Quantum Steering: Experiments and Applications

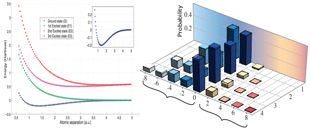
Devin H. Smith

Geoff Gillett, Marcelo P. de Almeida, Till J. Weinhold, Alessandro Fedrizzi, Thomas Gerrits*, Brice Calkins*, Adrianna Lita*, Sae Woo Nam*, Cyril Branciard, Howard G. Wiseman† and Andrew G. White

Introduction

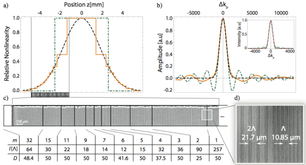
1. What is steering?
2. Why steering?
3. Demonstrating steering
4. Using steering

Quantum simulation & emulation



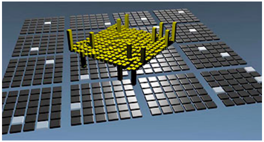
Nature Chemistry **2**, 106 (2010)
Physical Review Letters **104**, 153602 (2010)
New Journal of Physics **13**, 075003 (2011)
Nature Communications **3**, 882 (2012)

Quantum photonics



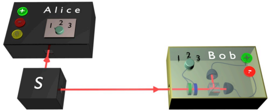
Optics Express **19**, 55 (2011)
Journal of Modern Optics **58**, 276 (2011)
Optics Express **19**, 22698 (2011)

Quantum computation



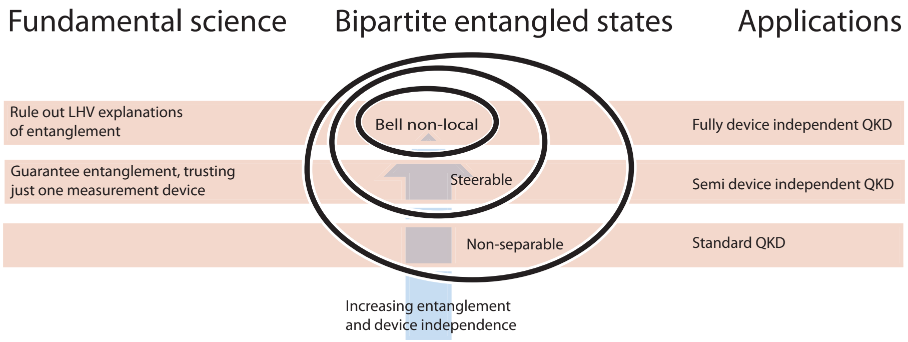
Nature Physics **5**, 134 (2009)
Journal of Modern Optics **56**, 209 (2009)
New Journal of Physics **12** 083027 (2010)
Physical Review Letters **106**, 100401 (2011)

Quantum foundations



Physical Review Letters **104**, 080503 (2010)
Proceedings of the National Academy of Sciences **108**, 1256 (2011)
New Journal of Physics **13**, 053038 (2011)
Physical Review Letters **106**, 200402 (2011)
Nature Communications **3**, 625 (2012)

Steering


Fundamental science
Bipartite entangled states
Applications
Rule out LHV explanations of entanglement
Bell non-local
Fully device independent QKD
Guarantee entanglement, trusting just one measurement device
Steerable
Semi device independent QKD
Non-separable
Standard QKD
Increasing entanglement and device independence

Steering as a game

1. Bob gives Alice a list of possible measurements he will perform
2. Alice sends Bob a state
3. Bob tells Alice which measurement from the list he will do
4. Alice predicts Bob's measurement outcome

How often can Alice win at this game?

Wiseman, Jones and Doherty Phys. Rev. Lett. 98 140402 (2007)

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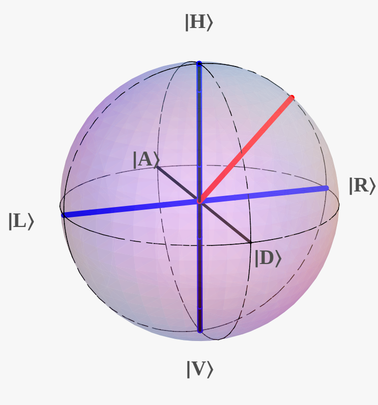
Classical Optimum

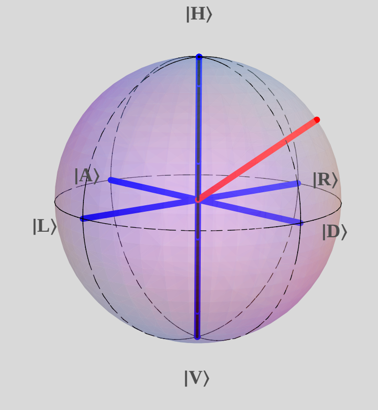
Two bases/2D System



$$P(\text{win}) = \left(\langle 0| \left(\cos\frac{\pi}{8}|0\rangle + \sin\frac{\pi}{8}|1\rangle \right) \right)^2 = \frac{1}{4}(2+\sqrt{2}) \approx 0.85$$

