LETTER

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Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres

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More than 50 years ago[1], John Bell proved that no theory of nature that obeys locality and realism[2] can reproduce all the predictions of quantum theory: in any local-realist theory, the correlations between outcomes of measurements on distant particles satisfy an inequality that can be violated if the particles are entangled. Numerous Bell inequality tests have been reported[3–13]; however, all experiments reported so far required additional assump- tions to obtain a contradiction with local realism, resulting in

sufficiently separated such that locality prevents communication between the boxes during a trial, then the following inequality holds under local realism:

$$S=\left|\langle x\cdot y\rangle_{(0,0)}+\langle x\cdot y\rangle_{(0,1)}+\langle x\cdot y\rangle_{(1,0)}-\langle x\cdot y\rangle_{(1,1)}\right|\leq 2 \qquad (1)$$

where $\langle x\cdot y\rangle_{(a,b)}$ denotes the expectation value of the product of x and y for input bits a and b. (A mathematical formulation of the concepts

Paper presentation

Which one is the Theory of Nature?

Local realism theory

1. *Locality*: Physical influences between systems can not propagate faster than light.

2. *Realistic*: The properties of a system have definite values which exists before and independend of possible measurements.

Supporter: Albert Einstein

Quantum Mechanics

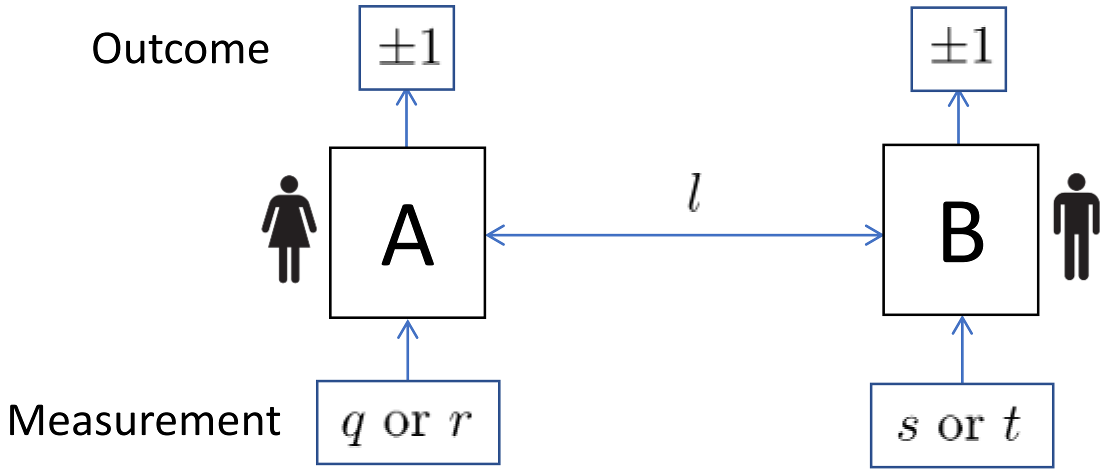
1. Quantum entanglement

Supporter: Niels Bohr

(*Bohr N. "Discussions with Einstein on Epistemological Problems in Atomic Physics"*)

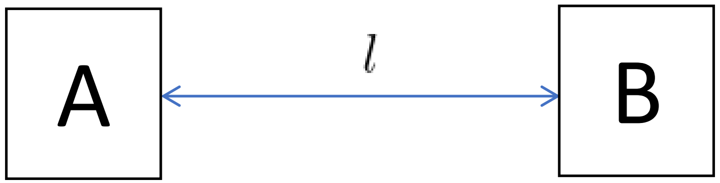
Bell Test

Bell test



- Prepared Systems A,B are separated in space one at Alice and one at Bob
- Both do a measurement on their system. Alice: {q,r} , Bob: {s,t} they choose randomly
- The measurement outcome can be +1 or -1 for each measurement
- Afterwards we study correlations between measurement and outcome

CHSH-Bell inequality in local realism theory



$$\begin{aligned} q &= \pm 1 \\ r &= \pm 1 \end{aligned} \qquad \begin{aligned} s &= \pm 1 \\ t &= \pm 1 \end{aligned}$$

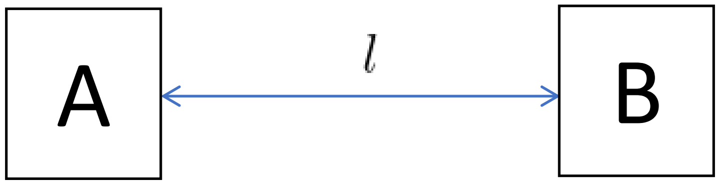
$$\begin{aligned} E\left(qs+rs+rt-qt\right) &= \sum_{q,r,s,t=\pm 1} p\left(q,r,s,t\right)\left(qs+rs+rt-qt\right) \\ &= \sum_{q,r,s,t=\pm 1} p\left(q,r,s,t\right)\underbrace{\left(\left(r+q\right)s+\left(r-q\right)t\right)}_{\pm 2} \\ &\leq \sum_{q,r,s,t=\pm 1} p\left(q,r,s,t\right)\cdot 2 \\ &= 2 \end{aligned}$$

$$E\left(qs+rs+rt-qt\right) \overset{\text{linearity}}{=} E\left(qs\right)+E\left(rs\right)+E\left(rt\right)-E\left(qt\right)$$

$$S_{Cl} = \left|E\left(qs\right)+E\left(rs\right)+E\left(rt\right)-E\left(qt\right)\right| \leq 2$$

Concept from: Quantum Computation and Quantum Information by Michael A.Nielsen and Isaac L. Chuang

CHSH-Bell inequality in QM



$$q = \hat{Z}_1$$
$$r = \hat{X}_1$$

$$s = \frac{1}{\sqrt{2}}\left(-\hat{Z}_2 - \hat{X}_2\right)$$
$$t = \frac{1}{\sqrt{2}}\left(\hat{Z}_2 - \hat{X}_2\right)$$

$$E\left(qs + rs + rt - qt\right) \quad \rightarrow \langle qs + rs + rt - qt \rangle$$

$$\hat{Z}_i = |\uparrow\rangle\langle\uparrow|_i - |\downarrow\rangle\langle\downarrow|_i$$

$$\hat{X}_i = |\uparrow\rangle\langle\downarrow|_i + |\downarrow\rangle\langle\uparrow|_i$$

$$\left|\Psi^-\right\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$

$$\langle qs \rangle = \langle rs \rangle = \langle rt \rangle = \frac{1}{\sqrt{2}}, \quad \langle qt \rangle = -\frac{1}{\sqrt{2}}$$

$$S_{QM} = |\langle qs \rangle + \langle rs \rangle + \langle rt \rangle - \langle qt \rangle| = 2\sqrt{2}$$

Violation of CHSH-Bell inequality ($S_{Cl} \leq 2$)

Concept from: Quantum Computation and Quantum Information by Michael A.Nielsen and Isaac L. Chuang

CHSH-Bell inequality

When we assume that the theory of nature is local-realistic

1. *Locality*: Physical influences between systems can not propagate faster than light.
2. ~~*Realistic*: The properties of a System have definite values which exists before and independend of possible measurements.~~

We have the issue that QM contradicts our assumptions:

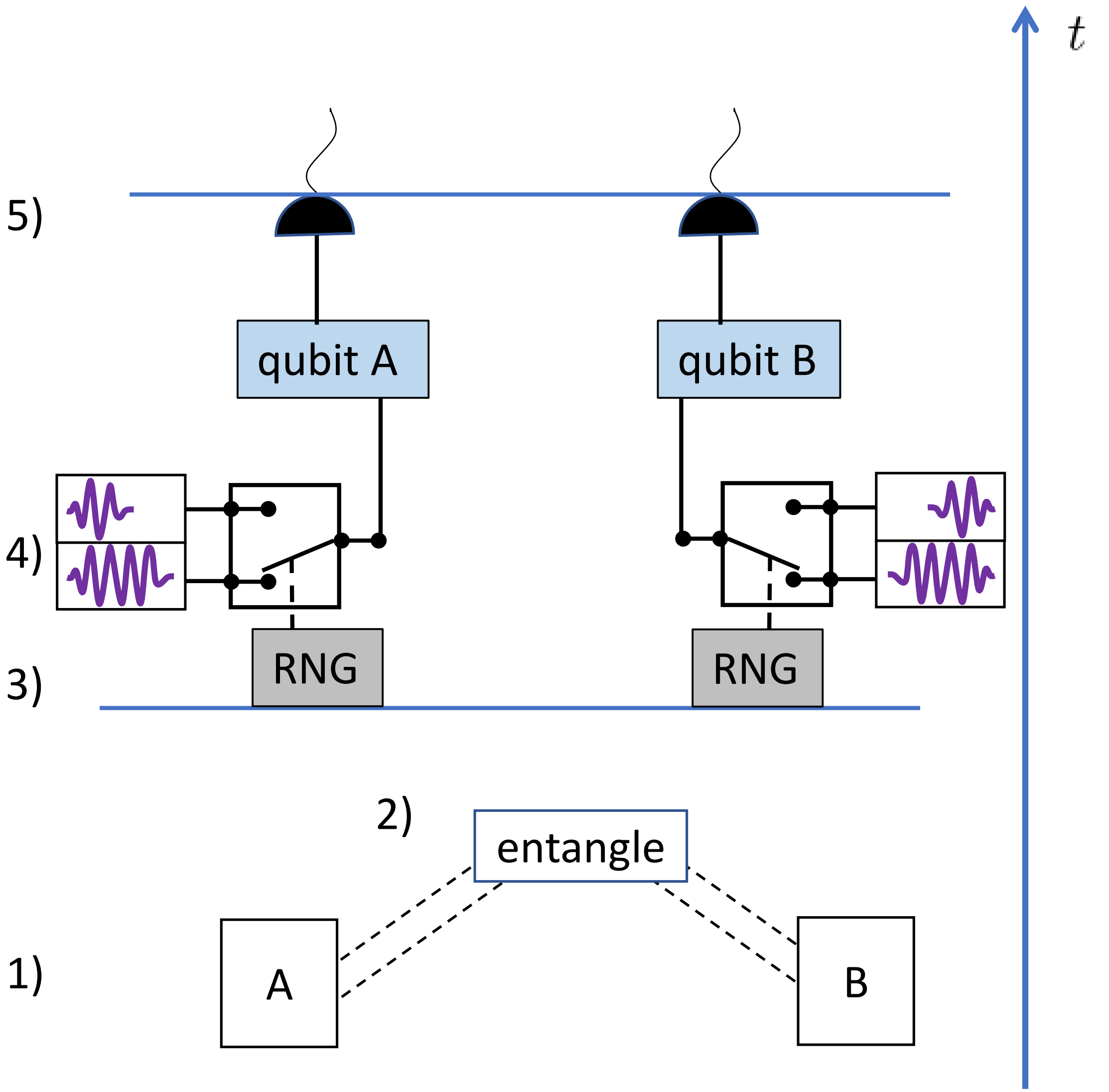
$$\cancel{S_{Cl} \leq 2} < S_{QM} = 2\sqrt{2}$$

