Advances in photonic quantum information science

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Quantum optics and information laboratory

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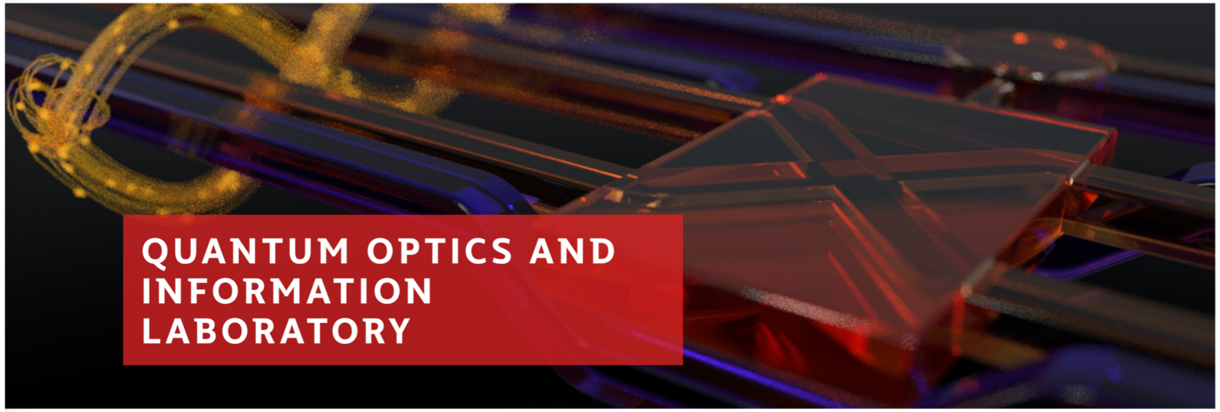

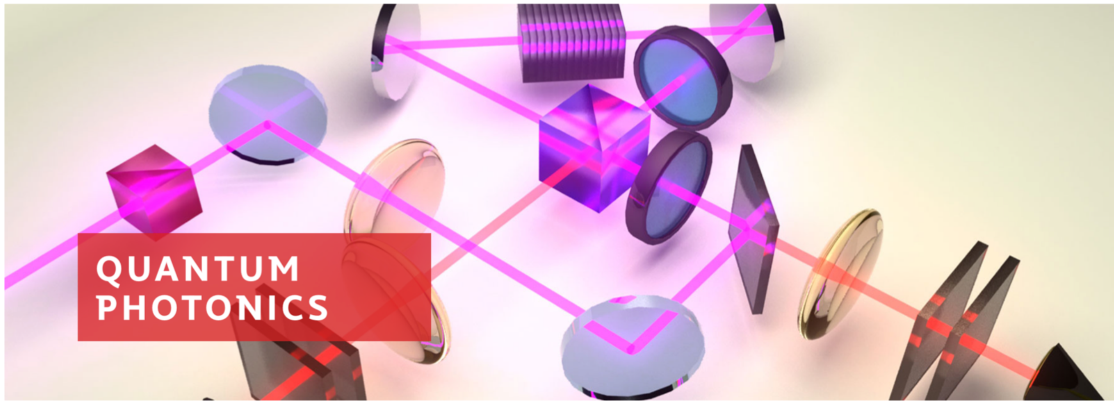

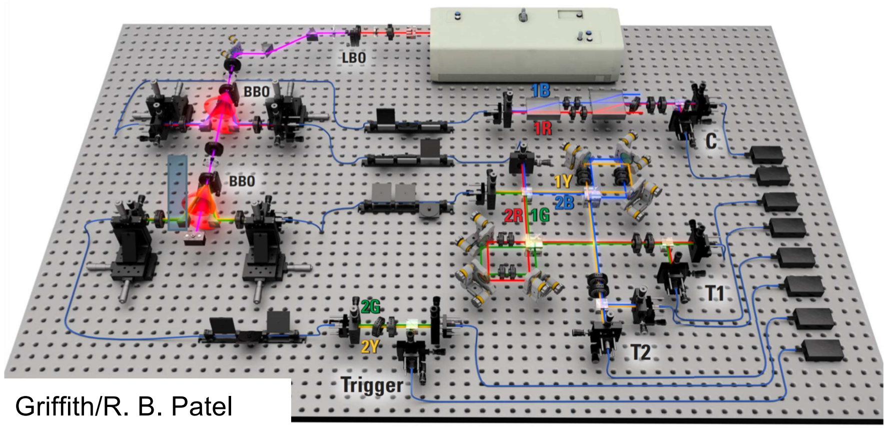

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PhD positions available – Griffith U., Brisbane, Australia

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Photonic quantum information science

A lecture in two parts:

1. Photons, photonic tools, and optical quantum information science
2. Quantum steering, demonstrated and studied with photons

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Part 1 outline

1. Optics **basics**
2. Quantum optical **encodings**
3. Quantum optics **technologies** – sources and detectors
4. Application: Unconditional **quantum metrology** with photons

Some reading:

Slussarenko and Pryde, "Photonic quantum information processing: a concise review," arXiv:1907.06331

Ralph and Pryde, "Optical quantum computation," *Progress in Optics* **54**, 209 (2009); arXiv:1103.6071

Banaszek et al., "Quantum states made to measure," Nature Photonics 3, 673 (2009); arXiv:0912.4092

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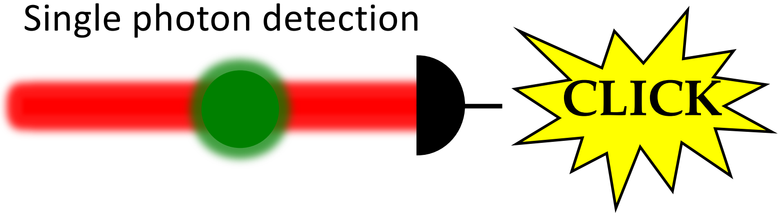
Why photons?

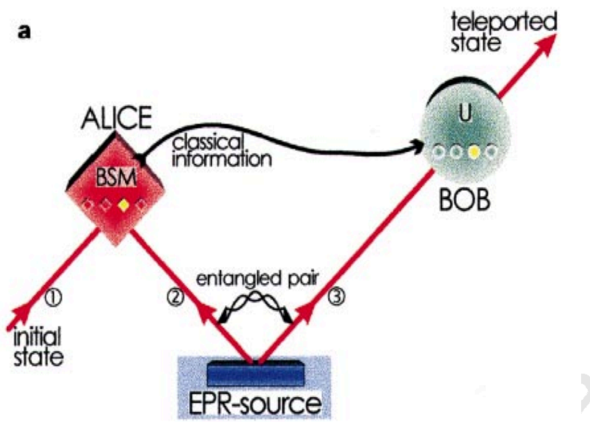
Optics provides low-noise quantum systems

- Encoded information can be robust
  - e.g. polarization is well maintained in vacuum – light from the Crab nebula is still polarized after travelling 6500 light years

- Technical noise is much lower than optical quantum noise

Single photon detection





Bouwmeester et al. Nature 390 ('97)

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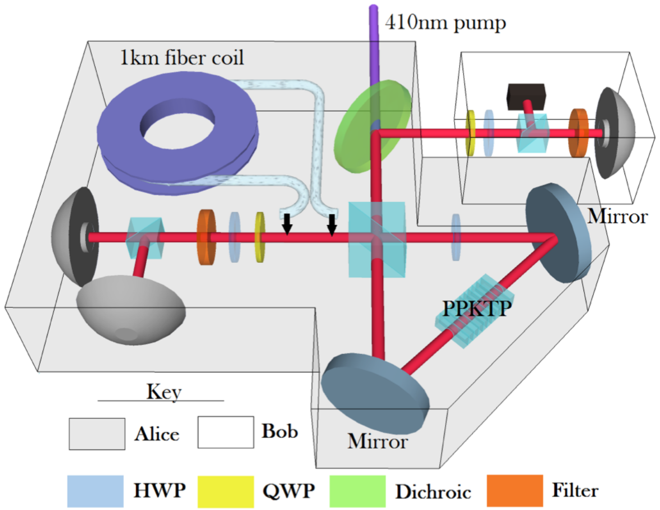
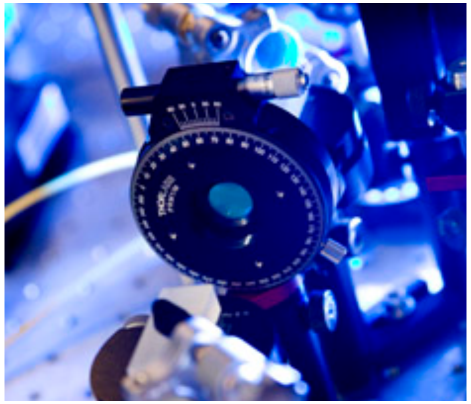
Why photons?

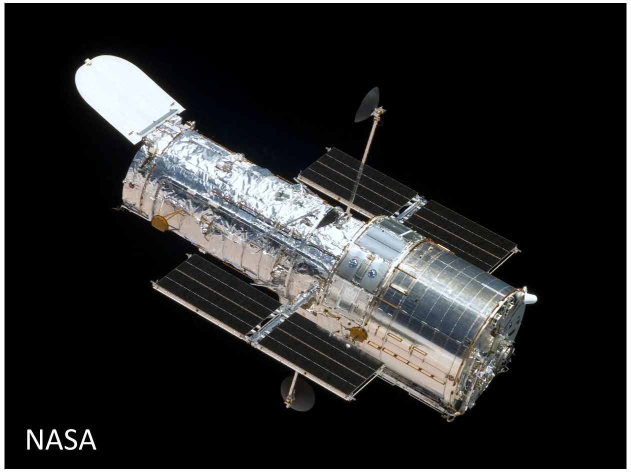
Optical systems are readily manipulated

- Precision control of optical beams, frequencies, polarization, intensity, etc

- Interferometry, imaging…







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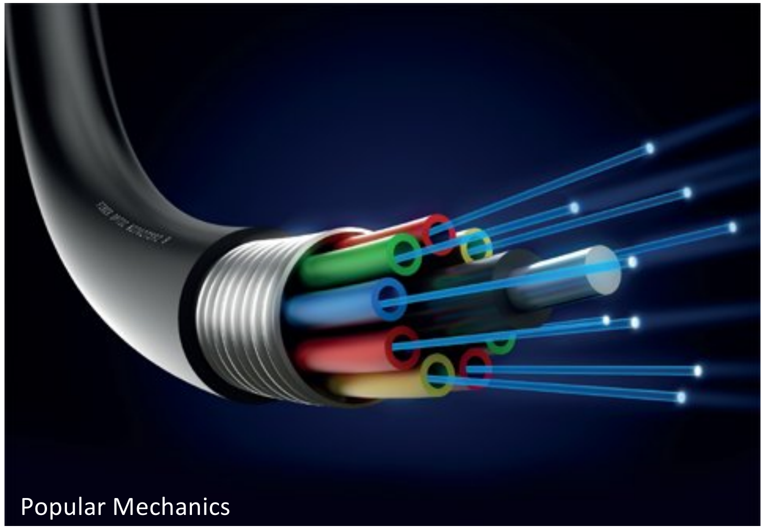
Why photons?

Light is excellent for transmitting information

- Existing optical communications industry
- Basis of telephony, internet, long-range sensing etc.

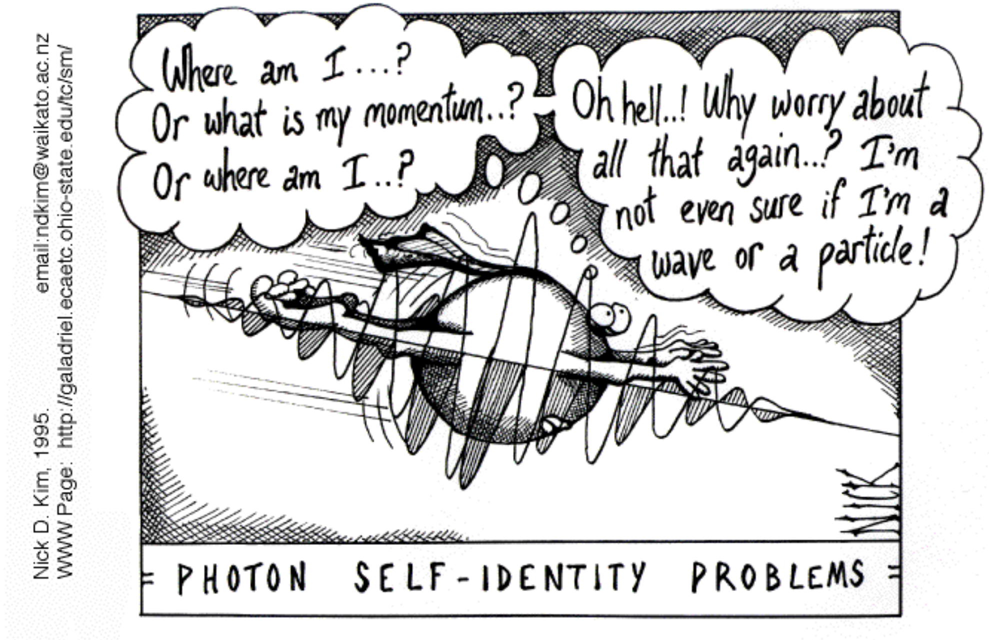


Popular Mechanics

OECD

Optics basics

- Light is a wave…
- … or a particle…
- … or both.



- Need two important concepts:

MODES

and

PHOTONS

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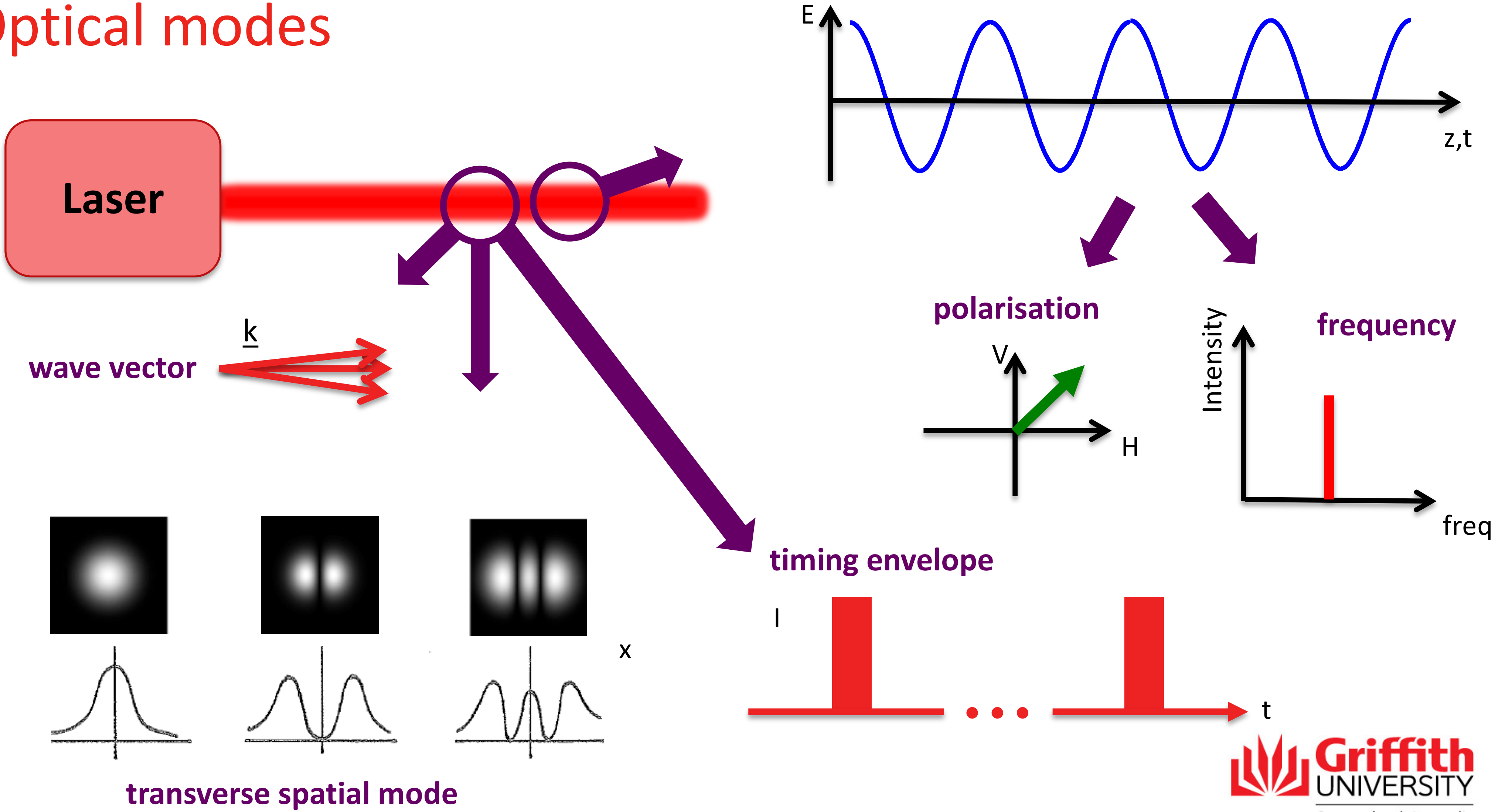
Optical modes



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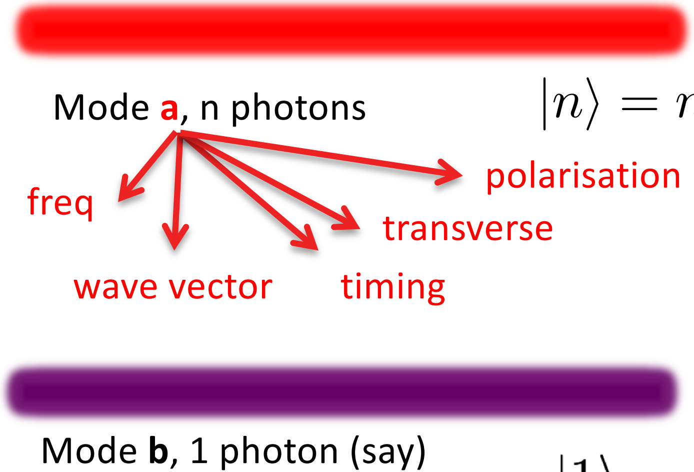
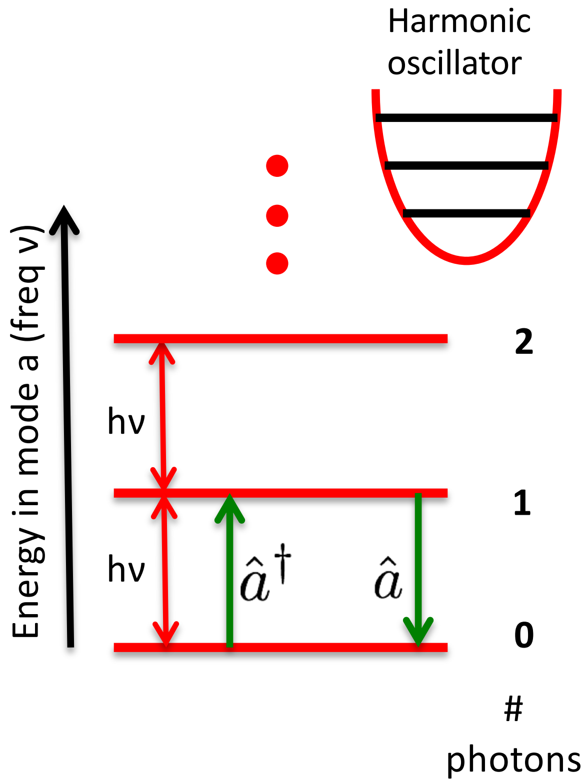
Photons

- Want to quantize optical fields
- Add energy in chunks ➔ photons
- Approx. view: wave packets (modes) with quanta of energy



$$|n\rangle = n \text{ photons}$$

$$|1\rangle = \hat{b}^{\dagger}|0\rangle$$



General (pure) state of mode: $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle + \gamma|2\rangle + \delta|3\rangle + \ldots$

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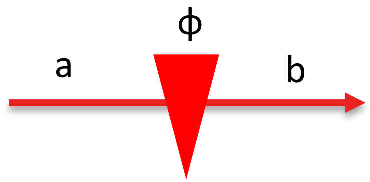
Modes and photons together

- Work in the Heisenberg picture…
  - … how creation operators change as they interact with optical elements
- Transforming photons means manipulating modes

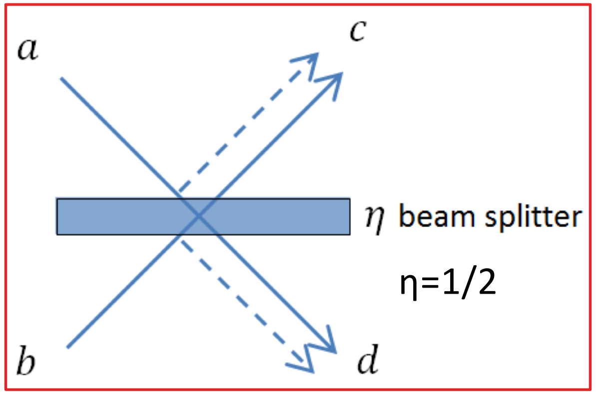


$$\hat{b}^\dagger = e^{i\phi}\hat{a}^\dagger$$

$$\hat{a}^\dagger \rightarrow \frac{i\hat{c}^\dagger + \hat{d}^\dagger}{\sqrt{2}}$$

$$\hat{b}^\dagger \rightarrow \frac{i\hat{d}^\dagger + \hat{c}^\dagger}{\sqrt{2}}$$

$$|0\rangle \rightarrow |0\rangle$$



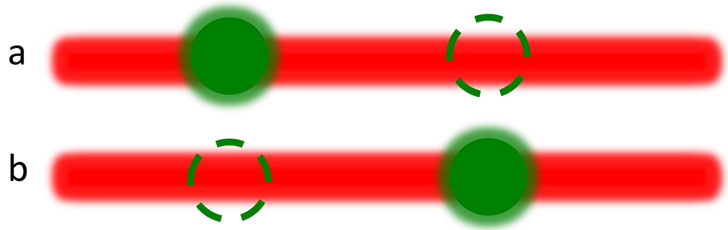
e.g. $|1_a 0_b\rangle = \hat{a}^\dagger|00\rangle \rightarrow \frac{i\hat{c}^\dagger + \hat{d}^\dagger}{\sqrt{2}}|00\rangle = \frac{i|1_c 0_d\rangle + |0_c 1_d\rangle}{\sqrt{2}}$

Quantum optical encodings

- The idea of quantum information science and technology is to encode information into quantum states
- We'll mostly be concerned with **qubits**
- Let's mention two encodings (others also possible):
  - Coherent states and continuous variables (not discussed today)
  - *Dual rail encoding of photons*

Dual rail encoding

- Encode a qubit in one photon across two modes



$$|0_L\rangle \equiv |1_a 0_b\rangle$$

$$|1_L\rangle \equiv |0_a 1_b\rangle$$

$$|\psi\rangle = \alpha|10\rangle + \beta|01\rangle$$

(implicit subscripts)

- Common case: same spatial mode; a = H; b = V

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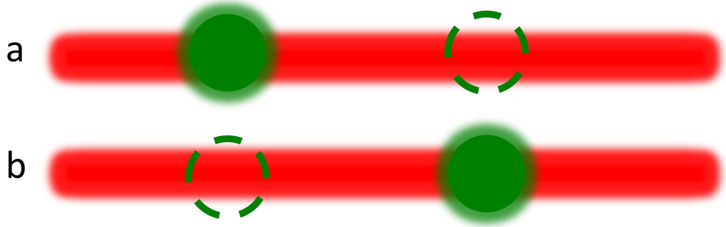
Dual rail encoding

- Encode a qubit in one photon across two modes



$$|0_L\rangle \equiv |1_a 0_b\rangle$$
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$$|\psi\rangle = \alpha|10\rangle + \beta|01\rangle$$

(implicit subscripts)

- Common case: same spatial mode; a = H; b = V

$$|10\rangle \equiv |H\rangle$$
$$|01\rangle \equiv |V\rangle$$

$$|\psi\rangle = \alpha|H\rangle + \beta|V\rangle$$

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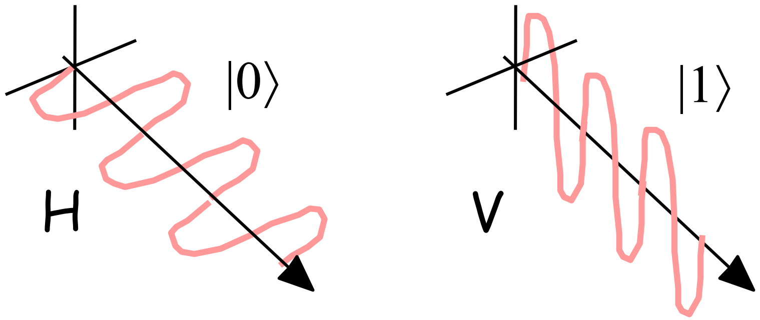
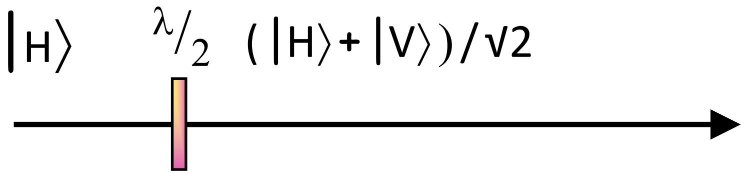
Rotating and measuring photon polarisation qubits

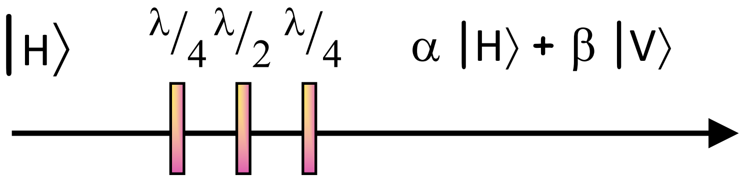
Polarisation qubits:



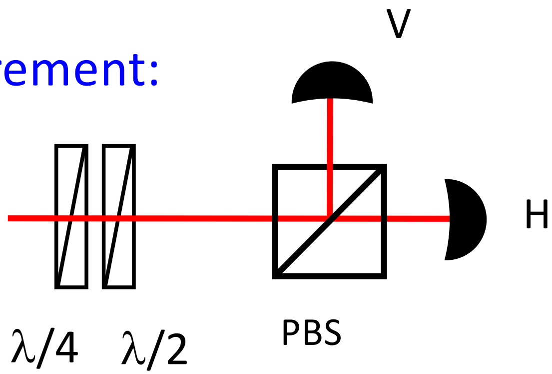
Hadamard gate



Arbitrary rotation gate



Measurement:



A. White

Quantum optics technologies

- How do we work with quantum states of light?
- We need to

  MAKE,

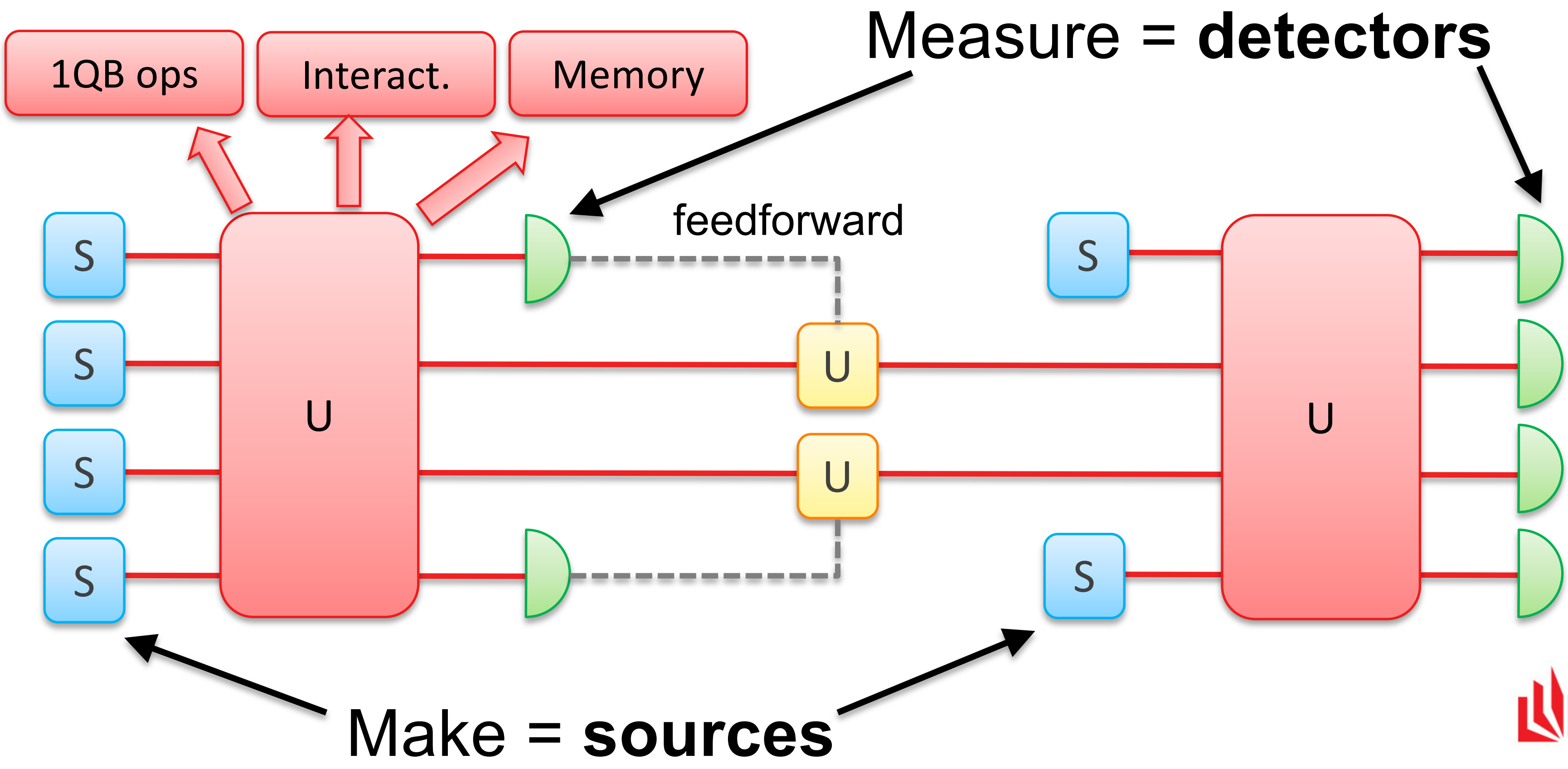
  MEASURE and

  MANIPULATE them.

