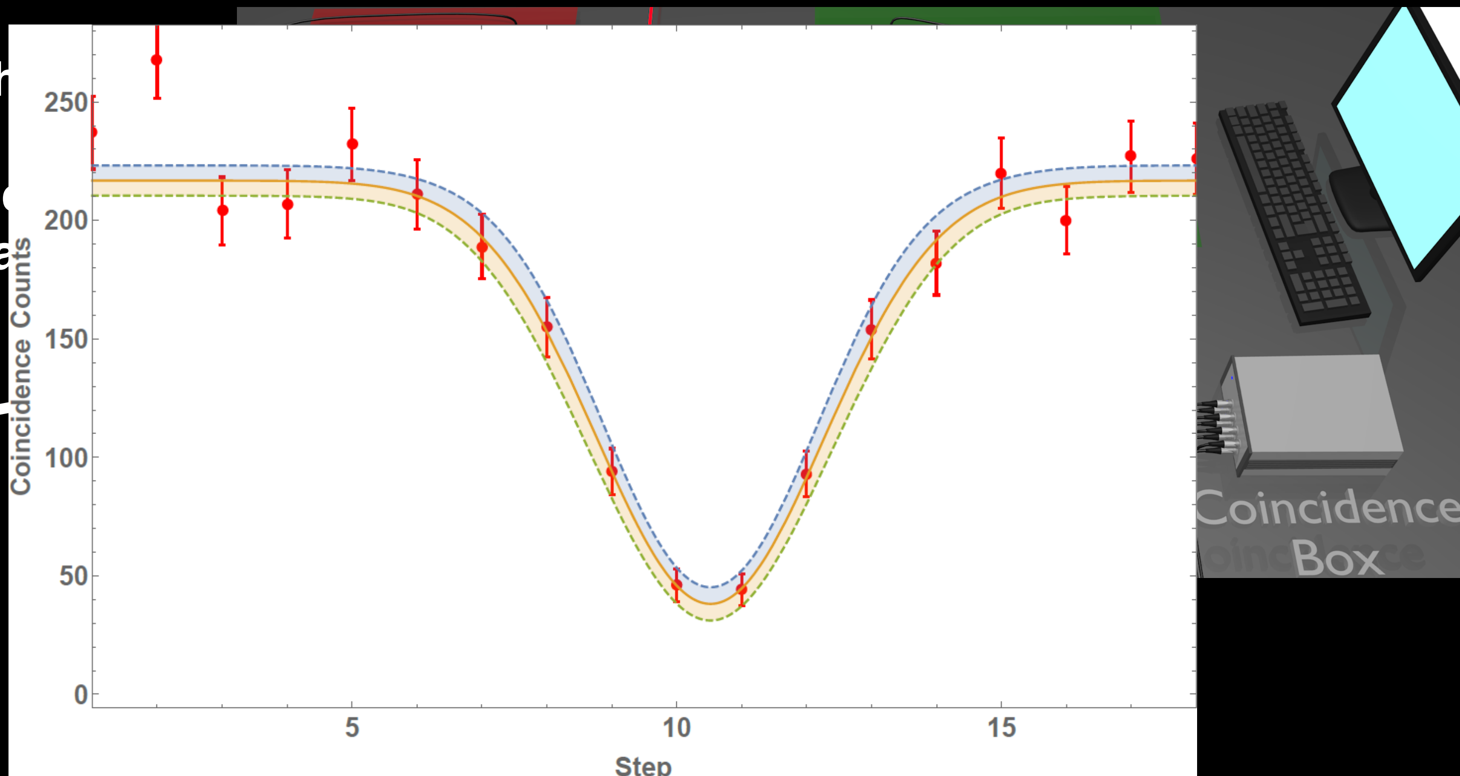
Optimization of the setup

Temporal matching between the two entangled pairs via Hong-Ou-Mandel effect

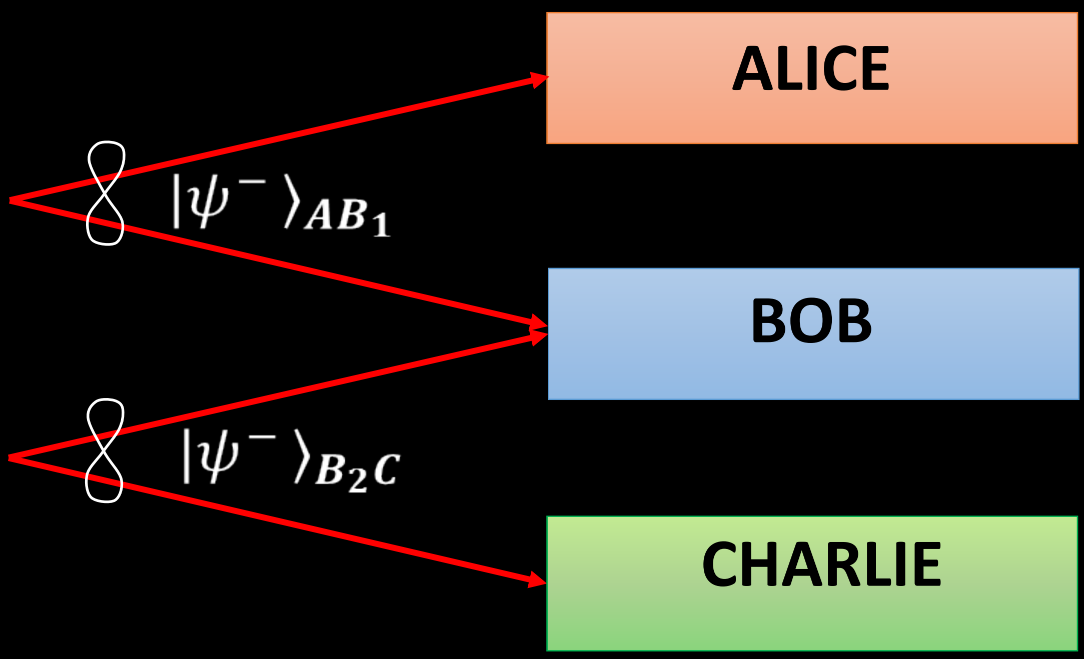


Optimization of the setup

Temporal match
between
the two entangl
via Hong-Ou-Ma
effect



Experimental bilocality violation in an entanglement swapping scenario



