From a loophole-free Bell test to a quantum Internet

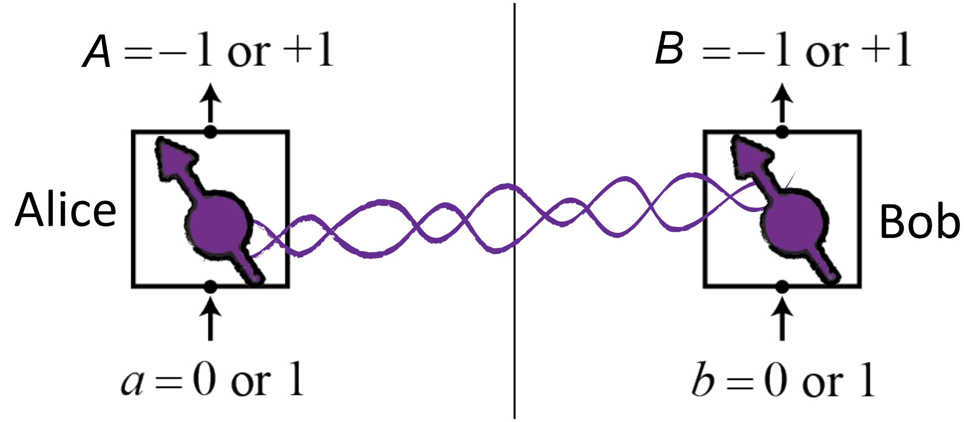
Ronald Hanson
QuTech, Delft University of Technology
http://hansonlab.tudelft.nl

Bas Hensen (PhD)
Hannes Bernien (PhD, now Harvard)
Machiel Blok (PhD, now Berkeley)
Norbert Kalb (PhD)
Julia Cramer (PhD)
Wolfgang Pfaff (PhD, now Yale)

Stefan Bogdanovic (PhD)
Suzanne van Dam (PhD)
Anais Dreau (postdoc)
Andreas Reiserer (postdoc)
Cristian Bonato (postdoc)

Joint work with:
Tim Taminiau group (Delft)
Stephanie Wehner (Delft)
David Elkouss
ElementSix (UK)
Morgan Mitchell group (ICFO)

Bell's theorem (CHSH game)



One rule:
no communication during a round!

Score: $S = |\langle A \cdot B \rangle_{00} + \langle A \cdot B \rangle_{01} + \langle A \cdot B \rangle_{10} - \langle A \cdot B \rangle_{11}|$

Local realism/causality holds
+ random inputs and final outputs

$$P(A|a,b,B,\lambda) = P(A|a,\lambda)$$
$$P(B|a,b,A,\lambda) = P(B|b,\lambda)$$

$$P(\lambda|a,b) = P(\lambda)$$

$\Rightarrow$ $S \leq 2$

Quantum mechanics holds
entangled states:

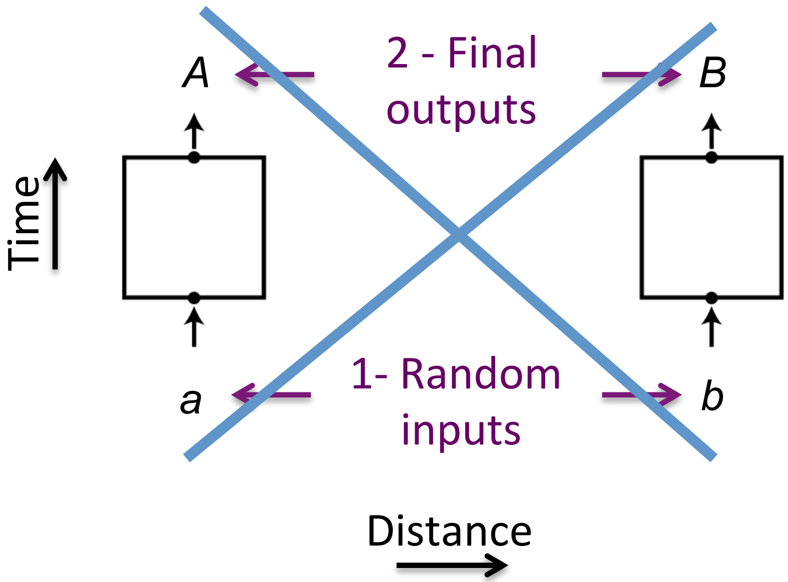
$$\left|\Psi^-\right\rangle = \frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\right\rangle - \left|\downarrow\uparrow\right\rangle\right)$$

$\Rightarrow$ $S \leq 2\sqrt{2}$

Local Realism and Quantum Mechanics are mathematically incompatible

From Bell's theorem to a Bell test: definition of "loophole free"

Testable local realistic theories:



Loophole-free Bell experiment =
test theories with
this **minimal** set of assumptions

Extra assumptions → loopholes:

For example:

1. Assume fair sampling
   (detection loophole)

2. Assume no communication
   (locality loophole)

3. Assume no memory
   (memory loophole)

Why close loopholes? Exclude:

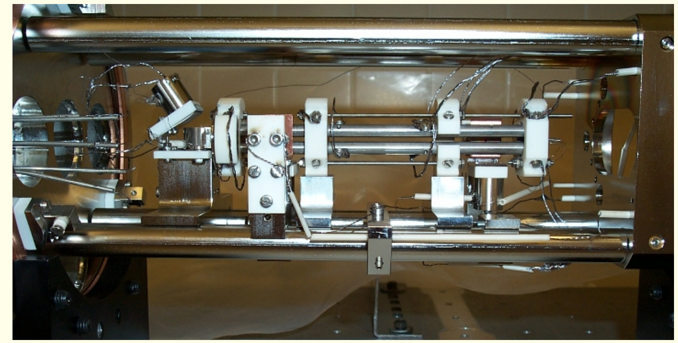
1. Local realist theories (Nature)
2. Systematic errors (Physicists)
3. Hacking (Adversaries)

Experimental Bell inequality violations

Distant photons
(assuming fair sampling)

Aspect (1982), Zeilinger (1998), Gisin (1998)

Nearby ions, superc. qubits, photons
(assuming no communication)



Wineland (2001), Monroe (2008), Martinis (2009), Weinfurter (2012), Zeilinger, Kwiat (2013)

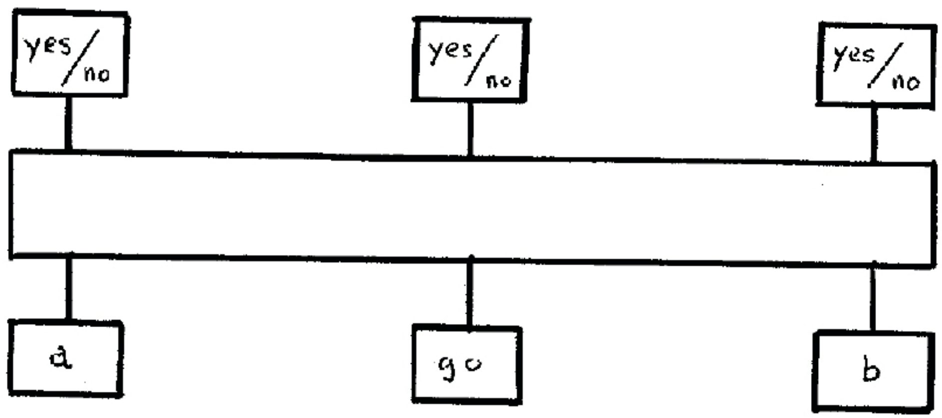
Conflicting requirements for loophole-free test:

- **Efficient state detection**
  ideally the boxes yield output values on each trial
- **Large separation**
  distance should ensure no communication occurs during a trial

For a recent review on Bell nonlocality see Brunner et al., RMP 86, 419 (2014)

Bell's own solution: an event-ready detector

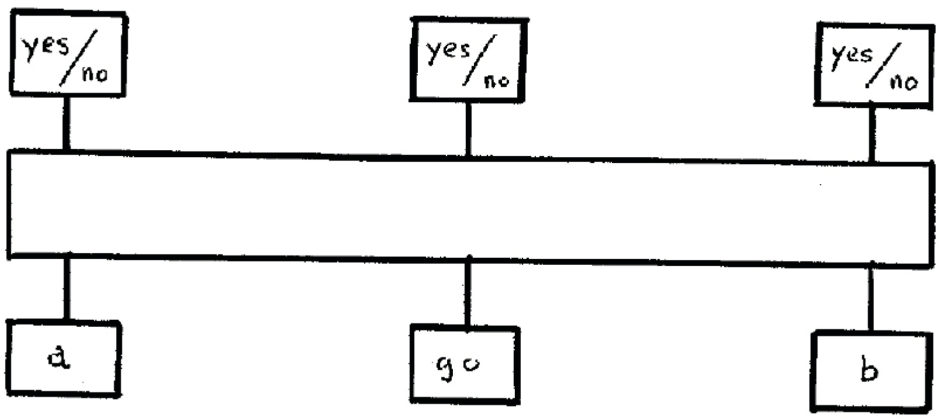
J.S. Bell, Bertlmann's socks and the nature of reality (1981)



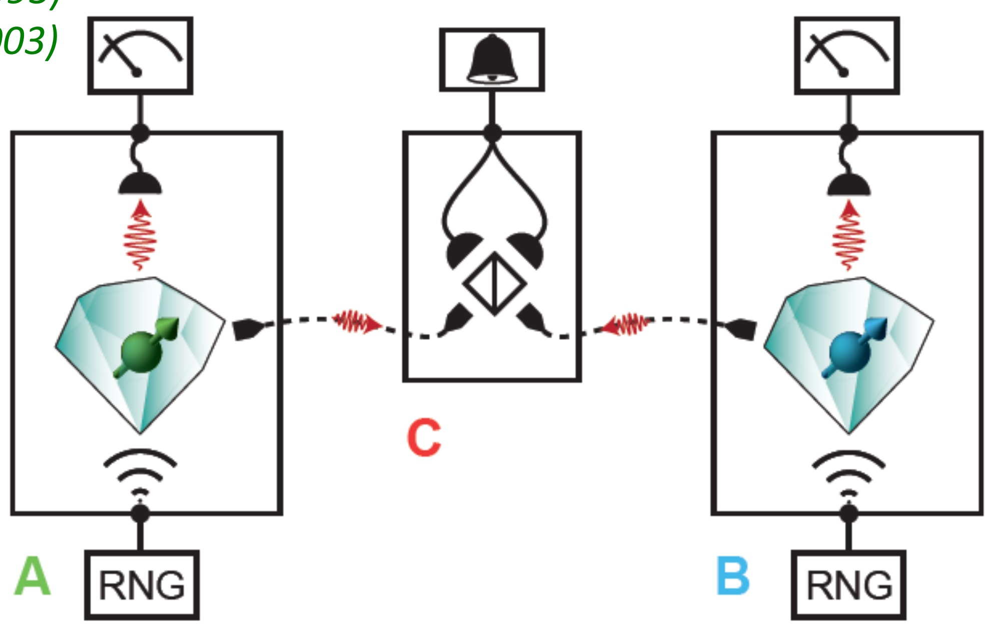
"We are only interested in the "yes"s, which confirm that everything has got off to a good start"

