EPR-Steering experiments with photons

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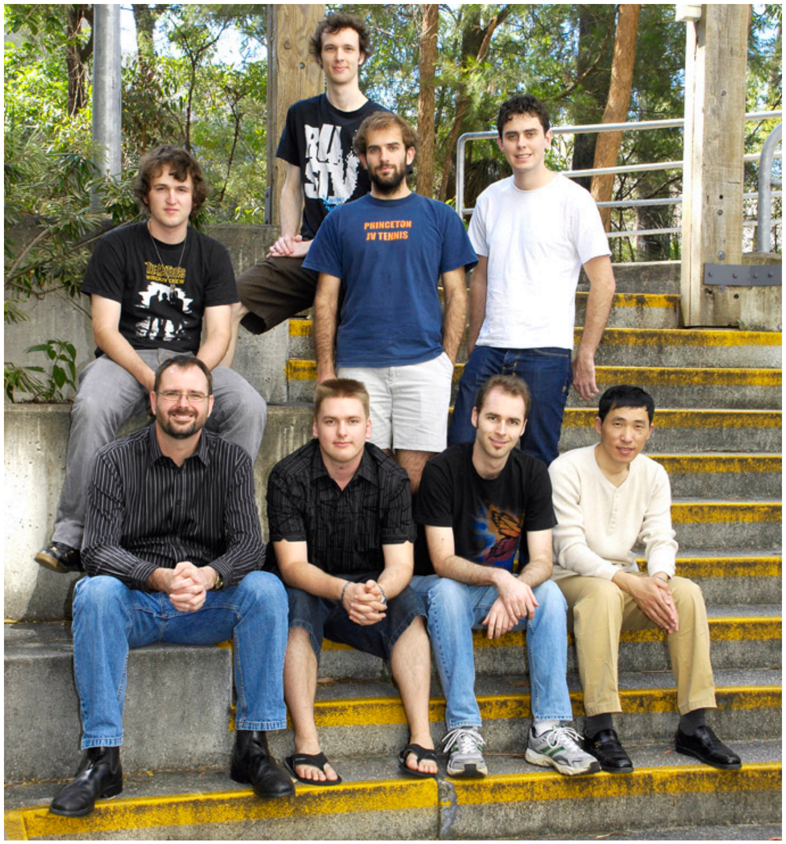
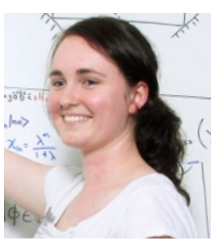




Quantum Information Science
- for quantum communications
- for quantum computing

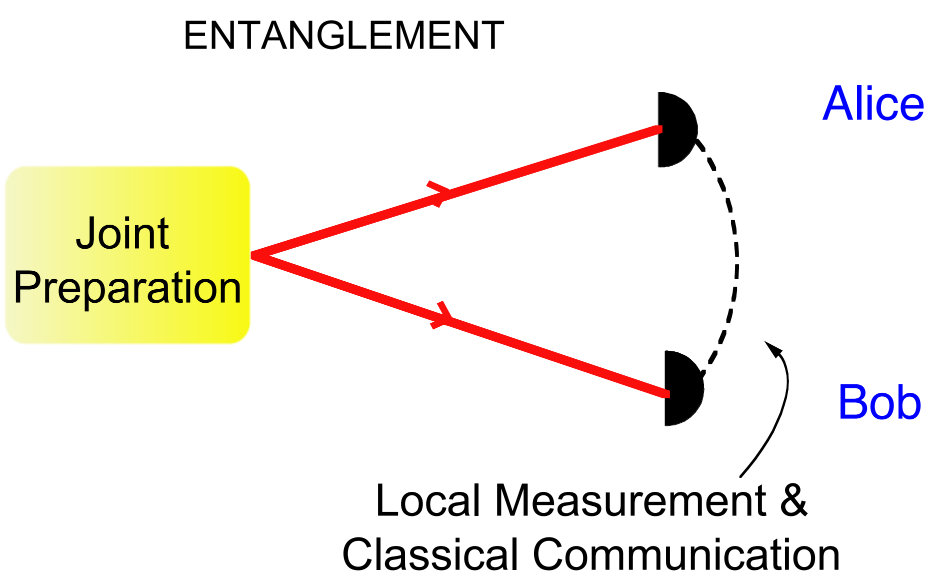
Quantum metrology and measurement
- Adaptive and nonadaptive algorithms for phase measurement
- Quantum phase measurement with entangled and unentangled states

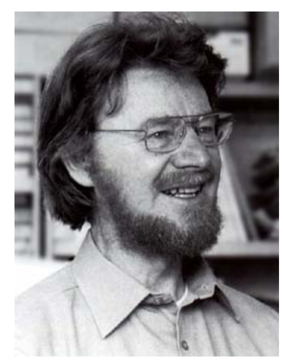
See talk by
Howard Wiseman
tomorrow

Outline

- **EPR-Steering** – Theoretical introduction
  - The pantheon of nonlocality
  - What is EPR-steering?
- **Experimental EPR-Steering of Bell-local states**
  - Resistance to noise
  - The power of many measurement *settings* ①
  - The power of many measurement *outcomes* ②
- **Detection-loophole-free EPR-steering**
  - Many measurements – now *even more powerful*! ③

A potted history of quantum nonlocality and EPR-steering





A potted history of quantum nonlocality and EPR-steering

EPR: Alice can measure p_A and find out p_B for Bob's particle or measure q_A and find out q_B. Either QM is incomplete or it violates relativity. Spooky action at a distance!

Schrodinger: Alice could measure any of a number of observables. She can *steer* Bob's state into an eigenstate of one of these. This is not due to the incompleteness of QM but is fundamental to QM. BTW, let's call the resource "entanglement".

Bell: The assumptions of EPR can be encoded into a Local Hidden Variable theory. Bell inequalities bound the correlations observable by Alice and Bob under such a theory, but the predictions of QM violate this bound. Schrodinger was right and EPR wrong!

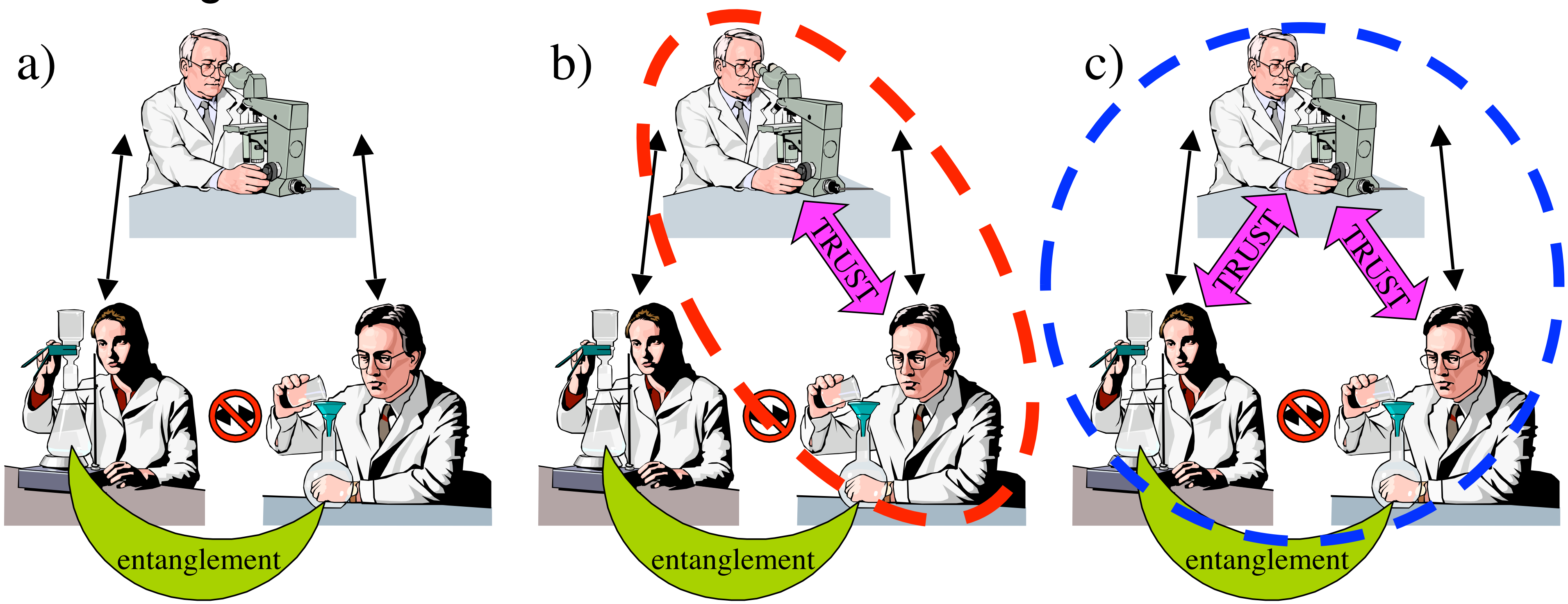
Operational definitions

Model	Alice (can not be explained by)	Bob (can not be explained by)
Non-Separability	Local Hidden State	Local Hidden State
EPR-Steering	Local Hidden Variable $\lambda_A(LHS_B)$	Local Hidden State
Bell Non-local	Local Hidden Variable	Local Hidden Variable

Wiseman et al., *PRL* **98**, 140402 (2007); Jones et al., *PRA* **76**, 052116 (2007)

Steering Quantum Information Task

For Alice and Bob to demonstrate to Charlie that they can create entanglement between their labs.



a) With no trust, they must demonstrate **Bell-nonlocality**.

b) With a trustworthy Bob, Alice must show **EPR-steering**.

c) With both trusted, all that is needed is **non-separability**.