If we have an experimental proof

Bell test protocol

1. separated 2-level systems (qubit)
2. Entanglement
3. Measurement decision
4. Measurement
5. Detection

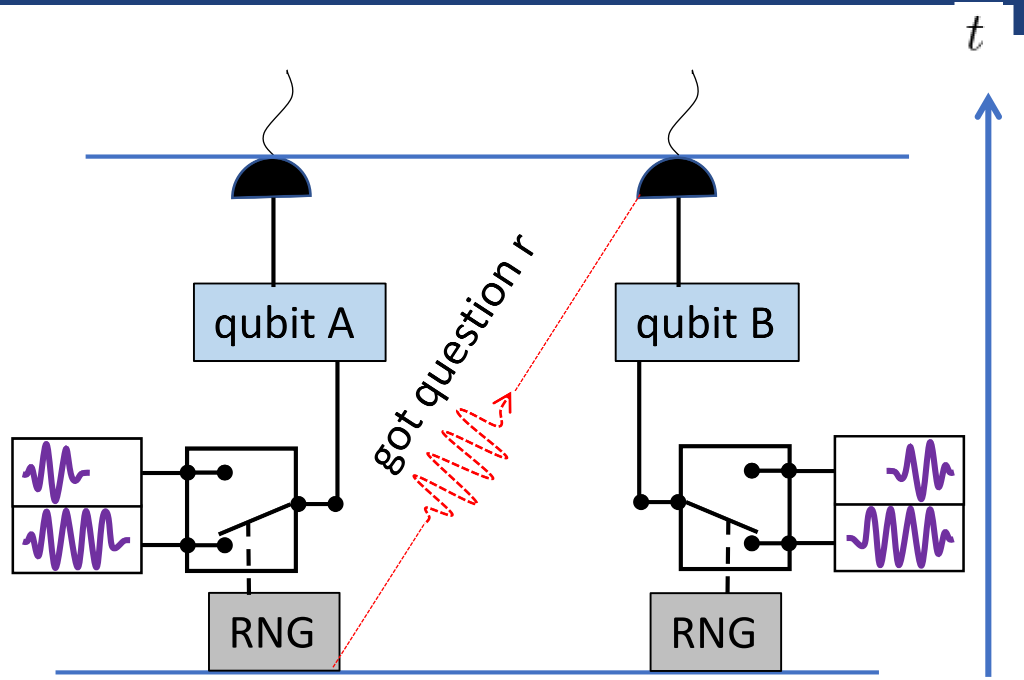
Almost ready to start but there are still some issues...



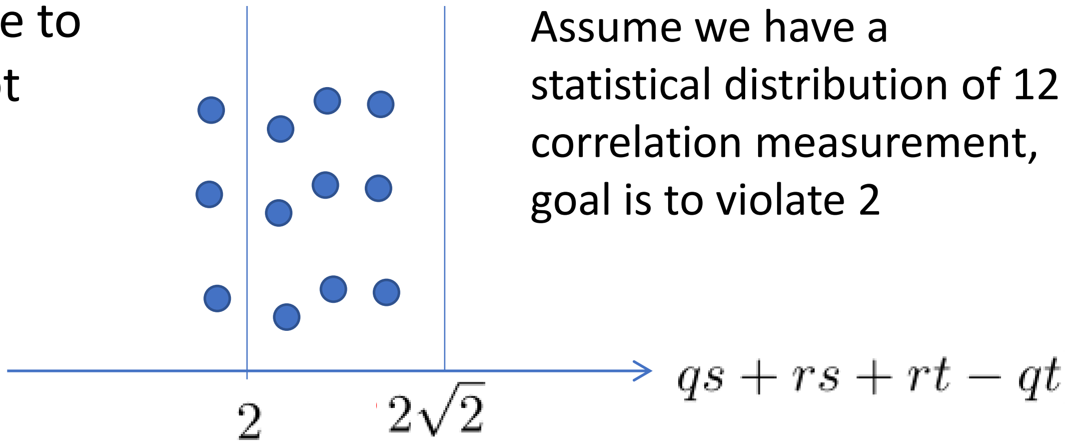
Loopholes

In an experiment different loopholes can arise.

1. Locality loophole: After Alice's RNG decides for a measurement axis to do a spin measurement on her qubit. A signaling photon could travel to Bob to inform his system about her question before Bob get's the measurement.



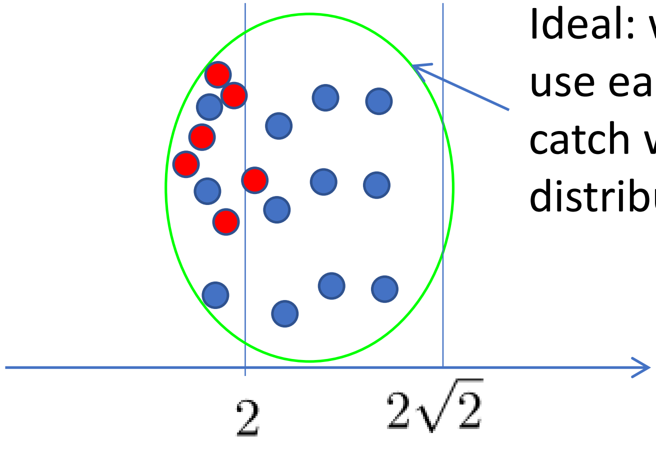
2. Detection loophole (fair-sampling assumption): Due to inefficient detection or loss some outcomes are not considered. We hope that the discarded outcomes have the same statistical distribution



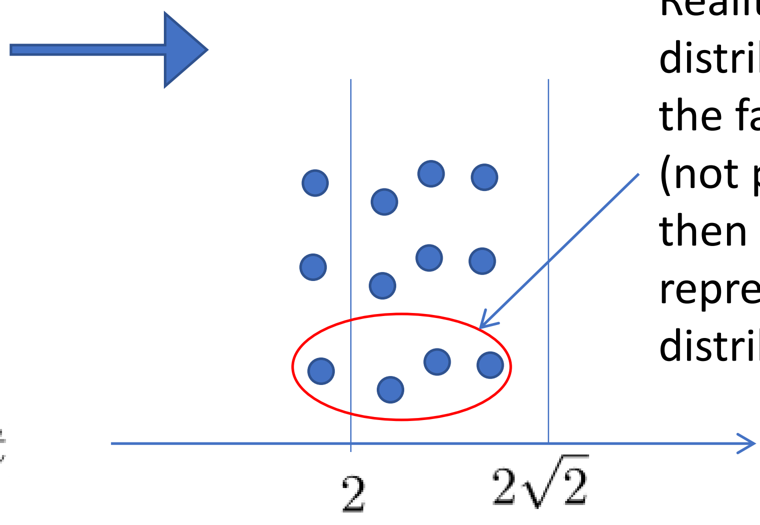
Assume we have a statistical distribution of 12 correlation measurement, goal is to violate 2

Loopholes

Real system has losses



Ideal: we can measure and use each outcome -> we catch whole statistical distribution



Reality: only subset of the distribution. If me make now the fair sampling assumption (not part of Bells inequality) then our subset is representative for the whole distribution

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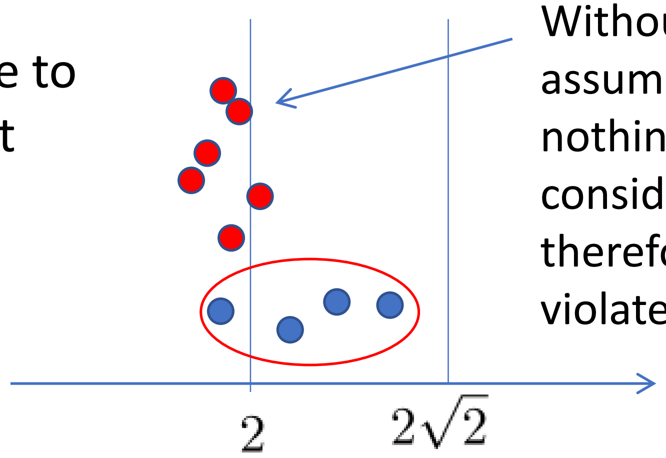


Without the fair sampling assumption we can say nothing about the not considered outcomes and therefore we might not violate Bells inequality

Historical overview

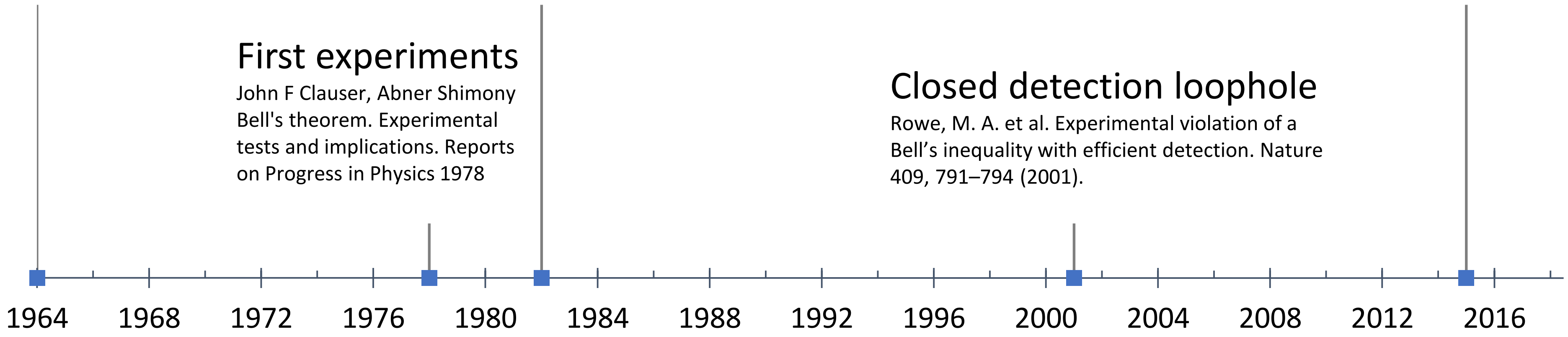
Bell inequality
Bell, J. S. On the Einstein–Podolsky–Rosen paradox. Physics 1, 195–200 (1964)

First experiments
John F Clauser, Abner Shimony Bell's theorem. Experimental tests and implications. Reports on Progress in Physics 1978

Closed locality loophole
Aspect, A., Dalibard, J. & Roger, G. Experimental test of Bell's inequalities using time-varying analyzers. Phys. Rev. Lett. 49, 1804–1807 (1982).

Closed detection loophole
Rowe, M. A. et al. Experimental violation of a Bell's inequality with efficient detection. Nature 409, 791–794 (2001).