- Let’s take a look at the technologies for each of these, with an emphasis on **photons**.

Cartoon picture of optical quantum information tech.

(not necessarily general or completely accurate, but indicative)



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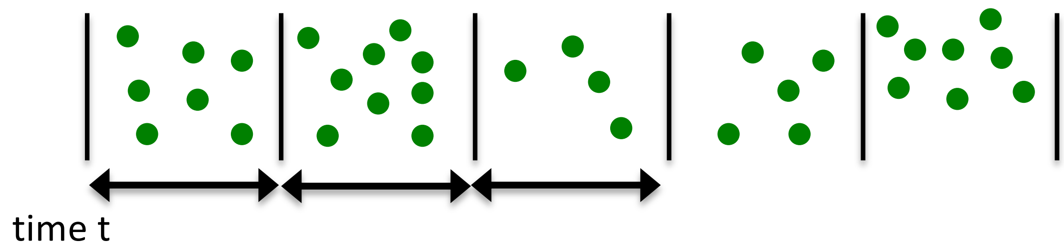
Photon sources

- What’s needed?
  - Sources of single photons and/or
  - Sources of entangled photons

Making photons

- Want 1 and only 1 photon in a mode

- Can't just attenuate another quantum state, e.g. coherent state from laser

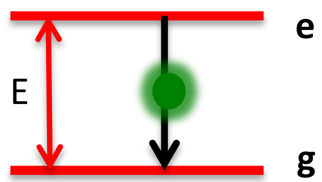


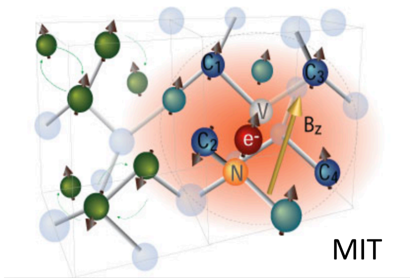
$$|\alpha\rangle = |\epsilon\rangle|\epsilon\rangle|\epsilon\rangle|\epsilon\rangle|\epsilon\rangle \ldots$$

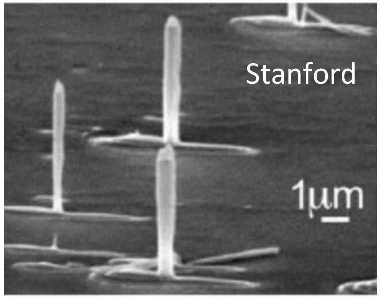
$$|\epsilon\rangle \approx |0\rangle + \epsilon|1\rangle + \frac{\epsilon^2}{2}|2\rangle + \cdots$$

Making photons

Single emitters

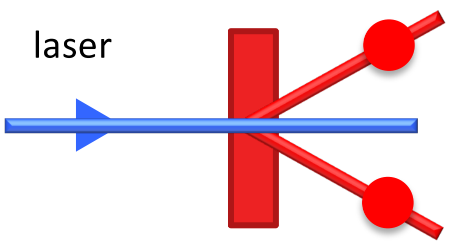


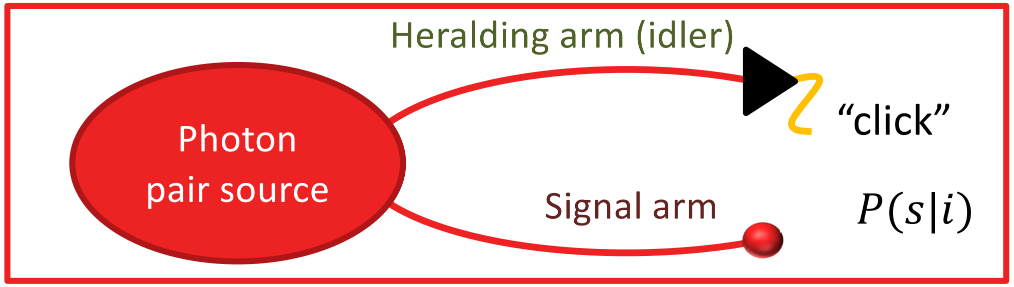




Want:
- Deterministic
- Pure
- Short
- Indistinguishable photons

Spontaneous parametric downconversion





Heralding efficiency

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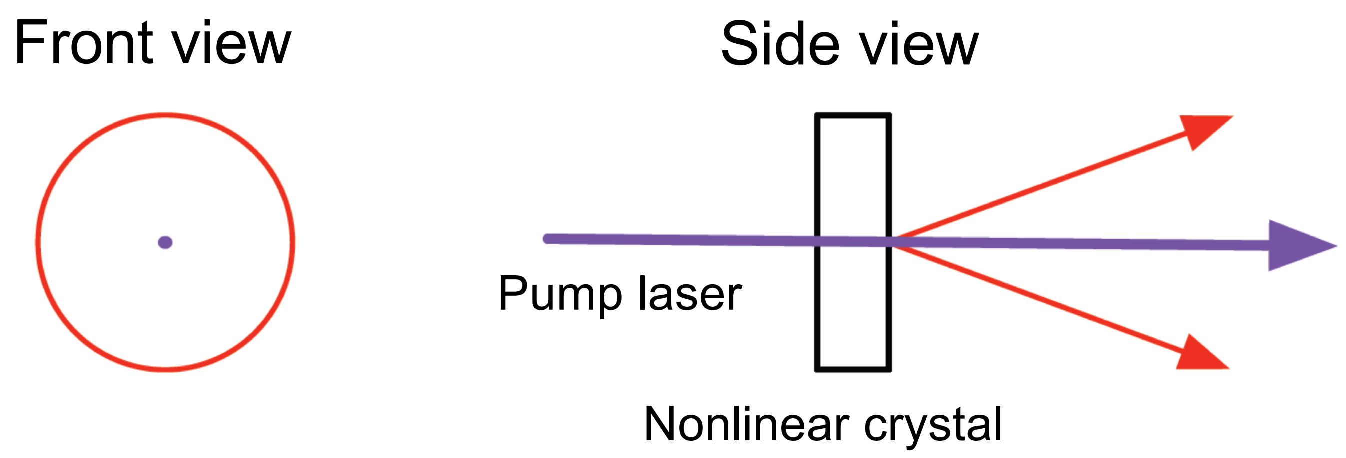
Spontaneous Parametric Down Conversion (basic)

$$\vec{k}_p = \vec{k}_s + \vec{k}_i \qquad f_p = f_s + f_i$$



don't want these

$$|\psi\rangle = \gamma\,|\mathbf{0}_a\mathbf{0}_b\rangle + \sqrt{p}\,|\mathbf{1}_a\mathbf{1}_b\rangle + p\,|\mathbf{2}_a\mathbf{2}_b\rangle + p^{3/2}\,|\mathbf{3}_a\mathbf{3}_b\rangle + \ldots$$

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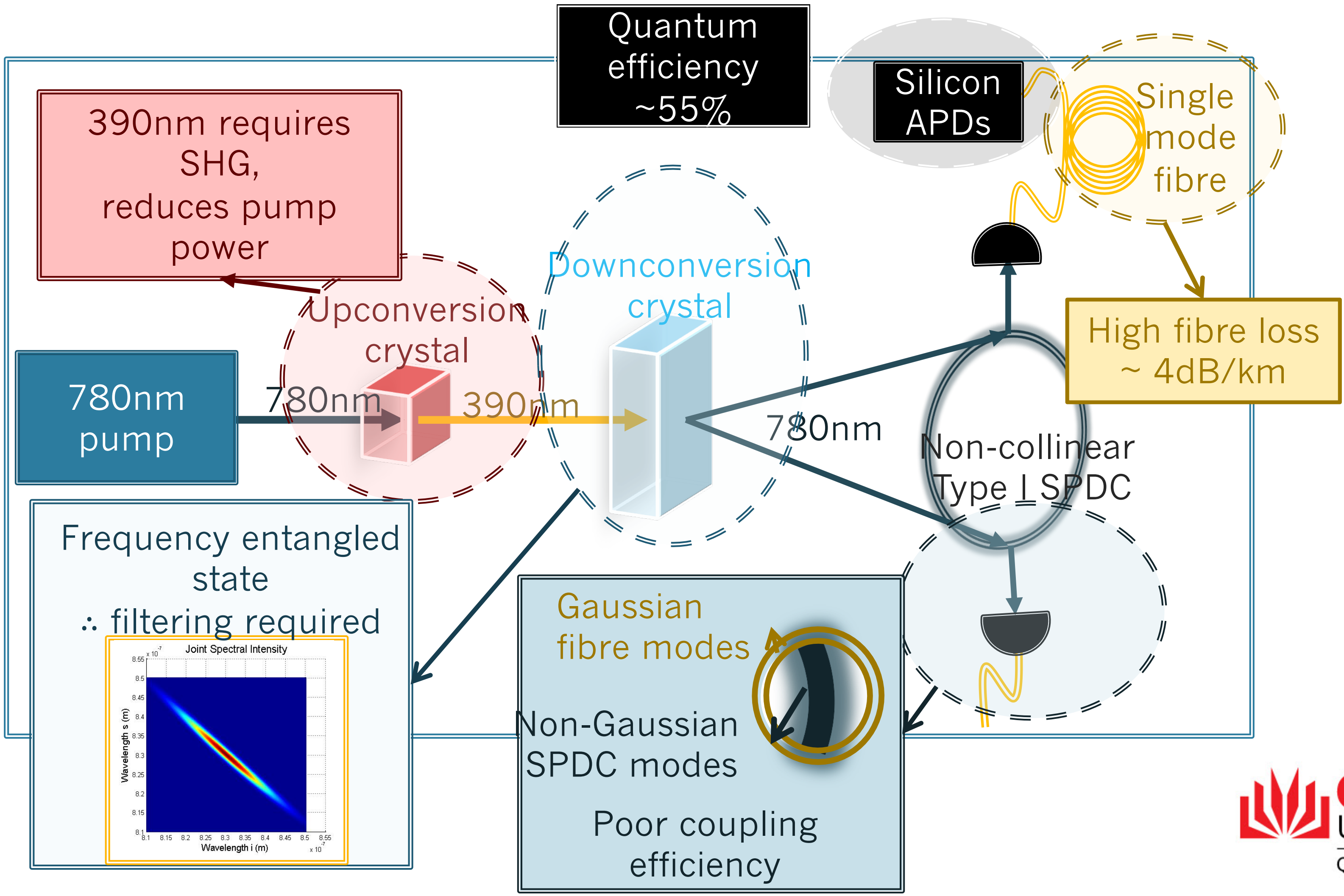
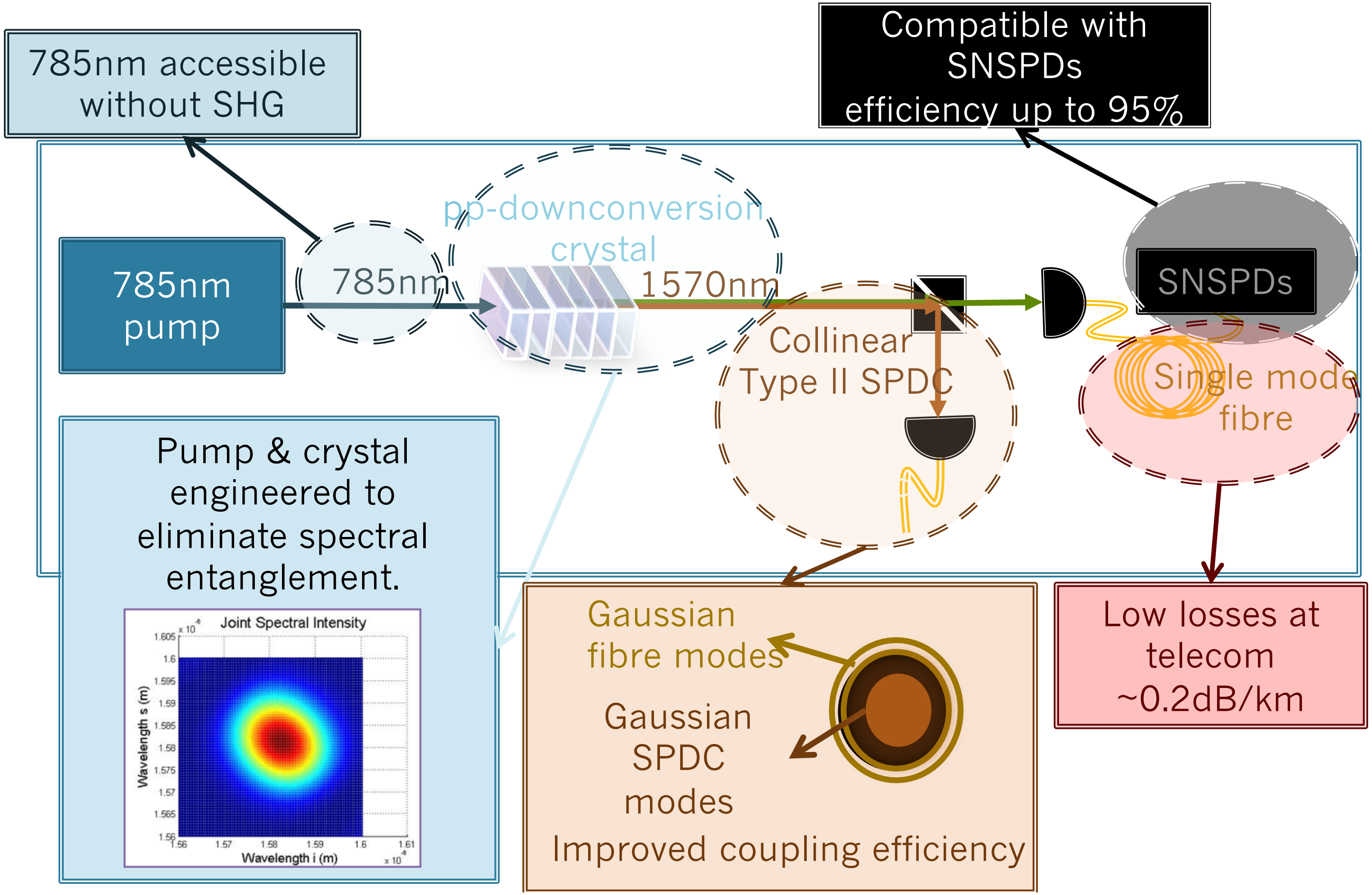
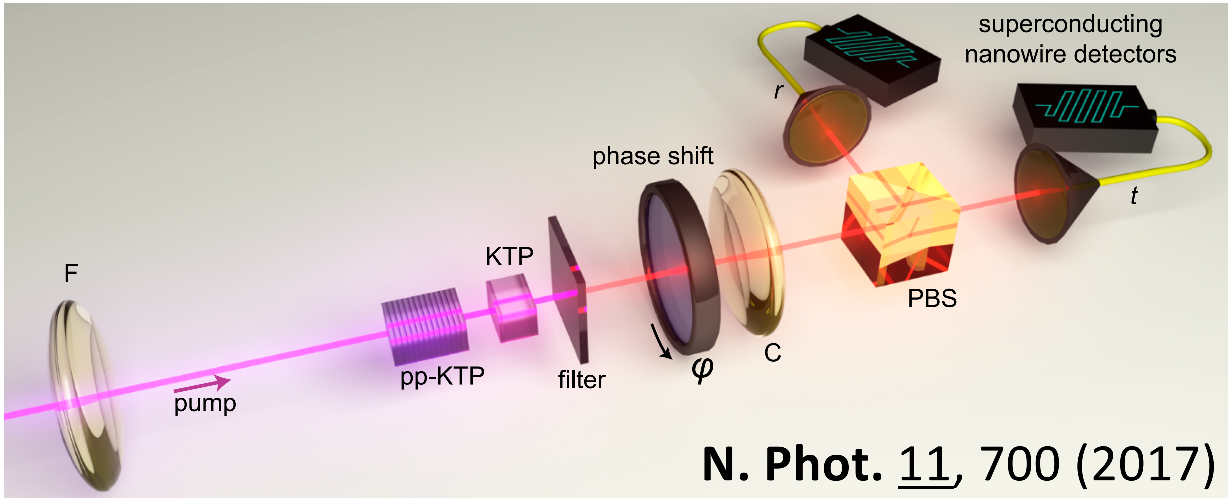
Typical SPDC source



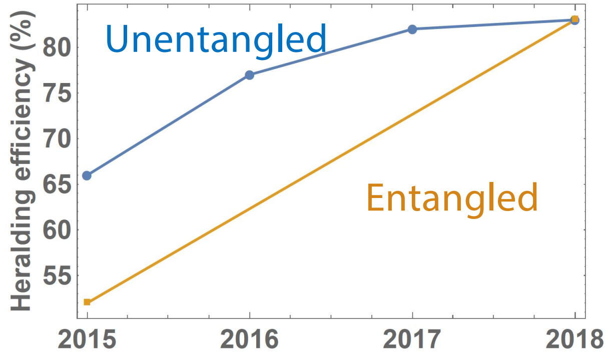
High heralding efficiency source

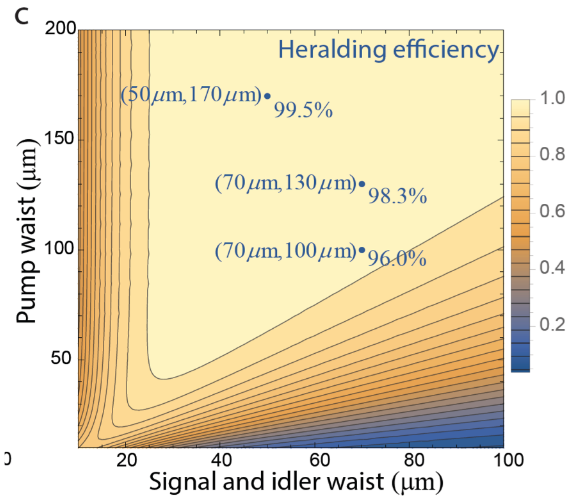




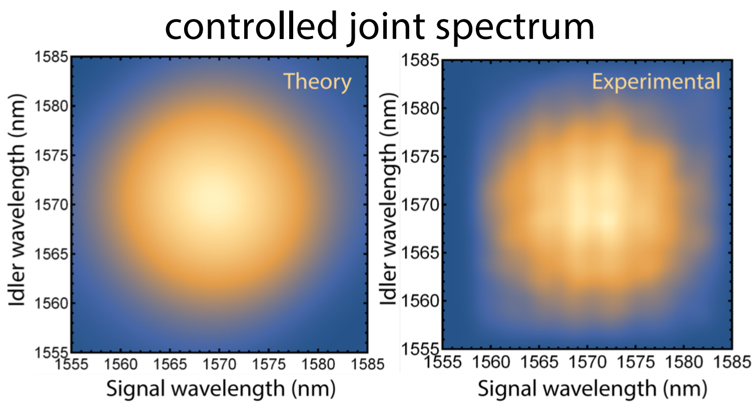
N. Phot. 11, 700 (2017)

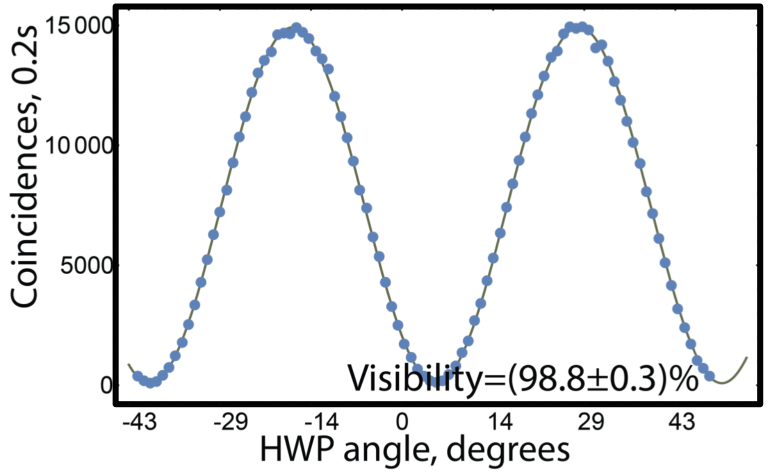
Heralding/ Klyshko efficiency (includes detector eff.)		
Unentangled source	@ 1570 nm	$(66 \pm 2)\%$
	@ 1550 nm	$(82 \pm 2)\%$



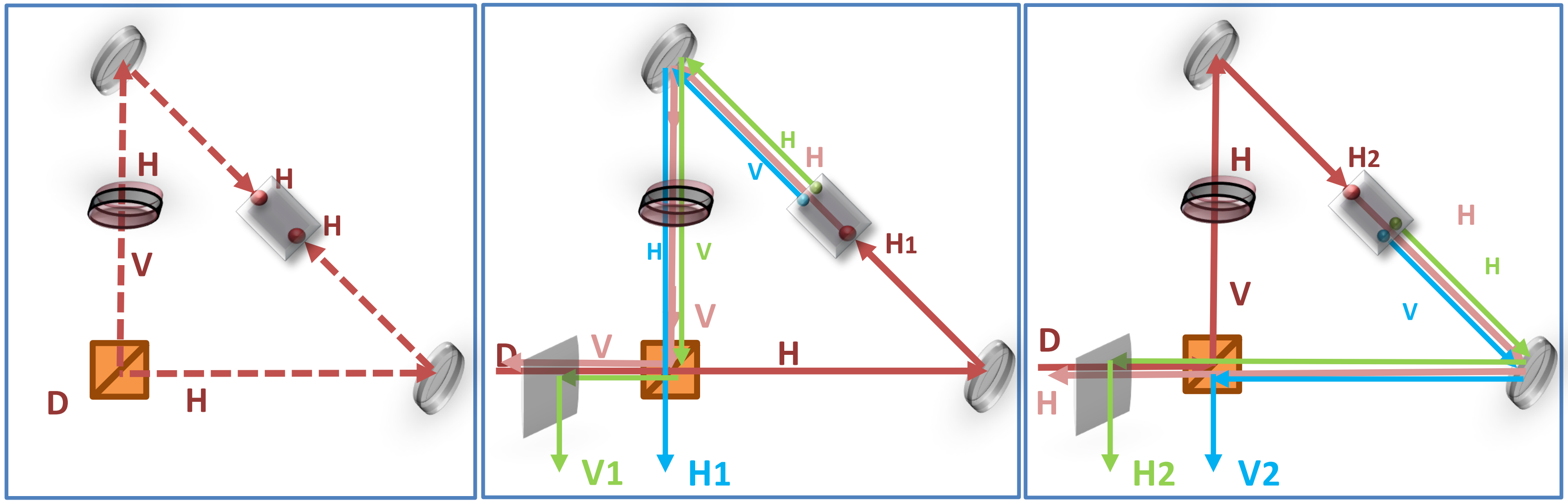


Bennink, PRA **81**, 053805 (2010)





Entangled source (one design)