One-sided device independent QKD

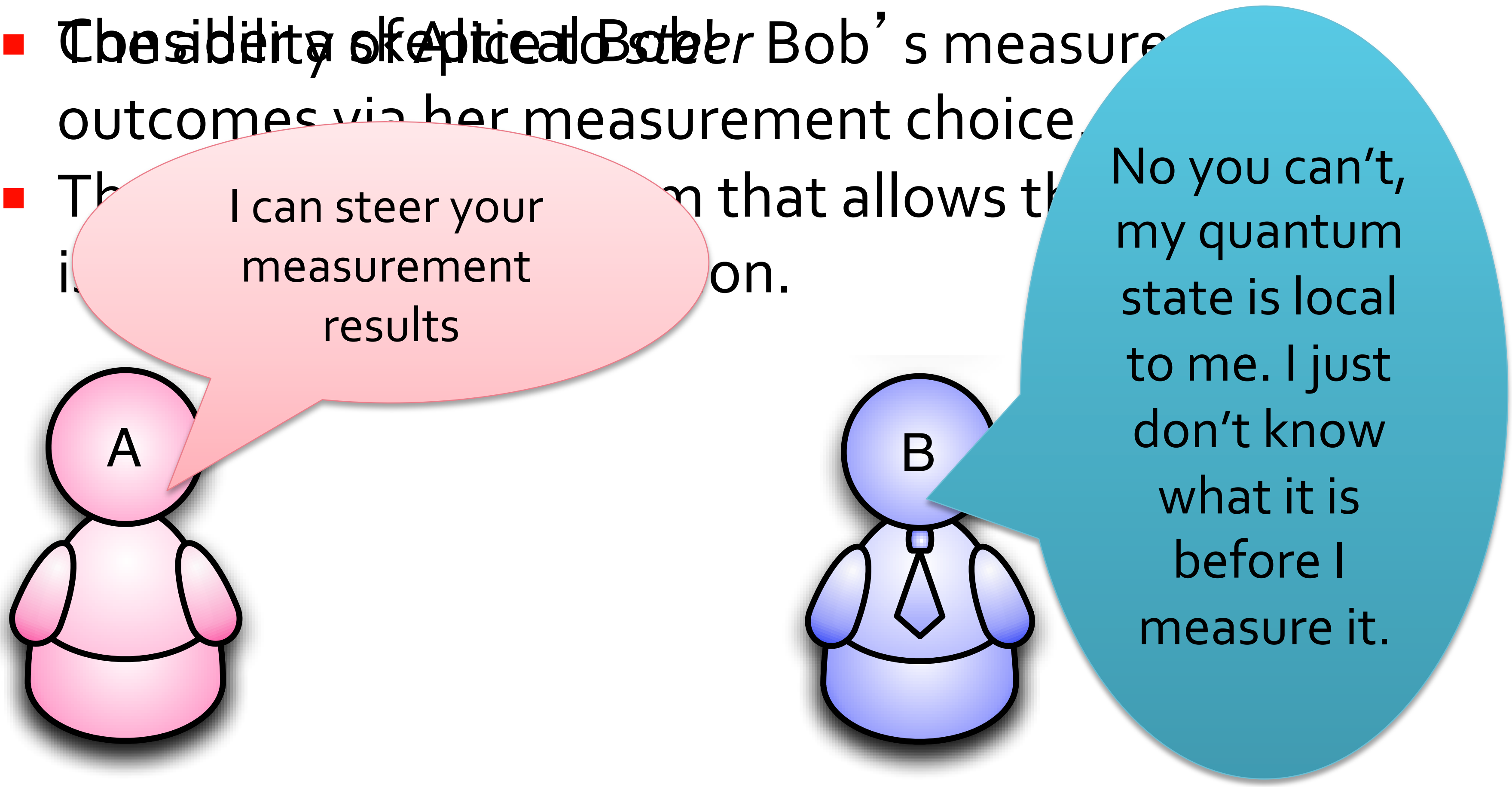
- Loophole-free Bell inequalities are known to be useful for *device-independent* QKD, to guarantee security even when an adversary has supplied Alice and/or Bob's measurement apparatus [Acin et al, *PRL* 2007]
- EPR-steering is equivalent to Bell inequality violation if one party (Bob) and his apparatus is trusted, implying the possibility of 1-sided DIQKD *
- This would be important if Bob was at "home base", communicating with a roaming Alice in the field.

Branciard, Cavalcanti, Walborn, Scarani, Wiseman
Phys. Rev. A **85**, 010301(R) (2012)

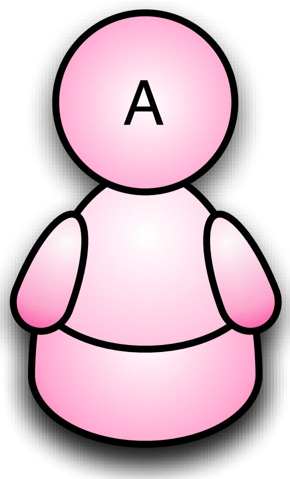
- Can this be extended to large number of settings *n*, making it loss-tolerant?

What is Steering?

- Consider a skeptical Bob!
- The ability of Alice to *steer* Bob's measure… outcomes via her measurement choice.
- Th… m that allows th… i… on.

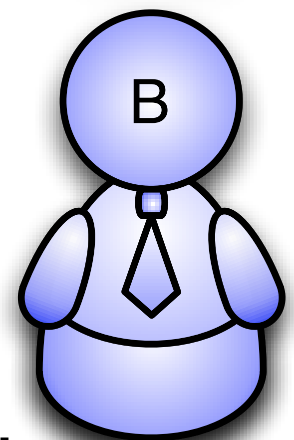


What is Steering?

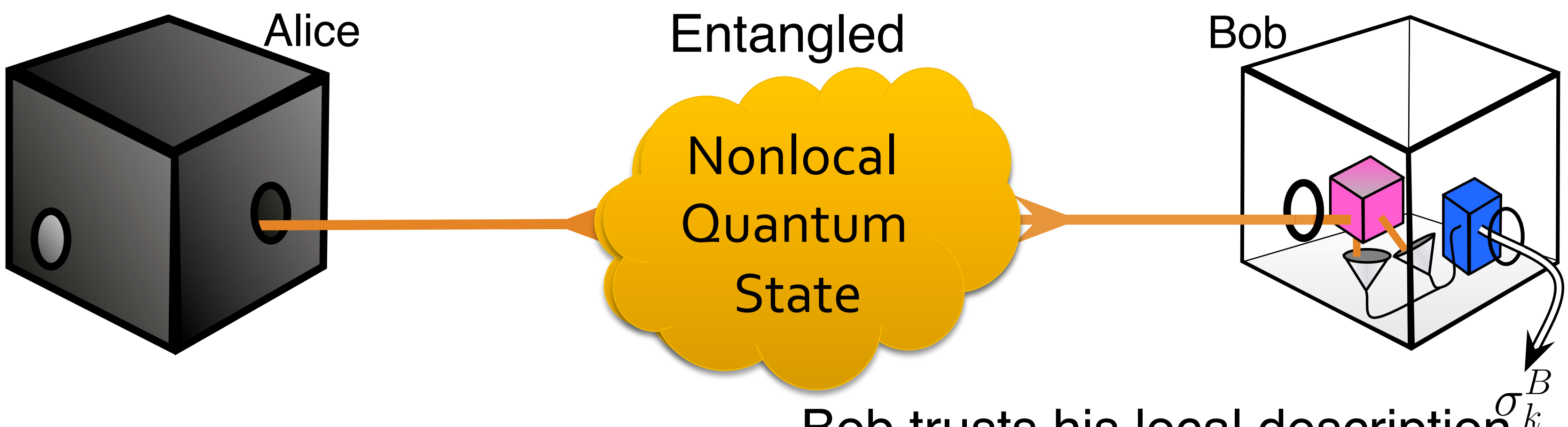


If and only if they share an entangled state:

Alice's local measurement operator will collapse their shared quantum state into an eigenstate of that particular operator. Her choice of local measurement gives her the ability to steer Bob's results via this choice



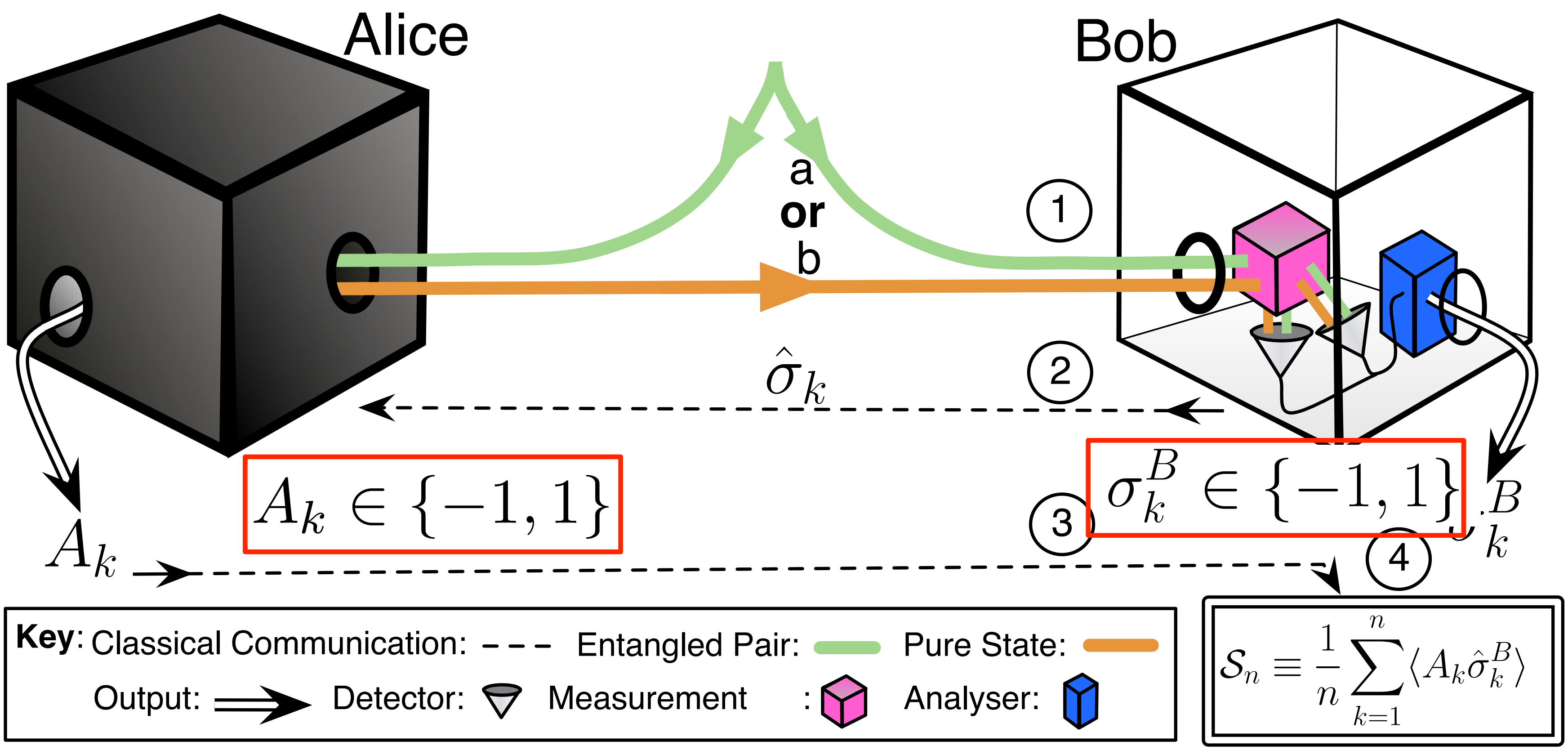
LHS Model



Bob trusts his local description of QM for his measurement device

Steering Task –
Convincing a skeptical Bob

1. Bob receives his quantum state, **2.** announces his measurement setting, **3.** measures and records his result as well as Alice's announced result, **4.** calculates the steering parameter



First Experiment:
The Power of Many Settings

Three Types of Inequality

Consider two pairs of binary measurements: $A, A', B, B' \in \{-1, 1\}$

These can arise from measuring a Pauli operator (e.g. $\hat{\sigma}_X$) on a qubit.

