40 years of Bell tests

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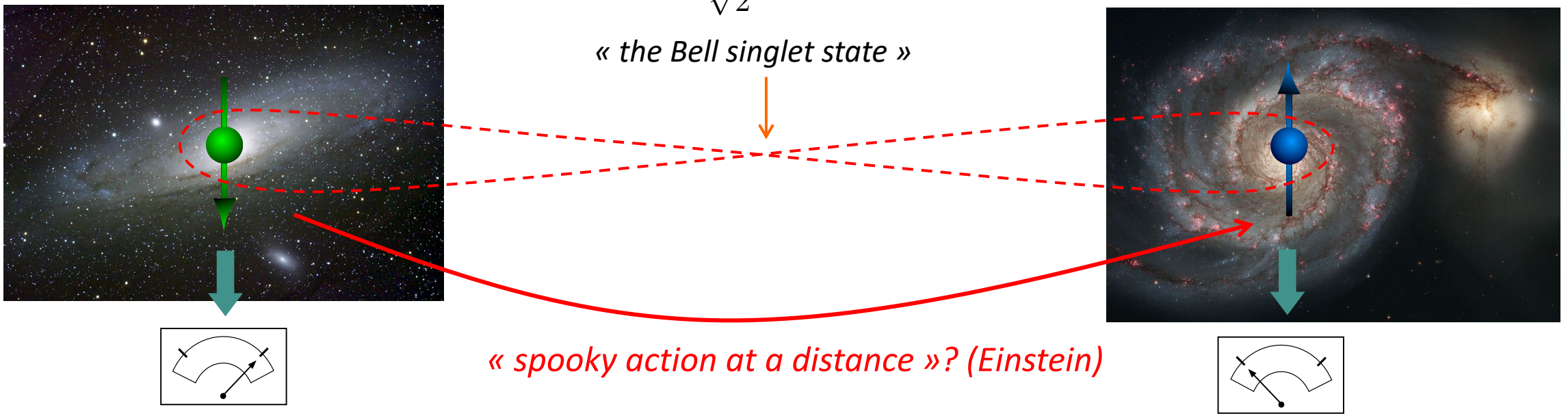
The strangeness of entanglement

maximally entangled state

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

« the Bell singlet state »

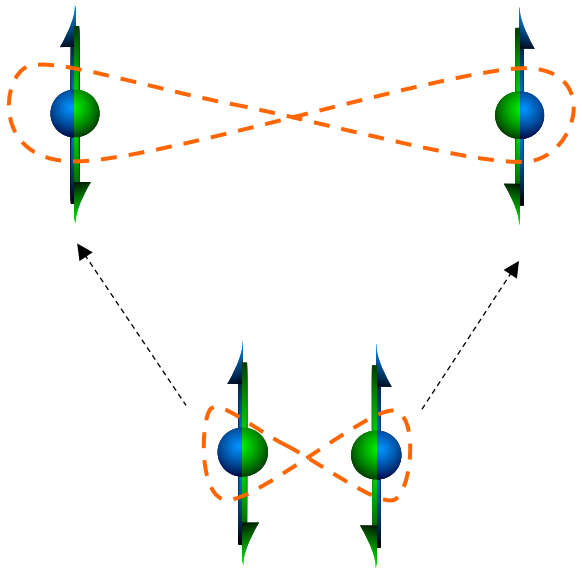


« spooky action at a distance »? (Einstein)

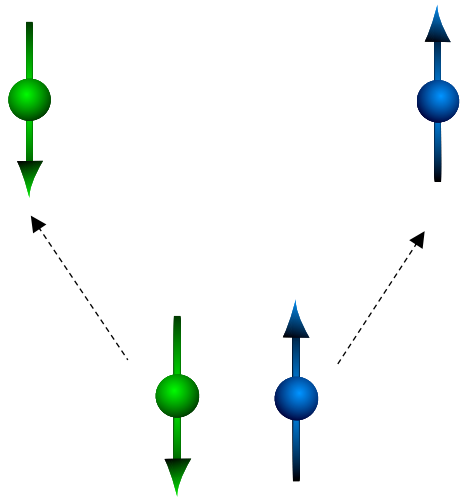
wikiwand.com

Quantum mechanics → measurement outcomes locally random but at distance perfectly correlated!

Quantum non-locality or local realism?



Quantum non-locality ?



local hidden variables ?

(local realism)

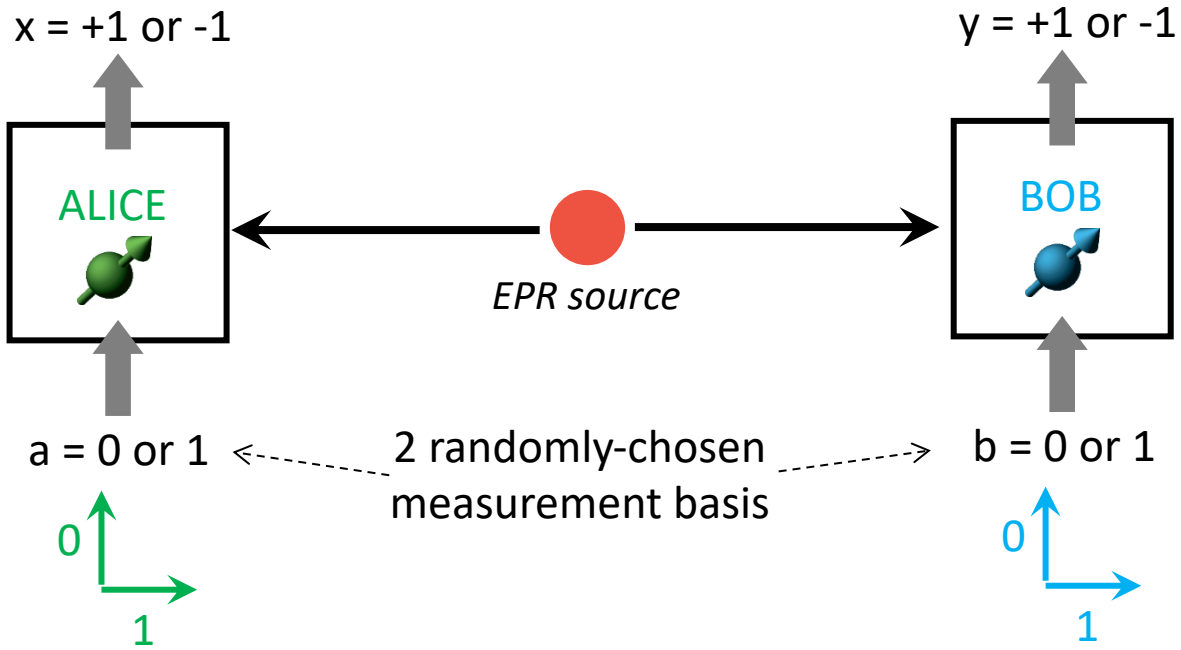
The answer: the Bell test

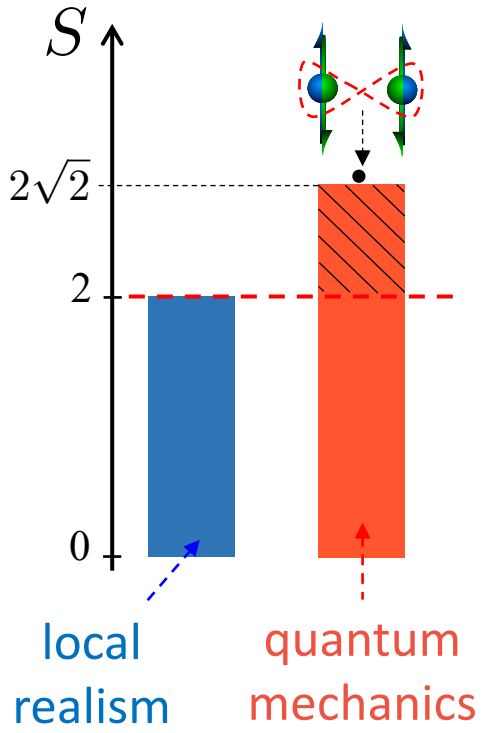
Bell theorem Bell, *Physics* (1964)

→ *analysis of the correlations between* ***independent*** *measurements*

CHSH inequality : Clauser, Horne, Shimony, Holt , *PRL* **23** (1969)

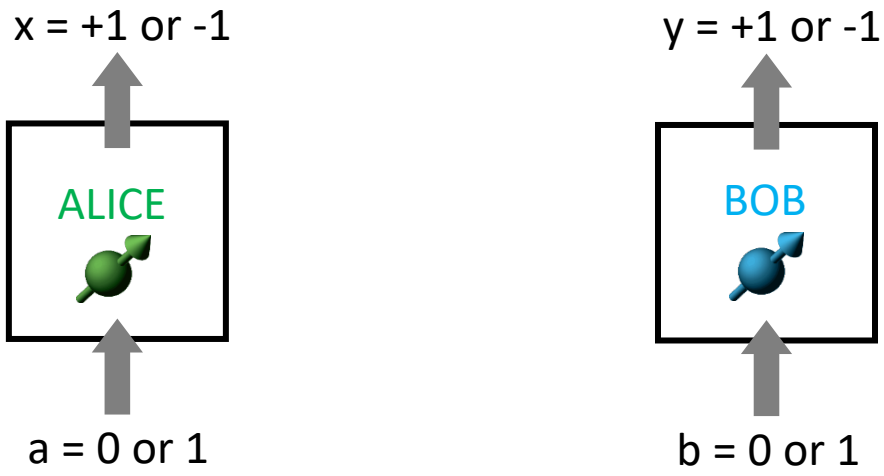
$$S = | \langle x \cdot y \rangle_{(0,0)} + \langle x \cdot y \rangle_{(0,1)} + \langle x \cdot y \rangle_{(1,0)} - \langle x \cdot y \rangle_{(1,1)} |$$





Cheating strategies on the CHSH game

CHSH game presentation inspired from N. Brunner, @GDR IQFA, Grenoble, France (2012)

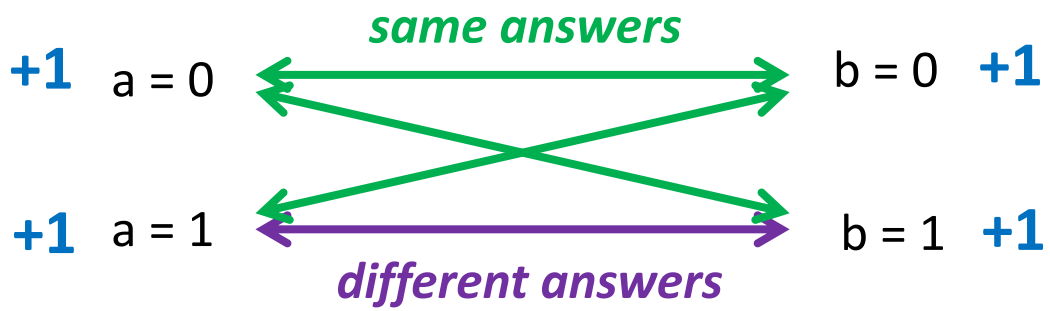


"Classical" strategy
local realism

$$Score \leq 3/4$$

RULES

win if :



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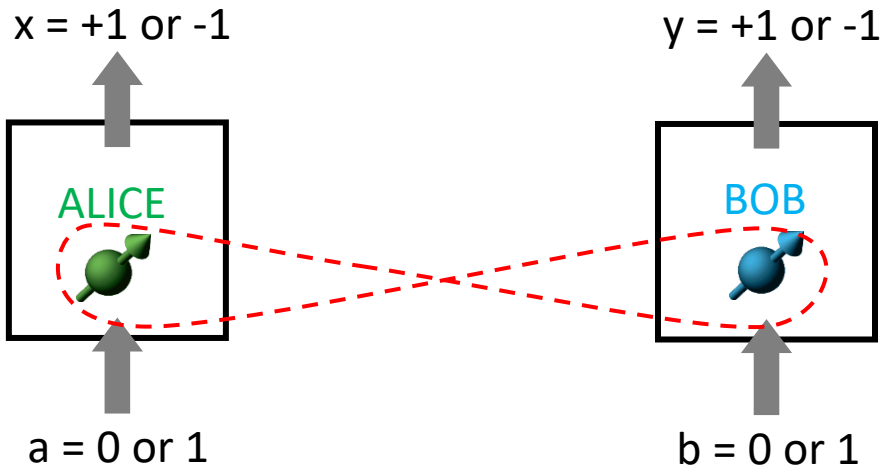


"Classical" strategy
local realism

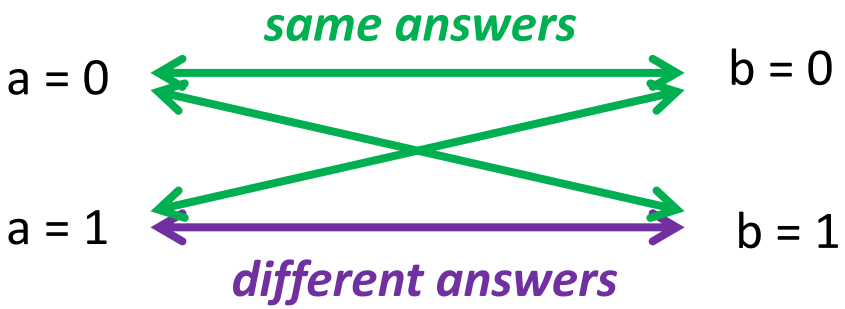
$$Score \leq 3/4$$

Quantum strategy
share entangled particules

$$Score \leq (2+\sqrt{2})/4 \simeq 0.85$$

RULES

win if :



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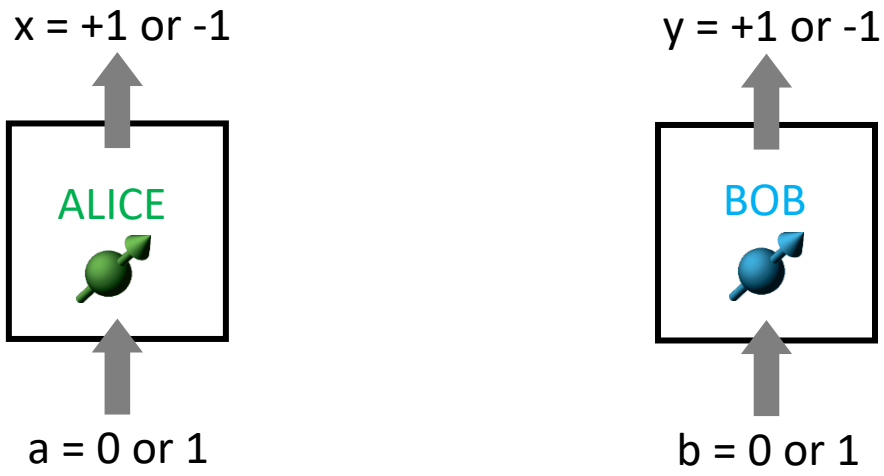


"Classical" strategy
local realism

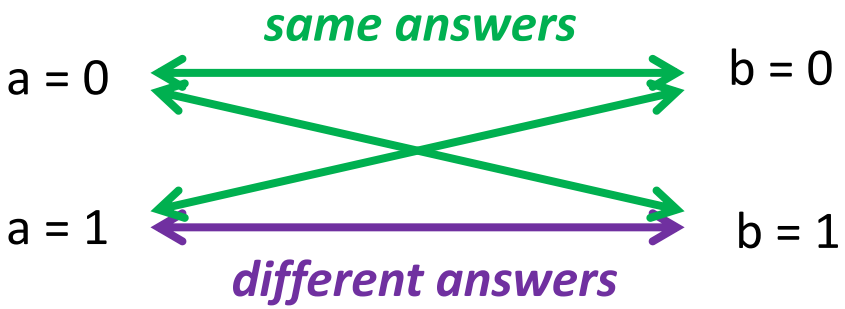
$$Score \leq 3/4$$

Quantum strategy
share entangled particules

$$Score \leq (2+\sqrt{2})/4 \simeq 0.85$$

RULES

win if :



"Cheating" strategy

$$Score = 1$$

-> communication ---> **locality loophole**

-> chosing when to answer ---> **detection loophole**

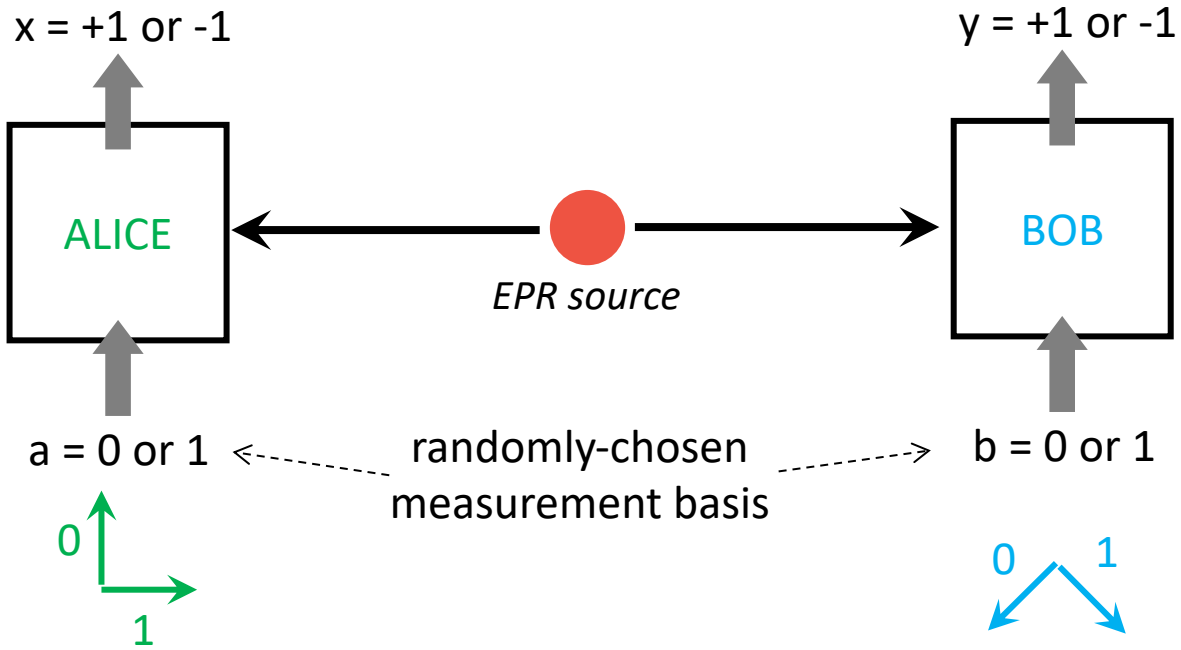
The answer: the Bell test while closing loopholes!

