From a loophole-free Bell test to a quantum Internet

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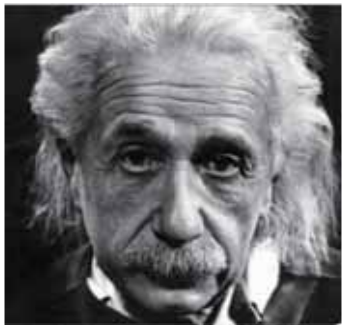
Bell's theorem



EPR 1935:

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

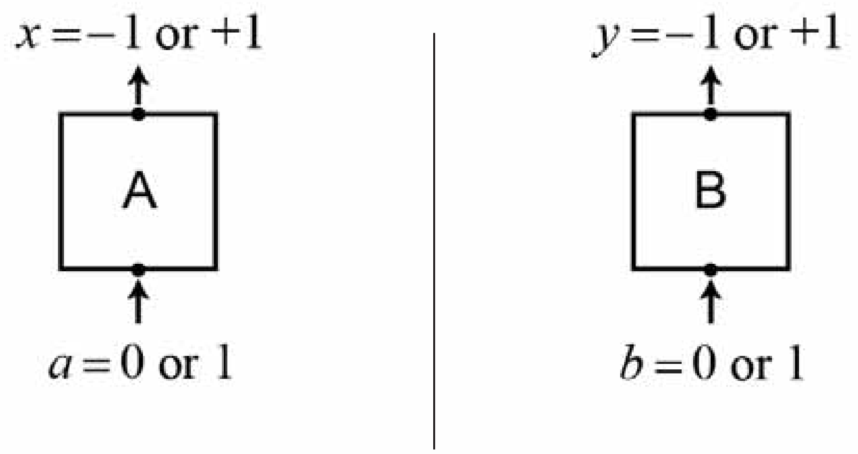
Under local realism: entangled states violate Heisenberg uncertainty =>
"Quantum mechanics is incomplete"

Bell 1964 (1976):

1. Correlations between distant measurement outcomes under (local causality) are bounded
2. Quantum entangled states can violate this bound

Experimentally testable!

Bell's theorem



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

Assumptions:

1. **local causality** holds
2. Input bits *a,b* can be freely chosen
3. fixed outputs *x, y* exist (realism)

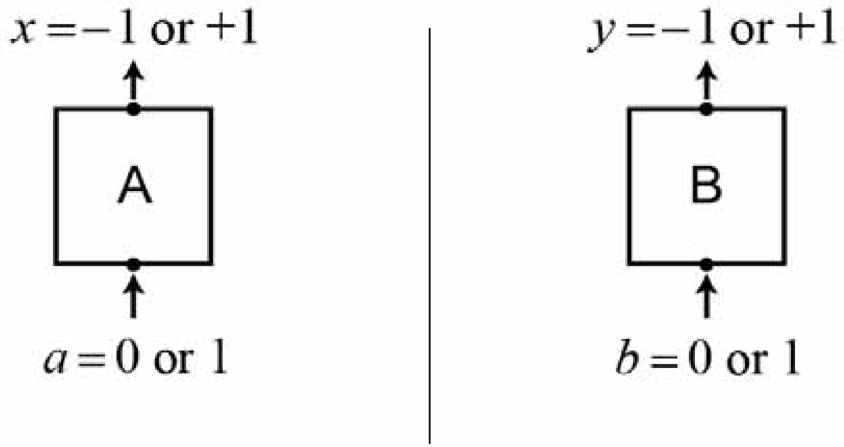
$$P(x|a,b,y,\lambda) = P(x|a,\lambda)$$
$$P(y|a,b,x,\lambda) = P(y|b,\lambda)$$
$$P(\lambda|a,b) = P(\lambda)$$

⇒ $S \leq 2$

1'. **Quantum theory** holds

⇒ $S \leq 2\sqrt{2}$

From Bell's theorem to a Bell test



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

Assumptions:

1. **local causality** holds
2. Input bits *a,b* can be freely chosen
3. fixed outputs *x, y* exist (realism)

⇒ $S \leq 2$

4'. To be falsifiable, a theory should predict *when* the free input bits are created and *when* the output bits are final.

From Bell's theorem to a Bell test

Loophole-free Bell test =
experiment that can test theories with the minimal set of assumptions below

(i.e. without adding assumptions!)

Assumptions:
1. **local causality** holds
2. Input bits *a,b* can be freely chosen
3. fixed outputs *x, y* exist (realism)

$$\Longrightarrow S \leq 2$$

4'. To be falsifiable, a theory should predict *when* the free input bits are created and *when* the output bits are final.

Device-independent security protocols

Device-independent QKD, randomness generation:
use loophole-free Bell test to guarantee security

"black-box approach": No assumption about the devices!

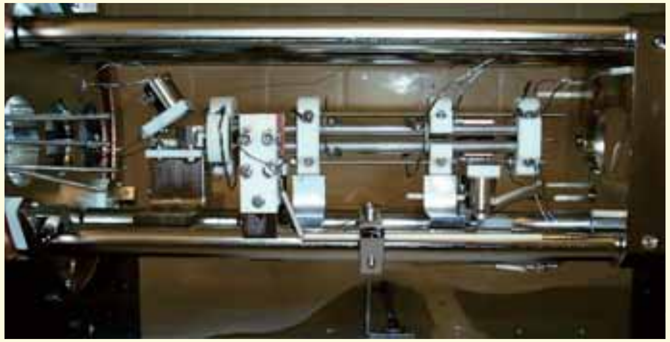
Acin, A. et al. PRL 98, 230501 (2007)
Colbeck, R. PhD thesis (2007), arxiv. 0911.3814
Pironio, S. et al. Nature 464, 1021 (2010)
For a recent review on Bell & privacy see Renner & Ekert, Nature 507, 443 (2014)

Experimental Bell inequality violations

Distant photons
(assuming fair sampling)

Freedman & Clauser (1972), 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:

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

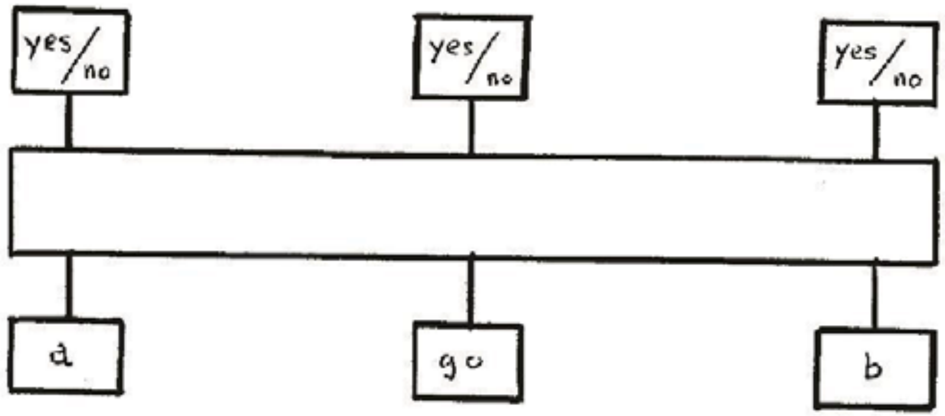
Delft, Vienna, NIST

No One ...

Nature 526, 682; ArXiv 1511.03190; ArXiv 1511.03189

Bell's own solution: an event-ready detector

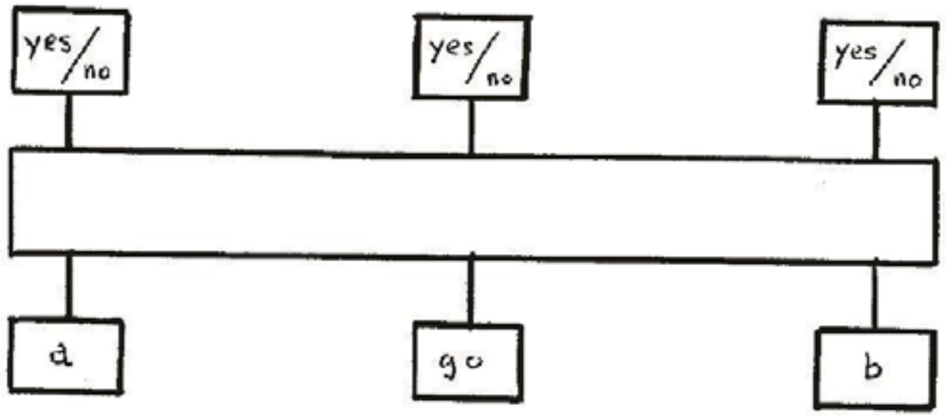
J.S. Bell, Bertlmann's socks and the nature of reality (1981)

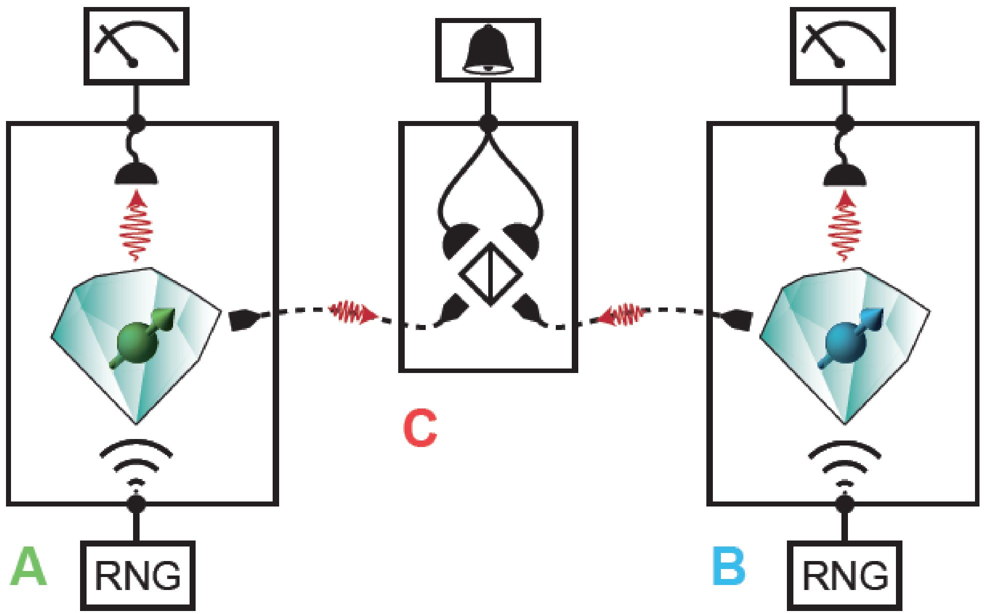


"We are only interested in the "yes"s, which confirm that everything has got off to a good start"

Bell's own solution: an event-ready detector

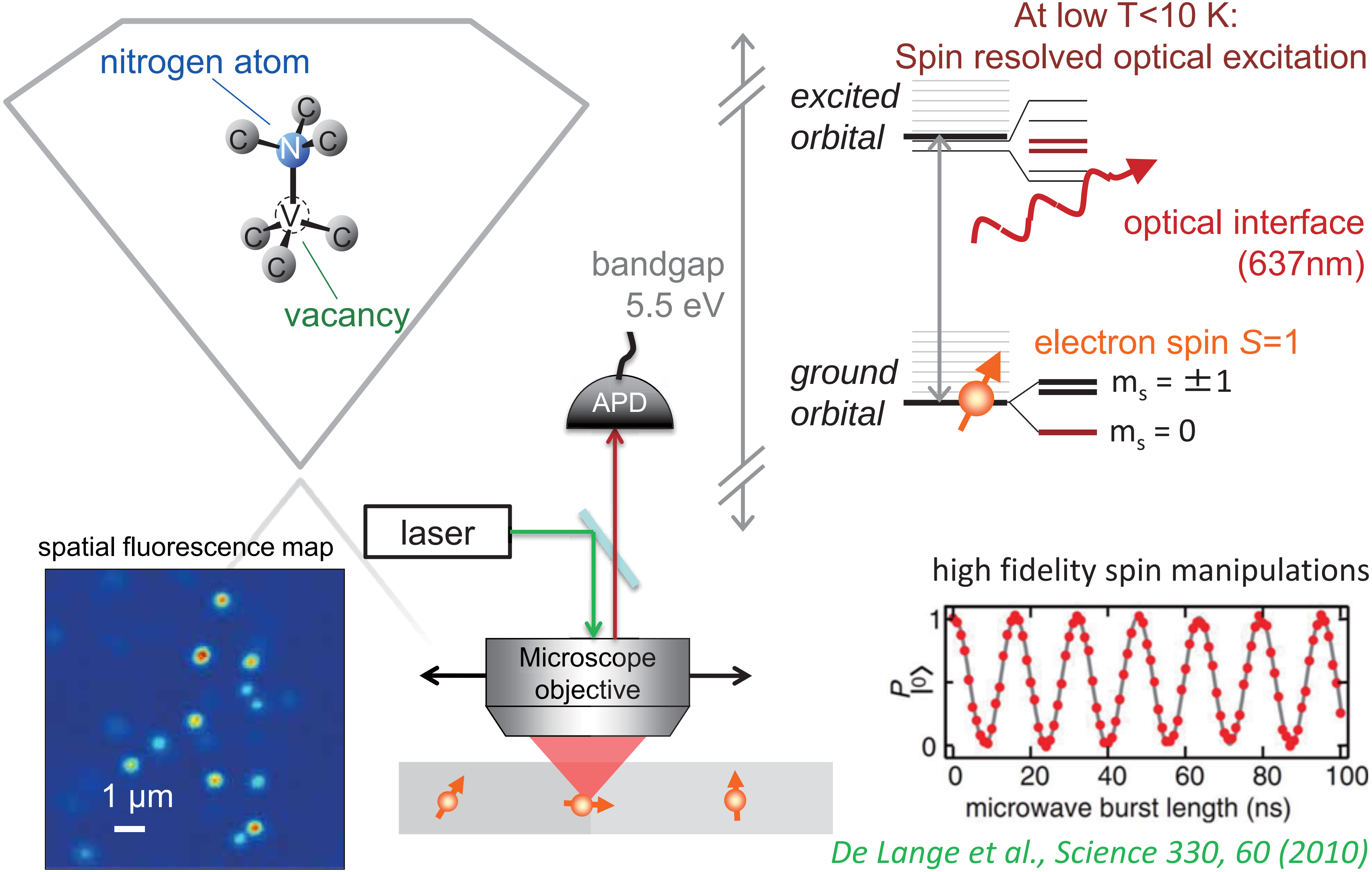
J.S. Bell, Bertlmann's socks and the nature of reality (1981)





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

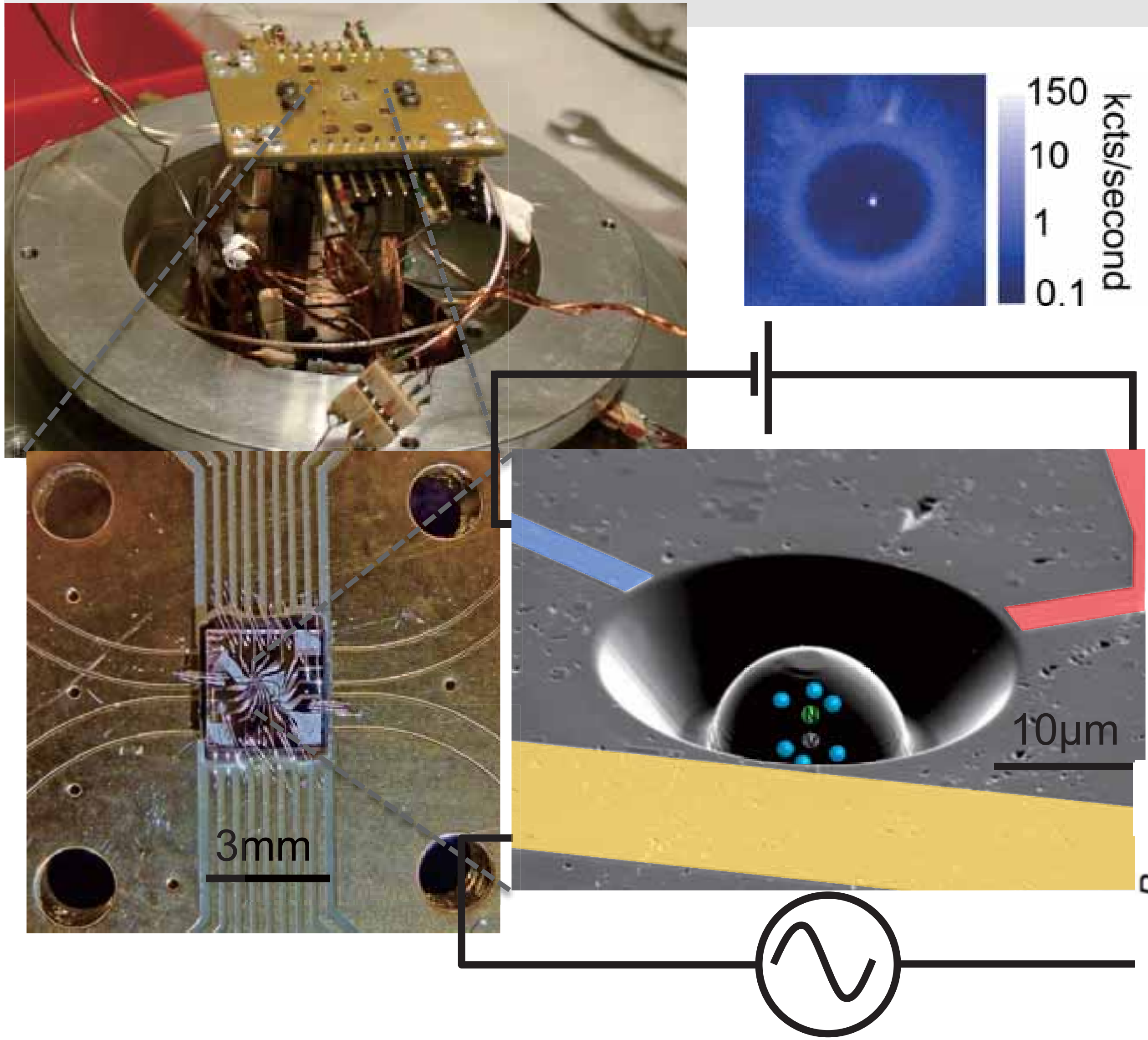
Nitrogen-Vacancy center: "Natures own trapped ion"



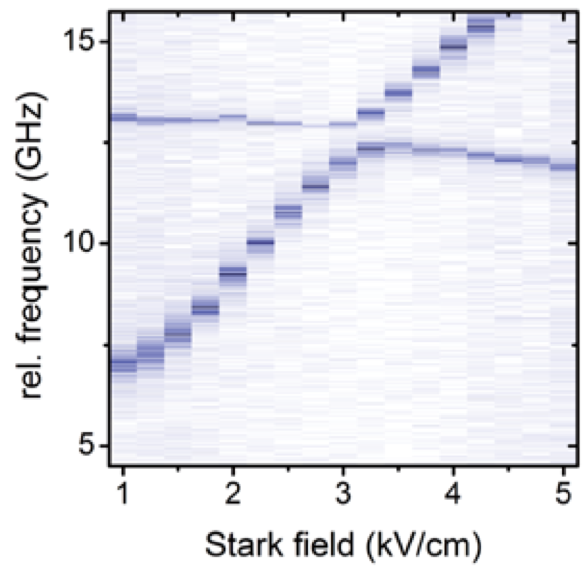
De Lange et al., Science 330, 60 (2010)

see e.g. Awschalom, Epstein & Hanson, Scientific American 297, 84 (2007)

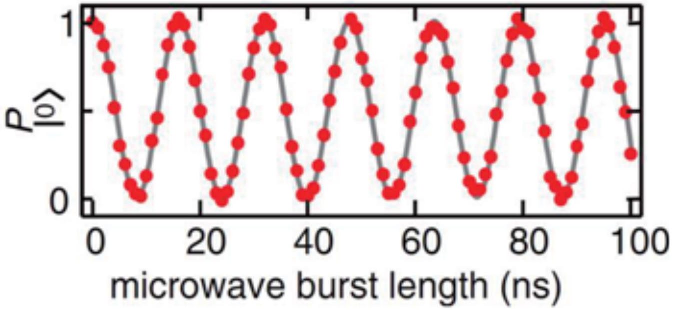
Wiring up NV centers



dc Stark tuning:



high fidelity spin manipulations

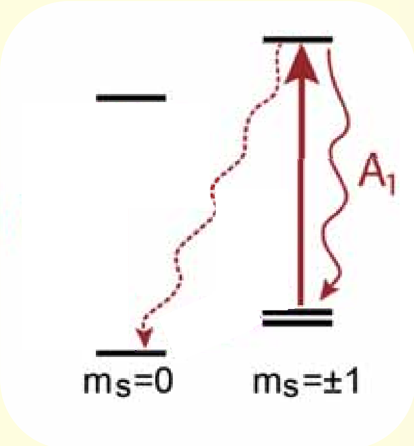


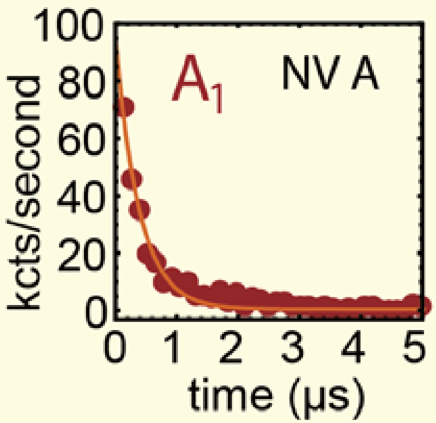
De Lange et al., Science 330, 60 (2010)