Bell's own solution: an event-ready detector

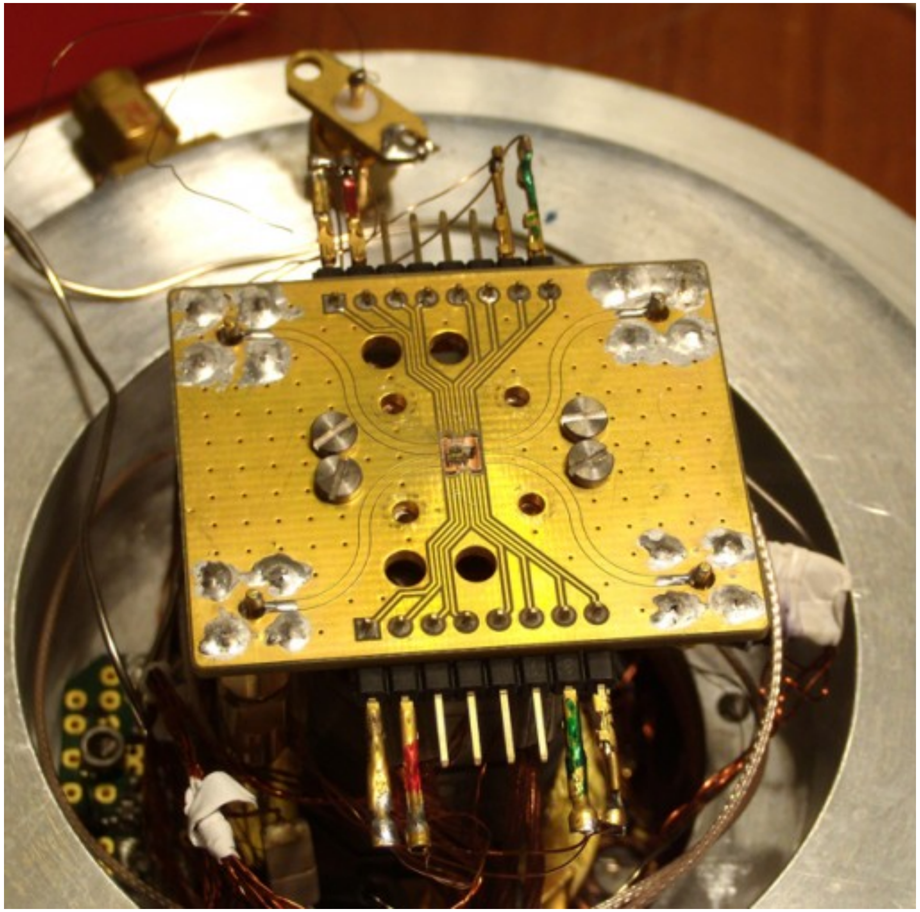
J.S. Bell, Bertlmann's socks and the nature of reality (1981)

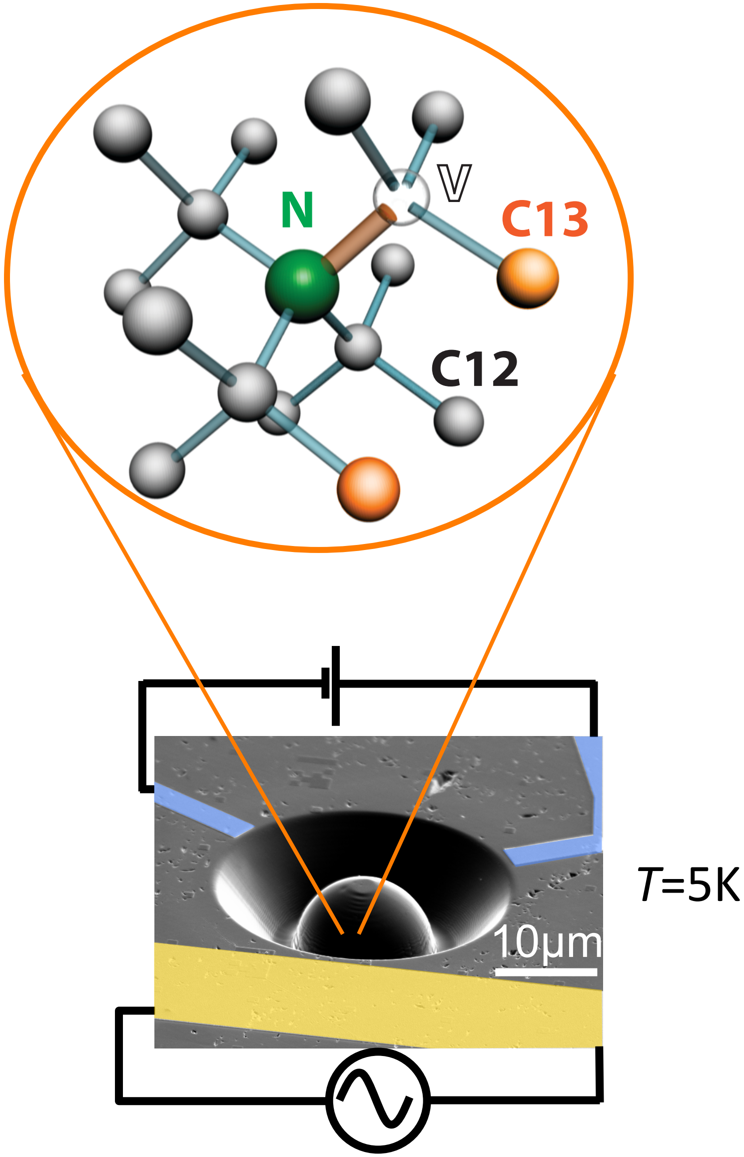


Proposals using entanglement swapping:
Zukowski et al., PRL (1993)
Simon & Irvine, PRL (2003)



NV centers in diamond: the toolbox

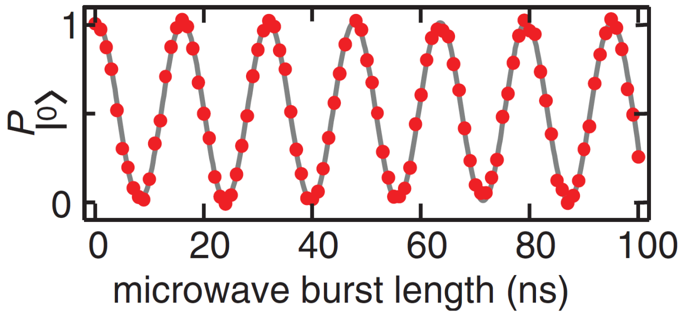




Pioneering work by Stuttgart, Harvard, Chicago, Ulm,…

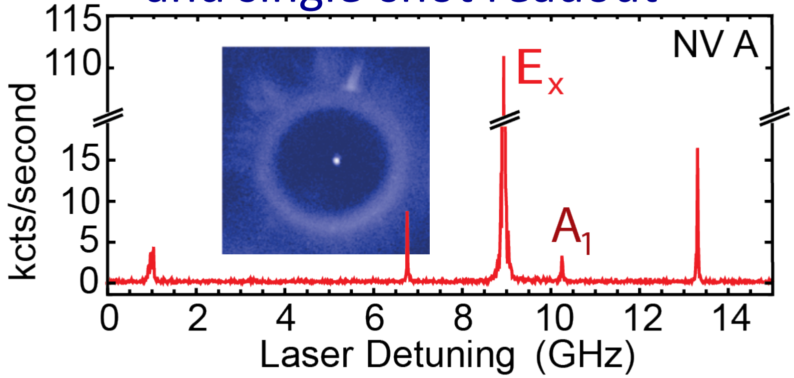
NV centers in diamond: our toolbox

High-fidelity electron spin control

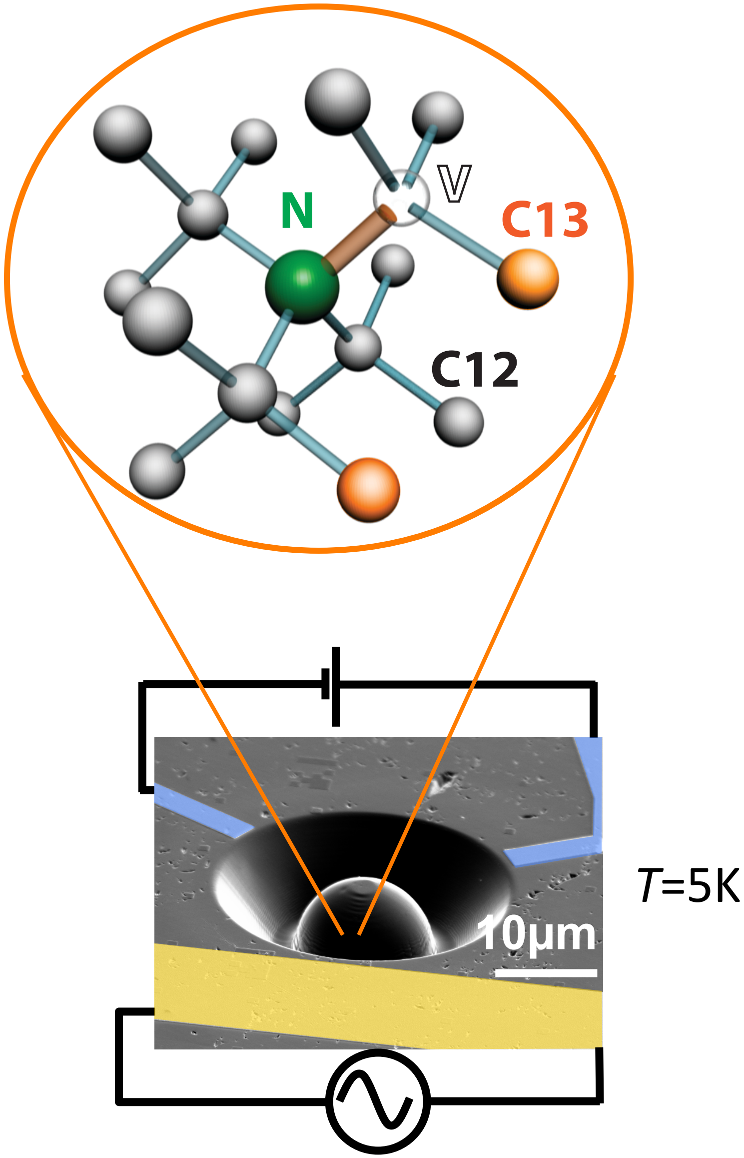


Science 330, 60 (2010)

