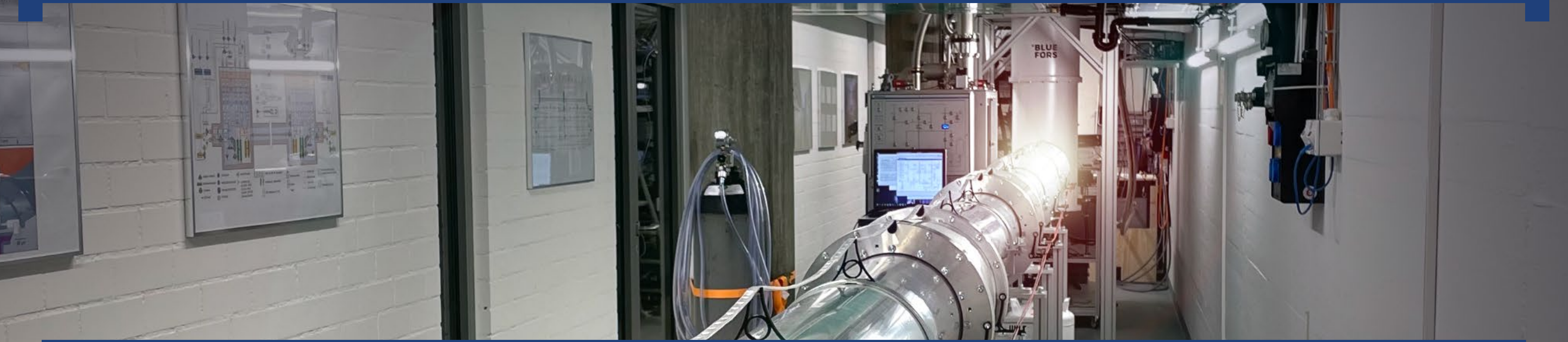
S. Storz *et al.*, *Nature* **617**, 265-270 (2023)

S. Storz *et al.*, *Nature* **617**, 265-270 (2023)



Loophole-free Bell Inequality Violation with Superconducting Circuits

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IARPA BE THE FUTURE

SuperQuLAN

FNSNF SWISS NATIONAL SCIENCE FOUNDATION

QSIT Quantum Science and Technology National Centre of Competence in Research

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ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich
FNSNF Swiss National Science Foundation
QSIT Quantum Science and Technology – National Centre of Competence in Research
QED Circuit and Cavity Quantum Electrodynamics
erc
Seventh Framework Programme
SOLID
aqute
GEOMDISS
scaleQIT

Bell Test: Foundations

- Quantum mechanics does not follow the principle of local causality
  A. Einstein, B. Podolsky, N. Rosen, Phys. Rev., 47(10):777-780 (1935)
  N. Brunner et al., Rev. Mod. Phys **86**(2) 419--478 (2014)

- Bell, 1964: This property can be tested experimentally
  J.S. Bell, Physics 1:195 (1964)

- A Bell test / non-locality is an important resource in *device-independent* quantum information processing
  - Independent verification of quantum devices and networks
  - Secure communication (quantum key distribution)
    U. Vazirani and Thomas Vidick, *Phys. Rev. Lett* 113:140501 (2014)
  - Production of certified random bits
    R. Colbeck, PhD thesis, University of Cambridge (2009)
    S. Pironio *et al.*, *Nature* **464**(7291) (2010)
    R. Colbeck and R. Renner, *Nat. Phys. 8(6):450-454* (2012)
    M. Kessler and R. Arnon-Friedman, IEEE Journal on Selected Areas in Information Theory, **1** no.2, 568-584 (2020)

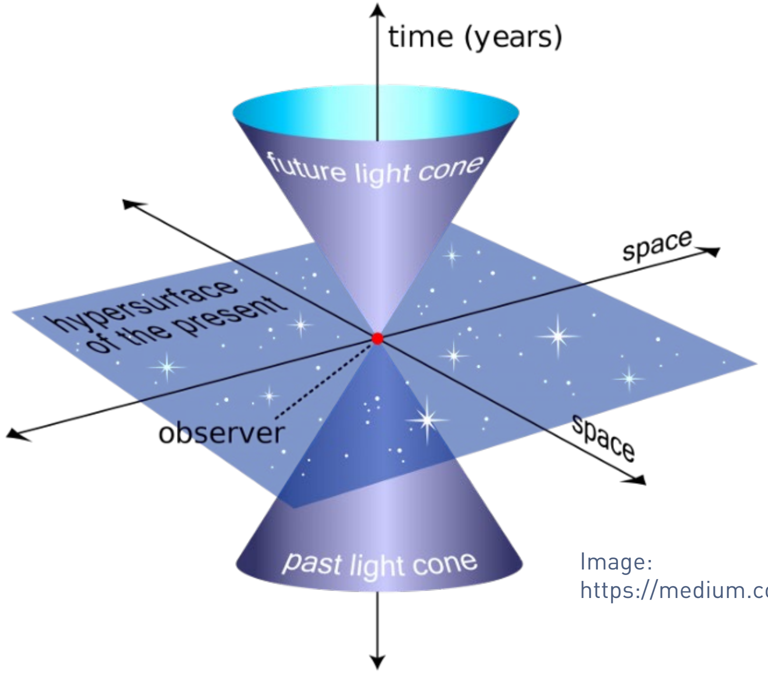


Image: https://medium.com/@felipehime

Locality: Events can only be influenced by actions in their past light-cone

Bell Test Protocol

Alice and Bob …

1. … prepare a shared non-local entangled state $|\psi^+\rangle = \frac{|g,g\rangle+|e,e\rangle}{\sqrt{2}}$
2. … randomly select local measurement bases $a, b \in \{0,1\}$
3. … read out state of qubits with local outcome $x, y \in \{1,-1\}$

- Repeat steps 1-3

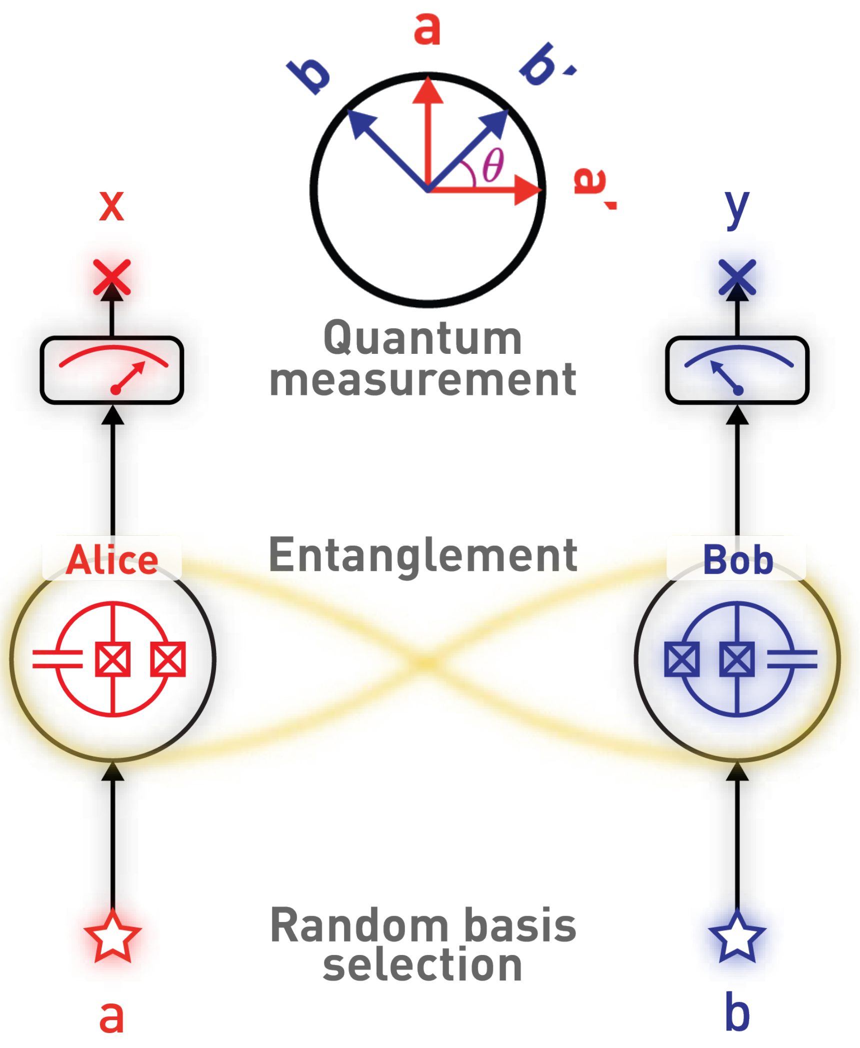
Calculate Clauser-Horne-Shimony-Holt S-value
J.F. Clauser et al., Phys. Rev. Lett., **23** 880-884, (1969)
from two qubit correlators xy with randomly selected basis a,b

$$\langle x \cdot y \rangle_{(\mathrm{a,b})}$$

$$S_{\mathrm{CHSH}} = \langle x \cdot y \rangle_{(0,0)} - \langle x \cdot y \rangle_{(0,1)} + \langle x \cdot y \rangle_{(1,0)} + \langle x \cdot y \rangle_{(1,1)}$$

Expect Bell inequality violation for entangled quantum systems

$$S_{\mathrm{CHSH}} > 2$$



Closing Loopholes

The locality loophole

Perform experiments with space-like separation between the entangled qubits being measured and the events defining the basis choice.
N. Brunner et al., Rev. Mod. Phys. **86**, 419-478 (2014)