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

Initialization and readout by resonant excitation

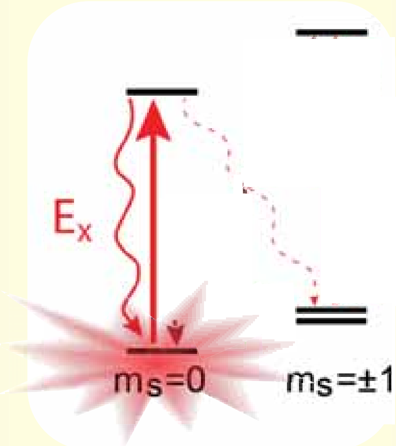
Initialization



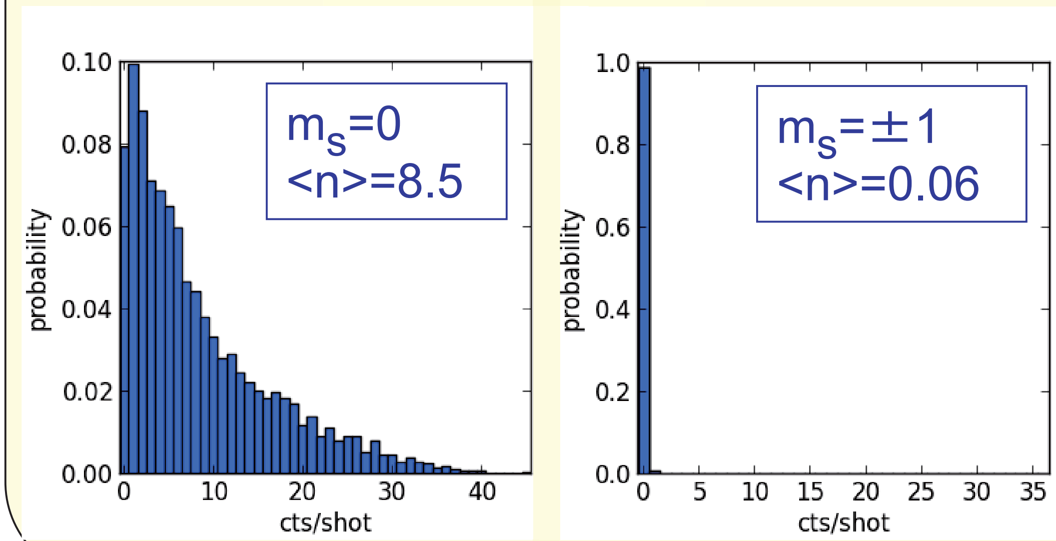


fidelity > 99%

Single-Shot Readout

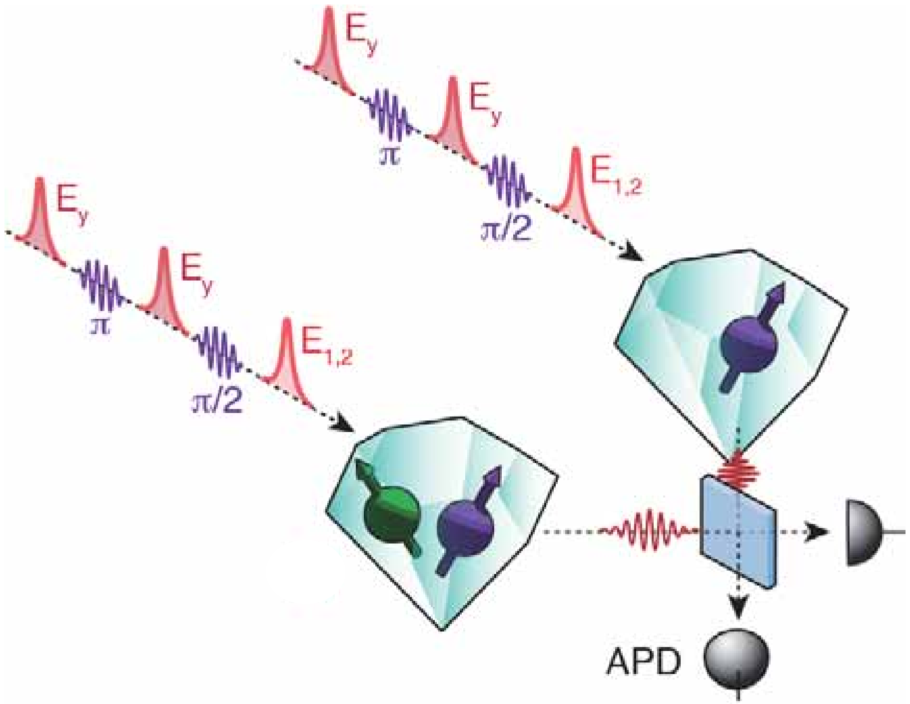


our best fidelity ≈ 98%



L. Robledo *et al. Projective readout of the register* Nature **477**, 574 (2011)

Entangling remote NV electron spins



Experiments with trapped atoms/ions:
Monroe group, Nature 2007
Weinfurter group, Science 2012
Rempe group, Nature 2012

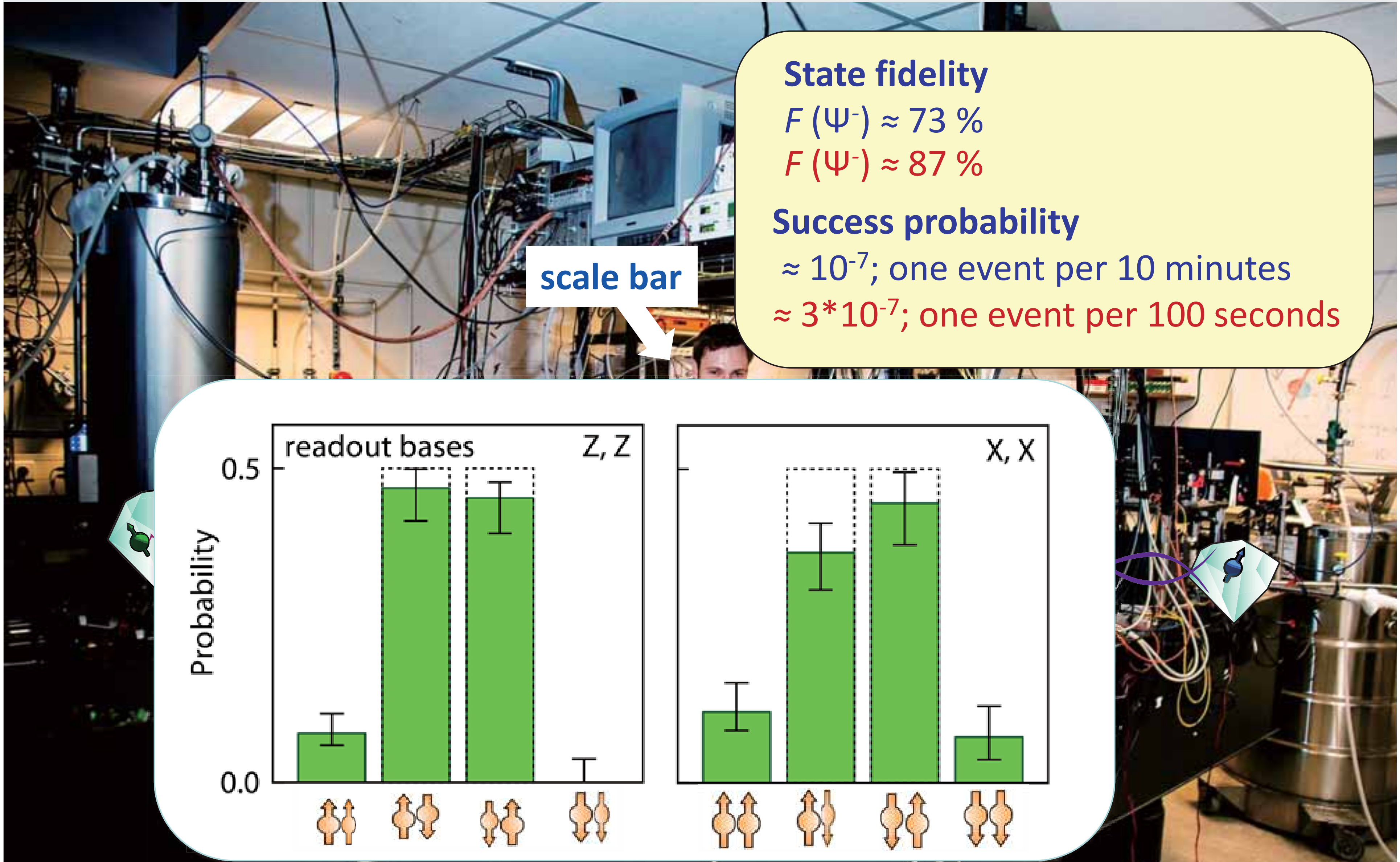
Recently also in QDs: Imamoglu group

we use the scheme proposed in:
Barrett and Kok, PRA 71, 060310 (2005)

- locally entangle electron spin and photon
- project spins onto entangled state by joint photon measurement

entanglement is *heralded* by photon detection

Heralded remote entanglement



State fidelity

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

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

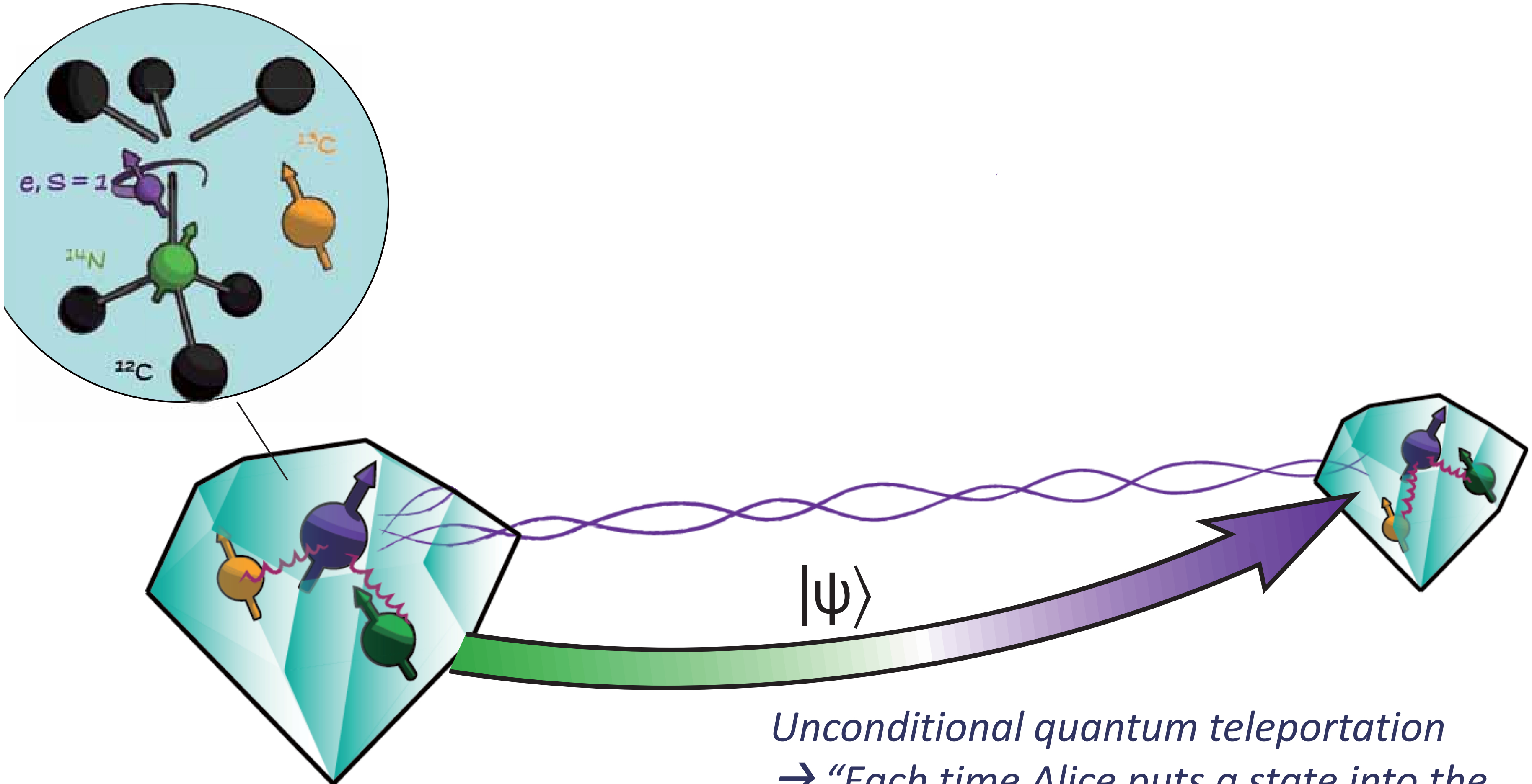
Success probability

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

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

H. Bernien, B.Hensen et al. Long-distance entanglement, Nature 497, 86 (2013)

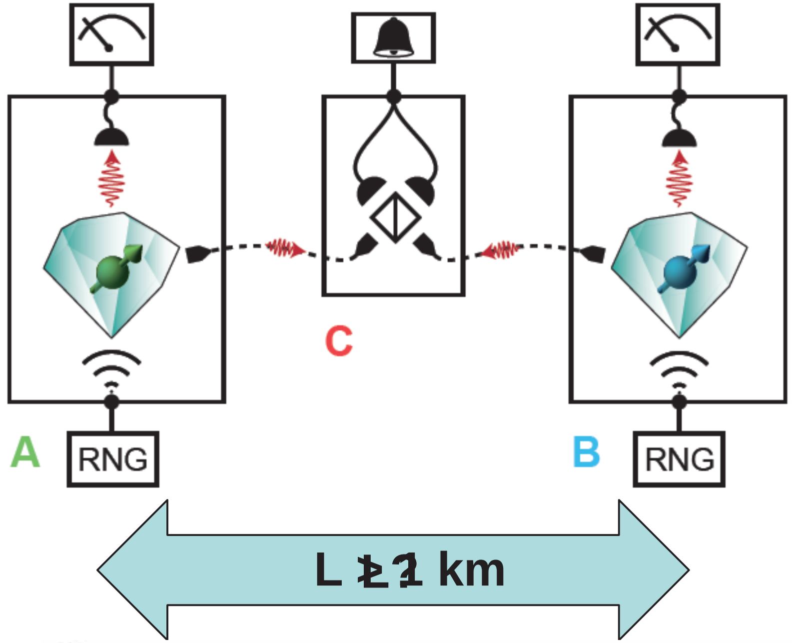
Heralded entanglement as a resource

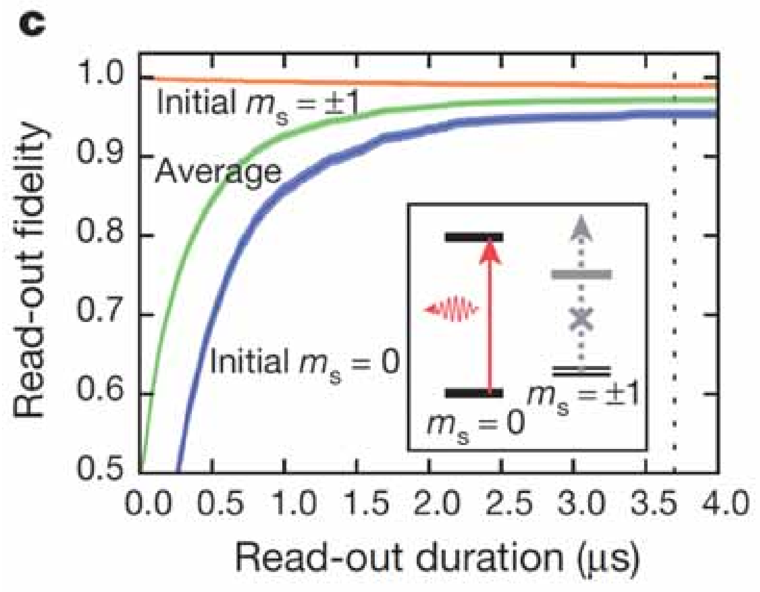


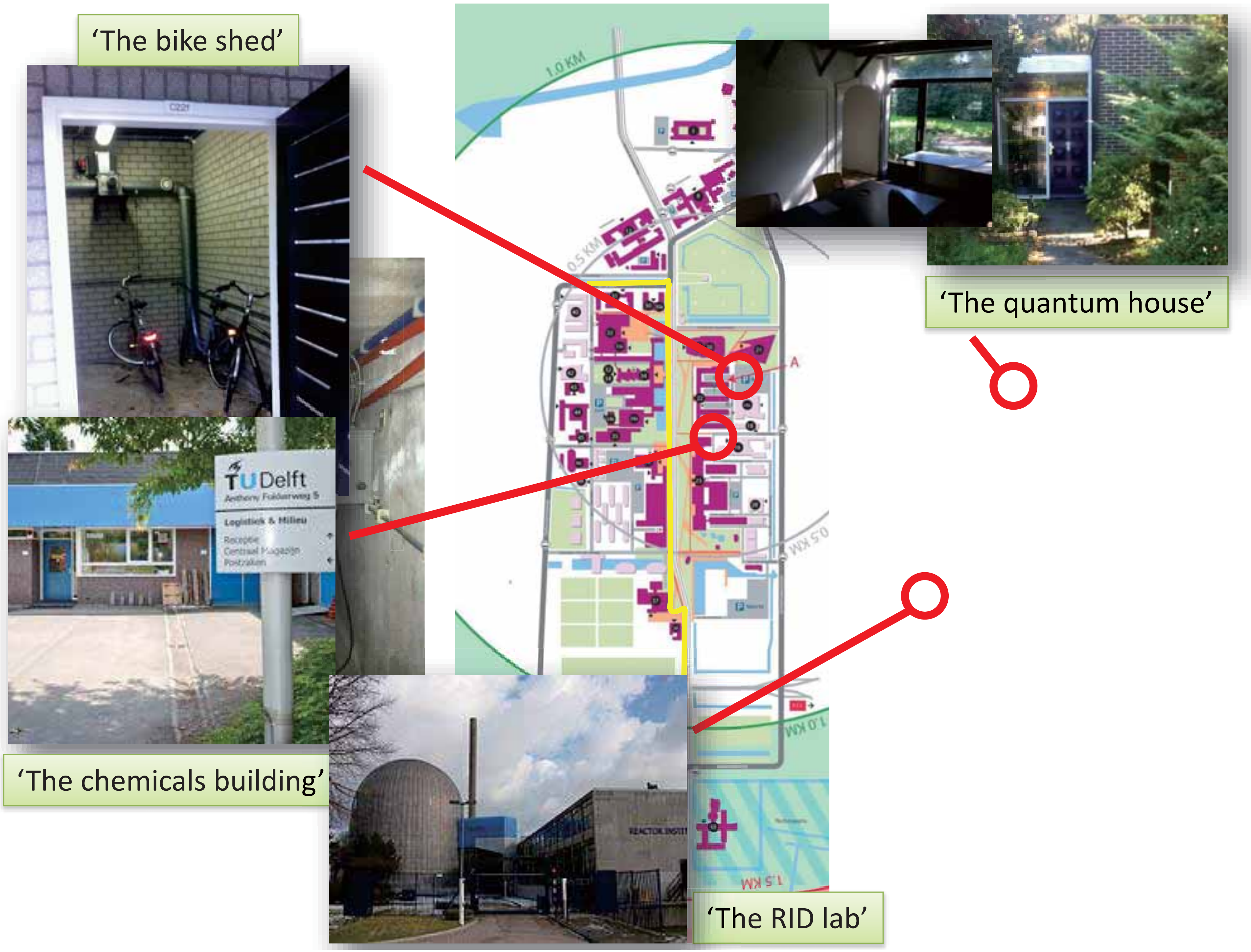
Unconditional quantum teleportation
→ "Each time Alice puts a state into the teleporter, it comes out at Bob's end"

W. Pfaff, et al. Science **345**, 532 (2014)

Minimum distance limited by the spin readout



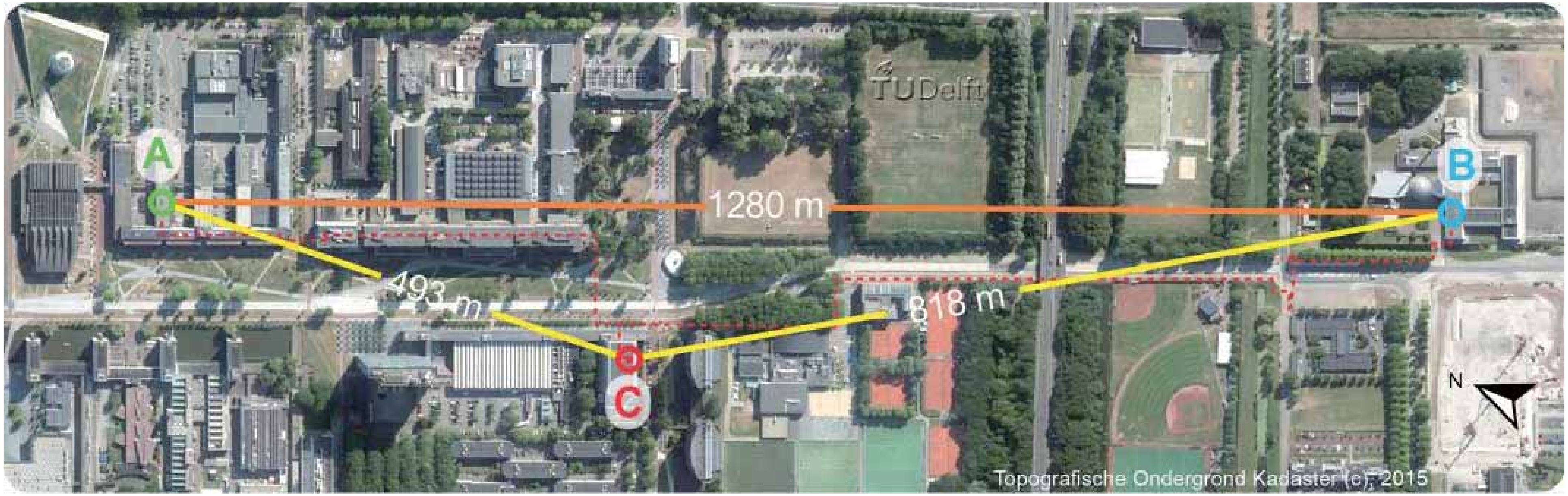


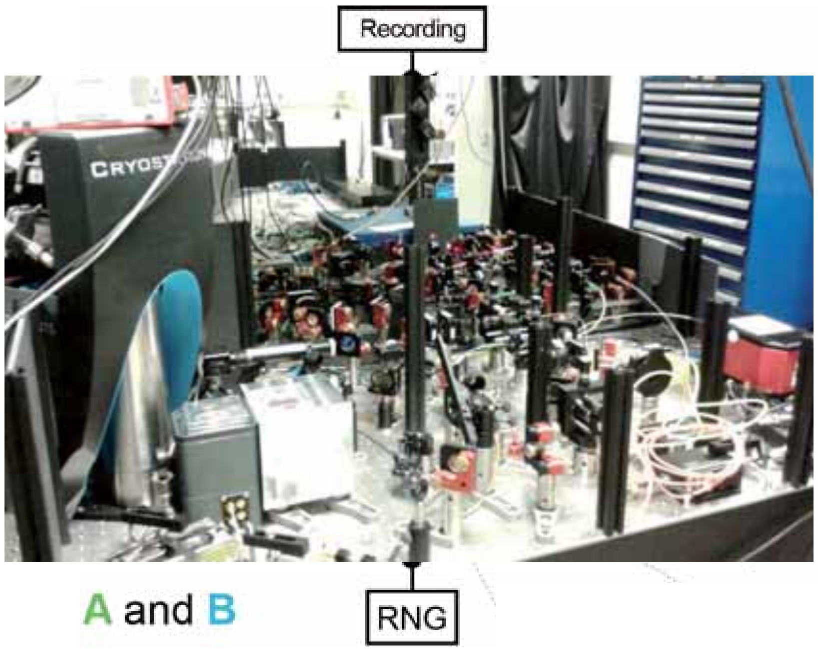

'The bike shed'
'The quantum house'
'The chemicals building'
'The RID lab'
TU Delft
Logistiek & Milieu
1.0 KM
0.5 KM
1.5 KM