Closed both loopholes (this paper 2015)

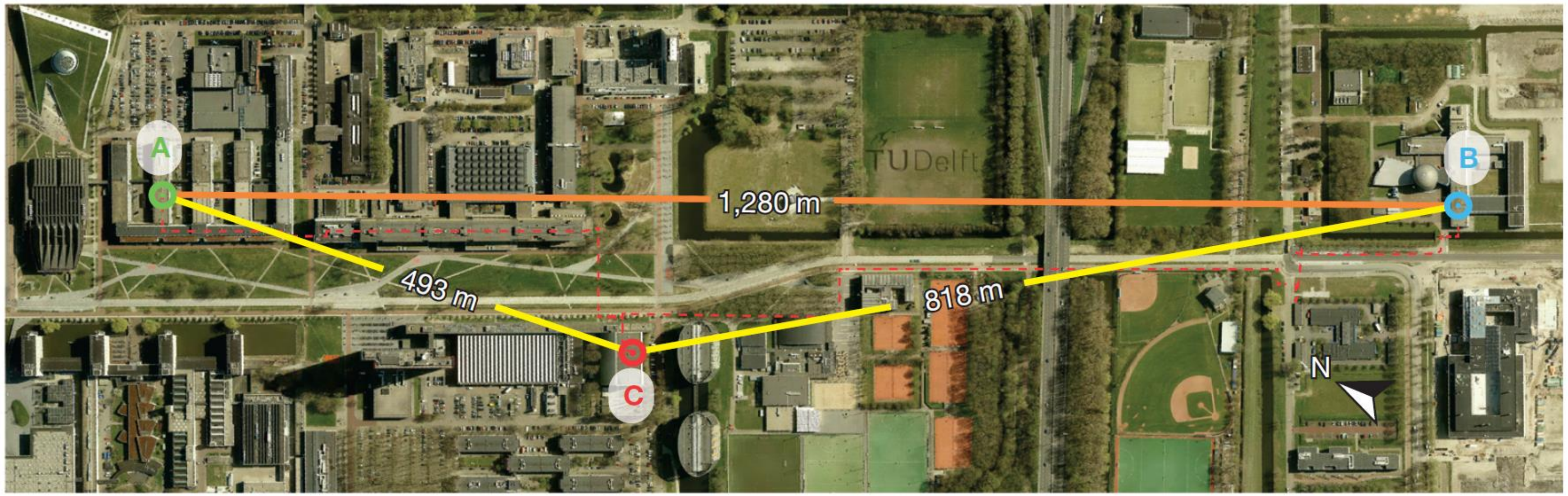


Setup

- Spatial separation of A and B
- Time window of 4.27 µs
- Fast operations

$\Rightarrow$ Locality loophole closed ☑

Hensen *et al.*, *Nature* **536**, 7575 [2015]



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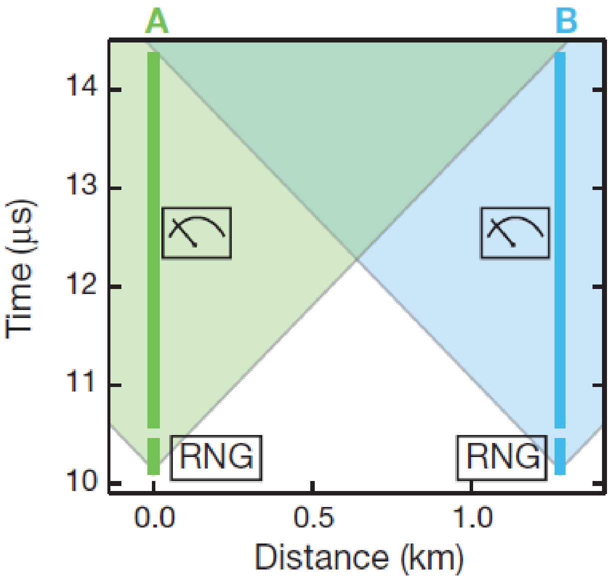
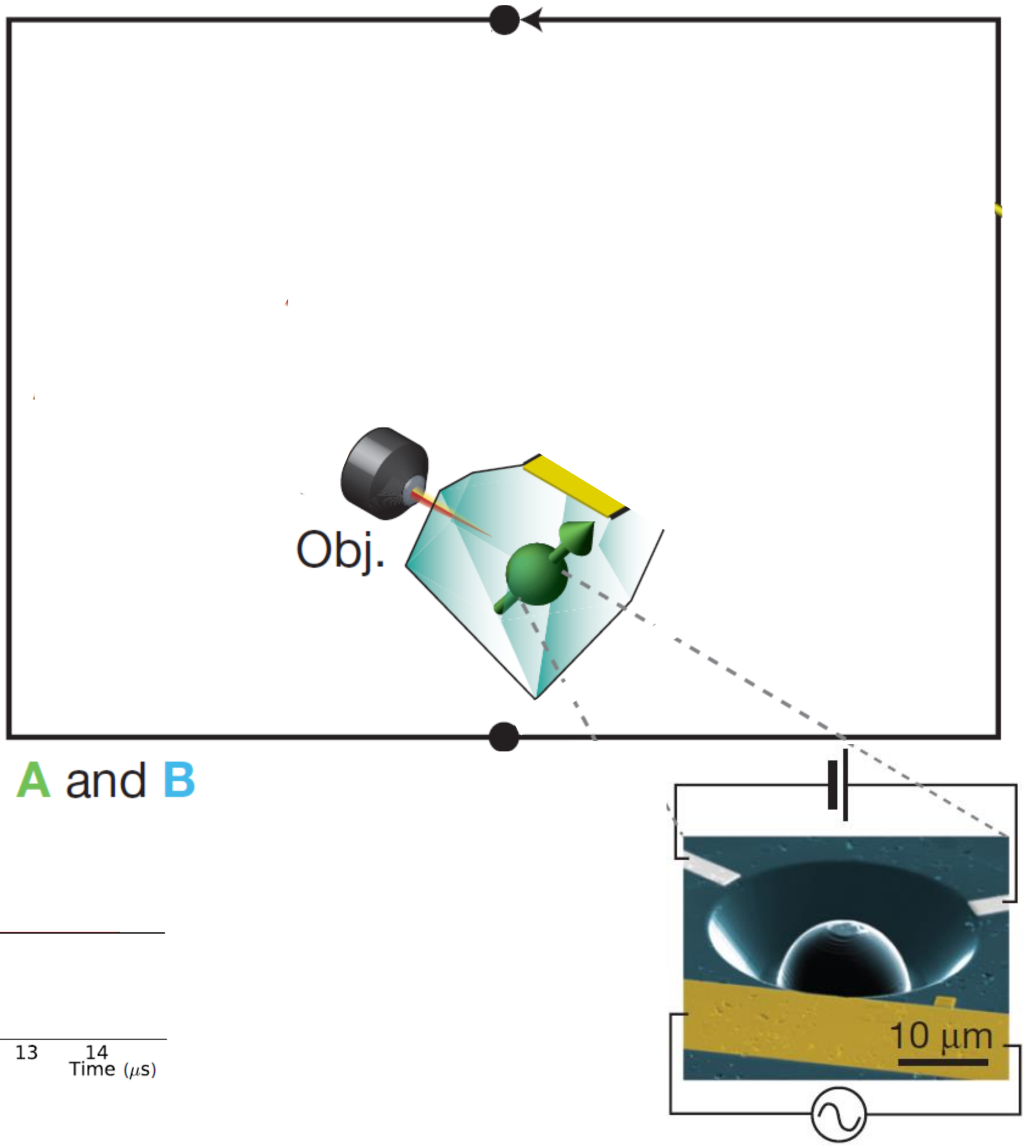
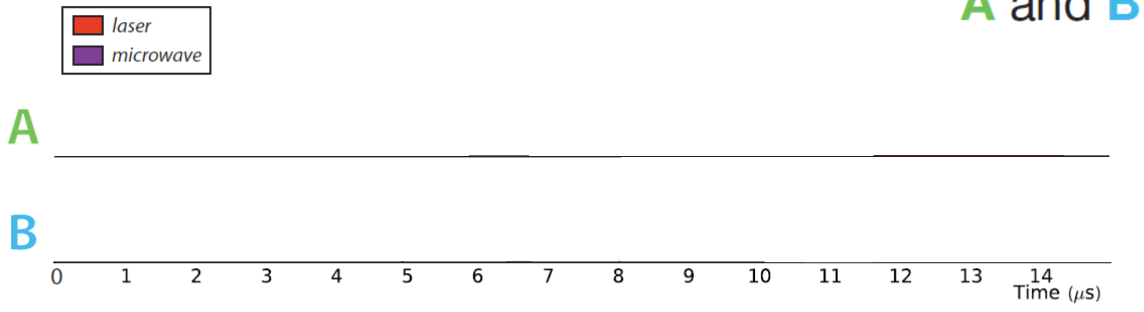


Implementation

1. Qubit: NV center
2. Initialize qubit
3. Entanglement swapping
4. Measurement decision
5. Mitigate decoherence
6. Read-out