A_0 $(\sigma_z + \sigma_x)/\sqrt{2}$

A_1 $(\sigma_z - \sigma_x)/\sqrt{2}$

$a = 0, 1$

Fixed measurement: Bell states

$b = b_0 b_1$

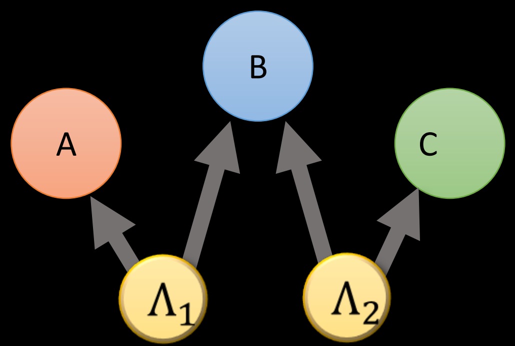
$b_0, b_1 = 0,1$

C_0 $(\sigma_z + \sigma_x)/\sqrt{2}$

C_1 $(\sigma_z - \sigma_x)/\sqrt{2}$

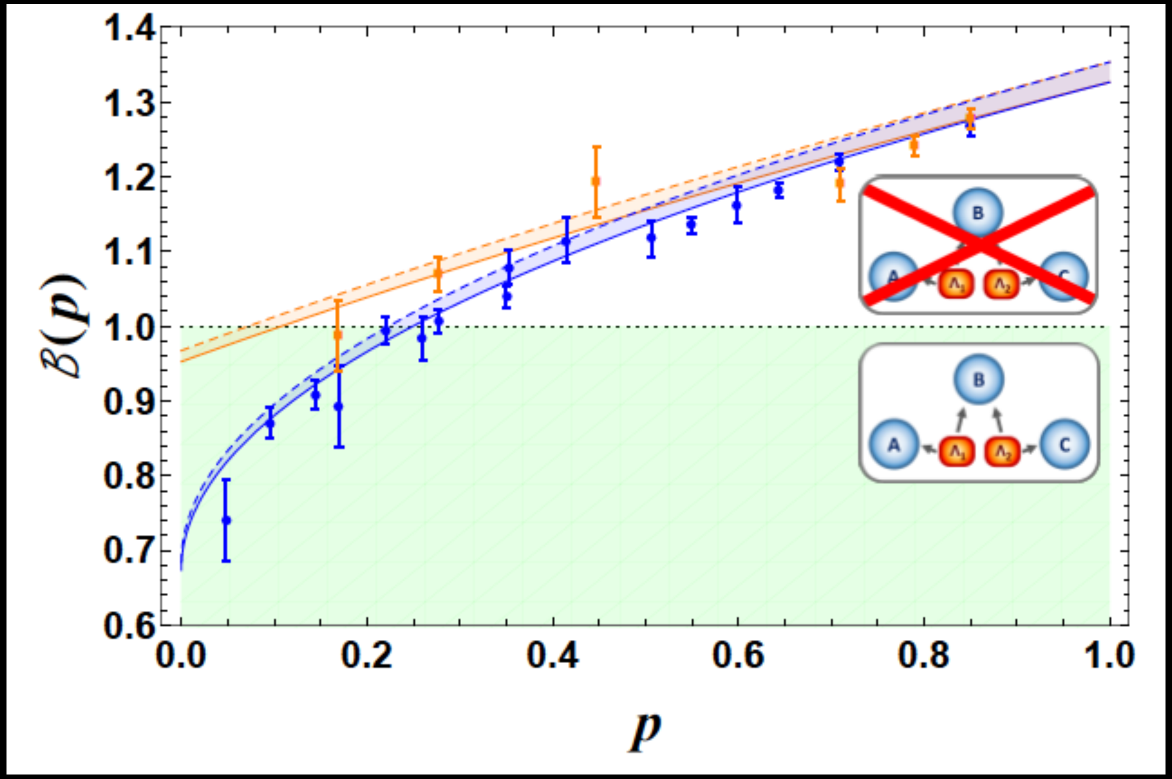
$b = 0, 1$

Violation of bilocality inequality versus the noise of Bell measurement