Alice & Bob's labs

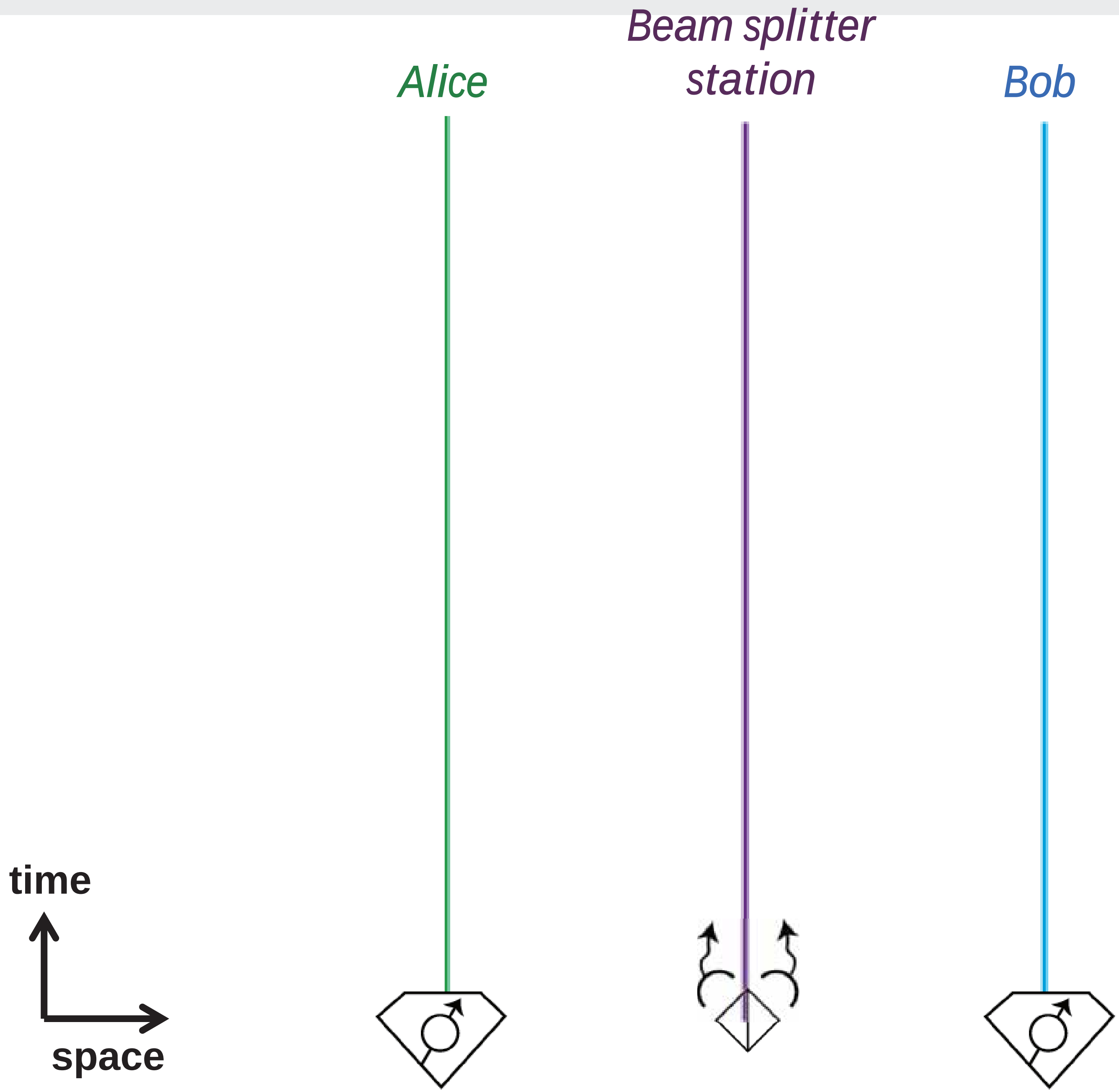
- 2013-11-25: Order Fiber Bundle
- 2014-01: First Cooldown Alice
- 2014-02: Bob Lab ready & Fiber arrives
- 2014-03: Fiber is put into the tunnel
- 2014-09: First Cooldown Bob
  & BS lab ready
- 2014-12: First entanglement measured between A & B

A loophole-free Bell test in Delft



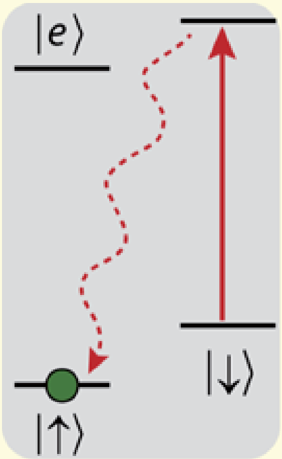


Proposed experimental scheme



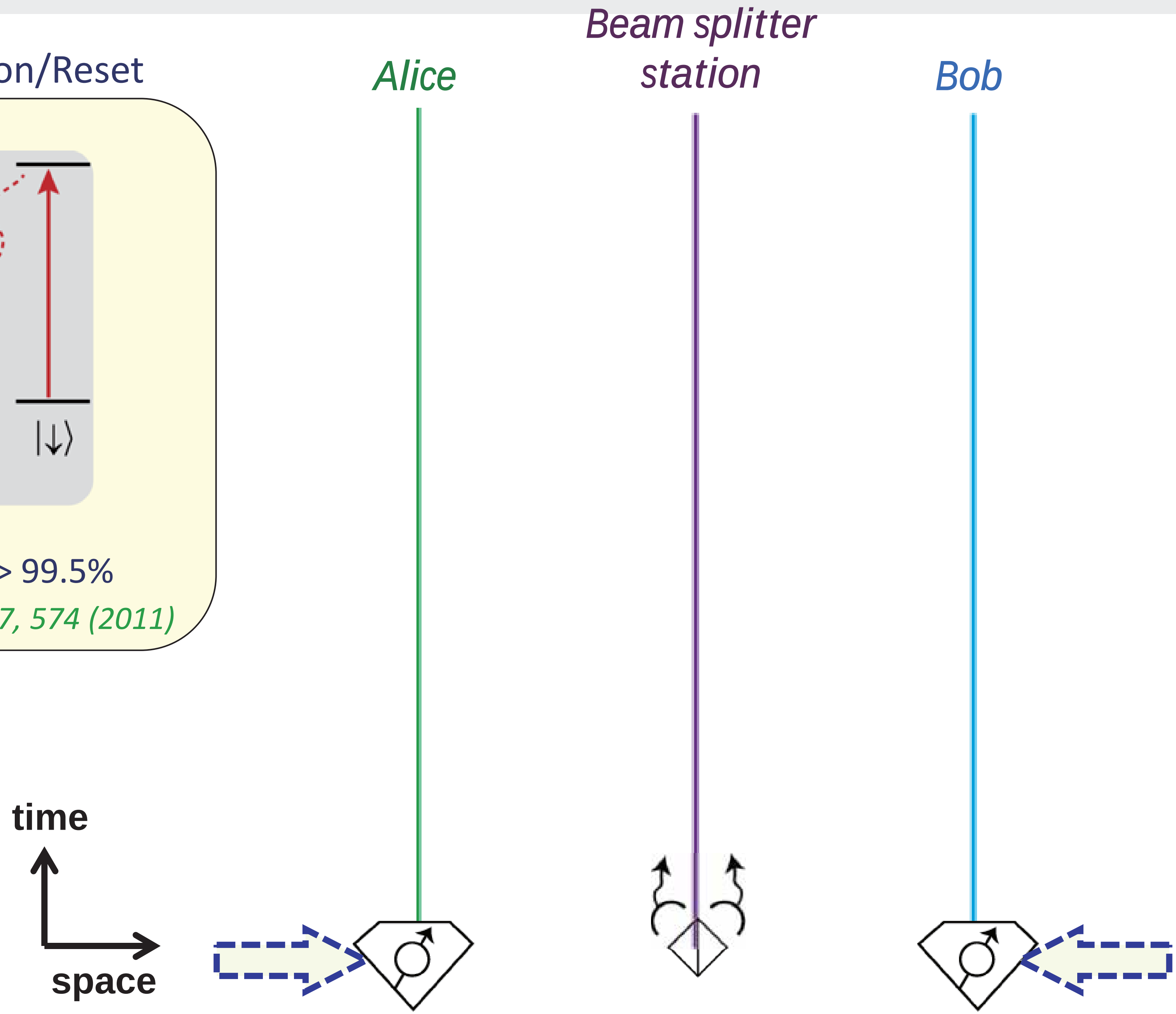
Proposed experimental scheme

Initialization/Reset

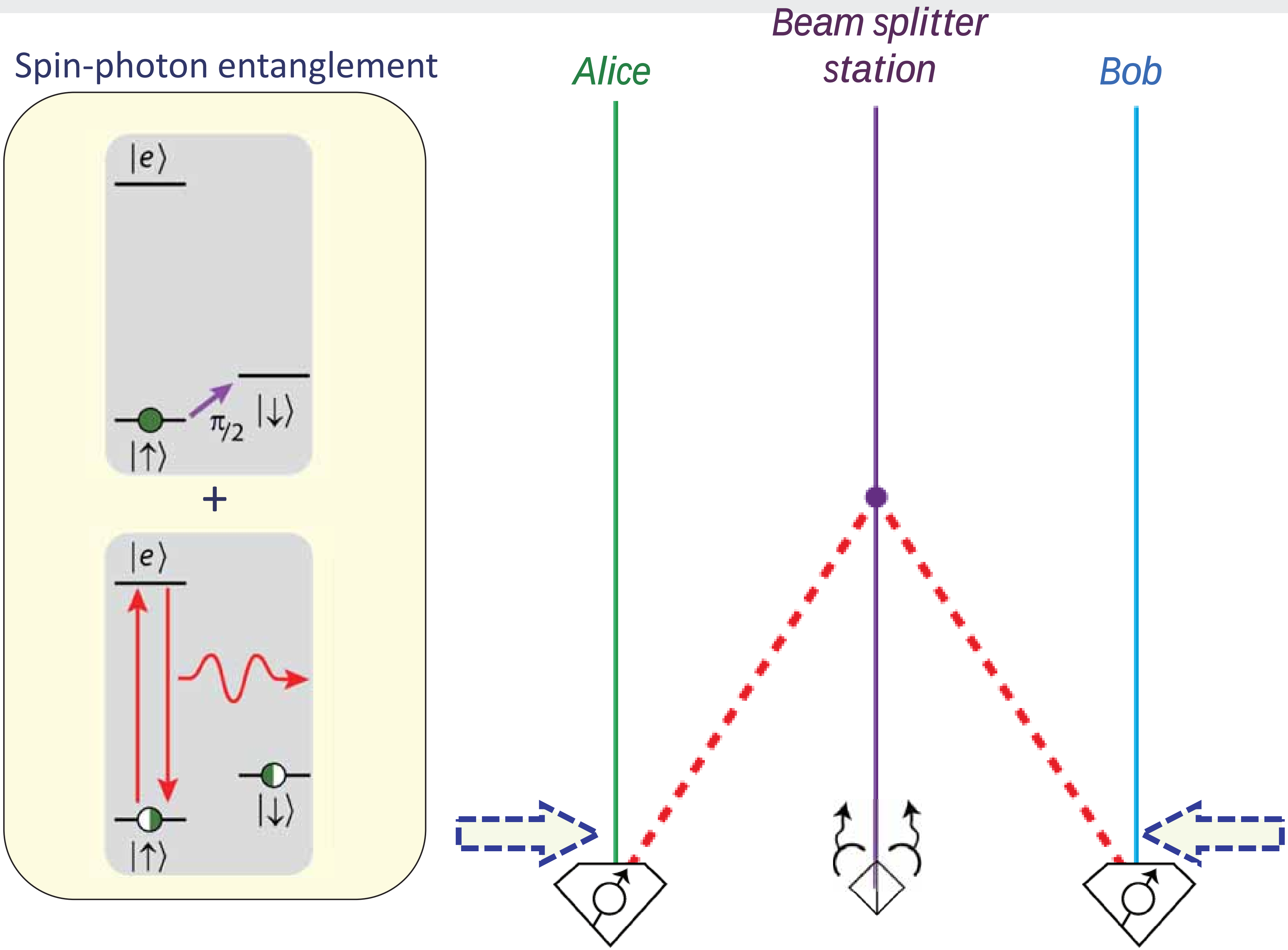


fidelity > 99.5%

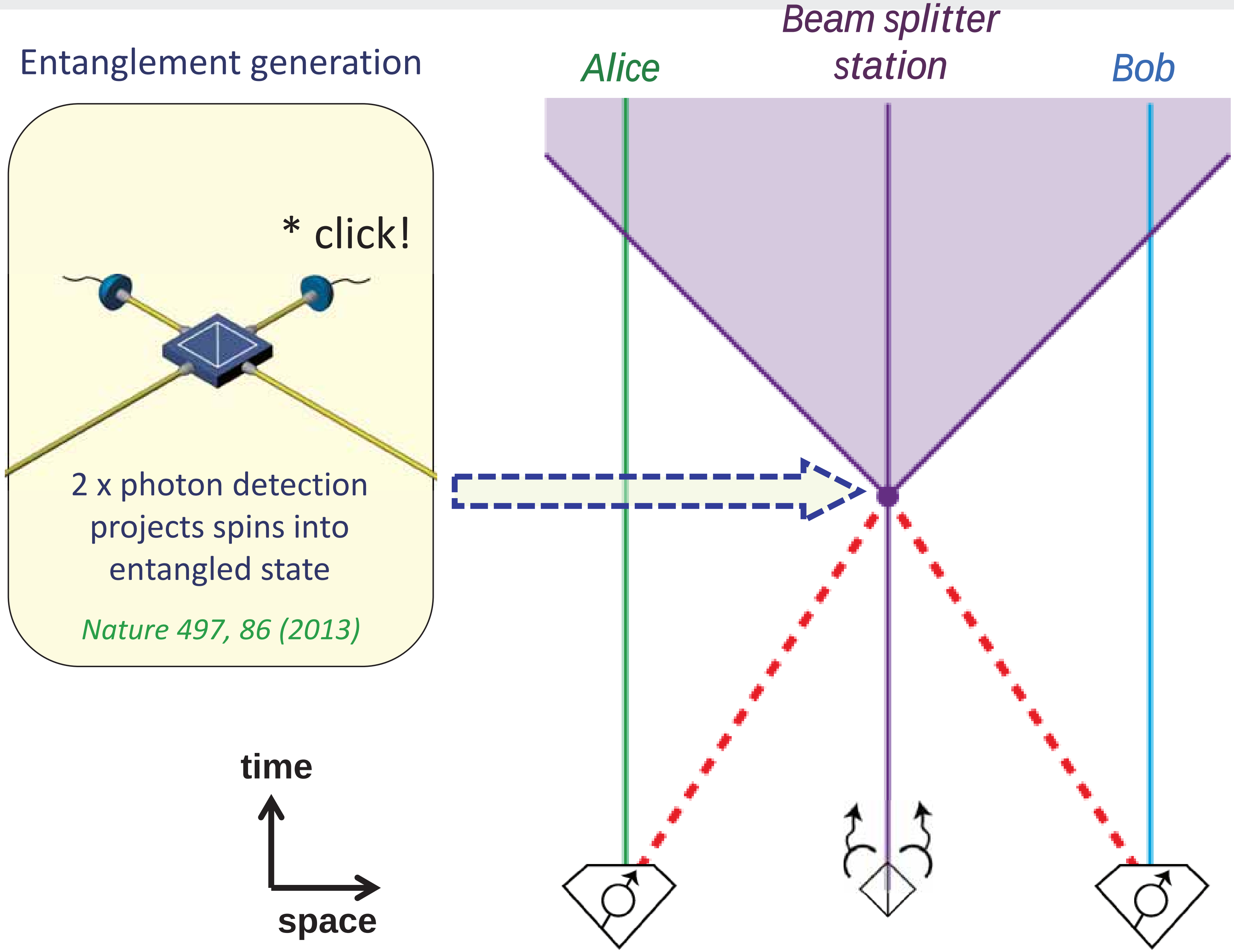
Nature 477, 574 (2011)



Proposed experimental scheme

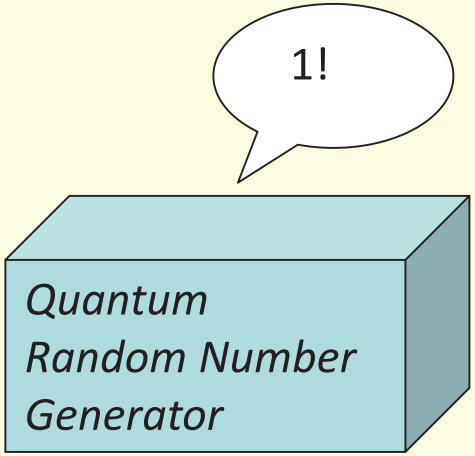


Proposed experimental scheme



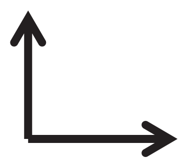
Proposed experimental scheme

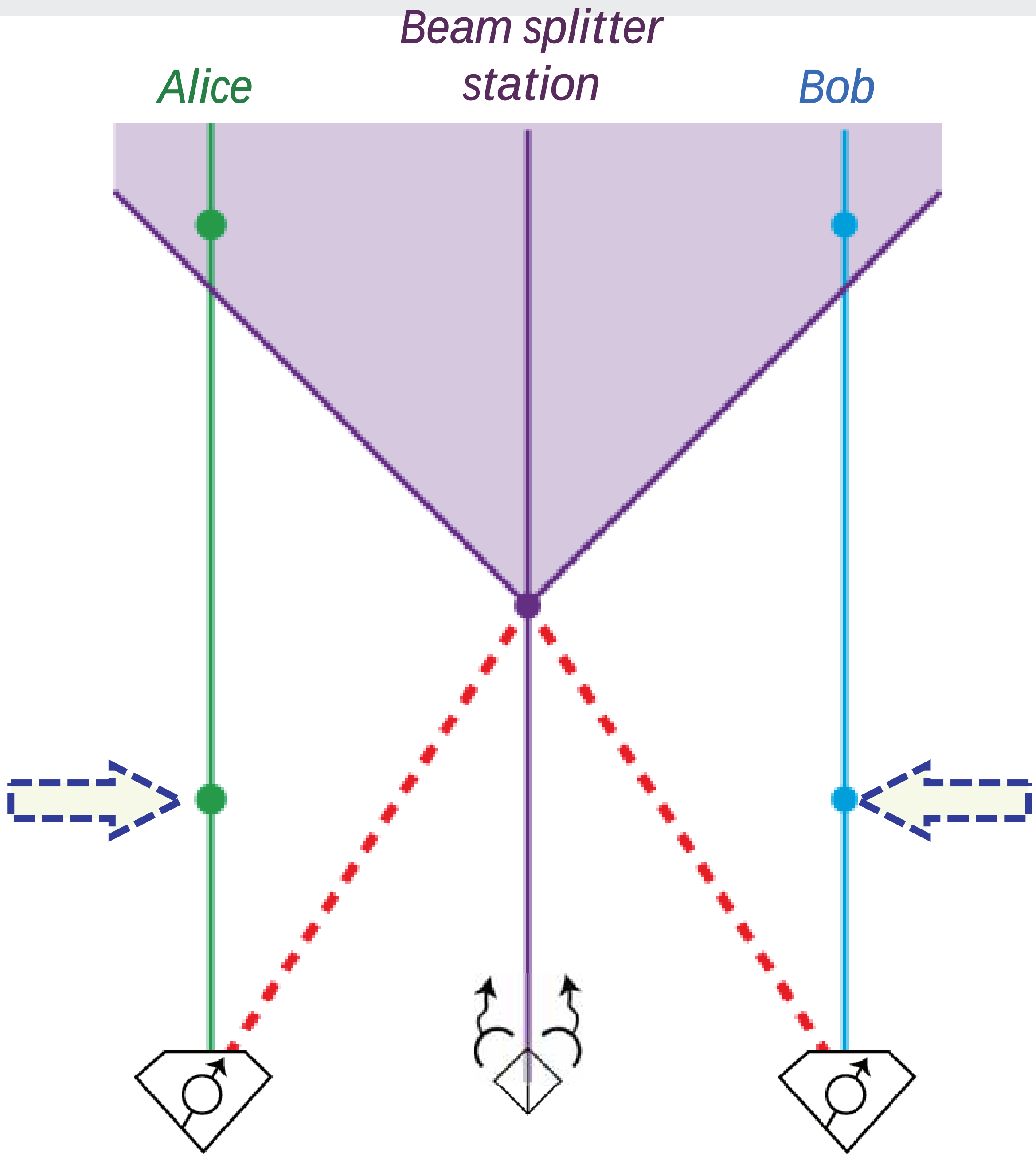
Random basis choice



Freshness of raw random bit 4 ns, we take the parity of k=32 raw bits

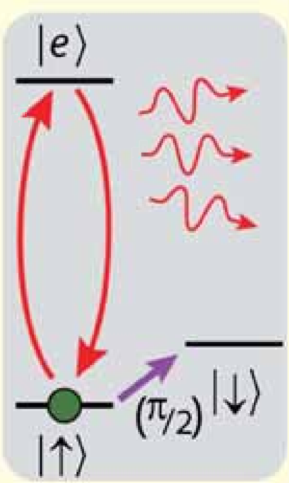
ICFO collaboration
Optics Express **22**, 1645