Classical Optimum

Three bases/2D System



$$P(\text{win}) = 2\left(1 - \frac{1}{\sqrt{3}}\right)$$

Classical Optimum

Infinite bases/2D System

Now any random pure state is optimal for Alice:

$$P(\text{win}) = \iint_{\theta>0} \langle H|\psi\rangle \, \mathrm{d}\psi = \frac{3}{4}$$

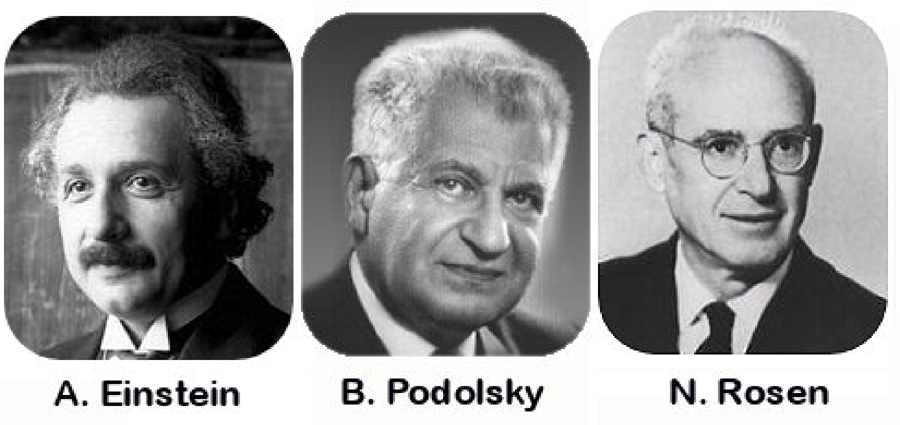
Quantum Optimum

Still 2D System

Alice sends Bob half of a maximally entangled state.
When Bob declares his basis choice, Alice uses it to make a measurement.
She can "steer" him perfectly

"It is rather discomforting that the theory should allow a system to be steered or piloted into one or the other type of state at the experimenter's mercy in spite of his having no access to it" – E. Schrödinger

Convince EPR



You could convince a skeptical second party of “spooky action at a distance” by steering their outcomes

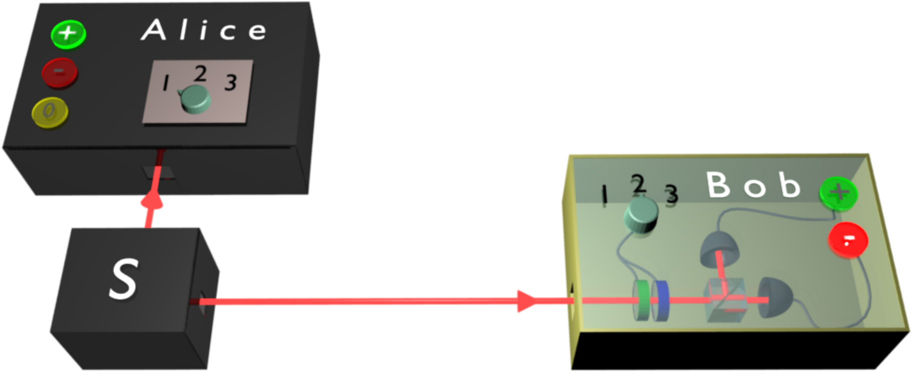
Photo deskarati.com

Nonlocality

	Steerability	Uncertainty
No-signalling	“Perfect”	Perfect
Quantum	Perfect	
Classical		Perfect

Oppenheim and Wehner, Science 330, 10721074 (2010).

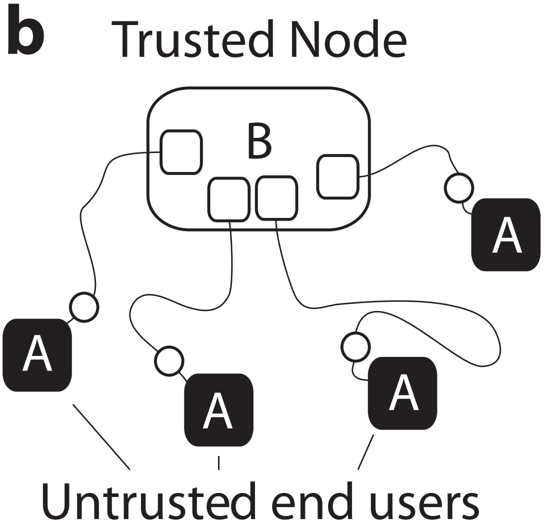
Convince your bank



You can convince your bank that you share entanglement with them even if they think you're a theorist.