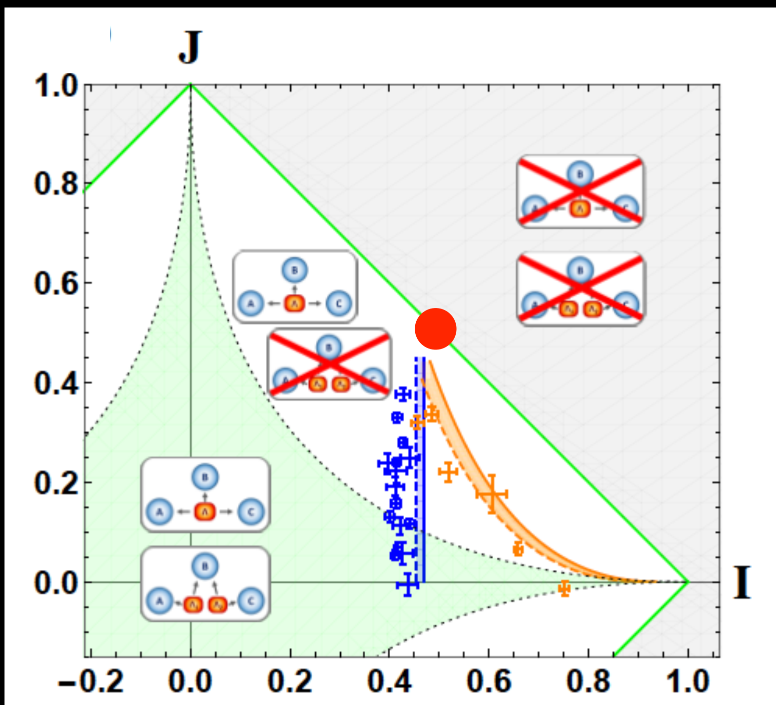
$$\mathfrak{B} = 1.268 \pm 0.014$$

Noise in Bell measurement
=
Distinguishability p between photons
(increase of temporal delay)

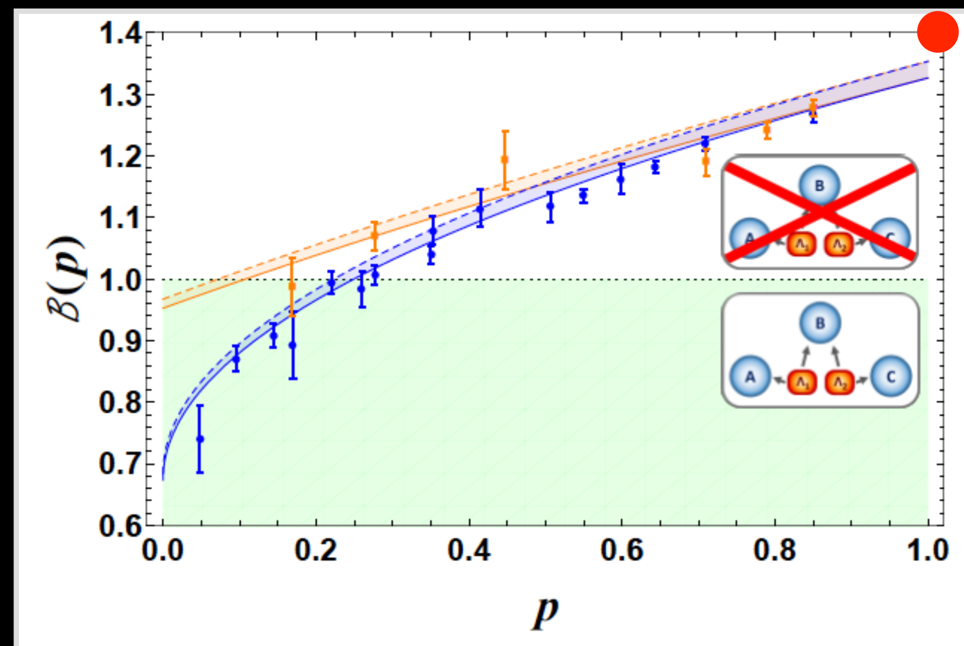


G. Carvacho, F. Andreoli, L. Santodonato, M. Bentivegna, R. Chaves, F. Sciarrino, *Nature Communications* 8, 14775 (2017)