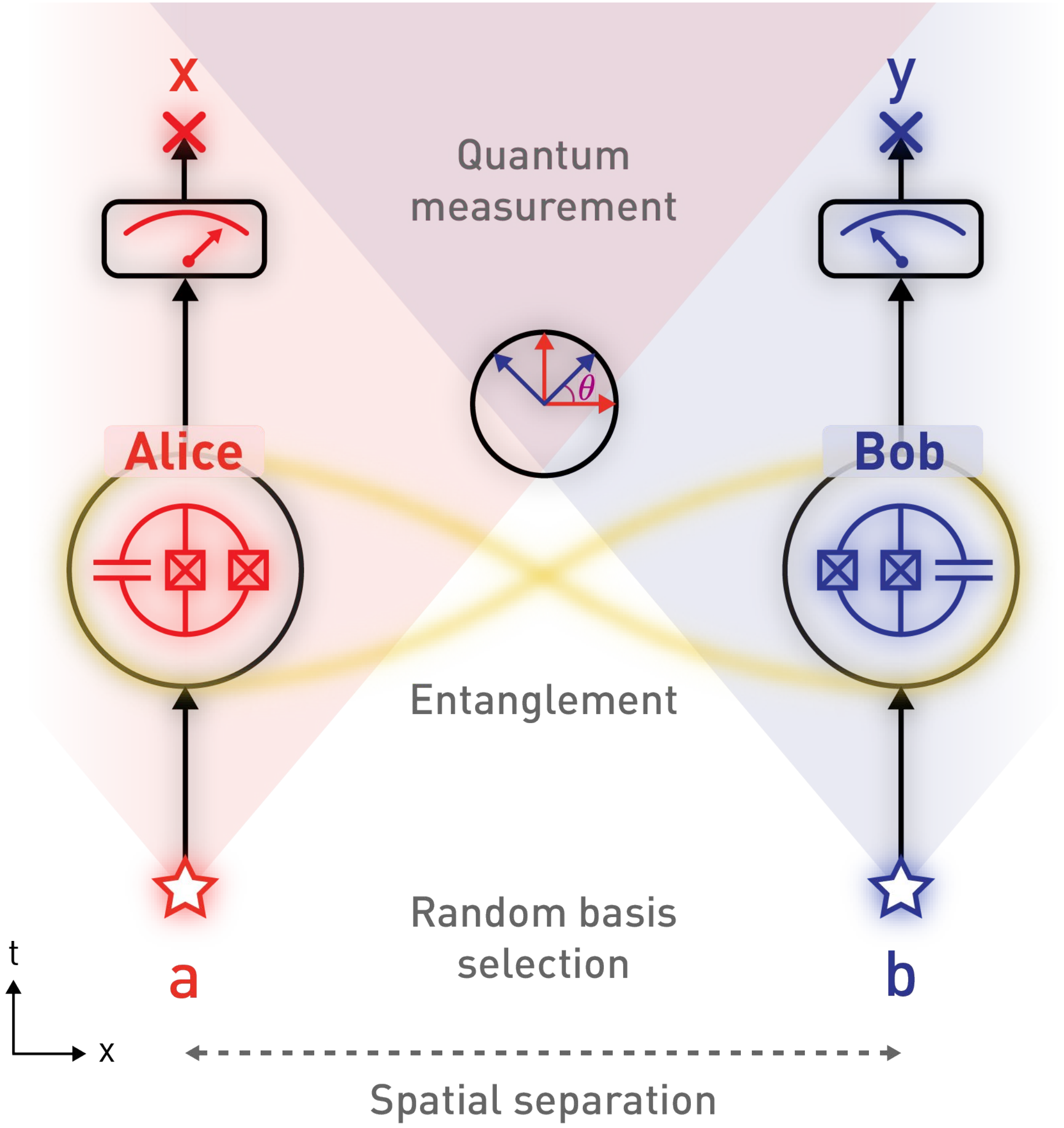
The detection loophole

Measure each and every Bell-pair created.
A. Garg et al., Phys. Rev. D **35,** 3831-3835 (1987)
H. Philippe Phys. Rev. A, **47**, R747-R750 (1993)

Freedom-of-choice loophole or **Measurement independence**

Choose measurement basis statistically independent from the qubits and their measurement devices.
J. S. Bell et al., Cambridge University Press, 2 edition, (2004)

S. Storz *et al., Nature* **617**, 265-270 (2023)



A Progression of Bell Test Experiments

A selection of **first experiments**

1972: S. J. Freedman, J. F. Clauser, PRL 28:938-941

1982: A. Aspect et al., PRL 49(25):1804-1807

1982: A. Aspect et al., PRL 49:91-94

→ relied on additional assumptions (were subject to loopholes)

Many steps taken towards successively closing loopholes

See review: A. Aspect, Closing the Door on Einstein and Bohr's Quantum Debate, Physics 8, 123 (2015).

Planning of a loophole-free experiment with superconducting circuits

2012: At ETHZ; European Research Council (ERC) Advanced Grant (**Superconducting Circuits**)

Successful loophole-free Bell test experiments

2015: B. Hensen et al., Nature 526:682-686 (**NV Centers**)
M. Giustina et al., PRL 115:250401 (**Photons**)
L. Shalm et al., PRL 115:250402 (**Photons**)

2017: W. Rosenfeld et al., PRL 119, 010402 (**Neutral atoms**)

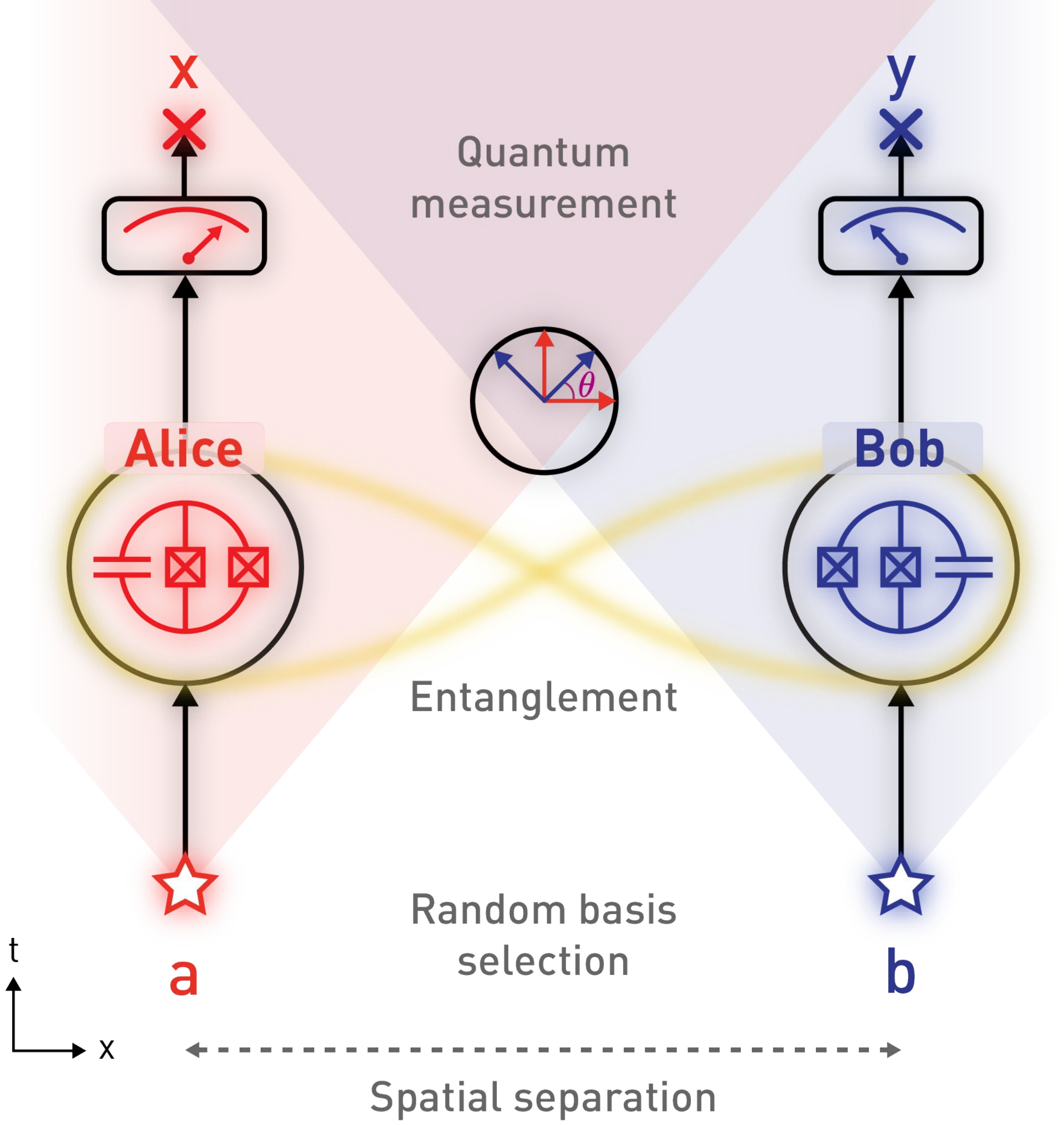
2018: M. Li et al., PRL 121, 080404 (**Photons**)

Requirements for a Successful Experiment ...

... with **superconducting circuits:**

- **Reach $|S_{CHSH}| > 2$**
  - high-fidelity entanglement
  - high-fidelity readout of qubits
- **Measurement independence**
  - Choose input bits using random number generators
- **Close detection loophole**
  - Use result of each and every measurement run
- **Close locality loophole**
  - Realize space-like separation between A and B
    - Readout: ~ 50 ns
    - Basis choice: ~30 ns
    - Margin & propagation: ~20 ns
    - Total: ~100 ns

    → **30 m** separation between qubits



S. Storz *et al.*, *Nature* **617**, 265-270 (2023)

Requirements on Entanglement Fidelity and Readout

Maximum observable S_{CHSH} value is limited by readout fidelity F_r and entanglement concurrence C