Output state = $|HV\rangle - |VH\rangle \equiv |01\rangle - |10\rangle$

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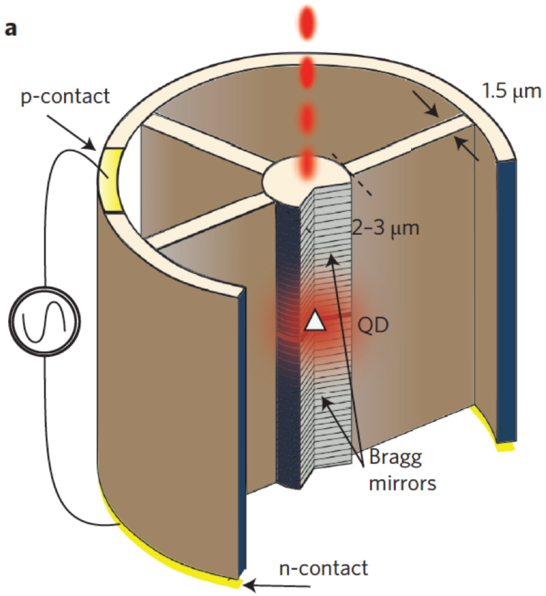
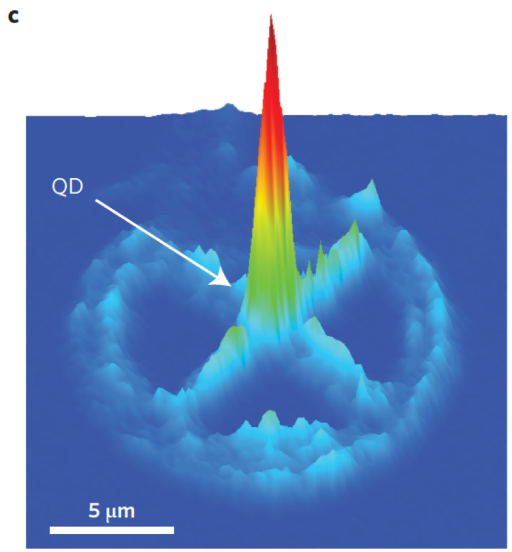
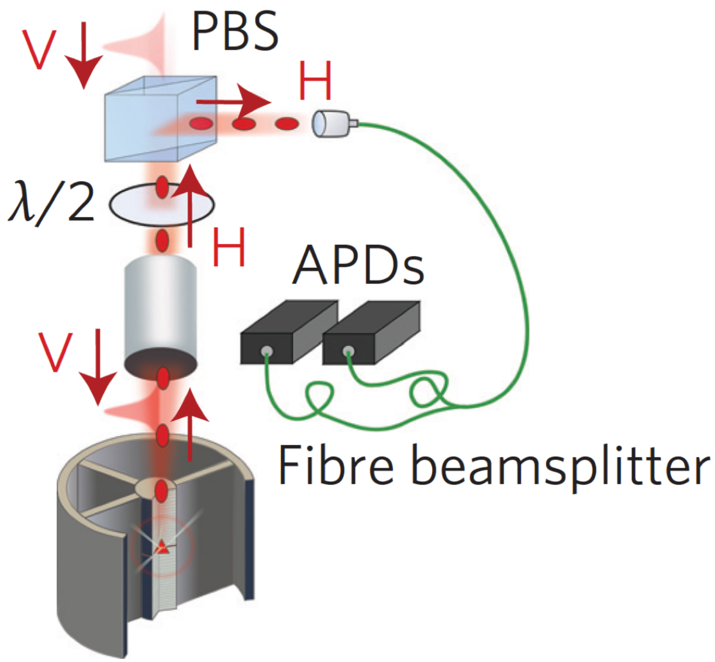
Quantum dot sources







Somaschi et al., Nature Photonics 10, 340 (2016)

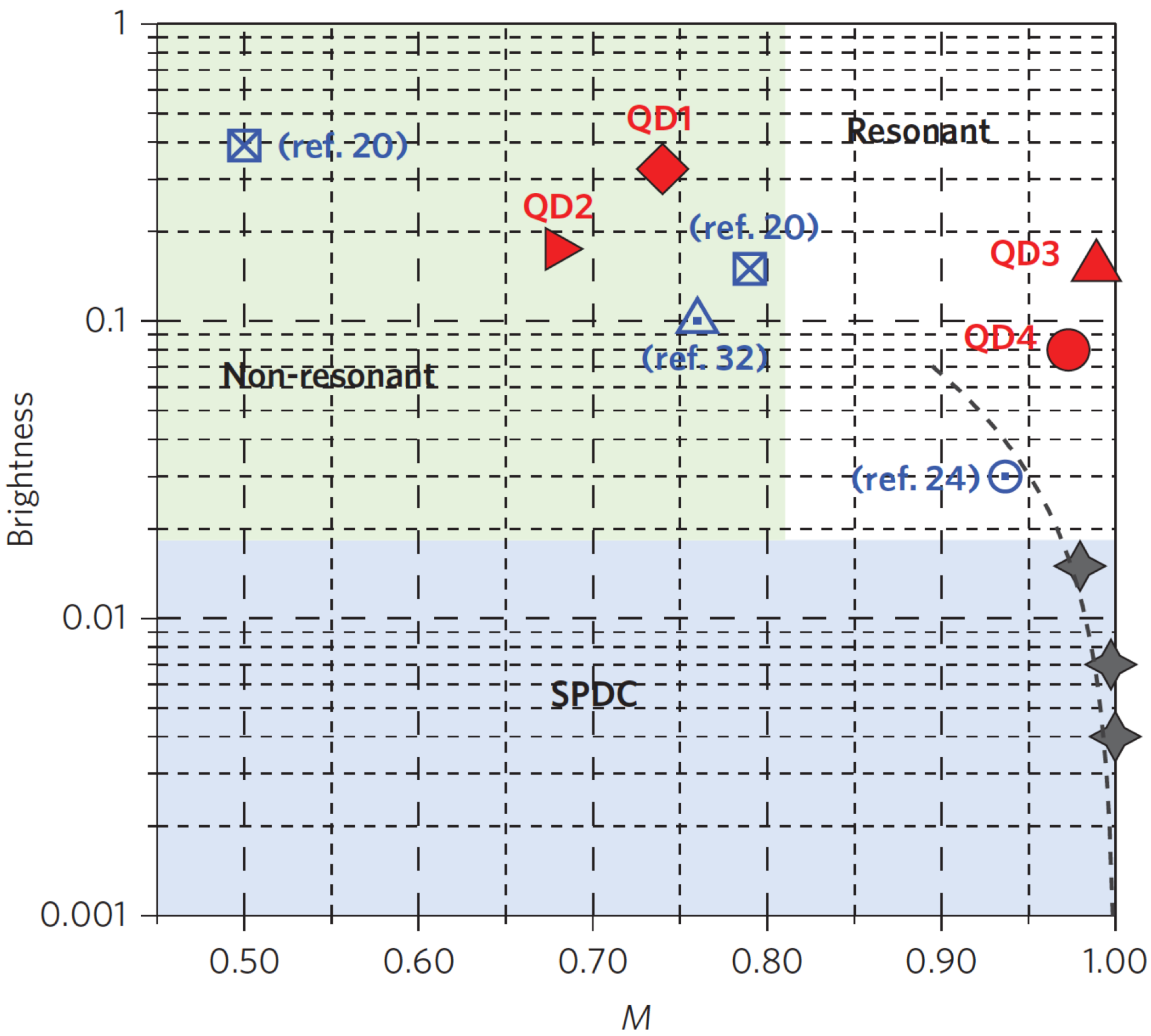
Sources - important ingredients

- Distinguishability of two photons from the same source (M)
- Distinguishability of two photons from different sources (M)
- Efficiency (B)
  - Generation efficiency, Heralding efficiency, Coupling efficiency
- $g^{(2)}(0)$ – correlation function (M)
  - (roughly, what is the probability of getting two photons when one expected)
- Speed/rate
- (B, M: see next slide)

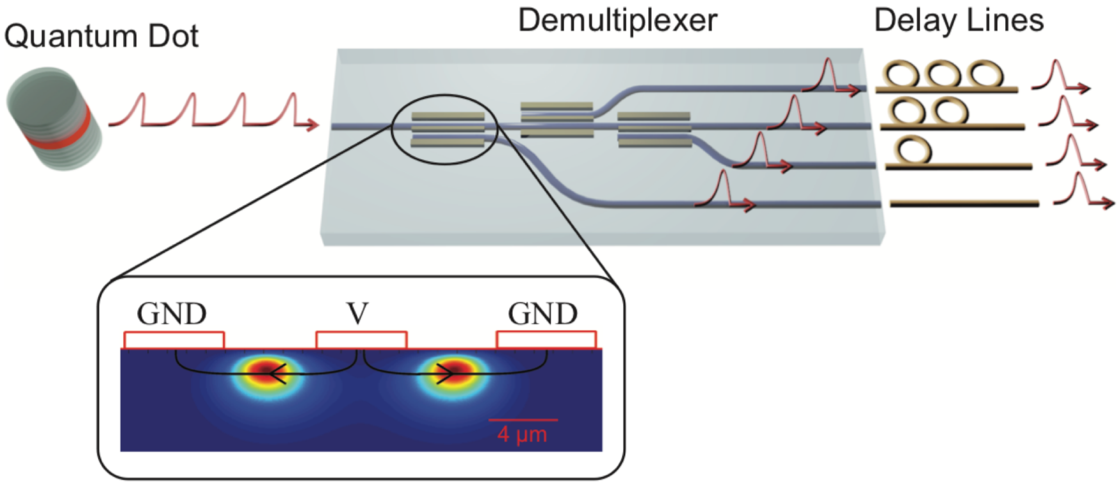
Sources

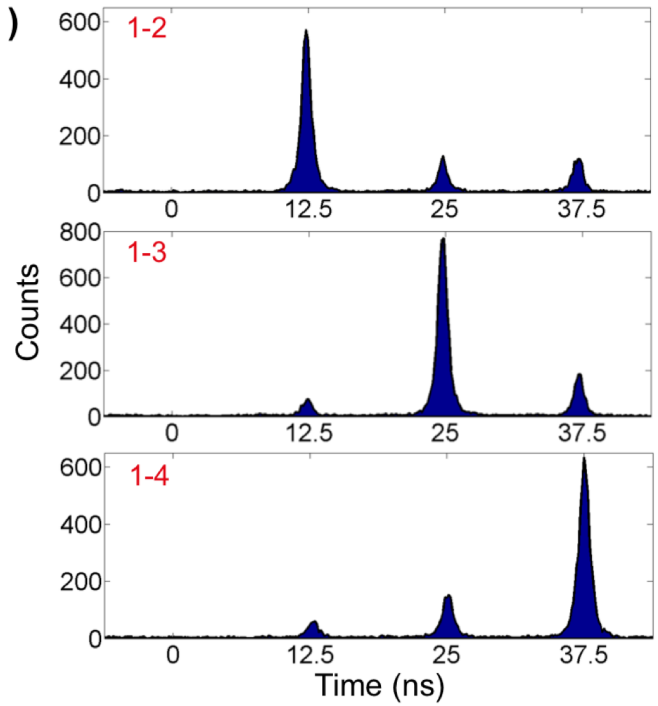
What is needed is to MUX/DEMUX sources

Somaschi et al., Nat. Phot. 10, 340 (2016)



Sources

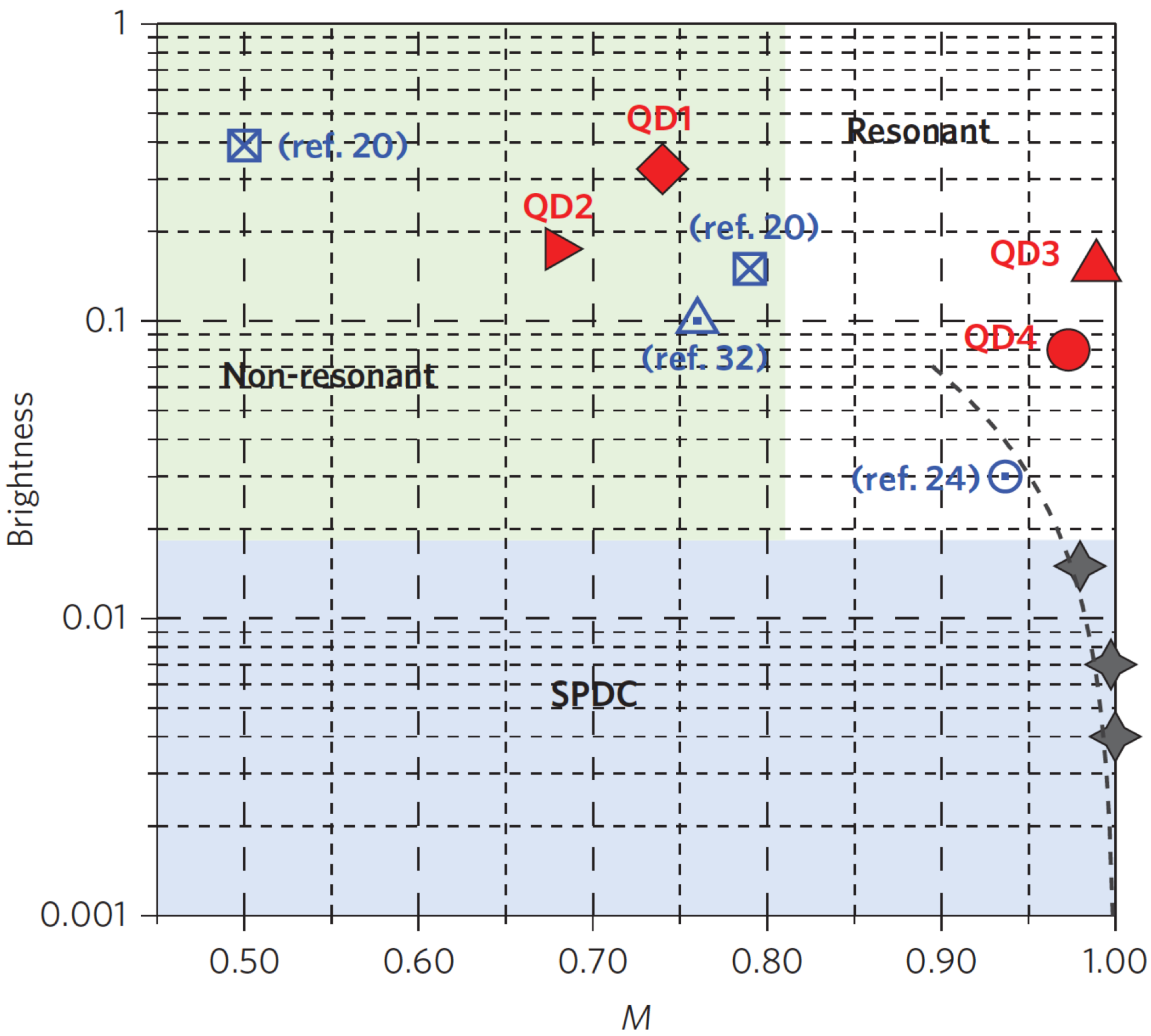




Lenzini et al., Laser & Photonics Reviews 11, 1600297 (2017)

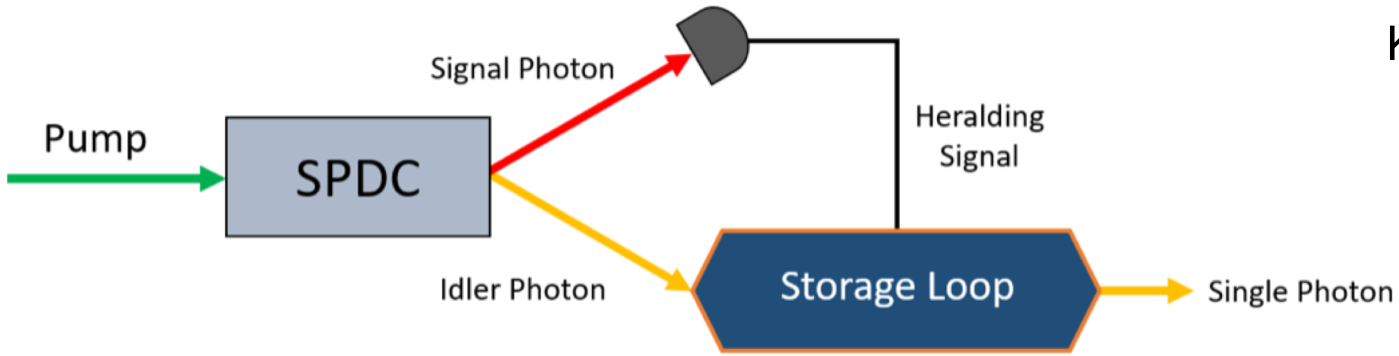
Sources

What is needed is to MUX/DEMUX sources

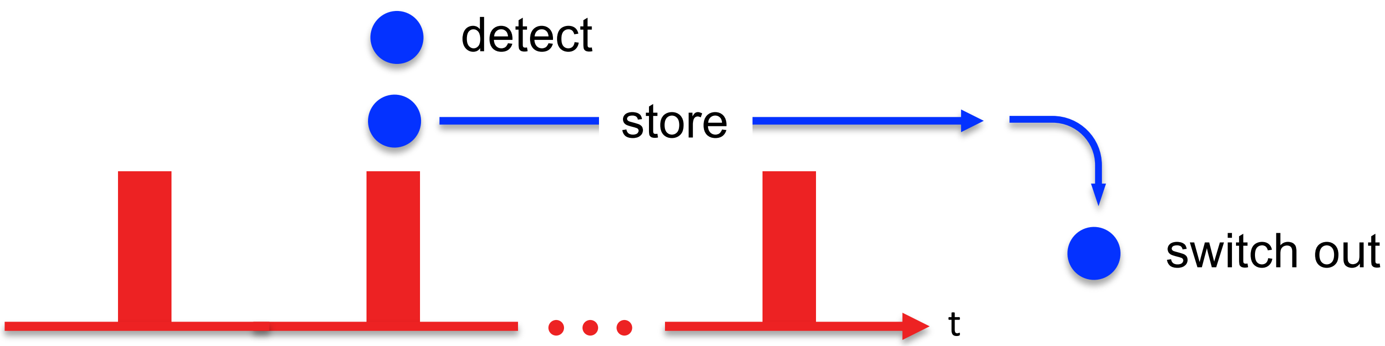


Somaschi et al., Nat. Phot. 10, 340 (2016)

Time-multiplexed source



Kwiat group



N pulses

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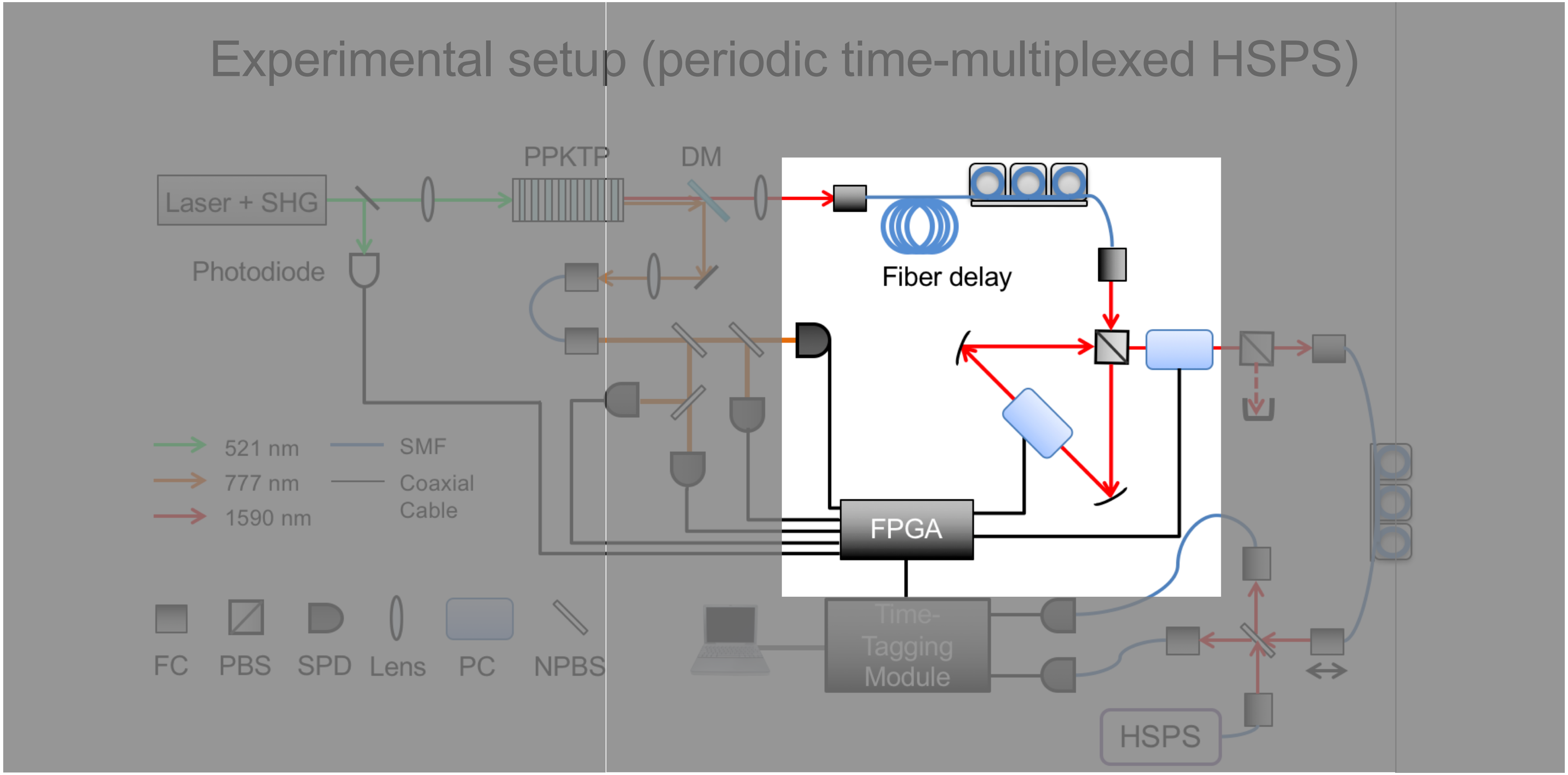
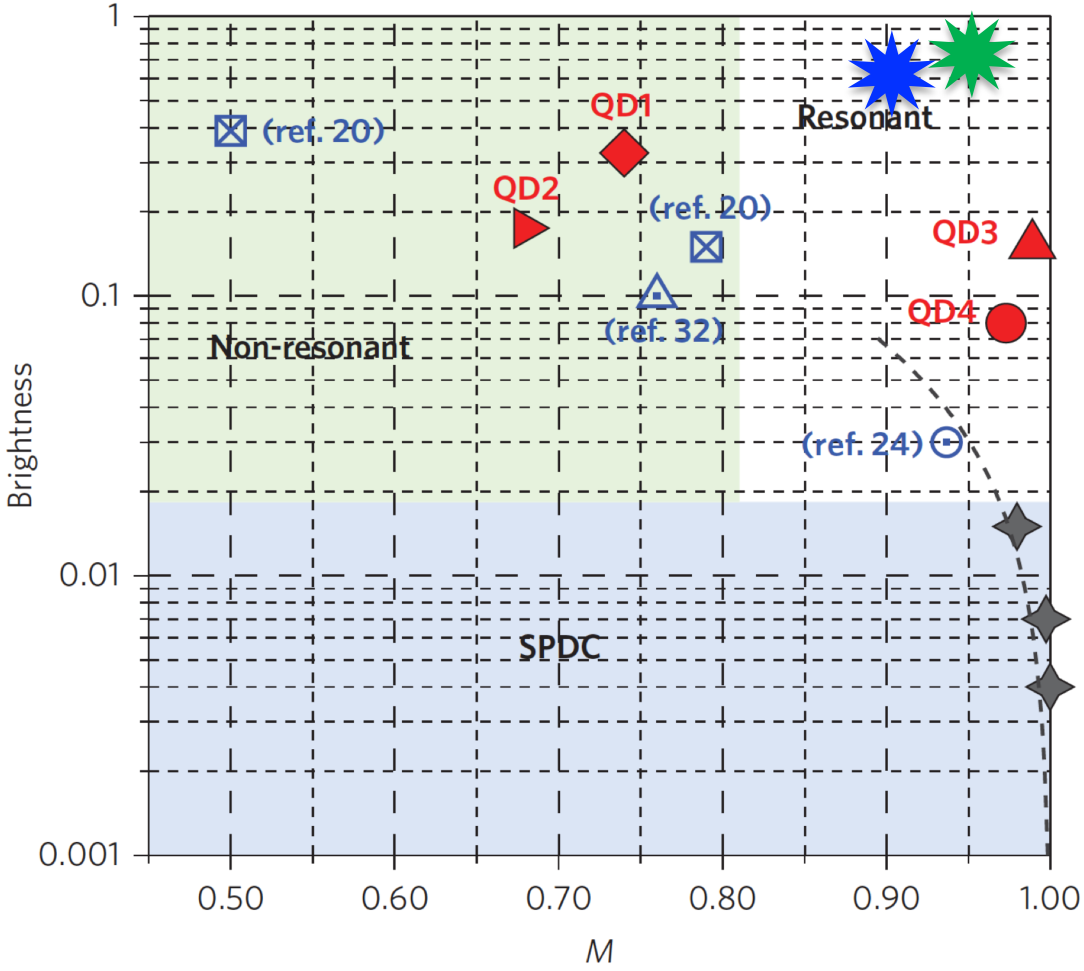


Kaneda and Kwiat, arXiv:1803.04803

Sources



Kaneda and Kwiat, arXiv:1803.04803

Somaschi et al., Nat. Phot. 10, 340 (2016)

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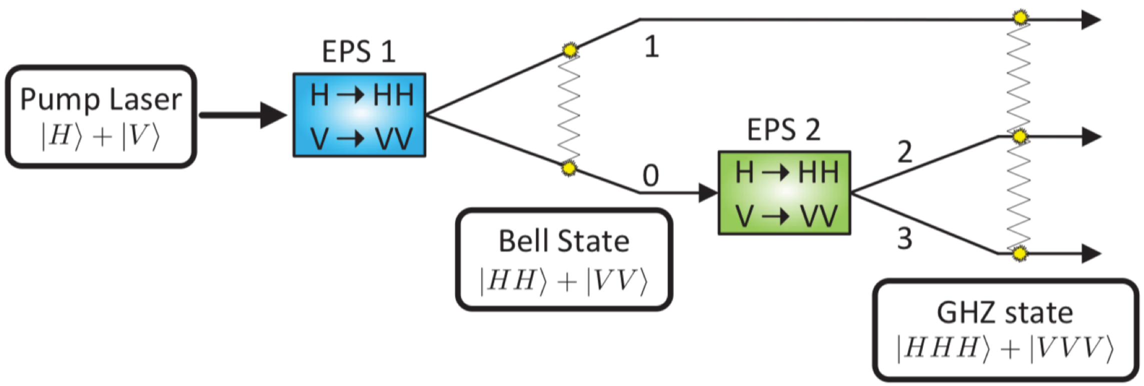
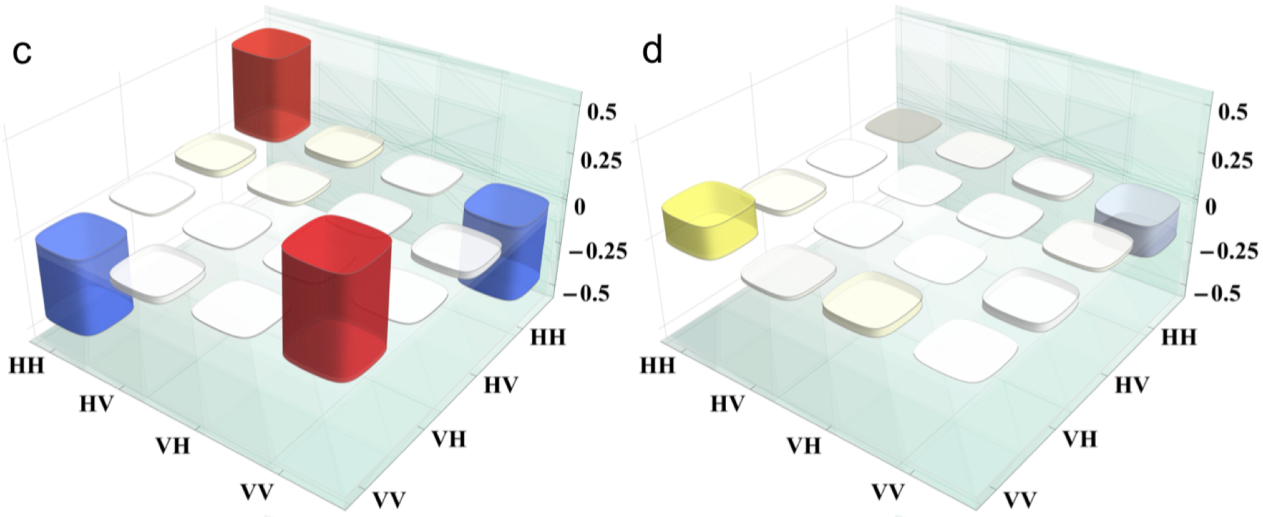
Heralded *entangled* photons (one way)