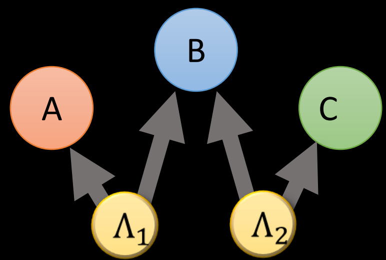
Experimental locality versus bilocality

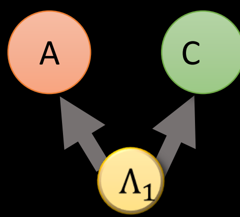


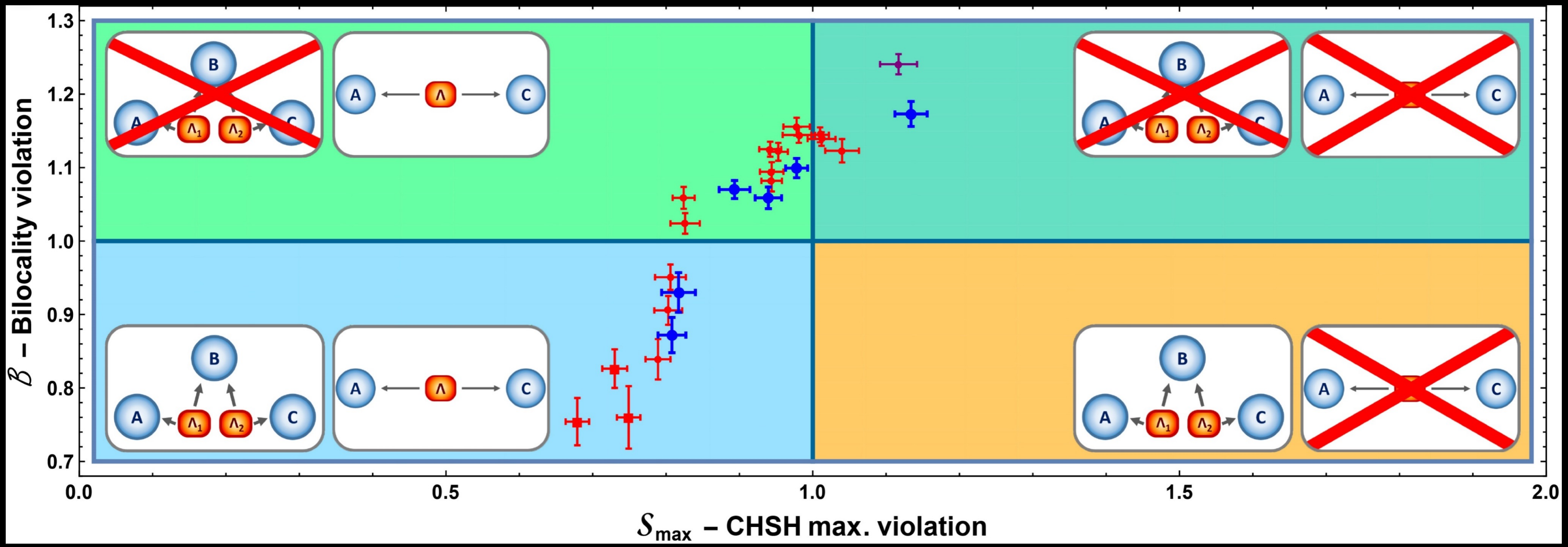
Specific LHV inequality



Experimental bilocality violation versus optimal CHSH violation on the swapped pair

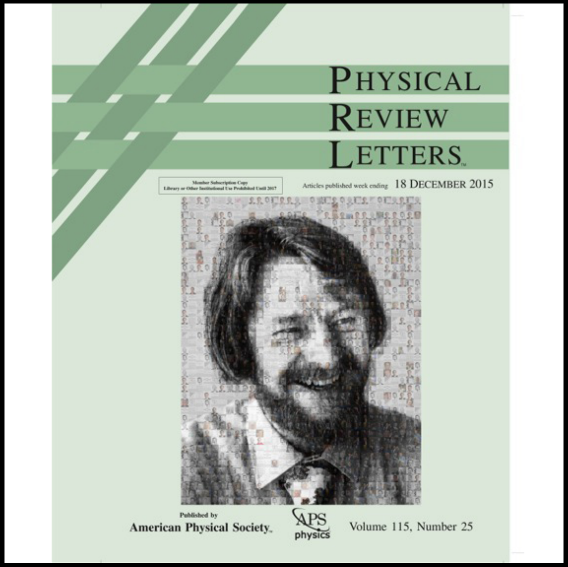






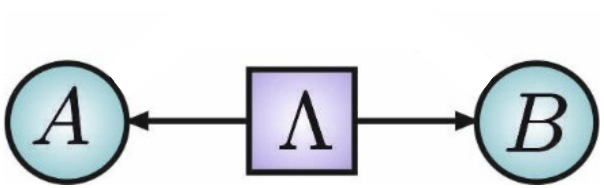
R. Horodecki, P. Horodecki, M. Horodecki, *Physics Letters A*, 200(5):340 – 344, 19

What is the simplest causal structure that admits a gap between classical and quantum causal models?



The simplest causal inference problem

Does A causally influence B?