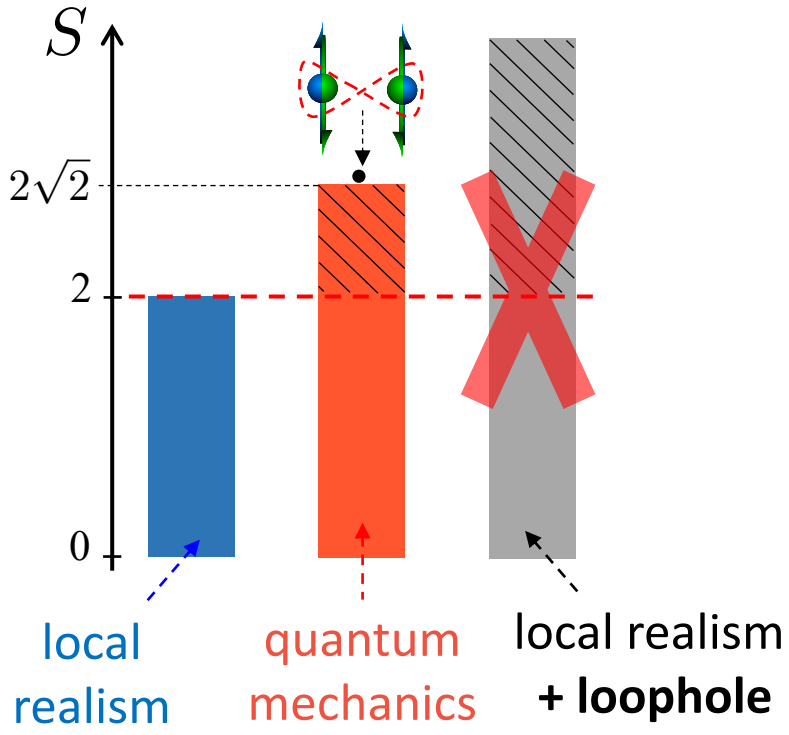
Bell theorem Bell, *Physics* (1964)

→ *analysis of the correlations between* ***independent*** *measurements*

CHSH inequality : Clauser, Horne, Shimony, Holt , *PRL* **23** (1969)

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





A journey through the Bell tests

1. **Closing the locality loophole**

2. **Closing the detection loophole**

3. **Loophole-free Bell tests**

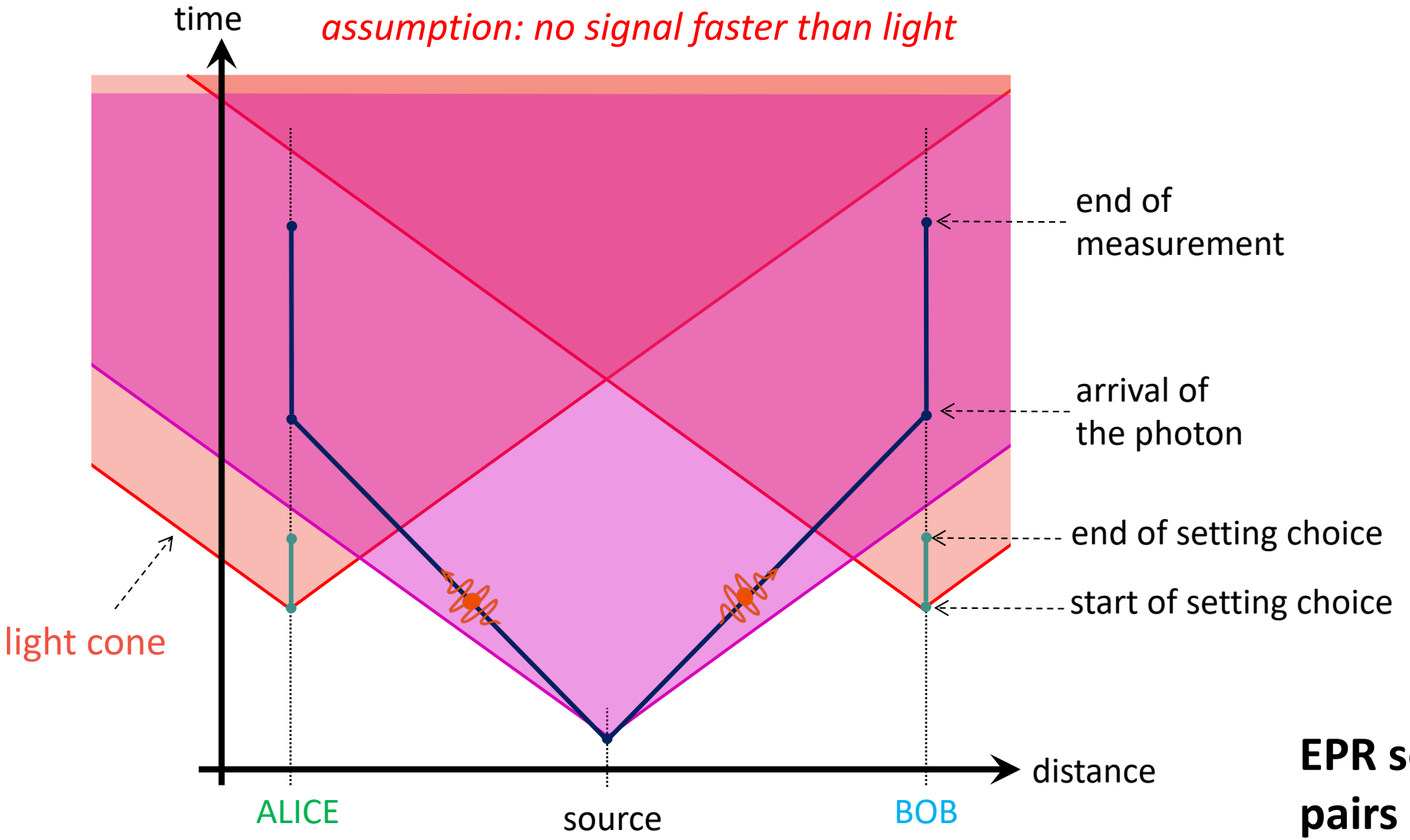
A journey through the Bell tests

1. **Closing the locality loophole**

2. Closing the detection loophole

3. Loophole-free Bell tests

Conditions to close the locality loophole



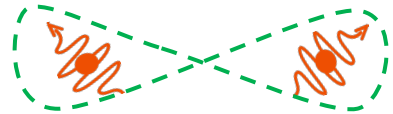
locality loophole

setting choices space-like separated with the source

&

measurements of the particles space-like separated

EPR source =

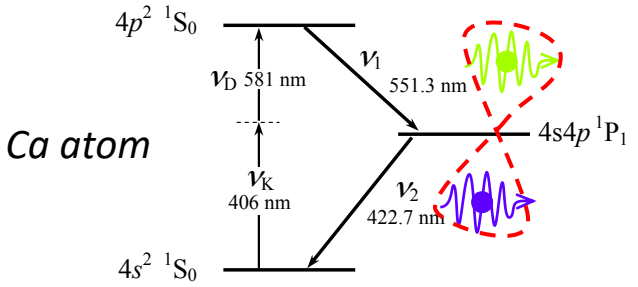


pairs of entangled photons

Changing the settings on the flight of the photons

Aspect, Dalibard and Roger, *Phys. Rev. Lett*. **49** (**1982**) – (Orsay, France)

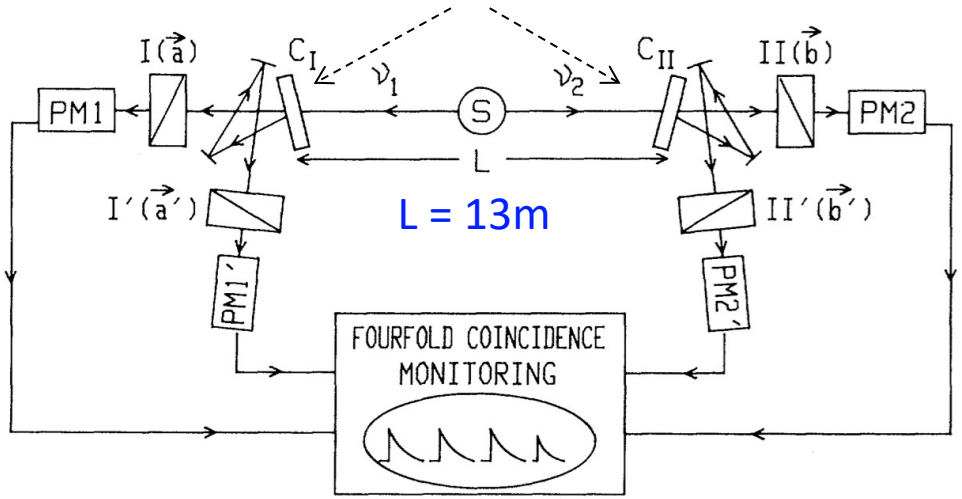
EPR source:



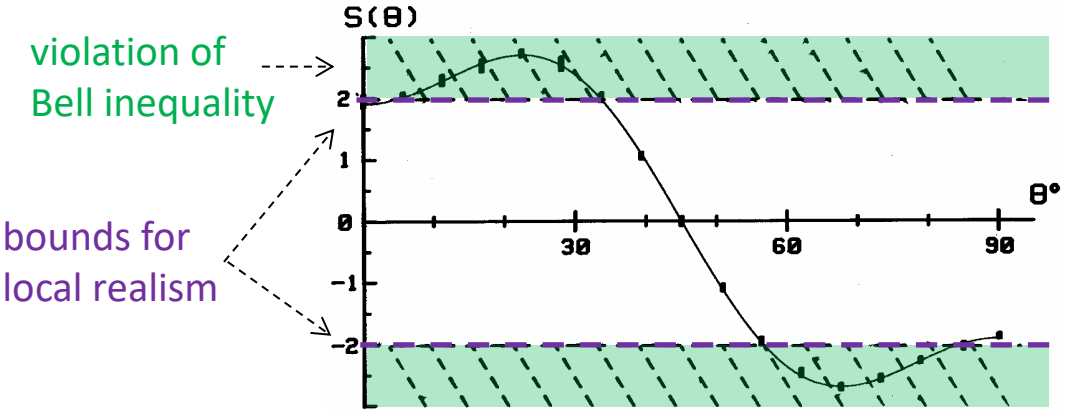
entanglement in polarization

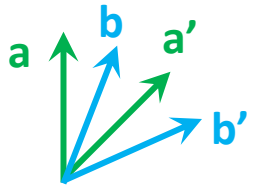
settings not random!

optical switching every 10 ns



Bell parameter S vs polarizers' relative angle





L/c = 40ns > setting switching time

adapted CHSH inequality: $-1 \leq S \leq 0$

$S_{exp} = 0.101 \pm 0.020$

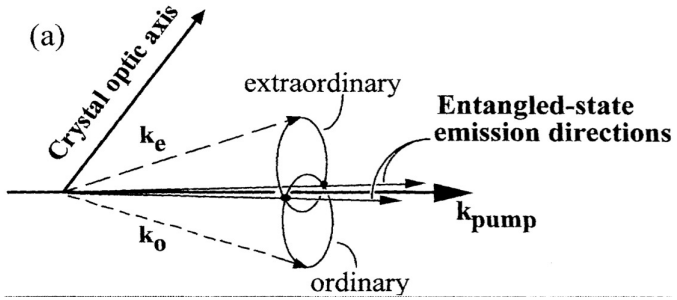
Bell inequality violation!

$(S_{QM} = 0.112, t_{acq} > 3\text{h})$

Aspect, arXiv:quant-ph/0402001 (2004)

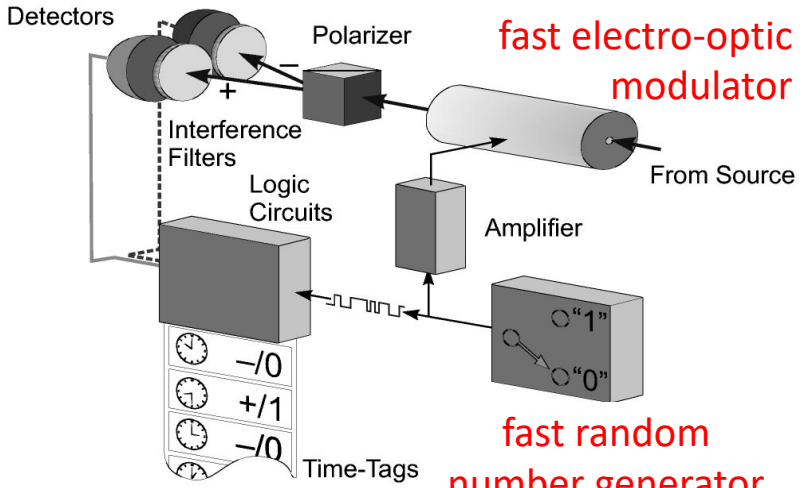
Settings chosen by fast random number generator

Weihs *et al.*, *Phys. Rev. Lett.* **81** (**1998**) – (Zeilinger's group, Innsbruck, Austria)



EPR source:
polarization-entangled photon pairs by parametric down-conversion

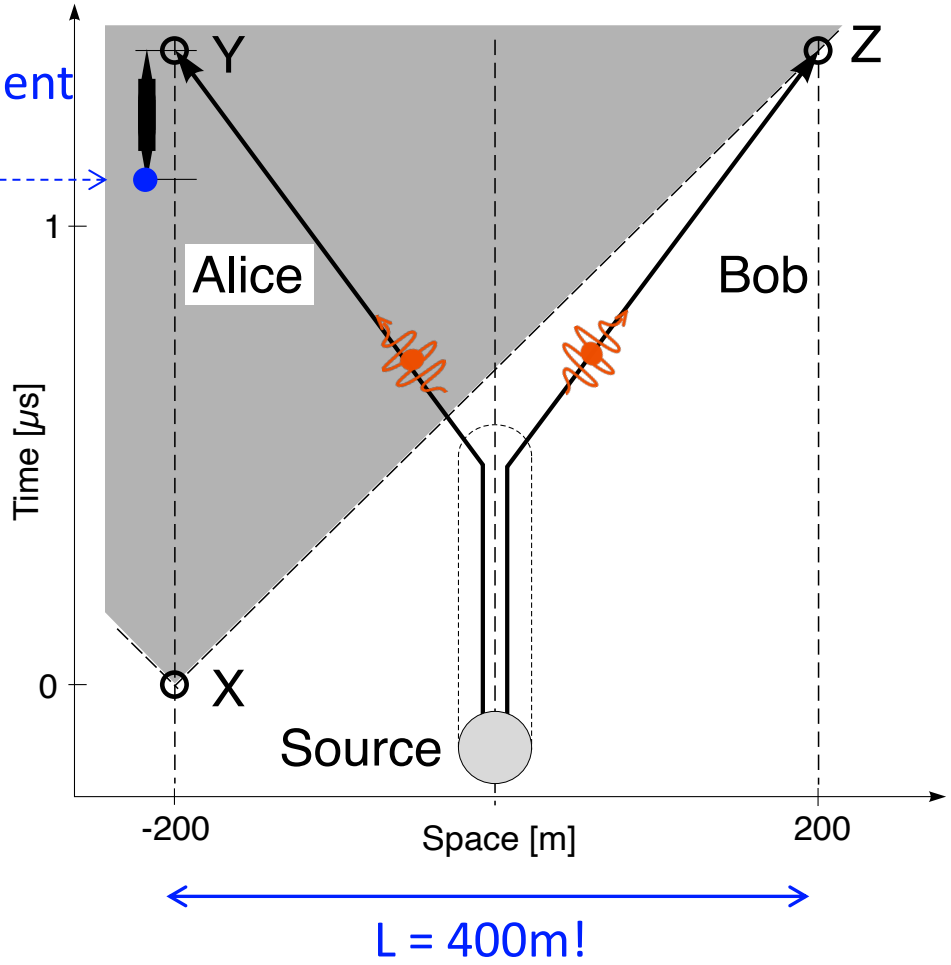
Kwiat *et al.*, *Phys. Rev. Lett.* **75** (1995)



CHSH inequality: $S \leq 2$

$$S = 2.73 \pm 0.02$$

$$(t_{acq} = 10\,\mathrm{s})$$



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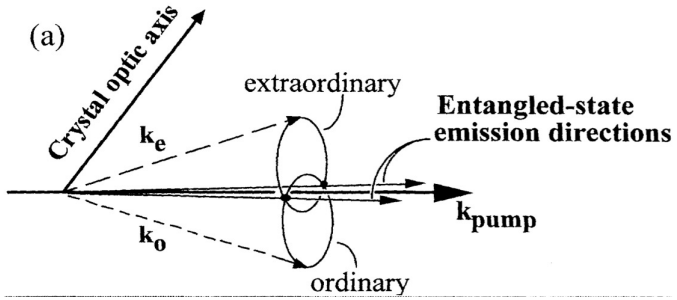

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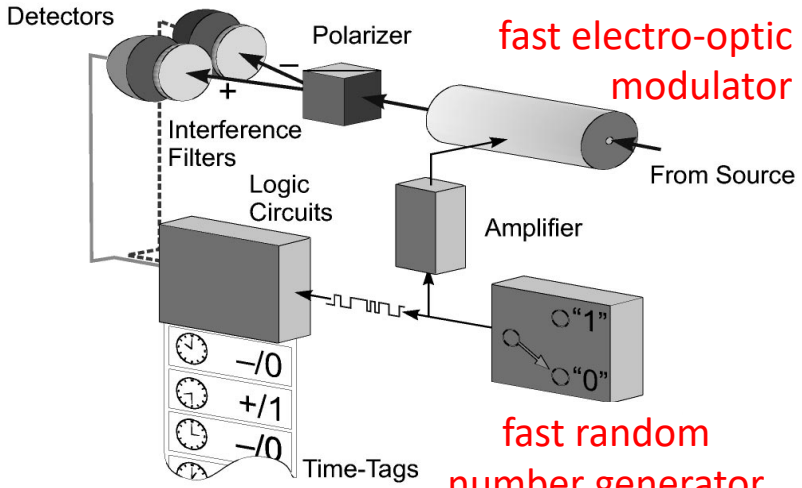