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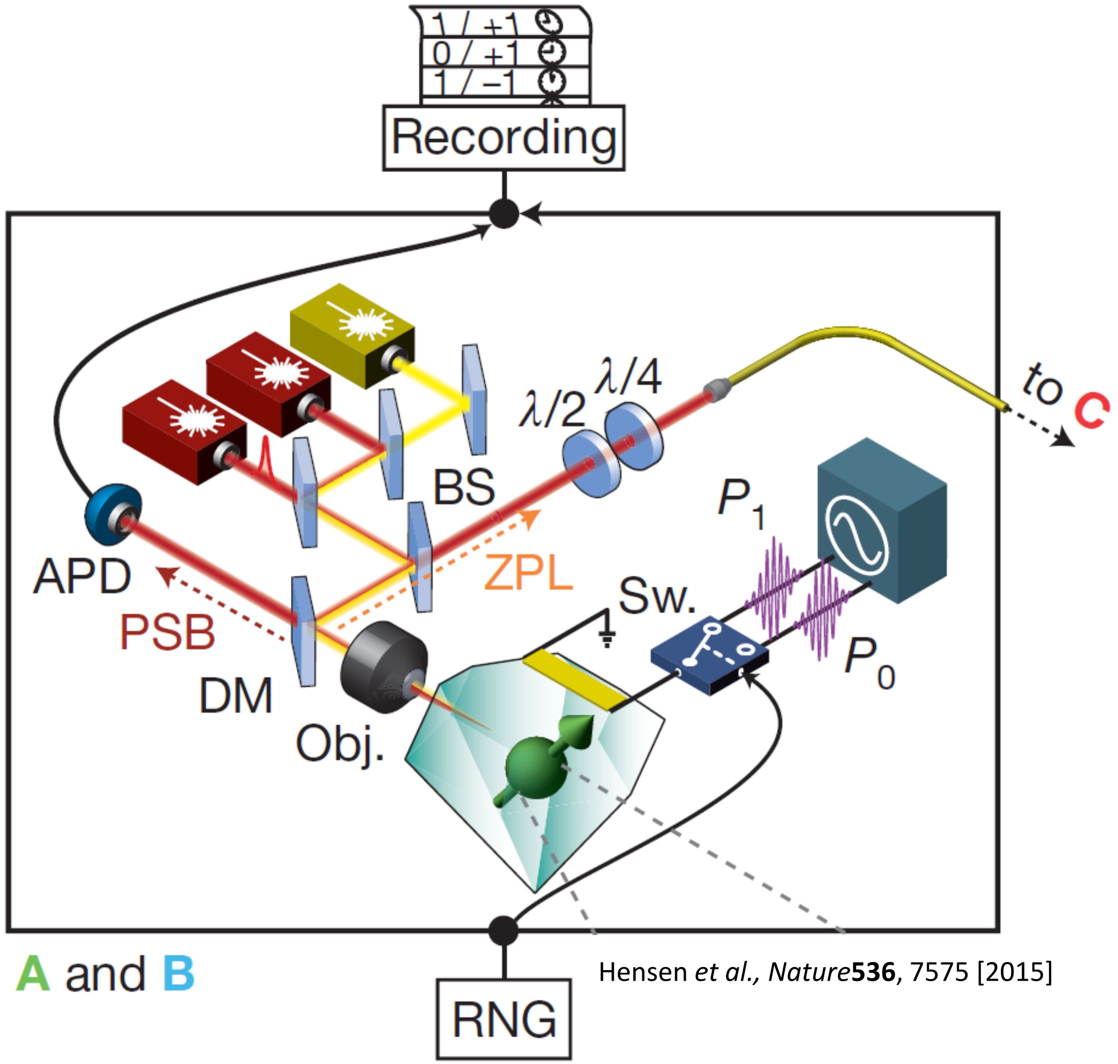
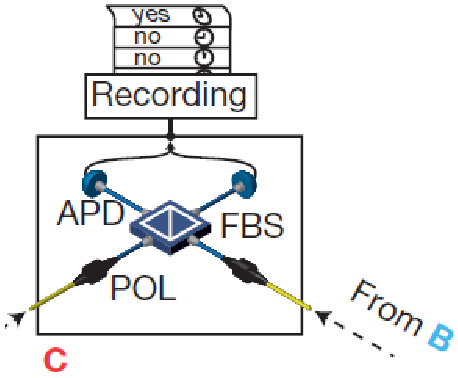
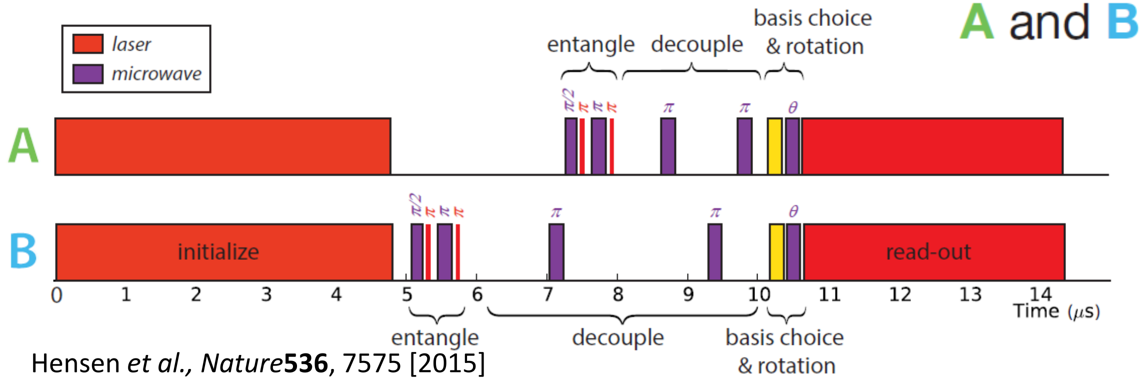


A and B

Hensen *et al.*, *Nature* **536**, 7575 [2015]



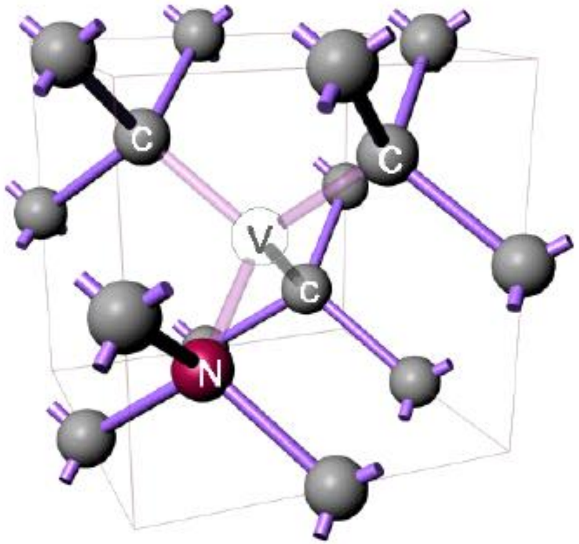


Hensen *et al.*, *Nature* **536**, 7575 [2015]

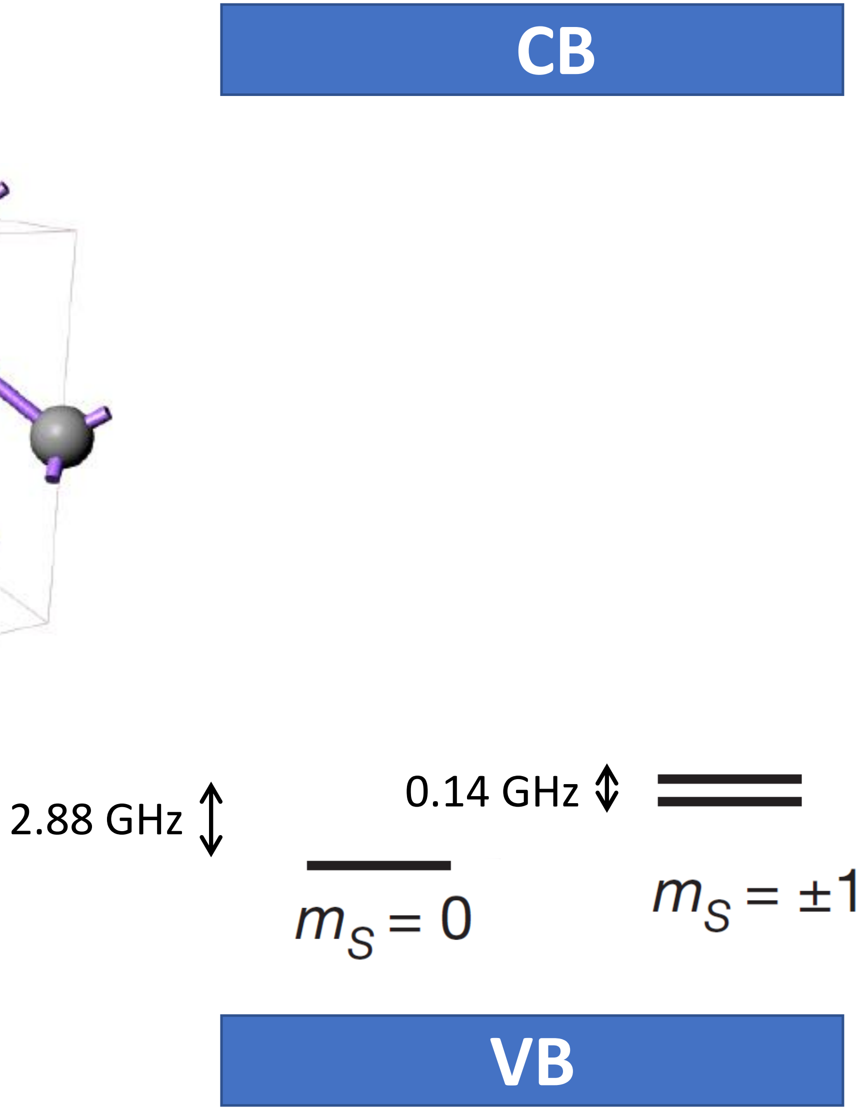
$\Rightarrow$ Detection loophole closed ☑

1. Qubit: NV center

- Defect in diamond
- Negatively charged
- 6 e^- system → 2 holes
- Total spin 1 → triplett
- In band gap
- Like an ion trap



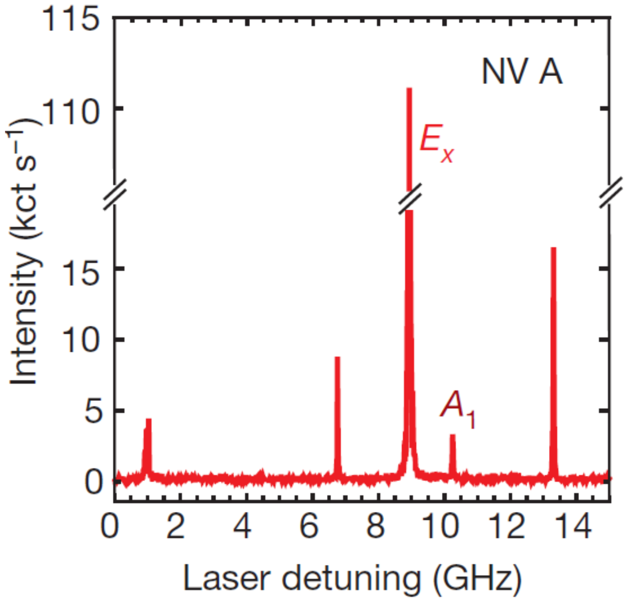
Slide material: Andreas Wallraff



1. Qubit: NV center

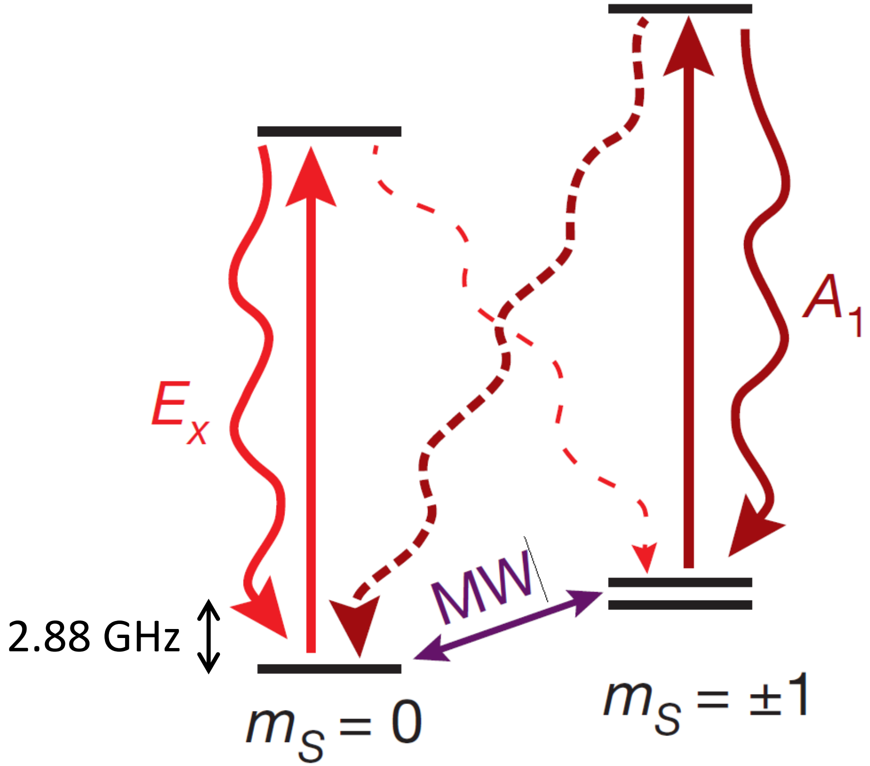
- Defect in diamond
- Negatively charged
- 6 e^- system $\rightarrow$ 2 holes
- Total spin 1 $\rightarrow$ triplett
- In band gap
- Like an ion trap
- Spin-selective optical transitions