W. K. Wootters et al., Phys. Rev. Lett. 80, 2245-2248 (1998)

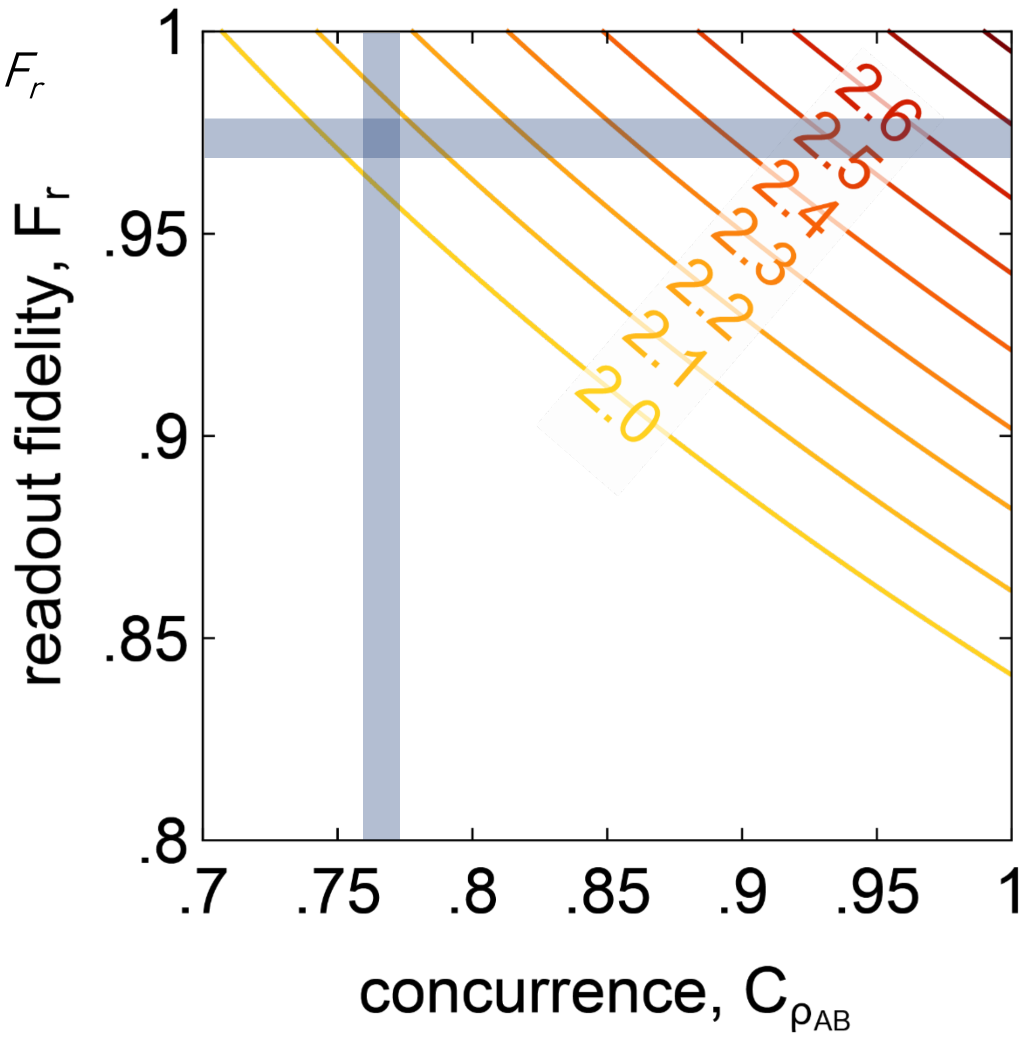
R. Horodecki et al., Physics Letters A 200, 340-344 (1995)

$$S_{CHSH}^{max} = 2\sqrt{2}\mathcal{F}_{\mathrm{r}}^{2}\mathcal{C}(\rho_{\mathrm{AB}})$$

$S_{CHSH} > 2$ can be realized with available devices

P. Magnard et al., Phys. Rev. Lett. **125**, 260502 (2020)

- Concurrence of Bell state $\mathcal{C}(\rho_{\mathrm{AB}}) \sim 0.76$
- 50-ns-long single-shot readout with fidelity $\mathcal{F}_{\mathrm{r}} \sim 0.98$



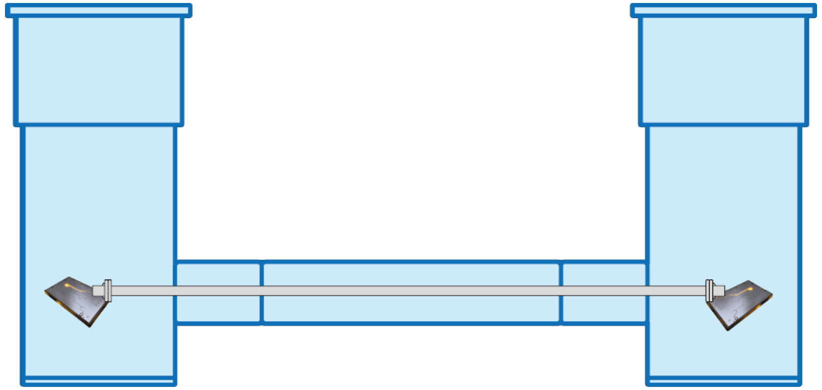
S. Storz *et al.*, *Nature* **617**, 265-270 (2023)

How to close the locality loophole with superconducting circuits?

Quantum Link between two Millikelvin Cryostats

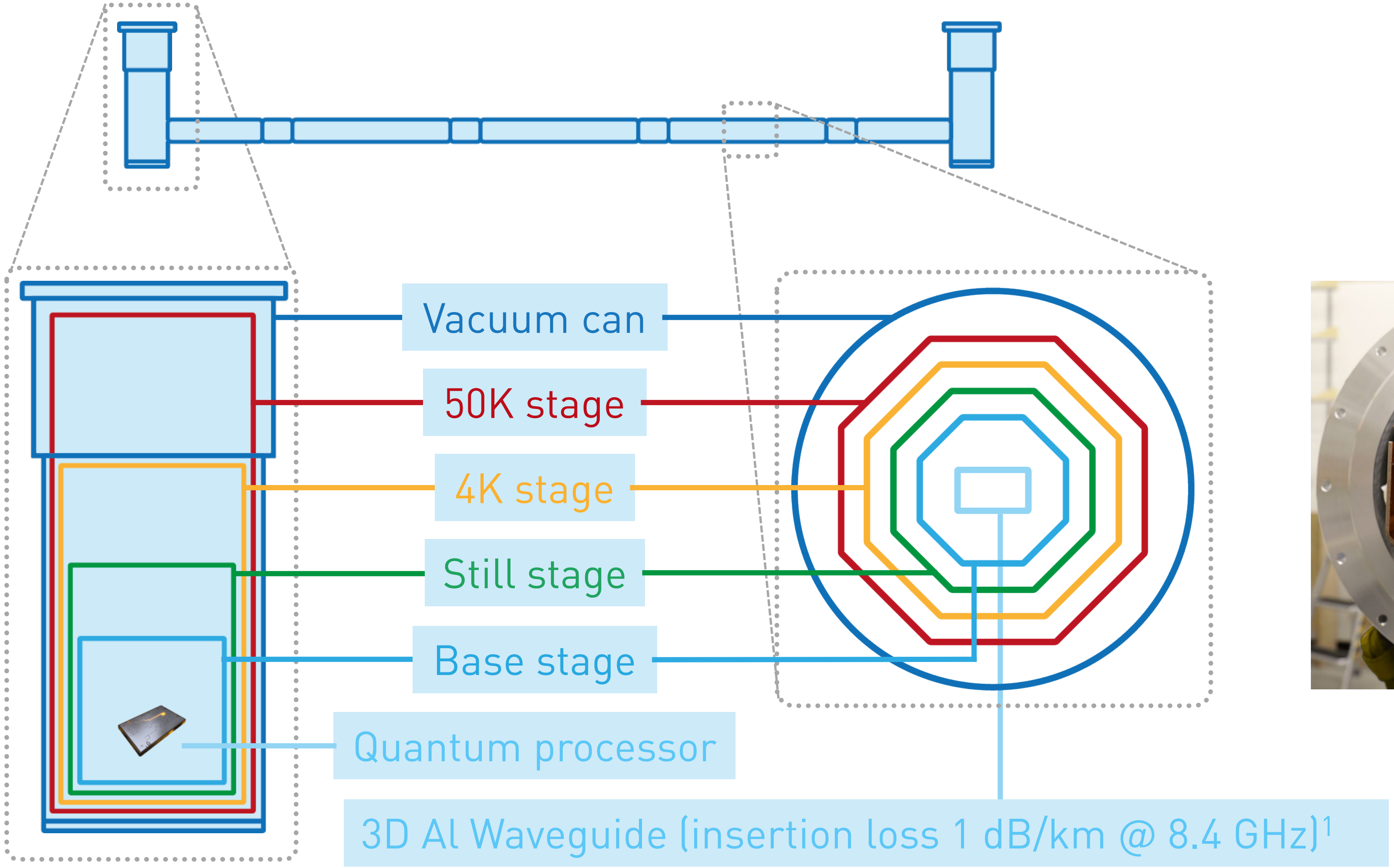
Desired Features

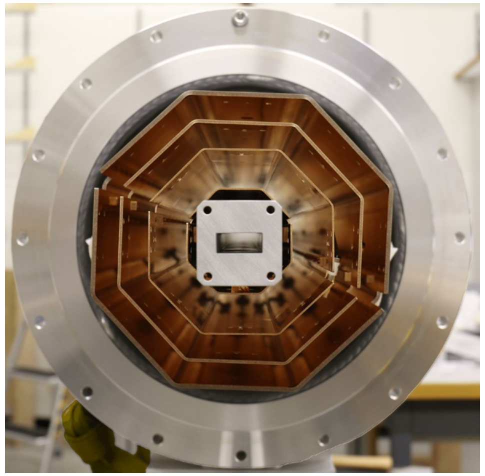
- Operates at microwave frequencies
  - Through a waveguide or coaxial cable
  - Compatibility with existing gates and protocols
- Operates at mK temperatures (just like on-chip quantum bus)
  - Uses low-loss waveguide (as low as telecom fiber)
    P. Kurpiers et al., *EPJ Quantum Technology* **4**, 8 (2017)
  - No thermal background
- Short cool down time
  - Similar to standard dilution refrigerators (1-2 days)
- Extensible solution
  - Modular design



P. Magnard *et al., Phys. Rev. Lett.* **125**, 260502 (2020)

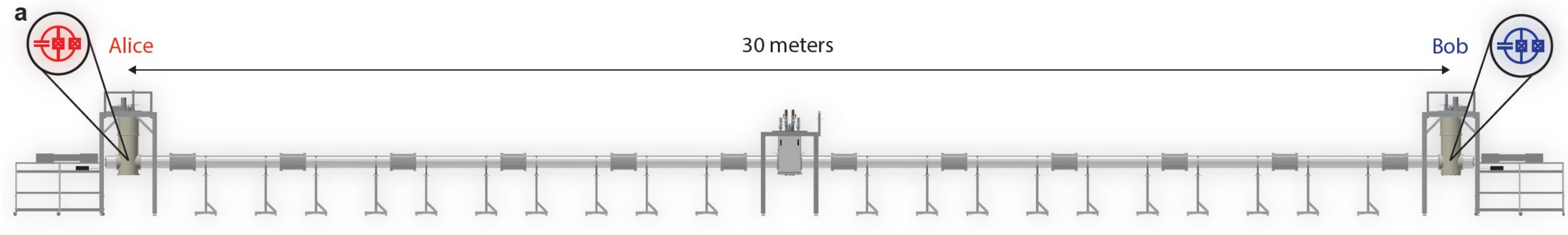
Concept for Realizing a Cryogenic Microwave Quantum Link