Bell pair here

Herald here

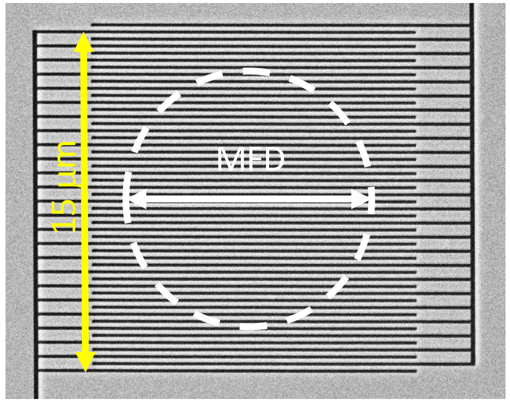
Can make other entangled states



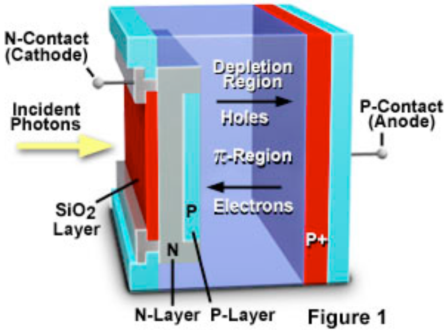
Hamel et al.,
Nature Phot. **8**, 801 (2014)

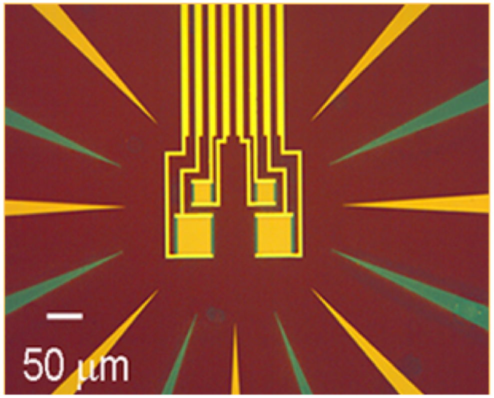
Measuring photons

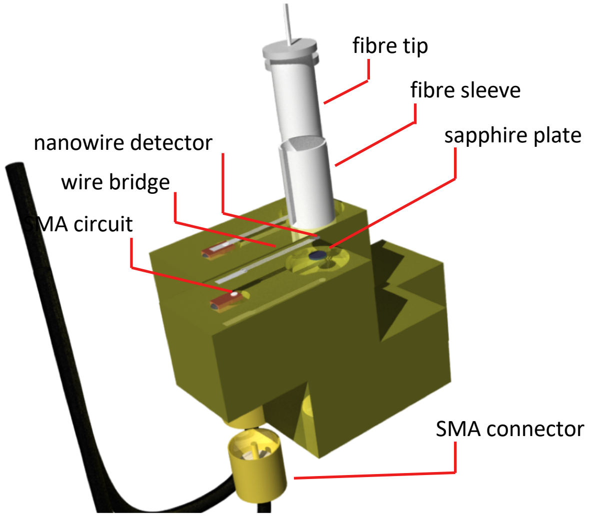
- Need to detect a very small energy: ~ 10^{-19} J for visible/near IR photons
- Some options:
  - Avalanche photodiodes
  - Superconductors



Avalanche Photodiode







Photon detection

- Desired photon detector
  - High efficiency
  - Fast
  - Photon number resolving
- Limitations at Telecom (~ 1500 nm)

Detector type	Detection efficiency (%)	Max count rate (CPS)	Timing jitter (ns)	Photon number resolution	System dark count rate (CPS)	Operation temperature (K)
InGaAs APD	10	10^8	0.05	No	10^4	240
W TES	99	$< 10^4$	100	Full	< 1	0.1
WSi SNSPD	95	$10^7 – 10^8$	0.2	No	< 10	1

Based on Rev. Sci. Instrum. **82**, 071101 ('11) with some updates and interpretations*

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Summary of quantum photonics overview

- Photons (and other optical quantum states) are robust and mobile
- Need to **make**, **manipulate** and **measure** photons
- Sources and detectors are approaching exceptional performance levels

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Application: true quantum advantage in entangled-photon metrology

- Photonic entanglement-enhanced interferometry

- The shot noise limit hasn't been surpassed unconditionally, until now

- We unconditionally surpass the shot noise limit

S. Slussarenko *et al.*, **Nature Photonics** 11, 700 (2017)

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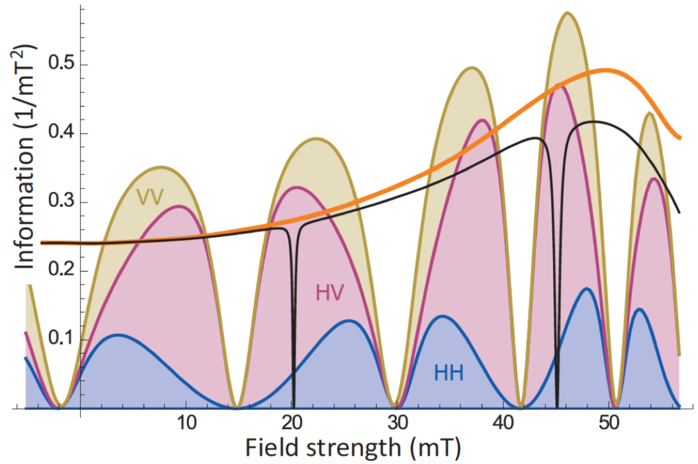
Photonic quantum metrology – **interferometry**

- "Photonic" means explicitly using photons, e.g. states of definite photon number and/or the use of photon counting (*not squeezing*)

- Promise of extracting the maximum phase information per photon

- Promise of extracting the better-than-classical phase information per unit of "destruction"

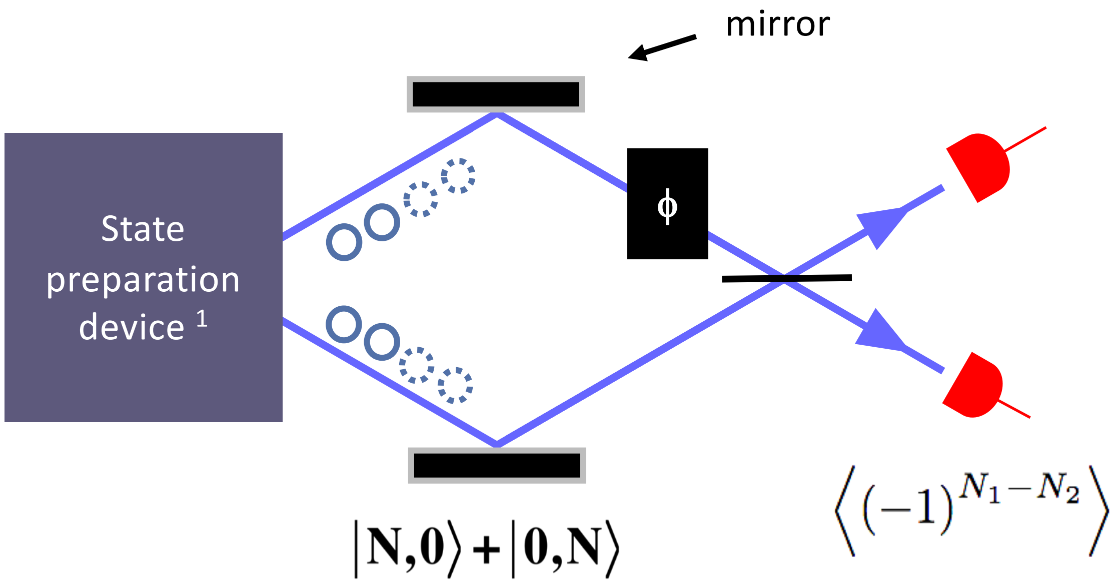


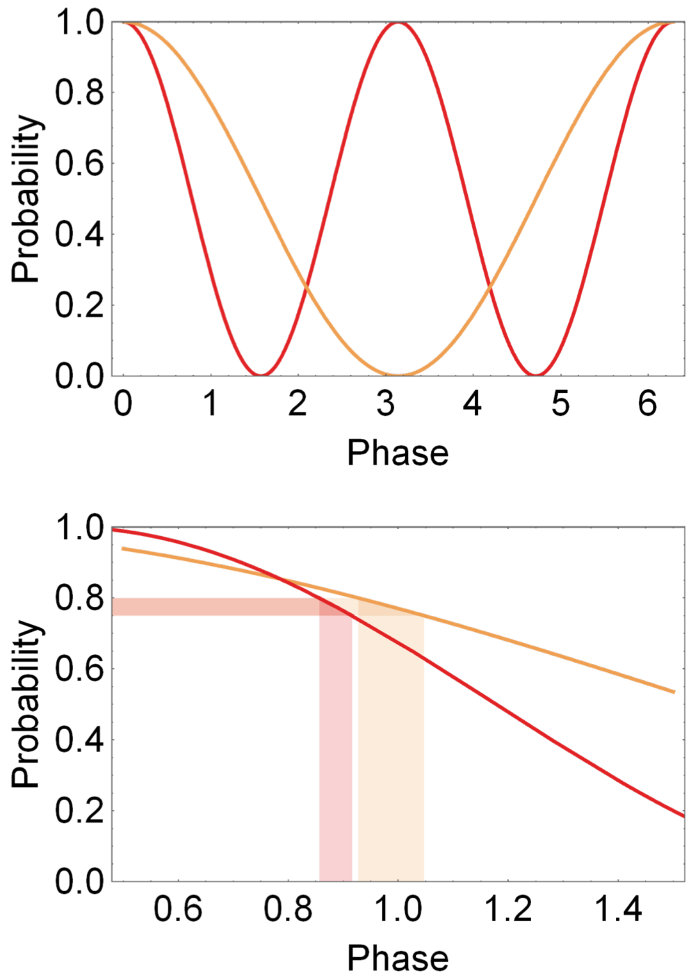
Wolfgramm et al., Nature Phot. 7, 28 (2013)

Genuine quantum-enhanced performance has been a goal for ~ 30 years

B. Yurke, Phys. Rev. Lett. **56**, 1515 (1986)
B. C. Sanders, Phys. Rev. A **40**, 2417 (1989)
A. N. Boto *et al.*, Phys. Rev. Lett. **85**, 2733 (2000)
…

Interferometry: NOON states

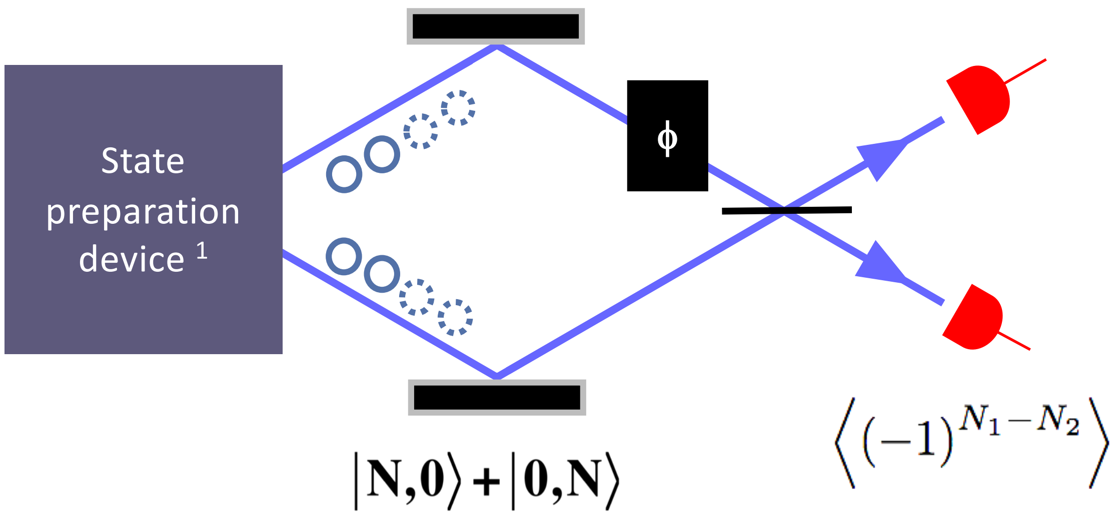


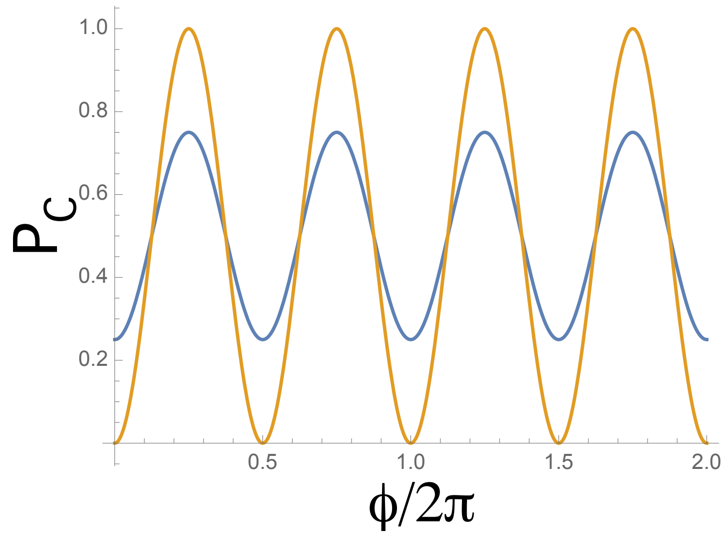


[1] e.g. McCusker and Kwiat, *PRL* **103**, 163602 (2009)

Resource (= N): Number of photons in the interferometer in a defined mode

NOON states with reduced interference visibility

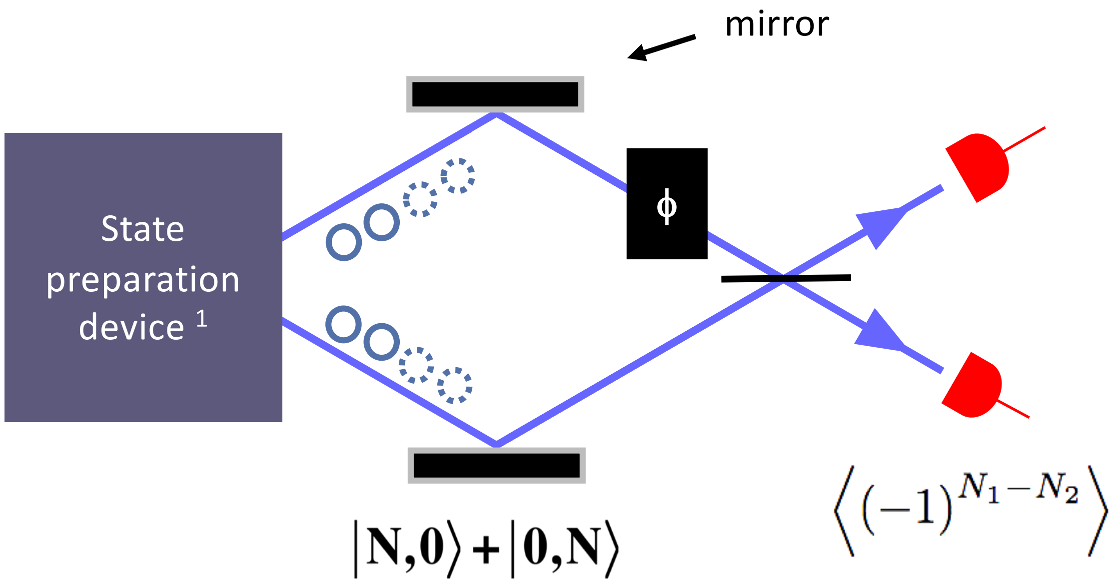


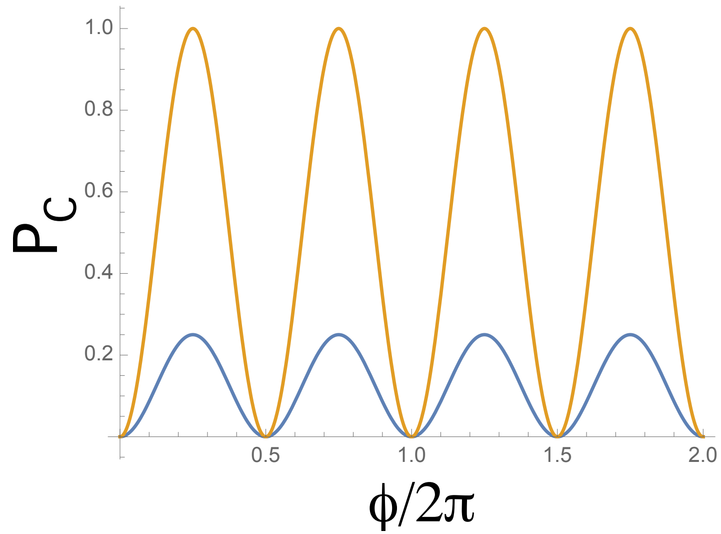


"Period 1/N" fringes

[1] e.g. McCusker and Kwiat, *PRL* **103**, 163602 (2009)

NOON with low arm efficiency (modes, loss, dets …)





"Period 1/N" fringes

[1] e.g. McCusker and Kwiat, *PRL* **103**, 163602 (2009)

Phase sensitivity heuristic

Phase sensitivity: $$\Delta\phi = \frac{\Delta A}{\left| d\langle A\rangle / d\phi \right|}$$

Fringe pattern: $$\frac{1}{2}(1 - V\cos N\phi) \times \eta^N$$

Gradient: $$d\langle A\rangle / d\phi = \frac{1}{2} NV \sin N\phi \times \eta^N$$

Classical (SNL): $$\Delta\phi_{\mathrm{classical}} = \frac{1}{\sqrt{N}}$$

Quantum enhancement if:

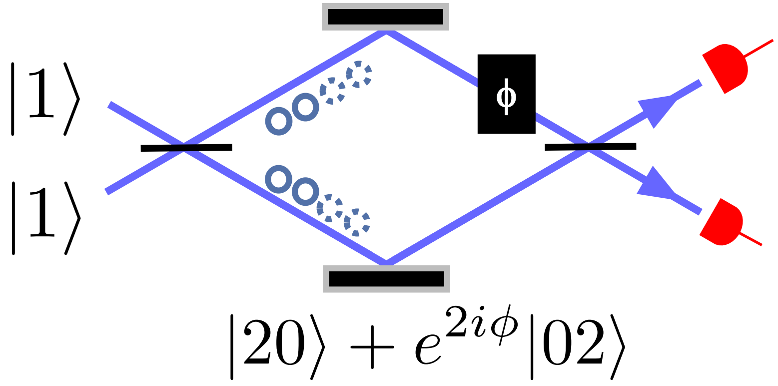
$$\eta^N V^2 N > 1$$

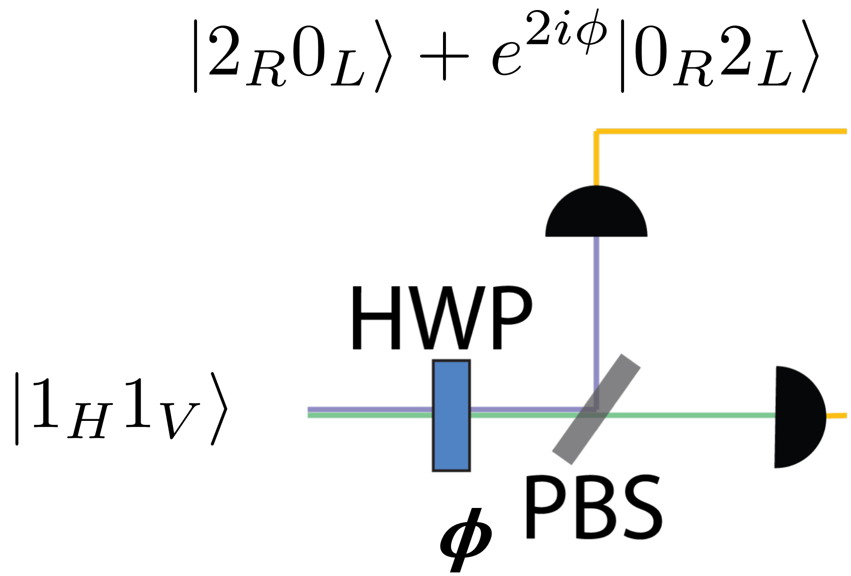
η	Heralding (arm) efficiency
V	Interference visibility
N	Number of photons

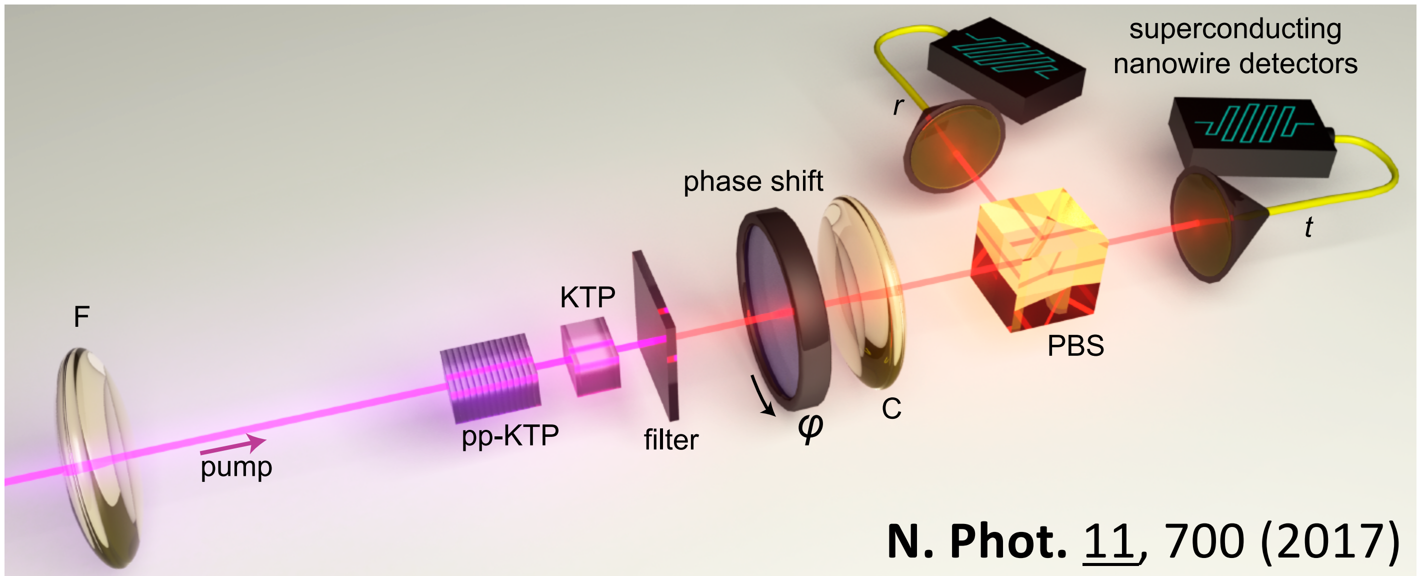
Resch et al., PRL **98**, 223601 (2007)
Okamoto et al, NJP **10** 073033 (2008)

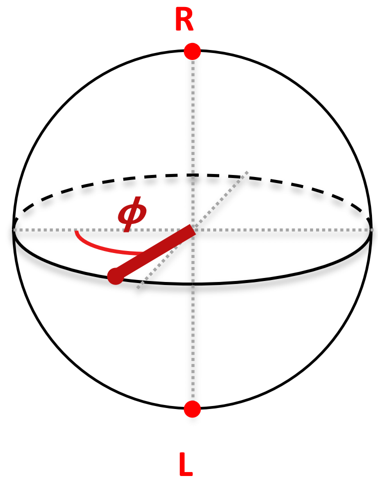
More rigorous: A. Datta et al., PRA 83, 063836 (2011)

Experimental setup









Back-of-the-envelope calculation

$$\eta \approx 0.82 \qquad V \approx 0.99 \qquad N = 2$$

$$\boxed{\eta^2 \, V^2 \, N \approx 1.32 > 1}$$

Two experiments

- We characterise the performance with two experiments

1. From the fringes, we can determine the Fisher information, and compare it with theory

(Not in this talk)

2. We can use multiple, *k*, trials (detections) to infer a phase value at a given phase setting.

   We can then use multiple, *s*, such phase samples to determine the uncertainty in the inferred phase.

   We use k = 10,000 trials and s = 14,500 samples.

   SNL: $N^{tot} = N \times k \times s \times$ correction factor = 304,375,500

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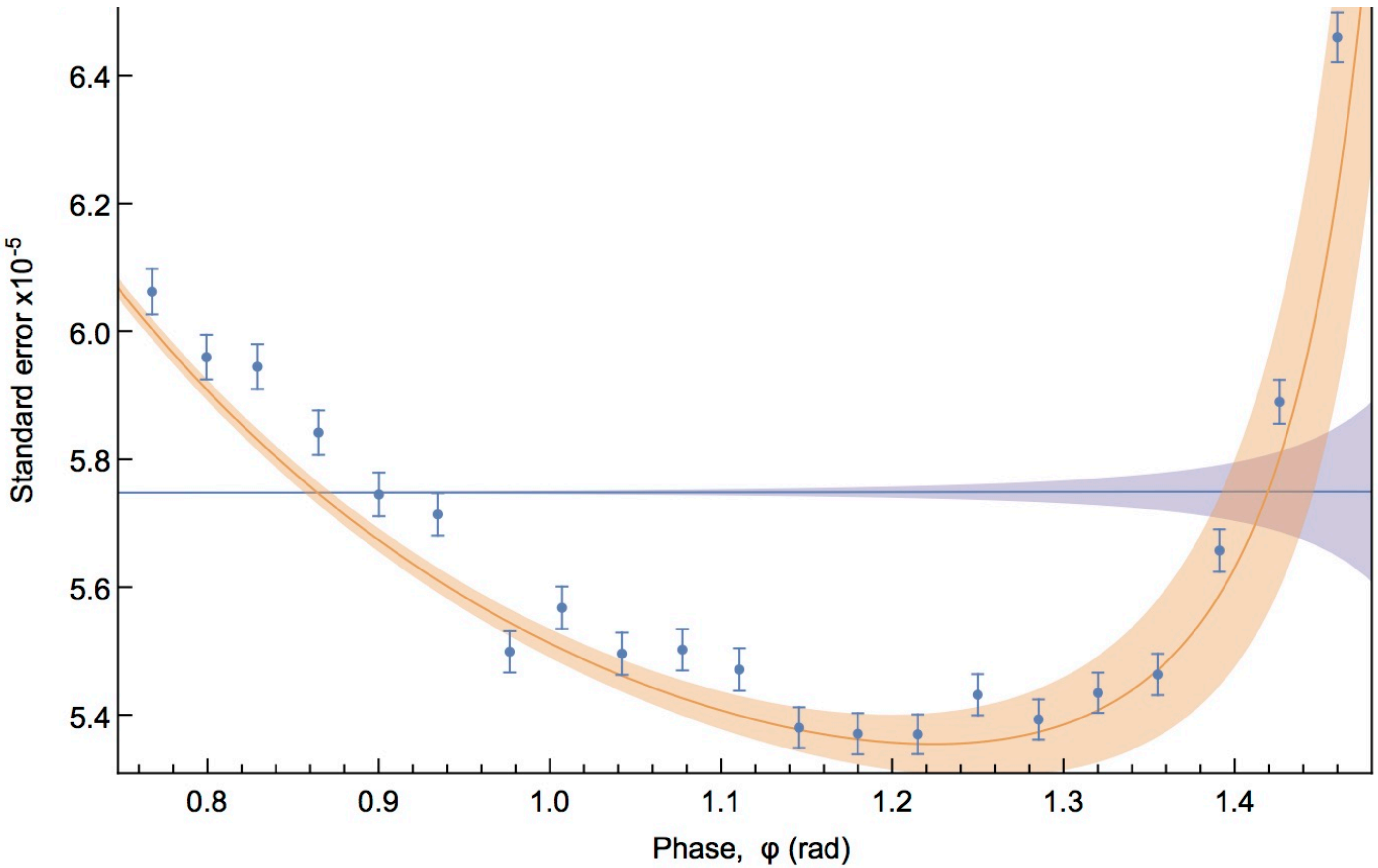
Experimental phase estimates



Slussarenko et al., **N. Phot.** 11, 700 (2017)

... on to part 2 !