fast electro-optic modulator

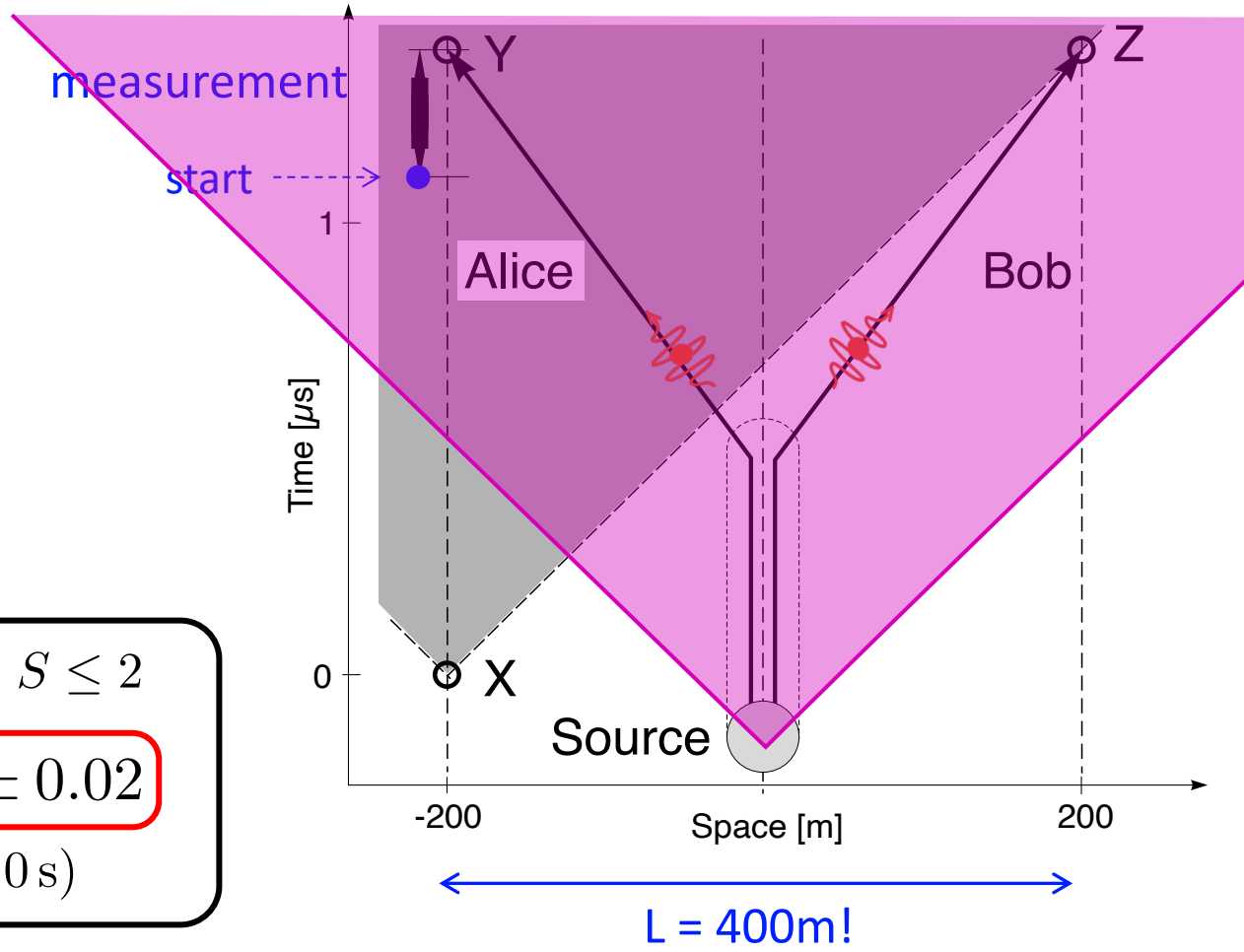
fast random number generator

CHSH inequality: $S \leq 2$

$$S = 2.73 \pm 0.02$$

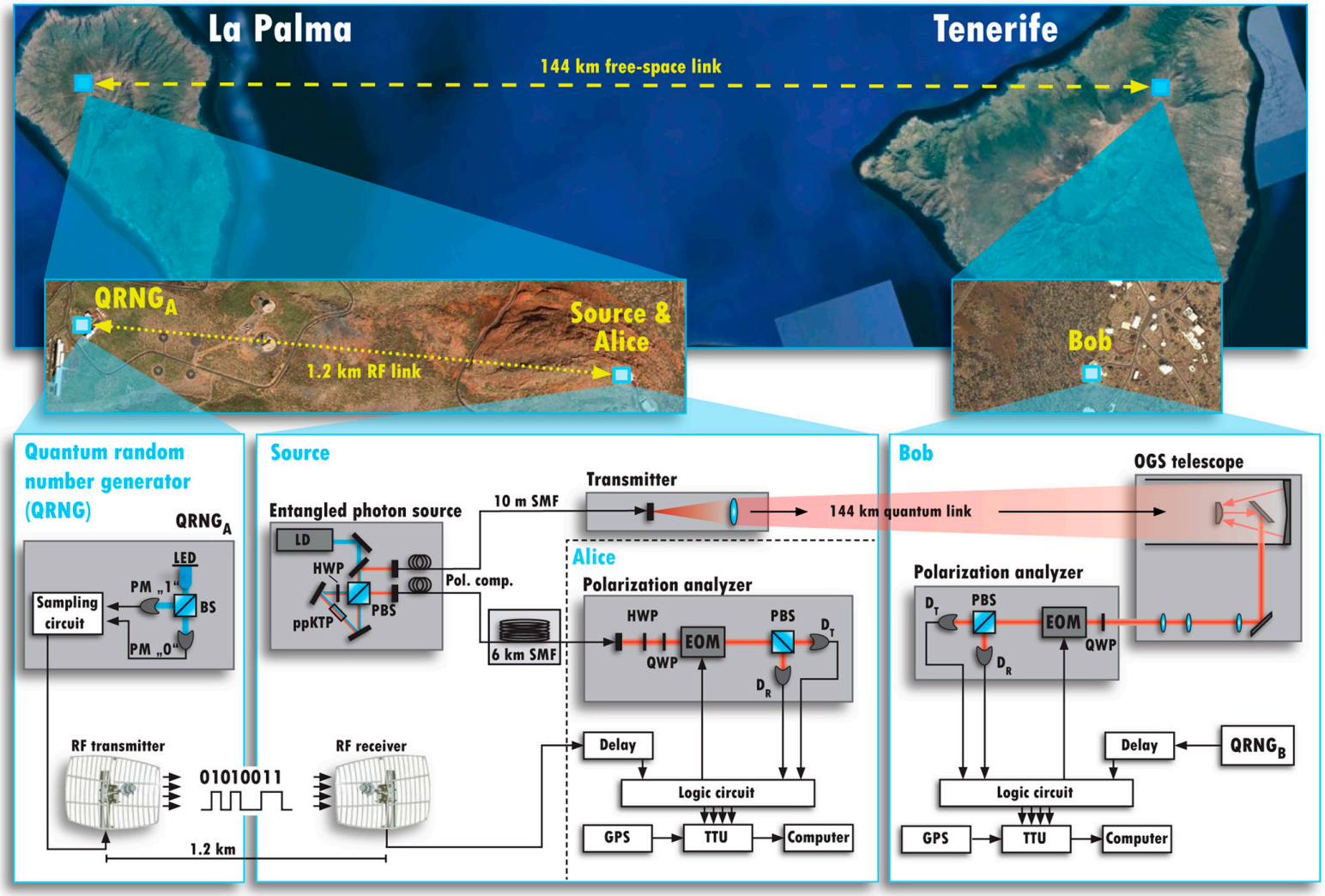
$$(t_{acq} = 10\,\mathrm{s})$$

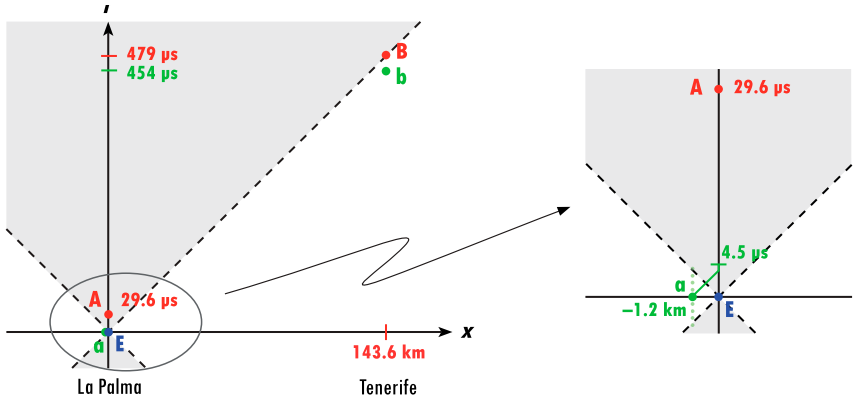
the source could influence the settings



Fully closing the locality loophole

Scheidl *et al.*, *PNAS* **107** (**2010**) – (Zeilinger's group, Vienna, Austria)





locality loophole closed

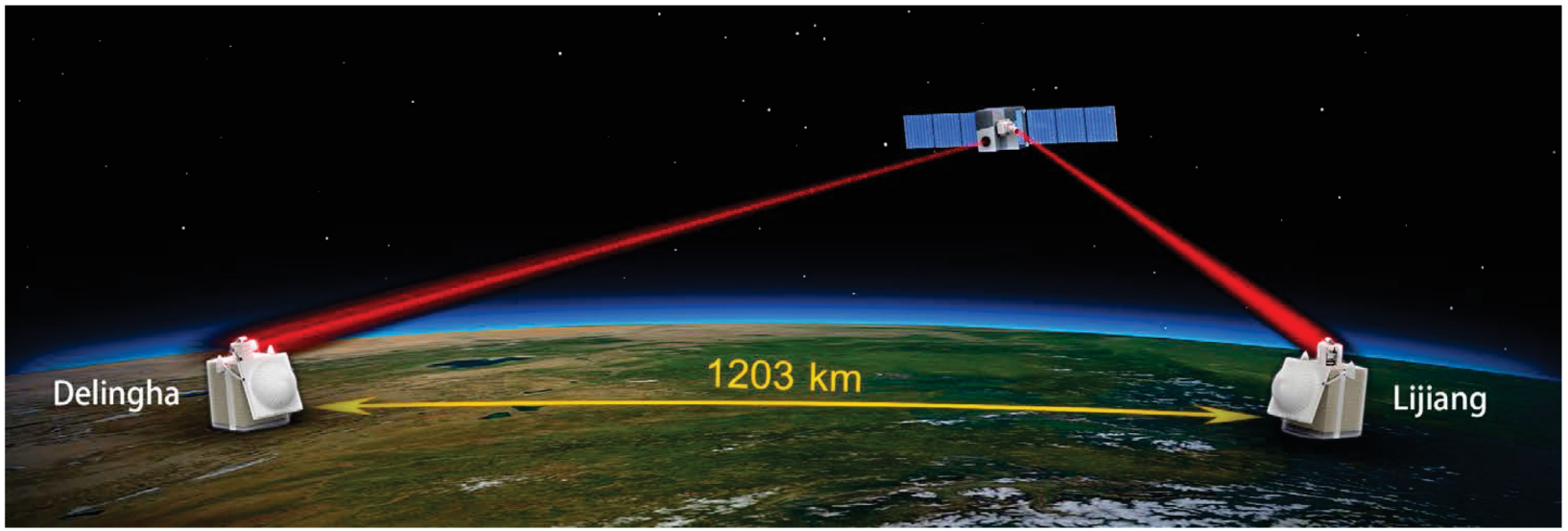
CHSH inequality: $S \leq 2$

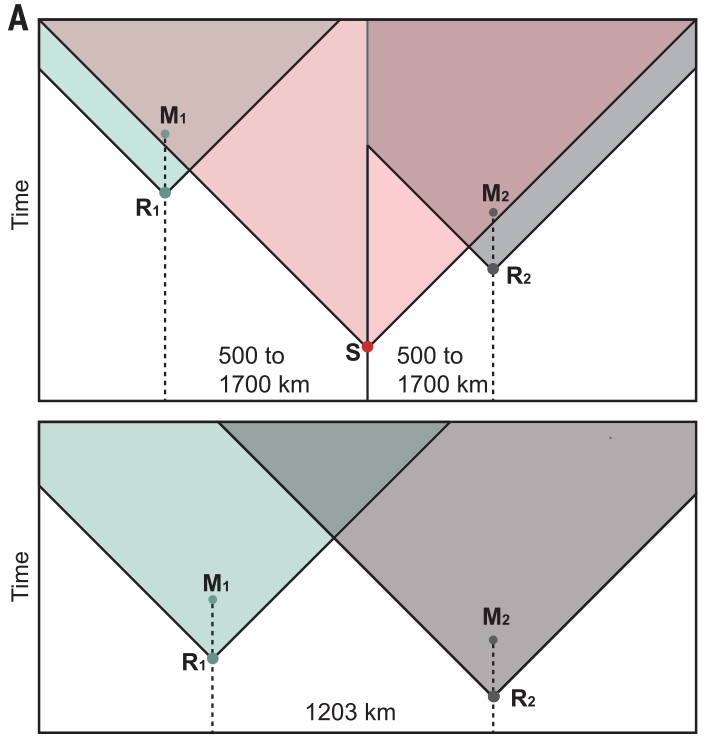
$$S = 2.37 \pm 0.02$$

$(t_{acq} = 40\,\mathrm{min})$

Closing the locality loophole with satellite-to-ground connections

Yin *et al.*, *Science* **356** (2017) – (Pan's group, Heifei, China)





1st Bell test with space-to-ground connection

CHSH inequality: $S \leq 2$

$$S = 2.37 \pm 0.09$$

$$(t_{acq} \simeq 20\,\mathrm{min})$$

locality loophole closed

A journey through the Bell tests

1. Closing the locality loophole *but fair-sampling assumption*

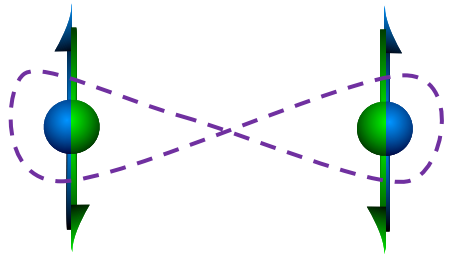
2. **Closing the detection loophole**

3. Loophole-free Bell tests

Condition to close the detection loophole

avoiding the
fair sampling assumption

very challenging
with photons



and with atomic
systems ?

detection loophole

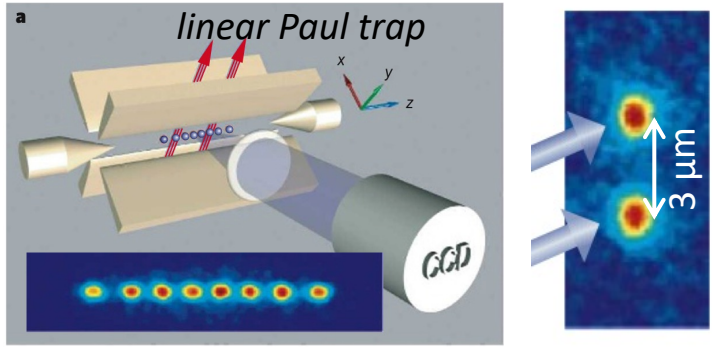
the entangled pairs are detected with high efficiency

Ex: CHSH for singlet state,
detection efficiency ***> 82.8%***

Eberhard, *PRA* **47** (1993)

Closing the detection loophole with trapped ions

Rowe *et al.*, *Nature* **401** (**2001**) – (Wineland's group, NIST, Boulder, USA)



Blatt & Wineland, *Nature* **453** (2008)

entangled pair:
two $^{9}Be^{+}$ trapped ions

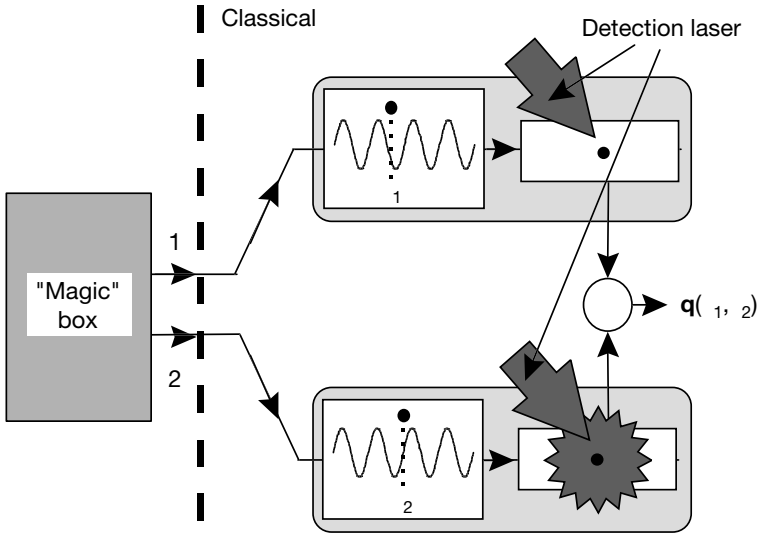
$$|\psi^-\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

detection loophole

the ions are detected all the time!

***single-shot readout** of the spin state:*

$|\downarrow\rangle$ = *bright state* $|\uparrow\rangle$ = *dark state*



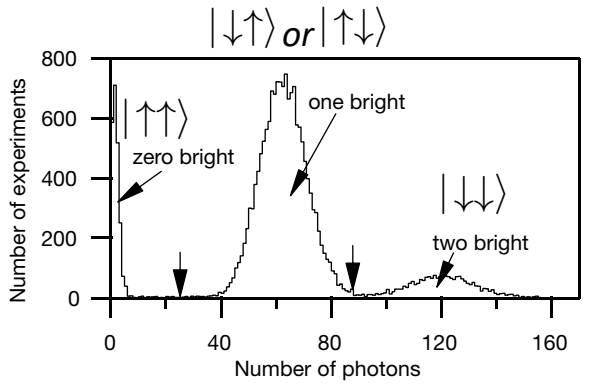
CHSH inequality: $S \leq 2$

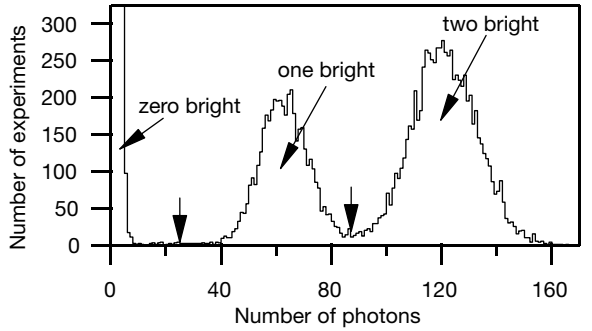
$$S = 2.25 \pm 0.03$$

increasing the distance between ions:

1m: Matsukevich et al., *PRL* **100** (2008)

20m: Hofman et al., *Science* ***337*** (2012)



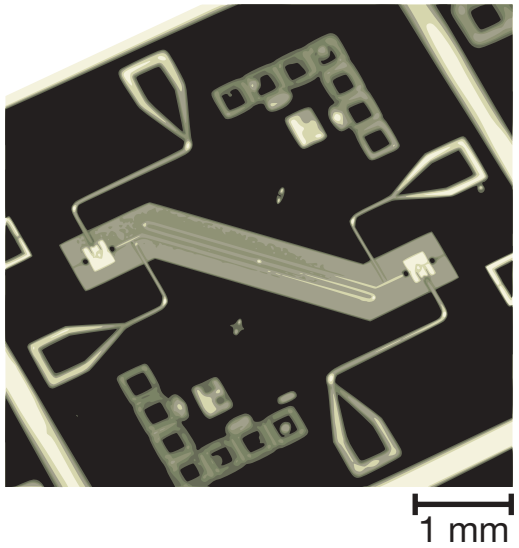


… and with superconducting circuits

Ansmann *et al.*, *Nature* **461** (**2009**) – (Martinis's group, Santa Barbara, USA)

detection loophole

the qubits are detected all the time!

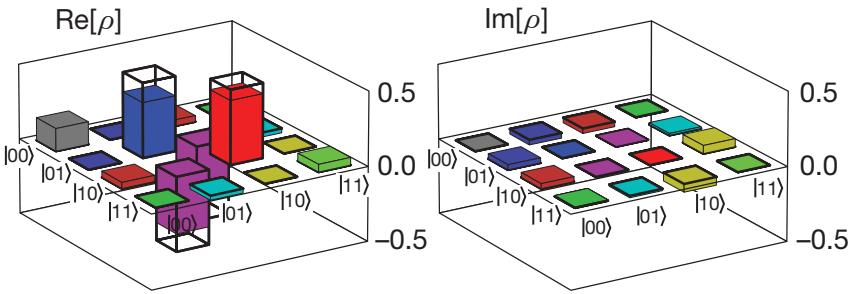


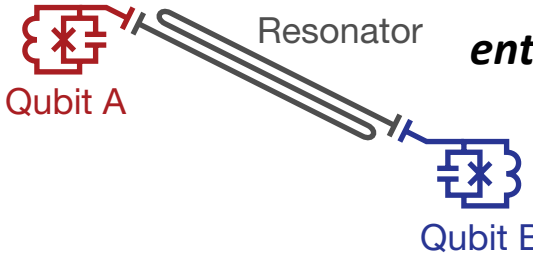
entangled pair: two Josephson phase qubits

single-shot readout *of the qubit state:*

measurement fidelities ~ 94%

entanglement fidelity with the Bell singlet state ~ 88%





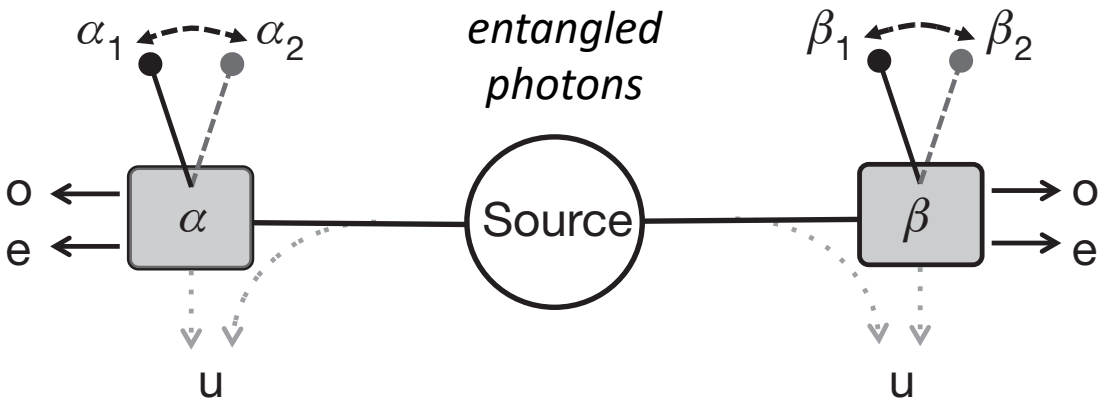
entanglement via an electromagnetic resonator

CHSH inequality: $S \leq 2$

$$S = 2.0732 \pm 0.0003$$

… and with photons!

Guistina *et al.*, *Nature* **497** (**2013**) – (Zeilinger's group, Vienna, Austria)



Eberhard inequality includes undetected events !

$$J = -n_{oo}(\alpha_1,\beta_1)+n_{oe}(\alpha_1,\beta_2)+n_{ou}(\alpha_1,\beta_2)+$$
$$n_{eo}(\alpha_2,\beta_1)+n_{uo}(\alpha_2,\beta_1)+n_{oo}(\alpha_2,\beta_2)\geq 0$$

detection loophole

closed if with efficiency >2/3

Alice's arm efficiency ~ 74%
Bob's arim efficiency ~ 79%

(detector: superconducting TESs)

Eberhard inequality: $J \geq 0$

$$J = -126,715 \pm 1,837$$

A journey through the Bell tests

1. Closing the locality loophole *but fair-sampling assumption*

2. Closing the detection loophole *but no-signaling assumption*

3. **Loophole-free Bell tests**

Loophole-free Bell tests

locality loophole & detection loophole both closed!