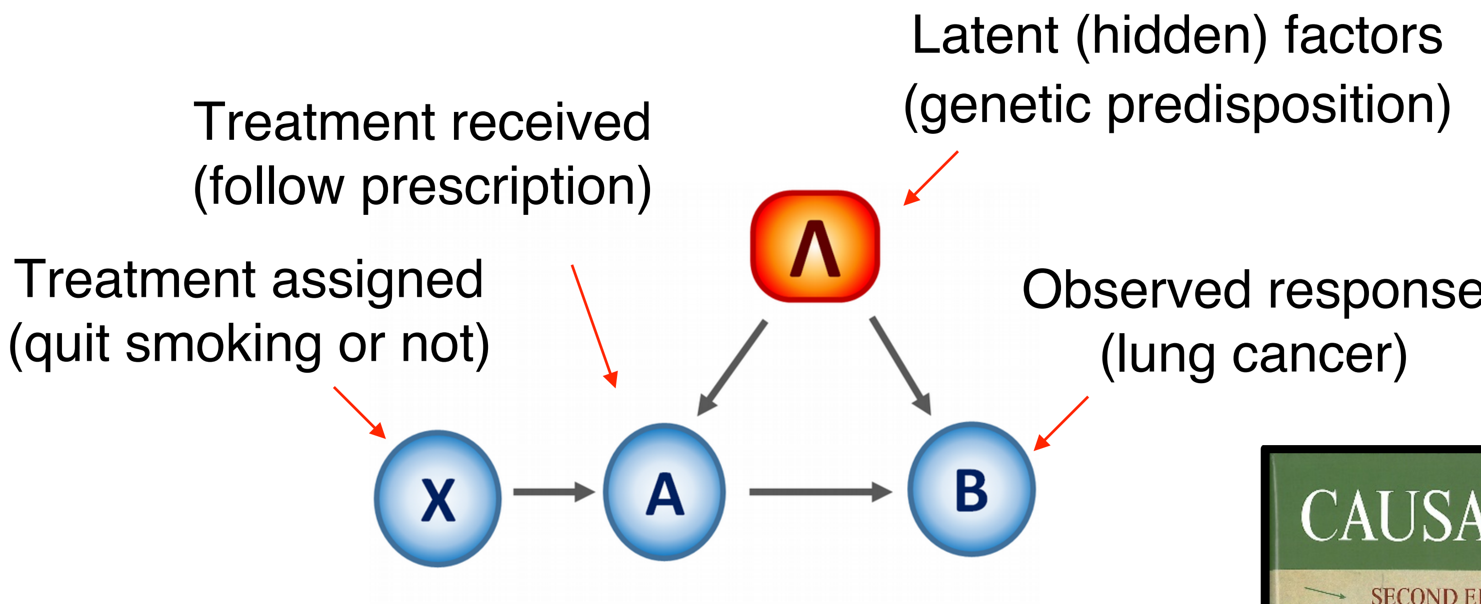
or

?

… but both causal models can explain all distributions $p(a, b)$

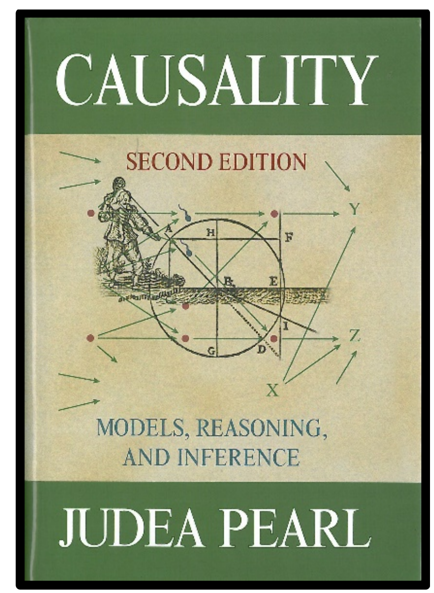
Instrumental test

Introduced in econometrics (Wright, 1928) to estimate parameters in linear models of supply and demand.



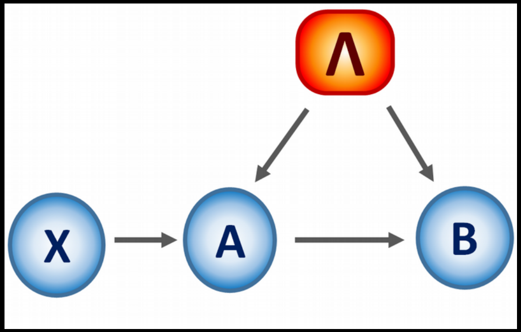
The instrumental DAG

(randomised clinical trials)



Instrumental inequalities

Instrumental causal models:



$$p(a,b|x) = \sum_\lambda p(\lambda)\, p(a|x,\lambda)\, p(b|a,\lambda)$$

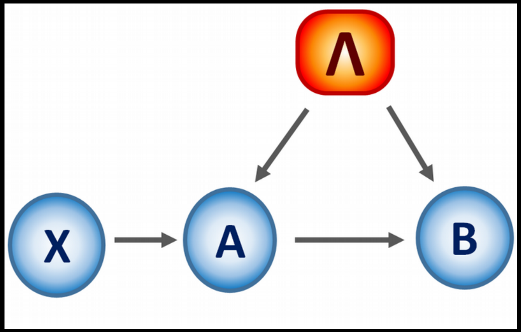
… they all satisfy:

$$\max_a \sum_b \max_x p(a,b|x) \leq 1$$

J. Pearl, UAI (1995).

Instrumental inequalities

Instrumental causal models:



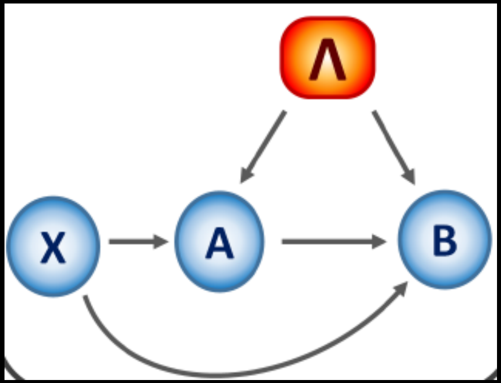
$$p(a,b|x) = \sum_\lambda p(\lambda)\, p(a|x,\lambda)\, p(b|a,\lambda)$$

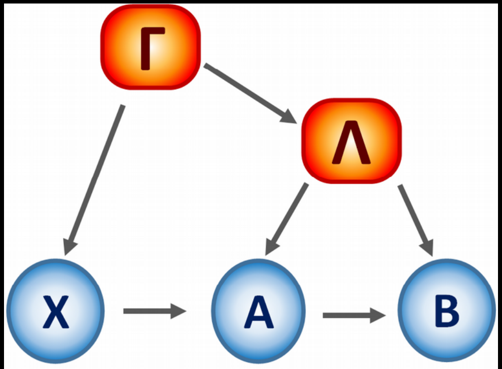
… they all satisfy:

$$\max_a \sum_b \max_x p(a,b|x) \leq 1$$

J. Pearl, UAI (1995).

- ***Classical*** instrumental-inequality ***violations possible only by non-instrumental*** *causal* ***models***





- Quantum mechanically ***no violation by quantum instrumental causal models.***

J. Henson, R. Lal, and M. Pussey, New J. Phys. **16**, 113043 (2014) .

Violation of a classical instrumental test with quantum instrumental causal models

If X is trichotomic, another instrumental inequality appears:

$$I_{\text{inst}} := -\langle B\rangle_{x=1} + 2\langle B\rangle_{x=2} + \langle A\rangle_{x=1} - \langle A\,B\rangle_{x=1} + 2\langle A\,B\rangle_{x=3} \leq 3$$

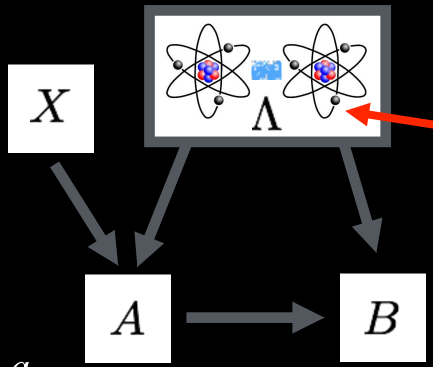
B. Bonet, UAI (2001).

Quantum instrumental causal models:

$$p_Q(a,b|x) := \mathrm{Tr}\left[M_x^{(a)} \otimes M_a^{(b)} \varrho_\Lambda\right]$$

(measurement setting x, measurement outcome a)

(measurement setting a, measurement outcome b)



$$\varrho_\Lambda = \varrho_{\Lambda_A \Lambda_B}$$

A quantum common cause

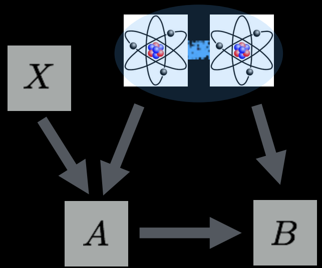
$$\varrho_\Lambda = |\Phi^+\rangle := \frac{1}{\sqrt{2}}\Big(|0_{\Lambda_A}\,0_{\Lambda_A}\rangle + |1_{\Lambda_A}\,1_{\Lambda_A}\rangle\Big) \Rightarrow I_{\text{inst}}(Q) = 1 + 2\sqrt{2} \approx 3.82 \;!!!$$

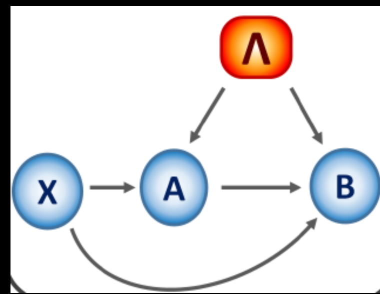
R. Chaves, G. Carvacho, I. Agresti, V. Di Giulio, L. Aolita, S. Giacomini, and F. Sciarrino, Nature Physics (2017).