Certify a channel

One-sided-device-independent Quantum Key Distribution



C Branciard *et al.*, Phys. Rev. A 85, 010301(R) (2012)

So why do we care?

- Alice can convince Bob of entanglement even if he doesn't believe in it.
- Alice can convince Bob of entanglement even if he doesn't trust her to operate experimental apparatus
- We can use it to certify quantum channels for use for other quantum communication primitives
- 1sDI-QKD

Alice is restricted by her loss!

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Steering Inequalities

Linear

$$S_N \equiv \frac{1}{n}\sum_{k=1}^{n}\left\langle A_k \hat{\sigma}_k^B \right\rangle \leqslant C_n(\eta)$$

$$C_\infty(\eta) = 1 - \frac{\eta}{2}$$

EG Cavalcanti *et al.* Phys. Rev. A 80, 032112 (2009)

Steering Inequalities

Quadratic

$$S_{N\in\{2,3\}} \equiv \sum_{i=1}^{N} \sum_{a=\pm1,0} P(A_i = a)\, \langle \hat{B}_i \rangle^2_{A_i=a} \leqslant 1$$

Error tolerance and loss

Alice *will* lose some photons. Solution?

1. Allow her a third outcome
2. Force her to choose an outcome

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Wiseman, Jones and Doherty Phys. Rev. Lett. 98 140402 (2007)

Why does loss matter?

Alice can use "loss" events to hide inconvenient results from Bob even when she doesn't have entanglement.

By losing $\frac{N-1}{N}$ of the photons she can "steer" perfectly

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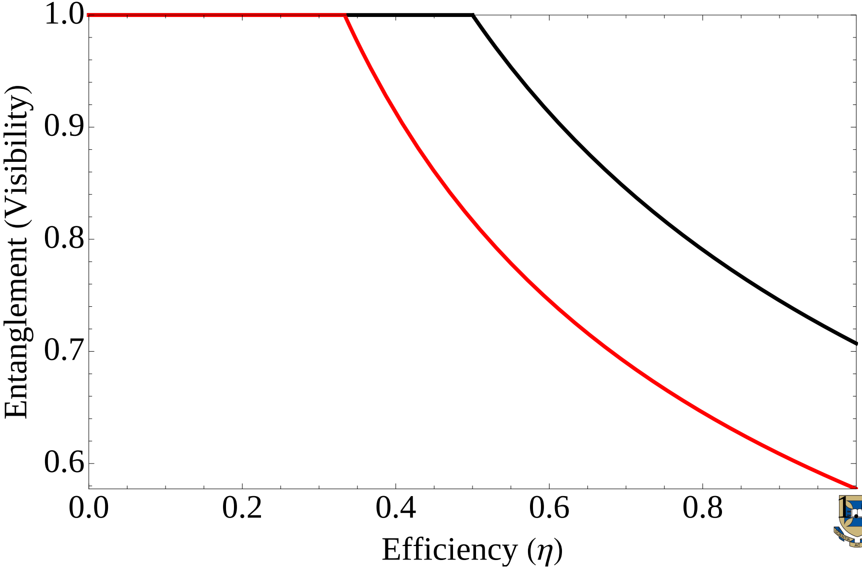
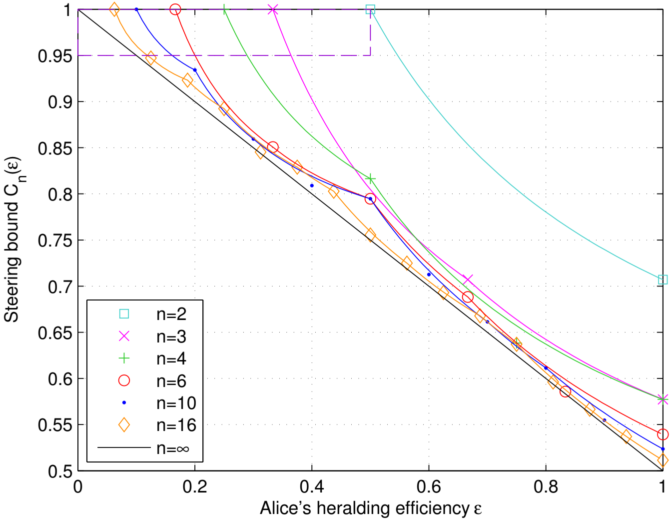
Quadratic Inequalities