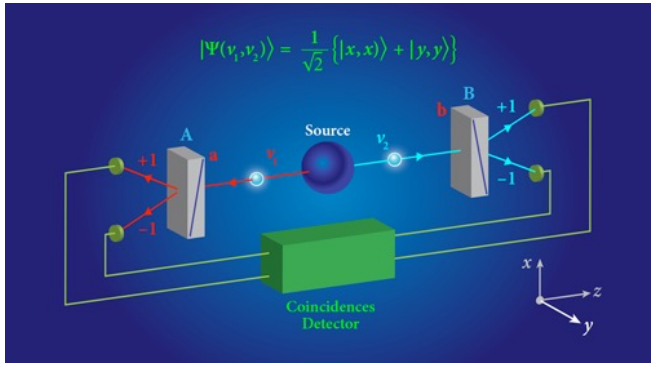
Entangled spins in diamond

Hanson's group (Delft) 2015

Hensen *et al.*, *Nature* **119** (2015)

Entangled photons

Zeilinger's group (Vienna) 2015
NIST (Boulder) 2015

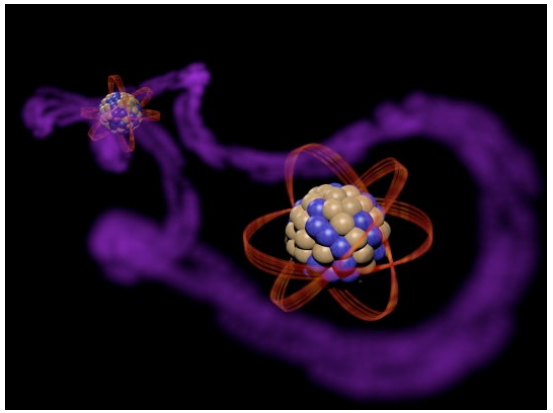


APS/Alan Stonebraker

Giustina *et al.*, *PRL* **115** (2015)
Shalm et al., *PRL* **115** (2015)

Entangled atoms

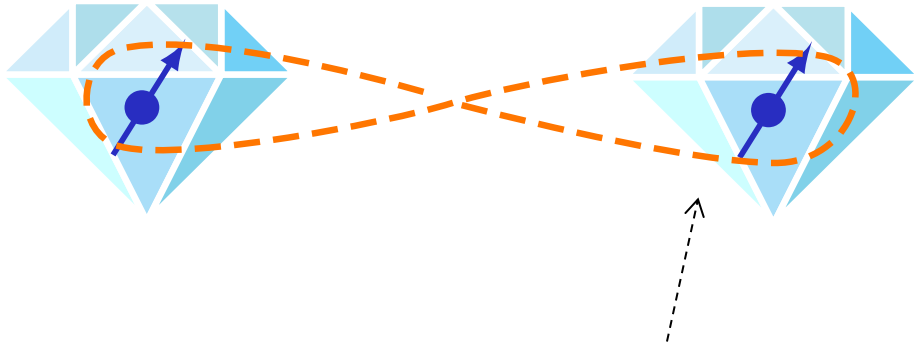
Weinfurter's group (Munich) 2016



Rosenfeld *et al.*, *PRL* **119** (2017)

The Delft loophole-free Bell test

a loophole-free Bell test with spins in diamond

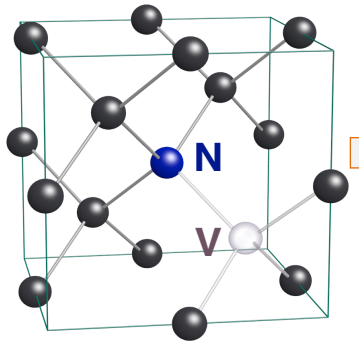


!!! solid-state artificial atom !!!

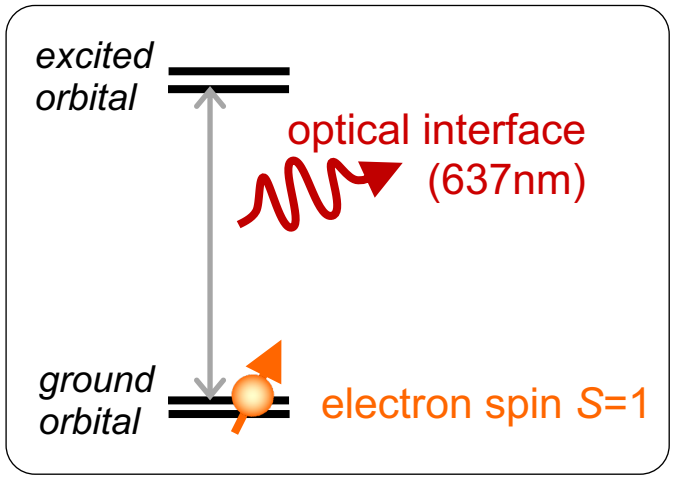
Requirements

- close both the detection and locality loopholes
- quantum correlations must exceeds the local realist bound
  -> high entanglement fidelity, fast manipulation with high fidelity, fast readout with high fidelity...

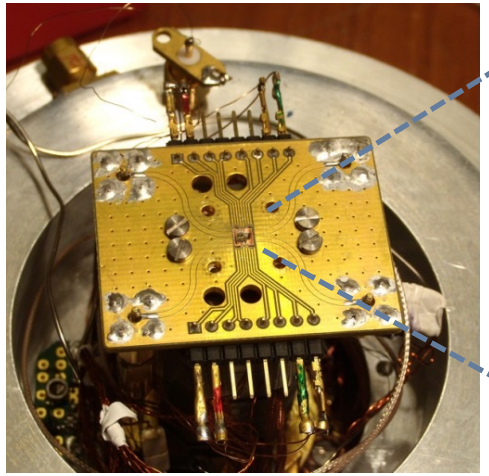
The NV center: a « trapped-atom » in diamond

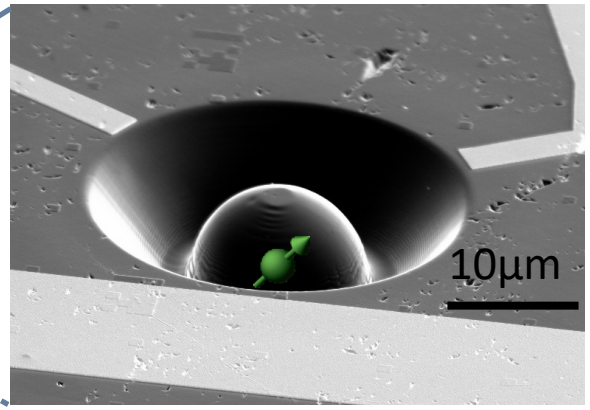


@ 3 K

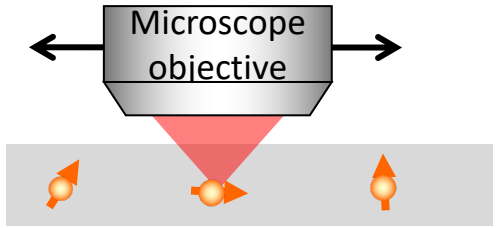


-> quantum sensing (talk tomorrow)

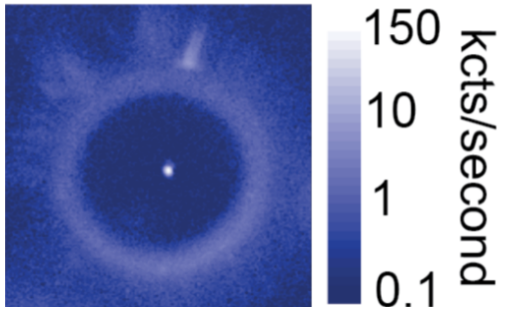




*detection of **single** NVs through confocal microscopy*



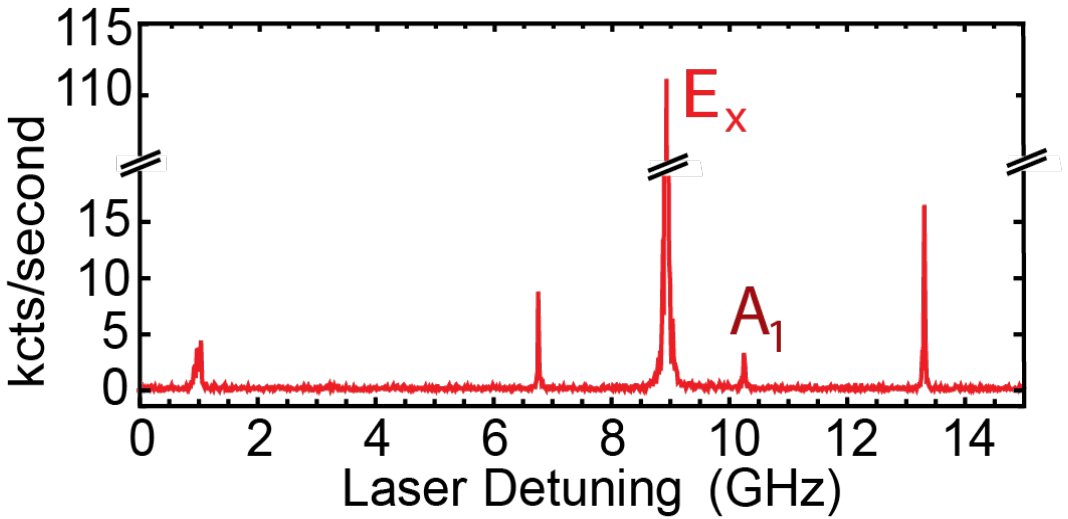
optical scan



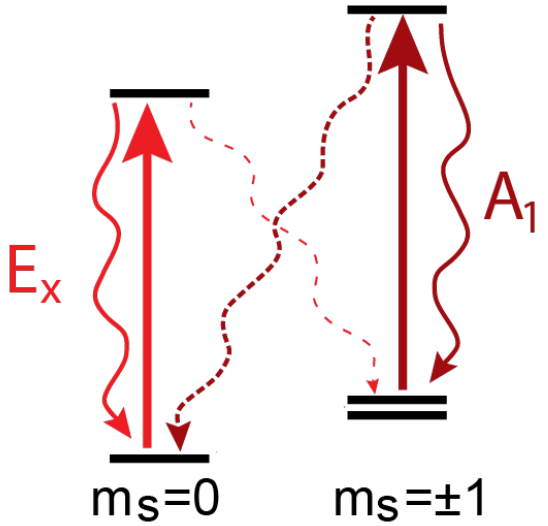
Spin-resolved optical excitation @ T< 10 K

Resonant excitation

Photoluminescence excitation spectrum



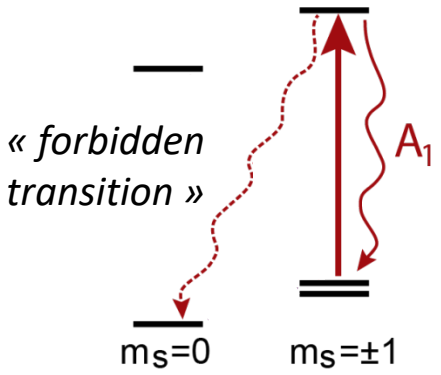
Spin-conserving transition

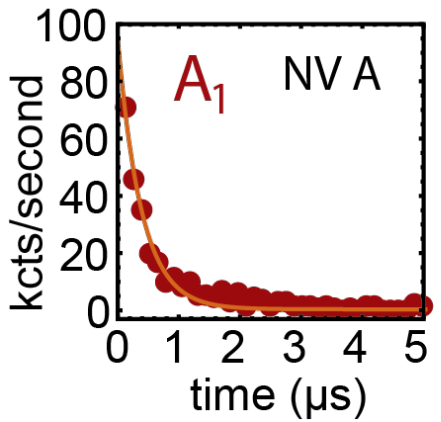


ground state =
electronic spin triplet (S = 1)

Initialization and readout by resonant excitation

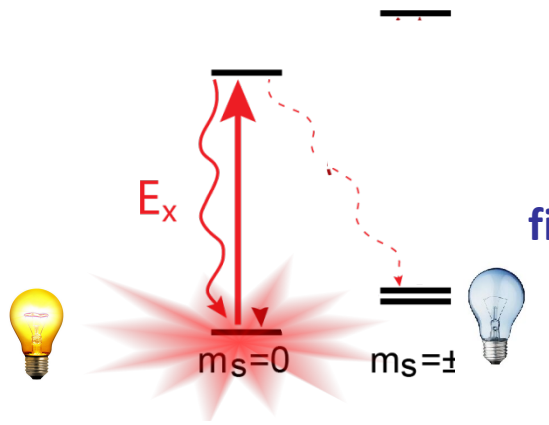
Initialization



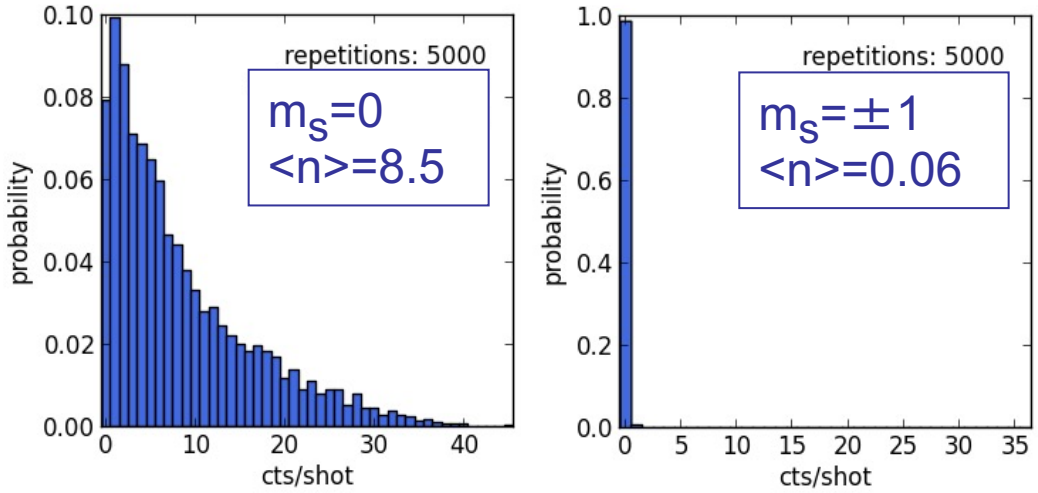


fidelity > 99.7%

Single-Shot Readout



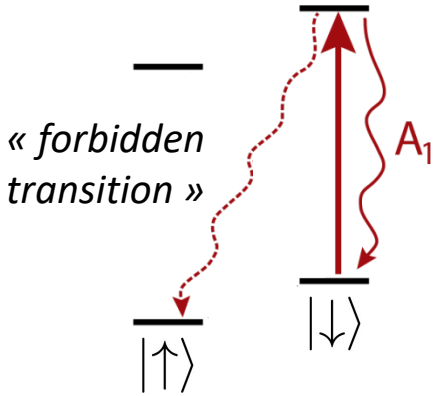
fidelity ≈ 97%

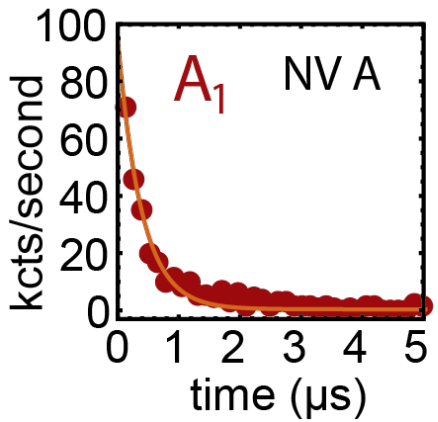


Robledo *et al., Nature* **477** (2011)

Initialization and readout by resonant excitation

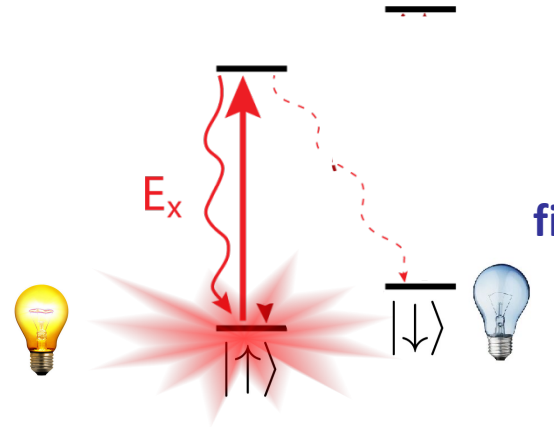
Initialization



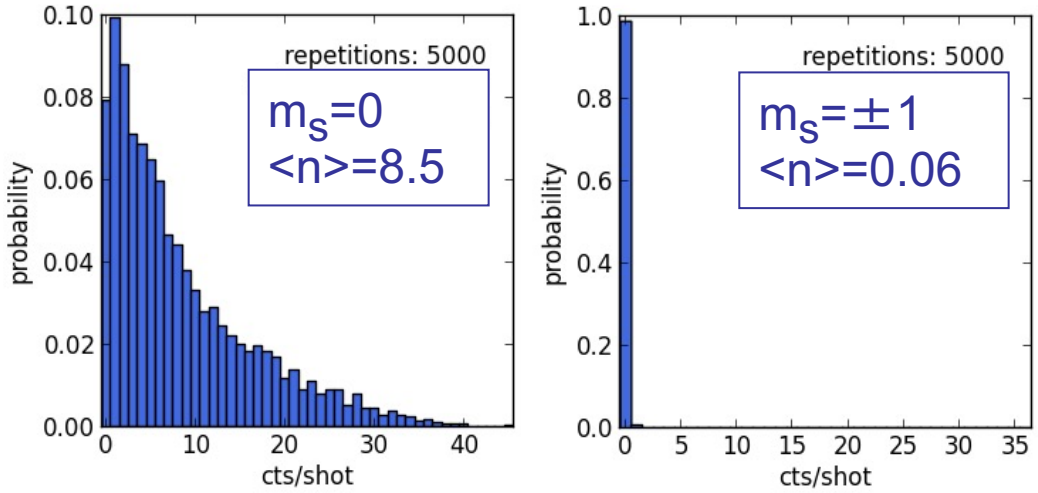


fidelity > 99.7%

Single-Shot Readout

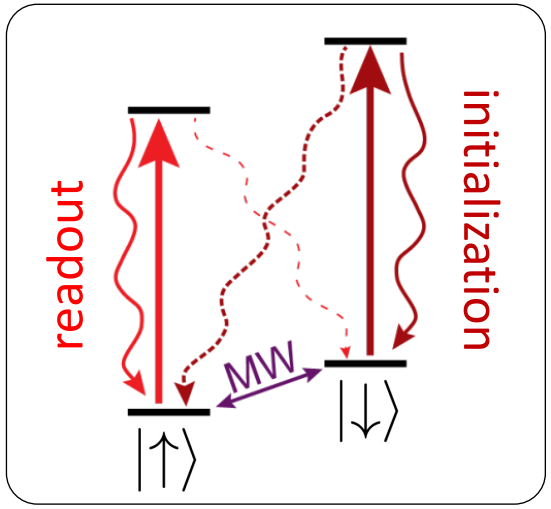


fidelity ≈ 97%



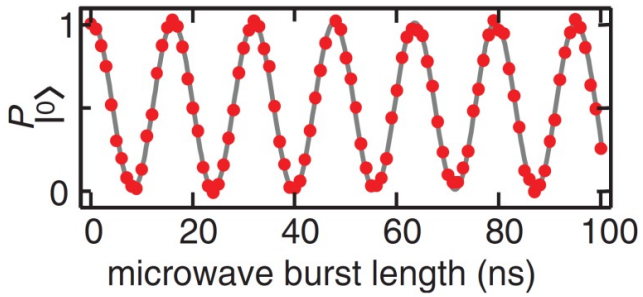
Robledo *et al., Nature* **477** (2011)

Microwave coherent control

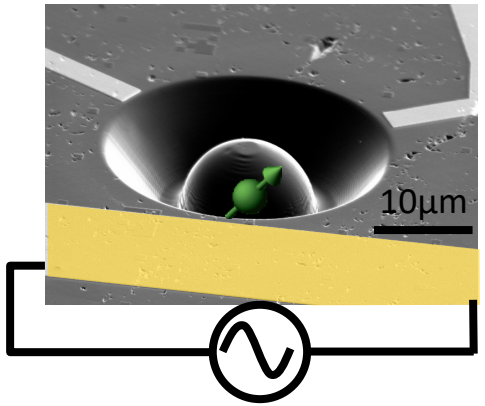


High fidelity spin manipulation

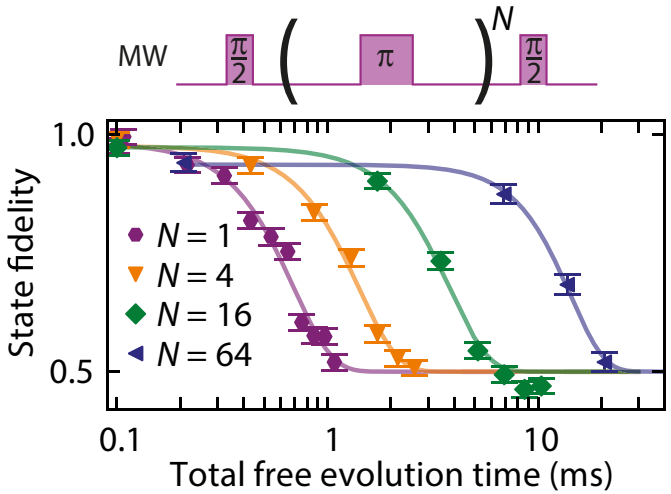
Rabi oscillations



De Lange *et al., Science* **23** (2010)