Robledo *et al.*, *Nature* **477**, 7366 [2011]



from 470.443 THz
$\leftrightarrow$ 1.94 eV
$\leftrightarrow$ 637 nm

CB



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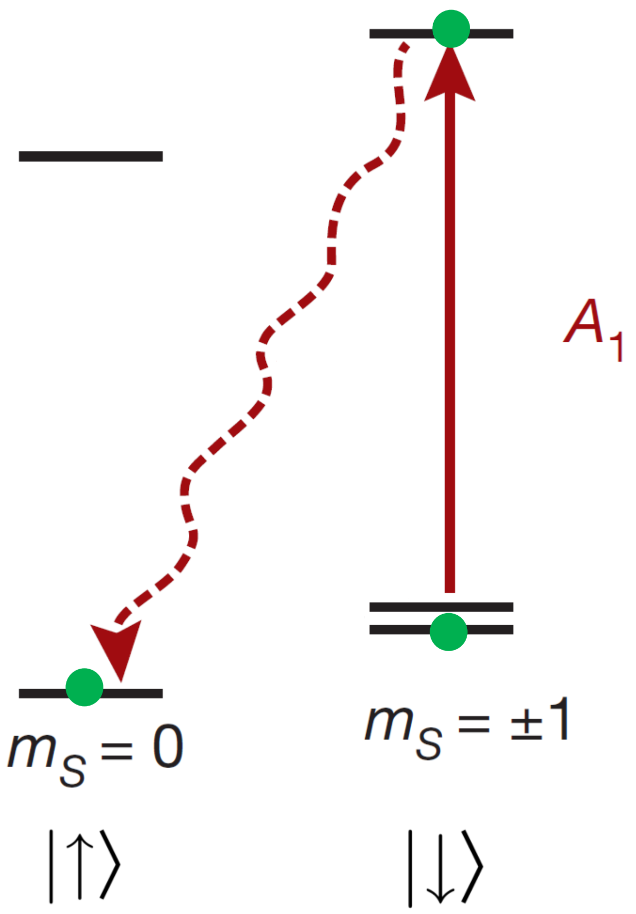
VB

2. Initialize qubit

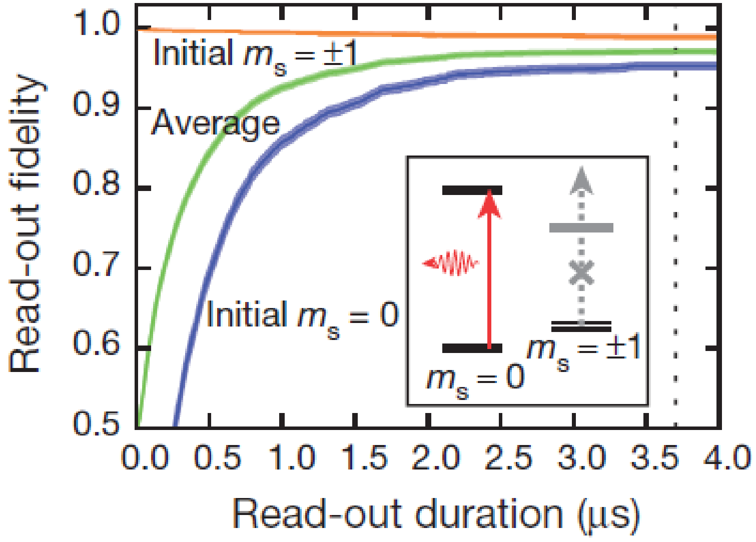
- Initialize to $|\uparrow\rangle$
- Resonant A_1 excitation
- Fast decay to dark $m_s = 0$ state via spin mixing in excited manifold
- Fidelity: 99.8 % in 5 μs

Assign: $|\uparrow\rangle \equiv m_s = 0$
$|\downarrow\rangle \equiv m_s = -1$

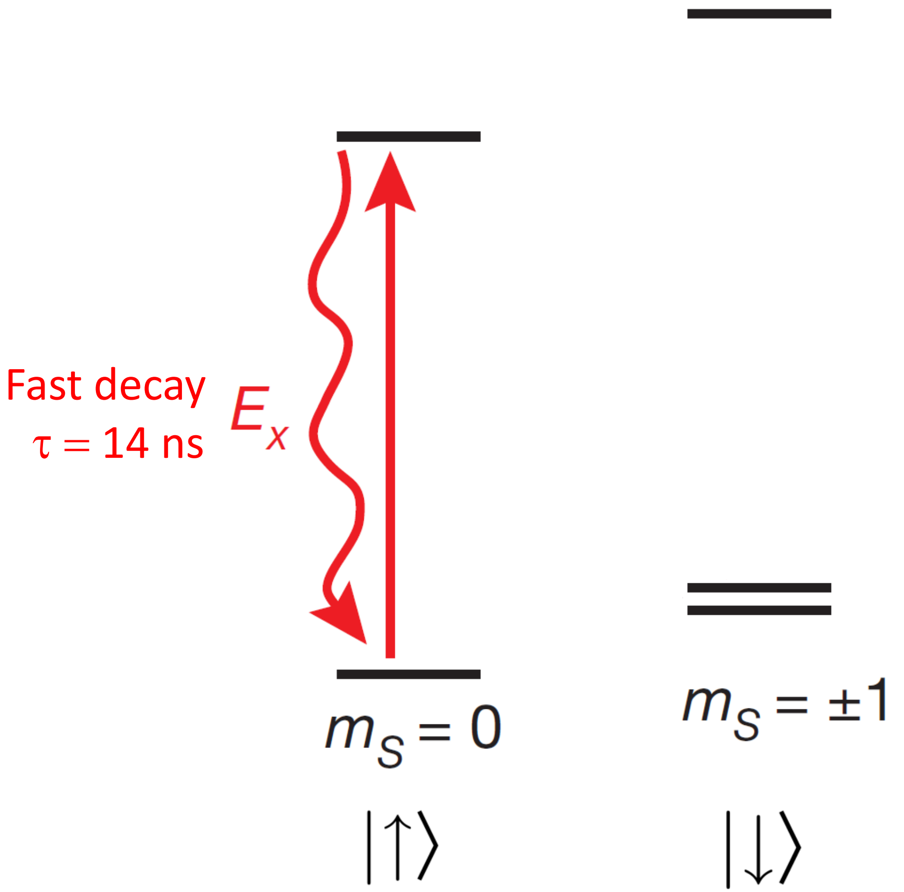


5. Read-out

- Excite resonantly with E_x transition
- $|\uparrow\rangle \leftrightarrow$ bright, $|\downarrow\rangle \leftrightarrow$ dark
- Wait for detections during 3.7 µs
- If at least 1 photon measured $\rightarrow |\uparrow\rangle$



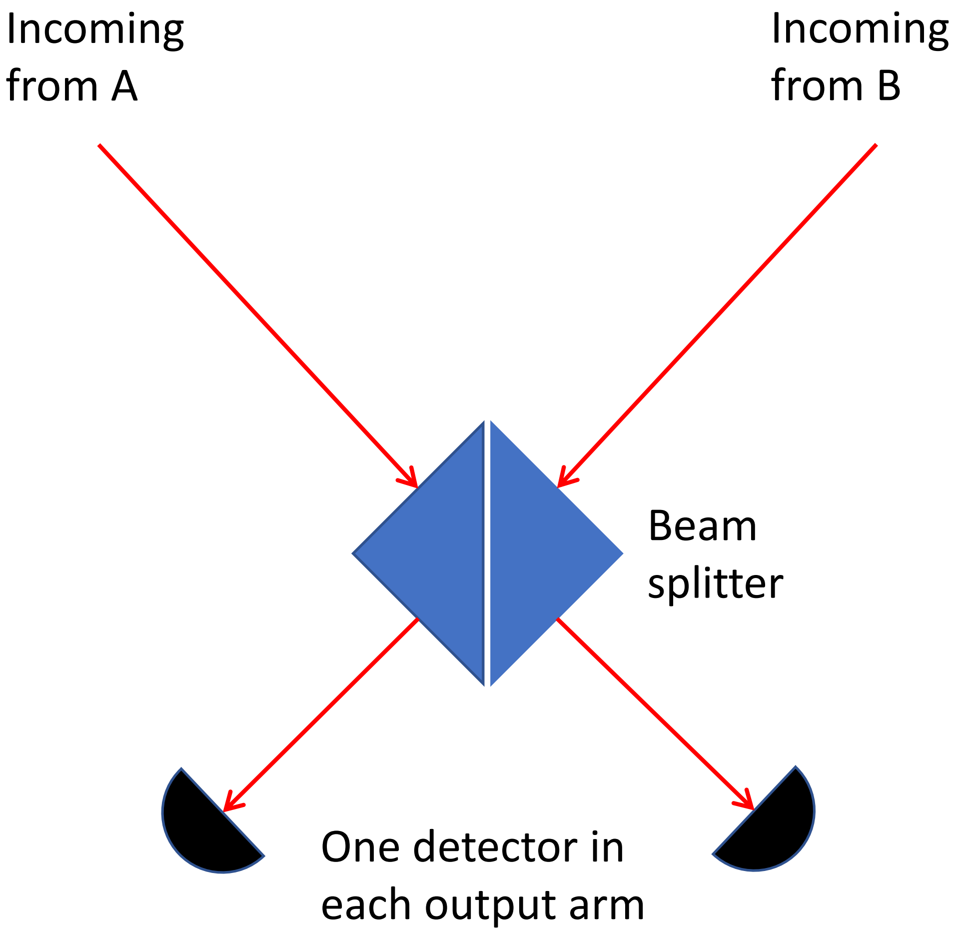
Hensen *et al., Nature* **536**, 7575 [2015]



3. Entanglement swapping

- Use Hong Ou Mandel interference
- Overlap beams at beam splitter
- Photons are: indistinguishable $\rightarrow$ bunching
  (= both photons in only one output arm)