Proposed experimental scheme

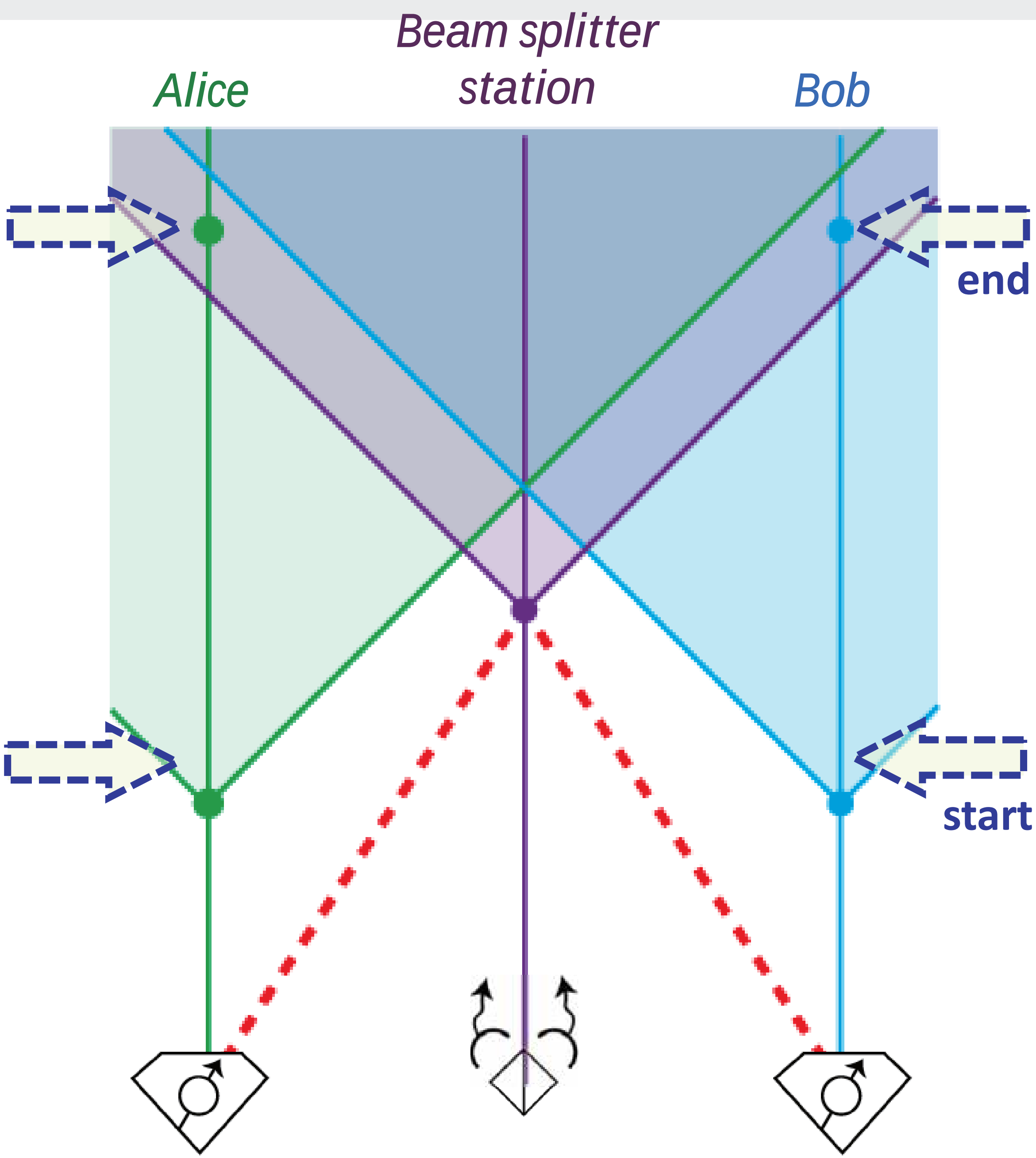
Basis rotation and readout



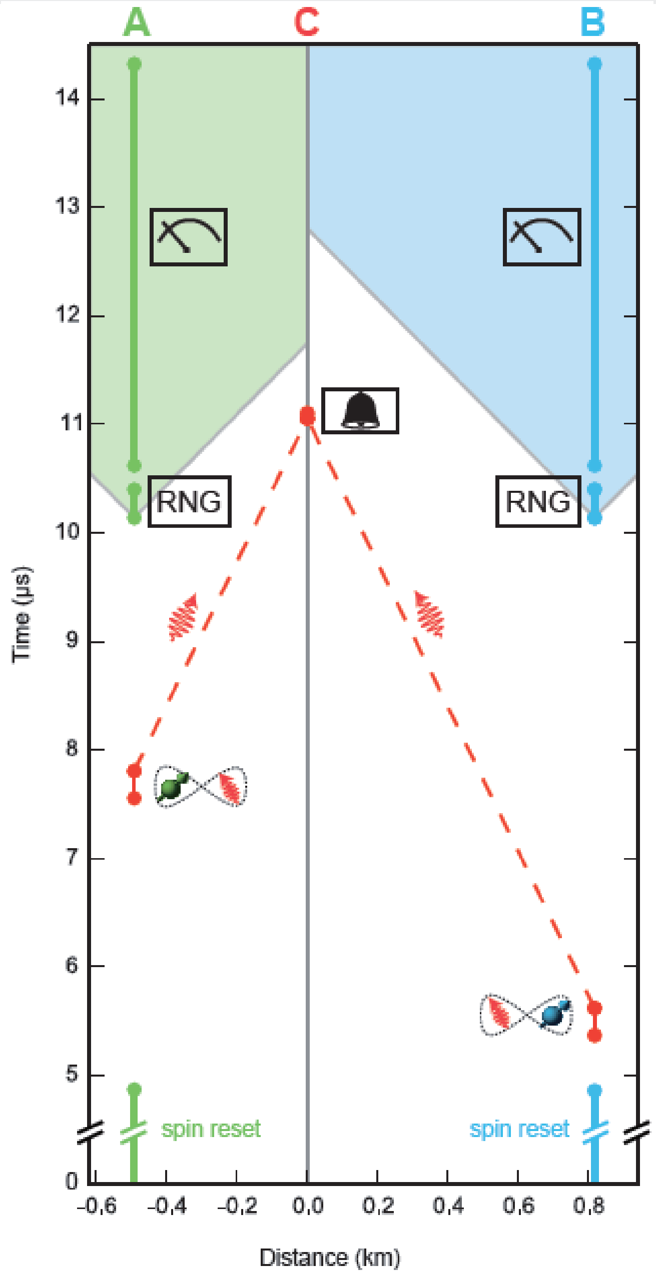
Nature 477, 574 (2011)

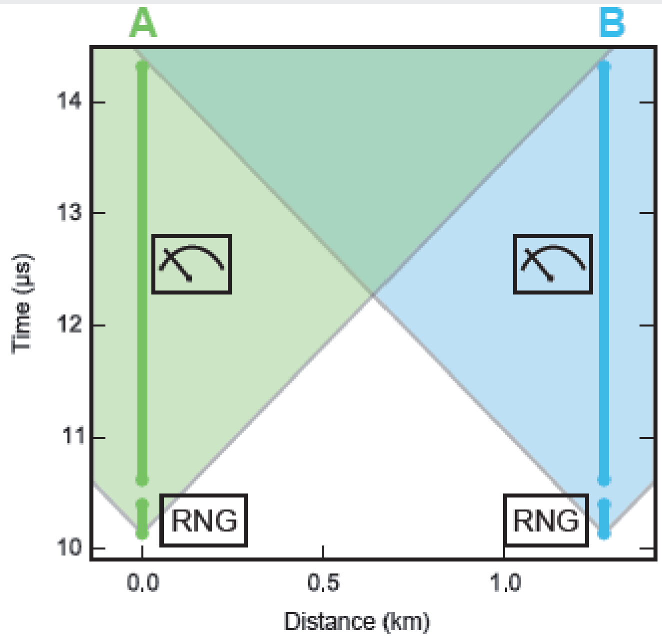
Single-shot readout:
Detection loophole closed

Duration < distance/c:
Locality loophole addressed



Actual experimental scheme

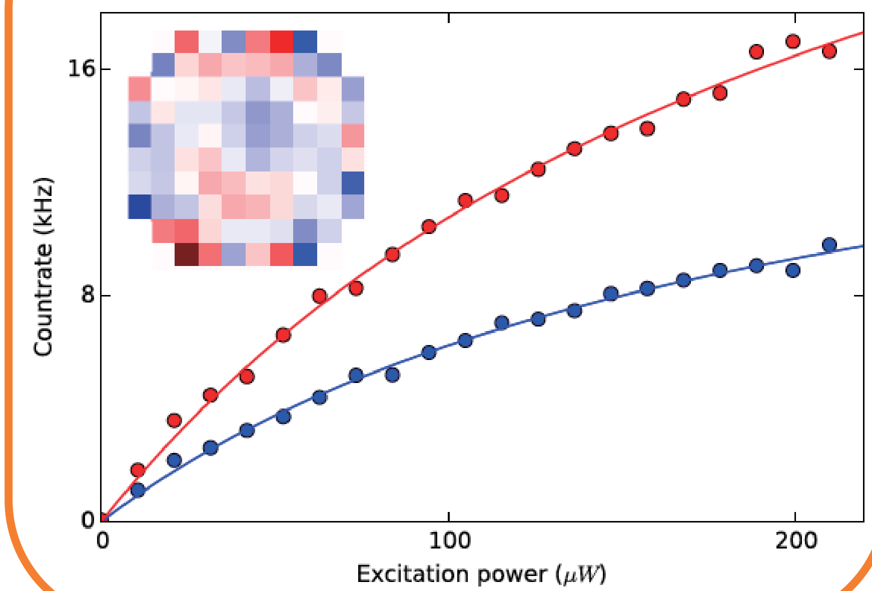




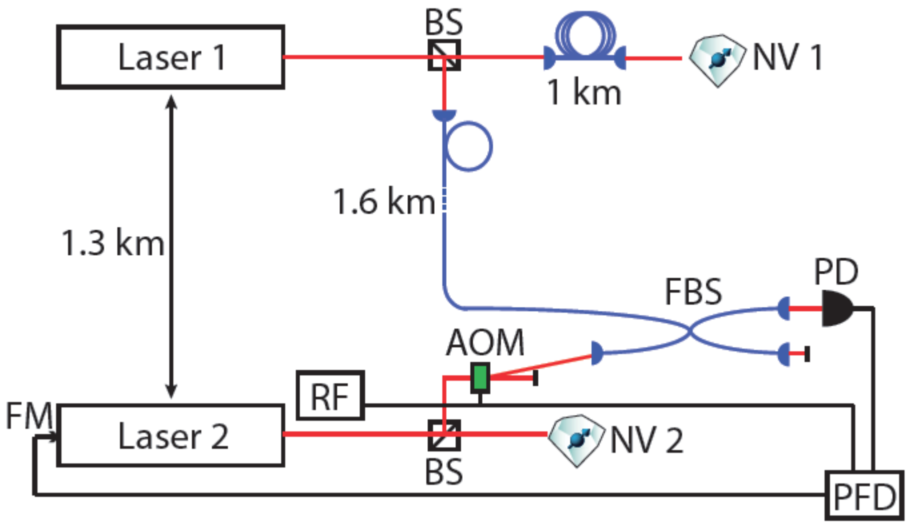
- Event-ready signal space-like separated from RNG
- A and B space-like separated during the trial
  (i.e. from RNG up to output recording)

Pushing the system to its limits…

Adaptive optics



Stabilizing relative laser frequencies over 1km

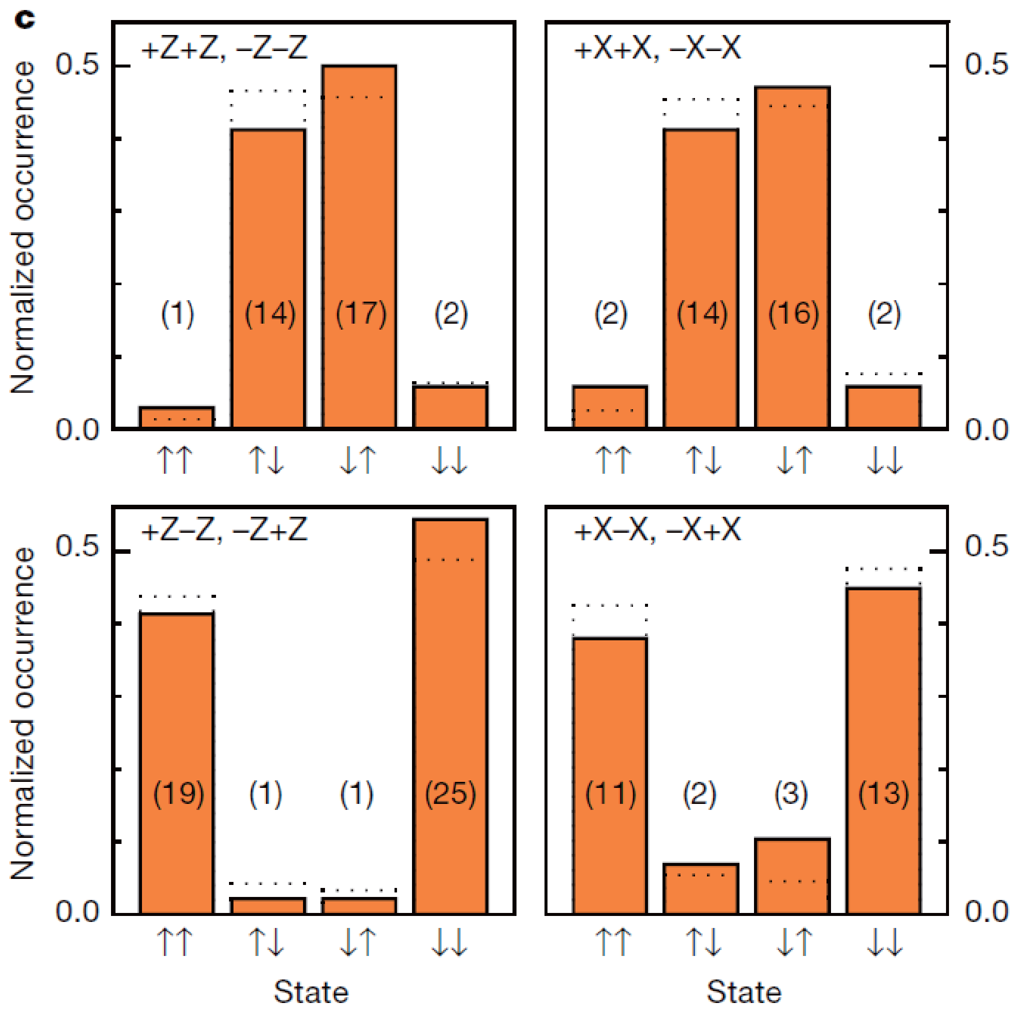


- Various feedback loops to ensure setup stability over time (microseconds - weeks)
- Microwave pulse shaping for spin control
- Spin dynamical decoupling protocols
- 2D d.c. Stark tuning to optimize readout fidelity
- Numerical optimization of readout angles
- ….

… keeping it stable over days

- Daily calibrations and alignment
- Every 10 seconds, we check
  - Proper setup synchronisation
  - Lasers locked
  - NV transition frequency on resonance
  - NV crystal strain splitting sufficiently low
  - Excitation laser rejection sufficient
  - …
  - If one of the above criteria is not met, a flag is recorded in the data marking the succeeding events invalid, until the fault is fixed (by automatic feedback or human interaction)

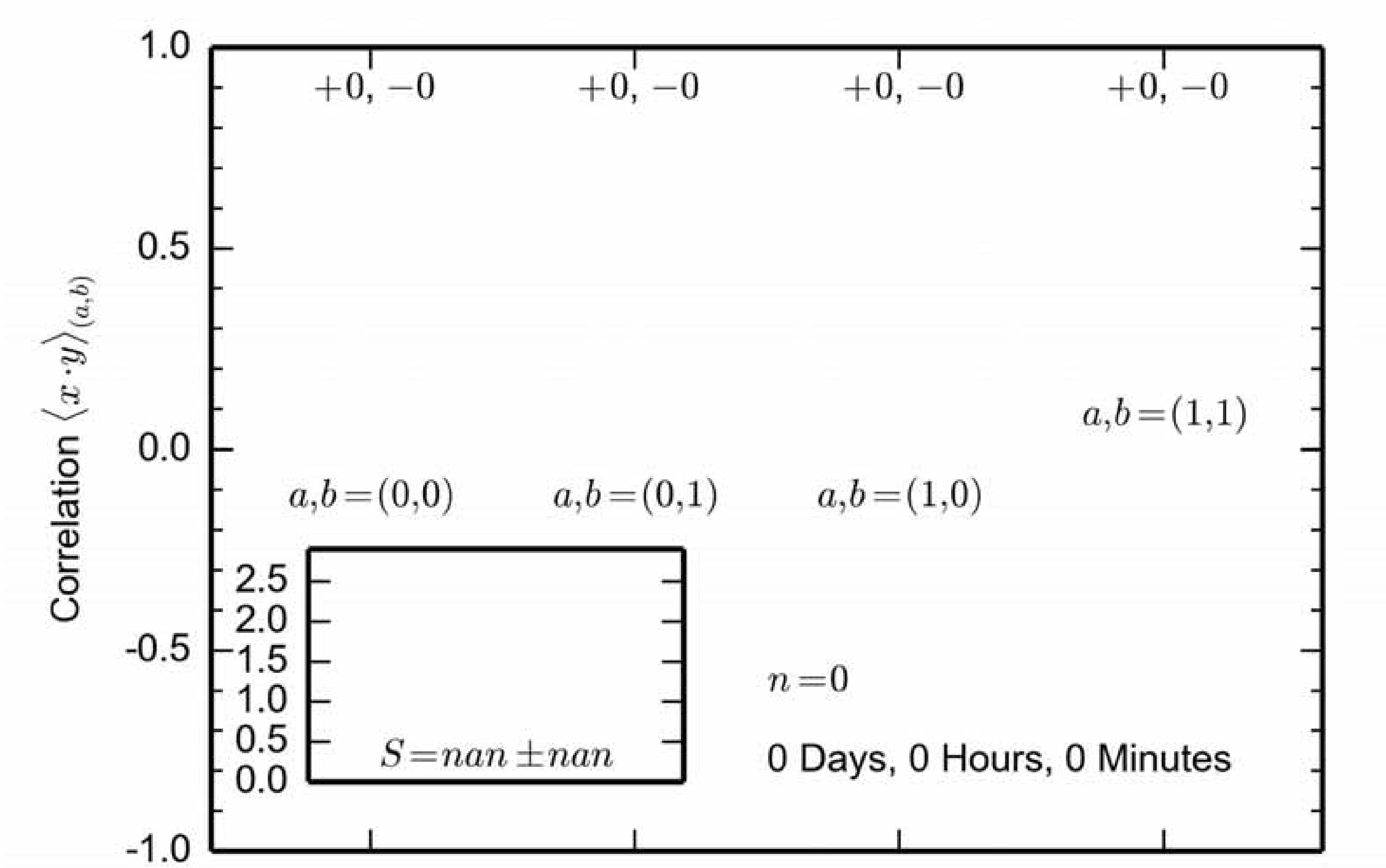
June 2015: correlation measurements



- state fidelity > (83±5)% (strict lower bound): proves entanglement
- best estimate for fidelity = 92%

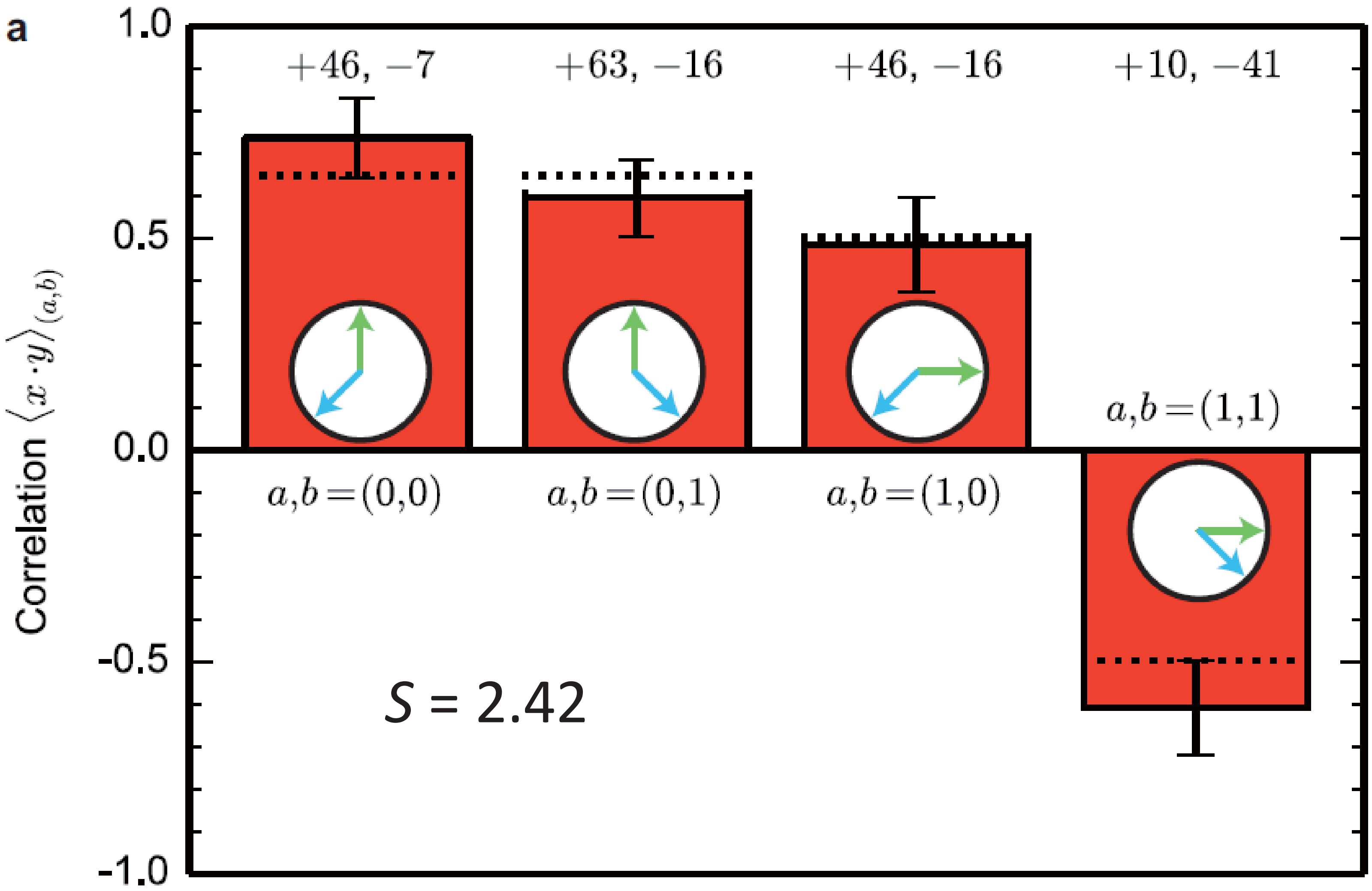
$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$

The results



1.0
0.5
0.0
-0.5
-1.0
Correlation $\langle x \cdot y \rangle_{(a,b)}$
$+0, -0$
$+0, -0$
$+0, -0$
$+0, -0$
$a,b=(1,1)$
$a,b=(0,0)$
$a,b=(0,1)$
$a,b=(1,0)$
2.5
2.0
1.5
1.0
0.5
0.0
$S=nan \pm nan$
$n=0$
0 Days, 0 Hours, 0 Minutes

The results



a
1.0
0.5
0.0
-0.5
-1.0
Correlation $\langle x \cdot y \rangle_{(a,b)}$
+46, −7
+63, −16
+46, −16
+10, −41
$a,b=(0,0)$
$a,b=(0,1)$
$a,b=(1,0)$
$a,b=(1,1)$
S = 2.42

What does it mean?