Interpretations of quantum violations

•**Causal-inference viewpoint**:

Quantum effects ***change the interpretation*** of instrumental-inequality violations:





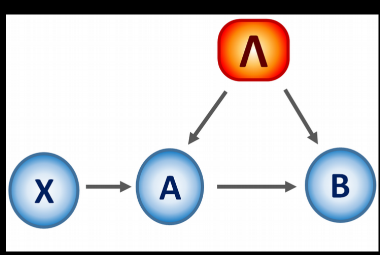
⇒

$$\min C_{X\to B} = \max\left[\frac{I_{\text{inst}}(Q)-3}{4},0\right]$$

Direct causal influence from X to B required to classically reproduce the quantum violation

•**Bell non-locality viewpoint**:

Instrumental-inequality violations by quantum instrumental causal models can be seen as a ***novel, stronger form of non-classicality***.



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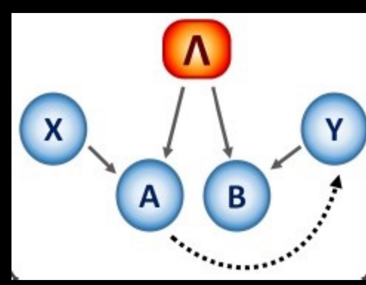
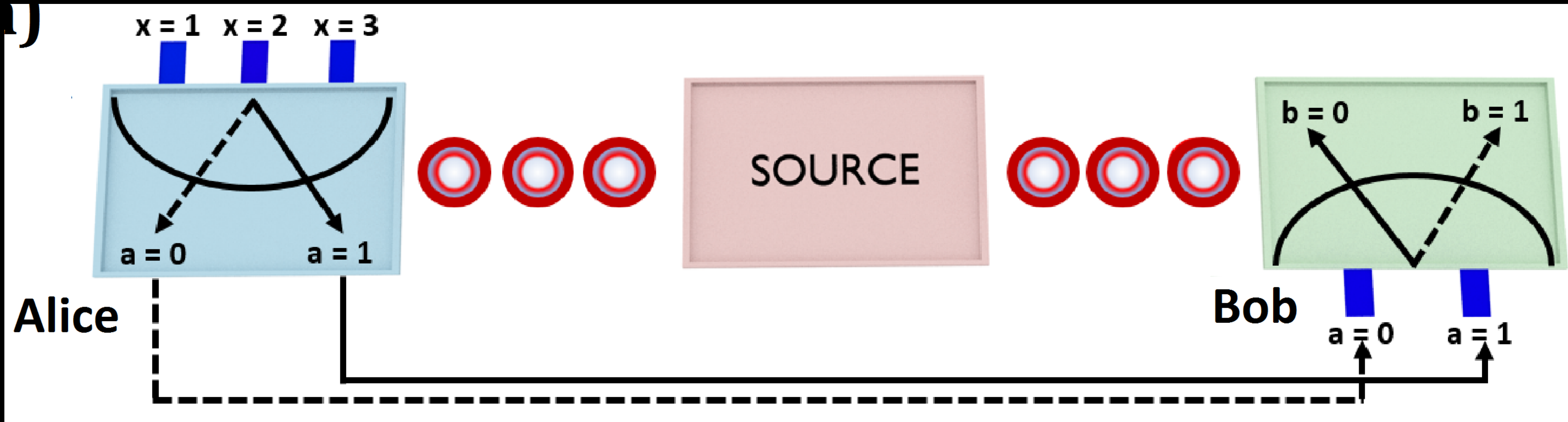


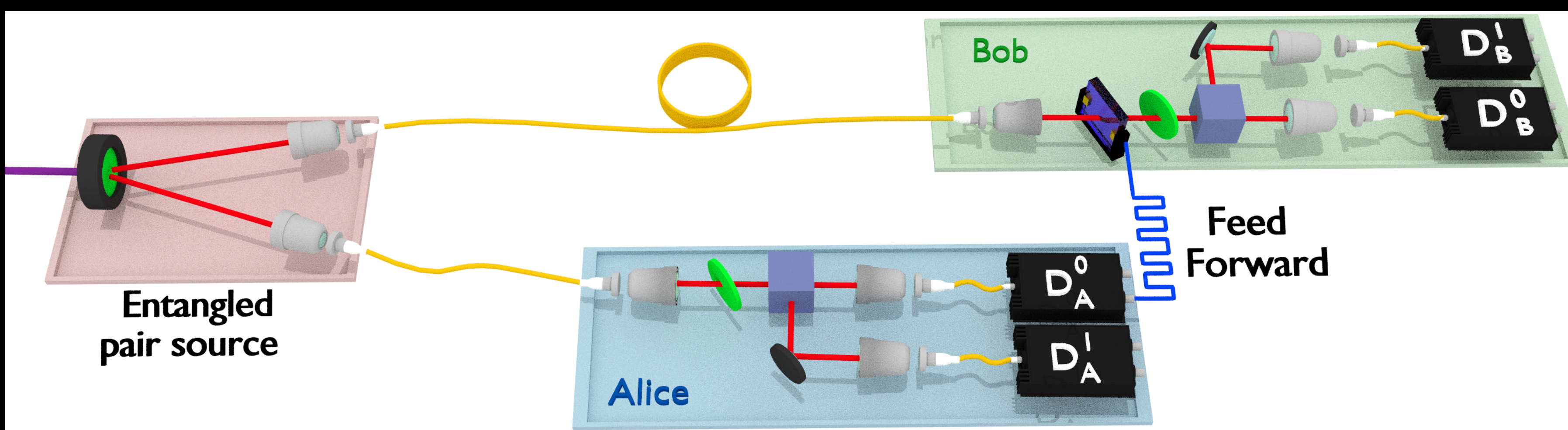
Quantum entanglement + outcome communication produces correlations more nonlocal than LHV models + outcome communication!!!