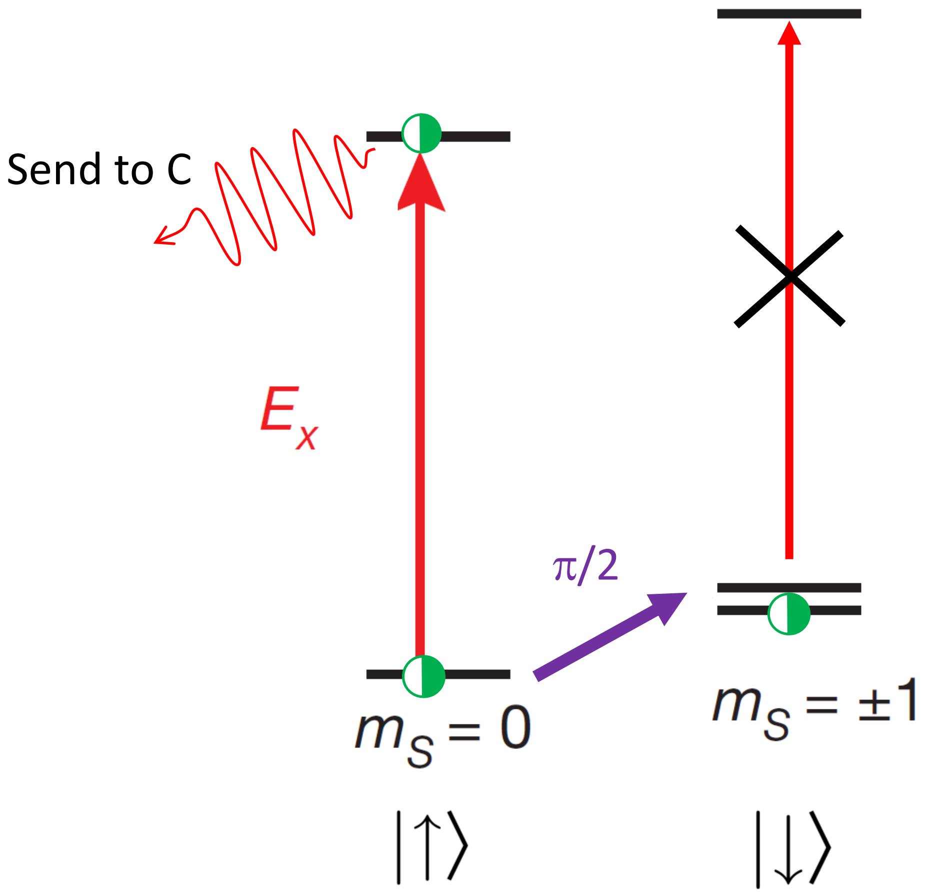
  distinguishable $\rightarrow$ coincidences
  (= one photon in each output arm)



3. Entanglement swapping

- Procedure at each qubit:

1. Initialized to: $|\uparrow\rangle + |\downarrow\rangle$
2. Excite resonantly at E_x transition $|\uparrow 1_e\rangle + |\downarrow 0_e\rangle$
   → photon and spin entangled
   early time bin (e)
3. π pulse $|\downarrow\rangle + |\uparrow\rangle$
4. Again drive E_x transition $|\downarrow 0_l\rangle + |\uparrow 1_l\rangle$
   → another photon
   late time bin (l)



3. Entanglement swapping

- Measurements at C and projections $\Rightarrow$ Scheme to herald successful entanglement

Early time bin — From A and B: $|\uparrow 1\rangle + |\downarrow 0\rangle$

$A \otimes B$:

$$\cancel{|\uparrow_A \uparrow_B\rangle|1_A 1_B\rangle} + |\uparrow_A \downarrow_B\rangle|1_A 0_B\rangle + |\downarrow_A \uparrow_B\rangle|0_A 1_B\rangle + \cancel{|\downarrow_A \downarrow_B\rangle|0_A 0_B\rangle}$$

Measuring one photon

Spin flip
Late time bin
(250 ns later) — $|\downarrow 0\rangle + |\uparrow 1\rangle$

$$\cancel{|\downarrow_A \downarrow_B\rangle|0_A 0_B\rangle} + |\downarrow_A \uparrow_B\rangle|0_A 1_B\rangle + |\uparrow_A \downarrow_B\rangle|1_A 0_B\rangle$$

Measuring one photon

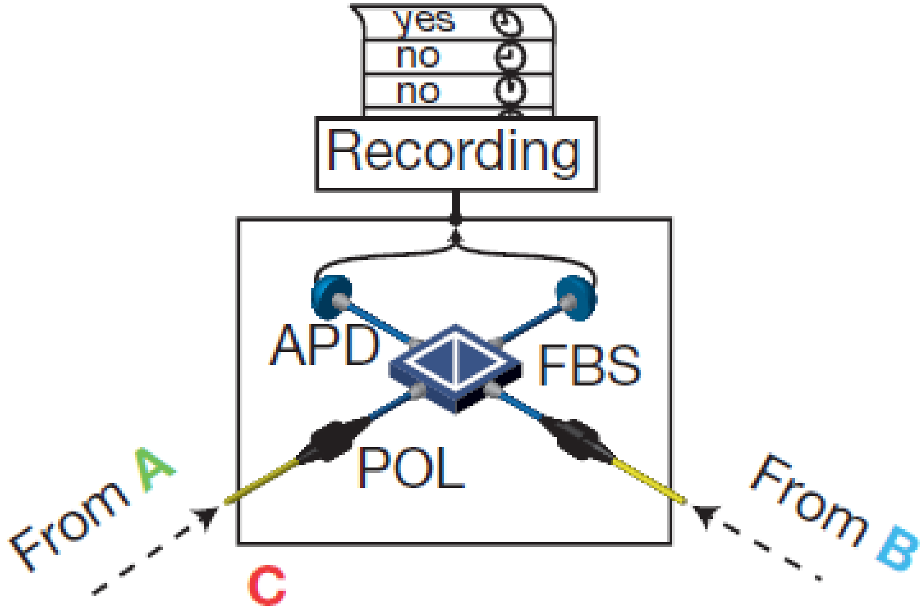
Projection onto $|\uparrow_A \downarrow_B\rangle \pm |\downarrow_A \uparrow_B\rangle$
- (+): photon detection in different (same) detectors

3. Entanglement swapping

- Measurements at C and projections

– Robust against photon loss

⇒ Scheme to herald successful entanglement



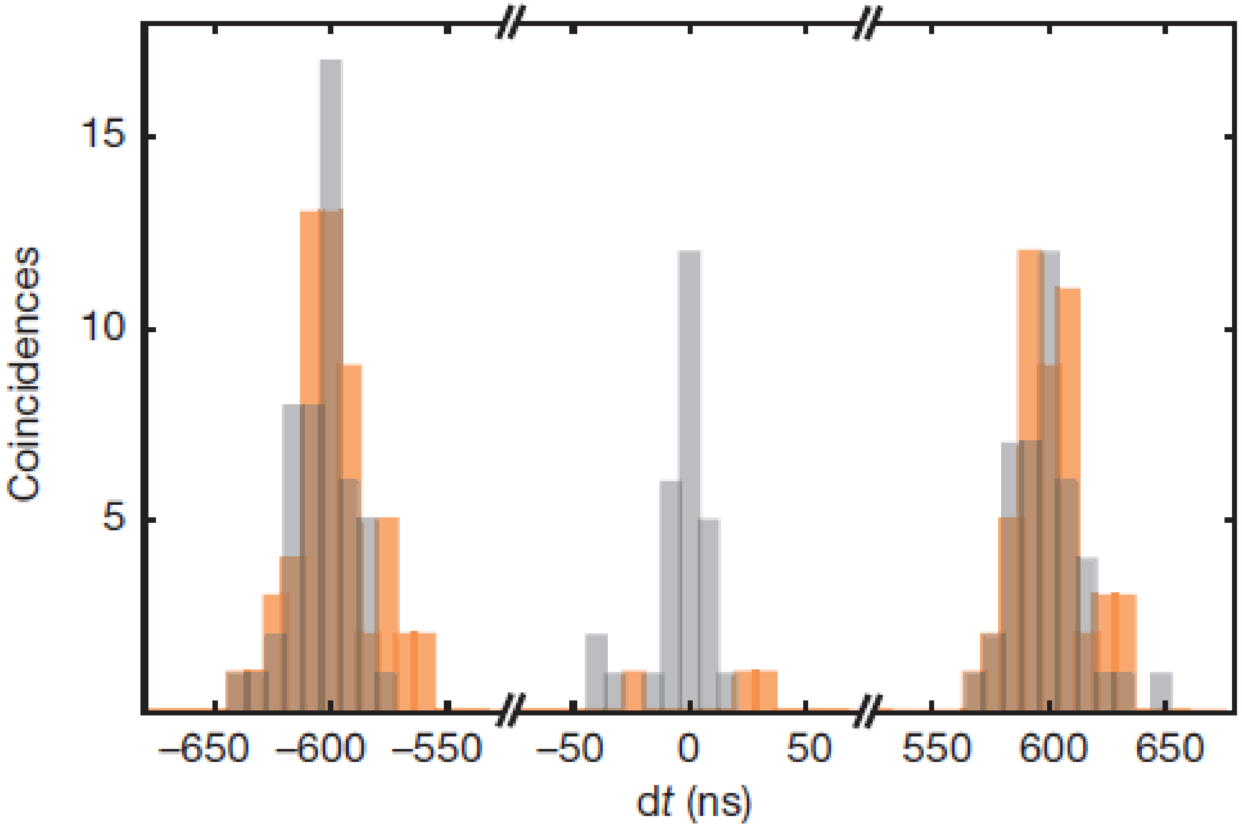
Hensen *et al.*, *Nature* **536**, 7575 [2015]

Projection onto $|\uparrow_A\downarrow_B\rangle \pm |\downarrow_A\uparrow_B\rangle$
- (+): photon detection in different (same) detectors

Degree of indistinguishability

- HOM interferometry
- Dip at dt=0 as expected
- Fidelity of $|\Psi^-\rangle$ 0.92 ±0.03
- Expect $S \sim 2.30 \ \pm 0.07$