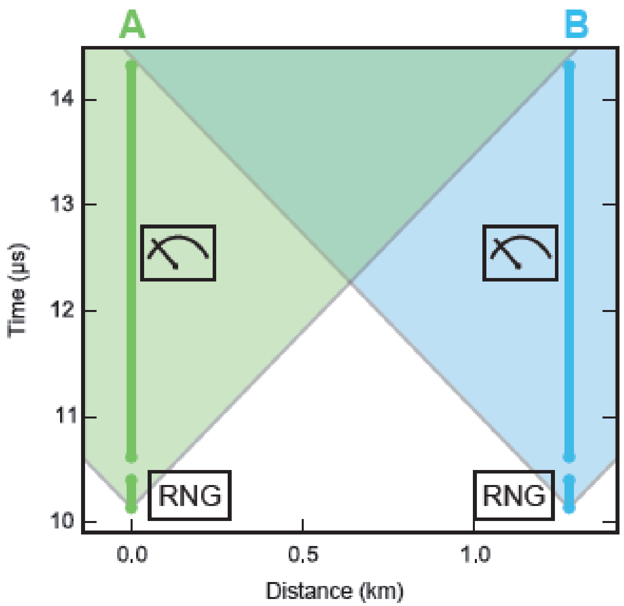
- a Bell test is a null hypothesis test
- the result is a p-value =
  probability that the observed data (or more extreme) would result
  under the assumption that our experiment is ruled by a local realist model*
- A small p-value can be interpreted as strong evidence against the null hypothesis
- p-value is **not** the probability that our experiment is ruled by a local realistic model

**as defined on next slide*

- "conventional" analysis: no memory, Gaussian distributed outcomes, perfectly random input bits: $S = 2.42 \pm 0.20$; p-value = 0.019

- "complete" analysis: memory allowed, no assumption on underlying distributions, partial predictability of input bits: p-value = 0.039

What theories are we testing?

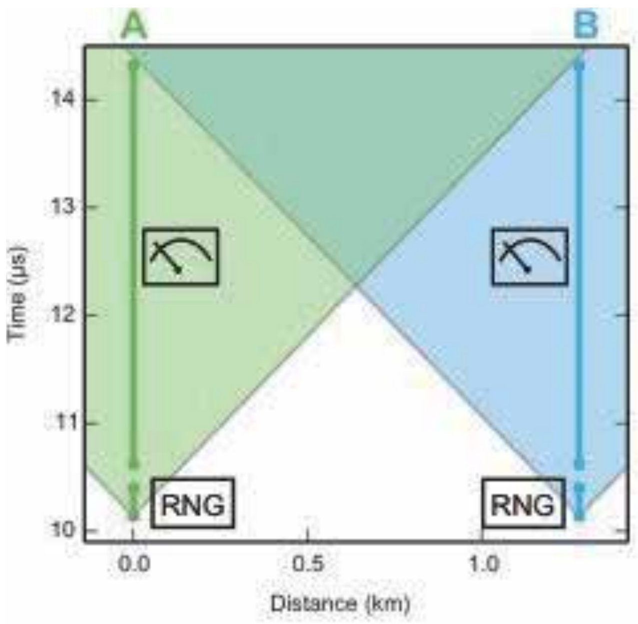


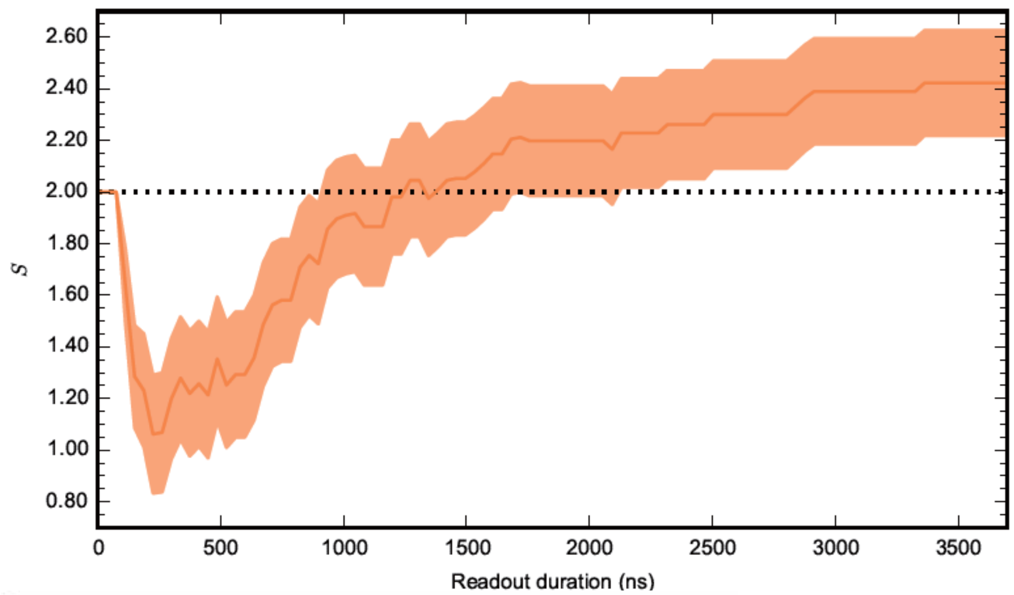
FACTS:

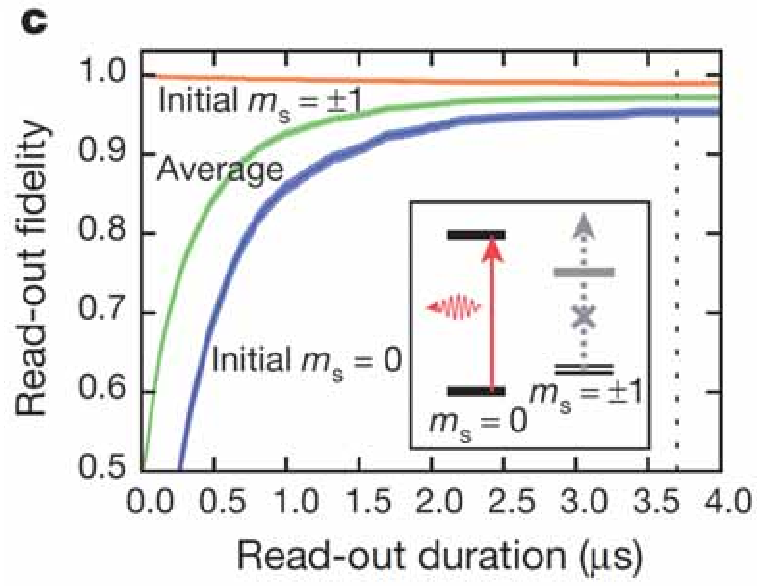
- We can not prove that/when free input bits were generated.
- We can not prove that measurement outcomes are final at a certain time.

Scope of our test: all local realist theories that predict that free input bits were generated in time and that outcomes are final once recorded in our electronics

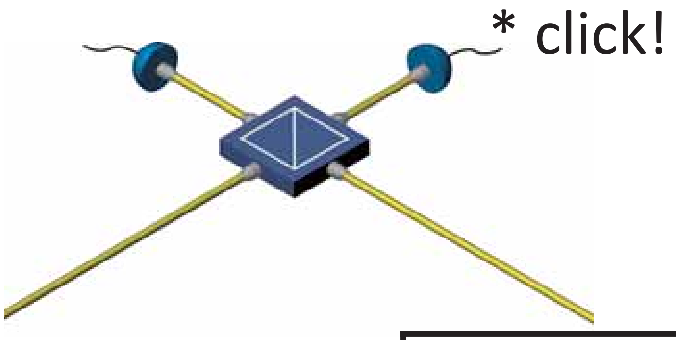
Violation remains for shorter read-out duration



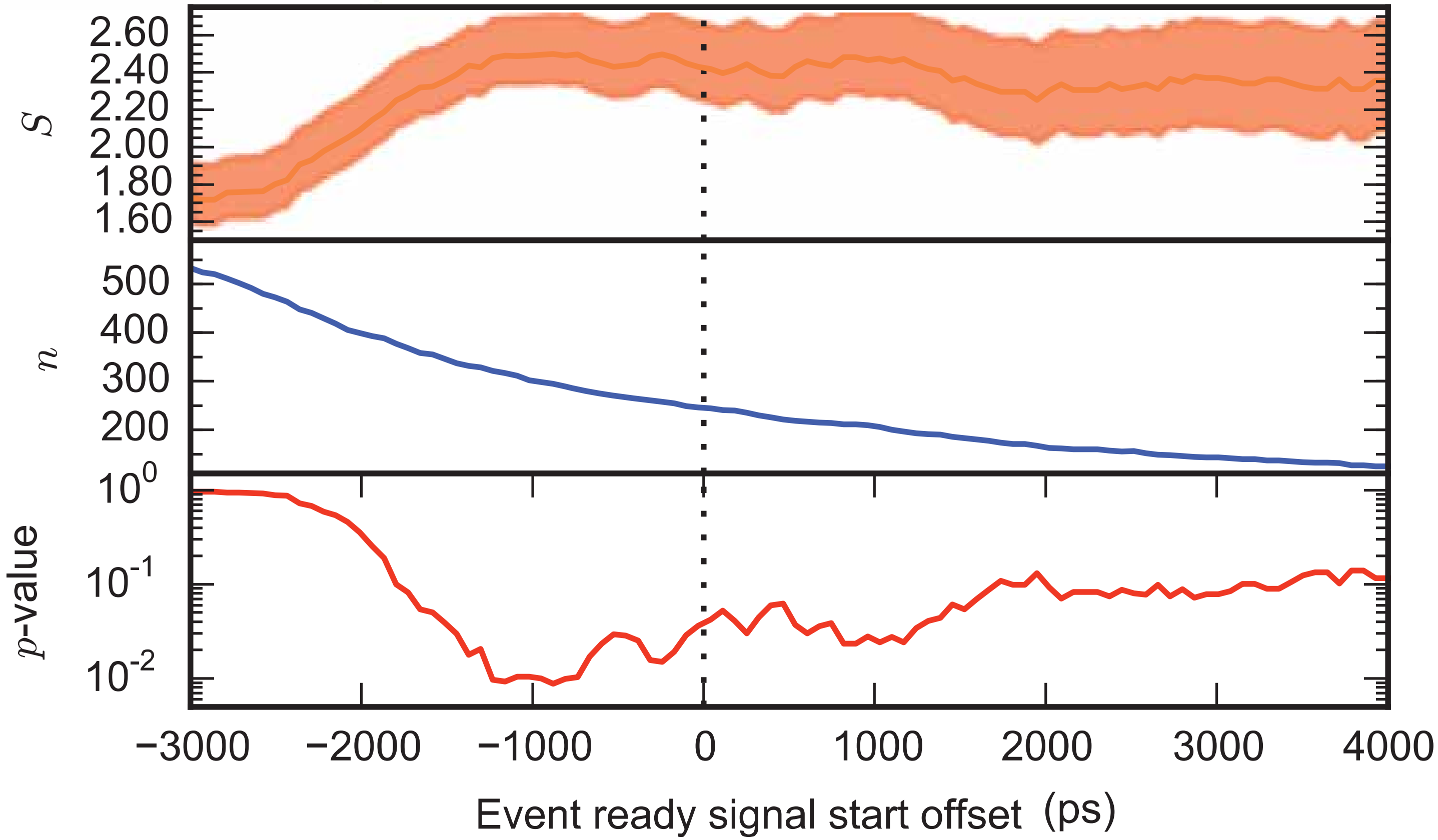




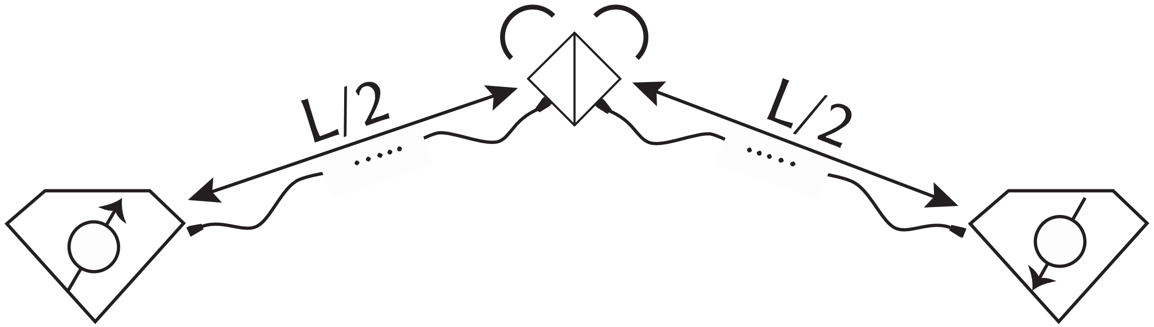
Beyond the pre-set parameter range



Raw data and analysis scripts are available via http://hansonlab.tudelft.nl

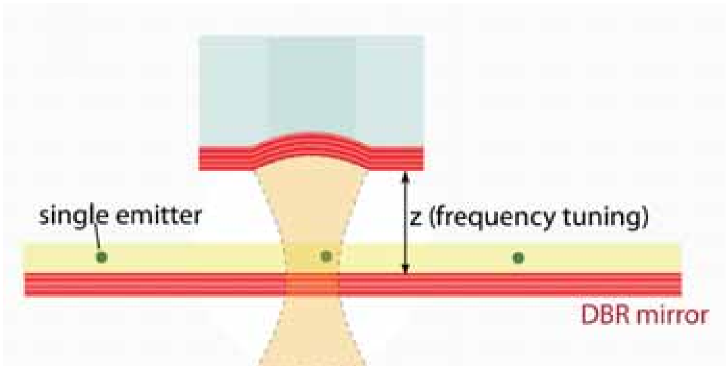


Towards higher rates?



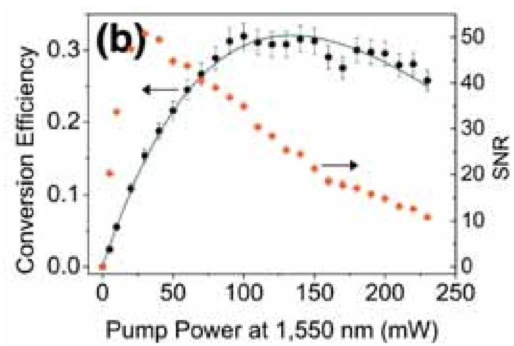
Success probability per attempt = 0.5 * (emission probability)^2 *(detection probability)^2

Higher rates: cavities!



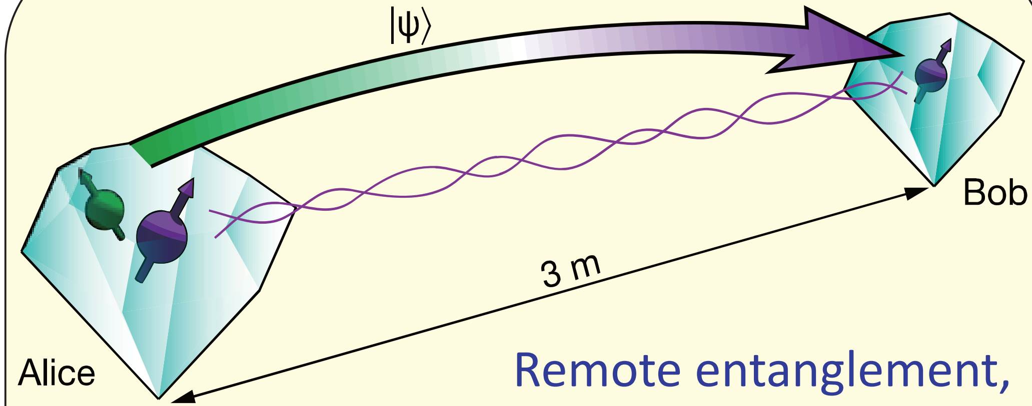
Micro-cavities: pioneered by Reichel group
First NV results Becher, Hunger groups

Telecom wavelength conversion



Zaske et al. PRL 109, 147404 (2012)