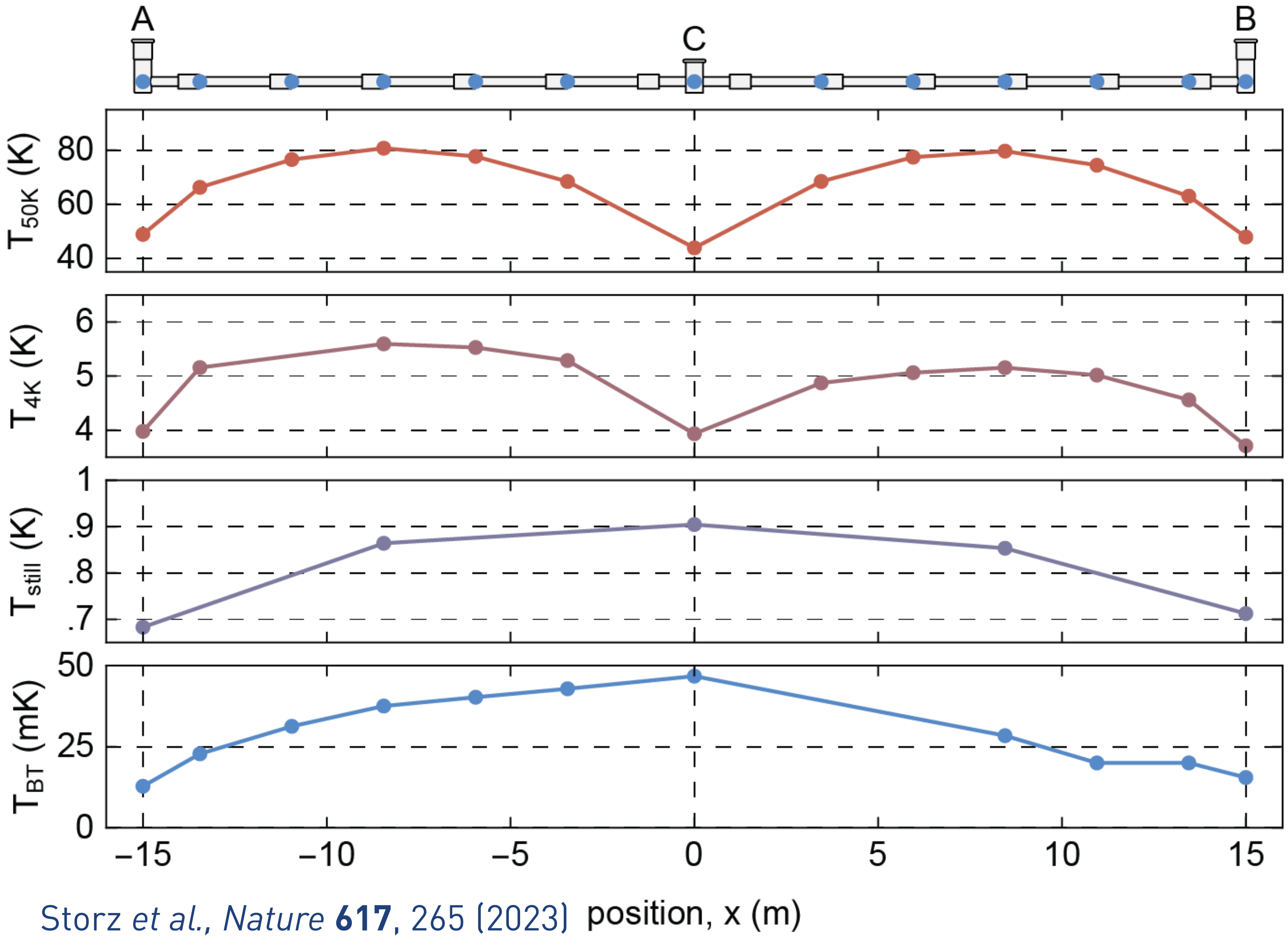
P. Magnard *et al.*, *Phys. Rev. Lett.* **125**, 260502 (2020)
P. Kurpiers *et al.*, *EPJ Quantum Technology* **4**, 8 (2017)

30-Meter-Long Cryogenic Microwave Quantum Link



S. Storz *et al.*, *Nature* **617**, 265-270 (2023)

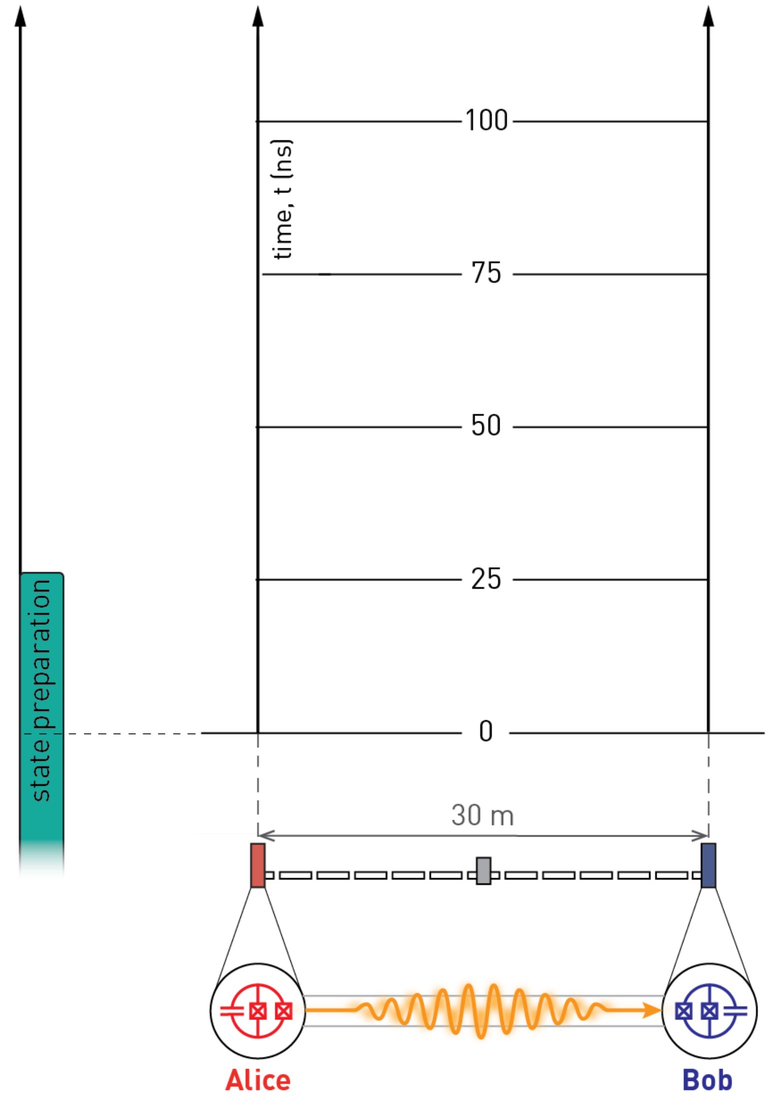
Temperature Profile of 30-m Cryogenic Link



Storz *et al.*, *Nature* **617**, 265 (2023)

- Heat flows from center towards cooling nodes
- Cooling power, heat load (thermal radiation) and thermal conductivity set the temperature profile
- Overall, only small temperature gradients
- Base temperature < **50 mK**
- Cool down time ~ **7 days**
- Quantum communication demonstrated with 5 m system P. Magnard *et al.* PRL **125**, 260502 (2020) and 30 m system

Preparation for Bell Test: Entanglement Generation



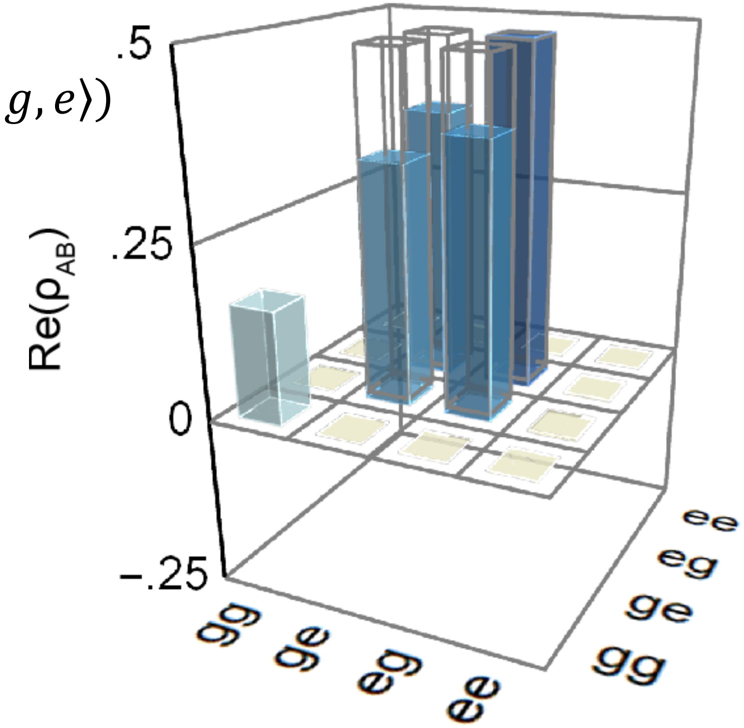
S. Storz *et al.*, *Nature* **617**, 265-270 (2023)

- Deterministic generation of remote entanglement
  P. Kurpiers *et al.*, *Nature* **558**, 264 (2018)
  J.I. Cirac *et al.*, *Phys. Rev. Lett* **78**, 3221-3224 (1997)
  M. Pechal *et al.*, *PRX* **4**, 041010 (2014)
  S. Zeytinoglu *et al.*, *PRA* **91**, 043846 (2015)