Loss tolerance



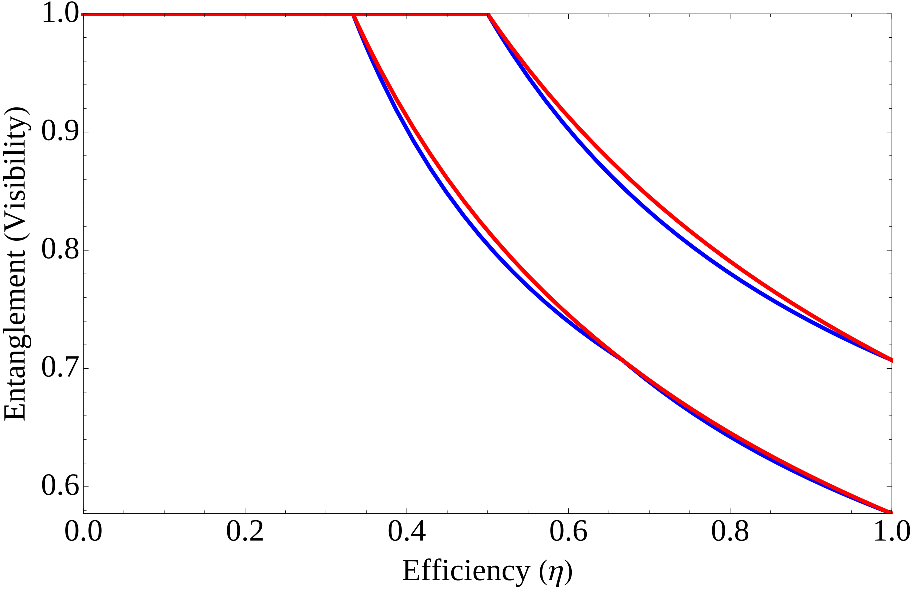
Linear Inequalities

Loss tolerance



A.J. Bennet *et al.*, Phys. Rev. X 2, 031003 (2012)

Comparison



1.0
0.9
0.8
0.7
0.6
Entanglement (Visibility)
0.0
0.2
0.4
0.6
0.8
1.0
Efficiency (η)

So why try it now?

After 70 years, why are we steering states *now?*

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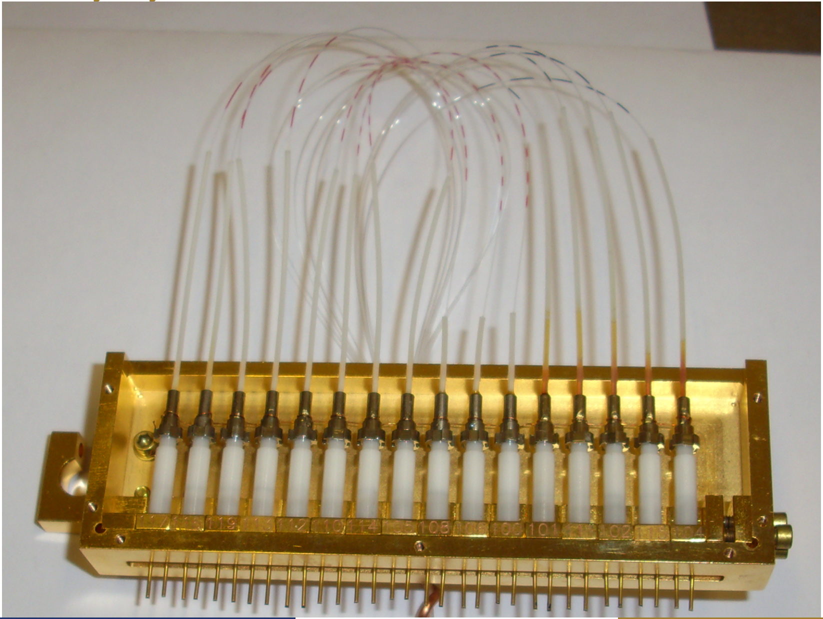
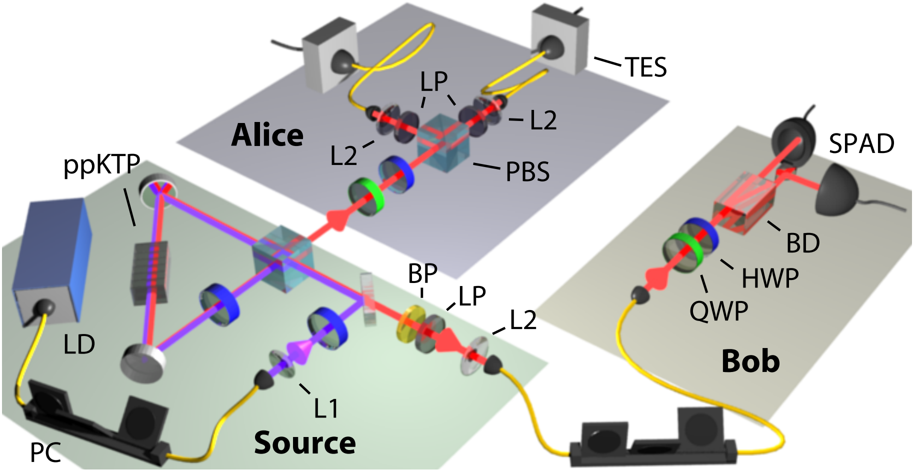