Outlook: towards quantum networks

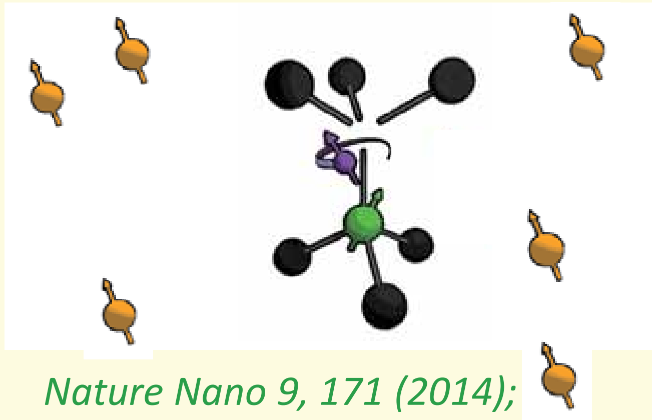


Remote entanglement, teleportation & loophole-free Bell test

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

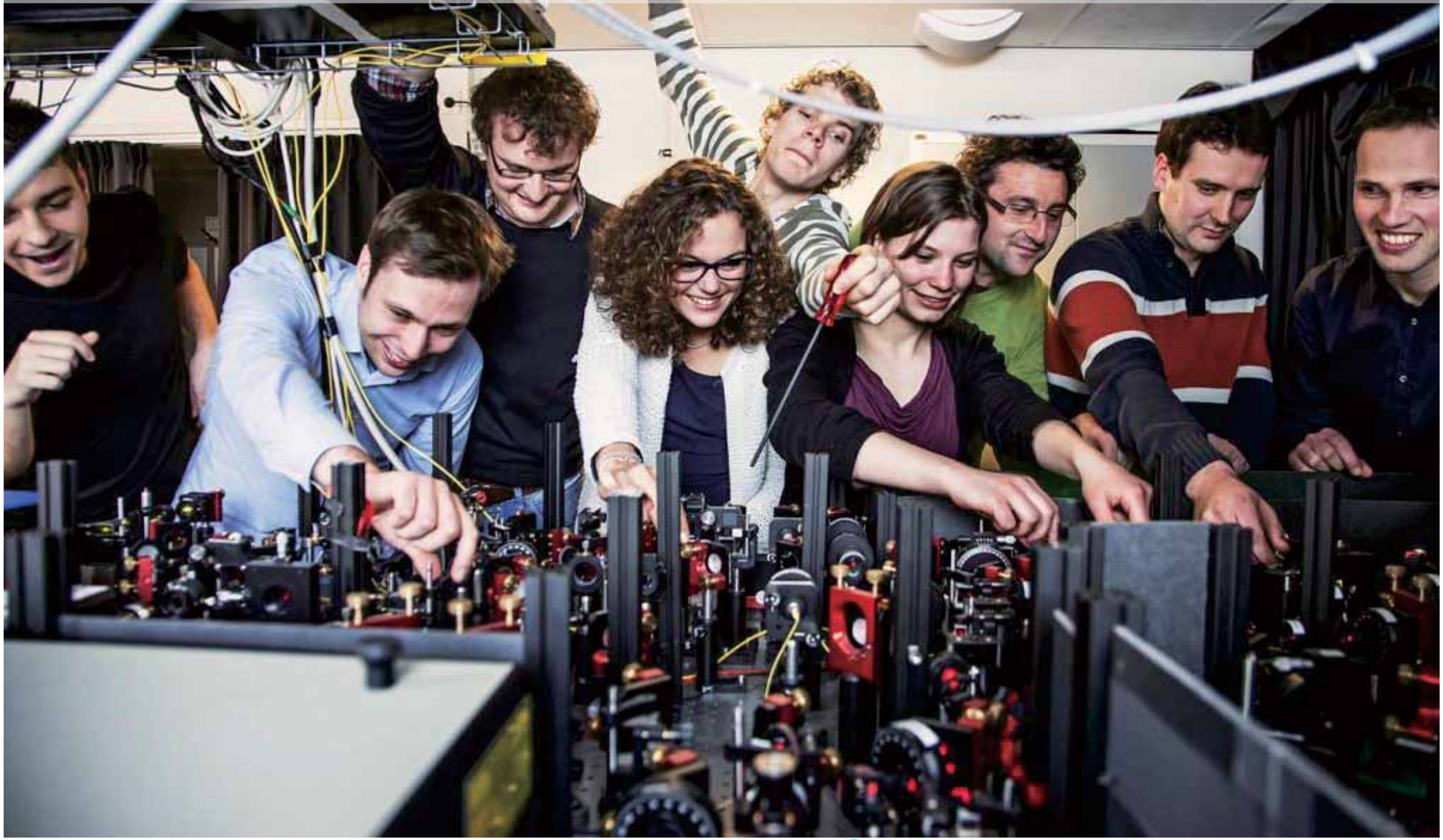
+

Control and readout of nuclear spin qubit registers

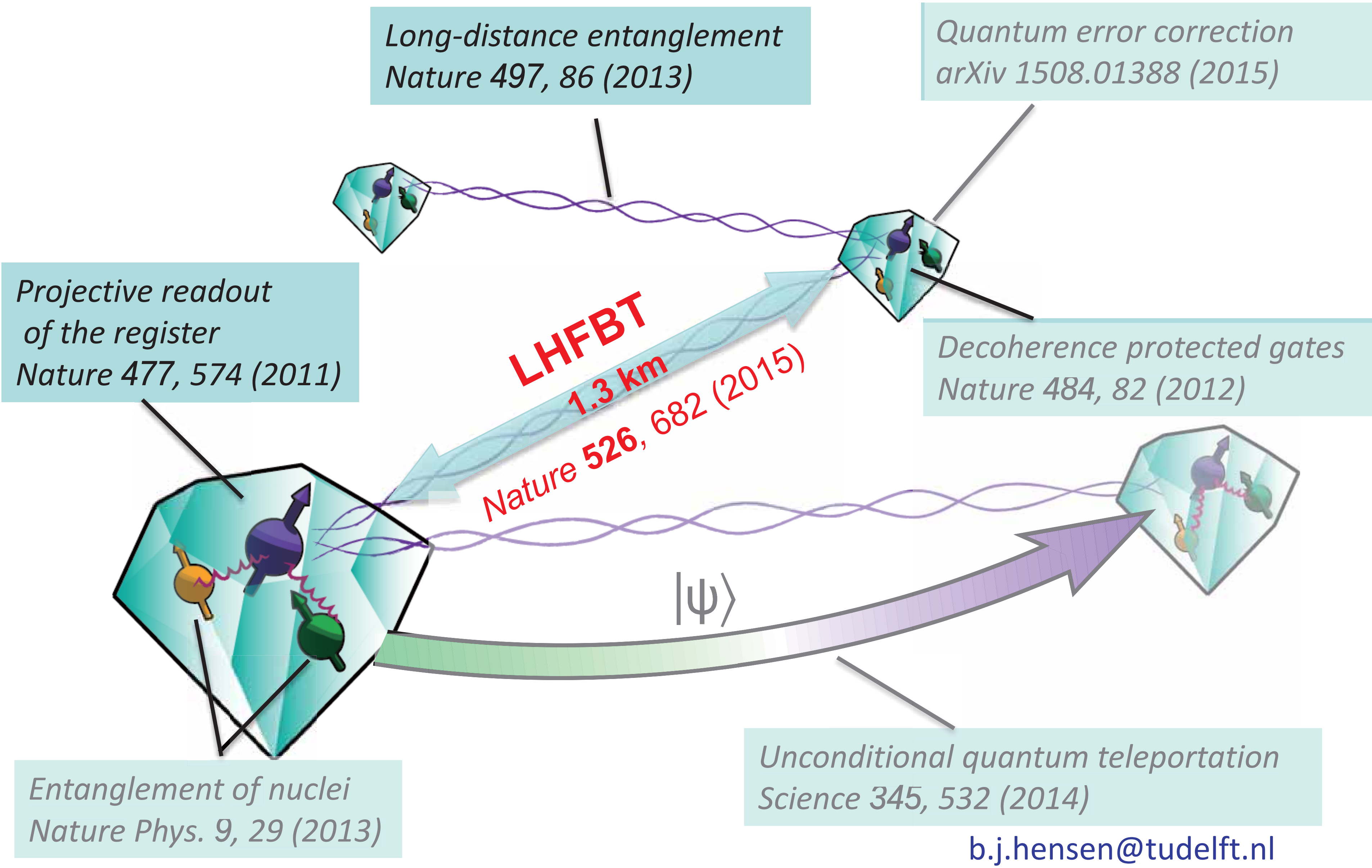


Nature Nano 9, 171 (2014); arXiv:1508.01388 (2015)

Thank you!

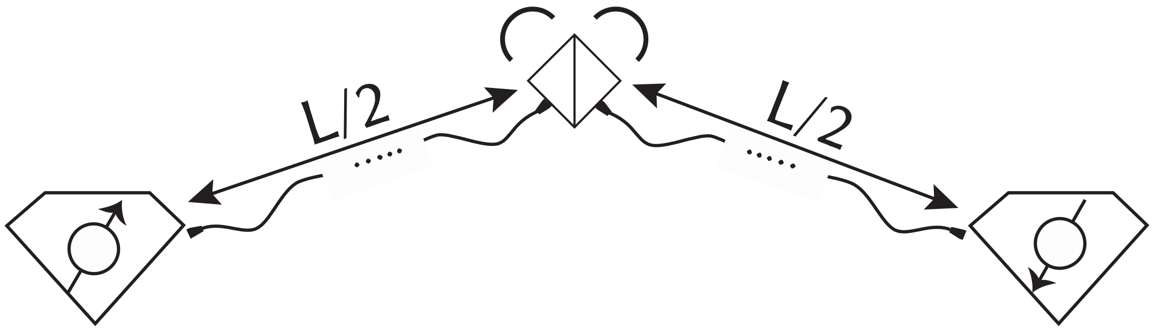


References

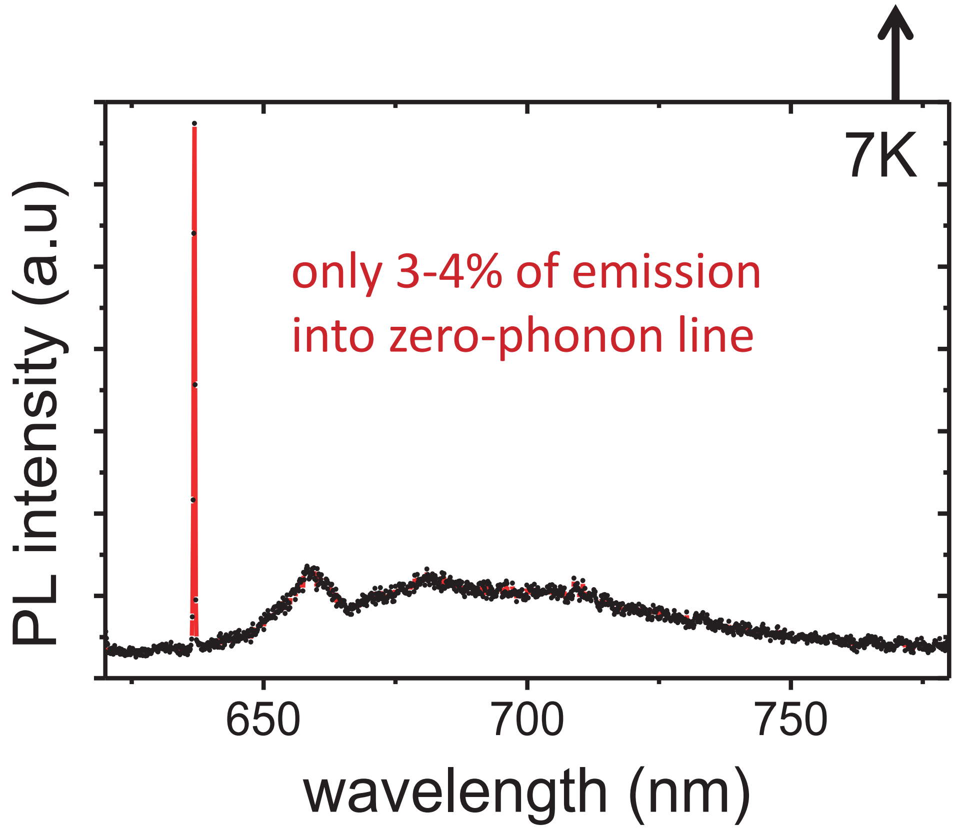


b.j.hensen@tudelft.nl
http://hansonlab.tudelft.nl

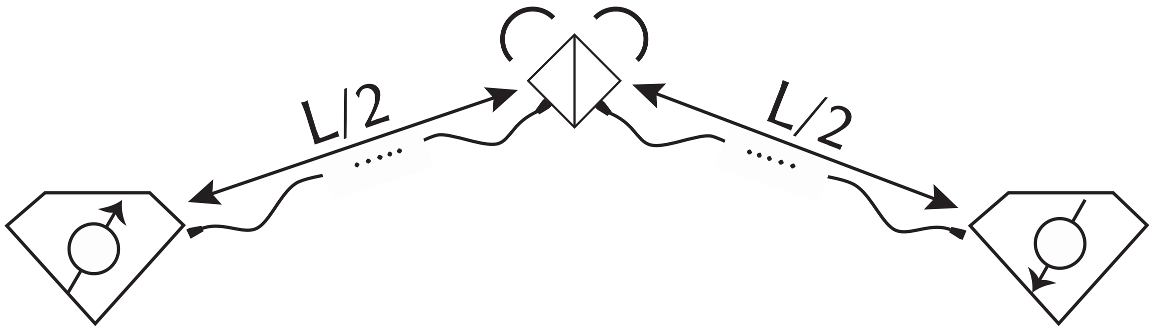
What is limiting the remote entangling rate?



Success probability per attempt = 0.5 * (emission probability)^2 *(detection probability)^2



What is limiting the remote entangling rate?



Success probability per attempt = 0.5 * (emission probability)^2 *(detection probability)^2

- Finite photon collection out of diamond
- Photon loss @637nm is about 8 dB/km
  (compare to 0.2 dB/km @1550nm)

Quantum superiority

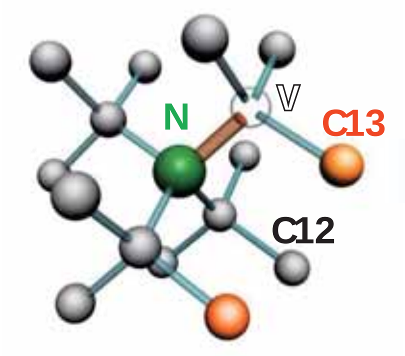
$x = -1 \text{ or } +1$

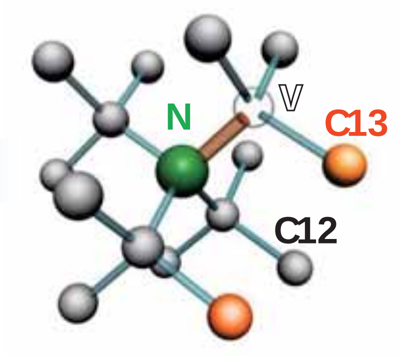
$y = -1 \text{ or } +1$

$a = 0 \text{ or } 1$

$b = 0 \text{ or } 1$

$\Rightarrow S \leq 2$

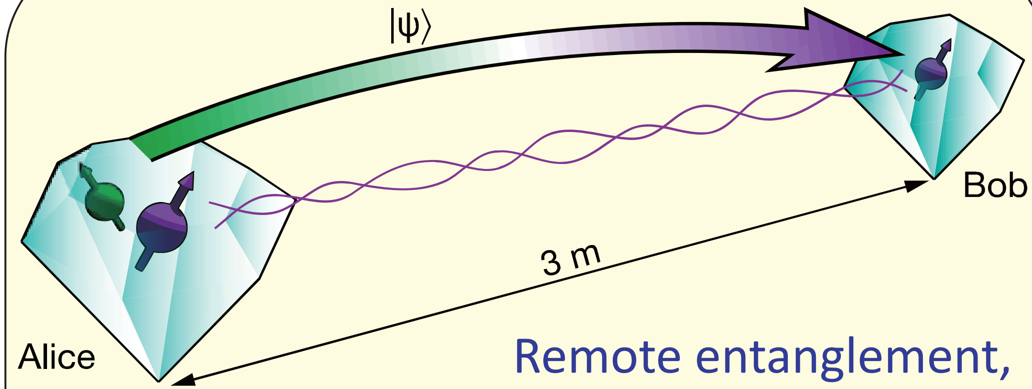




$\Rightarrow S = 2.42$

Delft: Nature 526, 682 (2015)
Vienna: ArXiv 1511.03190
NIST: ArXiv 1511.03189

Outlook: towards quantum networks



Remote entanglement,
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arXiv:1508.05949 (2015)

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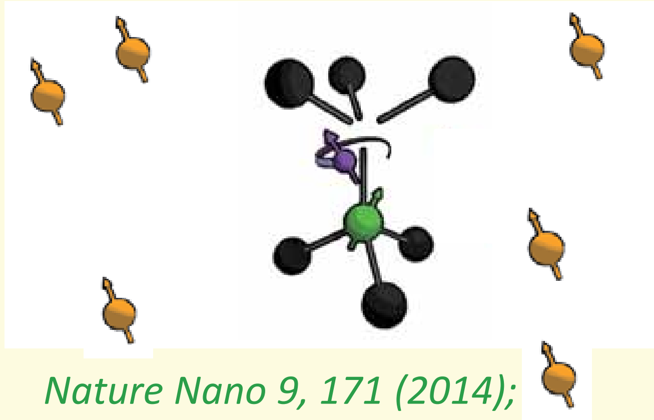

Nature Nano 9, 171 (2014);
arXiv:1508.01388 (2015)

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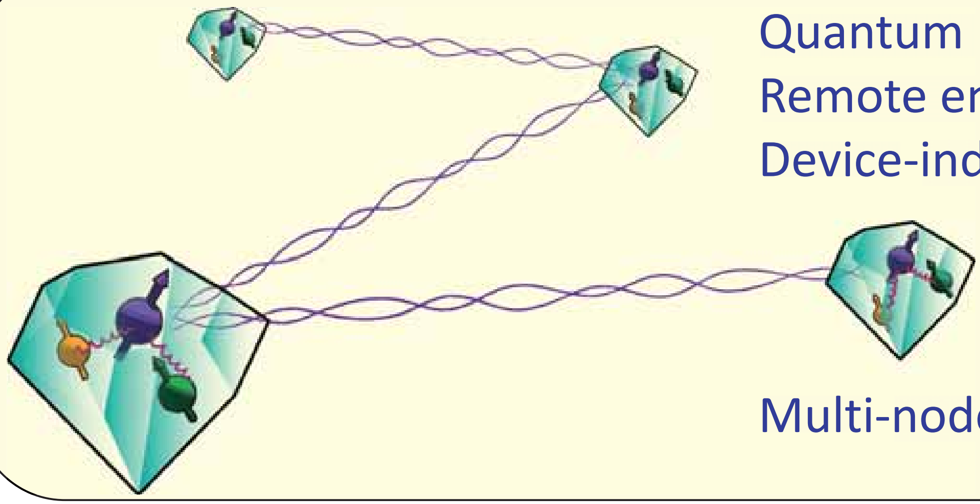


Quantum repeater
Remote entanglement purification
Device-independent QKD

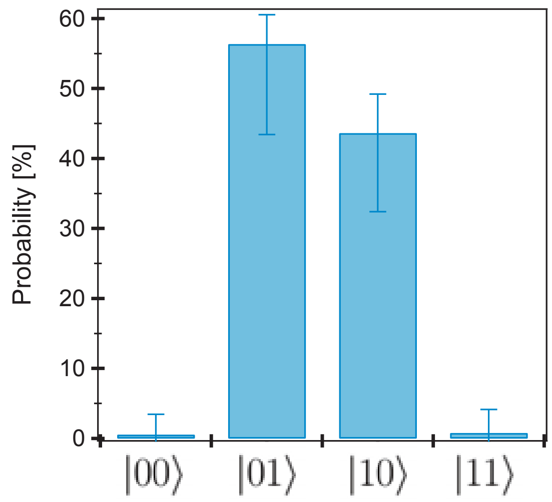
Multi-node quantum network

Entanglement of solid-state qubits over 1.3 km

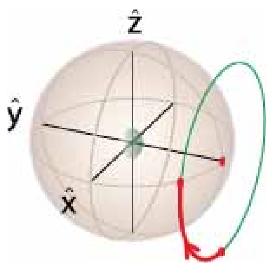
$$|\psi_-\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle) \qquad |\psi_+\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$$

Z-basis

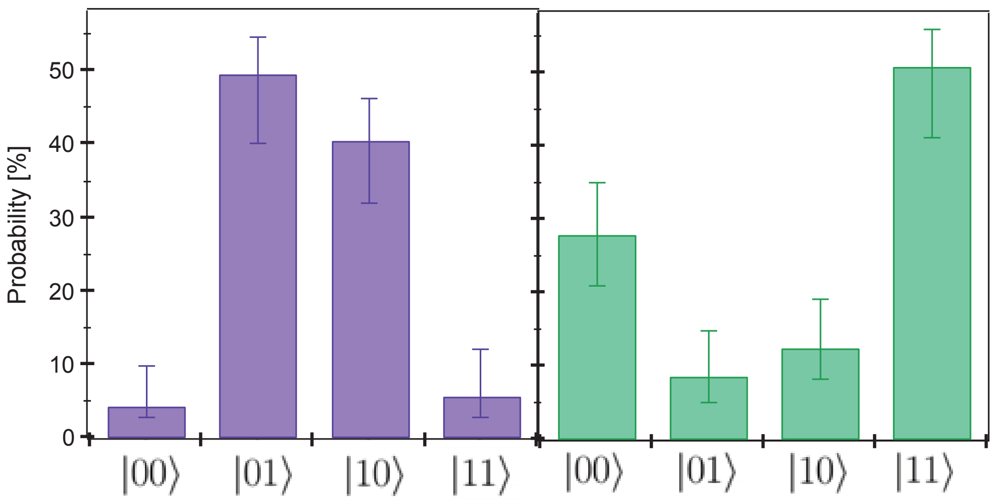
51 events



X-basis



95 events



State fidelity :

$$\mathcal{F}(|\psi_-\rangle) = 83 \pm 6\%$$

$$\mathcal{F}(|\psi_+\rangle) = 74 \pm 7\%$$

⇨ **1st km-scale entanglement state between matter qubits**

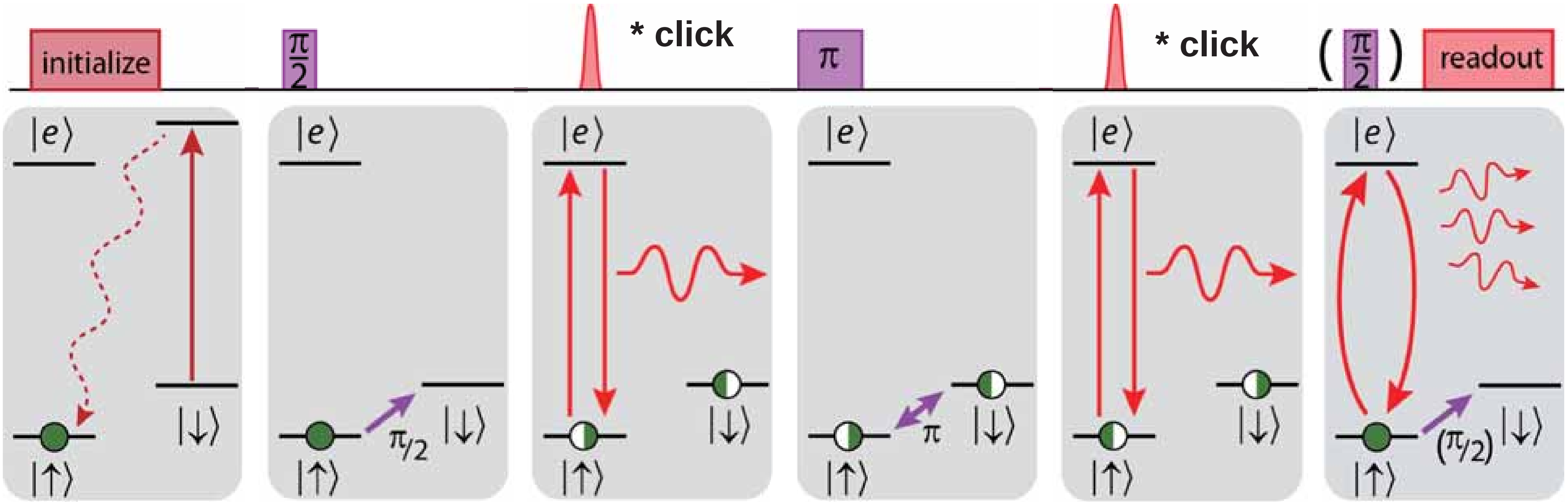
⇨ total acquisition time : ~ 53 h

→ ent. rate limitations ?