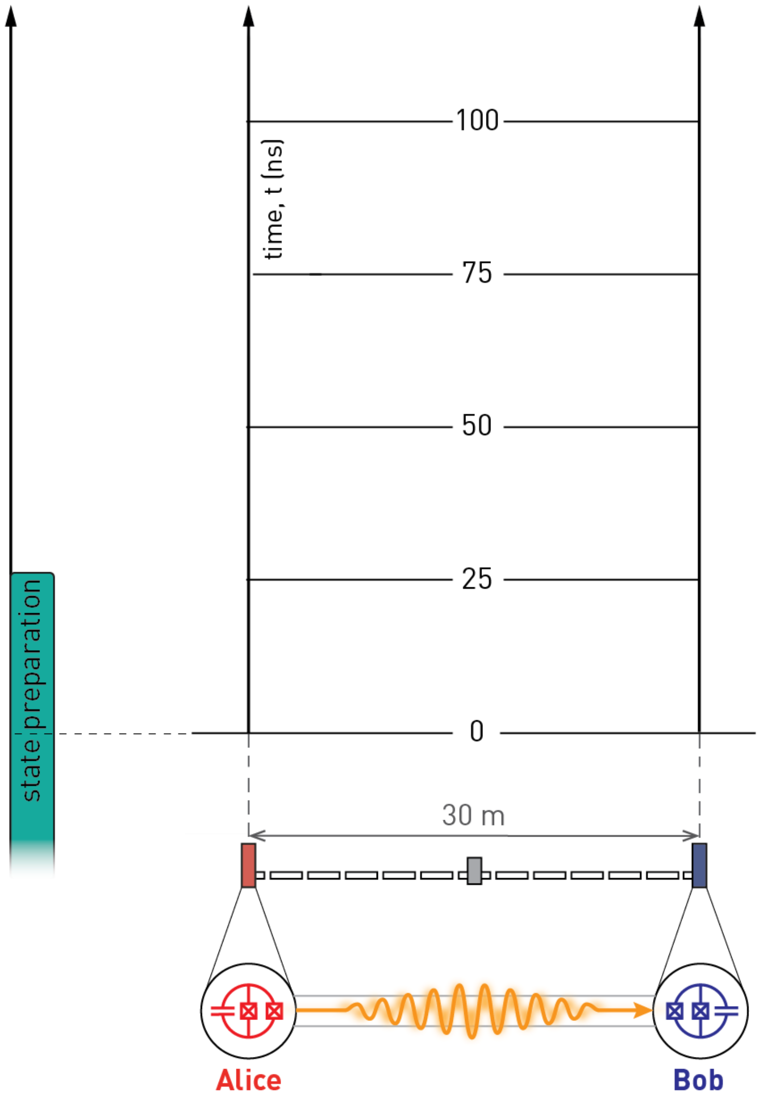
- Bell state $|\psi^+\rangle = \frac{1}{\sqrt{2}}(|e,g\rangle + |g,e\rangle)$

- Bell state fidelity: 80.4%

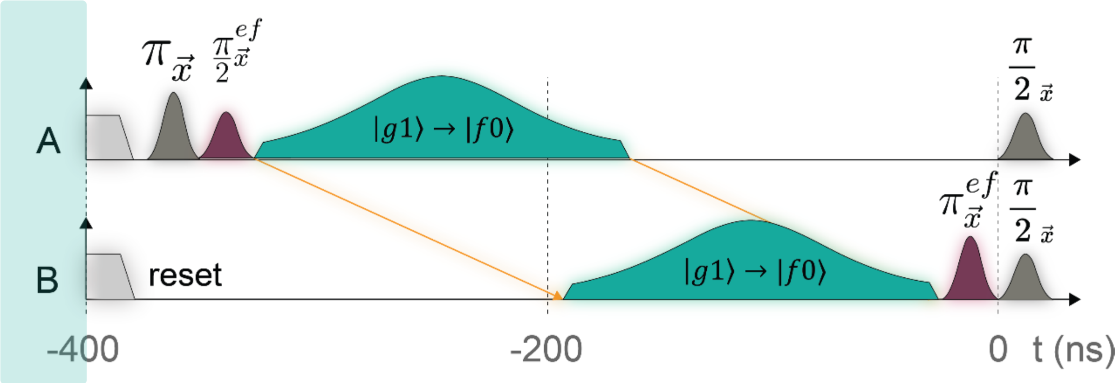
- Main source of infidelity: photon loss



Entanglement Generation: Pulse Sequence



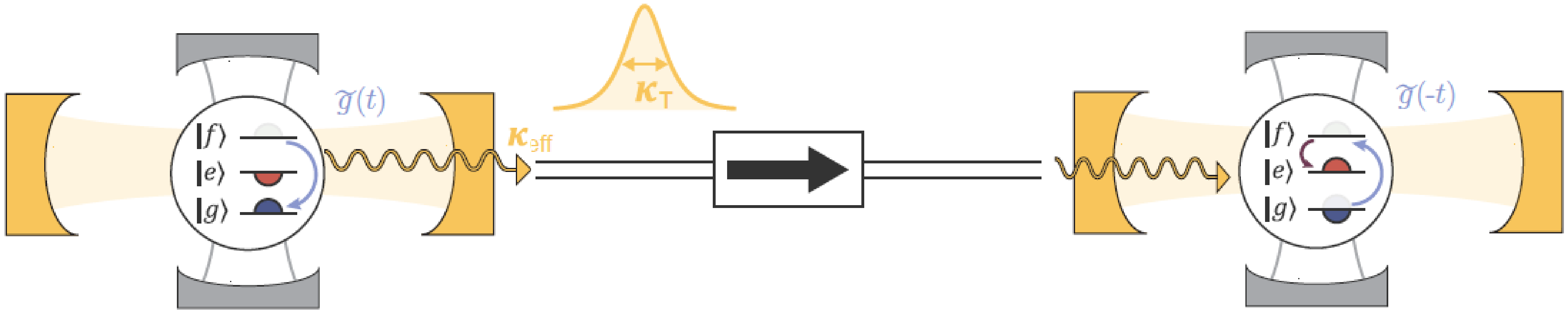
S. Storz *et al.*, *Nature* **617**, 265-270 (2023)



- Excite qubit A from g to e state
- Create superposition of e and f states
- Entangle qubit A with emitted photon
- Reabsorb photon and entangle with qubit B
- Map this state to $|\phi^+\rangle = \frac{1}{\sqrt{2}}(|g,g\rangle + |e,e\rangle)$

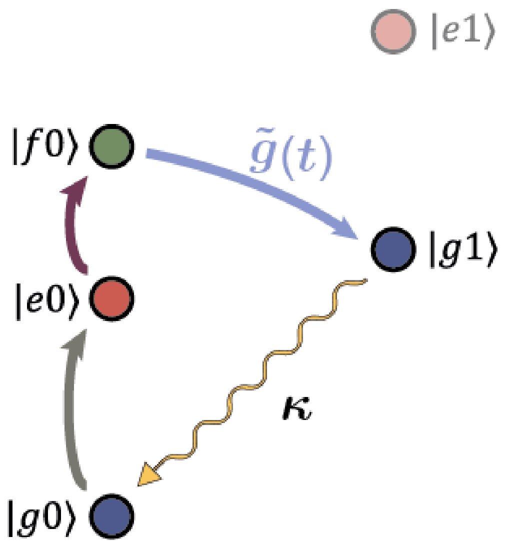
P. Kurpiers *et al.*, *Nature* **558**, 264 (2018)
J.I. Cirac *et al.*, *Phys. Rev. Lett* **78**, 3221-3224 (1997)

Generating Entanglement Between Remote Qubits



Emitter node:

- Qubit coupled to a transfer resonator
- Sideband transition
- $\tilde{g}(t) \rightarrow$ time-symmetric photon

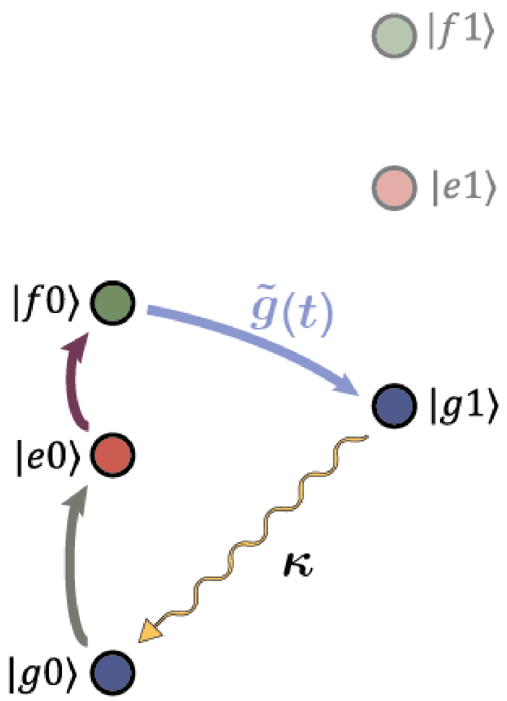


Receiver node:

- Identical chip
- Time-reversed drive $\tilde{g}(-t)$
- Unit absorption

I. Cirac *et al.*, PRL **78**, 3221 (1997)
P. Kurpiers*, P. Magnard* *et al.* Nature **558**, 264-267 (2018)

Time-Reversal Symmetric Photon Emission



$$H_{\mathrm{eff}} = \tilde{g}(t)|g,1\rangle\langle f,0| + h.c$$
$$\tilde{g}(t) \propto g\Omega(t)\, e^{i\phi}$$

Cavity QED

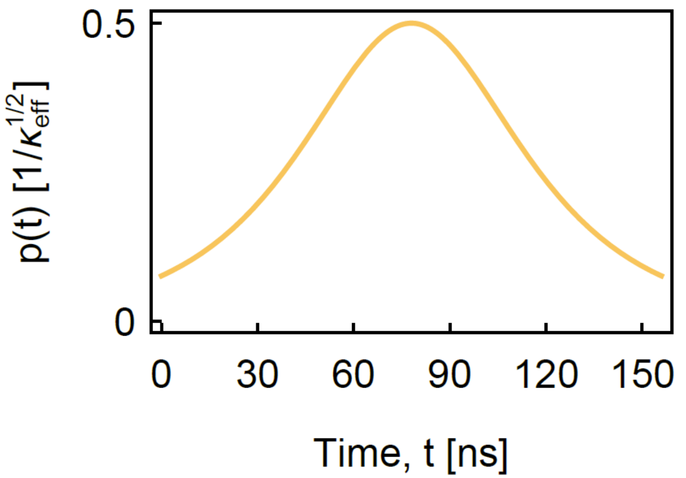
- Strong coupling
- Detuned dressed state level diagram

$|g,1\rangle$ population …

- … controls emission of shaped photon
- Amplitude and phase controled by drive $\tilde{g}(t)$
- All-microwave process
- Single photon emission enforced by trapping in dark state $|g,0\rangle$
- Stark-shift and Rabi-rate calibration is essential