High-fidelity spin initialization and single-shot readout

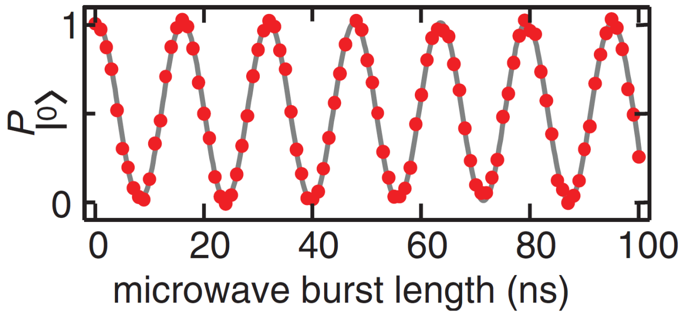


Nature 477, 574 (2011)



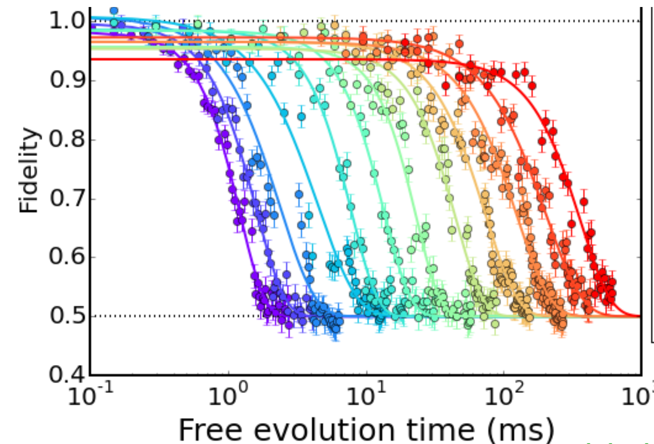
NV centers in diamond: our toolbox

High-fidelity electron spin control



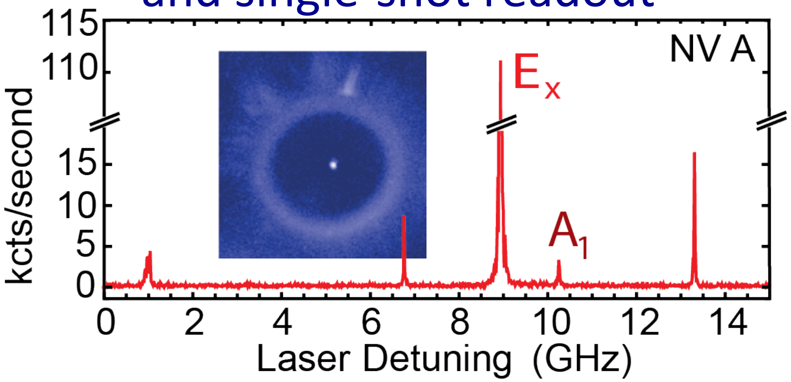
Science 330, 60 (2010)

Spin coherence ≈ a second



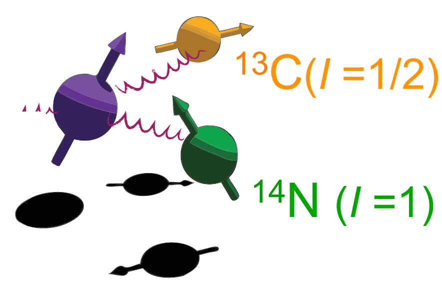
unpublished

High-fidelity spin initialization and single-shot readout



Nature 477, 574 (2011)

Nuclear spin control & readout



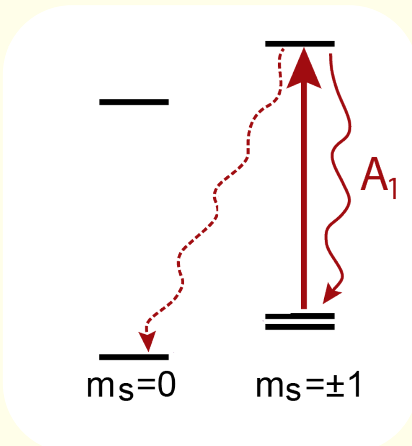
Nature Physics 9, 29 (2013)
Nature Nano. 9, 171-176 (2014)

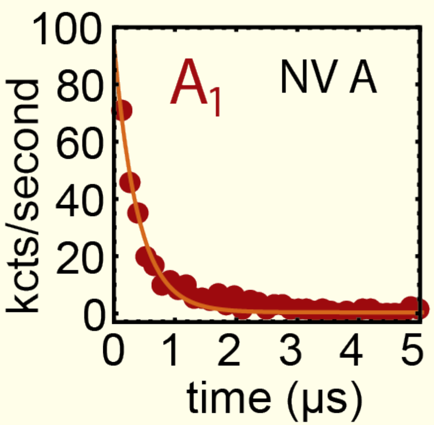
Many related works by Stuttgart, Chicago, Harvard, HP, …

Initialization and readout by resonant excitation

Nature 477, 574 (2011)

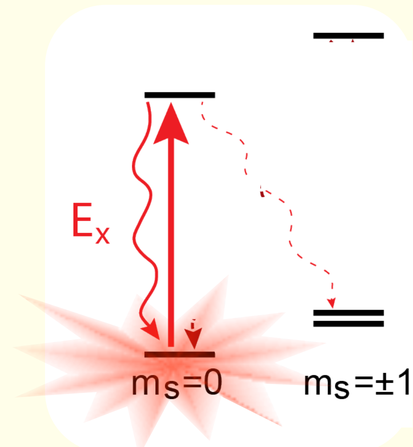
Initialization



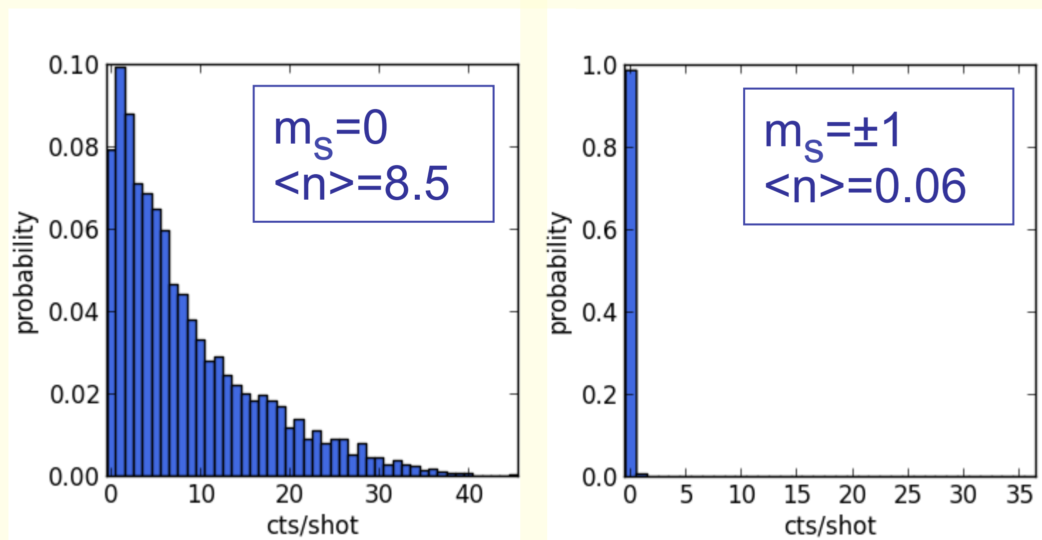


fidelity > 99.5%

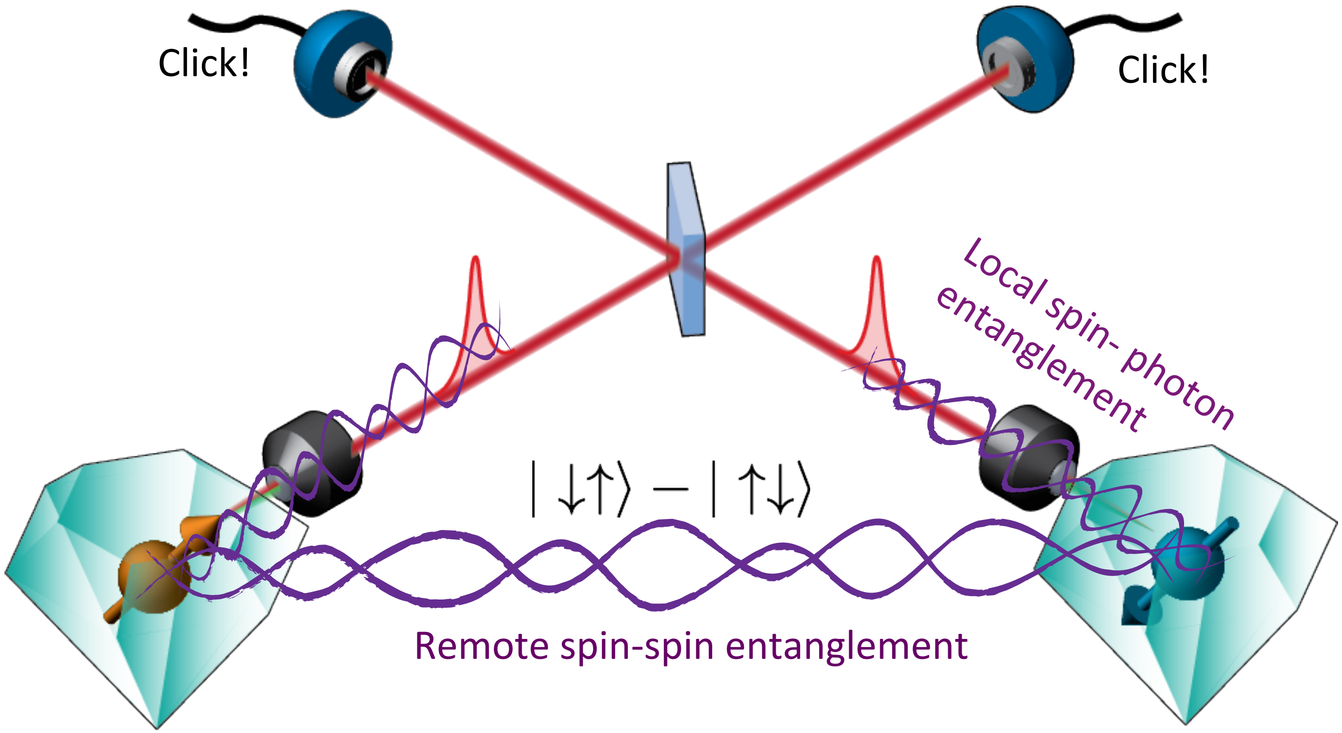
Single-Shot Readout



best fidelity so far ≈ 98%



Creating entanglement between distant electrons



We use **entanglement swapping** to realize an **event-ready** scheme

Bell test proposals using entanglement swapping:
Zukowski et al., PRL (1993)
Simon & Irvine, PRL (2003)
Our entanglement scheme: Barrett and Kok, PRA 2005