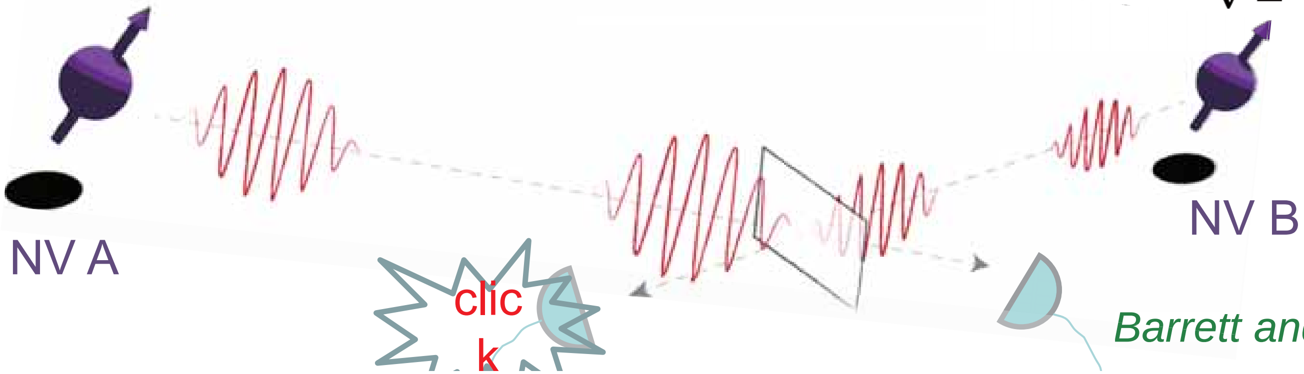
→ NV center emission properties

→ losses in fiber

Entangling distant NV centers: The protocol

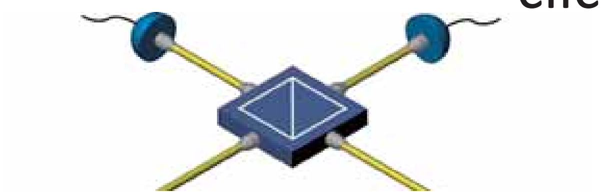


$\frac{1}{2}(|\uparrow_A\uparrow_B\ |\downarrow_A\downarrow_B\rangle + |\downarrow_A\downarrow_B\rangle|0_A0_B\rangle$ **OR** $|\psi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|\downarrow_A\uparrow_B\rangle \pm |\uparrow_A\downarrow_B\rangle)\ )$

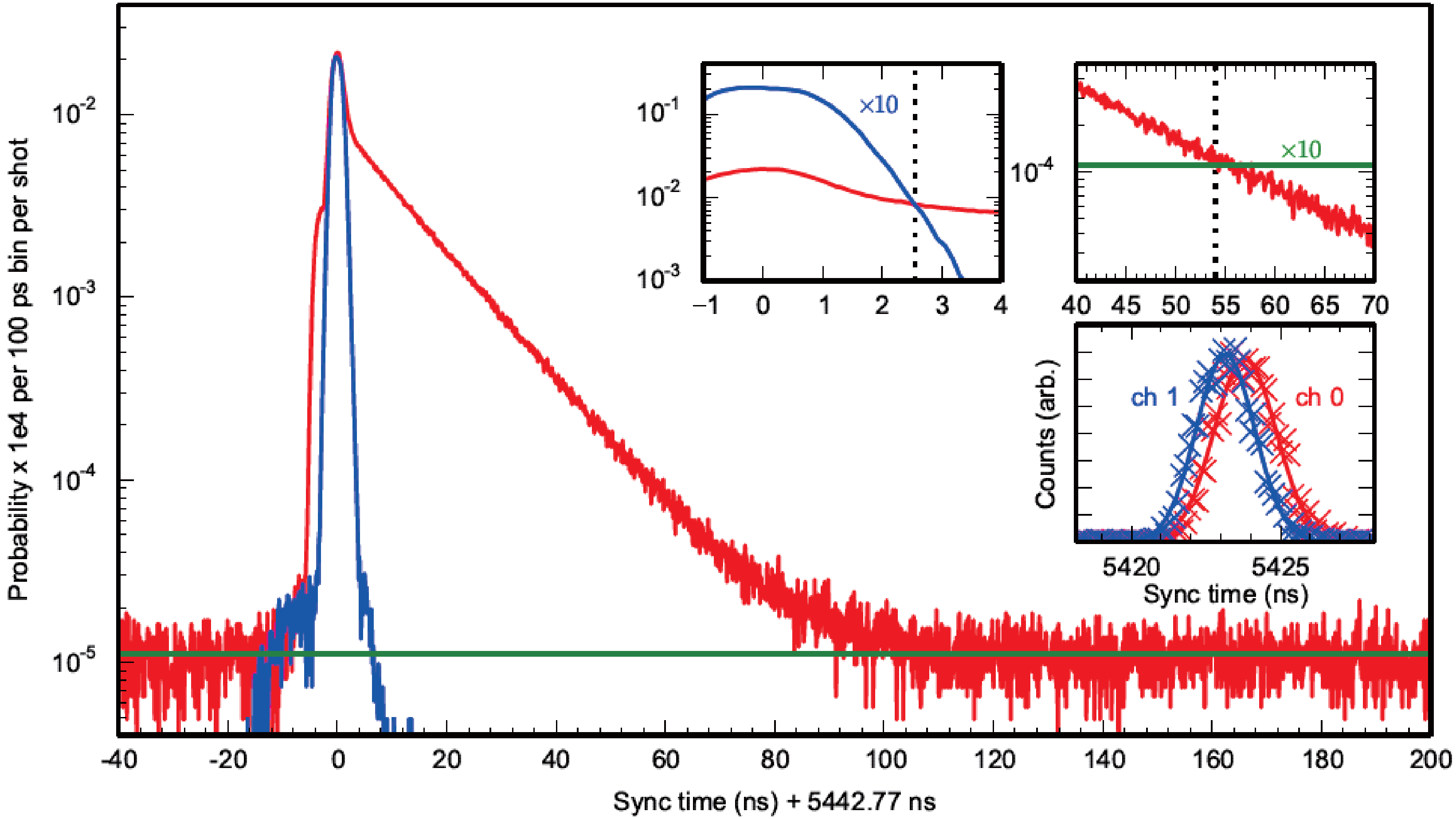


Barrett and Kok, PRA 71, 060310 (2005)

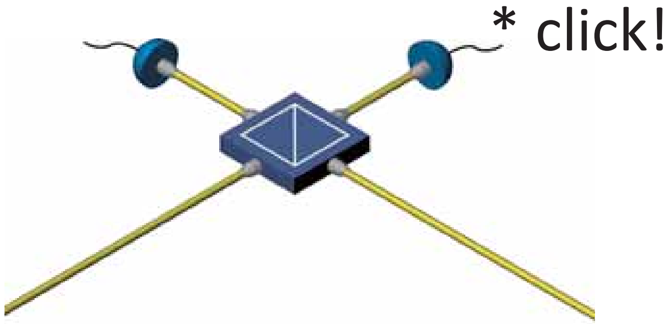
Beyond the pre-set parameter range



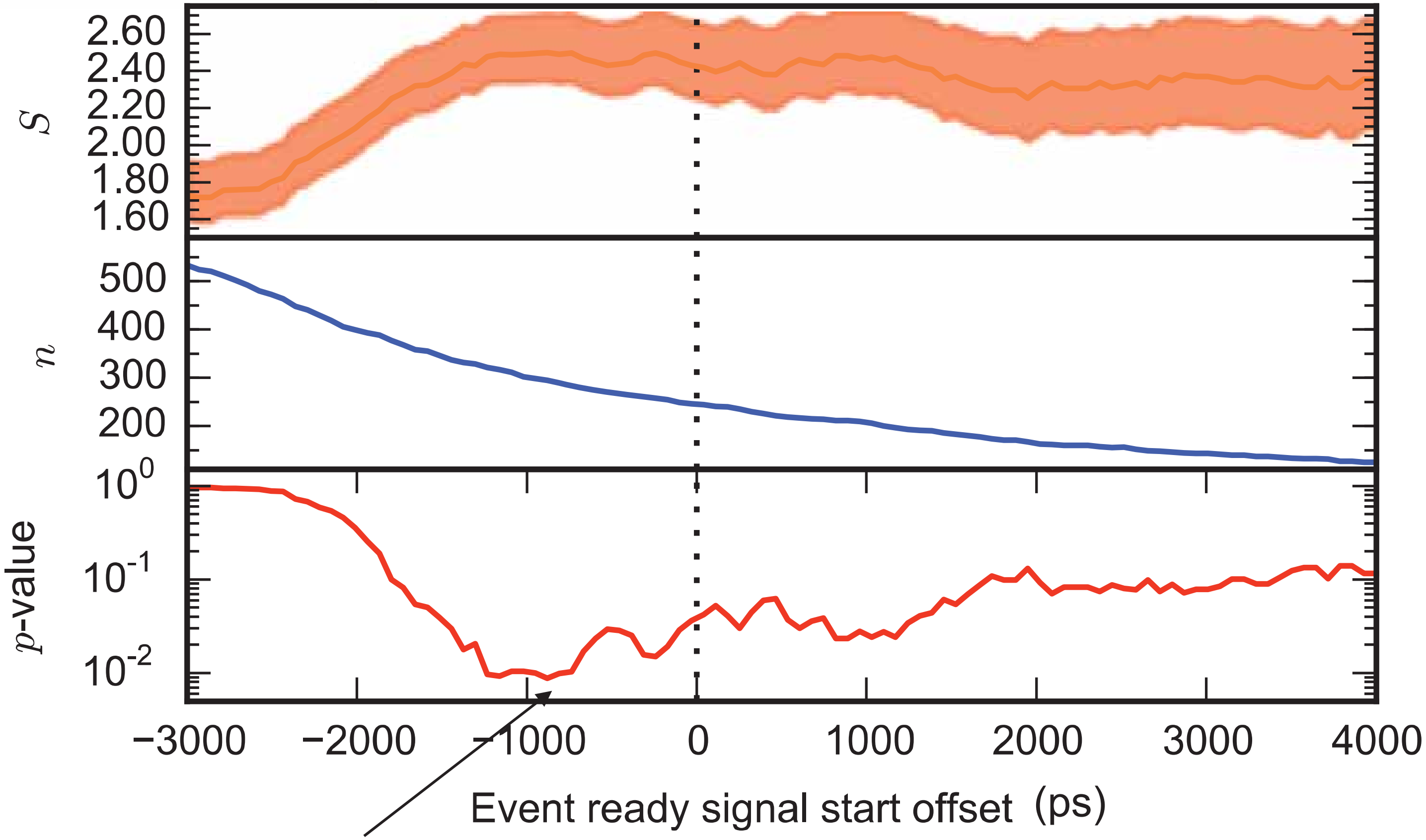
* click!



Beyond the pre-set parameter range



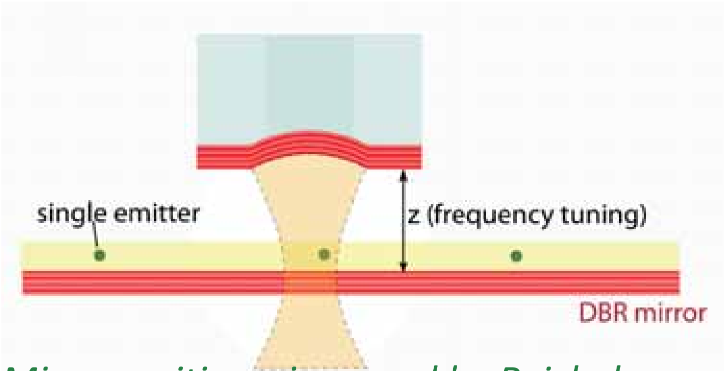
Raw data and analysis scripts are available via http://hansonlab.tudelft.nl



P-value ~ 0.01!

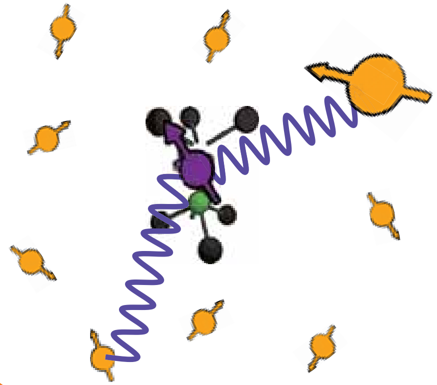
Towards scalable quantum networks

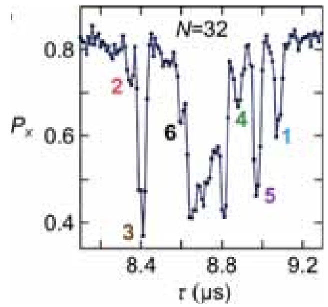
Higher rates: cavities!



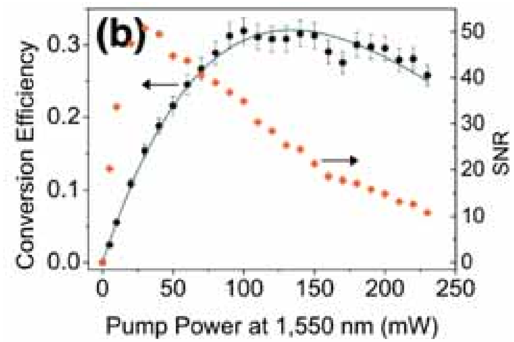
Micro-cavities: pioneered by Reichel group
First NV results Becher, Hunger groups

Preserve quantum memory while generating remote entanglement



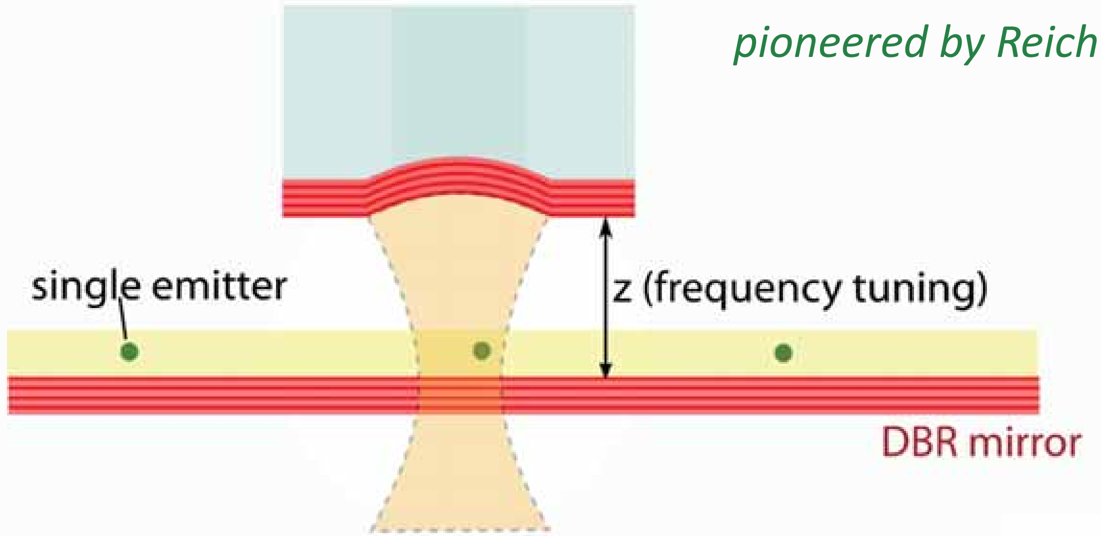


Telecom wavelength conversion



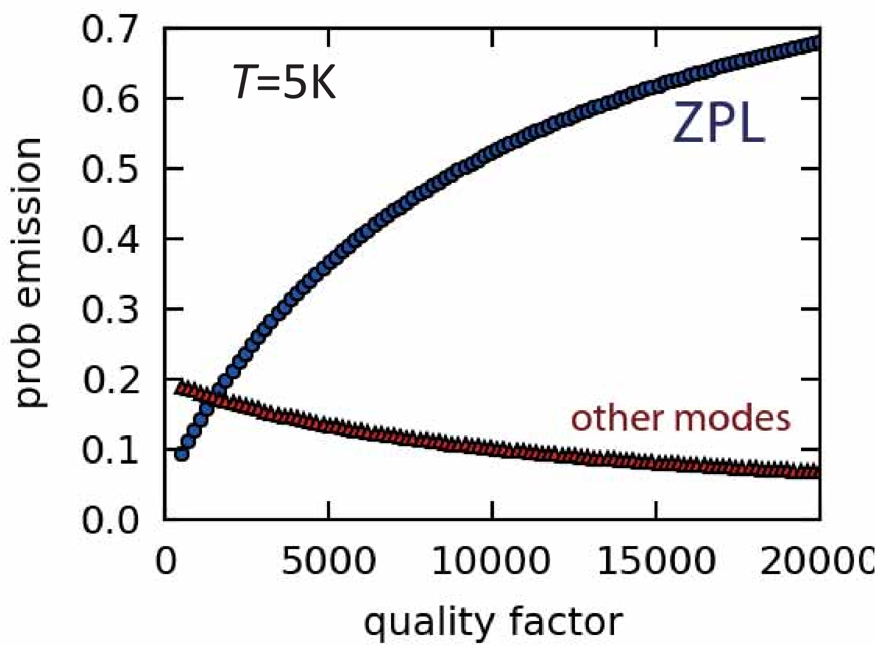
Zaske et al. PRL 109, 147404 (2012)

NV centers in fiber-based Fabry-Perot cavities



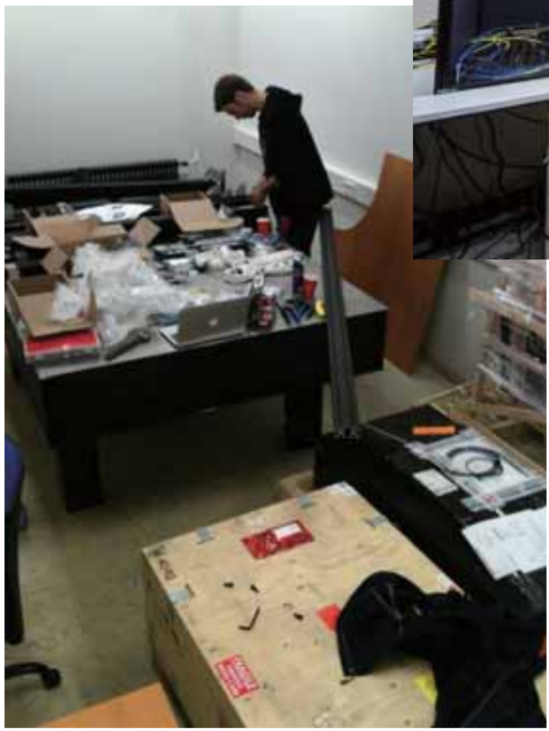
pioneered by Reichel group

- cavity can increase ZPL emission ≈20x => increases entangling rate 400x !
- entangling rate of >1 kHz appears feasible



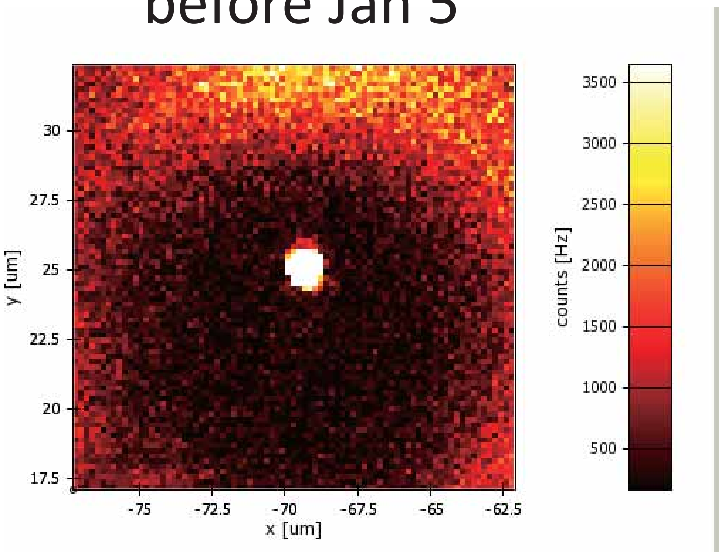
pioneering experiments with NV centers in nanocrystals by Becher and Hunger groups

2014-09 First Cooldown Bob & BS lab ready

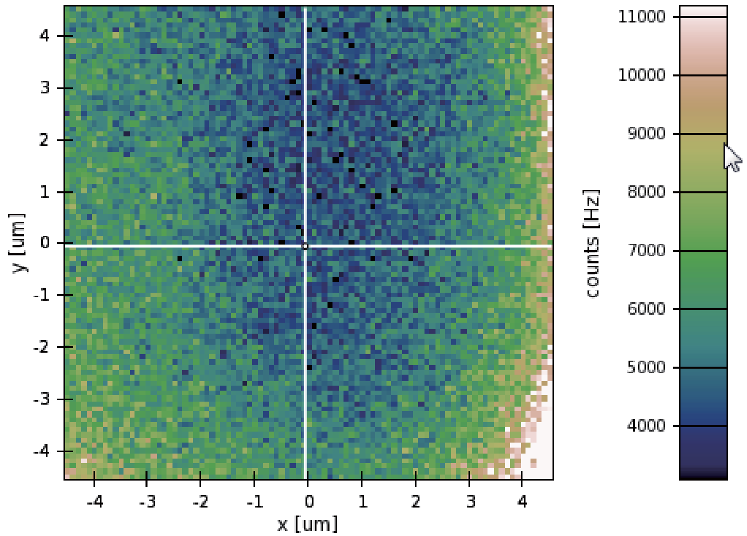


Bob's fate

before Jan 5



After Jan 5



Two good reasons to address the loopholes

John Bell

… you have ruled out that objects in our world can be described by local variables.

→ **Bell test**

Vadim Makarov
(the quantum hacker)

…you can use it to send encrypted data, then even I cannot hack it.