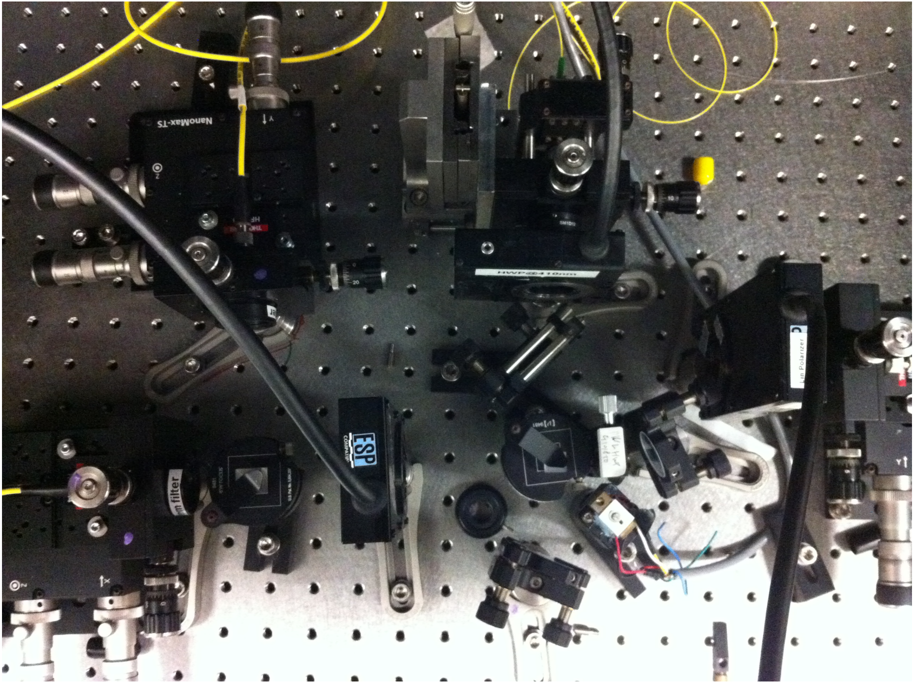
So why try it now?

After 70 years, why are we steering states *now?*

Transition Edge Sensors are approximately twice as efficient as standard SPADs.