Part 2: quantum steering

1. **What is quantum steering and how is it different to entanglement and Bell inequality violations?**

2. **Practical advantages of quantum steering**
   - **Loss tolerance**

3. **The asymmetry of quantum steering**
   - **The one-way steering effect**

Wiseman, Jones, Doherty *PRL* **98**, 140402 (2007)

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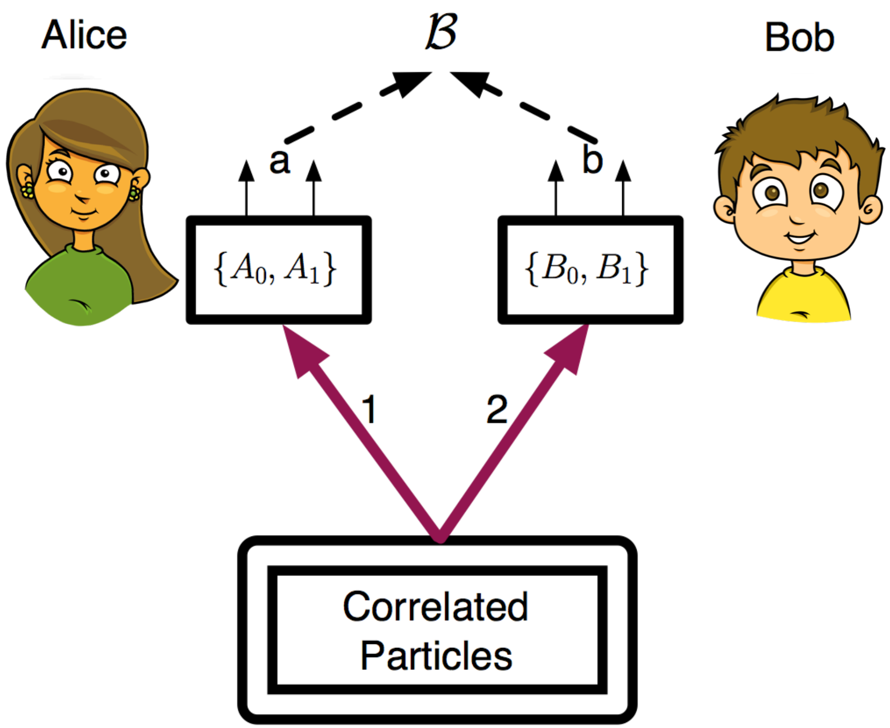
Entanglement sharing in a quantum network

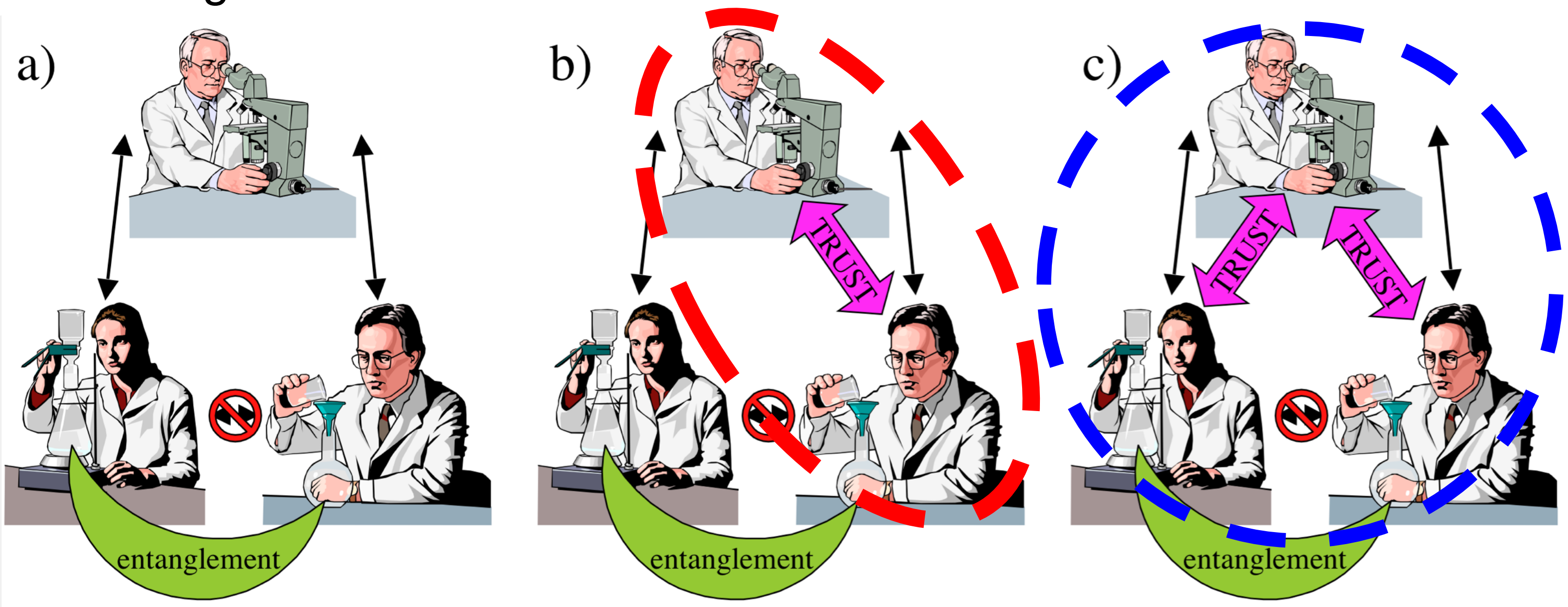


- Entanglement is a resource for quantum communications and processing (amongst other things)
- Alice and Bob can communicate securely if they share entanglement
- E.g., if they can violate a loophole-free Bell inequality, they can perform device-independent QKD

e.g. Ekert, *PRL* **67**, 661 (1991); Acin *et al.*, *PRL* **98**, 230501 (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**.

Wiseman, Jones, Doherty *PRL* **98**, 140402 (2007)

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)

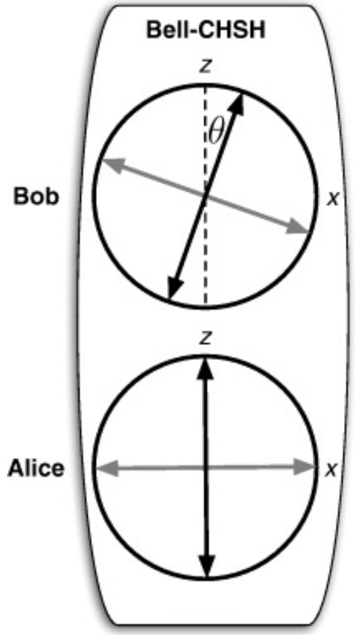
$$\langle AB \rangle + \langle A'B \rangle + \langle AB' \rangle - \langle A'B' \rangle \leq 2$$

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

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

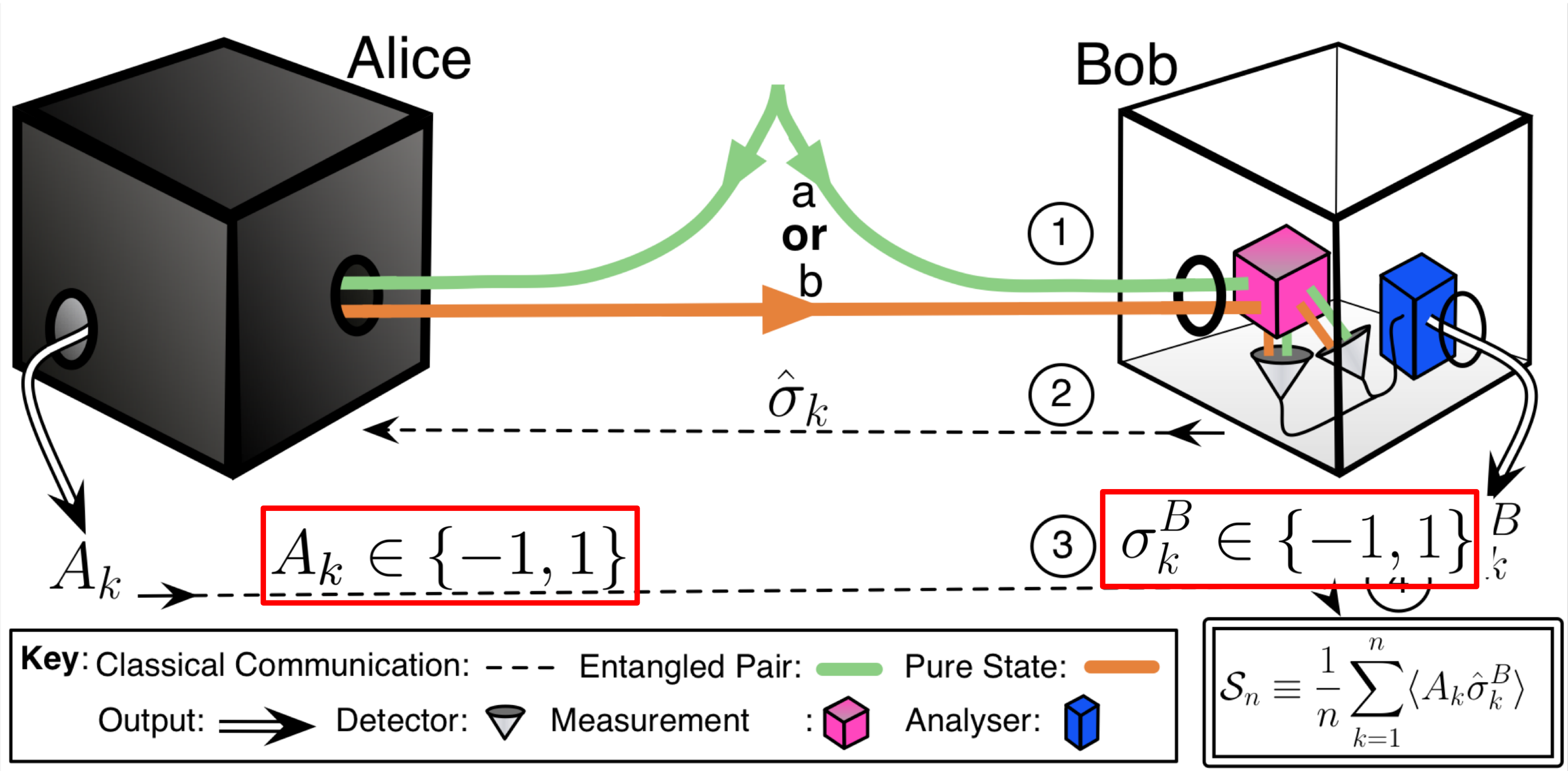
Non-separability (entanglement witness, mid-90s)

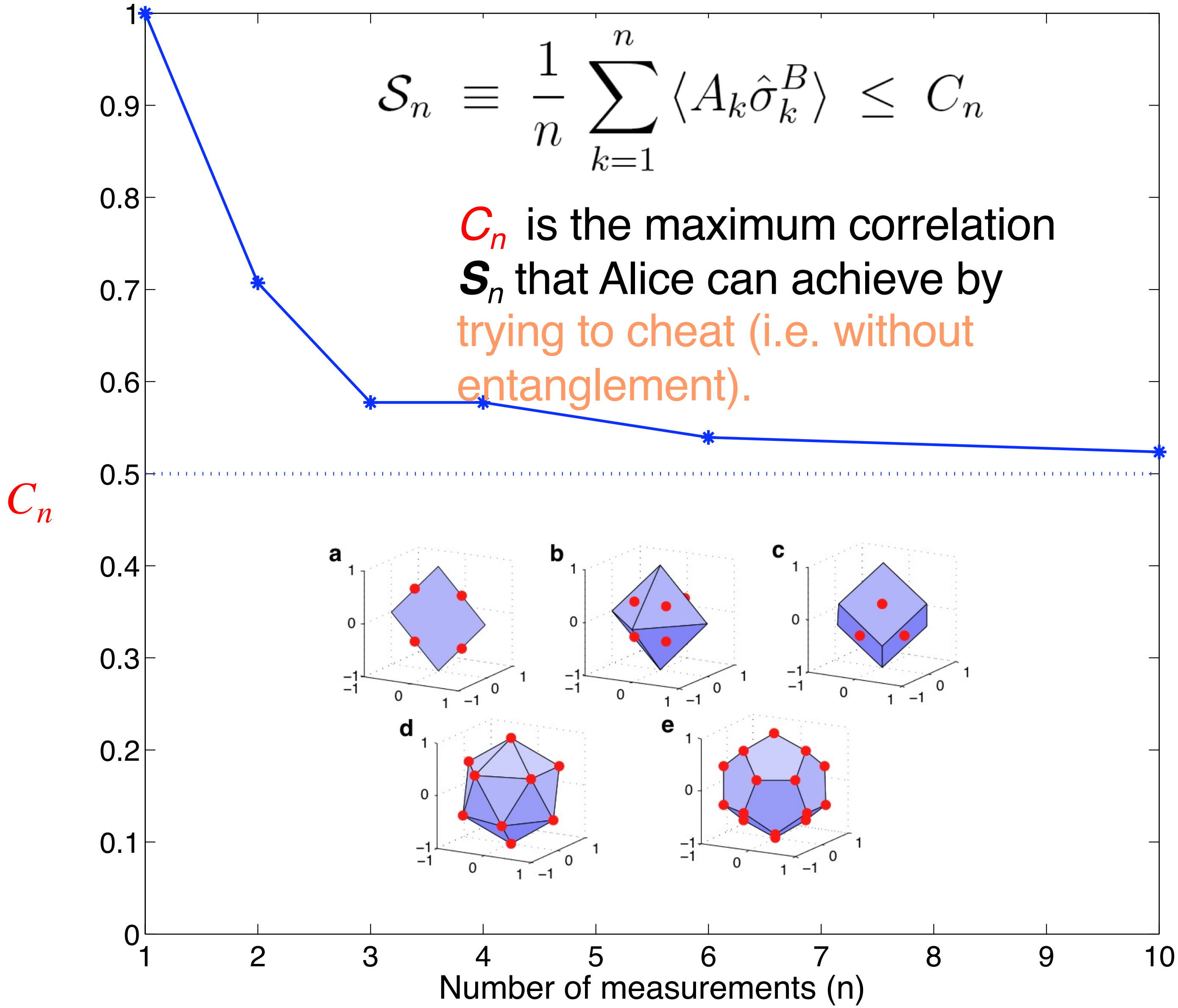
$$\langle \hat{\sigma}_X^A \hat{\sigma}_X^B \rangle + \langle \hat{\sigma}_Z^A \hat{\sigma}_Z^B \rangle \leq 1$$



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





$\mathcal{S}_n \equiv \frac{1}{n}\sum_{k=1}^{n}\langle A_k \hat{\sigma}_k^B \rangle \leq C_n$
C_n is the maximum correlation S_n that Alice can achieve by trying to cheat (i.e. without entanglement).
C_n
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
2
3
4
5
6
7
8
9
10
Number of measurements (n)
a
b
c
d
e

Steering is a superset of Bell inequality violation

(Result # 1)

D. J. Saunders, S. J. Jones, H. M. Wiseman and G. J. Pryde,
Nature Physics **6**, 845 (2010)

Steering noise tolerance

Werner state

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

$\mu \in [0,1]$

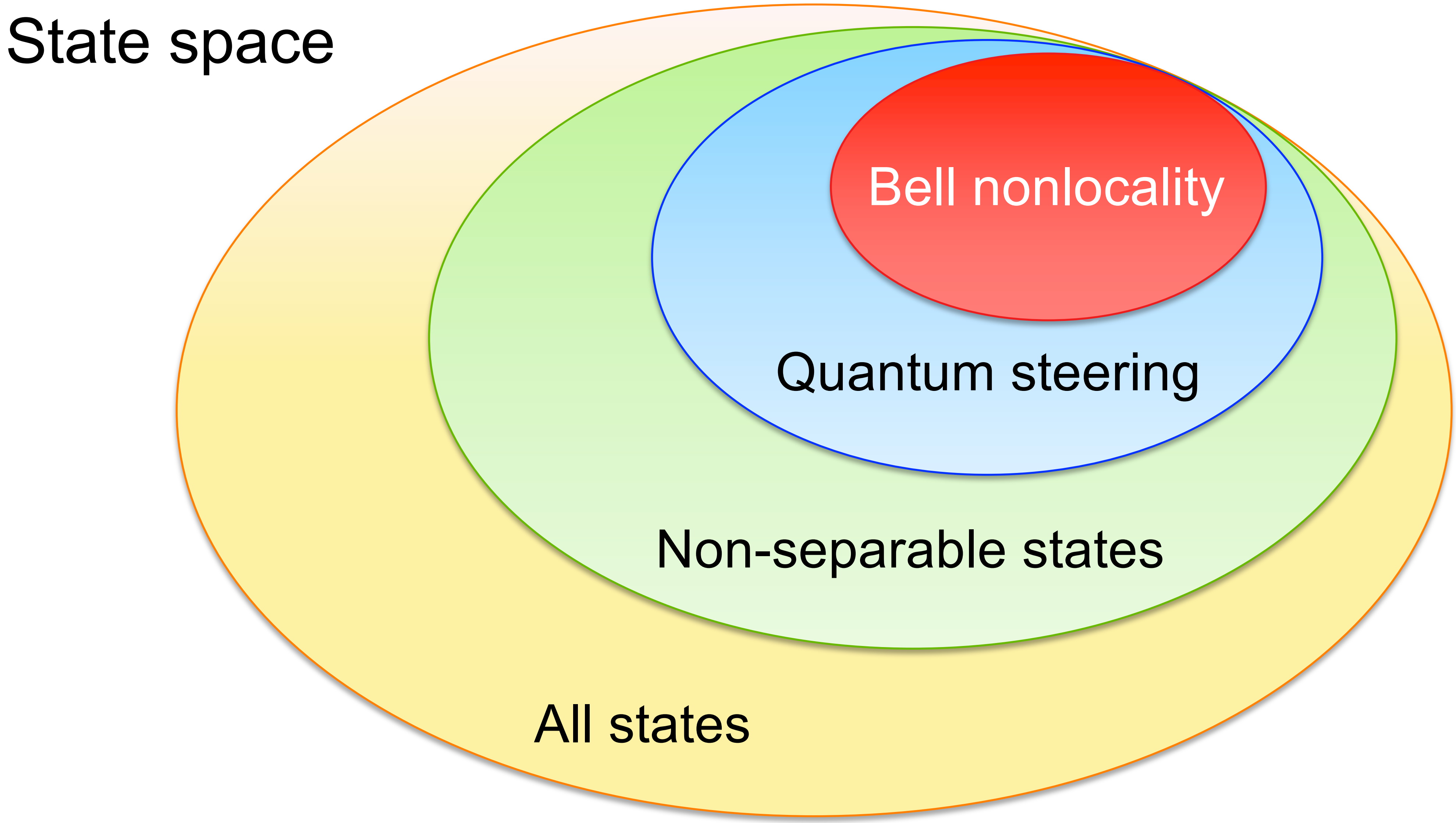
n = # of different measurement settings used by Alice & Bob.

- for $n = 2$, Bell-nonlocality exists *if* $\mu > 0.707$ [CHSH'69]
- for $n = 465$, Bell-nonlocality exists *if* $\mu > 0.7056$ [Vertesi'08]
- for $n = \infty$, Bell-nonlocality exists *only if* $\mu > 0.6595$ [Acin+'06]

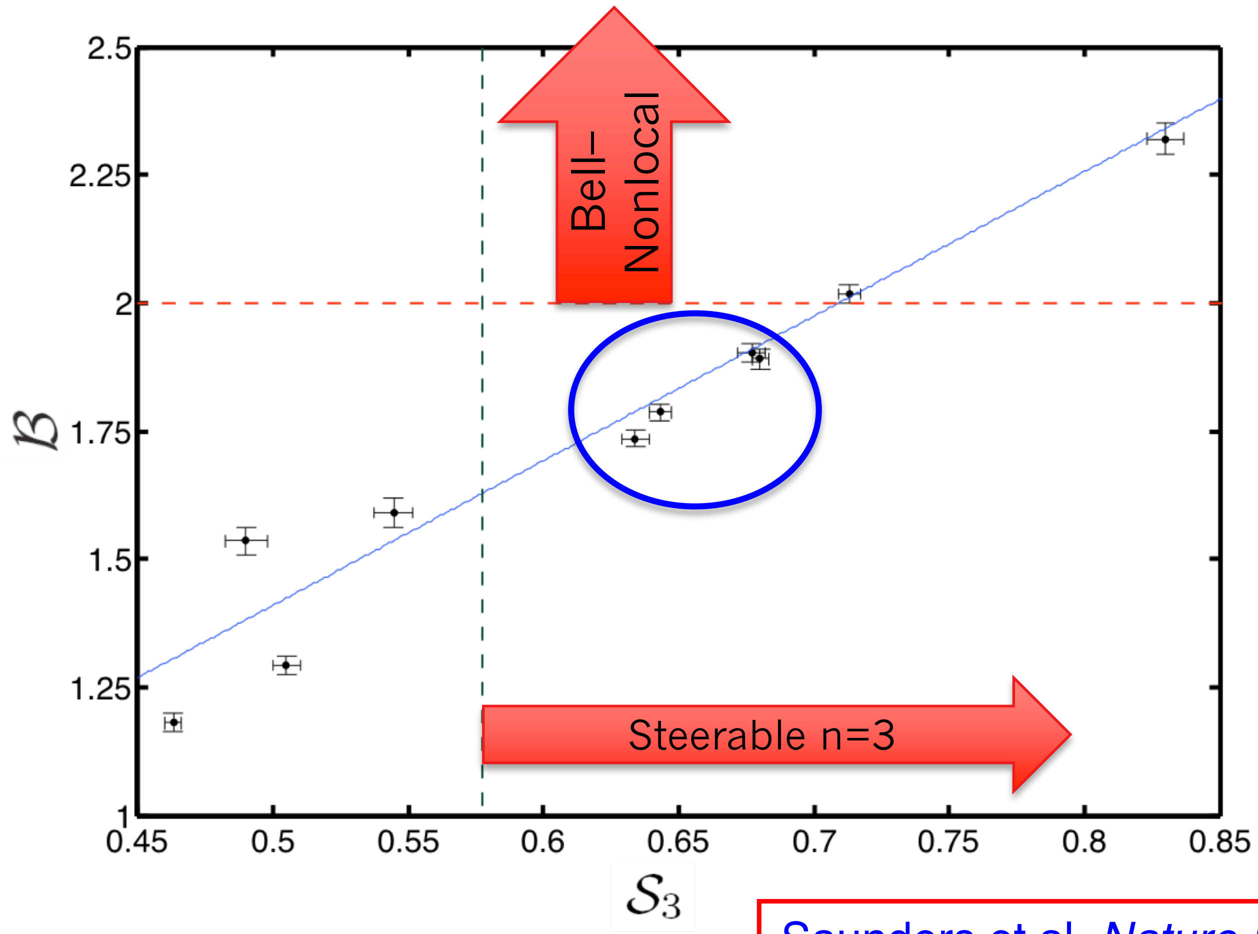
How about for EPR-steering?

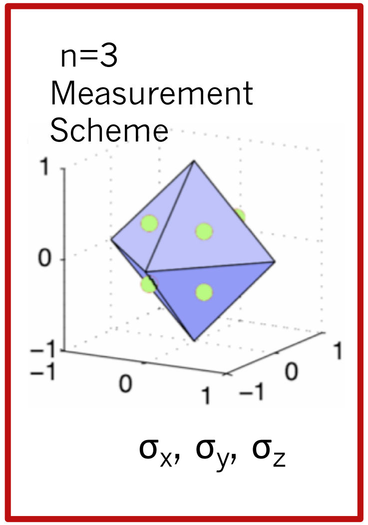
Traditionally (i.e. following EPR) one considers only $n = 2$.