- time-symmetric photon with envelope

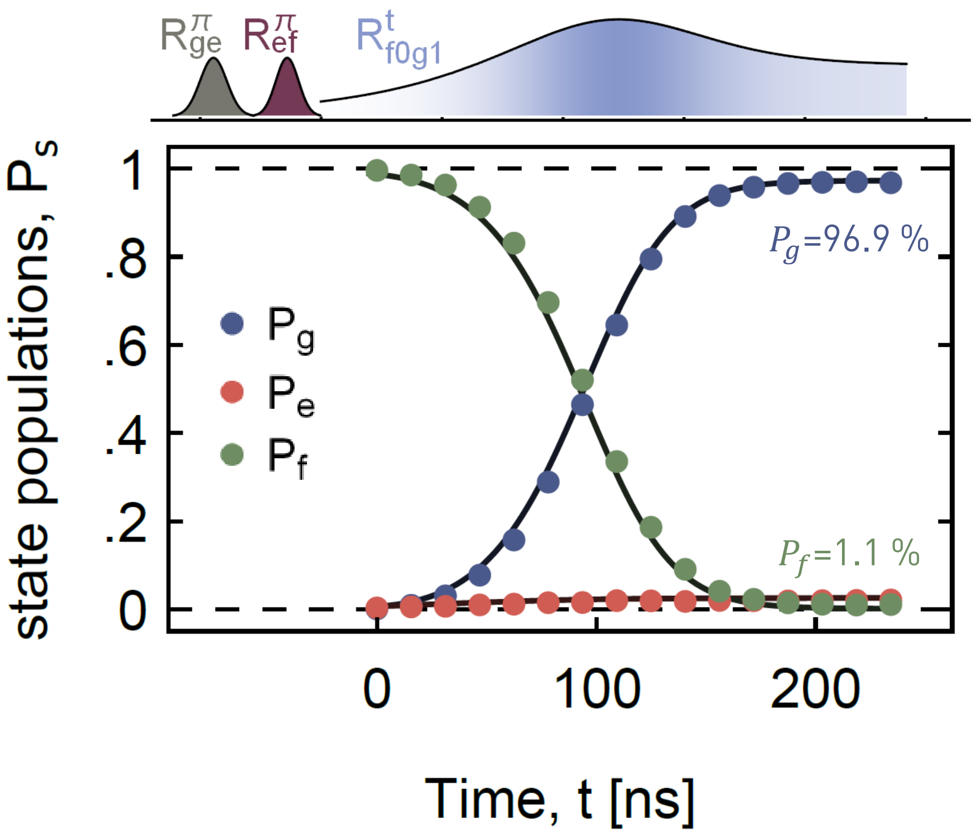
$$\frac{\sqrt{\kappa_{\mathrm{eff}}}}{2\cosh(\kappa_{\mathrm{eff}}\, t/2)}$$



M. Pechal *et al. Phys. Rev. X* **4**, 041010 (2014)
S. Zeytinoglu *et al., Phys. Rev. A* **91**, 043846 (2015)
P. Magnard *et al., Phys. Rev. Lett.* **121**, 060502 (2018)

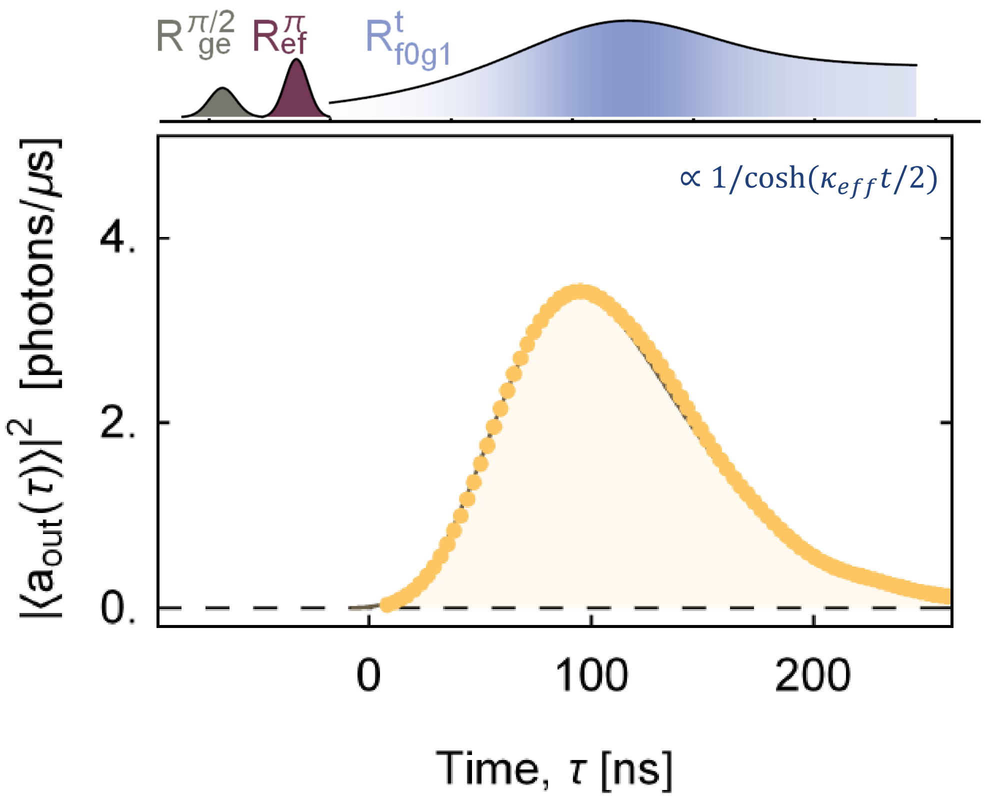
Example of Qutrit Population Dynamics upon Photon Emission

Qutrit population at node B:



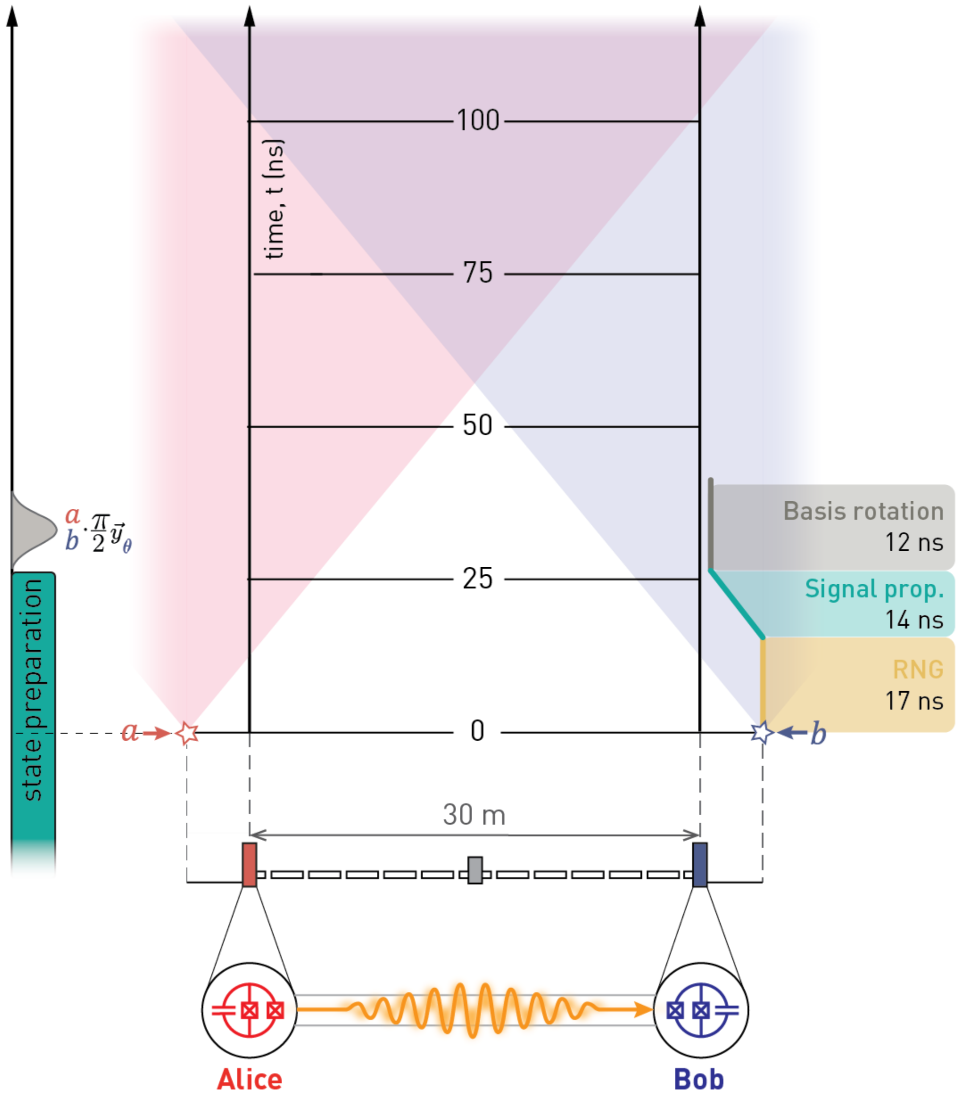
- Excellent agreement with master equation simulation

Envelope of emitted photon:



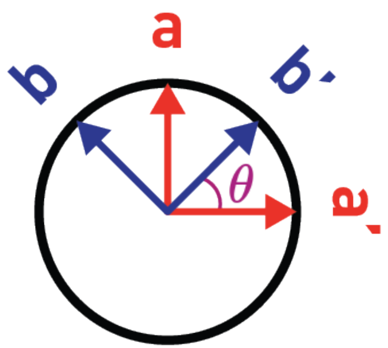
P. Kurpiers, P. Magnard *et al., Nature* **558**, 264 (2018)