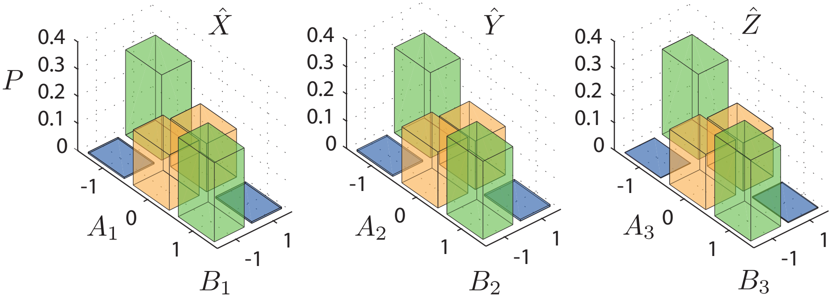
Apparatus diagram





NanoMax-TS
HWP@410nm
ESP
Lin Polarizer
filter

Experimental results

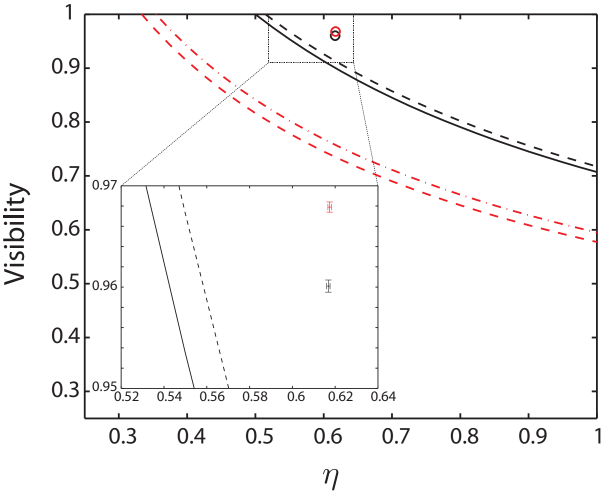


$$S_2 = 1.1410 \pm 0.0014 \gg 1,$$
$$S_3 = 1.7408 \pm 0.0017 \gg 1$$

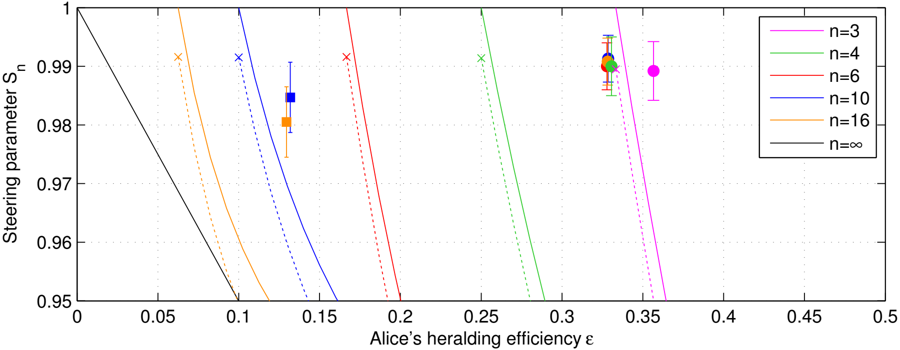
DH Smith, G Gillett *et al.*, Nat. Commun. 3:625 (2012)

Experimental results, con't

Loss tolerance

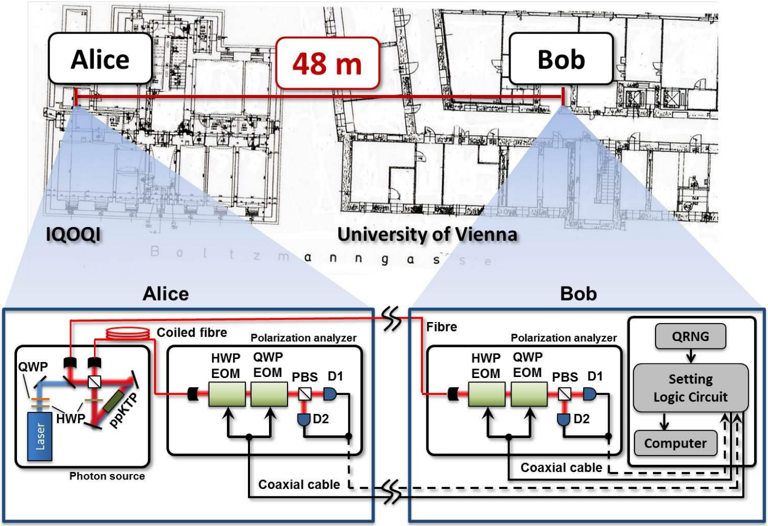


Griffith University's experimental results



AJ Bennet *et al.*, Phys. Rev. X 2, 031003 (2012).

And a third result from Vienna



$S_3 = 1.049 \pm 0.002 \gg 1$

B Wittmann, S Ramelow *et al.*, New J. Phys. 14, 053030 (2012)

Compare and contrast

	UQ	Griffith	Vienna
Inequality	Quadratic	Linear	Quadratic
Efficiency (%)	62	13–35	38
Nonlocality	No	No	Yes
Violation (σ)	67-200	2.6-5.3	25

DH Smith, G Gillett *et al.*, Nat. Commun. 3:625 (2012)
AJ Bennet *et al.*, Phys. Rev. X 2, 031003 (2012)
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Corrections for Bob's imperfections

It turns out that

$$S_N \equiv \sum_{i=1}^{N} \sum_{a=\pm 1,0} P(A_i = a) \, \langle \hat{B}_i \rangle^2_{A_i=a} \leqslant 1$$

only holds if $\hat{B}_i$ are perfect.

They aren't. They're neither orthogonal nor projective.

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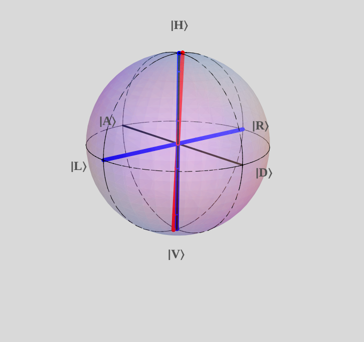
Nonorthogonal measurements



If the $\hat{B}_i$ aren't orthogonal, the classical limit goes up because results in different bases are correlated.

$$S_N \leqslant 1 + (N-1)\epsilon$$

where $\epsilon = \vec{b}_i \cdot \vec{b}_j$.