Experiments with other systems:
Monroe group, Nature 2007 (ions)
Weinfurter group, Science 2012 (atoms)
Rempe group, Nature 2012 (atoms)
Imamoglu group, Nat. Phys. 2015 (QDs)

Heralded remote entanglement

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

State fidelity

$F\,(\Psi^{-}) \approx 73\ \%$

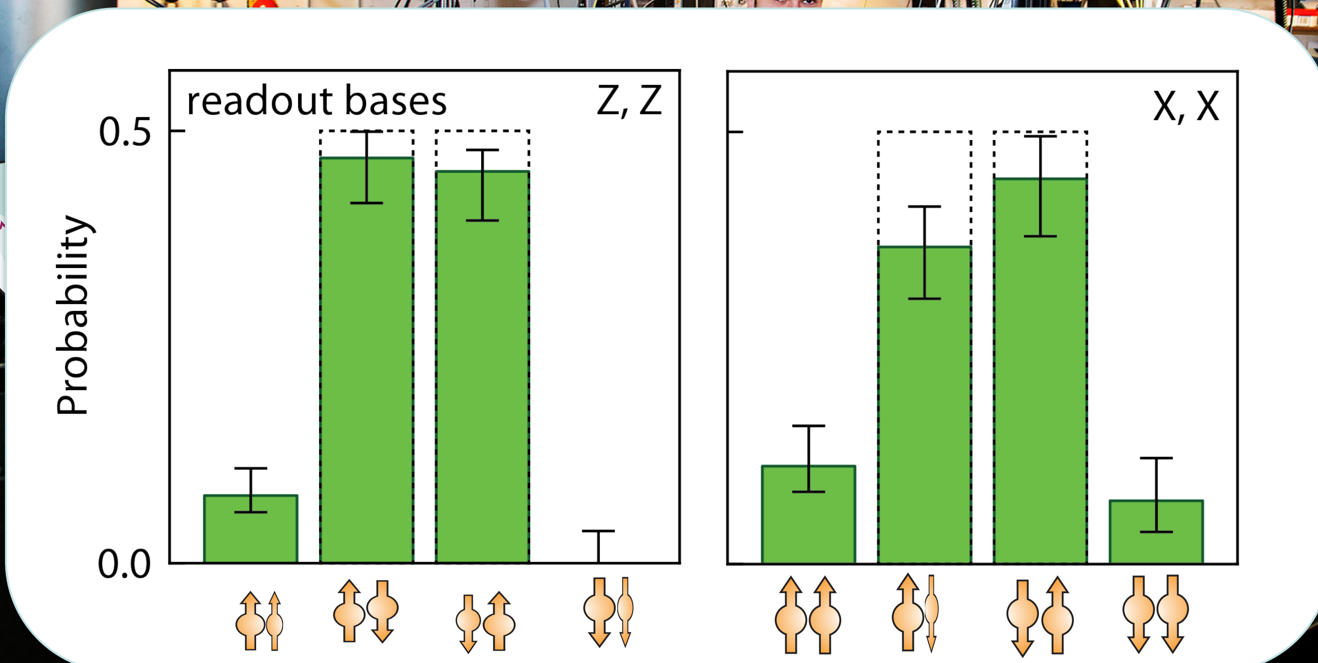
$F\,(\Psi^{-}) \approx 87\ \%$

Success probability

$\approx 10^{-7}$; one event per 10 minutes

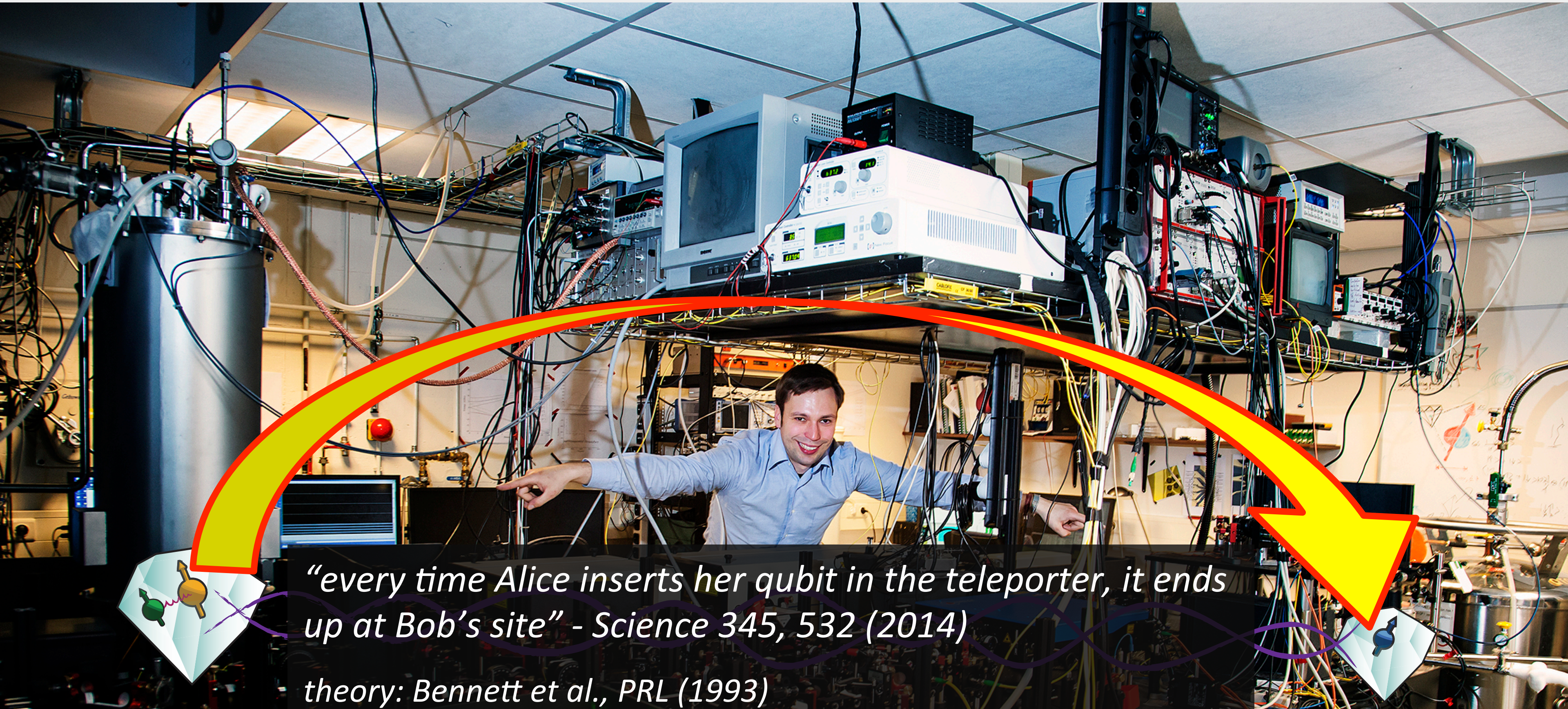
$\approx 3{*}10^{-7}$; one event per 100 seconds

scale bar



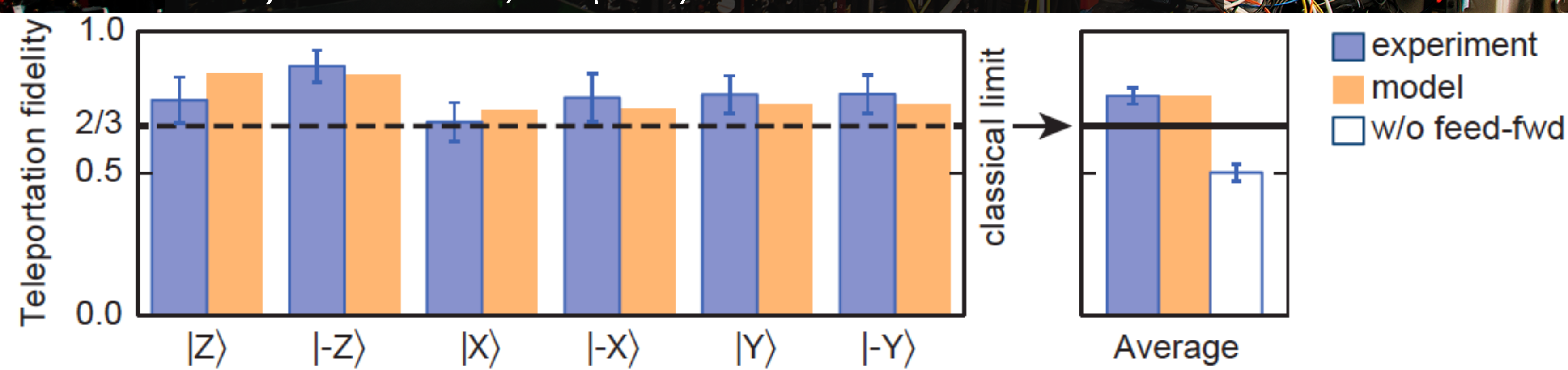
Nature 497, 86 (2013)