➡ violation of Bell inequality

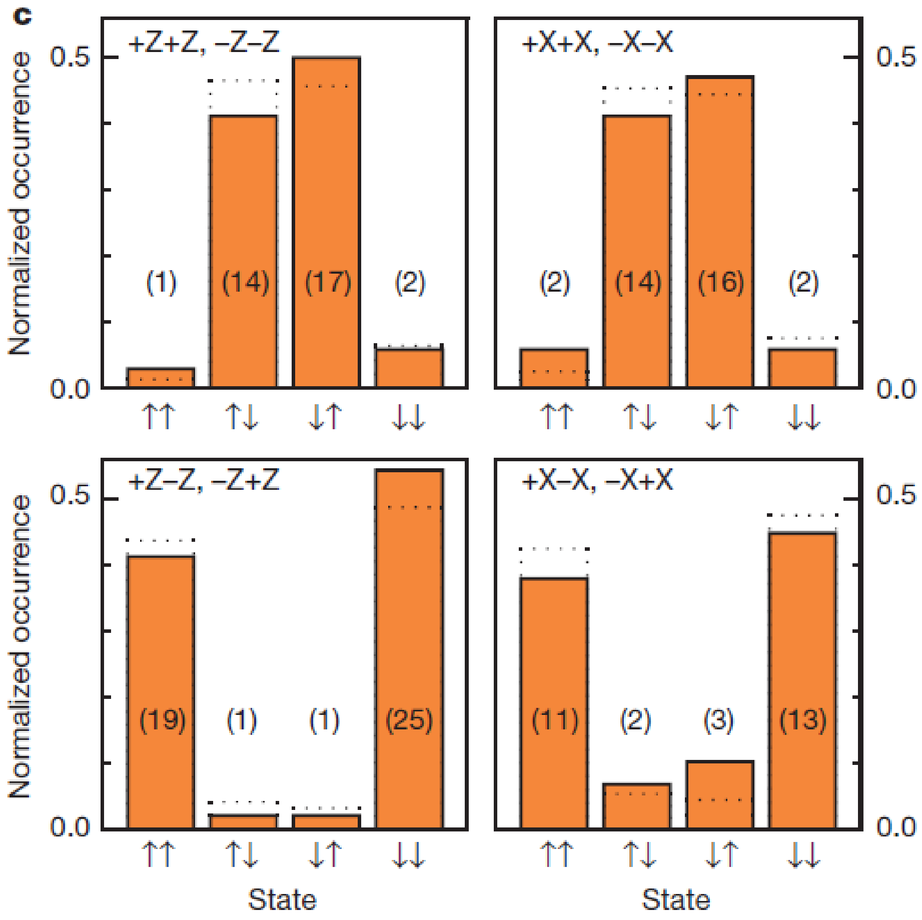


Hensen *et al., Nature* **536**, 7575 [2015]

Final characterization with collinear axes

- Test performance of setup
- Randomly choose + or – Z (X)
- Desired entangled state is generated

$$|\psi^-\rangle = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$$



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Characteristics

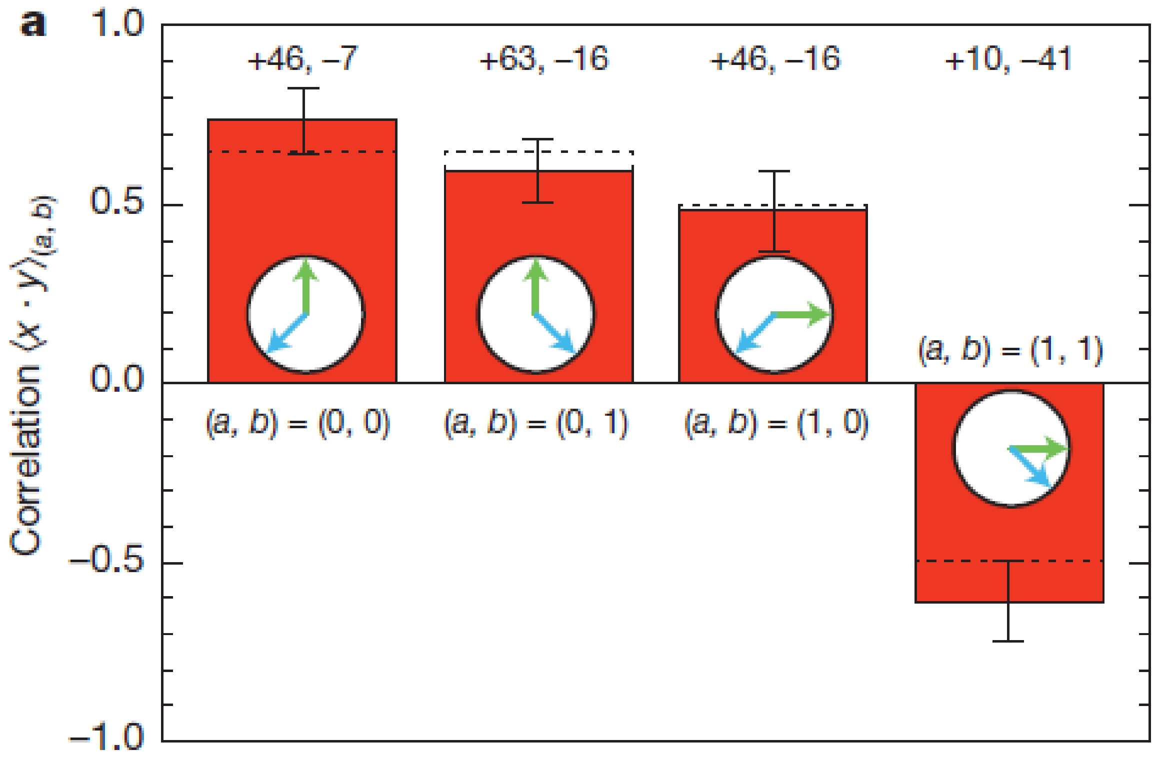
- Succes probability per entanglement generation attempt ~ $6.4 \cdot 10^{-9}$
- Separation of entangled NV-centres two orders higher than before
- Opimization yields angles along z-Axis for read out bases

Results

- Only 245 successful trials during 220 h
- Arrows: green (A) and blue (B)
- $S = 2.42 \pm 0.20$

  ➡ loophole-free violation of CHSH!
- $P = 0.039$

  ➡ statistically significant rejection of null-hypothesis



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$$S = \left| \langle x \cdot y \rangle_{(0,0)} + \langle x \cdot y \rangle_{(0,1)} + \langle x \cdot y \rangle_{(1,0)} - \langle x \cdot y \rangle_{(1,1)} \right| \leq 2$$

CHSH-Bell inequality

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2. ~~*Realistic*: The properties of a System have definite values which exists before and independend of possible measurements.~~

We have the issue that QM contradicts our assumptions:

$$\cancel{S_{Cl} \leq 2} < S_{QM} = 2\sqrt{2}$$

experimental proof

Second experiment half a year later

- Modified using classical random numbers as input
- Larger time window gives better data rate
- Also $|\Psi^+>$ state, combine into single hypothesis test

Result: $S = 2.38 \pm 0.14$

SCIENTIFIC REPORTS

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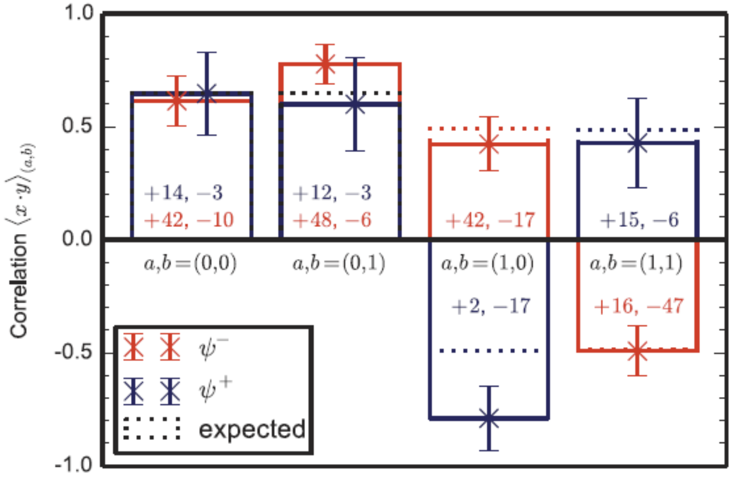
Loophole-free Bell test using electron spins in diamond: second experiment and additional analysis

B. Hensen[1,2], N. Kalb[1,2], M.S. Blok[1,2], A. E. Dréau[1,2], A. Reiserer[1,2], R. F. L. Vermeulen[1,2], R. N. Schouten[1,2], M. Markham[3], D. J. Twitchen[3], K. Goodenough[1], D. Elkouss[1], S. Wehner[1], T. H. Taminiau[1,2] & R. Hanson[1,2]

The recently reported violation of a Bell inequality using entangled electronic spins in diamonds (Hensen *et al.*, *Nature* 526, 682–686) provided the first loophole-free evidence against local-realist theories of nature. Here we report on data from a second Bell experiment using the same experimental setup with minor modifications. We find a violation of the CHSH-Bell inequality of 2.35 ± 0.18, in agreement with the first run, yielding an overall value of $S = 2.38 \pm 0.14$. We calculate the resulting



Outlook

- Strictly speaking,Bell cannot exclude all local-realist theories due to free-will loophole

- Combination of event-ready scheme with higher entanglement rate might be used for:
  - quantum key distribution
  - randomness certification

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sufficiently separated such that locality prevents communication between the boxes during a trial, then the following inequality holds under local realism:

$$S = \left| \langle x \cdot y \rangle_{(0,0)} + \langle x \cdot y \rangle_{(0,1)} + \langle x \cdot y \rangle_{(1,0)} - \langle x \cdot y \rangle_{(1,1)} \right| \leq 2 \qquad (1)$$

where $\langle x \cdot y \rangle_{(a,b)}$ denotes the expectation value of the product of x and y for input bits a and b. (A mathematical formulation of the concepts

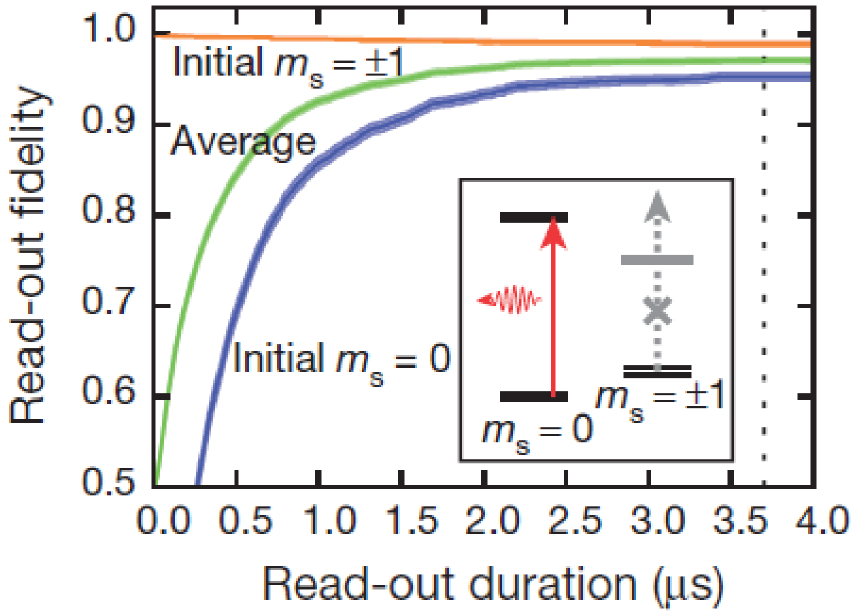
Thanks for your attention

Additional slides

4. Measurement decision

- Quantum Random number generator
- Driven by process (including spontaneous emission) that is unpredictable both in quantum and classical treatment
- Excess predictability below 10^{-5}
- 160 ns