Bell-nonlocality (CHSH, 1969)

$$\langle AB \rangle + \langle A'B \rangle + \langle AB' \rangle - \langle A'B' \rangle \leq 2$$

EPR-steering (Cavalcanti, Jones, Wiseman, Reid, PRA 2009)

$$\langle A \hat{\sigma}_X^B \rangle + \langle A' \hat{\sigma}_Z^B \rangle \leq \sqrt{2}$$

Non-separability (entanglement witness, mid-90s)

$$\langle \hat{\sigma}_X^A \hat{\sigma}_X^B \rangle + \langle \hat{\sigma}_Z^A \hat{\sigma}_Z^B \rangle \leq 1$$

The Steering Parameter

- The steering parameter is a steering witness.
- It is an inequality based on a LHS model for Bob and a LHV model for Alice.
- When the steering parameter is above a certain limit, C_n, Bob can be sure that he is observing steering.

$$\mathcal{S}_n \equiv \frac{1}{n} \sum_{k=1}^{n} \langle A_k \hat{\sigma}_k^B \rangle \leq C_n$$

$$A_k \in \{-1, 1\} \qquad \sigma_k^B \in \{-1, 1\}$$

Bob's Platonic Measurement Schemes

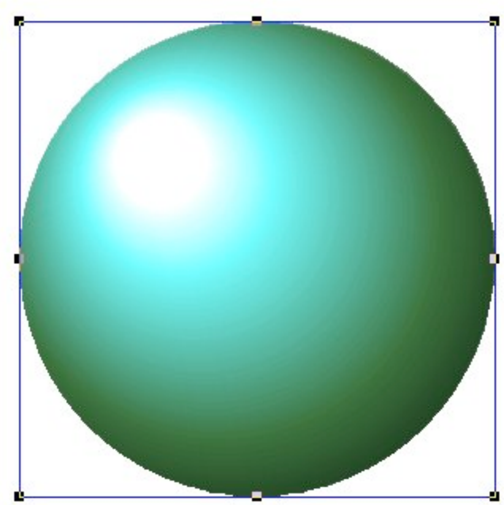
- To derive useful steering inequalities we consider equidistant measurements axes around the Bloch sphere. These can be represented by the platonic solids or a square for the n=2 case.
- Recall $\mathcal{S}_n > C_n$ to steer.

$$C_2 = 1/\sqrt{2} \approx .707$$
$$C_3 = C_4 = 1/\sqrt{3} \approx 0.5773$$
$$C_6 \approx 0.5393$$
$$C_\infty = 1/2$$

- It becomes easier to demonstrate steering (more difficult to cheat) when n increases!

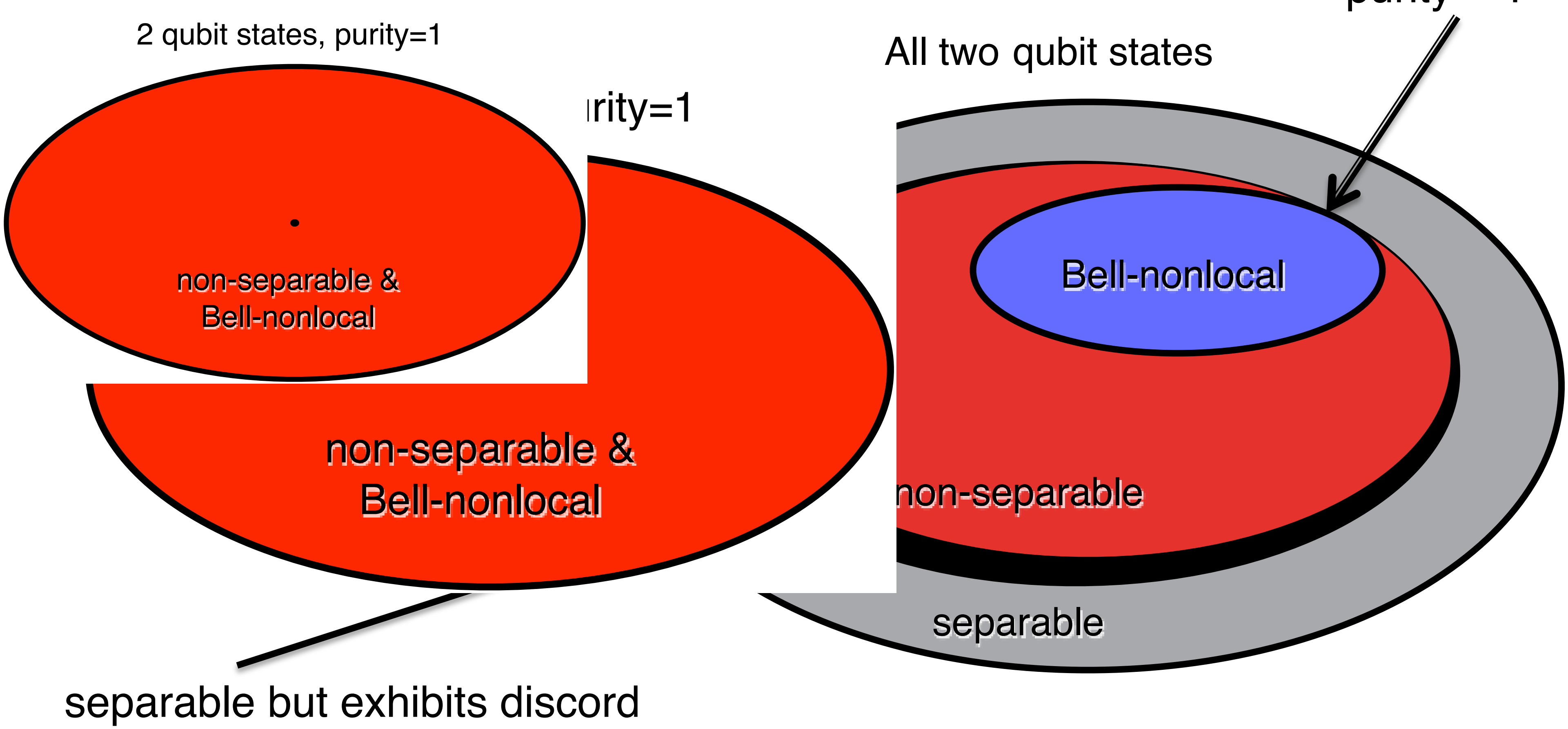
1 Qubit Hilbert Space

n=

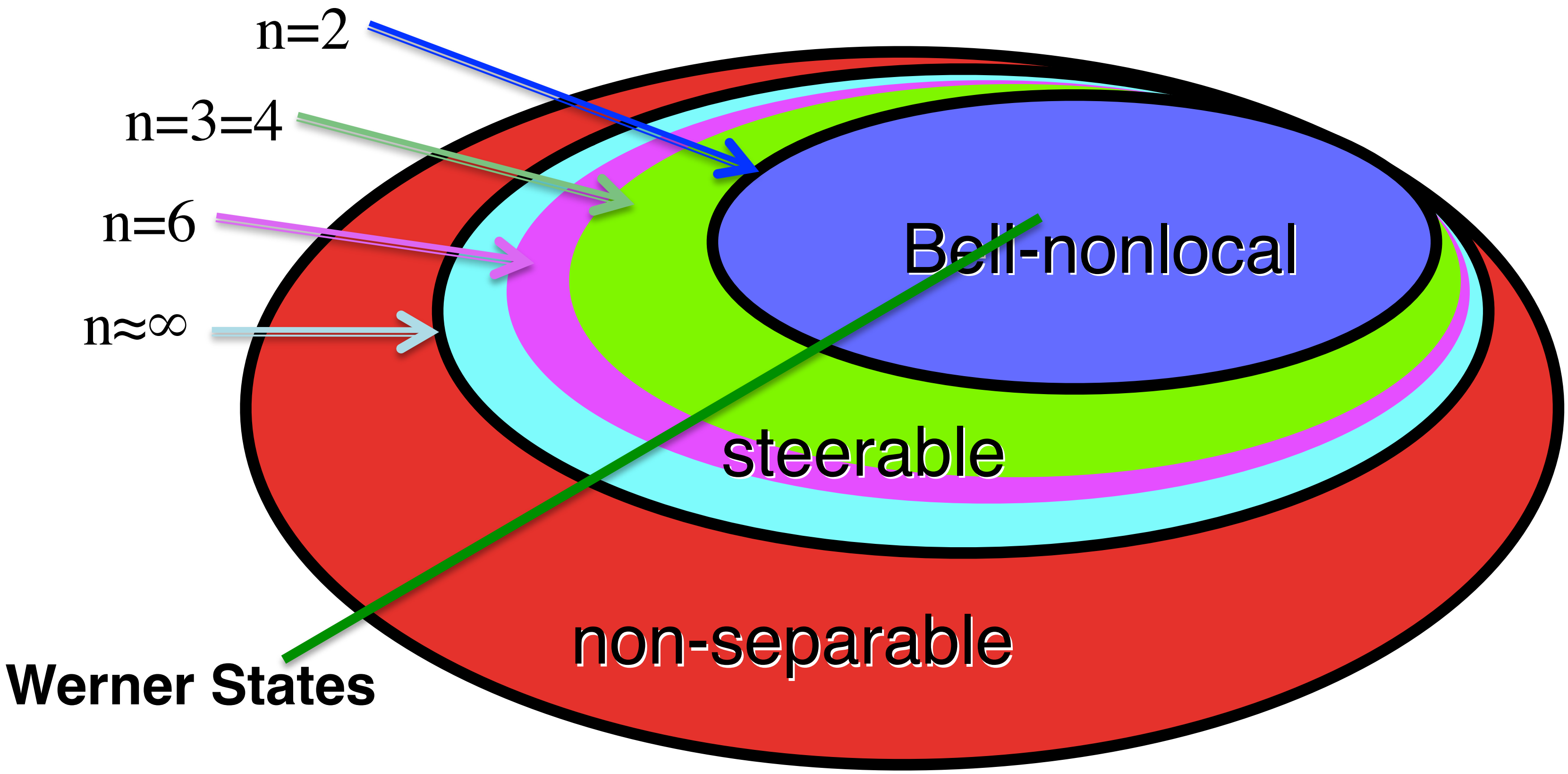


The space of two-qubits – LHV/LHS Models

PURE STATES



Different Steerable Regimes



$$\mathcal{S}_n \equiv \frac{1}{n}\sum_{k=1}^{n}\langle A_k\hat{\sigma}_k^B\rangle \leq C_n$$