- for $n = 2$, EPR-steering exists *if* $\mu > 0.707$ [Cavalcanti+'09]
- for $n = \infty$, EPR-steering exists *if and only if* $\mu > 0.5$ [Wiseman+'07]


State space
Bell nonlocality
Quantum steering
Non-separable states
All states

Quantum steering of Bell-local states





Saunders et al, *Nature Physics* **6**, 845 (2010)

Steering tolerant to loss

(Results # 2 & #3)

A. J. Bennet, D. A. Evans, D. J. Saunders, C. Branciard,
E. G. Cavalcanti, H. M. Wiseman and G. J. Pryde,
Physical Review X **2**, 031003 (2012)

M. M. Weston, S. Slussarenko, H. M. Chrzanowski, S. Wollmann,
L. K. Shalm, V. B. Verma, M. S. Allman, S. W. Nam, G. J. Pryde,
Science Advances **4**, e1701230 (2018)

Verification of remote shared entanglement

- To guarantee security offered by quantum mechanics a verification protocol must be performed loophole-free

= Violation of Bell inequality with no loopholes

- 3 main loopholes closed simultaneously [1]:
  - ✓ Locality loophole
  - ✓ Freedom of choice loophole
  - ✓ Detection loophole [2]

a.k.a. fair sampling assumption:
detected particles represent
a fair sample of the entire ensemble

- Demonstrated by recent experiments:
  - L. Shalm, *et. al*., PRL **115**, 250402 (2015)
  - M. Giustina, *et. al*., PRL **115**, 250401 (2015)
  - B. Hensen, *et. al*., Nature **526**, 682 (2015)

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[1] J.A. Larsson, J. Phys. A, **47,** 424003 (2014); [2] P. Pearle, Phys. Rev. D, **2**, 1418 (1970)

Completely photonic loophole-free Bell tests

A strong loophole-free test of local realism

Lynden K. Shalm,[1] Evan Meyer-Scott,[2] Bradley G. Christensen,[3] Peter Bierhorst,[1] Michael A. Wayne,[3,4] Martin J. Stevens,[1] Thomas Gerrits,[1] Scott Glancy,[1] Deny R. Hamel,[5] Michael S. Allman,[1] Kevin J. Coakley,[1] Shellee D. Dyer,[1] Carson Hodge,[1] Adriana E. Lita,[1] Varun B. Verma,[1] Camilla Lambrocco,[1] Edward Tortorici,[1] Alan L. Migdall,[4,6] Yanbao Zhang,[2] Daniel R. Kumor,[3] William H. Farr,[7] Francesco Marsili,[7] Matthew D. Shaw,[7] Jeffrey A. Stern,[7] Carlos Abellán,[8] Waldimar Amaya,[8] Valerio Pruneri,[8,9] Thomas Jennewein,[2,10] Morgan W. Mitchell,[8,9] Paul G. Kwiat,[3] Joshua C. Bienfang,[4,6] Richard P. Mirin,[1] Emanuel Knill,[1] and Sae Woo Nam[1]

Phys. Rev. Lett. 115, 250402 (2015)

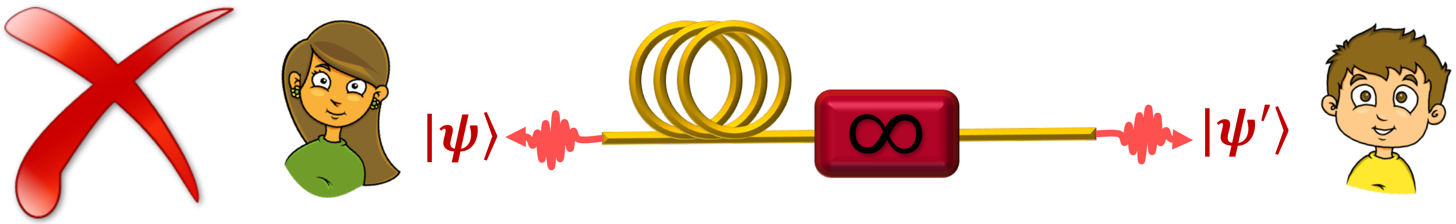
A significant-loophole-free test of Bell's theorem with entangled photons

Marissa Giustina,[1,2,*] Marijn A. M. Versteegh,[1,2] Sören Wengerowsky,[1,2] Johannes Handsteiner,[1,2] Armin Hochrainer,[1,2] Kevin Phelan,[1] Fabian Steinlechner,[1] Johannes Kofler,[3] Jan-Åke Larsson,[4] Carlos Abellán,[5] Waldimar Amaya,[5] Valerio Pruneri,[5,6] Morgan W. Mitchell,[5,6] Jörn Beyer,[7] Thomas Gerrits,[8] Adriana E. Lita,[8] Lynden K. Shalm,[8] Sae Woo Nam,[8] Thomas Scheidl,[1,2] Rupert Ursin,[1] Bernhard Wittmann,[1,2] and Anton Zeilinger[1,2,†]

Phys. Rev. Lett. 115, 250401 (2015)

Practical limitations

- Closing detection loophole requires channel transmission to be higher than a certain (high) threshold [1]



- Losses through the fiber open up the detection loophole

Want to achieve: **Entanglement verification over high-loss channel with detection loophole closed**

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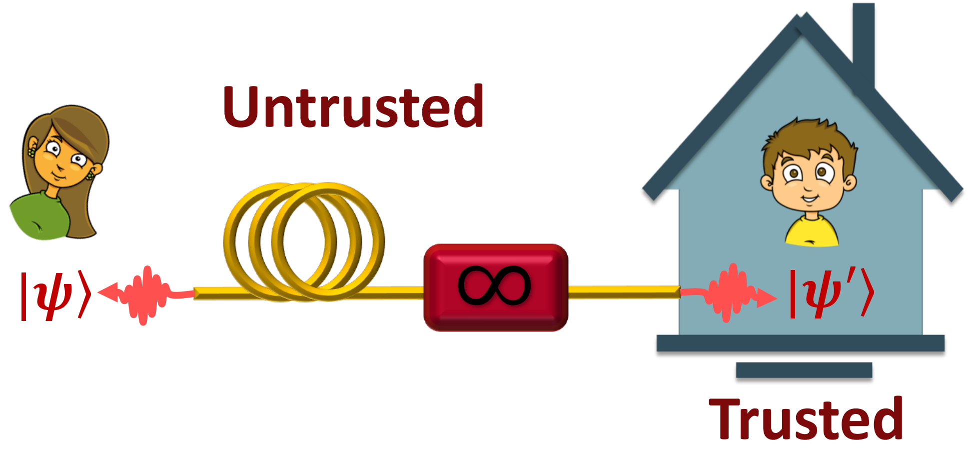
[1] P. H. Eberhard, Phys. Rev. A, **47**, R747 (1993)

Alternative test



- Additional assumption required:
  - Bob trusts quantum mechanics to describe his own measurements
- Uses entanglement to steer the state of distant quantum system by local measurements
- More robust to loss

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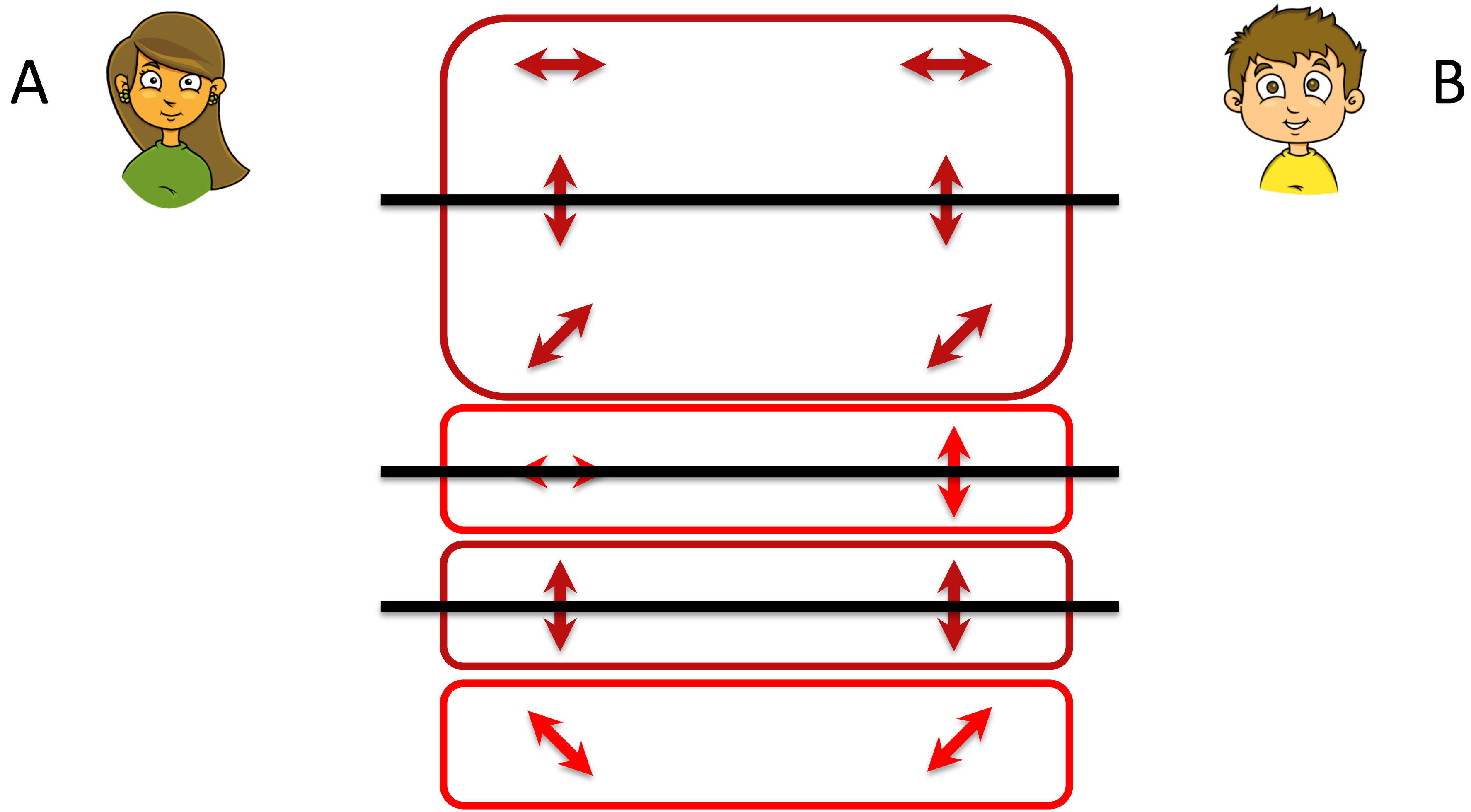
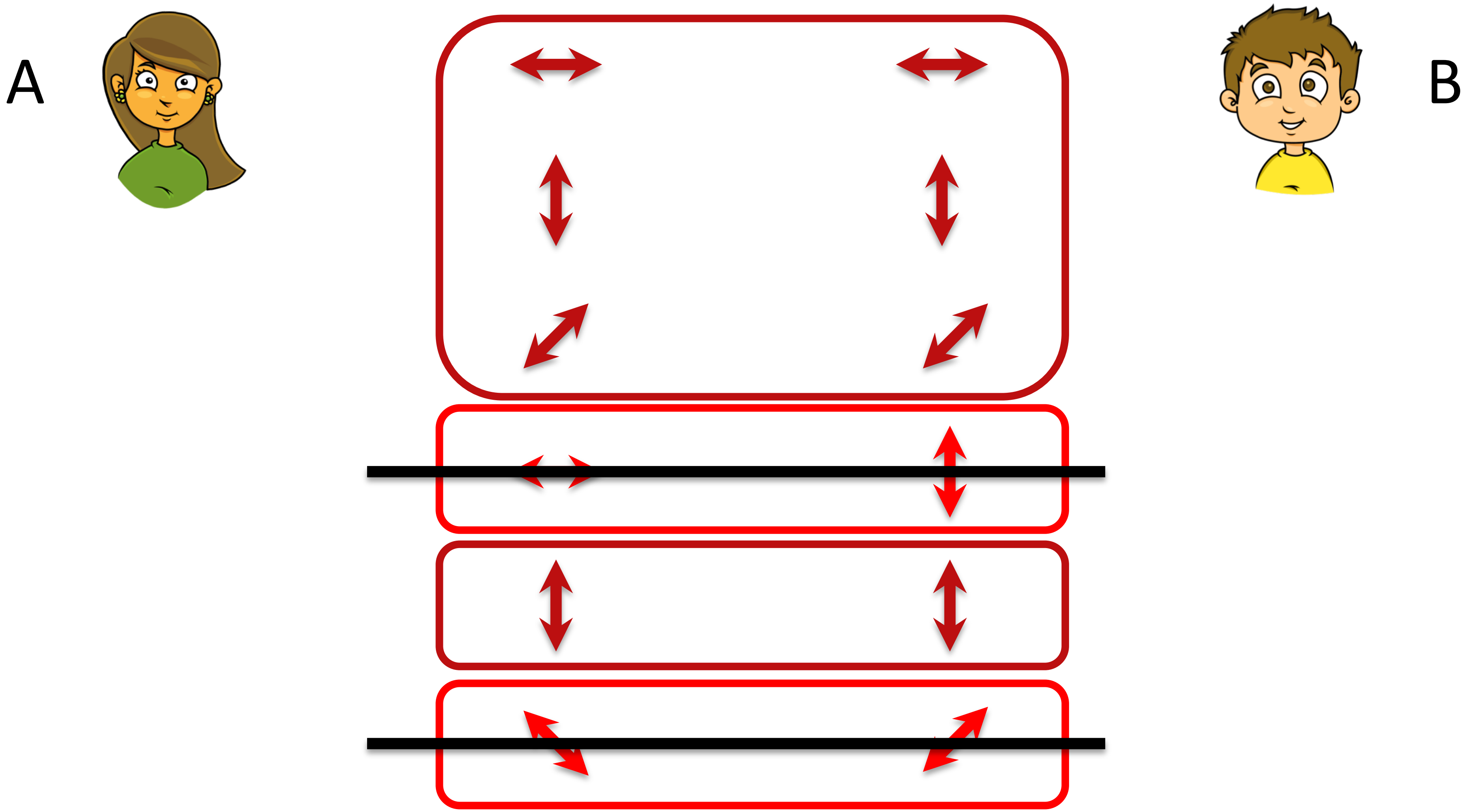
H. Wiseman, *et. al.*, PRL **98**, 140402 (2007); D. Saunders, *et.al.*, Nat. Phys. **6**, 845 (2010); A. Bennet, *et.al.*, PRX **2**, 031003 (2012)

Detection loophole in nonlocality tests?

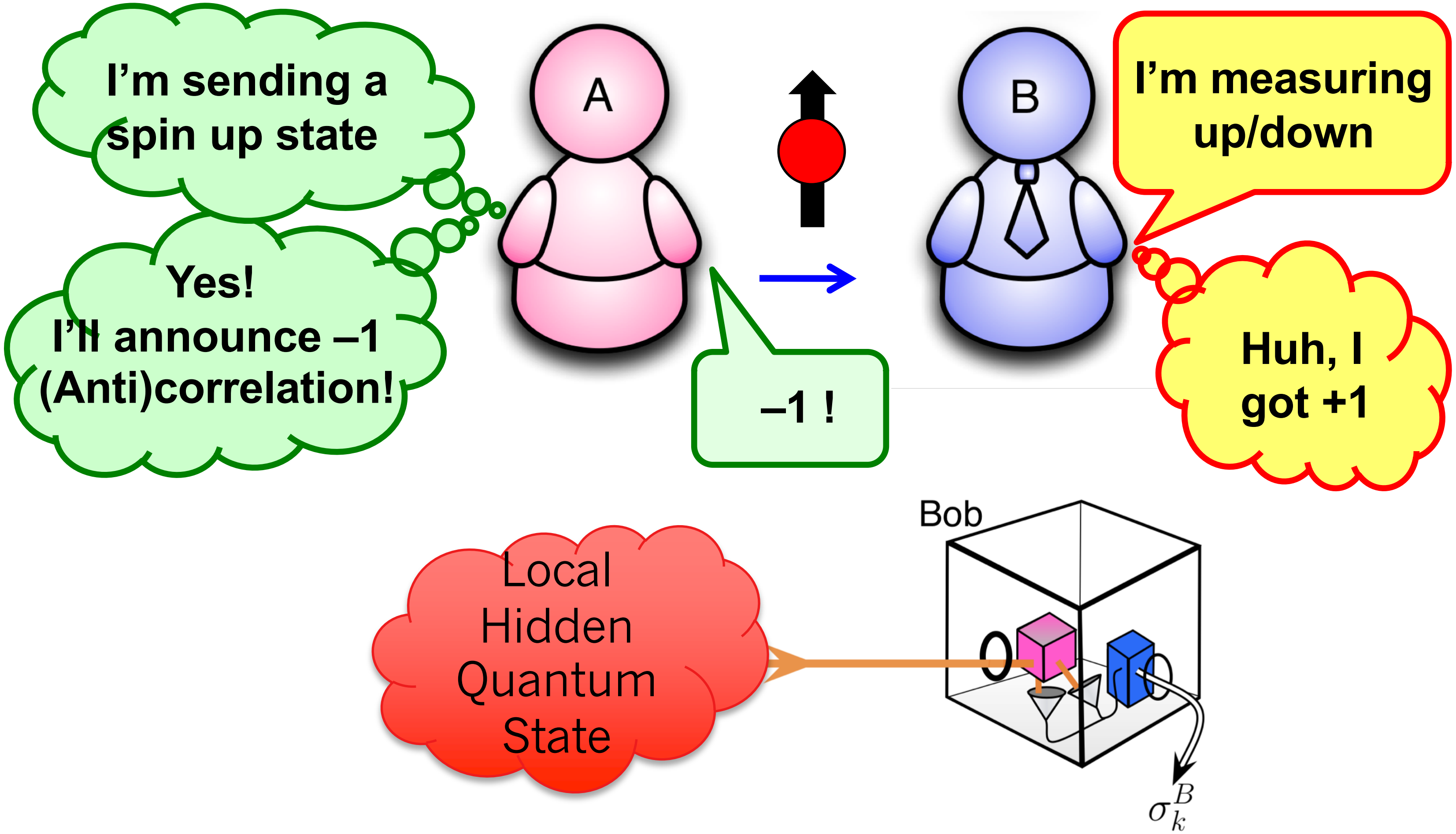


Detection loophole in nonlocality tests?



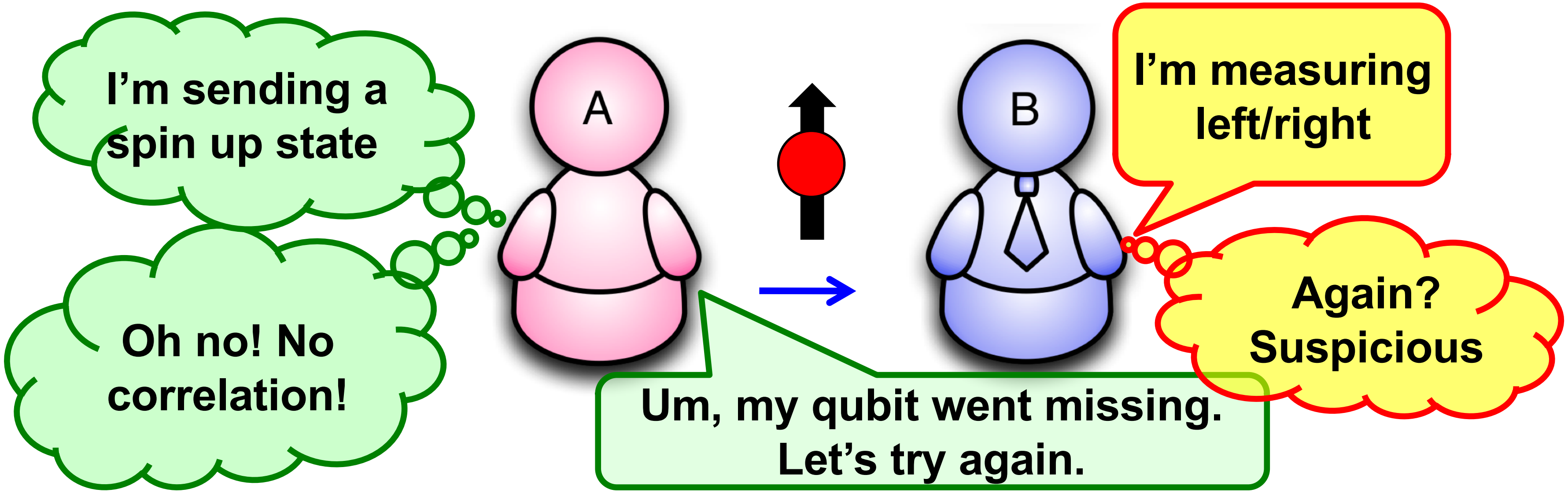
Fair sampling cheating strategy

- Alice can use the detection loophole to cheat



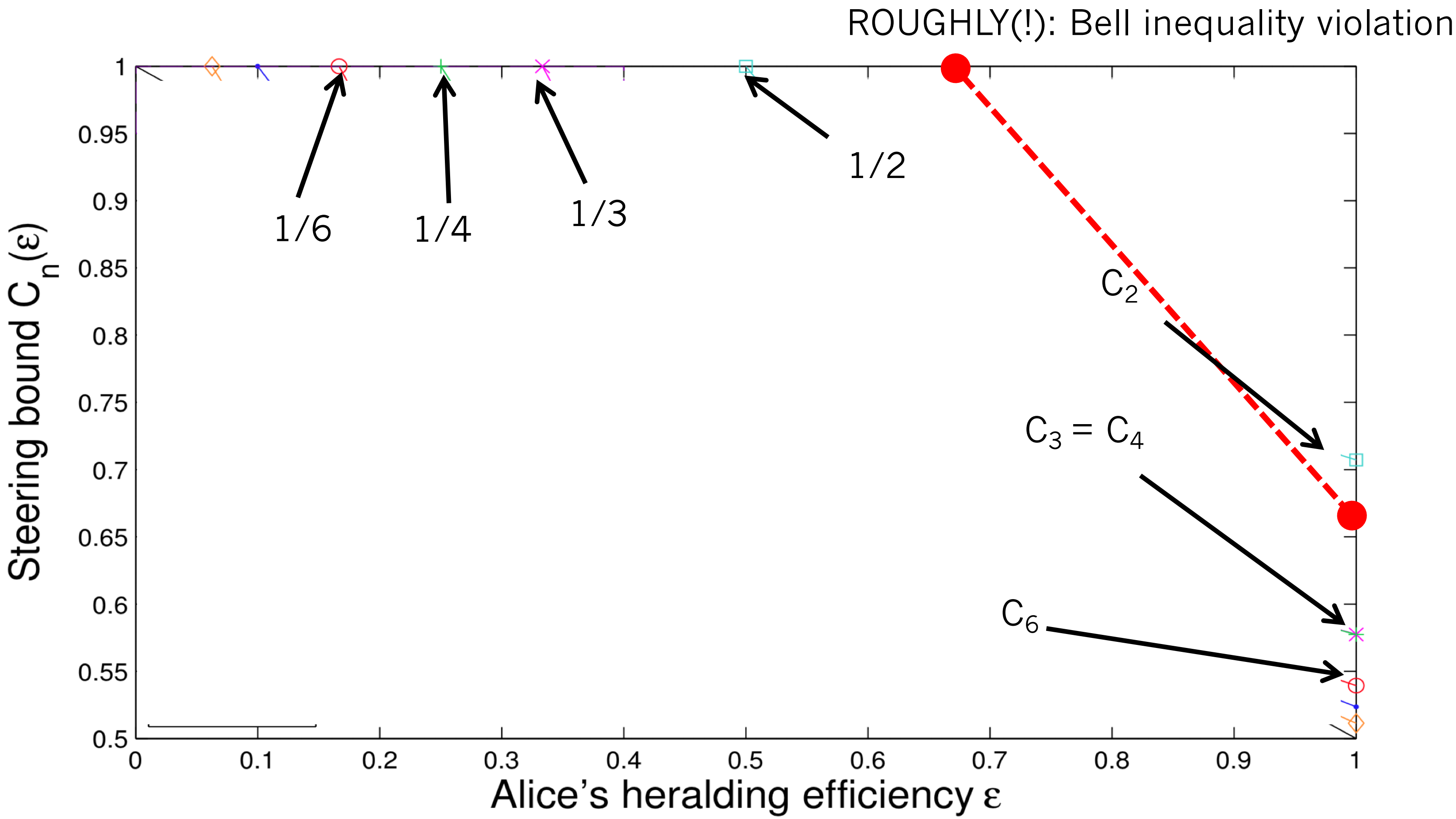
Fair sampling cheating strategy

- Alice can use the detection loophole to cheat



- 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!

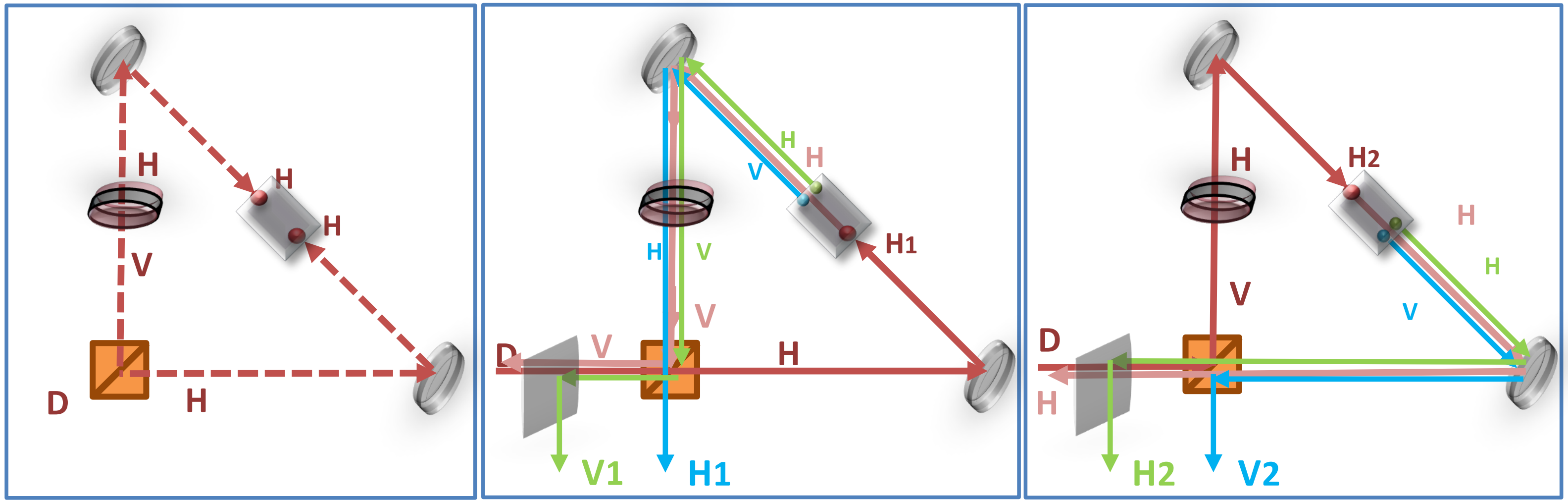
Loss-Dependent EPR-Steering Bound



Bennet ..., *PRX* **2**, 031003 (2012)

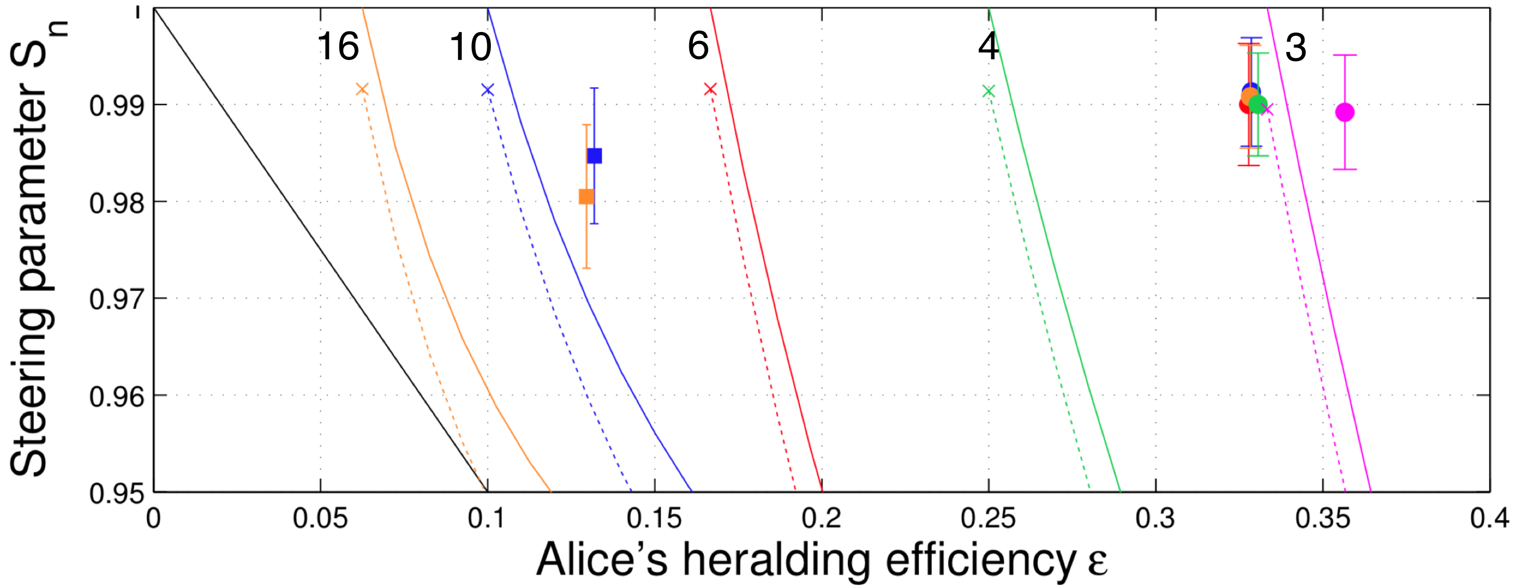
Saunders …, *Nature Phys.* **6**, 845 (2010)

Entangled source (one design)



Output state = $|HV\rangle - |VH\rangle \equiv |01\rangle - |10\rangle$

Measured steering parameters



Bennet *et al.*, Physical Review X **2**, 031003 (2012)

Related experiments:

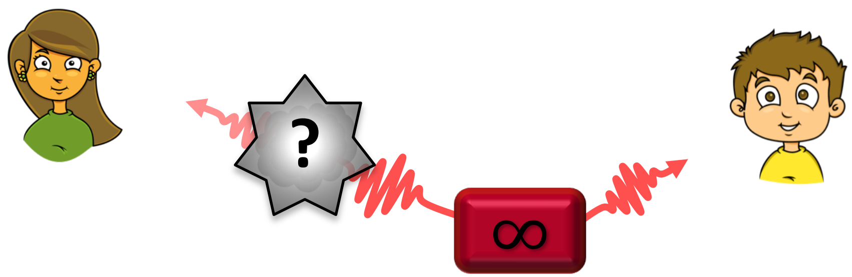
Smith *et al.*, Nature Comms 3, 625 (2012)

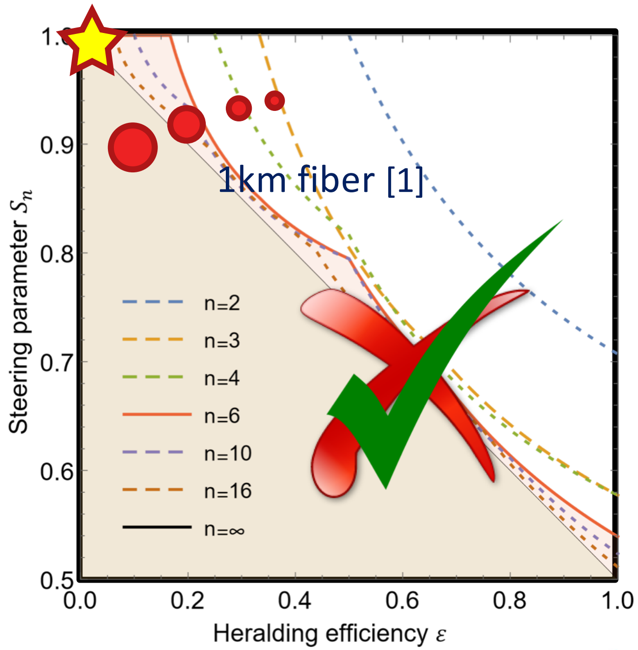
Wittmann *et al.*, New J. Phys 14, 053030 (2012)

Loss-tolerant steering bounds

- Secure steering with arbitrarily high loss
  - → max entangled state ($S_n = 1$)
  - → n=∞

Imperfect states & finite n ?