Unconditional remote qubit teleportation

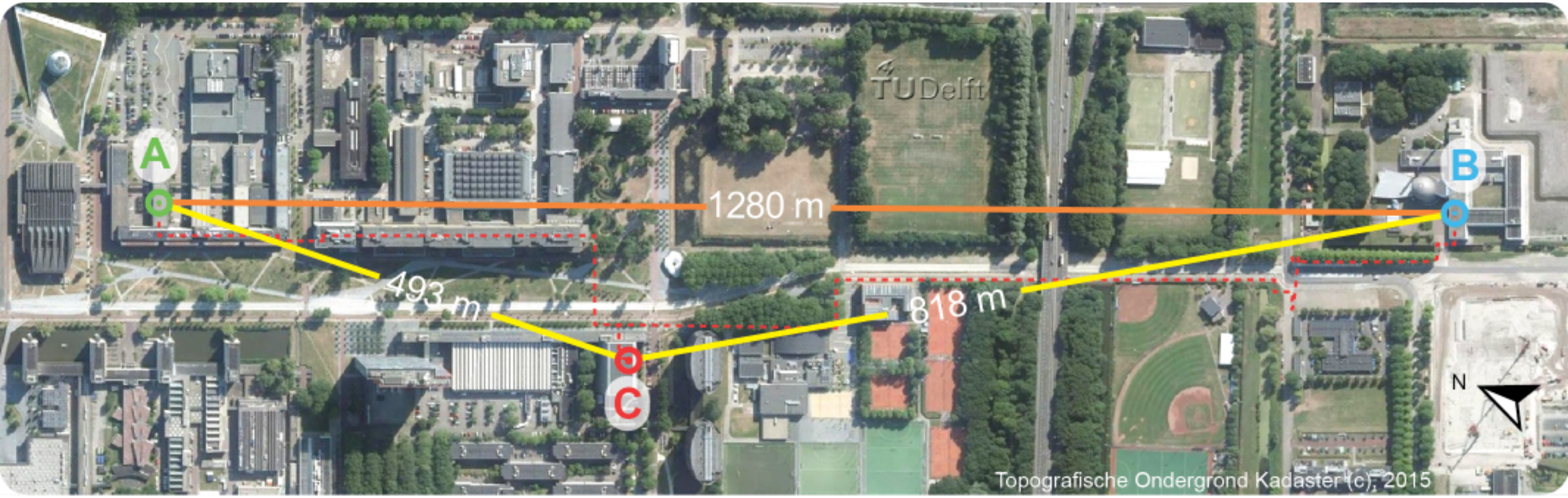


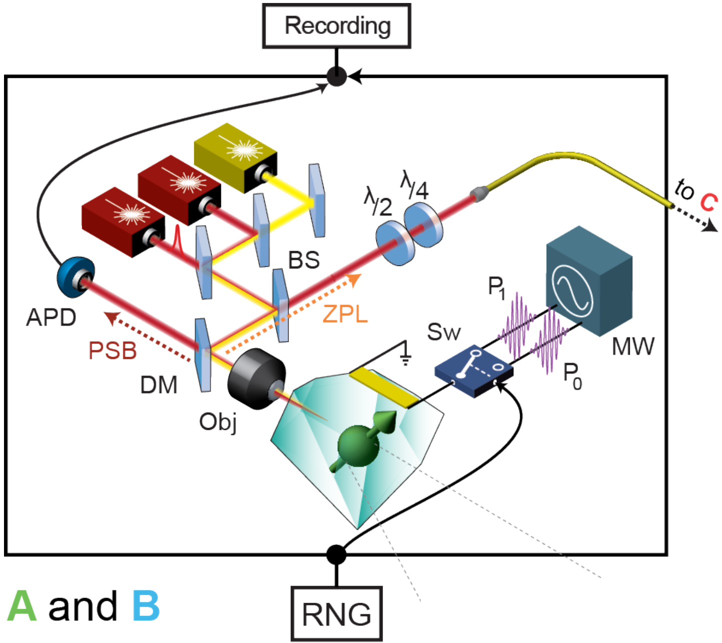
"every time Alice inserts her qubit in the teleporter, it ends up at Bob's site" - Science 345, 532 (2014)

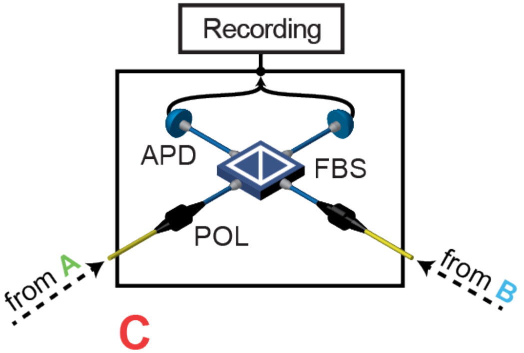
theory: Bennett et al., PRL (1993)



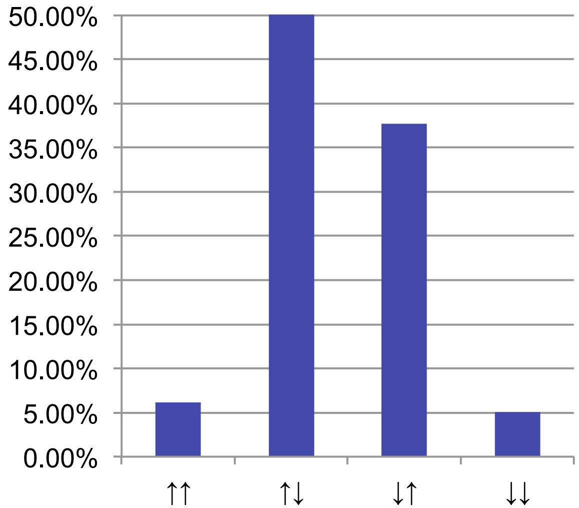
Fall 2014: loophole-free Bell setup ready



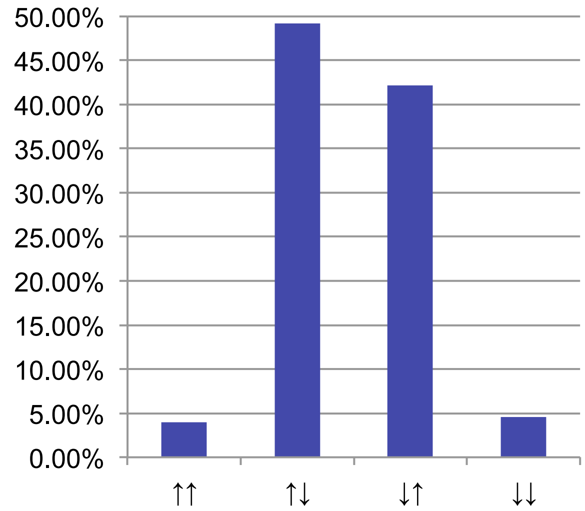




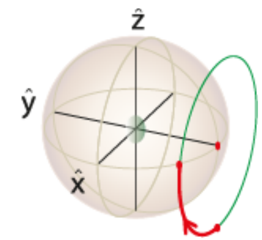
December 2014: entanglement over 1.3km!



Z-basis correlations
60 events



X-basis correlations
52 events

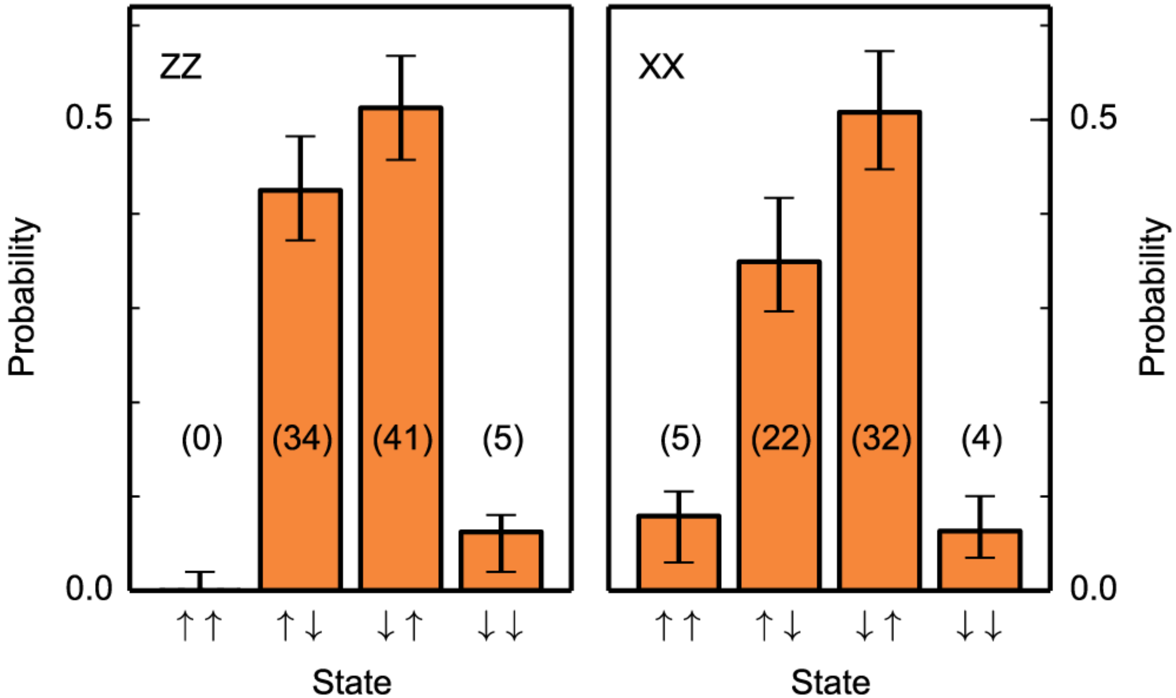


Estimated state fidelity = (84±6)% =>

ENTANGLEMENT!!!