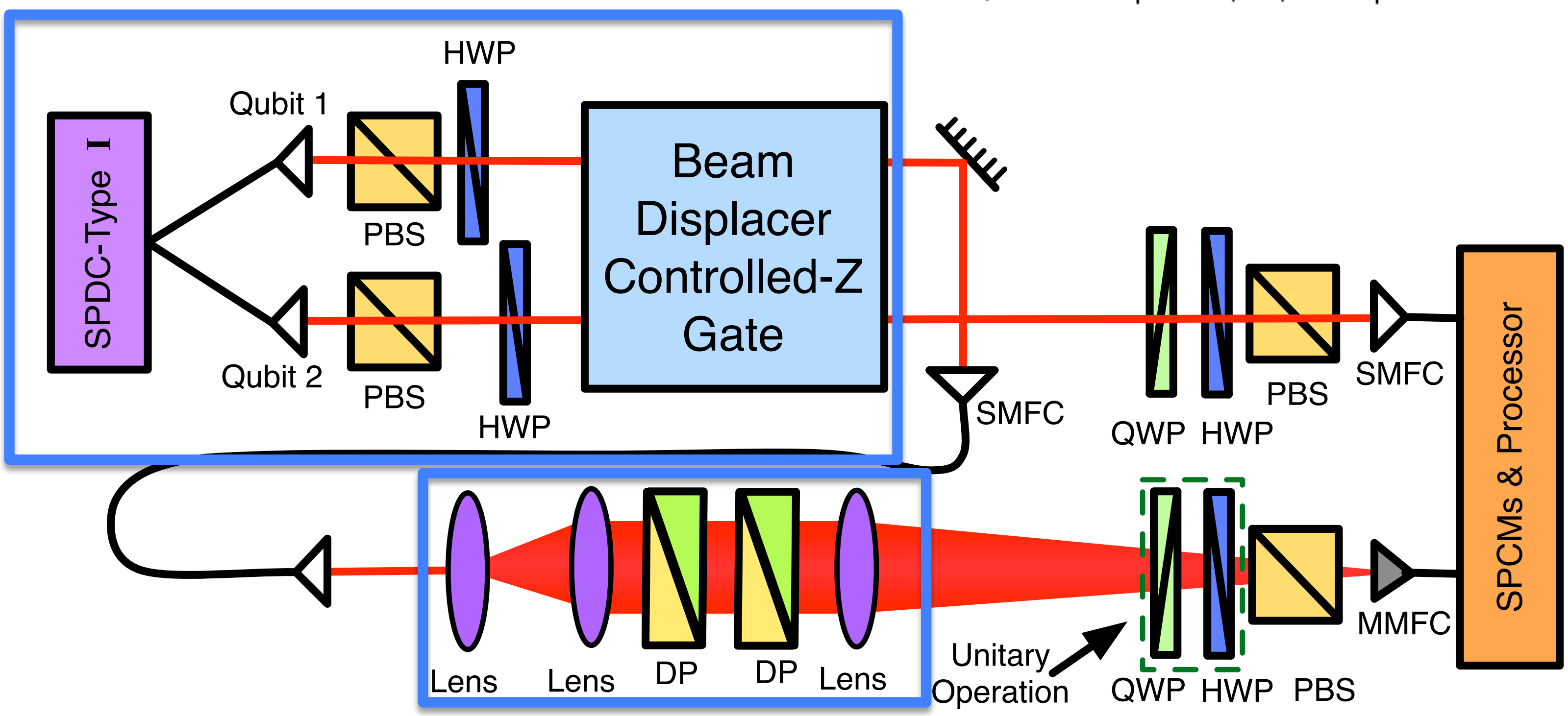
The Steering Experiment

- Goals
  - Generate Werner States of varying μ
  - Measure $\mathcal{S}_n$ for n=2,3,4,6 and also the CHSH-Bell inequality (to test the boundaries of these regions)
  - Implement the cheating strategy
  - To test two theoretical predictions:
    1. The set of Bell-nonlocal states is a strict subset of steerable states.
    2. Set of steerable states increases when *n* increases.

Experimental Setup

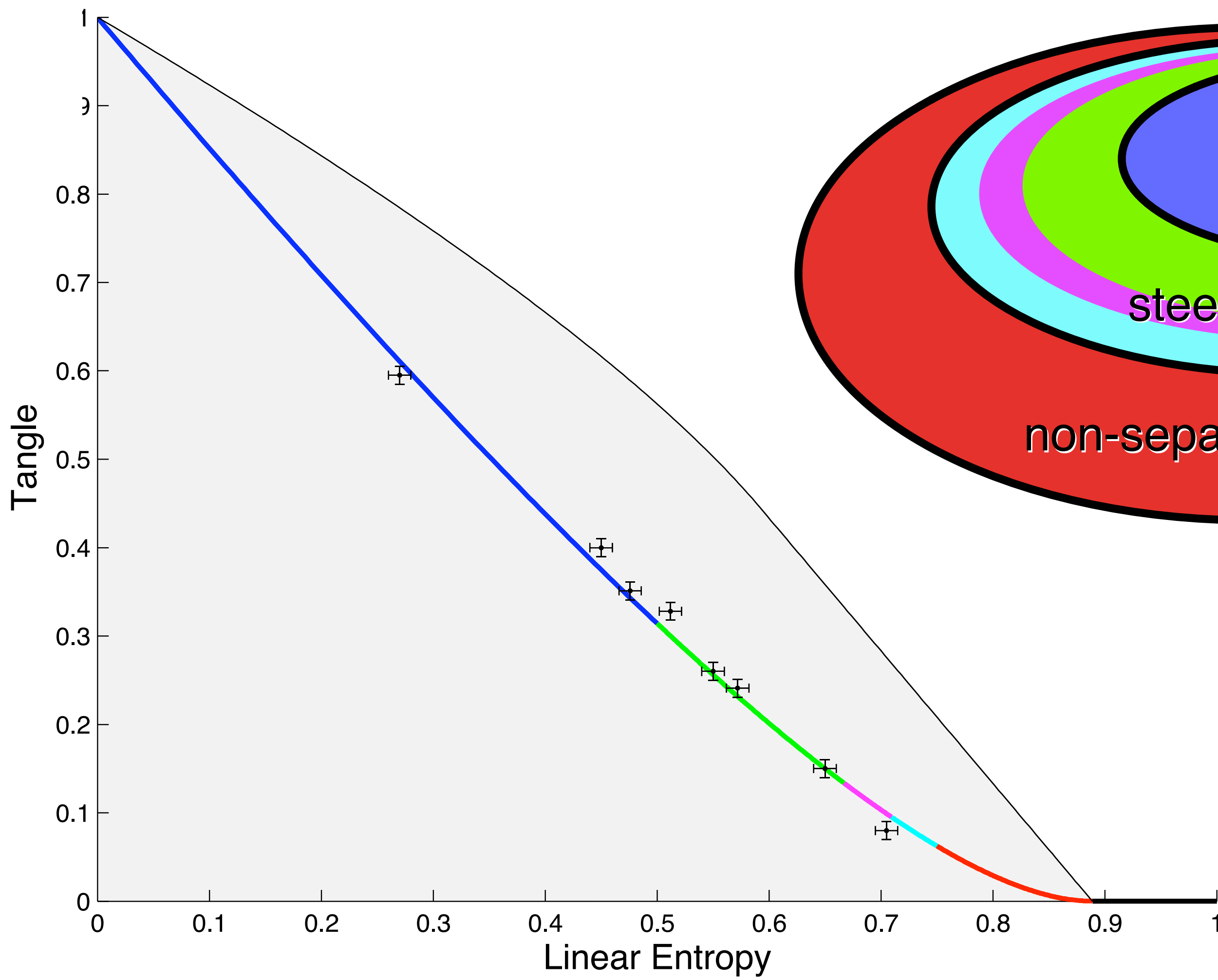
- Producing Werner States / Producing the singlet state

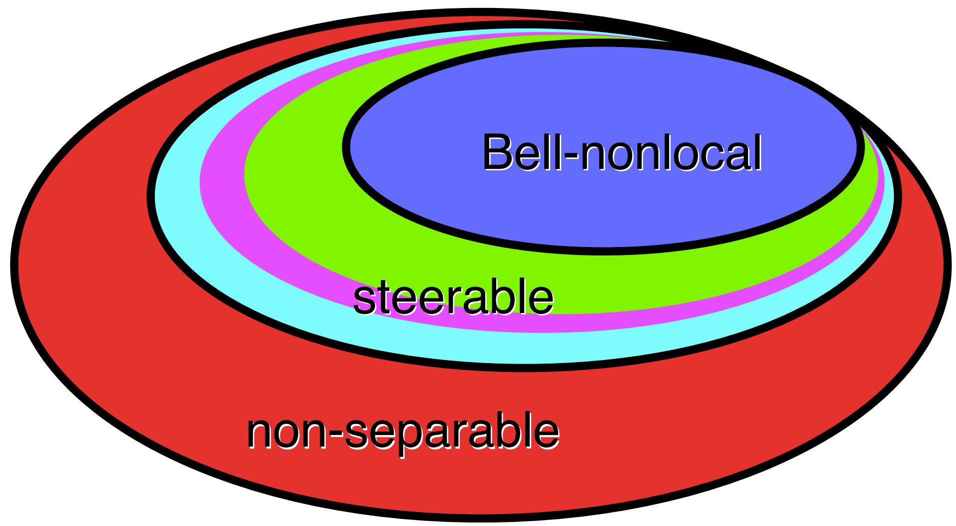
$$W_\mu = \mu \left|\Psi^-\right\rangle\left\langle\Psi^-\right| + (1-\mu)\,\mathbf{I}/4$$



[1] O'Brien, J. L. et al.. Nature 426, 264267 (2003)
[2] Puentes, G. *et al*. Opt. Lett. 31, 20572059 (2006)