Better than Bell test, but still not ready for real life applications

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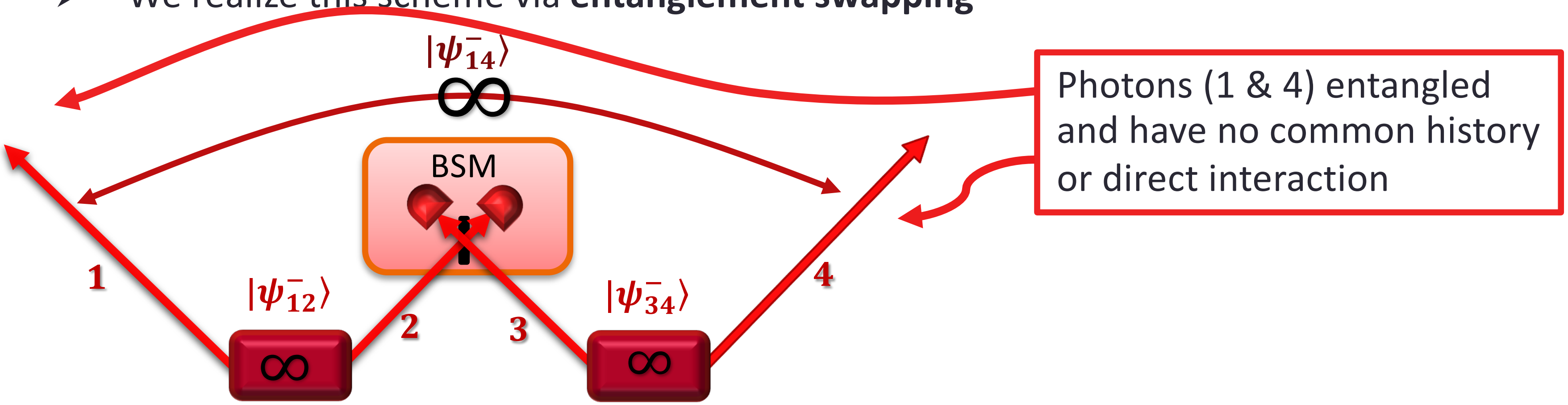
[1] A. Bennet, *et.al.*, PRX **2**, 031003 (2012)

The "event-ready" approach

- Record an additional "**heralding**" signal to indicate successful sharing
- Failed distribution events are excluded upfront from tests
- Allows Alice to maintain her effective heralding efficiency with loss
- We realize this scheme via **entanglement swapping**



$$|\psi^-\rangle = \frac{1}{\sqrt{2}}(|HV\rangle - |VH\rangle)$$

Event-ready: M. Zukowski, *et. al.*, PRL **71**, 4287 (1993); Entanglement swapping: J. Pan, *et.al.*, PRL **80**, 3891 (1998)

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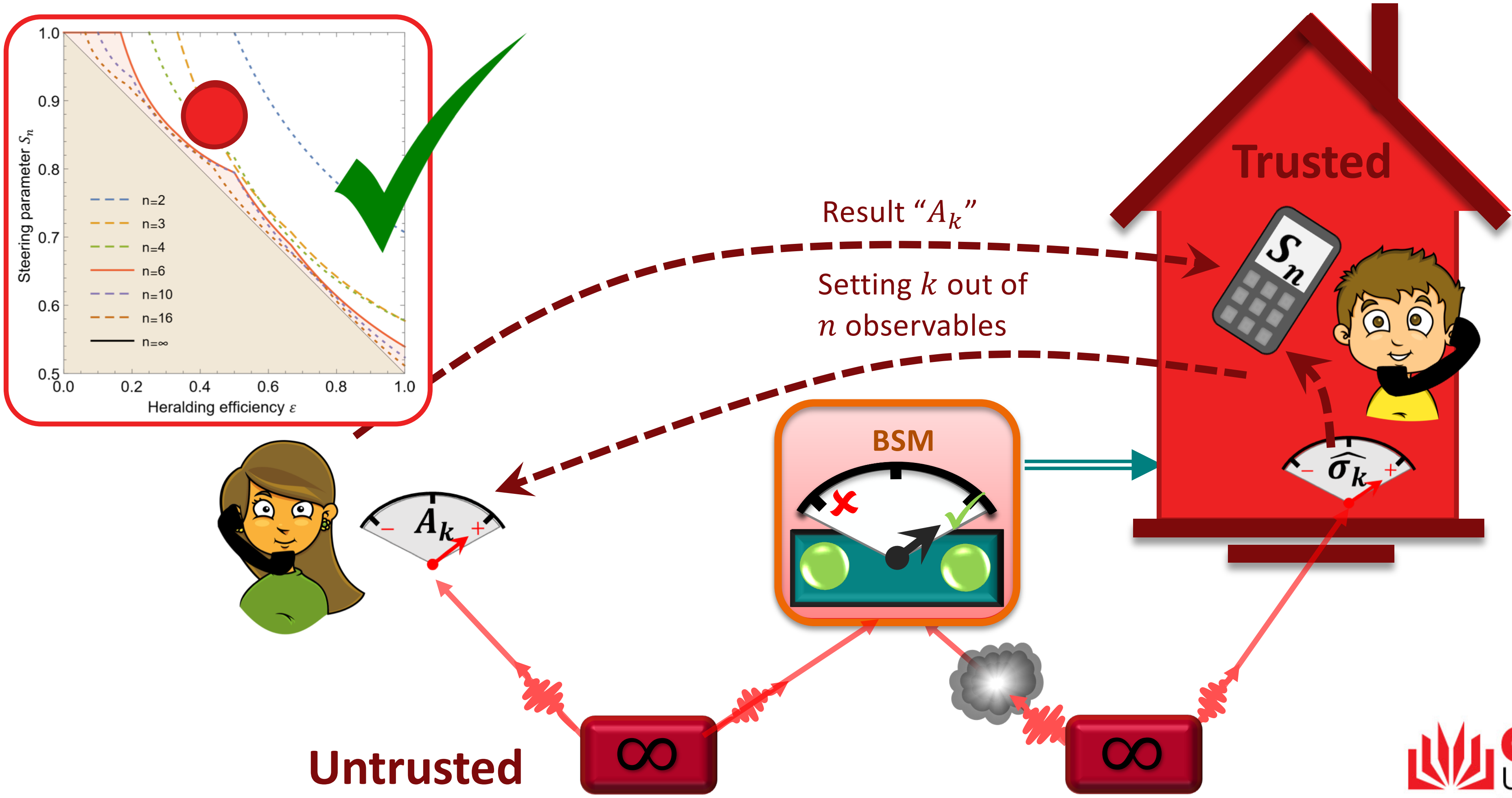
Heralded quantum steering



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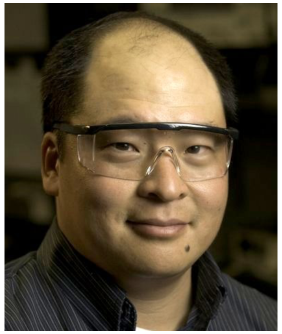
Experimental requirements

- ➢High visibility Hong-Ou-Mandel interference
- ➢High entangled state fidelity
- ➢High heralding efficiency (on Alice's side)

High-efficiency SNSPDs:



Sae Woo Nam

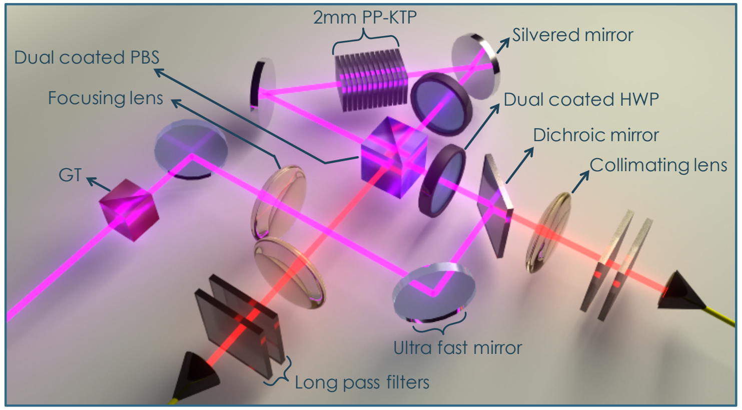
(+ team)

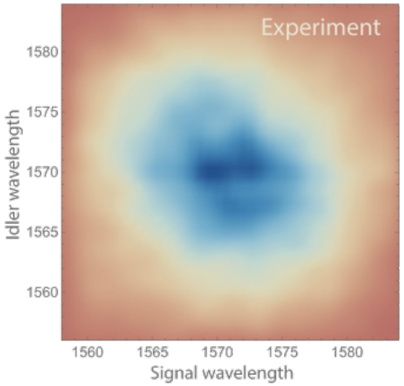
NIST

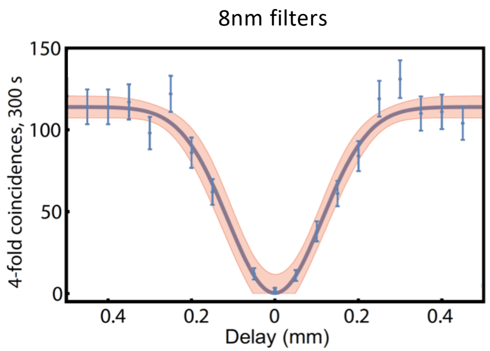
Made possible by:

- ➢ Group velocity matched source:
  M. Weston, *et. al.*, Opt. Exp. **24**, 10869 (2016)
- ➢ Superconducting nanowire photon dets:
  F. Marsili, et al., Nat. Photonics 7, 210 (2013)

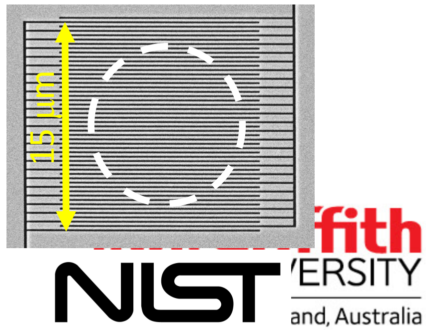
- ➢ Heralding efficiencies up to $(\mathbf{82 \pm 2})\%$
- ➢ HOM interference visibilities up to $\mathbf{100\%}$
- ➢ Singlet state fidelities up to $(\mathbf{99.0 \pm 0.2})\%$





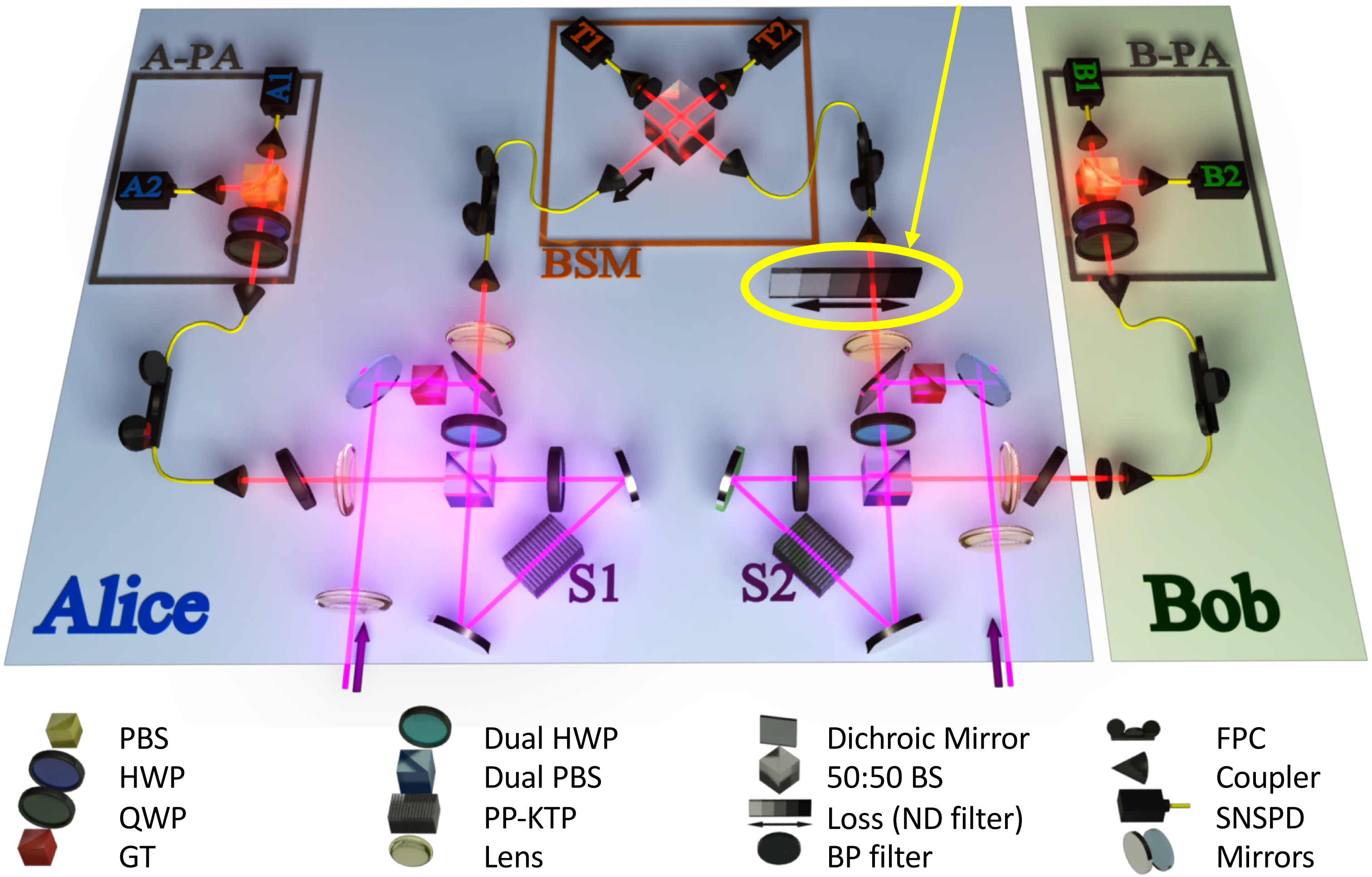


Visibility > 99%



Experimental demonstration

Channel loss **7.7dB, 11.3dB, 14.8dB**



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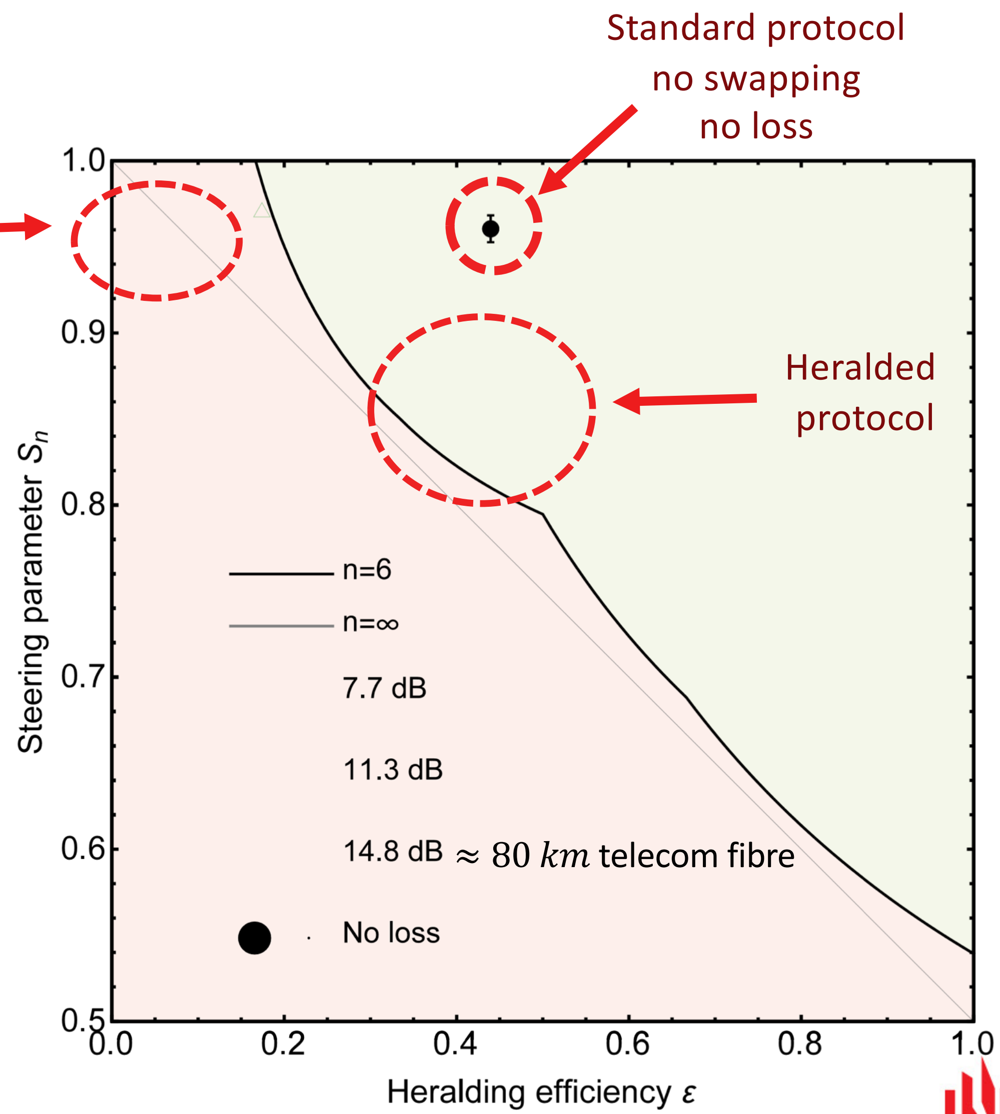
Results



Alice's **total** channel loss
$(\mathbf{20.0 \pm 0.1})\mathbf{dB}$
$\equiv 100$ km SM fibre

Did **not implement:**

- Randomized choice of measurement setting
- Time ordering of detection event

Required to close the freedom of choice and locality loopholes

Weston et al., *Science Advances* **4**, e1701230 (2018)

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Queensland, Australia

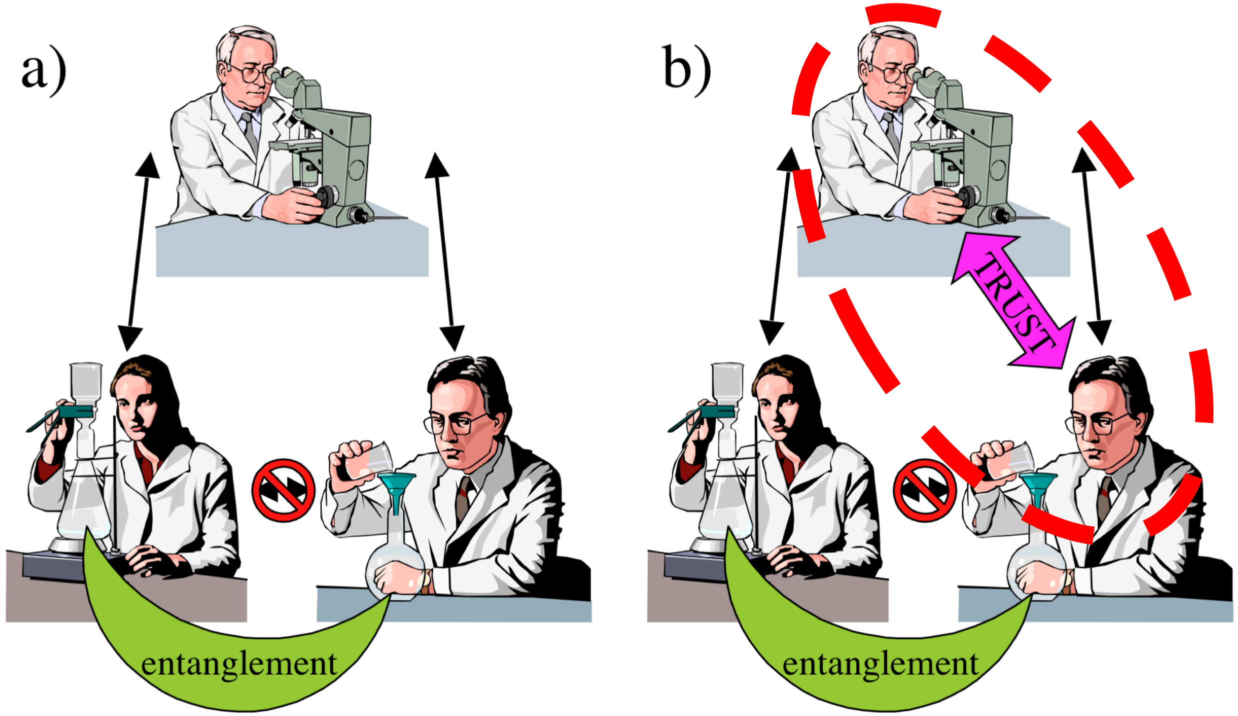
The asymmetry of quantum steering

(Result # 4)

S. Wollmann, N. Walk, A. J. Bennet, H. M. Wiseman and G. J. Pryde,
Physical Review Letters **116**, 160403 (2016)

Steering quantum information task

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

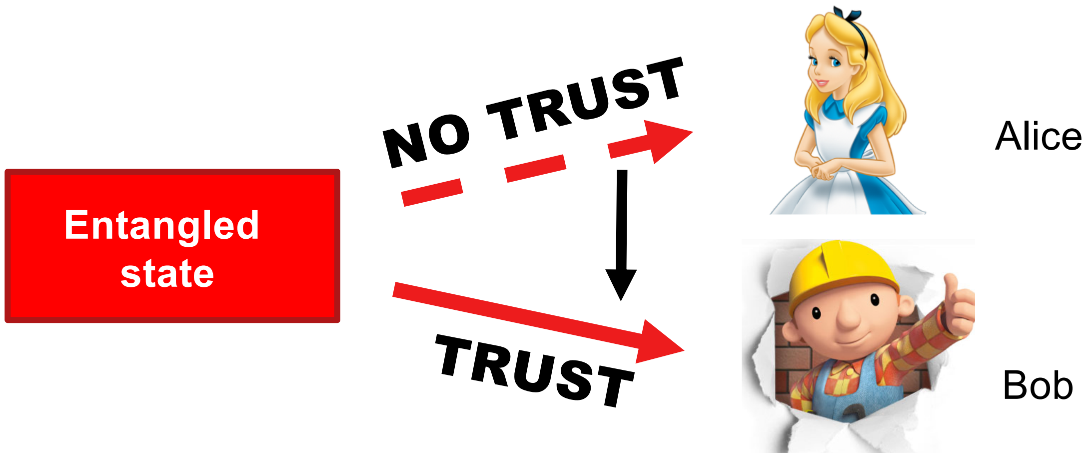


a) With no trust, they must demonstrate **Bell-nonlocality**.

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

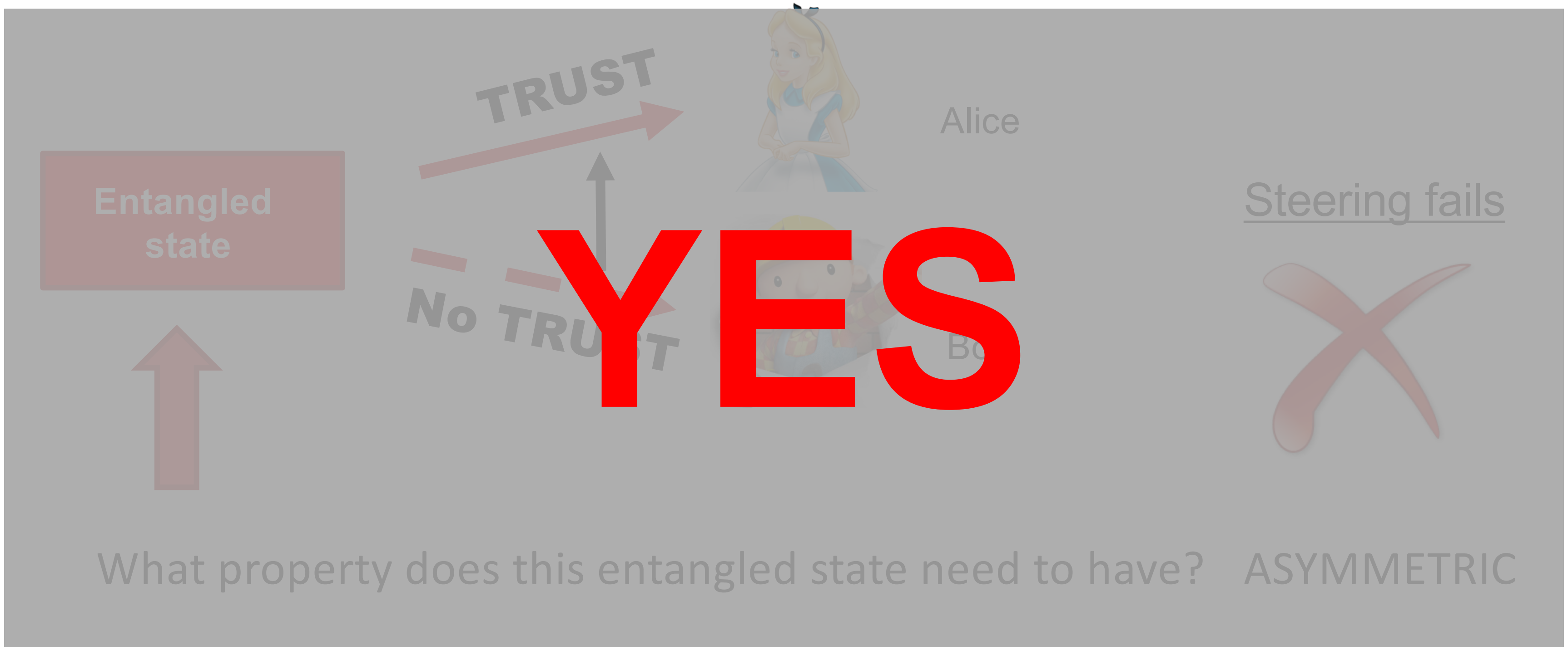
Wiseman, Jones, Doherty *PRL* **98**, 140402 (2007)

Can steering be one-way?