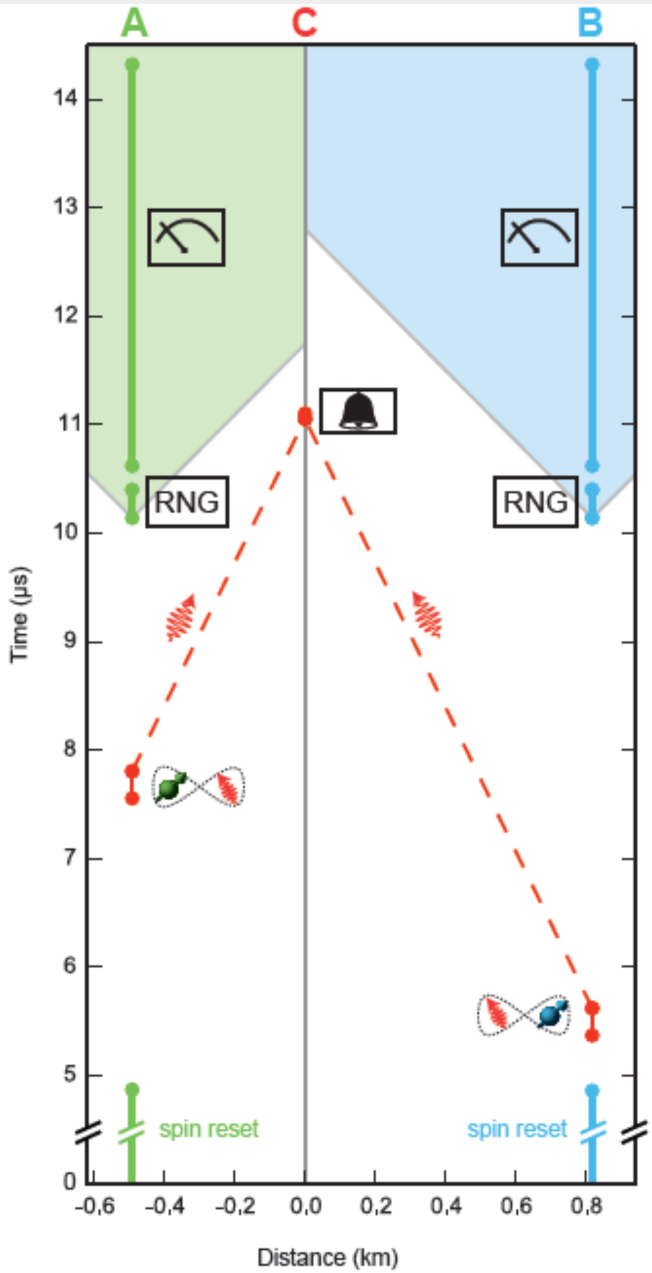
May 2015: correlation measurements on new Alice/Bob

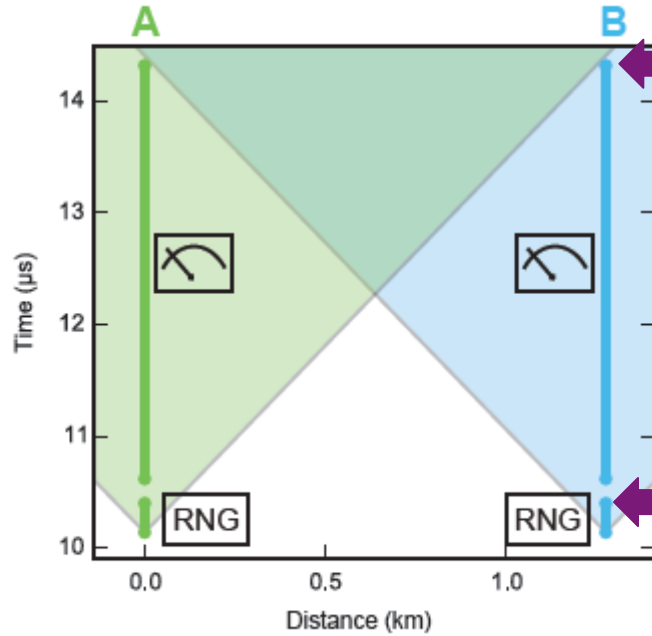
$$\left|\Psi^-\right\rangle = \frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\right\rangle - \left|\downarrow\uparrow\right\rangle\right)$$



- state fidelity > (83±5)% (strict lower bound): proves entanglement
- our best estimate for state fidelity = 92%
- using this data we fixed parameters for Bell test

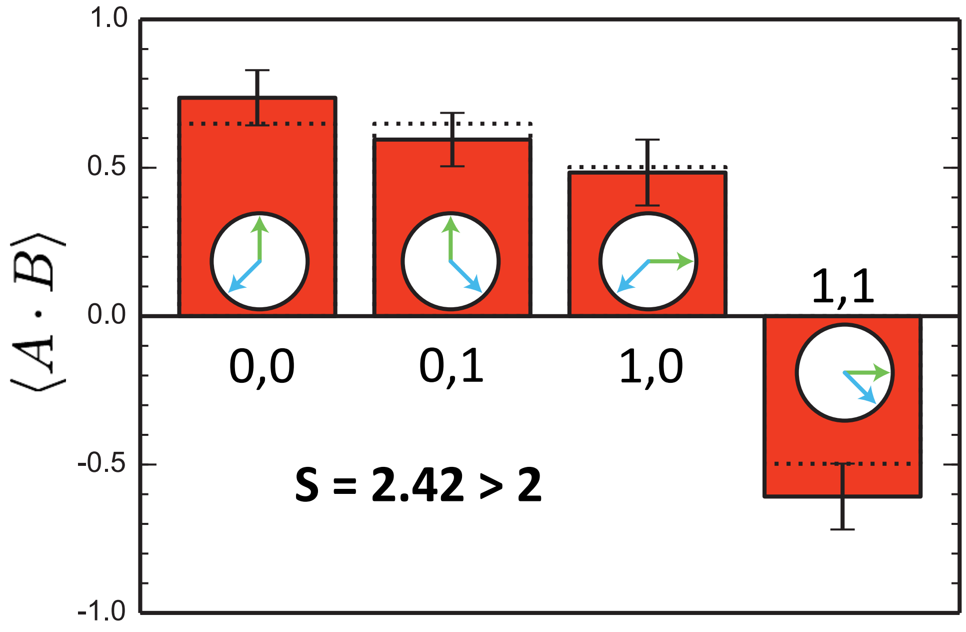
Experimental scheme





- Event-ready signal space-like separated from RNG
- A and B space-like separated during the trial (i.e. from RNG up to output recording)
- Additional timing buffer of 230ns

June/July 2015: first loophole-free Bell test



Null hypothesis test:
p-value = 0.039

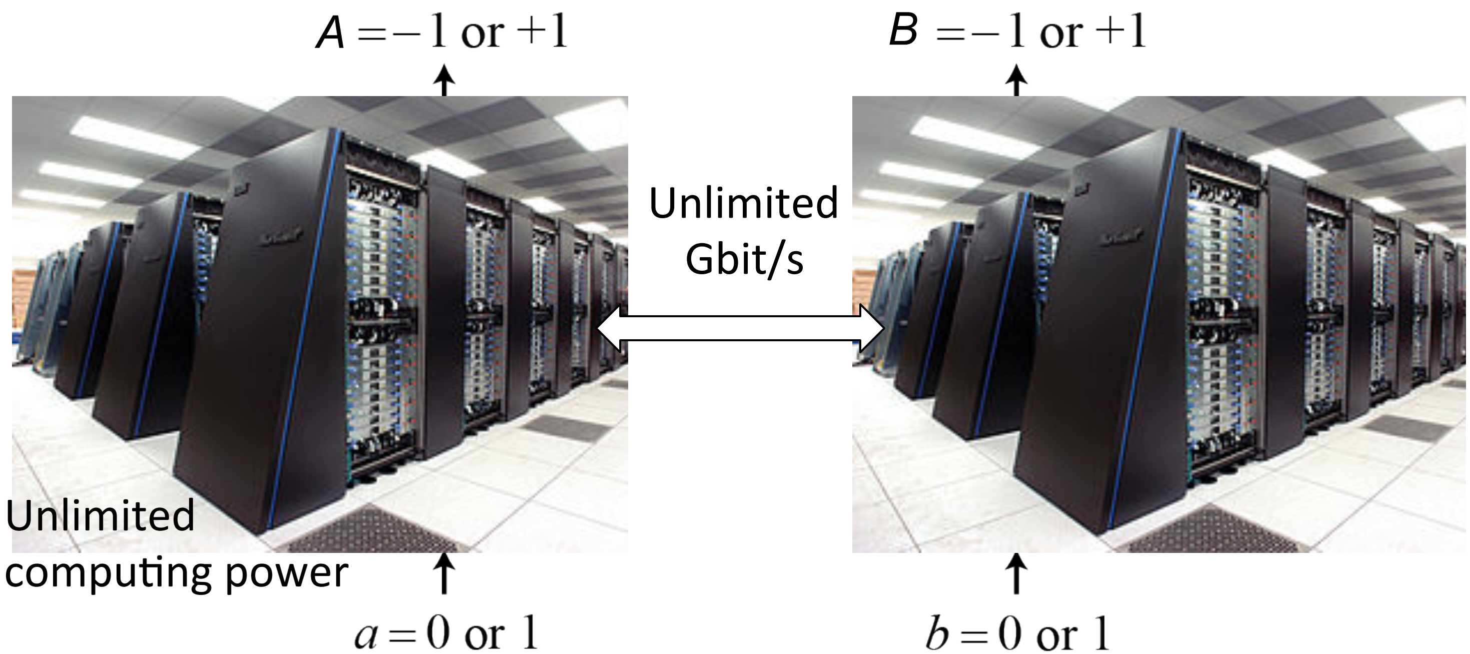
the probability that the observed data or more extreme could result under the assumption that the experiment is ruled by a local realist model.

Hensen et al., arXiv:1508.05949 (August 2015)
Nature 526, 682 (2015)

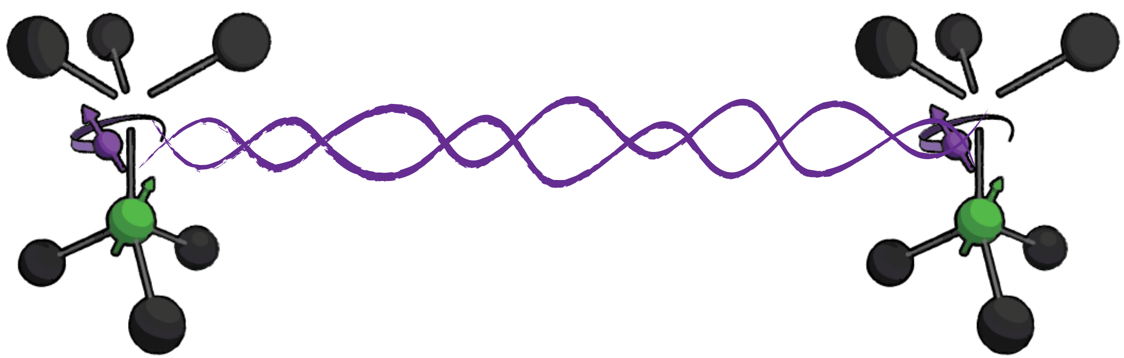
Science Top 10 Breakthroughs of the Year

nature One of the “10 science events that shaped 2015”