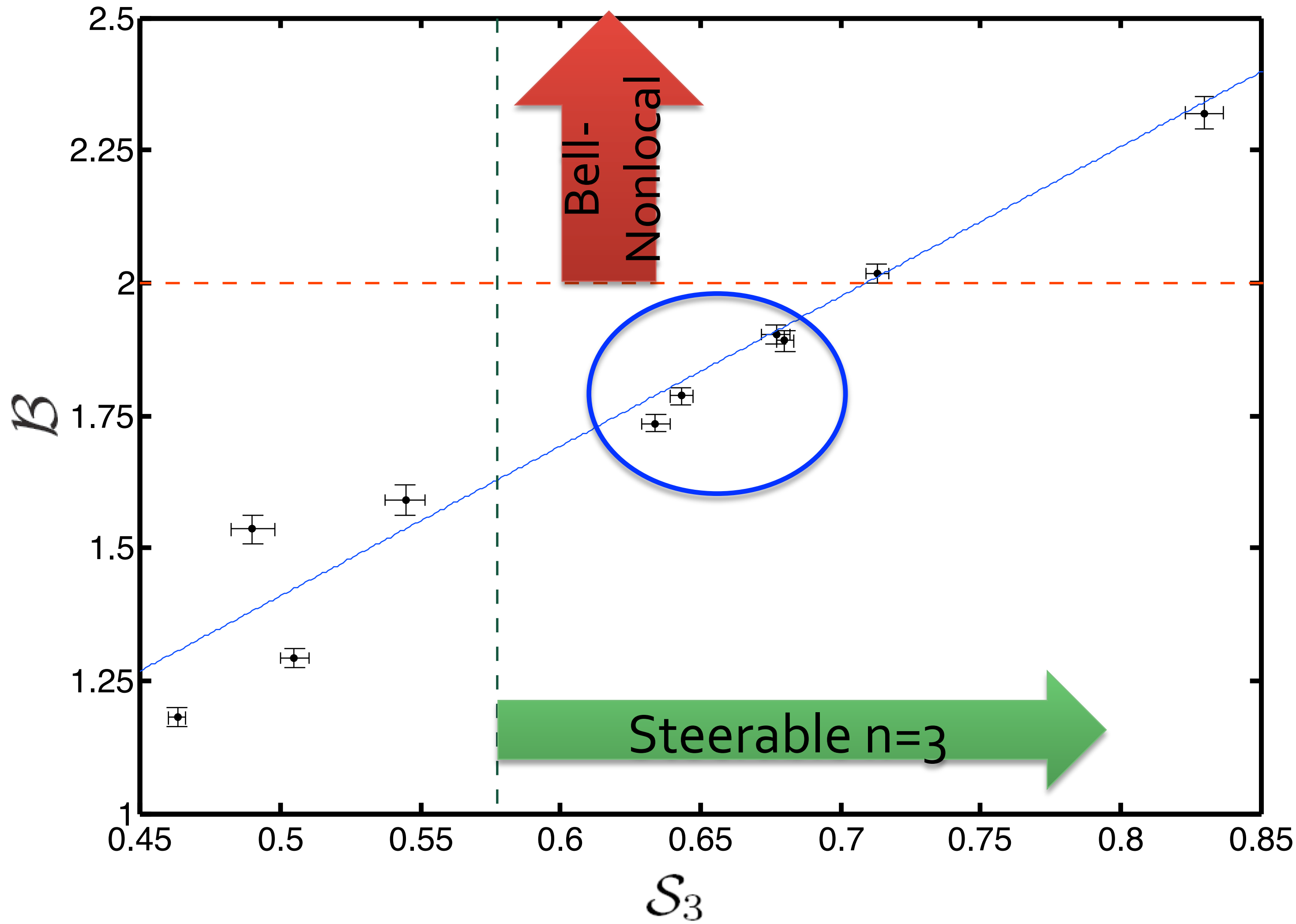
Produced Werner States

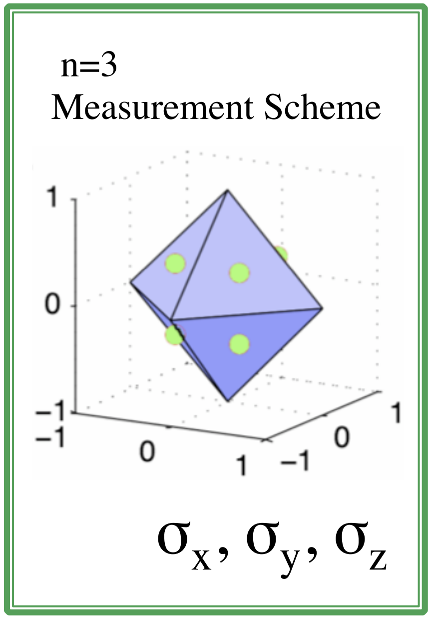




Saunders, Jones, Wiseman & Pryde, *Nature Physics* 2010

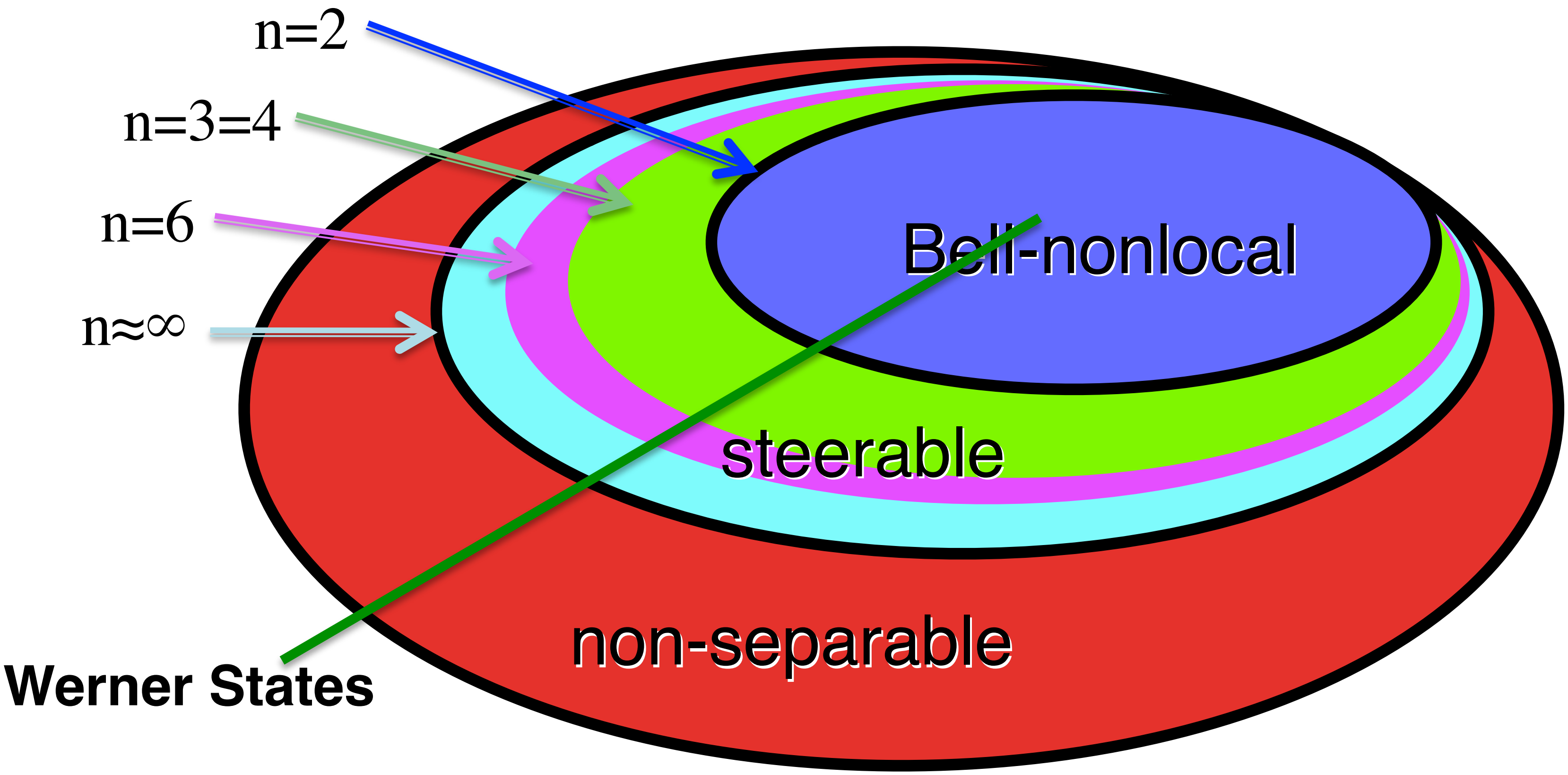
EPR Steering of Bell-local States





Saunders et al, *Nature Physics* 2010

Different Steerable Regimes



$$S_n = \frac{1}{n}\sum_{k=1}^{n}\left\langle A_k \hat{\sigma}_k^B \right\rangle \le C_n$$

Second Experiment:
The Power of Many Outcomes

The power to minimize complexity

We can quantify the complexity of a demonstration of nonlocality by *W*, the number of different types of joint outcomes (across *P* parties) that can occur in the experiment.