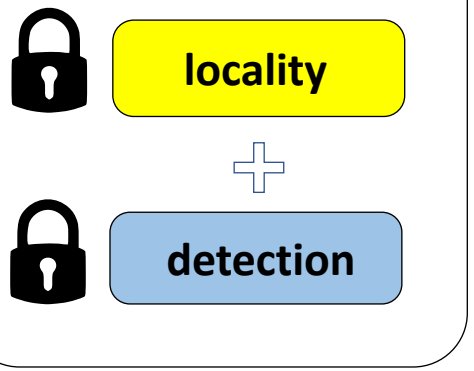
Long coherence time



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

Recap: requirements for a loophole-free Bell test

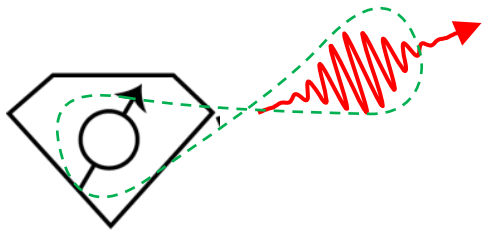
loopholes to close :



⇒ generation of a long-distance entangled pair of spins with high fidelity

⇒ fast single-shot readout of the spins with high fidelity

⇒ **Generating long-distance entanglement** Bernien et al., *Nature* **497** (2013)



Recap: requirements for a loophole-free Bell test

loopholes to close :

- **locality**
- **detection**

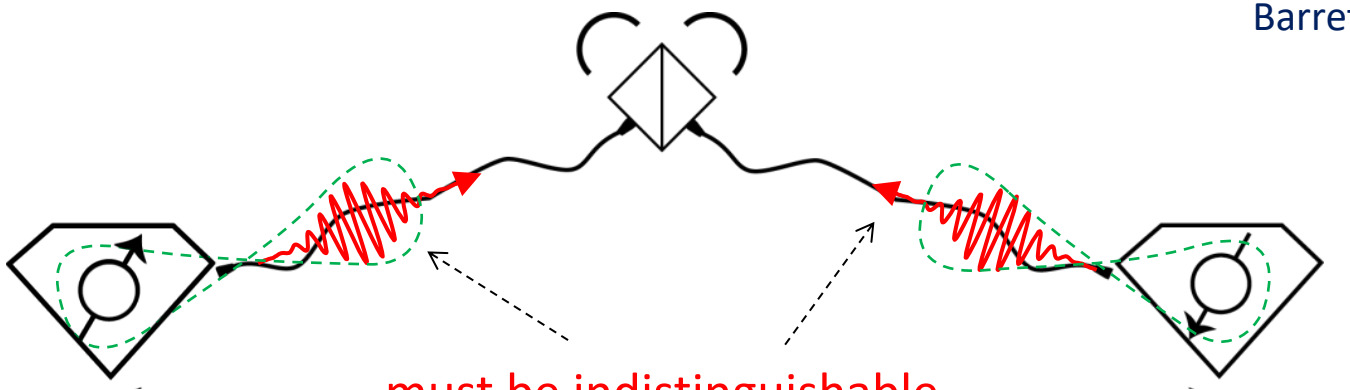
→ generation of a long-distance entangled pair of spins with high fidelity

→ fast single-shot readout of the spins with high fidelity

→ **Generating long-distance entanglement**

Bernien et al., *Nature* **497** (2013)

Barrett & Kok, *PRA* **71** (2005)



must be indistinguishable

Recap: requirements for a loophole-free Bell test

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Bernien et al., *Nature* **497** (2013)

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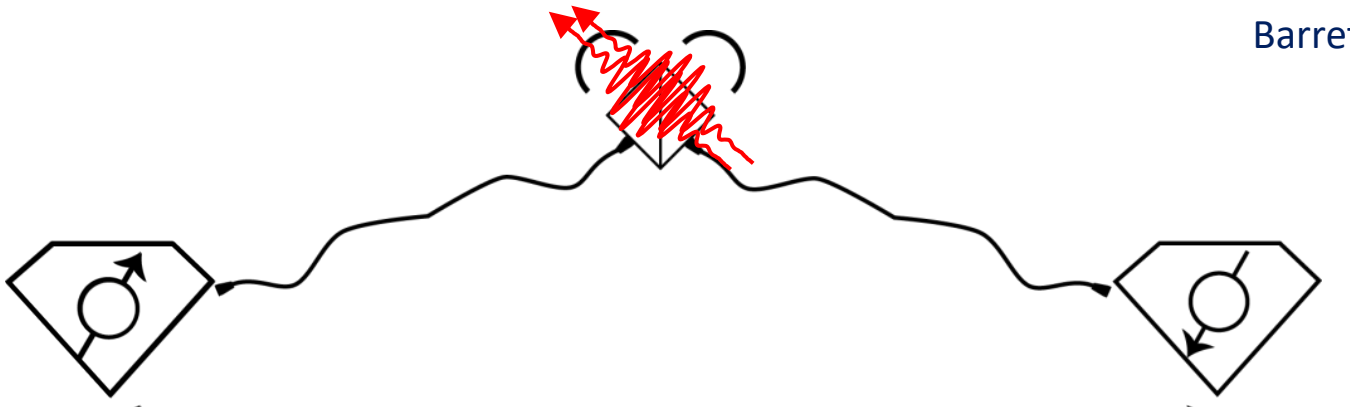

Recap: requirements for a loophole-free Bell test

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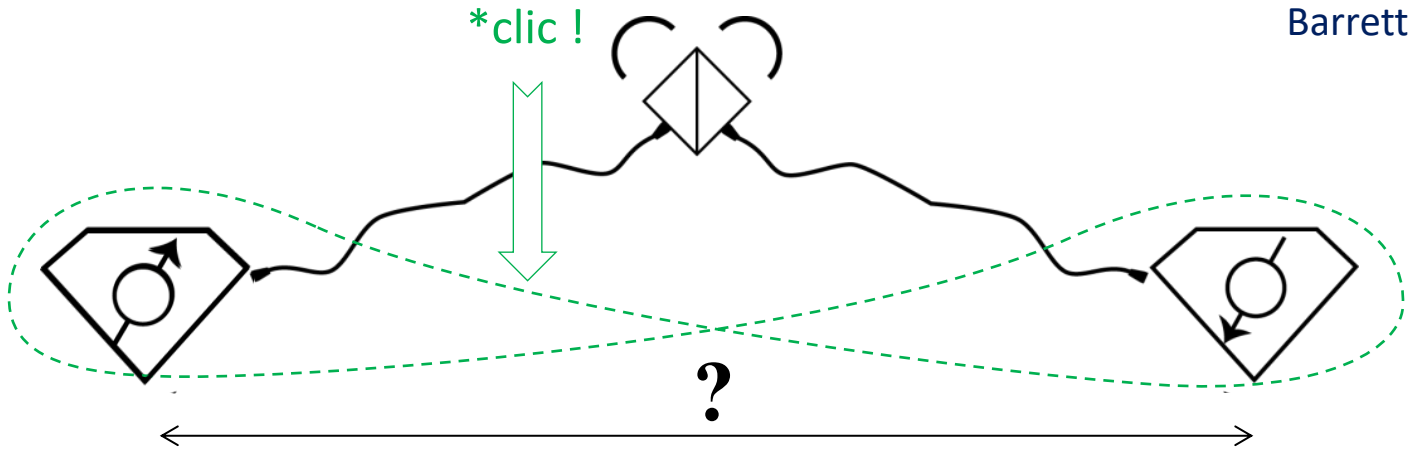
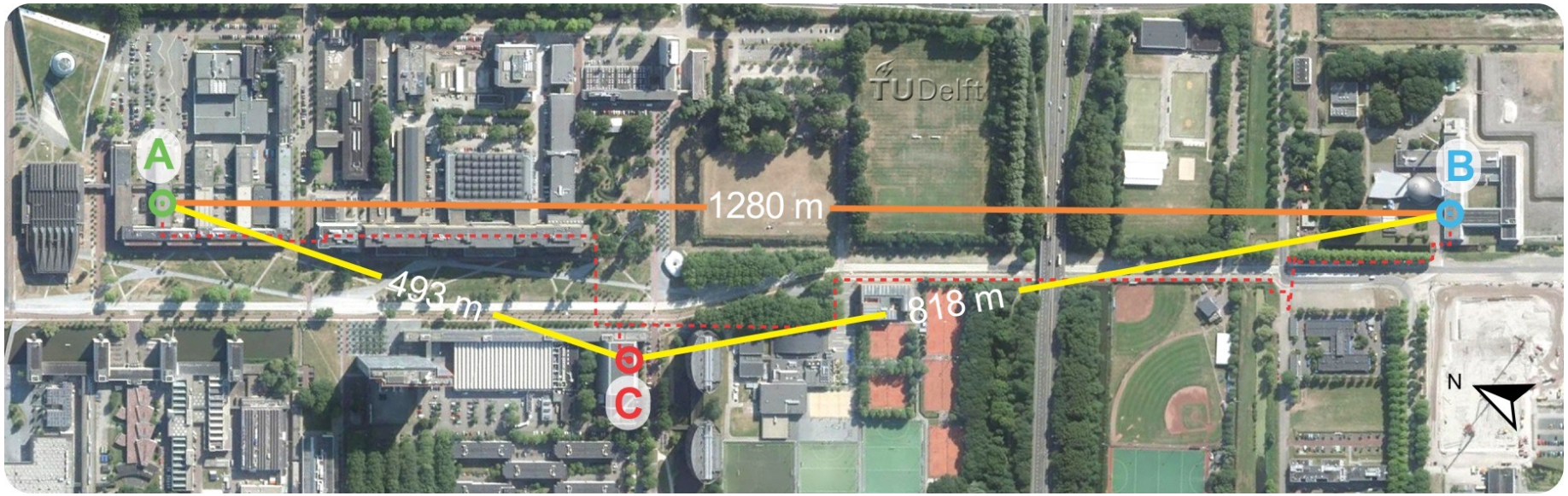
Bernien et al., *Nature* **497** (2013)

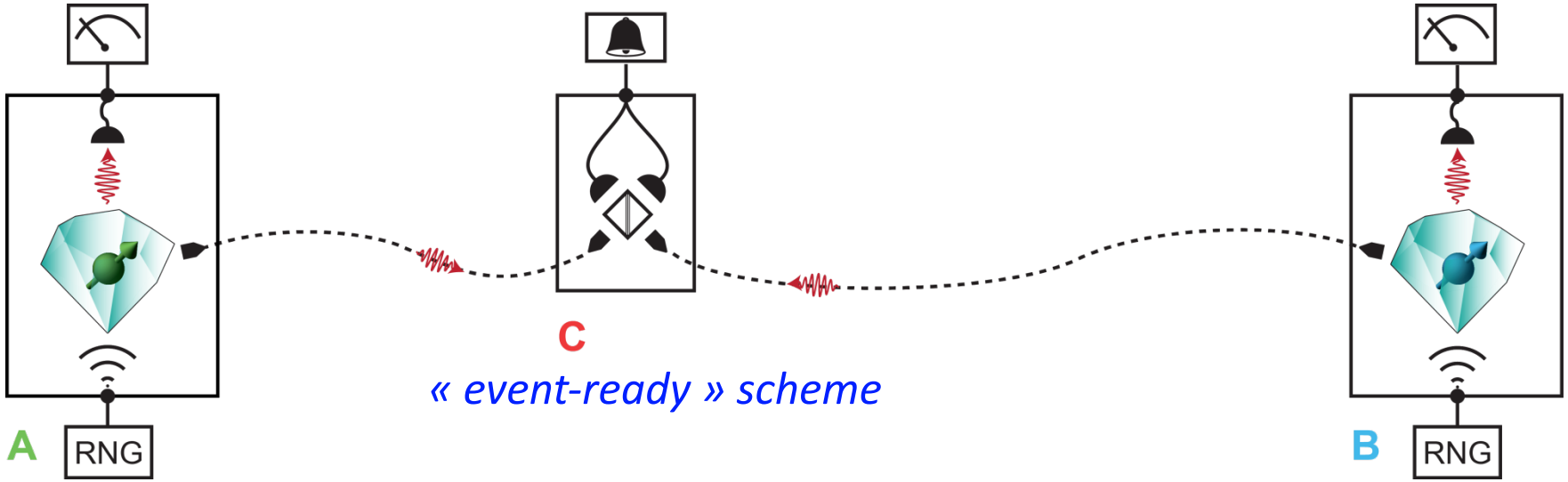
Barrett & Kok, *PRA* **71** (2005)



entanglement swapping

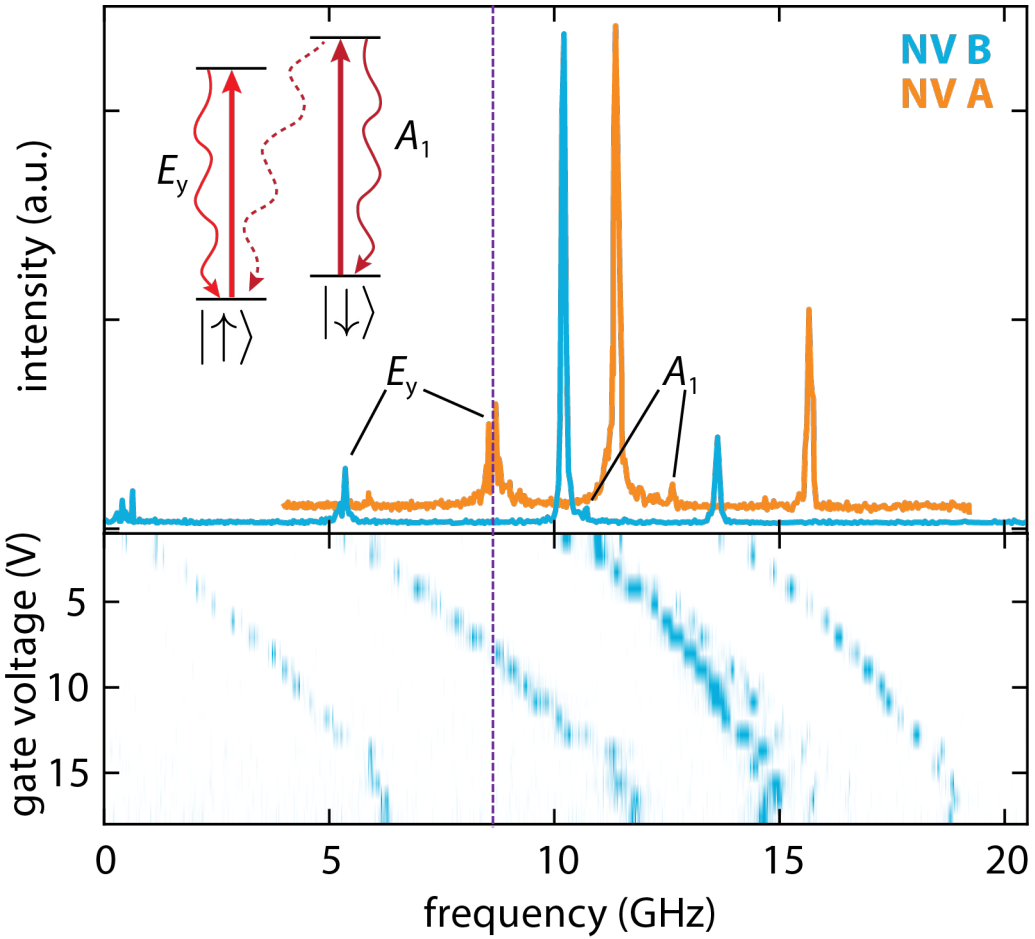
A loophole-free Bell test in Delft

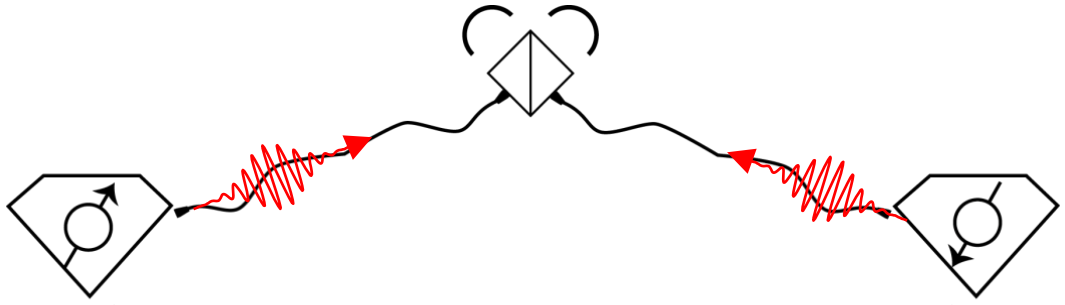


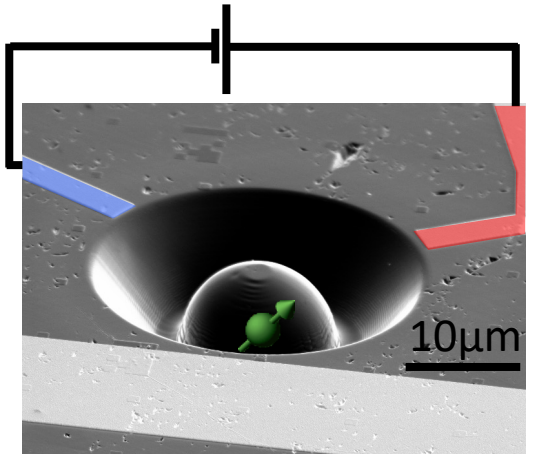


« event-ready » scheme

Challenge: getting indistinguishable photons





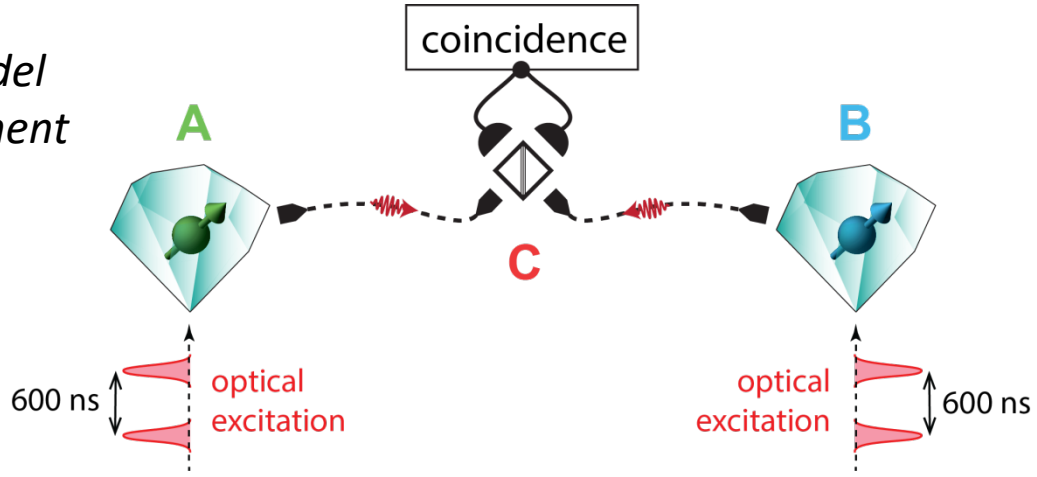


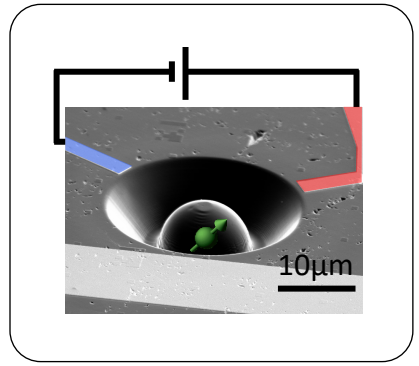
d.c. Stark tuning of NV centres:

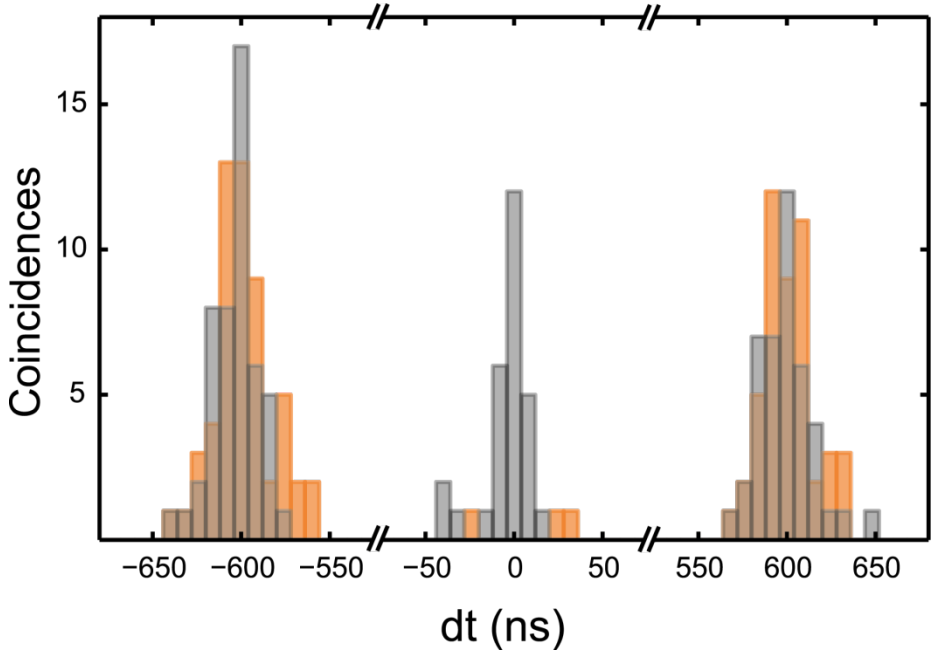
*Tamarat et al., PRL **97** (2006)*
*Bassett et al., PRL **107** (2011)*
*Bernien et al., PRL **108** (2012)*

Challenge: getting indistinguishable photons

Hong-Ou-Mandel (HOM) experiment







Distinguishable

Undistinguishable

Interference visibility

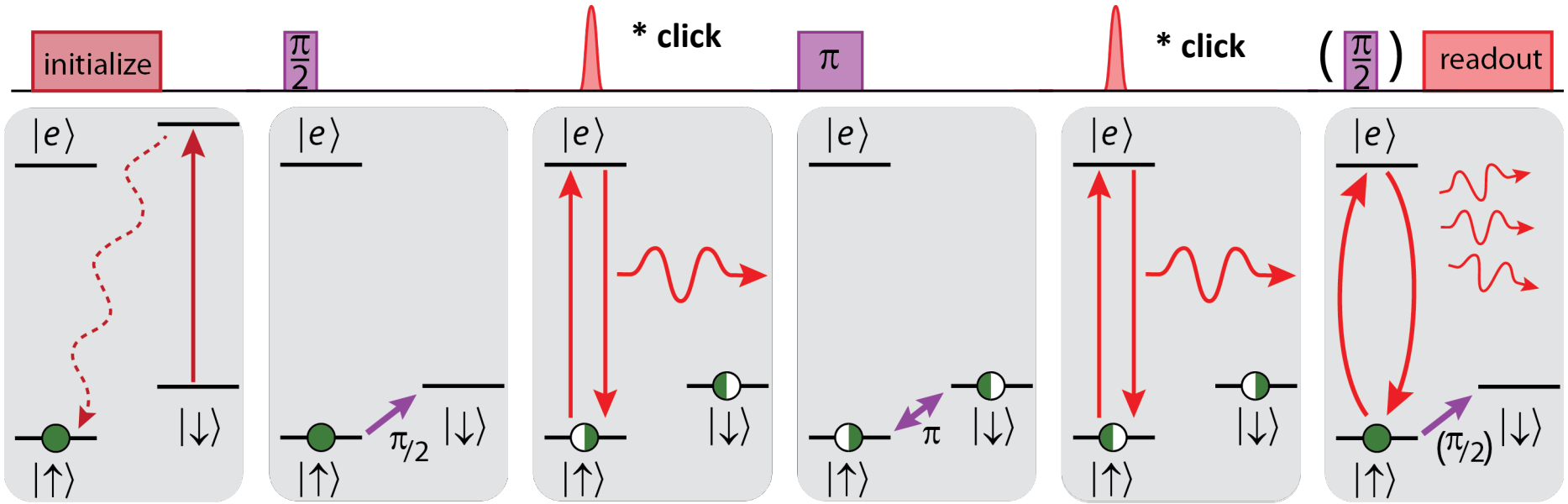
$$V = 90 \pm 6$$

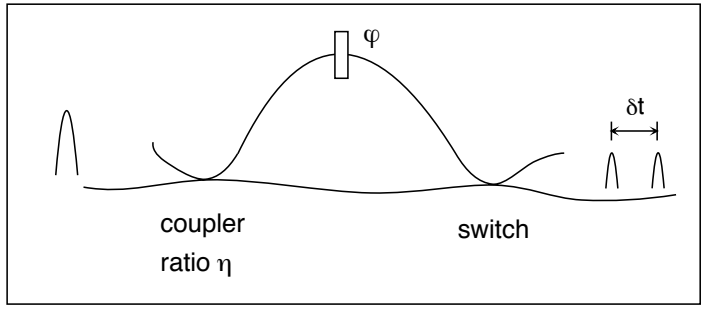
bound on entanglement fidelity :

$$\mathcal{F} < (1+V)/2$$

The long-distance entanglement protocol

*Barrett and Kok, PRA **71** (2005)*

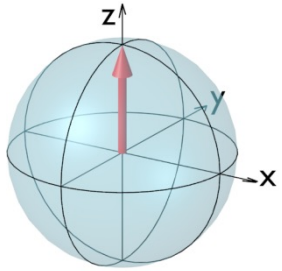




*Brendel et al., PRL **82** (1999)*

Entanglement check: correlation measurements

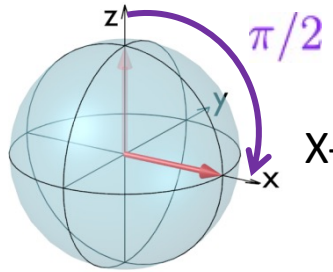
Z-basis



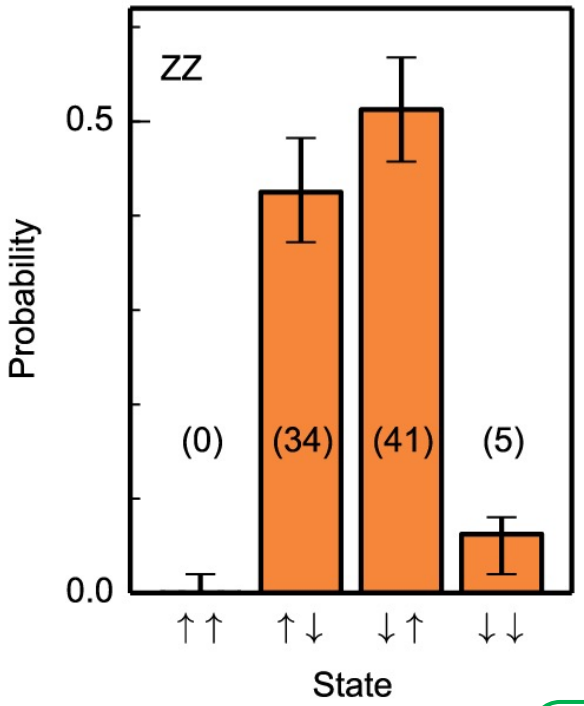
Perfect target state:

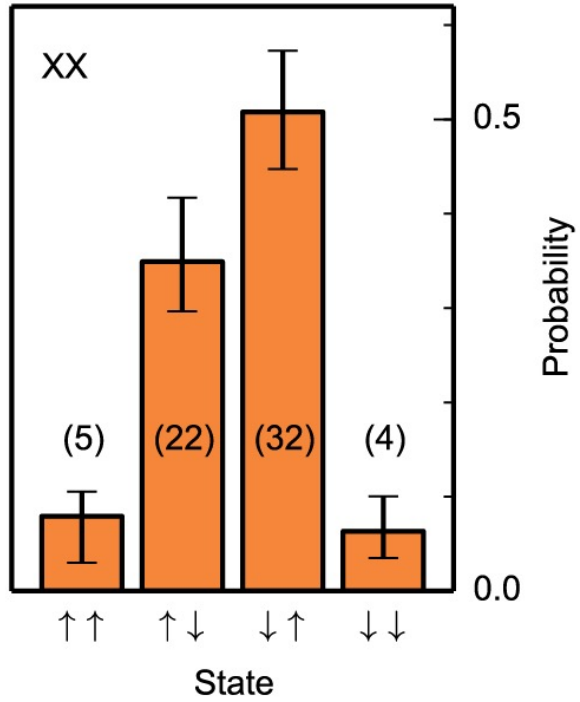
$$|\psi_-\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

"Bell singlet state"



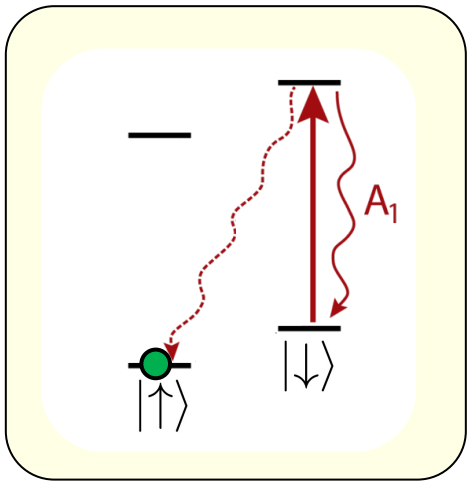
X-basis



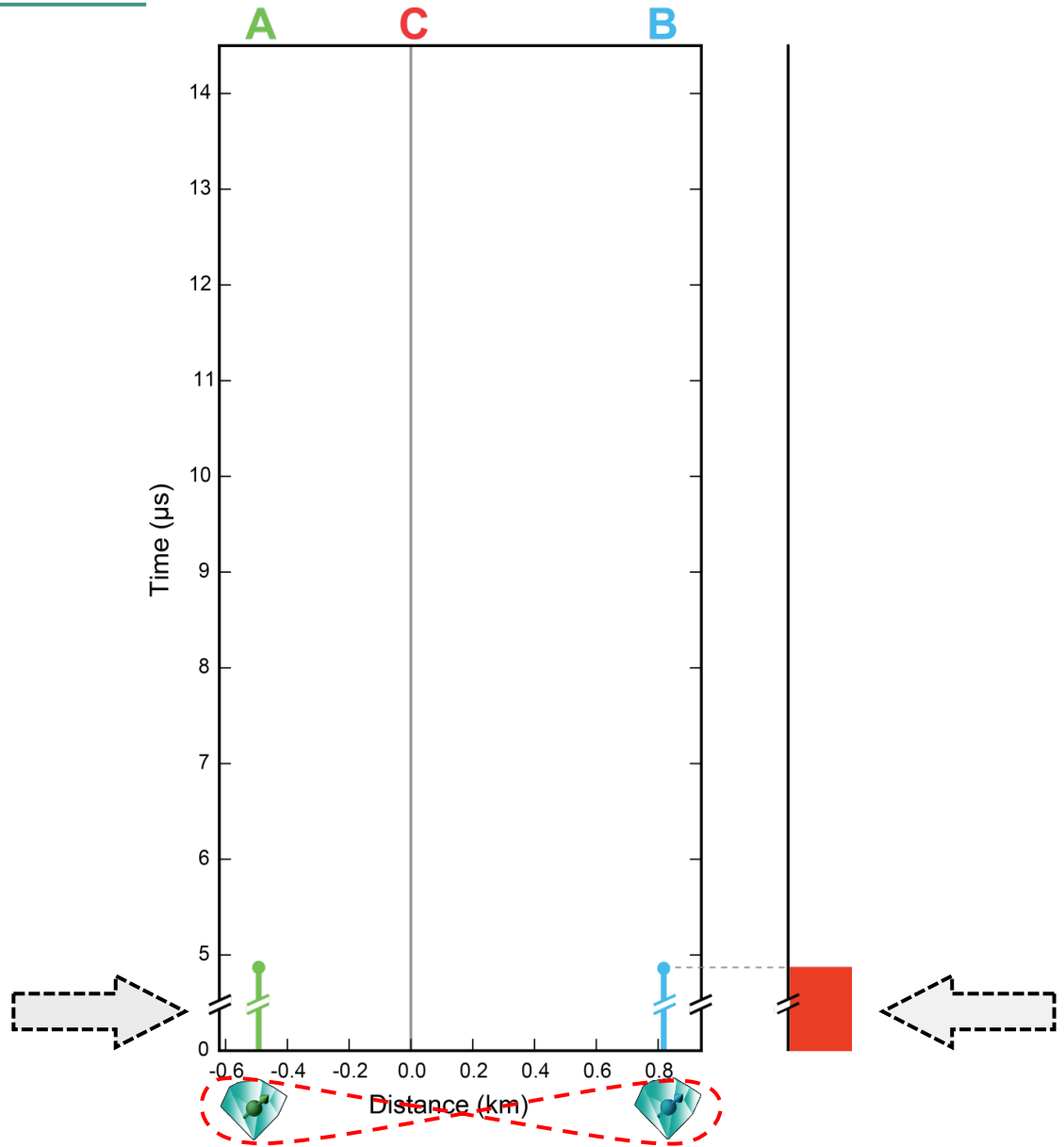


Entanglement fidelity = 92 ± 3 %

Experimental scheme (1)

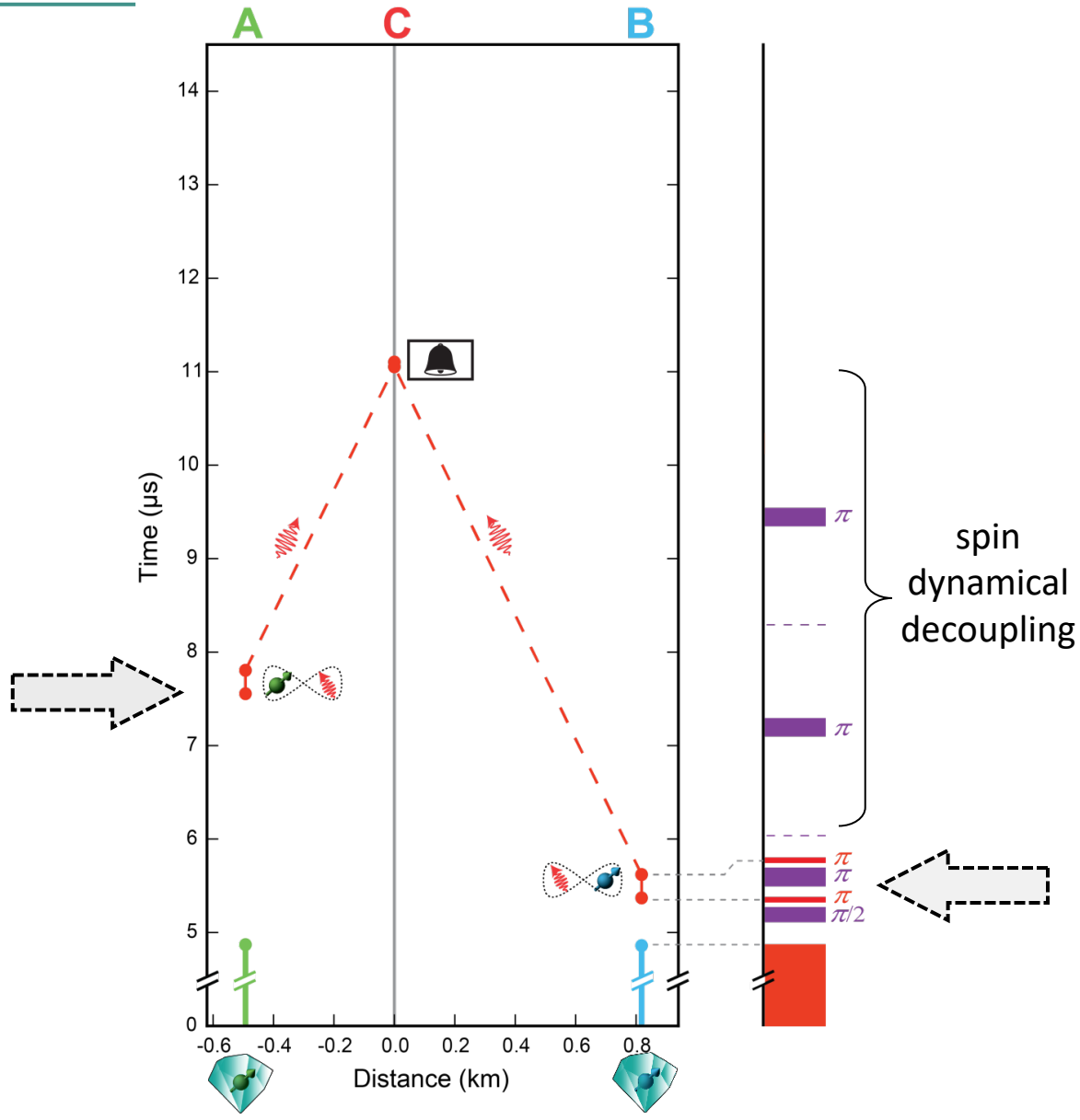


1 **Initialization/Reset**



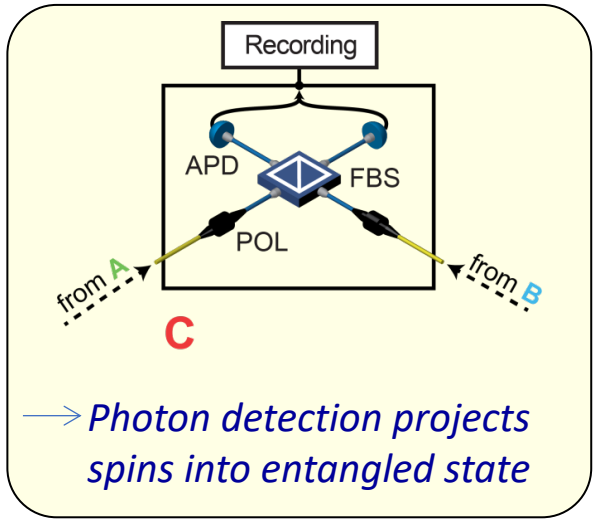
Experimental scheme (2)

2 **Spin-photon entanglement**

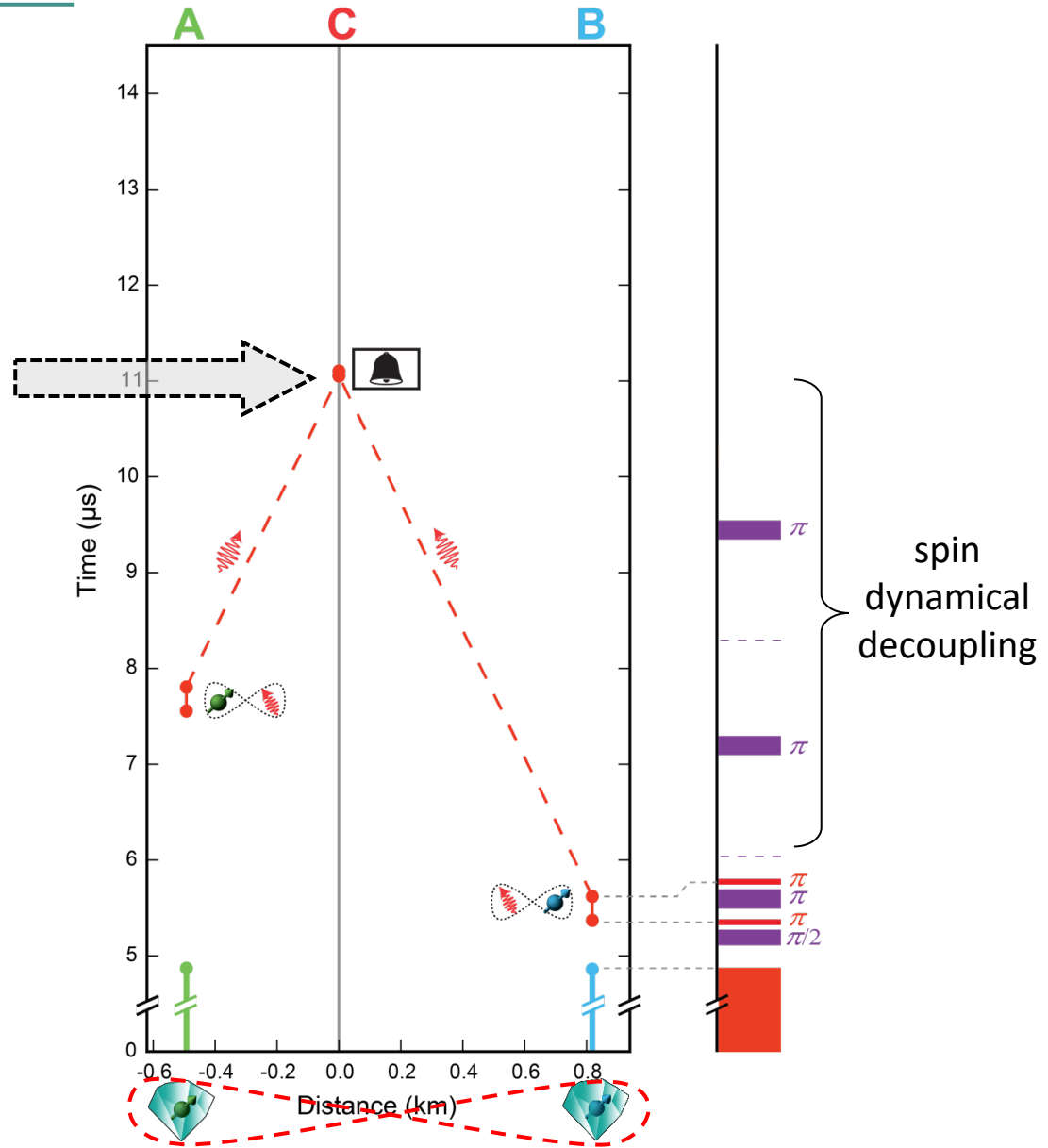


Experimental scheme (3)