Demonstration of quantum superiority



$$\Rightarrow \quad S \leq 2$$



$$\Rightarrow \quad S = 2.42$$

Results corroborated by 4 more recent Bell tests

PRL **115,** 250401 (2015) PHYSICAL REVIEW LETTERS week ending 18 DECEMBER 2015

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,†]

arXiv:1511.03190 (Nov 2015); PRL 115, 250401

PRL **115,** 250402 (2015) PHYSICAL REVIEW LETTERS week ending 18 DECEMBER 2015

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,‡]

arXiv:1511.03189 (Nov 2015); PRL 115, 250402

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second Bell test @Delft (december 2015)
$S \approx 2.35$ on 300 trials, in agreement with our first result

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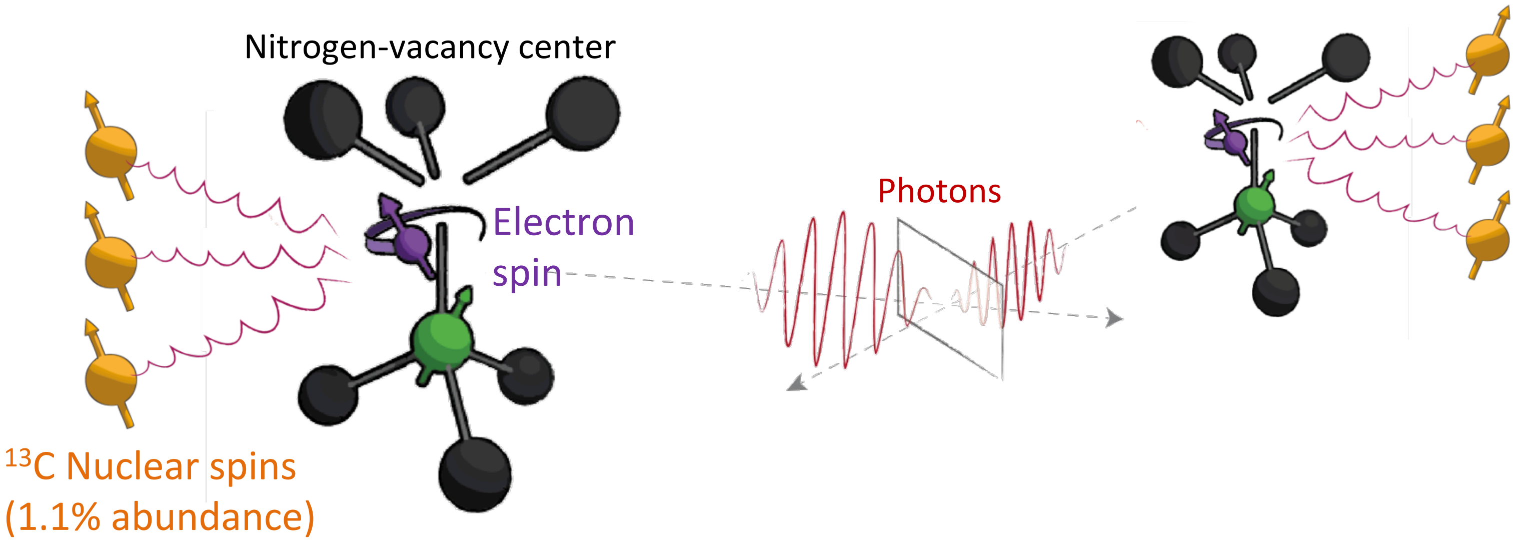
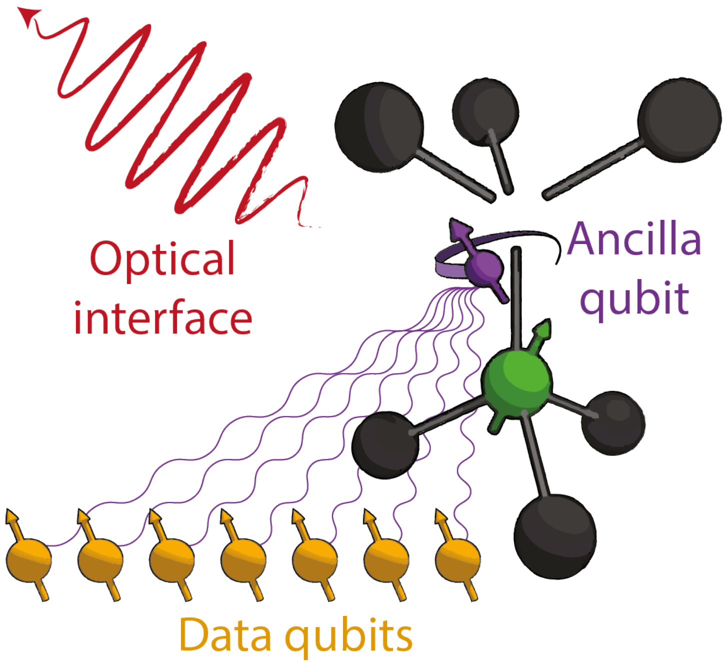
Weinfurter group @Munich (december 2015)
"Showing violations but setup not yet fully stable" – Harald Weinfurter