Allowing the parties to choose their setting *s* freely,

$$W = \prod_{p=1}^{P} \sum_{s_p=1}^{S_p} O_{s_p} .$$

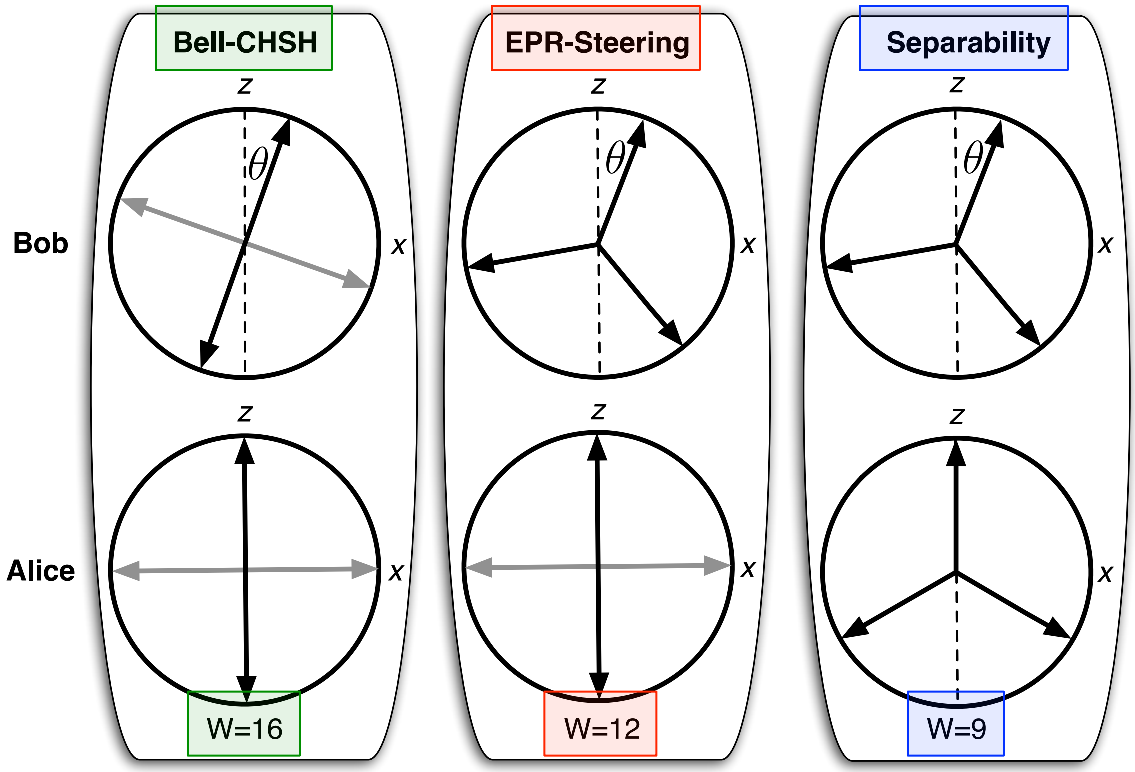
In all cases, the minimum complexity is achieved for *P*=2 parties, and can be achieved for measurements on qubits.

For Bell-nonlocality the minimum *W* is 16, and can be achieved by the CHSH inequality with projective (*O*=2) measurements.

But what about EPR-steering and non-separability?

In these cases *non-projective* (many-outcome) measurements help.

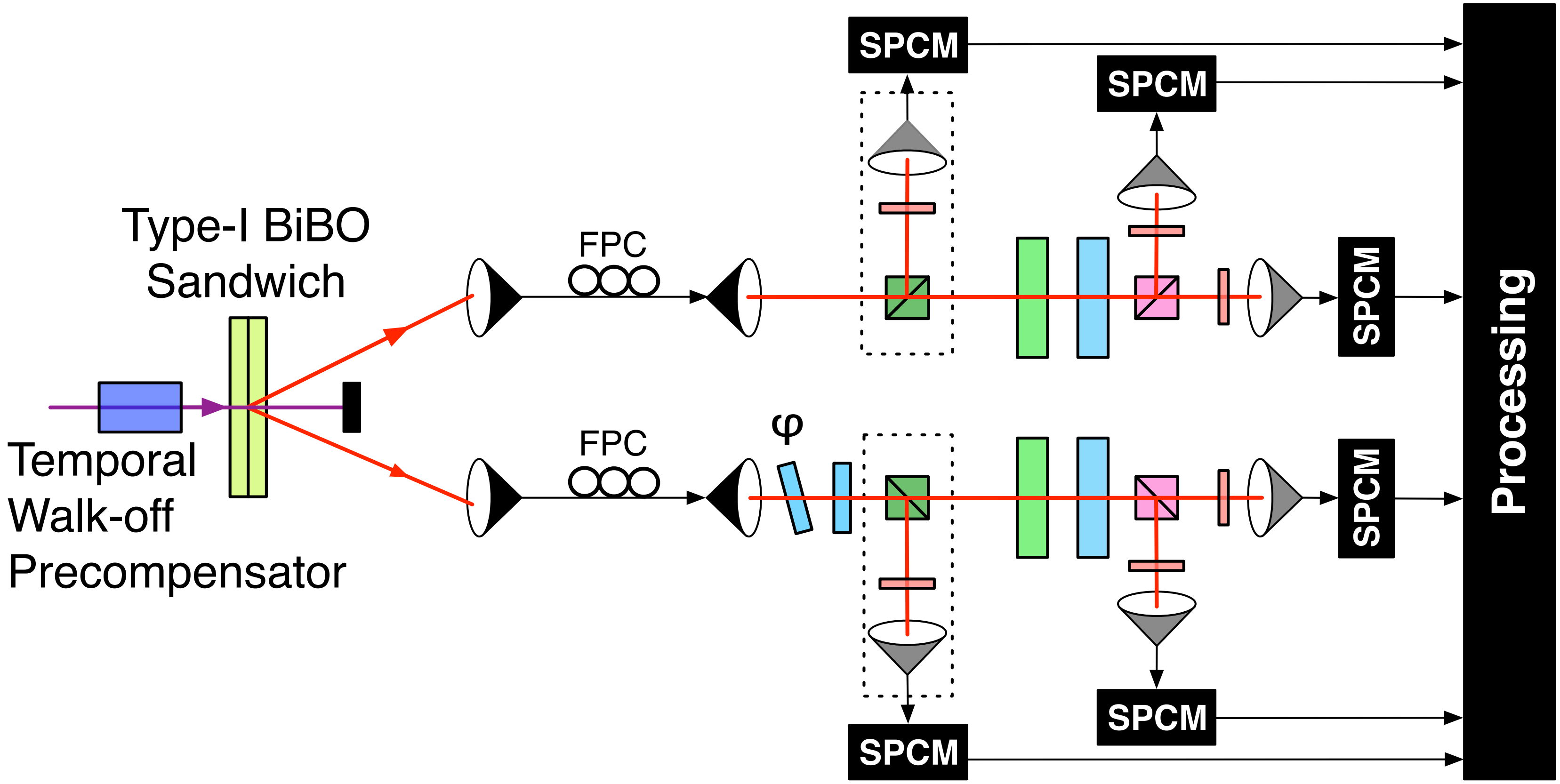
The most parsimonious settings



By labelling each outcome as a *unit Bloch vector* pointing in the direction of the associated POVM element, we can write very simple inequalities whose violation demonstrates

EPR-steering: $\left|\left\langle\left(\vec{A}+\vec{A}'\right)\bullet\vec{B}\right\rangle\right| \leq \frac{1}{\sqrt{2}}$ and entanglement: $\left|\left\langle\vec{A}\bullet\vec{B}\right\rangle\right| \leq \frac{1}{4}$

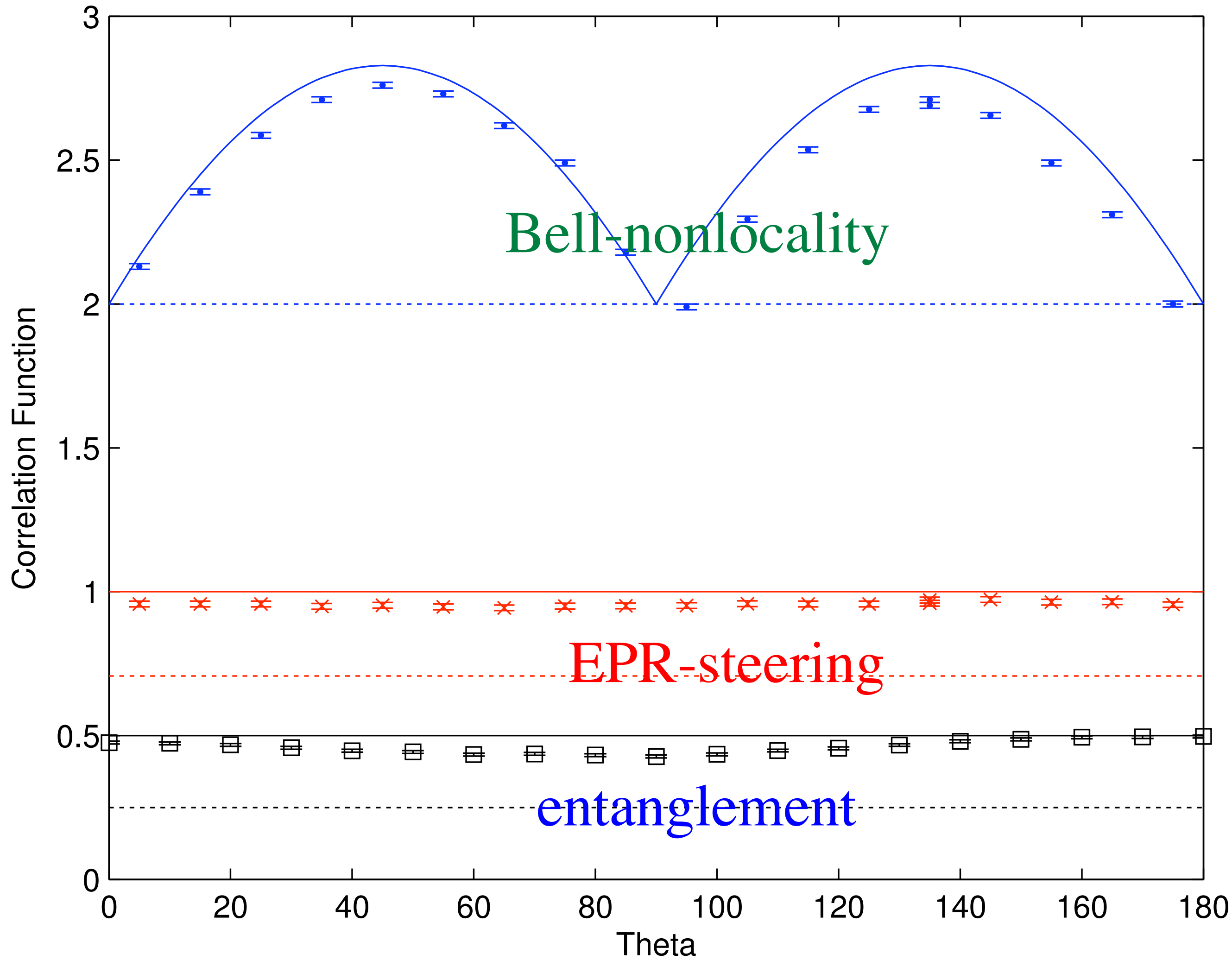
The experimental design



We use partially polarizing beam splitters to implement the three-outcome “trine” measurement.