In our experiment, $\epsilon_3 = 0.0134 \pm .0007$ and $\epsilon_2 = (1.3 \pm 1.5) \times 10^{-4}$

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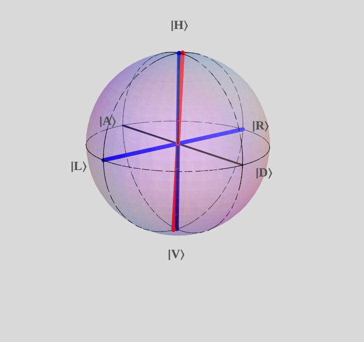

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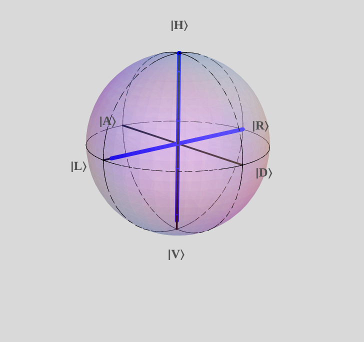
Non-ideal Projection



If there is a systematic bias in the B_i, the classical limit goes up due to that bias. The dominant source of bias in our experiment was differential loss between the detectors, which leads to

$$S_N \leqslant \frac{\eta_>}{\eta_<}[1 + (N-1)\epsilon]$$

We had $\frac{\eta_>}{\eta_<} = 1.0115 \pm 0.0007$

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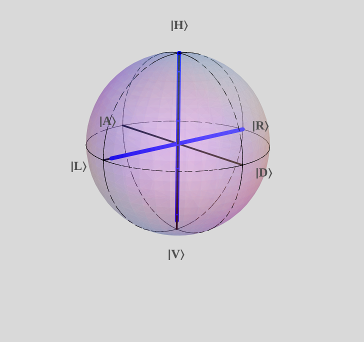

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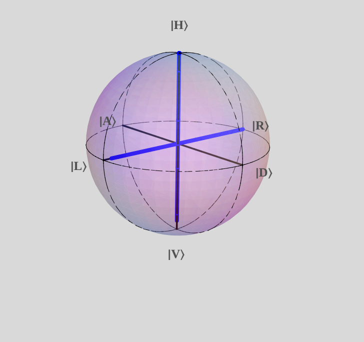

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Larger Hilbert space

What happens if additional degrees of freedom are sent to Bob?

We don't rigorously know.

We conjecture that a squashing argument like one used in QKD will show that this is an "easy" problem to solve in two bases

Randomized outcomes when multiple photons are detected is the hopeful solution

It is known that such a squashing argument doesn't apply to 3 bases

T Moroder *et al.*,Phys. Rev. A 81, 052342 (2010).

N Baudry, private communication

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Conclusion

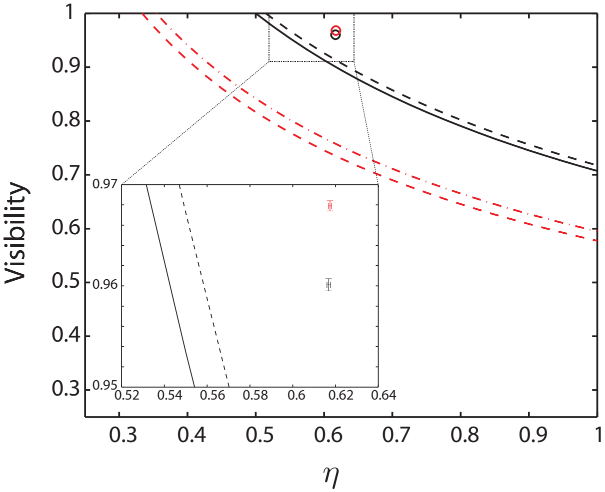
We correct our bounds, finding that, classically:

$$S_{2c} = 1.0291 \pm 0.0019$$
$$S_{3c} = 1.062 \pm 0.003$$

So we have violated a 2-setting steering inequality by 48σ and a 3-setting inequality by over 200σ.

$$S_2 = 1.1410 \pm 0.0014 \gg 1.0291 \pm 0.0019,$$
$$S_3 = 1.7408 \pm 0.0017 \gg 1.0291 \pm 0.0019$$