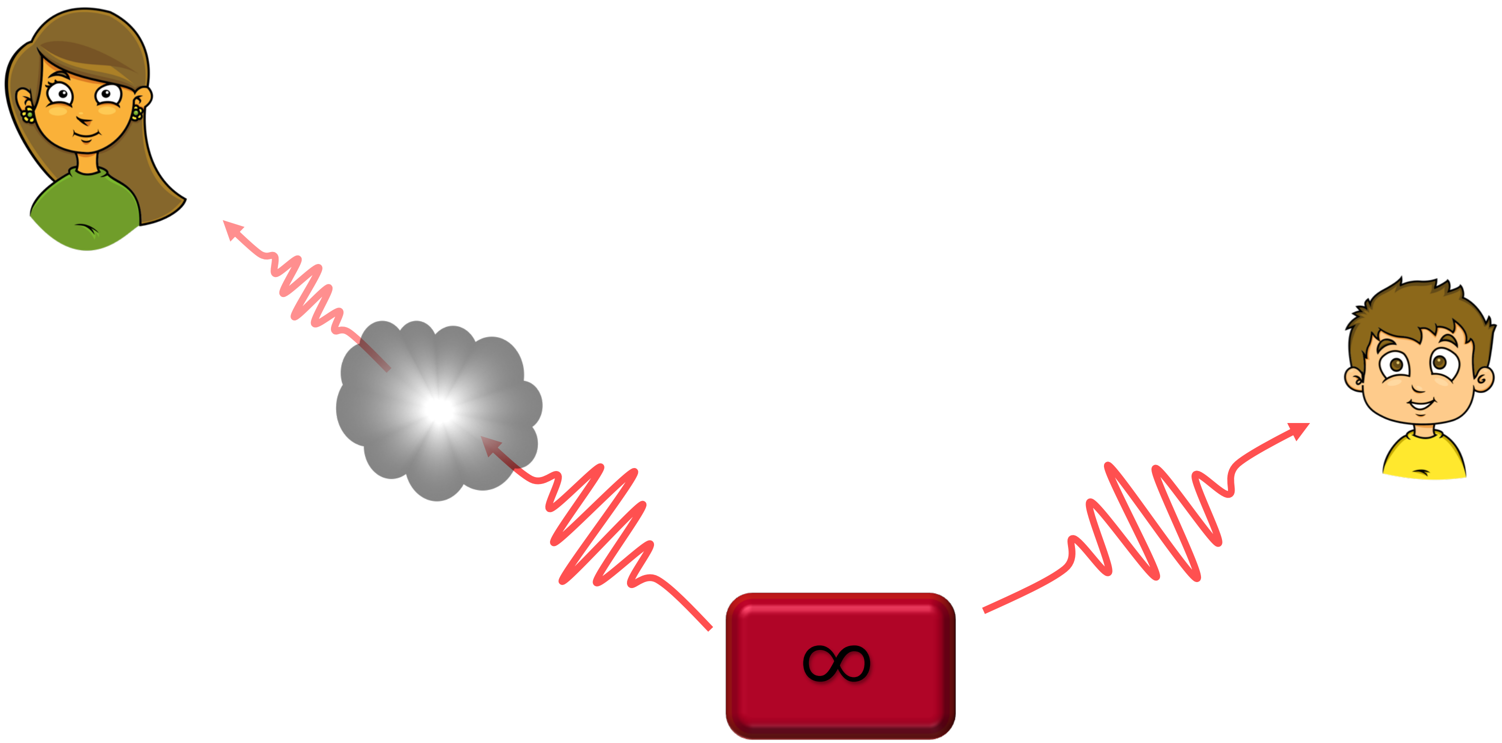
<u>Steering demonstrated</u>

Can steering be one-way?

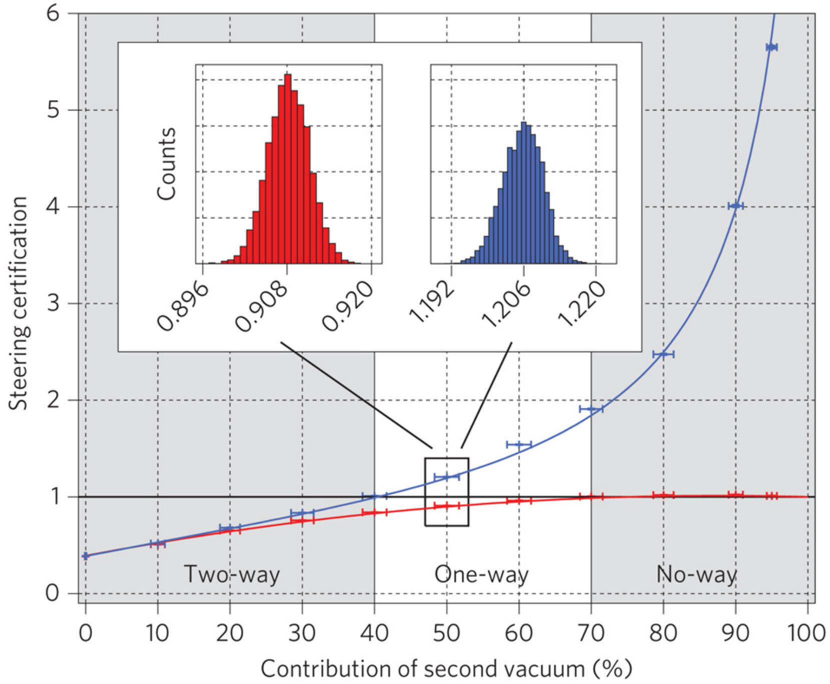


Requires an asymmetric state

- Easiest way is to add *loss* to one side.



Homodyne detection of Gaussian states



V. Handchen et al., Nat. Photon **6**, 598 (2012)

Successful Gaussian one-way steering with two-mode squeezed states

But:

Gaussian measurements are insufficient to capture the full nonlocality of Gaussian states

Explicit examples of one-way steerable Gaussian states which are two-way steerable for appropriate measurements

S. Wollmann et al., Phys. Rev. Lett. **116**, 160403 (2016)

Do states exist which are one-way steerable for arbitrary measurements?

Do any *genuinely* one-way steerable states exist? **YES!**

PHYSICAL REVIEW A **92**, 032107 (2015)

Inequivalence of entanglement, steering, and Bell nonlocality for general measurements

Marco Túlio Quintino,[1] Tamás Vértesi,[1,2] Daniel Cavalcanti,[3] Remigiusz Augusiak,[3] Maciej Demianowicz,[3] Antonio Acín,[3,4] and Nicolas Brunner[1]

Theoretical proof for infinite-setting POVMs

PHYSICAL REVIEW A **90**, 012114 (2014)

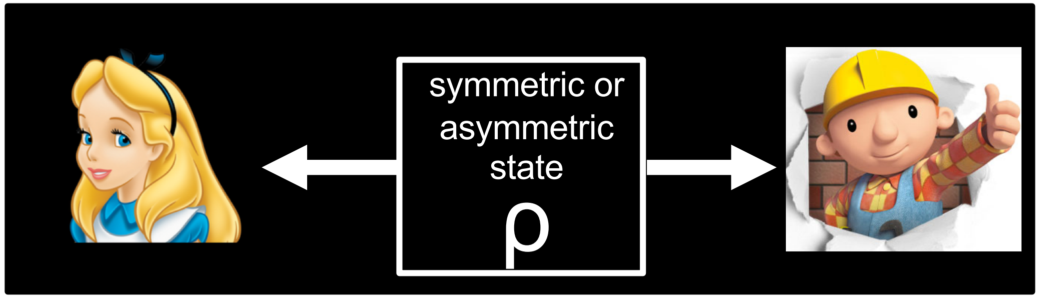
Optimal measurements for tests of Einstein-Podolsky-Rosen steering with no detection loophole using two-qubit Werner states

D. A. Evans and H. M. Wiseman

One-way steerable state for projective measurements

J. Bowles et al., Rev. Lett. **112**, 200402 (2014), P. Skrzypczyk et al., PRL **112**, 180404 (2014), R. F. Werner, PRA **40**, 4277 (1989).

What is a genuine one-way steerable state?



Using the theorem of Quintino et al. to extend to arbitrary measurements

$$\rho_{AB} = \left(\frac{1-p}{3}\right)\rho_W + \left(\frac{p+2}{3}\right)\left(\frac{I_A}{2} \otimes |v\rangle_B \langle v|_B\right)$$

$$\rho_W = \mu\, |\psi_s\rangle\langle \psi_s| + \frac{1-\mu}{4} I_4$$ with μ = [0,1]

What this means:
Just add a lot more loss

one-way steerable for arbitrary measurements if

$$p > \frac{2\mu+1}{3}$$

S. Wollmann et al., Phys. Rev. Lett. **116**, 160403 (2016)

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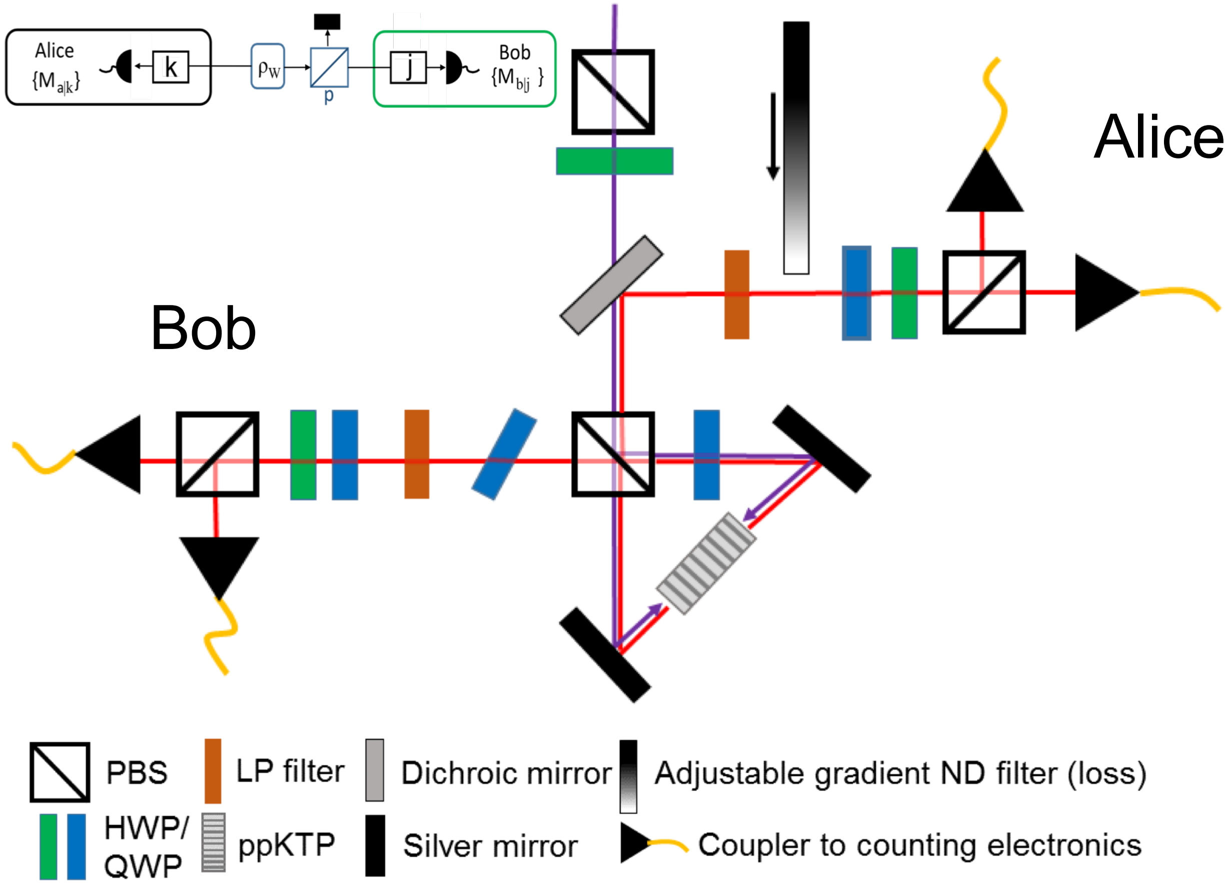
Queensland, Australia

Experimental generation of steerable state

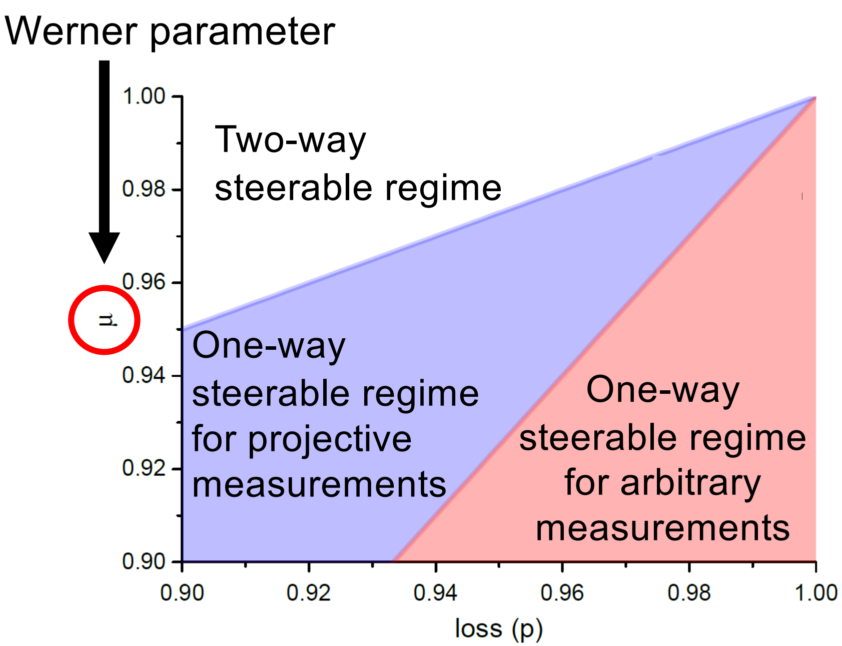


cw pumped Sagnac Ring interferometer with λ_p = 410 nm

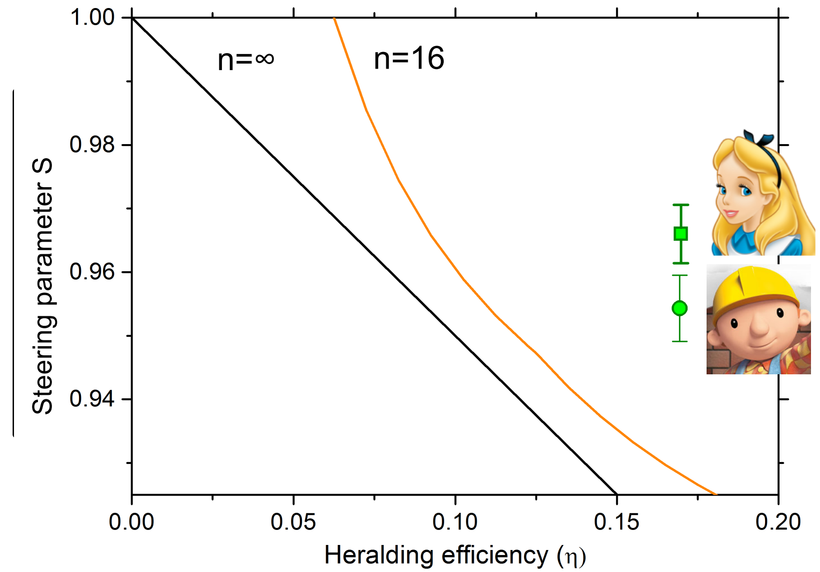
Fidelity of F=99.6% with ideal singlet state, and Tangle of T=98.6% (uncertainties < 1%)

T. Kim et al., *PRA* **73**, 012316 (2006),
A. Fedrizzi et al., *Opt. Exp*. **15**, 15377 (2007)

Two-way steering



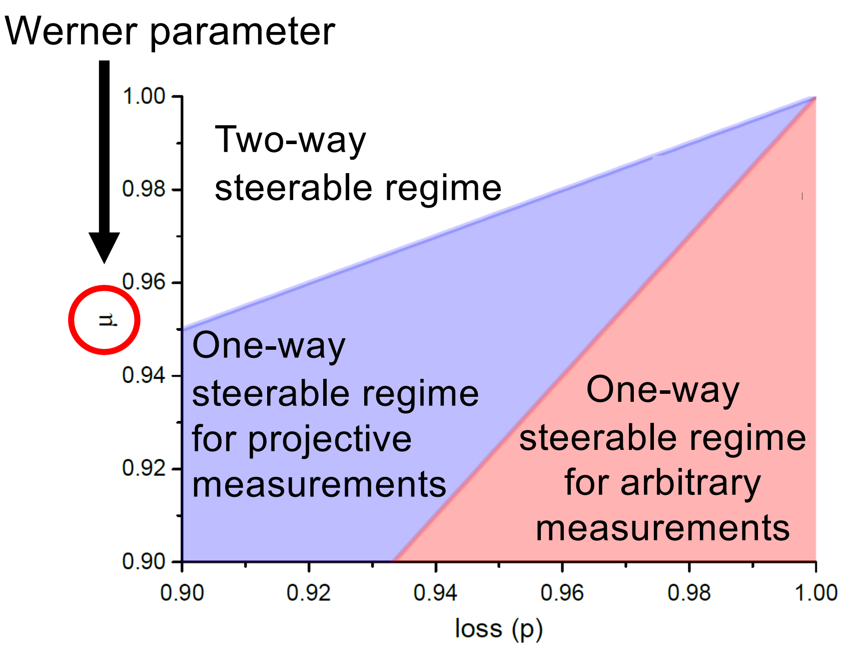
$$S_{16} \equiv \frac{1}{16}\sum_{k=1}^{n}\langle A_k\, \sigma_k^{B}\rangle \leq C_{16}$$



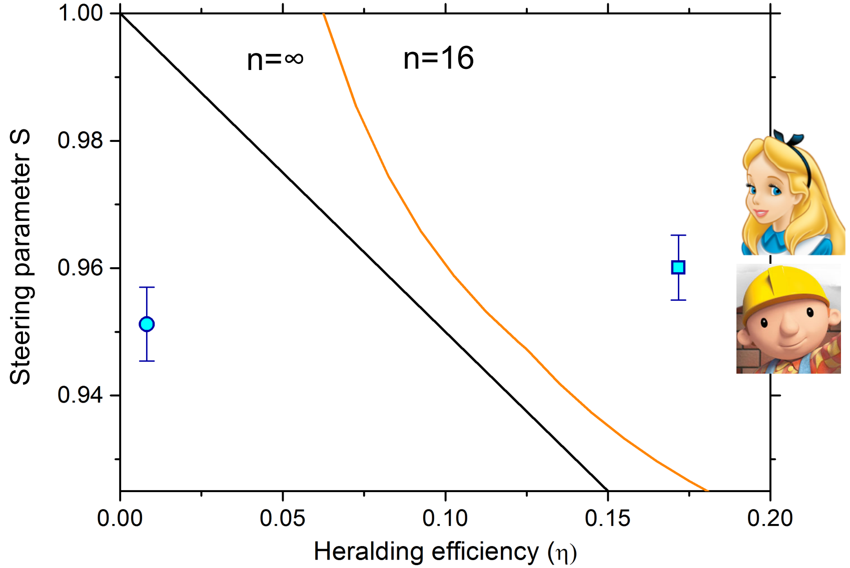
For Alice S_{16} = 0.966 ± 0.005 at η_A = (16.98 ± 0.02)%

For Bob S_{16} = 0.954 ± 0.005 at η_B = (16.94 ± 0.02)%

One way steering



$$S_{16} \equiv \frac{1}{16}\sum_{k=1}^{n}\langle A_k\,\sigma_k^{B}\rangle \leq C_{16}$$

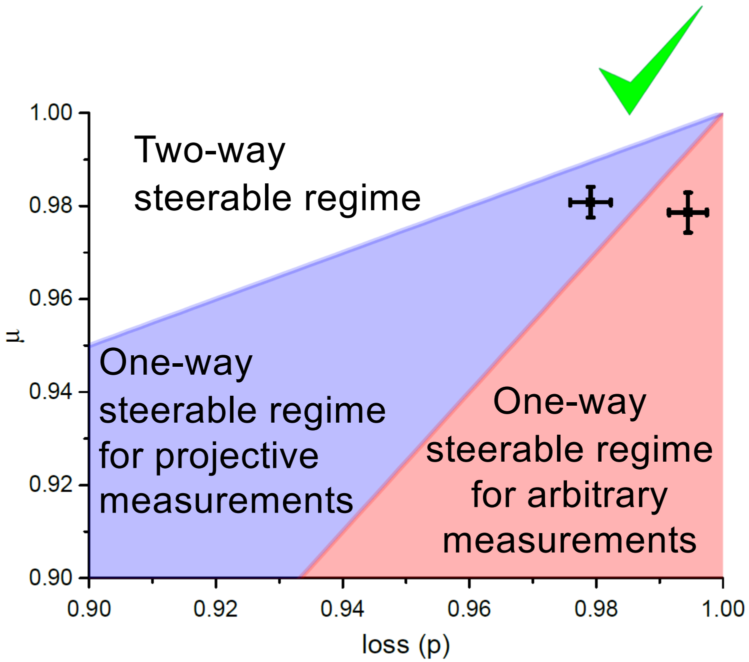


For Alice S_{16} = 0.960 ± 0.005 at η_A = (17.17 ± 0.04)% ✓

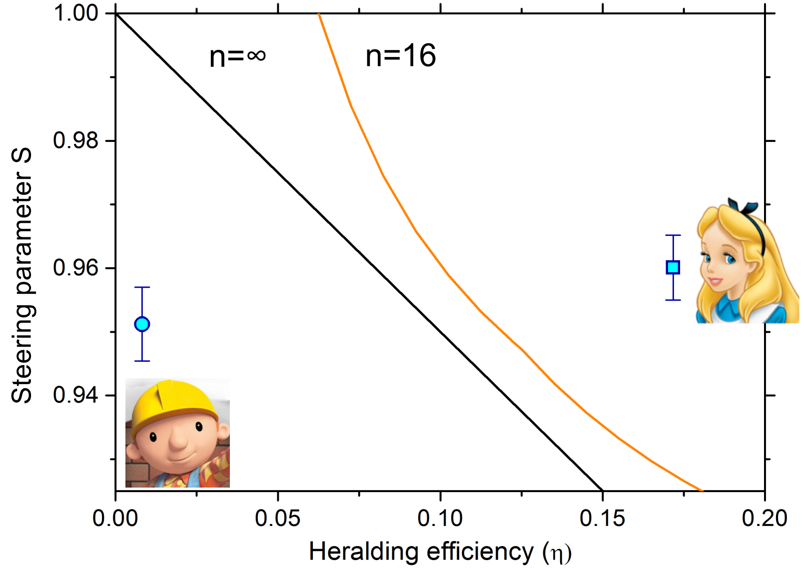
For Bob S_{16} = 0.951 ± 0.006 **no violation**

for n measurement directions on Bloch sphere, here: n=16

One-way steering for arbitrary measurements



$$S_{16} \equiv \frac{1}{16}\sum_{k=1}^{n}\langle A_k\,\sigma_k^B\rangle \leq C_{16}$$



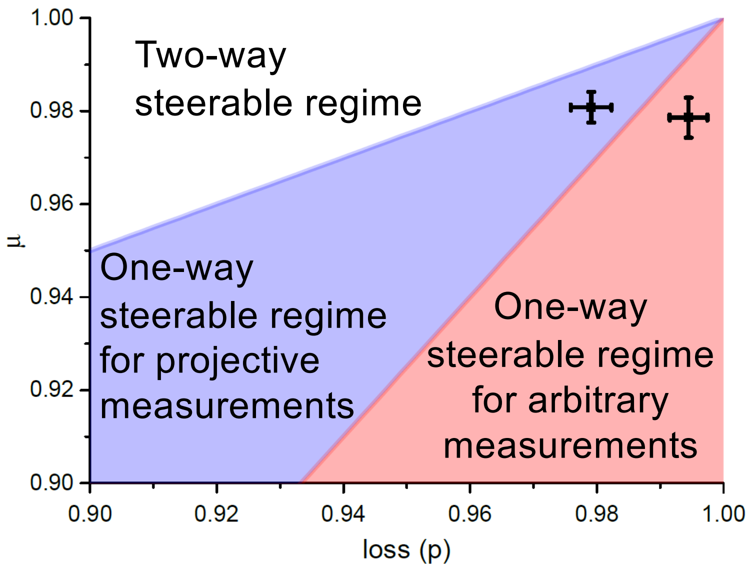
For Alice S_{16} = 0.960 ± 0.005 at η_A = (17.17 ± 0.04)%

For Bob S_{16} = 0.951 ± 0.006 **no violation**

for n measurement directions on Bloch sphere, here: n=16

Wollmann et al., *Physical Review Letters* **116**, 160403 (2016)

Not so fast!



- This result assumes that the state is exactly a Werner state.
- Our Werner state fidelity is 99% – 99.5%
- Close enough, right?
- WRONG!

Solution:

- (1) Derive a more general bound; and/or (2) Make a better state
- We did both, then demonstrated conclusive one-way steering

Tischler et al., Phys. Rev. Lett. 121, 100401 (2018)

Conclusions

- Quantum steering is an asymmetric form of nonlocality that is different from Bell inequality violations and entanglement witnessing
- It is more robust to noise and loss than Bell inequality violation
- It can be configured into a heralded protocol in order to verify nonlocality over a channel with many dB of loss, with the detection loophole closed
- It is a fundamentally asymmetric protocol, and can be shown to be unidirectional for arbitrary choice of measurements
- Steering requires trust in one party, and in QM. There are a variety of scenarios in which this trust seems to be justified, and so steering may be useful for rigorously verifying entanglement in those cases.

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