5. Read-out



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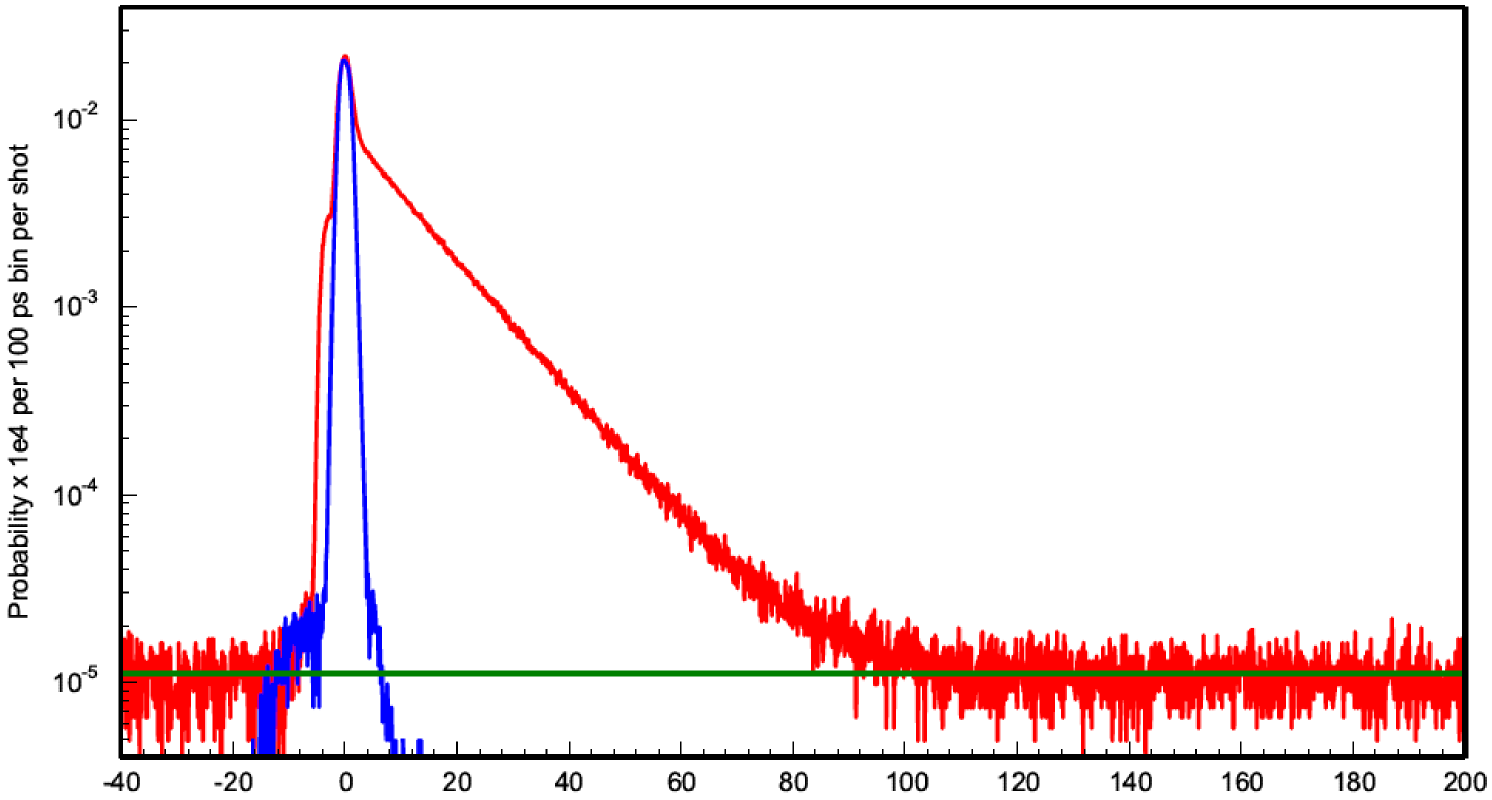

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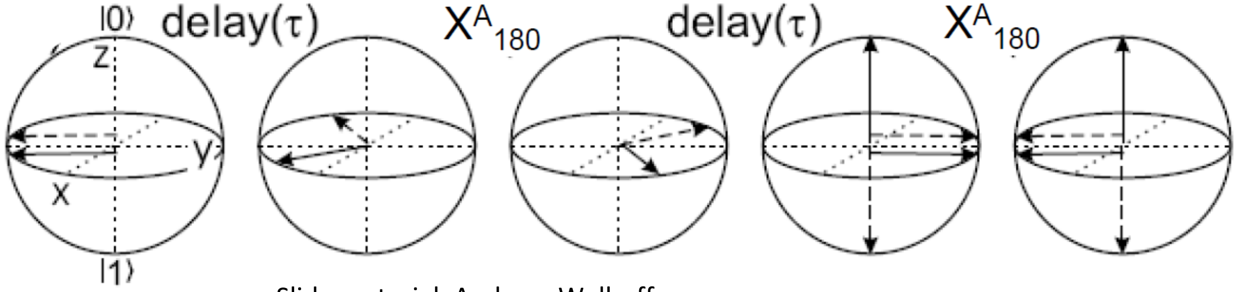
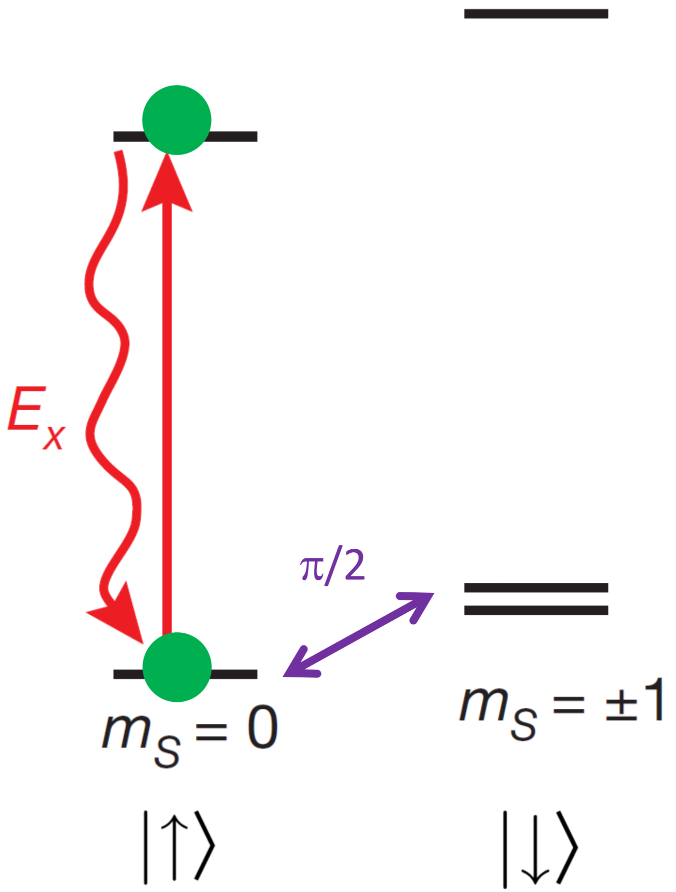
6. Mitigate decoherence - refocusing

- Coherence limited by bath of ^{13}C nuclear spins
- Dephasing time ~ few µs
- Apply dynamical decoupling sequence: two MW $\pi/2$ pulses
- Probability to end up in initial state is > 99 %

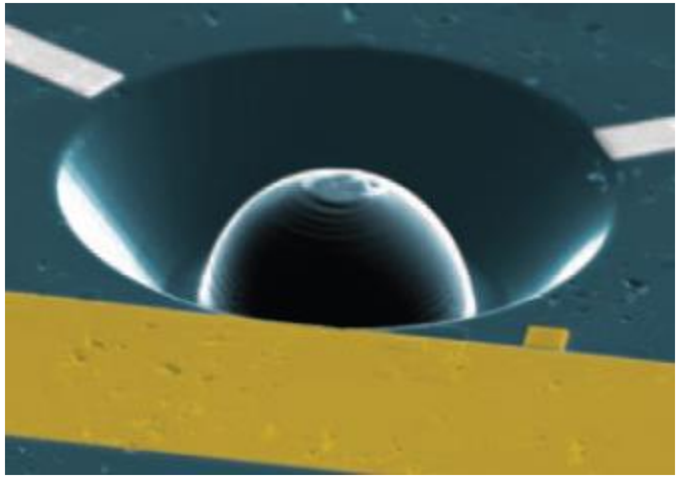


Slide material: Andreas Wallraff



7. Detection

- Photon mulitpliers
- Photon detector
- Solid immersion lens to enhance collection efficiency



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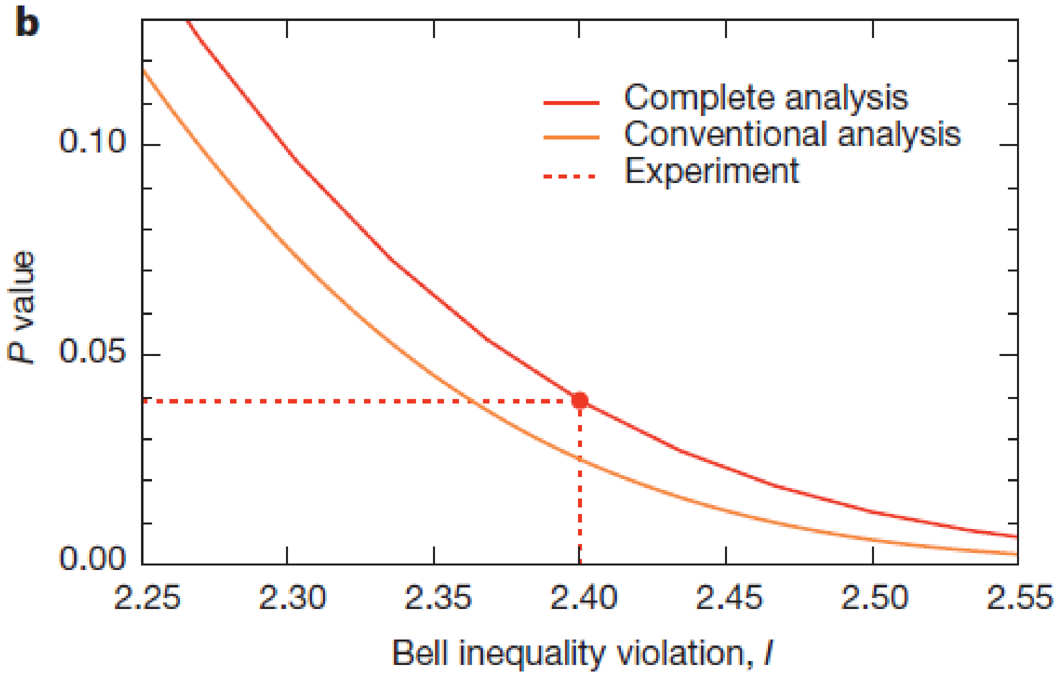
Statistical analysis of result

- Conventional analysis: no memory of devices, independent trials, absolute randomness of RNG
  → P=0.019
- Complete: arbitrary memory, partial predictability…
  → P=0.039



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