Corrections



Device independent QKD

S-QKD

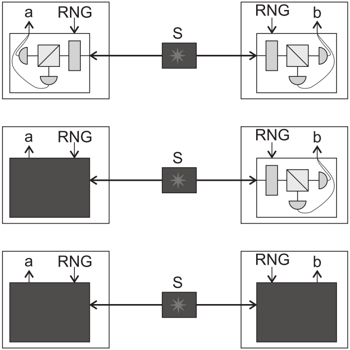
Entanglement

1sDI-QKD

EPR-steering

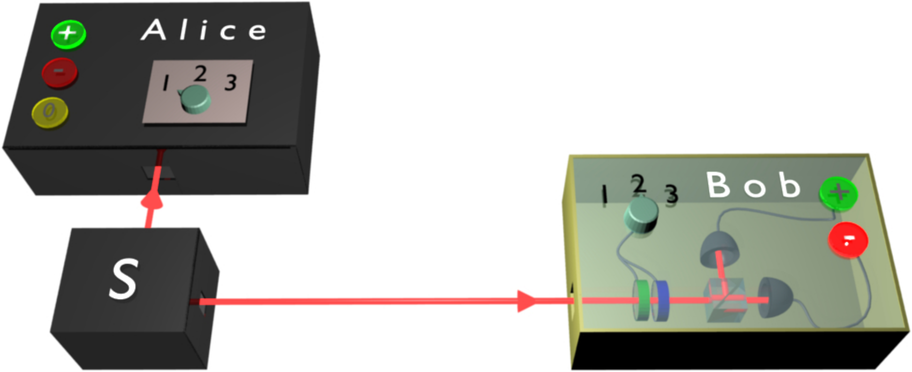
DI-QKD

Bell nonlocality

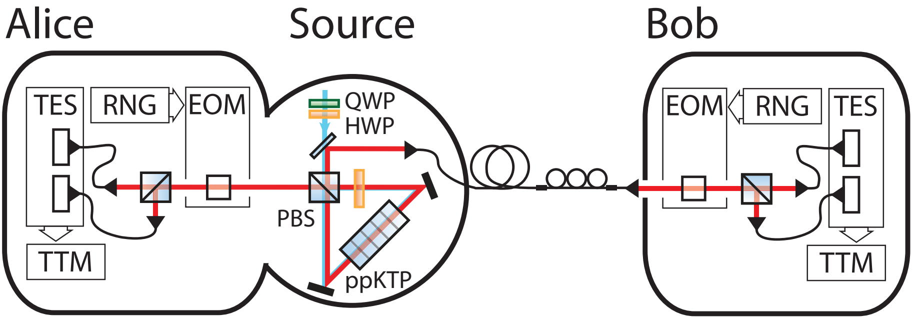


C Branciard *et al.*, Phys. Rev. A 85, 010301(R) (2012), Ma and Lütkenhaus, Quantum Information and Computation 12, 0203-0214 (2012)

One-Sided-Device-Independent Quantum Key Distribution



Apparatus Diagram



Rates

$$r = \eta_A[1 - h(Q_1^{ps})] - h(Q_2) - (1 - q)$$

where

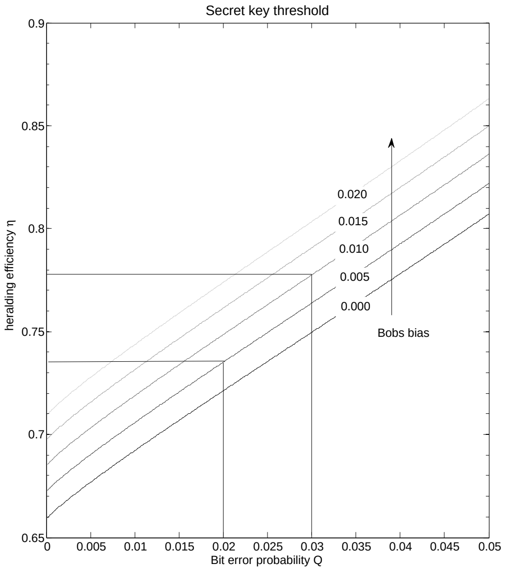
- η_A Alice's heralding efficiency,
- $h(\cdot)$ the binary entropy
- Q_i the quantum bit error rate in the i^{th} basis
- ps indicating post-selection on coincidence
- q the orthogonality of Bob's measurements ($q = -\log_2 \max_{z,x} \left\| \sqrt{B_1^z}\sqrt{B_2^x} \right\|_\infty^2$)

Rates

$$r = \eta_A[1 - h(Q_1^{ps})] - h(Q_2) - (1 - q)$$

This leads to a required heralding efficiency of $> 65.9\%$

Requirements



Advertisements

- If you have experiments that require high efficiency, I want to hear about them
- If you have potential PhD candidates that would like to work on this kind of thing, Andrew White wants to hear about it
- If you want to solve our squashing problems, please do

Summary

1. Steering of Quantum States is of practical and philosophical significance
2. Steering has been demonstrated in several different contexts recently
3. We are implementing a QKD protocol based on steering

Thank you for your attention

Questions?