Start of Bell Test: Random Basis Selection

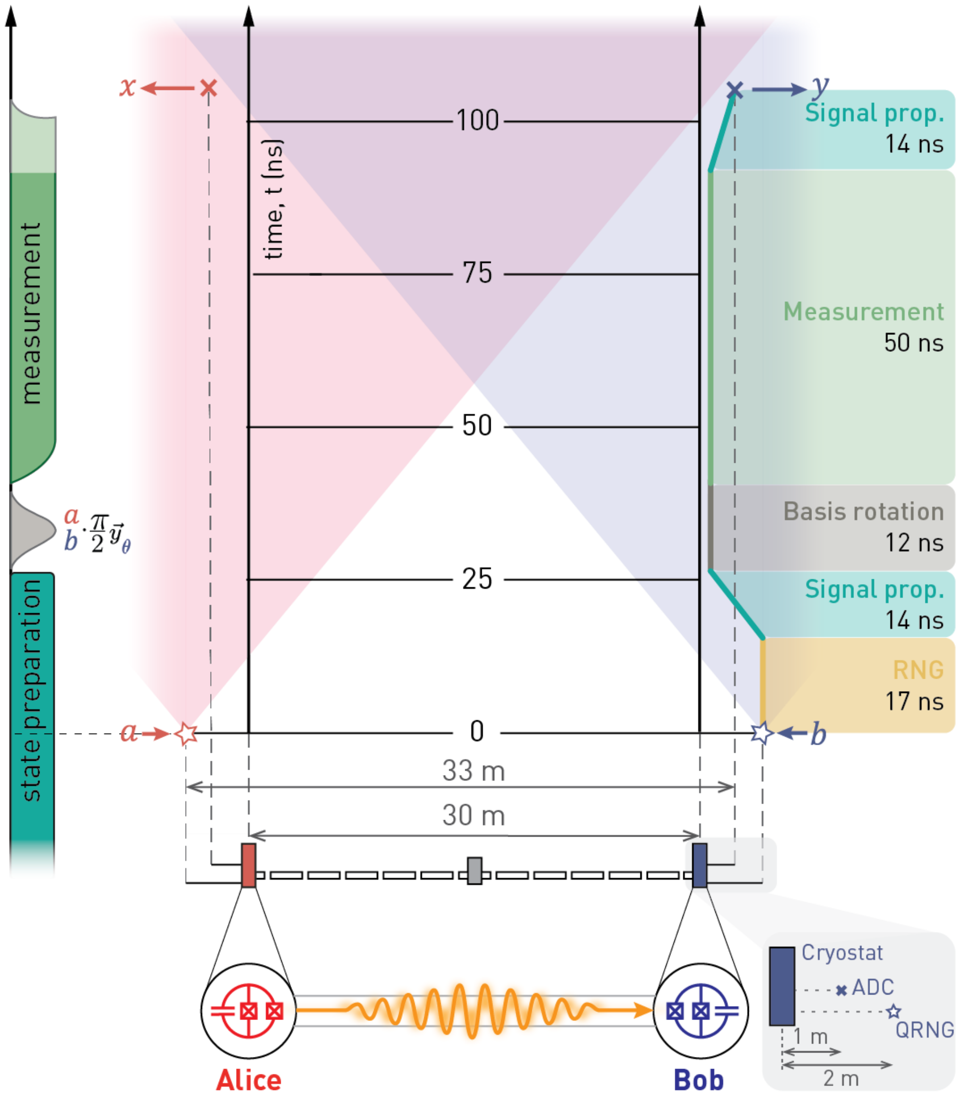


S. Storz *et al.*, *Nature* **617**, 265-270 (2023)

- Select input bits a,b using random number generators (bit generation time 17 ns)
  C. Abellan *et al., Phys. Rev. Lett. 115, 250403* (2015)
- a,b control the measurement basis choices
- Measurement basis choice is physically implemented using a microwave switch (signal propagation delay 14 ns) ...
- ... applying (or not) a $\pi/2$ pulse (duration of 12 ns) to the qubit



Finalizing the Bell Test: Qubit Readout



S. Storz *et al.*, *Nature* **617**, 265-270 (2023)

- Perform single-shot qubit readout
  - ... in 50 ns
  - ... with high readout fidelity 98%
    T. Walter *et al.*, *Phys. Rev. Applied* 7, 054020 (2017)
- Record readout signal with ADC (propagation delay 14 ns)
- Assign integrated readout signal to local measurement outcome at each qubit,
  either
  $|g > \rightarrow x = +1$
  or
  $|e > \rightarrow x = -1$

Reminder: Bell Test Protocol

Alice and Bob …

1. … prepare a shared non-local entangled state $|\psi^+\rangle = \frac{|g,g\rangle+|e,e\rangle}{\sqrt{2}}$
2. … randomly select local measurement bases $a, b \in \{0,1\}$
3. … read out state of qubits with local outcome $x, y \in \{1,-1\}$

- Repeat steps 1-3

Calculate Clauser-Horne-Shimony-Holt S-value
J.F. Clauser et al., Phys. Rev. Lett., 23(15):880-884, Oct 1969
from two qubit correlators xy with randomly selected bases a,b

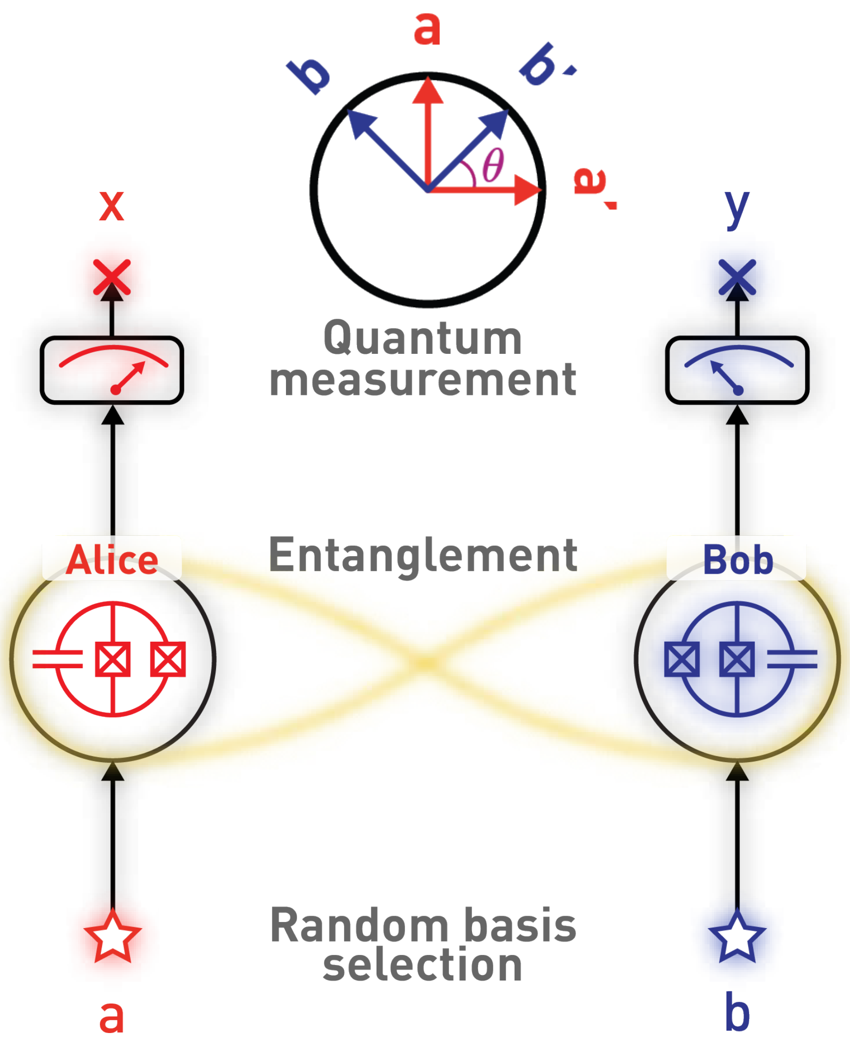
$$\langle x \cdot y \rangle_{(\mathrm{a,b})}$$

$$S_{\mathrm{CHSH}} = \langle x \cdot y \rangle_{(0,0)} - \langle x \cdot y \rangle_{(0,1)} + \langle x \cdot y \rangle_{(1,0)} + \langle x \cdot y \rangle_{(1,1)}$$

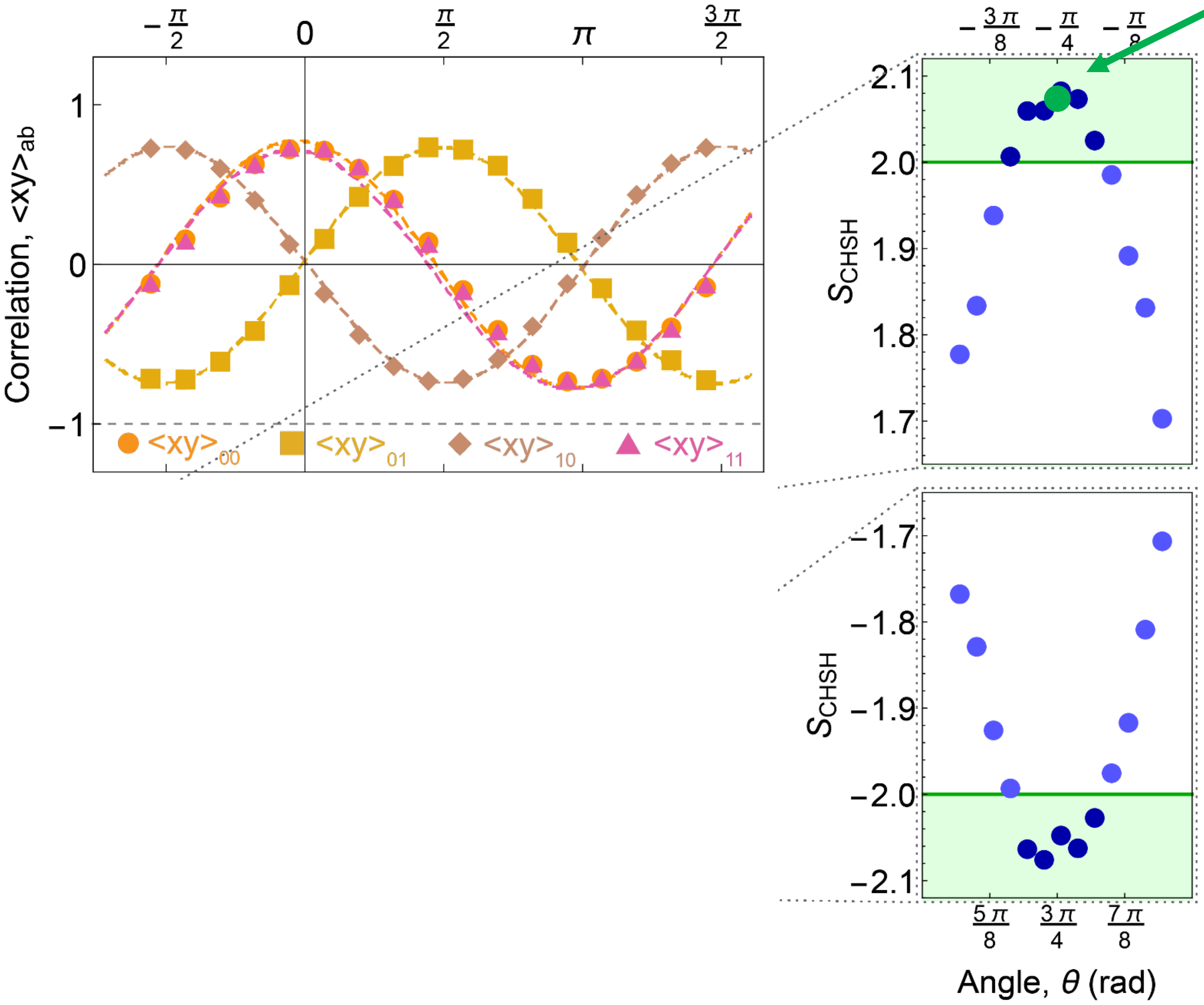
Expect Bell inequality violation for entangled quantum systems

$$S_{\mathrm{CHSH}} > 2$$

S. Storz *et al.*, *Nature* **617**, 265-270 (2023)



Experimental Results



S = 2.0747 +- 0.0033 **> 2**

- Determine correlators from msrmnts
  - Sinusoidal oscillations
  - Contrast slightly reduced from 1
- Calculate S_{CHSH}-value
  - Observe $S_{CHSH} > 2$
- Good agreement with Master equation simulation (- - -)
- Repeat experiment at maximum violation
- Perform experiment at optimal angle
  - 2^{20} ($\sim 10^6$) repetitions
- Violates Bell inequality by
  - 22 σ
  - p-value of $p = 10^{-108}$