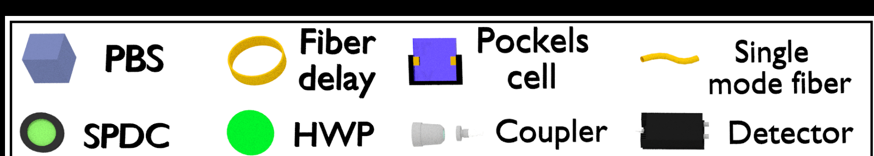
R. Chaves, G. Carvacho, I. Agresti, V. Di Giulio, L. Aolita, S. Giacomini, and F. Sciarrino, Nature Physics (2017).

Experimental scheme:



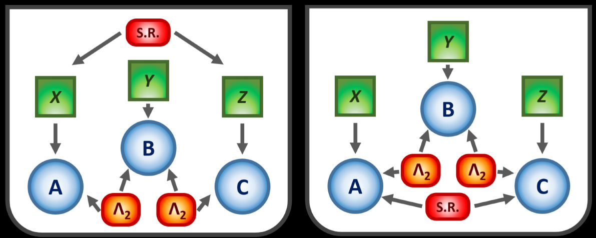
Implementation:

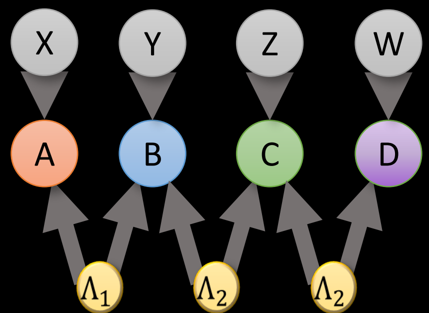




$$I_{\text{inst}}(Q_{\text{exp}}) = 3.258 \pm 0.020$$

Conclusion





I. Experimental violation of bilocality based on entanglement Swapping.

II. Experimental quantum violation of instrumentality tests

III. Device independent certification of a quantum delayed choice experiment

Next steps.. to experimentally address

Other causal structures

Application for quantum information processing

More complex scenarios

E. Polino, I. Agresti, D.Poderini, G. Carvacho, G. Milani, G. Barreto Lemos, R. Chaves, F.Sciarrino, arXiv:1806.00211
R. Chaves, G. Carvacho, I. Agresti, V. Di Giulio, L. Aolita, S. Giacomini, F. Sciarrino. Quantum violation of an instrumental test. Nature Physics (2017).
F. Andreoli, G. Carvacho, L. Santodonato, R. Chaves, F. Sciarrino, Maximal qubit violation of n-locality inequalities in a star-shaped quantum network, New J. Phys. 19 113020 (2017).
G. Carvacho, F. Andreoli, L. Santodonato, M. Bentivegna, R. Chaves, F. Sciarrino. "Experimental violation of local causality in a quantum network", Nature Communications 8, 14775 (2017)

QUANTUM LAB

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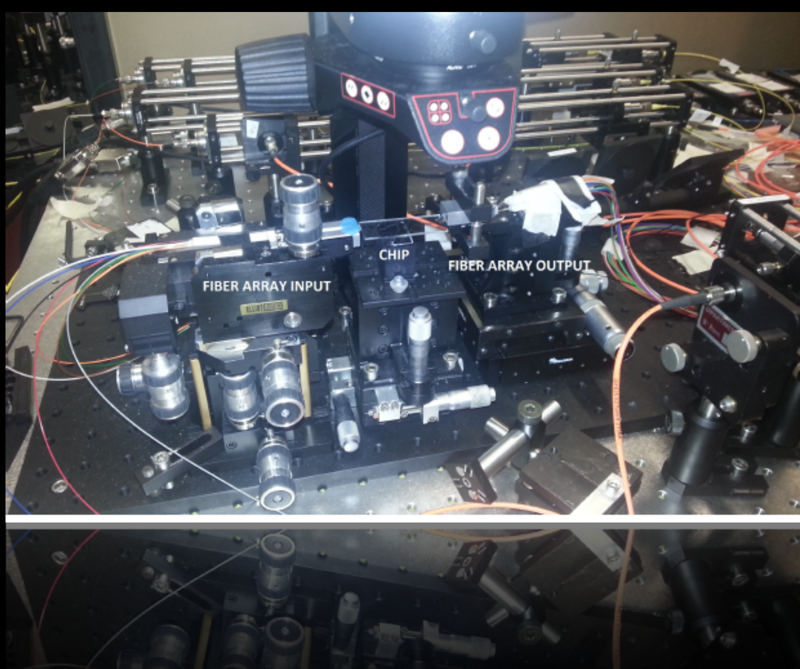

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