[Clarke *et al.*, PRA **64**, 012303 (2001)]

Experimental results



Saunders et al., arXiv:1103.0306

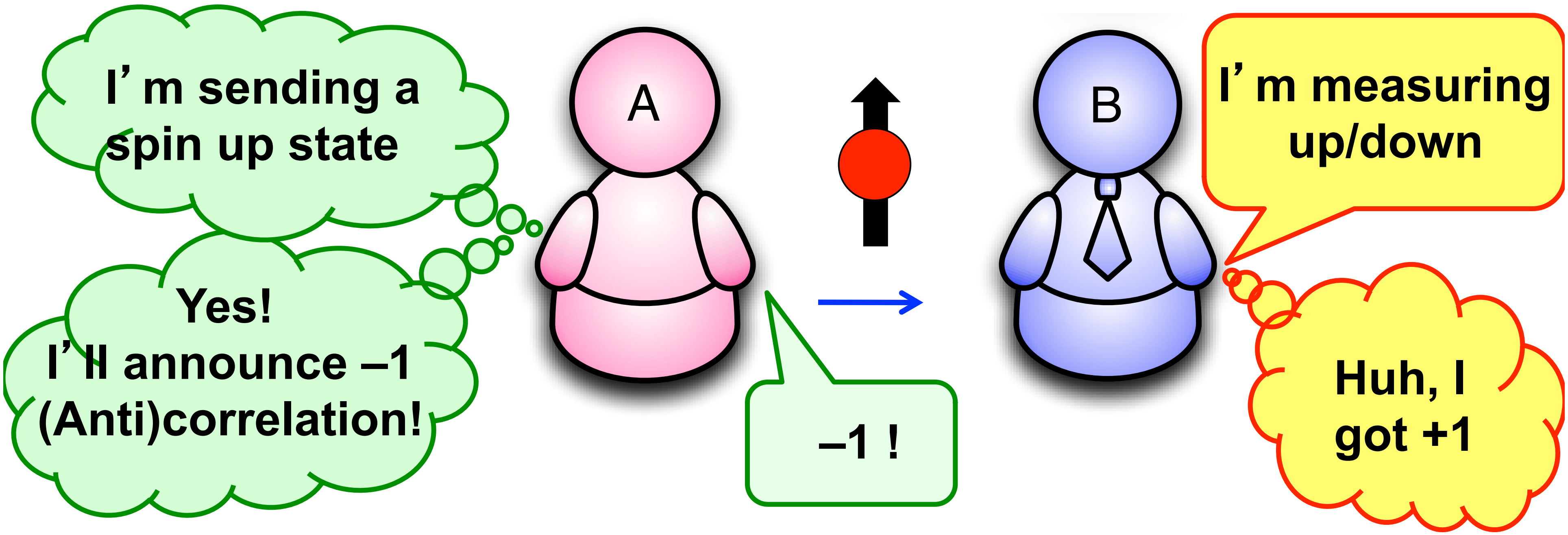
Third Experiment:
The *super*-Power of Many Settings

Entanglement, nonlocality and the detection loophole

- Entanglement is interesting from a fundamental point of view
- Entanglement is useful as a resource for quantum technologies
- In both cases, one ultimately wants to share entanglement over long distances
- Ultimately, entanglement is most useful when correlations are verified with *no loopholes*
  - To date, Bell inequality violations (or EPR-steering) have not been demonstrated with all loopholes closed
- Most problematic loophole for long-distance tasks is the *detection loophole* (negates direct photonic entanglement sharing)
  - Arises from an inability to justify the *fair sampling assumption*: that (say) Alice's loss is independent of measurement setting.

Another cheating strategy

- Alice can use the detection loophole to cheat



Another cheating strategy

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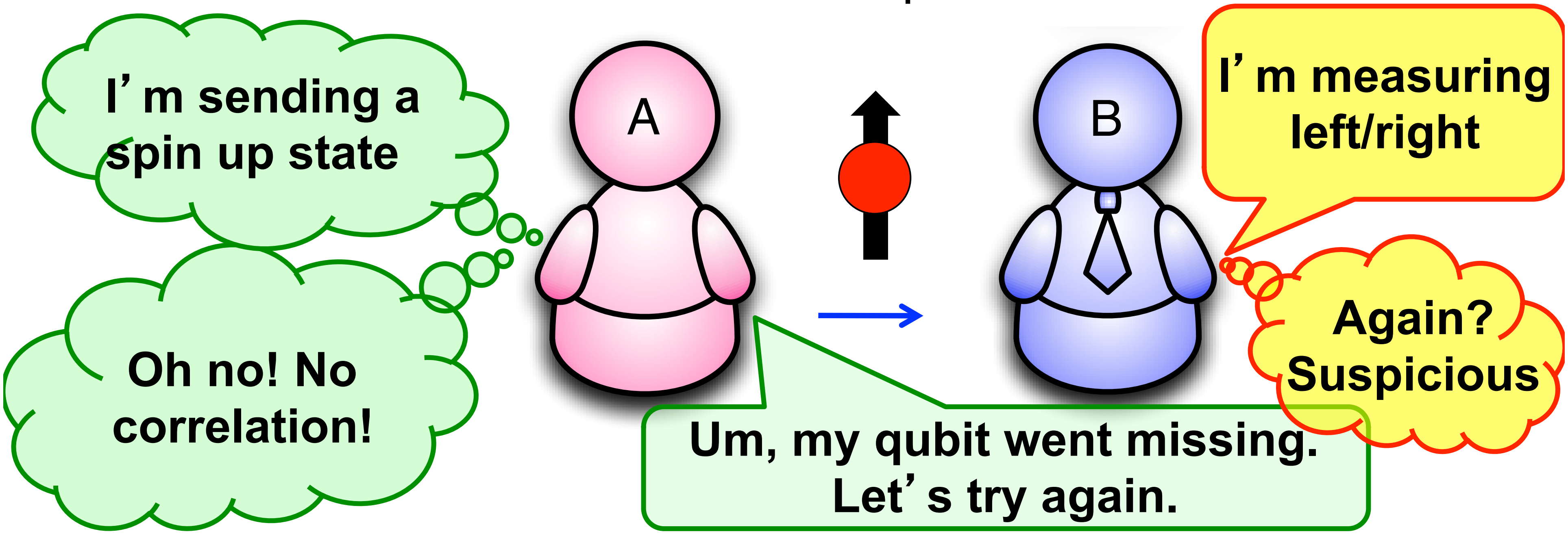


- Her heralding efficiency (fraction of times she announces a result) is only 1/n…
- … but these announcements lead to steering parameter of $S_n = 1$, the maximum!

Bob's response

- Bob can protect against this by demanding a higher heralding efficiency.

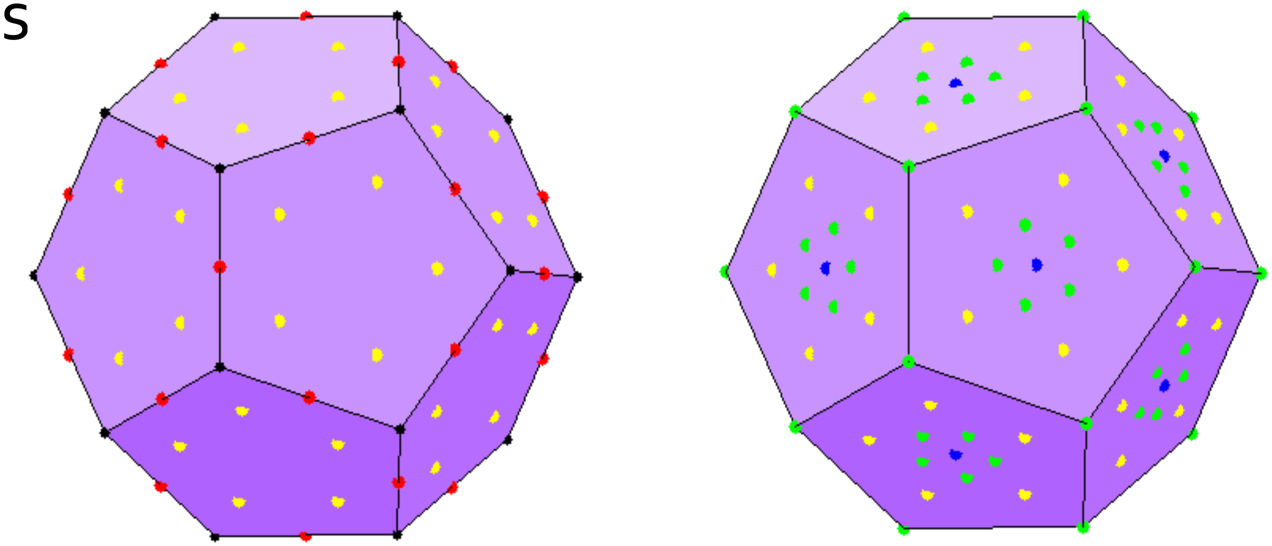
- But how high is high enough? And how large should the correlations be?

- And what if Alice really is honest, and there are just large line losses (e.g. a long fibre for comms)?