S. Storz *et al.*, *Nature* **617**, 265-270 (2023)

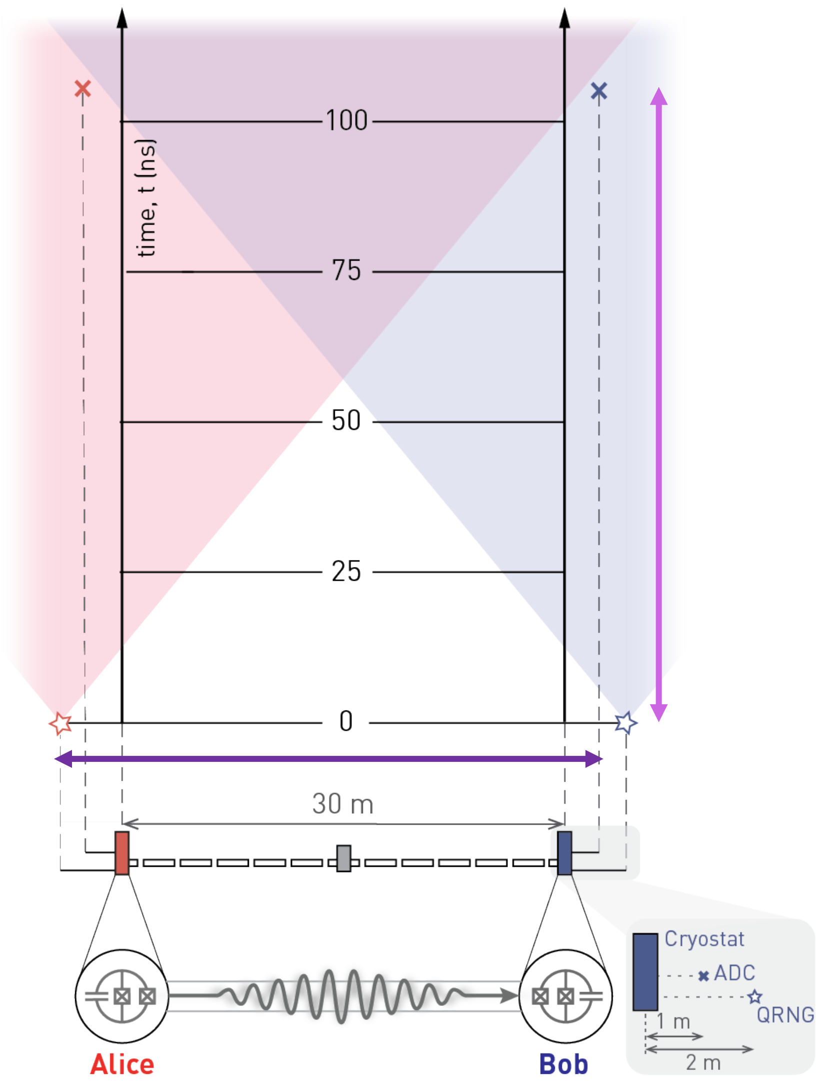
Addressing the Loopholes

Freedom-of-choice loophole
Closed by choosing measurement basis at random using RNGs

Detection loophole
Closed by taking into account each and every measurement result

Locality loophole
Closed by measurements of the space-time distance of the start & stop events:

Distance between start & stop events	= 32.824 ± 0.05 m
Time budget:	= 109.48 ± 0.02 ns
Protocol duration:	= 107.4 ± 0.25 ns
Margin:	= 2.08 ns
	→ 8σ (std. devs.)

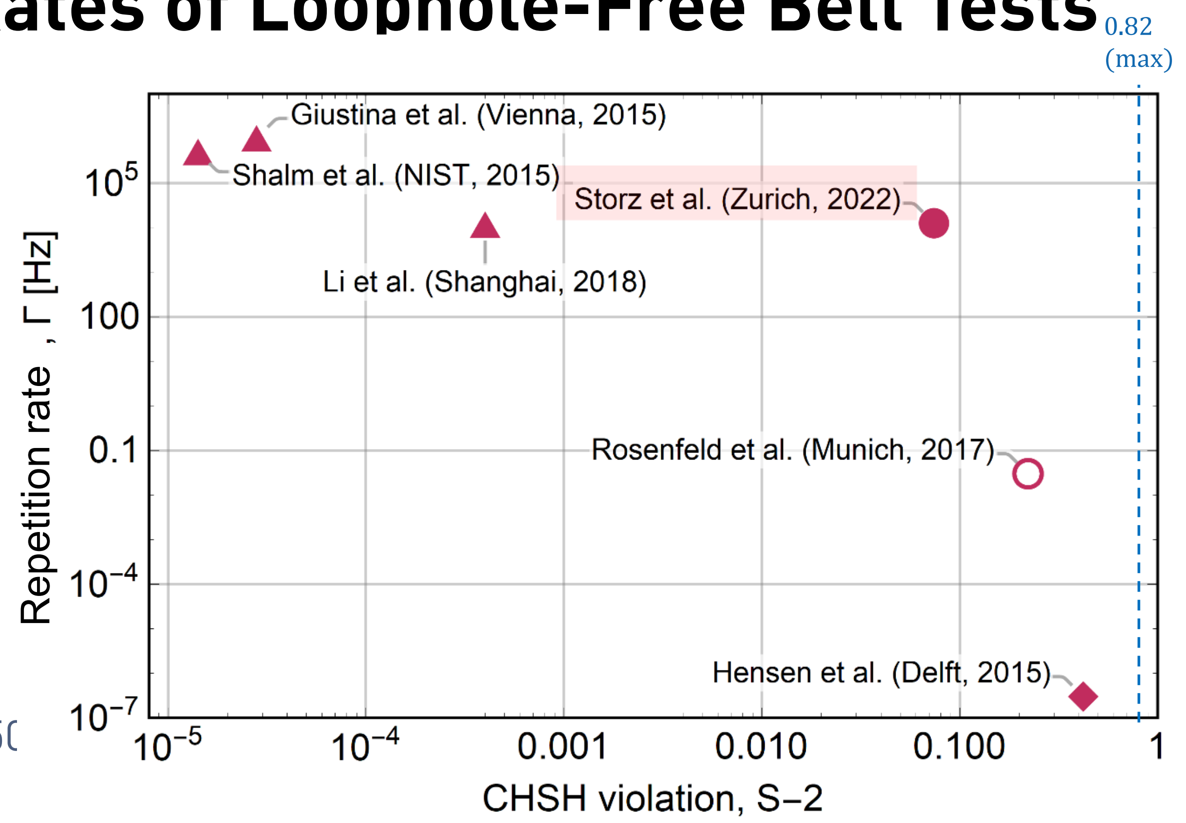


S. Storz *et al.*, *Nature* **617**, 265-270 (2023)

Bell Violation (S-2) and Repetition Rates of Loophole-Free Bell Tests

Comparison of **Bell tests** with
- **polarization-encoded photons** ▲
  High repetition rates, low S-value
- **NV-centers** ◆/ **neutral atoms** ○
  Low repetition rates, high S-value
- **superconducting circuits** ●
  Combination of high repetition rates *and* S-value

- **High rate** and **high violation** is interesting for implementation of device-independent QIP protocols
  - Quantum key distribution
    U. Vazirani and Thomas Vidick, *Phys. Rev. Lett* 113:1405(
  - Randomness generation
    R. Colbeck, *PhD thesis*, University of Cambridge (2009)
  - Randomness expansion
    S. Pironio *et al.*, *Nature* **464**(7291) (2010)
  - Randomness amplification
    R. Colbeck and R. Renner, *Nat. Phys. 8(6):450-454* (2012); M. Kessler and R. Arnon-Friedman, IEEE J. on Selected Areas in Information Theory, **1** no.2, 568-584 (2020)



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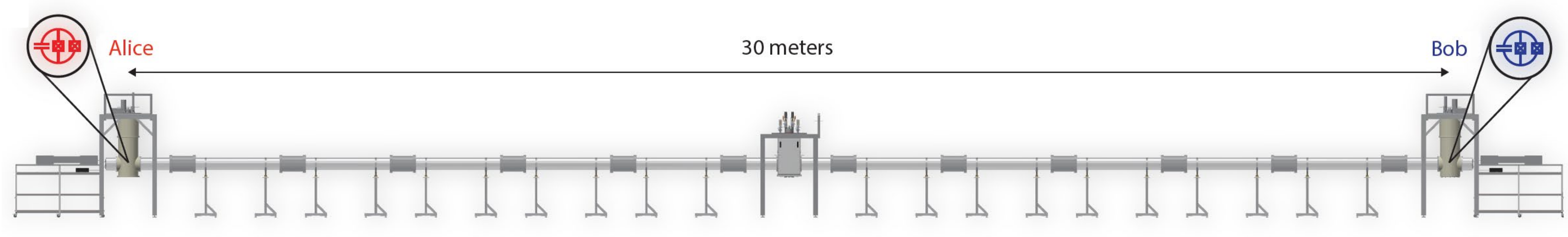
Potential Future Experiments



- Demonstrations of device independence
- Exploration of non-local physics

- Waveguide QED physics with 30-m line

- Demonstration of basic building blocks of a networked QC
- Realization of distributed quantum algorithms

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