→ **Device independent quantum cryptography**

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

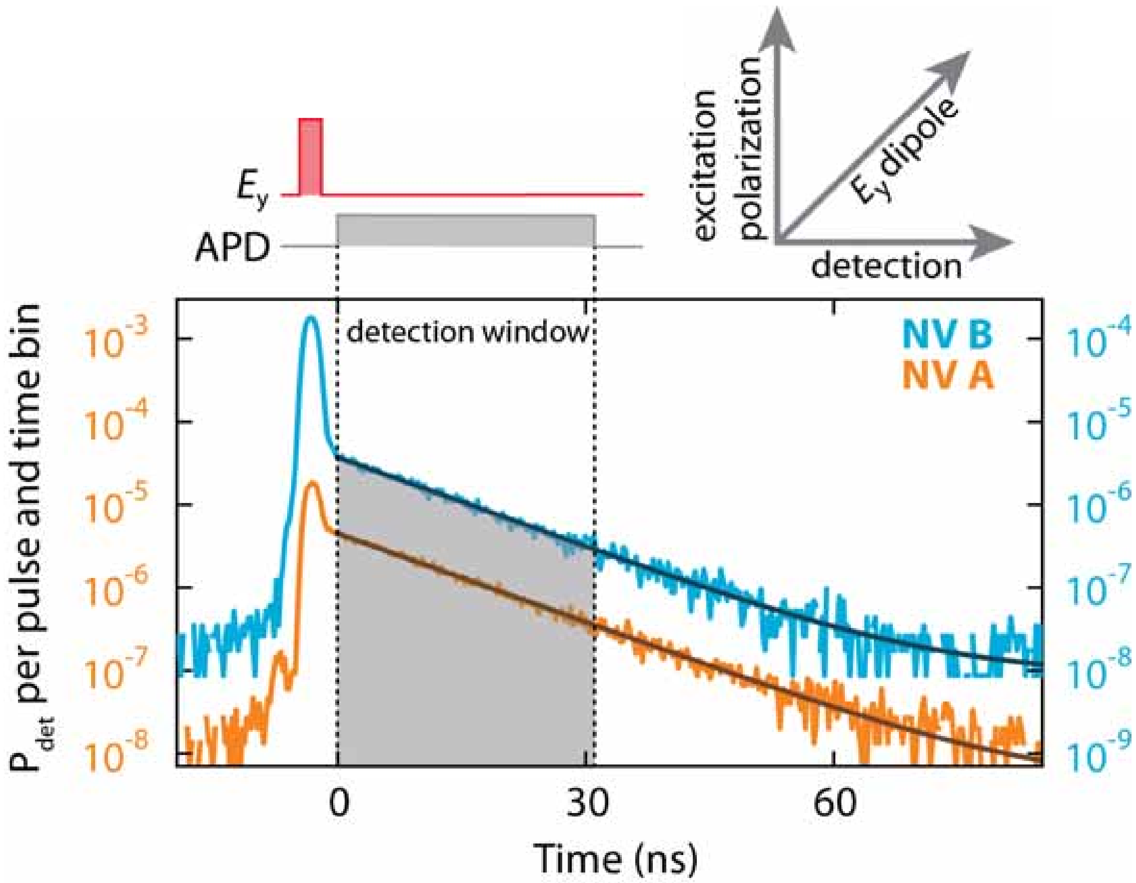
Challenge 1: Resonant excitation + detection

Challenge:

laser pulse contains 10^4 photons

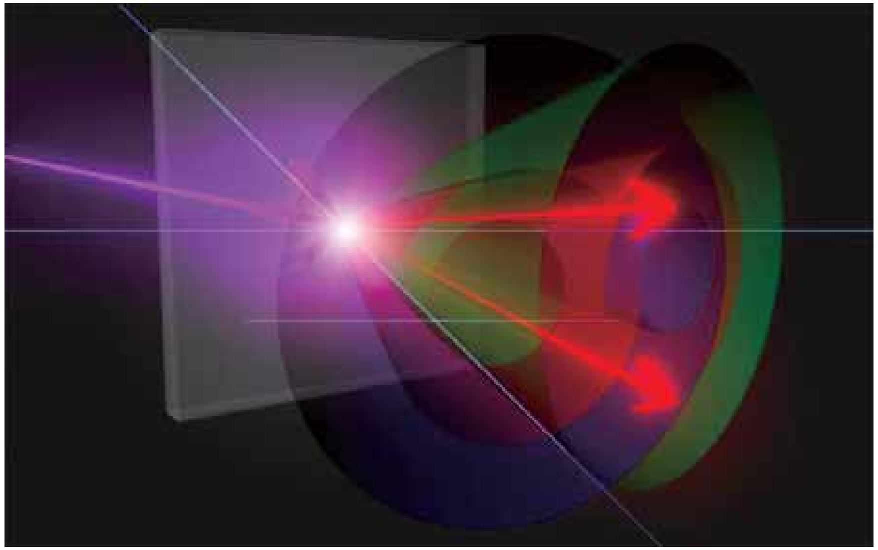
NV emits just 1 photon
+ probability for *resonant* photon emission is only 0.03

need $>10^6$ suppression of laser!

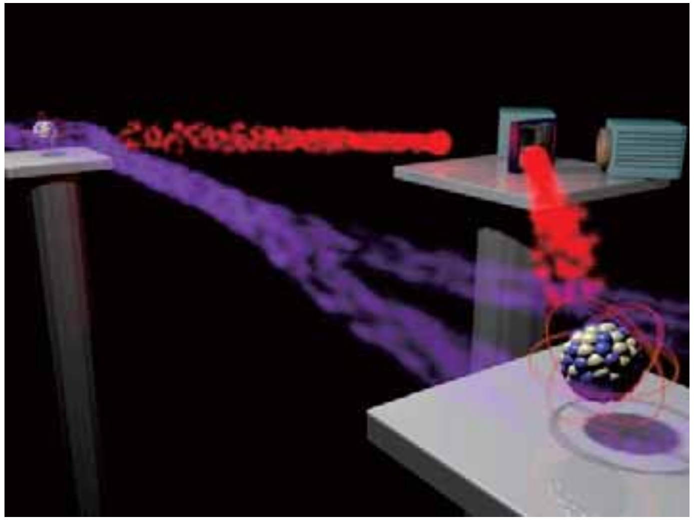


- Time-filtering
- Cross-polarized excitation/detection scheme
- Yields signal-to-background of 70

Race for the first loophole-free Bell test



Photon pairs
Zeilinger group, Vienna
Kwiat group, Illinois
Shalm group, NIST

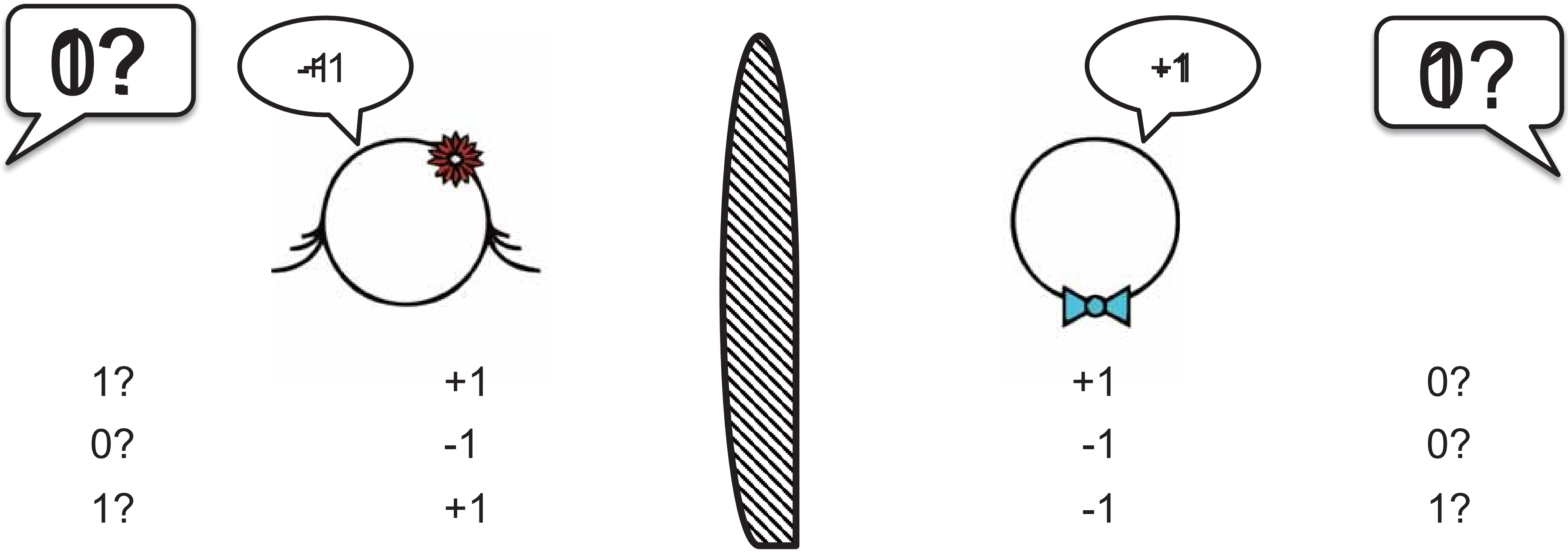


Trapped atoms
Weinfurter group, LMU

Stability

The rules of the game

Two players: Alice and Bob   Two questions: 0? or 1?   Two answers: +1 or -1

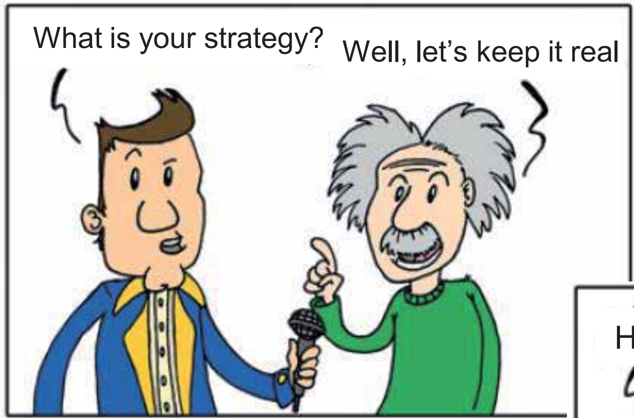


Alice question	Alice answer	Bob answer	Bob question
1?	+1	+1	0?
0?	-1	-1	0?
1?	+1	-1	1?
…	…	…	…

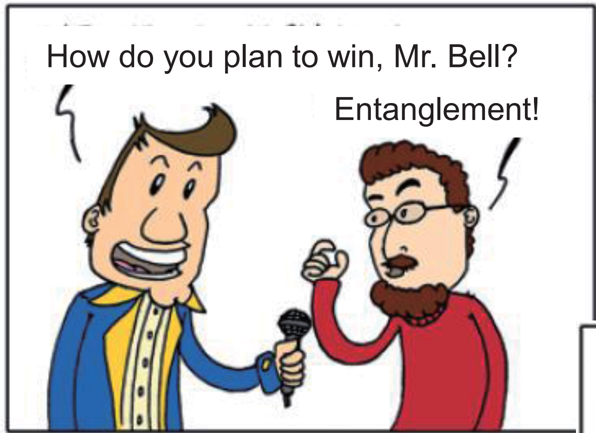
Final score is fraction of correct answers

Questions A, B	Correct answers A, B A, B
0, 0	+1,+1 or -1,-1
0, 1	+1,+1 or -1,-1
1, 0	+1,+1 or -1,-1
1, 1	+1,-1 or -1,+1

Competing teams

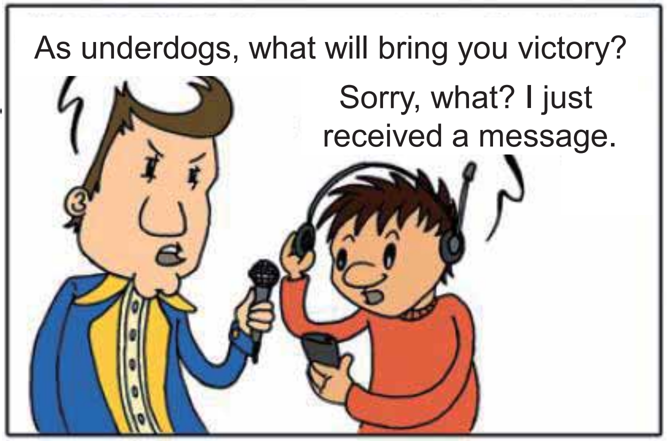


Classical (LHV) strategies:
Max score 3/4 ($S \leq 2$)



Quantum resources:
Max score ~0.85 ($S \leq 2\sqrt{2}$)

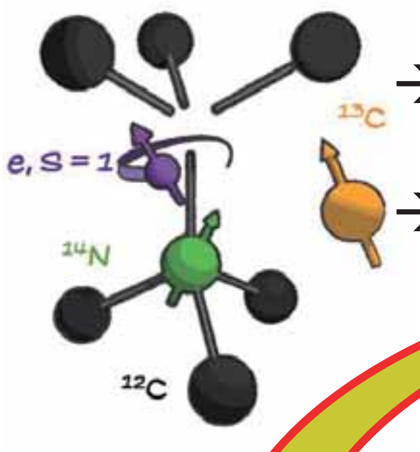
Cheating
(using loopholes):
Max score 100%
($S \leq 4$)



Questions A, B	Correct answers A, B A, B
0, 0	+1,+1 or -1,-1
0, 1	+1,+1 or -1,-1
1, 0	+1,+1 or -1,-1
1, 1	+1,-1 or -1,+1

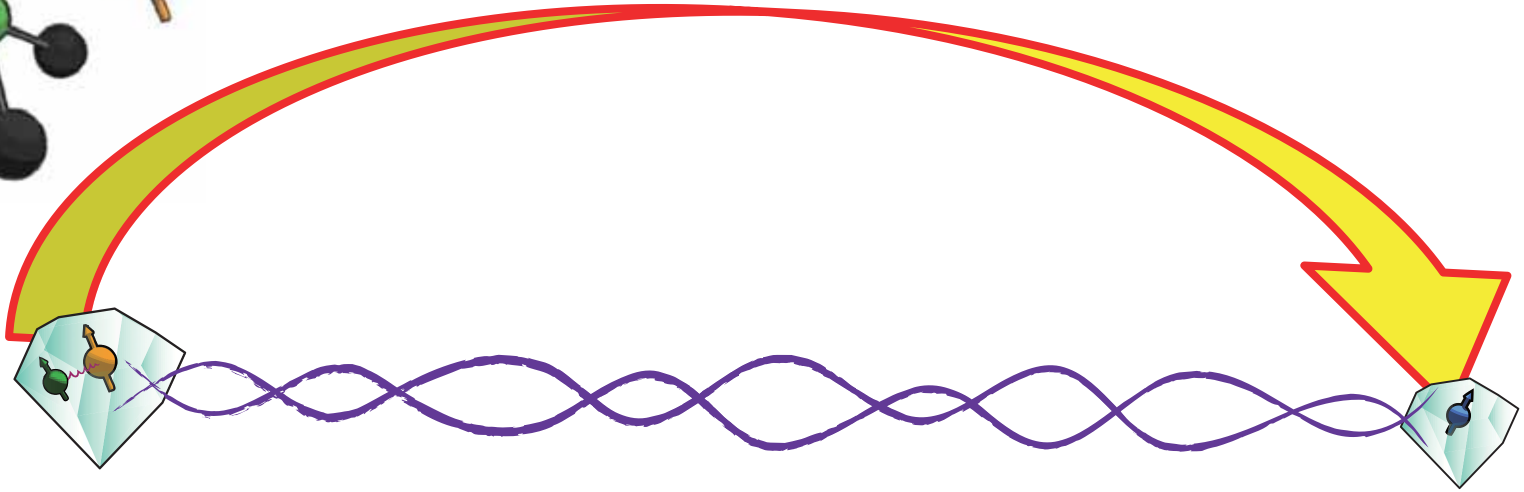
Cartoons by Martijn van Roovert

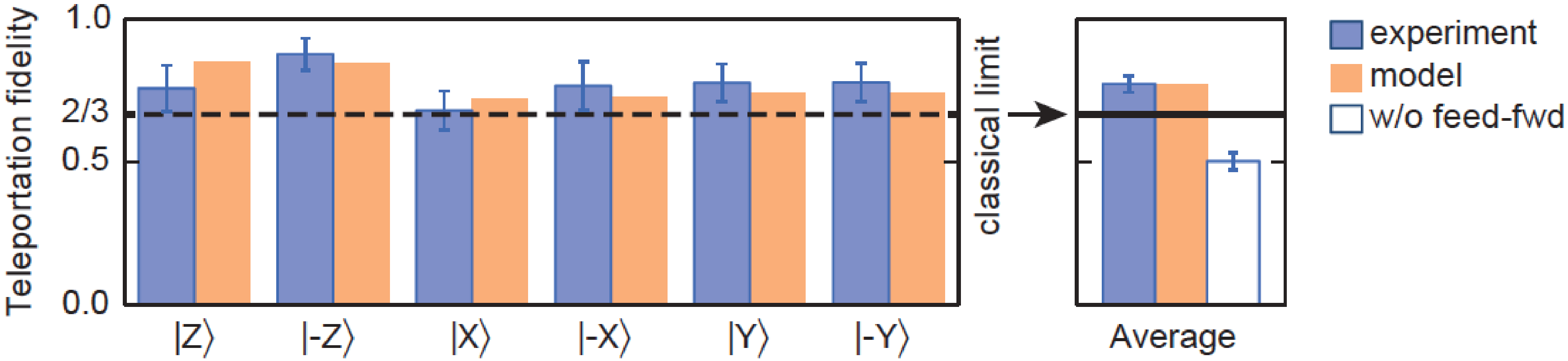
Unconditional remote quantum teleportation



→ Use the host nitrogen **nuclear spin** as an additional qubit and **teleport** its state **to a remote** NV **electronic spin**

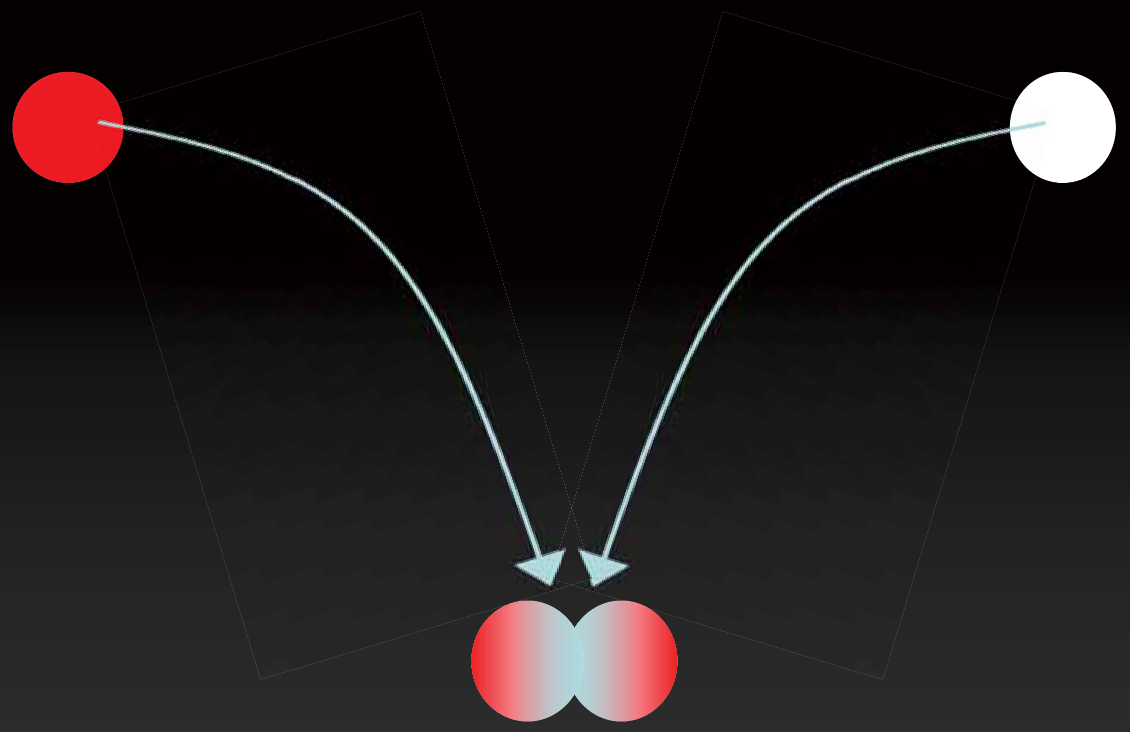
→ **Unconditionally**





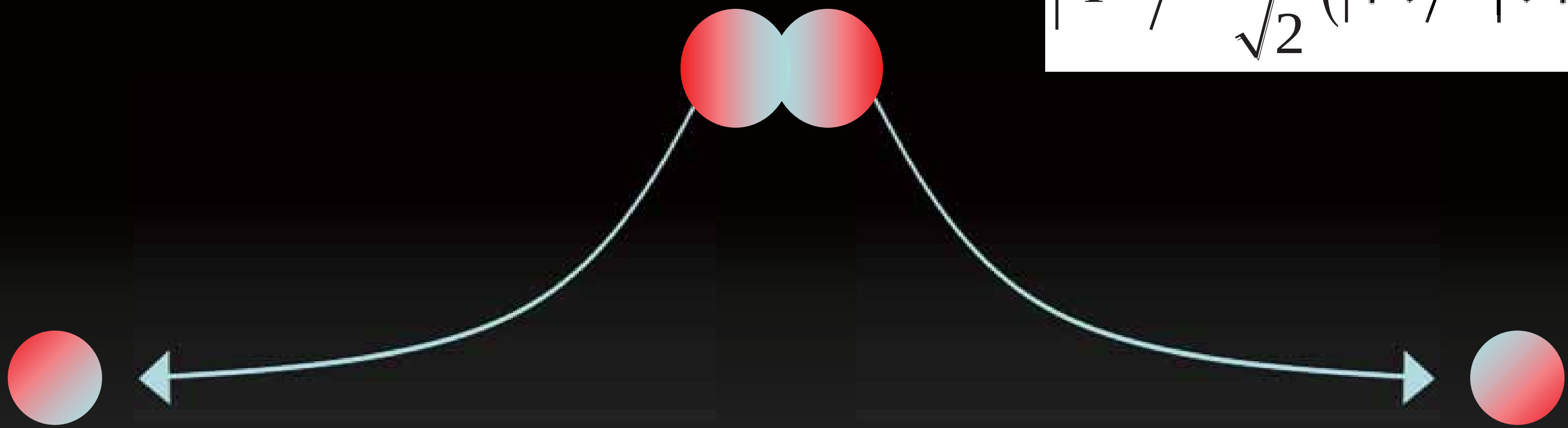
W. Pfaff, et al. Science **345**, 532 (2014)

Quantum entanglement



Quantum entanglement

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



"Properties remain entangled irrespective of distance"

"Instantaneous effect at a distance"

Bas Hensen
Kavli Institute of Nanoscience Delft

A loophole-free Bell test with spin qubits in diamond

H. Bernien (now at Harvard), W. Pfaff (now at Yale), M. Blok, J. Ruitenberg,
J. Cramer, S. Bogdanovic, N. Kalb, A. Dreau,
A. Reiserer, C. Bonato, T. Taminiau
Ronald Hanson

Collaborations:
Wehner group (Delft),
Childress group (McGill), Element 6 (UK)
Morgan Mitchell (ICFO)