- Find a bound for S_n from Alice's optimal cheating strategy

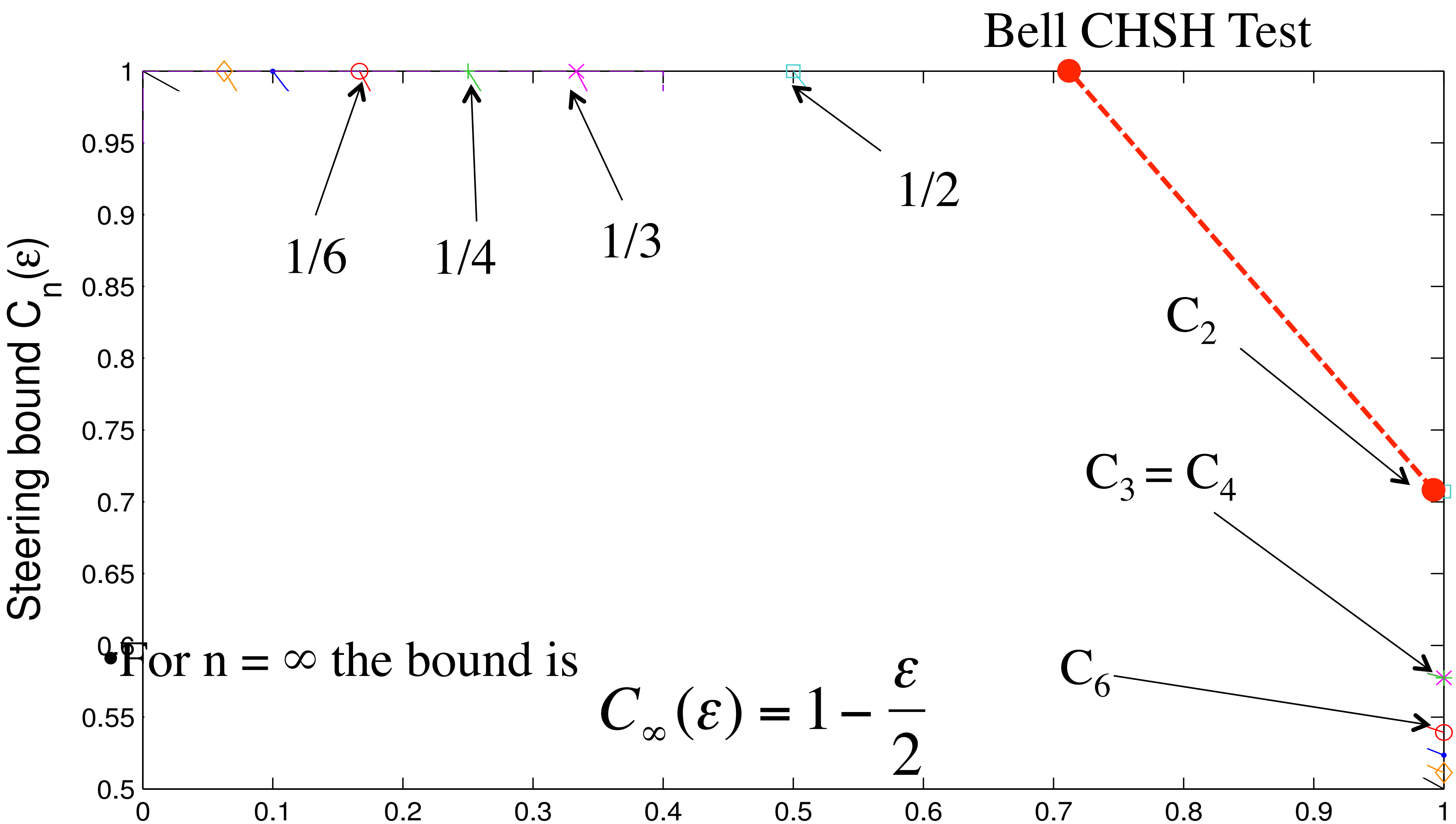
Ensembles figure

- Bob needs to work out Alice's optimal strategy for any ε
- These involve picking states from a "cheating ensemble" and choosing a corresponding strategy for announcing (or not) the A_k's



$$S_n^{\text{cheat}} = \sum_{k=1}^{n} \frac{1}{n} \sum_{m=m',m''} w_m \sum_{i=1}^{p(m)} \frac{1}{p(m)} \mathbf{A}_{k,i}^{(m)} \langle \xi_i^{(m)} | \hat{\sigma}_k^B | \xi_i^{(m)} \rangle \leq C_n(\epsilon)$$

Loss Dependant EPR-Steering Bound

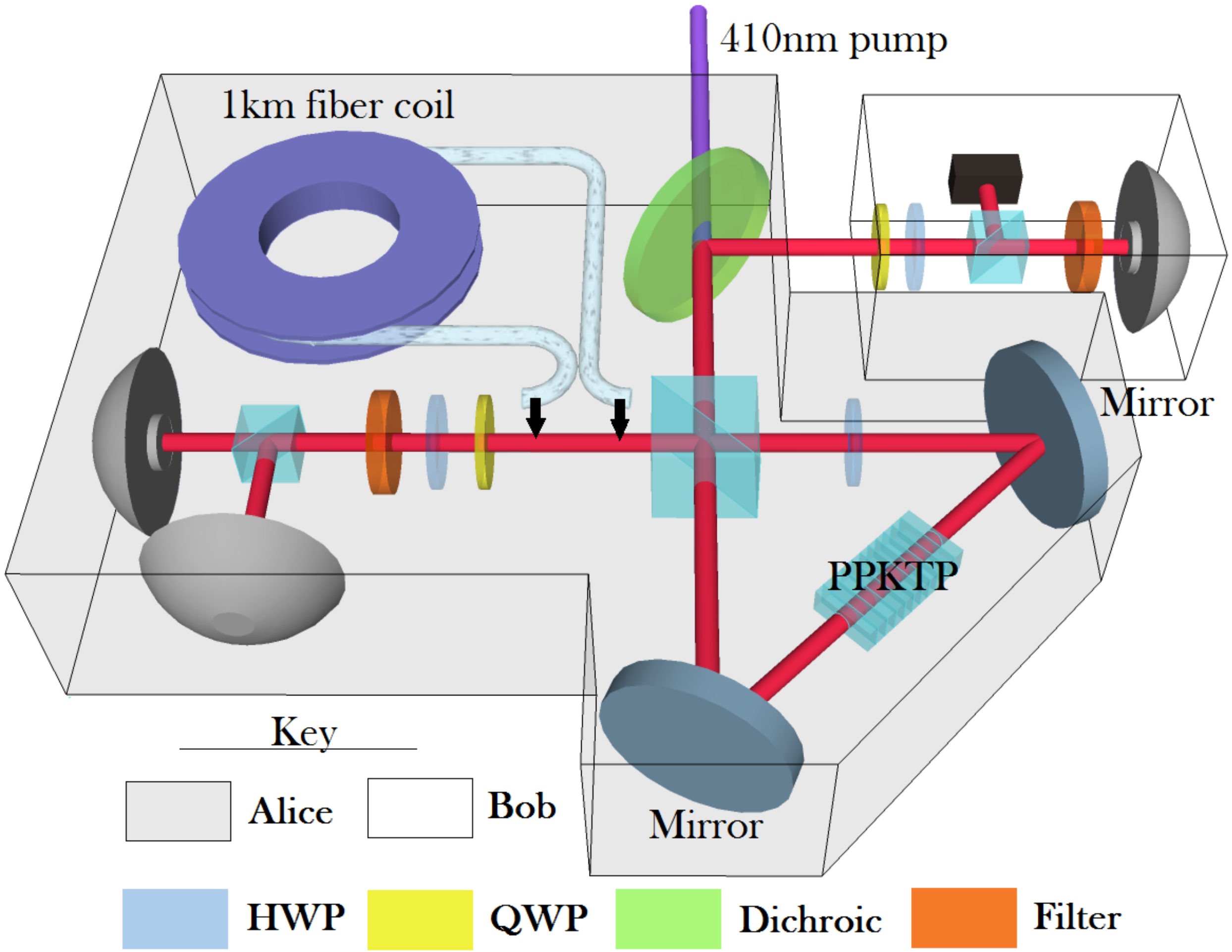


- For n = ∞ the bound is

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

- **Therefore a loss-tolerant protocol exists for all $\varepsilon > 0$**

Violating the steering bound, loophole-free



$\varepsilon_{max} = 0.354(1)$

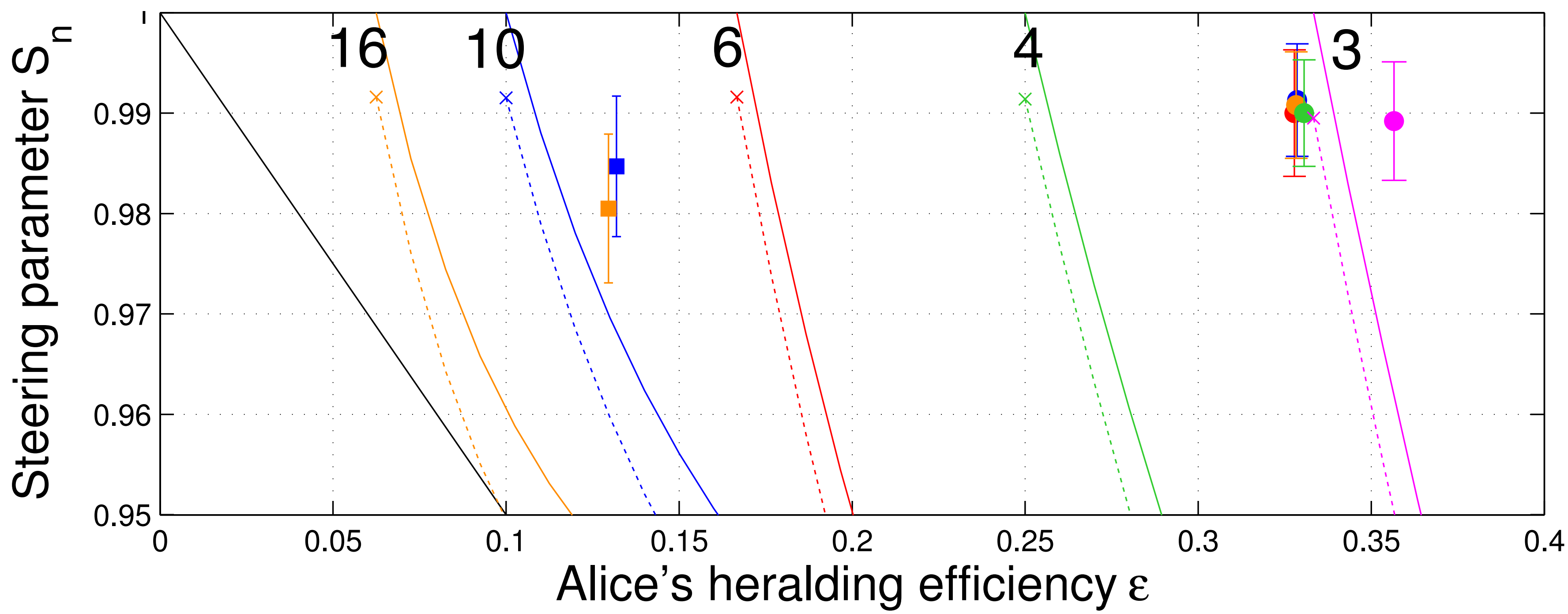
$\varepsilon_{fibre} = 0.130(1)$

$F_{singlet} = 0.992(2)$

$S_n \sim 0.99$

$R_c(1\ mW) \sim 6k/s$

Measured steering parameters



Similar experiments

- Smith *et al* (UQ, Australia), NComms **3**, 625 (2012)
  - Use very high efficiency superconducting detectors to close the detection loophole for n = 2,3

- Wittmann *et al* (Vienna, Austria): arXiv:1111.0760
  - Get sufficient source efficiency for n = 3
  - Close all loopholes simultaneously

Conclusions

- EPR-steering is a formalization, as a quantum information task, of EPR's and Schrodinger's notion of 'nonlocality'
- Completing the task/violating the EPR-steering inequality allows one party to verify that he shares entanglement with another, even though he may not trust her or her equipment
- We have shown that EPR-steering is easier in than violating a Bell inequality but harder than witnessing entanglement, in the sense that:
  - It is more robust to noise
  - It requires less complexity to demonstrate
- We have demonstrated EPR-steering with the detection loophole closed, even in the presence of high loss, over 1 km of optical fibre.
- Loss-tolerant EPR-steering may have application to device-independent QKD.

[redacted]