Towards quantum networks



Quantum network node

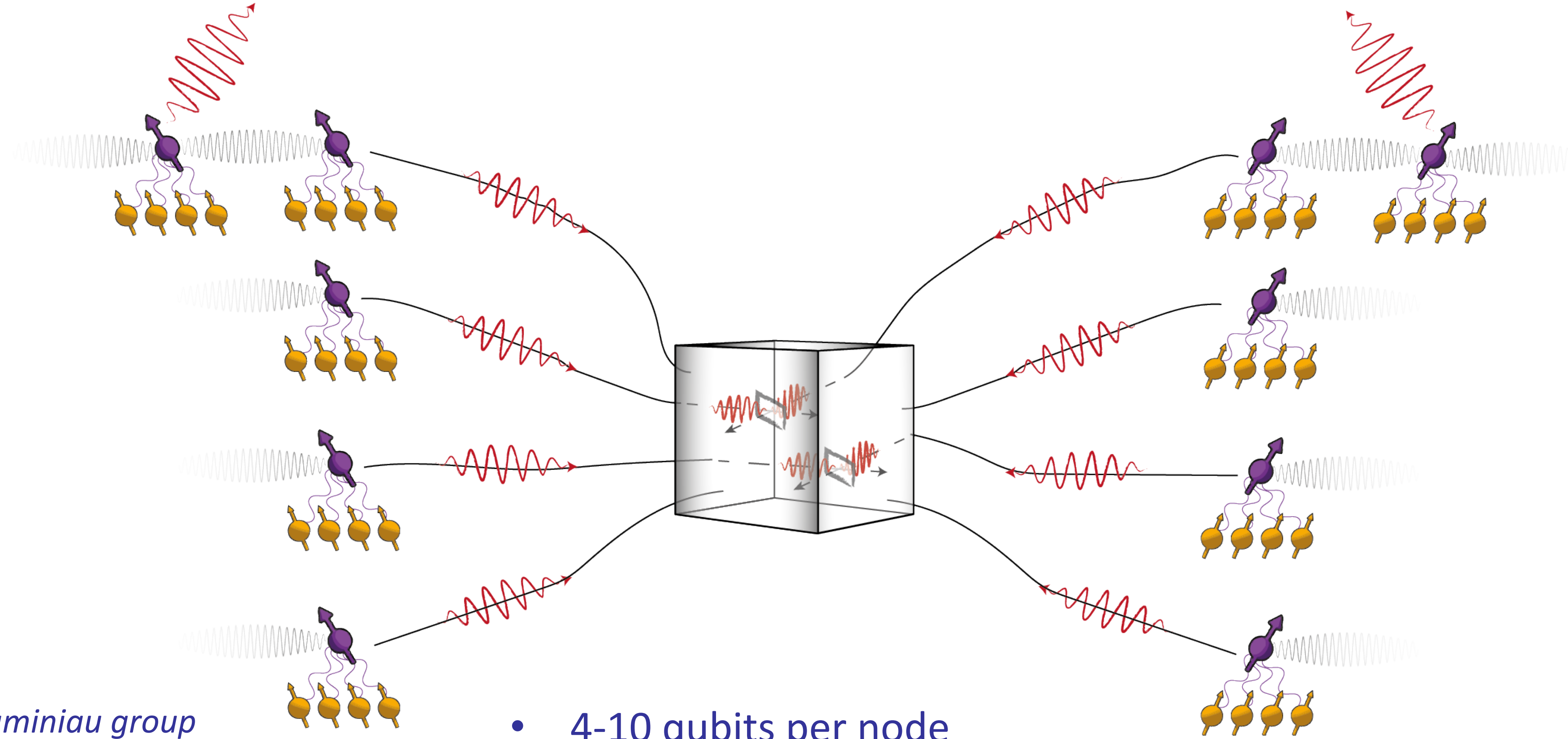


Optical interface

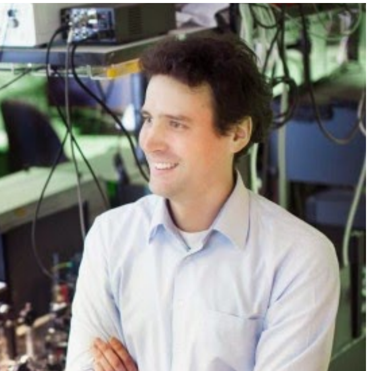
Ancilla qubits

Data qubits

Goal 1: modular quantum computing architecture



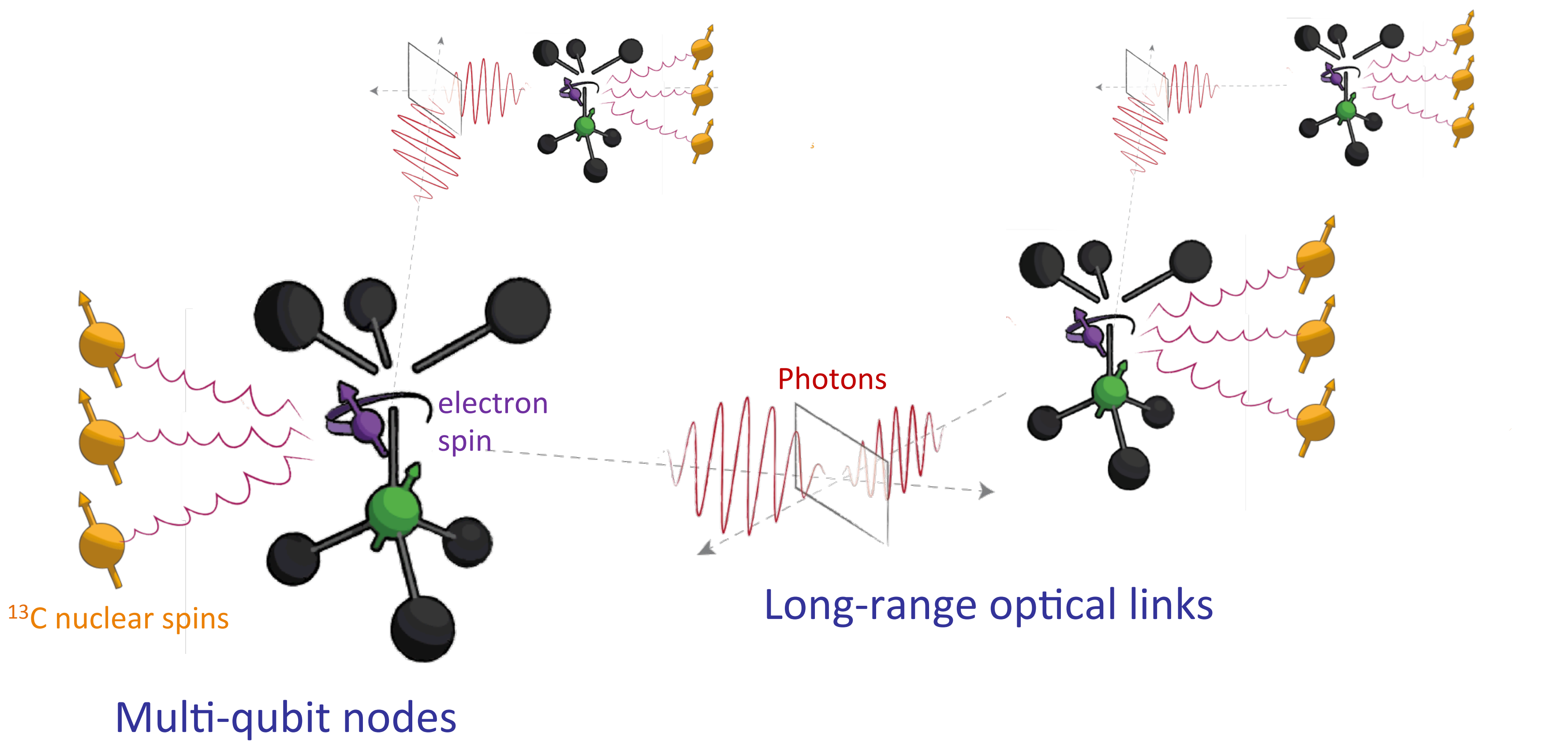
Taminiau group



- 4-10 qubits per node
- Modular optical connections

Similar to ion trap quantum computing architectures, pursued by e.g. Monroe/Kim groups, Lucas group

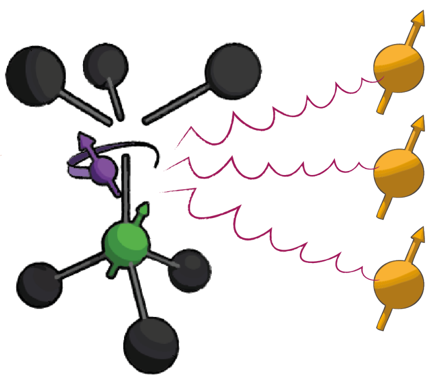
Goal 2: long-range quantum networks



- Fundamental tests
- Quantum Internet (for e.g device-independent crypto)

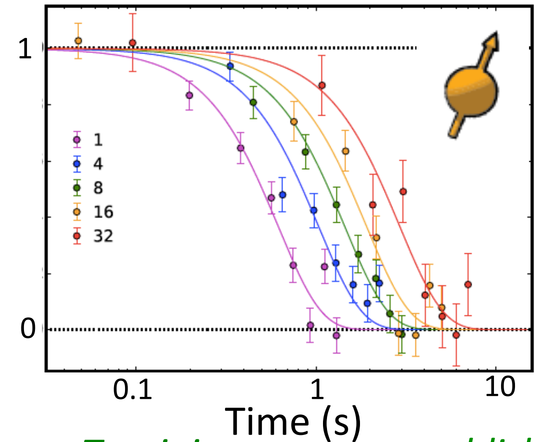
Recent Delft results on quantum network nodes

Each NV is a 5+ qubit register



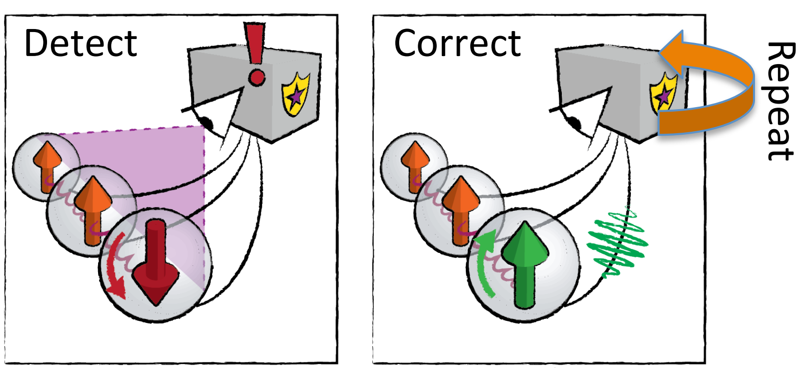
Nature Nanotech. 9, 171 (2014)

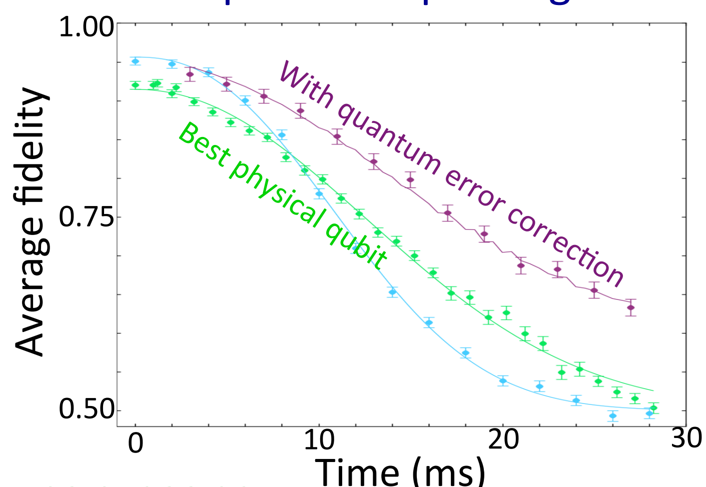
Nuclear spin coherence > 3 seconds



Taminiau group, unpublished

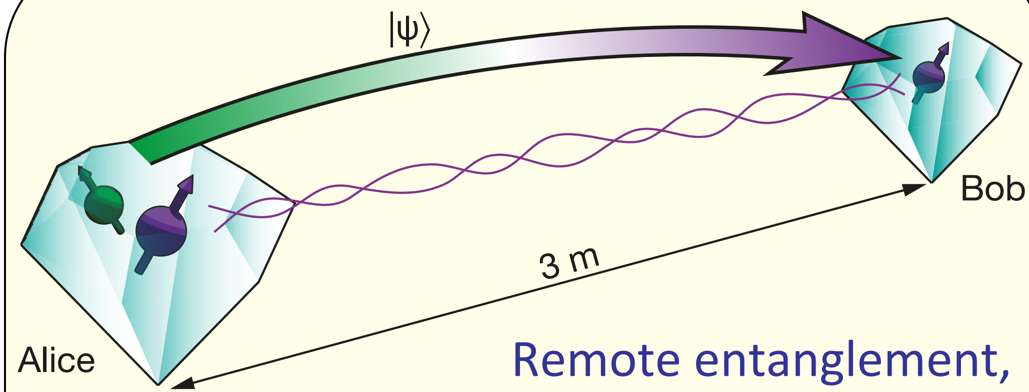
Active quantum error correction: logical qubit with improved dephasing times





Taminiau group, arXiv:1508.01388 2015

Summary & outlook: towards quantum networks



Remote entanglement, teleportation & loophole-free Bell test

Nature 497, 86 (2013); Science 345, 532 (2014); Nature 526, 682 (2015)

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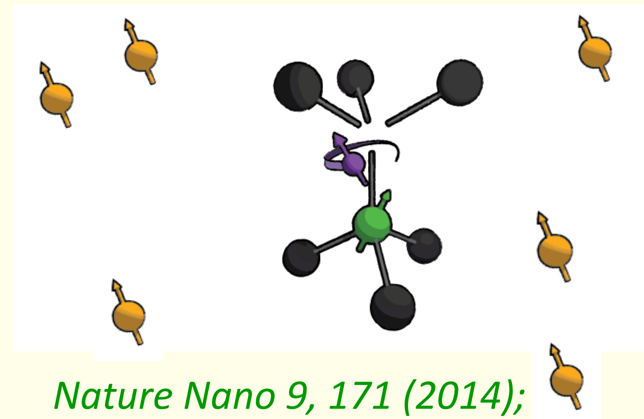
Control and readout of nuclear spin qubit registers



Nature Nano 9, 171 (2014); arXiv:1508.01388 (2015)

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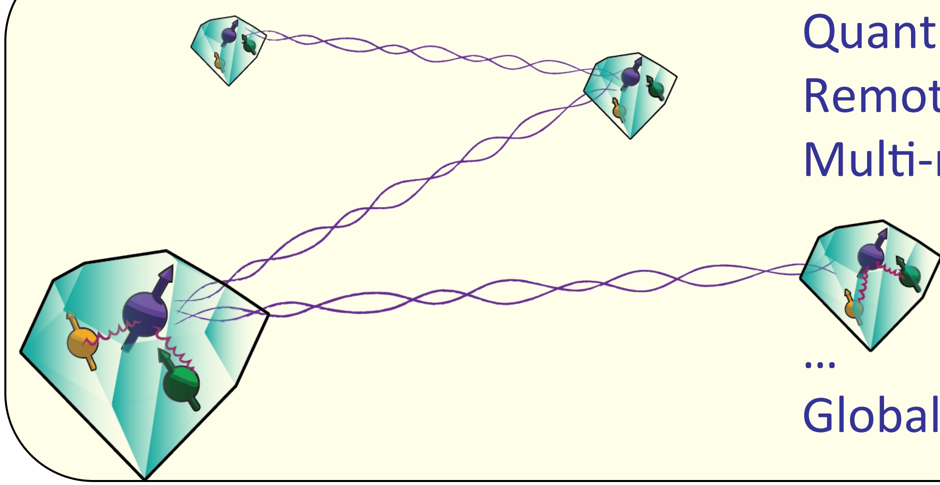

Quantum repeater
Remote entanglement purification
Multi-node quantum network
…
Global quantum Internet

Thank you!

QuTech FOM NWO STW Enabling new technology erc