3 Entanglement generation

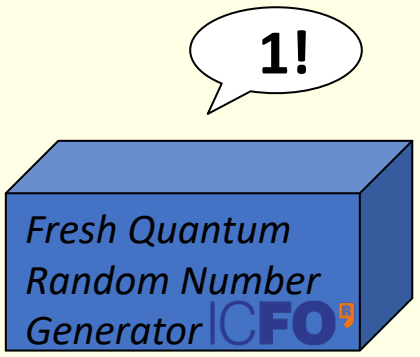


→ *Photon detection projects spins into entangled state*



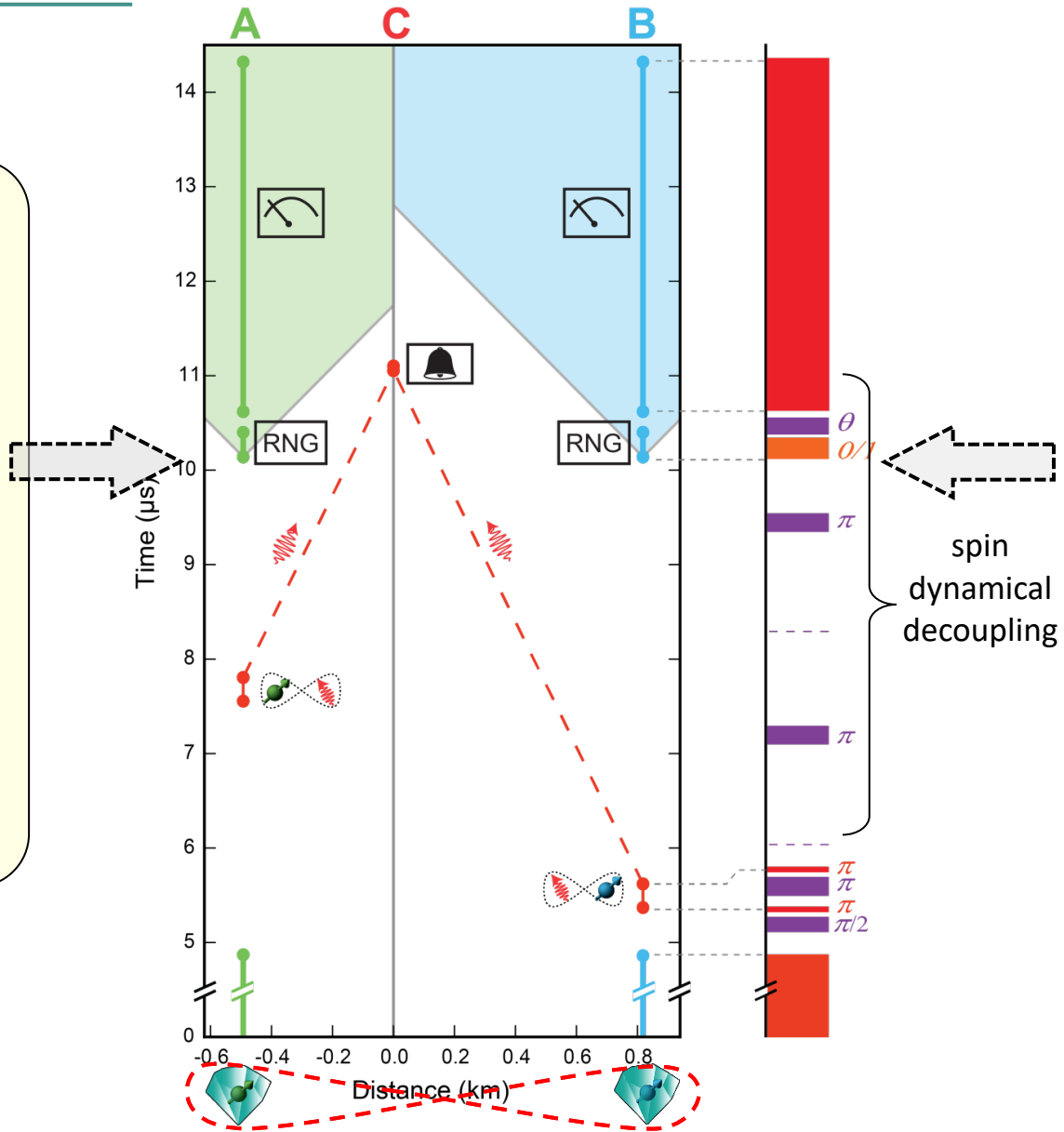
Experimental scheme (4)

4 **Random basis choice**



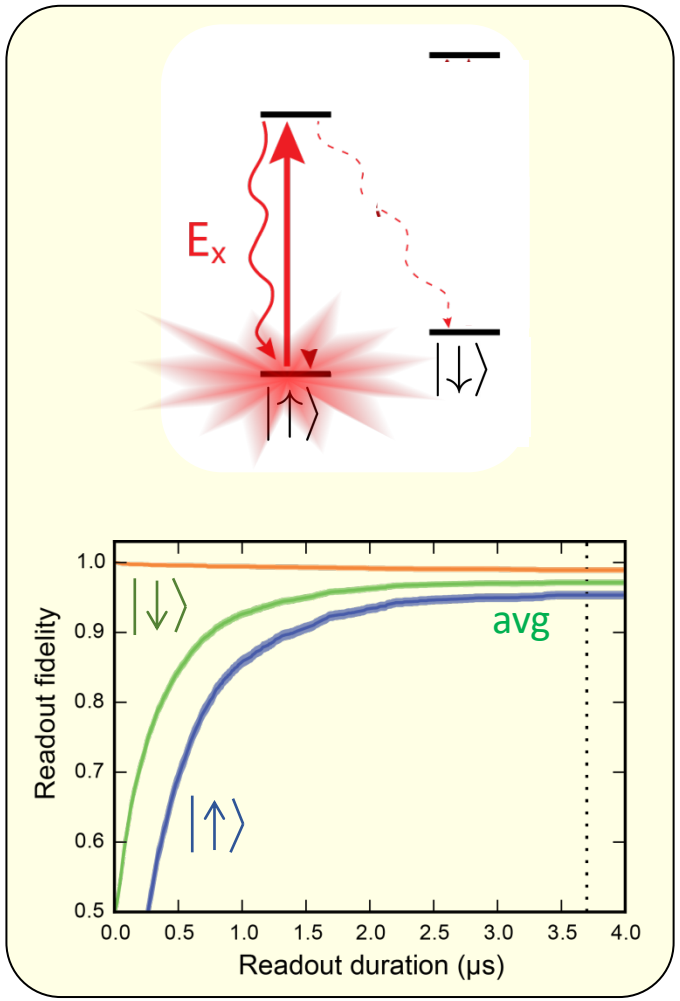
Abellán *et al.*, PRL **115** (2015)
(Mitchell's group, Barcelona, Spain)

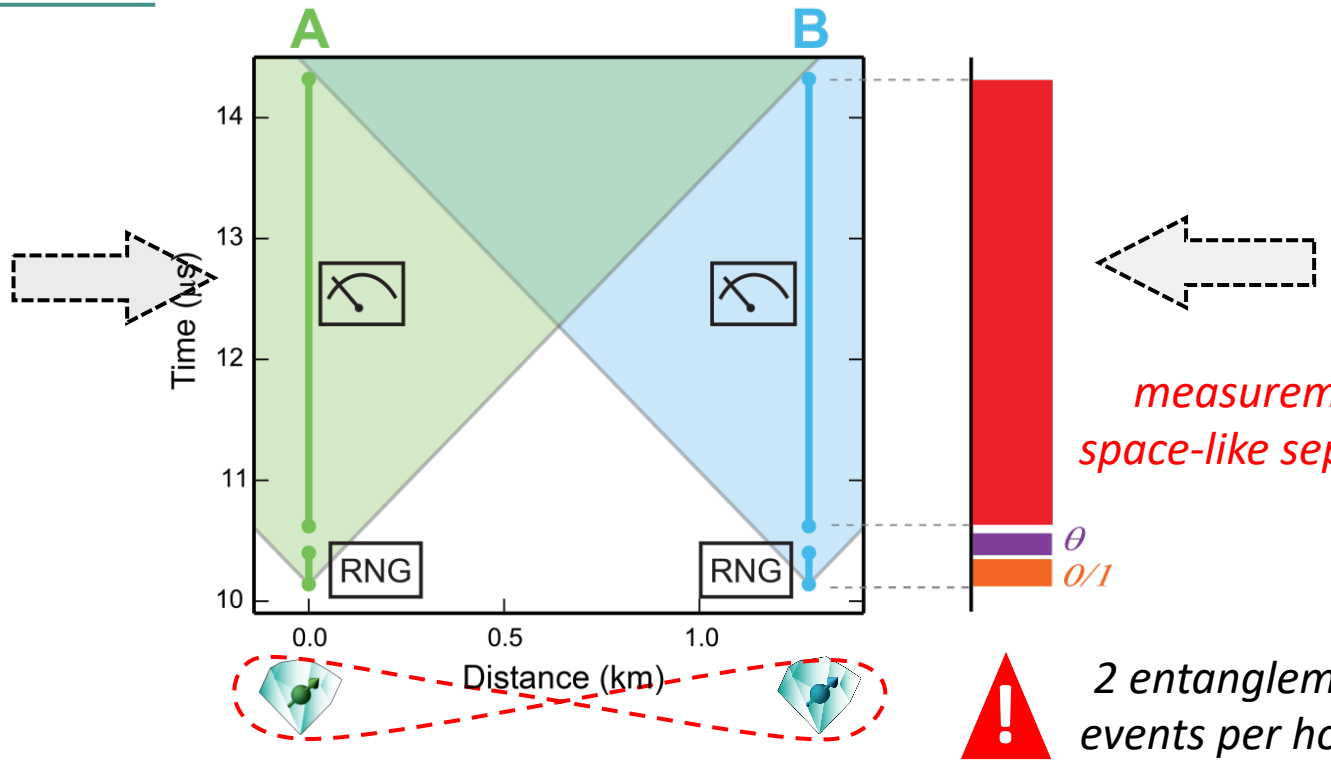
Event-ready signal space-like separated from random number generation (RNG)



Experimental scheme (5)

5 **Basis rotation and readout**





measurements space-like separated

2 entanglement events per hour...

A, B & C space-like separated → ~~locality loophole~~

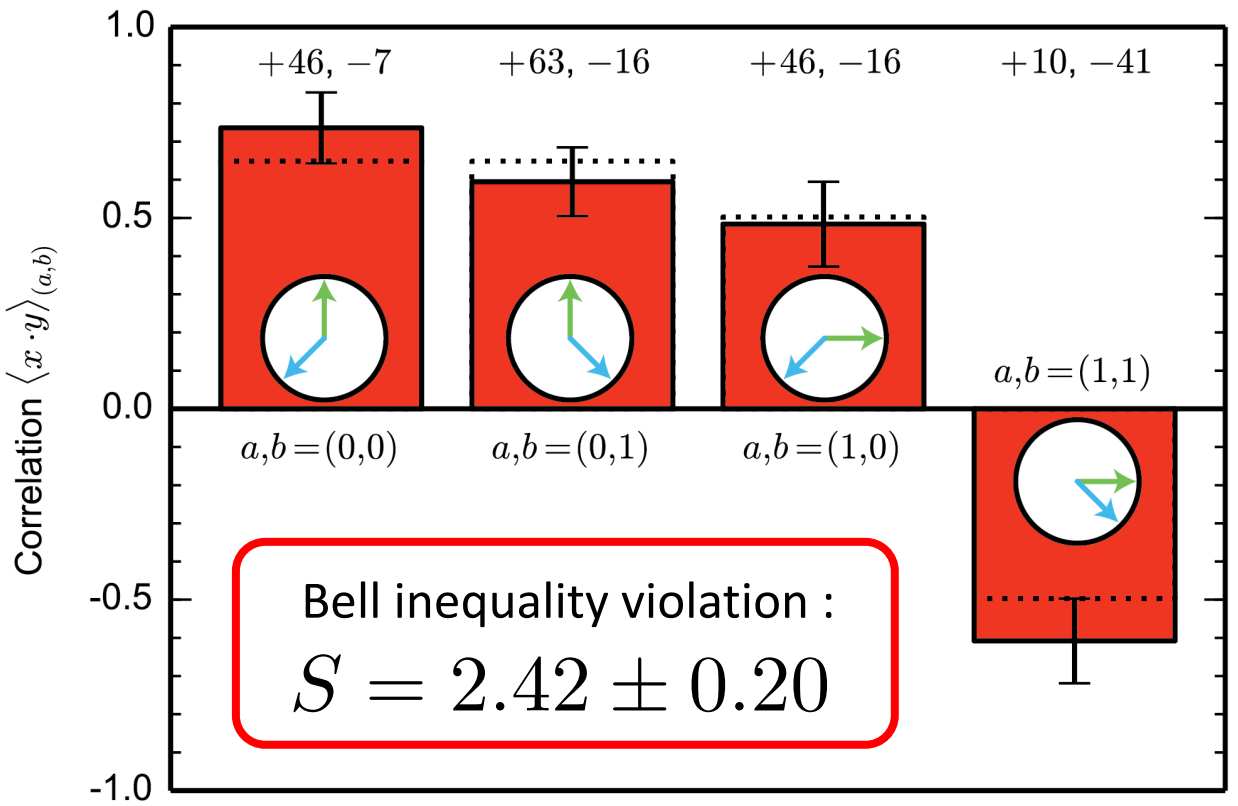
single-shot readout → ~~detection loophole~~

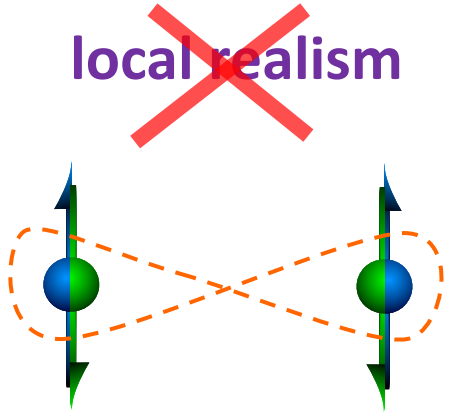
Experimental scheme (5)

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

local realist bound

... 18 days and nights later:



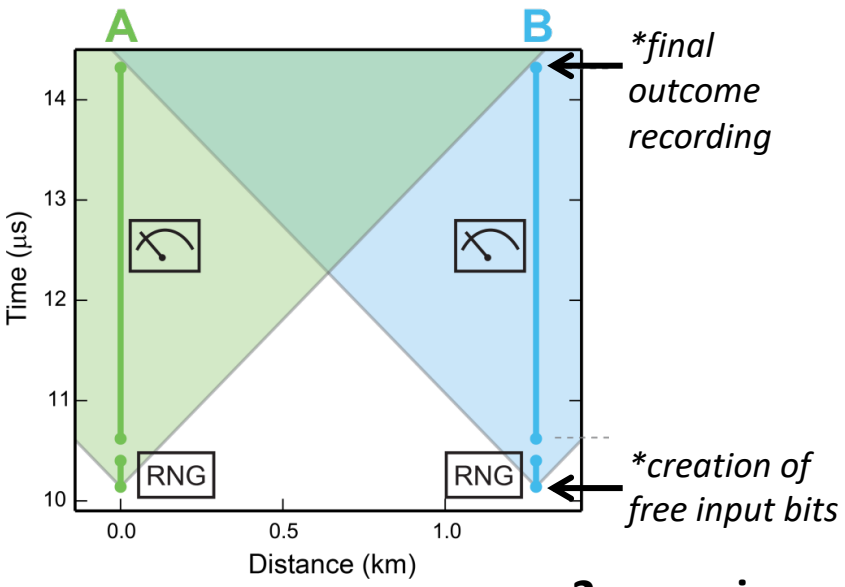


quantum non-locality

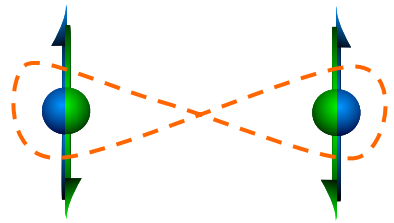
B. Hensen *et al., Nature* **526** (2015)

probability that any local realist model could have produce the data : **p-value = 0.039**

Level of significance?



probability that the observed data (or more extreme) would result under the assumption that our experiment is ruled by a local realist model* ?
= p-value



2 scenarios :	**Conventional**	**Complete**
Memory ?	No	Yes
Outcome distribution	Gaussian	Arbitrary
Random bit unpredictability	Perfect	Partial
p-value	S = 2.42 ± 0.20 p = 0.019	p = 0.039

New realization: Dec. 2015

+ 300 events (210h over 22 days)

$$S_{\mathrm{tot}} = 2.380 \pm 0.136$$

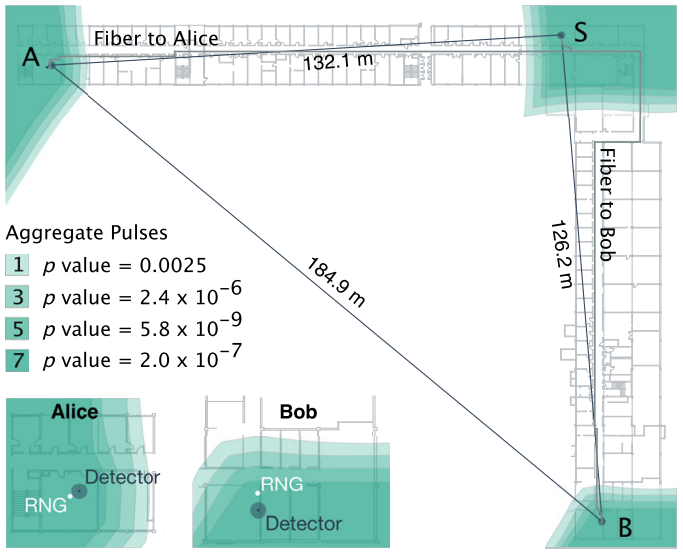
p= 0.017 (independent runs)
p = 0.008 (single run)

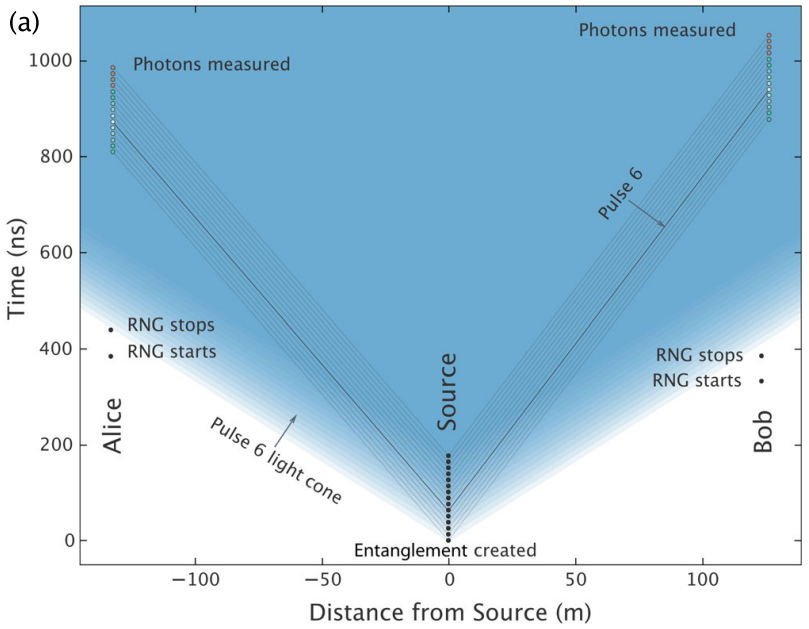
Hensen *et al.*, *Scient. Rep.* **6** (2016)

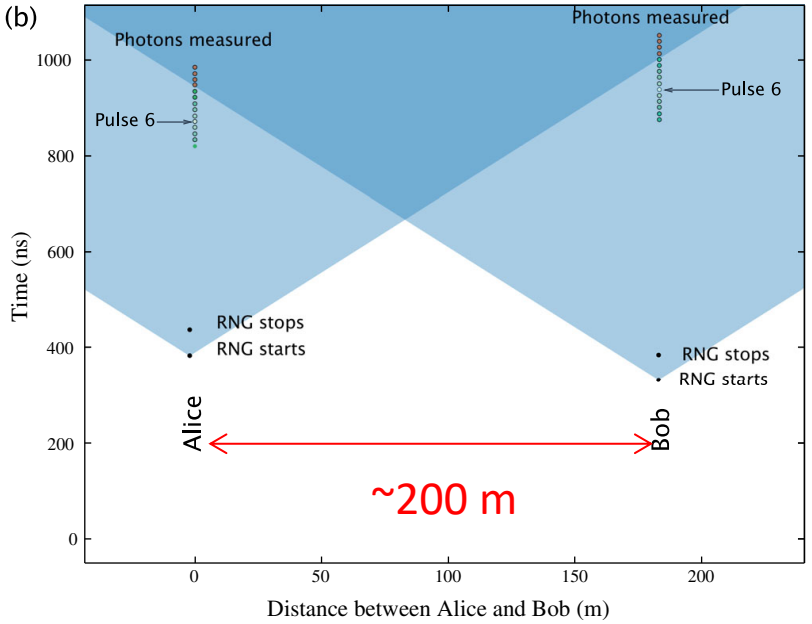
The Boulder loophole-free Bell test with photons

Shalm et al., *PRL* **115** (2015) (NIST)

+ detection efficiency > 72.5%







Clauser-Horne type inequality:

$$P(++|ab) \leq P(+0|ab') + P(0+|a'b) + P(++|a'b').$$

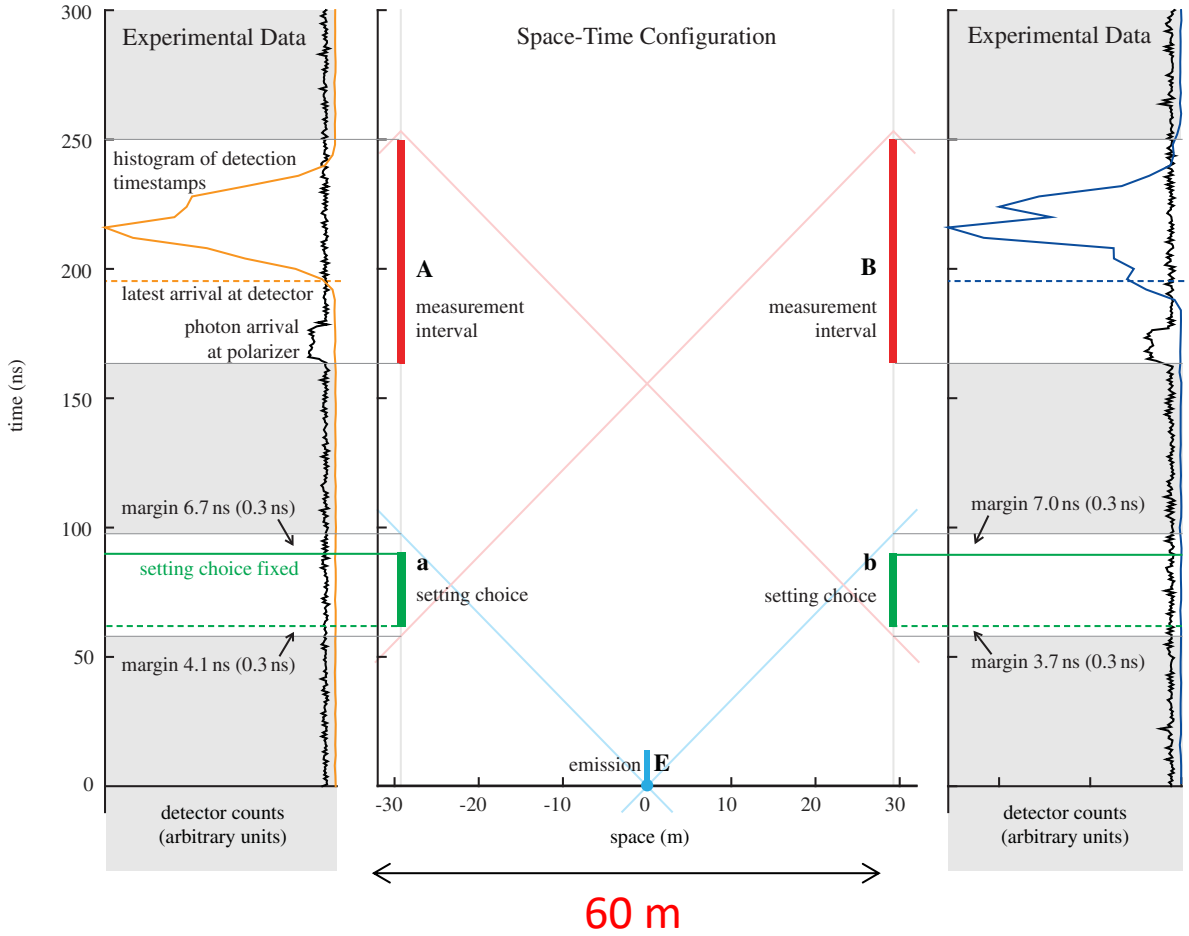
30 min per run,
180 millions entangled pairs detected!

maximum propability that experiment statistics produced by local realim:

$$p = 2.3 \cdot 10^{-7}$$

The Vienna loophole-free Bell test with photons

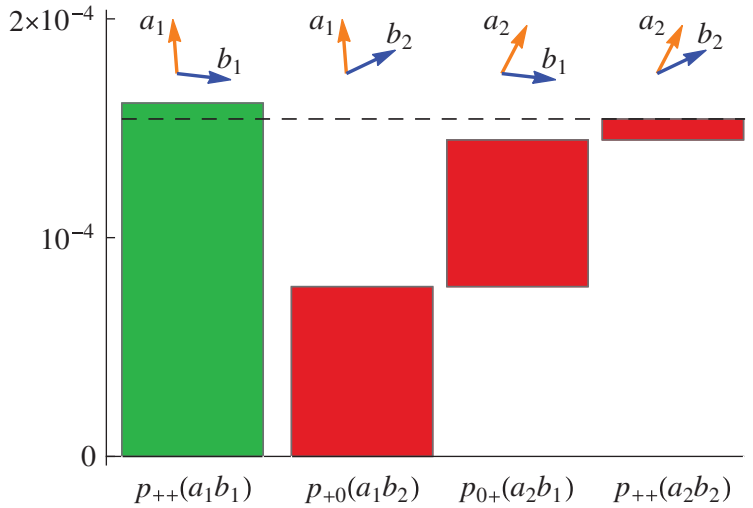
Giustina *et al.*, *PRL* **115** (2015) – (Zeilinger's group)



+ detection efficiencies > 2/3

CH-Eberhard type-inequality:

$$J \equiv p_{++}(a_1 b_1) - p_{+0}(a_1 b_2) - p_{0+}(a_2 b_1) - p_{++}(a_2 b_2) \leq 0.$$



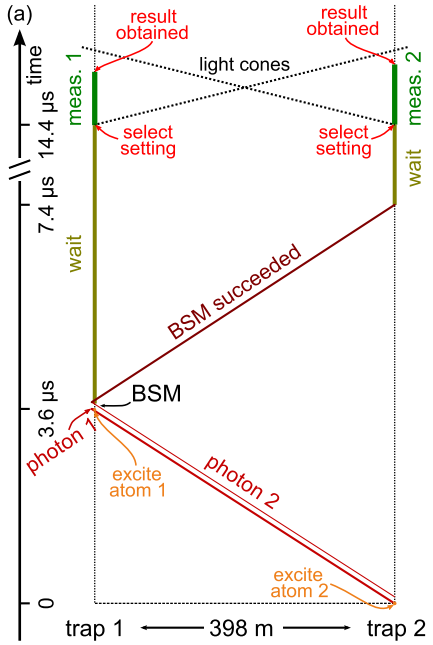
$$J = 7.27 \cdot 10^{-6}$$

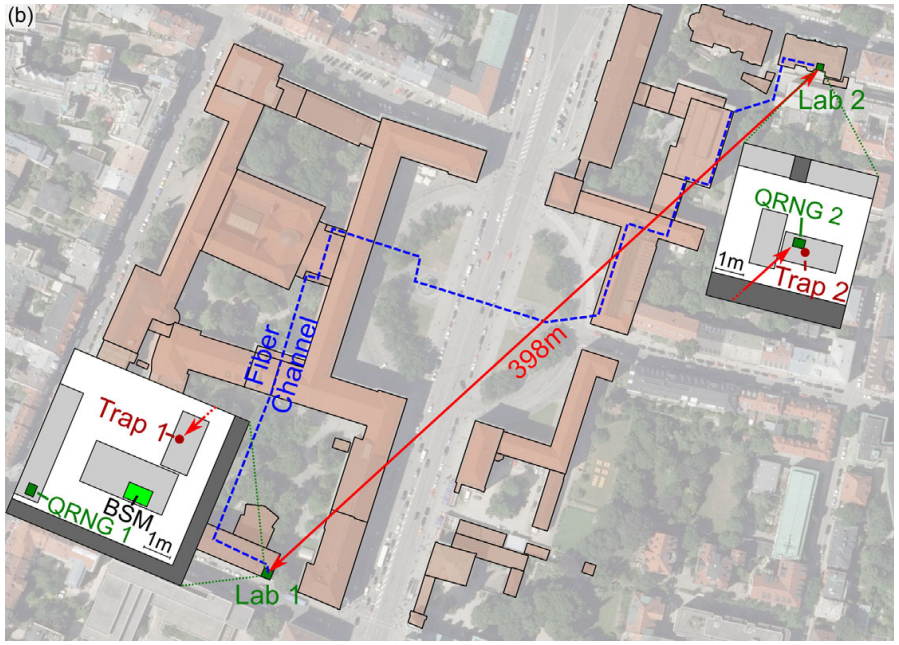
$$p = 3.7 \cdot 10^{-31}$$

3500 entangled pairs per second!

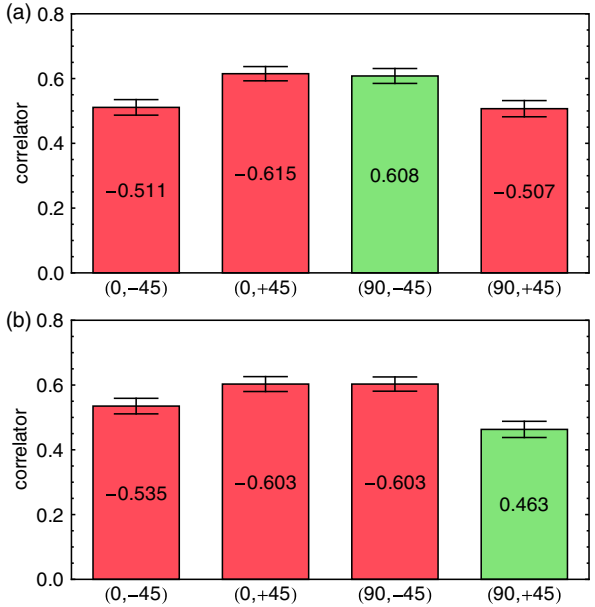
The Munich loophole-free Bell test with atoms

Rosenfeld *et al.*, *PRL* **119** (2017) – (Weinfurter's group)





entanglement between 2 single ^{87}Rb atoms in an optical dipole trap



CHSH inequality: $S \leq 2$

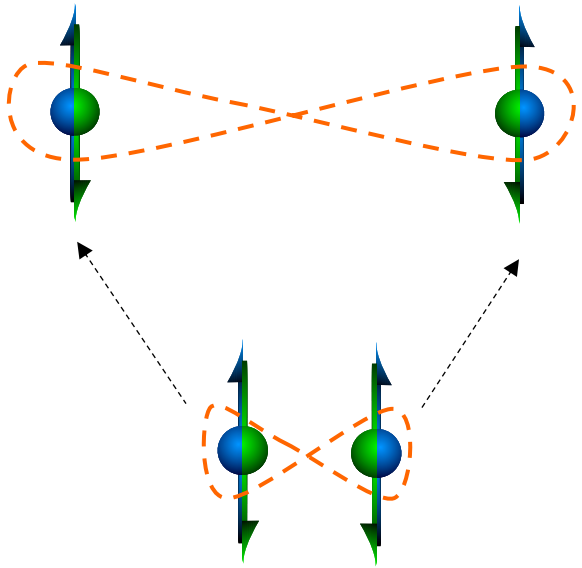
$$S = 2.221 \pm 0.033$$

$$p < 2.57 \cdot 10^{-9}$$

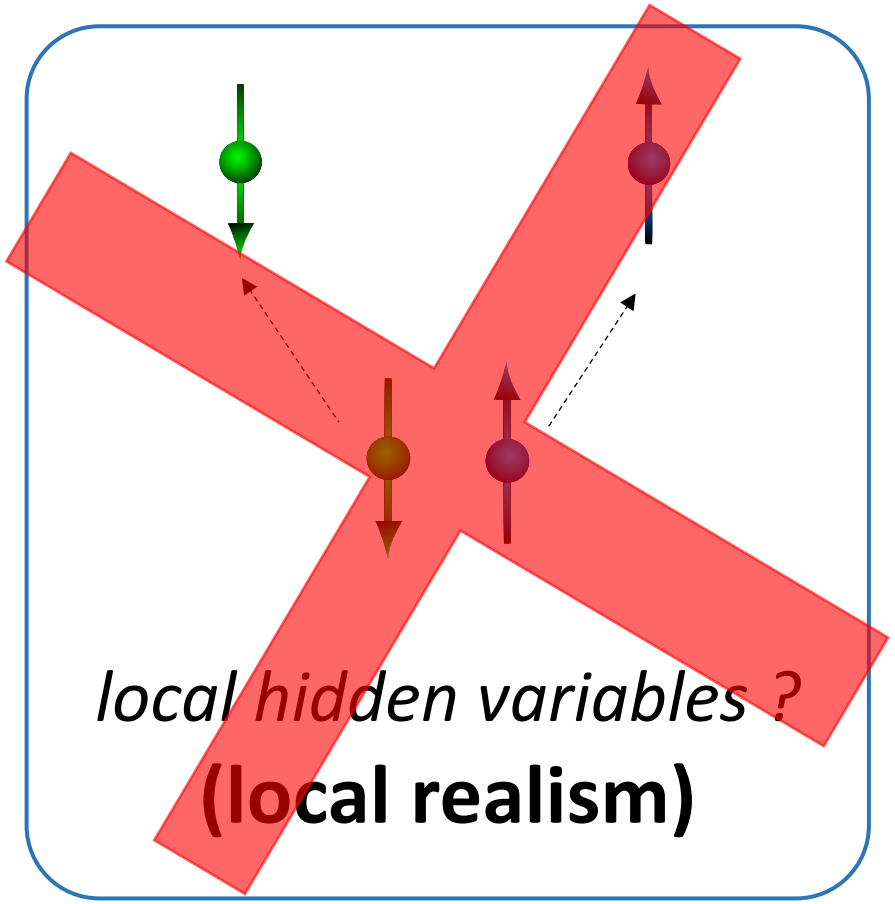
5000 events during 4 days!

« Death by experiment of local realism »

Wiseman, *Nature* ***526*** (2015)



Quantum non-locality ?



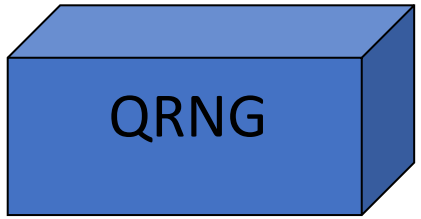
local hidden variables ?

(local realism)

What is next?

True randomness? True free-will?

measurements settings chosen by



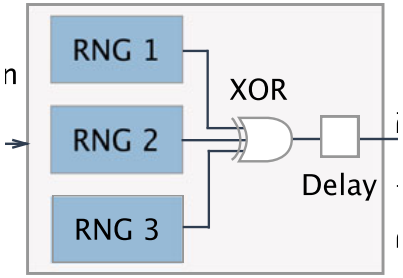
quantum random number generator ?

or human choice?

or combine them?

the NIST loophole-free Bell test

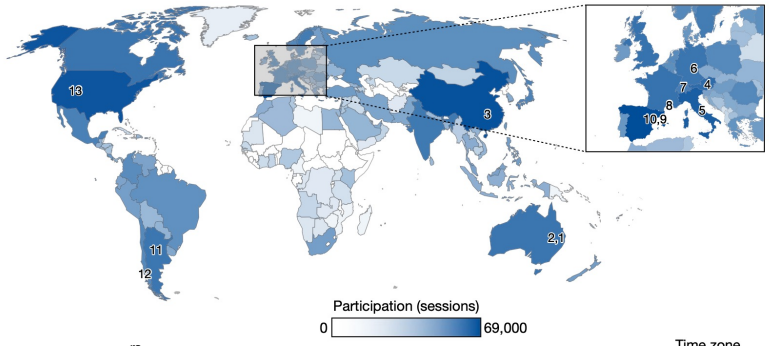
Shalm et al., *PRL* **115** (2015)



settings chosen by humans with online game

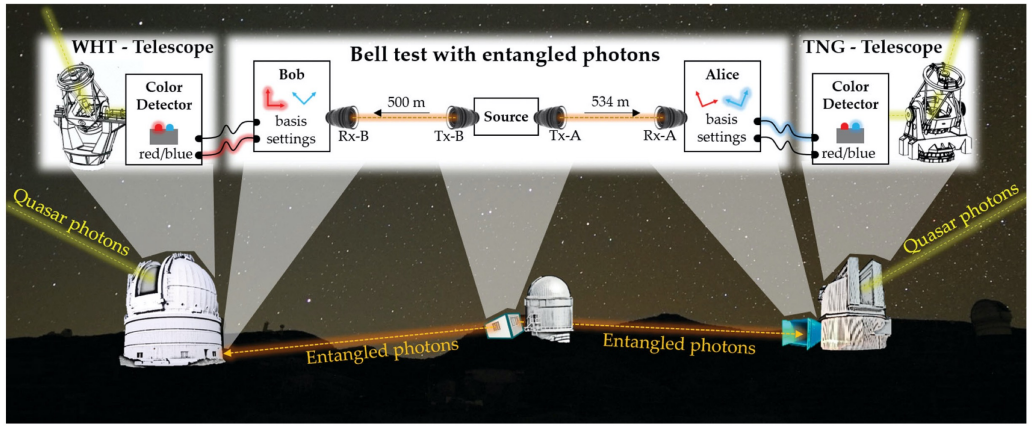
the Big Bell test

Abellan *et al.*, *Nature* **557** (2018)



settings chosen by quasars billions of years ago

Rauch *et al.*, *PRL* **121** (2018) – (Zeilinger's group)

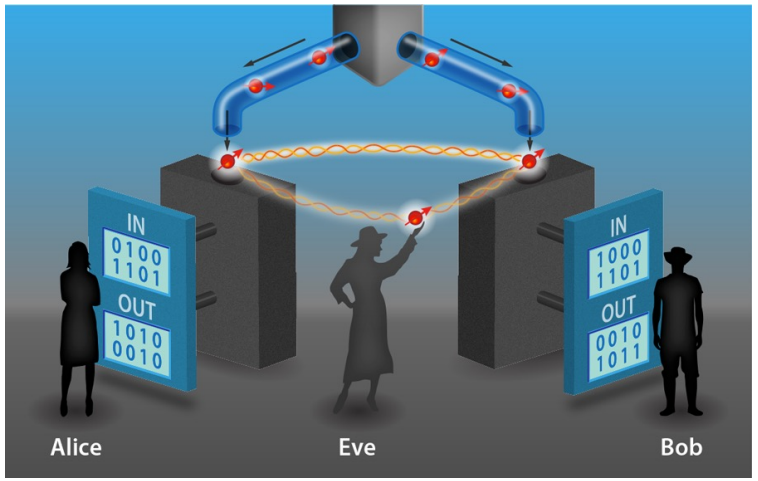


Applications of Bell tests

⇨ Applications : device-independent protocols

→ randomness expansion Pironio *et al.*, *Nature* **464** (2010)

→ quantum key distribution Acín *et al.*, *PRL* **98** (2007)



Colbeck, *Physics* **7** (2014)

⇨ towards quantum networks…